

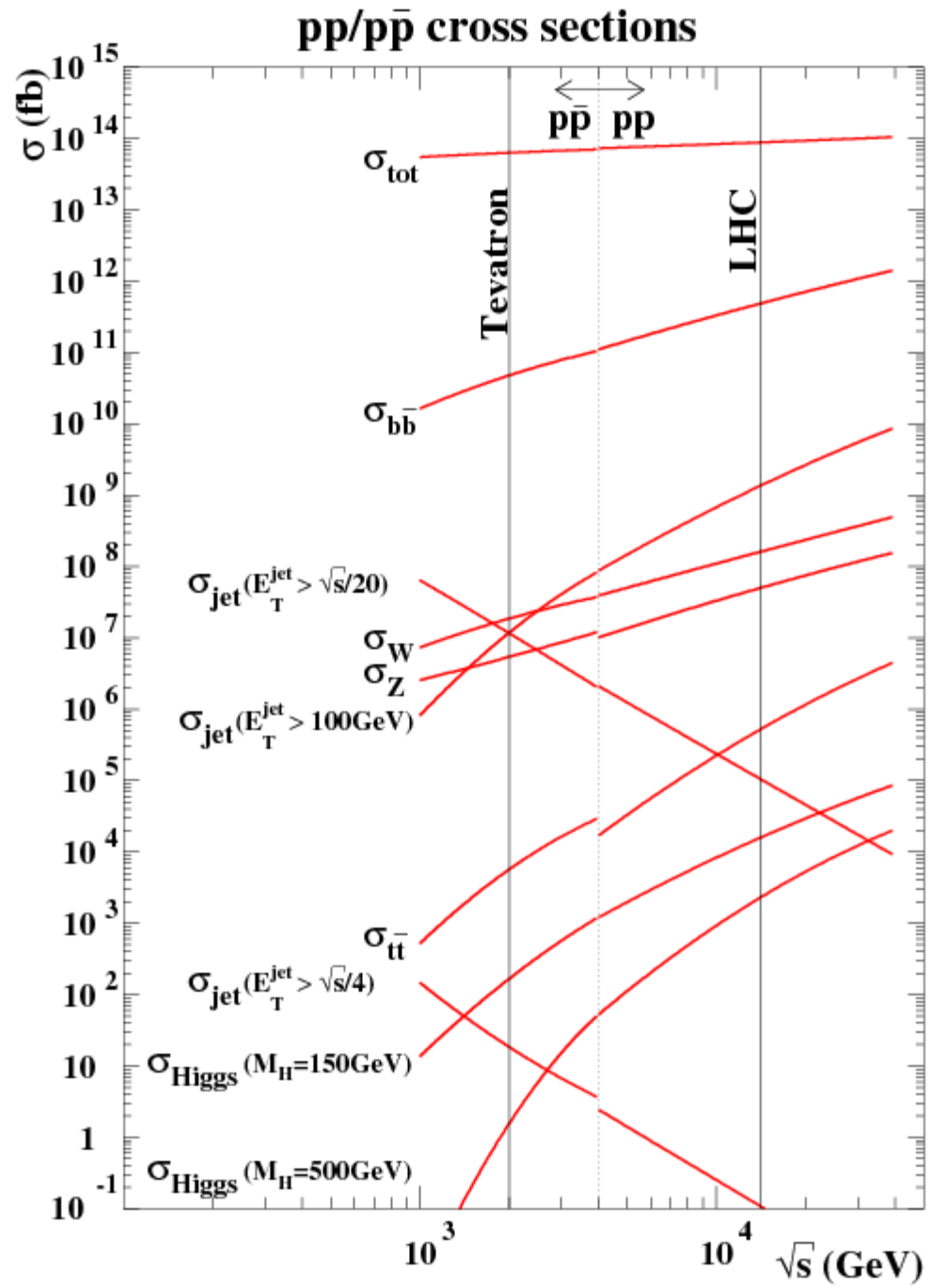
# FYST17 Lecture 6

## LHC Physics II

# Today & Monday

- The LHC accelerator
- Challenges
- The experiments (mainly CMS and ATLAS)
- Important variables
- Preparations
- Soft physics
- EWK physics
- Some recent results
- Focus on LHCb

# 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:

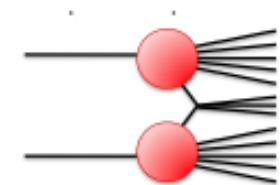
soft-QCD affecting the high  $p_T$  physics program at hadron colliders:

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

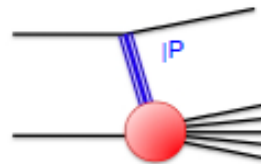
Multi Parton Interactions: An interesting parton-parton interaction will have many additional parton-parton interactions occurring in the same proton-proton interaction, they will almost always be soft-QCD processes

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

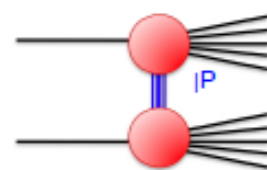
Dominant processes in inelastic hadron-hadron interactions :



Non-Diffractive  
(ND)  $\sigma \sim 49$  mb

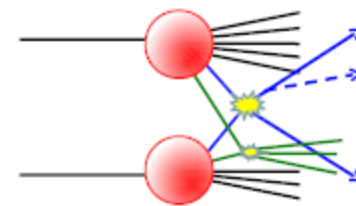


Single-Diffractive-Dissociation  
(SD)  $\sigma \sim 14$  mb



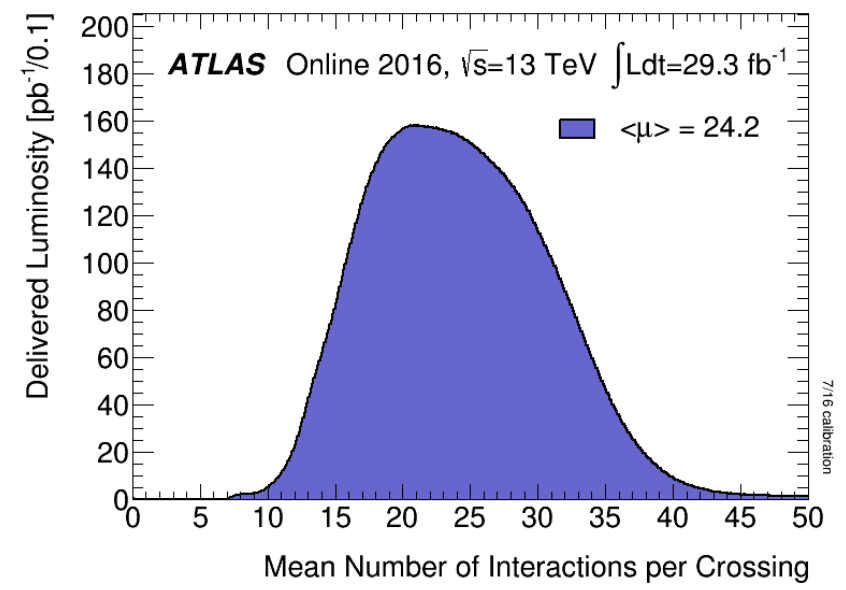
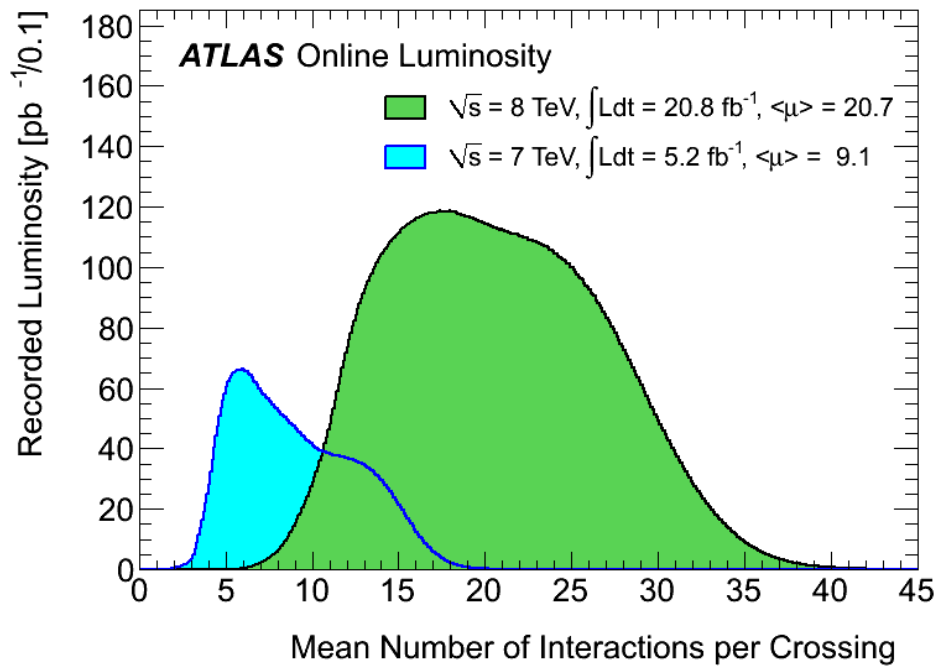
Double-Diffractive-Dissociation  
(DD)  $\sigma \sim 9$  mb

