Experimental Particle Physics at the LHC: Standard Model

Albert De Roeck
CERN, Geneva, Switzerland
Antwerp University Belgium
UC-Davis California USA
IPPP, Durham UK
BUE, Cairo, Egypt

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New Trends in High Energy Physics and QCD
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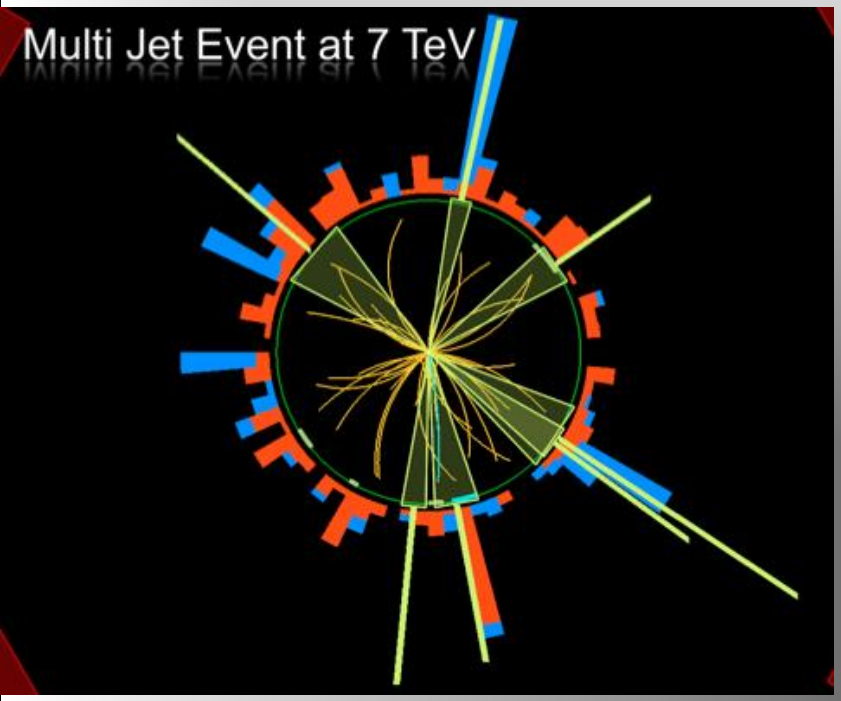
Lecture Plan

Overview of the 3 lectures in the next days

- Lecture 1: Introduction to Experimental Particle Physics at the LHC
- Lecture 2: Measurements and test of the Standard Model, (excluding the Higgs)
- Lecture 3: Searches beyond the Standard Model at the LHC



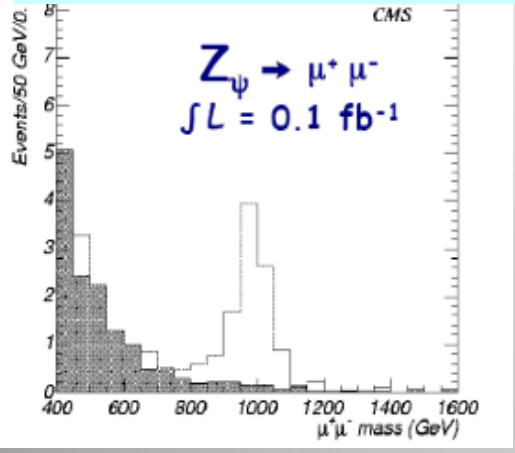
Outline Lecture II

- pp collision characteristics
- Soft pp collisions and multi-particle production
- QCD hard scattering
- Electroweak processes
- Top production
- (The Higgs particle)
- Summary

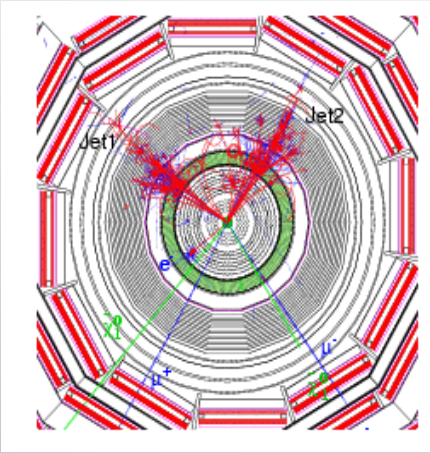
A Proton-Proton Collider…

Search for New Physics?

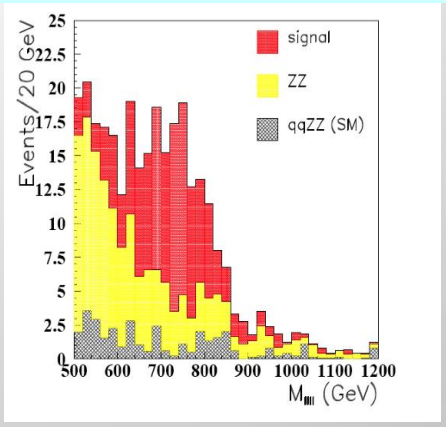
New Gauge Bosons?



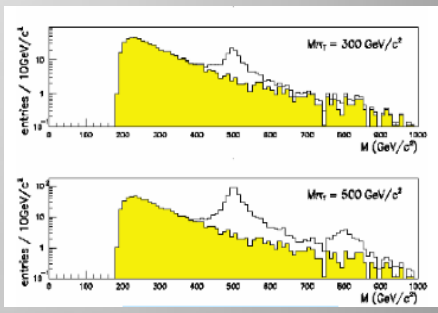
Supersymmetry



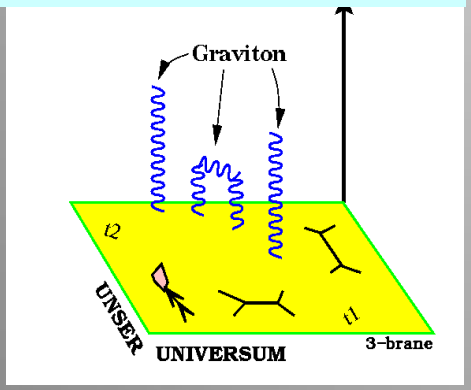
ZZ/WW resonances?



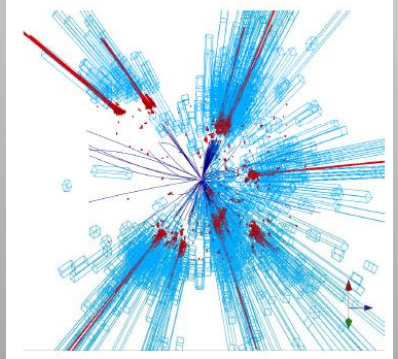
Technicolor?



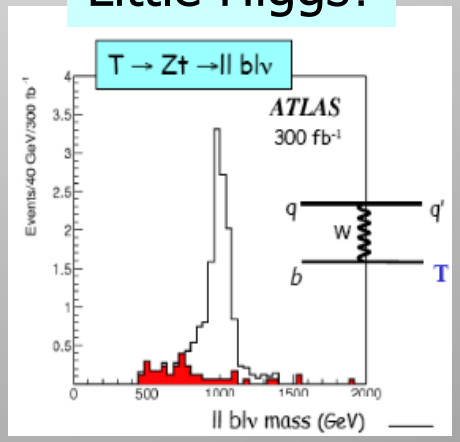
Extra Dimensions?



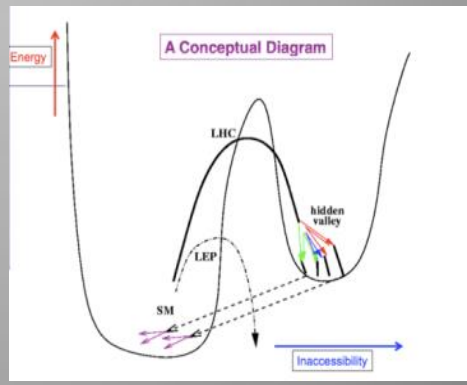
Black Holes???



Little Higgs?



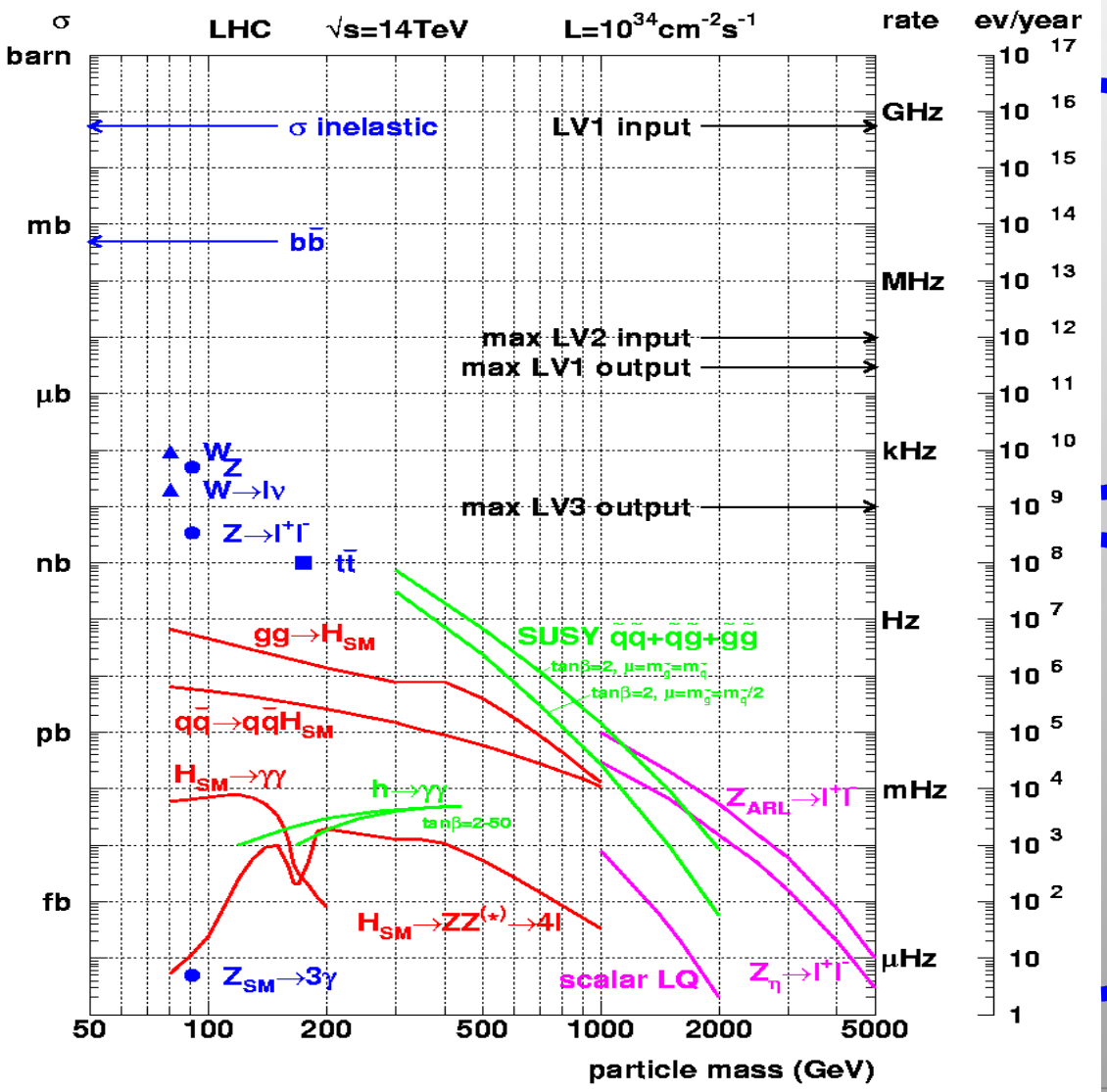
Hidden Valleys?



What stabelizes the Higgs Mass? Many ideas, not all viable any more

A large variety of possible signals. We have to be ready for that

Cross sections at the LHC



"Well known" processes, don't need to keep all of them …

New Physics!!

This we want to keep!!

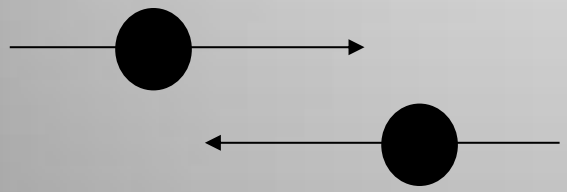
Proton-proton Collisions

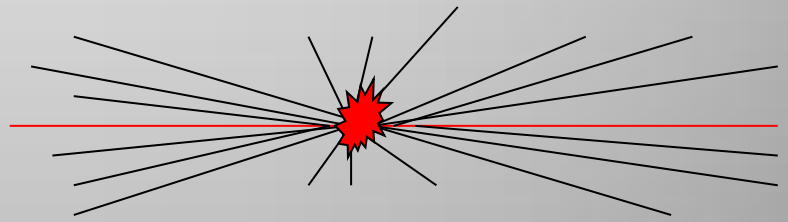
Most interactions due to collisions at large distance between incoming protons where protons interact as " a whole "

→ small momentum transfer ($\Delta p \approx \hbar / \Delta x$)

→particles in final state have large longitudinal momentum but small

→transverse momentum (scattering at large angle is small)





$< p_T > \approx 500$ MeV of charged particles in final state

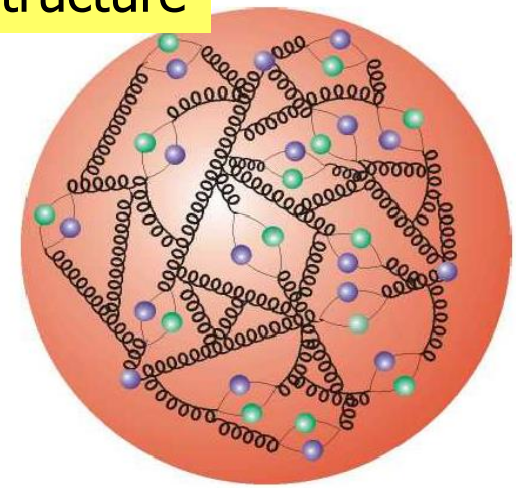
Most energy escapes down the beam pipe.

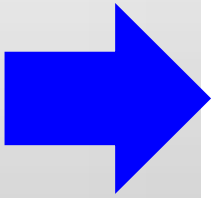
These are called soft events…

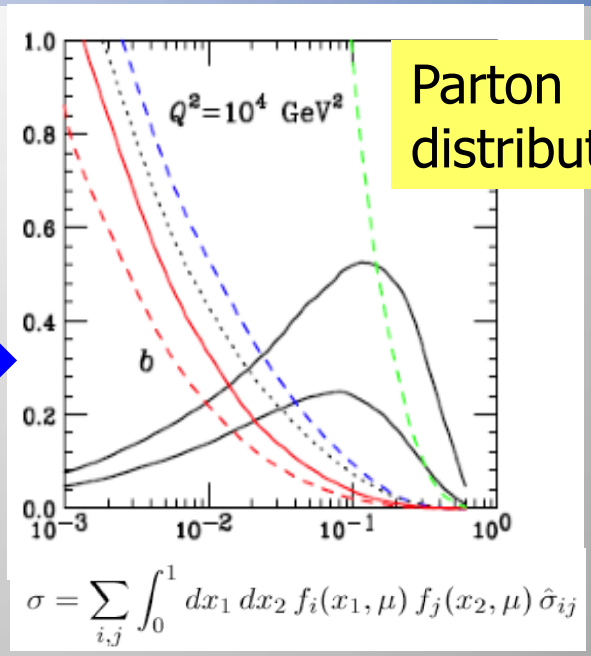
A minimum bias data event sample is dominated by soft events

Pp Collisions : Complications

Protons have structure

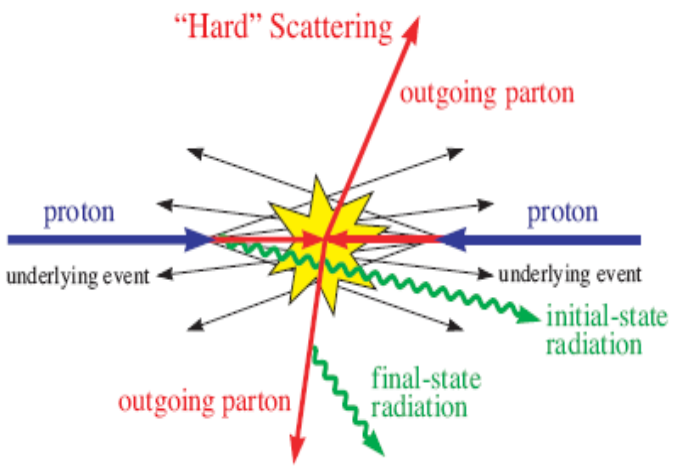




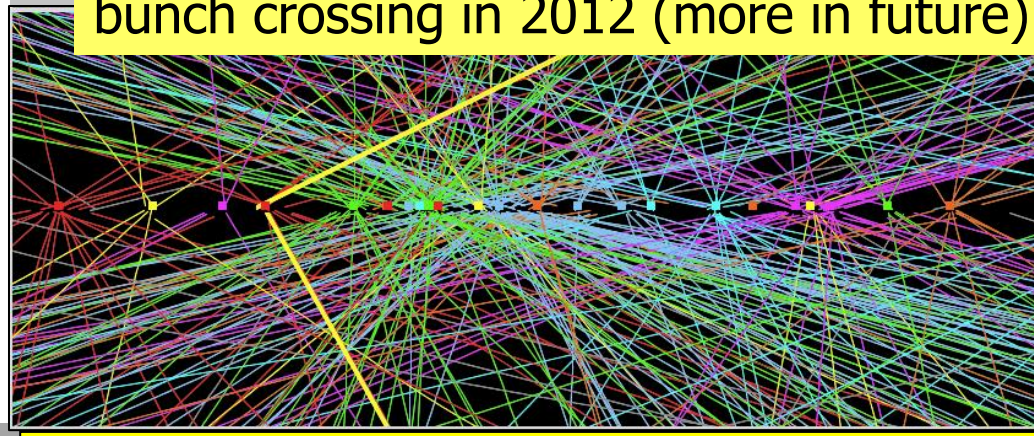


Parton distributions

Underlying event



Pile-up: approximate 20 collisions per bunch crossing in 2012 (more in future)



