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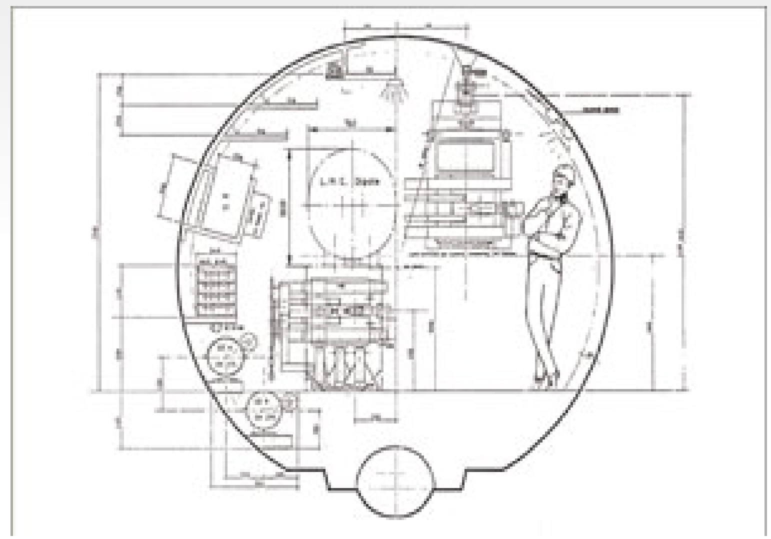
Atlas Collaboration


- The machine: why the LHC is a unique collider
- Characteristics of ATLAS and CMS
- Parton density functions and luminosity
- QCD physics
- Production of vector bosons and top
- Higgs boson
- Search for physics beyond SM

In the eighties, CERN built LEP, the large electron-positron collider, in a 26.6 km tunnel at average depth of 100m.

It was the largest civil-engineering project in Europe at that time.



Already in spring 1984 (5 years before LEP started operations!) a workshop was held on the possibility of building ”a Large Hadron Collider” in the LEP tunnel

At that time, the US was building a very ambitious hadron collider, the SSC in Texas.

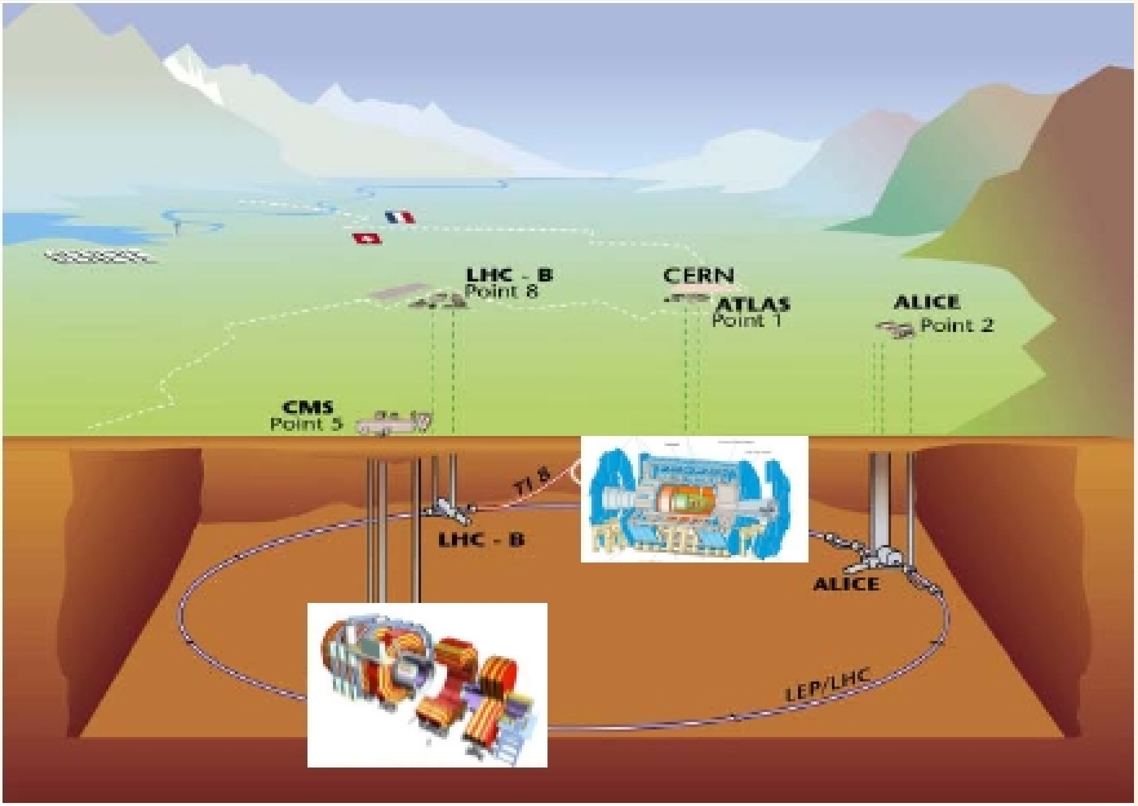
In 1993 the US congress canceled the SSC project due to budget cuts, the LHC was the only viable project for the energy frontier (and approved in 1994)



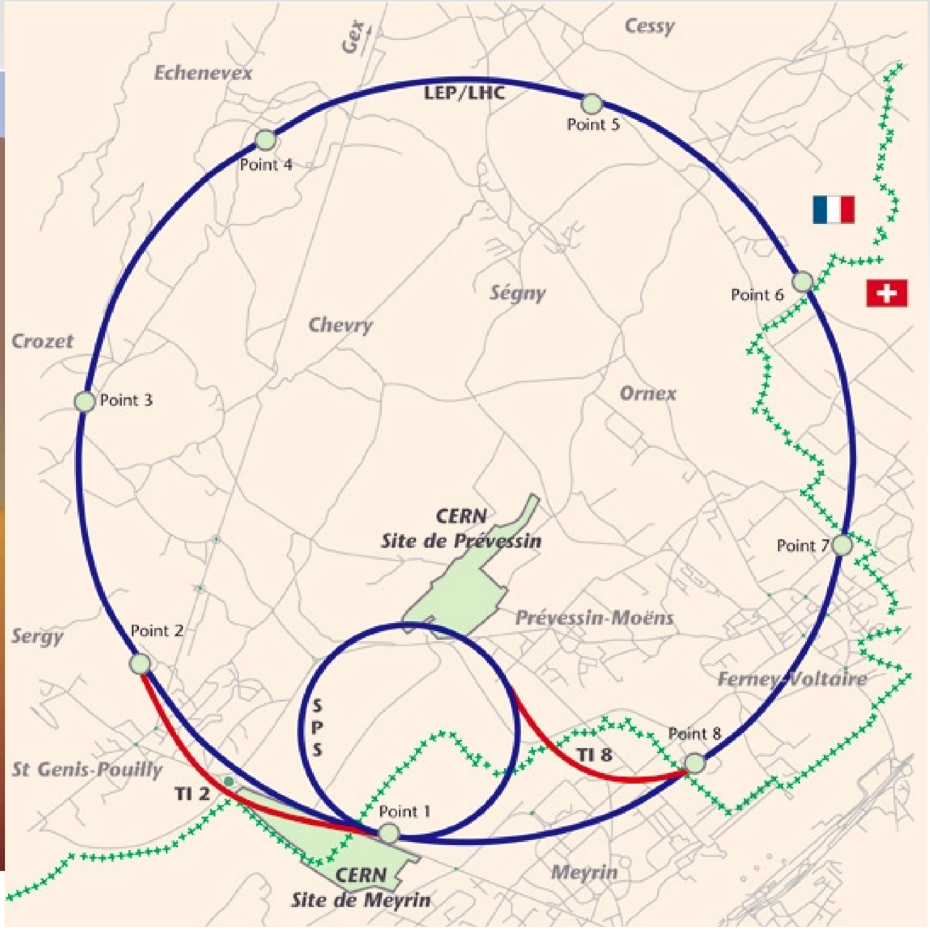
...maybe not so bad for our health...

The discussion on detectors was well under way, and after many merges ATLAS and CMS were approved in 1995


This is of course a joke... but this image (of a rock band of Cern secretaries active in the first 90es) was THE FIRST IMAGE EVER ON THE WEB



LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
TI 8
LHC - B
ALICE
LEP/LHC



Cessy
Gex
Echenevex
LEP/LHC
Point 5
Point 4
Point 6
Ségny
Chevry
Crozet
Ornex
Point 3
Point 7
CERN
Site de Prévessin
Prévessin-Moëns
Sergy
Point 2
Ferney-Voltaire
S
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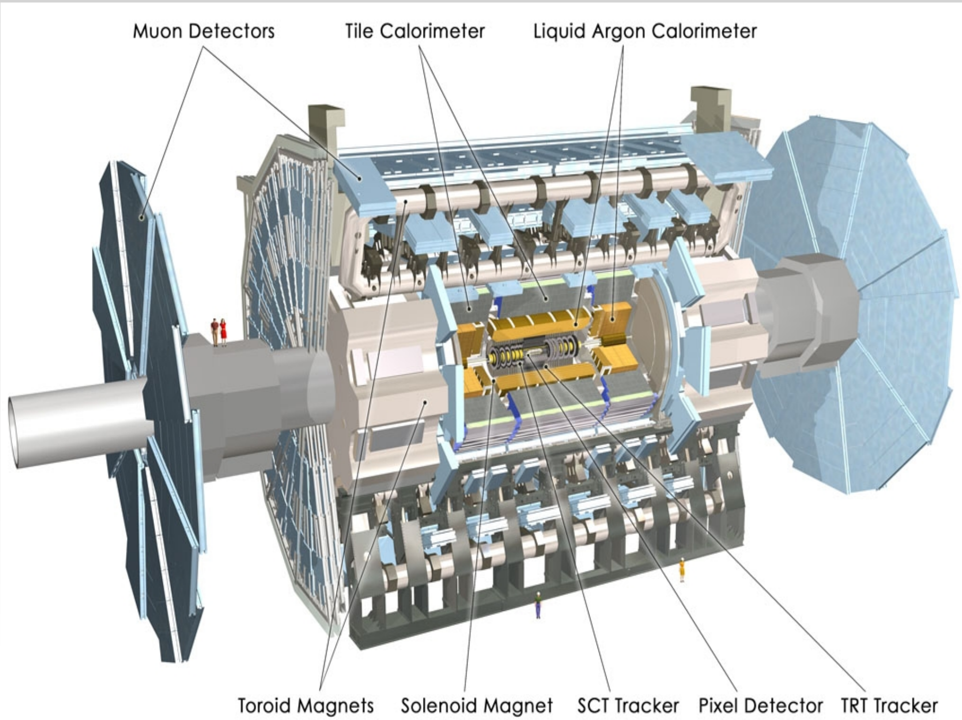
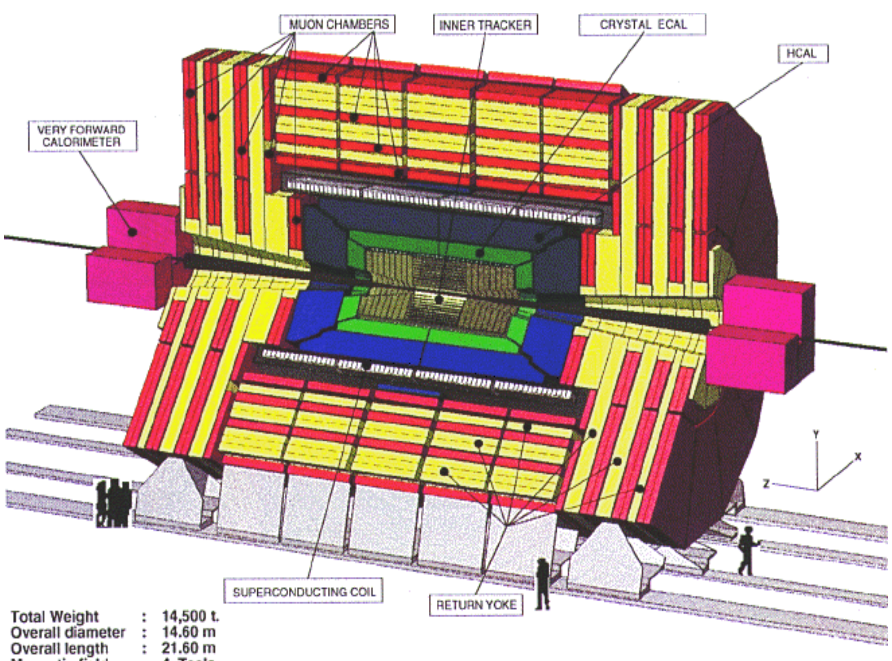
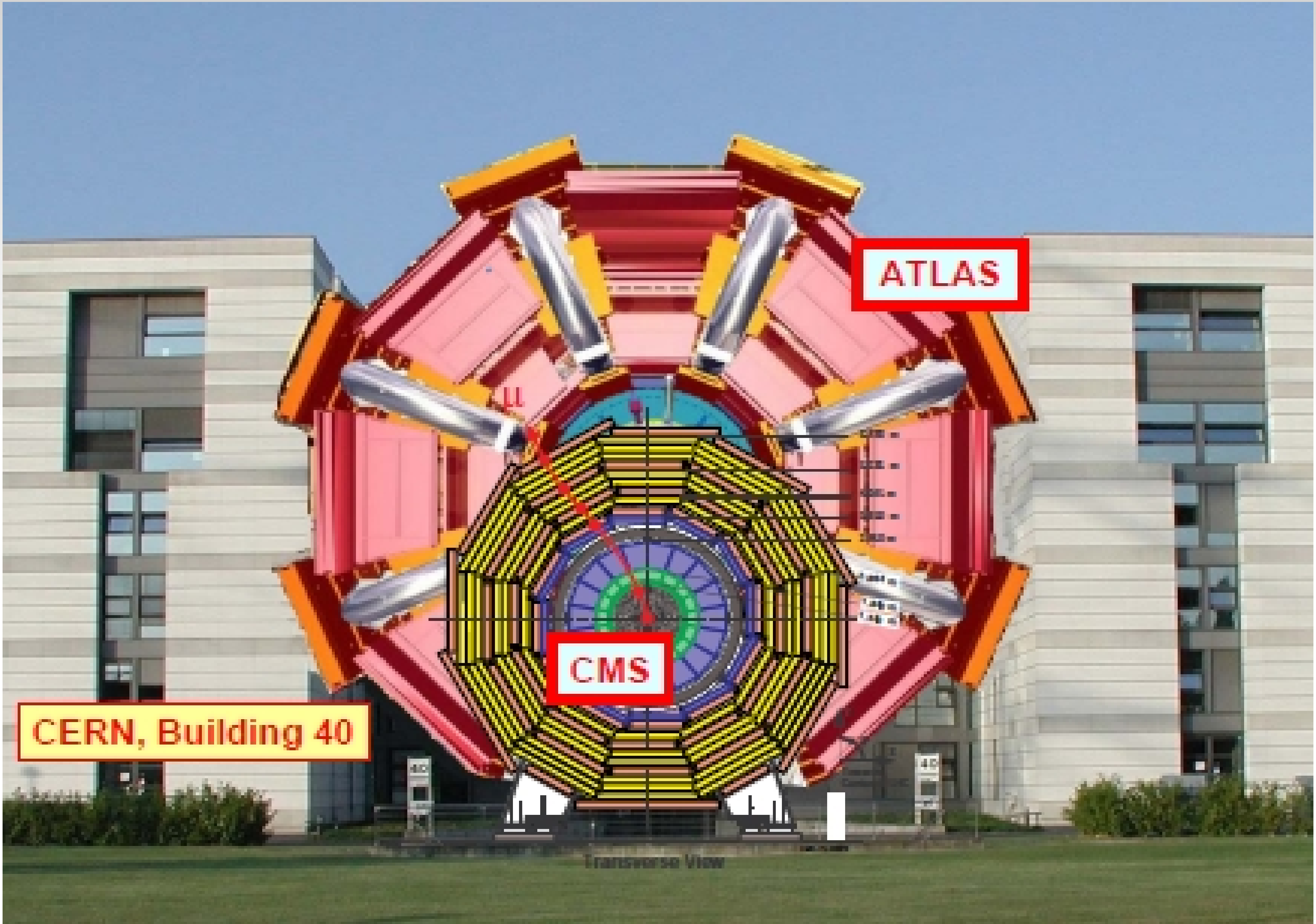
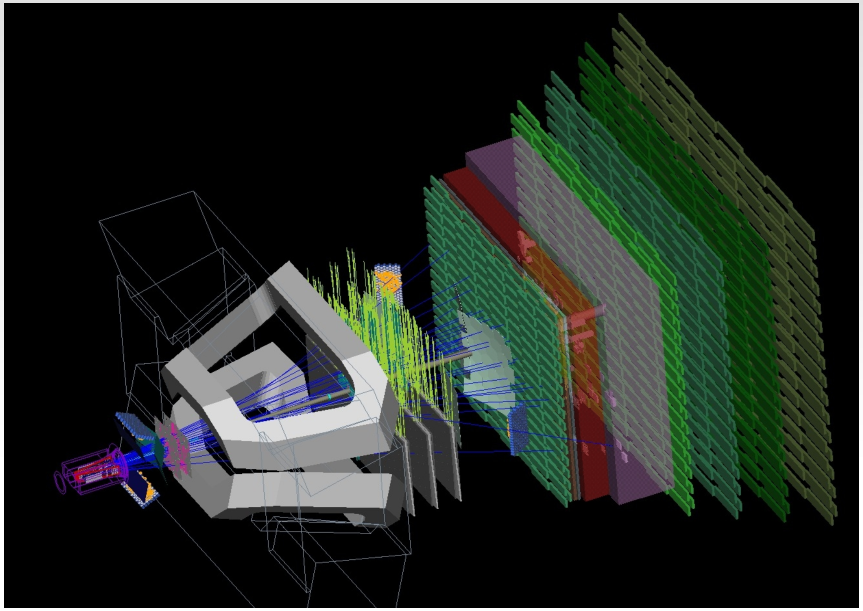
S
Point 8
TI 8
St Genis-Pouilly
TI 2
Point 1
CERN
Site de Meyrin
Meyrin

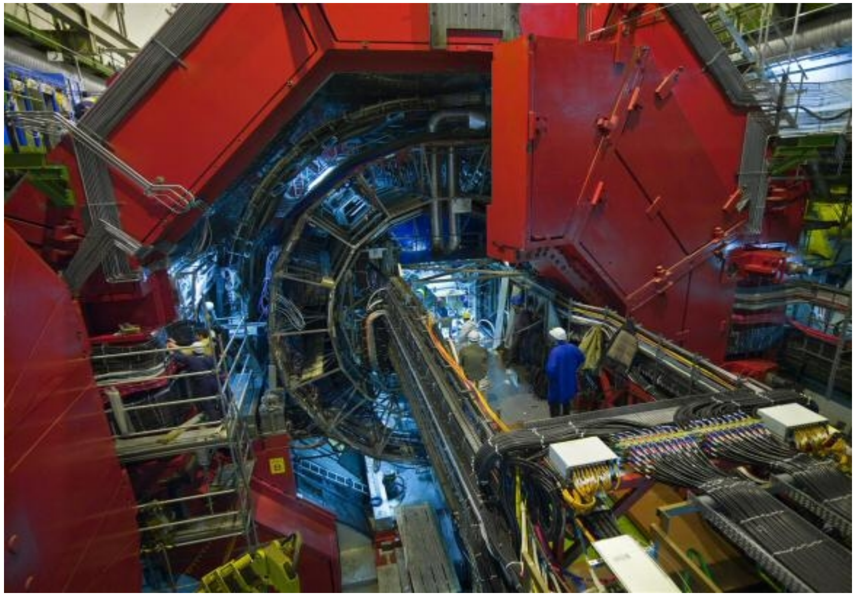


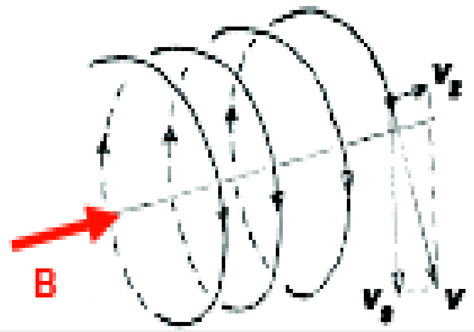

- Atlas: 1 solenoid (2T) and 8 + 2 toroid magnets (!)
  - Air-core muon chambers (good stand-alone muons)
  - Liquid Argon e.m. Calorimeter
- CMS: 1 solenoid magnet (4T) creates field inside and outside
  - Muon chambers in return yoke
  - 80000 $PbWO_4$ crystals as e.m. calorimeter


ATLAS
CMS
CERN, Building 40
Transverse View





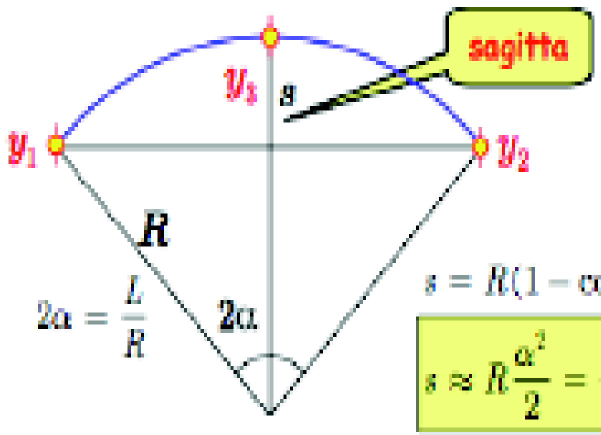
- LHCb dedicated to forward low-andgle physics (especially b-quark production) looks like a pyramid with axis on the beam
- Very good particle identification
- Alice looks for high-mutiplicity events in nucleus-nucleus collisions- the only LHC detector to have a gas tracker due to low-lumi and high-occupancy operation




$$R(m) = \frac{p_\perp(GeV)}{0.3B(T)}$$

Since the transverse momentum is proportional to the bending radius, the momen resolution depend on the accuracy in measuring R

$$R = \frac{p}{0.3B} \qquad \frac{\delta p}{p} = \frac{\delta R}{R}$$




$$s = y_3 - \frac{y_1 + y_2}{2} \qquad \delta s = \sqrt{\frac{3}{2}}\delta y \sim \delta y$$

$$s = R(1 - \cos\alpha)$$

$$s \approx R\frac{\alpha^2}{2} = \frac{L^2}{8R}$$

$$|\delta s| = \frac{L^2}{8R}\frac{\delta R}{R} \sim \delta y \qquad \frac{L^2}{8R}\frac{\delta p}{p} = \delta y$$

$$\frac{\delta p}{p} = \frac{8R}{L^2}\delta y \qquad \frac{\delta p}{p} = \frac{8p}{0.3BL^2}\delta y$$

$$\frac{\delta p}{p^2} = \frac{8\delta y}{0.3BL^2}$$

Pixel Detector

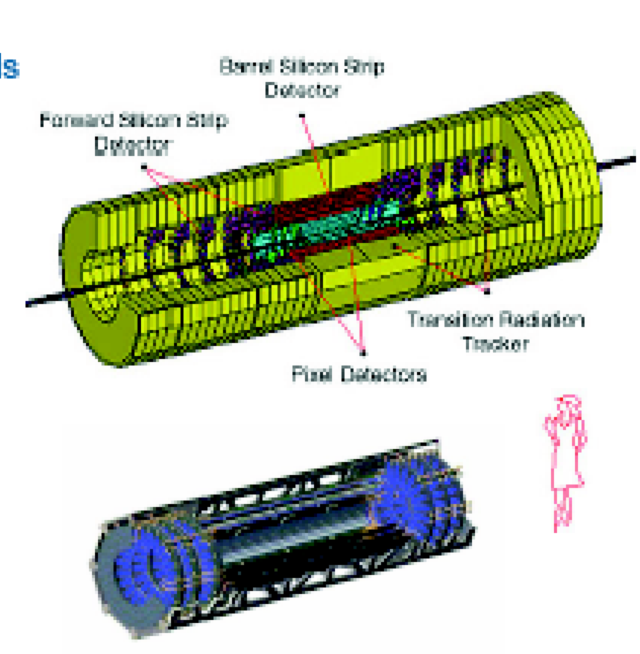
- 3 barrels, 3+3 disks: 80x10$^6$ pixels
- barrel radii: 4.7, 10.5, 13.5 cm
- pixel size 50x400 µm
- $s_{rf}$= 6-10 µm $s_z$ = 66 µm

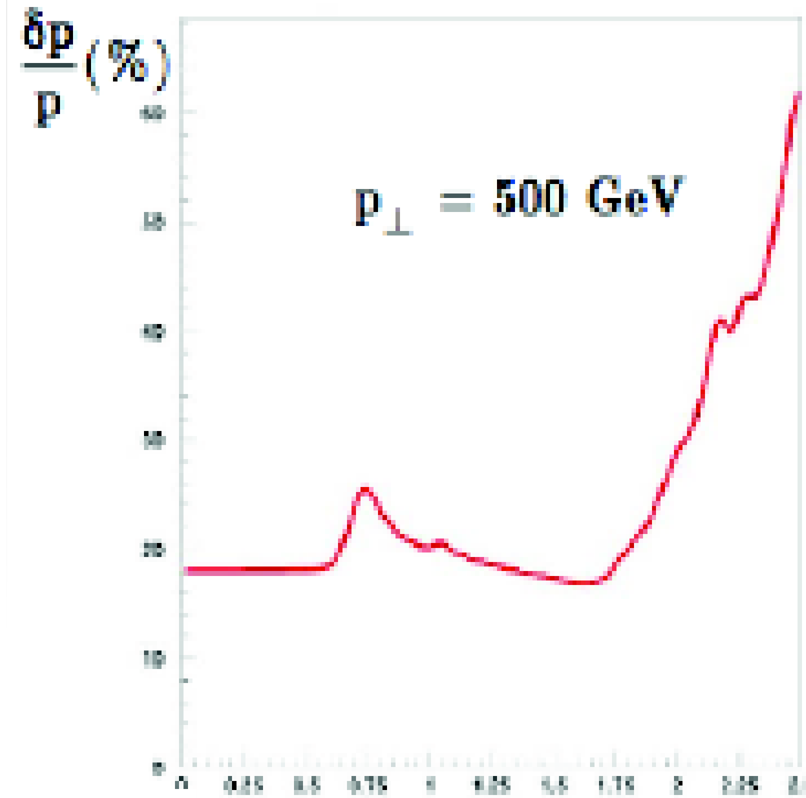
SCT

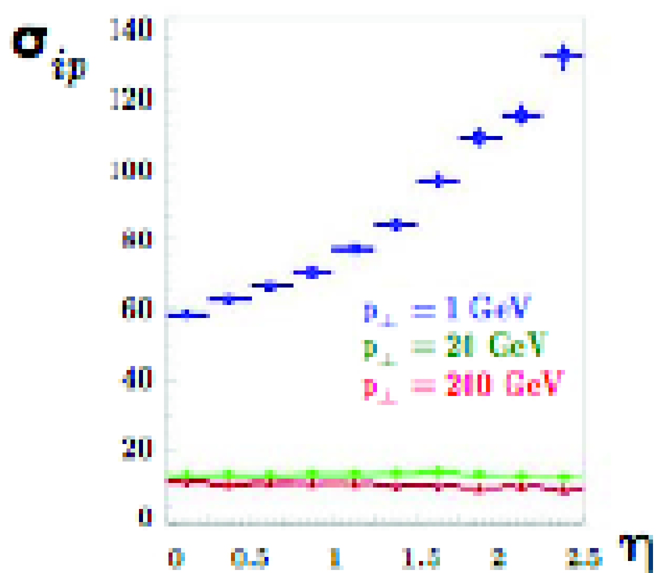
- 4 barrels, disks: 6.3x10$^6$ strips
- barrel radii:30, 37, 44 ,51 cm
- strip pitch 80 µm
- stereo angle ~40 mr
- $s_{rf}$= 16 µm $s_z$ = 580µm

TRT

- barrel: 55 cm < R < 105 cm
- 36 layers of straw tubes
- $s_{rf}$= 170 µm
- 400.000 channels



Pixel Detector

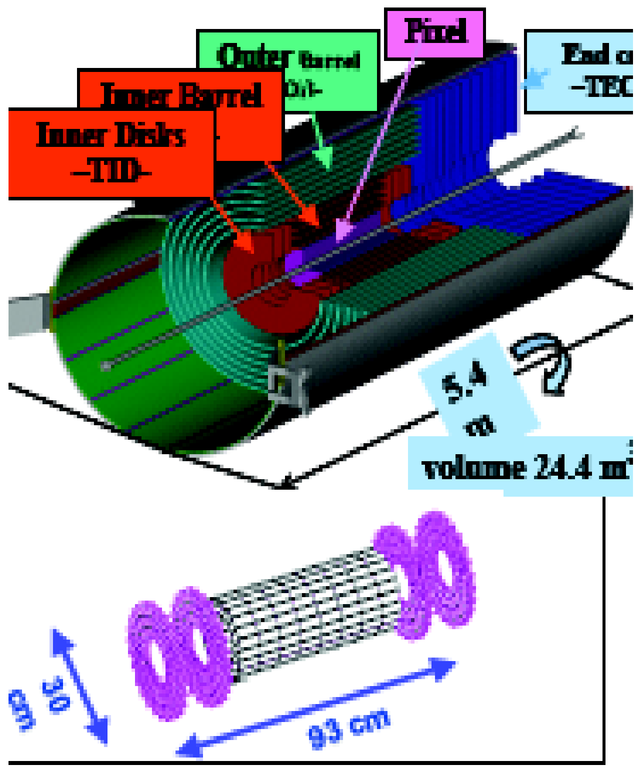
- 2 barrels, 2 disks: 40x10⁶ pixels
- barrel radii: 4.1, ~10. cm
- pixel size 100x150 μm
- $\sigma_{r\phi}$= 10 μm $\sigma_z$ = 10 μm

Internal Silicon Strip Tracker

- 4 barrels, many disks: 2x10⁶ strips
- barrel radii:
- strip pitch 80,120 μm
- $\sigma_{r\phi}$= 20 μm $\sigma_z$ = 20 μm

External Silicon Strip Tracker

- 6 barrels, many disks: 8x10⁶ strips
- barrel radii: max 110 cm
- strip pitch 80, 120 μm
- $\sigma_{r\phi}$= 30 μm $\sigma_z$ = 30 μm

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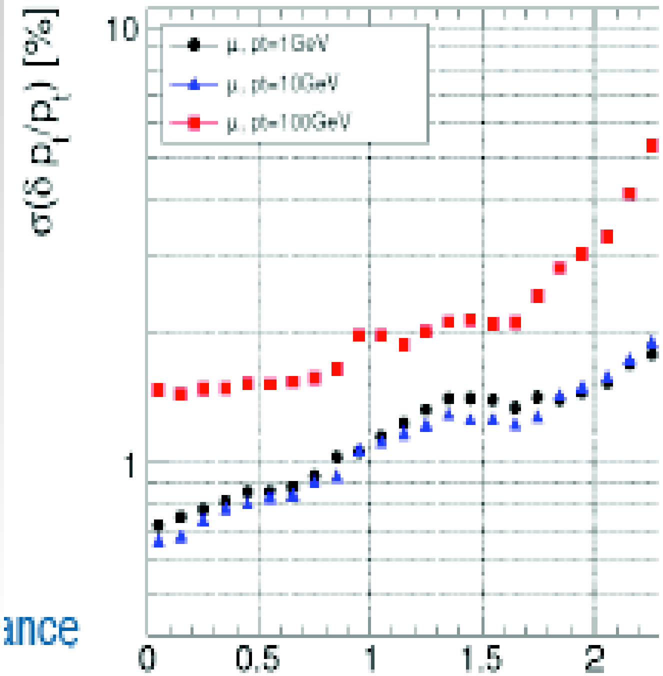
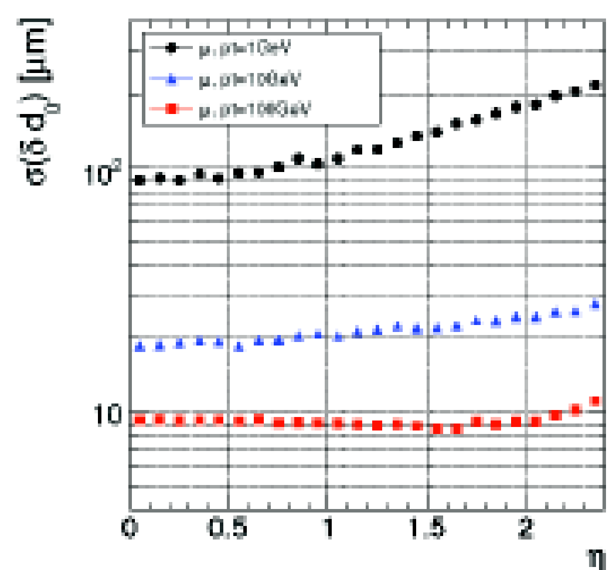
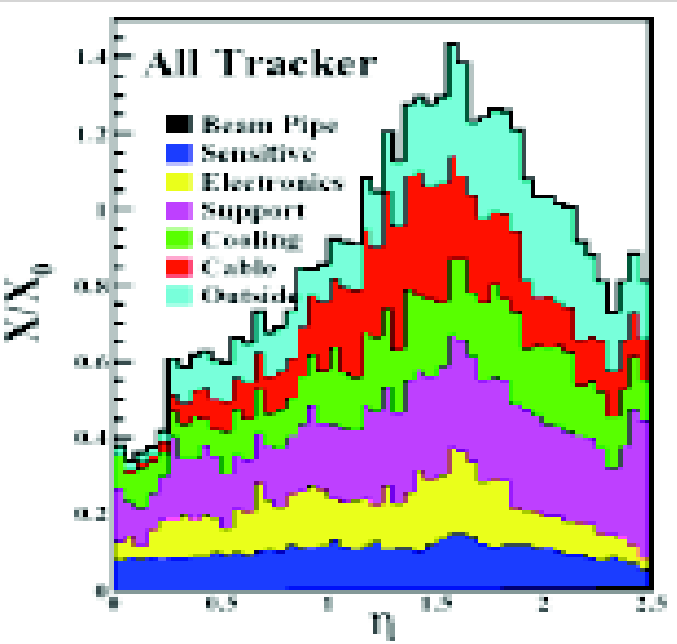
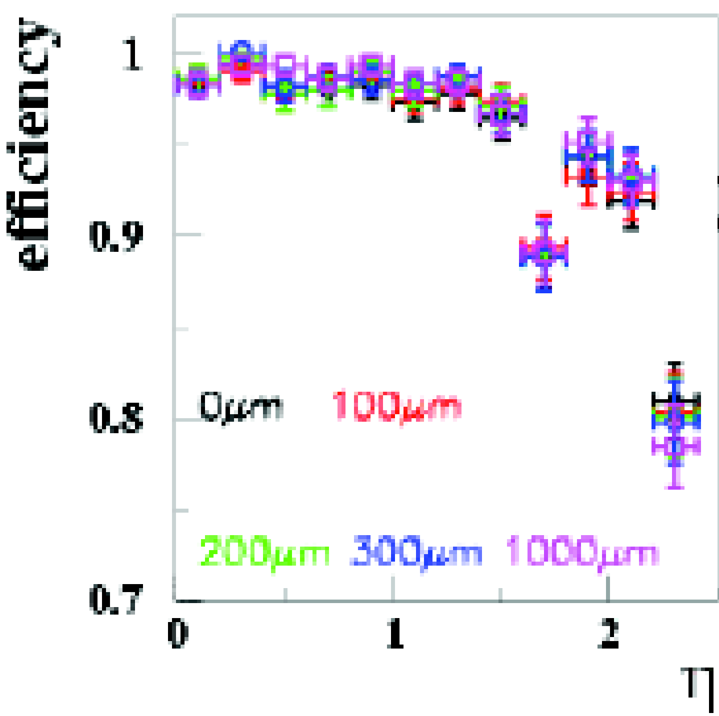
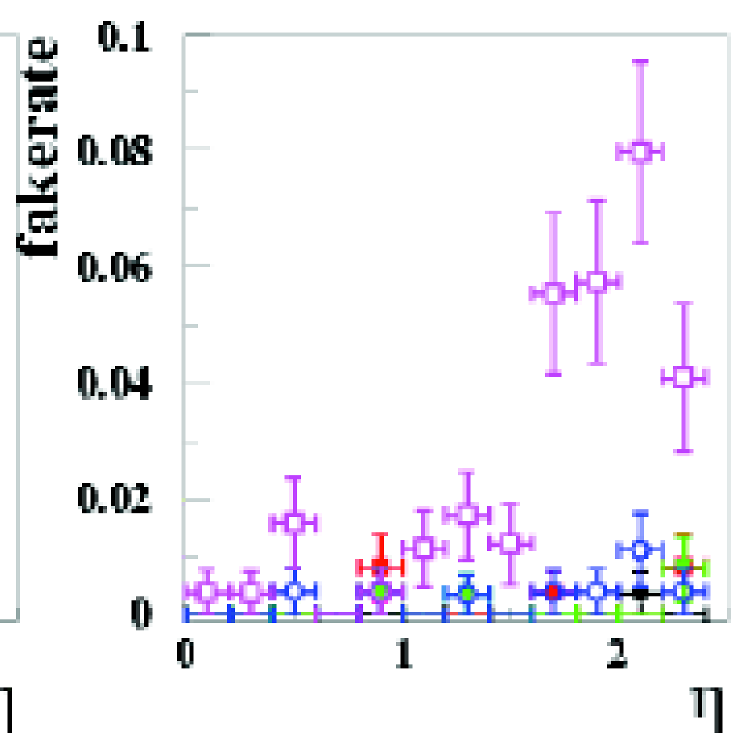


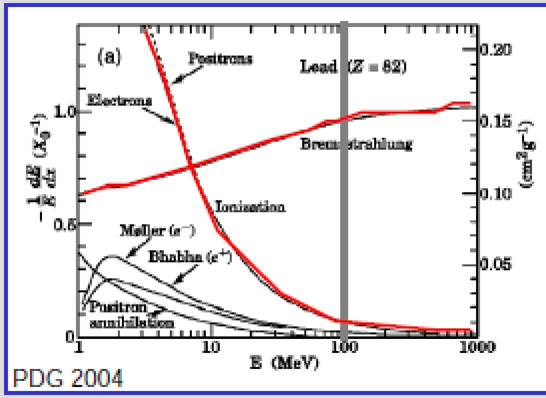



Detector should be thick enough to collect enough signal, and thin enough to minimise photon conversions. Also overlap between modules needed for alignment (starts to be critical at the mm level)

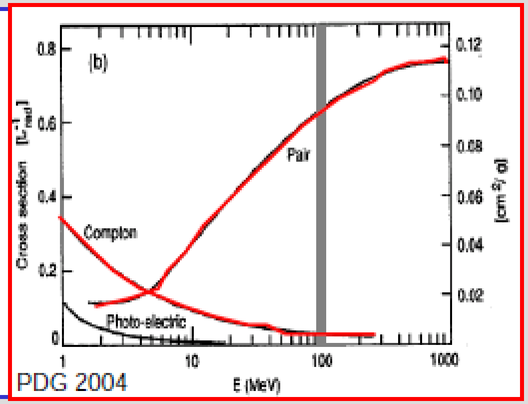


Electrons and Positrons

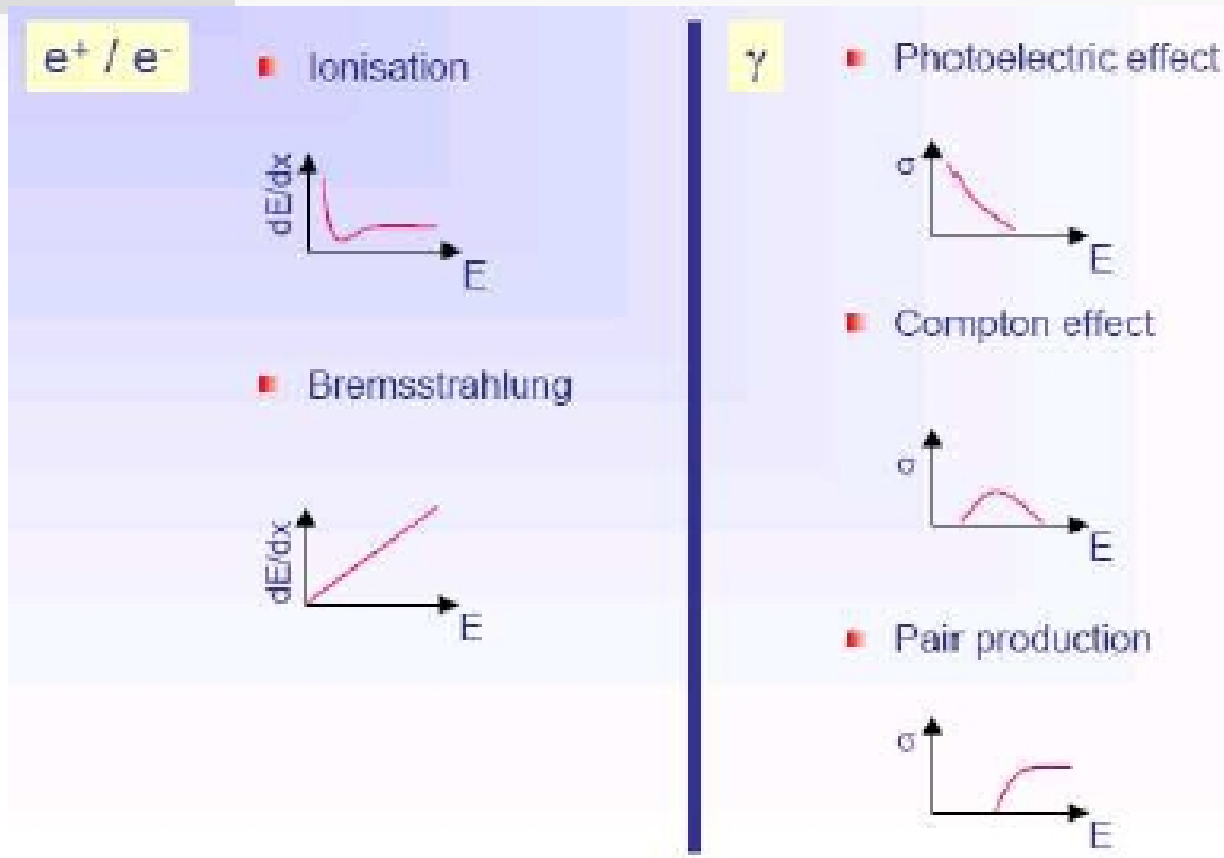



Photon




Electromagnetic showers occur earlier and are shorter than hadronic ones. Also detector resolution can be very good

Electron- or photon-initiated showers almost impossible to distinguish without preshower detector in front of calorimeter, despite very different interaction properties



Natural width: for $M_H \approx 100$ GeV $\rightarrow \Gamma_H / M_H \leq 10^{-3}$

Experimental width of $m\gamma\gamma = 2 E_1 E_2 (1 - \cos\theta_{\gamma\gamma})$ :

$$\frac{\sigma_m}{m} = \frac{1}{\sqrt{2}}\left[\left(\frac{\sigma_1}{E_1}\right) \oplus \left(\frac{\sigma_2}{E_2}\right) \oplus \left(\frac{\sigma_\theta}{tg\theta_{\gamma\gamma}/2}\right)\right]$$

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

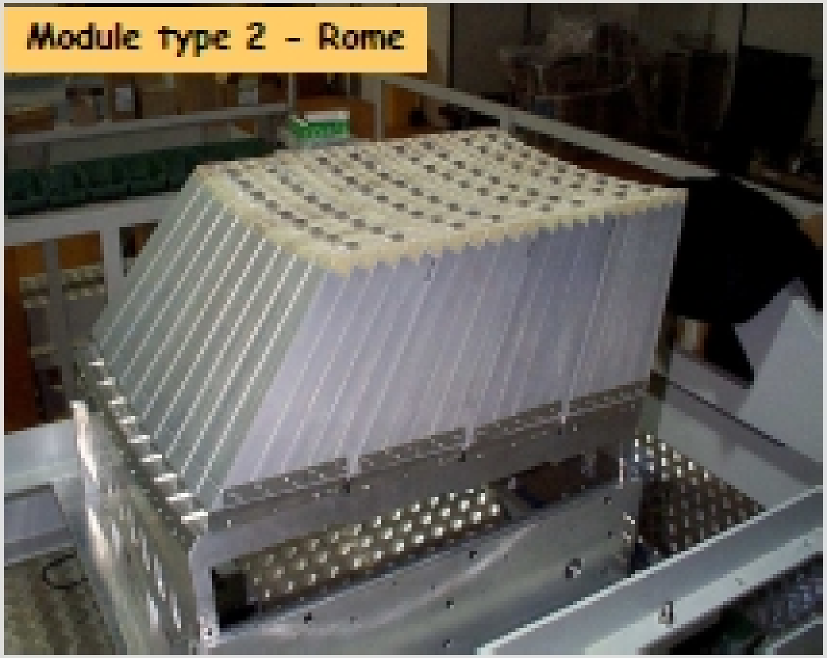
$$\sigma(\theta) \approx \frac{50\ \mathrm{mrad}}{\sqrt{\mathrm{E}}}$$

Same for ATLAS and CMS ...

| CMS | ATLAS |
| --- | --- |
| • Compact<br>• Excellent energy resolution<br>• Fast<br>• High granularity<br>• Radiation resistance<br>• E range MIP → TeV<br><br>Homogeneous calorimeter made of 75000 $PbW0_4$ scintillating crystals | • good energy resolution<br>• Fast<br>• High granularity<br>• Longitudinally segmented<br>• Radiation resistance<br>• E range MIP → TeV<br><br>Sampling LAr-Pb, 3 Longitudinal layers + PS |

✓ Compact
✓ Transverse segmentation

| Material | $X_0$/cm | Ec/MeV | $R_M$/cm |
|---|---|---|---|
| Fe | 1.8 | 22 | 1.7 |
| Lead | 0.56 | 7.4 | 1.6 |
| $PbWO_4$ | 0.89 | | 2.2 |

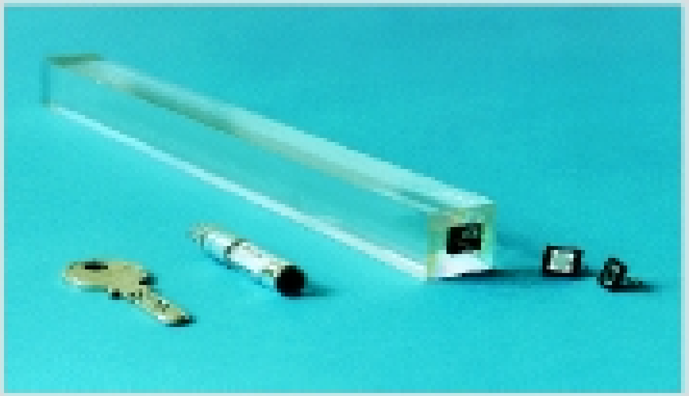



Crystal dimensions:

longitudinal 25 $X_0$ = 22.2 cm

Transverse 1 $R_M$ = 2.2 cm

95% of the shower contained in 2 $R_M$



- Longitudinal dimension:

≈25 $X_0$ = 47 cm (CMS 22 cm)

- 3 longitudinal layers

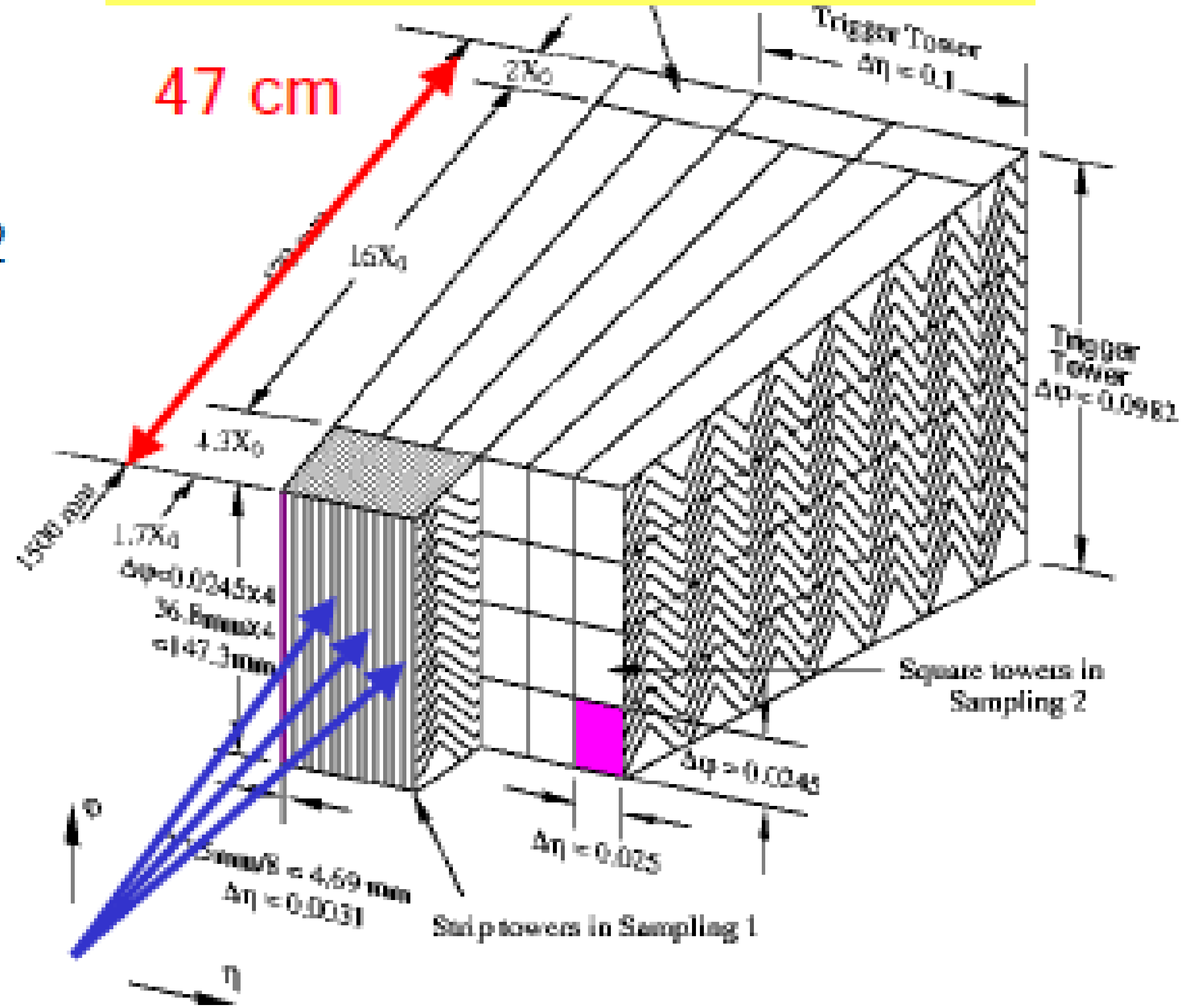
**4 $X_0$** $\pi^0$ rejections separation of 2 photons very fine grain in $\eta$

**16 $X_0$** for shower core

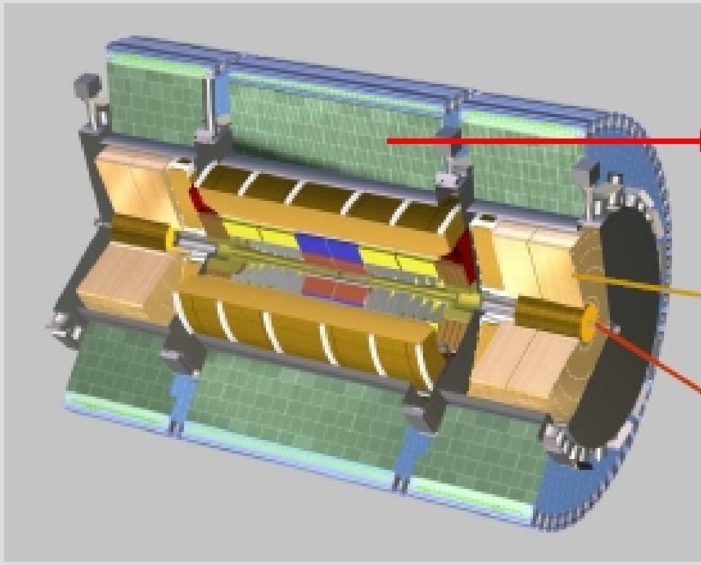
**2 $X_0$** evaluation of late started showers

- Total channels = 170000

Sampling: accordion lead structure filled with LAr




Particles from collisions

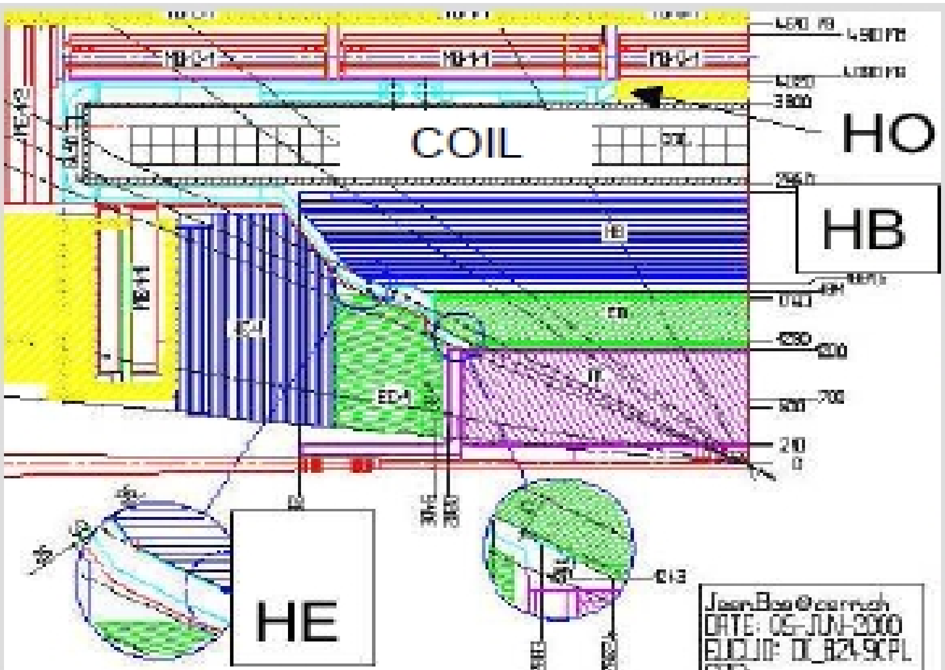


Tile Calorimeter $|\eta| < 1.7$
Fe / Scintillator
3 longitudinal sections

LAr/Cu $1.7 < |\eta| < 3.2$
4 longitudinal sections

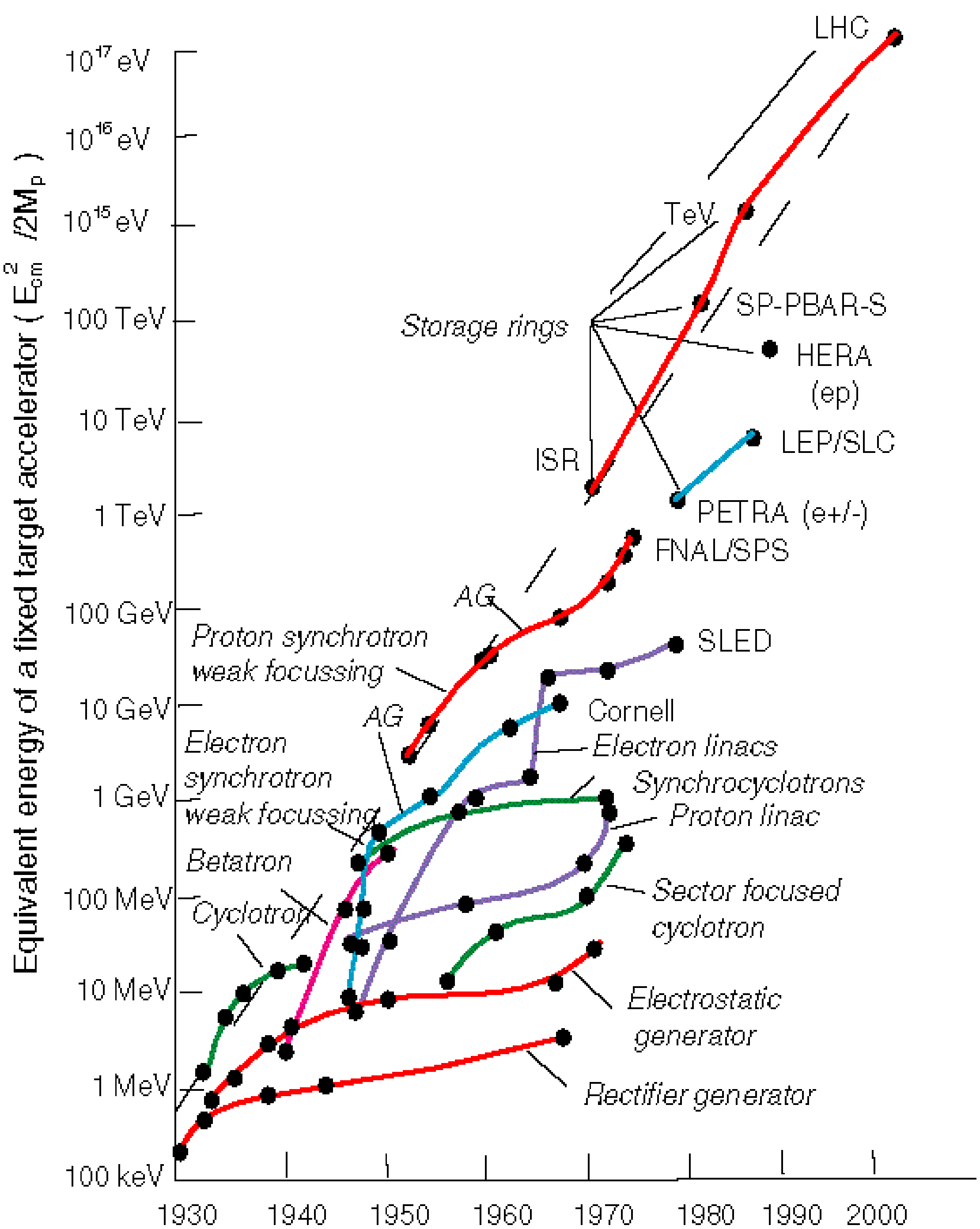
Both hadronic and em
LAr/Cu or W $3.2 < |\eta| < 4.9$
3 longitudinal sections

Fluctuations in hadronic showers pose an intrinsic limit to the resolution of hadron calorimetry; this (and the size) is why usually HCALs are less sophisticated then ECALs




Central Hadronic $|\eta| < 1.7$ :
Brass/Scintillator + WLS
2 + 1 (HO) Longitudinal section
$5.9 + 3.9\ \lambda$ ($|\eta| = 0$)
Endcap Hadronic $1.3 < |\eta| < 3$ :
Brass/Scintillator + WLS
2/3 Longitudinal sections

Forward calorimeter $2.85 < \eta < 5.19$:
Ferro/fibre di quarzo




Lepton colliders provide cleaner events, and all energy is available in the final state. But:

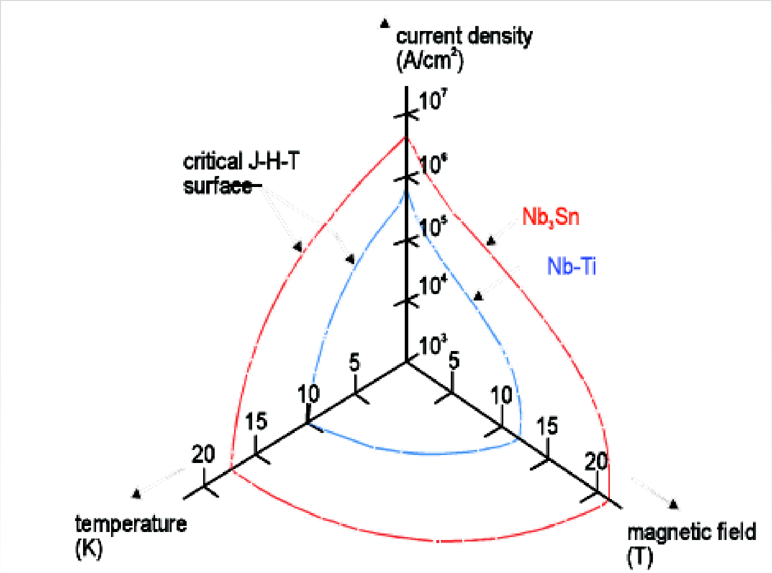
a hadron collider is not limited by synchrotron radiation, and can go to much higher energy.

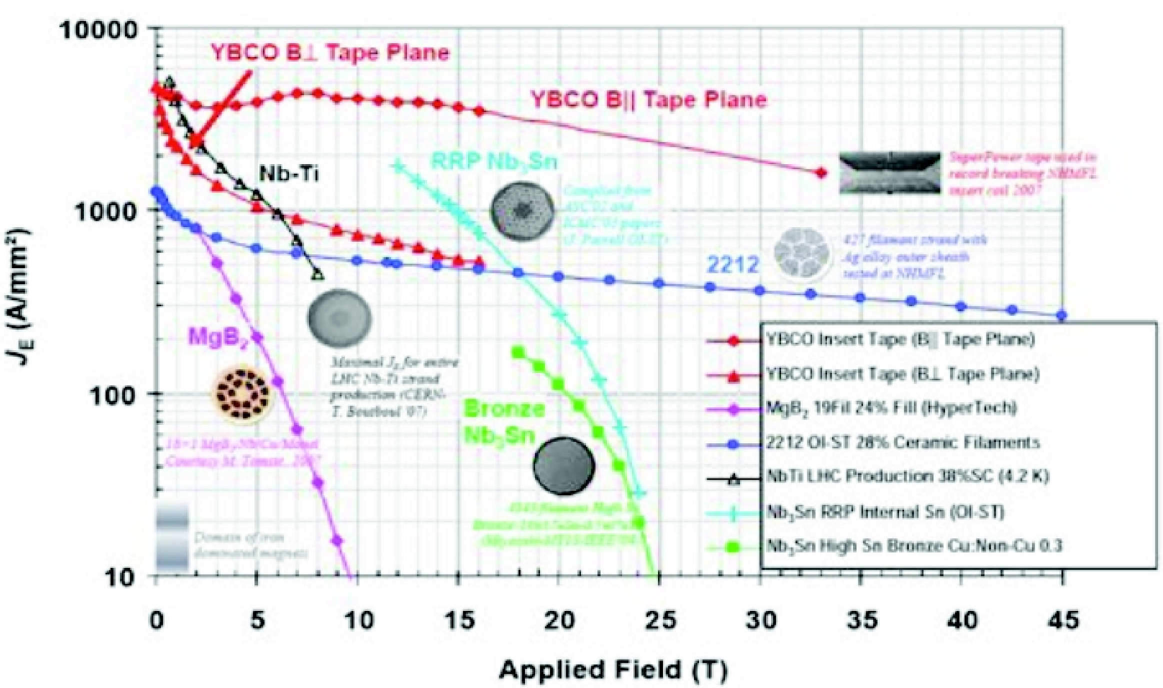
For a given ring size, the only limitation comes from the magnetic field of the bending magnets:

P (TeV) = 0.3 B(T) R (Km)

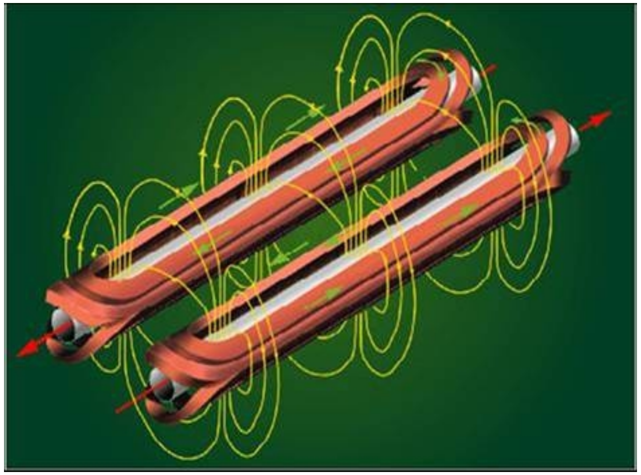
The highest currents, therefore the largest fields, are obtained using superconducting cables.

