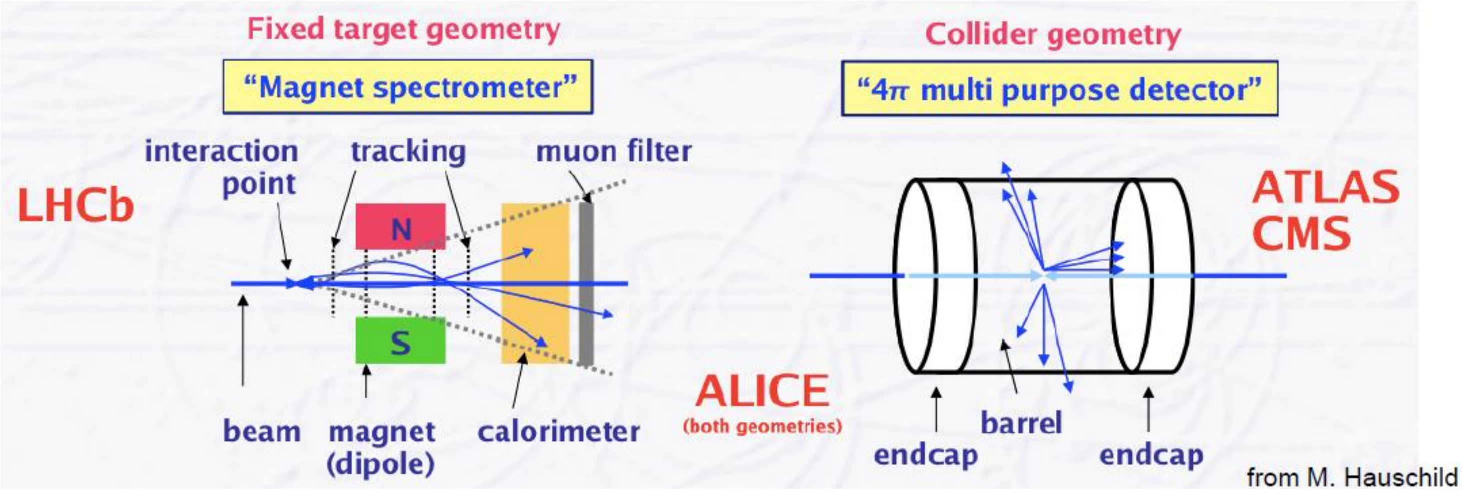
FASER, somewhere?

FYST17 Lecture 6
LHC Physics II



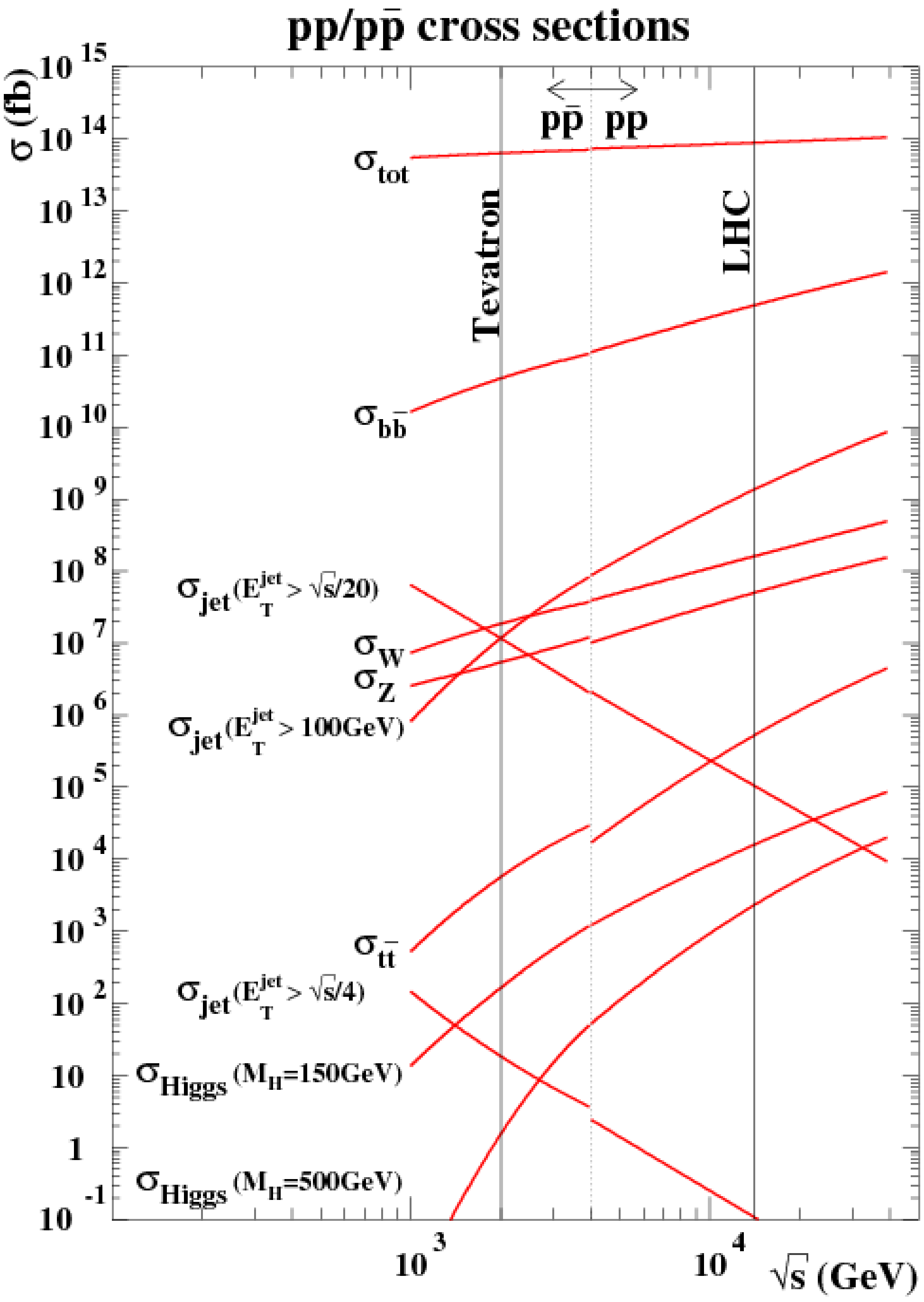
from M. Hauschild

Suggested reading: chap 13 (but mostly spread out throughout the book)

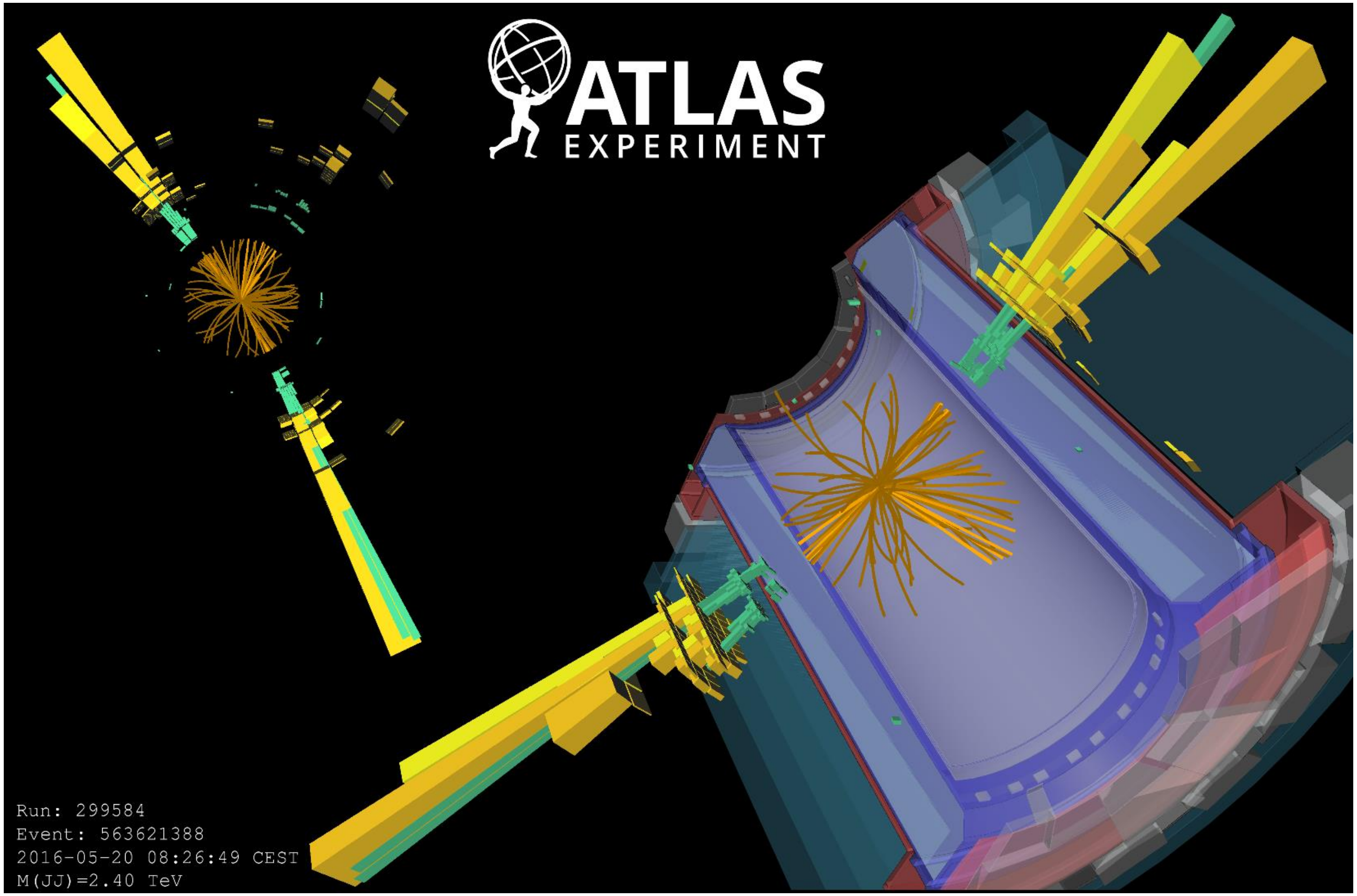
Today & Next week

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

Cross sections for different processes



Dijet event

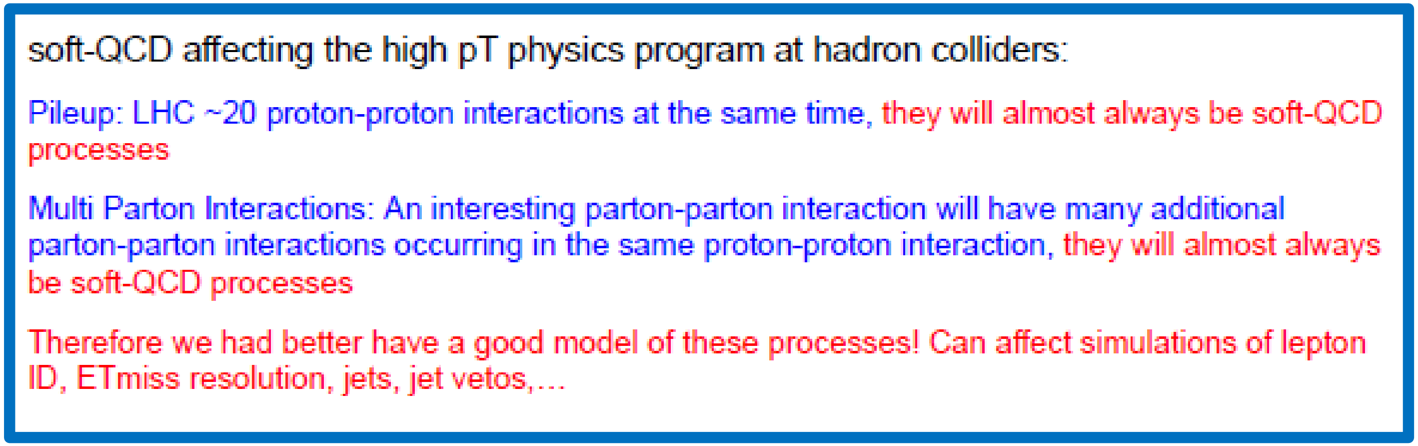


Diboson?

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:



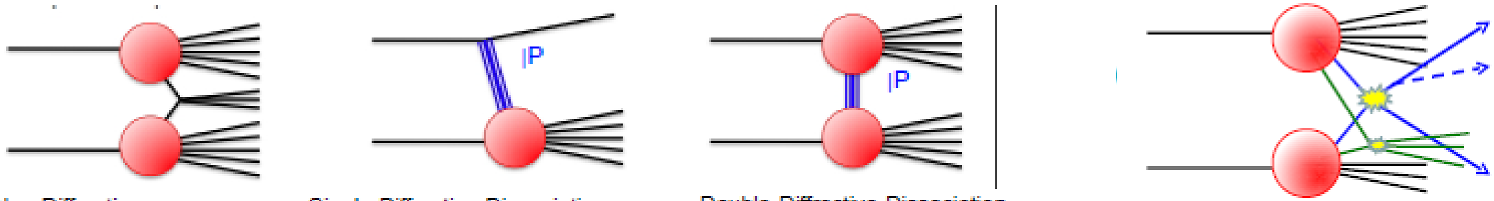
soft-QCD affecting the high pT physics program at hadron colliders:

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

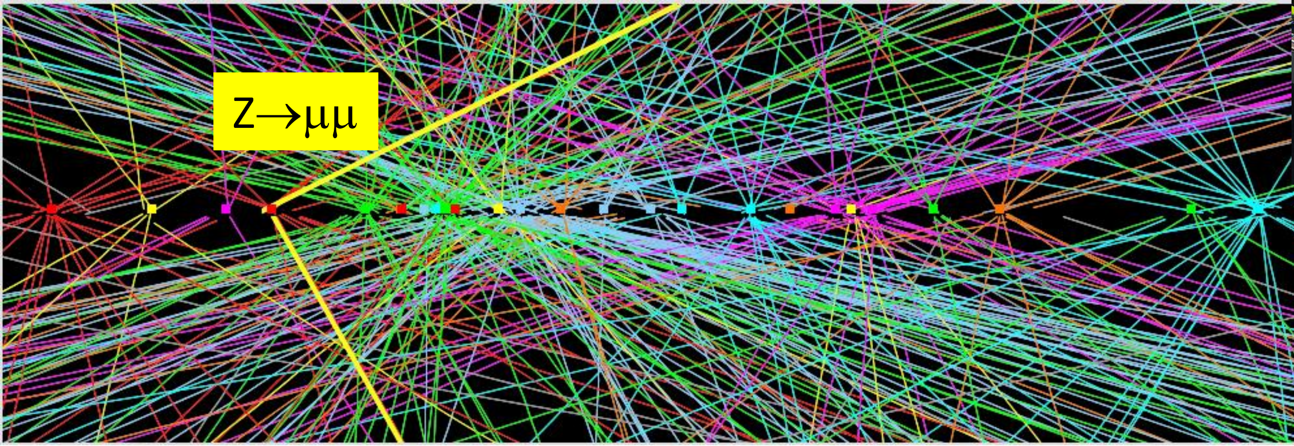
Single-Diffractive-Dissociation (SD) σ~14 mb

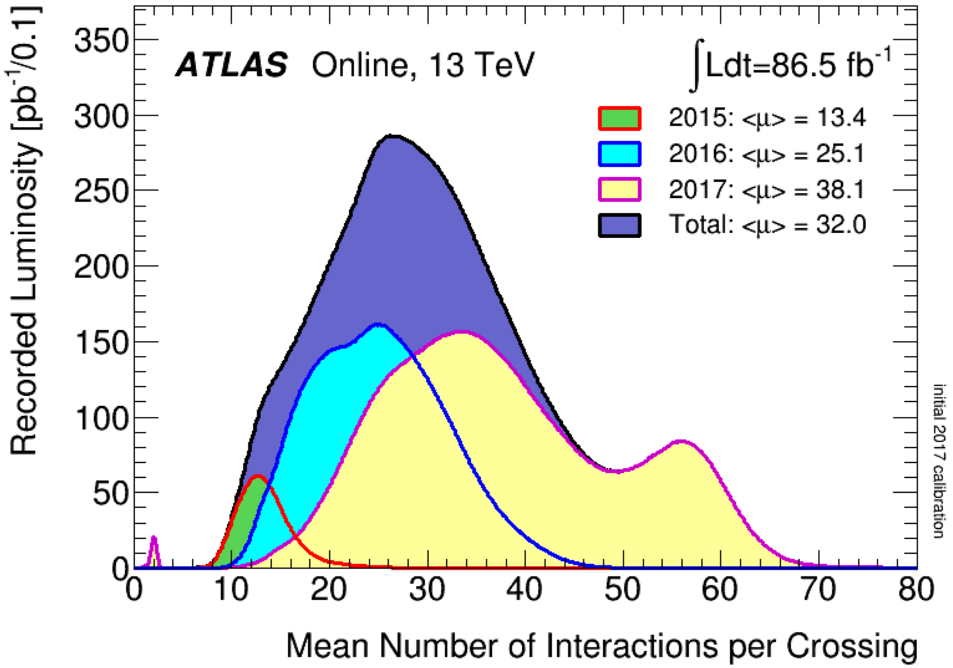
Double-Diffractive-Dissociation (DD) σ~9 mb