Z→ μμ event with ~20 reconstructed vertices (2012)

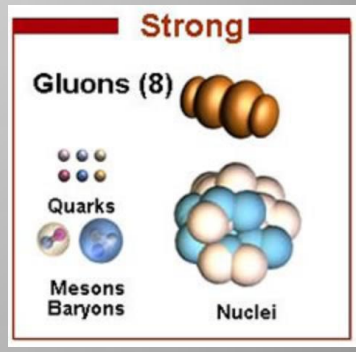
QCD

QCD plays a major role in basically every topic under discussion at this Symposium. For precision physics, or discovery physics we need to understand the role of QCD corrections: QCD is all around us at the LHC

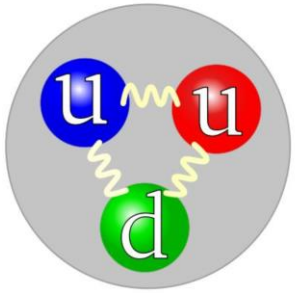
Quantum chromodynamics

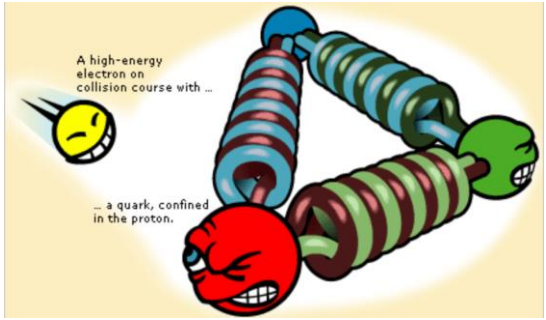
From Wikipedia, the free encyclopedia

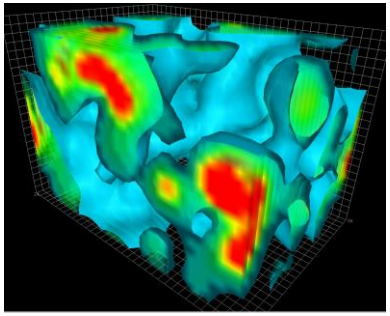
In theoretical physics, **quantum chromodynamics** (**QCD**) is a theory of the strong interaction (color force), a fundamental force describing the interactions between quarks and gluons which make up hadrons (such as the proton, neutron or pion). It is the study of the **SU**(3) Yang–Mills theory of color-charged fermions (the quarks). QCD is a quantum field theory of a special kind called a non-abelian gauge theory, consisting of a 'color field' mediated by a set of exchange particles (the gluons). The theory is an important part of the Standard Model of particle physics. A huge body of experimental evidence for QCD has been gathered over the years.



$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} F_a^{\mu\nu} F^a_{\mu\nu} + \sum_f \bar{\psi}_i^{(f)} \left(i \not{D}_{ij} - m_f \delta_{ij} \right) \psi_j^{(f)}$$

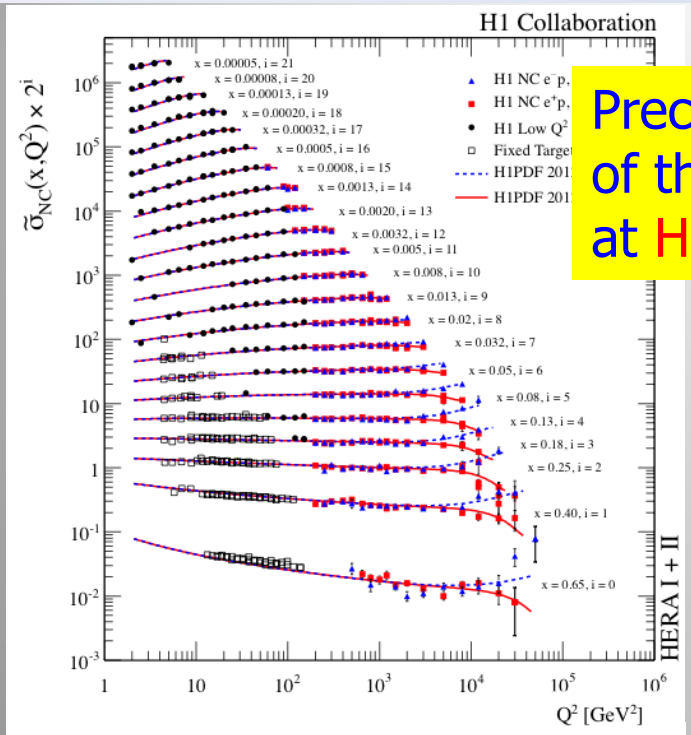




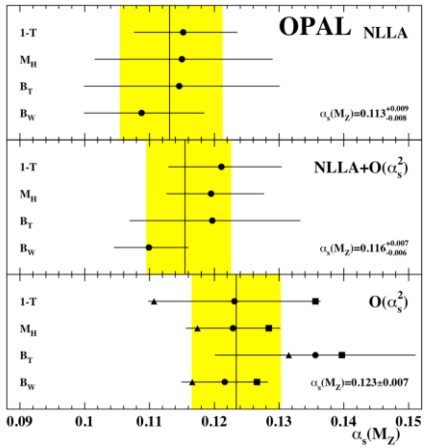


QCD at Recent Colliders

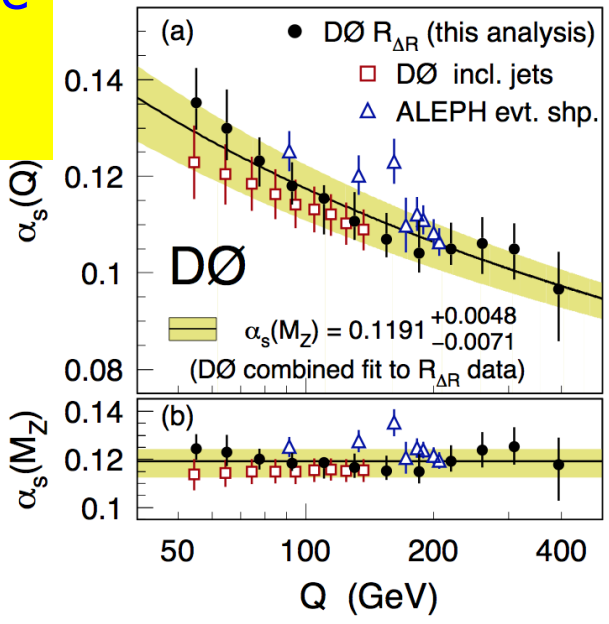
Precision measurements of the proton structure at HERA



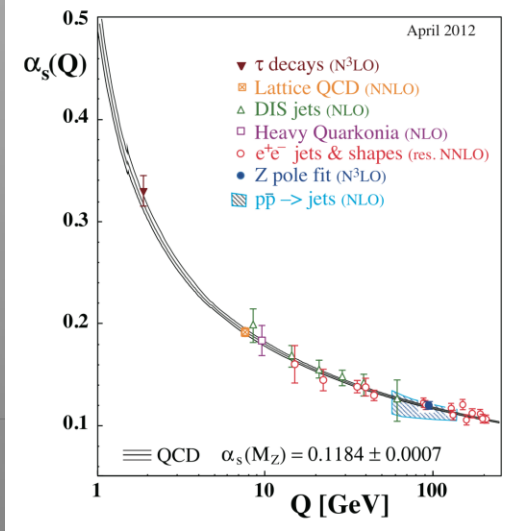
Precision measurements at the Z factory LEP



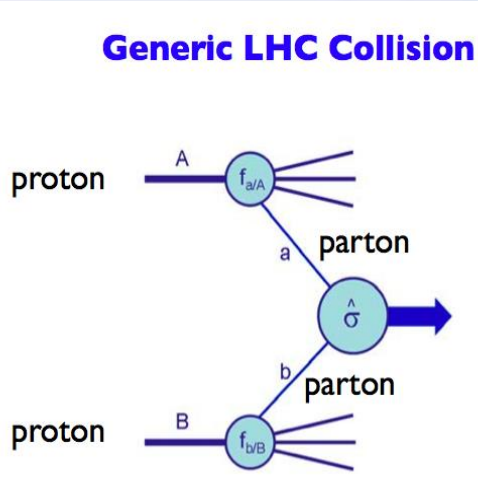
QCD studies at the hadron collider Tevatron



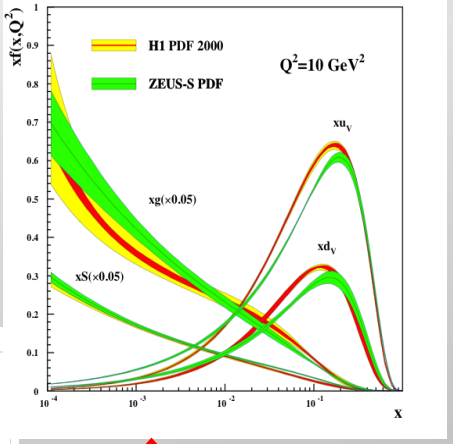
Summary on α_s results

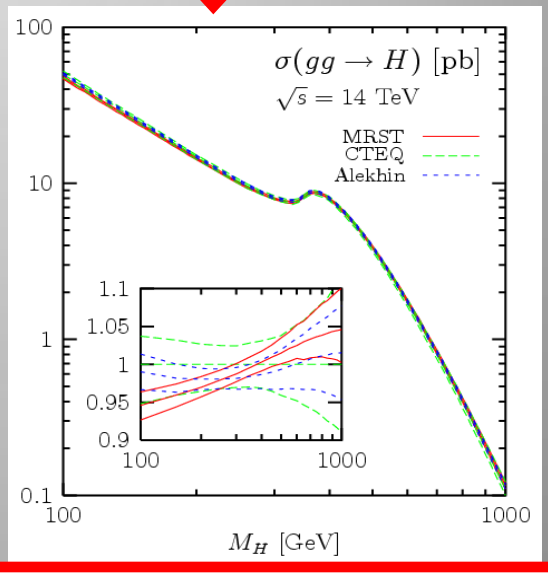


Proton-proton collisions and PDFs

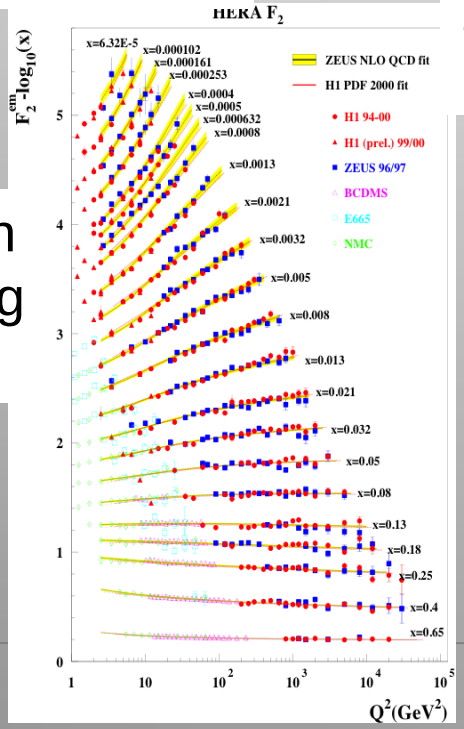


Parton Distribution Functions: the probability of finding a parton with momentum fraction x in the proton





Structure function measurements eg from HERA



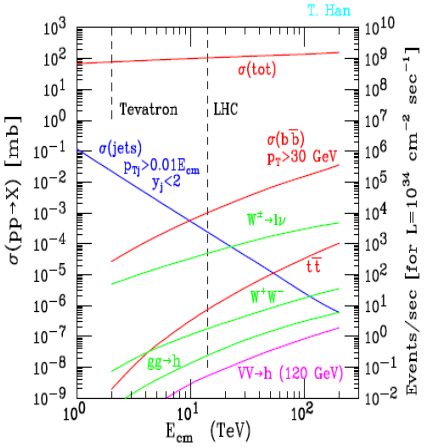
Simple spread of existing PDFs gives up to 10% uncertainty on Higgs cross section. Possible gain ~ factor of 2 with final HERA data (PDF4LHC)

Soft QCD Dynamics

Understanding Soft Collisions

Most collisions at the LHC do not involve a hard scattering scale: these are so called soft collisions. They make up most of a "minimum bias" event sample

Scattering cross sections for various SM processes:

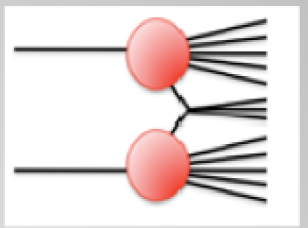


- Detailed studies of multi-particle production in pp
- Monte Carlos tunes, eg for describing the pile-up

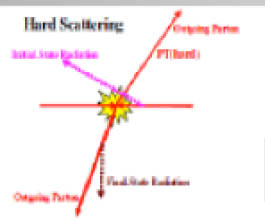
Pile-up 2012!!
Much more in 2015+

Event Types and Underlying Event

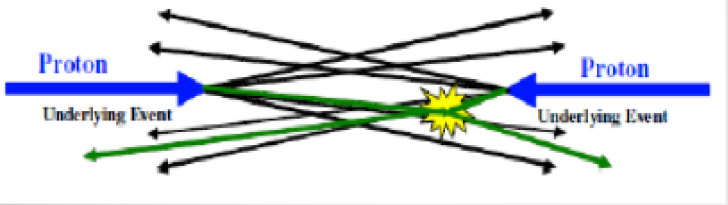
$$\sigma_{tot} = \sigma_{EL} + \sigma_{SD} + \sigma_{DD} + \sigma_{ND/HC}$$



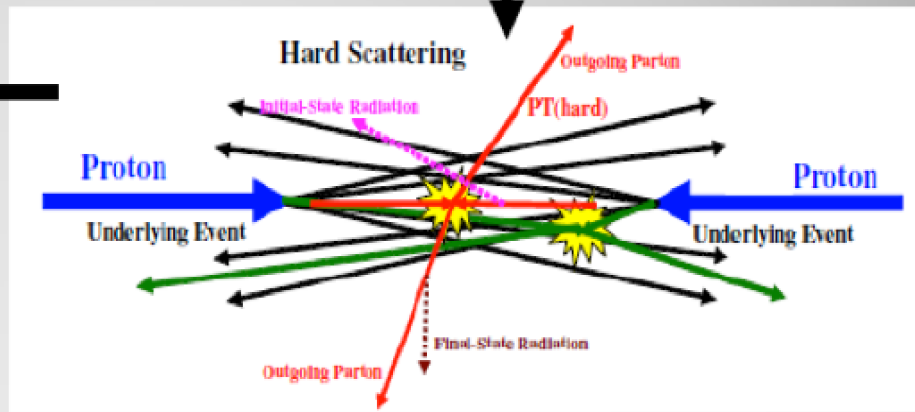
- Elastic Scattering
- Single diffraction
- Double diffraction
- Non-diffraction



