Standard Model Physics at the Large Hadron Collider

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Atlas Collaboration

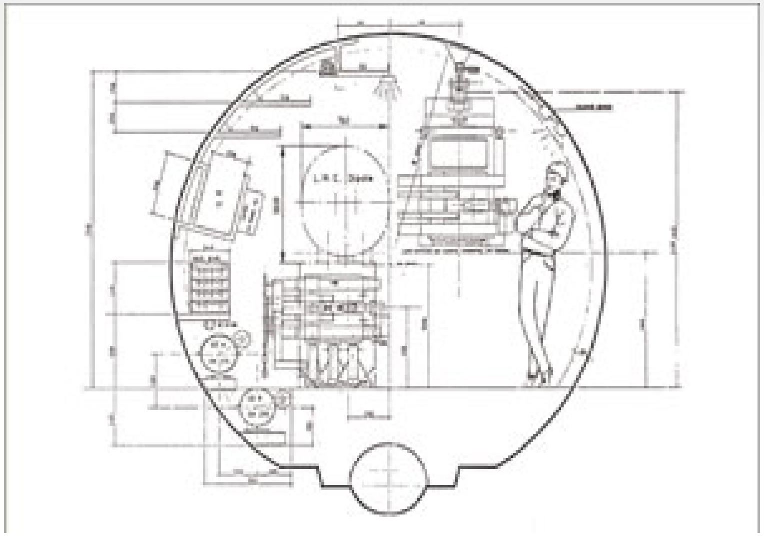
Outline

- The machine: why the LHC is a unique collider
- Present status
- Parton density functions and luminosity
- QCD physics
- Production of vector bosons and top
- Higgs boson

A bit of history...

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

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



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

Towards the LHC

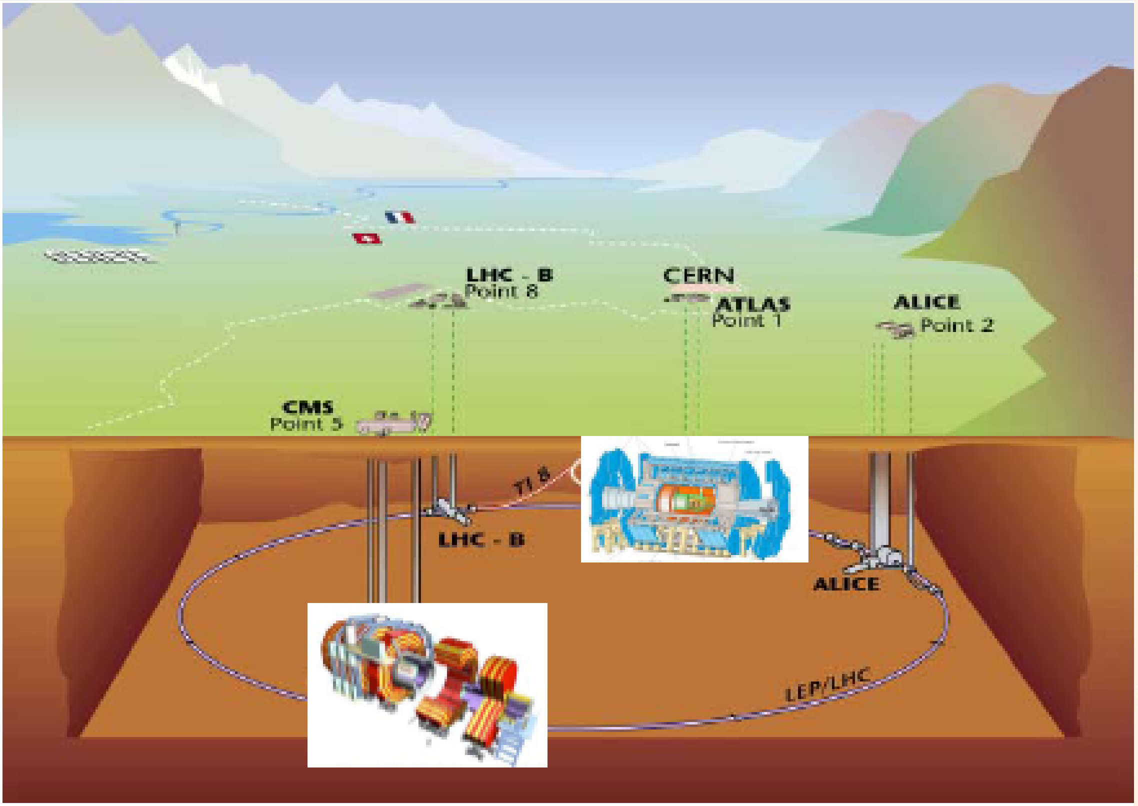
At that time, the US was building a very ambitious hadron collider, the SSC in Texas.

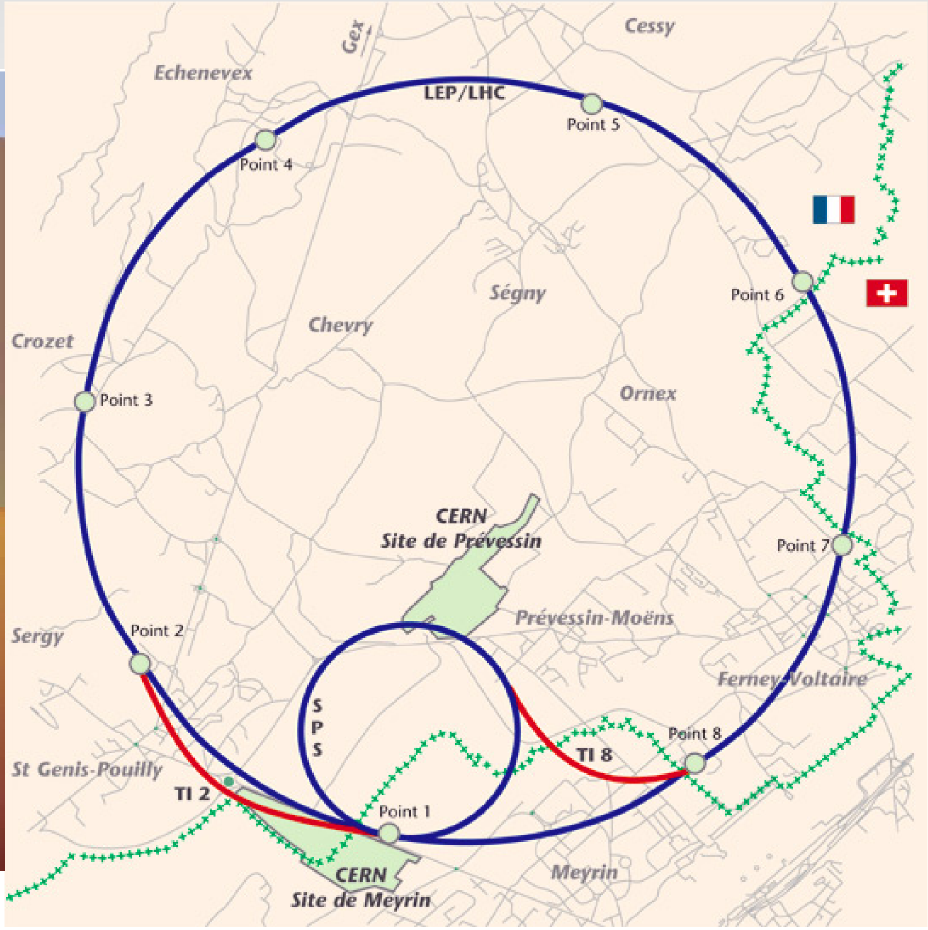
In 1993 the US congress canceled the SSC project due to budget cuts, the LHC was the only viable project for the energy frontier (and approved in 1994)

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

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

LHC layout


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


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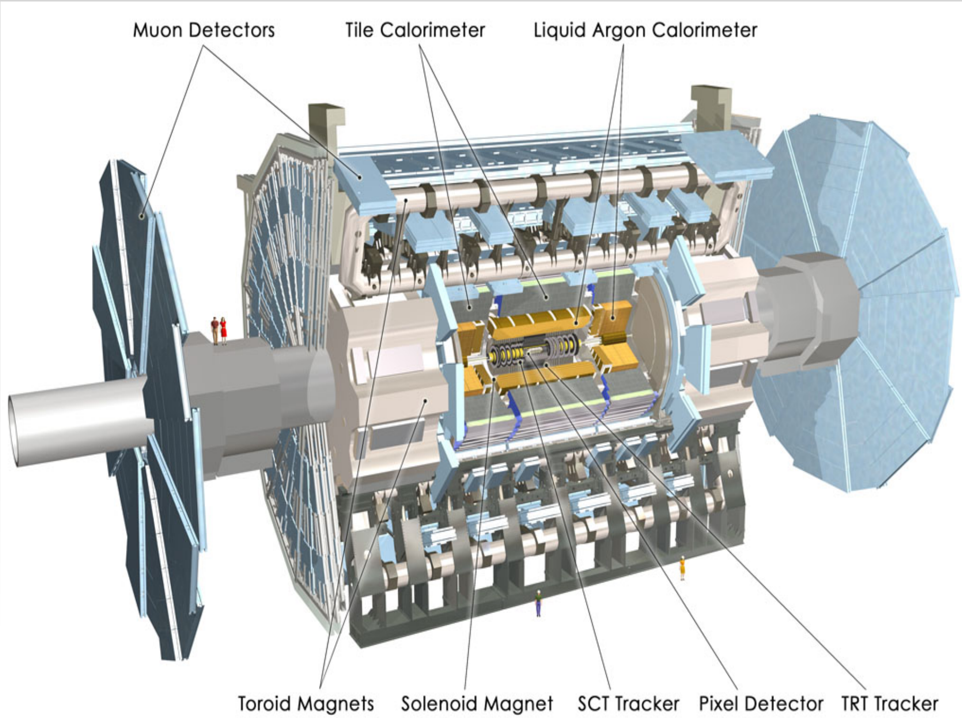
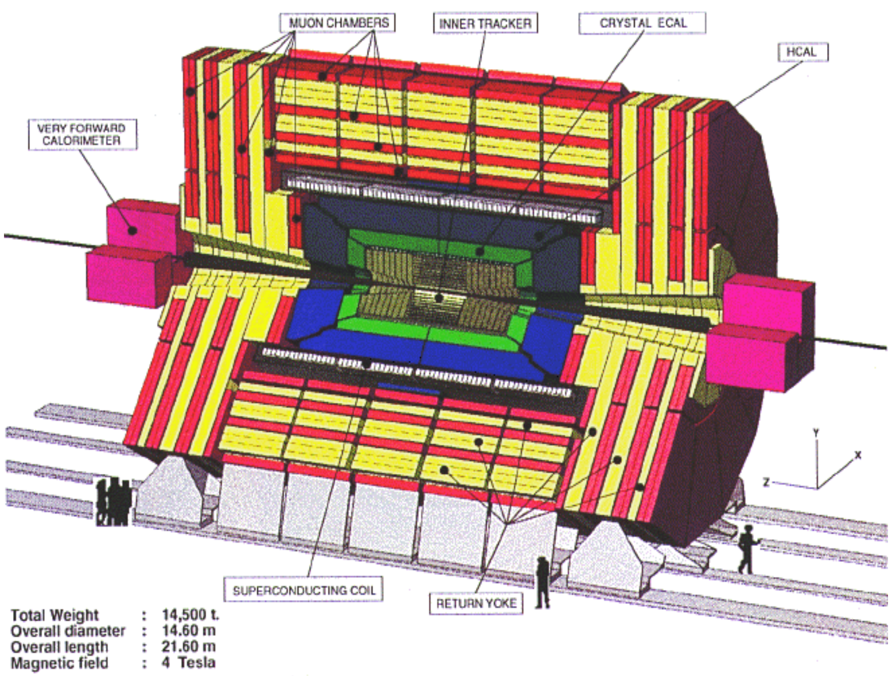
Point 8
TI 8
St Genis-Pouilly
TI 2
Point 1
Meyrin
CERN
Site de Meyrin

Two general-purpose detectors

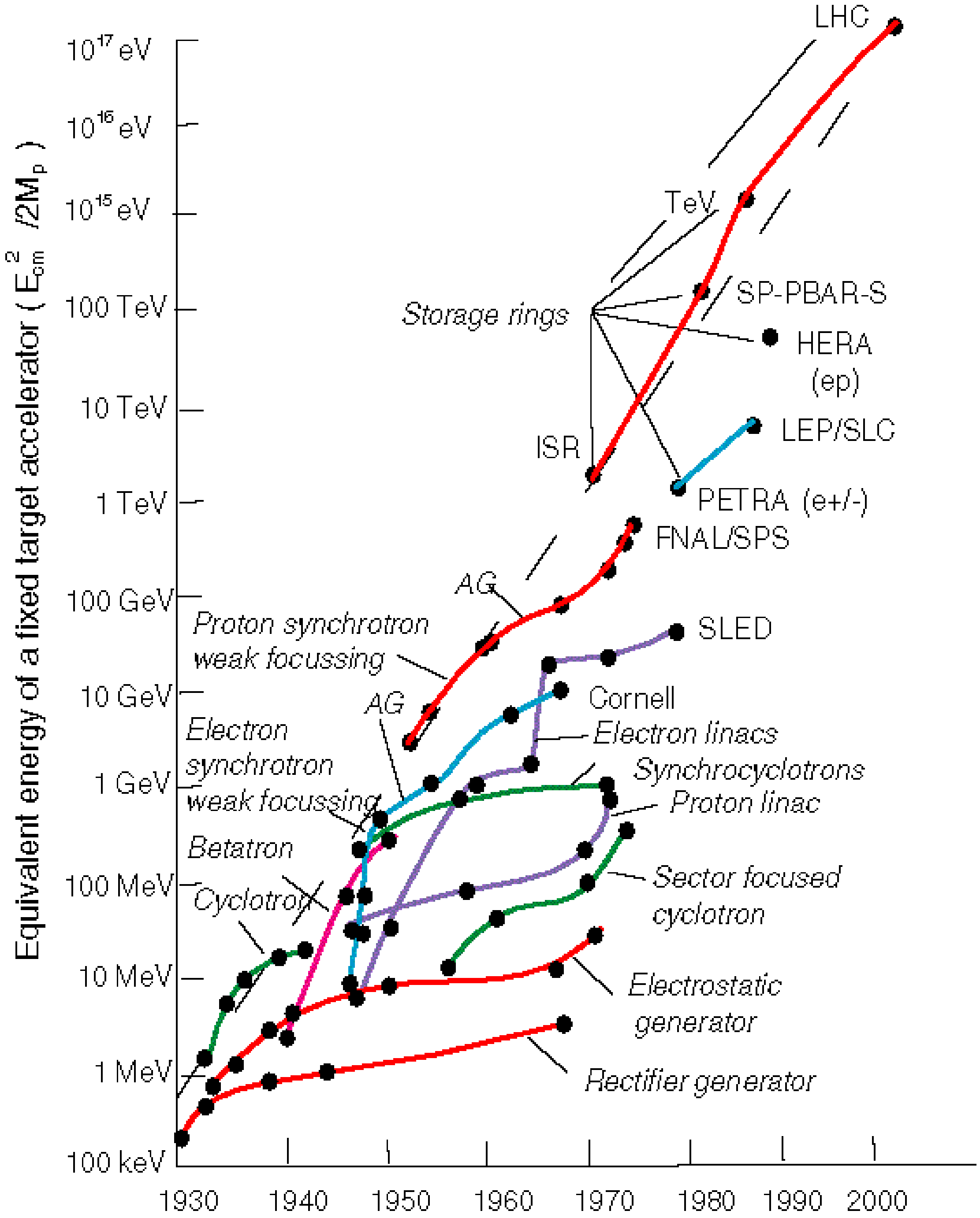




- Atlas: 1 solenoid (2T) and 8 + 2 toroid magnets (!)
  - Air-core muon chambers (good stand-alone muons)
  - Liquid Argon e.m. Calorimeter
- CMS: 1 solenoid magnet (4T) creates field inside and outside
  - Muon chambers in return yoke
  - 80000 $PbWO_4$ crystals as e.m. calorimeter

Why CMS stands for 'compact'

...ler?



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

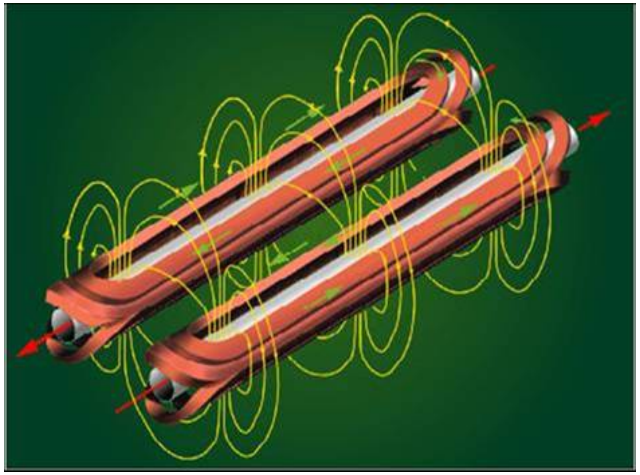
a hadron collider is not limited by synchrotron radiation, and can go to much higher energy.

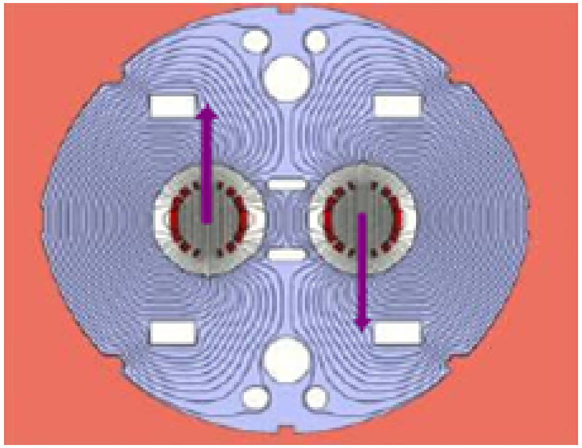
For a given ring size, the only limitation comes from the magnetic field of the bending magnets:

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

2-in-1 configuration

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





Event rate and luminosity

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

where luminosity L is given by

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

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

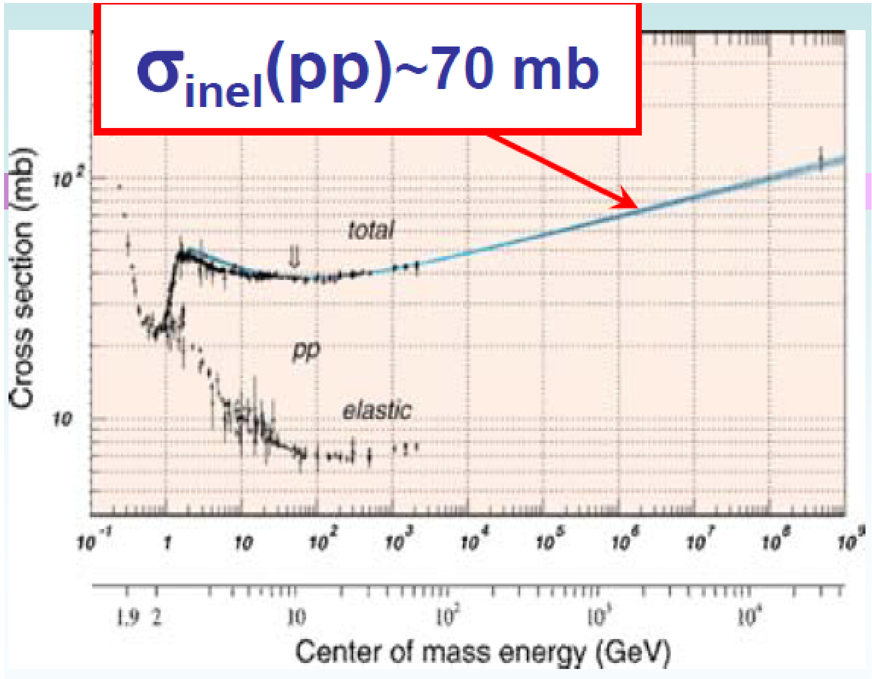
Integrated luminosity and pileup

- These numbers correspond to a range between

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

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

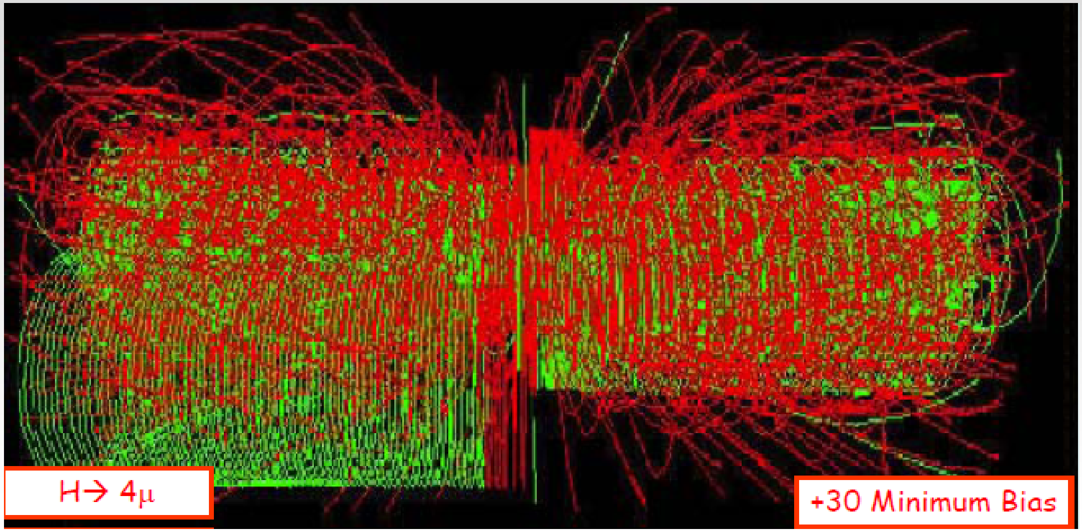
The total pp cross section is about 70 mb:



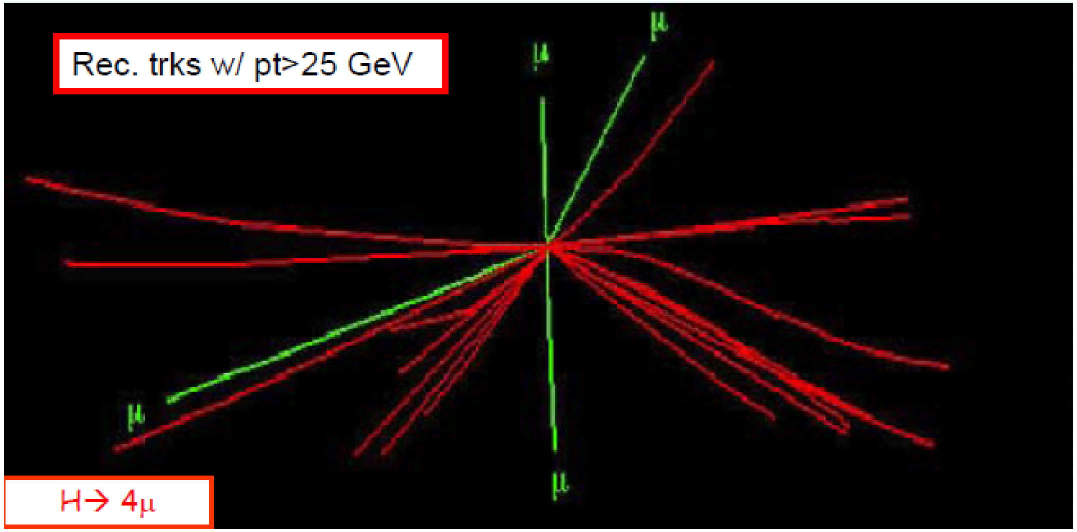
So, rate can go up to 700MHz! Divided by 40MHz bunch crossing rate, and accounting for empty bunches, we can have > 20 collisions/bunch crossing (pileup)

Pileup

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

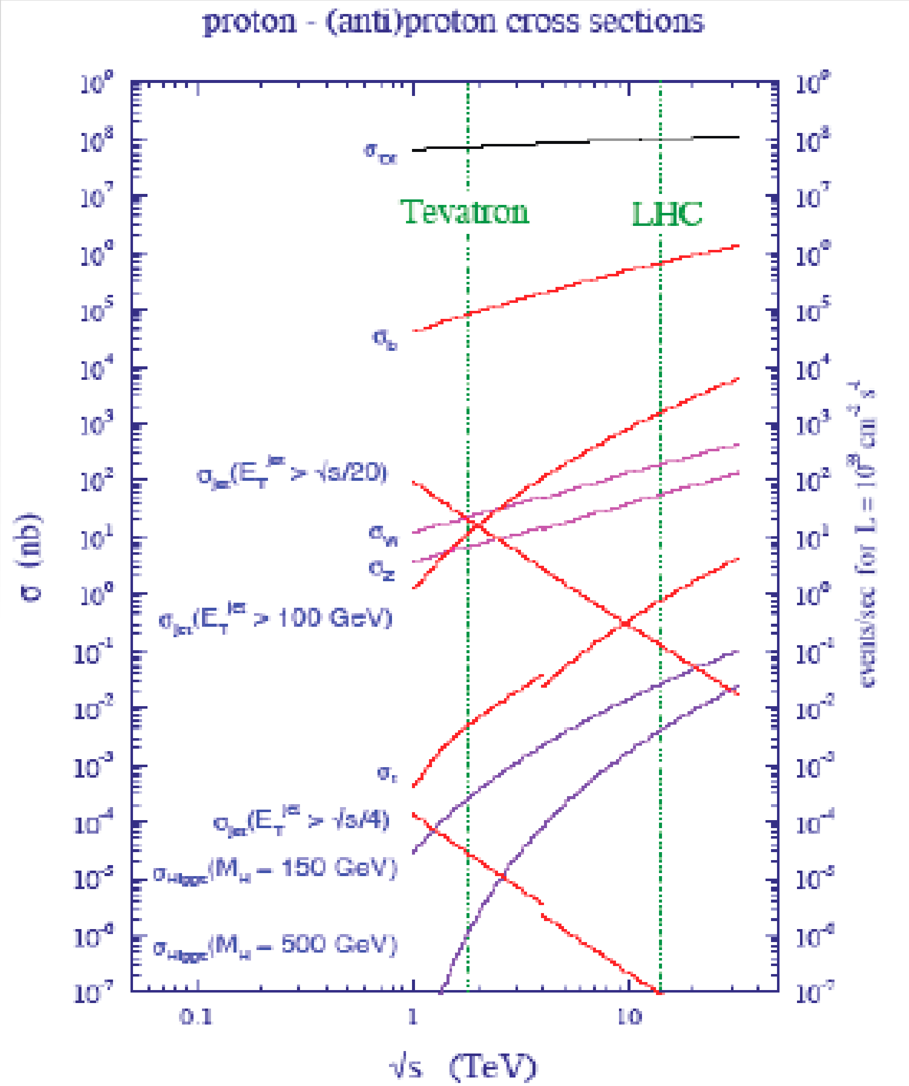


It gets much better if you just look at the energetic particles:



Cross sections in pp interactions

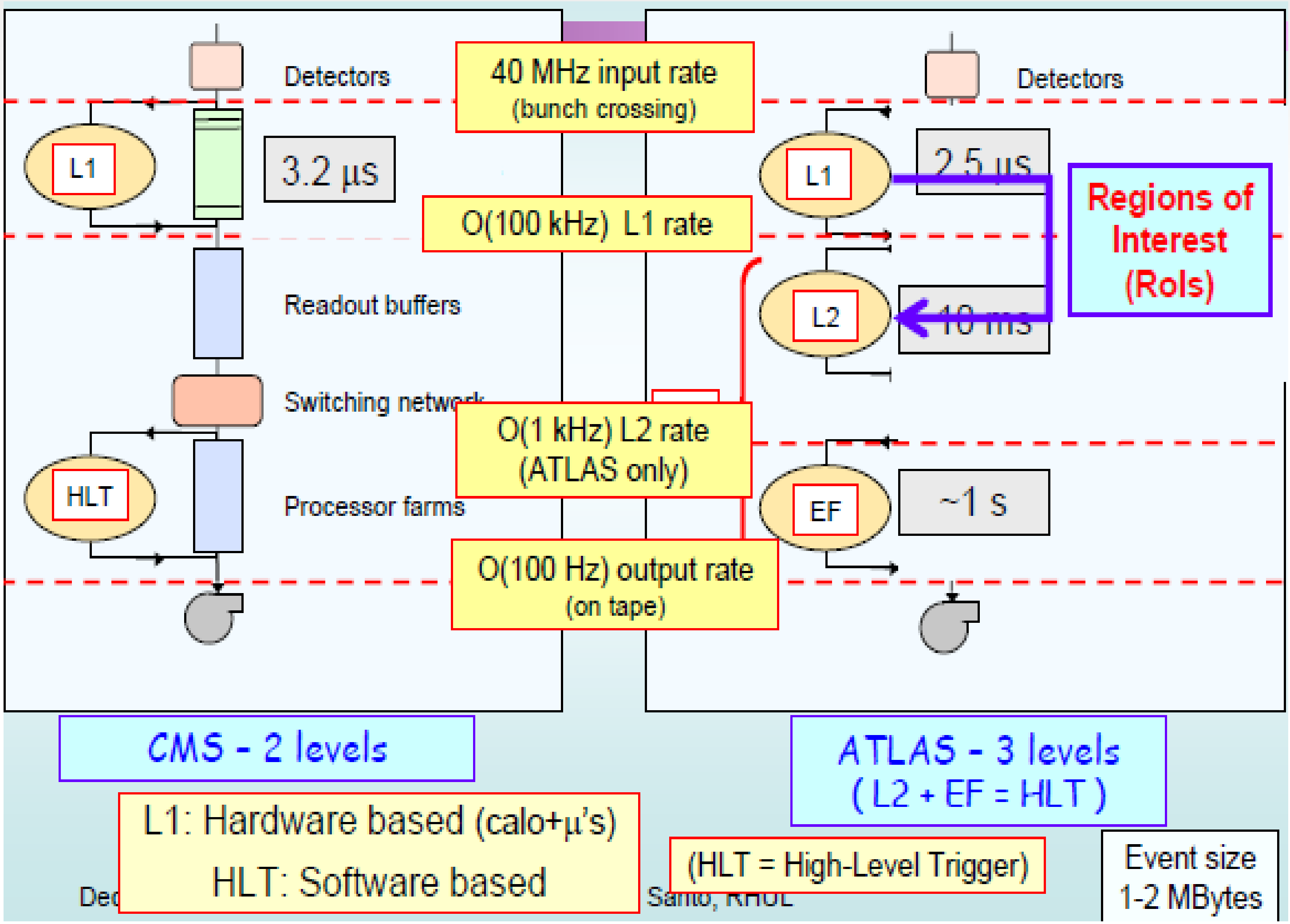
- No real thresholds
- Total cross section (including elastic) almost constant
- Some lines 'broken' going from Tevatron to LHC due to antiprotons vs protons
- Several orders of magnitude between discoveries and background



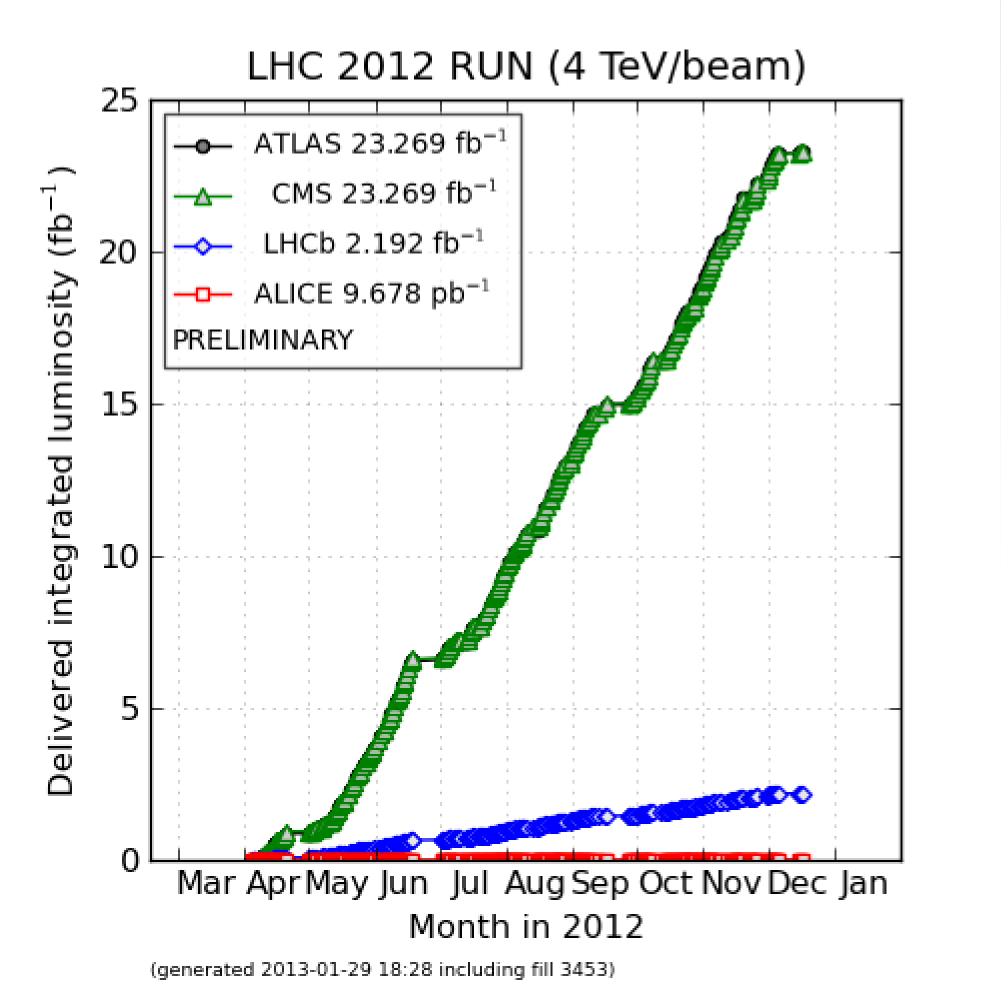
History of this first year can be summarised as: going down this plot

