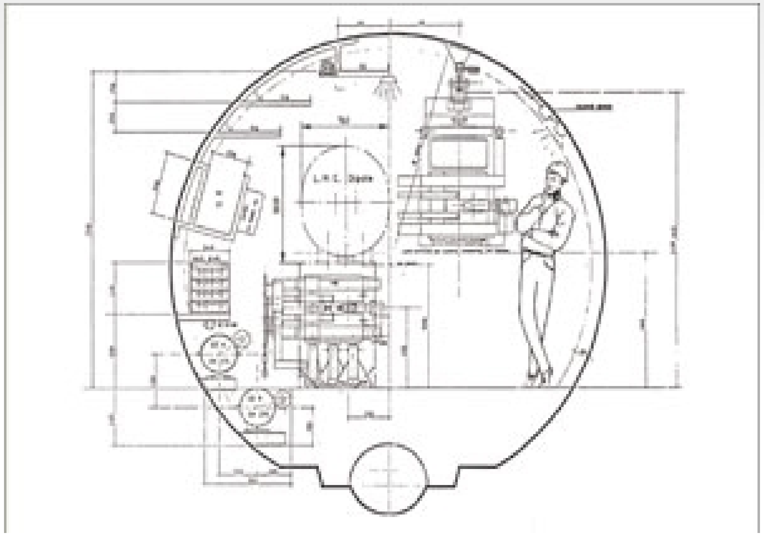
Mario Campanelli
University College London
Atlas Collaboration

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

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

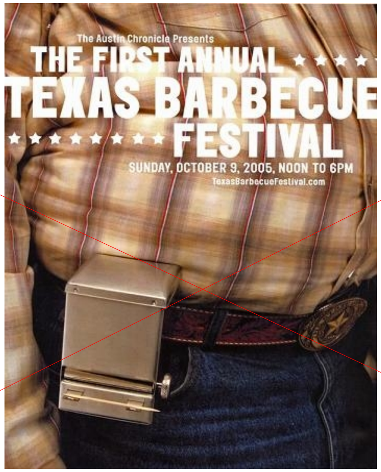
It was the largest civil-engineering project in Europe at that time.



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

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

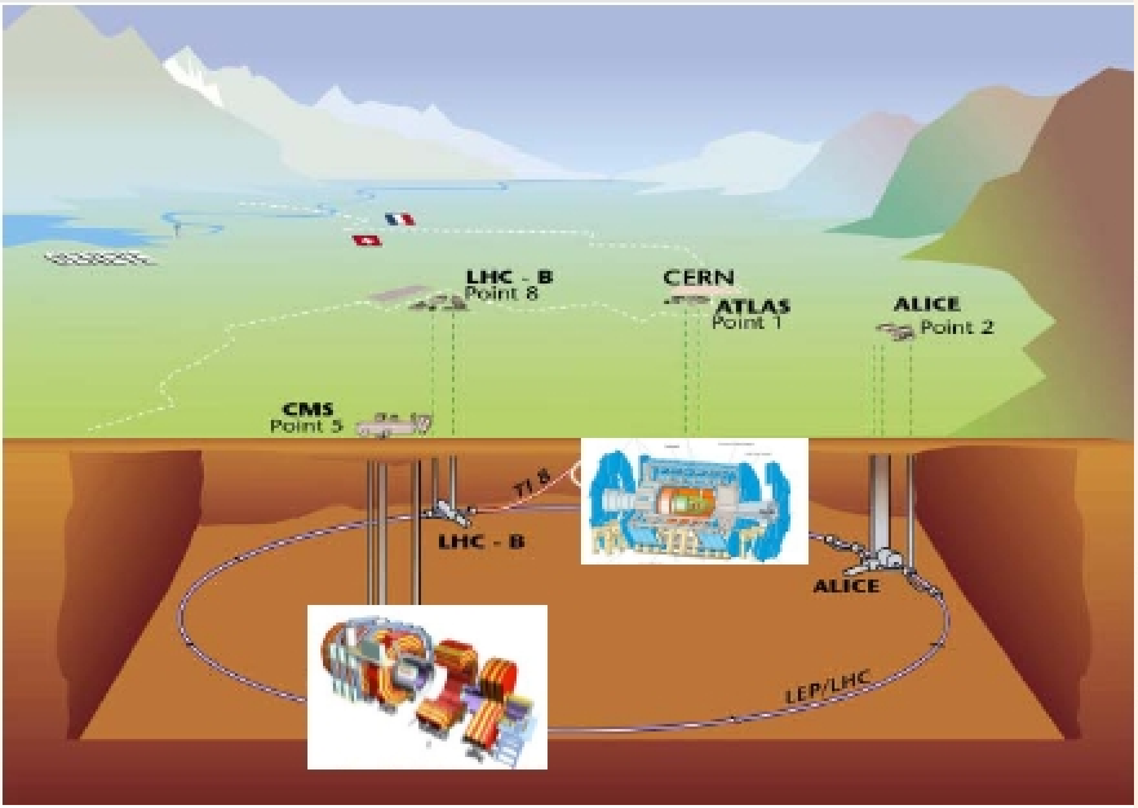
In 1993 the US congress canceled the SSC project due to budget cuts, the LHC was the only viable project for the energy frontier (and approved in 1994)

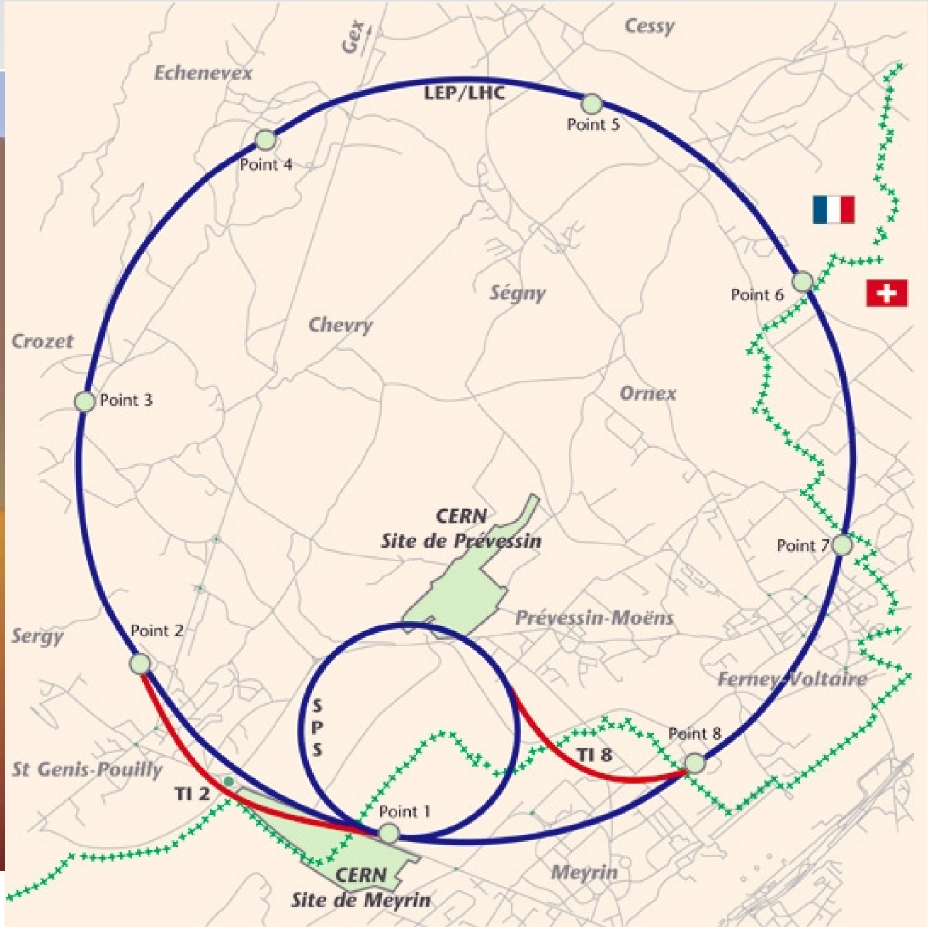


...maybe not so bad for our health...

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

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


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


Gex
Cessy
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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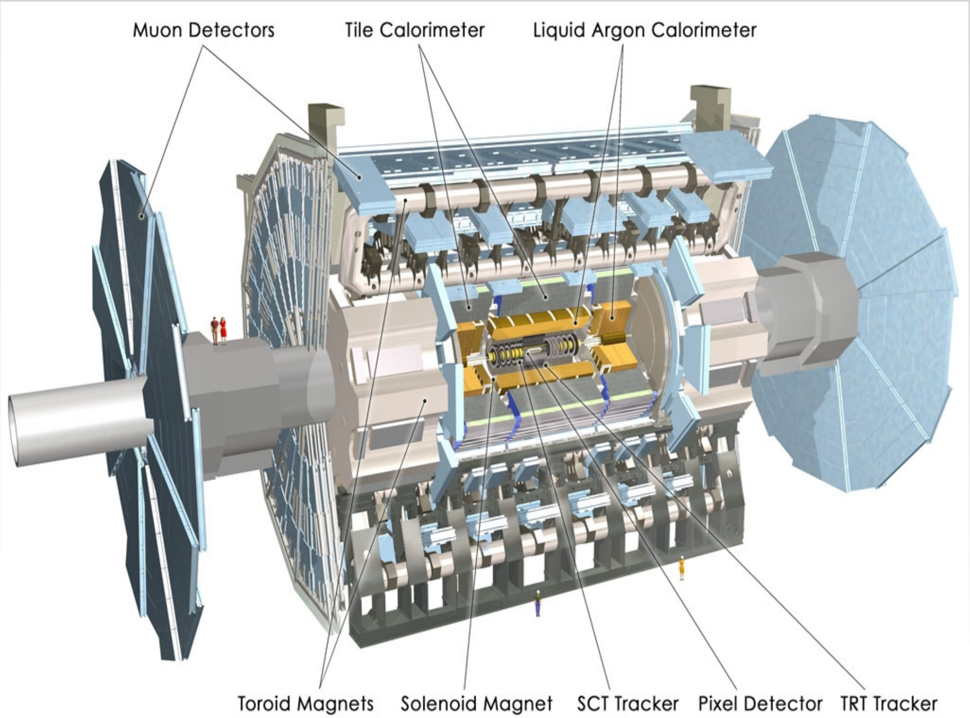
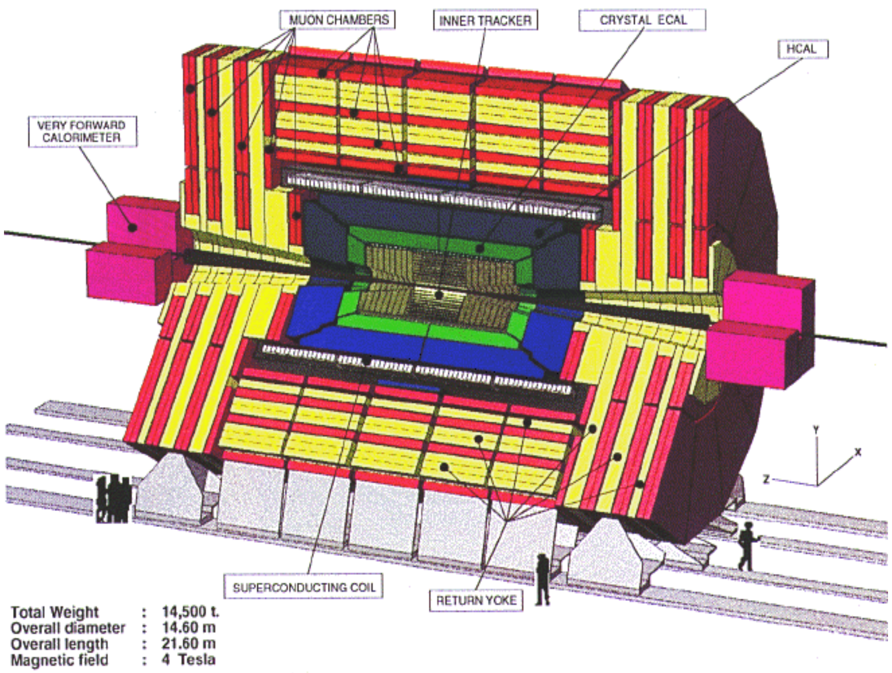
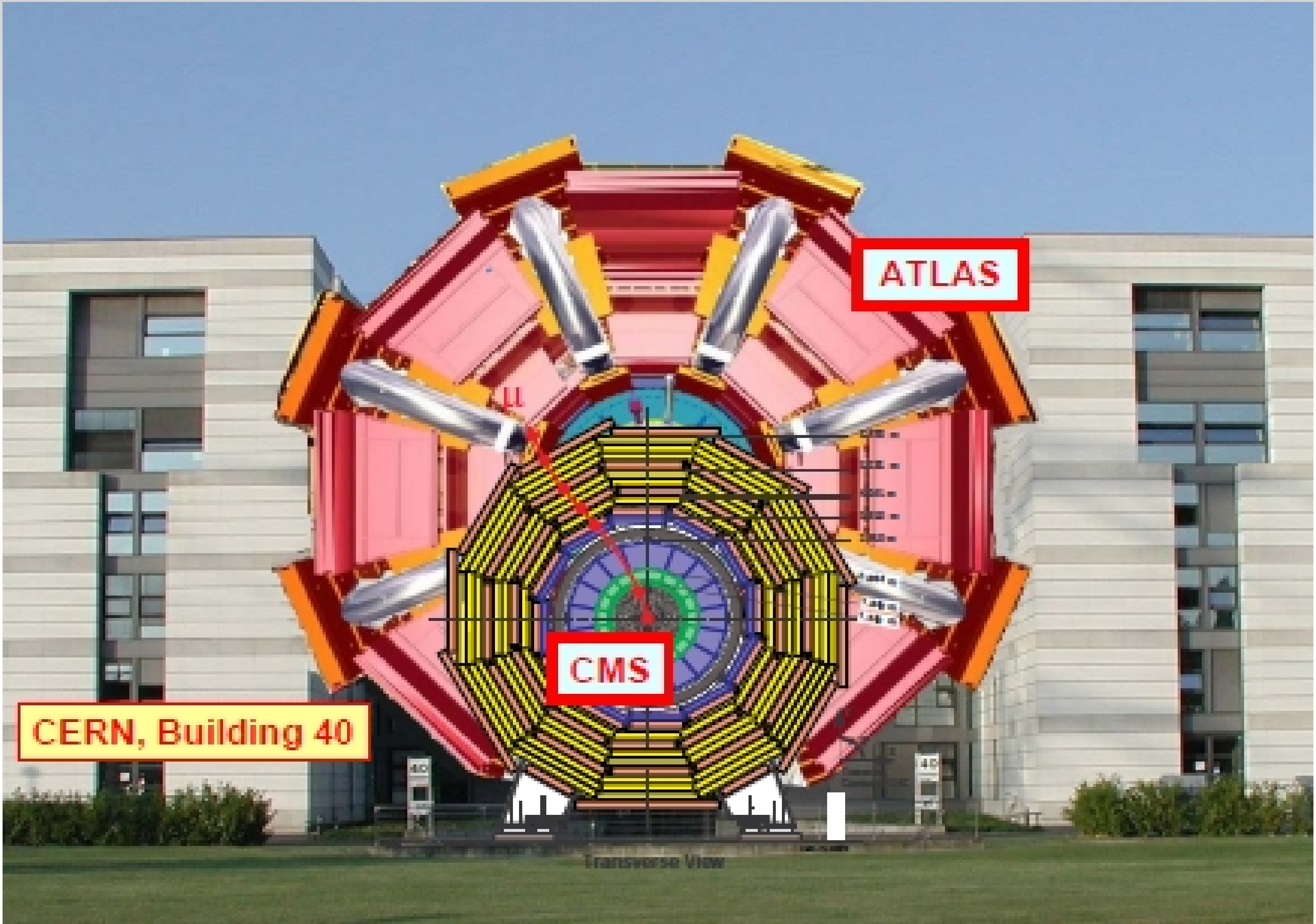
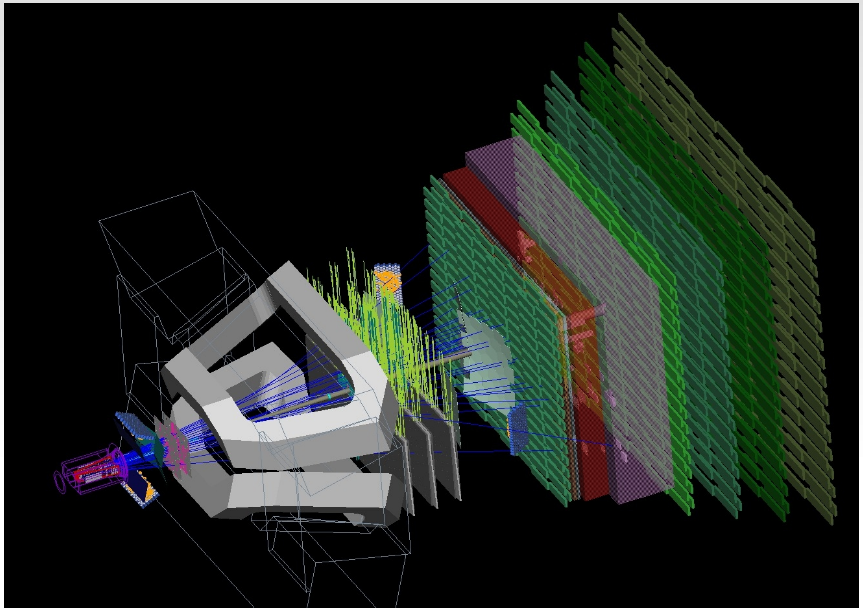
Point 8
TI 8
St Genis-Pouilly
TI 2
Point 1
CERN
Site de Meyrin
Meyrin

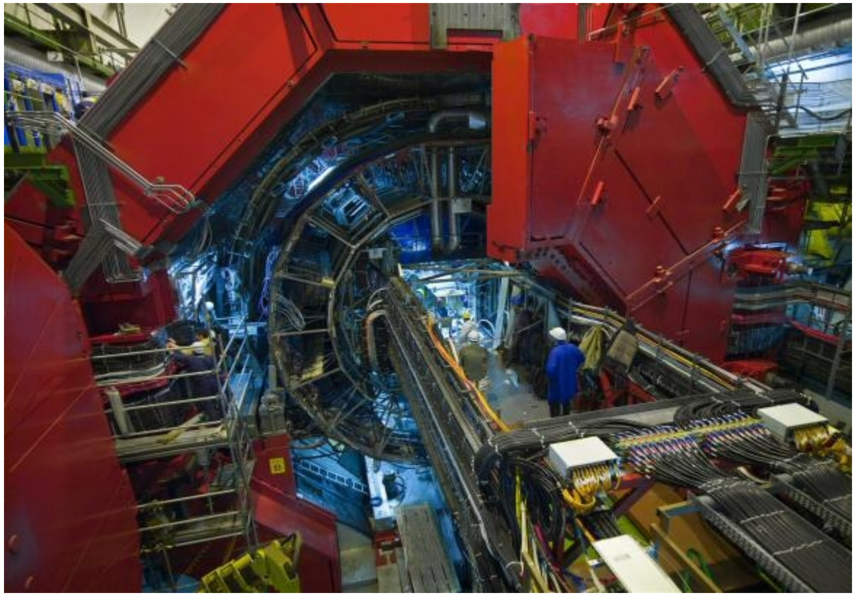




- Atlas: 1 solenoid (2T) and 8 + 2 toroid magnets (!)
  - Air-core muon chambers (good stand-alone muons)
  - Liquid Argon e.m. Calorimeter
- CMS: 1 solenoid magnet (4T) creates field inside and outside
  - Muon chambers in return yoke
  - 80000 $PbWO_4$ crystals as e.m. calorimeter


ATLAS
CMS
CERN, Building 40
Transverse View

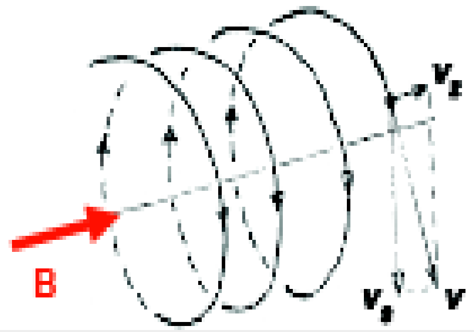




LHCb dedicated to forward low-andgle physics (especially b-quark production) looks like a pyramid with axis on the beam

Very good particle identification

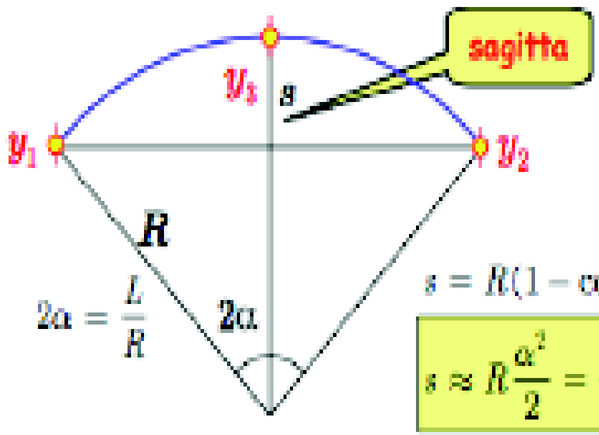
Alice looks for high-mutiplicity events in nucleus-nucleus collisions- the only LHC detector to have a gas tracker due to low-lumi and high-occupancy operation



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

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

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



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

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

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

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

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

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

Pixel Detector

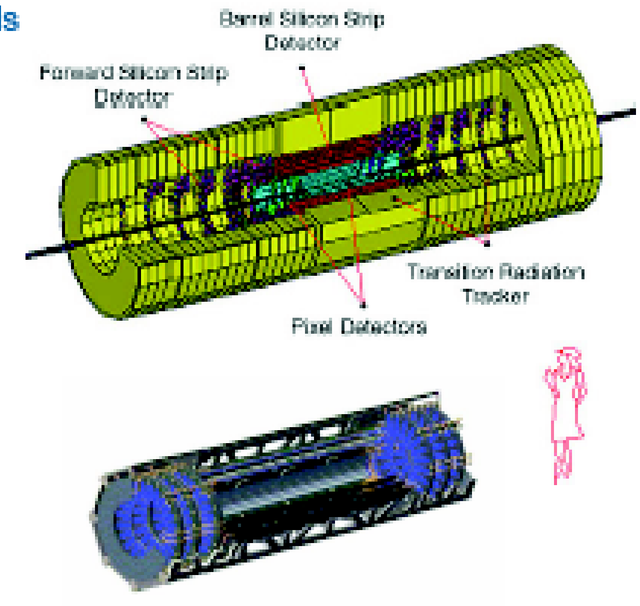
- 3 barrels, 3+3 disks: 80×10^6 pixels
- barrel radii: 4.7, 10.5, 13.5 cm
- pixel size 50×400 μm
- s_{rf}= 6-10 μm s_z = 66 μm

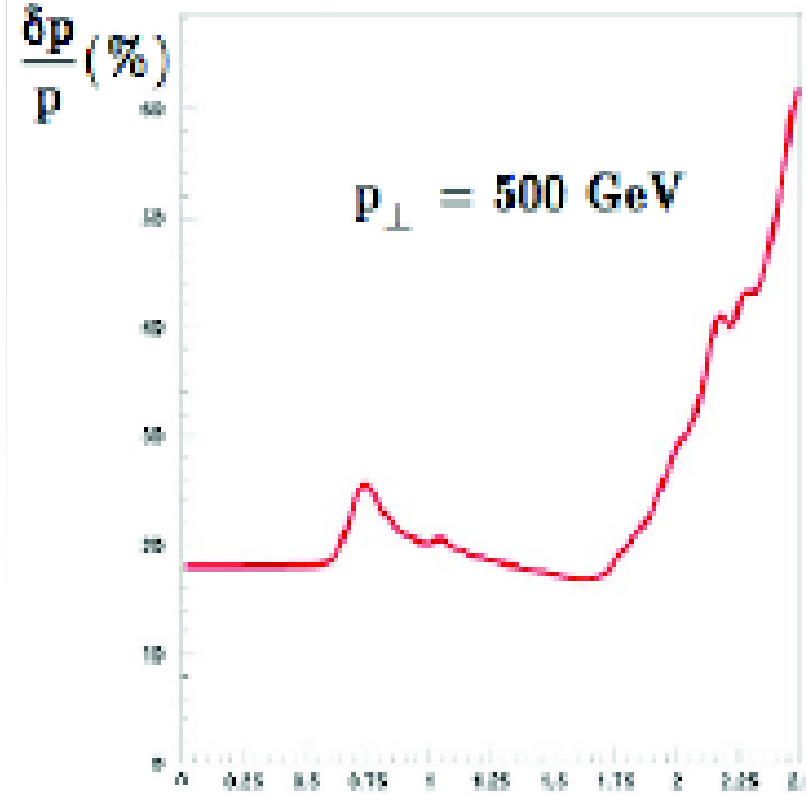
SCT

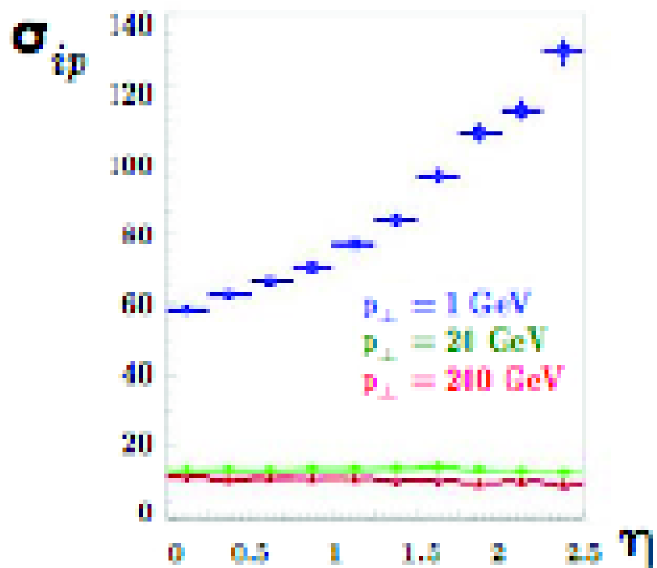
- 4 barrels, disks: 6.3×10^6 strips
- barrel radii:30, 37, 44 ,51 cm
- strip pitch 80 μm
- stereo angle ~40 mr
- s_{rf}= 16 μm s_z = 580μm

TRT

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







Pixel Detector

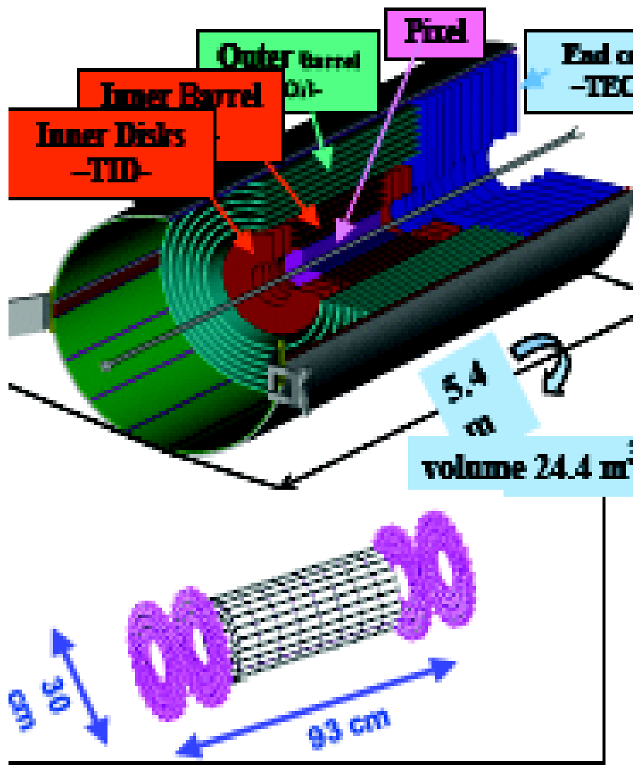
- 2 barrels, 2 disks: 40×10^6 pixels
- barrel radii: 4.1, ~10. cm
- pixel size 100×150 μm
- $\sigma_{r\phi}$= 10 μm σ_z = 10 μm

Internal Silicon Strip Tracker

- 4 barrels, many disks: 2×10^6 strips
- barrel radii:
- strip pitch 80,120 μm
- $\sigma_{r\phi}$= 20 μm σ_z = 20 μm

External Silicon Strip Tracker

- 6 barrels, many disks: 8×10^6 strips
- barrel radii: max 110 cm
- strip pitch 80, 120 μm
- $\sigma_{r\phi}$= 30 μm σ_z = 30 μm



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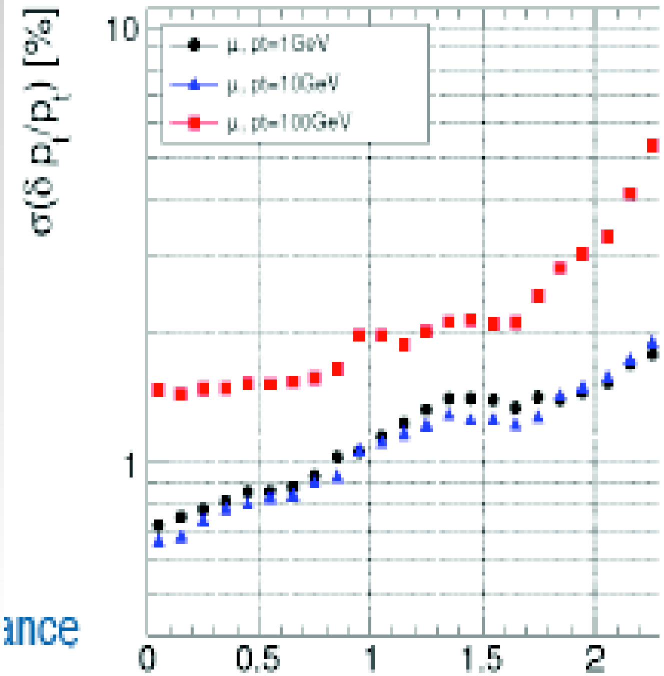
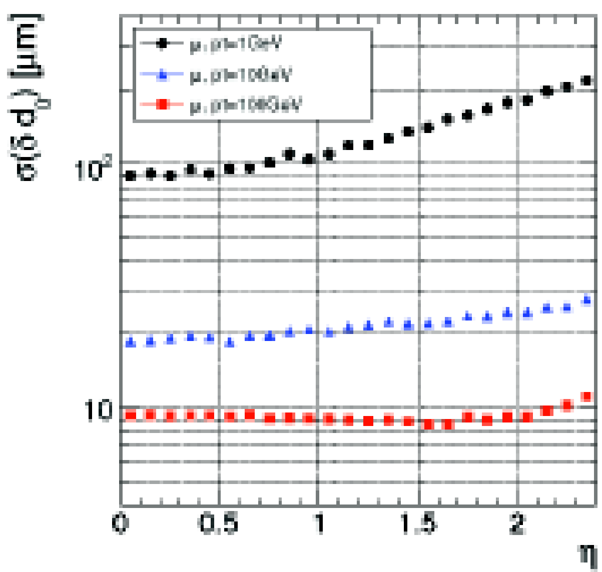
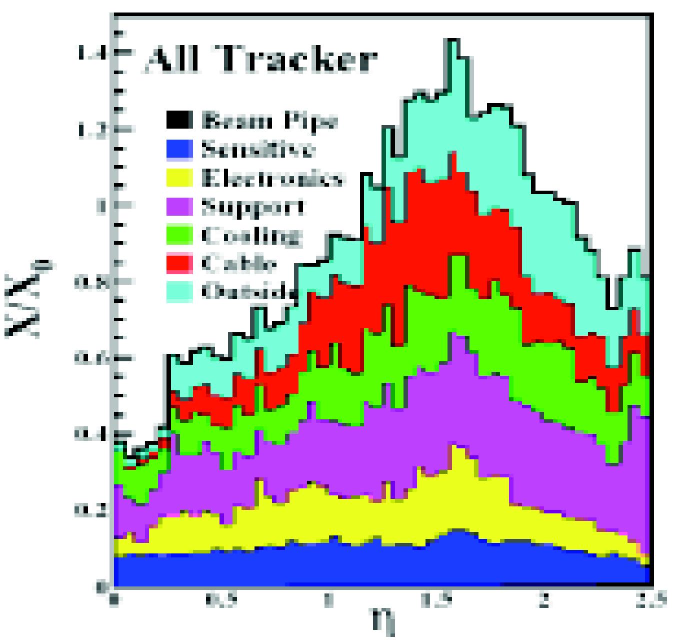
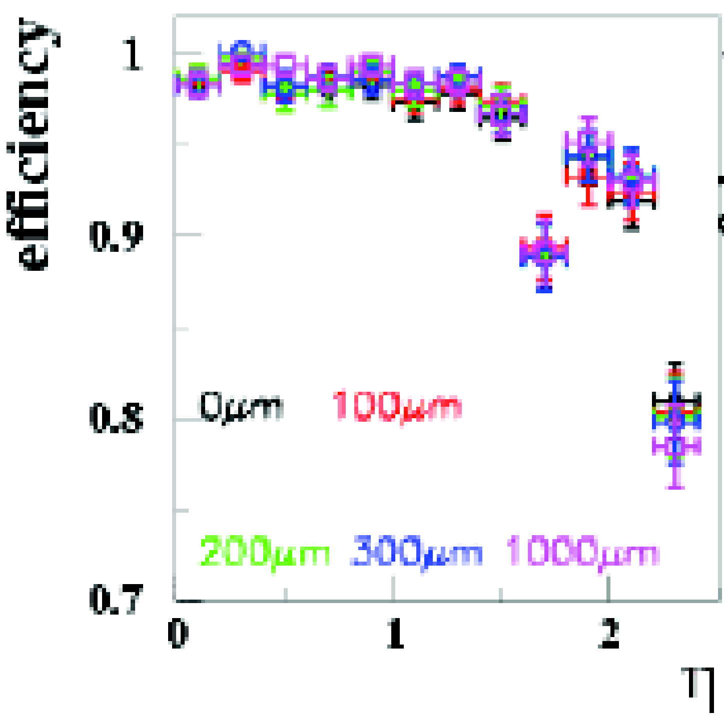
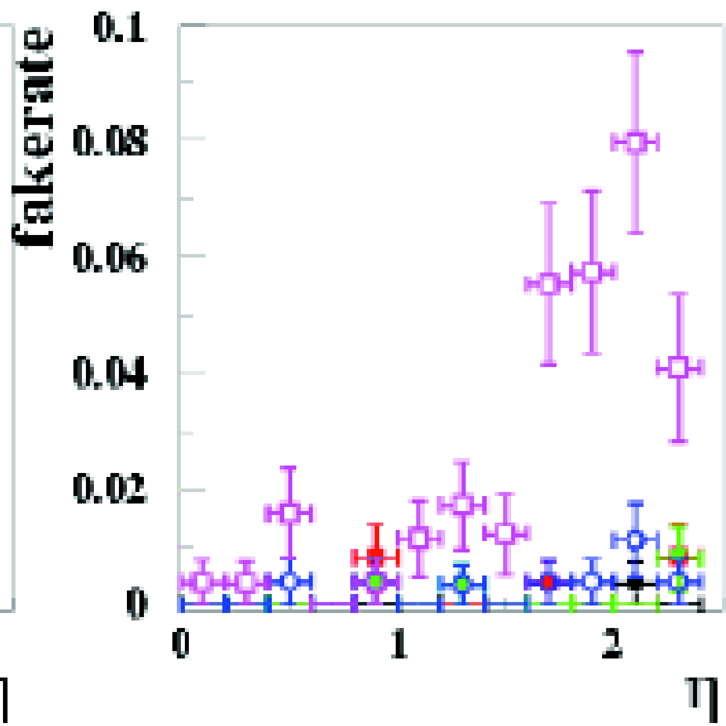




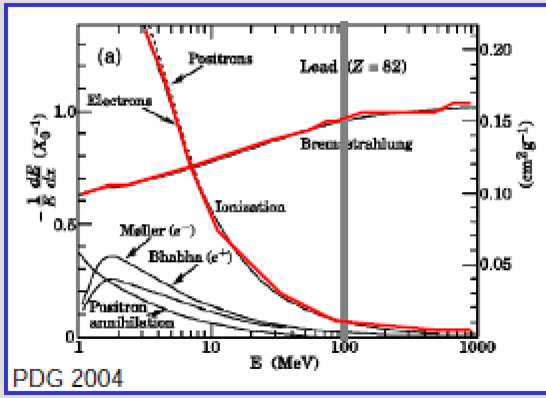


Detector should be thick enough to collect enough signal, and thin enough to minimise photon conversions. Also overlap between modules needed for alignment (starts to be critical at the mm level)

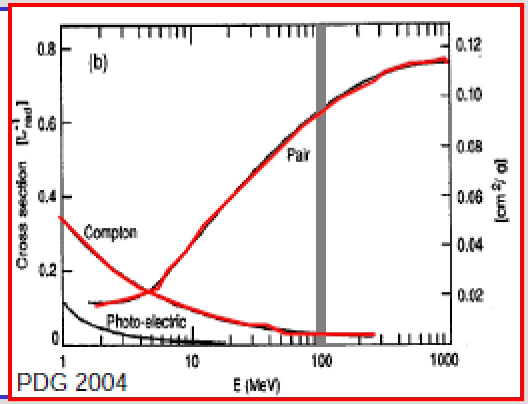




Electrons and Positrons

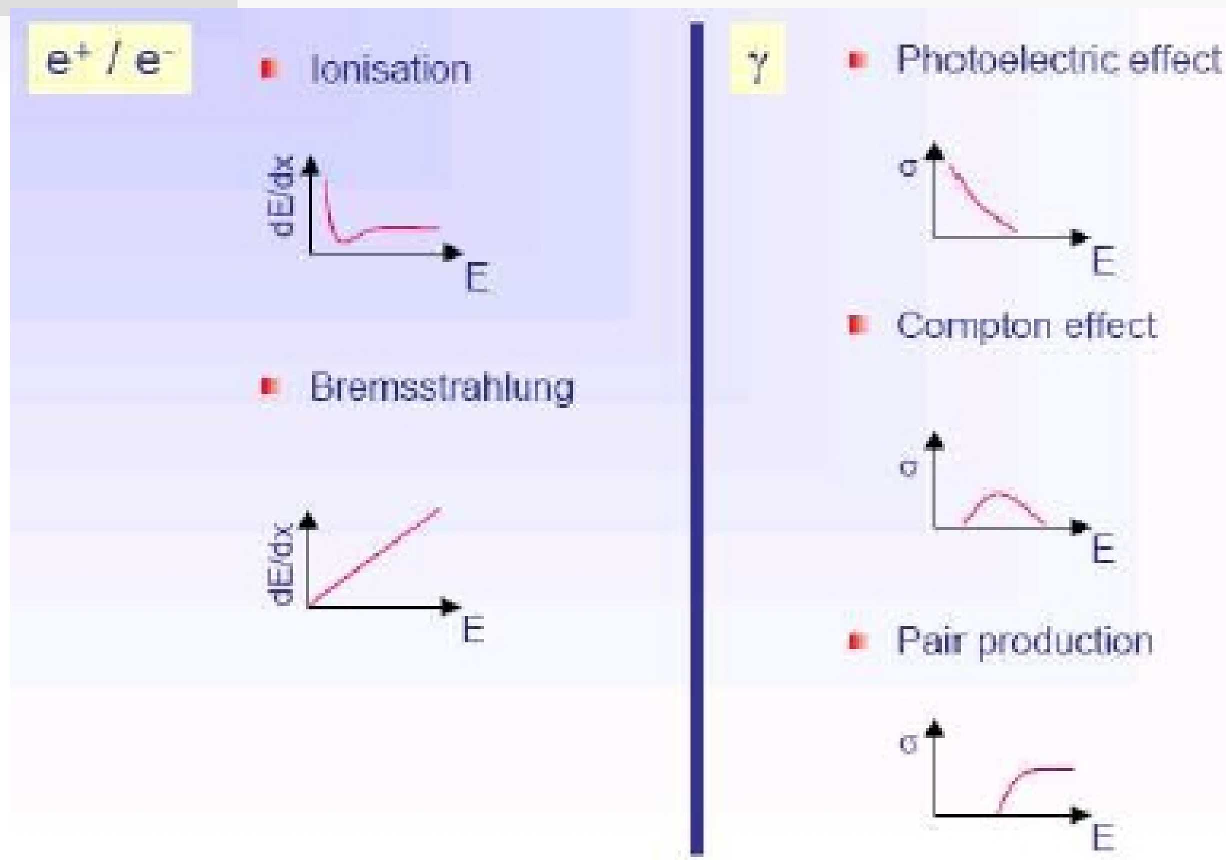


Photon



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

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



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

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

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

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

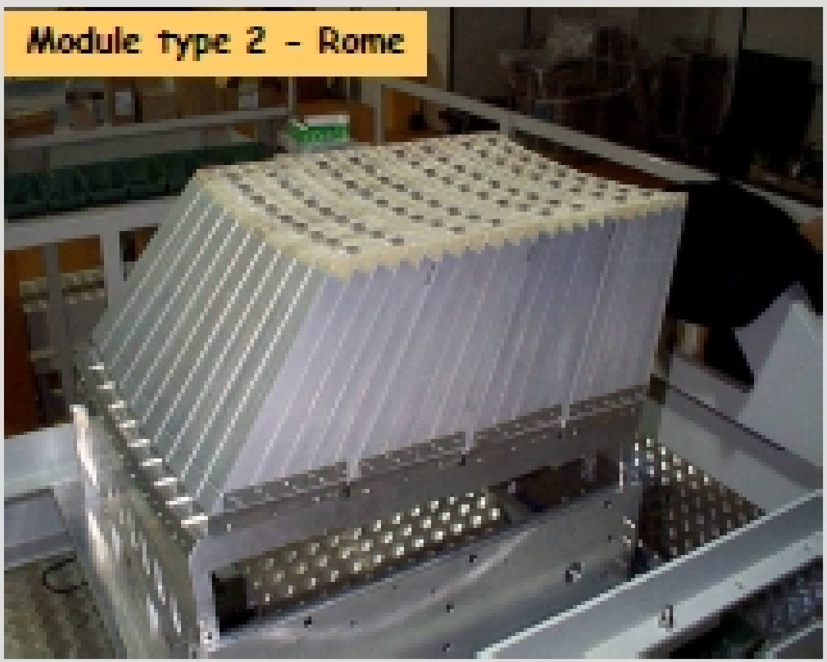
$$\sigma(\theta) \approx \frac{50 \text{ mrad}}{\sqrt{\text{E}}}$$

Same for ATLAS and CMS …

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

- ✓ Compact
- ✓ Transverse segmentation

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



Crystal dimensions:

longitudinal 25 X_0 = 22.2 cm

Transverse 1 R_M = 2.2 cm

95% of the shower contained in 2 R_M

Sampling: accordion lead structure filled with LAr

- Longitudinal dimension:

$\approx 25\ X_0$ = 47 cm (CMS 22 cm)

