Physics of (Large) Hadron Colliders

Mario Campanelli

University College London

Atlas/CDF Collaborations

Outline

- Introduction to hadron collider physics
- Machine considerations: Tevatron vs LHC
- Present status
- Parton density functions and luminosity
- QCD physics
- Production of vector bosons and top
- Search for the Higgs boson
- Search for physics beyond SM

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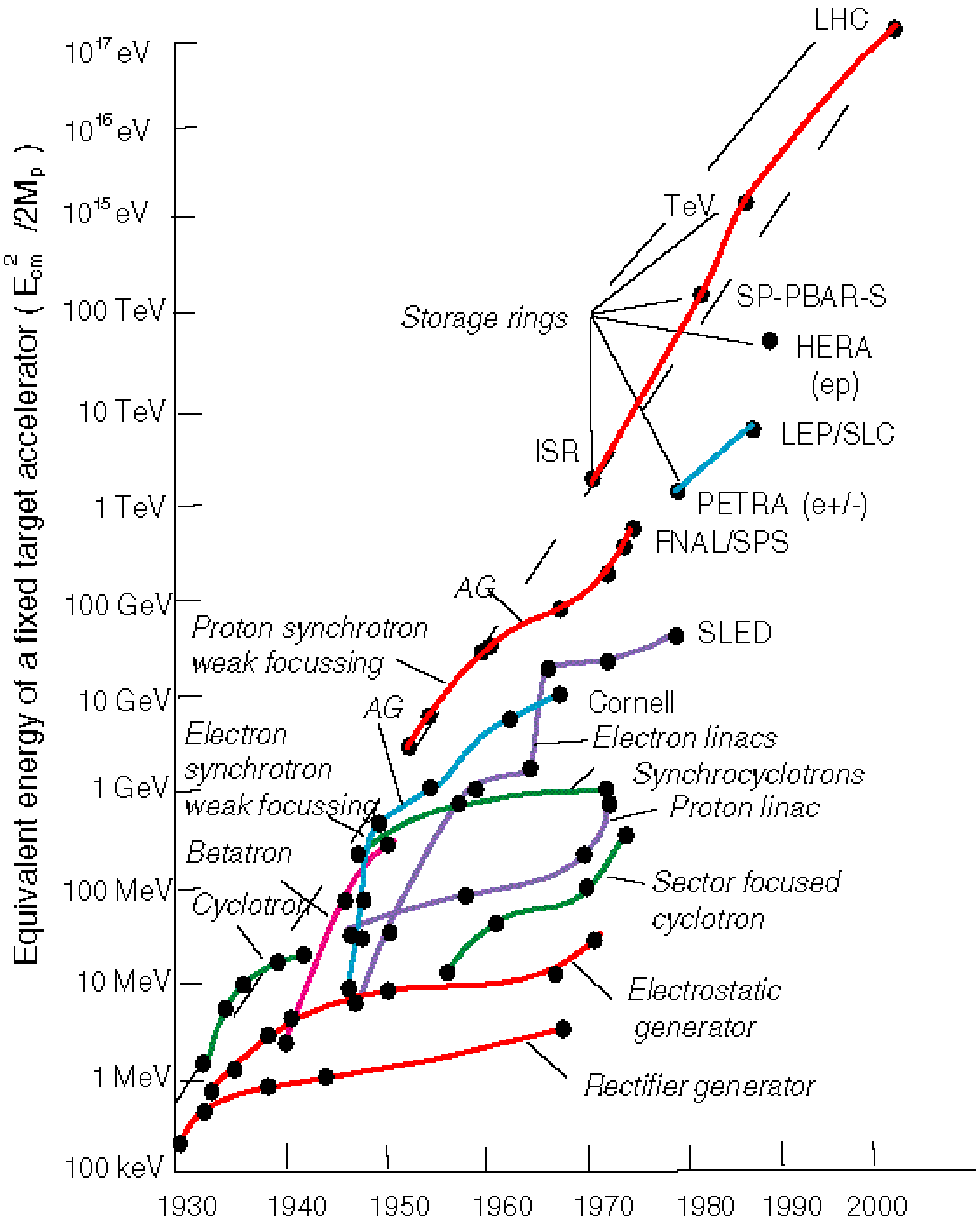


Lepton colliders provide cleaner events, and all energy is available in the final state. But:

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

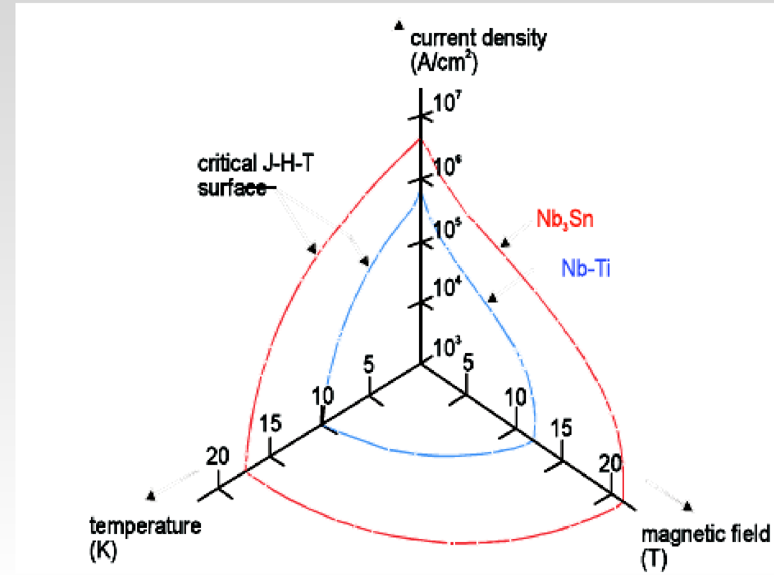
The highest currents, therefore the largest fields, are obtained using superconducting cables.

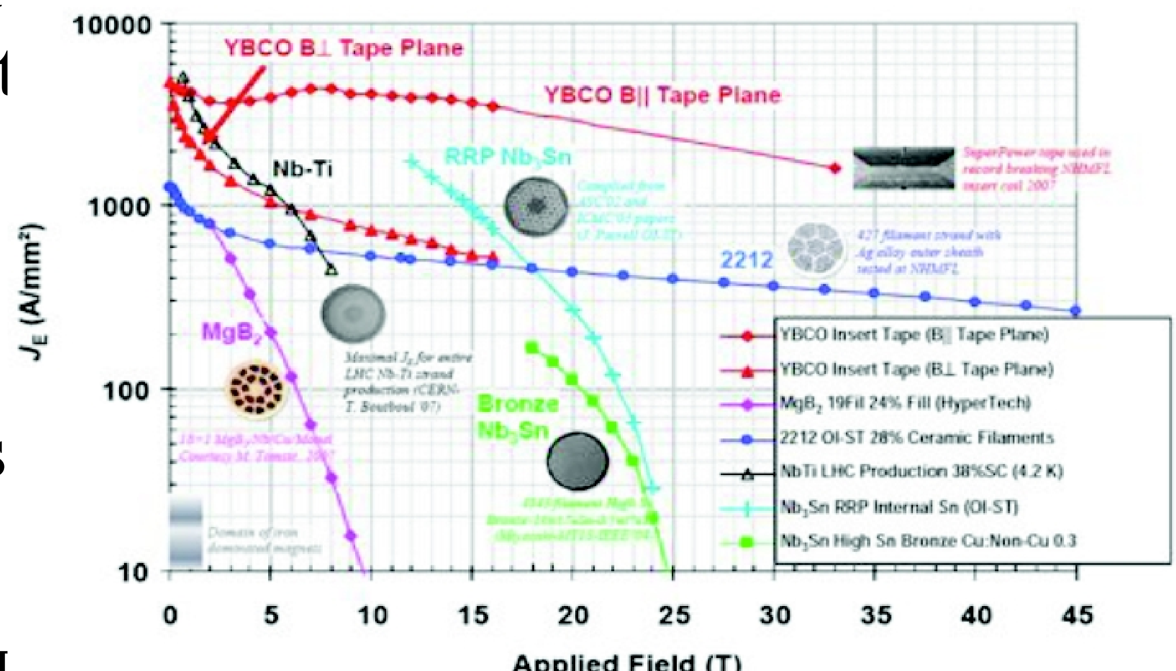
Unfortunately, phase transition between super-and normal conducting phase depends not only on temperature bu on magnetic fields. This se maximum field to 8.4T (100K times earth!).

Usually, about 70% of circumference has magnets

LHC: 0.3*8(T)*4.3(Km)*.7= 7 TeV

Tevatron: 0.3*4.2(T)*1(Km)*.7 = 1 T





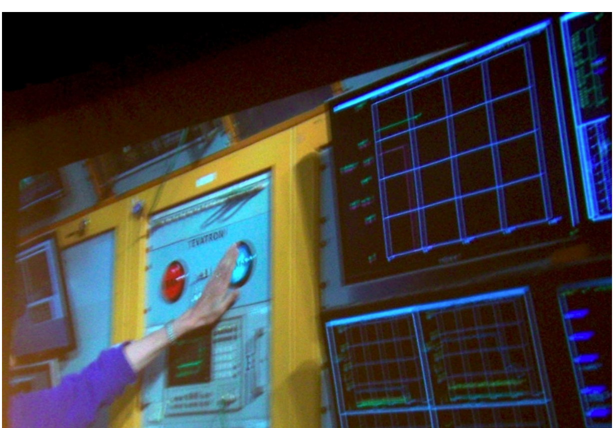
A bit of history... Tevatron

Curiously, both hadron colliders in the world are located in a second-hand tunnel.

Te Fermilab main ring was a 400 GeV accelerator started in 1972 working in fixed-target mode

In 1985, the ”energy doubler/saver” (Tevatron) was built just below the main ring, that was used as pre-accelerator

In 1999, a new main injector statred operation, for a 10x increase in luminosity.

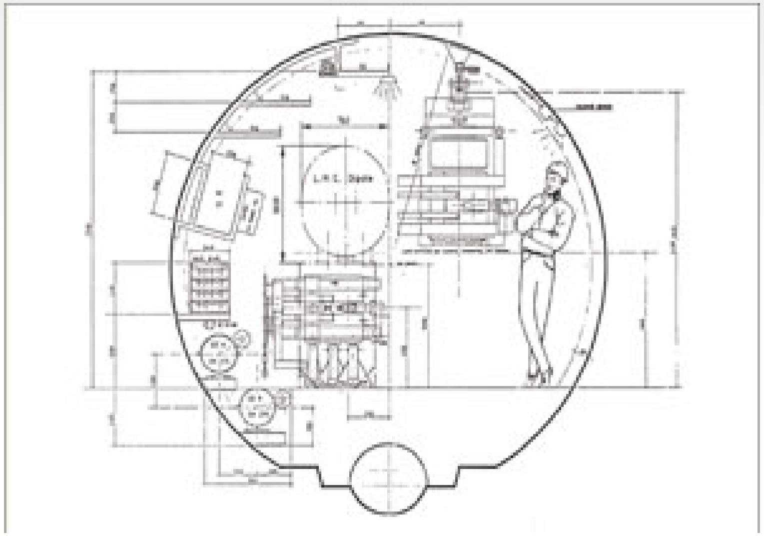


Tevatron was shut down on Friday Sept 30, 2011

A bit of history... LHC

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.

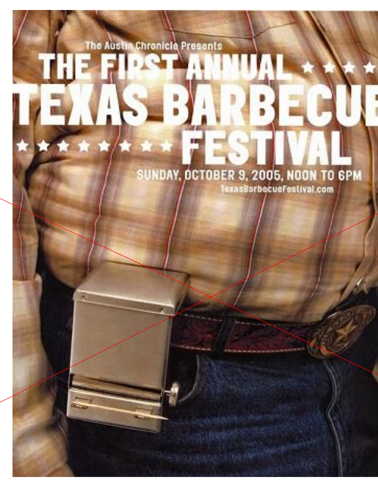


Already in spring 1984 (5 years before LEP started operations!) a workshop was held on the possibility of building ”a Large Hadron Collider” in the LEP tunnel

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)



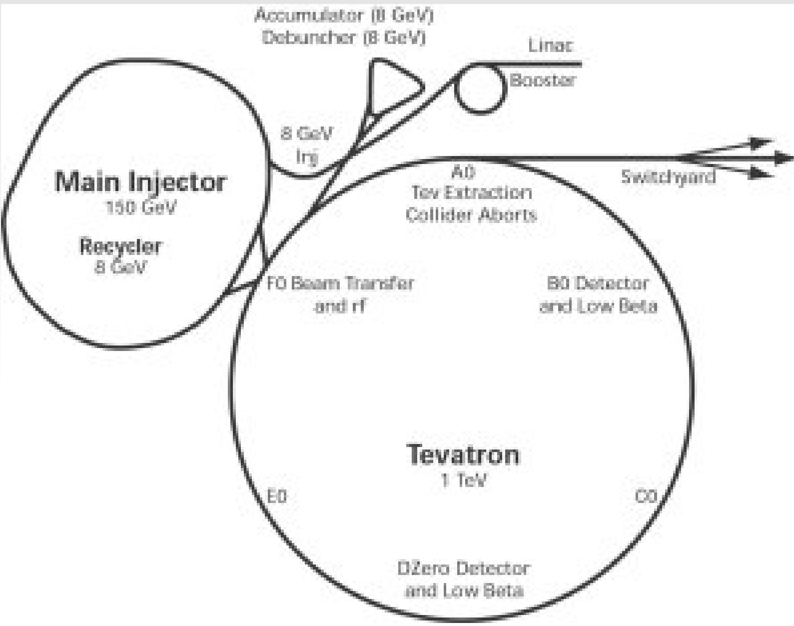
...maybe not so bad for our health...

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

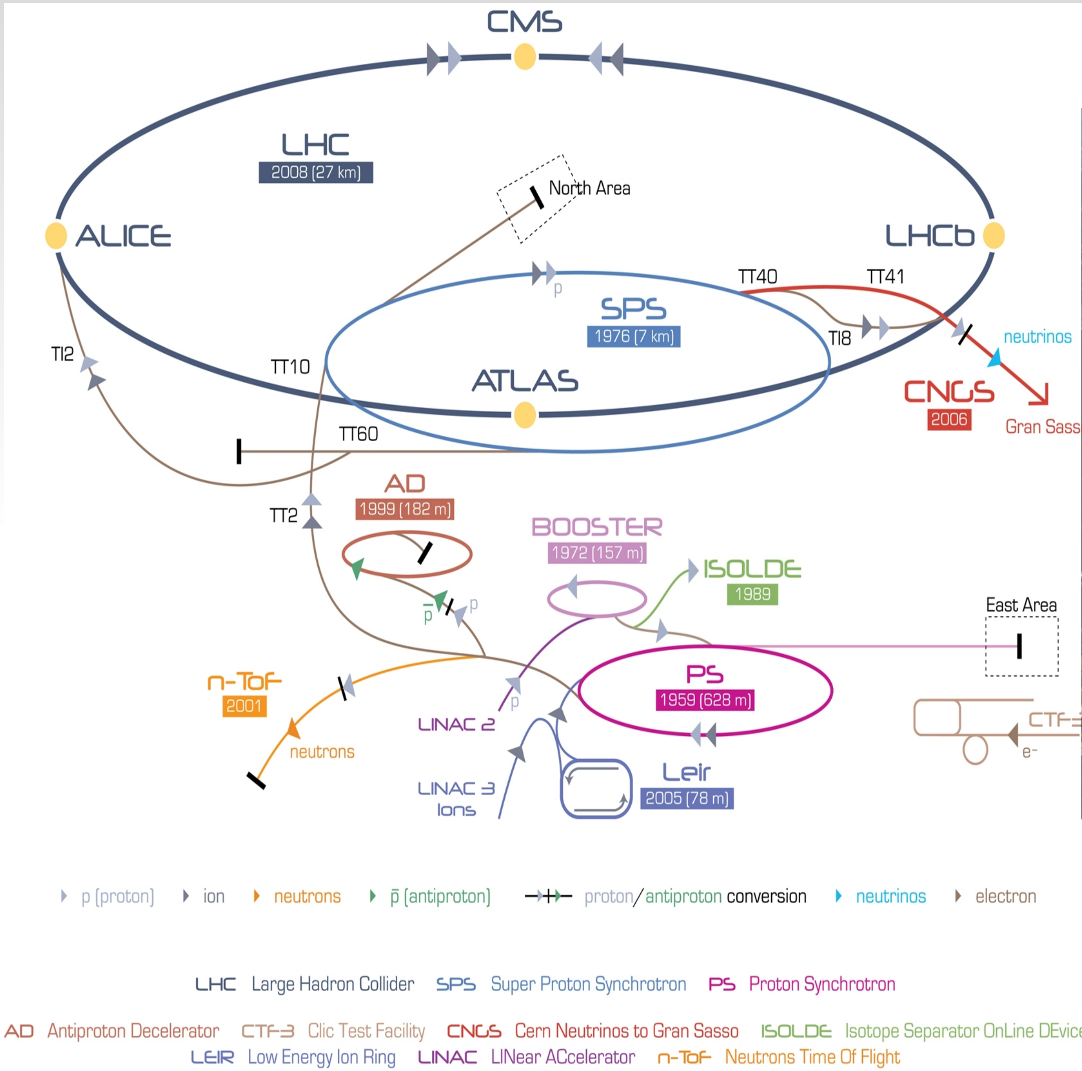
What LHC does not stand for (non examinable ;-)

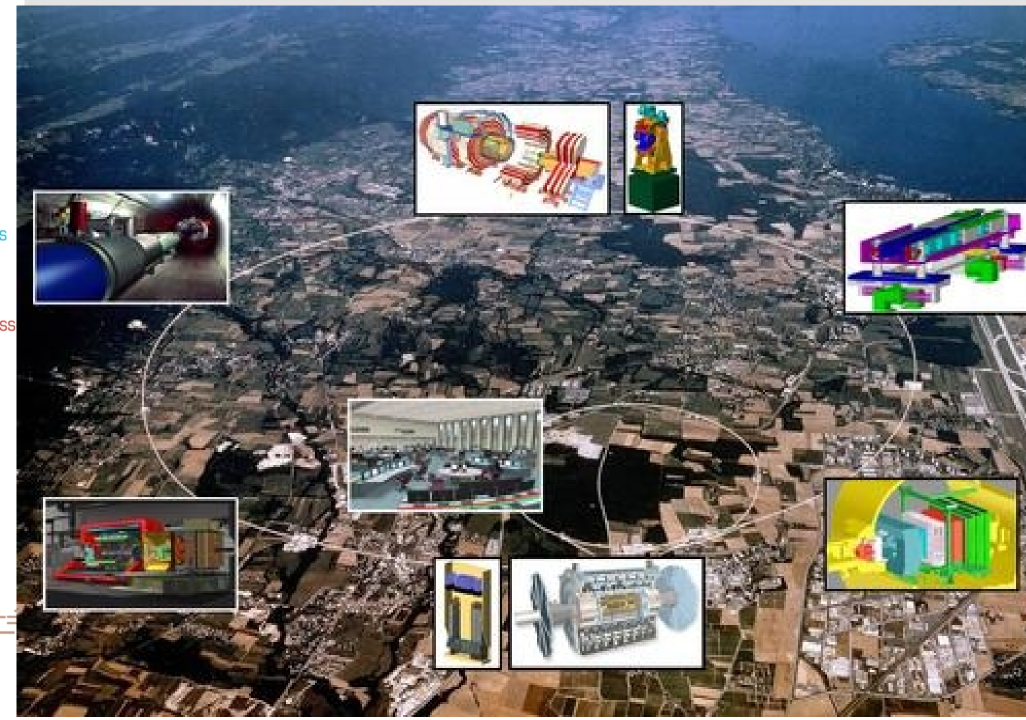
This is of course a joke... but this image (of a rock band of Cern secretaries active in the first 90es) was THE FIRST IMAGE EVER ON THE WEB

Fermilab accelerator complex



CERN accelerator complex



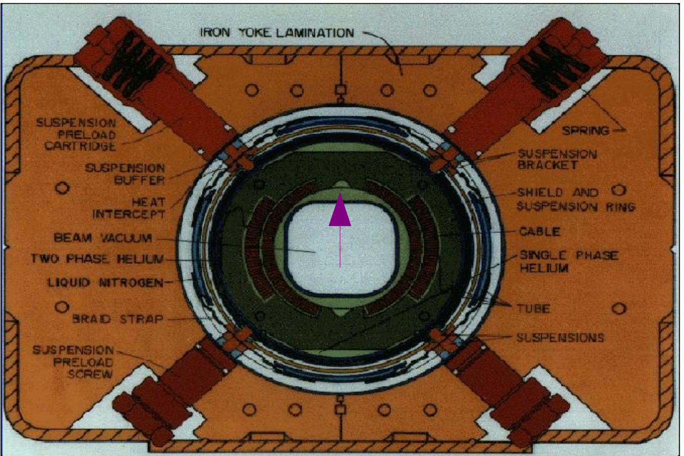


Geneva

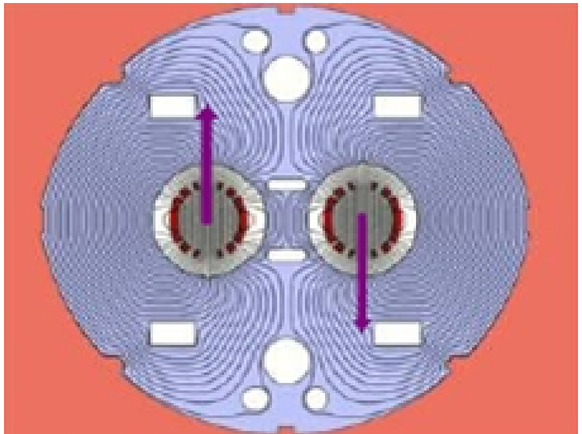
$p\bar{p}$ (Tevatron) vs pp (LHC)

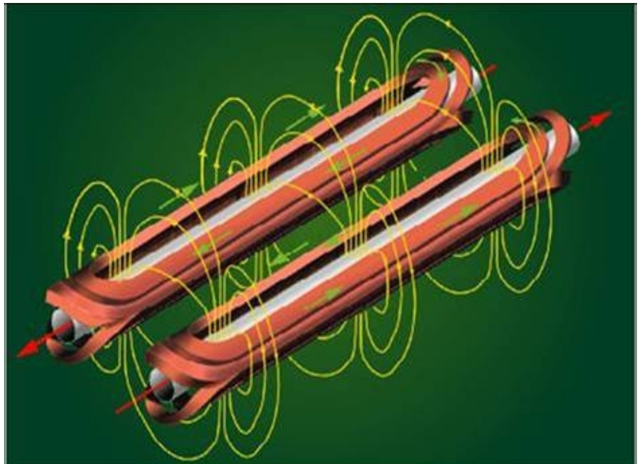
- Record number of protons in a Tevatron beam: 18E12
- Record number of anti-protons: 6E12; limiting factor
- It was decided at the LHC to collide protons-protons; already O(1E14) per beam achieved
- Most of interactions will be gluon-gluon (see later)
- Technical difficulty: get a very accurately opposite magnetic field

Tevatron magnet

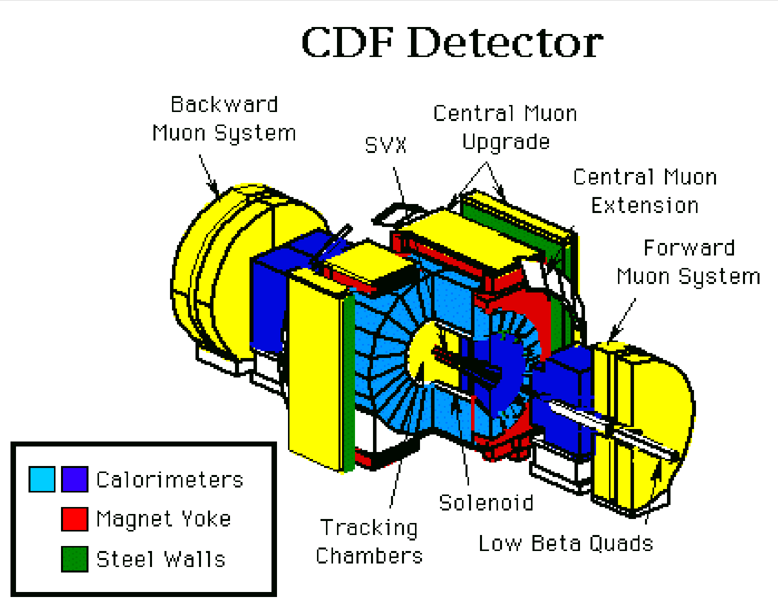


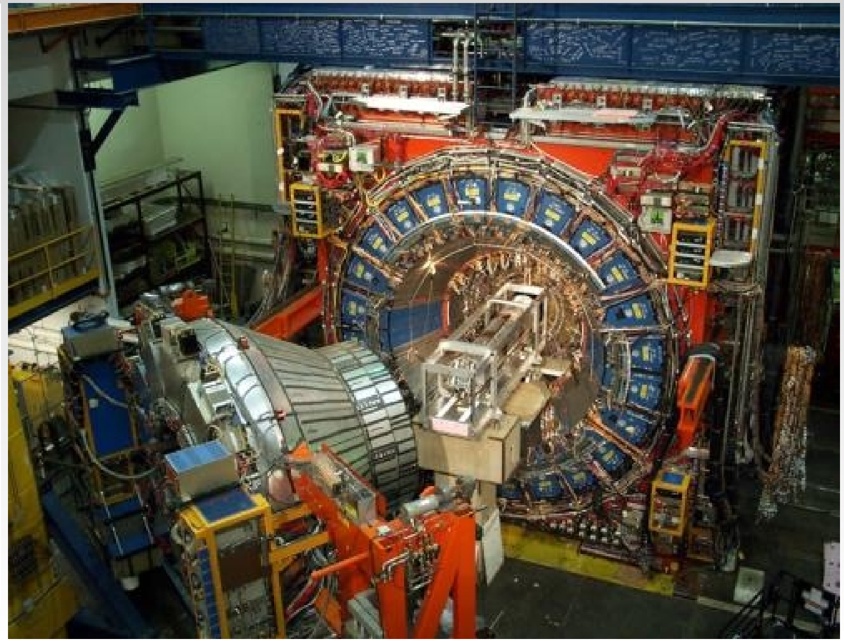
LHC magnet: much more complex magnetic configuration



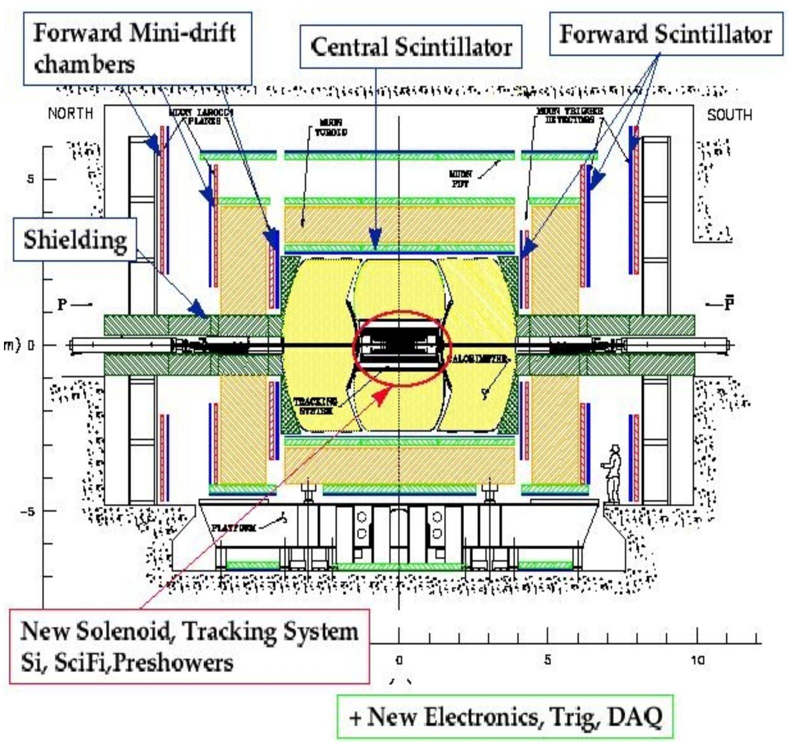


The Tevatron detectors



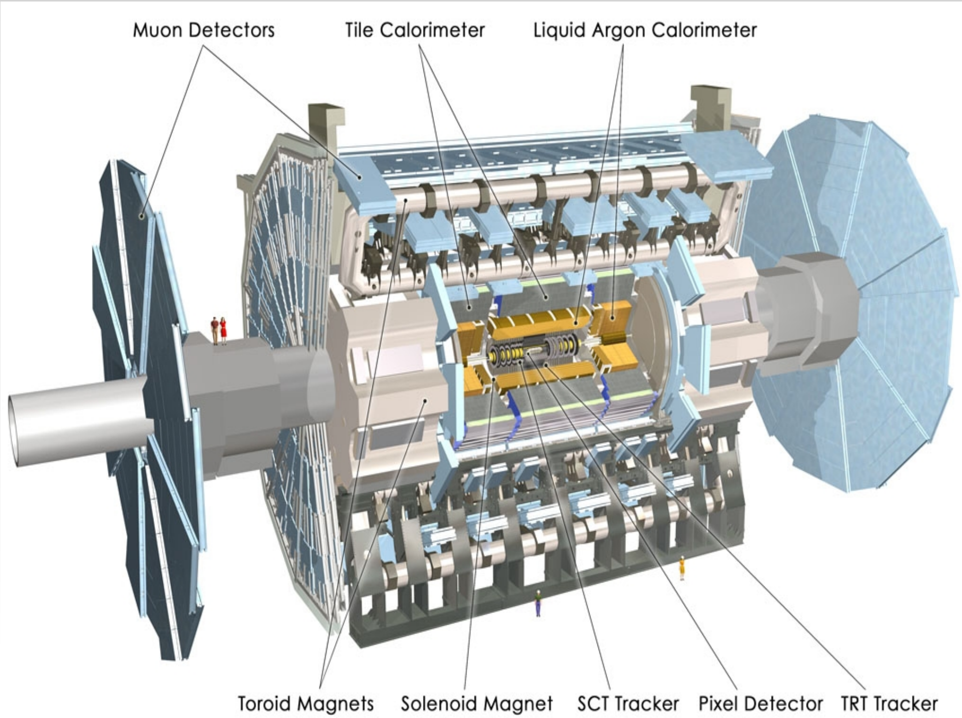


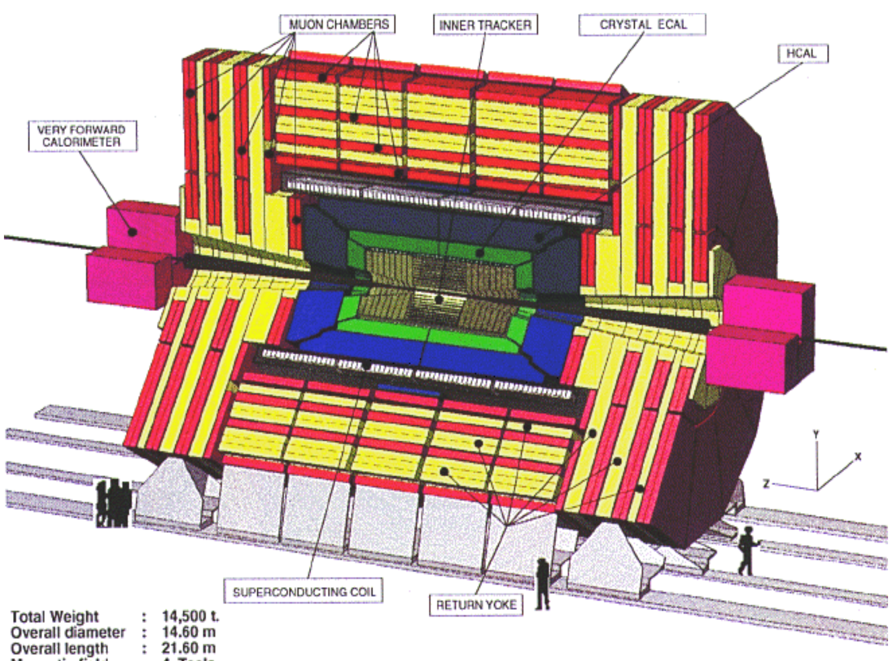
CDF had better tracker and muon detection, as well as a b-physics dedicated trigger



D0 had a Lar calorimeter with very good resolution and pointing; weaker magnetic field (none in RunI!)

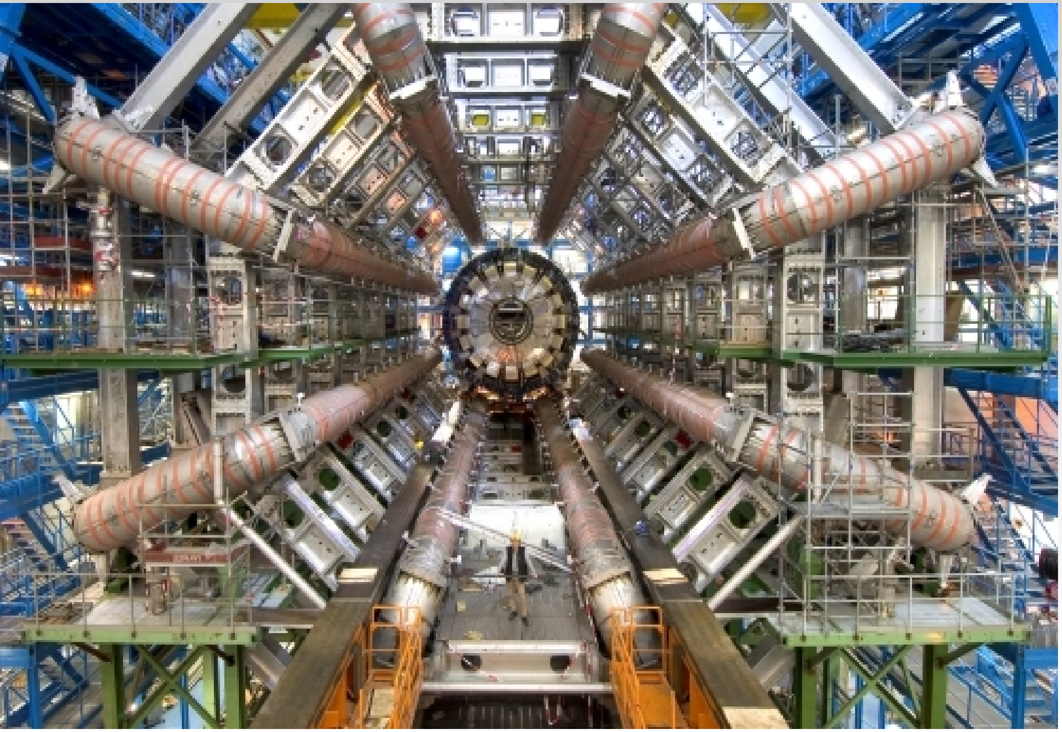
General-purpose LHC detectors

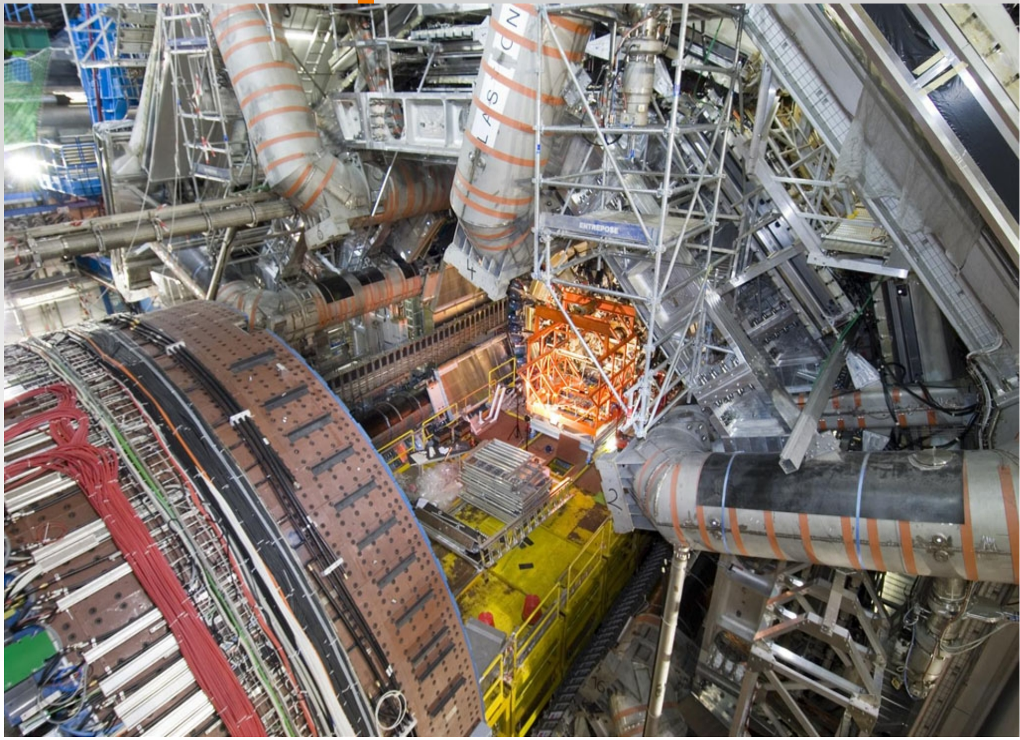


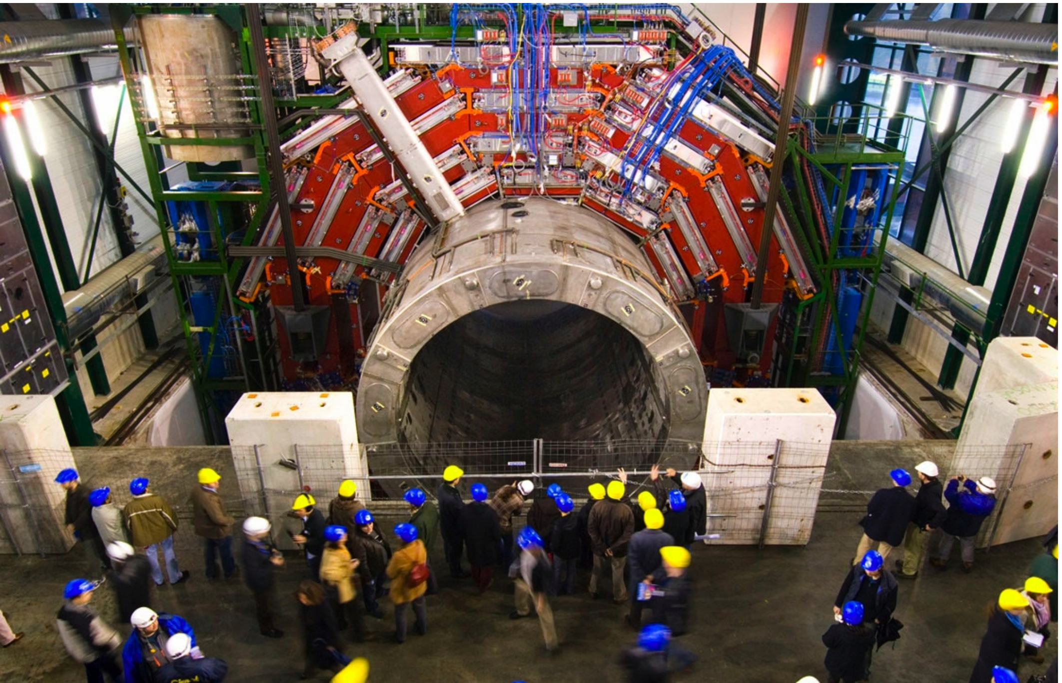


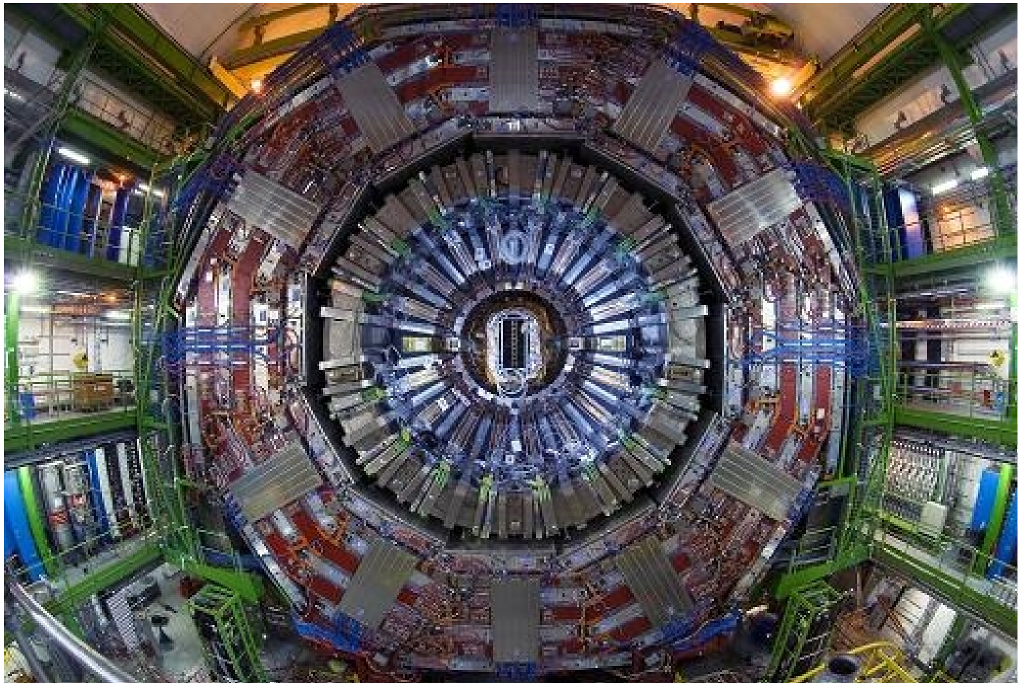
- Atlas: 1 solenoid (2T) and 8 + 2 toroidal magnets (!)
  - Air-core muon chambers (good stand-alone muons)
  - Liquid Argon e.m. Calorimeter
- CMS: 1 solenoid magnet (4T) creates field inside and outside
  - Muon chambers in return yoke
  - 80000 $PbWO_4$ crystals as e.m. calorimeter

ATLAS and CMS-real pictures

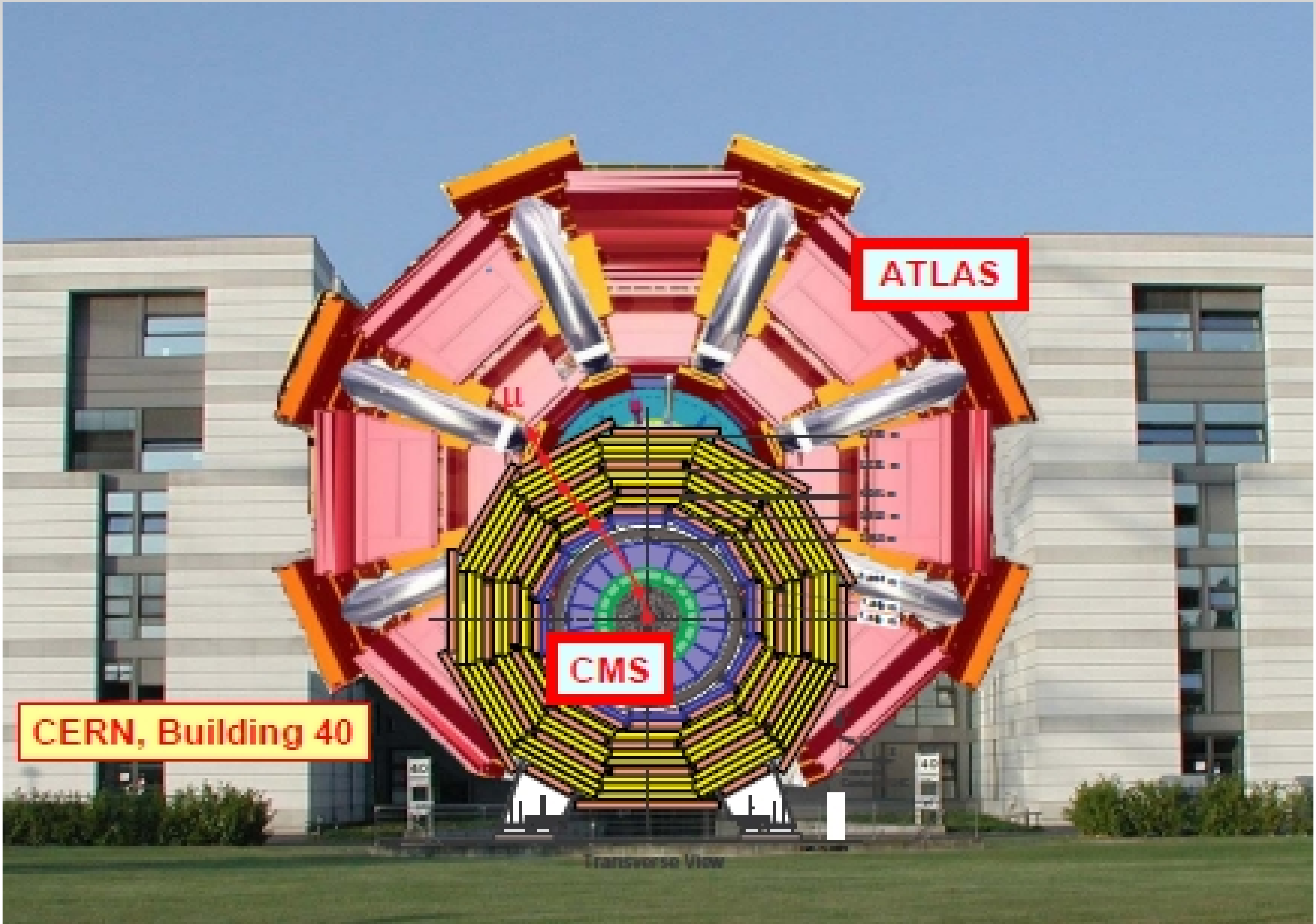




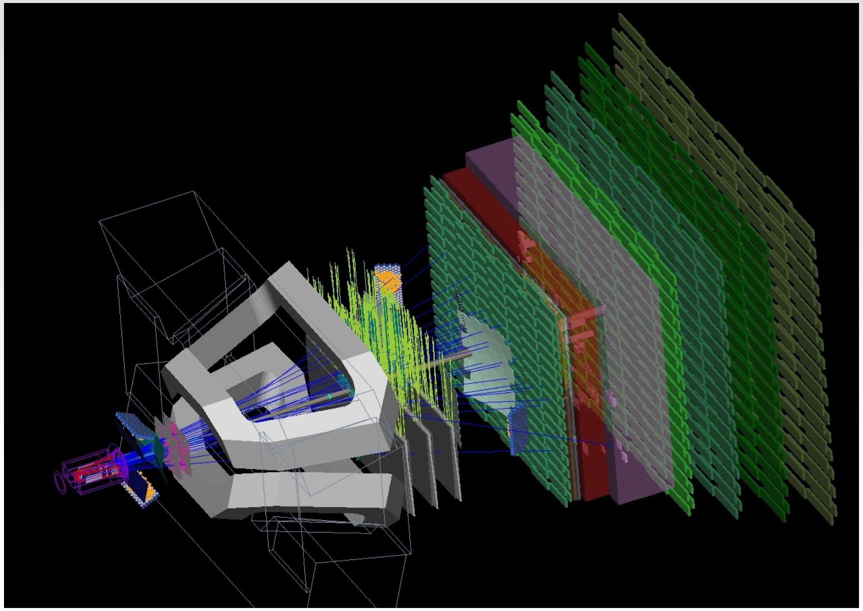


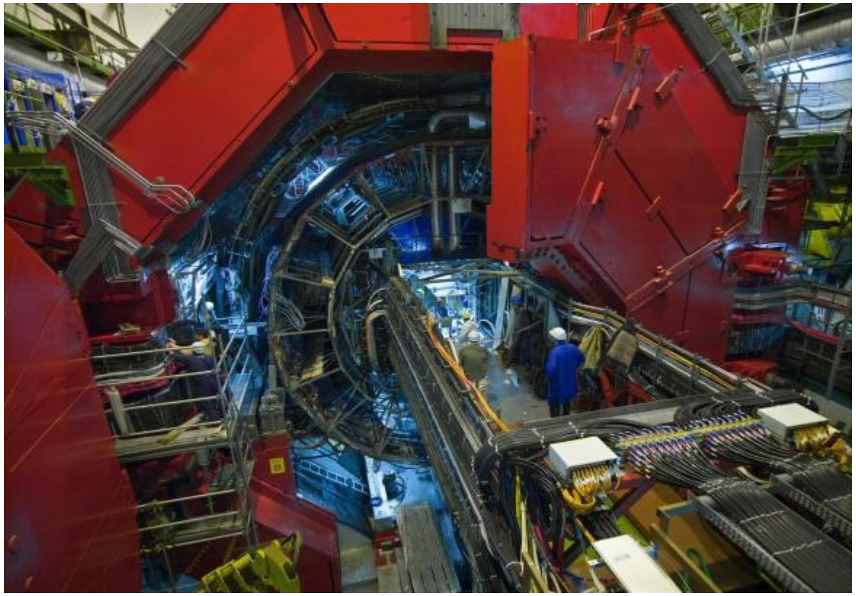


Why CMS stands for 'compact'



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

Some LHC beam 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 (2.5 Mhz at Tevatron; 20 Mhz at the LHC, with about 1000/3564 bunches occupied; LHC goal is 40 Mhz, with 2835/3564 bunches)
- A = crossing area = πr^2 where r (rms of transverse beam profile) is 35 μm at Tevatron 16 μm at LHC

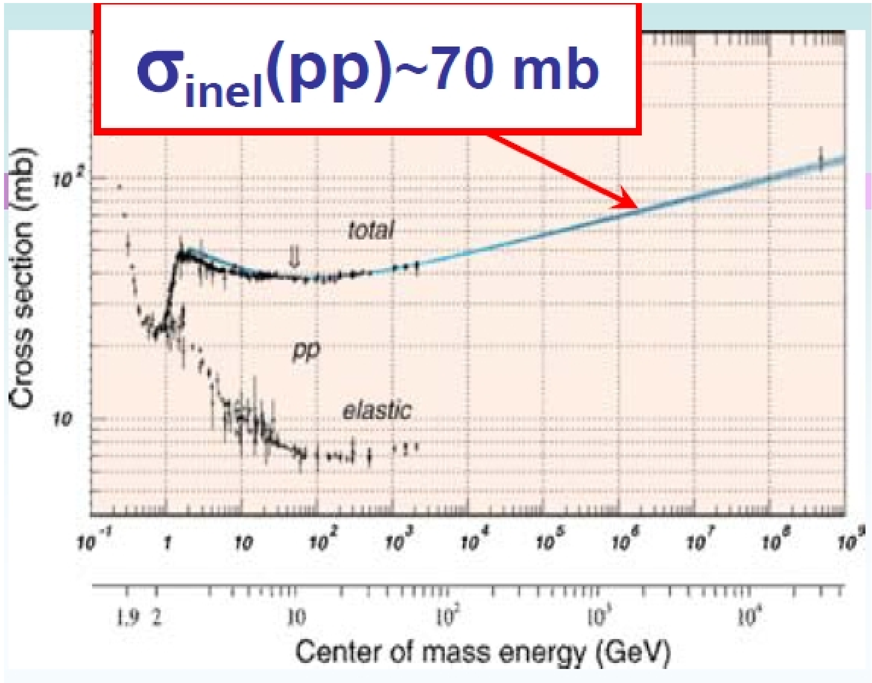
Integrated luminosity and pileup

- For LHC 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}

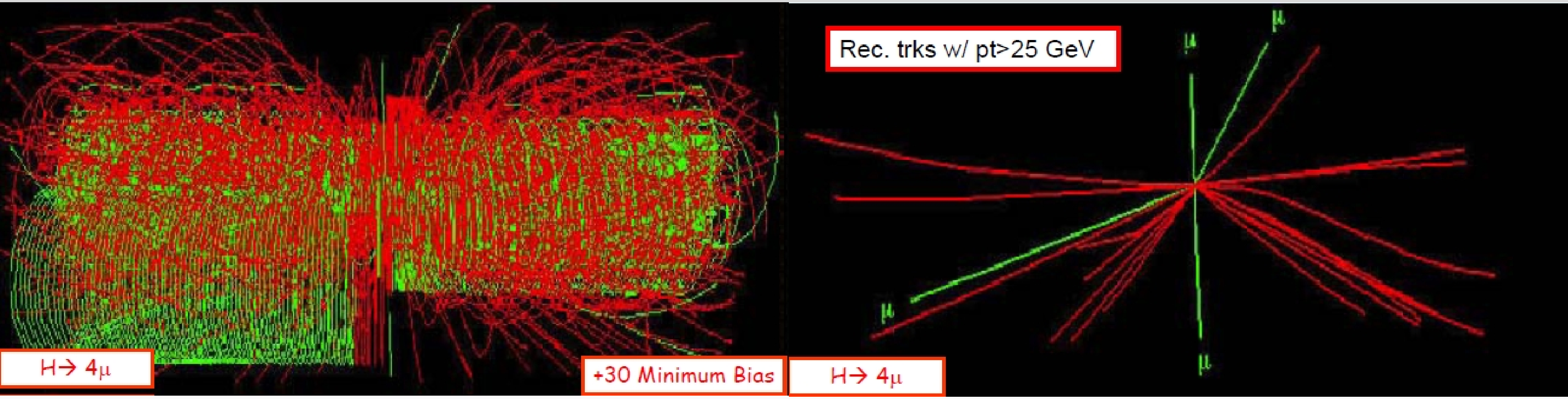
The total pp cross section is about 70 mb:



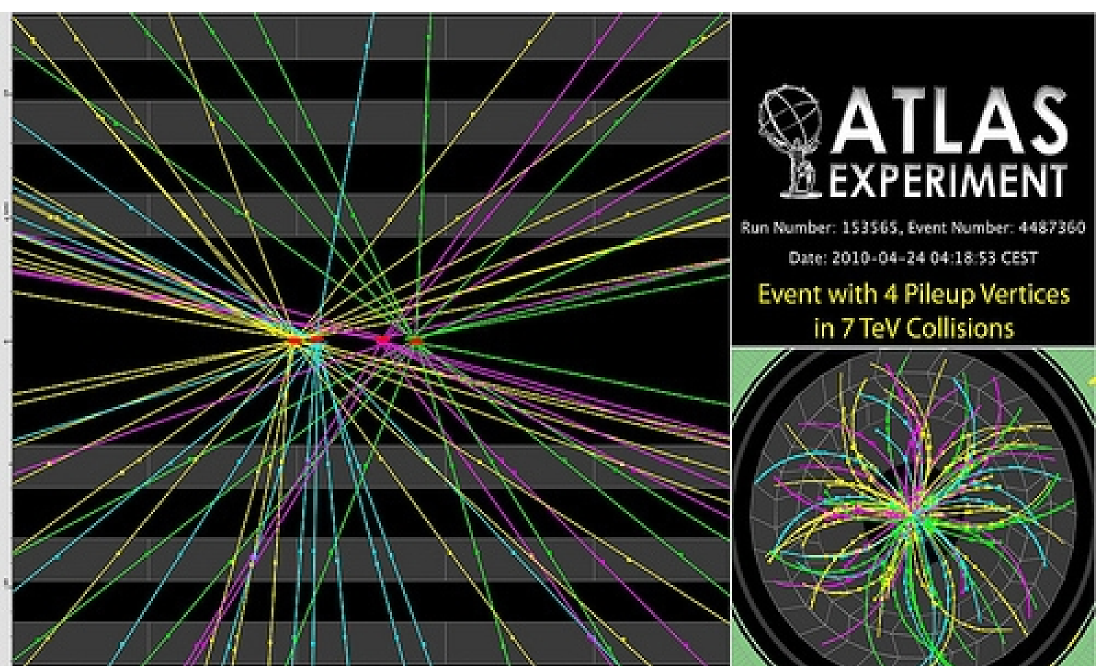
So, rate can go up to 700MHz! Divided by 40MHz bunch crossing rate, and accounting for empty bunches, we can have > 20 collisions/bunch crossing (pileup)

Pileup

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



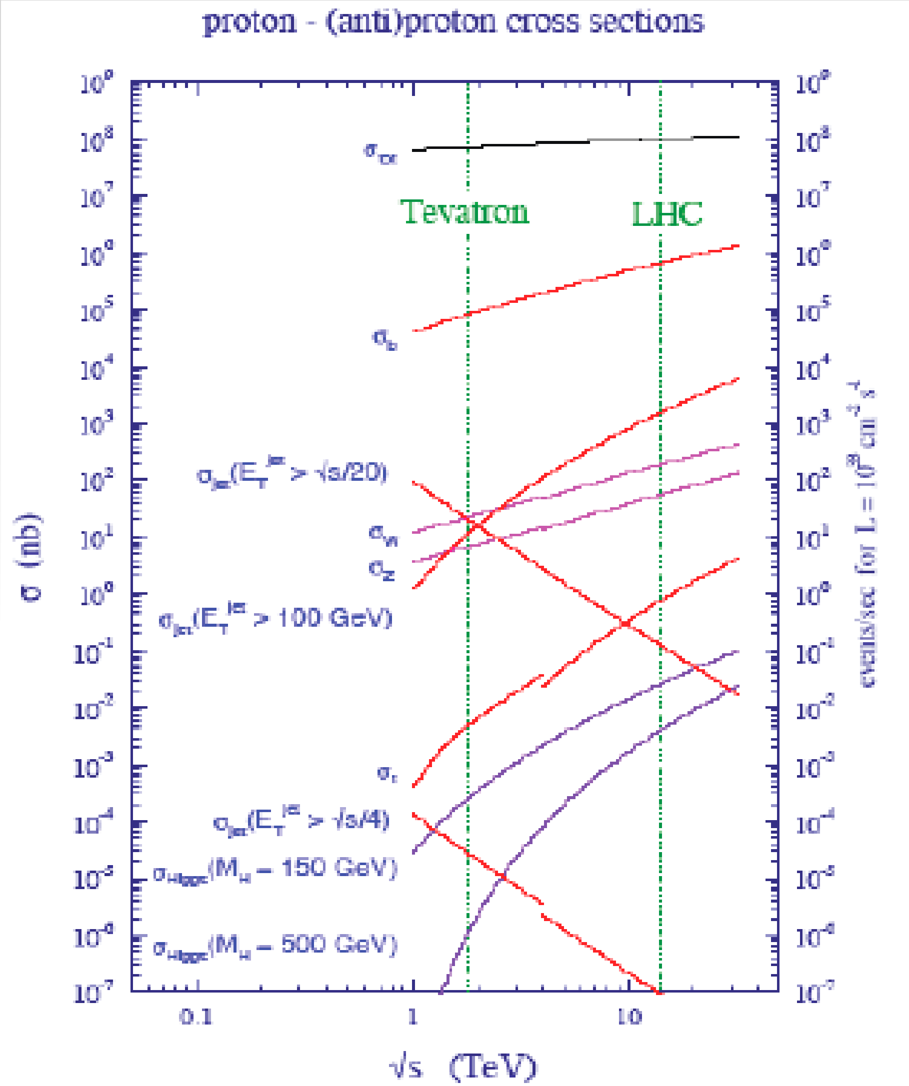
It gets much better if you just look at the energetic particles...



