# FYST17 Lecture 6
# LHC Physics II



Fixed target geometry — "Magnet spectrometer" — LHCb; Collider geometry — "4π multi purpose detector" — ATLAS CMS, ALICE (both geometries). from M. Hauschild
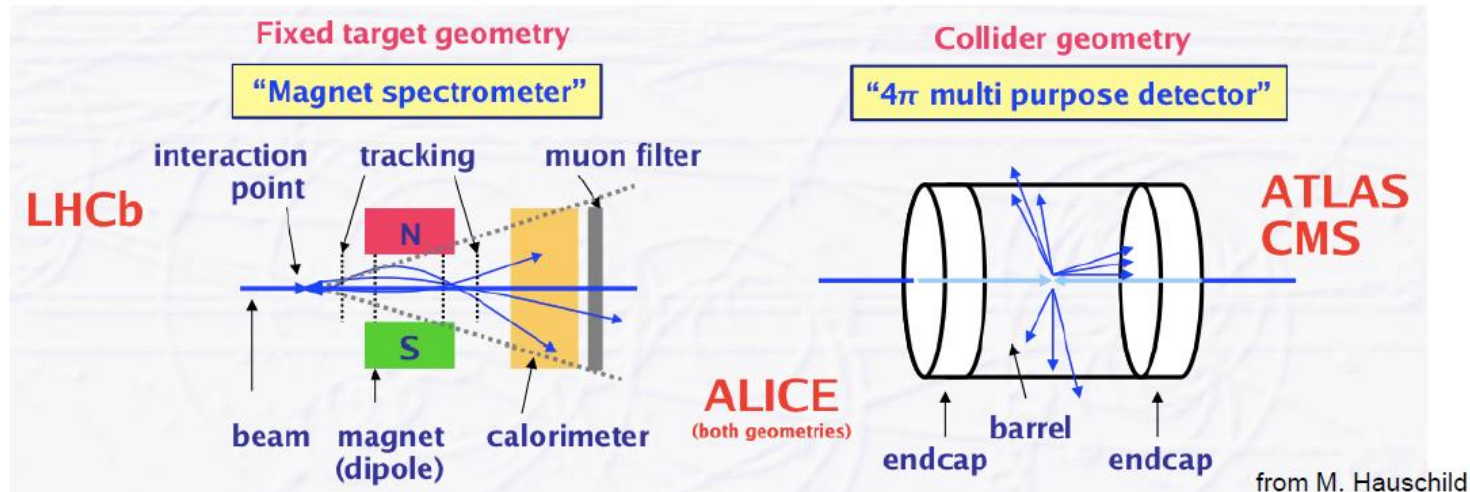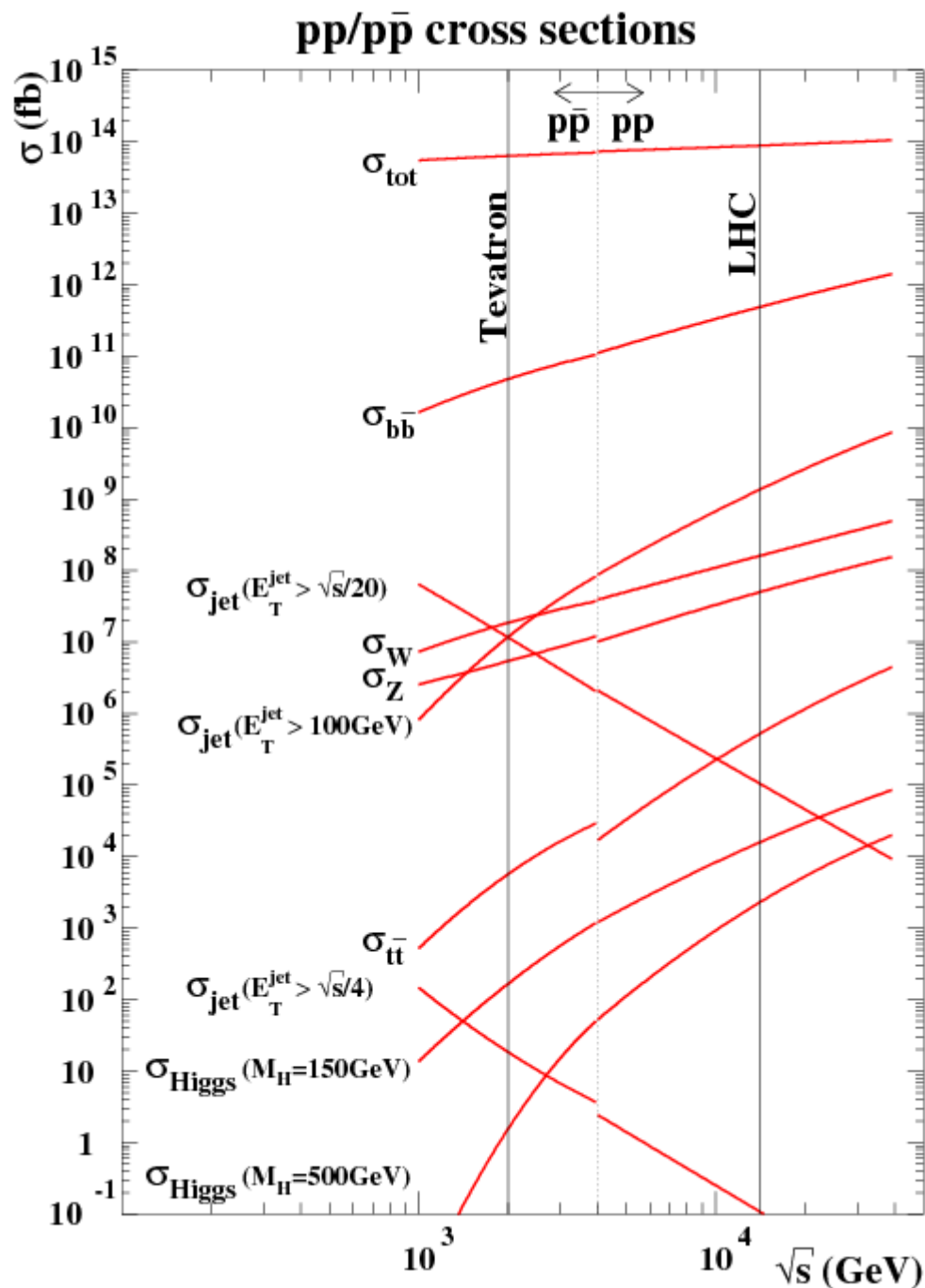
# Today, (tomorrow) & Next week

- The LHC accelerator
- Challenges
- The experiments (mainly CMS and ATLAS)
- Important variables
- Preparations
- "Soft" physics – minímum bias, underlying event
- EWK physics -  high $p_T$ physics
- Identification of jets and leptons
- Some recent SM results from ATLAS + CMS
- Recent LHCb results

## pp/pp̄ cross sections

Cross sections for different processes

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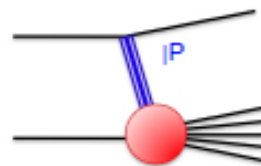
Multi Parton Interactions: An interesting parton-parton interaction will have many additional parton-parton interactions occurring in the same proton-proton interaction, they will almost always be soft-QCD processes

Therefore we had better have a good model of these processes! Can affect simulations of lepton ID, ETmiss resolution, jets, jet vetos,…
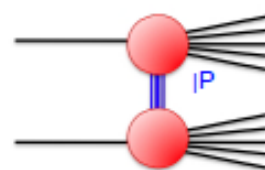
Dominant processes in inelastic hadron-hadron interactions :
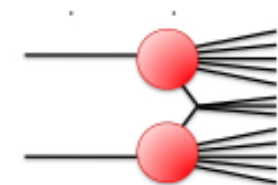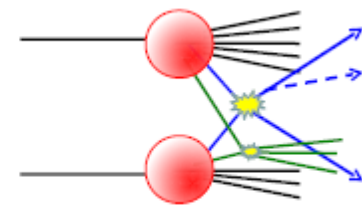
Non-Diffractive
(ND)  σ~49 mb

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

Double-Diffractive-Dissociation
(DD)  σ~9 mb          @ 7 TeV

Multiple parton interactions

# Pile-up



Z→μμ





ATLAS Online, 13 TeV ∫Ldt=86.5 fb⁻¹

- 2015: ⟨μ⟩ = 13.4
- 2016: ⟨μ⟩ = 25.1
- 2017: ⟨μ⟩ = 38.1
- Total: ⟨μ⟩ = 32.0

initial 2017 calibration
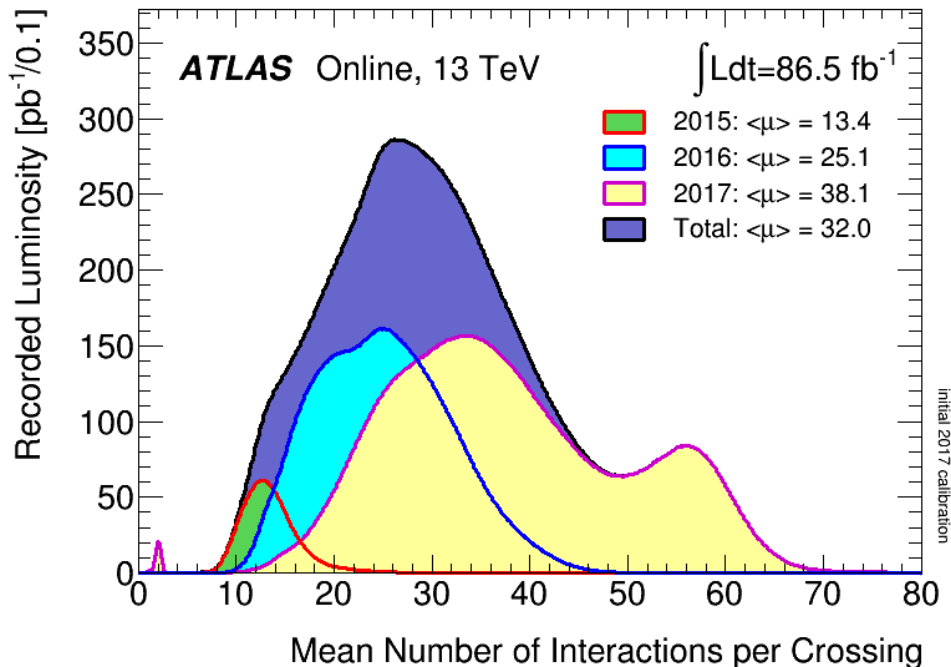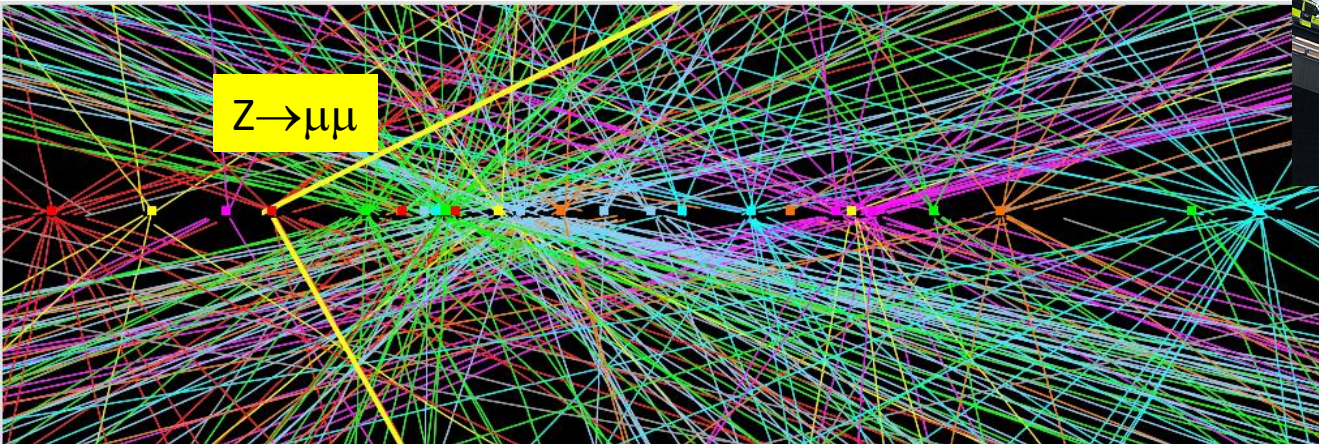
Due to the high number of protons/bunch  high probability of multiple interactions

Majority of these uninteresting – but difficult to disentangle from the "most" interesting hard scatter

7

LHC Bunch Crossing
1ns Clip

-0.11ns

-0.12ns

0.02ns

0.4ns

0.11ns

0.15ns

-0.05ns

0.2ns

0ns

(define to be t=0)
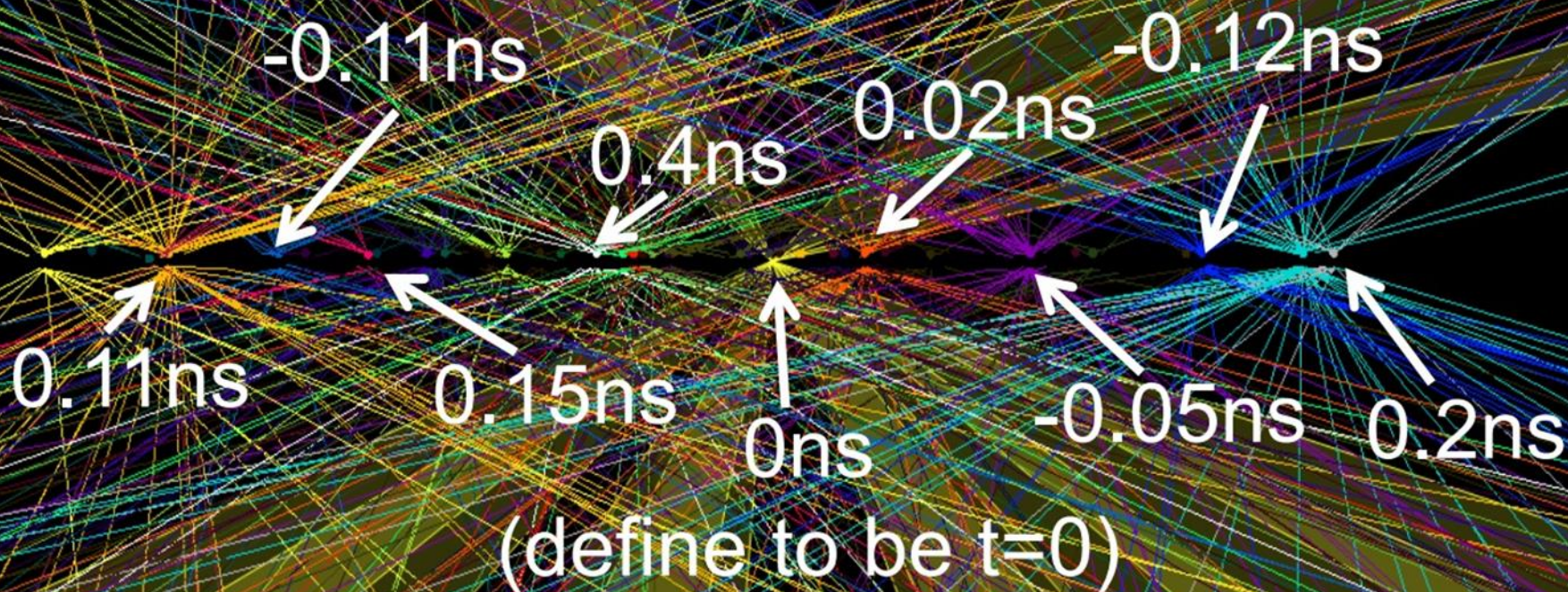
Raw $\Sigma E_T$ ~2 TeV
14 jets with $E_T$>40
Estimated PU~50