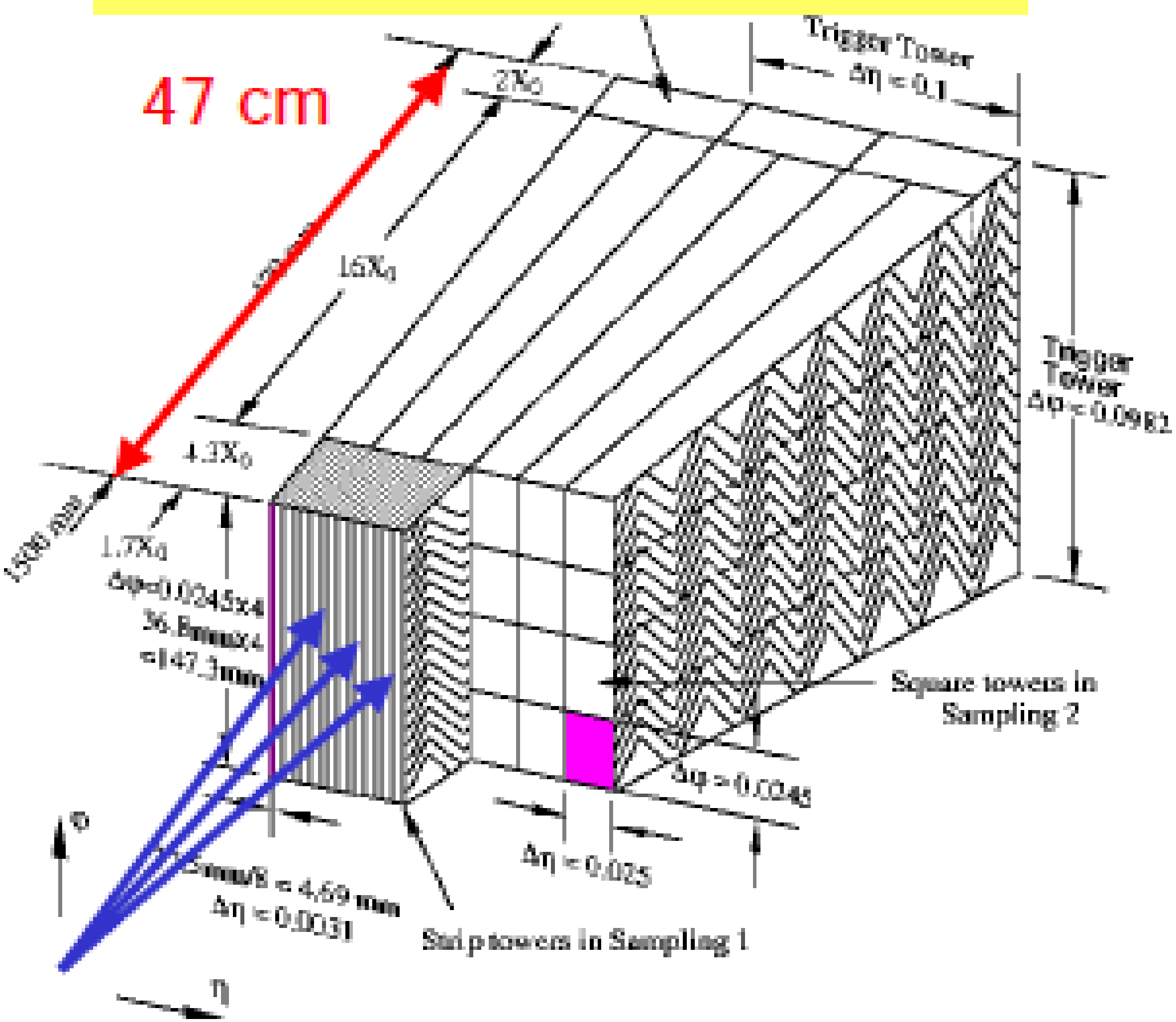
- 3 longitudinal layers

4 X_0 π^0 rejections separation of 2 photons very fine grain in η

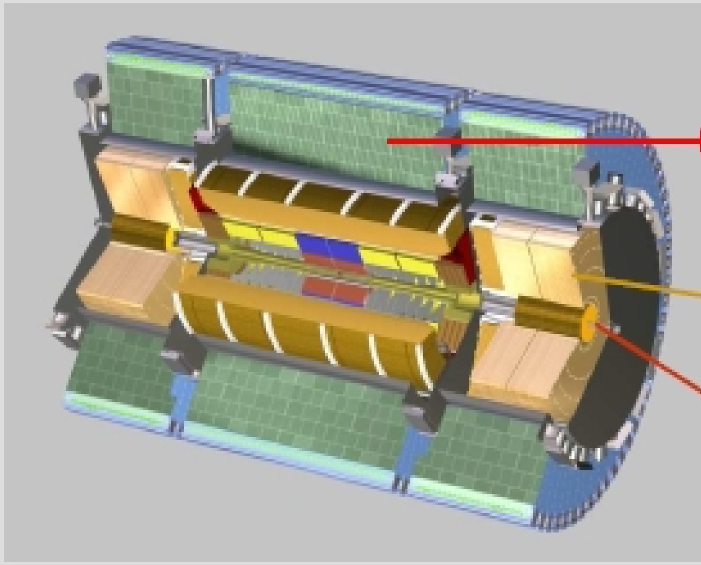
16 X_0 for shower core

2 X_0 evaluation of late started showers

- Total channels = 170000



Particles from collisions

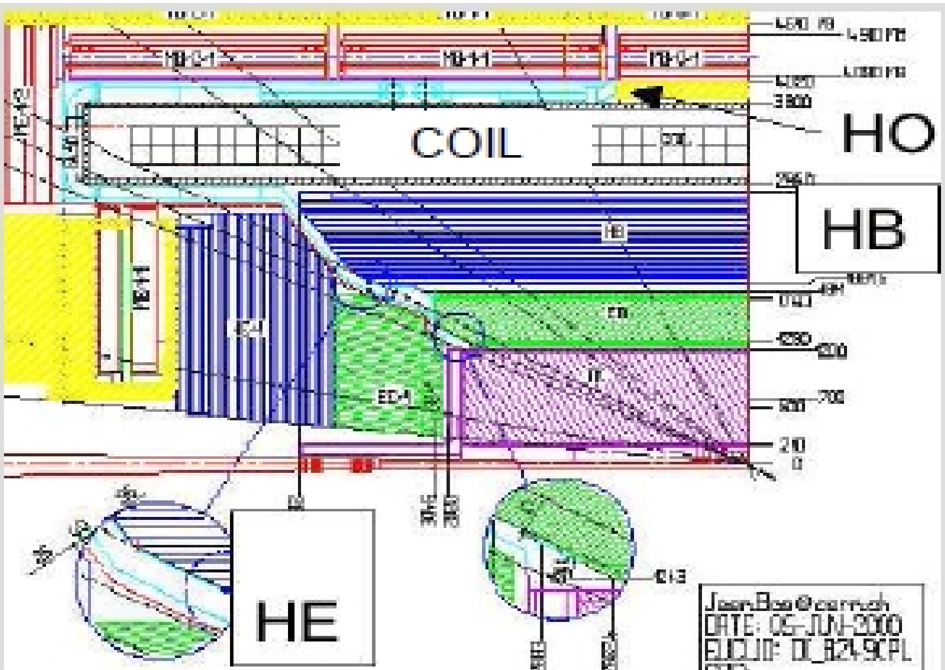


Tile Calorimeter $|\eta| < 1.7$
Fe / Scintillator
3 longitudinal sections

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

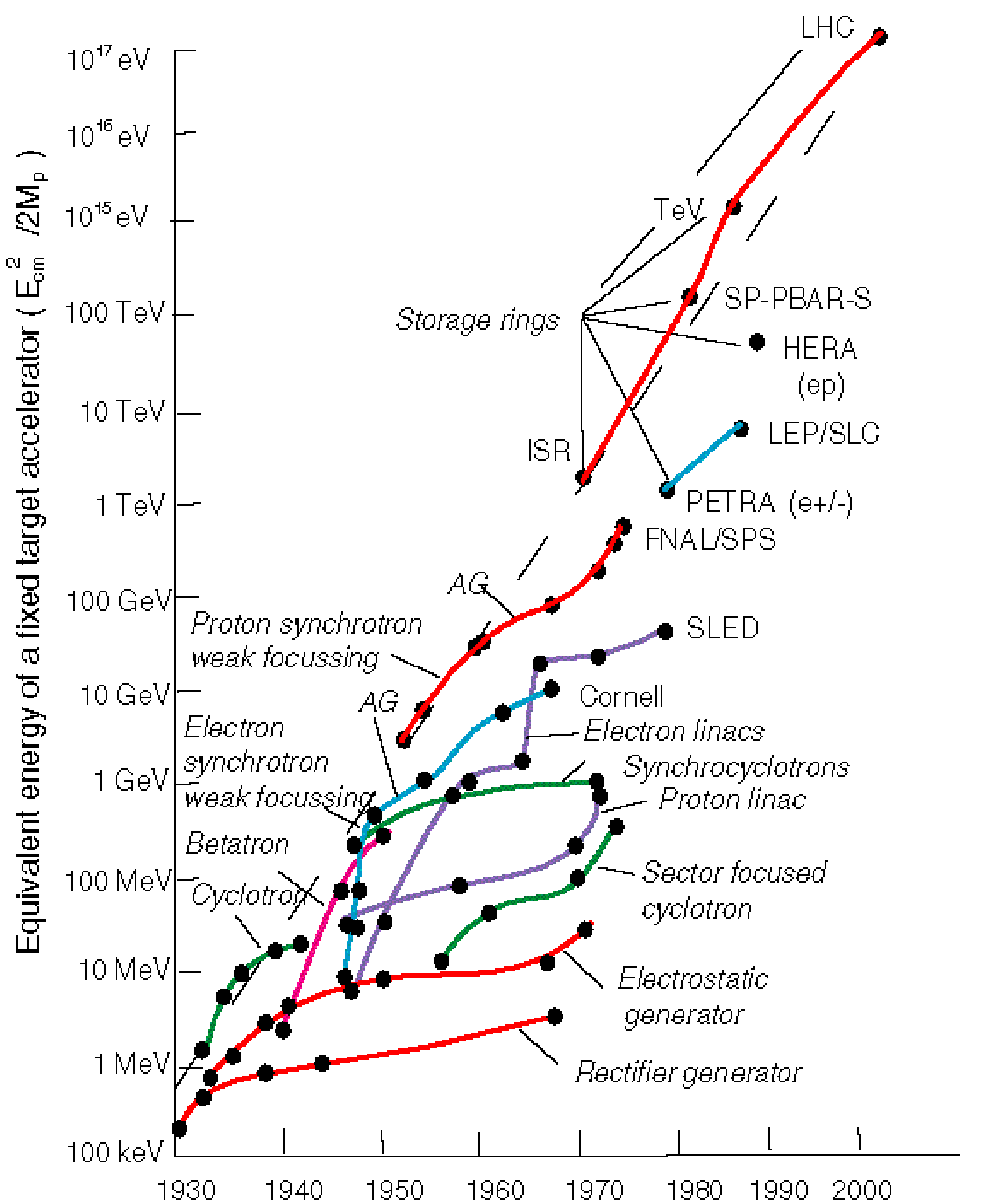
Both hadronic and em
LAr/Cu or W $3.2 < |\eta| < 4.9$
3 longitudinal sections

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



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

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



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

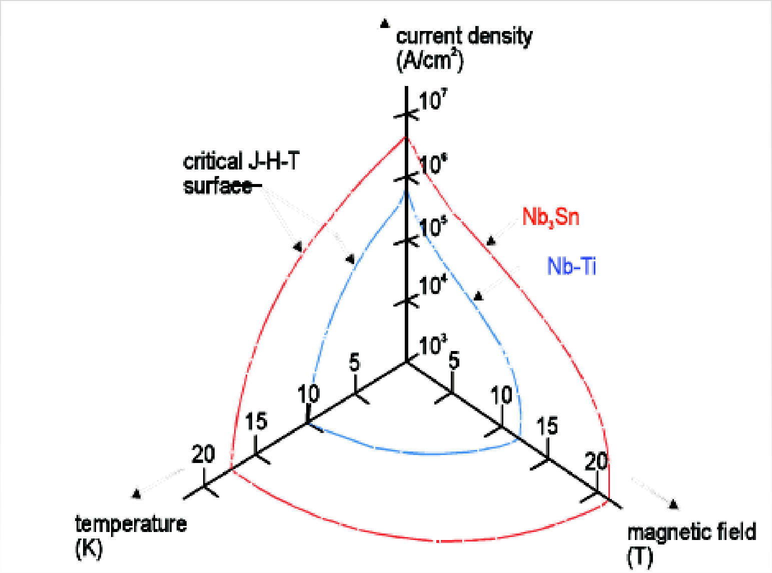
a hadron collider is not limited by synchrotron radiation, and can go to much higher energy.

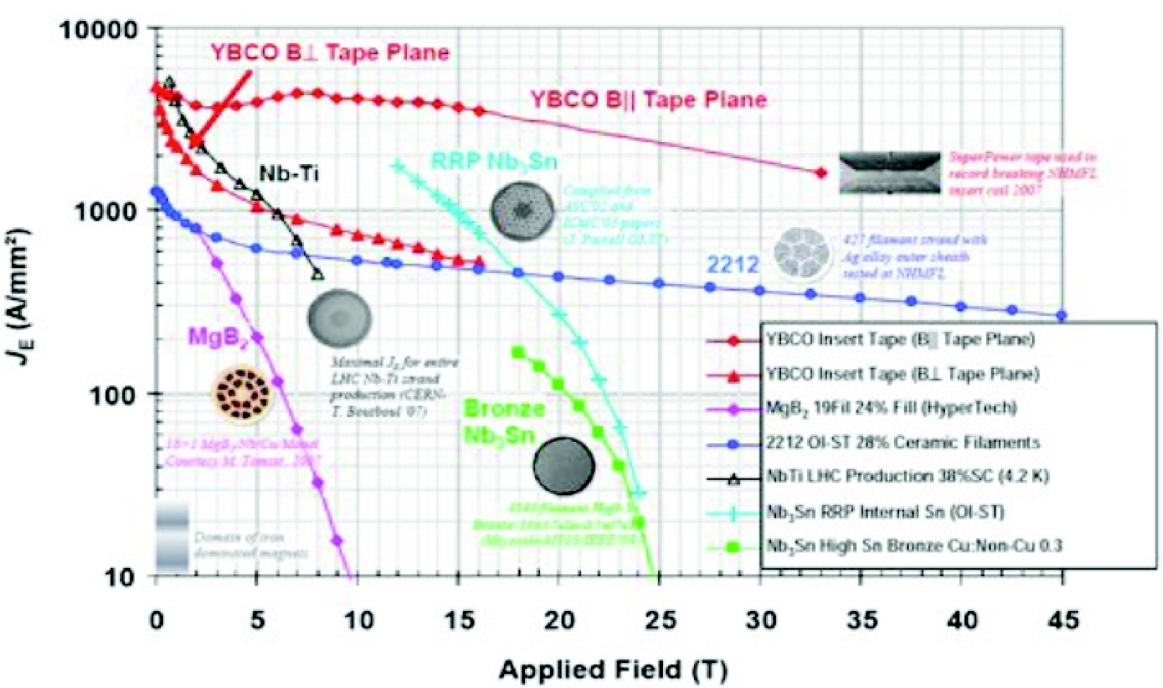
For a given ring size, the only limitation comes from the magnetic field of the bending magnets:

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

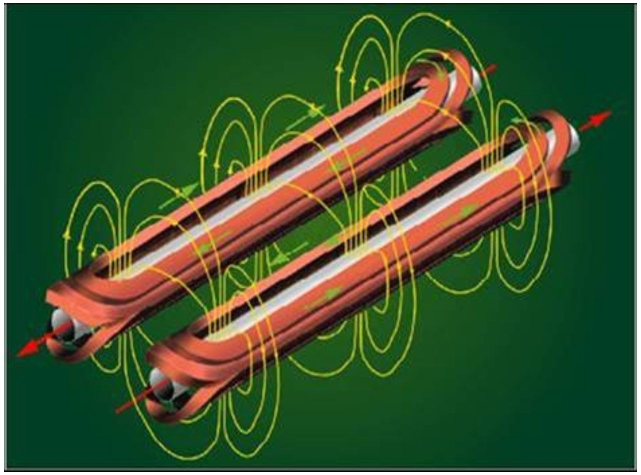
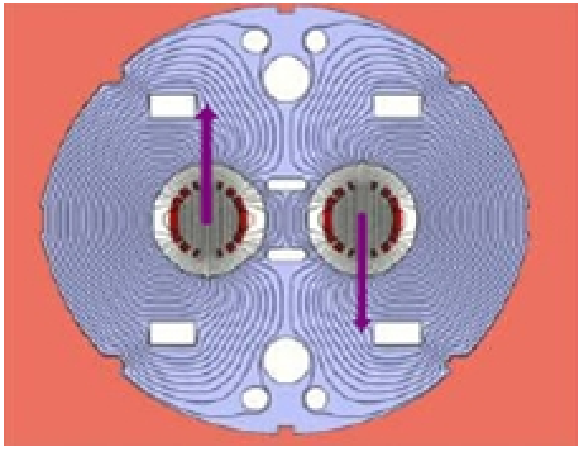
The highest currents, therefore the largest fields, are obtained using superconducting cables.

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





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


LHC General Parameters (Protons)

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

Main Dipole magnet

Summary Table

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

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

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

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

MB cold mass main dimensions at 293K :

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

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

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

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

where luminosity L is given by

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

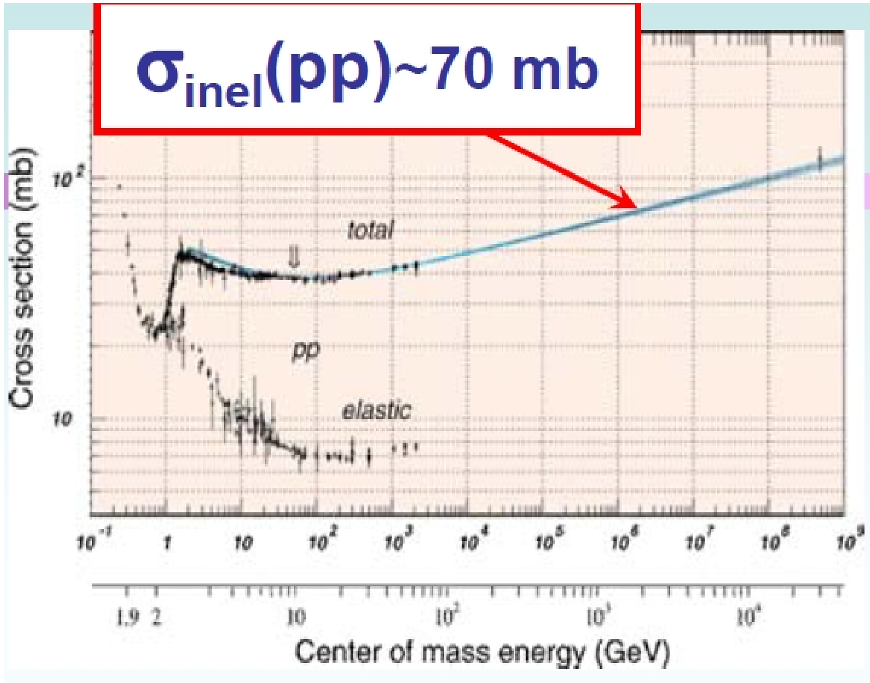
- $n_1 n_2$ number of particles per beam ($O(10^{11})$)
- f crossing frequency (40 Mhz, with 2835/3564 bunches occupied)
- A = crossing area = πr^2 where $r = 16\ \mu m$ (rms of transverse beam profile)

- These numbers correspond to a range between

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

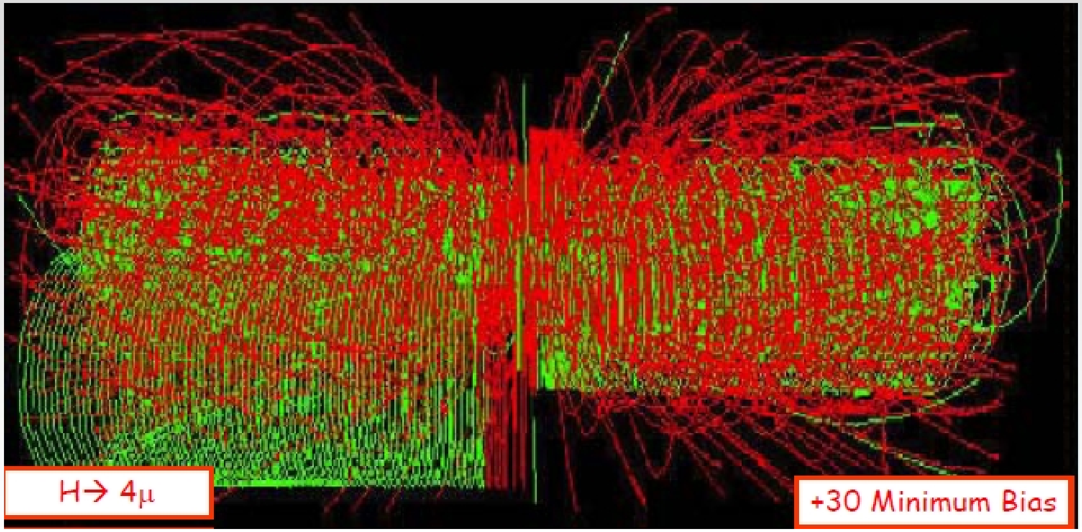
And in one year (8-9 months of data taking) to 10-100 fb^{-1}

The total pp cross section is about 70 mb:

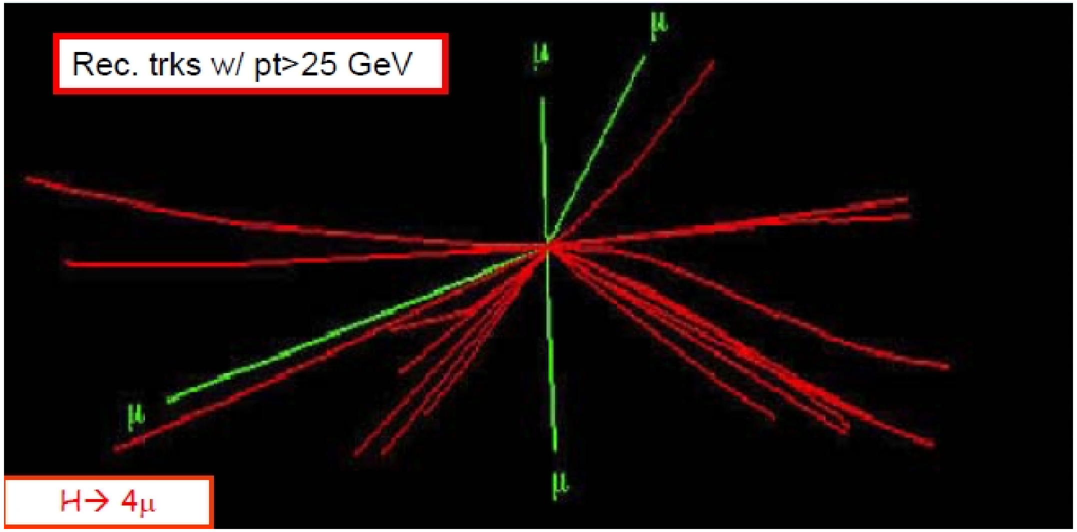


So, rate can go up to 700MHz! Divided by 40MHz bunch crossing rate, and accounting for empty bunches, we can have > 20 collisions/bunch crossing (pileup)

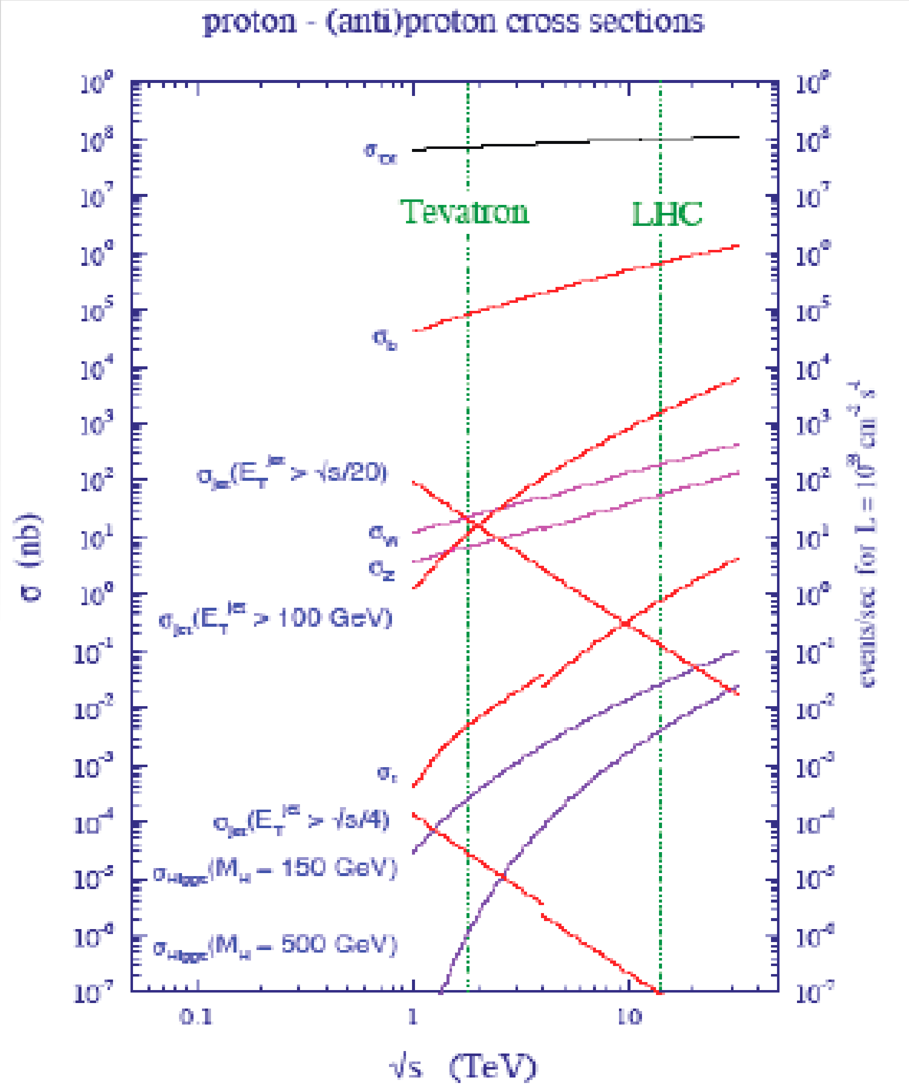
Can you find four muons coming from a Higgs boson from this event?



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

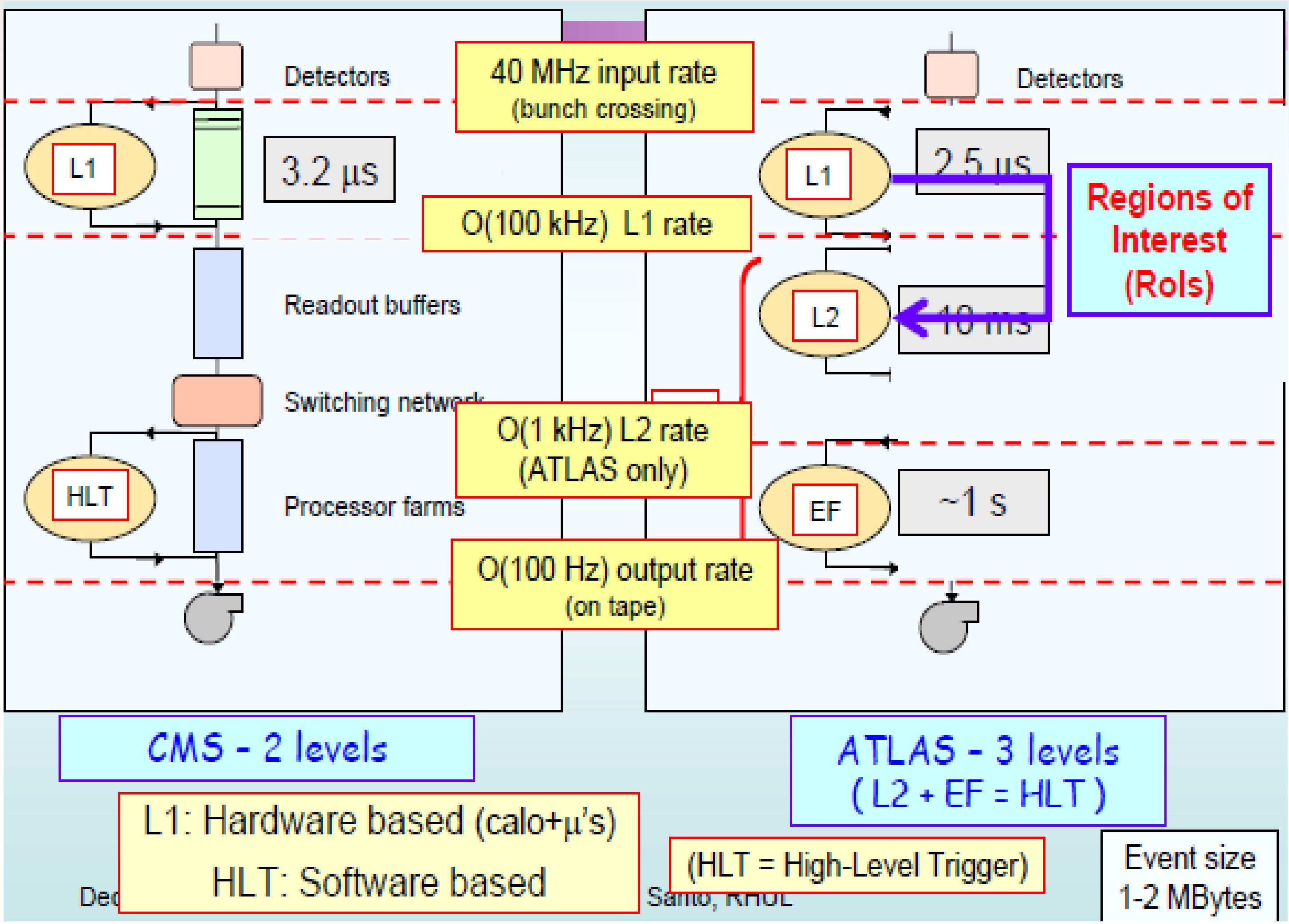


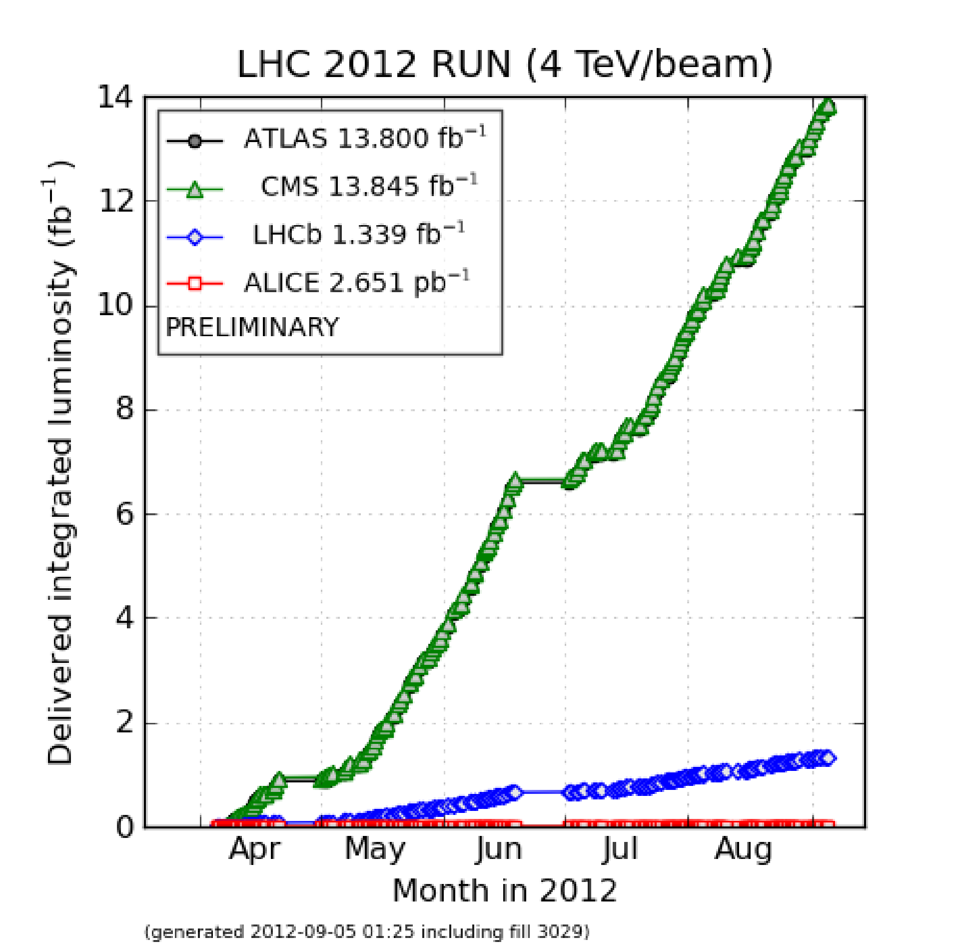
- No real thresholds
- Total cross section (including elastic) almost constant
- Some lines 'broken' going from Tevatron to LHC due to antiprotons vs protons
- Several orders of magnitude between discoveries and background

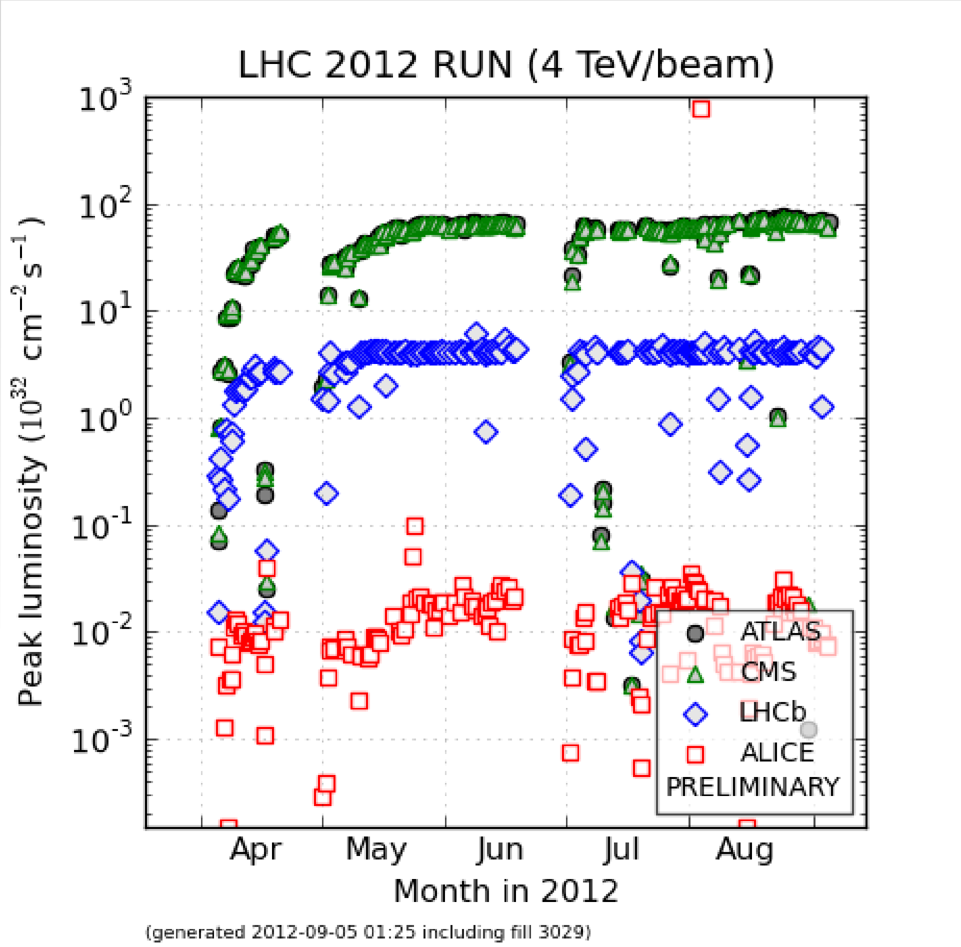


History of this first year can be summarised as: going down this plot

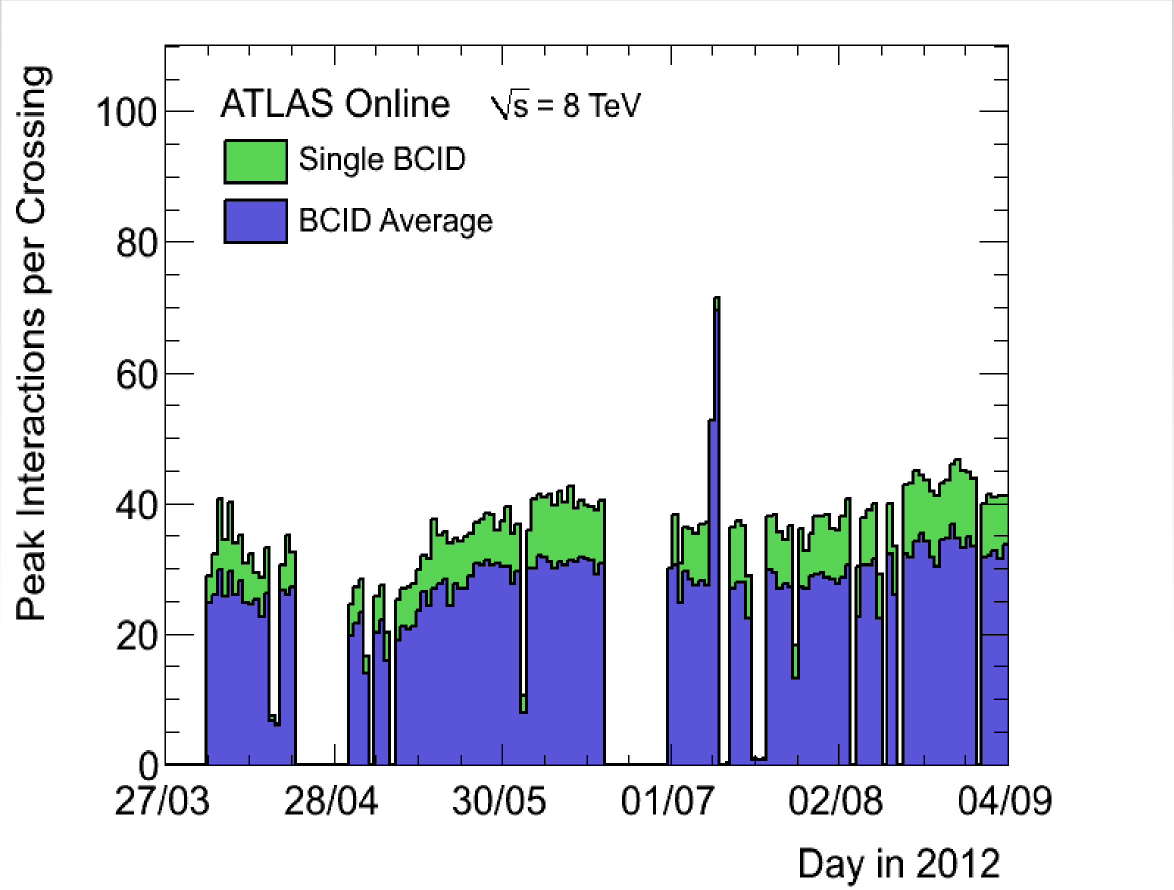
- DAQ can only take O(100 Hz), so rejection factors on BG of order 1M are needed, while keeping high efficiency on rare signal events. Different stategies:

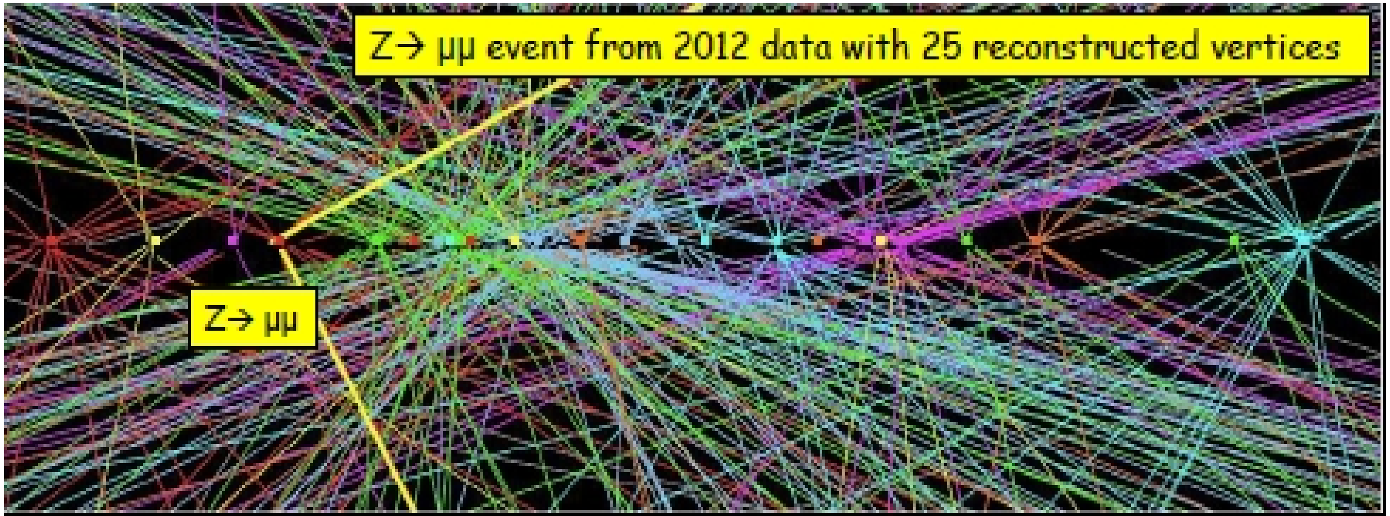


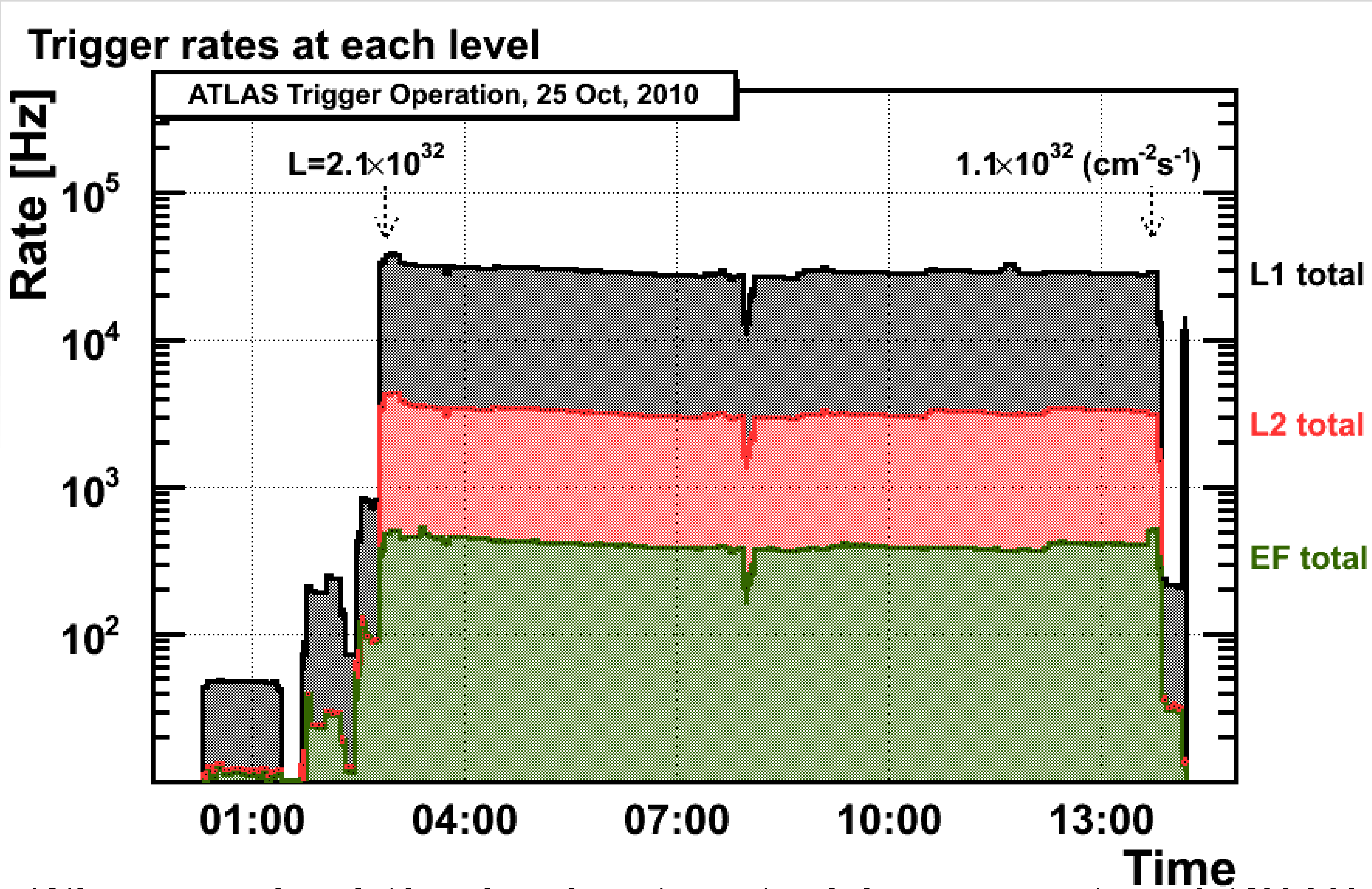




- Integrated luminosity ~15 fb-1
- Peak luminosity ~7E32


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

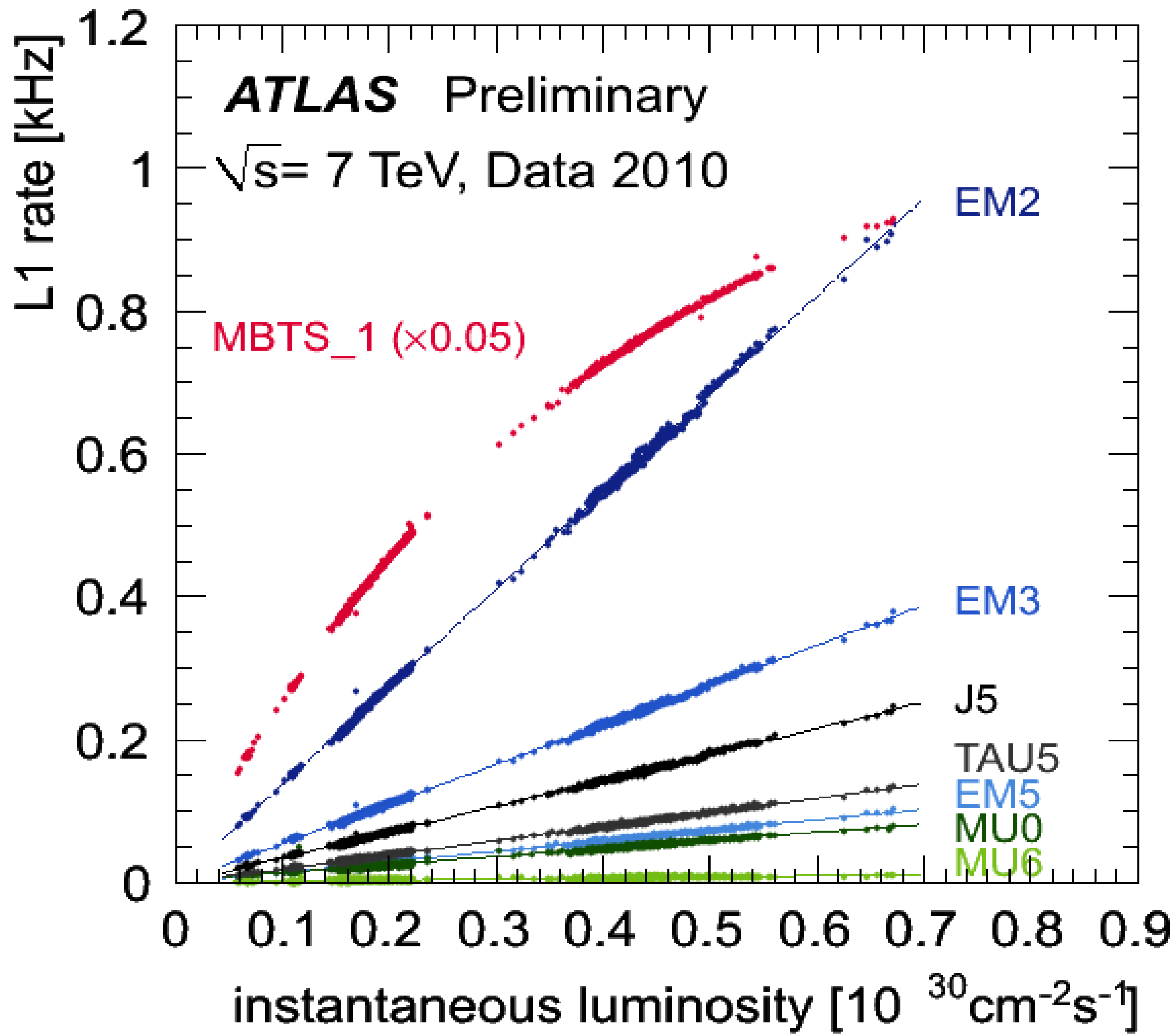

Z→ μμ event from 2012 data with 25 reconstructed vertices
Z→ μμ

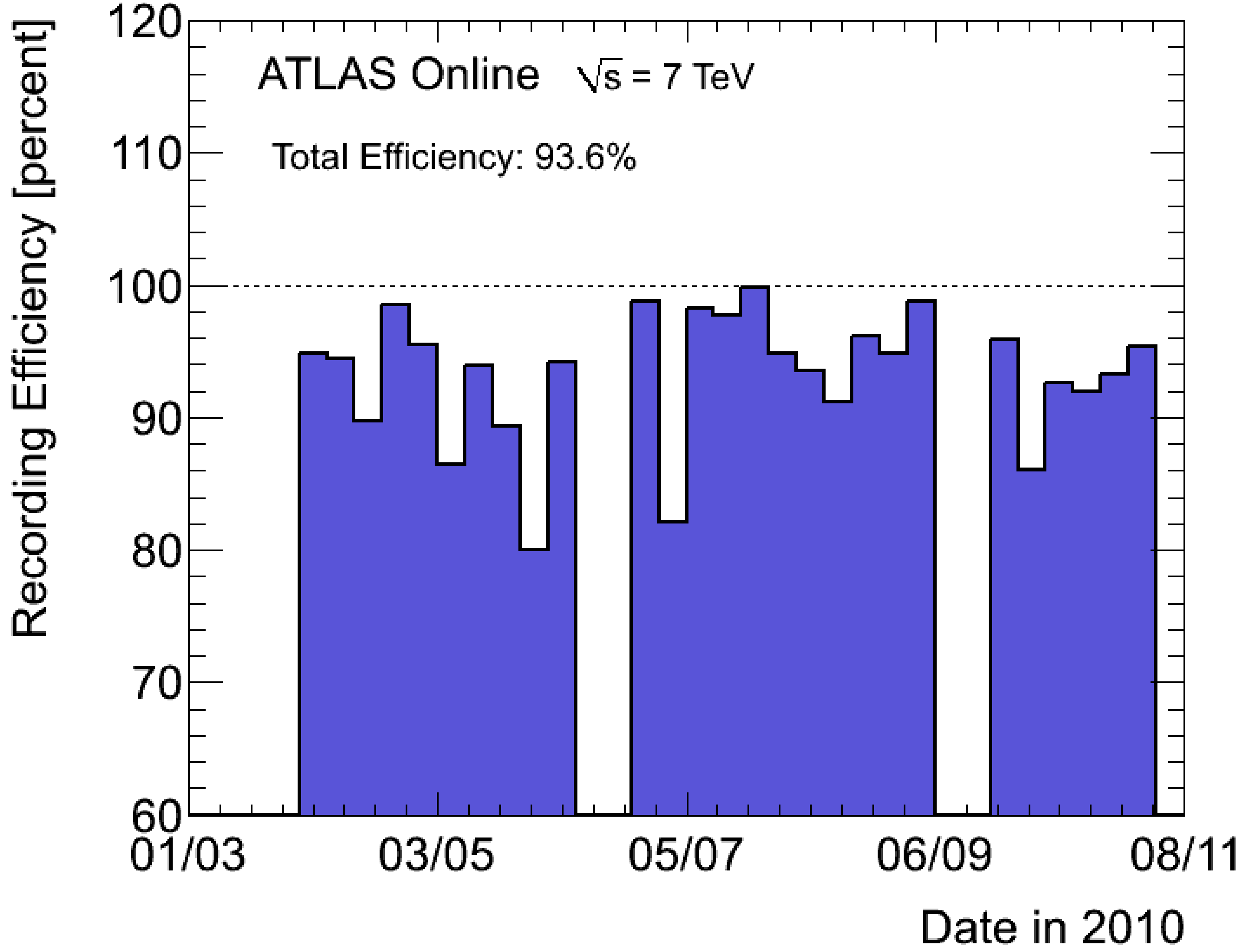


- This run had the highest initial luminosity of 2010
- Trigger bandwidth saturated at the three levels

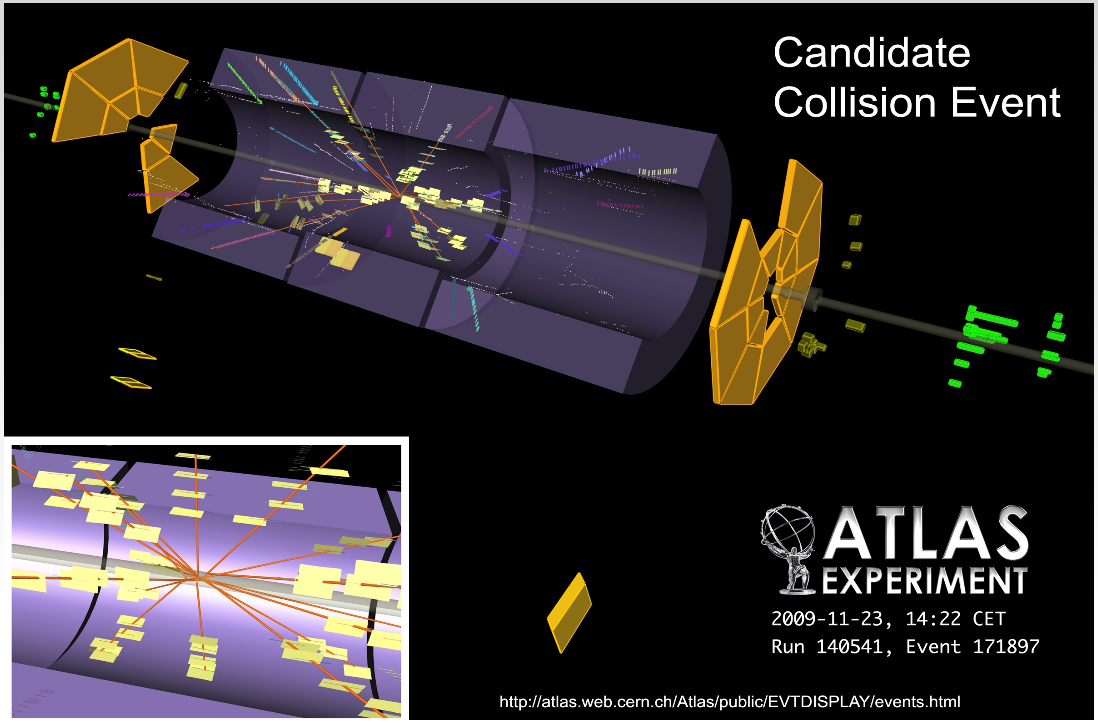
Rates still linear since in no-pileup region.

Non-linearities observed at the highest luminosities

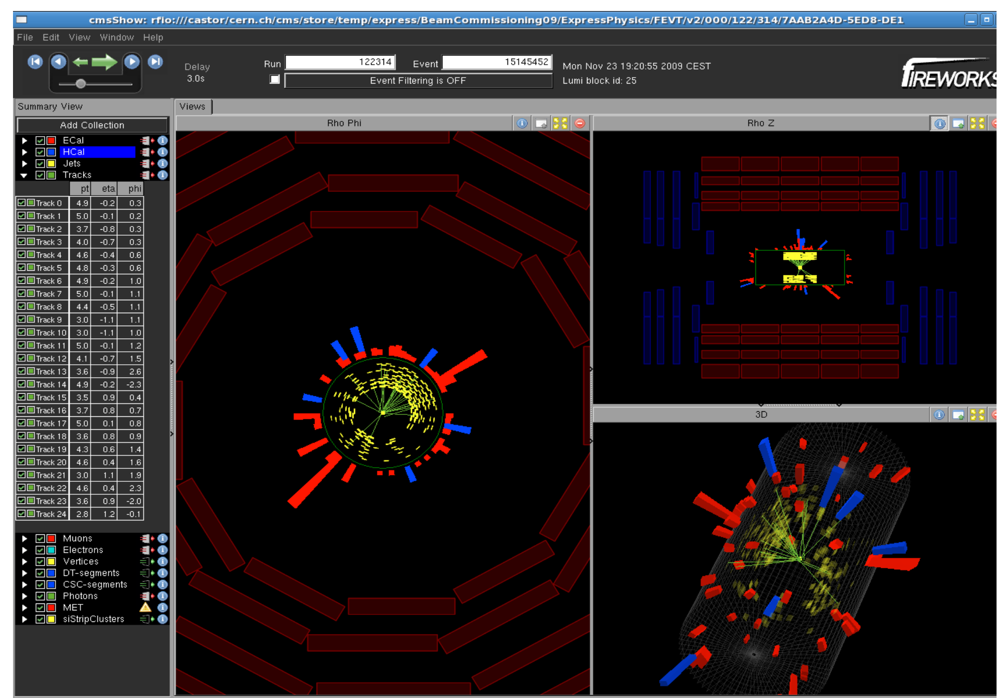


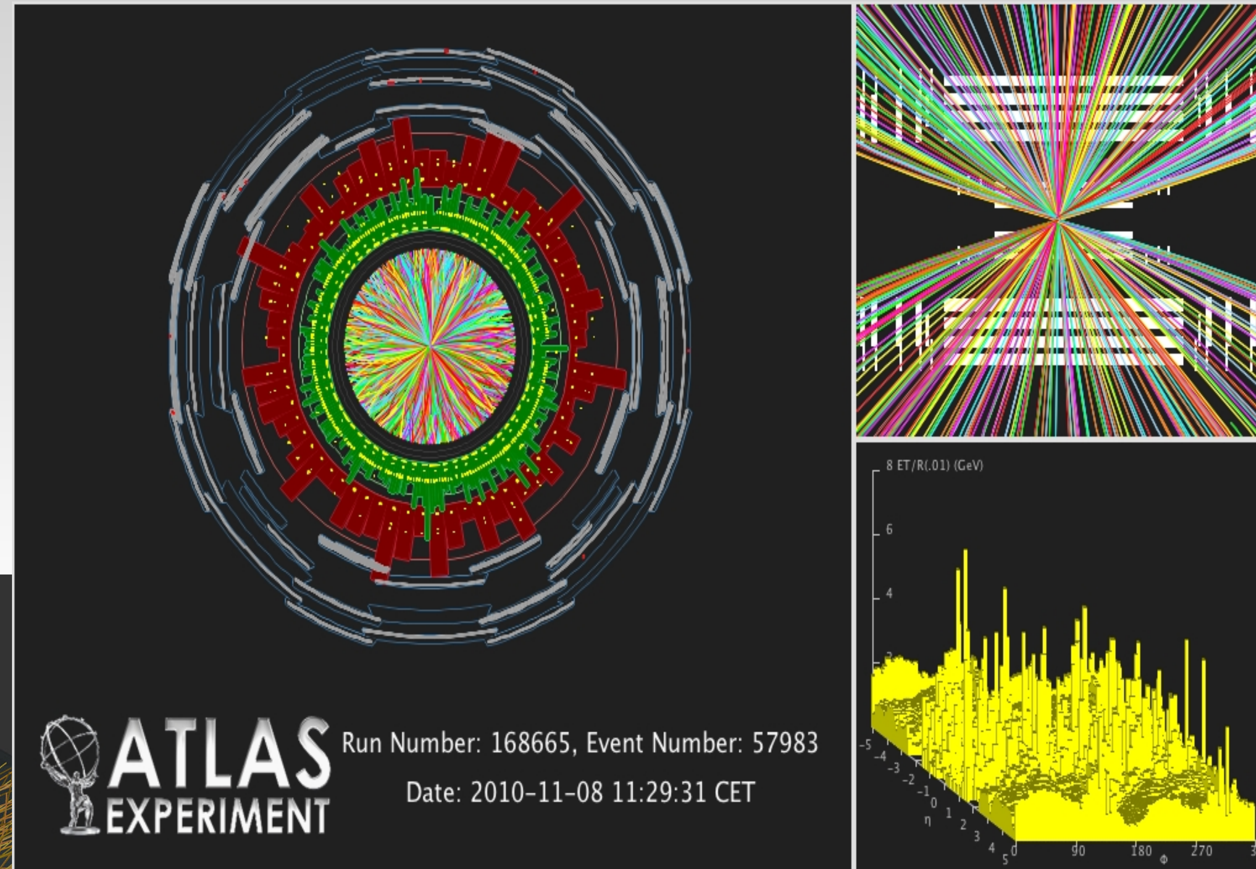


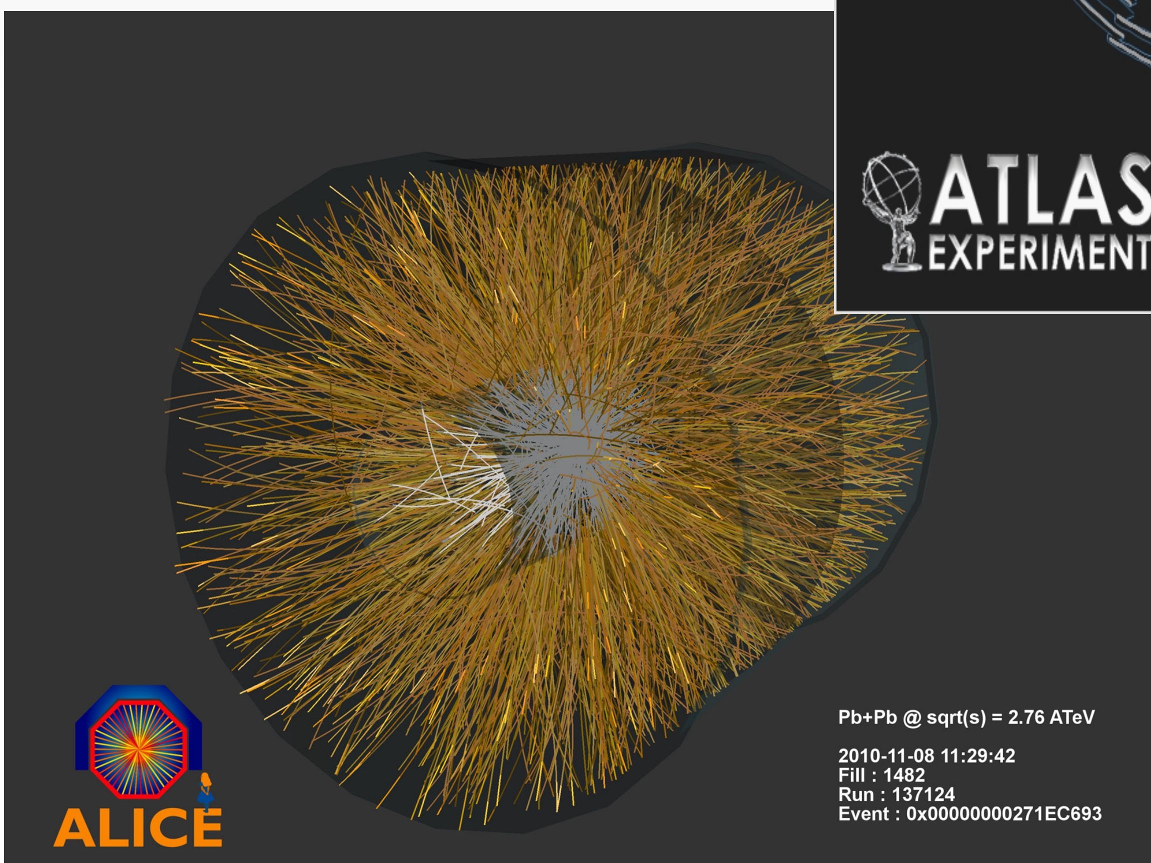
ATLAS Online $\sqrt{s}$ = 7 TeV
Total Efficiency: 93.6%
Recording Efficiency [percent]
120
110
100
90
80
70
60
01/03
03/05
05/07
06/09
08/11
Date in 2010



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



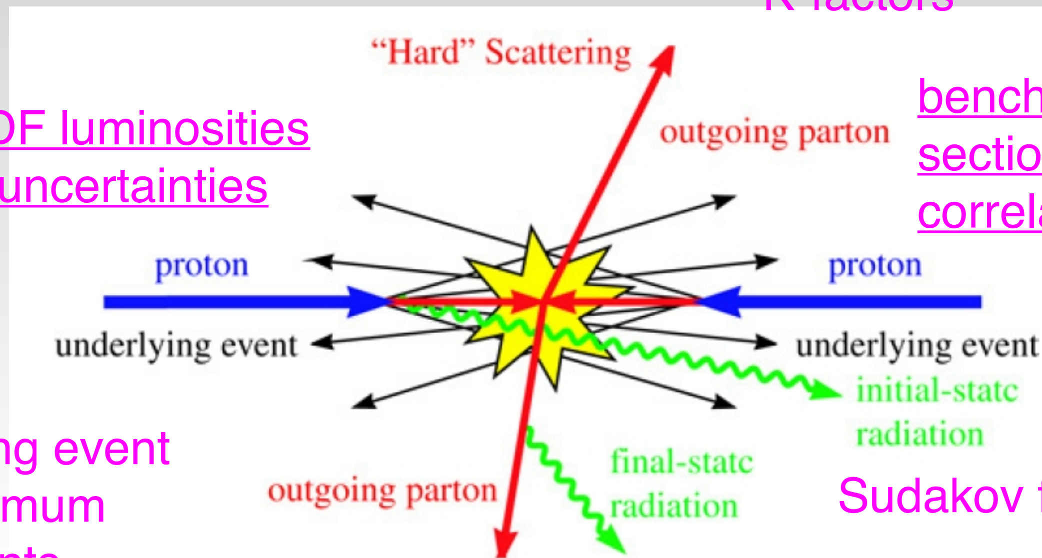

ATLAS
EXPERIMENT
Run Number: 168665, Event Number: 57983
Date: 2010-11-08 11:29:31 CET
8 ET/R(.01) (GeV)
6
4
η
φ
0
90
180
270
360


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

LO, NLO and NNLO calculations
K-factors

PDF’s, PDF luminosities and PDF uncertainties

benchmark cross sections and pdf correlations



underlying event and minimum bias events

Sudakov form factors

jet algorithms and jet reconstruction

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

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

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

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

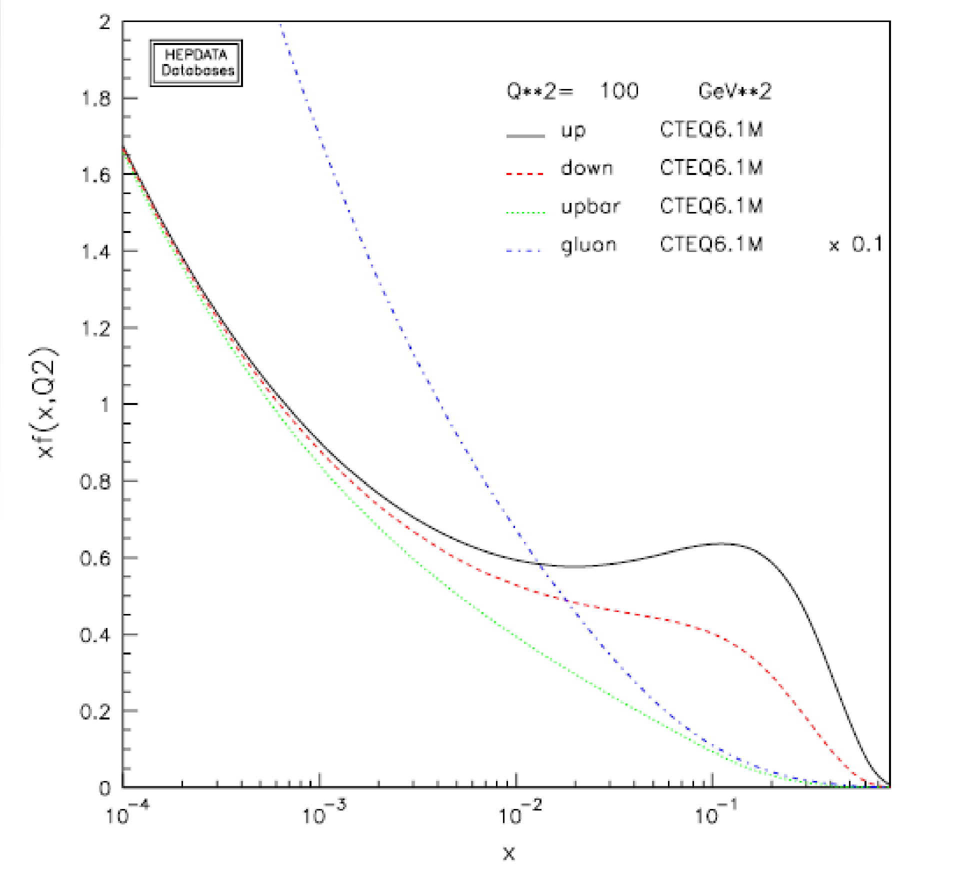


Figure 27. The CTEQ6.1 parton distribution functions evaluated at a Q of 10 GeV.

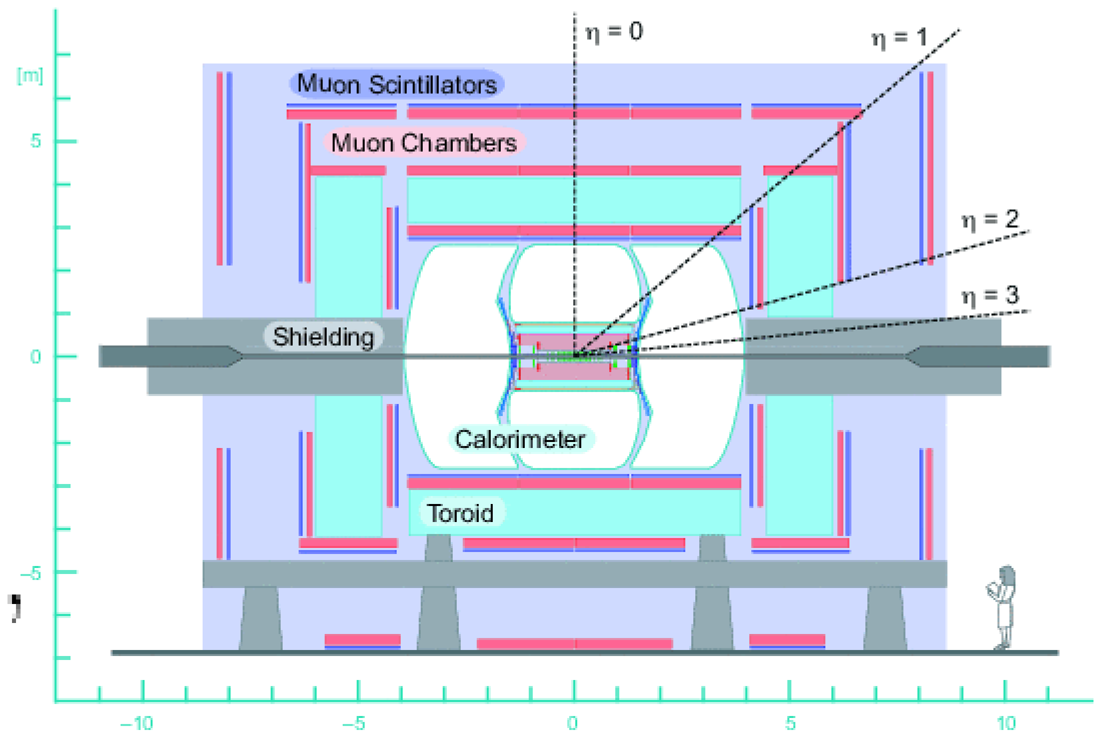
Typically the two colliding partons will have different x → event will be longitudinally unbalanced (Lorentz-boosted)

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

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

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

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



Kinematic region of the LHC

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

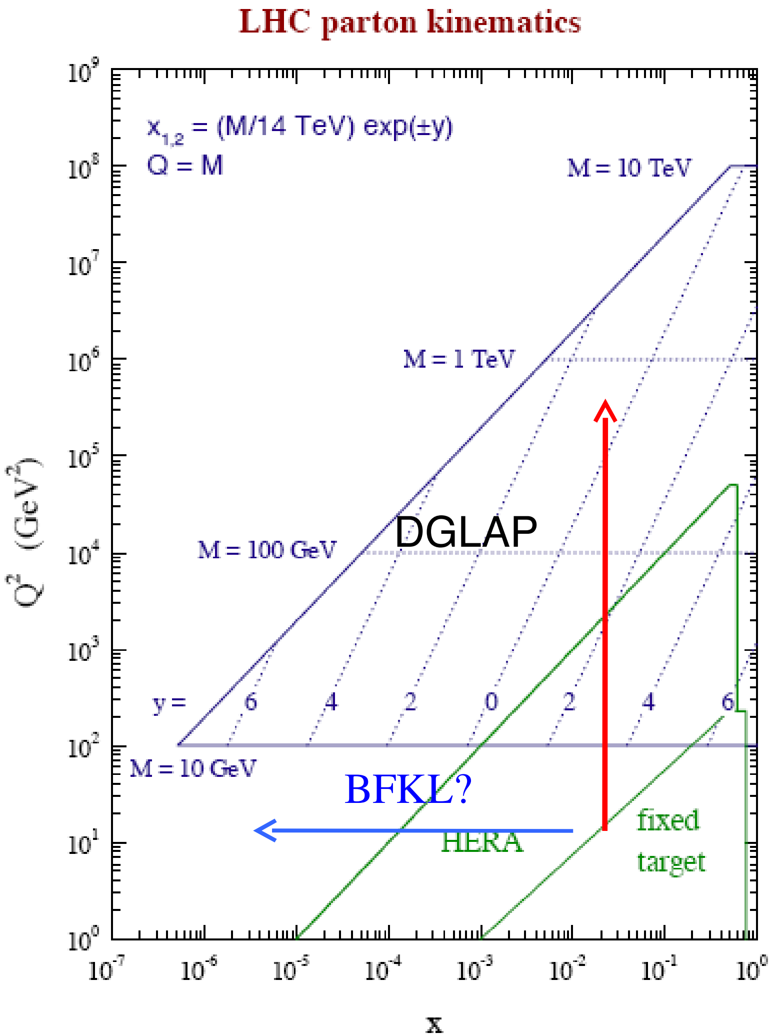
We will access pdf's down to 1E-6 (crucial for the underlying event) and Q^2 up to 100 TeV^2

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

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

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

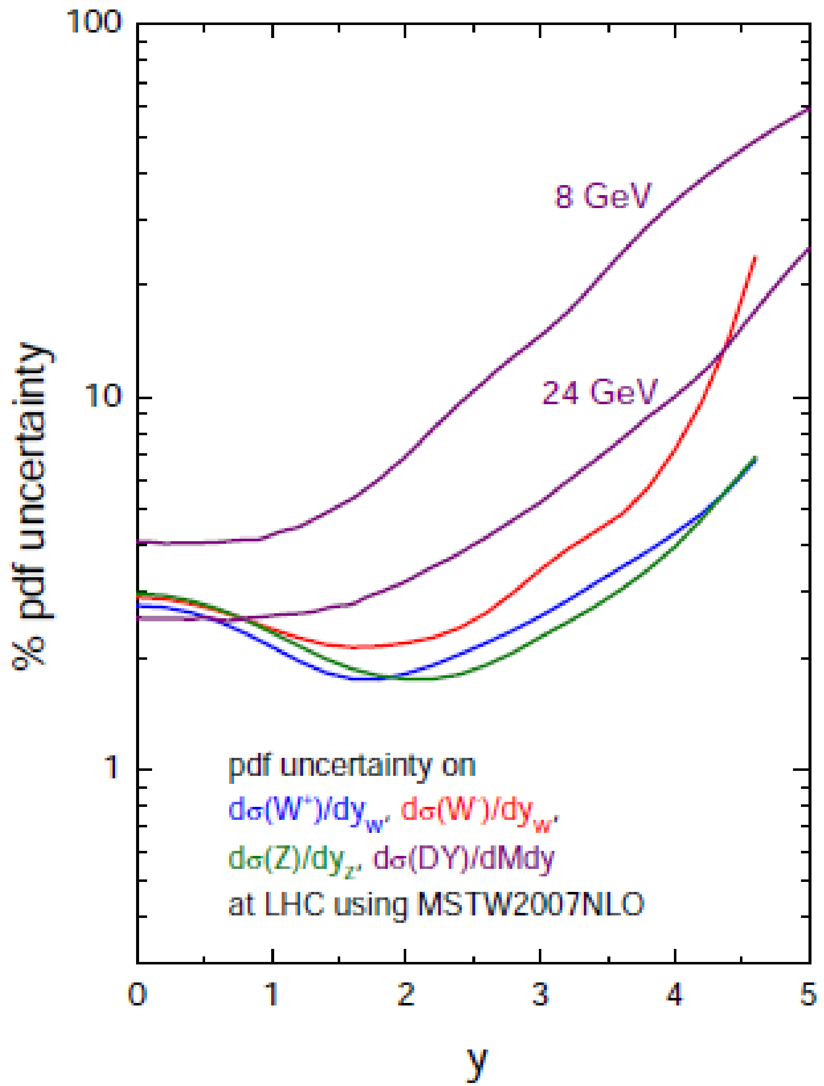
$$\frac{d\sigma}{dM^2 dy} = \frac{\hat{\sigma}_0}{Ns}\Big[\sum_k Q_k^2\big(q_k(x_1, M^2)\bar{q}_k(x_2, M^2) + [1 \leftrightarrow 2]\big)\Big]$$



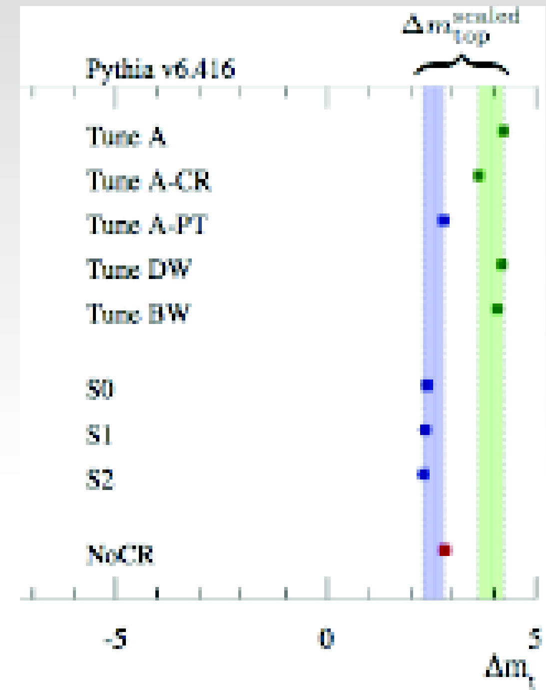
Uncertainty on $\sigma(Z)$ and $\sigma(W^+)$ grows at high rapidity.

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

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



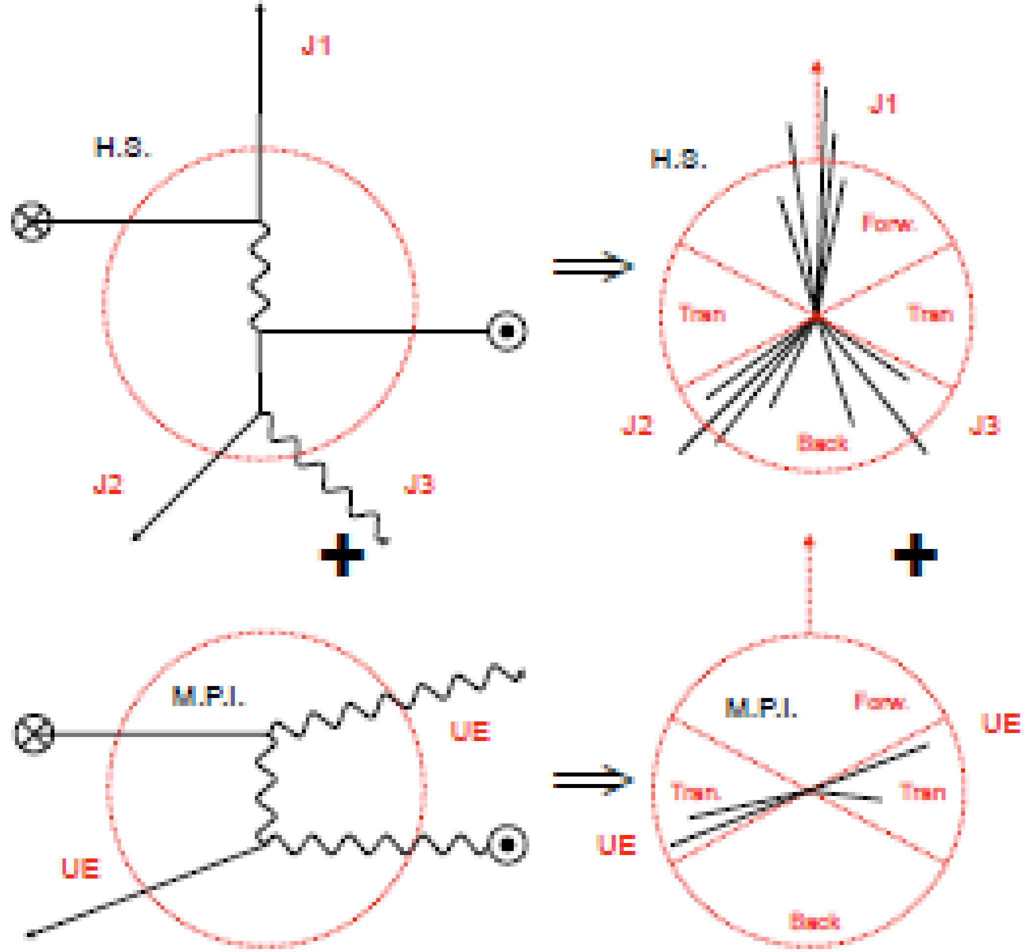
- UE: everything apart from the hard scattering (beam remnant, Multiple Parton Interctions, etc.)
- Will pollute all your physics events (especially ”rapidity gaps”), and influence precision measurements
- normally softer (but with large fluctuations)

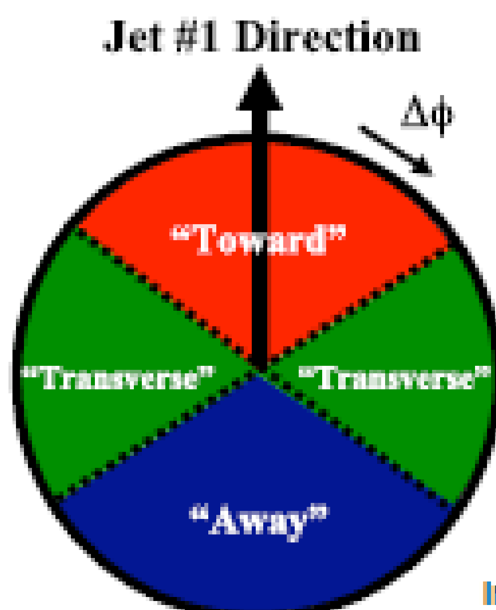


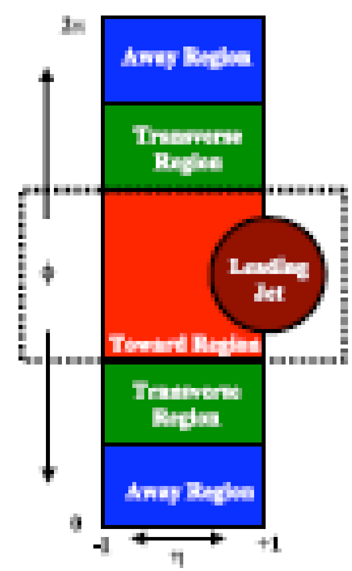
- We are in the realm of non-perturbative QCD, so only possible to do empiric models to be tuned on data
- These models are similar to those use to model soft scattering events (the Minimum Bias), which are the events we are taking right now
- Various models implemented in generators: Pythia, Herwig,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

UE Characterization

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



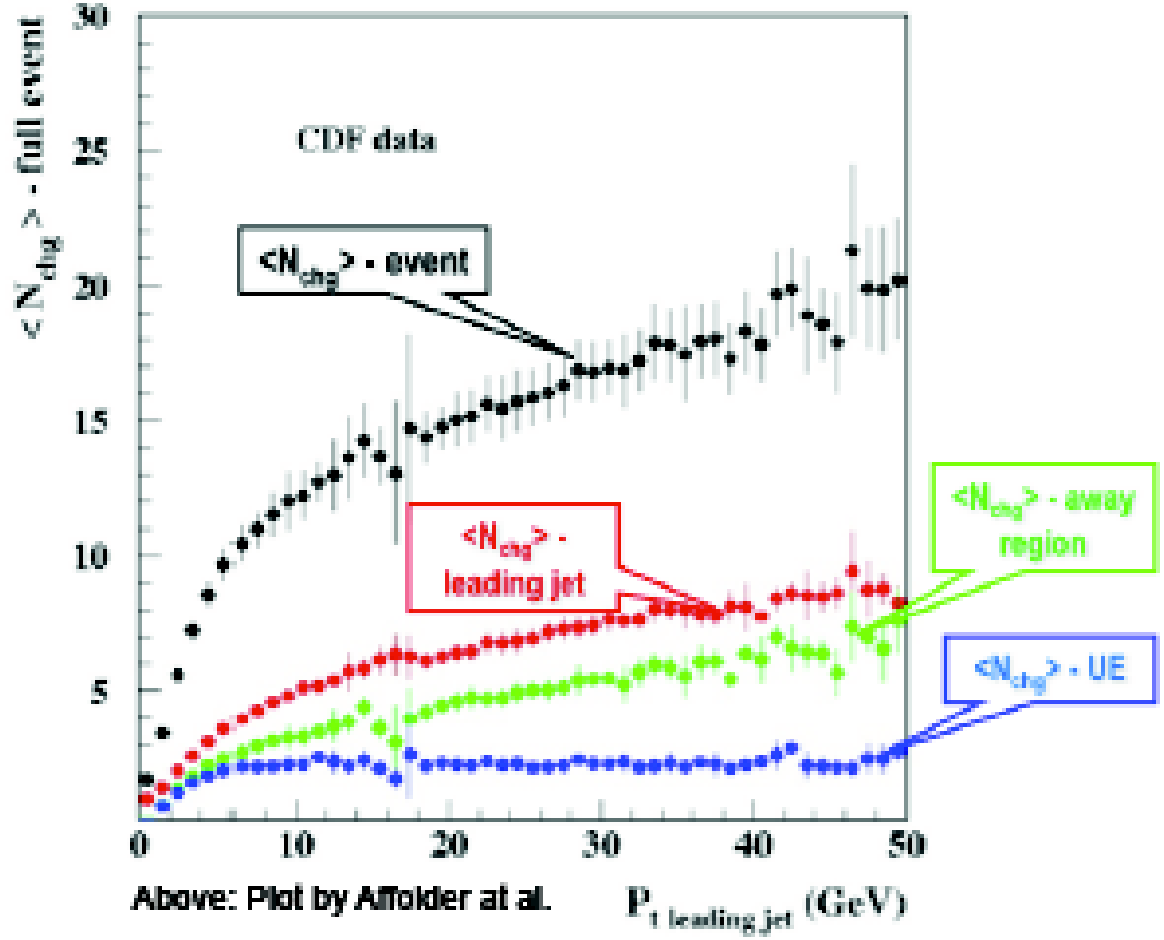




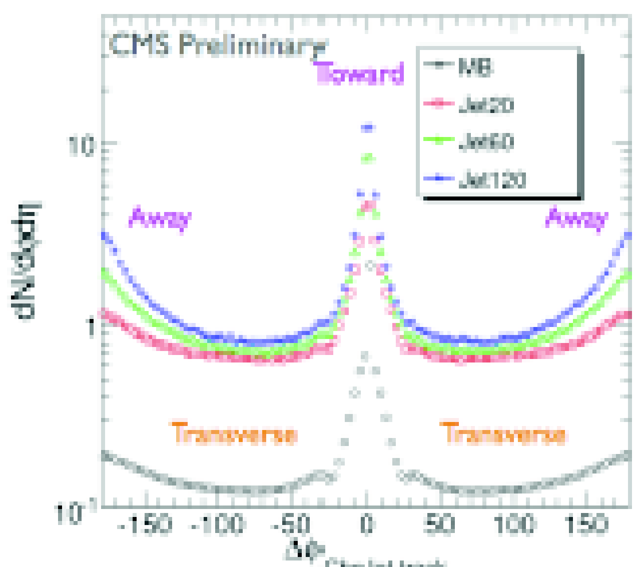
Images from R. Field.