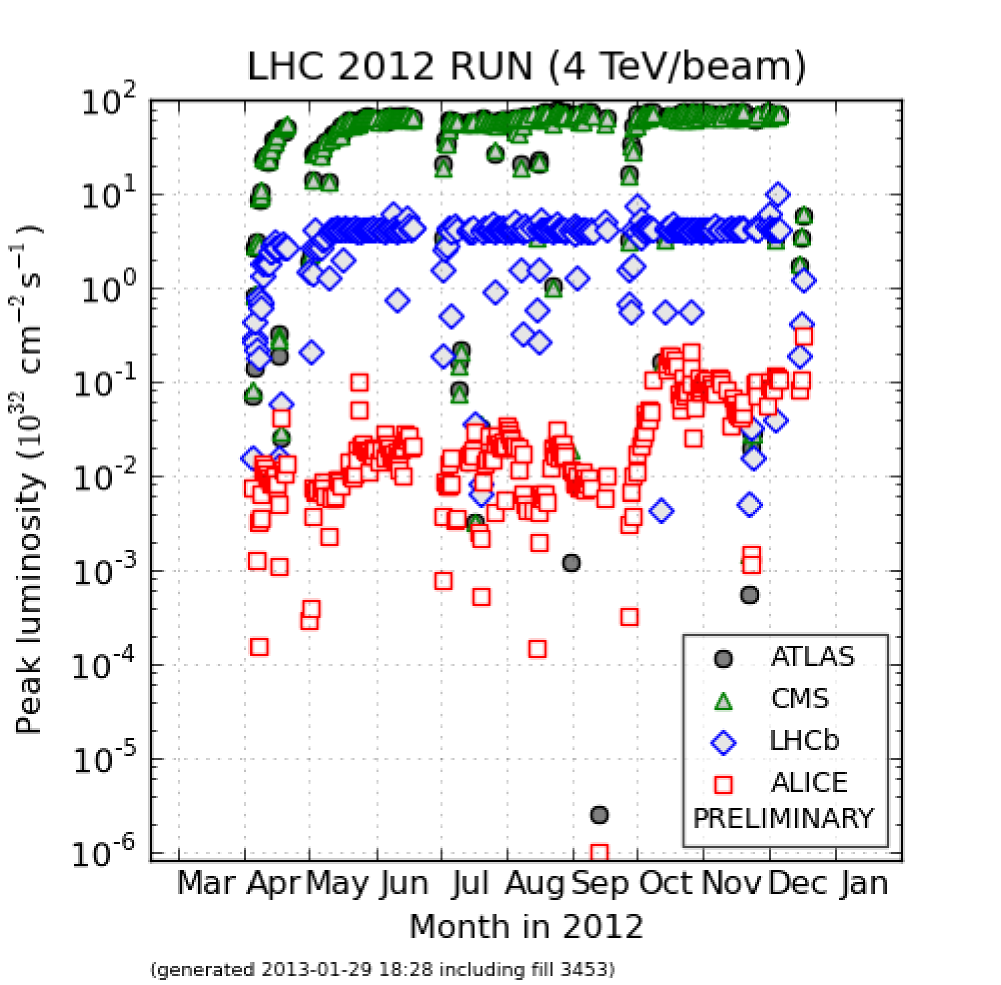
Triggering

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



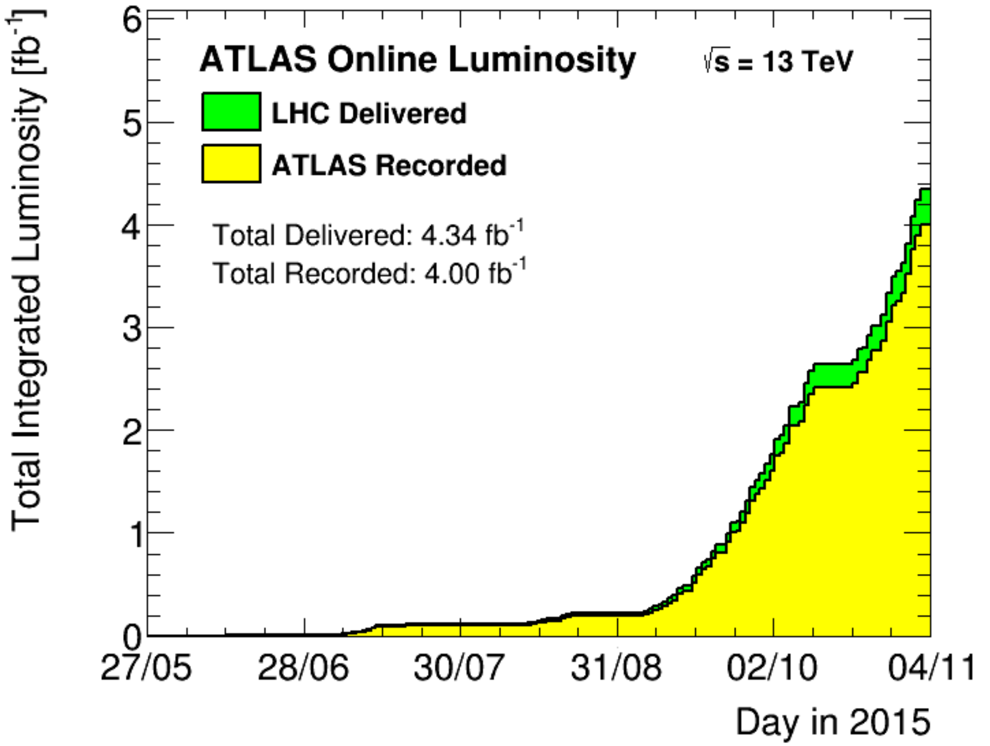
Luminosity evolution Run I

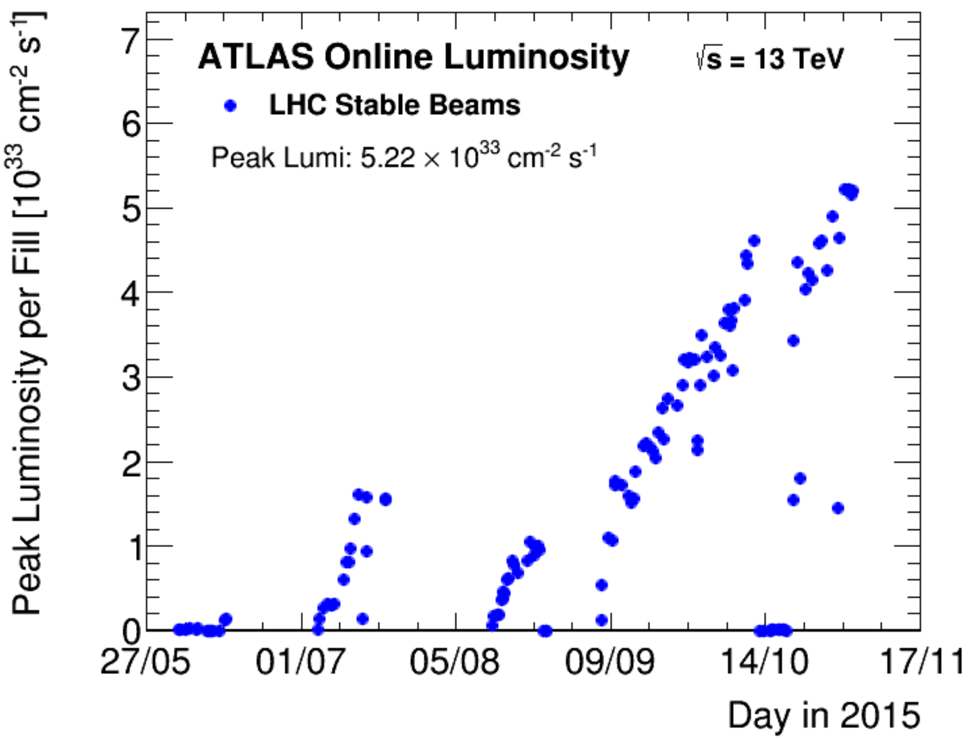




- Integrated luminosity ~23 fb-1
- Peak luminosity ~7E33
- Peak energy: 8 TeV

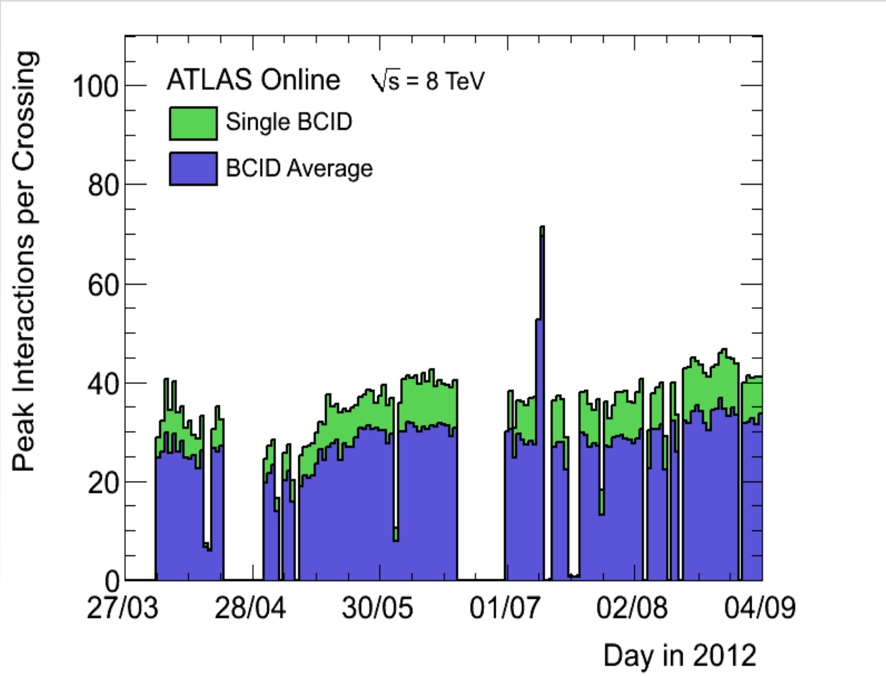
Run-2 lumi evolution (ATLAS)

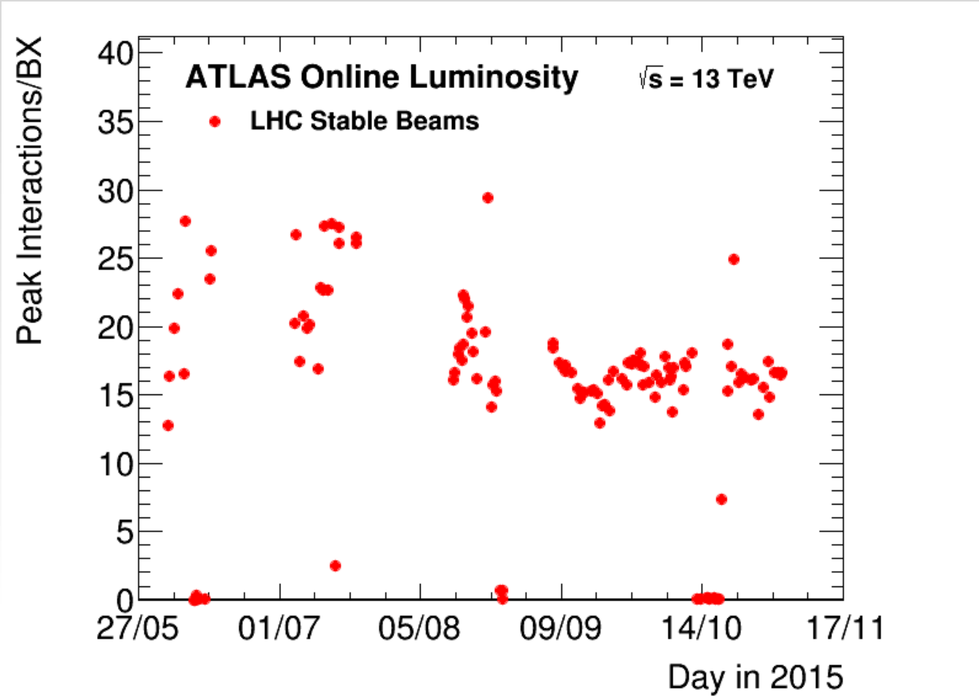


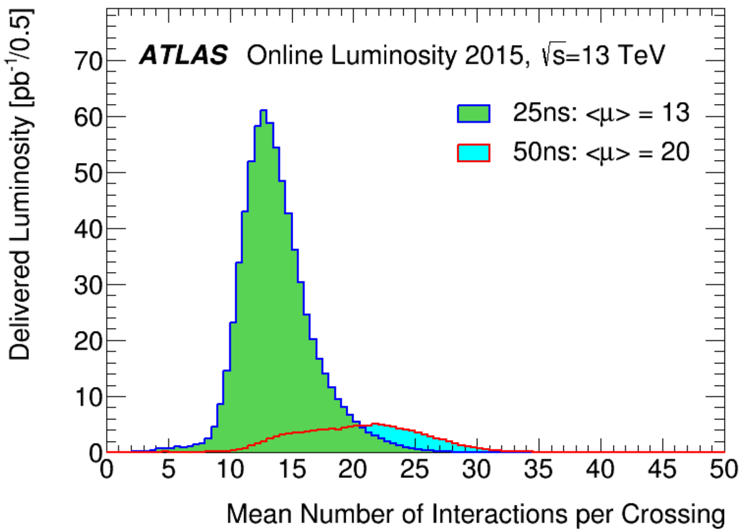


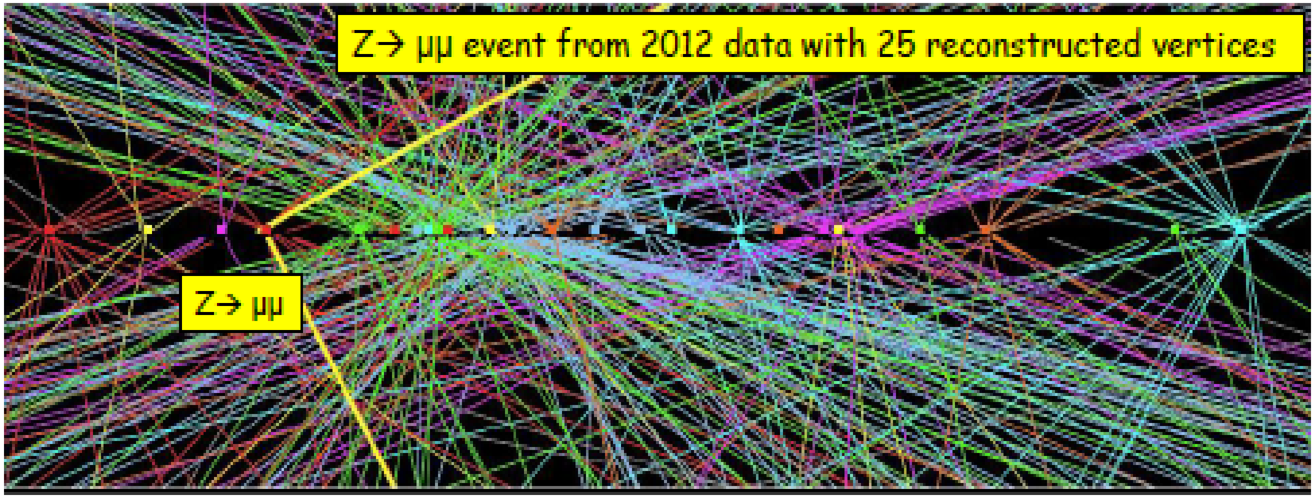
- Energy > 50% higher
- Exploratory year: 4 times less int. lumi
- Similar peak lumi

Pileup evolution



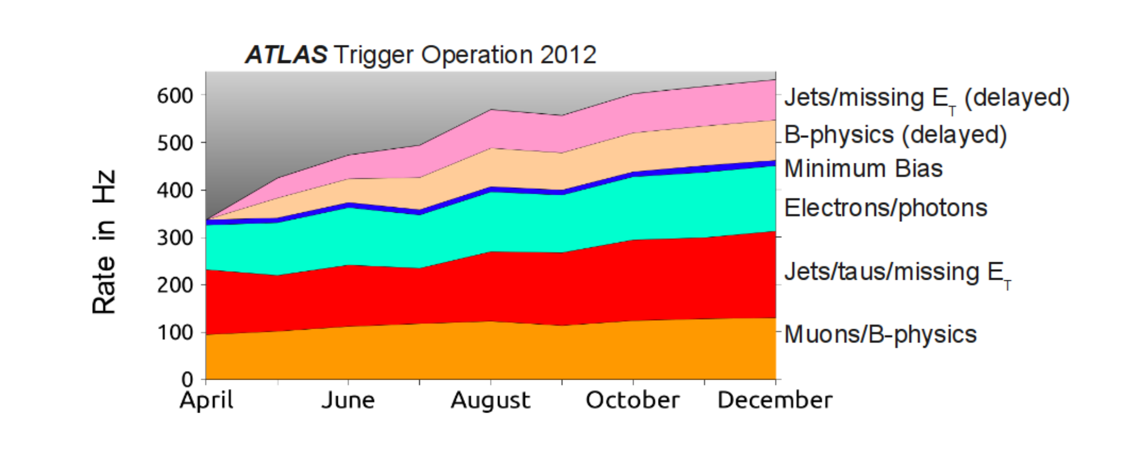


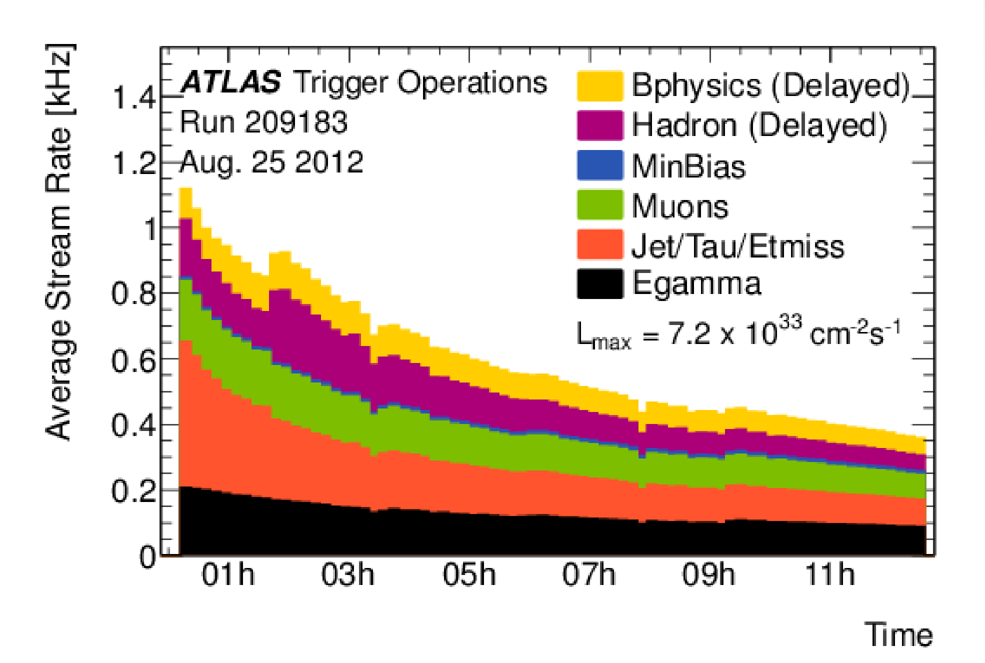




From August 2015, 25 ns operations reduced in-time pileup for same luminosity
However, next year luminosity will increase, and pileup conditions could be similar to Run 1

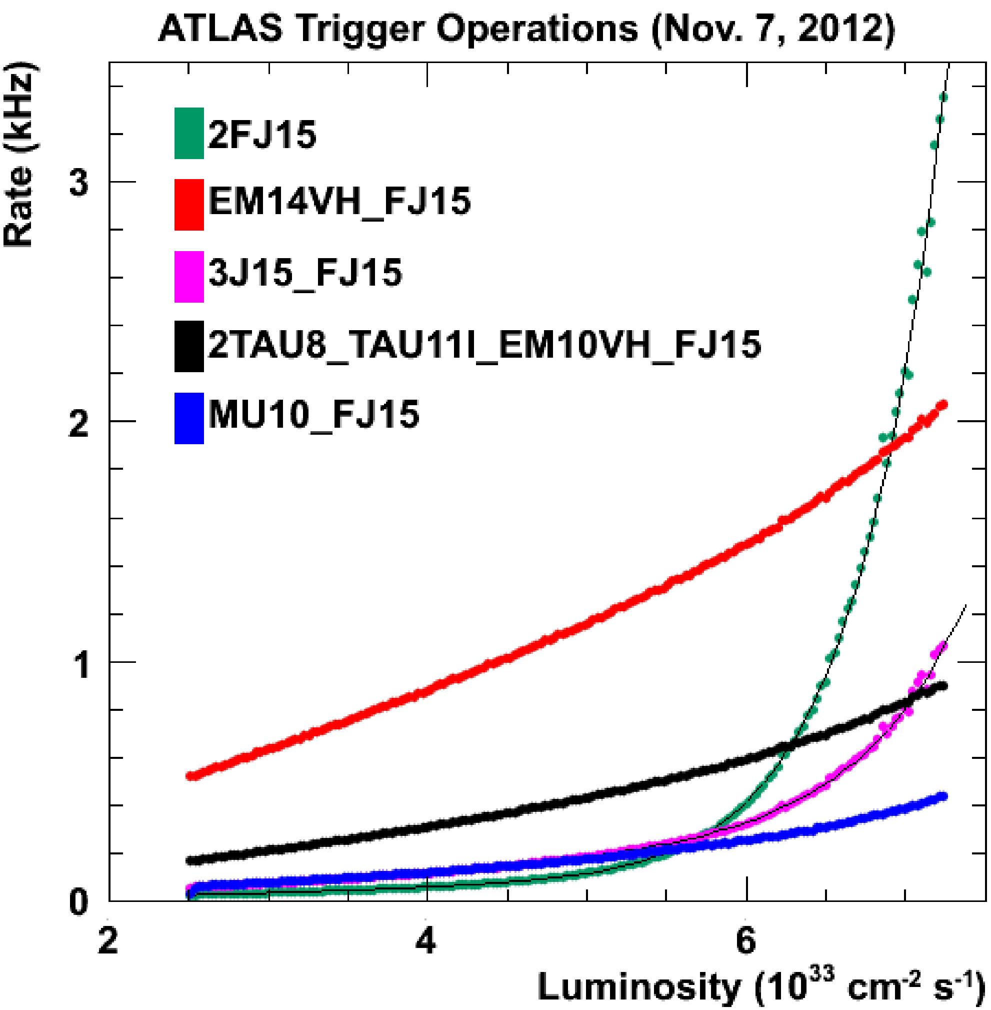
ATLAS trigger rates

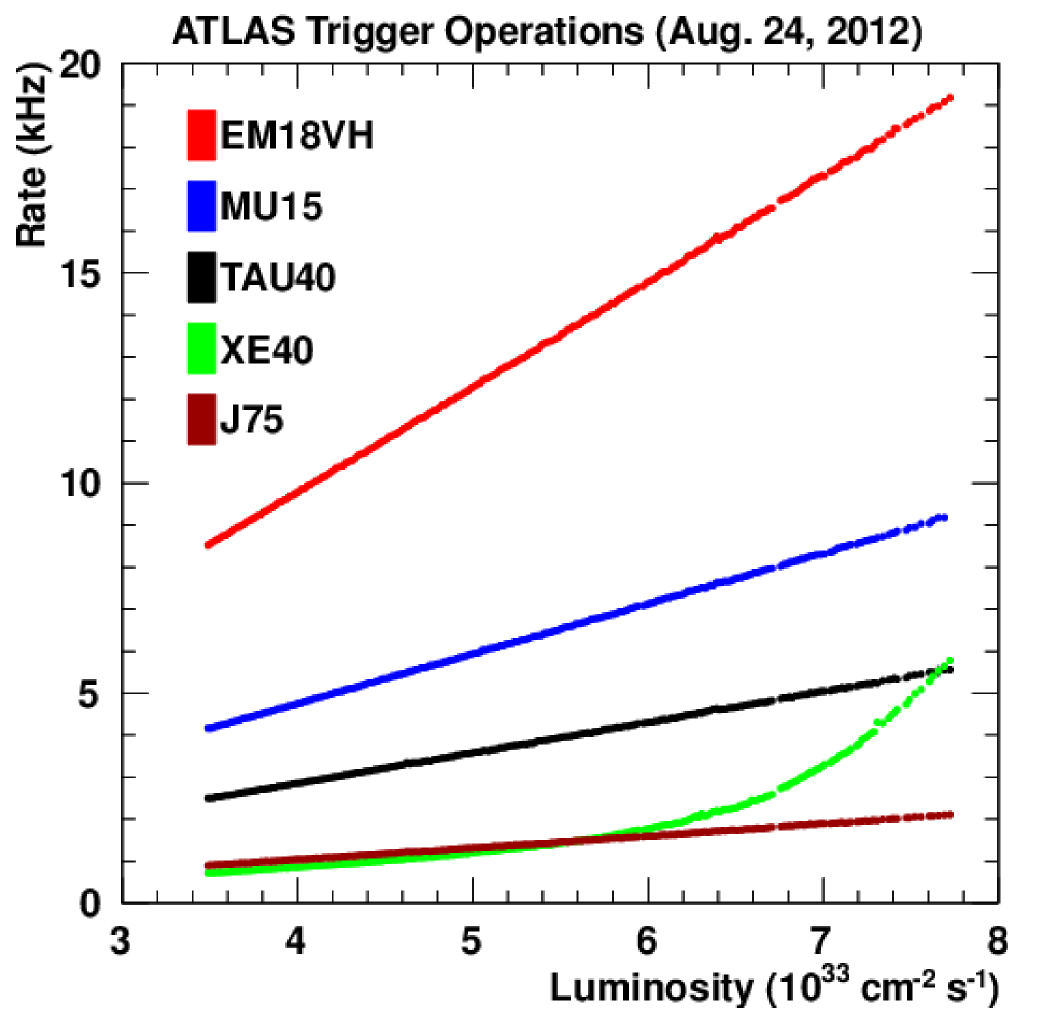




- The trigger menu has to dynamically adapt to the changed data-taking conditions

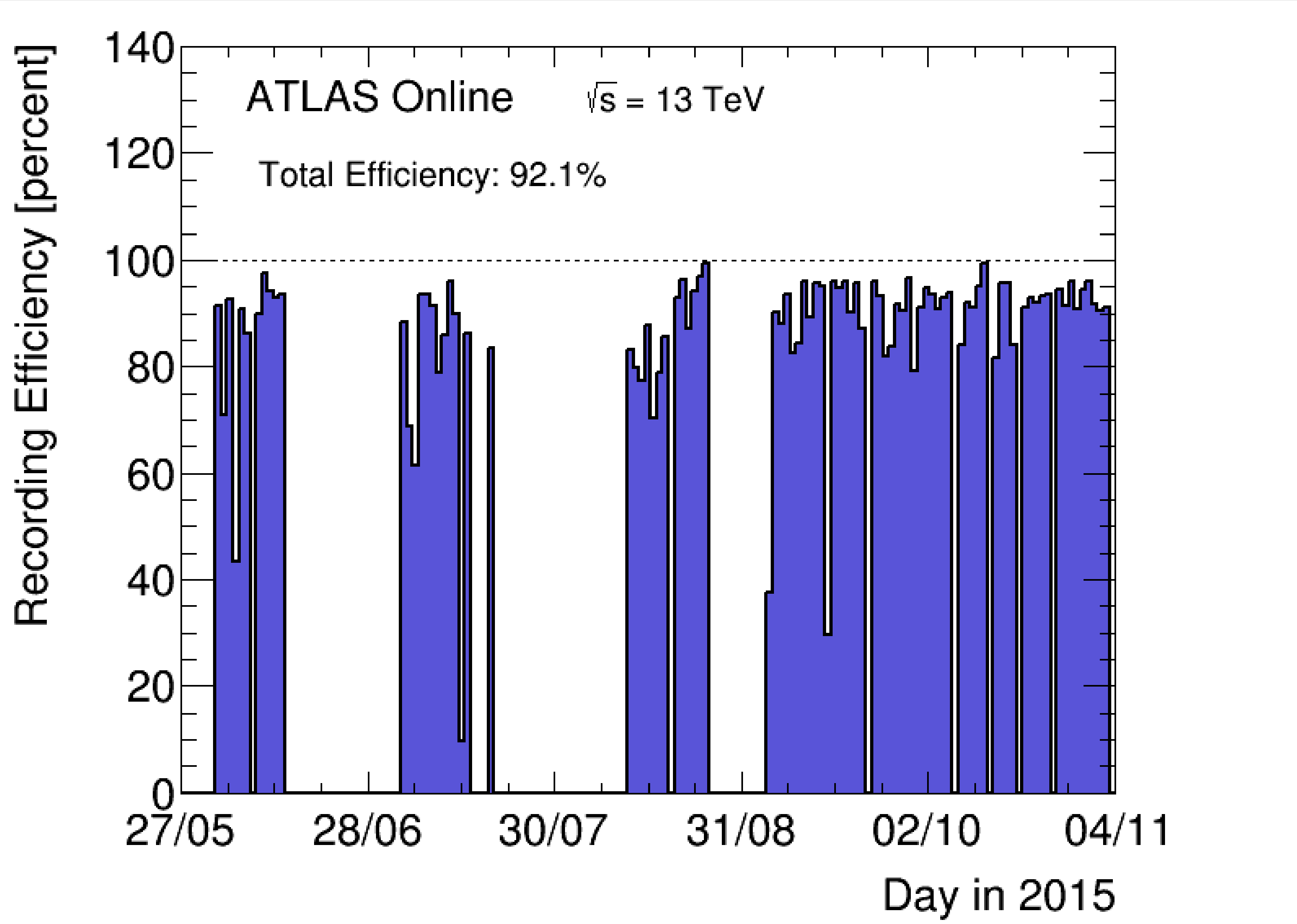
L1 Trigger rates vs luminosity



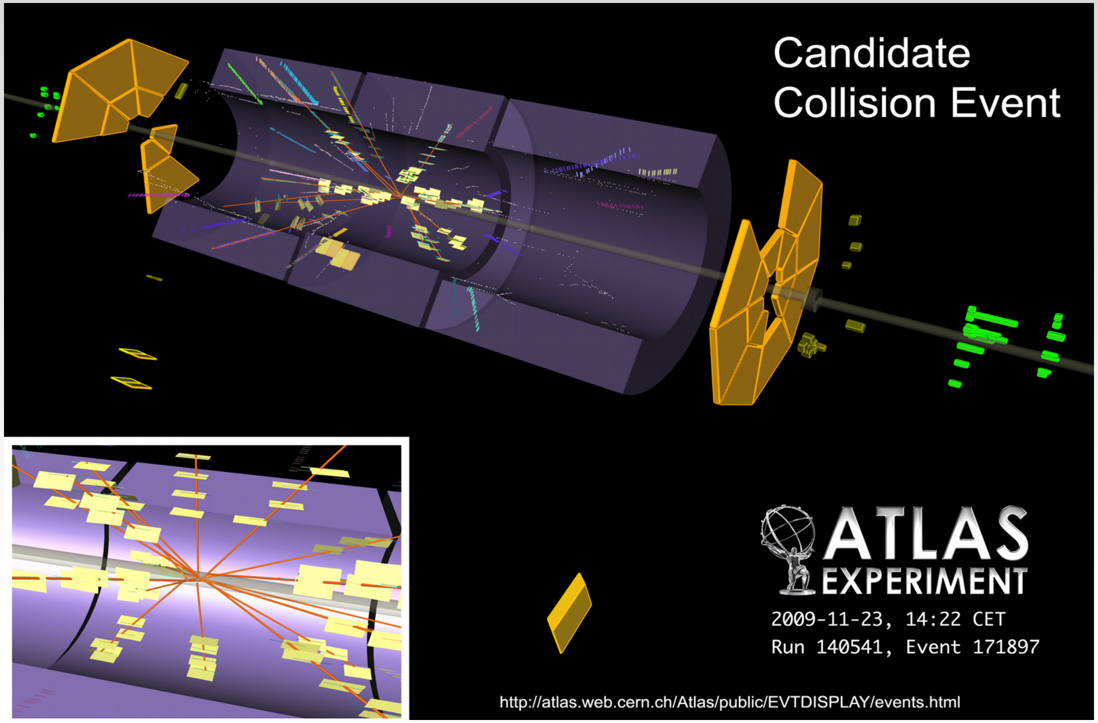


Strong non-linearities observed at the highest luminosities for jets (esp. forward) and MET

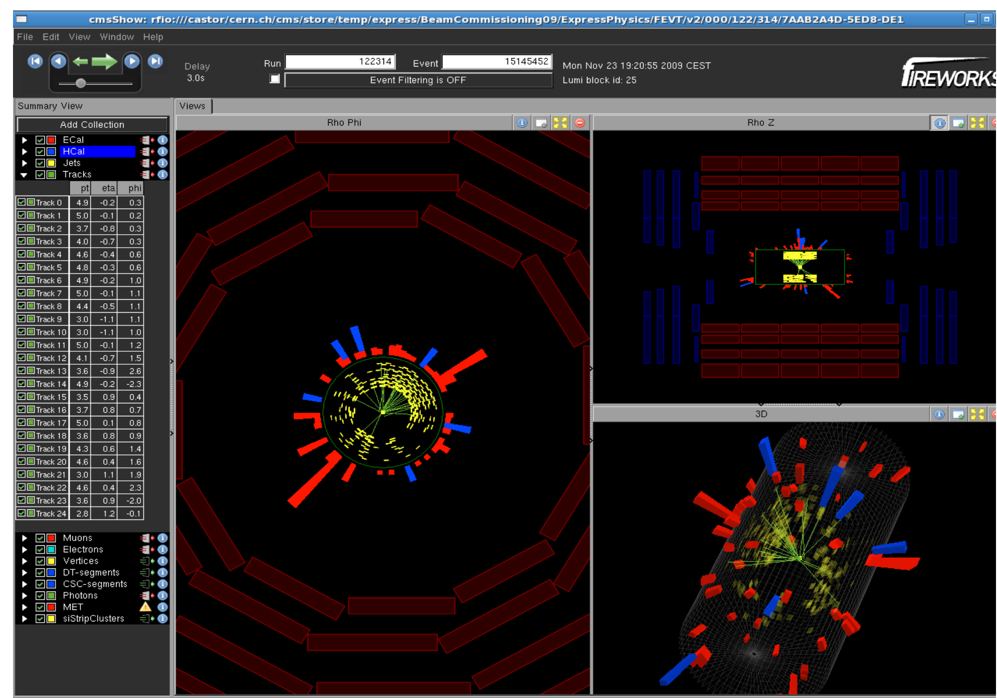
ATLAS data taking efficiency



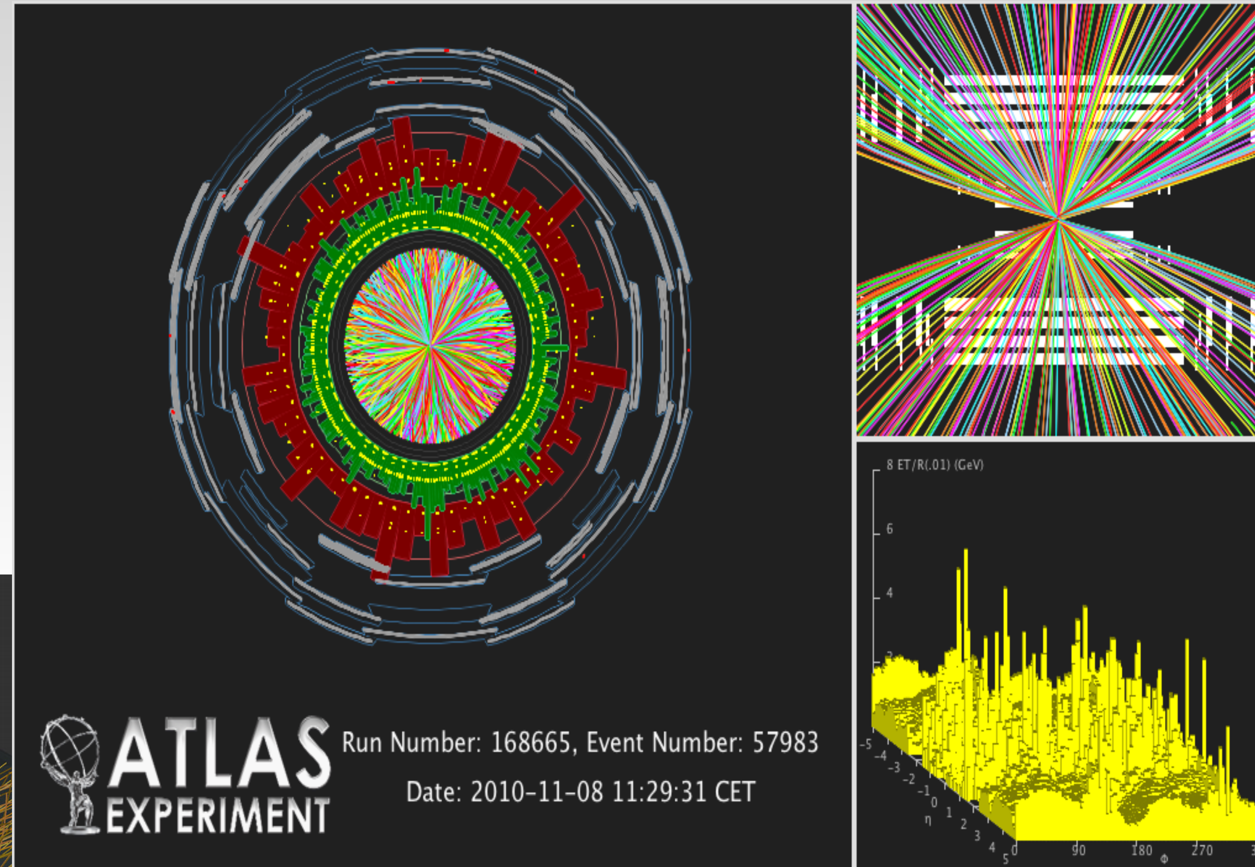
First events in Atlas/CMS

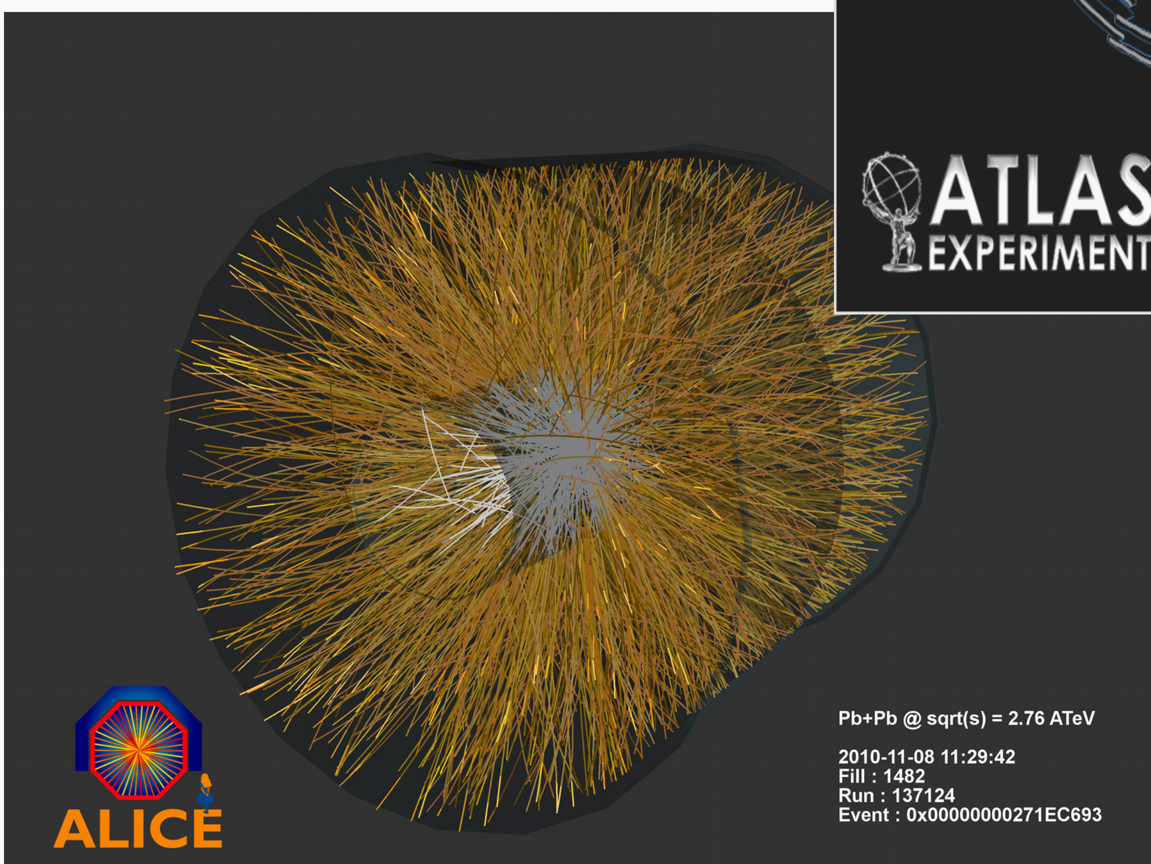


Soft collisions with just few tracks but important for alignment and trigger studies



The other extreme: HI collisions





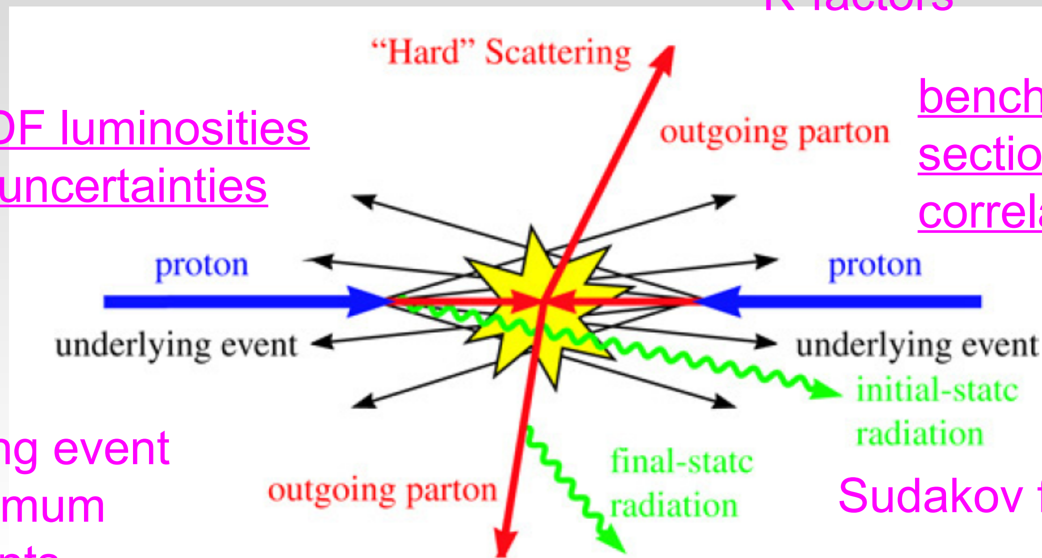
Physics in a hadron collider

LO, NLO and NNLO calculations

K-factors

PDF’s, PDF luminosities and PDF uncertainties

benchmark cross sections and pdf correlations



underlying event and minimum bias events

Sudakov form factors

jet algorithms and jet reconstruction

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

Parton distribution functions

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

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

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

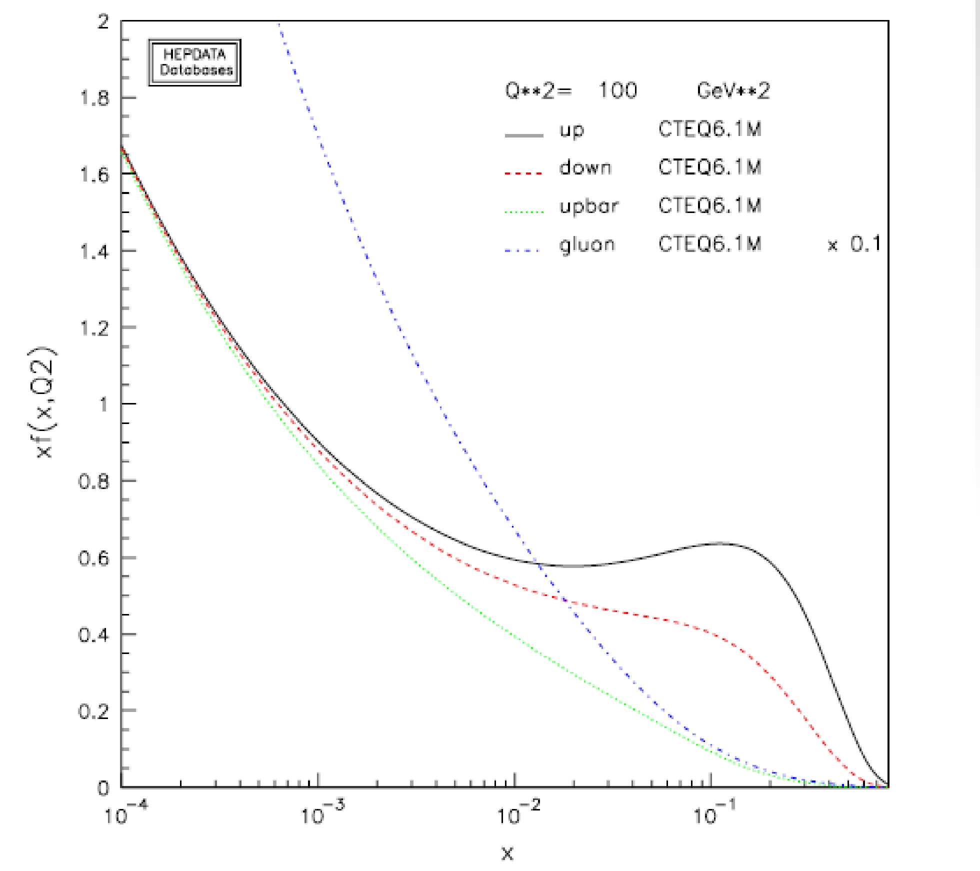


Figure 27. The CTEQ6.1 parton distribution functions evaluated at a Q of 10 GeV.

