Physics at the Large Hadron Collider

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Atlas Collaboration

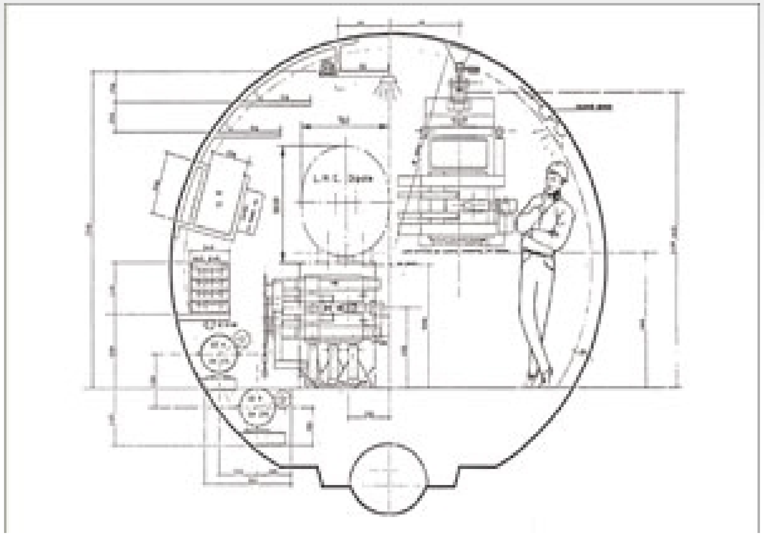
Outline

- The machine: why the LHC is a unique collider
- Present status (to be followed over the lectures)
- Parton density functions and luminosity
- QCD physics
- Production of vector bosons and top
- Search for the Higgs boson
- Search for physics beyond SM

A bit of history…

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

Towards the LHC

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)

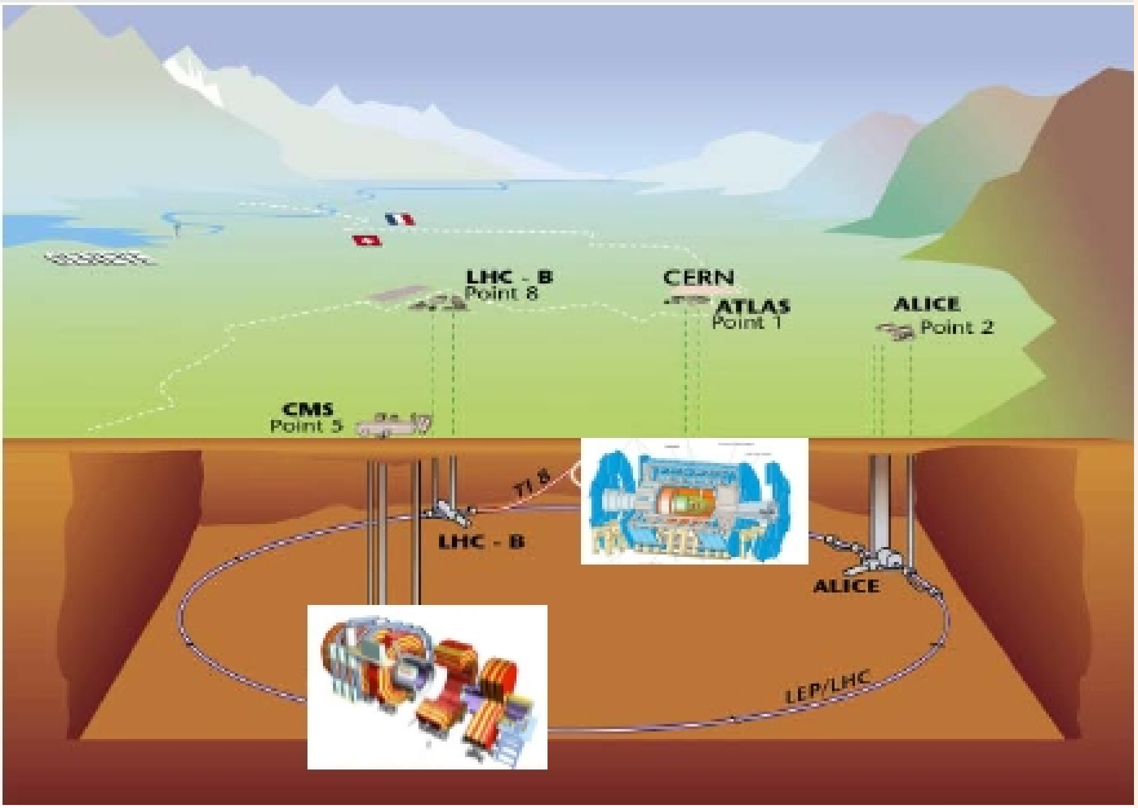
...maybe not so bad for our health...

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

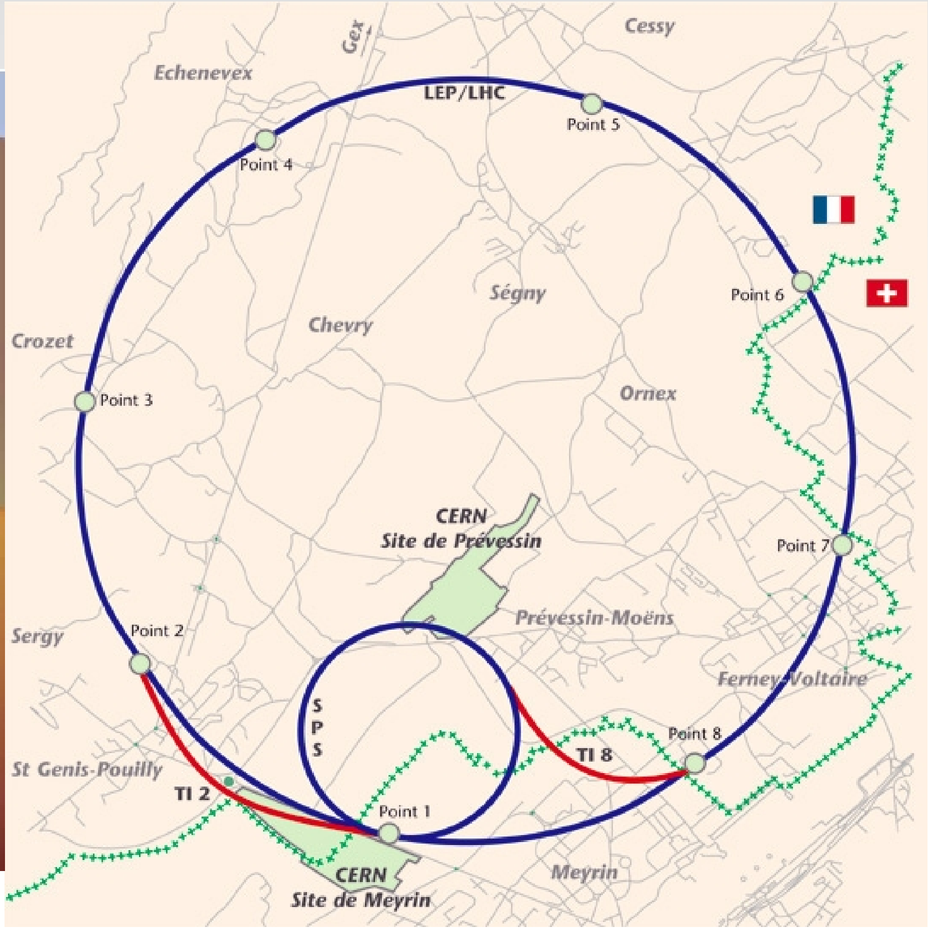
What LHC does not stand for (non examinable ;-)

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 layout



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
CERN
Site de Prévessin
Point 7
Prévessin-Moëns
Sergy
Point 2
Ferney-Voltaire
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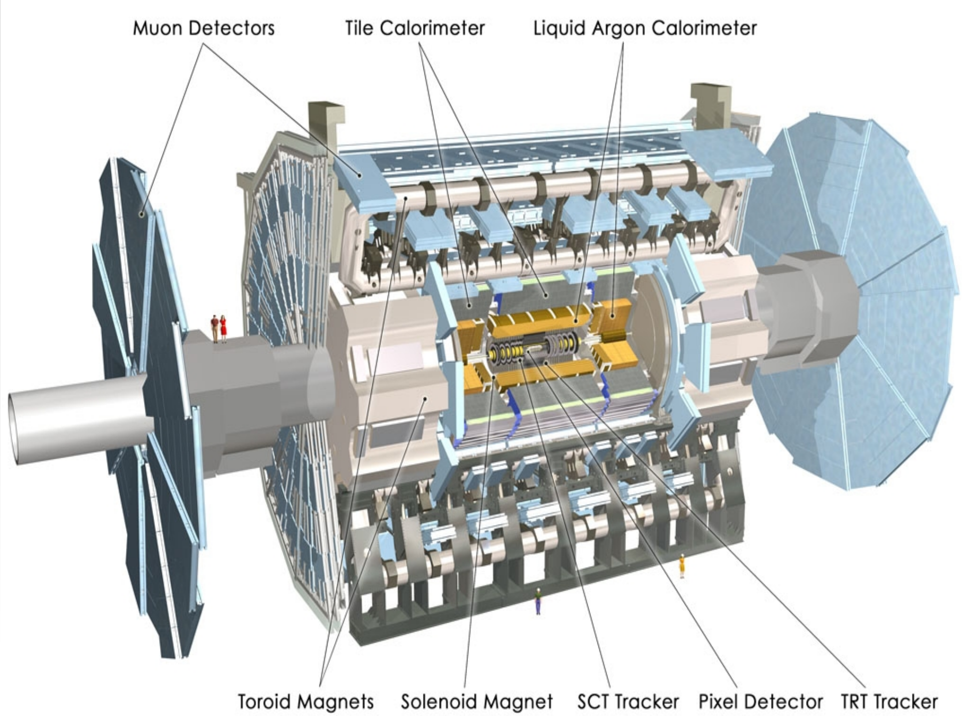
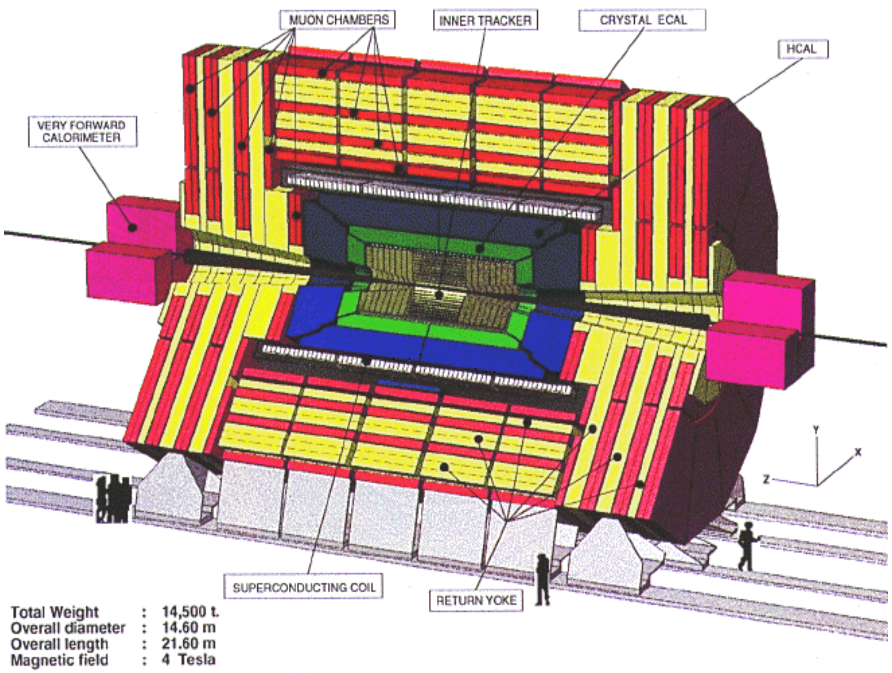
Point 8
TI 8
St Genis-Pouilly
TI 2
Point 1
CERN
Site de Meyrin
Meyrin

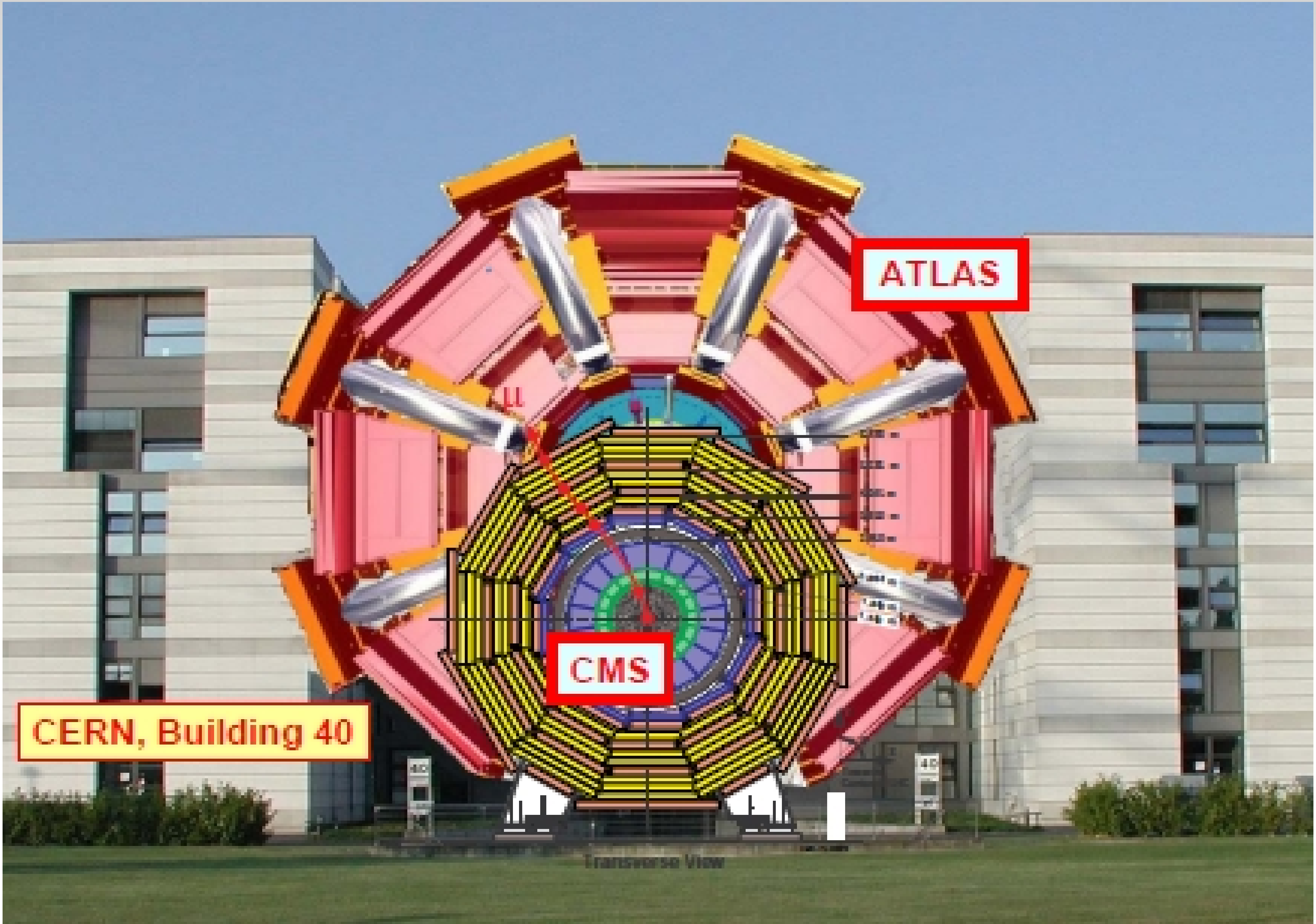
Two general-purpose detectors



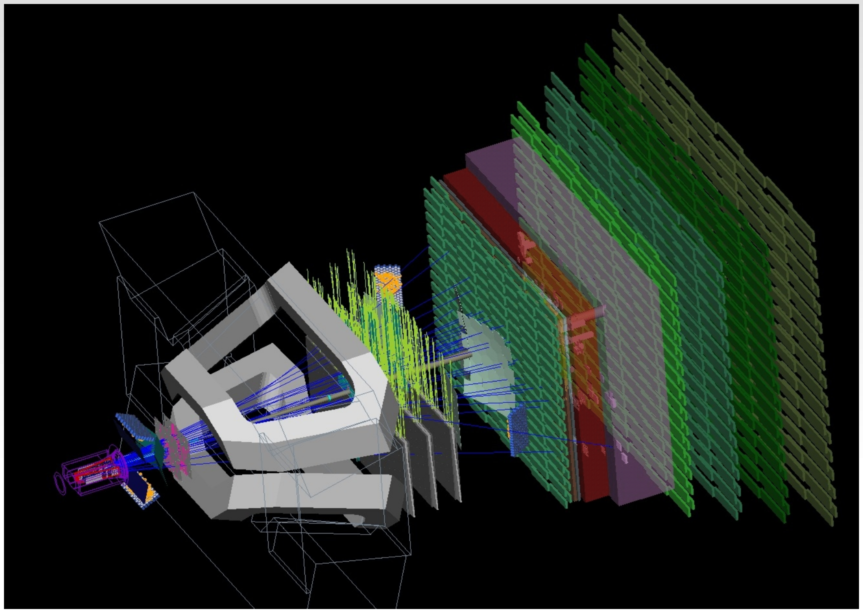


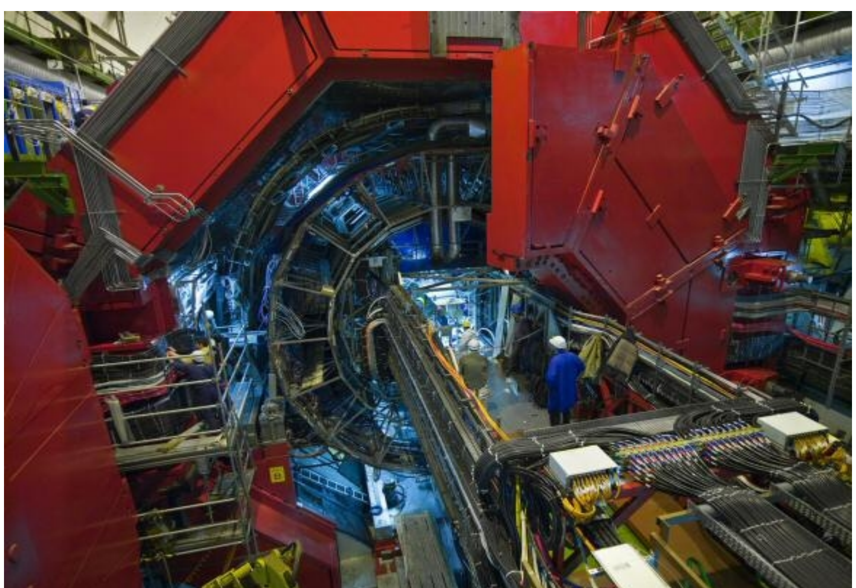
- Atlas: 1 solenoid (2T) and 8 + 2 toroid magnets (!)
  - Air-core muon chambers (good stand-alone muons)
  - Liquid Argon e.m. Calorimeter
- CMS: 1 solenoid magnet (4T) creates field inside and outside
  - Muon chambers in return yoke
  - 80000 $PbWO_4$ crystals as e.m. calorimeter

Why CMS stands for 'compact'



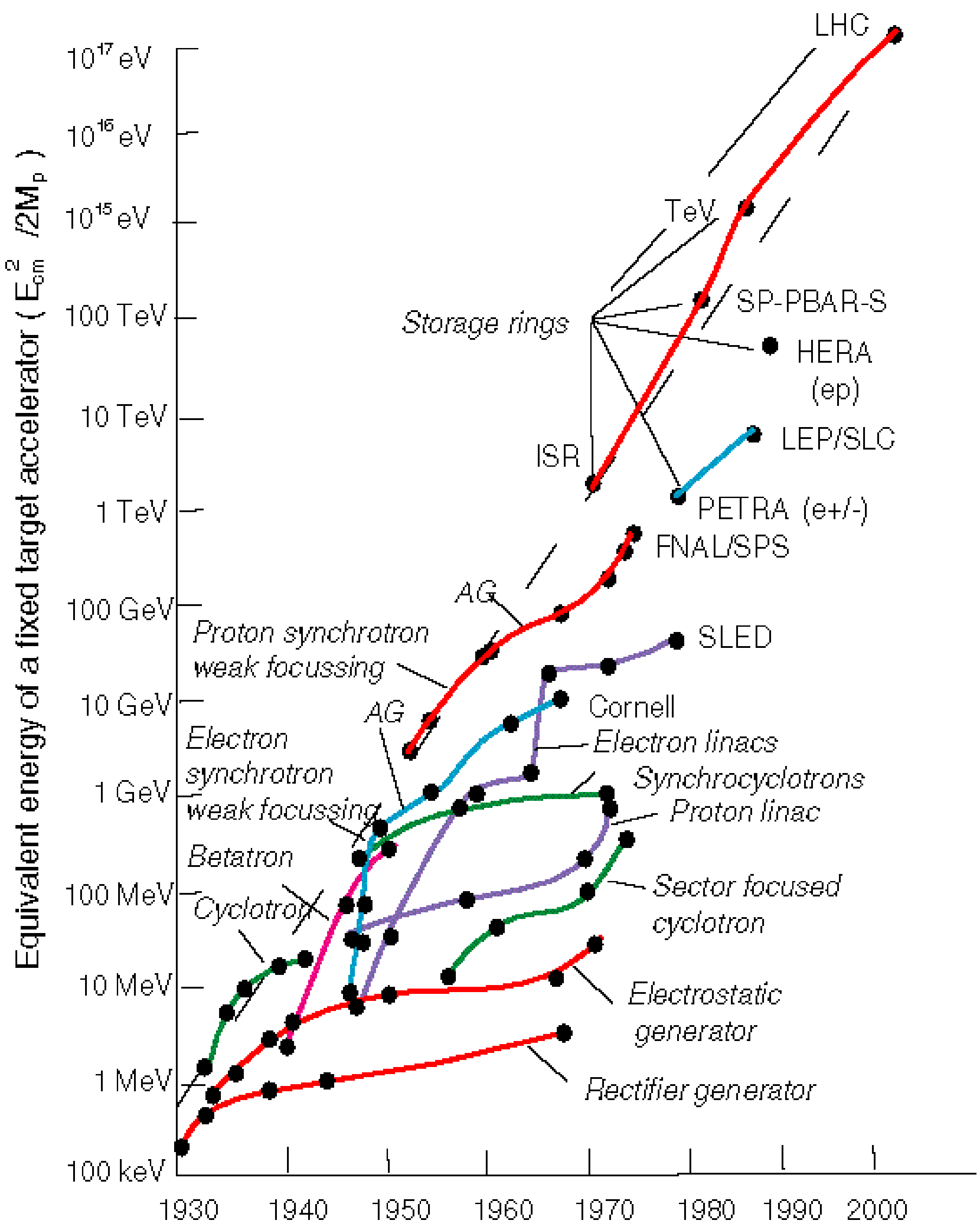
Two dedicated 'low-rate' experiments (not covered)





- 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

ler?



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

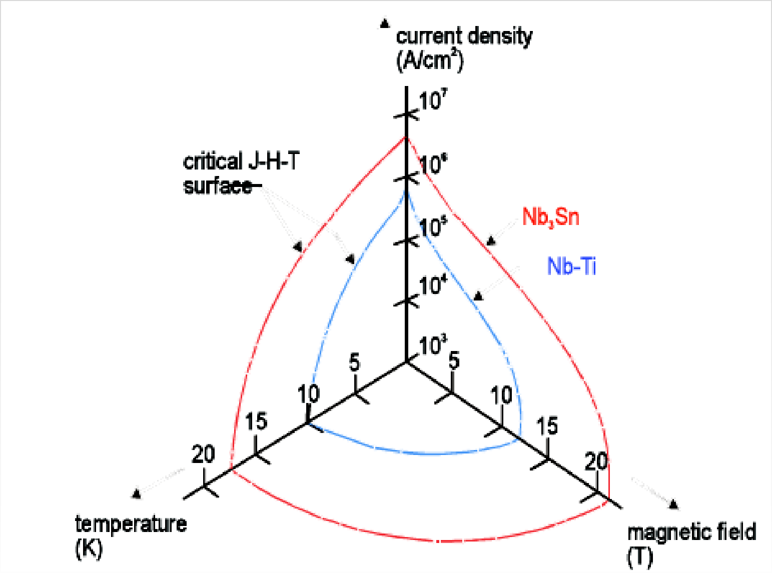
a hadron collider is not limited by synchrotron radiation, and can go to much higher energy.

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

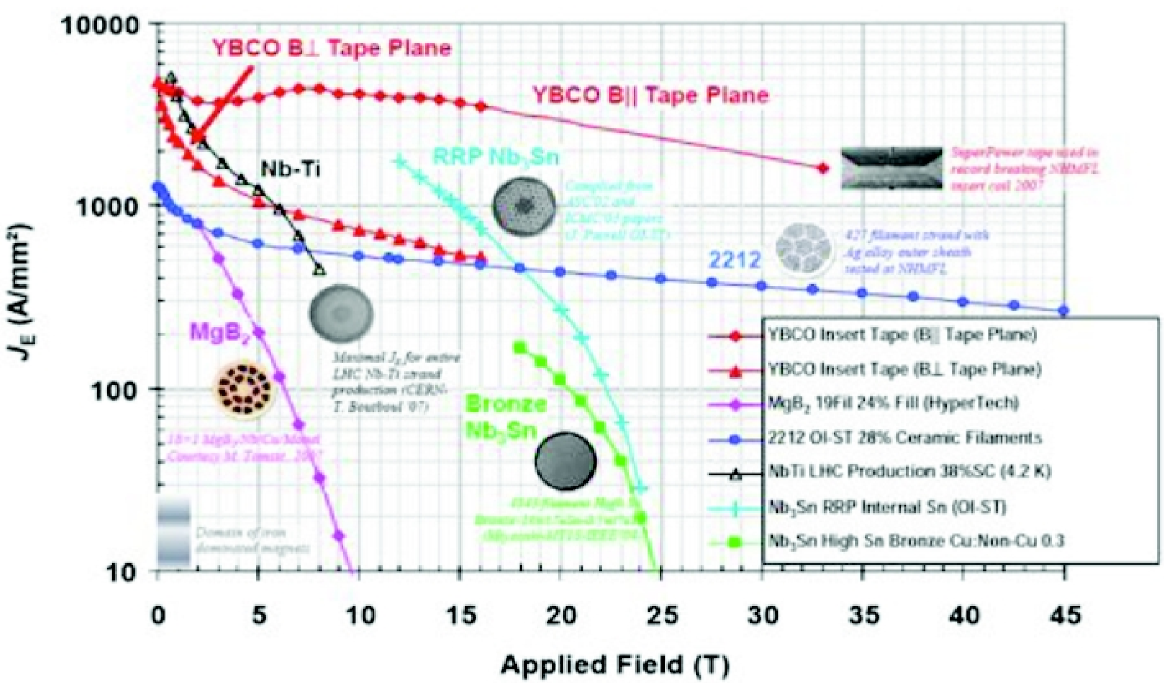
P (TeV) = 0.3 B(T) R (Km)

Limitation to magnetic field

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

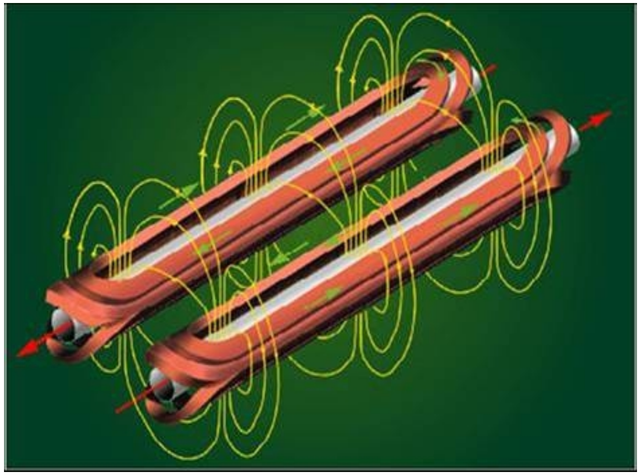


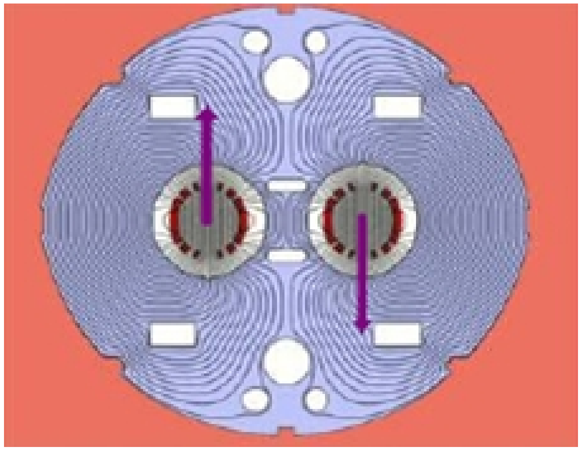
Unfortunately, phase transition between super-and normal conducting phase depends not only on temperature but on magnetic fields. This sets maximum field to 8.4T (100K times earth!) and defines P = 14 TeV (60% of circumference has magnets)



2-in-1 configuration

- 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





Some parameters

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 :

Event rate and luminosity

- 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 = πr^2 where r = 16 μm (rms of transverse beam profile)

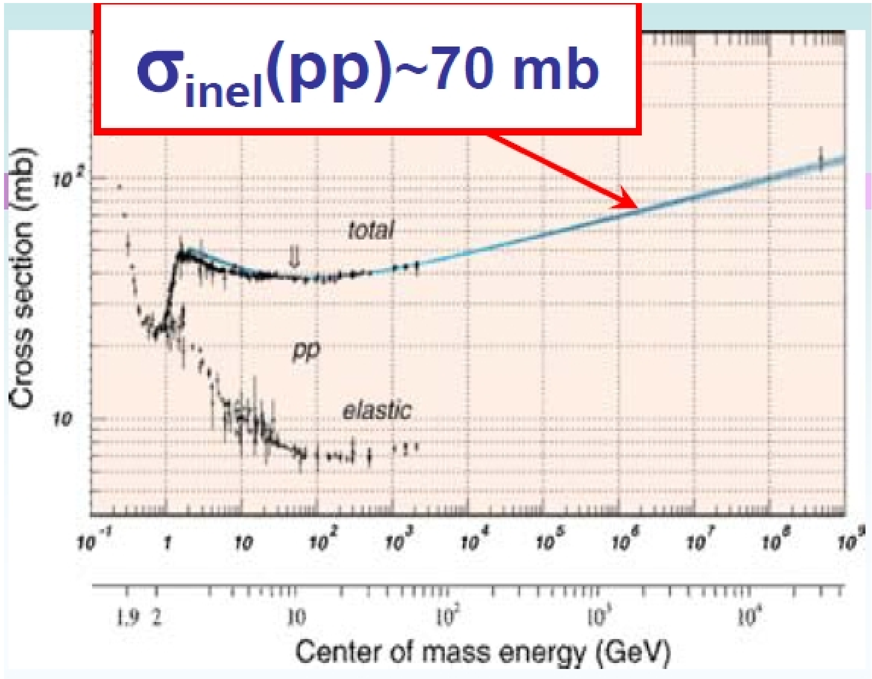
Integrated luminosity and pileup

- 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}

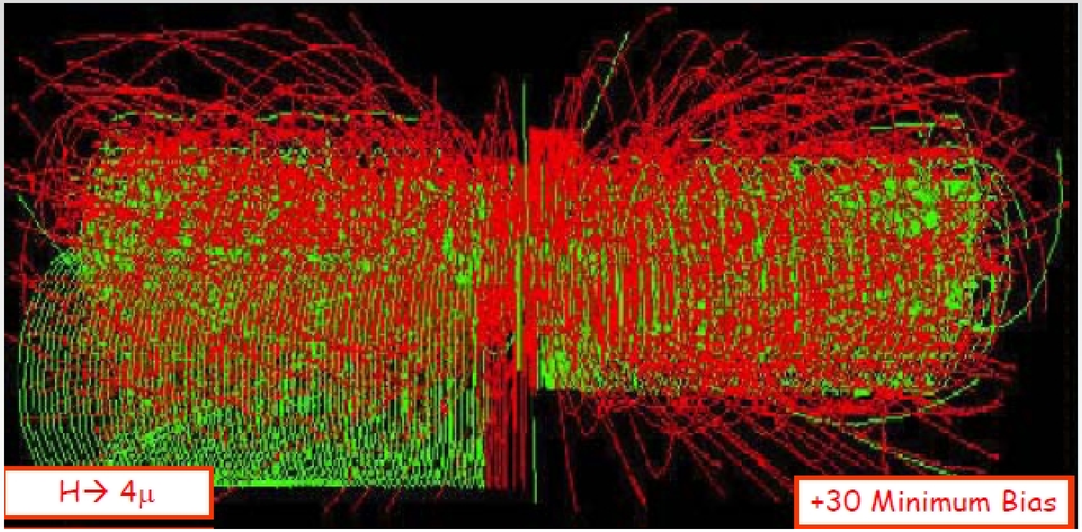
The total pp cross section is about 70 mb:



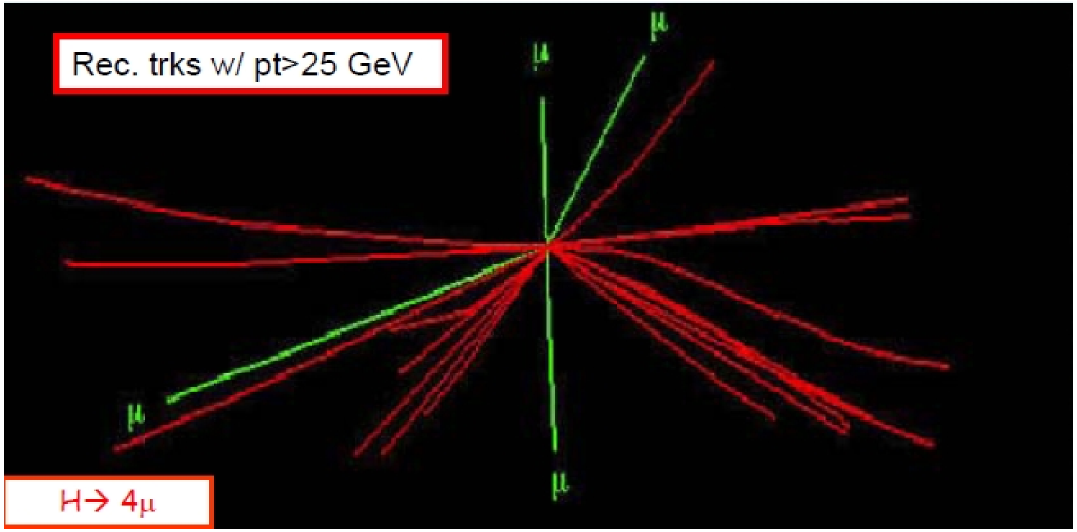
So, rate can go up to 700MHz! Divided by 40MHz bunch crossing rate, and accounting for empty bunches, we can have > 20 collisions/bunch crossing (pileup)

Pileup

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

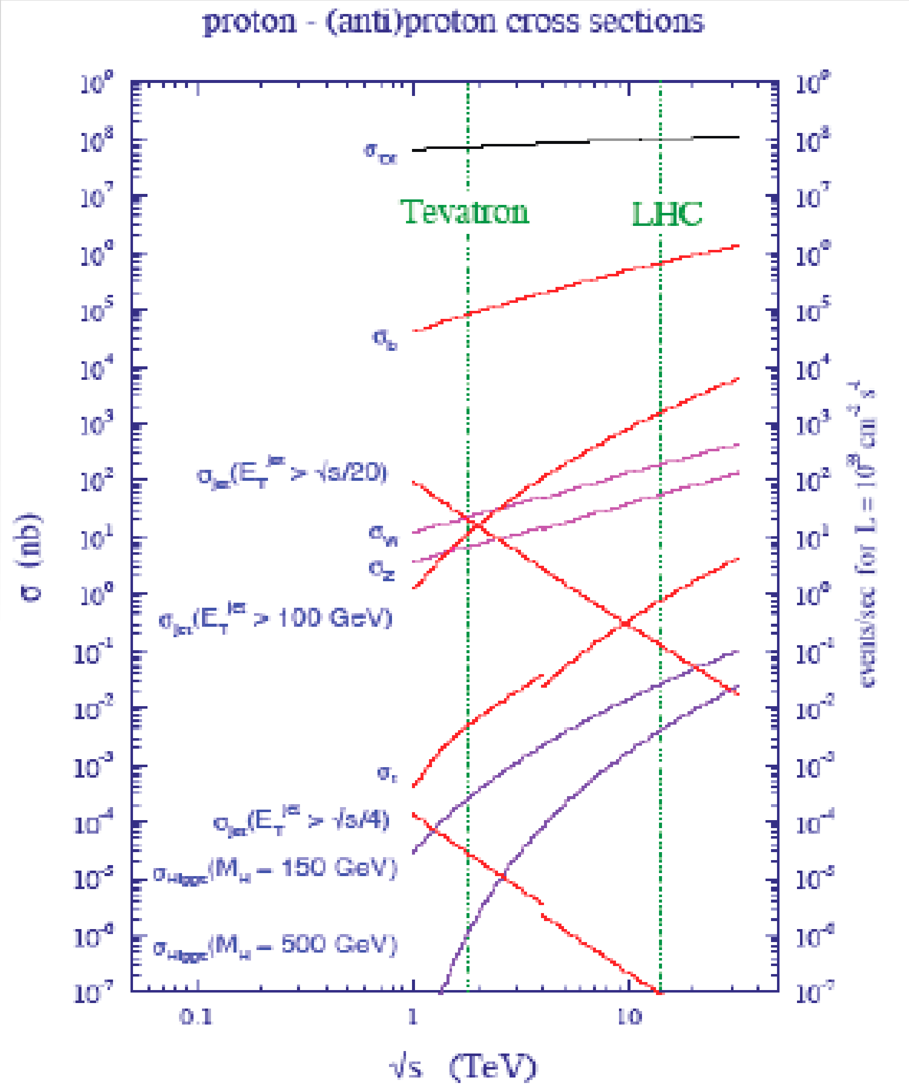


It gets much better if you just look at the energetic particles:



Cross sections in pp interactions

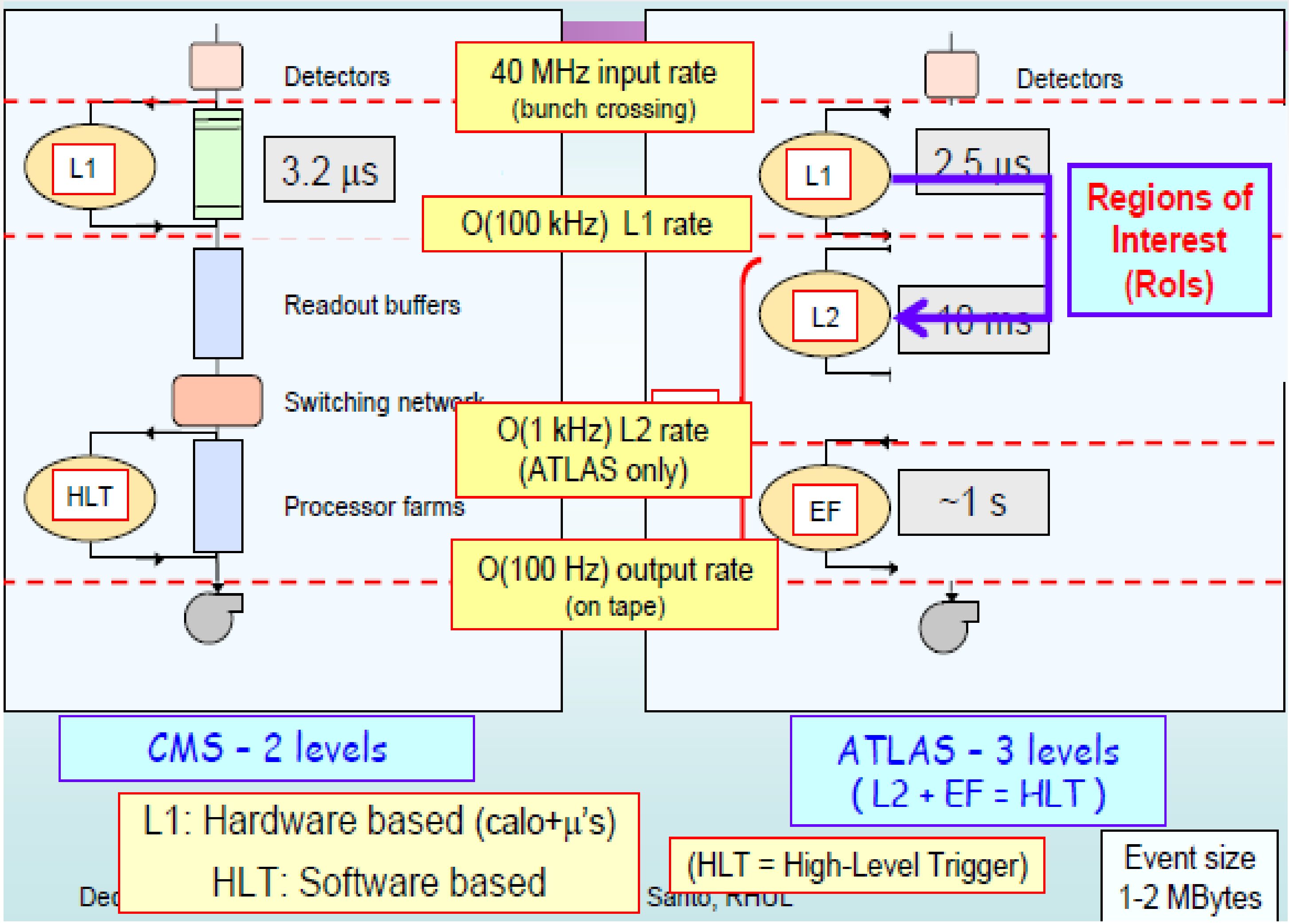
- No real thresholds
- Total cross section (including elastic) almost constant
- Some lines 'broken' going from Tevatron to LHC due to antiprotons vs protons
- Several orders of magnitude between discoveries and background



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

Triggering

- 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:

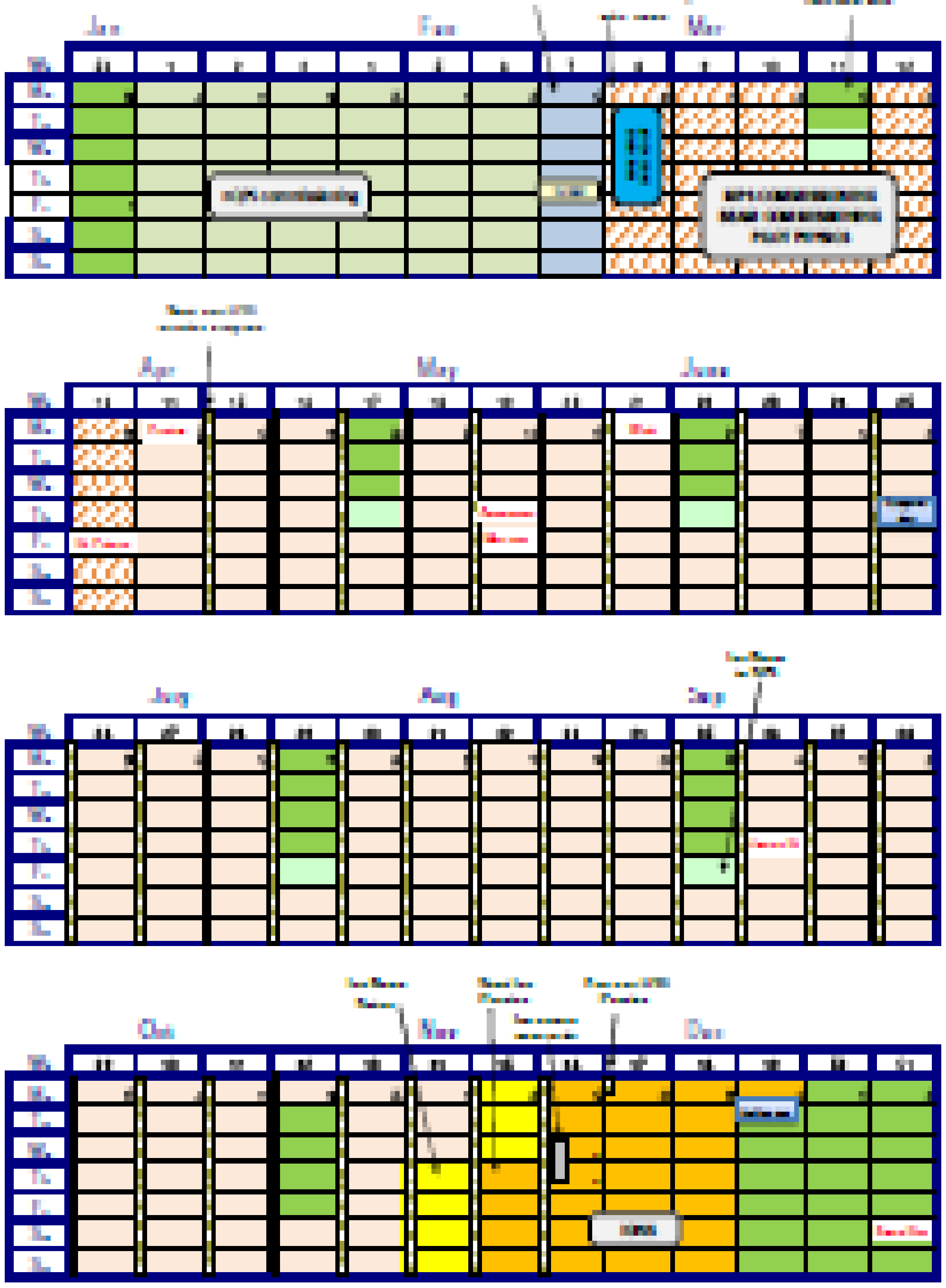


The end of 2009

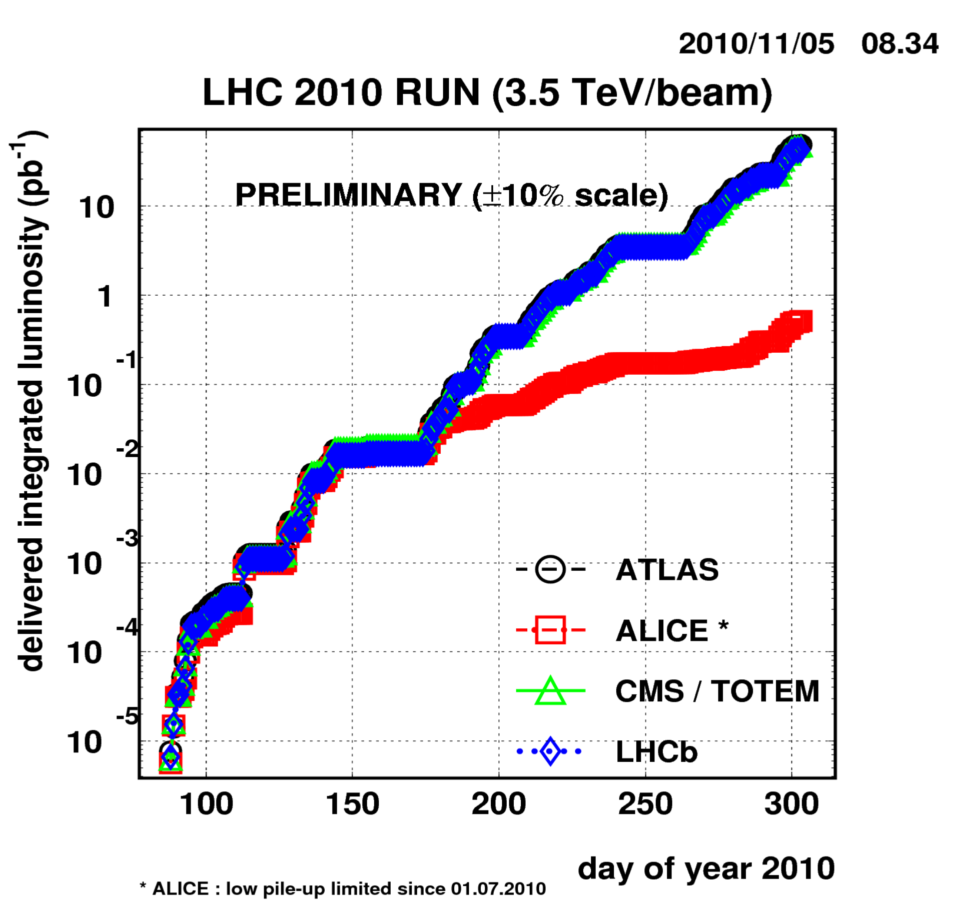
Friday November 20th Injection of both beams - rough RF capture
Saturday November 21st Beam 1 circulating - lifetime 10 hours
Sunday November 22nd Beam 2 circulating - lifetime 3 hours
Monday November 23rd First pilot collisions at 450 GeV
First trial ramp (lost 560 GeV - tunes) tune feedback on 1 beam
Tuesday November 26th Precycle established
Energy matching between SPS & LHC
Sunday November 29th Ramp to 1.07 TeV and then 1.18 TeV (00:43 Monday) Tune PLL commissioned
Monday 30th November Solenoids on Coupling & orbit compensated
Tuesday 1st - Sunday 6th December Aperture, collimation and beam dump studies continued - protection qualified to a sufficent level at 450 GeV to allow "stable beams" to be declared.
Sunday 6th 06:55 Stable beams at 450 GeV - 4 on 4 pilot intensities Initial struggle with vertical tune
Tuesday 8th December Ramp 2 on 2 - lost one beam after 3 minutes - but first collisions in Atlas (21:40) at 1.18 TeV No logging - suspect loss due tune swing at end of ramp
Friday 11th December (01:30) Stable beam collisions at 450 GeV with high bunch intensities: 4 x 2 10^10 per beam
Monday 14th December Ramp 2 on 2 to 1.18 TeV - quiet beams - collisons in all four experiments
Monday 14th December 16 on 16 at 450 GeV - stable beams
Wednesday 16th December Ramped 4 on 4 to 1.18 TeV - squeezed to 7 m in IR5 - collisions in all four experiments
Wednesday 16th December 18:00 End of run

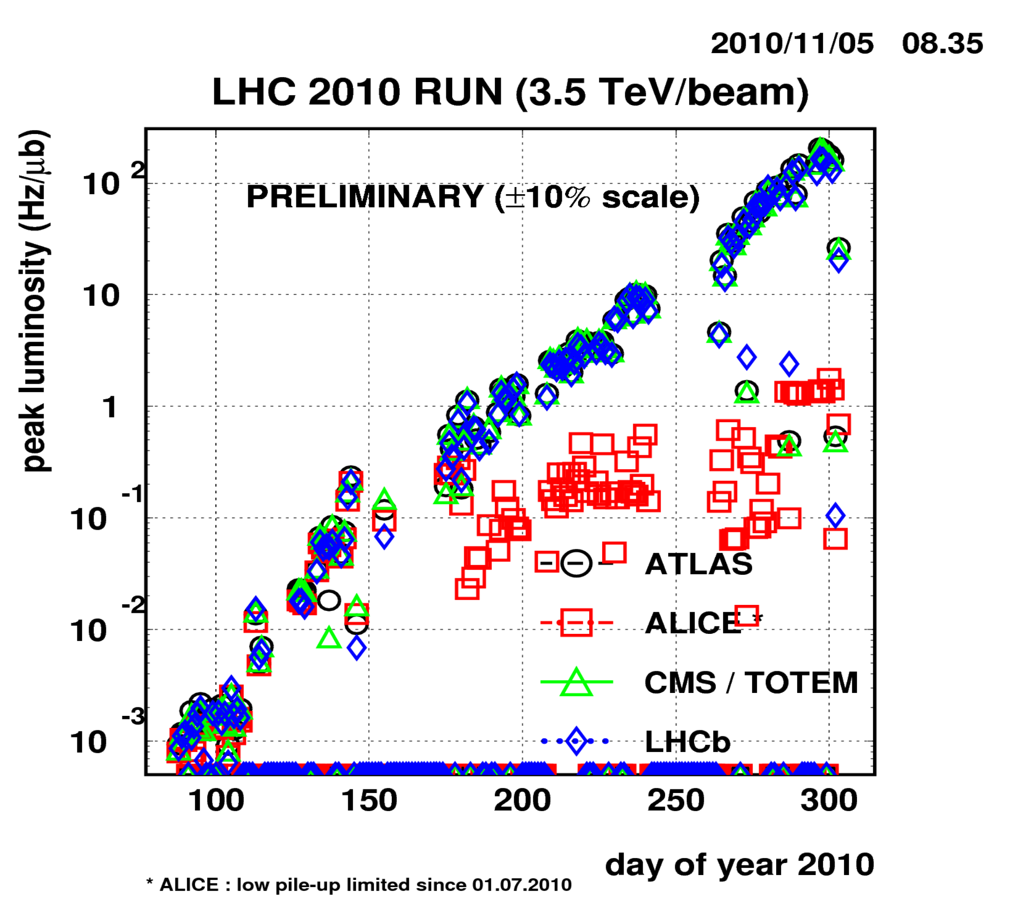
2010 data taking schedule

- More than 7 months of proton physics, followed by
- 1 month of heavy ion (lead beams) physics (not yet finished)



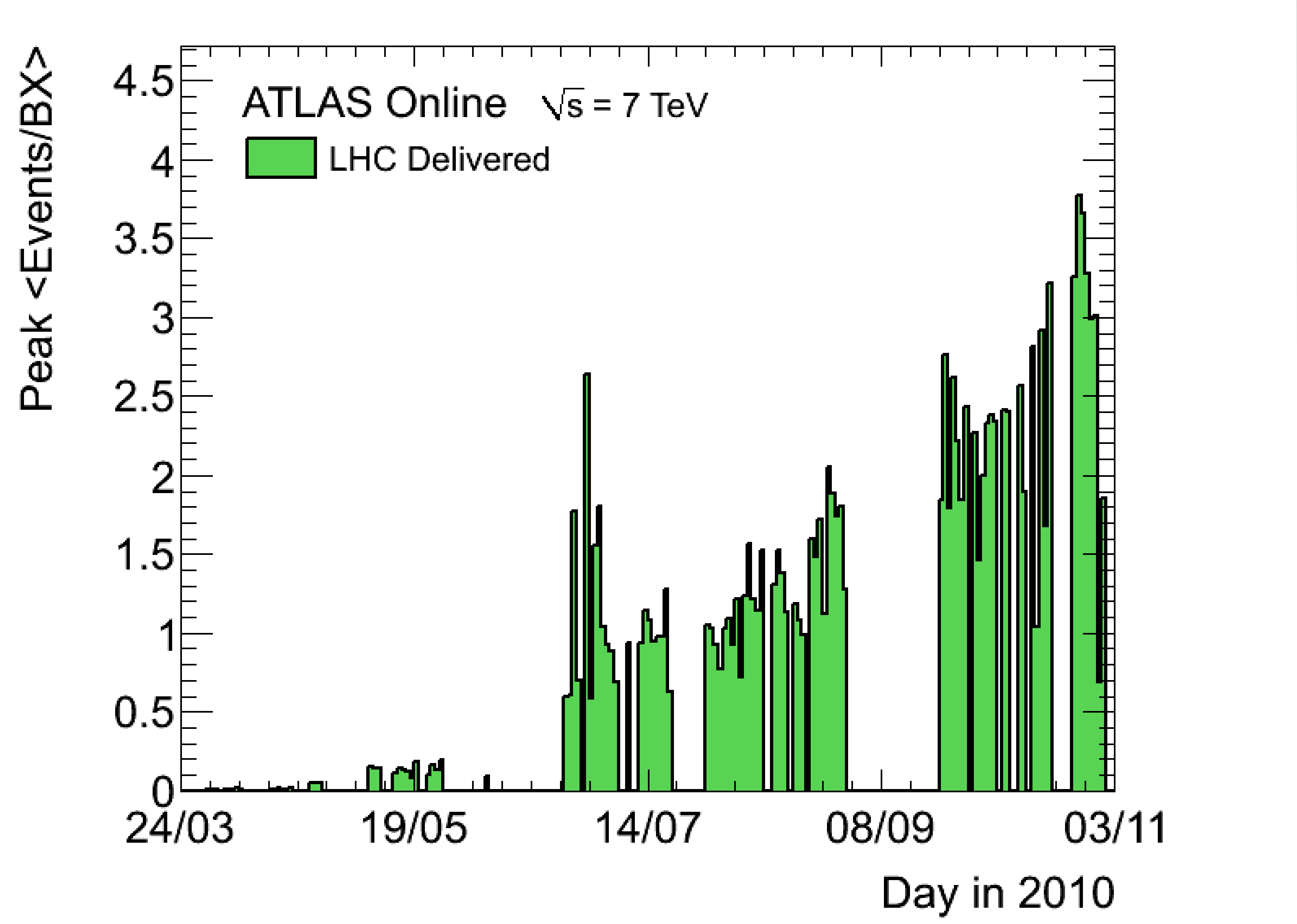
Luminosity evolution



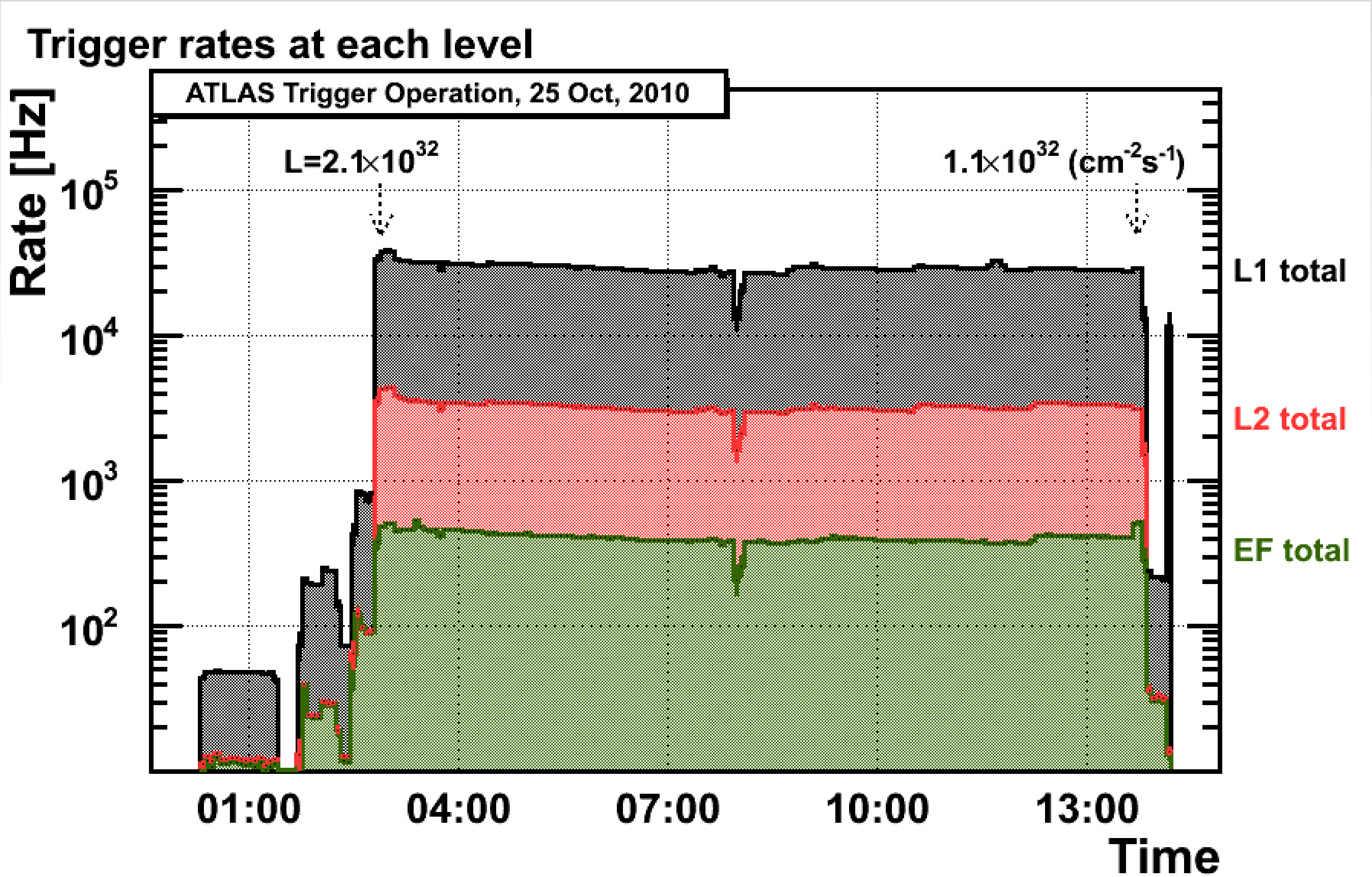


- Integrated luminosity ~50 pb-1
- Peak luminosity ~2E32

What that means in terms of pileup



ATLAS trigger rates

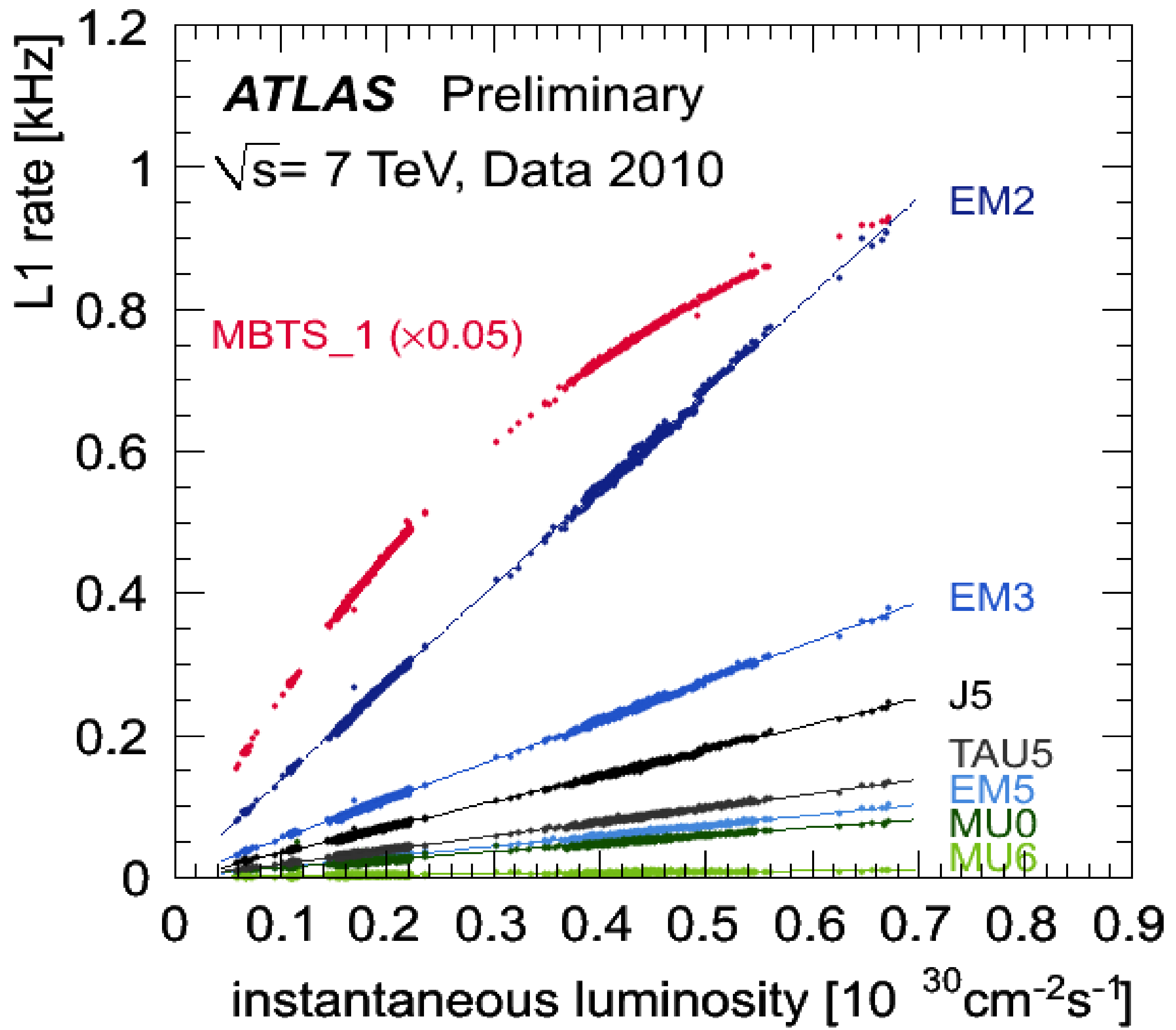


- This run had the highest initial luminosity of 2010
- Trigger bandwidth saturated at the three levels

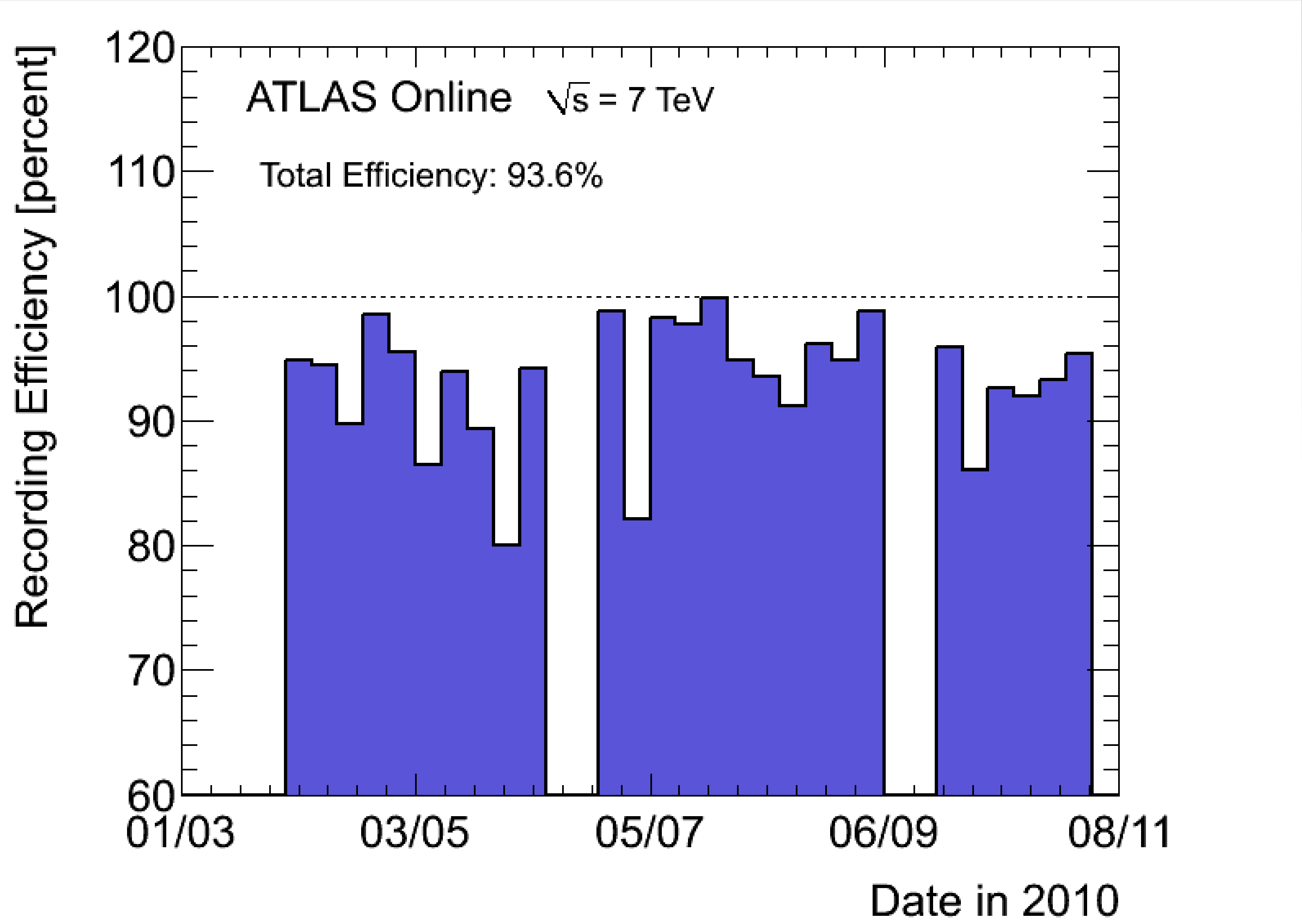
L1 Trigger rates vs luminosity

Rates still linear since in no-pileup region.

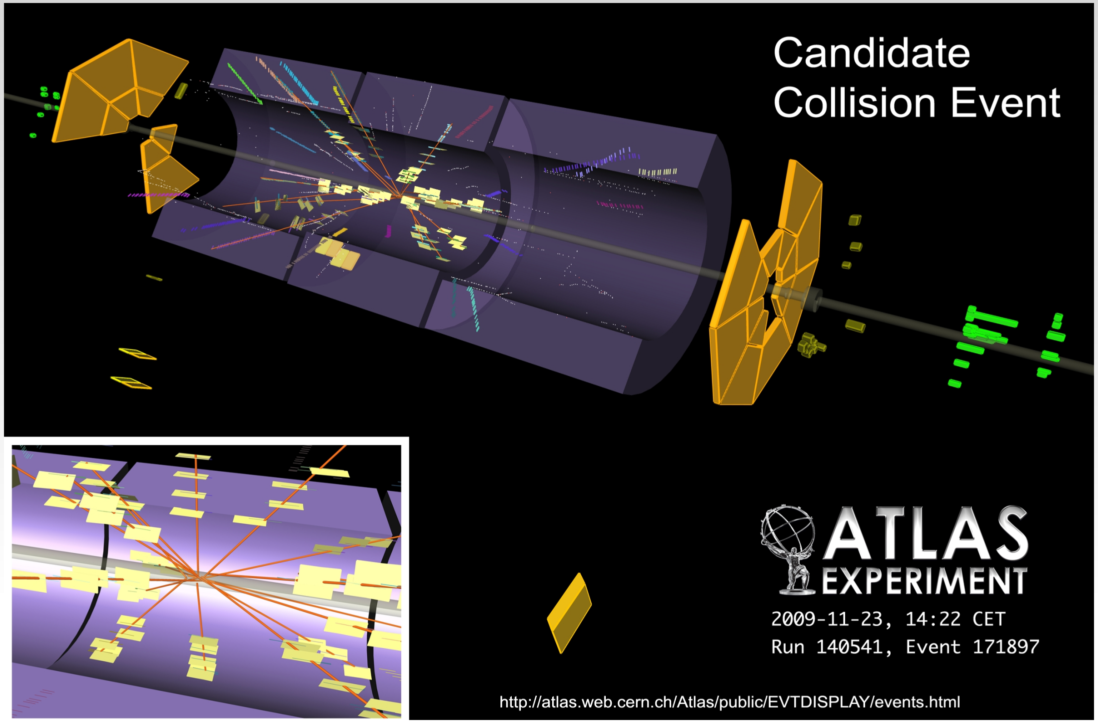
Non-linearities observed at the highest luminosities



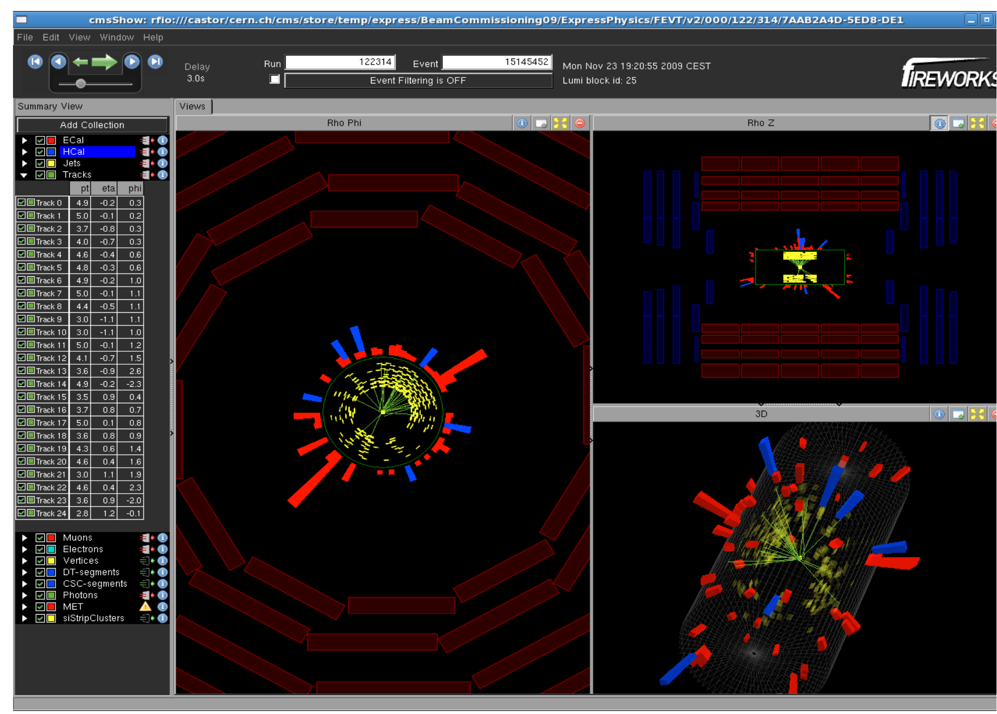
ATLAS data taking efficiency



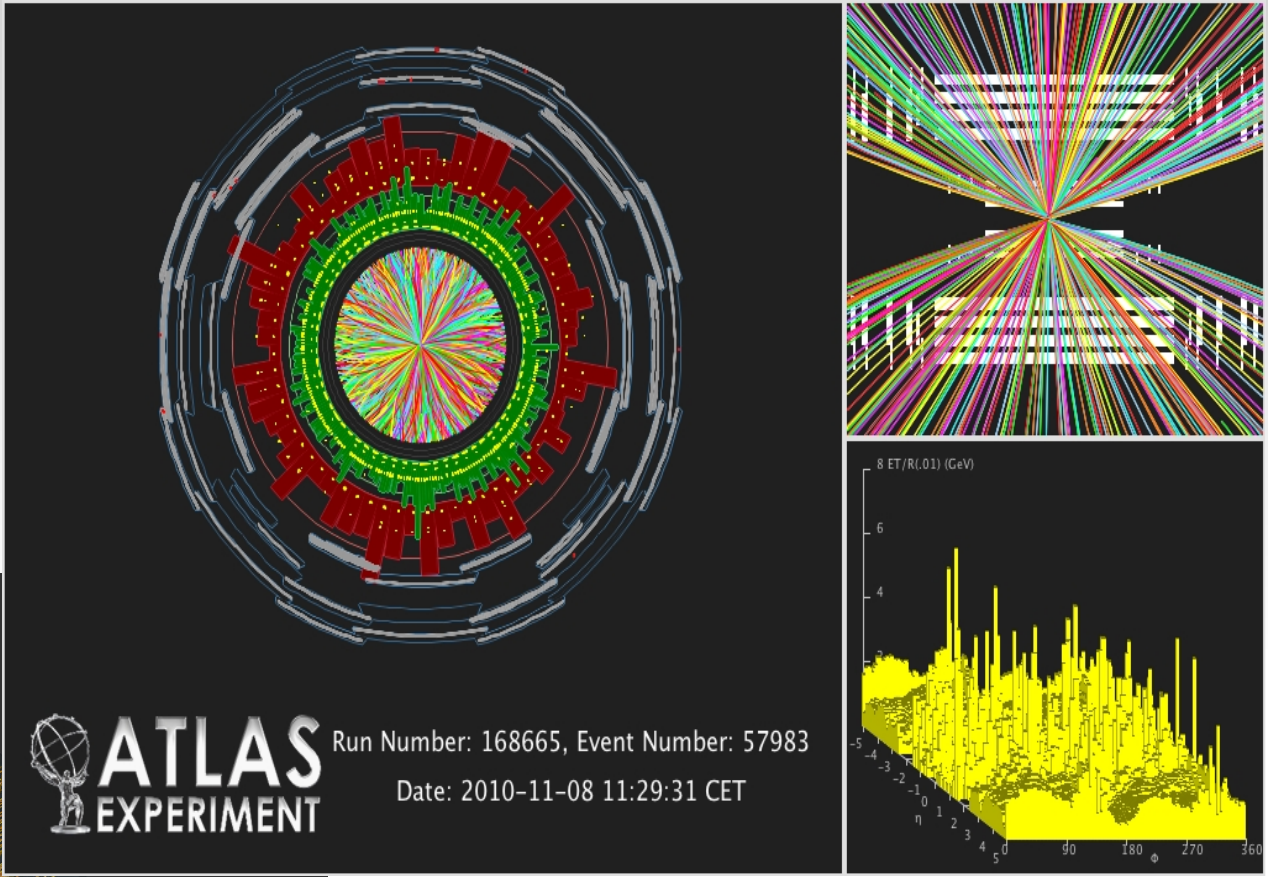
First events in Atlas/CMS

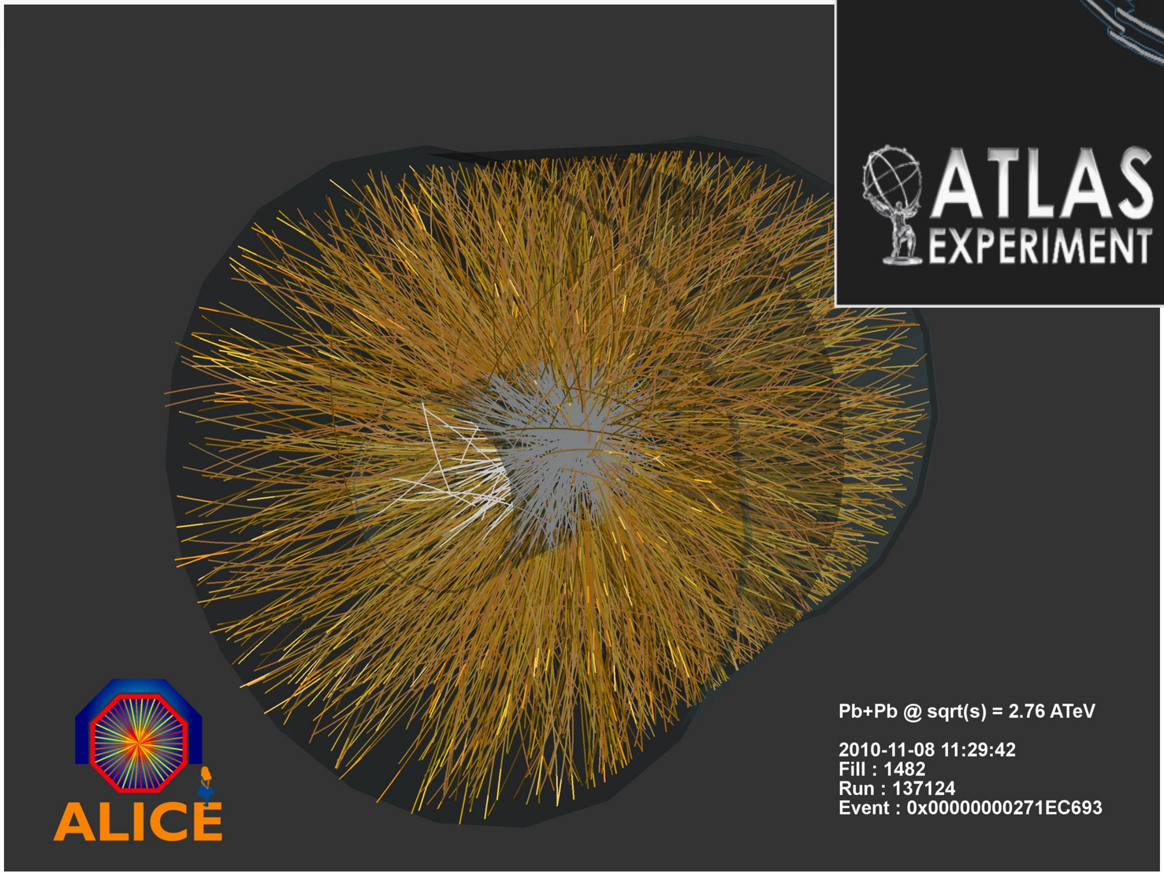


Soft collisions with just few tracks but important for alignment and trigger studies



The other extreme: HI collisions





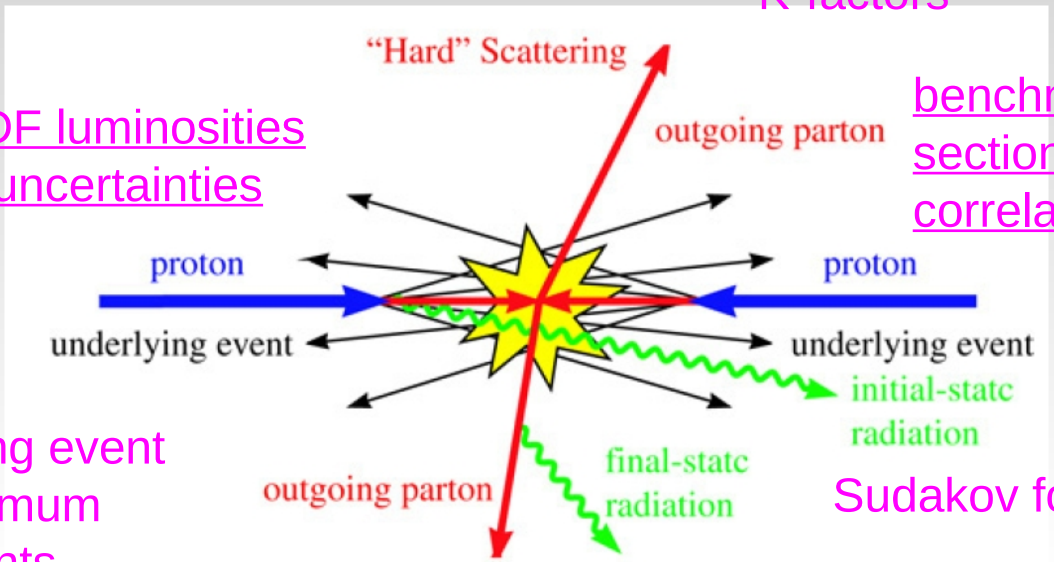
Physics in a hadron collider

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

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

Parton distribution functions

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

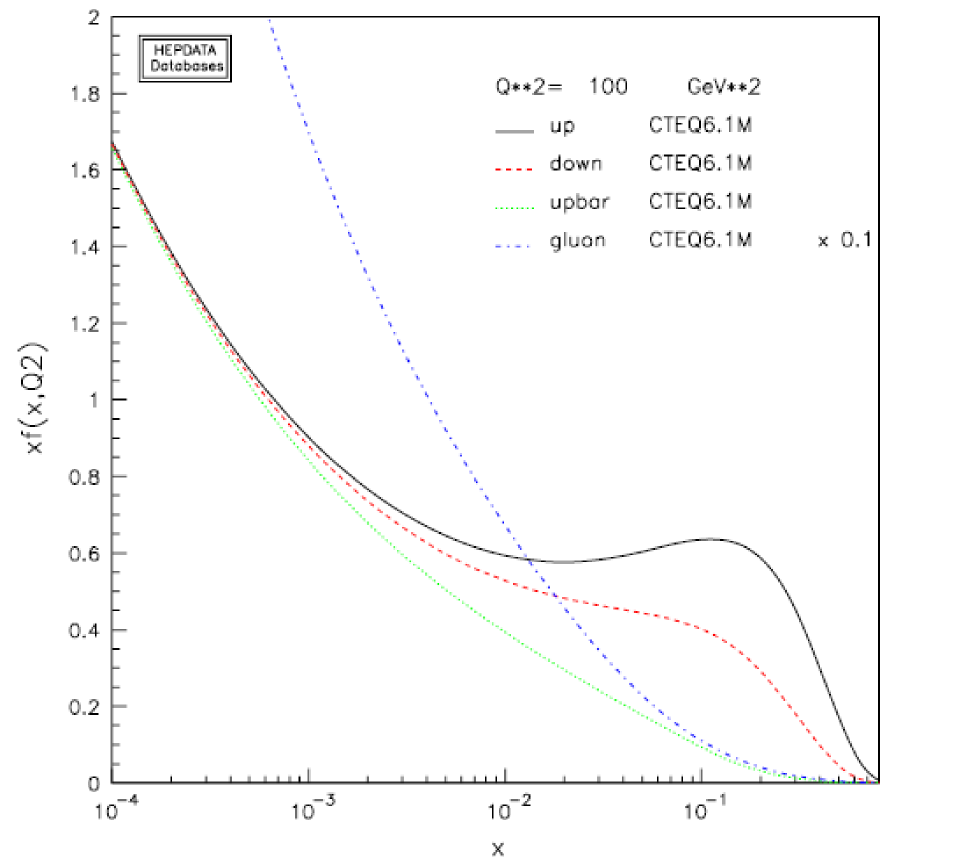


Figure 27. The CTEQ6.1 parton distribution functions evaluated at a Q of 10 GeV.