@ 7 TeV

Multiple parton interactions

Pile-up

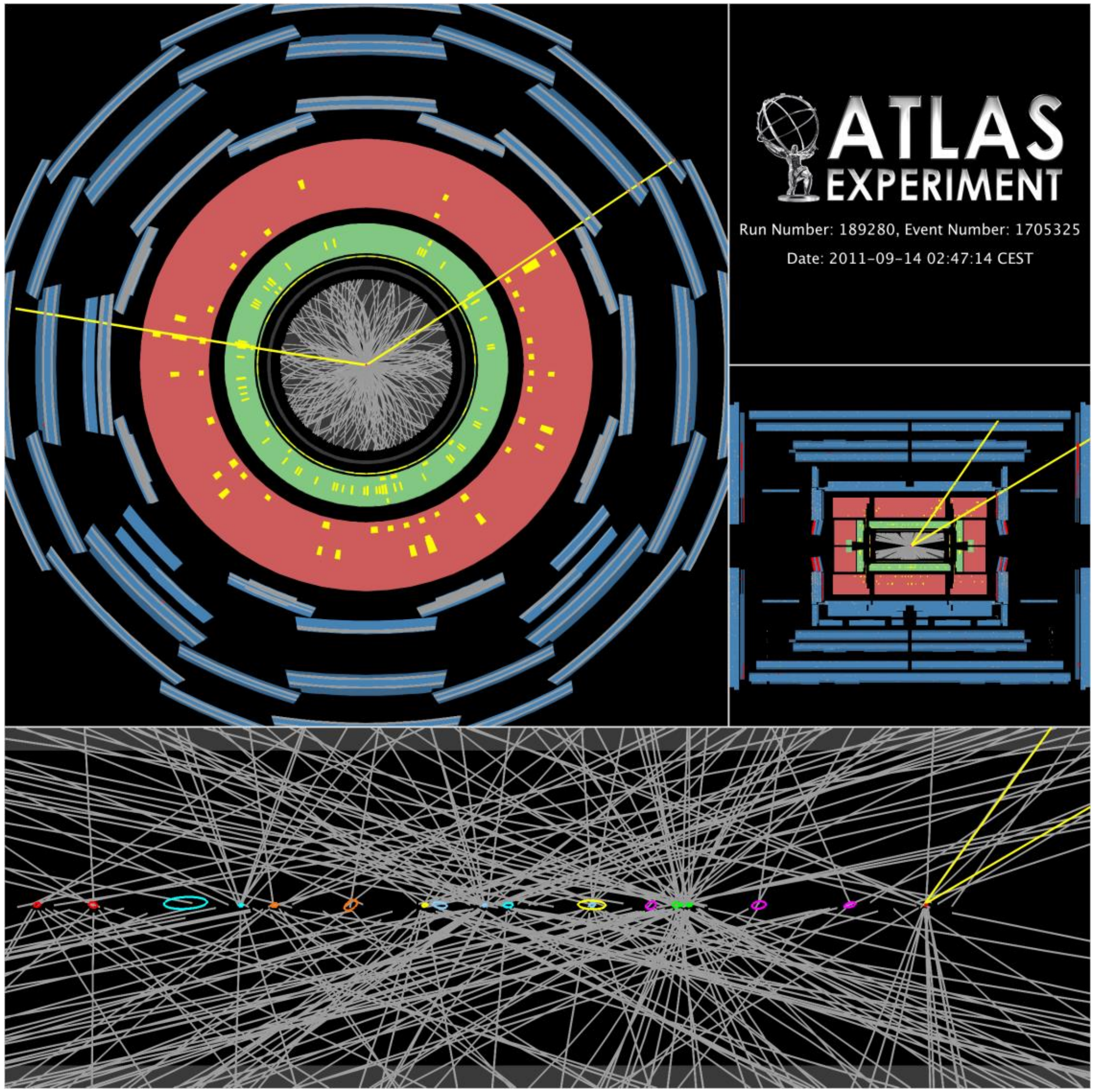




Due to the high number of protons/bunch high probability of multiple interactions

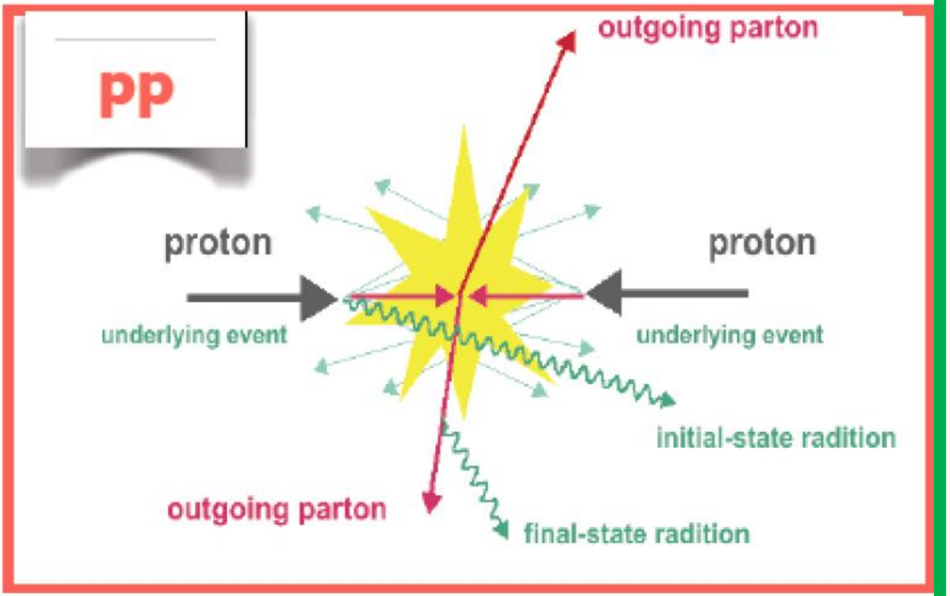
Majority of these uninteresting – but difficult to disentangle from the ”most” interesting hard scatter

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

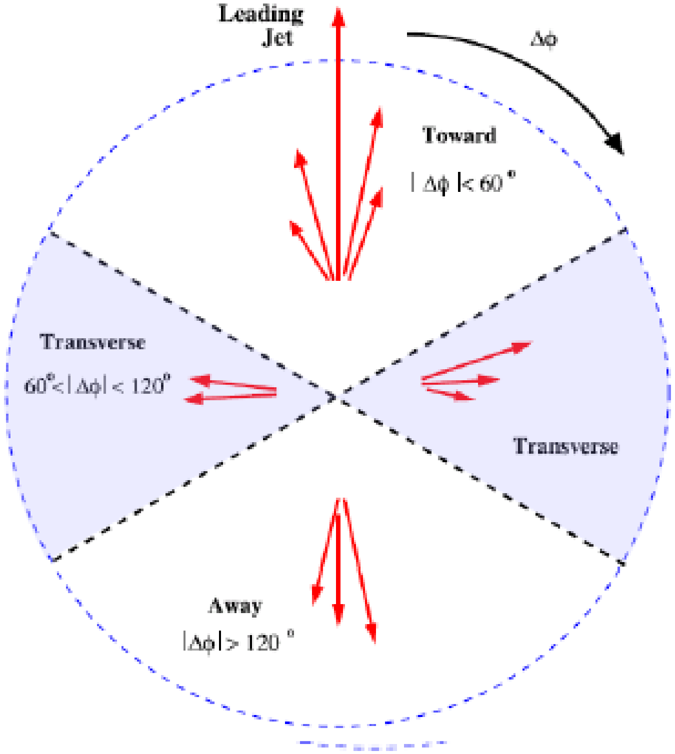
Jet events ideal for studying underlying event

- ✓ 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 <Σ p_T>

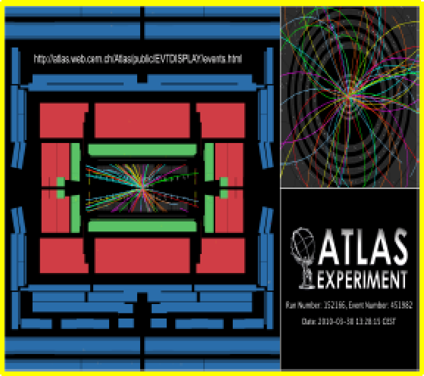


EPJ C 50, 435 (2007)

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)

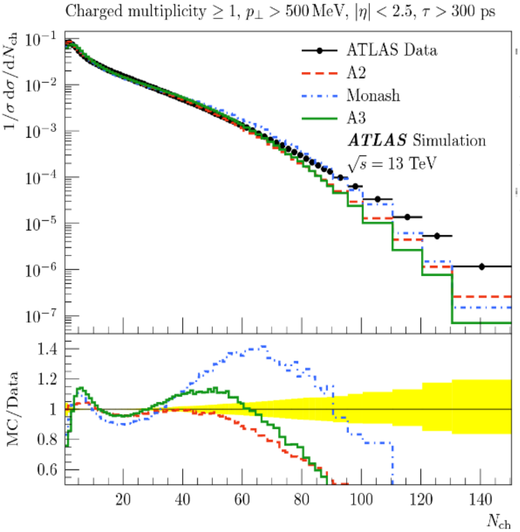
definition of minimum bias in each analysis

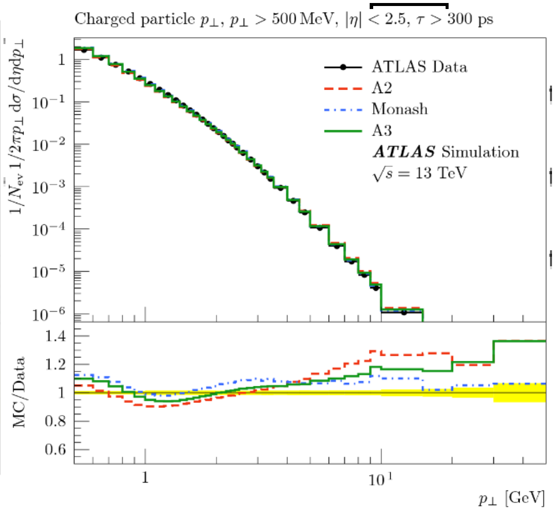
High p_T / EWK physics

Physics Modelling

A2 Minbias tune (for PU)

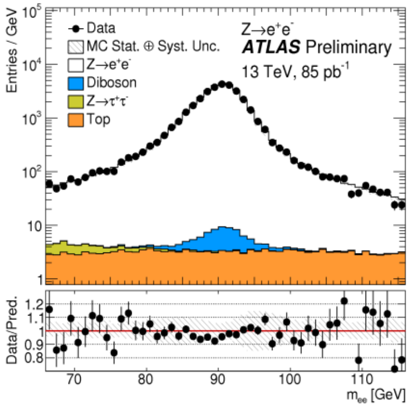
Pythia 6 and 8 (using 7 TeV ATLAS data only)

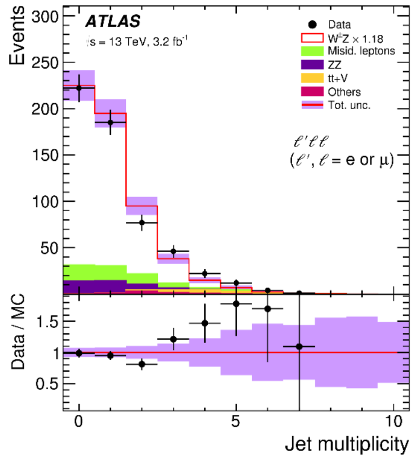




V+Jets , Dibosons, Tribosons

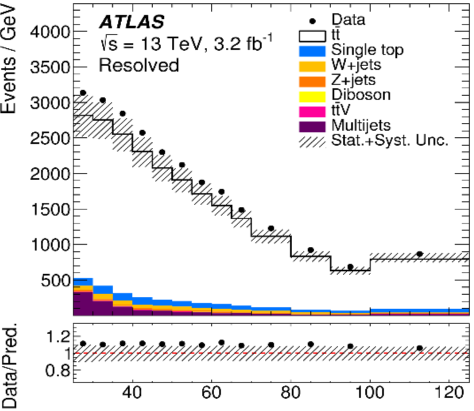
Sherpa NLO (2partons) and LO (up to 4 partons) 2.1.1

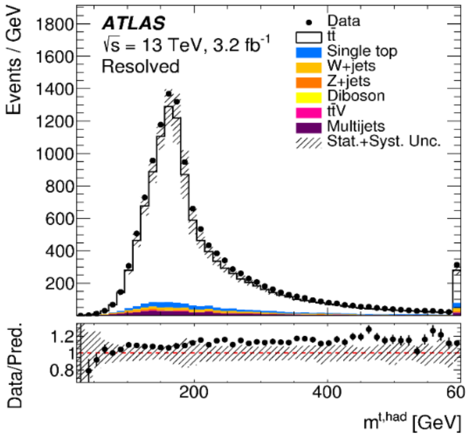




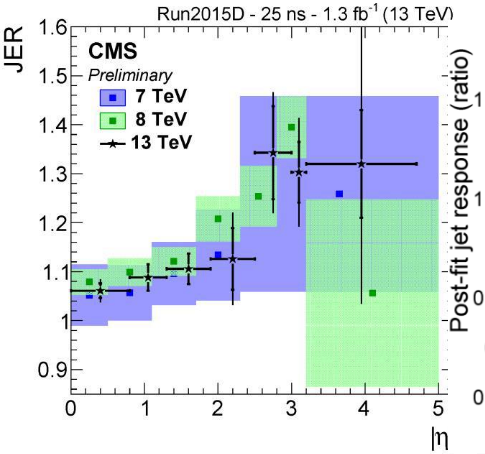
Top pair production

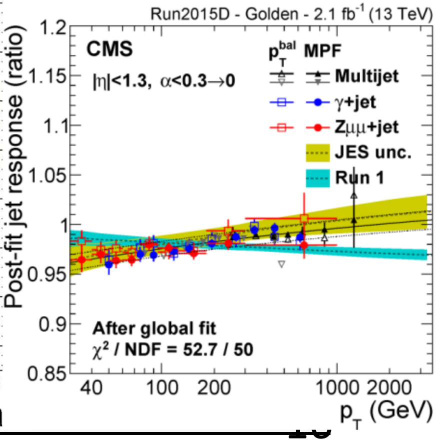
Powheg-Box v2 (hdamp =m_t) – Pythia 6.428 – EvtGen (HF decays) - CT10 PDFs – Perugia 2012 tune