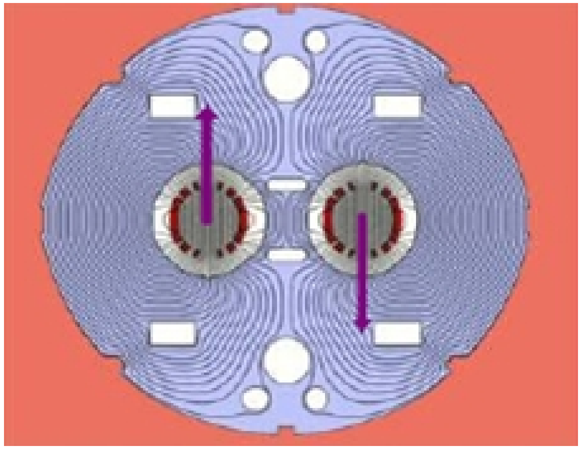
Unfortunately, phase transition between super-and normal conducting phase depends not only on temperature but on magnetic fields. This sets maximum field to 8.4T (100K times earth!) and defines P = 14 TeV (60% of circumference has magnets)



- Unlike LEP or the Tevatron, the LHC is a proton-proton (matter-matter) machine
- Why? Not possible to produce enough antiprotons to have the large luminosities needed for rare processes
- Most of interactions will be gluon-gluon (see later)
- Technical difficulty: get a very accurately  opposite magnetic field





# LHC General Parameters (Protons)

| LHC General Parameters | | |
|---|---|---|
| Energy at collision | 7 | TeV |
| Energy at injection | 450 | GeV |
| Dipole field at 7 TeV | 8.33 | T |
| Coil inner diameter | 56 | mm |
| Distance between aperture axes (1.9 K) | 194 | mm |
| Luminosity | 1 | E34 cm-2s-1 |
| Beam beam parameter | 3.6 | E-3 |
| DC beam current | 0.56 | A |
| Bunch spacing | 7.48 | m |
| Bunch separation | 24.95 | ns |
| Number of particles per bunch | 1.1 | E11 |
| Normalized transverse emittance (r.m.s.) | 3.75 | μm |
| Total crossing angle | 300 | μrad |
| Luminosity lifetime | 10 | h |
| Energy loss per turn | 7 | keV |
| Critical photon energy | 44.1 | eV |
| Total radiated power per beam | 3.8 | kW |
| Stored energy per beam | 350 | MJ |
| Filling time per ring | 4.3 | min |

# Main Dipole magnet

## Summary Table

| | $l_{Magn}$ (Top) | $T_{op}$ | $B_N$ | $I_N$ | Ap Sep (Top) | Mag Ap (293K) | Number |
|---|---|---|---|---|---|---|---|
| | m | K | T | A | mm | mm | |
| **MB** | 14.3 | 1.9 | 8.33 | 11796 | 194 | 56 | 1232 |

(Click on the underlined magnet name to display its parameters full list)

The **MB** cold mass consists of 2 coils per aperture clamped around the cold bores by a common austenitic steel collar surrounded by an iron yoke and a shrinking cylinder.

The shrinking cylinder and the cold bore (beam vacuum chamber) are the outer and the inner parts of the helium tank.

MB cold mass main dimensions at 293K :

| | |
|---|---|
| Cold bore Øi/Øe | 50/ 53 mm |
| Coil Øi/Øe | 56 / 120.5 mm |
| Coil Length (not incl. end plates) | 14567 mm |
| Iron Yoke Øe | 550 mm |
| Iron Yoke Length (incl. end plates) | 14497 mm |
| Shrinking cylinder Øi/Øe | 550 / 570 mm |
| Shrinking cylinder Length | 15180mm (15160mm between ref. planes) |
| Overall cold mass weight | 23.8 t |

The coils are formed by two winding layers using two Rutherford (keystone) cables (same width and different thickness) grouped in 6 blocks. The inner and outer coils have 15 and 25 turns per pole respectively.

Two types of MBs depending on connections and the associated local spool piece corrector :

- Rate: number of collisions/s for a given process:
    - $R = \sigma L$

where luminosity L is given by

- $L = f\, n_1\, n_2 / A$

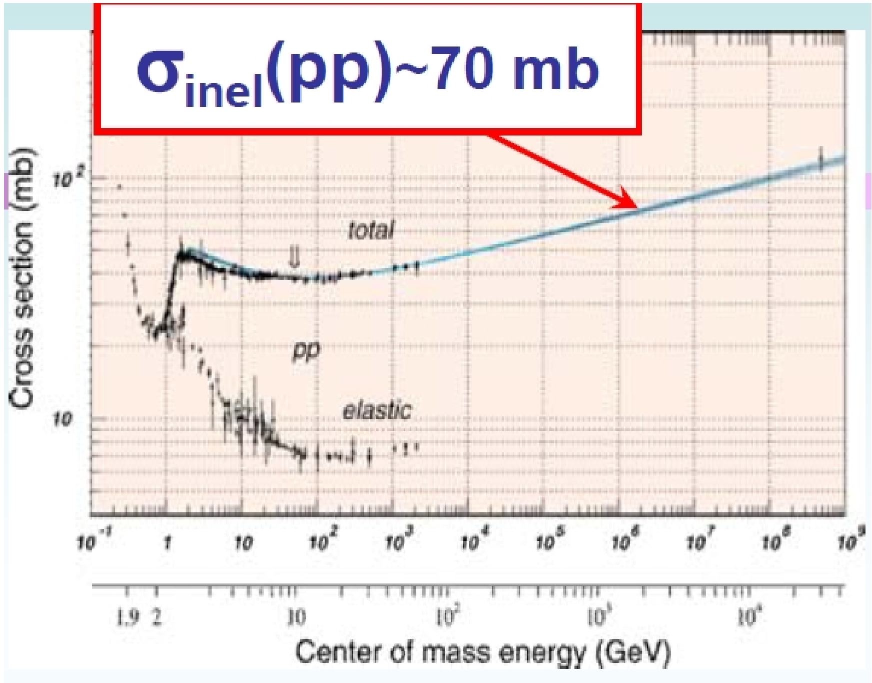
- $n_1\, n_2$ number of particles per beam ($O(10^{11})$)
- f crossing frequency (40 Mhz, with 2835/3564 bunches occupied)
- $A$ = crossing area = $\pi r^2$ where $r = 16\ \mu m$ (rms of transverse beam profile)

- These numbers correspond to a range between

$10^{33}$ and $10^{34}$ $cm^2/s$ ($10^6$-$10^7$ $mb^{-1}$) Hz

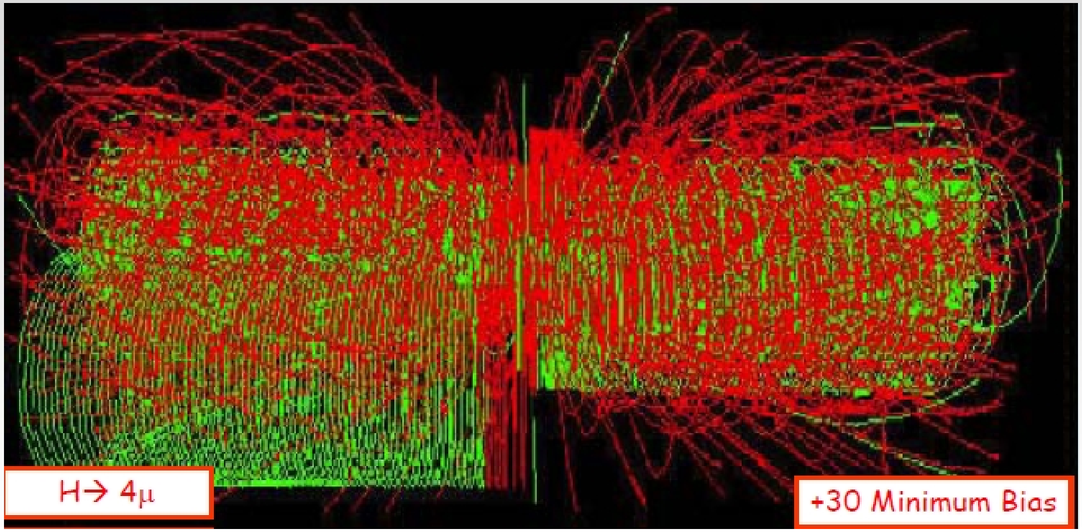
And in one year (8-9 months of data taking) to 10-100 $fb^{-1}$

The total pp cross section is about 70 mb:

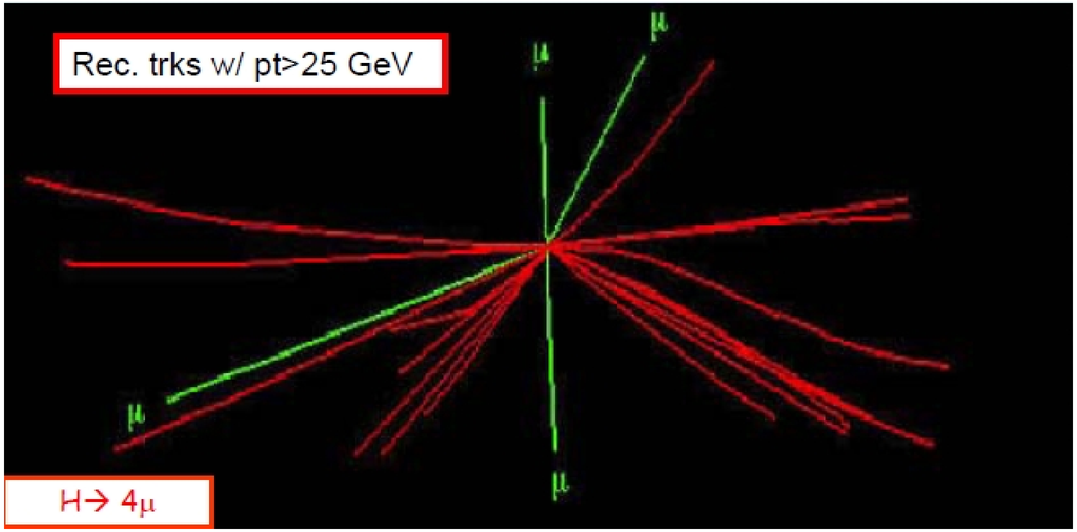



So, rate can go up to 700MHz! Divided by 40MHz bunch crossing rate, and accounting for empty bunches, we can have > 20 collisions/bunch crossing (pileup)

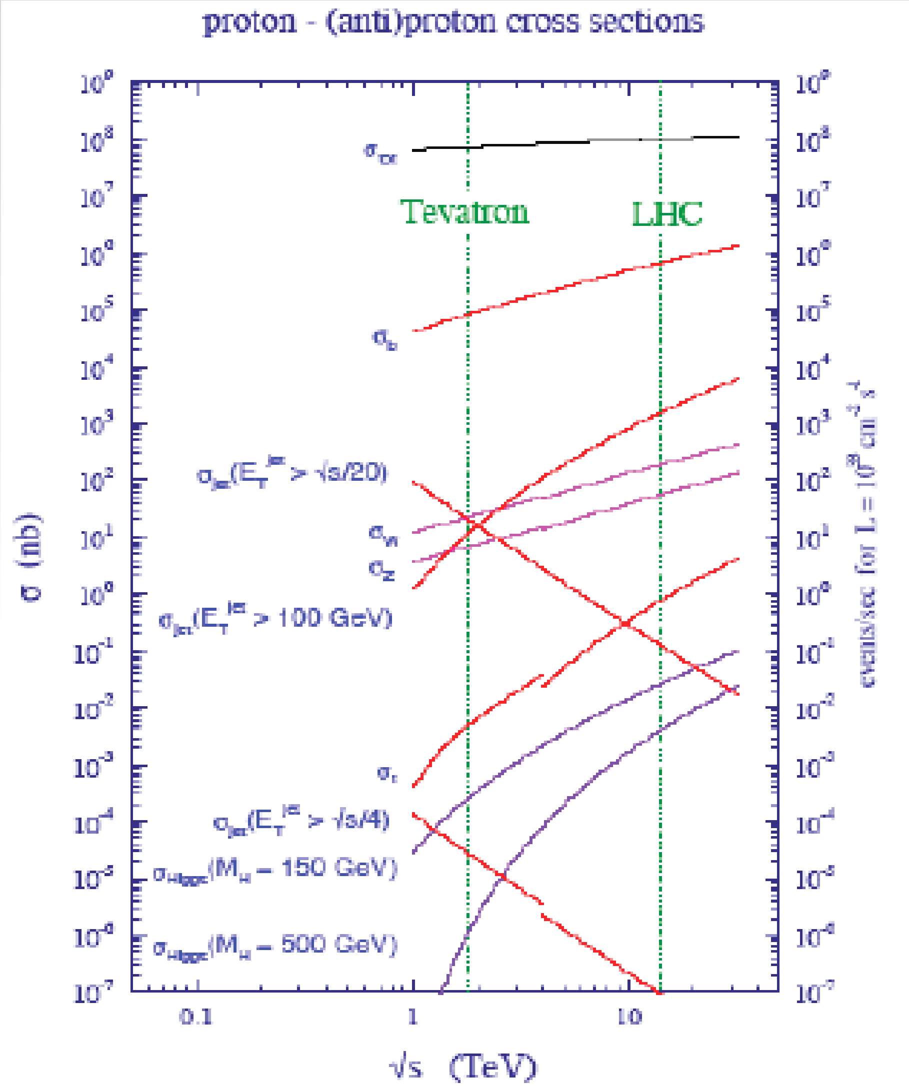
Can you find four muons coming from a Higgs boson from this event?




It gets much better if you just look at the energetic particles:

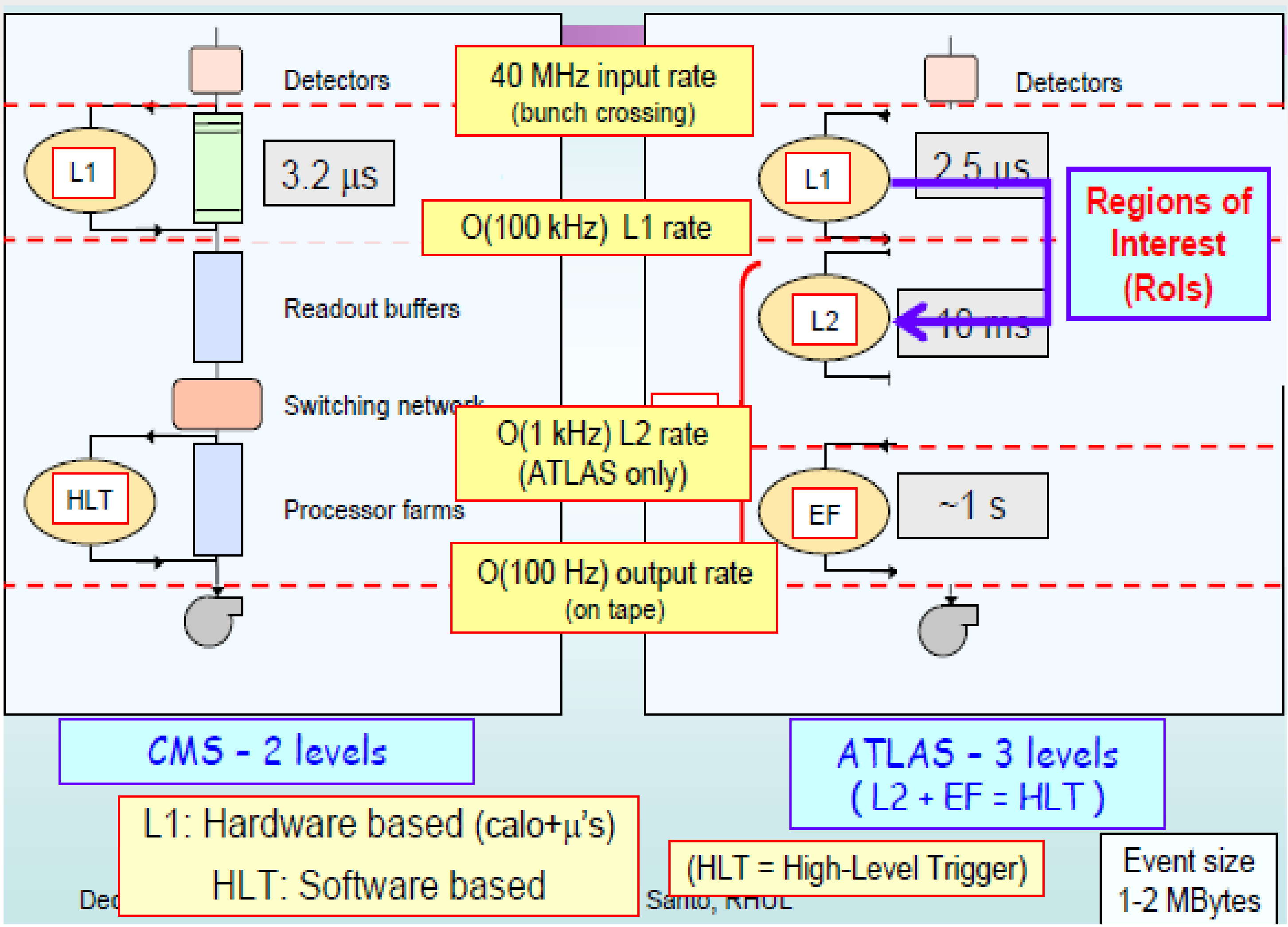


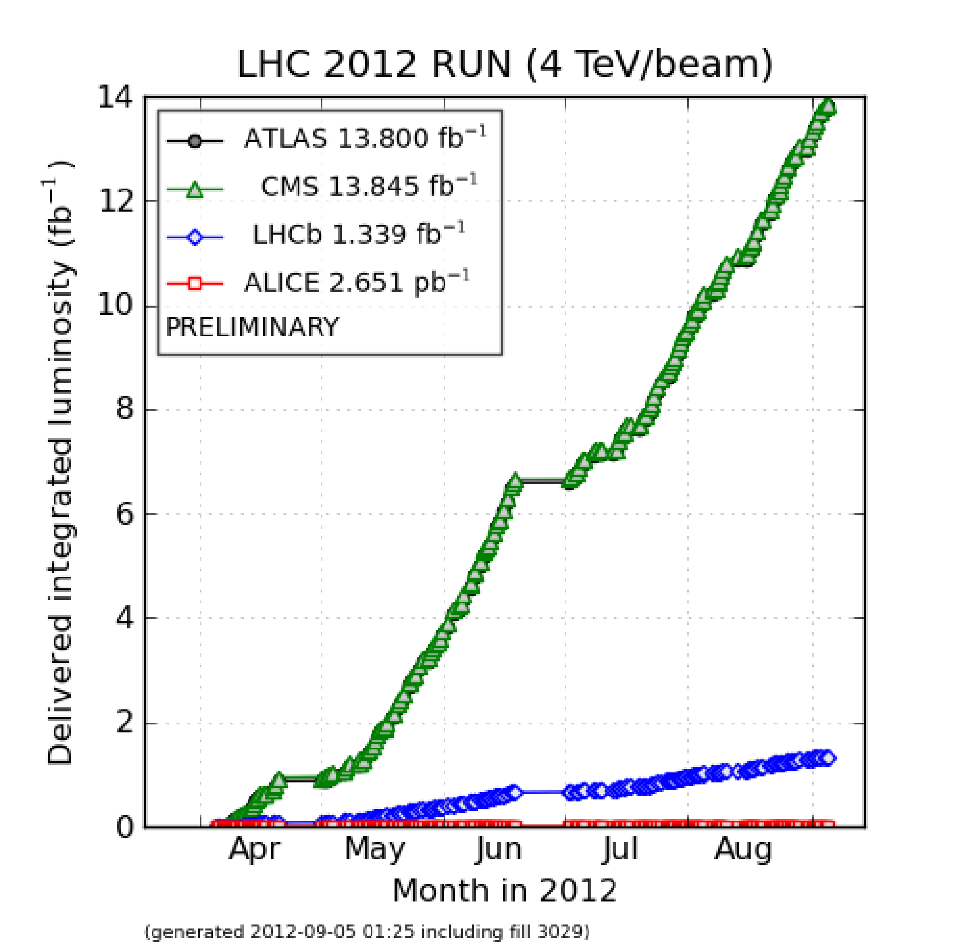
- No real thresholds
- Total cross section (including elastic) almost constant
- Some lines 'broken' going from Tevatron to LHC due to antiprotons vs protons
- Several orders of magnitude between discoveries and background

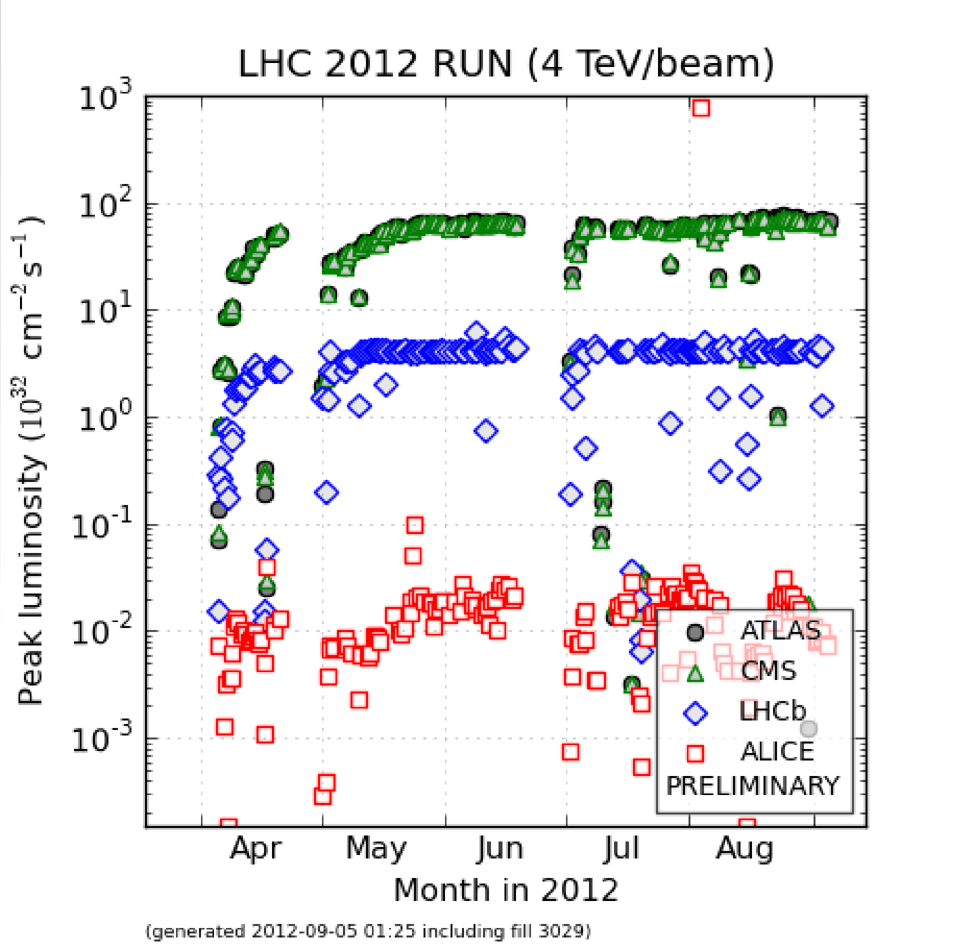



History of this first year can be summarised as: going down this plot

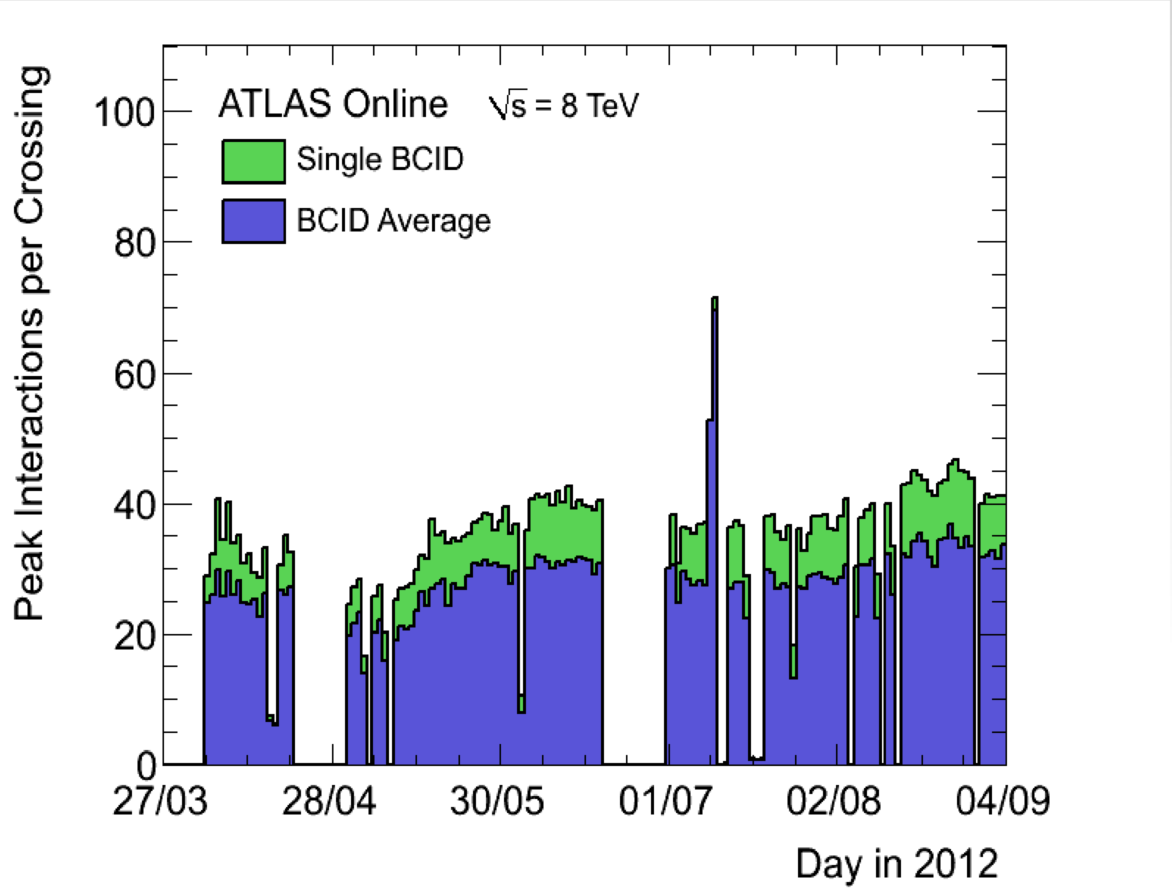
- DAQ can only take O(100 Hz), so rejection factors on BG of order 1M are needed, while keeping high efficiency on rare signal events. Different stategies:



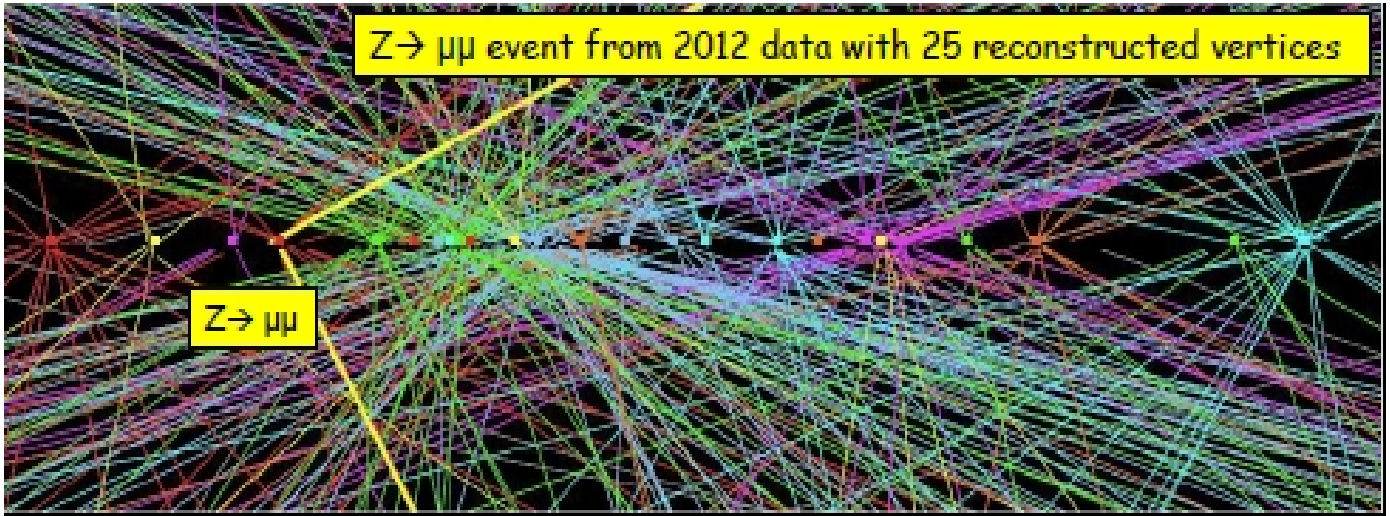


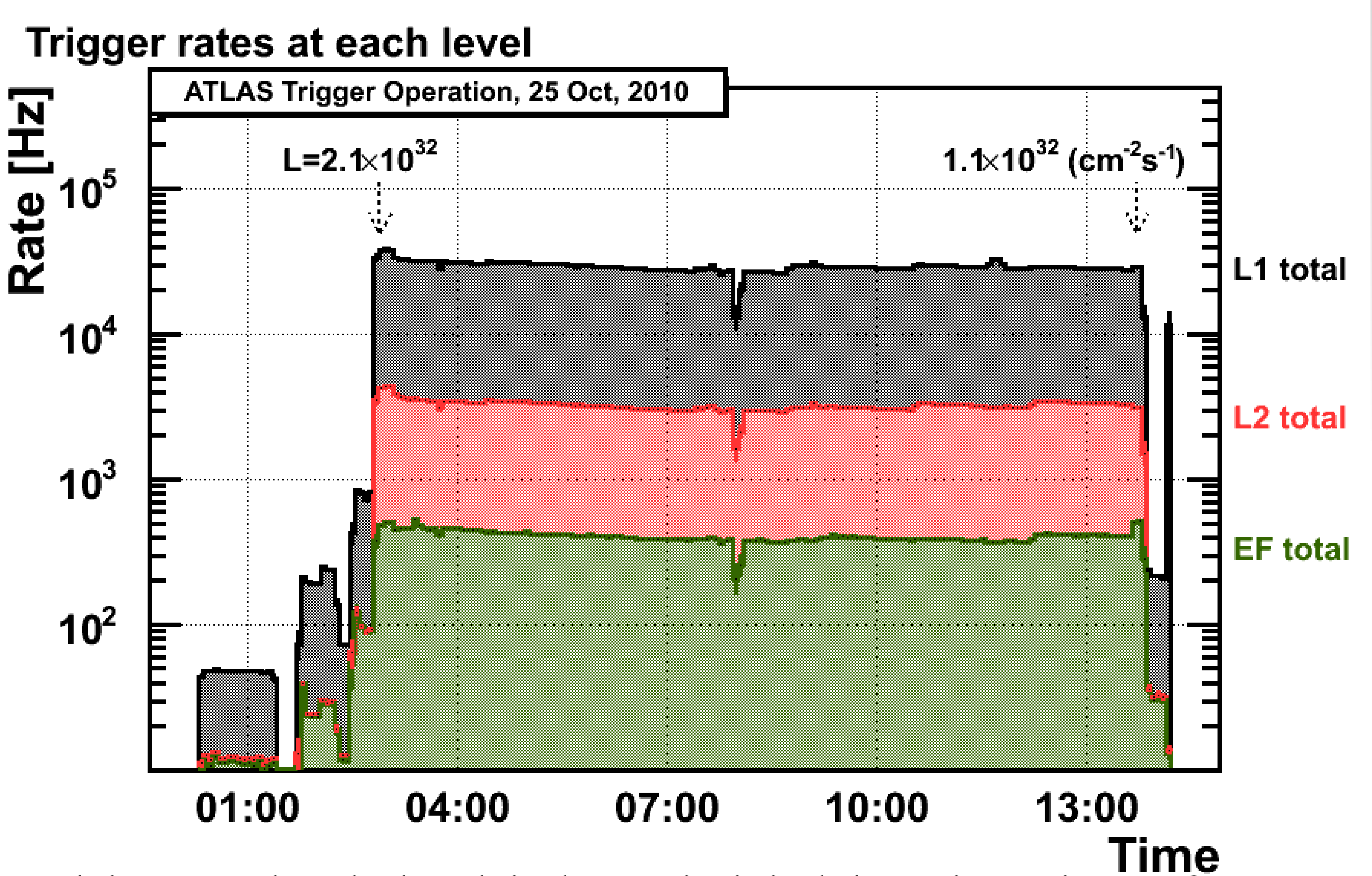

- Integrated luminosity ~15 fb-1
- Peak luminosity ~7E32



ATLAS Online √s = 8 TeV
Single BCID
BCID Average
Peak Interactions per Crossing
100
80
60
40
20
0
27/03
28/04
30/05
01/07
02/08
04/09
Day in 2012

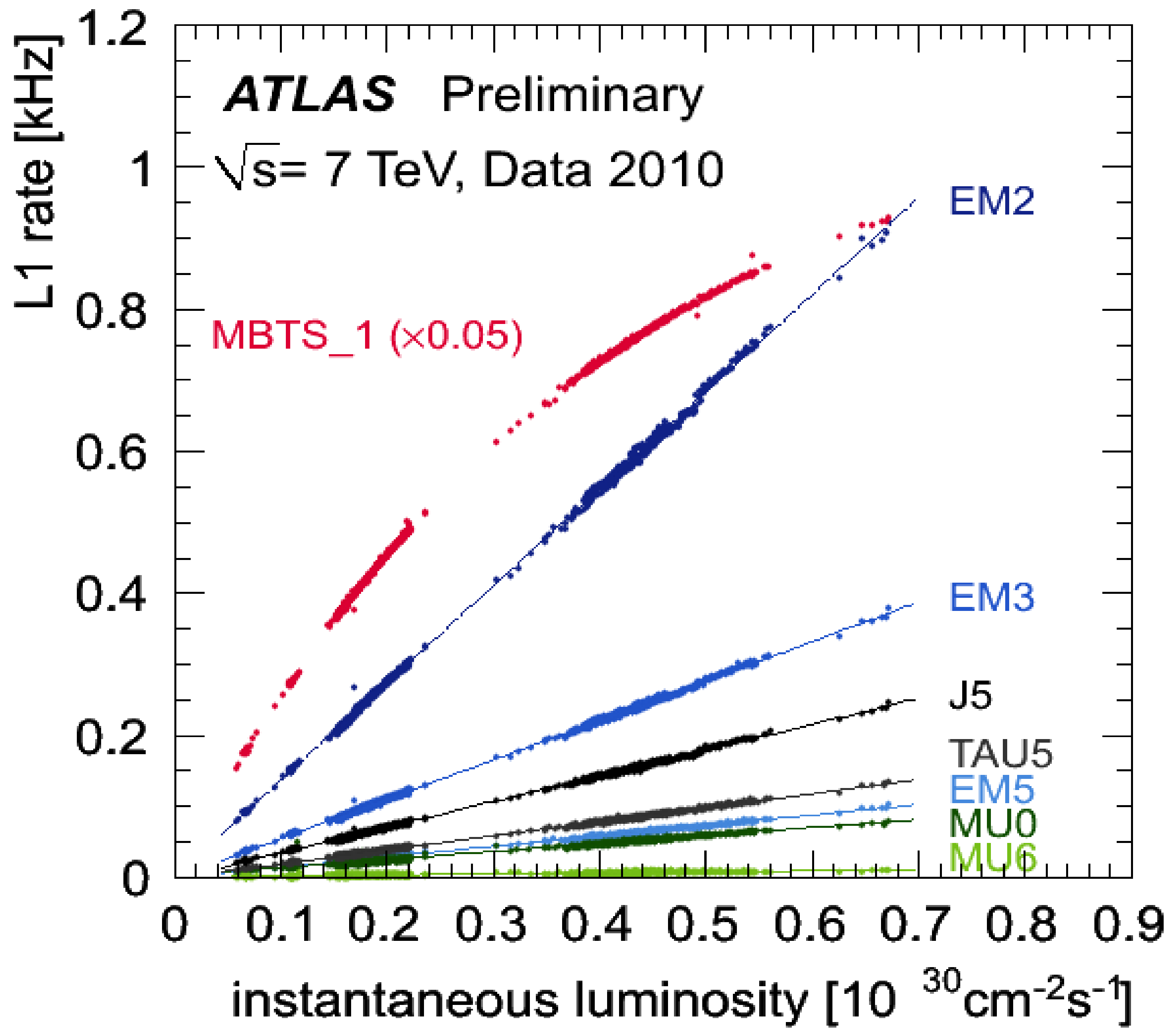
Z→ μμ event from 2012 data with 25 reconstructed vertices
Z→ μμ

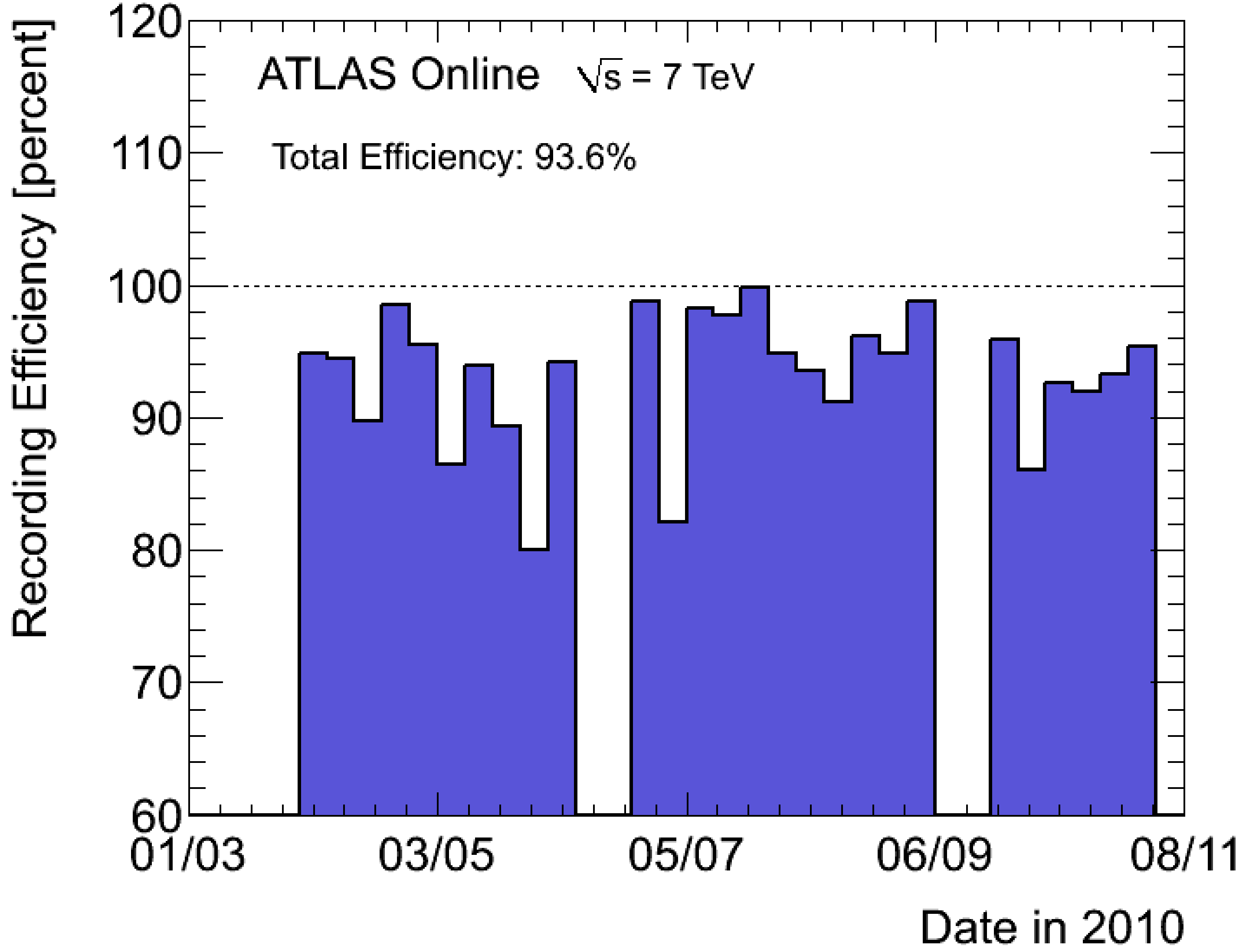



- This run had the highest initial luminosity of 2010
- Trigger bandwidth saturated at the three levels

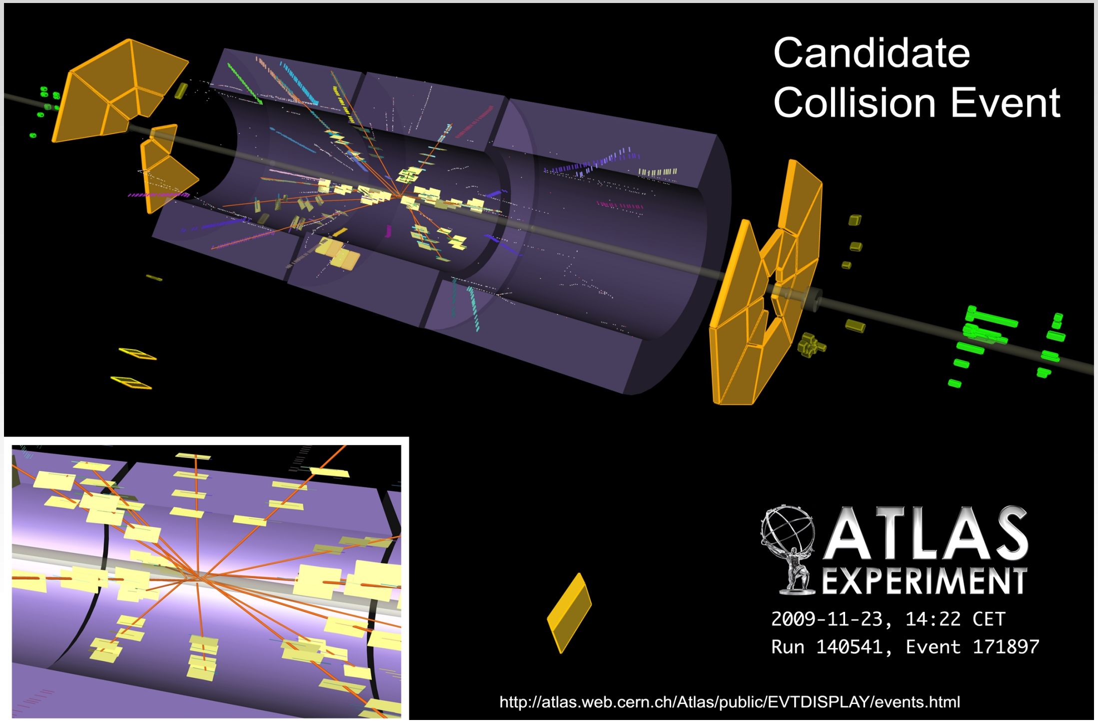
Rates still linear since in no-pileup region.

Non-linearities observed at the highest luminosities

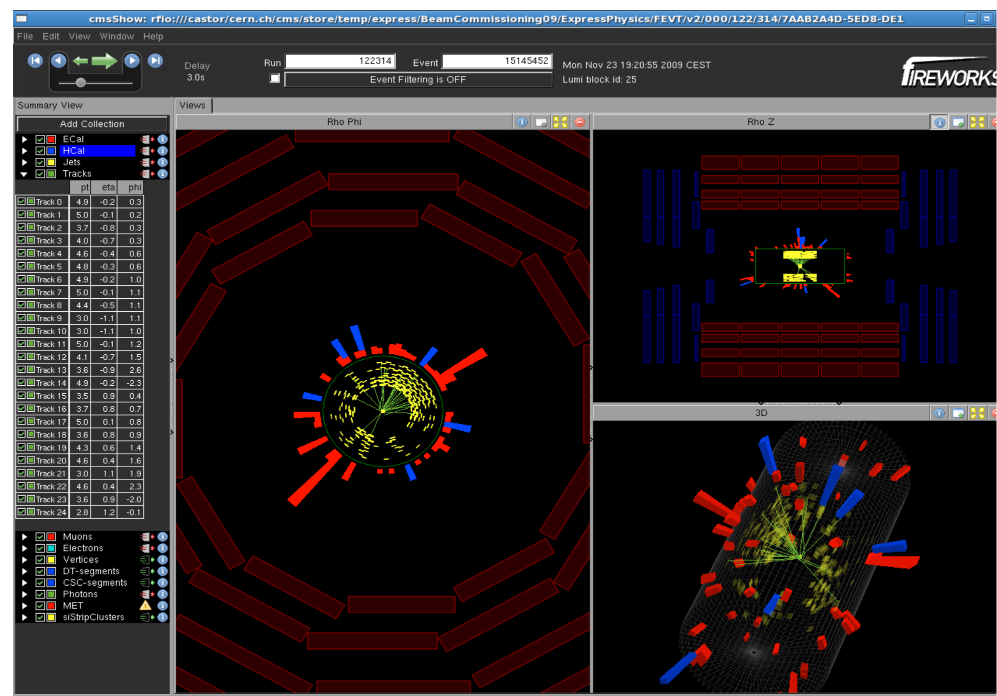


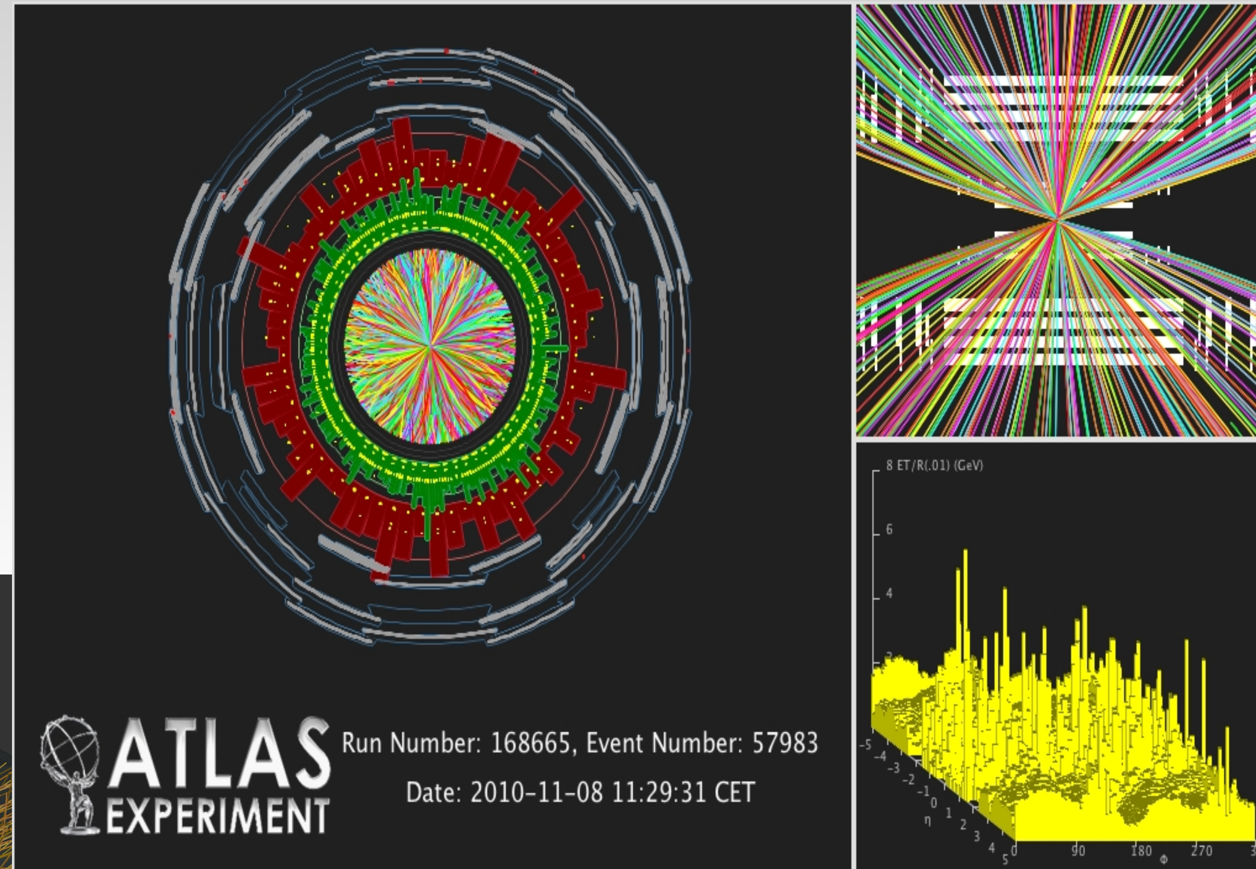


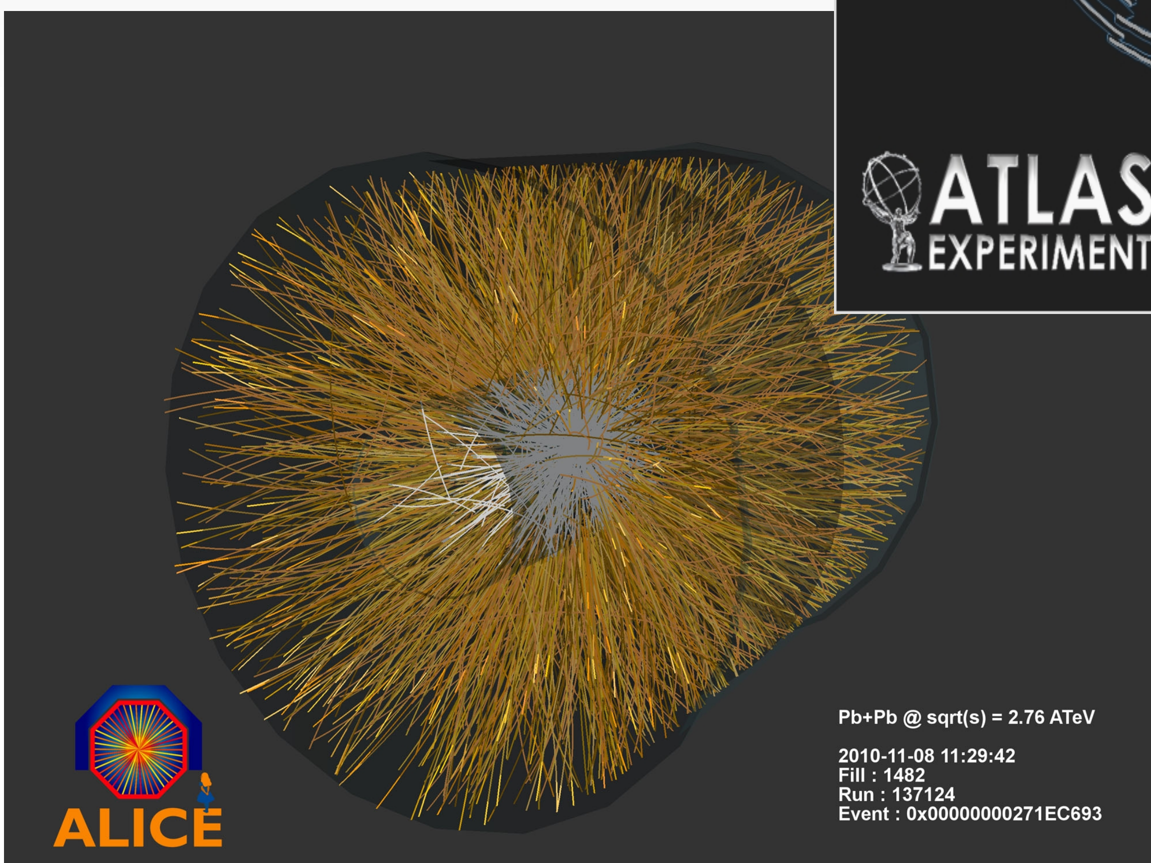
ATLAS Online $\sqrt{s}$ = 7 TeV
Total Efficiency: 93.6%
Recording Efficiency [percent]
120
110
100
90
80
70
60
01/03
03/05
05/07
06/09
08/11
Date in 2010




Soft collisions with just few tracks but important for alignment and trigger studies



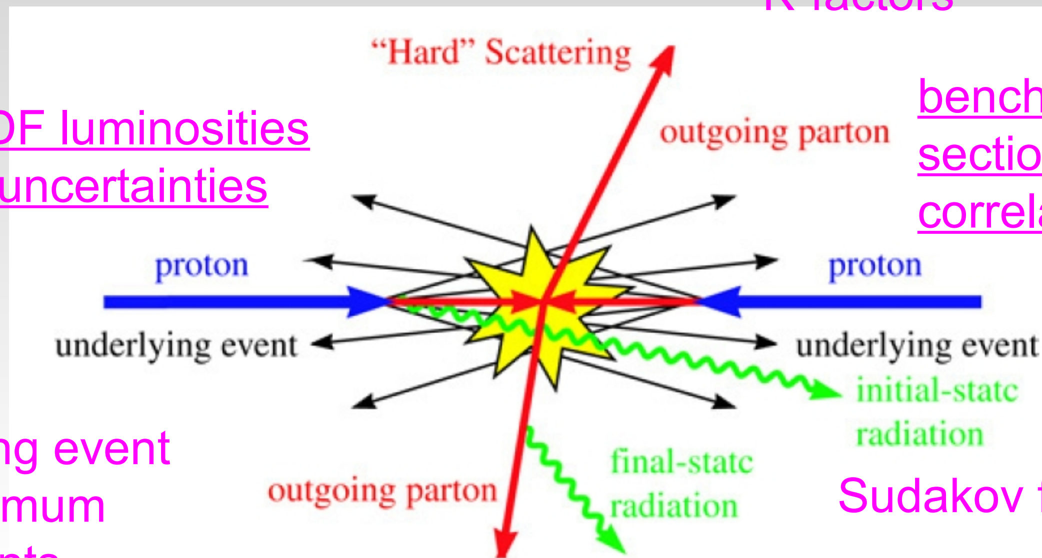

ATLAS EXPERIMENT
Run Number: 168665, Event Number: 57983
Date: 2010-11-08 11:29:31 CET
8 ET/R(.01) (GeV)
90
180
270
360


Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:29:42
Fill : 1482
Run : 137124
Event : 0x00000000271EC693
ALICE

LO, NLO and NNLO calculations
K-factors

PDF's, PDF luminosities and PDF uncertainties

benchmark cross sections and pdf correlations




underlying event and minimum bias events

Sudakov form factors

jet algorithms and jet reconstruction

$$\sigma = \sum_{i,j} \int_0^1 dx_1\, dx_2\, f_i(x_1, \mu)\, f_j(x_2, \mu)\, \hat{\sigma}_{ij}$$

The functions $f_1$, $f_2$ (PDF's) are fractional momentum distributions (x = Pp/Pbeam) of the partons inside a proton.

Gluons and quarks other than the valence (uud) are present, with steeply falling distributions

This is why for low-mass objects a pp or p-antip collider are almost the same

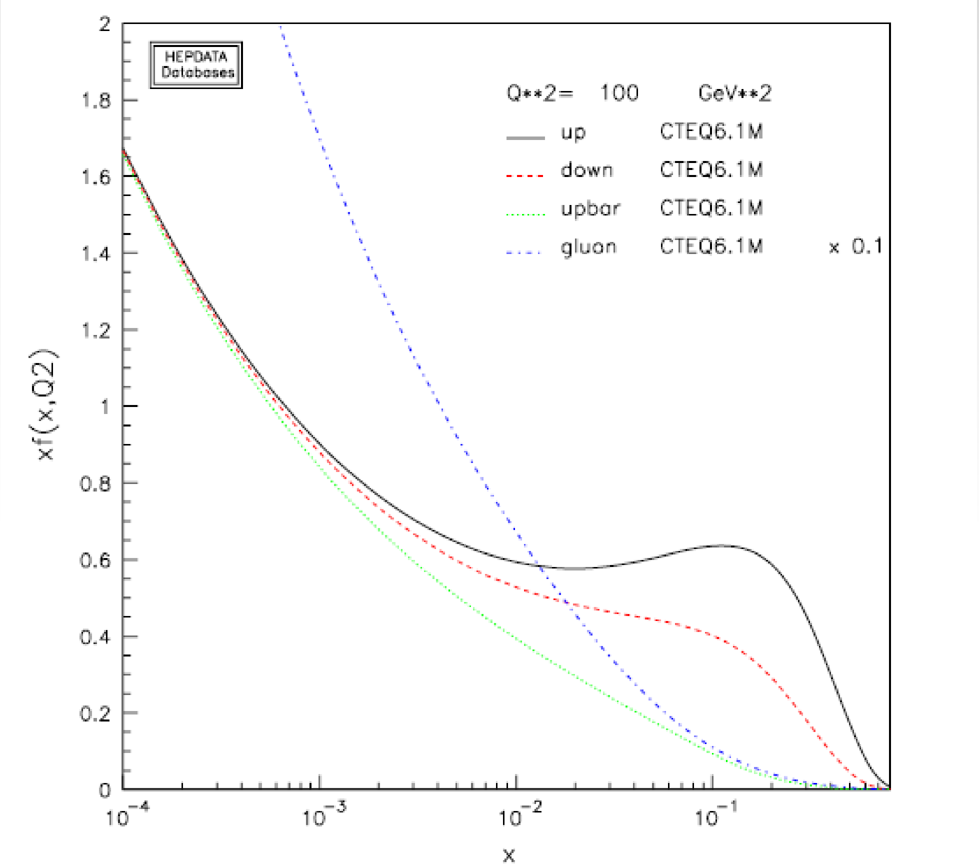



**Figure 27.** The CTEQ6.1 parton distribution functions evaluated at a $Q$ of 10 GeV.

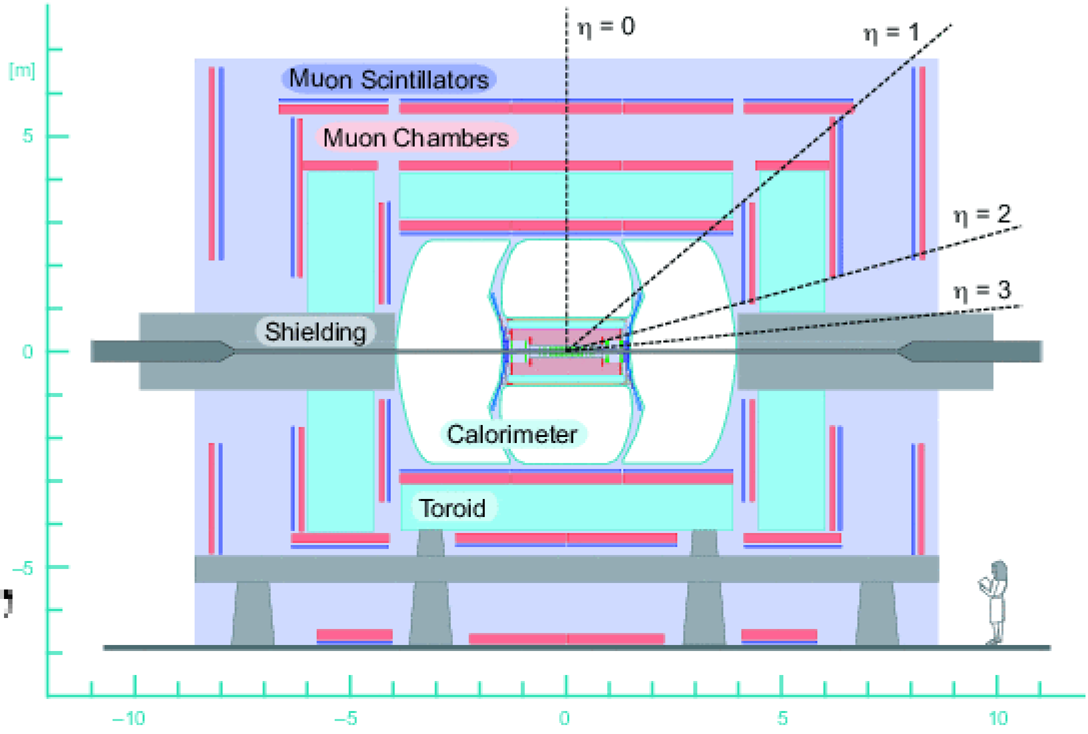
Typically the two colliding partons will have different x → event will be longitudinally unbalanced (Lorentz-boosted)

- Only variables invariant under z-boost should be used.
- This is why cuts are expressed in terms of Et and not E, and instead of the angle θ we use rapidity

$$\phi_z = \frac{1}{2}\log_e\frac{E+p_z c}{E-p_z c}$$

It depends on the mass of an object, so it cannot directly reference to a detector location; for that we use pseudorapidity, equal to rapidity for massless particles:

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$



# Kinematic region of the LHC

Note that the data from HERA and fixed target cover only part of kinematic range accessible at the LHC

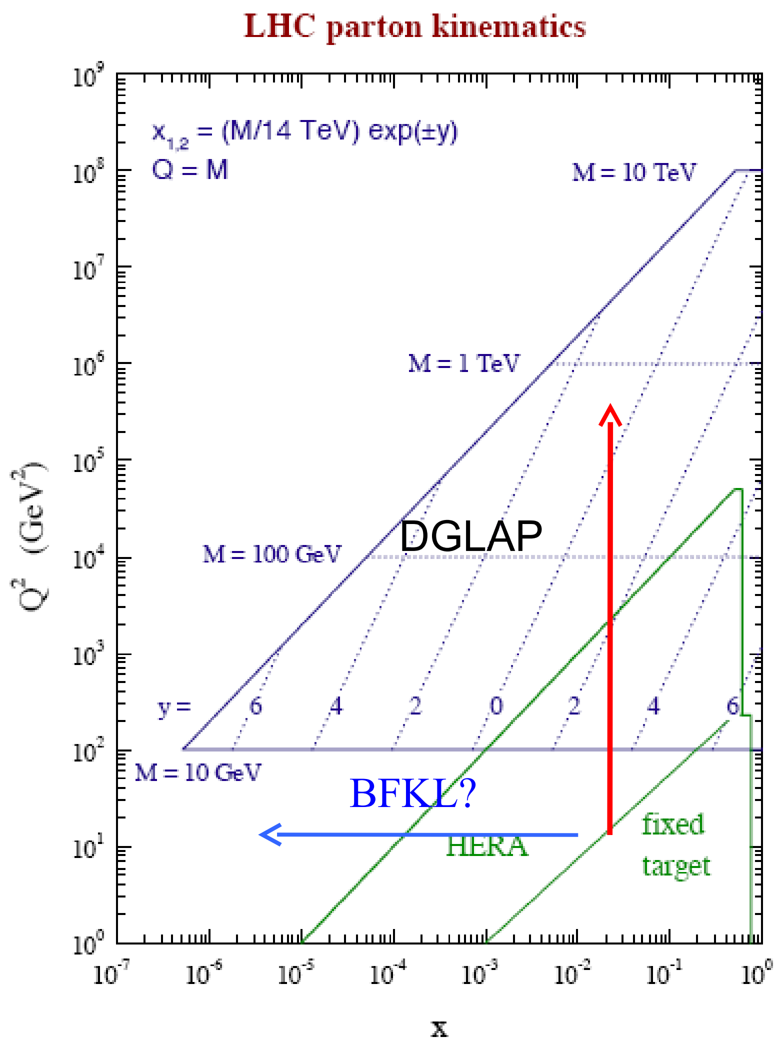
We will access pdf's down to 1E$^{-6}$ (crucial for the underlying event) and $Q^2$ up to 100 TeV$^2$

We can use the DGLAP equations to evolve to the relevant x and $Q^2$ range, but…

we're somewhat blind in extrapolating to lower x values than present in the HERA data, so uncertainty may be larger than currently estimated

we're assuming that DGLAP is all there is; at low x BFKL type of logarithms may become important

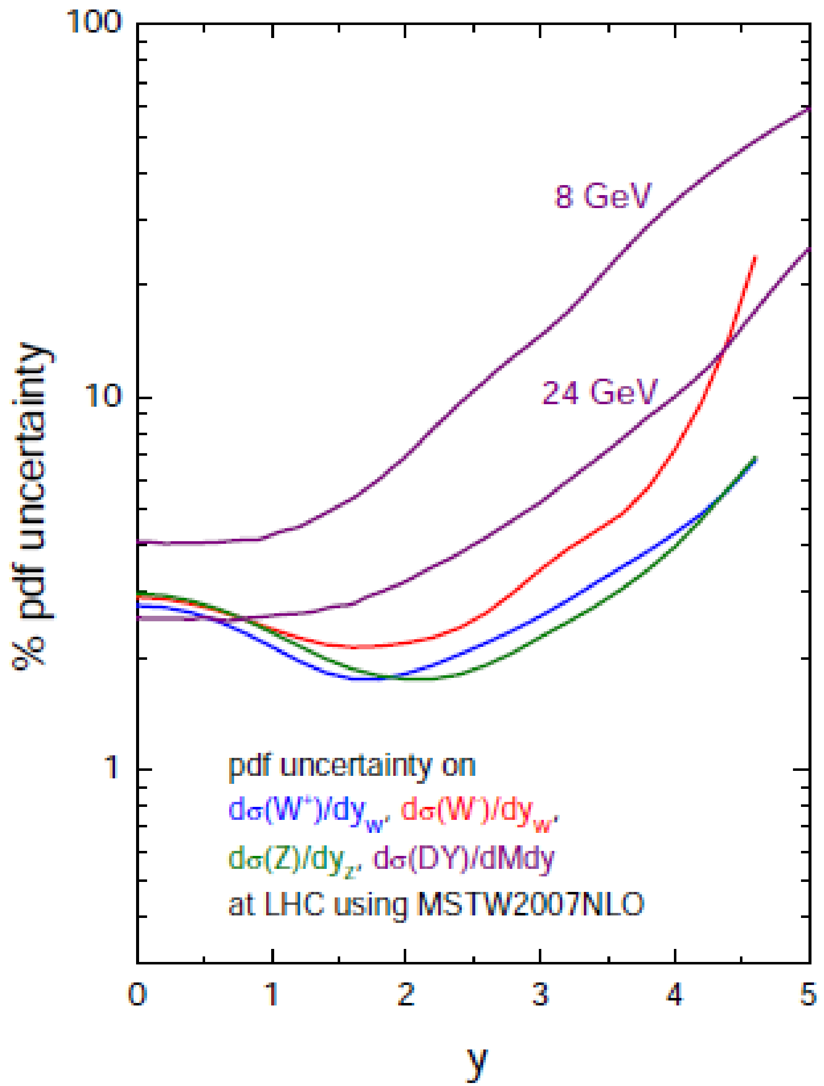
$$\frac{d\sigma}{dM^2 dy} = \frac{\hat{\sigma}_0}{Ns}\left[\sum_k Q_k^2 (q_k(x_1, M^2)\bar{q}_k(x_2, M^2) + [1 \leftrightarrow 2])\right]$$



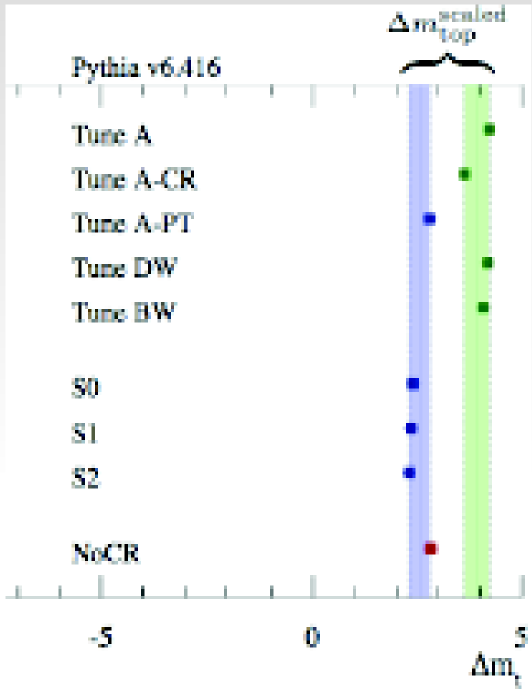
Uncertainty on $\sigma(Z)$ and $\sigma(W^+)$ grows at high rapidity.