Hard Scattering Component

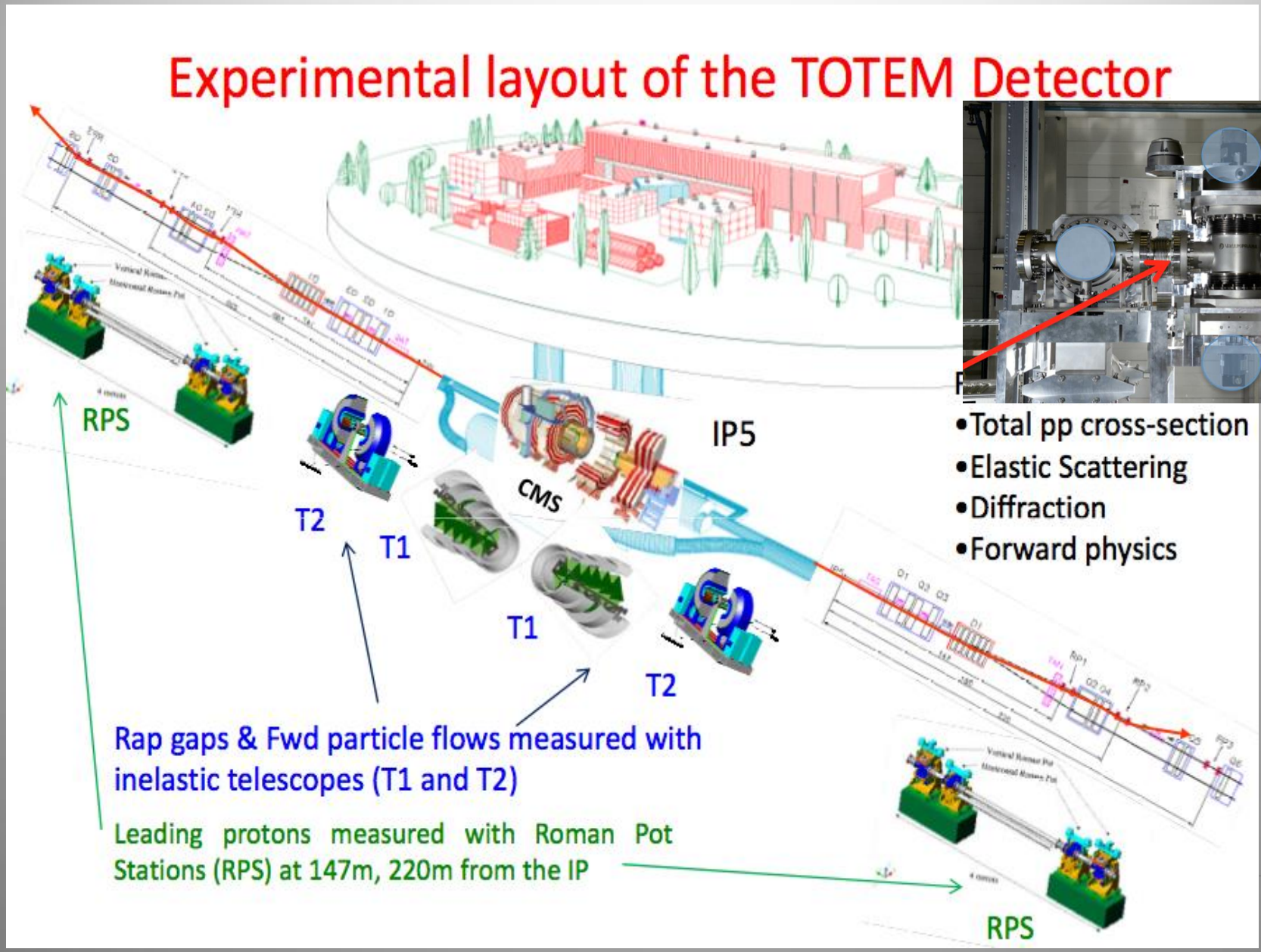


Underlying Event



…Not always easy to classify individual events

CMS + TOTEM



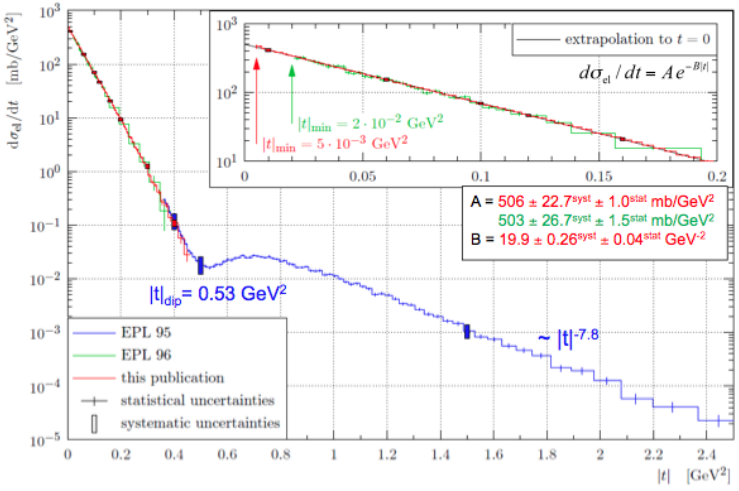
- Total pp cross-section
- Elastic Scattering
- Diffraction
- Forward physics

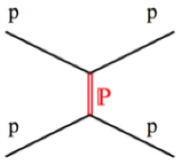
Elastic/Total pp Cross Section

TOTEM = Roman Pots + Forward Detectors
TOTEM uses the same IP as CMS (IP5)

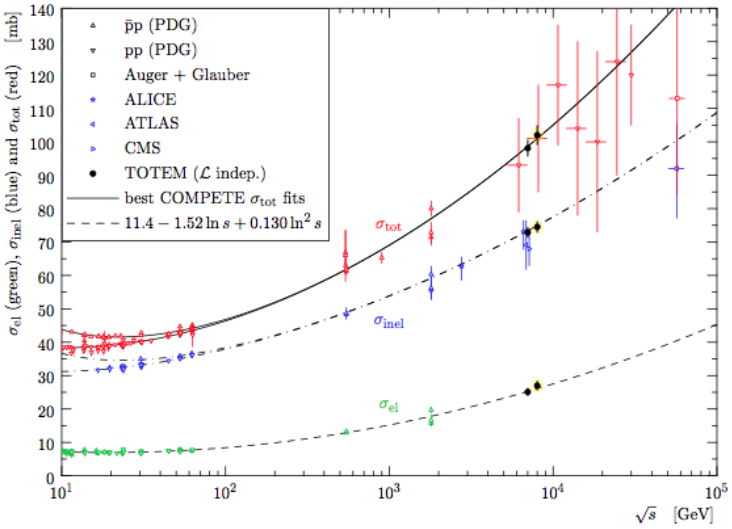
EPL 101 21004 (2003)

7 TeV elastic differential cross section





8TeV cross sections



$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \frac{dN_{el}/dt\big|_0}{N_{el} + N_{inel}}$$

$$\sigma_{tot} = (101.7 \pm 2.9)mb$$

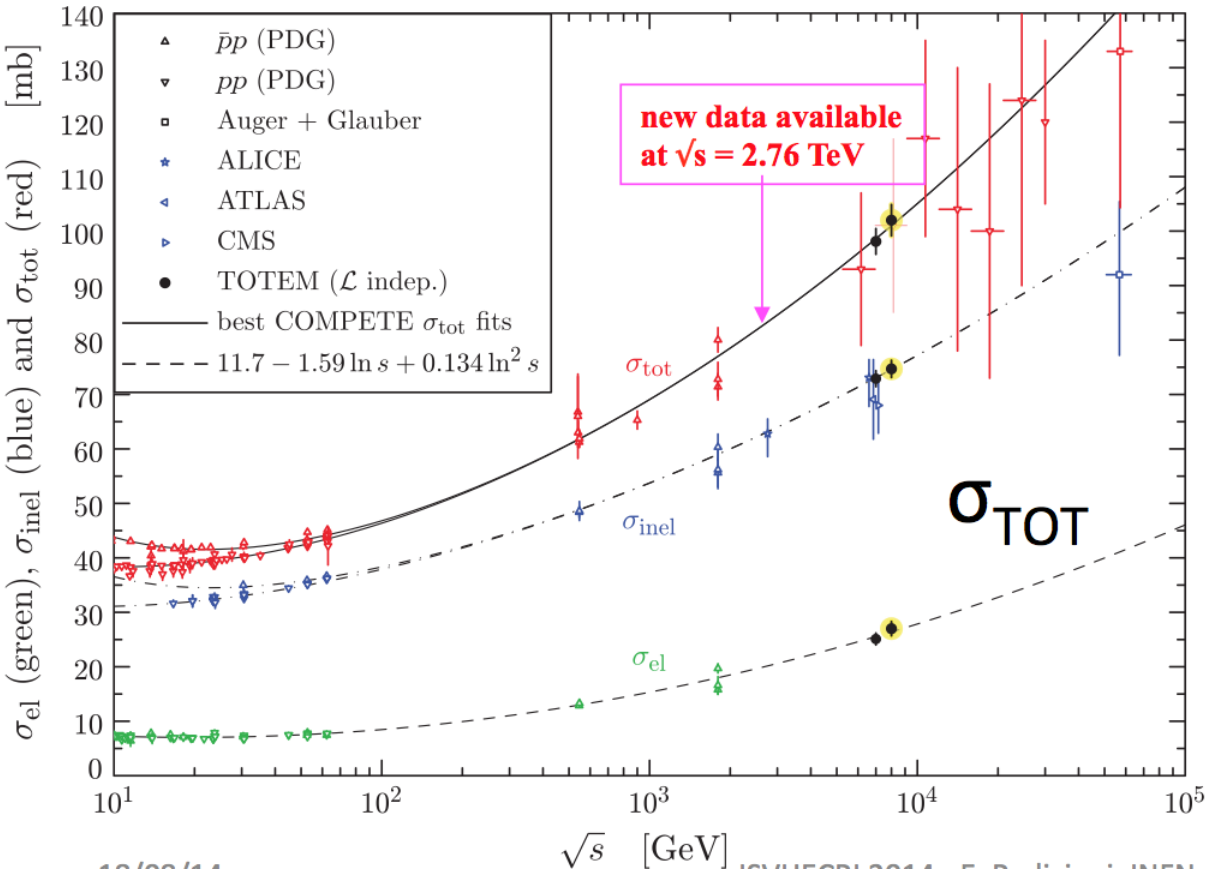
$$\sigma_{inel} = (74.7 \pm 1.7)mb$$

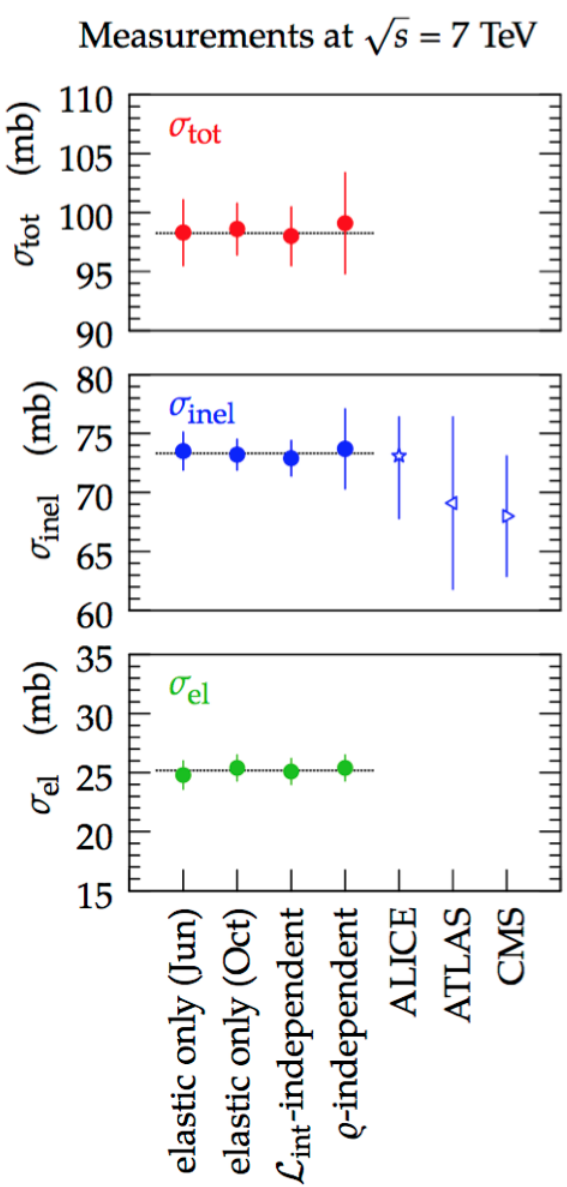
$$\sigma_{el} = (27.1 \pm 1.4)mb$$

Future: •High beta measurements for Coulomb-Nuclear interference, ALFA

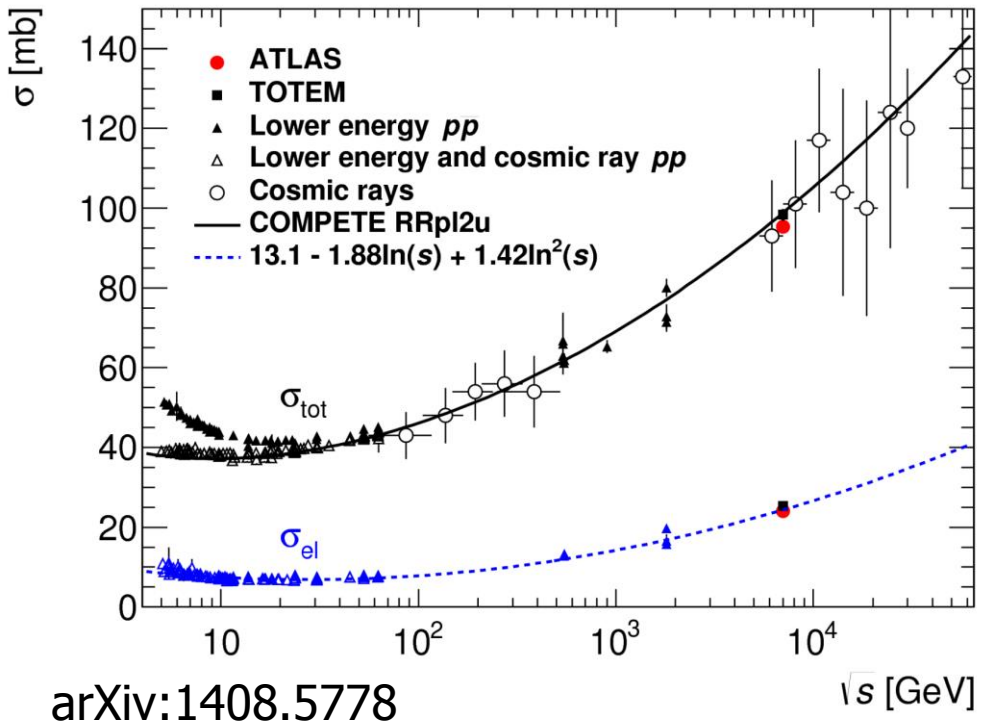
TOTEM total cross-section

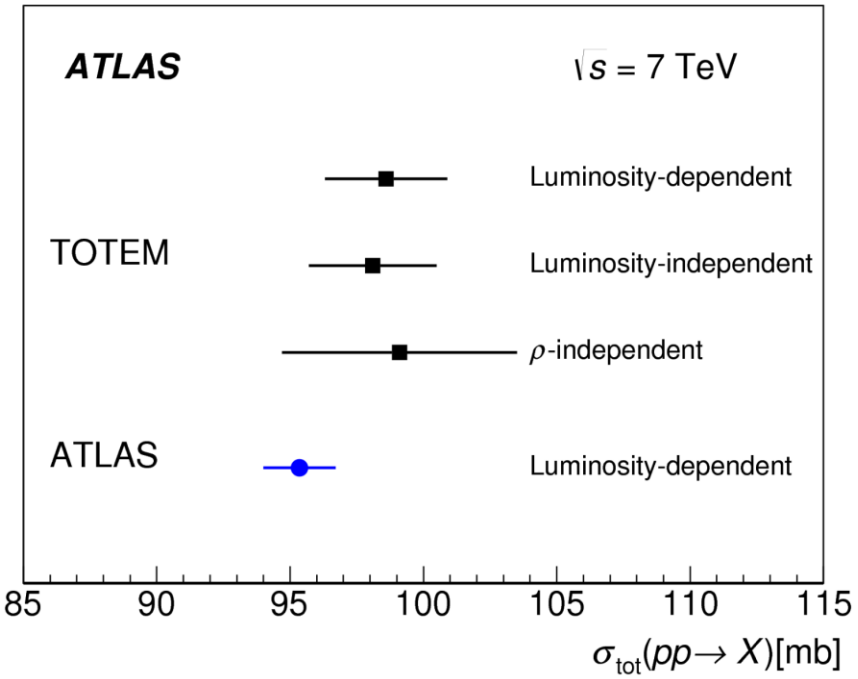
√S [TeV]	method	value
7	elastic only	98.6±2.3 mb
7	ρ independent	99.1±4.4 mb
7	lumi independent	98.1±2.4 mb
8	lumi independent	101.7±2.9 mb





Elastic/Total pp Cross Section





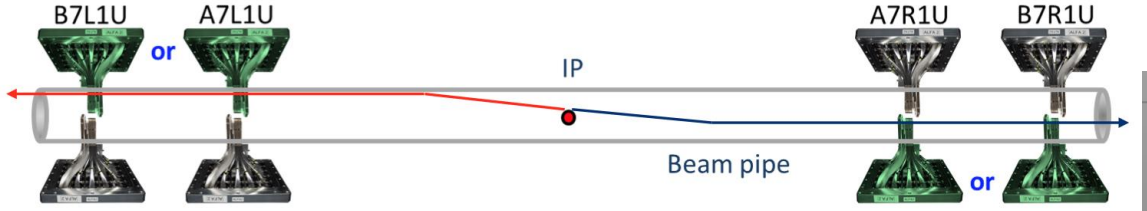
arXiv:1408.5778

Energy evolution of σ_{tot} and σ_{el}

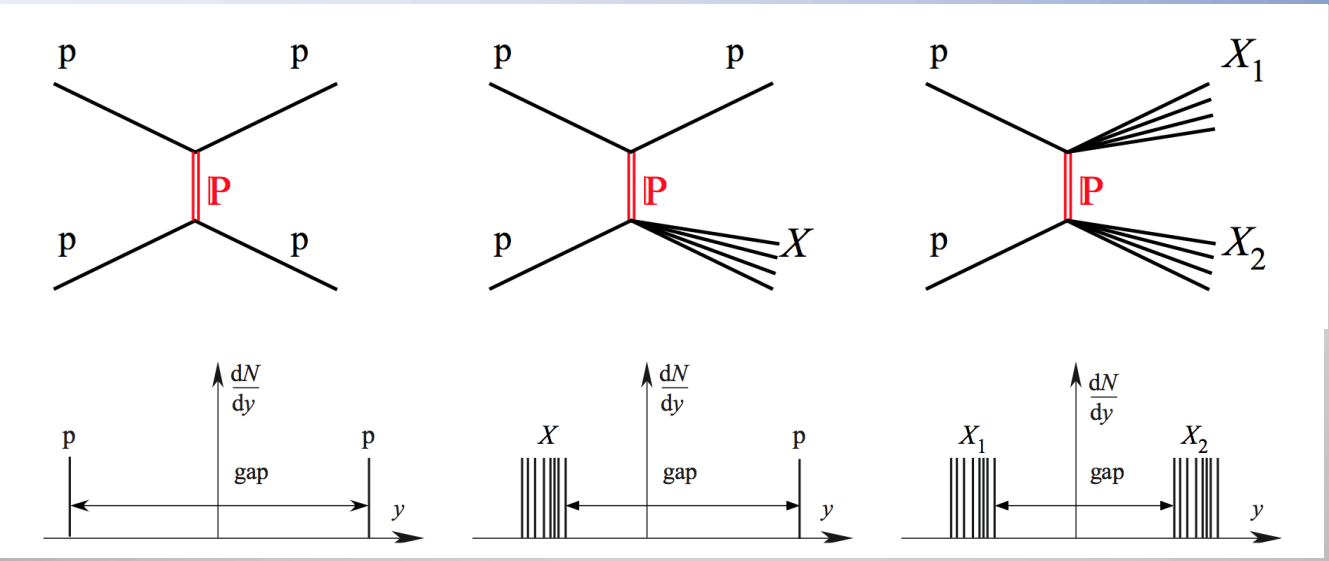
ATLAS σ_{tot} = 95.4±1.4 mb B = 19.7 ± 0.3 GeV^{-2}

TOTEM σ_{tot} = 98.6±2.2 mb B = 19.9 ± 0.3 GeV^{-2}

The ATLAS measurement is 3.2 mb lower than TOTEM, the difference corresponds to 1.3 σ, assuming uncorrelated uncertainties.