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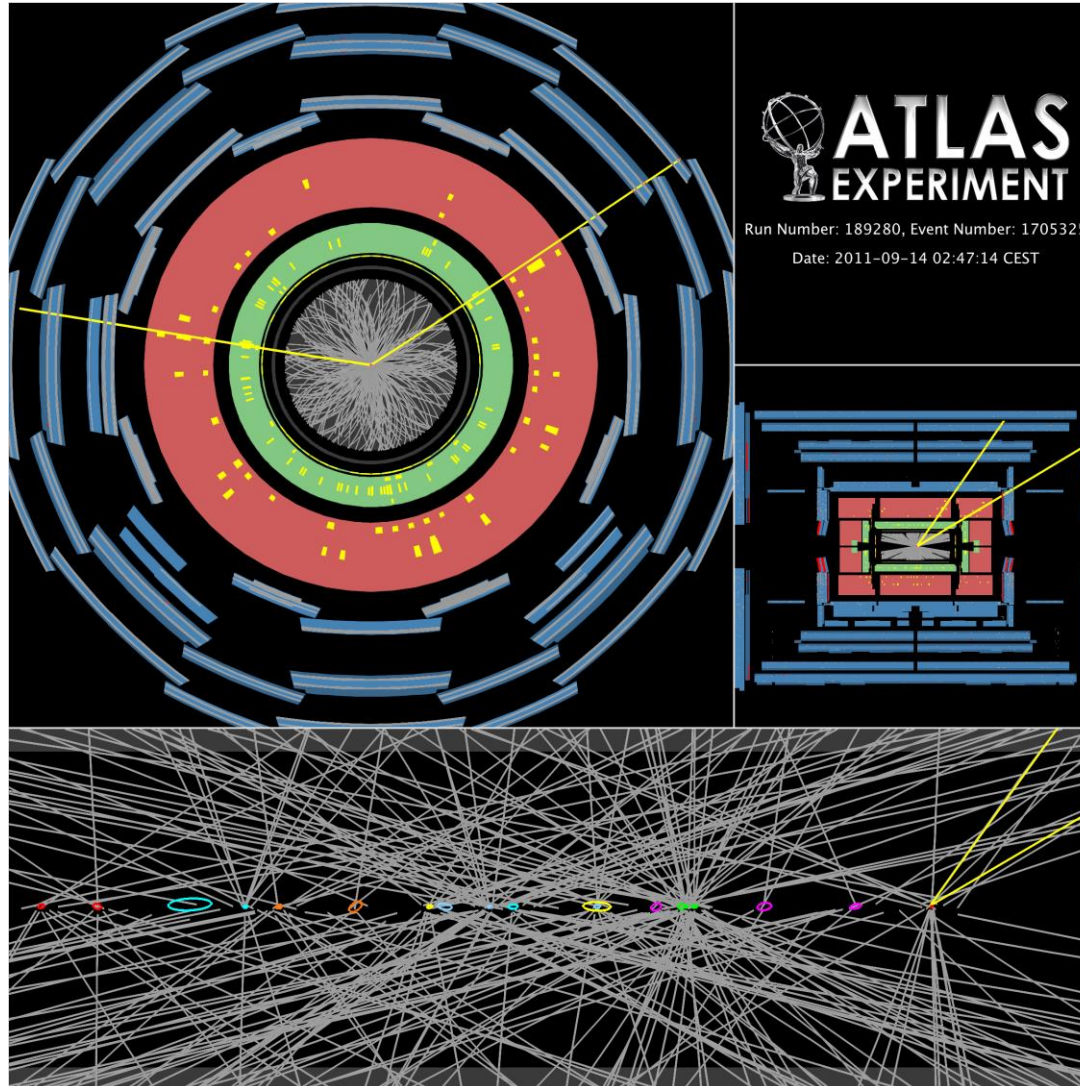Orbit/Crossing: 16992111 / 2295

10

8
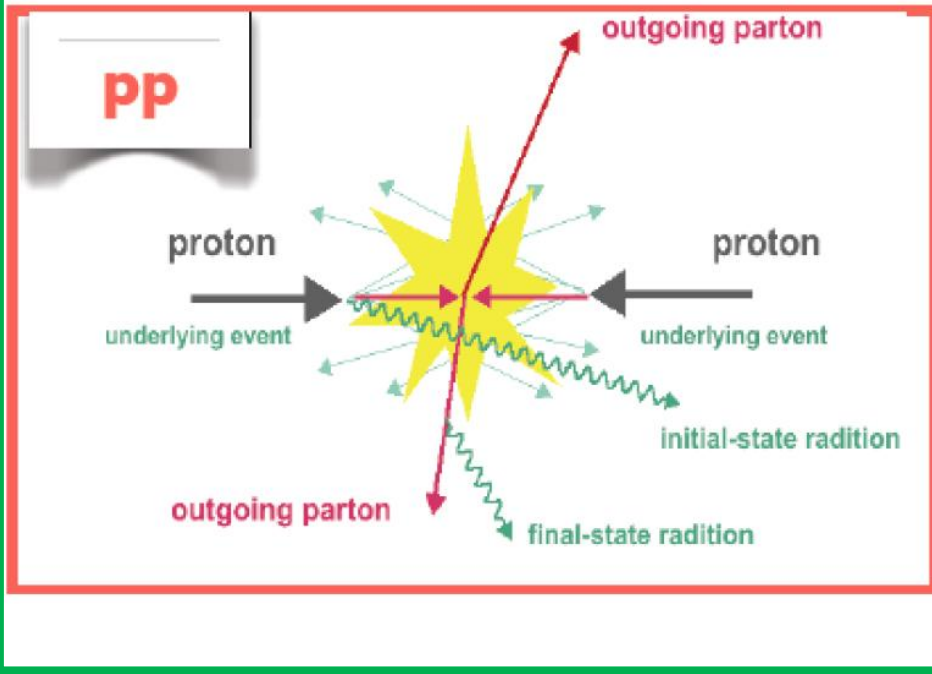
# Z →μμ with 20 vertices

# Underlying event

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



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
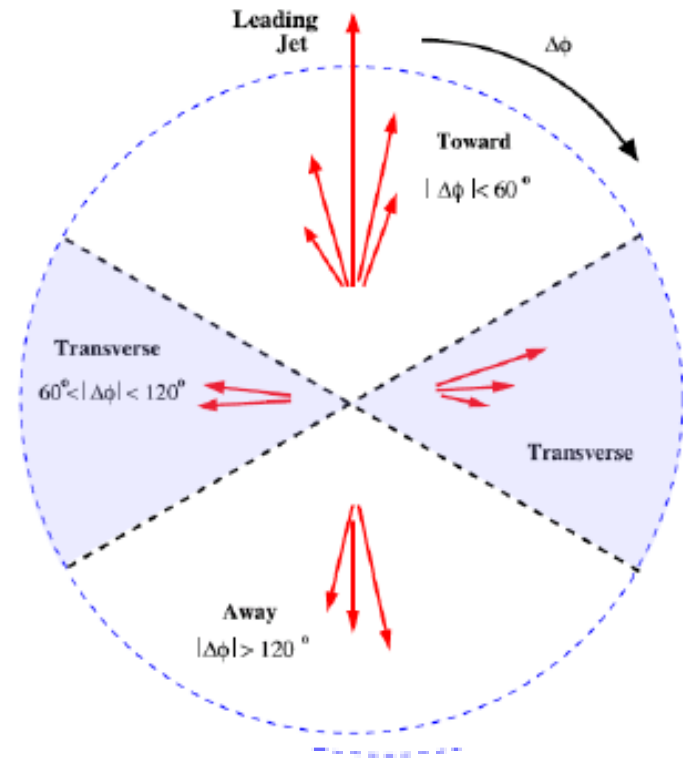
# Studying the underlying event

**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  $<N_{chg}>$
Transverse $<\Sigma\ p_T>$

# 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
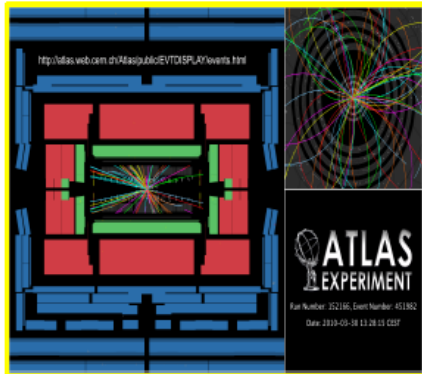


Charged particles moving through a magnetic field will bend by an amount inversely proportional to pT

e.g. ATLAS: (a) At least two charged particles with pT > 100 MeV, |η| < 2.5 (most inclusive)
(b) At least six charged particles with pT > 500 MeV, |η| < 2.5 (suppresses diffraction)
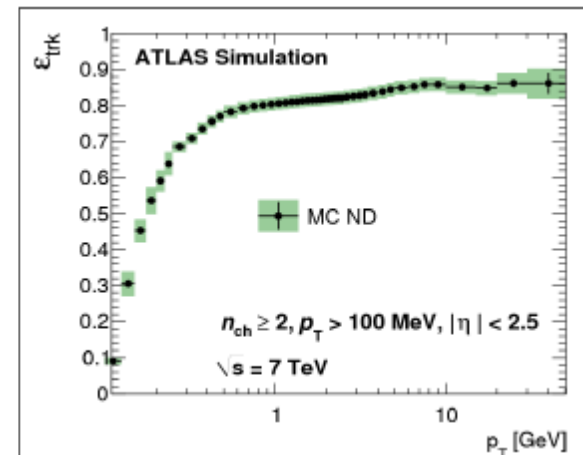
definition of minimum bias in each analysis

# Testing the soft QCD predictions
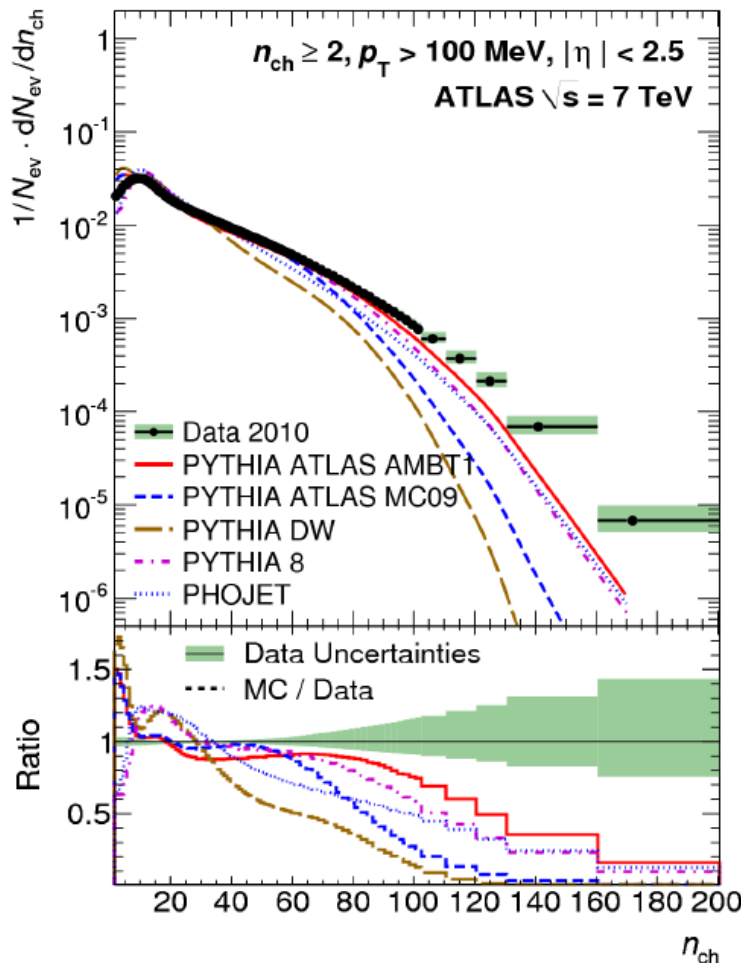


Examples of tuning of simulation (Monte Carlo, MC)
(This includes of course features like the rapidity gap etc)

Low $p_T$ tracking: will particle make it through tracking volume?
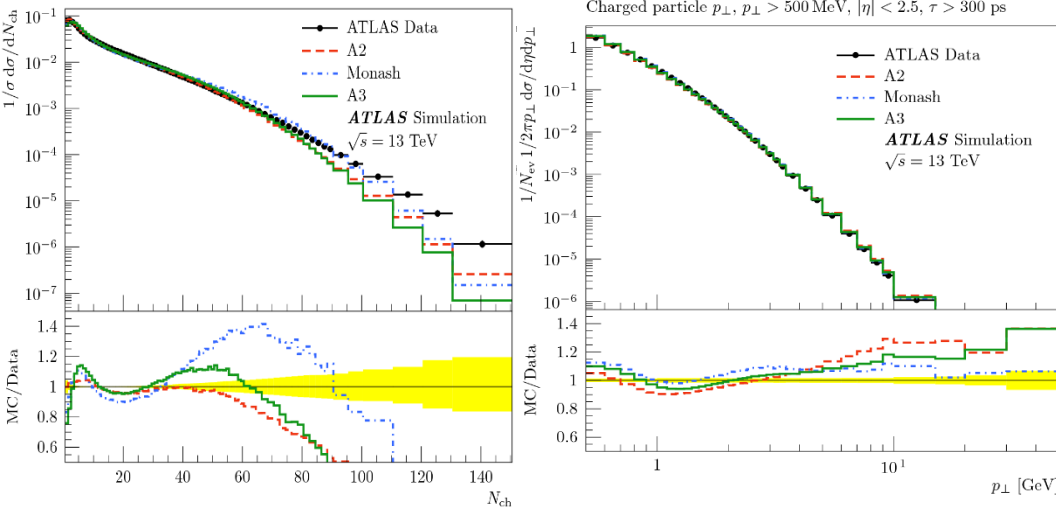
# High $p_T$ / EWK physics

