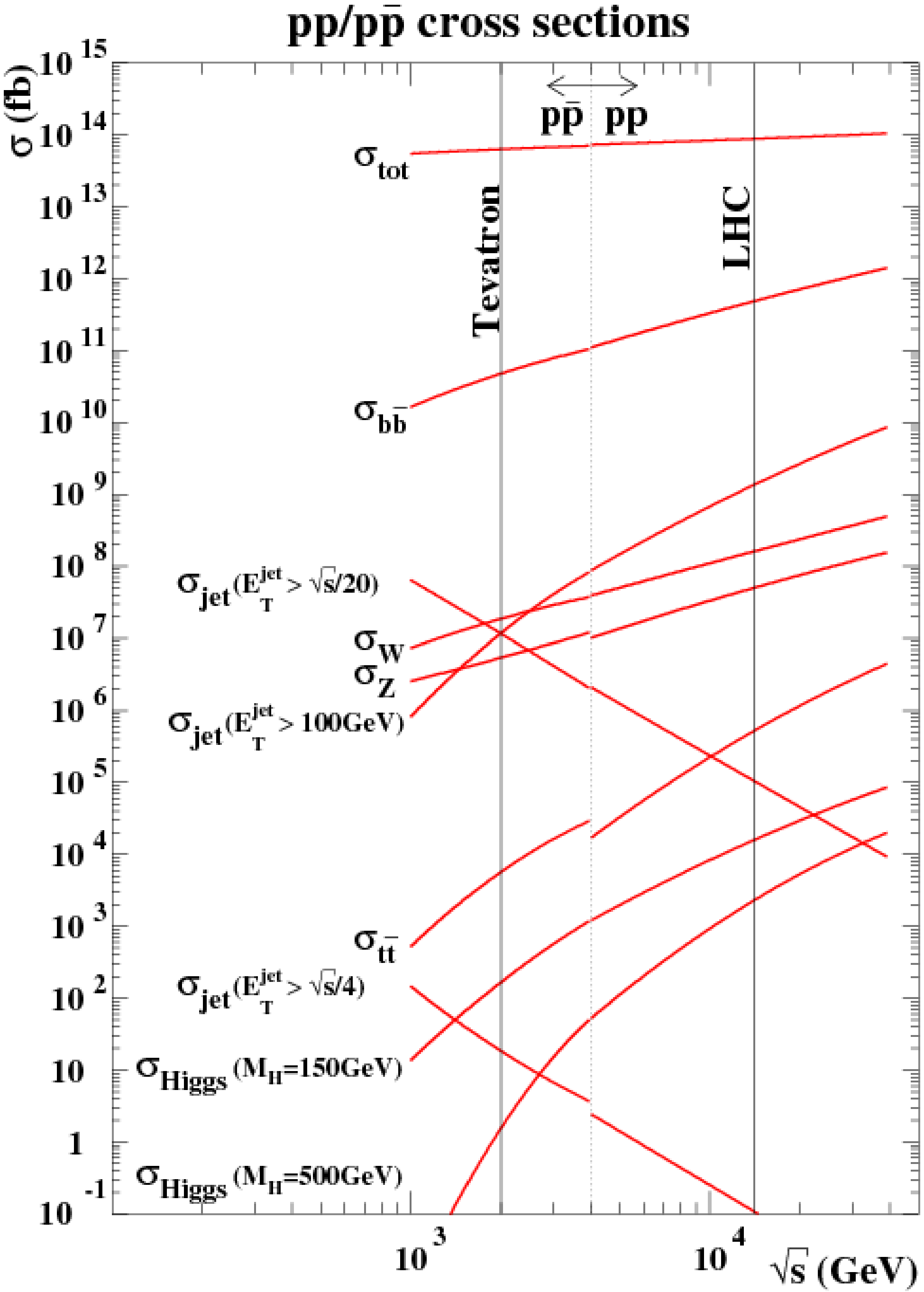
FYST17 Lecture 6
LHC Physics II

Today & Monday

- The LHC accelerator
- Challenges
- The experiments (mainly CMS and ATLAS)
- Important variables
- Preparations
- Soft physics
- EWK physics
- LHCb
- A few more recent results



Cross sections for different processes

First (and ever-present) physics at the LHC

Soft QCD

”Soft” refers to low p_T transfer, dominant in pp collisions. Often this is used as umbrella-name for everything not hard scattering:

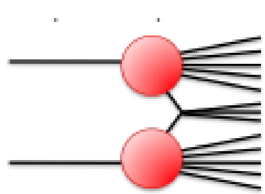
soft-QCD affecting the high pT physics program at hadron colliders:

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

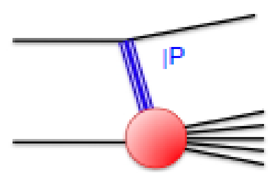
Multi Parton Interactions: An interesting parton-parton interaction will have many additional parton-parton interactions occurring in the same proton-proton interaction, they will almost always be soft-QCD processes

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

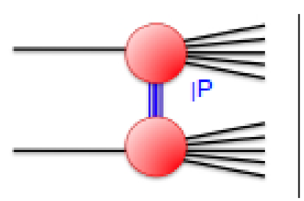
Dominant processes in inelastic hadron-hadron interactions :



Non-Diffractive (ND) σ~49 mb

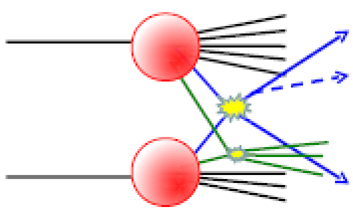


Single-Diffractive-Dissociation (SD) σ~14 mb



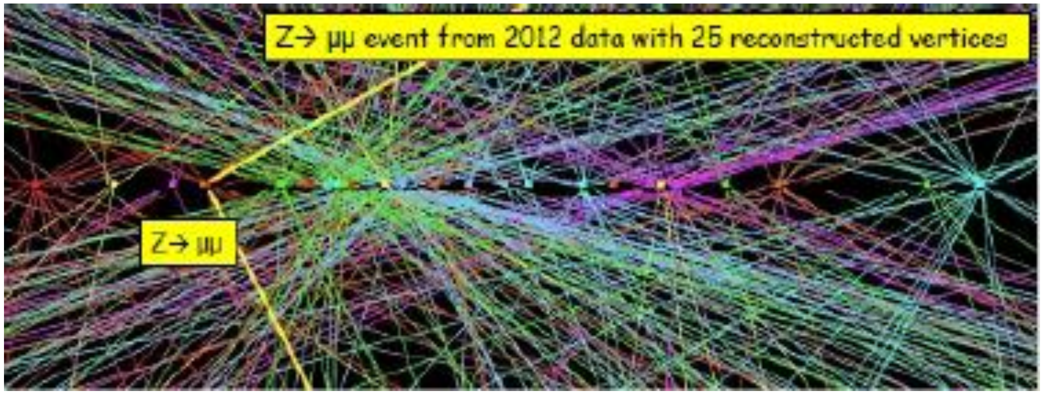
Double-Diffractive-Dissociation (DD) σ~9 mb