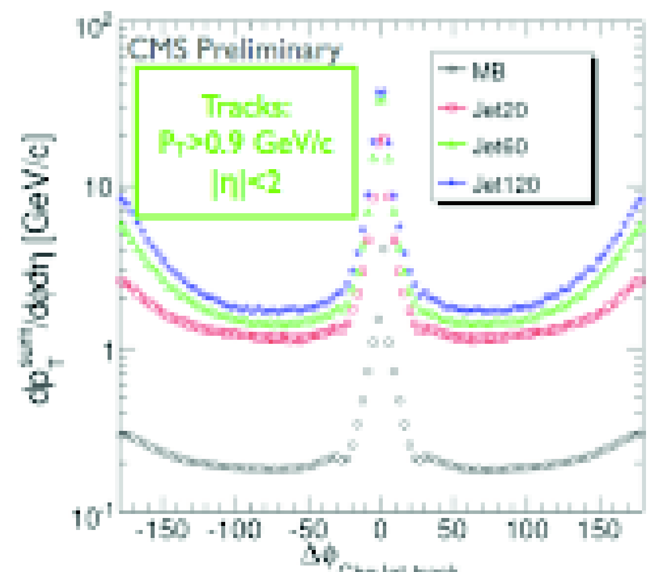
UE Characterization

- 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.
- <u>Track Jets</u> are used, so that low energy calorimeter response is not involved.
  - Also simplifies comparison to models.
- <u>Drell-Yan</u>: Look for $\mu^+\mu^-$ there is no FSR associated with their production.
  - The entire φ range characterizes the UE.



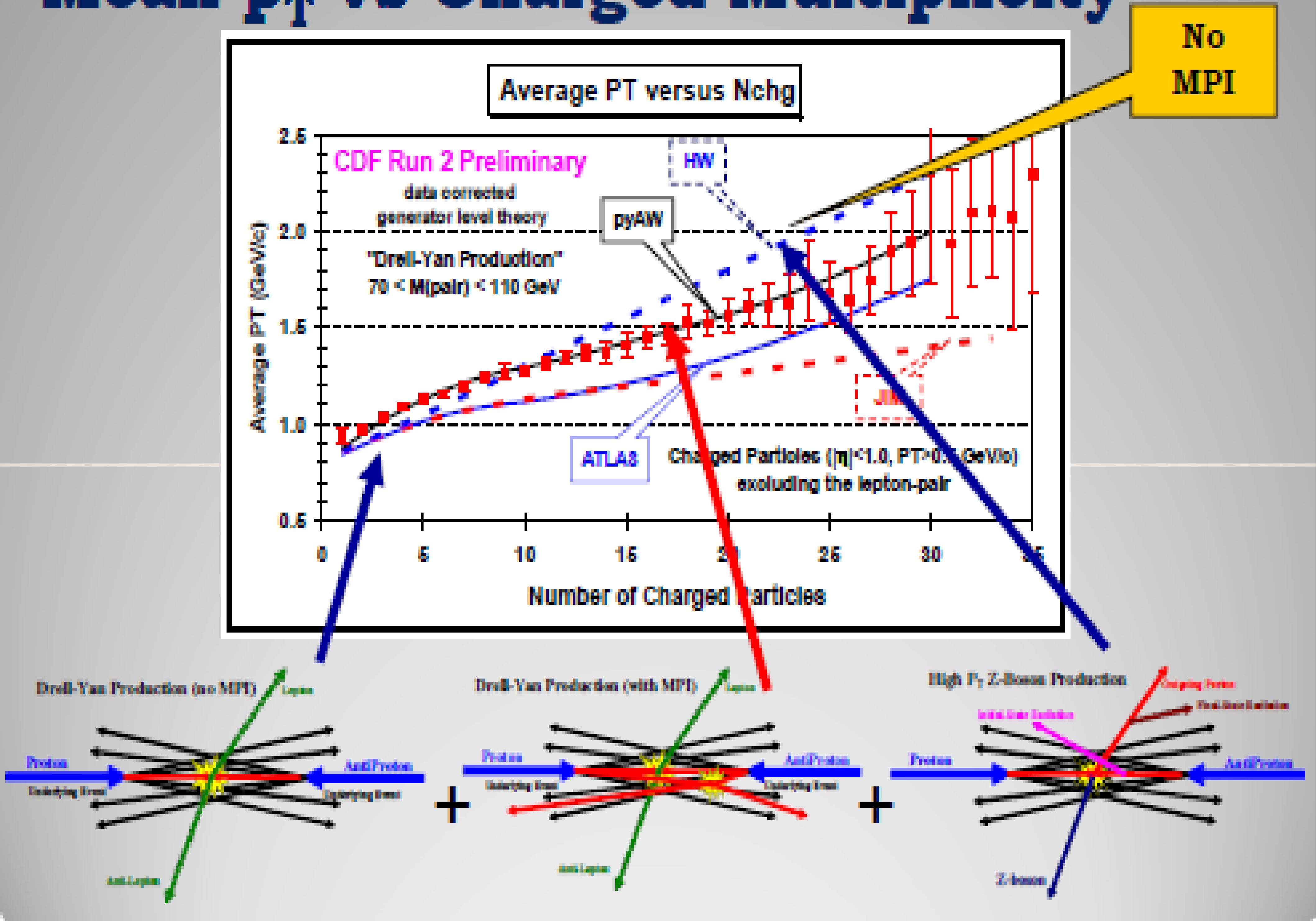
Above: Plot by Affolder at al.

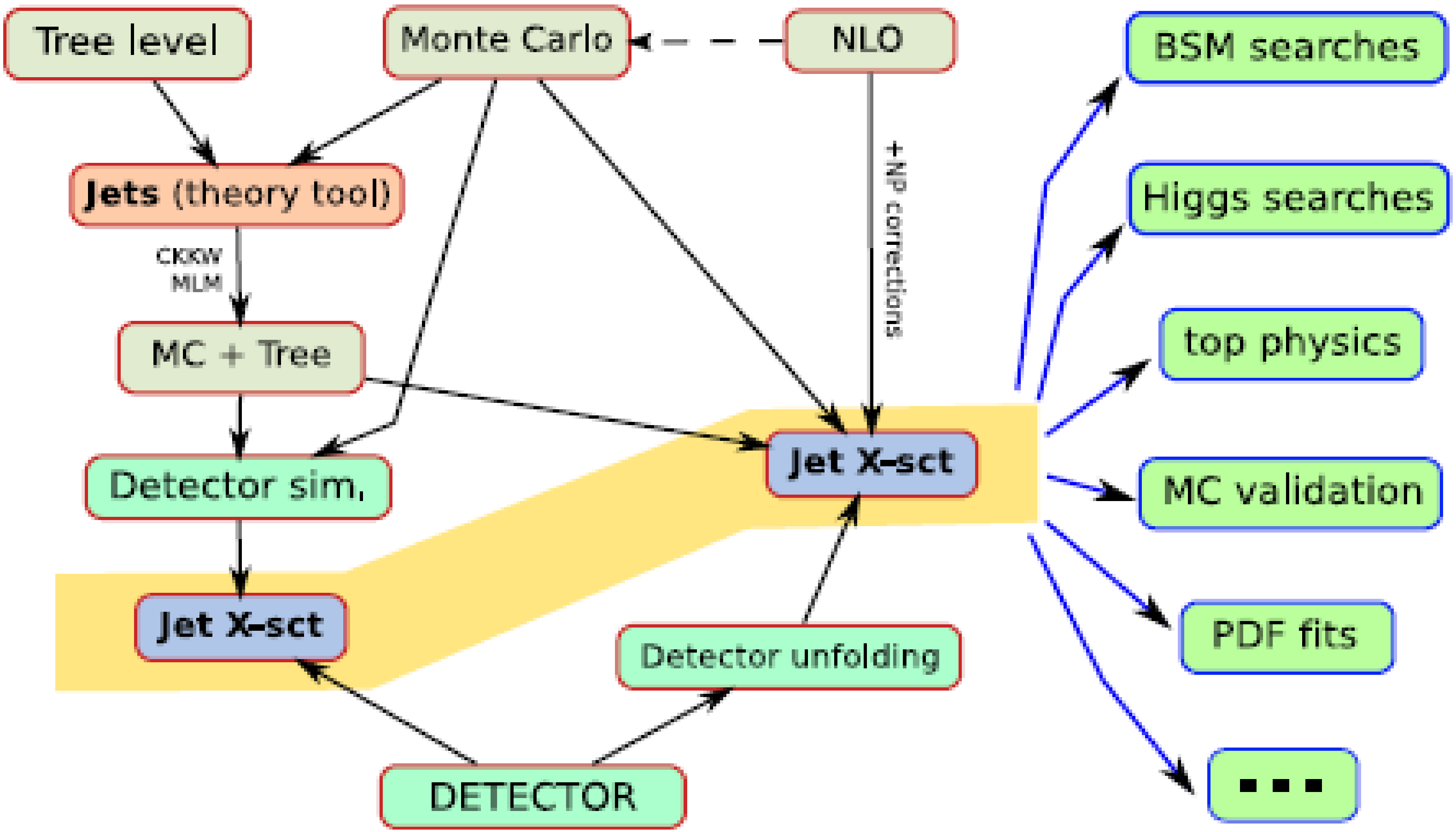




Above: Plots from F. Ambroglini

Mean p_T vs Charged Multiplicity



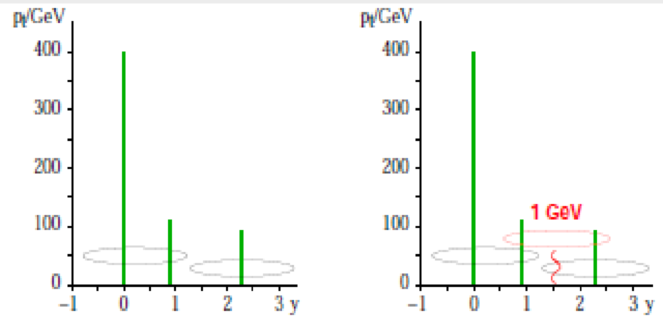


Jet (definitions) provide central link between expt., "theory" and theory

And jets are an input to almost all analyses

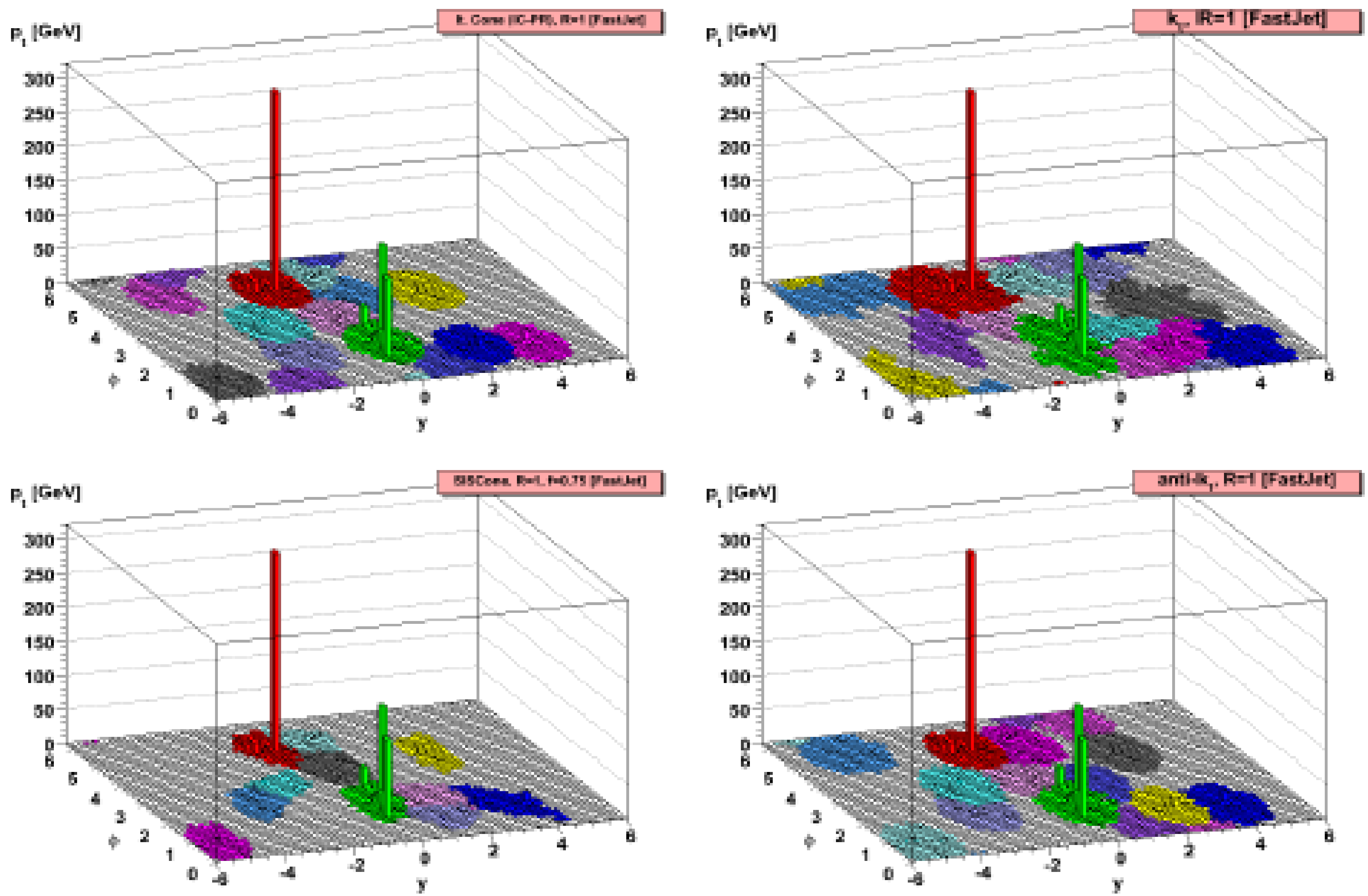
- Cone algorithms:
  - start with a high-Pt deposition, then take everything with distance smaller than a given radius in (η,ϕ) space
  - ex. JetClu, Atlas cone, CMS cone, MidPoint, PxCone, SISCone
- Iterative recombination:
  - Merge nearby clusters, and combine them into a single one; continue until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

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

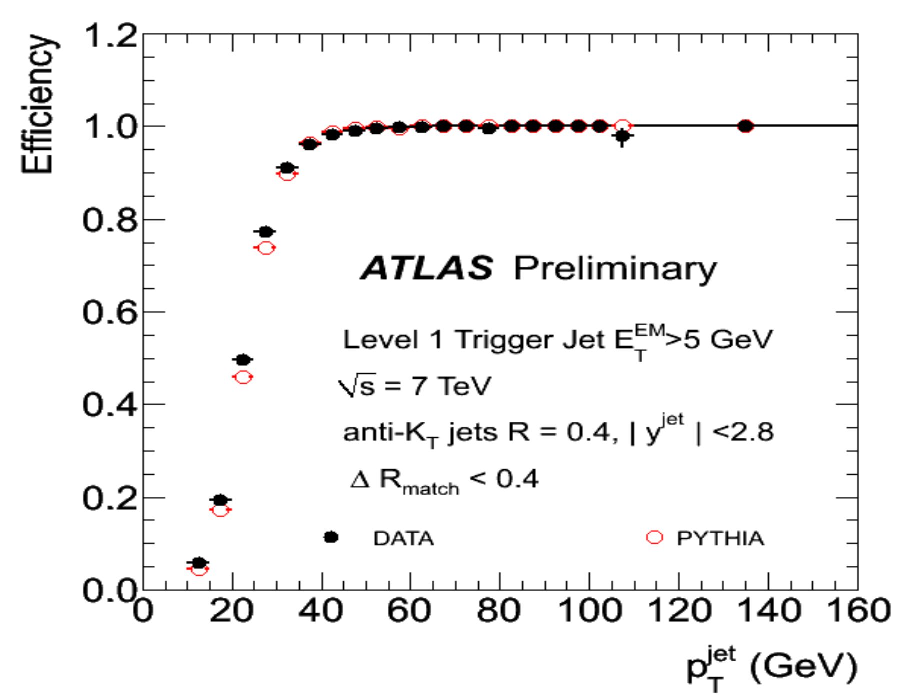


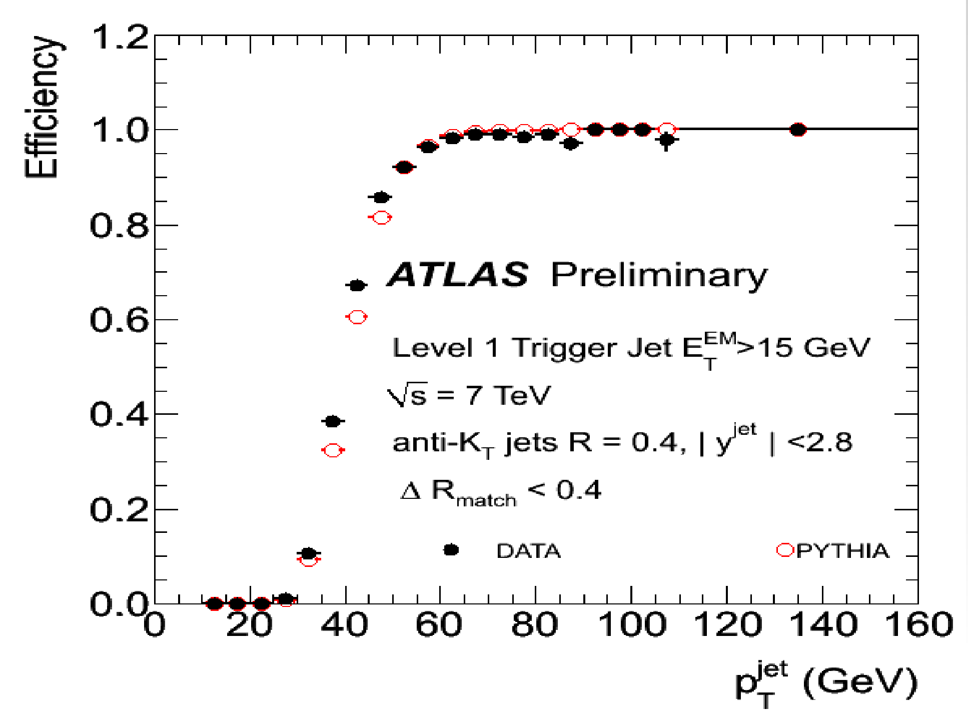
Stable cones with midpoint:	{1,2} & {3}	{1,2} & {2,3} & {3}
Jets with midpoint ($f = 0.5$)	{1,2} & {3}	{1,2,3}

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

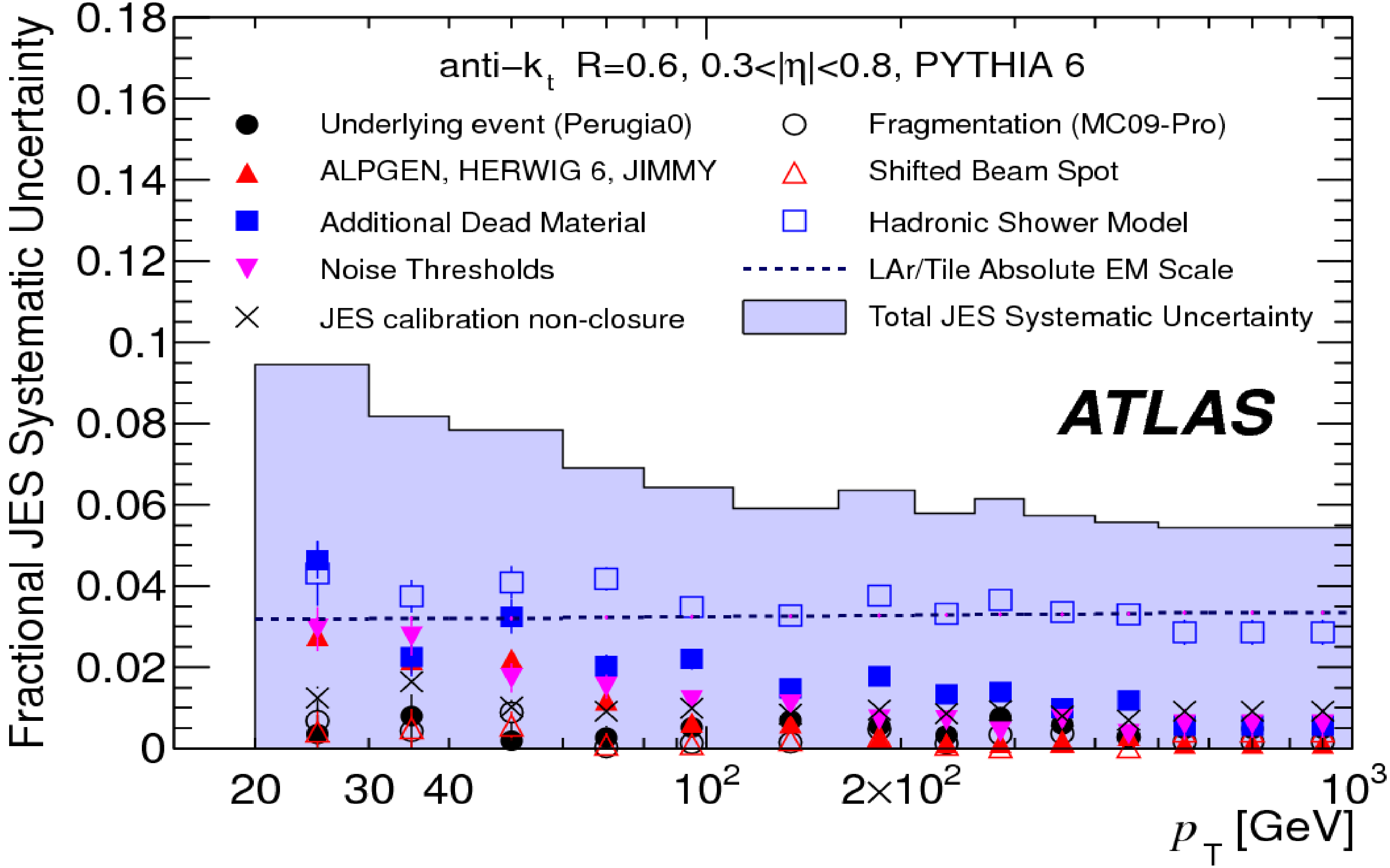


Anti-kt now default algorithm in Atlas

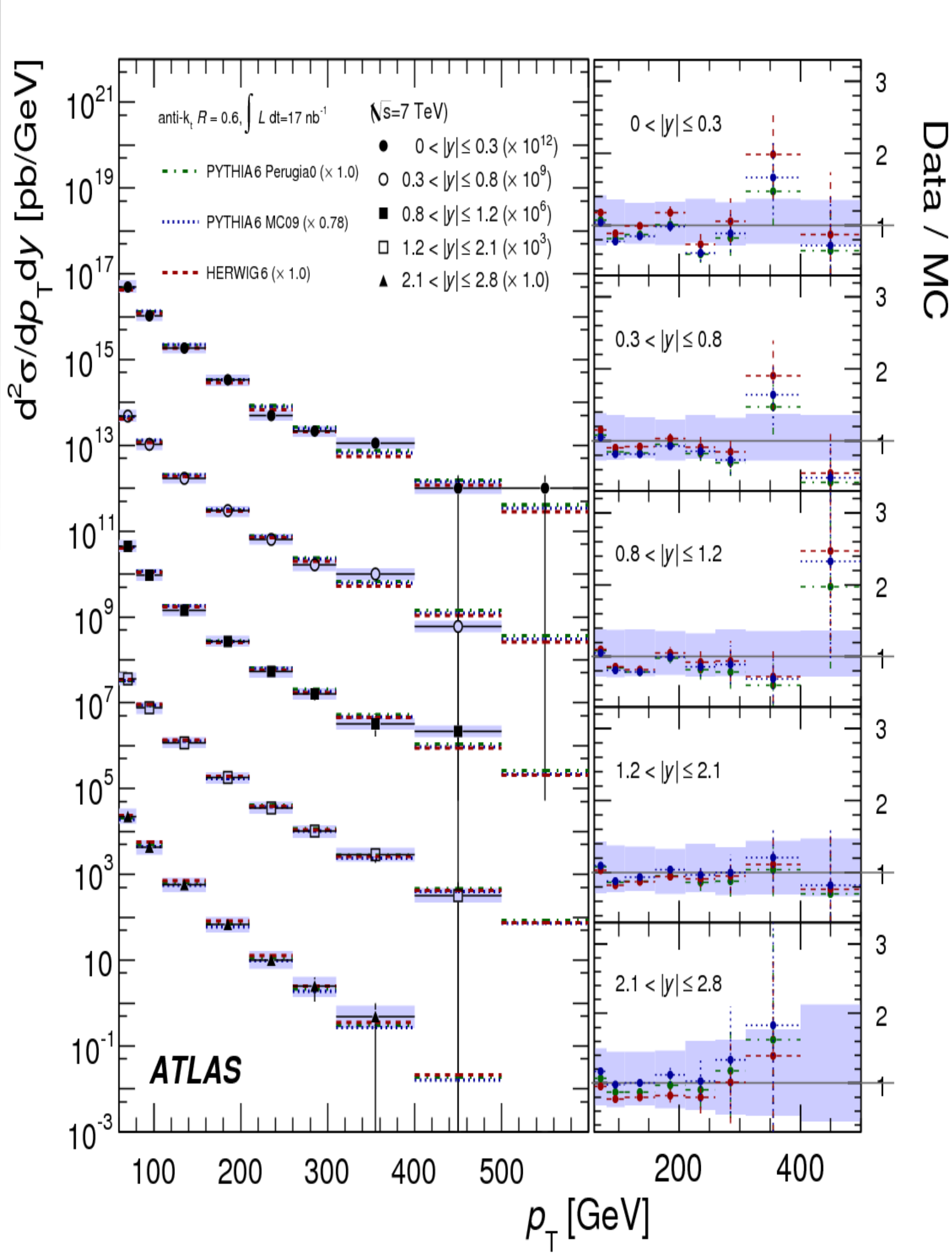




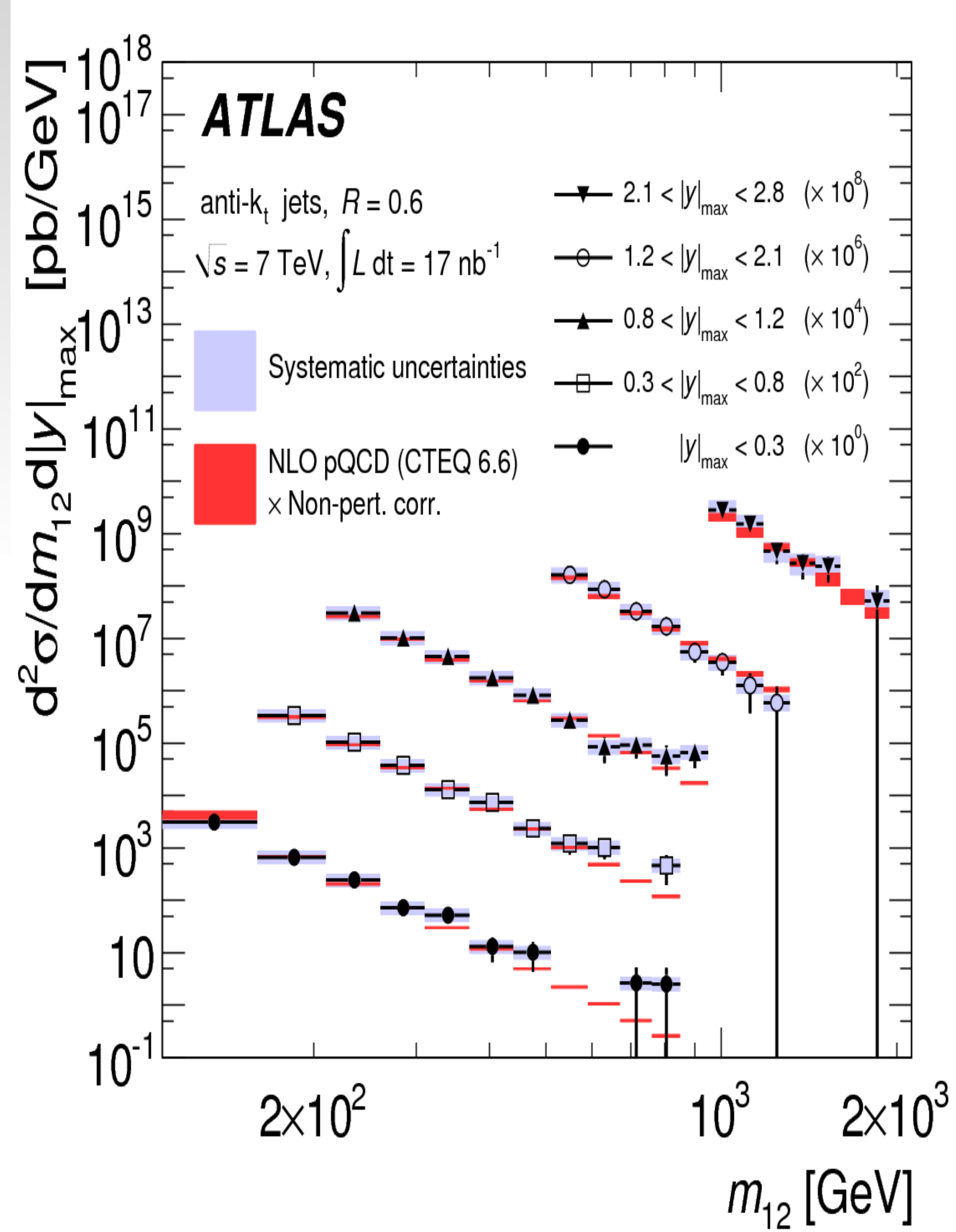
- Not to correct for the efficiency in the steeply rising part of the curve, jet cross section was first measured above the 100% efficiency point
- This results in the measurement being performed in different Pt bins in the various periods, because higher luminosities forced heavy prescales on lowest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



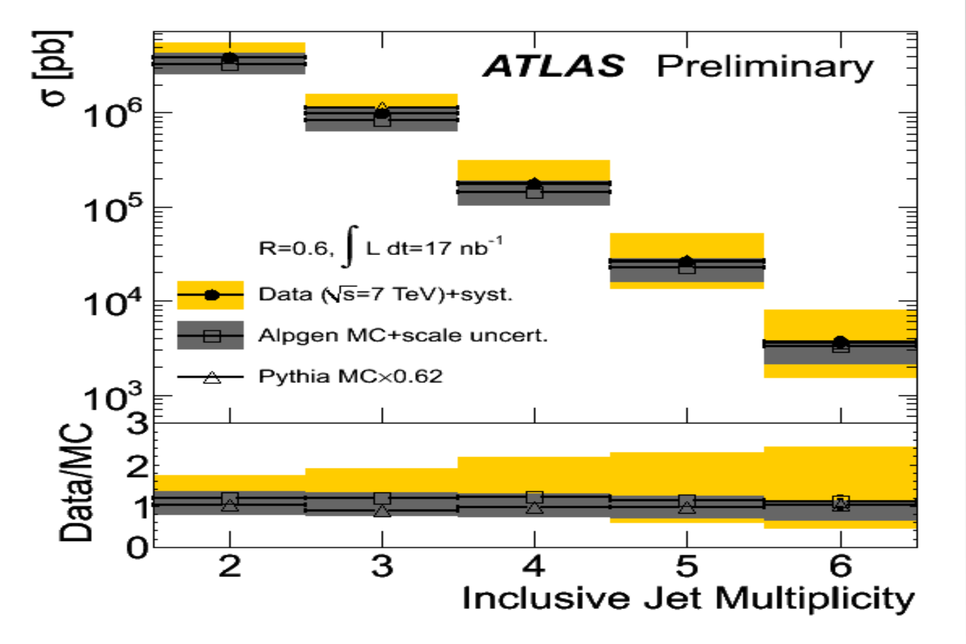
- Jets measured at EM scale (summing Ecal and Hcal contributions), scaled by factors derived from MC and cross-checked with track jets

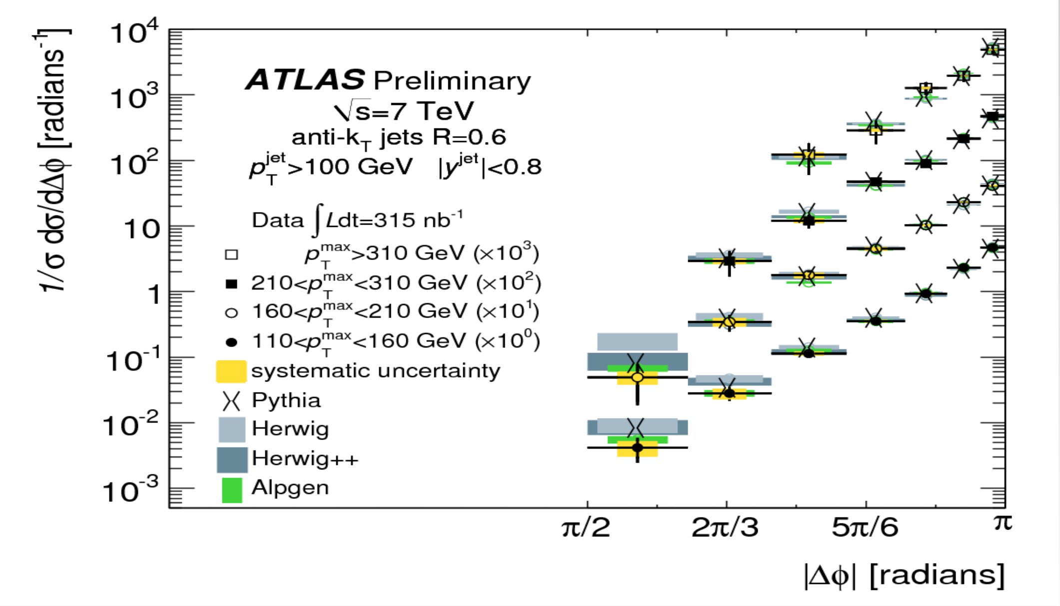


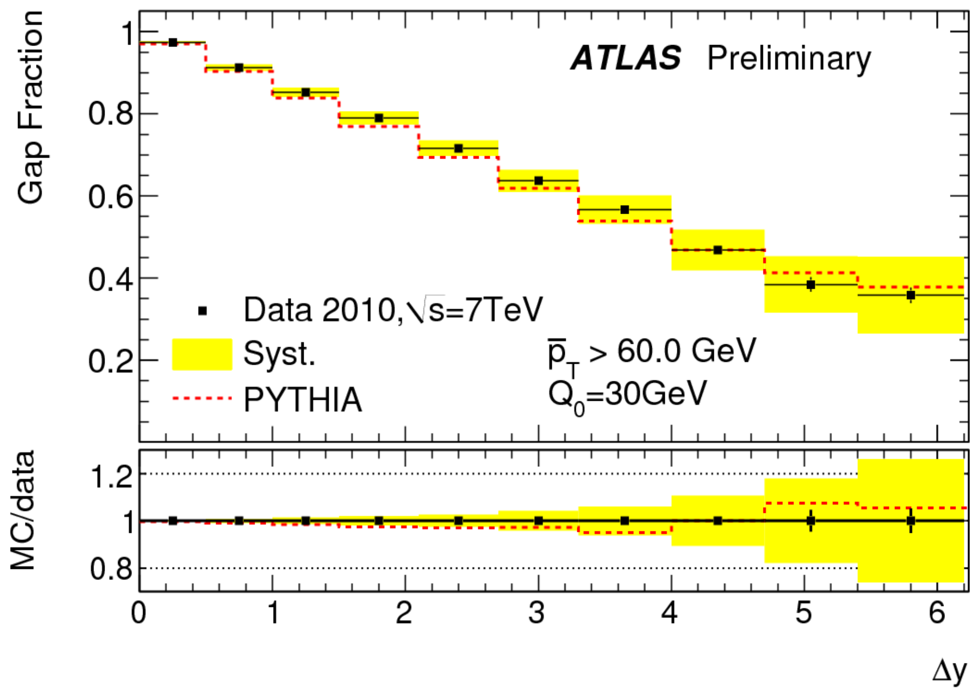
$d^2\sigma/dp_T dy$ [pb/GeV]
anti-k_t $R = 0.6$, $\int L\,dt = 17\ nb^{-1}$
$\sqrt{s}$=7 TeV)
$0 < |y| \leq 0.3$ ($\times 10^{12}$)
$0.3 < |y| \leq 0.8$ ($\times 10^{9}$)
$0.8 < |y| \leq 1.2$ ($\times 10^{6}$)
$1.2 < |y| \leq 2.1$ ($\times 10^{3}$)
$2.1 < |y| \leq 2.8$ ($\times 1.0$)
PYTHIA6 Perugia0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



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

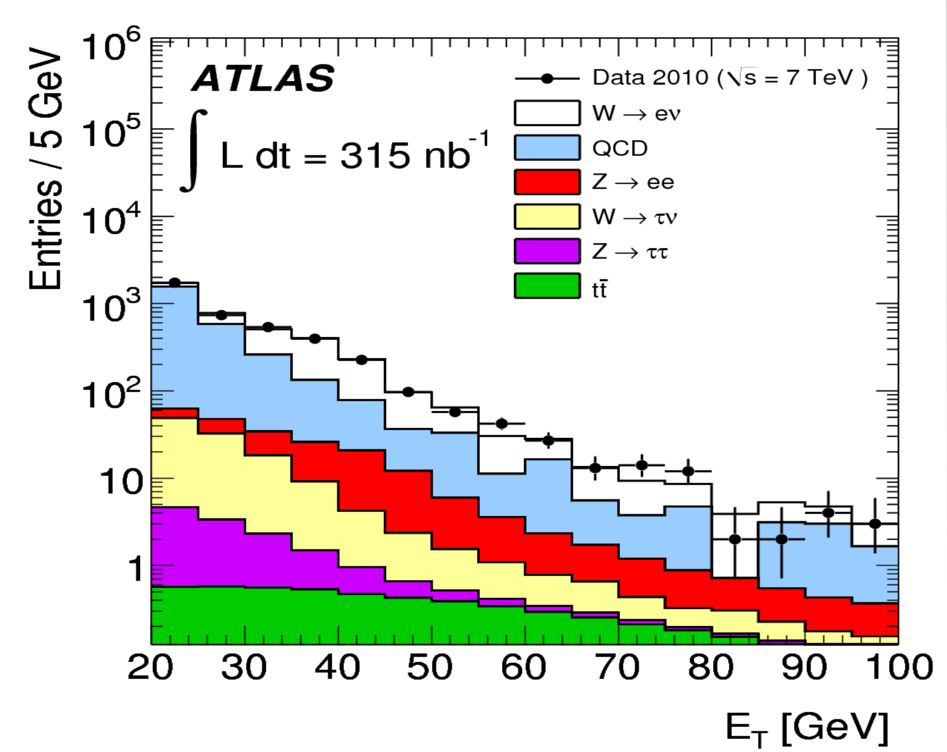


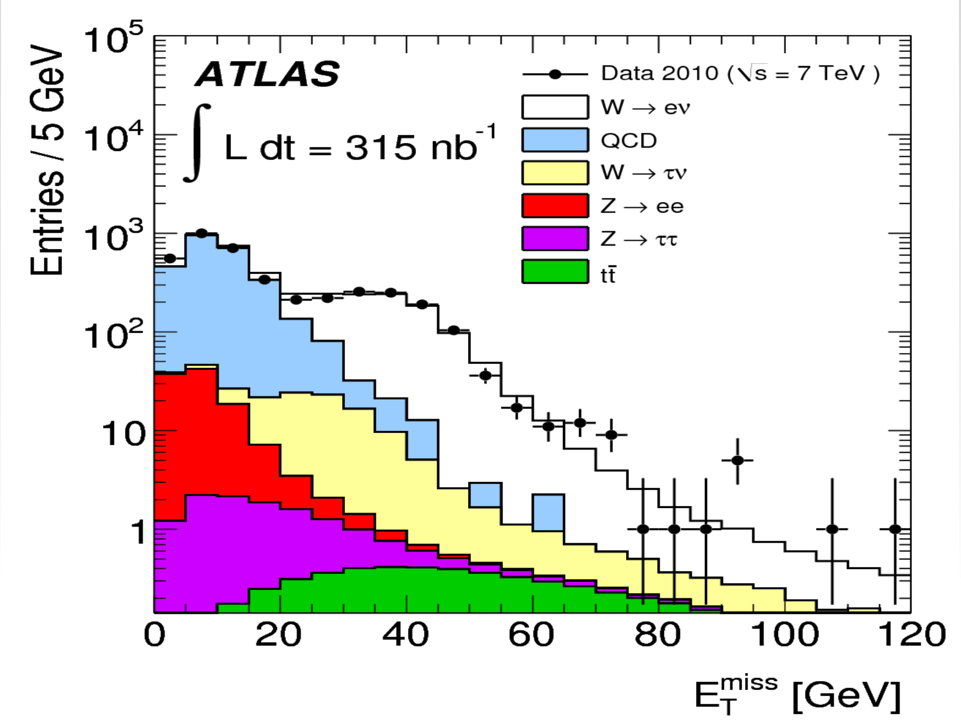




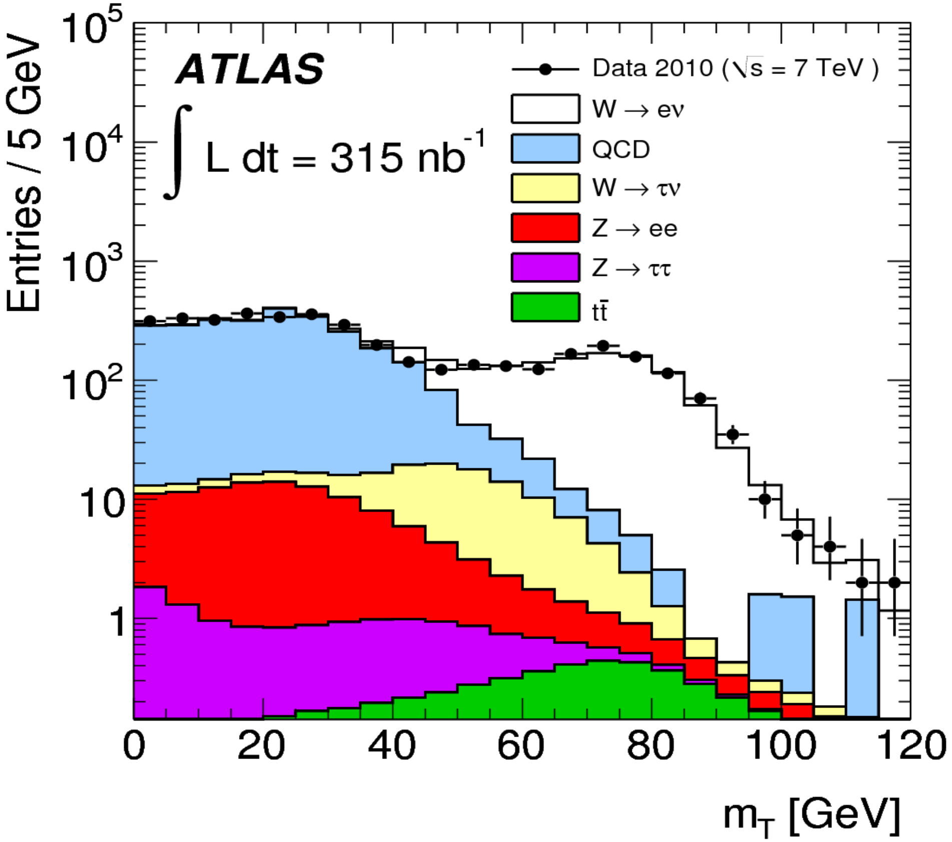
Several QCD tests performed on jets, looking at multiplicity, angular distribution, radiation between dijets