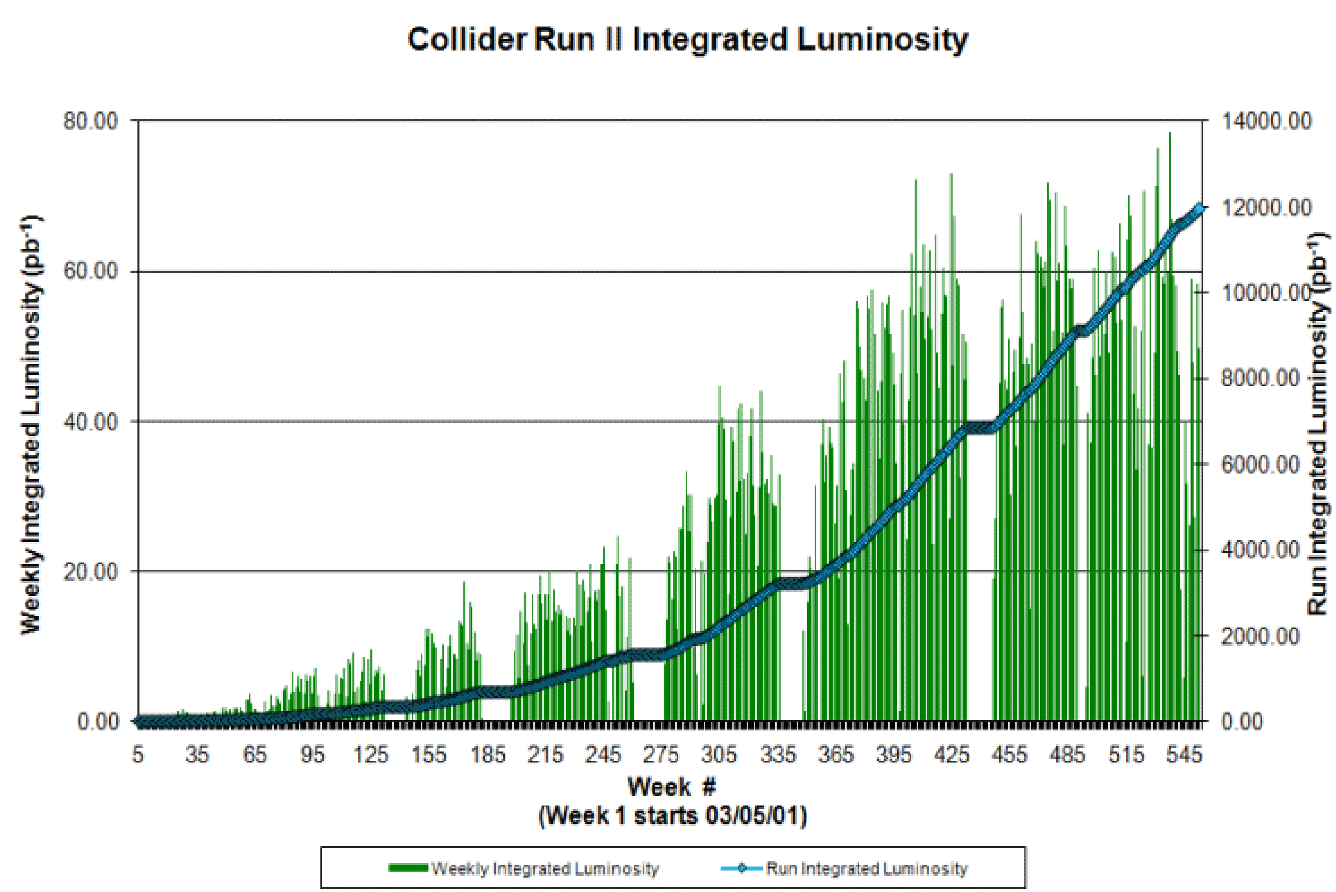
The best way to deal with pileup is to reconstruct along the beam axis the separate vertices from which charged tracks are coming from. Not obvious how to assign them to calorimetric clusters, especially now that number of pileup is about 20

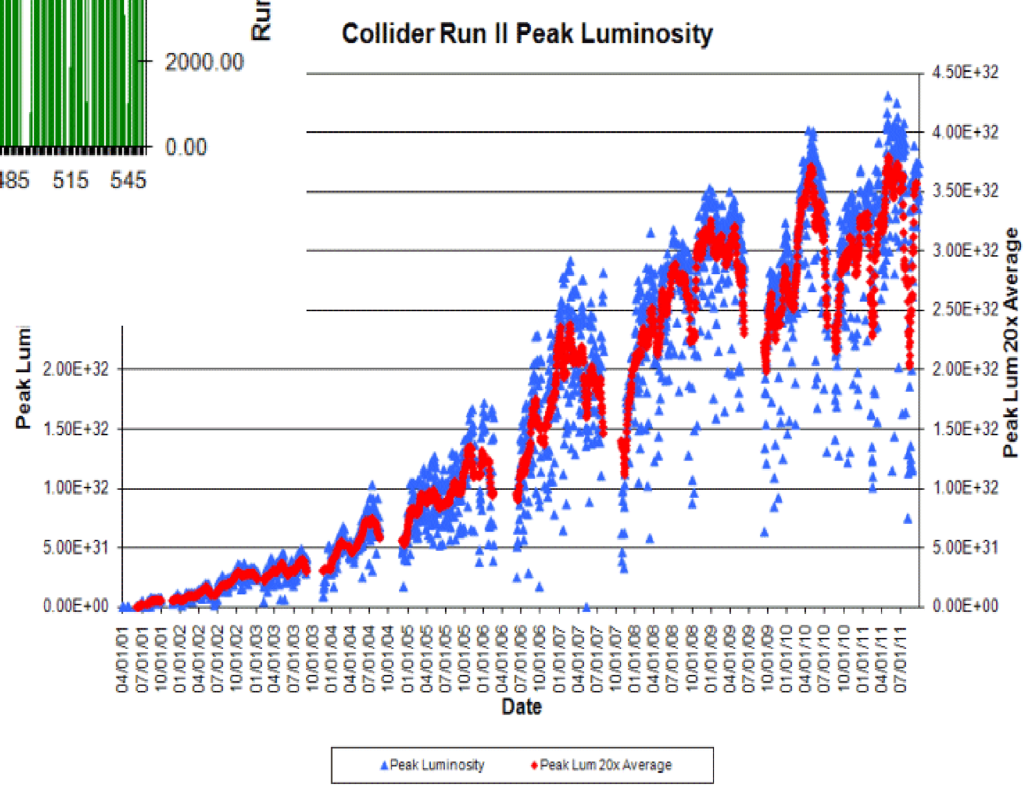
Cross sections in pp interactions

- 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



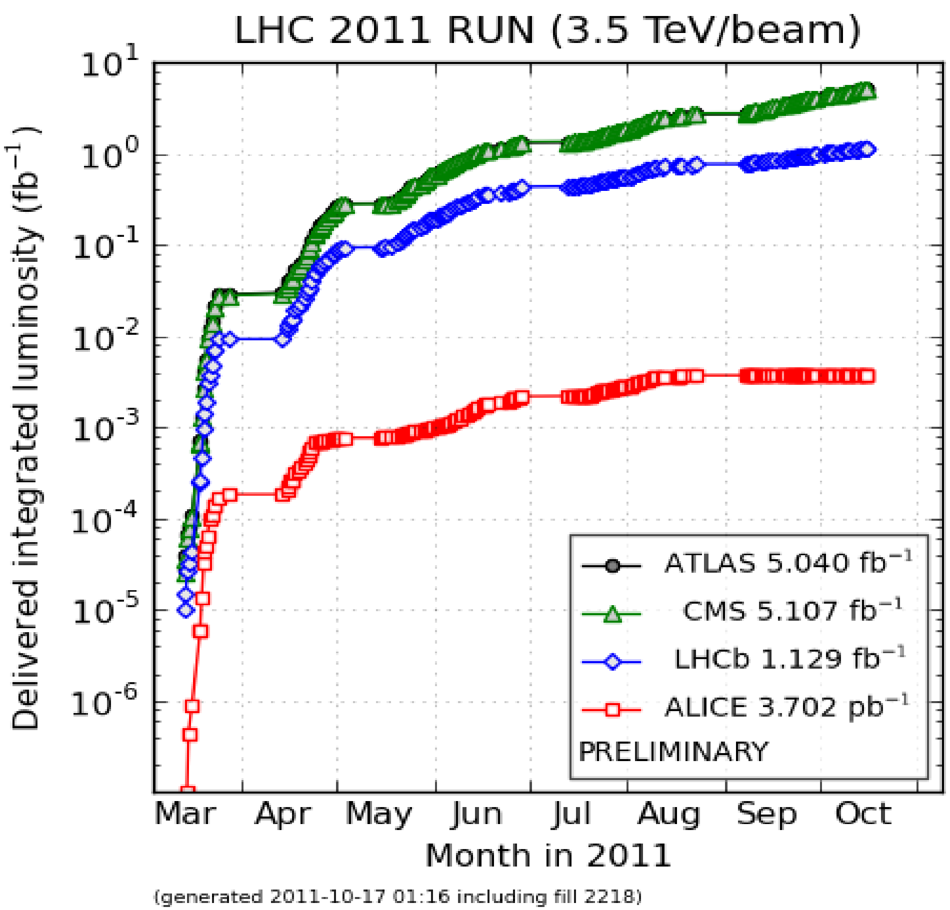
Tevatron luminosity

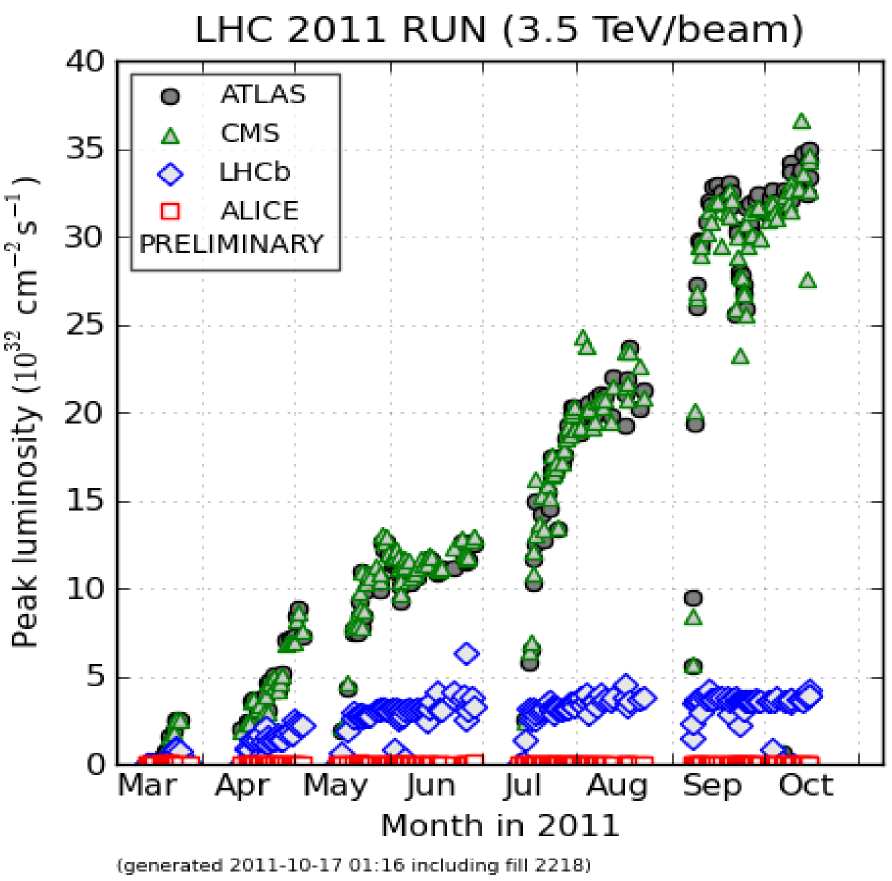




- Detector received >10 fb-1
- Peak luminosity ~4E32

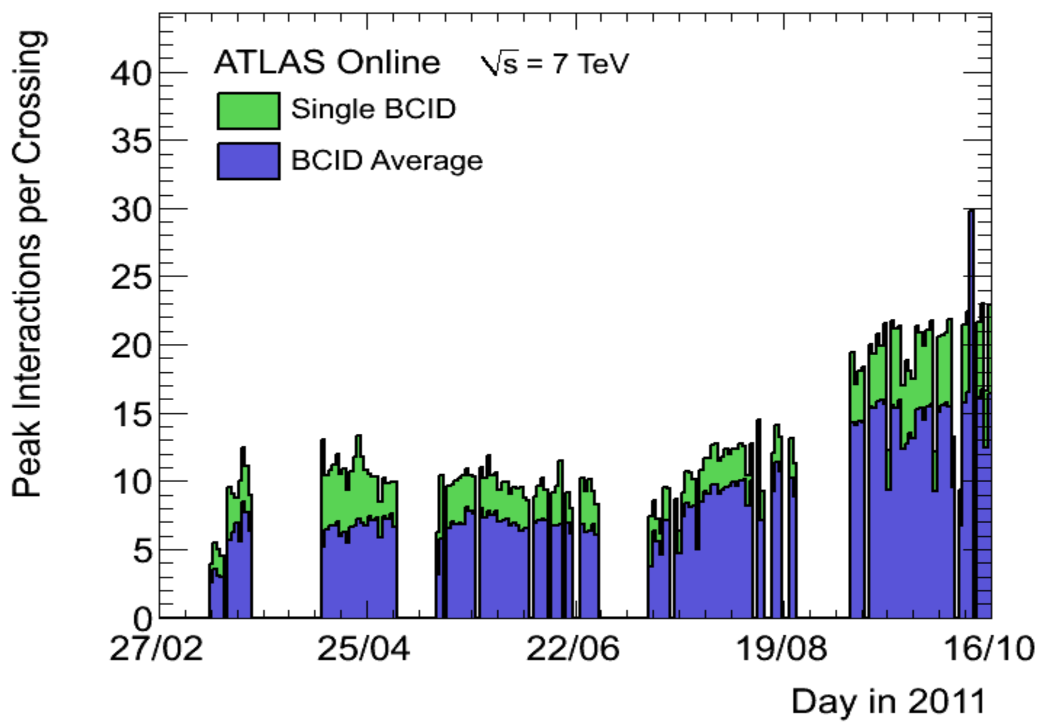
LHC Luminosity





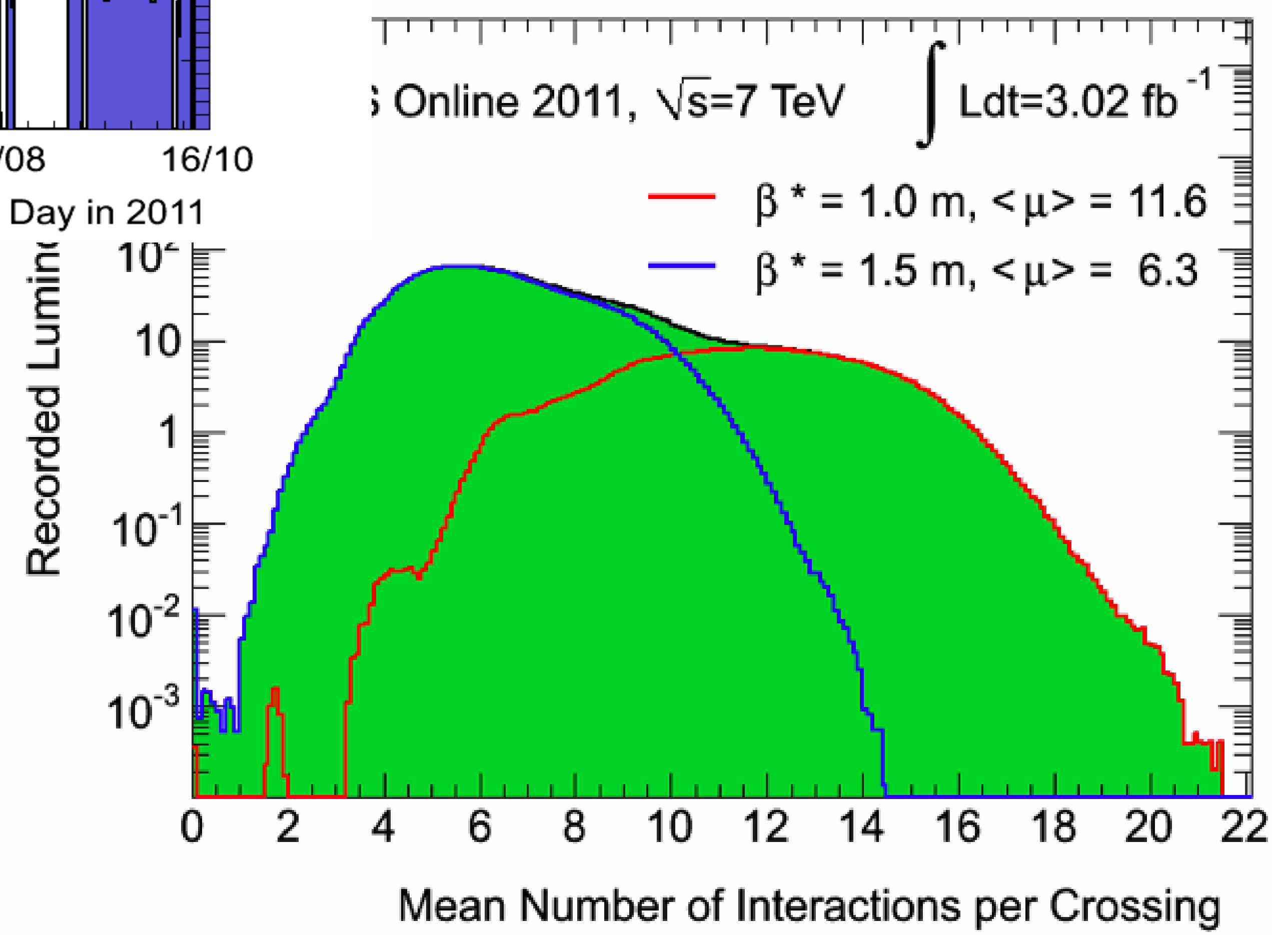
- In < 2 years, half the luminosity collected by Tevatron in 25 years
- 10x the peak luminosity (default for 2012: 1E34)

Pileup distributions



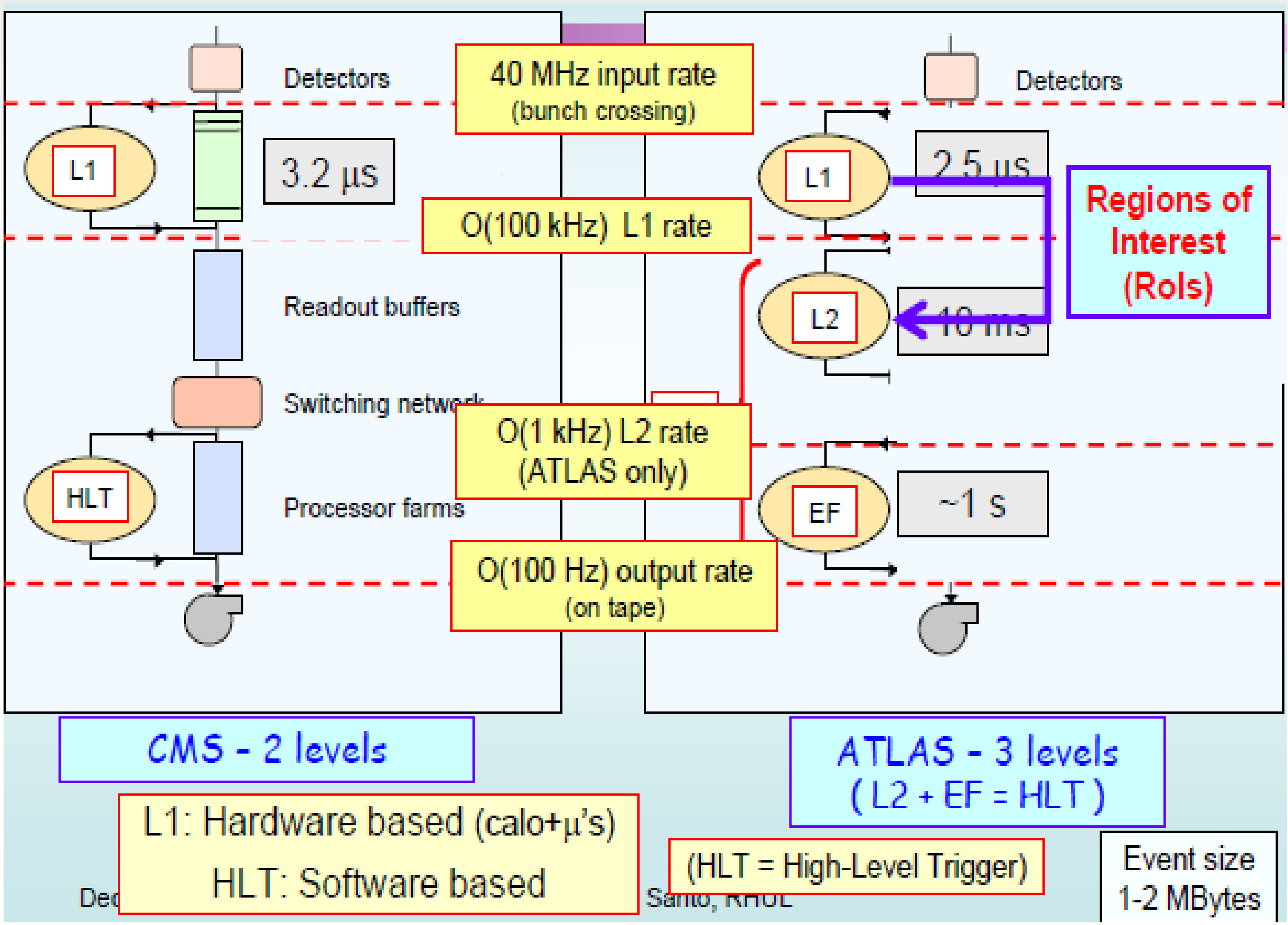
For most of 2011, the LHC has run with an average between 5 and 10 pileup events; after the focusing of the final magnets has been increased, pileup almost doubled

A way to increase luminosity without more pileup is to go from 20 KHz to 40 KHz operations, but injection issues may make this difficult next year

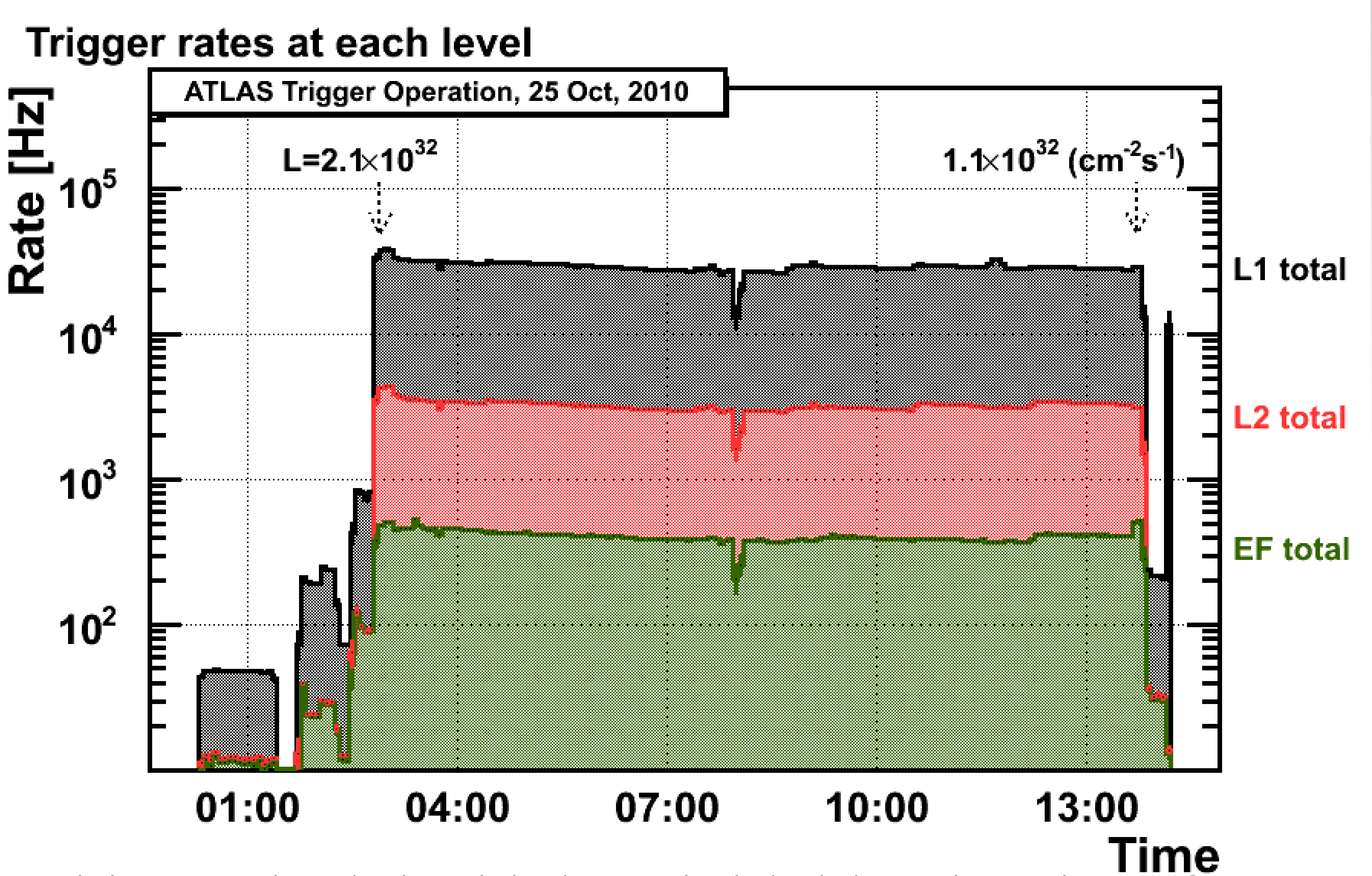


Triggering

- 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:



ATLAS trigger rates

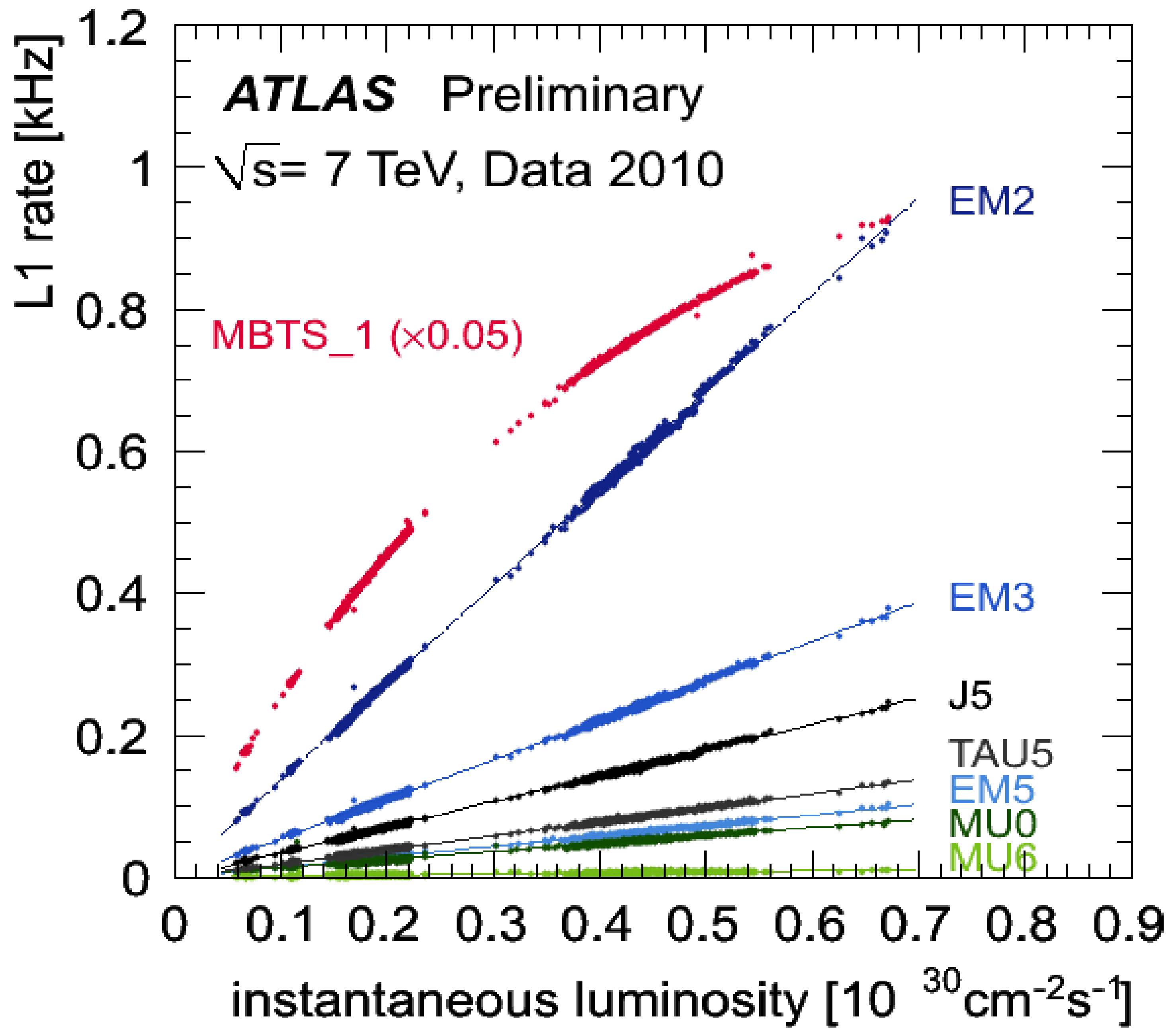


- This run had the highest initial luminosity of 2010
- Trigger bandwidth saturated at the three levels

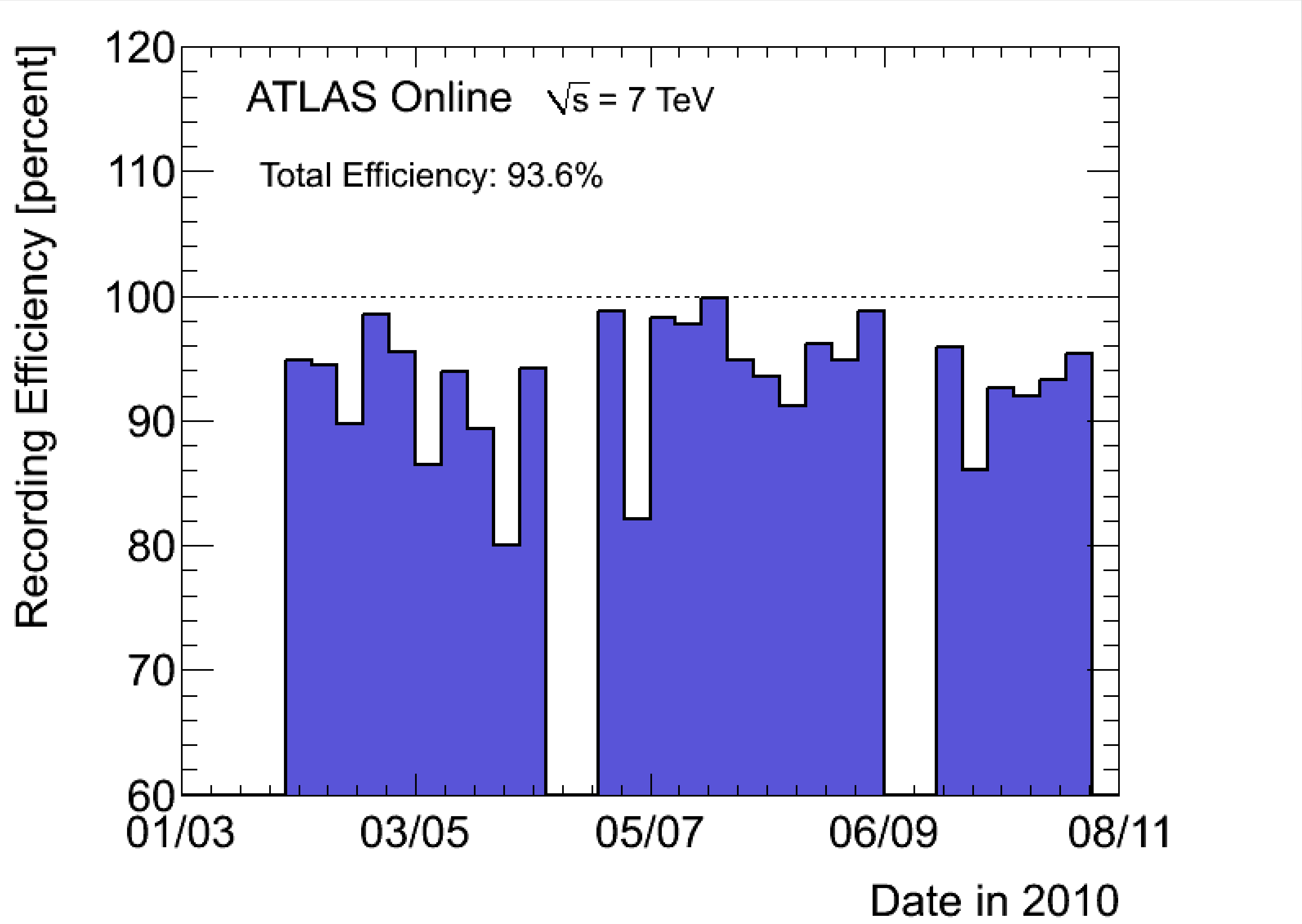
L1 Trigger rates vs luminosity

Rates still linear since in no-pileup region.

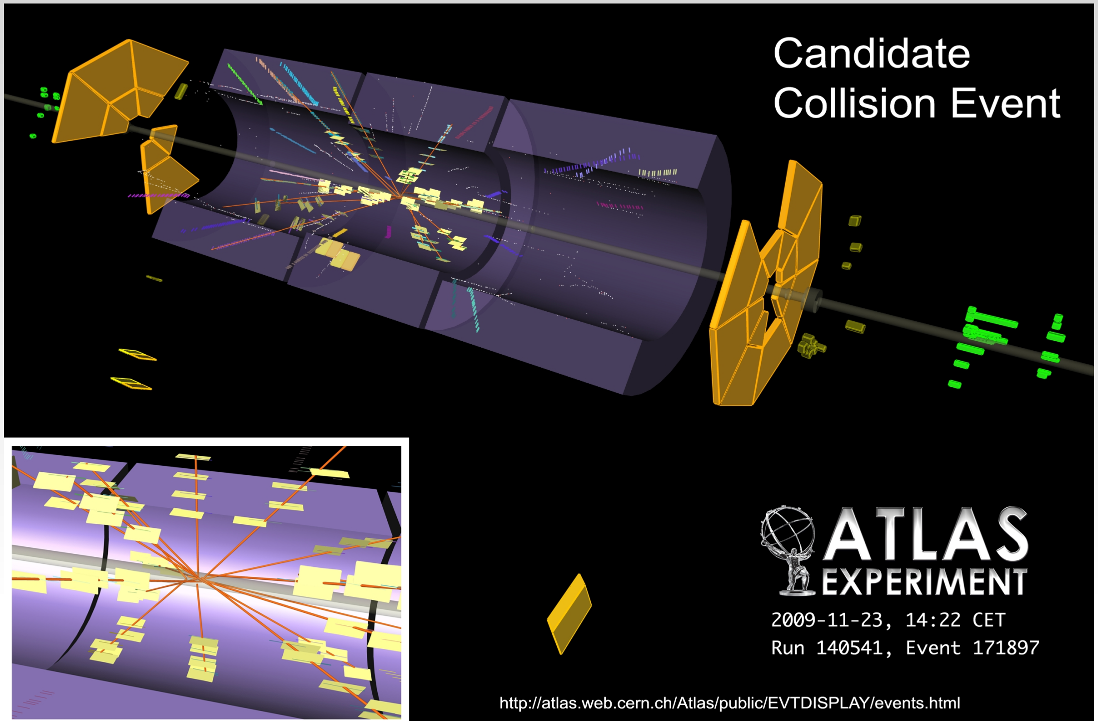
Non-linearities observed at the highest luminosities



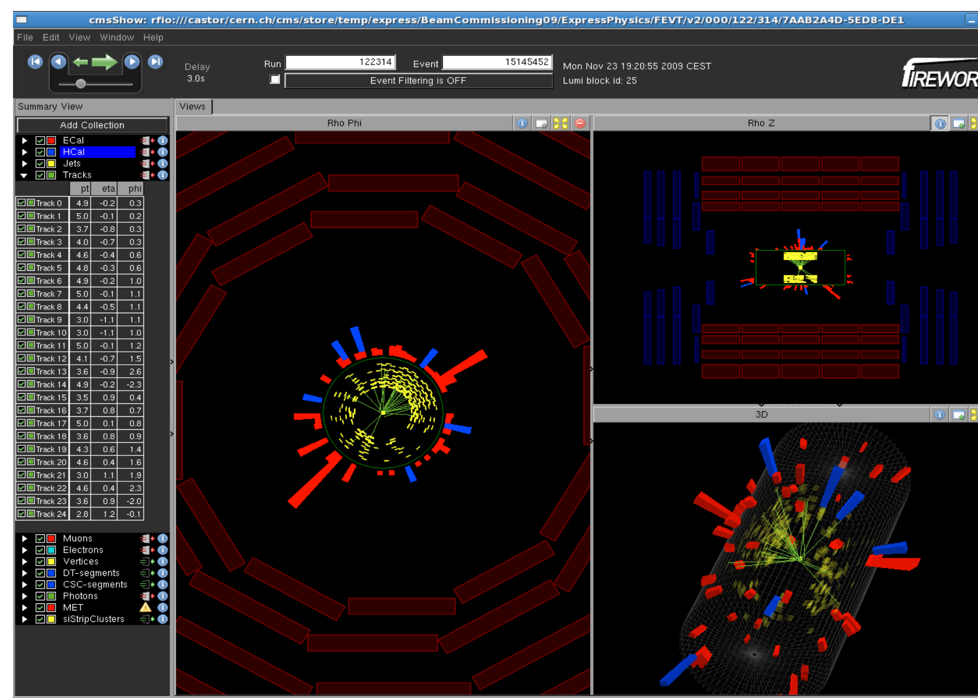
ATLAS data taking efficiency



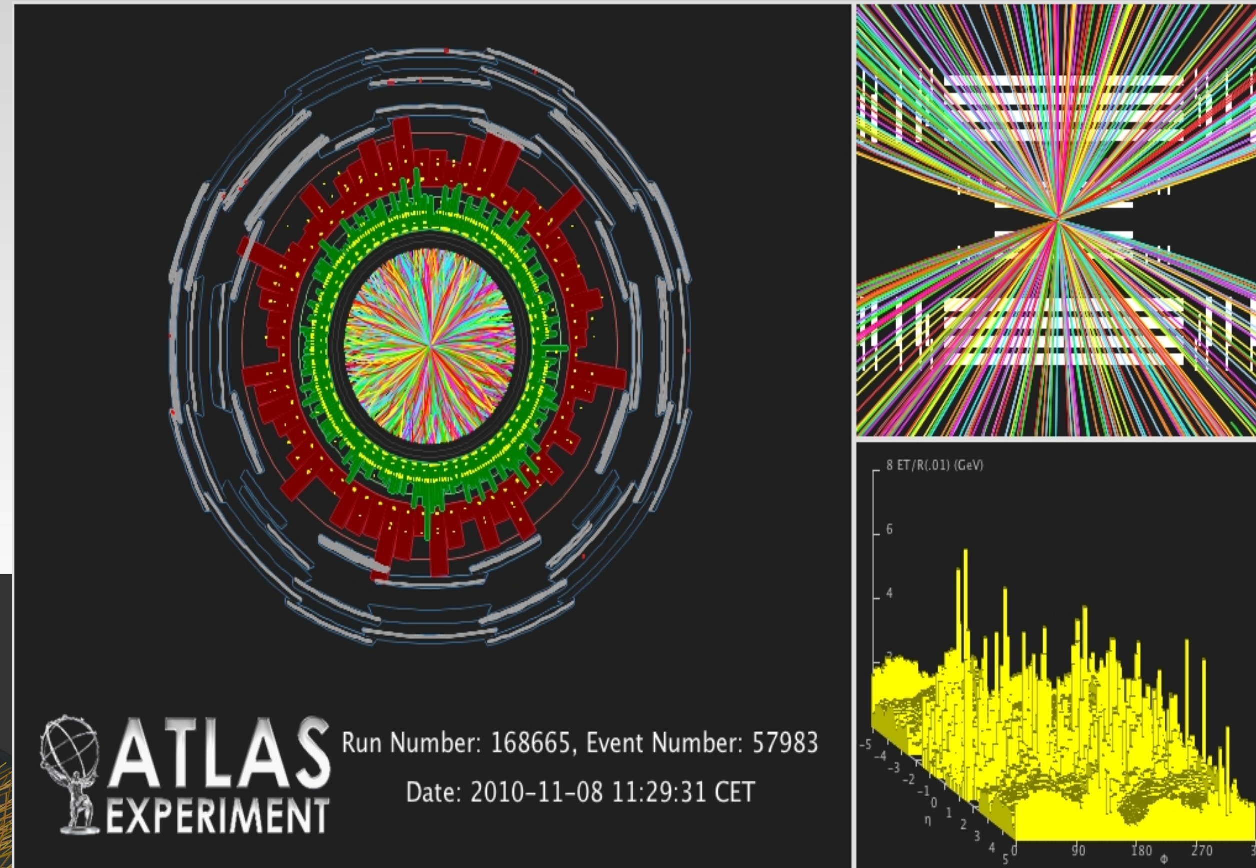
First events in Atlas/CMS

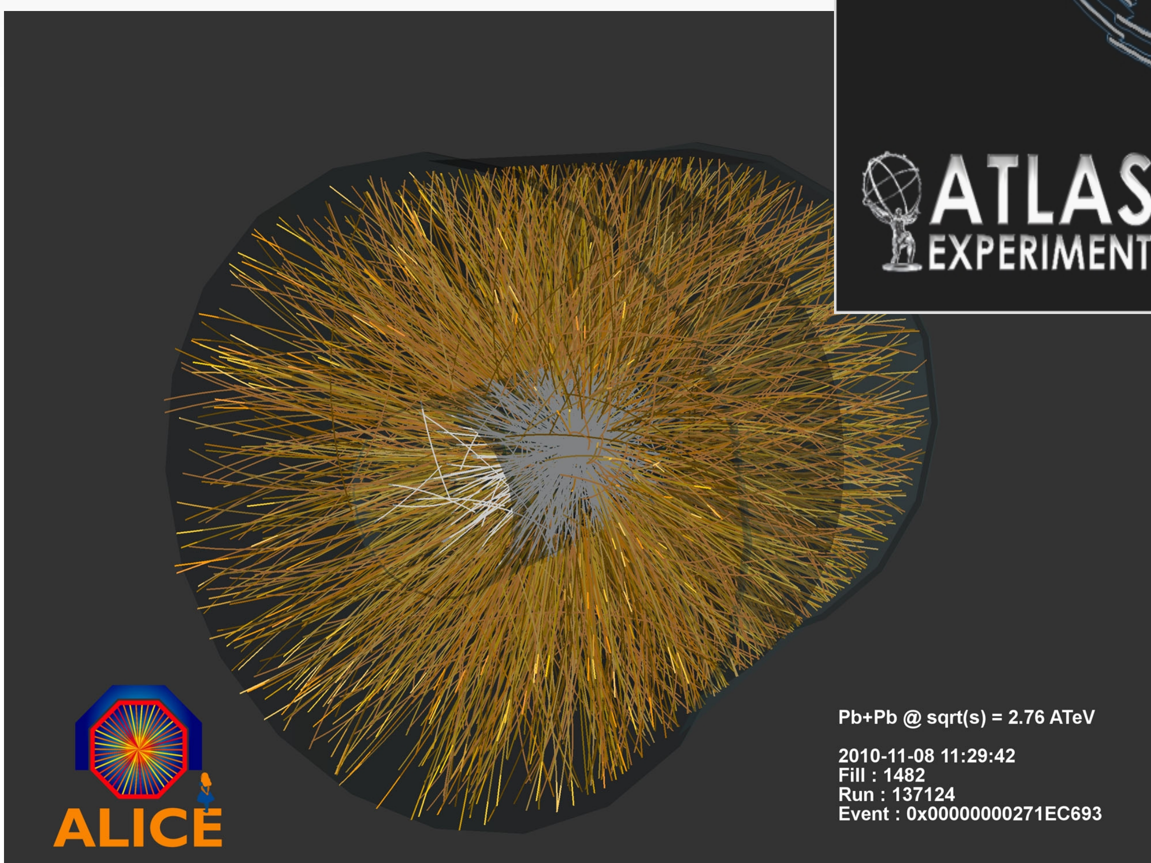


Soft collisions with just few tracks but important for alignment and trigger studies



The other extreme: HI collisions





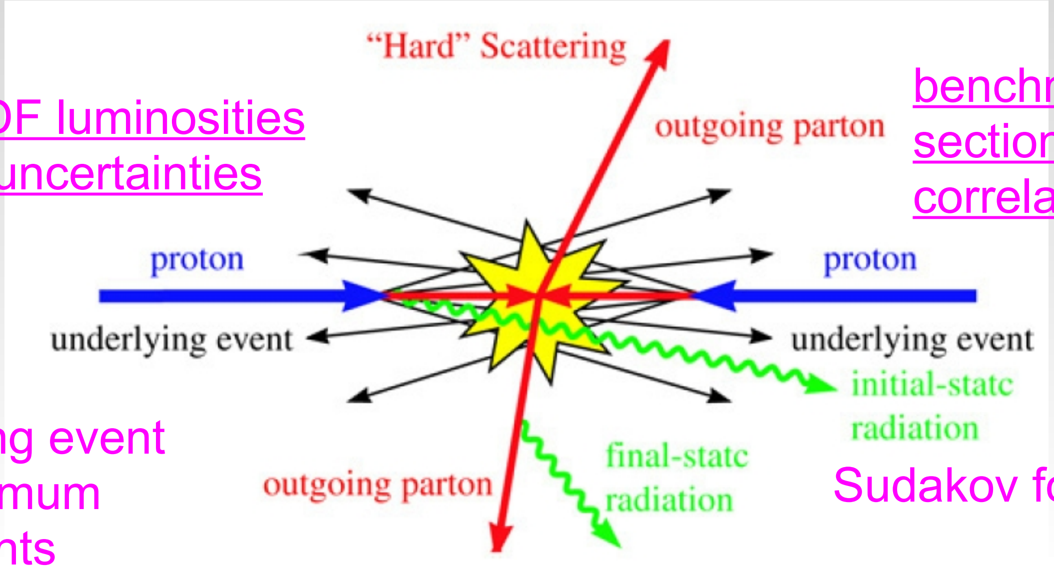
Physics in a hadron collider

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

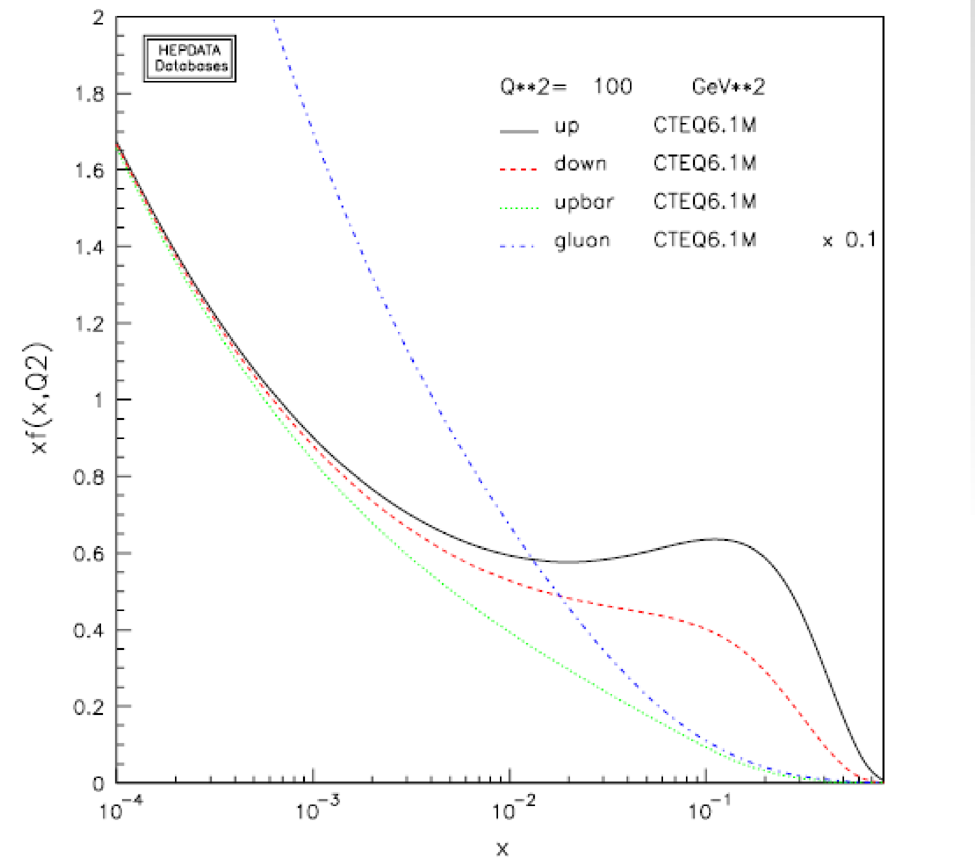


Figure 27. The CTEQ6.1 parton distribution functions evaluated at a Q of 10 GeV.

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

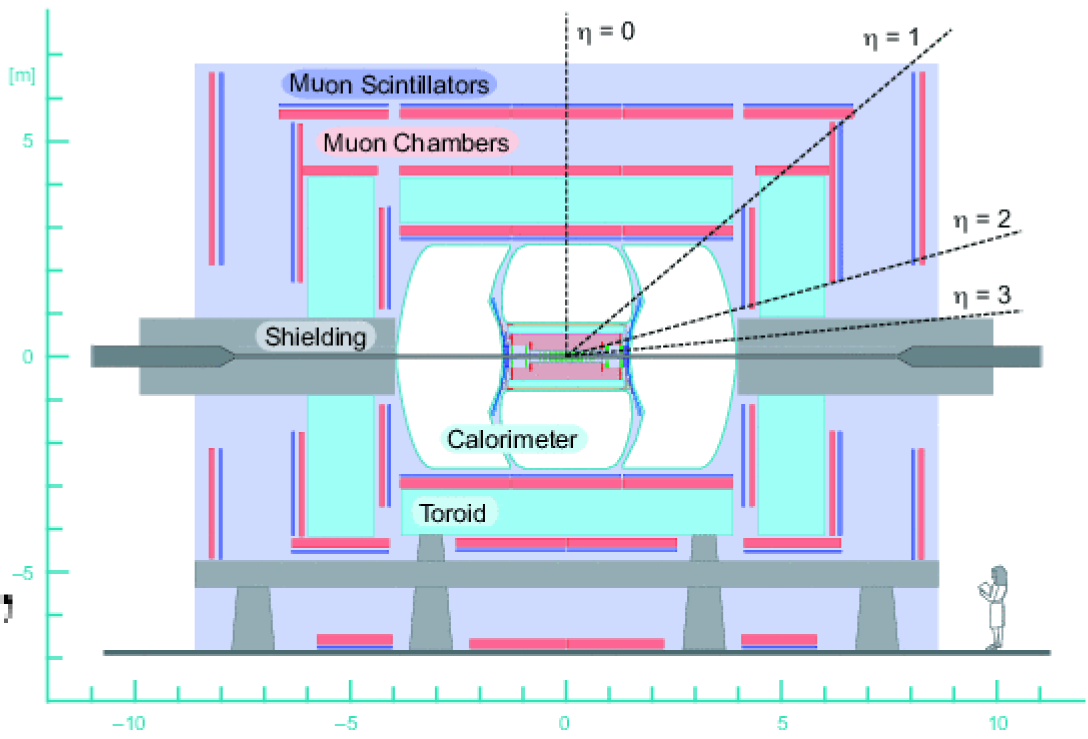
Relevant variables

- 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/Tevatron

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

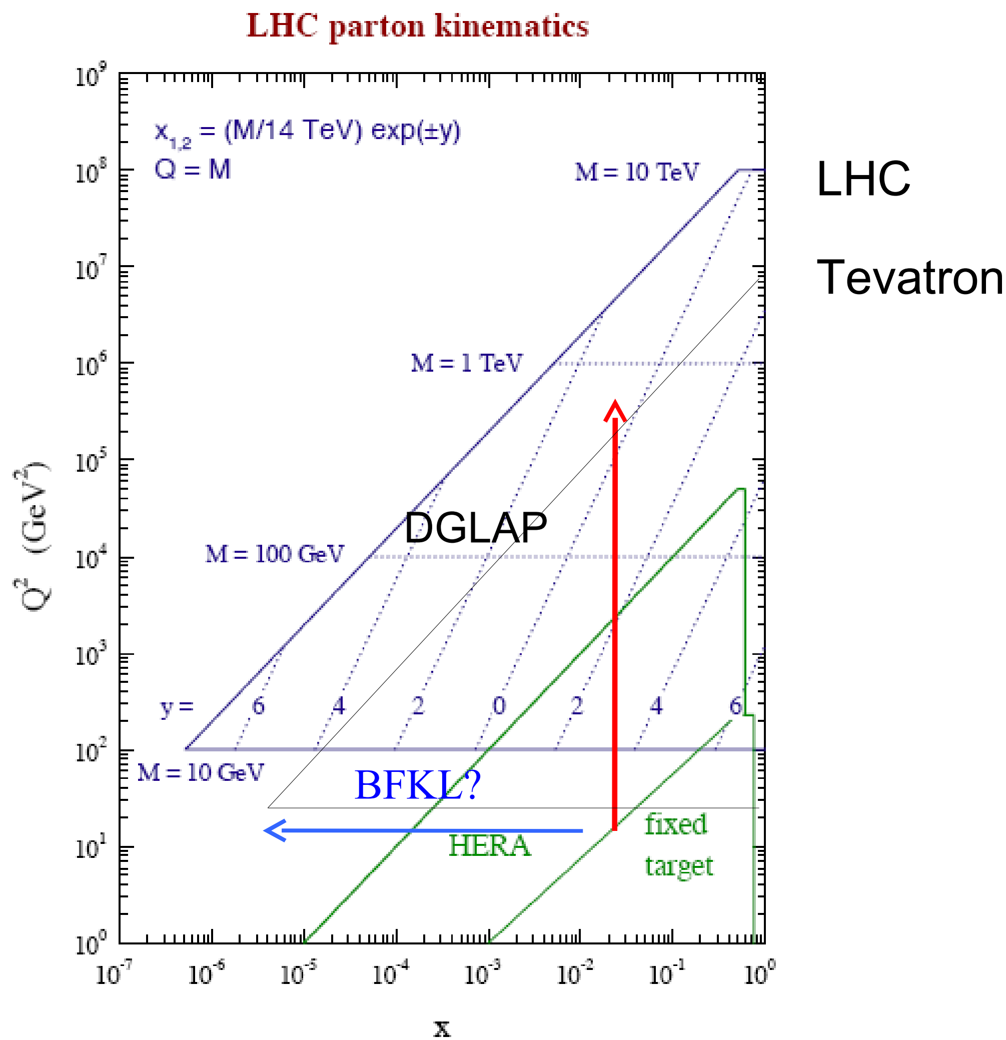
We will access pdf's down to 1E-6 (crucial for the underlying event) and Q^2 up to 100 TeV^2

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

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



PDF uncertainties at the LHC

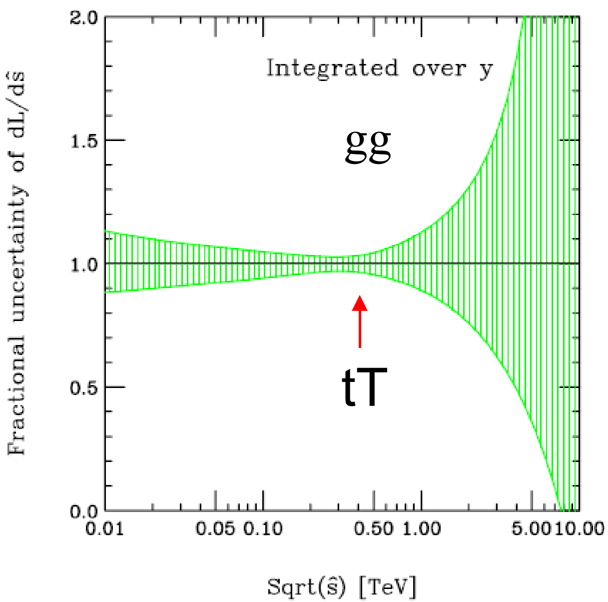


Fig. 4: Fractional uncertainty of gg luminosity integrated over y.

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

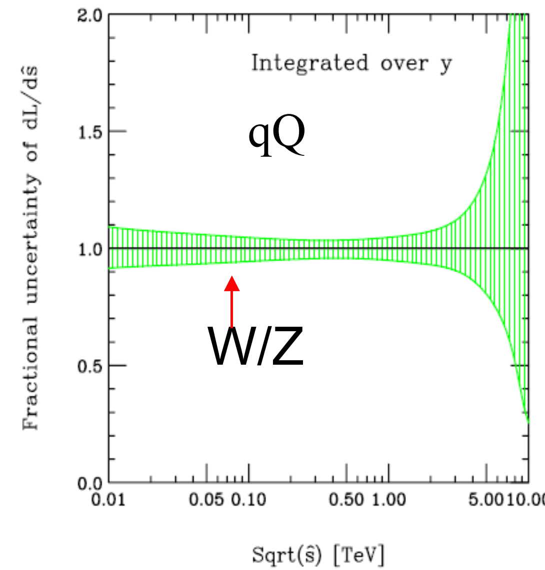


Fig. 7: Fractional uncertainty for Luminosity integrated over y for $d\bar{d} + u\bar{u} + s\bar{s} + c\bar{c} + b\bar{b} + \bar{d}d + \bar{u}u + \bar{s}s + \bar{c}c + \bar{b}b$.