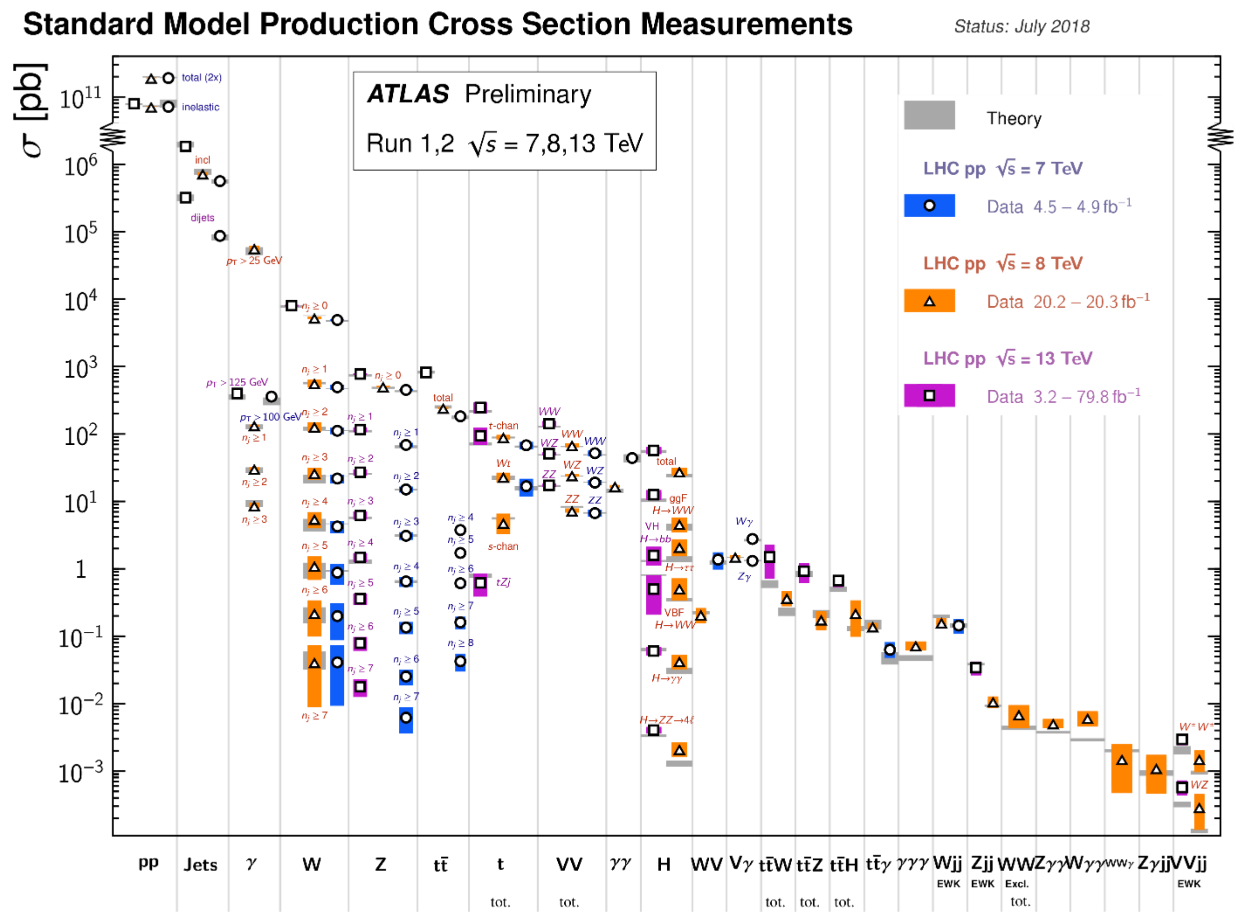


Jet quality

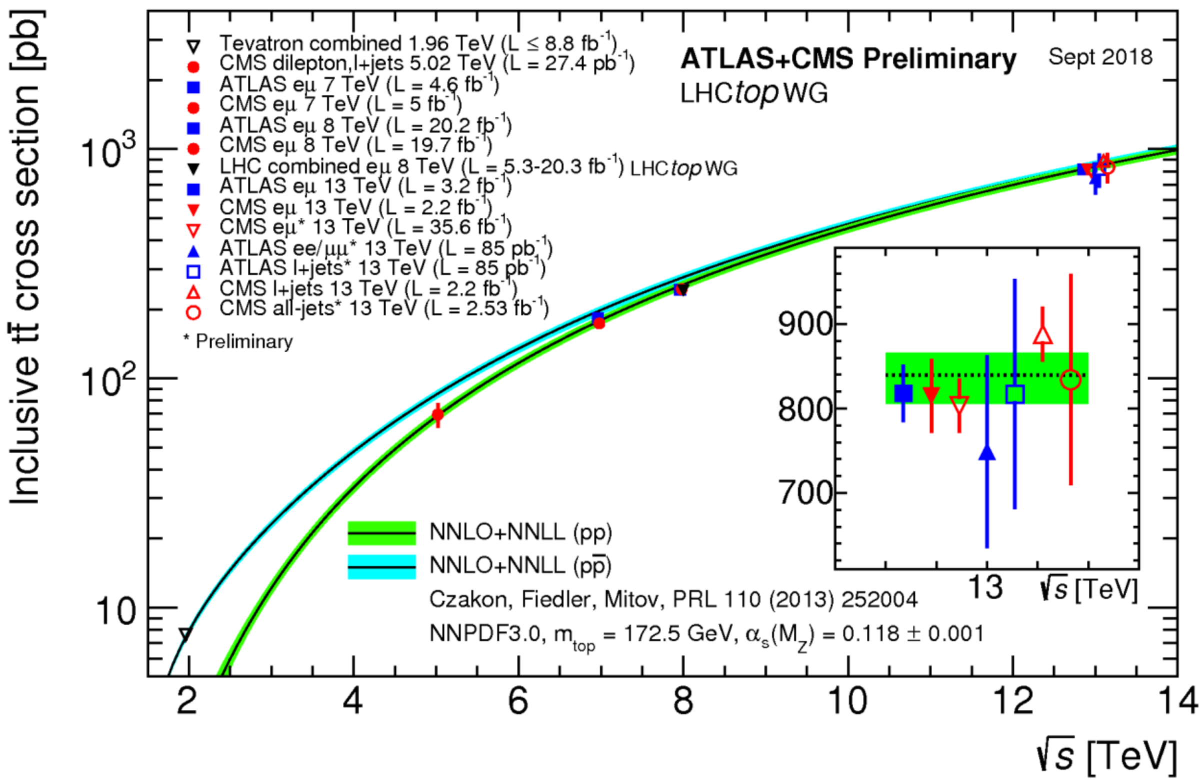


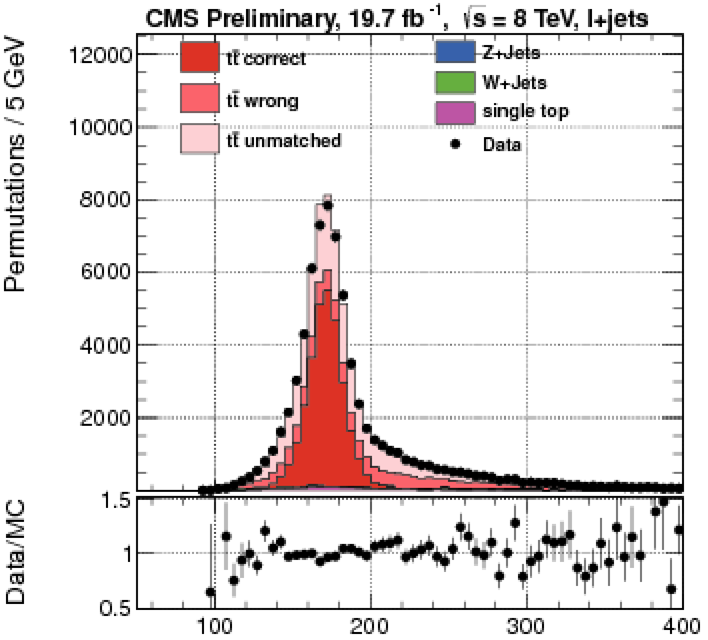


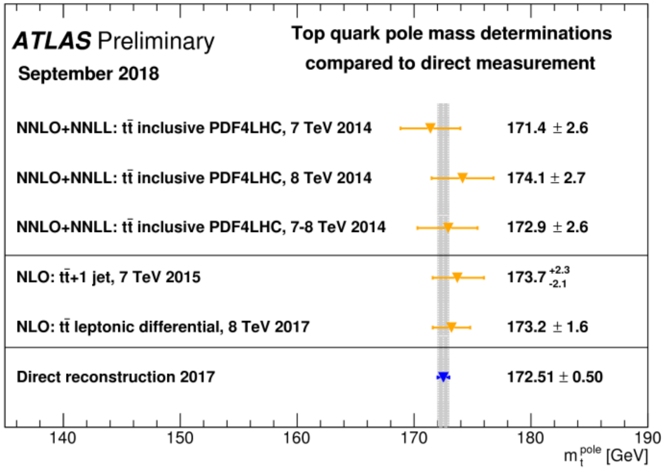
Standard Model measurements



Close-in on the top quark



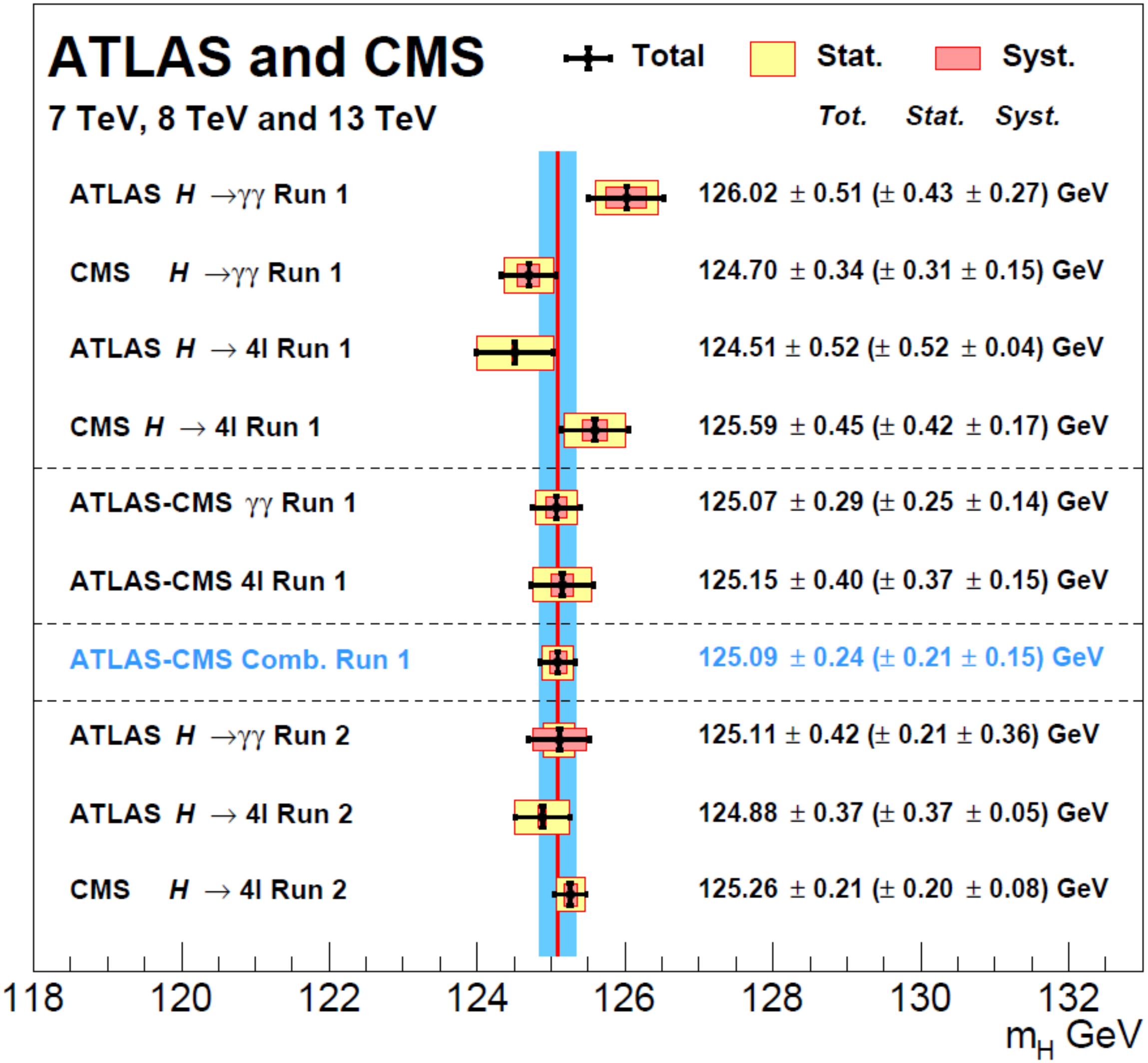




World combined (2014)

M_{top} = 173.34 ± 0.76 GeV

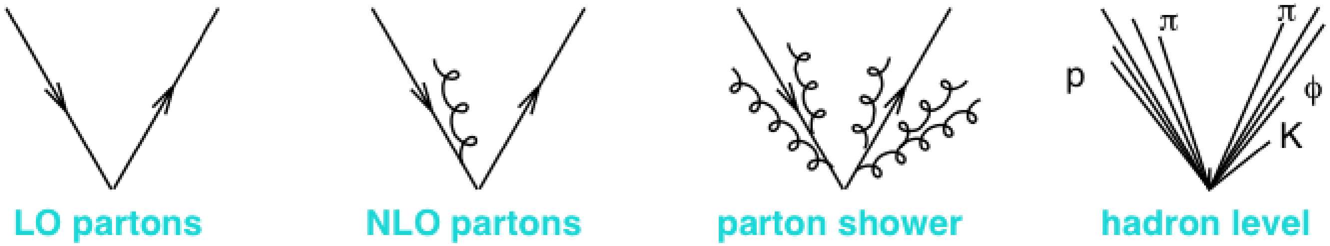
Higgs measurements

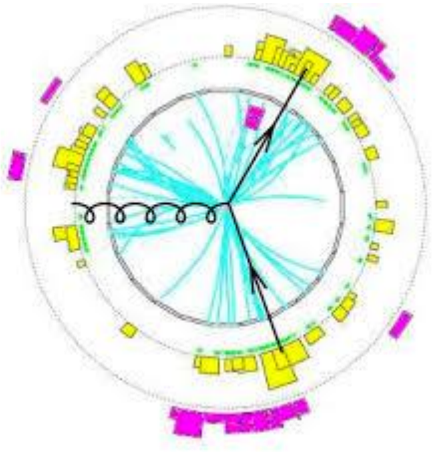


PDG

Identification of jets and leptons

Jet algorithms

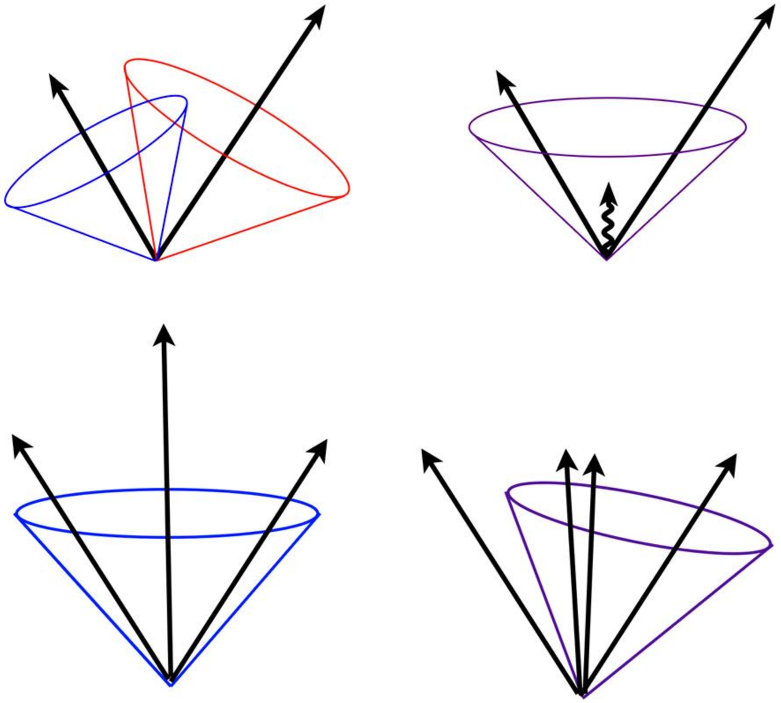




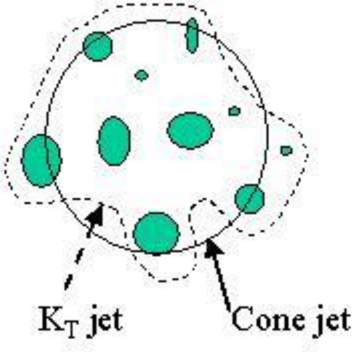
How to define a ”jet”? A few different approaches:

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

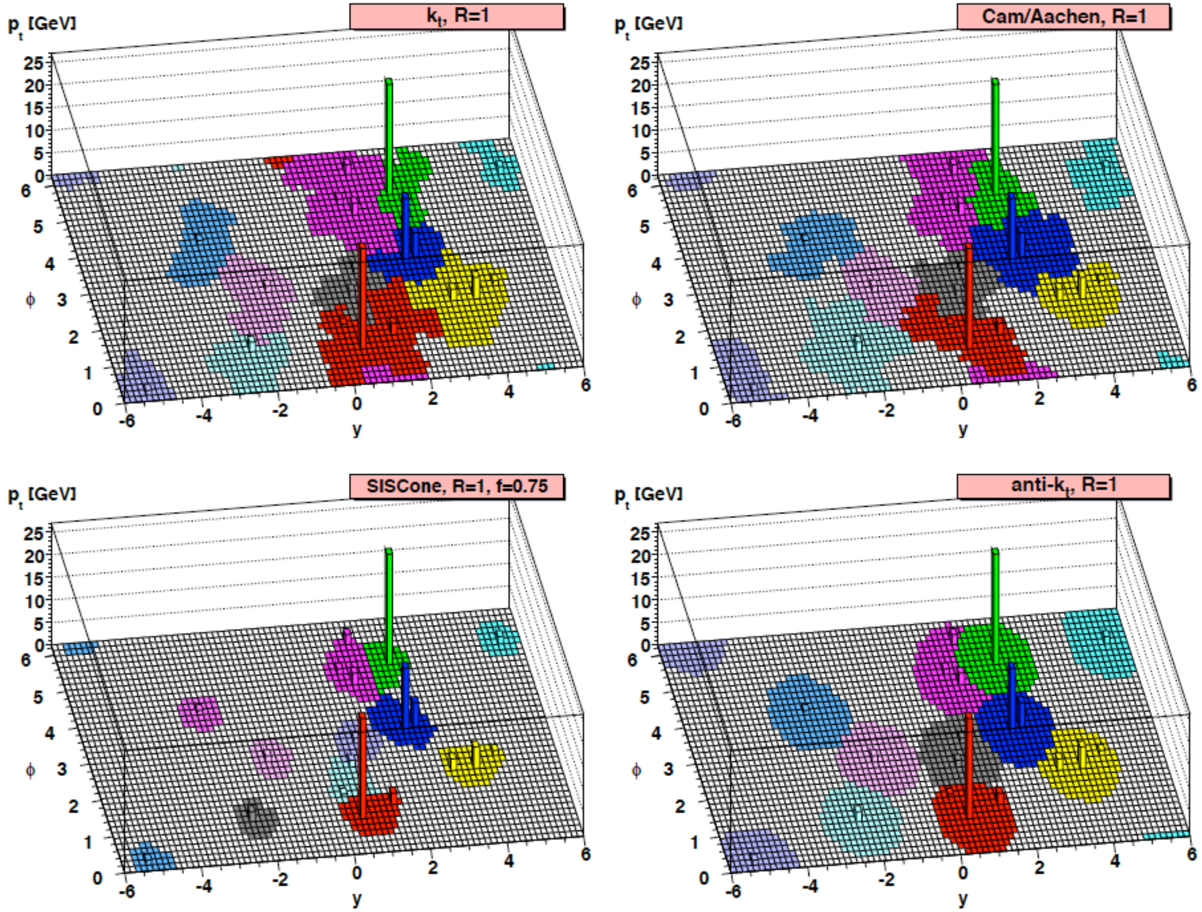
p=+1: k_T algorimth. p =-1: anti-k_T algorithm (favoring recombination of high-pt particles)