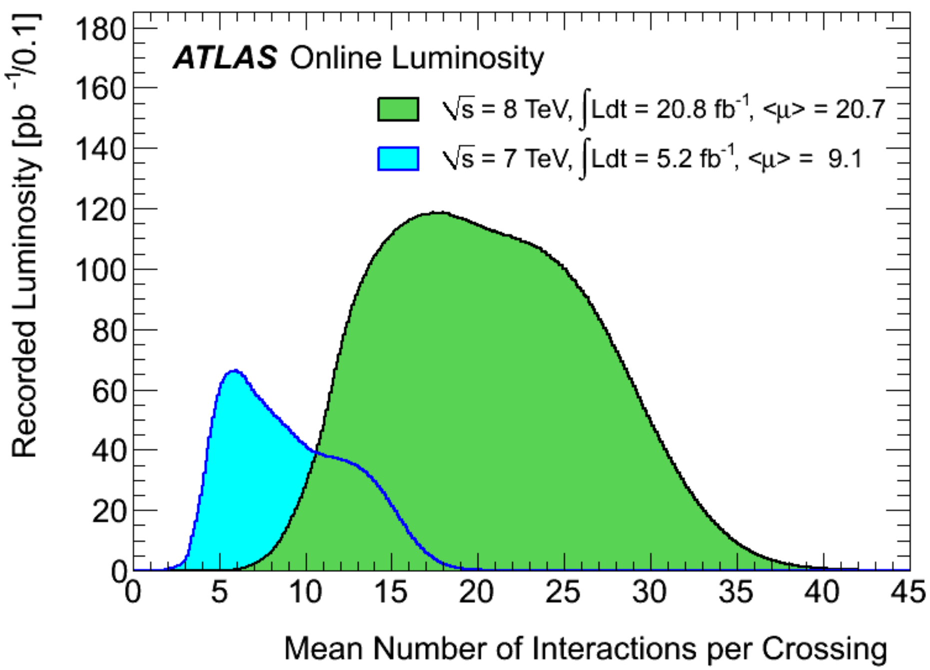
@ 7 TeV



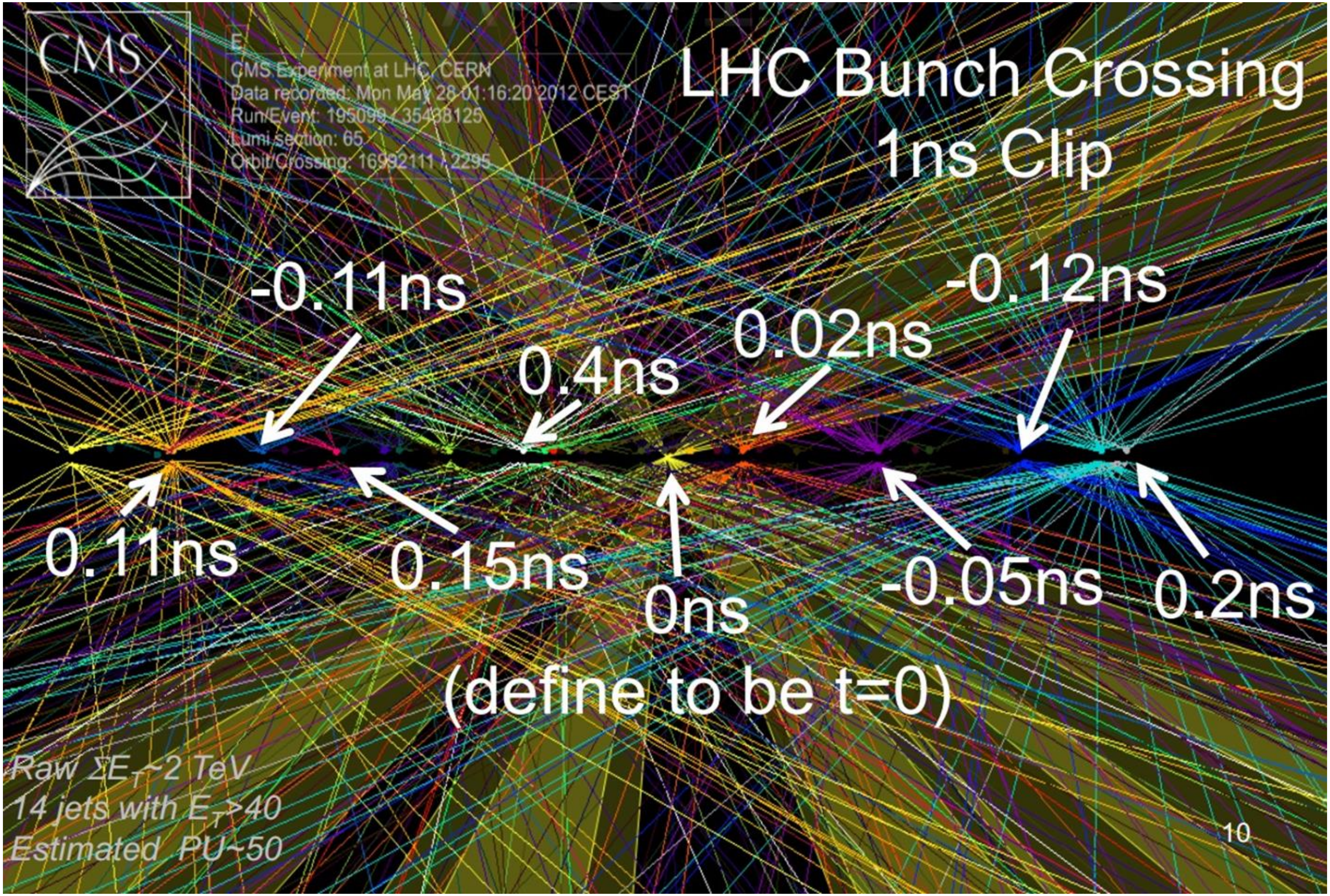
Multiple parton interactions

Pile-up

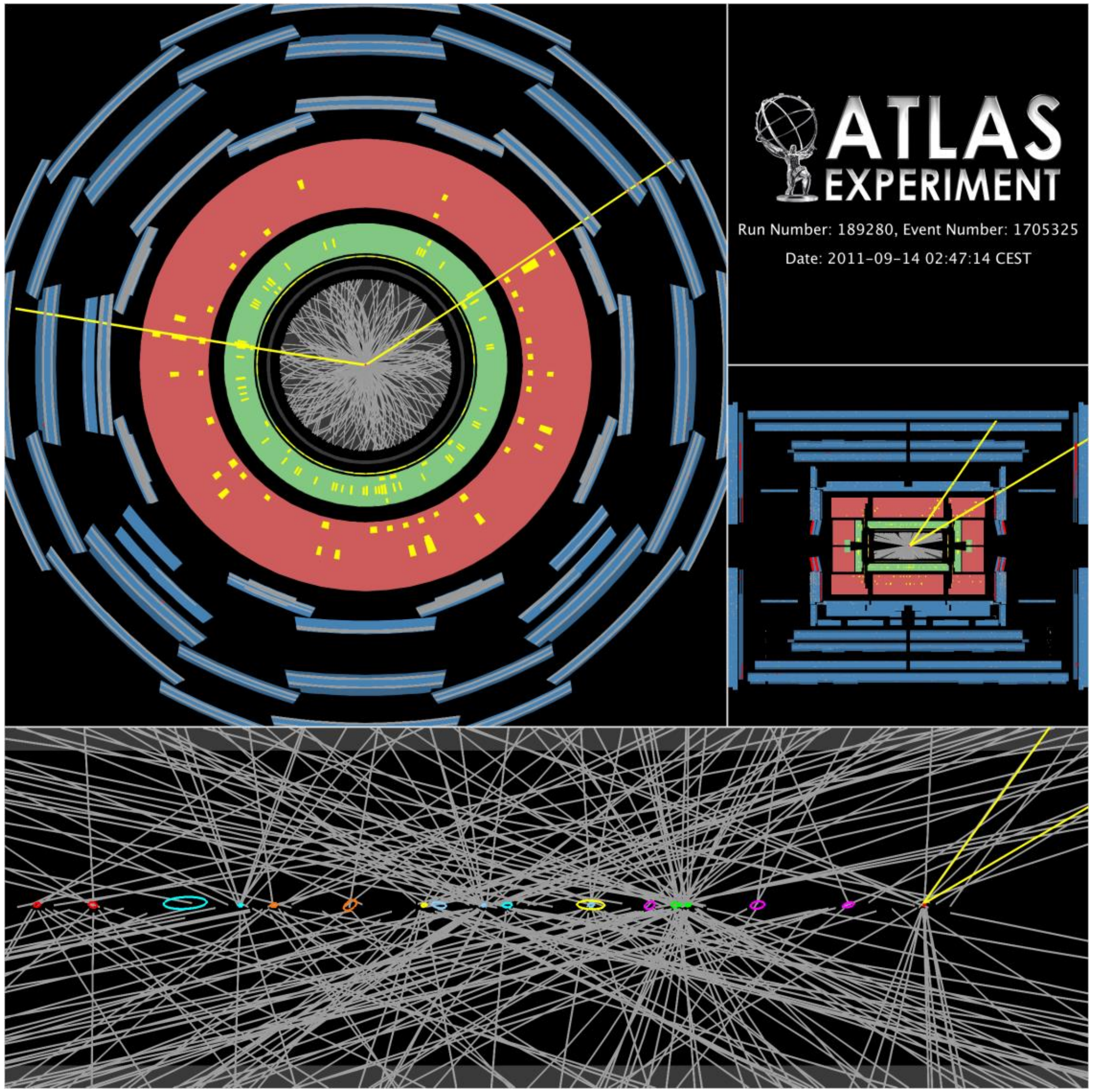




Due to the high number of protons/bunch high probability of multiple interactions
Majority of these uninteresting – but difficult to disentangle from the "most" interesting hard scatter

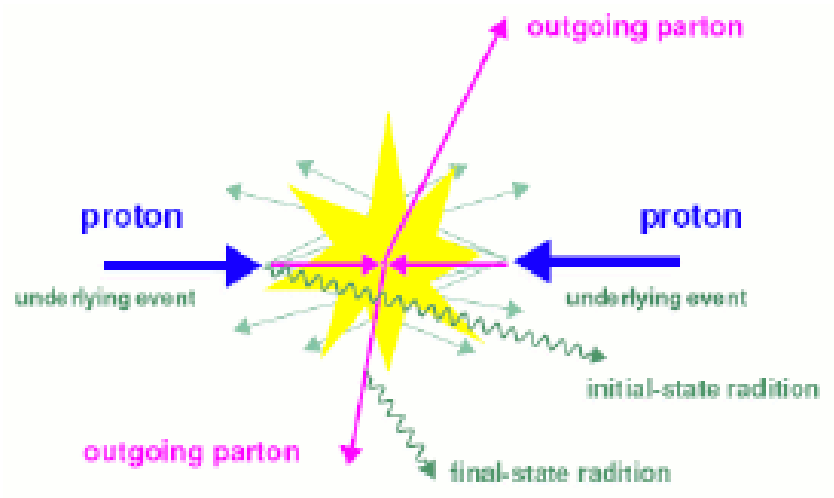

CMS
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295
LHC Bunch Crossing
1ns Clip
-0.11ns
0.4ns
0.02ns
-0.12ns
0.11ns
0.15ns
0ns
-0.05ns
0.2ns
(define to be t=0)
Raw ΣE_T~2 TeV
14 jets with E_T>40
Estimated PU~50
10

Z $\rightarrow$ μμ with 20 vertices



Underlying event

The hard scattering is not the only process, the proton is a composite object



CMS PAS QCD-08-005

Includes multi-parton interactions and beam remnants

- ”Pollutes” the hard scattering process and influence precision measurement
- Normally much softer – but large fluctuations
- Non-perturbative QCD so need to model this with empirical models tuned to data

Studying the underlying event

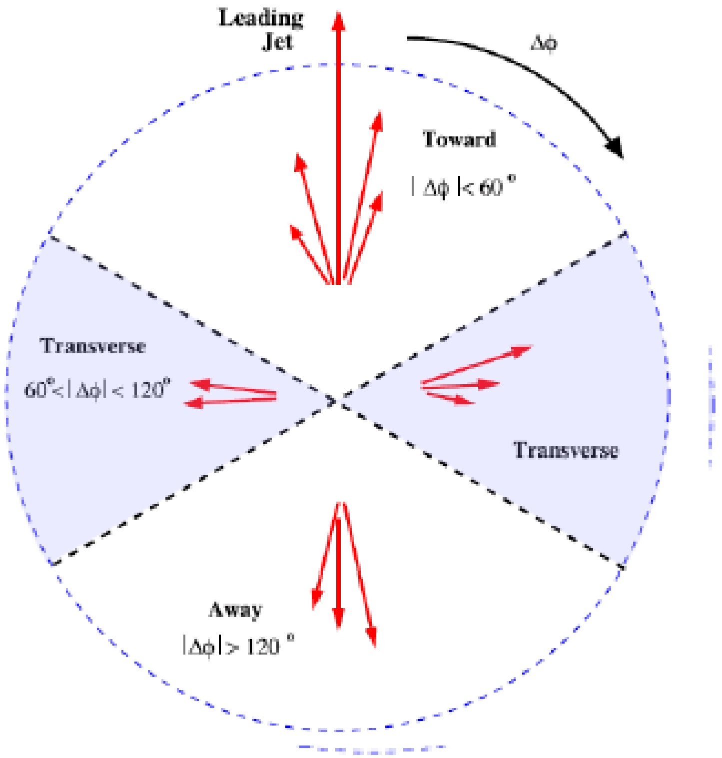
Jet events ideal for studying UE

- Tons of jet events at the LHC
- 'Transverse' region wrt direction of leading jet is very sensitive to the UE (c.f. CDF)

UE observables:

Transverse $<N_{chg}>$

Transverse $<\Sigma p_T>$



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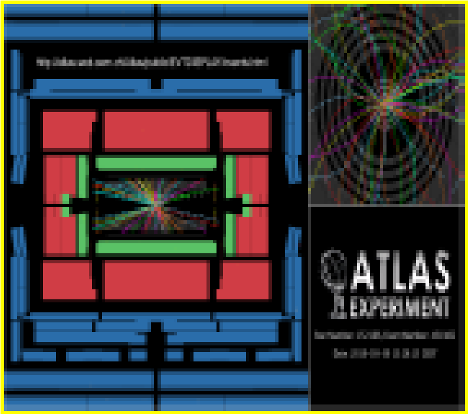
Minimum bias