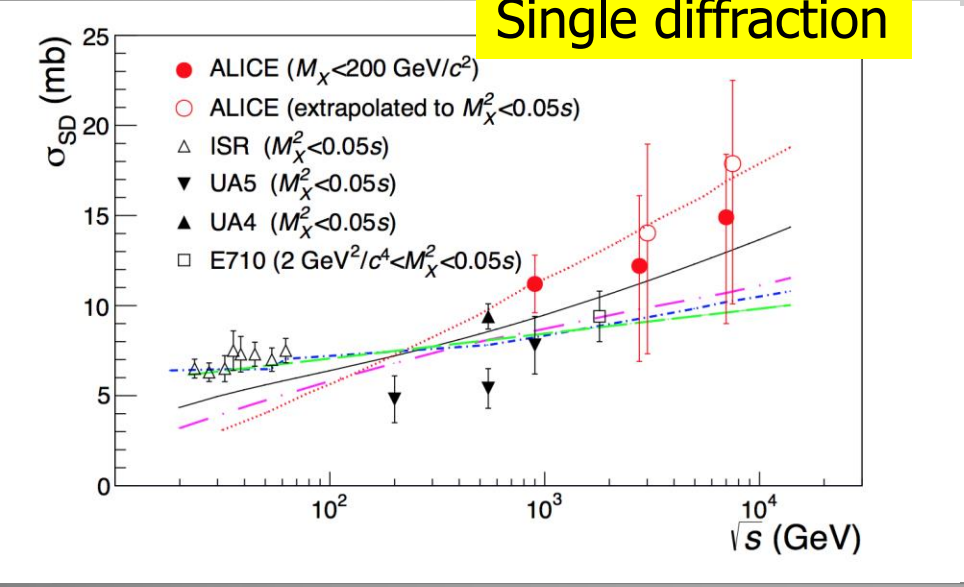


Diffractive Cross Sections

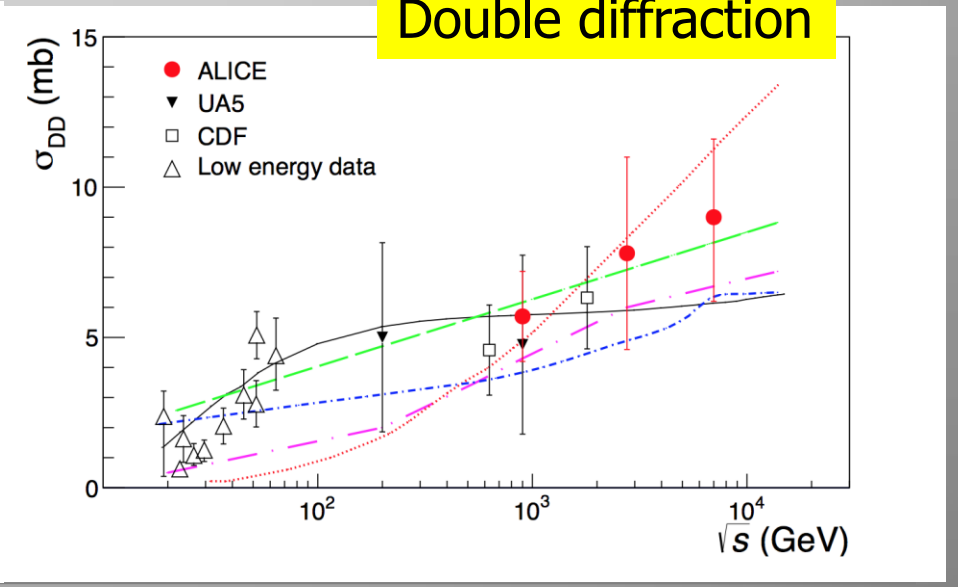


arXiv:1208.4968

Single diffraction

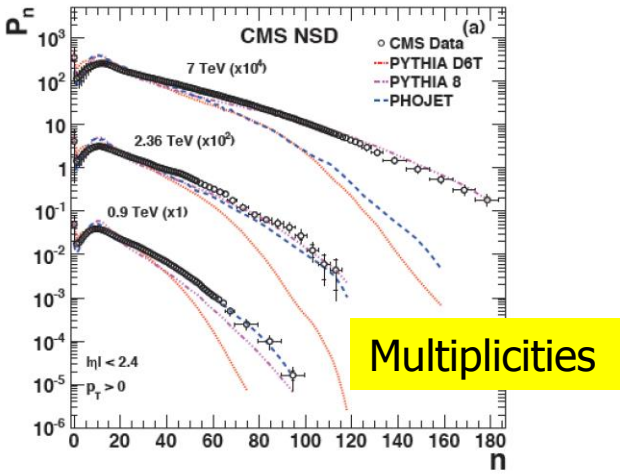


Double diffraction

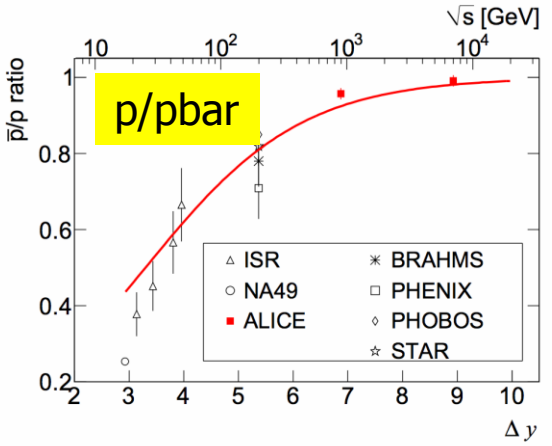


Understanding Particle Production

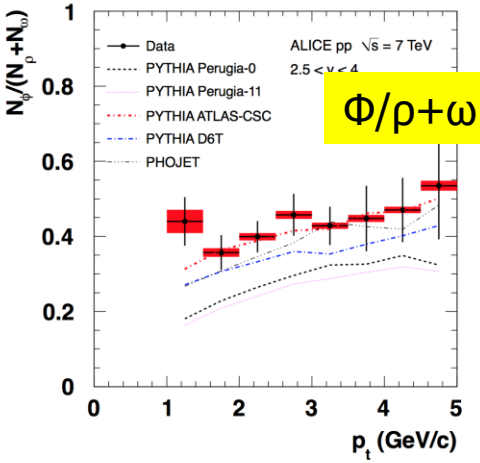
- Single particles, multiplicities etc. vs phenomenological models…
- LHC detectors are excellent and complementary for such studies



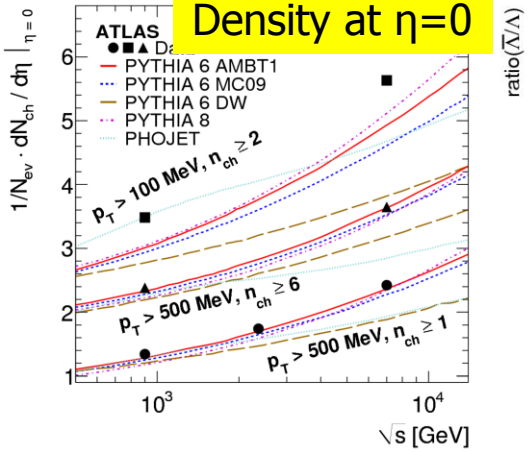
Multiplicities



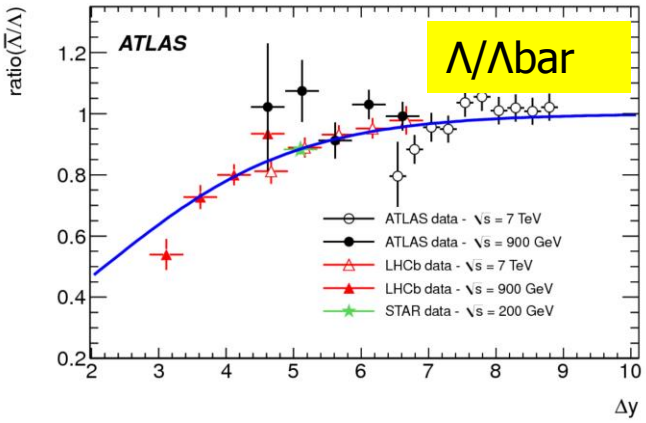
p/pbar



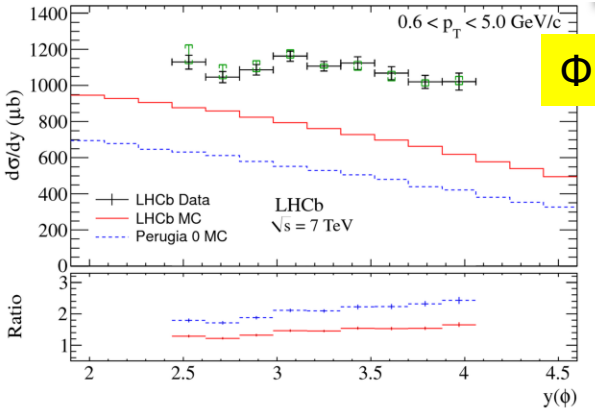
Φ/ρ+ω



Density at η=0



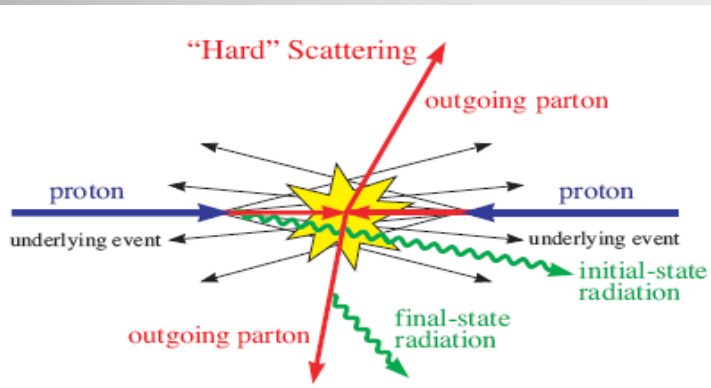
Λ/Λbar

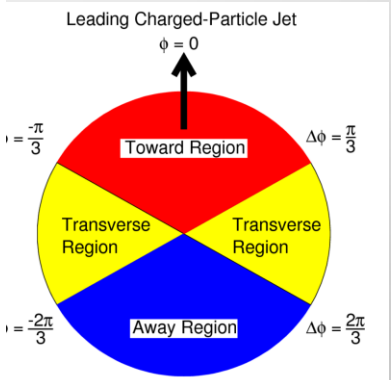


Φ

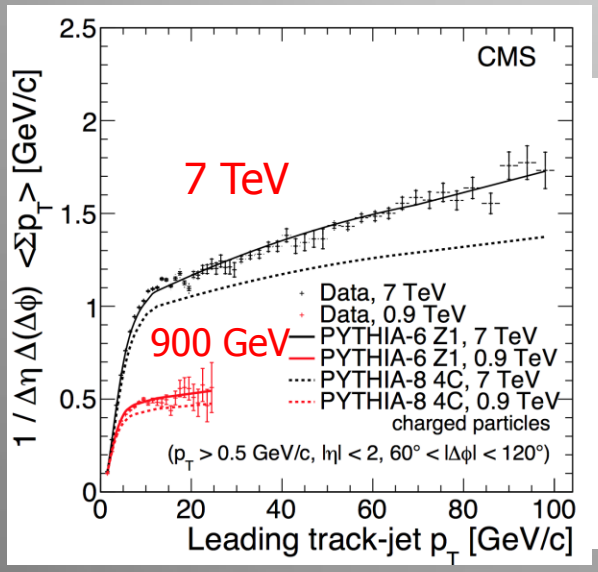
Underlying Event Studies

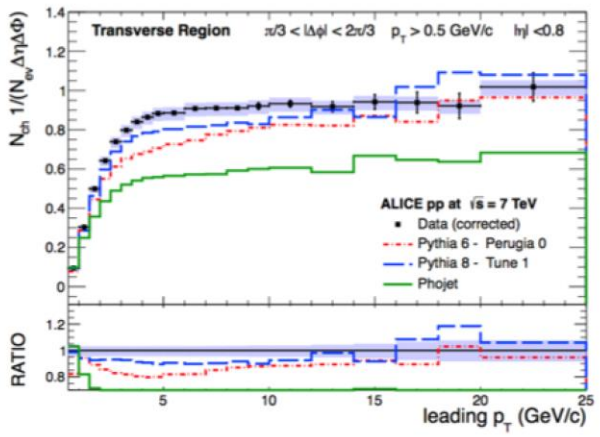
An important systematic effect for precision measurements, eg top mass
All central detectors have made measurements in the 'transverse' region:

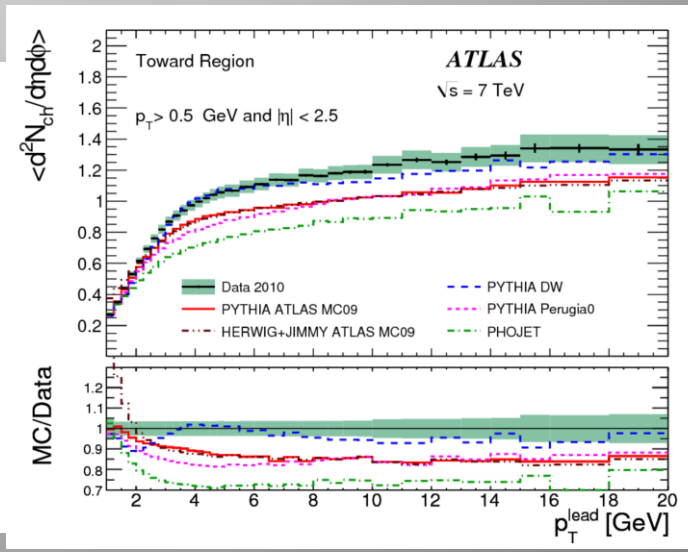




Measure the particle flow in transverse region as function of the hard scale



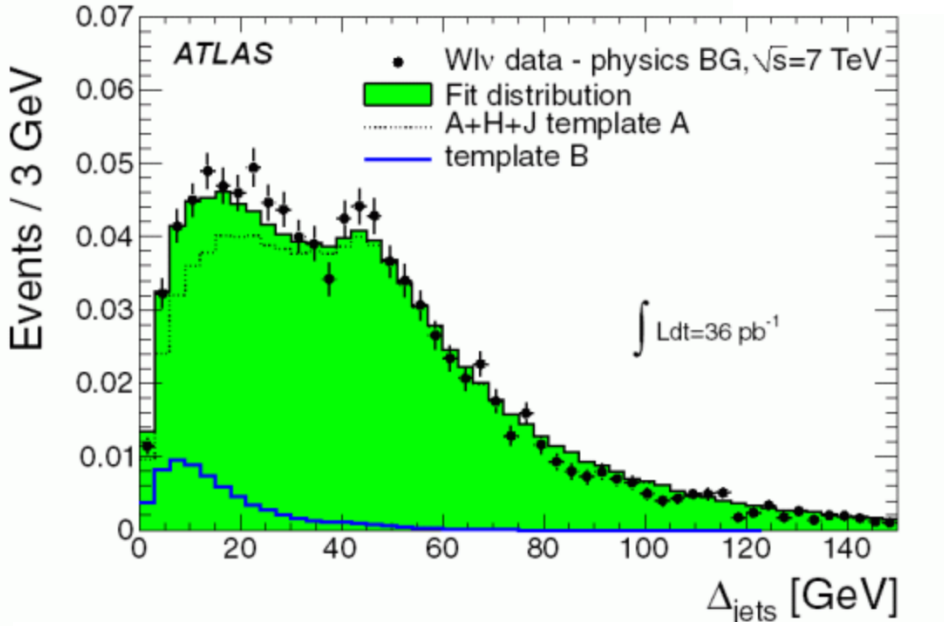




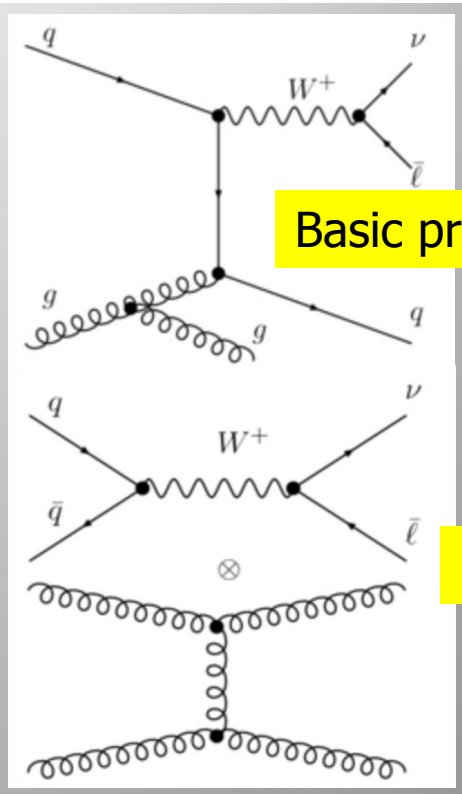
Double Parton Scattering

Example: angular correlations study of W+ 2jet events: The fraction of the cross section attributed to DPS= 0.08 ± 0.01 (stat.) ± 0.02 (sys.)