@ 7 TeV



Multiple parton interactions

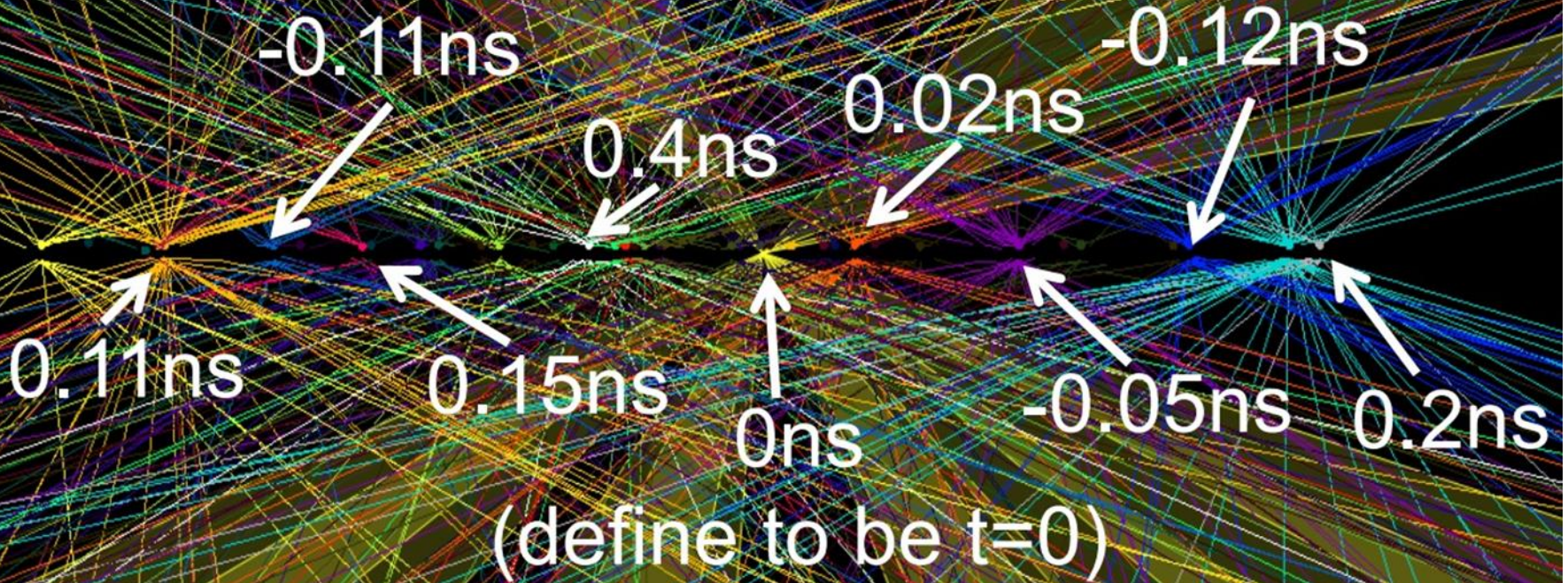
# Pile-up





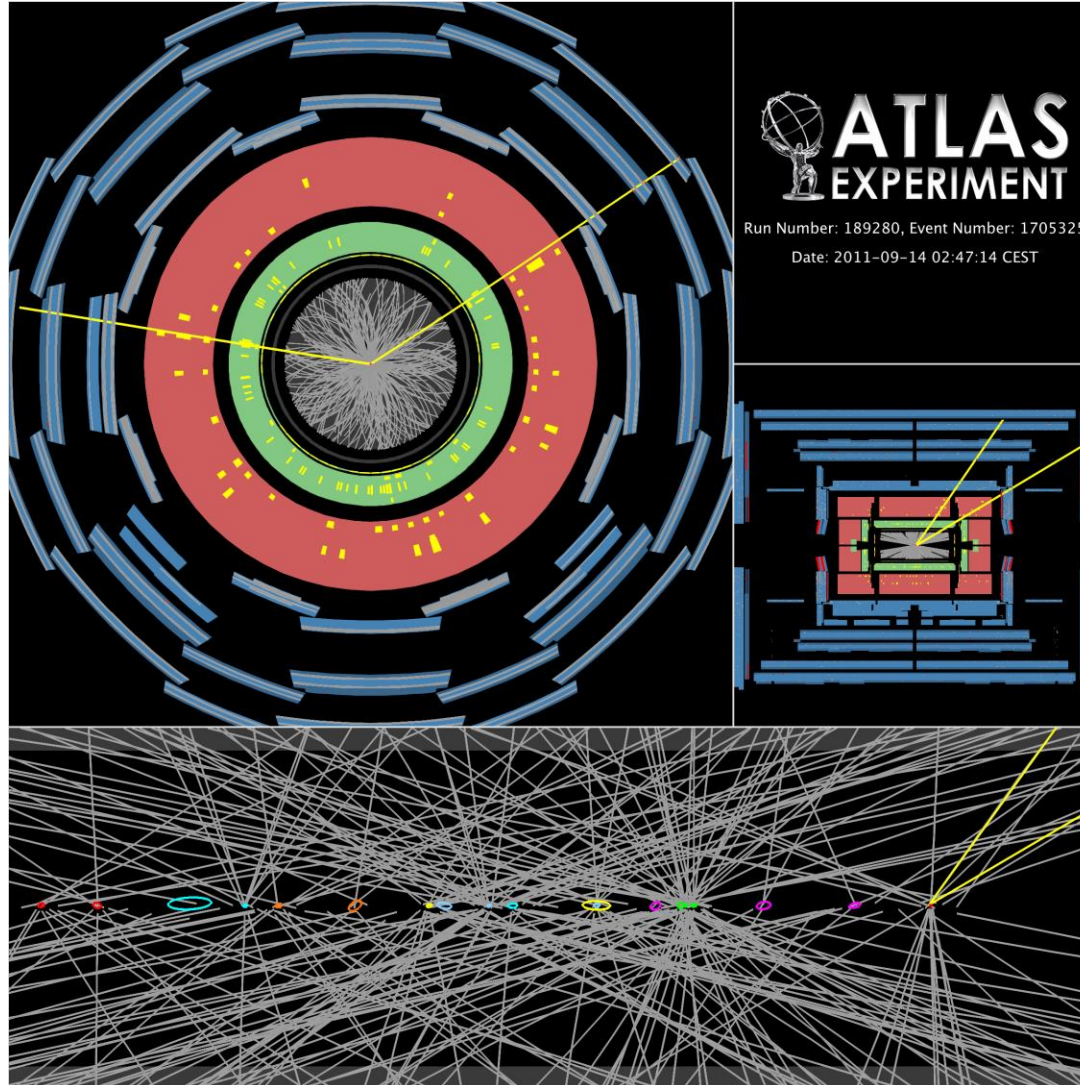
CMS Experiment at LHC, CERN  
Data recorded: Mon May 28 01:16:20 2012 CEST  
Run/Event: 195099 / 35438125  
Lumi Section: 65  
Orbit/Crossing: 16992111 / 2295

# LHC Bunch Crossing 1ns Clip



Raw  $\Sigma E_T \sim 2$  TeV  
14 jets with  $E_T > 40$   
Estimated PU  $\sim 50$

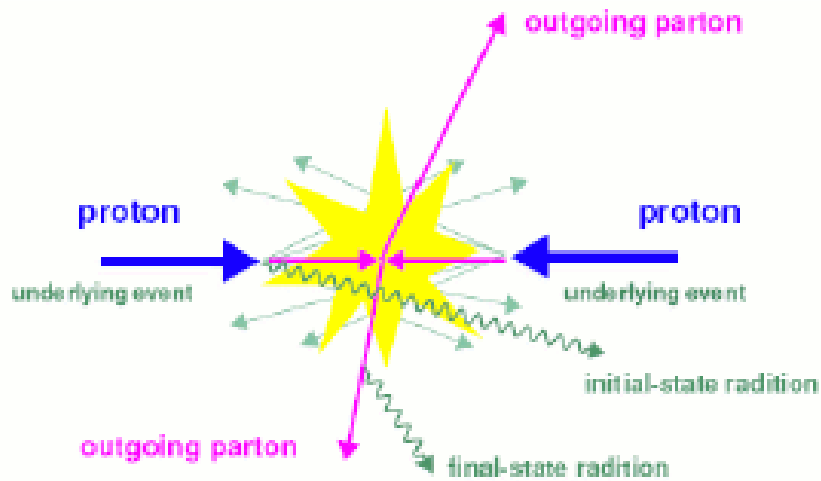
# $Z \rightarrow \mu\mu$ with 20 vertices





# 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

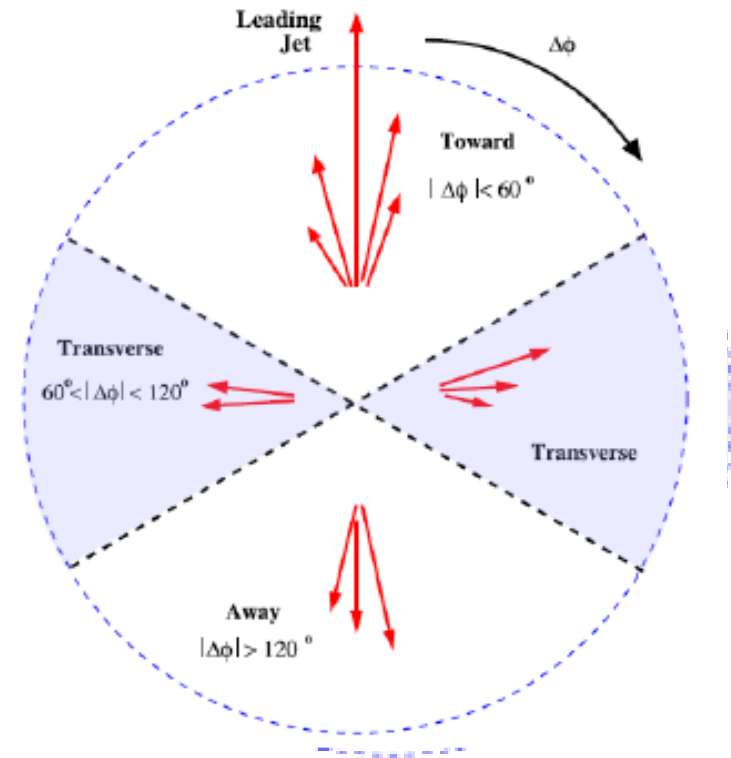
## Jet events ideal for studying underlying event

- ✓ Lots and lots of jet events at the LHC
- ✓ The “transverse” region wrt direction of the leading jet is very sensitive to the underlying event

### Underlying event observables:

Transverse  $\langle N_{\text{chg}} \rangle$

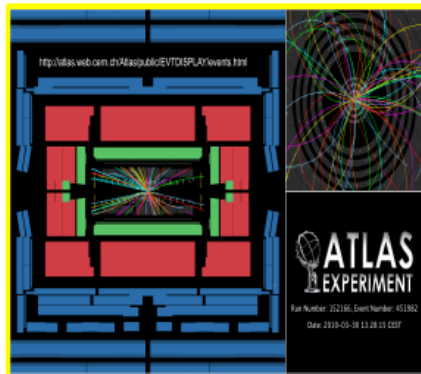
Transverse  $\langle \sum p_T \rangle$



# 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,  $p_T$  and  $\eta$  spectra, etc) of charged particles in “minimum bias” events using central tracking detectors
- Monte Carlo parameters will be tuned to these distributions

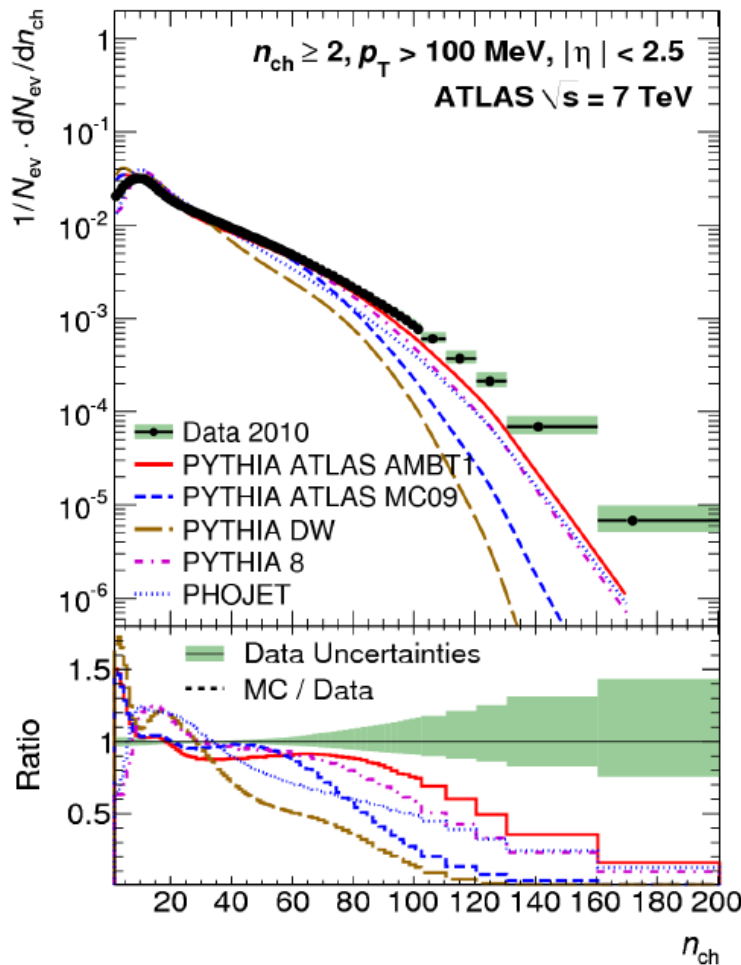


Charged particles moving through a magnetic field will bend by an amount inversely proportional to  $p_T$

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

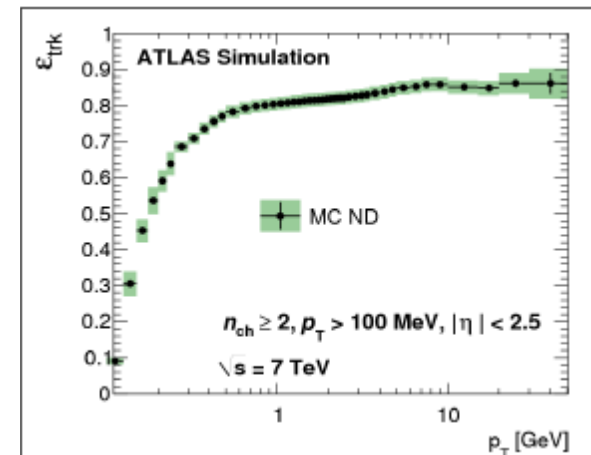
definition of minimum bias in each analysis

# Testing the soft QCD predictions



Examples of tuning of simulation (Monte Carlo, MC)  
 (This includes of course features like the rapidity gap etc)

Low  $p_{\text{T}}$  tracking: will particle make it through tracking volume?