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

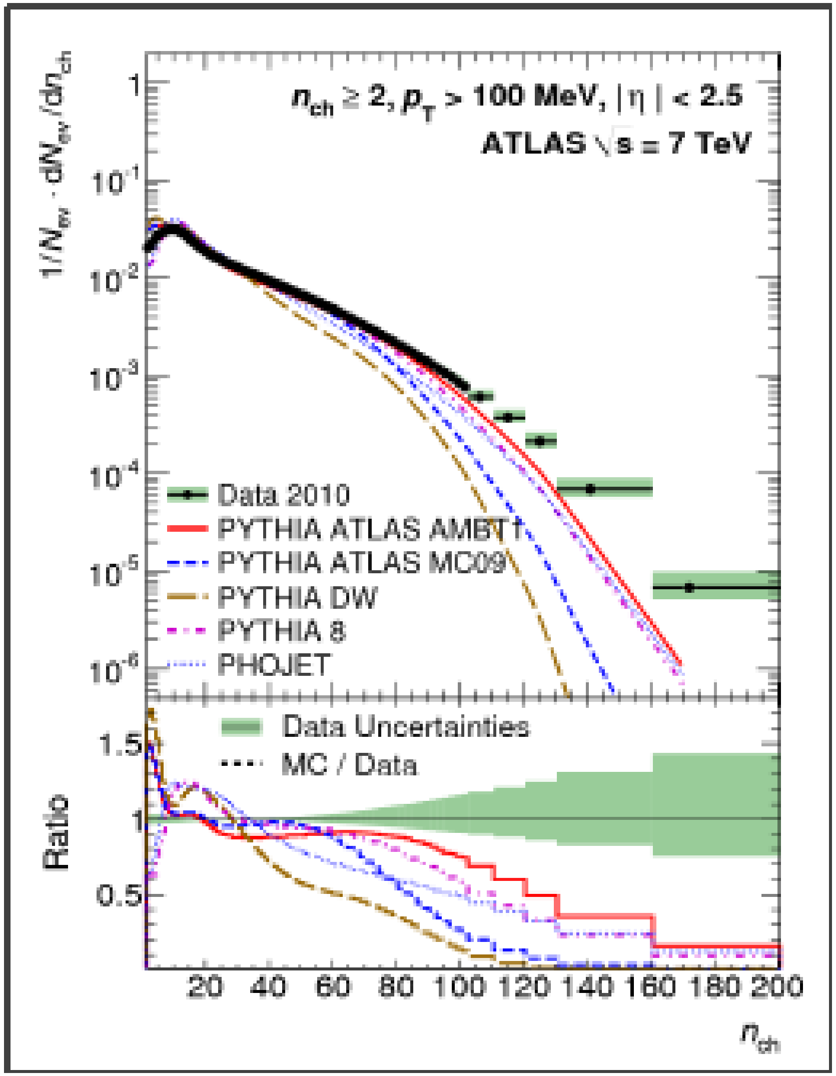
- Exact definition depends on detector (and analysis)
- Typically measure kinematics (multiplicity, pT and η spectra, etc) of charged particles in "minimum bias" events using central tracking detectors
- Monte Carlo parameters will be tuned to these distributions

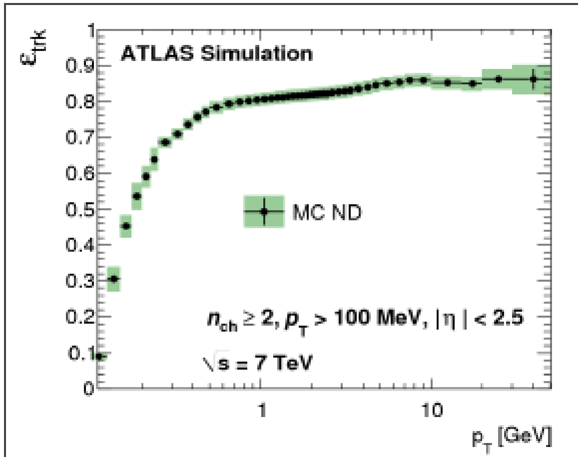


Charged particles moving through a magnetic field will bend by an amount inversely proportional to pT

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

Testing the soft QCD predictions



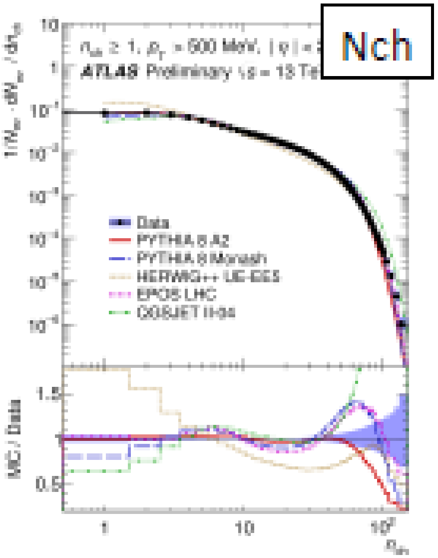


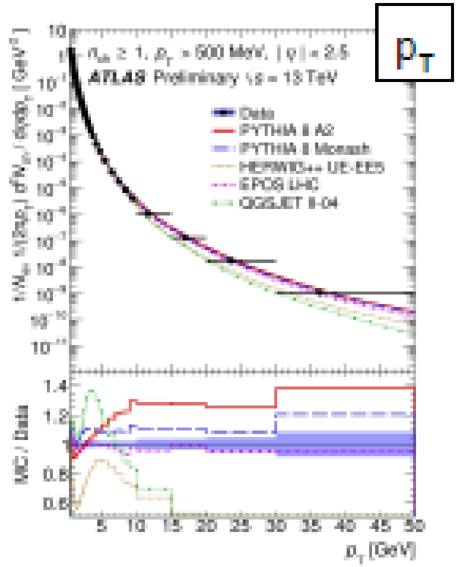
High p_T / EWK physics

Physics Modelling

A2 Minbias tune (for PU)

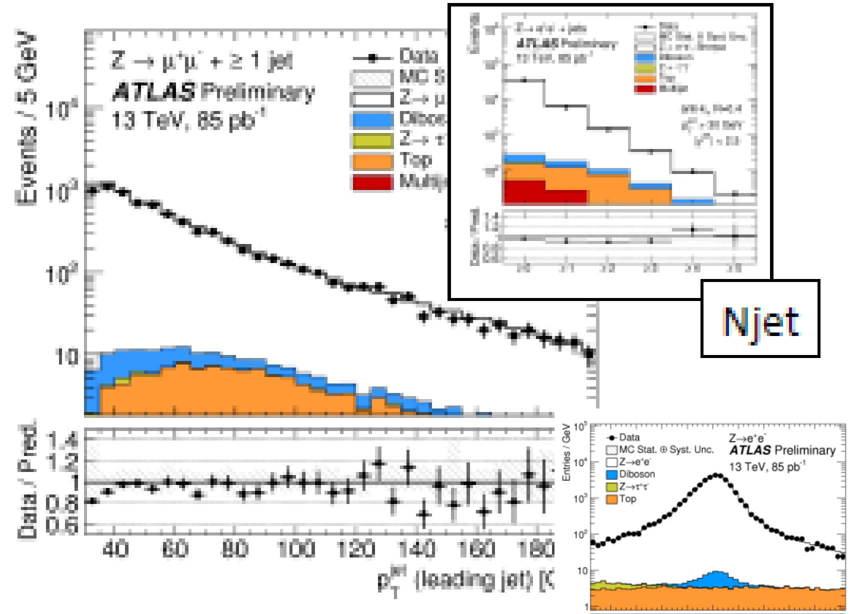
Pythia 6 and 8 (using 7 TeV ATLAS data only)

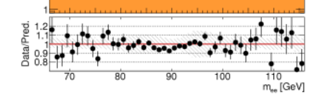




V+Jets , Dibosons, Tribosons

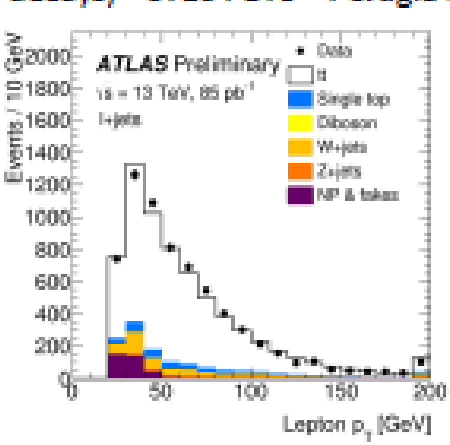
Sherpa NLO (2partons) and LO (up to 4 partons) 2.1.1

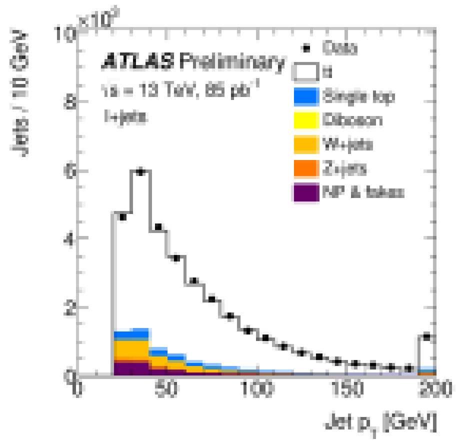




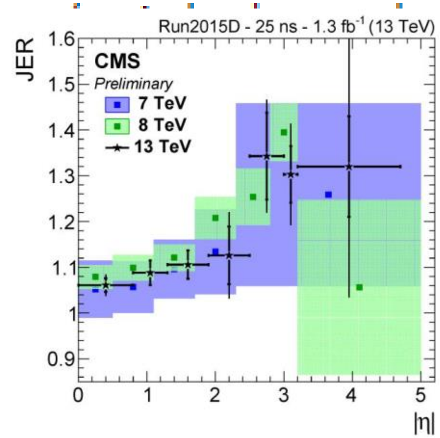
Top pair production

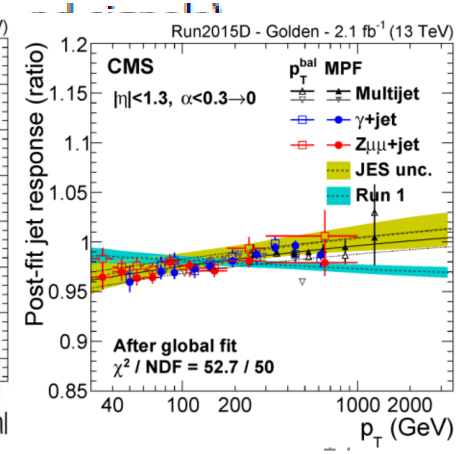
Powheg-Box v2 (hdamp =m_t) – Pythia 6.428 – EvtGen (HF decays) - CT10 PDFs – Perugia 2012 tune