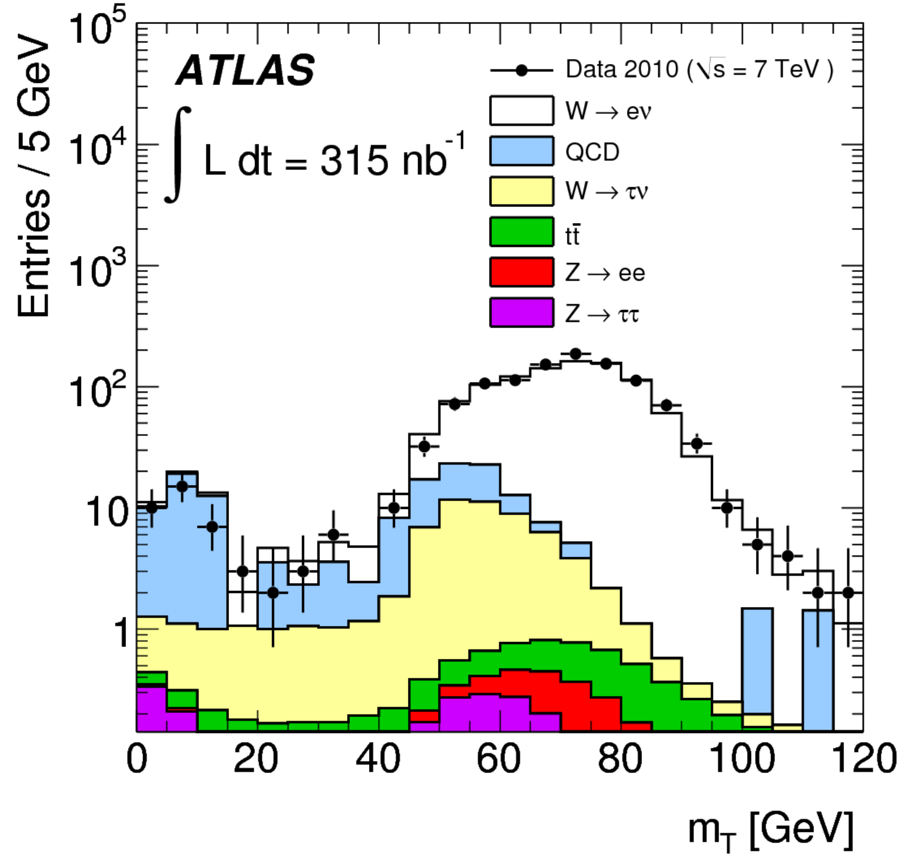
- Next important SM benchmark are W and Z productin, always accompanied by jets at the LHC.
- Relevant for Pdf determination, QCD studies
- W production about 10 times larger than Z, but analysis more difficult: no way to perform full reconstruction, so only transverse mass can be reconstructed
- Different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



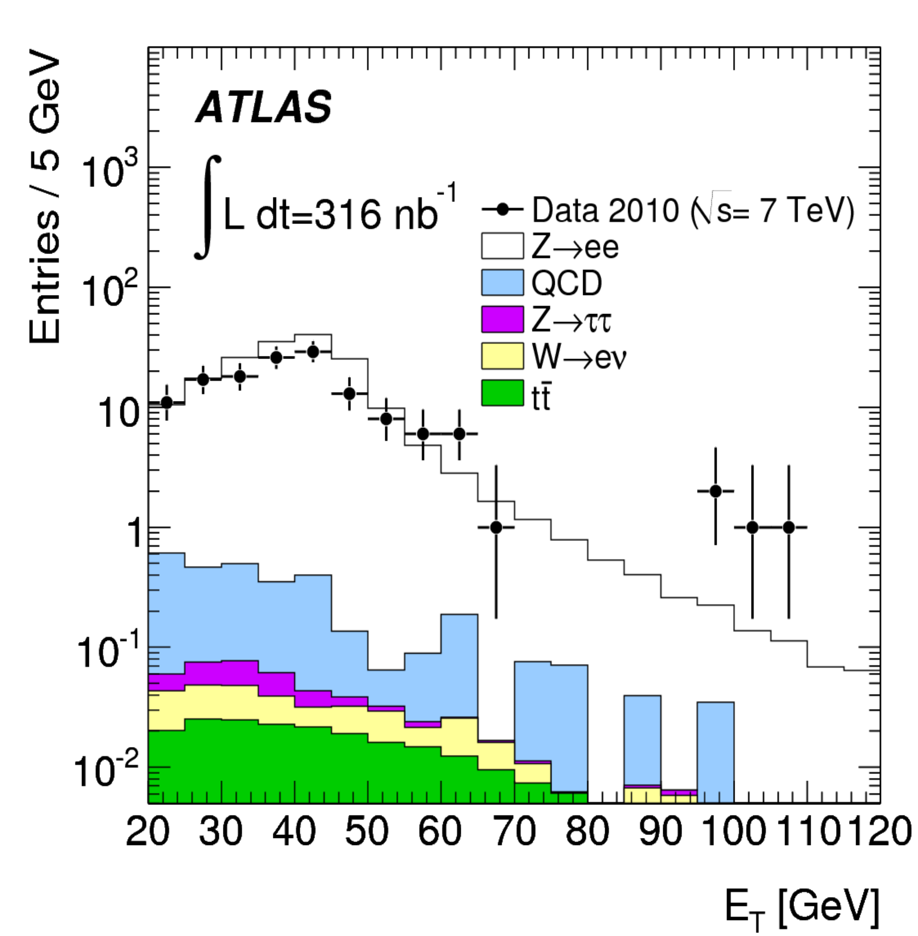


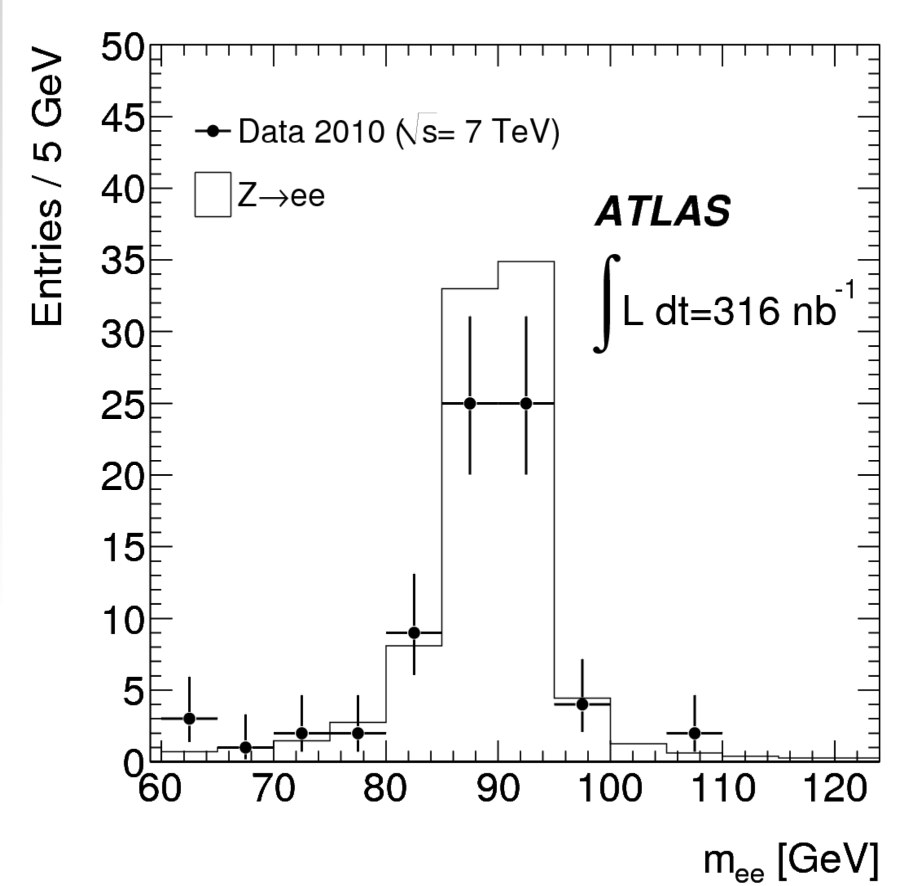
- Electron Pt MET
- for W->enu events
- Signal purity quite low for individual variables



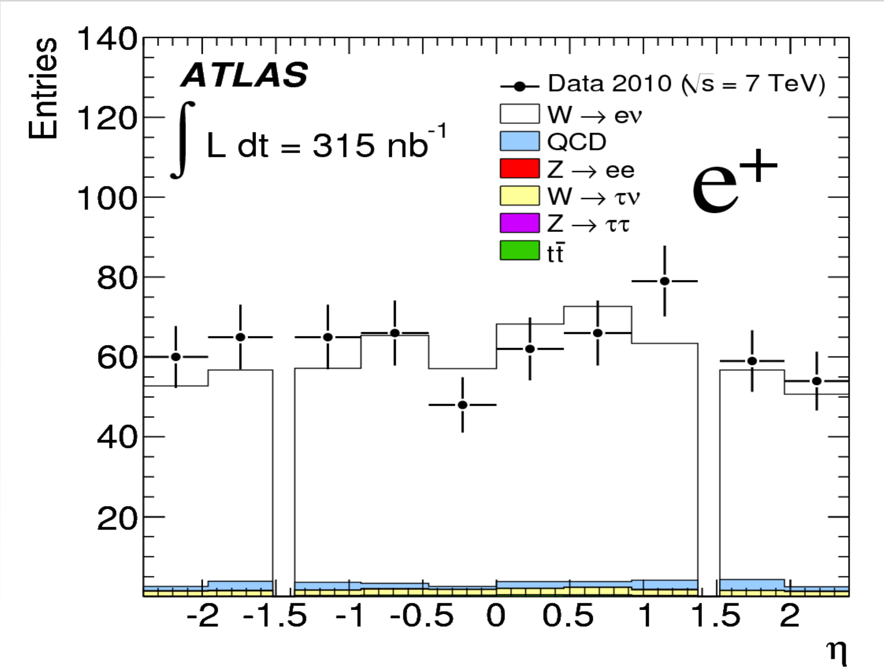


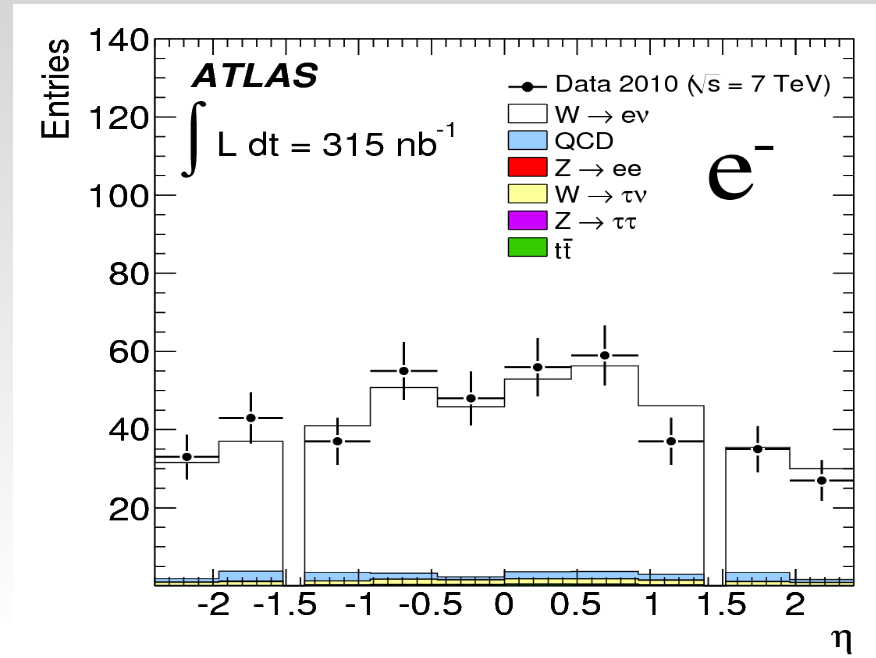
- Despite the transverse mass distribution being very broad, Tevatron experiments provide now a measurement of the W mass more precise than that of LEP, where the full mass could be reconstructed

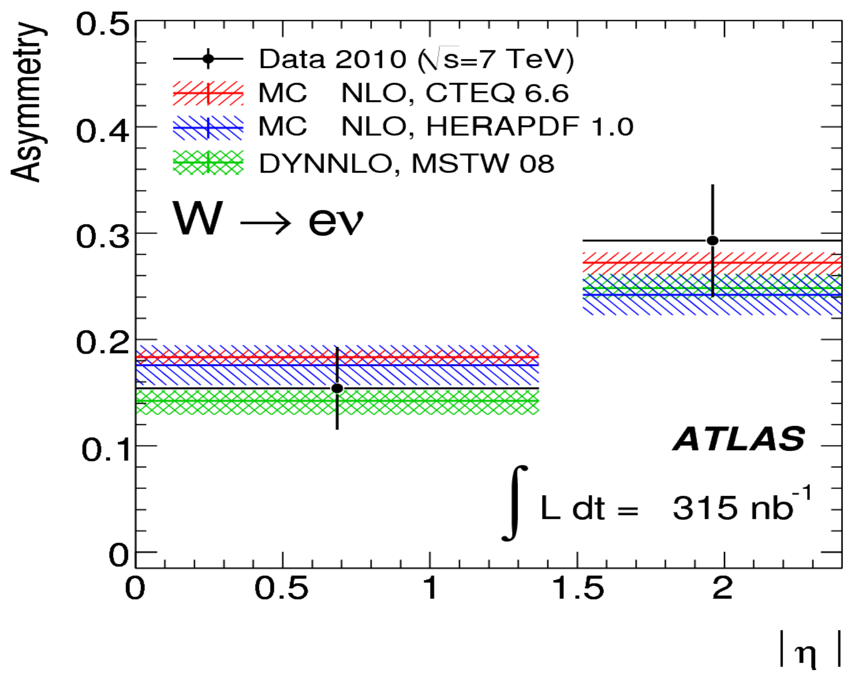




- 2-lepton requirement makes Z channel much cleaner, but statistics is poorer-hard to beat LEP's 4 million Z collected per experiment (and lineshape fit). Fundamental tool for calibration



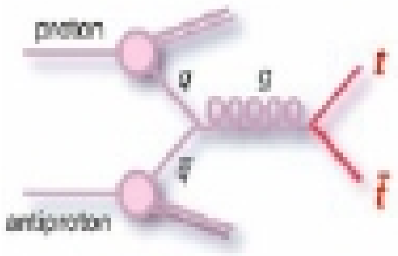




The idea: from Pdf's, u-quarks have higher average x, so W+ tend to be produced more forward. Even in pp, W asymmetry distribution can constraint Pdf's

Top quark production and decay

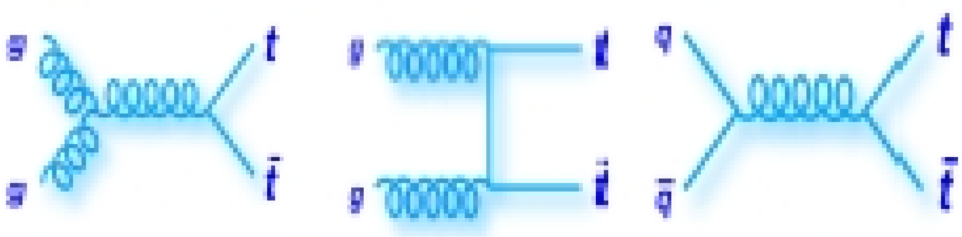
- Produced mainly in pairs
  - σ ≃ 7 pb @ 2 TeV



85%

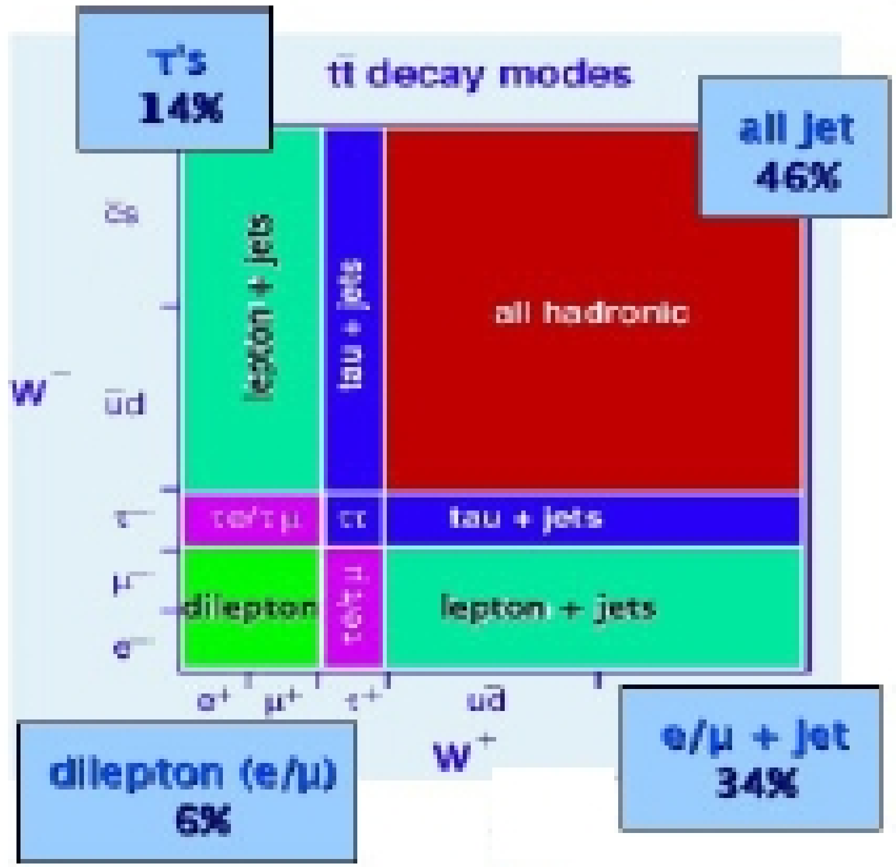
15%

  - σ ≃ 400 pb @ 10 TeV



90% 10%

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



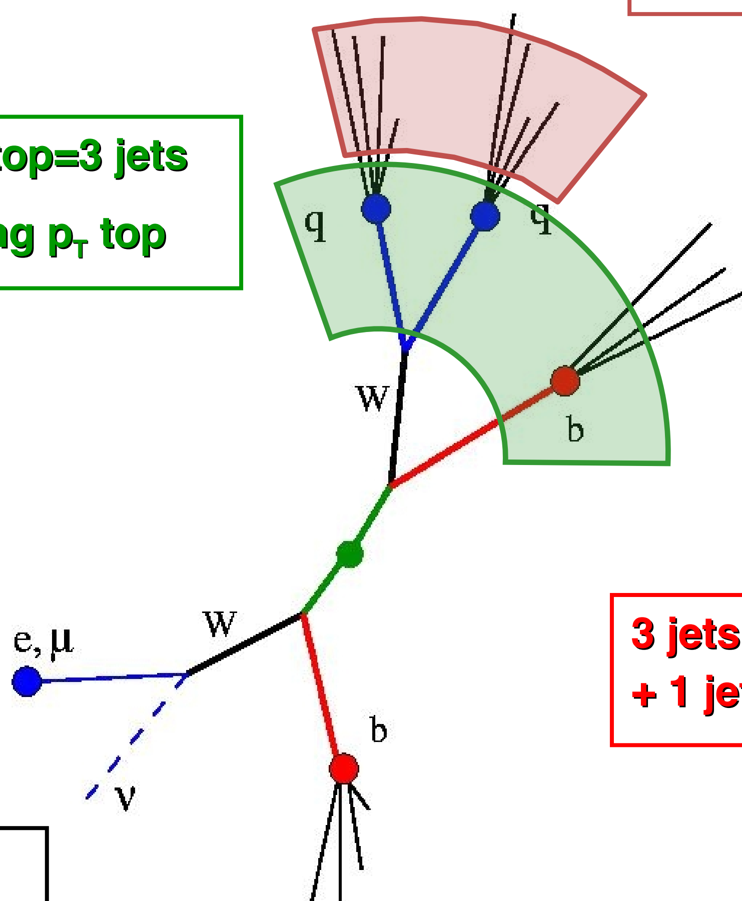
Top quark physics measurements

Keep it as simple as possible:

W =2 jets maximising p_T W in jjj rest frame

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

Hadronic top=3 jets maximising p_T top



Isolated lepton $p_T > 20$ GeV

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

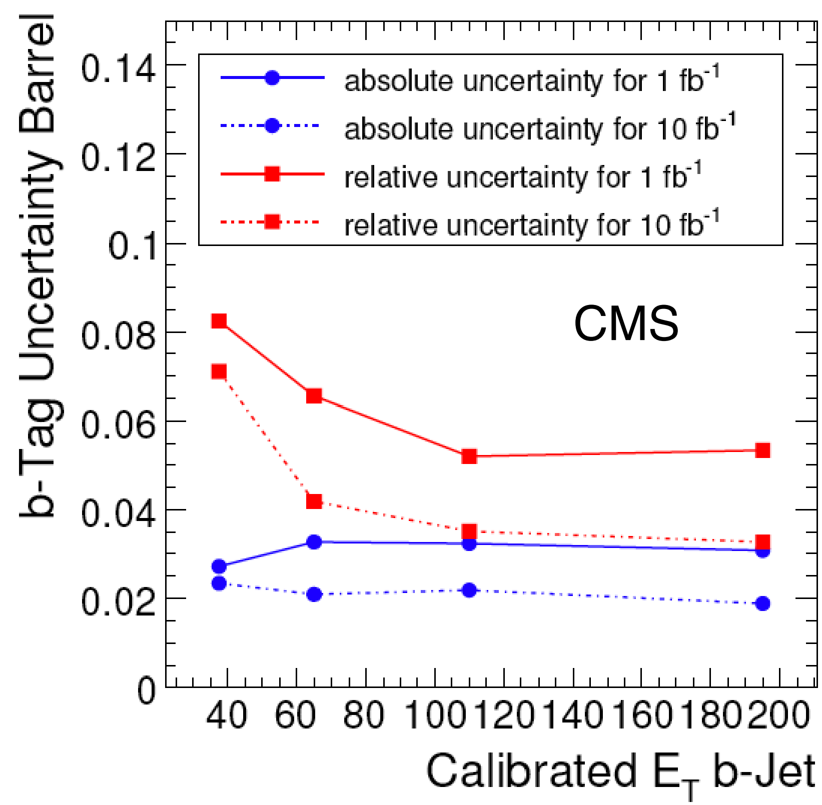
$E_{T,miss} > 20$ GeV

b-tag efficiency

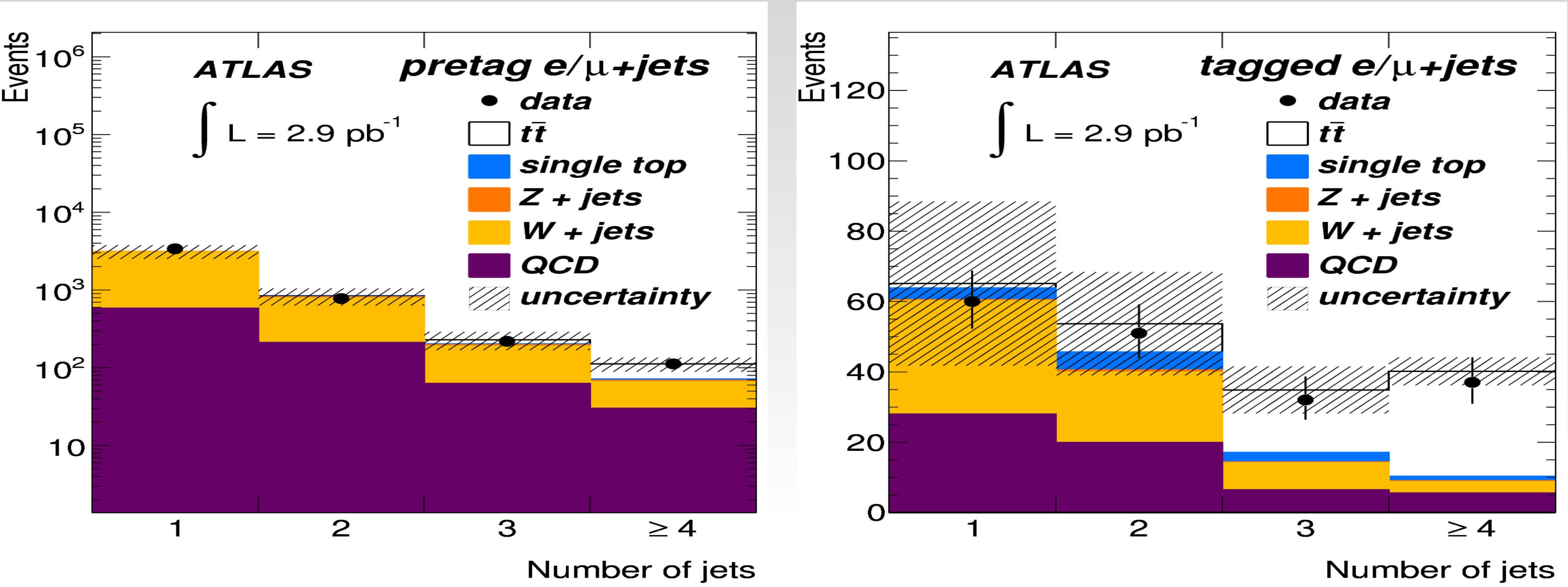
Select b-enriched samples using tt sample

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

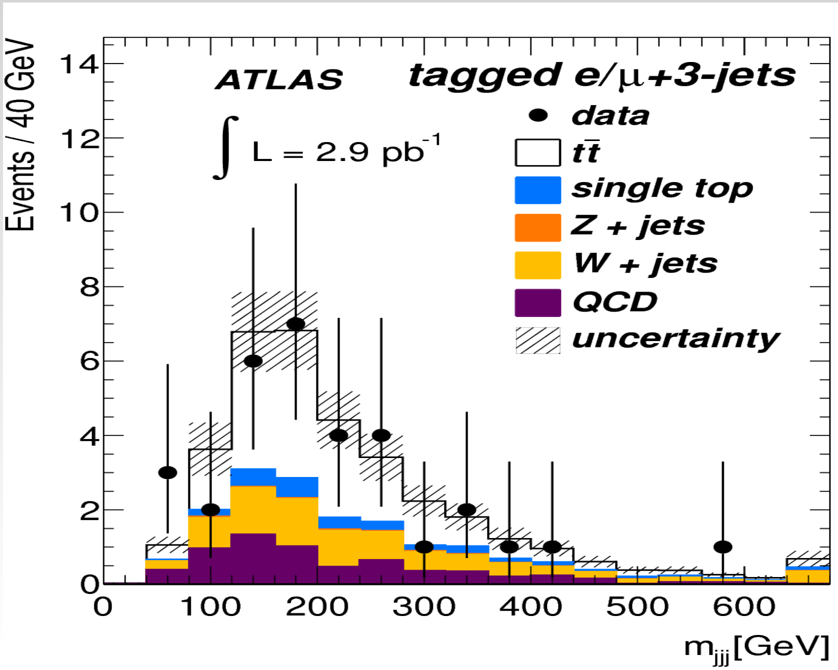
- CMS study 1(10) fb^{-1}
  - Efficiencies 40% to 60% (at $E_{T,b\text{-}Jet}$ > 100) GeV
  - Uncertainty 4-6% for large data samples

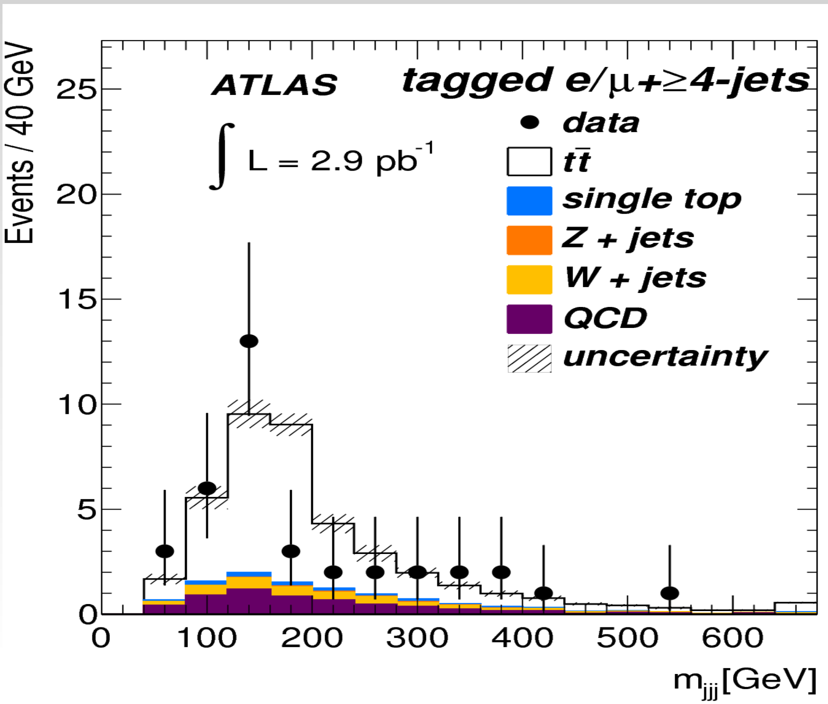


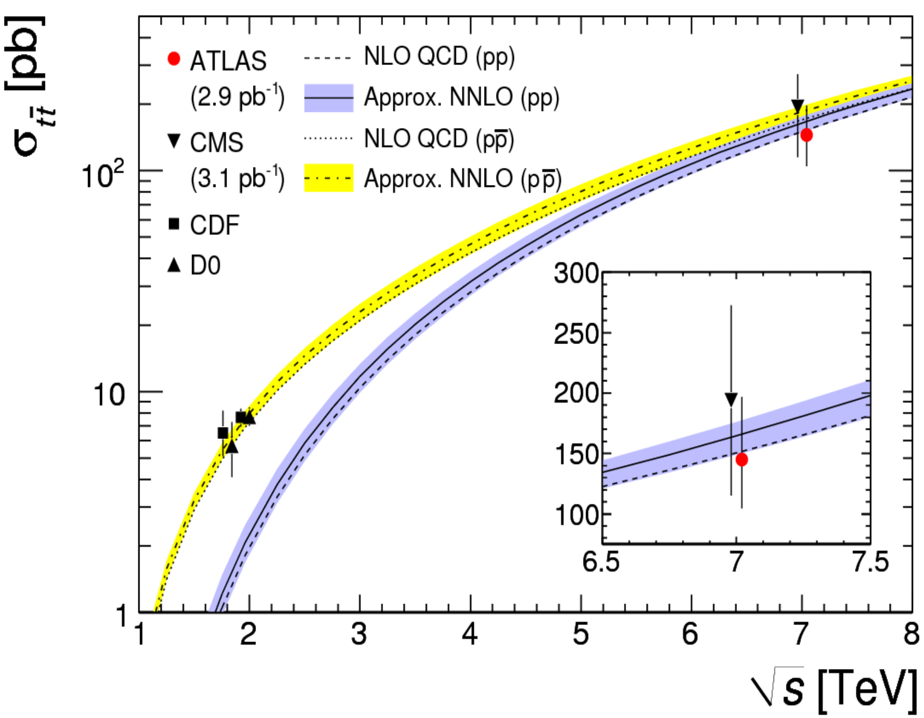
- ATLAS study 100 pb^{-1}
  - Similar efficiencies, purities
  - Estimated uncertainty ~10%



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

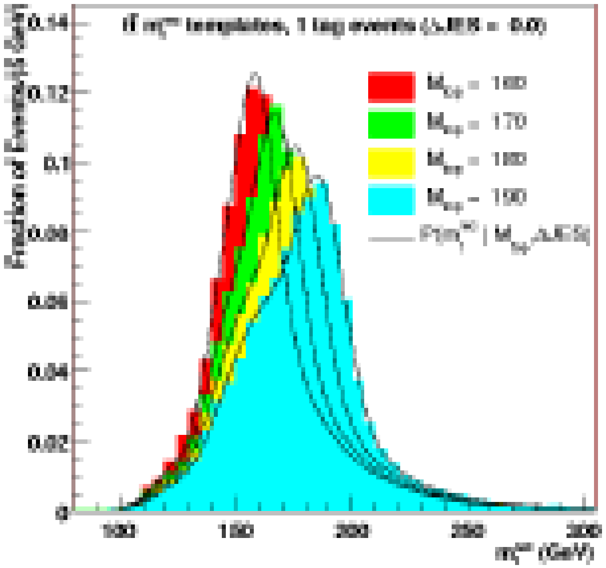


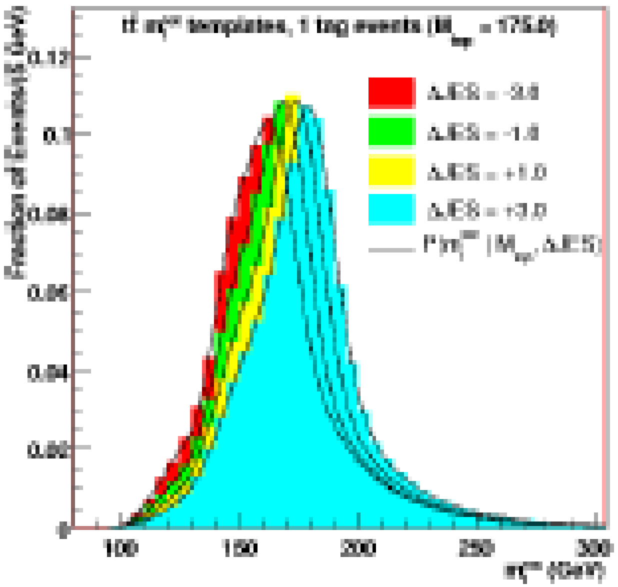




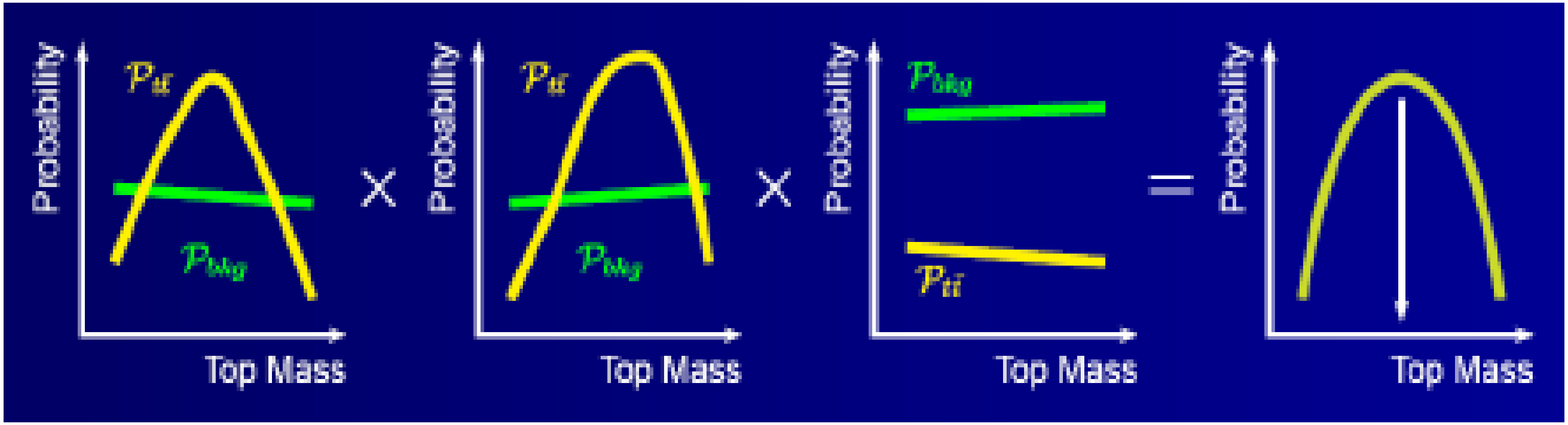
- First measurement of many top production, mass and properties ones

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





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



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

Normalization
acceptance
& efficiency

Differential cross section based on LO ME

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

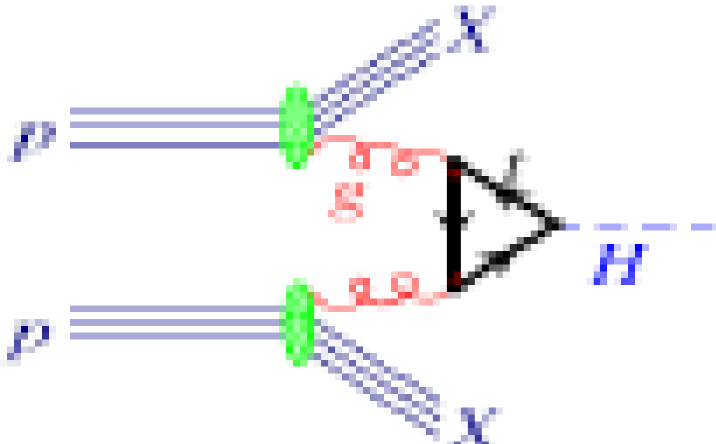
Probability to observe a set of kinematic variables x for a given mass and JES

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

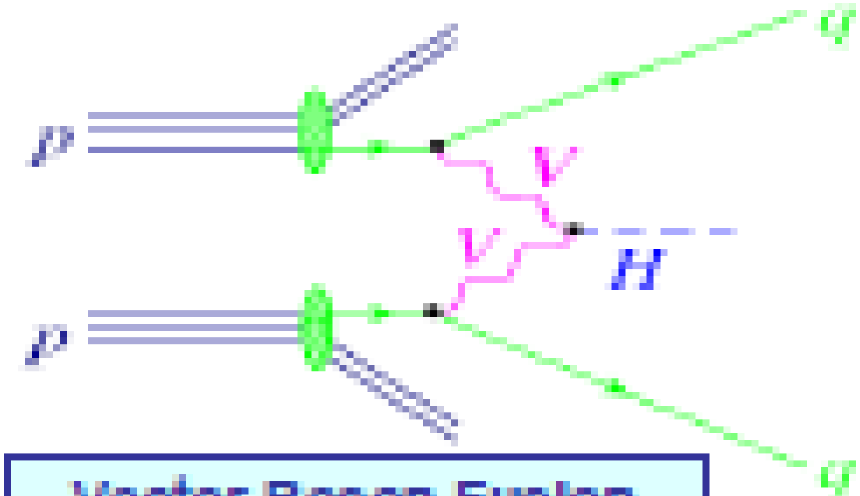
Transfer function
Probability to measure x when parton-level y was produced

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

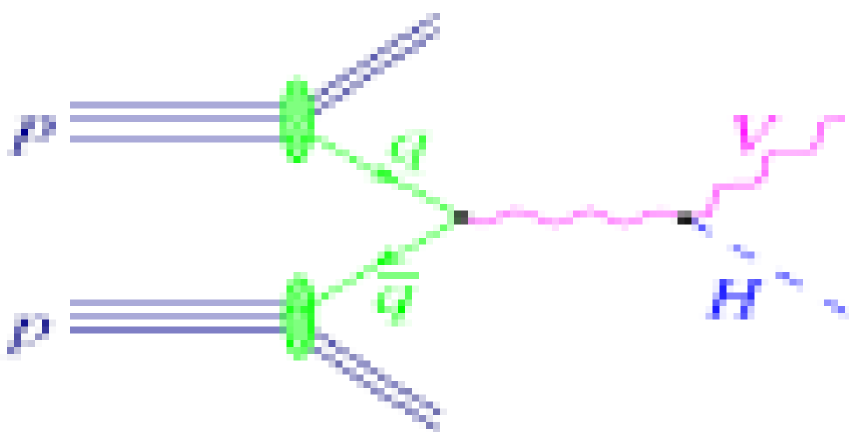
$$\mathcal{P}_{event}(x; m_t, \mathrm{JES}) = f_t\, \mathcal{P}_{tt}(x; m_t, \mathrm{JES}) + (1 - f_t)\mathcal{P}_{bkg}(x, \mathrm{JES})$$