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

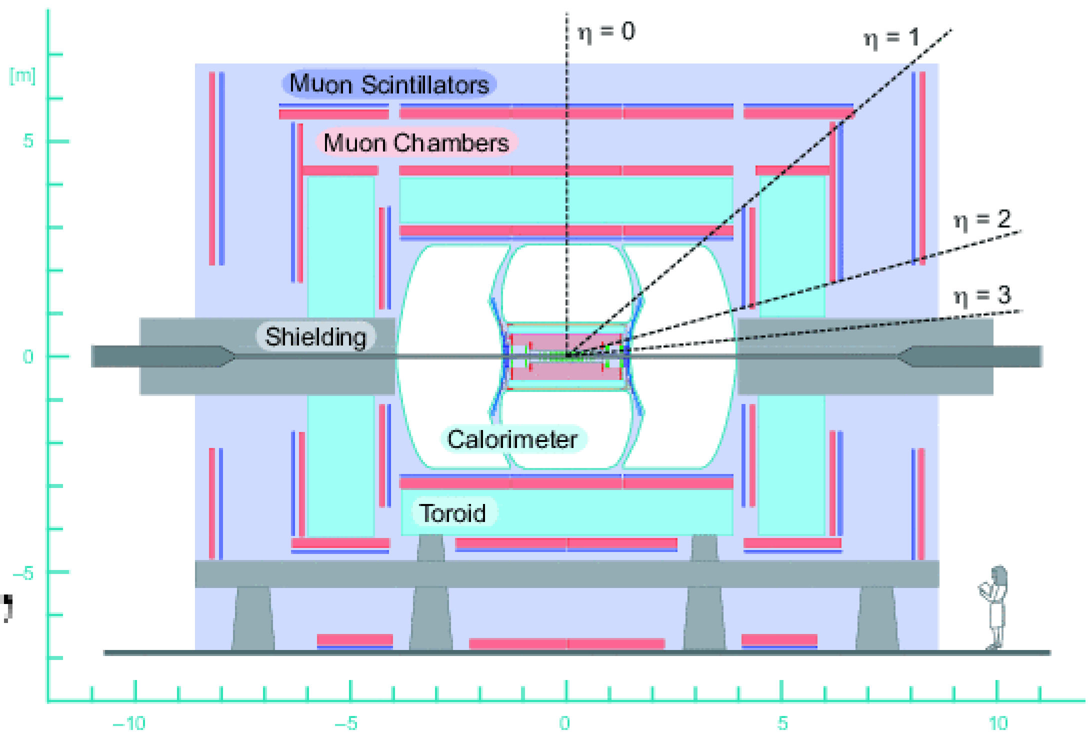
Relevant variables

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

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

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

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



Kinematic region of the LHC

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

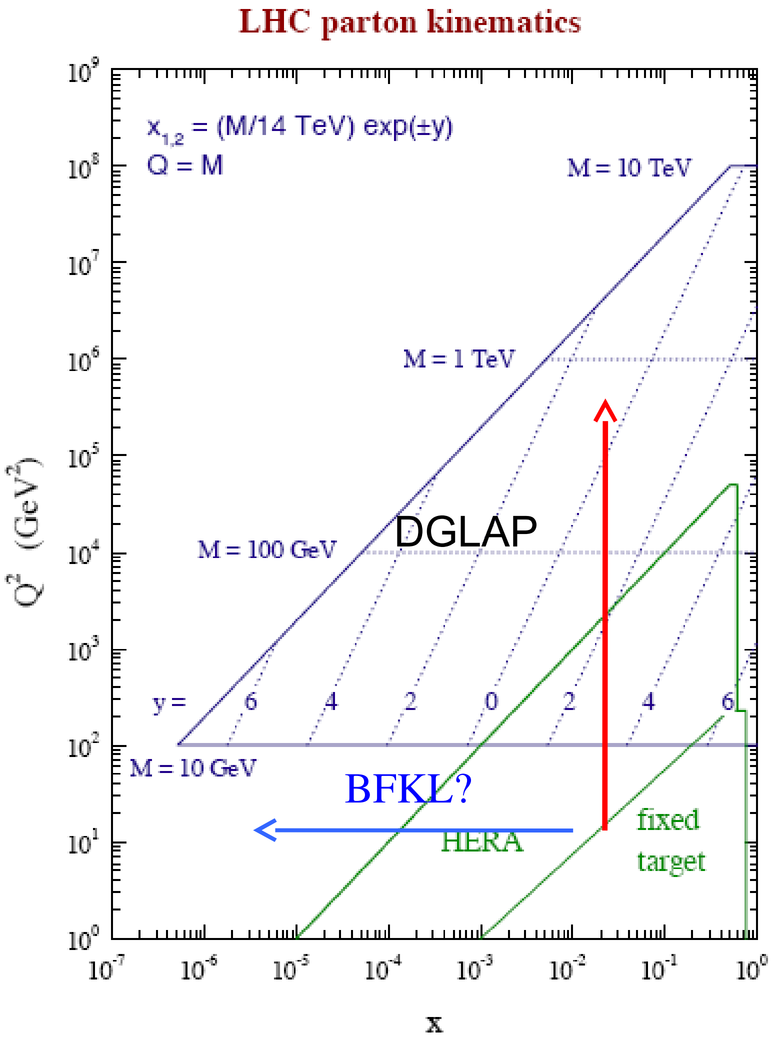
We will access pdf's down to 1E-6 (crucial for the underlying event) and Q^2 up to 100 TeV^2

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

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

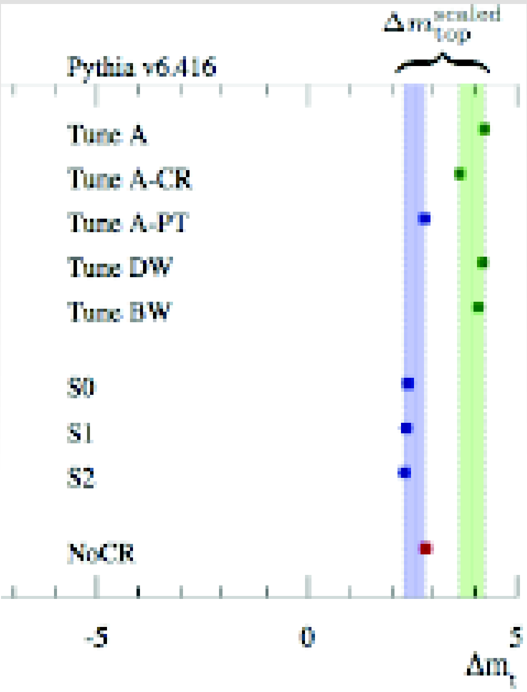
we're assuming that DGLAP is all there is; at low x BFKL type of logarithms may become important

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



The underlying event and the minimum bias

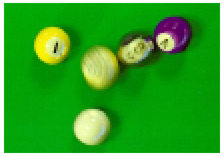
- UE: everything apart from the hard scattering (beam remnant, Multiple Parton Interctions, etc.)
- Will pollute all your physics events (especially ”rapidity gaps”), and influence precision measurements
- normally softer (but with large fluctuations)



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

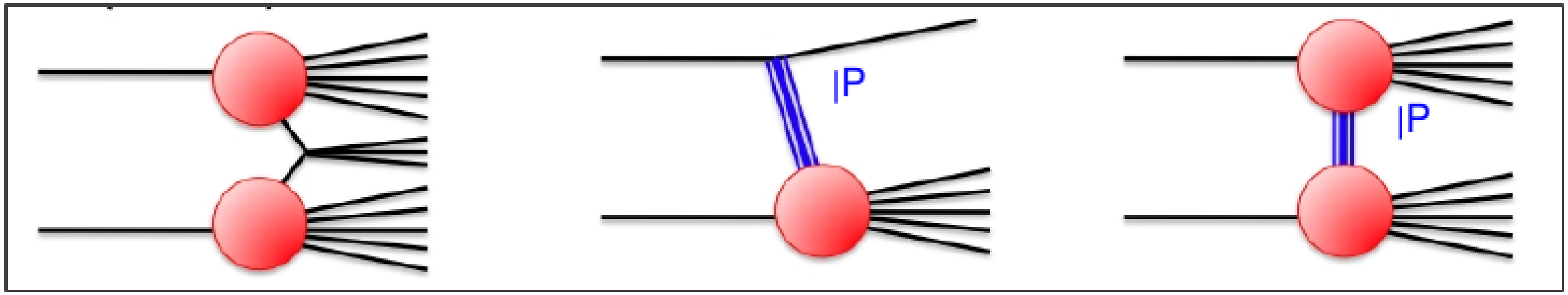
Elastic vs inelastic

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



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

Dominant processes in inelastic hadron-hadron interactions :



Non-Diffractive (ND) σ~49 mb

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

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

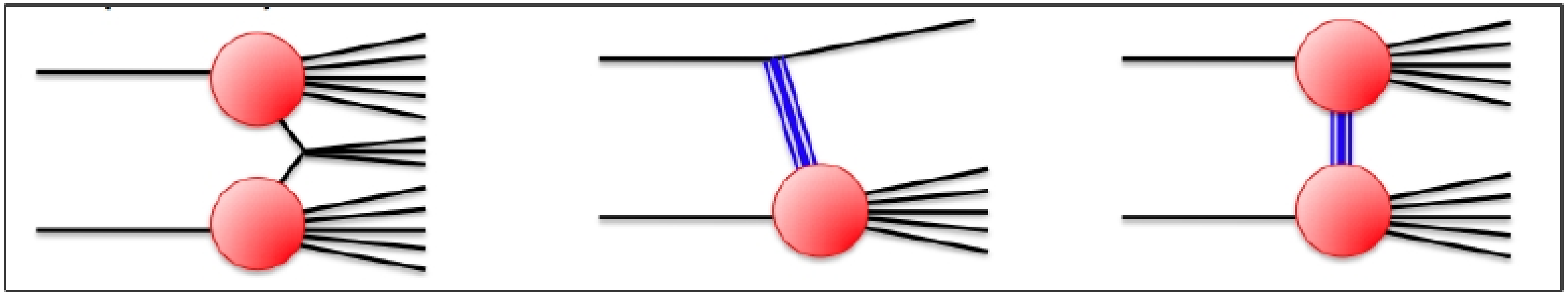
@ 7 TeV

|P = Pomeron (quantum numbers of the vacuum)

Measurement philosophy

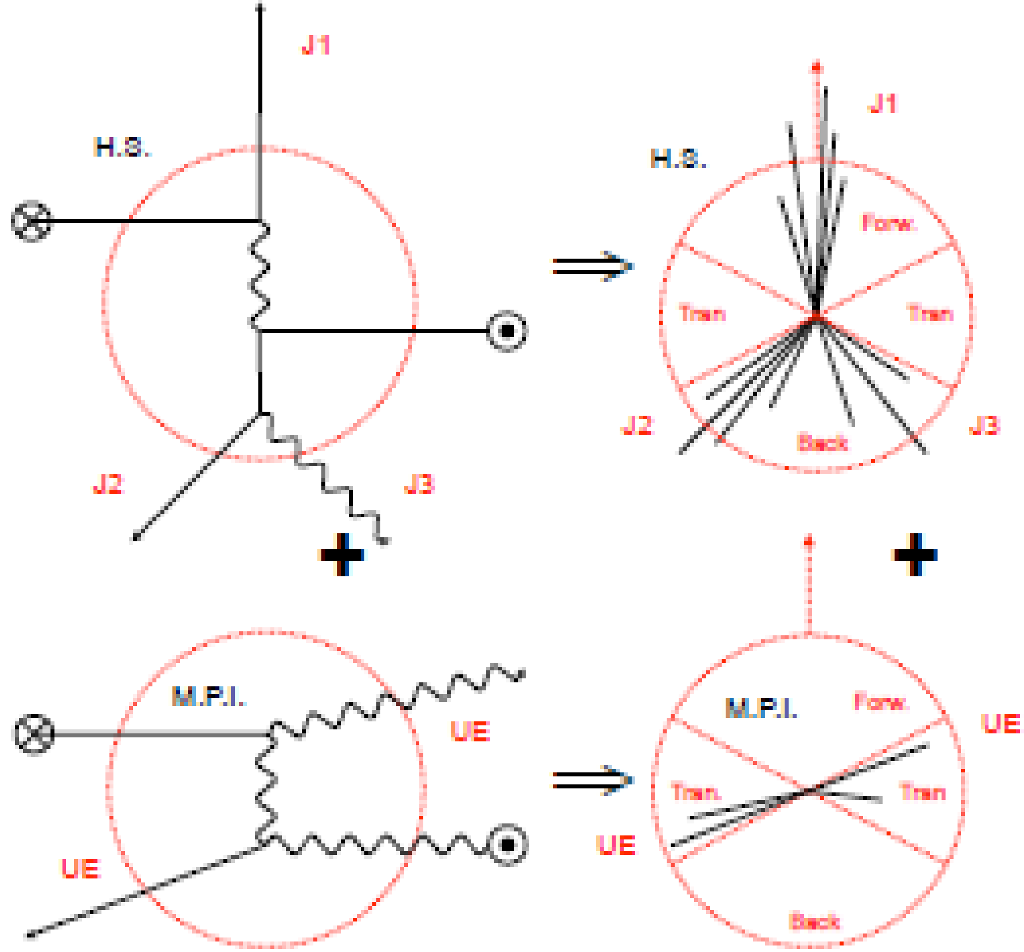
How should you do a measurement that is optimally useful for theory validation and MC tuning?

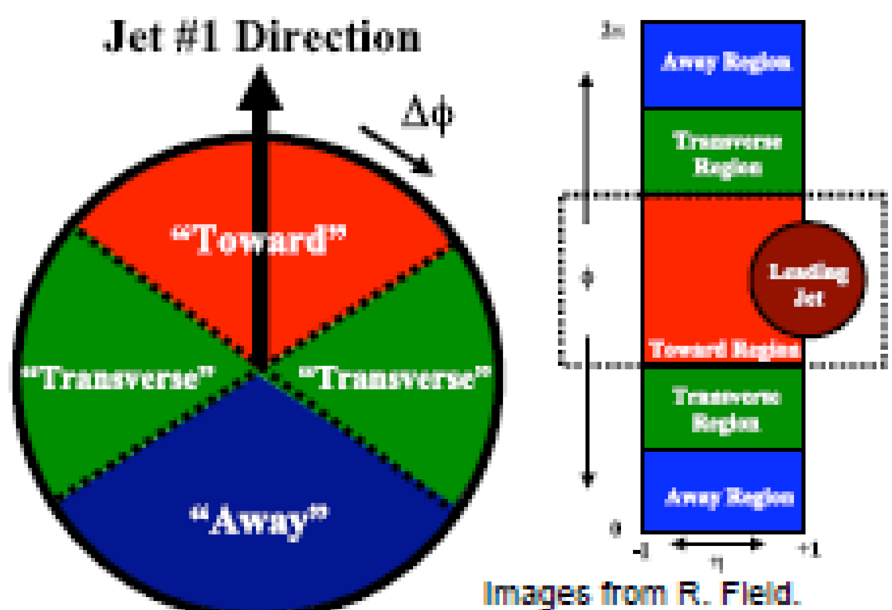
- Correct measurements for detector inefficiencies and resolutions (e.g. measure pT spectrum of charged particles, not of ATLAS tracks)
- No extrapolations into regions not “seen” by ATLAS (such as very low pT or far-forward particles)
  - We measure what we see, not what the MC tells us we should have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



UE Characterization

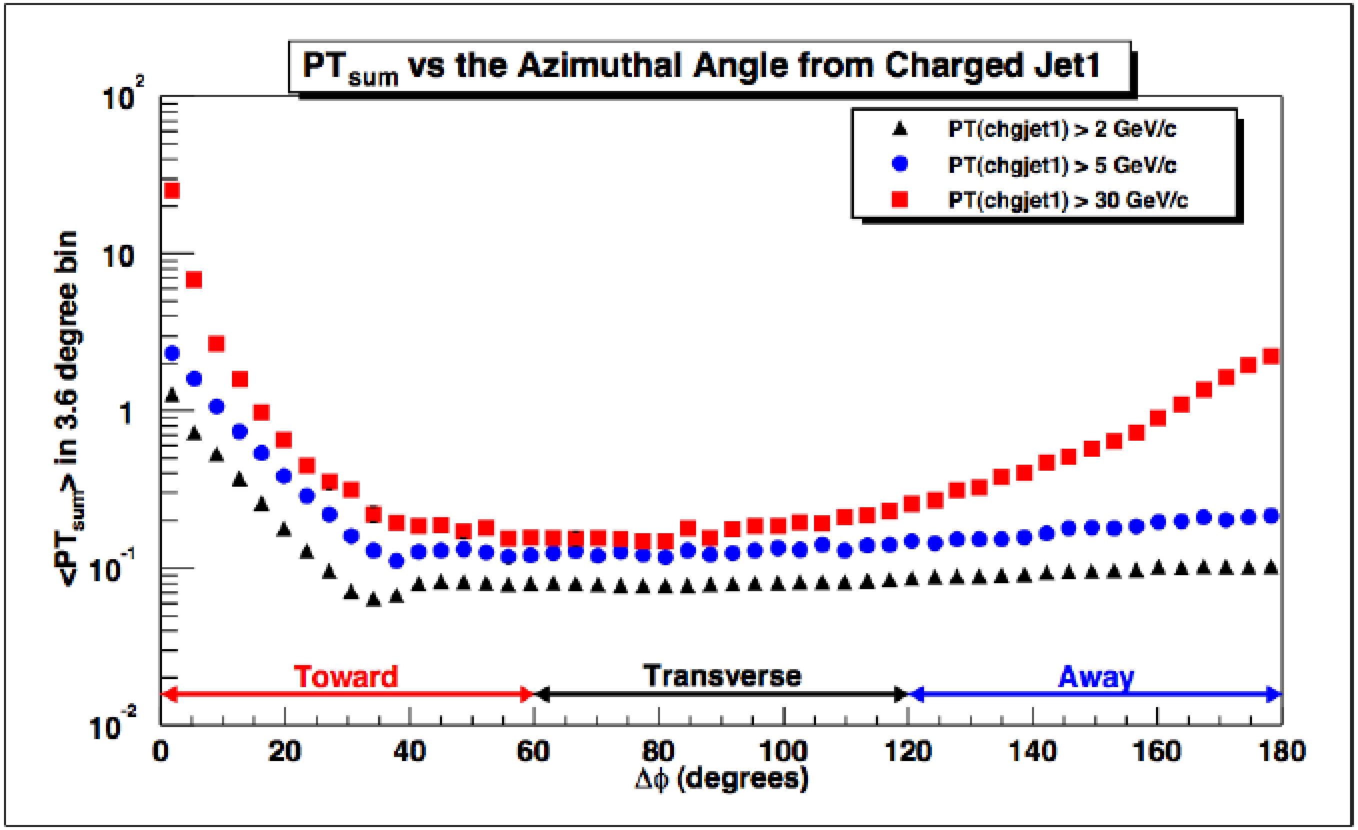
- Hard Scatter yields* 2 or 3 hard jets.
  *Given sufficient qualifying statements...
- Two equally hard jets will be roughly back-to-back.
- Additional interactions yield softer particles whose directions are not correlated to the hard scatter axis.
- Fragmentation, especially due to connections to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

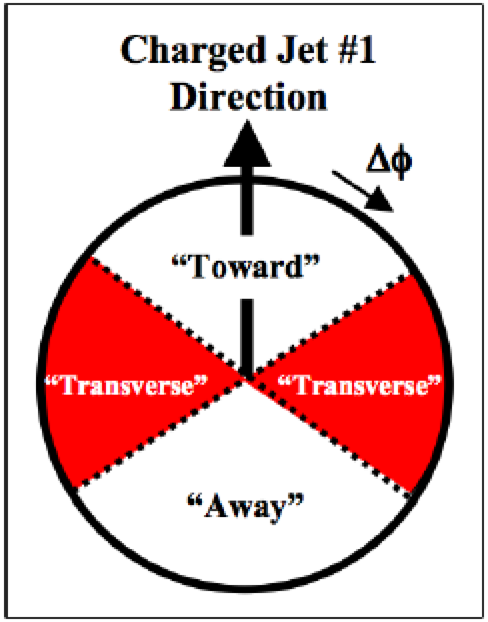




Images from R. Field.

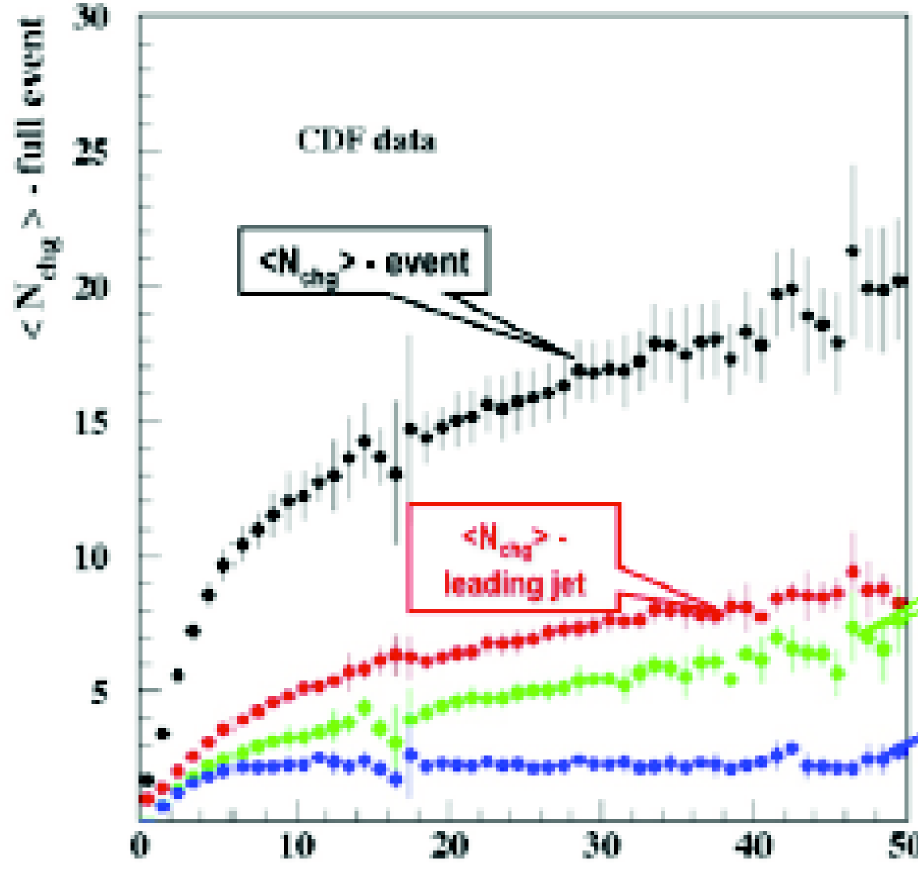
Particle multiplicity vs direction



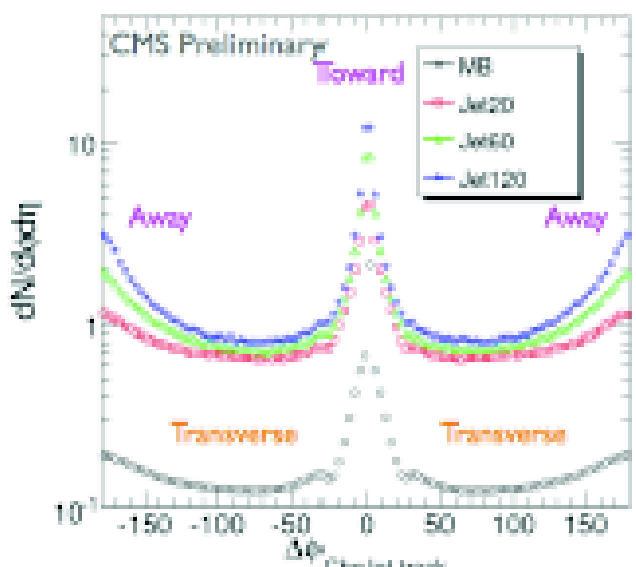


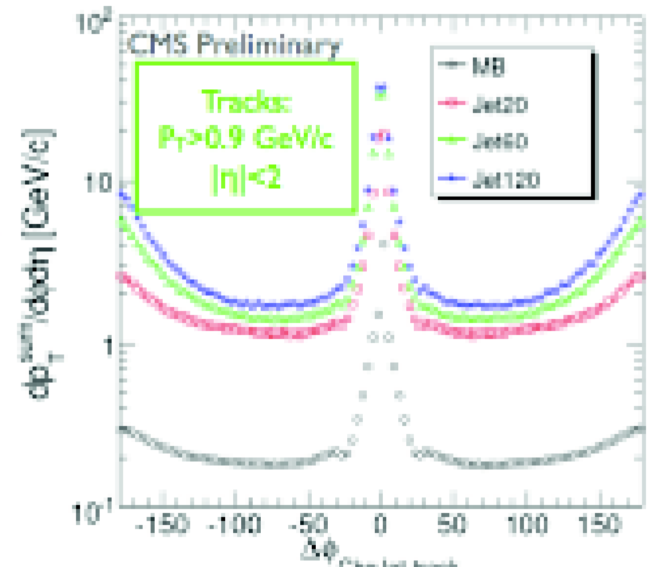
UE Characterization

- 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.



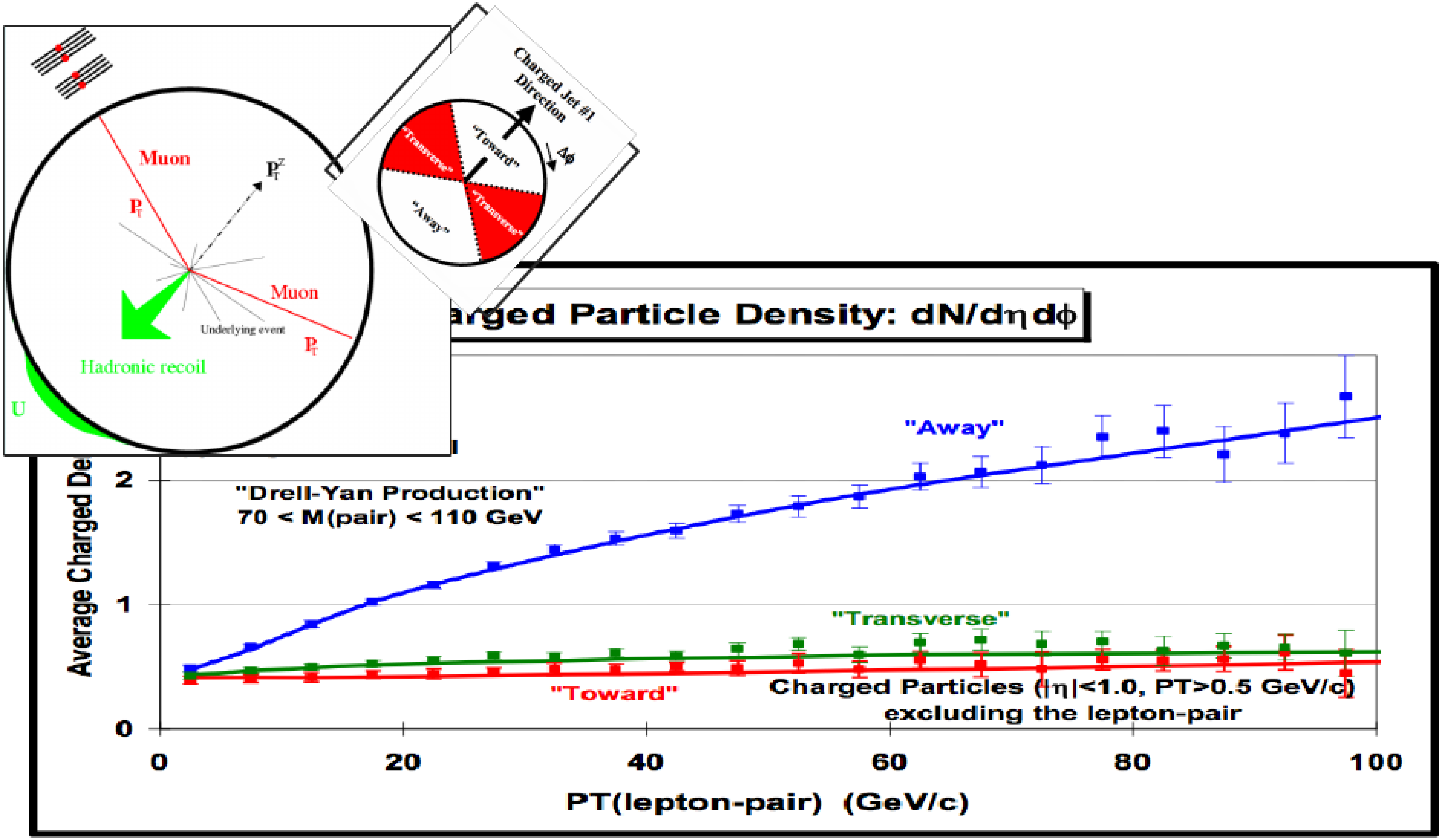
Above: Plot by Affolder at al.