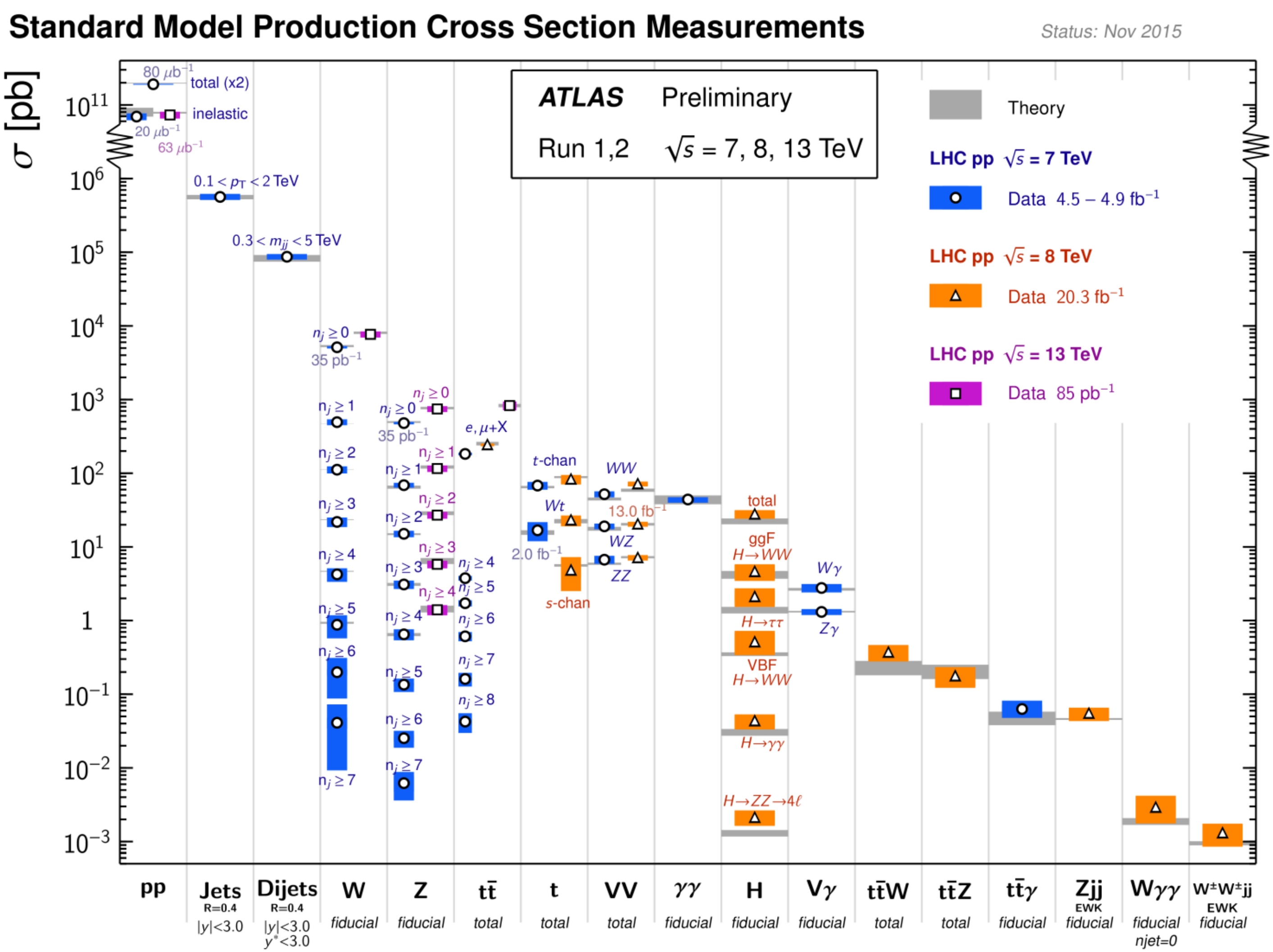


Jet quality

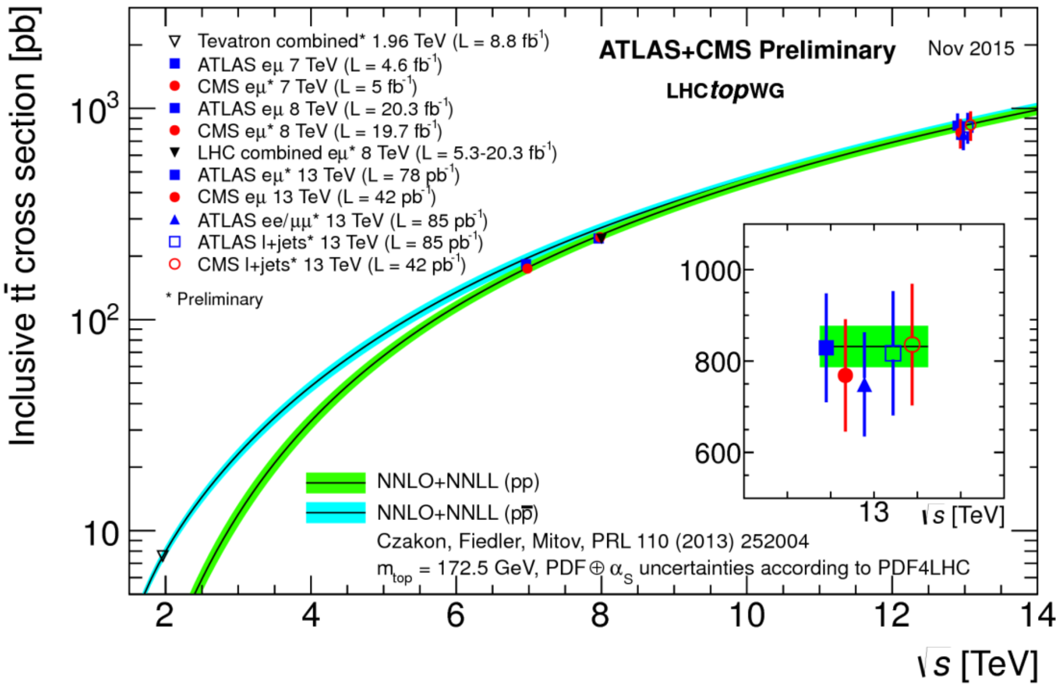


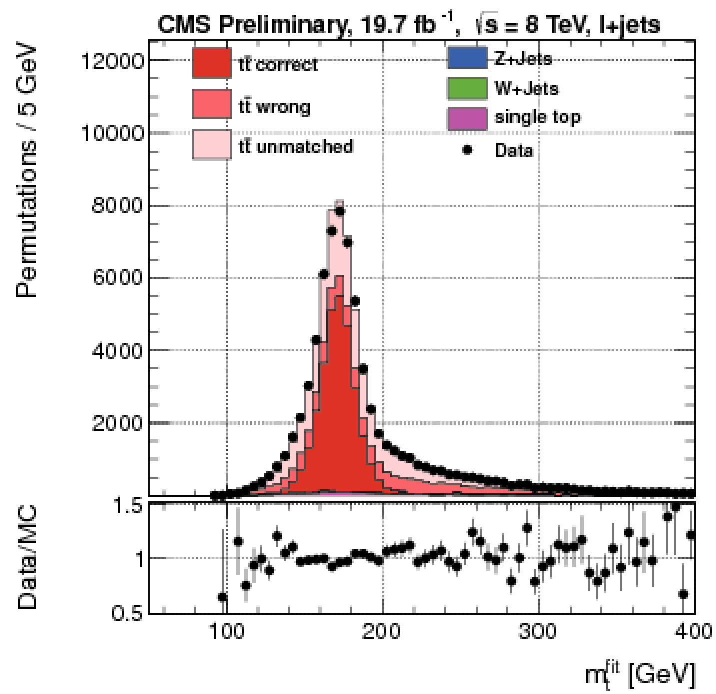


Standard Model measurements



Close-in on the top quark

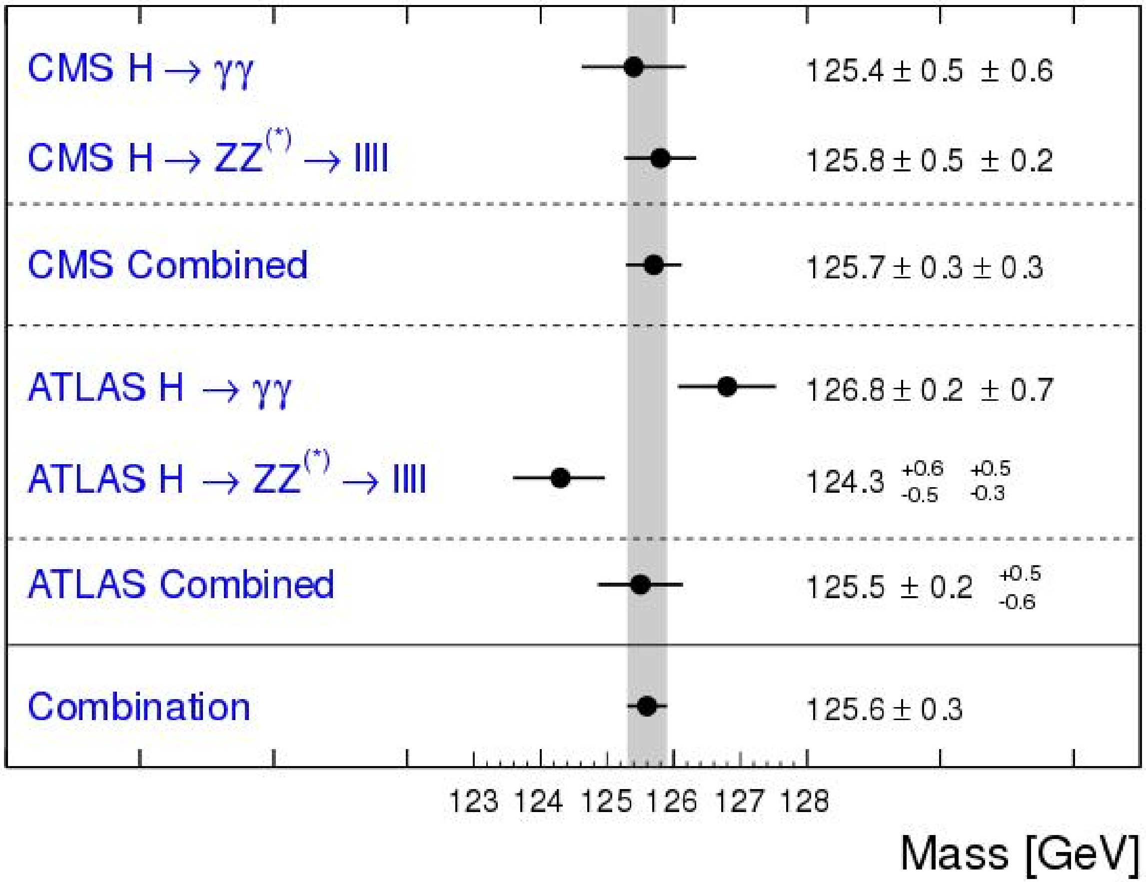




$M_{top} = 173.34 \pm 0.36 \pm 0.67$ GeV

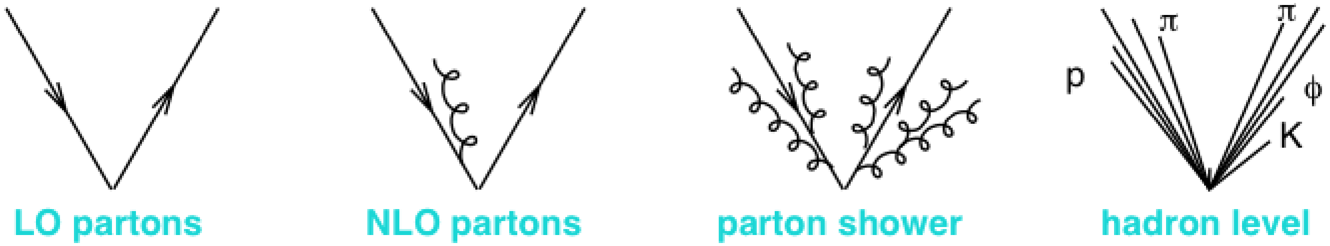
Higgs measurements

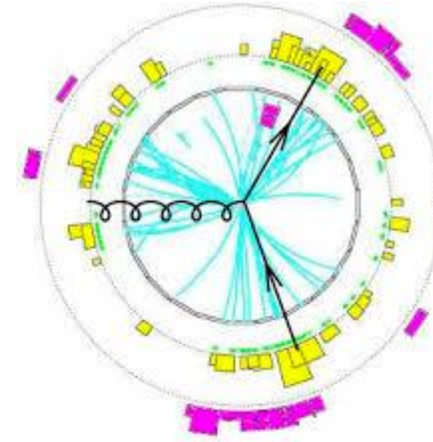
PDG



Identification of jets and leptons

Jet algorithms

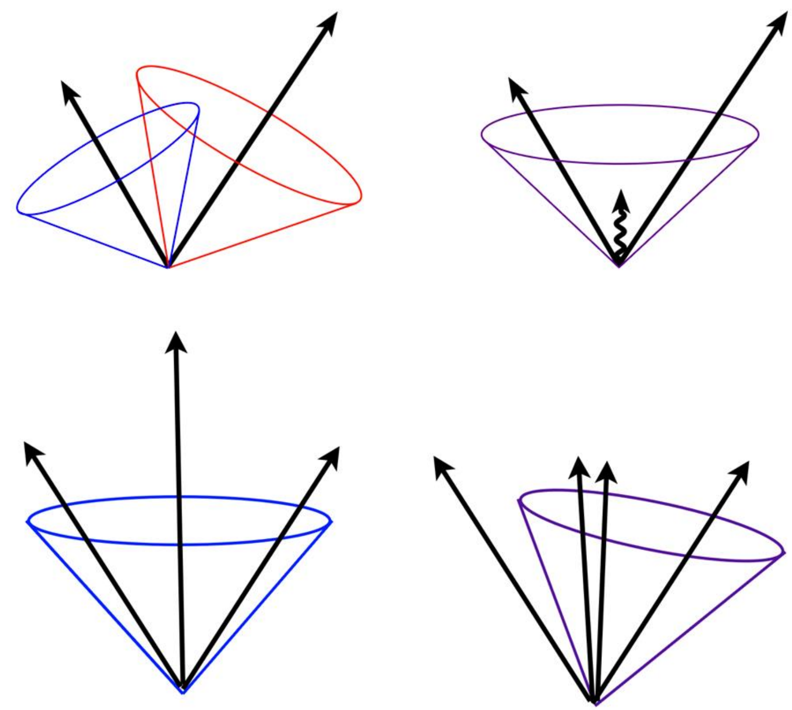




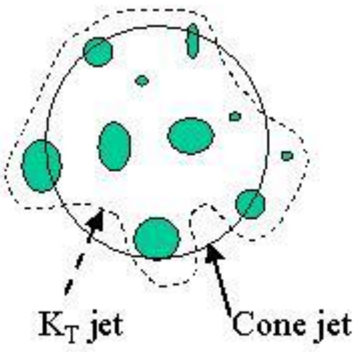
How to define a ”jet”? A few different approaches:

Cone algorimth: include all particles inside a cone of given radius