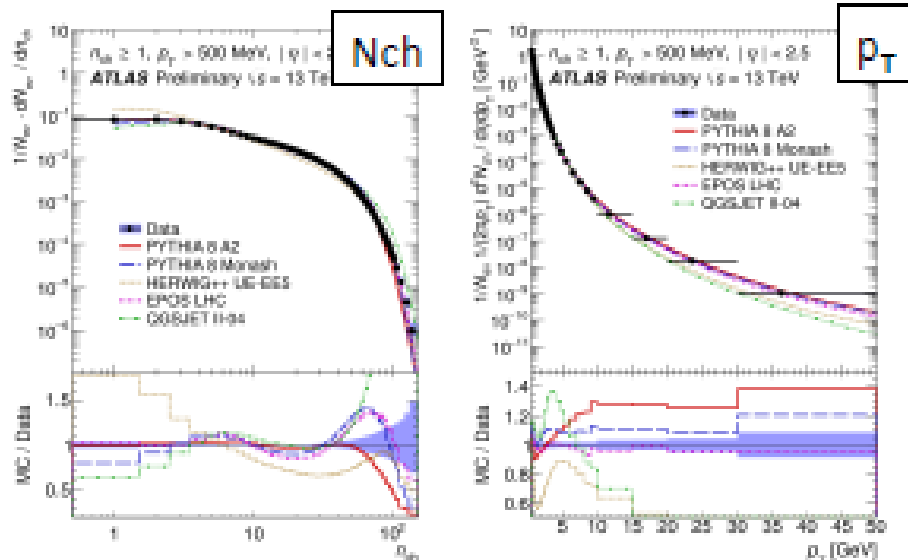


# High $p_T$ / EWK physics

# Physics Modelling

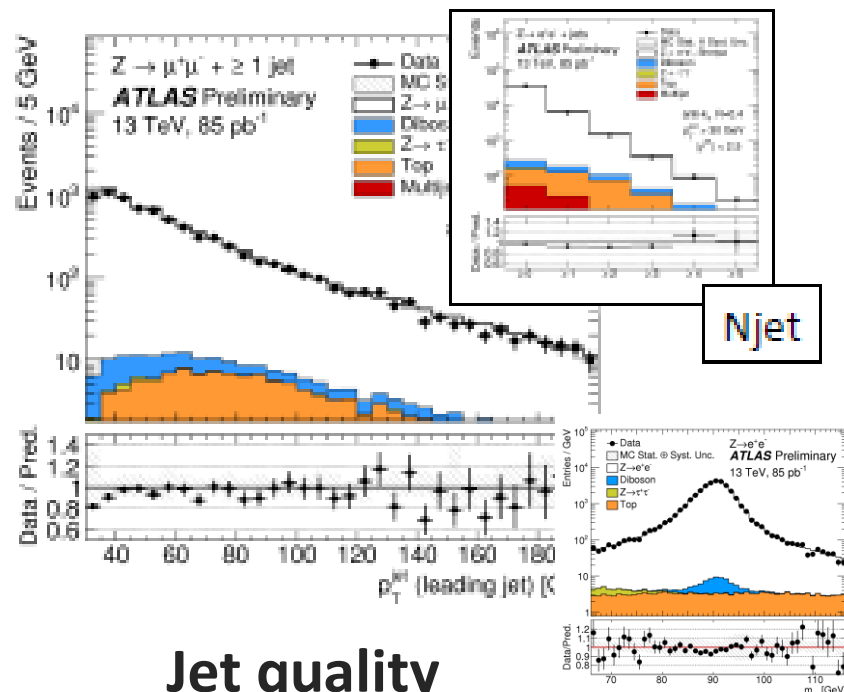
A2 Minbias tune (for PU)

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



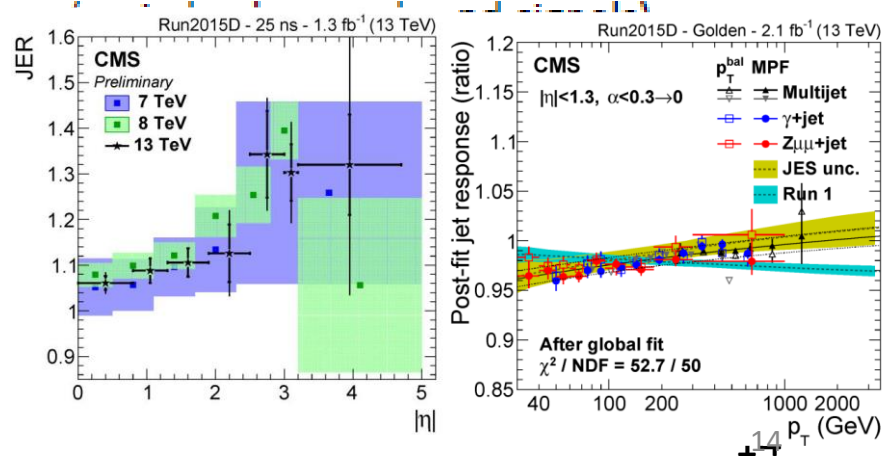
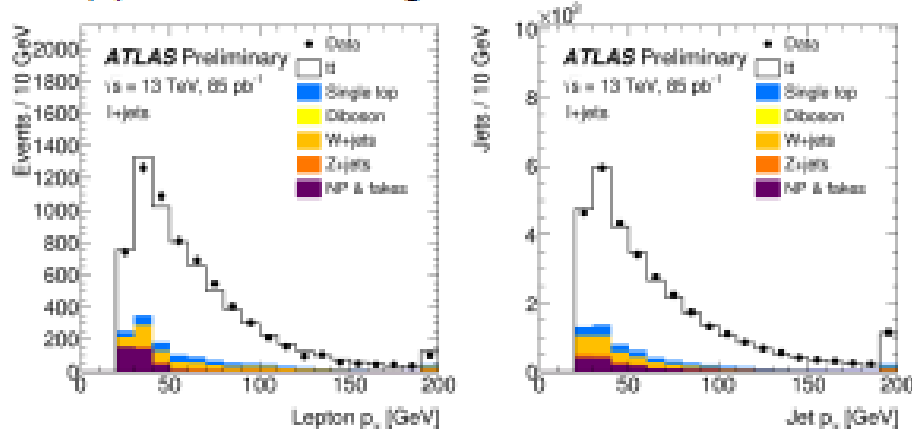
# V+Jets, Dibosons, Tribosons

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

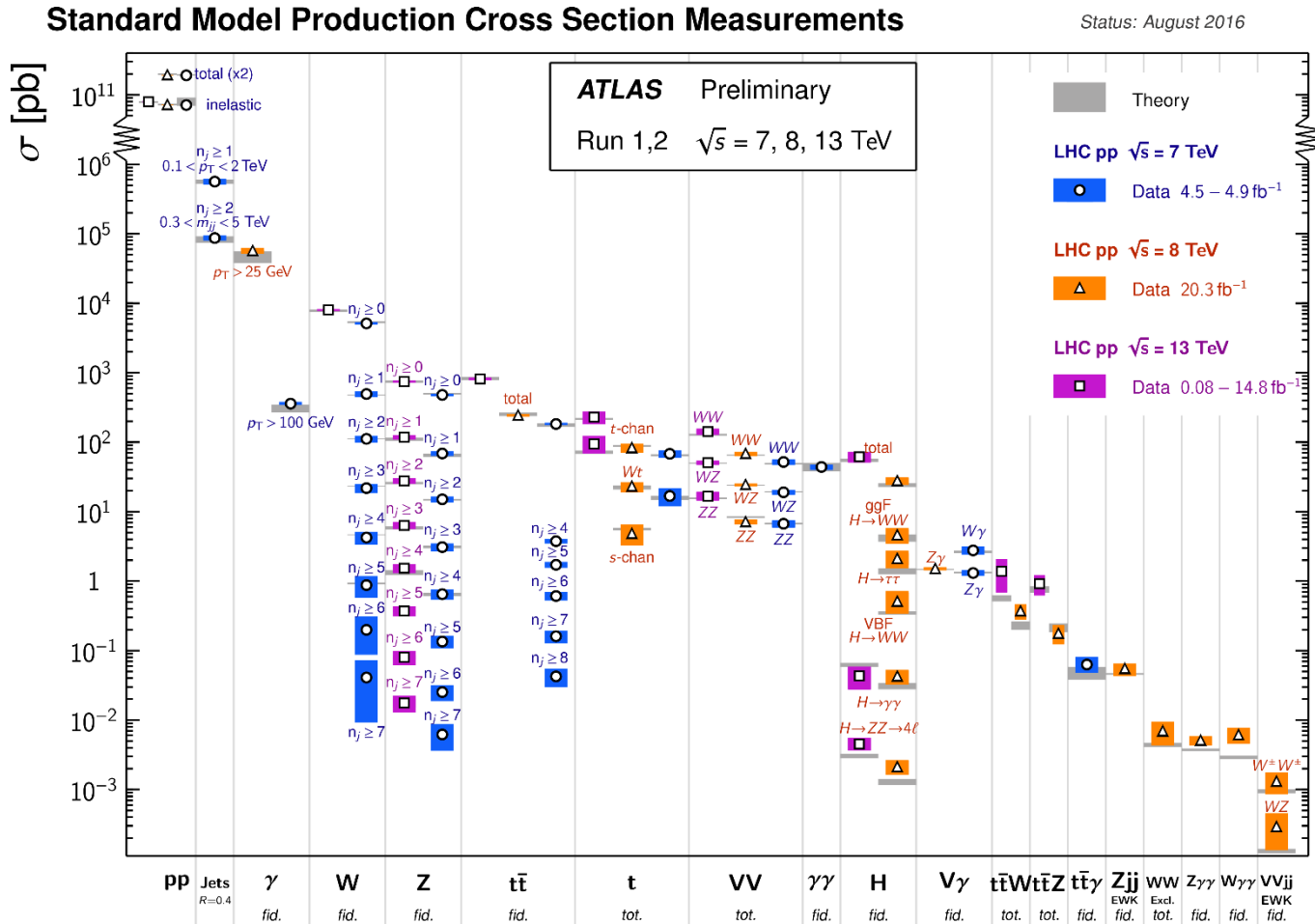


# Top pair production

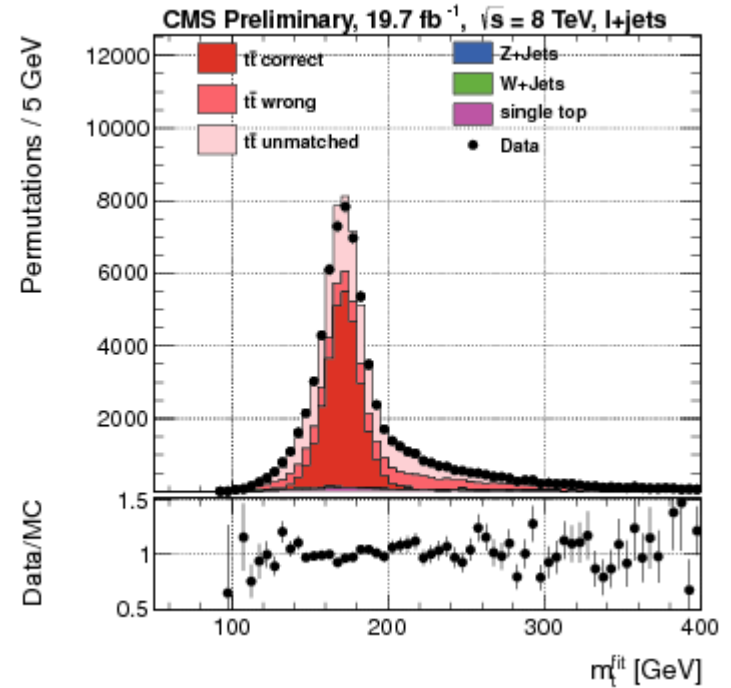
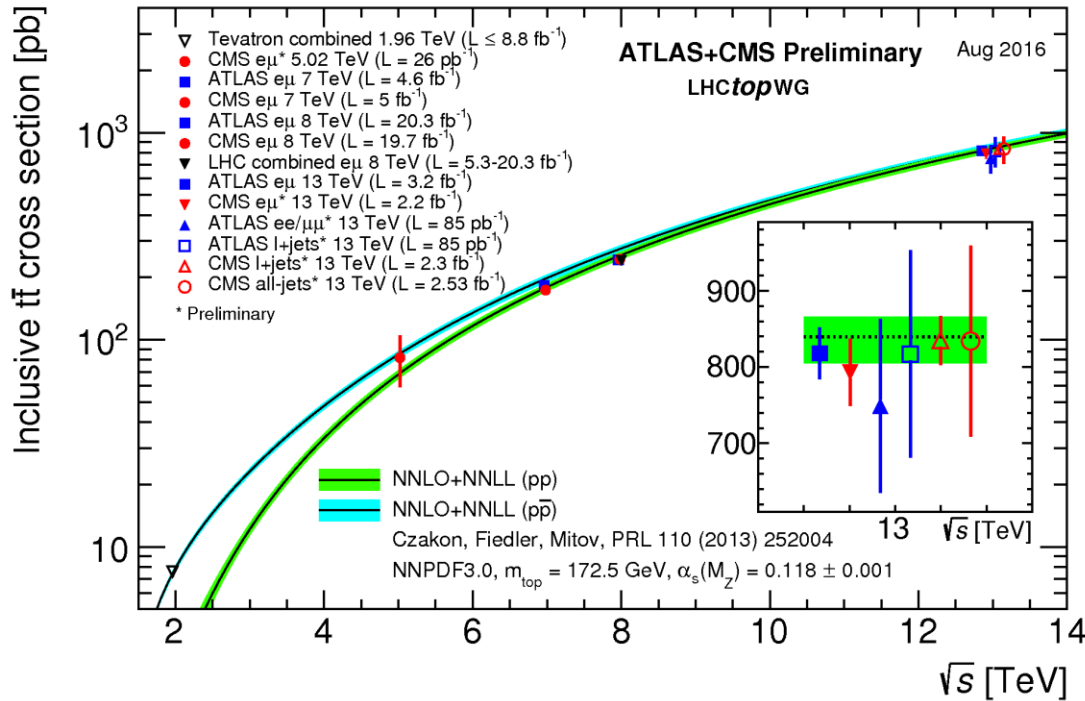
Powheg-Box v2 (hdamp =  $m_t$ ) – Pythia 6.428 – EvtGen (HF decays) - CT10 PDFs – Perugia 2012 tune