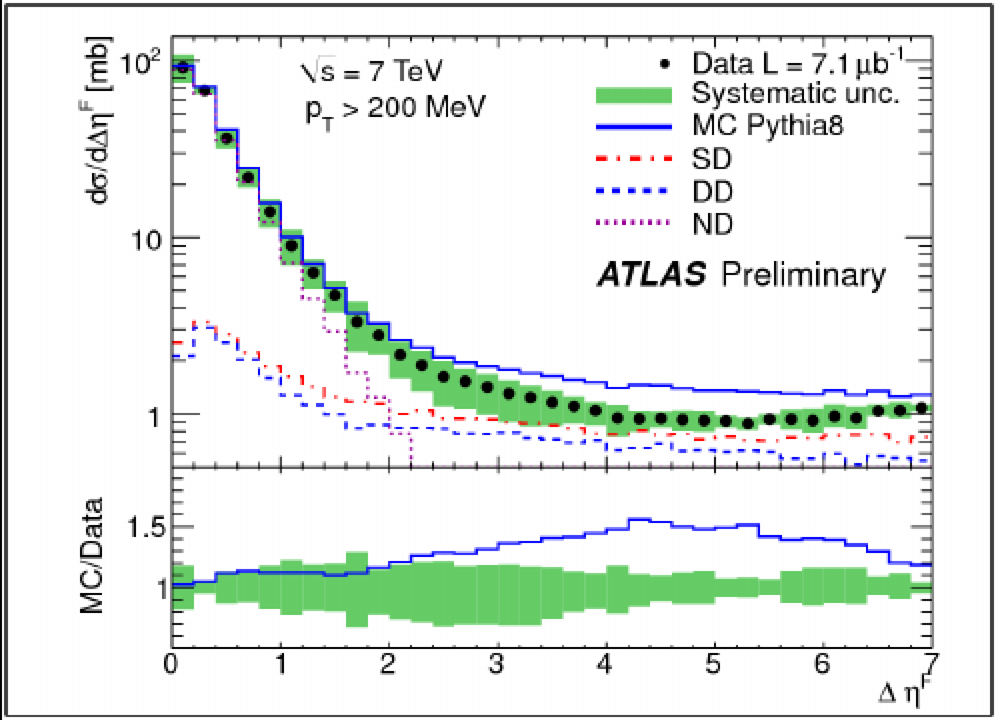


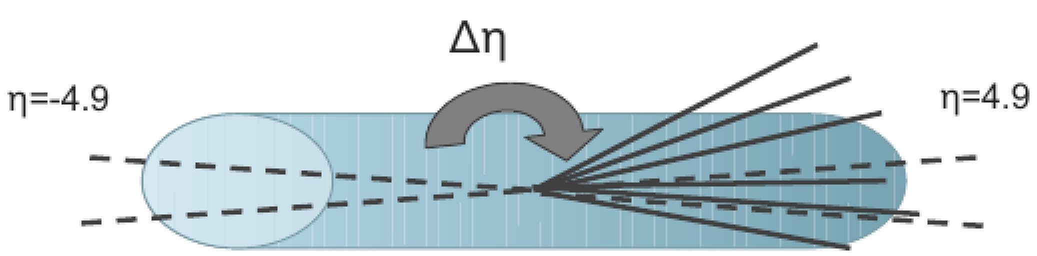
Above: Plots from F. Ambroglini

Underlying event in Z->ll

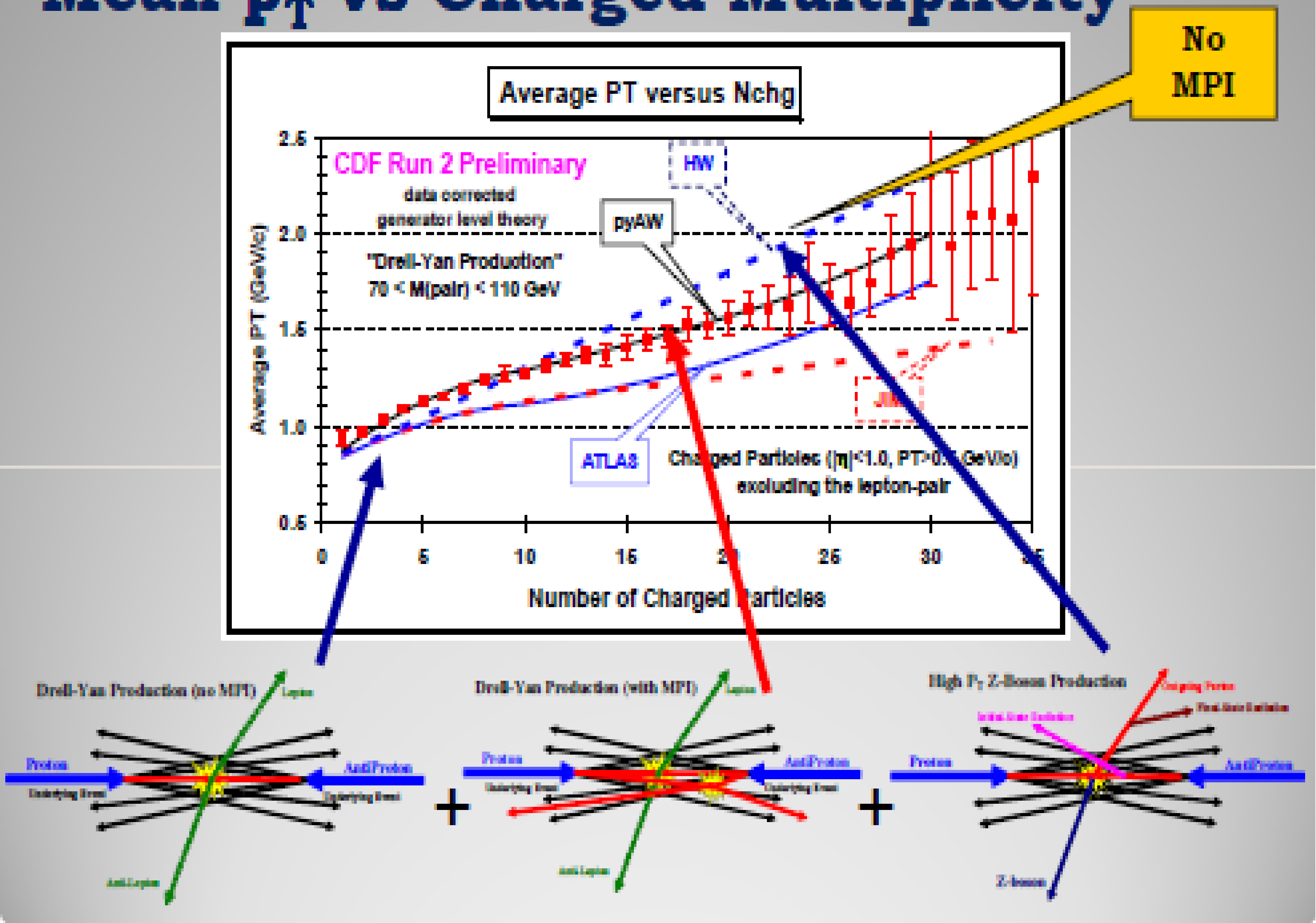


Enhancing diffractive component: rapidity gaps

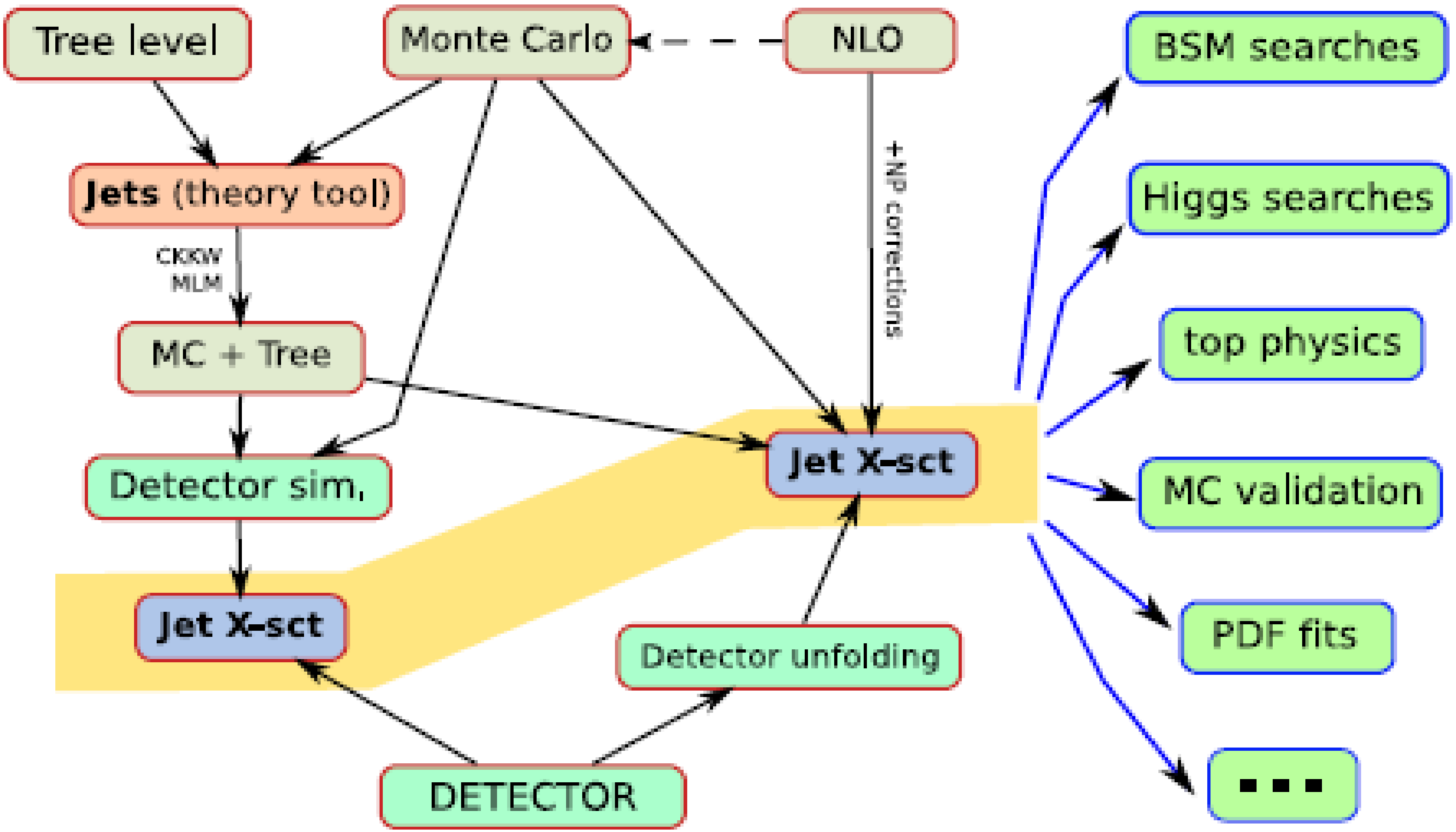




Mean p_T vs Charged Multiplicity



QCD and Jets



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

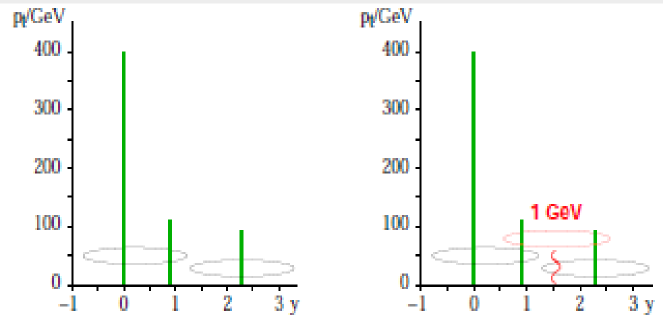
And jets are an input to almost all analyses

Two types of jet finders

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

Issues with cones

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



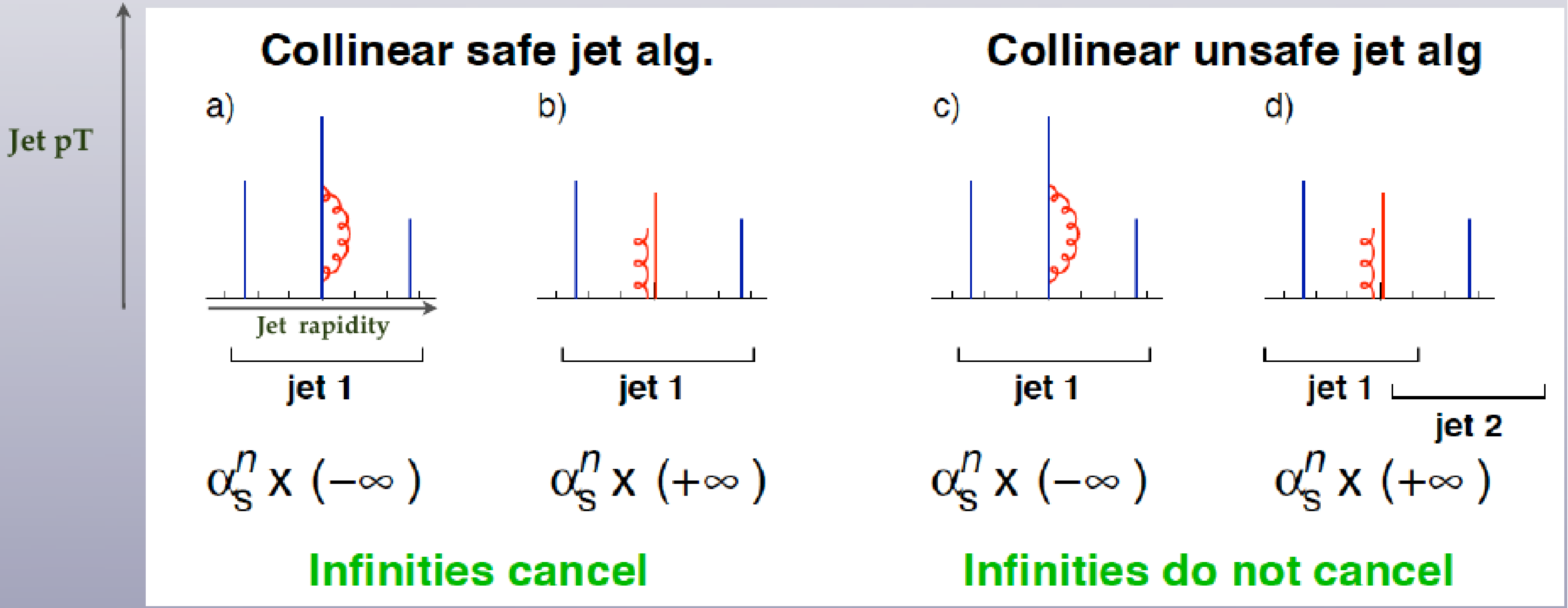
Stable cones with midpoint:	{1,2} & {3}	{1,2} & {2,3} & {3}
Jets with midpoint ($f = 0.5$)	{1,2} & {3}	{1,2,3}

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

Jet algorithms

- In the particular case of jet algorithms, **infrared safety** can be formulated as the requirement that if the **final state particles** are modified by a **soft emission** or a **collinear splitting** then the set of hard jets found should be unchanged

- Failing this criterion, a jet definition will produce **infinite results** at some point in the perturbative expansion because of the **lack of cancellation** of infrared divergences



In the **IRC unsafe algorithm**, a **collinear splitting** leads to a **different set of final state jets** and thus to the lack of cancellation of soft and collinear divergences (KLN theorem)

Sequential recombination jet algorithms

It is possible to **generalize the kt algorithm** by introducing a modified distance as follows

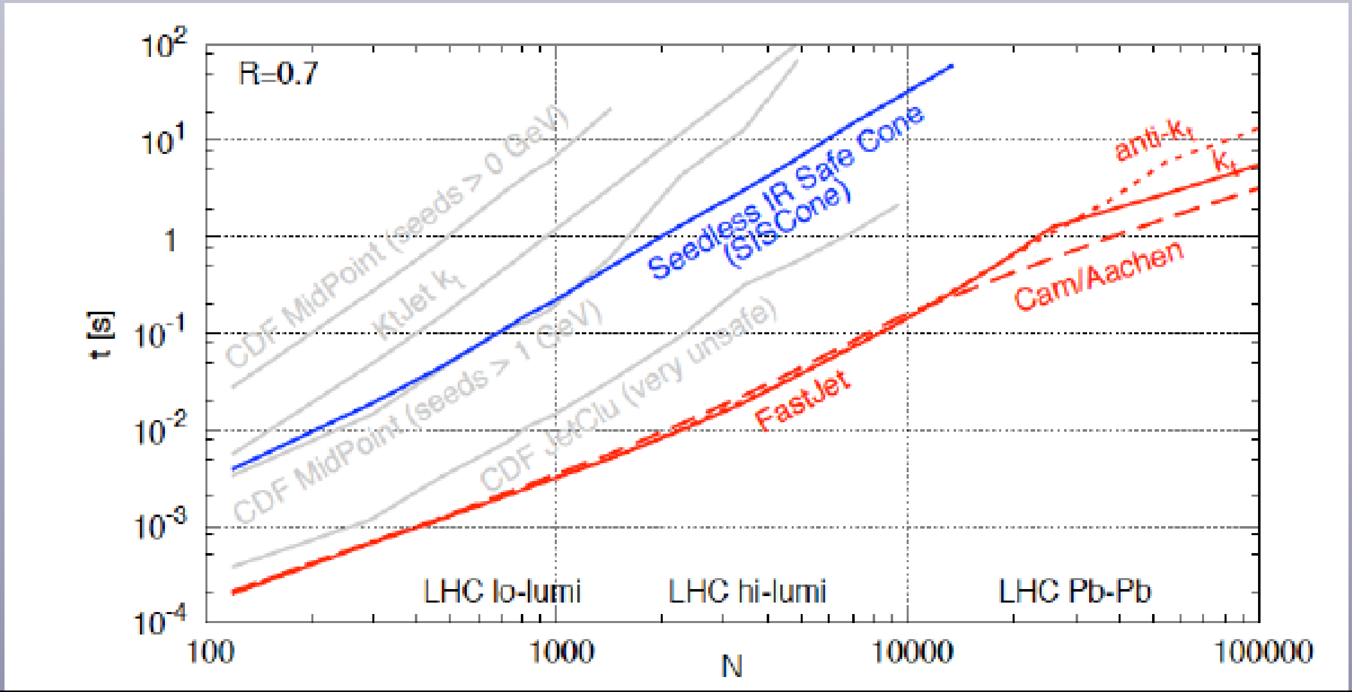
$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p})\frac{\Delta R_{ij}^2}{R^2}, \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2,$$

$$d_{iB} = p_{ti}^{2p},$$

- **p = 1 ->** kt algorithm: follows QCD branching structure in pt and in angle
- **p = 0 -> Cambridge/Aachen:** follows QCD branching structure **only in angle**
- **p = -1 -> Anti-kT algorithm:** unrelated to QCD branching structure, with clustering measure favouring recombination of high-pT particles

By construction, these sequential recombination algorithms are **infrared safe**

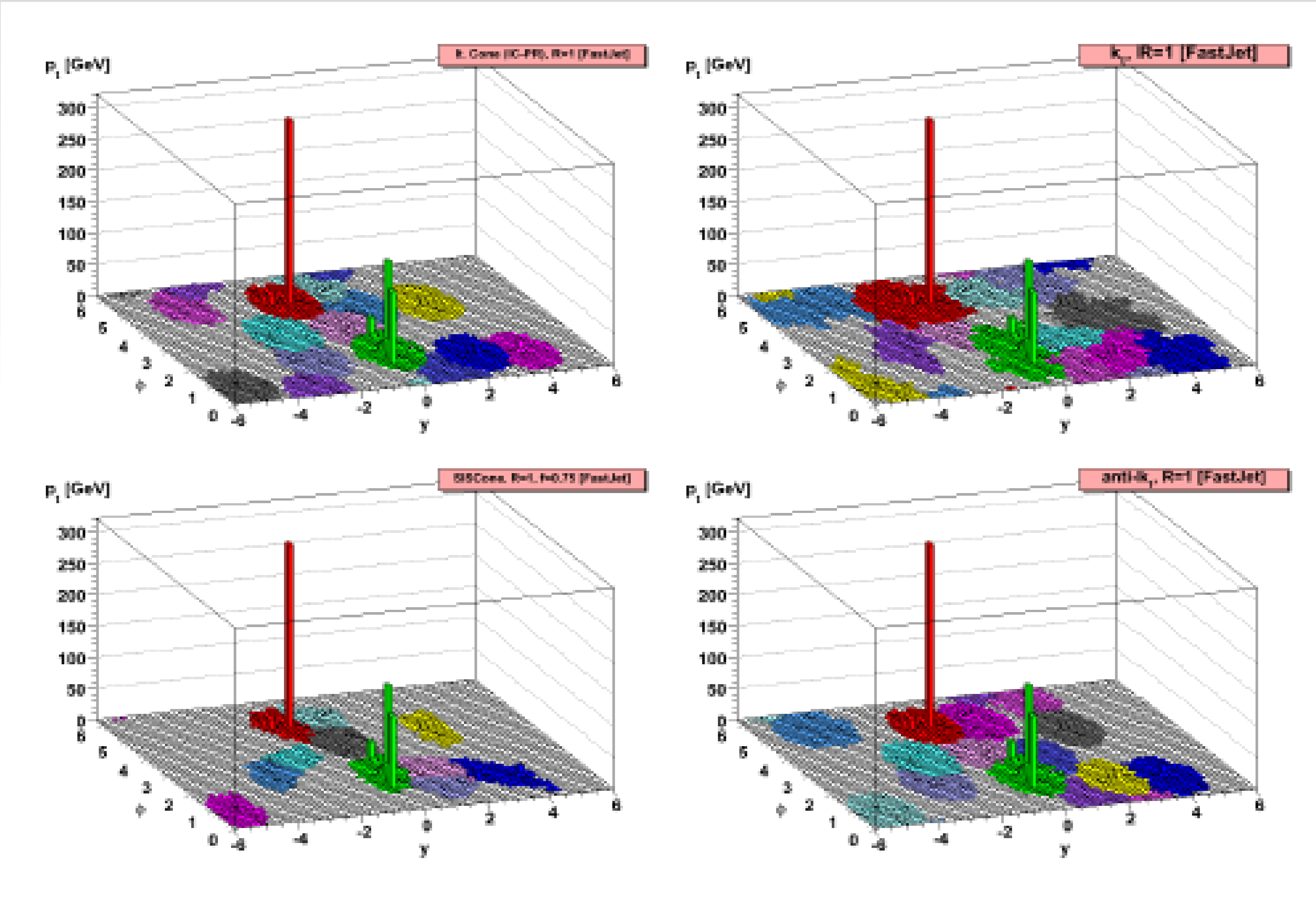
At the LHC, the default jet algorithm is the **Anti-KT** algorithm, for reasons that we discuss now



Original implementations of kt algorithm very **slow, T=O(N³)**, making it unpractical for high-multiplicity hadron collisions

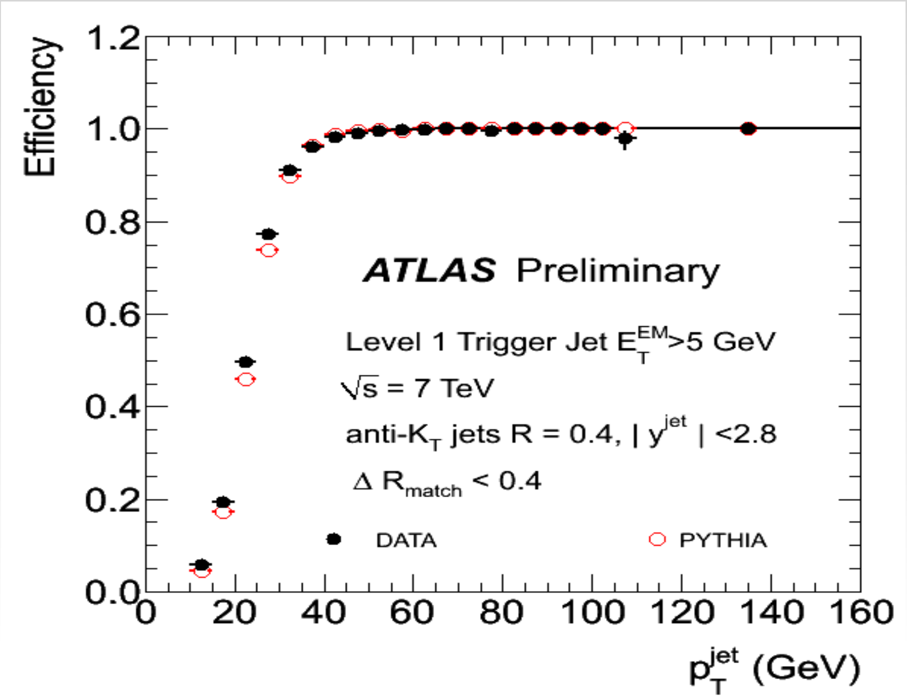
Modern implementations (**FastJet**) much more efficient using computational geometry, amd achieve **T=O(N log N)**

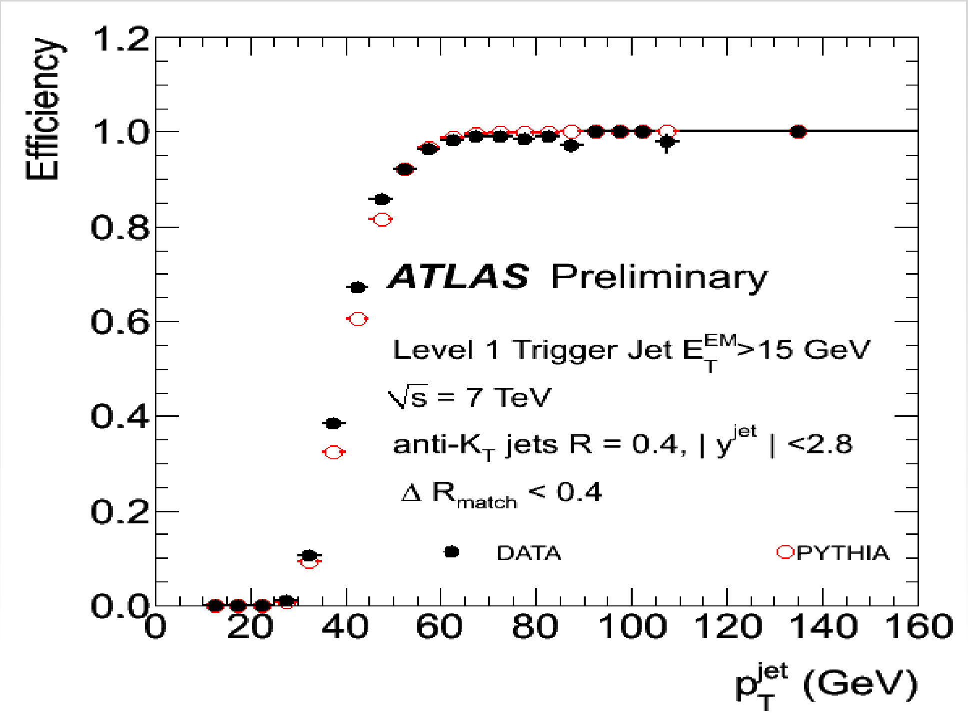
But the most conical cone is not a cone!



Anti-kt now default algorithm in Atlas

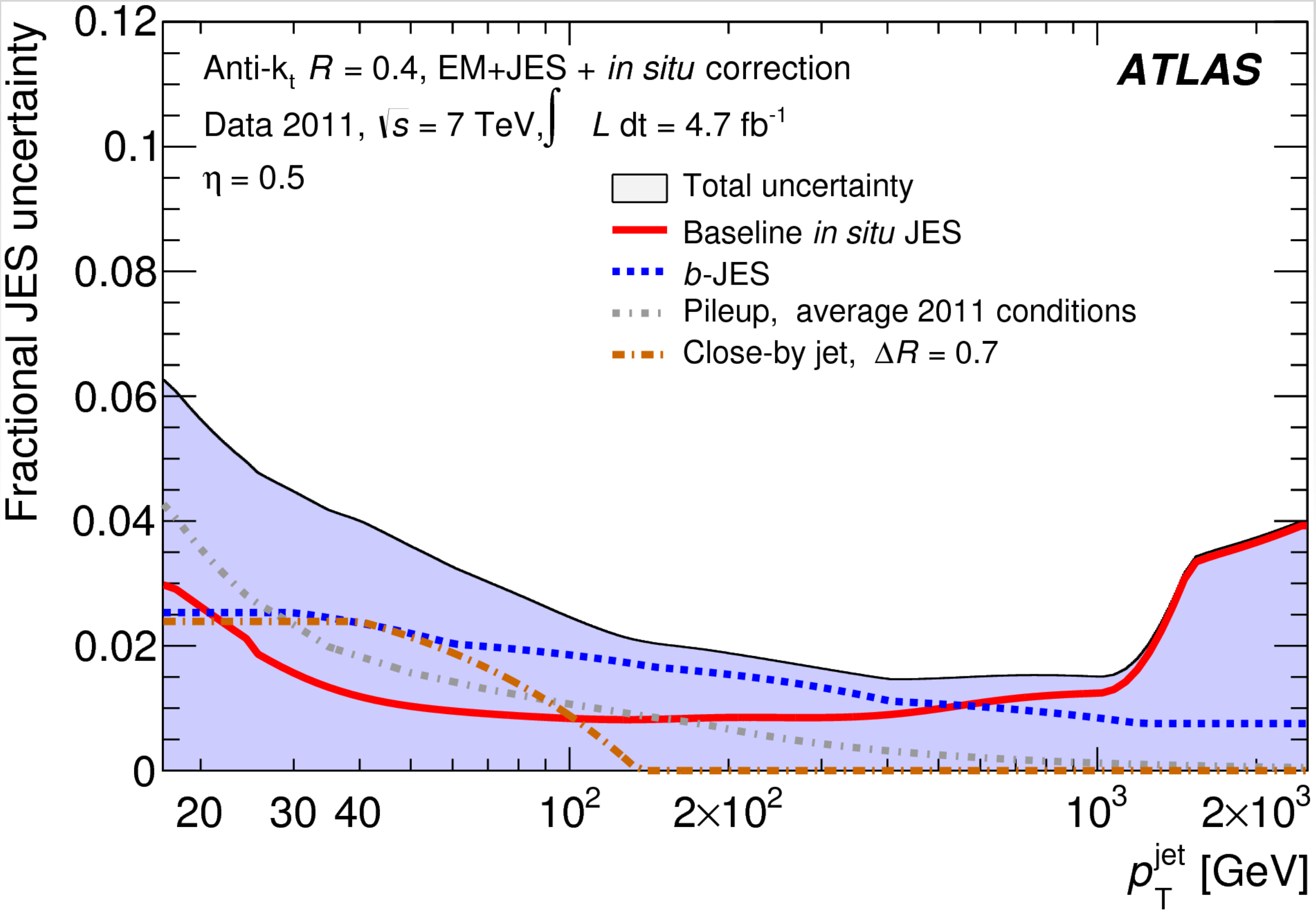
Measuring jet production: trigger





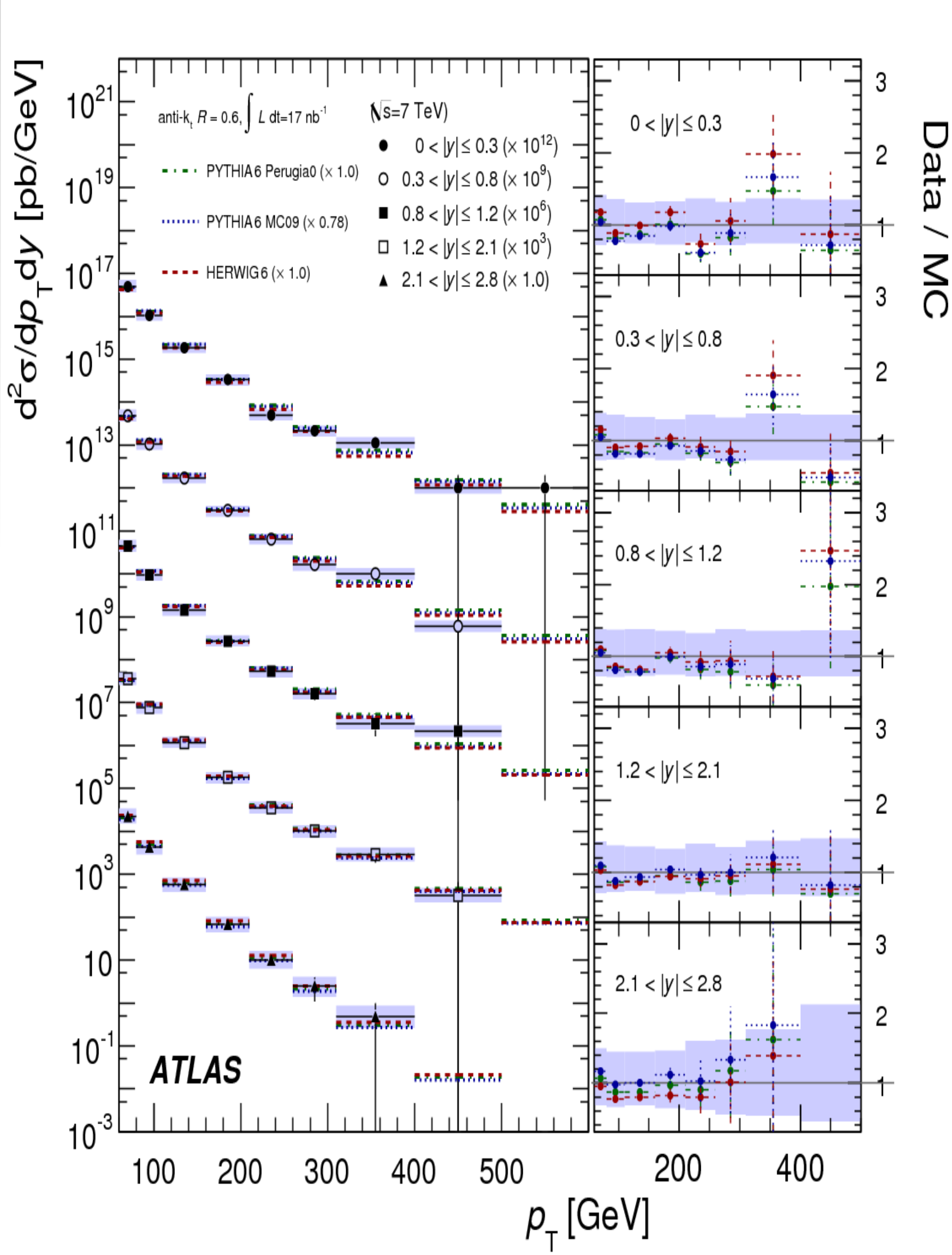
- Not to correct for the efficiency in the steeply rising part of the curve, jet cross section was first measured above the 100% efficiency point
- This results in the measurement being performed in different Pt bins in the various periods, because higher luminosities forced heavy prescales on lowest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

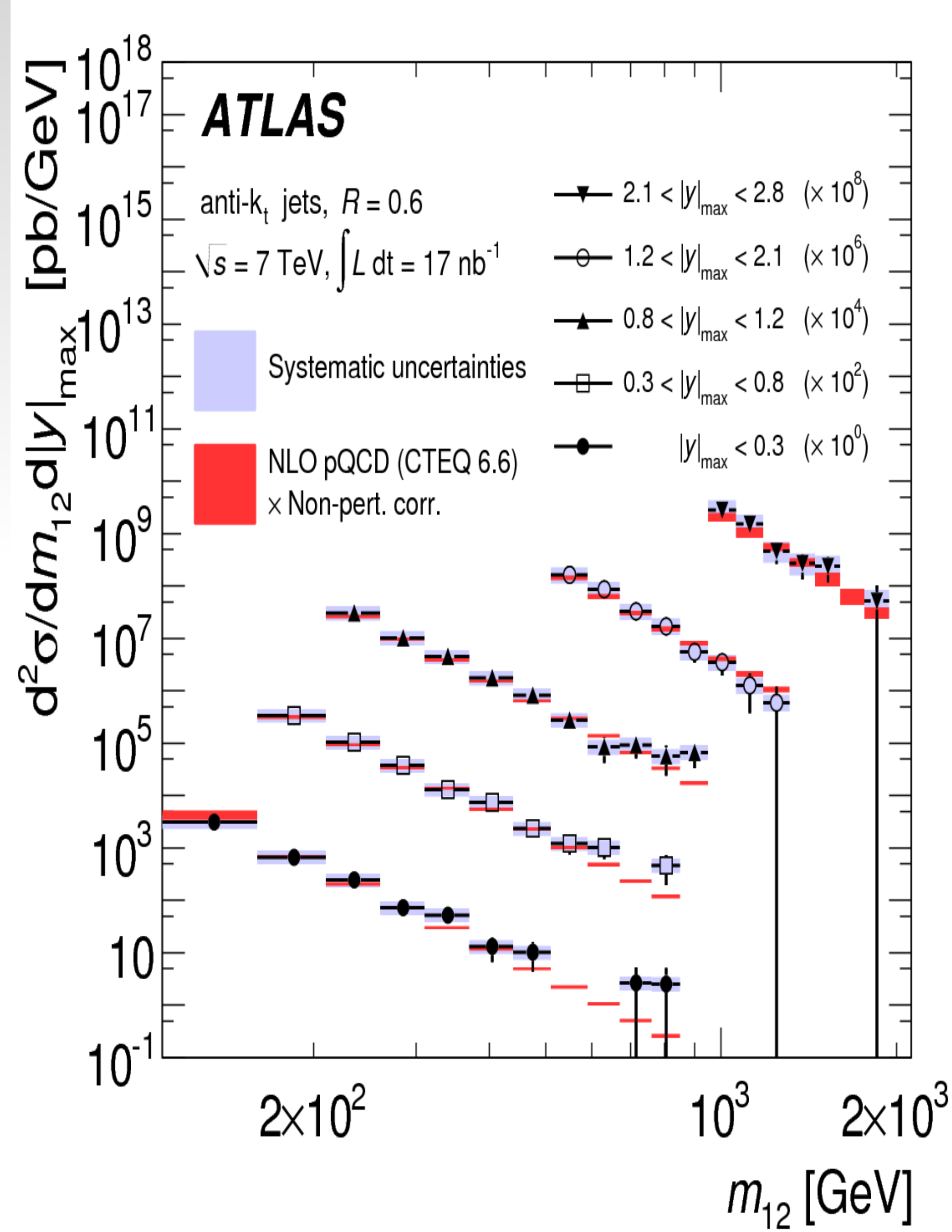
Jet Energy scale



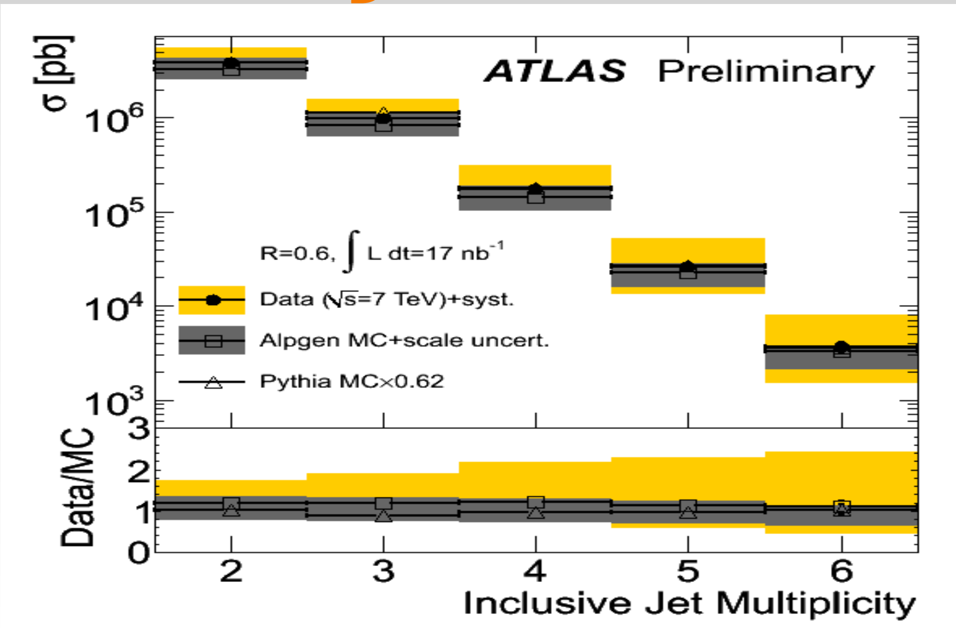
Primary calibration from MC, using information from various calorimeter layers. Uncertainties from modelling, and from in-situ techniques (like photon-jet balance)