experimentally easiest , theoretically unsafe



k_T / anti-k_T algorithm



- How likely that two partons arise from QCD
- splitting? From all final state particles calculate:

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

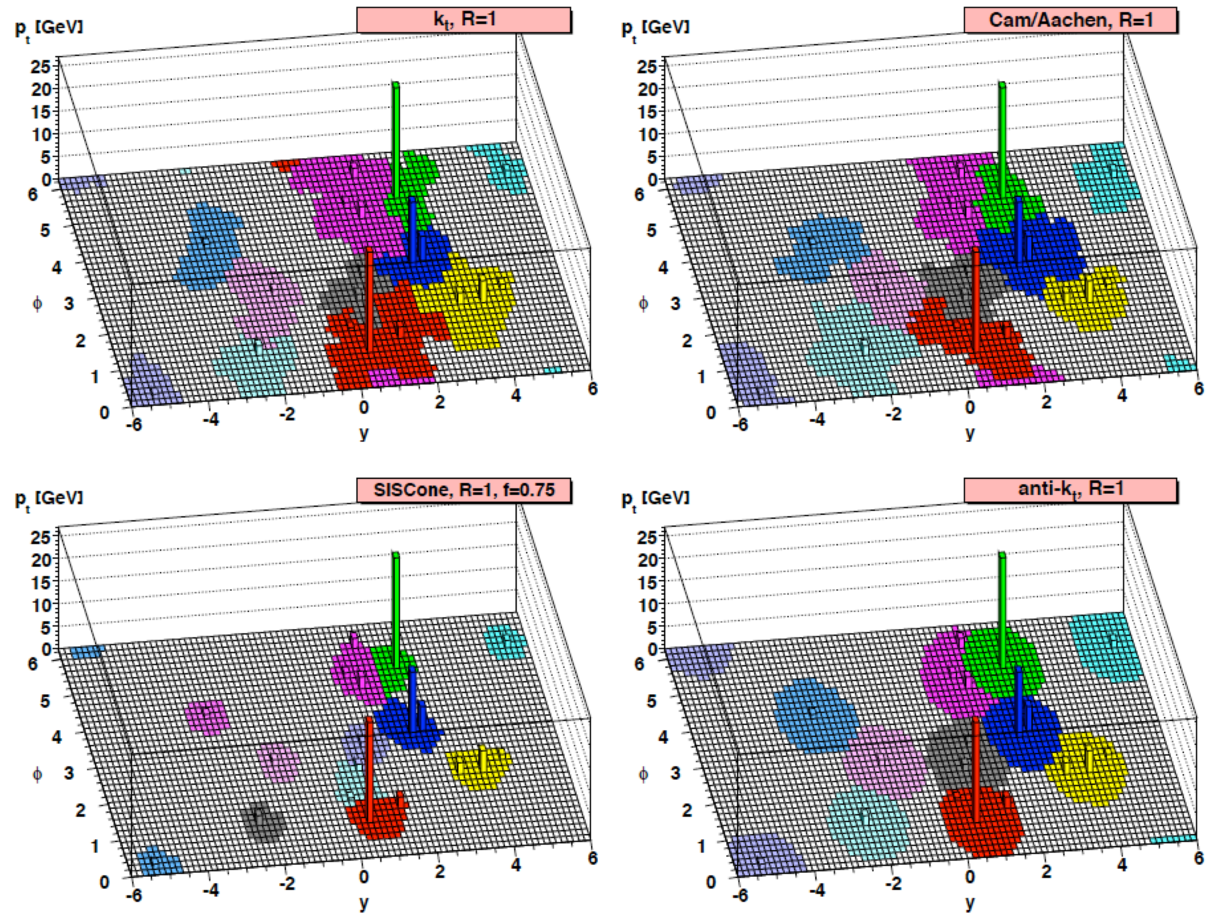
- Find minimum. If d_{ij} , combine i and j into a jet, then loop over all particles again. If d_{iB}, call it a jet, and remove particle i from list

p=+1: k_T algorimth. p =-1: anti-k_T algorithm (favoring recombination of high-pt particles)

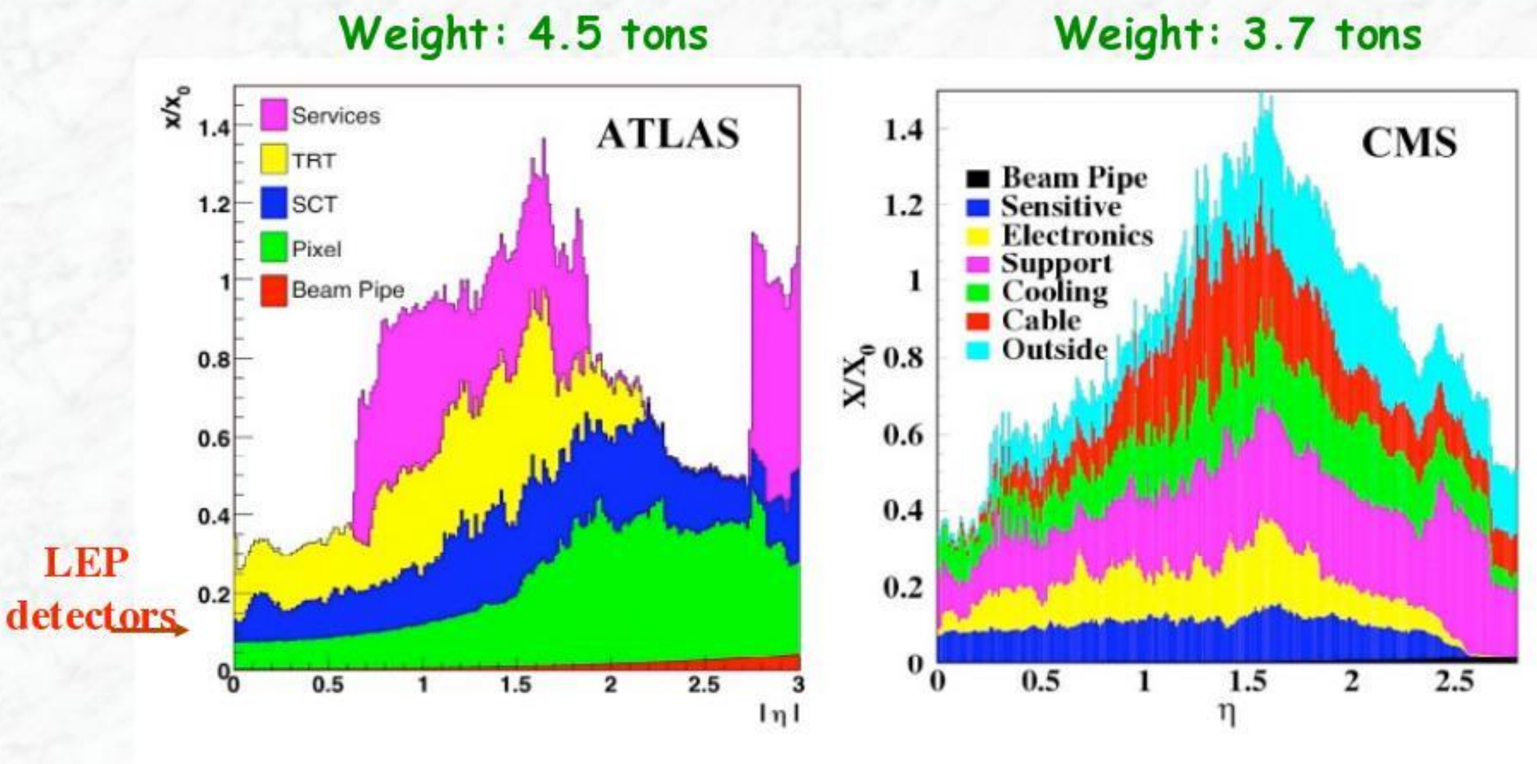
Comparison

Anti-kt mostly used at the LHC

Gives more regular jets (almost like cones!) because soft particles clustered only at the end