arXiv:1301.6872



Difference between the transverse momenta of the two jets (p_T > 20 GeV)

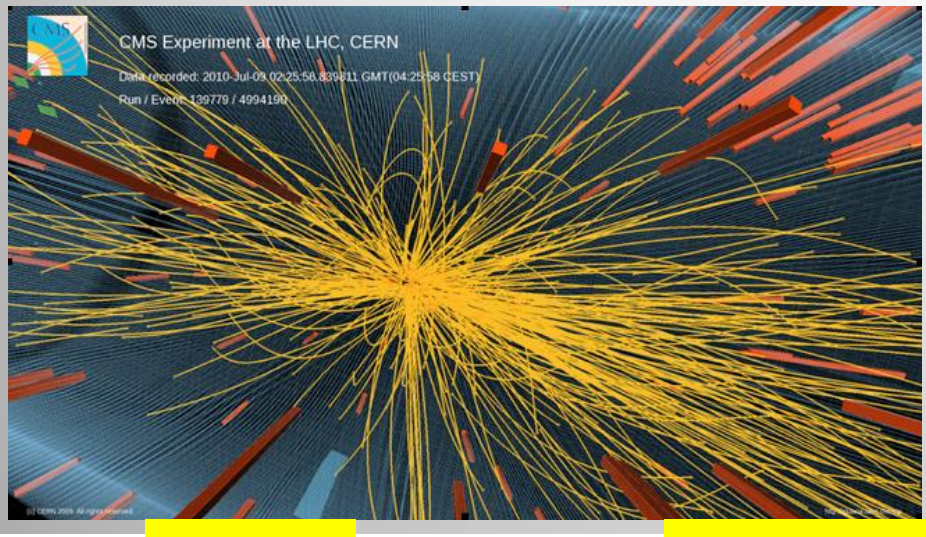


Basic process

DPS

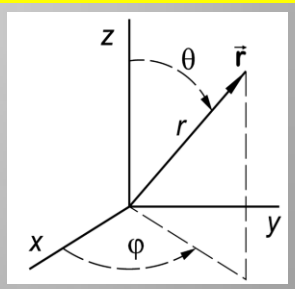
DPS can be important for searches where after cuts only a few events remain…

Correlations Between Produced Particles



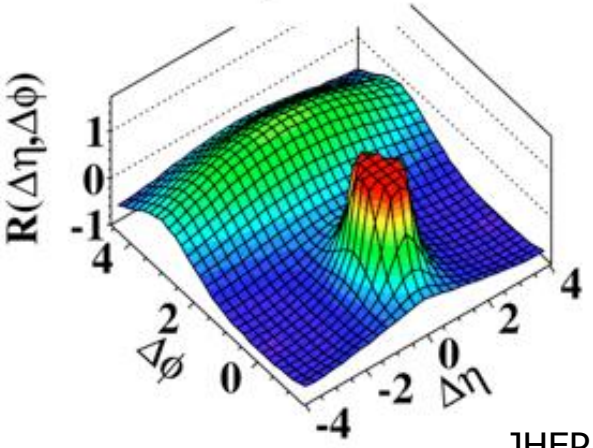
- Select high multiplicity events
- Study the correlation between two charged particles in the angles φ (transverse): Δφ and θ (longitudinal): Δθ

$\eta = -\ln \tan\theta/2$



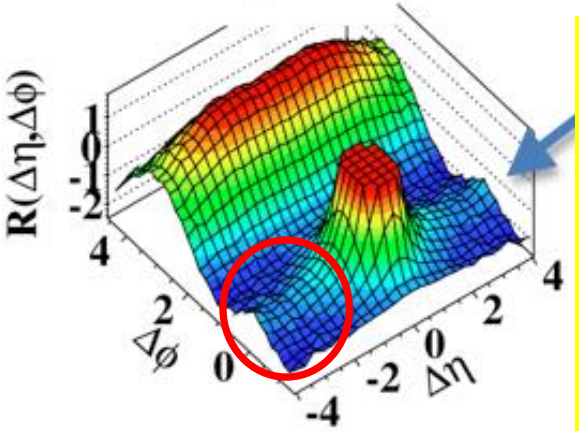
All events

MinBias, 1.0GeV/c<p_T<3.0GeV/c



High multiplicity events

N>110, 1.0GeV/c<p_T<3.0GeV/c



JHEP 1009 (2010) 091

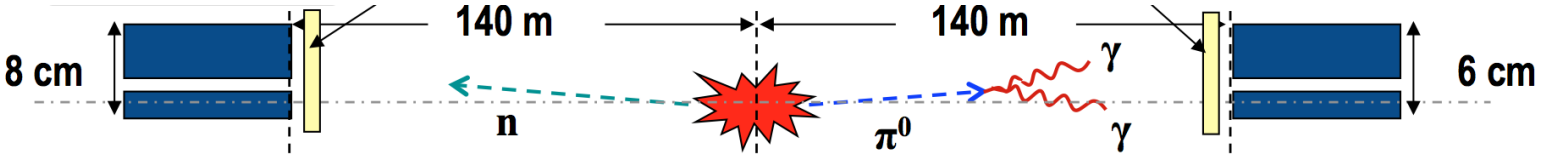
A new phenomenon in the 'stronge force'?

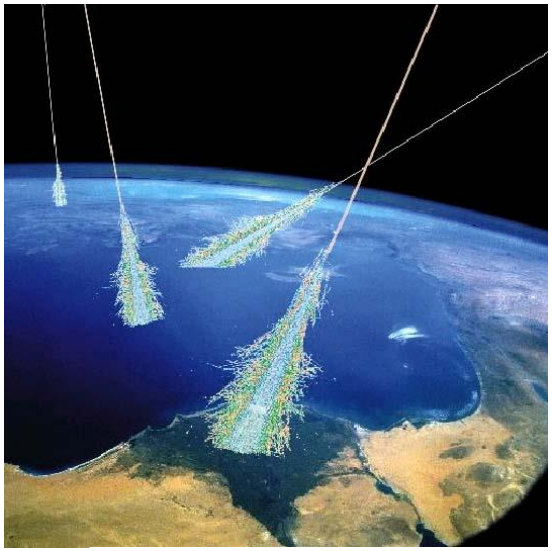
- Multiple interactions?
- Glass condensates?
- Hydrodynamic models?

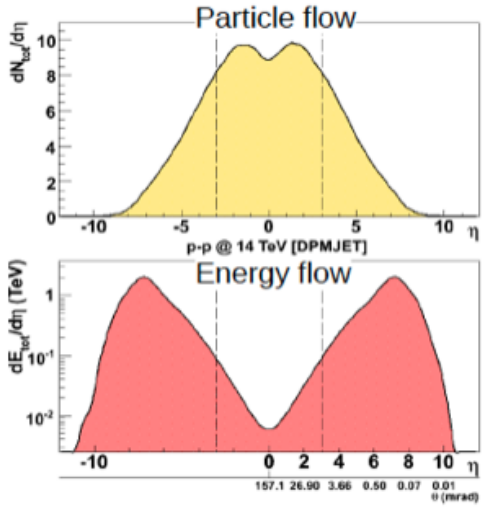
…

Forward Particles Measurements

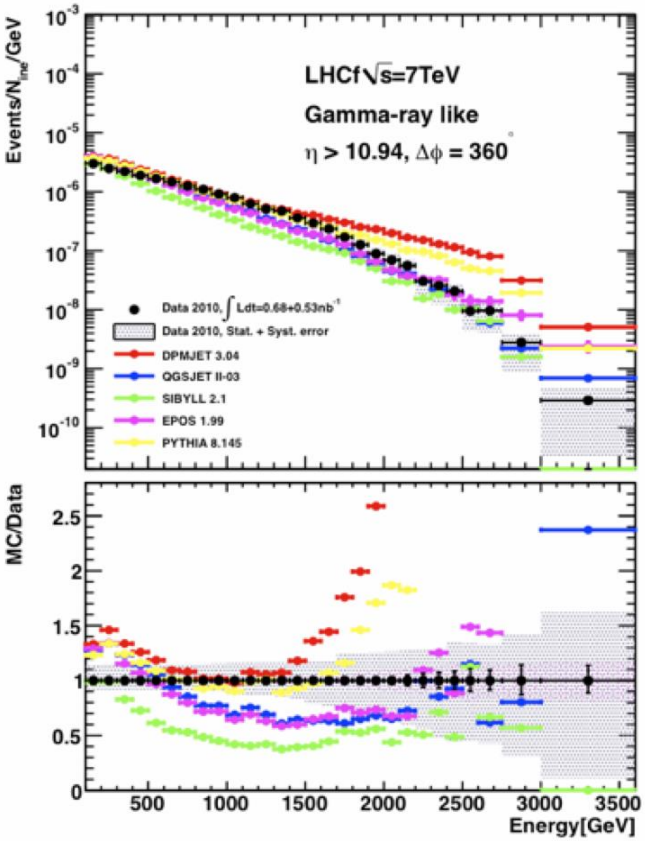
- LHCf uses the same Interaction Point as ATLAS (IP1)
- LHCf has forward detectors at zero degrees seen from the IP (140 away from the IP): Measure the forward photons/pions for cosmic ray studies







PLB 703 (2011) 128



Forward gamma measurement compared to Monte Carlos for Cosmic Ray studies

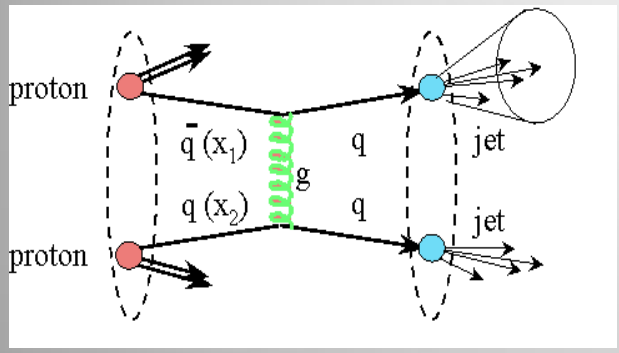
No model reproduces the data well !!

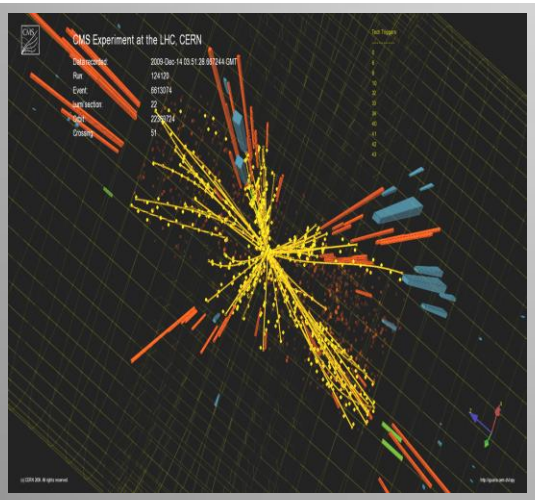
Important for understanding of cosmic ray data

Hard Scattering
Perturbative QCD

Strong Interaction: Jets Production!

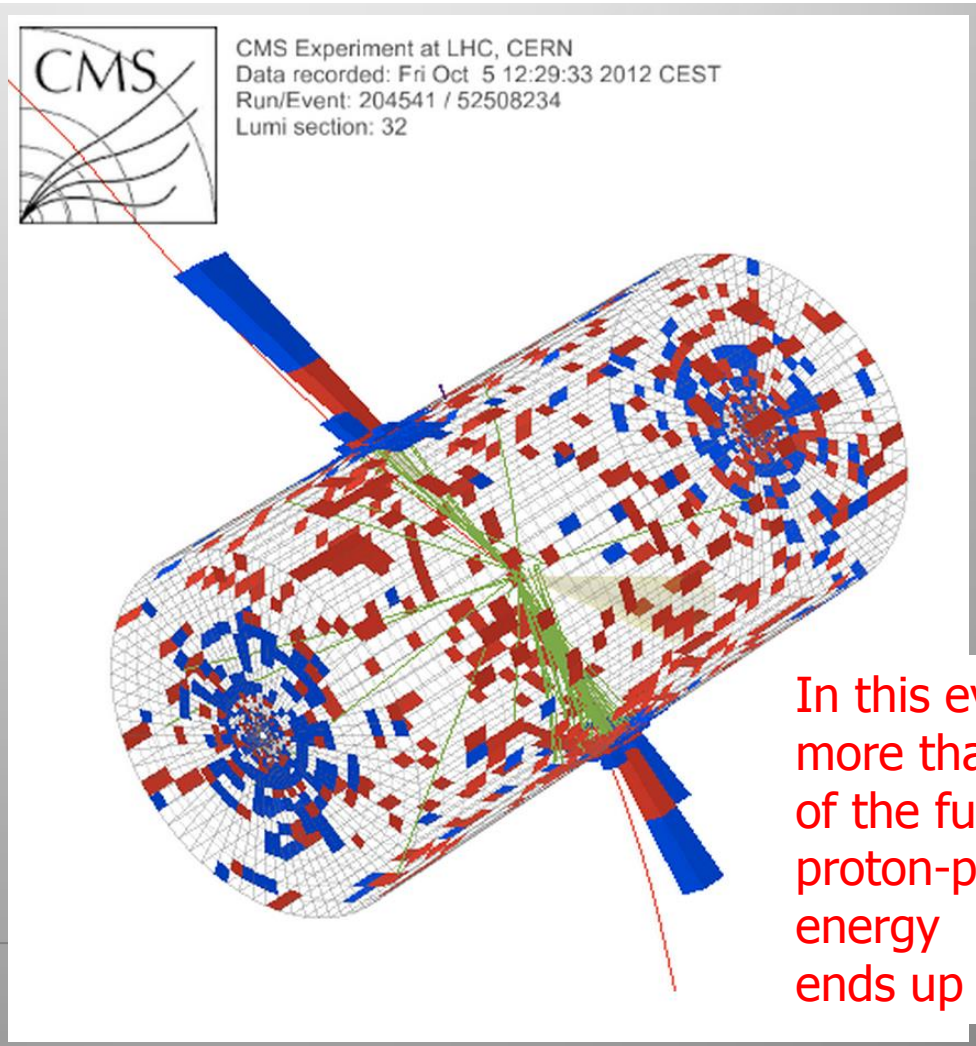
Study the strong force using jet production





Jets of particles emerge after a high energy parton-parton Scattering

Di-jet invariant mass = 5.15 TeV (R=1.1 jets)



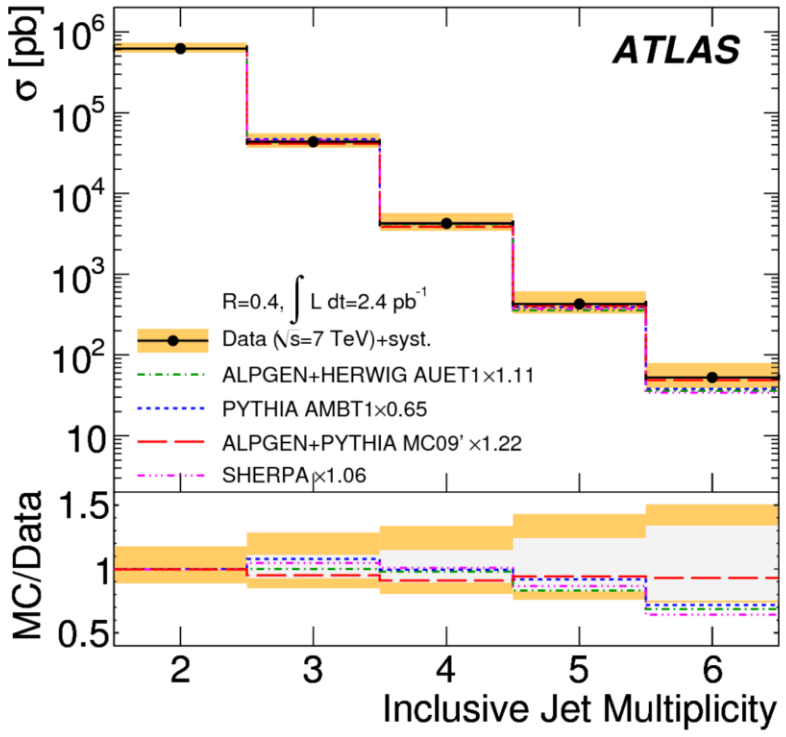
In this event more than 60% of the full proton-proton energy ends up in jets