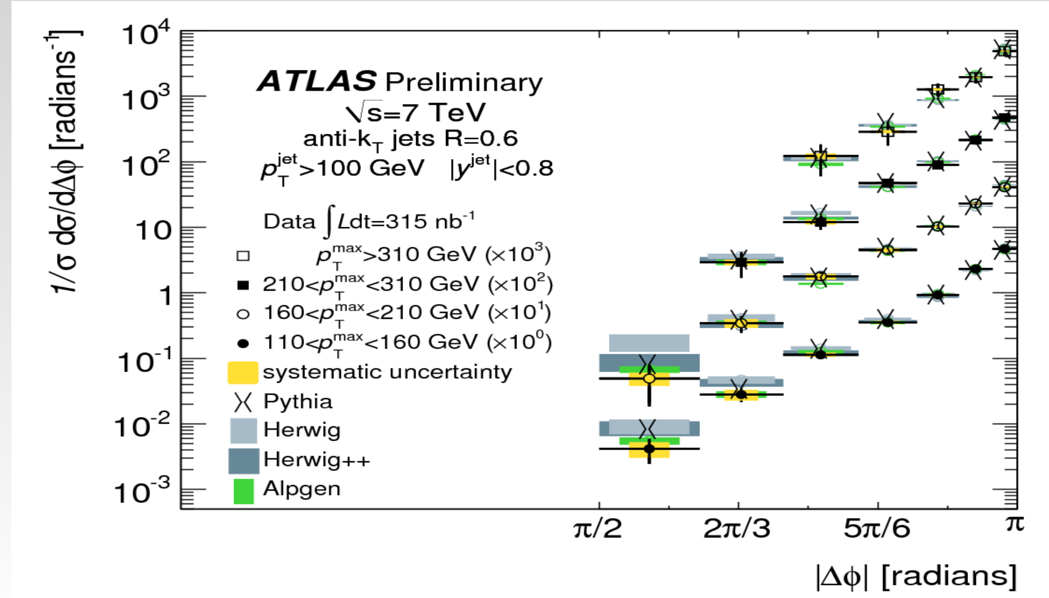
Jet and dijet cross-sections

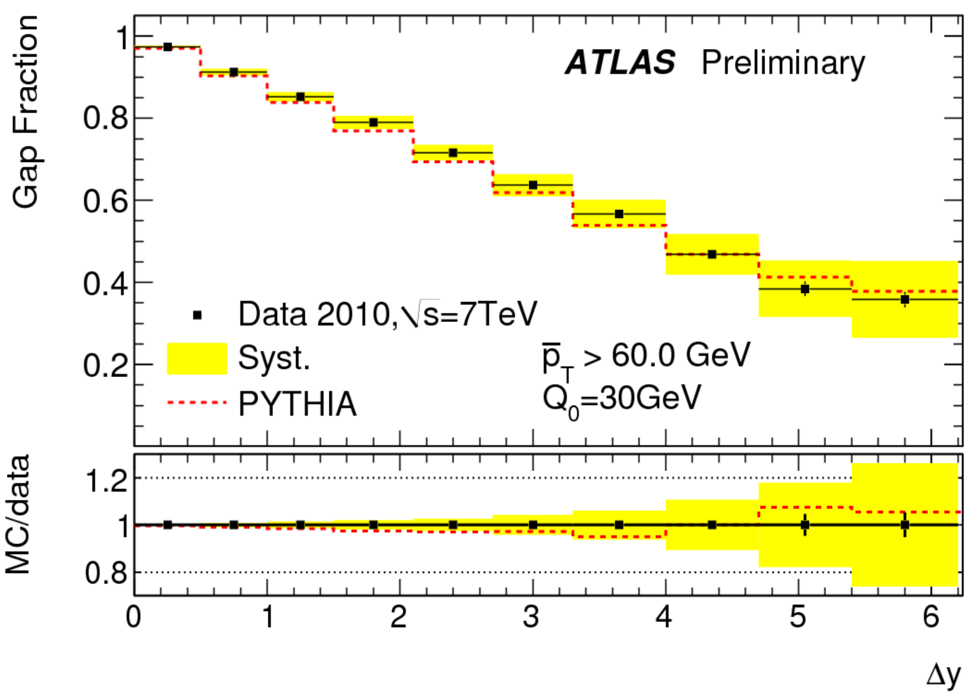




Multijet, de-correlation, gaps





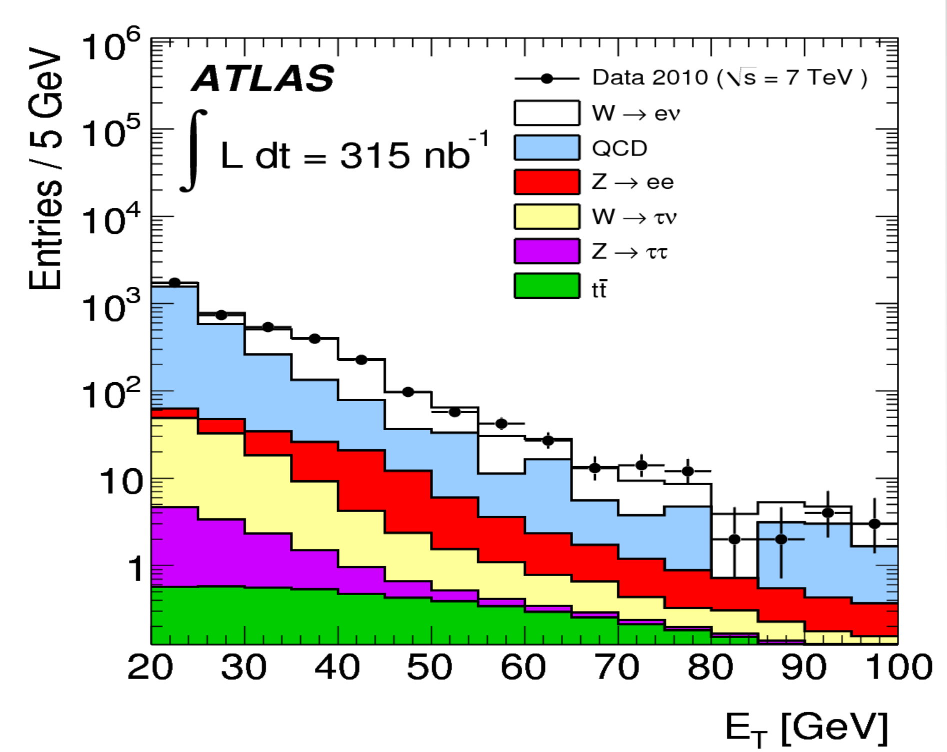


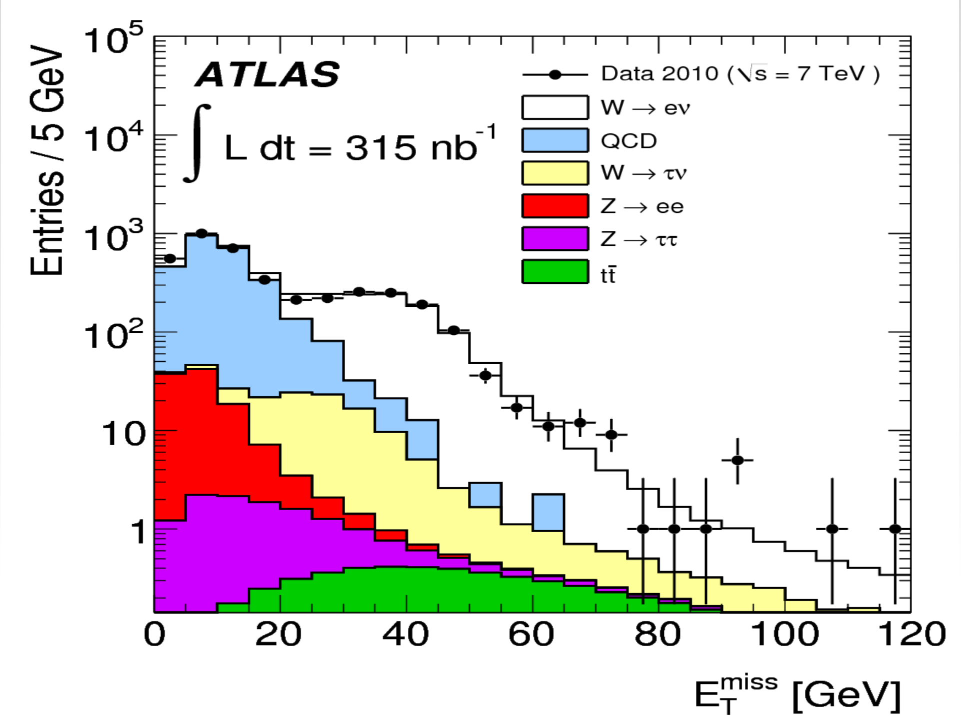
Several QCD tests performed on jets, looking at multiplicity, angular distribution, radiation between dijets

Vector boson production

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

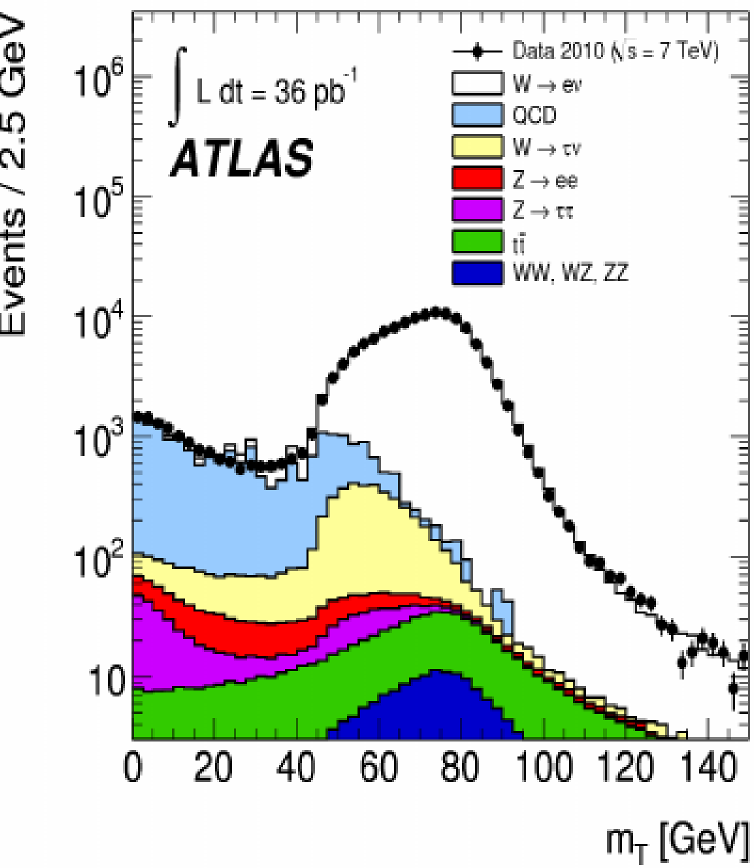
Ingradients of the analysis

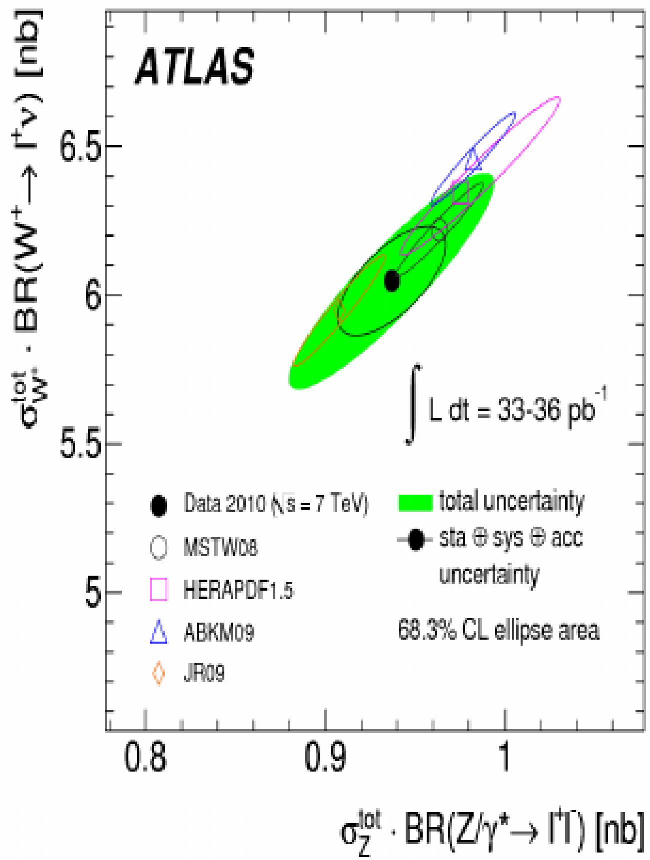


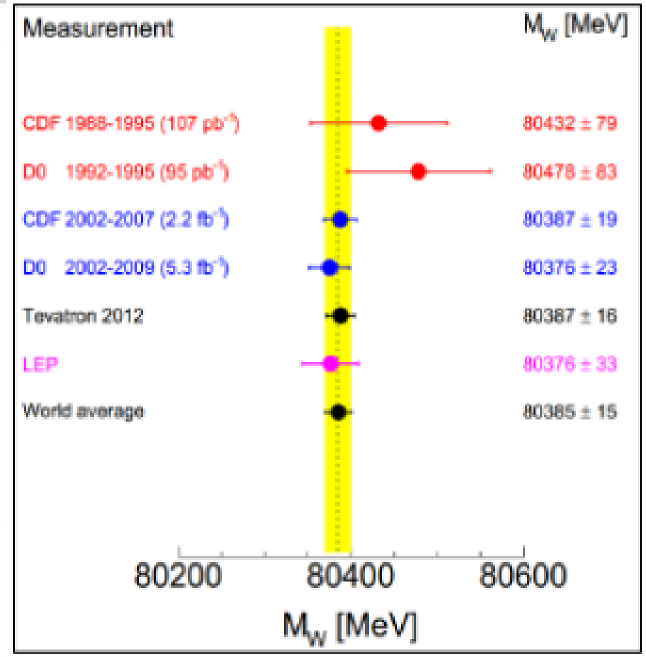


- Electron Pt MET
- for W->enu events
- Signal purity quite low for individual variables

W->e nu transverse mass

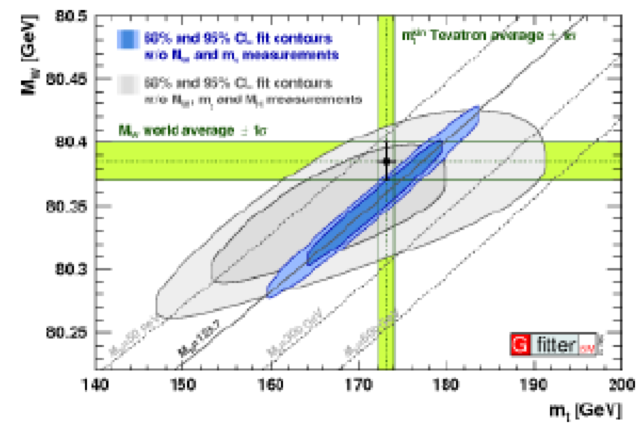






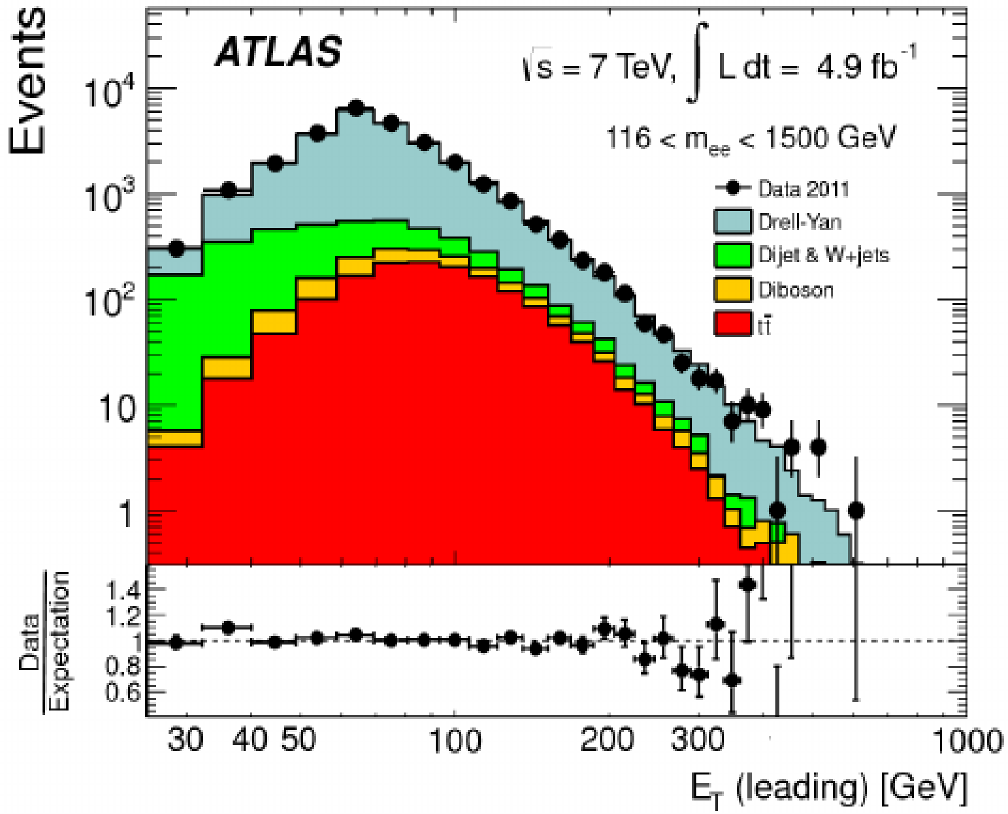
arxiv:1307.7627

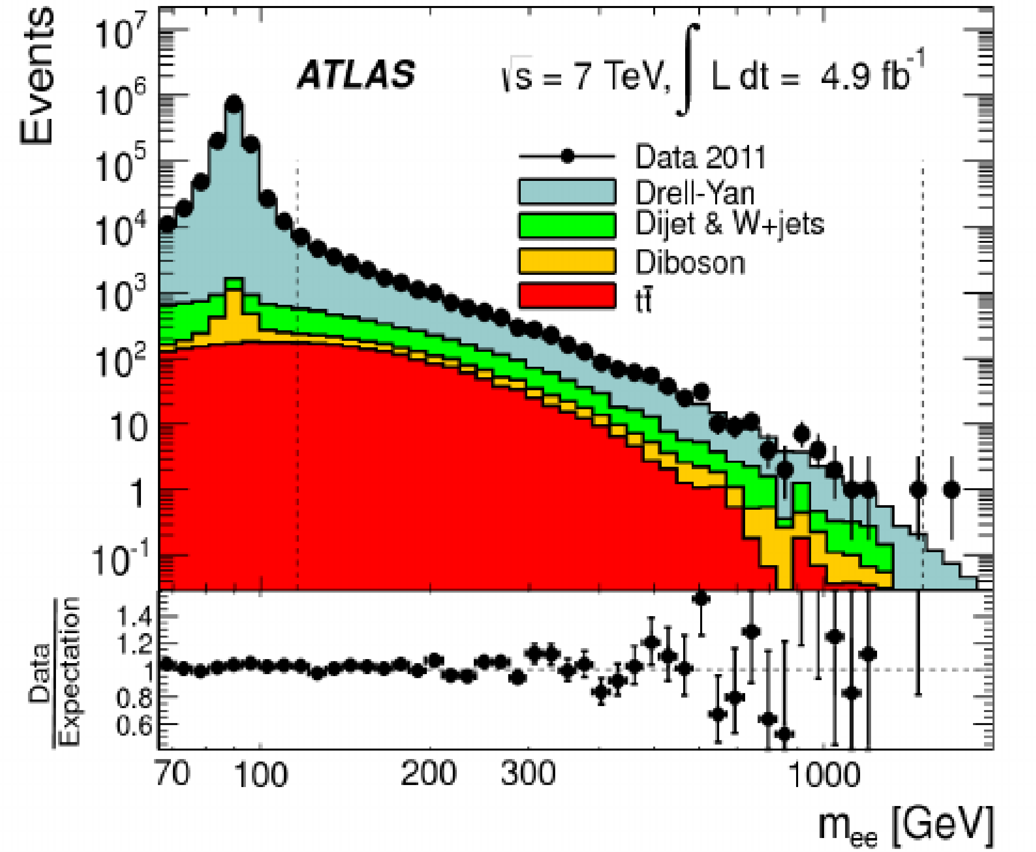
arxiv:1209.2716



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

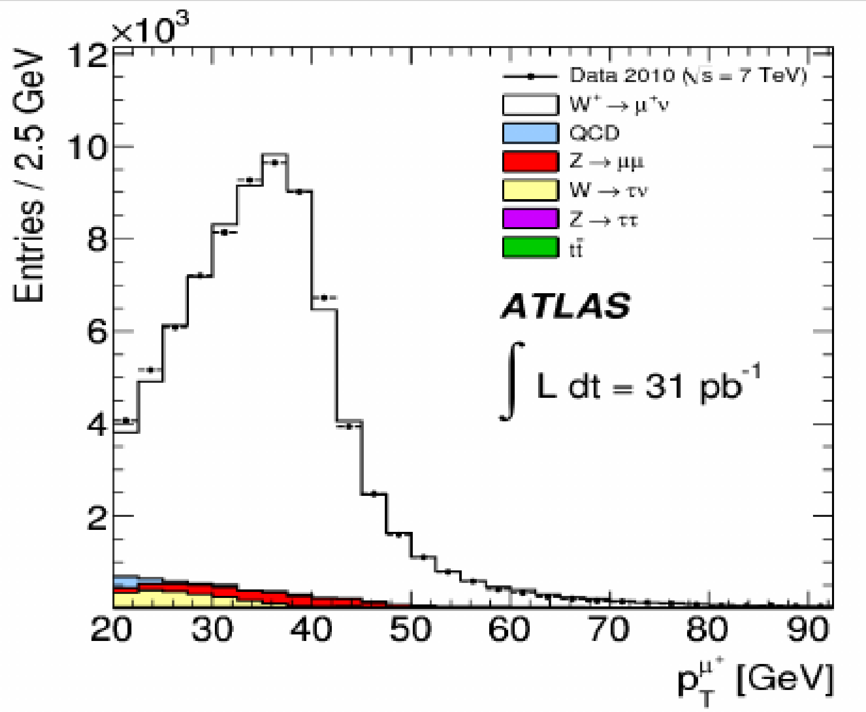
Z->ll analysis

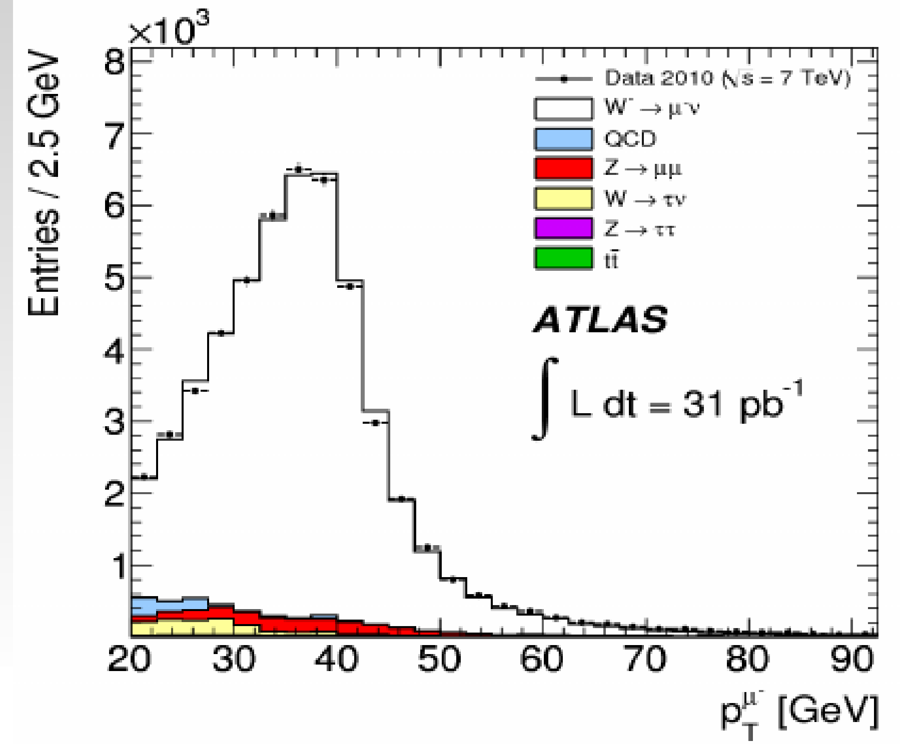


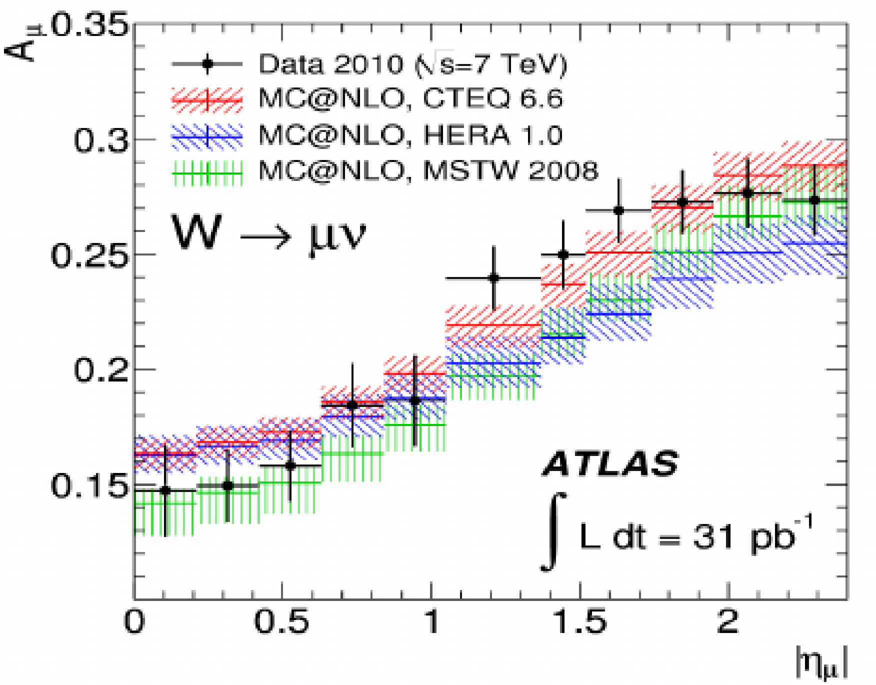


2-lepton requirement makes Z channel much cleaner, but statistics is poorer than W-hard to beat LEP's 4 million Z collected per experiment (and lineshape fit) in clean environment. Fundamental tool for calibration

W charge asymmetry



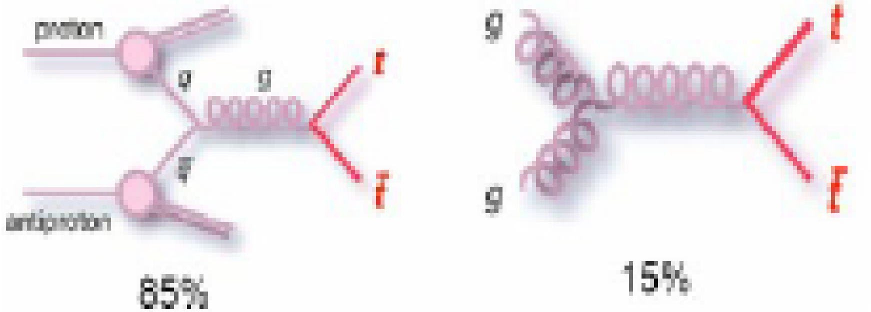




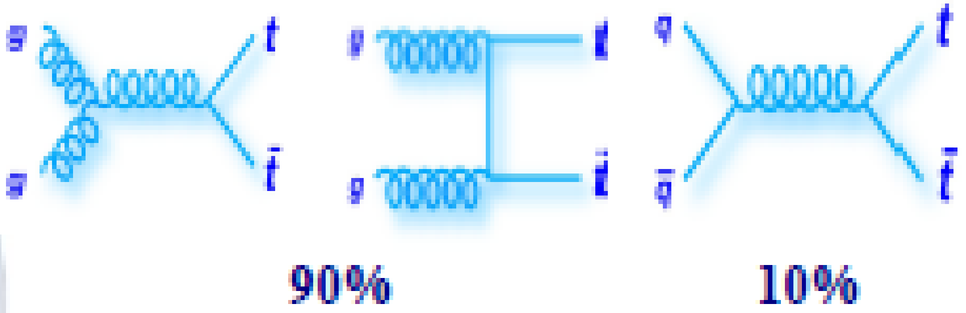
The idea: from Pdf's, u-quarks have higher average x, so W+ tend to be produced more forward. Even in pp, W asymmetry distribution can constraint Pdf's

Top quark production and decay

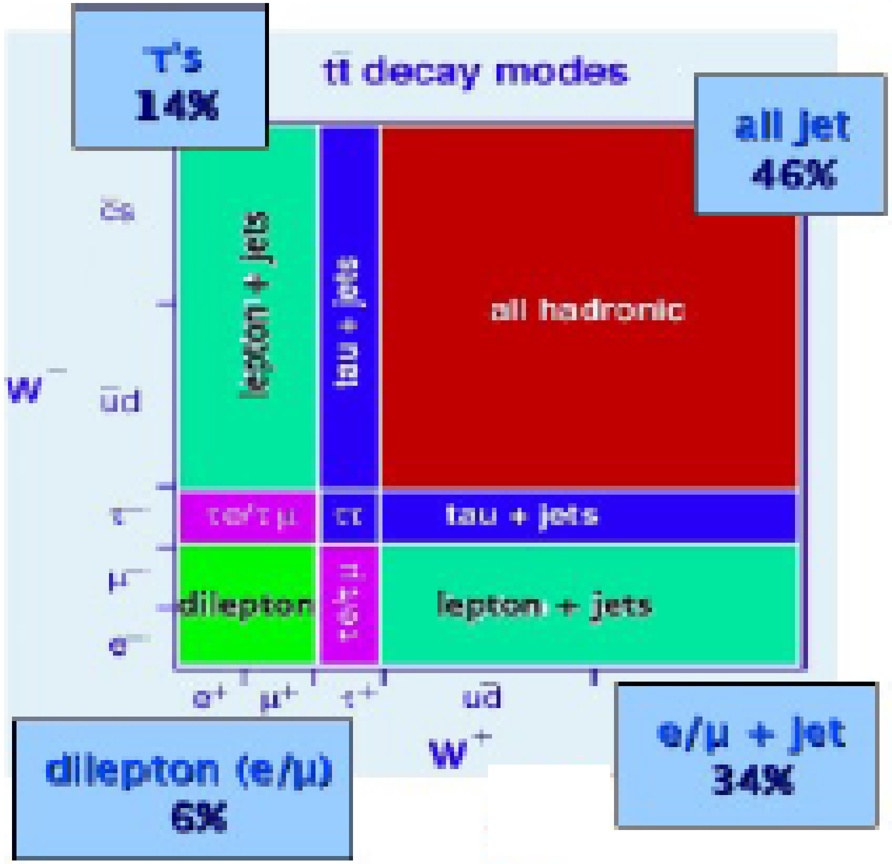
- Produced mainly in pairs
  - σ ≃ 7 pb @ 2 TeV



  - σ ≃ 400 pb @ 10 TeV



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



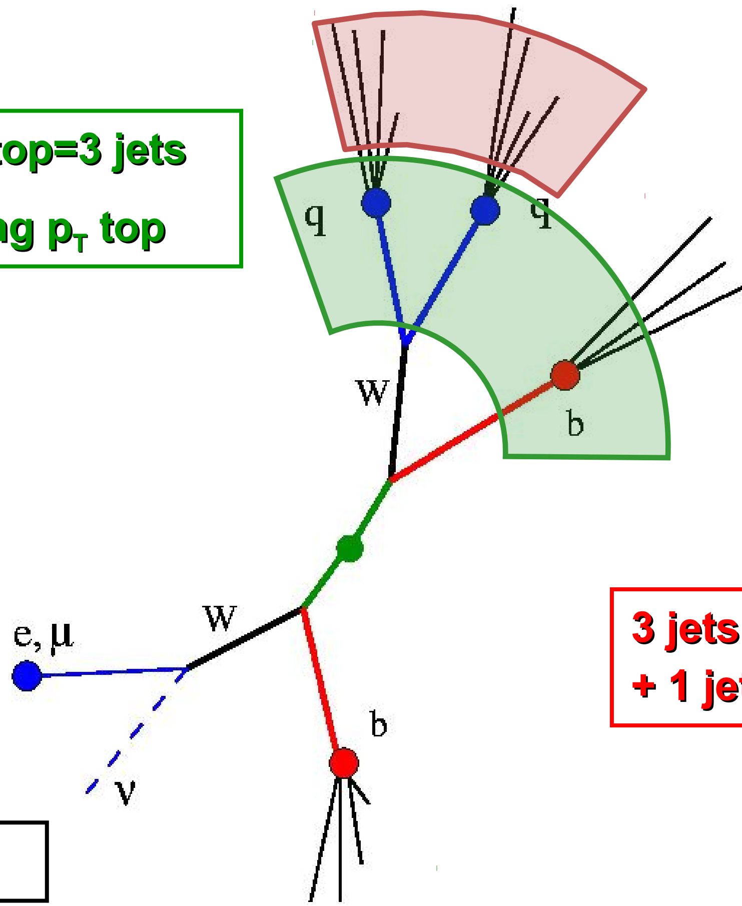
Top quark physics measurements

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

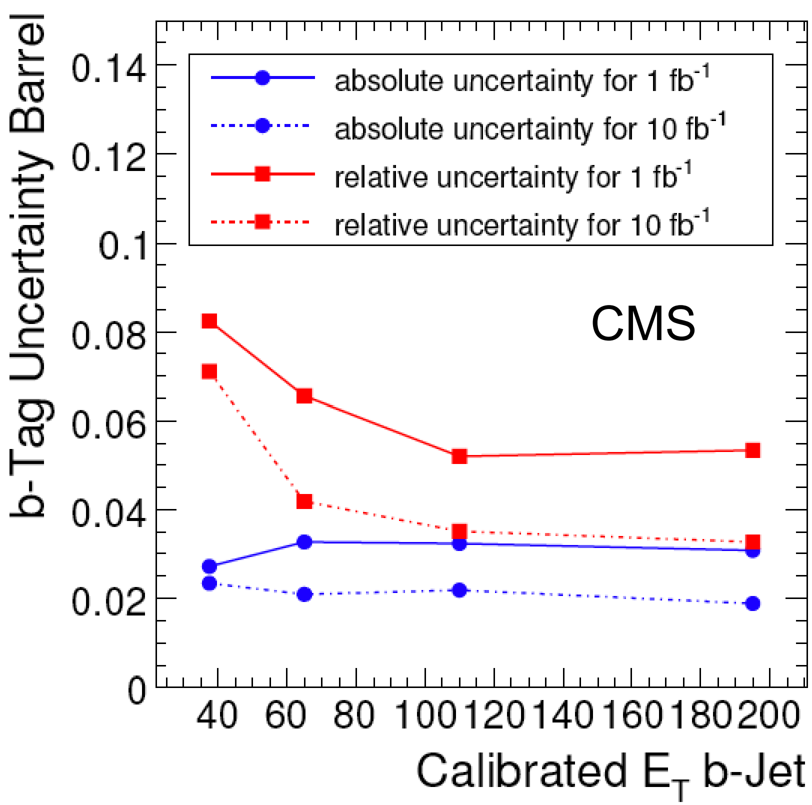
$E_{T,miss}$ > 20 GeV

b-tag efficiency

Select b-enriched samples using tt sample

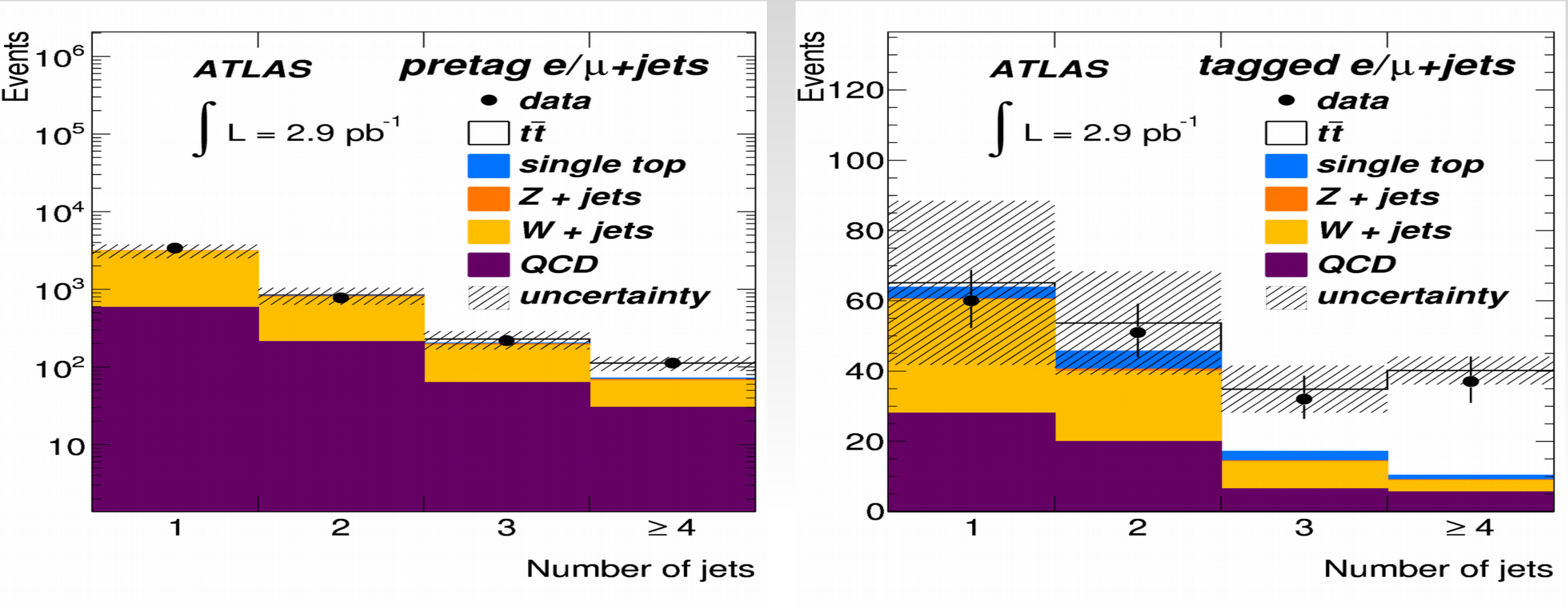
- t → W b ~ 100% → tagging top = tagging b
- Select pure b sample by using tt event topologies
  - 1(2) high p_T leptons, $E_{T,miss}$, m_W & m_t constraints
  - 70-80% b-purity after selection