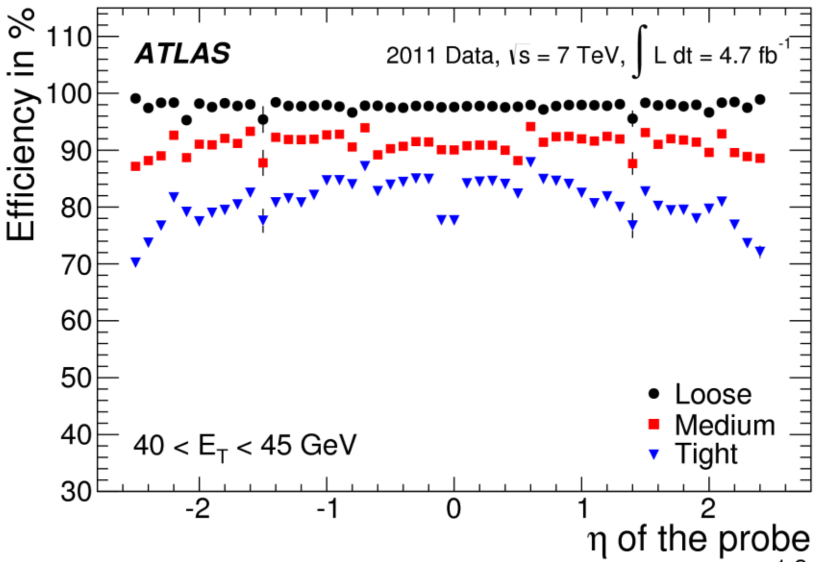


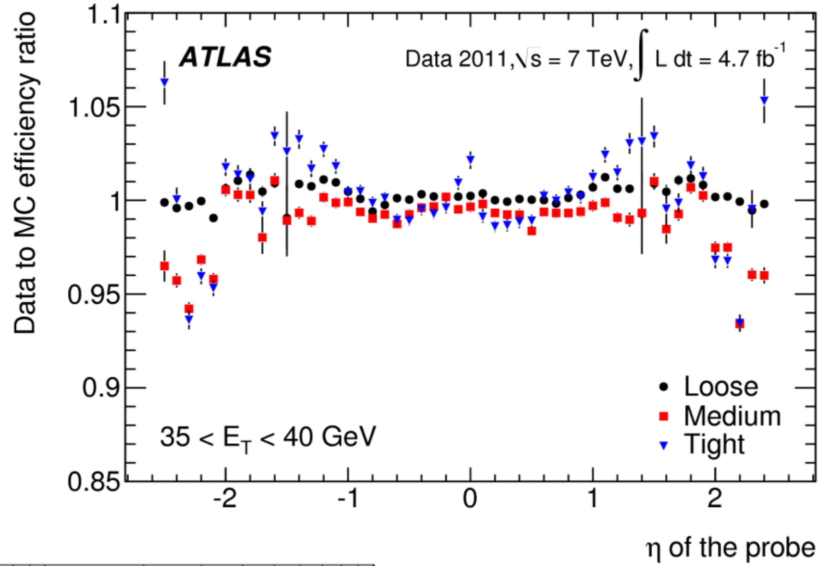
Amount of material in ATLAS and CMS inner trackers

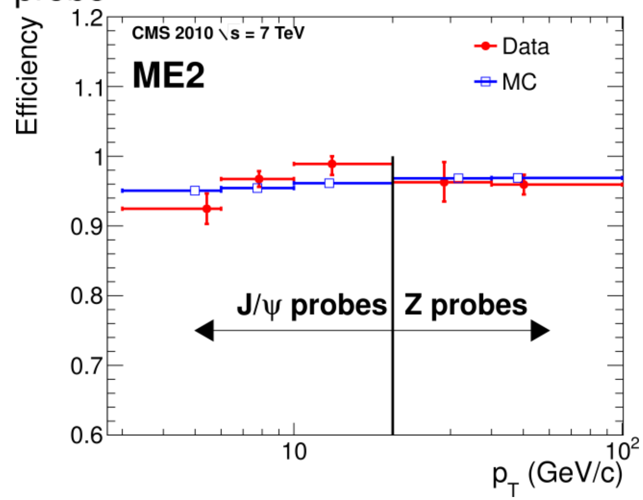


- Active sensors and mechanics account each only for ~ 10% of material budget
- Need to bring 70 kW power into tracker and to remove similar amount of heat
- Very distributed set of heat sources and power-hungry electronics inside volume: this has led to complex layout of services, most of which were not at all understood at the time of the TDRs

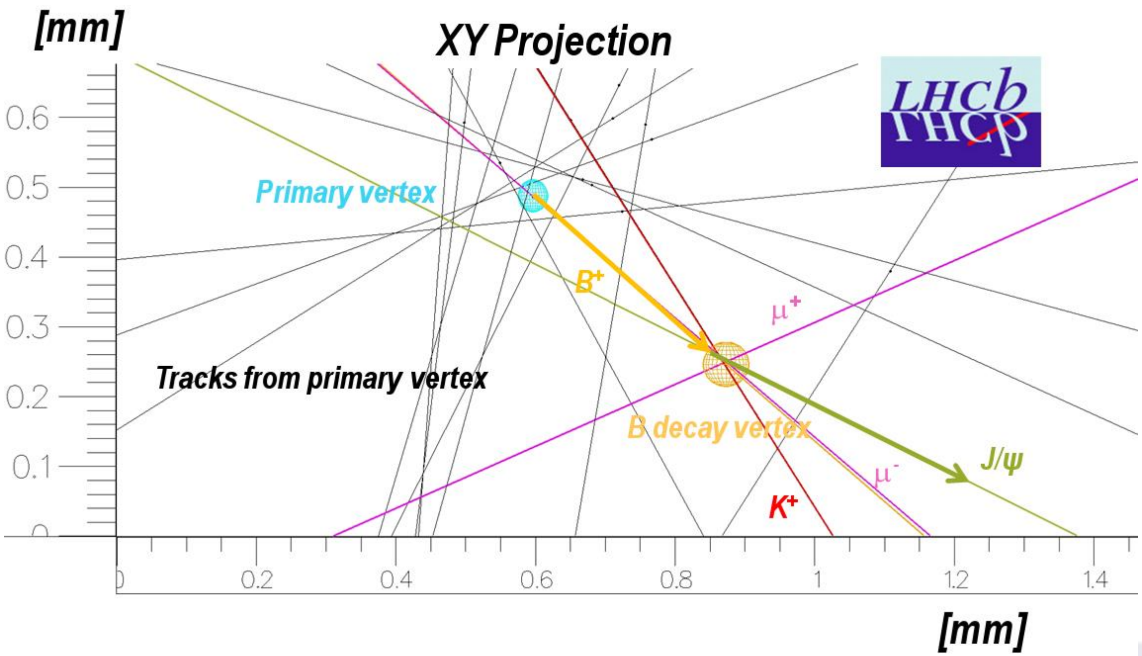
Leptons and efficiencies

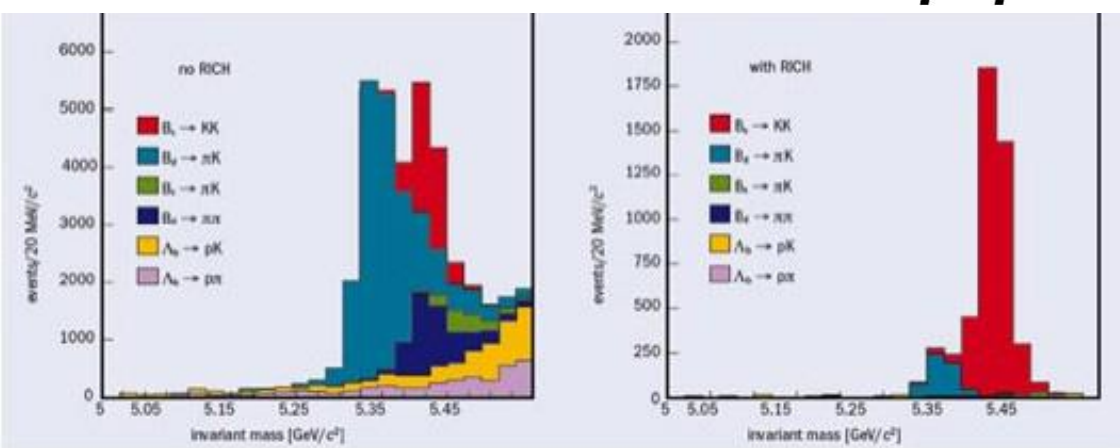






More on LHCb

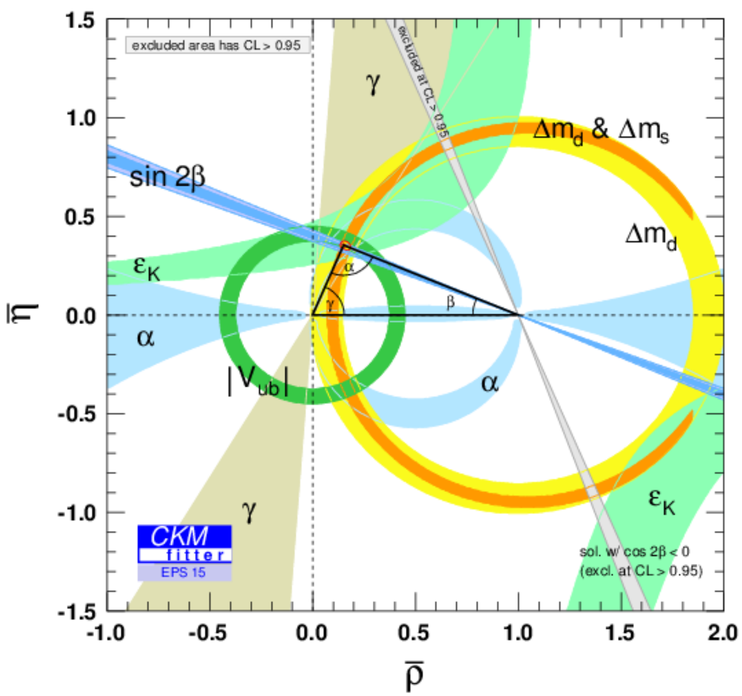




Focus on B-physics, physics involving B hadrons
Secondary vertex detector to identify potential B decays + particle ID

Physics programme mainly devoted to searches for rare decays + precision measurements to check loop effects and CP violation

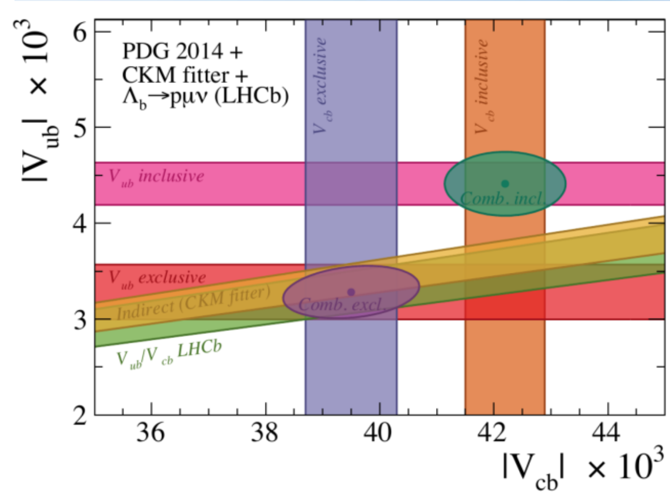
Despite being the ”little brother”, a lot of interesting results (interesting = tension with SM) have come from just LHCb



You’ll remember the pentaquarks…

Results from the main area of expertise CP violation, for instance:

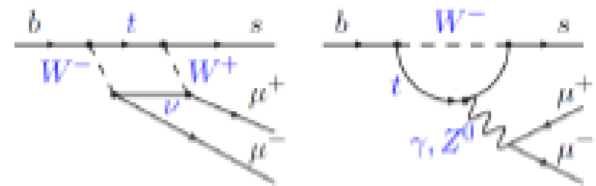
$|V_{ub}|/|V_{cb}|$ from $\Lambda_b^0 \rightarrow p\mu\nu_\mu$