Early Measurements of Multi-jets

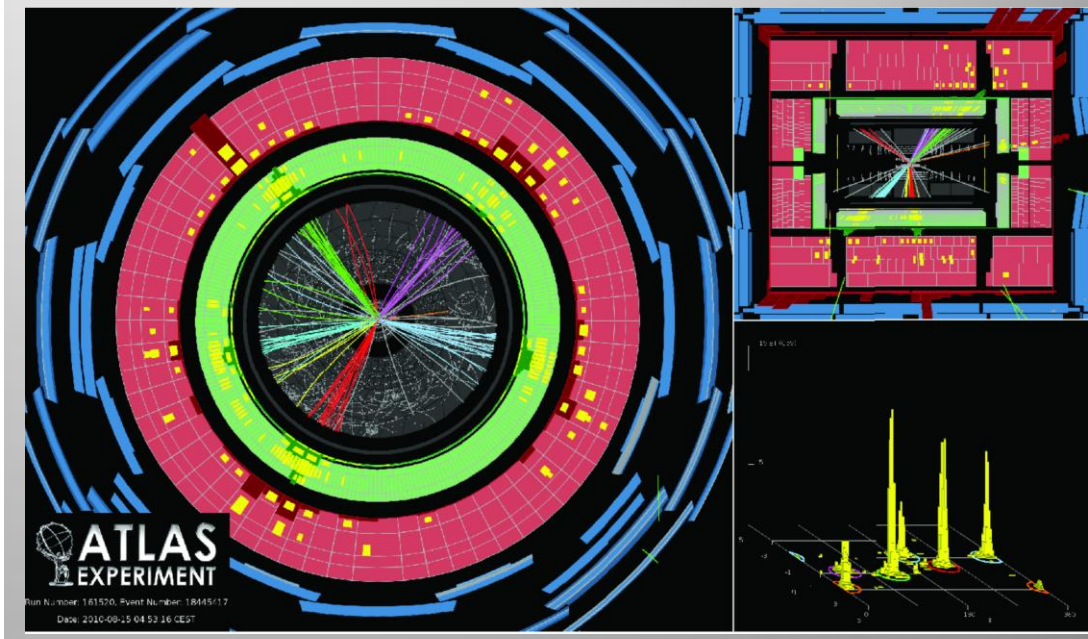
Early 2010 data…

Jet Multiplicity distribution

Eur.Phys.J. C71 (2011) 1763



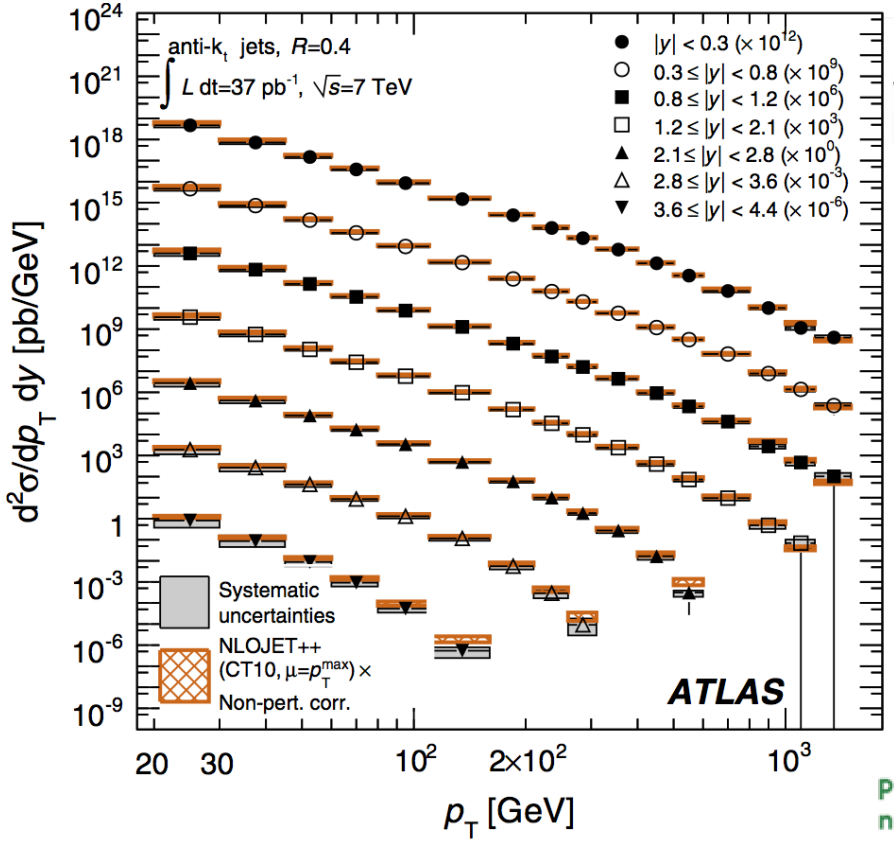
A six jet event



Multi-jet distribution in good agreement with theory - LO matrix elements plus matched parton showers - apart from normalization

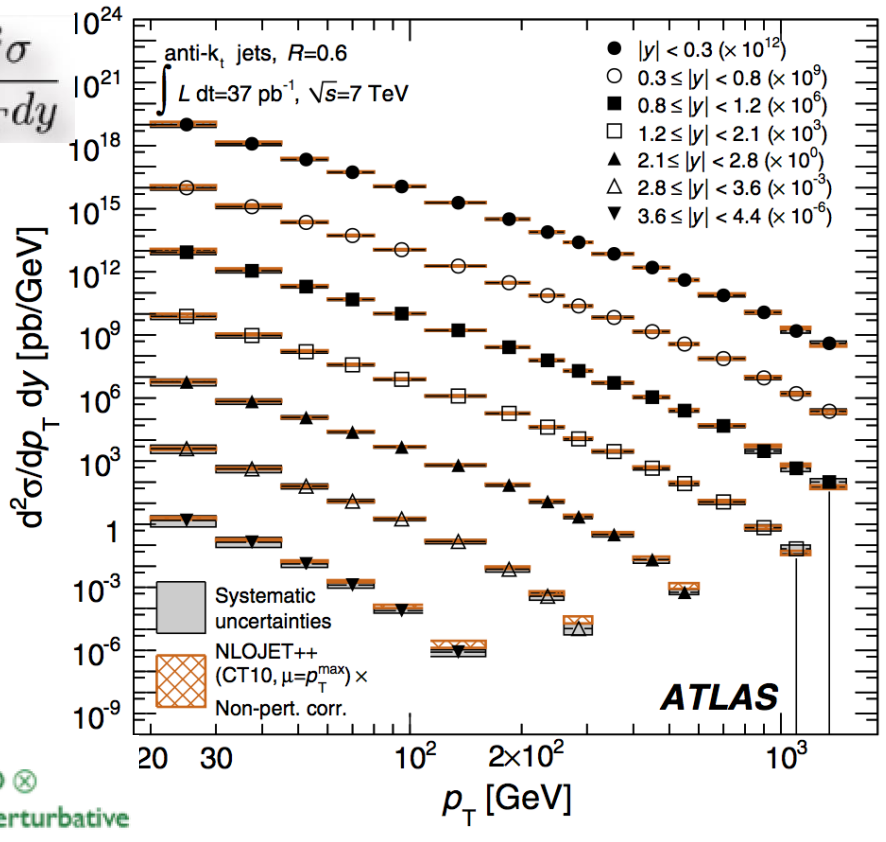
Inclusive Jet Production (7 TeV)

Phys.Rev. D86 (2012) 014022



$$\frac{d^2\sigma}{dp_T dy}$$

pQCD ⊗ non-perturbative corrections



Agreement with NLO calculations over the full range, up to 2 TeV jets

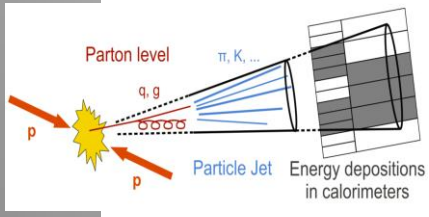
The anti-kT jet algorithm is used in most studies. The 'cone' chosen for this algorithm is different for ATLAS and CMS -> no direct comparison possible

ATLAS uses R=0.4 and R=0.6

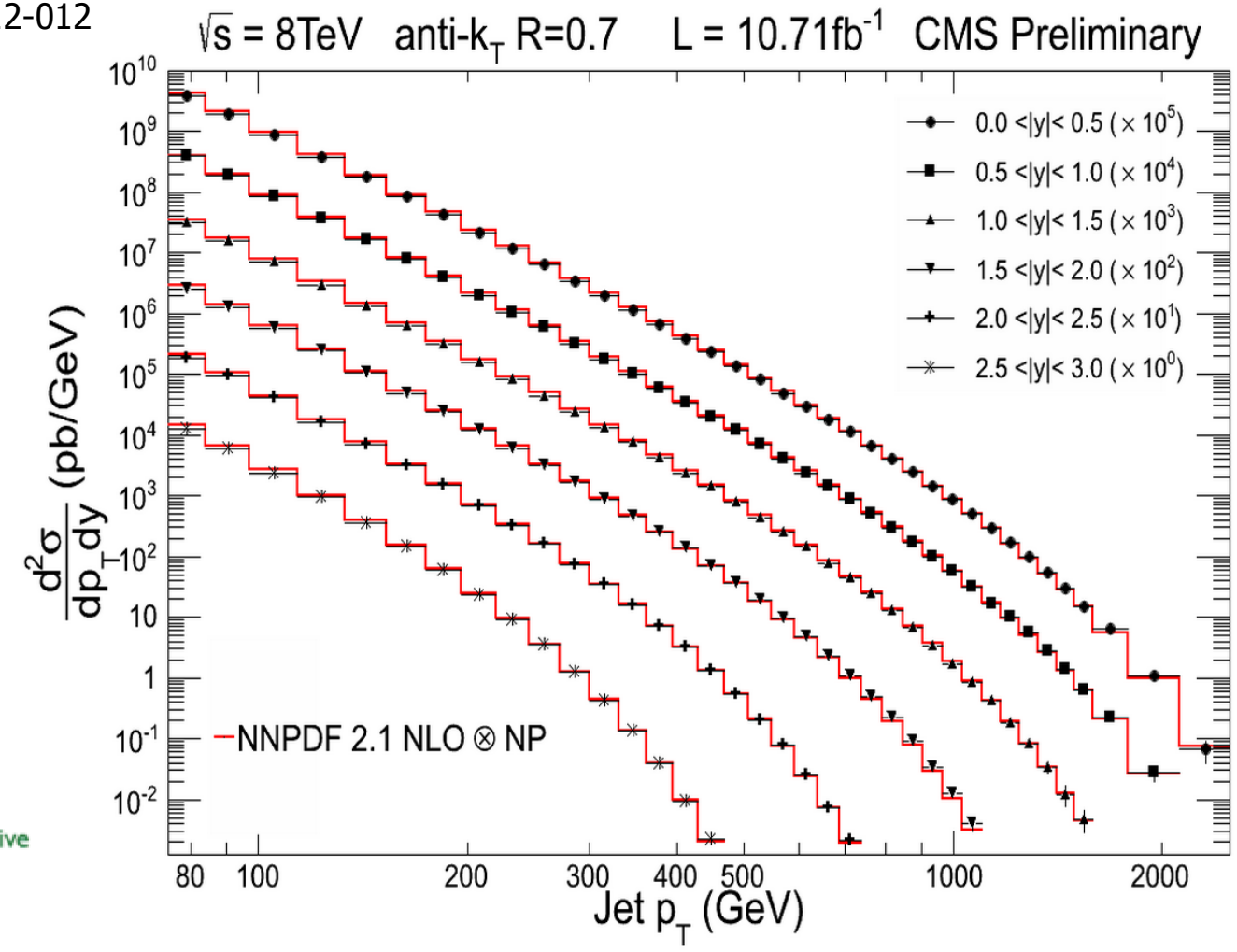
Inclusive Jet Production (8 TeV)

CMS-PAS-SMP-12-012

$$\frac{d^2\sigma}{dp_T dy}$$



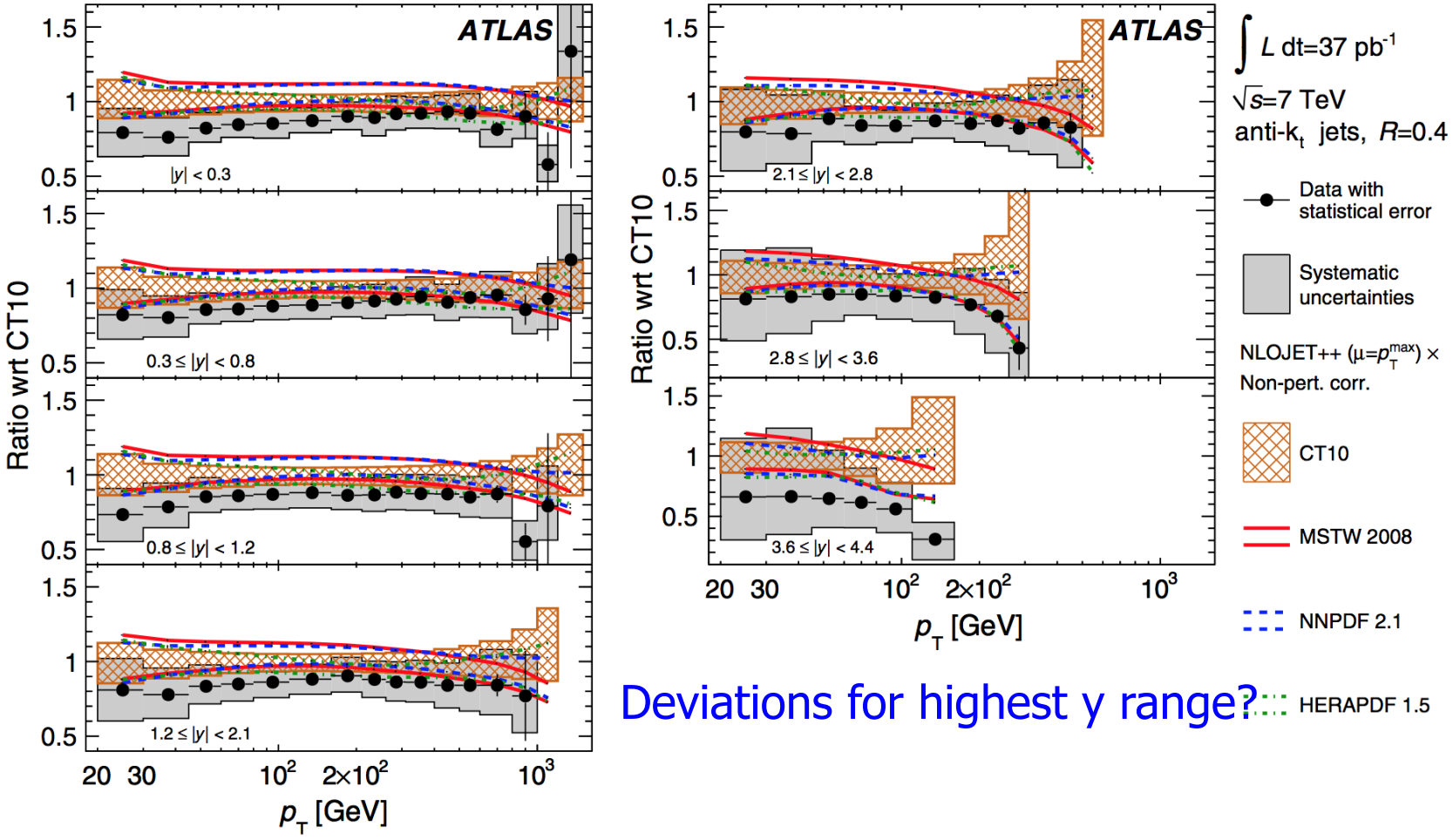
pQCD ⊗
non-perturbative
corrections



Agreement with NLO calculations over the full range, up to and beyond 2 TeV jets

Inclusive Jet Production

Comparison with NLO calculations with the data in some detail, for different proton structure function parameterizations.

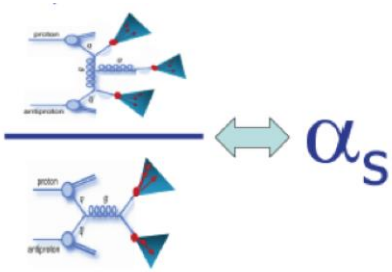


Deviations for highest y range?