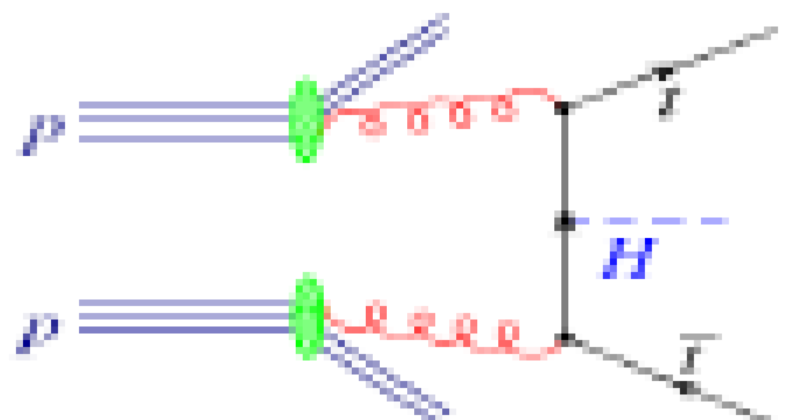
Gluon Fusion



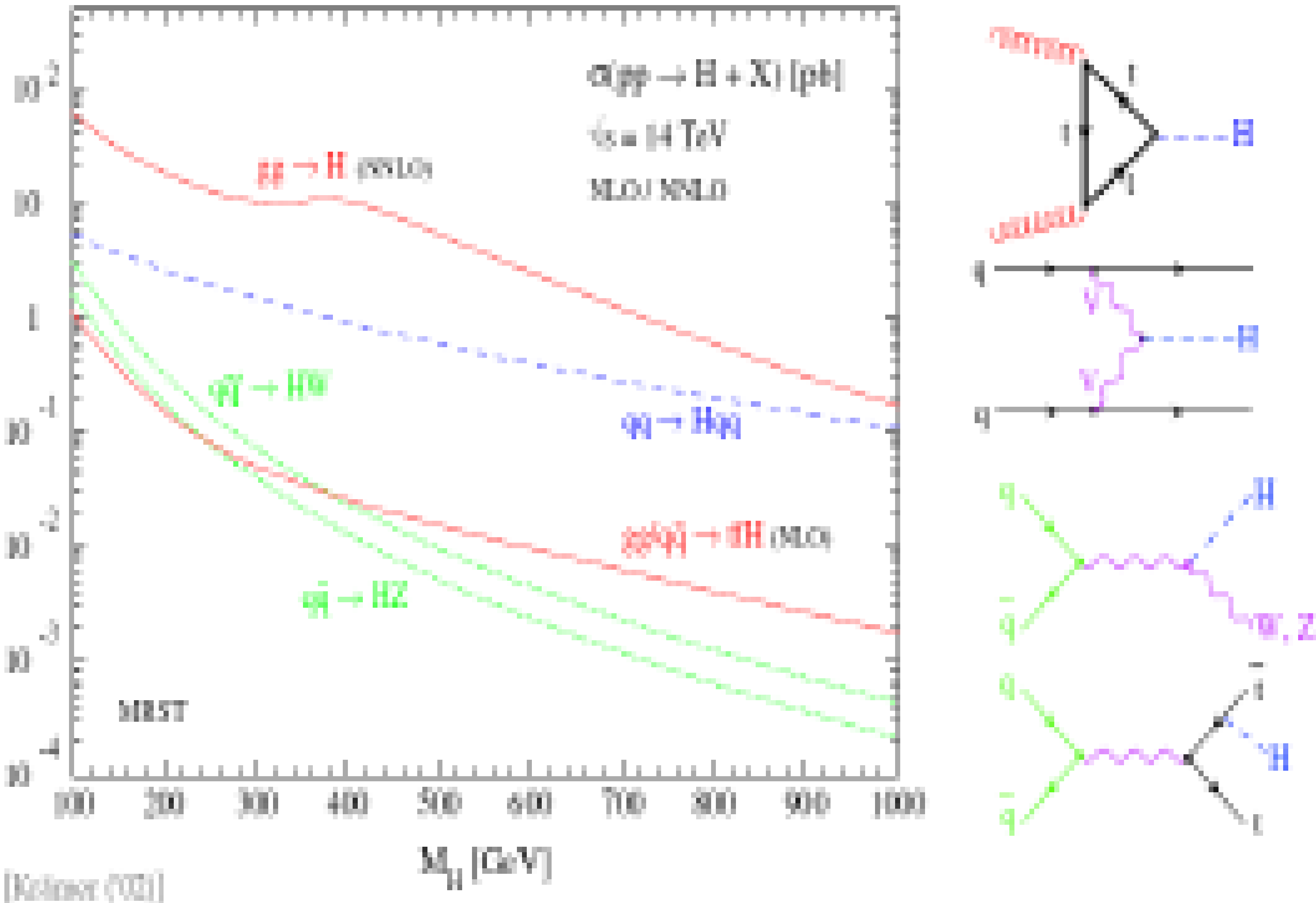
Vector Boson Fusion



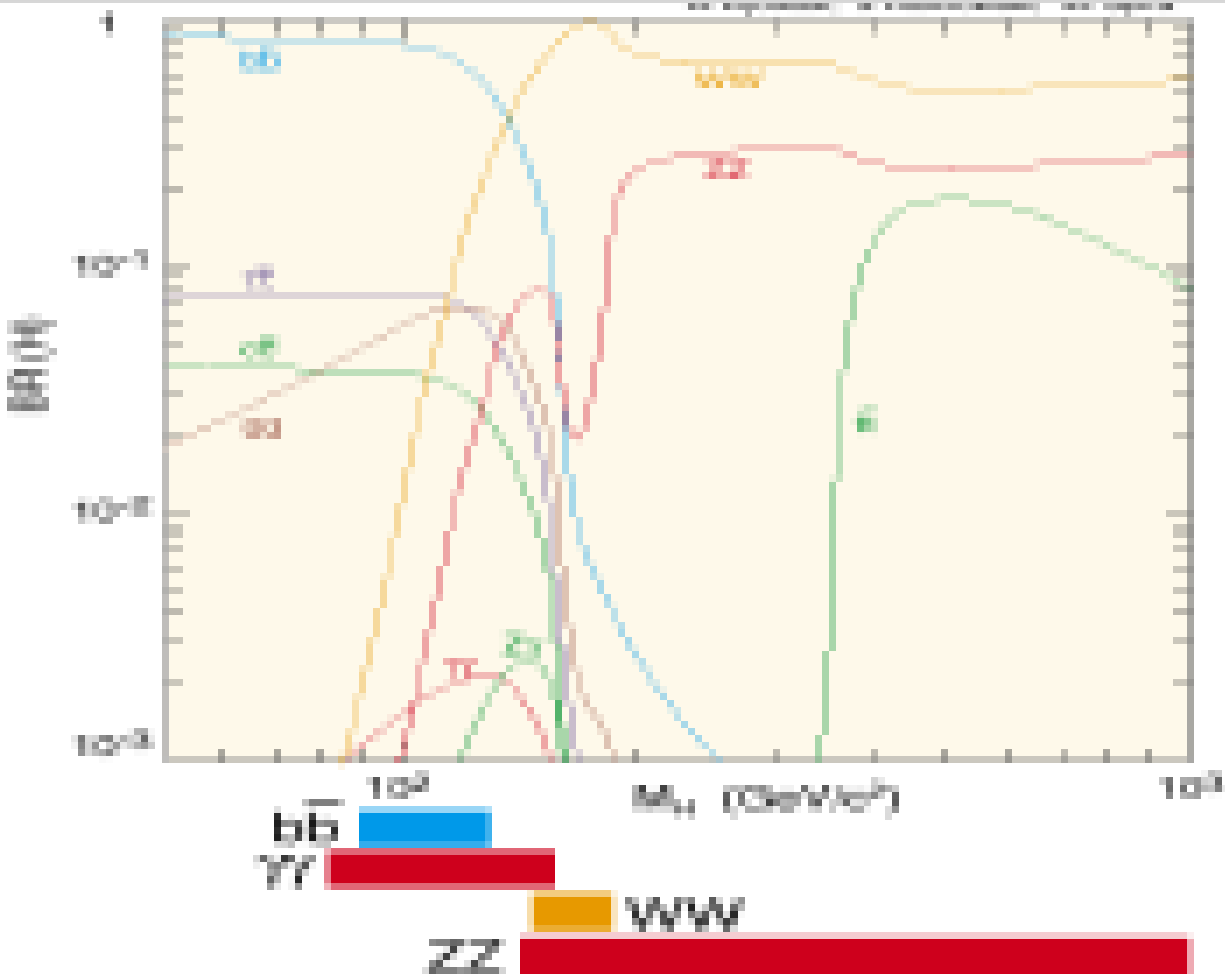
Higgs-strahlung



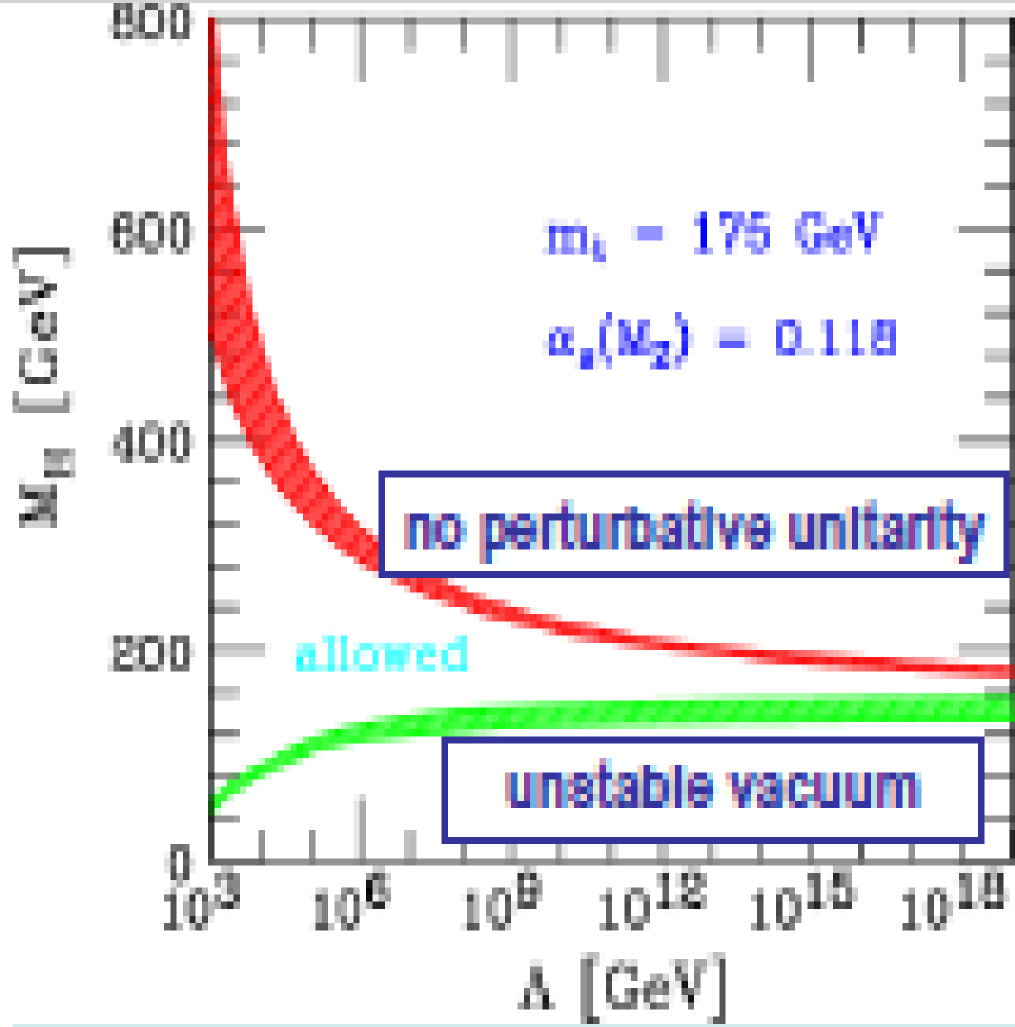
ttbar H ("associated" production)



Higgs width ~ (m_H)



1
BR(H)
WW
ZZ
10^2
M_H (GeV/c^2)
10^3
bb̄
γγ
WW
ZZ



Upper bound

(triviality) :

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

Lower bound

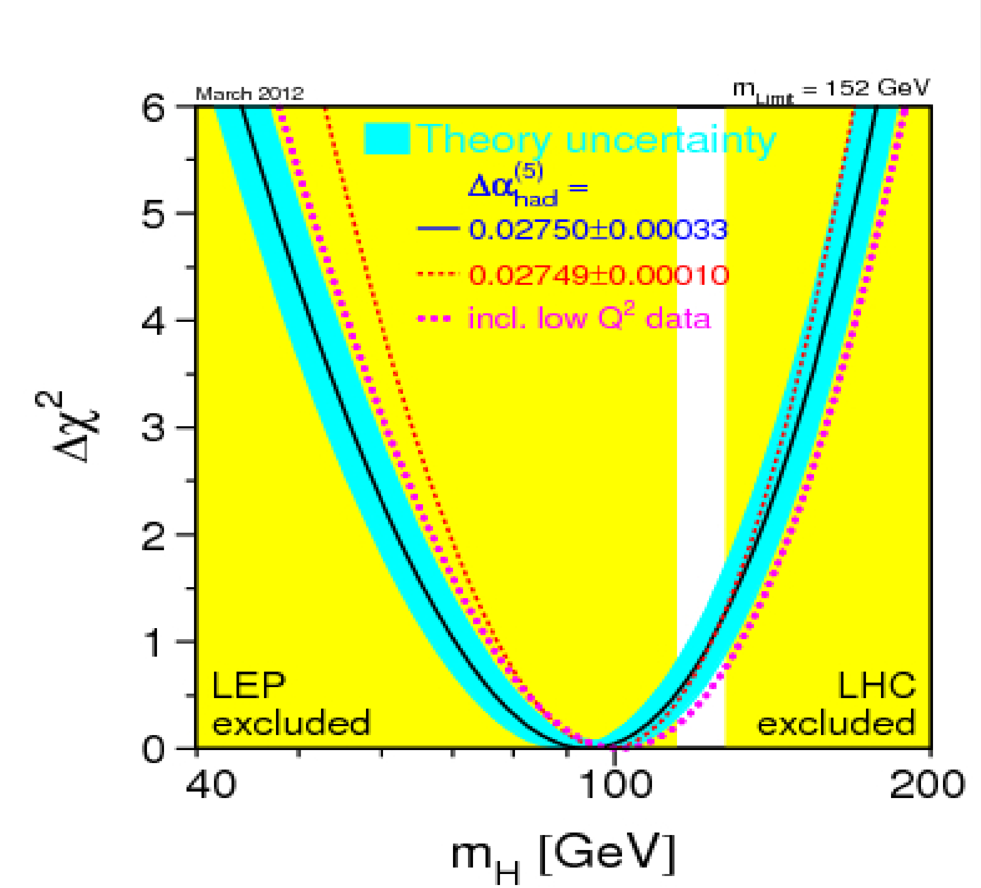
(vacuum stability) :

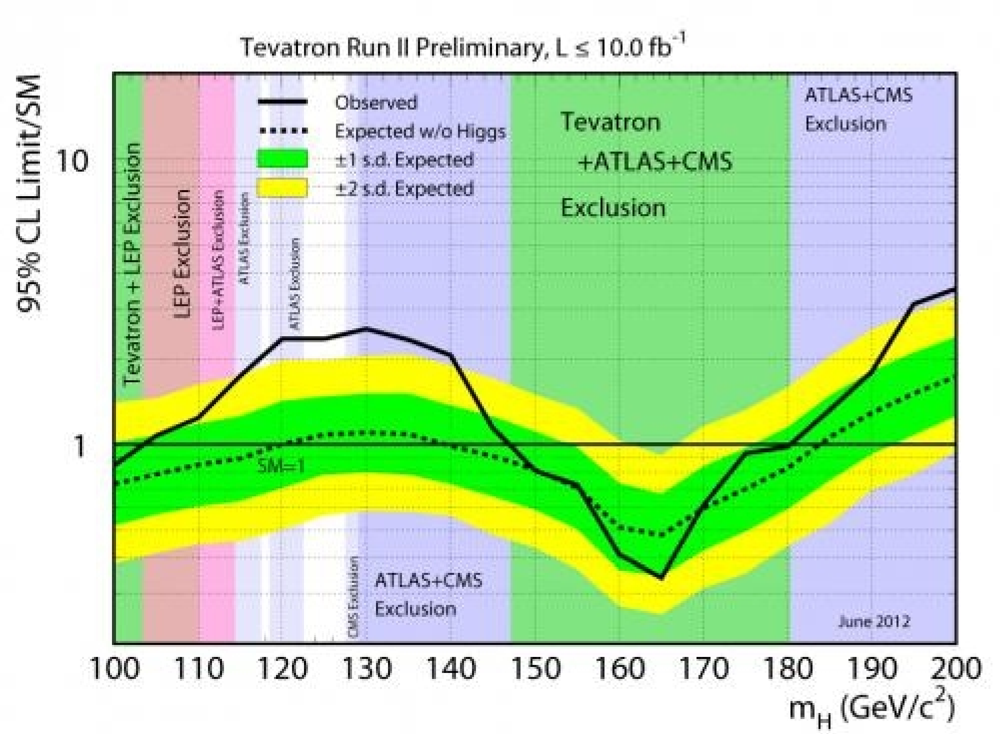
$$M_H^2 > \frac{3G_F\sqrt{2}}{8\pi^2} F \log\left(\Lambda^2 / v^2\right)$$

(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

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





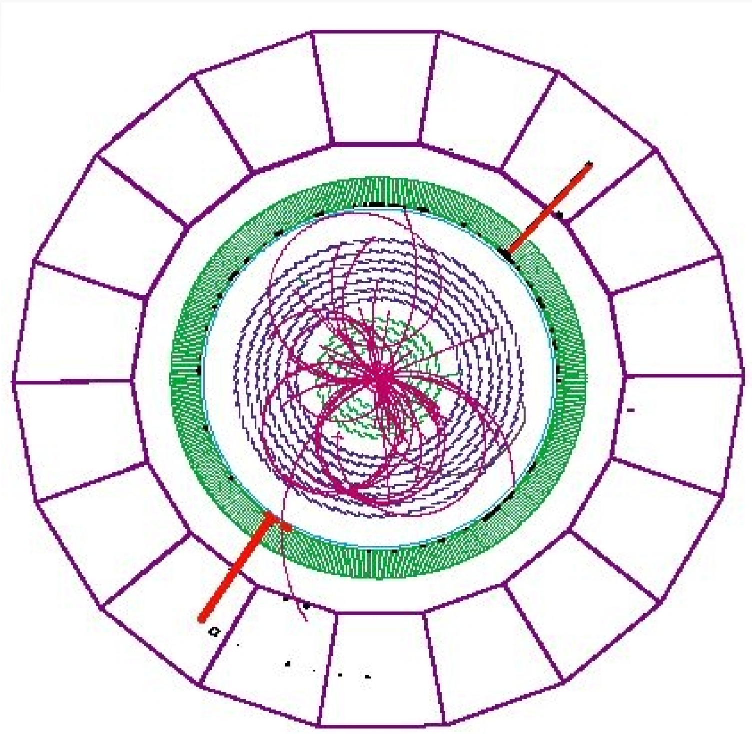
Best-fit value already escluded by LEP; ”big desert” scenario soon to be excluded by Tevatron?

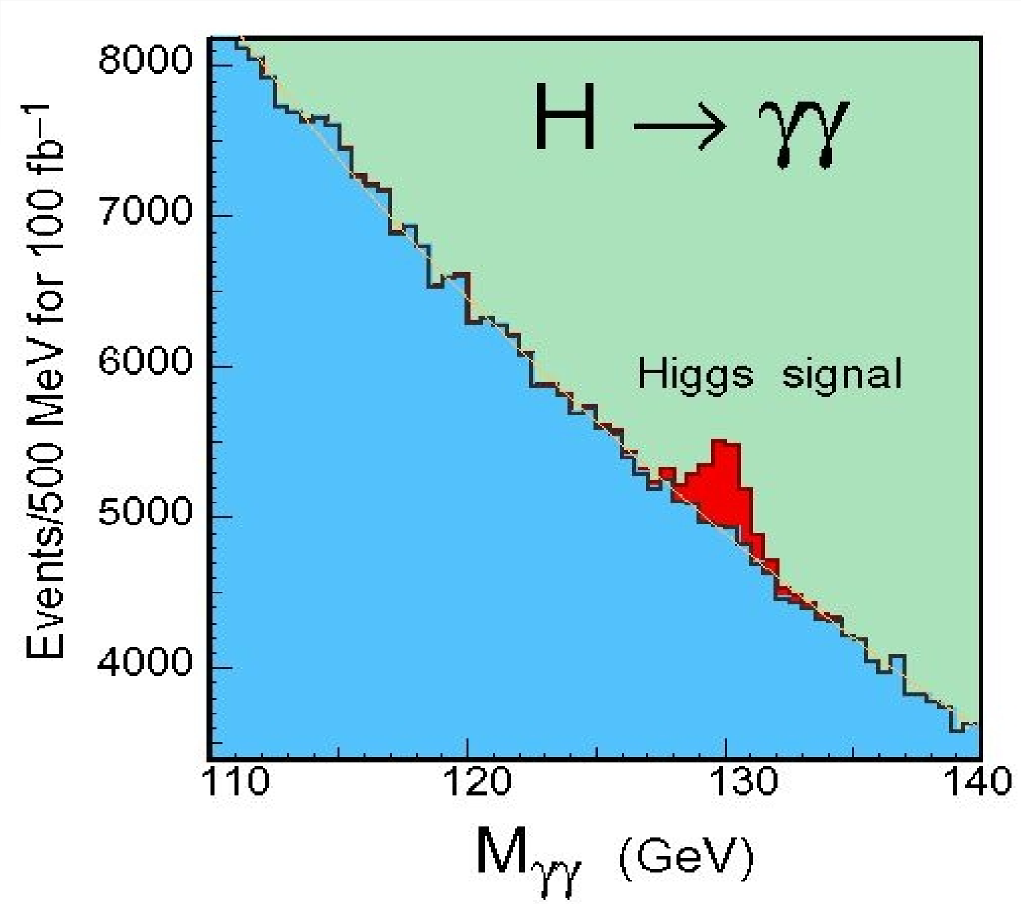
Only unknown is mass, so we are searching in several channels, depending on our bet on the Higgs mass:

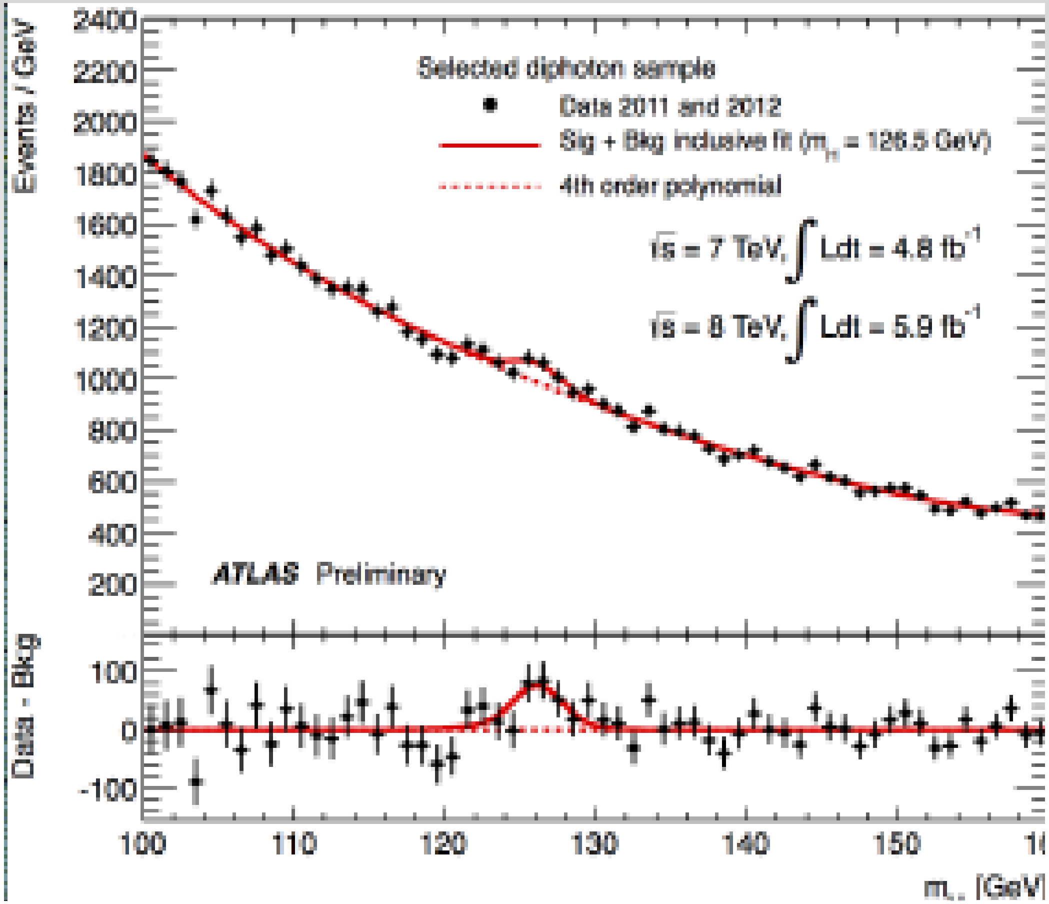
- Light Higgs: 114 < mH < 140
  - $H \rightarrow \gamma\gamma$, $qqH \rightarrow qq\tau\tau$
  - $qqH \rightarrow qq\, WW^*$, $ttH \rightarrow ttbb$
- As soon as two (even virtual) vector bosons can be produced
  - $H \rightarrow WW^{(*)}$
  - $H \rightarrow ZZ^{(*)}$, ZH->llbb
- At high masses, the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

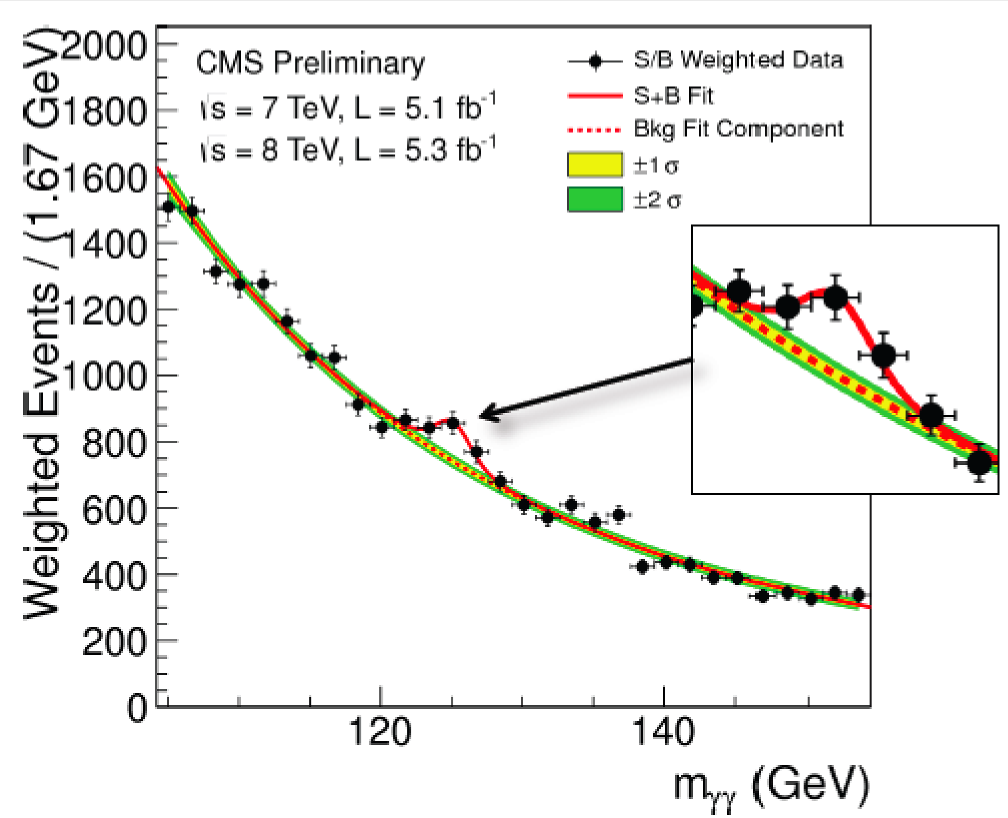
$\gamma\gamma$

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

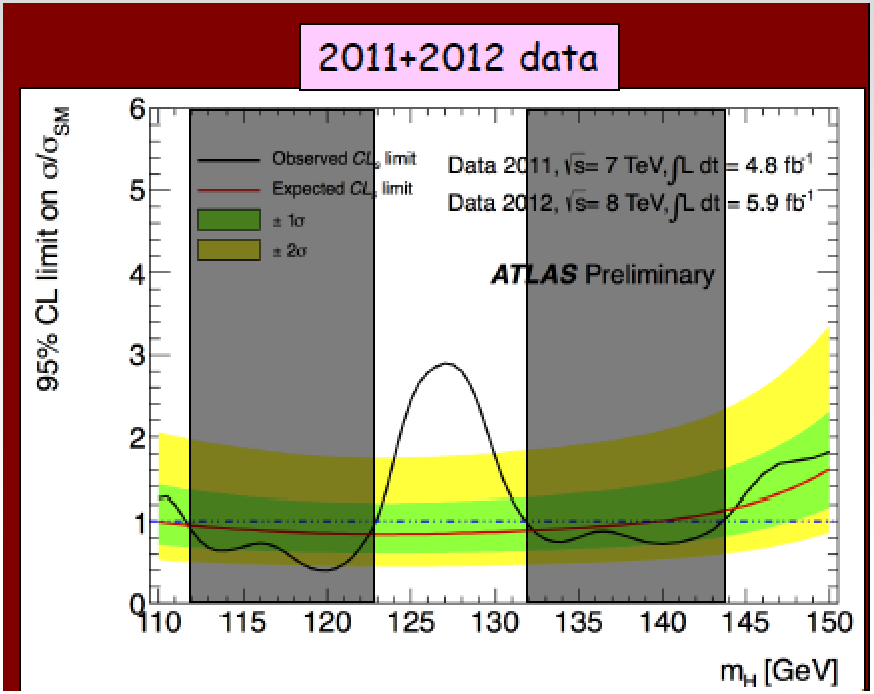


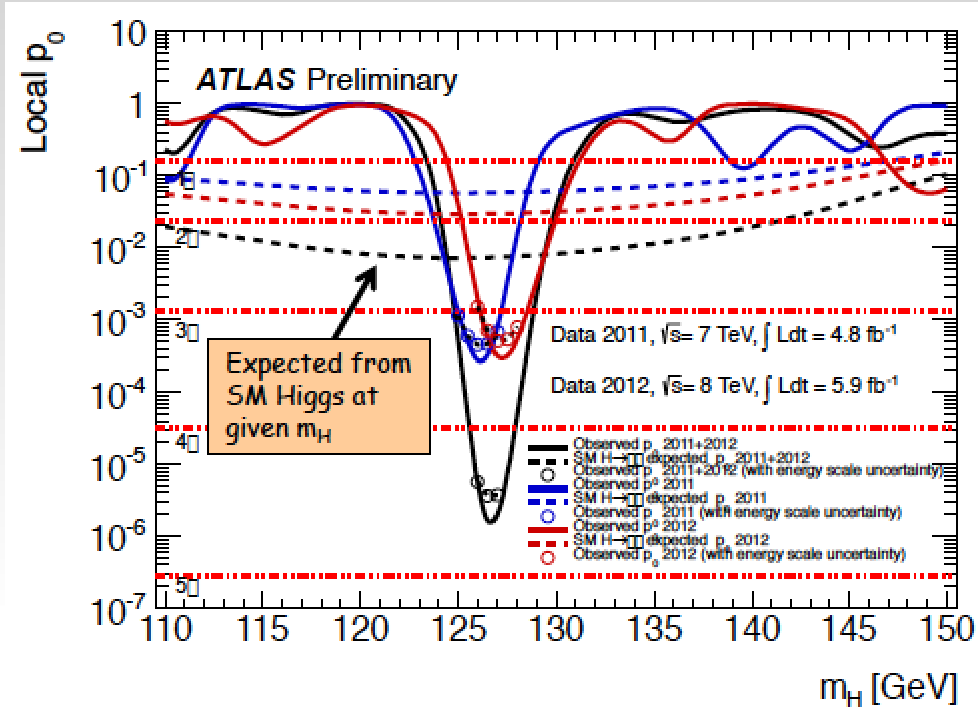


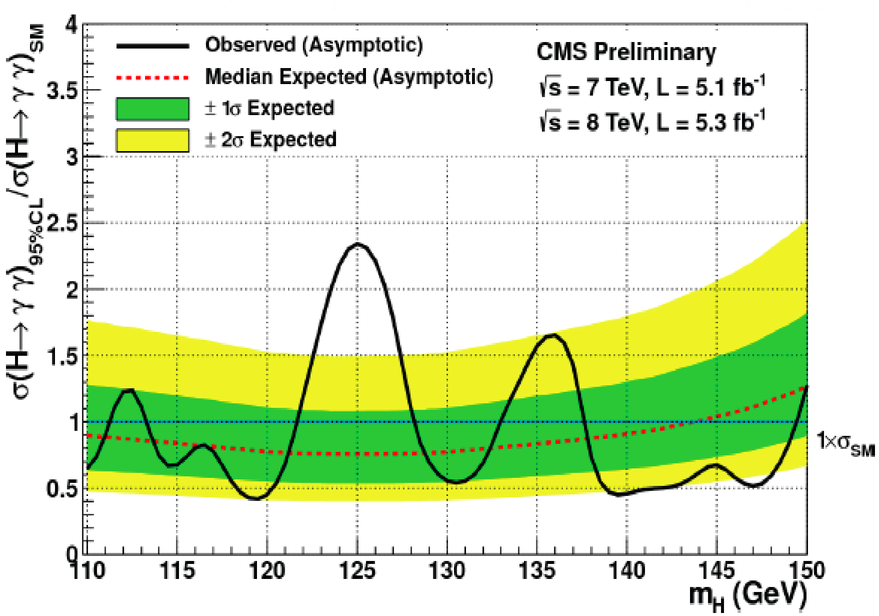




Despite complementary detector technologies, and resolutions (better in energy for CMS, better in angle for ATLAS), width and strength of observed peaks are the same!



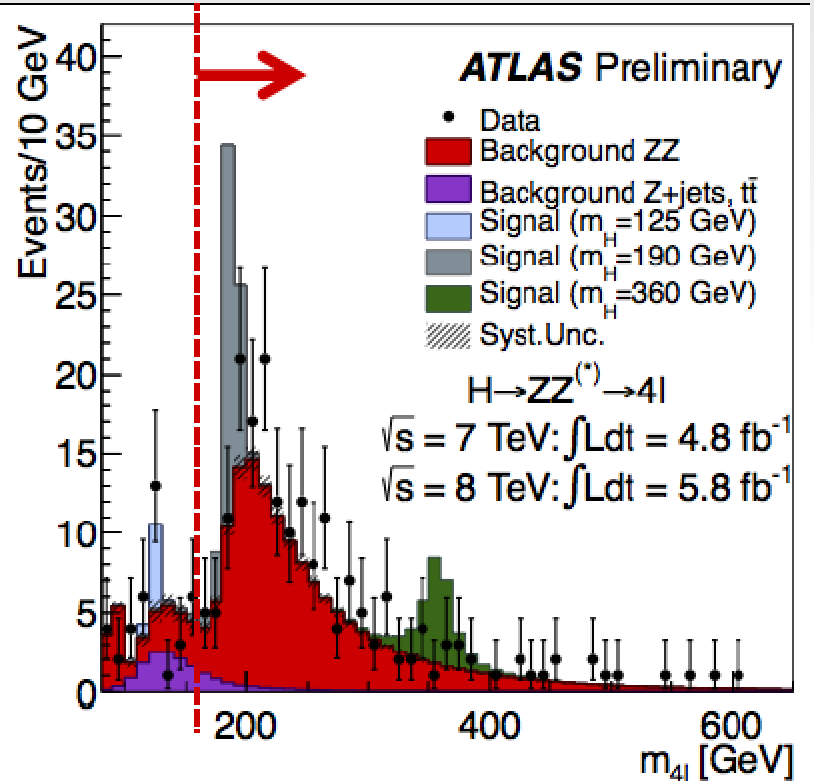


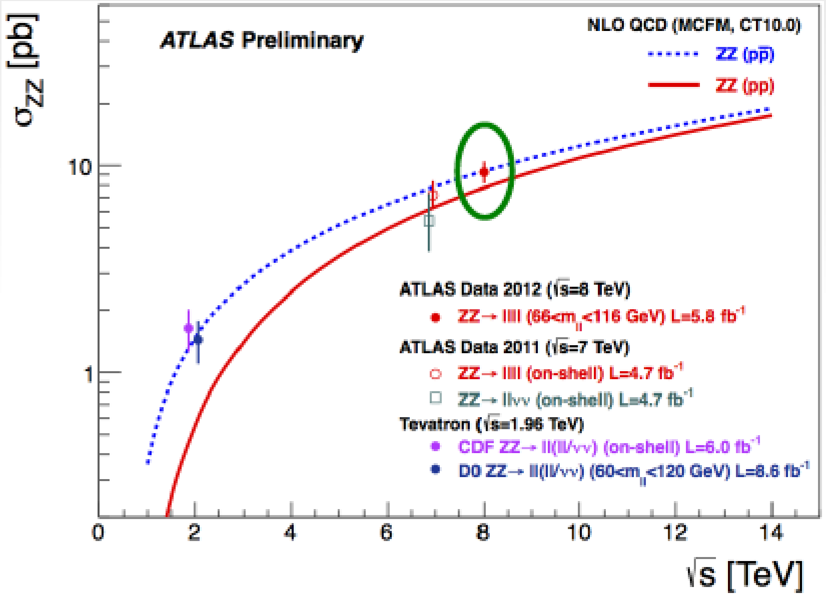


Very similar signal in both experiments, with a σ*BR twice as much as expected from the Higgs (but compatible within errors).

Is it just "discovery bias"?

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

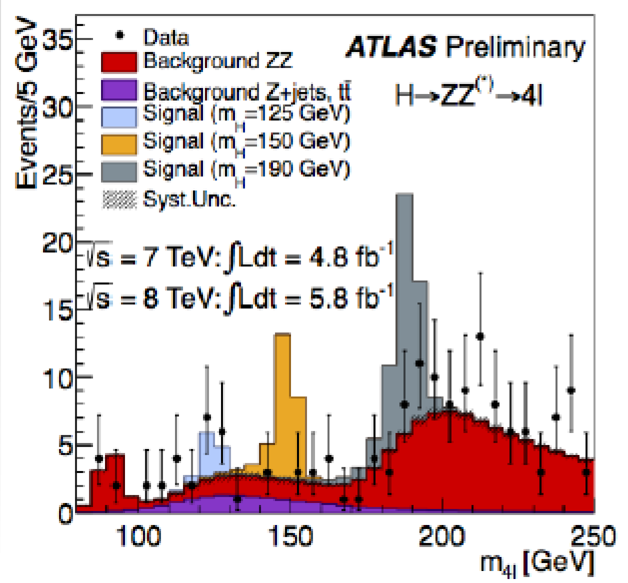




ZZ invariant mass spectrum well reproduced, and measured cross-section in agreement with NLO predictions

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

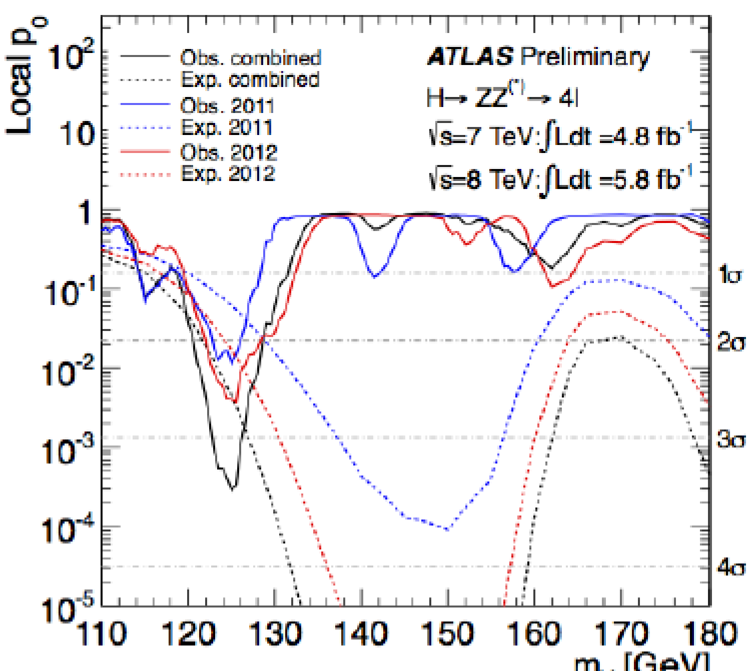
2011+2012 data

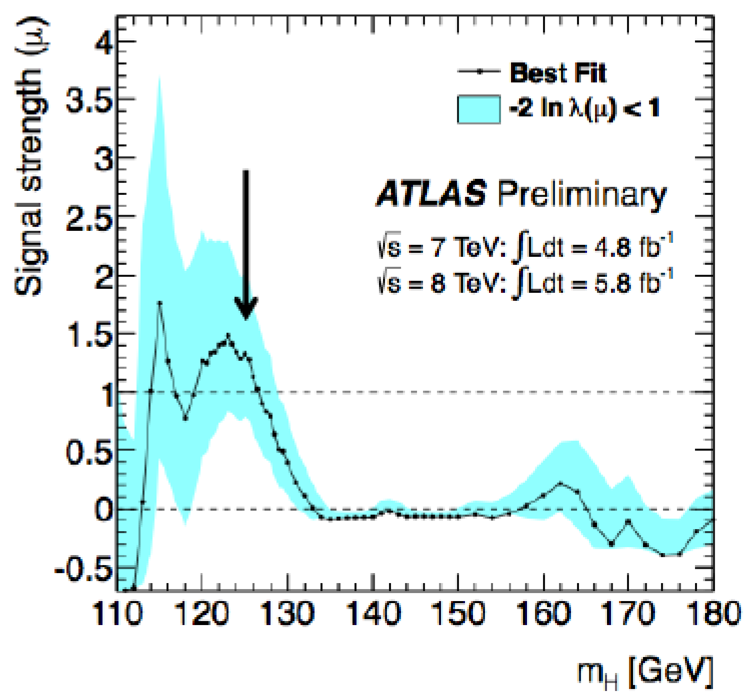


In the region 125 ± 5 GeV

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

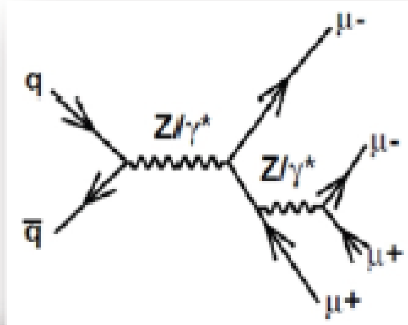
2011+ 2012	4μ	2e2μ	4e
Data	6	5	2
Expected S/B	1.6	1	0.5
Reducible/total background	5%	45%	55%