- 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



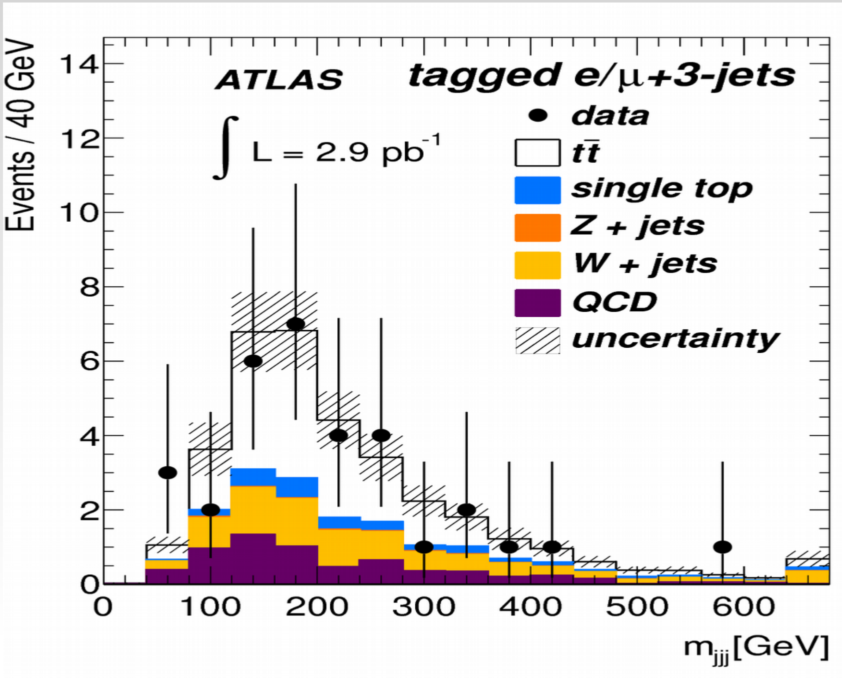
- ATLAS study 100 pb^{-1}
  - Similar efficiencies, purities
  - Estimated uncertainty ~10%

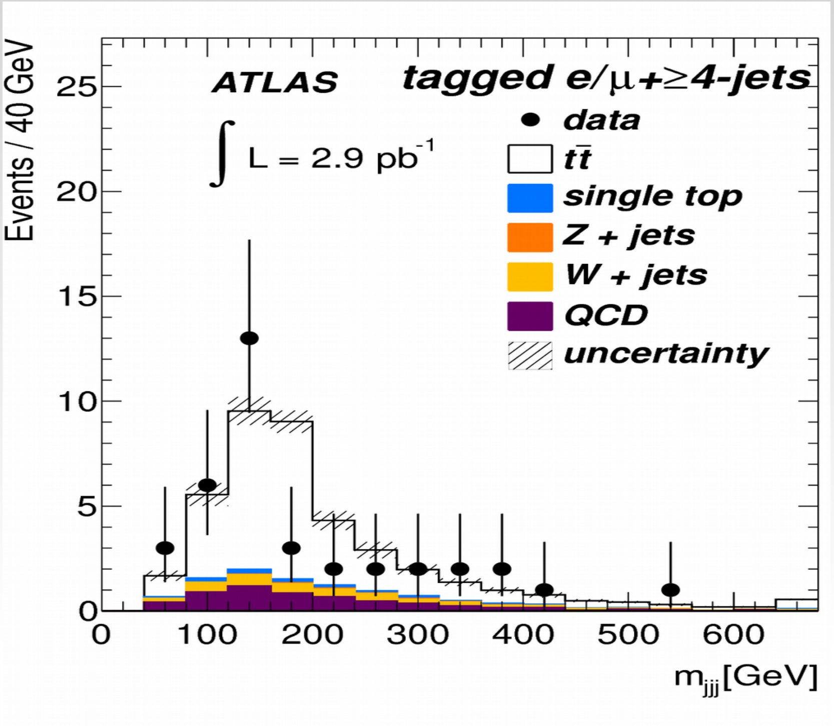
Influence of b-tagging

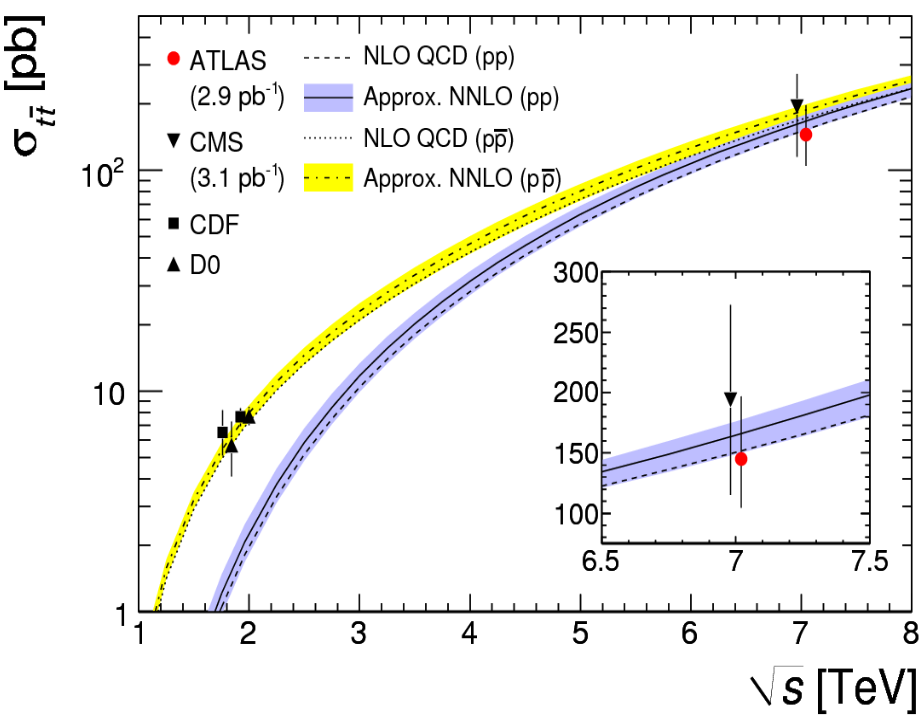


- Top signal (in high-multiplicity bins) hardly visible wrt W + jets background but largely enhanced by requiring two b-jets

Reconstructed top mass



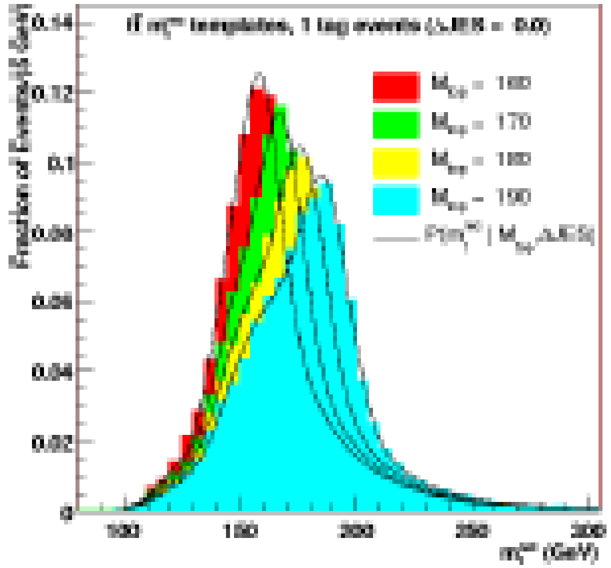


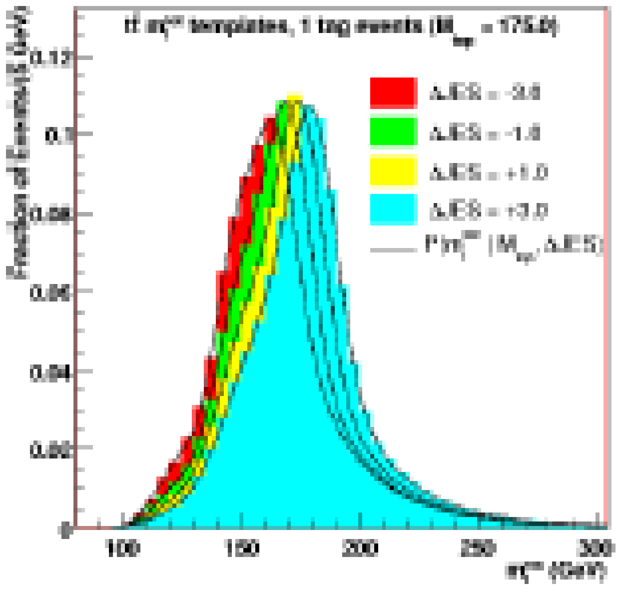


- First measurement of many top production, mass and properties ones

Top mass: template method

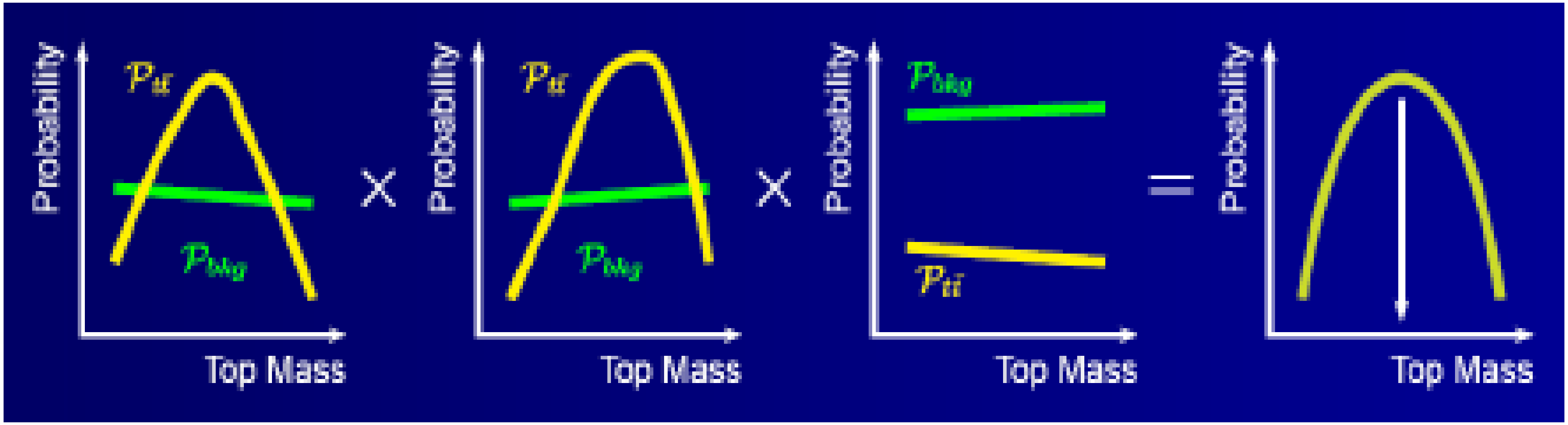
- Choose and calculate per event one or more observables sensitive to true m_t
- Build templates for signal and background distributions in this observable at different m_t (and JES) values
- Determine most likely top mass from templates fit to data





Matrix element method

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



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

Details of ME method

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

Normalization acceptance & efficiency → $\frac{1}{\sigma(m_t)}$

Differential cross section based on LO ME → $d^n\sigma(y,m_t)$

Initial state Probability distribution that a parton will have a momentum q → $dq_1\,dq_2\,f(q_1)f(q_2)$

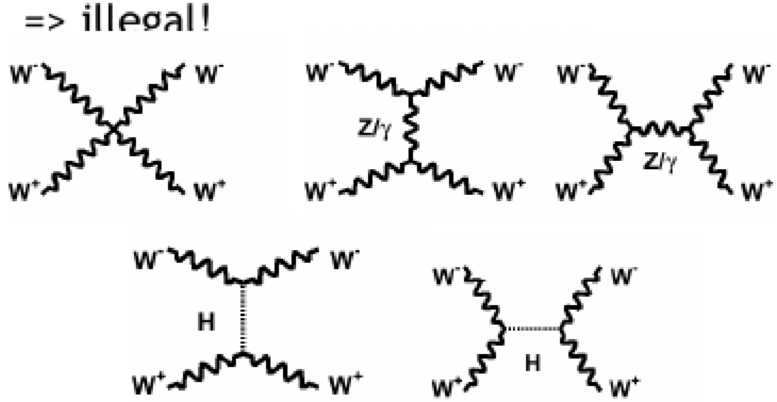
Transfer function Probability to measure x when parton-level y was produced → $W(x,y,JES)$

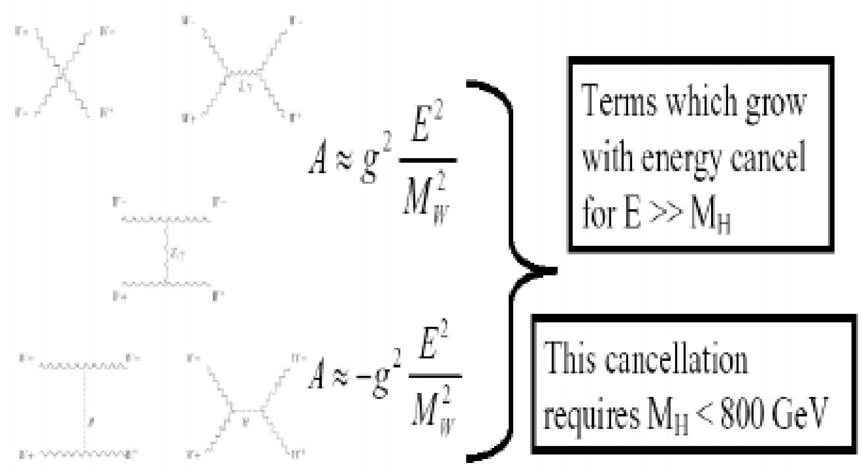
Probability to observe a set of kinematic variables x for a given mass and JES → $P_{t\bar{t}}(x;m_t,JES)$

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

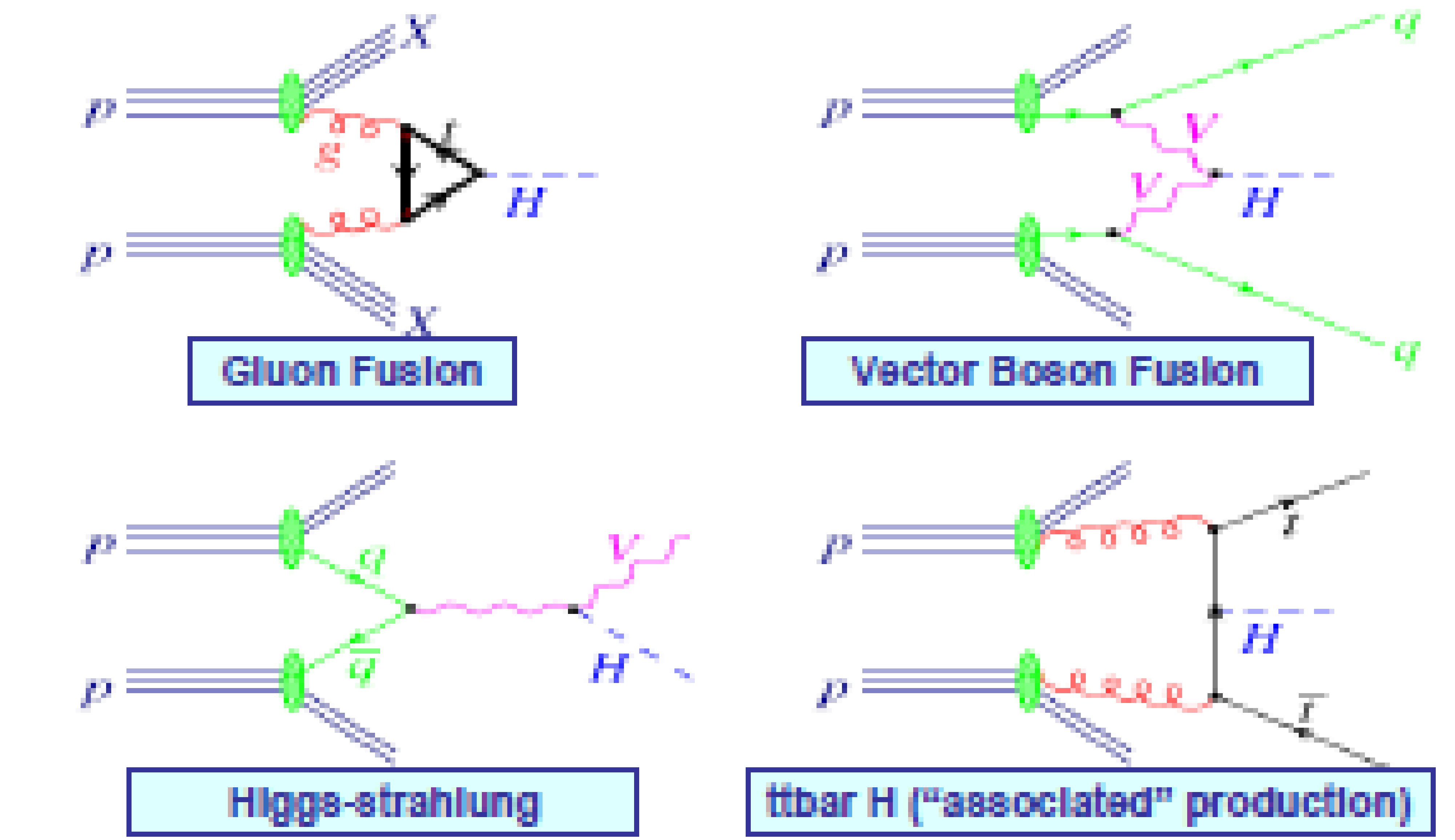
$$\mathcal{P}_{event}(x;m_t,\mathrm{JES})=f_t\,\mathcal{P}_{t\bar{t}}(x;m_t,\mathrm{JES})+(1-f_t)\mathcal{P}_{bkg}(x,\mathrm{JES})$$

Introduction to the Higgs boson

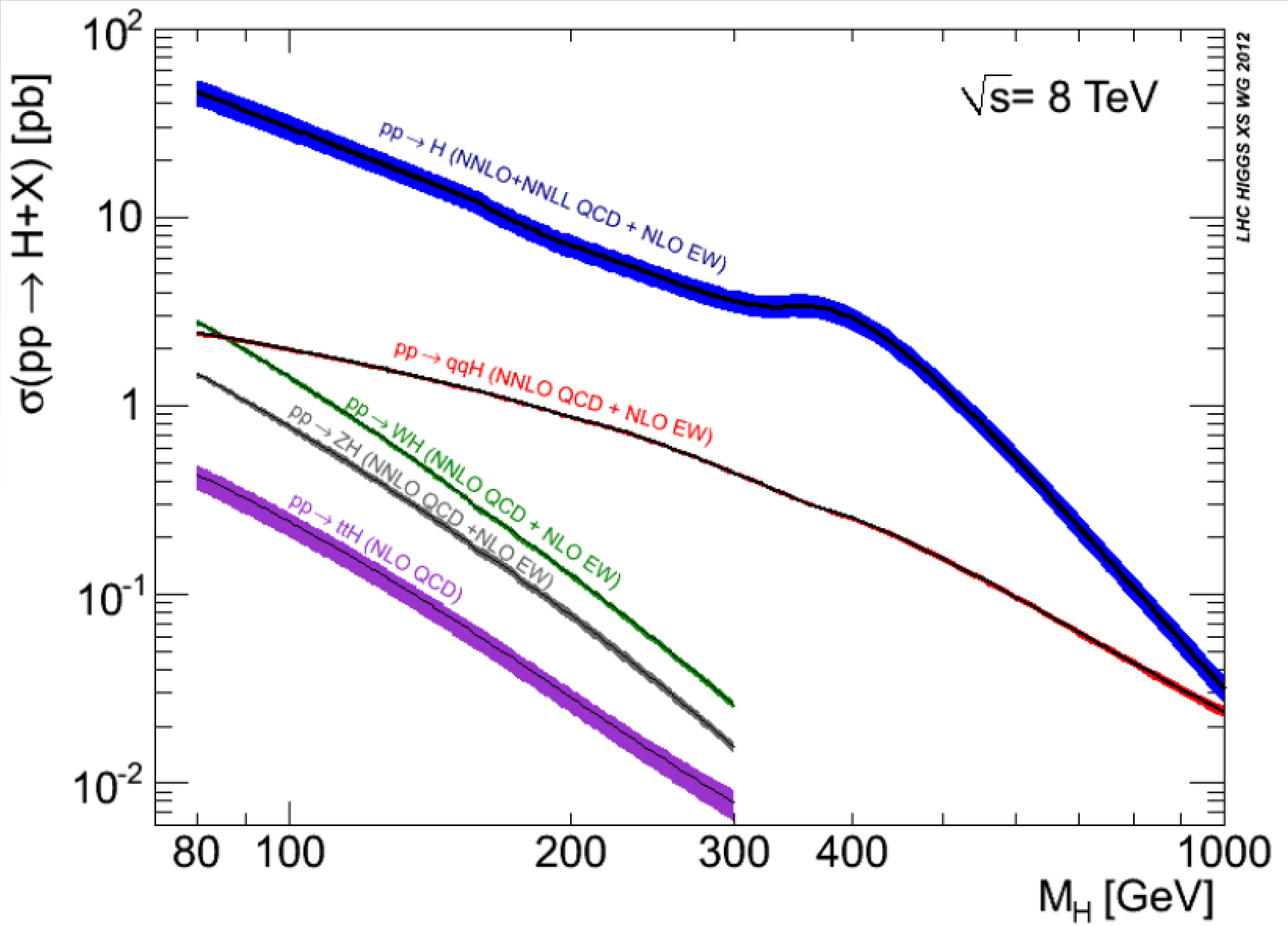
- EWSB caused by scalar Higgs field
- vacuum expectation value of the Higgs field <[illegible]> =246 GeV/c2
  - gives mass to the W and Z gauge bosons,
    - MW ♦ gW<[illegible]>
  - fermions gain a mass by Yukawa interactions with the Higgs field,
    - mf ♦ gf<[illegible]>
  - Higgs boson couplings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



Standard model Higgs production

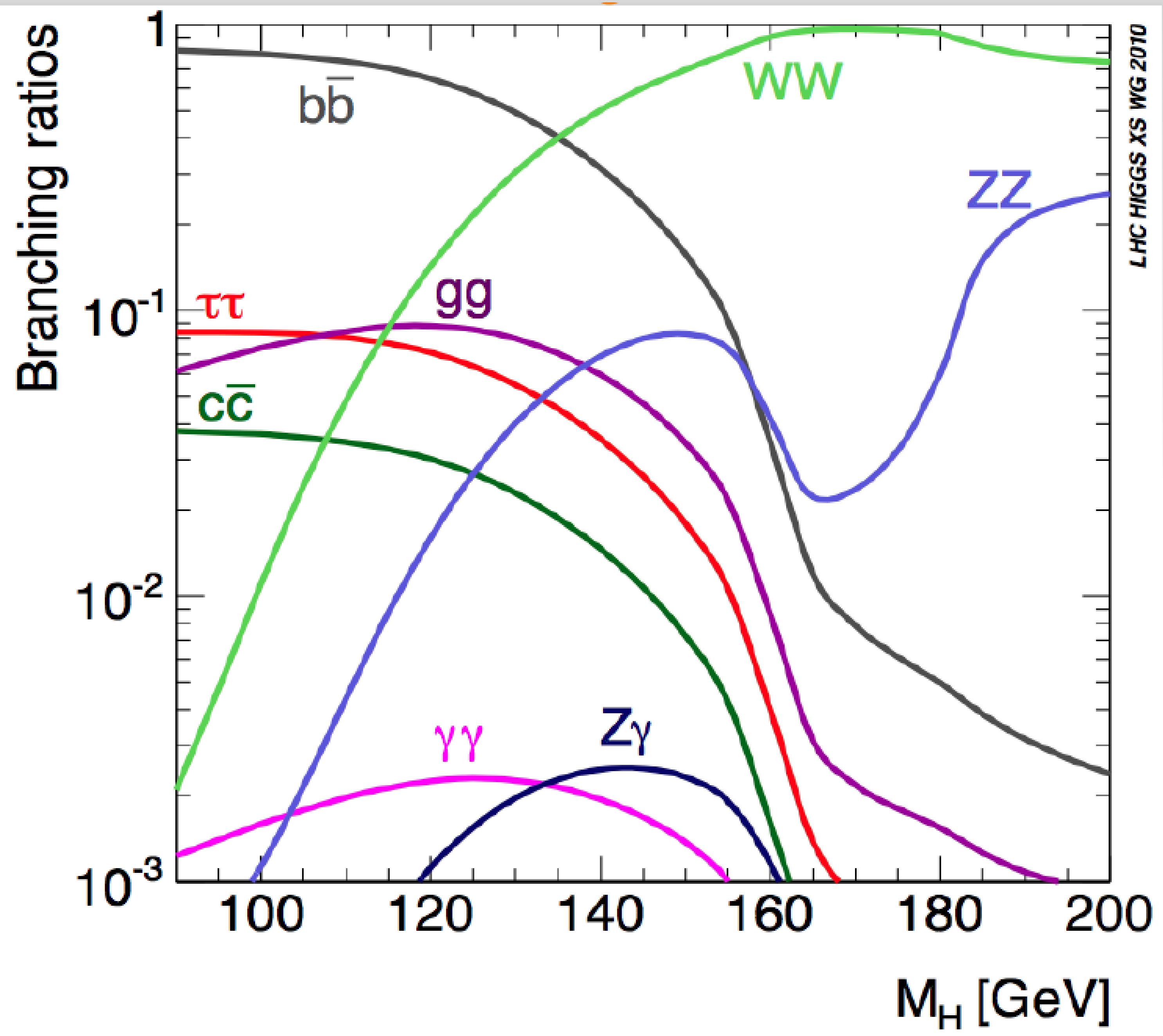


Higgs cross section

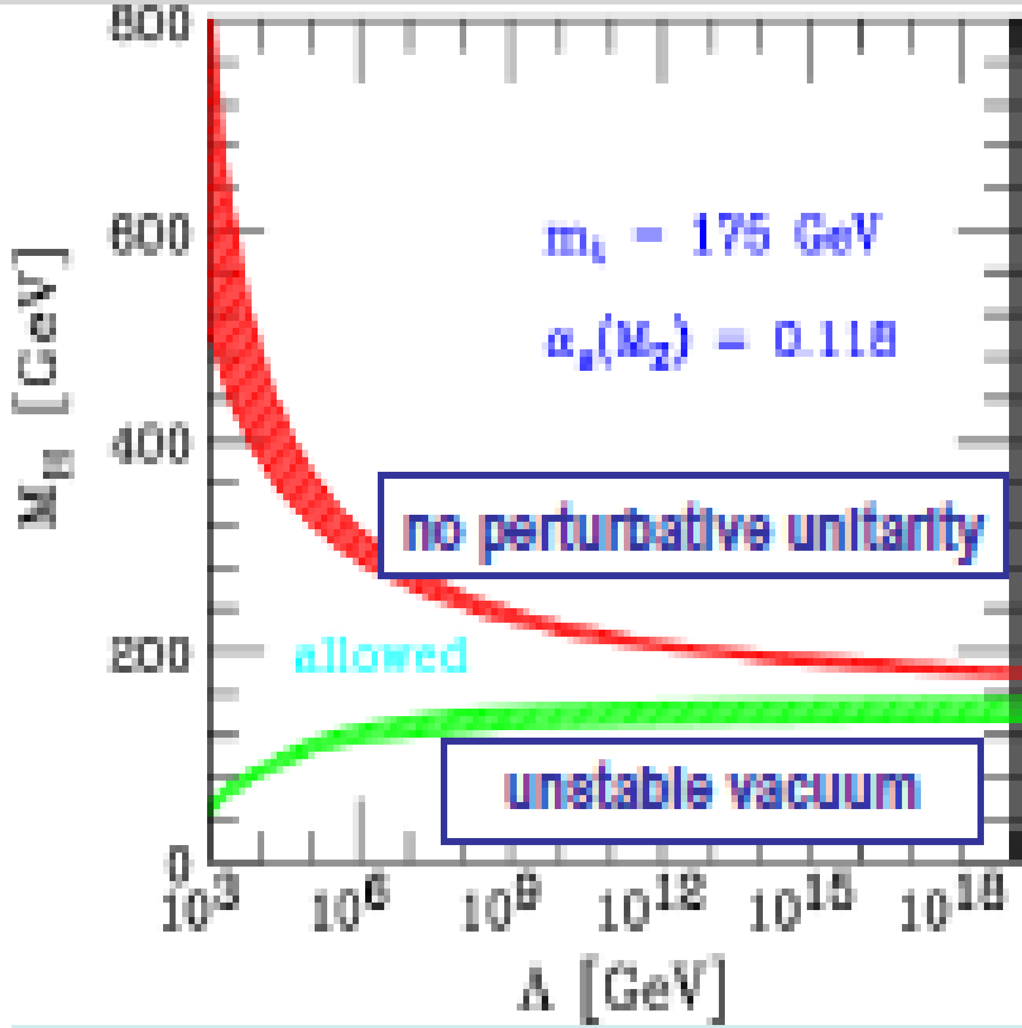


Higgs width ~ (m_H)

Main decay modes



Theory constraints to mass



Upper bound (triviality) :

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

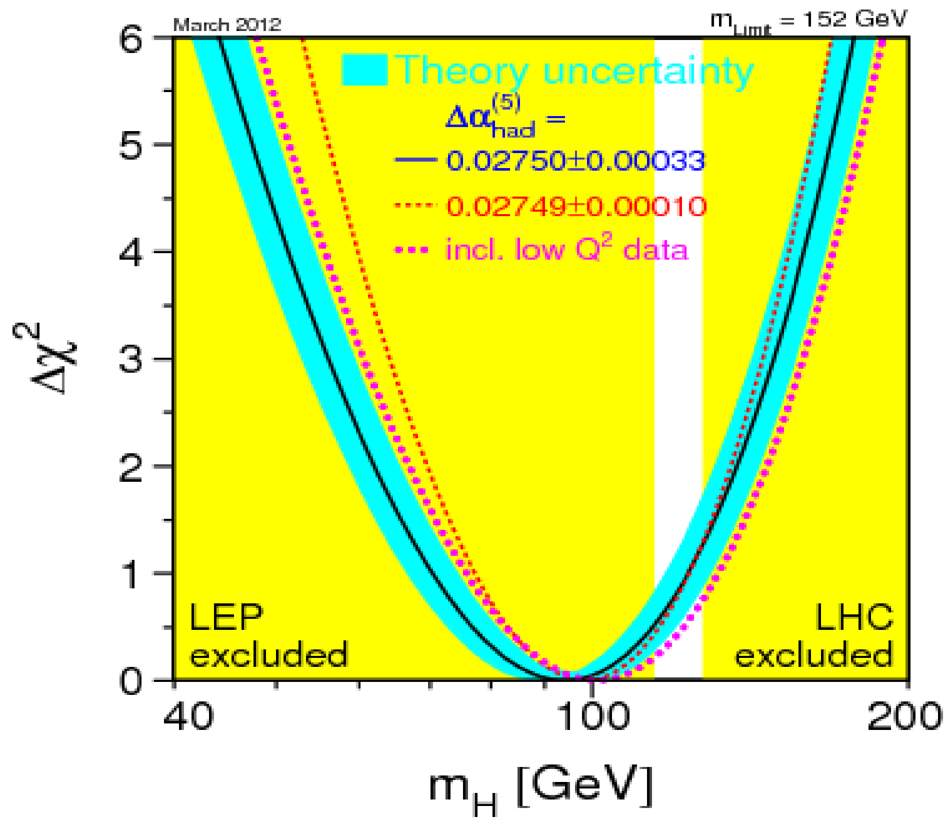
Lower bound (vacuum stability) :

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

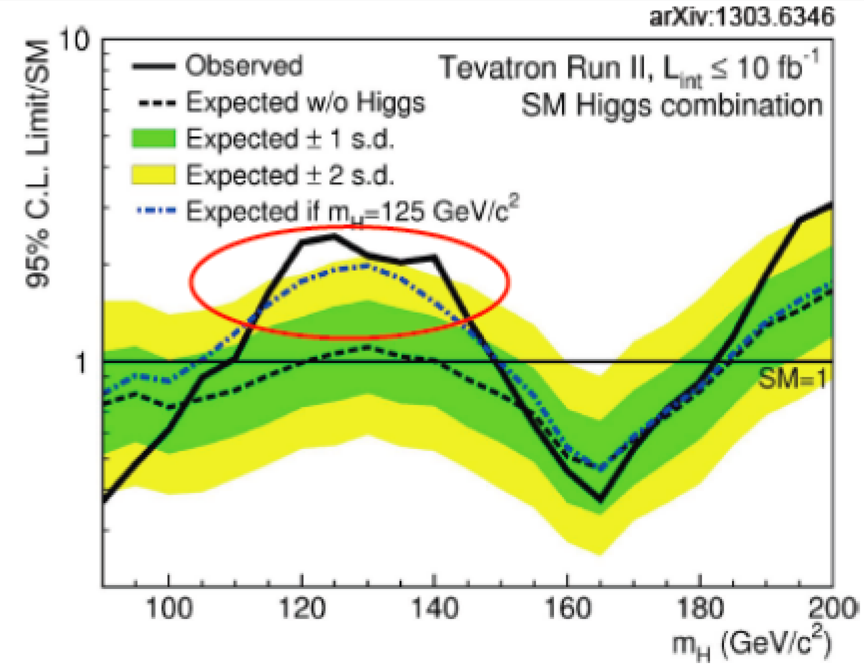
(Λ = cut-off scale at which new physics becomes important)

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

Experimental constraints to Higgs mass



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



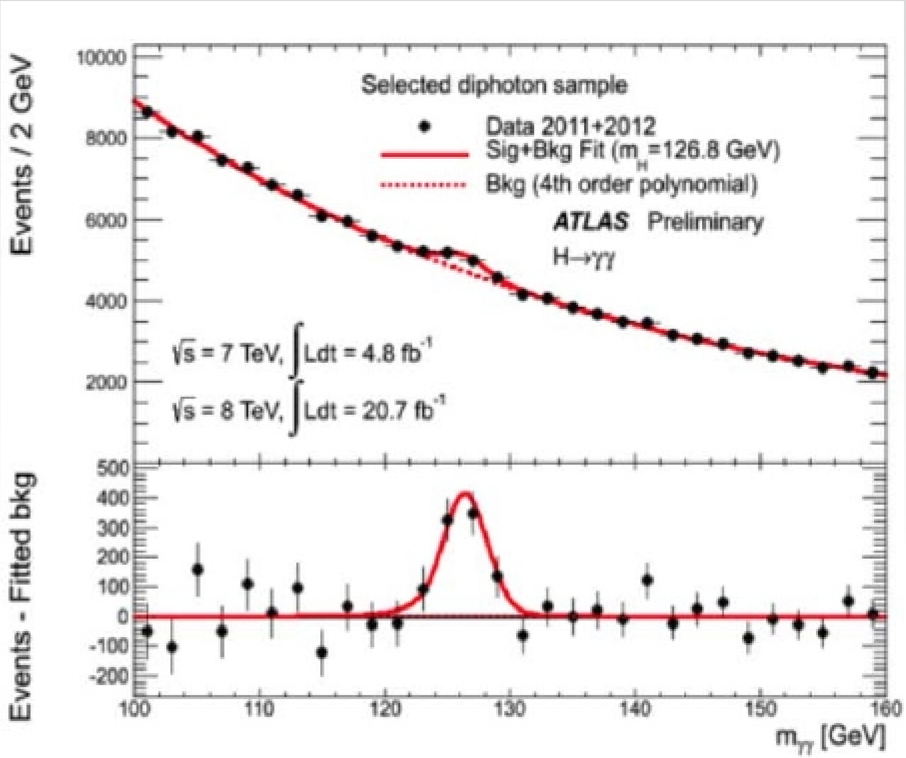
Best-fit value already escluded by LEP; "big desert" scenario soon to be excluded by Tevatron?