# Standard Model measurements



# Close-in on the top quark

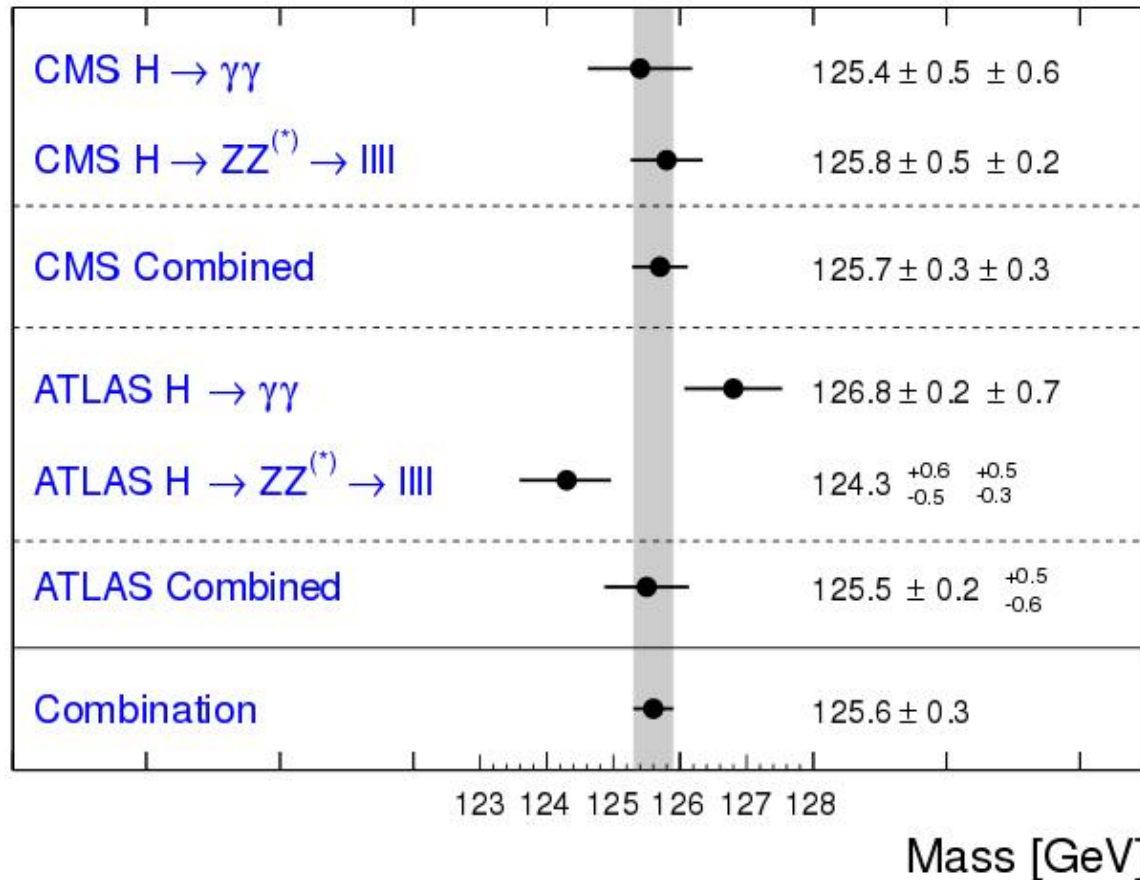


$$M_{\text{top}} = 173.34 \pm 0.36 \pm 0.67 \text{ GeV}$$



# Higgs measurements

PDG



# Identification of jets and leptons

# Jet algorithms



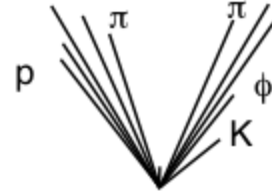
LO partons



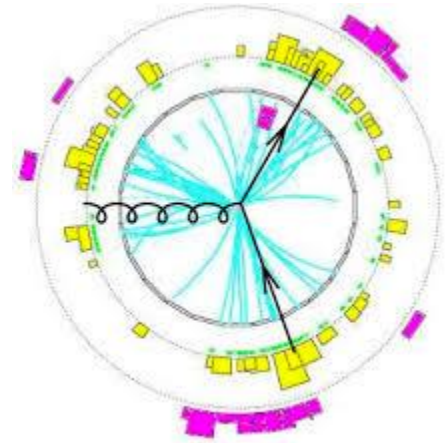
NLO partons



parton shower



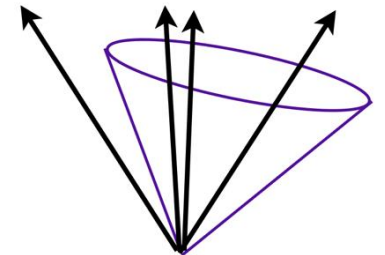
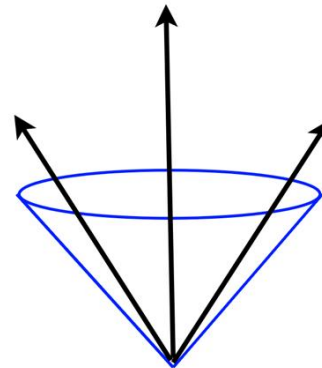
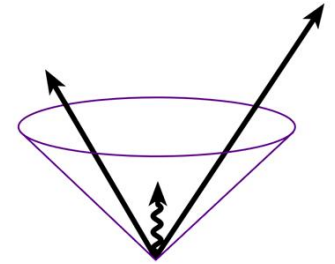
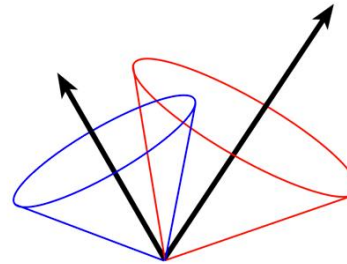
hadron level



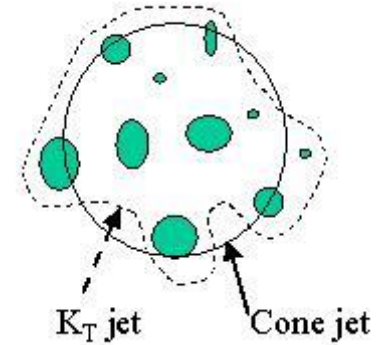
How to define a "jet"? A few different approaches:

Cone algorithm: 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:

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

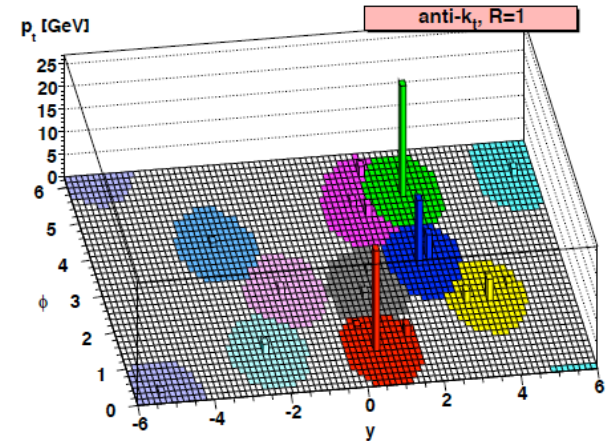
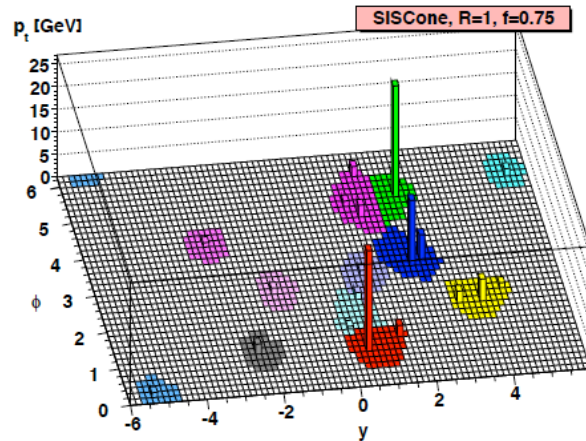
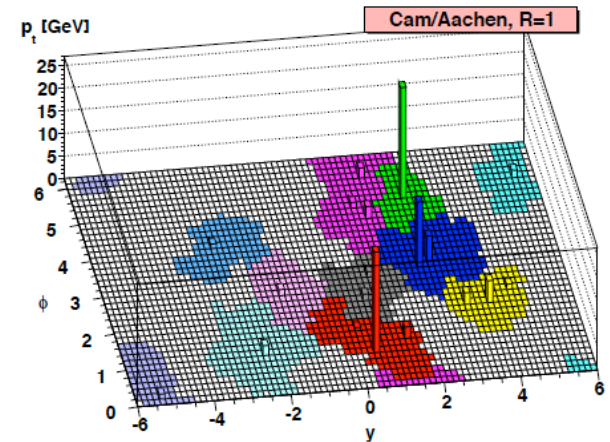
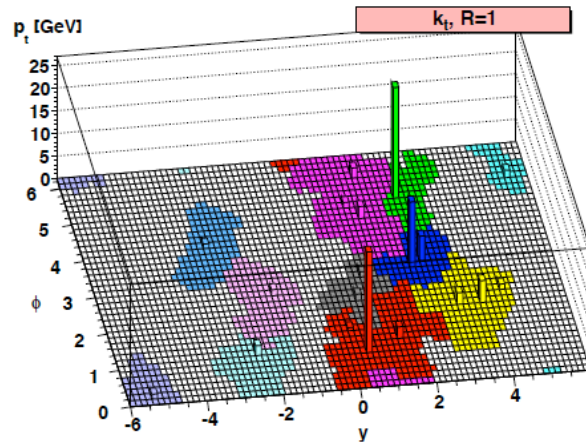
- Find minimum. If  $d_{ij}$ , combine  $i$  and  $j$  into a jet, then loop over all particles again. If  $d_{iB}$ , call it a jet, and remove particle  $i$  from list