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

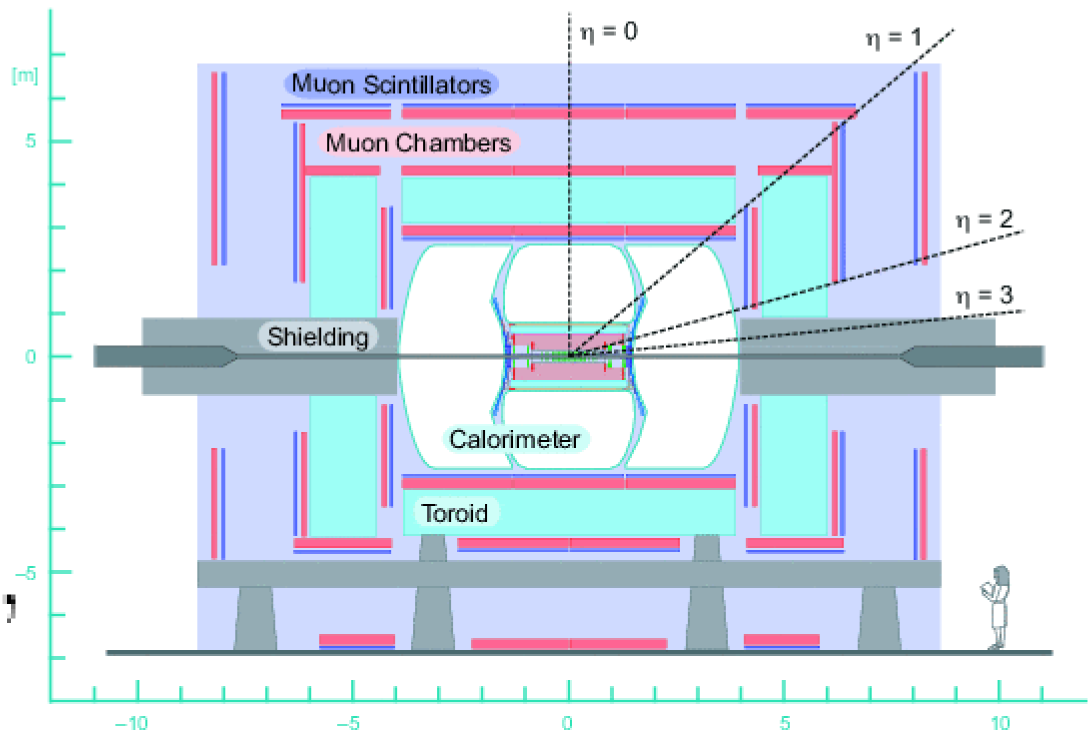
Relevant variables

- 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

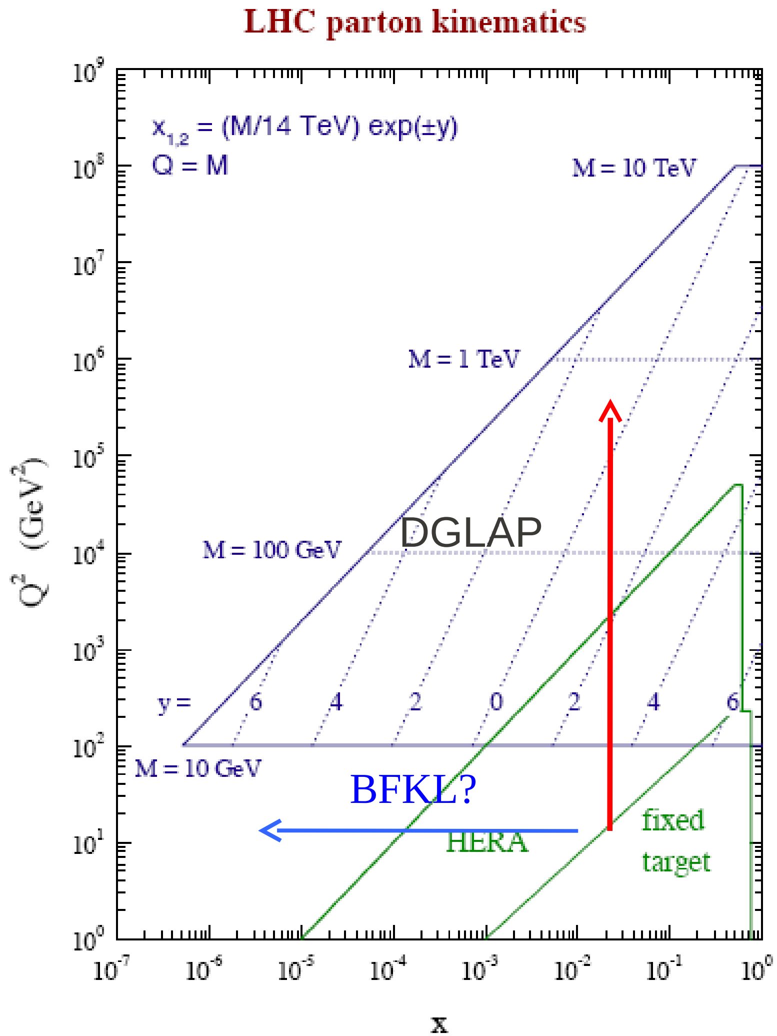
We will access pdf's down to 1E-6 (crucial for the underlying event) and Q^2 up to 100 TeV^2

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

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



Look at ratios of pdf's at 1.96 and 10 TeV

- The plan is to run the LHC in 2009-2010 accumulating at least 200 pb^{-1}
- Take a discovery region (~1 TeV, say for squark pair production)
- The LHC is a factor of 50 more efficient at producing a 1 TeV object through a qQ initial state…so it would take 10 fb^{-1} at the Tevatron to equal the 200 pb^{-1} at the LHC
- …which the Tevatron will probably get (per expt)
- …with much better understood detectors and much lower backgrounds
- So don't count the Tevatron out just yet for discovery physics
- In other words, since no big discoveries at the Tevatron so far, chances for the LHC in the first run are also small

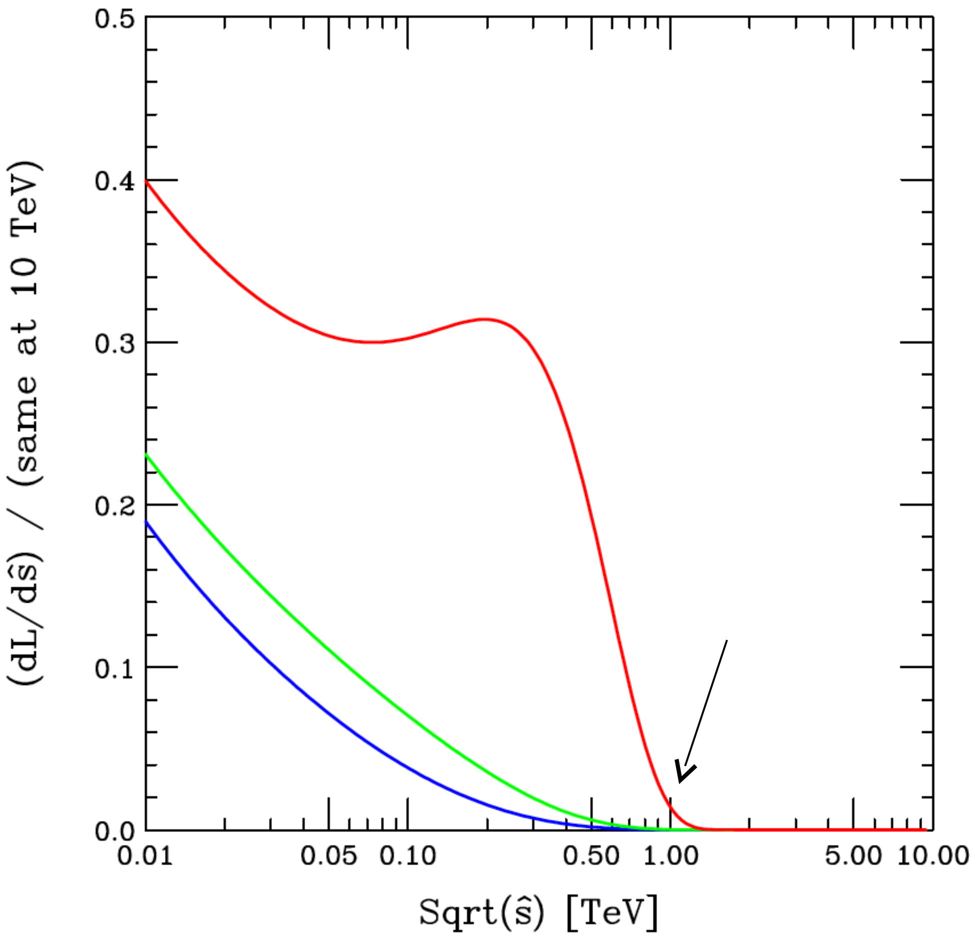


Figure 13: ($p\bar{p}$ at 1.96 TeV) / (pp at 10 TeV). luminosity integrated over y.
Blue: gg; Green: $gq + g\bar{q}$; Red: $u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c} + b\bar{b}$.

So, what are we doing?

- Starting an accelerator like the LHC is not an easy task, and the same is true for detectors as complex as CMS and ATLAS
- We need time to verify trigger efficiencies, detector resolutions, alignment, dead channels, missing Et etc.
- The ideal case would be to 'switch off' the discovery physics for some time, re-discover the Standard Model and once we are confident make the discoveries! ;-)
- Not so far from the actual scenario (dictated by the need not to push the accelerator too close to the limits from the beginning): discovery potential of first run close to present Tevatron
- We will be however running at higher energies and covering a lerger eta range, and the Standard Model has still some surprises

PDF uncertainties at the LHC

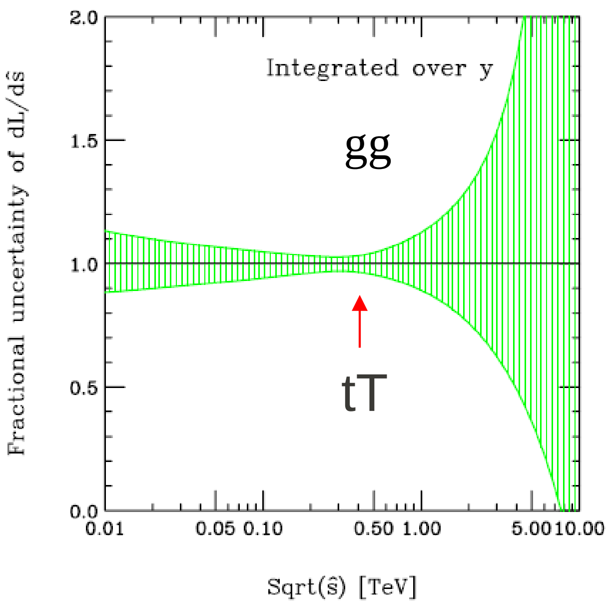


Fig. 4: Fractional uncertainty of gg luminosity integrated over y.

Note that for much of the SM/discovery range, the pdf luminosity uncertainty is small

Need similar level of precision in theory calculations

It will be a while, i.e. not in the first fb^{-1}, before the LHC data starts to constrain pdf's

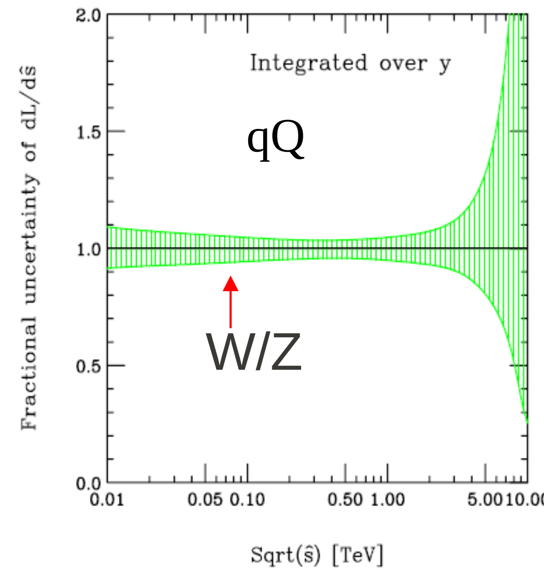


Fig. 7: Fractional uncertainty for Luminosity integrated over y for $d\bar{d} + u\bar{u} + s\bar{s} + c\bar{c} + b\bar{b} + \bar{d}d + \bar{u}u + \bar{s}s + \bar{c}c + \bar{b}b$.

NBIII: tT uncertainty is of the same order as W/Z production

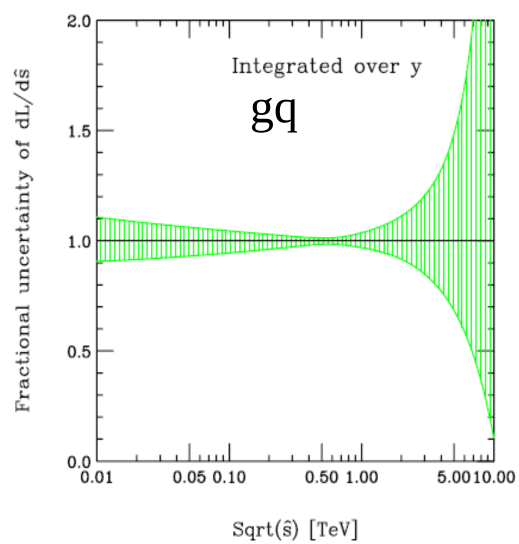


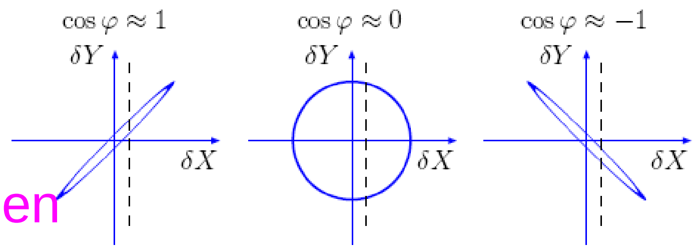
Fig. 6: Fractional uncertainty for Luminosity integrated over y for $g(d+u+s+c+b) + g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b}) + (d+u+s+c+b)g + (\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$,

NB I: the errors are determined using the Hessian method for a $\Delta\chi^2$ of 100 using only experimental uncertainties,i.e. no theory uncertainties

NB II: the pdf uncertainties for W/Z cross sections are not the smallest

Correlations with Z, tT

Define a correlation cosine between two quantities



igure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.

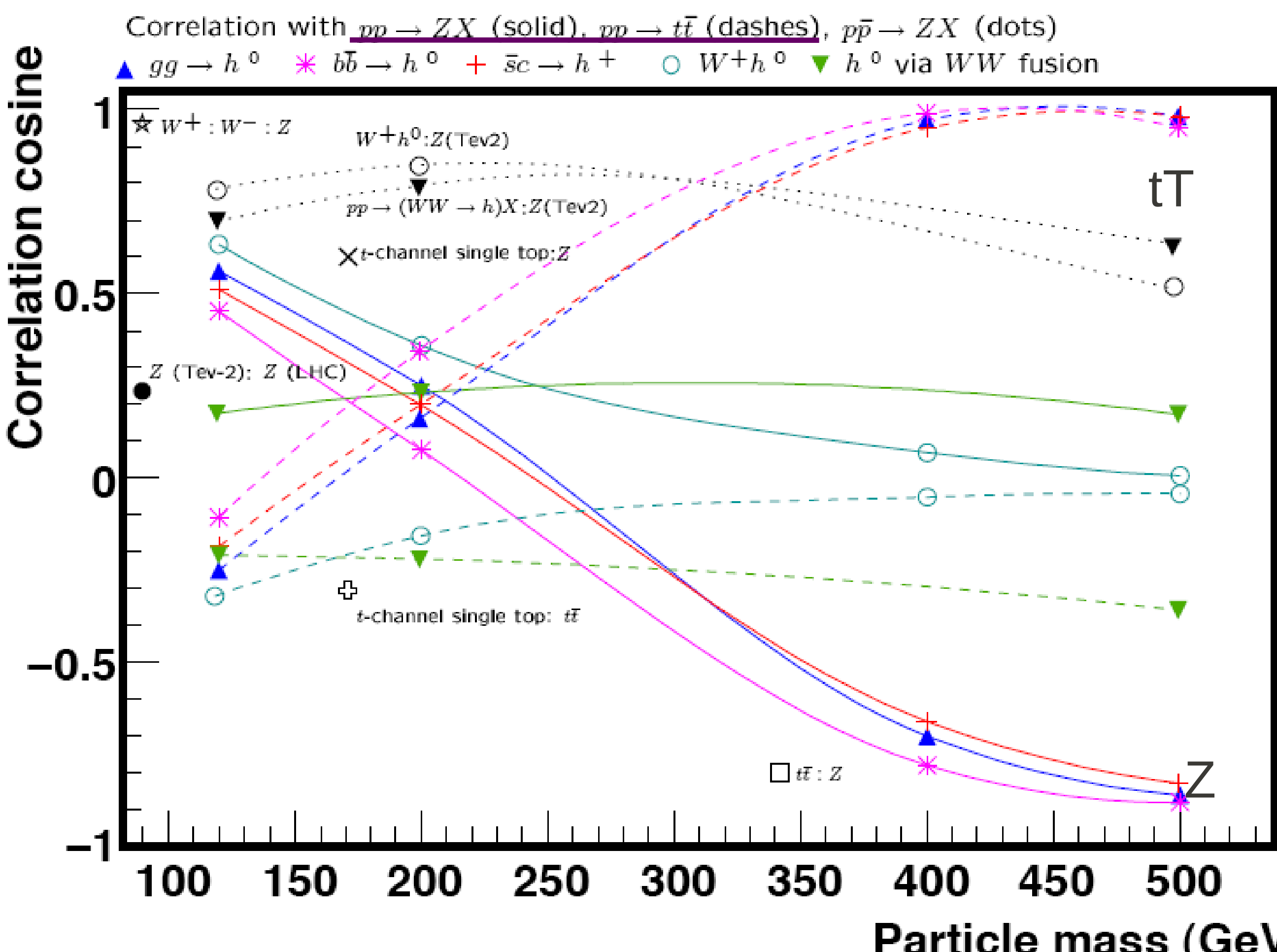
- If two cross sections are very correlated, then cosϕ~1
- …uncorrelated, then cosϕ~0
- …anti-correlated, then cosϕ~-1

- Note that correlation curves to Z and to tT are mirror images of each other

- By knowing the pdf correlations, can reduce the uncertainty for a given cross section in ratio to a benchmark cross section **iff** cos ϕ > 0;e.g. $\Delta(\sigma_W+/\sigma_Z)$~1%

- If cos ϕ < 0, pdf uncertainty for one cross section normalized to a benchmark cross section is larger

- So, for gg->H(500 GeV); pdf uncertainty is 4%; $\Delta(\sigma_H/\sigma_Z)$~8%

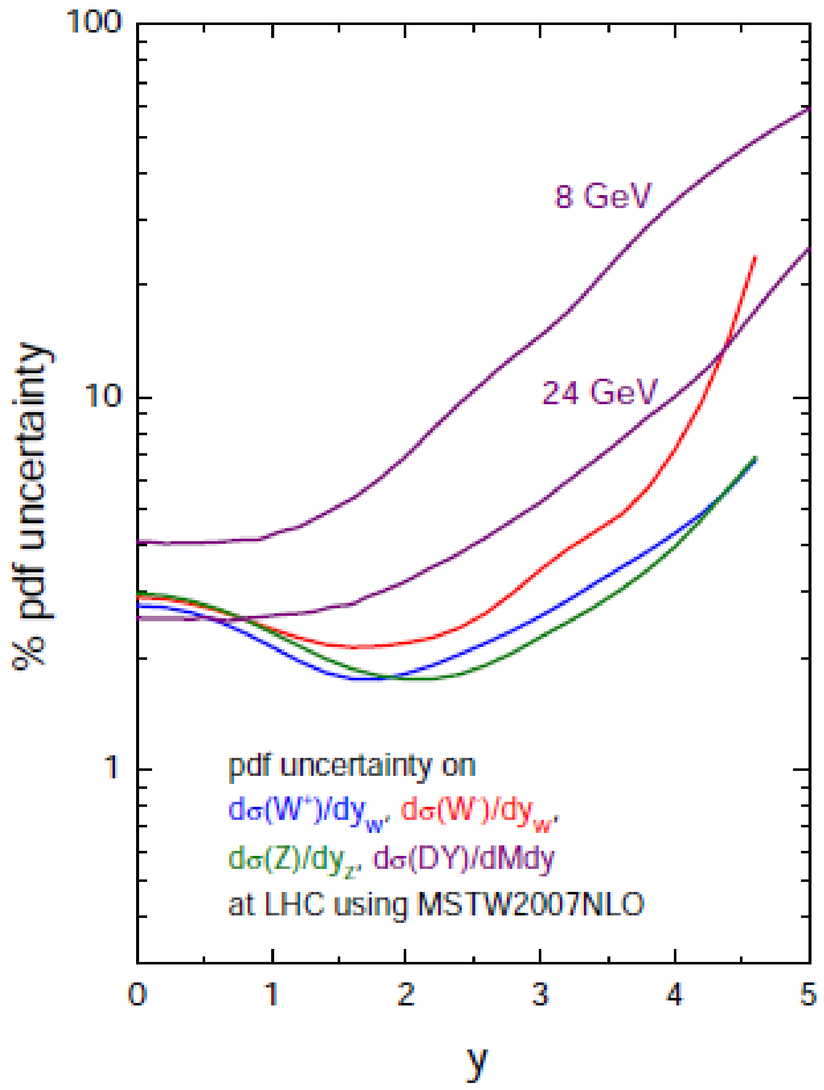


Pdf uncertainties

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.



More on uncertainties (R.Thorne)

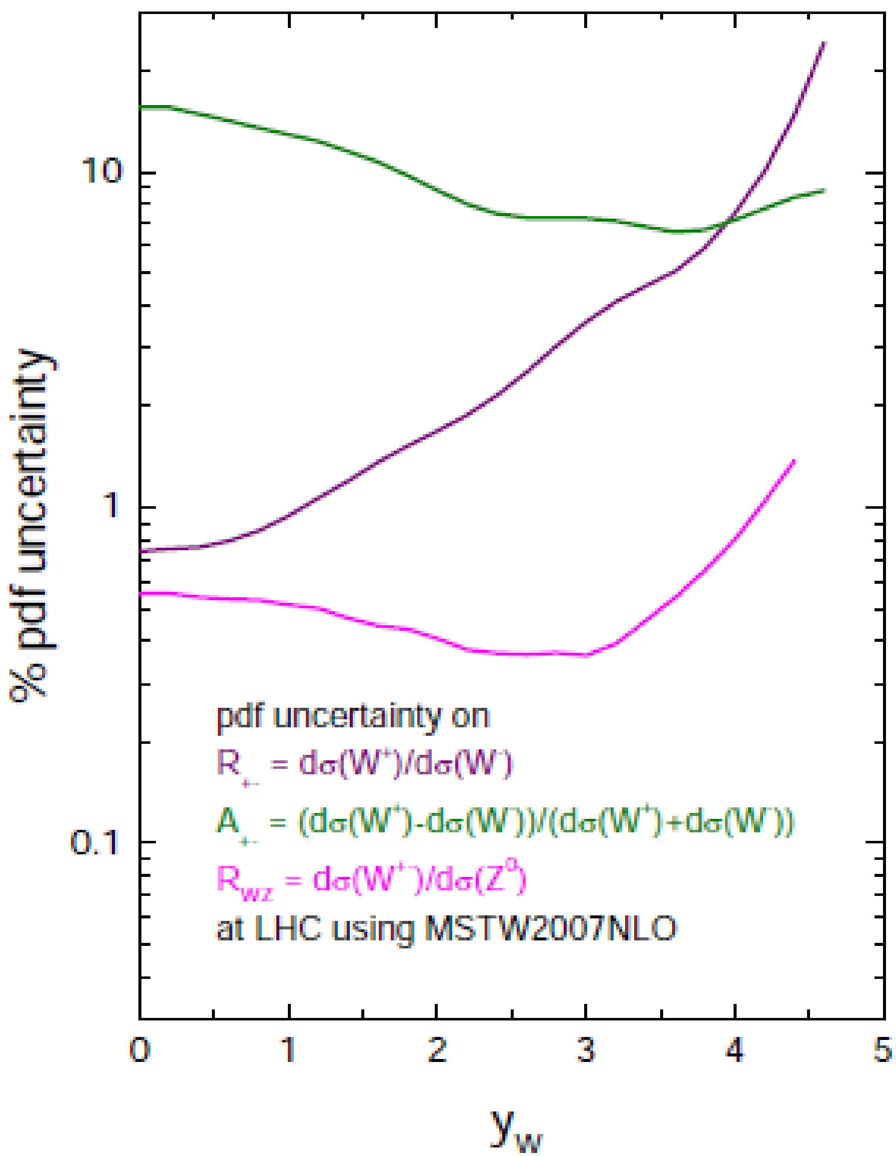
More information from ratios including $\sigma(Z)$, $\sigma(W^-)$ and $\sigma(W^+)$.

Cleaner experimentally.

Uncertainty on A_W large even just from experimental sources.

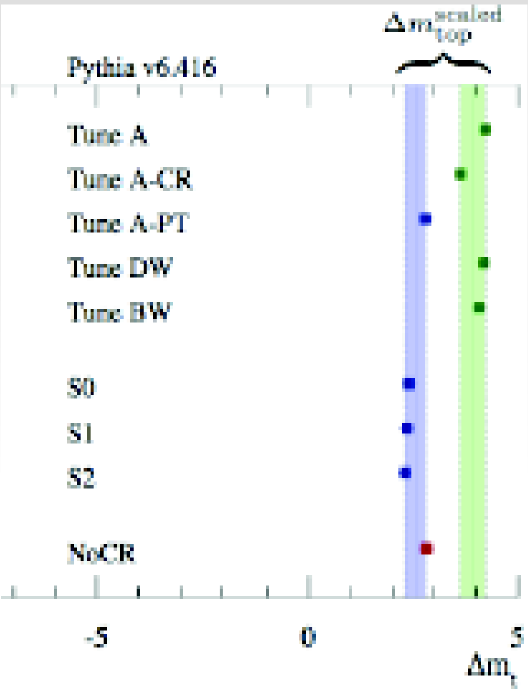
But $y = 0$ is $x_1 = x_2 = 0.006$ – range of extrapolation of valence quarks. Differences in different PDF extractions.

One of most useful inputs to PDFS with very little data.



The underlying event and the minimum bias

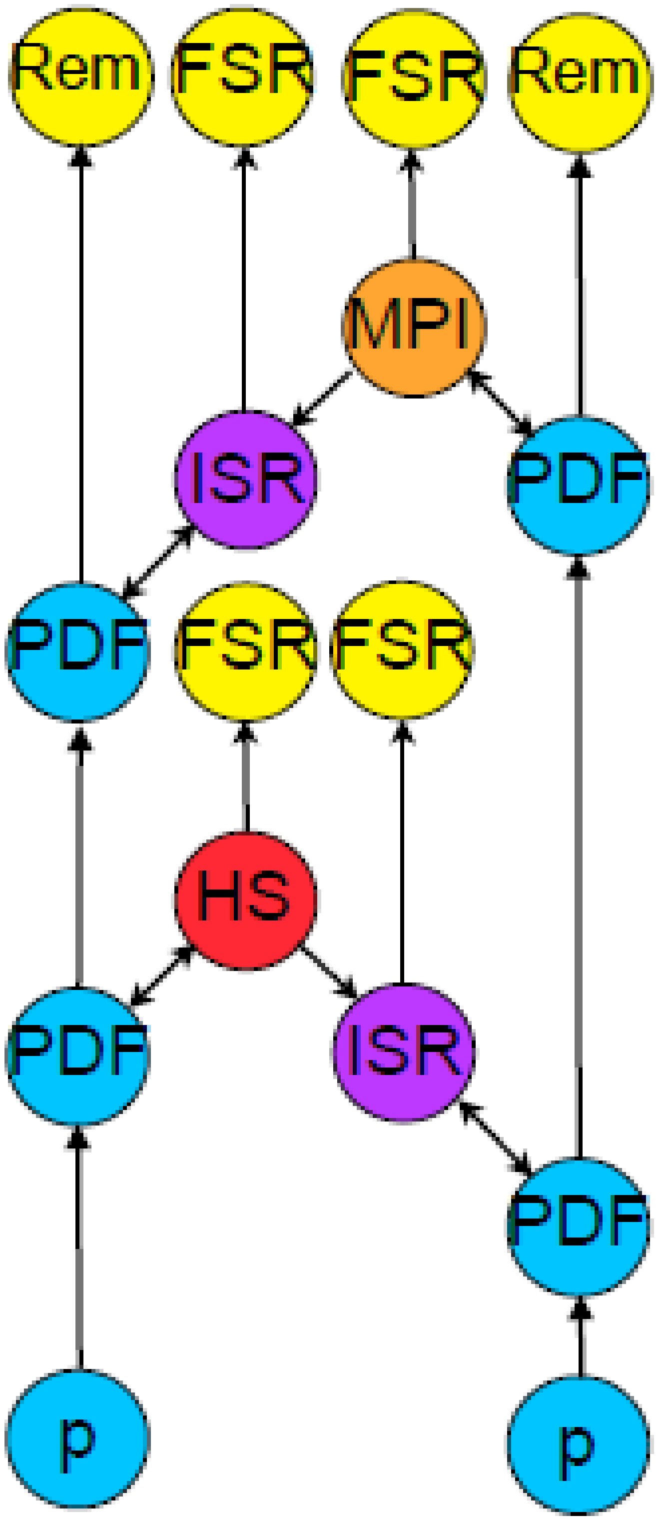
- UE: everything apart from the hard scattering (beam remnant, Multiple Parton Interctions, etc.)
- Will pollute all your physics events (especially ”rapidity gaps”), and influence precision measurements
- normally softer (but with large fluctuations)



•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

Pythia 6.4 model (roughly)

- The incoming partons to the hard scatter are back-evolved to lower Pt by including:
  - (ISR) Initial State Radiation using Pt shower weighted by back-evolved PDFs.
  - (MPI) Multiple Parton Interactions that amend the PDFs in question.
- The full event (ISR and MPI included) is forward evolved (FSR) to lower Pt by a Sudakov shower.
  - Primary ordering is by Pt.
- The final collection of partons and remnants are assigned to strings and fragmented using the Lund model.
- Minimum bias cross-sections are calculated using a pomeron and reggeon exchange model.
  - MPI are rescaled to match pomeron & reggeon predictions.

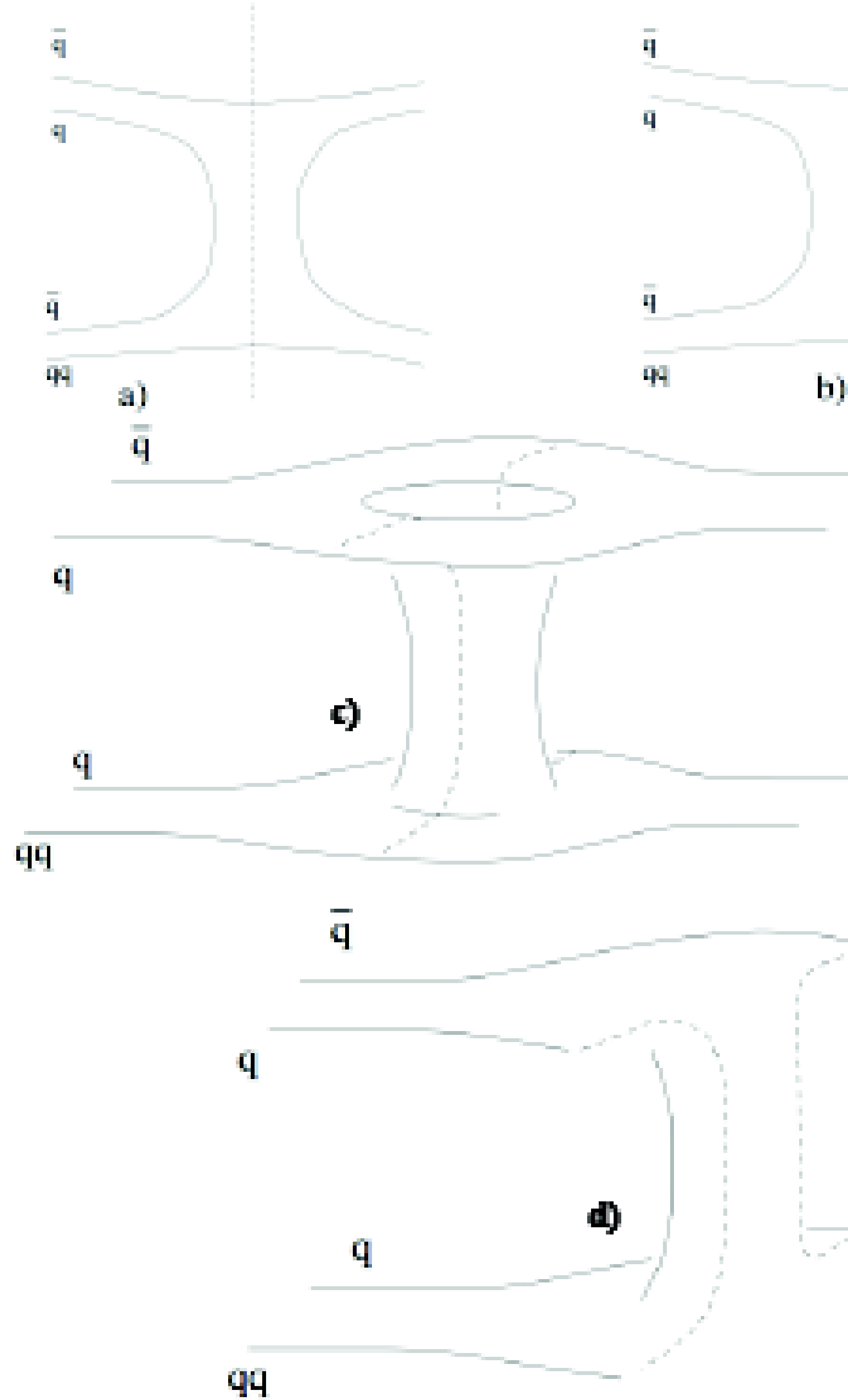


Herwig (Jimmy) model

- Multiple interactions, including the primary Hard Scatter are introduced by Jimmy.
  - Assumes a Poisson distribution of parton interactions.
  - The hard scatters are identified as a subset of the general parton interactions.
- HS incoming partons high Pt are back-evolved to lower Pt by including:
  - Initial State Radiation (ISR) using Sudakov method weighted by PDFs.
  - Angular ordering is applied between the proton on the radiated partons.
- Final State Radiation (FSR) from the hard scatter is forward evolved by a parton shower.
  - Primary ordering is by angle. This limits the solid angle that is populated by the shower.
- The final collection of partons is made by splitting gluons to consist only of quarks (or diquarks), which are paired to form color-singlet clusters. These are then fragmented to on-shell hadrons.
- Minimum Bias events are generated using a negative binomial distribution for the particles in the event.

PhoJet 1.12 model (roughly)

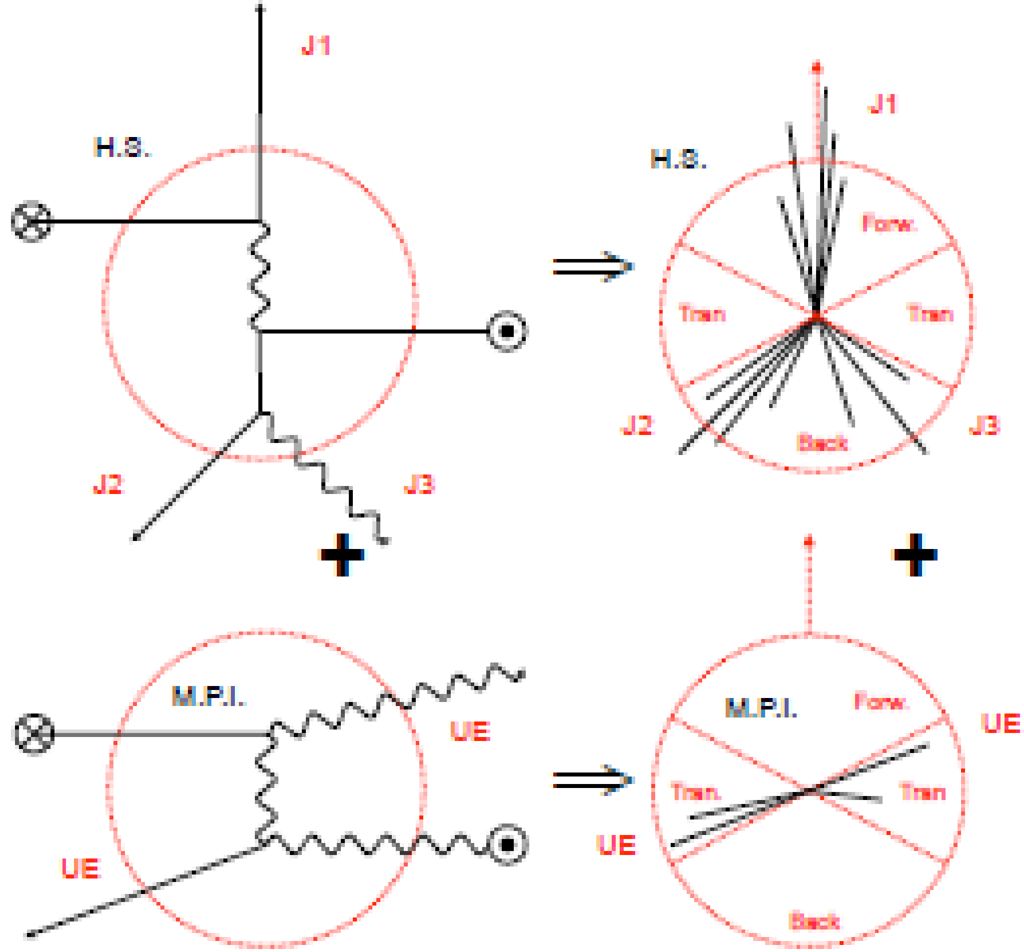
- Cut Reggeon & Pomeron exchanges are calculated.
  - Elastic scattering occurs via Pomeron exchange (c), and in resonances by Reggeon exchange (a).
  - Inelastic scattering includes string pairs from cut Pomerons (d) and from cut Reggeons (b) that account for MPI.
- The hard scatter (2→2) matrix element is calculated.
  - Parton exchange, rather than Reggeon or Pomeron.
- The ISR & FSR for partons from the hard scatter is calculated.
- The FSR partons and proton remnants are assigned to strings. These strings and the strings from cuts are then fragmented using the Lund model.

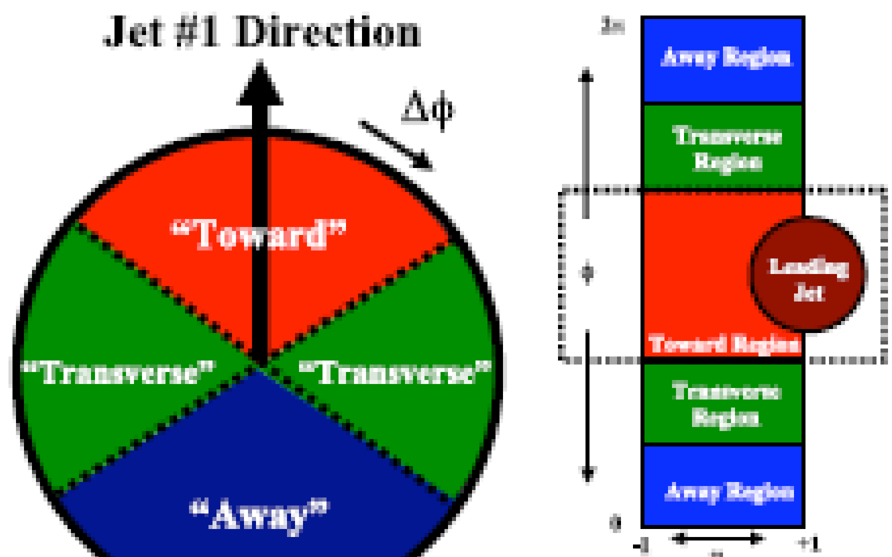


Figures from PhoJet Manual

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.
- $\pi/3 < |\Delta\phi| < 2\pi/3$ and $|\eta| < 1$ defines the transverse region.
- For the third hardest jet to be in the transverse region it must be softened.

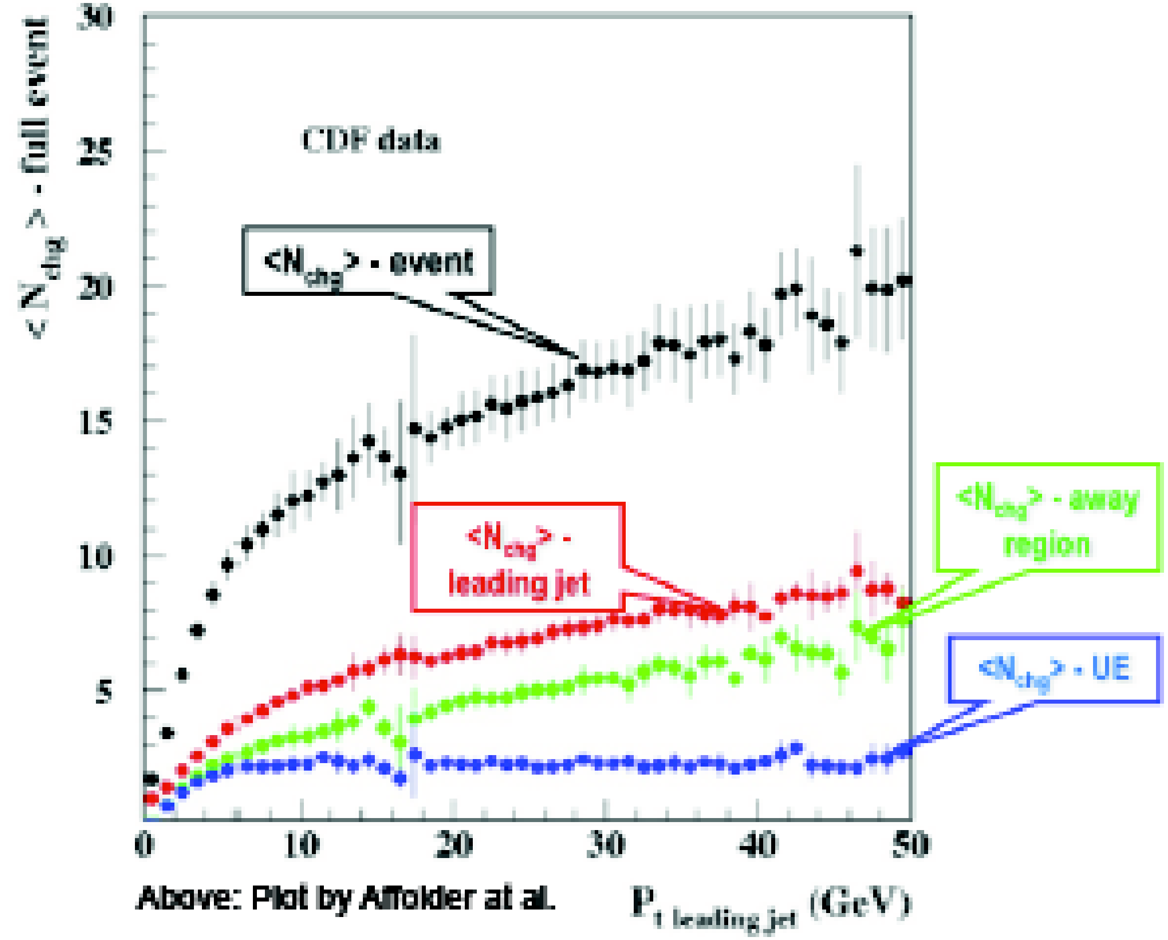




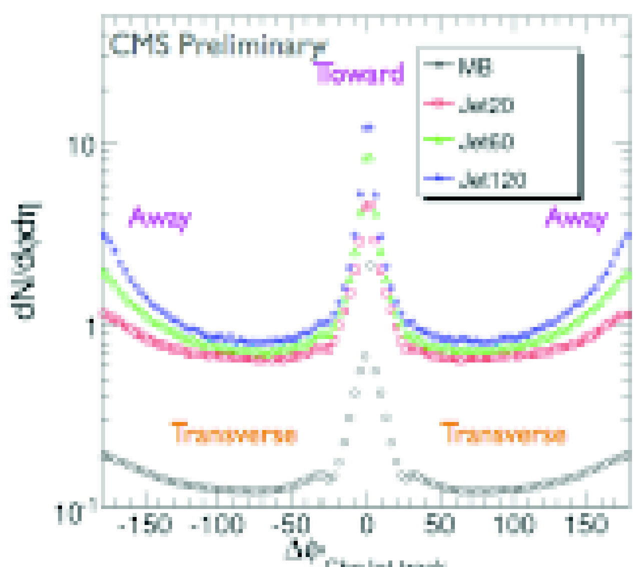
Images from R. Field.