Extracting the Strong Coupling Constant

Measure the ratio of 3-jet to 2-jet events

This measurement is sensitive to the fundamental QCD parameter α_s
Di-jets within the range of 420 - 1390 GeV, p_T of all jets larger than 150 GeV

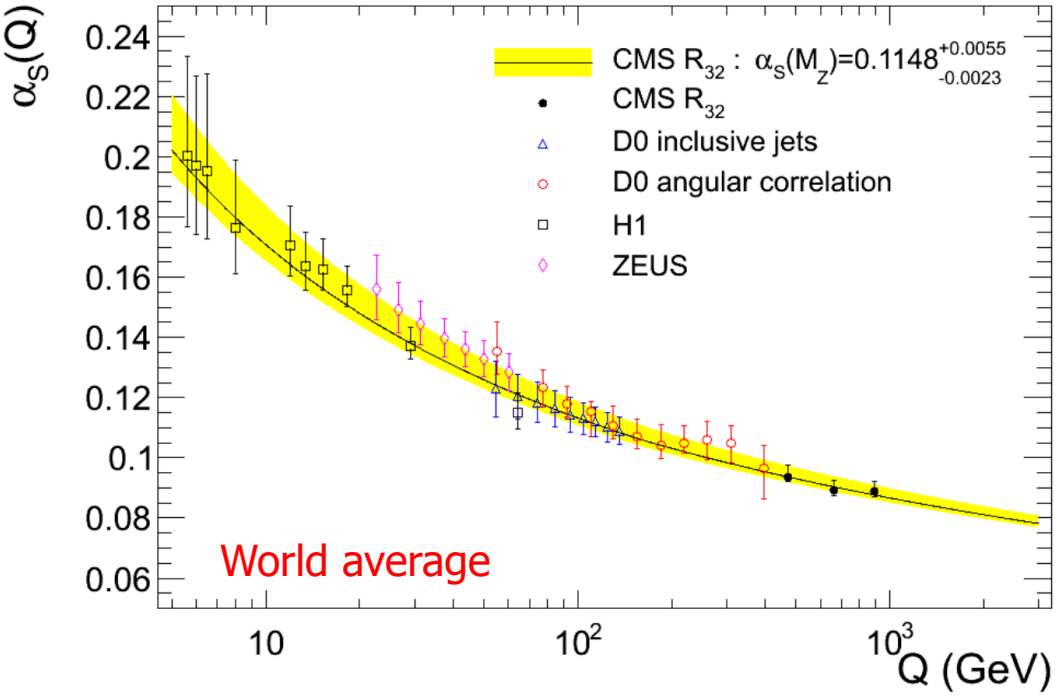


$$R_{32} = \frac{d\sigma_{3+}/dp_T}{d\sigma_{2+}/dp_T} \propto \alpha_s(Q)$$

$$Q = \langle p_{T1,2} \rangle = \frac{p_{T1} + p_{T2}}{2}$$

$\langle p_{T1,2} \rangle$ range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	$\alpha_S(Q)$
420–600	474	$0.1147\,^{+0.0061}_{-0.0021}$	$0.0936\,^{+0.0040}_{-0.0014}$
600–800	664	$0.1132\,^{+0.0050}_{-0.0031}$	$0.0894\,^{+0.0031}_{-0.0019}$
800–1390	896	$0.1170\,^{+0.0058}_{-0.0032}$	$0.0889\,^{+0.0033}_{-0.0018}$

More methods are being used



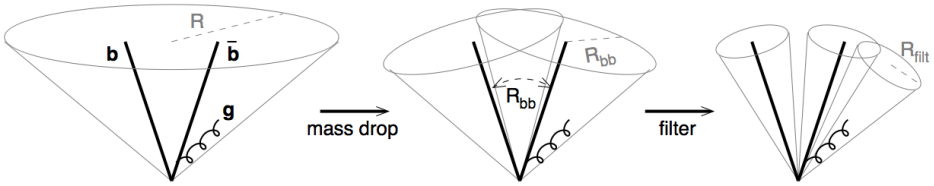
$\alpha_S(M_Z) = 0.1148 \pm 0.0014\,(\text{exp.}) \pm 0.0018\,(\text{PDF})\,^{+0.0050}_{-0.0000}\,(\text{scale}) = 0.1148\,^{+0.0055}_{-0.0023}$ arXiv:1304.7498

ATLAS prelim: $\alpha_s(M_Z) = 0.111 \pm 0.006(\text{exp.})\,^{+0.016}_{-0.003}(\text{theory})$. ATLAS-CONF-2013-041

New Directions: Boosted Jets & Substructure

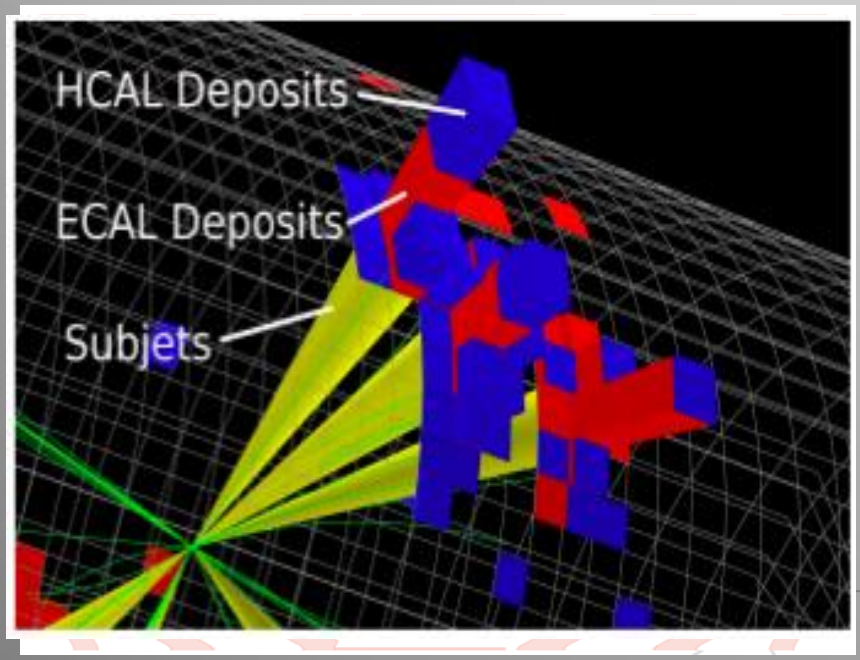
Analyse boosted/merged jets

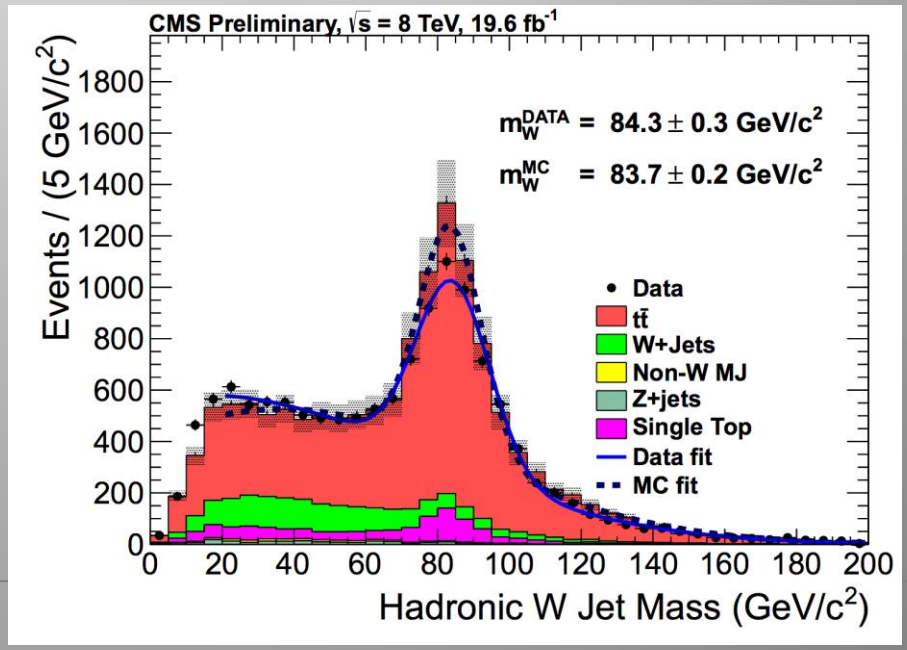
arXiv:0802.2470



- Start from Cambridge-Aachen FAT jets and apply jet "pruning" to find sub-jets
- Many methods being developed to analyse the jet substructure: grooming-> mass drop filtering, trimming, pruning…

Example: Boosted top events with b-jet and two merged jets from the W

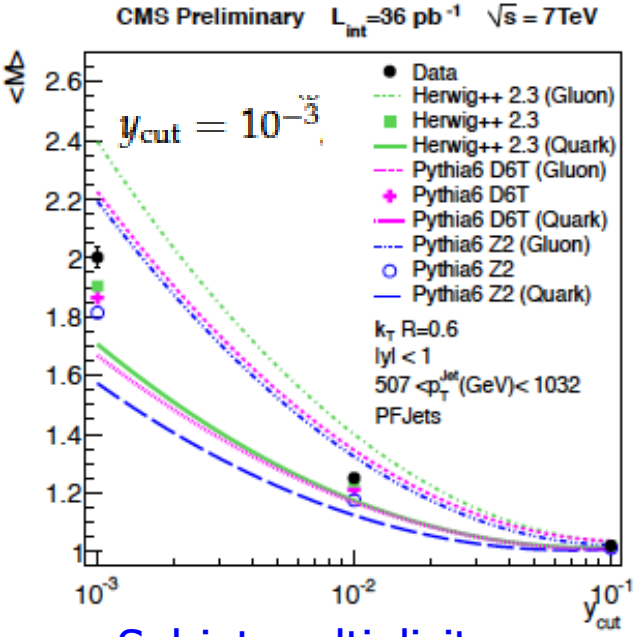




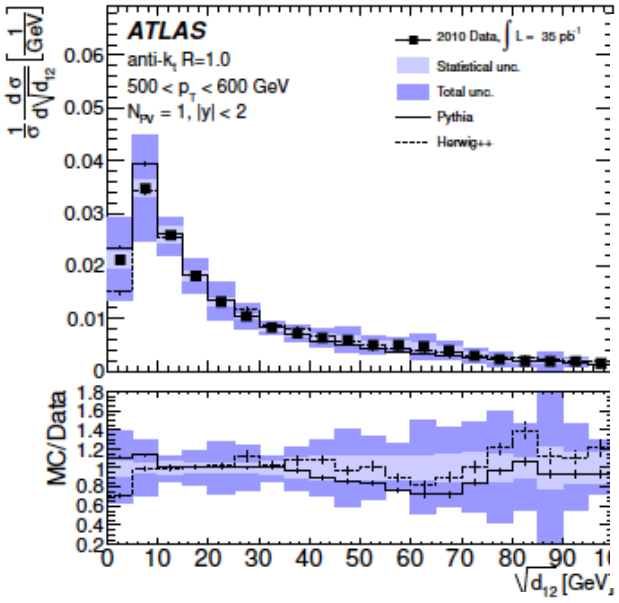
Detailed QCD Jet-structure Studies

- Detailed QCD jet studies such as substructure grooming are important to get:
  - Deeper insight into pQCD evolution in jets
  - To perform searches for New Physics in a new way

CMS-QCD-10-41

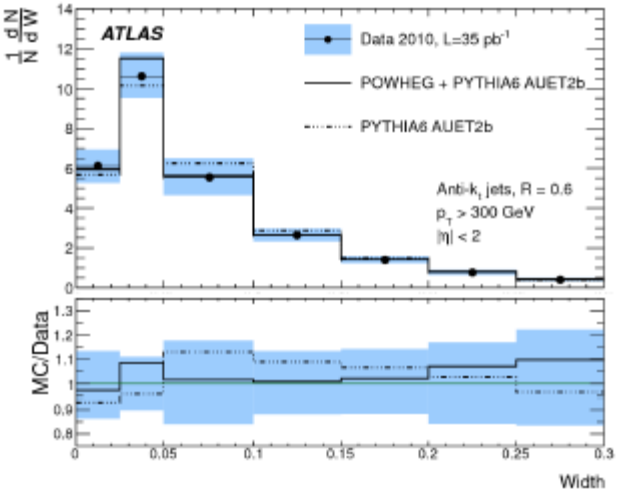


Subjet multiplicity



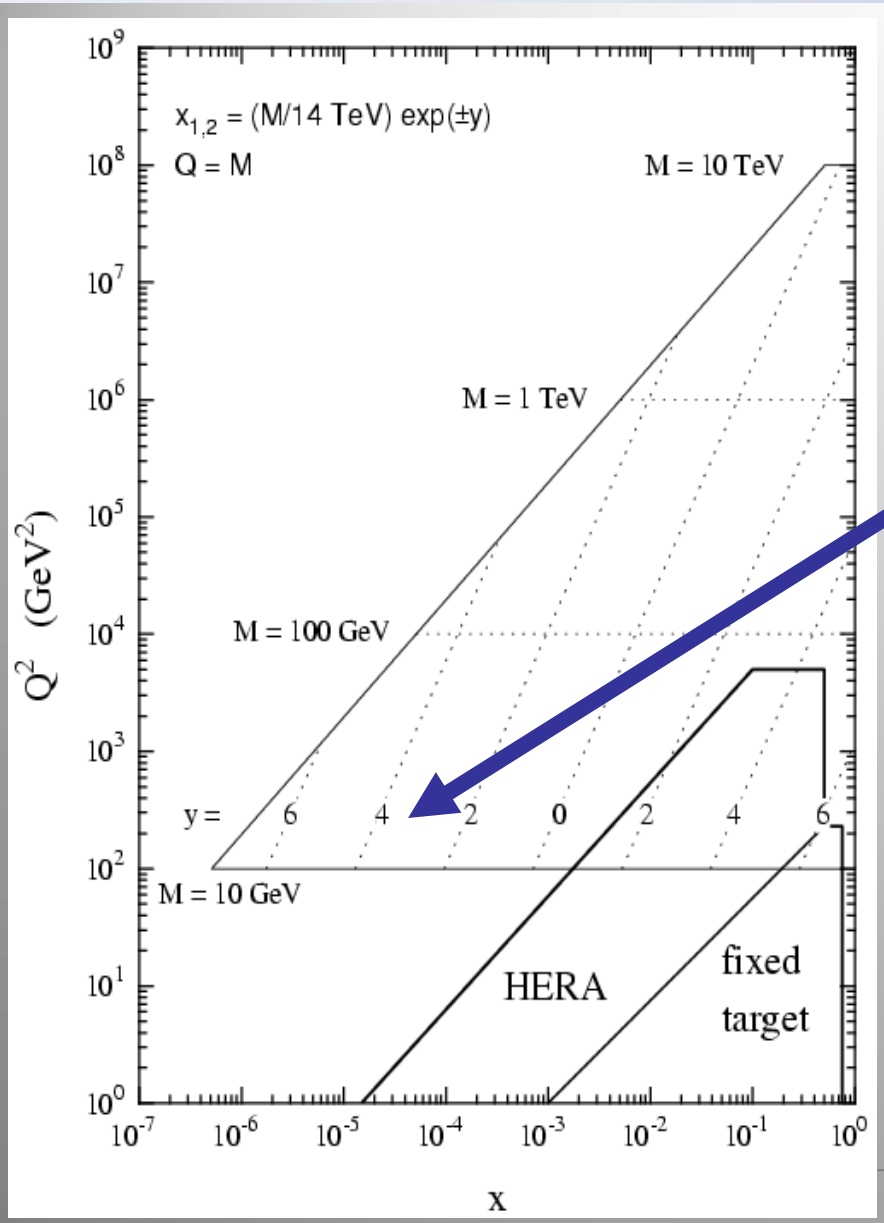
k_T splitting scale

arXiv:1203:4606



Jet width

Low-x Studies at the LHC



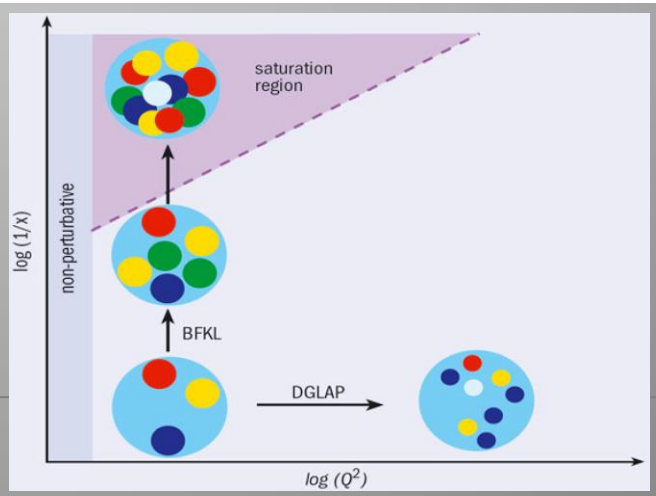
High energy of the LHC allows to access regions of low Bjorken-x Detector coverage to large |η| is important! Typical measurements:

- Low mass Drell-Yan, Jpsi…
- Prompt photon production
- Jet production with large rapidity

QCD Dynamics studies:

DGLAP: Dokshitzer, Gribov, Lipatov, Altarelli Parisi

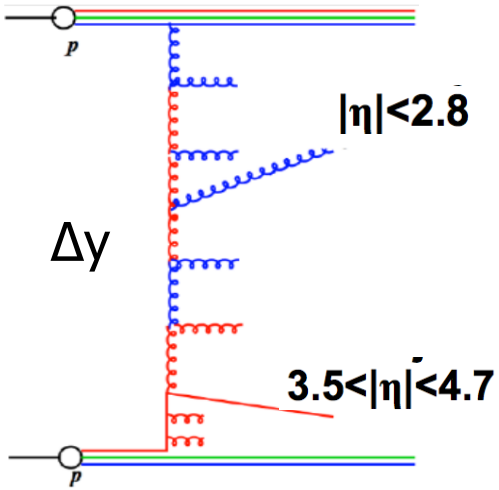
BFKL: Balitskii, Fadin, Kuraev, Lipatov



Low-x: Mueller-Navelet Jet Studies

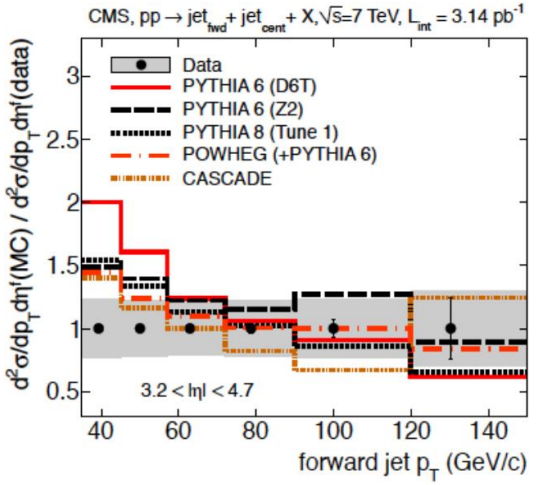
- Look at correlations between jets -with p_T> 35 GeV- at large rapidity distance
- Proposed in the early '90's to as sensitivity test to BFKL and DGLAP evolution