Uncertainty on $\sigma(W^-)$ grows more quickly at very high $y$ – depends on less well-known down quark.

Uncertainty on $\sigma(\gamma^\star)$ is greatest as $y$ increases. Depends on partons at very small $x$.



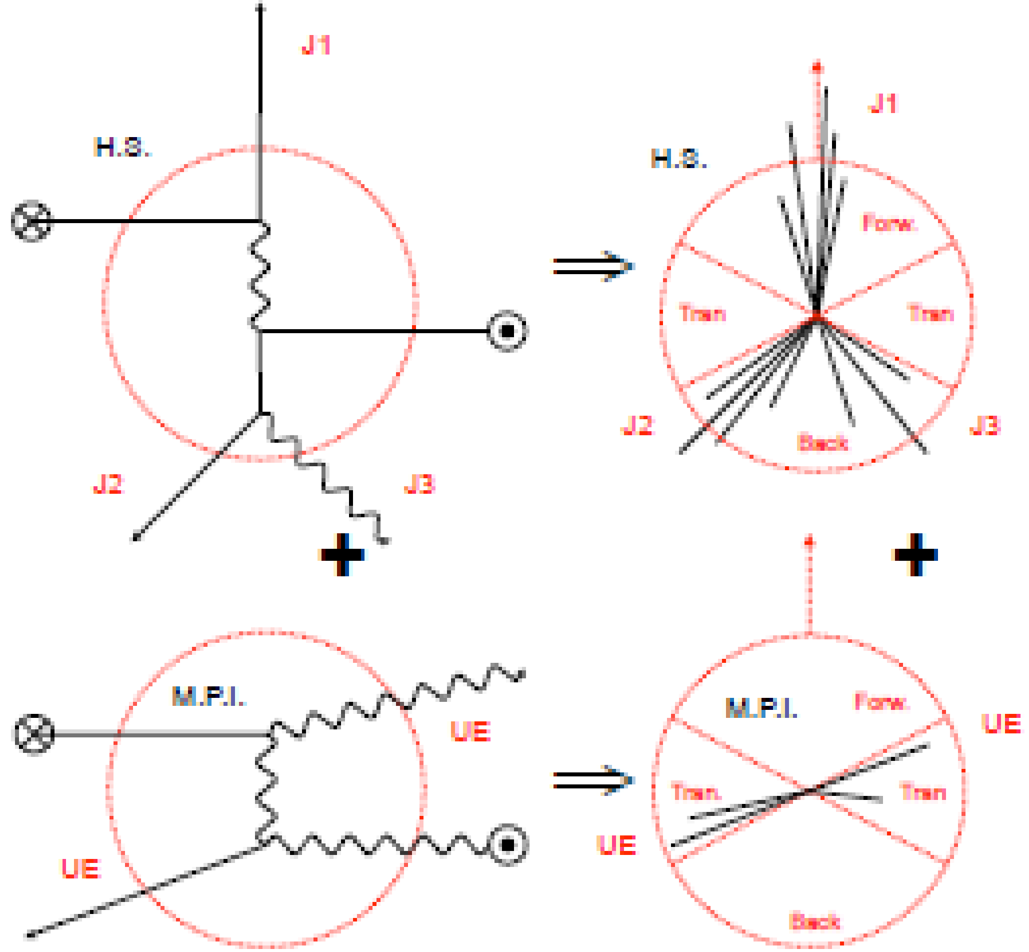
- UE: everything apart from the hard scattering (beam remnant, Multiple Parton Interctions, etc.)
- Will pollute all your physics events (especially ”rapidity gaps”), and influence precision measurements
- normally softer (but with large fluctuations)

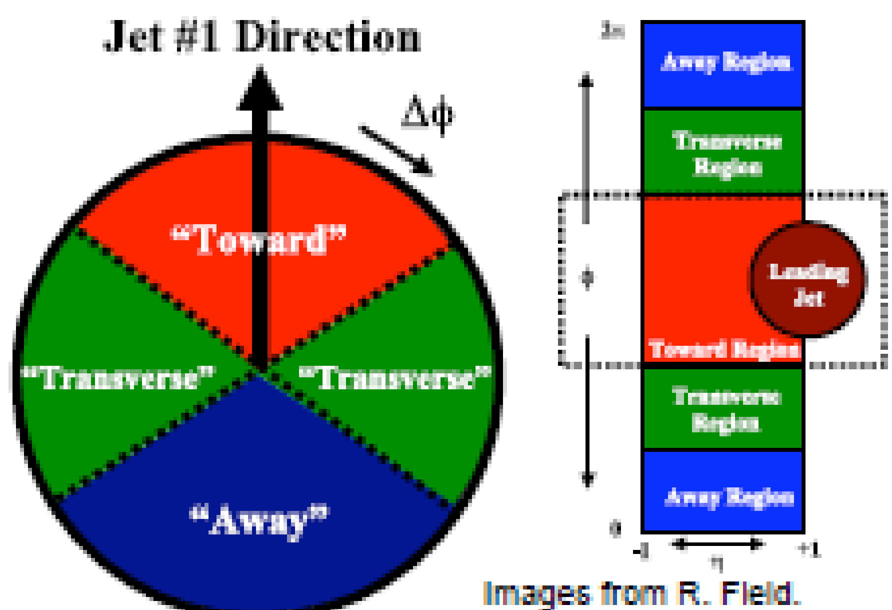



- We are in the realm of non-perturbative QCD, so only possible to do empiric models to be tuned on data
- These models are similar to those use to model soft scattering events (the Minimum Bias), which are the events we are taking right now
- Various models implemented in generators: Pythia, Herwig, Phojet

# UE Characterization

- Hard Scatter yields* 2 or 3 hard jets.
  *Given sufficient qualifying statements…
- Two equally hard jets will be roughly back-to-back.
- Additional interactions yield softer particles whose directions are not correlated to the hard scatter axis.
- Fragmentation, especially due to connections to remnants, can yield additional particles.
- Three equally hard jets are roughly at $2\pi/3$ intervals.
- $\pi/3 < |\Delta\varphi| < 2\pi/3$ and $|\eta| < 1$ defines the transverse region.
- For the third hardest jet to be in the transverse region it must be softened.




Images from R. Field.

# What is soft-QCD?

QCD = Quantum ChromoDynamics (i.e. the strong force)

soft = low momentum transfer

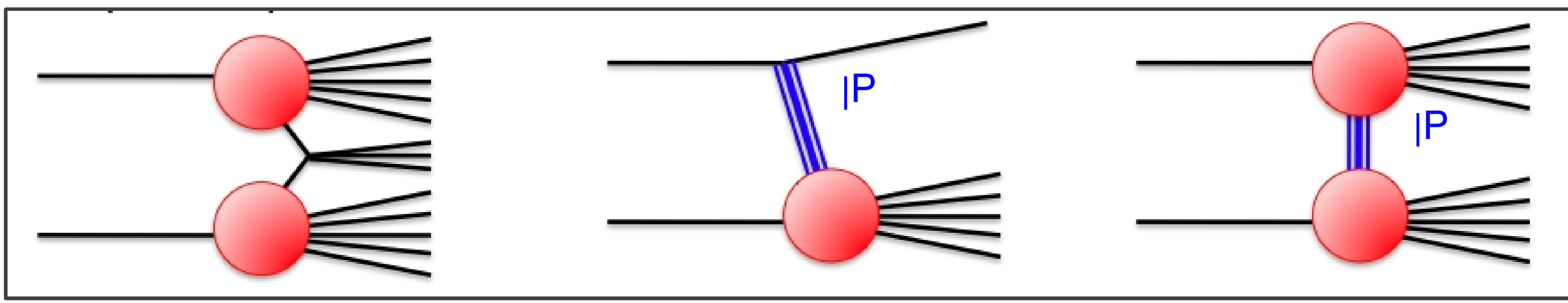
These are the dominant types of interaction at hadron colliders

# What is soft-QCD?

Elastic interaction: A(pA) + B(pB) → A(pA‘) + B(pB‘)

Inelastic interaction: A + B → Σxi (≠ A + B)

Dominant processes in inelastic hadron-hadron interactions :




Non-Diffractive (ND) σ~49 mb

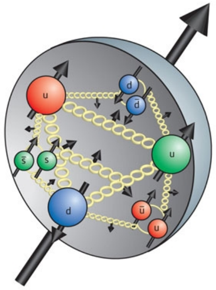
Single-Diffractive-Dissociation (SD) σ~14 mb

Double-Diffractive-Dissociation (DD) σ~9 mb

@ 7 TeV

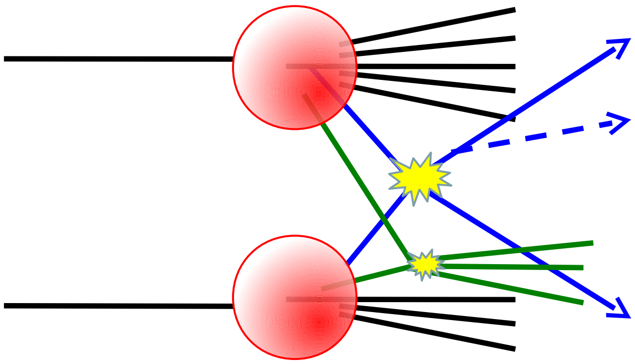
|P = Pomeron (quantum numbers of the vacuum)

# What is soft-QCD?



Soft-QCD processes also occur in the same proton-proton interaction as a (more interesting) hard interaction:

Multiple Parton Interactions (MPI)



The Underlying Event (UE) is everything not associated with the hard parton-parton interaction

# Why do we care ?

These processes cannot be calculated from first principles (the strong coupling blows up at low scales and perturbative calculations are not possible). What is going on at these scales?

soft-QCD affecting the high pT physics program at hadron colliders:

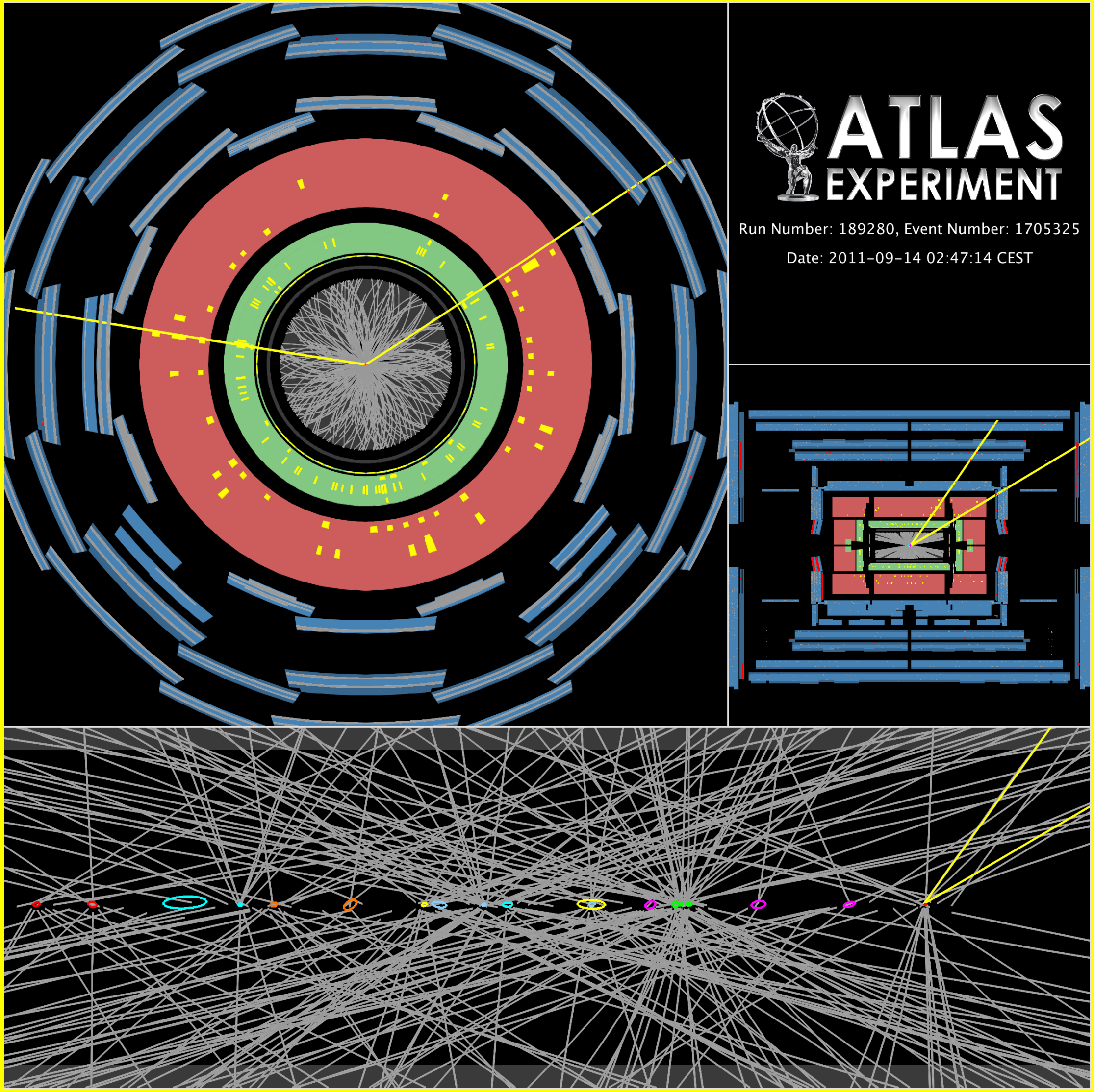
Pileup: LHC ~20 proton-proton interactions at the same time, they will almost always be soft-QCD processes

Multi Parton Interactions: An interesting parton-parton interaction will have many additional parton-parton interactions occurring in the same proton-proton interaction, they will almost always be soft-QCD processes

Therefore we had better have a good model of these processes! Can affect simulations of lepton ID, ETmiss resolution, jets, jet vetos,…

# Pileup

Important for understanding 20 pp interactions on top of your Higgs!!



# Monte Carlo Event Generators

See Glen Cowan's course next week for all the details

In brief:

Theoretical tools that simulate events at colliders

Extensively used to simulate signal and background processes, to help us understand our data and enable us to make measurements

High pT interactions are calculated using perturbation theory

Soft-QCD processes use phenomenological models with theoretical motivation that must be validated against data

These models contain parameters that must be tuned to the data

It is therefore necessary to make measurements of soft-QCD processes

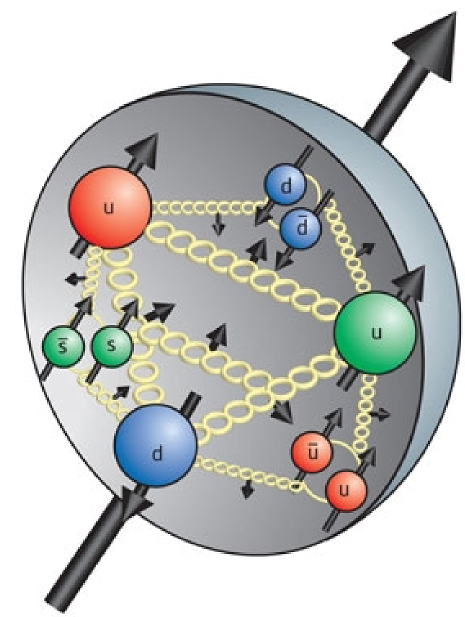
# Soft-QCD models

e.g. Pythia

| | |
|---|---|
| QCD $2 \to 2$ scattering | $\sim \alpha_S^2(p_T^2)/p_T^4$ |
| Dampen divergence at low pT ⇒ | $\sim \alpha_S^2(p_T^2 + p_{T0}^2)/(p_T^2 + p_{T0}^2)^2$ |

smaller pT0 ⇒ more low pT activity

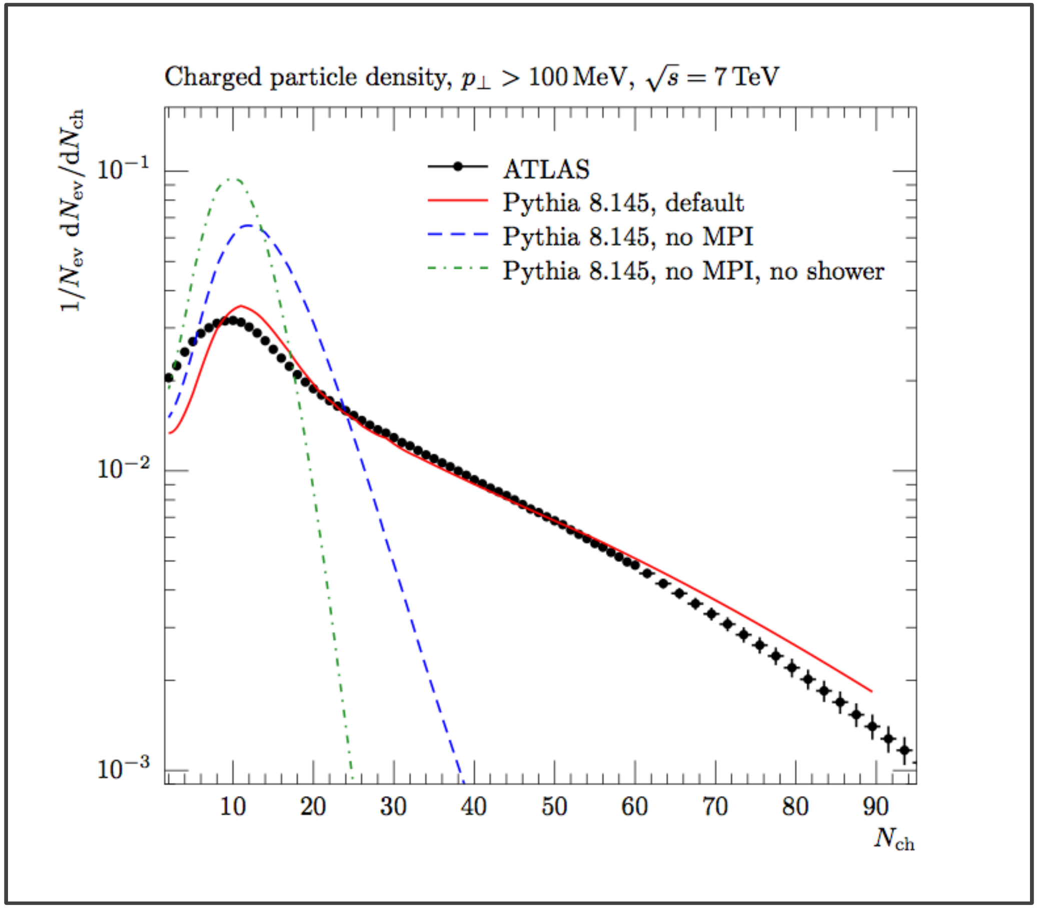
Screening : At low pT wavelength of exchanged particle becomes too large to resolve colour charges



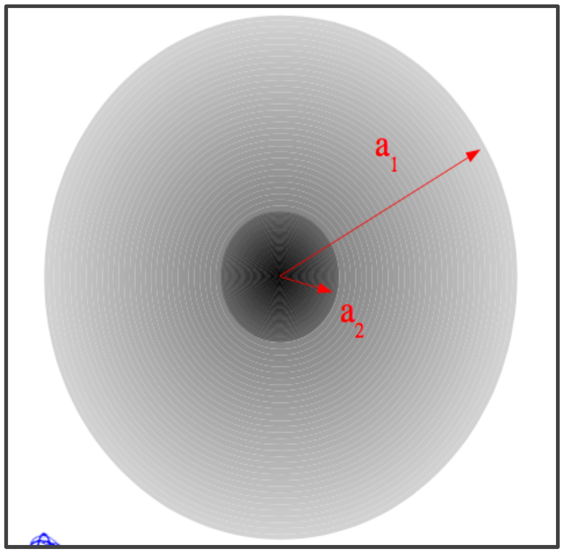

$p_{T0} = P_1 \, (E_{COM} / 1.8 \text{ TeV})^{P_2}$

# Multiple Parton Interactions

The soft-QCD models need to include MPI



# Soft-QCD models




Matter distribution in proton described by double Gaussian

P3 = fraction in core Gaussian
P4 = a2 / a1

(denser matter distribution ☾ more multiple interactions ☾ more activity)

# Experimental Measurements

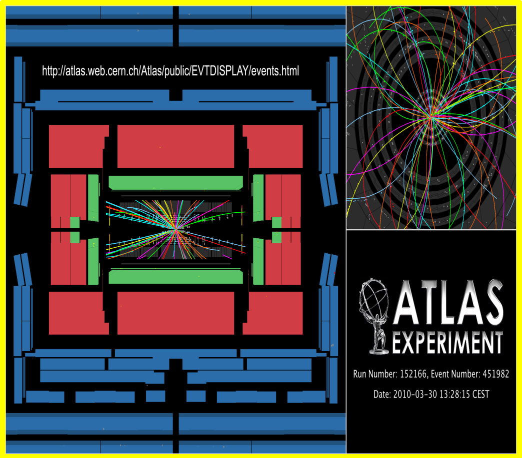
1. Minimum Bias
2. Underlying Event
3. Total cross-section
4. Diffractive cross-sections
5. Particle Correlations

1. Minimum Bias
2. Underlying Event
3. Total cross-section
4. Diffractive cross-sections
5. Particle Correlations

# Minimum bias measurements

**Minimum bias** adj. experimental term, to select events with the minimum possible requirements that ensure an inelastic collision occurred.

- Exact definition depends on detector (and analysis)
- Typically measure kinematics (multiplicity, pT and η spectra, etc) of charged particles in "minimum bias" events using central tracking detectors
- Monte Carlo parameters will be tuned to these distributions




Charged particles moving through a magnetic field will bend by an amount inversely proportional to pT

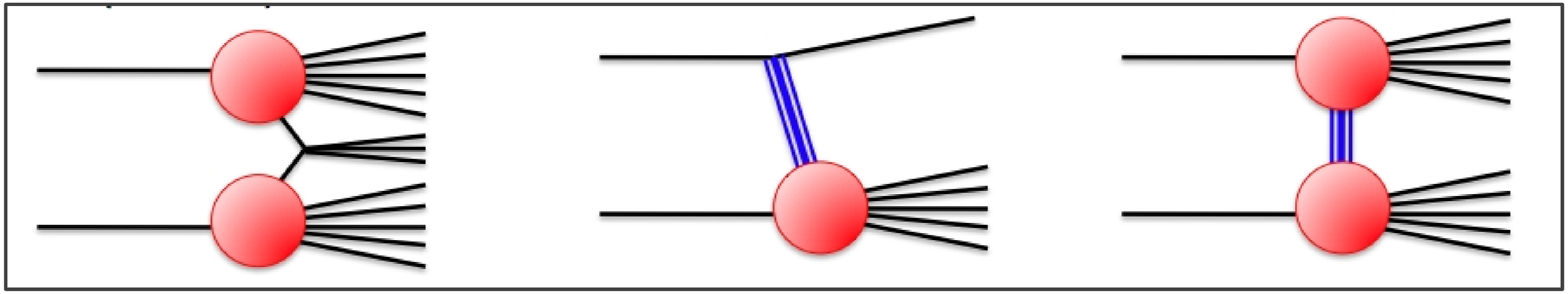
e.g. ATLAS: (a) At least two charged particles with $p_T > 100$ MeV, $|\eta| < 2.5$ (most inclusive)
(b) At least six charged particles with $p_T > 500$ MeV, $|\eta| < 2.5$ (suppresses diffraction)

definition of minimum bias in each analysis

# Measurement philosophy

How should you do a measurement that is optimally useful for theory validation and MC tuning?

- Correct measurements for detector inefficiencies and resolutions (e.g. measure pT spectrum of charged particles, not of ATLAS tracks)
- No extrapolations into regions not “seen” by ATLAS (such as very low pT or far-forward particles)
  - We measure what we see, not what the MC tells us we should have seen!
- No corrections for diffractive events (rather make reproducible cuts that suppress diffraction) ~~Non-Single-Diffractive~~
  - On an event-by-event basis we do not know what process occurred



# Triggering the events

Measurement performed with early data

Few interactions per crossing (mean ~ 0.007)

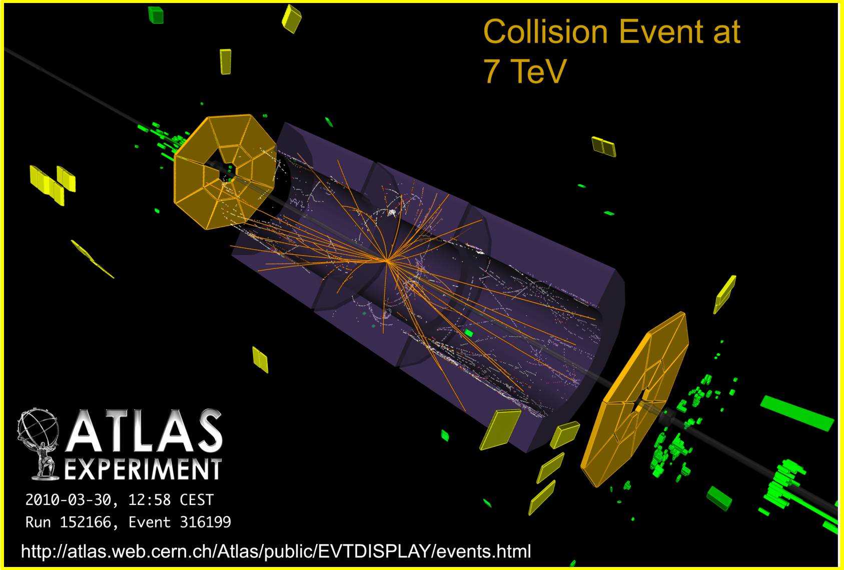
~ No additional interactions

But … 99.3% of beam crossings have no interaction!

Need to “trigger” on inelastic interactions

Use Minimum Bias Trigger Scintillators (very inclusive)

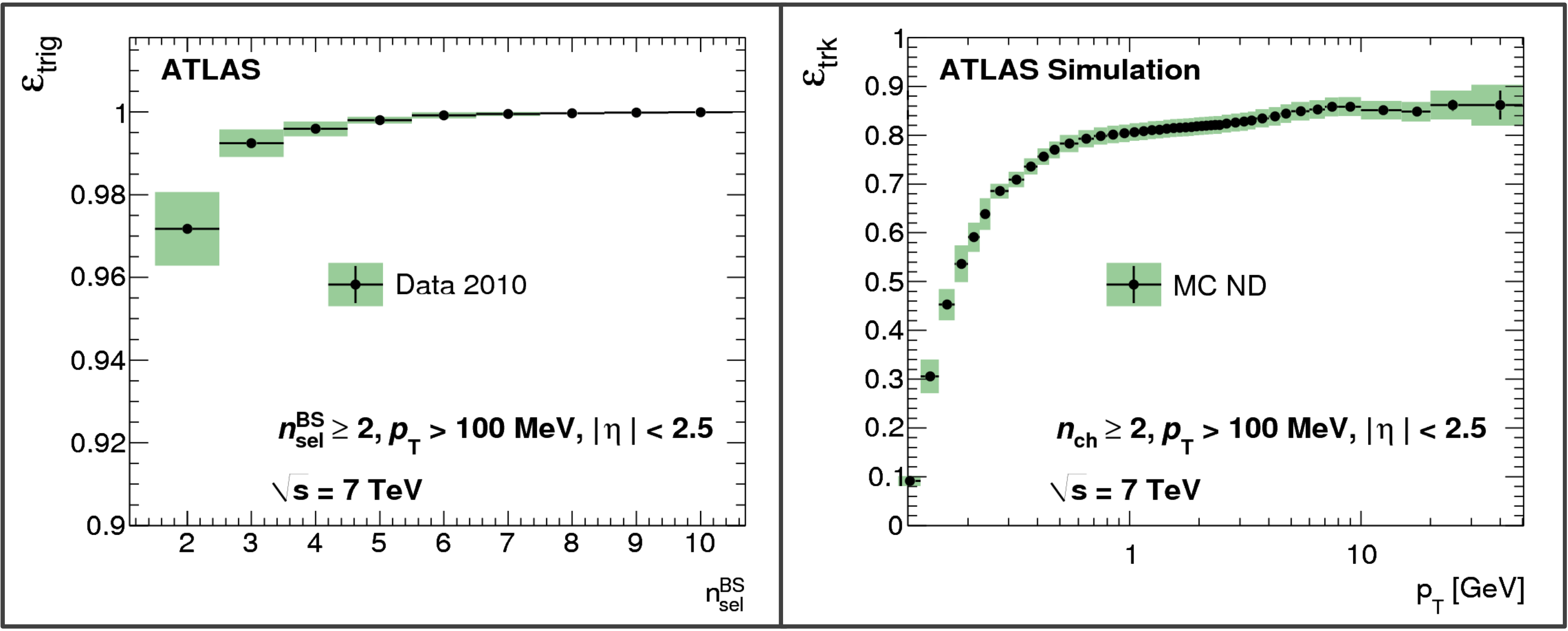
Minimum Bias Trigger Scintillator disks trigger on any charged particle with $2.09 < |\eta| < 3.84$



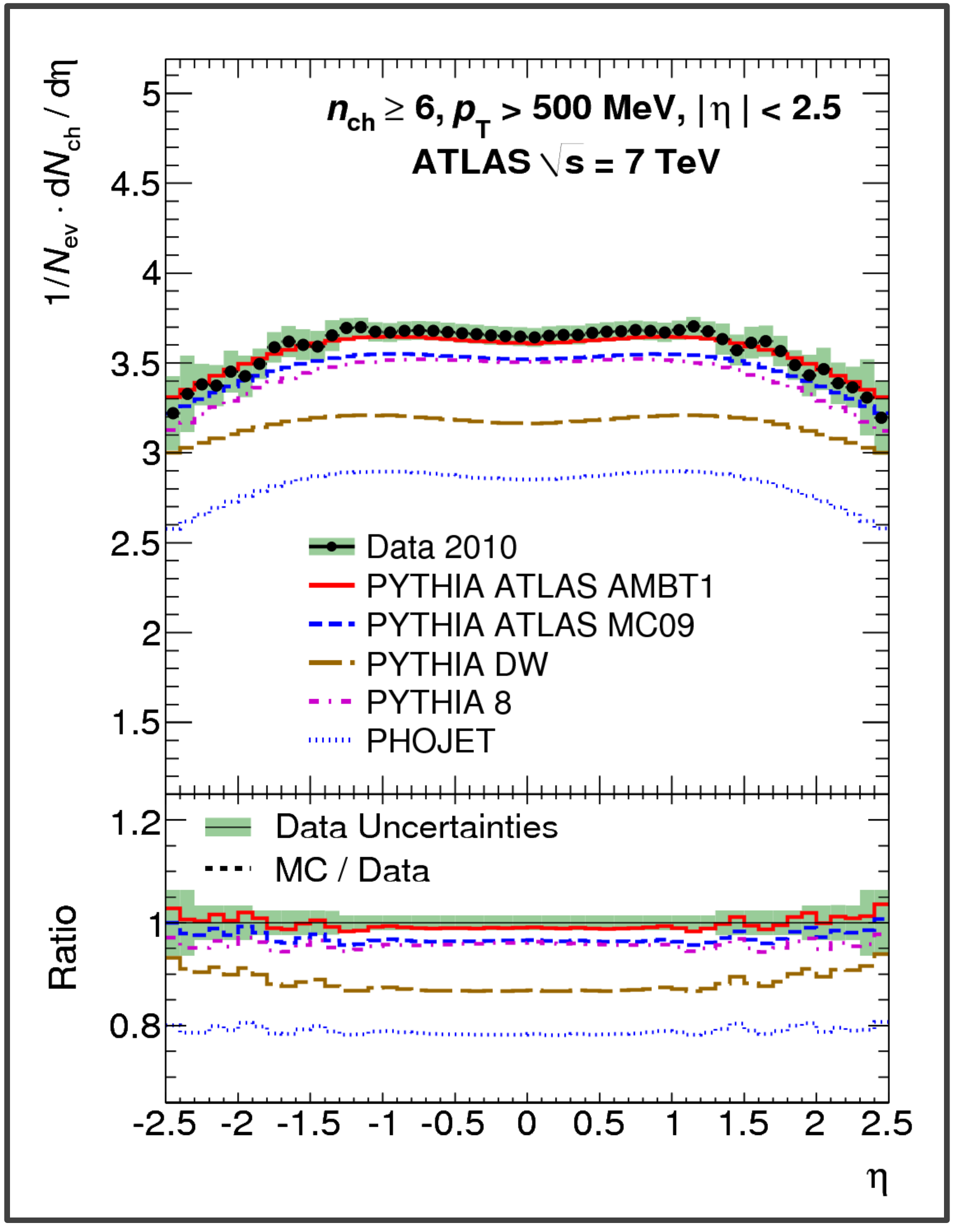
# Correcting the data

Trigger efficiency from data (small "control" sample recorded with different trigger)

Tracking efficiency from Monte Carlo with GEANT detector simulation (systematic uncertainties determined from checks with data)



# η spectra

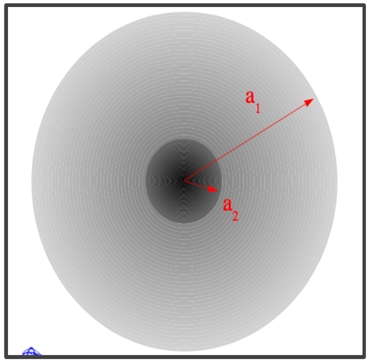




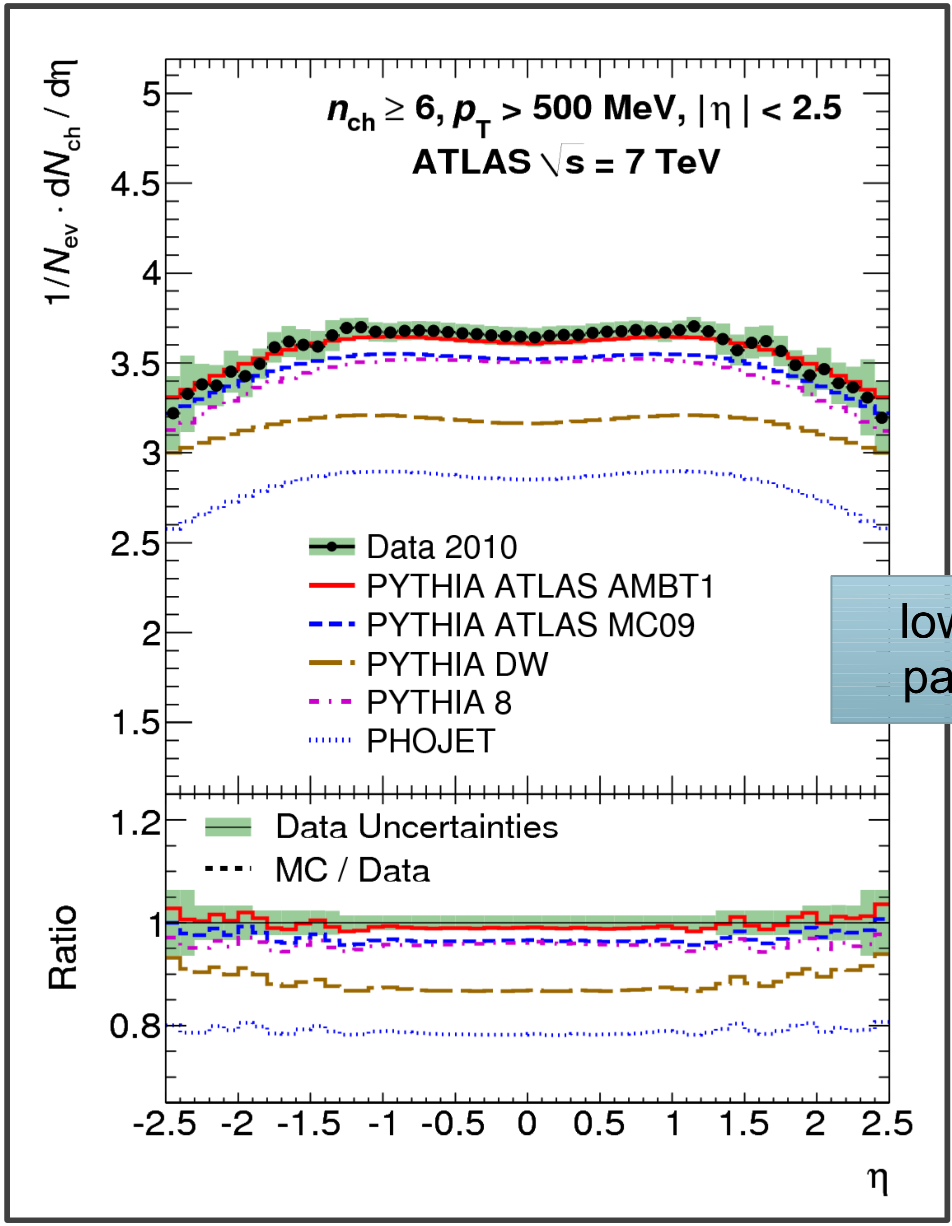
dNch/dη : Number of charged particles per unit η

All but Pythia AMBT1 are tuned to Tevatron data

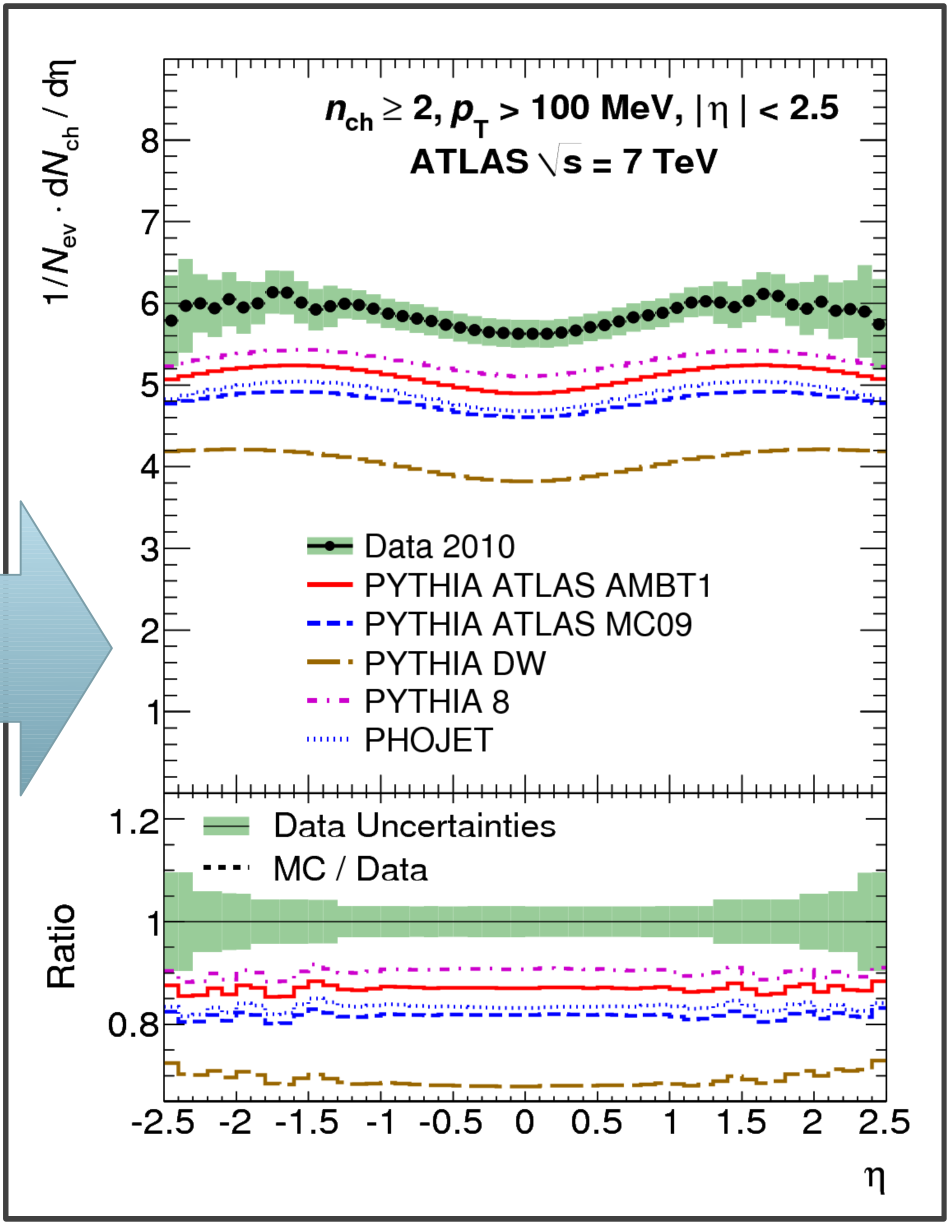
Slight increase in activity in AMBT1 (achieved by a denser proton)



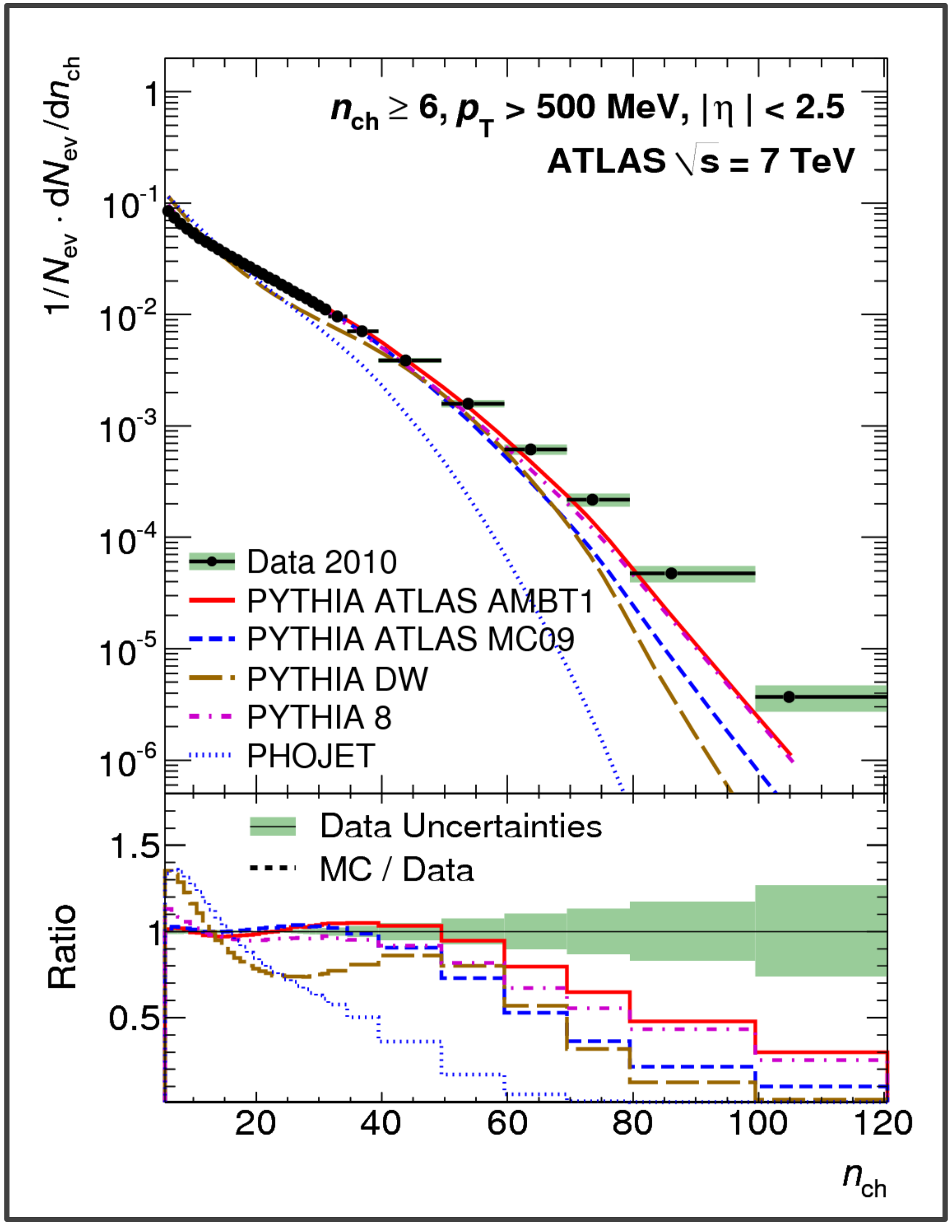
# η spectra

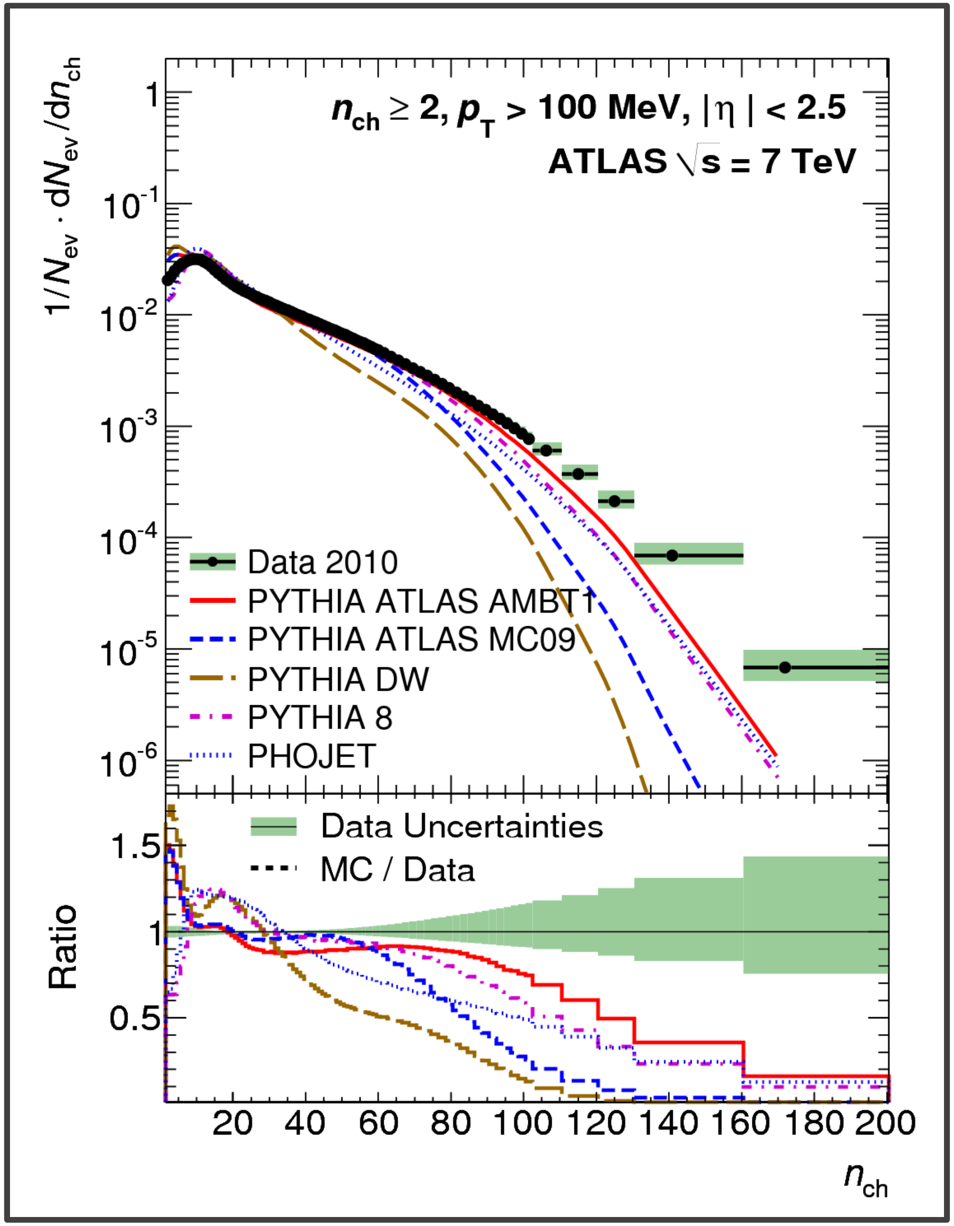



lower pT particles

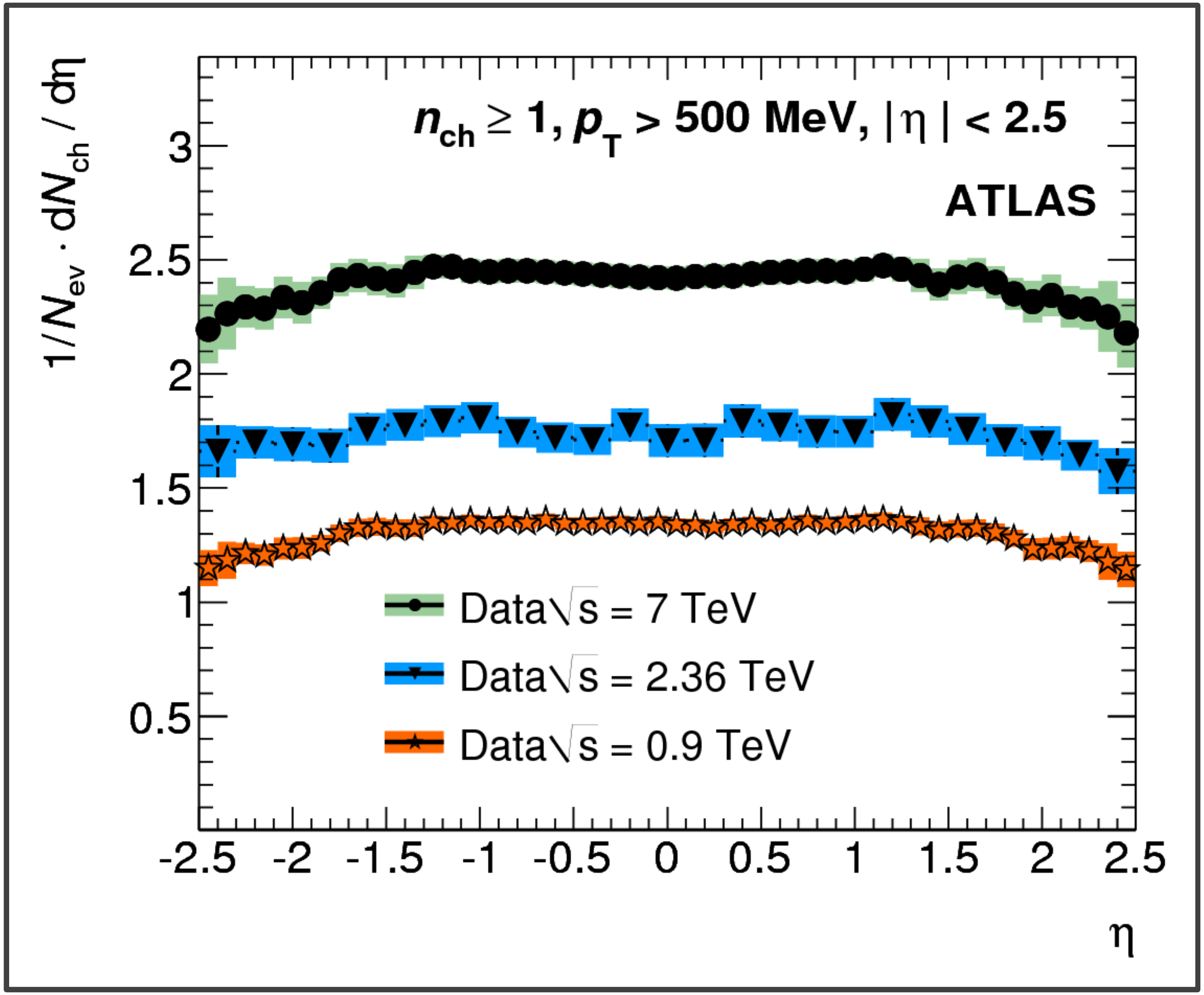


# particle multiplicity



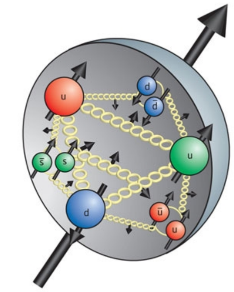
# Results at 0.9, 2.36 and 7 TeV




Higher energy ☾ probing more partons

1. Minimum Bias
2. **Underlying Event**
3. Total cross-section
4. Diffractive cross-sections
5. Particle Correlations

# Reminder : Underlying Event



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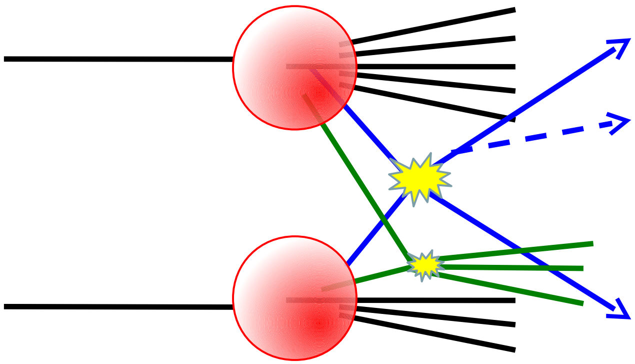


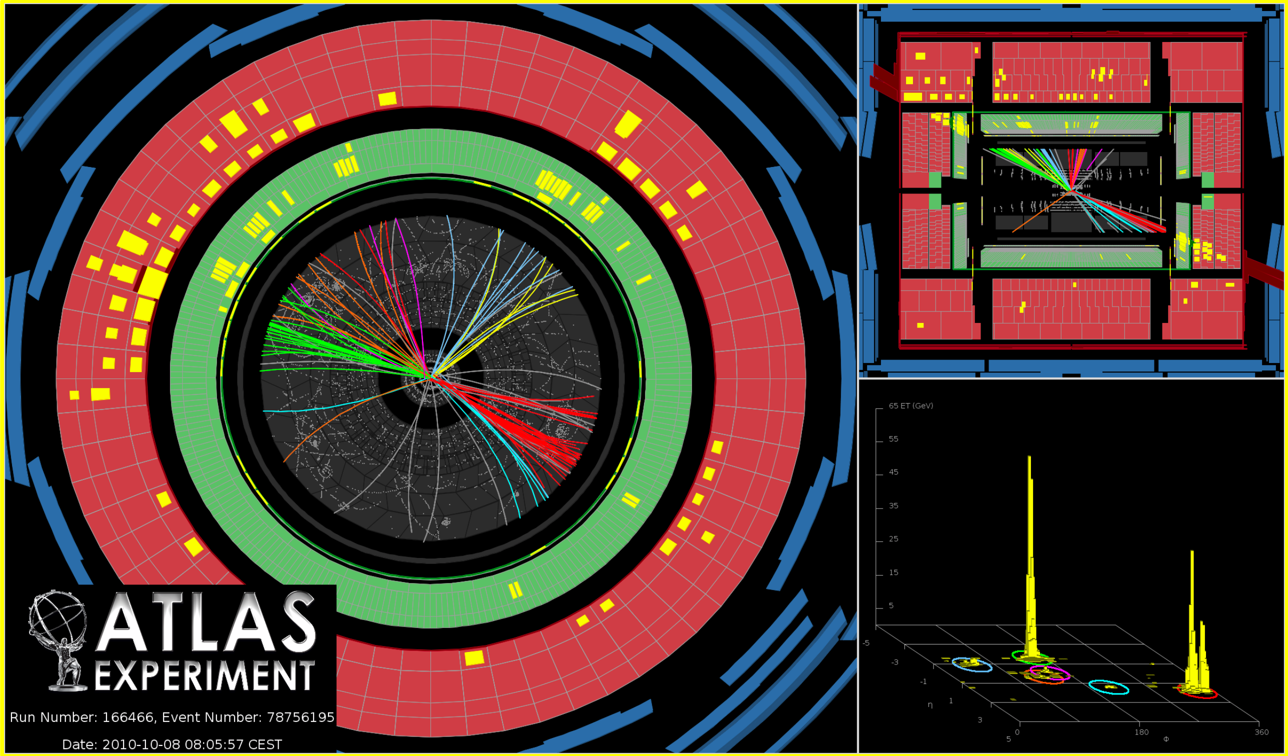
The Underlying Event (UE) is everything not associated with the hard parton-parton interaction

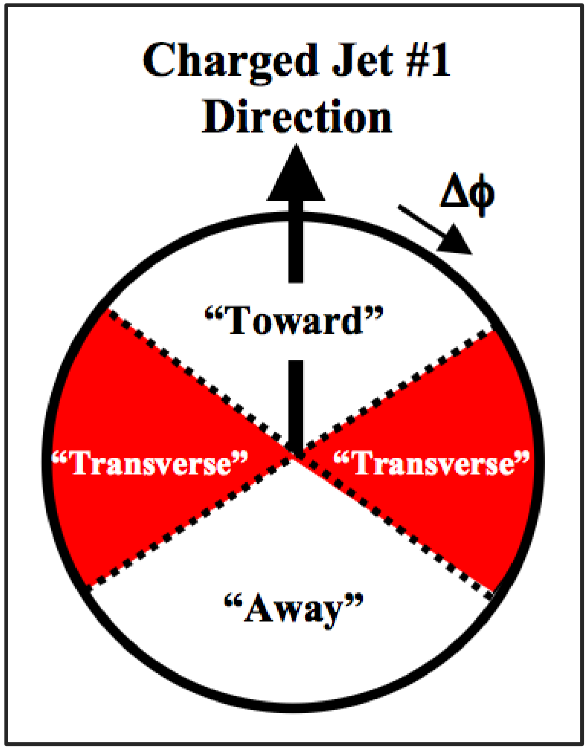
# Underlying Event Measurements

How can we make measurements of the particle activity from the Underlying Event ?