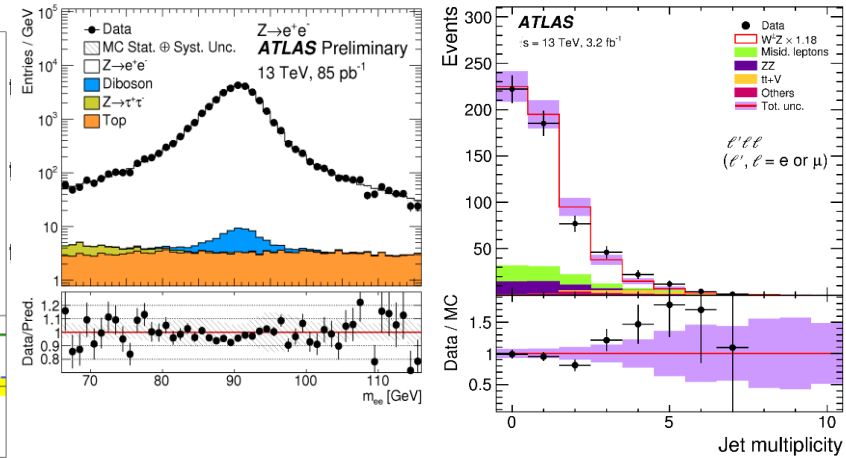# Physics Modelling

## A2 Minbias tune (for PU)

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



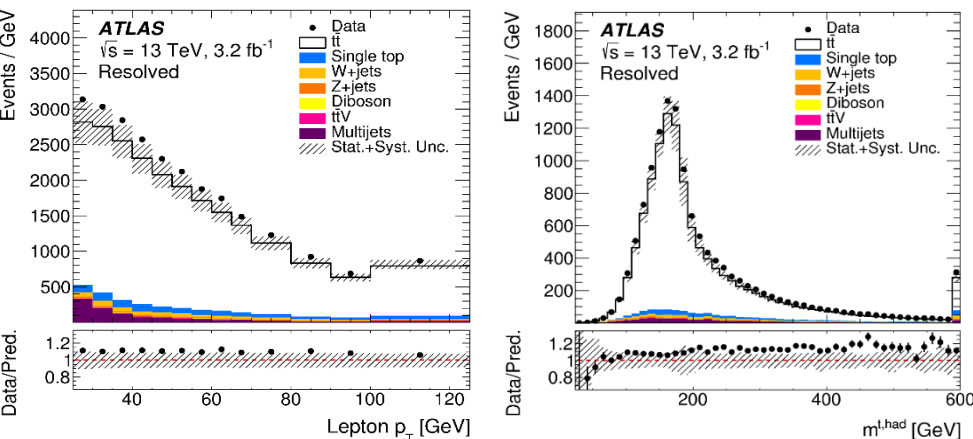Charged multiplicity $\geq 1$, $p_\perp > 500$ MeV, $|\eta| < 2.5$, $\tau > 300$ ps



Charged particle $p_\perp$, $p_\perp > 500$ MeV, $|\eta| < 2.5$, $\tau > 300$ ps

## V+Jets , Dibosons, Tribosons
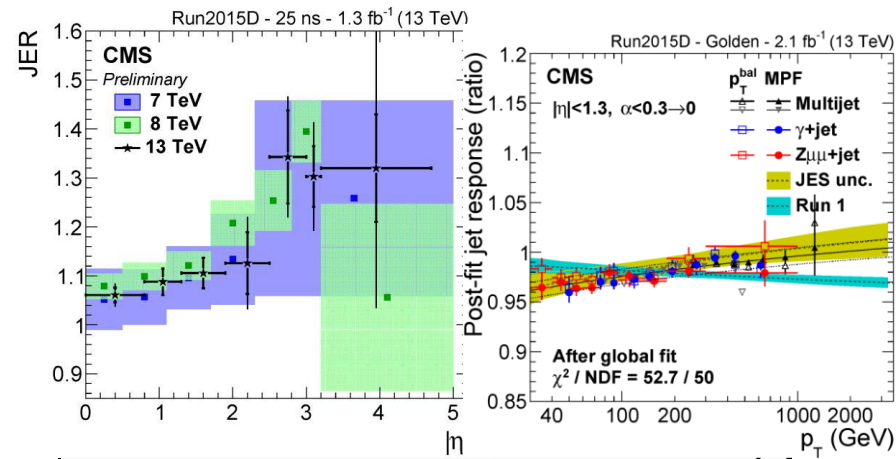
### Sherpa NLO (2partons) and LO (up to 4 partons) 2.1.1





## Top pair production

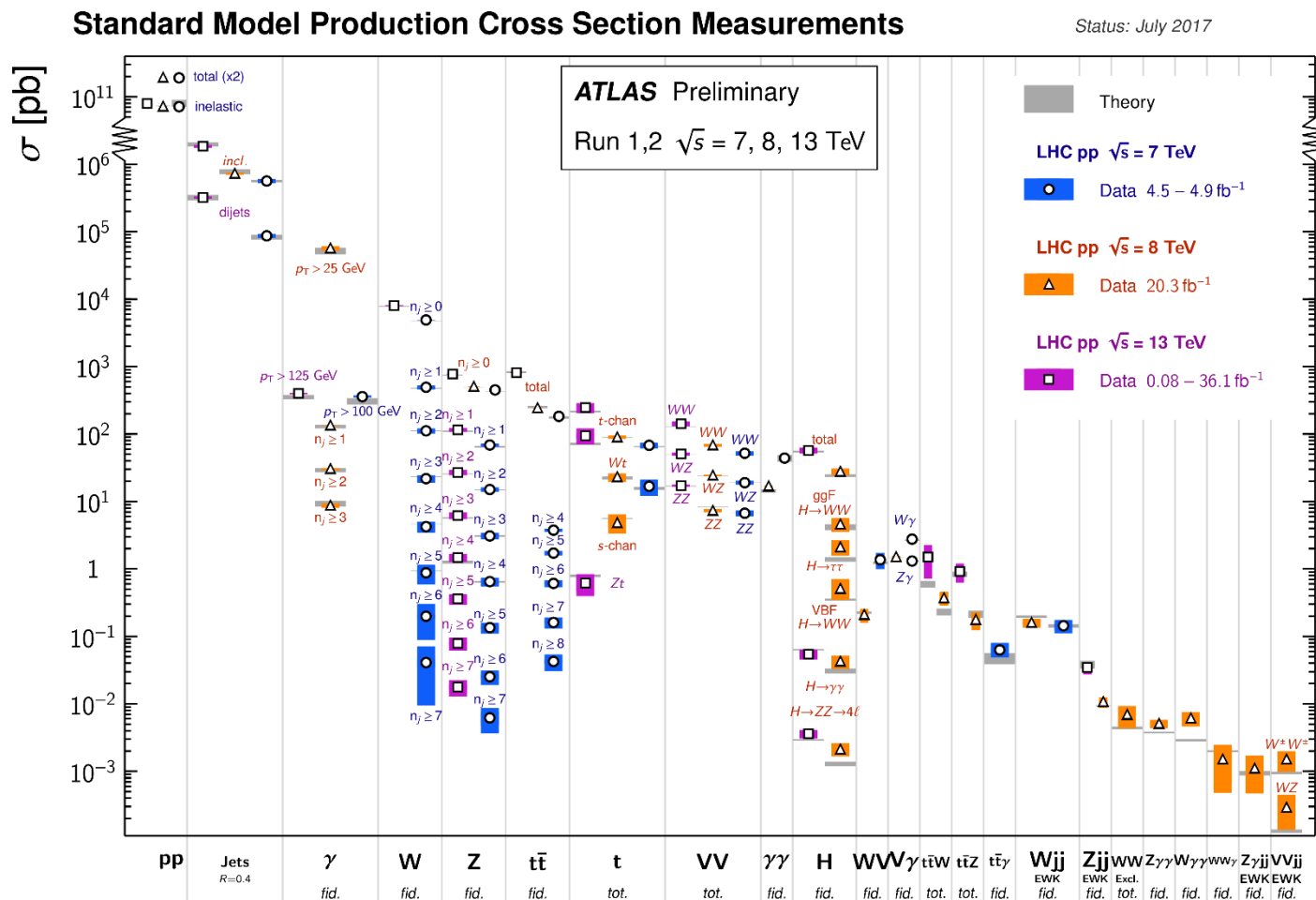### Powheg-Box v2 (hdamp =$m_t$) – Pythia 6.428 – EvtGen (HF decays) - CT10 PDFs – Perugia 2012 tune





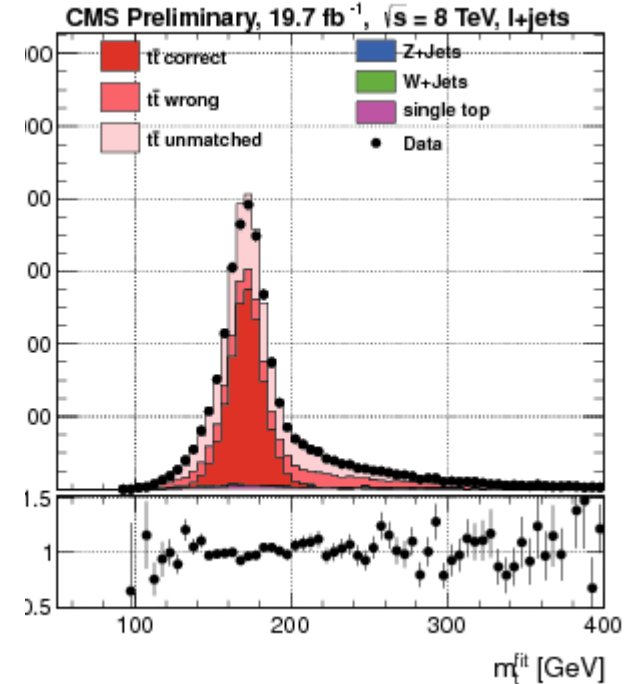## Jet quality
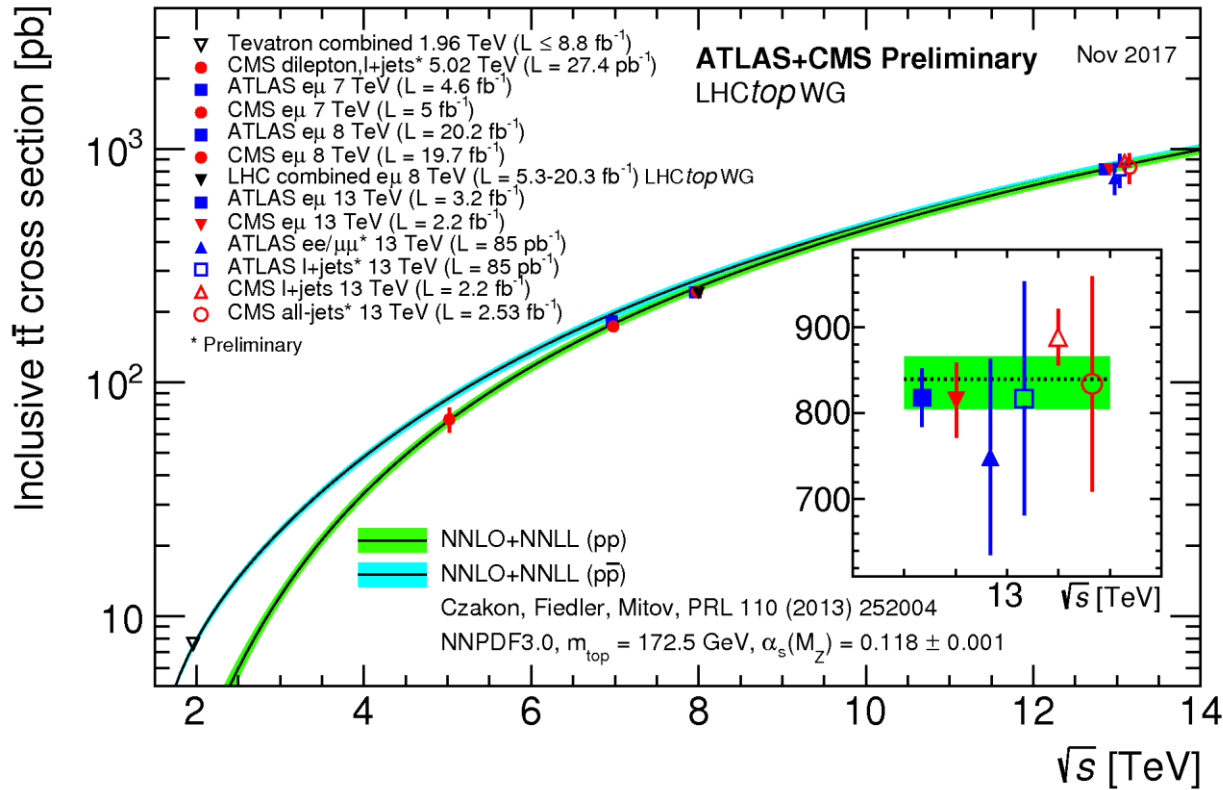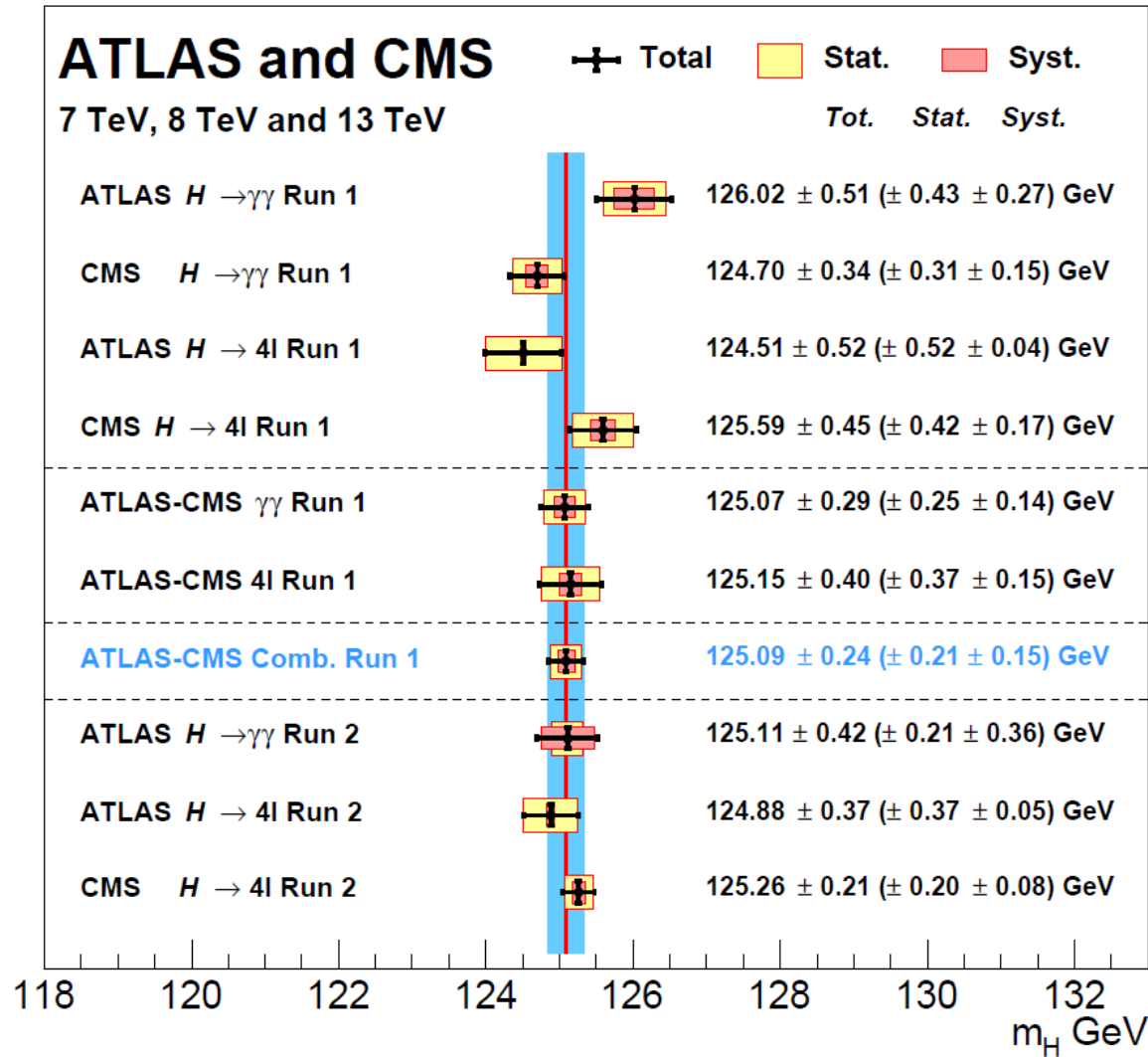
# Standard Model measurements