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

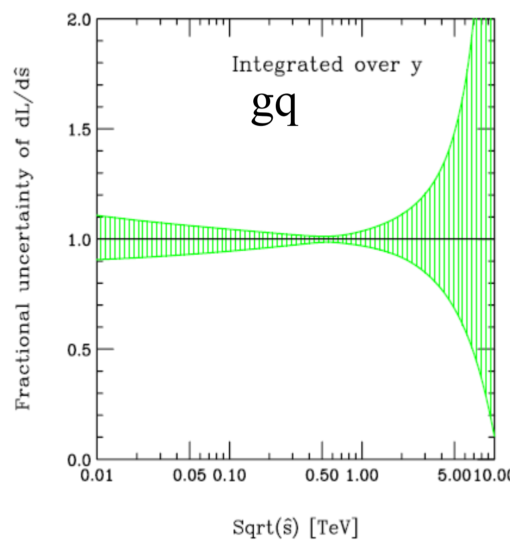


Fig. 6: Fractional uncertainty for Luminosity integrated over y for $g(d+u+s+c+b) + g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b}) + (d+u+s+c+b)g + (\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$,

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

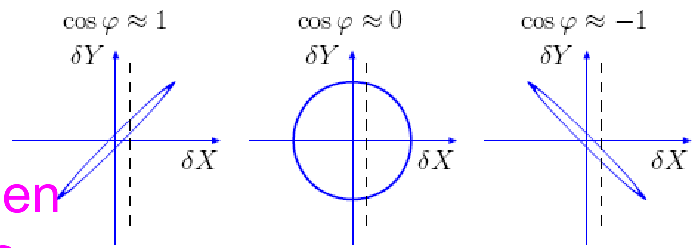
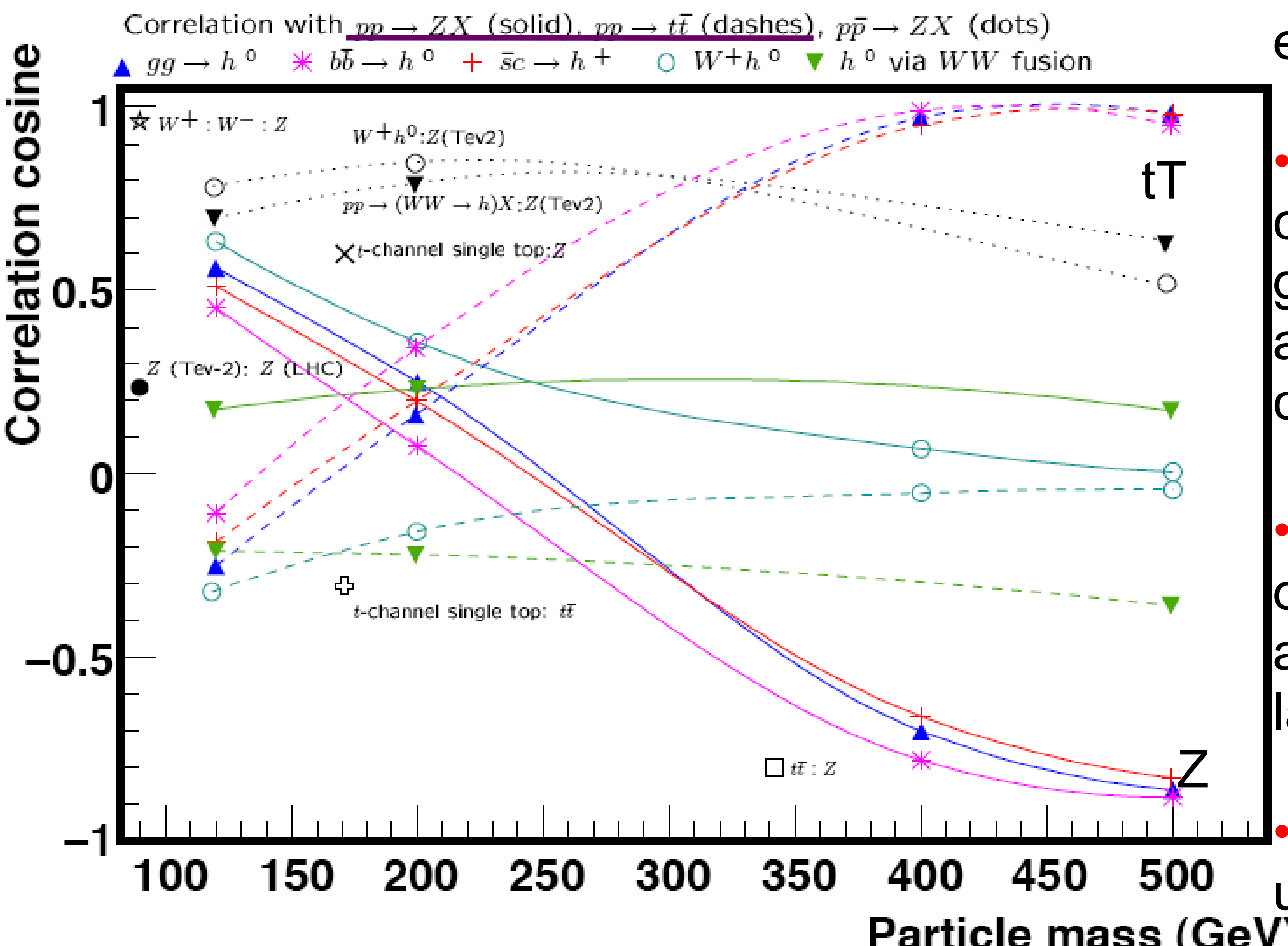


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.

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



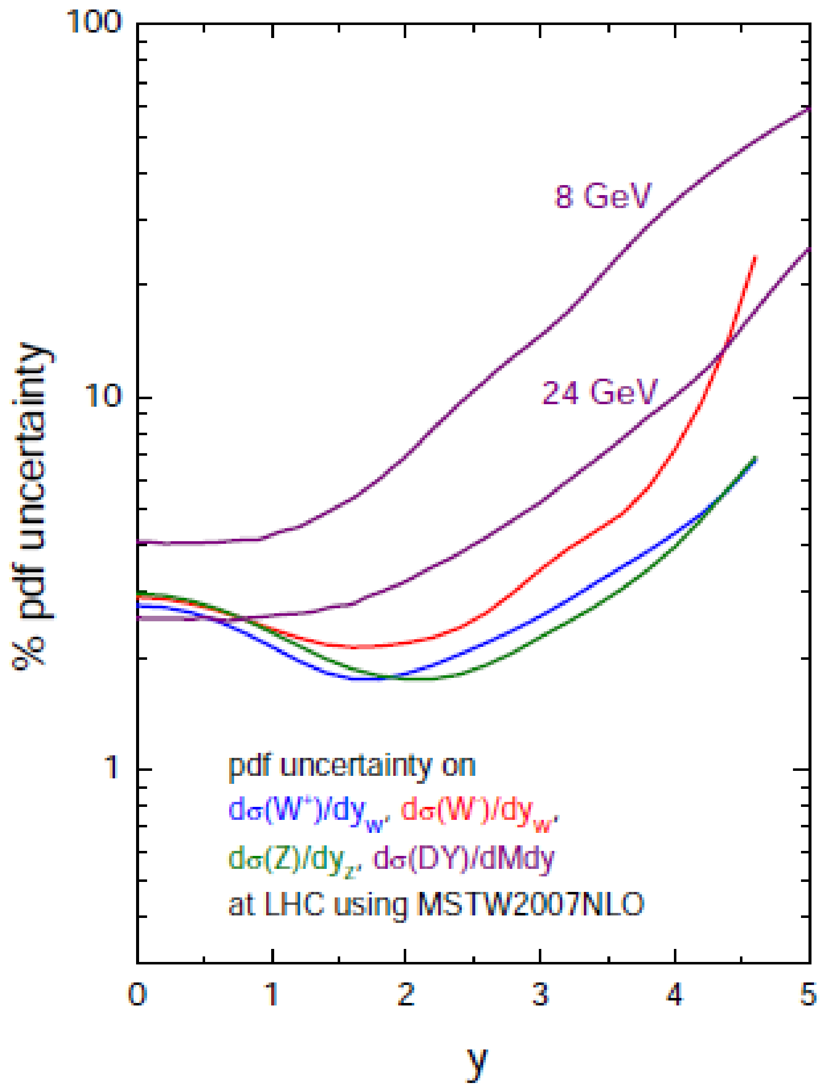
- Note that correlation curves to Z and to tT are mirror images of each other
- By knowing the pdf correlations, can reduce the uncertainty for a given cross section in ratio to a benchmark cross section **iff** cos φ > 0;e.g. $\Delta(\sigma_{W^+}/\sigma_Z)$~1%
- If cos φ < 0, pdf uncertainty for one 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)

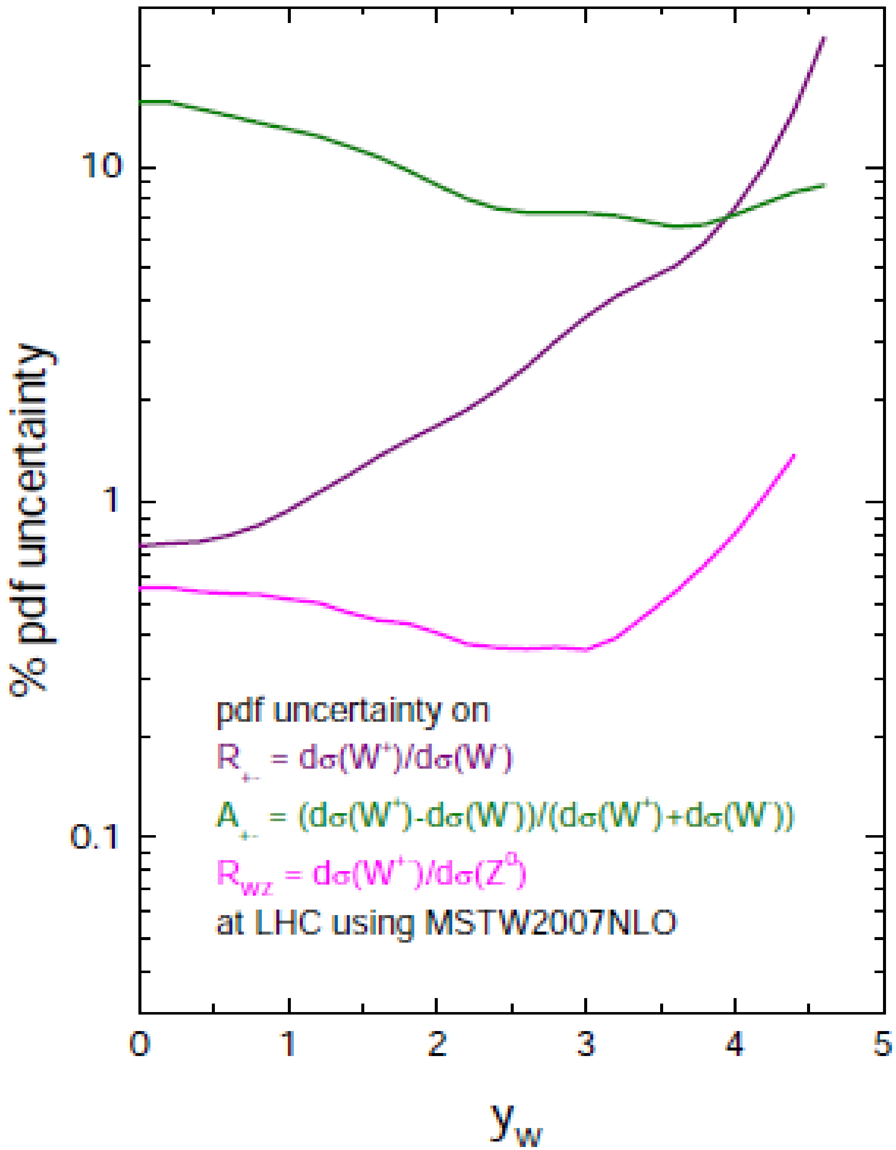
More information from ratios including $\sigma(Z)$, $\sigma(W^-)$ and $\sigma(W^+)$.

Cleaner experimentally.

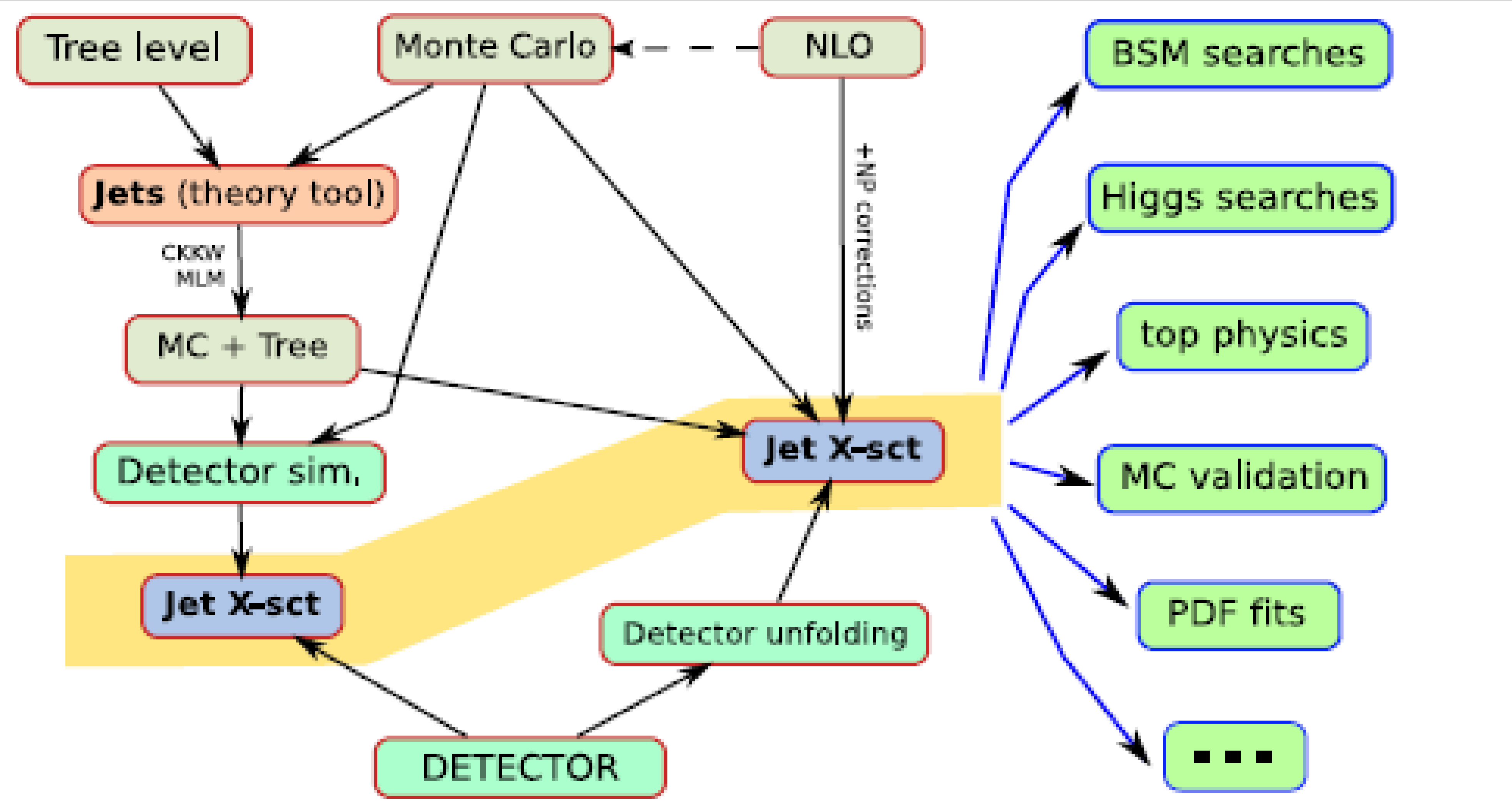
Uncertainty on A_W large even just from experimental sources.

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.



QCD and Jets



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

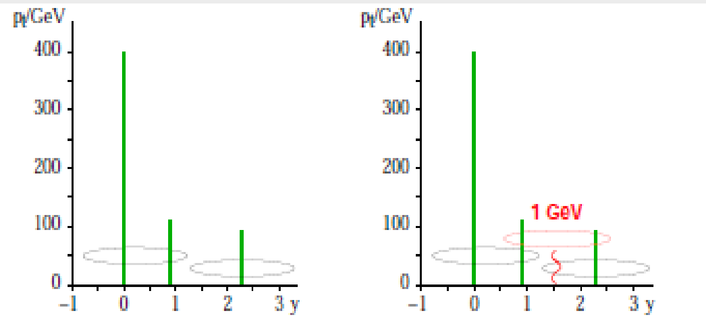
And jets are an input to almost all analyses

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

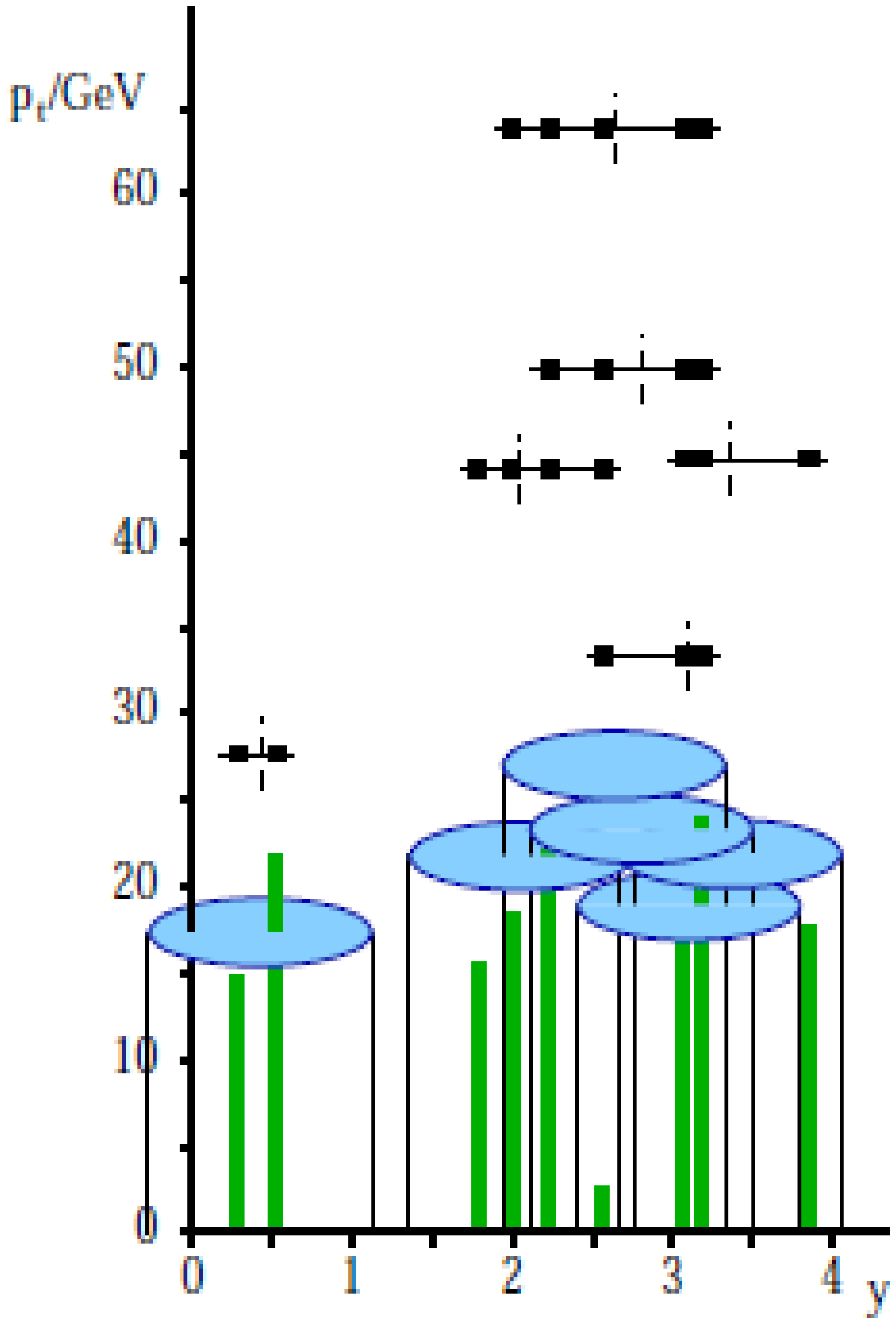
- Cone algorithms are apparently simple to understand and fast; but what happens if two cones overlap? Does the result depend on the choice of seed? (it shouldn't)



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			
	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

SISCone



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

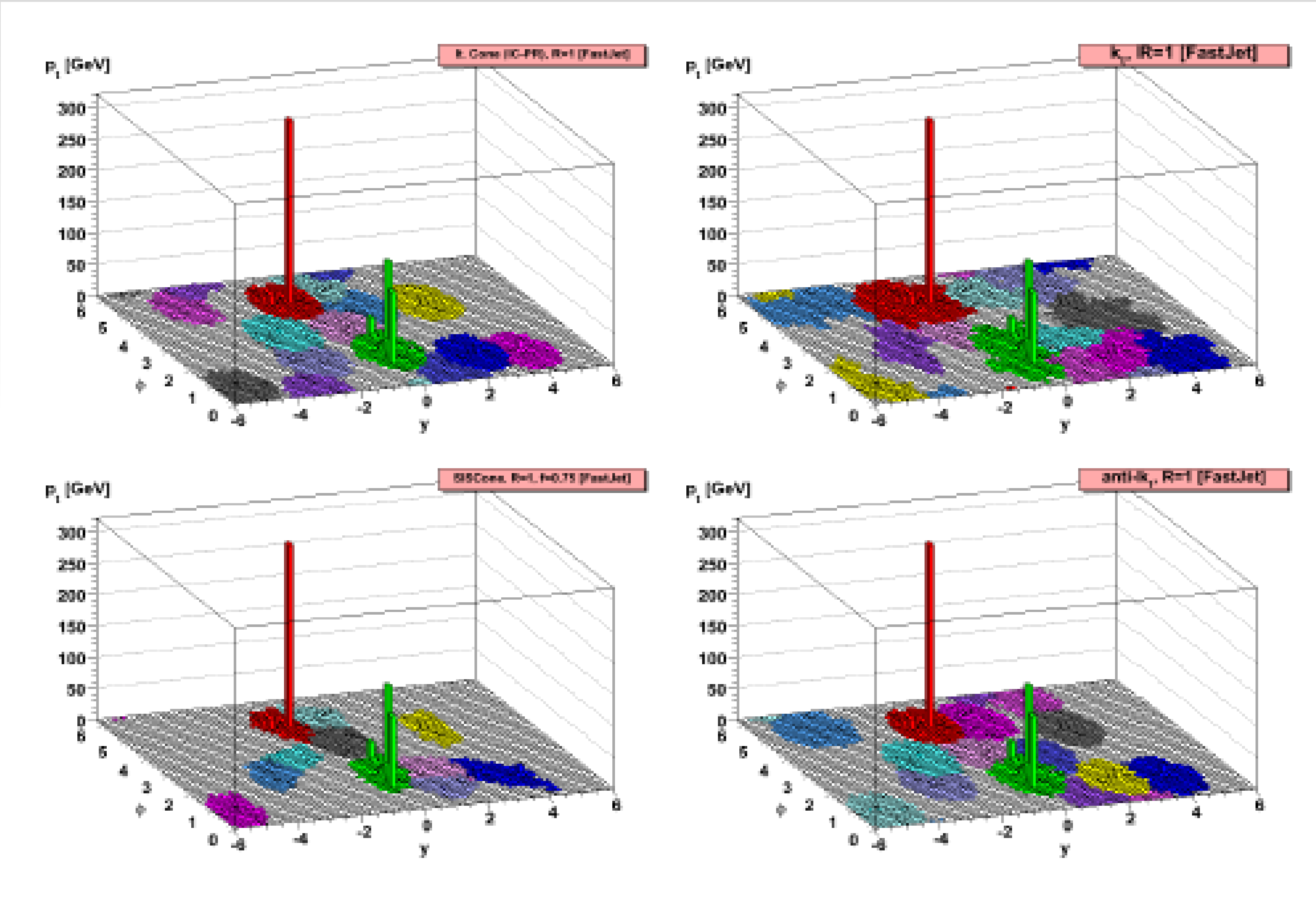
Procedure in 1 dimension (y):

- 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

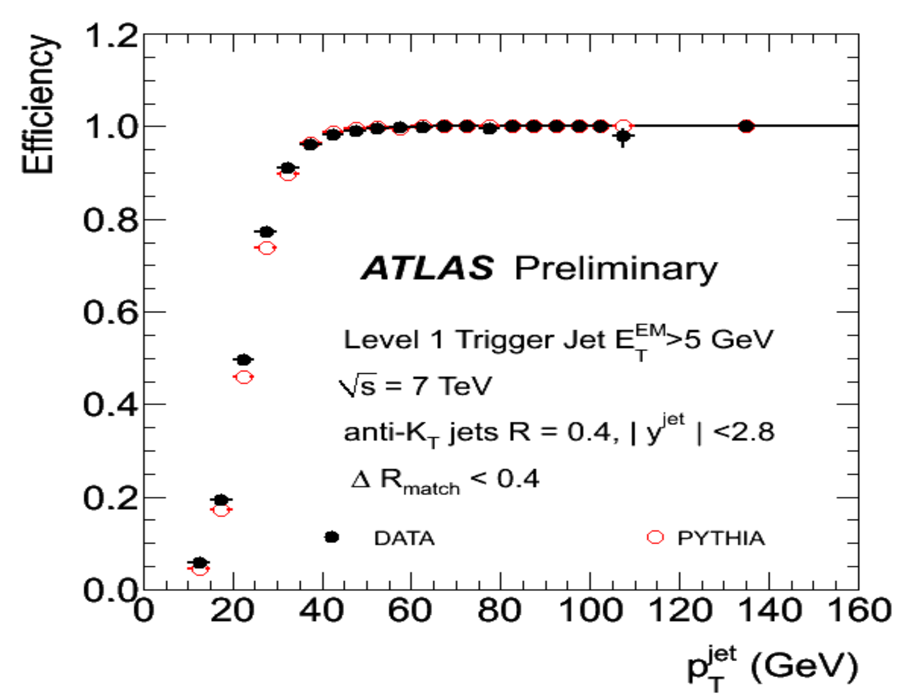
This gives an IRC safe cone alg.

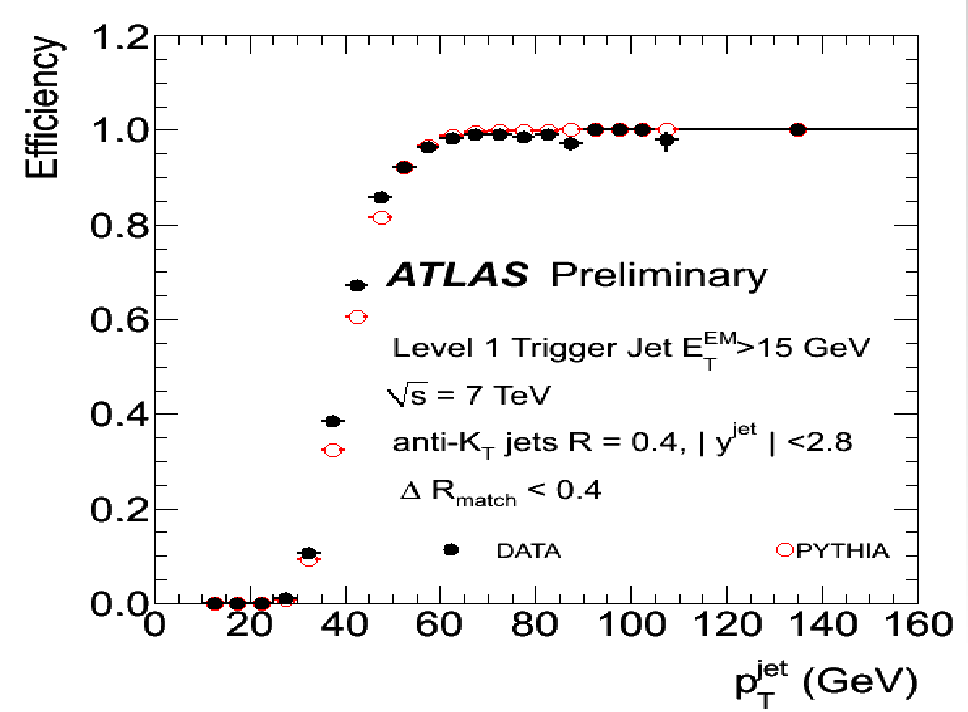
But the most conical cone is not a cone!



Anti-kt now default algorithm in Atlas

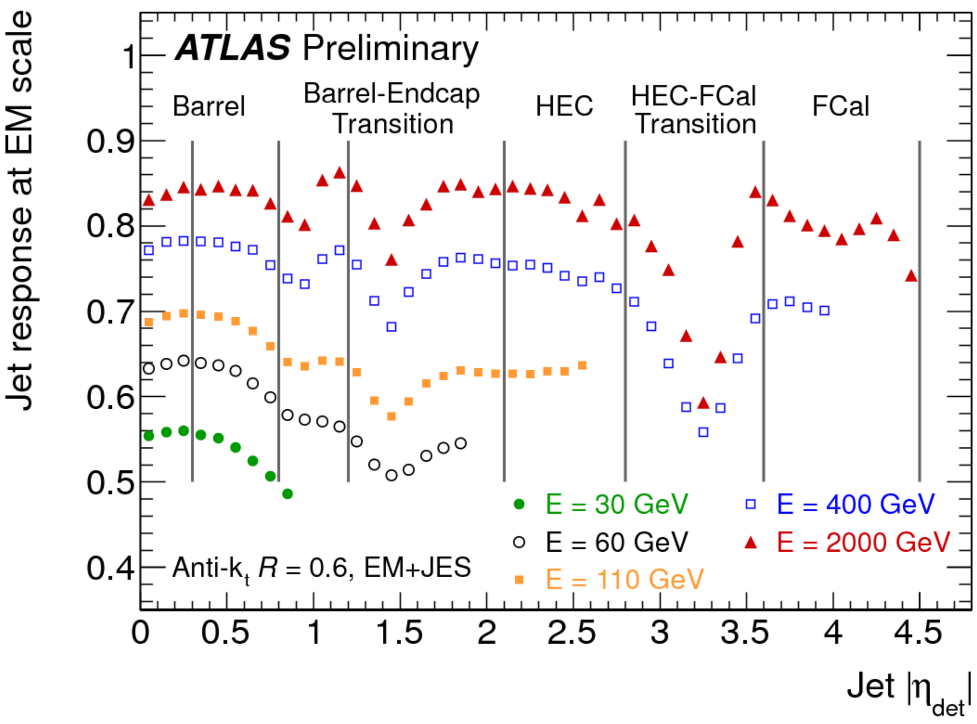
Measuring jet production: trigger

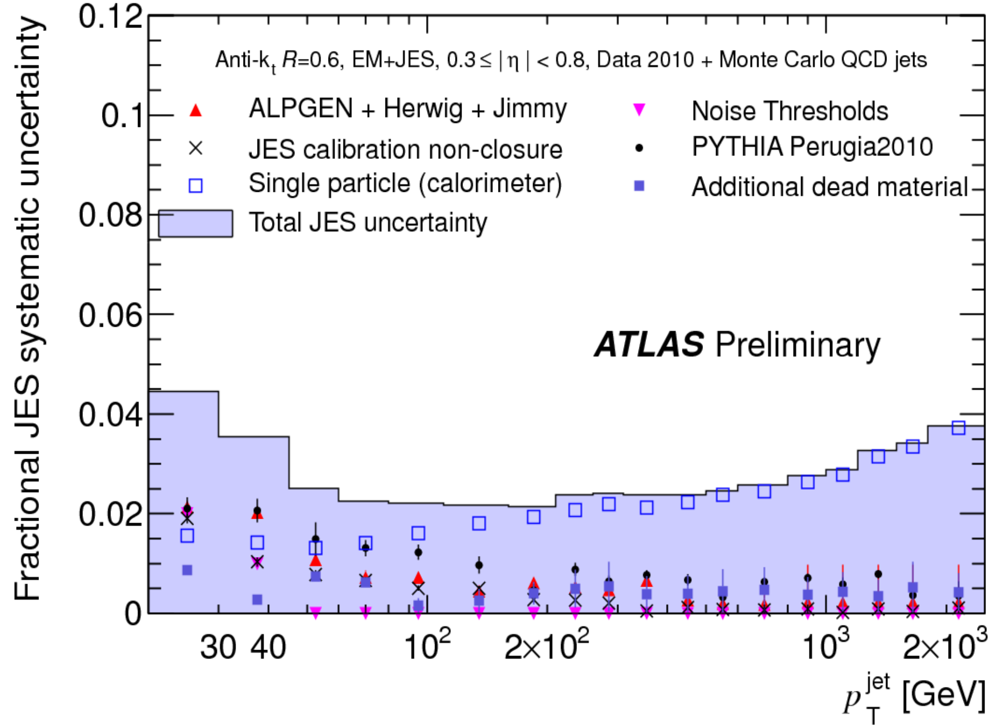




- Not to correct for the efficiency in the steeply rising part of the curve, jet cross section was first measured above the 100% efficiency point
- This results in the measurement being performed in different Pt bins in the various periods, because higher luminosities forced heavy prescales on lowest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

Jet Energy scale in ATLAS



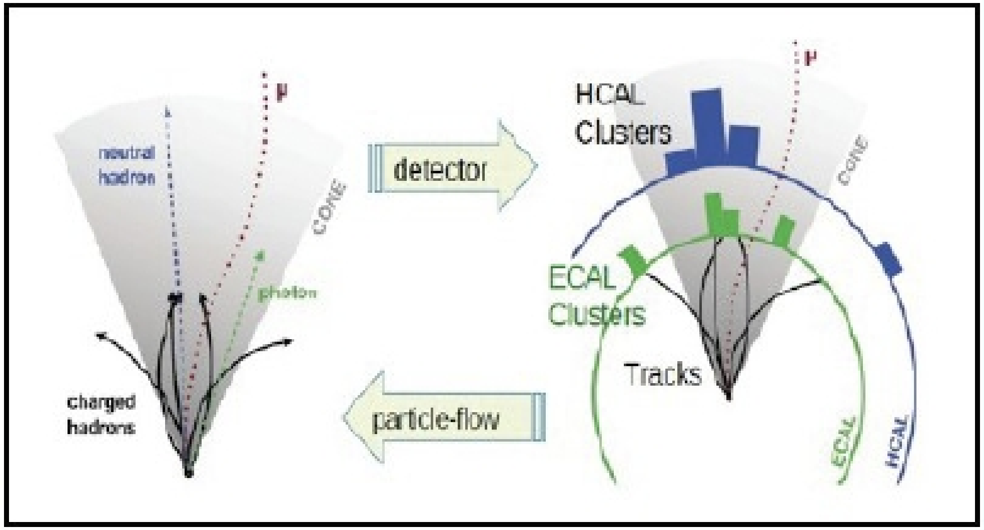


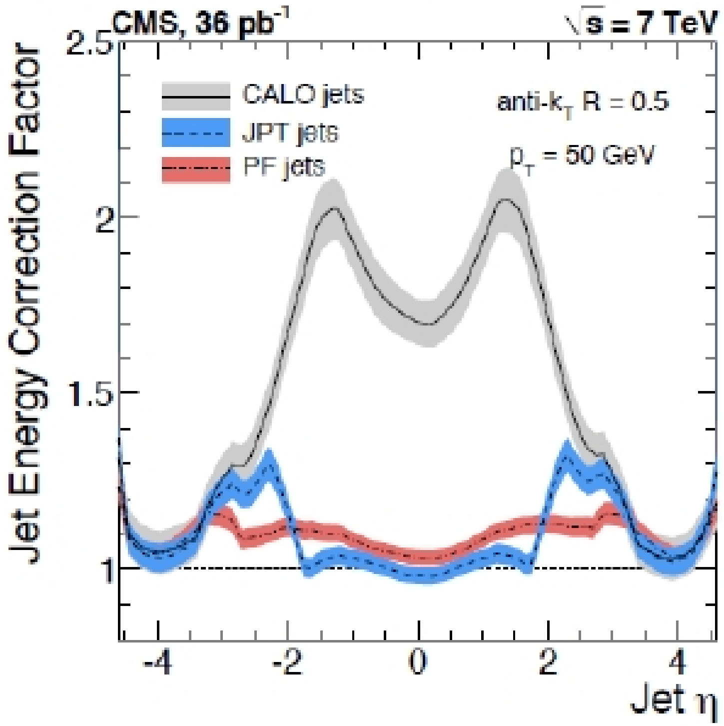
- Jets measured at EM scale (summing Ecal and Hcal contributions), scaled by factors derived from MC and cross-checked with track jets

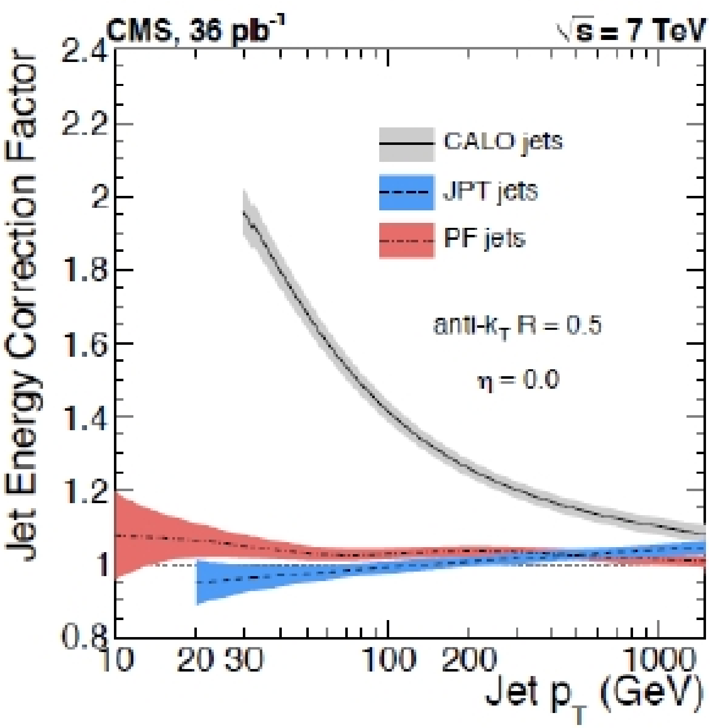
Particle-flow in CMS

✦ **Sophisticated "particle flow" reconstruction algorithm**
- exploits the excellent tracker performance and the fine ECAL granularity

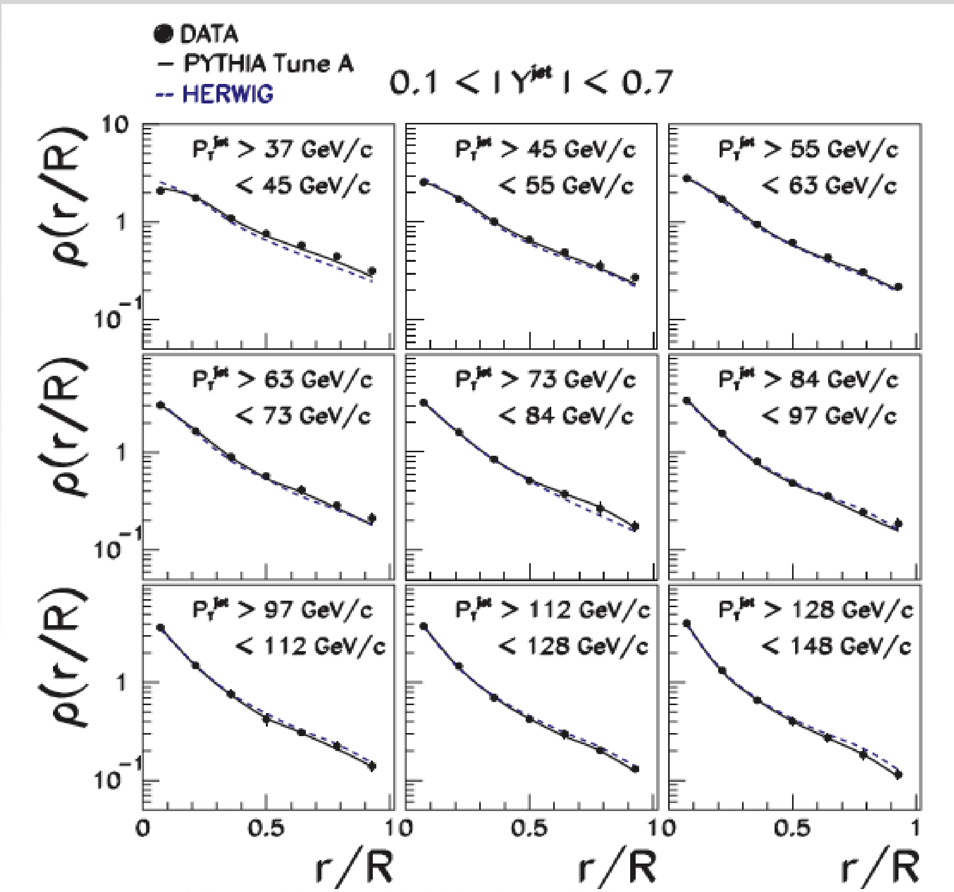
✦ **Reconstructed individual particles according to their detection signature**

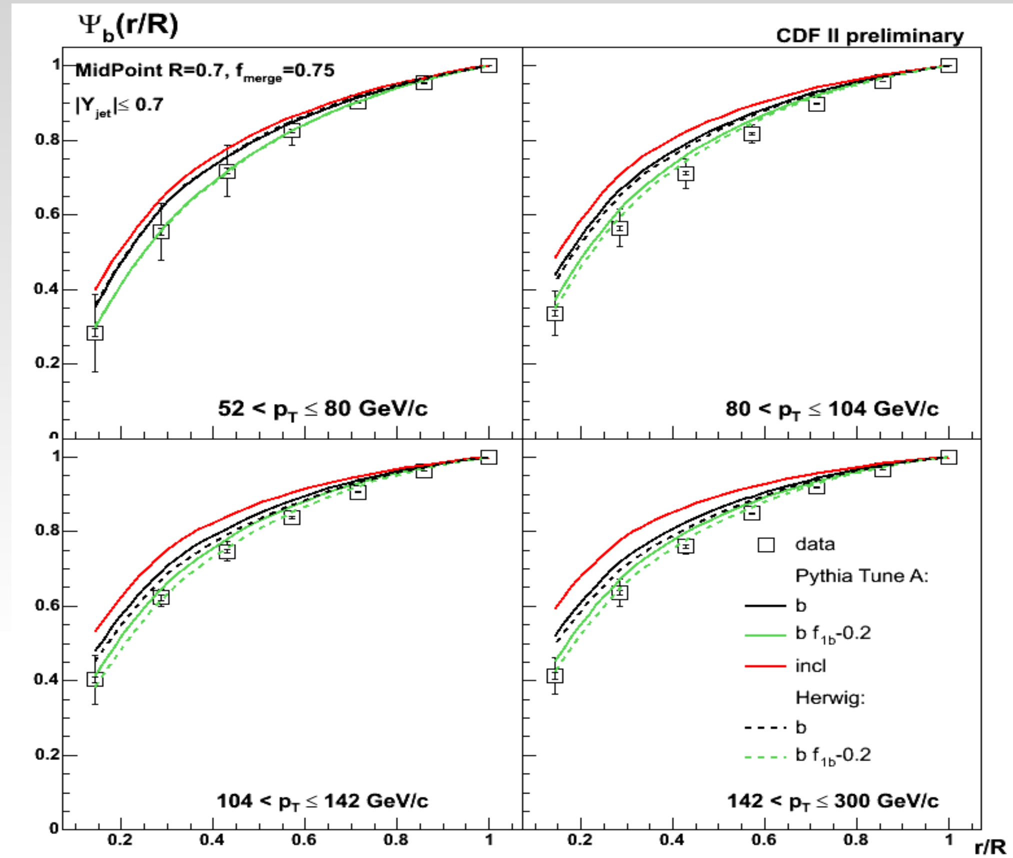






Jet shapes (at the Tevatron)

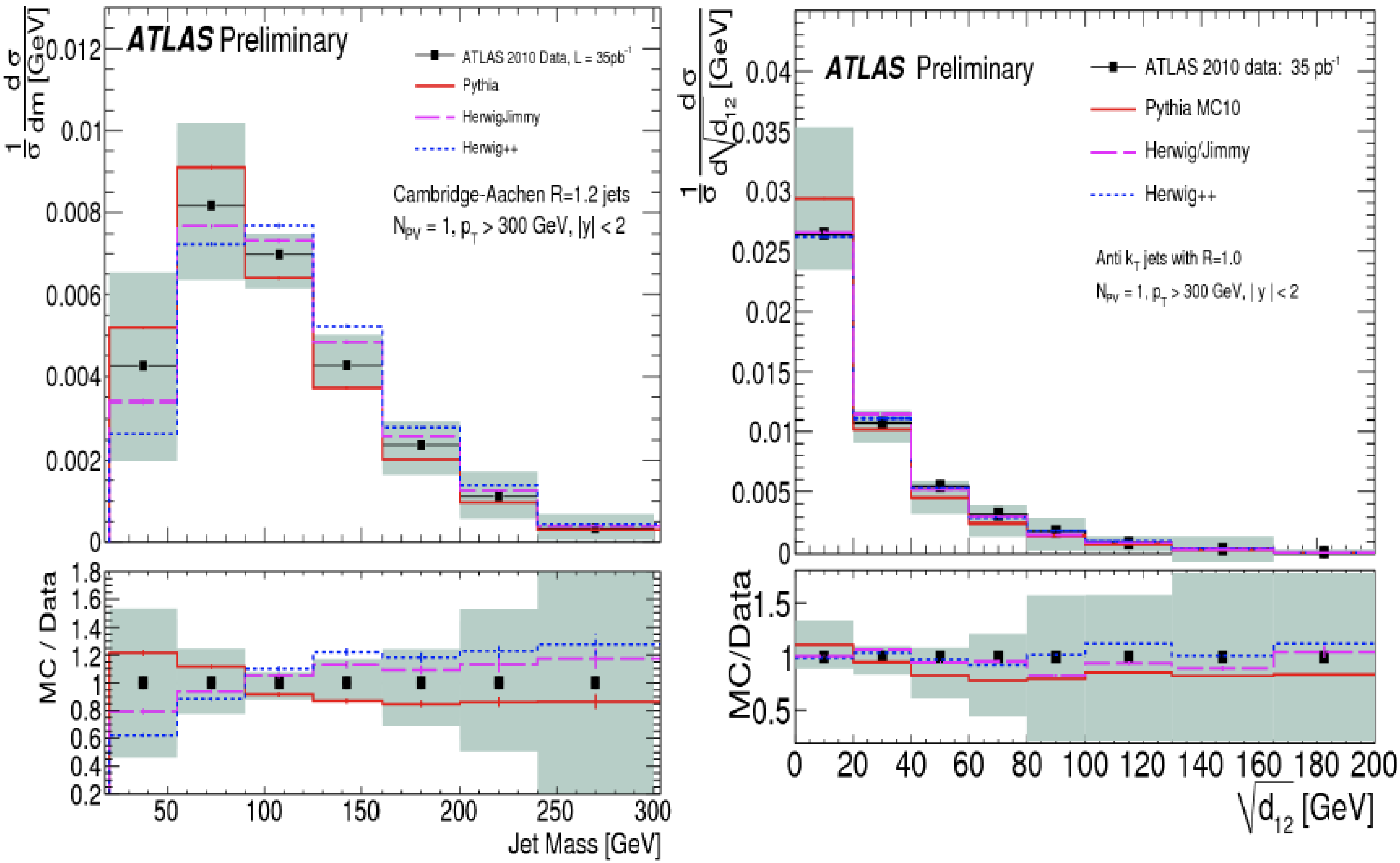




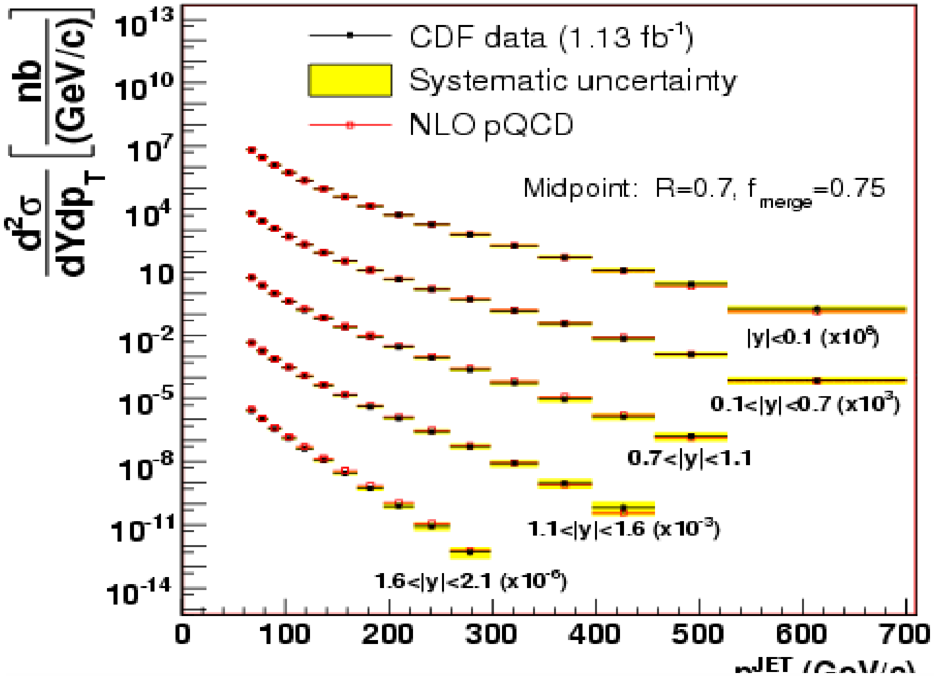
$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N^{jet}}\sum_{jets}\frac{p_T(r-\Delta r/2, r+\Delta r/2)}{p_T(0,R)}, \quad \Delta r/2 \le r \le R-\Delta r/2, \qquad \Psi(r) = \int_0^r \frac{p_T(r')}{p_T^{jet}}dr' = \frac{1}{N_{jets}}\sum_{jets}\frac{p_T(0,r)}{p_T(0,R)}$$

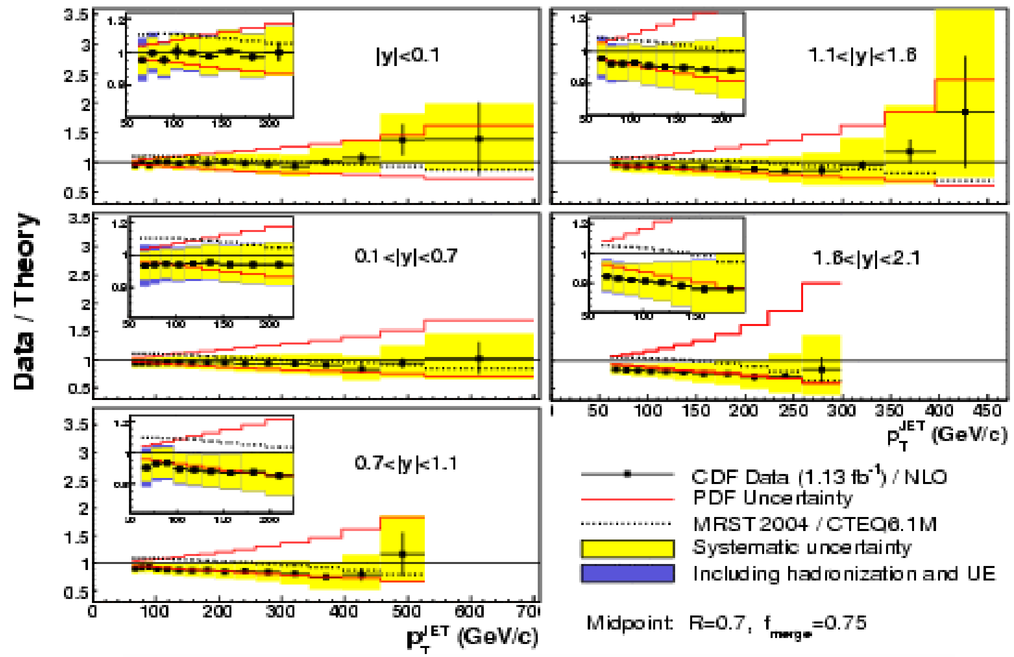
- Typical first jet measurement, to prove that what is observed are the jets as predicted by QCD; also performed on early LHC data

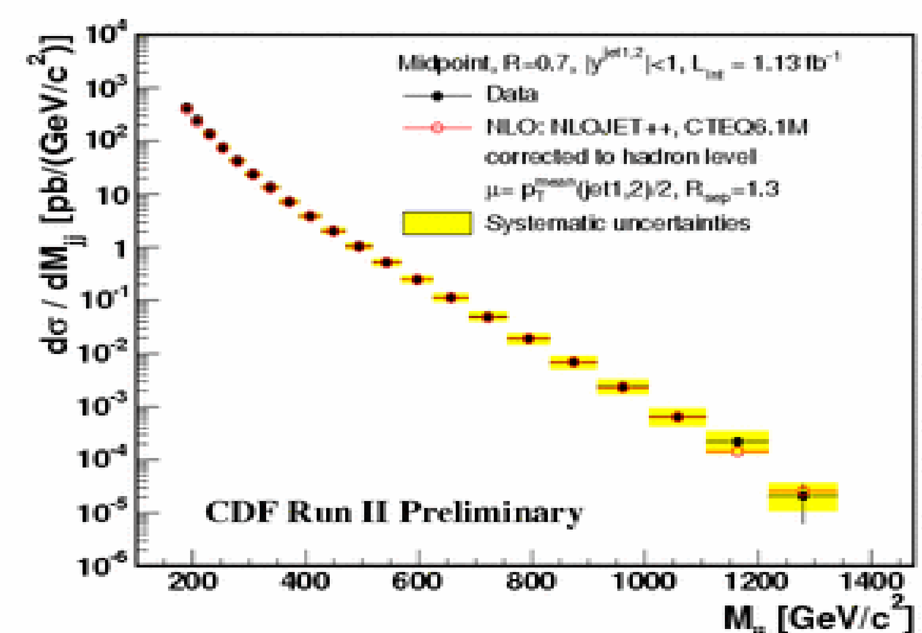
Properties of calorimeter jets: mass, y12

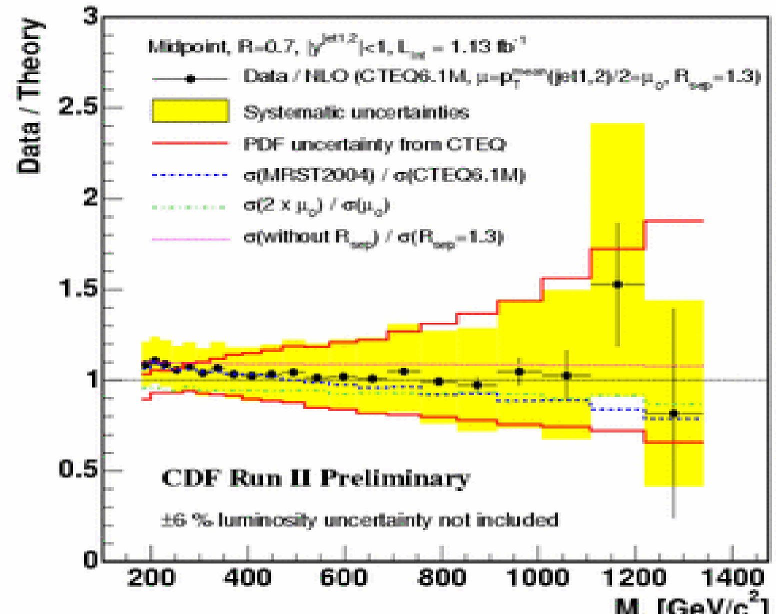


Jets and dijets in CDF (midpoint!)

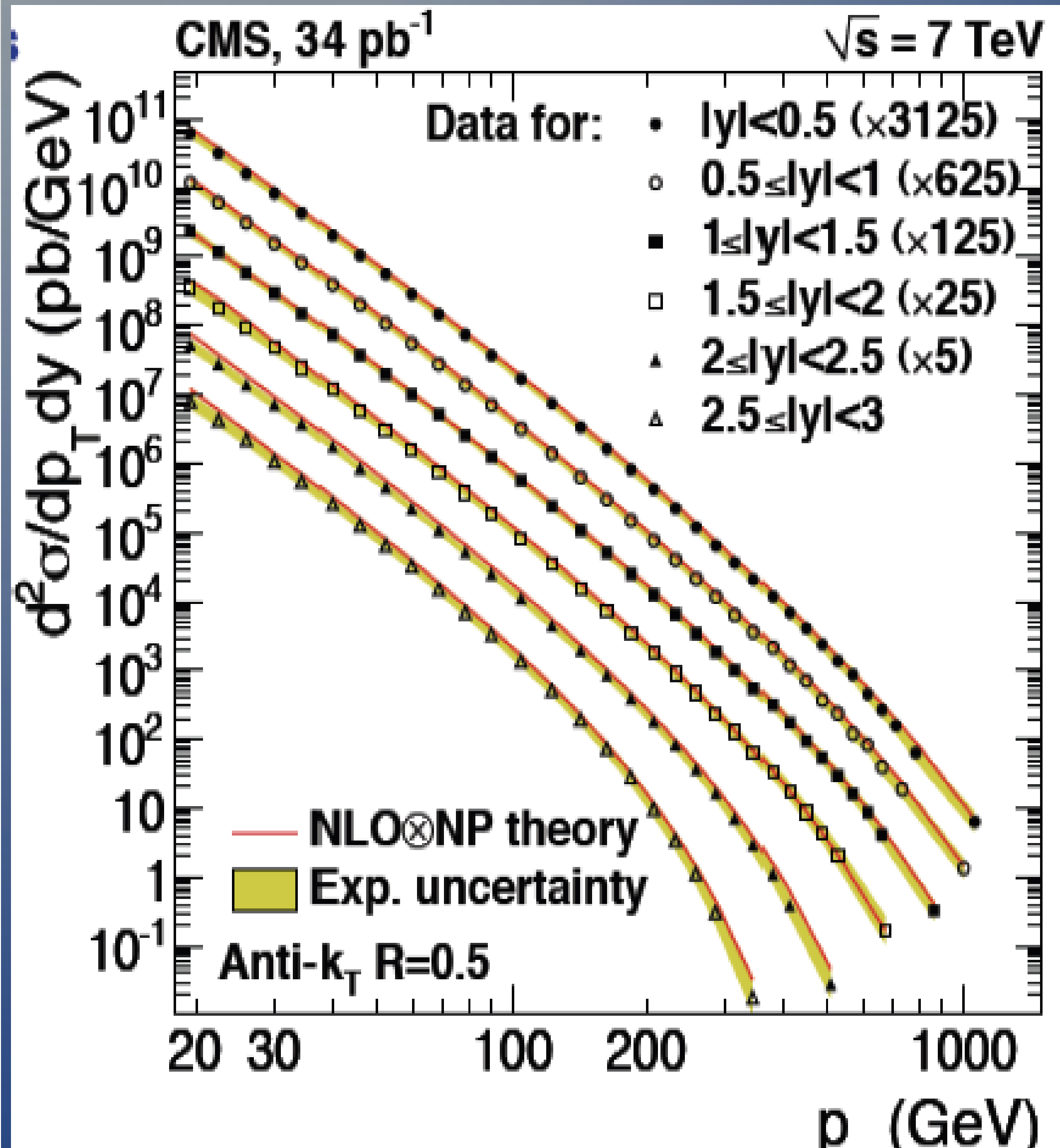


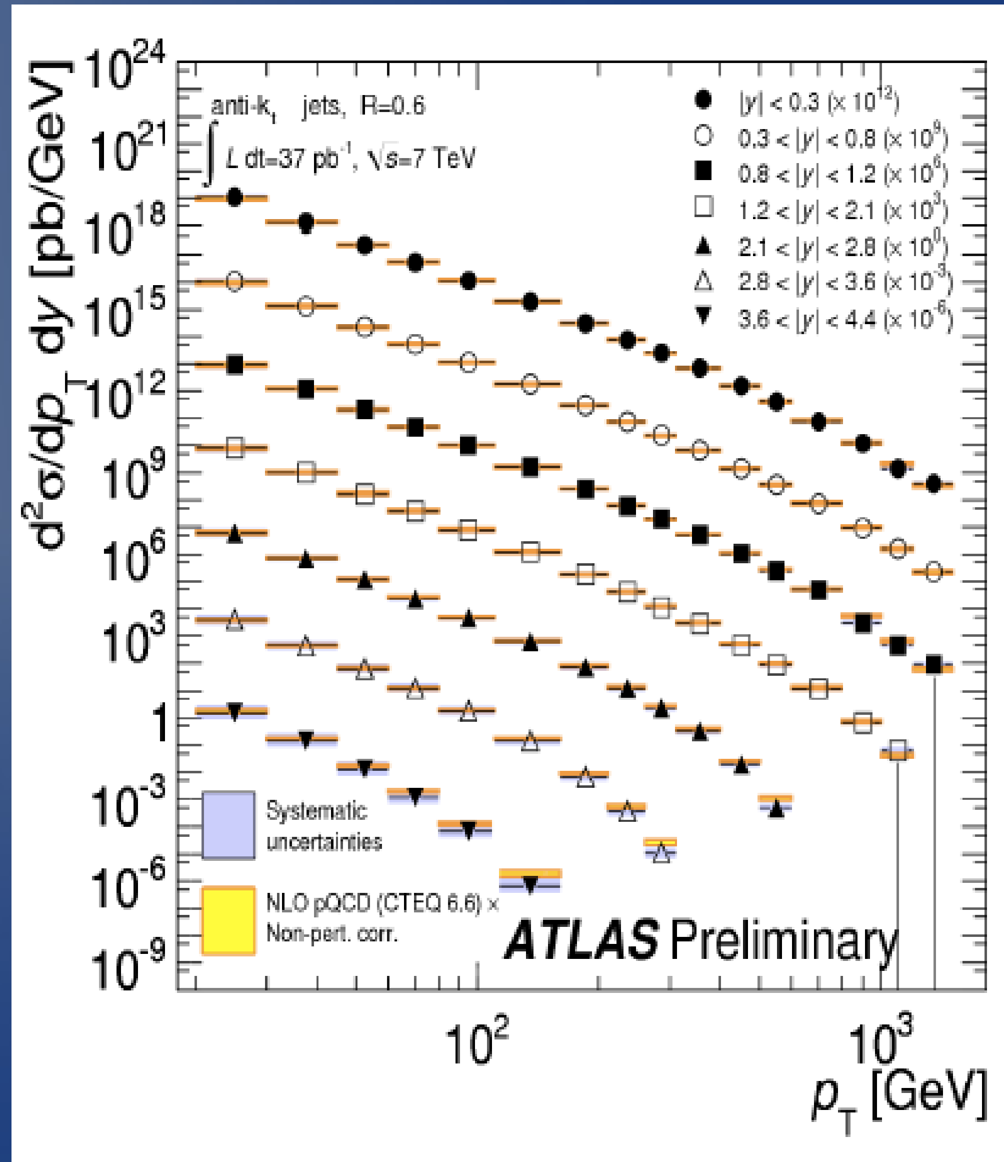




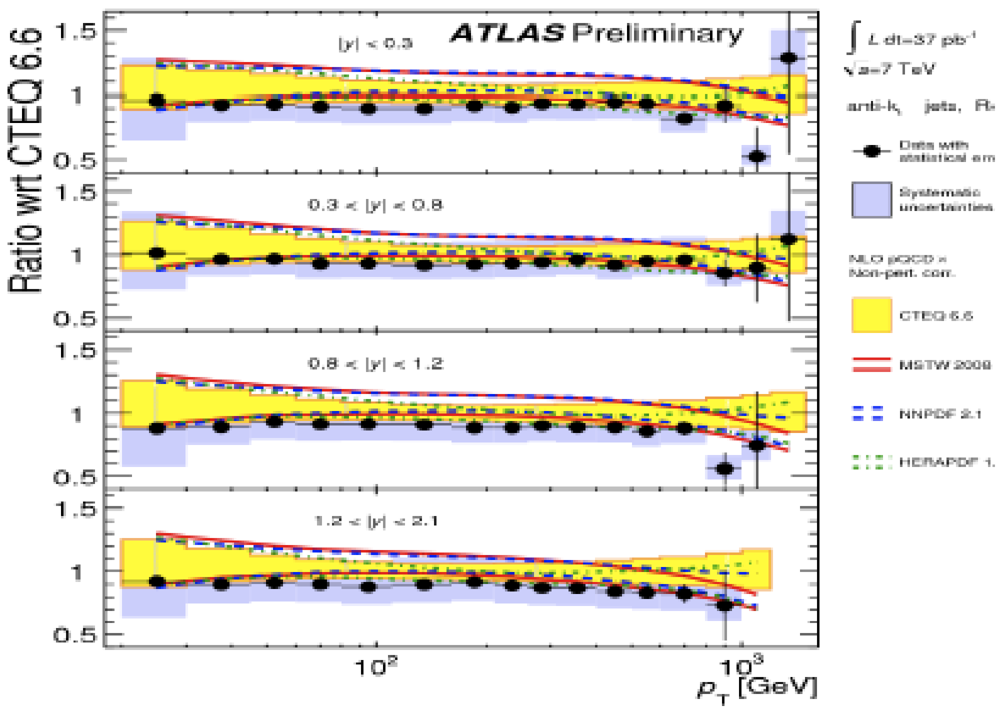


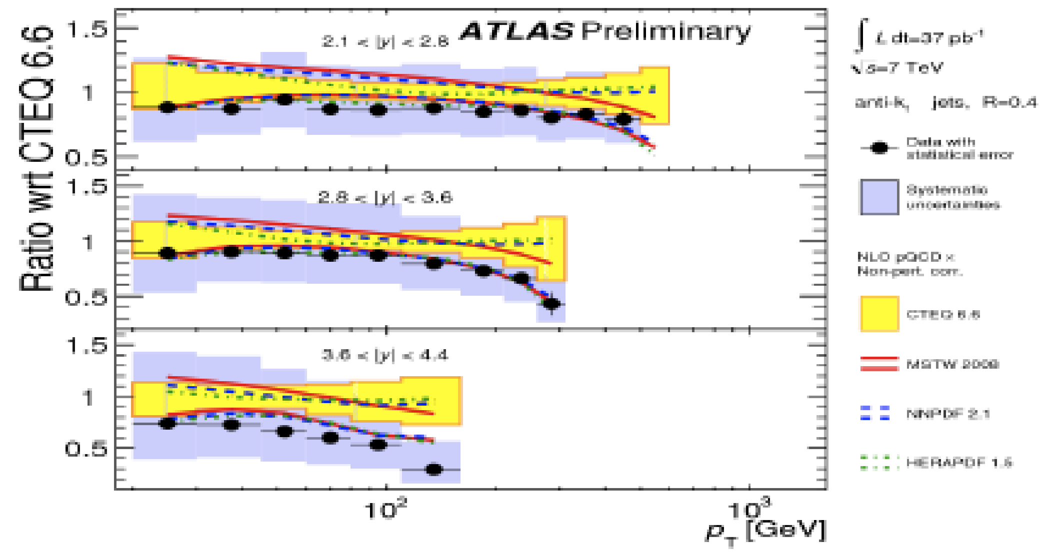
Inclusive jet cross section for antikt jets: (0.4, 0.6 width in Atlas, 0.5, 0.7 in CMS) jets after detector unfolding.