Simple technique pioneered by CDF during Tevatron Run I

e.g. in di-jets : the activity from the hard parton-parton interaction produces two back-to-back jets (in the transverse plane)



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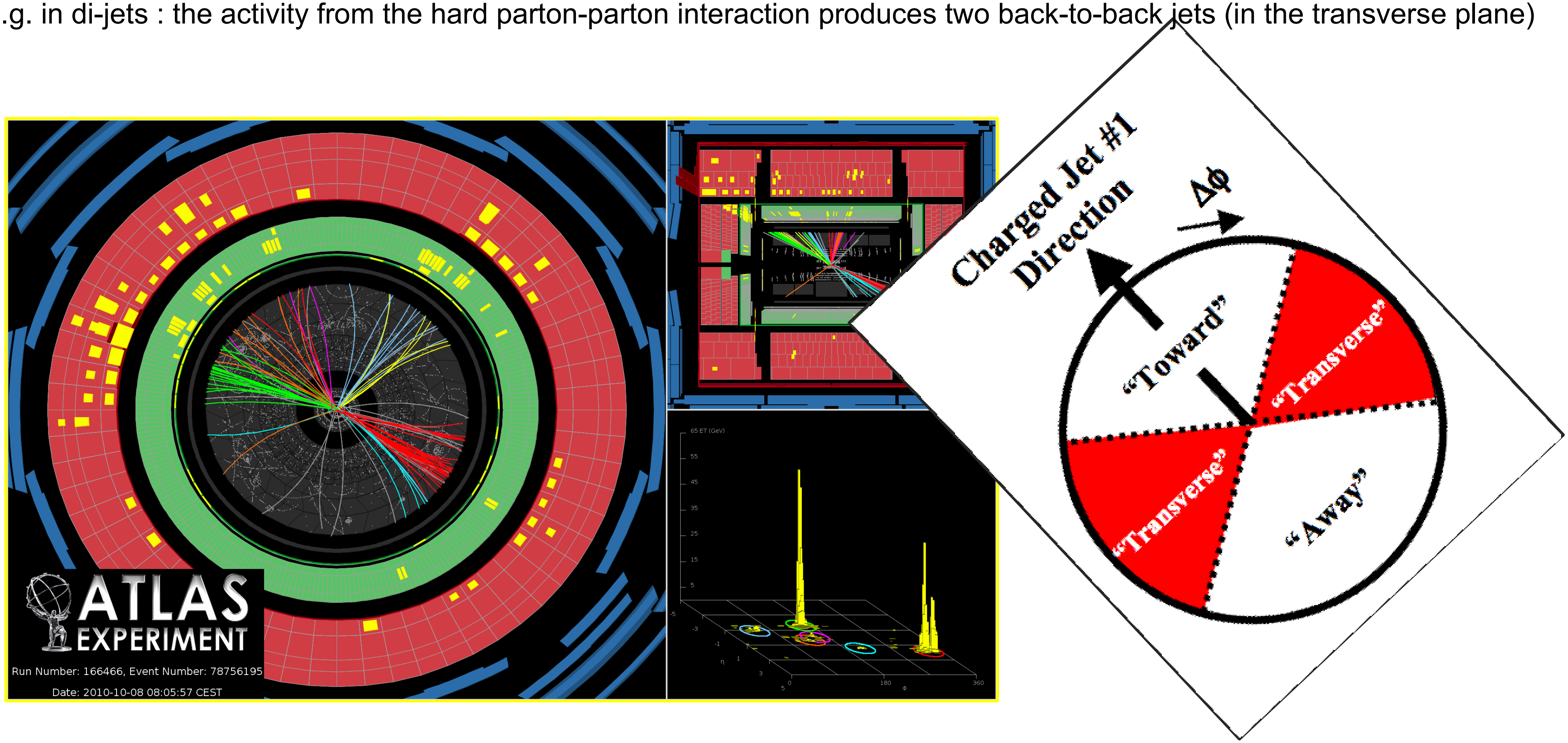
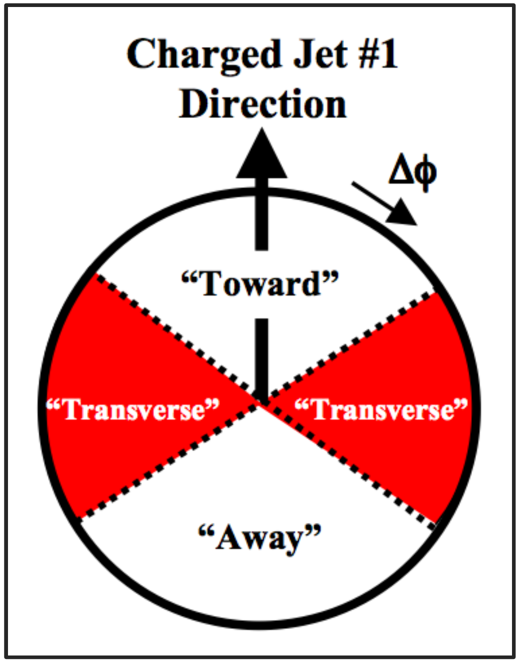
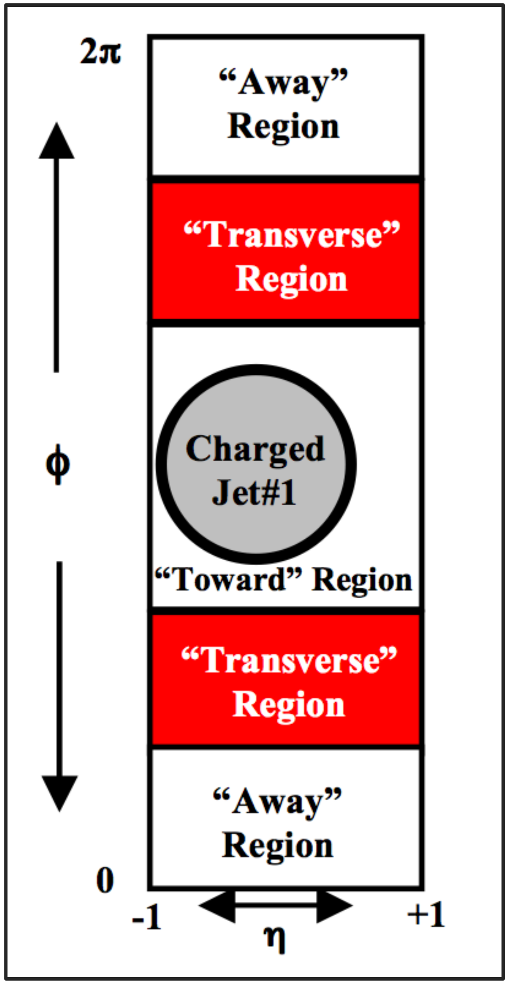


# Underlying Event Measurements

60° < |ΔΦ| < 120°

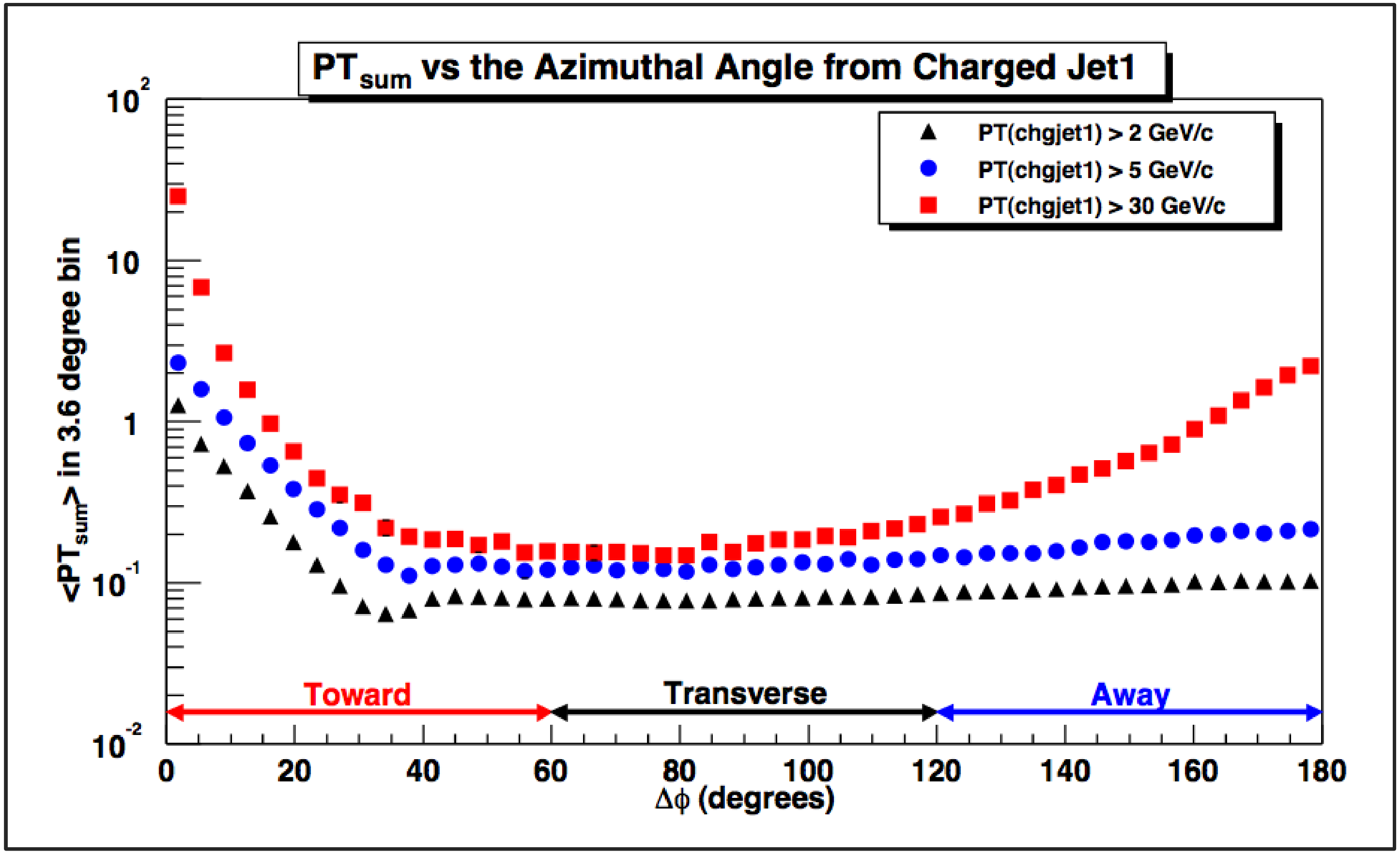


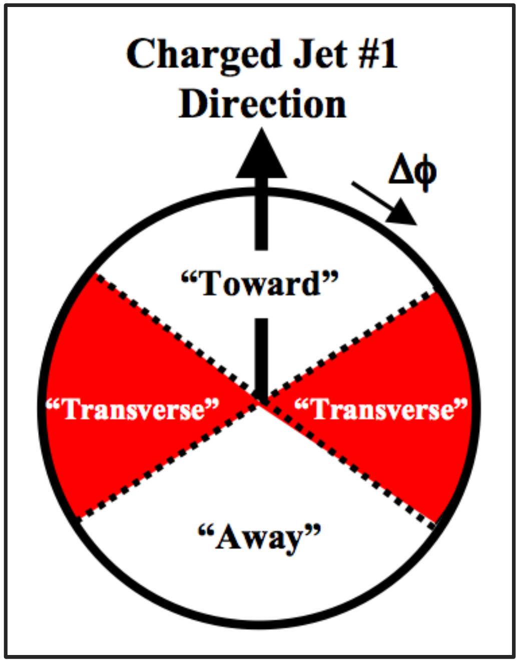




Define the direction of the "hard scatter" (highest pT jet /particle)

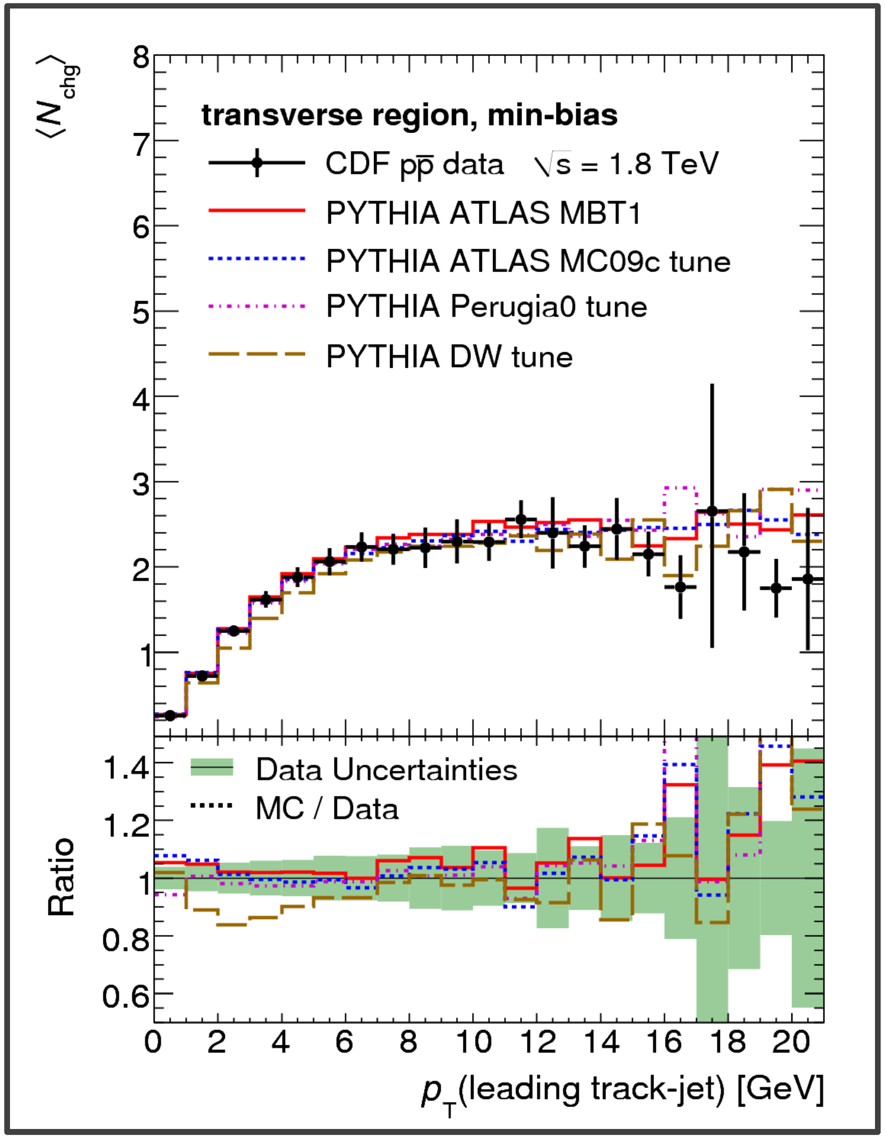
Study the activity (# of particles or ΣpT) in the region "transverse" to the hard scatter

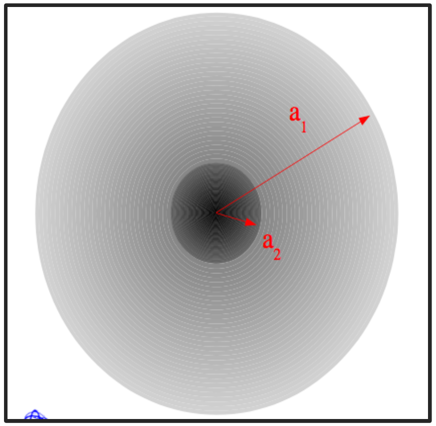
# Underlying Event Measurements



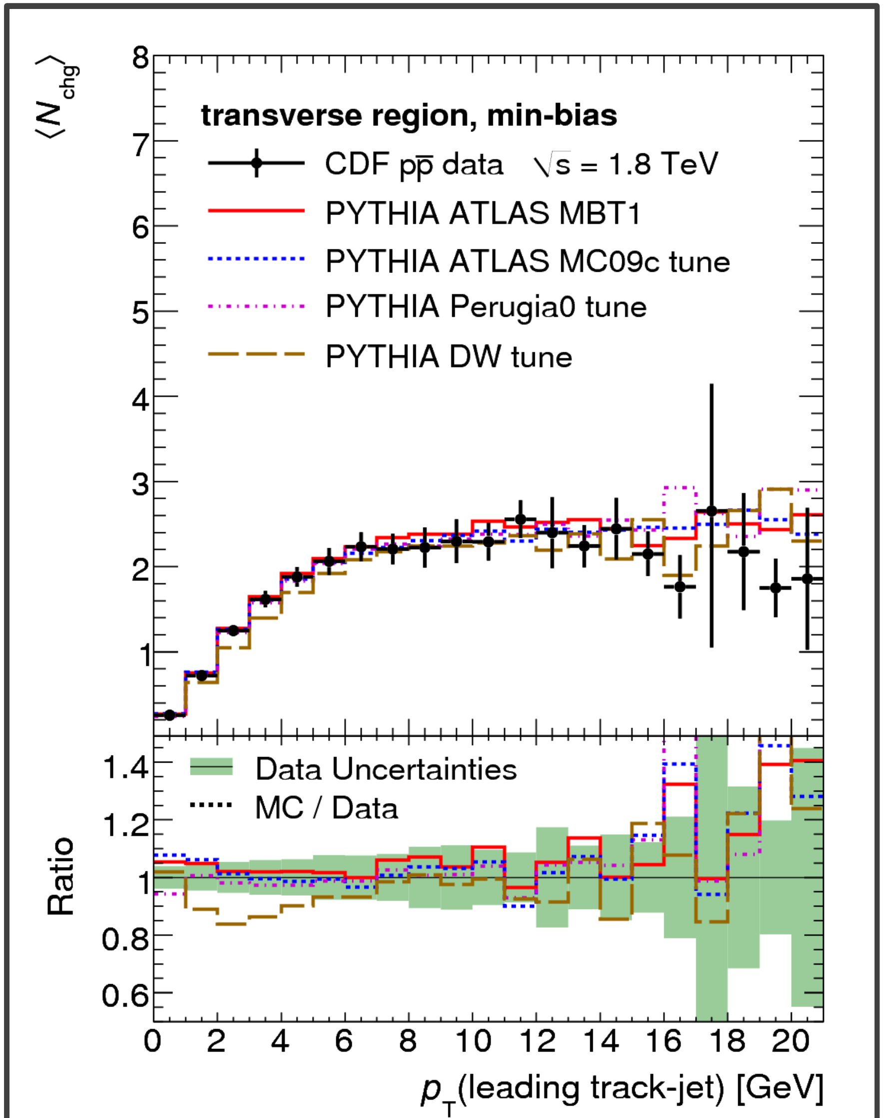
# Underlying Event Measurements

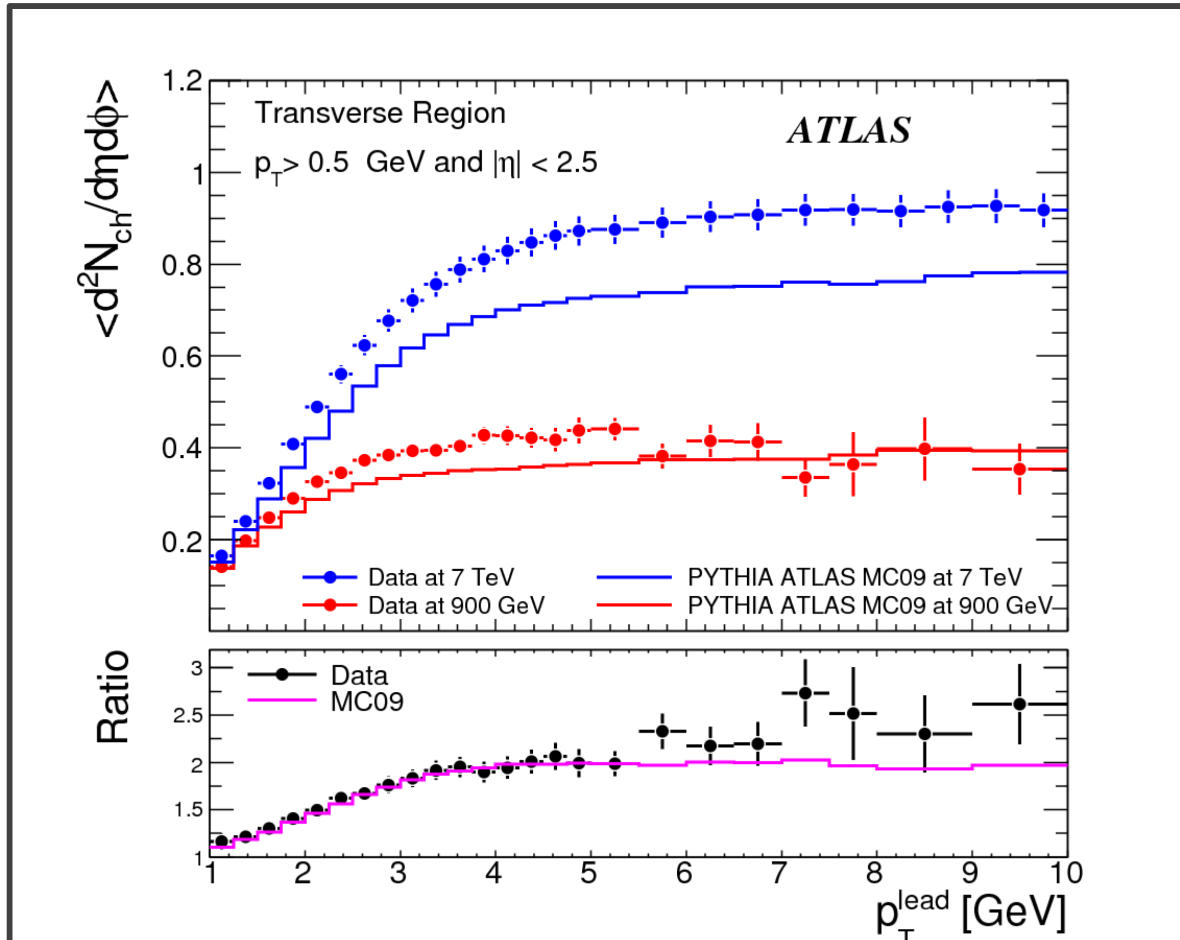



Proton matter distribution

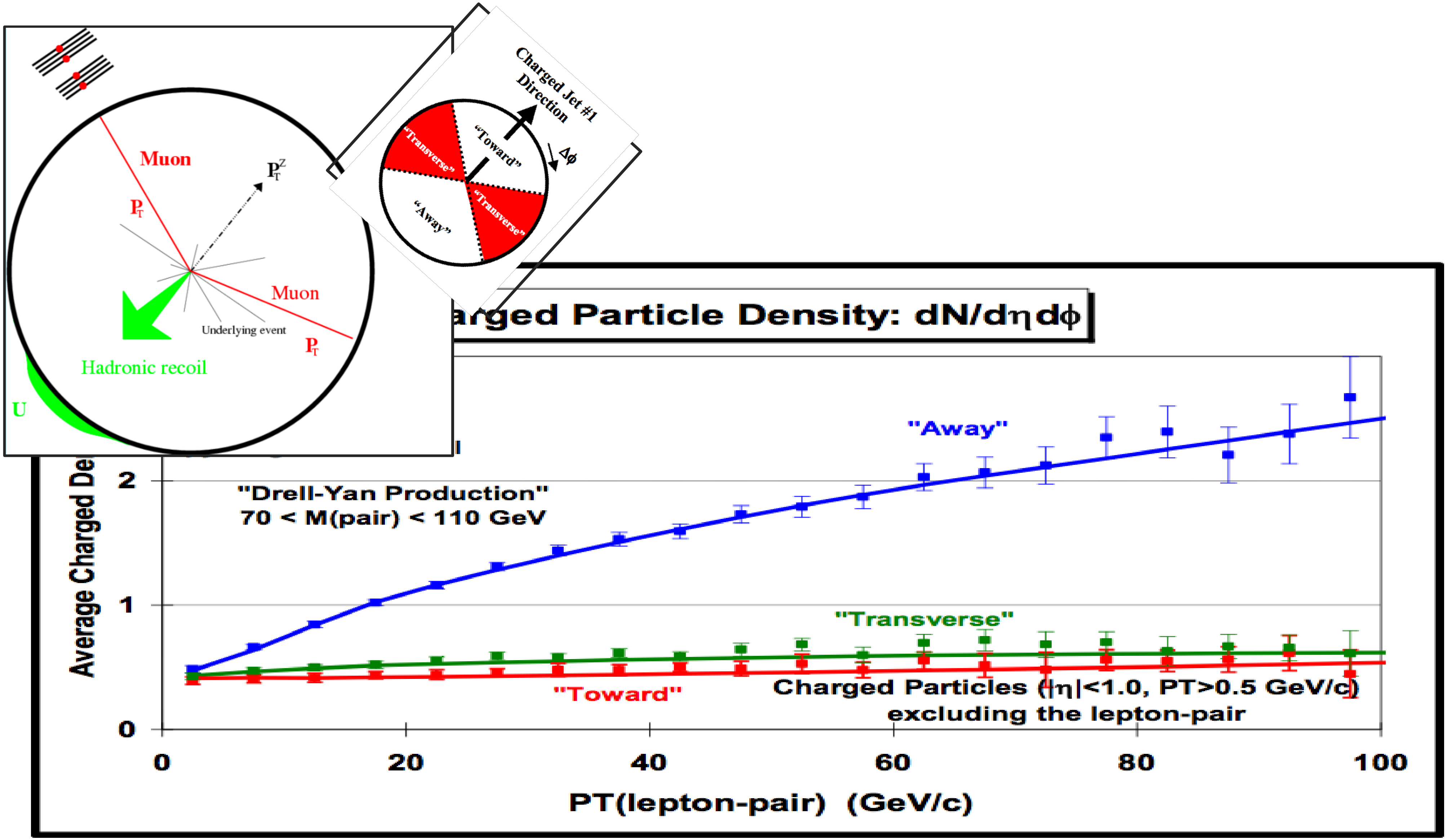
# Underlying Event Measurements



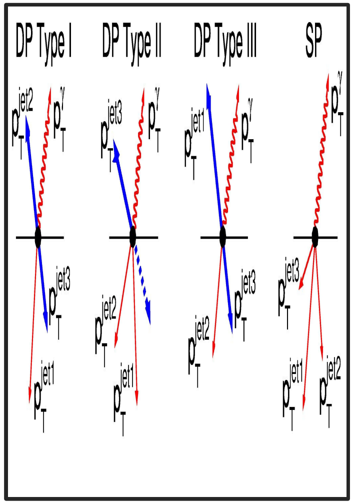

Inconsistency between LHC and Tevatron results?
Currently analysing 2.76 TeV LHC and 0.9 TeV Tevatron data to resolve the issue

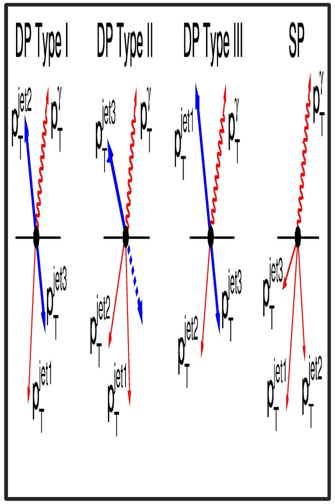
# Underlying Event in Z->ℓℓ

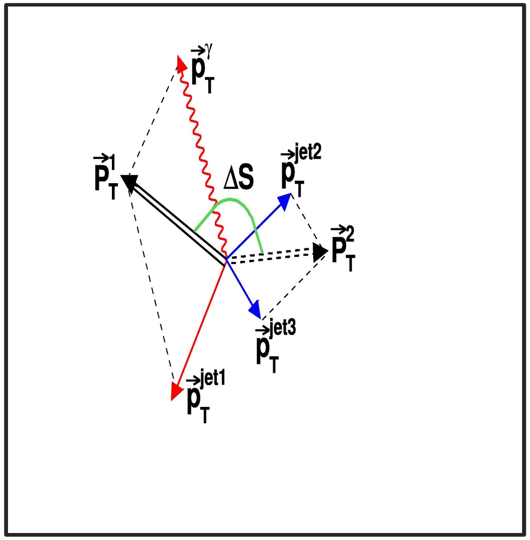


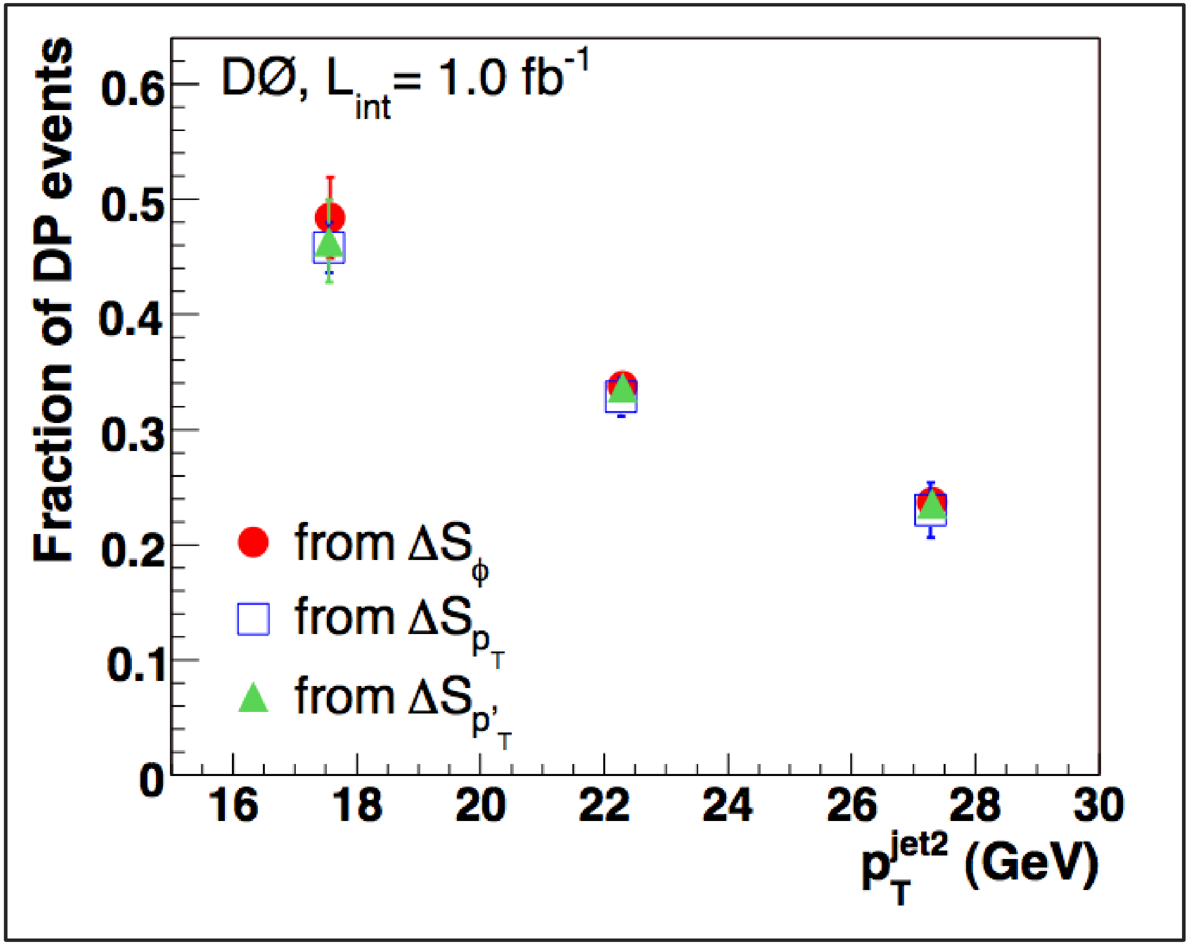
# Double parton scattering

The high pT tails of the Underlying Event… (not really soft-QCD anymore)



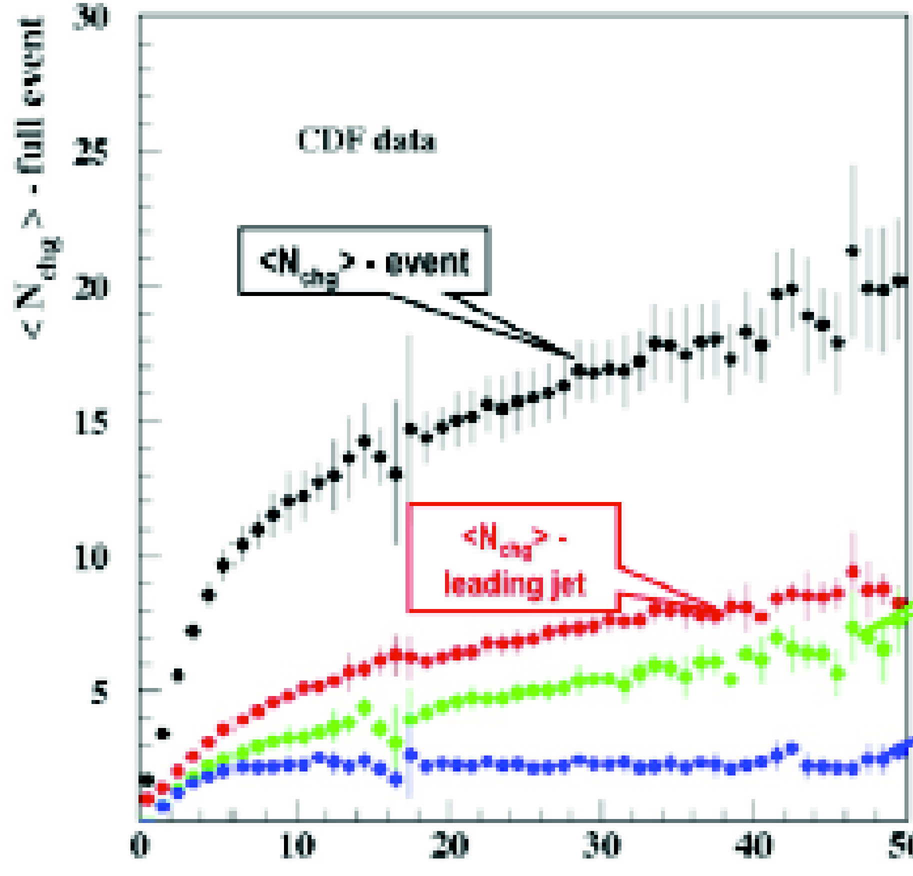



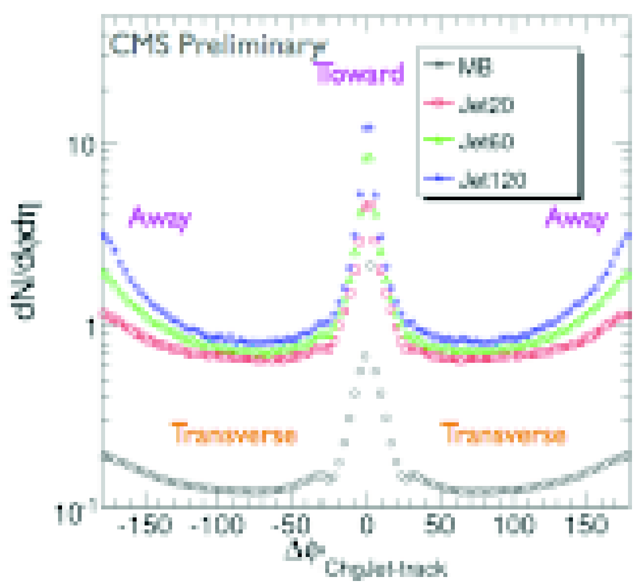



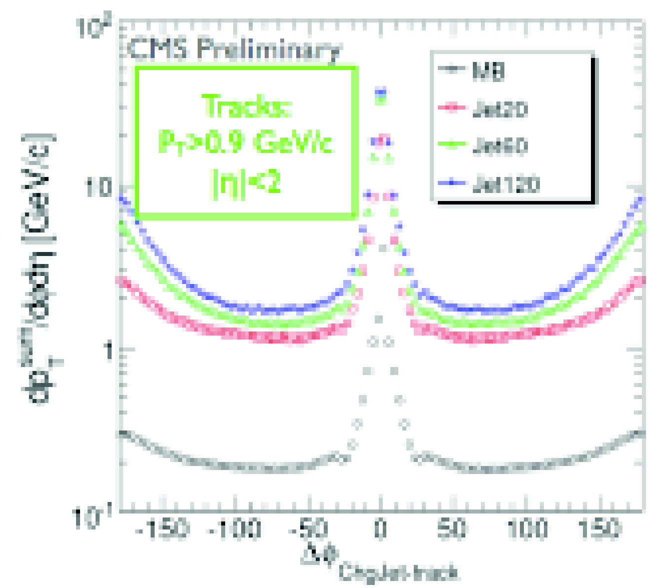
# UE Characterization

- The number of tracks in the transverse region is less correlated to the lead jet energy.
- Sources of transverse tracks:
  - MPI
  - Fragmentation of string connections to remnants.
- Track Jets are used, so that low energy calorimeter response is not involved.
  - Also simplifies comparison to models.
- Drell-Yan: Look for $\mu^+\mu^-$ there is no FSR associated with their production.
  - The entire φ range characterizes the UE.



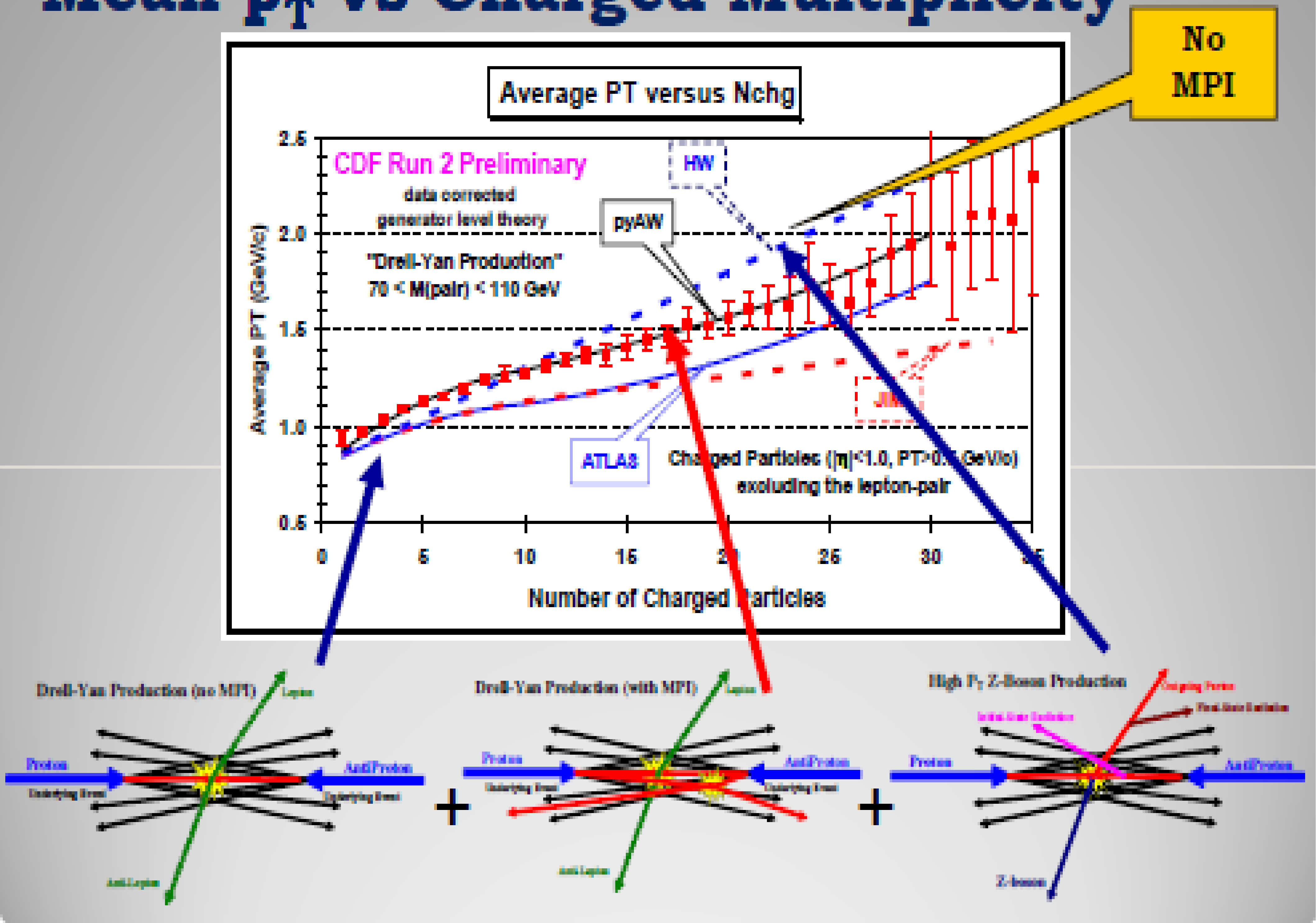

Above: Plot by Affolder at al.




Above: Plots from F. Ambroglini

# Mean $p_T$ vs Charged Multiplicity

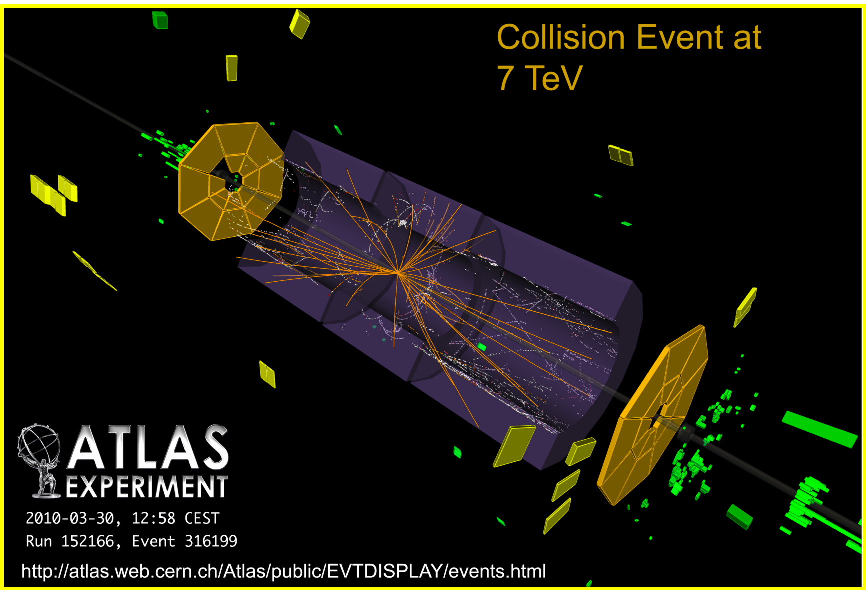


1. Minimum Bias
2. Underlying Event
3. **Total cross-section**
4. Diffractive cross-sections
5. Particle Correlations

# Inelastic cross-section measurement

$$\sigma_{inel} = \frac{N_{evts} - N_{bck}}{\varepsilon \times \mathcal{L}}$$

1. Nevts : count inelastic collisions
2. ε : Correct for detector efficiency
3. $\mathcal{L}$ : Normalise with luminosity




Minimum Bias Trigger Scintillators :
$2.09 < |\eta| < 3.84$

Nevts = # events with ≥ 2 counters above threshold

$\sigma_{inel}$ ($\xi > 5\times10^{-6}$) = 60.3 ± 0.05(stat) ± 0.5(syst) ± 2.1(lumi) mb

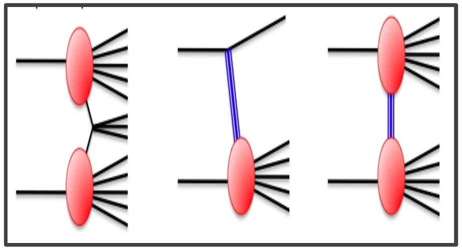
Measurement restricted to region in which we are sensitive (e.g. at least one charged particle with $|\eta| < 3.84$)

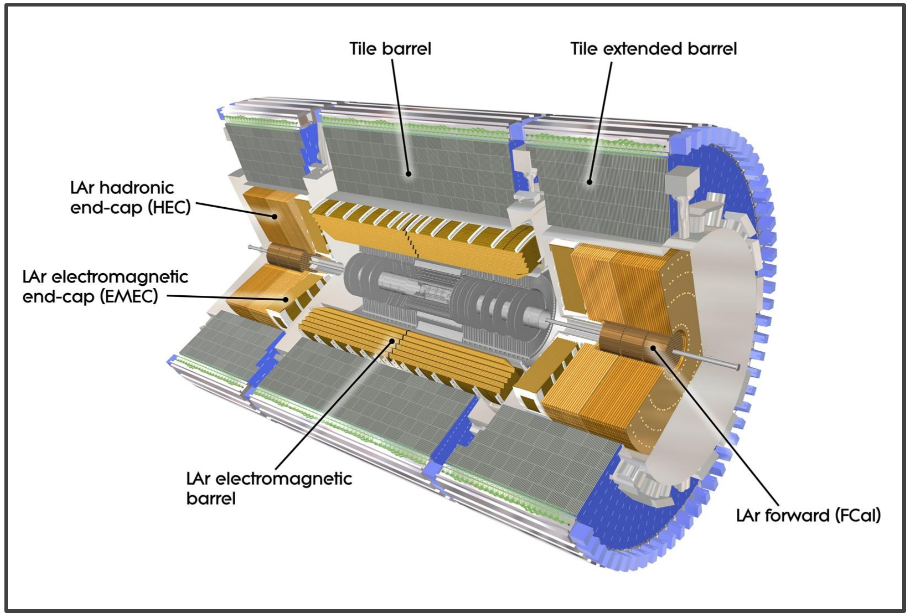
1. Minimum Bias
2. Underlying Event
3. Total cross-section
4. **Diffractive cross-sections**
5. Particle Correlations

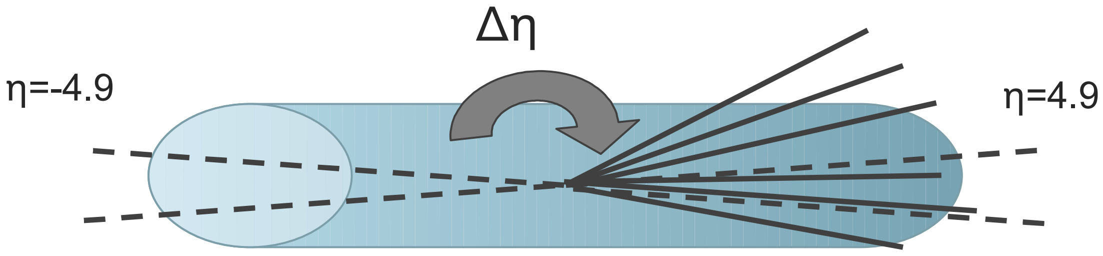
# Gap cross-section

Diffractive events tend to have large “rapidity gaps”

Measure σ vs Δη (large Δη dominated by diffraction)

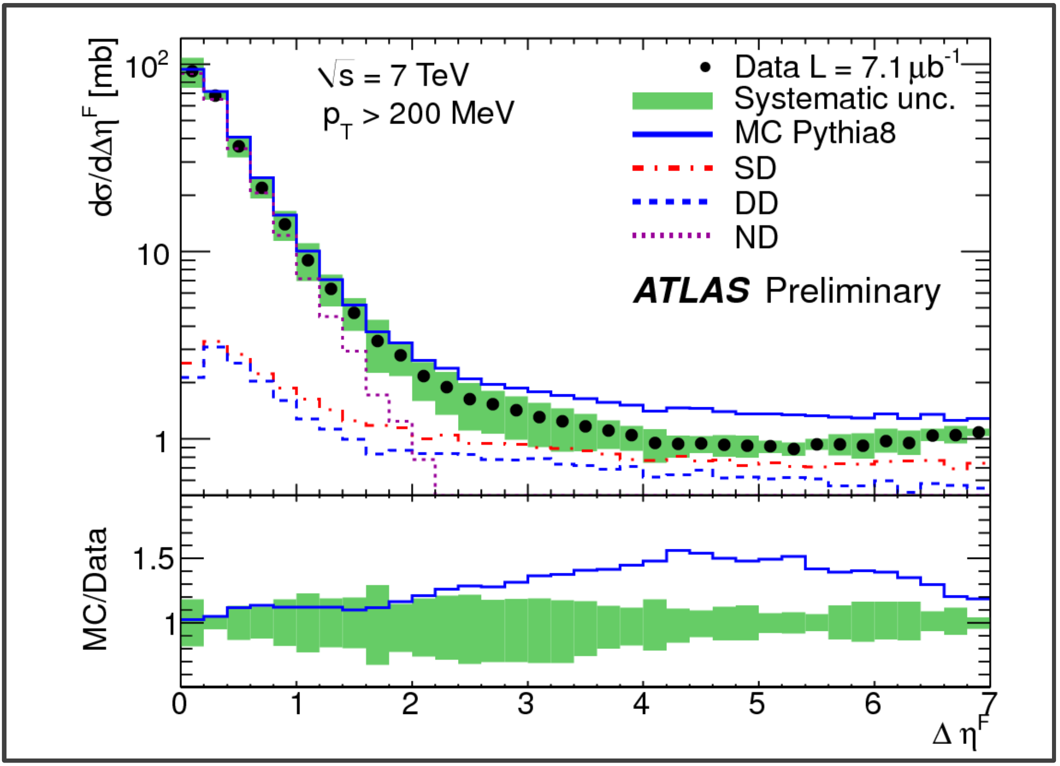


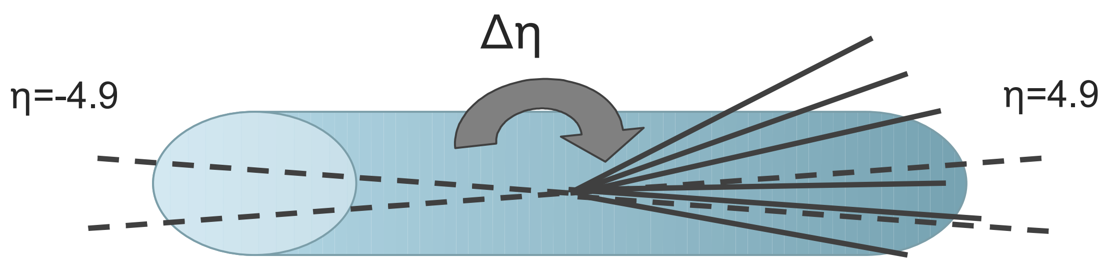



Calorimeters : |η| < 4.9
Inner Tracking Detector : |η| < 2.5

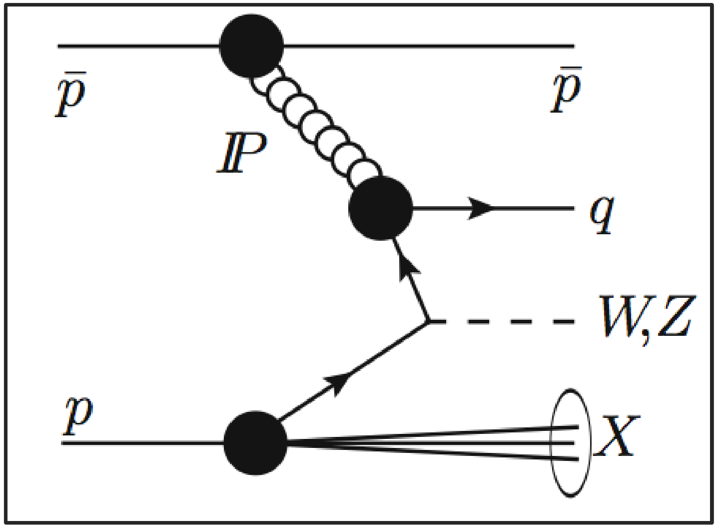
# Gap cross-section

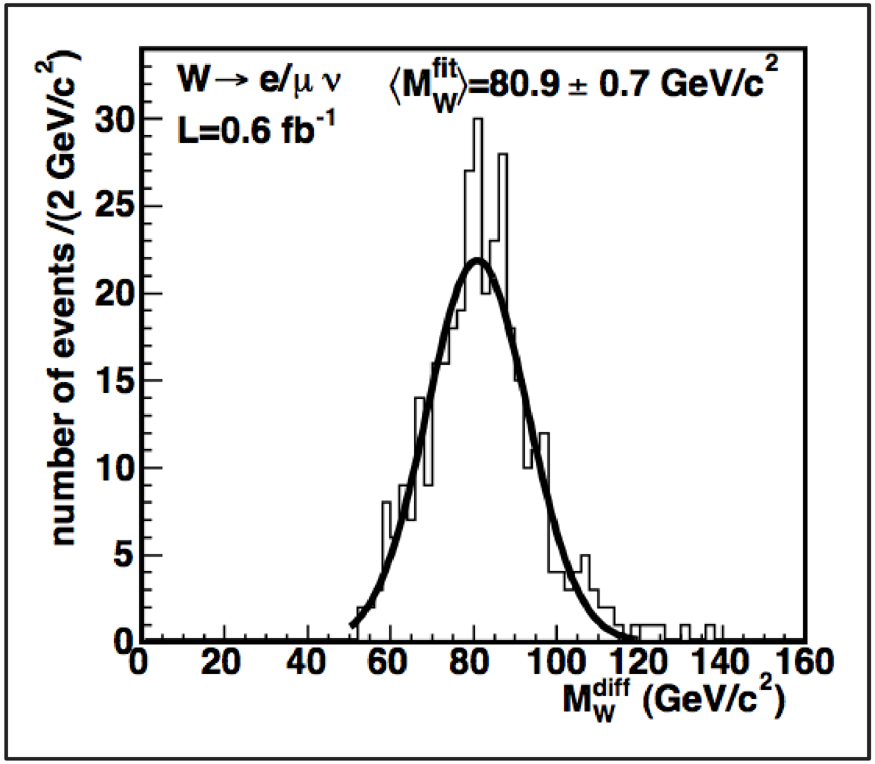


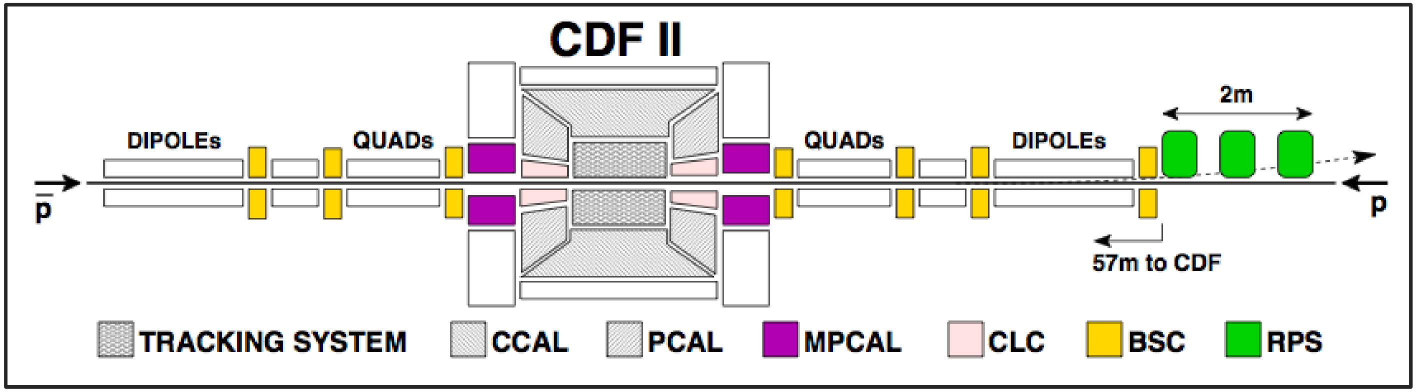



# Other diffractive processes

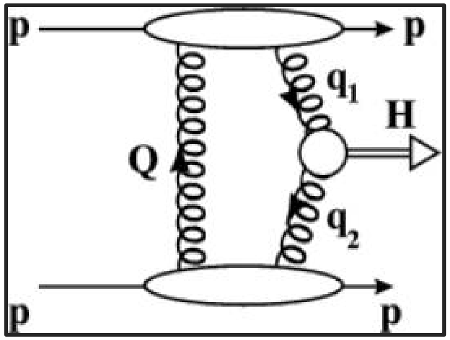
Not really soft-QCD anymore….



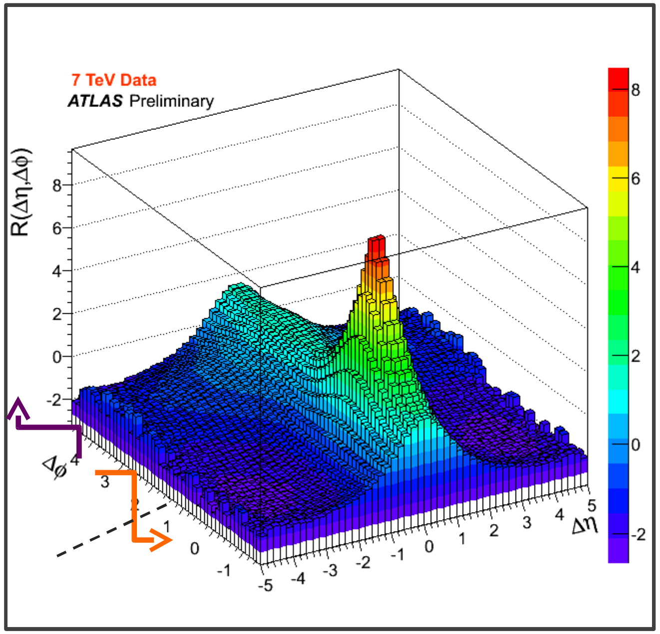




Higgs?



1. Minimum Bias
2. Underlying Event
3. Total cross-section
4. Diffractive cross-sections
5. **Particle Correlations**

# Two particle correlations

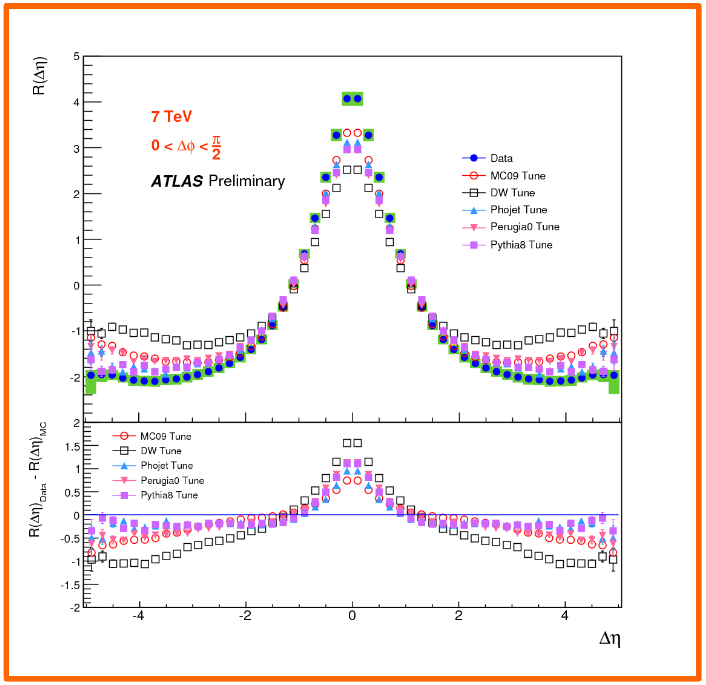


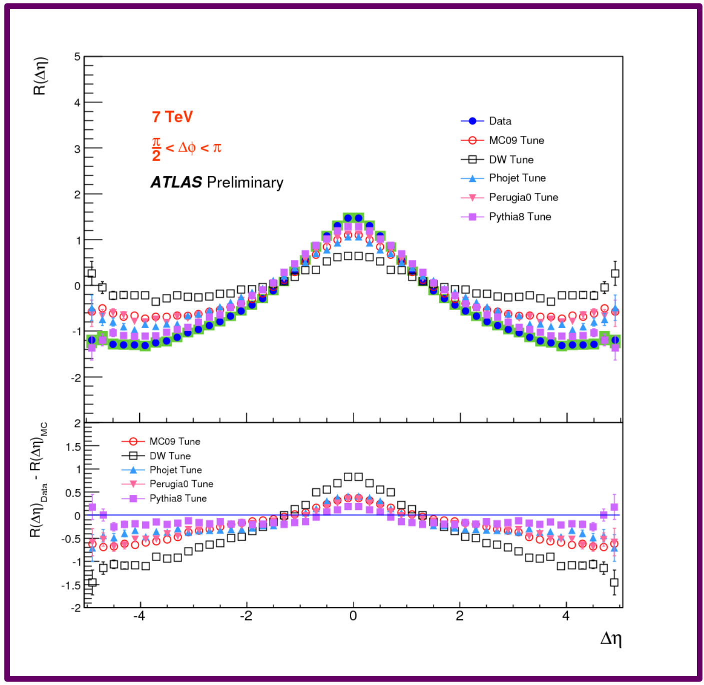

$$R(\Delta\eta,\Delta\Phi) = \left(F(\Delta\eta,\Delta\Phi) - B(\Delta\eta,\Delta\Phi)\right) / B(\Delta\eta,\Delta\Phi)$$

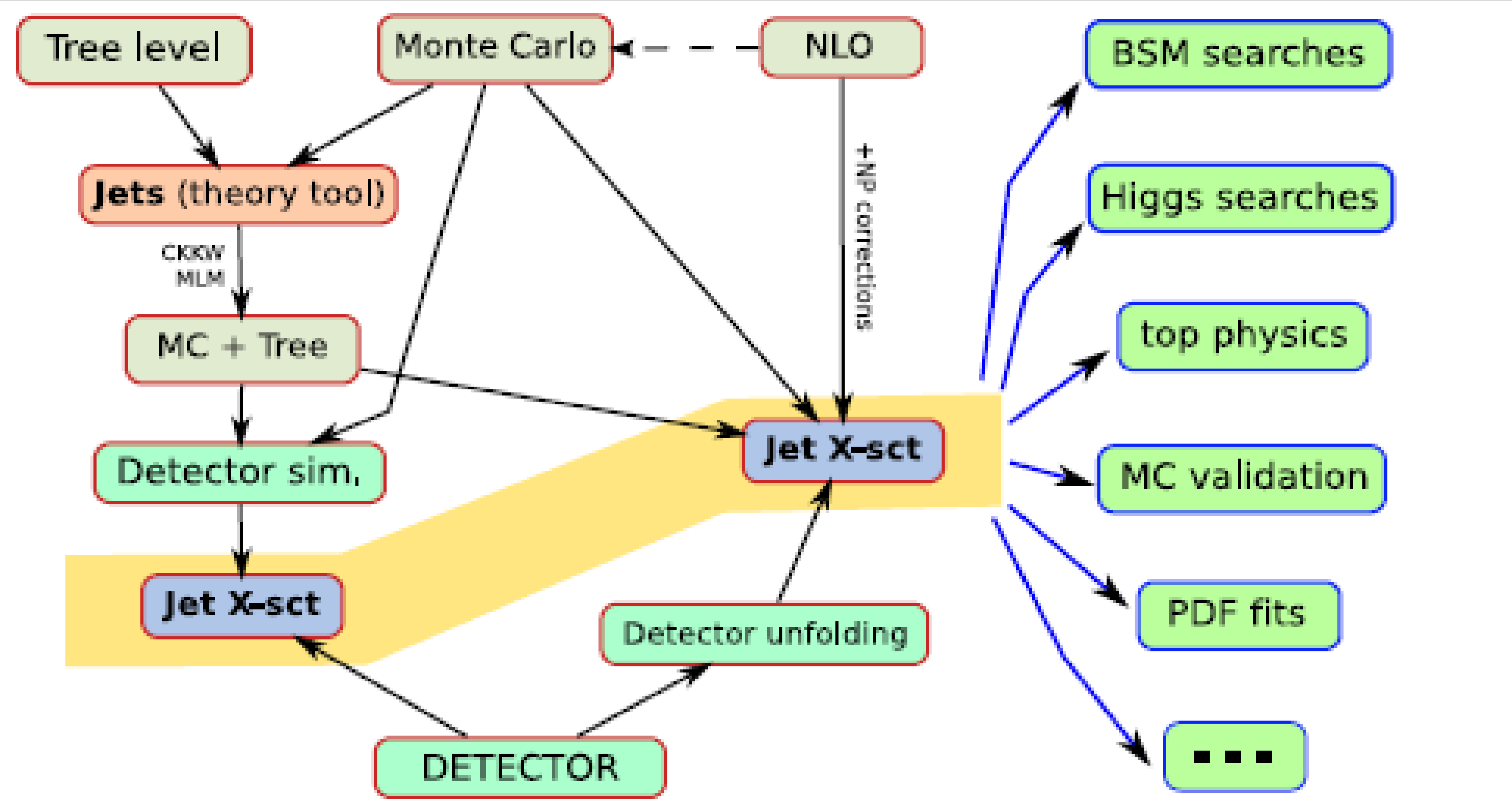
(+ normalisation factors)

F : all particle pairs in same event
B : pair particles from different events

1D projections on Δη axis :
(ΔΦ projections not shown)



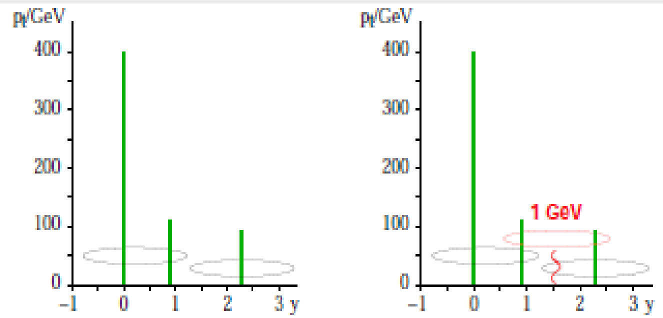



Jet (definitions) provide central link between expt., "theory" and theory

**And jets are an input to almost all analyses**

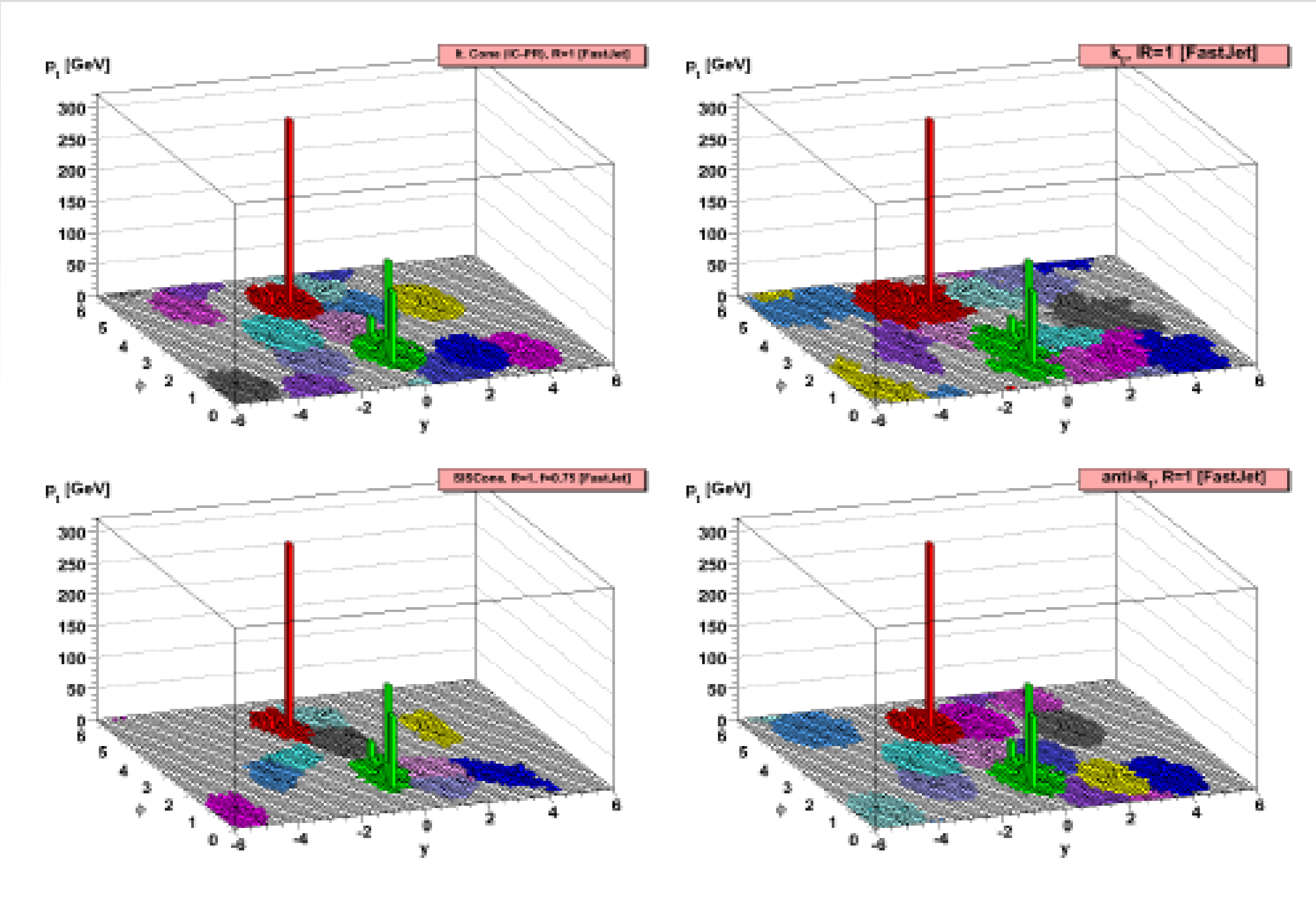
- Cone algorithms:
  - start with a high-Pt deposition, then take everything with distance smaller than a given radius in $(\eta,\phi)$ space
  - ex. JetClu, Atlas cone, CMS cone, MidPoint, PxCone, SISCone
- Iterative recombination:
  - Merge nearby clusters, and combine them into a single one; continue until can't find any more 'super clusters' close enough
  - ex. Kt, Anti-kt, Cambridge