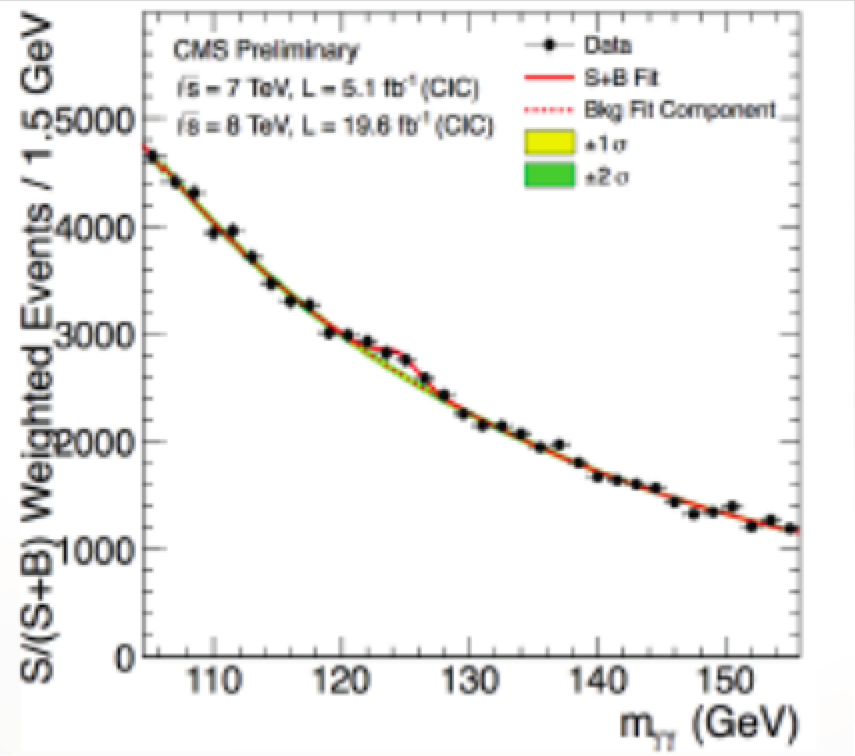
How to look for the SM Higgs

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

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

Results from data

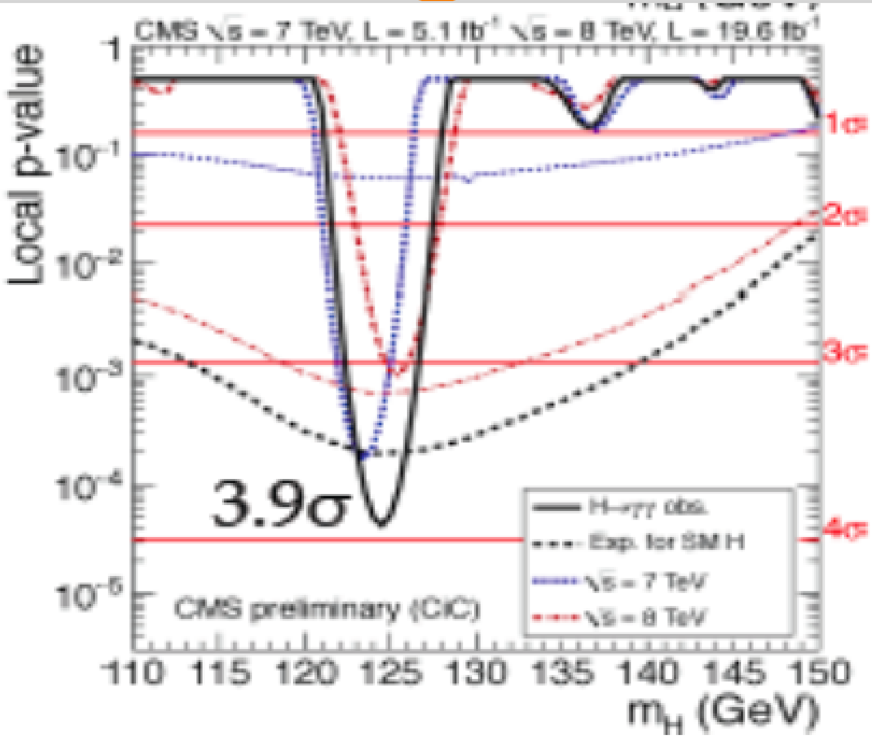


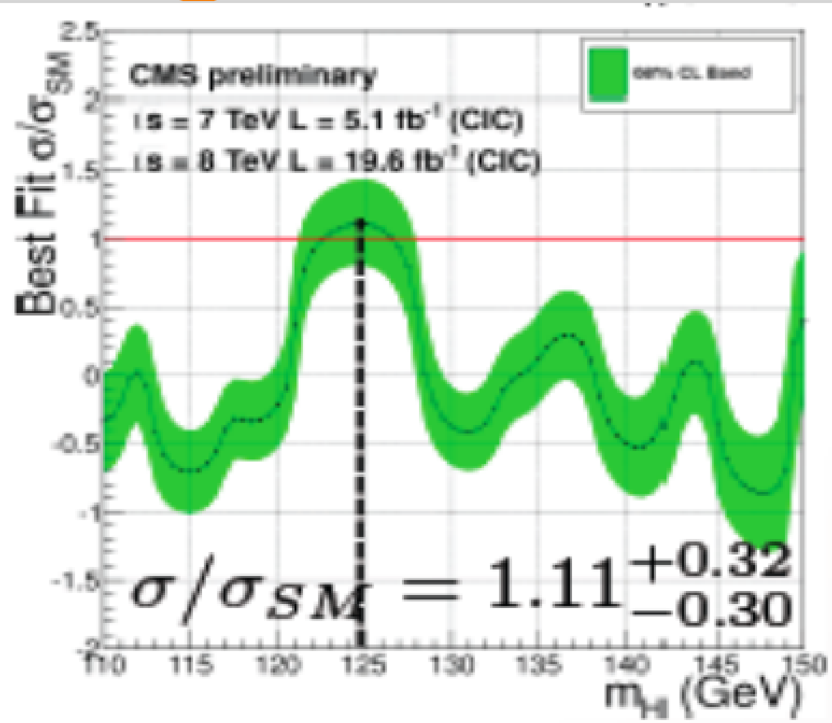


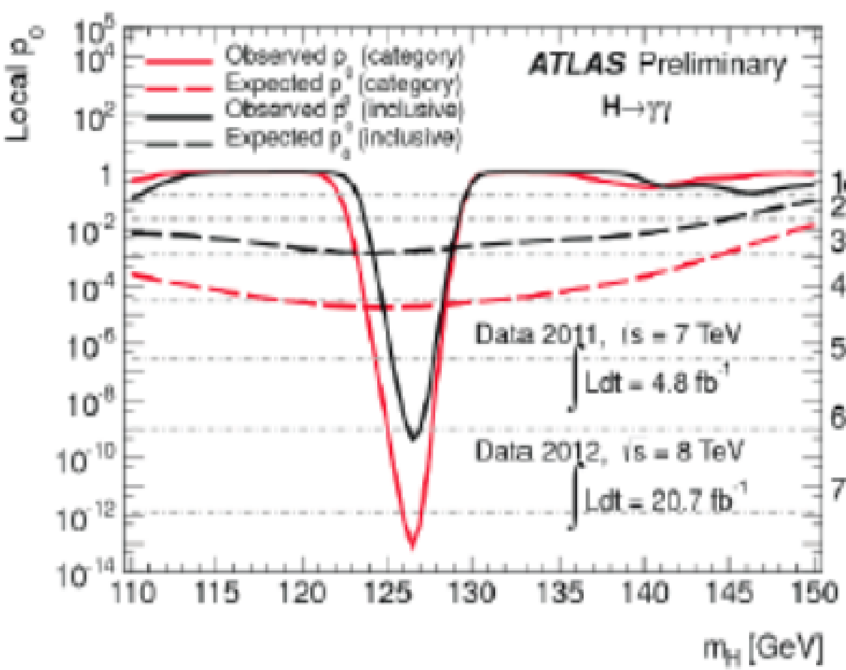
Despite complementary detector technologies, and resolutions (better in energy for CMS, better in angle for ATLAS), width and strength of observed peaks are the same!

Signal strength

Cut Based



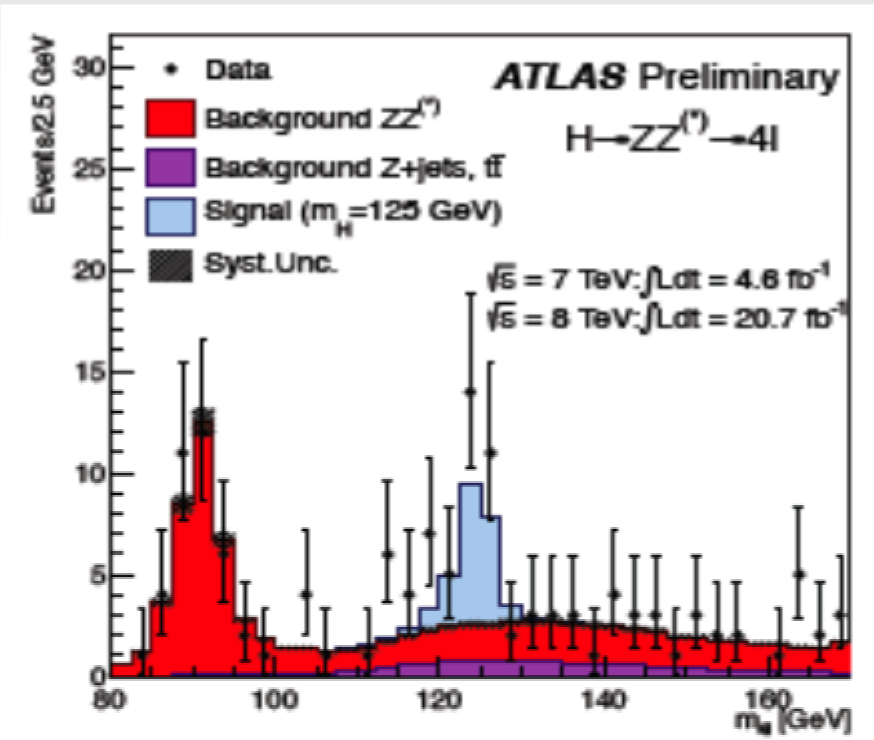


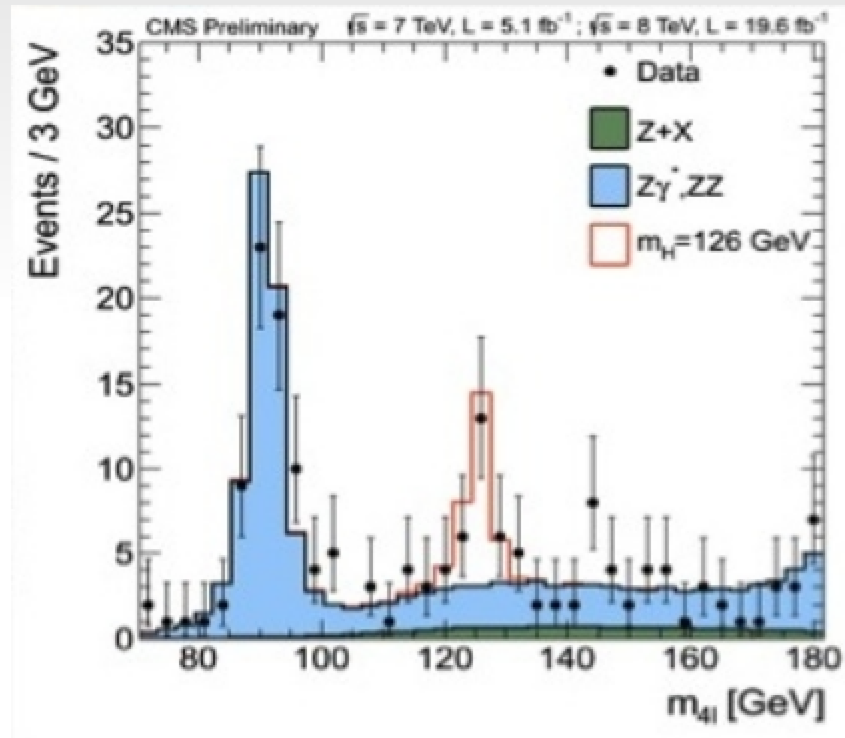


Similar signal in both experiments, with a σ*BR now in agreement with SM after initial larger vlue

H->ZZ*->4l

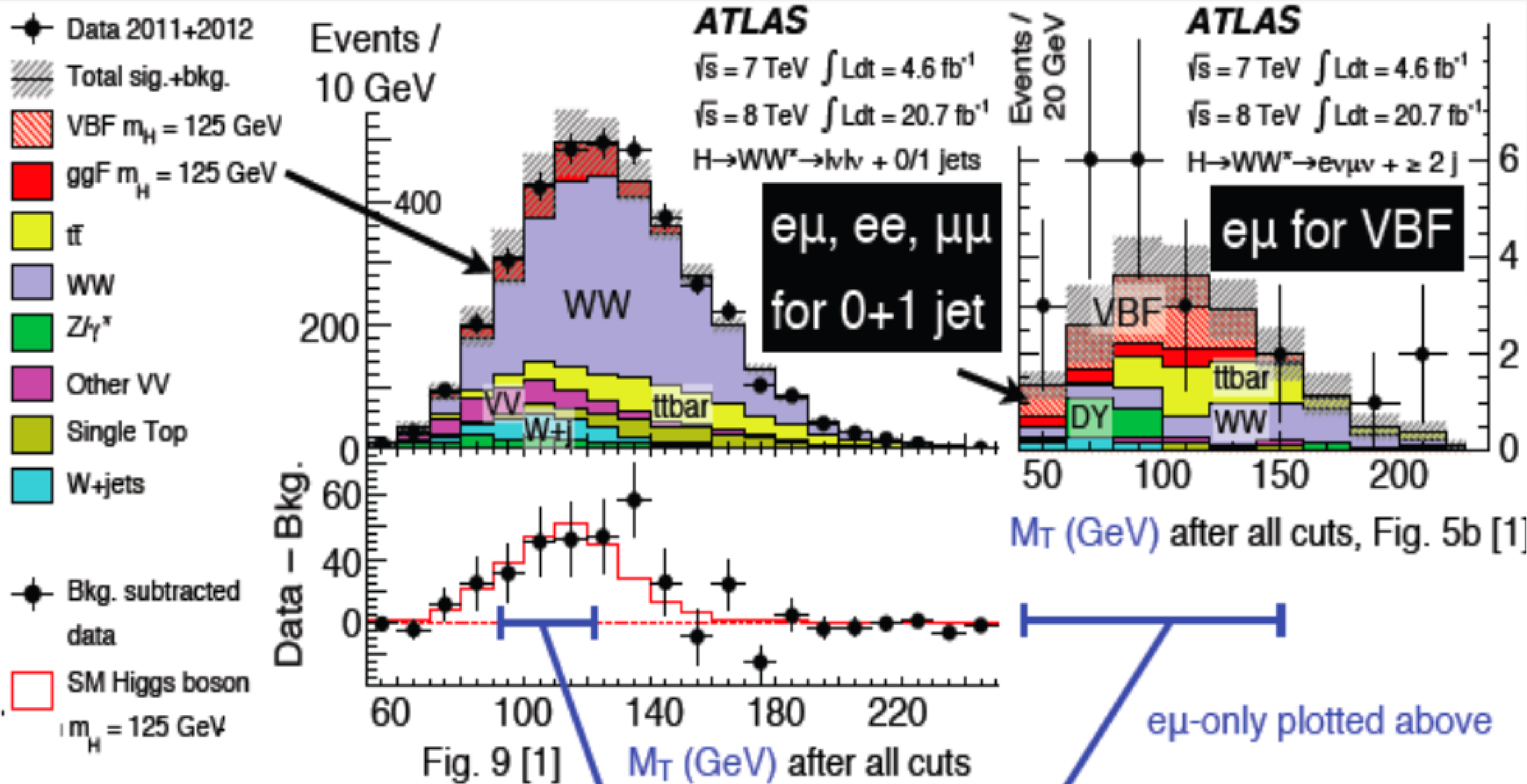
- The other discovery channel (would have been ”golden” for MH > 2 MZ) σ* BR = 2.5 fb





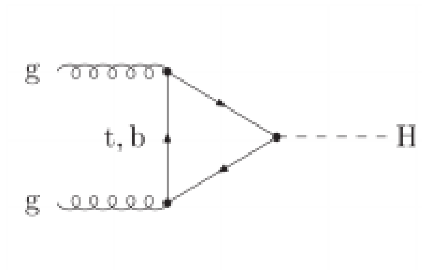
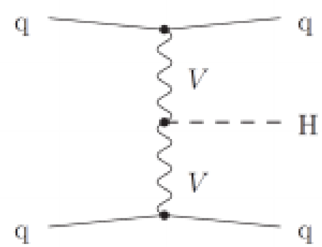
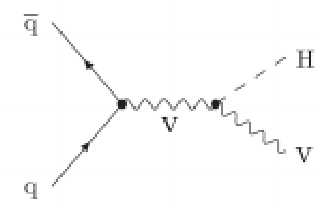
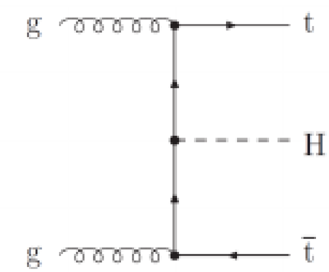
Added bonus: the ZZ peak used for calibrations, efficiencies etc.

WW channel: no peak, look at MET distribution

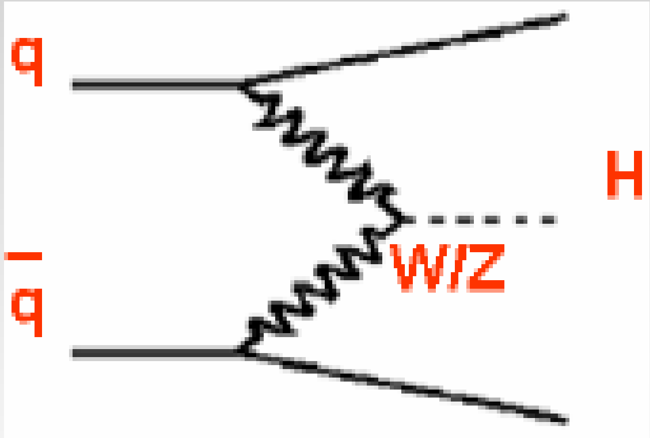


$N_{jet} = 0$ $N_{jet} = 1$ $N_{jet} \geq 2$ After M_T cut in

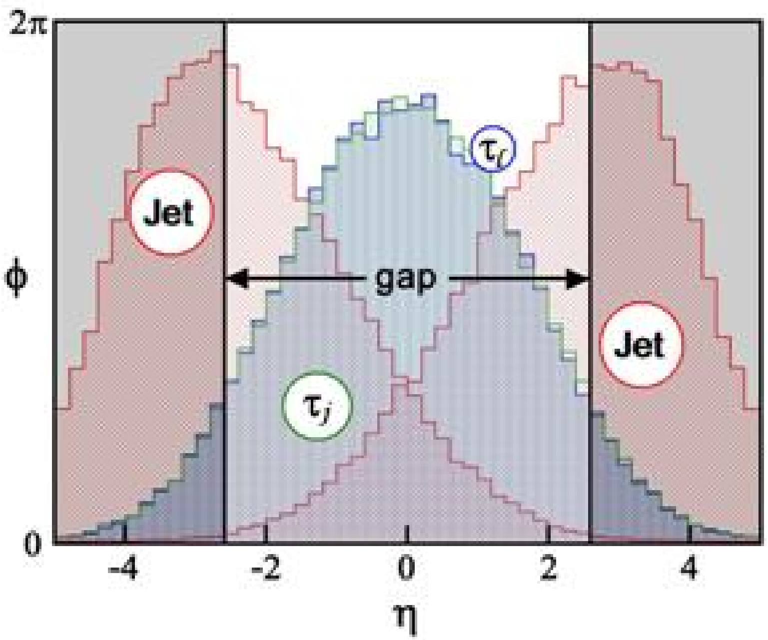
Higgs decays into two fermions

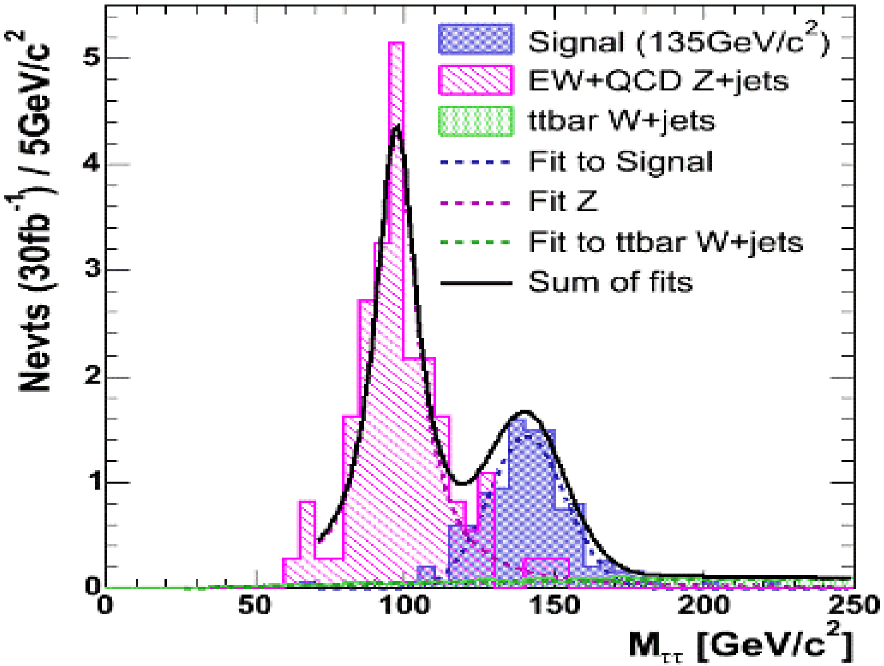
	ggH	VBF	VH	ttH
				
$H \rightarrow bb$	(QCD bkg. too large)	Large QCD bkg. Low mass resolut.	Small x-sec*BR VV, V+jets, tt bkg. Low mass resolution	Small x-sec*BR tt+jets backgrounds Low mass resolution
$H \rightarrow \tau\tau$	Large $Z \rightarrow \tau\tau$ bkg. Very low mass resol.	Small x-sec*BR $Z \rightarrow \tau\tau$ bkg. Low mass resolut.	Small x-sec*BR $Z \rightarrow \tau\tau$ bkg. Low mass resolut.	Very small x-sec. Low mass resolution
$H \rightarrow \mu\mu$	Small x-sec*BR. Large $Z \rightarrow \mu\mu$ bkg. High mass resol.	Very small x-sec*BR. Small $Z \rightarrow \mu\mu$ bkg. High mass resol.	Very small x-sec*BR. Small $Z \rightarrow \mu\mu$ bkg. High mass resol.	(x-section and BR are too small)

Vector Boson Fusion (VBF)



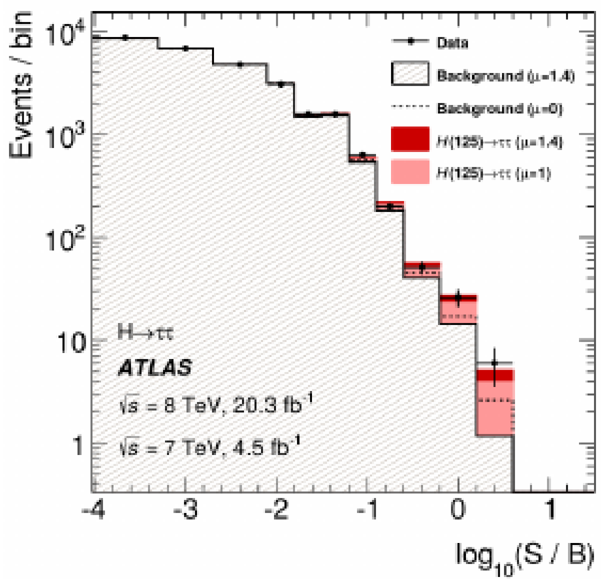
- Remnants of the final-state quarks emitted in the forward region (up to η~ 3.5)
- Hard scattering has no colour flow between the two jets → rapidity gap between them
- It would be a very clean signature, if not for the UE and pileup!
- Depending on mass, look for ττ or WW decays

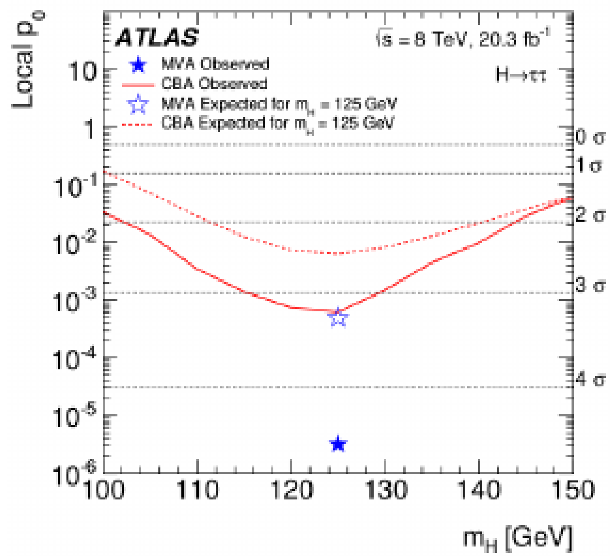


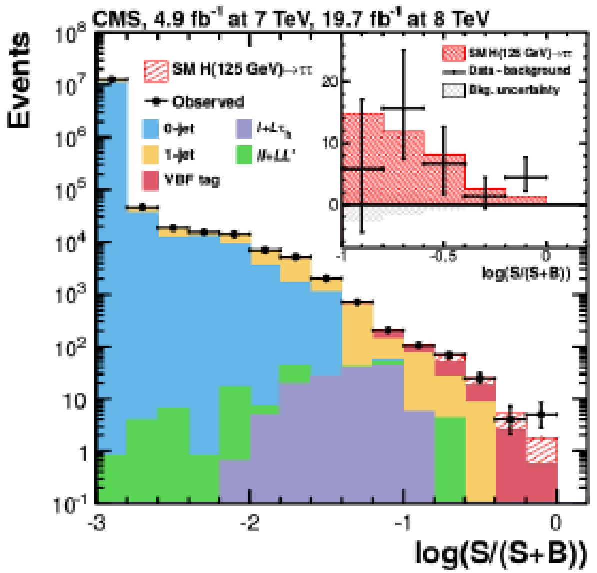


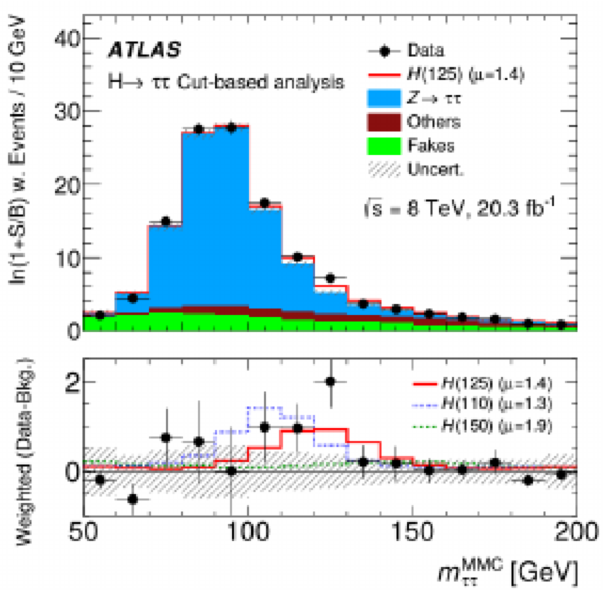
Higgs → ττ

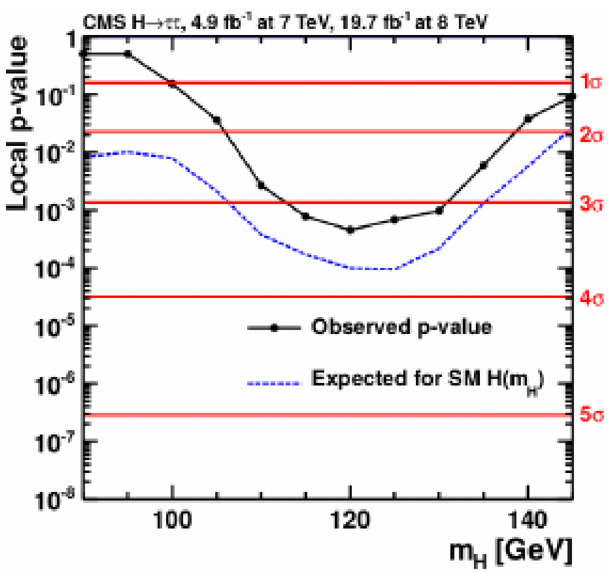
- Signal strength:
  - ATLAS: $\boldsymbol{\mu = 1.43^{+0.43}_{-0.37}}$;
  - CMS: $\boldsymbol{\mu = 0.78^{+0.27}_{-0.27}}$.
- Observed (expected) p-value:
  - ATLAS: **4.5σ (3.4σ)**;
  - CMS: **3.2σ (3.7σ)**.





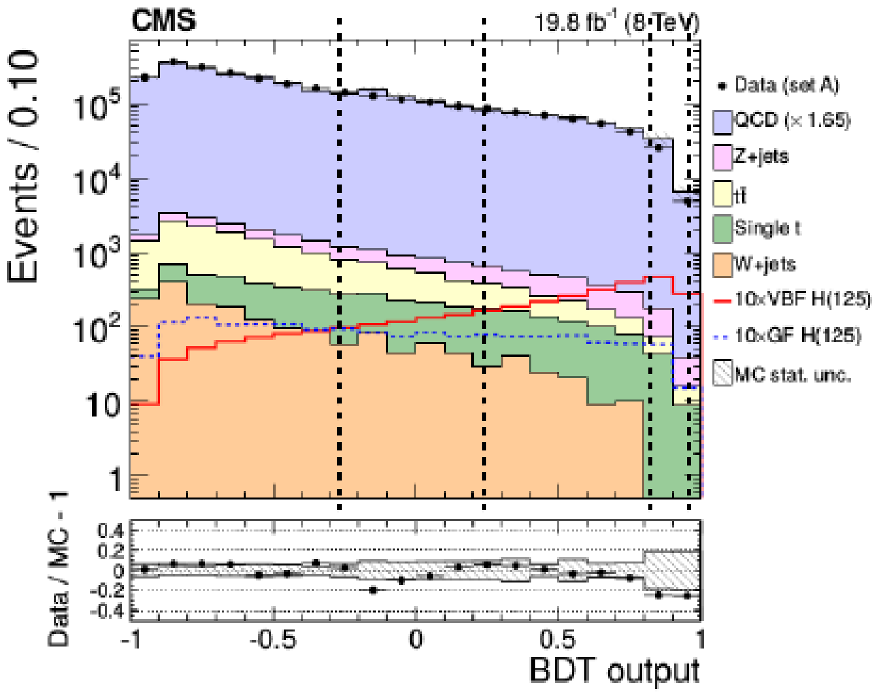






VBF H->bb

- Events are divided in 7 categories, with different S/B, using a multivariate discriminator (uncorrelated with m_{bb}).
- Signal is extracted with a simultaneous fit on m_{bb} in all categories.
- QCD is fitted in all categories with a common fifth order polynomial.
- QCD shape corrected with a category-dependent quadratic transfer function.



Signal strength

Normalization and shapes of signal, Z and top

Free parameter

Fixed parameter (simulation)

$$f_i(m_{bb}) = \mu_H \cdot N_{i,H} \cdot H_i(m_{bb}; k_{JES}, k_{JER}) + N_{i,Z} \cdot Z_i(m_{bb}; k_{JES}, k_{JER}) + N_{i,t} \cdot T_i(m_{bb}; k_{JES}, k_{JER}) + N_{i,QCD} \cdot K_i(m_{bb}) \cdot B(m_{bb}; \vec{p}_{set}),$$

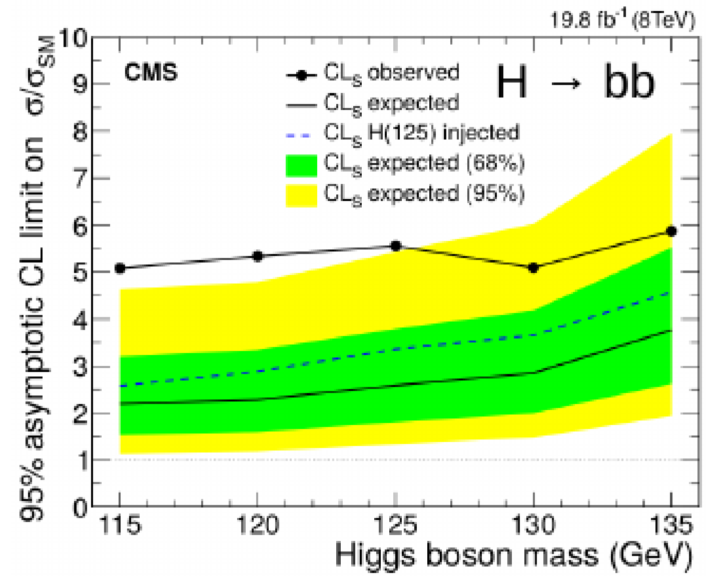
QCD normalization

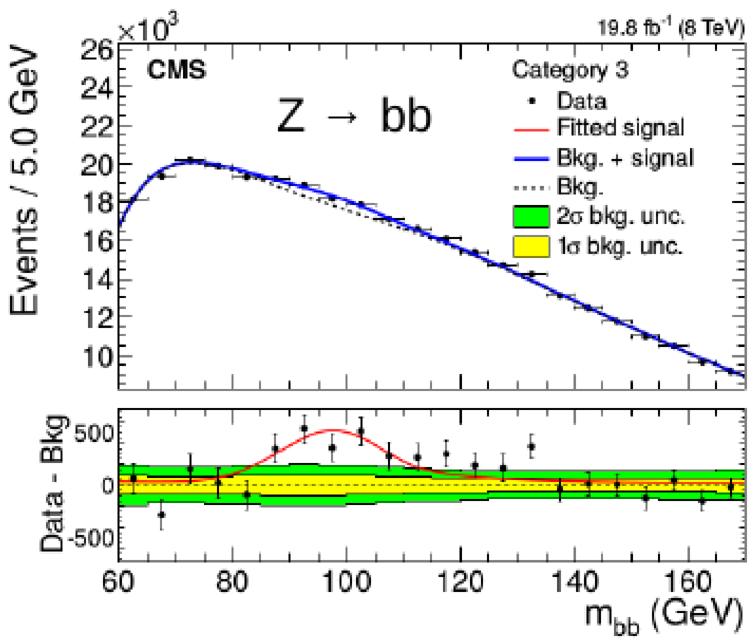
Transfer function (linear or quadratic)

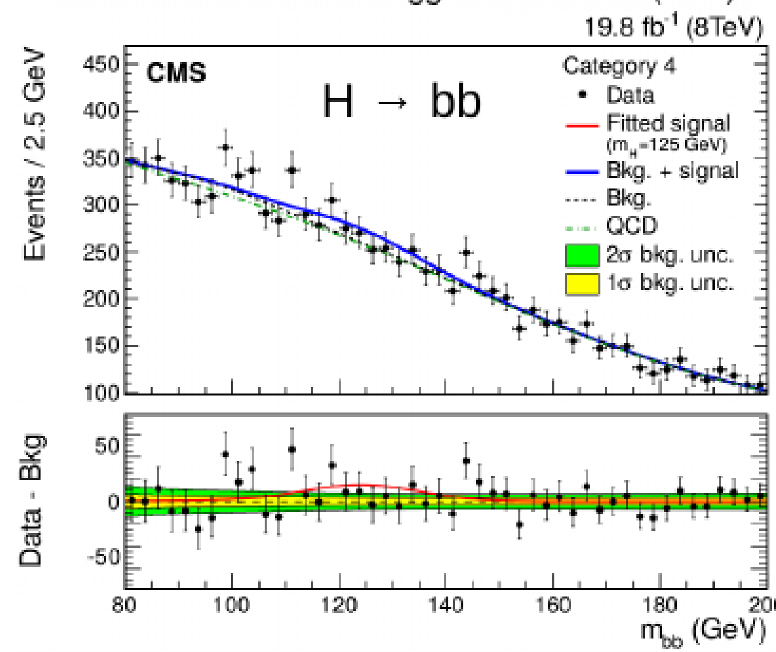
Polynomial QCD shape with free parameters.

H→bb CMS result

- Signal strength: $\boldsymbol{\mu = 2.8^{+1.6}_{-1.4}}$.
- Observed (exp.) 95% CL upper limit: **5.5 (2.5).**
- Observed p-value (exp.): **2.2σ (0.8σ)**.
- Cross-check Z→bb resonance:
  - $\mu_Z = 1.10^{+0.44}_{-0.33}$; p-value$_Z$ 3.6σ (3.3σ).