Comparison

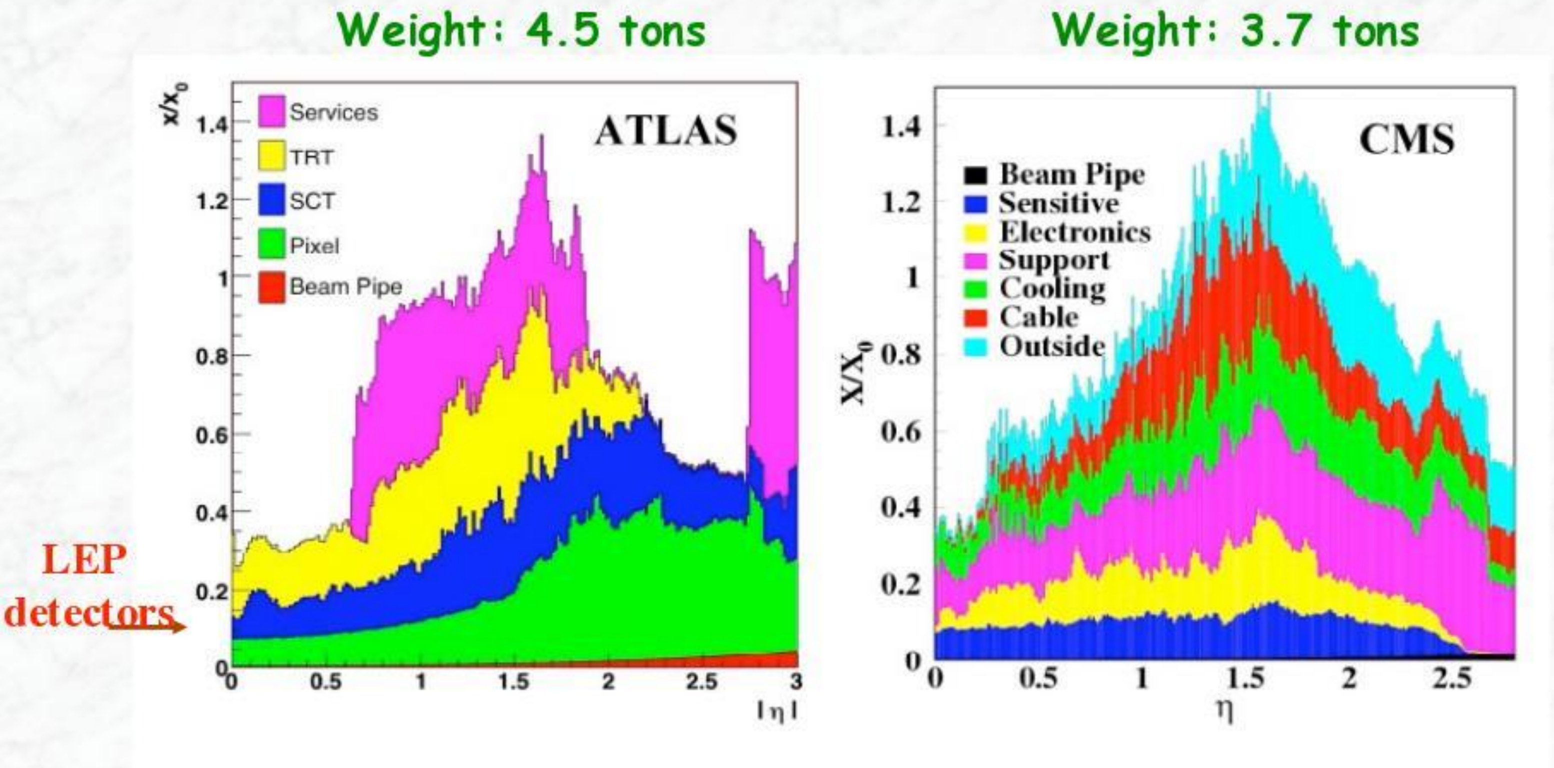
Anti-kt mostly used at the LHC

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

(p=0)



Amount of material in ATLAS and CMS inner trackers


Weight: 4.5 tons

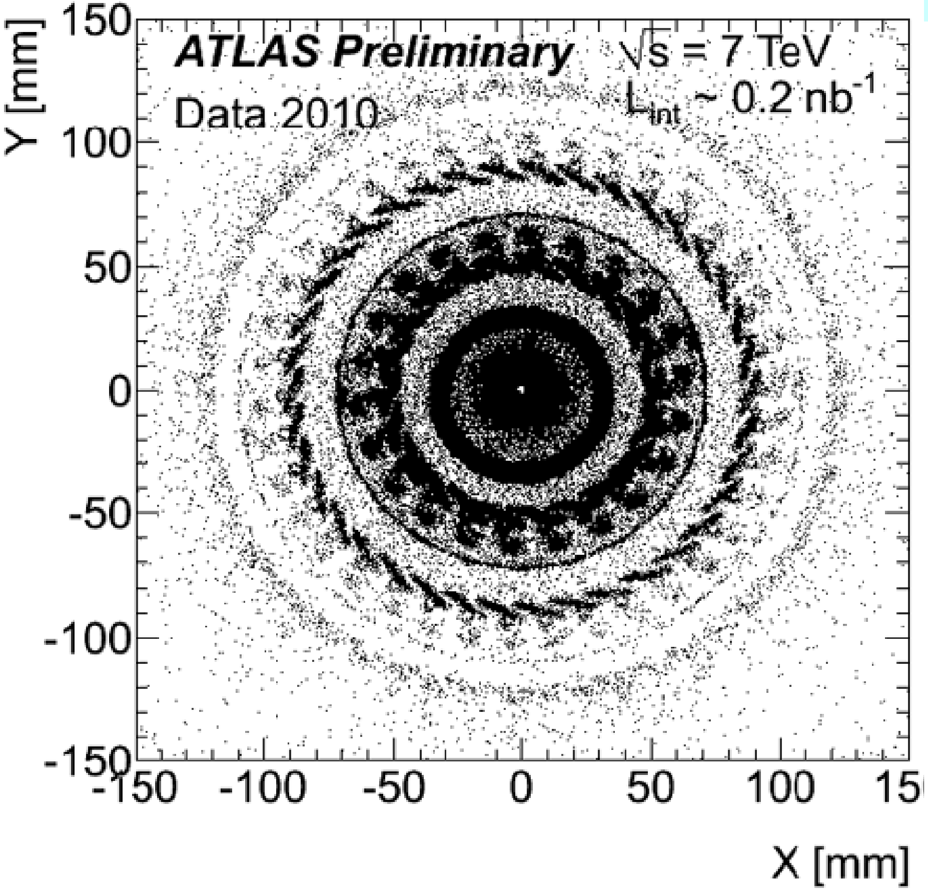
Weight: 3.7 tons

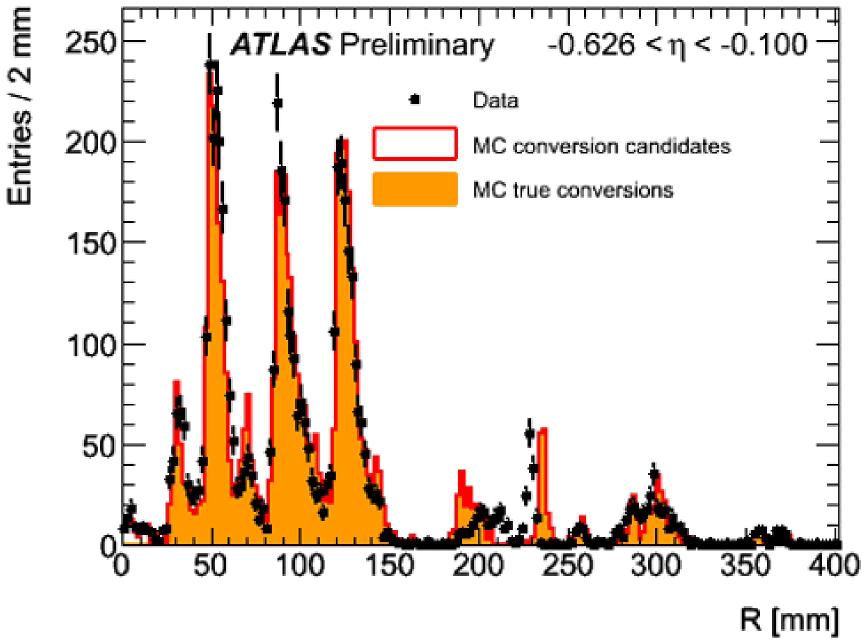
LEP detectors

- 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

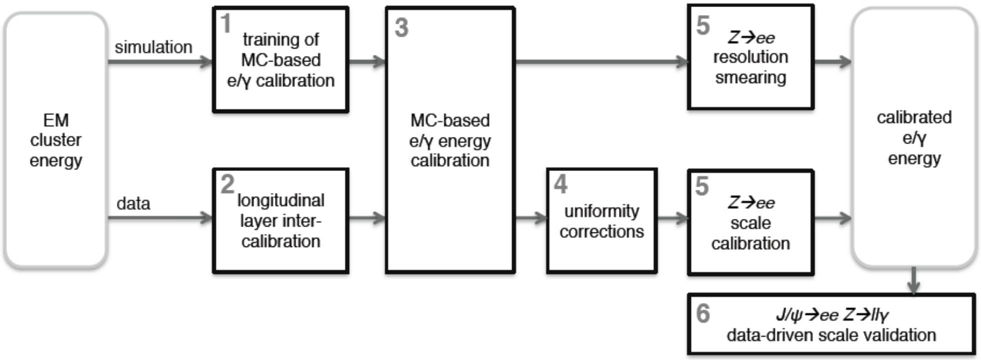
Reconstructed photon conversions show clearly the location of (Si) tracking modules!

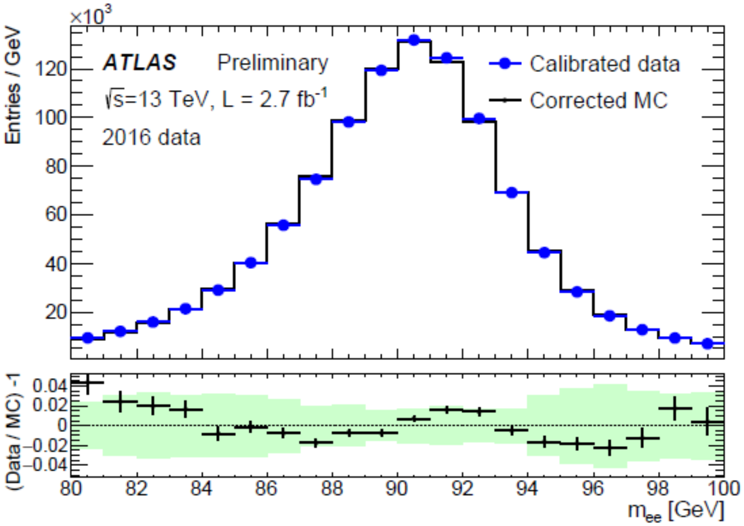




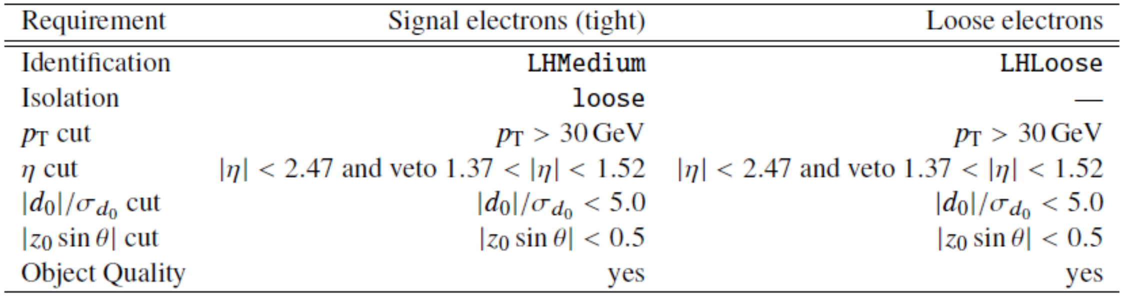
Example: electrons in ATLAS

Calibration of EM calo reponse



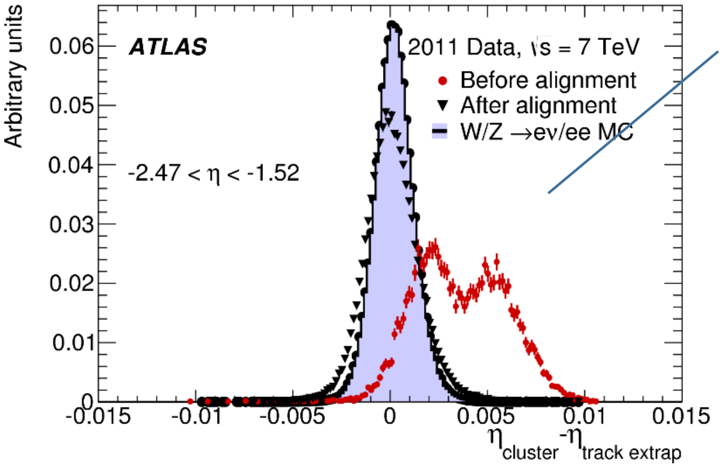


What is an electron? A matter of definition.
In my current analysis we decided for:

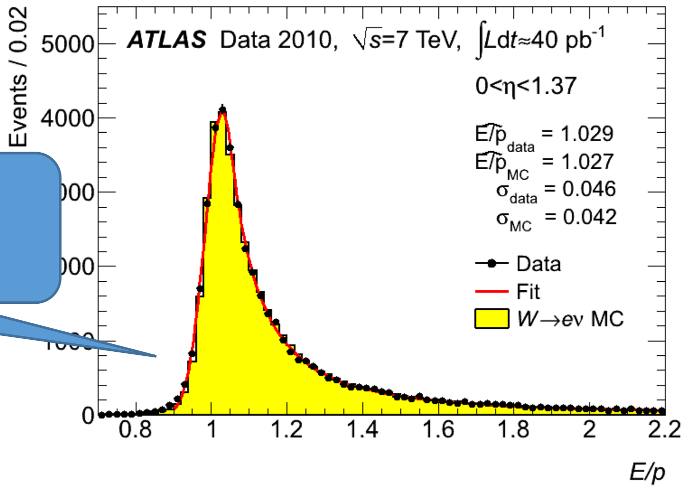


Requirement	Signal electrons (tight)	Loose electrons
Identification	`LHMedium`	`LHLoose`
Isolation	`loose`	—
p_T cut	$p_T > 30\,\text{GeV}$	$p_T > 30\,\text{GeV}$
η cut	$\lvert\eta\rvert < 2.47$ and veto $1.37 < \lvert\eta\rvert < 1.52$	$\lvert\eta\rvert < 2.47$ and veto $1.37 < \lvert\eta\rvert < 1.52$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

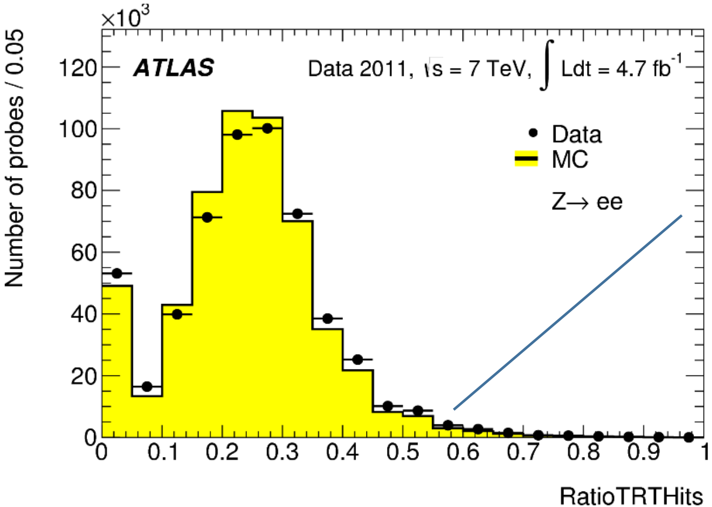
Several variables to play with, for instance



How well are the track and the EM cluster matched?