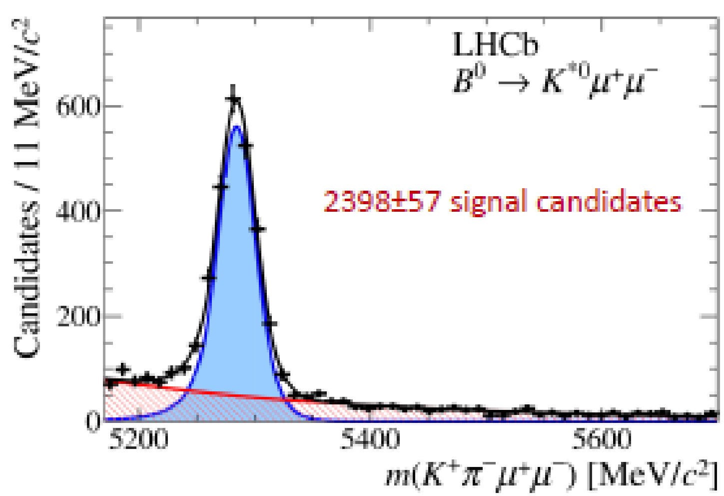


More on LHCb results

- Rare decays:
  - Only allowed through loops in the SM

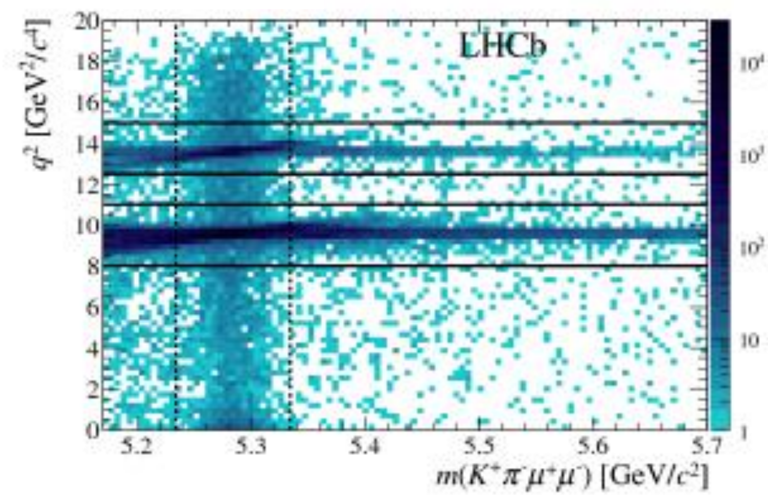
$B^0 \to K^{*0}\, \mu^+ \mu^-$





Full q² range with J/ψ and ψ(2S) veto

$q^2 = M(\mu^+\mu^-)^2$



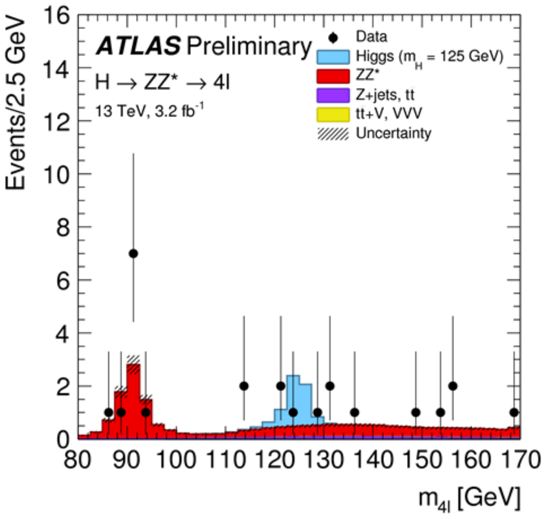
Dalitz plot

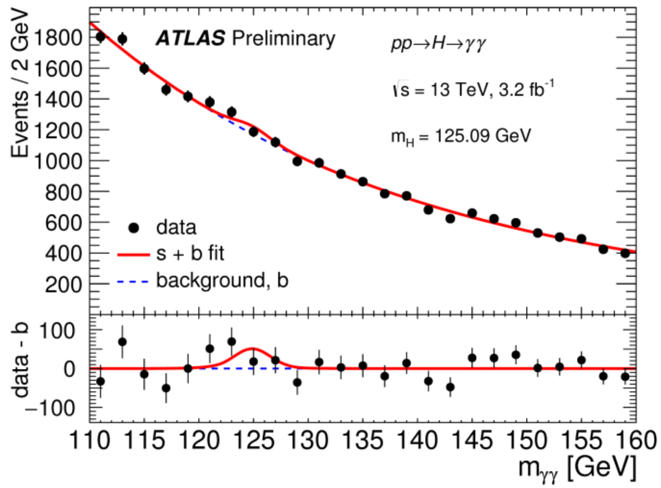
- Heavy ion physics

Latest on the Standard Model: a few 13 TeV results

The Higgs @ 13 TeV ?

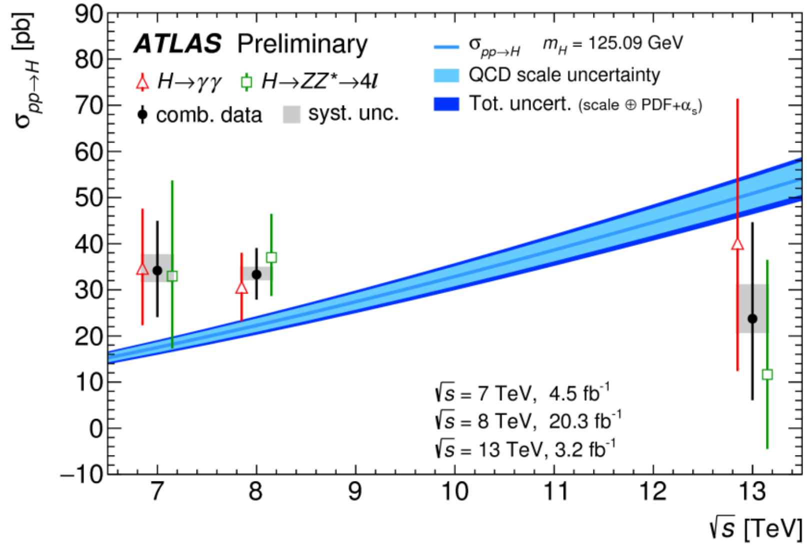
ATLAS doesn't really see it yet … but still consistent with the old





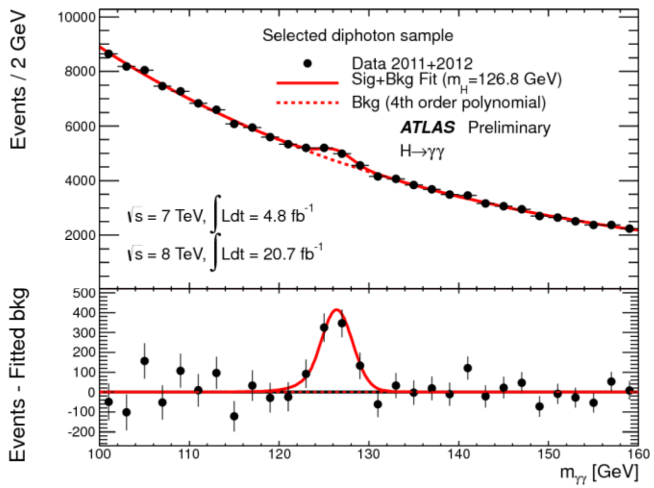
Combined observation significance:

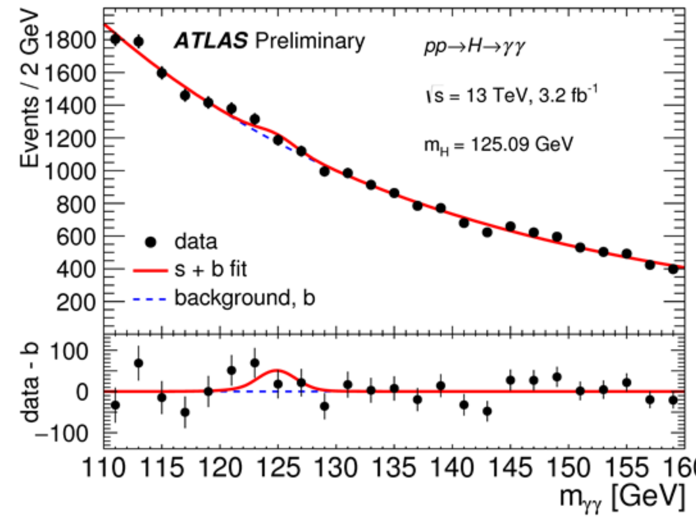
- Expected: 3.4σ
- Observed: 1.4σ



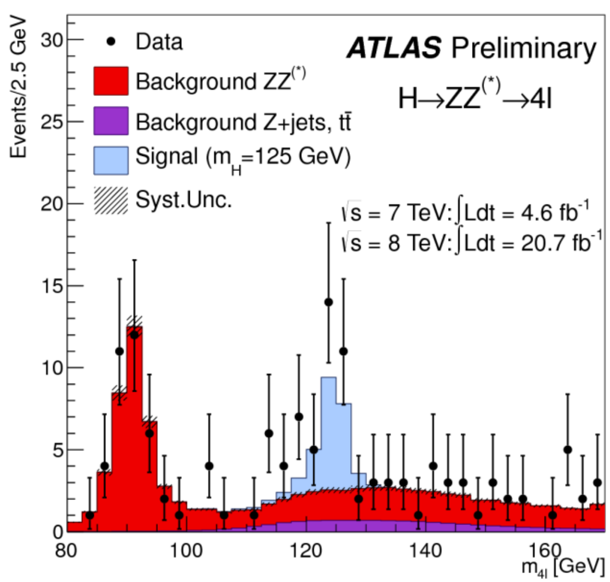
Comparing to 8 TeV plots

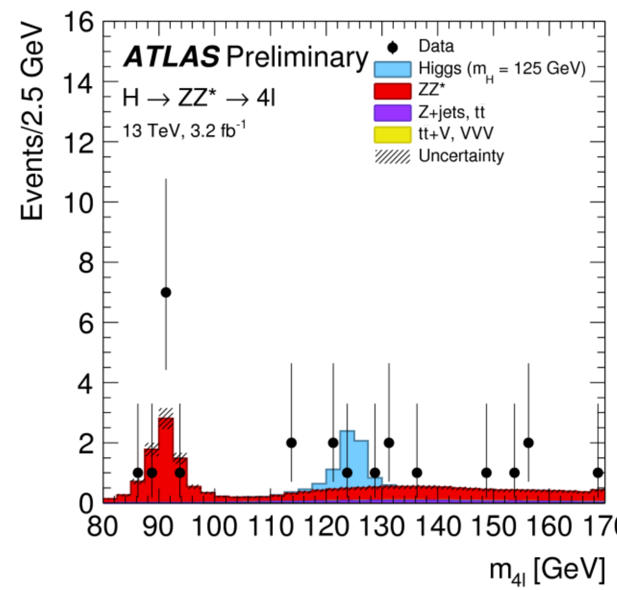
$\gamma\gamma$





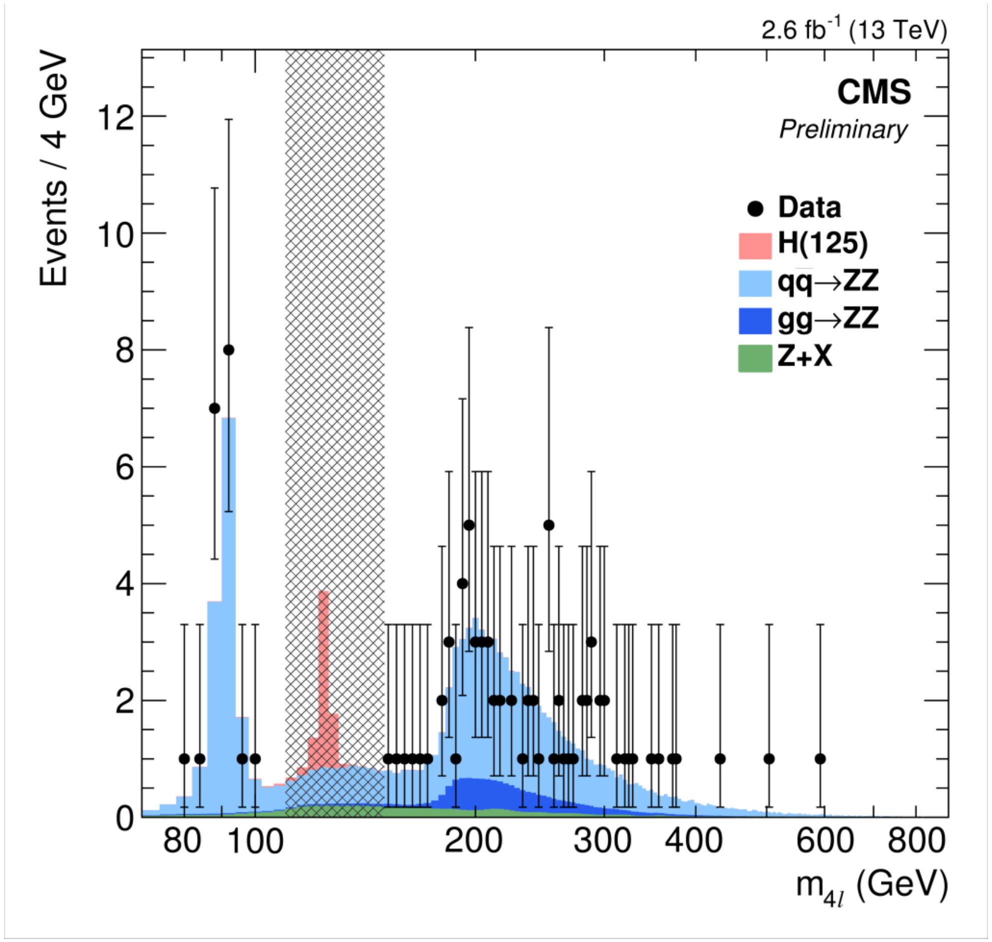
4 leptons





CMS: Higgs @ 13 TeV ?

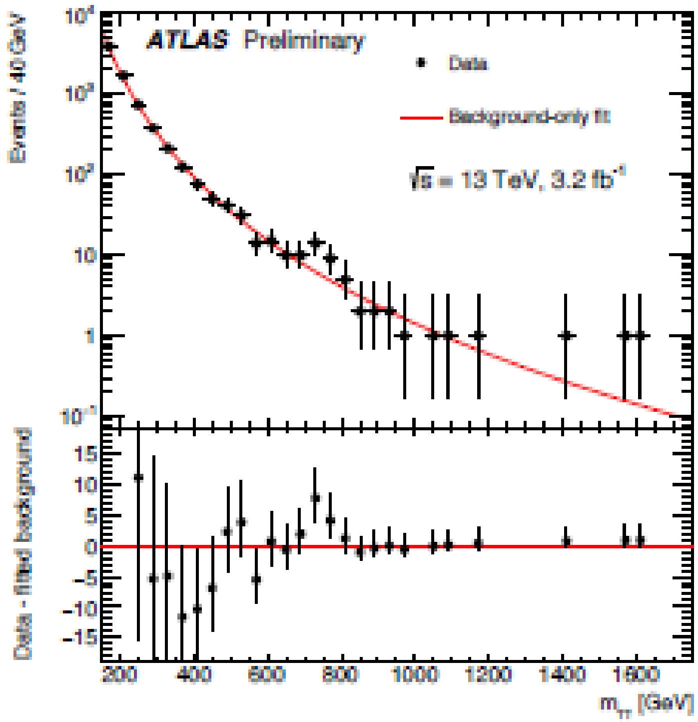
We don't know yet, result still "blinded"



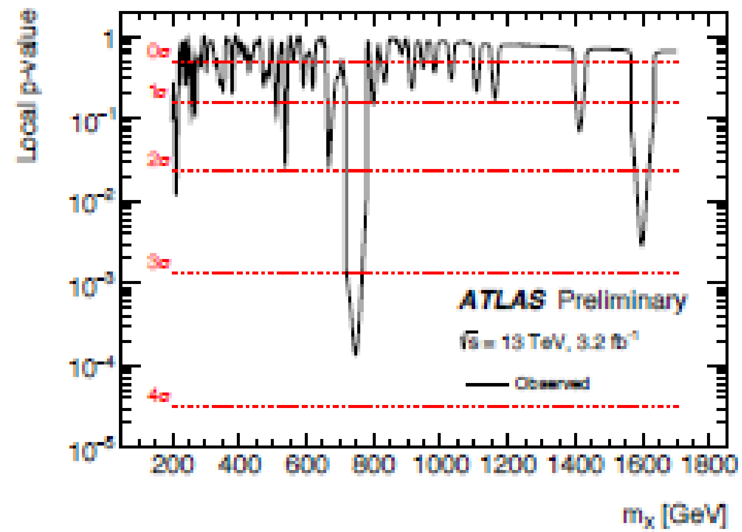
They do expect less 3 σ, *though (magnet trouble, less data than ATLAS*) so we may not know the fate of the Higgs boson until later this year

Search for a Two Photons Resonance (II) ATLAS results

Results: Events with mass in excess of 200 GeV are included in unbinned fit



- In the NWA search, an excess of 3.6σ (local) is observed at a mass hypothesis of minimal p_0 of 750 GeV
- Taking a LEE in a mass range (fixed before unblinding) of 200 GeV to 2.0 TeV the global significance of the excess is **2.0σ**

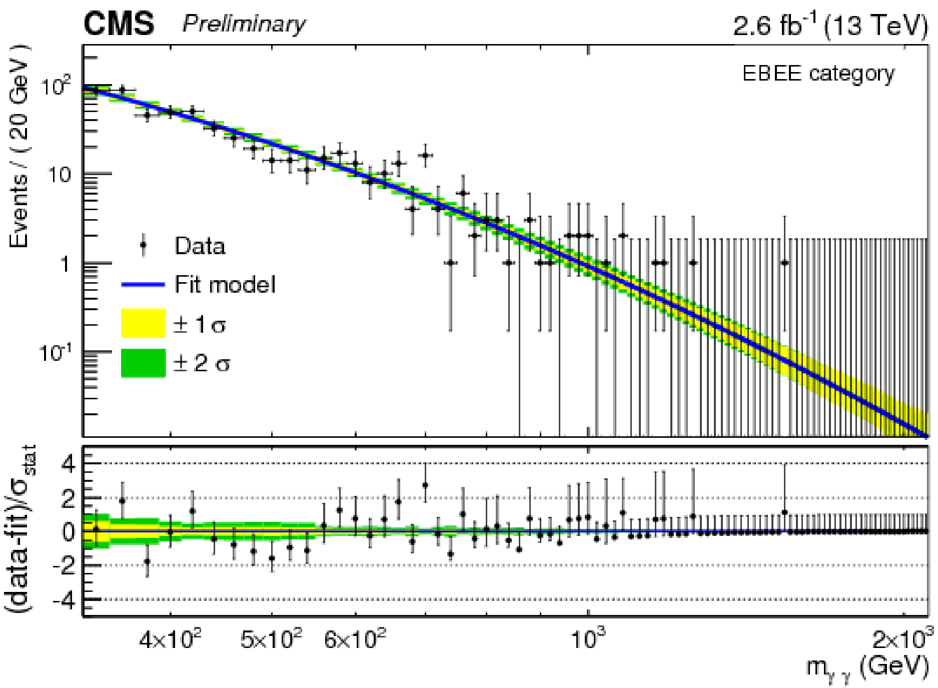


In the NWA fit the resolution uncertainty is profiled in the NWA fit and is pulled by 1.5σ

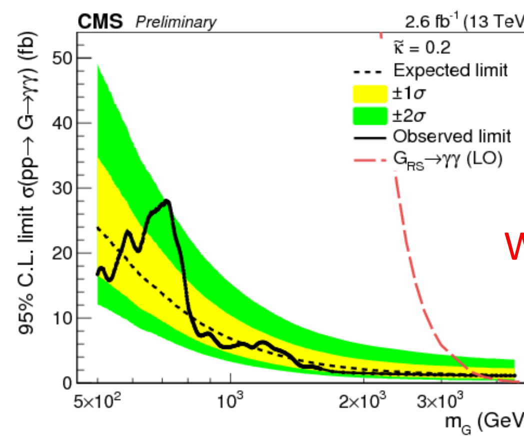
The data was then fit under a **LW hypothesis** yielding a width of approximately 45 GeV (Approx. 6% of the best fit mass of approximately 750 GeV)

- As expected the local significance increases to 3.9σ
- Taking into account a LEE in mass and width of up to 10% of the mass hypothesis of 2.3σ (Note: upper range in resolution fixed after unblinding)

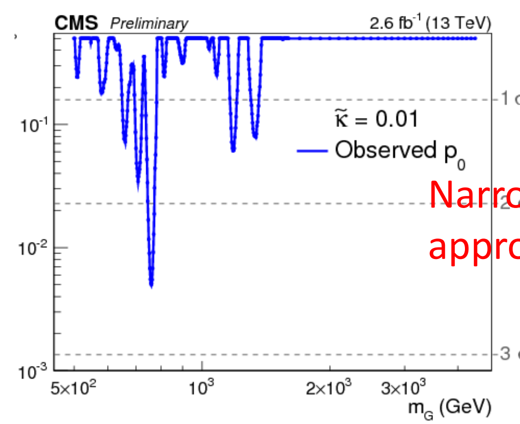
CMS



Sees a structure in the same place!



Wide width



Narrow width approximation

Taking into account the Look-elsewhere-effect this is only ~ 1.2 σ so could be coincidence

Summary

- The LHC is a fantastic multi-purpose machine
- It was not trivial to design and commission – problems from previous accelerators do not necessarily scale
- Detectors have chosen fairly different techniques but sensitivity remains similar
  - Thousands of papers with results out
  - Apologies to ALICE – you will hear more later
- The Standard Model , including the Higgs, is now well established
  - A few tensions and bumps but nothing really against the SM yet
  - This talk didn't really cover the Beyond Standard Model but we will get to that later