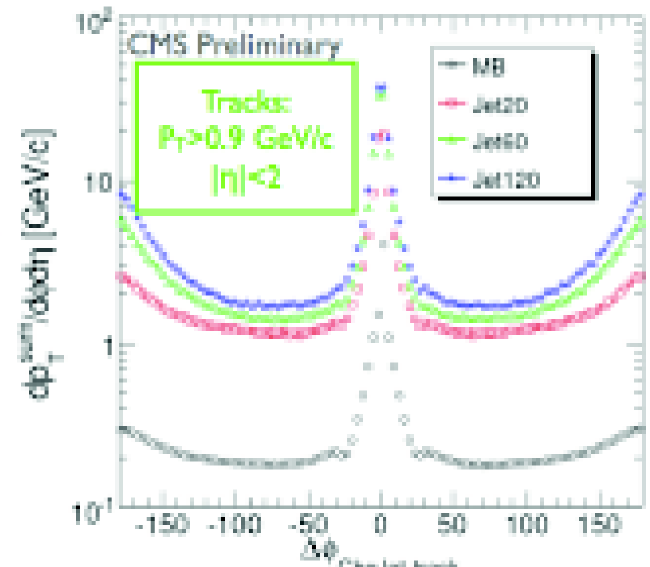
UE Characterization

- 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.



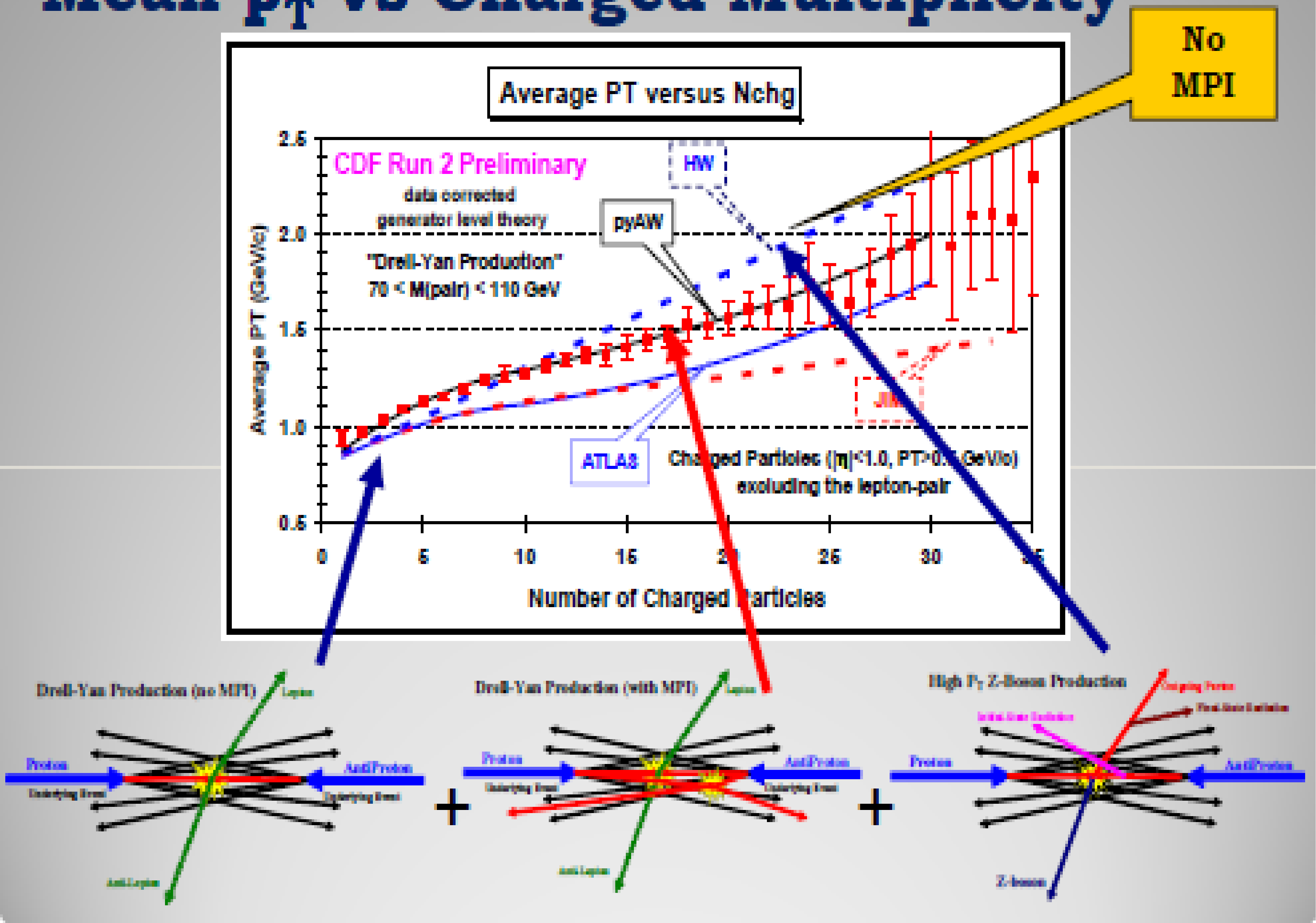
Above: Plot by Affolder at al.



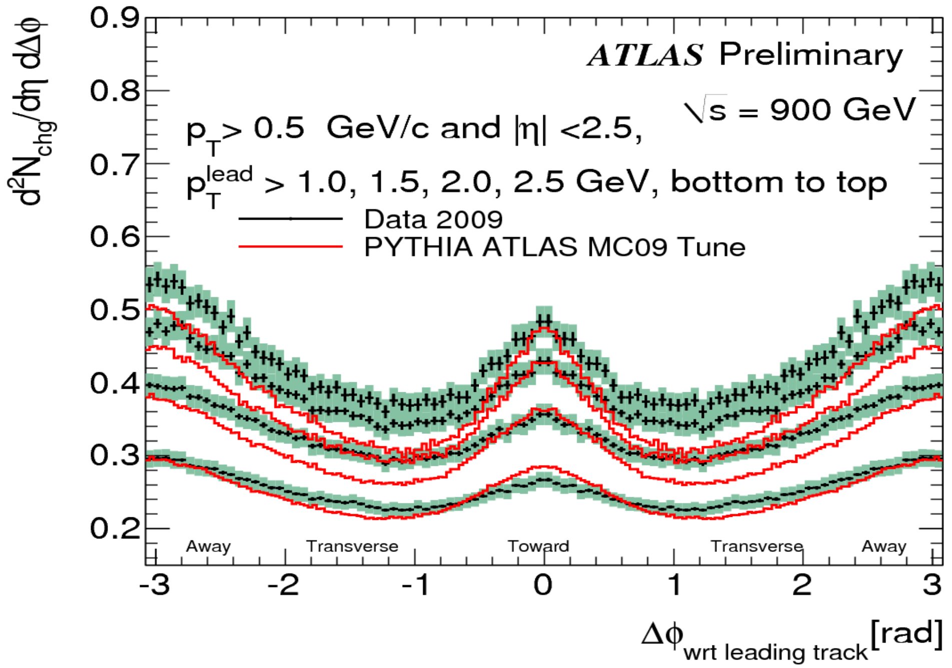


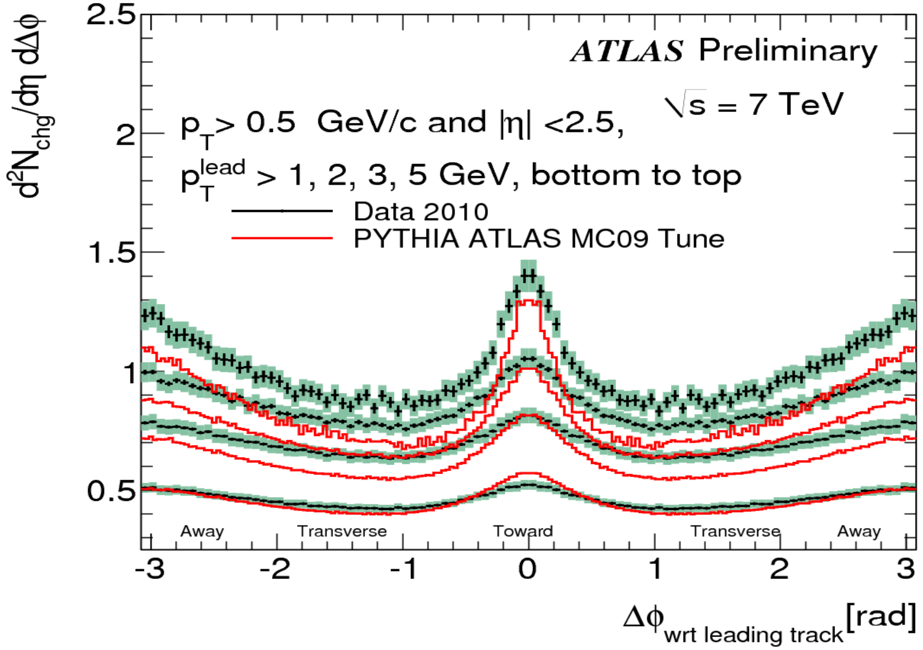
Above: Plots from F. Ambroglini

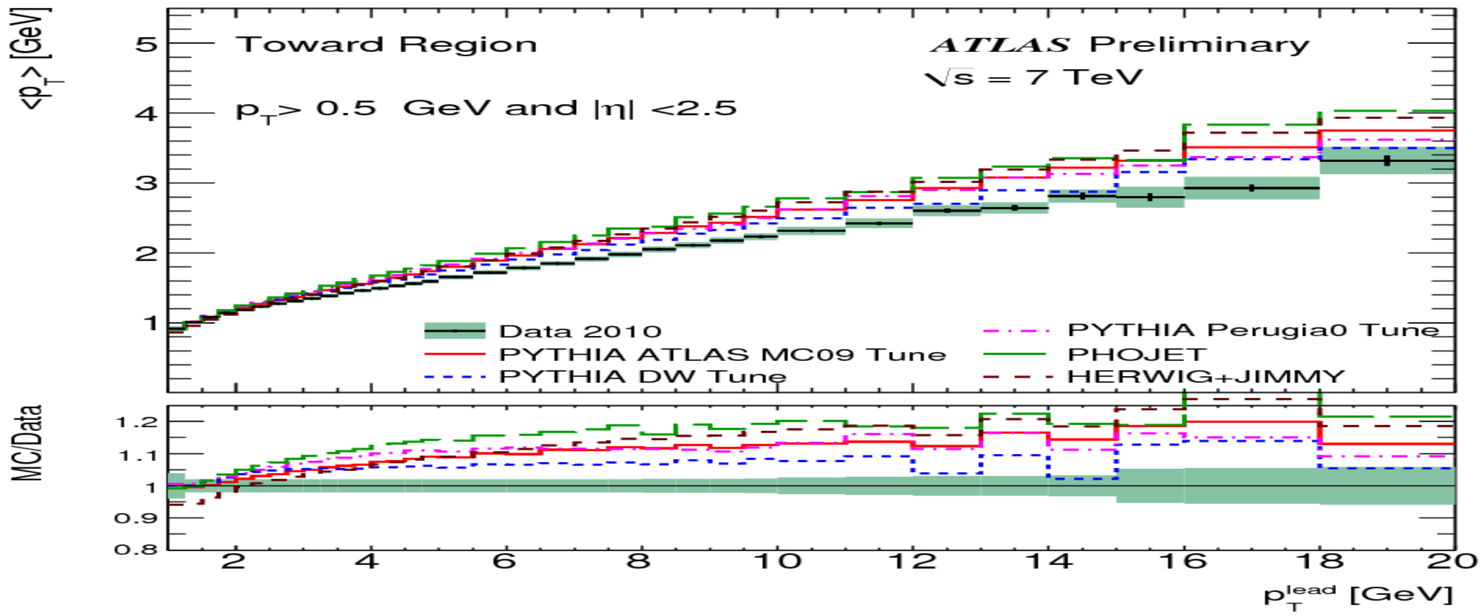
Mean p_T vs Charged Multiplicity



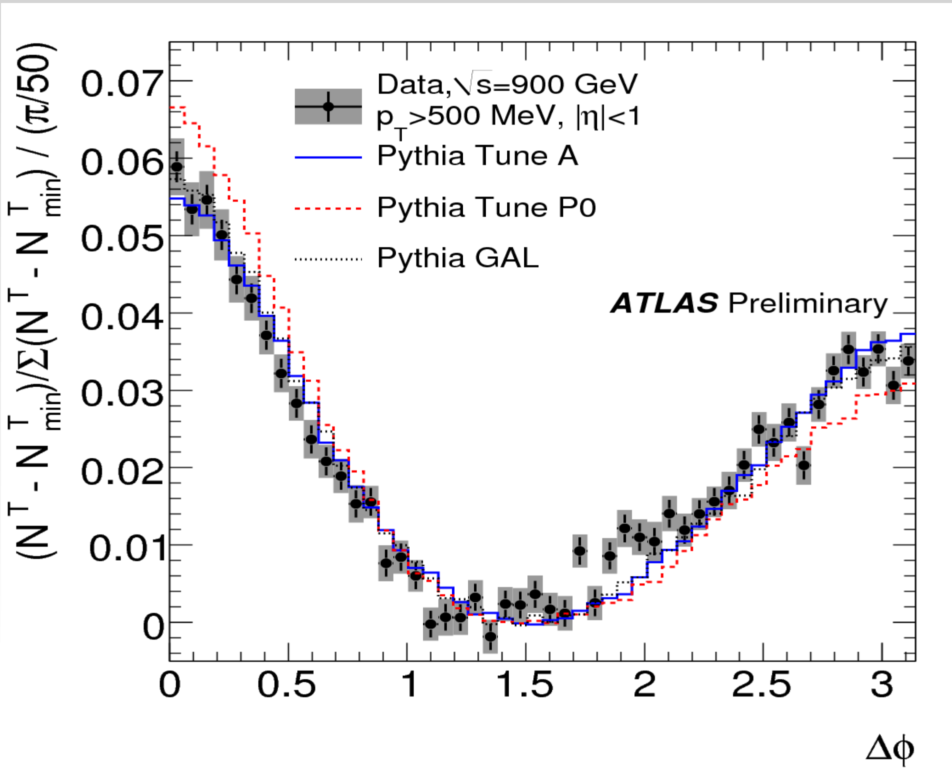
Atlas results at 0.9 and 7 TeV

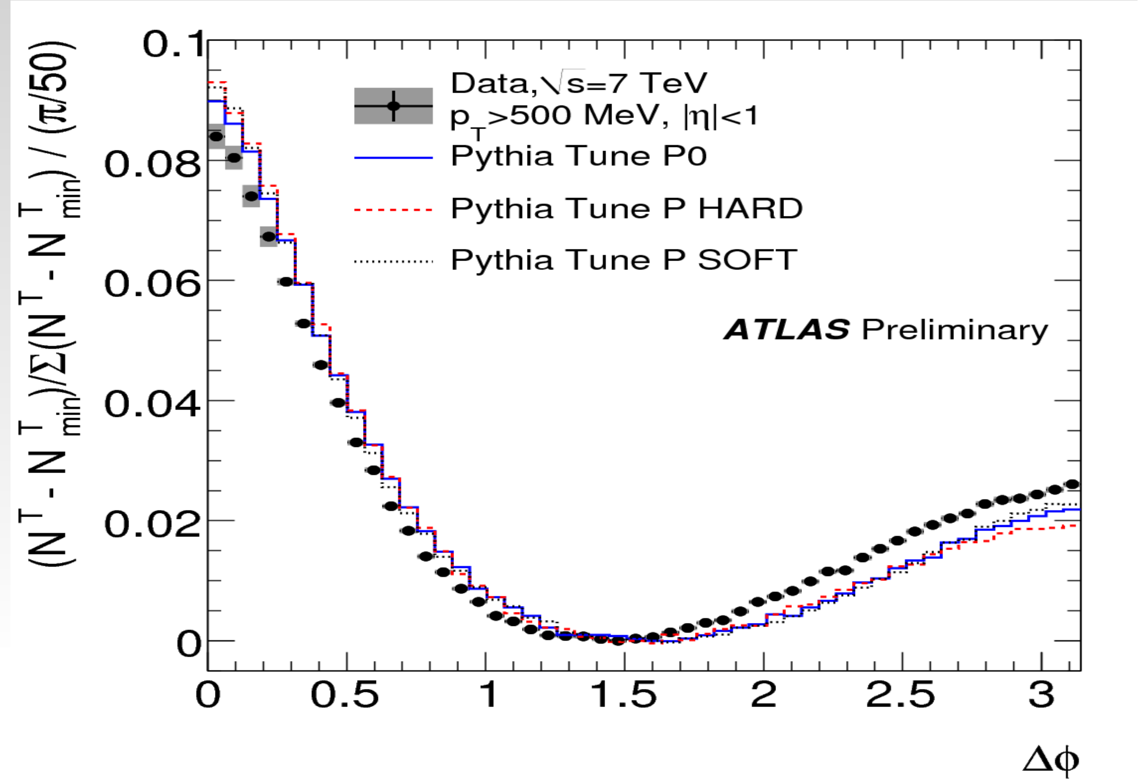






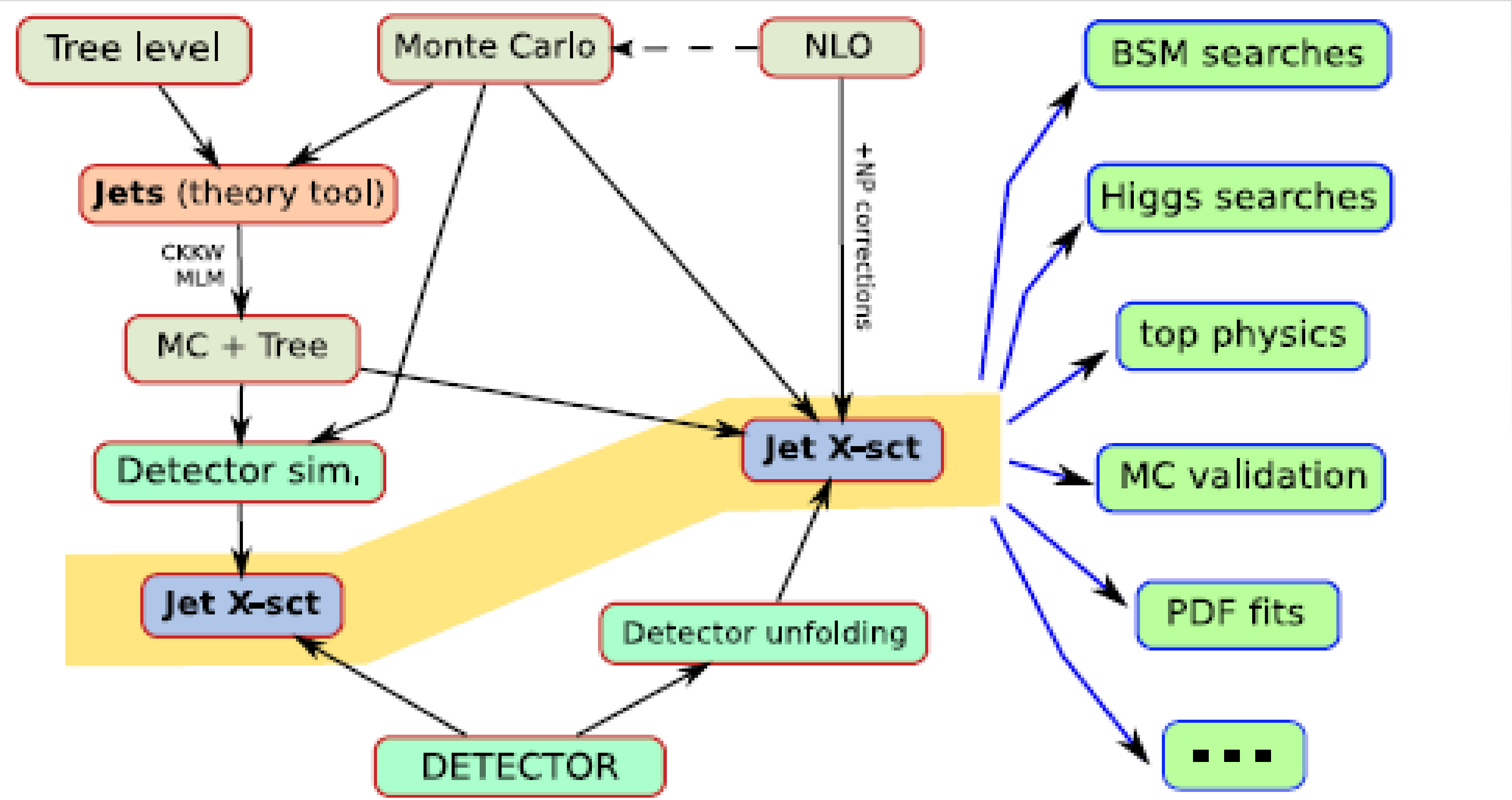
Angular correlations between tracks





- Tune A is a representative of the family of tunes that use virtuality-ordered showers. Perugia0 is a representative of the family of tunes that use p_T-ordered showers GAL is a tune using the Generalized Area Law of color reconnections and is a representative of the family of tunes that use different color reconnection models.
- Perugia 0, Perugia HARD and Perugia SOFT, are all pT-ordered. Tune P0 is a well-balanced tune that has near-perfect agreement with the Drell-Yan pT spectrum. Tune P HARD has a larger contribution to particle activity from perturbative, hard components relative to P0, while P SOFT has lower perturbative contribution.

QCD and Jets



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

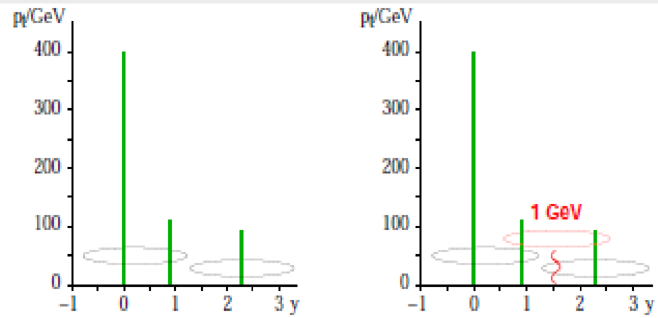
And jets are an input to almost all analyses

Two types of jet finders

- Cone algorithms:
  - start with a high-Pt deposition, then take everything with distance smaller than a given radius in (η,ϕ) 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

Issues with cones

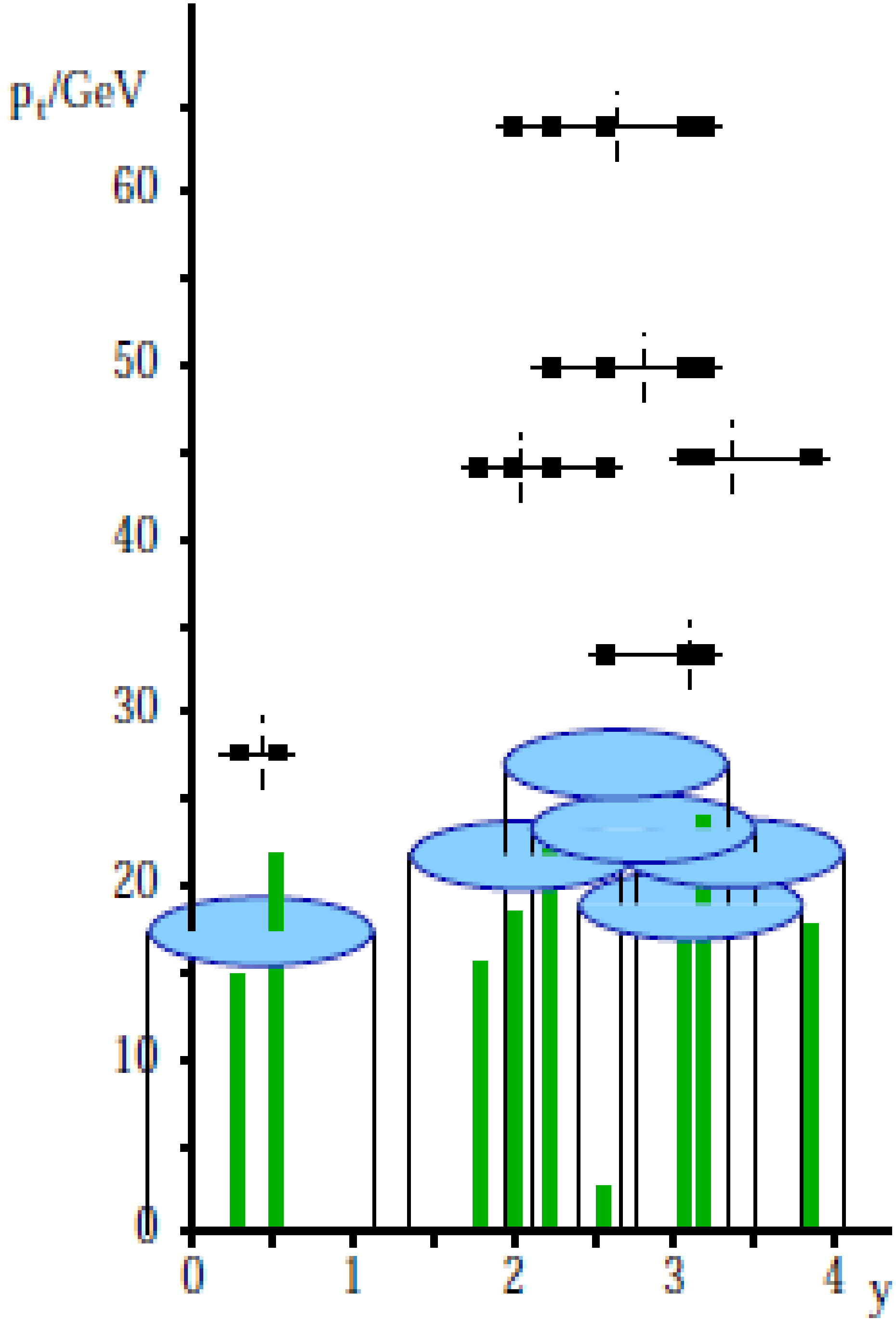
- Cone algorithms are apparently simple to understand and fast; but what happens if two cones overlap? Does the result depend on the choice of seed? (it shouldn't)



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			Known at
	JetClu, ATLAS cone [IC-SM]	MidPoint [IC$_{mp}$-SM]	CMS it. cone [IC-PR]	
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

SISCone



Aim to identify *all* stable cones, independently of any seeds

Procedure in 1 dimension (y):

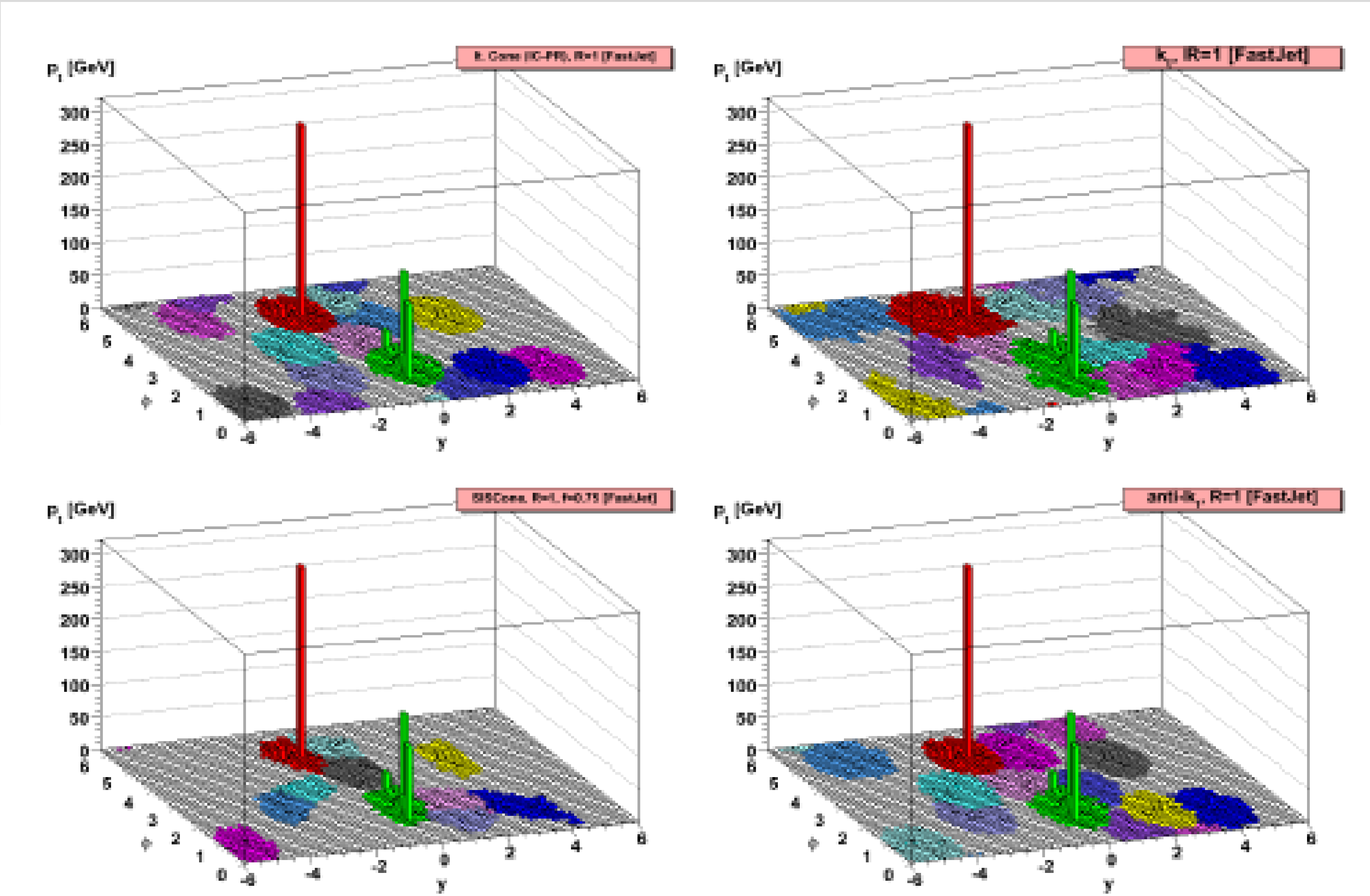
- find all distinct enclosures of radius R by repeatedly sliding a cone sideways until edge touches a particle
- check each for stability
- then run usual split–merge

In 2 dimensions (y,ϕ) can design analogous procedure SISCone

GPS & Soyez '07

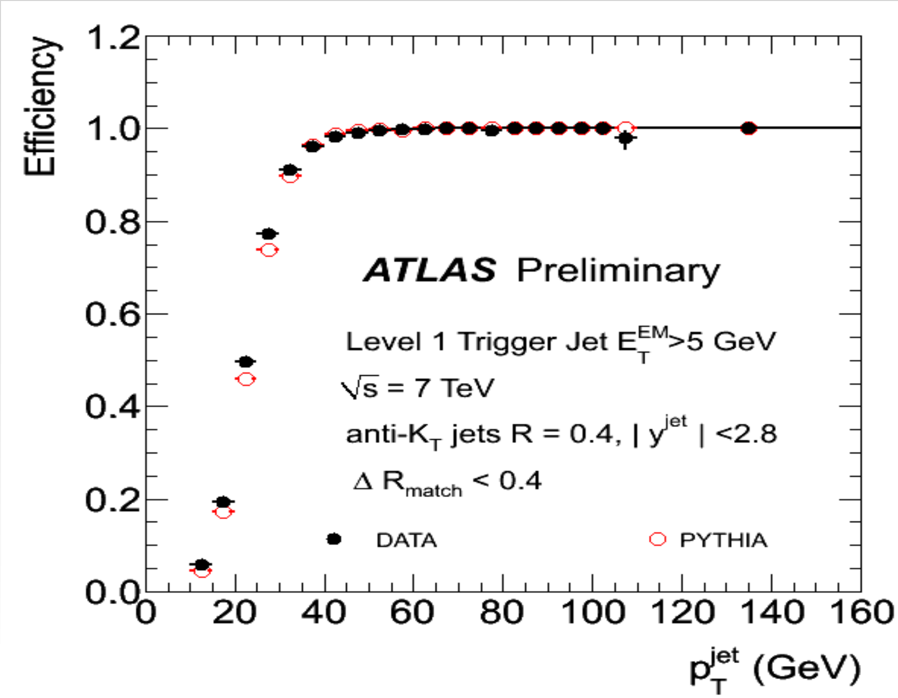
This gives an IRC safe cone alg.

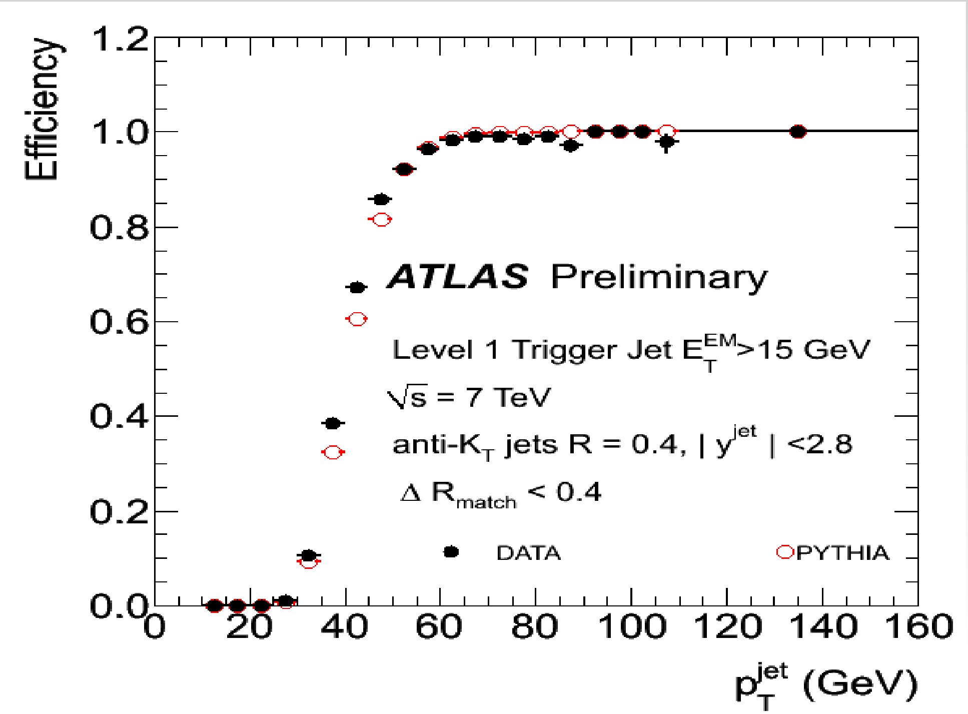
But the most conical cone is not a cone!



Anti-kt now default algorithm in Atlas

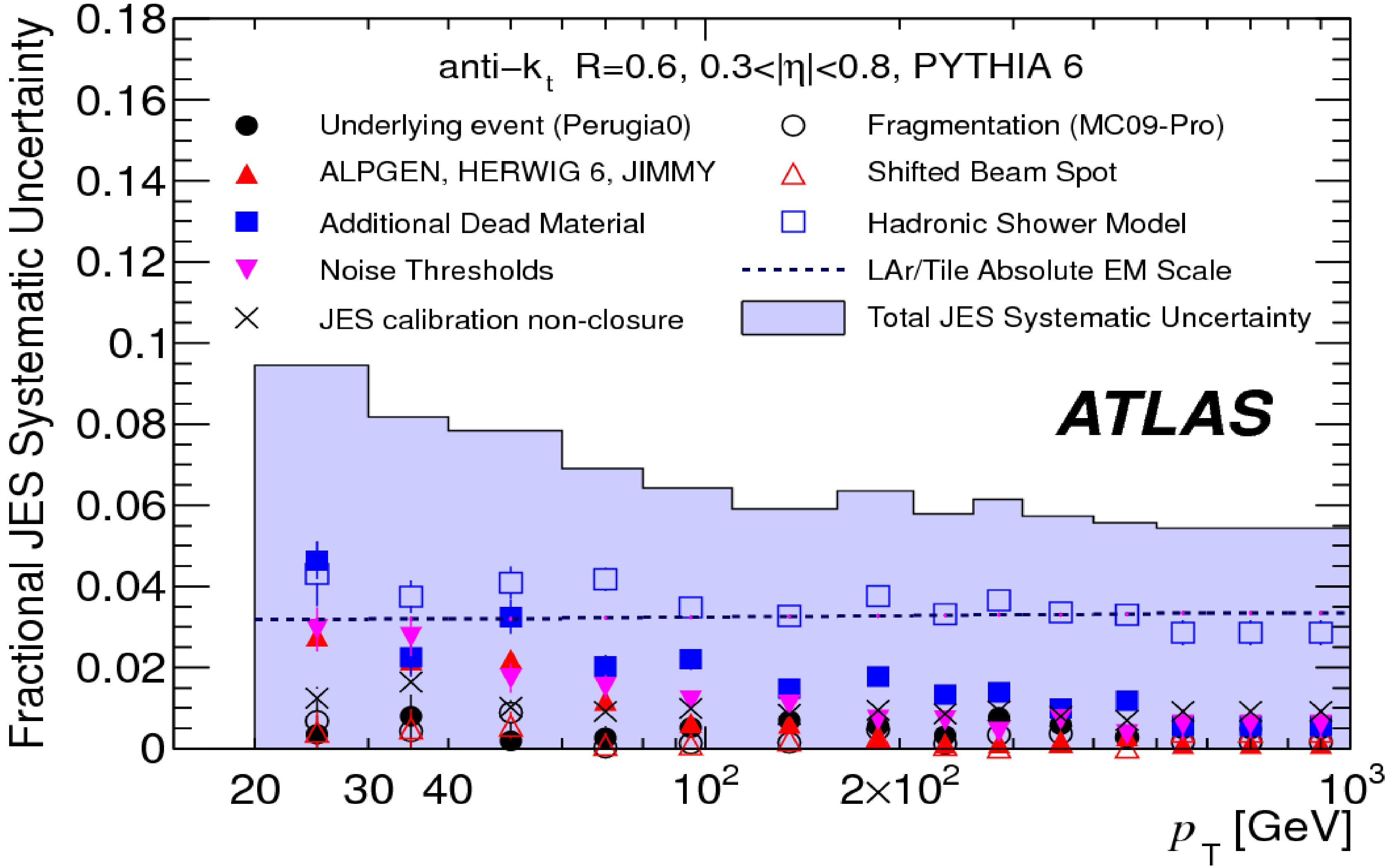
Measuring jet production: trigger





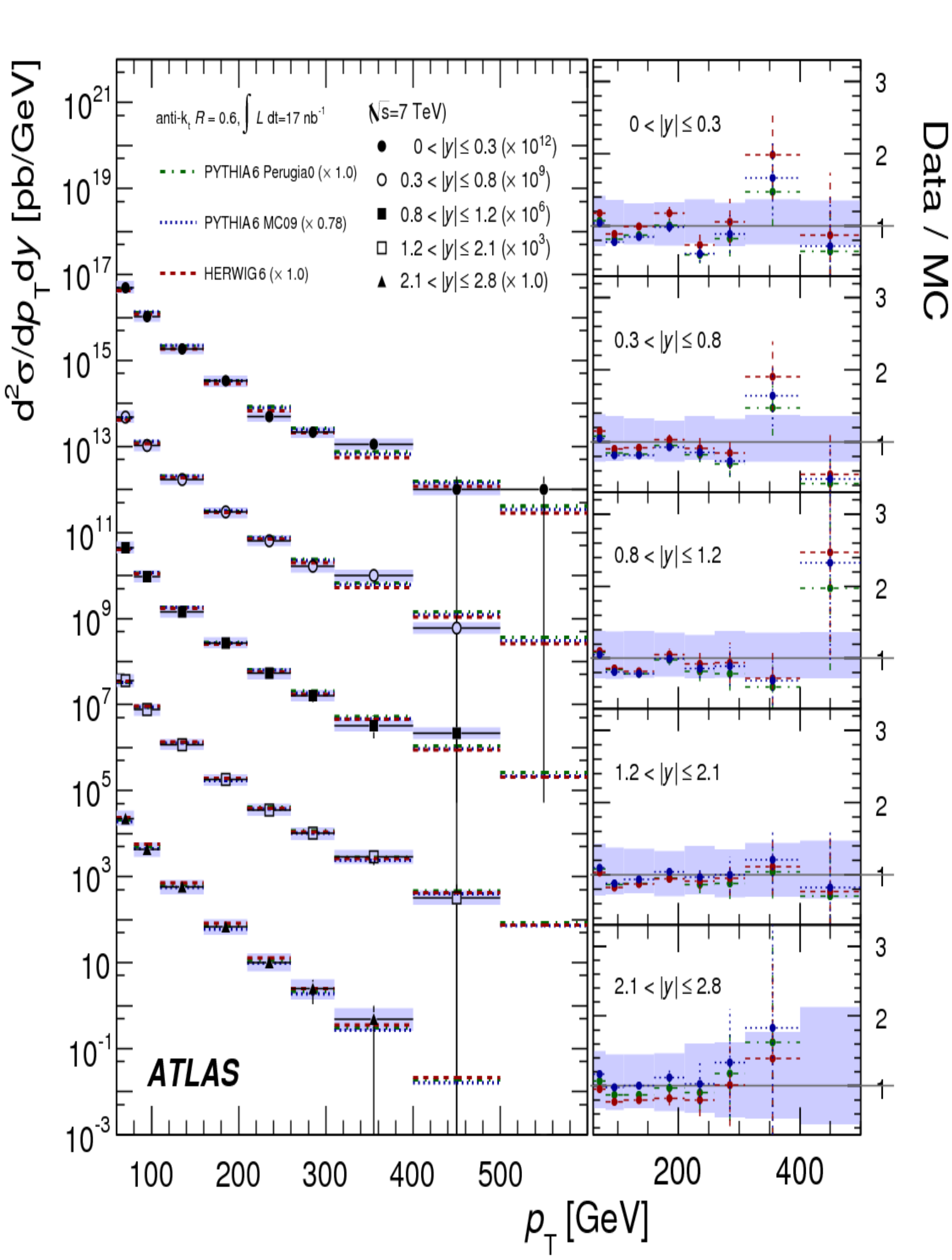
- Not to correct for the efficiency in the steeply rising part of the curve, jet cross section was first measured above the 100% efficiency point
- This results in the measurement being performed in different Pt bins in the various periods, because higher luminosities forced heavy prescales on lowest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