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

# Comparison

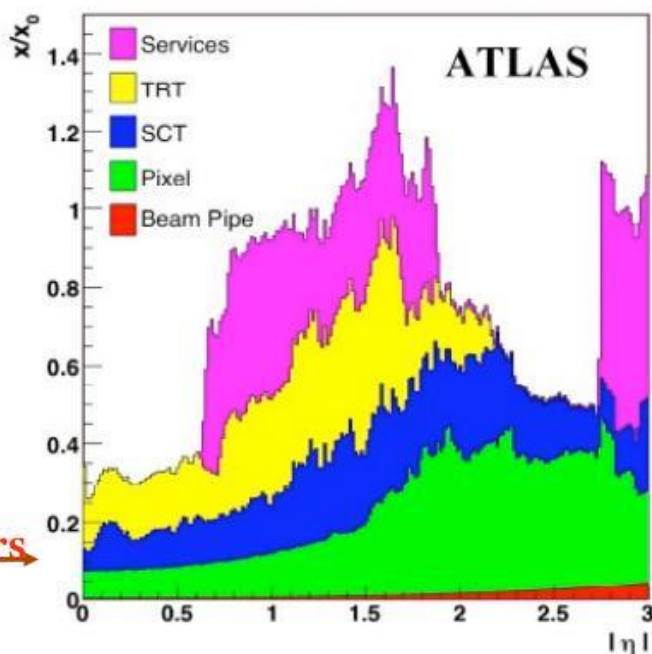
Anti-kt mostly used at the LHC

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

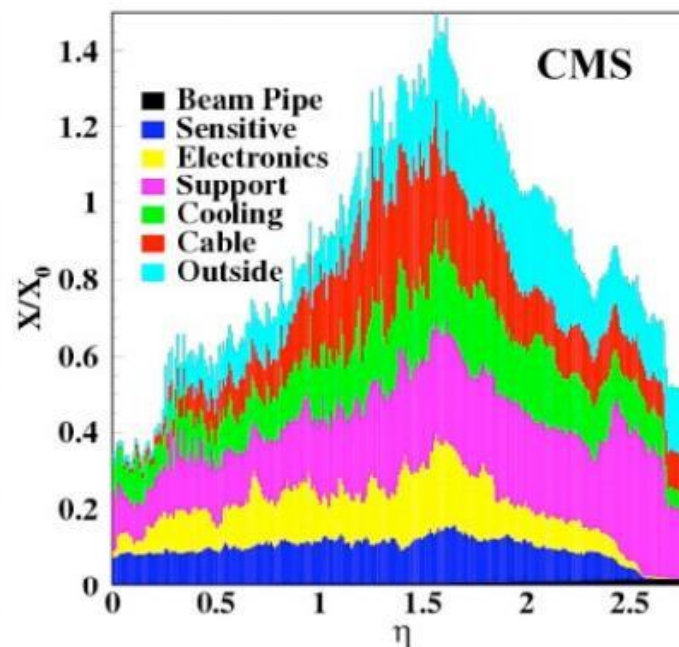


## Amount of material in ATLAS and CMS inner trackers

Weight: 4.5 tons



Weight: 3.7 tons

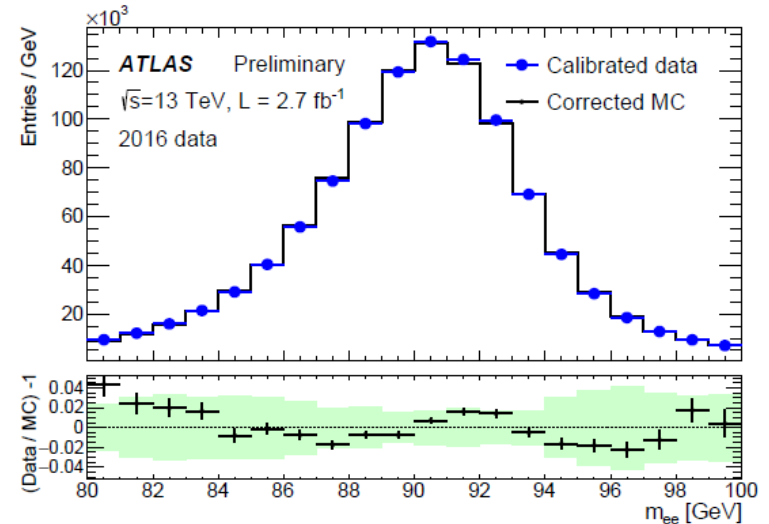
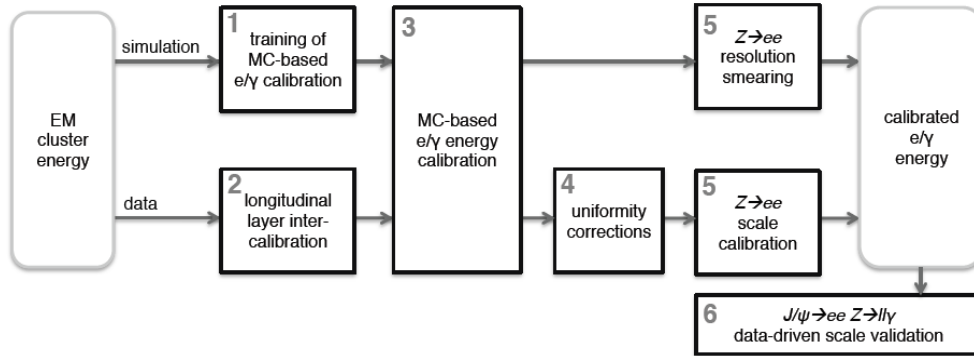


LEP  
detectors

- Active sensors and mechanics account each only for  $\sim 10\%$  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

# Example: electrons in ATLAS

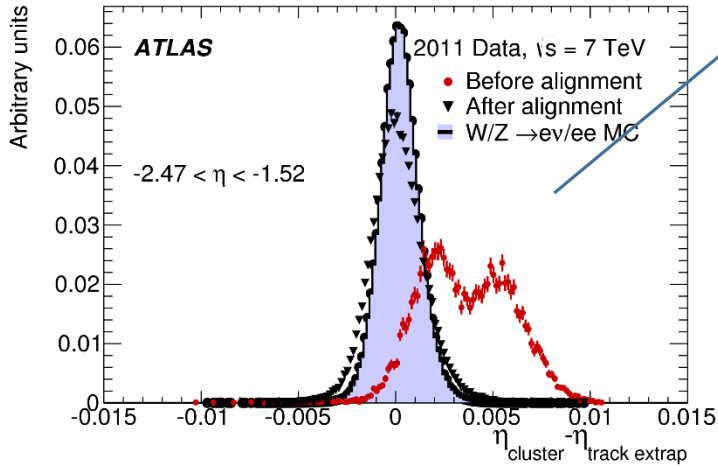
## Calibration of EM calo reponse



What is an electron? A matter of definition.  
In my current analysis we decided for:

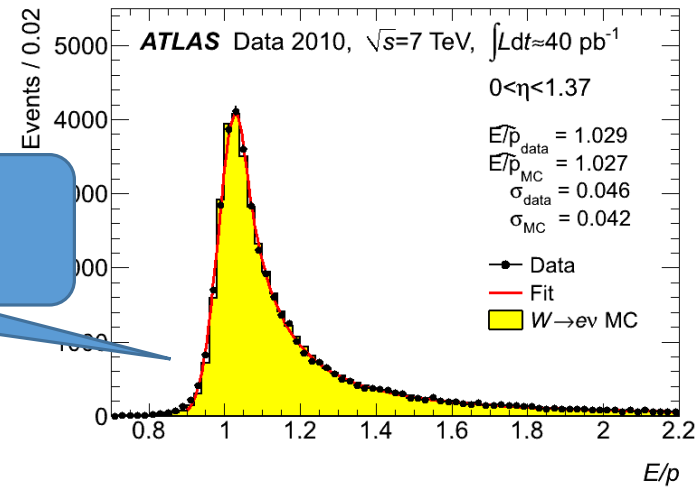
Requirement	Signal electrons (tight)	Loose electrons
Identification	LHMedium	LHLoose
Isolation	loose	—
$p_T$ cut	$p_T > 30$ GeV	$p_T > 30$ GeV
$\eta$ cut	$ \eta  < 2.47$ and veto $1.37 <  \eta  < 1.52$	$ \eta  < 2.47$ and veto $1.37 <  \eta  < 1.52$
$ d_0 /\sigma_{d_0}$ cut	$ d_0 /\sigma_{d_0} < 5.0$	$ d_0 /\sigma_{d_0} < 5.0$
$ z_0 \sin \theta $ cut	$ z_0 \sin \theta  < 0.5$	$ z_0 \sin \theta  < 0.5$
Object Quality	yes	yes

# Several variables to play with, for instance

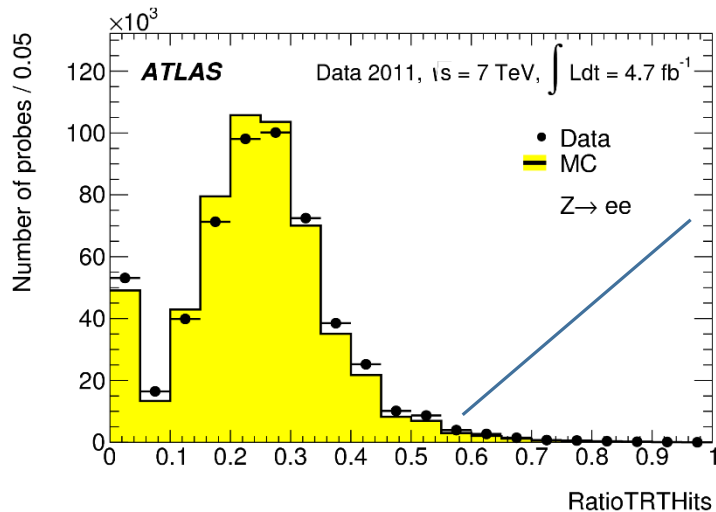


How well are the track and the EM cluster matched?

Is the E/p ratio close to 1?

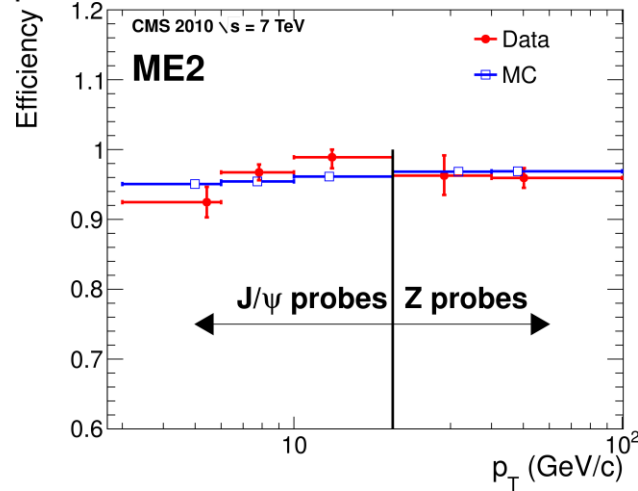
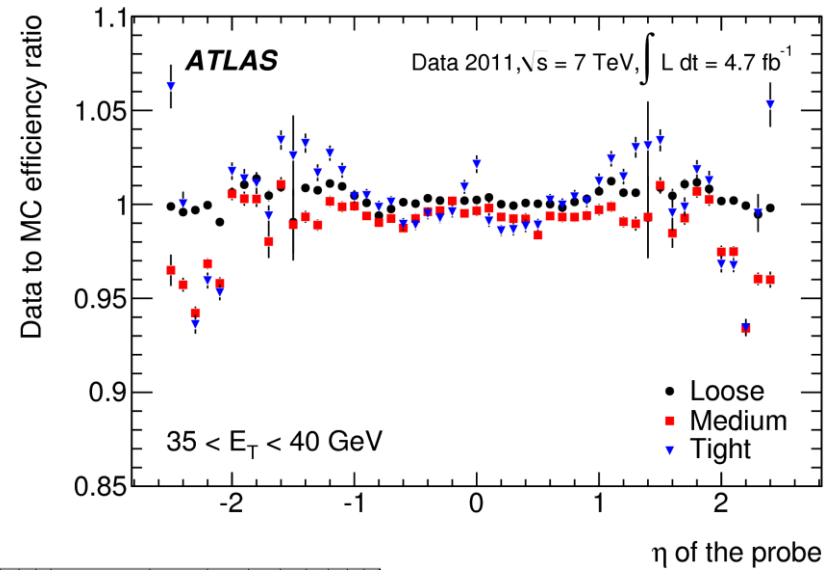
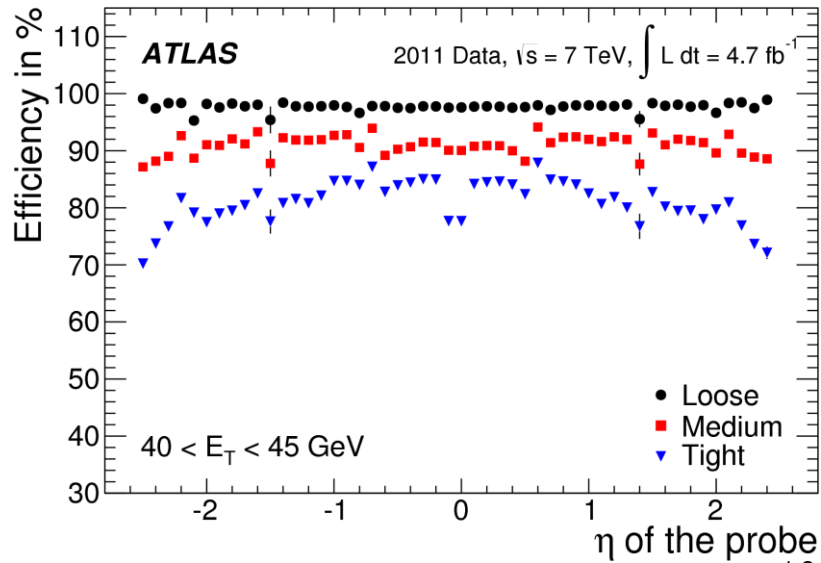


Are the number of transition radiation hits high enough?