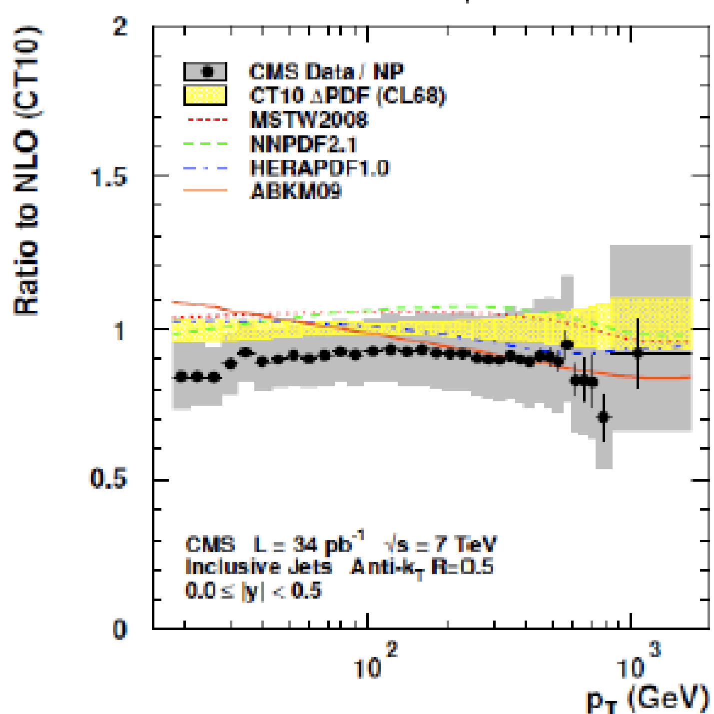


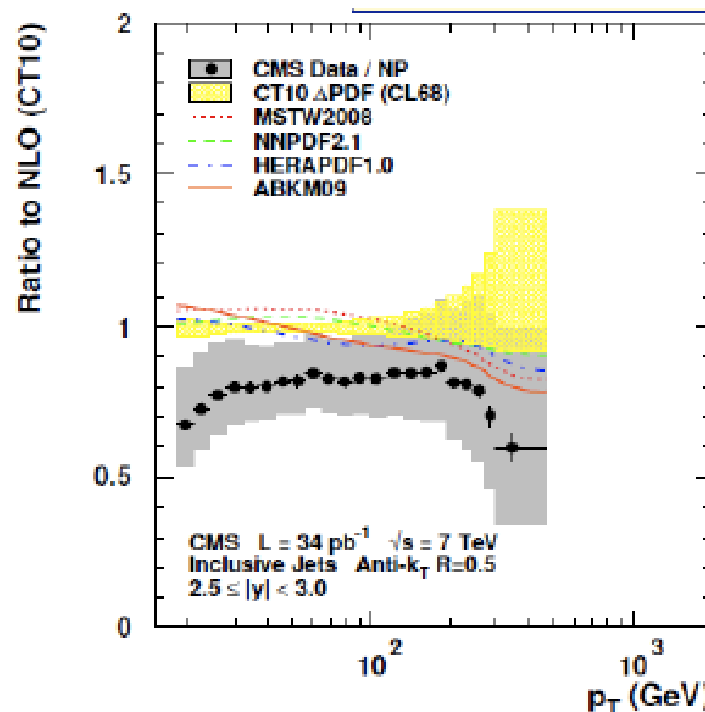


Comparison with various Pdf sets (0.4)

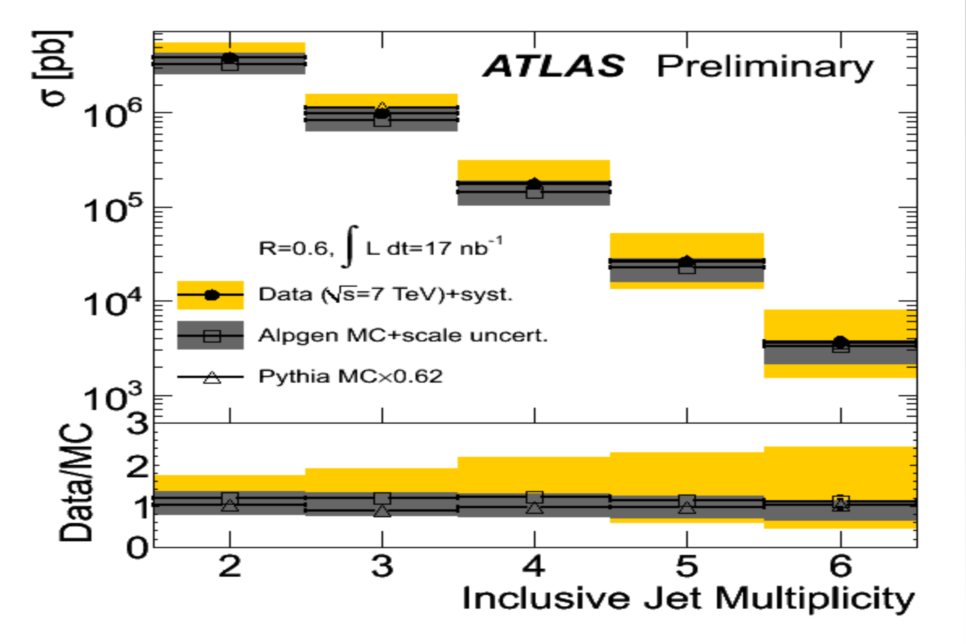


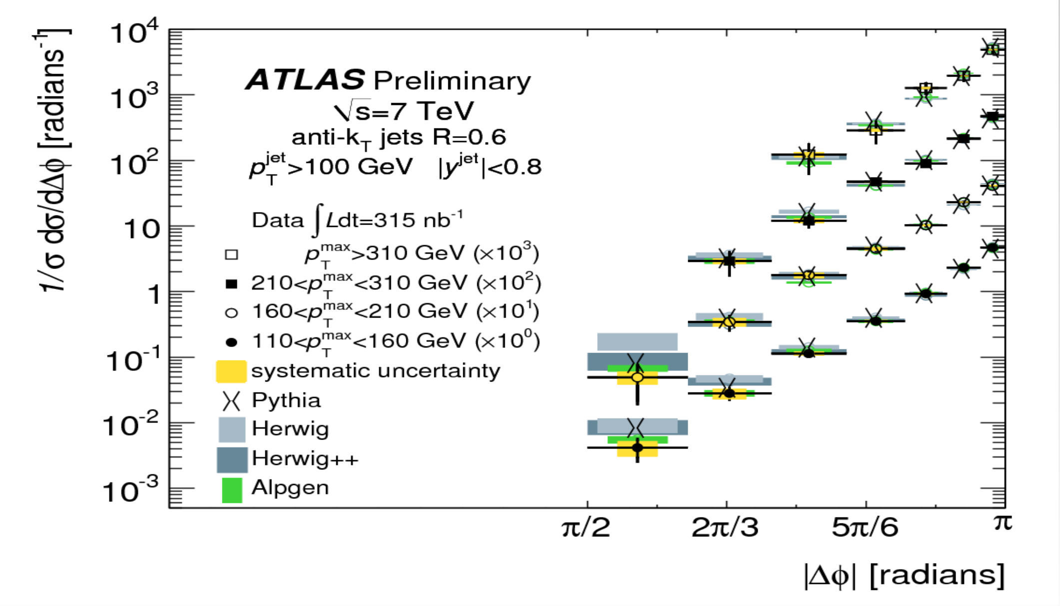


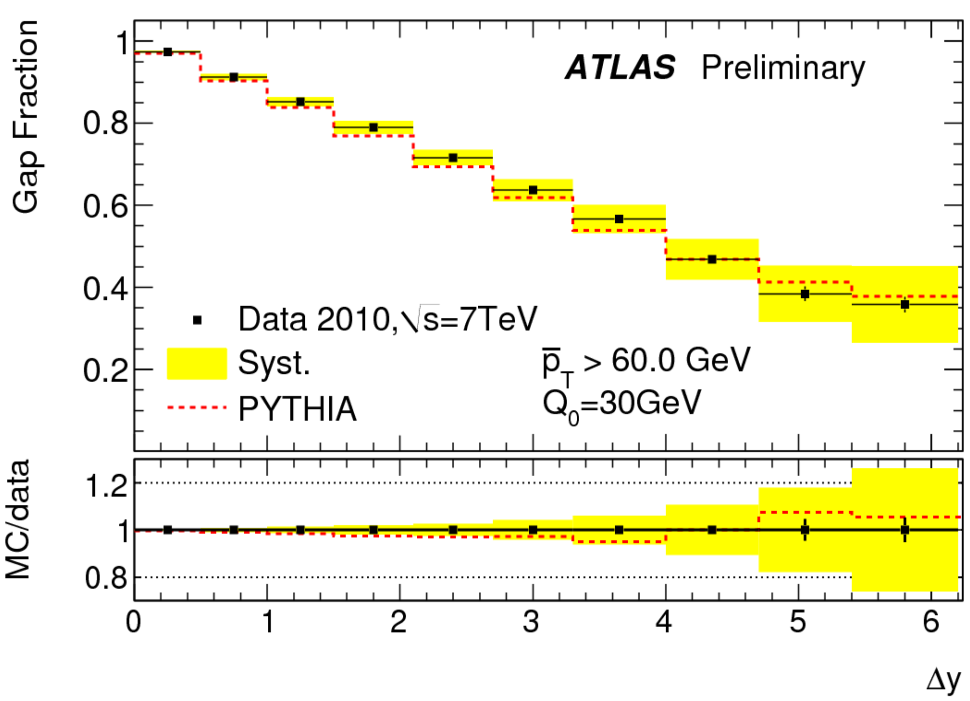




More QCD at the LHC



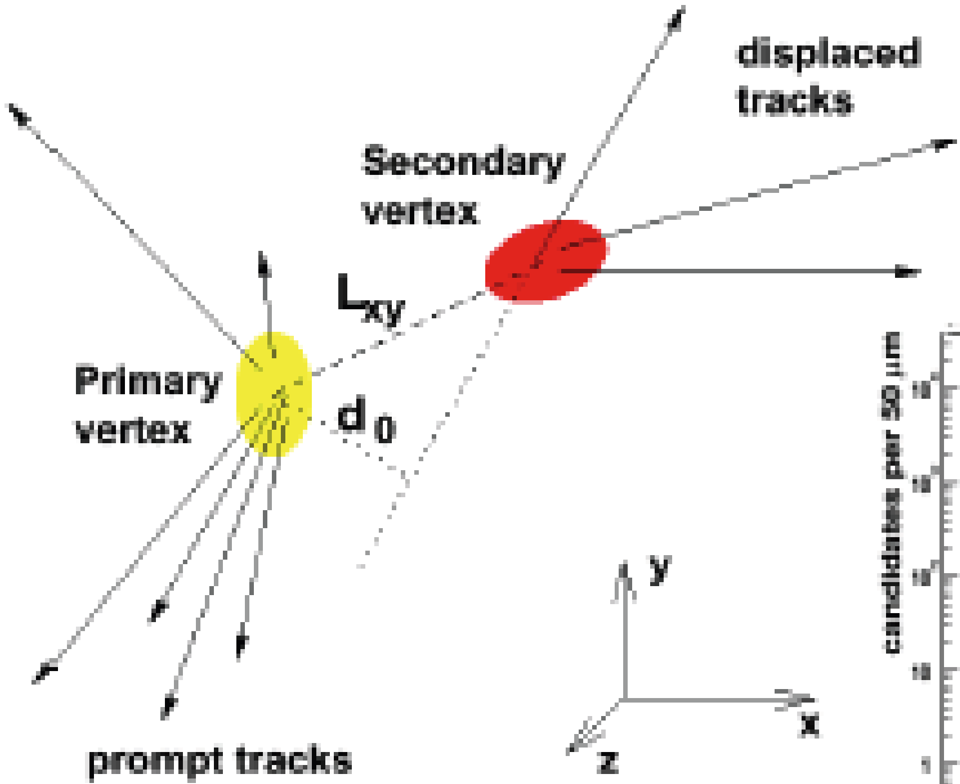


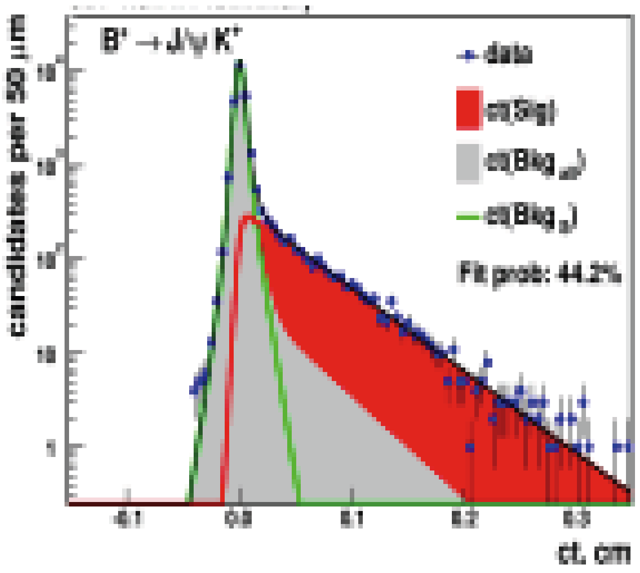


Several QCD tests performed on jets, looking at multiplicity, angular distribution, radiation between dijets

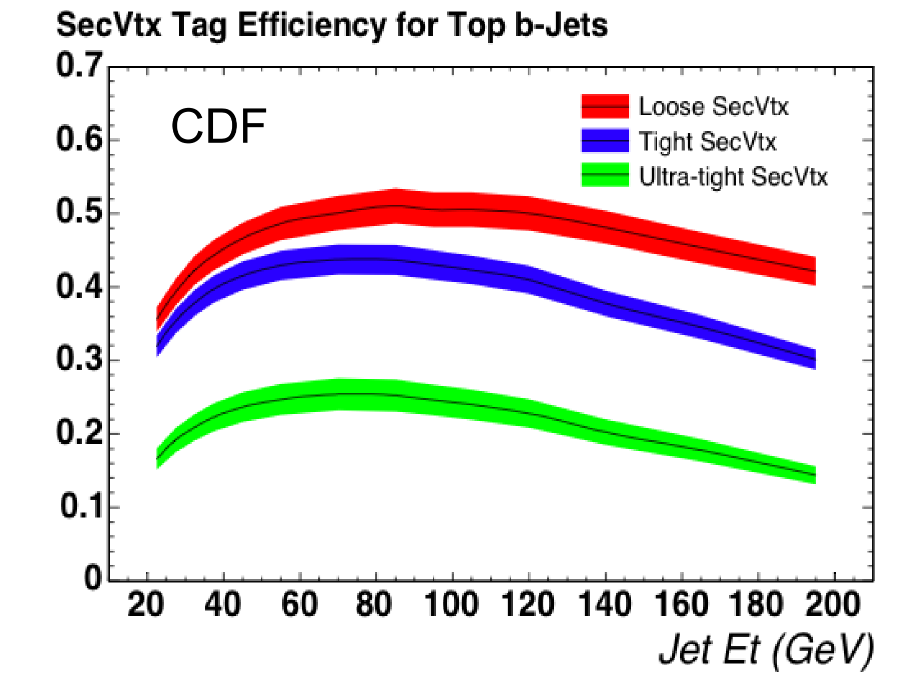
Experimental techniques: b-tagging

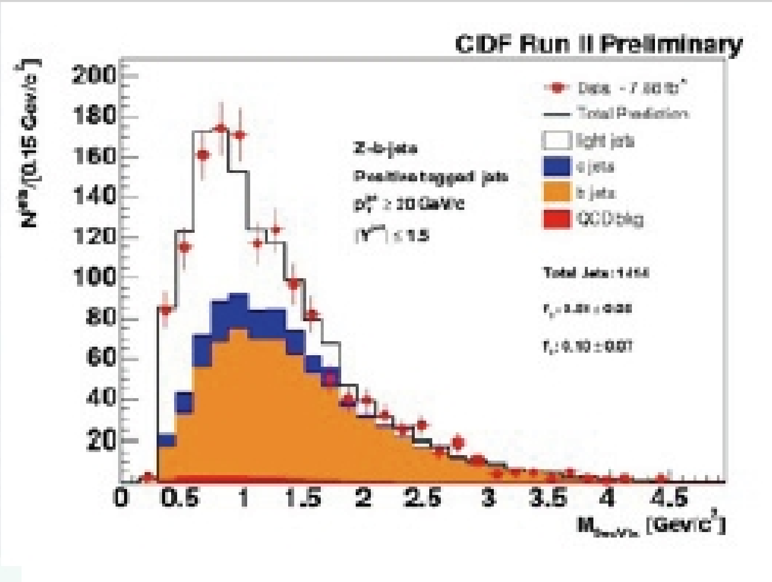
- – need to measure **a displaced secondary vertex.**
  - d_0 is called the "impact parameter"
  - L_{XY} is a pseudo-decay distance (related to lifetime of particle)

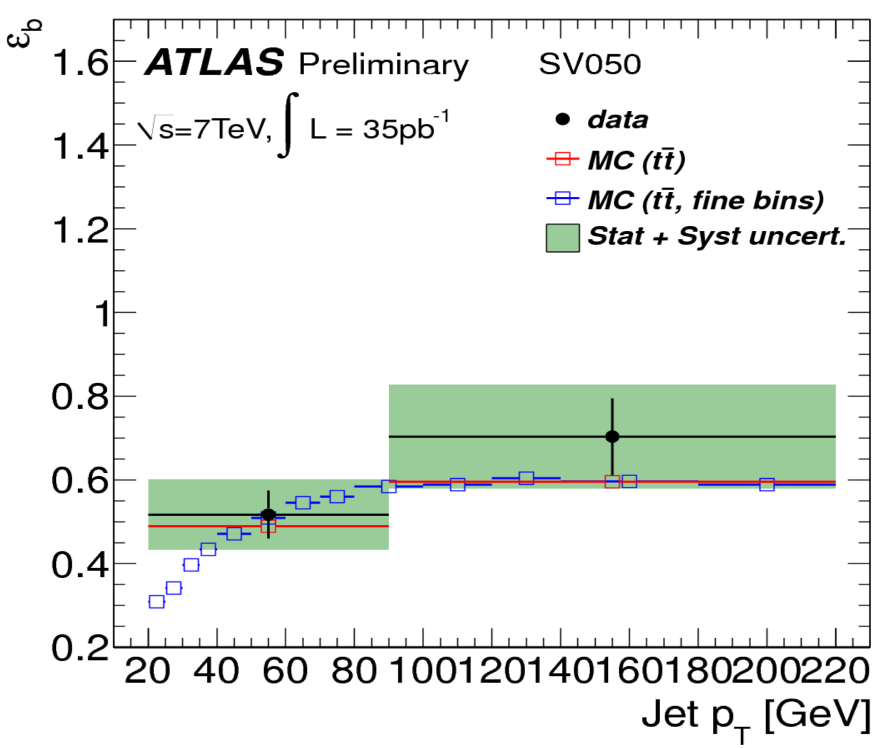


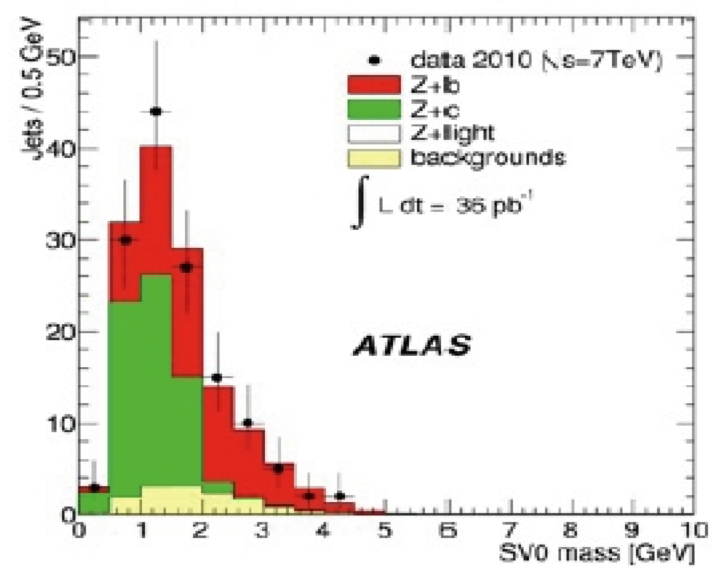


Efficiency and purity of b-tagged jets





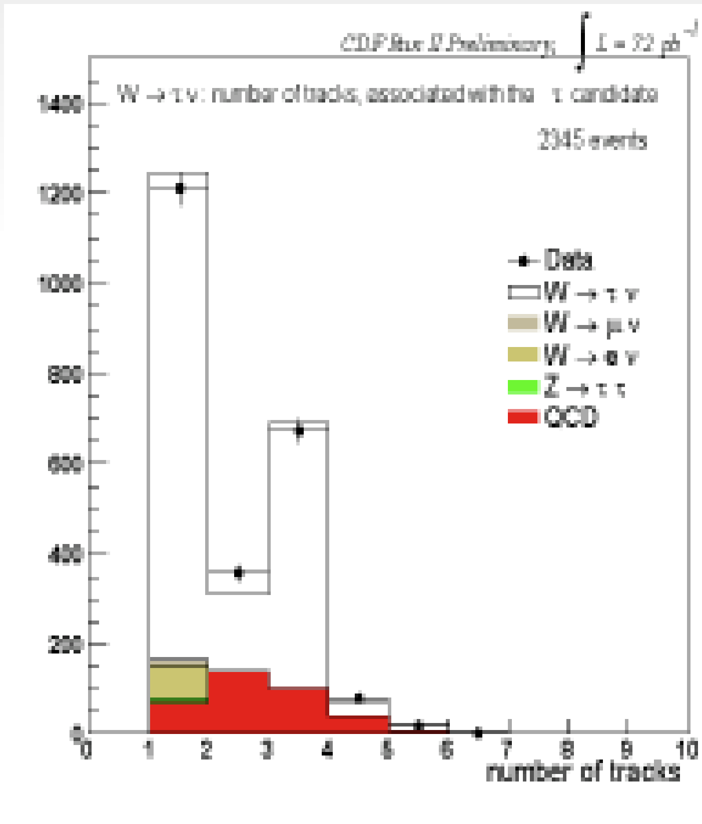


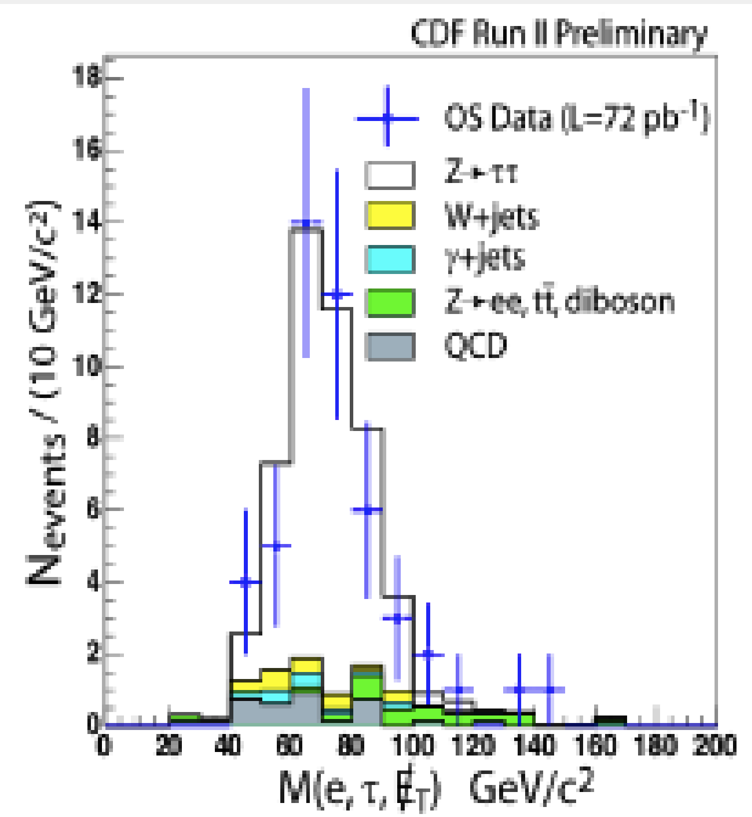


Purity from mass of tracks coming from secondary vertex: almost no light background at the LHC detectors!

Experimental techniques: taus

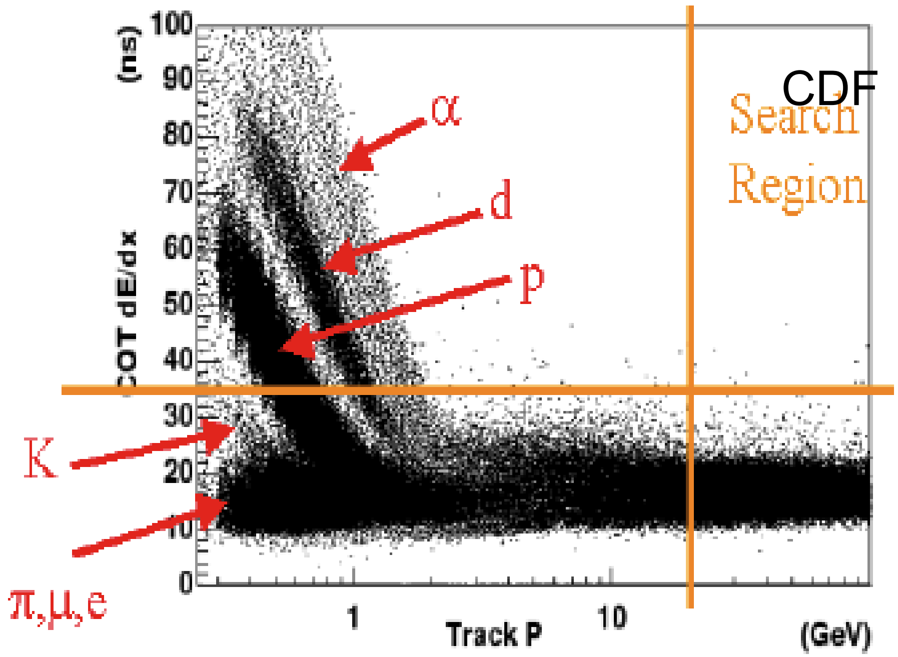
- Taus decay immediately into lepton-neutrino (BR~18%) or qq pairs
- Hadronic decays produce an odd number of charged particles (prong) with possibly neutral pions. Experimentally, a ”narrow jet”, with 1 or 3 tracks

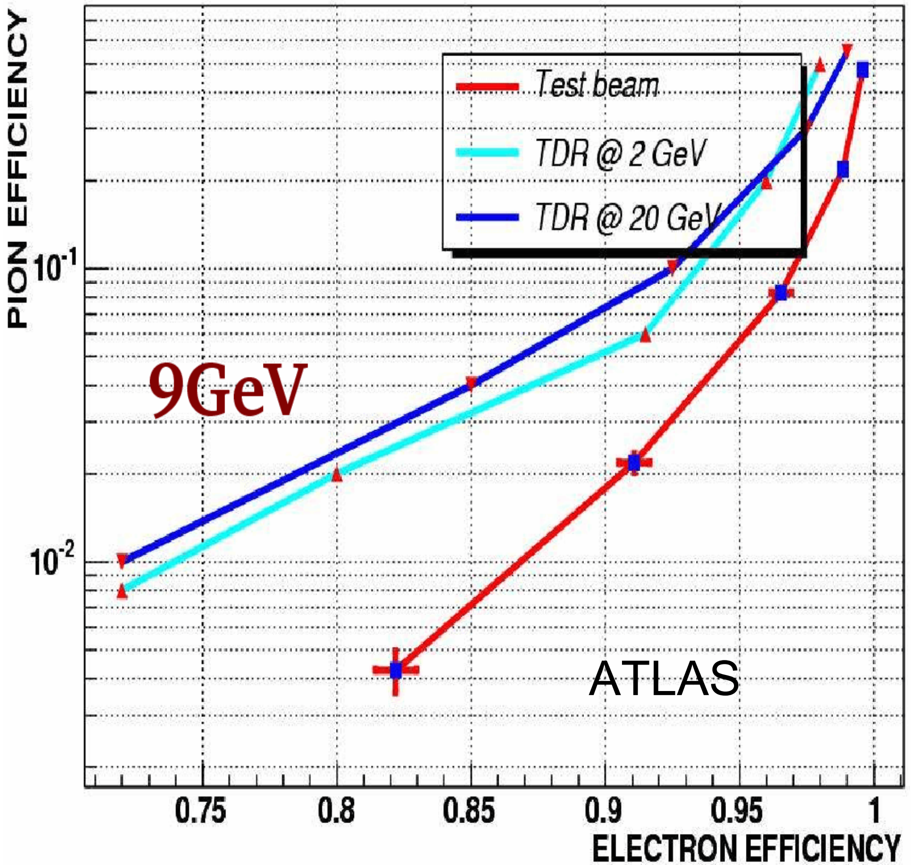




Experimental techniques: Particle Identification

- vital for B physics : knowing difference between pion, kaon & proton
- use TOF or Cerenkov counter or dE/dX





Detectors with gas trackers can use the energy lost by particles (dE/dx) as a function of track P as a powerful particle identification tool.

Drift in gas is way too slow to cope with the 25 ns bunch crossing of the LHC, so ATLAS uses instead to separate electrons from charged + neutral pion background a Transition Radiation Tracker, a straw tube tracker where relativistic electrons have a much higher detection efficiency than pions.

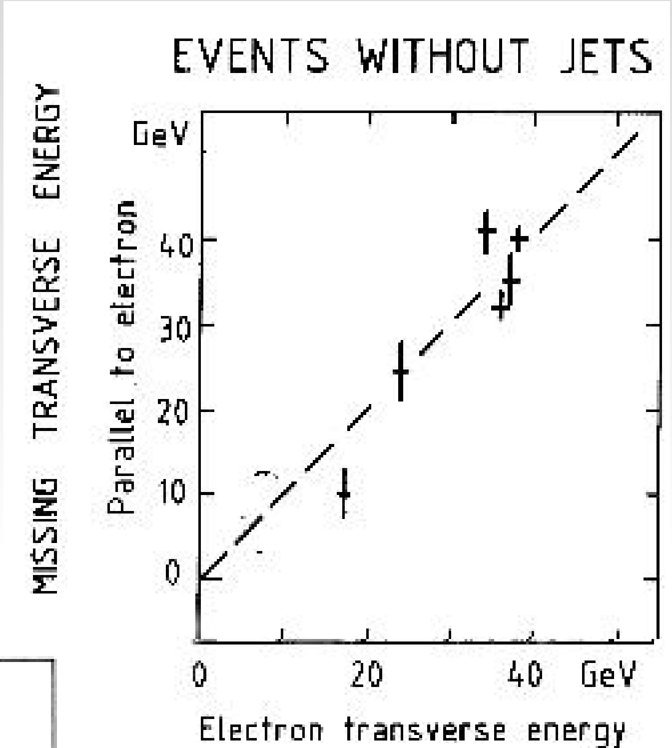
Vector boson production

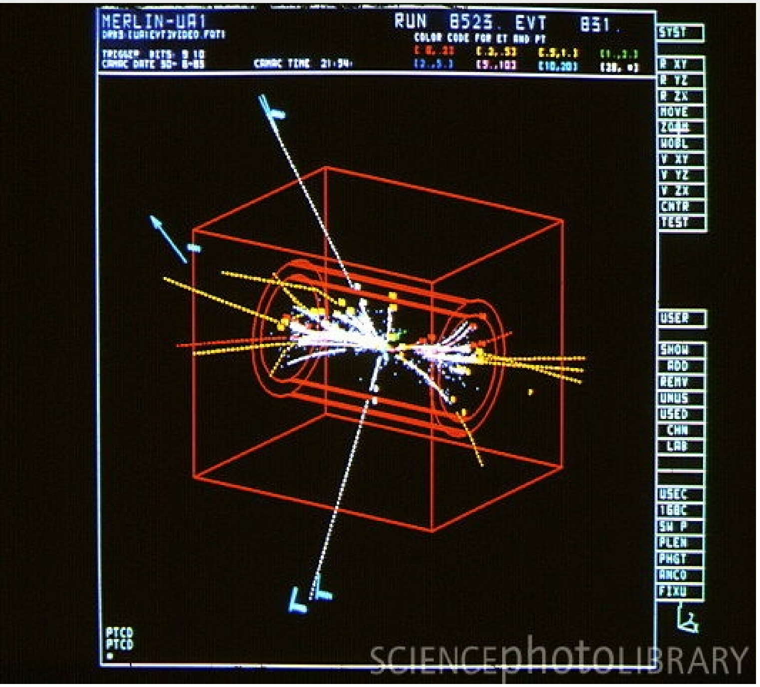
- Next important SM benchmark are W and Z production, often accompanied by jets.
- Relevant for Pdf determination, QCD studies
- W production about 10 times larger than Z, but analysis more difficult: no way to perform full reconstruction, so only transverse mass can be reconstructed
- Different BG from 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??)

Discovery in UA1/UA2 (1982/83)

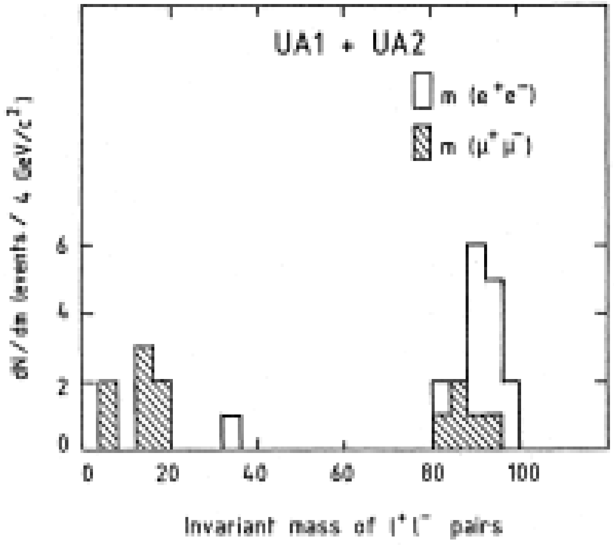
At the end of 70's, the SPS ring at Cern was run in proton/antiproton collider mode thanks to stochastic cooling

First observation of W bosons consisted of 5 events with large electron pT, large MET and no jets





The Z was discovered one year later, always with 5 events (4 ee and 1 μ μ)
In both cases, estimated background was negligible

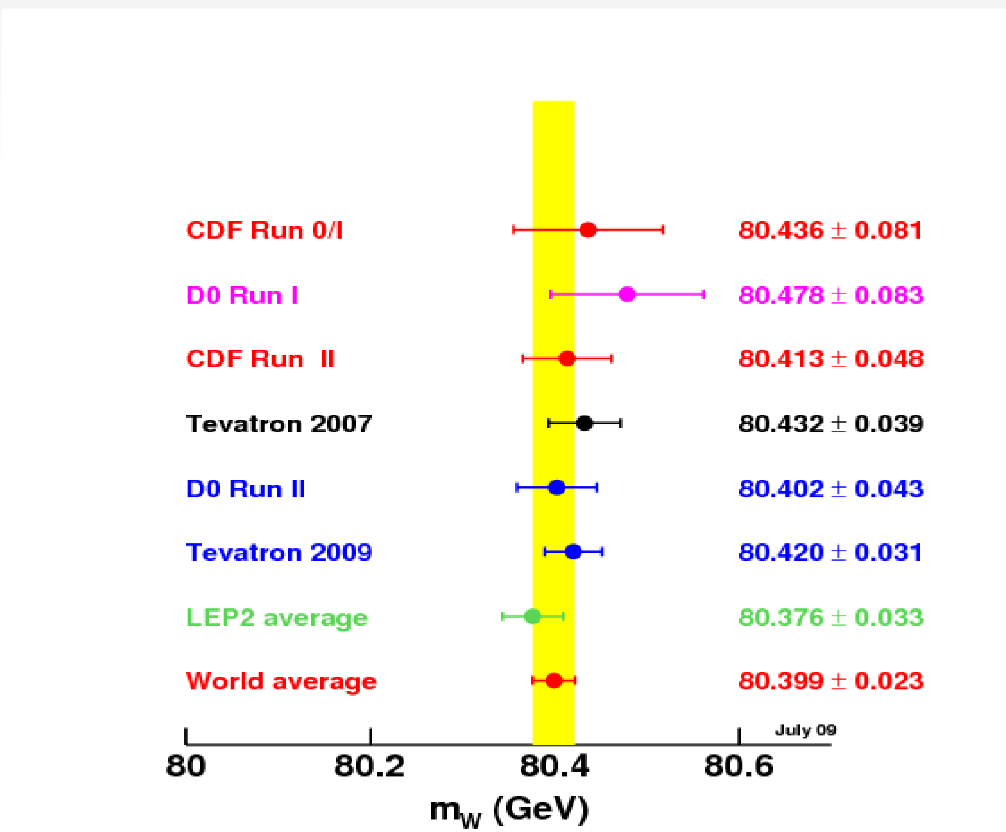


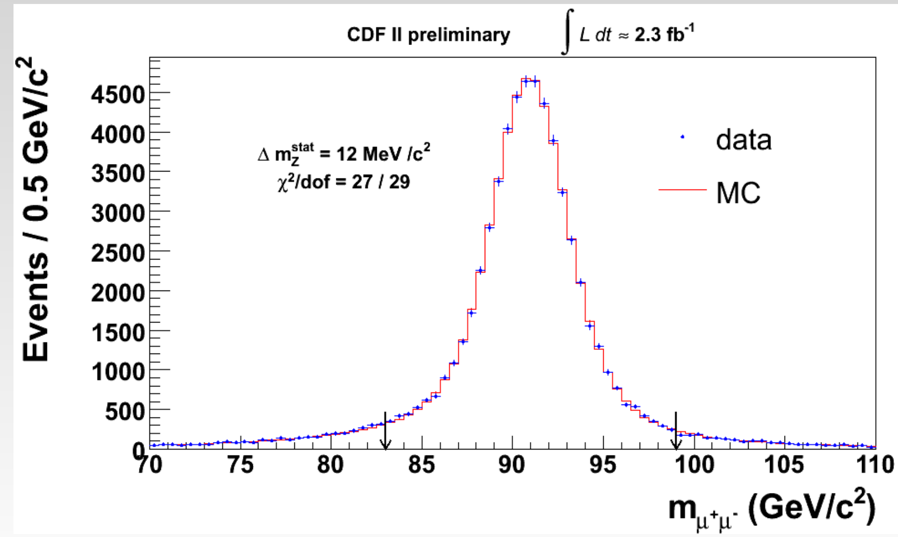
Nobel prize awarded in 1984 (Rubbia/Van der Meer)

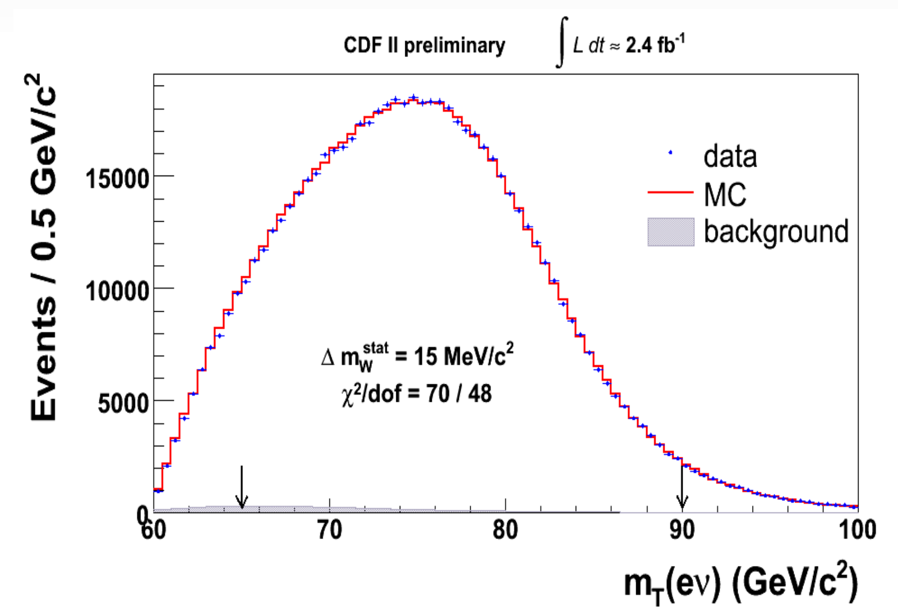
Vector boson masses at Tevatron

LEP experiments recorded O(1E7) Z bosons (mass known at 1 MeV level) and O(1E5) W bosons (mass known at ~35 MeV)

Hard to improve on the Z, but the very precise LEP measurement can be used as calibration to improve on the W



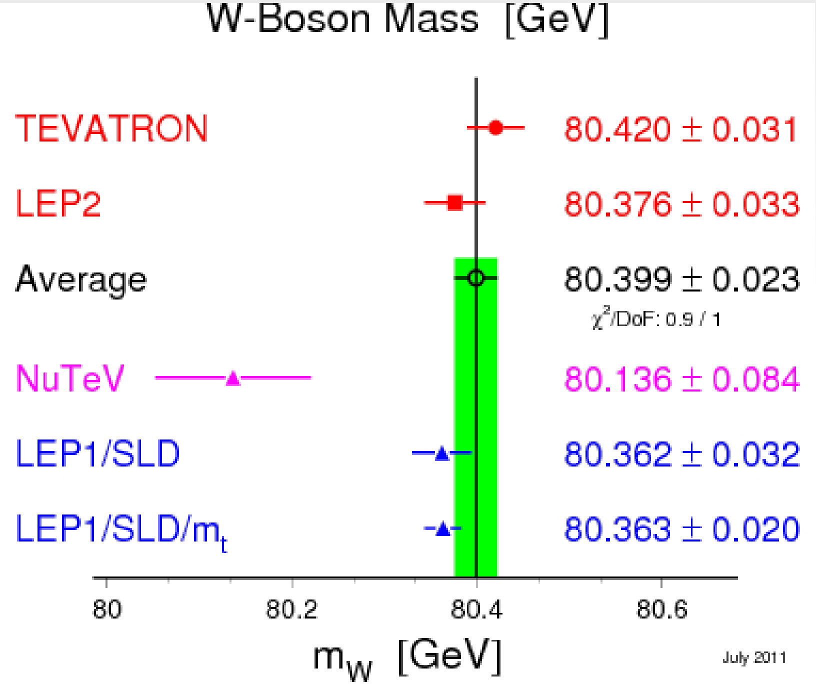




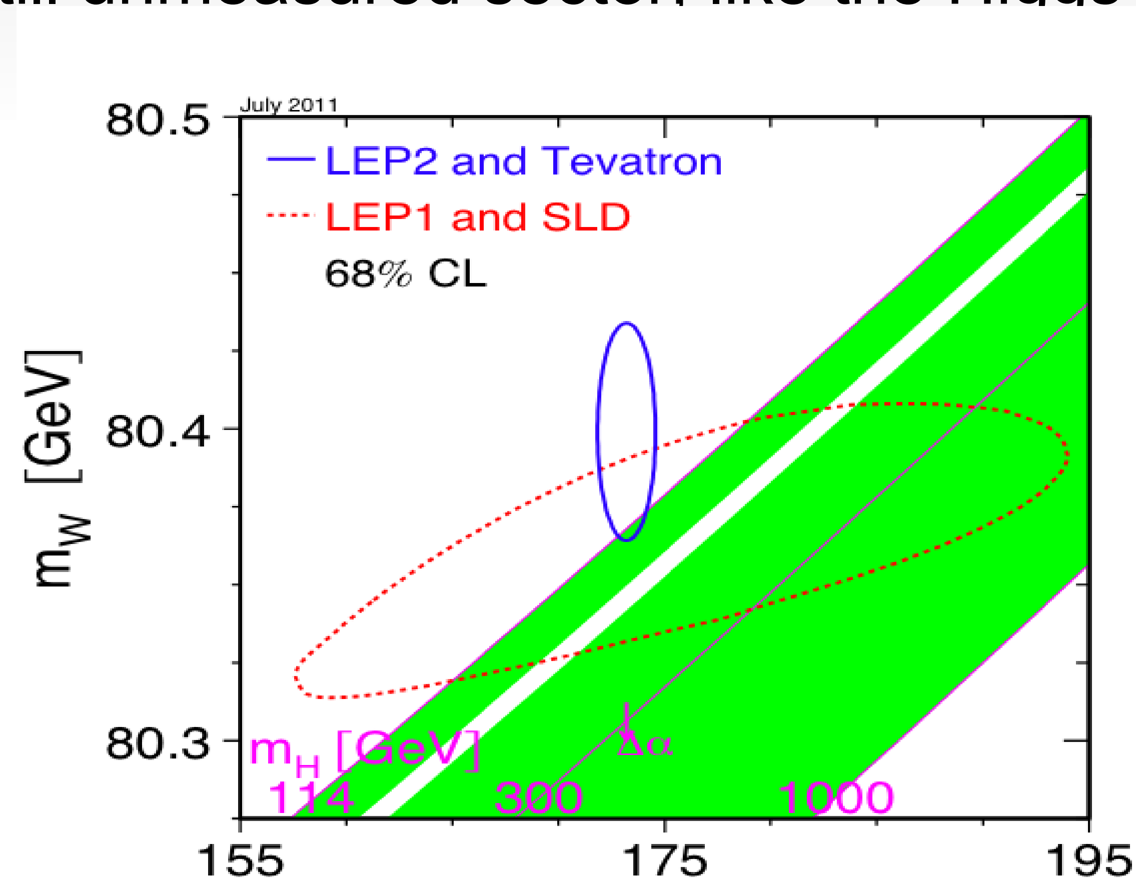
Only transverse mass can be measured and fitted with Jacobian function. Low BG, but sensitive to many small effects

Electroweak fits

The point of pushing so hard on the precision of measuring the SM parameters is that all these values are connected to each other via quantum loop effects: the W mass can be predicted indirecly without even measuring it:

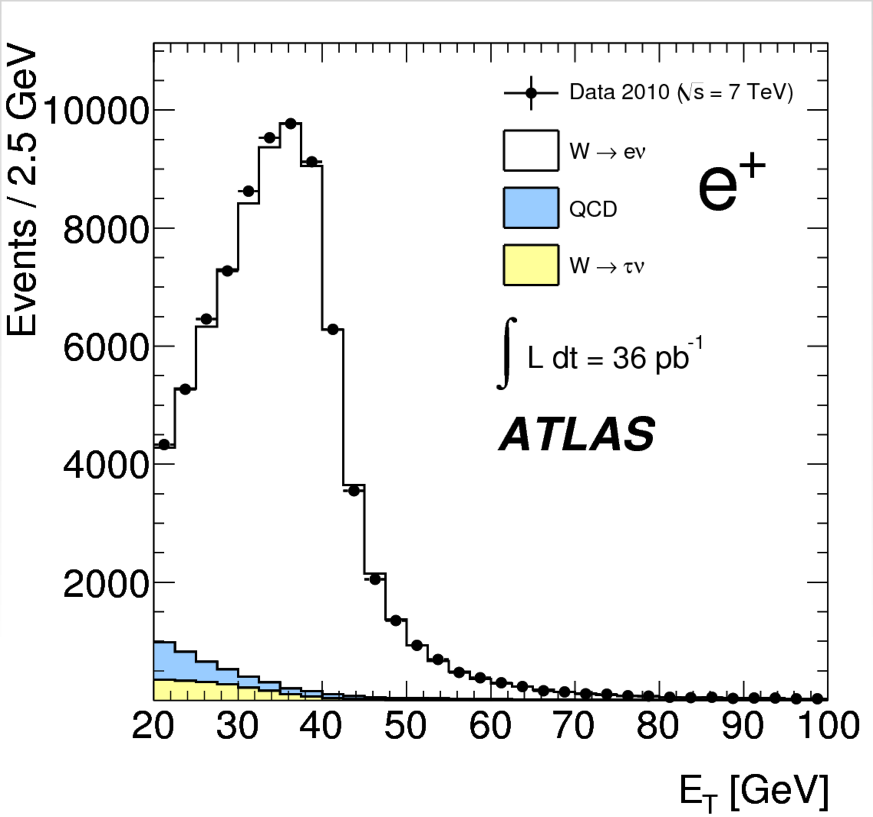


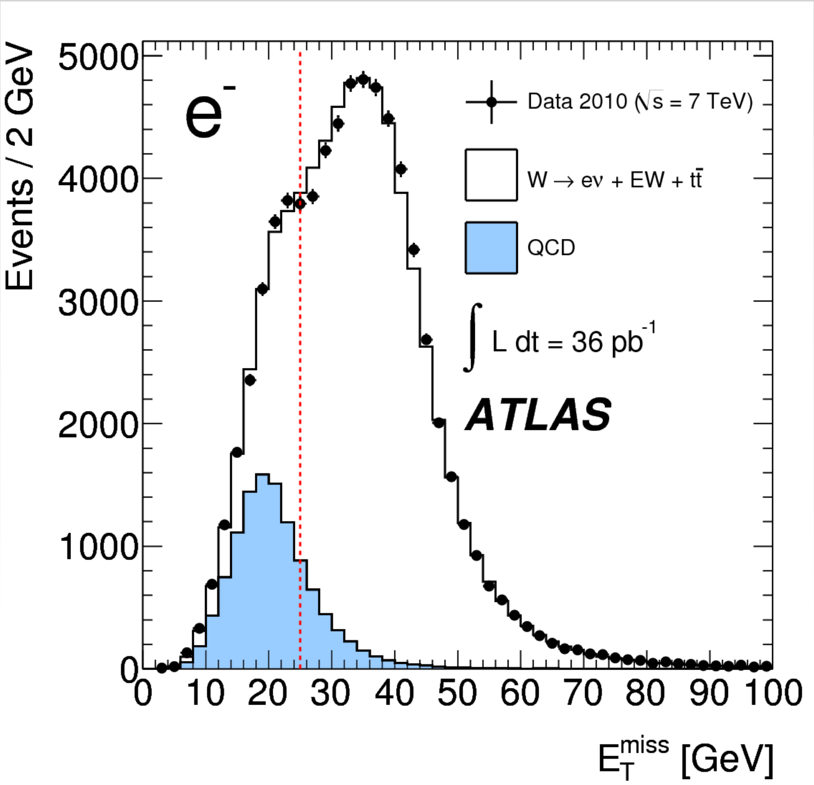
The combination of indirect predictions and measurements can constraint the still unmeasured sector, like the Higgs



The combination of direct and indirect measurements of the W and top masses is only compatible at 68% with a light Higgs, just above the LEP limit

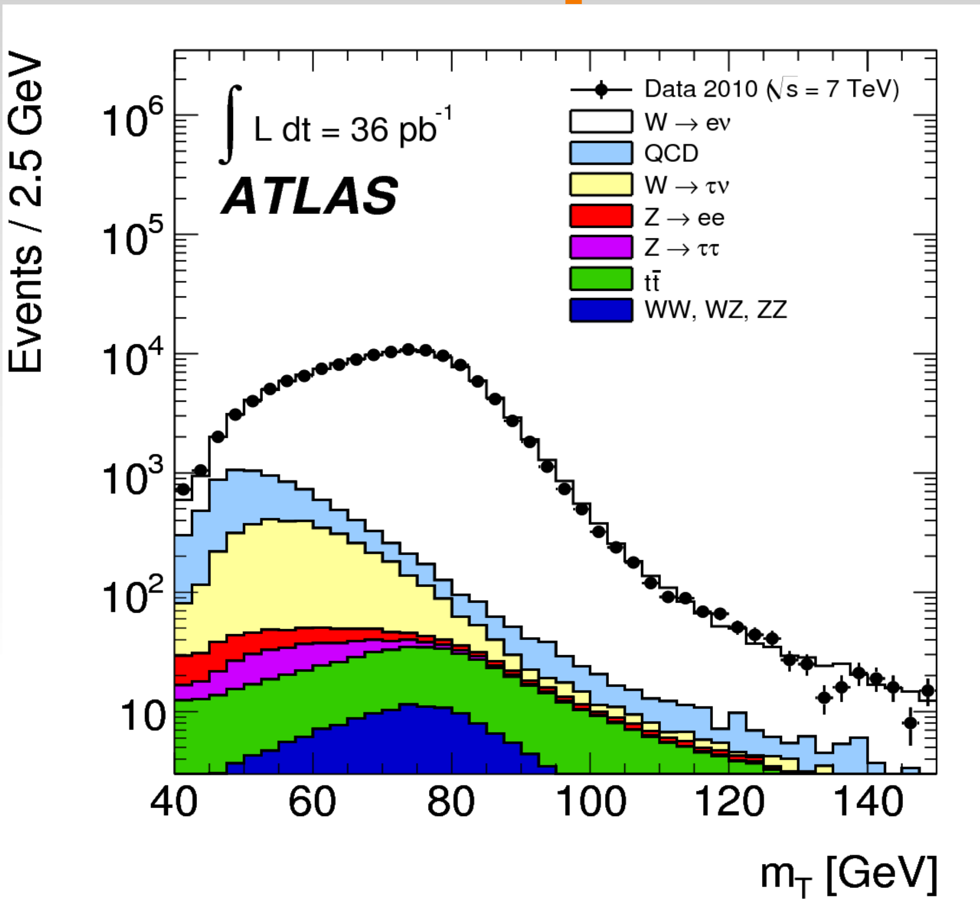
Ingredients of the LHC analysis

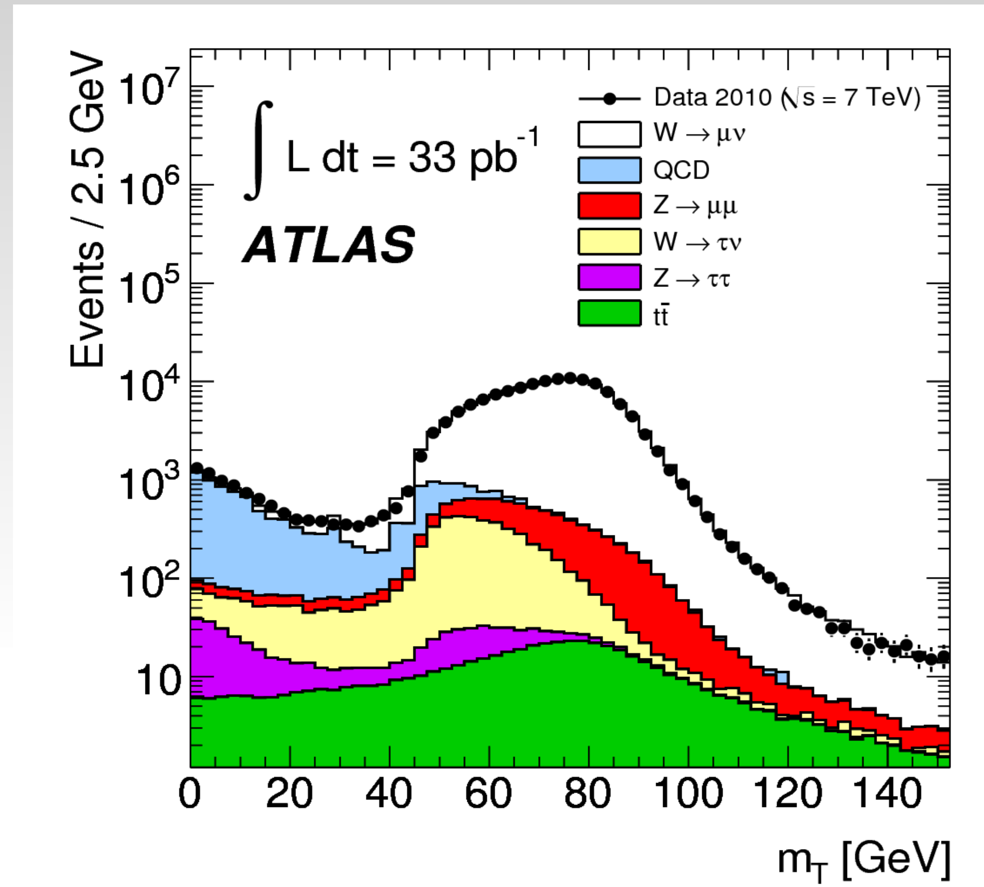




- Electron Pt MET
- for W->enu events
- Signal purity quite high even for individual variables