Standard Model Production Cross Section Measurements — Status: July 2017. ATLAS Preliminary, Run 1,2 $\sqrt{s}$ = 7, 8, 13 TeV.

# Close-in on the top quark



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

# Higgs measurements



**ATLAS and CMS**
7 TeV, 8 TeV and 13 TeV

PDG

|  | | Tot. | Stat. | Syst. |
| --- | --- | --- | --- | --- |

ATLAS $H \to \gamma\gamma$ Run 1 — $126.02 \pm 0.51 \, (\pm 0.43 \pm 0.27) \, \text{GeV}$

CMS $H \to \gamma\gamma$ Run 1 — $124.70 \pm 0.34 \, (\pm 0.31 \pm 0.15) \, \text{GeV}$

ATLAS $H \to 4l$ Run 1 — $124.51 \pm 0.52 \, (\pm 0.52 \pm 0.04) \, \text{GeV}$

CMS $H \to 4l$ Run 1 — $125.59 \pm 0.45 \, (\pm 0.42 \pm 0.17) \, \text{GeV}$

ATLAS-CMS $\gamma\gamma$ Run 1 — $125.07 \pm 0.29 \, (\pm 0.25 \pm 0.14) \, \text{GeV}$

ATLAS-CMS 4l Run 1 — $125.15 \pm 0.40 \, (\pm 0.37 \pm 0.15) \, \text{GeV}$

ATLAS-CMS Comb. Run 1 — $125.09 \pm 0.24 \, (\pm 0.21 \pm 0.15) \, \text{GeV}$

ATLAS $H \to \gamma\gamma$ Run 2 — $125.11 \pm 0.42 \, (\pm 0.21 \pm 0.36) \, \text{GeV}$

ATLAS $H \to 4l$ Run 2 — $124.88 \pm 0.37 \, (\pm 0.37 \pm 0.05) \, \text{GeV}$

CMS $H \to 4l$ Run 2 — $125.26 \pm 0.21 \, (\pm 0.20 \pm 0.08) \, \text{GeV}$
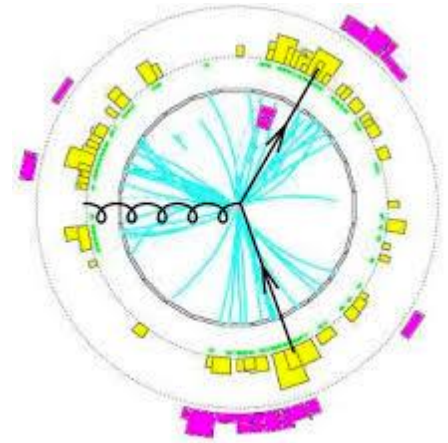
$m_H$ GeV

# Identification of jets and leptons

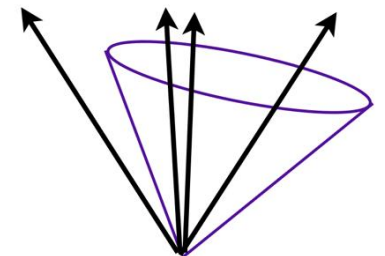# Jet algorithms
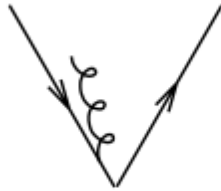


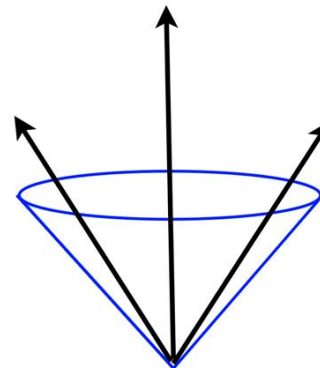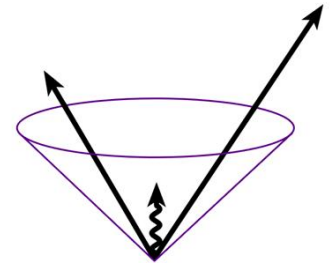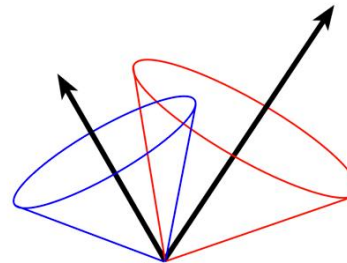LO partons    NLO partons    parton shower    hadron level
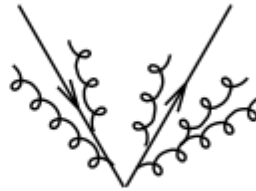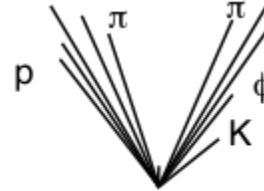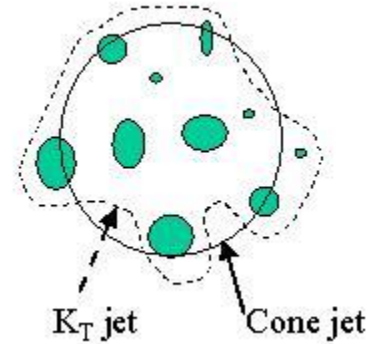
How to define a "jet"? A few different approaches:

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

experimentally easiest , theoretically unsafe

# $k_T$ / anti-$k_T$ algorithm



$K_T$ jet          Cone jet

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

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

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

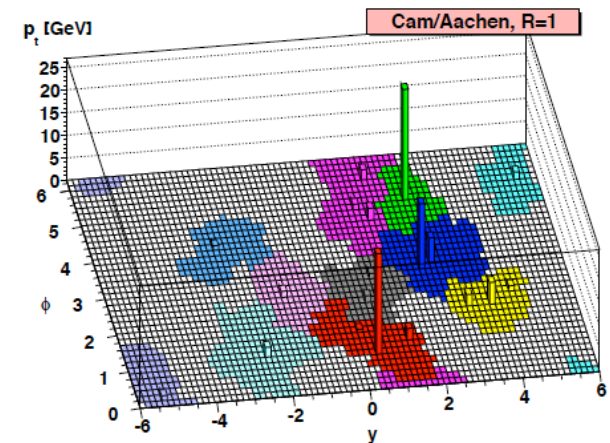- Find minimum. If $d_{ij}$ , combine i and j into a jet, then loop over all particles again. If $d_{iB}$, call it a jet, and remove particle i from list
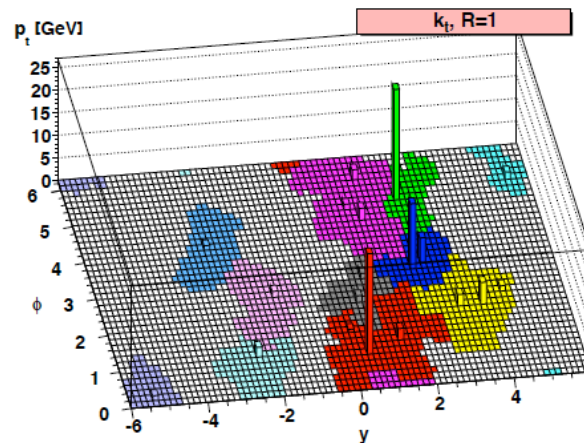
p=+1: $k_T$ algorimth. p =-1: anti-$k_T$ algorithm (favoring recombination of high-pt particles)
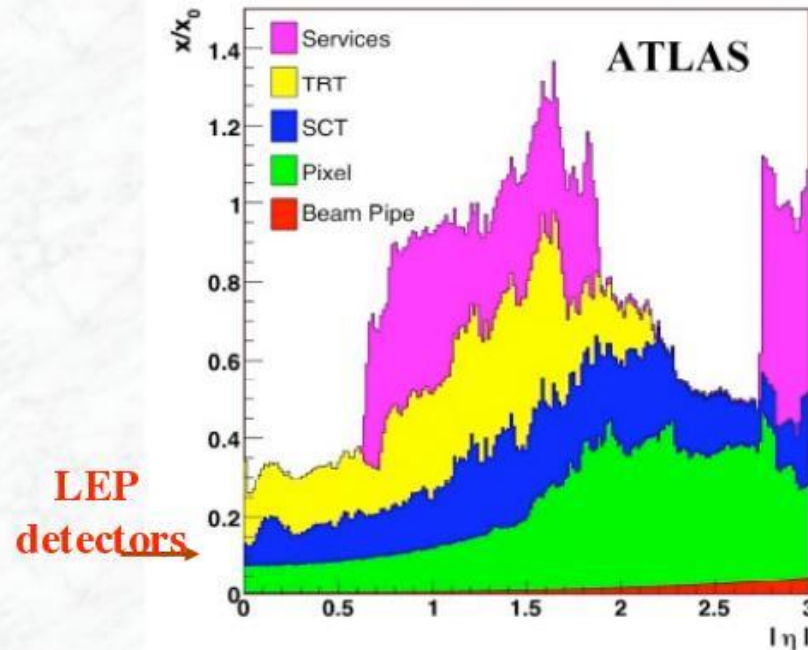
# Comparison

Anti-kt mostly used at the LHC

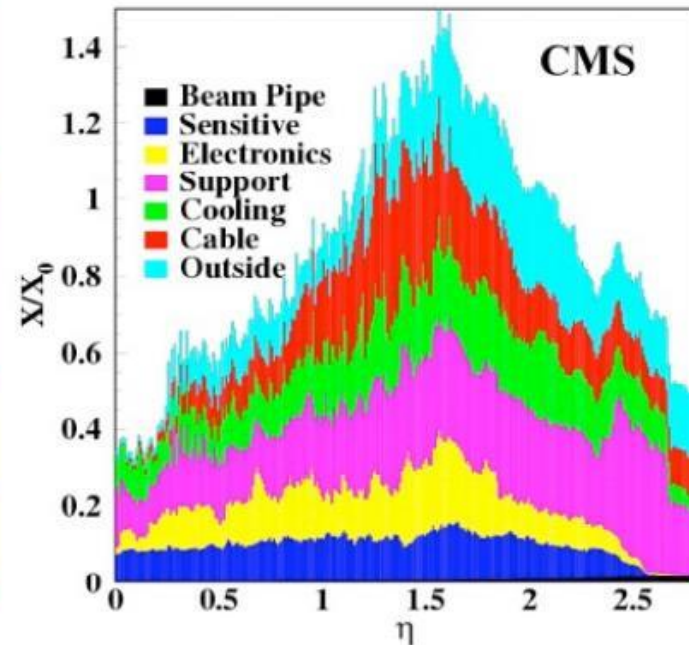Gives more regular jets (almost like cones!) because soft particles clustered only at the end
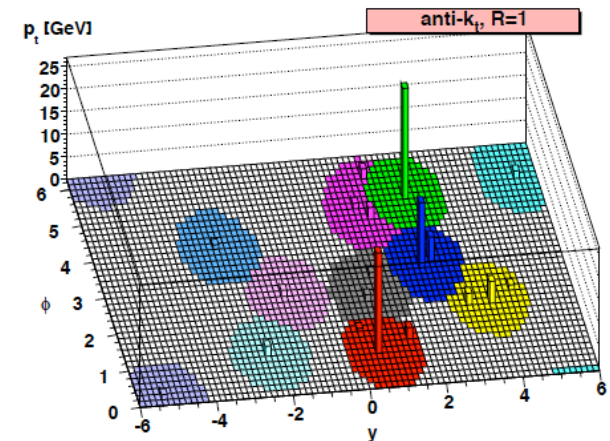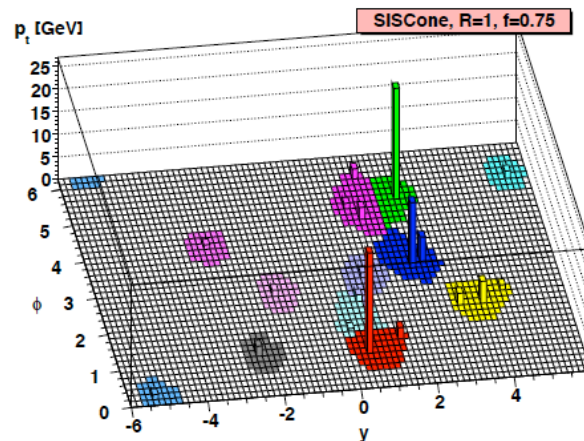
# Amount of material in ATLAS and CMS inner trackers