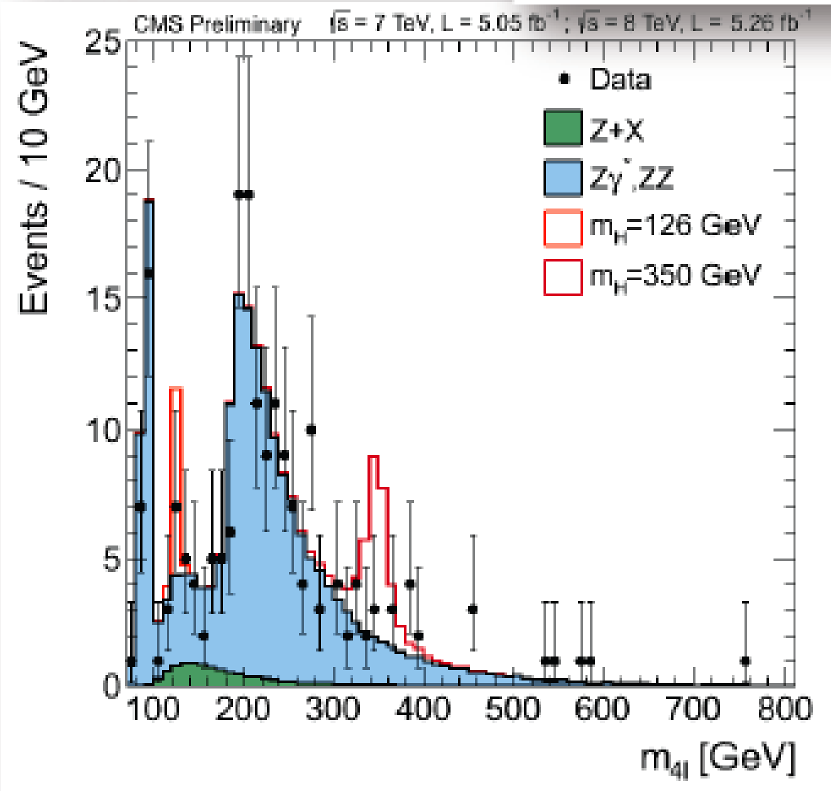


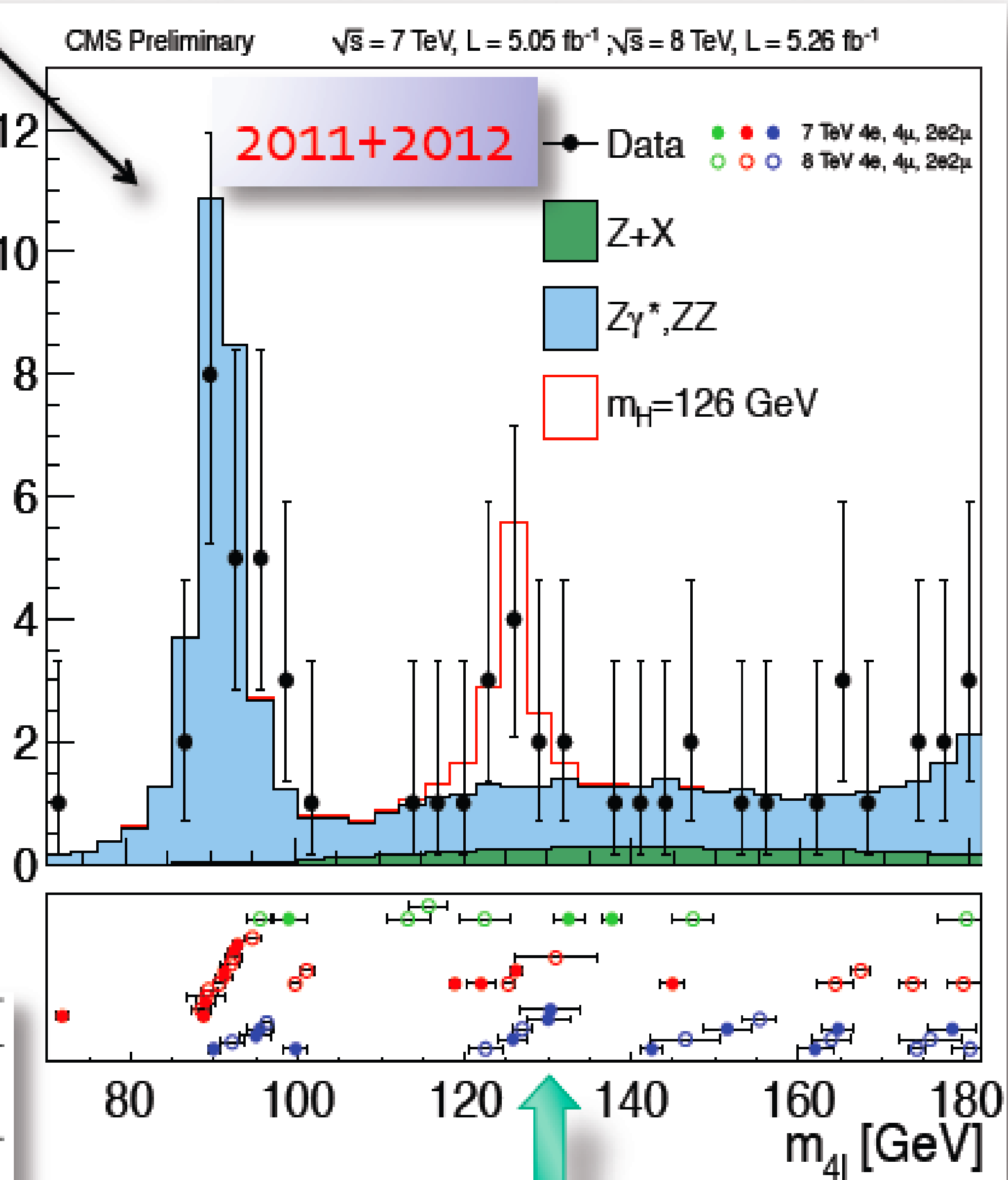


Excess seen in same region as in γγ

Results: m(4l) spectrum







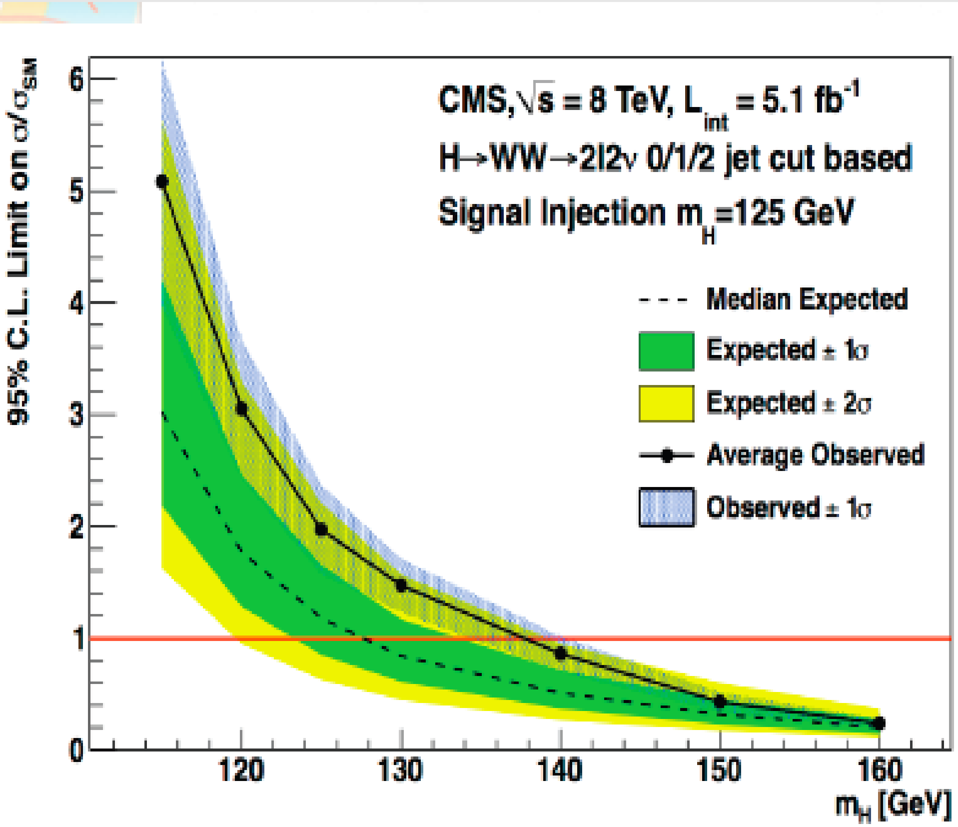
Yields for m(4l)=110..160 GeV

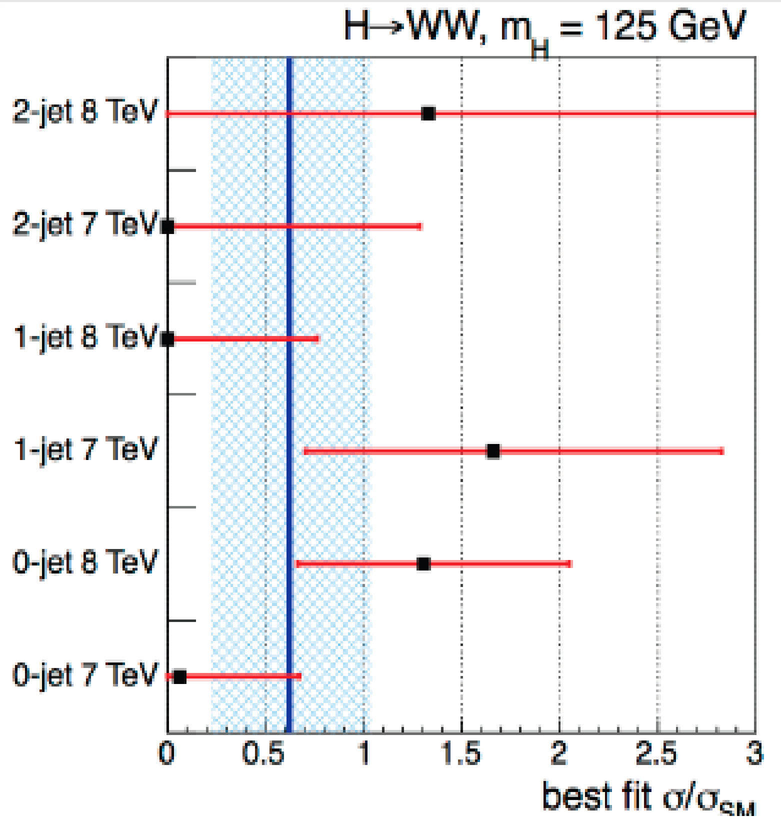
Channel	4e	4μ	2e2μ	4ℓ
ZZ background	2.65 ± 0.31	5.65 ± 0.59	7.17 ± 0.76	15.48 ± 1.01
Z+X	$1.20^{+1.08}_{-0.78}$	$0.92^{+0.65}_{-0.55}$	$2.29^{+1.81}_{-1.36}$	$4.41^{+2.21}_{-1.66}$
All backgrounds	$3.85^{+1.12}_{-0.84}$	$6.58^{+0.88}_{-0.81}$	$9.46^{+1.96}_{-1.56}$	$19.88^{+2.43}_{-1.95}$
$m_H = 126$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

164 events expected in [100, 800 GeV]

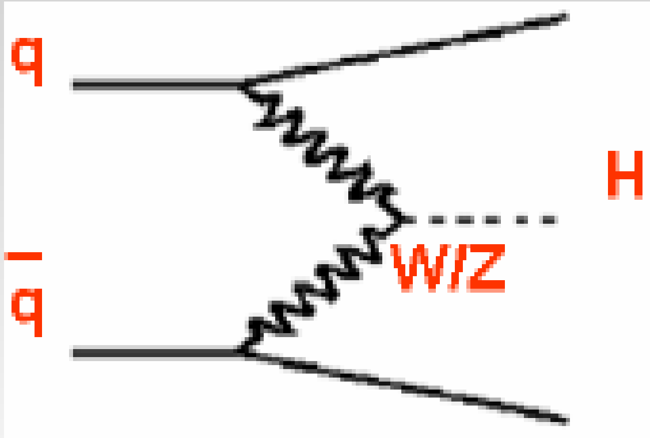
172 events observed in [100, 800 GeV]

Event-by-event errors

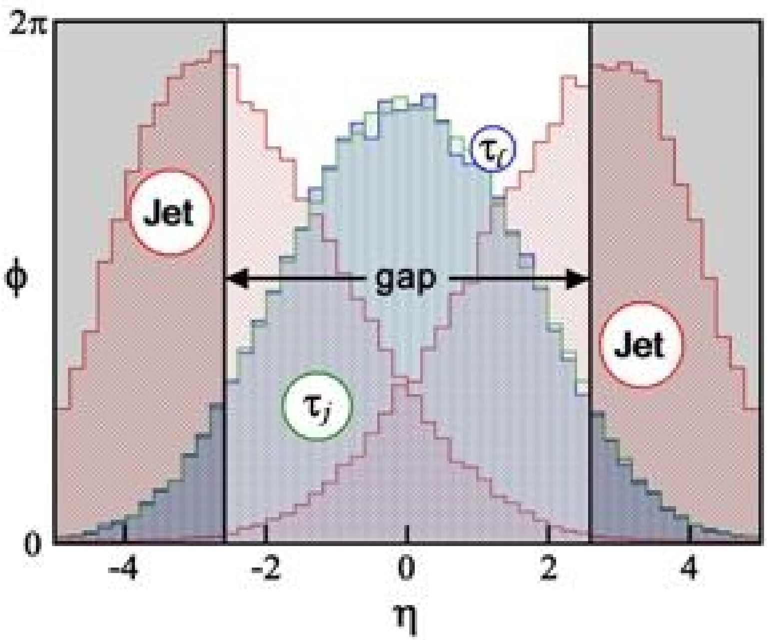


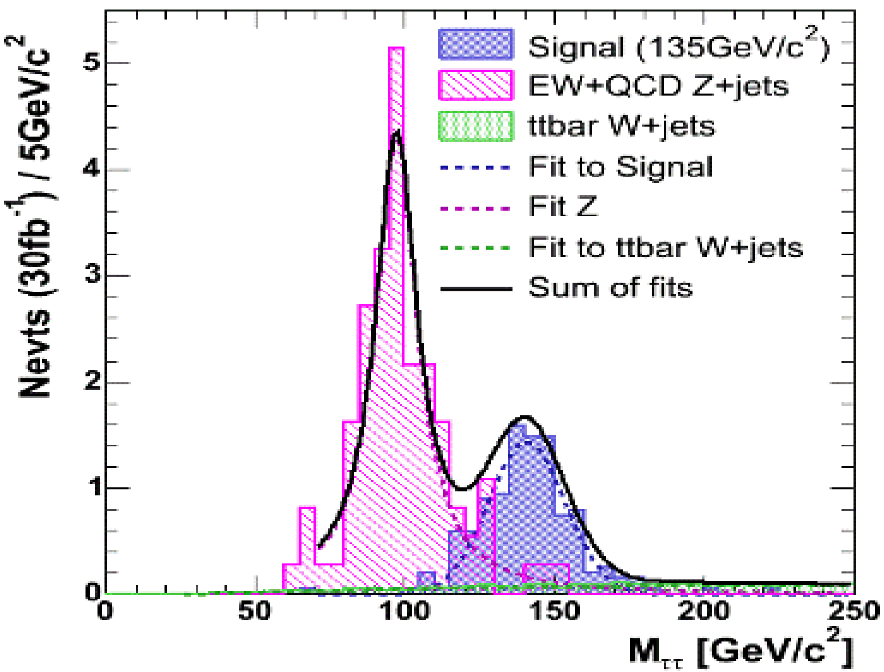


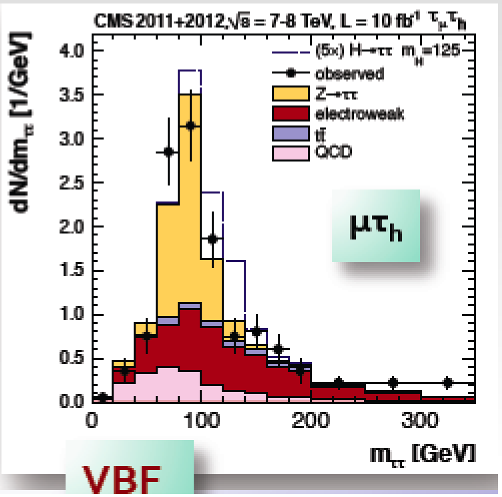
- Similar result recently published by ATLAS

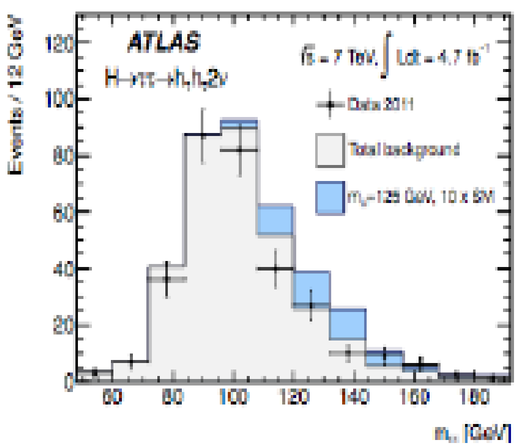


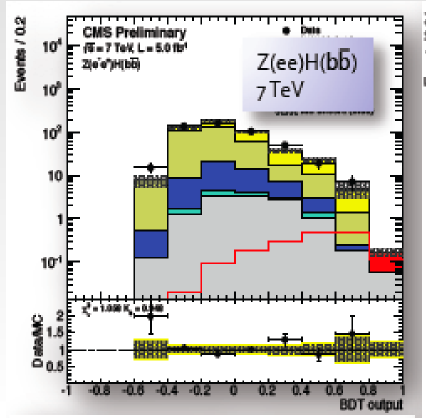
- Remnants of the final-state quarks emitted in the forward region (up to $\eta \sim 3.5$)
- Hard scattering has no colour flow between the two jets → rapidity gap between them
- It would be a very clean signature, if not for the UE and pileup!
- Depending on mass, look for $\tau\tau$ or WW decays

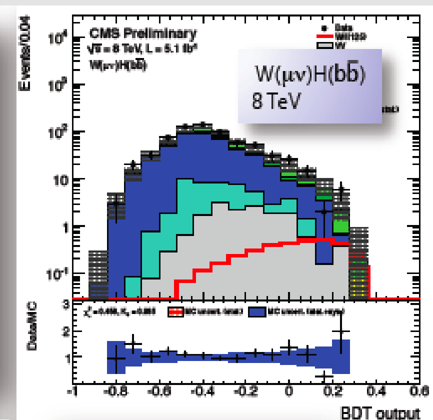




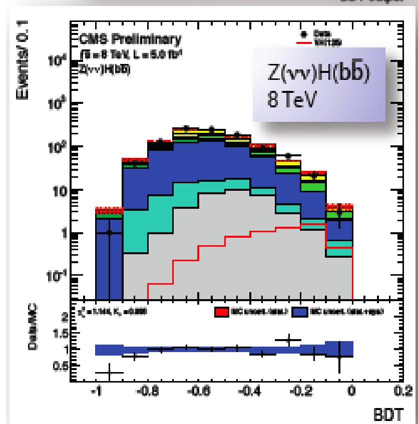


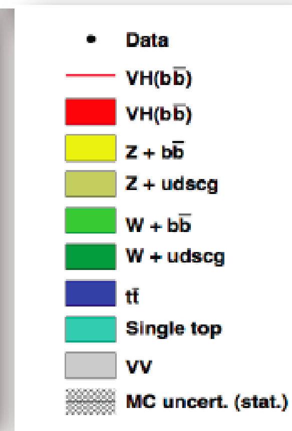


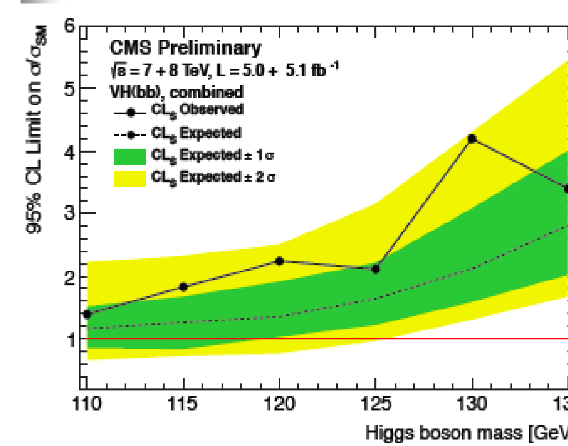




- Observed limits:
  - Compatible with either background or signal from a 125 GeV Higgs



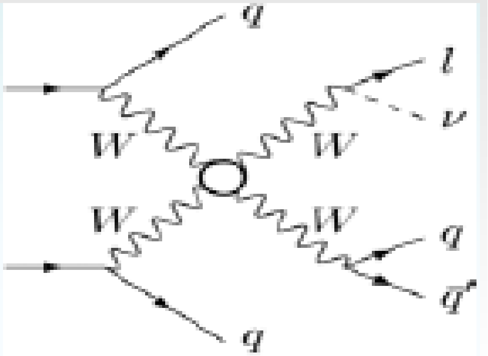




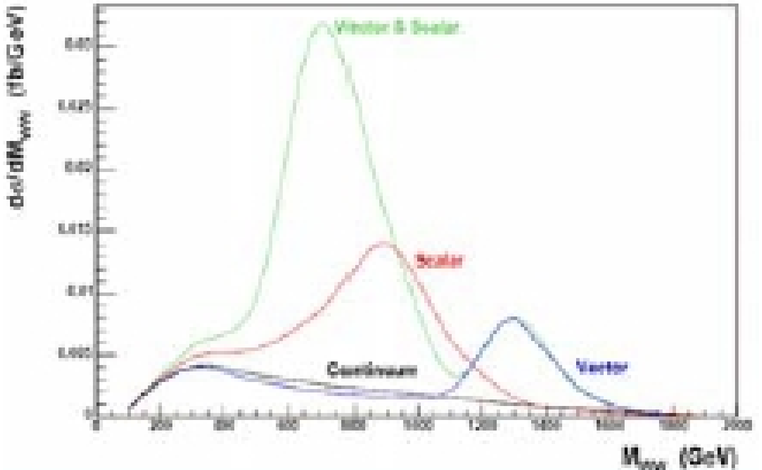
H->ττ

H->bb

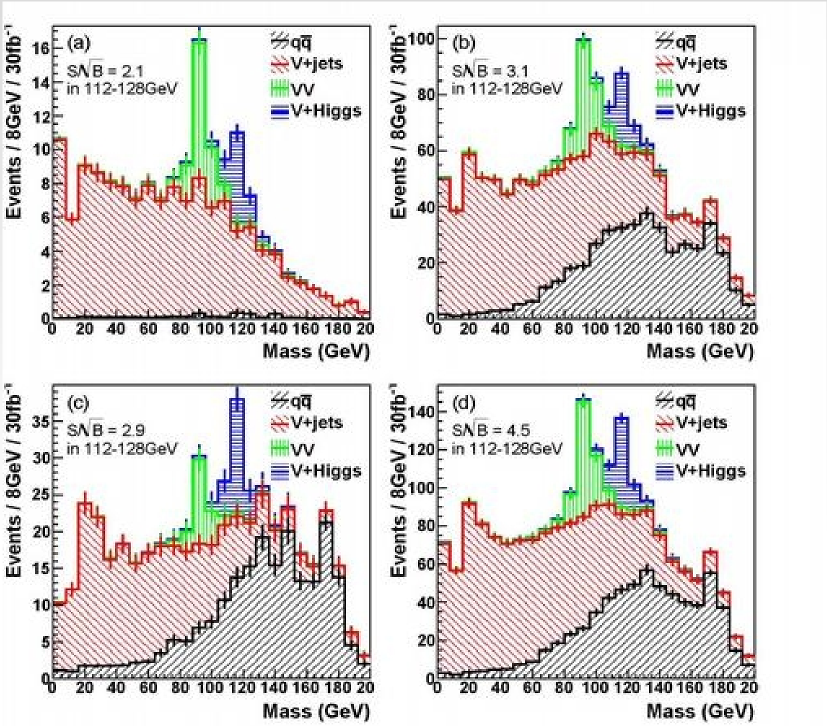
- Apart for giving mass to all other particles, the Higgs is needed in the SM to stabilise the $W_L W_L \rightarrow W_L W_L$ scattering process
- This cross section is divergent in the SM, but if the Higgs is there a diagram with Higgs exchange restores finiteness



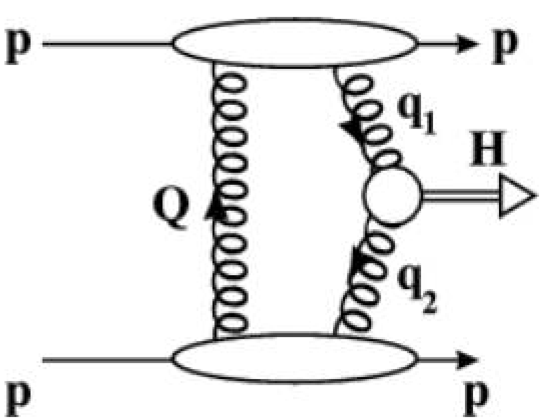
- Does not work if Higgs is too heavy, in that case some other resonance could be produced in WW final states
- More than one Higgs could be present, even in a pure SM scenario, with broad mass spectrum

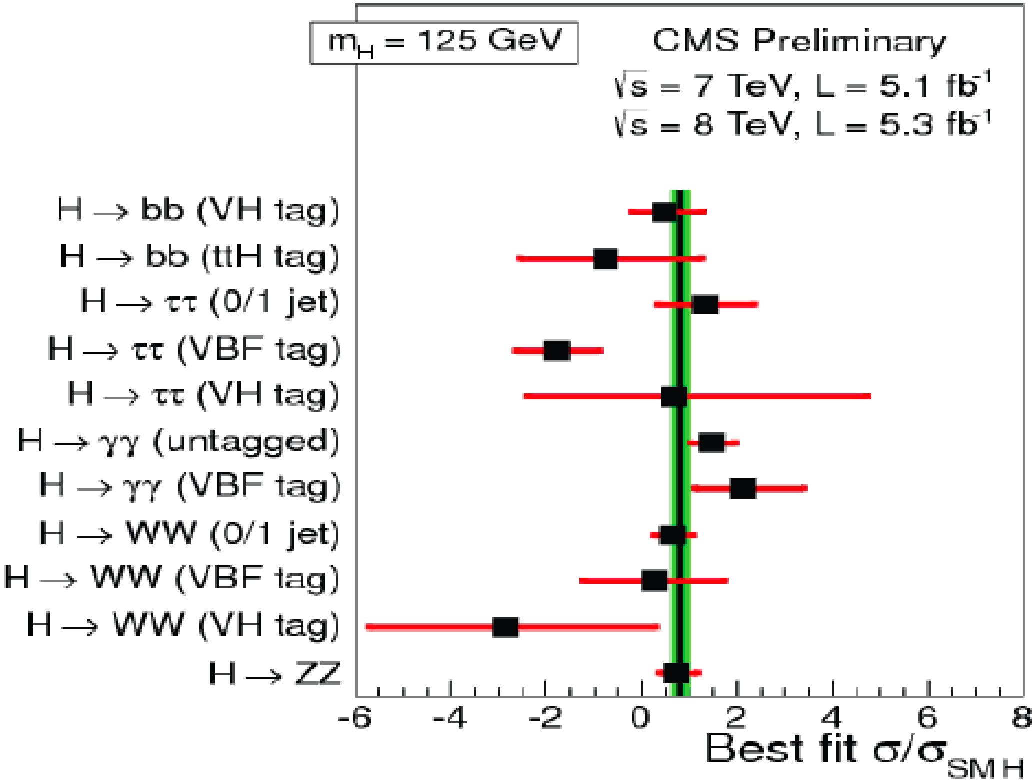


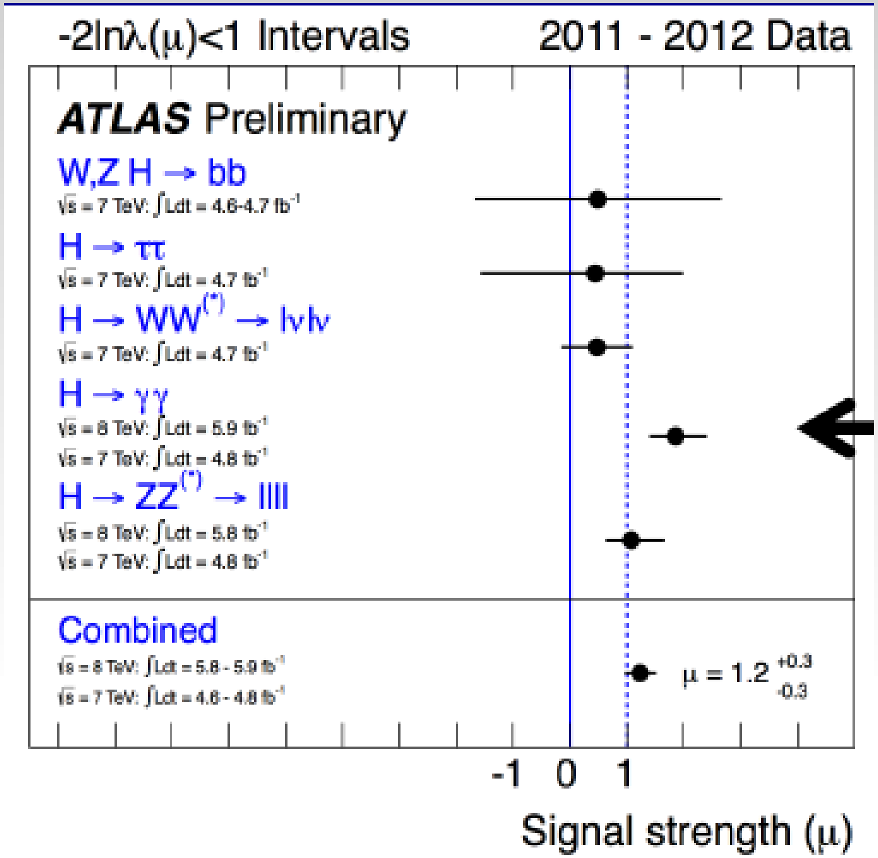
- HZ: S/BG ratio increases for high-Pt Higgs. In that case, and for the main decay channel H->bb, Higgs decay channels end up in a single jet, substructure used to find it

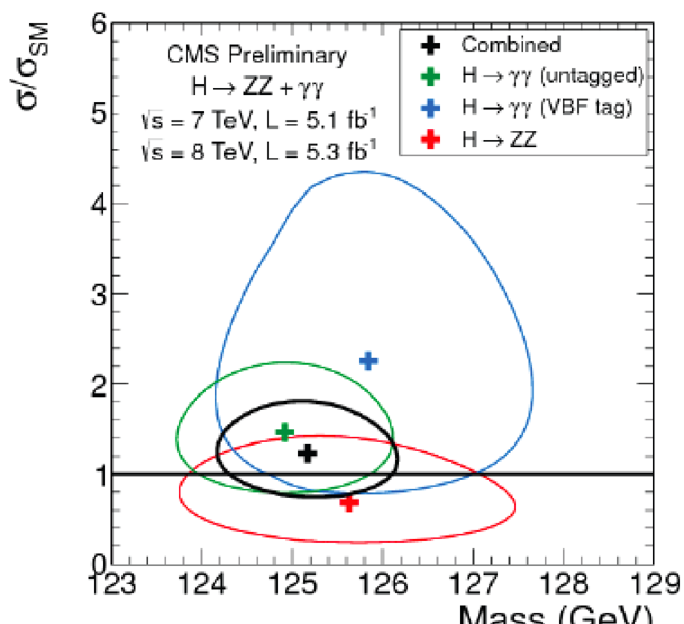


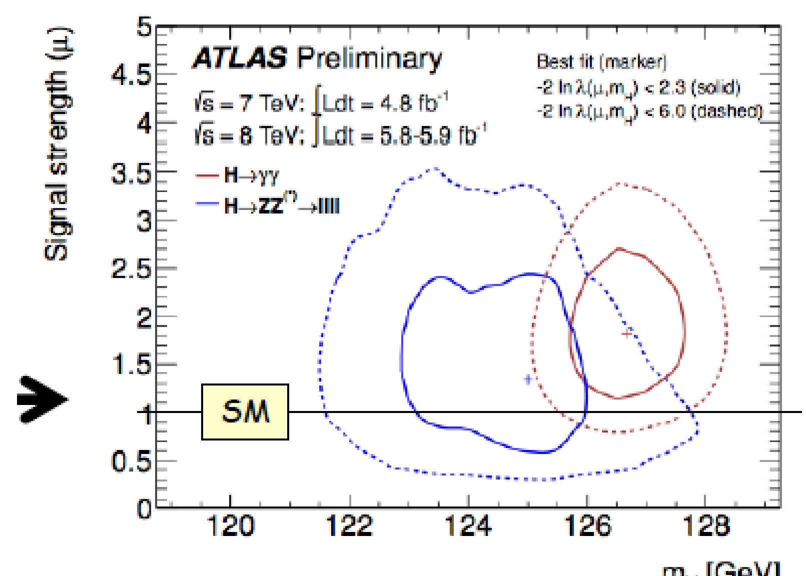
- Diffractive Higgs: Higgs can be produced in diffractive mode, with the two protons stay intact after collision. Only possible with 1^{++} quantum numbers, requires installation of forward proton taggers



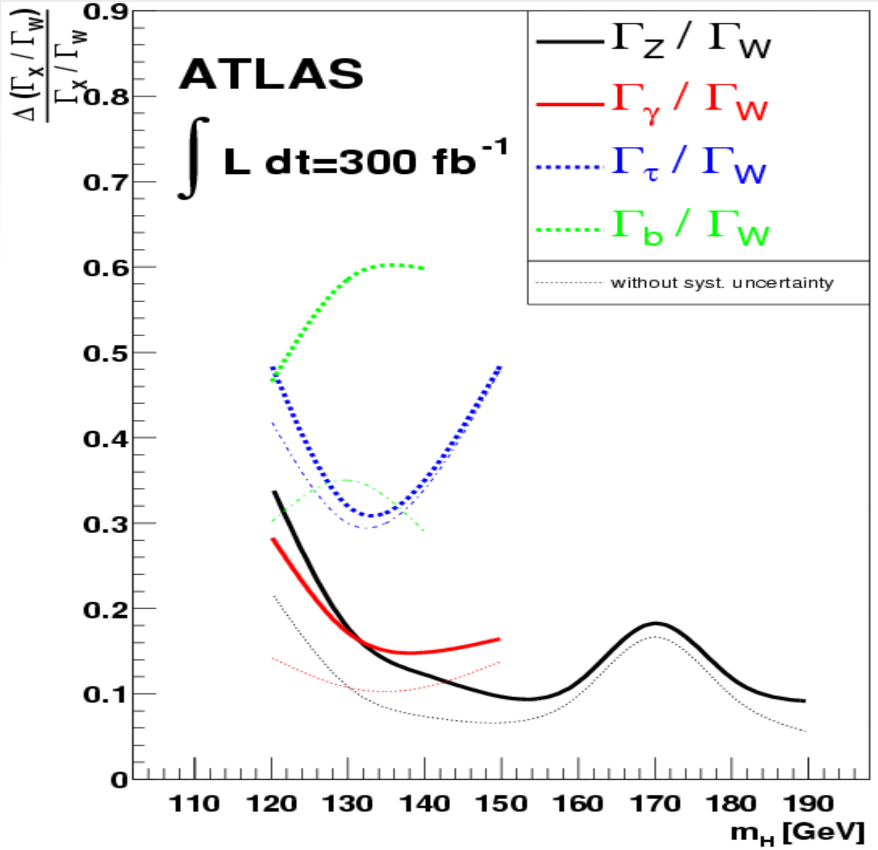

m_H = 125 GeV
CMS Preliminary
√s = 7 TeV, L = 5.1 fb⁻¹
√s = 8 TeV, L = 5.3 fb⁻¹
H → bb (VH tag)
H → bb (ttH tag)
H → ττ (0/1 jet)
H → ττ (VBF tag)
H → ττ (VH tag)
H → γγ (untagged)
H → γγ (VBF tag)
H → WW (0/1 jet)
H → WW (VBF tag)
H → WW (VH tag)
H → ZZ
-6 -4 -2 0 2 4 6 8
Best fit σ/σ_SM H

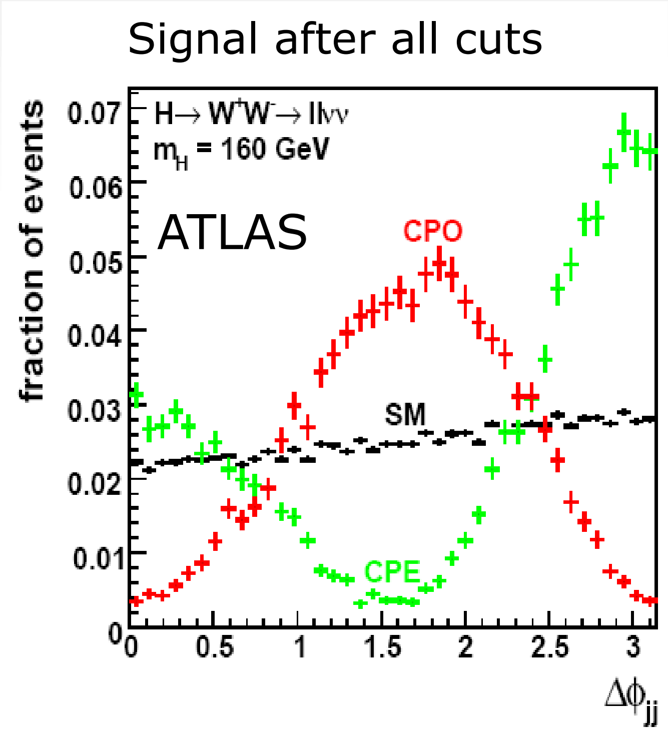

-2lnλ(μ)<1 Intervals
2011 - 2012 Data
ATLAS Preliminary
W,Z H → bb
√s = 7 TeV: ∫Ldt = 4.6-4.7 fb⁻¹
H → ττ
√s = 7 TeV: ∫Ldt = 4.7 fb⁻¹
H → WW(*) → lνlν
√s = 7 TeV: ∫Ldt = 4.7 fb⁻¹
H → γγ
√s = 8 TeV: ∫Ldt = 5.9 fb⁻¹
√s = 7 TeV: ∫Ldt = 4.8 fb⁻¹
H → ZZ(*) → llll
√s = 8 TeV: ∫Ldt = 5.8 fb⁻¹
√s = 7 TeV: ∫Ldt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


CMS Preliminary
H → ZZ + γγ
√s = 7 TeV, L = 5.1 fb⁻¹
√s = 8 TeV, L = 5.3 fb⁻¹
Combined
H → γγ (untagged)
H → γγ (VBF tag)
H → ZZ
σ/σ_SM
Mass (GeV)

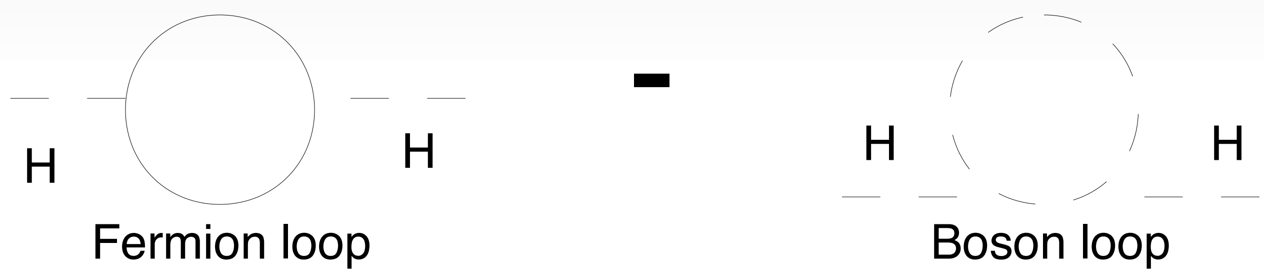

ATLAS Preliminary
√s = 7 TeV: ∫Ldt = 4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 5.8-5.9 fb⁻¹
Best fit (marker)
-2 ln λ(μ,m_H) < 2.3 (solid)
-2 ln λ(μ,m_H) < 6.0 (dashed)
H→γγ
H→ZZ(*)→llll
SM
Signal strength (μ)
m_H [GeV]

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

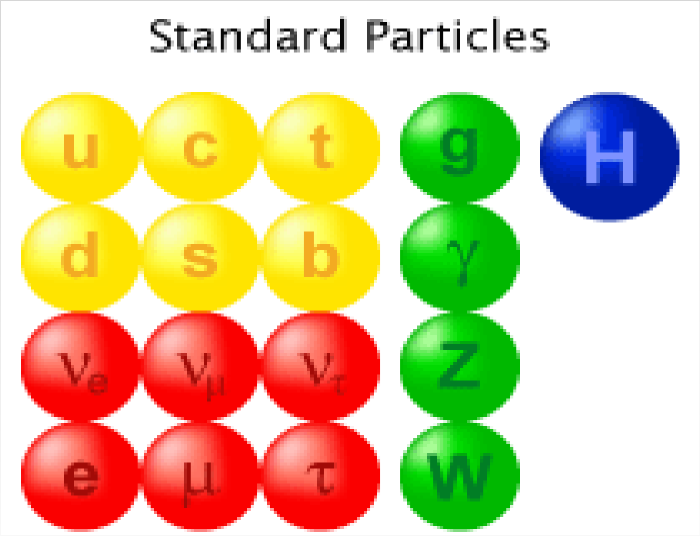


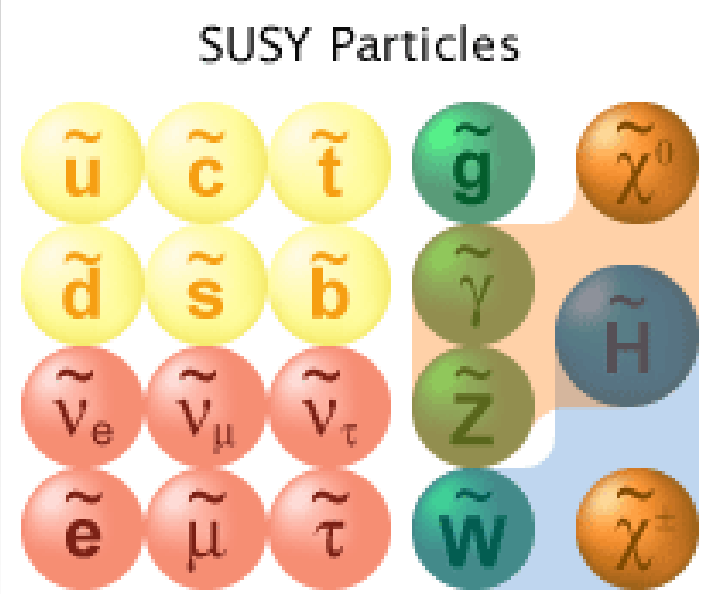


- Gravity not included → SM only low-energy effective theory valid to a scale Λ << Mplank
- The Higgs mass has a loop correcton $\delta m \sim \alpha\Lambda^2$, so to prevent it from becoming super-heavy it requires a compensation or unnatural fine-tuning of parameters



- 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





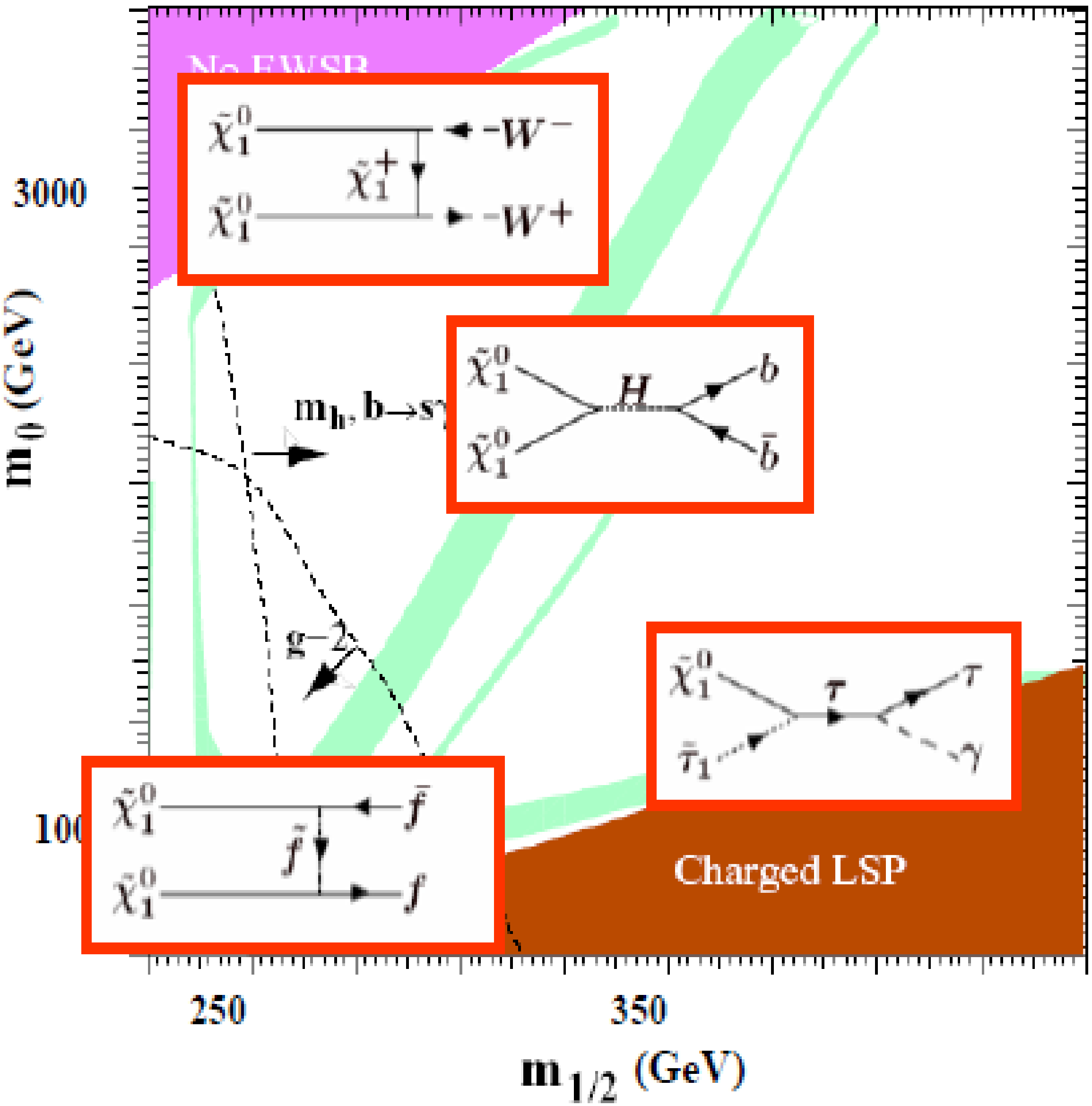
- SUSY equivalants of fermions have prefix s-
- SUSY equicalents of bosons have suffix -ino
- At least two Higgs doublets with lightest Higgs mass < 135 GeV (this can kill SUSY!)
- Charged Higgsinos mix with Winos → charginos
- Neutral Higgsinos mix with Zino/photino → neutralinos

- 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!)