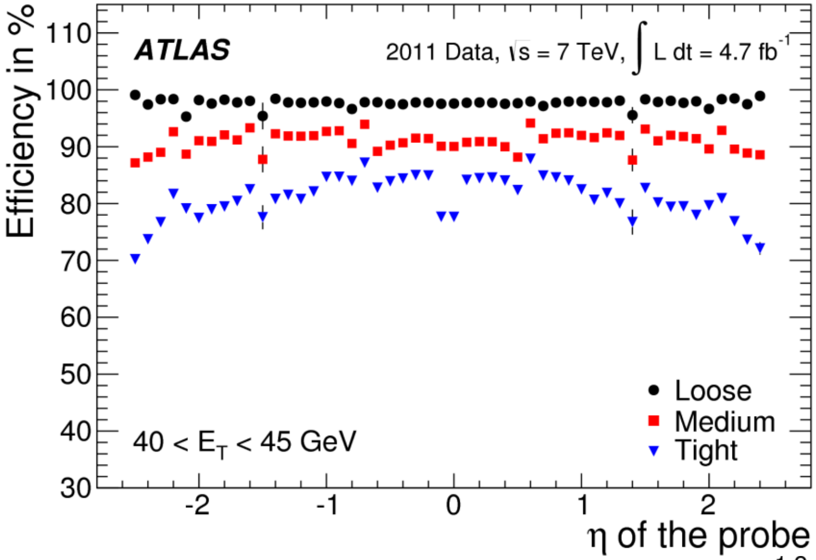


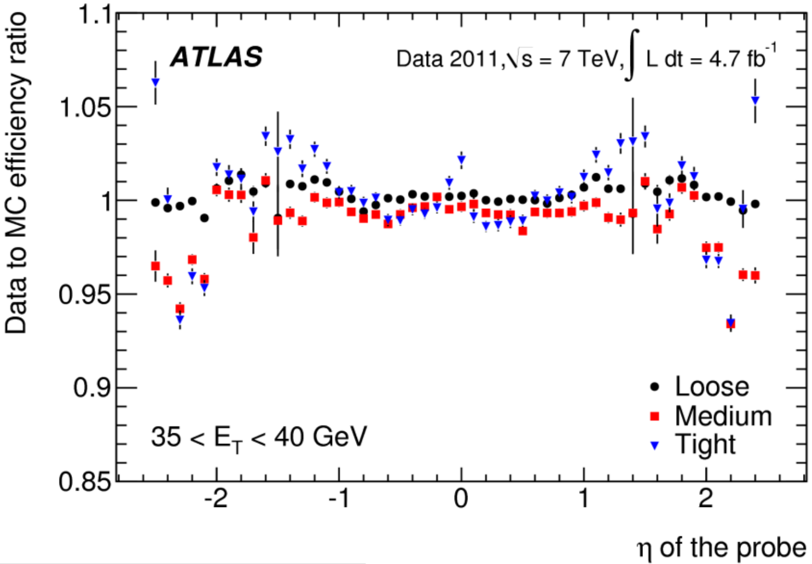
Is the E/p ratio close to 1?

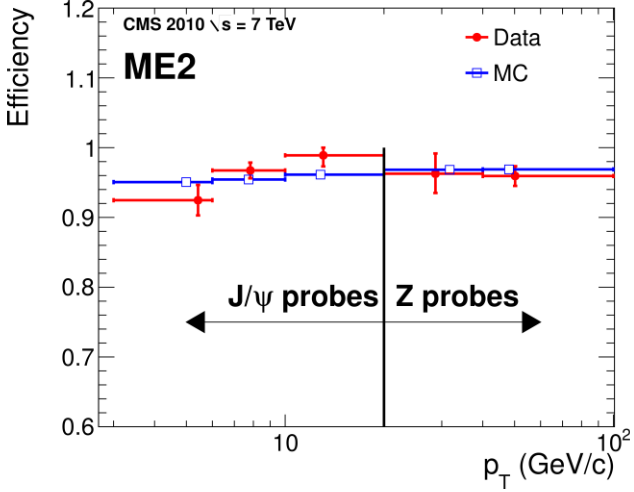


Are the number of transition radiation hits high enough?

Leptons identification efficiencies

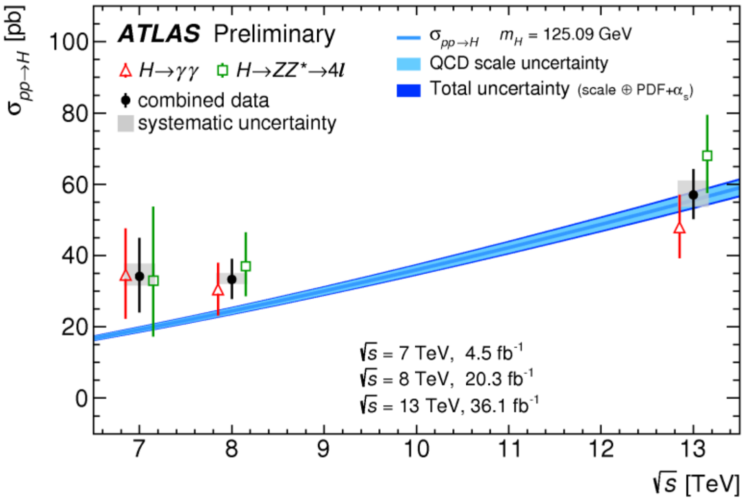




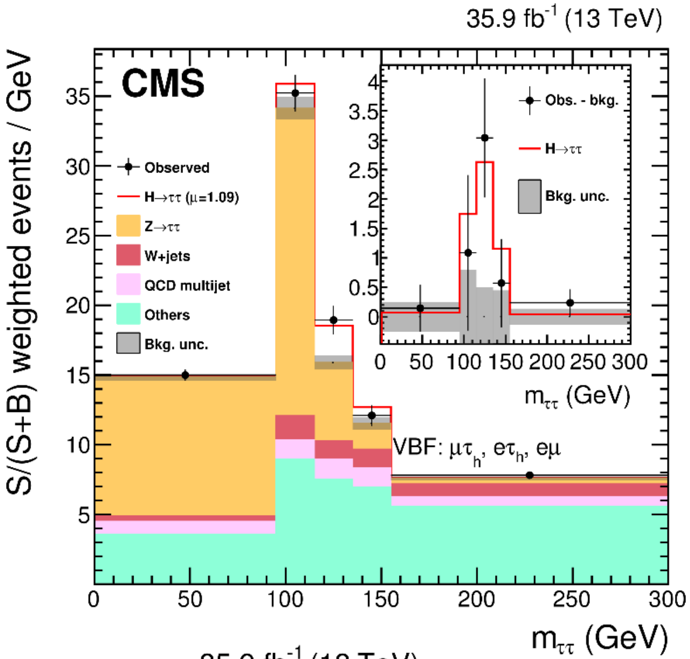


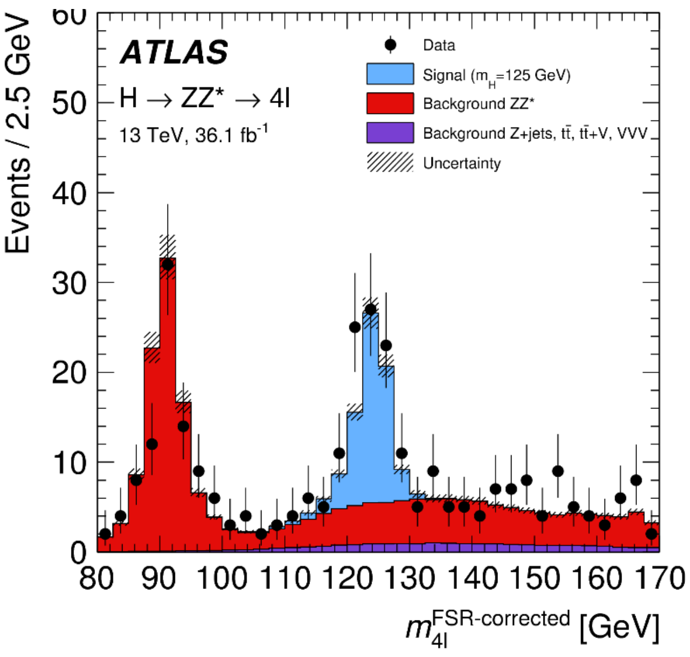
Latest on the Standard Model: a few recent results

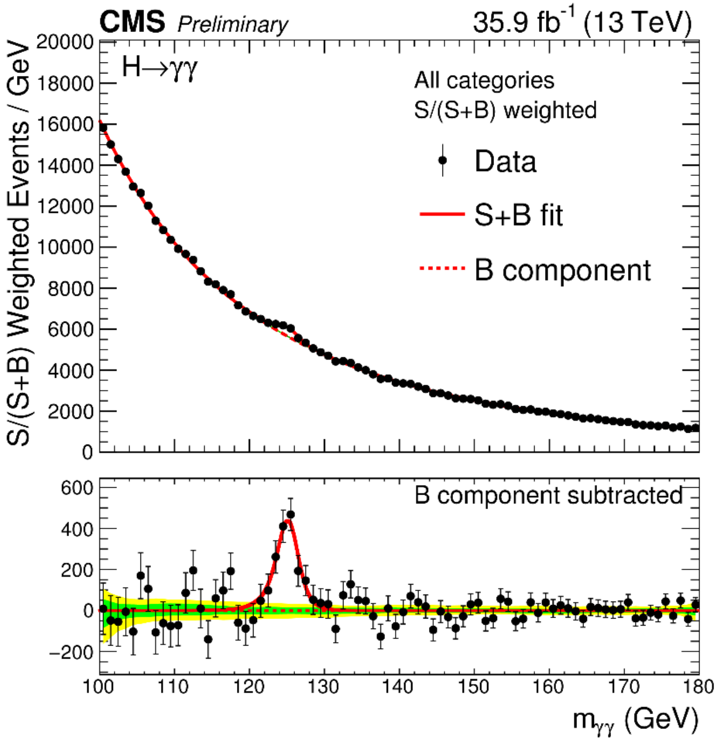
The Higgs @ 13 TeV



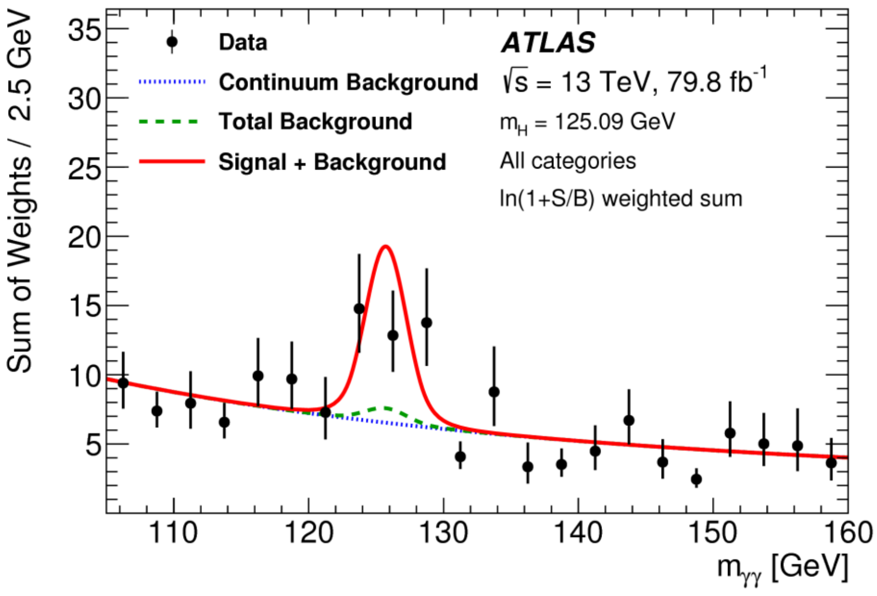
Consistent picture with the higher energy

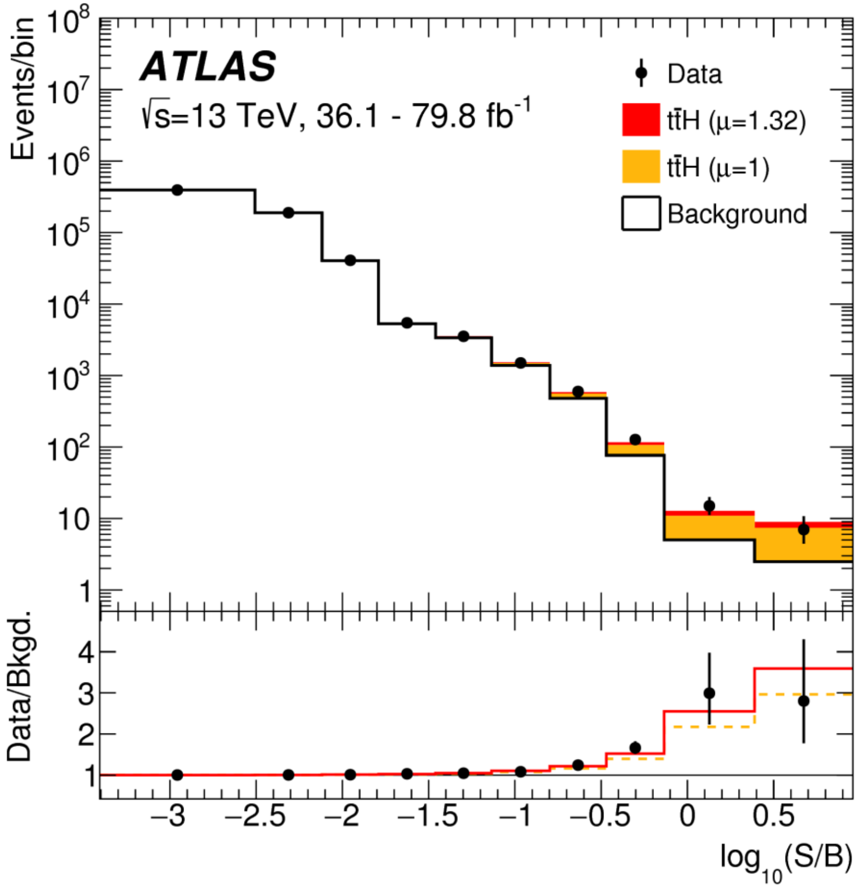






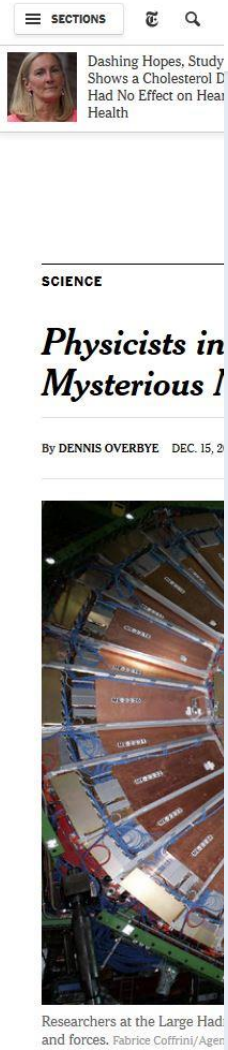
ttH coupling





Now observed above 5 sigma level
Combination of several channels / decay modes of the Higgs

A New Particle?