- Cone algorithms are apparently simple to understand and fast; but what happens if two cones overlap? Does the result depend on the choice of seed? (it shouldn't)

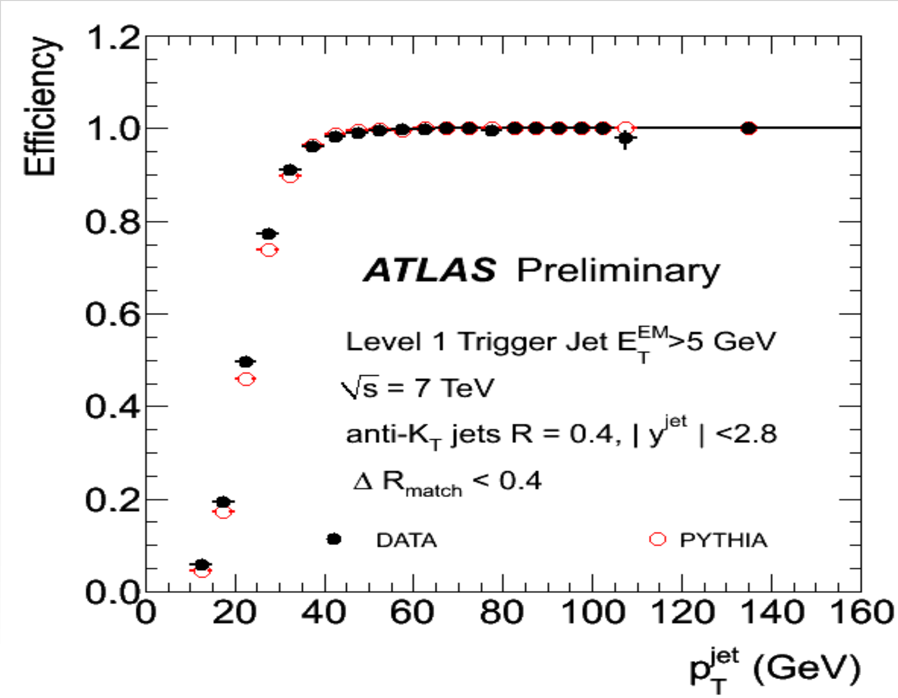


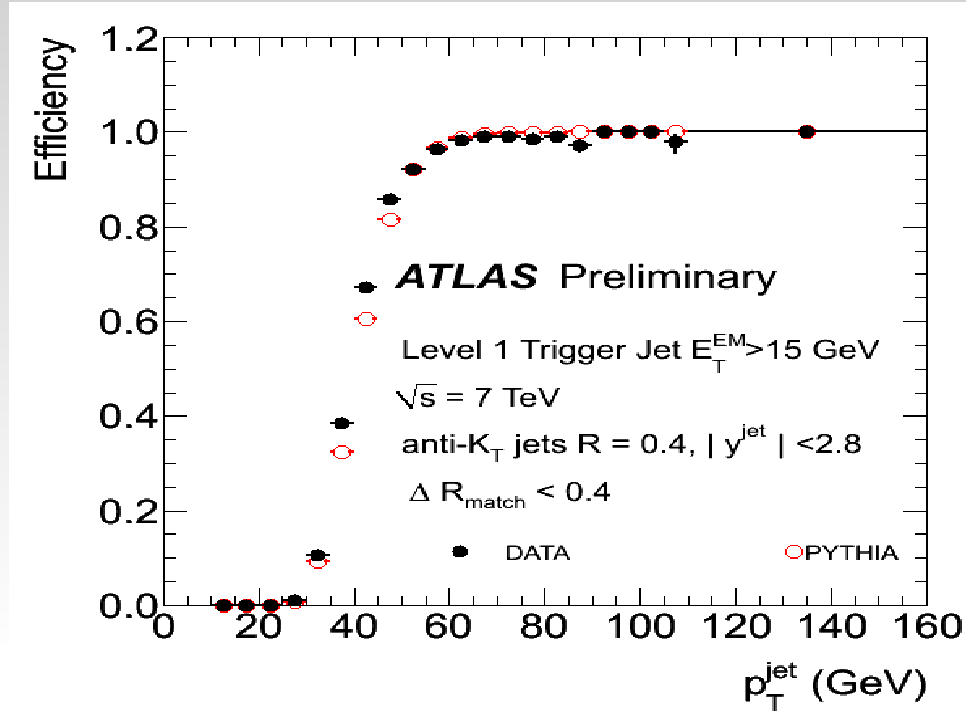

| | | |
|---|---|---|
| Stable cones with midpoint: | {1,2} & {3} | {1,2} & {2,3} & {3} |
| Jets with midpoint ($f = 0.5$) | {1,2} & {3} | {1,2,3} |

| | *Last meaningful order* | | | |
|---|---|---|---|---|
| | JetClu, ATLAS cone [IC-SM] | MidPoint [$IC_{mp}$-SM] | CMS it. cone [IC-PR] | Known at |
| Inclusive jets | LO | NLO | NLO | NLO |
| $W/Z + 1$ jet | LO | NLO | NLO | NLO |
| 3 jets | none | LO | LO | NLO [nlojet++] |
| $W/Z + 2$ jets | none | LO | LO | NLO [MCFM] |
| $m_{jet}$ in $2j + X$ | none | none | none | LO → NLO |

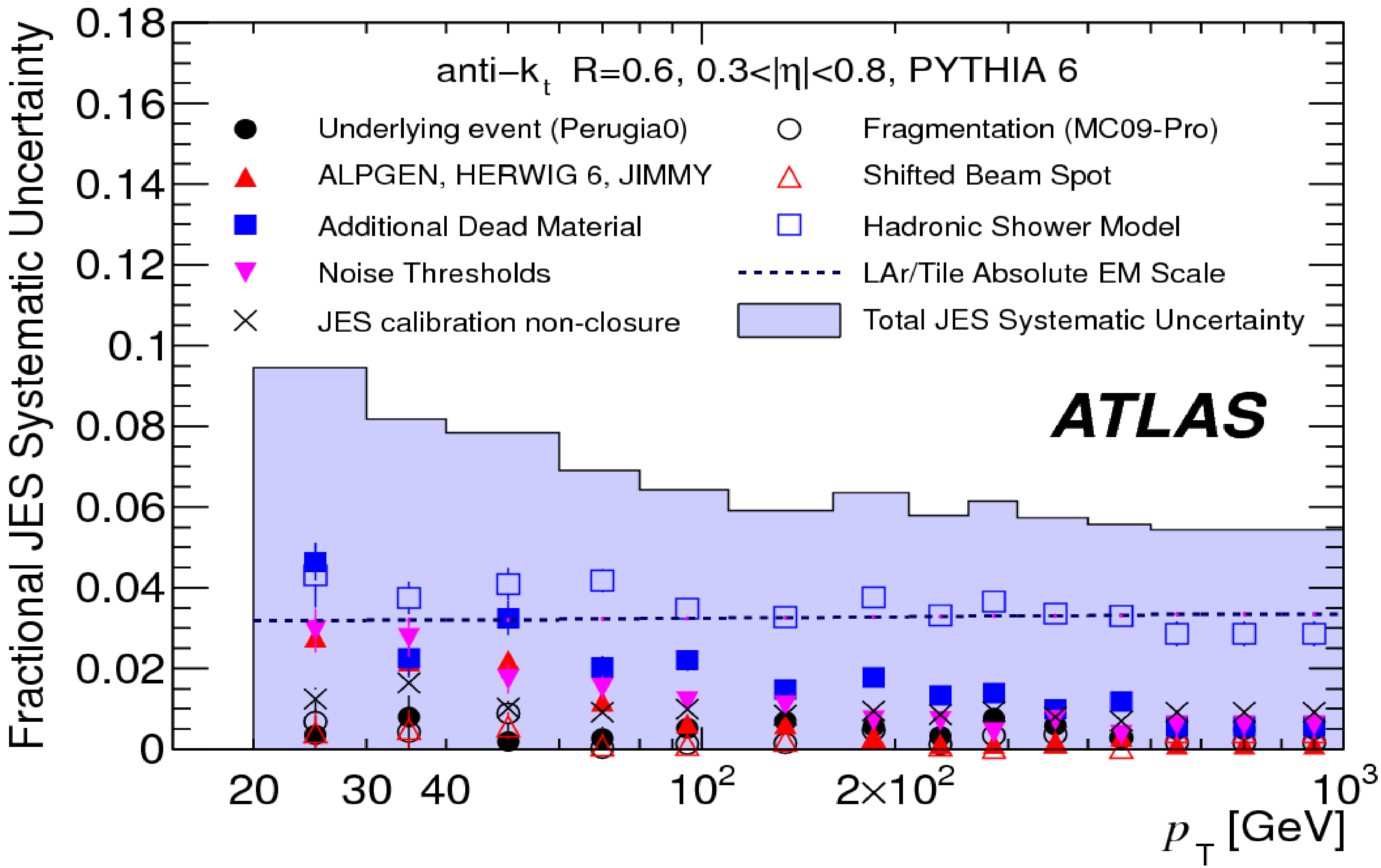



Anti-kt now default algorithm in Atlas

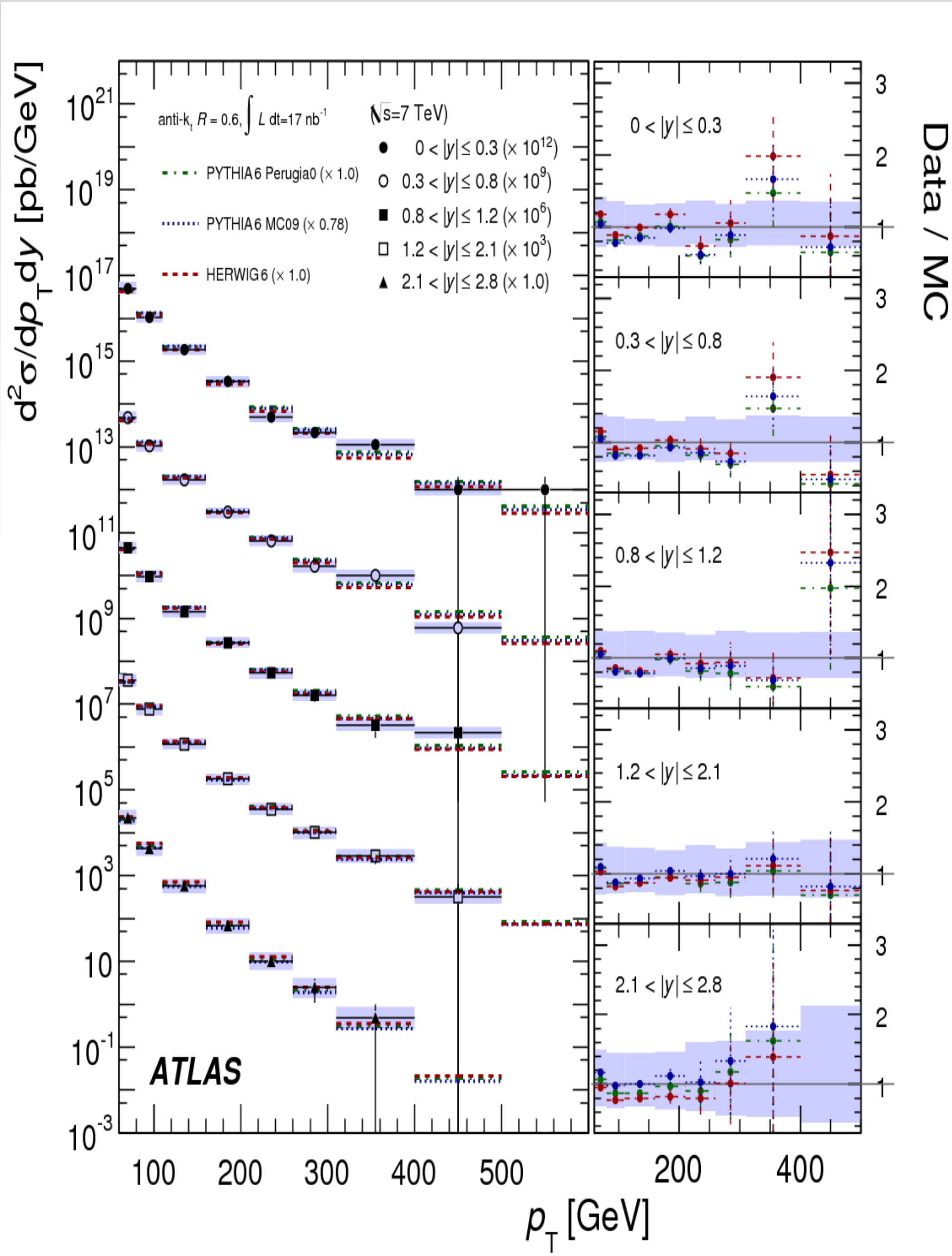


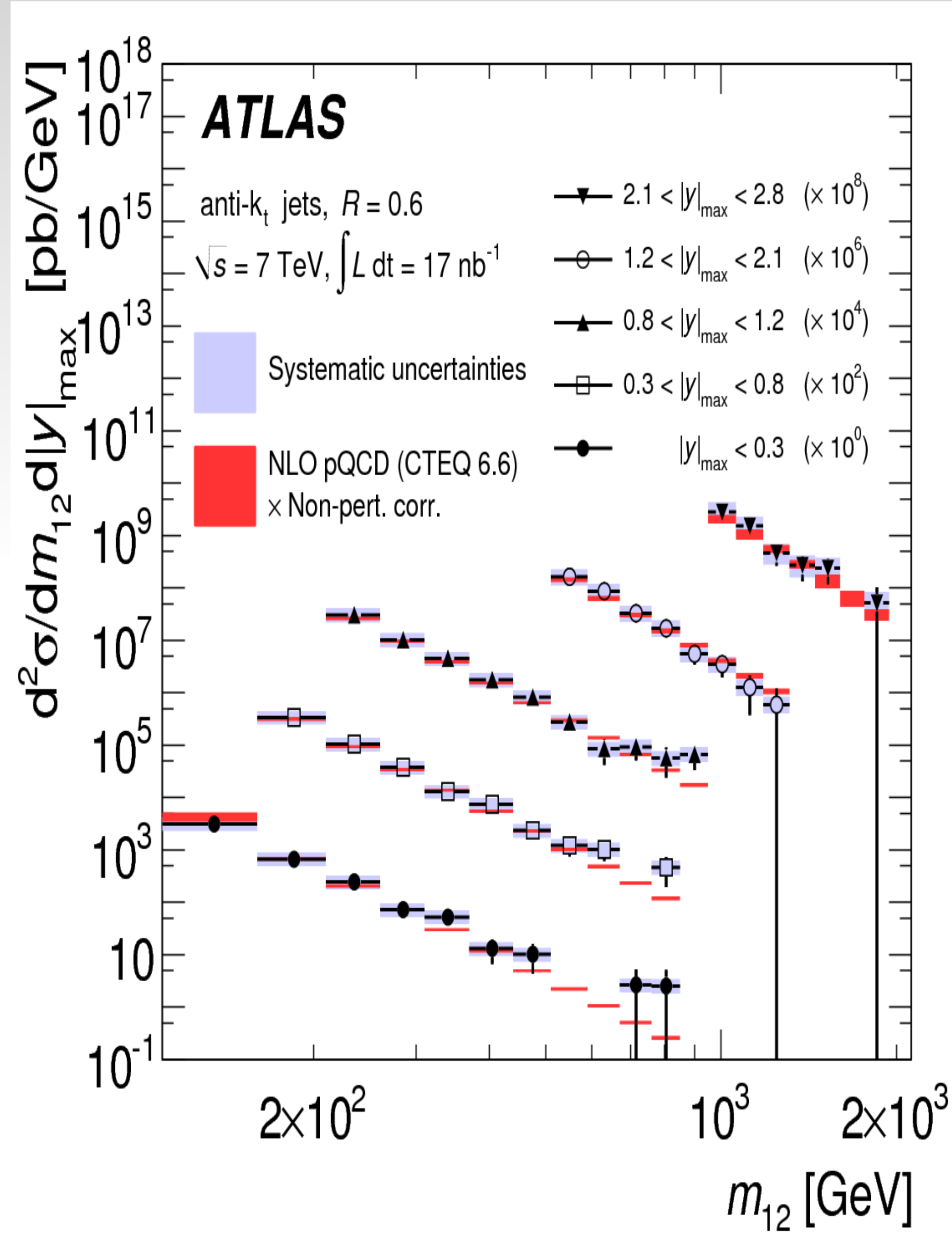

- Not to correct for the efficiency in the steeply rising part of the curve, jet cross section was first measured above the 100% efficiency point
- This results in the measurement being performed in different Pt bins in the various periods, because higher luminosities forced heavy prescales on lowest thresholds



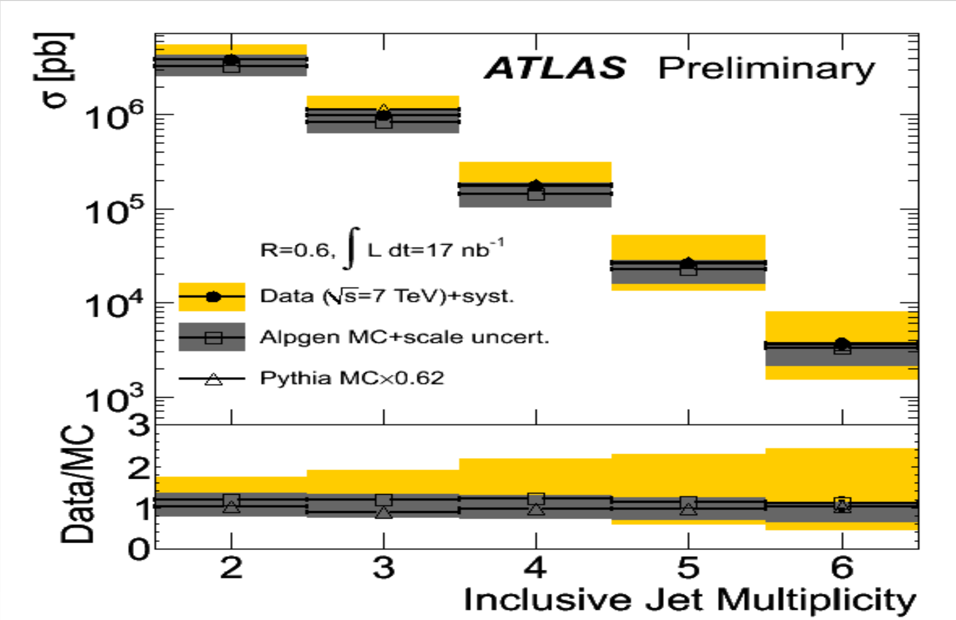

- Jets measured at EM scale (summing Ecal and Hcal contributions), scaled by factors derived from MC and cross-checked with track jets

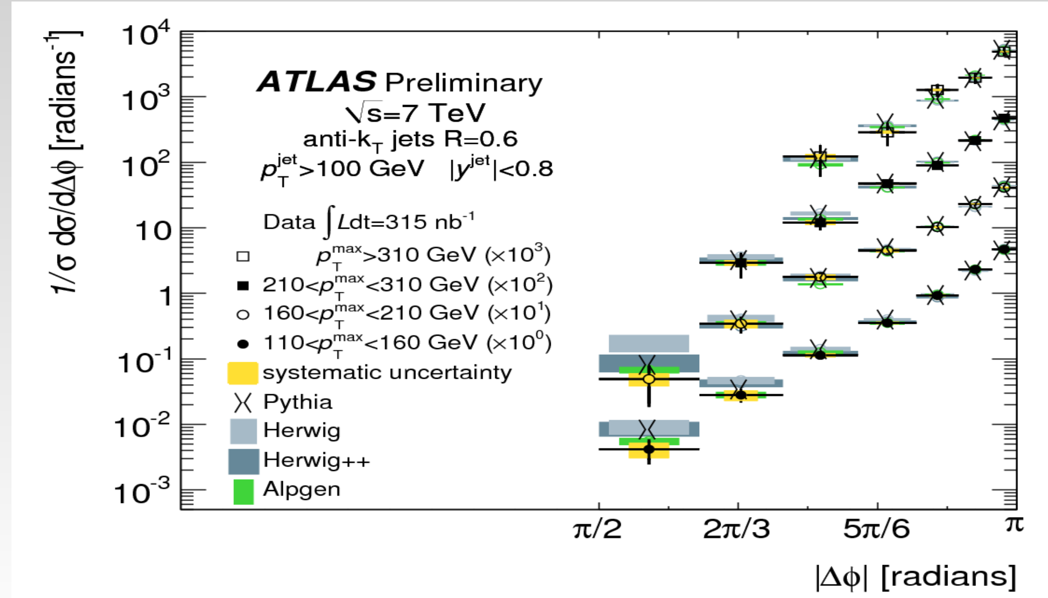


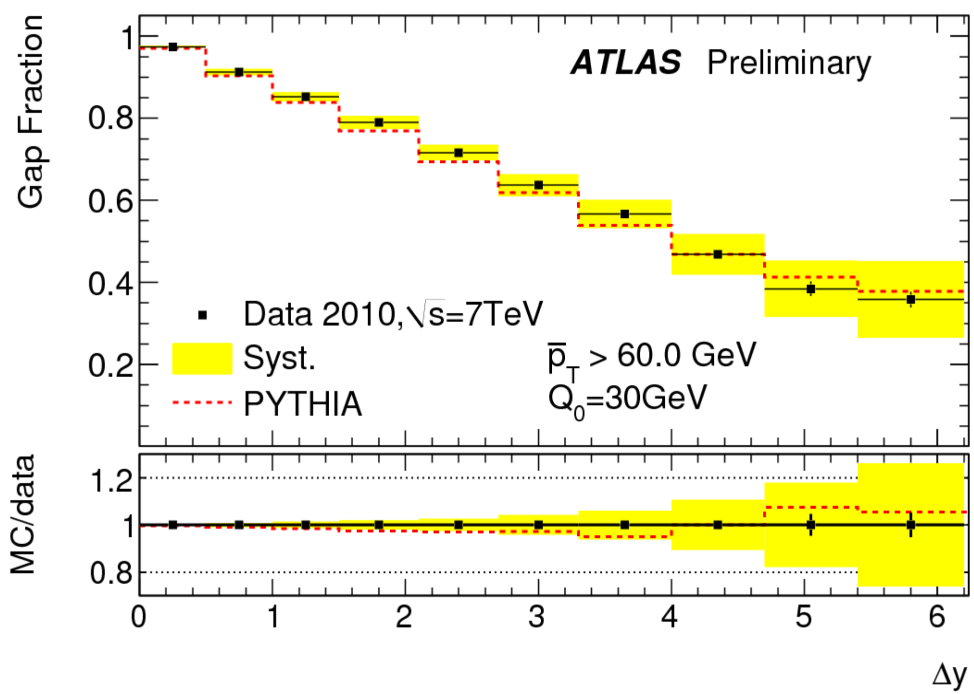
anti-k$_t$ $R$ = 0.6, $\int L\,dt$=17 nb$^{-1}$
$\sqrt{s}$=7 TeV)
0 < |y| ≤ 0.3 (× 10$^{12}$)
0.3 < |y| ≤ 0.8 (× 10$^9$)
0.8 < |y| ≤ 1.2 (× 10$^6$)
1.2 < |y| ≤ 2.1 (× 10$^3$)
2.1 < |y| ≤ 2.8 (× 1.0)
PYTHIA6 Perugia0 (× 1.0)
PYTHIA6 MC09 (× 0.78)
HERWIG6 (× 1.0)
ATLAS
$d^2\sigma/dp_T dy$ [pb/GeV]
$p_T$ [GeV]
Data / MC



ATLAS
anti-k$_t$ jets, $R$ = 0.6
$\sqrt{s}$ = 7 TeV, $\int L\,dt$ = 17 nb$^{-1}$
Systematic uncertainties
NLO pQCD (CTEQ 6.6)
× Non-pert. corr.
2.1 < |y|$_{max}$ < 2.8 (× 10$^8$)
1.2 < |y|$_{max}$ < 2.1 (× 10$^6$)
0.8 < |y|$_{max}$ < 1.2 (× 10$^4$)
0.3 < |y|$_{max}$ < 0.8 (× 10$^2$)
|y|$_{max}$ < 0.3 (× 10$^0$)
$d^2\sigma/dm_{12}d|y|_{max}$ [pb/GeV]
$m_{12}$ [GeV]

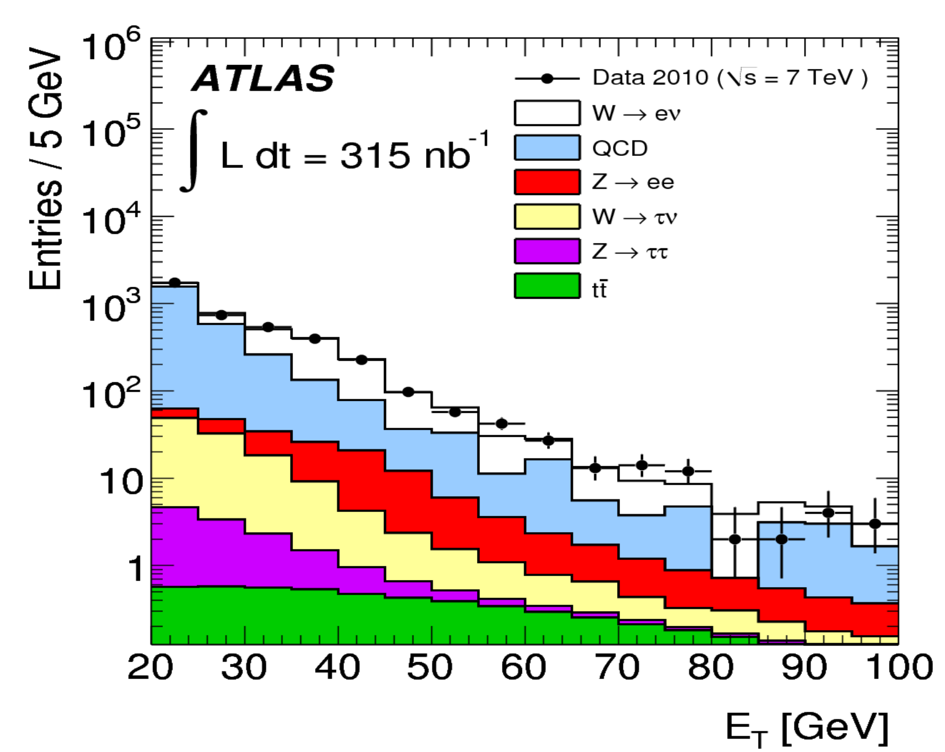


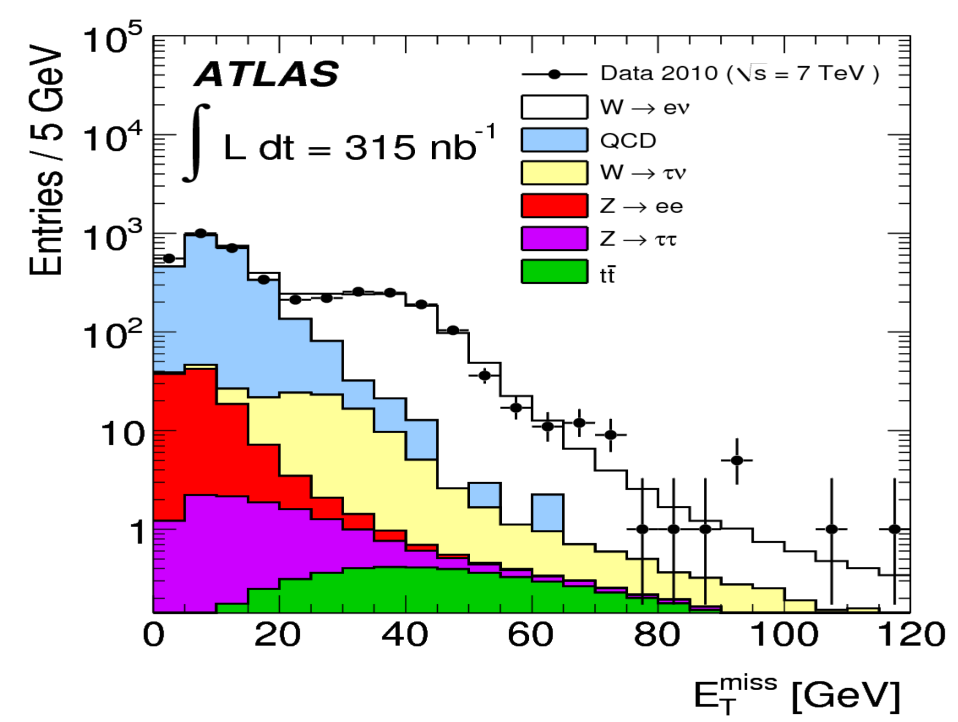



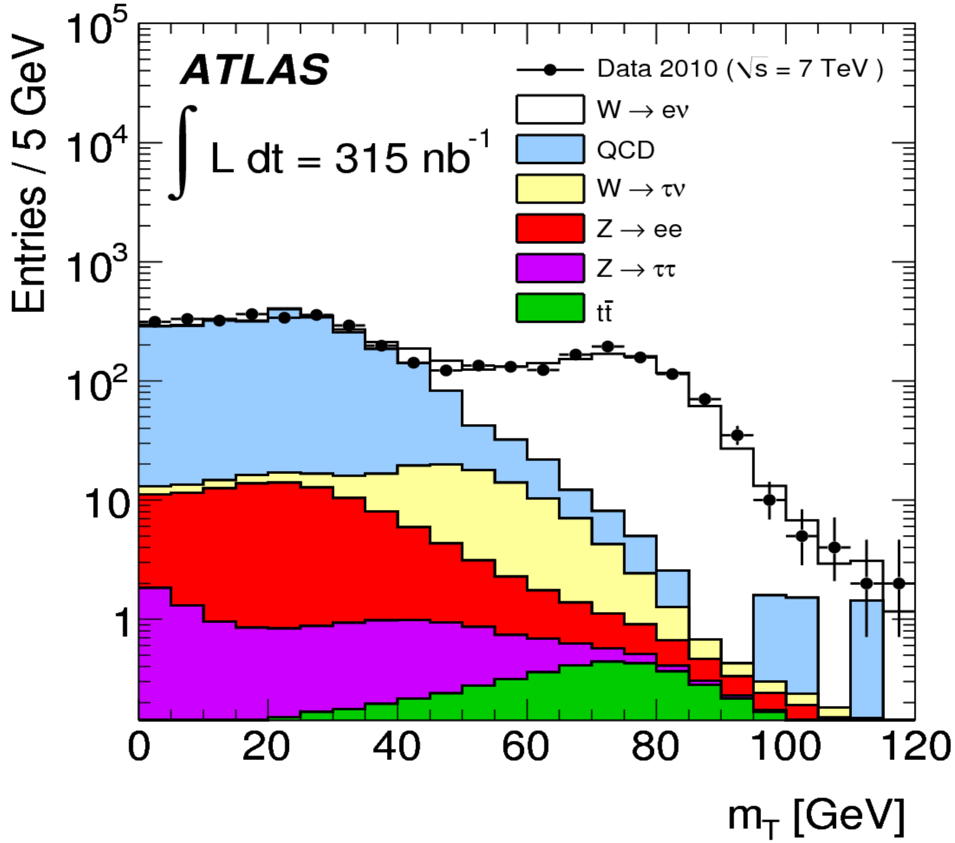

Several QCD tests performed on jets, looking at multiplicity, angular distribution, radiation between dijets

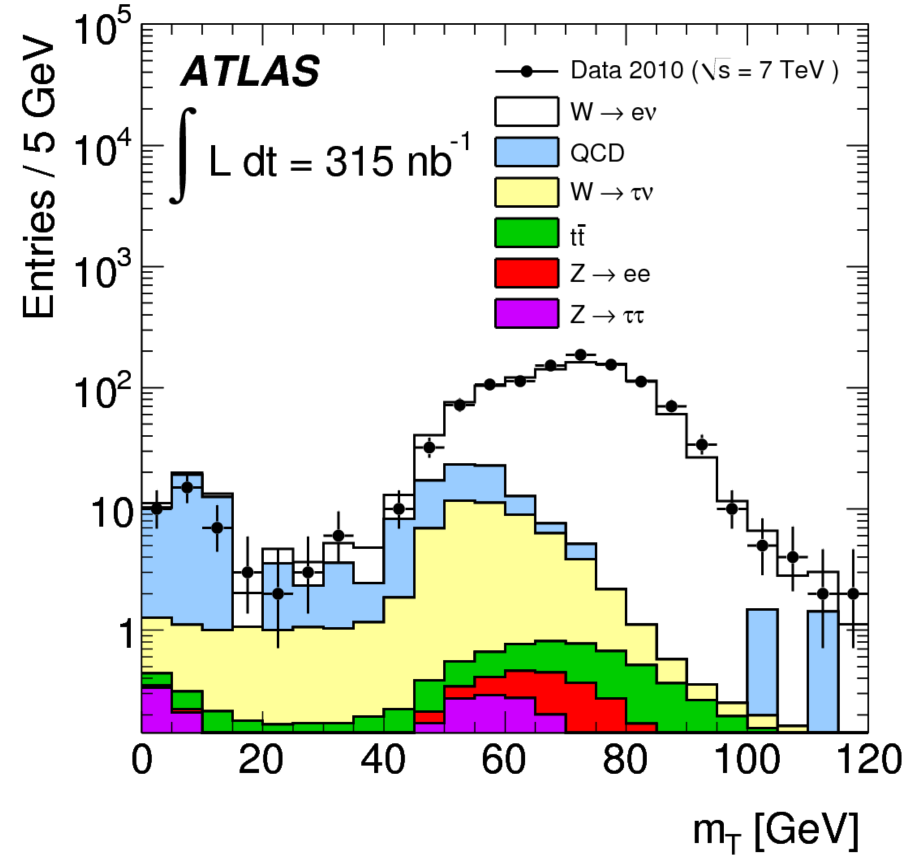
- Next important SM benchmark are W and Z productin, always accompanied by jets at the LHC.
- Relevant for Pdf determination, QCD studies
- W production about 10 times larger than Z, but analysis more difficult: no way to perform full reconstruction, so only transverse mass can be reconstructed
- Different BG from electron and muon channel:
  - Neutral pions faking electrons
  - Punch-through hadrons in muon chambers
- W forward-backward charge asymmetry very useful for Pdf's (how to define it in a pp machine??)



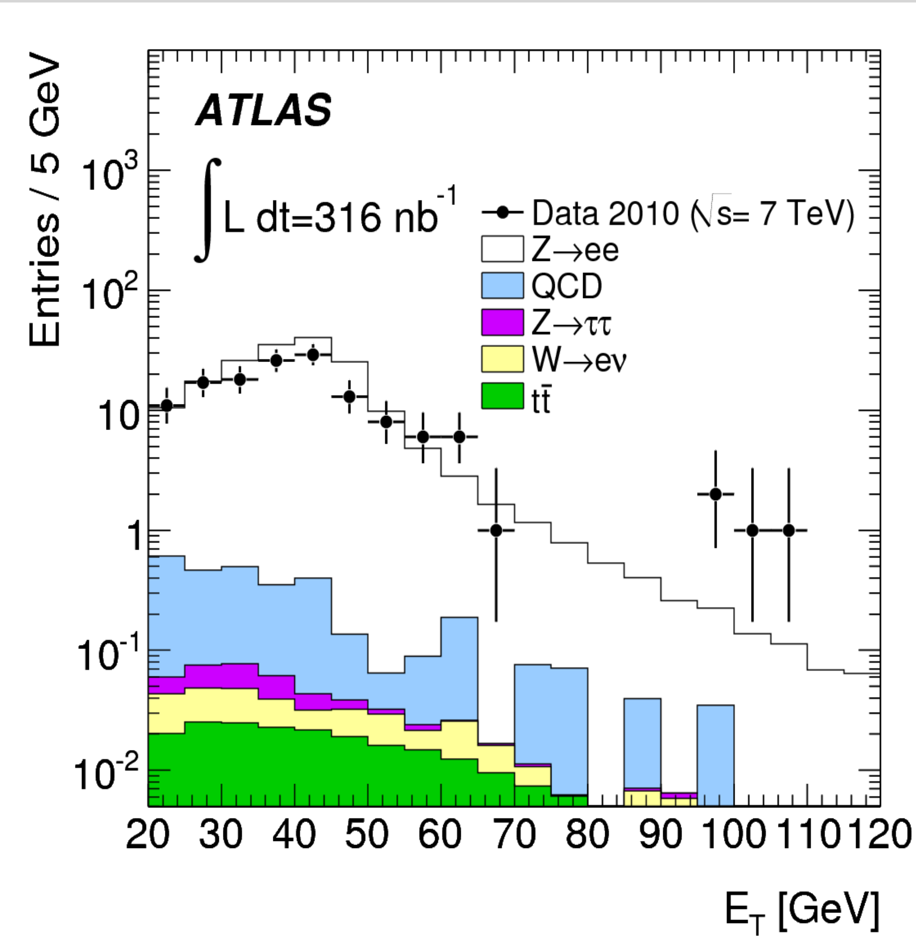



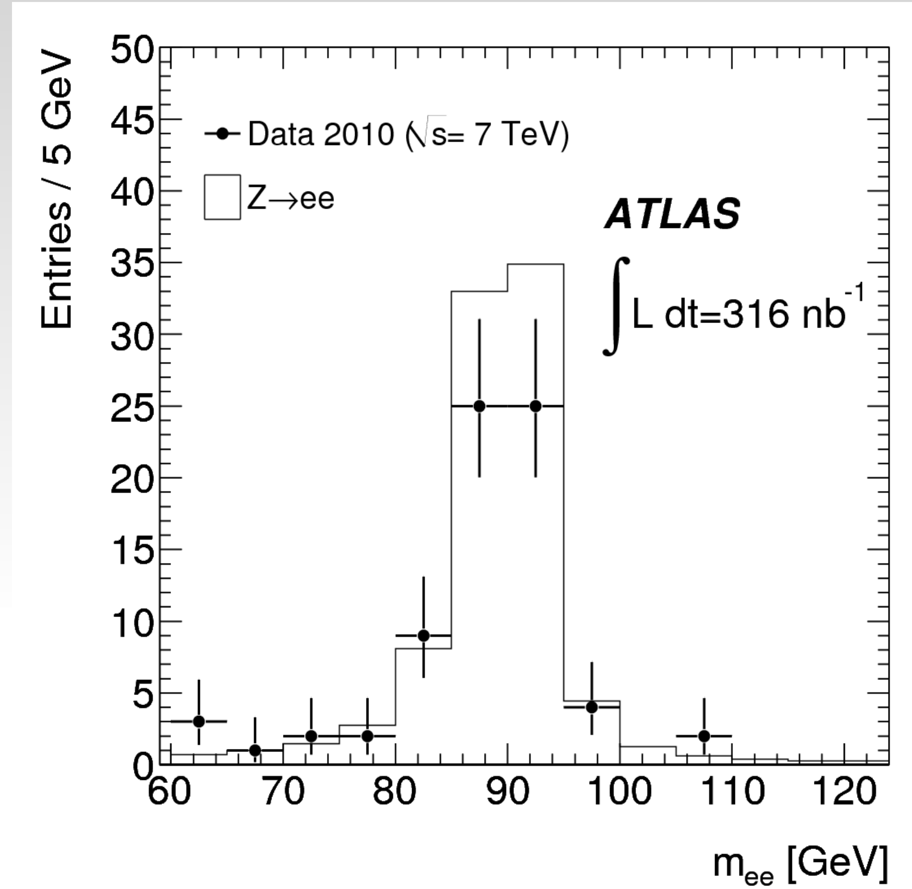

- Electron Pt MET
- for W->enu events
- Signal purity quite low for individual variables



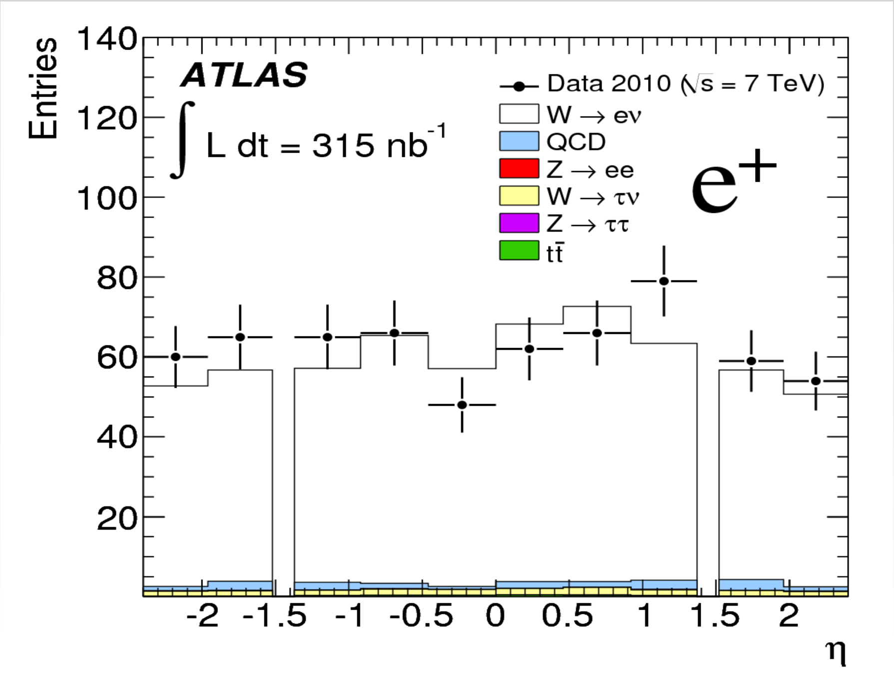



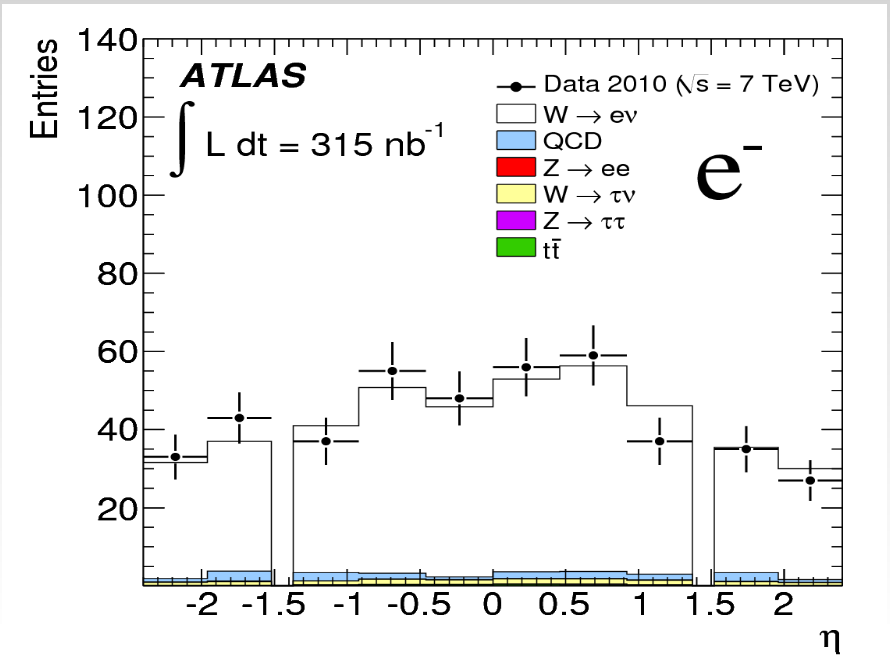

- Despite the transverse mass distribution being very broad, Tevatron experiments provide now a measurement of the W mass more precise than that of LEP, where the full mass could be reconstructed

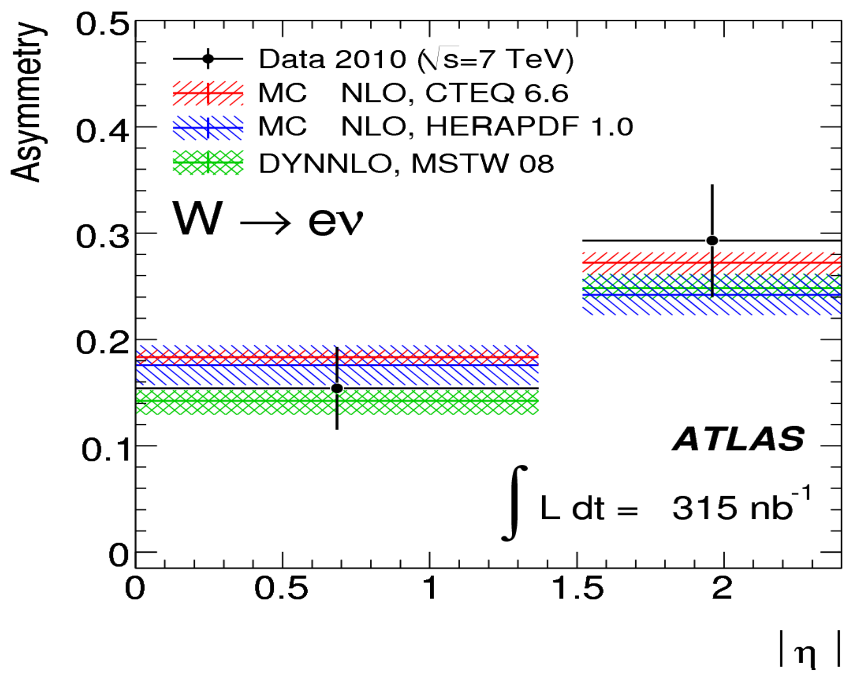



- 2-lepton requirement makes Z channel much cleaner, but statistics is poorer-hard to beat LEP's 4 million Z collected per experiment (and lineshape fit). Fundamental tool for calibration



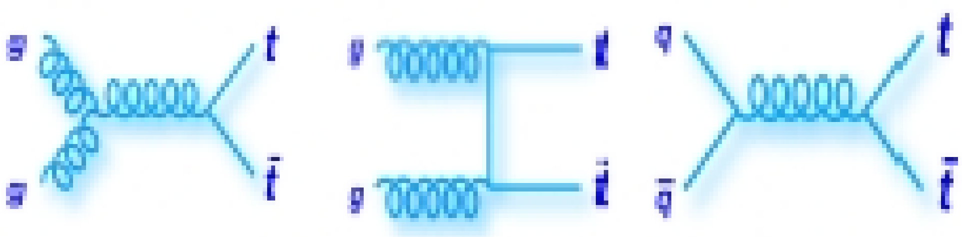

The idea: from Pdf's, u-quarks have higher average x, so W+ tend to be produced more forward. Even in pp, W asymmetry distribution can constraint Pdf's

# Top quark production and decay

- Produced mainly in pairs
  - σ ≃ 7 pb @ 2 TeV

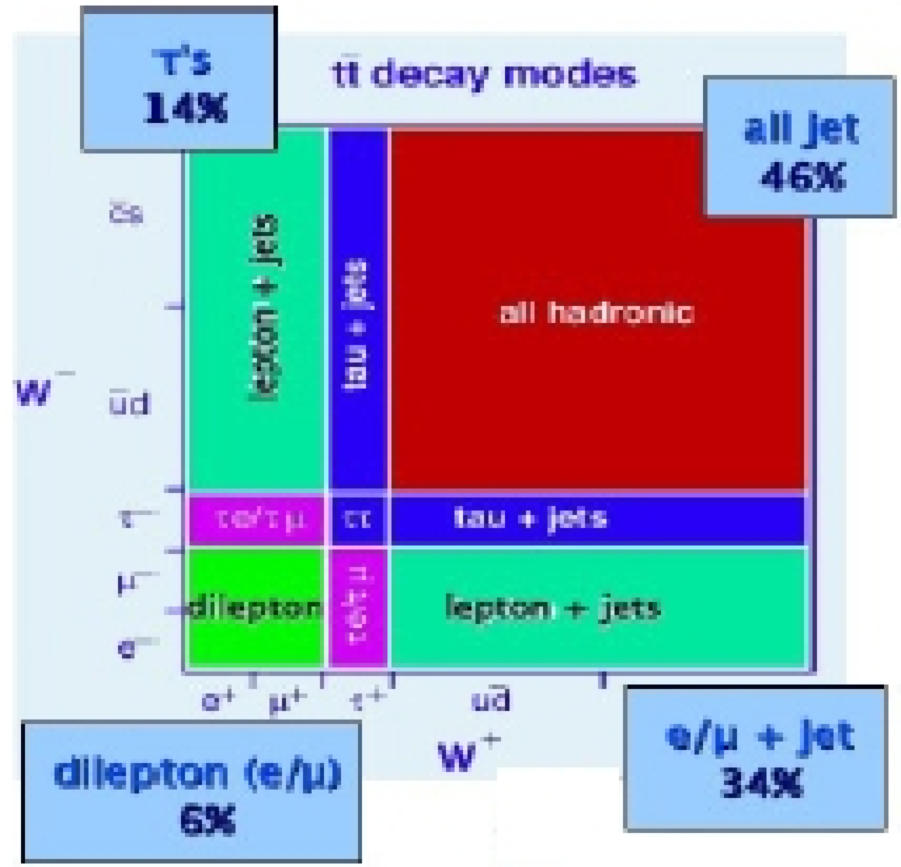

85%     15%

- σ ≃ 400 pb @ 10 TeV




90%     10%

- SM decay: t→Wb ~100%
- W decays define final state



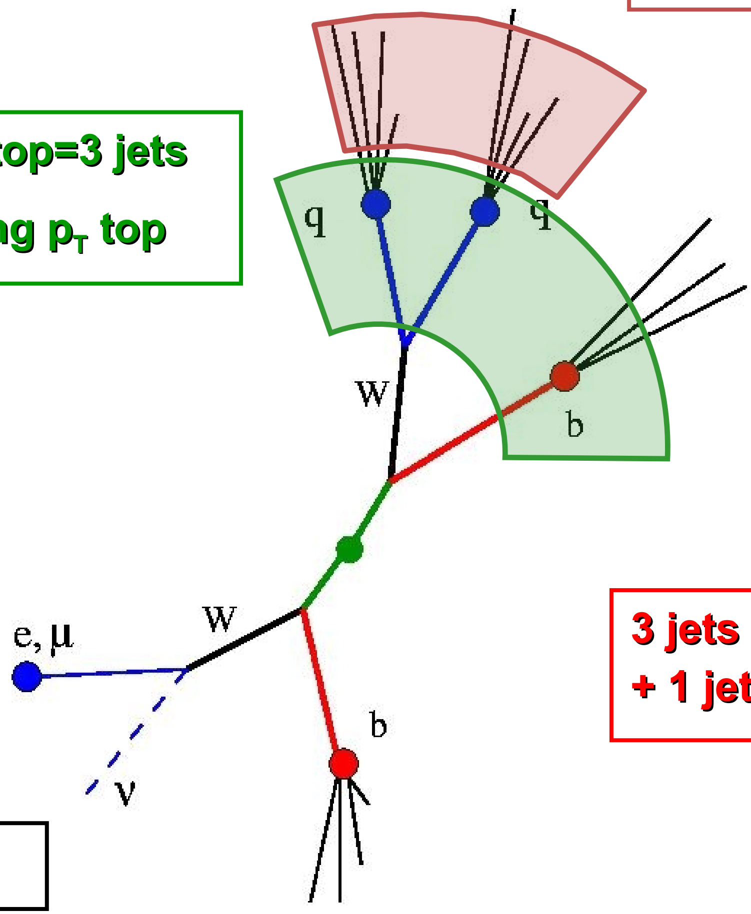
# Top quark physics measurements

Keep it as simple as possible:

**W =2 jets maximising $p_T$ W in jjj rest frame**

**$|m_{jj}-m_W| < 20$ GeV**

**Hadronic top=3 jets maximising $p_T$ top**




**Isolated lepton $p_T > 20$ GeV**

**3 jets $p_T > 40$ GeV + 1 jet $p_T > 20$ GeV**

**$E_{T,miss} > 20$ GeV**

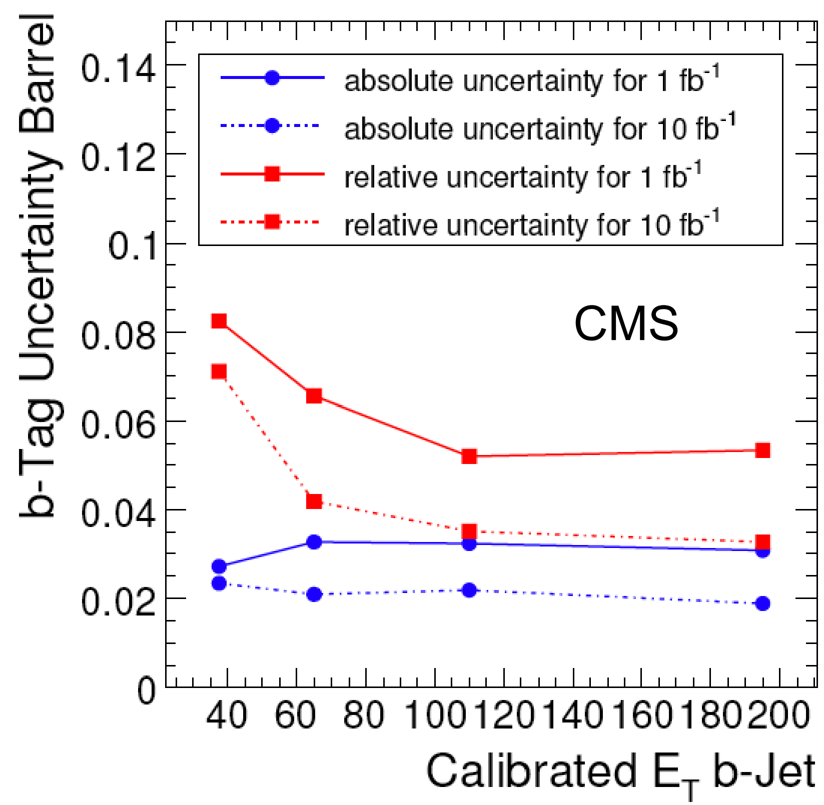
# b-tag efficiency

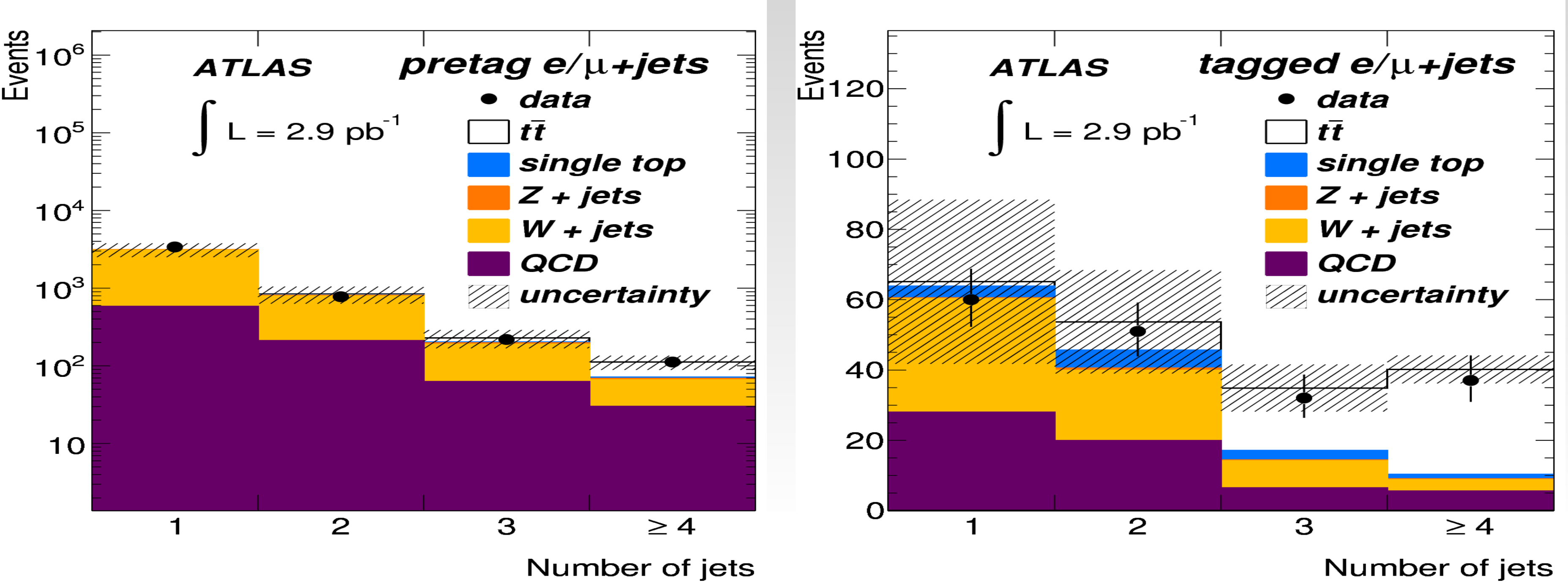
## Select b-enriched samples using tt sample

- t → W b ~ 100% → tagging top = tagging b
- Select pure b sample by using tt event topologies
  - 1(2) high $p_T$ leptons, $E_{T,miss}$, $m_W$ & $m_t$ constraints
  - 70-80% b-purity after selection

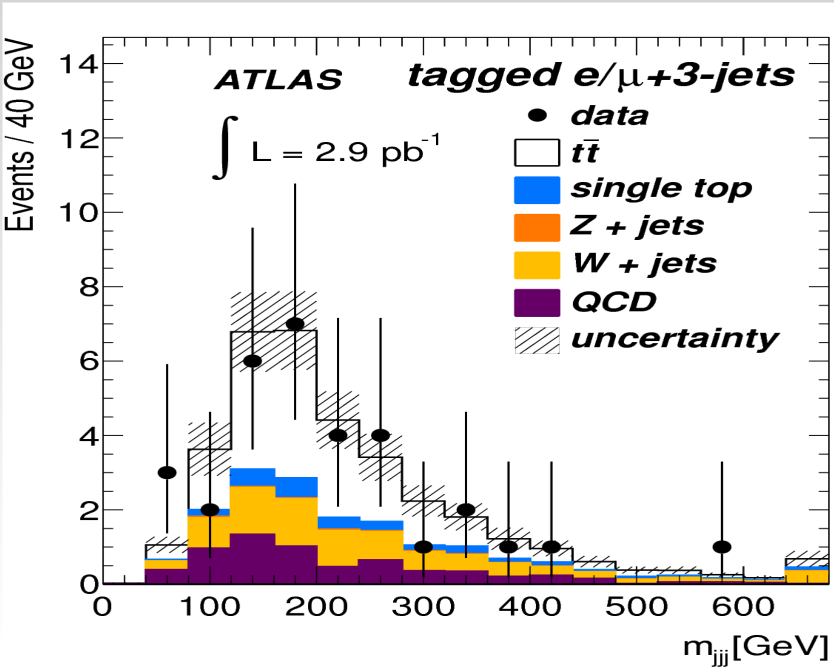
- CMS study 1(10) $fb^{-1}$
  - Efficiencies 40% to 60% (at $E_{T,b\text{-}Jet}$ > 100) GeV
  - Uncertainty 4-6% for large data samples

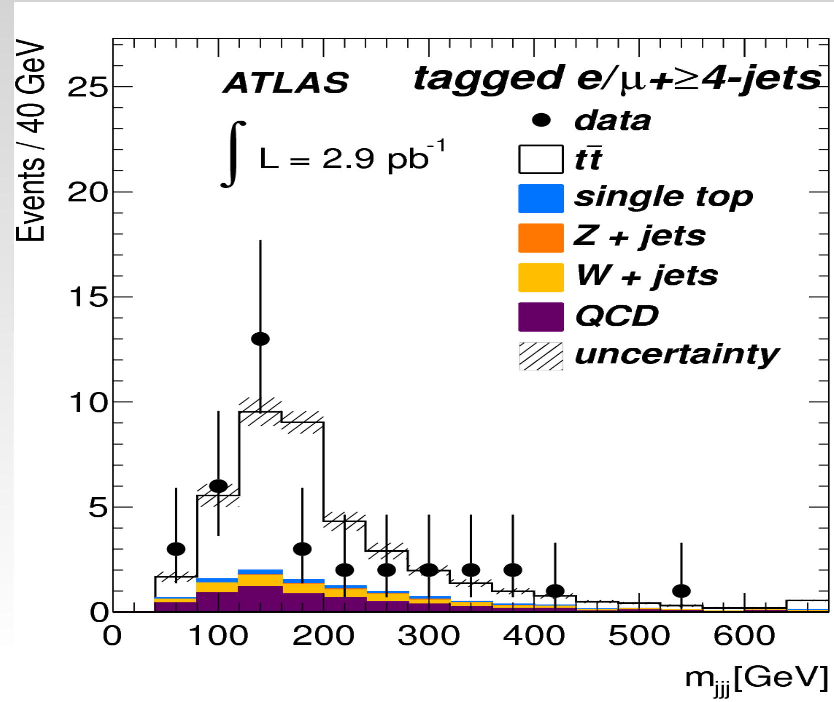
- ATLAS study 100 $pb^{-1}$
  - Similar efficiencies, purities
  - Estimated uncertainty ~10%

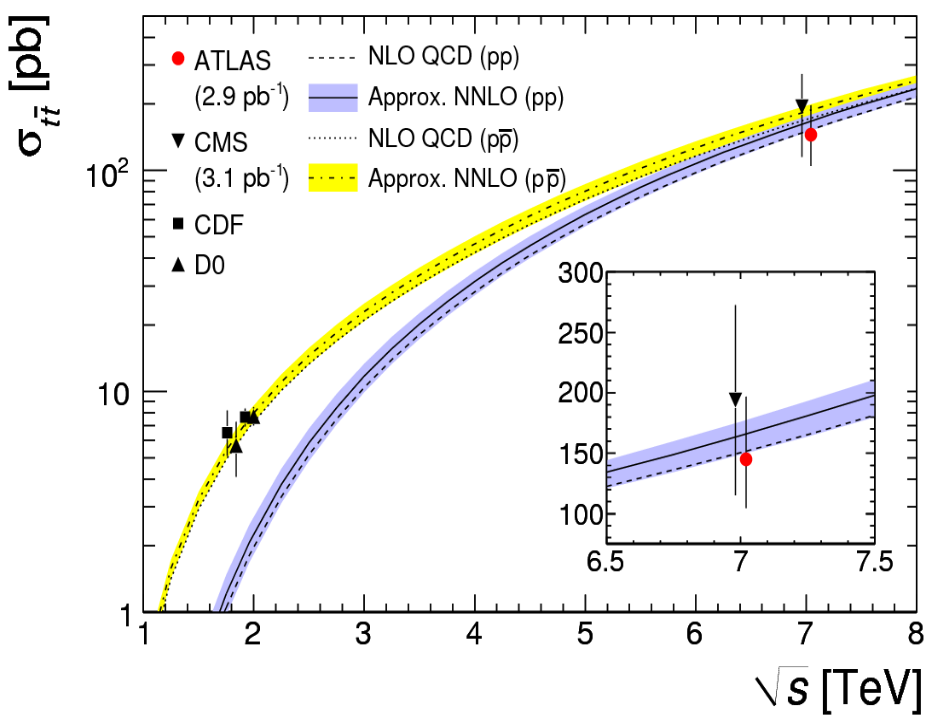





- Top signal (in high-multiplicity bins) hardly visible wrt W + jets background but largely enhanced by requiring two b-jets