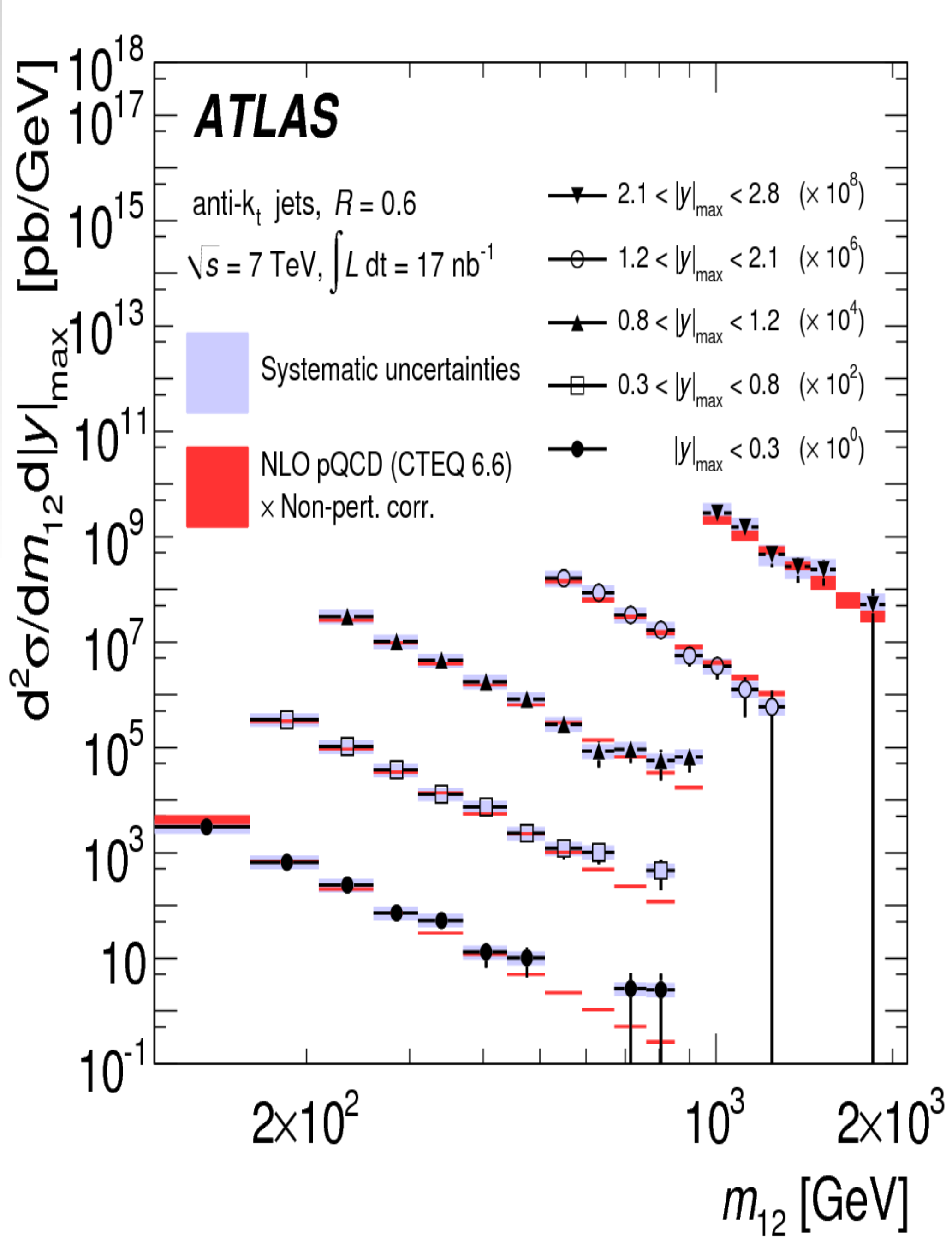
Jet Energy scale



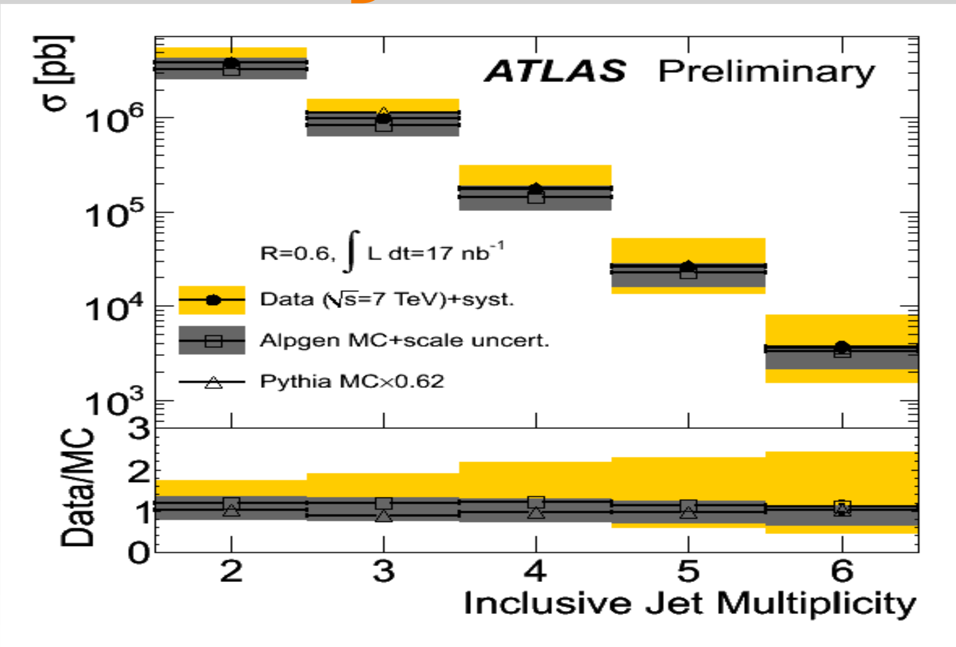
- Jets measured at EM scale (summing Ecal and Hcal contributions), scaled by factors derived from MC and cross-checked with track jets

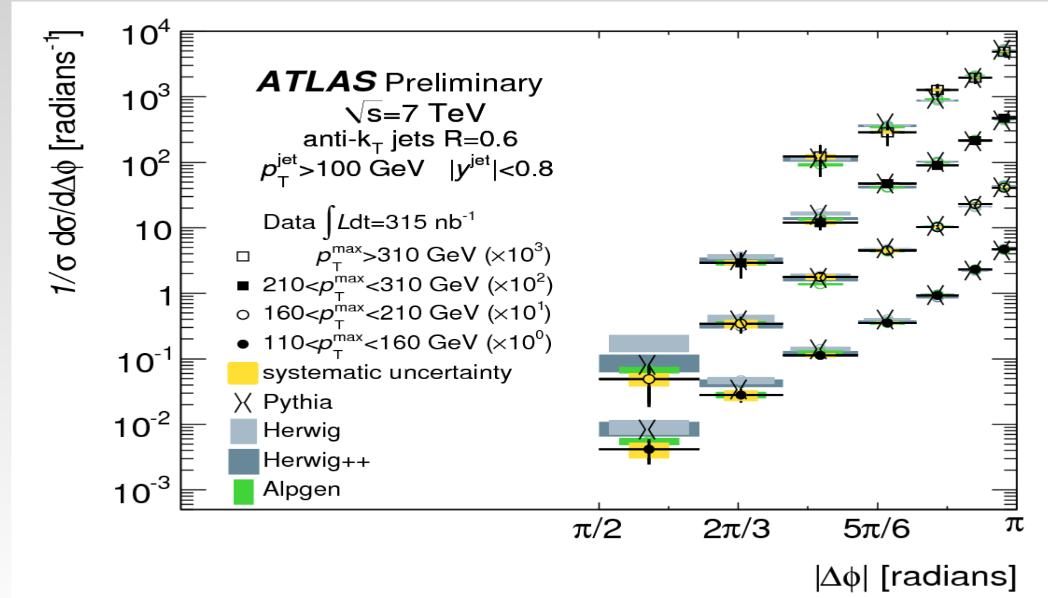
Jet and dijet cross-sections

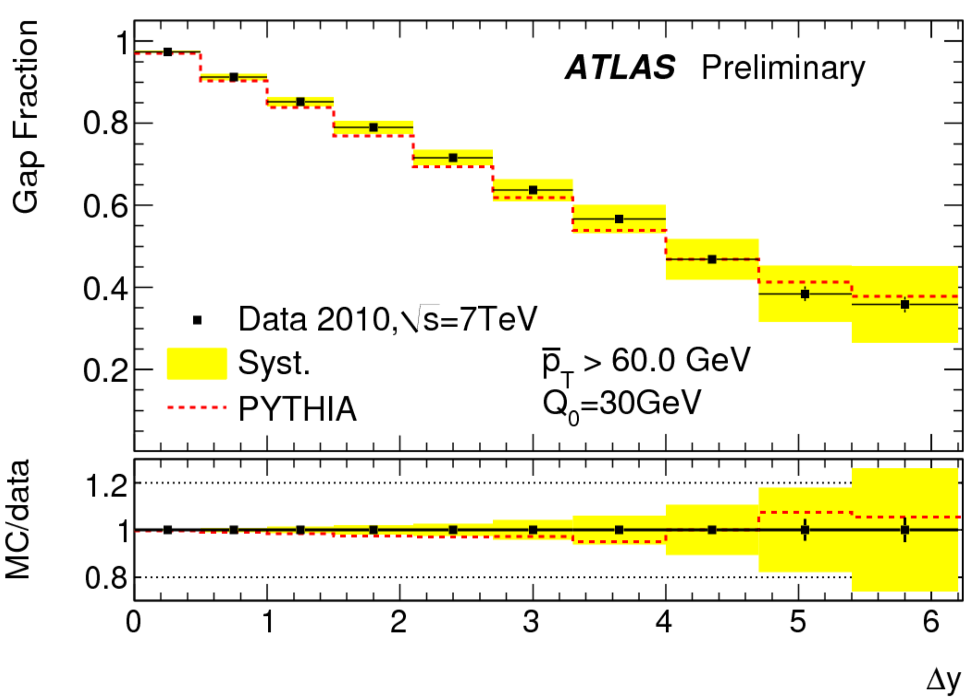




Multijet, de-correlation, gaps





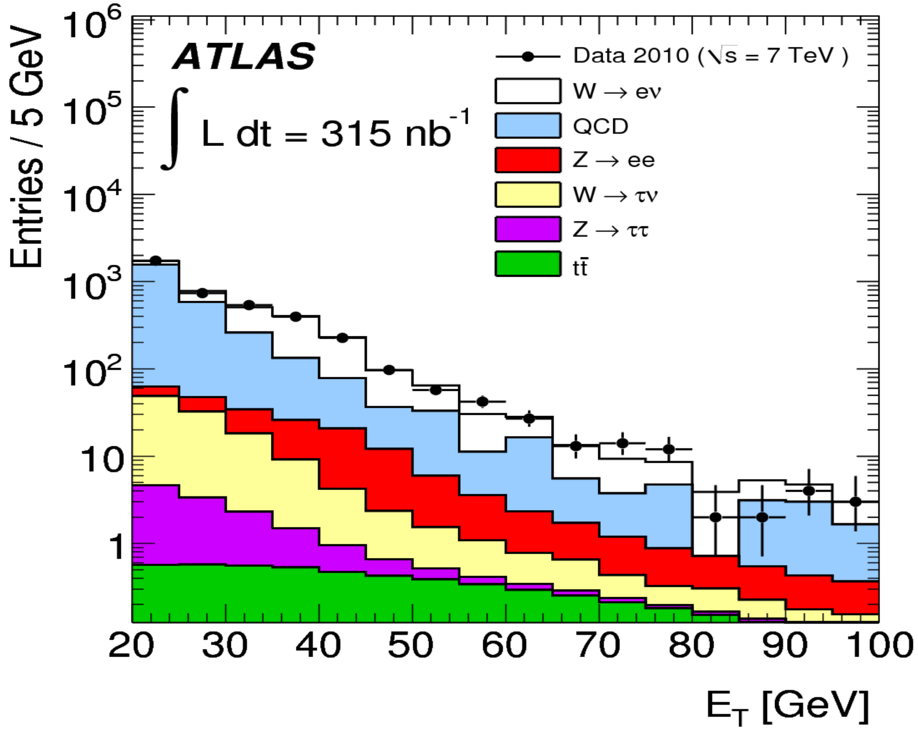


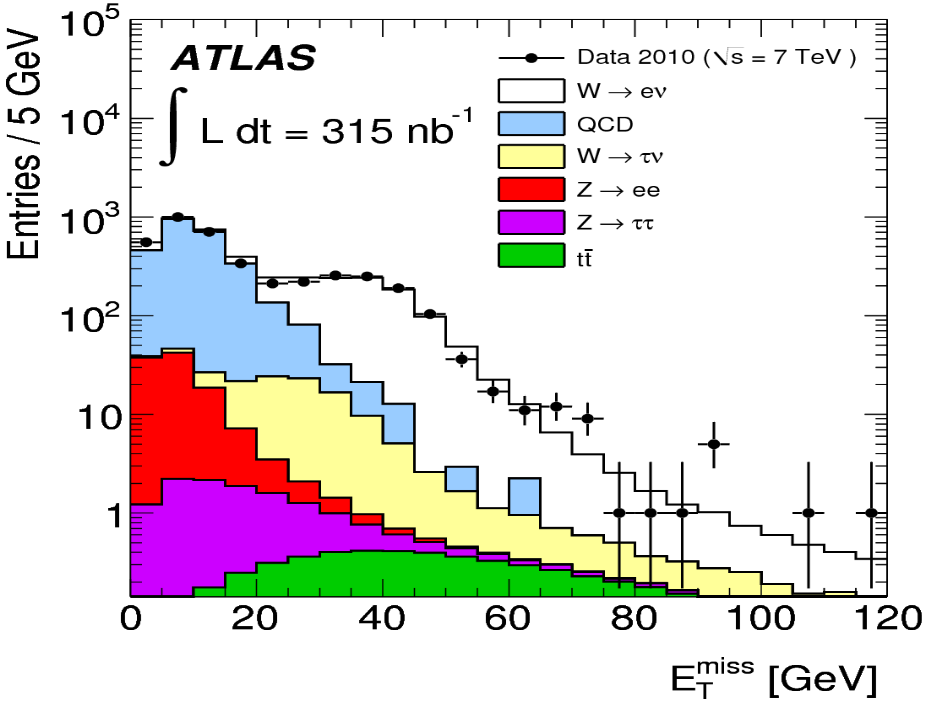
Several QCD tests performed on jets, looking at multiplicity, angular distribution, radiation between dijets

Vector boson production

- 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??)

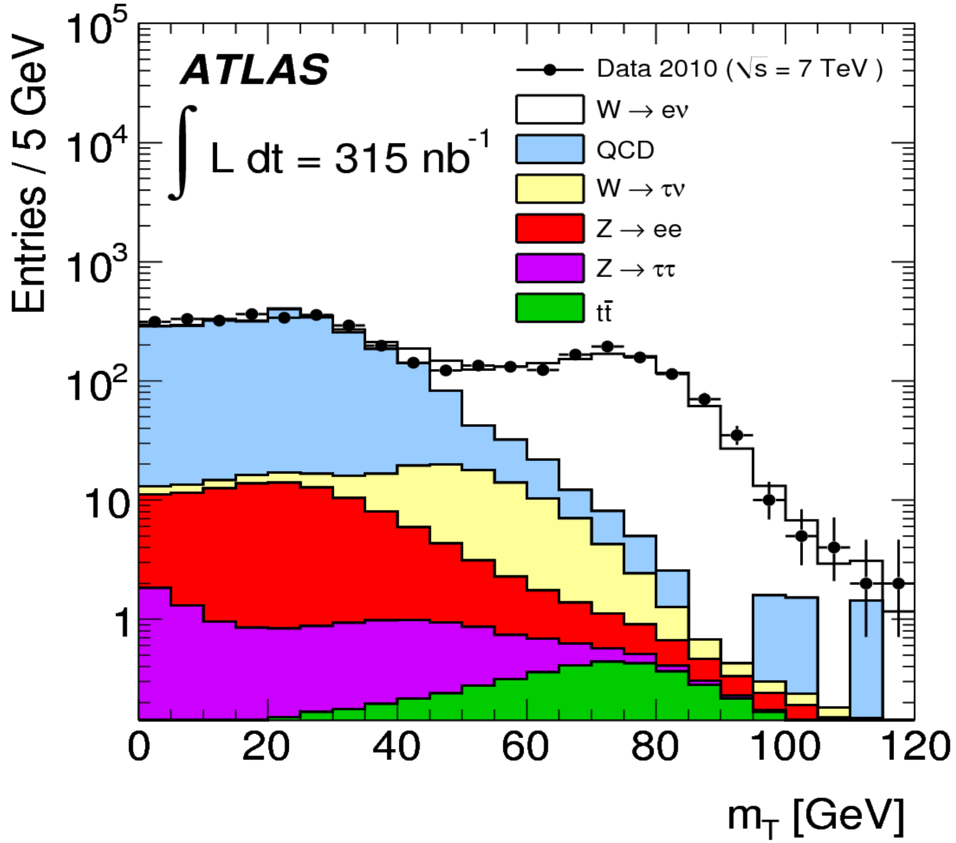
Ingradients of the analysis

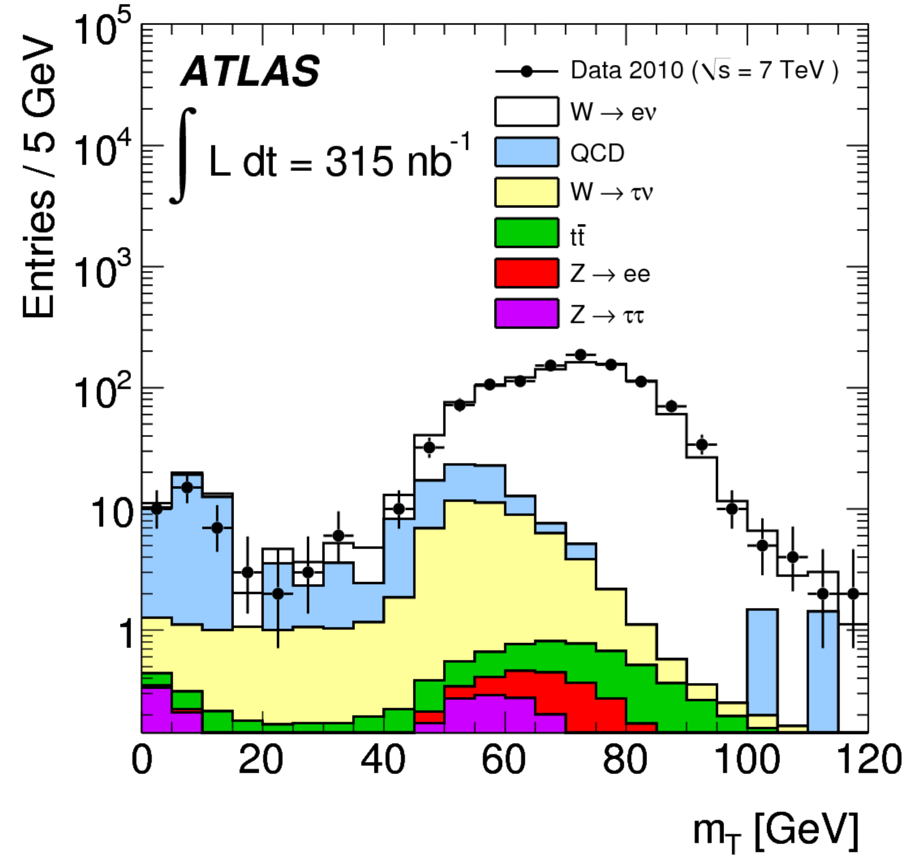




- Electron Pt MET
- for W->enu events
- Signal purity quite low for individual variables

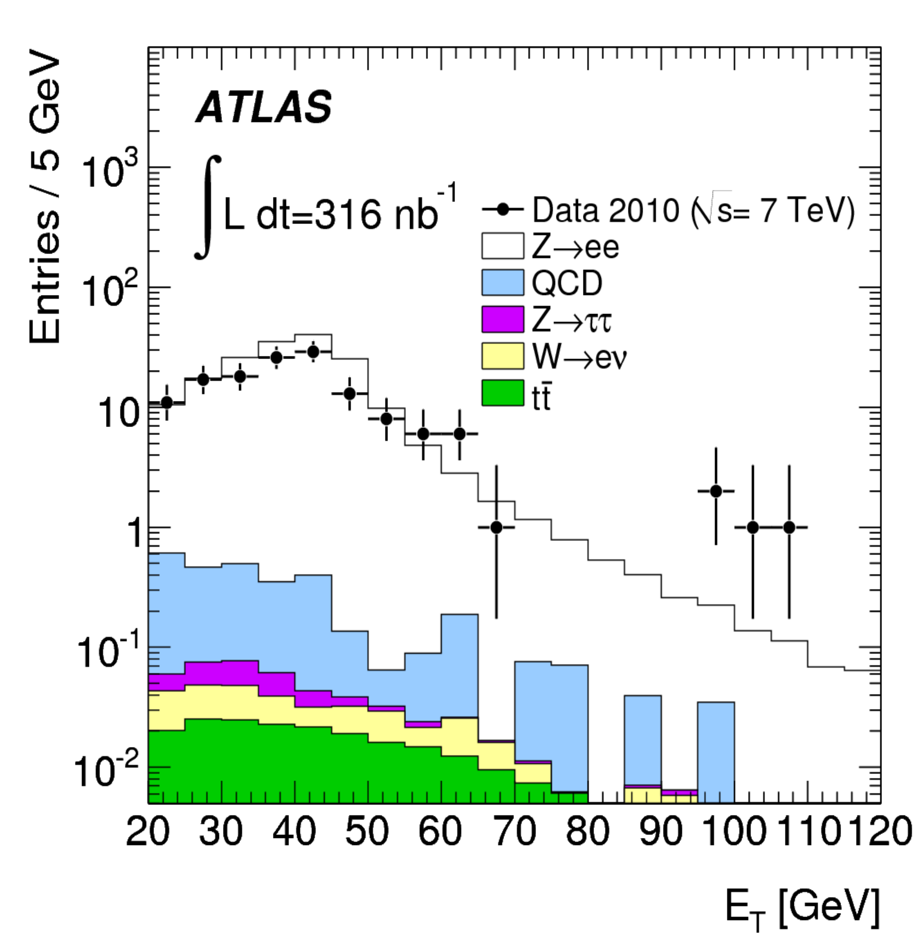
W->e nu transverse mass

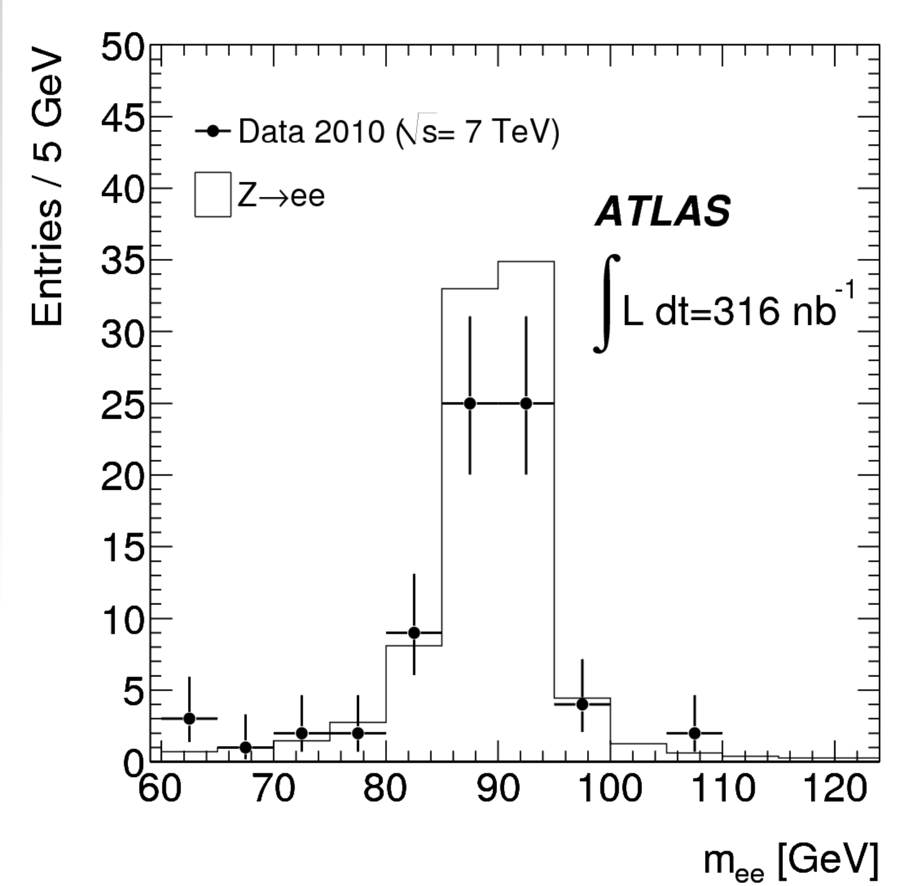




- Despite the transverse mass distribution being very broad, Tevatron experiments provide now a measurement of the W mass more precise than that of LEP, where the full mass could be reconstructed

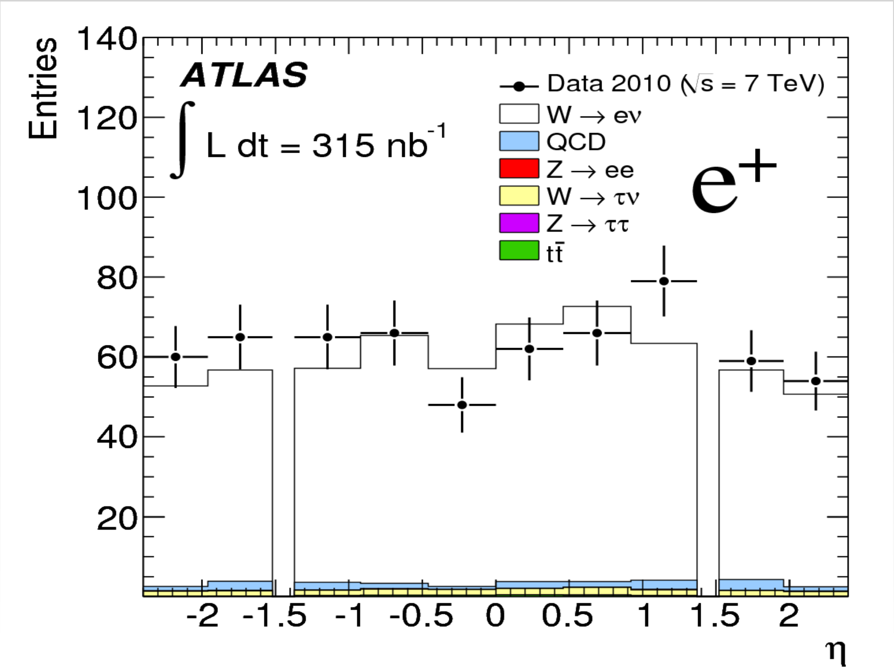
Z->ll analysis

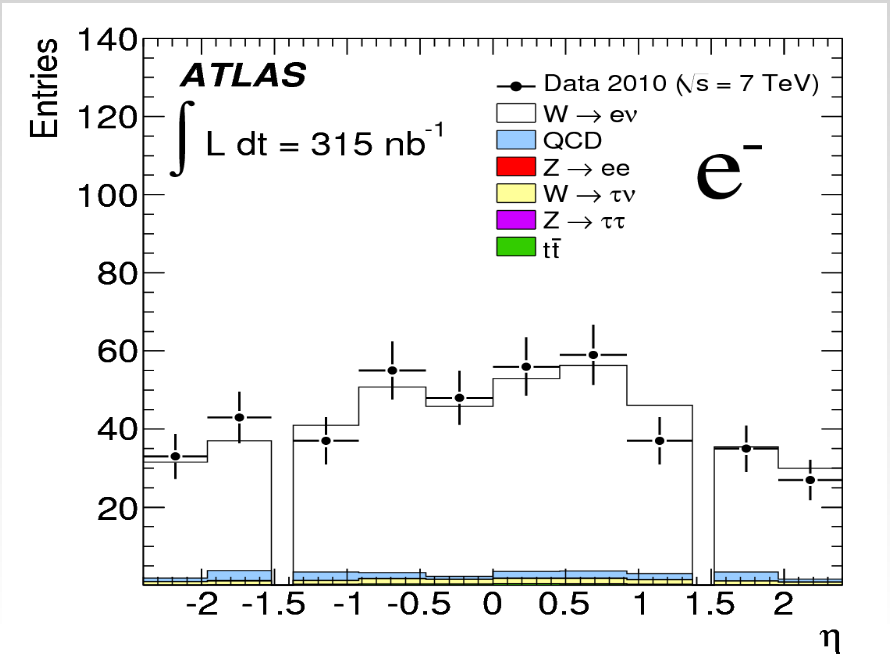


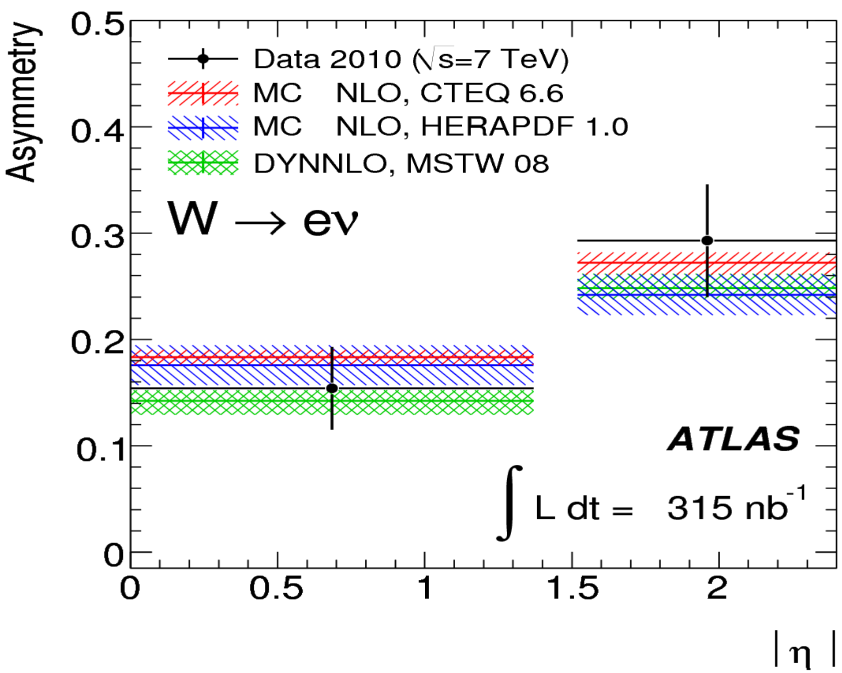


- 2-lepton requirement makes Z channel much cleaner, but statistics is poorer-hard to beat LEP's 4 million Z collected per experiment (and lineshape fit). Fundamental tool for calibration

W charge asymmetry







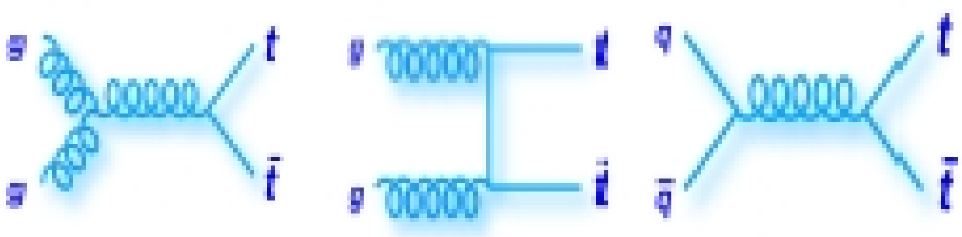
The idea: from Pdf's, u-quarks have higher average x, so W+ tend to be produced more forward. Even in pp, W asymmetry distribution can constraint Pdf's

Top quark production and decay

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

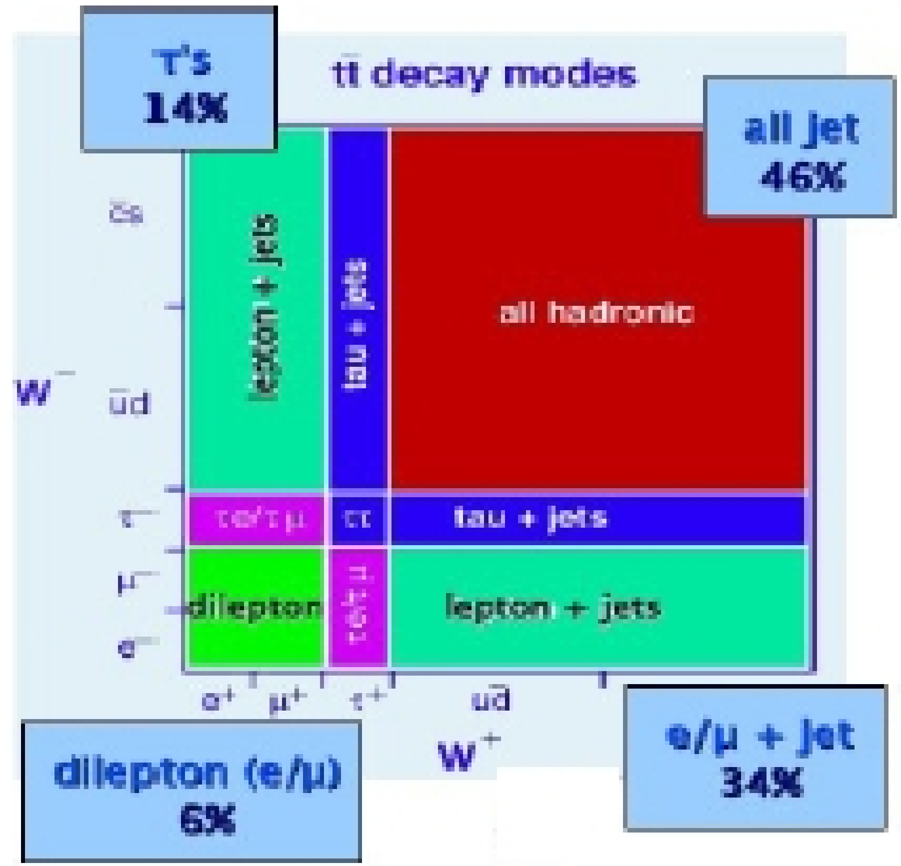
85% 15%

  - σ ≃ 400 pb @ 10 TeV



90% 10%

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



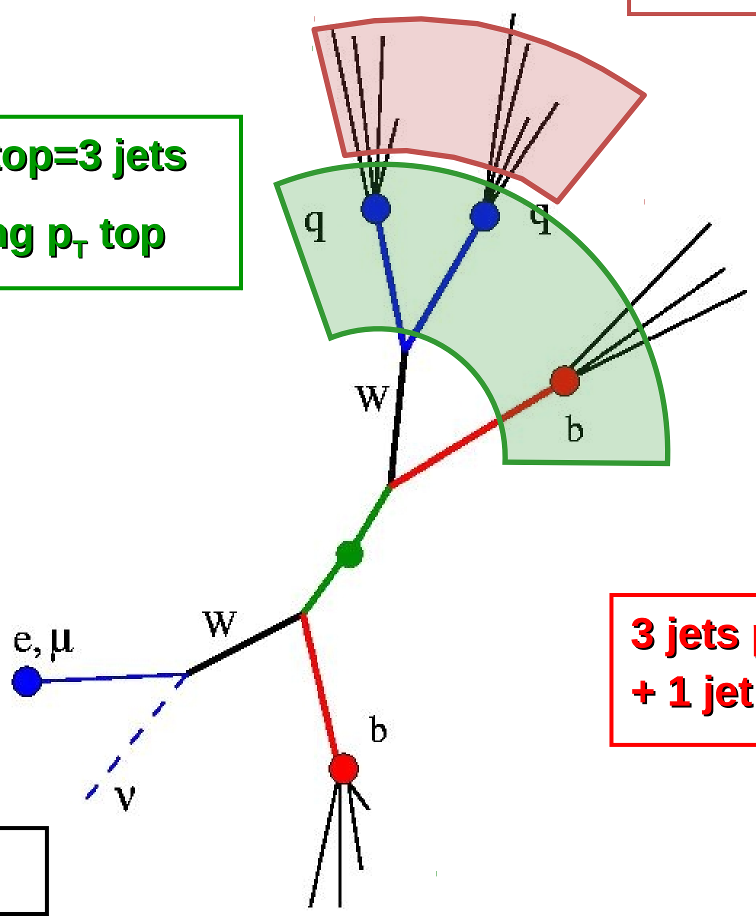
Top quark physics: early measurements

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

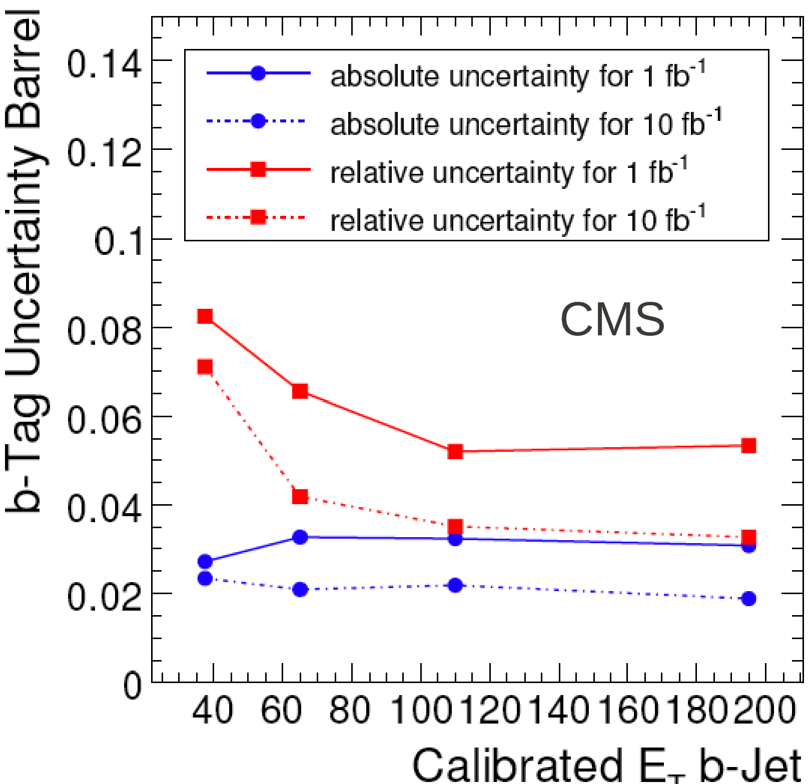
b-tag efficiency

Select b-enriched samples using tt sample

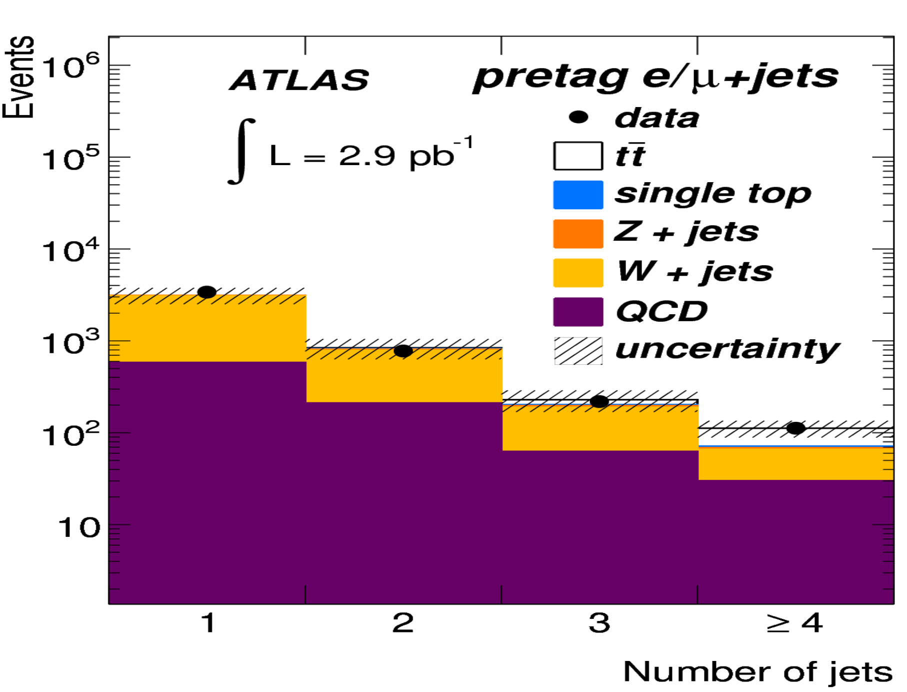
- t → W b ~ 100% → tagging top = tagging b
- Select pure b sample by using tt event topologies
  - 1(2) high p_T leptons, $E_{T,miss}$, m_W & m_t constraints
  - 70-80% b-purity after selection