SECTIONS

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

SCIENCE

Physicists in Mysterious

By DENNIS OVERBYE DEC. 15, 2

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

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

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

lture business lifest ≡ all

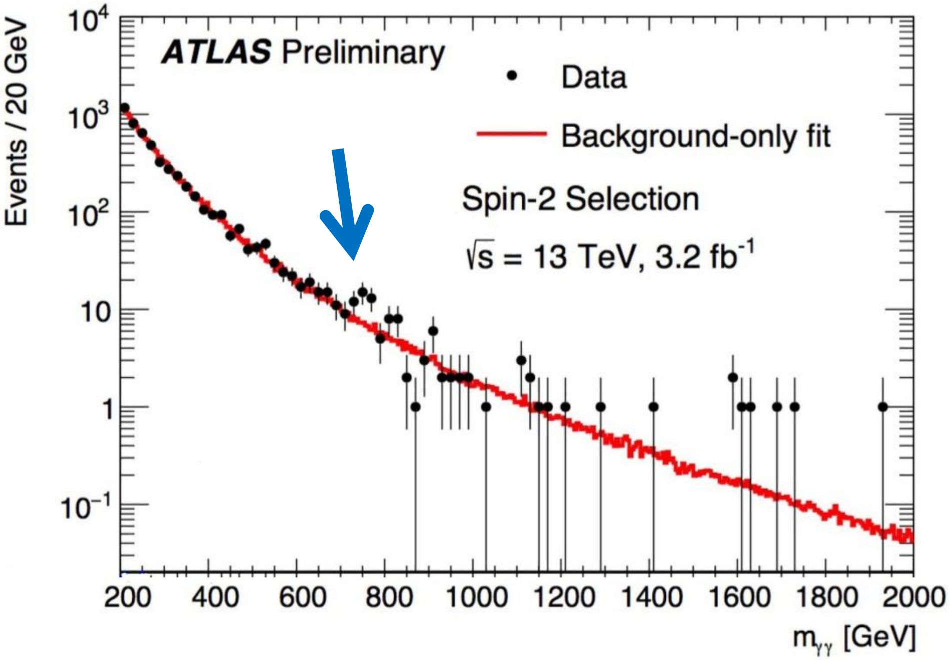
ron Collider

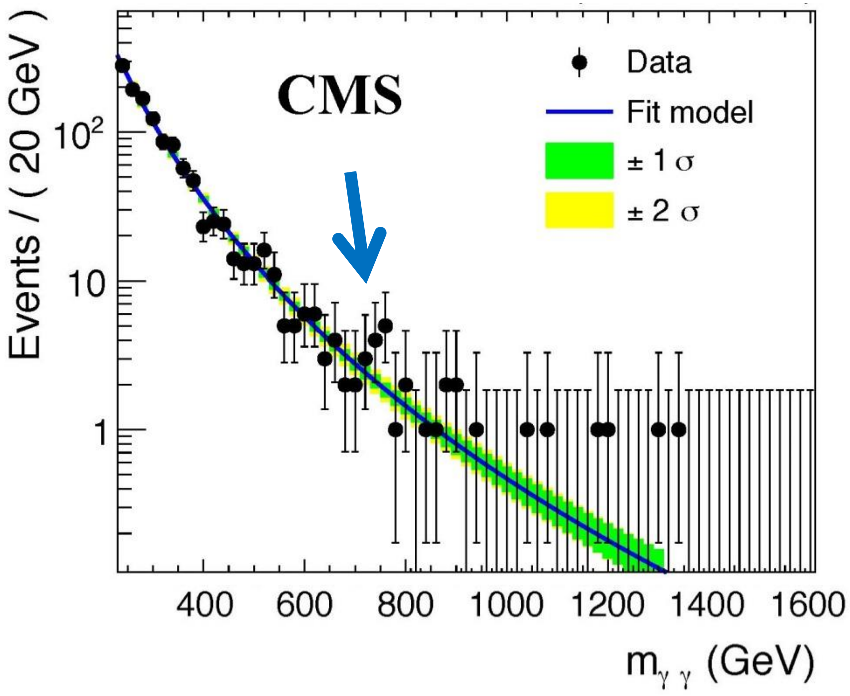
shes of light spotted inside

nd destruction of a new

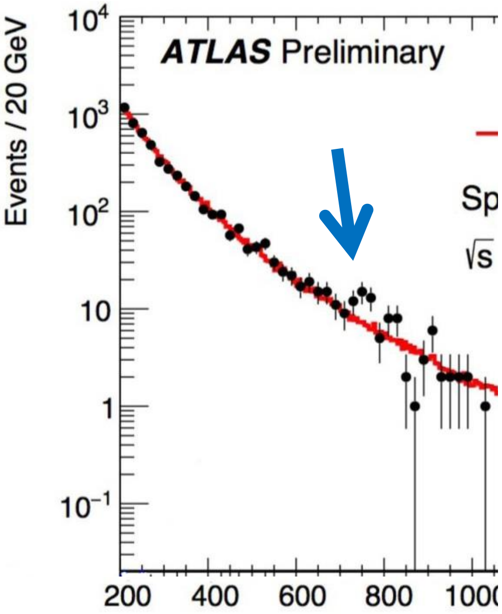
A New Particle?!

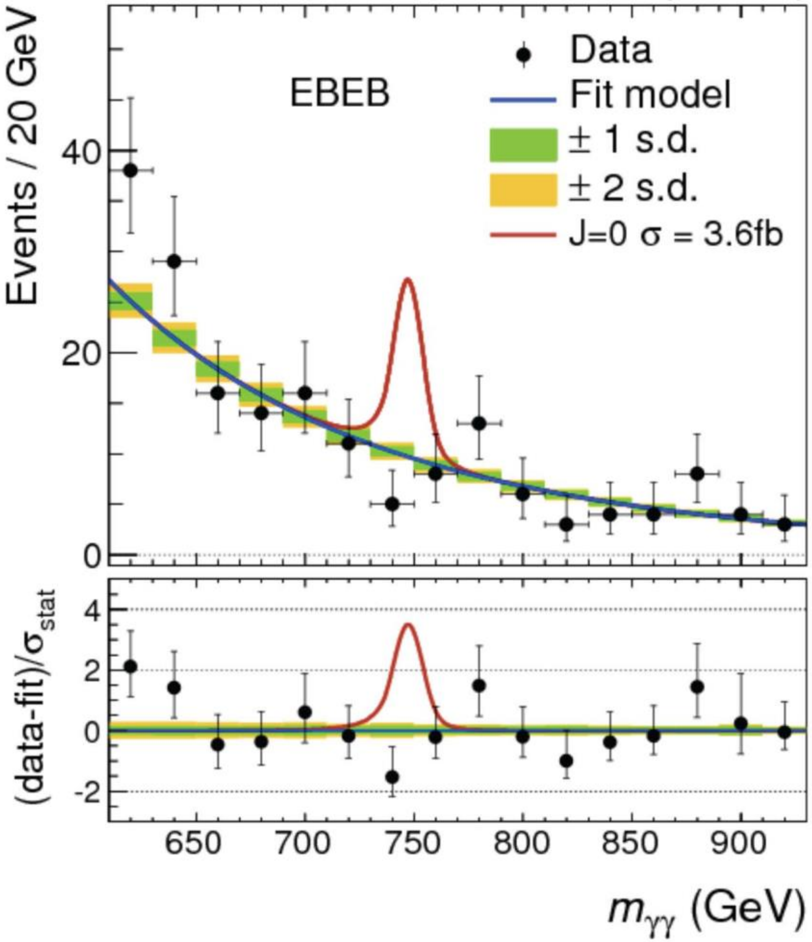
Both ATLAS and CMS sees a little peak in the diphoton invariant mass spectrum in the same spot when investigating the first 13 TeV collisions in 2015!

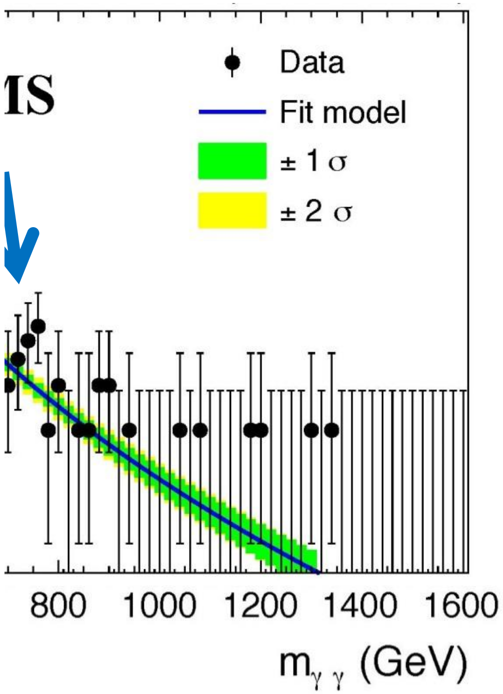




A New Particle?!

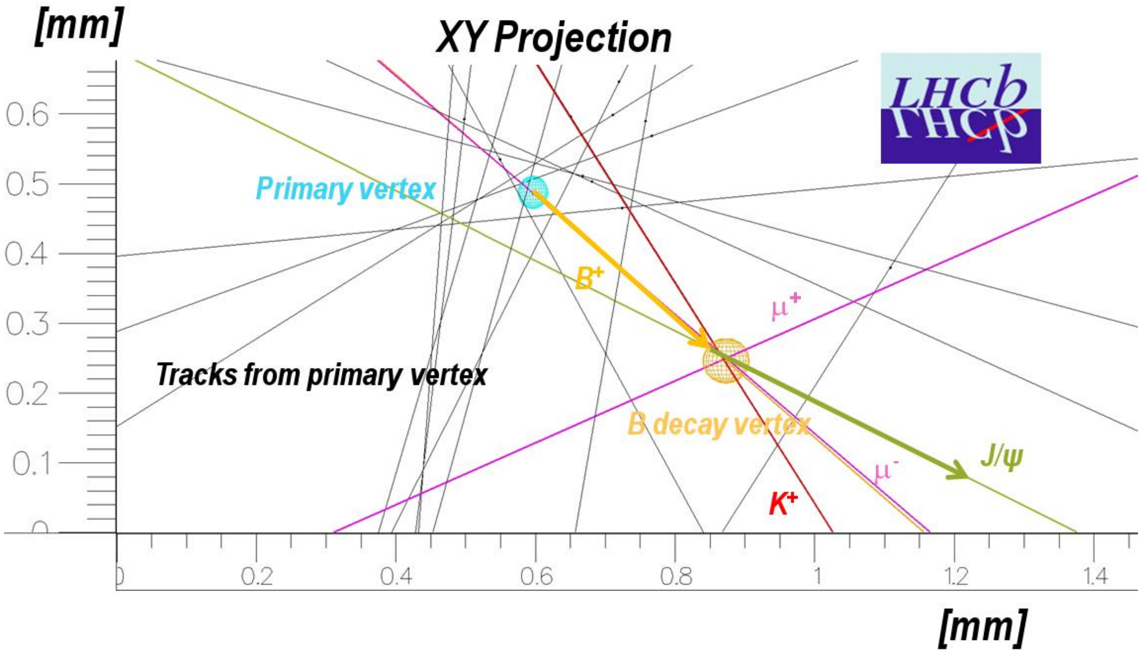


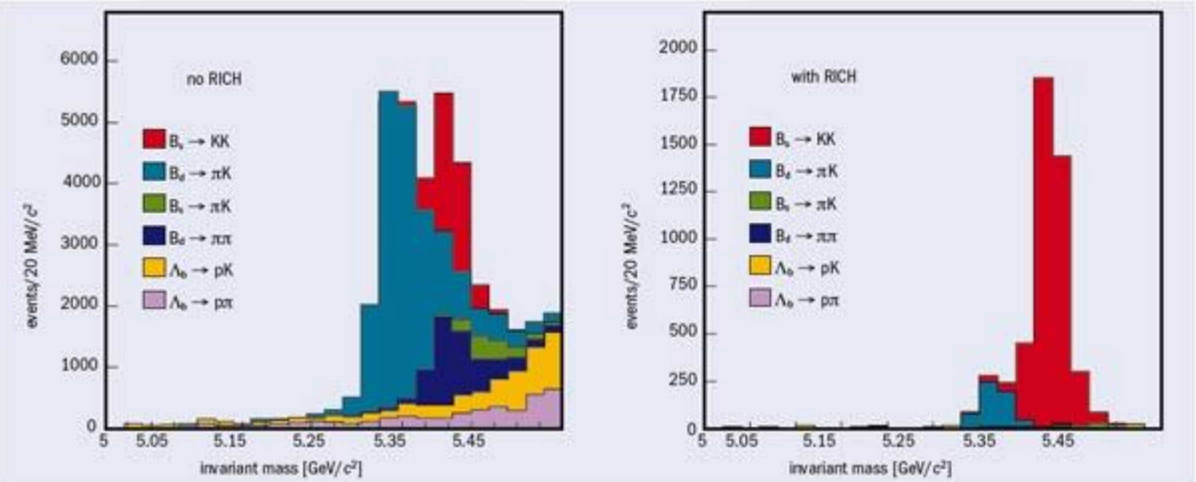




Unfortunately it disappeared when the experiments added more data in 2016

More on LHCb



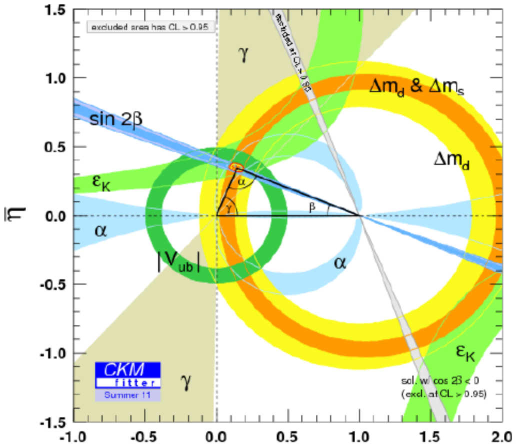


Focus on B-physics, physics involving B hadrons
Secondary vertex detector to identify potential B decays + particle ID

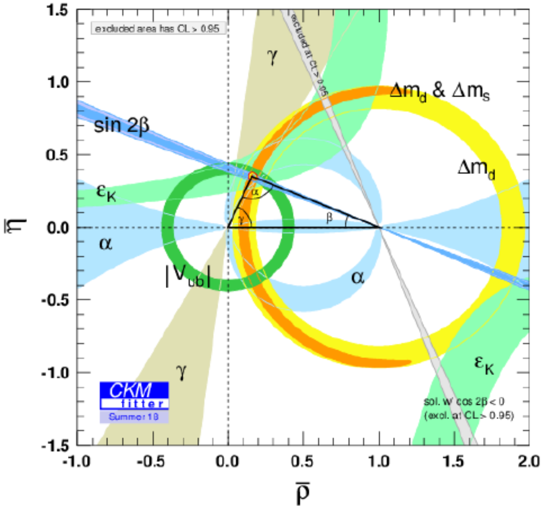
Physics programme mainly devoted to searches for rare decays + precision measurements to check loop effects and CP violation

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

CKM unitary triangle as of summer 2011



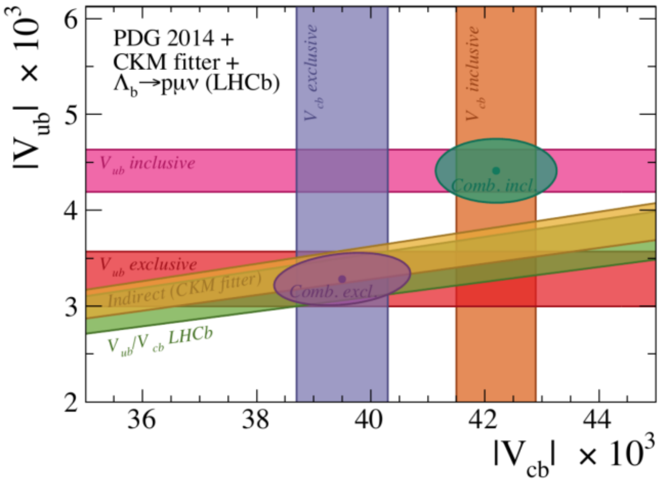
CKM unitary triangle as of summer 2018



You’ll remember the pentaquarks…

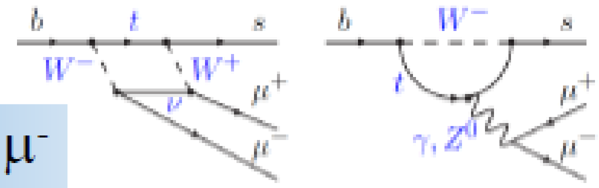
Results from the main area of expertise CP violation, for instance:

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



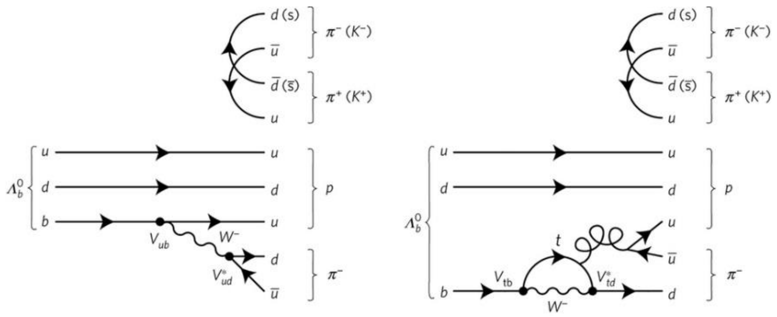
Measurements of rare decays:

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



LHCb also found CPV in Λ decays

Nature Physics **volume 13**, pages 391–396 (2017)



First evidence of CP violation in baryons!!