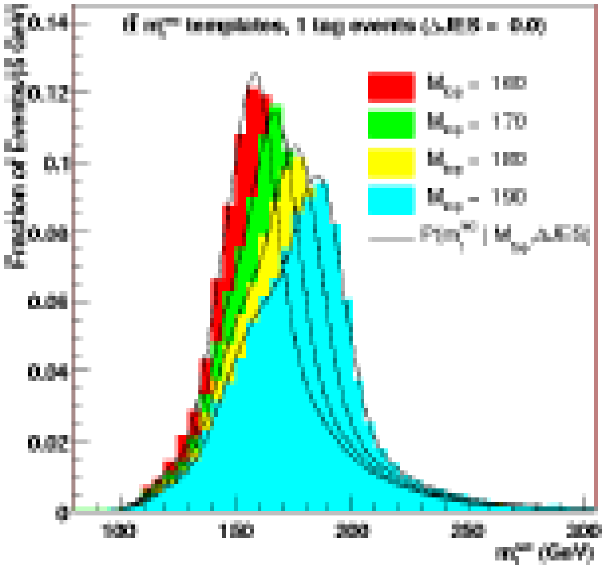


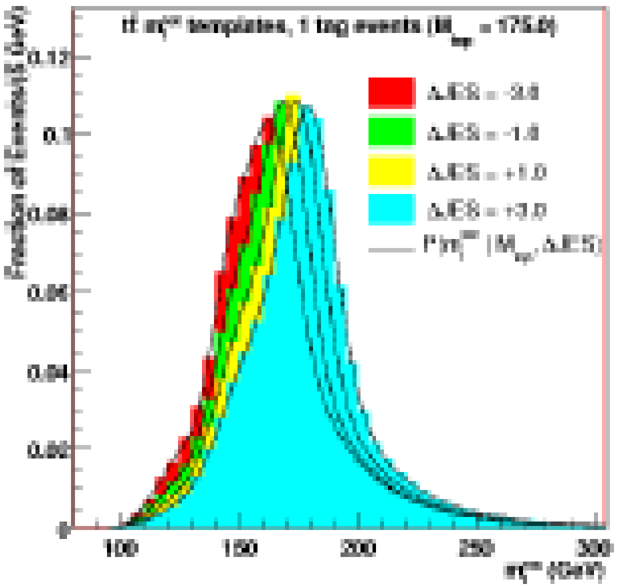



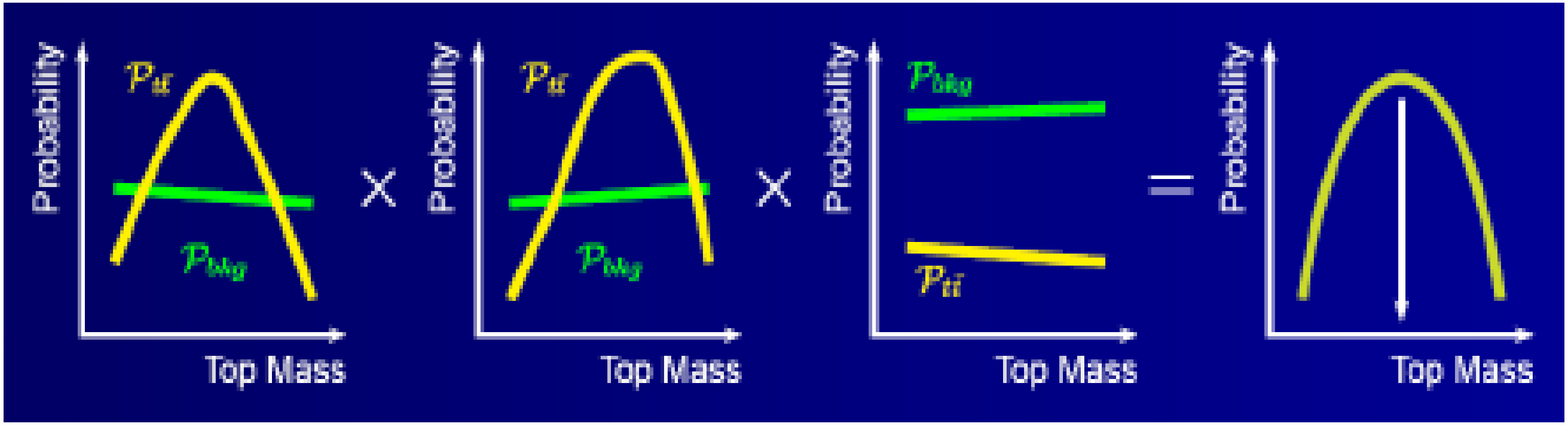

- First measurement of many top production, mass and properties ones

- Choose and calculate per event one or more observables sensitive to true $m_t$
- Build templates for signal and background distributions in this observable at different $m_t$ (and JES) values
- Determine most likely top mass from templates fit to data



- The most accurate measurement of the top quark mass
- Provides advantage in statistically limited regime
  - Calculate per-event probability density for signal and background as a function of the top quark mass using 4-vectors of reconstructed objects
  - Multiply the event probabilities to extract the most likely mass




  - Maximizes statistical power by using all event information
  - Extremely CPU intensive

**Normalization**
acceptance
& efficiency

**Differential cross section based on LO ME**

$$P_{t\bar{t}}(x; m_t, JES) = \frac{1}{\sigma(m_t)} \int d^n\sigma(y, m_t)\, dq_1\, dq_2\, f(q_1)\, f(q_2)\, W(x, y, JES)$$

Probability to observe a set of kinematic variables x for a given mass and JES

**Initial state**
Probability distribution that a parton will have a momentum q

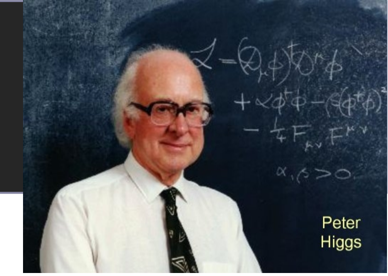
**Transfer function**
Probability to measure x when parton-level y was produced

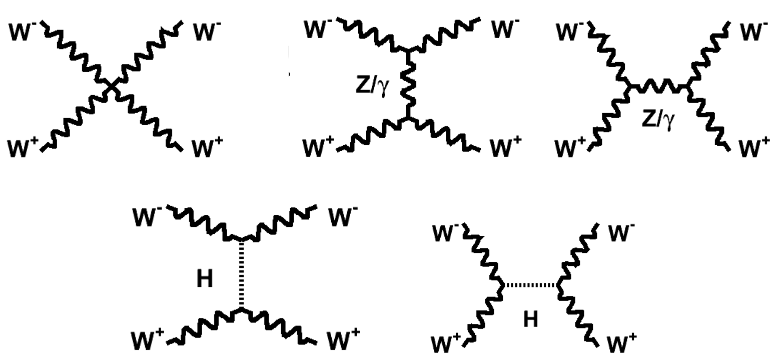
- Integrate over unknown $q_1$, $q_2$, y
- The jet energy calibration (JES) is a free parameter in the fit, constrained in-situ by the mass of hadronically decaying W

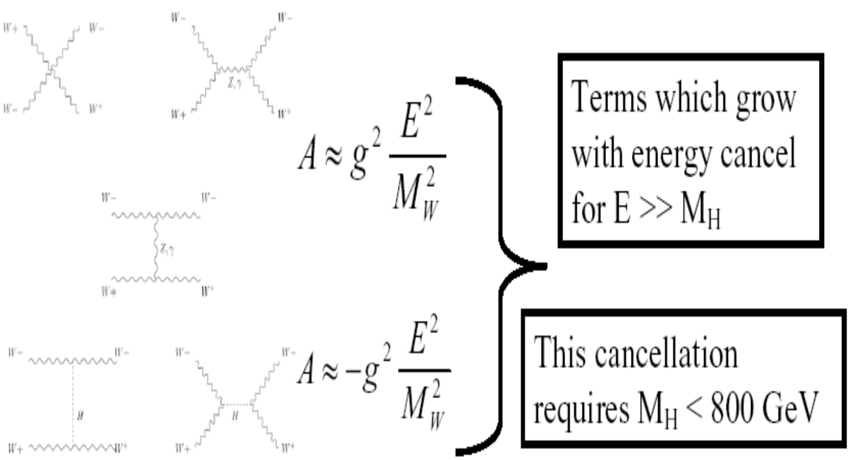
$$\mathcal{P}_{event}(x; m_t, \mathrm{JES}) = f_t\, \mathcal{P}_{t\bar{t}}(x; m_t, \mathrm{JES}) + (1 - f_t)\mathcal{P}_{bkg}(x, \mathrm{JES})$$

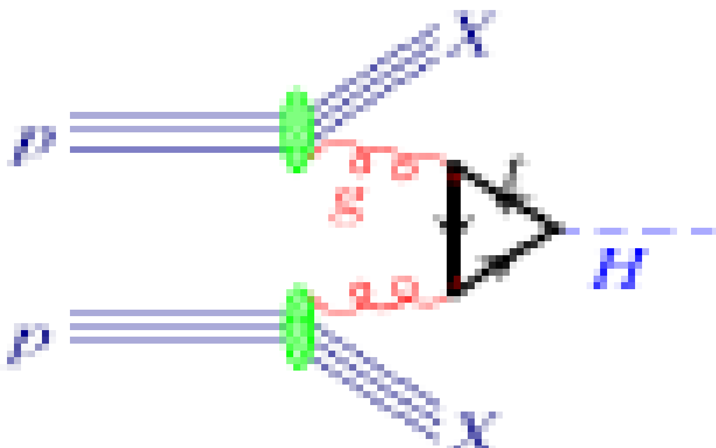
# The Higgs Boson

Peter Higgs

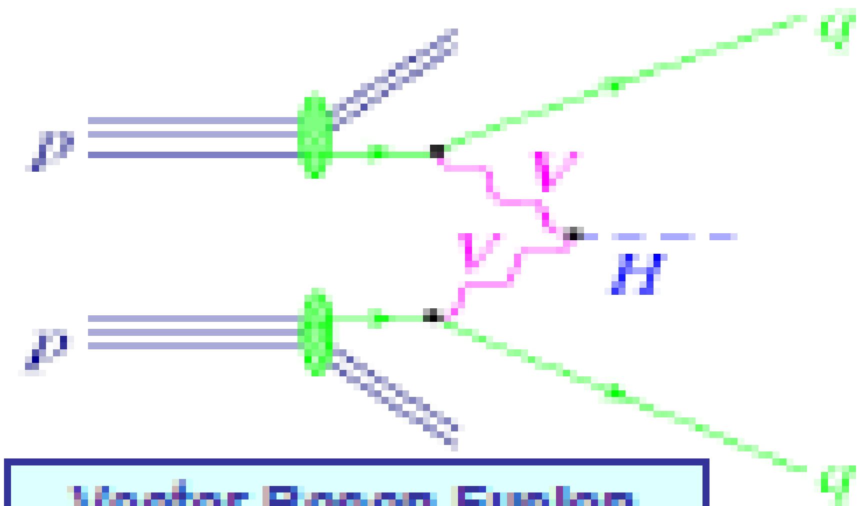



- EWSB caused by scalar Higgs field
- vacuum expectation value of the Higgs field <🏭> =246 GeV/c2
  - gives mass to the W and Z gauge bosons,
    - MW 📷 gW<🏭>
  - fermions gain a mass by Yukawa interactions with the Higgs field,
    - mf 📷 gf<🏭>
  - Higgs boson couplings are proportional to mass
- Higgs boson prevents unitarity violation of WW cross section
  - ? (pp🎭WW) > ? (pp 🎭 anything)
    - => illegal!
    - 

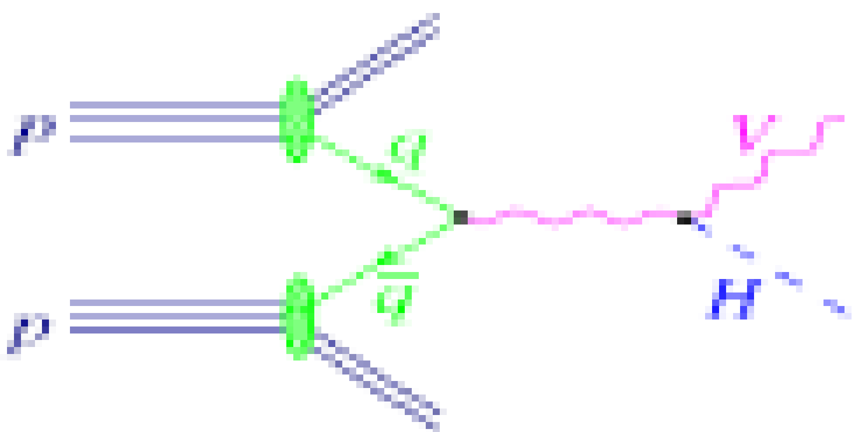





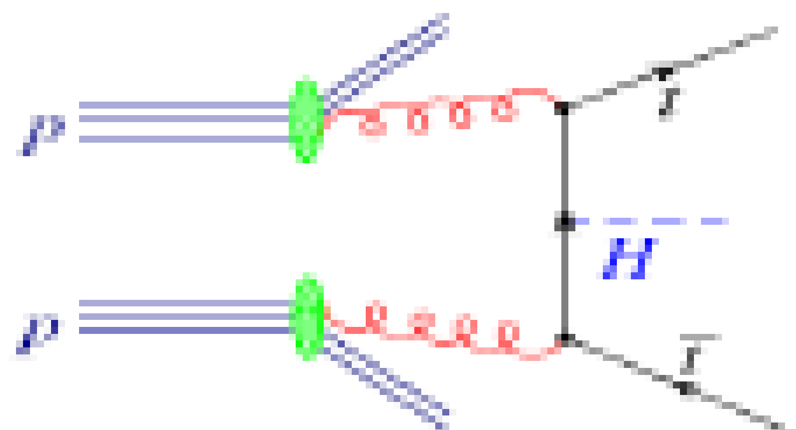

Gluon Fusion



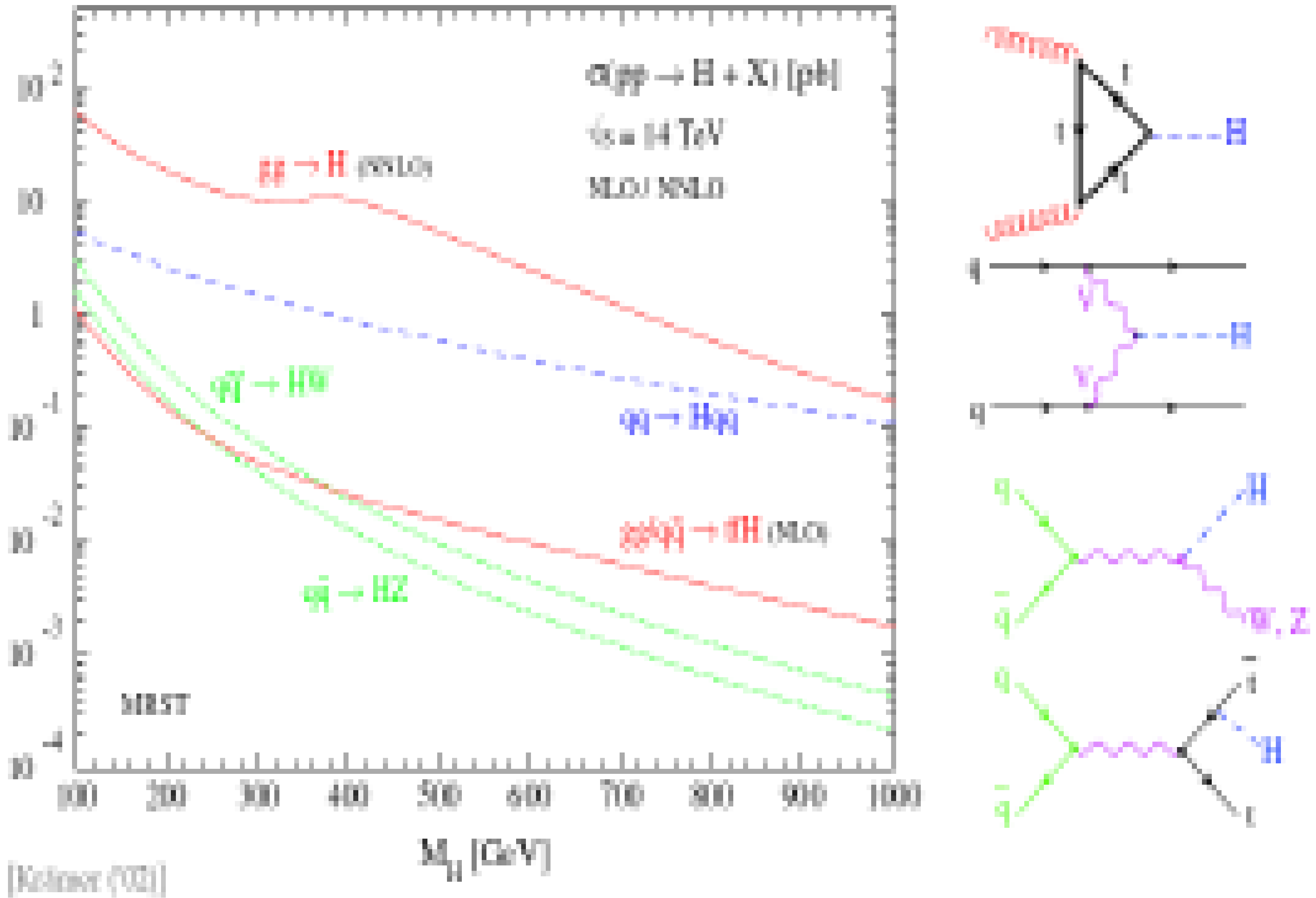

Vector Boson Fusion



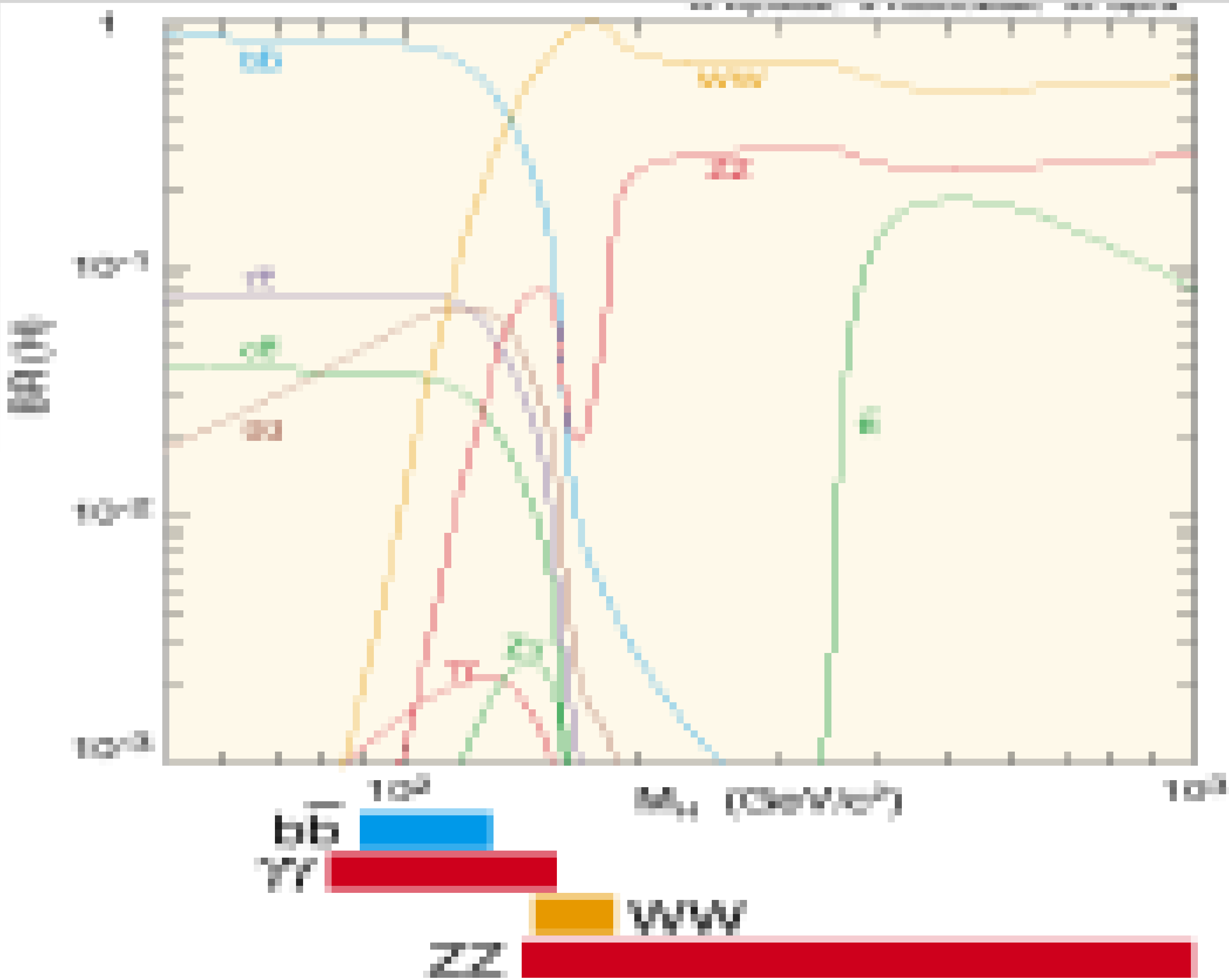

Higgs-strahlung



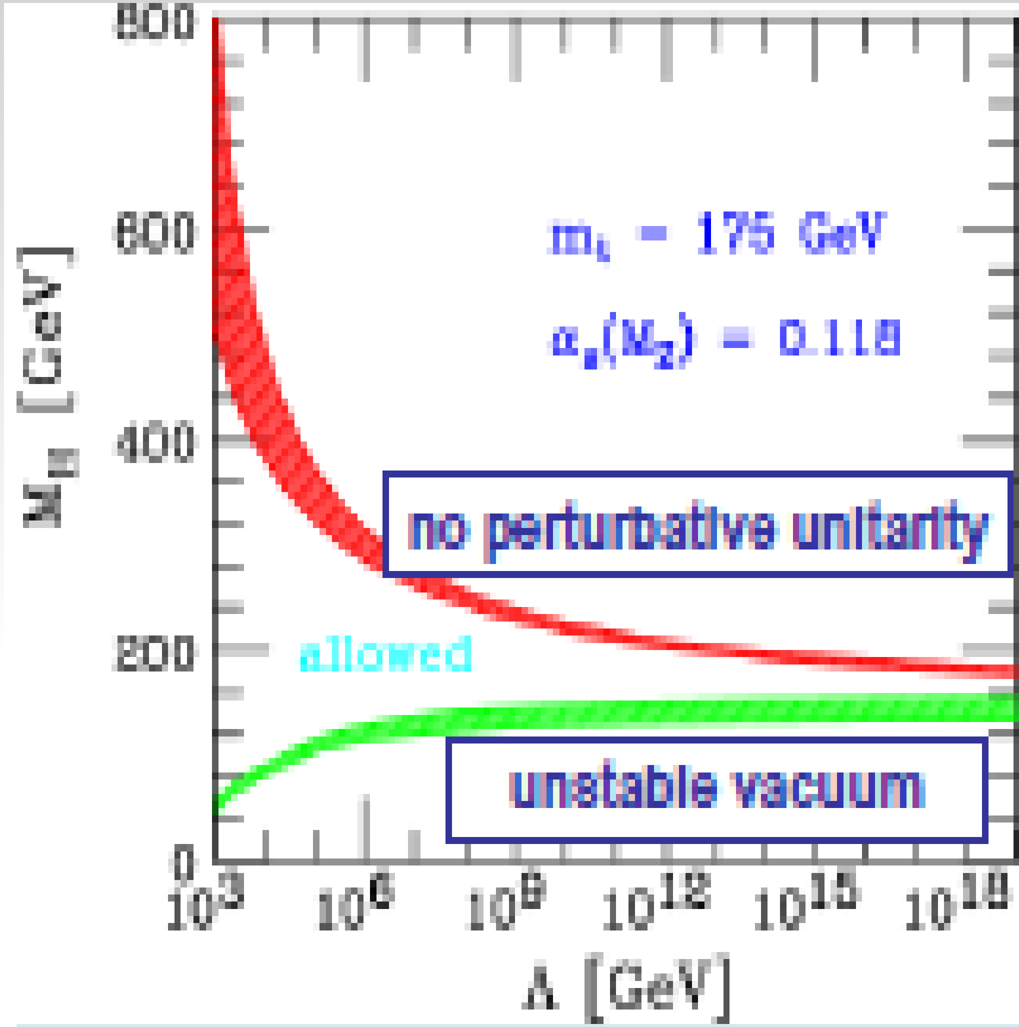

ttbar H ("associated" production)




Higgs width ~ $(m_H)$



bb̄
γγ
WW
ZZ




Upper bound

(triviality) :

$$\Lambda \le M_H \exp\left(\frac{4\pi^2 v^2}{3M_H^2}\right)$$

Lower bound

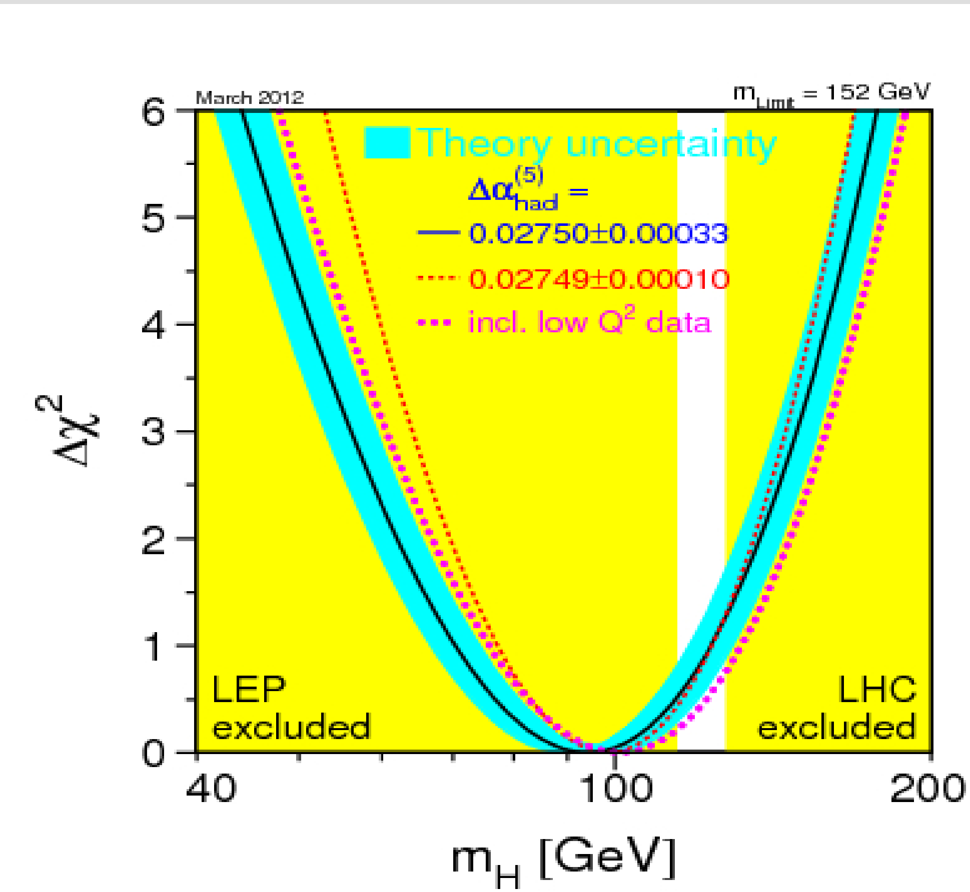
(vacuum stability) :

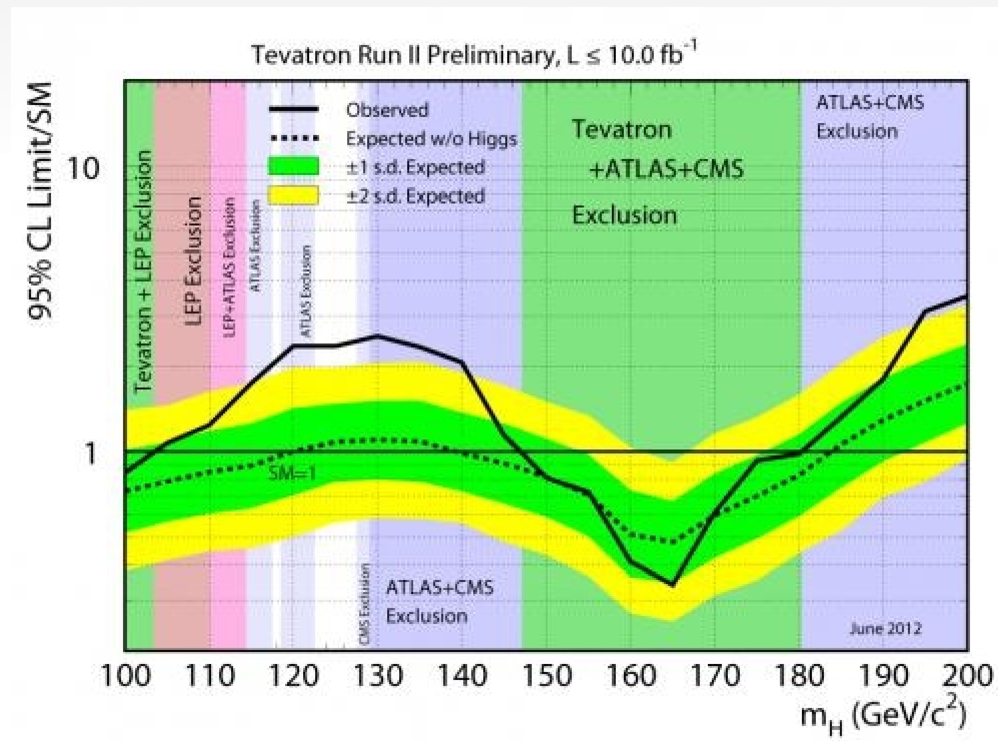
$$M_H^2 > \frac{3G_F\sqrt{2}}{8\pi^2} F \log\left(\Lambda^2 / v^2\right)$$

(Λ = cut-off scale at which new physics becomes important)

A light or heavy higgs requires early SM breakdown, and new physics to be discovered soon; worst case scenario mH ~ 180 Gev

- Indirect from EW fits, direct from LEP and Tevatron searches



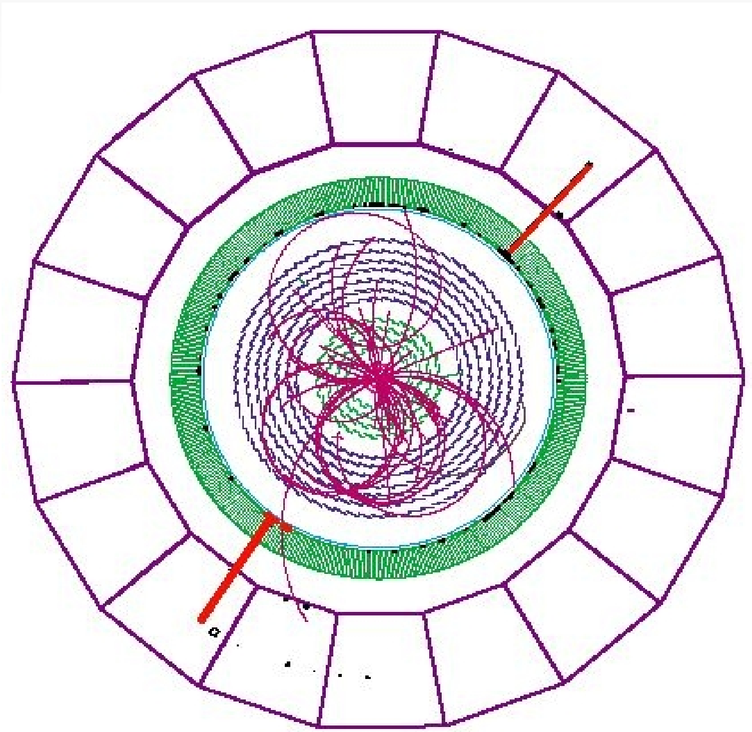

Best-fit value already escluded by LEP; ”big desert” scenario soon to be excluded by Tevatron?

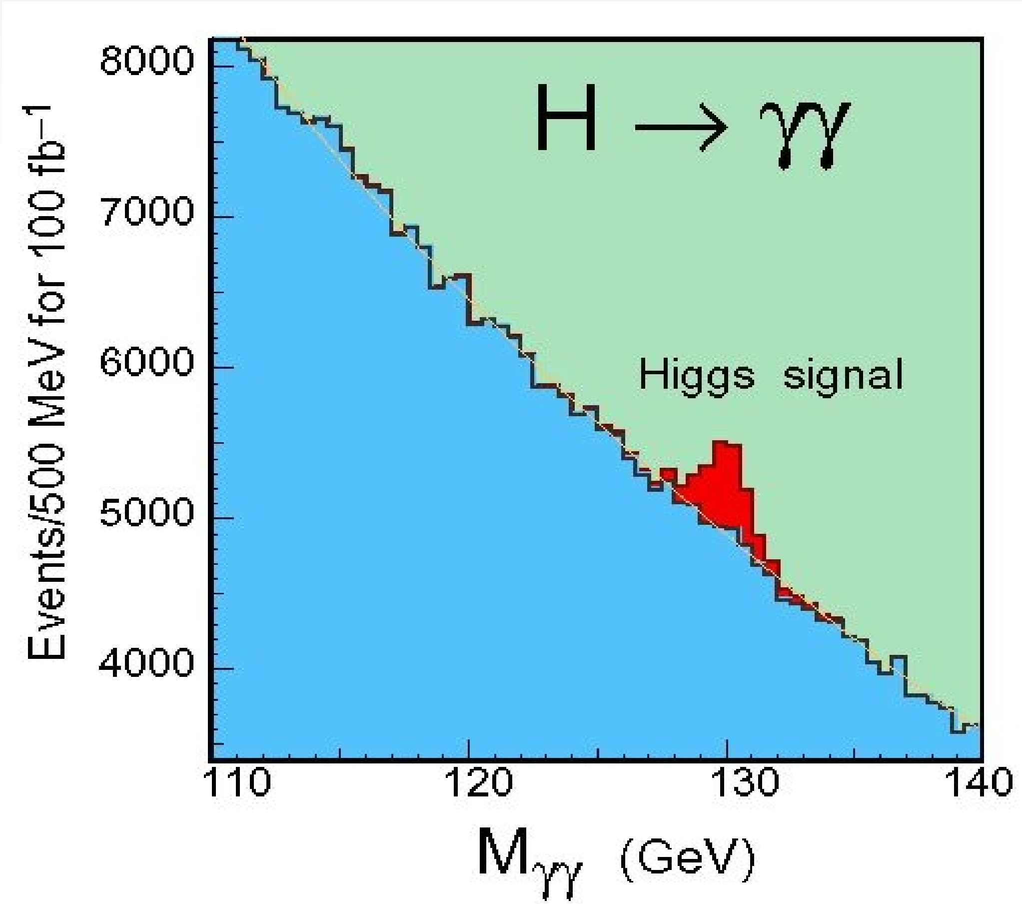
Only unknown is mass, so we are searching in several channels, depending on our bet on the Higgs mass:

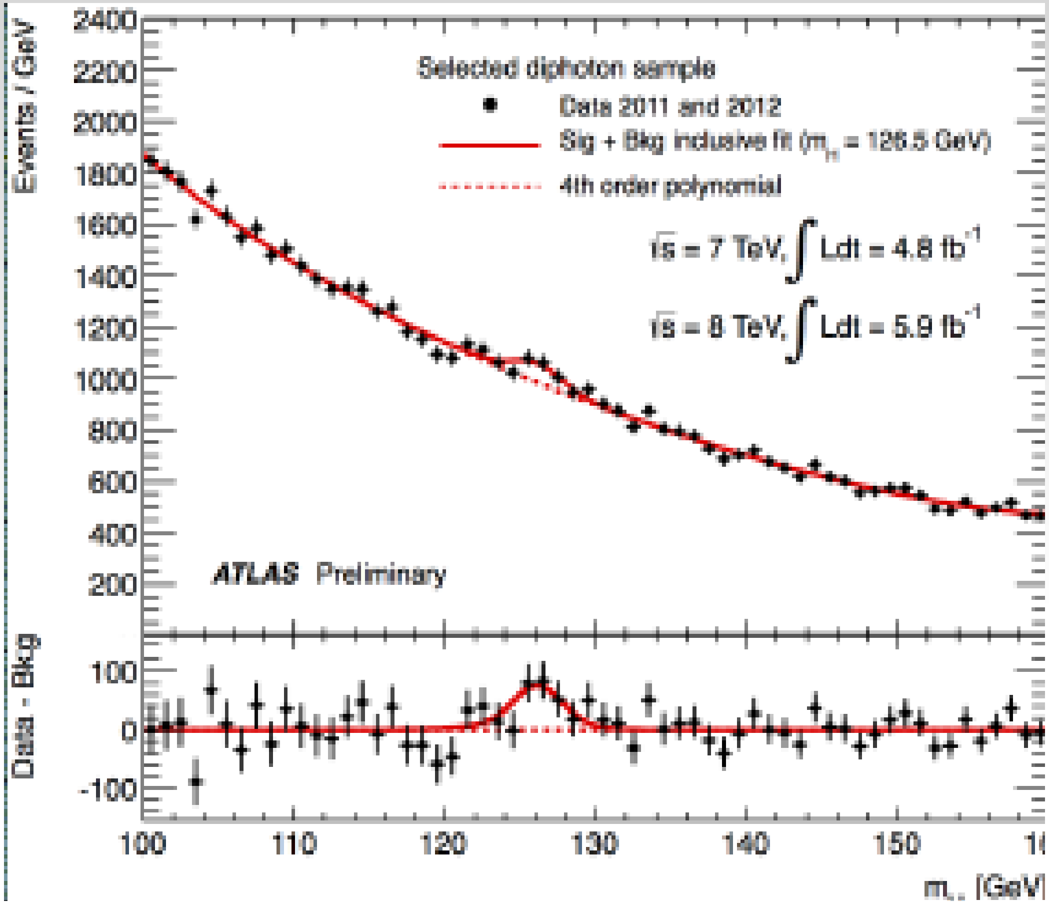
- Light Higgs: 114 < mH <  140
  - $H \rightarrow \gamma\gamma$, $qqH \rightarrow qq\tau\tau$
  - $qqH \rightarrow qq\, WW^*$, $ttH \rightarrow ttbb$
- As soon as two (even virtual) vector bosons can be produced
  - $H \rightarrow WW^{(*)}$
  - $H \rightarrow ZZ^{(*)}$, ZH->llbb
- At high masses, the width becomes very large, so we would see a shoulder rather than a resonance

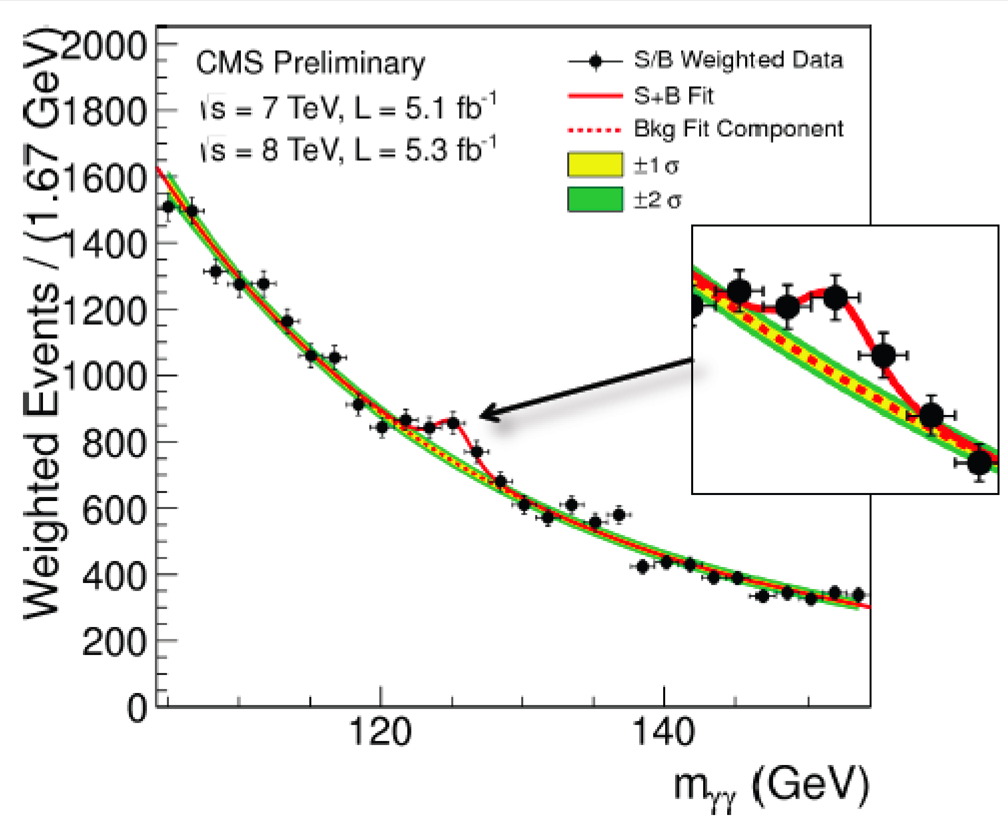
# $\gamma\gamma$

- Small signal (BR~$10^{-3}$), over a 20 times larger BG.
- But full mass reconstruction possible, and for these masses Higgs is a very narrow resonance (Ecal energy and pointing resolution essential!)

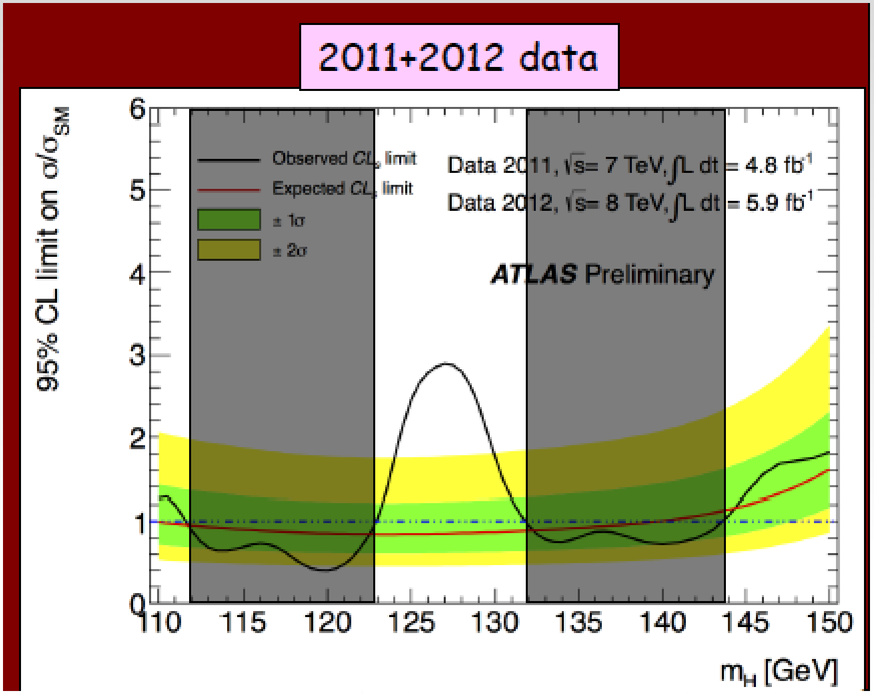


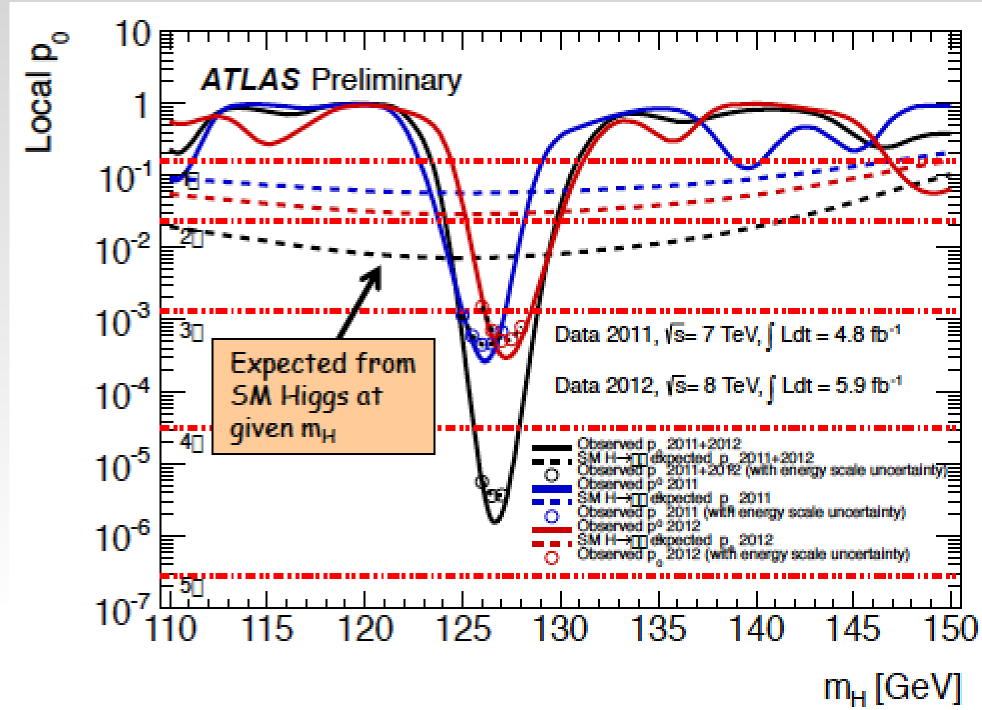


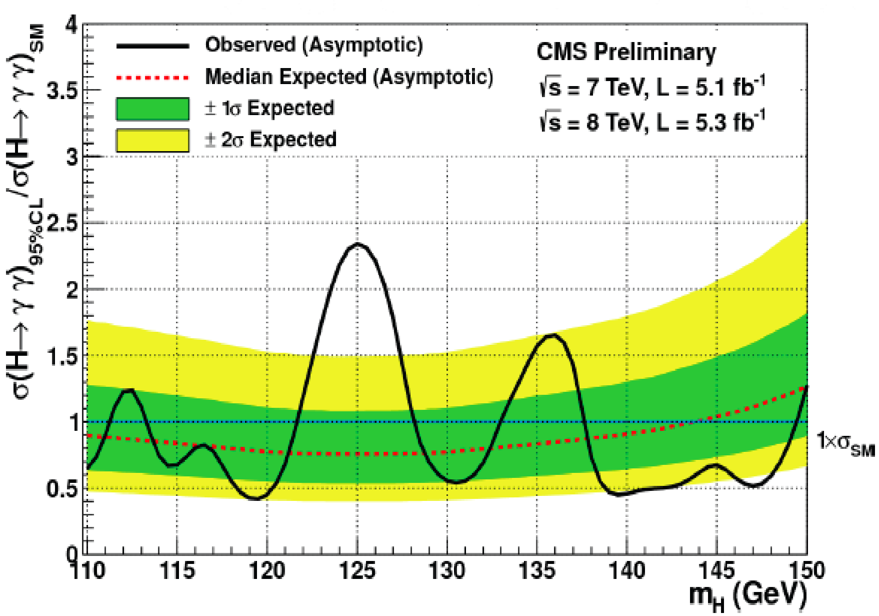



Despite complementary detector technologies, and resolutions (better in energy for CMS, better in angle for ATLAS), width and strength of observed peaks are the same!



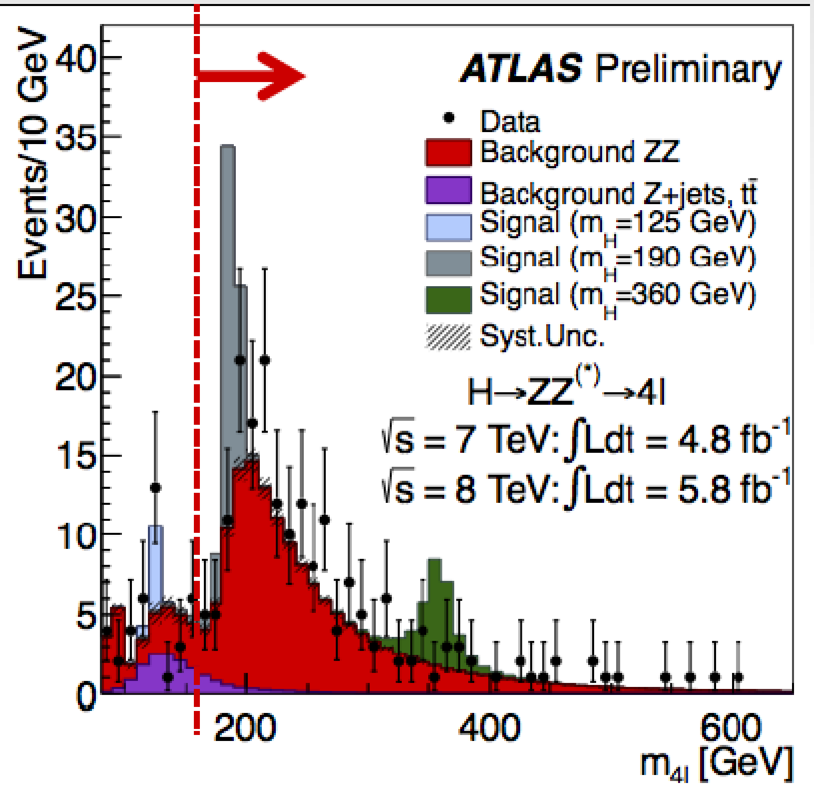



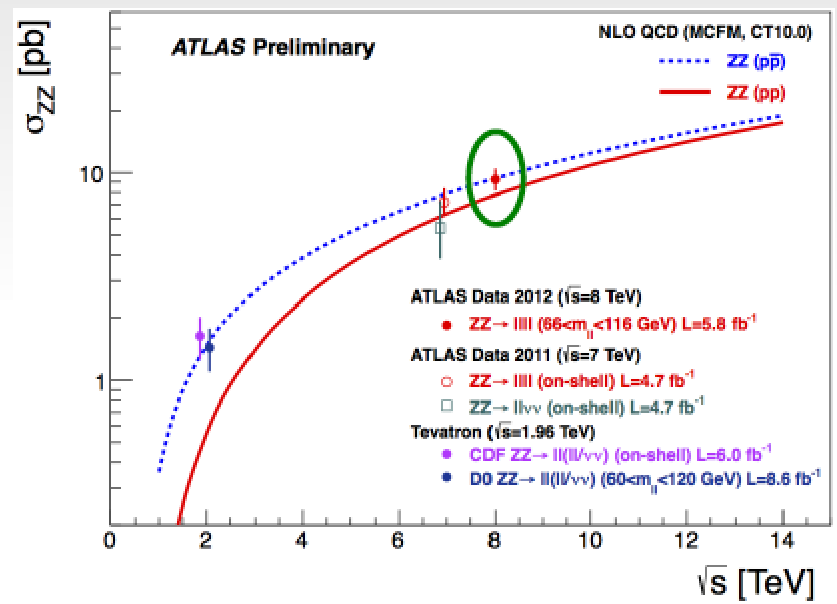

Very similar signal in both experiments, with a σ*BR twice as much as expected from the Higgs (but compatible within errors).

Is it just "discovery bias"?

→

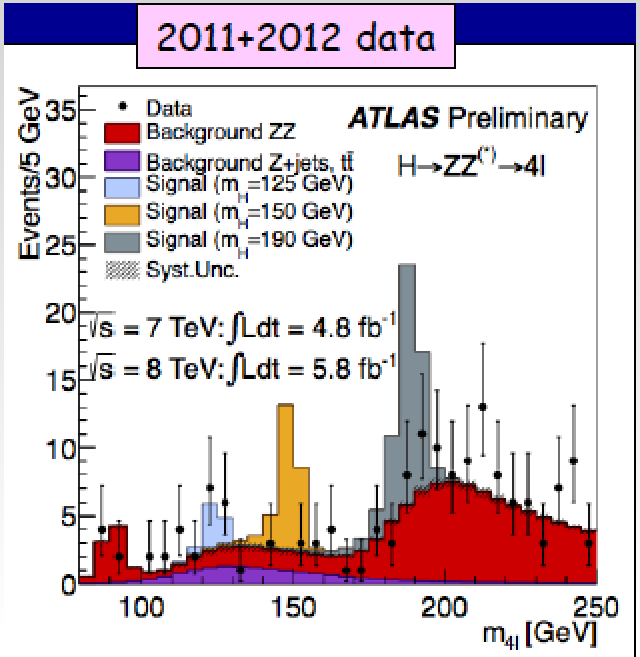
- Golden channel if mass is >2 Mz, it still plays a role at low masses. Small σ*BR: 2.5 fb



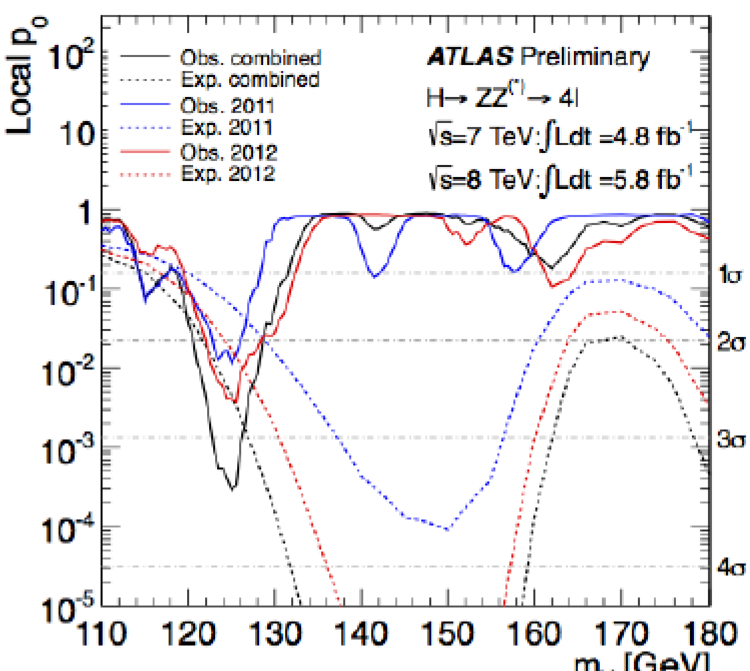

ZZ invariant mass spectrum well reproduced, and measured cross-section in agreement with NLO predictions

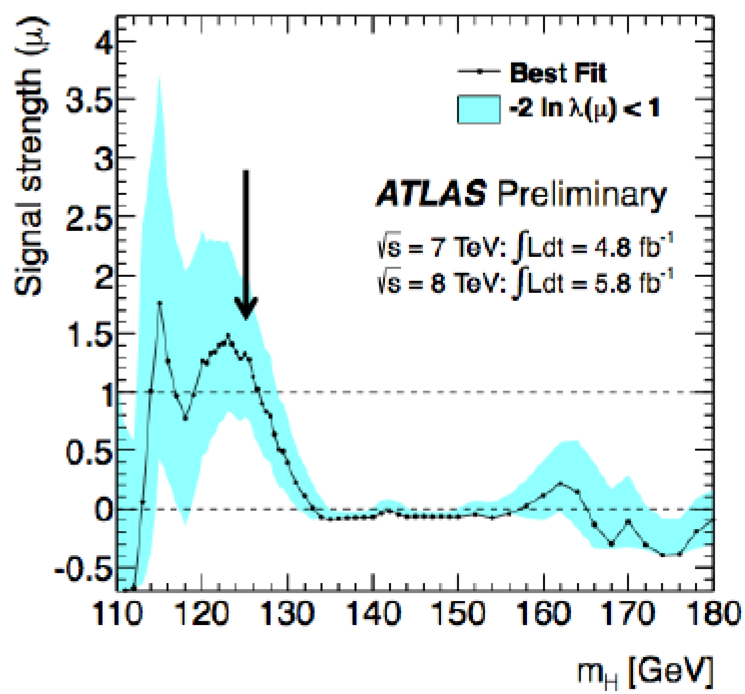
But... what is happening at low mass values?




| In the region 125 ± 5 GeV | | | |
|---|---|---|---|
| Dataset | 2011 | 2012 | 2011+2012 |
| Expected B only | 2±0.3 | 3±0.4 | 5.1±0.8 |
| Expected S $m_H$=125 GeV | 2±0.3 | 3±0.5 | 5.3±0.8 |
| Observed in the data | 4 | 9 | 13 |

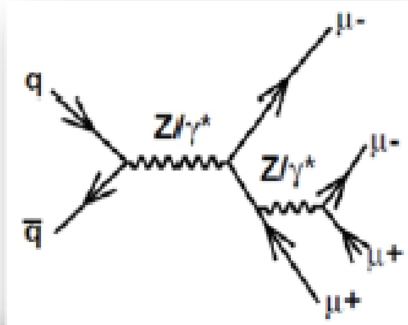
| 2011+ 2012 | 4μ | 2e2μ | 4e |
|---|---|---|---|
| Data | 6 | 5 | 2 |
| Expected S/B | 1.6 | 1 | 0.5 |
| Reducible/total background | 5% | 45% | 55% |

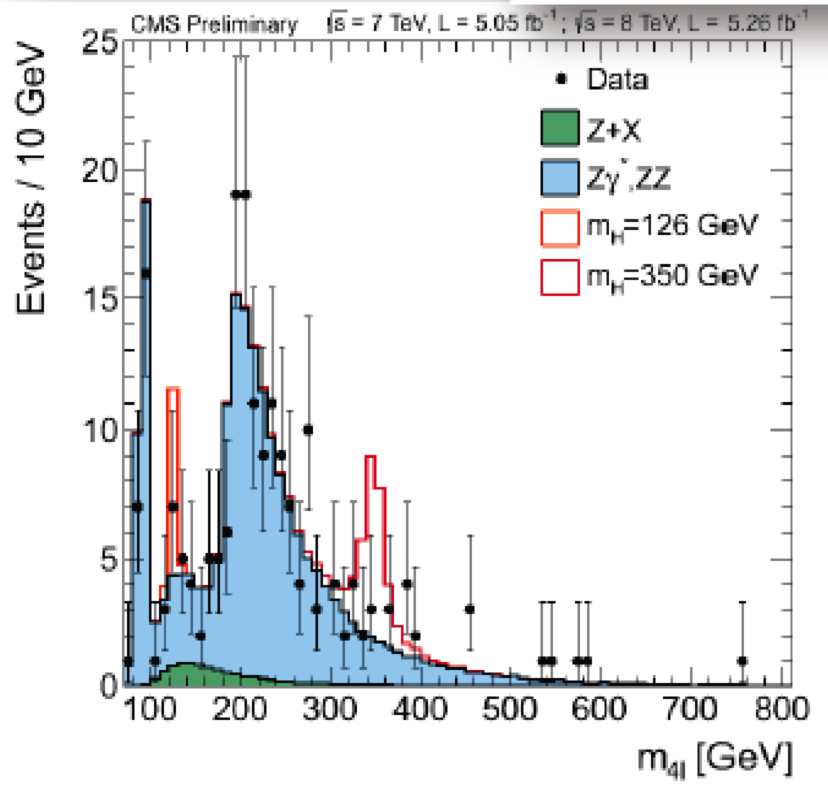


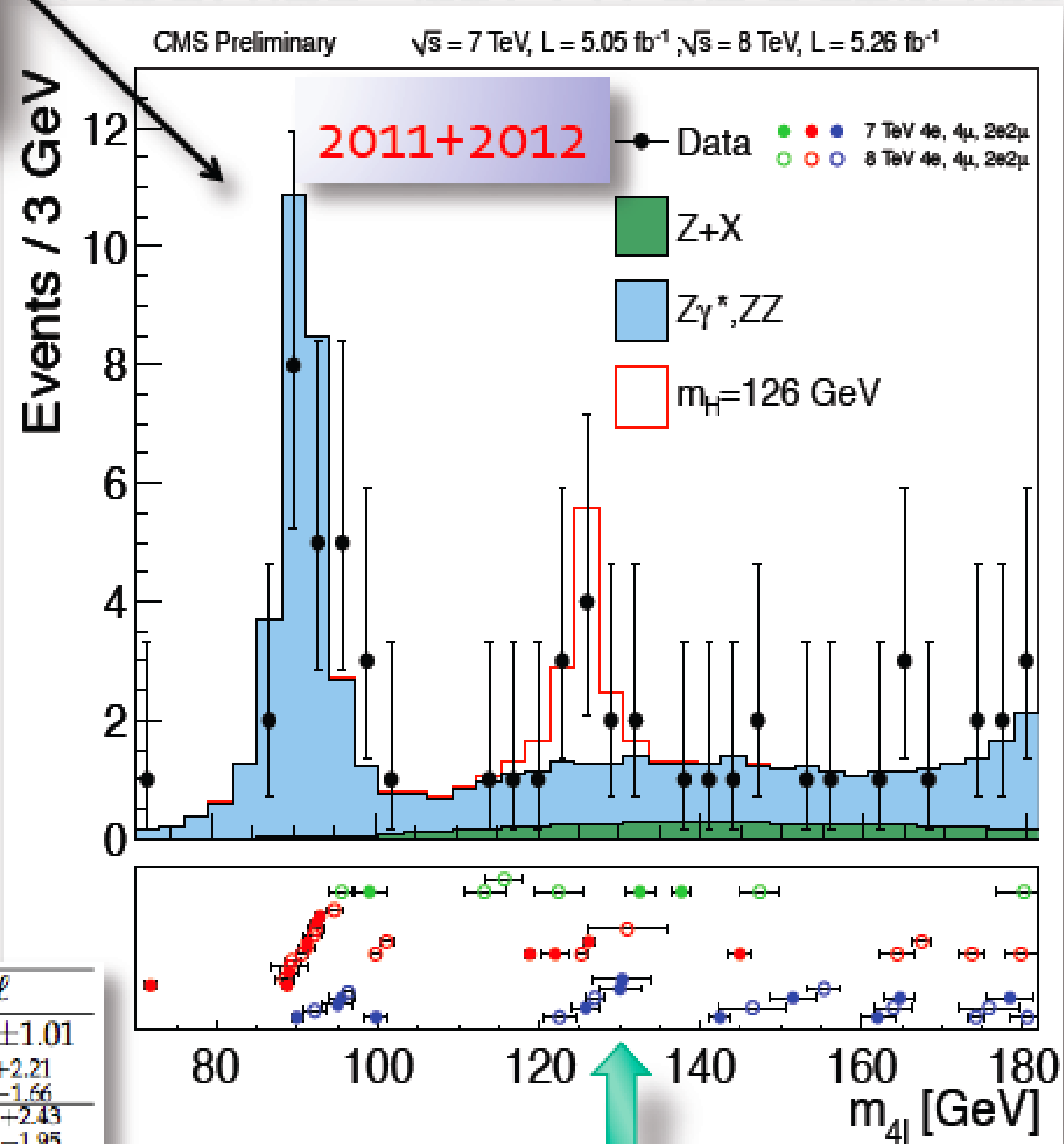




Excess seen in same region as in γγ

# Results: m(4l) spectrum



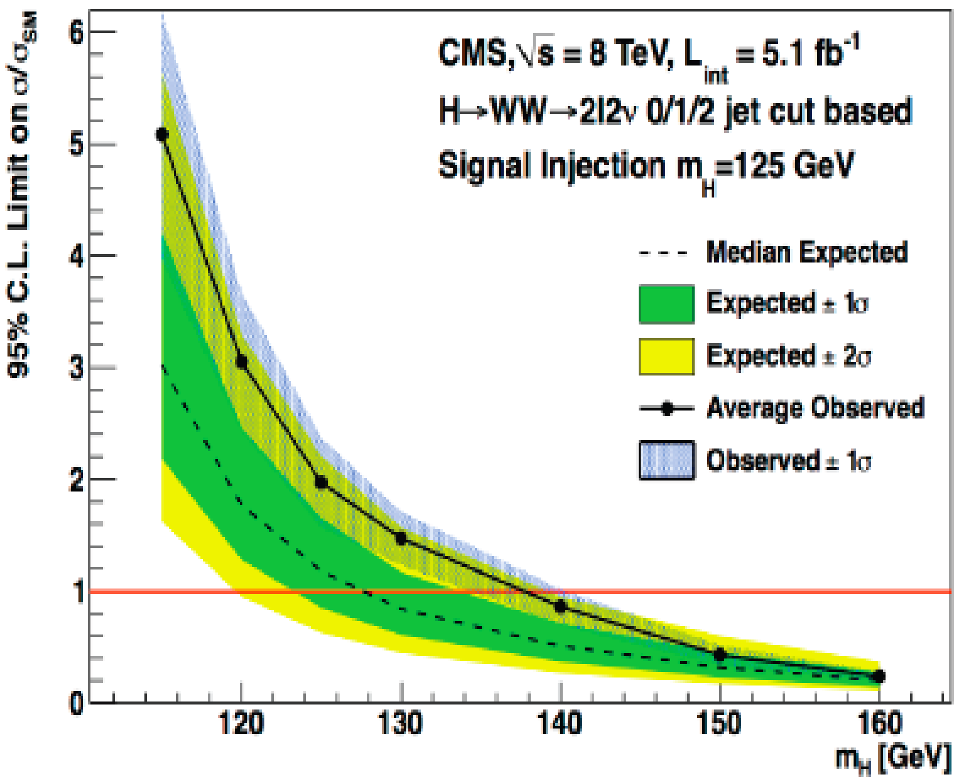



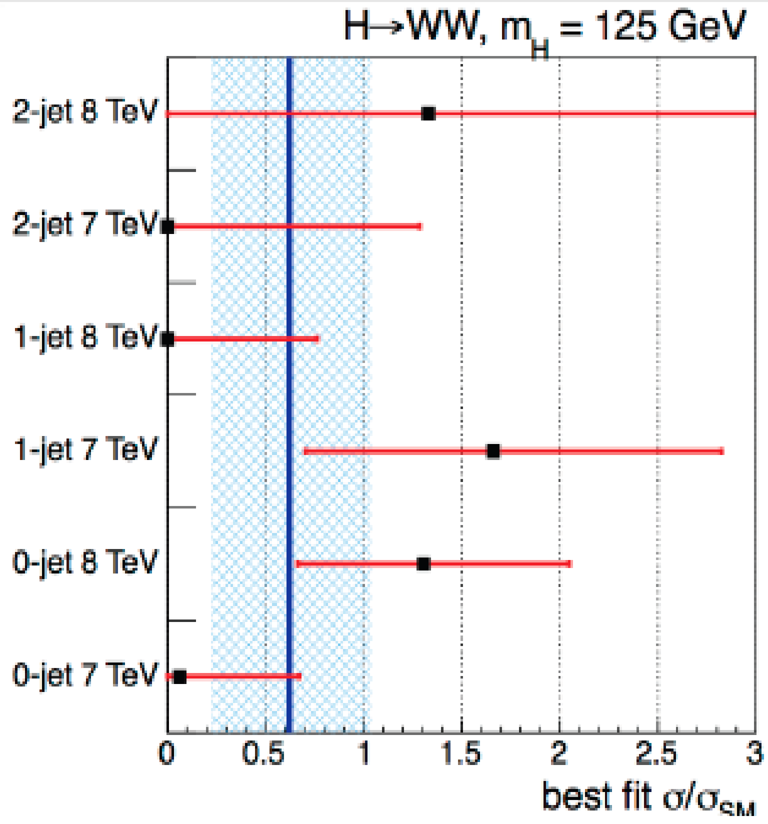

Event-by-event errors

Yields for m(4l)=110..160 GeV

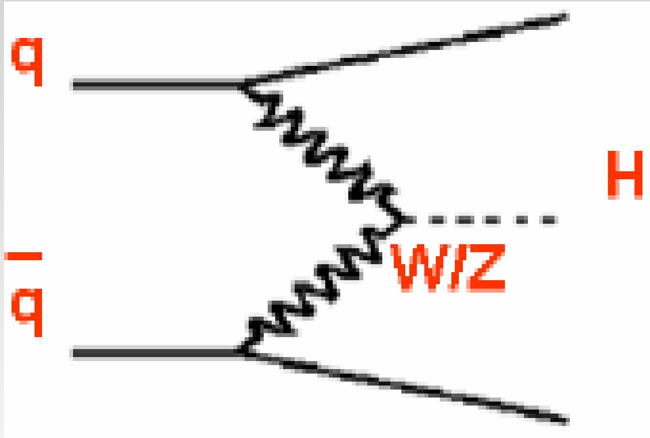
| Channel | 4e | 4μ | 2e2μ | 4ℓ |
|---|---|---|---|---|
| ZZ background | $2.65 \pm 0.31$ | $5.65 \pm 0.59$ | $7.17 \pm 0.76$ | $15.48 \pm 1.01$ |
| Z+X | $1.20^{+1.08}_{-0.78}$ | $0.92^{+0.65}_{-0.55}$ | $2.29^{+1.81}_{-1.36}$ | $4.41^{+2.21}_{-1.66}$ |
| All backgrounds | $3.85^{+1.12}_{-0.84}$ | $6.58^{+0.88}_{-0.81}$ | $9.46^{+1.96}_{-1.56}$ | $19.88^{+2.43}_{-1.95}$ |
| $m_H = 126$ GeV | $1.51 \pm 0.48$ | $2.99 \pm 0.60$ | $3.81 \pm 0.89$ | $8.31 \pm 1.18$ |