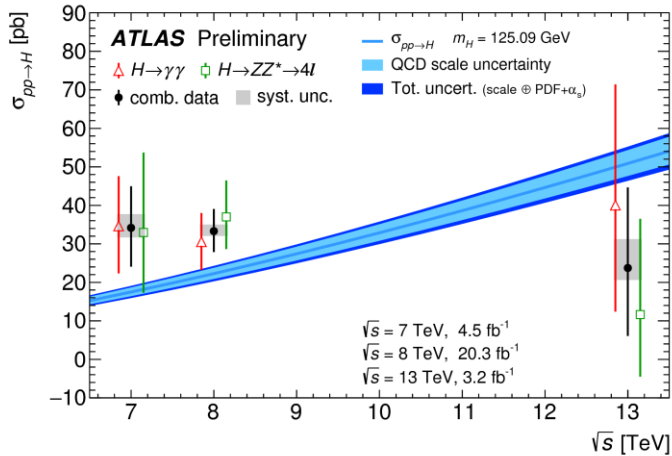


# Leptons identification efficiencies

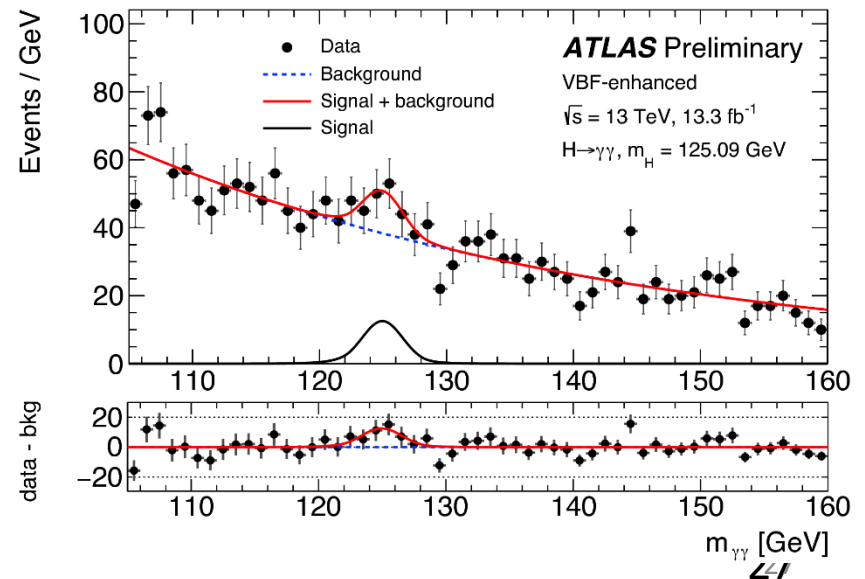
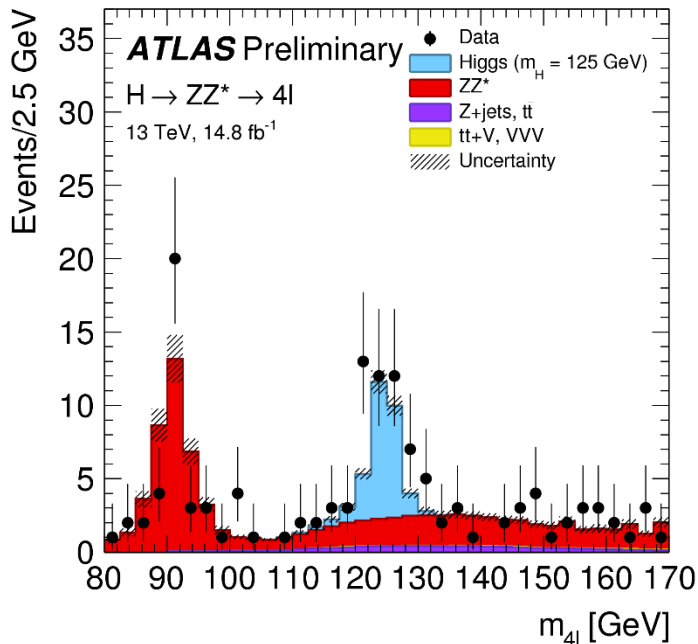
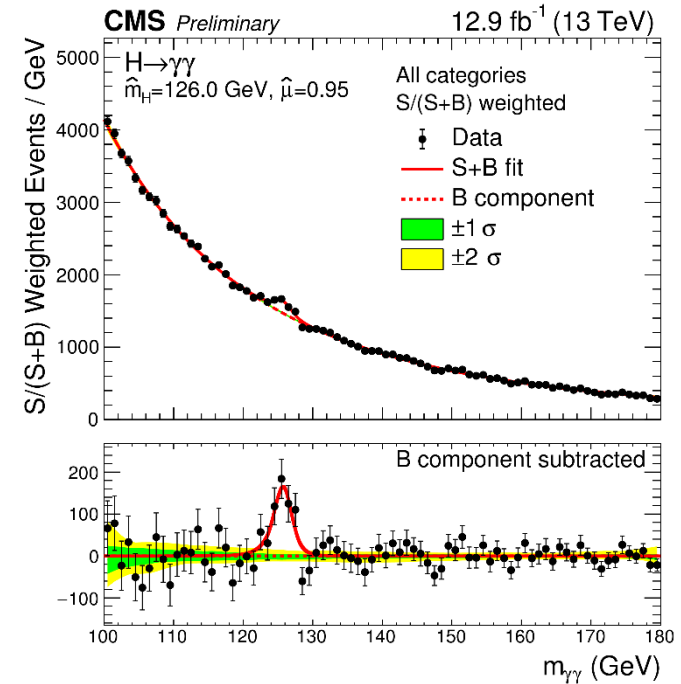


# Latest on the Standard Model: a few 13 TeV results

# The Higgs @ 13 TeV



Consistent picture with the higher energy

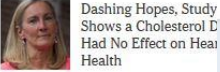


# A New Particle?

NyTeknik

DIGITALISERING ENERGI FORDON NYSTARTAT TEKNIKREVYN LEDIGA JOBB A-Ö

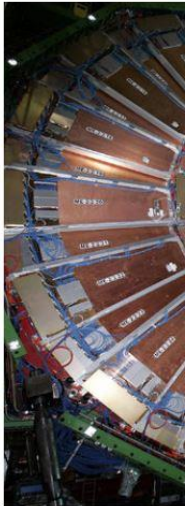
SECTIONS



SCIENCE

## Physicists in Mysterious l

By DENNIS OVERBYE DEC. 15, 2



Researchers at the Large Had and forces. Fabrice Coffrini/Ager

INNOVATION

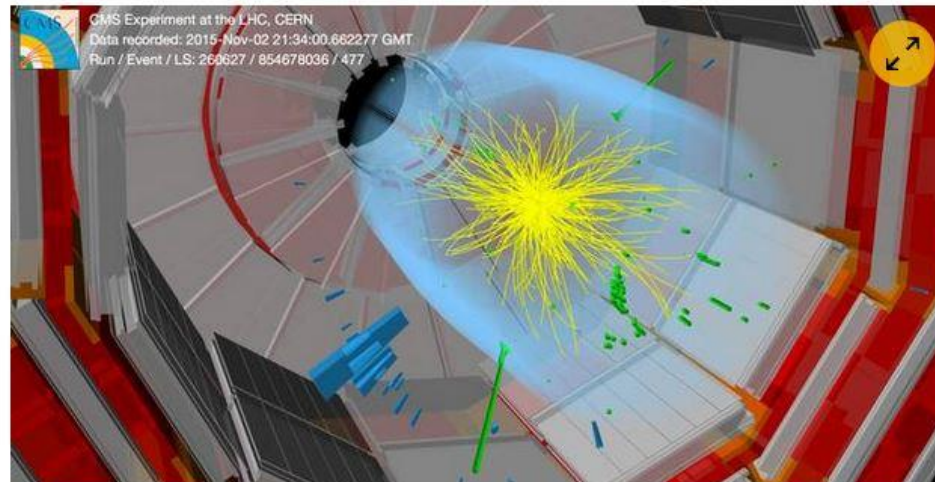
Cern

## Cern: Tecken på ny okänd partikel

2016-03-30 12:49

Av: Ulla Karlsson-Ottosson

6 KOMMENTARER



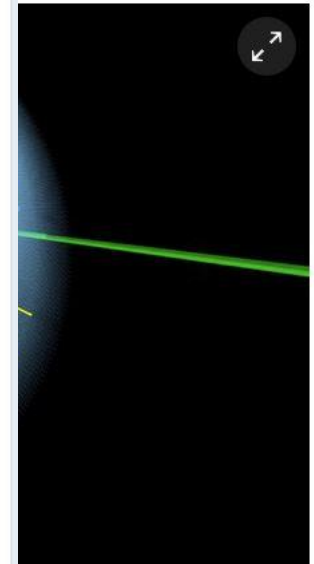
Har forskare vid Cern hittat spår efter en ny helt okänd partikel? Mätdata från körningar under 2015 antyder att det kan vara så. Uppsalaforskare lanserar teorin om en naturkonstant som förändrats.