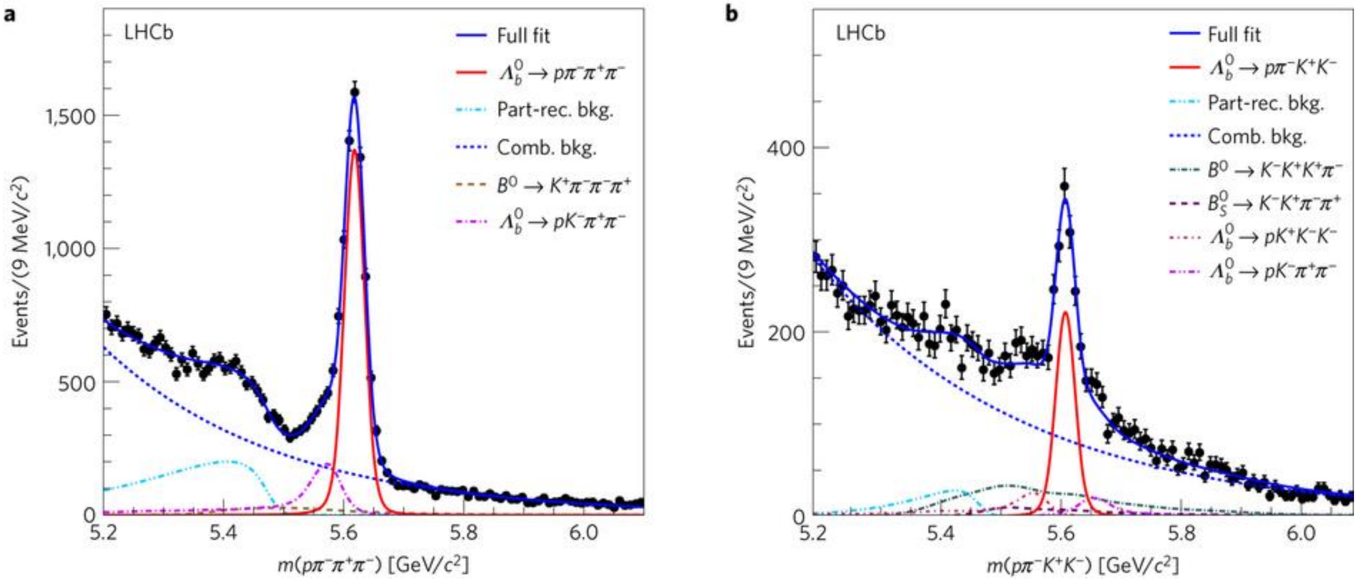
Looking at two rare decays:

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

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

Diagrams similar magnitude (weak)

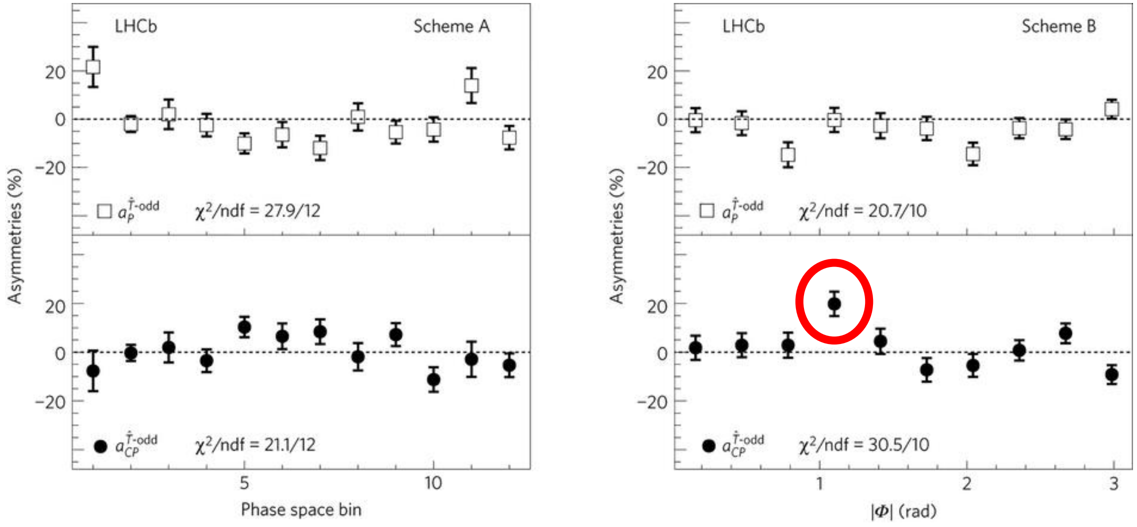
CP violation would be parametrized in CKM angle α



Reconstructed Λ_b masses

Evidence of new CP violation

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

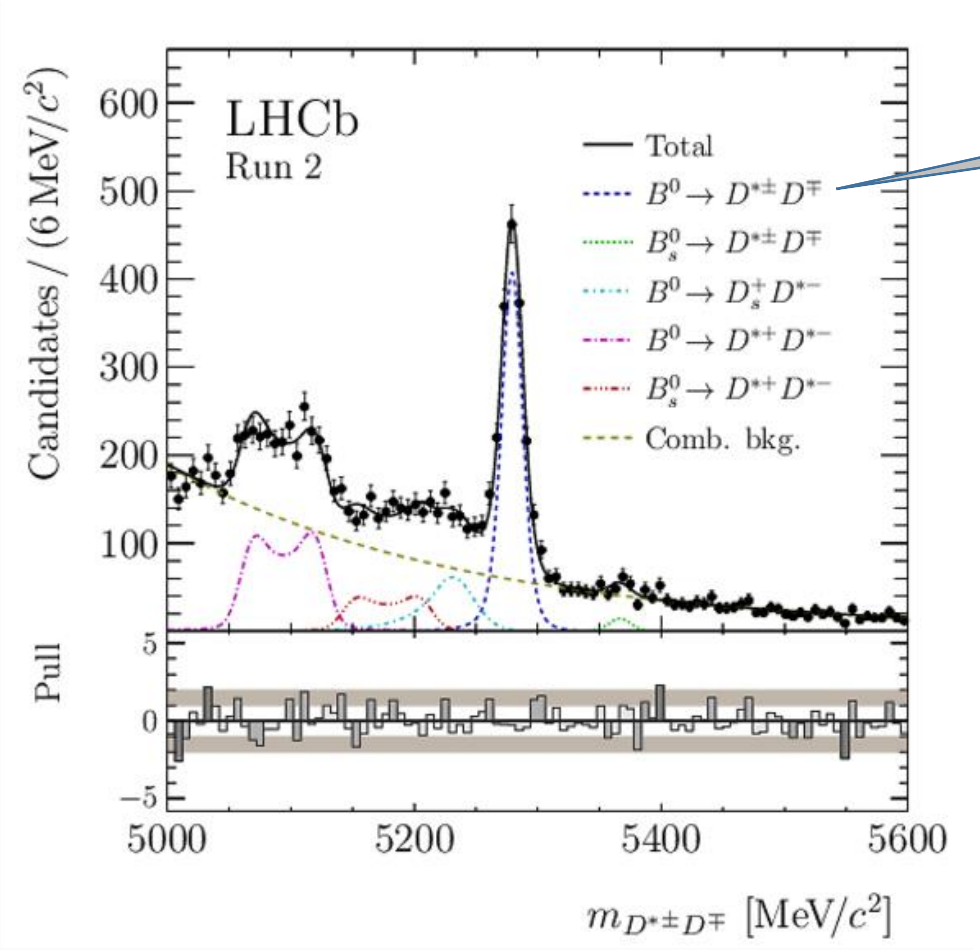


Asymmetry $19.79 \pm 4.95 \pm 0.60$

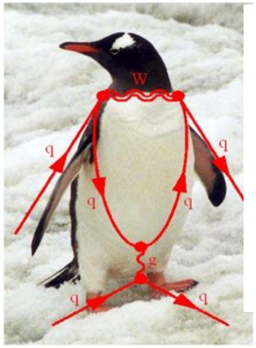
Beware: total effect is only 3.3 σ … but tantalizing and much needed

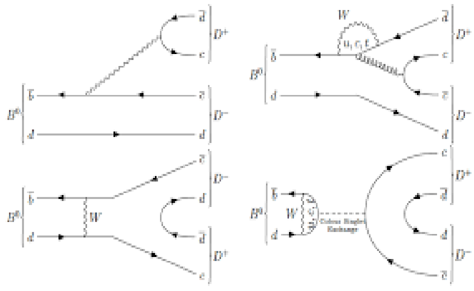
And in mesons with c-quarks ...

CP violation – life time dependent



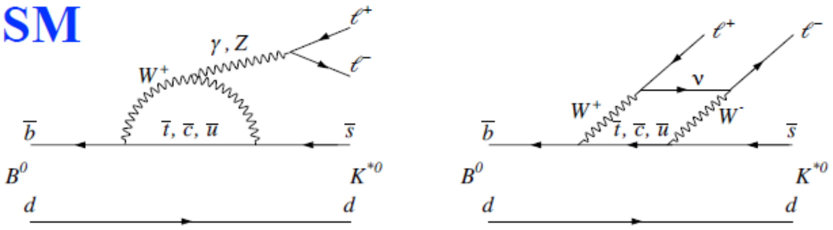
Several contributions to this channel
Only some of them CP violating
Penguin diagrams a la





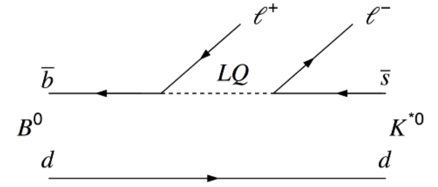
Lepton flavor universality?

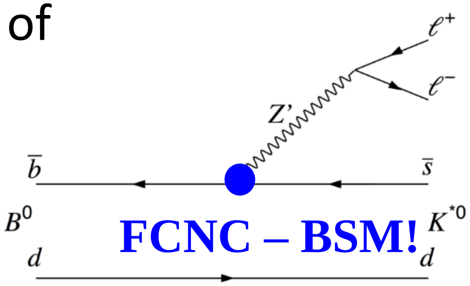
The $b \rightarrow s\ell^+\ell^-$ transition in the SM only through loops



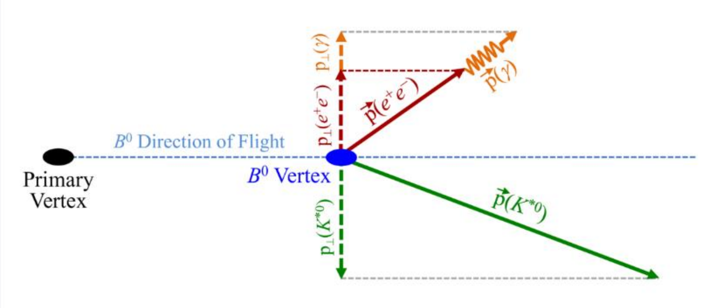
New particles potentially contribute directly, providing test of lepton universality

Is it same coupling for e , μ, and τ?





Explored by LHCb paper arXiv:1705:05802

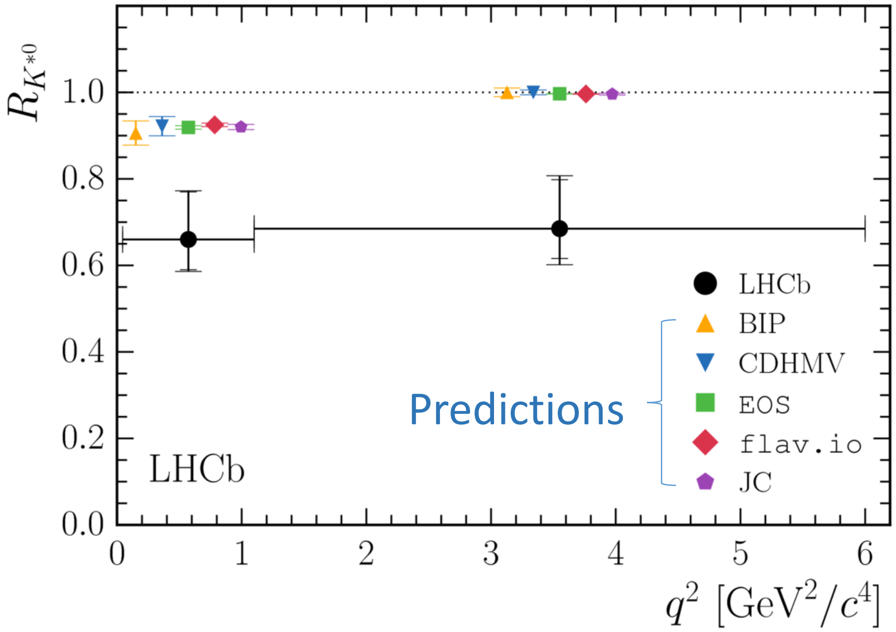


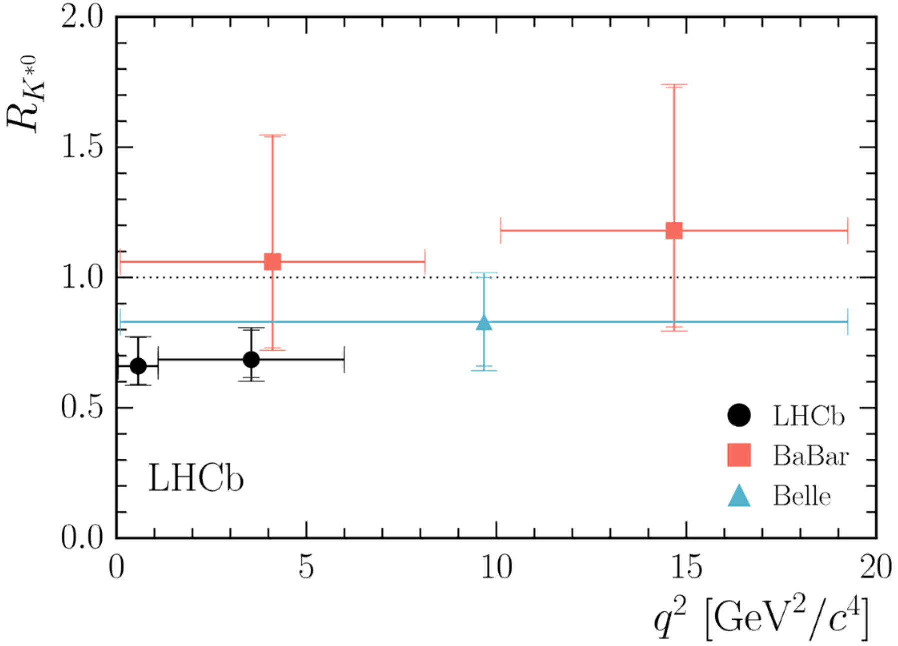
No lepton universality in detection:

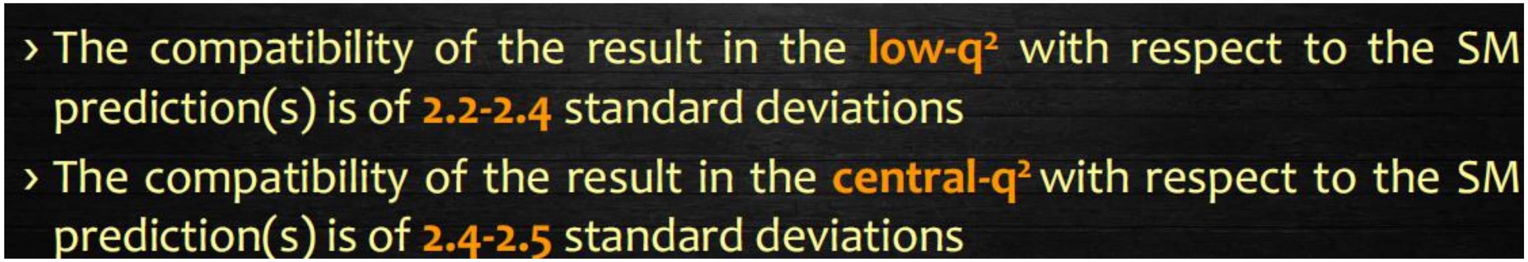
Electron energy often lost to bremsstrahlung

Advanced recovery algorithms to correct for this but brem + trigger constraints means ε(μ) ≅ 5 x ε(e)

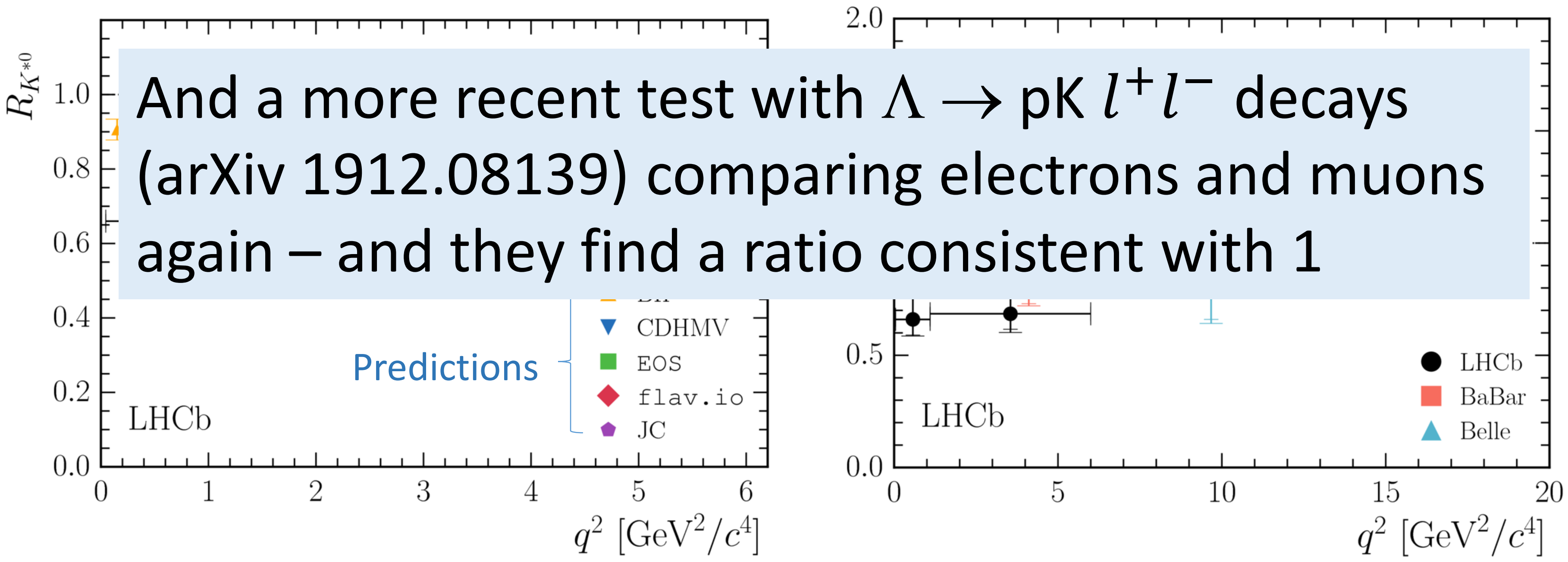
$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$