Weight: 4.5 tons　　　　Weight: 3.7 tons



LEP detectors

- 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
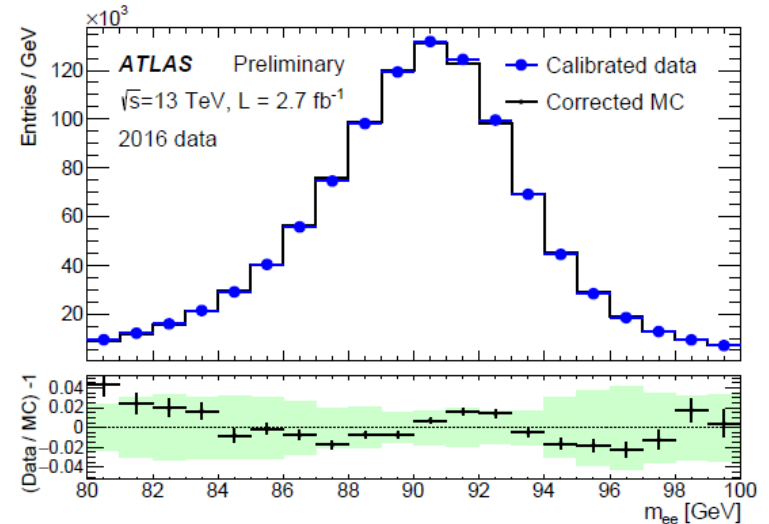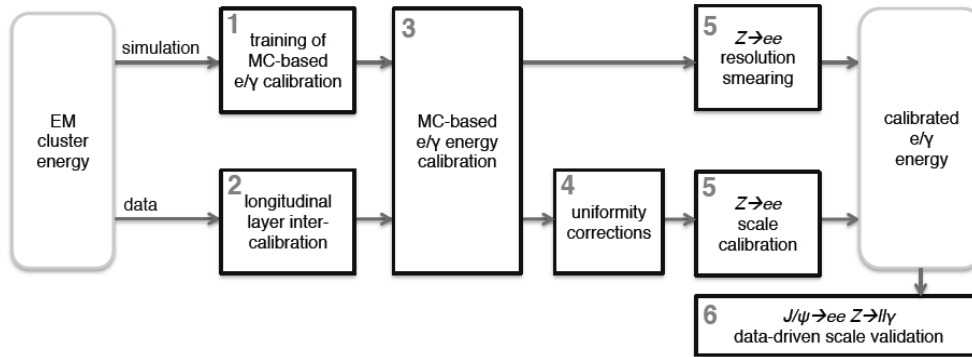
# From lecture 4: The ATLAS tracker as seen by photon conversions

Reconstructed photon conversions show clearly the location of (Si) tracking modules!
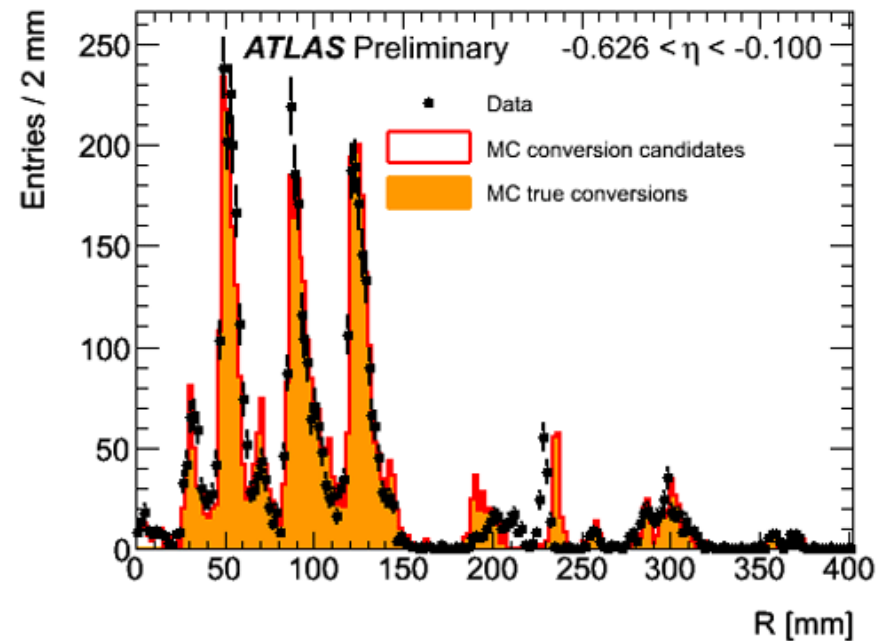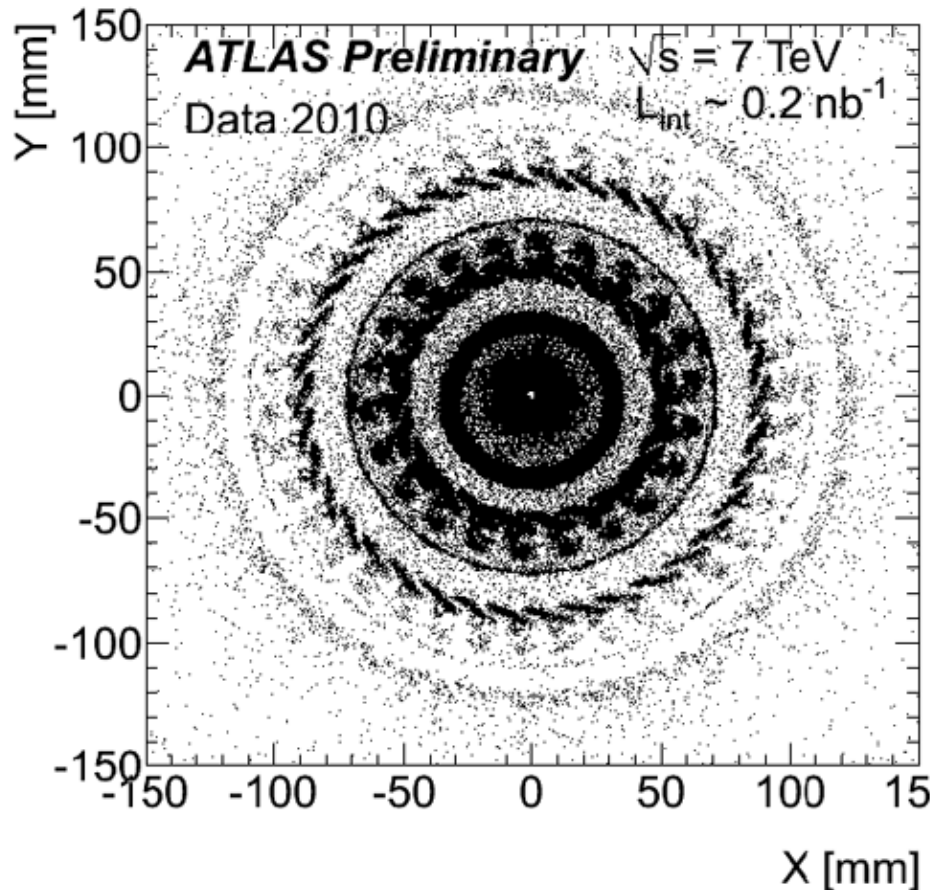
# Example: electrons in ATLAS

Calibration of EM calo reponse





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

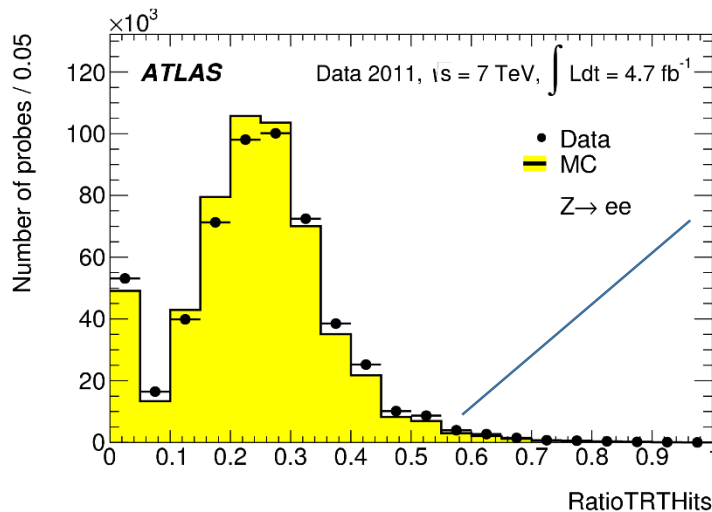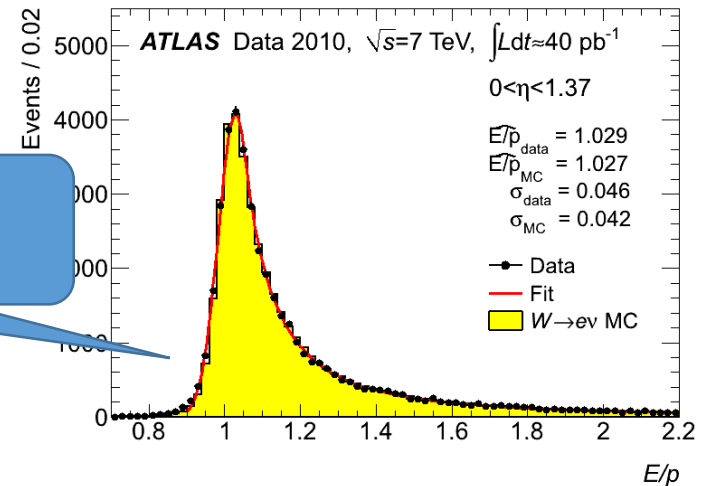| Requirement | Signal electrons (tight) | Loose electrons |
|---|---|---|
| Identification | LHMedium | LHLoose |
| Isolation | loose | — |
| $p_T$ cut | $p_T > 30\,\mathrm{GeV}$ | $p_T > 30\,\mathrm{GeV}$ |
| $\eta$ cut | $|\eta| < 2.47$ and veto $1.37 < |\eta| < 1.52$ | $|\eta| < 2.47$ and veto $1.37 < |\eta| < 1.52$ |
| $|d_0|/\sigma_{d_0}$ 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
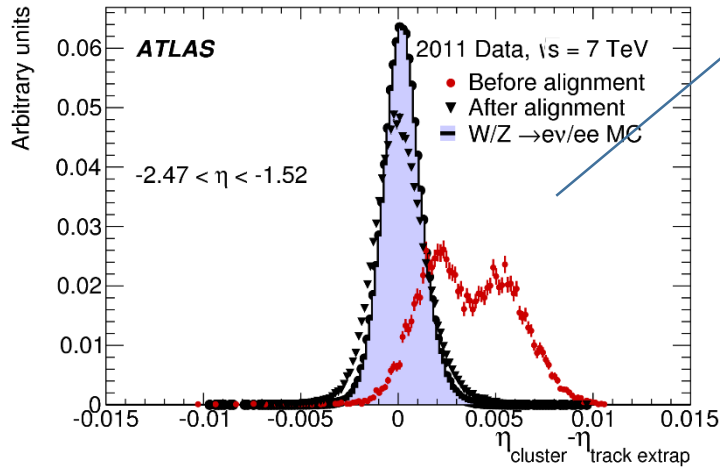


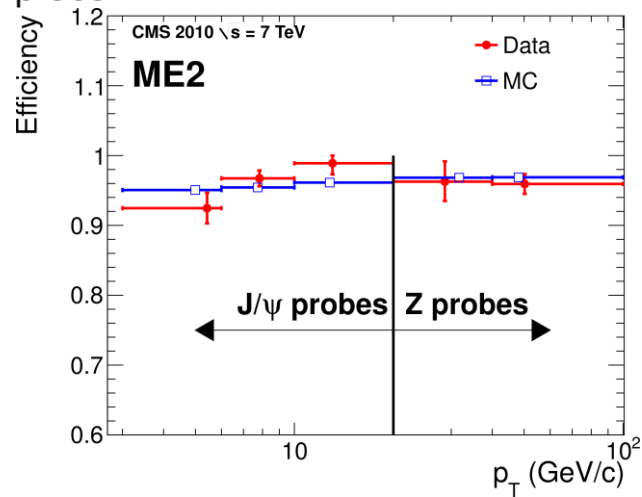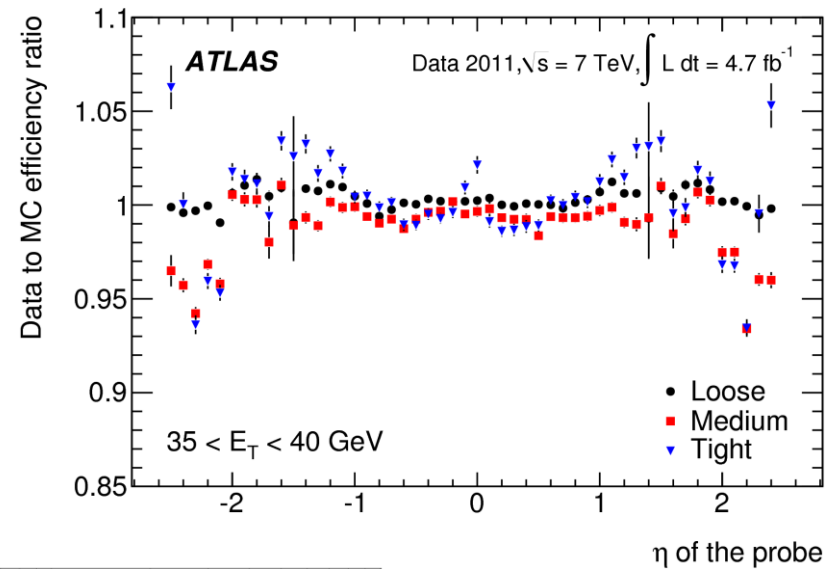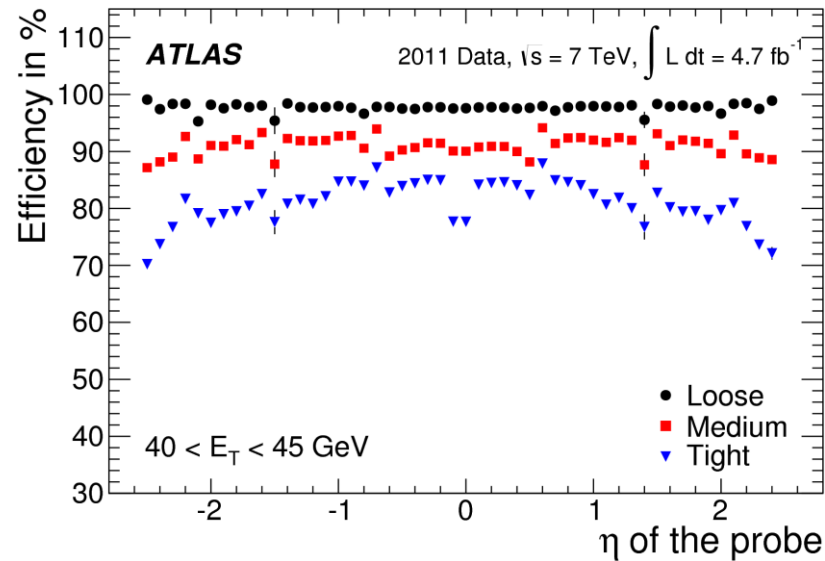How well are the track and the EM cluster matched?