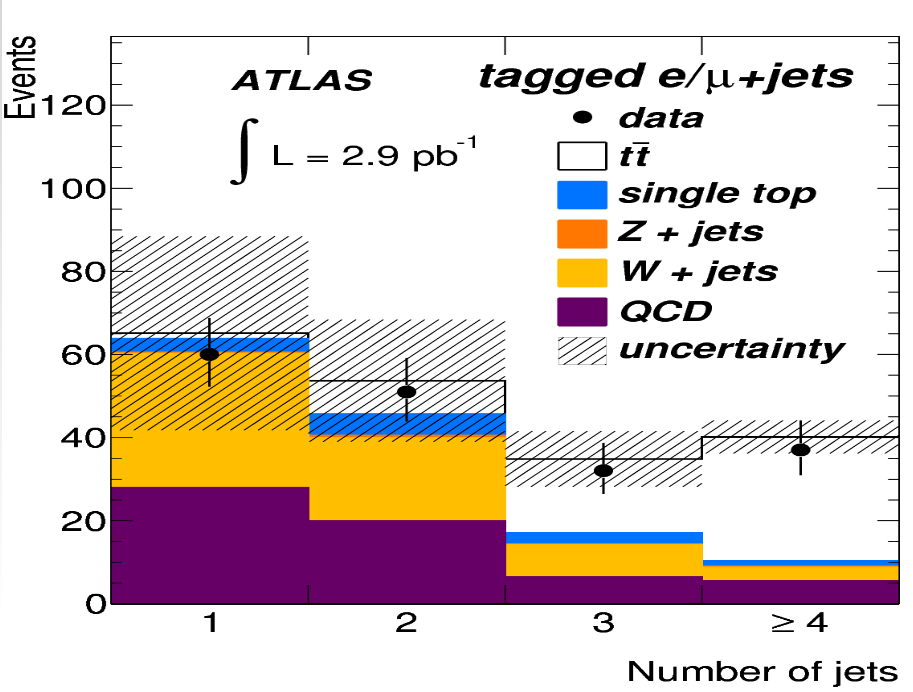
- CMS study 1(10) fb^{-1}
  - Efficiencies 40% to 60% (at $E_{T,b\text{-}Jet}$ > 100) GeV
  - Uncertainty 4-6% for large data samples

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



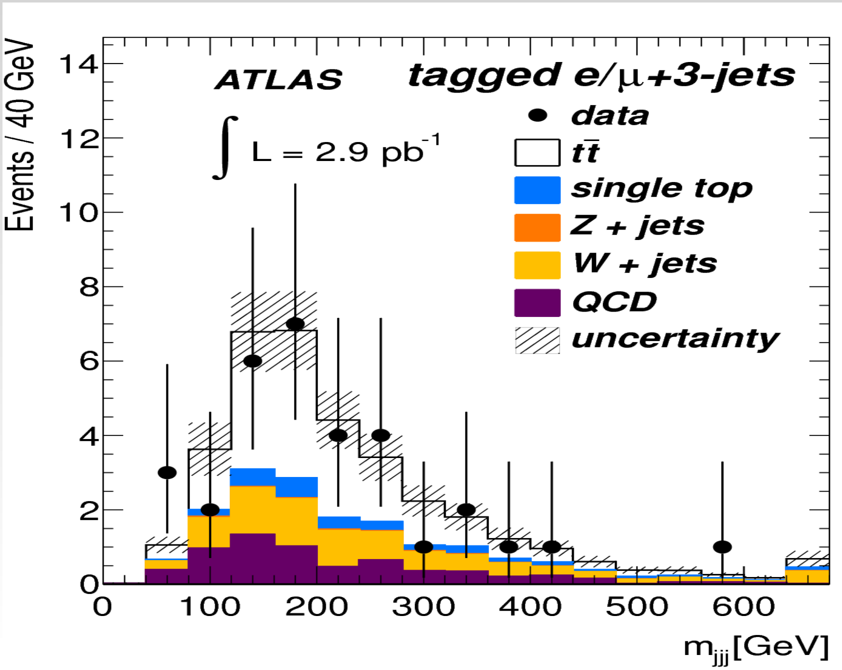
Influence of b-tagging

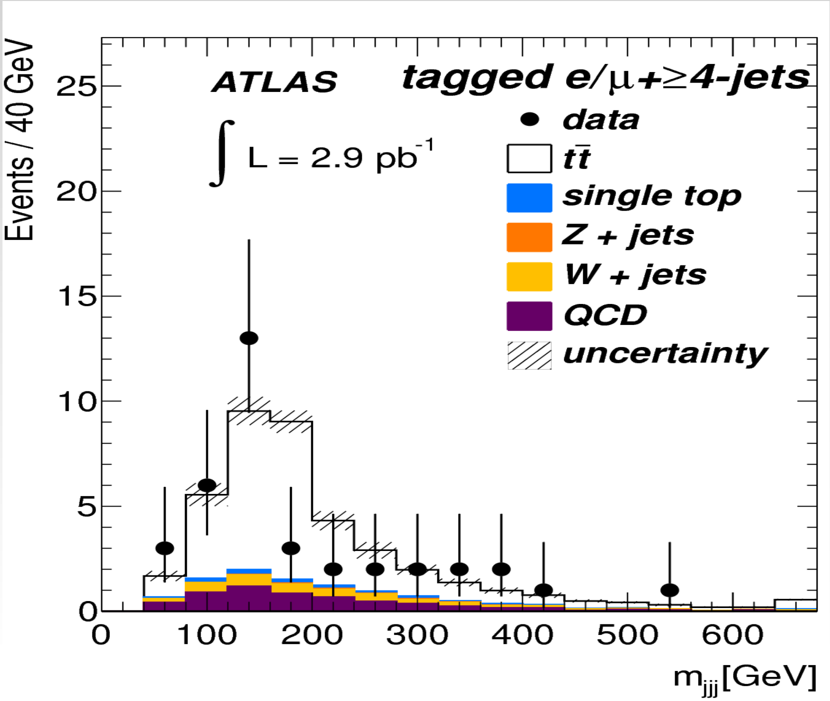


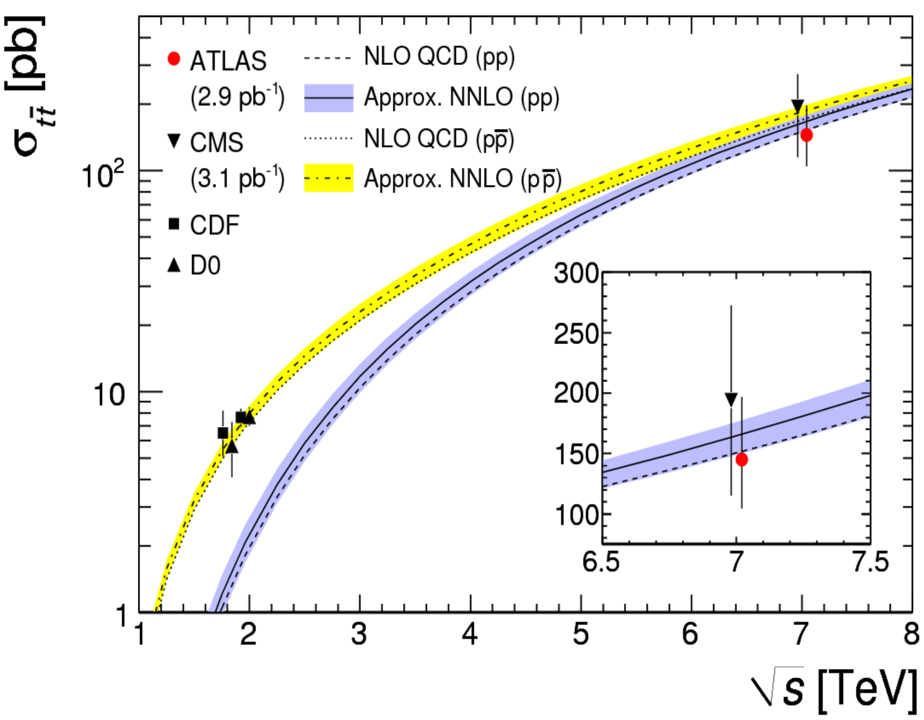


- Top signal (in high-multiplicity bins) hardly visible wrt W + jets background but largely enhanced by requiring two b-jets

Reconstructed top mass



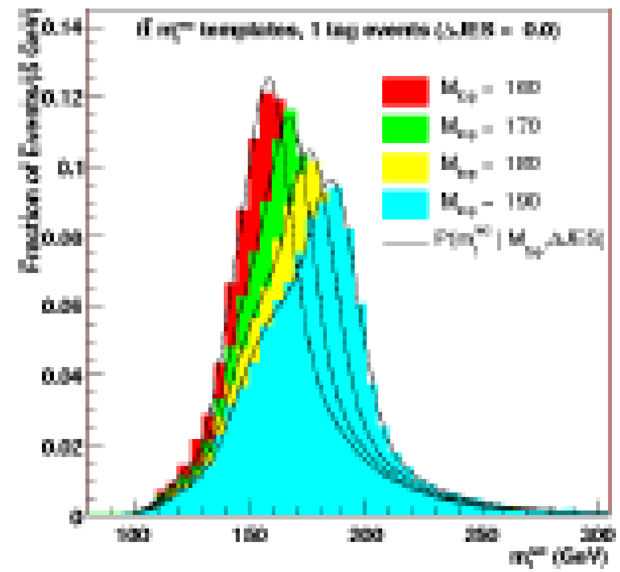


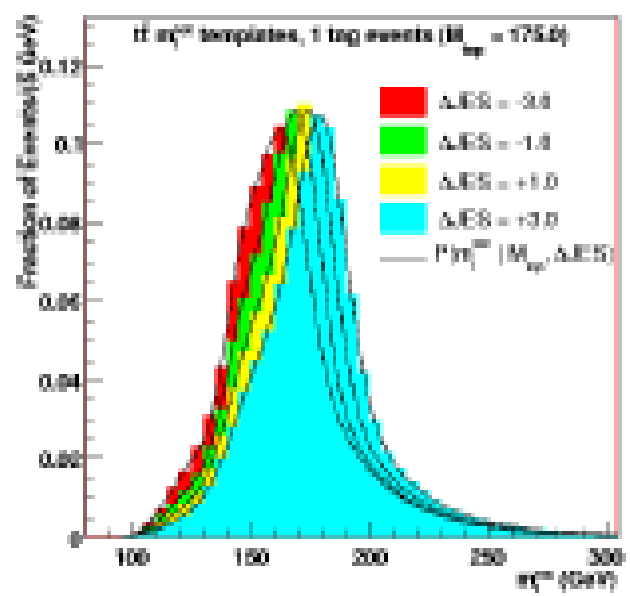


- First measurement of many top production, mass and properties ones

Top mass: template method

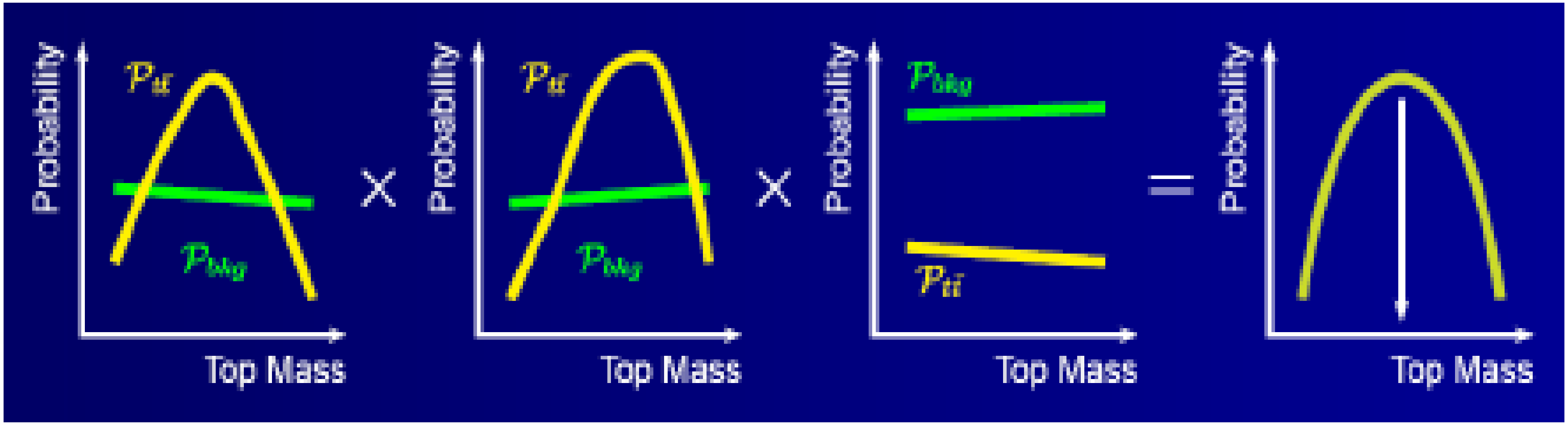
- Choose and calculate per event one or more observables sensitive to true m_t
- Build templates for signal and background distributions in this observable at different m_t (and JES) values
- Determine most likely top mass from templates fit to data





Matrix element method

- 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

Details of ME method

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

Normalization
acceptance
& efficiency

Differential cross section based on LO ME

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

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

First-data expectations

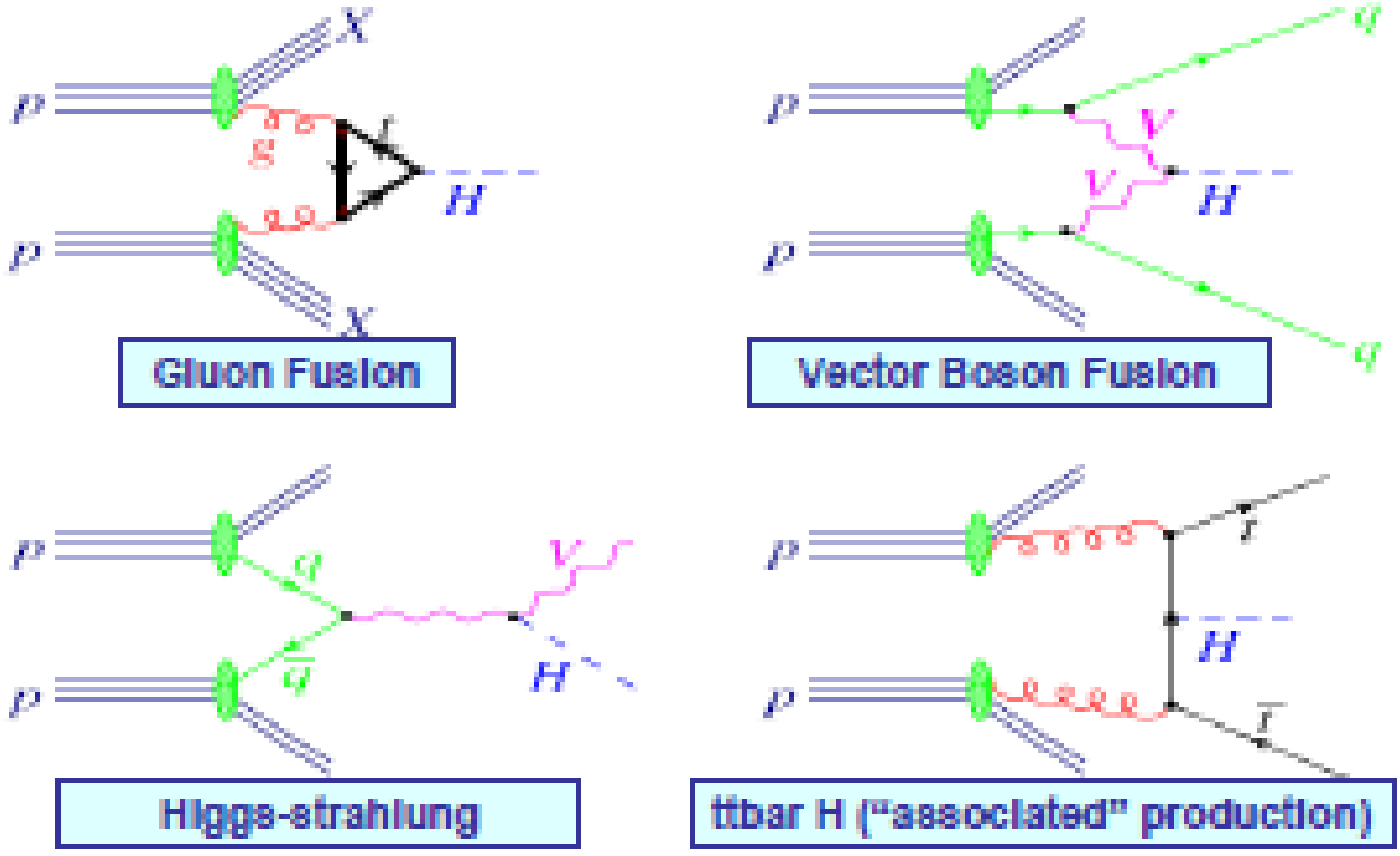
- @ 10 TeV and ~50 pb^{-1}
- 40 times less signal
  - ~1000 signal events before b-tagging
- Similar to current statistics at Tevatron but smaller background
- Methods based on per event information (ME-type) are expected to have a better performance
- Allow 2D fits and will help to perform JES calibration
  - constrain top mass to Tevatron average and fit JES

CERN-OPEN-2008-020

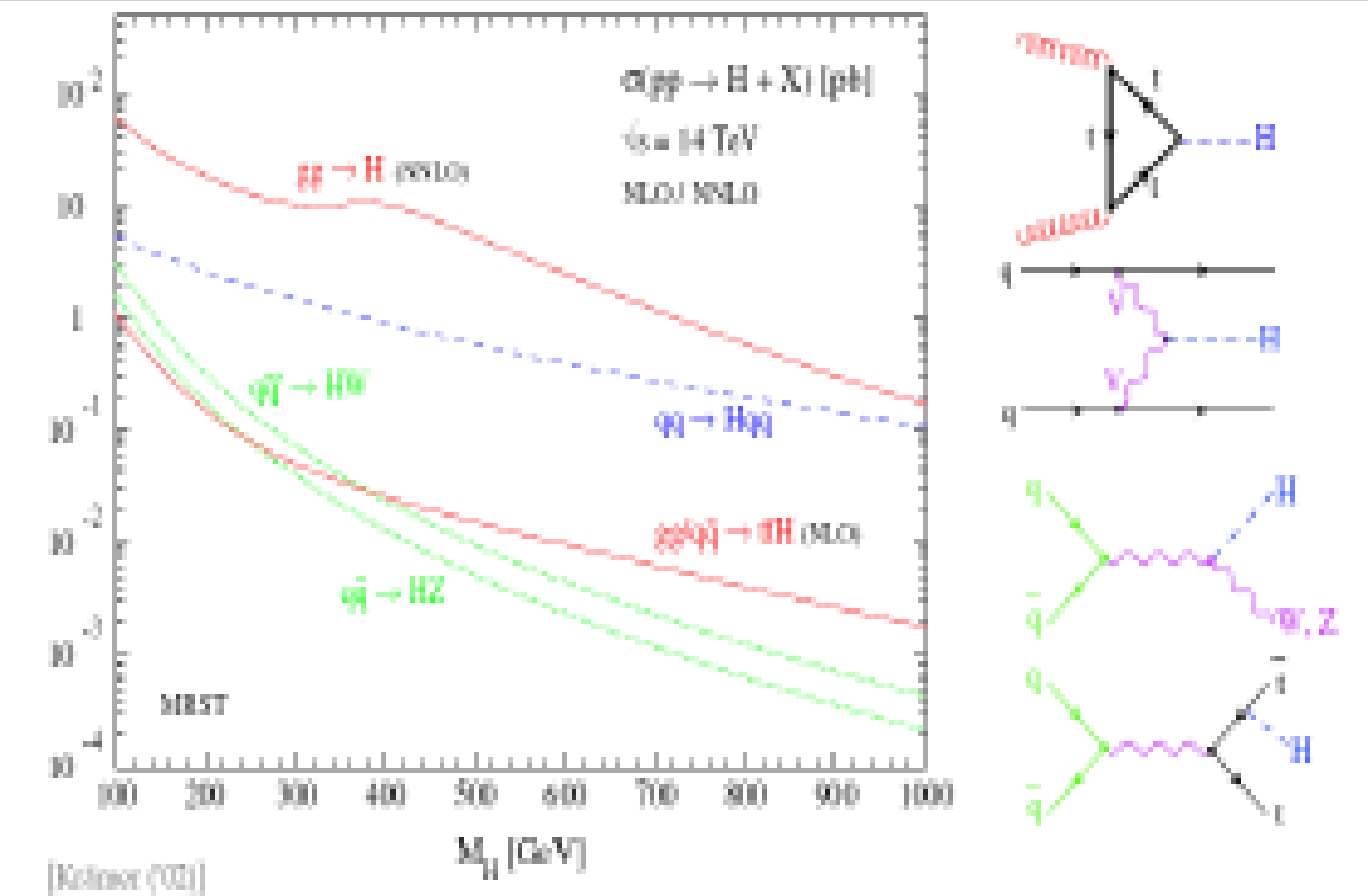
Process	>= 4 jets $p_T > 40$ GeV	2 b-jets $p_T > 40$ GeV
Signal	43370	15780
W boson backgrounds	9450	200
all-jets (top pairs)	560	160
di-lepton (top pairs)	2050	720
single top, t channel	1230	330
single top, W t channel	770	170
single top, s channel	11	5

- ~2% for light <JES> with 50 pb^{-1} (Atlas)
- ~1% for light <JES> and b<JES> with 100 pb^{-1} (CMS)
- perform ME analysis in 3D ?

Standard model Higgs production

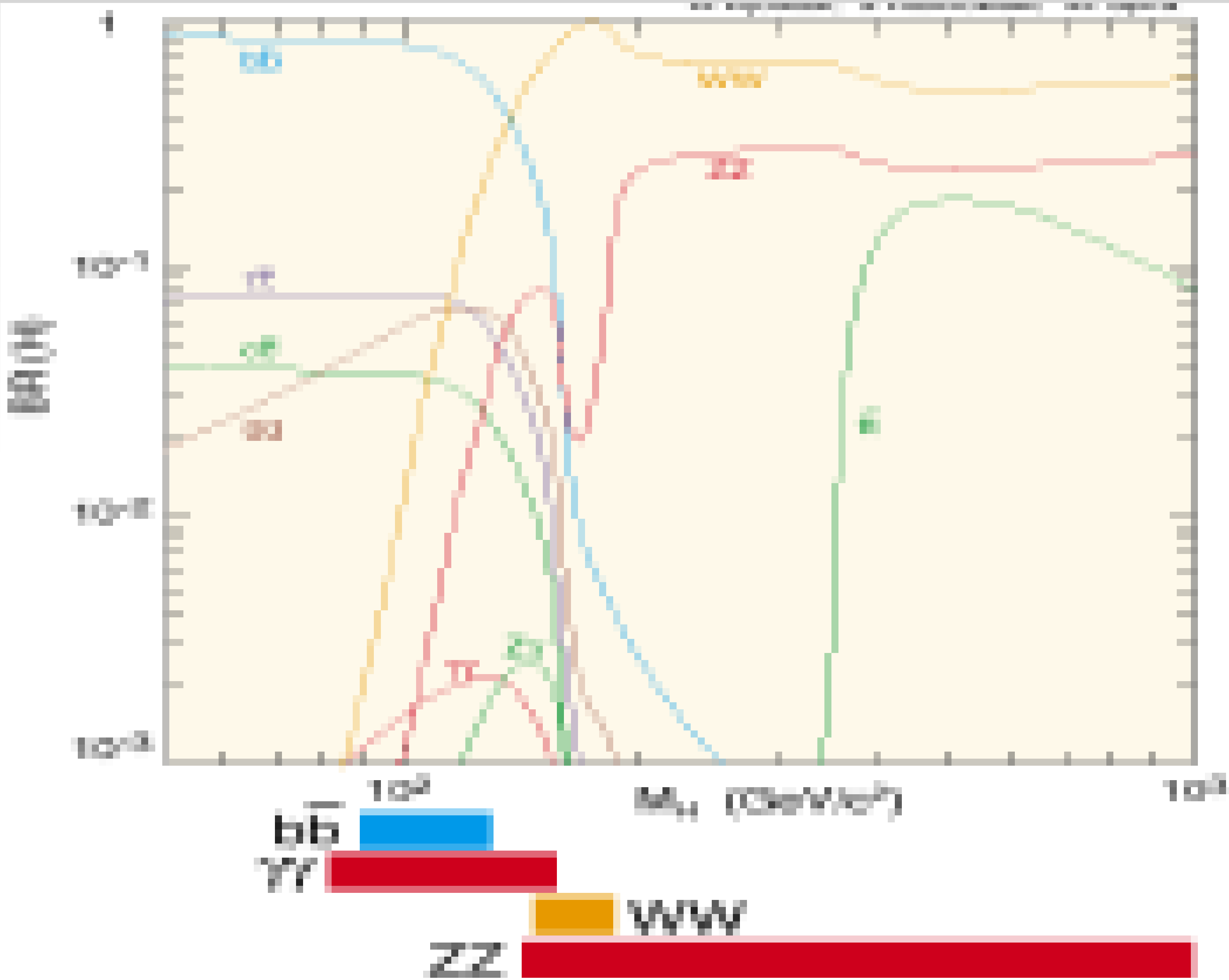


Higgs cross section

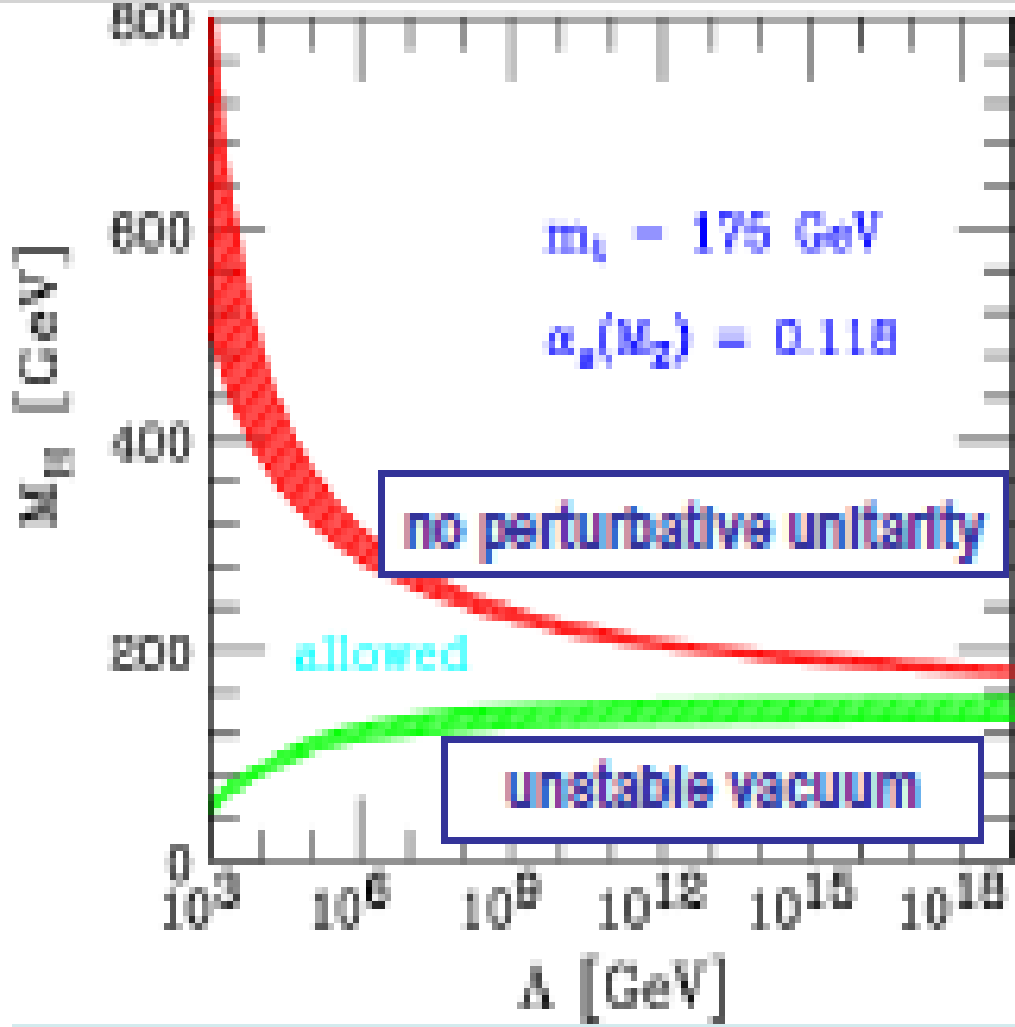


Higgs width ~ (m_H)

Main decay modes



Theory constraints to mass



Upper bound

(triviality) :

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

Lower bound

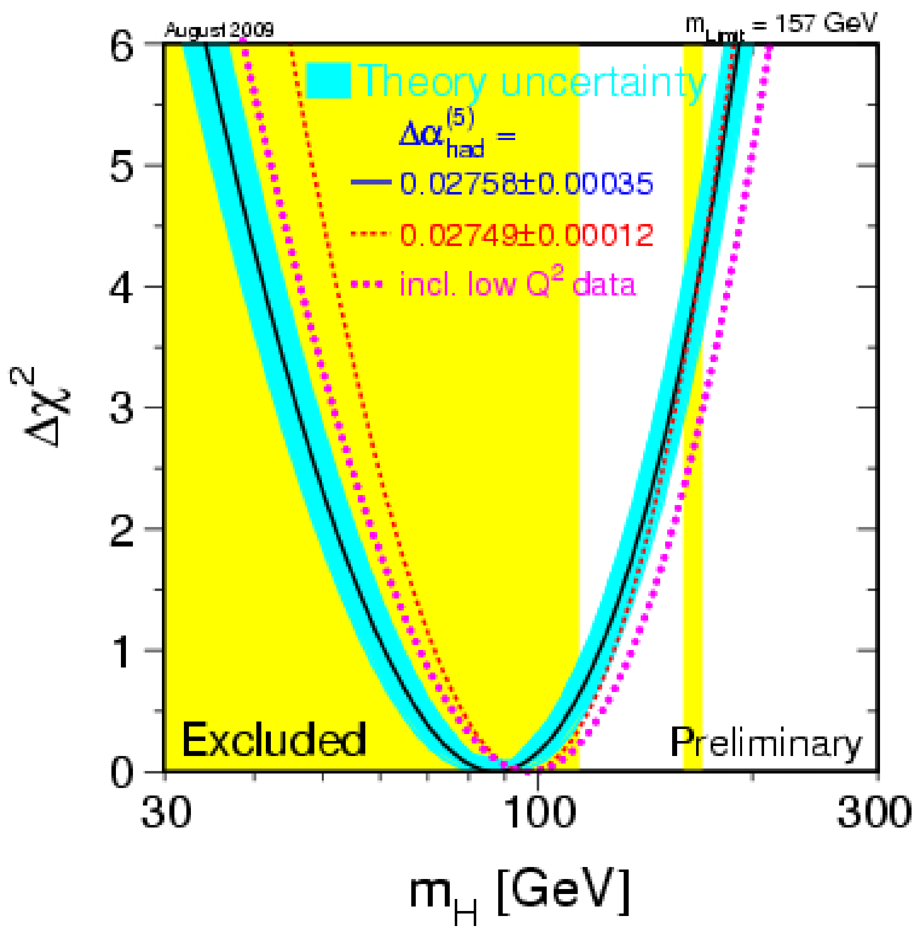
(vacuum stability) :

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

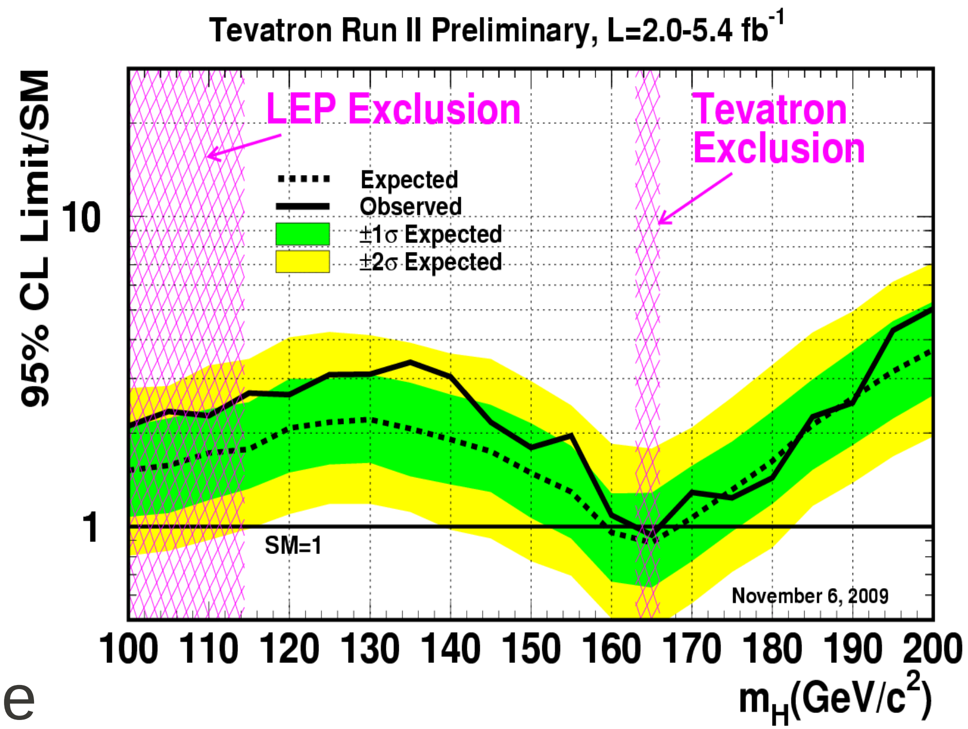
(Λ = cut-off scale at which new physics becomes important)

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

Experimental constraints to Higgs mass



- 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?

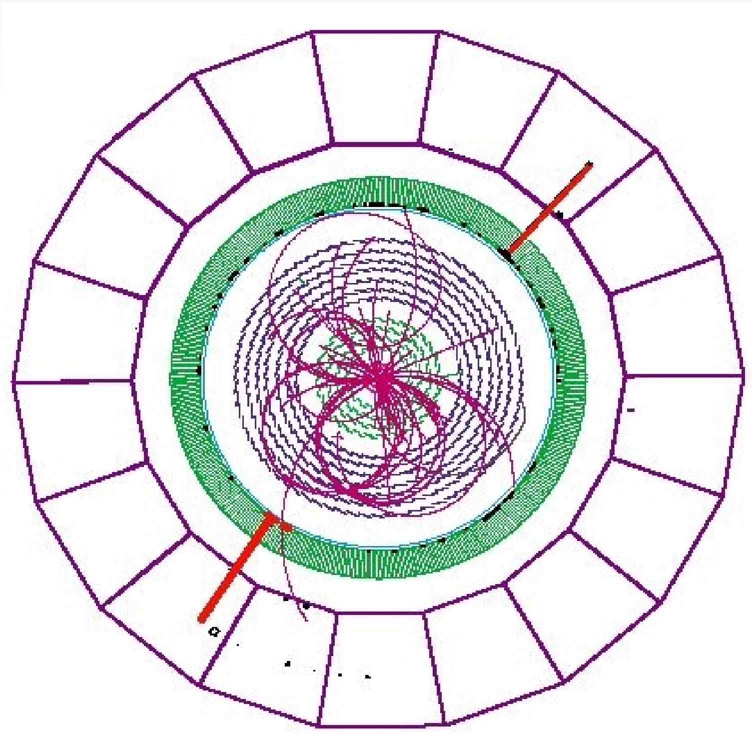
How to look for the SM Higgs

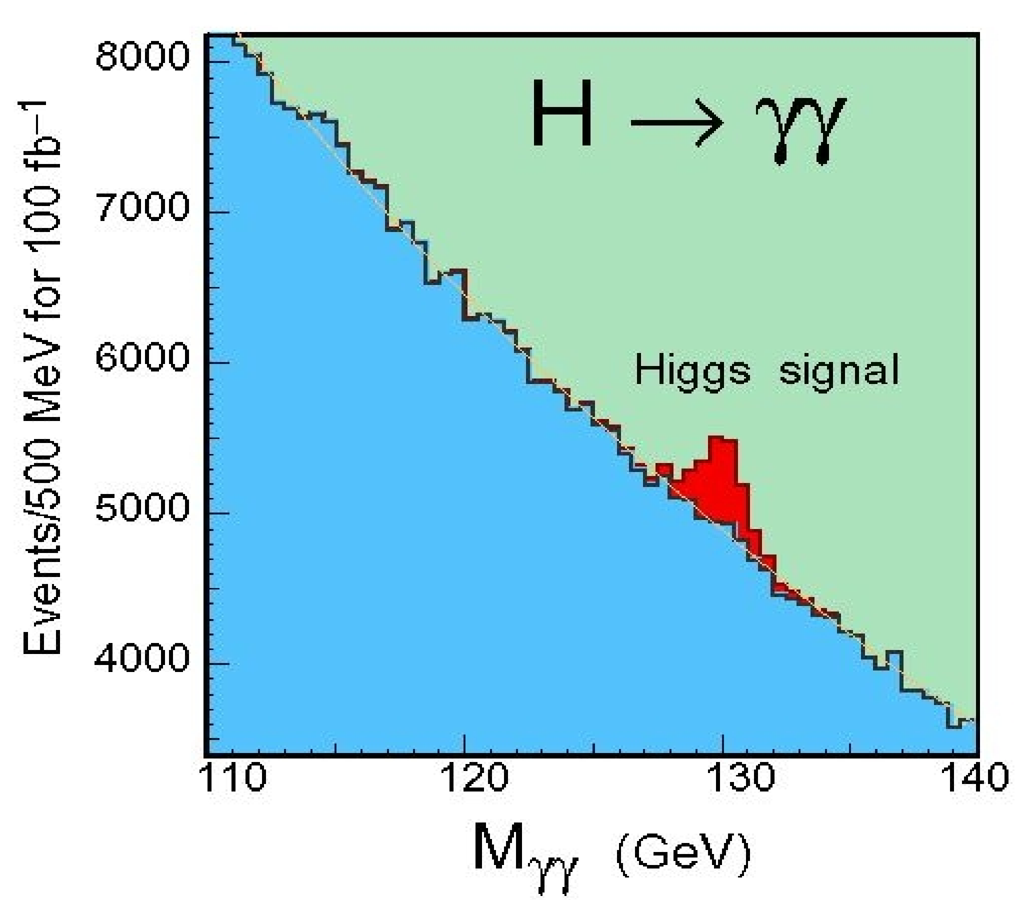
Only unknown is mass, so we are searching in several channels, depending on our bet on the Higgs mass:

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

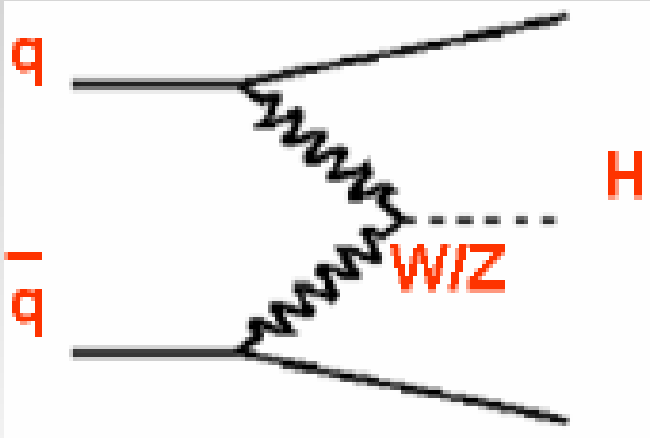
H->$\gamma\gamma$

- 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!)