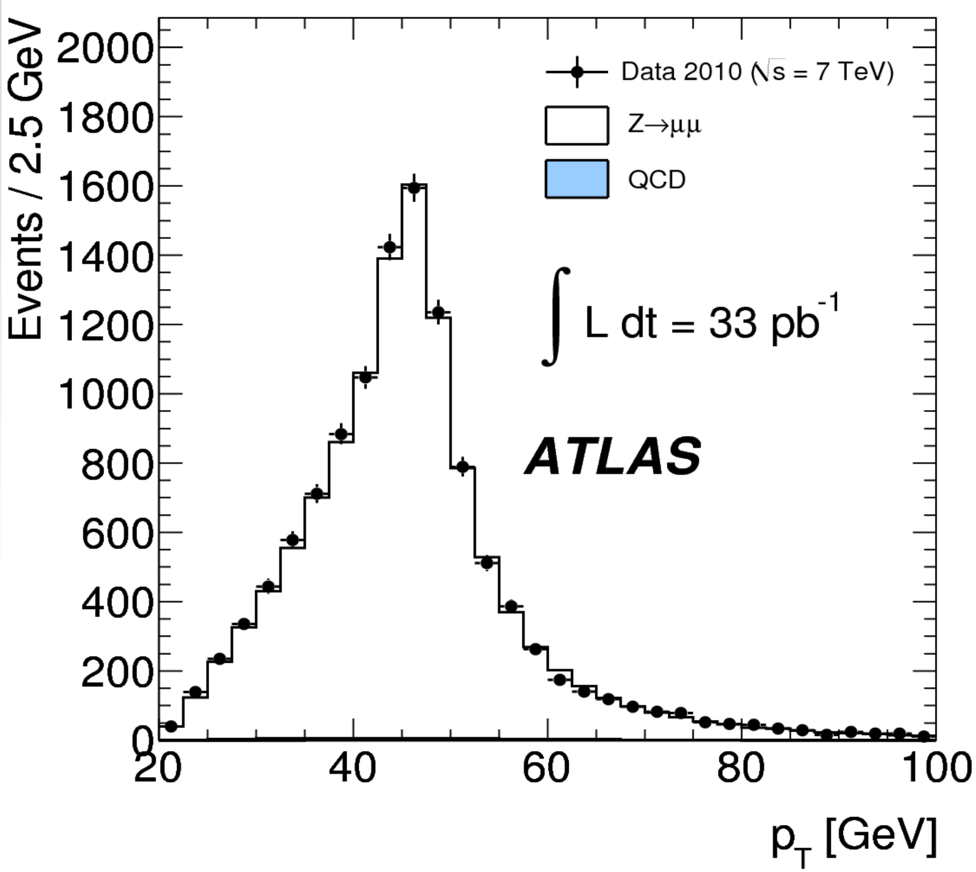
W->e,μ + nu transverse mass

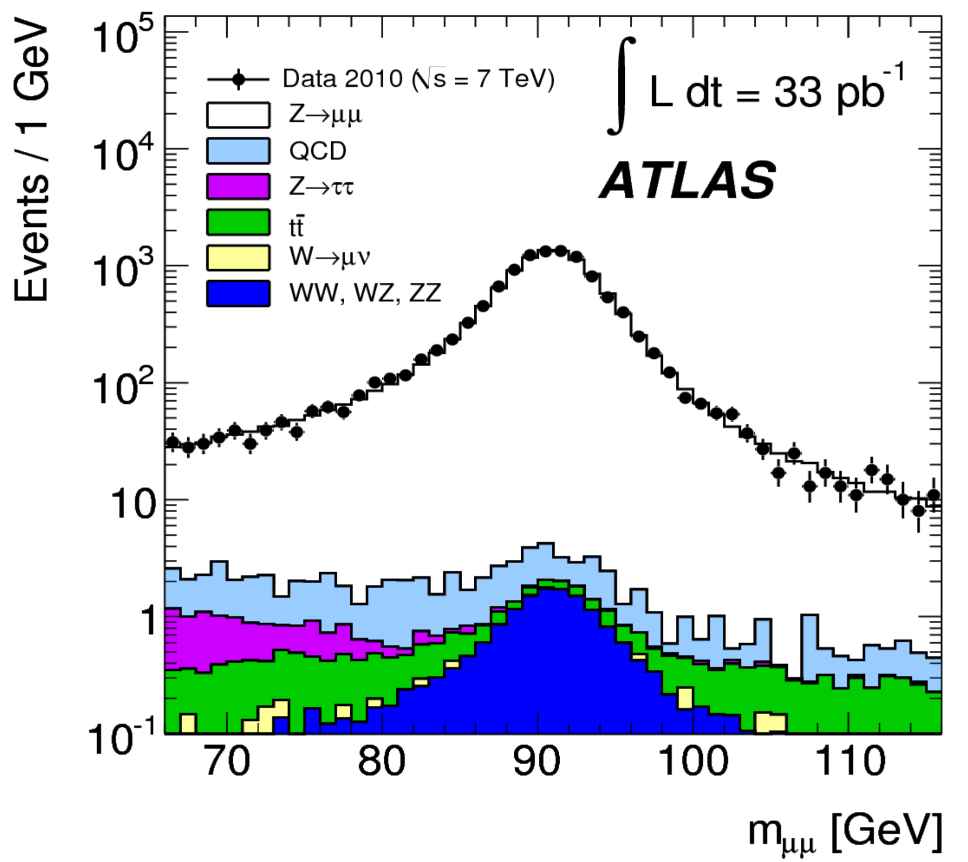




- Different background contribution mainly due to different reslution and rapidity coverage for electrons and muons in the detector

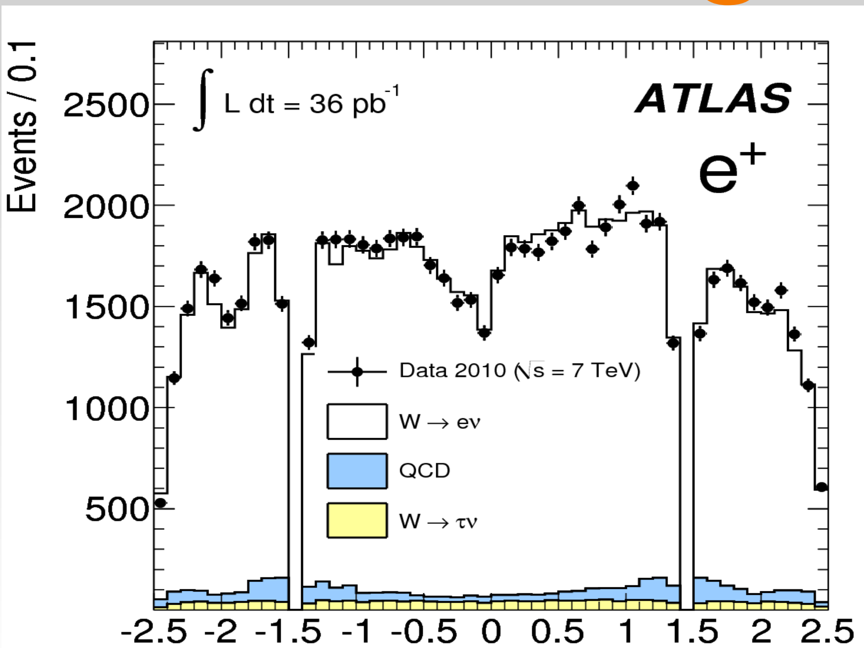
Z->ll analysis

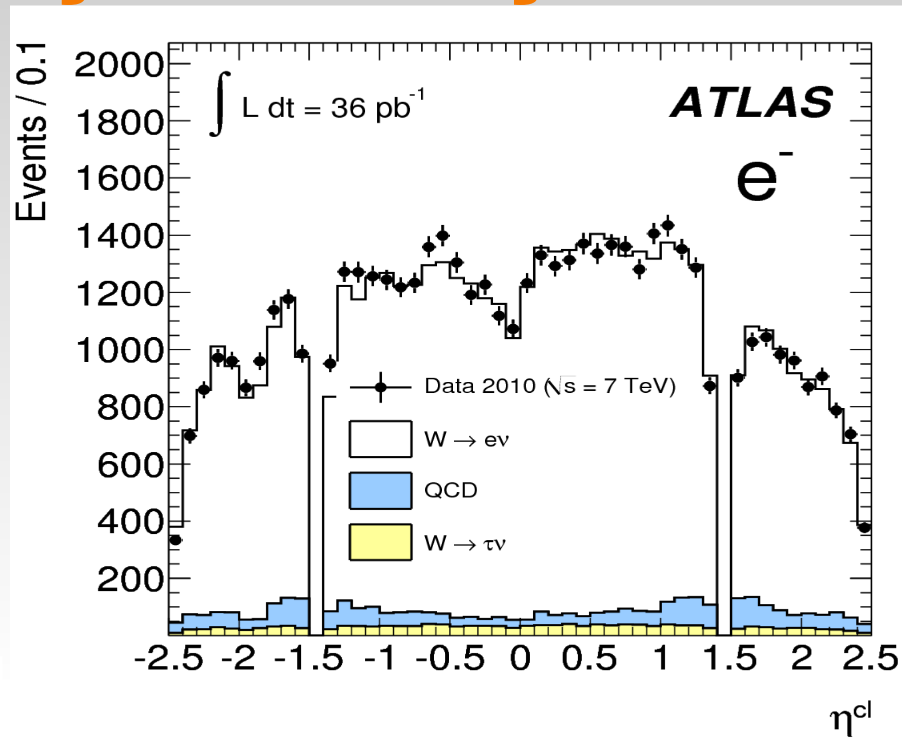


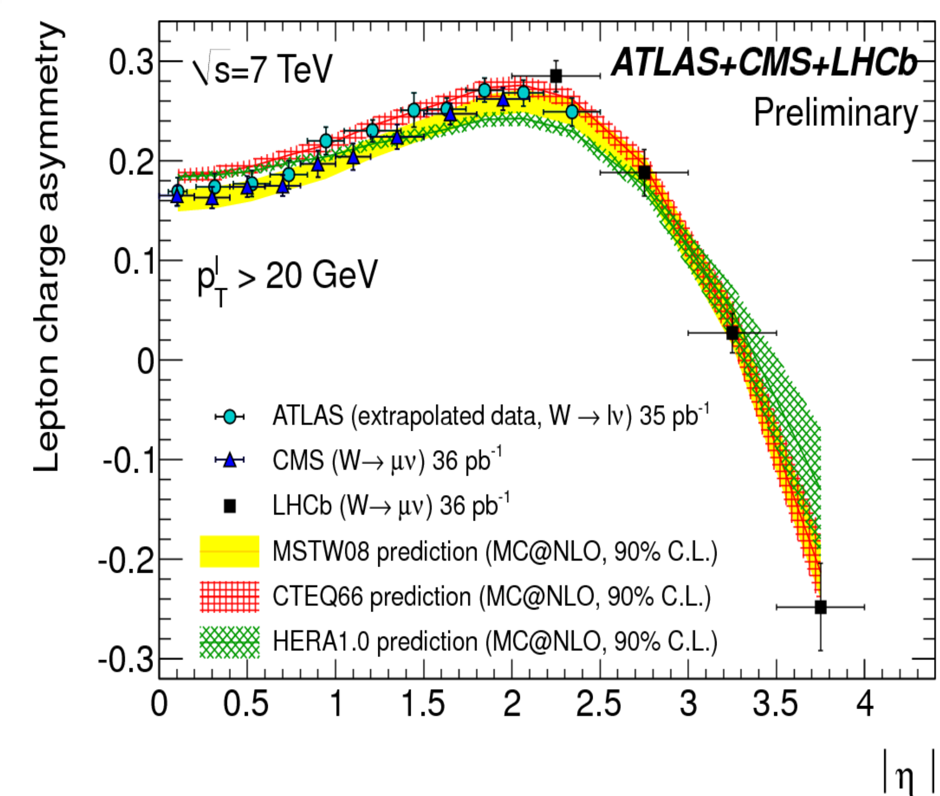


- 2-lepton requirement makes Z channel much cleaner, but statistics is poorer-hard to beat LEP's 4 million Z collected per experiment (and lineshape fit). Fundamental tool for calibration

W charge asymmetry







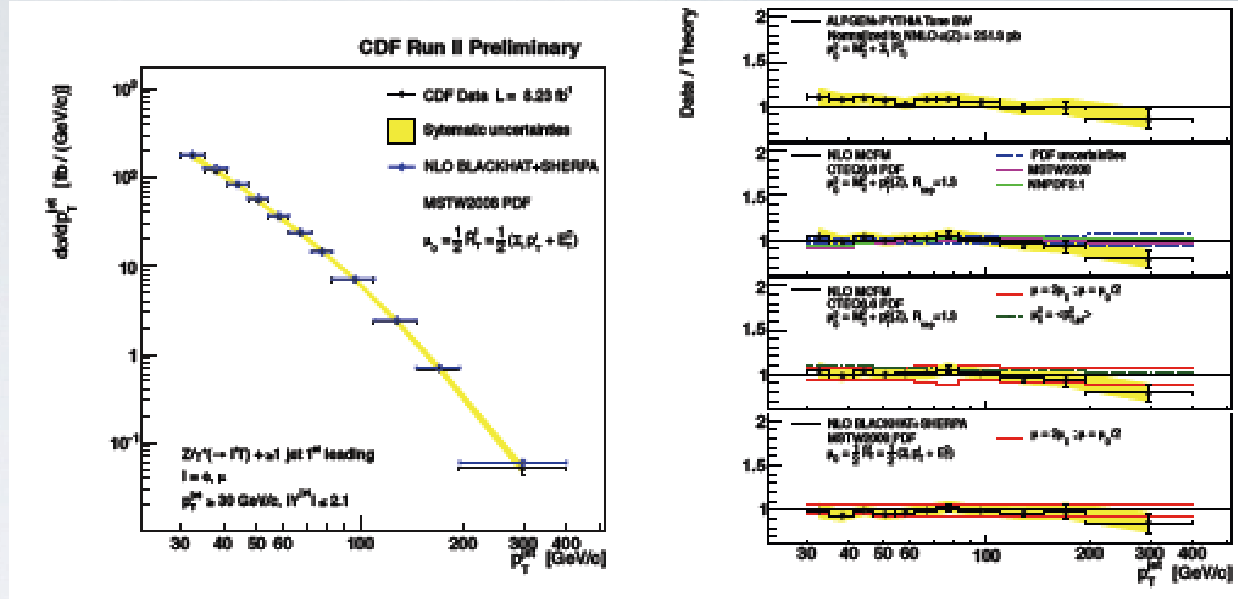
The idea: from Pdf's, u-quarks have higher average x, so W+ tend to be produced more forward. Even in pp, W asymmetry distribution can constraint Pdf's

Z+jet Results

Muons and electrons Combined.

- MidPoint algorithm with R=0.7
- Hadron level jets with p_T^{jet} > 30 GeV/c and $|y^{jet}|$ < 2.1
- $\Delta R(l,\text{jet})$ > 0.7
- Theory prediction corrected for non-pQCD effects

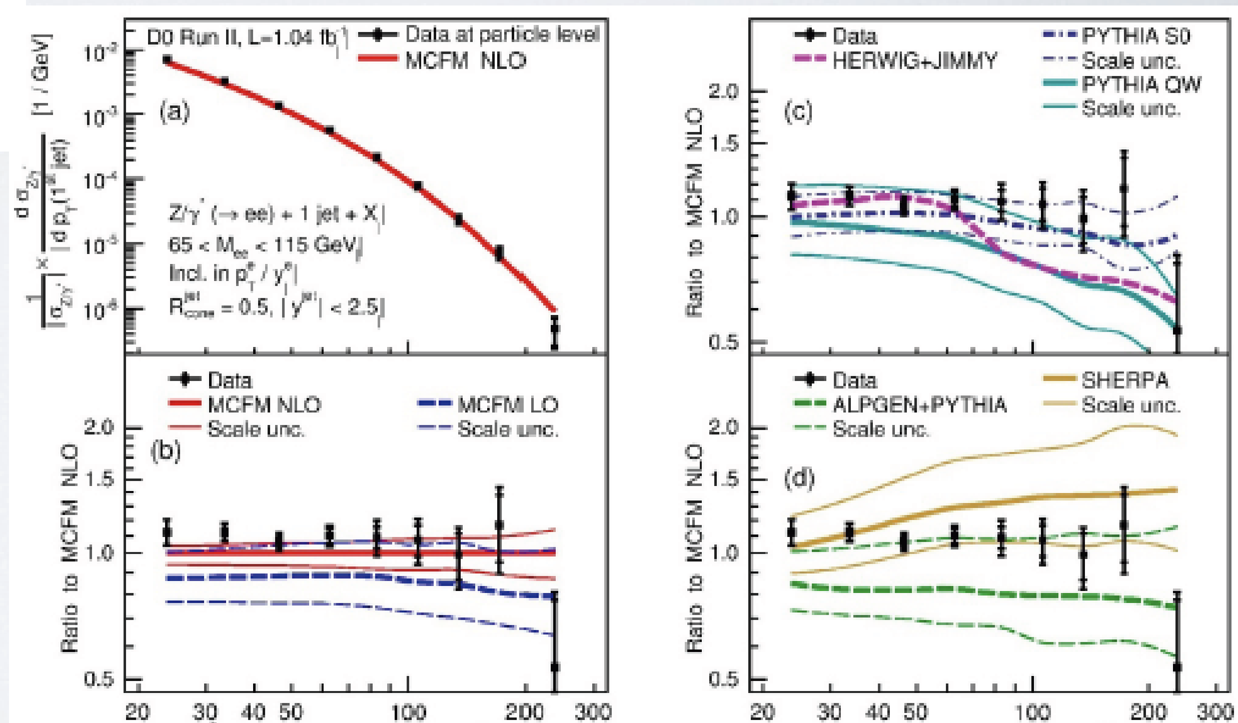
Good agreement with NLO pQCD



PLB 678, 45 (2009)

- Jets reconstructed with midpoint algorithm with R=0.5, pT > 20 GeV and |η|< 2.5
- Measurements normalized to inclusive Z XS and MCFM prediction corrected for non-pQCD effects

NLO pQCD well described the data. Compared to event generators, ME+PS show reasonable description of shapes but large scale uncertainties



W + jet results

- Jets clustered by the anti-kt algorithm (size parameter = 0.5).

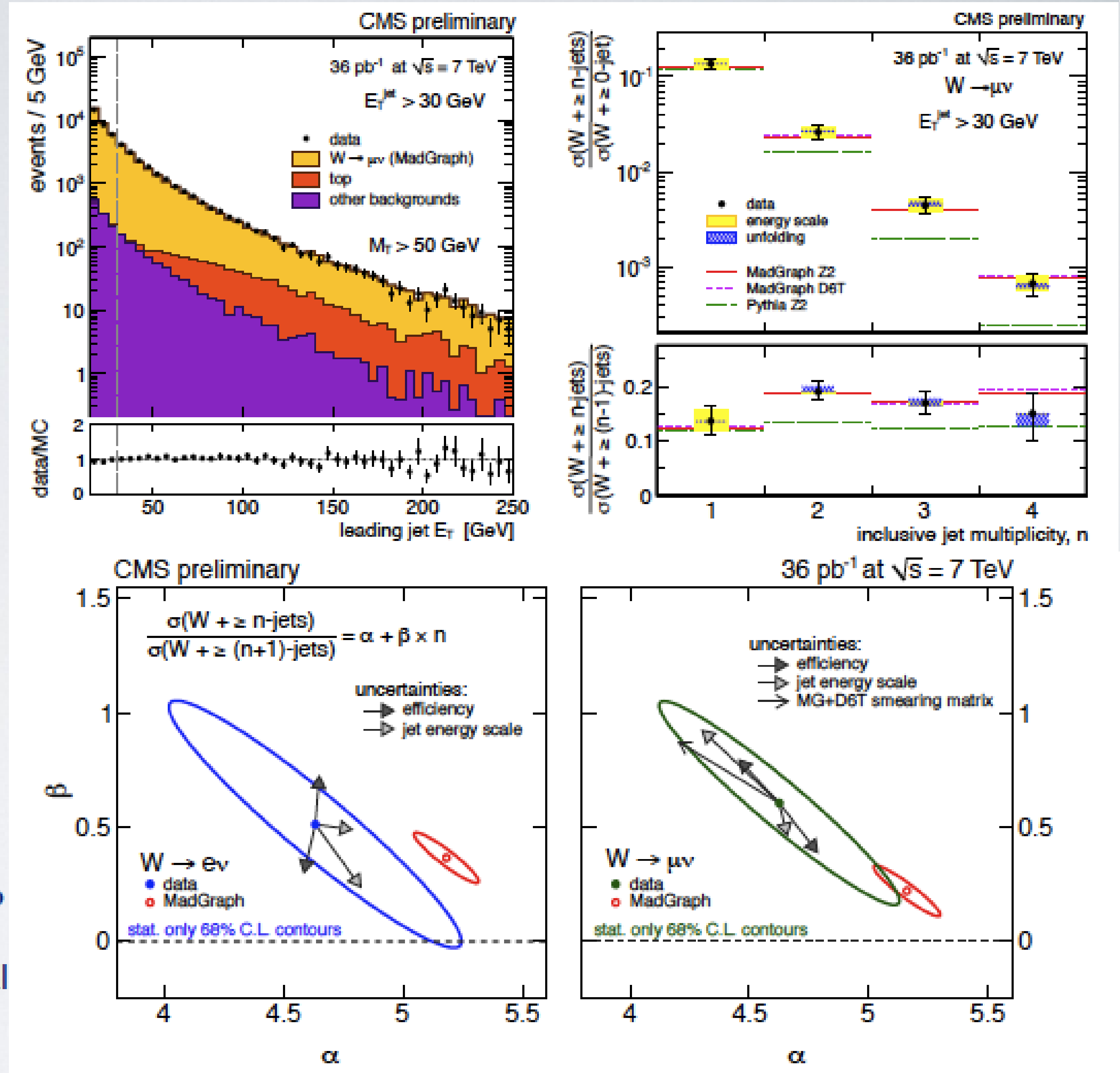
  Particle Flow technique used to reconstruct the jet constituents.
- Count jets with:
  - pT > 30 GeV/c
  - |η|<2.4
- Unfolding procedure applied to correct for migration between Njet bins due to imperfect jet energy resolution and reconstruction efficiency.
- Measurement of:

σ(W + n jets) / σ(W) and σ(W + n jets) / σ(W + (n-1) jets)

Test of Berends-Giele scaling behaviour

Cn =σ(V+njets)/σ(V+(n+1)jets)

- Cn = α + βn: allow for deviations from LO.
- Use measurements of cross section ratios to fit for α and β.
- 68% CL countours on the plots for statistical uncertainty only. Systematic uncertainties shown as arrows.



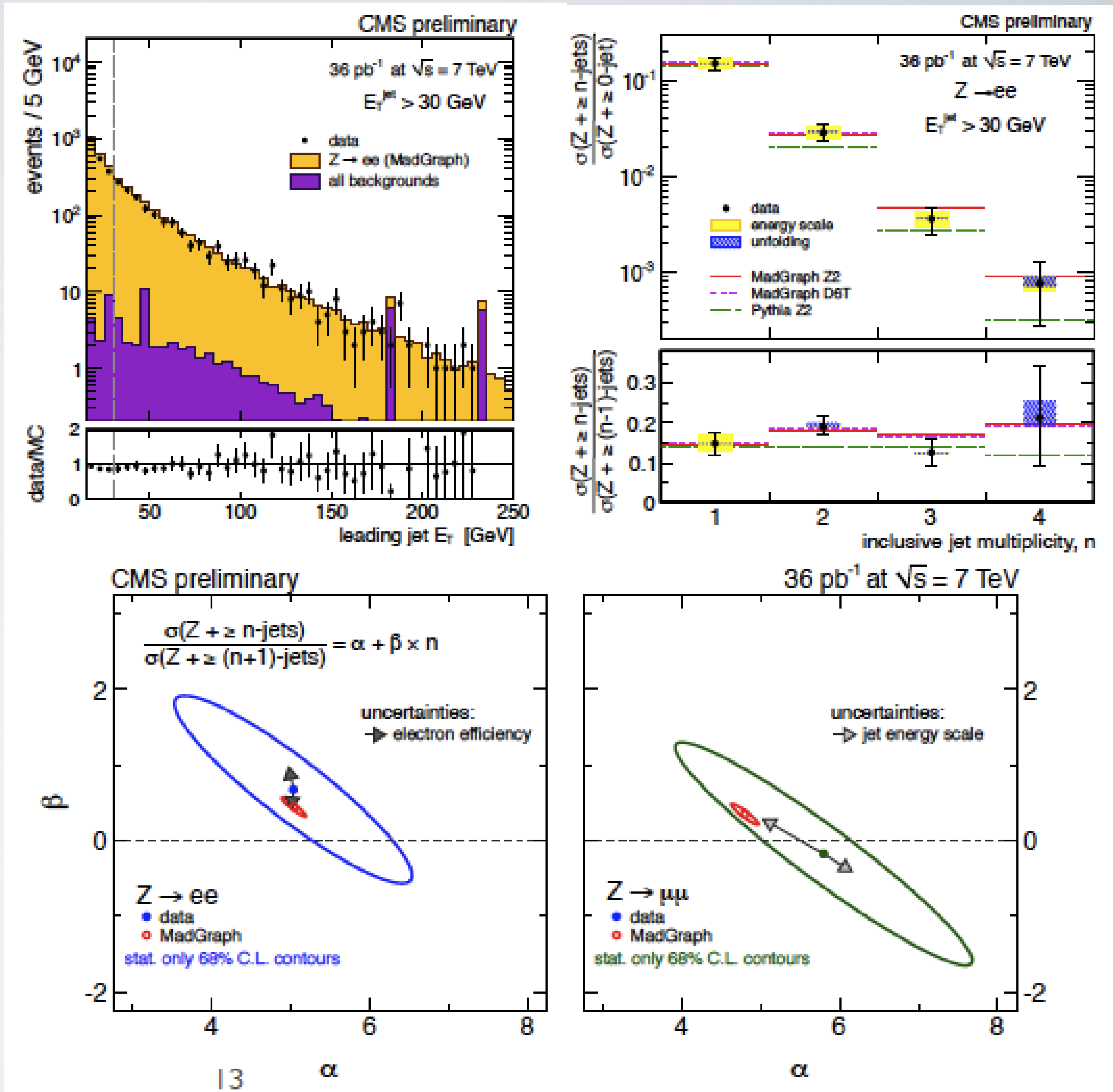
Z+jet results

- Same technique of W+jet.
- Measurement of:

σ(Z + n jets) / σ(Z) and σ(Z + n jets) / σ(Z + (n-1) jets)

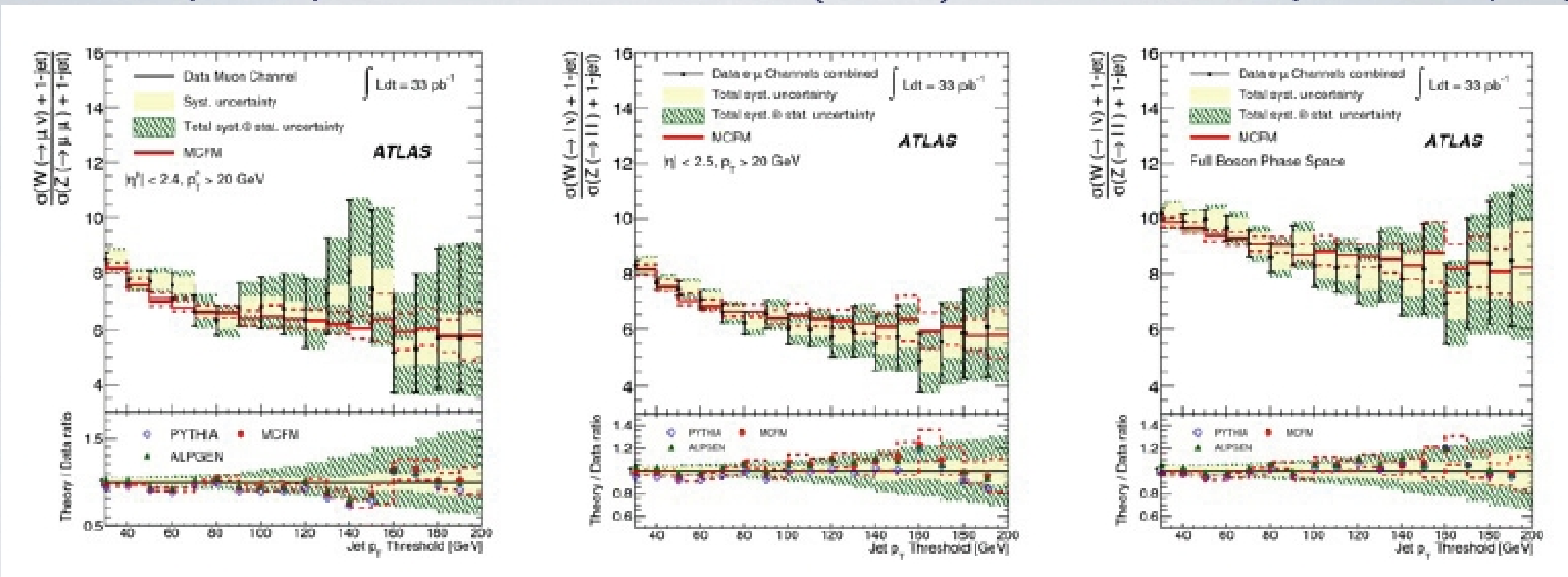
Both W+jet and Z+jet show:

- Good agreement between data and MadGraph in control plots.
- Good agreement with MadGraph, poor agreement with Pythia at high jet multiplicity as expected.
- Berends-Giele scaling behaviour: MadGraph shows reasonable agreement with data.



(Z+1 jet)/(W+1 jet) Rjet ratio

Muon (Fiducial) Combined (Fiducial) Combined (Full Phase Space)

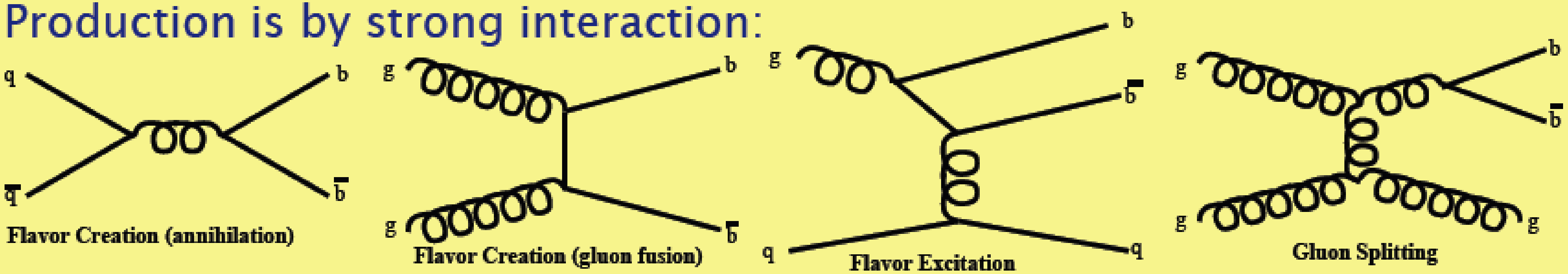


- Probe QCD dynamics without QCD uncertainties
- Theory uncertainty is reduced in the Rjet ratio(control on systematics at few precent level): in particular there is significantly reduced dependence on the PDF
- The Rjet is measured for events with only one jet with p_T>30 GeV and |η|<2.8 as a function of the minimum jet p_T
- Results are given for the electron and muon channel separately and also combined, both in the fiducial and total bosons phase space

Very good agreement of NLO prediction from MCFM
Very good agreement with matched LO prediction from AlpGen and PYTHIA (norm. to data)

B Physics at the Tevatron

Production is by strong interaction:



Pros

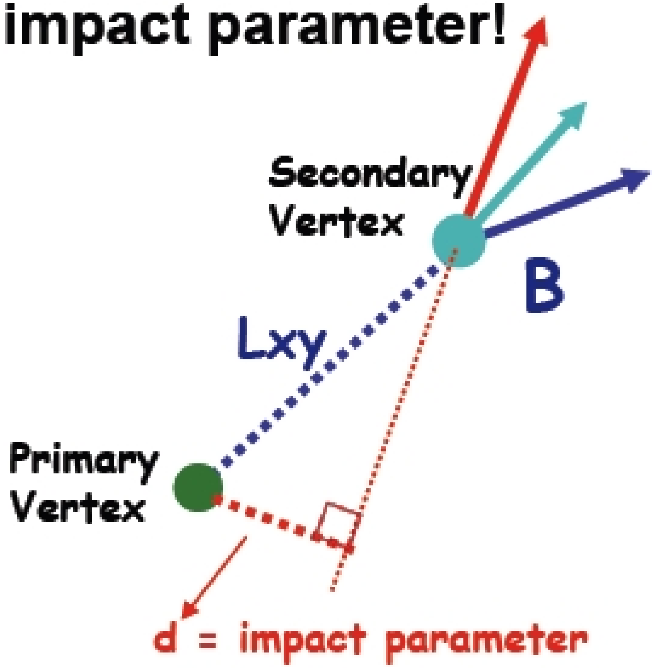
- Large cross-section
  - ~3-5 μbarn "reconstructable"
  - At $2\text{x}10^{32}\text{cm}^{-2}\text{s}^{-1} \Rightarrow$ ~800Hz of reconstructable *BB*!!
- All *B* species produced
  - $B_u, B_d, B_s, B_c, \Lambda_b$,…
- *CP* symmetric initial state
  - Equal numbers of q and $\bar{q}$

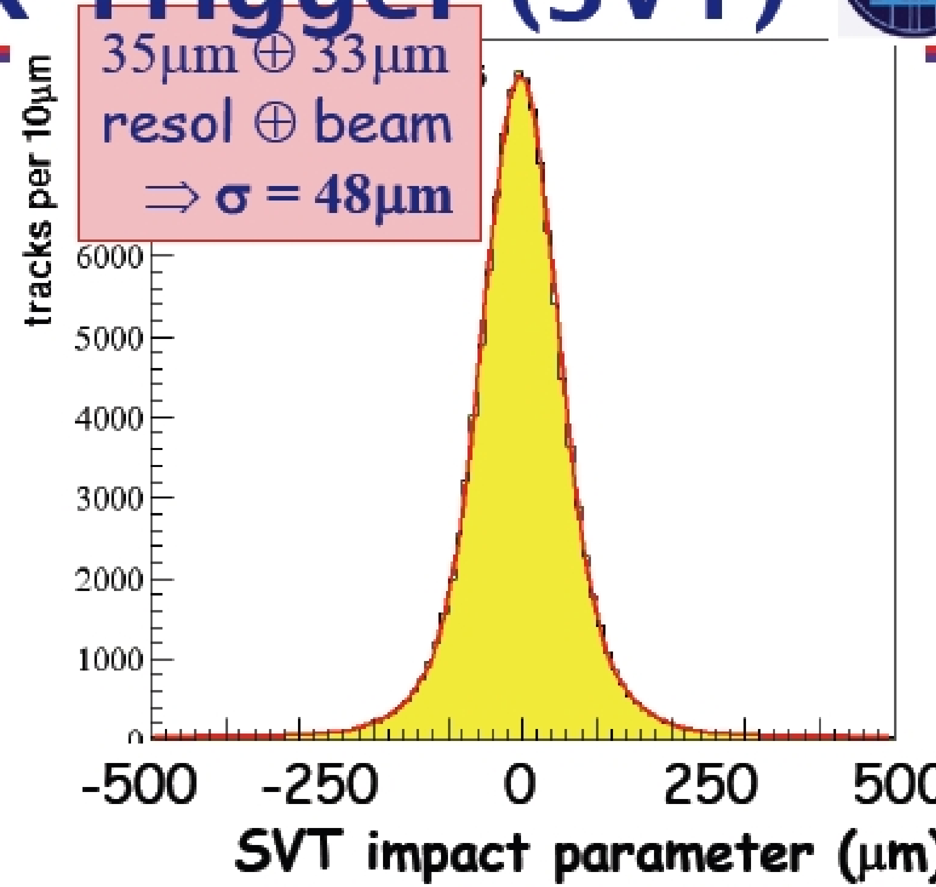
Cons

- Large inelastic background
  - Triggering and reconstruction are challenging
  - Modes with π^0's are tough
- Reconstruct a *B* hadron,~20-40% chance 2nd *B* is within detector acceptance
- p_T spectrum relatively soft
  - Typical $p_T(B)$~10-15 GeV for reconstructed *B*'s ($\beta\gamma \approx$ 2-3)

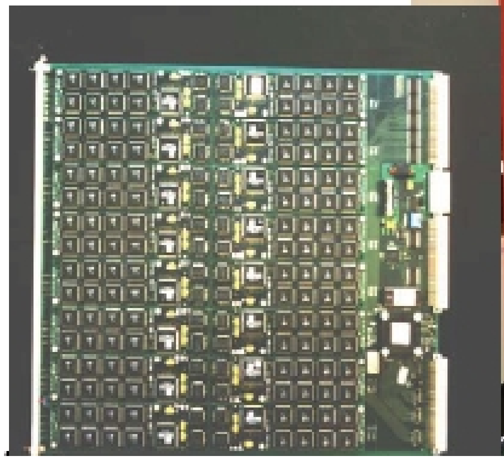
Silicon Vertex Trigger (SVT)

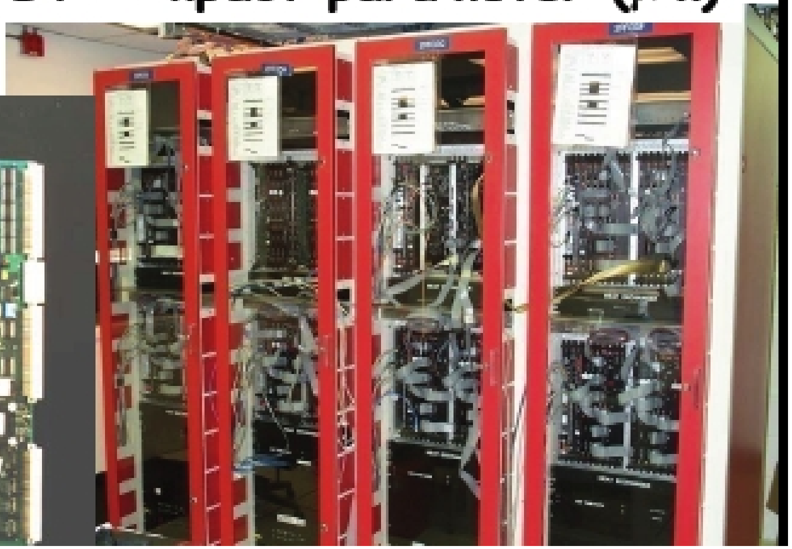
- SVT incorporates silicon info in the Level 2 trigger… select events with large impact parameter!





- Uses fitted beamline
- impact parameter per track
- System is "deadtimeless":
  - ~35μsec/event for readout + clustering + track fitting





B_s^0-$\bar{B}_s^0$ system

- B_s mesons are $\bar{b}s$ bound states, which, like B_d, D and K neutral mesons, exhibit particle-antiparticle oscillations due to the flavor changing weak interactions.

- B_s-$\bar{B}_s$ time evolution is described by a 2×2 complex effective Hamiltonian, M - iΓ/2:

$$i\frac{\partial}{\partial t}\begin{pmatrix} B^0 \\ \overline{B^0} \end{pmatrix} = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}\begin{pmatrix} B^0 \\ \overline{B^0} \end{pmatrix}$$

- Mass eigenstates are a linear combination of flavor eigenstates:

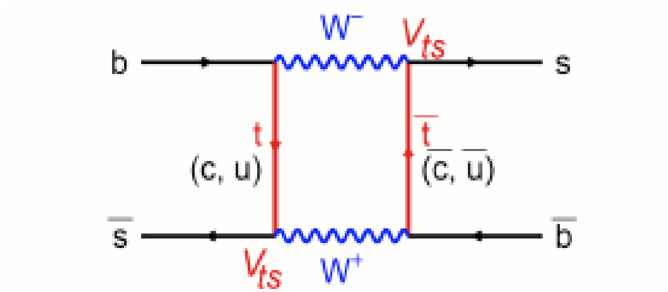
$$|B_H\rangle = p\,|B_s\rangle + q\,|\bar{B}_s\rangle$$
$$|B_L\rangle = p\,|B_s\rangle - q\,|\bar{B}_s\rangle$$

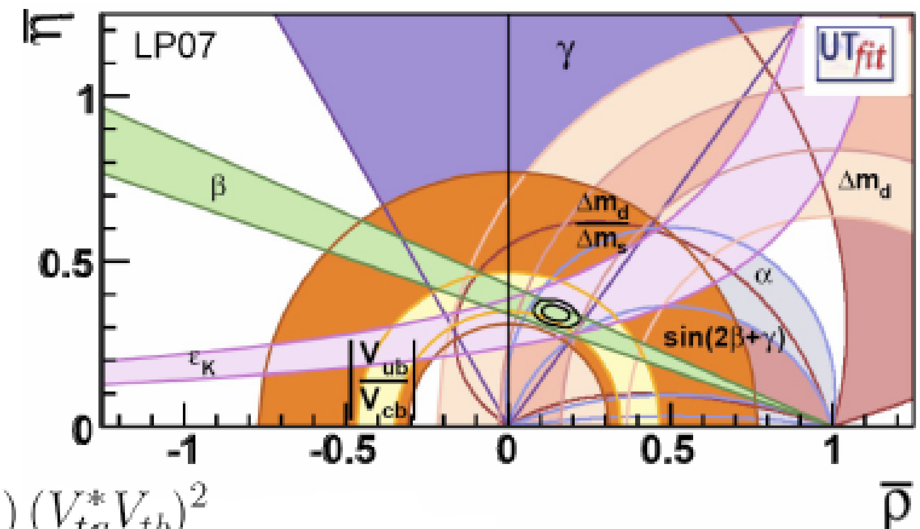
- B_s-$\bar{B}_s$ oscillations involve three physical quantities:

$$\Delta m_s = M_H - M_L = 2\,|M_{12}|$$
$$\Delta\Gamma_s = \Gamma_L - \Gamma_H = 2\,|\Gamma_{12}|\,cos\,\phi_s$$
$$\phi_s = arg(-M_{12}/\Gamma_{12})$$

B_s^0-$\bar{B}_s^0$ system in the SM

- In the Standard Model the $B_s \leftrightarrow \bar{B}_s$ transitions are described at lower order by W-exchange box diagrams:





$$M_{12} = -\frac{G_F^2 m_W^2 \eta_B m_{B_q} B_{B_q} f_{B_q}^2}{12\pi^2} S_0(m_t^2/m_W^2)\,(V_{tq}^* V_{tb})^2$$

$$\Gamma_{12} = \frac{G_F^2 m_b^2 \eta'_B m_{B_q} B_{B_q} f_{B_q}^2}{8\pi} \times \left[(V_{tq}^* V_{tb})^2 + V_{tq}^* V_{tb} V_{cq}^* V_{cb}\, \mathcal{O}\left(\frac{m_c^2}{m_b^2}\right) + (V_{cq}^* V_{cb})^2\, \mathcal{O}\left(\frac{m_c^4}{m_b^4}\right)\right]$$

- Recent SM calculations (A.Lenz and U.Nierste, hep-ph/0612167):

$$\Delta m_s = (19.3 \pm 6.7)\ \mathrm{ps}^{-1}$$

$$\Delta\Gamma_s = (0.088 \pm 0.017)\ \mathrm{ps}^{-1}$$

$$\phi_s = (4.2 \pm 1.4) \times 10^{-3}$$

- Many uncertainties cancel in the ratio:

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

from lattice QCD: $\xi = 1.21^{+0.047}_{-0.035}$

(M.Okamoto, hep-lat/0510113)

Δm_s measurement overview

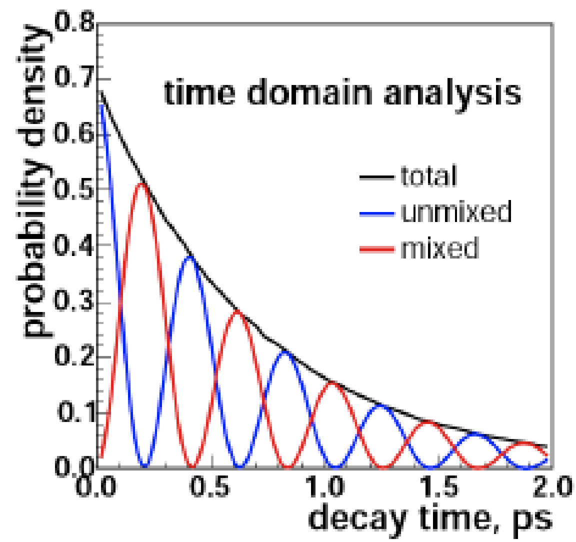
- Time-dependent measurement: detect an oscillatory pattern in proper time distribution of B_s decays:

$$P(t)_{B^0\to B^0} = \frac{1}{2\tau}e^{-t/\tau}(1+\cos\Delta m t)$$
$$P(t)_{B^0\to \overline{B^0}} = \frac{1}{2\tau}e^{-t/\tau}(1-\cos\Delta m t)$$

- Three ingredients:

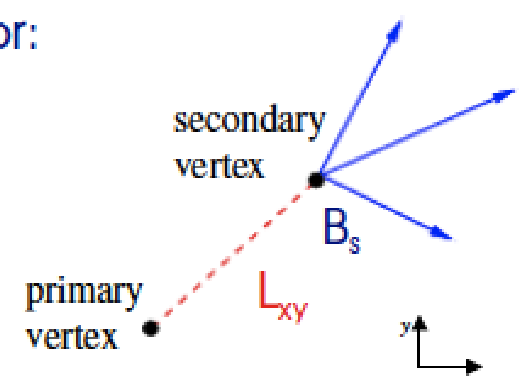
$$\mathrm{Sig} = \sqrt{\frac{S\epsilon D^2}{2}}\, e^{-\frac{(\Delta m_s \sigma_t)^2}{2}} \sqrt{\frac{S}{S+B}}$$

proper time resolution; signal; tagging efficiency; dilution = 1 – 2 × (mistag probability); background



1. Measurement of B_s decay flavor: inferred from B_s decay products;
2. measurement of B_s production flavor: flavor tagging techniques;
3. proper decay time measurement:

$$ct = L_{xy}\frac{m_B}{p_T(B)}$$

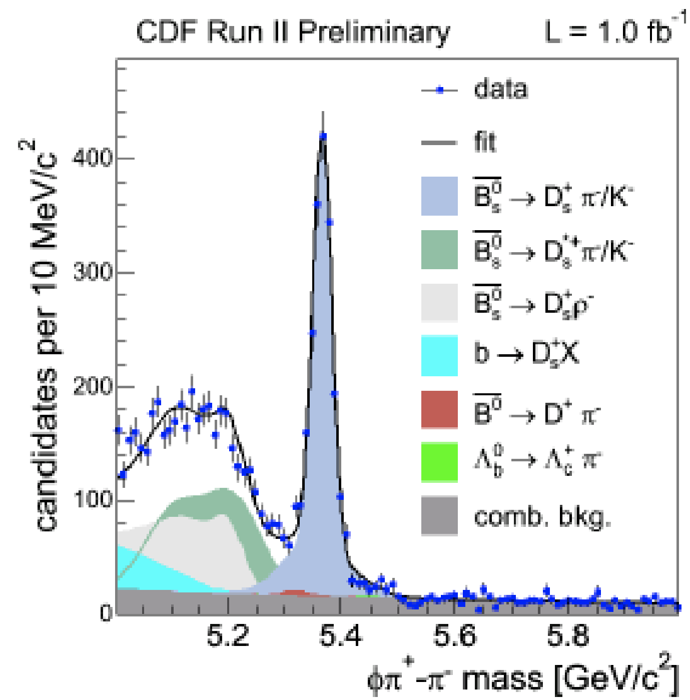


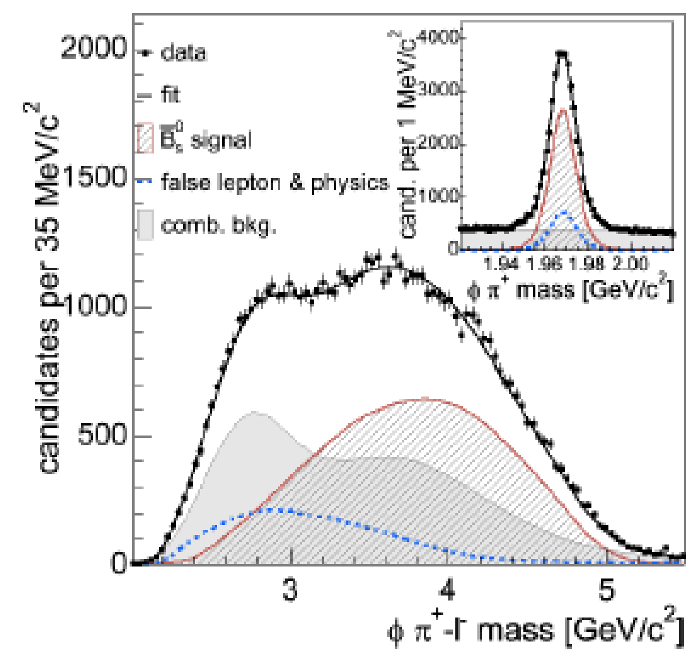
CDF B_s samples

- 1 fb^{-1} collected with displaced track trigger;
- hadronic and semileptonic signal samples: NN selection.

channel	yield
$B_s \to D_s^-\pi^+$, $D_s^- \to \phi\pi^-$, $\phi \to K^+K^-$	2000
$B_s \to D_s^{*-}\pi^+$, $D_s^{*-} \to D_s^-\gamma/\pi^0$ and $B_s \to D_s^-\rho^+$, $\rho^+ \to \pi^+\pi^0$	3100
$B_s \to D_s^-\pi^+$, $D_s^- \to K^{*0}K^-$, $K^{*0} \to K^+\pi^-$	1400
$B_s \to D_s^-\pi^+$, $D_s^- \to \pi^-\pi^+\pi^-$	700
$B_s \to D_s^-\pi^+\pi^-\pi^+$, $D_s^- \to \phi\pi^-$, $\phi \to K^+K^-$	700
$B_s \to D_s^-\pi^+\pi^-\pi^+$, $D_s^- \to K^{*0}K^-$, $K^{*0} \to K^+\pi^-$	600
$B_s \to D_s^-\pi^+\pi^-\pi^+$, $D_s^- \to \pi^-\pi^+\pi^-$	200
TOTAL	**8700**

channel	yield
$B_s \to \ell^+ D_s^- X$, $D_s^- \to \phi\pi^-$, $\phi \to K^+K^-$	29600
$B_s \to \ell^+ D_s^- X$, $D_s^- \to K^{*0}K^-$, $K^{*0} \to K^+\pi^-$	22000
$B_s \to \ell^+ D_s^- X$, $D_s^- \to \pi^-\pi^+\pi^-$	9900
TOTAL	**61500**

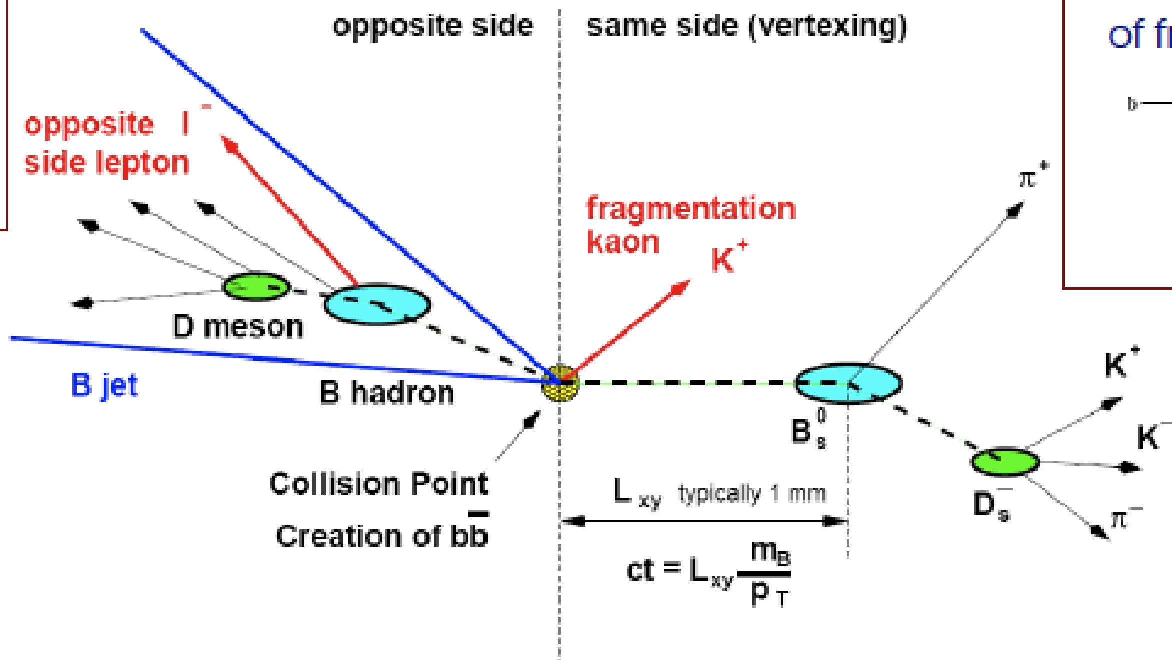




B_s production flavor tagging

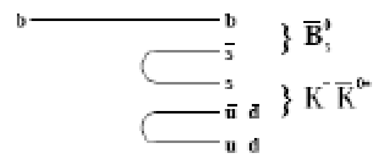
Opposite side taggers:

- lepton charge: $b \to \ell^- X$, but $b \to c \to \ell^+ X$
- jet charge: momentum weighted charge
- K charge: $b \to c \to K^- X$



Same side tagger:

- correlation between B_s flavor and the charge of fragmentation K



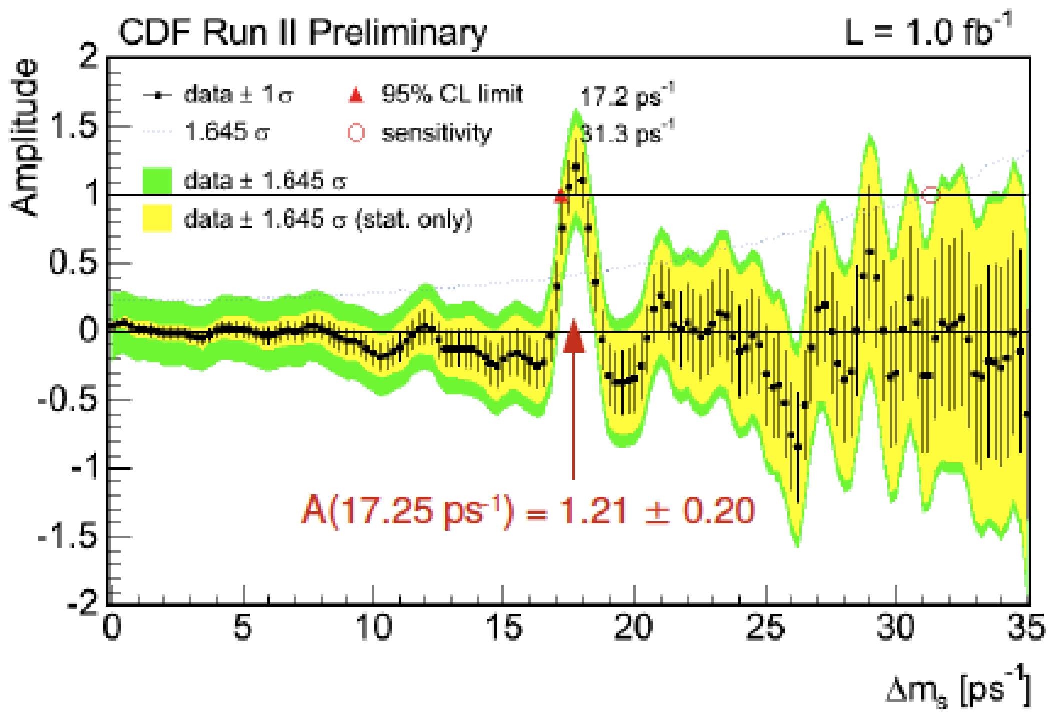
CDF:

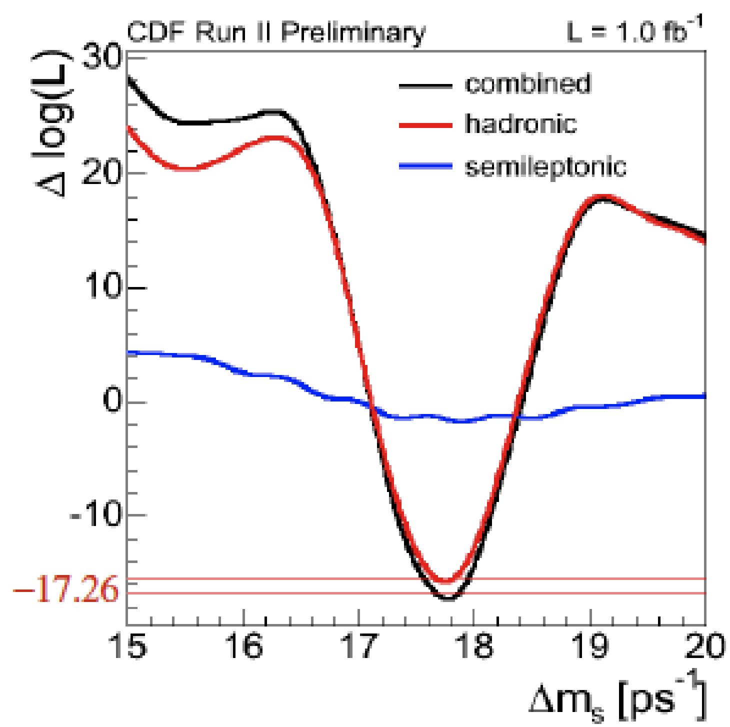
- NN combination of opposite side jet charge, kaon and lepton tags: εD^2 = 1.8%;
- NN kinematic and PID variables for same side kaon tag: εD^2 = 3.7% (had.), 4.8% (semilep.).

DØ:

- opposite side tagging uses lepton information or secondary vertex: εD^2 = 2.5%;
- combined single and multi-track tag: εD^2 = 4.5%.