Is the E/p ratio close to 1?

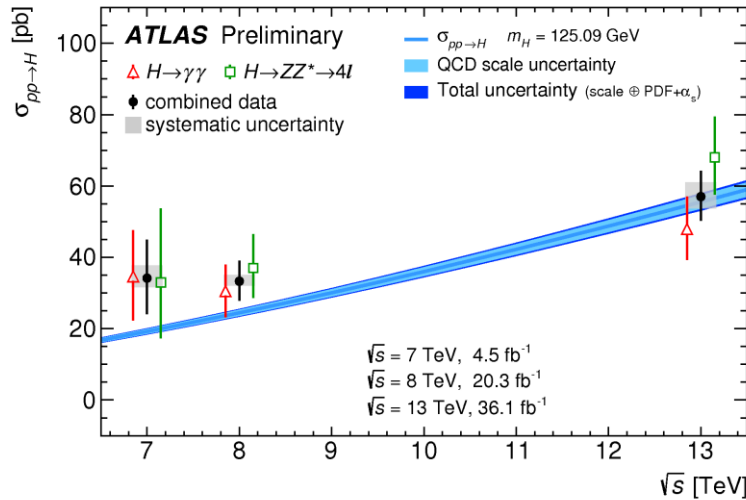Are the number of transition radiation hits high enough?

# Leptons identification efficiencies
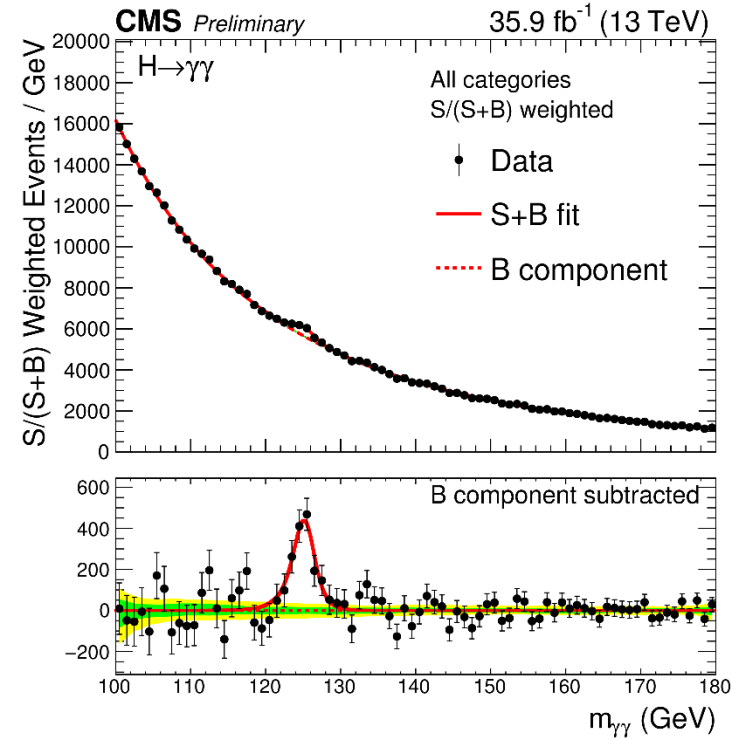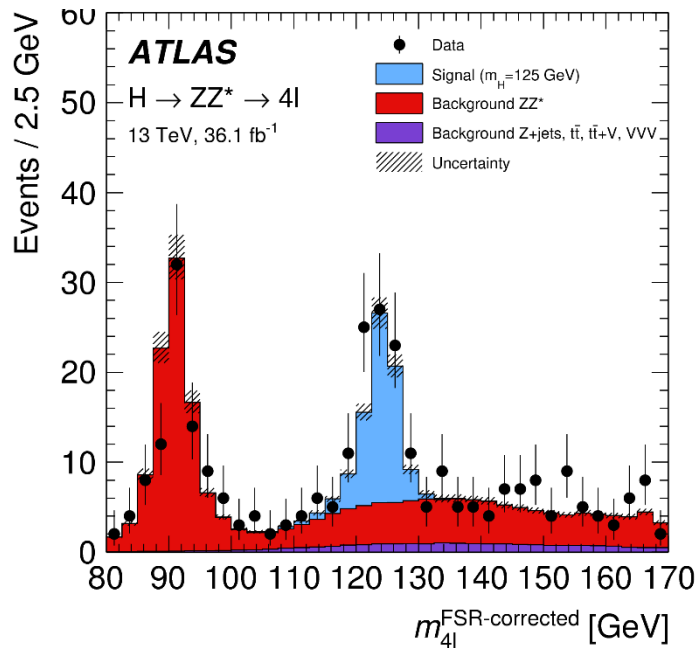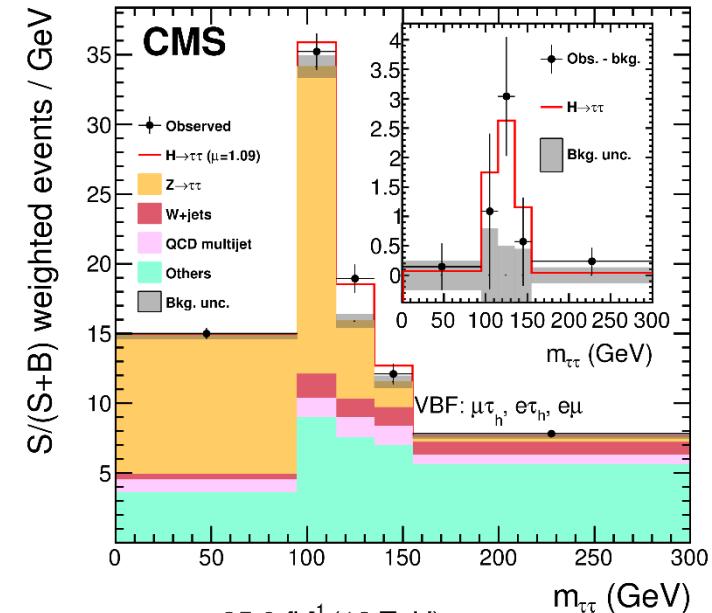
# Latest on the Standard Model: a few recent results

# The Higgs @ 13 TeV

Consistent picture with the higher energy

# A New Particle?



## NyTeknik
DIGITALISERING  ENERGI  FORDON  NYSTARTAT  TEKNIKREVYN  LEDIGA JOBB  A-Ö

INNOVATION

Cern

# Cern: Tecken på ny okänd partikel

2016-03-30 12:49    Av: Ulla Karlsson-Ottosson              6 KOMMENTARER



CMS Experiment at the LHC, CERN
Data recorded: 2015-Nov-02 21:34:00.662277 GMT
Run / Event / LS: 260627 / 854678036 / 477
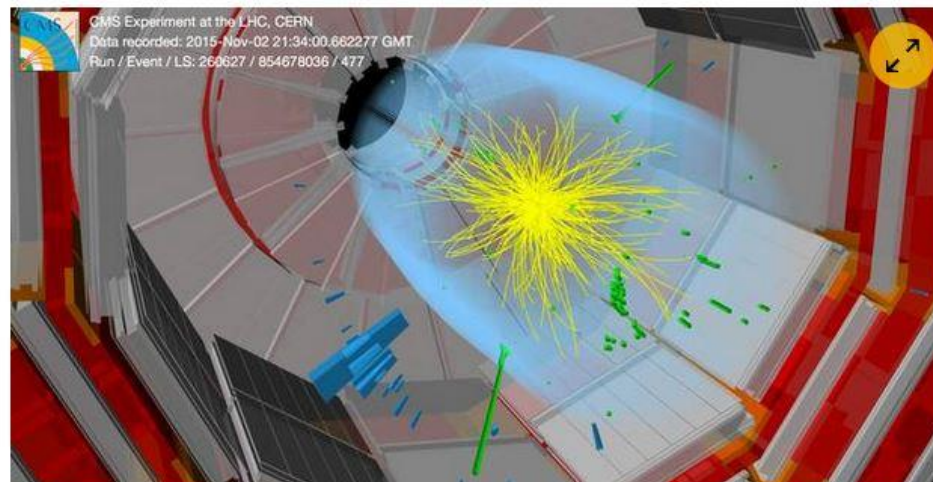
Har forskare vid Cern hittat spår efter en ny helt okänd partikel? Mätdata från körningar under 2015 antyder att det kan vara så. Uppsalaforskare lanserar teorin om en naturkonstant som förändrats.
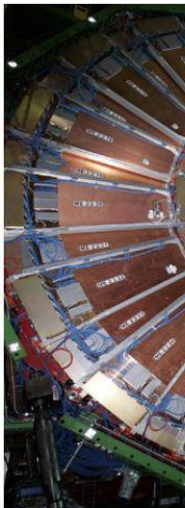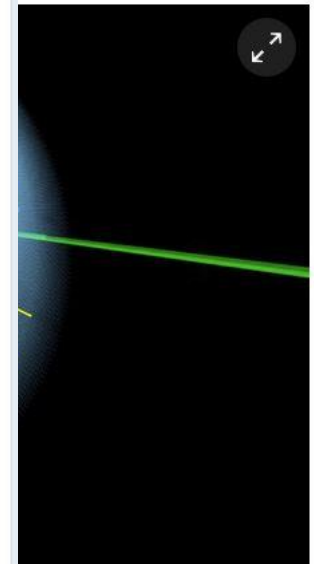
## SECTIONS

Dashing Hopes, Study Shows a Cholesterol D Had No Effect on Hear Health

SCIENCE

Physicists in
Mysterious I

By DENNIS OVERBYE  DEC. 15, 2

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

## guardian
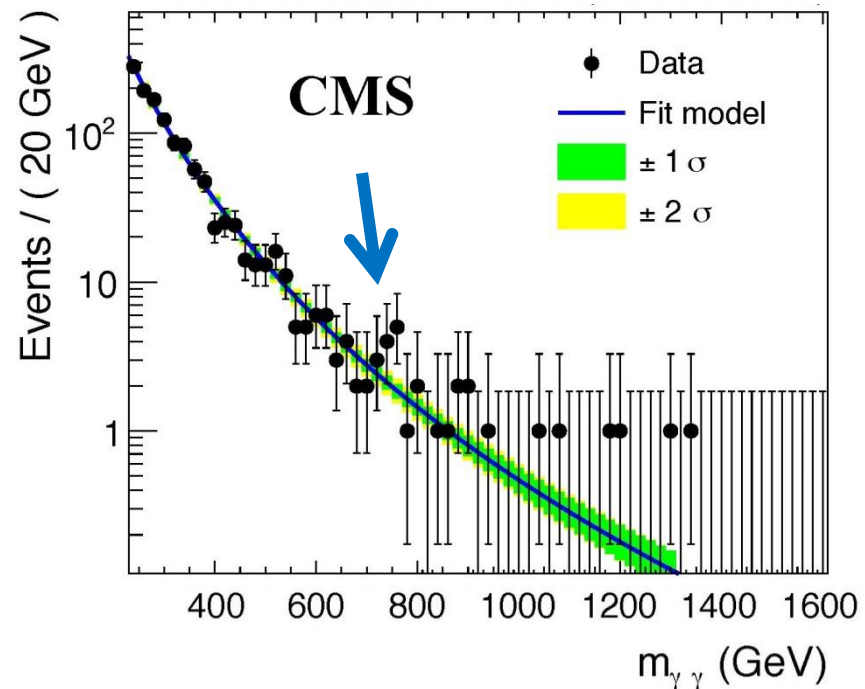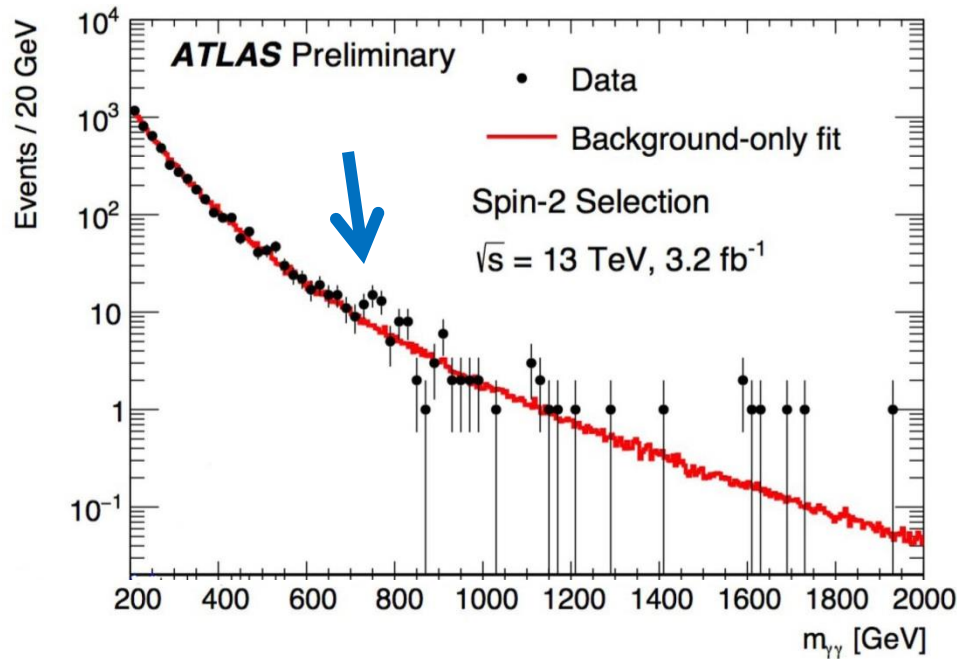ulture   business   lifest ≡ all