164 events expected in [100, 800 GeV]
172 events observed in [100, 800 GeV]

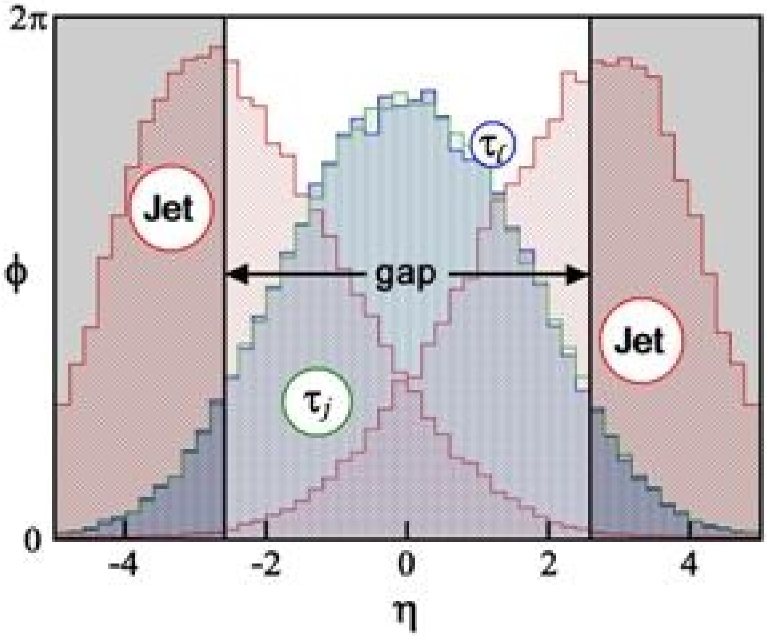


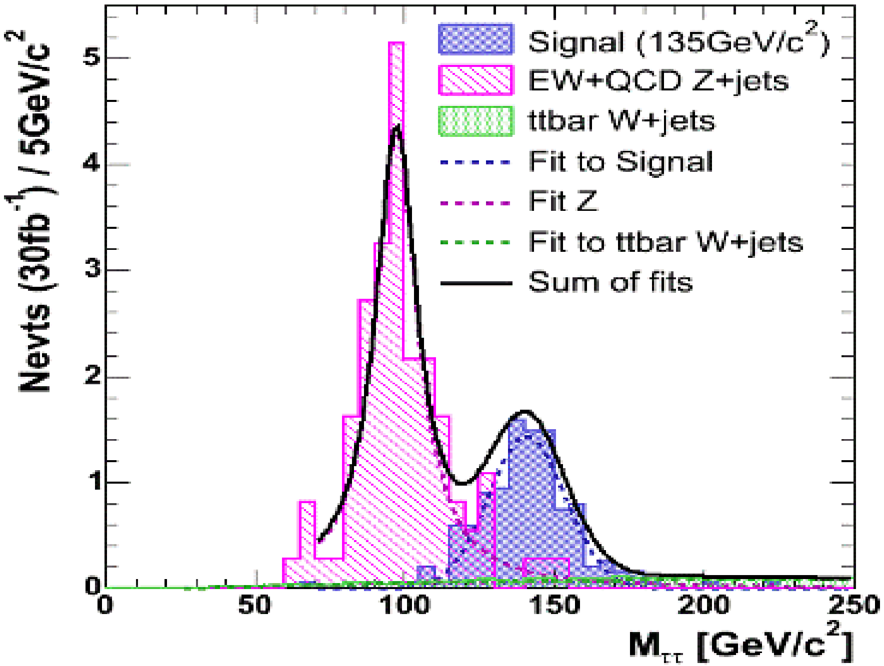



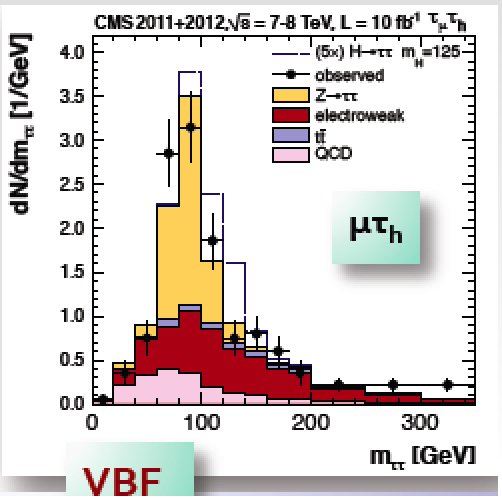

- Similar result recently published by ATLAS

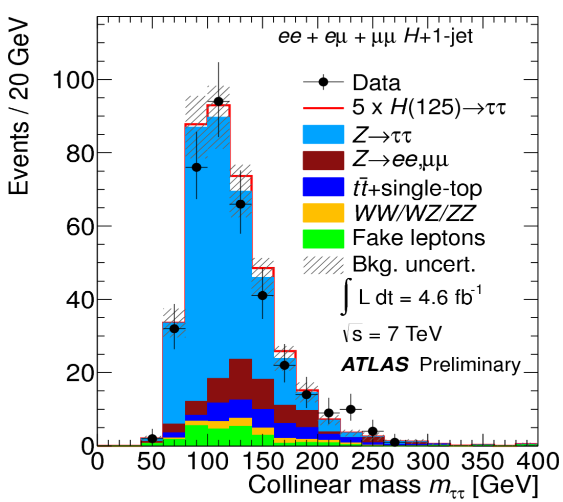



- Remnants of the final-state quarks emitted in the forward region (up to $\eta$~ 3.5)
- Hard scattering has no colour flow between the two jets → rapidity gap between them
- It would be a very clean signature, if not for the UE and pileup!
- Depending on mass, look for $\tau\tau$ or WW decays

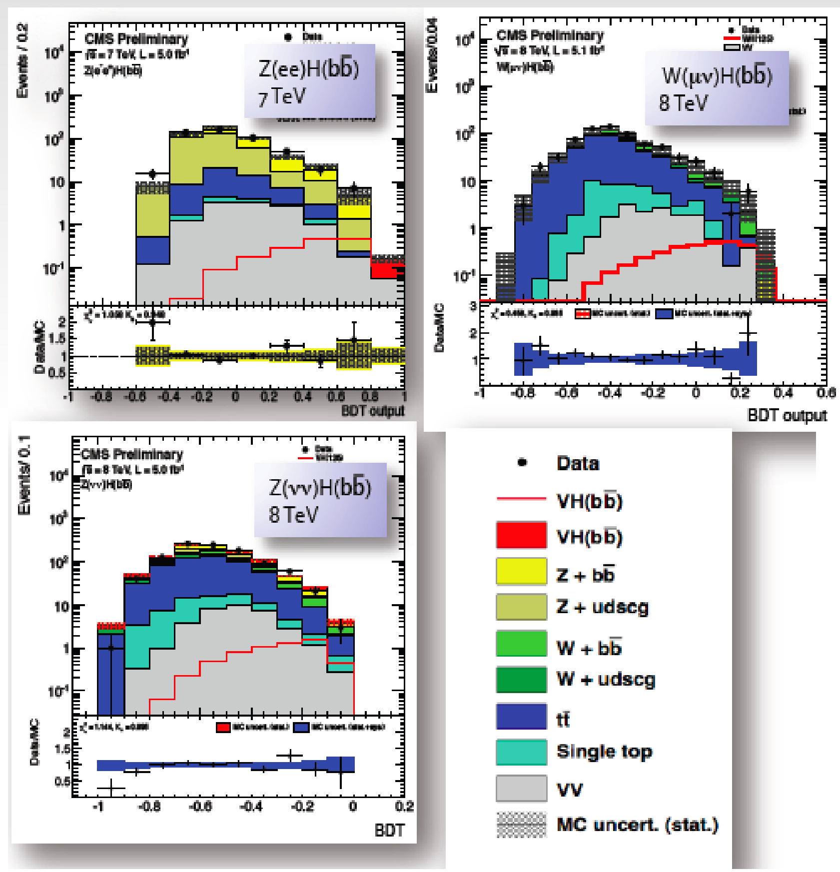


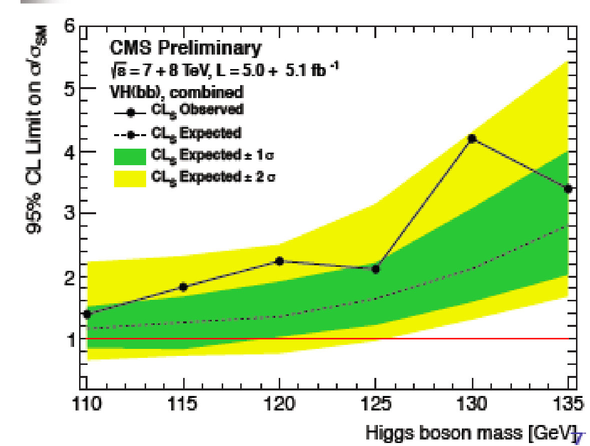



# H->ττ

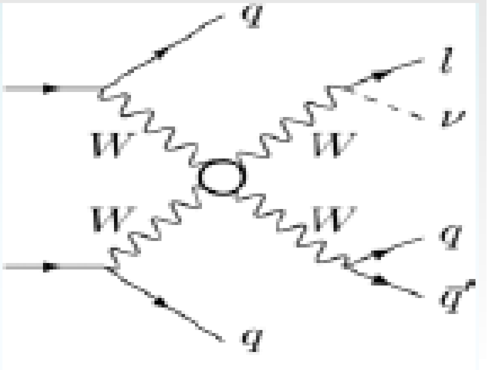



- Observed limits:
  - Compatible with either background or signal from a 125 GeV Higgs

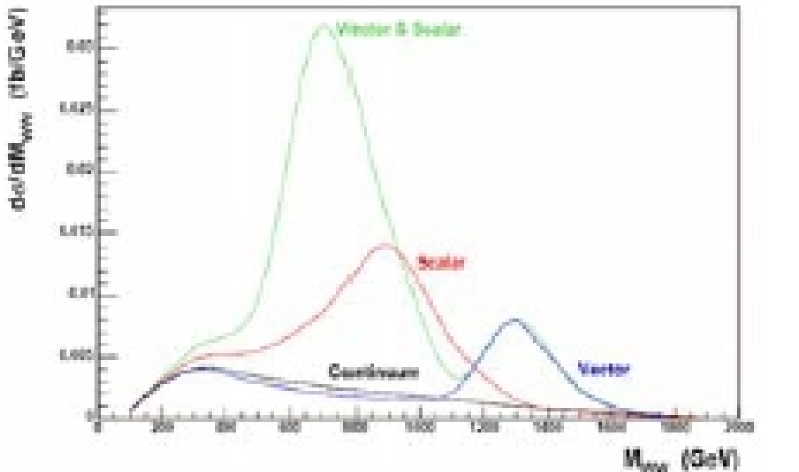



# H->bb

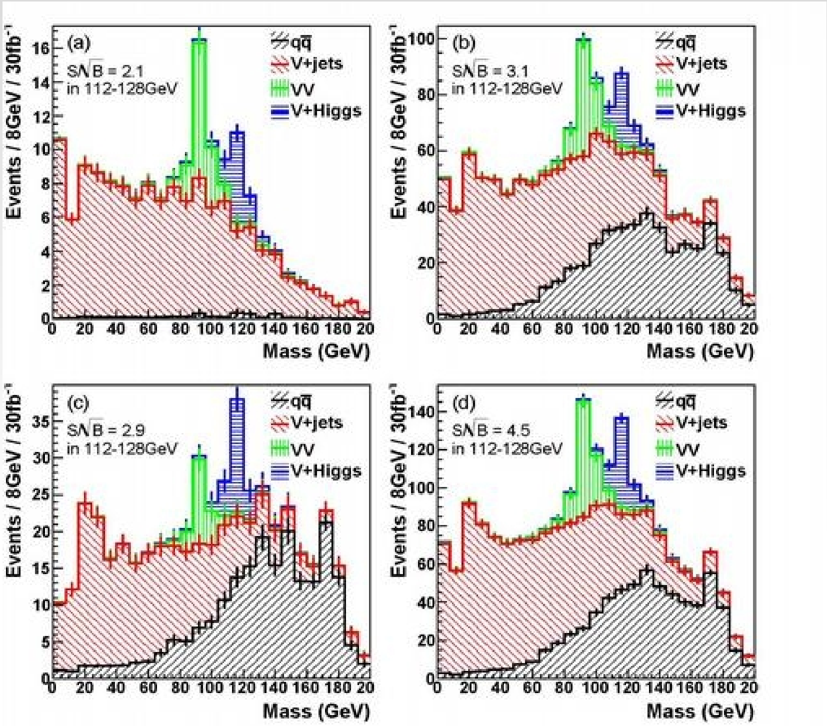
- Apart for giving mass to all other particles, the Higgs is needed in the SM to stabilise the $W_L W_L \rightarrow W_L W_L$ scattering process



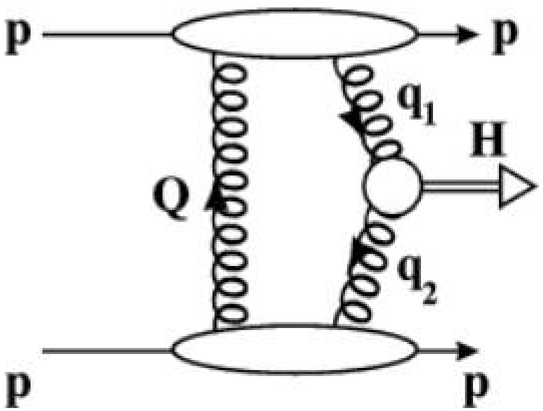

- This cross section is divergent in the SM, but if the Higgs is there a diagram with Higgs exchange restores finiteness
- Does not work if Higgs is too heavy, in that case some other resonance could be produced in WW final states
- More than one Higgs could be present, even in a pure SM scenario, with broad mass spectrum

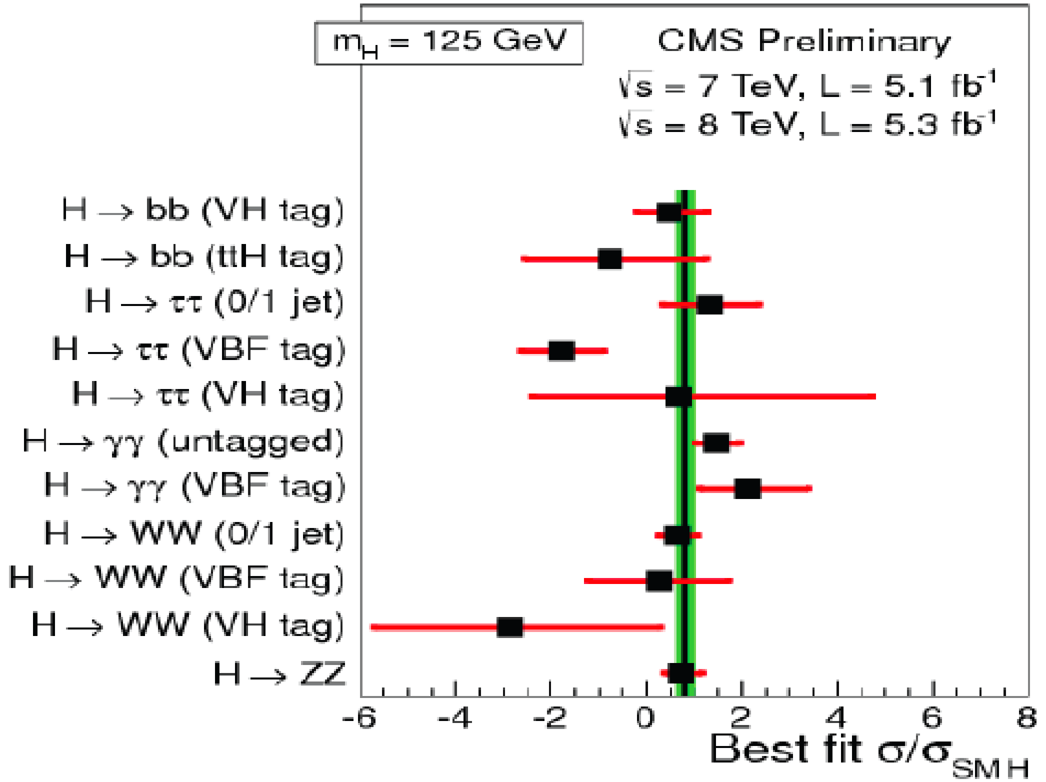


- HZ: S/BG ratio increases for high-Pt Higgs. In that case, and for the main decay channel H->bb, Higgs decay channels end up in a single jet, substructure used to find it

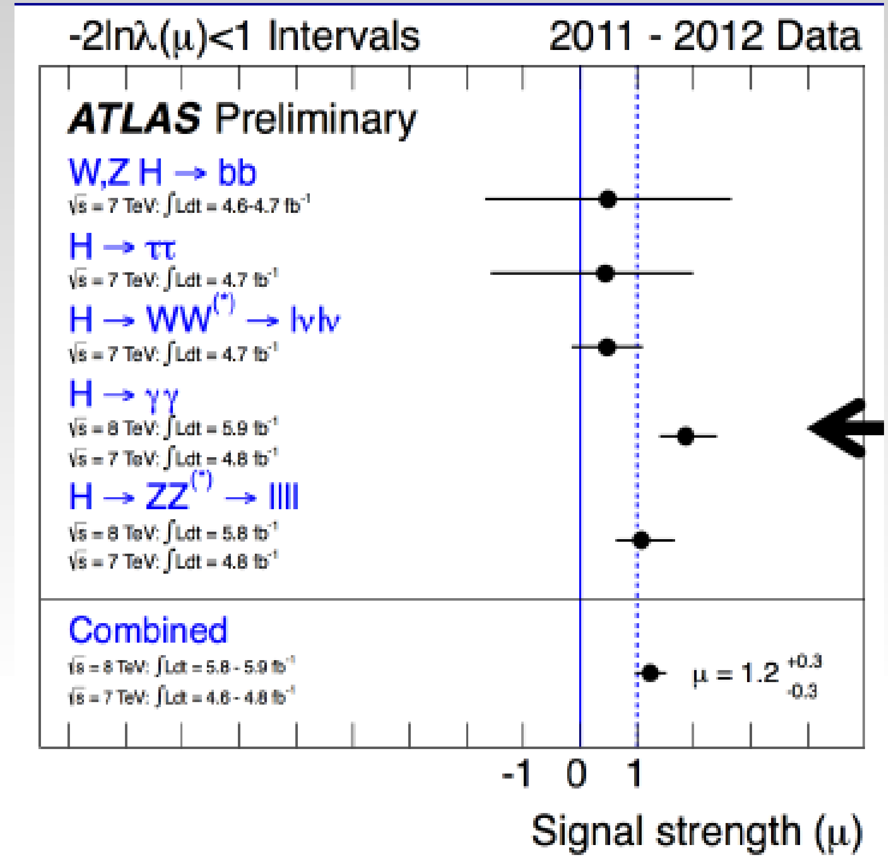



- Diffractive Higgs: Higgs can be produced in diffractive mode, with the two protons stay intact after collision. Only possible with $1^{++}$ quantum numbers, requires installation of forward proton taggers

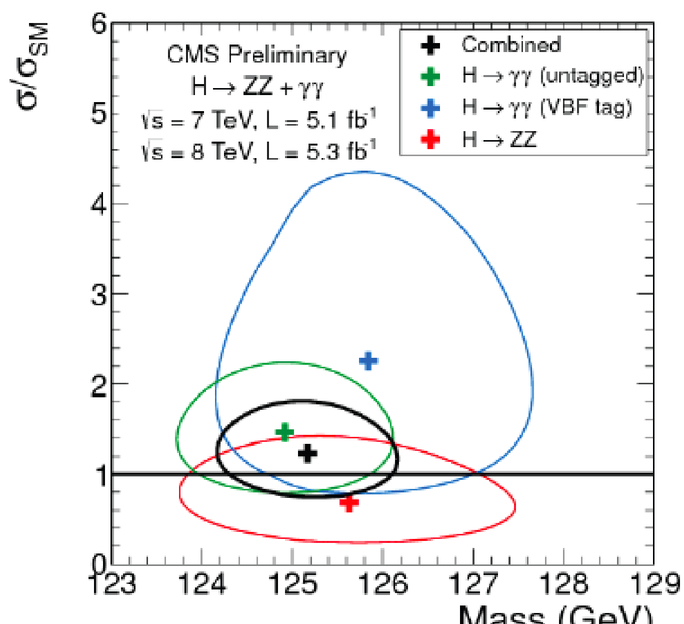




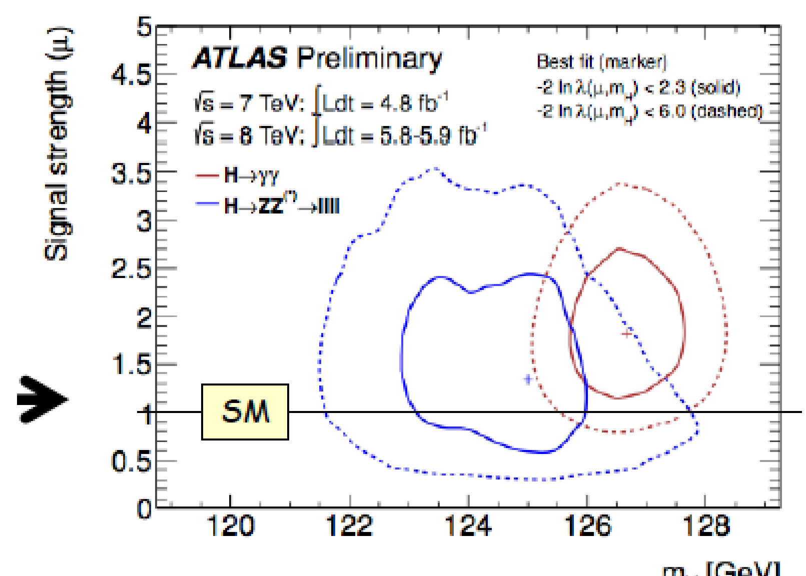
$m_H$ = 125 GeV
CMS Preliminary
$\sqrt{s}$ = 7 TeV, L = 5.1 fb$^{-1}$
$\sqrt{s}$ = 8 TeV, L = 5.3 fb$^{-1}$
H → bb (VH tag)
H → bb (ttH tag)
H → ττ (0/1 jet)
H → ττ (VBF tag)
H → ττ (VH tag)
H → γγ (untagged)
H → γγ (VBF tag)
H → WW (0/1 jet)
H → WW (VBF tag)
H → WW (VH tag)
H → ZZ
-6 -4 -2 0 2 4 6 8
Best fit $\sigma/\sigma_{SM\,H}$

-2lnλ(μ)<1 Intervals
2011 - 2012 Data
ATLAS Preliminary
W,Z H → bb
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.6-4.7 fb$^{-1}$
H → ττ
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.7 fb$^{-1}$
H → WW$^{(*)}$ → lνlν
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.7 fb$^{-1}$
H → γγ
$\sqrt{s}$ = 8 TeV: ∫Ldt = 5.9 fb$^{-1}$
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.8 fb$^{-1}$
H → ZZ$^{(*)}$ → llll
$\sqrt{s}$ = 8 TeV: ∫Ldt = 5.8 fb$^{-1}$
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.8 fb$^{-1}$
Combined
$\sqrt{s}$ = 8 TeV: ∫Ldt = 5.8 - 5.9 fb$^{-1}$
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.6 - 4.8 fb$^{-1}$
$\mu = 1.2^{+0.3}_{-0.3}$
-1 0 1
Signal strength (μ)

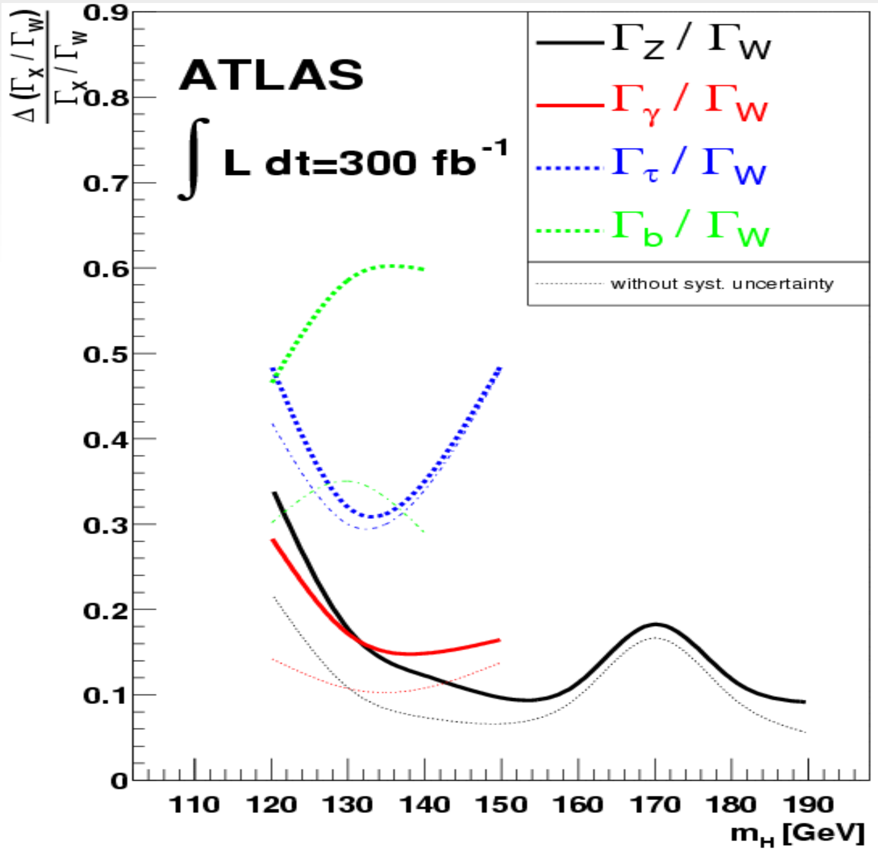



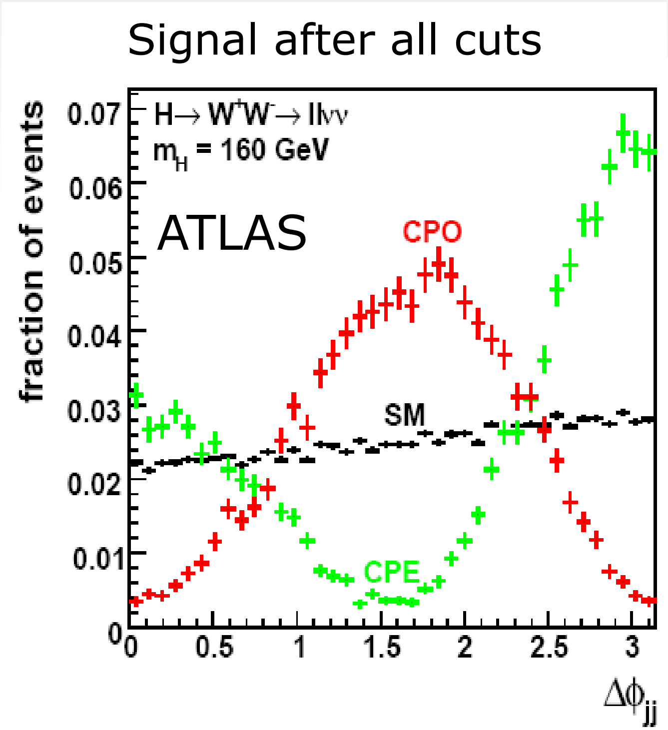
$\sigma/\sigma_{SM}$
CMS Preliminary
H → ZZ + γγ
$\sqrt{s}$ = 7 TeV, L = 5.1 fb$^{-1}$
$\sqrt{s}$ = 8 TeV, L = 5.3 fb$^{-1}$
Combined
H → γγ (untagged)
H → γγ (VBF tag)
H → ZZ
0 1 2 3 4 5 6
123 124 125 126 127 128 129
Mass (GeV)

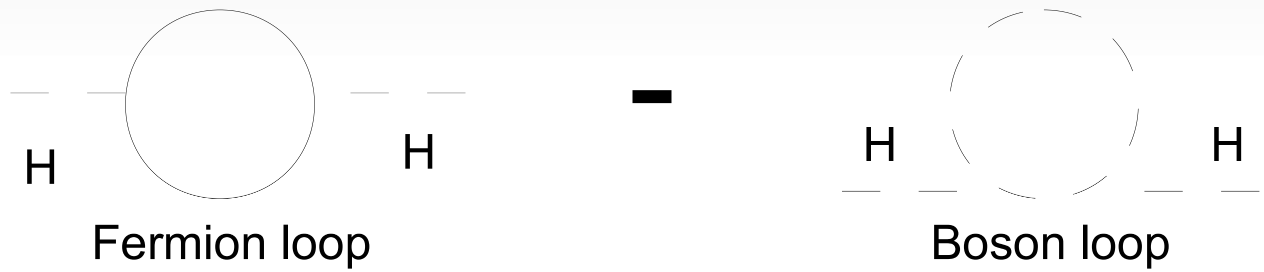
Signal strength (μ)
ATLAS Preliminary
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.8 fb$^{-1}$
$\sqrt{s}$ = 8 TeV: ∫Ldt = 5.8-5.9 fb$^{-1}$
Best fit (marker)
-2 ln λ(μ,$m_H$) < 2.3 (solid)
-2 ln λ(μ,$m_H$) < 6.0 (dashed)
H→γγ
H→ZZ$^{(*)}$→llll
SM
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
120 122 124 126 128
$m_H$ [GeV]

- If a particle is found in any Higgs search, is it really it?
- Measure width (or ratios of) and quantum numbers

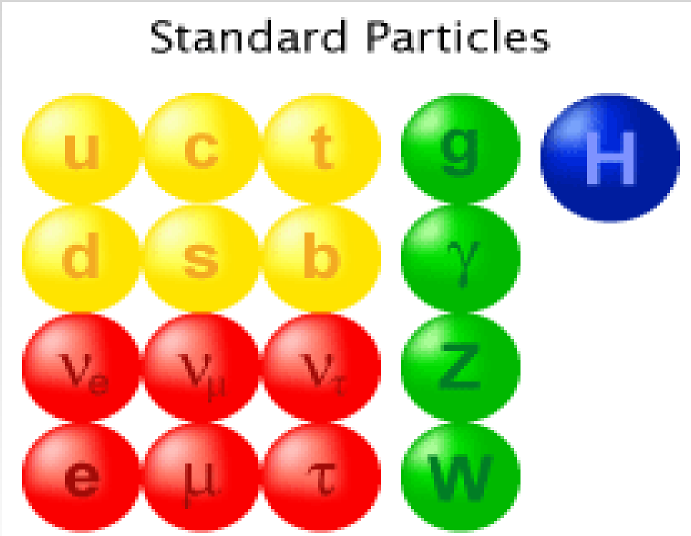


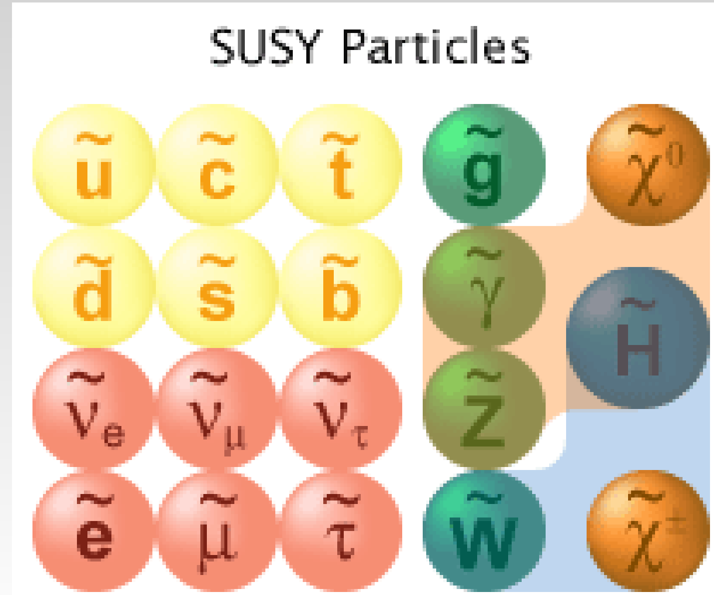



- Gravity not included → SM only low-energy effective theory valid to a scale $\Lambda$ << Mplank
- The Higgs mass has a loop correcton $\delta m \sim \alpha\Lambda^2$, so to prevent it from becoming super-heavy it requires a compensation or unnatural fine-tuning of parameters




- Compensation would arise if for each fermion in the loop there was a new boson with similar mass
- This has lead to speculate that the ultimate symmetry of a gauge lagrangian, between fermions and bosons (SUSY) could indeed be realised in nature




- SUSY equivalants of fermions have prefix s-
- SUSY equicalents of bosons have suffix -ino
- At least two Higgs doublets with lightest Higgs mass < 135 GeV (this can kill SUSY!)
- Charged Higgsinos mix with Winos → charginos
- Neutral Higgsinos mix with Zino/photino → neutralinos

# Building a MSSM model

| Isospin | Supersymmetry |
|---|---|
| N = nucleon field | S = Chiral Superfield |
| Isospin invariant action | SUSY invariant action |

- If Hu, Hd, e, u, d, Q, L are the corresponding supermultiplets of SM and SUSY particles:

$$W_{\mathrm{MSSM}} = \bar{u}\,\mathrm{y_u} Q H_u - \bar{d}\,\mathrm{y_d} Q H_d - \bar{e}\,\mathrm{y_e} L H_d + \mu H_u H_d$$

Dimentioneless yukawa couplings

Hu and Hd give masses to all quarks and leptons (and both are needed)

m-term: SUSY version of the higgs boson from SM

# SUSY new particles

| SM |
|---|
| SUSY |

Eigenstates of mass

| Spin 0 | Spin 1/2 | Spin 1 |
|---|---|---|
| $\tilde{\ell}_1, \tilde{\ell}_2$ | l | |
| $\tilde{q}_1, \tilde{q}_2$ | q | |
| h0, H0, A0, H | $\tilde{\chi}^0_1 \tilde{\chi}^0_2 \tilde{\chi}^0_3 \tilde{\chi}^0_4$ | |
| | $\tilde{\chi}^\pm_1, \tilde{\chi}^\pm_2$ | ■, Z0, W |
| | $\tilde{g}$ a | ga |

'organized' in super-multiplets

Neutralinos: mass eigenstates of photinos, zinos, neutral higgsinos
Charginos : mass eigenstates of winos and charged higgsinos

Squark/slepton mixing proportional to the SM partner masses

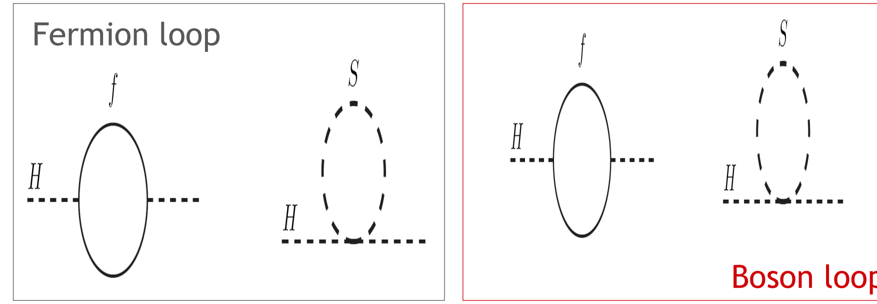
☾ largest for 3rd gen.

àcan become lightest squarks / sleptons

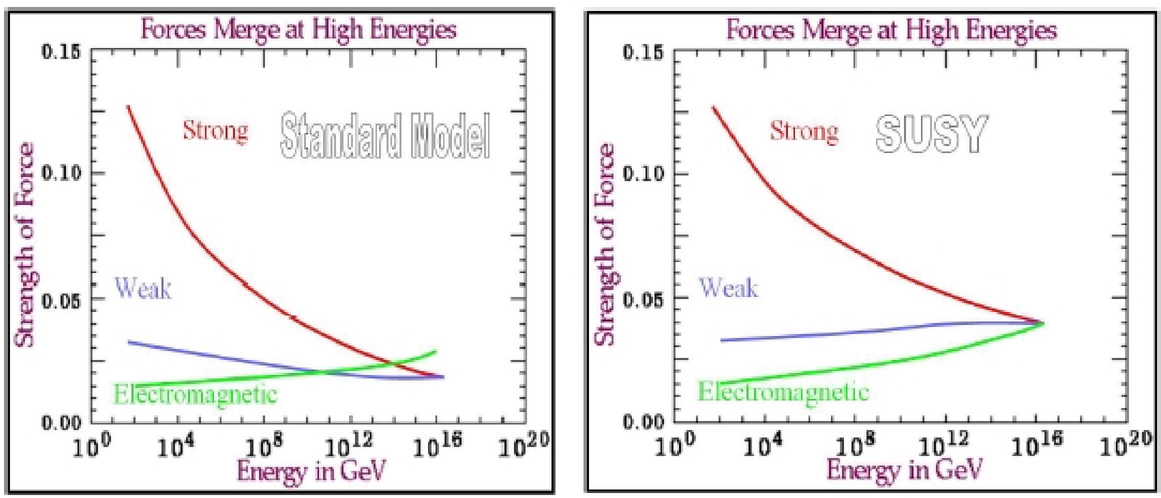
- A SUSY particle would have spin ½ smaller than its non-SUSY equivalent (apart from the Higgs!)
- Introduce a new quantity, $R = (-1)^{3(B-L)+2S}$ which is
  - R = +1 for SM particles
  - R = -1 for SUSY particles
- In most SUSY versions R is conserved
  - SUSY particles produced in pairs
  - Lightest SUSY Particle (LSP, usually neutralino) stable, and being weakly interacting typical SUSY signature is missing momentum (also, good candidate for dark matter!)

# Why people like SUSY

- Predicts a low mass Higgs and naturally solve the hierarchy problem
  - No fine-tuning required

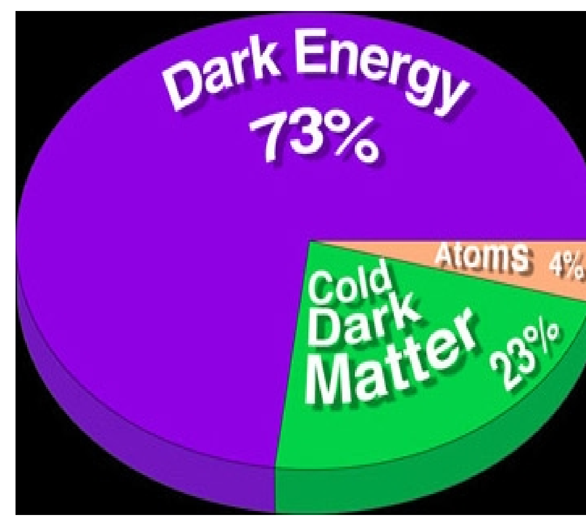



- Enables gauge couplings to unify




Energy (GeV)

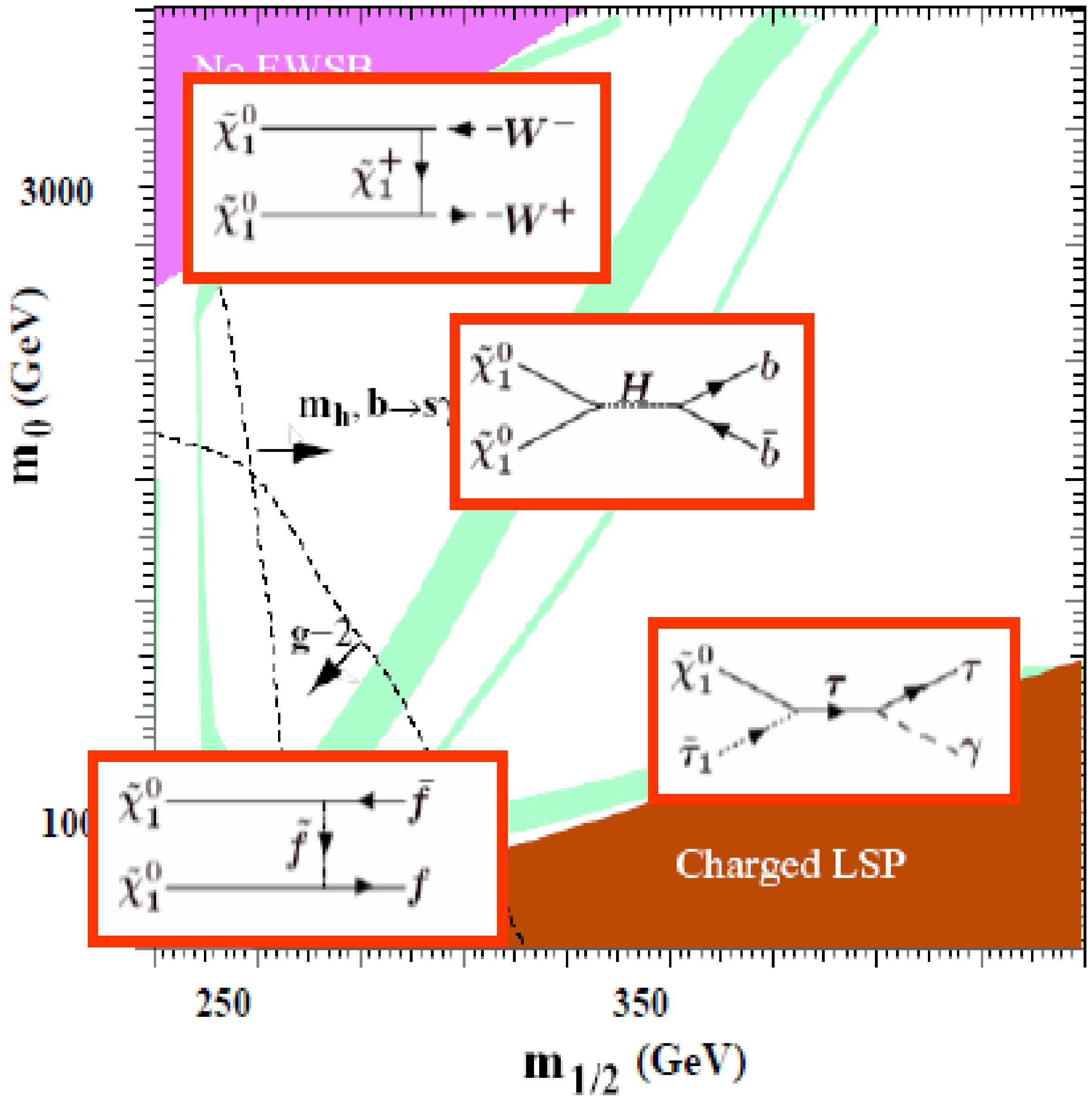
- Provides Dark Matter Candidate
  - If R-parity is conserved, the LSP is the perfect candidate



- Since no SUSY particles discovered so far, their masses have to be larger than their SM correspondents. Supersimmetry has to be broken, and spontaneous symmetry breaking does not work (would predict particles lighter than SM correspondents)
- SUSY breaking confined to hidden sector at high scale, and transmitted through flavour-blind interactions:
  - Gravity-mediated (mSUGRA,cMSSM)
  - Anomay-Mediated (AMSM)
  - Gauge-mediated (GMSM)
  - Gaugino-mediated (brane-world scenarios)

- SUSY theories can have a huge number of parameters. To provide benchmark scenarios to compare experimental reach and predictions, some arbitrary assumptions can be made; ex. MSUGRA, with only 5 parameters:
  - $m_0$ universal scalar mass
  - $m_{1/2}$ mass of all gauginos
  - $A_0$ trilinear soft breaking term
  - Tan $\beta$ ratio of vacuum expectation values of Higgses
  - sign($\mu$) sign of SUSY Higgs mass term (its abs value is the EW symmetry breaking)

Four regions compatible with WMAP value for $\Omega h^2$, different mechanisms for neutralino annihilation:




## bulk

neutralino mostly bino, annihilation to ff via sfermion exchange

## focus point

neutralino has strong higgsino component, annihilation to WW, ZZ

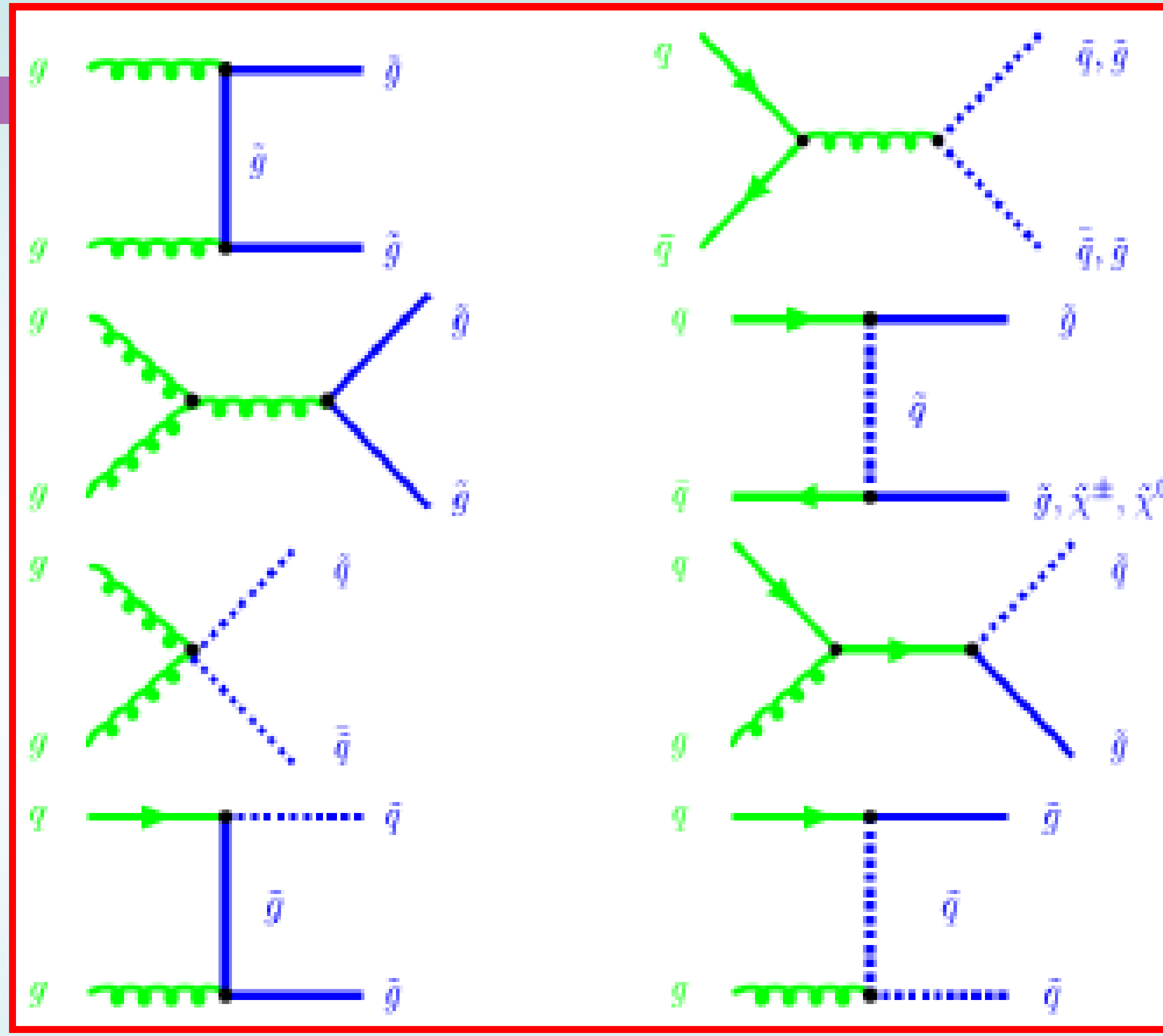
## co-annihilation

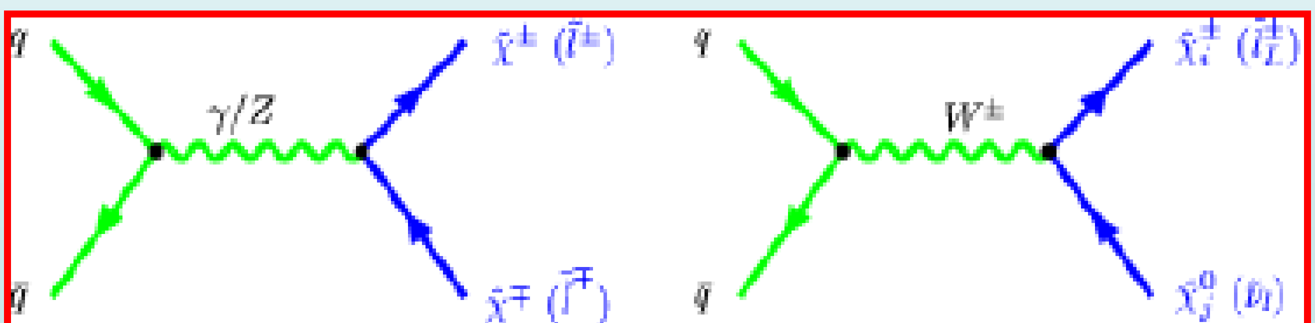
pure bino, small NLSP-LSP mass difference, typically coannihilation with stau

## Higgs funnel

decay to fermion pair through resonant A exchange $\left(m_A \approx 2\,\tilde{\chi}_1^0\right)$ – high tanβ

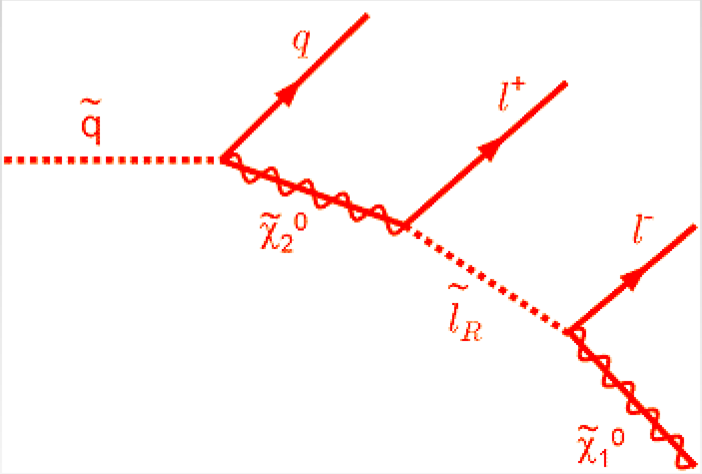
Squark/Gluino Production

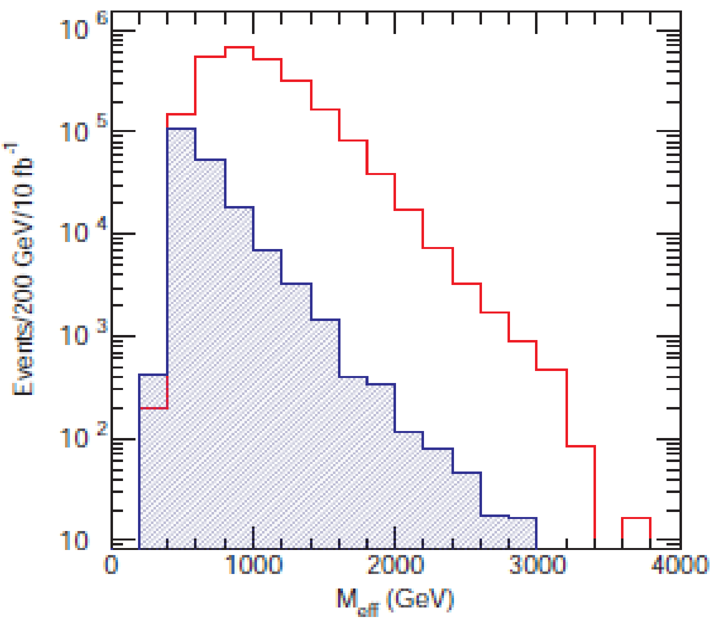


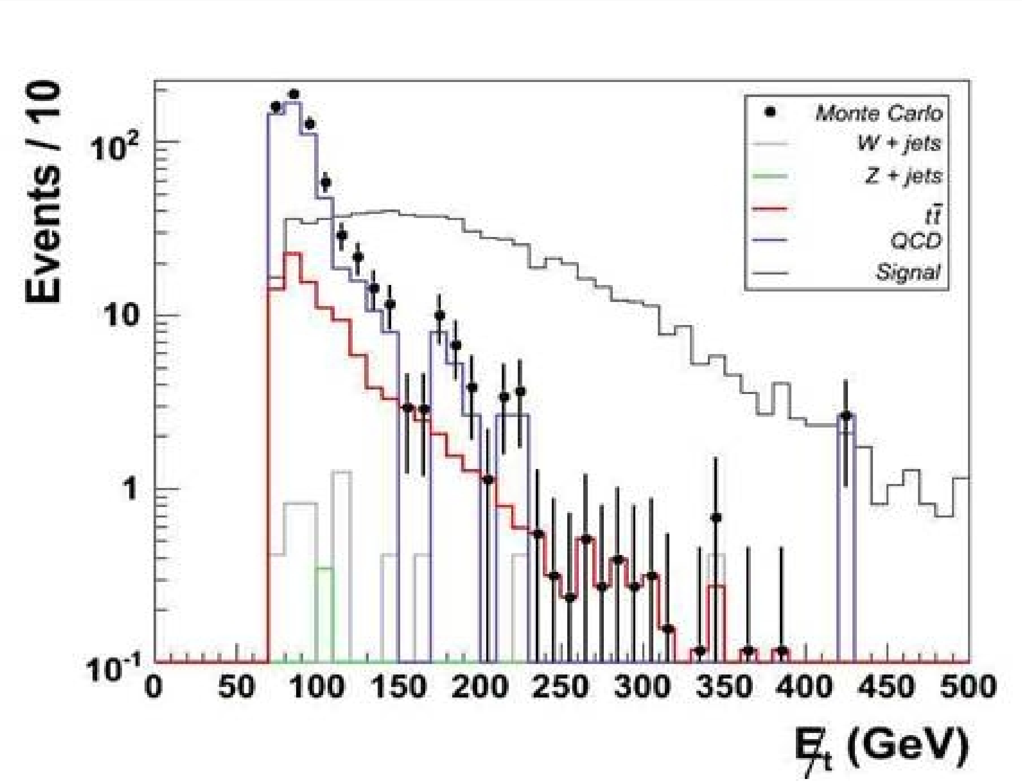



Direct Gaugino Production

- Most SUSY channels involve several successive decays, until the LSP is reached.
- Signature of SUSY would be an excess in missing Et (or missing + visible Et)

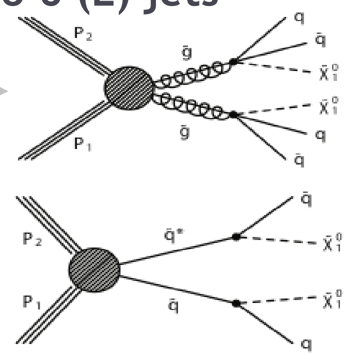


# Strong Production with 0-lepton signature

- Searches in inclusive jets + *E*tmiss events
  - from 2 (A) to 6 (E) jets



≥ 4 jets

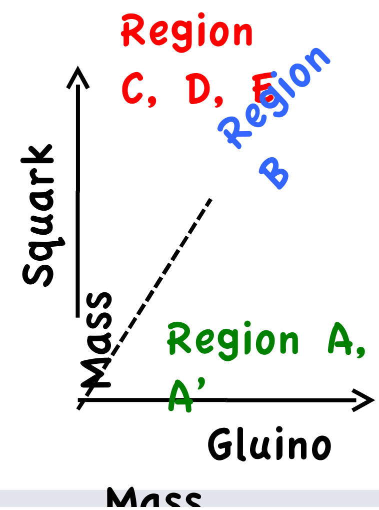
≥ 2 jets

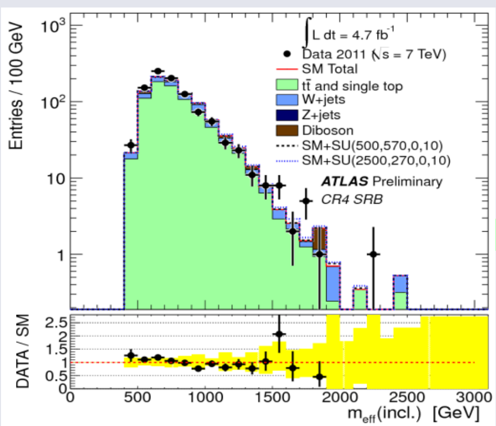
$\tilde{q} \rightarrow q\tilde{\chi}_1^0$

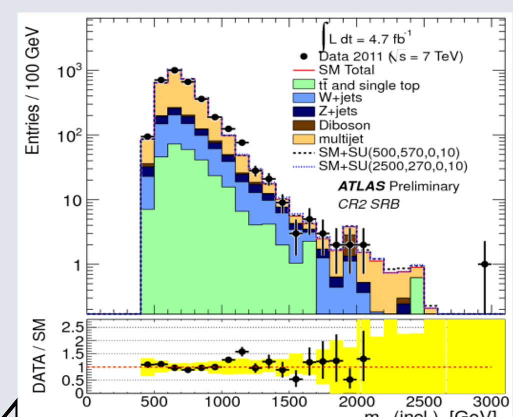
$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$

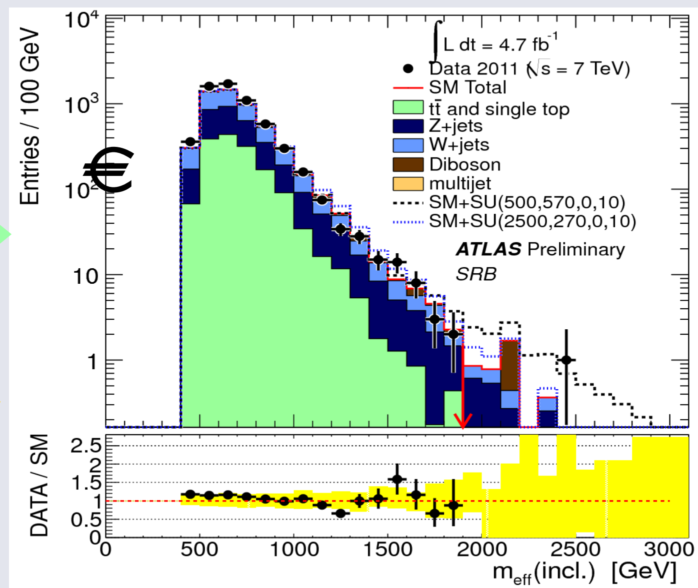
**Expect significant ''effective mass''**