CDF results





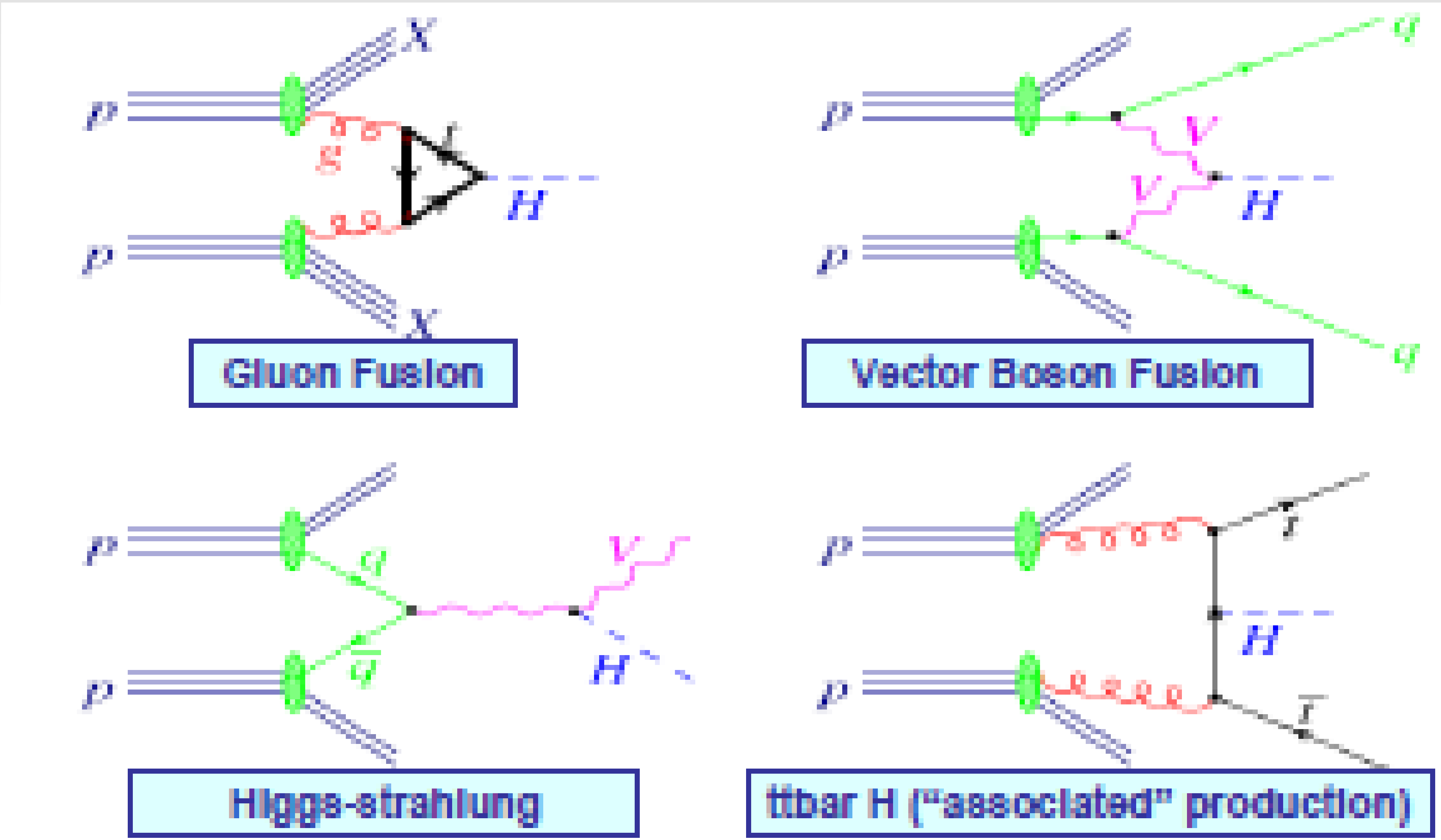
$$\Delta m_s = 17.77 \pm 0.10\ (\text{stat}) \pm 0.07\ (\text{syst})\ \text{ps}^{-1}$$

- 5.4σ statistical significance.
- From $\dfrac{\Delta m_s}{\Delta m_d} = \dfrac{m_{B_s}}{m_{B_d}} \xi^2 \dfrac{|V_{ts}|^2}{|V_{td}|^2}$:

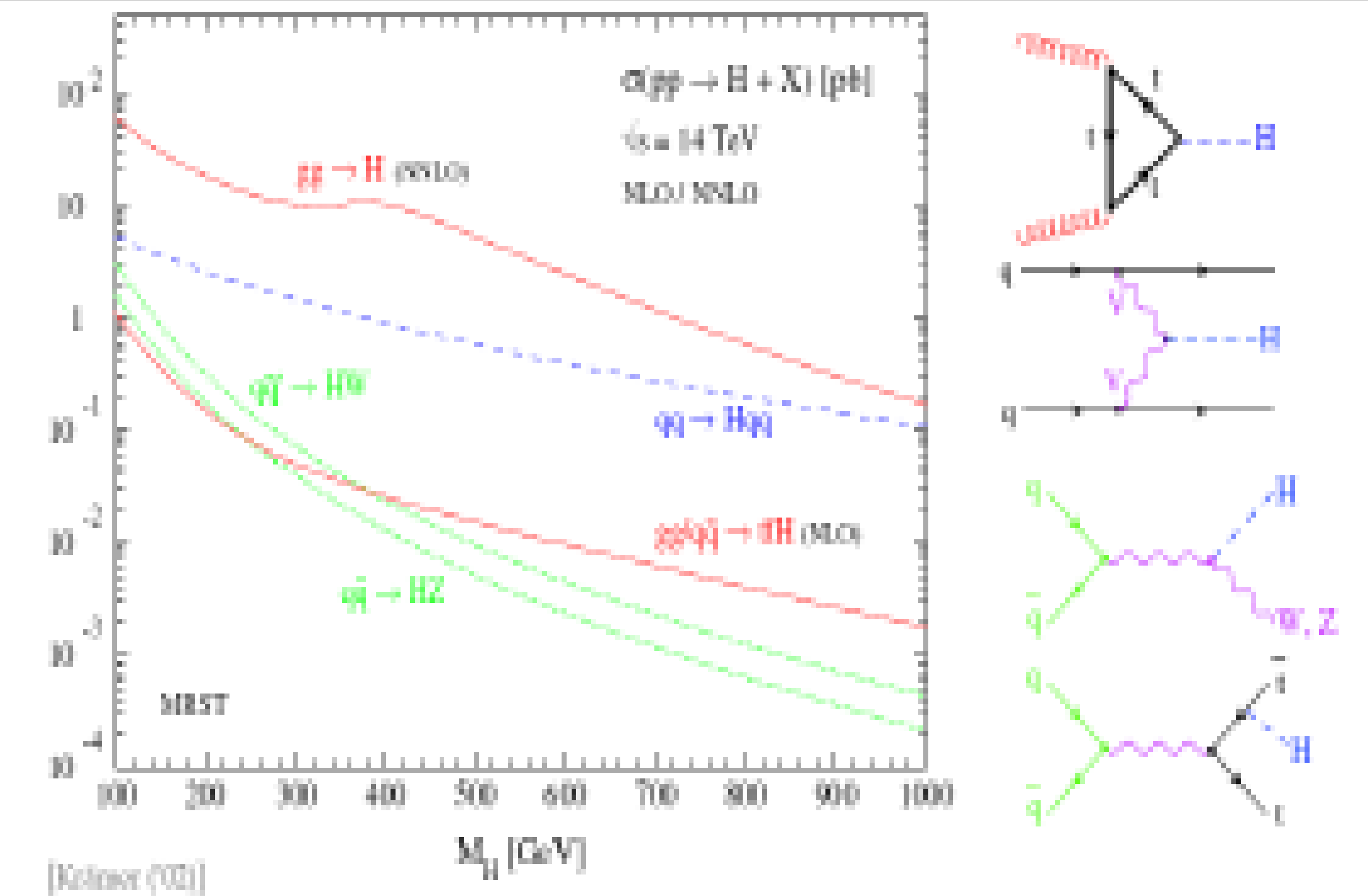
$$|V_{td}| / |V_{ts}| = 0.2060 \pm 0.0007(\text{exp})\ ^{+0.0081}_{-0.0060}\ (\text{theor})$$

CDF PRL 97, 242003 (2006)

Standard model Higgs production

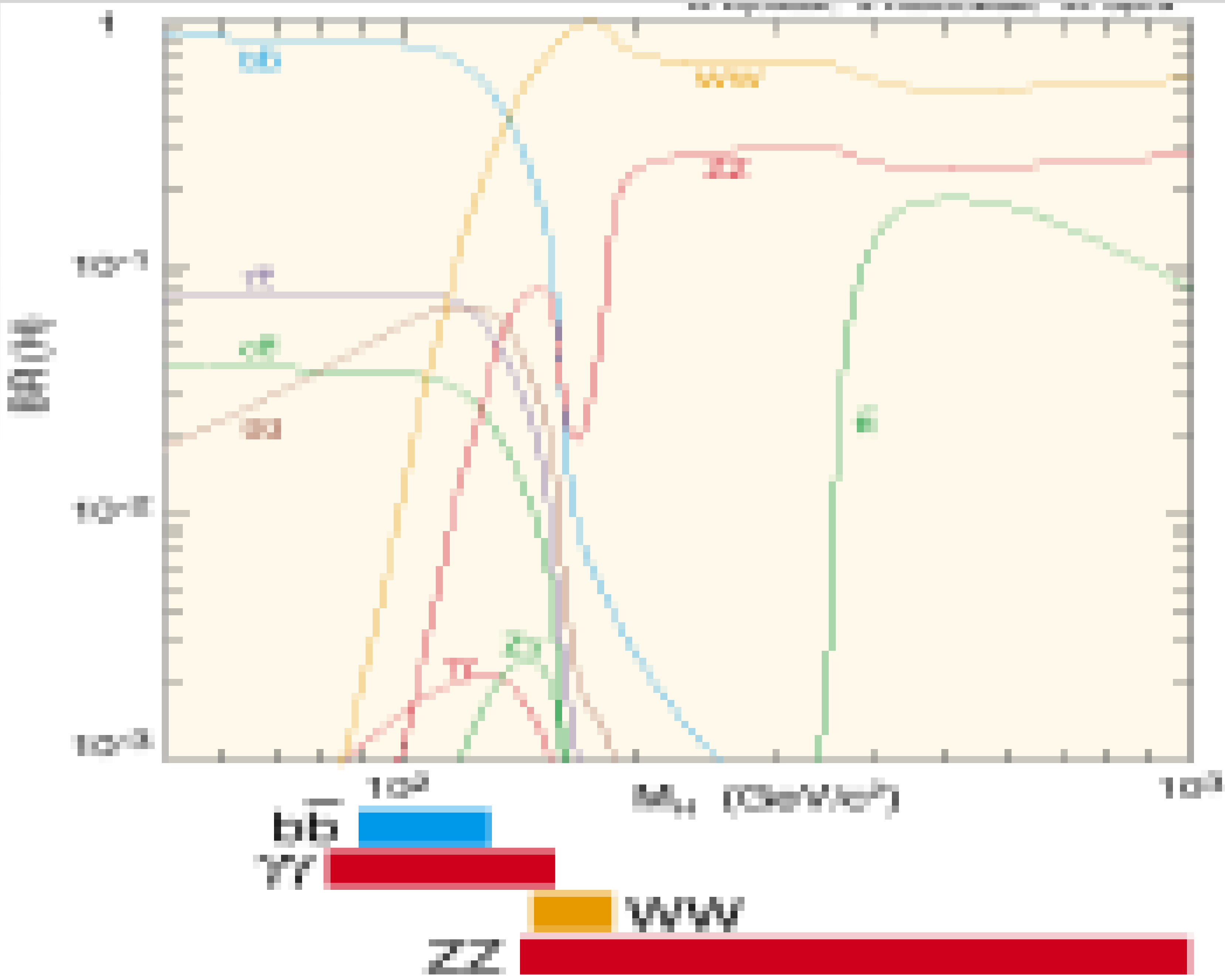


Higgs cross section

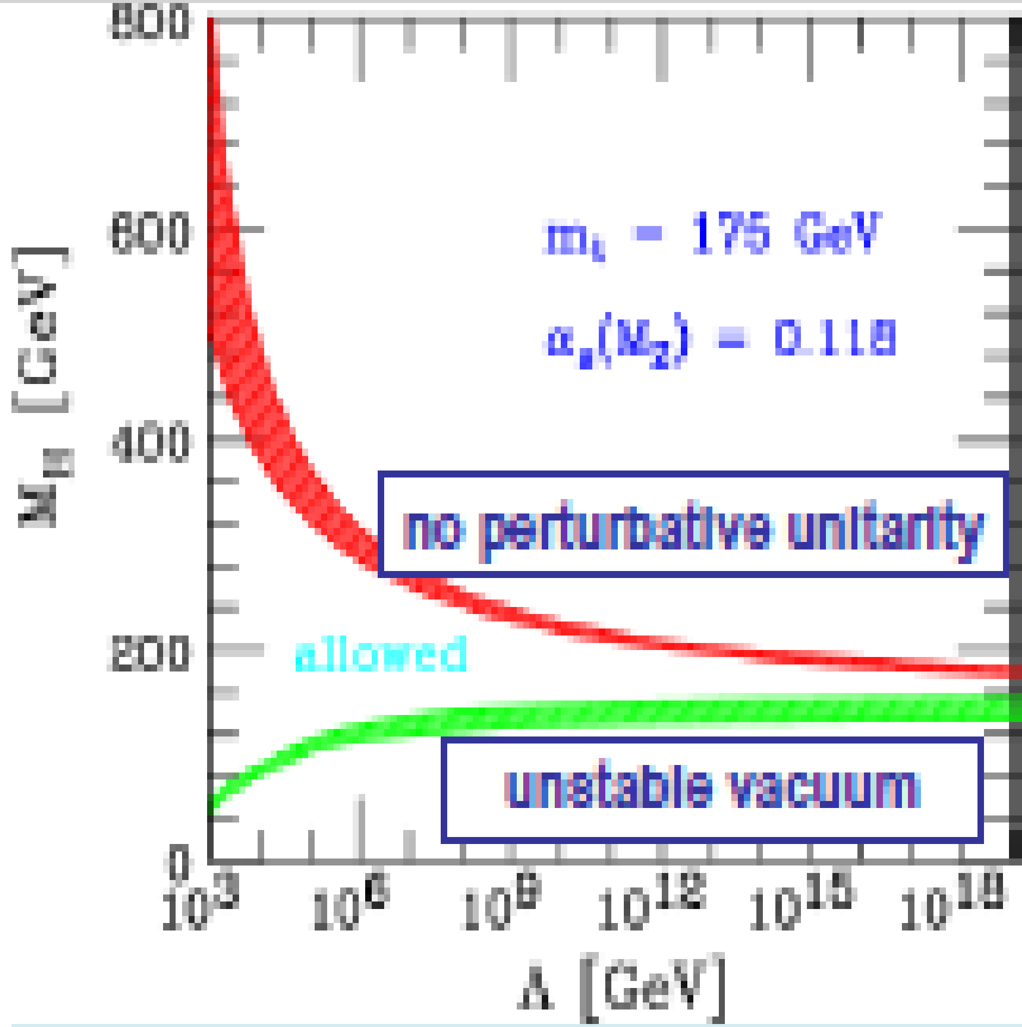


Higgs width ~ (m_H)

Main decay modes



Theory constraints to mass



Upper bound

(triviality) :

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

Lower bound

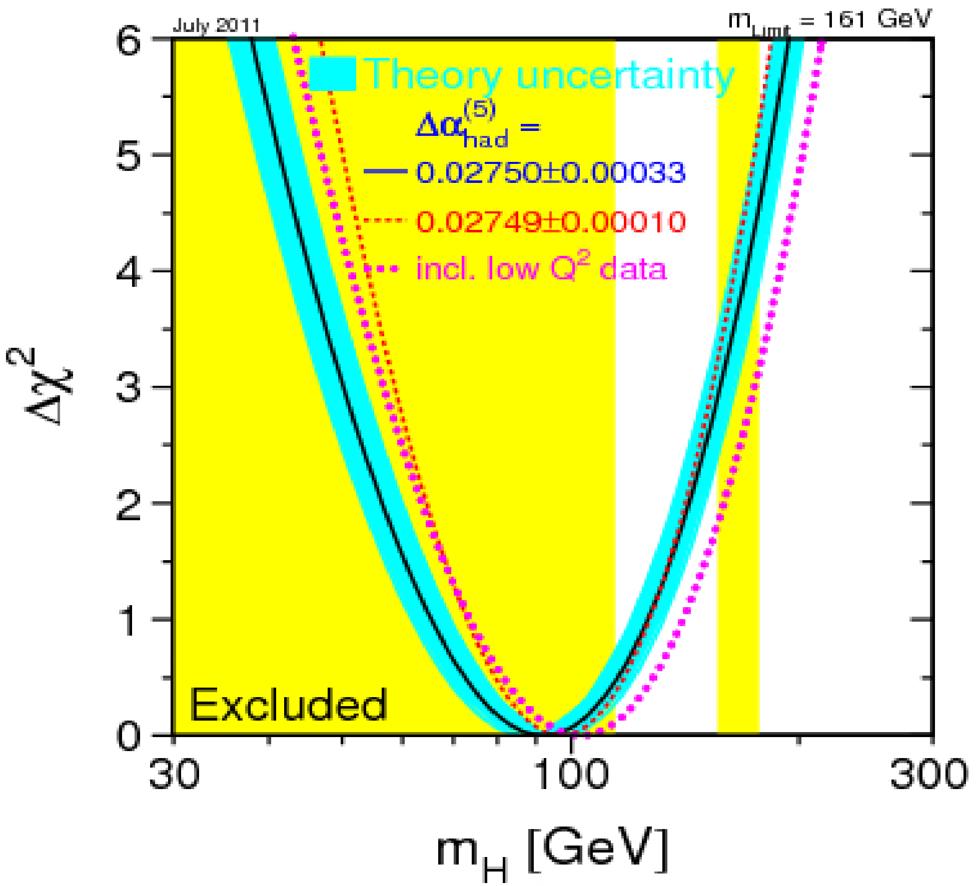
(vacuum stability) :

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

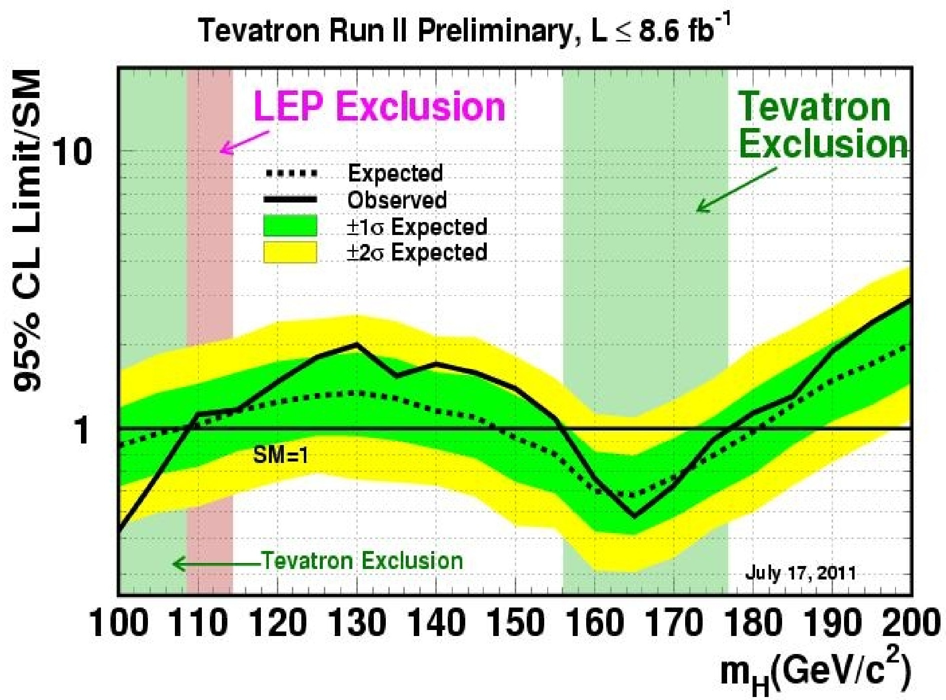
(Λ = cut-off scale at which new physics becomes important)

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

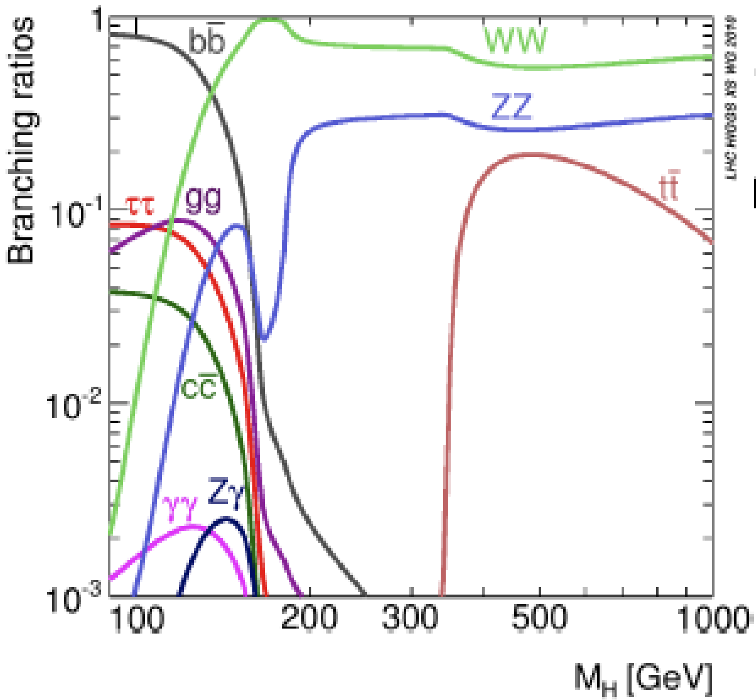


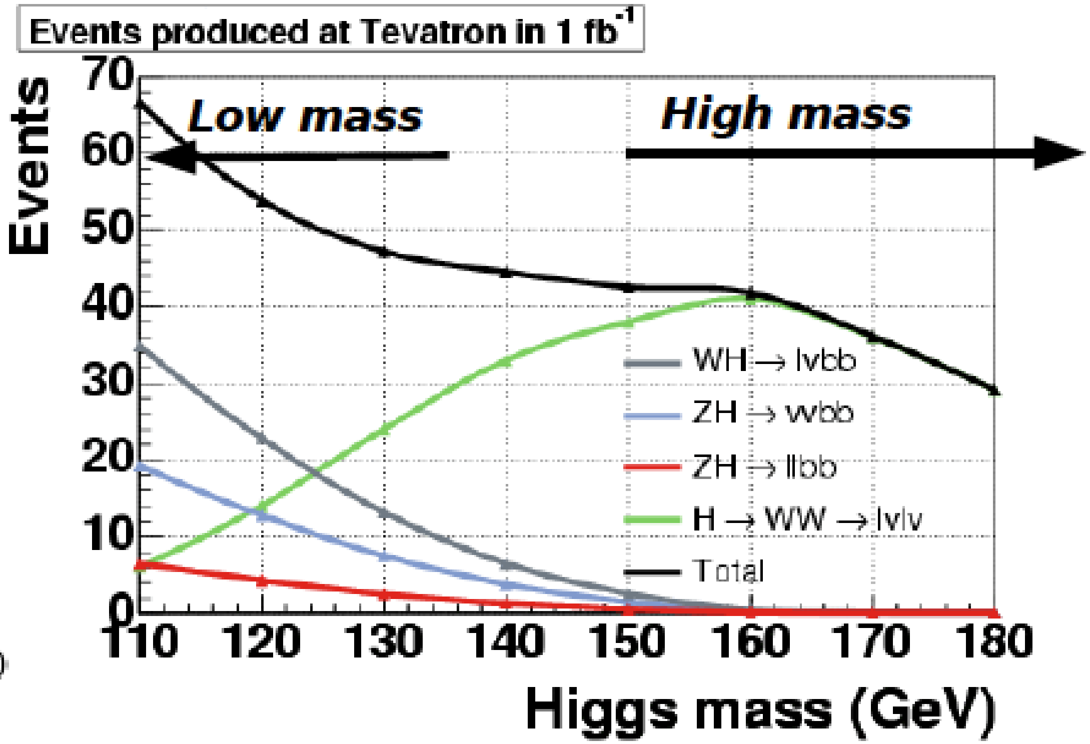
- Indirect from EW fits, direct from LEP and Tevatron searches



Best-fit value already escluded by LEP; ”big desert” scenario excluded by Tevatron

Higgs Production @ Tevatron





Reconstruction/selection/tagging efficiencies:

~10% in $H \rightarrow b\bar{b}$

~25% in $H \rightarrow WW$

Maximize sensitivity:

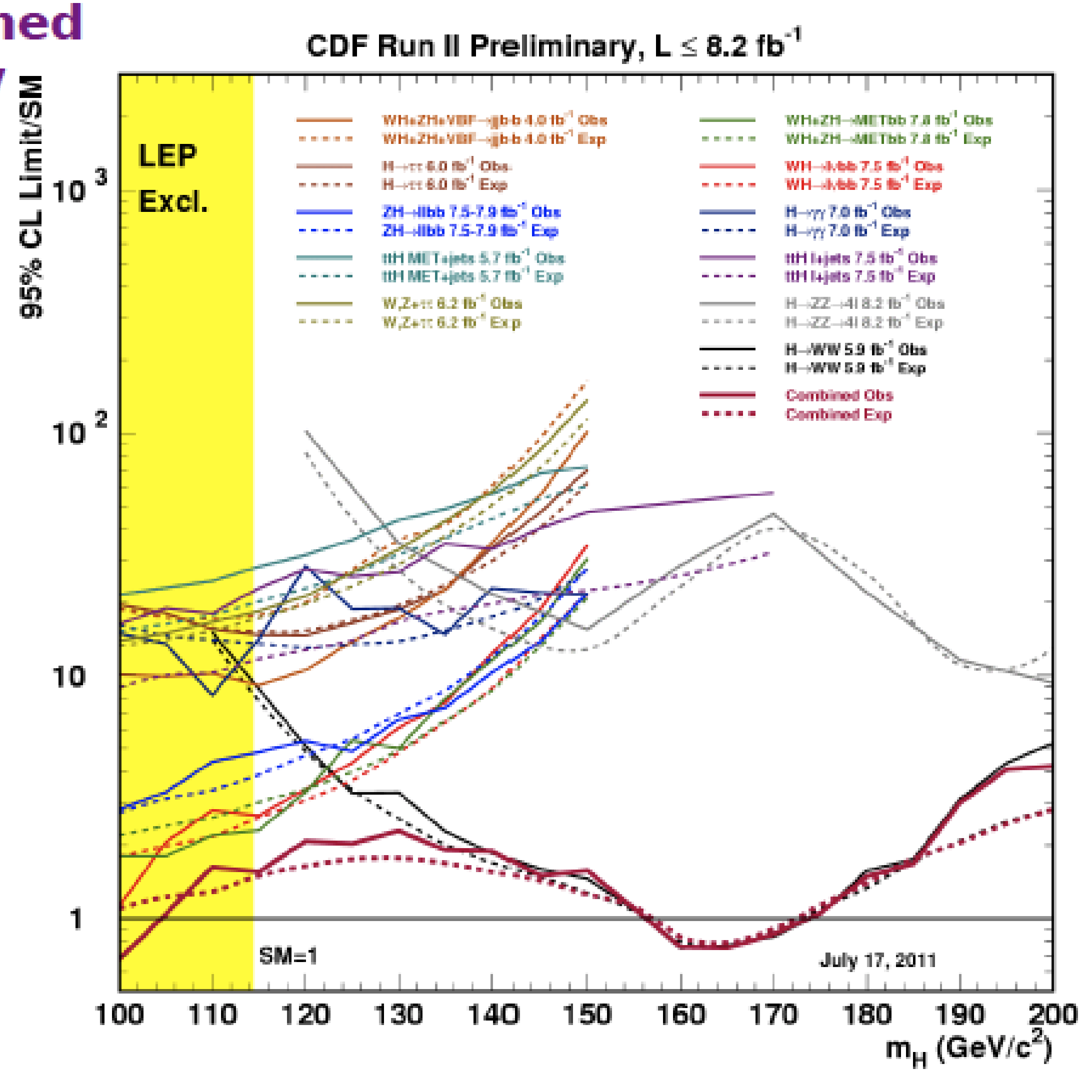
combine many decay channels

use all production modes

Channel Combination

SM: best sensitivity obtained from combination of many independent channels:

- ***$WH \rightarrow l\nu b\bar{b}$***
- ***$ZH \rightarrow \nu\bar{\nu}b\bar{b}$***
- ***$ZH \rightarrow llb\bar{b}$***
- ***$WH/ZH \rightarrow jjb\bar{b}$***
- ***$t\bar{t}H \rightarrow WbWbb\bar{b}$***
- ***$H \rightarrow \gamma\gamma$***
- ***$H \rightarrow \tau\tau$***
- ***$WH \rightarrow l\nu\tau\tau$ / $ZH \rightarrow ll\tau\tau$***
- ***$WH/ZH/qqH \rightarrow jj\tau\tau$***
- ***$H \rightarrow WW \rightarrow l\nu l\nu$ / $l\nu jj$***
- ***$WH \rightarrow WWW$ / $ZH \rightarrow ZWW$***
- ***$H \rightarrow ZZ \rightarrow llll$ / $lljj$***



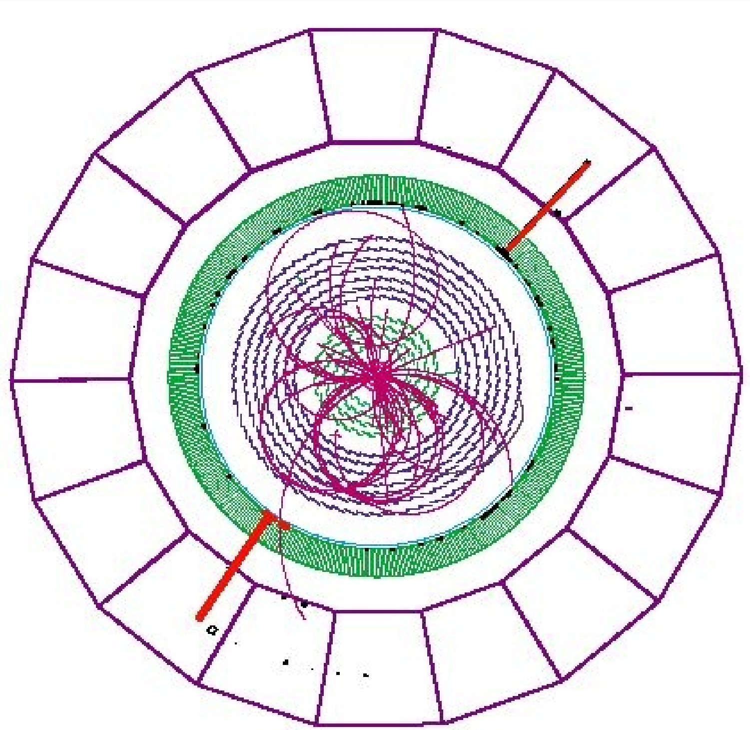
The SM Higgs at the LHC

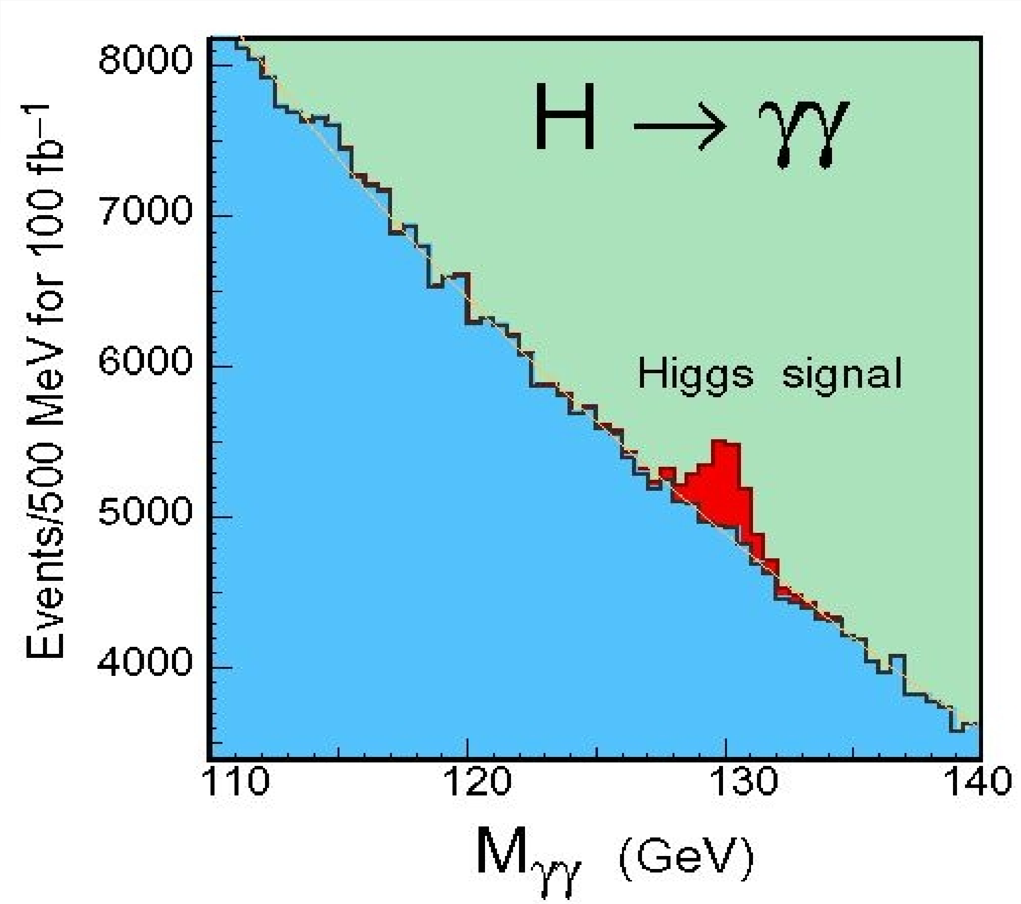
Only unknown is mass, so we are searching in several channels, depending on our bet on the Higgs mass:

- 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

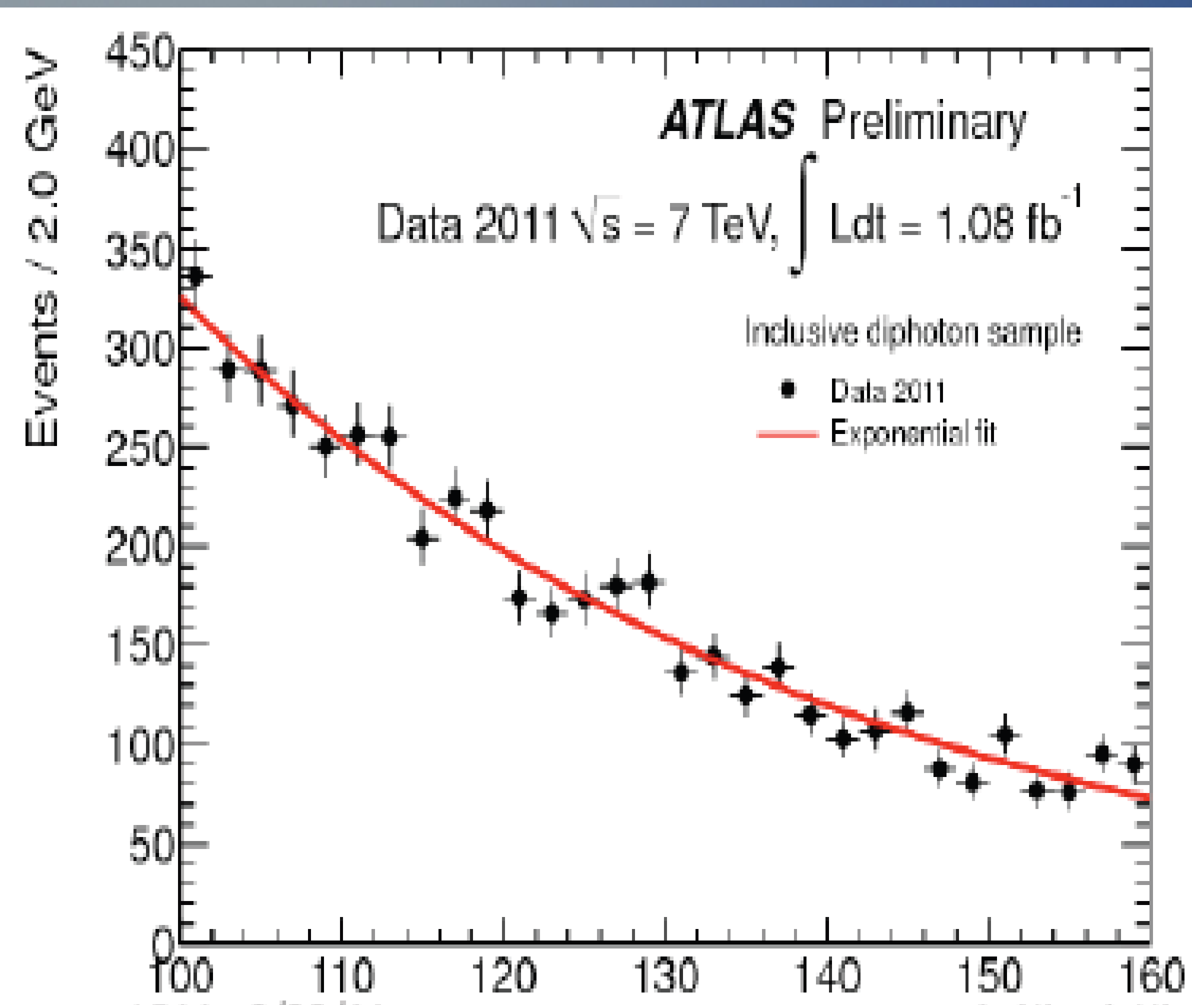
H -> $\gamma\gamma$

- 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!)

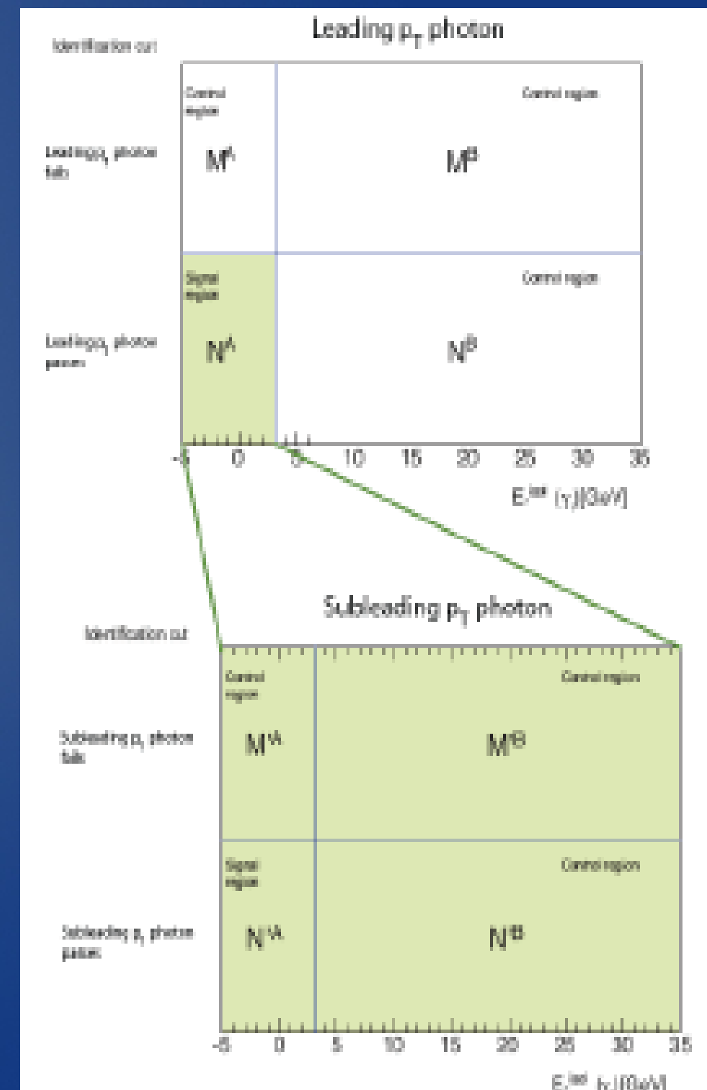




H->γγ: Large neutral pion background reduced using preshower, and measured using control regions

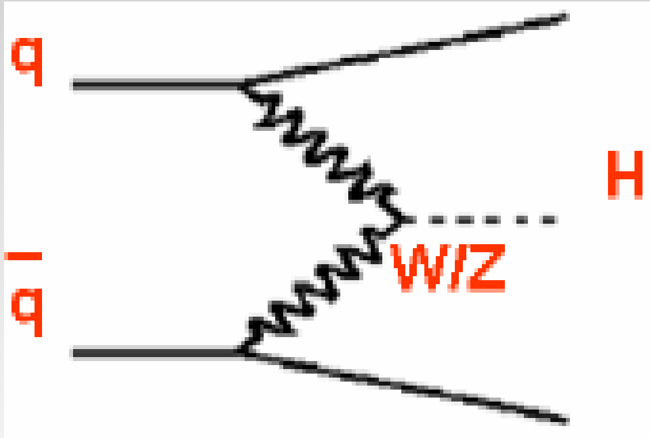


ArXiv:1108.5895v1

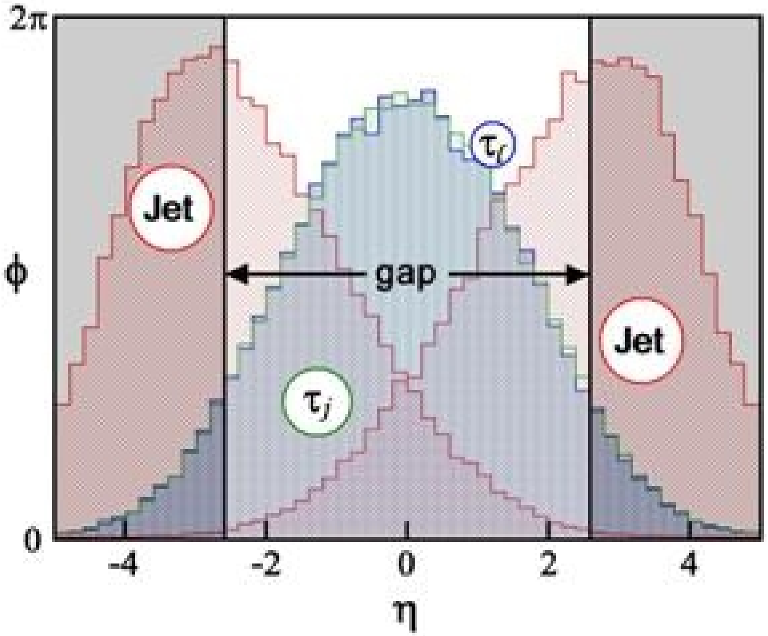


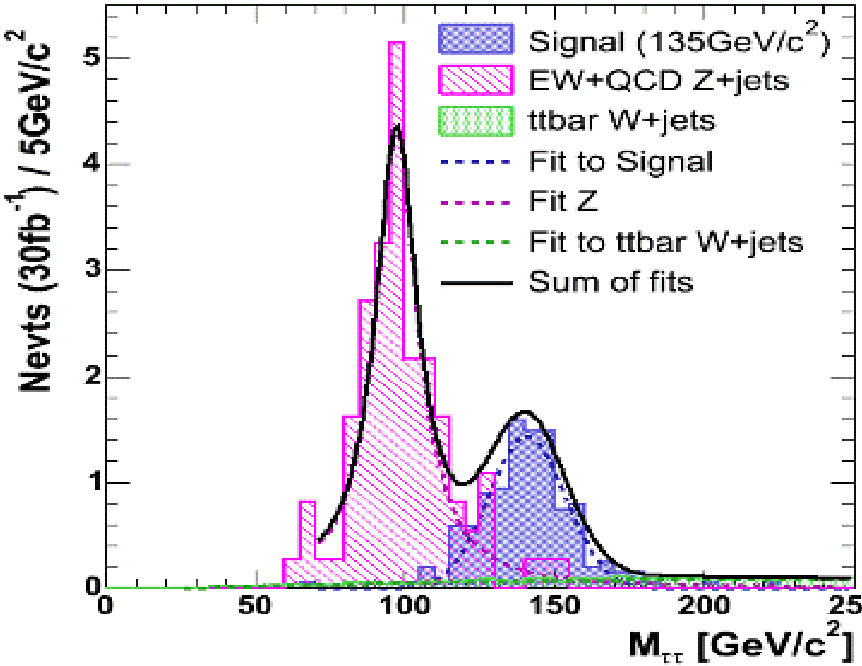
After cuts, expect about 15 signal events in a Higgs mass range 110-140

Vector Boson Fusion (VBF)



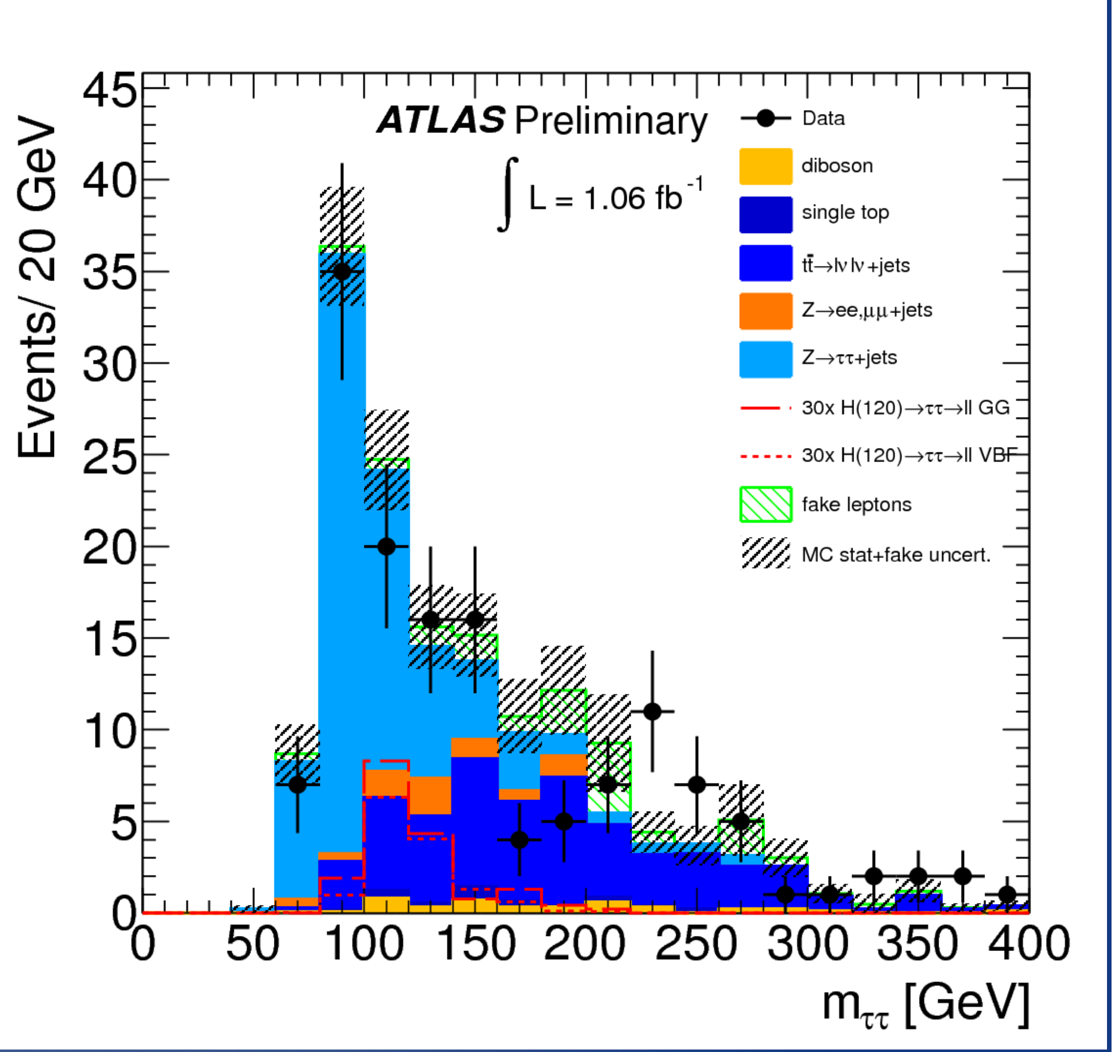
- Remnants of the final-state quarks emitted in the forward region (up to $\eta \sim 3.5$)
- Hard scattering has no colour flow between the two jets → rapidity gap between them
- It would be a very clean signature, if not for the UE and pileup!
- Depending on mass, look for $\tau\tau$ or WW decays





H->ττ

- Semileptonic and fully leptonic final states studied (right plot for ll)
- Lepton cut at 10 GeV in central rapidities (2.5)
- MET cut at 20 or 30 GeV
- Main BG form Z and W + jets



	yield
observed	46
expected	47.4±3.9
gg→H(120 GeV)	0.44±0.05
VBF H(120 GeV)	0.38±0.02

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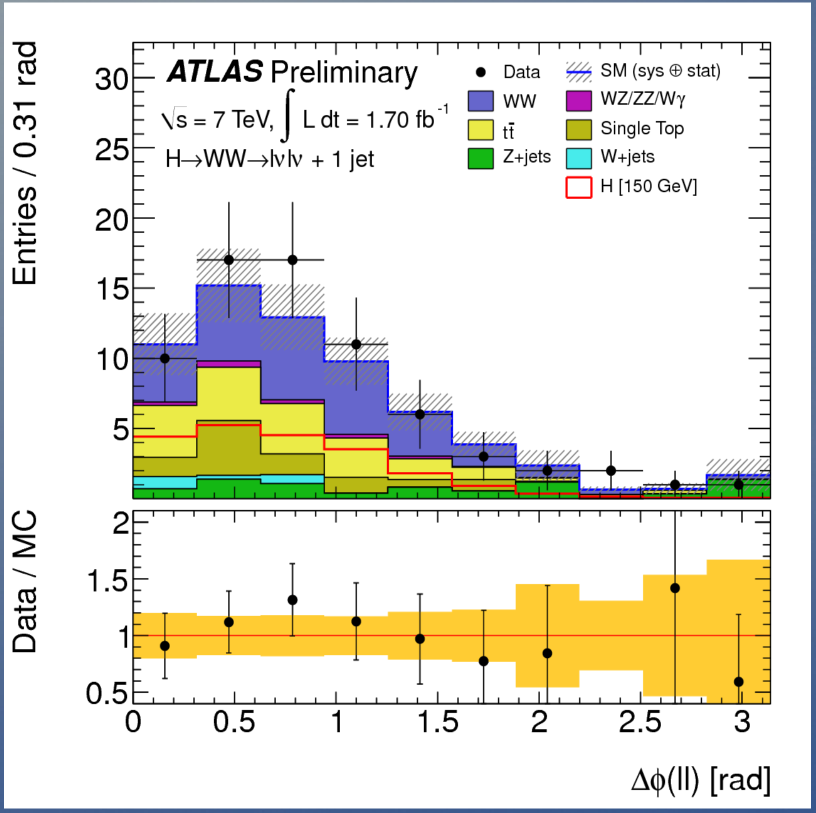
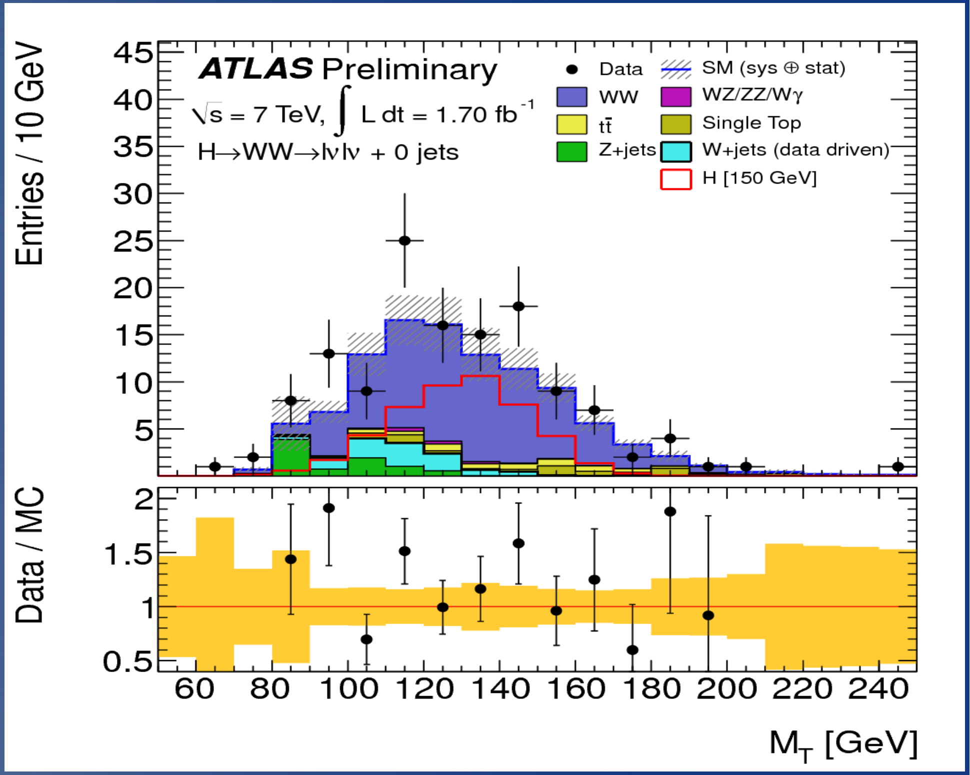
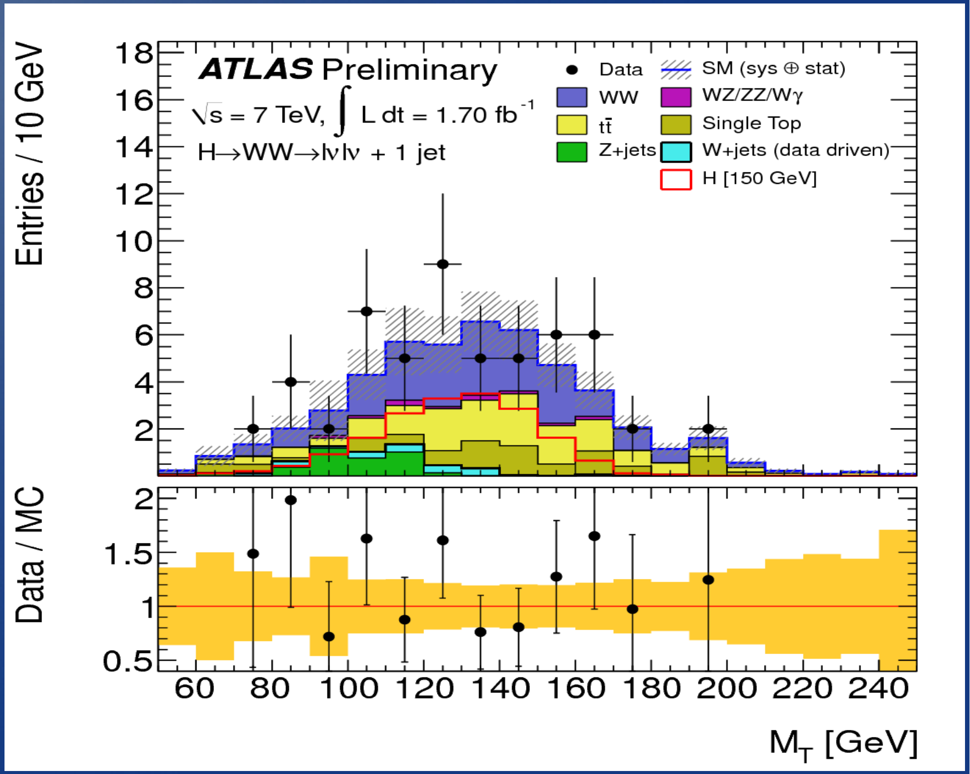
Transverse mass in H->WW(*)

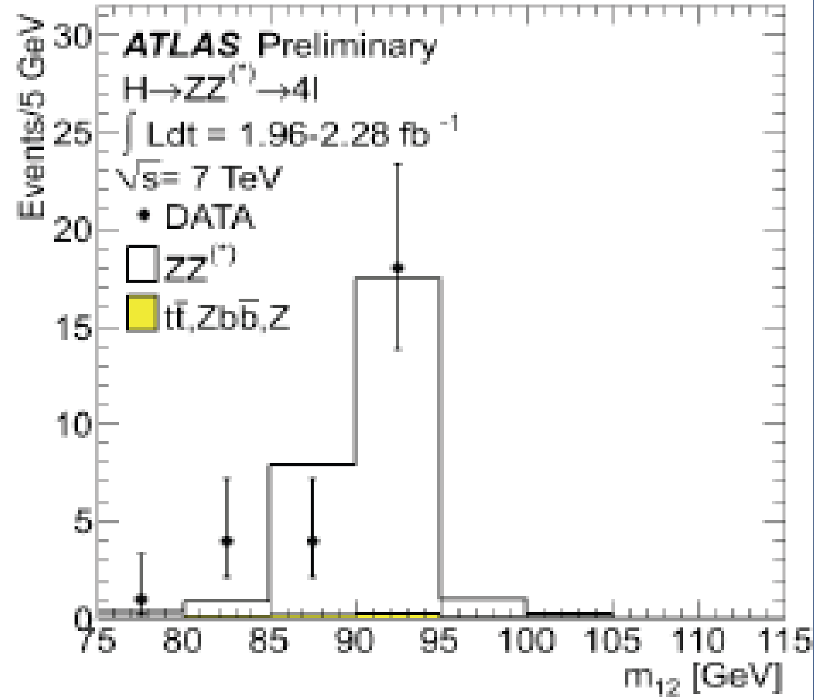


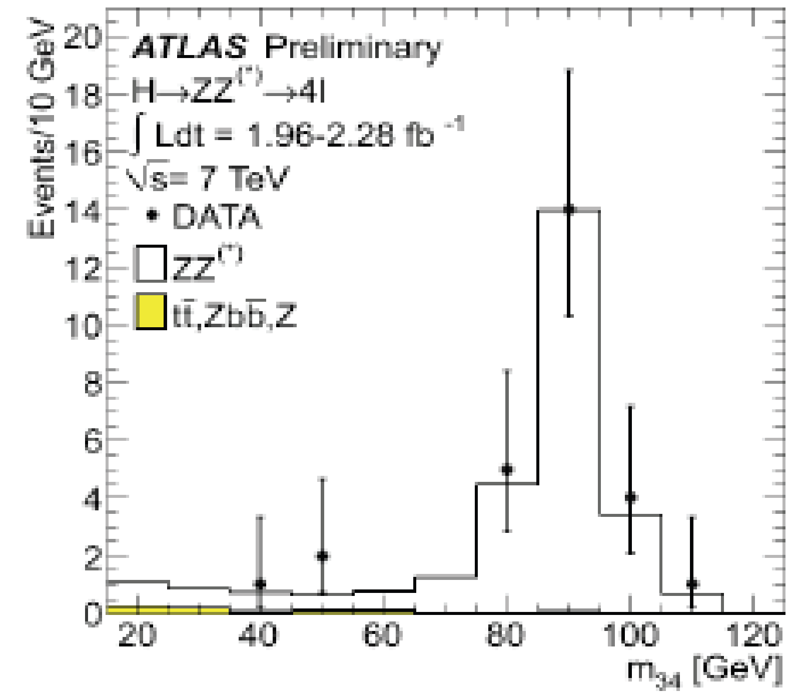


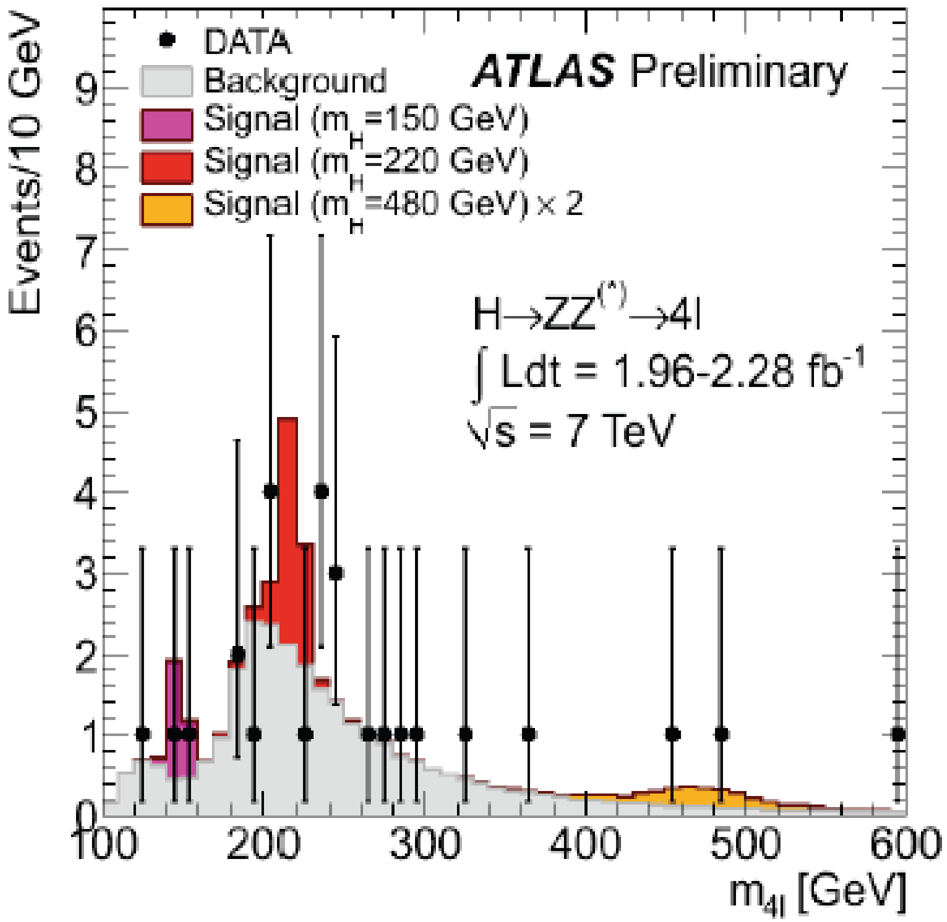


	WW	ttbar	Total SM back.	Data	Higgs m_H=150
0-jet	43±6	2.2±1.4	53±9	70	34±7
1-jet	10±2	6.9±1.9	23±4	23	12±3