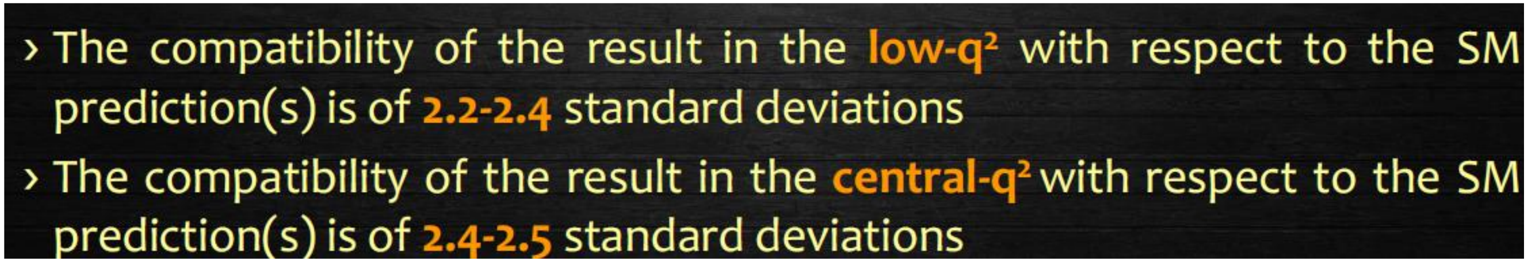



- The compatibility of the result in the **low-q²** with respect to the SM prediction(s) is of **2.2-2.4** standard deviations
- The compatibility of the result in the **central-q²** with respect to the SM prediction(s) is of **2.4-2.5** standard deviations

$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi\,(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi\,(\to e^+e^-))}$$



And a more recent test with $\Lambda \rightarrow$ pK l^+l^- decays (arXiv 1912.08139) comparing electrons and muons again – and they find a ratio consistent with 1



› 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

Also excluded sources of CP violation

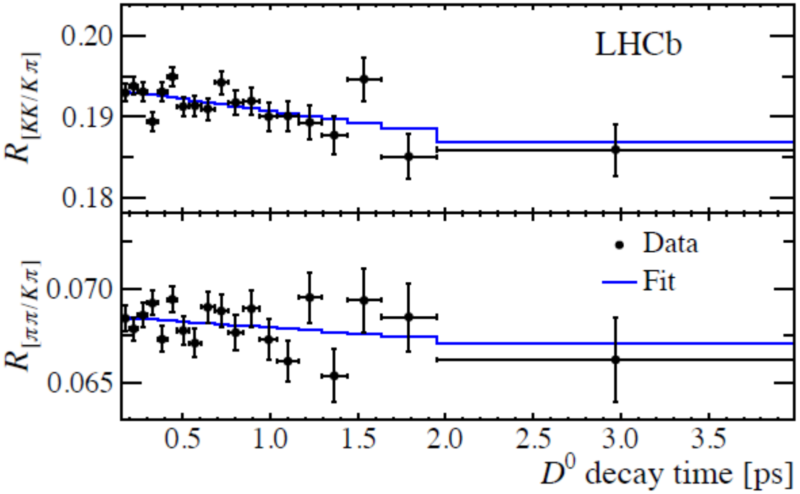
$D^0 \rightarrow \pi^+\pi^-, K^+K^-$ CP-even states

$D^0 \rightarrow K^+\pi^-$ CP mixed states

Use these ratios to measure y=$\frac{\Delta\Gamma}{2\Gamma}$ and $y_{CP} = \frac{\Gamma_{CP+}-\Gamma}{\Gamma}$

If same then no CP violation

LHCb-PAPER-2018-038



y_{CP} = (0.57 ± 0.13(stat) ± 0.09(syst))%
consistent and as precise as world average.

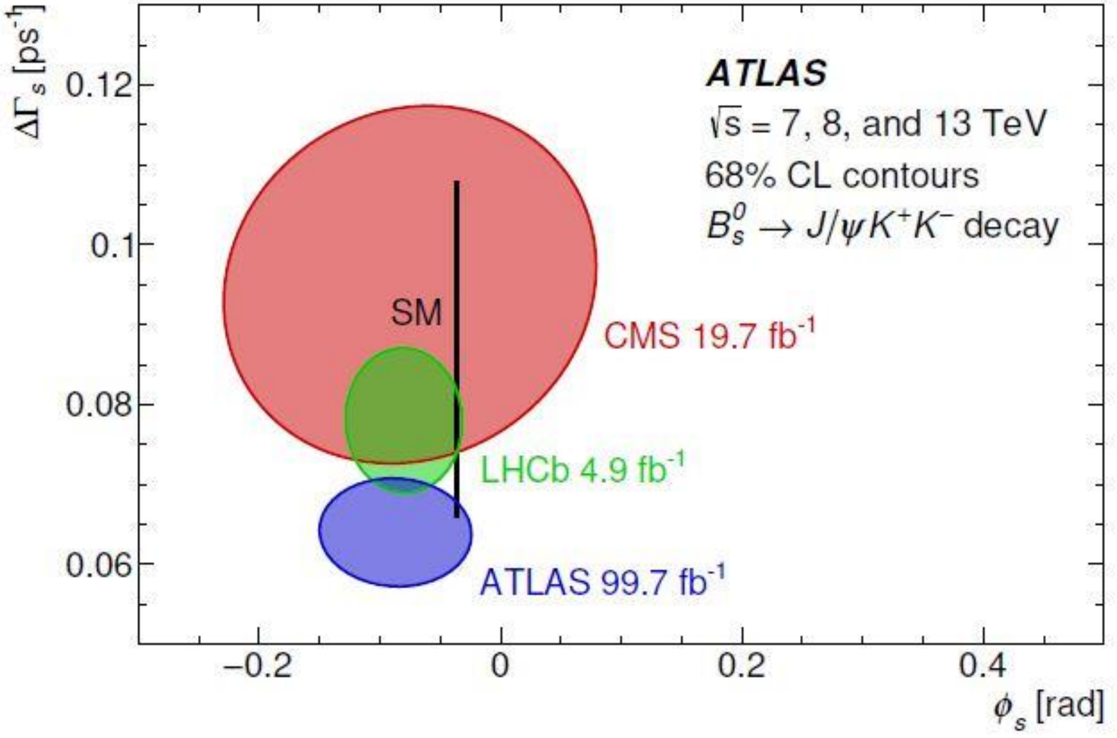
Result is consistent with y=(0.62±0.07)%

This shows no evidence of CP violation in charm mixing.

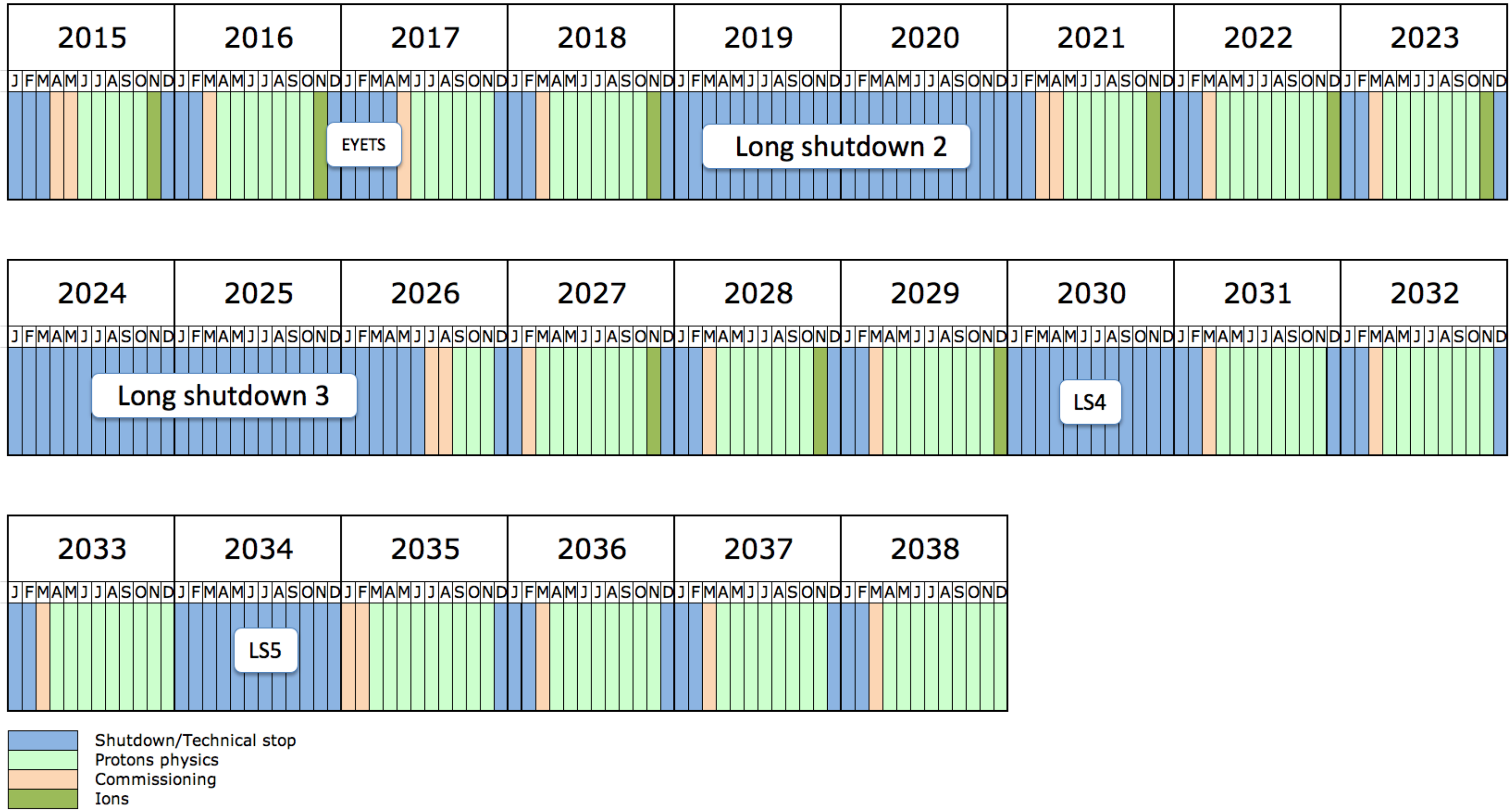
Also tested the suppressed $D^0 \rightarrow \pi^+\pi^-K^+K^-$ with amplitude fitting. 26 amplitudes were included in the description $\Rightarrow$ no sign of CP violation LHCb-PAPER-2018-041

All the experiments weighing in

https://arxiv.org/abs/2001.07115



LHC schedule



EYETS = extended year-end technical stop

Summary

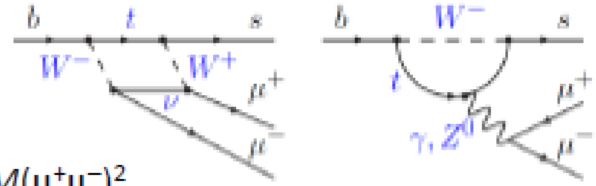
- The LHC is a fantastic multi-purpose machine
- It was far from trivial to design and commission
  - Problems and solutions from previous accelerator facilities do not necessarily scale
- Detectors have chosen fairly different techniques but sensitivity remains similar
  - Thousands of papers with results out
  - Apologies to ALICE – you will hear more later from Peter
  - Also parasitic experiments – google for instance FASER & TOTEM
- 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 (much) the Beyond Standard Model but we will get to that later

More on LHCb results

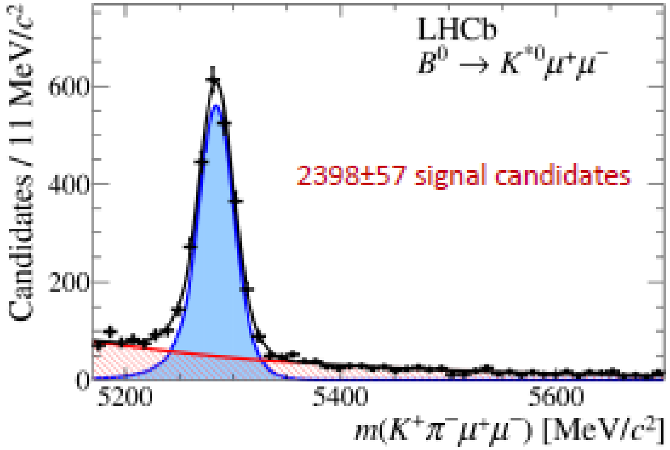
$B^0 \to K^{*0} \mu^+ \mu^-$

New results on rare decays:

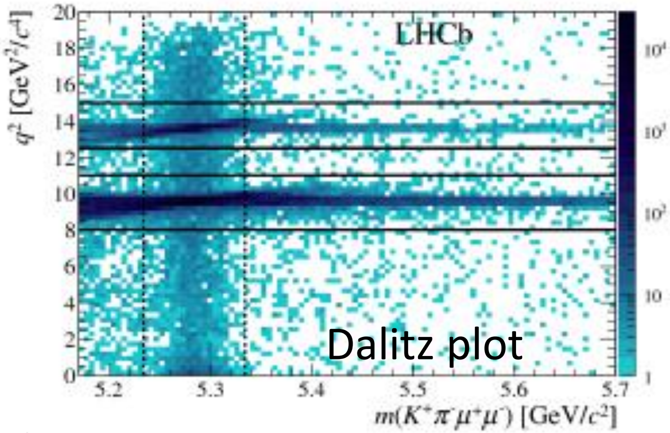
- Only allowed through loops in the SM



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

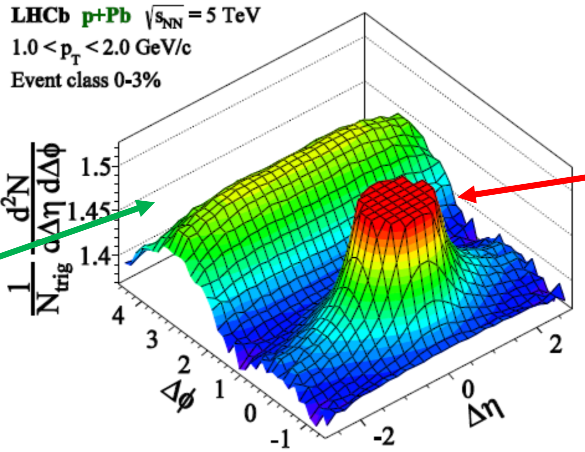


Full q² range with J/ψ and ψ(2S) veto



Dalitz plot

Heavy ion physics



Jet peak

Away-side ridge

ATLAS & CMS: Design & Performance Overview

	ATLAS (7 ktons)	**CMS (12.5 ktons)**
INNER TRACKER	• Silicon pixels + strips • TRT with particle identification • $B = 2$ T • $\sigma(p_T) \sim 3.8\%$ (at 100 GeV, $\eta = 0$)	• Silicon pixels + strips • No dedicated particle identification • $B = 3.8$ T • $\sigma(p_T) \sim 1.5\%$ (at 100 GeV, $\eta = 0$)
MAGNETS	• 4 Magnets • Solenoid + Air-core muon toroids • Calorimeters outside solenoid field	• 1 Magnet • Solenoid • Calorimeters inside field
EM CALORIMETER	• Pb / Liquid Ar sampling accordion • $\sigma(E) \sim 10–12\% / \sqrt{E} \oplus 0.2–0.35\%$ • Longitudinal segmentation • Saturation at ~ 3 TeV	• $PbWO_4$ scintillation crystals • $\sigma(E) \sim 3–5.5\% / \sqrt{E} \oplus 0.5\%$ • No longitudinal segmentation • Saturation at 1.7 TeV
HAD CALORIMETER	• Fe / Scint. tiles (EC: Cu-liquid Ar) • $\sigma(E) \sim 45\% / \sqrt{E} \oplus 1.3\%$ (Barrel)	• Cu (EC: brass) / Scint. tiles • Tail catchers outside solenoid • $\sigma(E) \sim 100\% / \sqrt{E} \oplus 8\%$ (Barrel)
MUON	• Drift tubes & CSC (fwd) + RPC/TGC • $\sigma(p_T) \sim 10.5\% / 10.4\%$ (1 TeV, $\eta = 0$) (standalone / combined with tracker)	• Drift tubes & CSC (EC) + RPC • $\sigma(p_T) \sim 13\% / 4.5\%$ (1 TeV, $\eta = 0$) (standalone / combined with tracker)