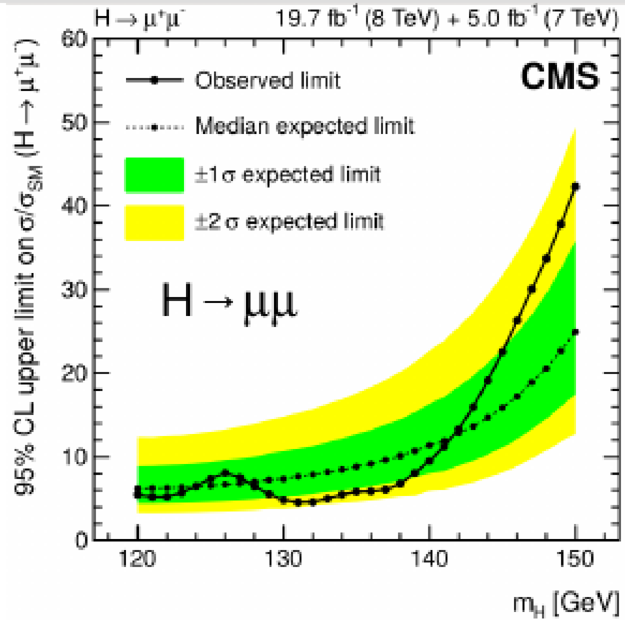


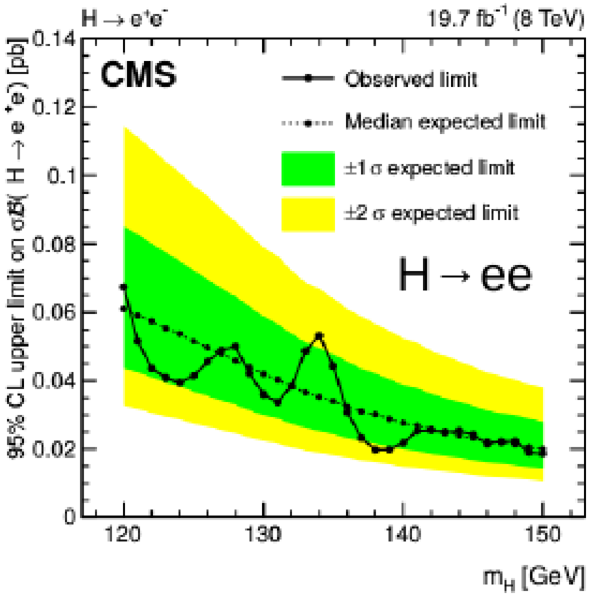


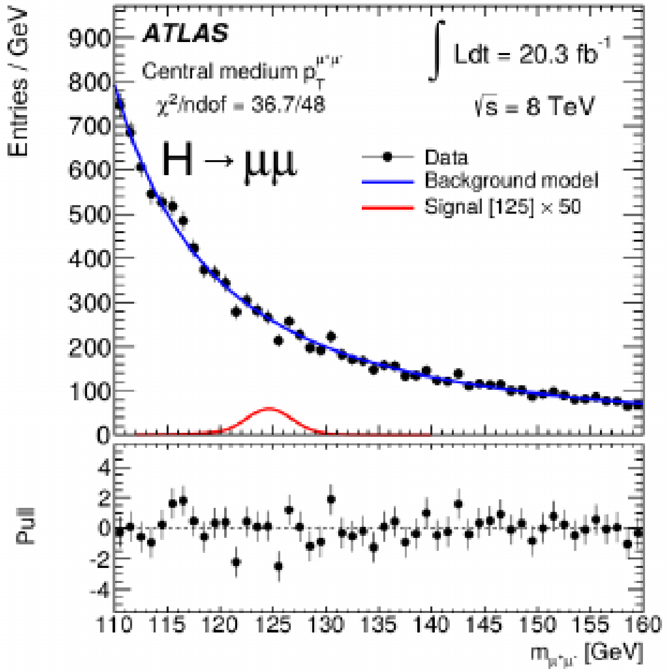


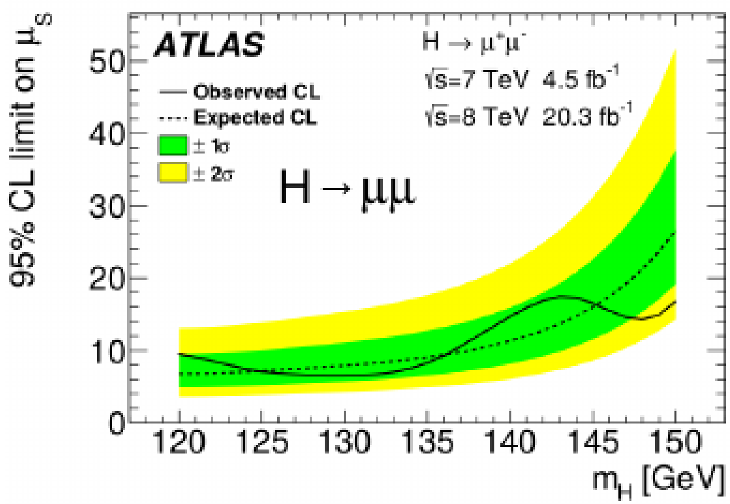
Higgs→ μμ, ee

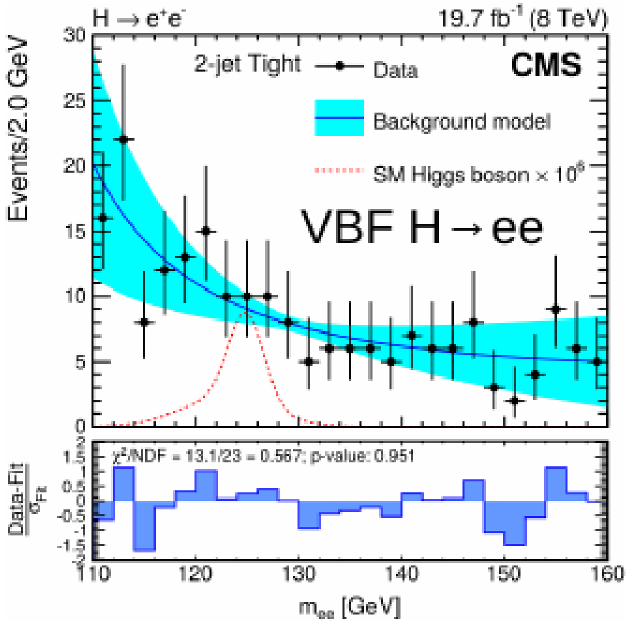
- Standard Model predicts small BR for H→μμ,ee:
  - good probe to look for New Physics with at 125 GeV.
- No excess has been found.



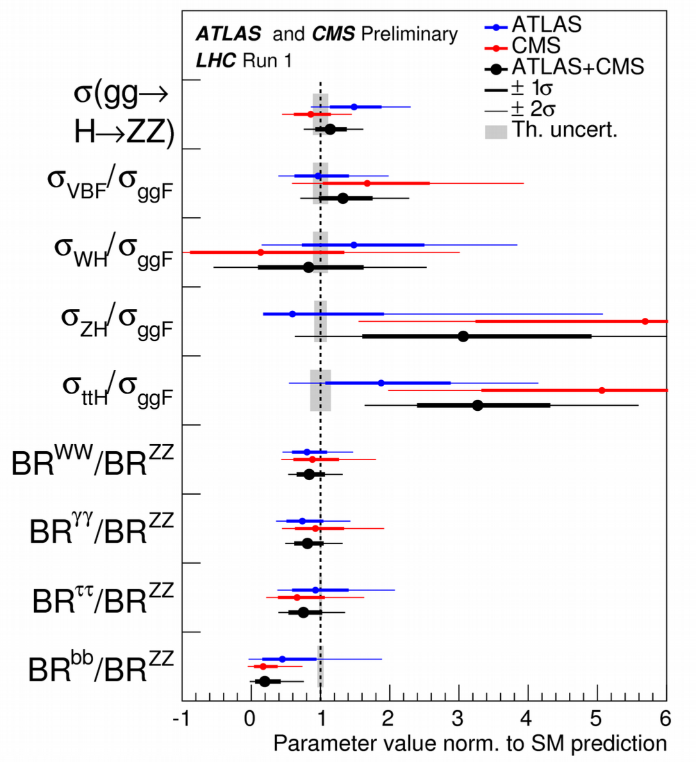


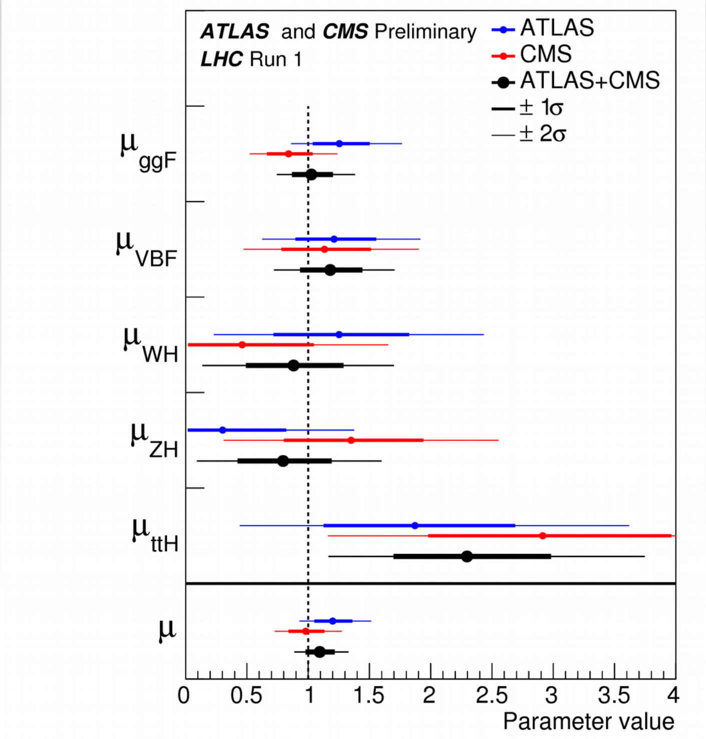


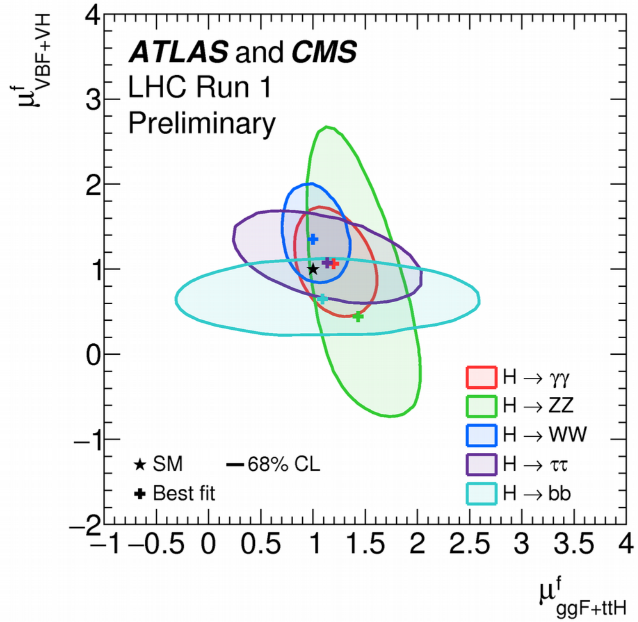


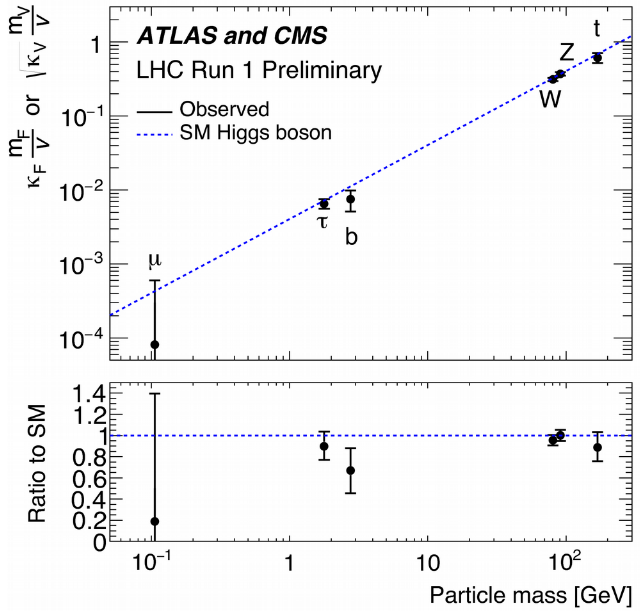


ATLAS + CMS combination









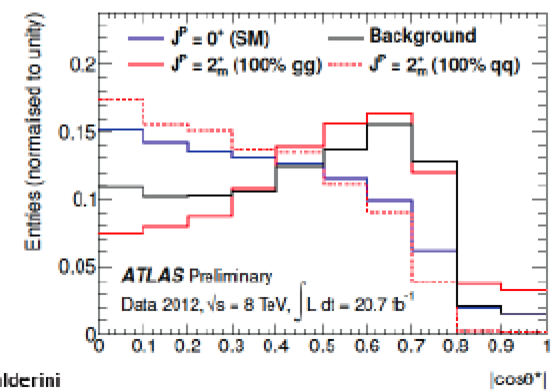
Spin studies: from H->γγ

1Dx1D fit to $m_{\gamma\gamma}$ vs $|\cos\theta^*|$ (Collins-Soper frame)

Try to distinguish SM Higgs (0^+) from a singly-produced $J=2^+$ state
(hypothesis tested here: minimal couplings graviton-like model)

dN/d(cosθ*) distribution (before detector acceptance)

flat	for 0^+
$1 + 6\cos^2\theta^* + \cos^4\theta^*$	for gg -> X_2 state
$1 - \cos^4\theta^*$	for qq -> X_2 state



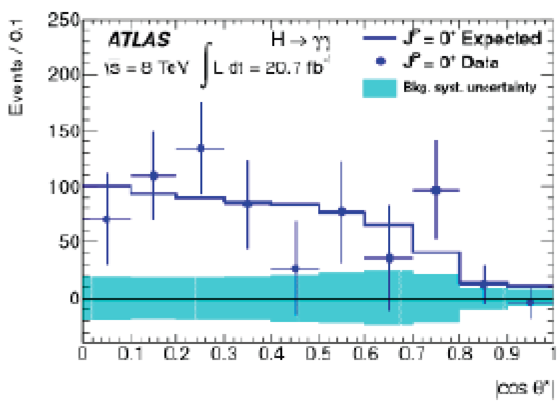
G.Calderini

background shape from data $m_{\gamma\gamma}$ sidebands

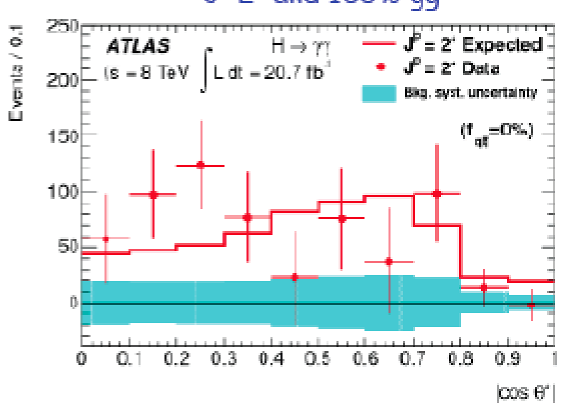
same as inclusive analysis but P_T cuts modified to remove correlation with $m_{\gamma\gamma}$ and cosθ* in background

-> use $P_T/m_{\gamma\gamma}$

Standard Model



J=2⁺ and 100% gg



- About 60% probability of SM compatibility

Quantum numbers in H->ZZ

- Use the ratio of **LO** matrix elements to build kinematic discriminants

Discriminator D_{J^P} to separate SM from an alternative J^P hypothesis:

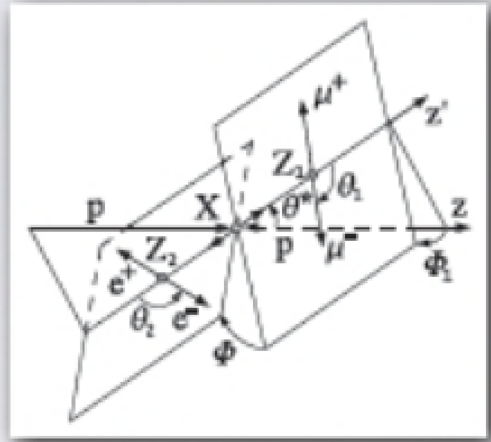
$$D_{J^P} = \left[1 + \frac{\mathcal{P}_{J^P}(\vec{p}_i)}{\mathcal{P}_{\rm Higgs}(\vec{p}_i)}\right]^{-1}$$

Discriminator D_{BKG} to separate SM Higgs from backgrounds:

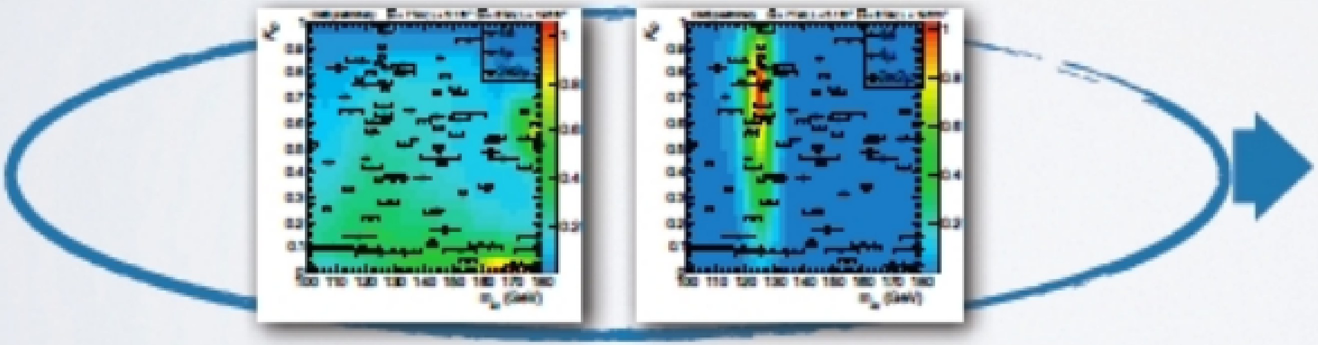
$$D_{\rm BKG} = \left[1 + \frac{\mathcal{P}_{\rm BKG}(\vec{p}_i) \cdot \mathcal{P}(m_{4\ell}|{\rm BKG})}{\mathcal{P}_{\rm Higgs}(\vec{p}_i) \cdot \mathcal{P}(m_{4\ell}|{\rm Higgs})}\right]^{-1}$$

Probabilities $\mathcal{P}$ defined by the LO matrix elements for each value of m_{4l}.

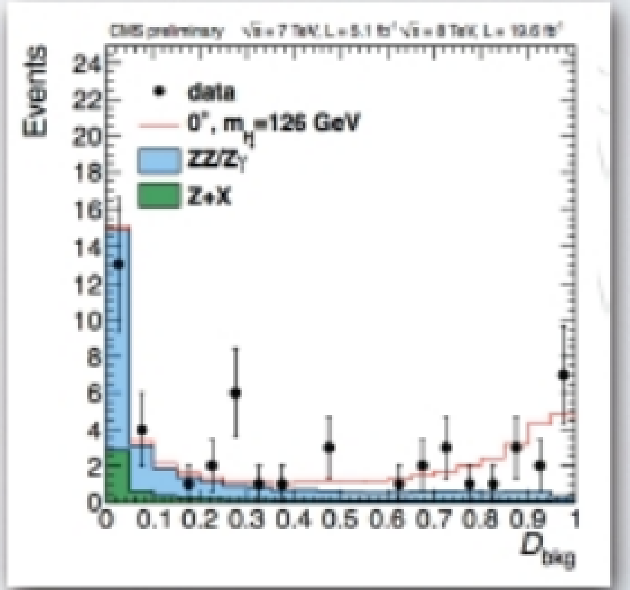
Use kinematics of the 4l system



Combined kinematics and m_{4l} information into one discriminant



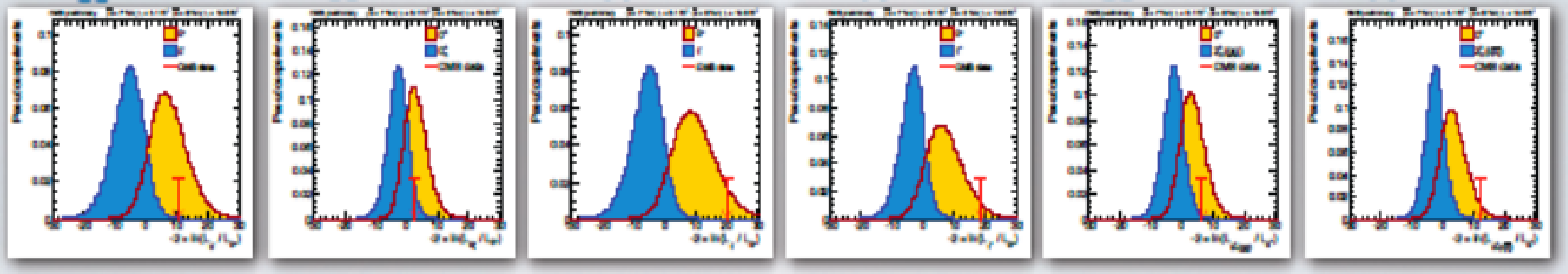
106 < m_{4l} < 141 GeV



- Statistical analysis based on 2D distributions $\mathcal{P}(D_{J^P}, D_{BKG})$

Quantitative study of quantum numbers

- Test statistics for the separation between J^P hypotheses (expected and observed):



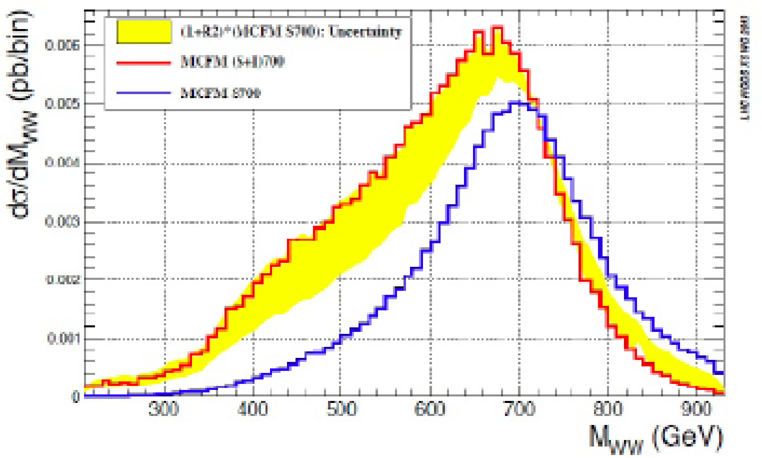
- Expected separation between J^P hypotheses and the observed results with the data:

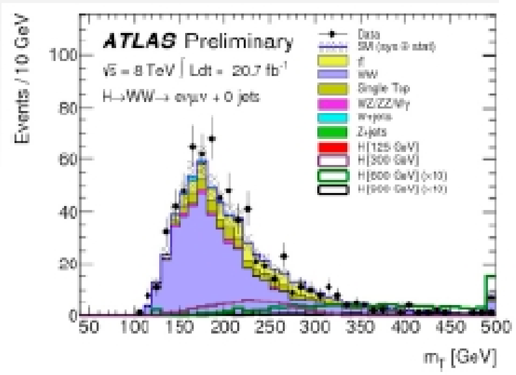
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL$_s$
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	>4.0σ	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	>4.0σ	<0.1%

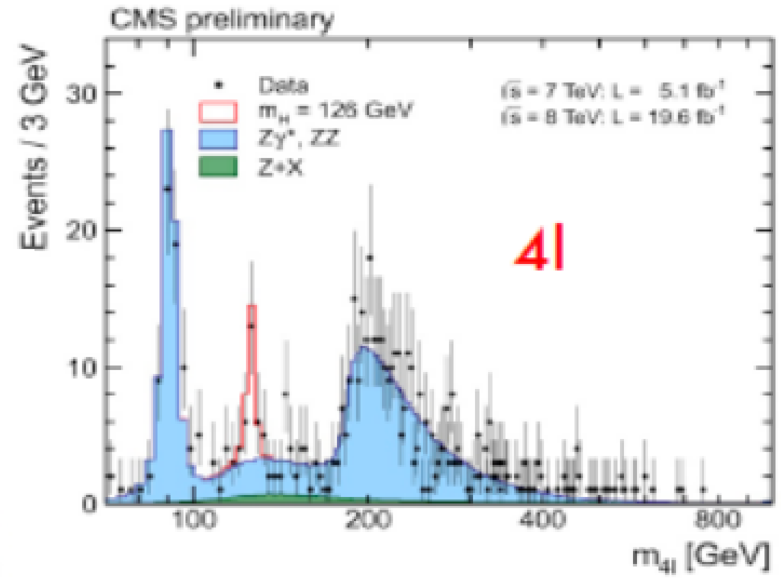
in case a hypothesis is disfavoured with large confidence we quote > 4.0σ,

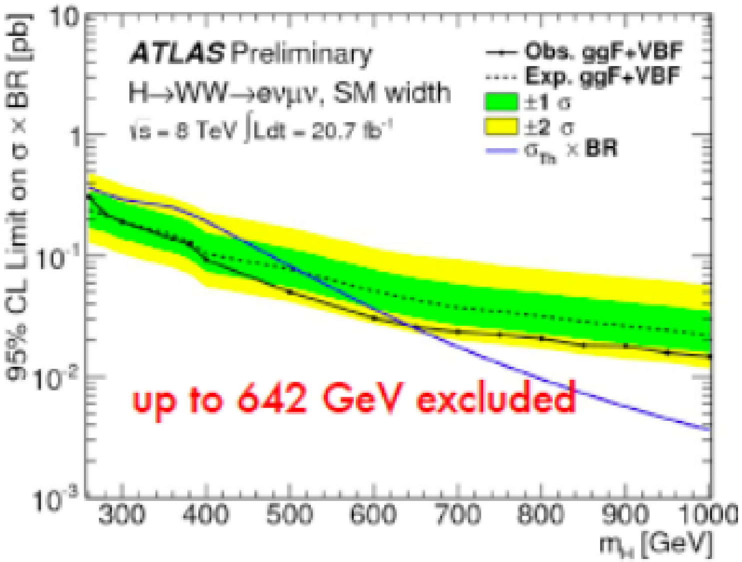
➡ **All tested alternative hypotheses (except 0_h^+) excluded with at least 95% C.L.**

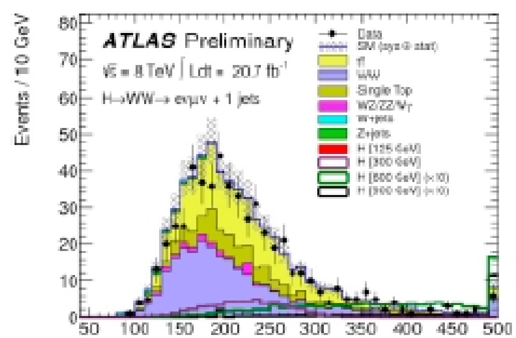
Search for high-mass Higgses

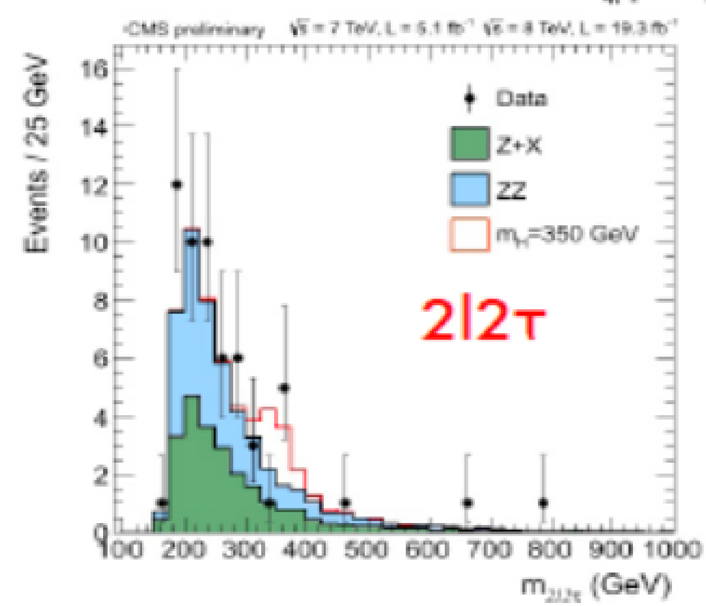








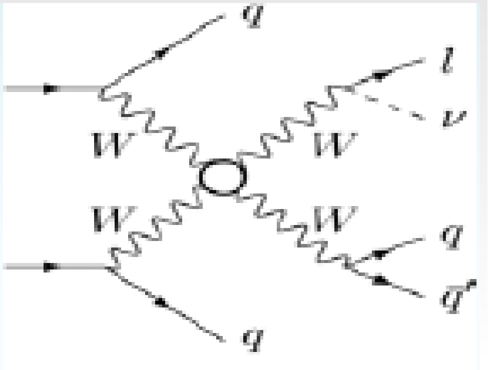




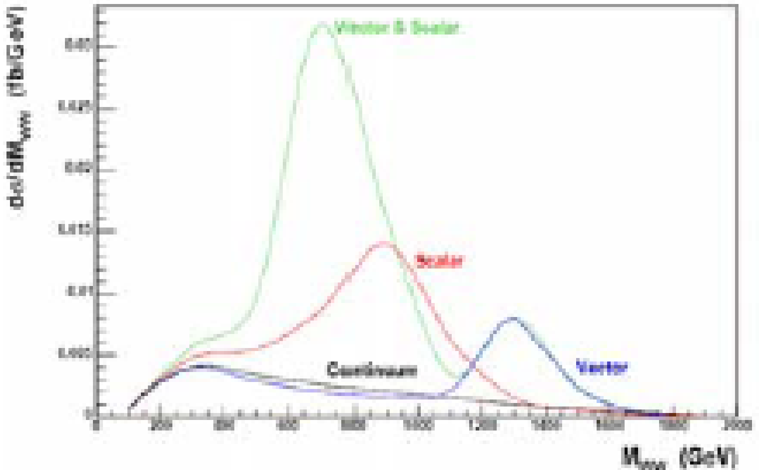
Both direct searches, and interference in the line shape

Very high-mass Higgs

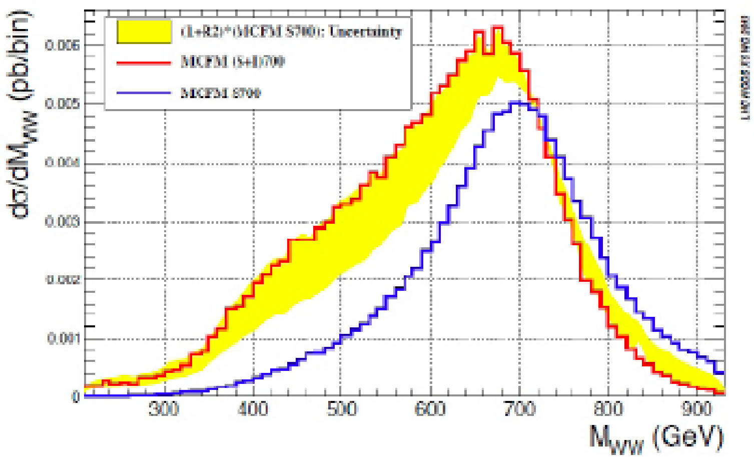
- Apart for giving mass to all other particles, the Higgs is needed in the SM to stabilise the $W_L W_L \rightarrow W_L W_L$ scattering process

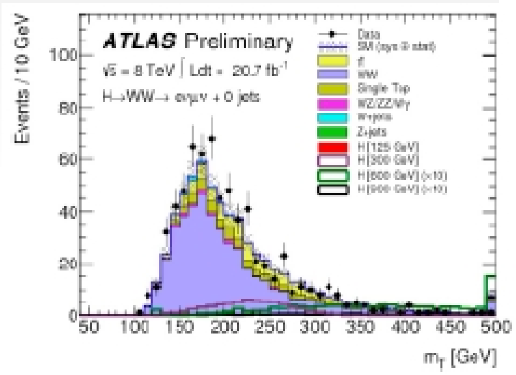


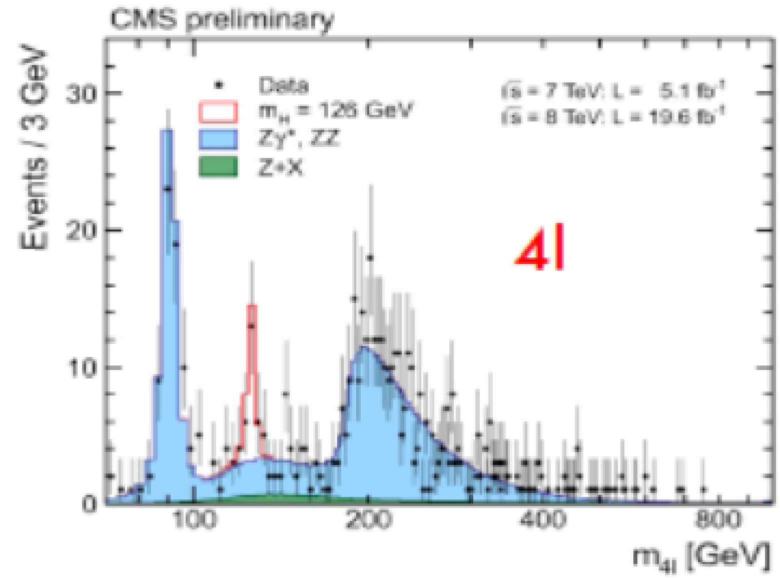
- This cross section is divergent in the SM, but if the Higgs is there a diagram with Higgs exchange restores finiteness
- Does not work if Higgs is too heavy, in that case some other resonance could be produced in WW final states
- More than one Higgs could be present, even in a pure SM scenario, with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

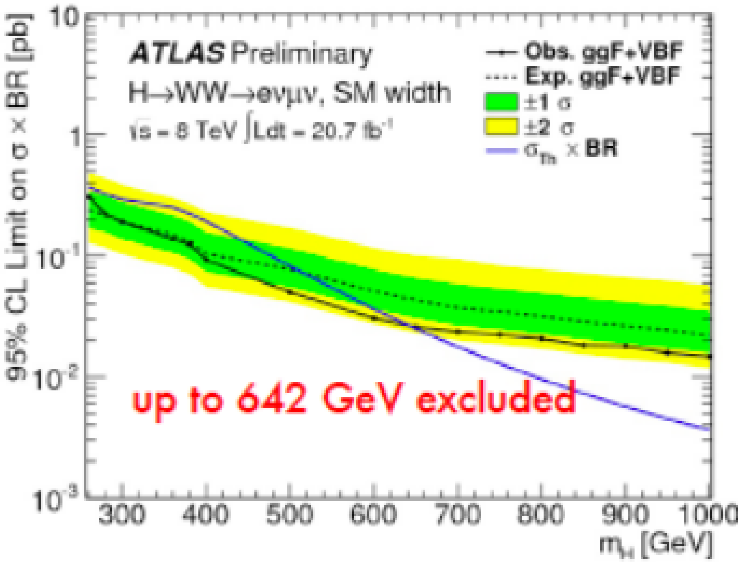


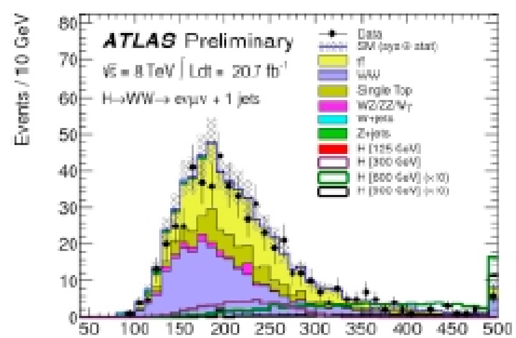
Search for high-mass Higgses

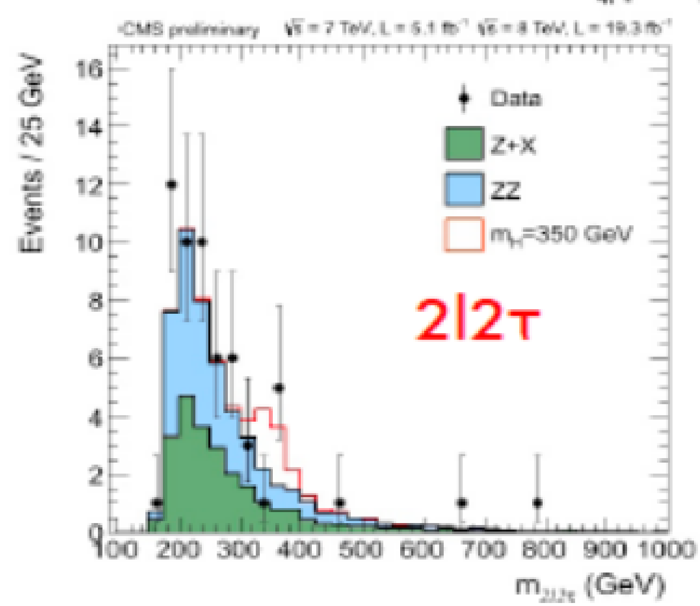












Both direct searches, and interference in the line shape

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; has been redone very quickly for Run 2
- The Higgs boson has been discovered in 2012, and all its properties are consistent with those predicted by the SM
- This discovery is not in contradiction with new physics like SUSY, even if the SM could be valid to very high scales
- No convincing NP signal observed in direct searches, however some intriguing hints are present
- Next years will be crucial for the future of collider HEP