Golden channel: H->ZZ->llll





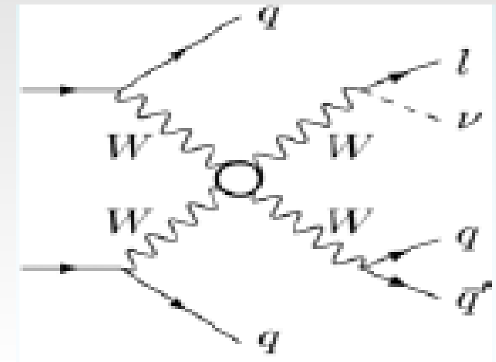


- A total of 27 events are selected by the analysis algorithm: 6ee, 9eμ, 12μμ
- Expected: 28±4

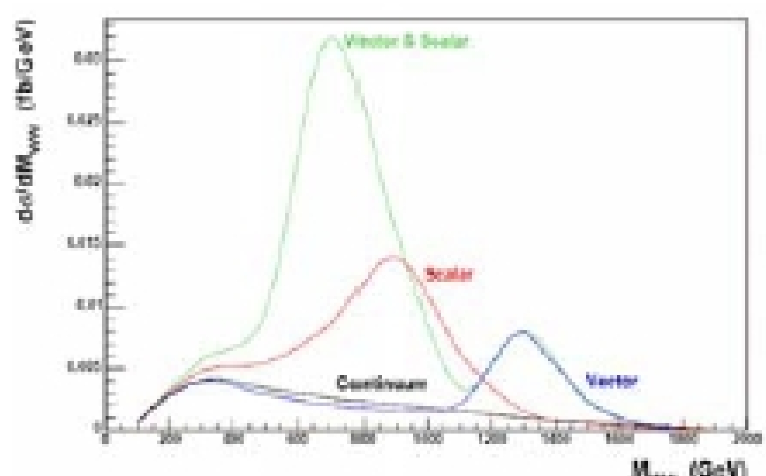
ArXiv:1108.5064,
ATLAS-CONF-2011-131

Very high-mass Higgs

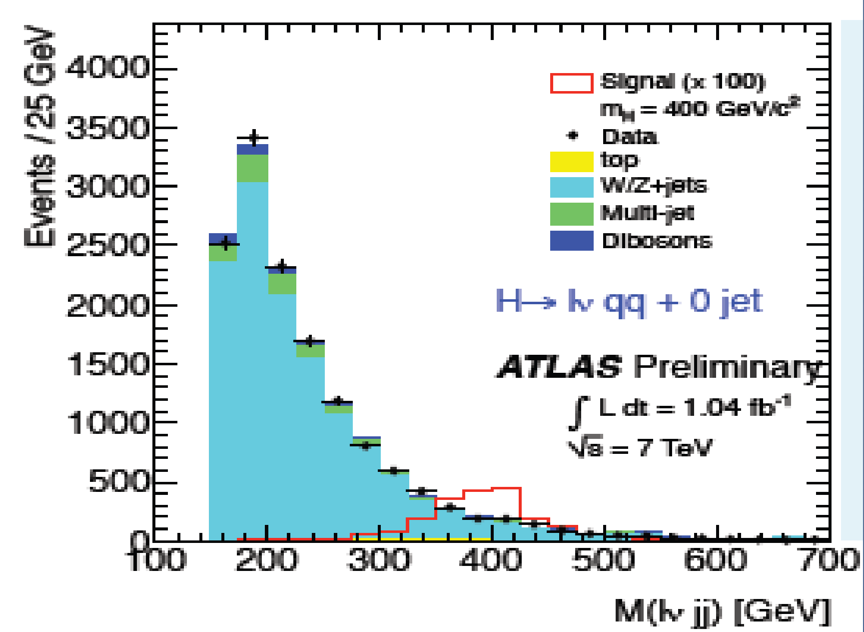
- Apart for giving mass to all other particles, the Higgs is needed in the SM to stabilise the $W_L W_L \rightarrow W_L W_L$ scattering process

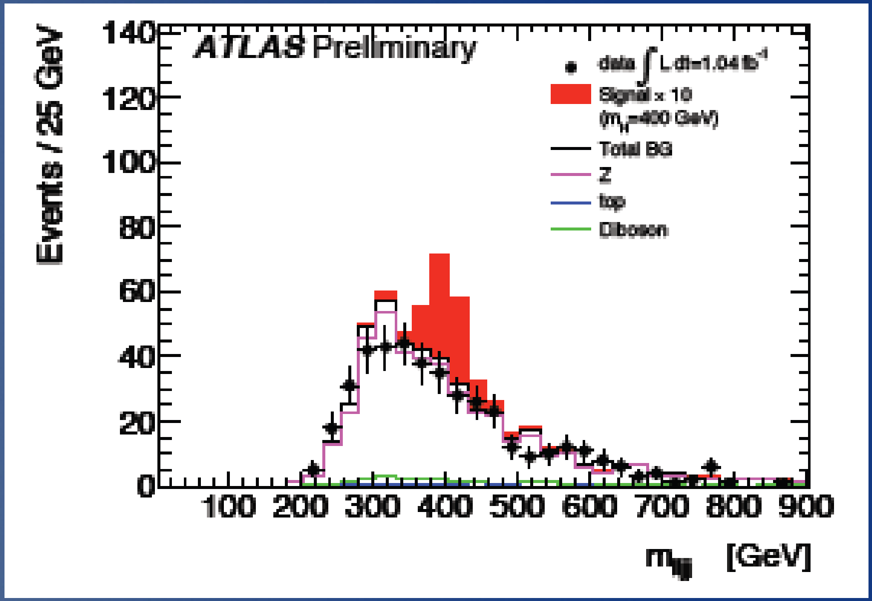


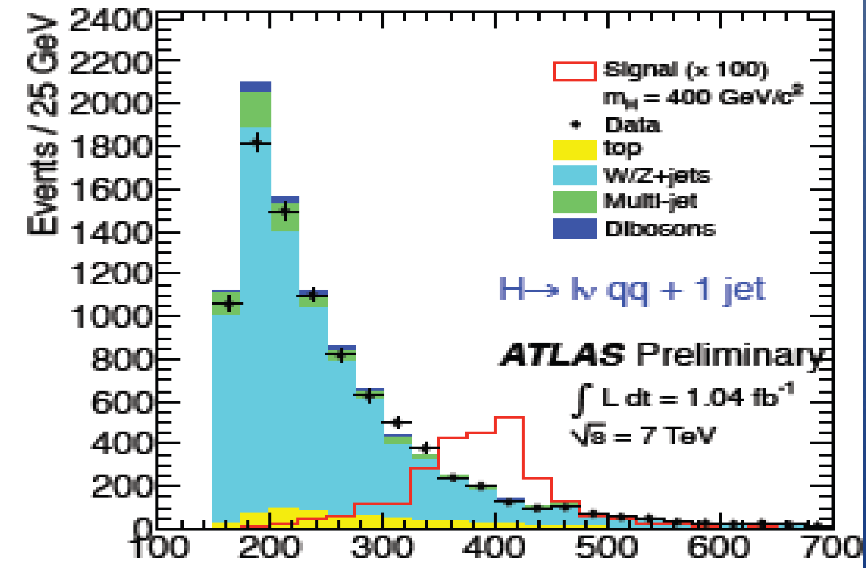
- This cross section is divergent in the SM, but if the Higgs is there a diagram with Higgs exchange restores finiteness
- Does not work if Higgs is too heavy, in that case some other resonance could be produced in WW final states
- More than one Higgs could be present, even in a pure SM scenario, with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

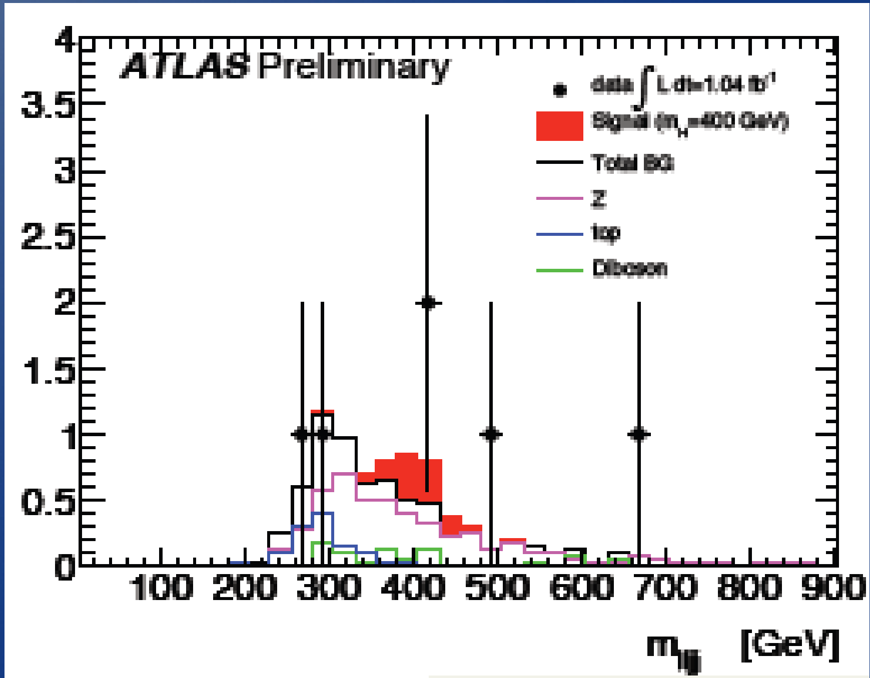


Going to high masses: semileptonic H->WW and H->ZZ arXiv:1108.5064



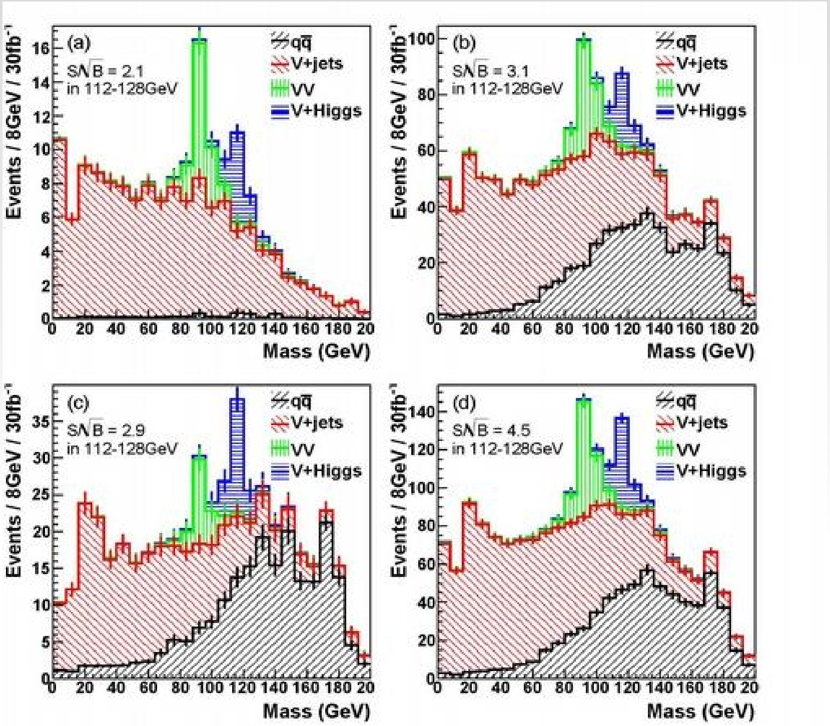




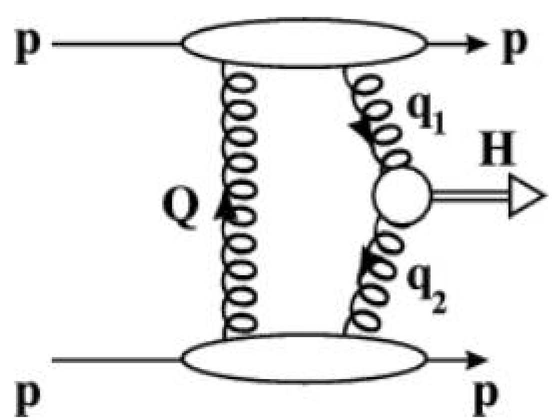


Non-conventional search channels

- 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



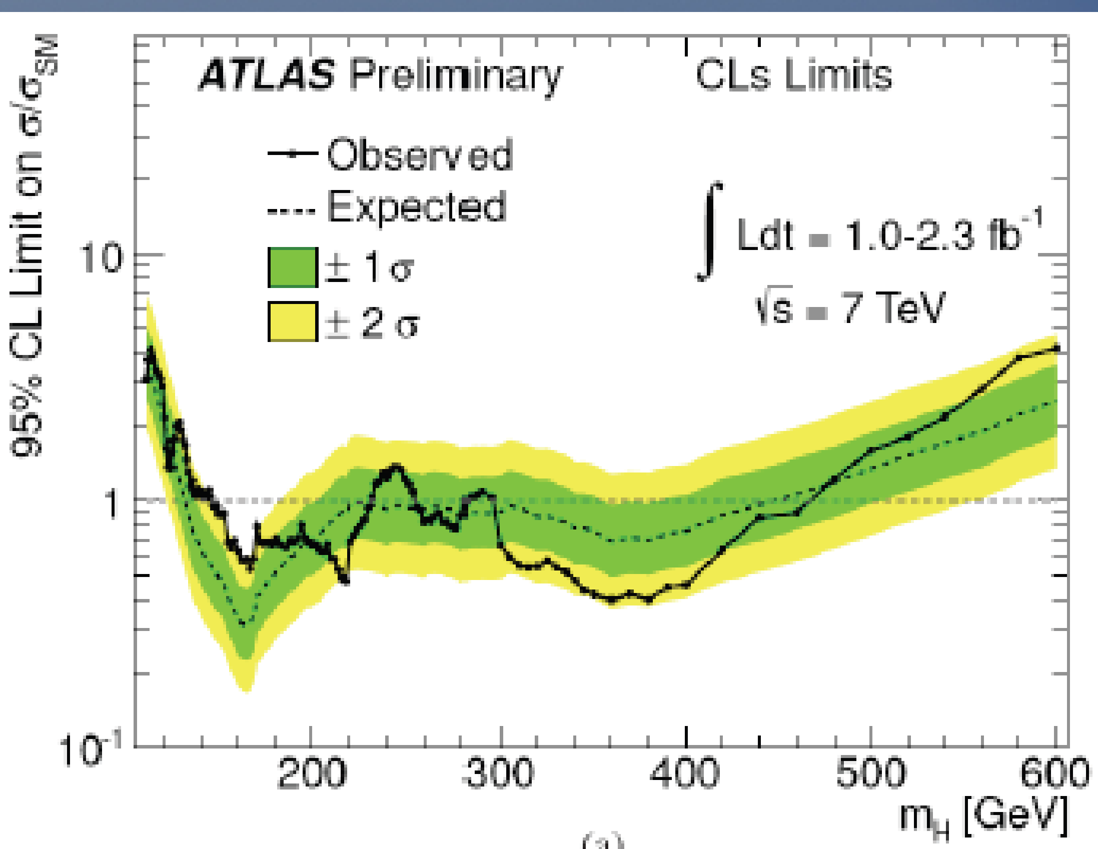
SM Higgs combination

Results shown above, plus VH->bb and H->ZZ->llvv, without H-> WW ->qqlv, are combined accounting for correlated uncertainties, from theory and experiment.

Statistics used is the profile likelihood

Distribution of test statistics performed:

- With toy MC (fully frequentistic)



e likelihood ratio

Only excess around 240 GeV (2σ), not really confirmed by CMS

Mass ranges excluded at 95% C.L.:

- 146-232 GeV
- 256-282 GeV
- 296-466 GeV

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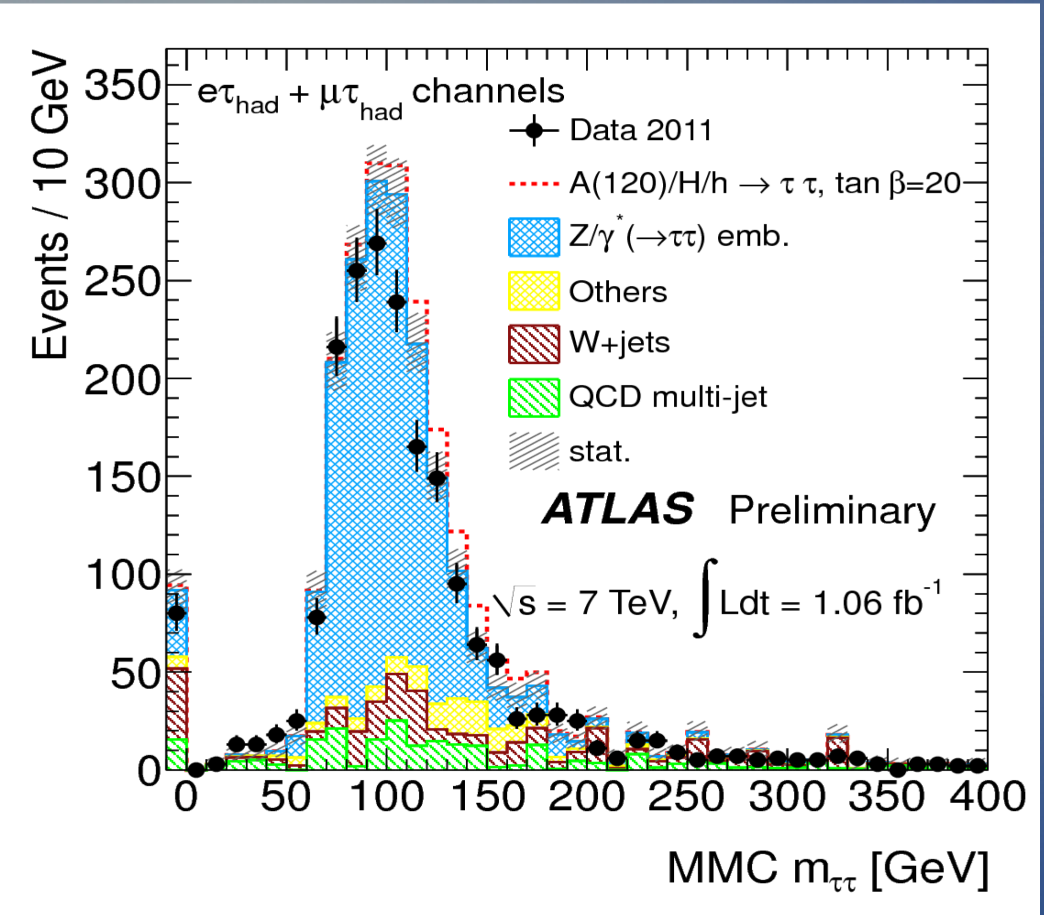
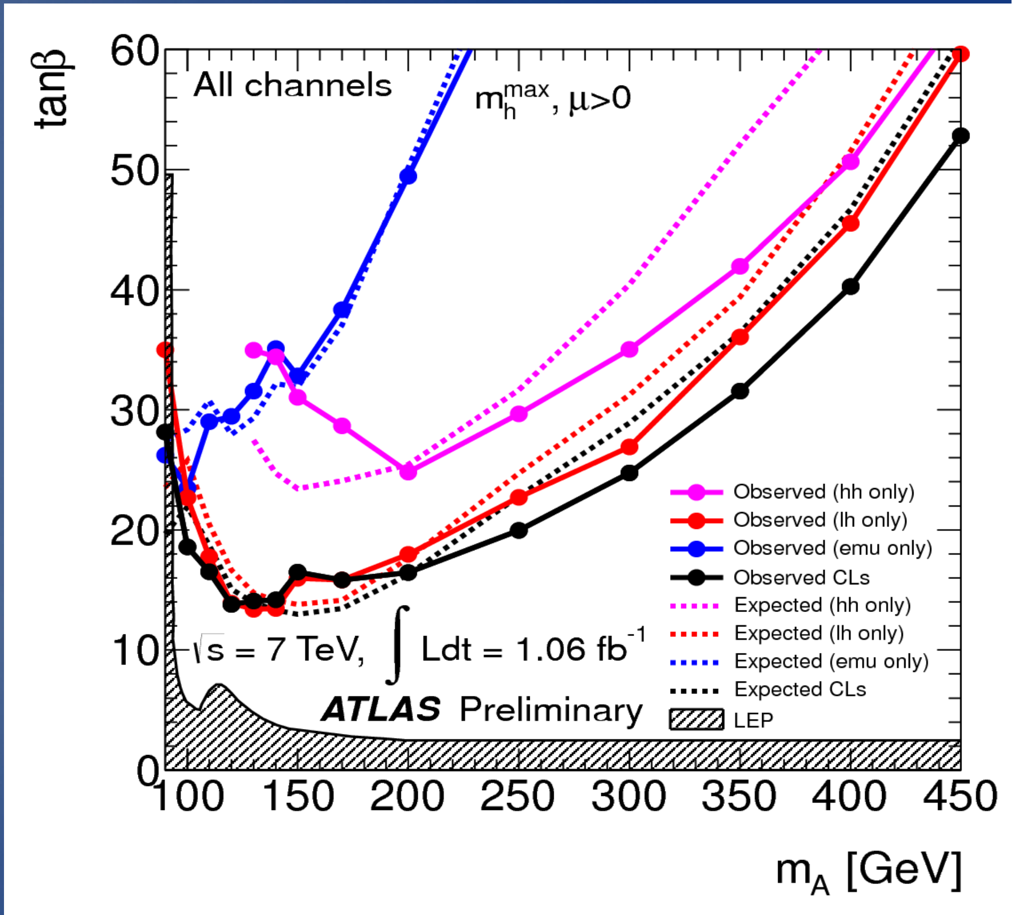
MSSM H/A → ττ + nν



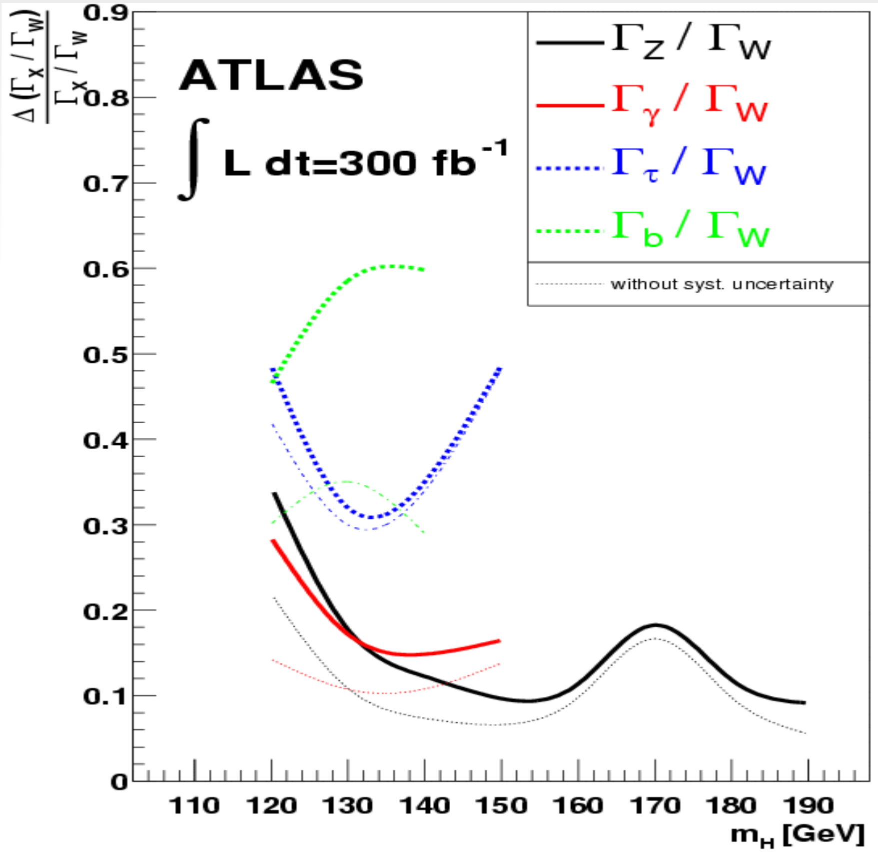


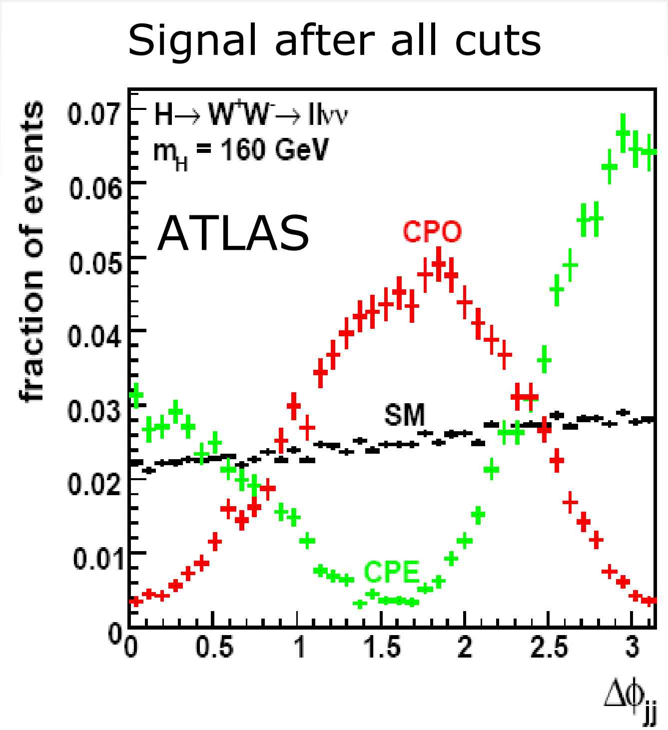
Effective mass accounts for undetected neutrinos

Background estimated using a same sign-opposite sign subtraction ATLAS-CONF-2011-132

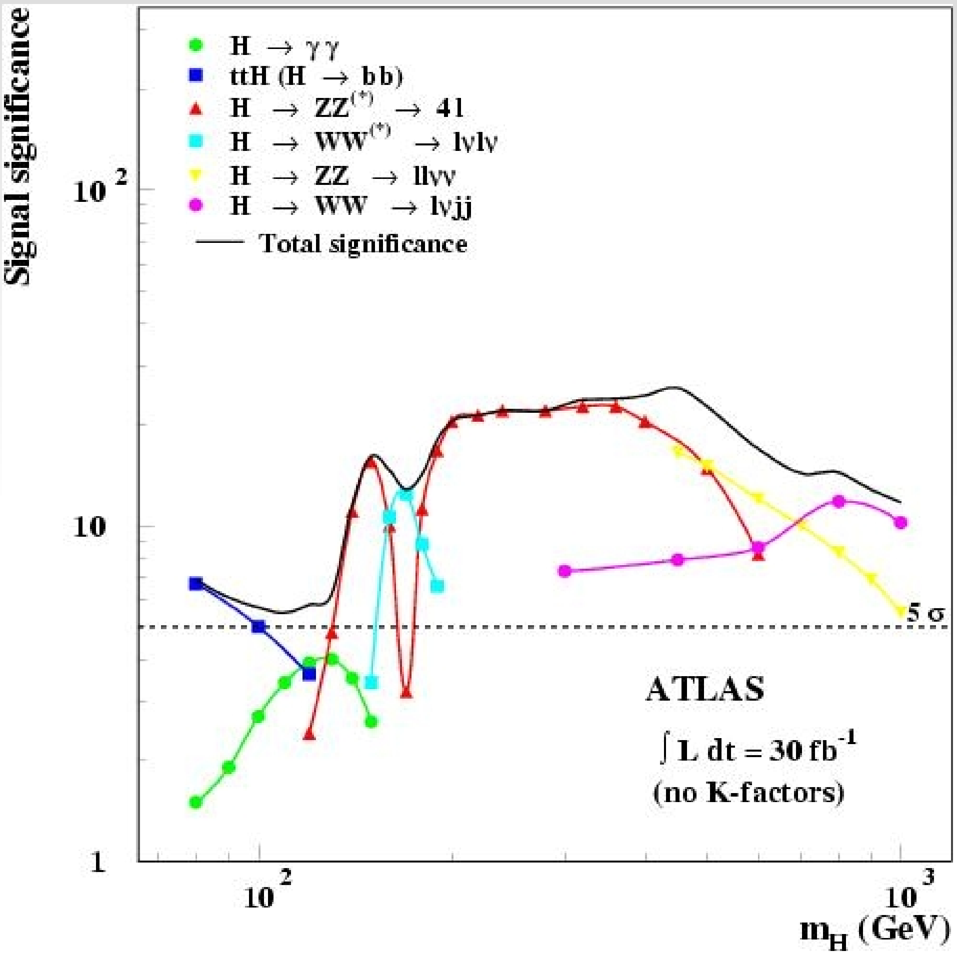
Is it really the Higgs?

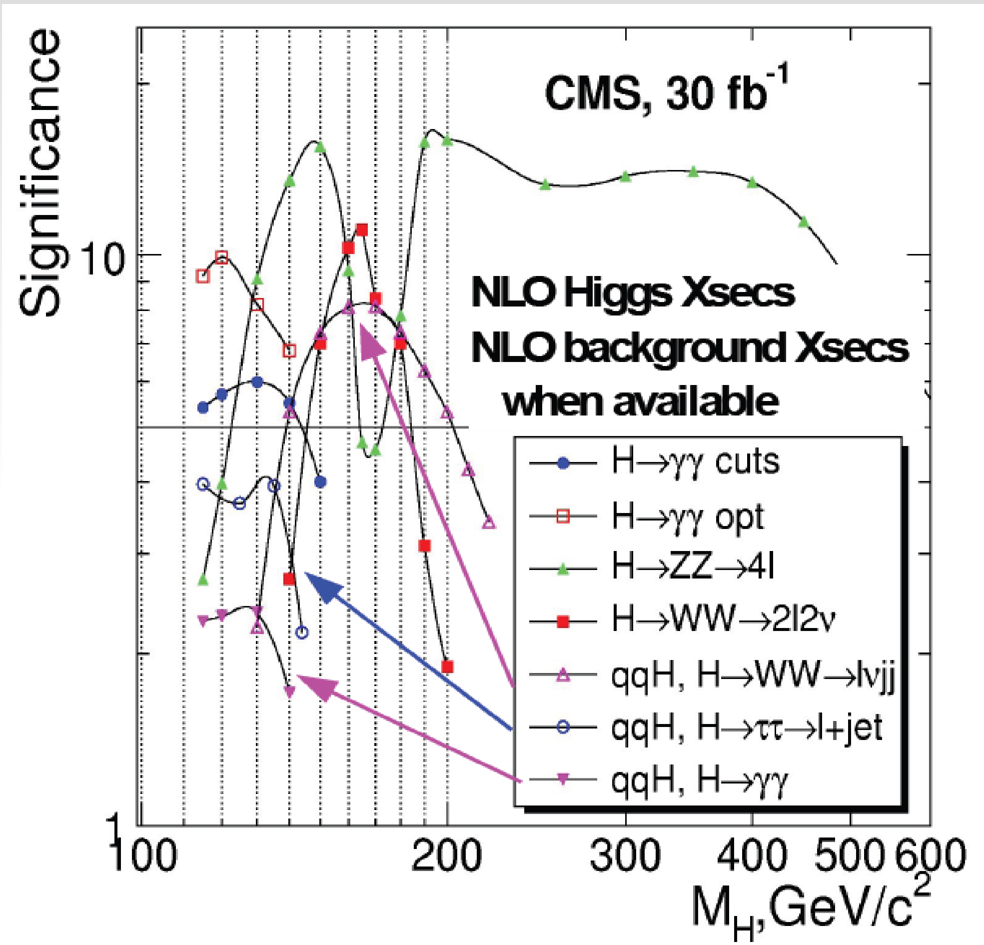
- If a particle is found in any Higgs search, is it really it?
- Measure width (or ratios of) and quantum numbers





Summary: discovery potential



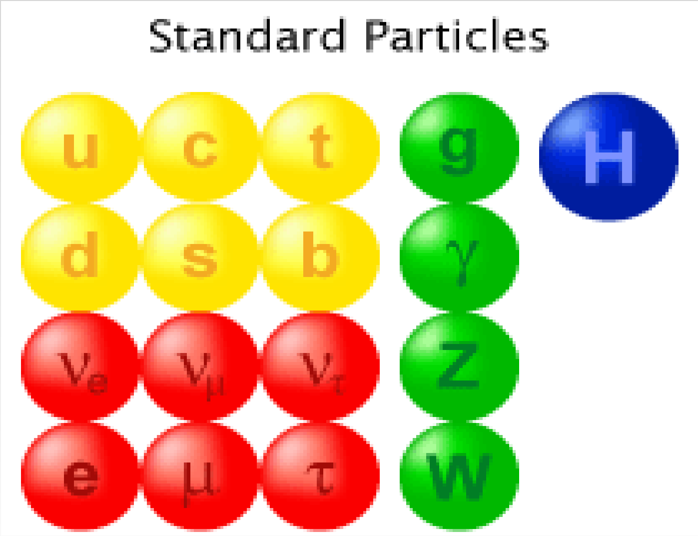


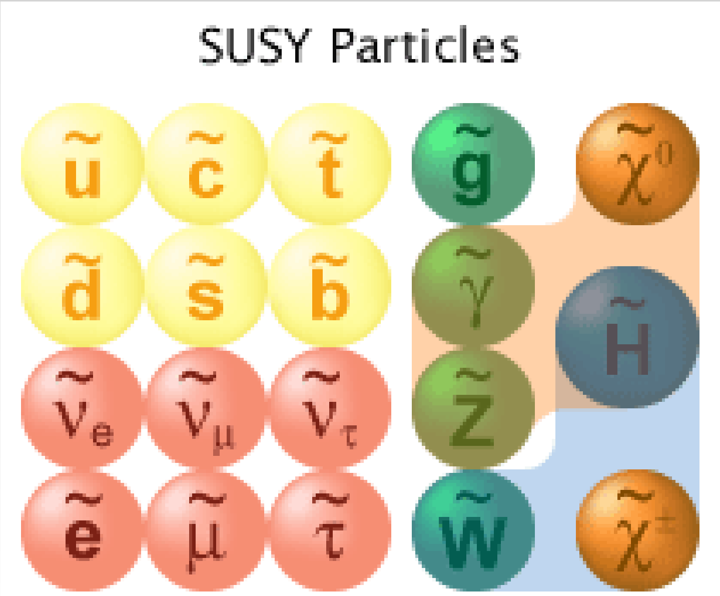
Issues with the Standard Model

- 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

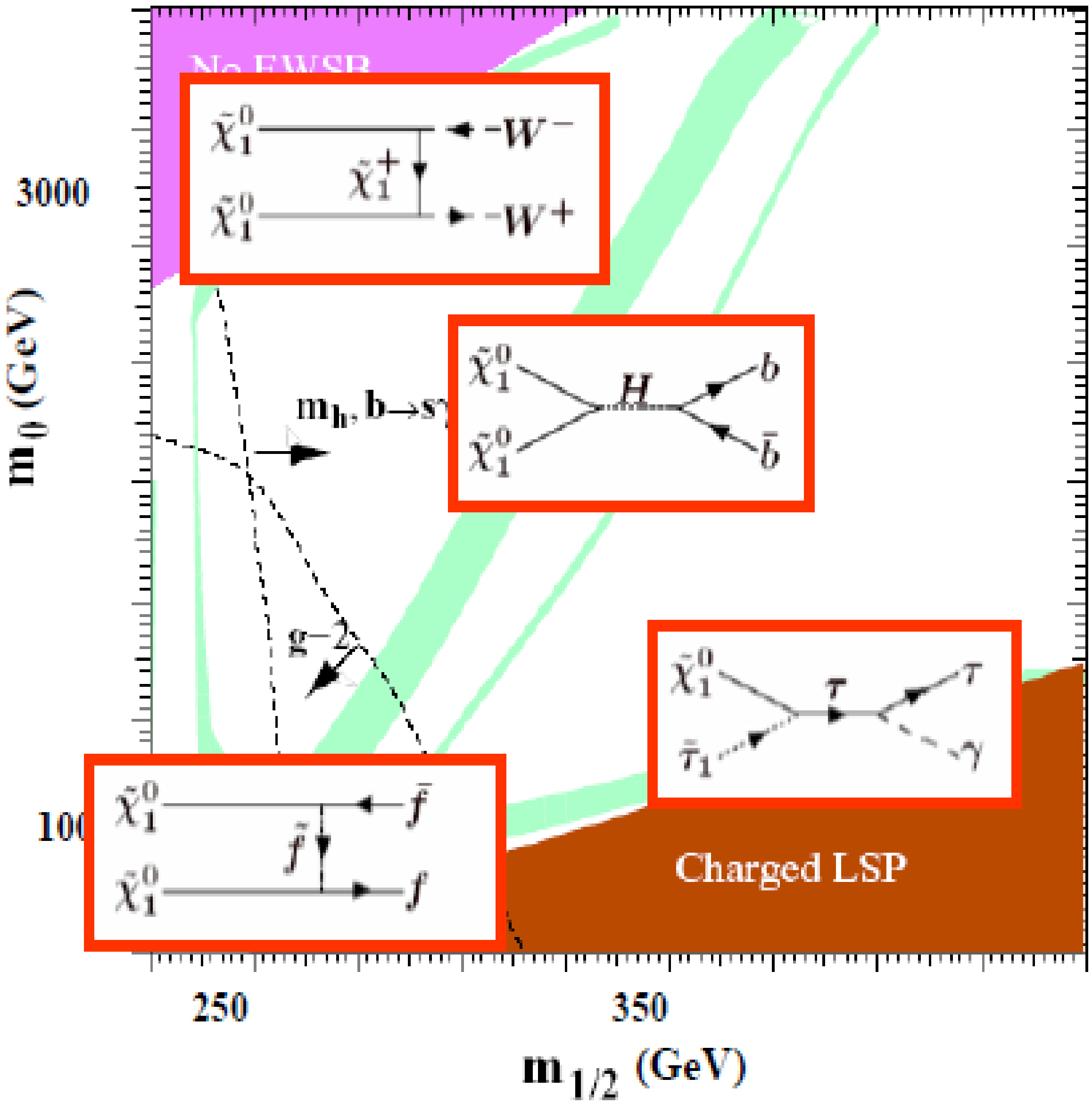
- Since no SUSY particles discovered so far, their masses have to be larger than their SM correspondents. Supersimmetry has to be broken, and spontaneous symmetry breaking does not work (would predict particles lighter than SM correspondents)
- SUSY breaking confined to hidden sector at high scale, and 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

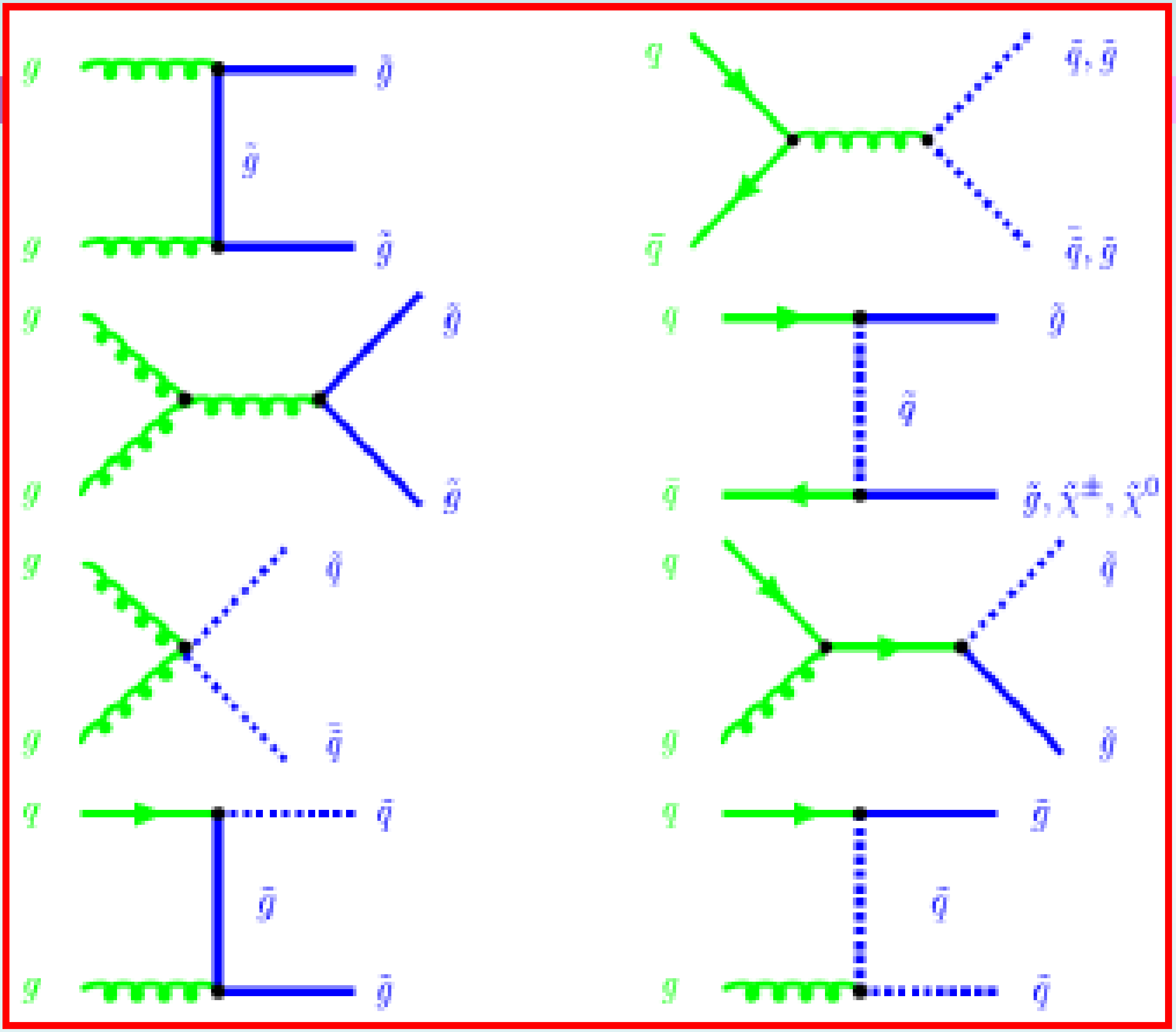
pure bino, small NLSP-LSP mass difference, typically coannihilation with stau

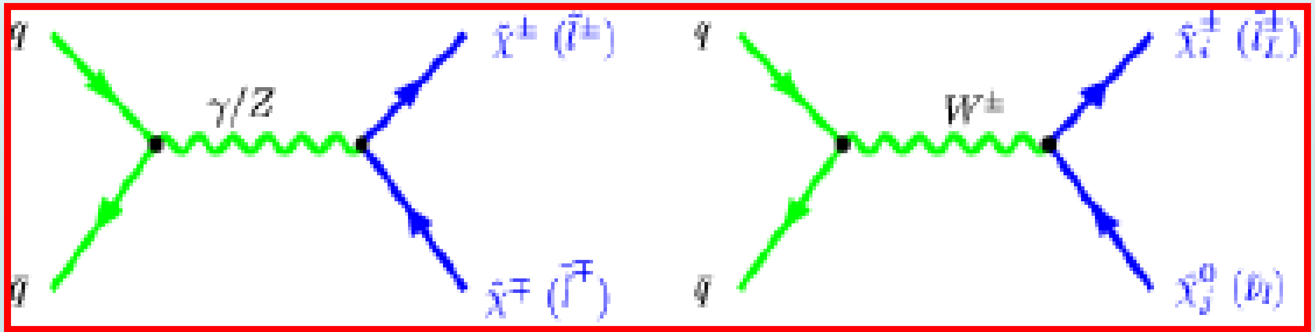
Higgs funnel

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

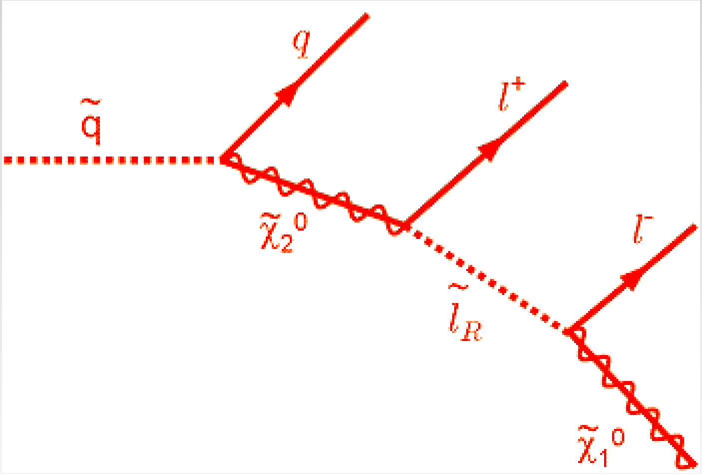


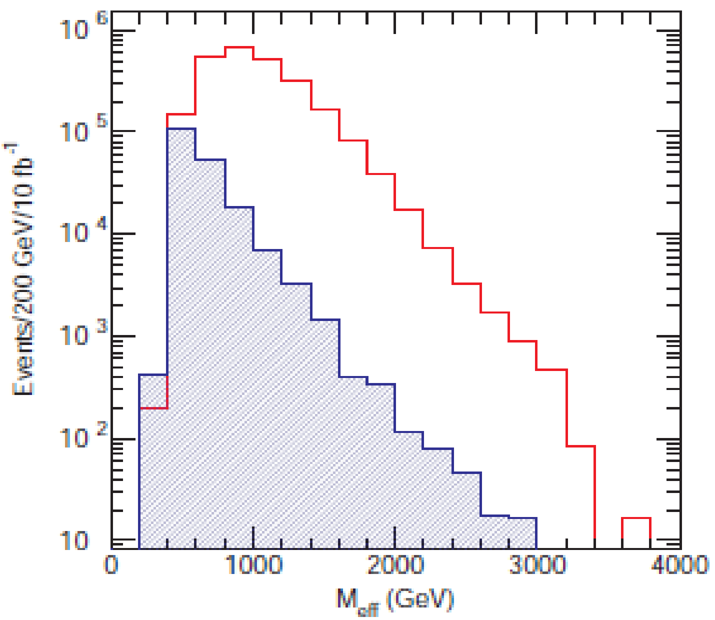


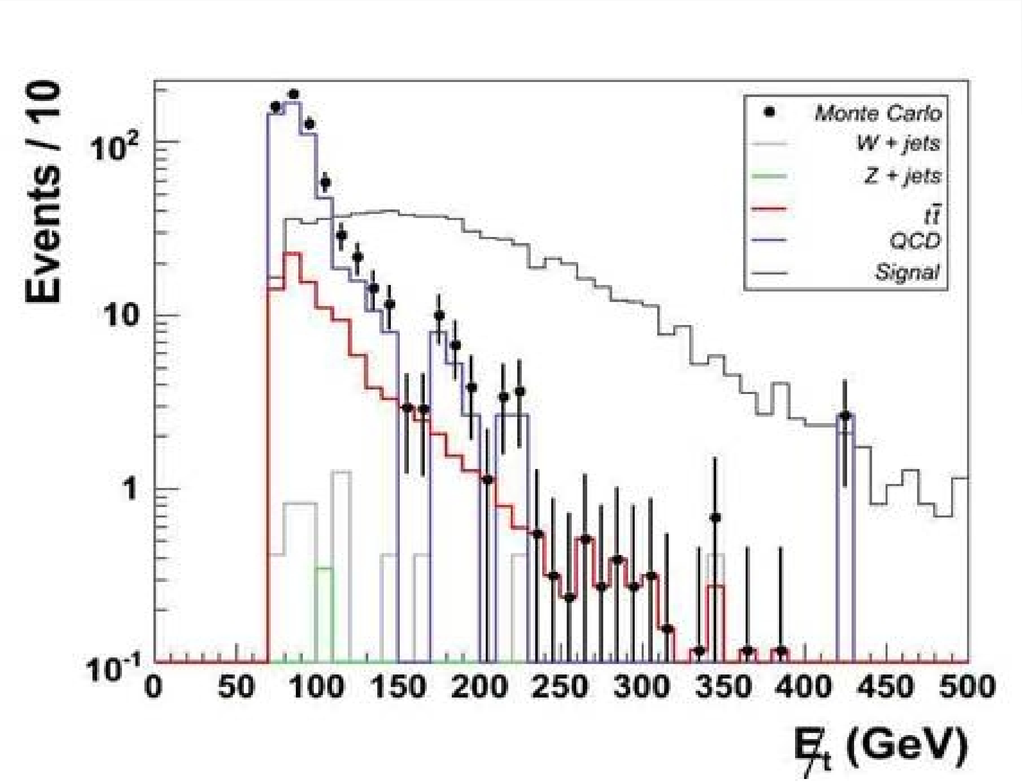
Direct Gaugino Production

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)

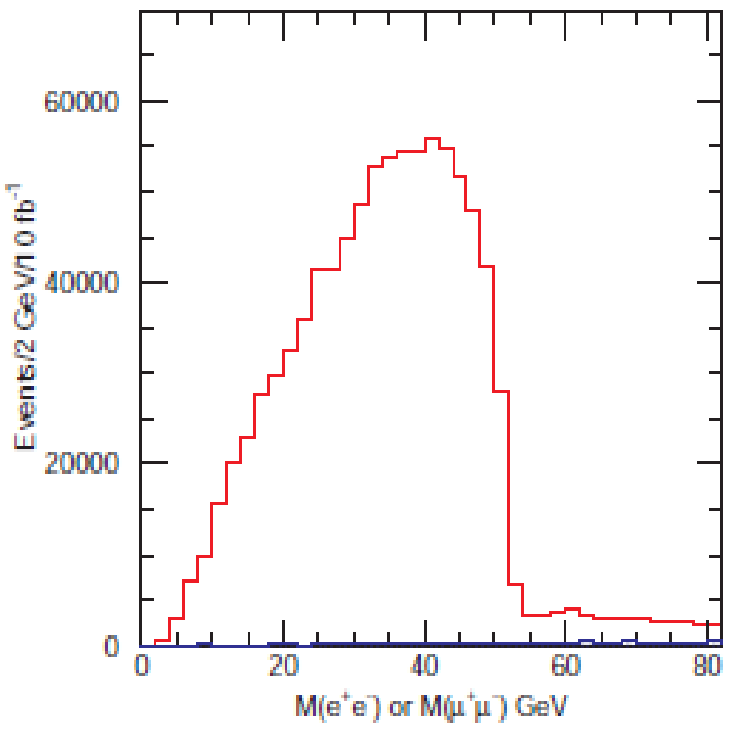


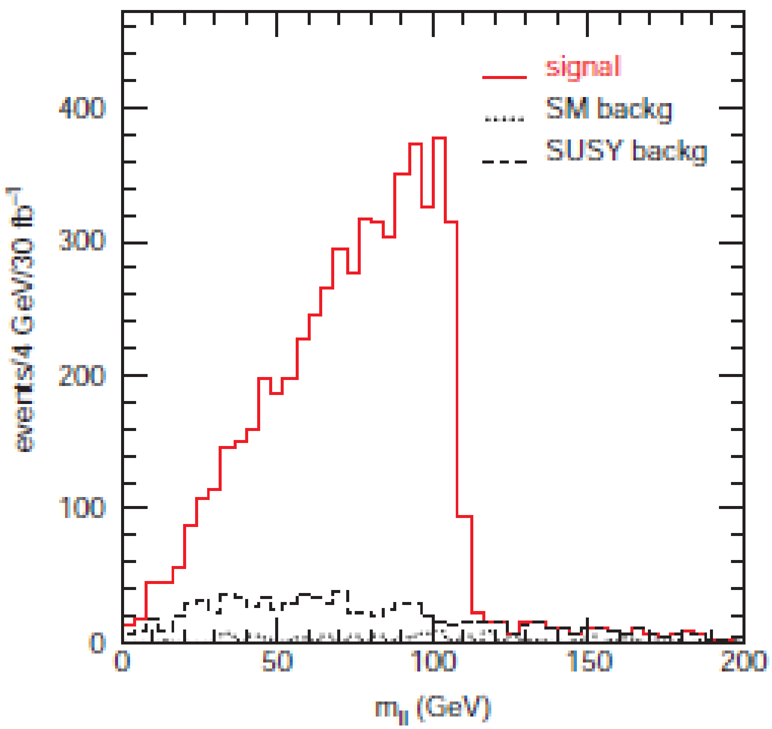




Dilepton signatures

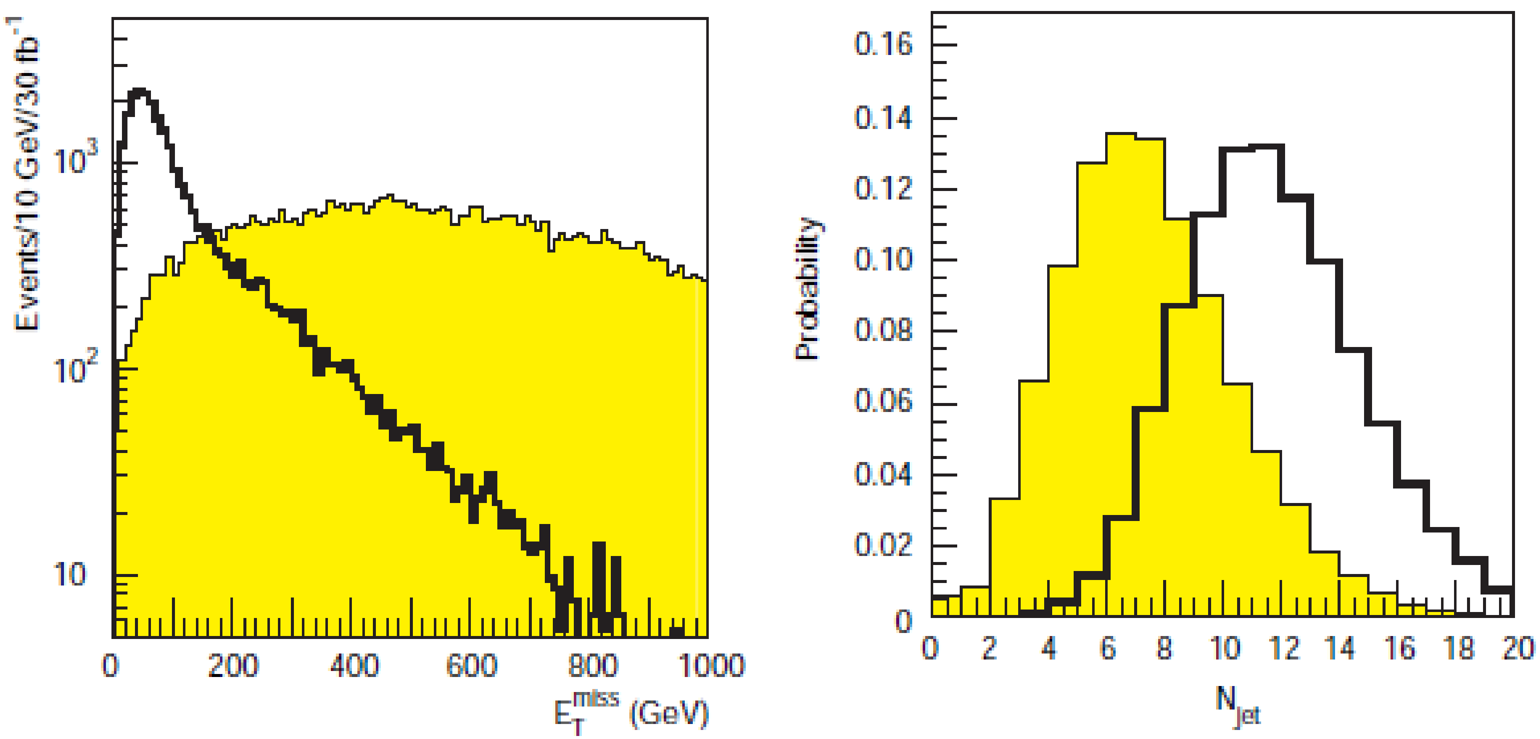
- In most of the parameter space, charginos and neutralinos have no 2-body decay, so a dominant decay is 3-body $\chi_2 \rightarrow \chi_1\ l^+l^-$. The lepton invariant mass will have a sharp edge corresponding to the SUSY mass difference. Signal can be very clean.