guardian

culture business lifest all

## ron Collider

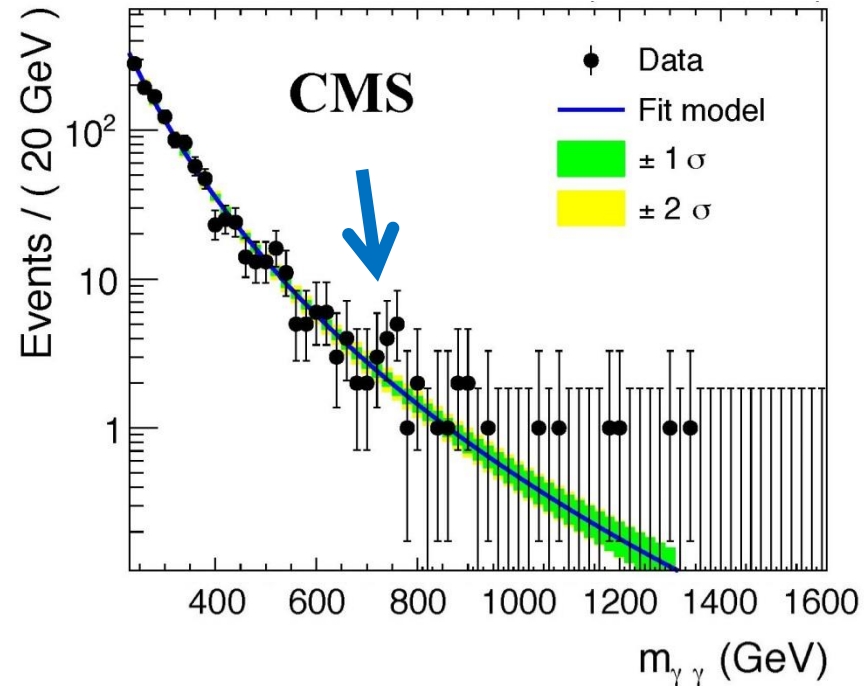
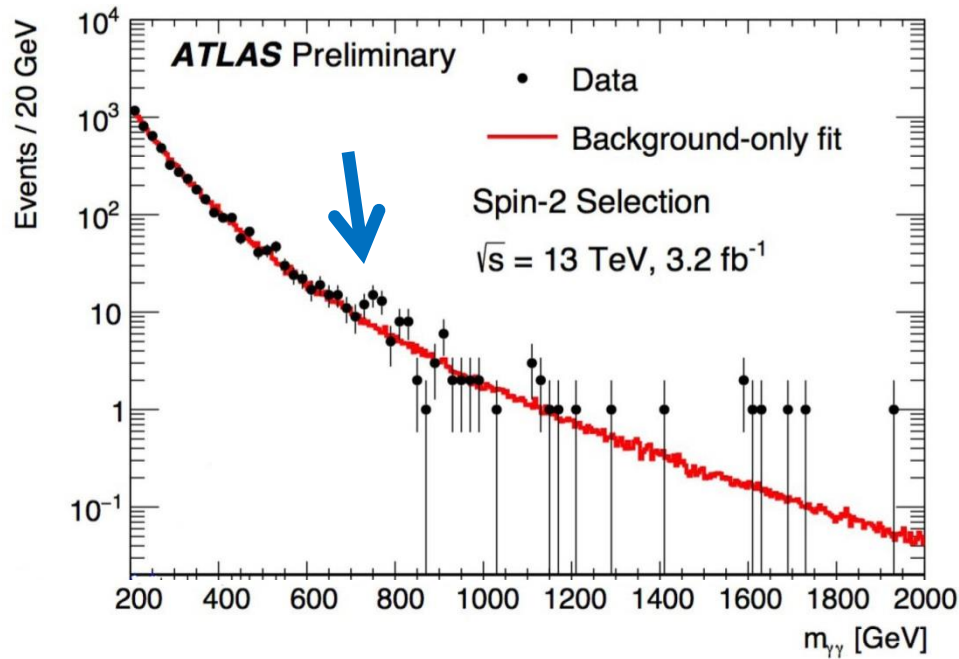
shes of light spotted inside



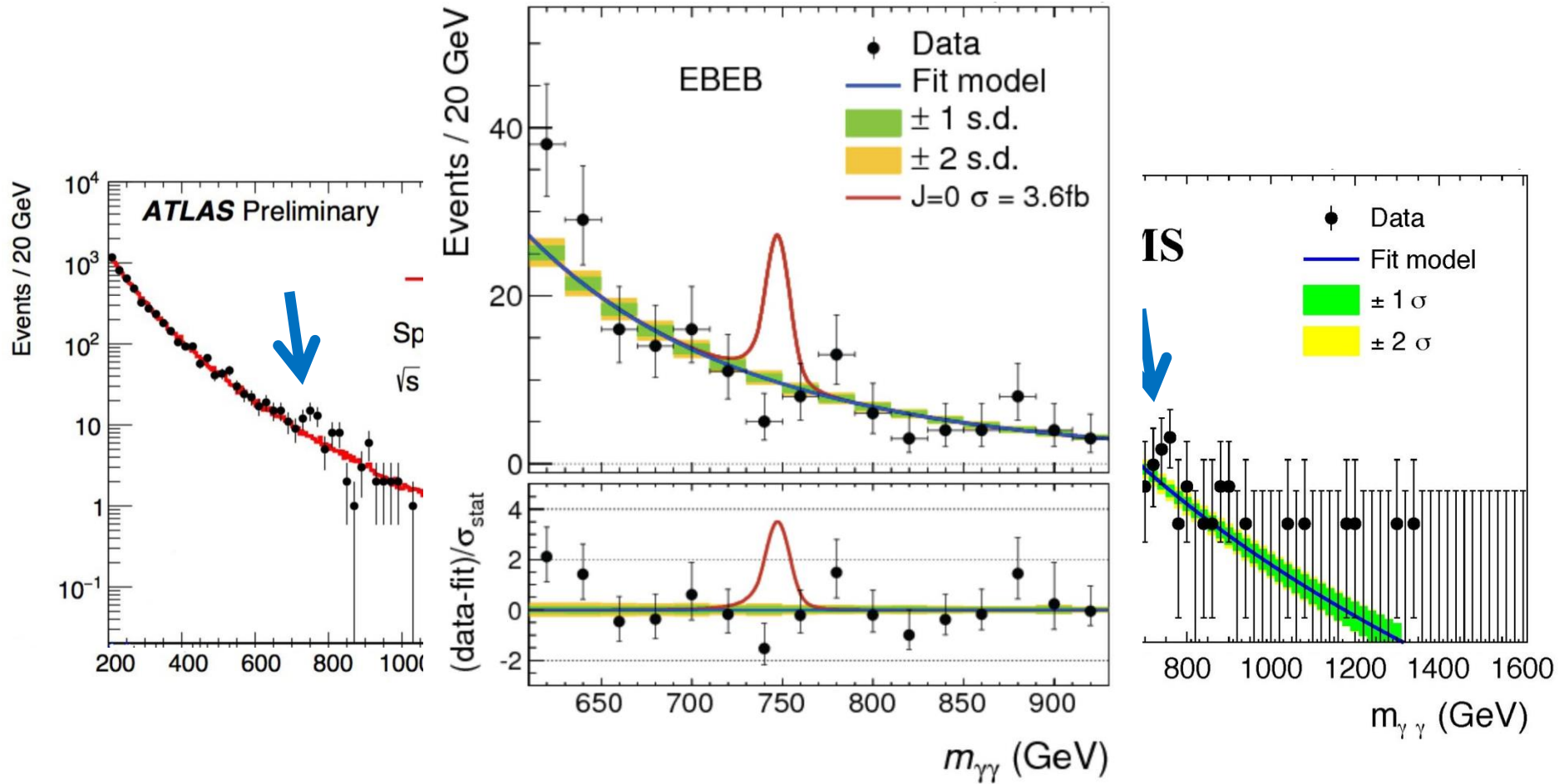
and destruction of a new

# A New Particle?!

Both ATLAS and CMS sees a little peak in the diphoton invariant mass spectrum in the same spot when investigating the first 13 TeV collisions in 2015!

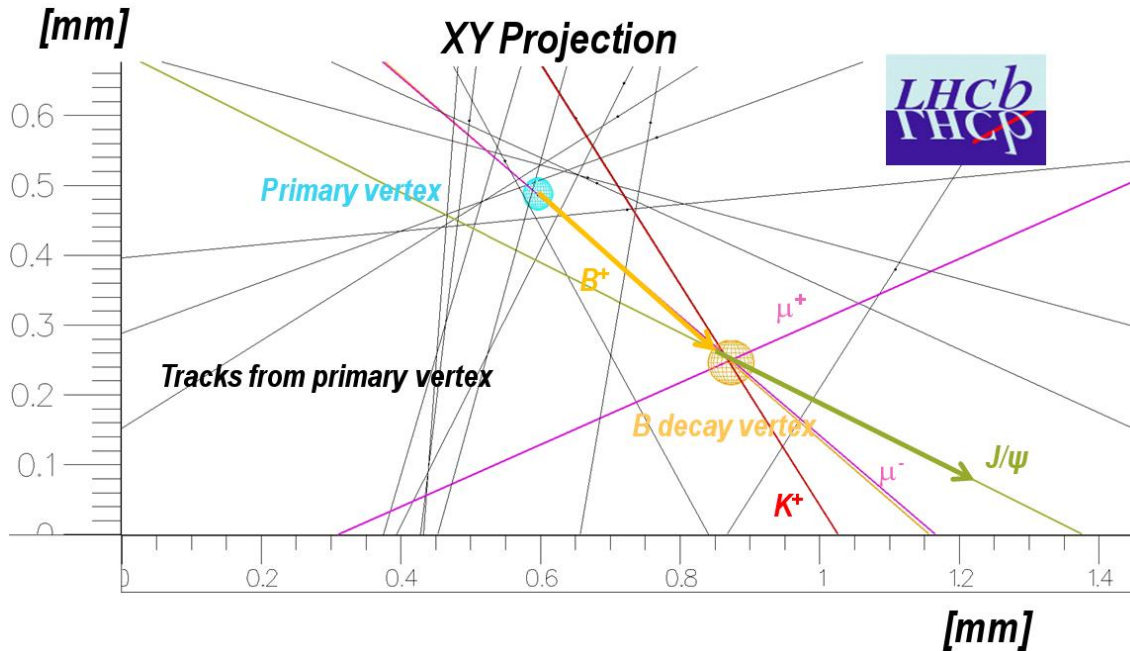


# A New Particle?!



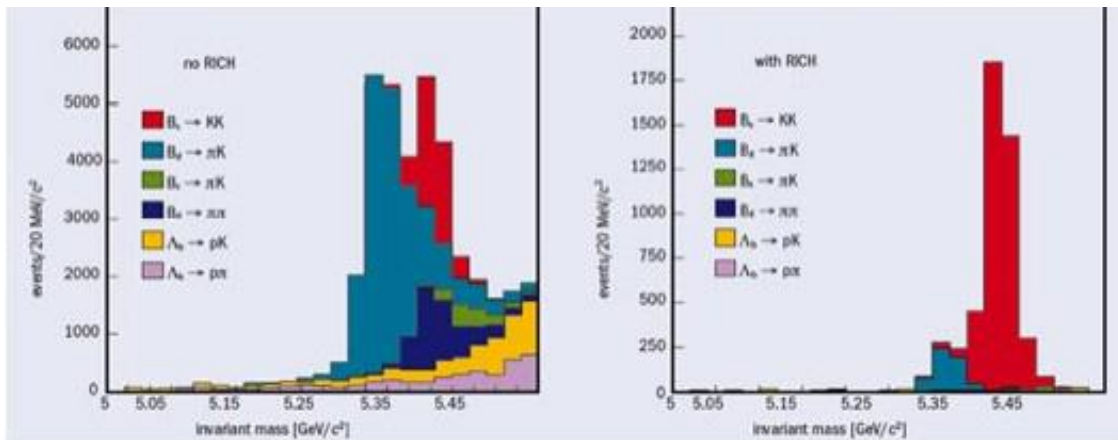
Unfortunately it disappeared when the experiments added more data in 2016

# More on LHCb



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

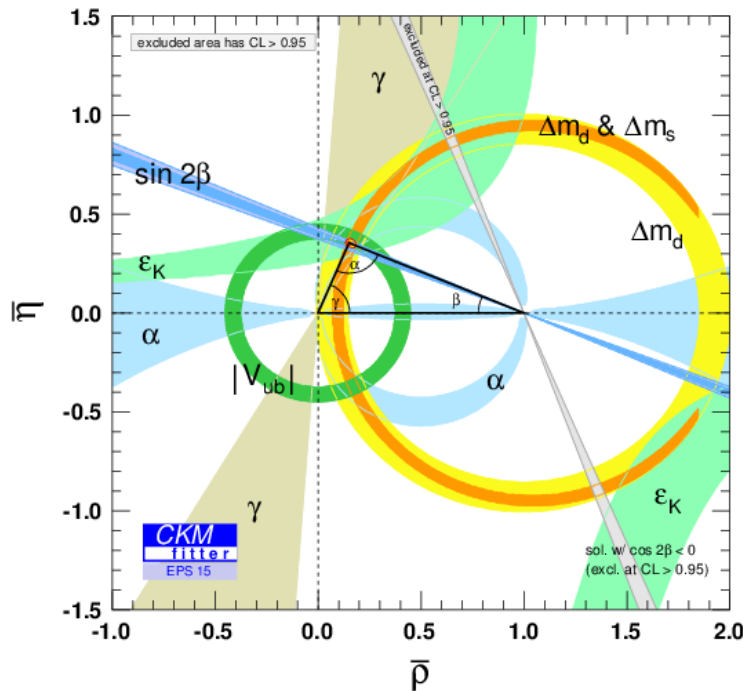
Physics programme mainly devoted to searches for rare decays + precision measurements to check loop effects and CP violation



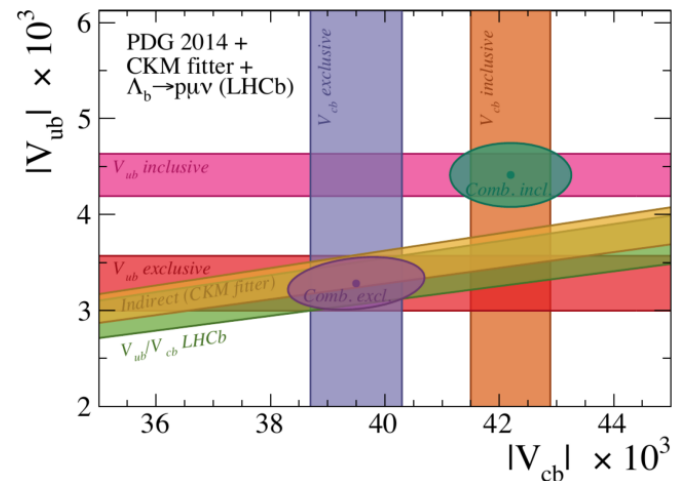
Despite being the "little brother", a lot of interesting results (here interesting = tension with SM) have come from just LHCb

You'll remember the pentaquarks...