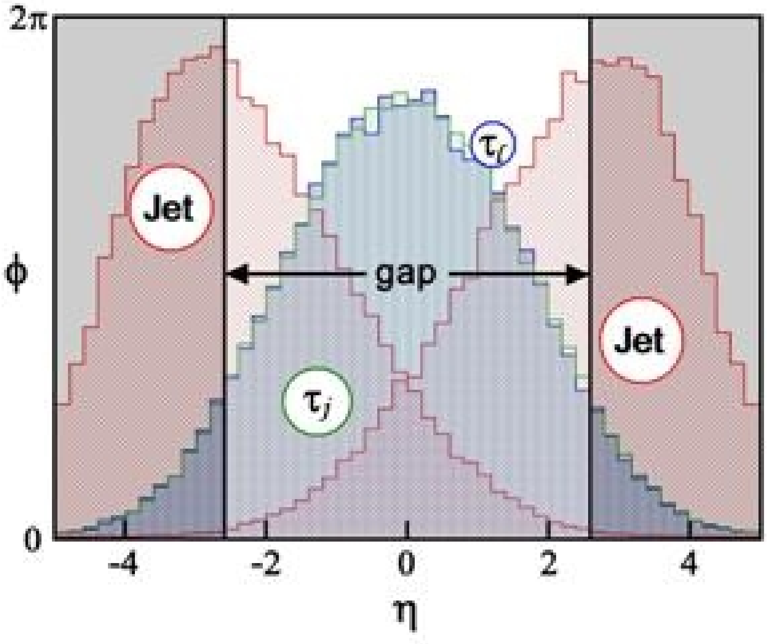


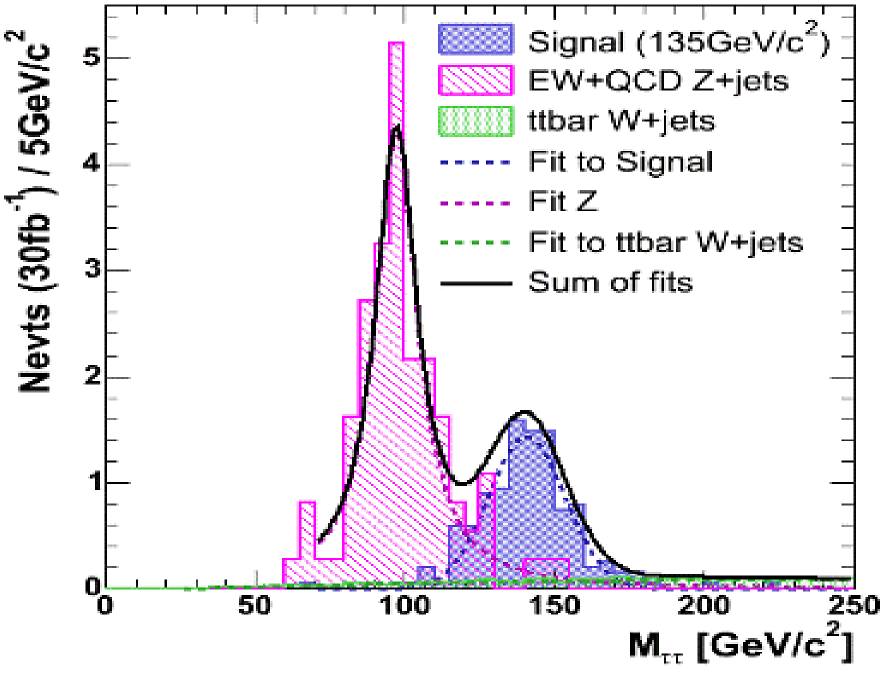


Vector Boson Fusion (VBF)



- Remnants of the final-state quarks emitted in the forward region (up to η~ 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

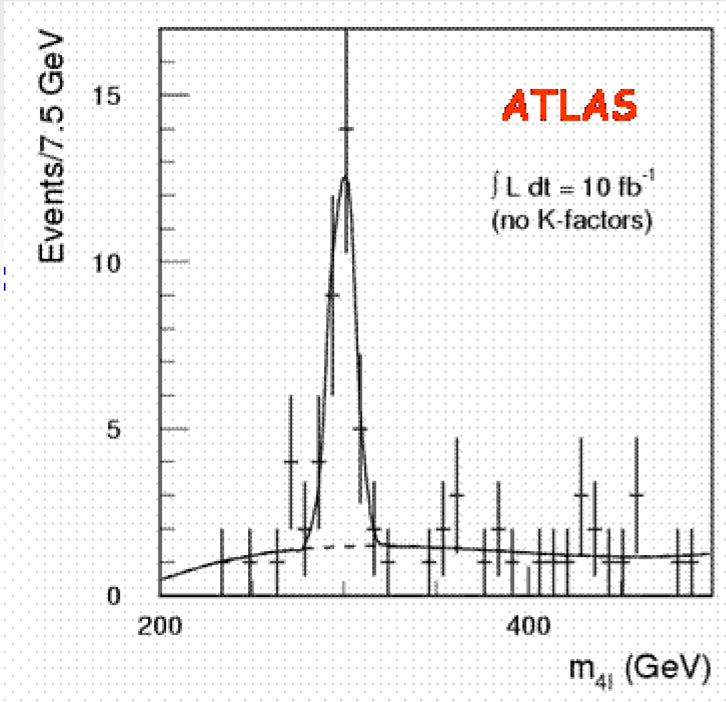


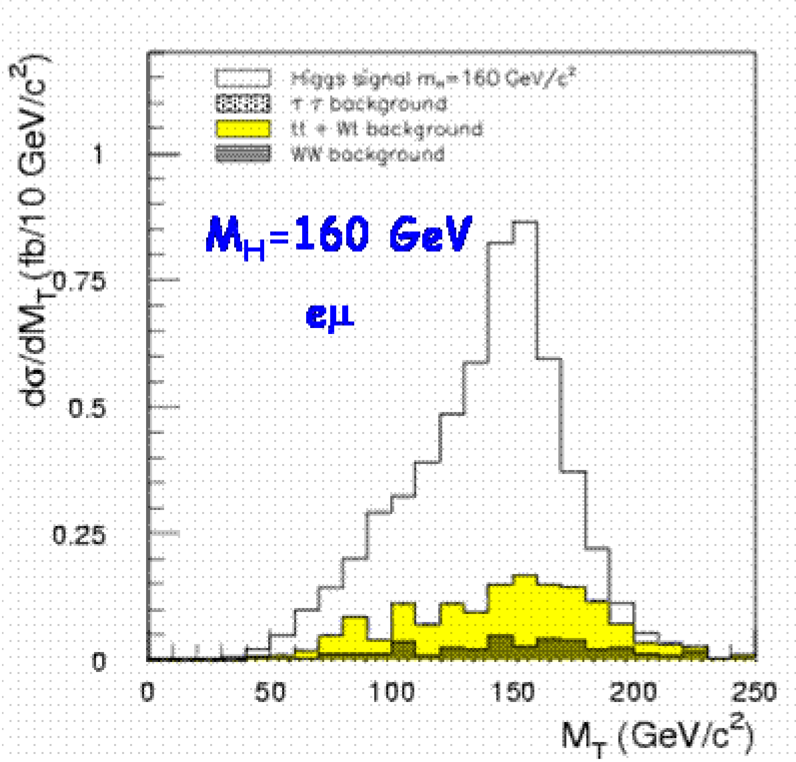


Higgs → vector boson pair

- Golden channel if mass is high enough (very small BG, full mass reconstruction in the ZZ case)

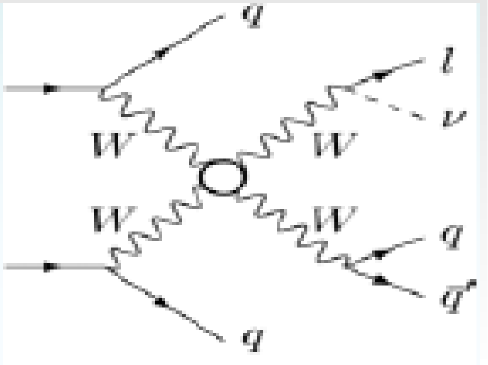
Main BG: ZZ, Zbb, tt, $\tau\tau$
Can be used in a wide mass range



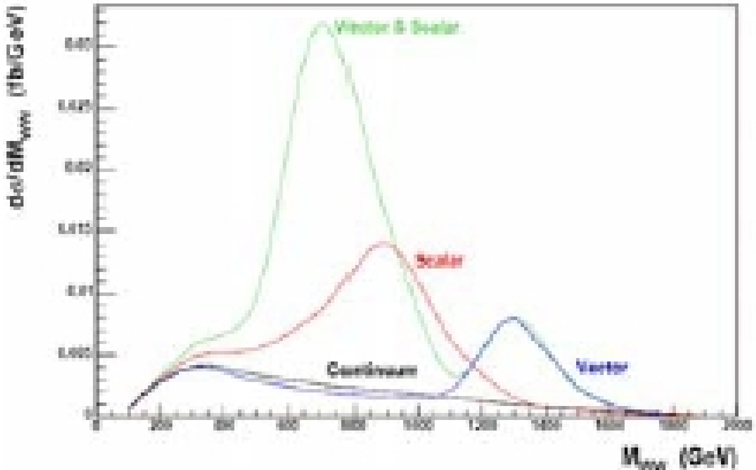


Very high-mass Higgs

- 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

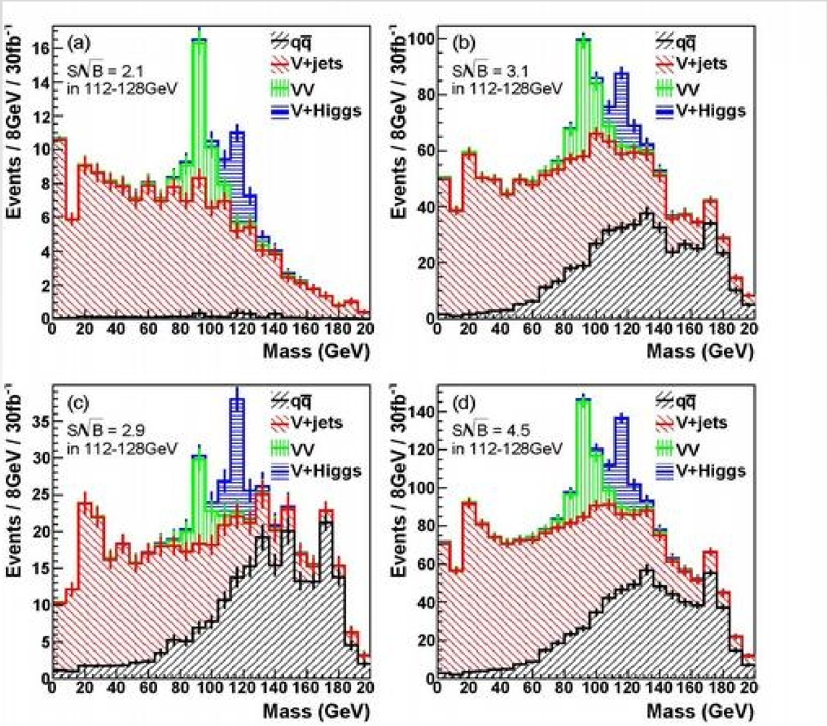


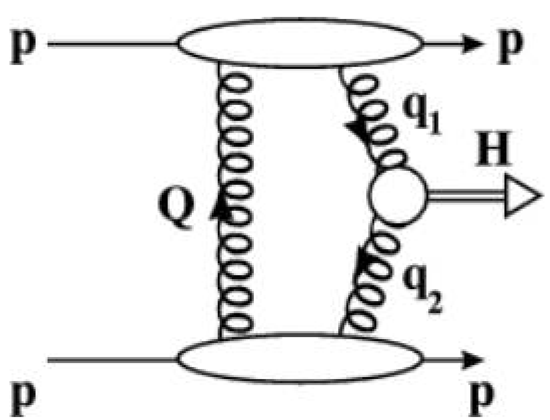
- This cross section is divergent in the SM, but if the Higgs is there a diagram with Higgs exchange restores finiteness
- Does not work if Higgs is too heavy, in that case some other resonance could be produced in WW final states
- More than one Higgs could be present, even in a pure SM scenario, with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



Non-conventional search channels

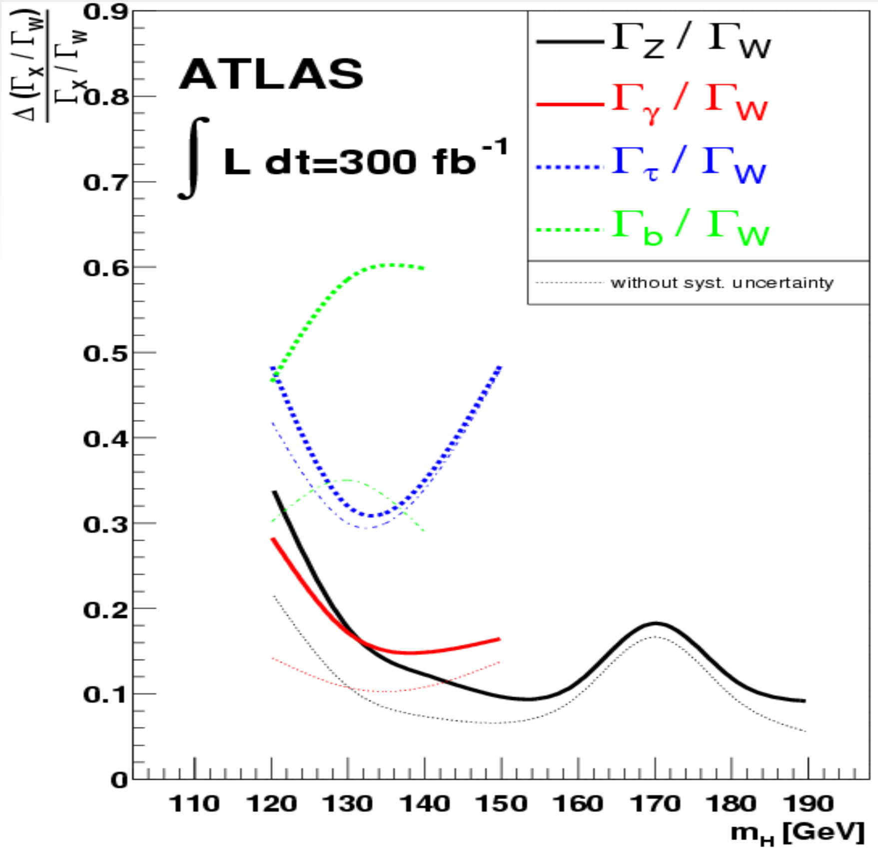
- HZ: S/BG ratio increases for high-Pt Higgs. In that case, and for the main decay channel H->bb, Higgs decay channels end up in a single jet, substructure used to find it
- Diffractive Higgs: Higgs can be produced in diffractive mode, with the two protons stay intact after collision. Only possible with 1^{++} quantum numbers, requires installation of forward proton taggers

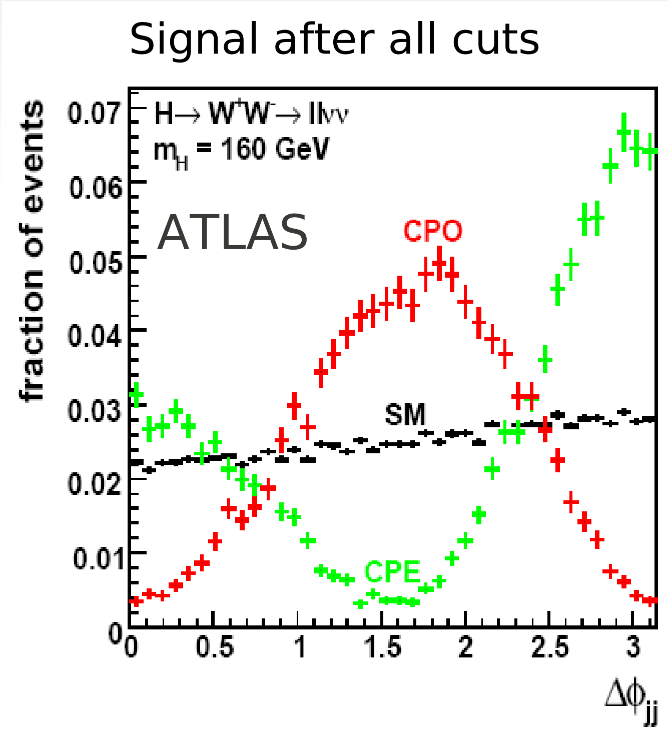




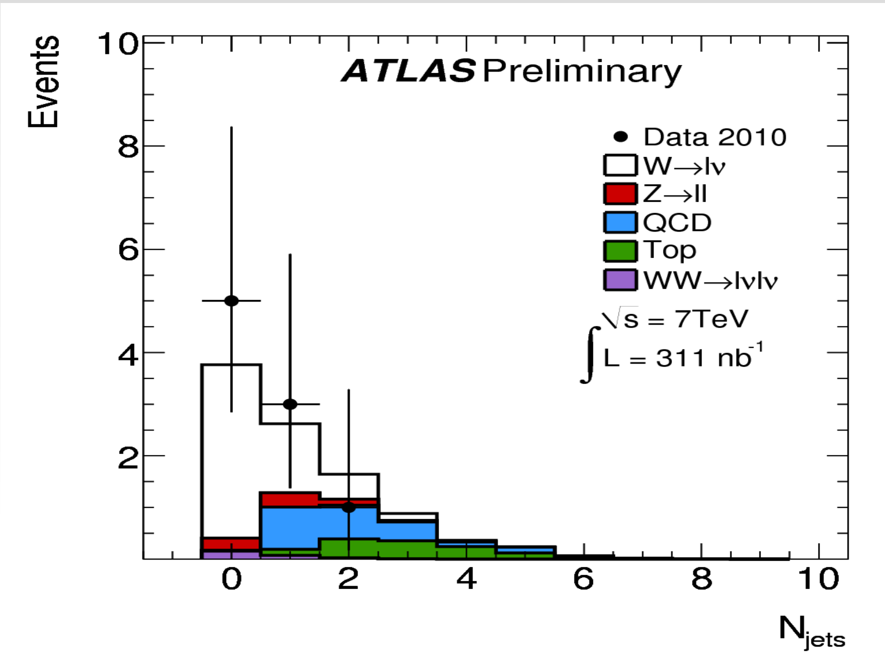
Is it really the Higgs?

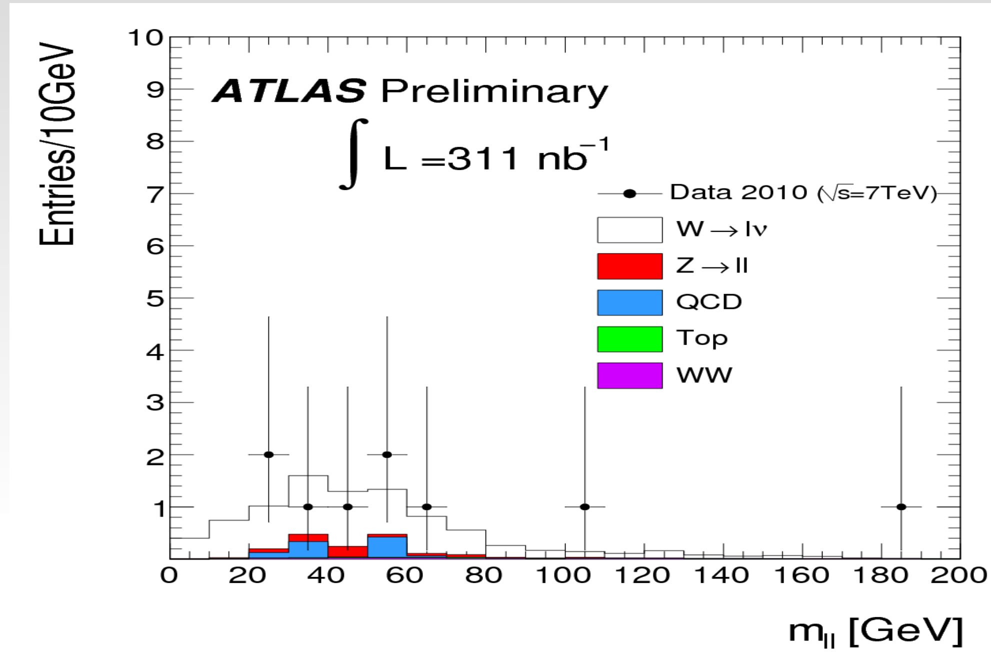
- If a particle is found in any Higgs search, is it really it?
- Measure width (or ratios of) and quantum numbers

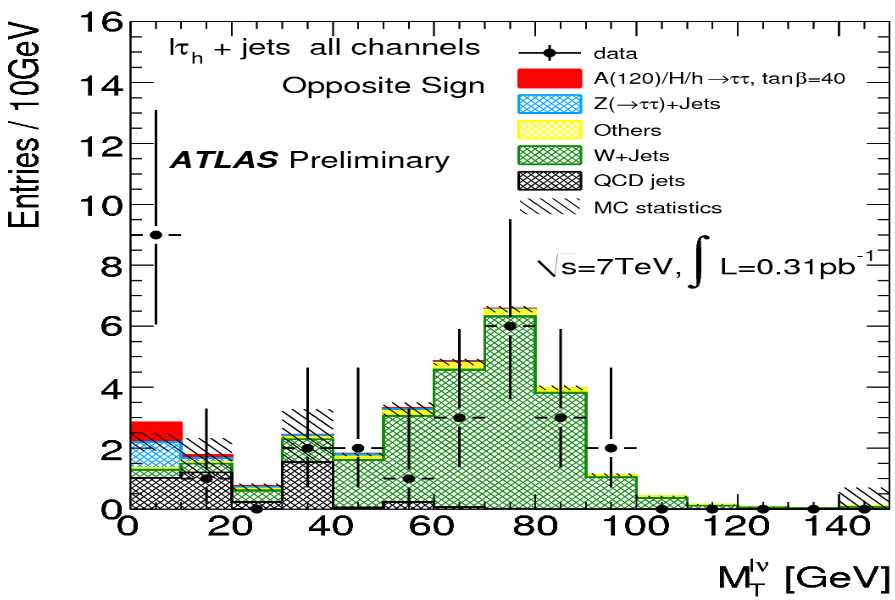


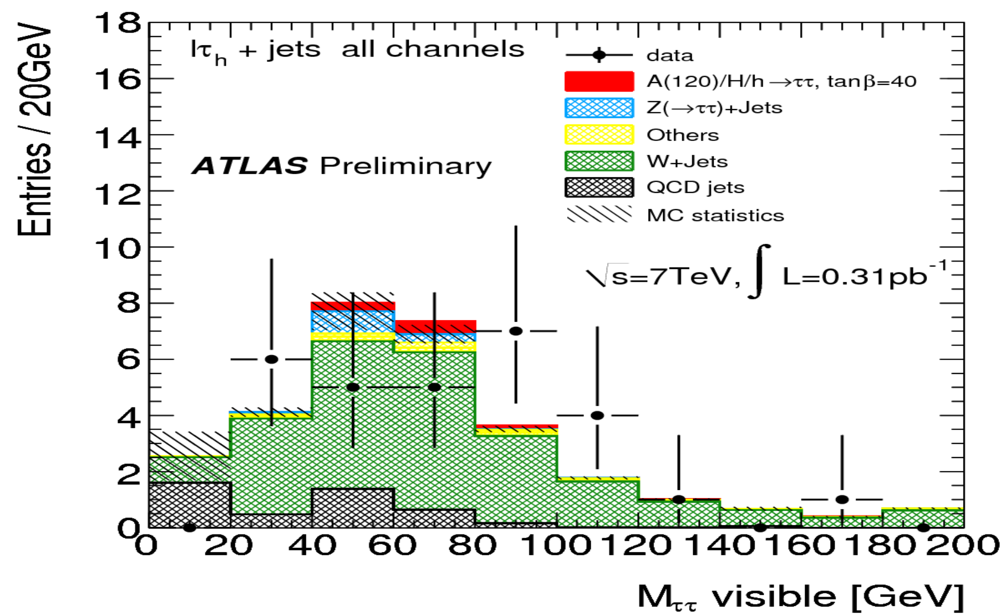


First measurements: checking BG for WW and ττ

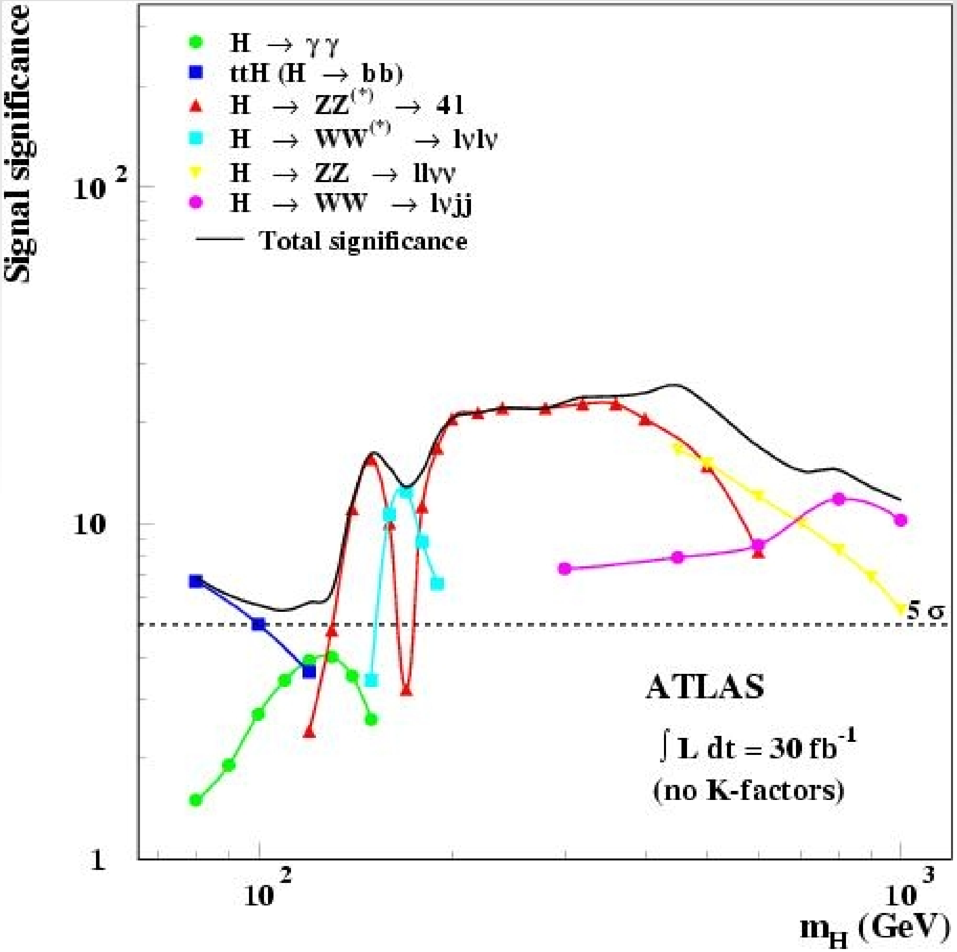


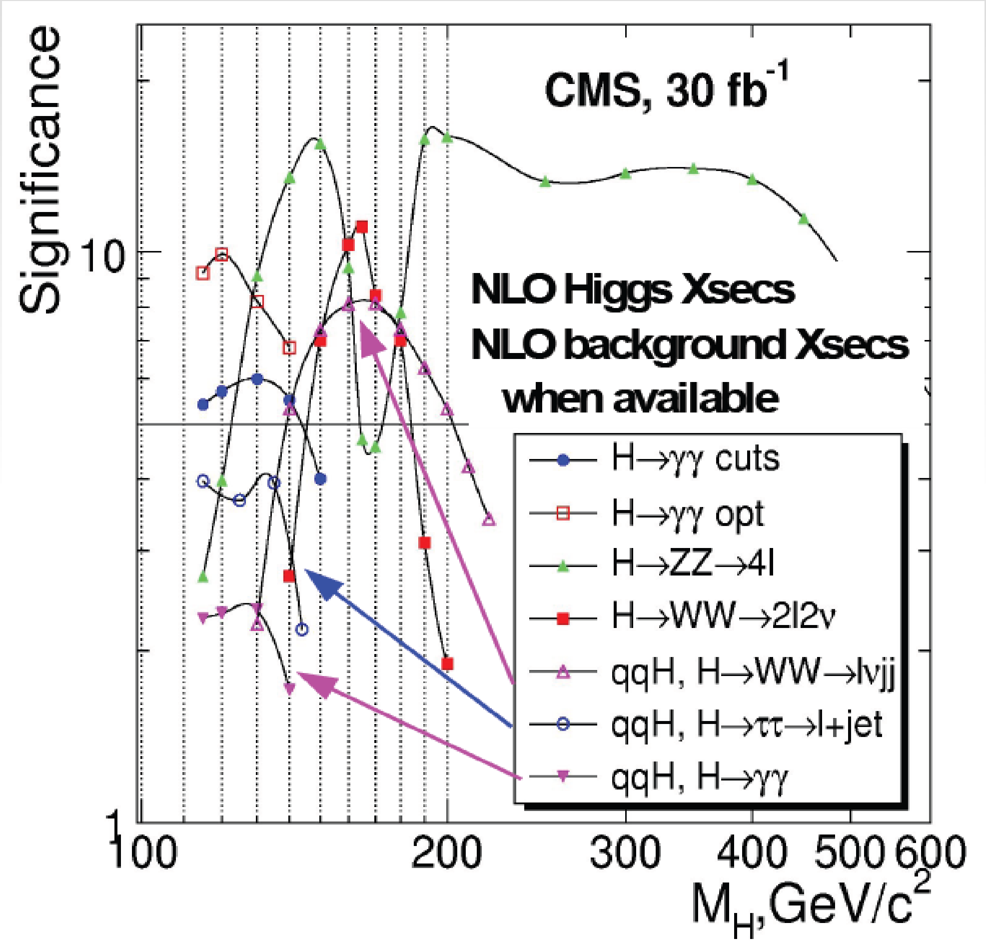






Summary: discovery potential



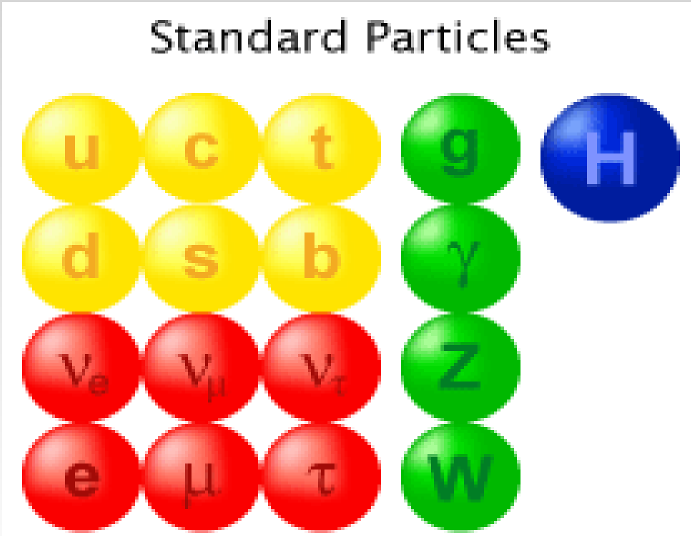


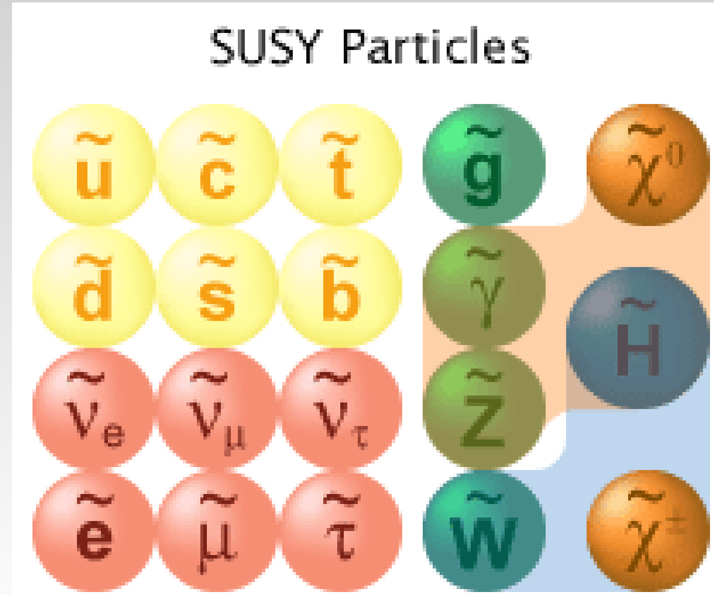
Issues with the Standard Model

- Gravity not included → SM only low-energy effective theory valid to a scale Λ << 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

Minimal SUSY Standard Model (MSSM) particles





- 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

R-parity

- 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!)

SUSY breaking

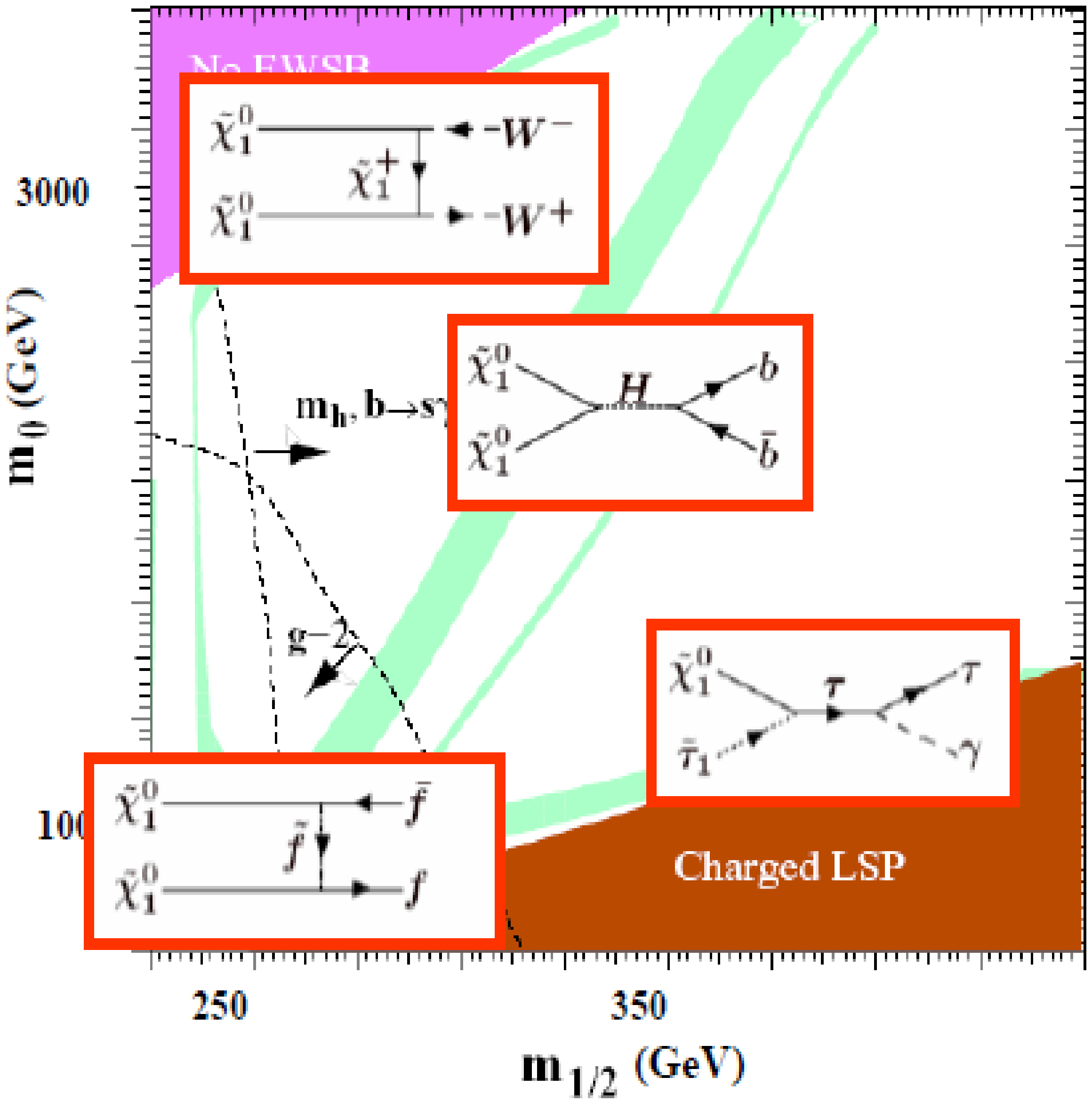
- Since no SUSY particles discovered so far, their masses have to be larger than their SM correspondents. Supersimmetry has to be broken, and spontaneous symmetry breaking does not work (would predict particles lighter than SM correspondents)
- SUSY breaking confined to hidden sector at high scale, and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

A minimal scenario: mSUGRA

- 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 β ratio of vacuum expectation values of Higgses
  - sign(μ) sign of SUSY Higgs mass term (its abs value is the EW symmetry breaking)

MSUGRA parameter space

Four regions compatible with WMAP value for Ωh^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

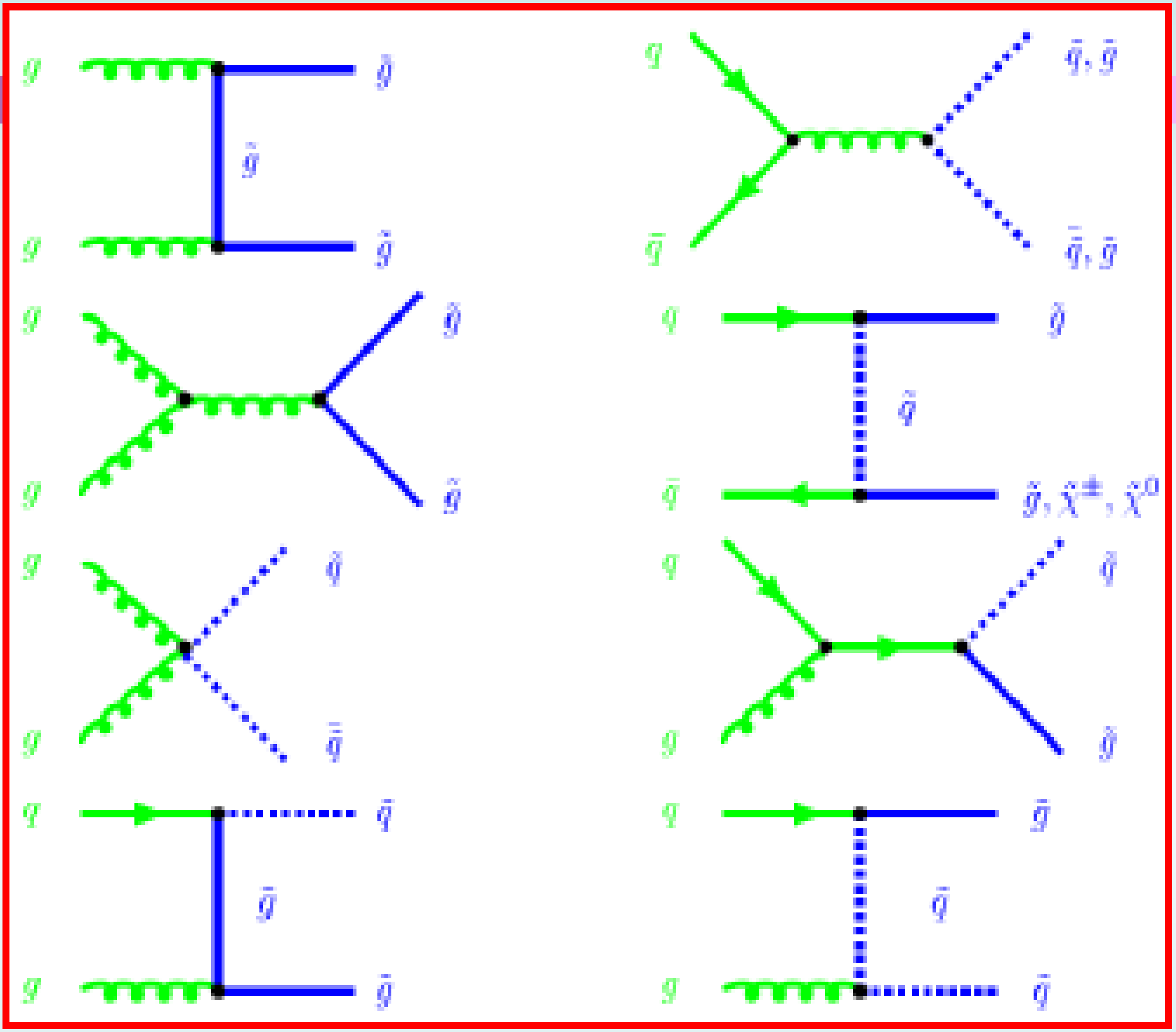
pure bino, small NLSP-LSP mass difference, typically coannihilation with stau

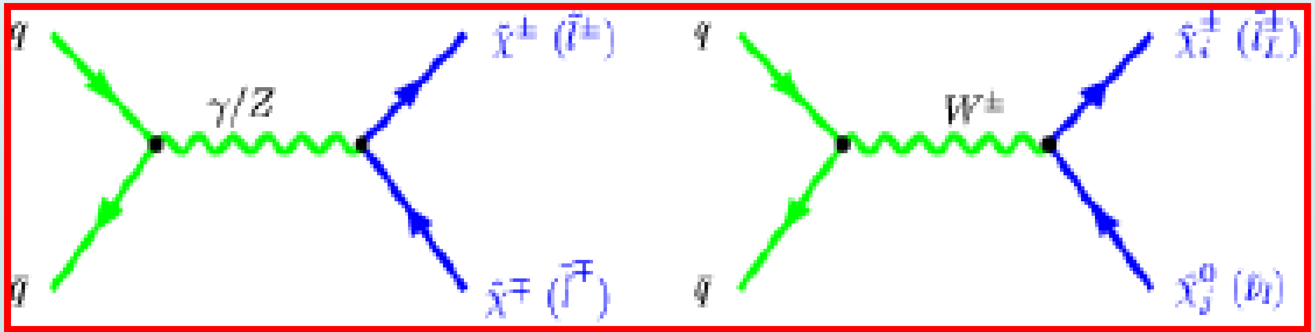
Higgs funnel

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

Production mechanisms

Squark/Gluino Production

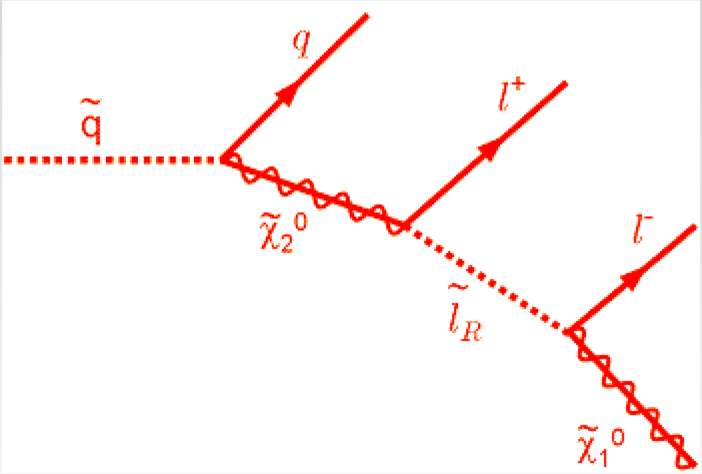


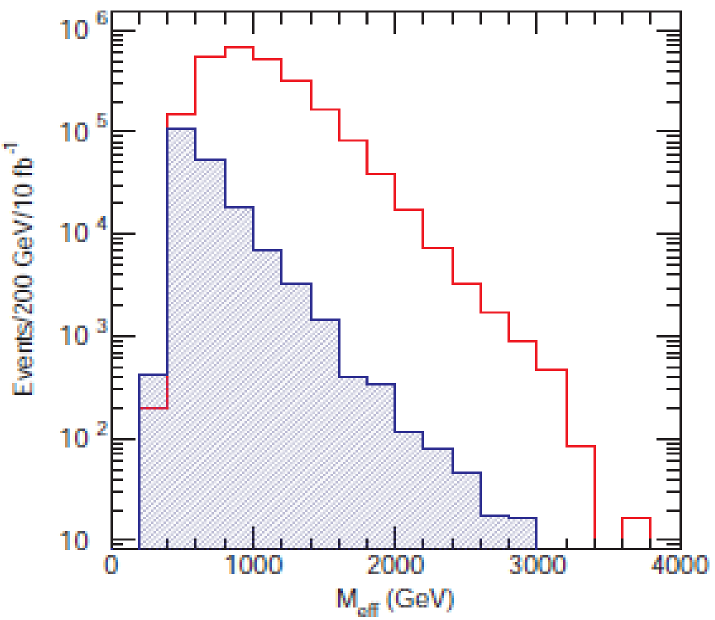


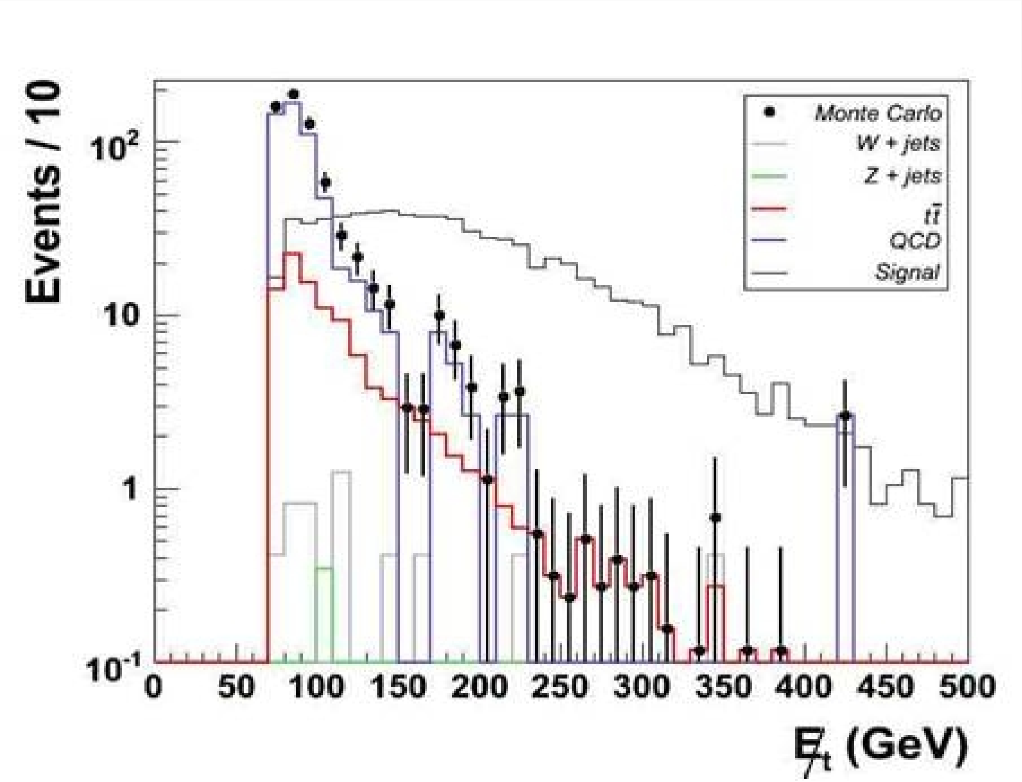
Direct Gaugino Production

Decay cascades

- 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)