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

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

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

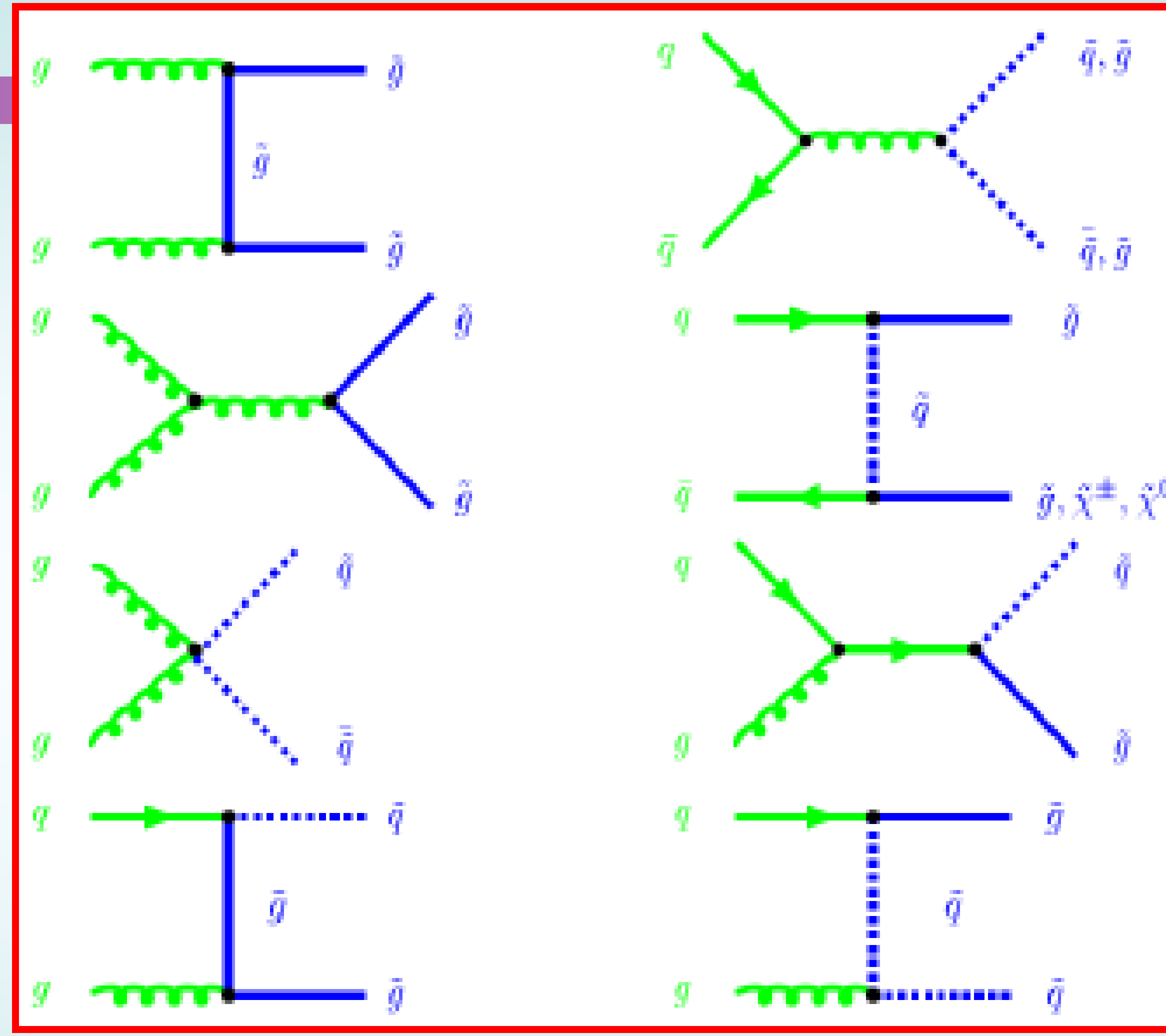
co-annihilation

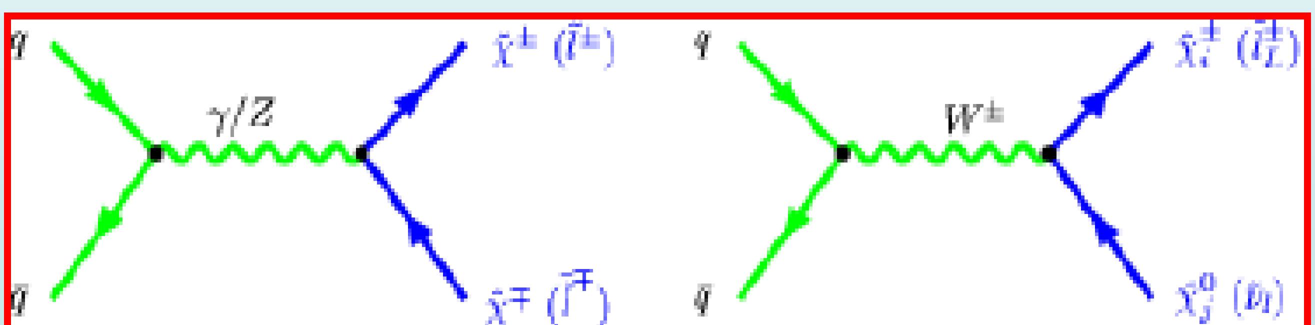
pure bino, small NLSP-LSP mass difference, typically coannihilation with stau

Higgs funnel

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

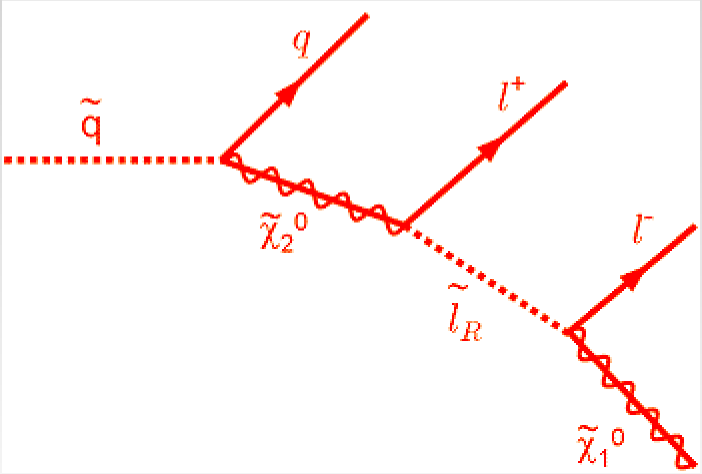
Squark/Gluino Production

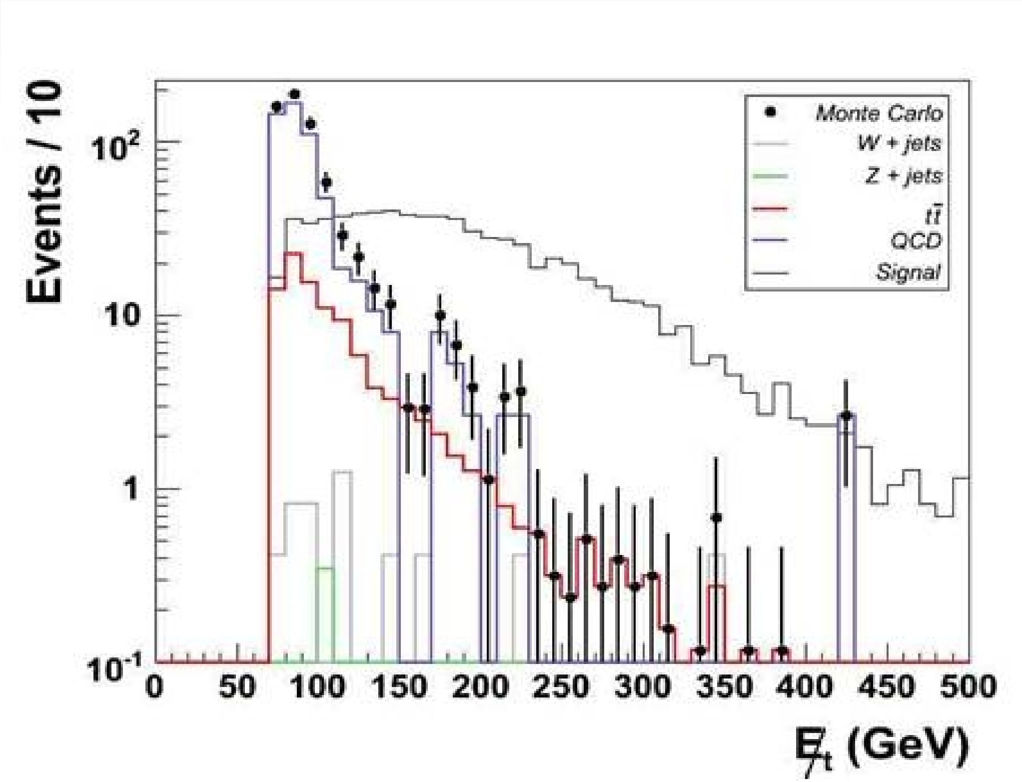


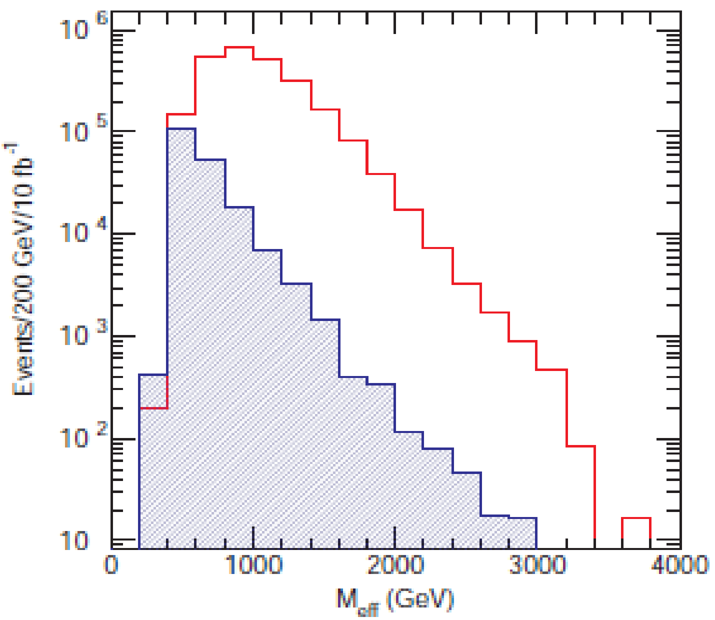


Direct Gaugino Production

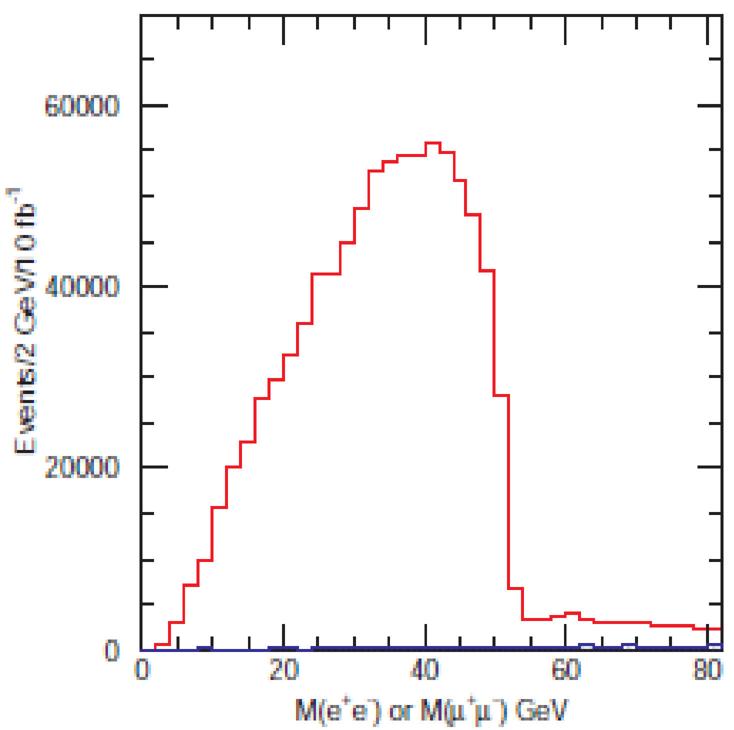
- Most SUSY channels involve several successive decays, until the LSP is reached.
- Signature of SUSY would be an excess in missing Et (or missing + visible Et)

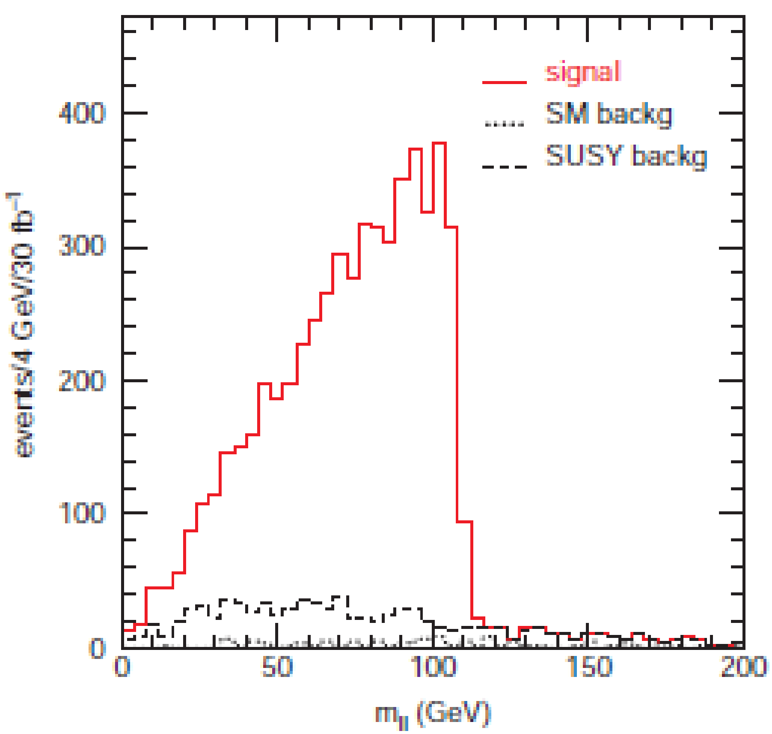




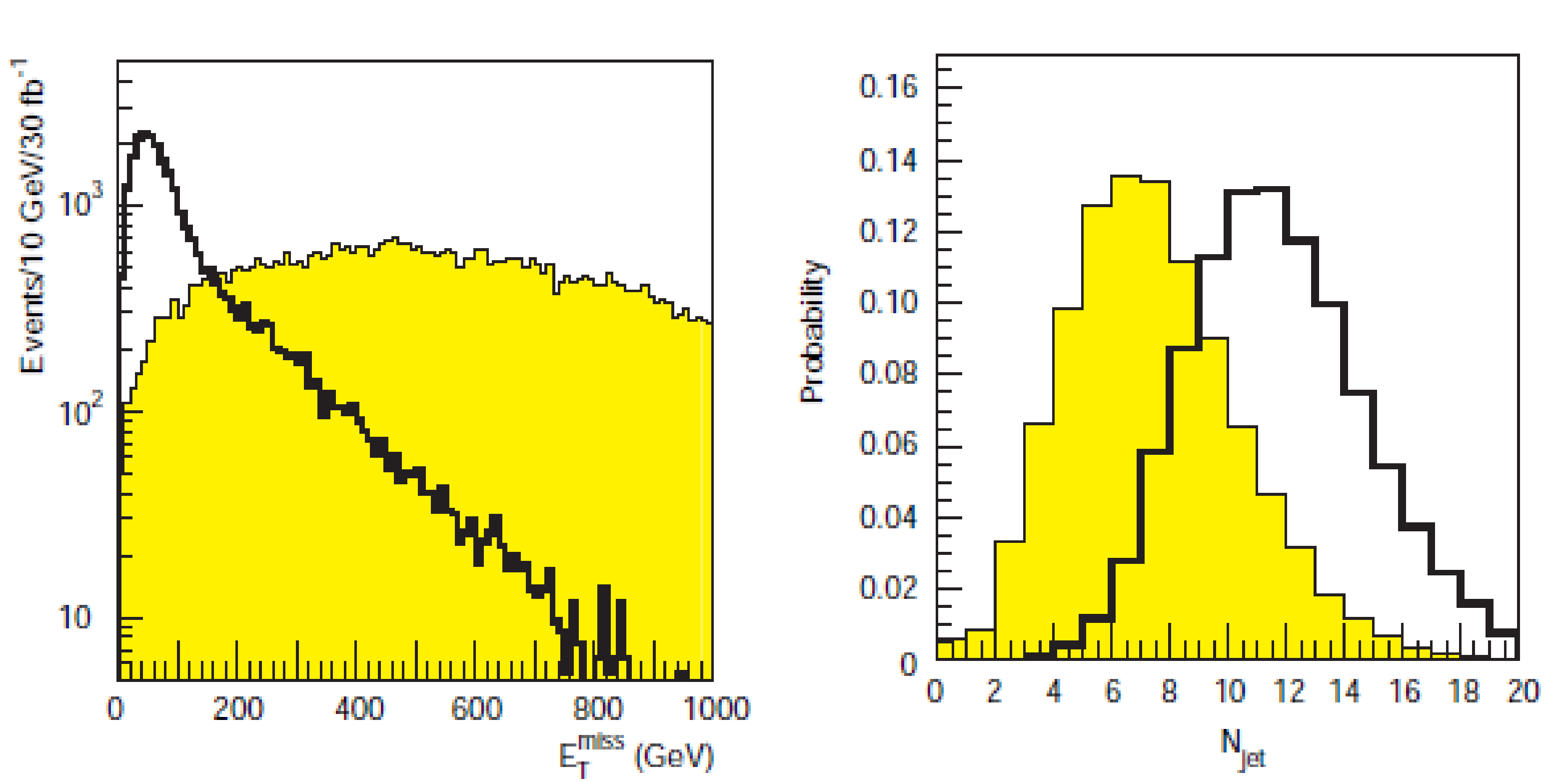


- In most of the parameter space, charginos and neutralinos have no 2-body decay, so a dominant decay is 3-body $\chi_2 \rightarrow \chi_1\ l^+l^-$. The lepton invariant mass will have a sharp edge corresponding to the SUSY mass difference. Signal can be very clean.



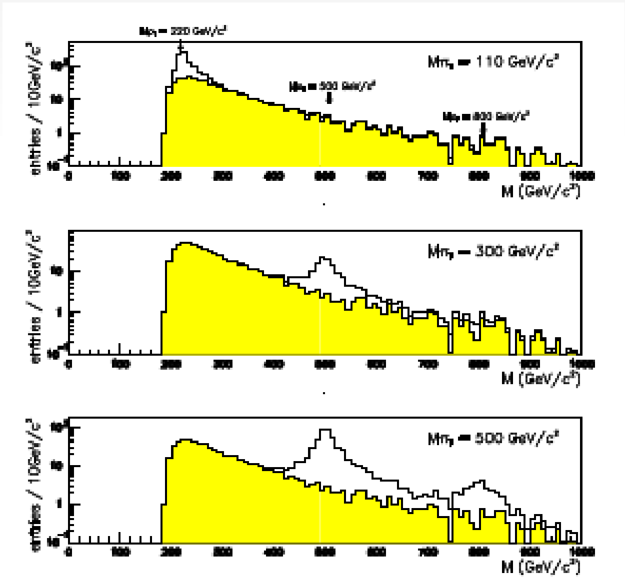


- If R is not conserved, SUSY particles can decay into SM ones, so events do not have the characteristic MET signature, but rather an anomalously high number of jets or leptons:

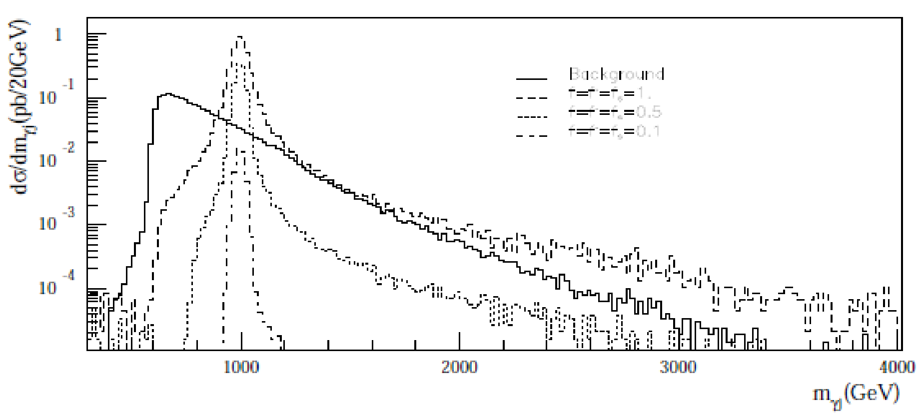


R-parity violating R-parity conserving

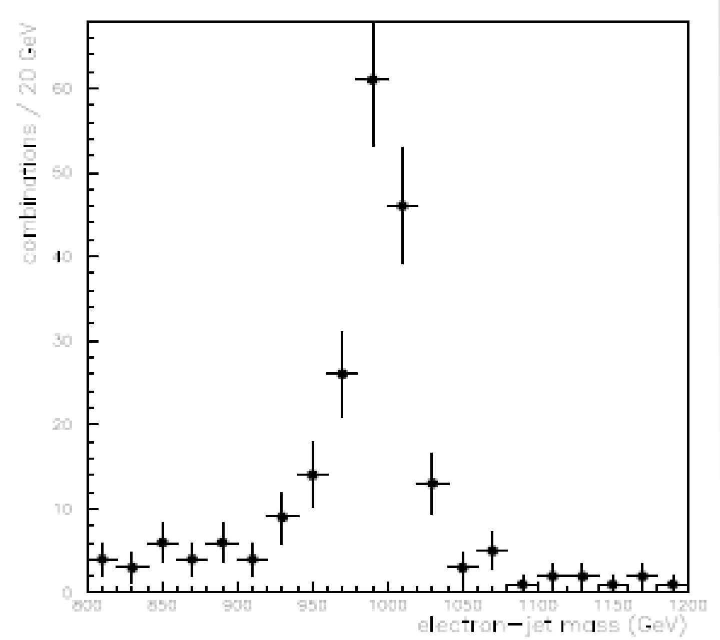
- Technicolour: an additional interaction modeled after QCD colour simmetry replaces the Higgs mechanism to give mass to the other particles. Predicts unobserved FCNC but some variants compatible with experimental data. Signature are resonances decaying into W and Z, like rho decays into pions



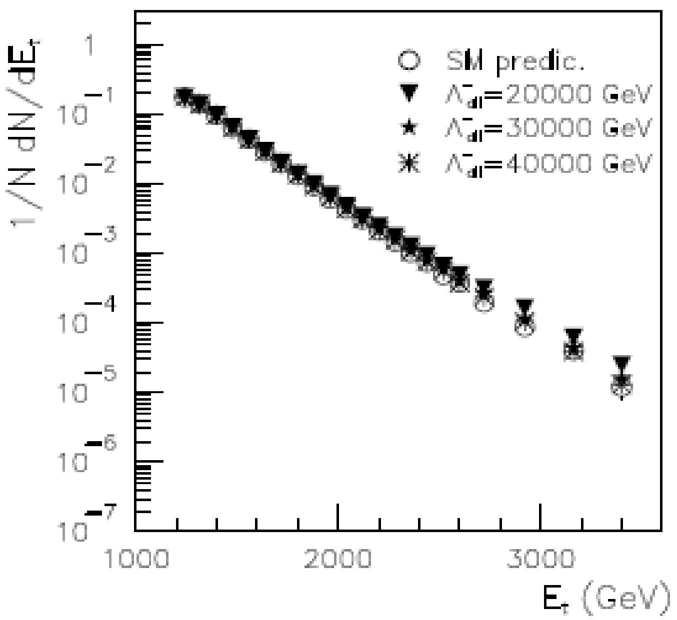
•Excited quarks/leptons: decay into a photon and a quark/lepton, producing a mass peak in that distribution



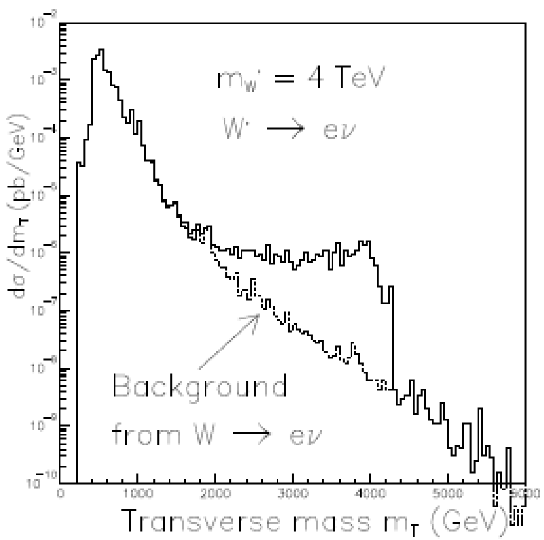
- Leptoquarks: a new symmetry between leptons and quarks could produce particles strongly coupling (and decaying) to both



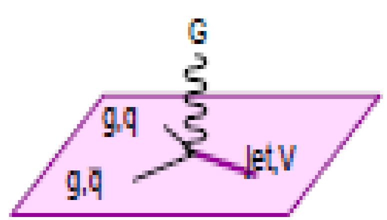
Compositeness: if quarks are composed of something even smaller, that would result in increased high-mass dijet tail



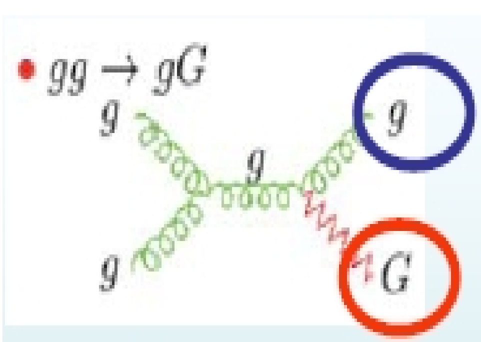
Z', W': from additional SU(2) symmetry, behave like high-mass W's and Z's

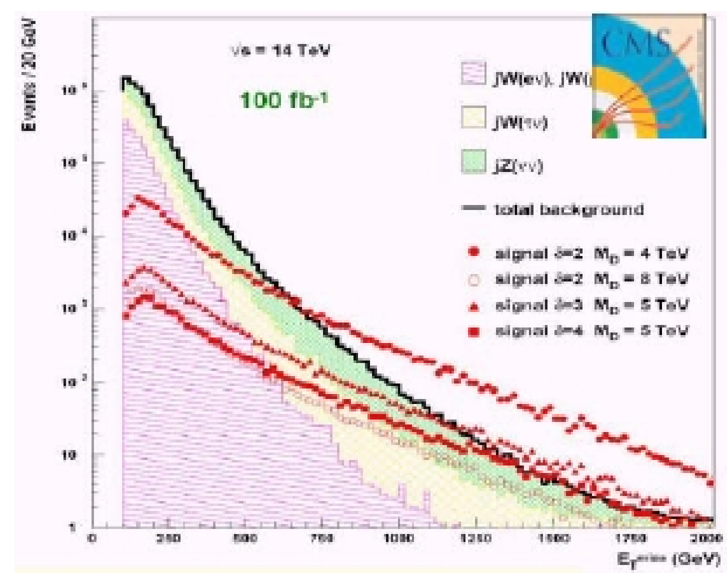


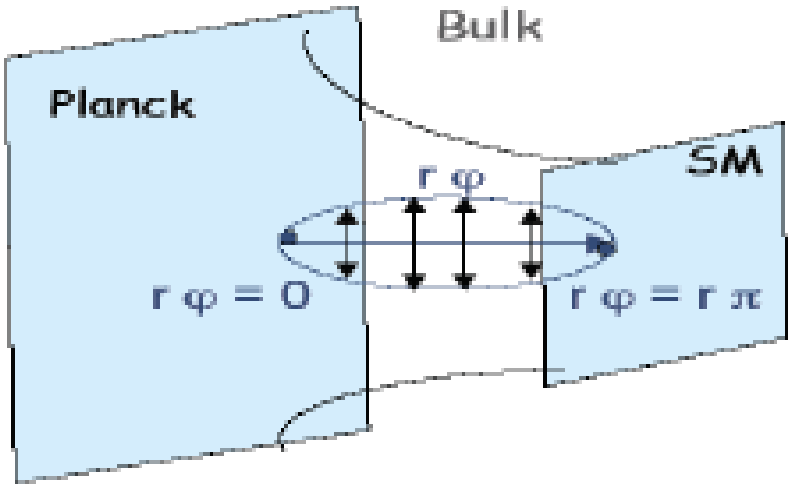
- The three space dimensions we live in are just a membrane of a multi-dimensional space.
- This would reduce the hierarchy problem to geometry
- Gravity could deviate from Newton's law at small scale (< 1 mm, very few experiments on that), and could propagate to the extra dimensions; a graviton would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



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





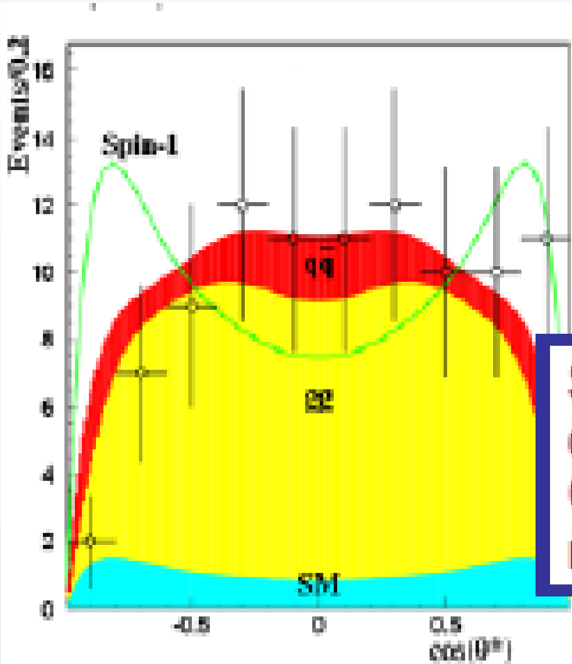


A small, highly curved ("warped") extra dimension connects the SM brane (at O(TeV)) to the Planck scale brane

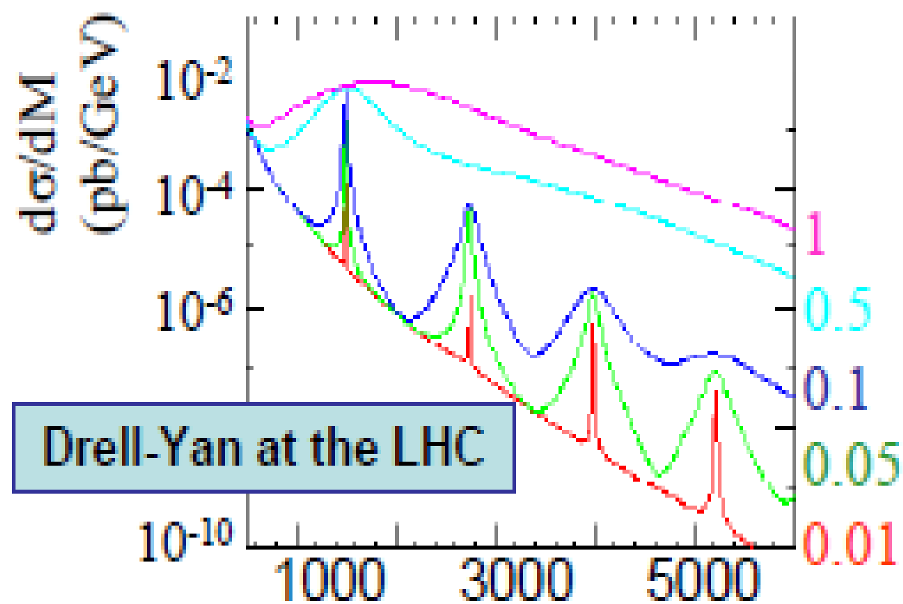
Gravity small in our space because warped dimension decreases exponentially between the two branes

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

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

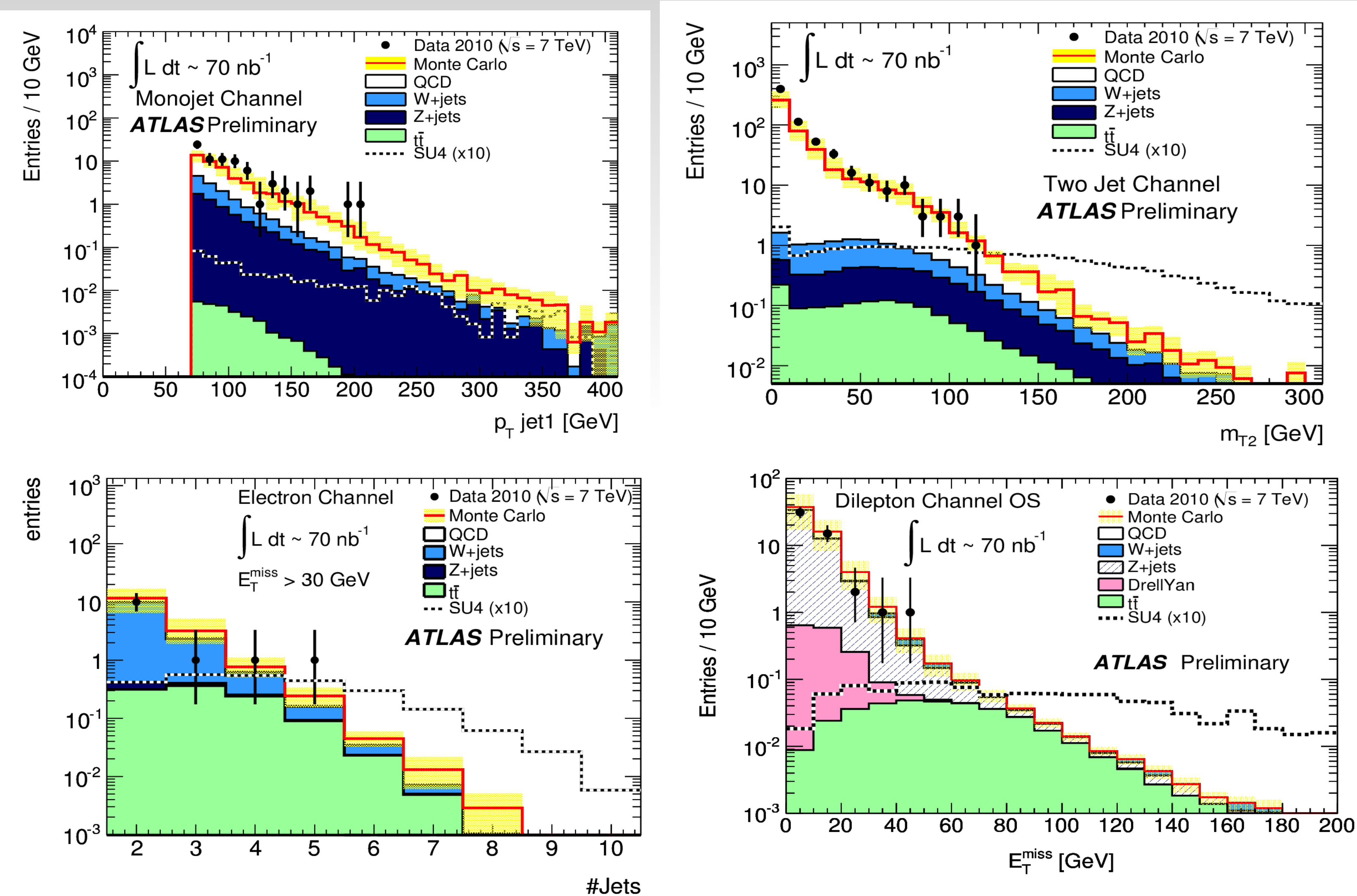


Spin analysis to distinguish spin-2 G from spin-1 Z' resonance



Dilepton mass

Antonella De



Entries / 10 GeV
∫L dt ~ 70 nb⁻¹
Monojet Channel
ATLAS Preliminary
Data 2010 (√s = 7 TeV)
Monte Carlo
QCD
W+jets
Z+jets
tt̄
SU4 (x10)
p_T jet1 [GeV]
Entries / 10 GeV
∫L dt ~ 70 nb⁻¹
Two Jet Channel
ATLAS Preliminary
Data 2010 (√s = 7 TeV)
Monte Carlo
QCD
W+jets
Z+jets
tt̄
SU4 (x10)
m_T2 [GeV]
entries
Electron Channel
∫L dt ~ 70 nb⁻¹
E_T^miss > 30 GeV
ATLAS Preliminary
Data 2010 (√s = 7 TeV)
Monte Carlo
QCD
W+jets
Z+jets
tt̄
SU4 (x10)
#Jets
Entries / 10 GeV
Dilepton Channel OS
∫L dt ~ 70 nb⁻¹
ATLAS Preliminary
Data 2010 (√s = 7 TeV)
Monte Carlo
QCD
W+jets
Z+jets
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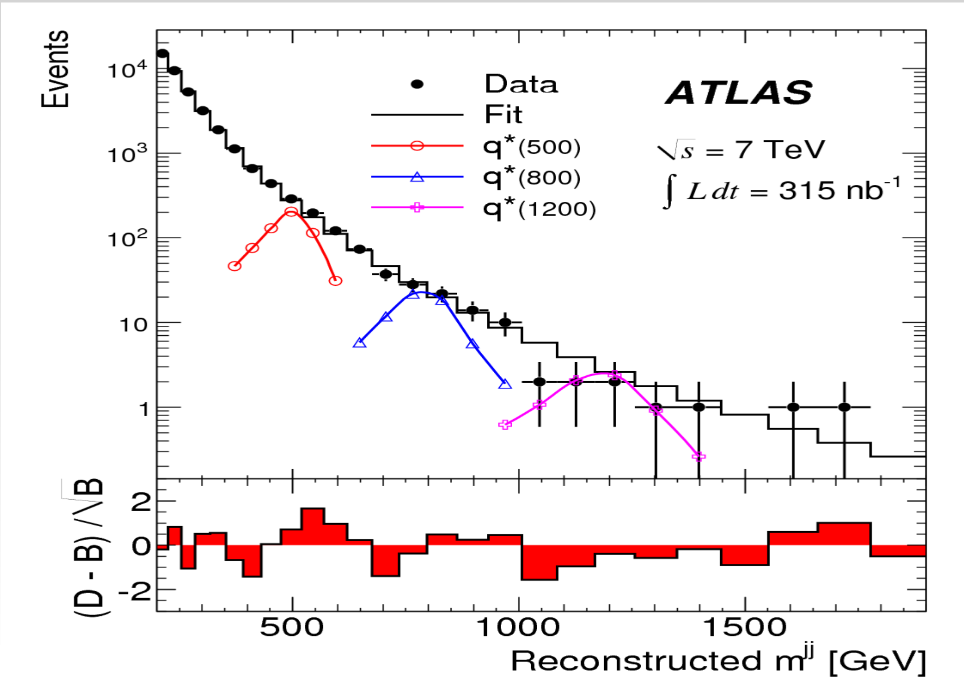
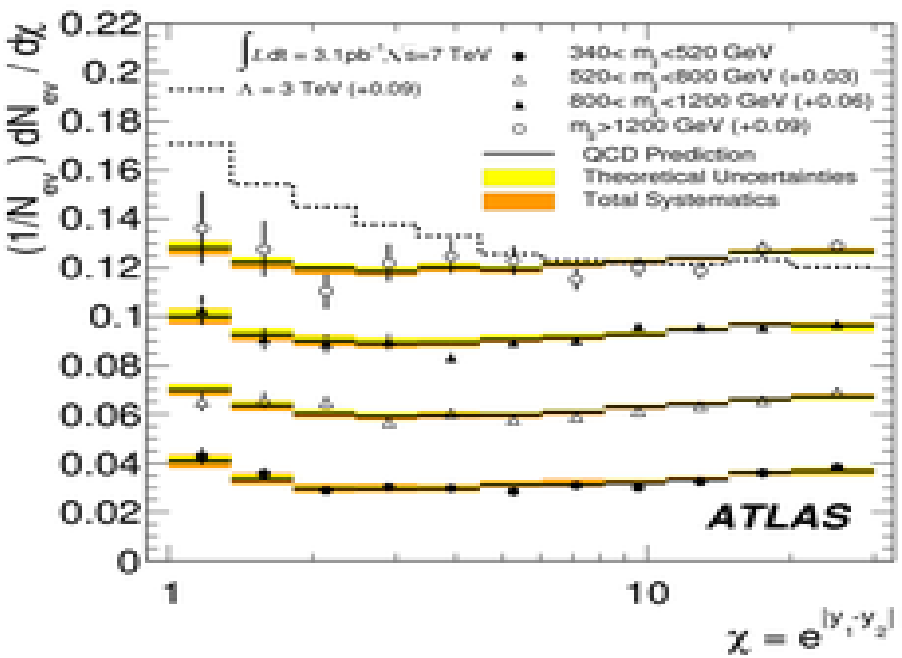
SU4 (x10)
E_T^miss [GeV]





- 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

- 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
- Searching for the SM Higgs, a new boson has been discovered by both experiments for mass values around 125 GeV.
- The branching fraction into photon pairs is larger than the SM predictions for Higgs, but consistent within 20% C.L.
- Existence confirmed in the ZZ* channel, as well as injected signal in WW (but no mass determination there)
- No fermionic decay of this new state observed so far. It is most likely a Higgs, but is it the scalar SM one??