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

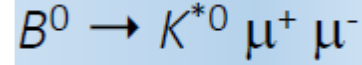


$$|V_{ub}|/|V_{cb}| \text{ from } \Lambda_b^0 \rightarrow p\mu\nu_\mu$$



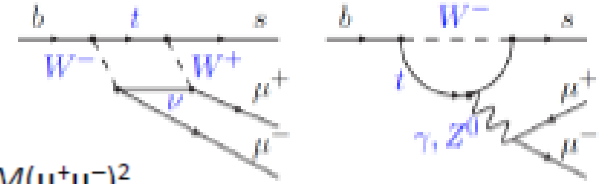


# More on LHCb results

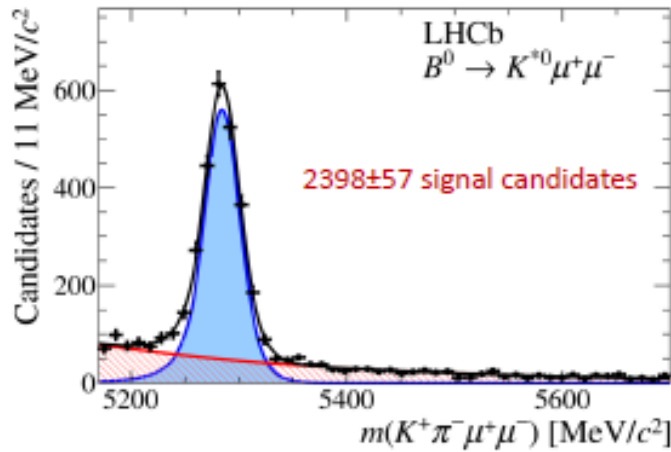


New results on rare decays:

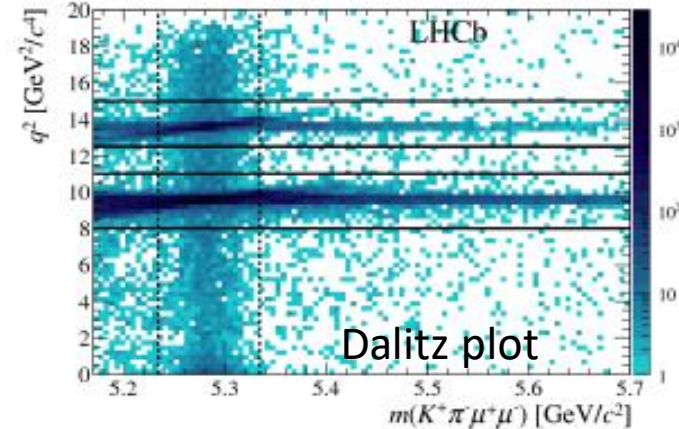
- Only allowed through loops in the SM



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

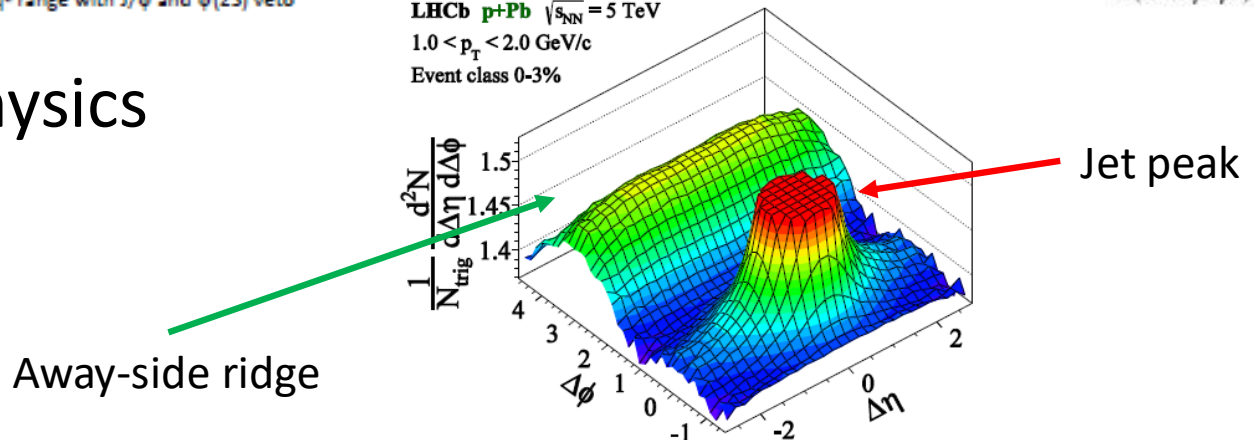


Full  $q^2$  range with  $J/\psi$  and  $\psi(2S)$  veto

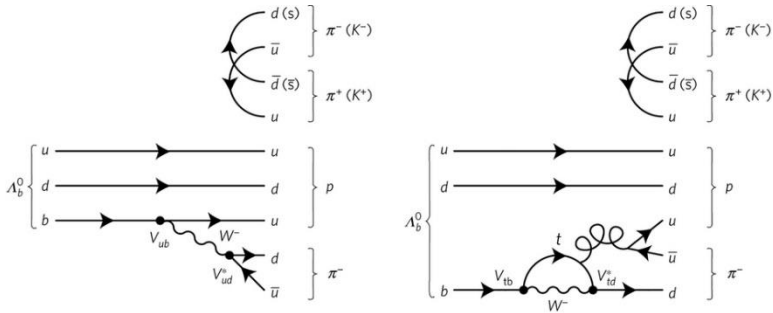


Heavy ion physics

LHCb p+Pb  $\sqrt{s_{NN}} = 5$  TeV  
 $1.0 < p_T < 2.0$  GeV/c  
 Event class 0-3%



# New LHCb result from Monday



**First evidence of CP violation in baryons!!**

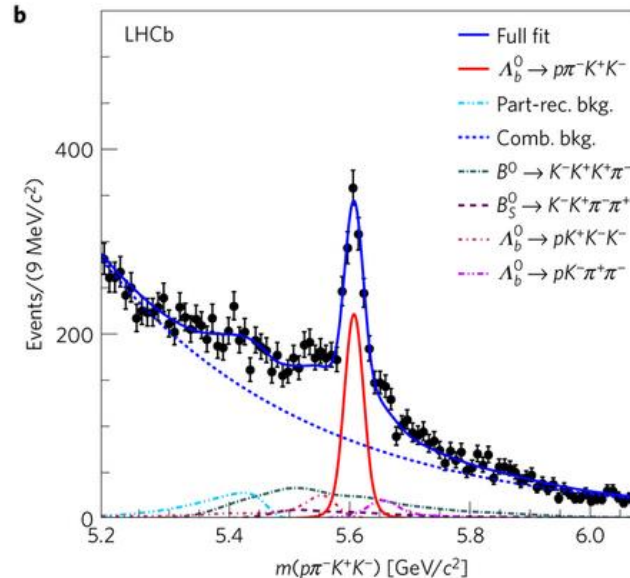
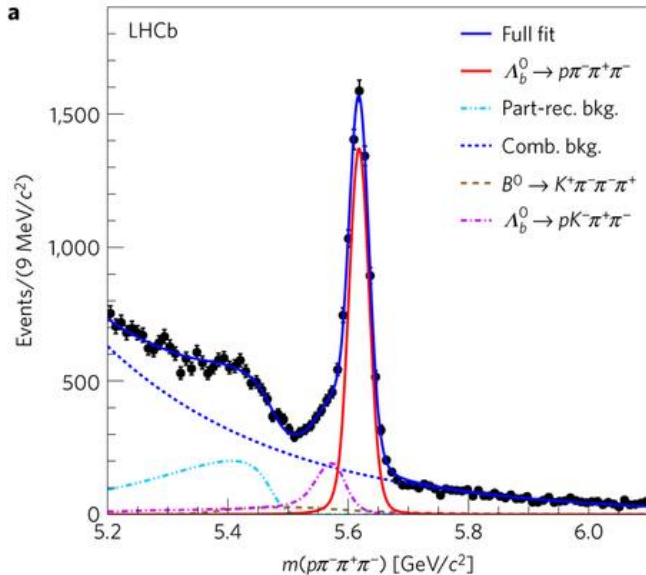
Looking at two rare decays:

a)  $\Lambda_b^0 \rightarrow p \pi^- \pi^+ \pi^-$

b)  $\Lambda_b^0 \rightarrow p \pi^- K^+ K^-$

Diagrams similar magnitude (weak)

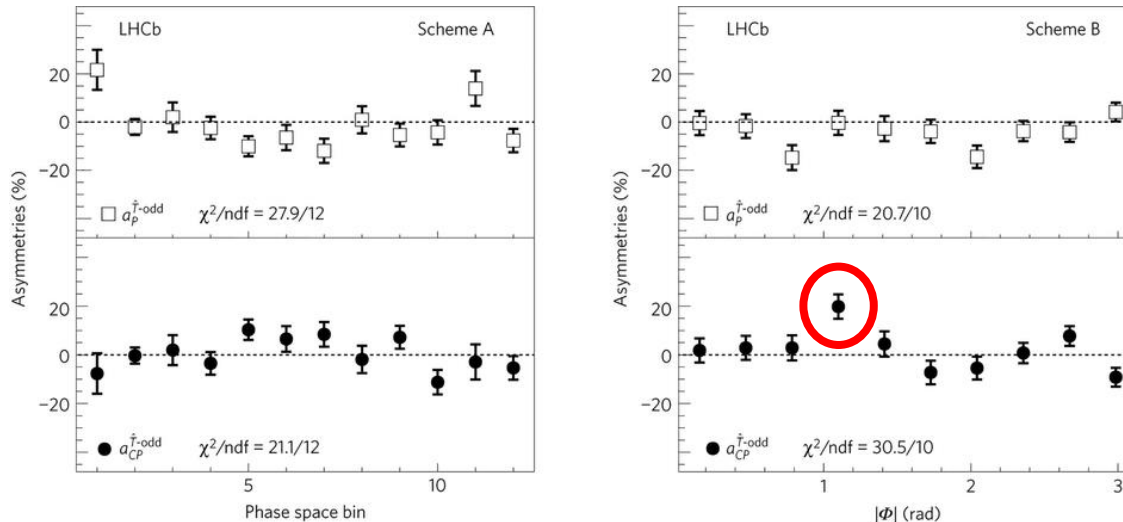
CP violation would be parametrized in CKM angle  $\alpha$



Reconstructed  $\Lambda_b$  masses

# Evidence of new CP violation

Not enough statistics for fine-grained analysis in  $\Lambda \rightarrow KK$  case but for three pion final state, with two different binning schemes:



Asymmetry  $19.79 \pm 4.95 \pm 0.60$

Beware: total effect is only  $3.3 \sigma$  ... but tantalizing and much needed

# Summary

- The LHC is a fantastic multi-purpose machine
- It was far from trivial to design and commission
  - Problems and solutions from previous accelerator facilities 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 from Peter
- The Standard Model , including the top quark and 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