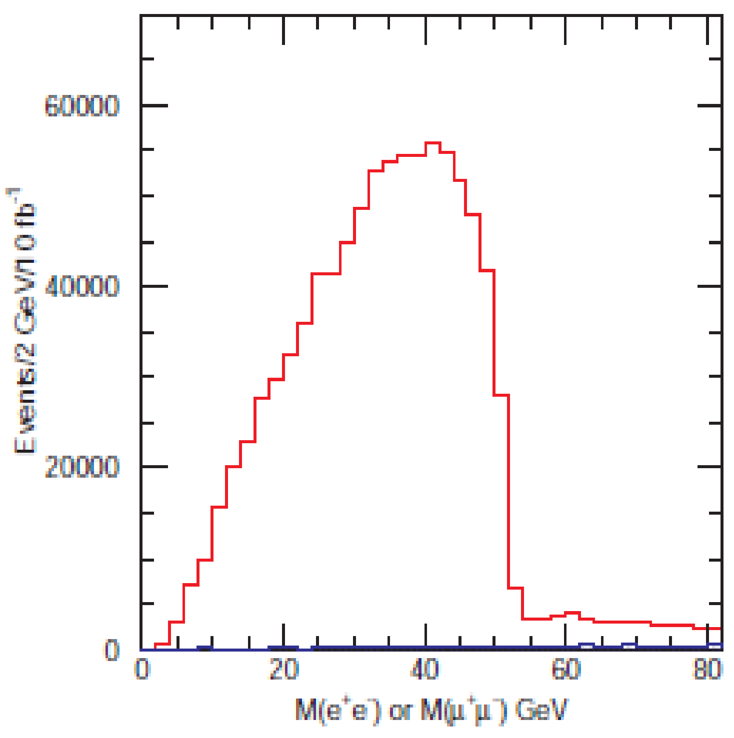


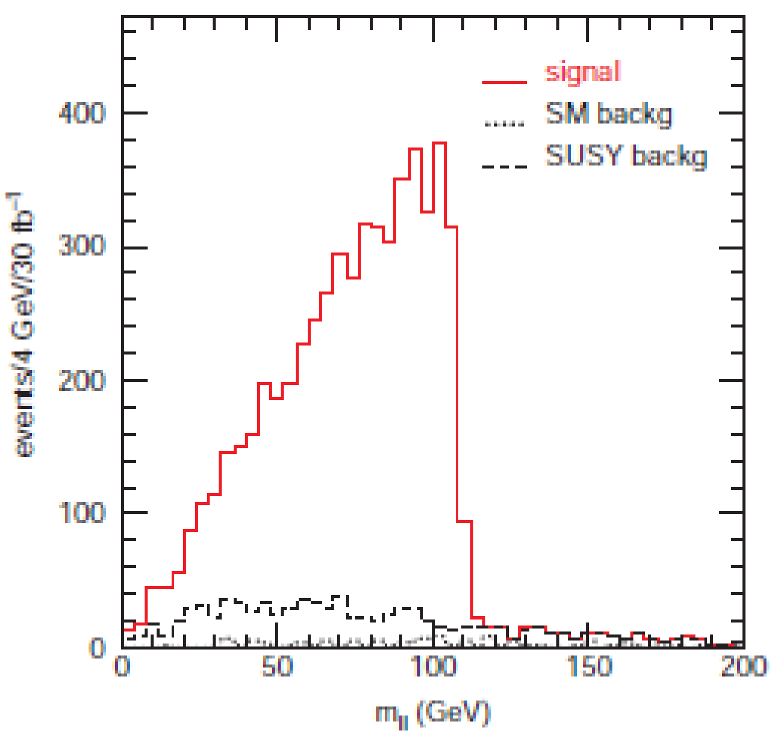




Dilepton signatures

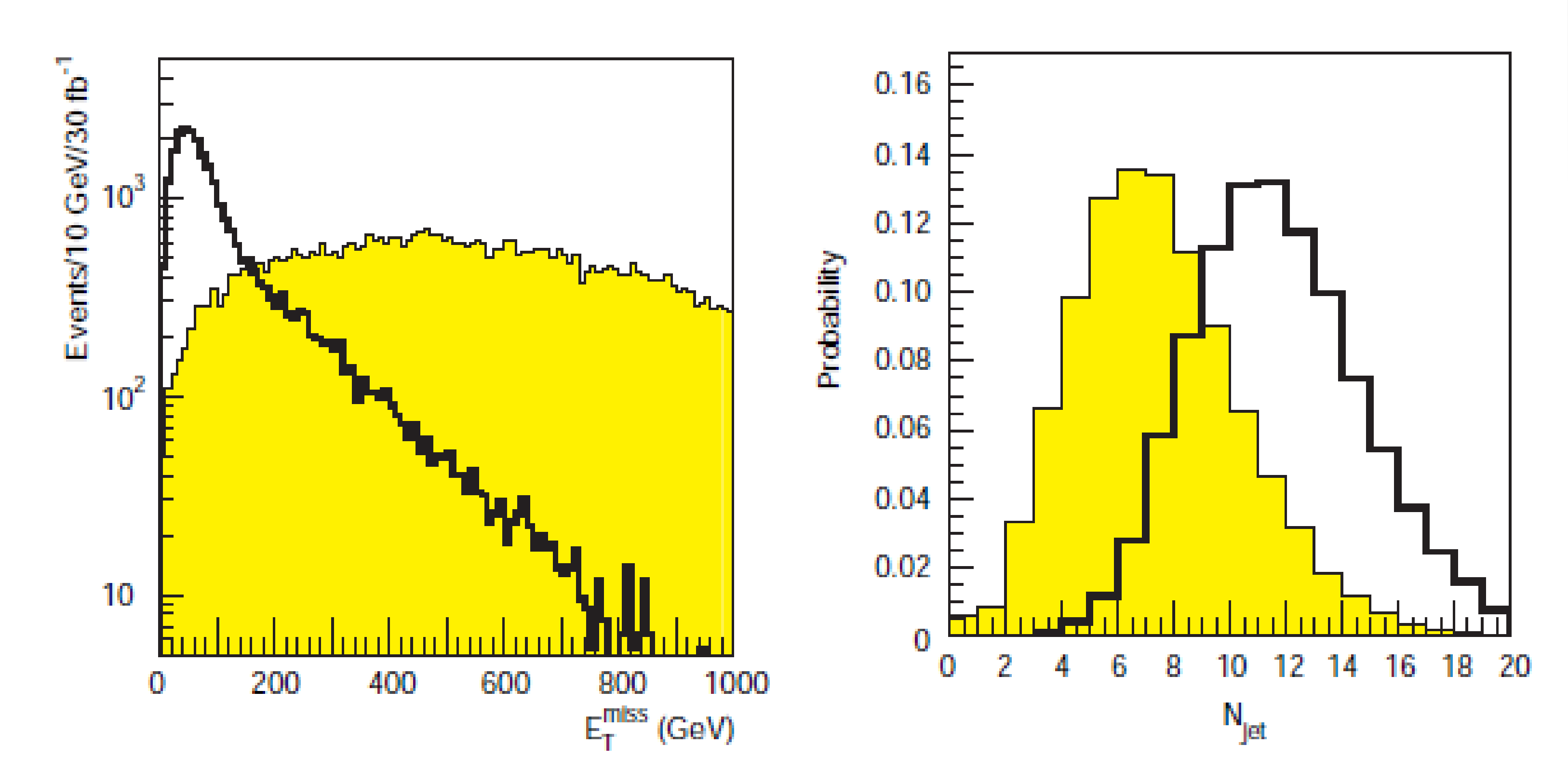
- In most of the parameter space, charginos and neutralinos have no 2-body decay, so a dominant decay is 3-body $\chi_2 \rightarrow \chi_1\ l^+l^-$. The lepton invariant mass will have a sharp edge corresponding to the SUSY mass difference. Signal can be very clean.





R-parity violating models

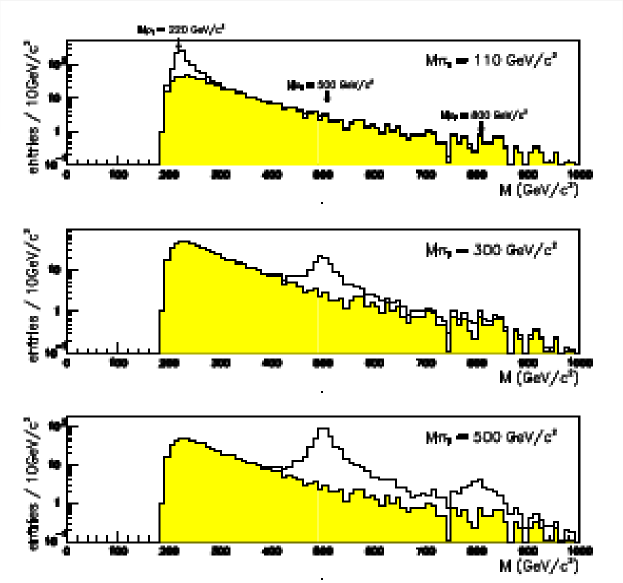
- If R is not conserved, SUSY particles can decay into SM ones, so events do not have the characteristic MET signature, but rather an anomalously high number of jets or leptons:



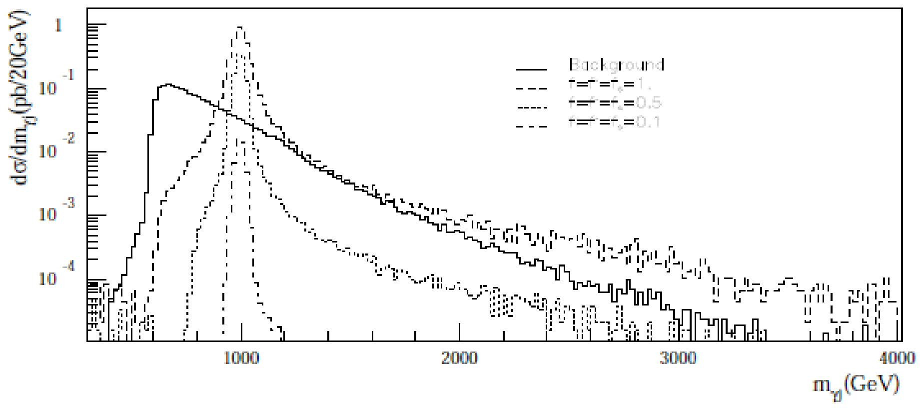
R-parity violating R-parity conserving

Other new physics models

- 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

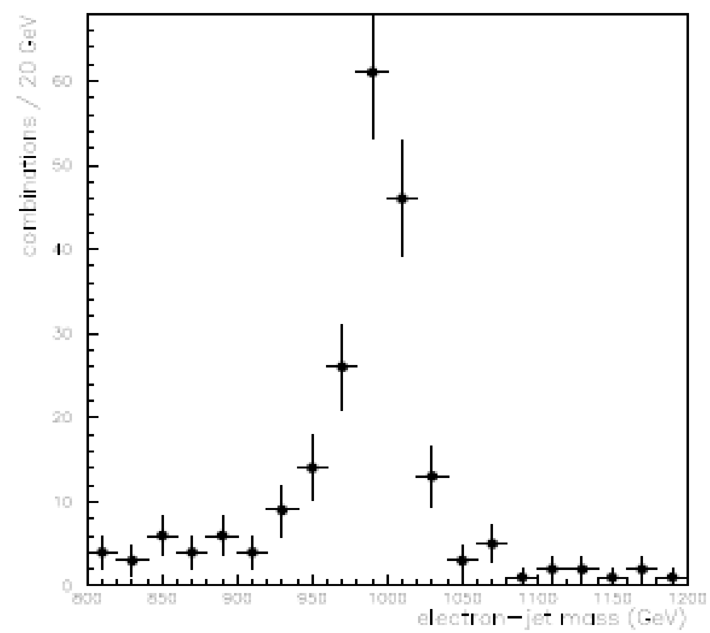


•Excited quarks/leptons: decay into a photon and a quark/lepton, producing a mass peak in that distribution

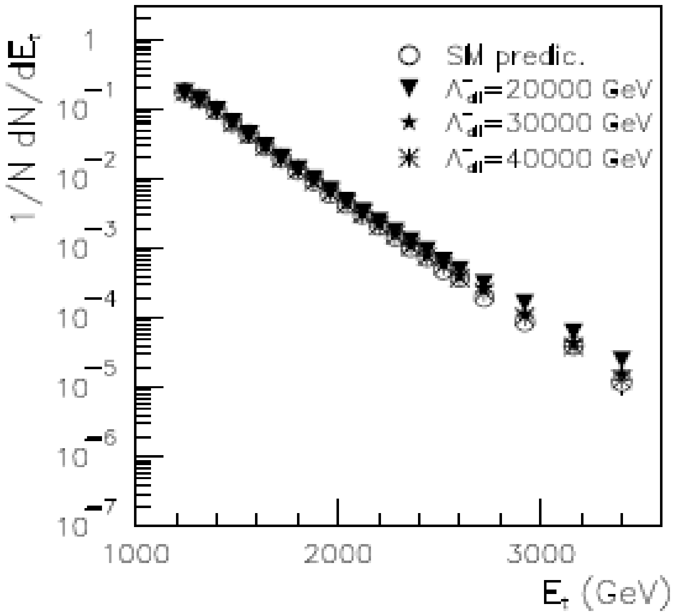


More new physics

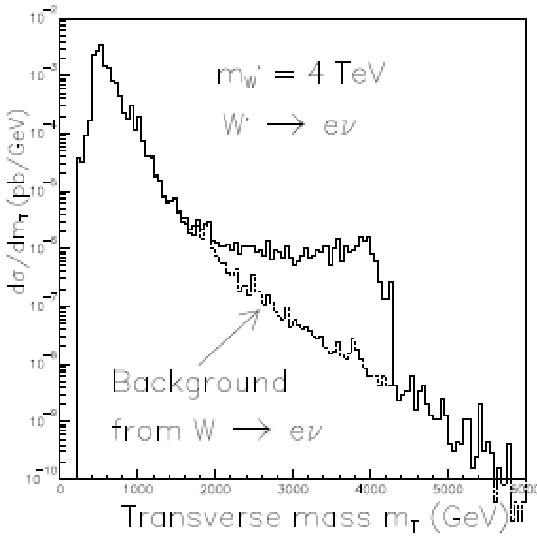
- Leptoquarks: a new symmetry between leptons and quarks could produce particles strongly coupling (and decaying) to both



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

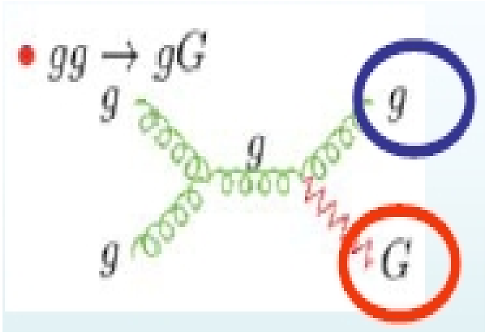


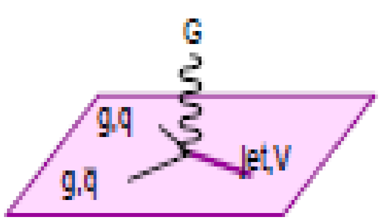
Z', W': from additional SU(2) symmetry, behave like high-mass W's and Z's



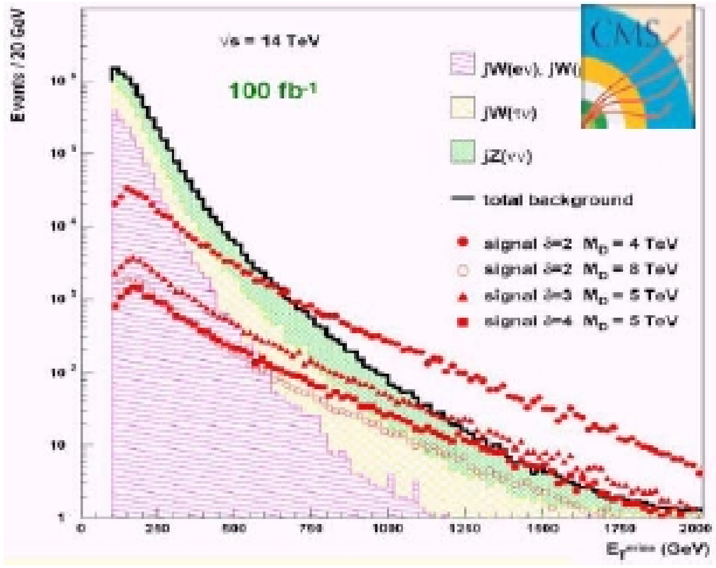
Extra dimensions

- 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

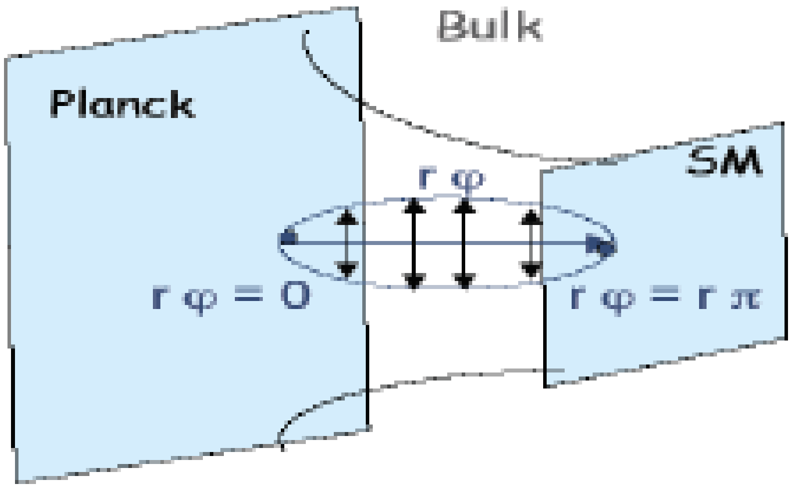




Great way to escape from the in-laws???



Randall-Sundrum models

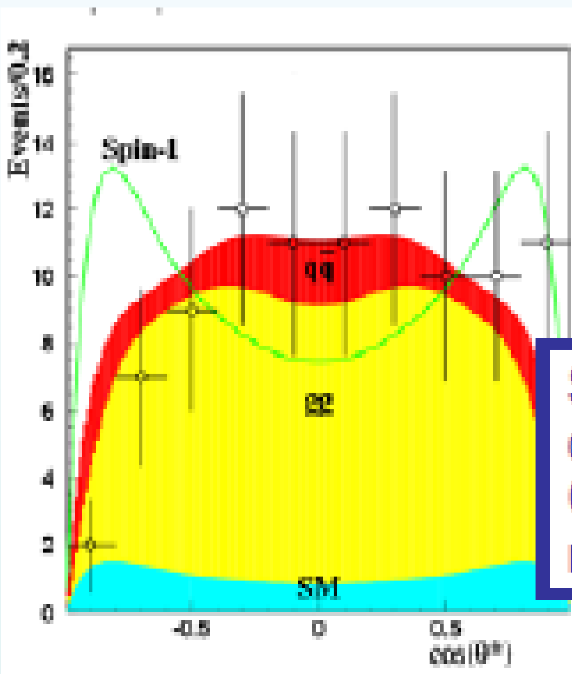


A small, highly curved ("warped") extra dimension connects the SM brane (at O(TeV)) to the Planck scale brane

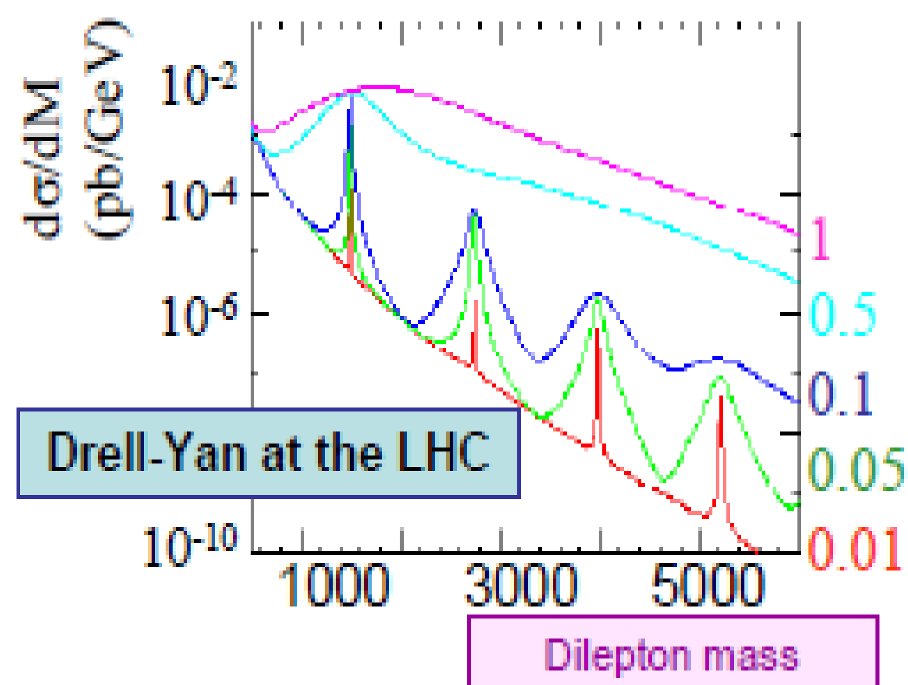
Gravity small in our space because warped dimension decreases exponentially between the two branes

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

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

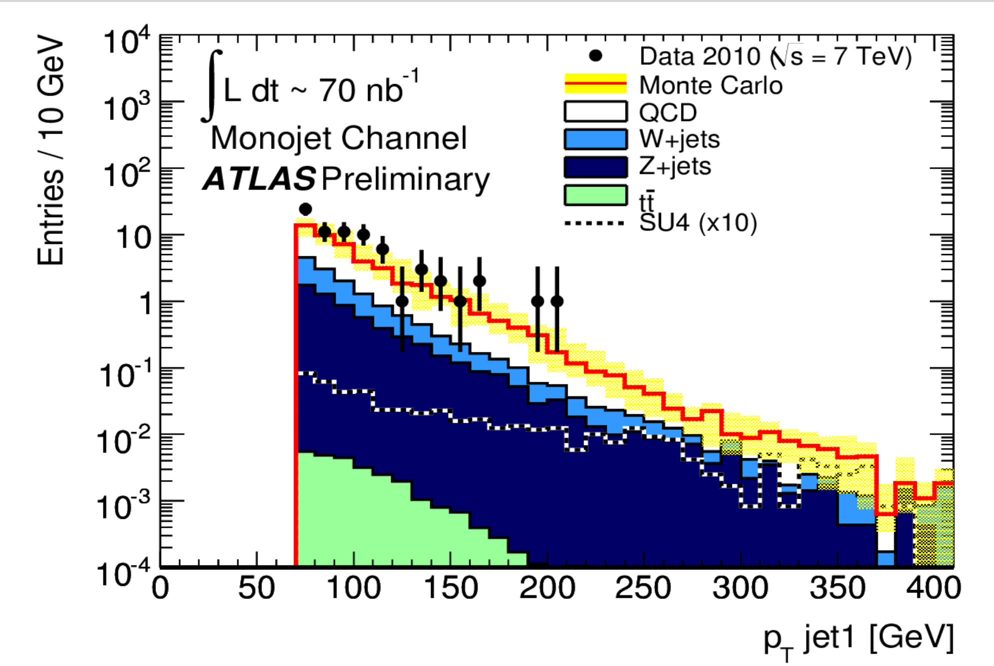


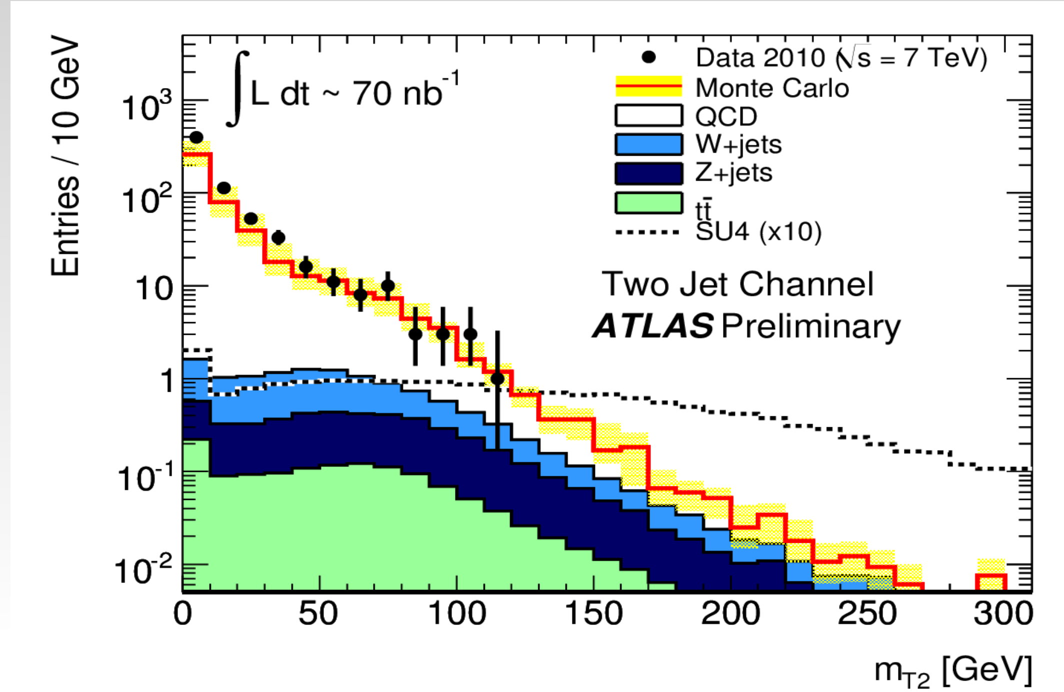
Spin analysis to distinguish spin-2 G from spin-1 Z' resonance

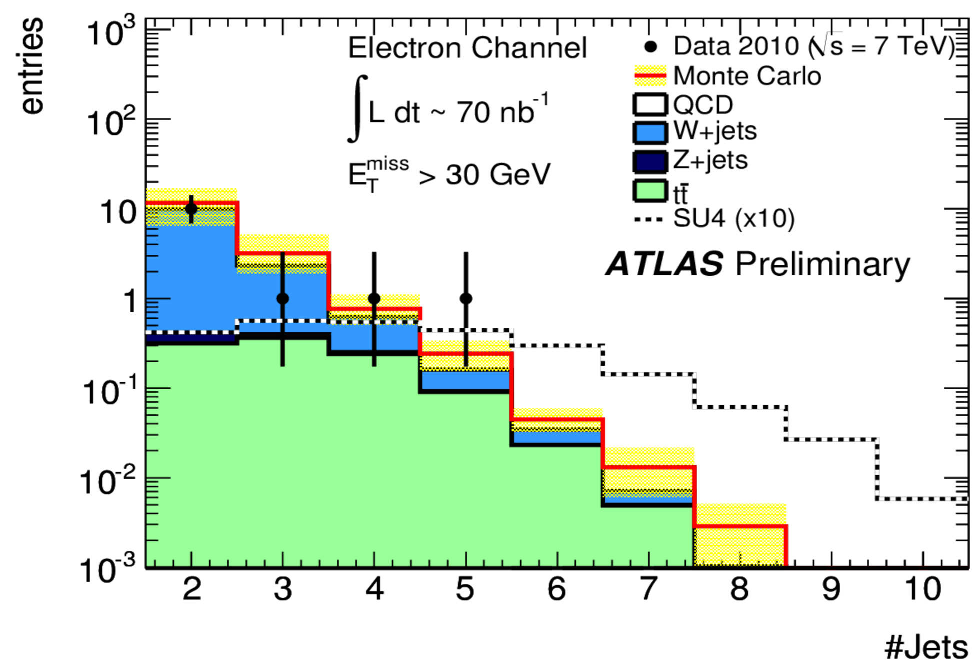


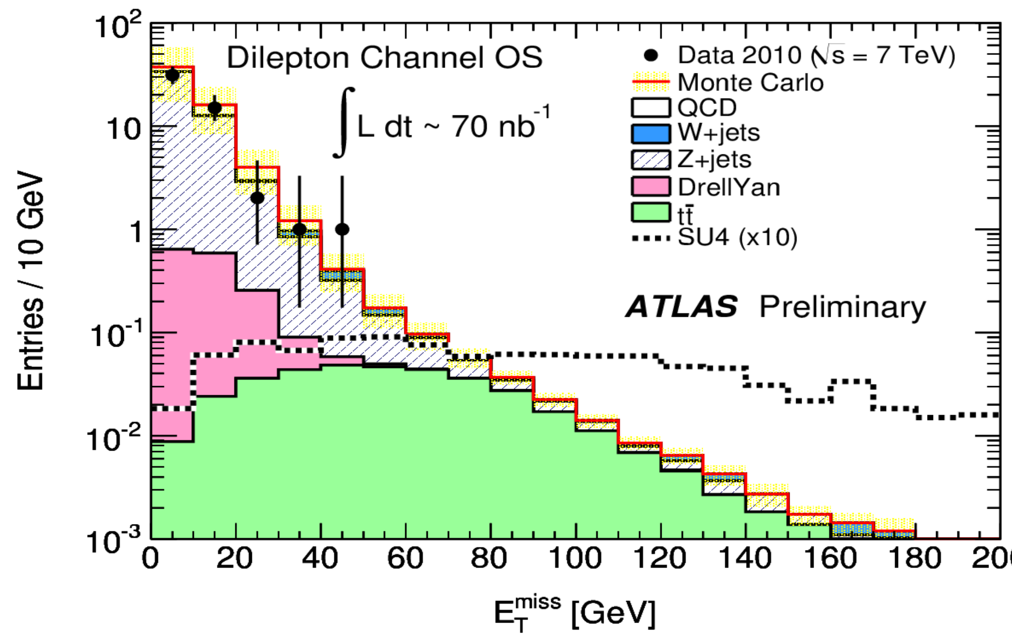
Antonella De

Early SUSY searches

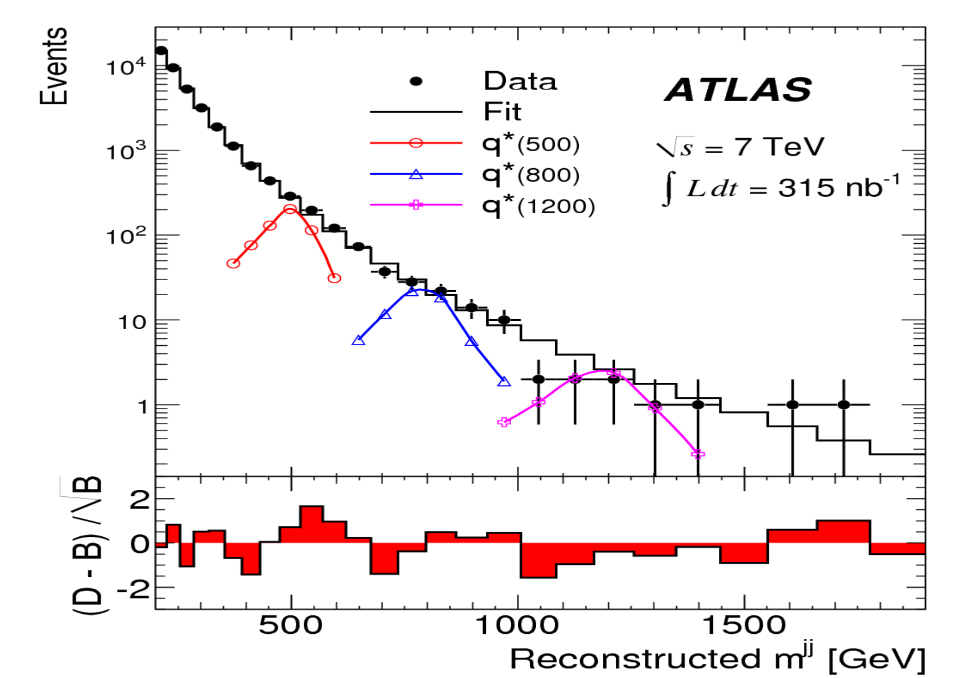


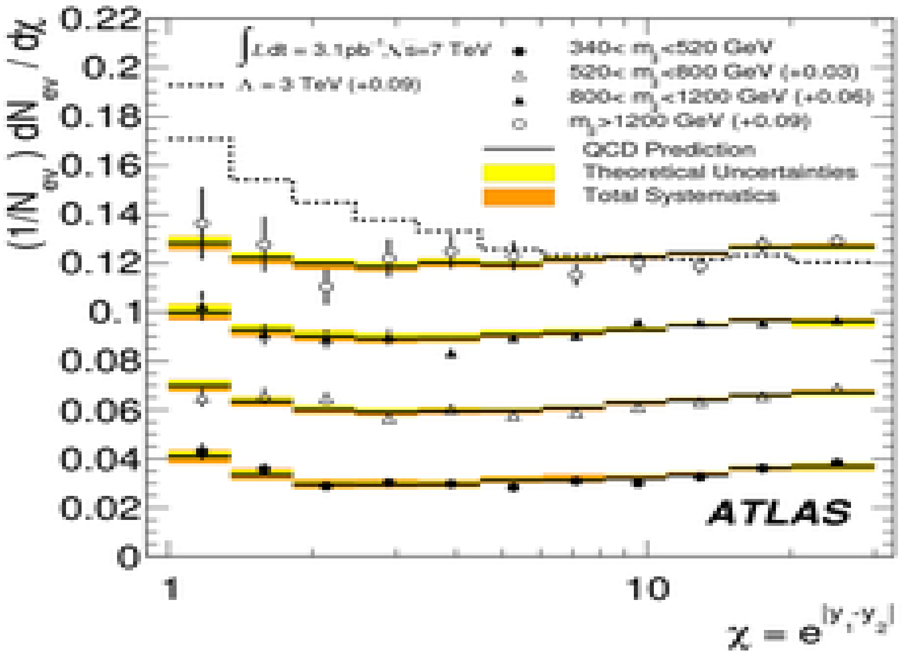






Exotic seaches with dijets



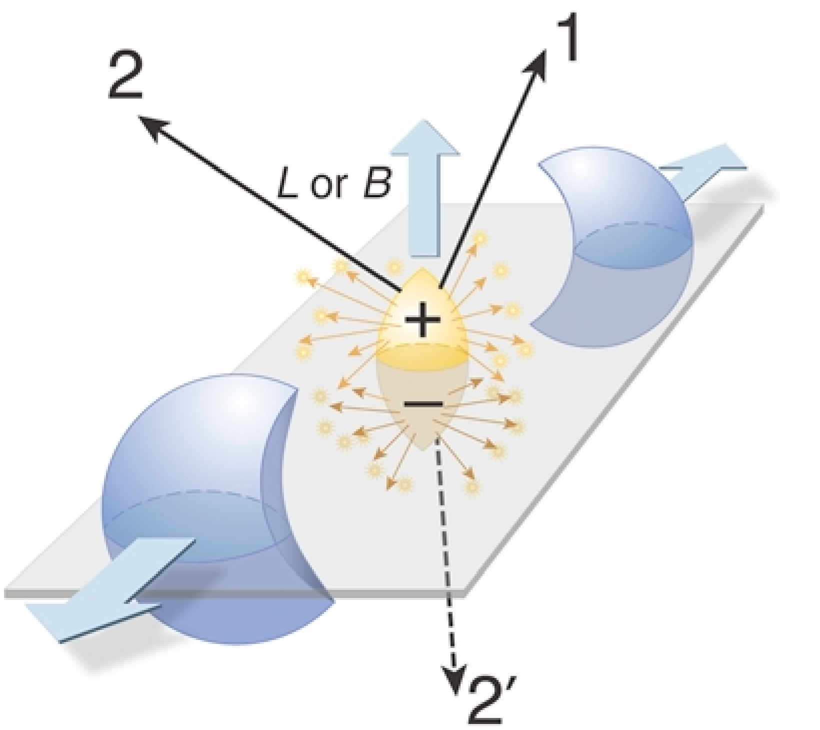


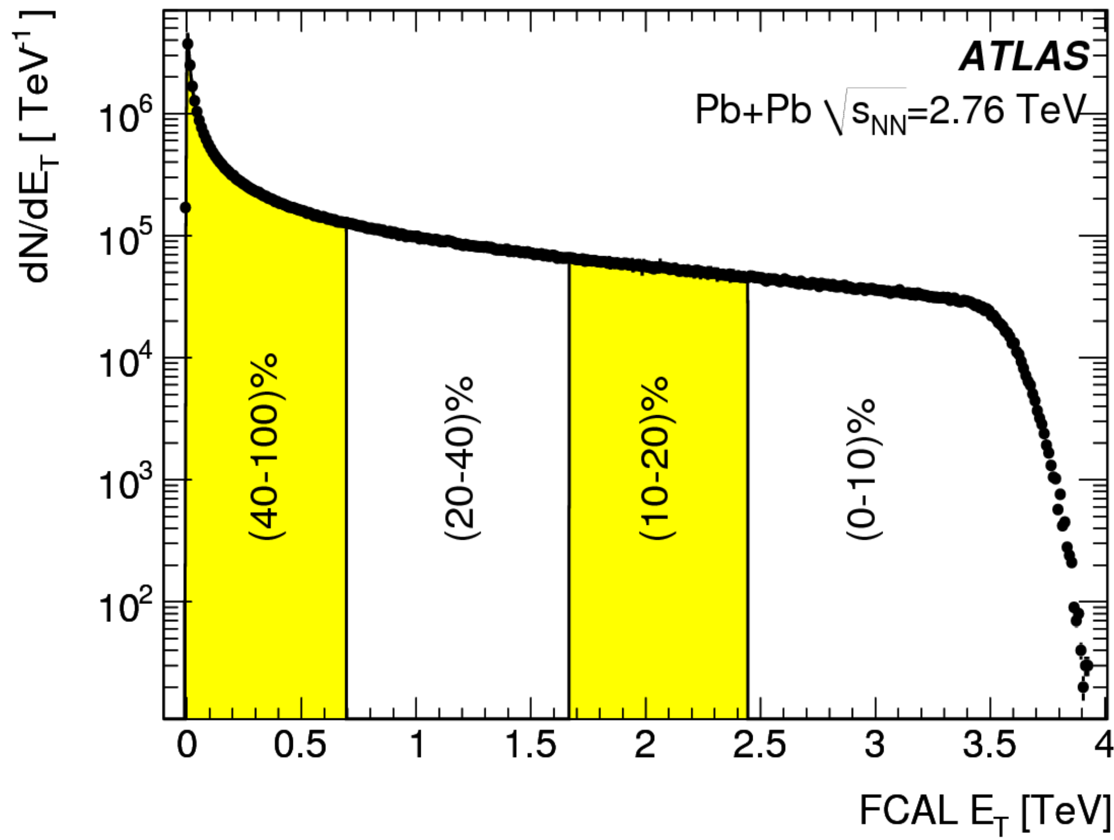
- Technicolor, colour interaction and low-mass gragvity models all predict productin of resonances, mainly decaying into dijets. Dijet distributions can be interpreted in the framework of new physics search

HI collisions: monojets

- Last month of LHC running in 2010 was dedicated to lead collisions, to see if a new state of matter, a quark-gluon plasma expected to precede quark hadron formation after the big bang can be seen
- One of the predictions is observation of events with an isoloated jet one side, and sparse activity on the other, sign that a parton from a periferal collision had to cross the plasma and was scattered (while the one exiting the other direction was not, giving a nice jet)

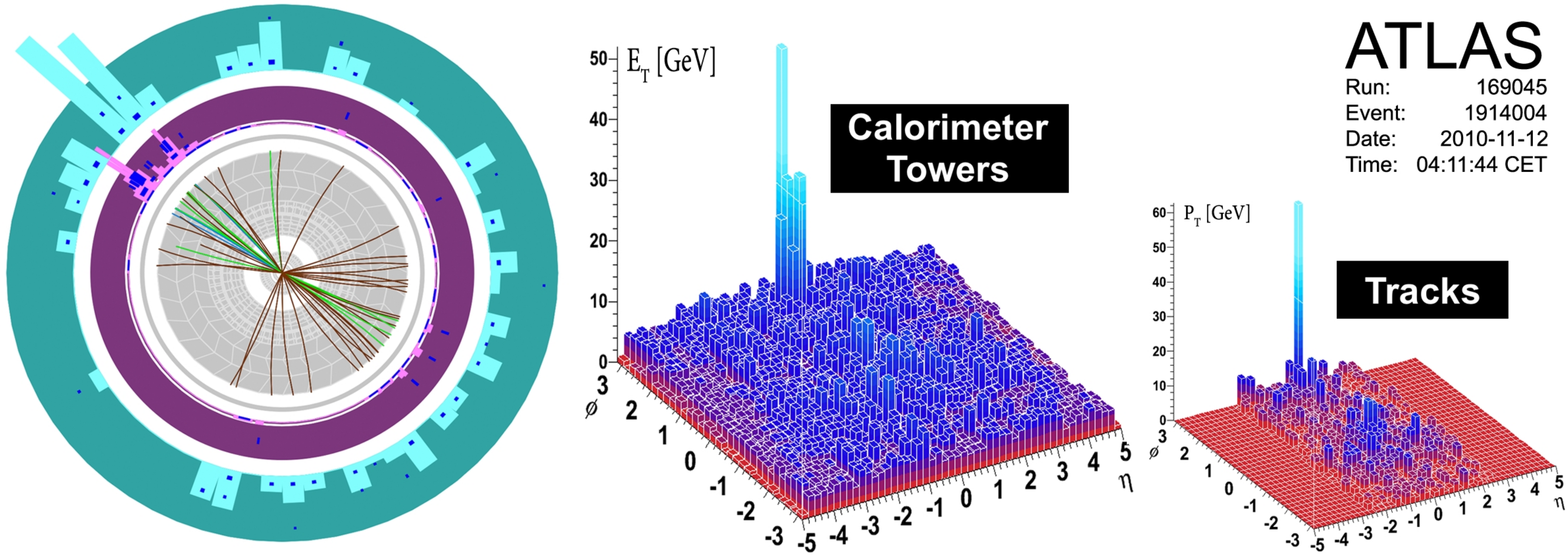
Centrality





- Nucleai are not pointlike, so behaviour depends on overlap between them in space. This can be measured from the energy deposition in the forward calorimeter
- Jet quenching due to QGP expected in ultraperipheral events

Monojet events



- Clear evidence for jet quenching have been found and very quickly published- also distributions for ultra-peripheral events do not agree with unquenched MonteCarlo
- Great success of the HI program, first LHC discovery

Conclusions

- As you saw, the physics program of the LHC is huge (only gave a few snapshots), and even if legions of physicists 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
- Higgs and new physics search just started, checking out BG first
- Baseline program: run at 7 TeV in 2011 to collect 1 fb-1
- Insistent rumors: we may run at 8 TeV, and extend to 2012
- If something is found, it will be hard to understand what it is, and in the past nature has often been more creative than our imagination.