ron Collider

shes of light spotted inside
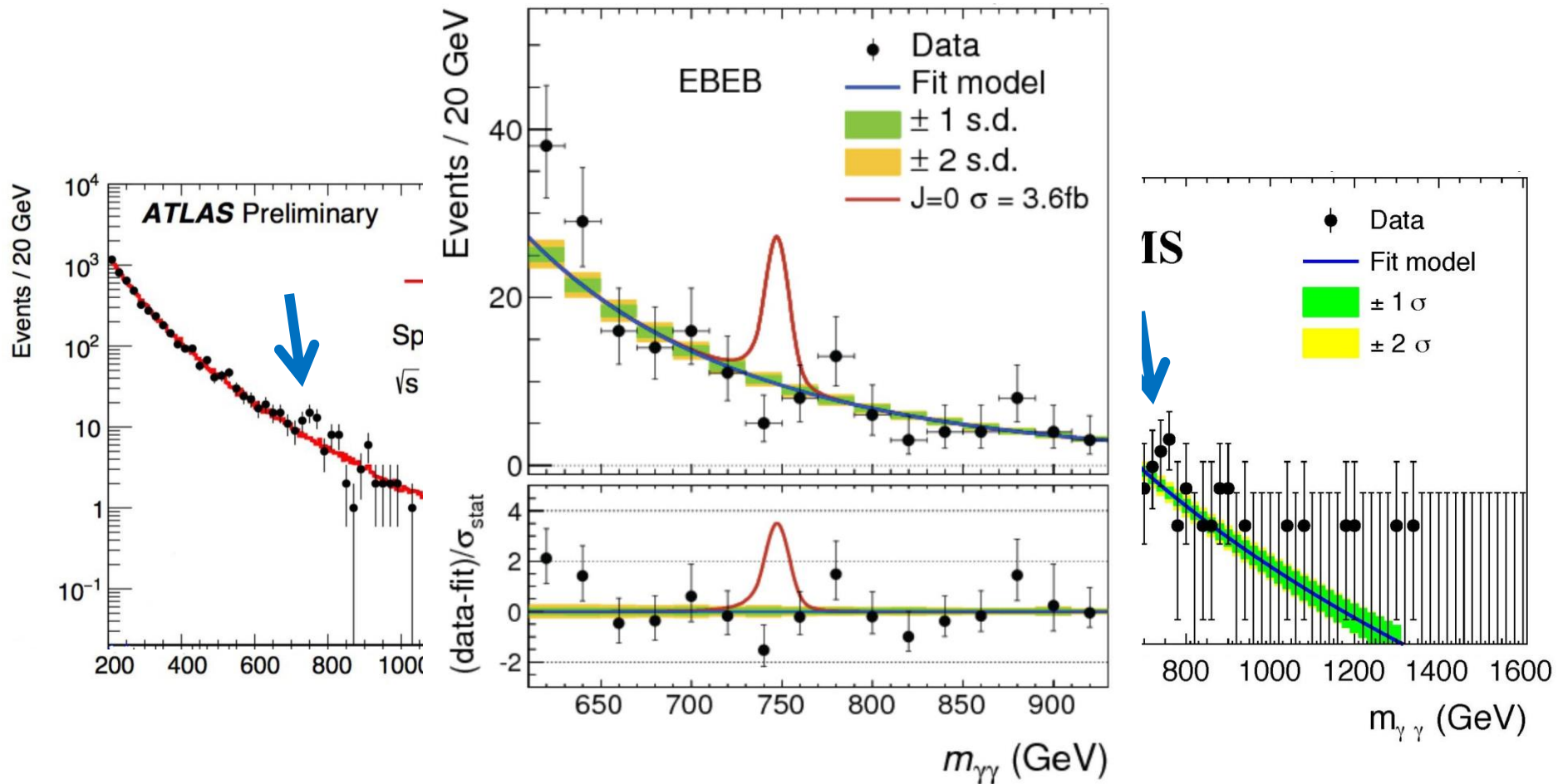
and destruction of a new

30

# 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!
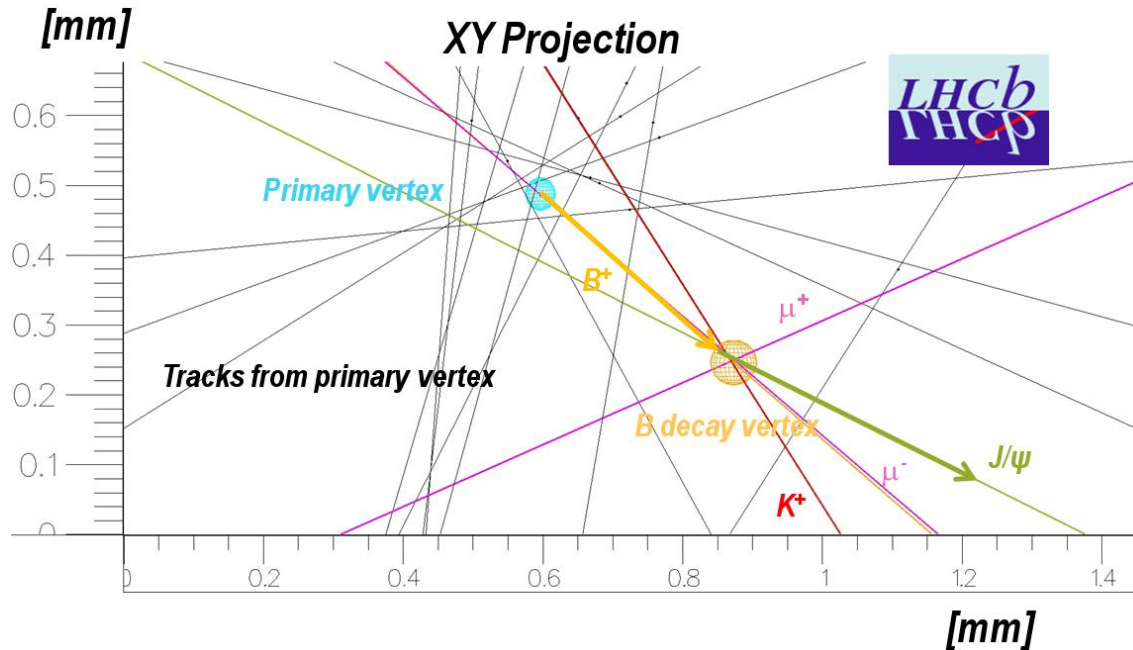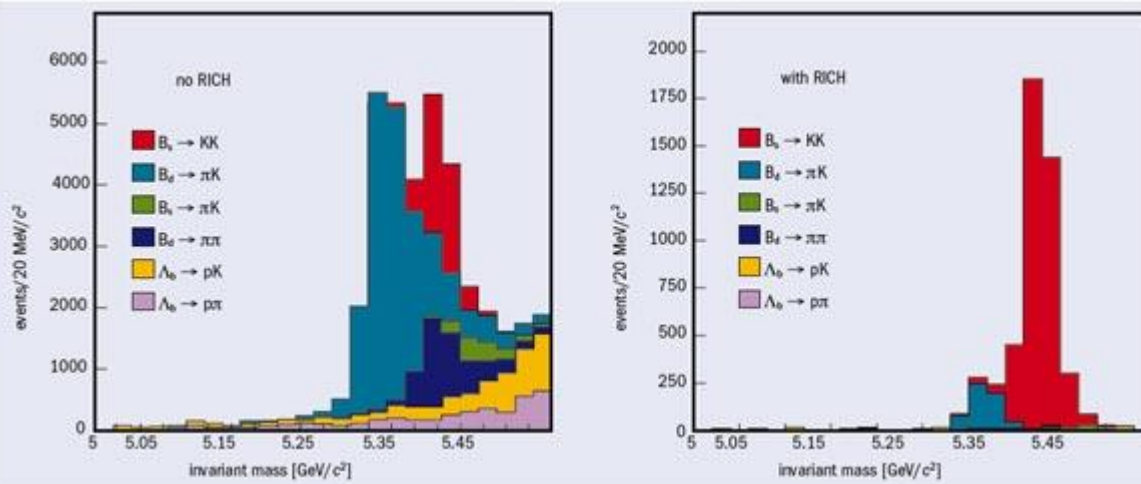
# A New Particle?!



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
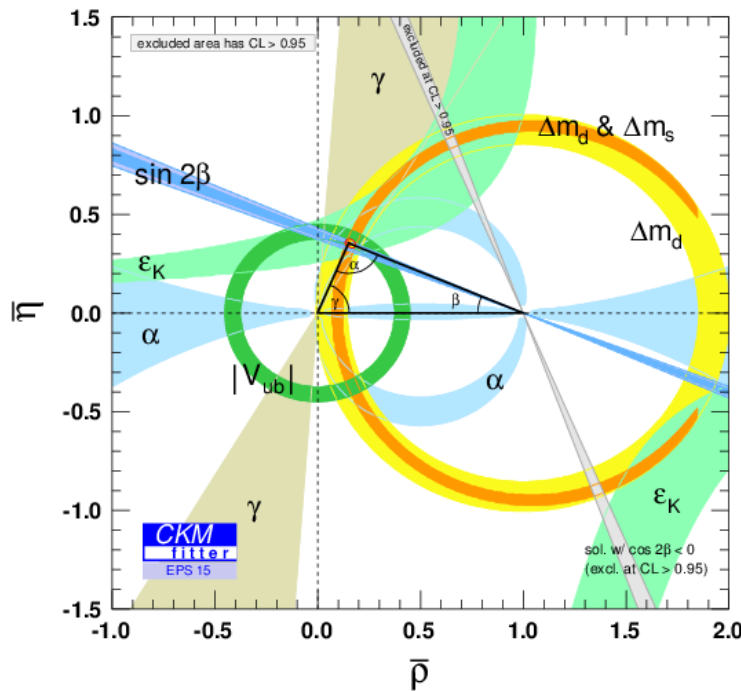
Physics programme mainly devoted to searches for rare decays + precision measurements to check loop effects and CP violation
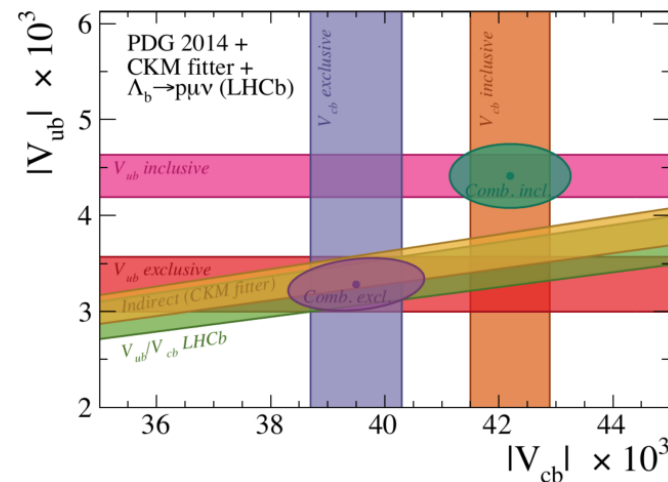
Despite being the "little brother", a lot of interesting results (here interesting = tension with SM) have come from just LHCb

You'll remember the pentaquarks…

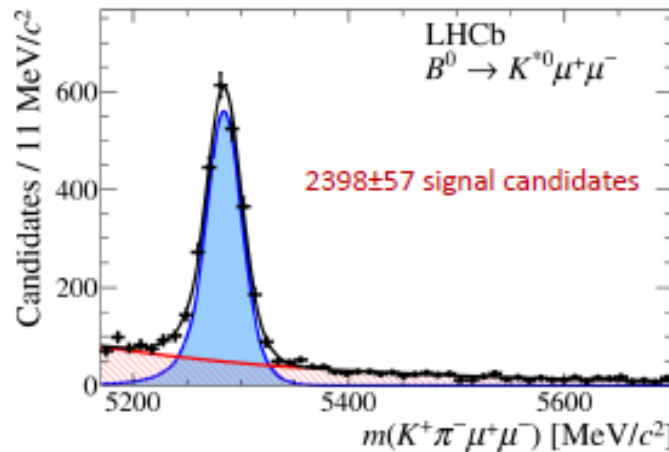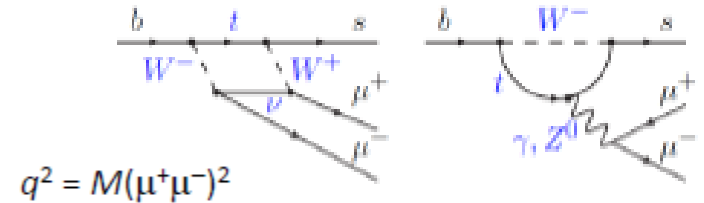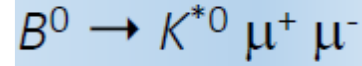Results from the main area of expertise CP violation, for instance:
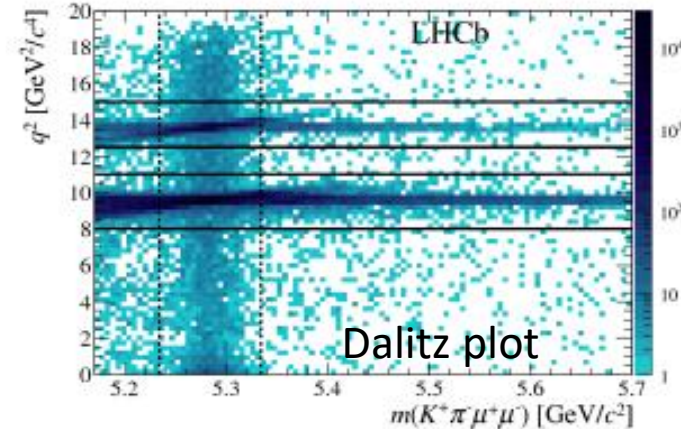


$|V_{ub}|/|V_{cb}|$ from $\Lambda_b^0 \to p\mu\nu_\mu$

# More on LHCb results

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

## New results on rare decays:

– Only allowed through loops in the SM



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

LHCb
$B^0 \rightarrow K^{*0}\mu^+\mu^-$

2398±57 signal candidates

Candidates / 11 MeV/$c^2$

$m(K^+\pi^-\mu^+\mu^-)$ [MeV/$c^2$]