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:

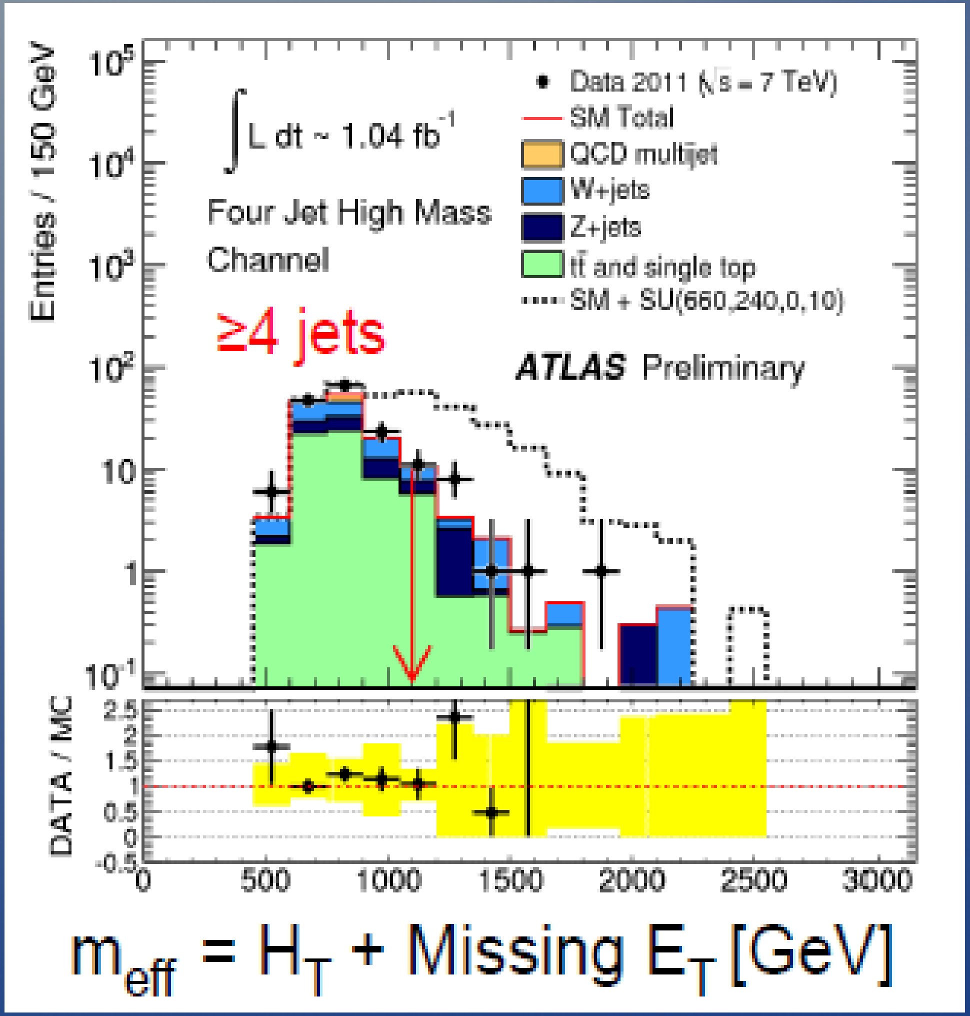


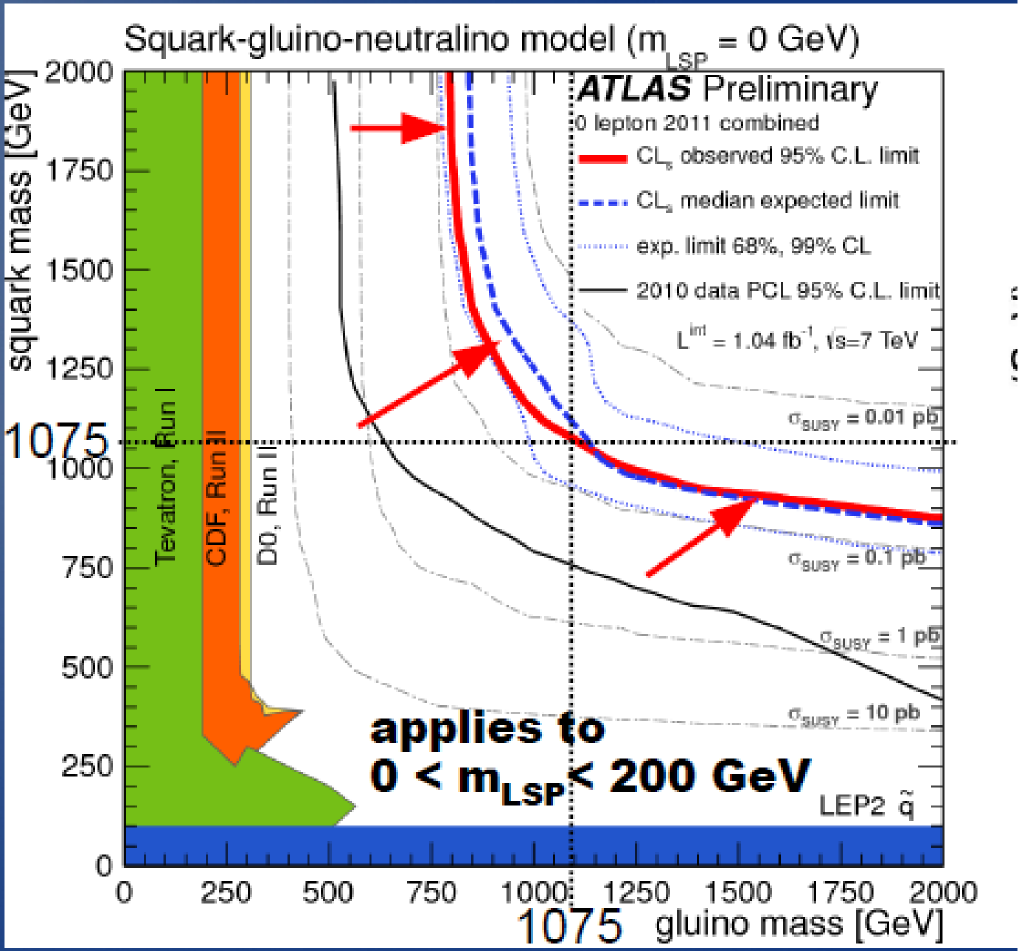
R-parity violating R-parity conserving

SUSY: Jets + MET

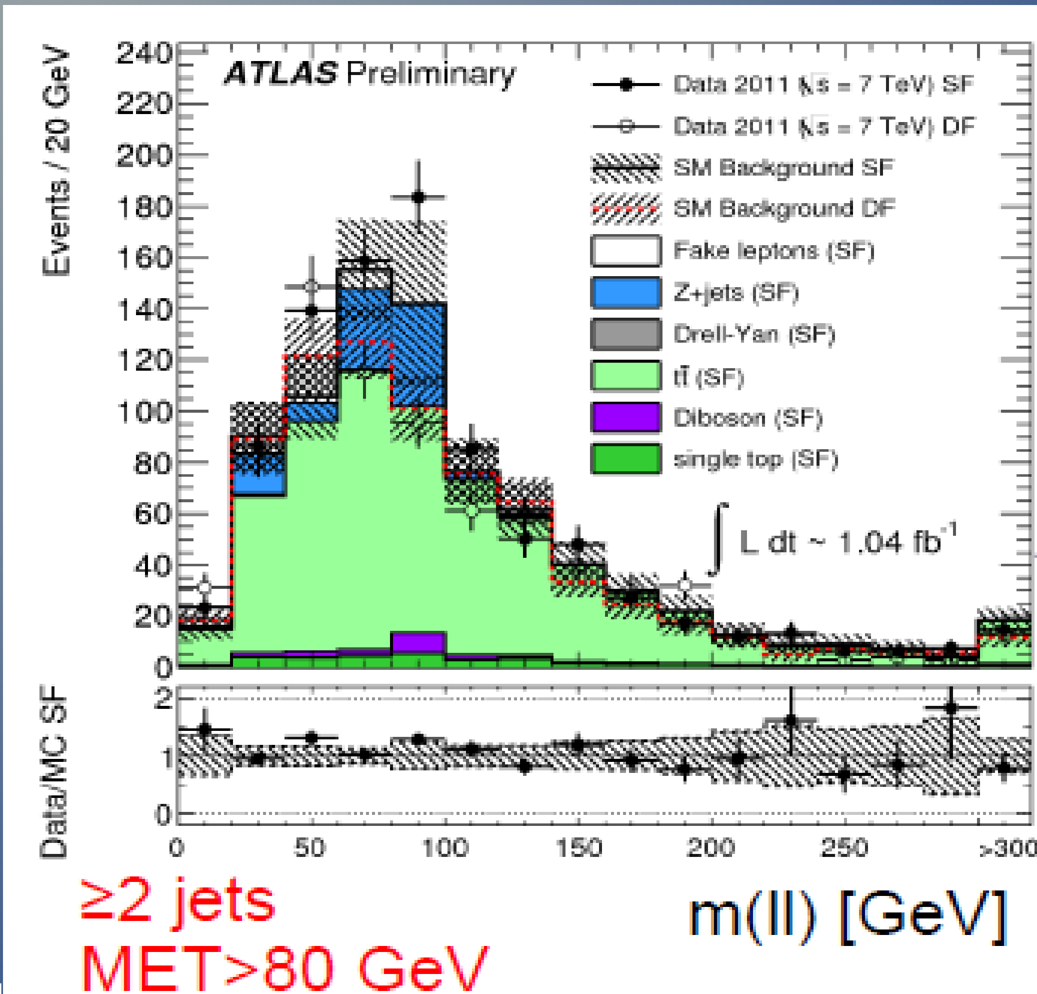
$$\tilde{q} \rightarrow q\tilde{\chi}_1^0$$
$$\tilde{g} \rightarrow qq\tilde{\chi}_1^0$$

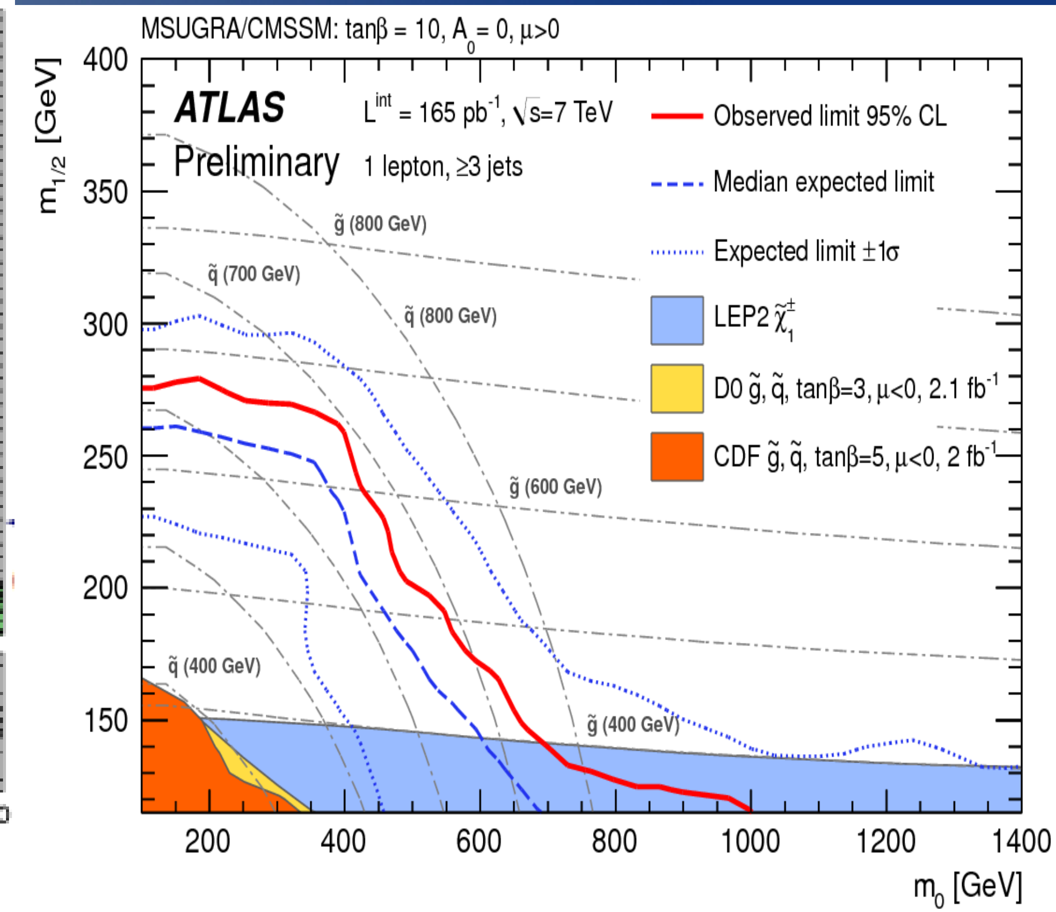
If R-parity is conserved, long decay chains lead to many jets and MET
→ cut on effective mass





SUSY: leptons + jets + MET





Leptons from sleptons or charginos or V decays

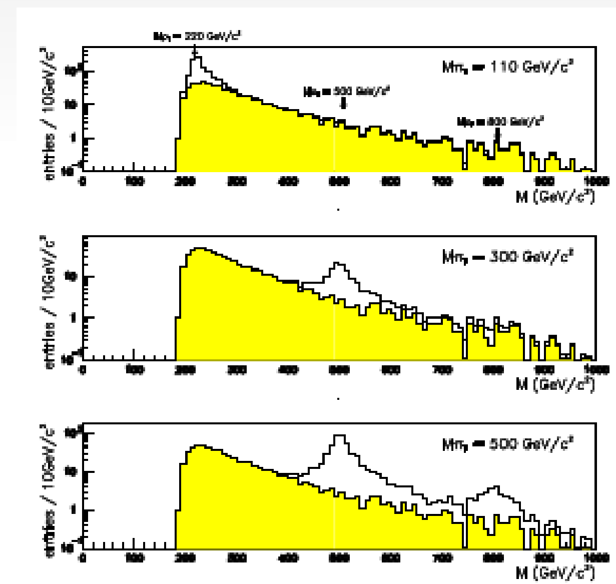
Complementary to fully hadronic modes

Much better limits than Tevatron, LEP

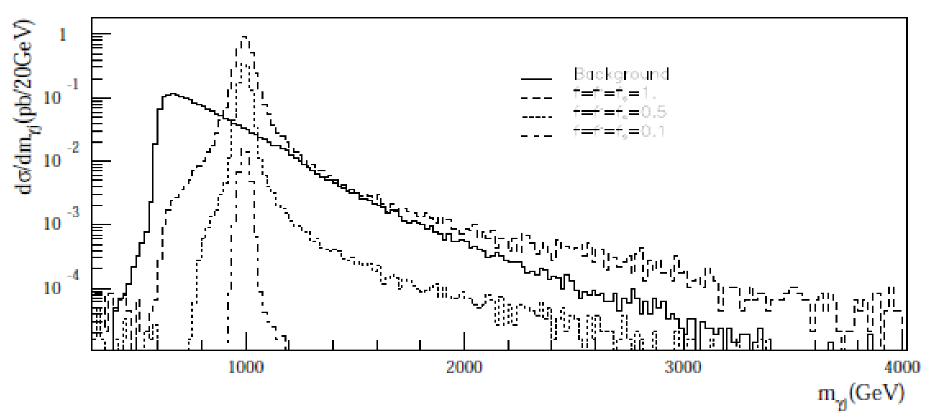
ATLAS-CONF-2011-090

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



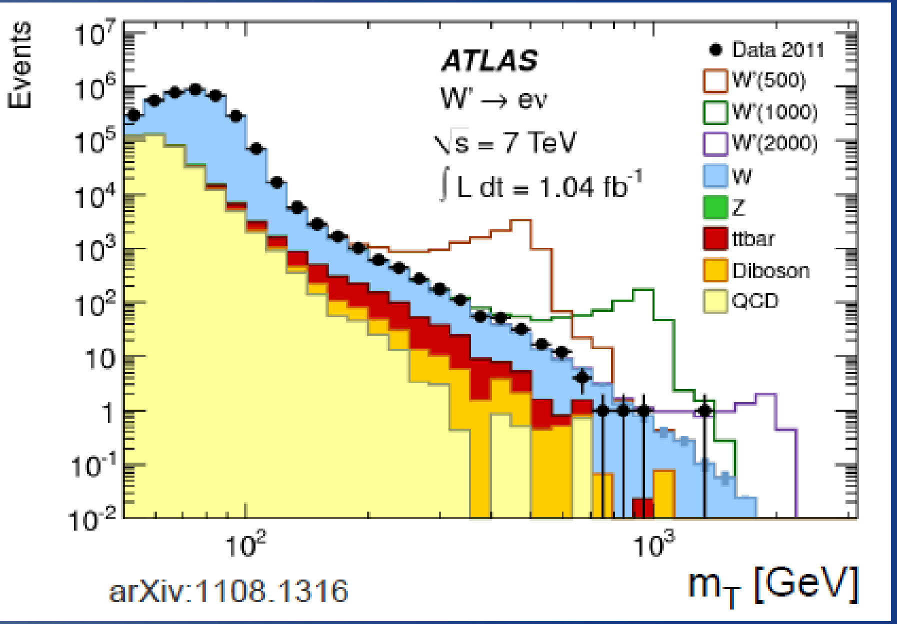
W' and same sign dilepton

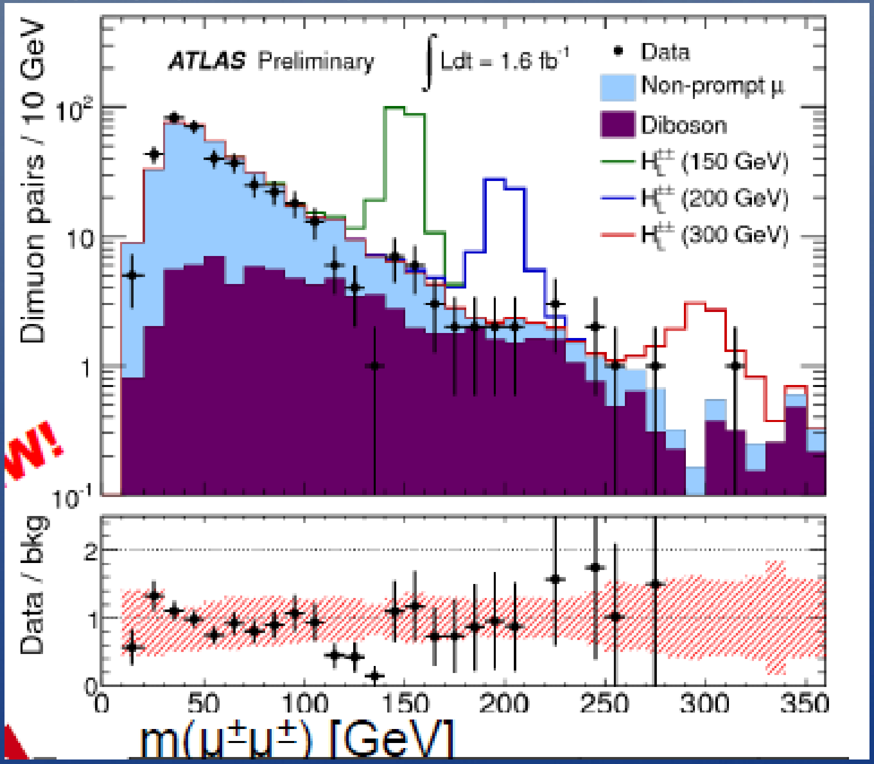
Look for jacobian peak in lepton + MET transverse mass distribution

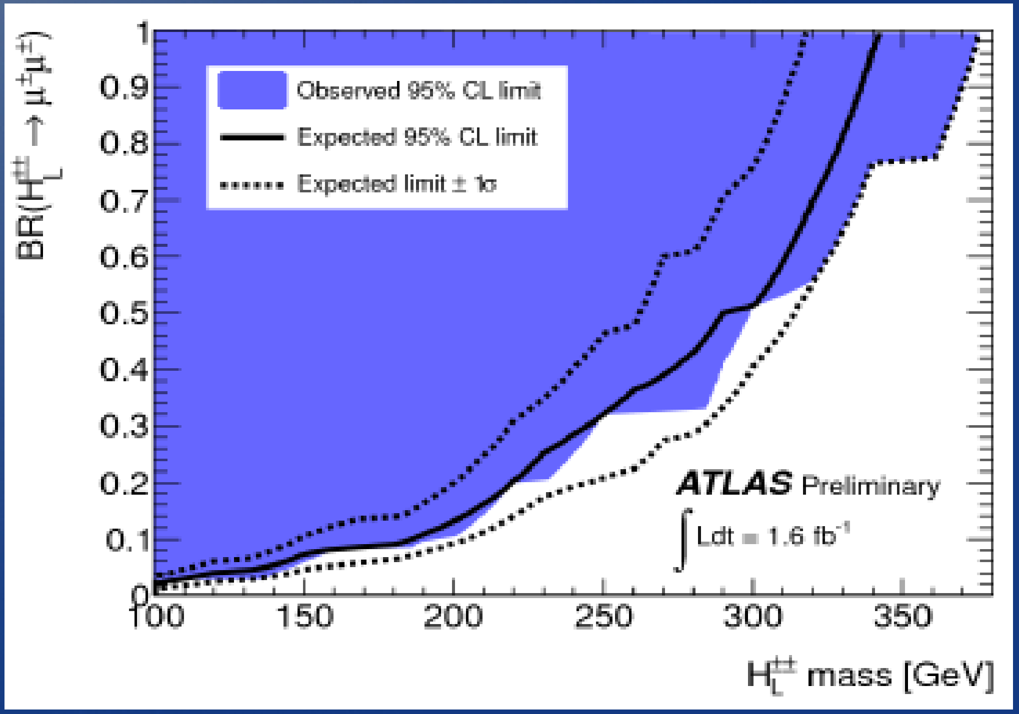
Same-sign muons from could come from doubly-charged H

ArXiv:1108.1316

ATLAS-CONF-2011-127

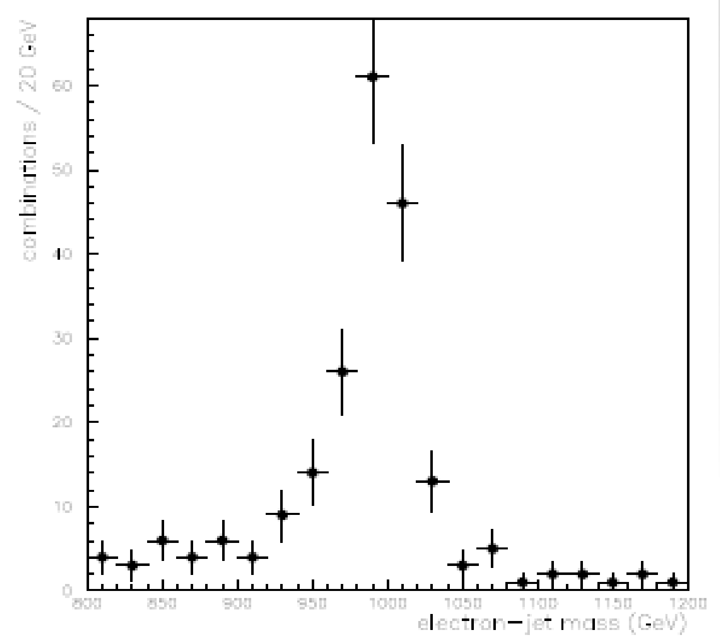




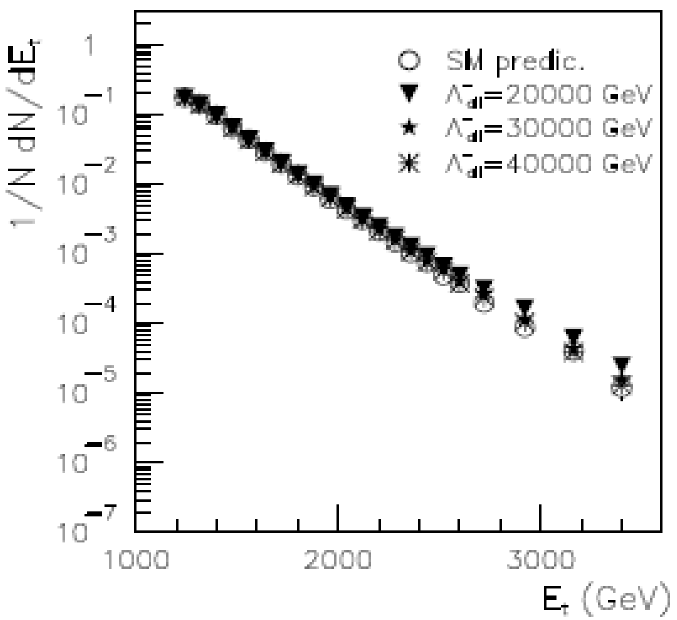


More new physics

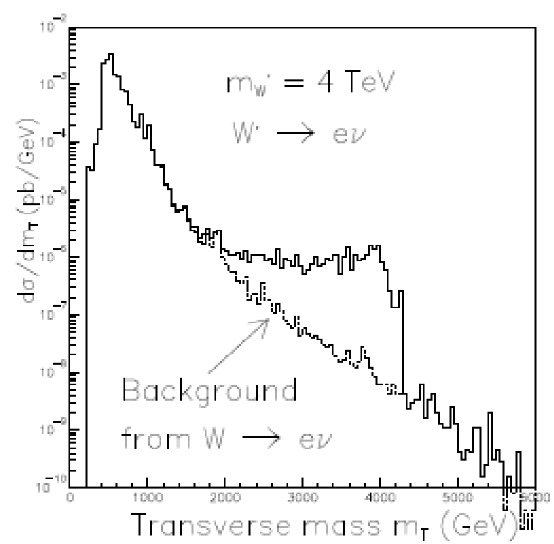
- Leptoquarks: a new symmetry between leptons and quarks could produce particles strongly coupling (and decaying) to both



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

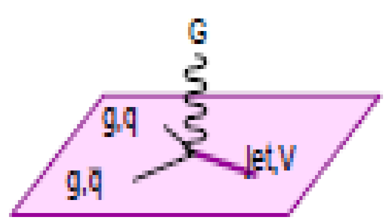


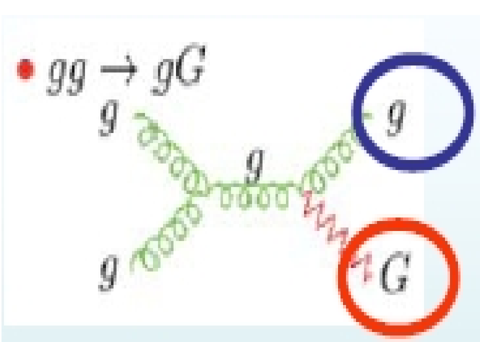
Z', W': from additional SU(2) symmetry, behave like high-mass W's and Z's



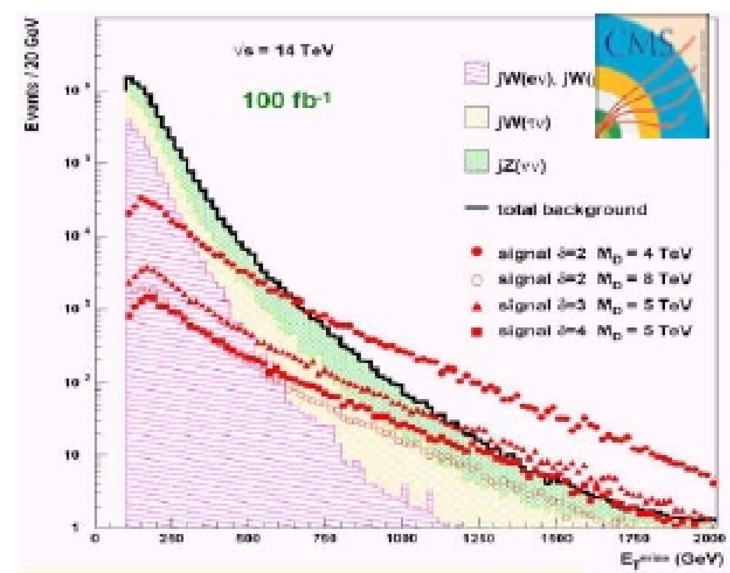
Extra dimensions

- 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

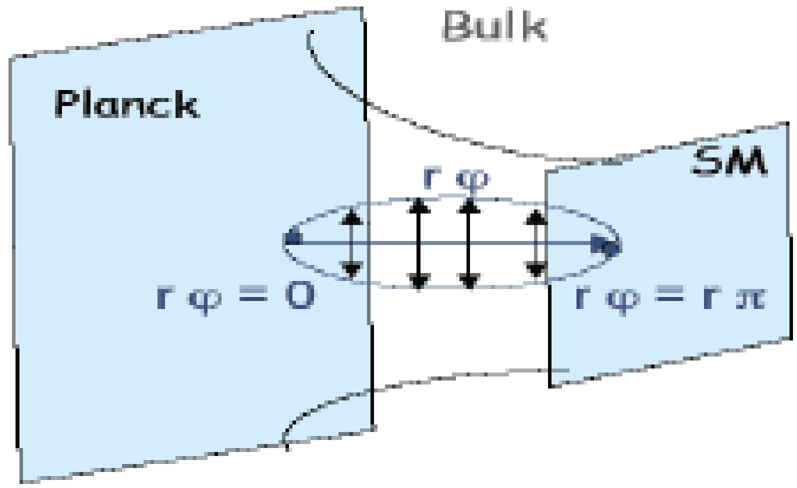




Great way to escape from the in-laws???



Randall-Sundrum models

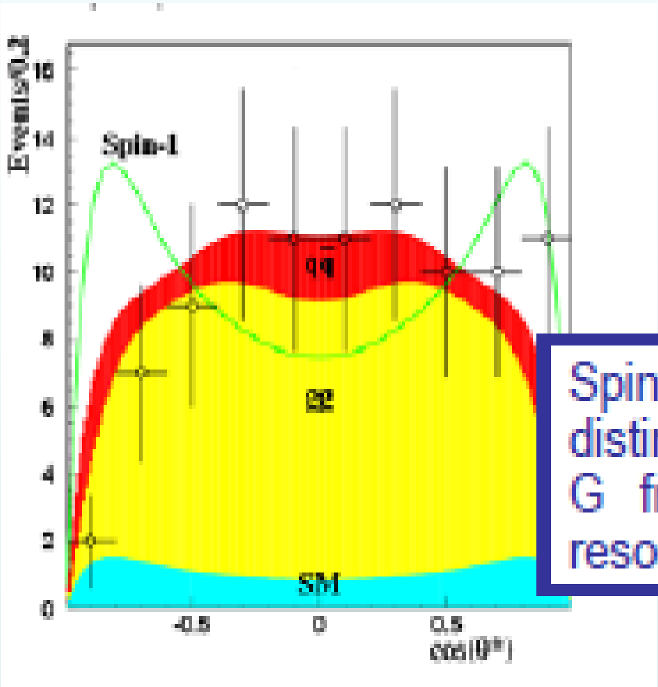


A small, highly curved ("warped") extra dimension connects the SM brane (at O(TeV)) to the Planck scale brane

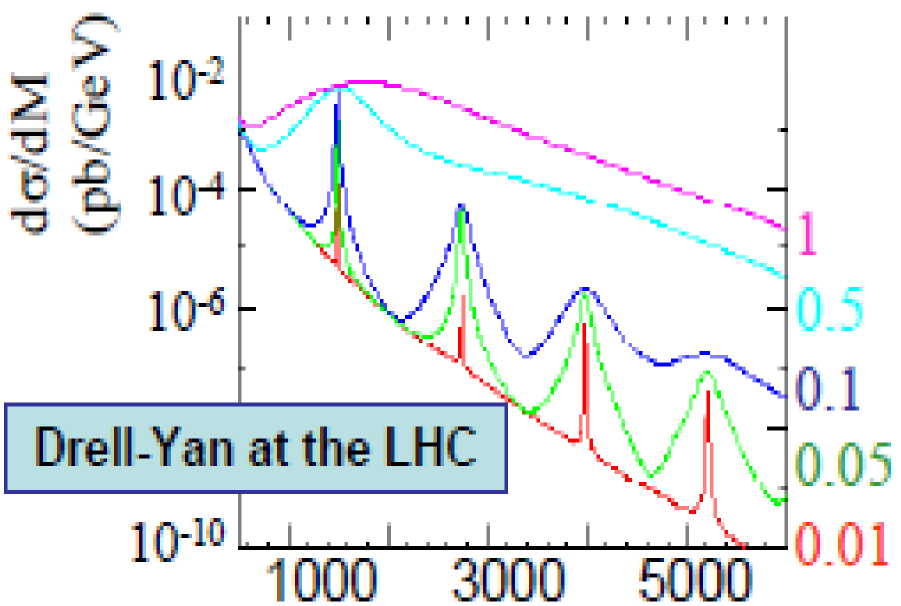
Gravity small in our space because warped dimension decreases exponentially between the two branes

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

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



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



Drell-Yan at the LHC

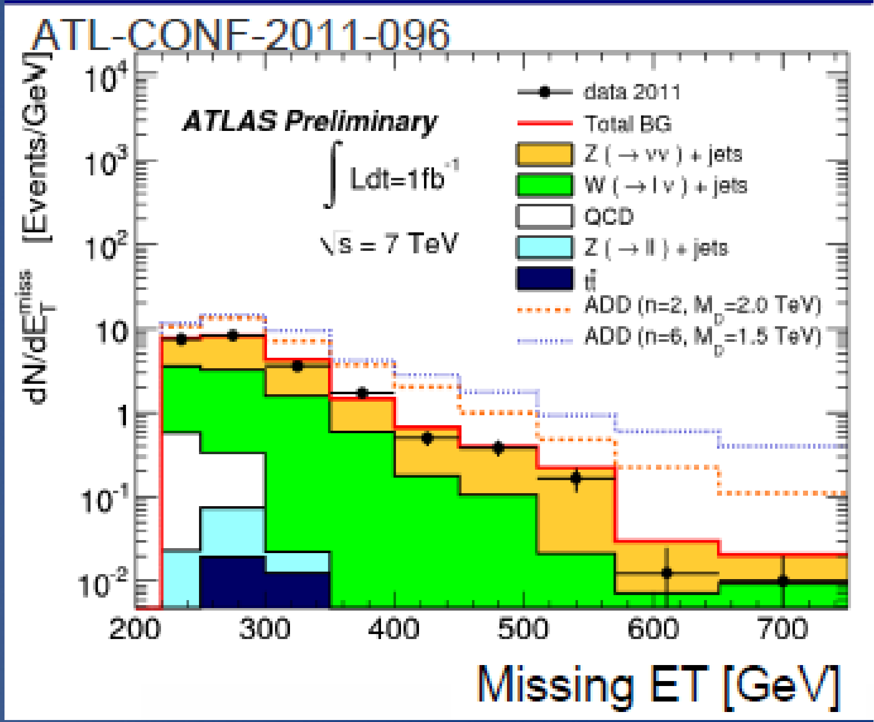
Dilepton mass

Antonella De

Strong-coupling gravity

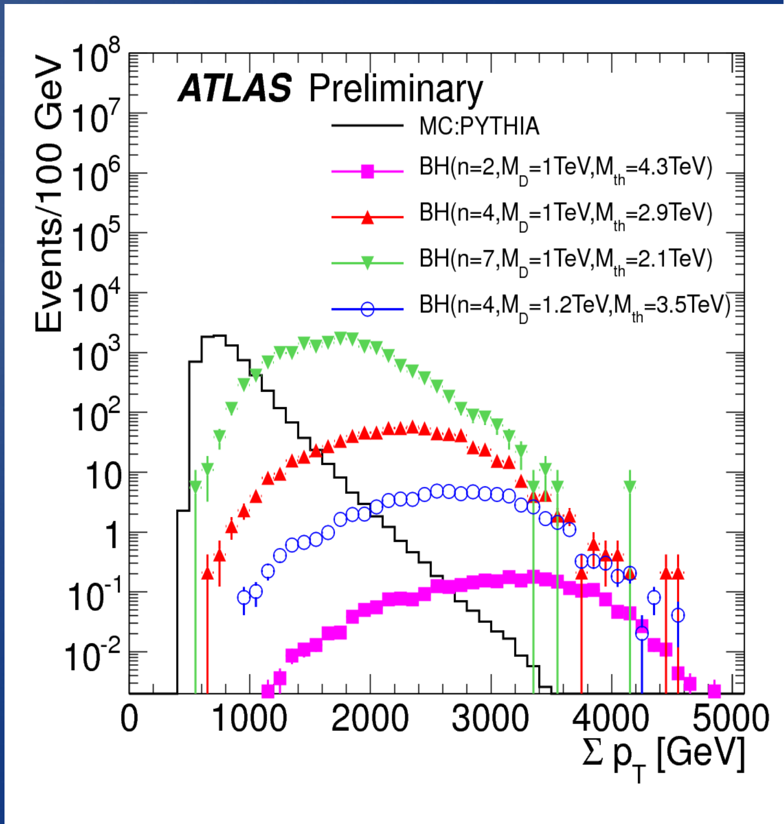
- Quark + graviton final state → monojet

ATLAS-CONF-2011-096

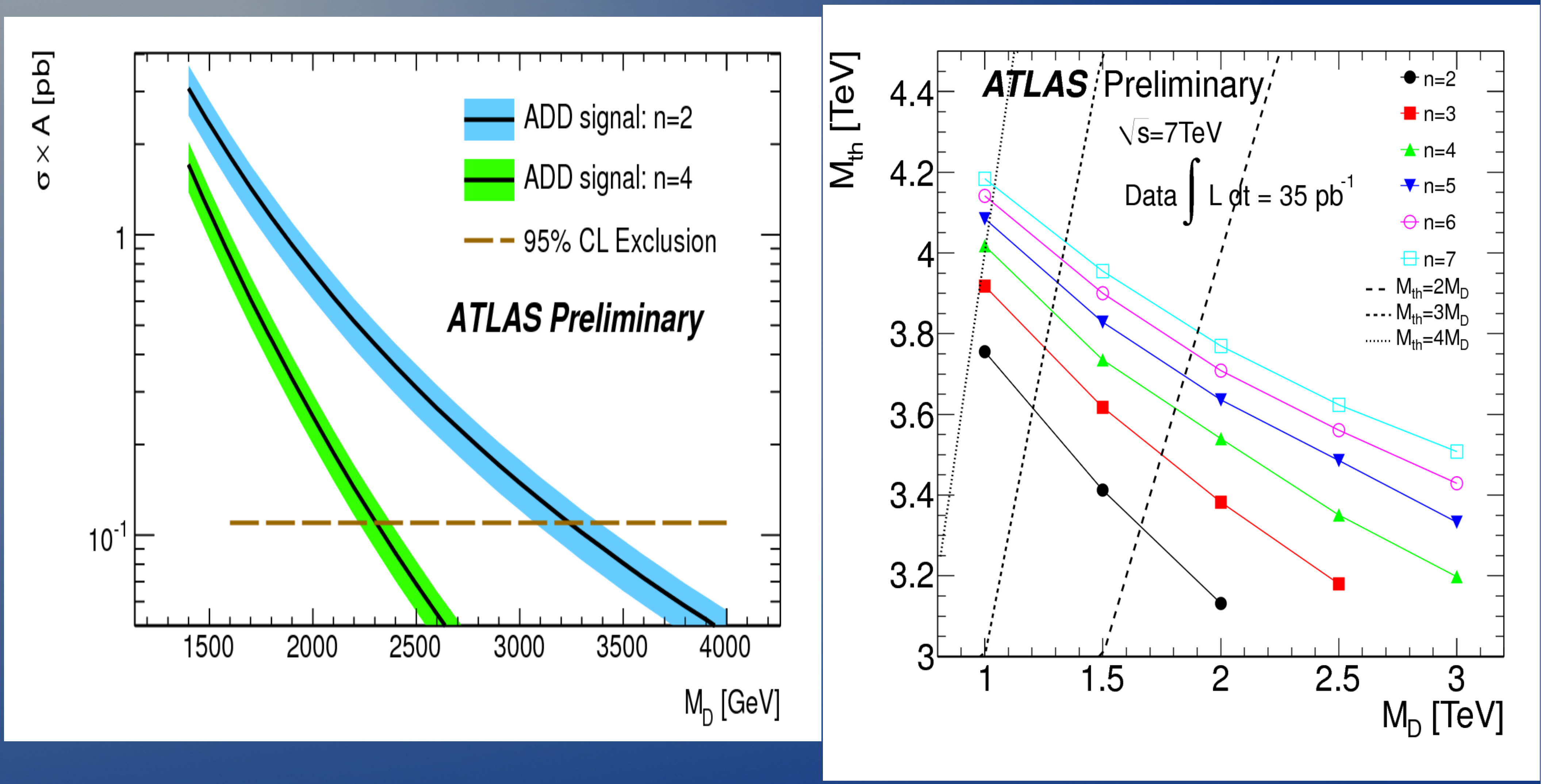


- Black holes: multiple objects filling the detector; look for large track multiplicities in peculiar events with same-sign muons (to reduce BG)

ATLAS-CONF-2011-068



Limits on strong-coupling gravity

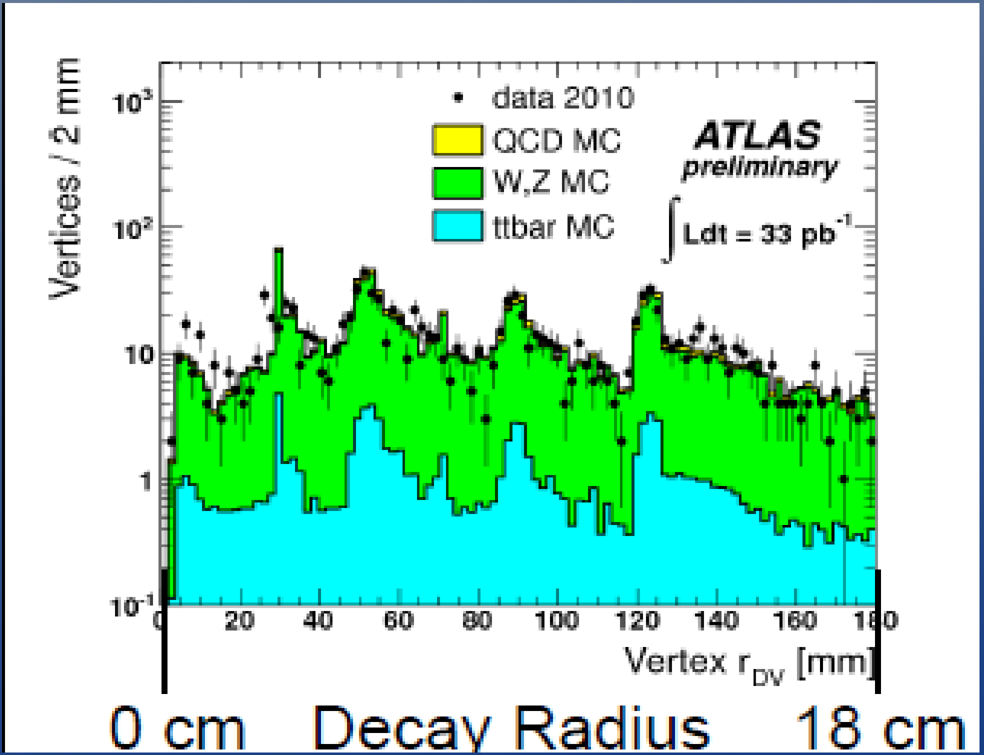


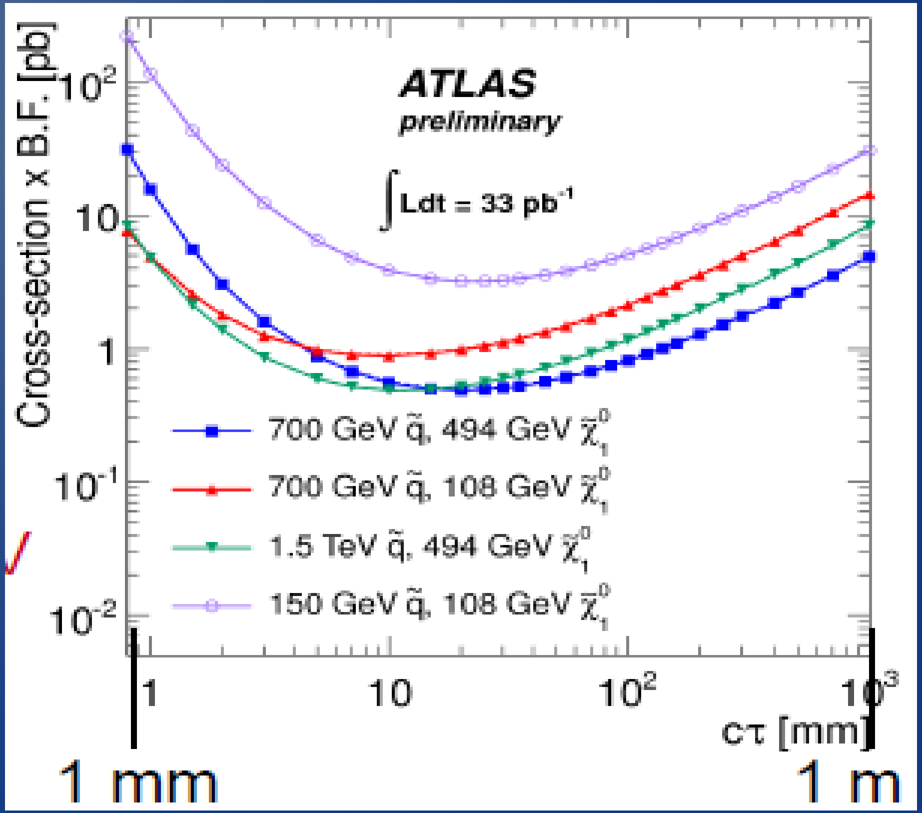
Displaced vertices

R-parity violating SUSY has no MET, but can lead to a heavy (> 10 GeV) displaced vertex in association with a muon

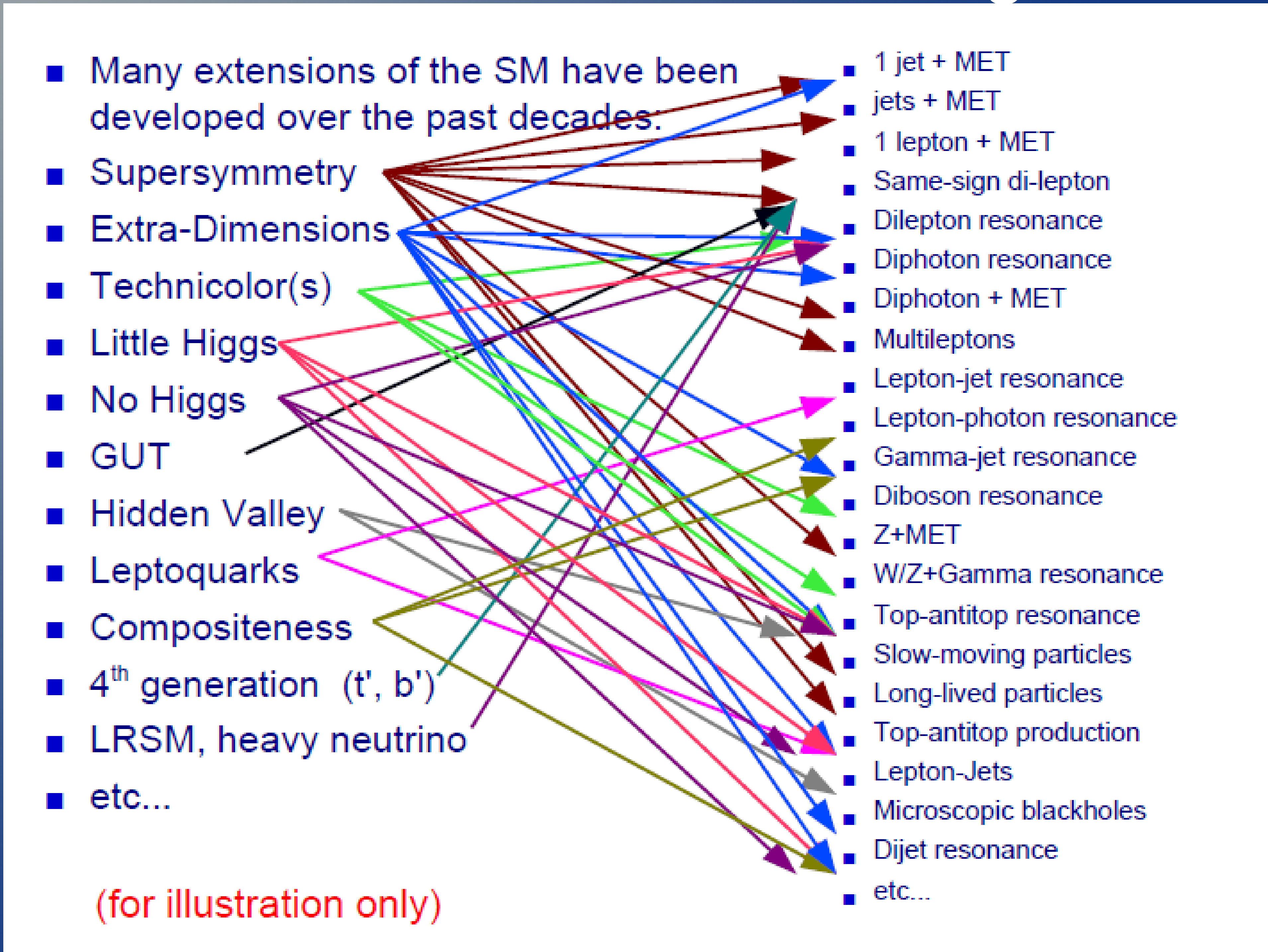
Good understanding of material budget distribution is needed

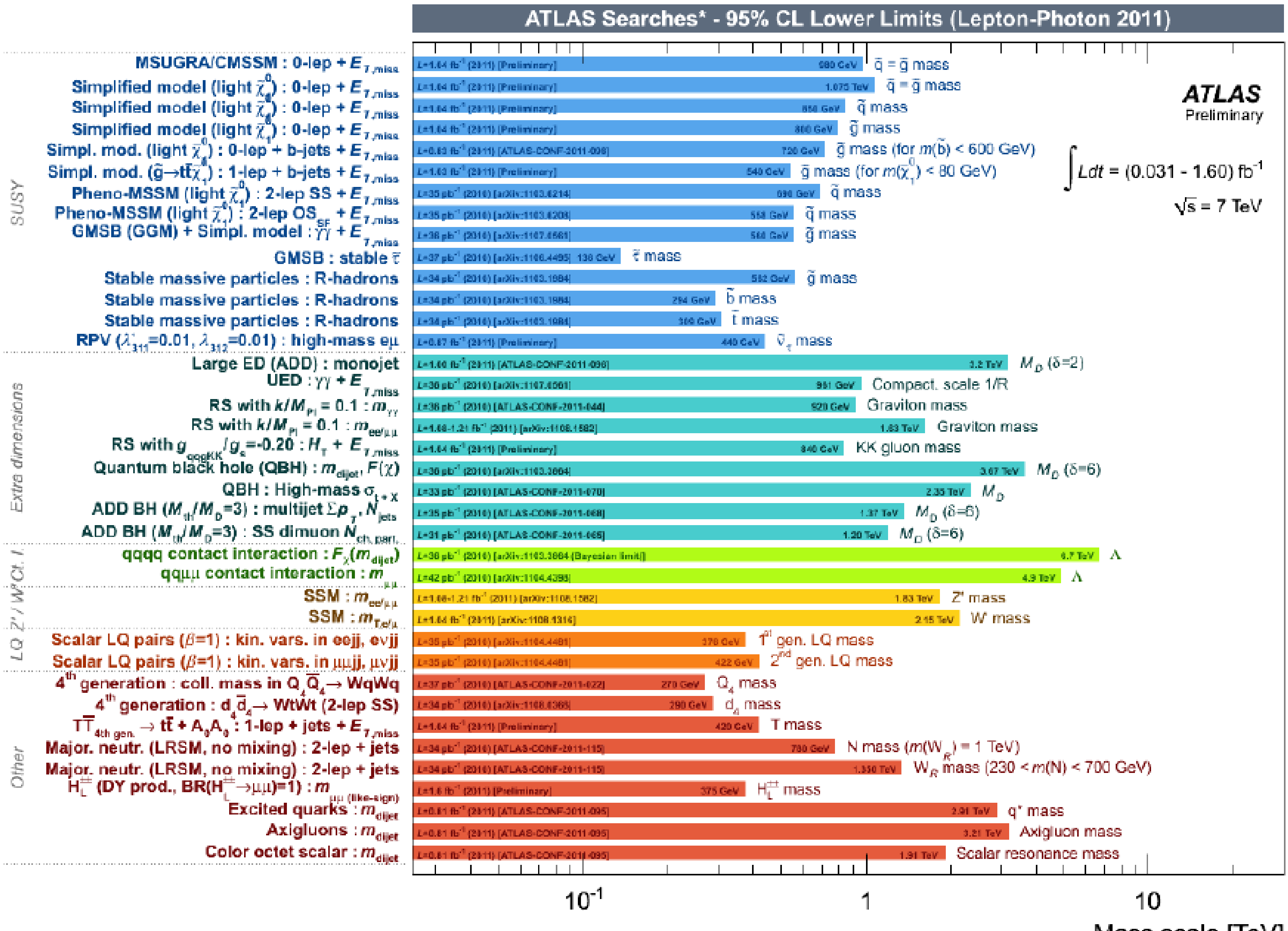
ArXiV:1106.4495





BSM searches: models and signatures





*Only a selection of the available results leading to mass limits shown

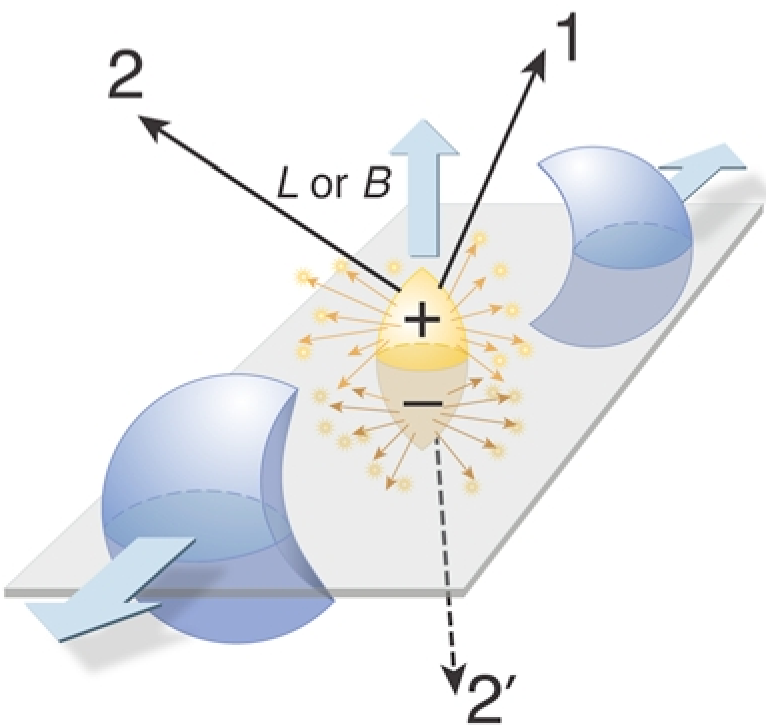
Summary on searches

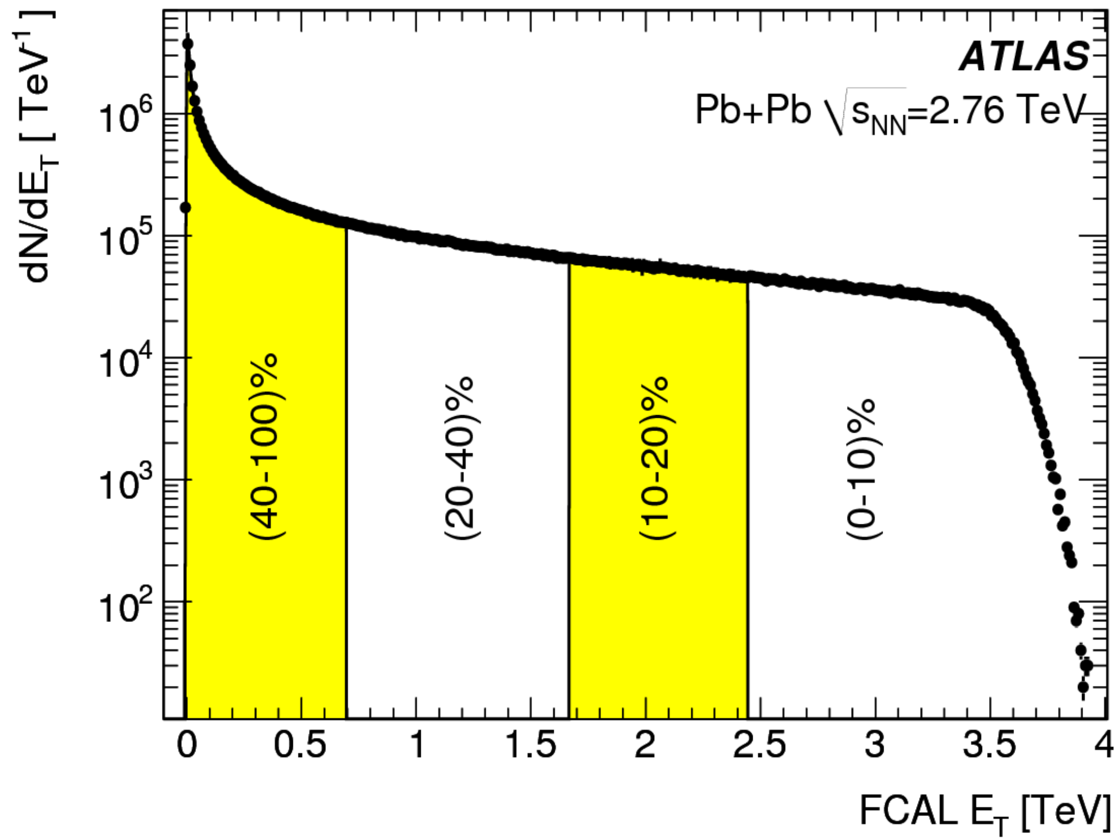
- LHC has a wide spectrum of new physics searches, from very specific models to signature-based model-independent ones
- "around the corner" SUSY was not found, now searching "in the corner" (of phase space); mass limits around TeV on sparticles
- Contact interactions and resonances excluded up to masses of several TeV
- No indications yet of low-energy manifestations of gravity

HI collisions: monojets

- Last month of LHC running in 2010 (just started in 2011!) 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)

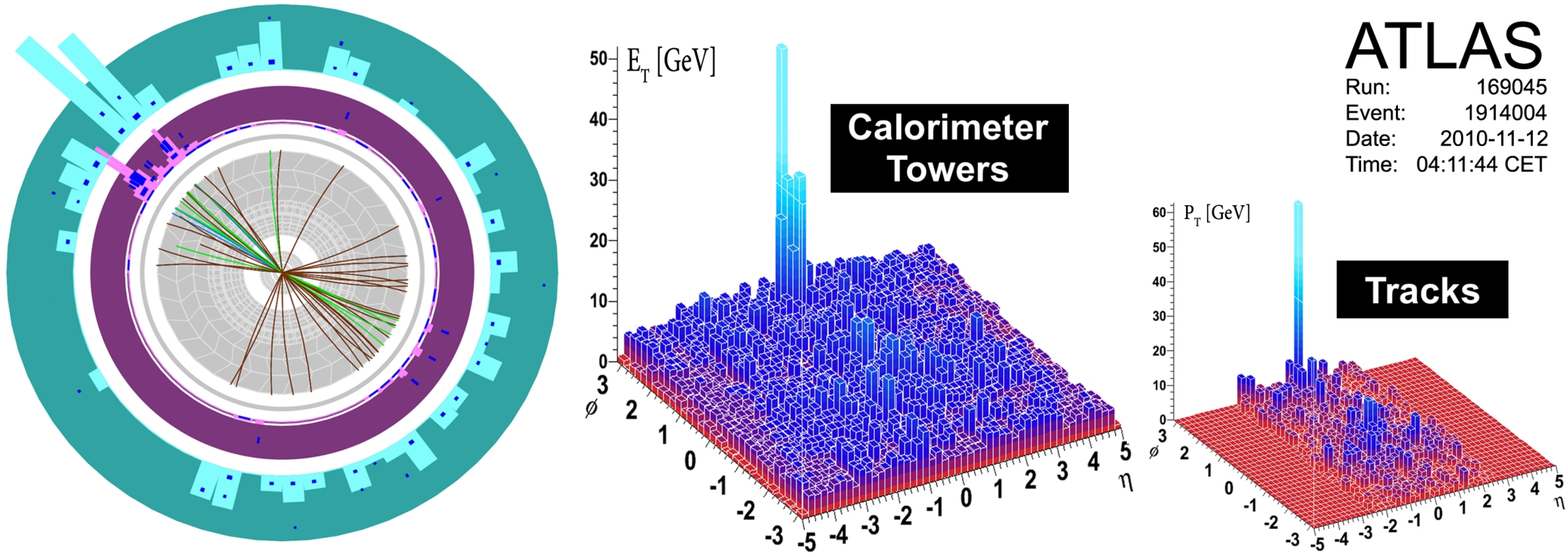
Centrality





- 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 now in full swing
- Run at 7 TeV in 2011 and collected 5 fb-1
- Insistent rumors: we may run at 8 TeV in 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.