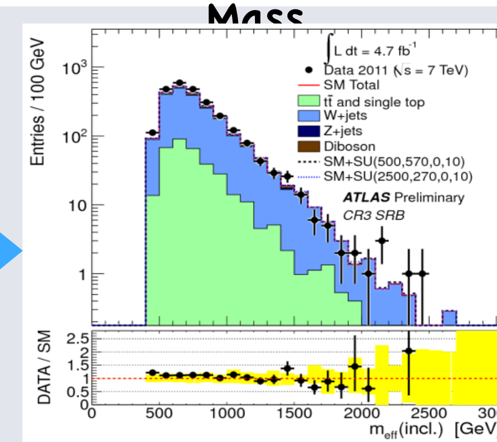
$$\sum_{jet} E_{T,\,jet} + E_T^{miss}$$

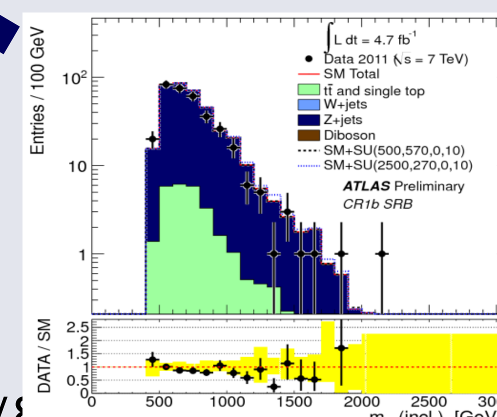


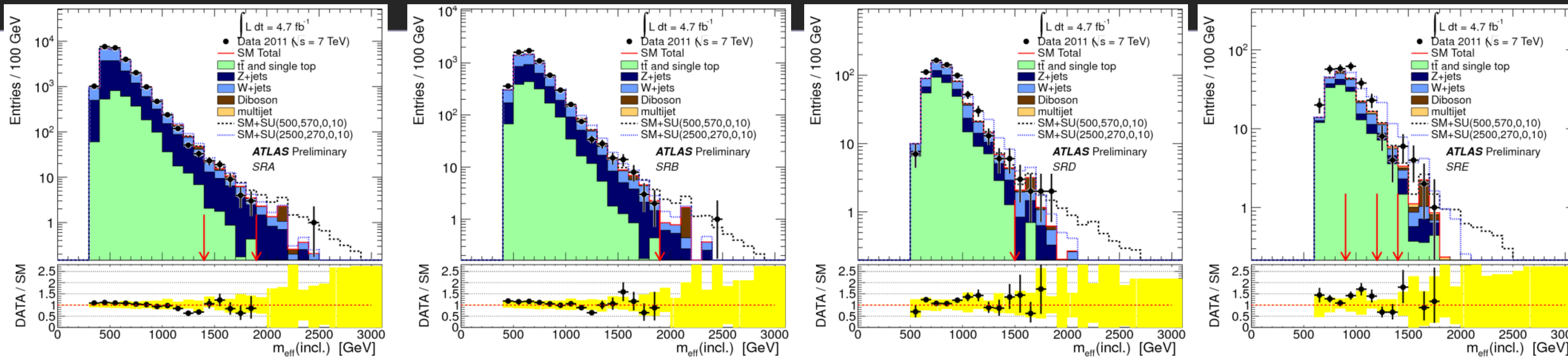



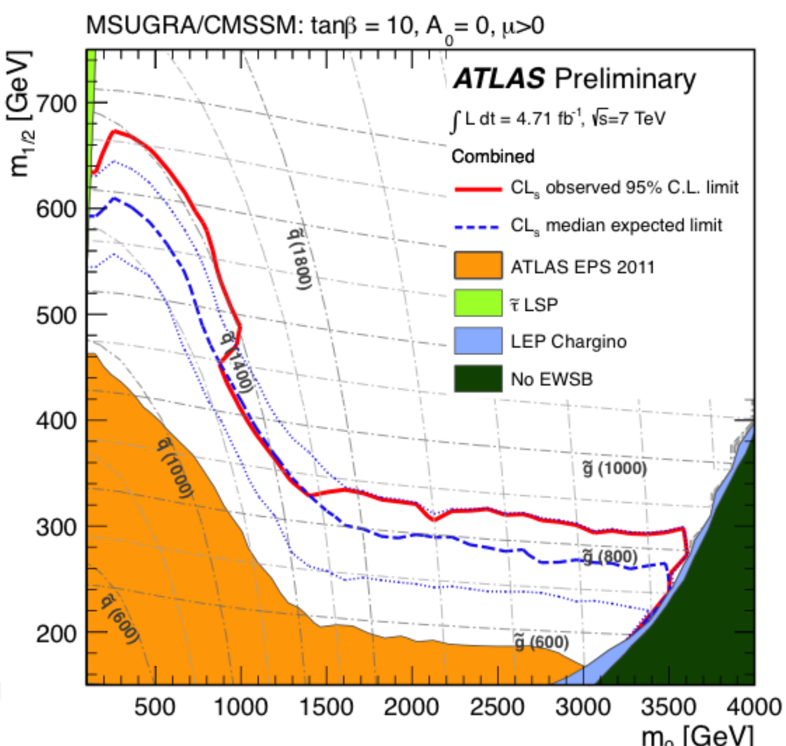



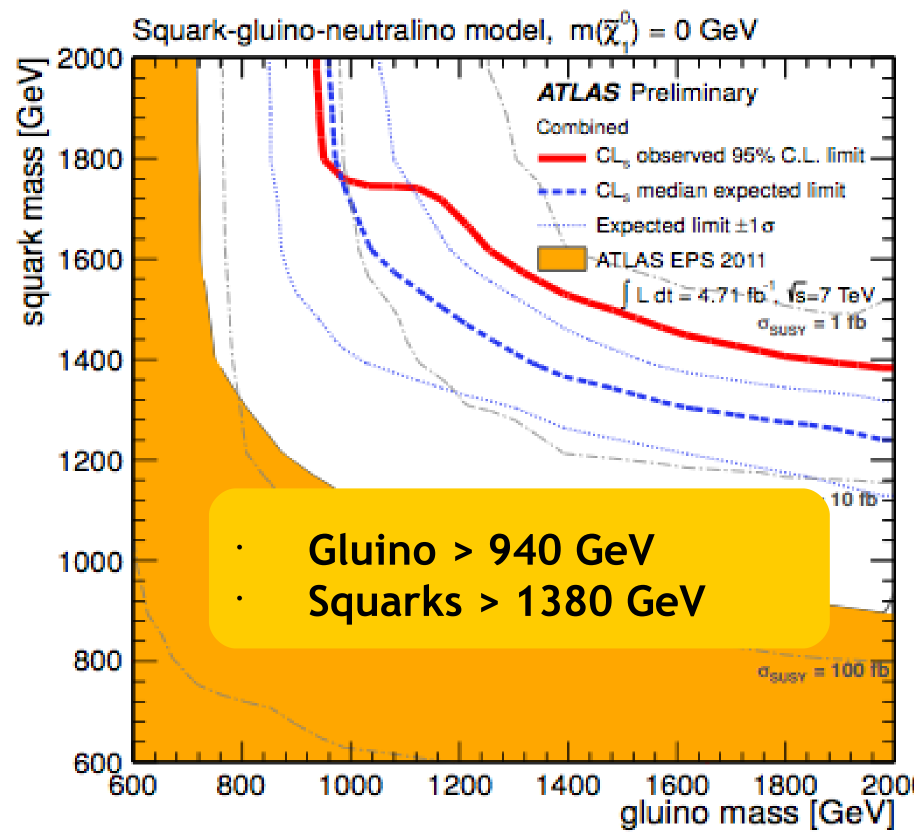

Normalizations obtained in all CR and extrapolated to signal regions simultaneously by combined maximum likelihood fit

# Results of inclusive jets + *Etmiss*



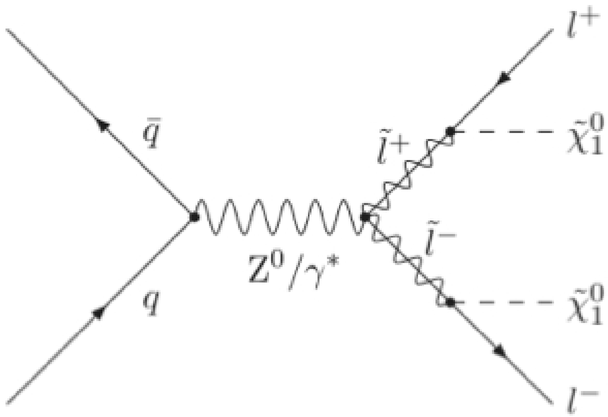

- Interpretation of the results in mSUGRA and phenomenological models

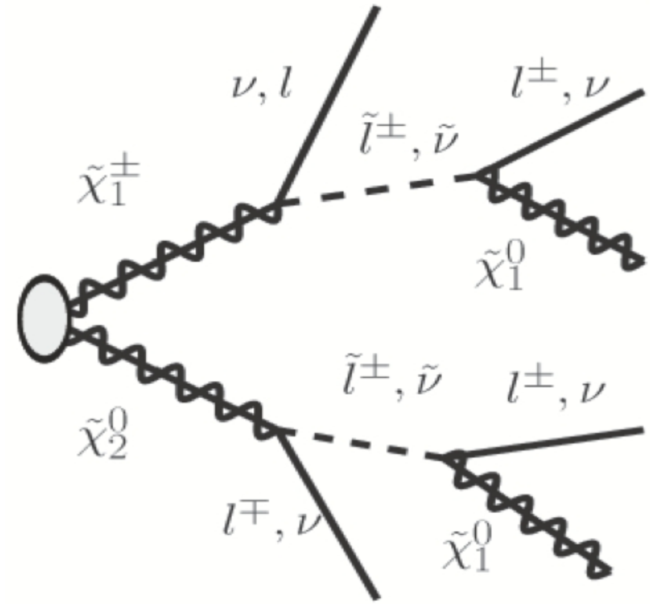


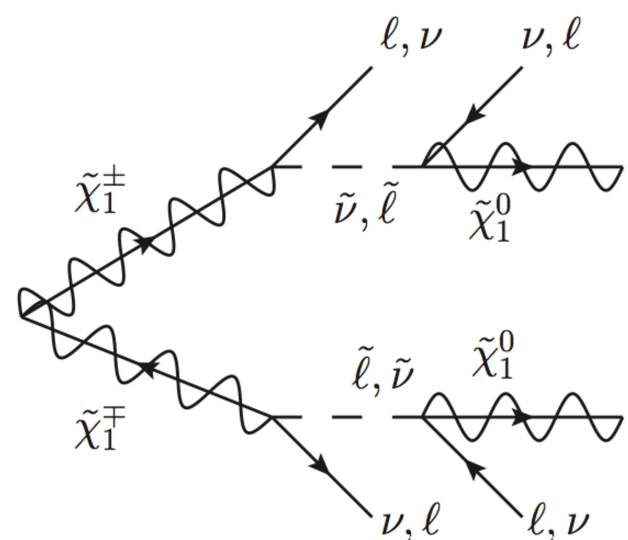

- **Gluino > 940 GeV**
- **Squarks > 1380 GeV**

# Weak Production



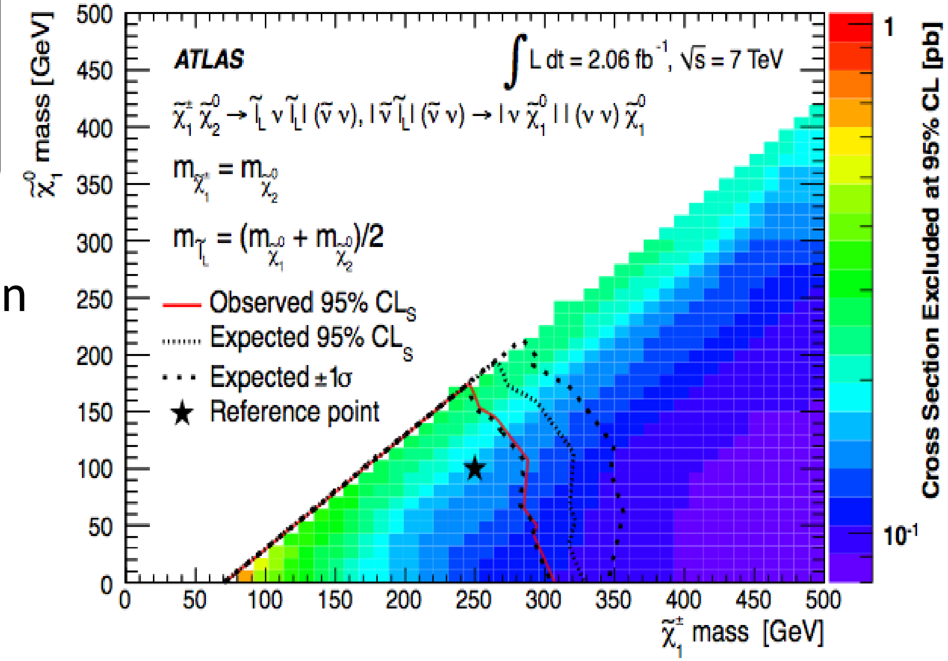



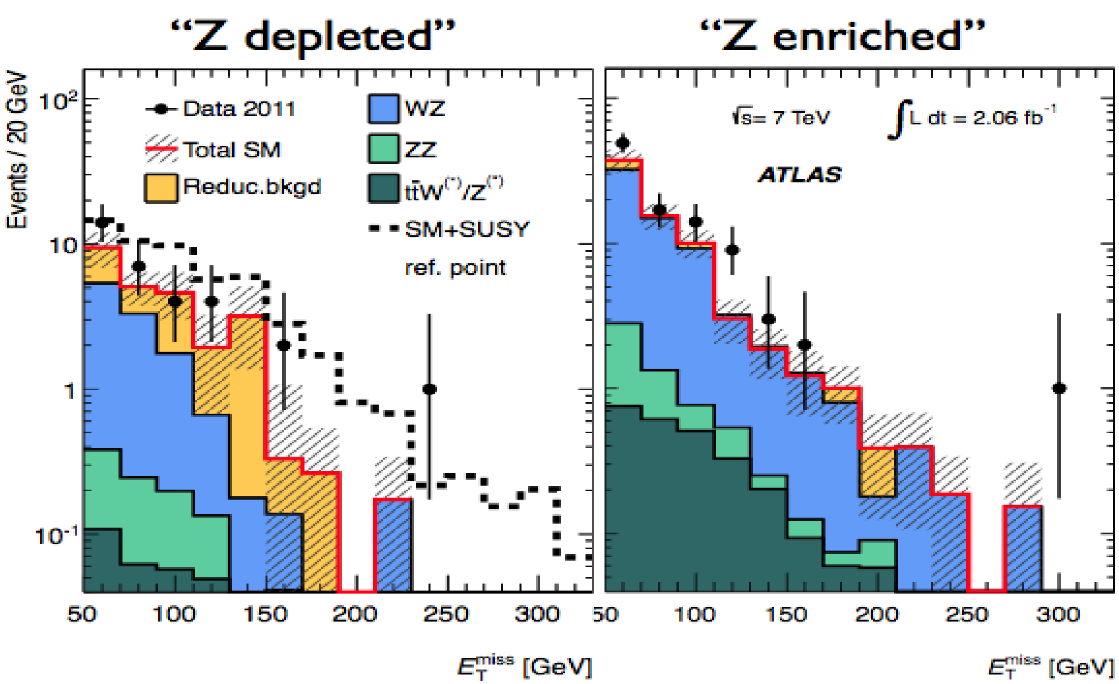

| Decay | Number of identified leptons |
|---|---|
| | $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ |
| $\tilde{\chi}_2^0\tilde{\chi}_1^\pm \rightarrow (\ell^+\ell^-\tilde{\chi}_1^0) + (\ell^\pm\nu\tilde{\chi}_1^0)$ | 3 |
| $\tilde{\chi}_2^0\tilde{\chi}_1^\pm \rightarrow (\ell^+\ell^-\tilde{\chi}_1^0) + (\ell^\pm_{mis}\nu\tilde{\chi}_1^0)$ | 2 |
| $\tilde{\chi}_2^0\tilde{\chi}_1^\pm \rightarrow (\ell^+\ell^-_{mis}\tilde{\chi}_1^0) + (\ell^\pm\nu\tilde{\chi}_1^0)$ | 2 |
| $\tilde{\chi}_2^0\tilde{\chi}_1^\pm \rightarrow (\ell^+_{mis}\ell^-\tilde{\chi}_1^0) + (\ell^\pm\nu\tilde{\chi}_1^0)$ | 2 |
| $\tilde{\chi}_2^0\tilde{\chi}_1^\pm \rightarrow (\ell^+\ell^-\tilde{\chi}_1^0) + (q\bar{q}'\tilde{\chi}_1^0)$ | 2 |
| | $\tilde{\chi}_1^\mp\tilde{\chi}_1^\pm$ |
| $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm \rightarrow (\ell^\pm\nu\tilde{\chi}_1^0) + (\ell^\mp\nu\tilde{\chi}_1^0)$ | 2 |
| | $\tilde{\chi}_2^0\tilde{\chi}_2^0$ |
| $\tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow (\ell^\pm\ell^\mp\tilde{\chi}_1^0) + (\ell^\pm\ell^\mp\tilde{\chi}_1^0)$ | 4 |
| $\tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow (\ell^\pm\ell^\mp\tilde{\chi}_1^0) + (qq\tilde{\chi}_1^0)$ | 2 |

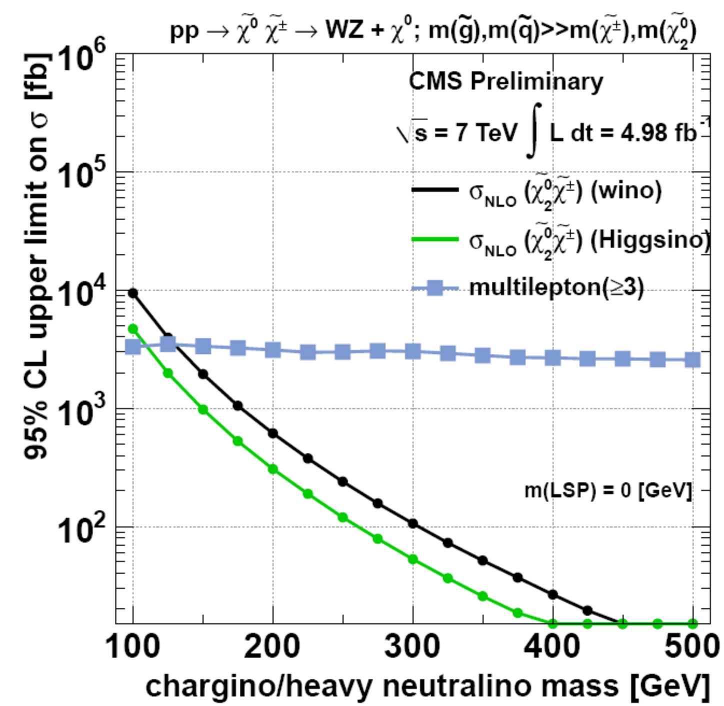


# Direct Weak Gaugino

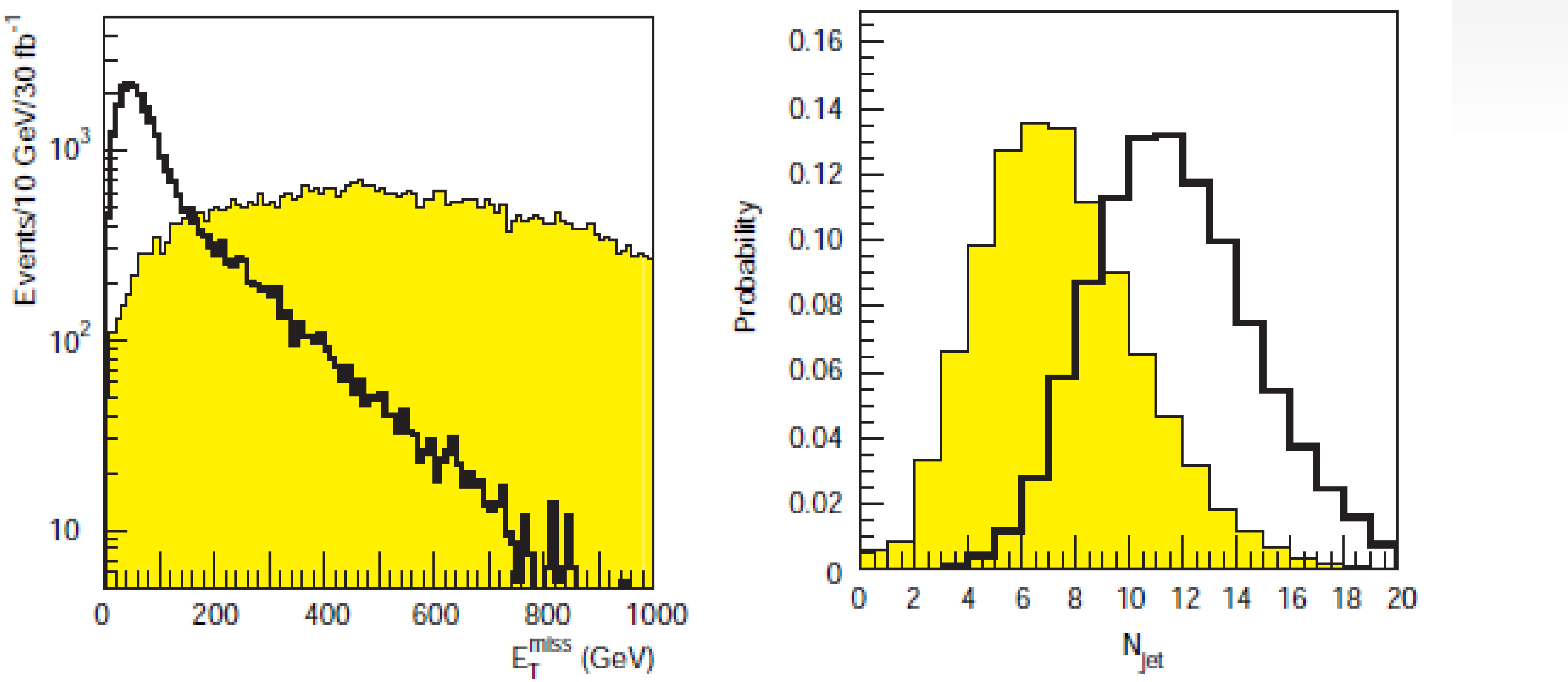
- Search for chargino and neutralino production in the **3-lepton and ETmiss final state**
  - Z-depleted SR (slepton mediated)
  - Z-enriched SR (Z mediated)
- Simplified Model and pMSSM



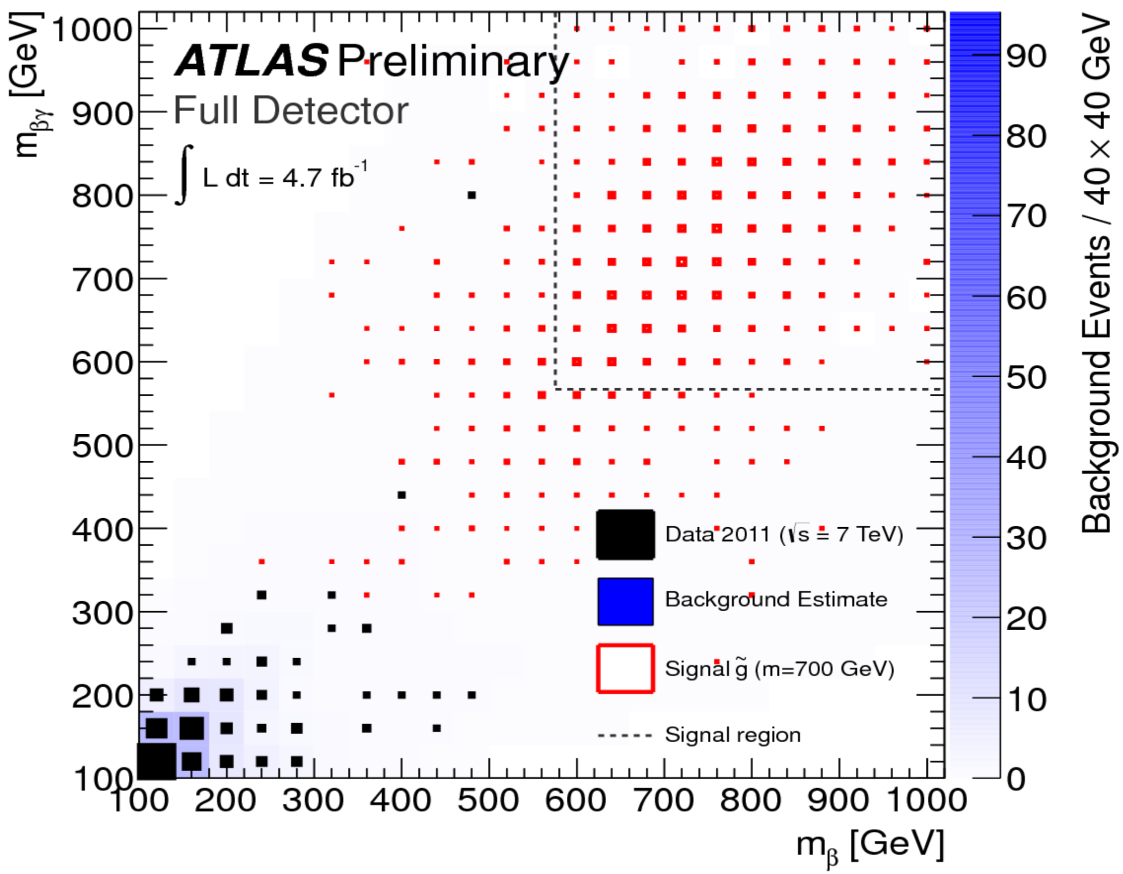



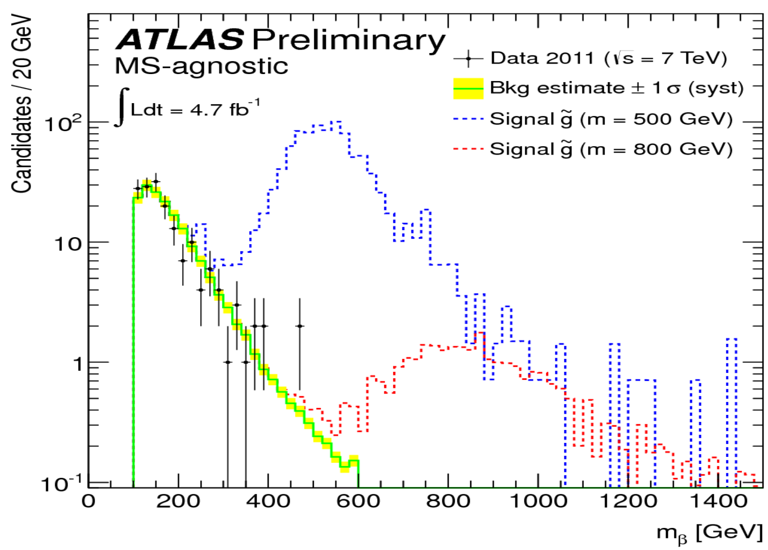
- If R is not conserved, SUSY particles can decay into SM ones, so events do not have the characteristic MET signature, but rather an anomalously high number of jets or leptons:

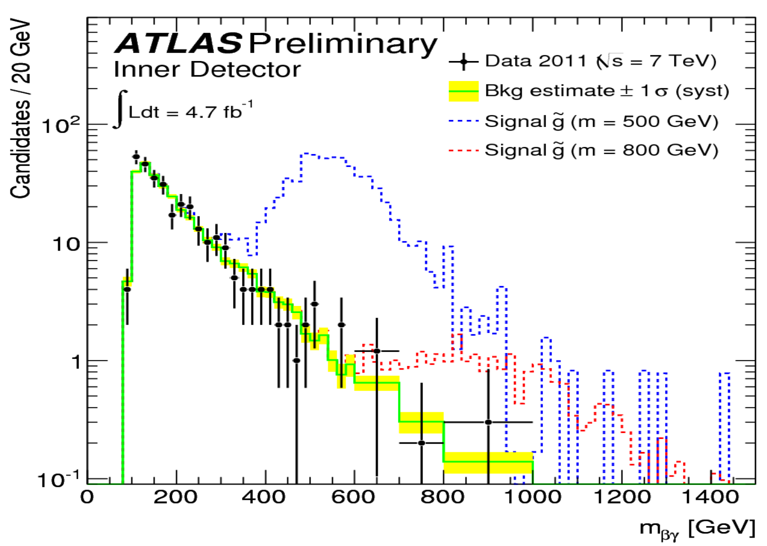



R-parity violating R-parity conserving

# R-hadron searches - results

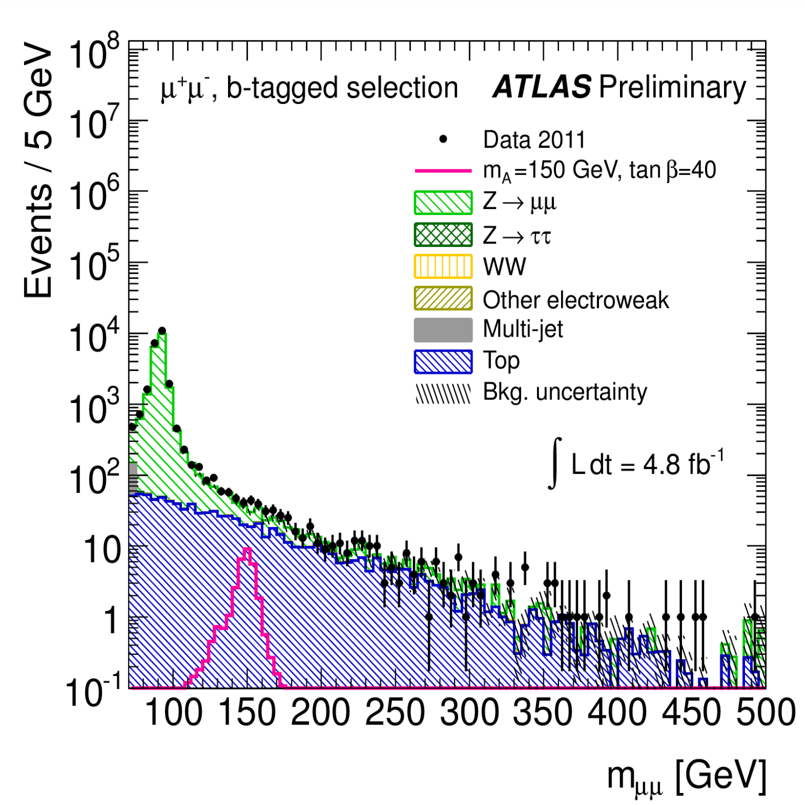


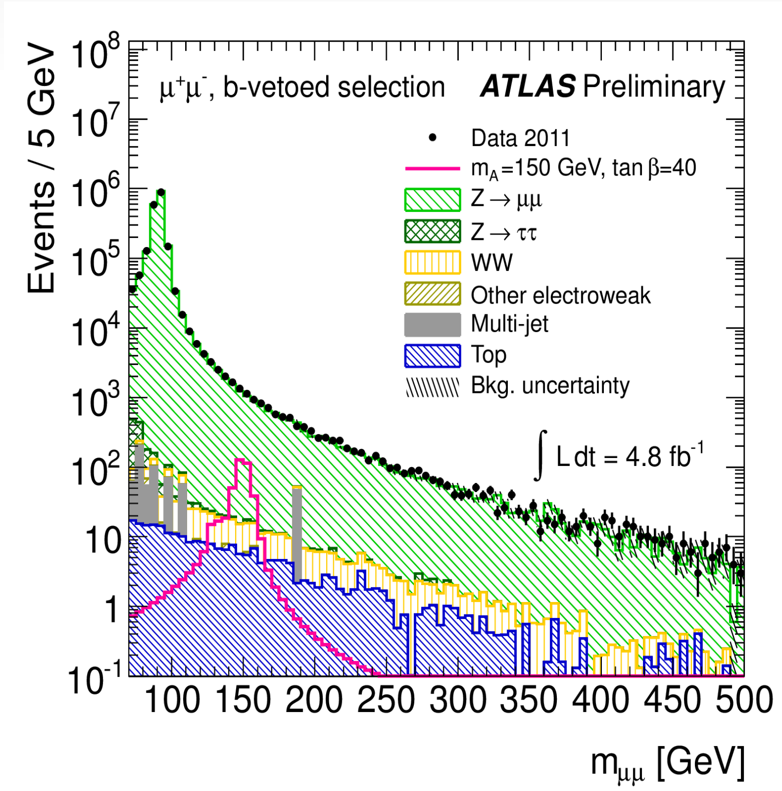



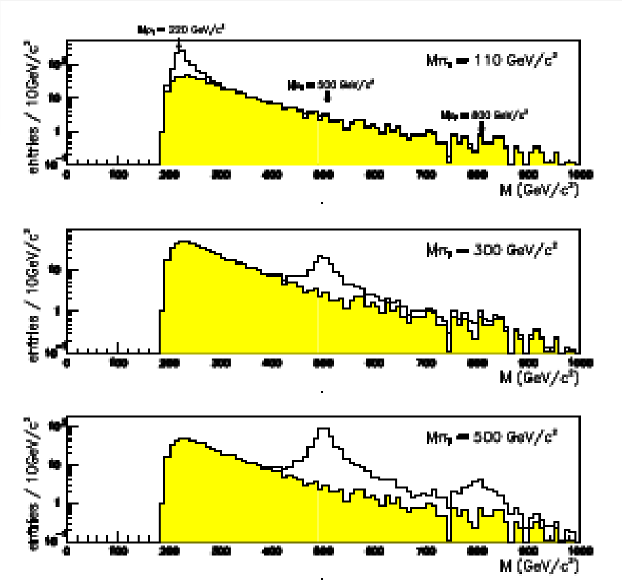

- ID-only: selection based on exceeding dE/dx thresholds

- In MSSM, 5 Higgs bosons: 2 charged (H+/-) three neutral h/A/H
- For some regions of SUSY parameter space, one of them may behave similarly to the SM one, so if the 125 GeV resonance is a SM-like Higgs, this does not rule out SUSY
- Nothing found on dedicated h/A/H searches in lepton pairs + jets

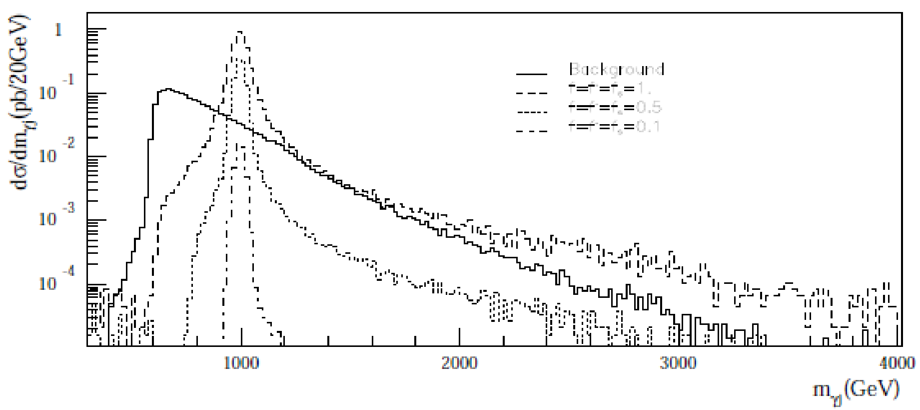


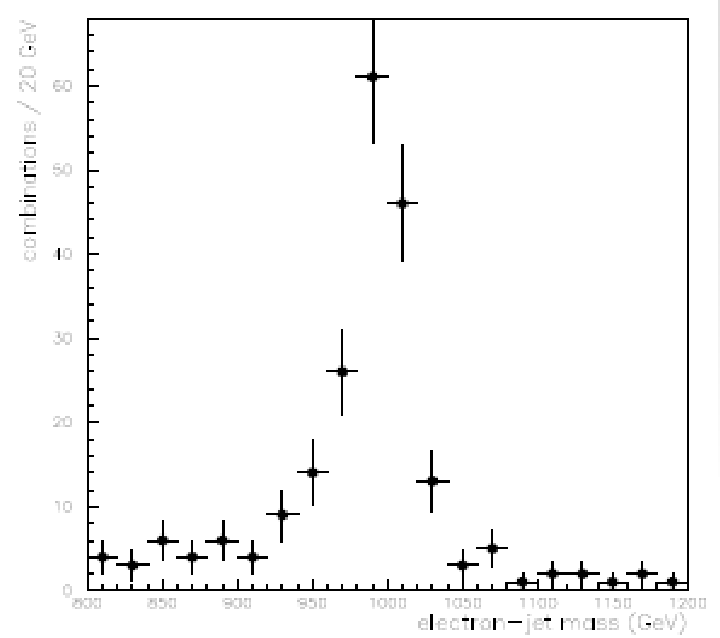
- Technicolour: an additional interaction modeled after QCD colour simmetry replaces the Higgs mechanism to give mass to the other particles. Predicts unobserved FCNC but some variants compatible with experimental data. Signature are resonances decaying into W and Z, like rho decays into pions



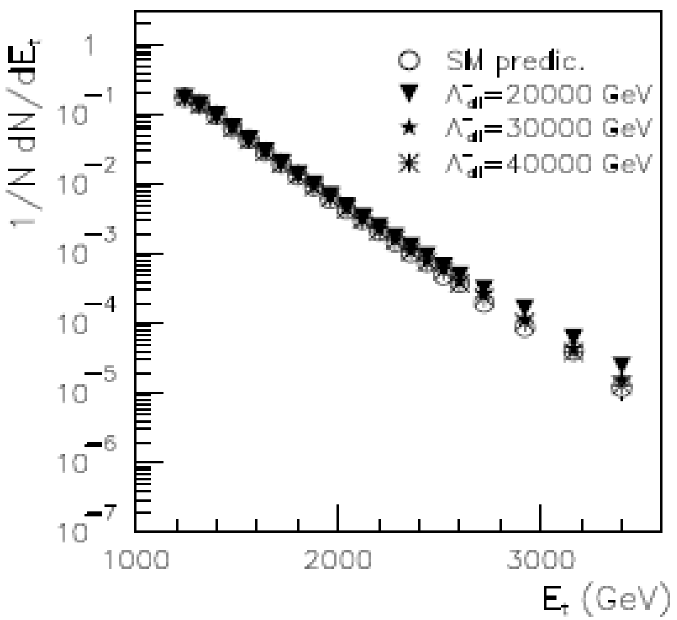

•Excited quarks/leptons: decay into a photon and a quark/lepton, producing a mass peak in that distribution



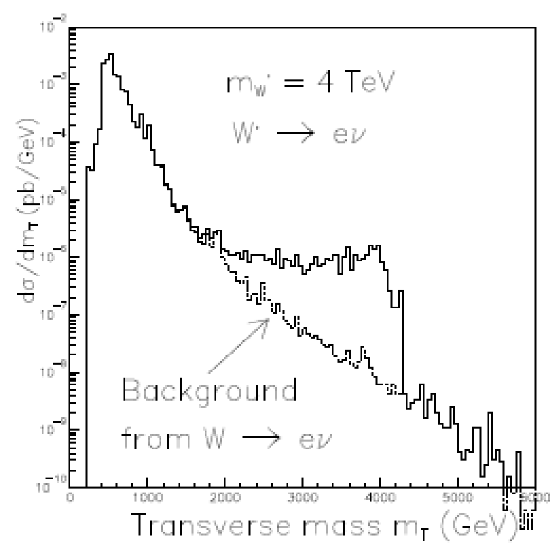
- Leptoquarks: a new symmetry between leptons and quarks could produce particles strongly coupling (and decaying) to both



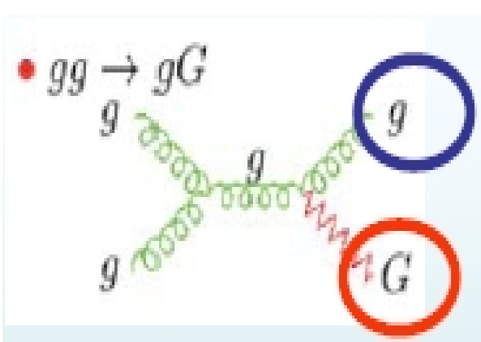

Compositeness: if quarks are composed of something even smaller, that would result in increased high-mass dijet tail

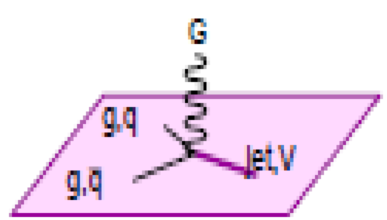



Z', W': from additional SU(2) symmetry, behave like high-mass W's and Z's

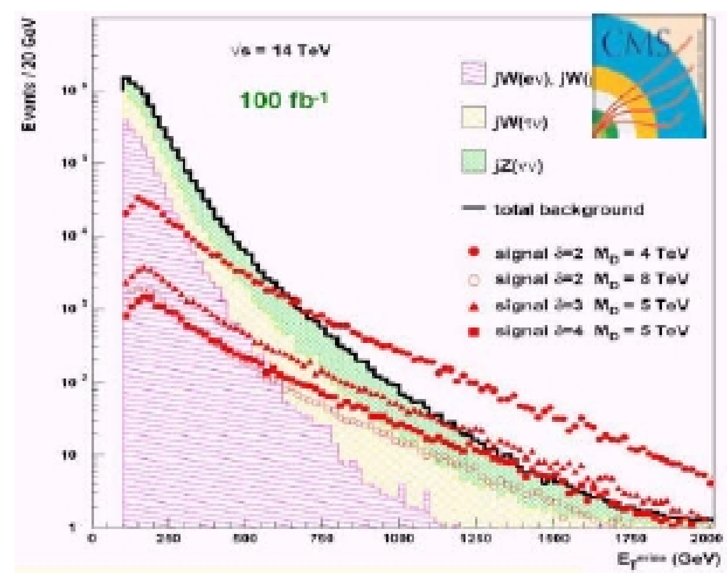


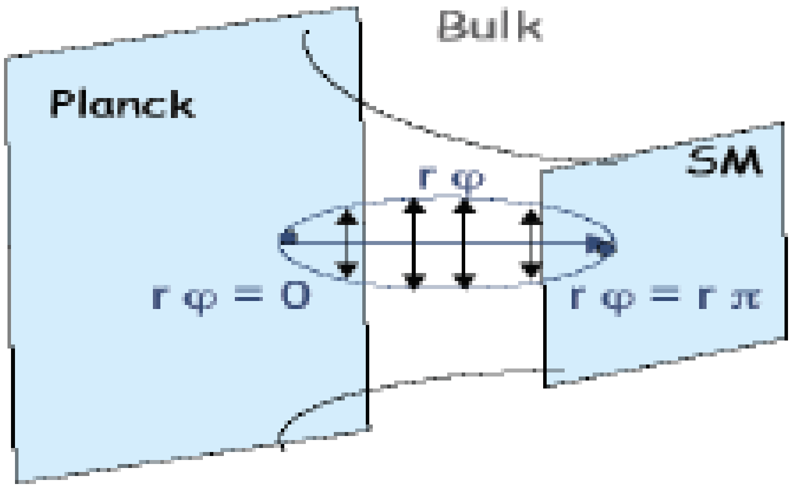
- The three space dimensions we live in are just a membrane of a multi-dimensional space.
- This would reduce the hierarchy problem to geometry
- Gravity could deviate from Newton's law at small scale (< 1 mm, very few experiments on that), and could propagate to the extra dimensions; a graviton would disappear from our universe and be seen as missing energy




Great way to escape from the in-laws???



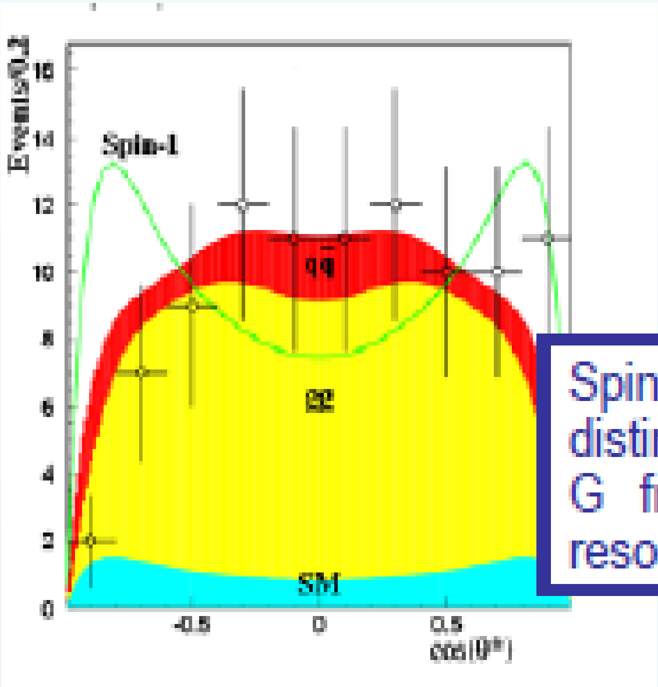



A small, highly curved ("warped") extra dimension connects the SM brane (at O(TeV)) to the Planck scale brane

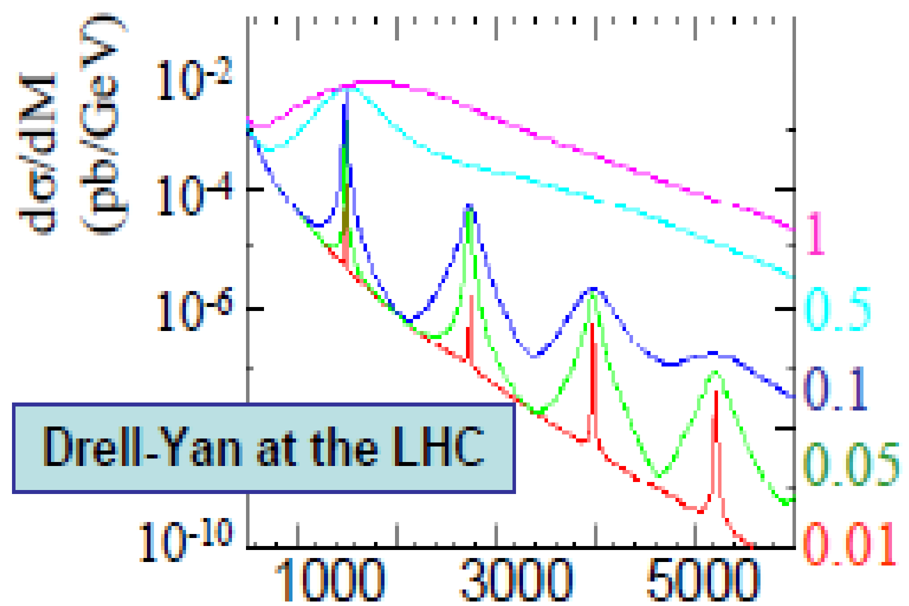
Gravity small in our space because warped dimension decreases exponentially between the two branes

Series of narrow, high-mass resonances:
(only first peak visible at LHC, due to PDFs)

$$q\bar{q}, gg \rightarrow G_{KK} \rightarrow \ell^+\ell^-, \gamma\gamma, j+j$$



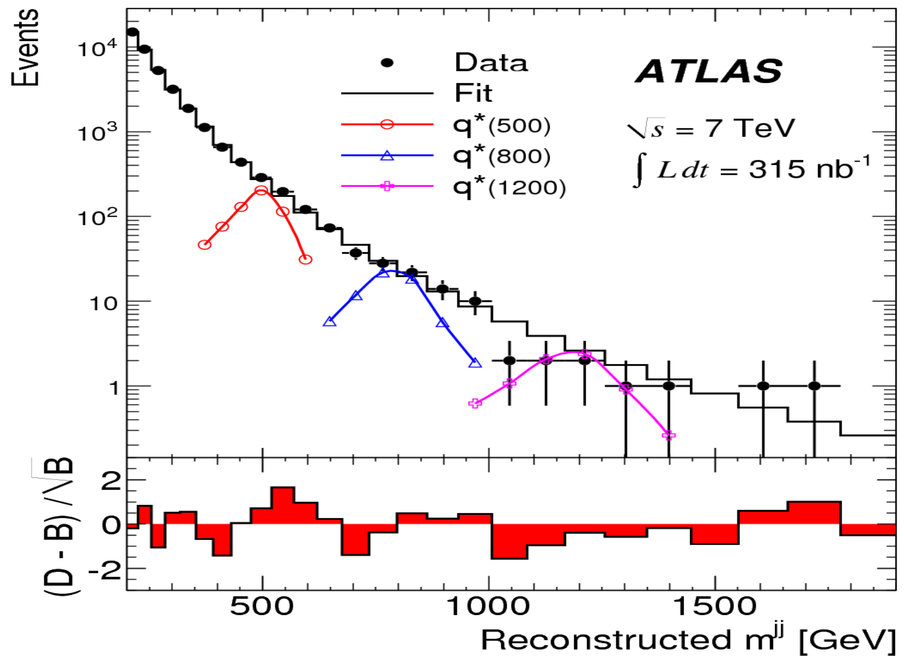

Spin analysis to distinguish spin-2 G from spin-1 Z' resonance

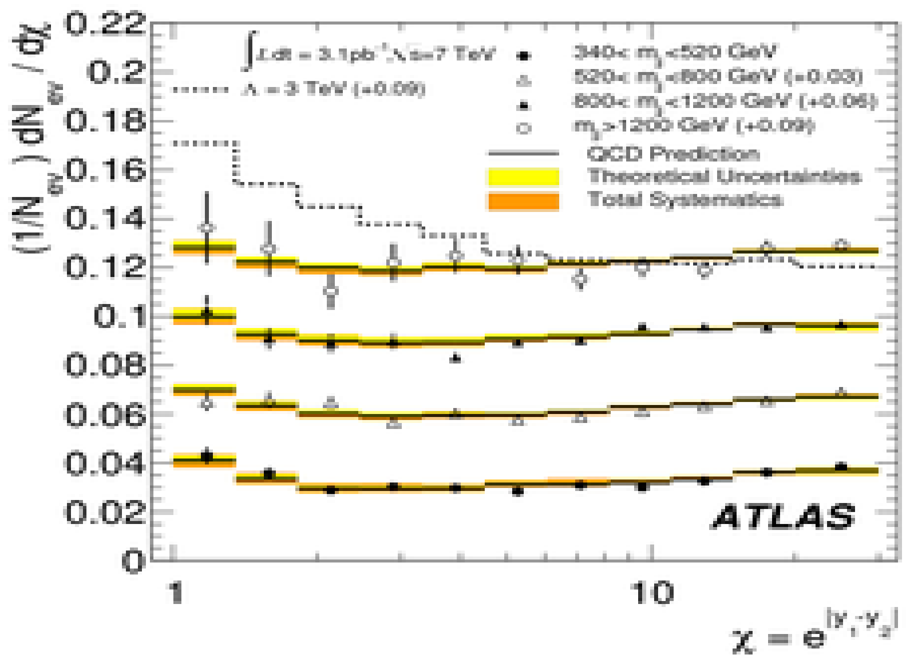



Drell-Yan at the LHC

Dilepton mass

Antonella De

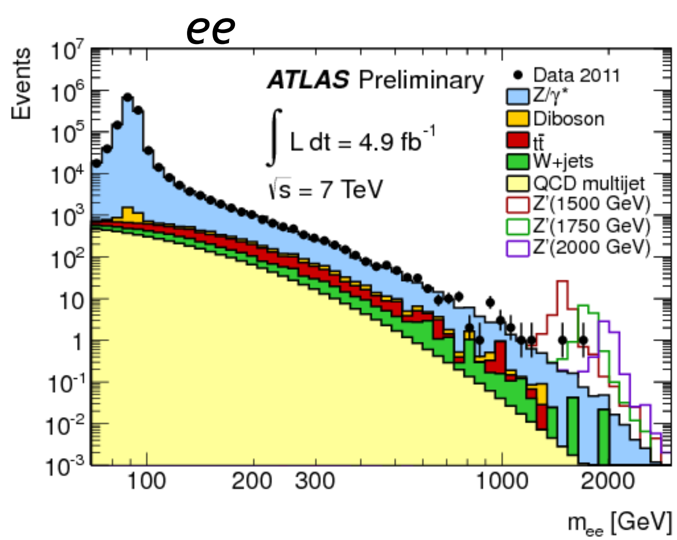


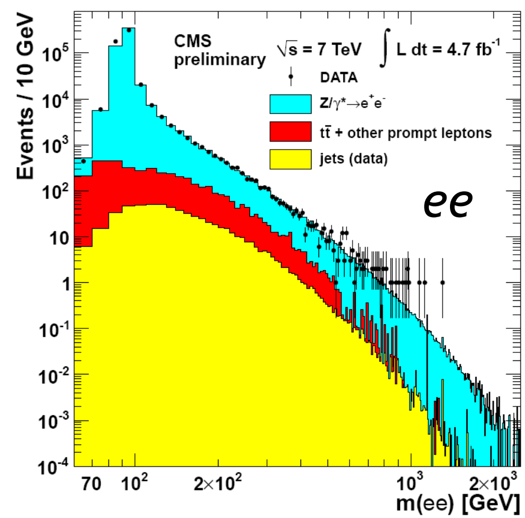



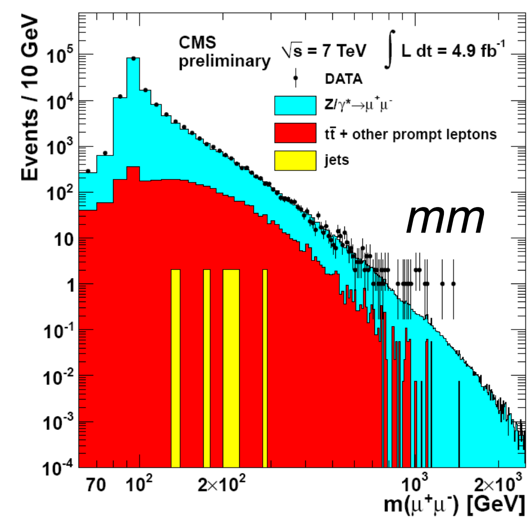

- Technicolor, colour interaction and low-mass gragvity models all predict productin of resonances, mainly decaying into dijets. Dijet distributions can be interpreted in the framework of new physics search

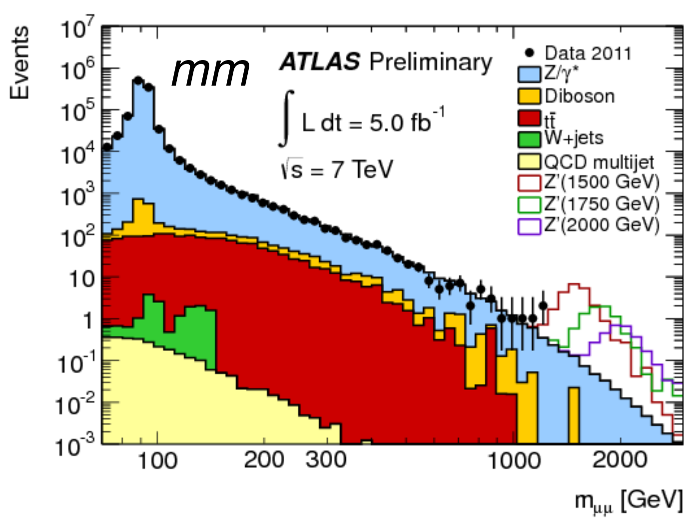
Constrain Z’ and RS graviton (G*) production in e+e- and m+m- invariant mass distributions

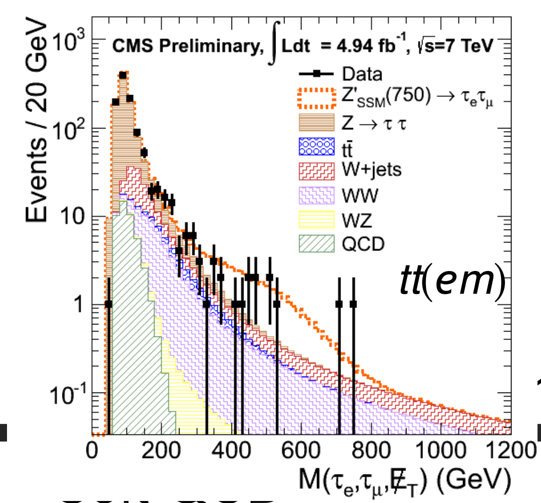
- Search also in for tt final states  for t(e)t(m), t(e)t(h), t(m)t(h), t(h)t(h)



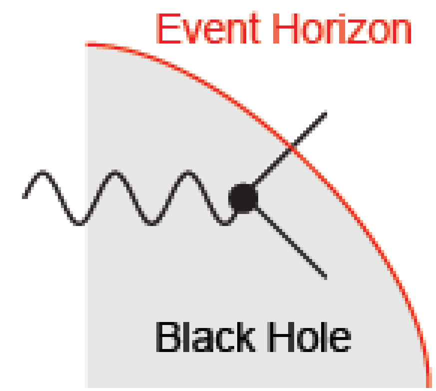



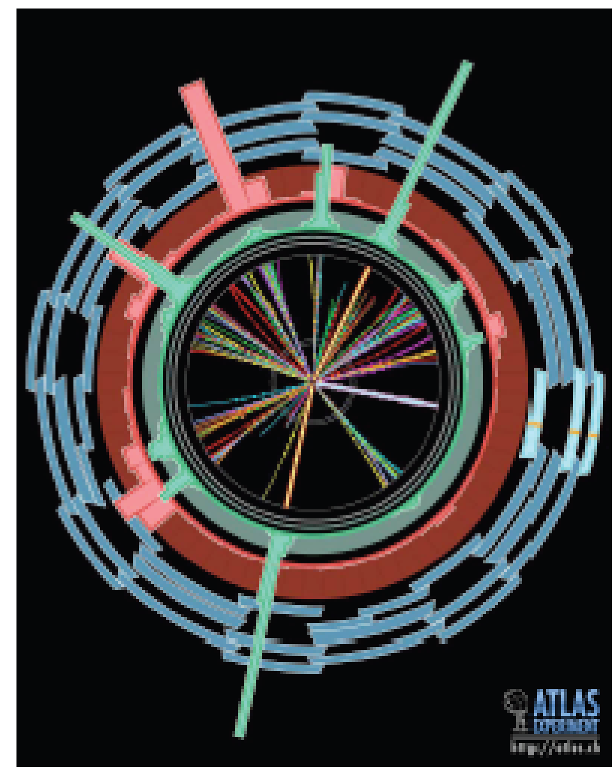
# Black hole phenomenology

- BH decay:
  - BH loses energy by Hawking radiation: pair production close to event horizon → one particle tunnels through horizon
  - BH lifetime for $M_D$ = 1 TeV:

$$\tau \sim \frac{M_{BH}^{(n+3)/(n+1)}}{M_D^{2(n+2)/(n+1)}} \approx 10^{-26}\ \mathrm{s}$$

  - "Democratic" thermal decay (obeying all conservation laws): equal fractions of all SM particles
  - Spectacular signature: spherical high-multiplicity events ("hard to be missed")



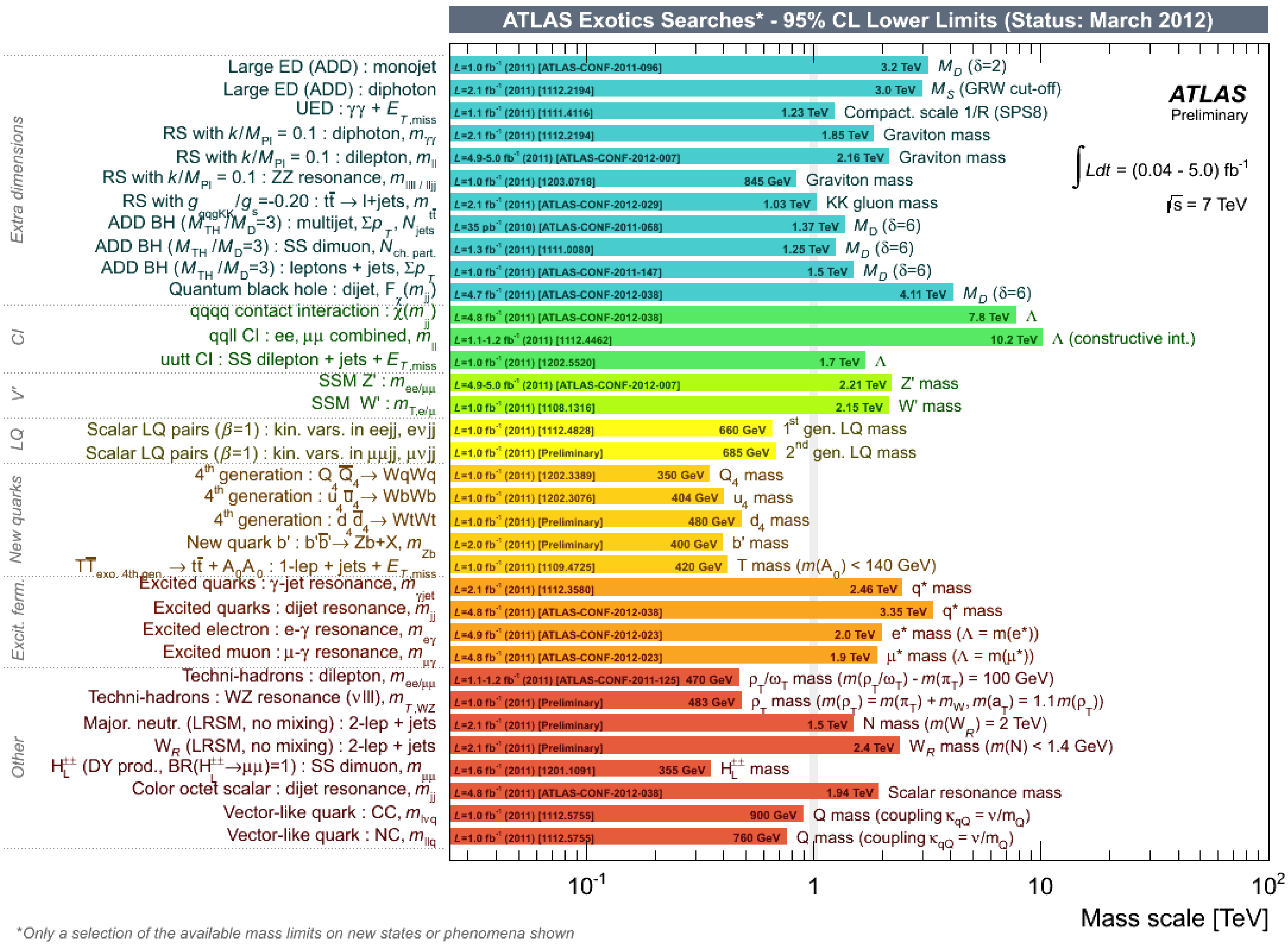




[atlas.ch]

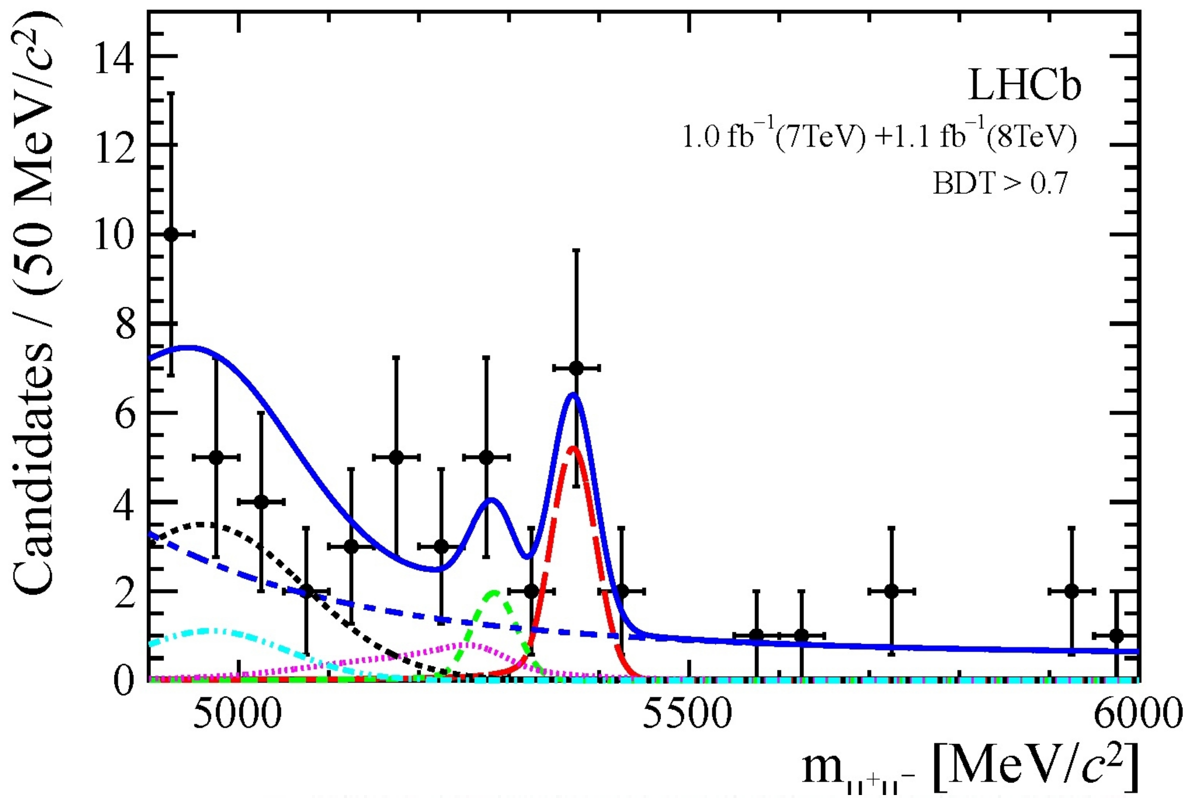
# Search summary table (theory)

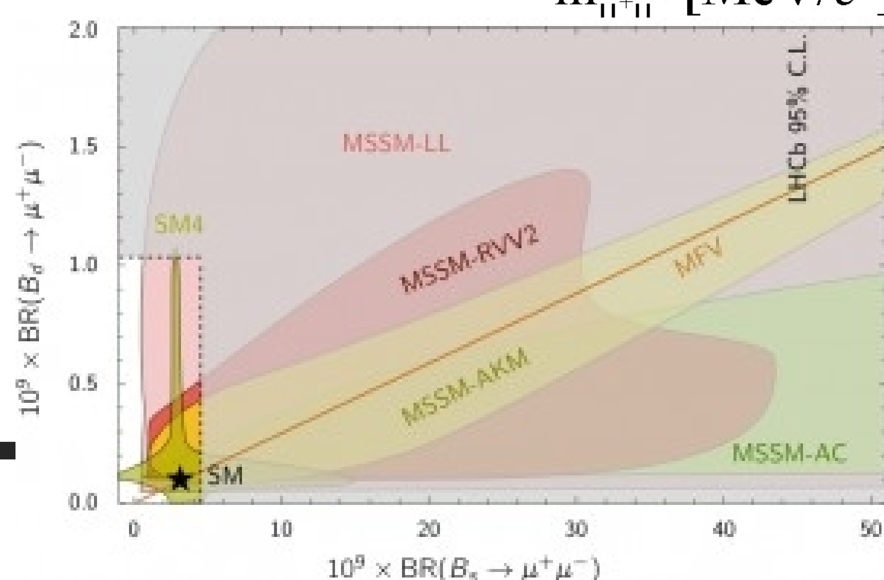
[Hitoshi Murayama]

# Search summary table (experimental)



# What does B-physics say?




Some rare decays like Bs->μμ only occur through loop diagrams.
If new particles exist, they can also be produced in these loops, leading to big modifications of the SM branching fractions.

B-physics, not covered in these lectures, is a powerful tool to get indications and limits on the existance of new particles with masses much higher than those directly accessible at the LHC

After all, both the top and the Higgs masses have been predicted with good precision before discovery, using virtual loop techniques

The bad news is that in this case no deviation from SM behaviour is in sight

- As you saw, the physics program of the LHC is huge (only gave a few snapshots), and even if legions of physicicists will analyse the data, there is really a lot to be occupied over many years
- Detector understanding and calibration is crucial; first data taking period was used to understand detectors and re-discover the SM, and study some missing details
- Many measurements already performed on jets, W, top physics
- Searching for the SM Higgs, a new boson has been discovered by both experiments  for mass values around 125 GeV.
- The branching fraction into photon pairs is larger than the SM predictions for Higgs, but consistent within 20% C.L.
- Existence confirmed in the ZZ* channel, as well as injected signal in WW (but no mass determination there)
- The SM has never been stronger