Full q² range with J/ψ and ψ(2S) veto

Dalitz plot

$q^2$ [GeV$^2$/$c^4$]

$m(K^+\pi^-\mu^+\mu^-)$ [GeV/$c^2$]

## Heavy ion physics

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

$\frac{1}{N_{trig}} \frac{d^2N}{d\Delta\eta \, d\Delta\phi}$

Jet peak

Away-side ridge

$\Delta\phi$

$\Delta\eta$
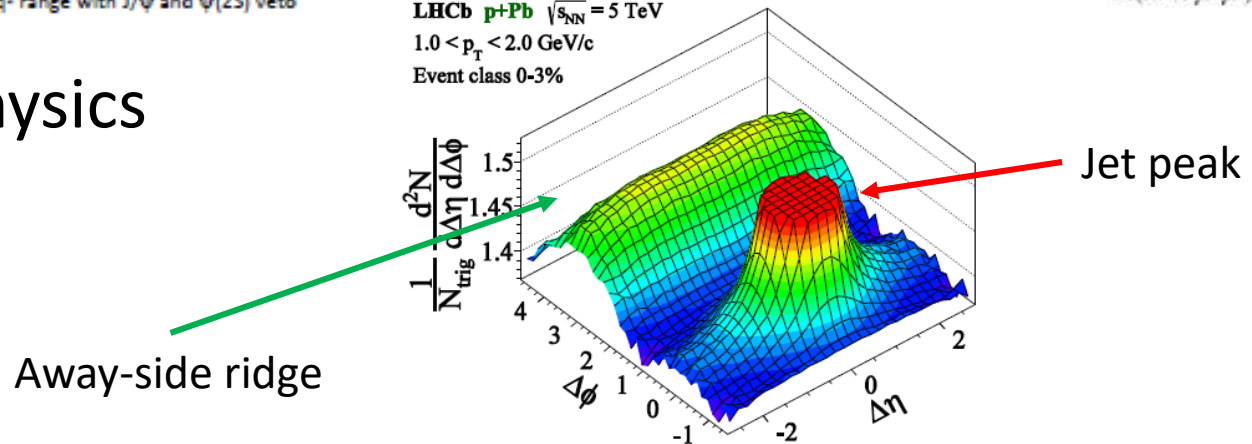
# LHCb also found CPV in $\Lambda$ decays
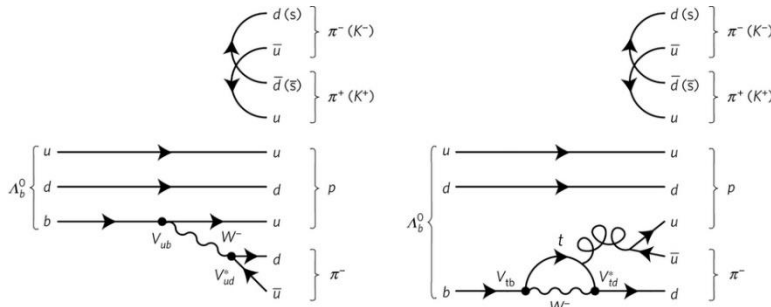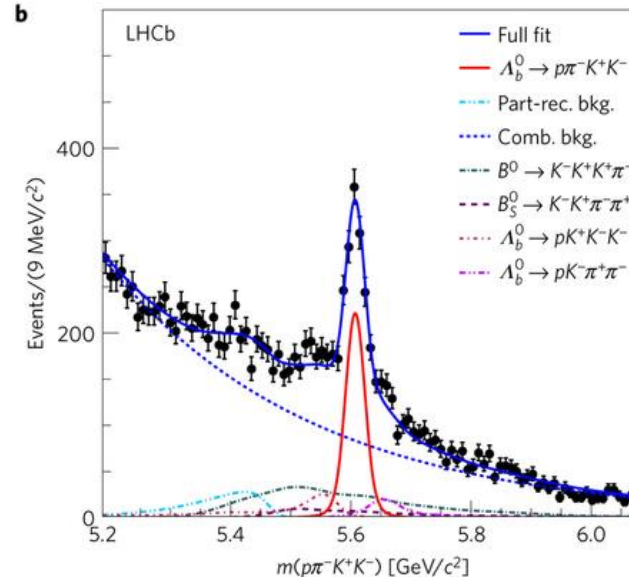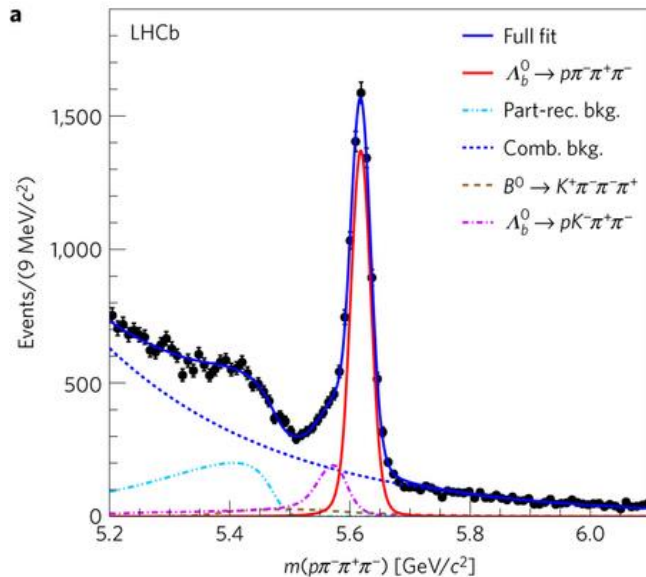


**First evidence of CP violation in baryons!!**
Looking at two rare decays:

a) $\Lambda_b^0 \to p\,\pi^-\pi^+\pi^-$

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

Diagrams similar magnitude (weak)
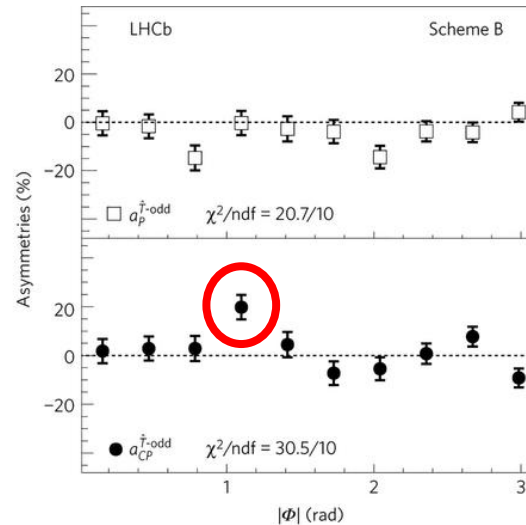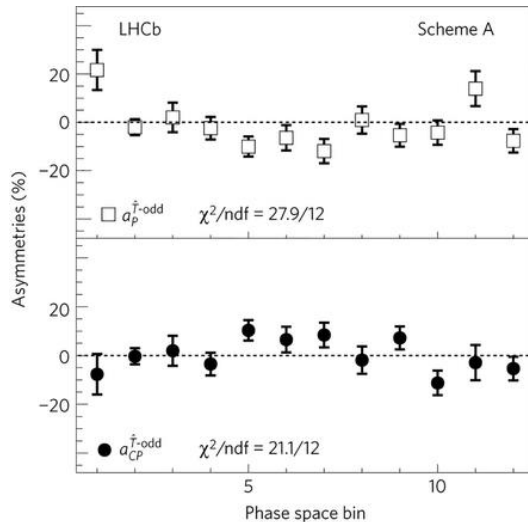CP violation would be parametrized in CKM angle $\alpha$



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:
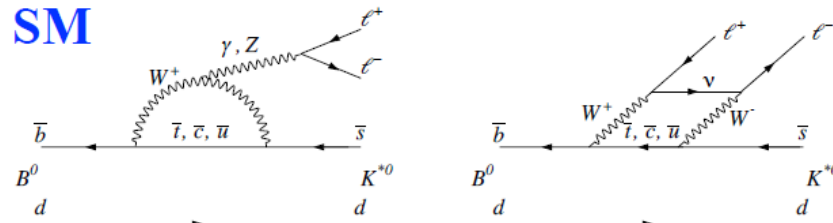


Asymmetry $19.79 \pm 4.95 \pm 0.60$

Beware: total effect is only 3.3 $\sigma$ ... but tantalizing and much needed
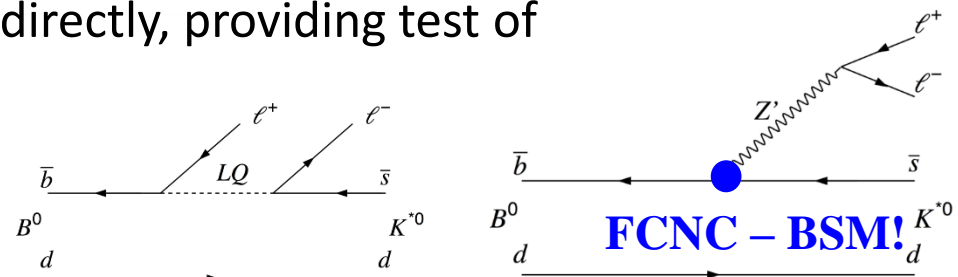
# Lepton flavor universality?

The $b \to s\ell^+\ell^-$ transition in the SM only through loops



New particles potentially contribute directly, providing test of lepton universality

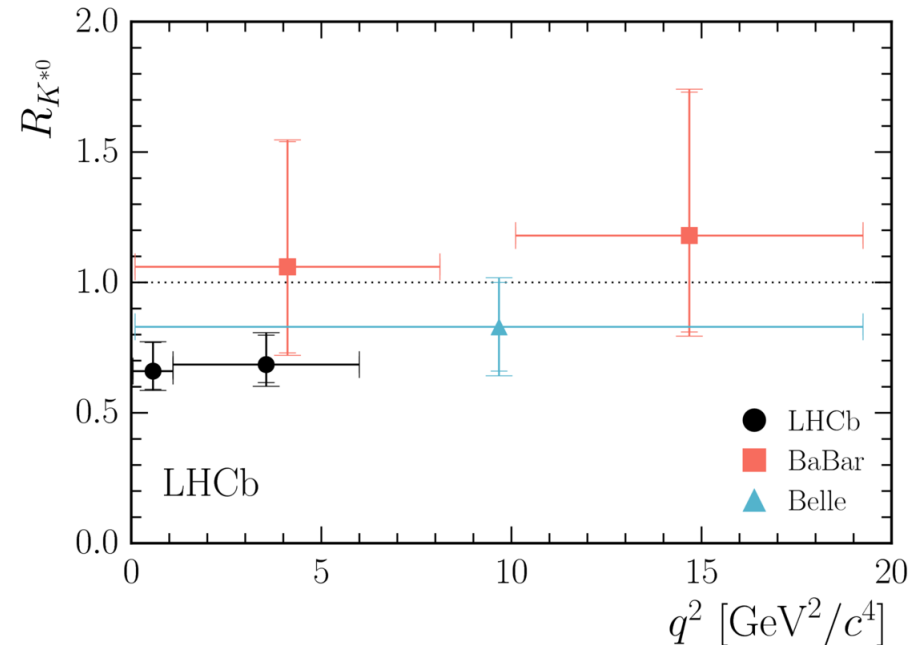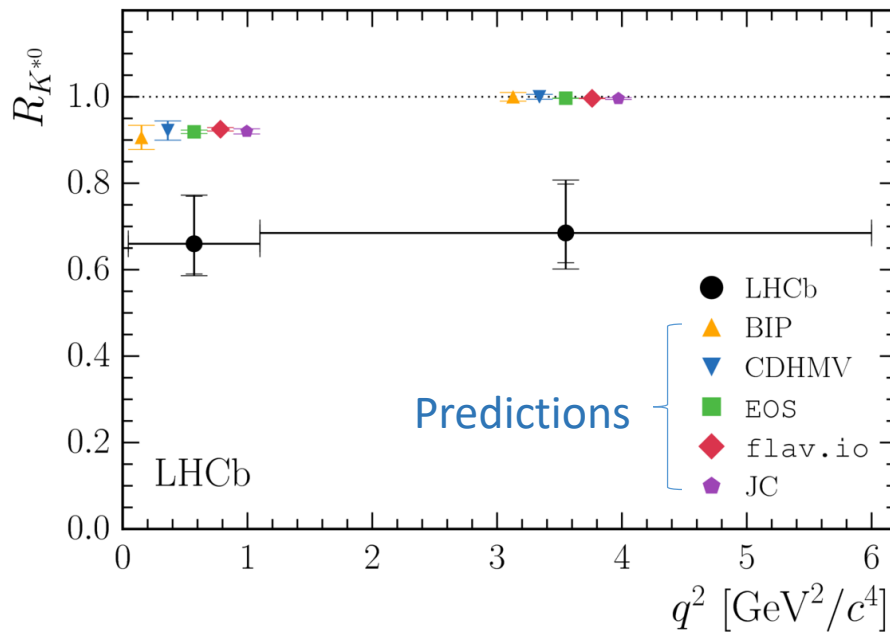Is it same coupling for e , $\mu$, and $\tau$?



Explored by LHCb paper arXiv:1705:05802



No lepton universality in detection:
Electron energy often lost to bremsstrahlung
Advanced recovery algorithms to correct for this but brem + trigger constraints means $\varepsilon(\mu) \cong 5 \times \varepsilon(e)$
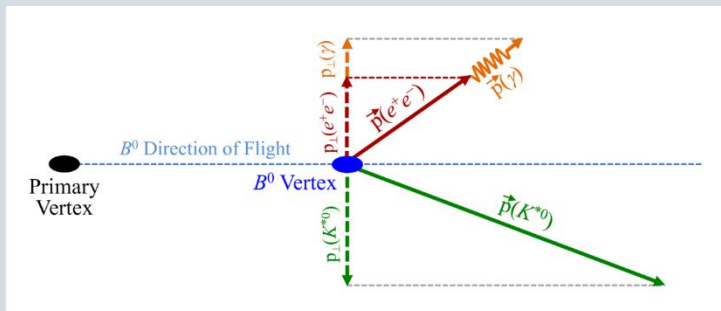
$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$



> The compatibility of the result in the **low-q²** with respect to the SM prediction(s) is of **2.2-2.4** standard deviations

> The compatibility of the result in the **central-q²** with respect to the SM prediction(s) is of **2.4-2.5** standard deviations

# 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 theHiggs, 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