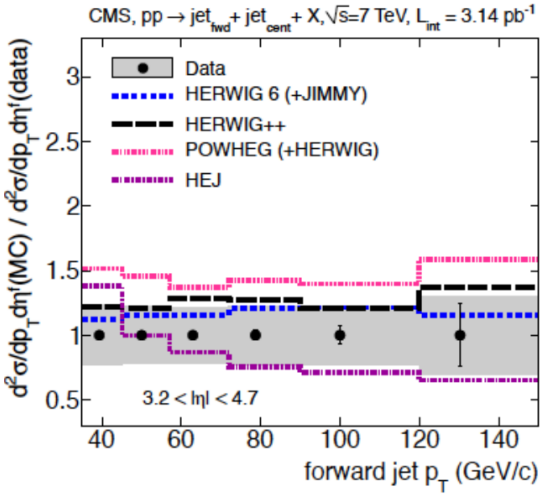
CMS-PAS-FSQ-12-002



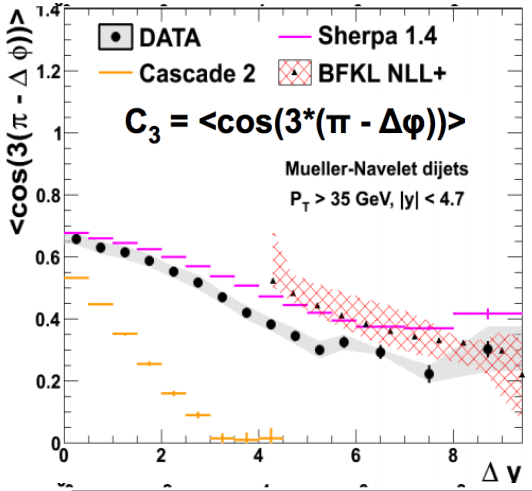
No model describes all these measurements very well

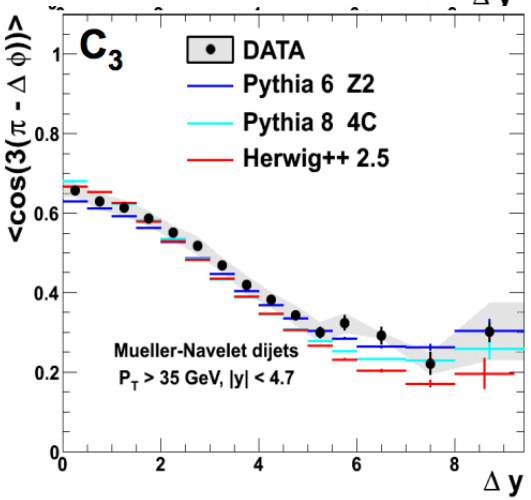
central + forward jet





azimuthal correlation vs Δy

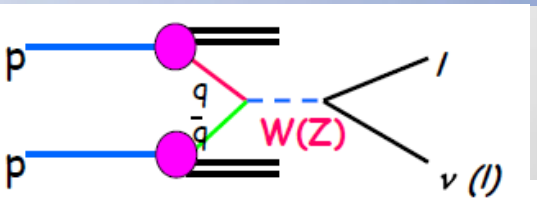




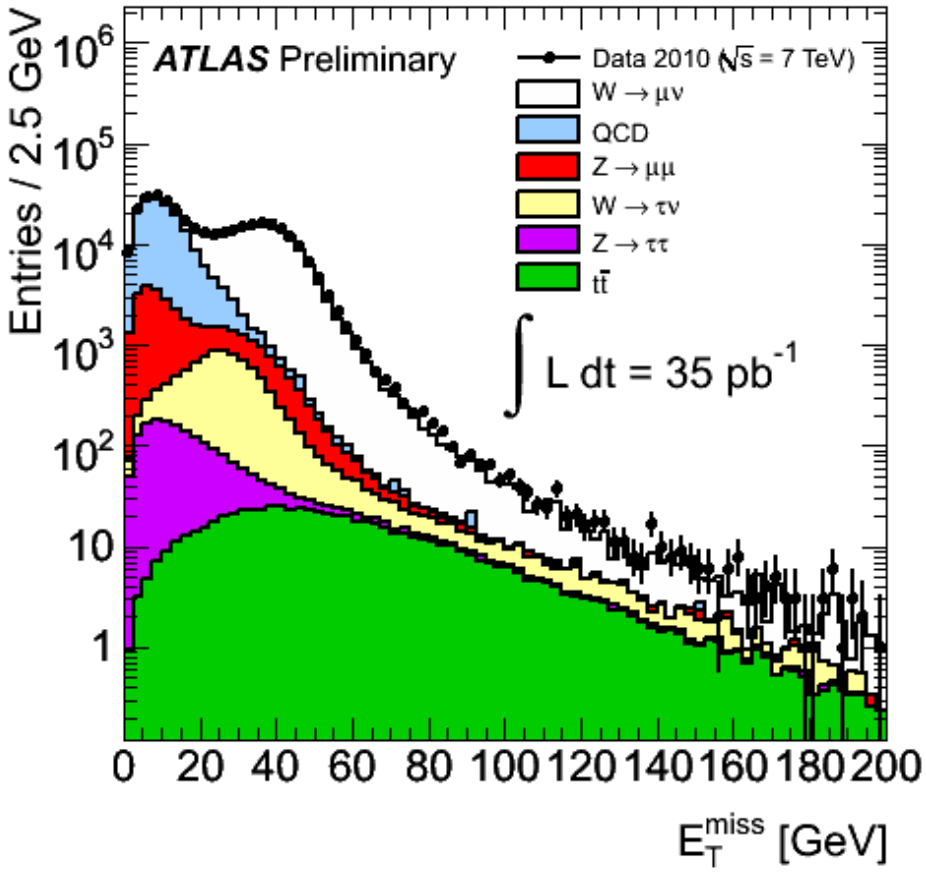
W and Z Boson Production

W and Z Boson Production

Select final states with leptons

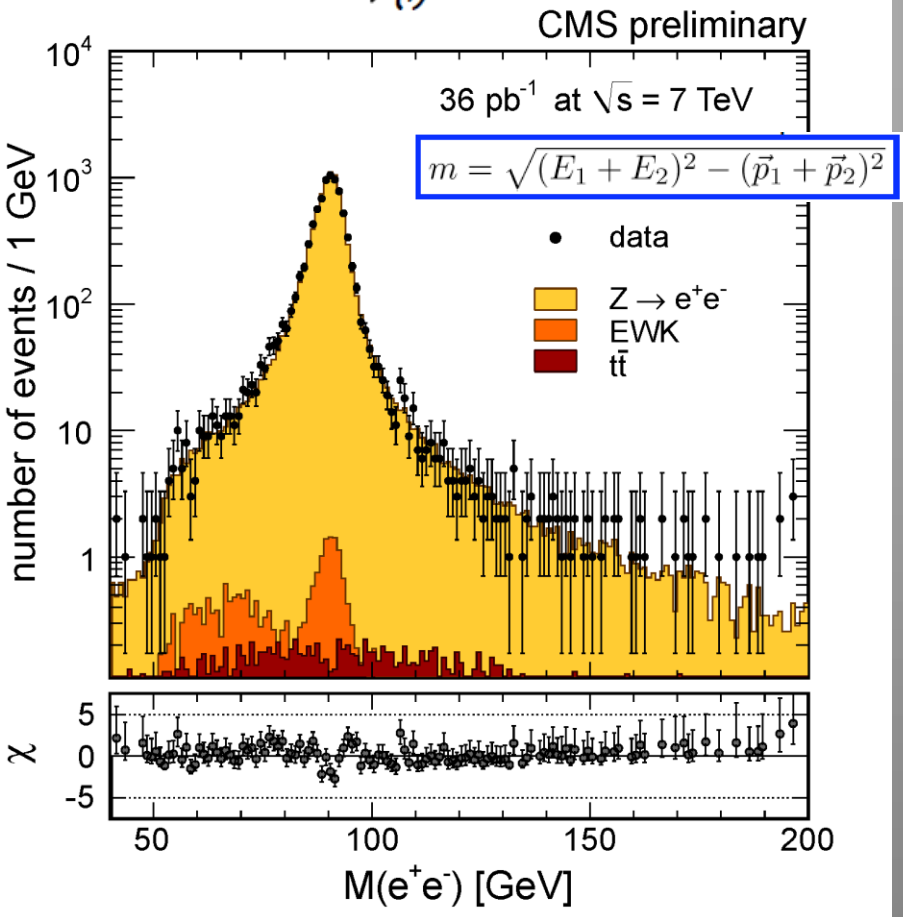


arXiv:1109.5141



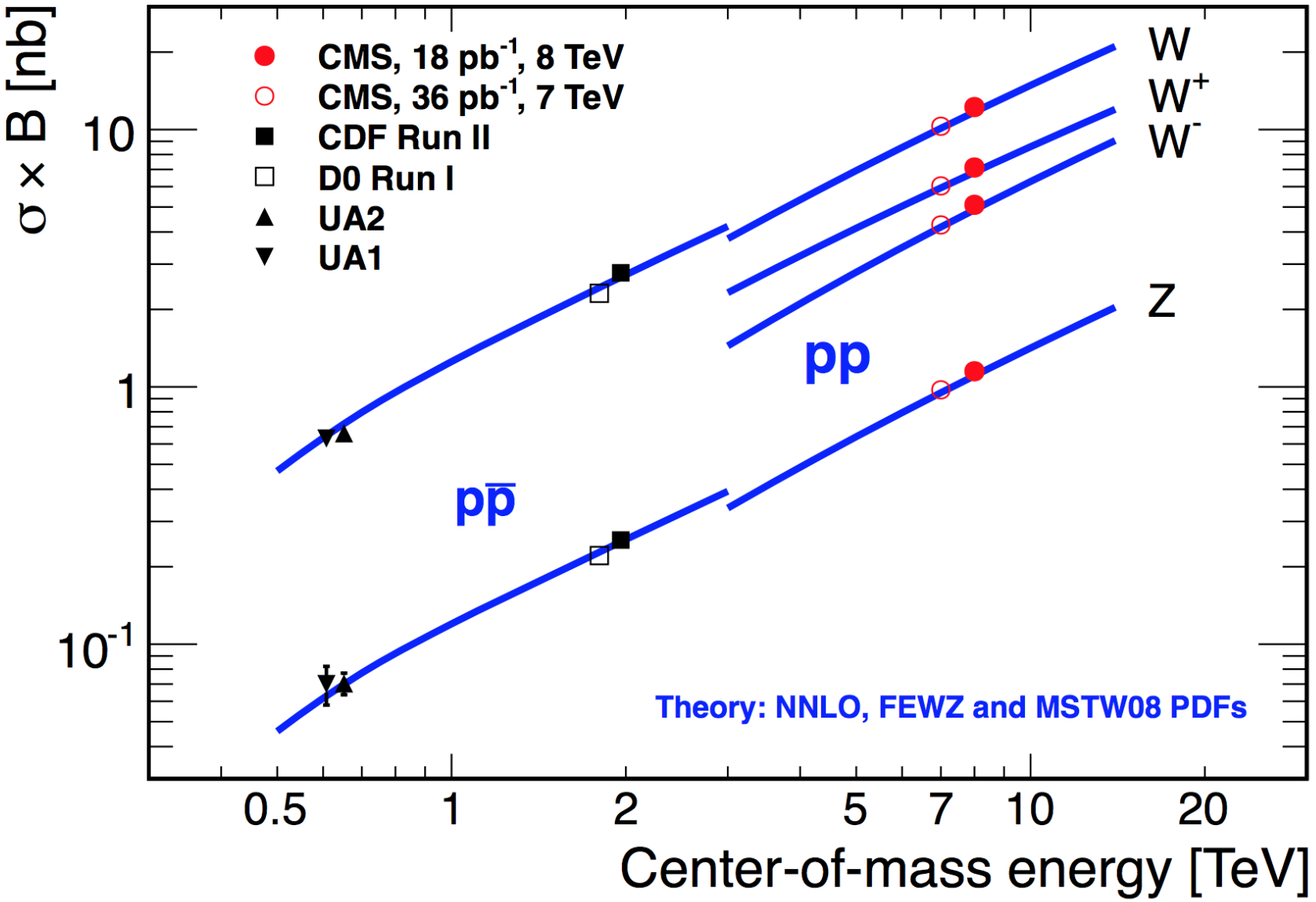
Missing transverse energy from the W → μ+ν decays

arXiv:1107.4789



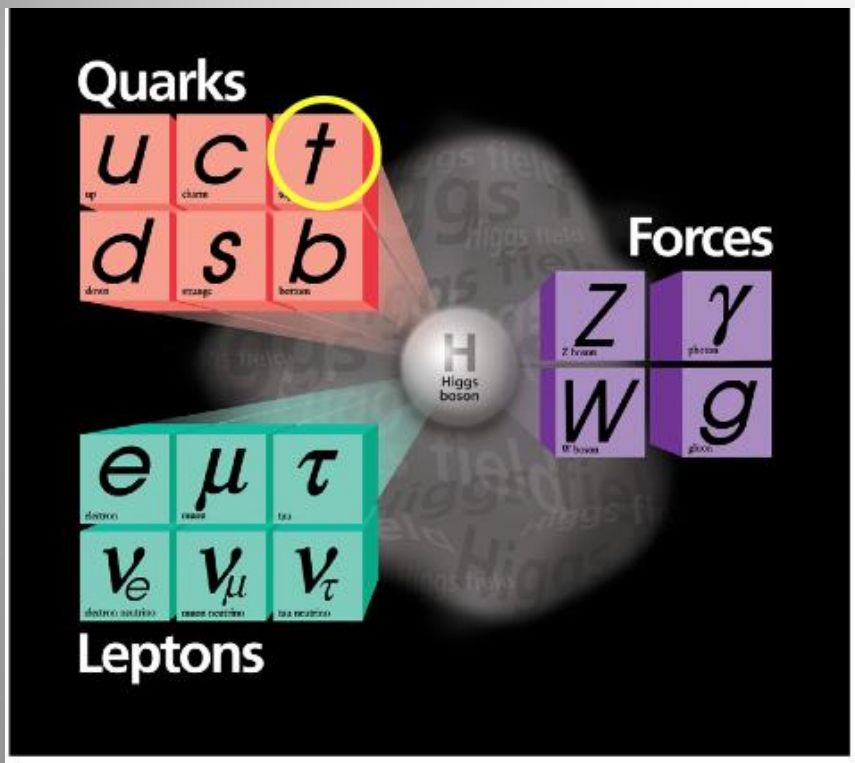
Z peak (di-lepton pair mass distributions)

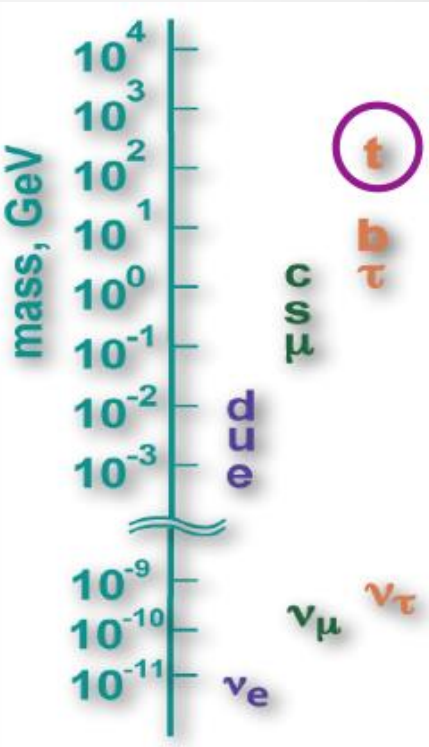
W and Z Boson Production

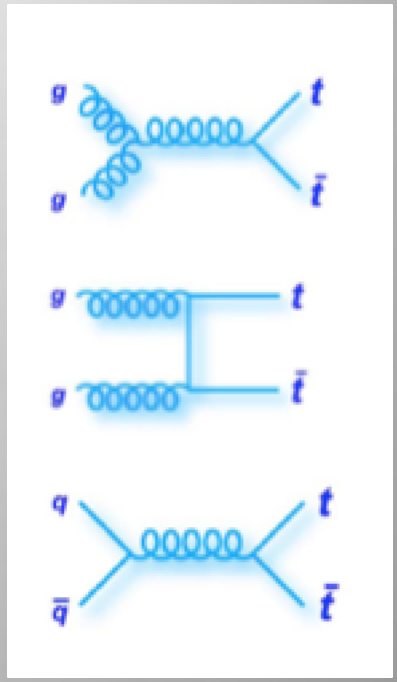


Top Quark Production

Top Quark Physics



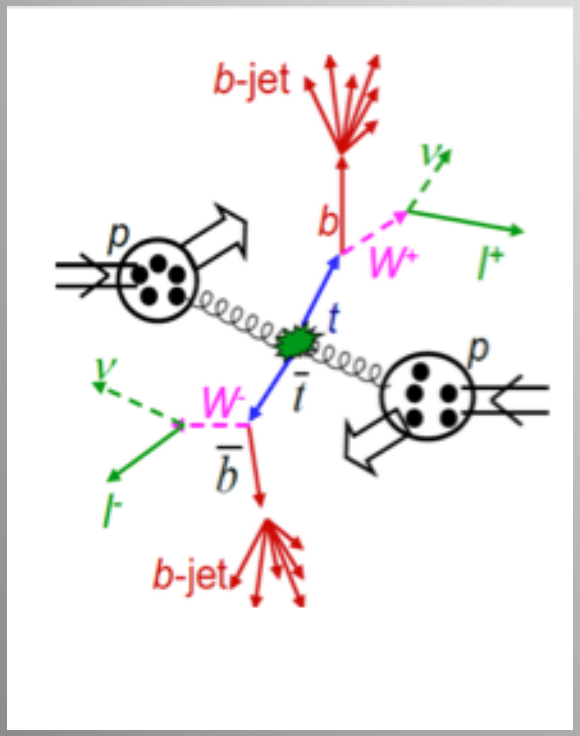


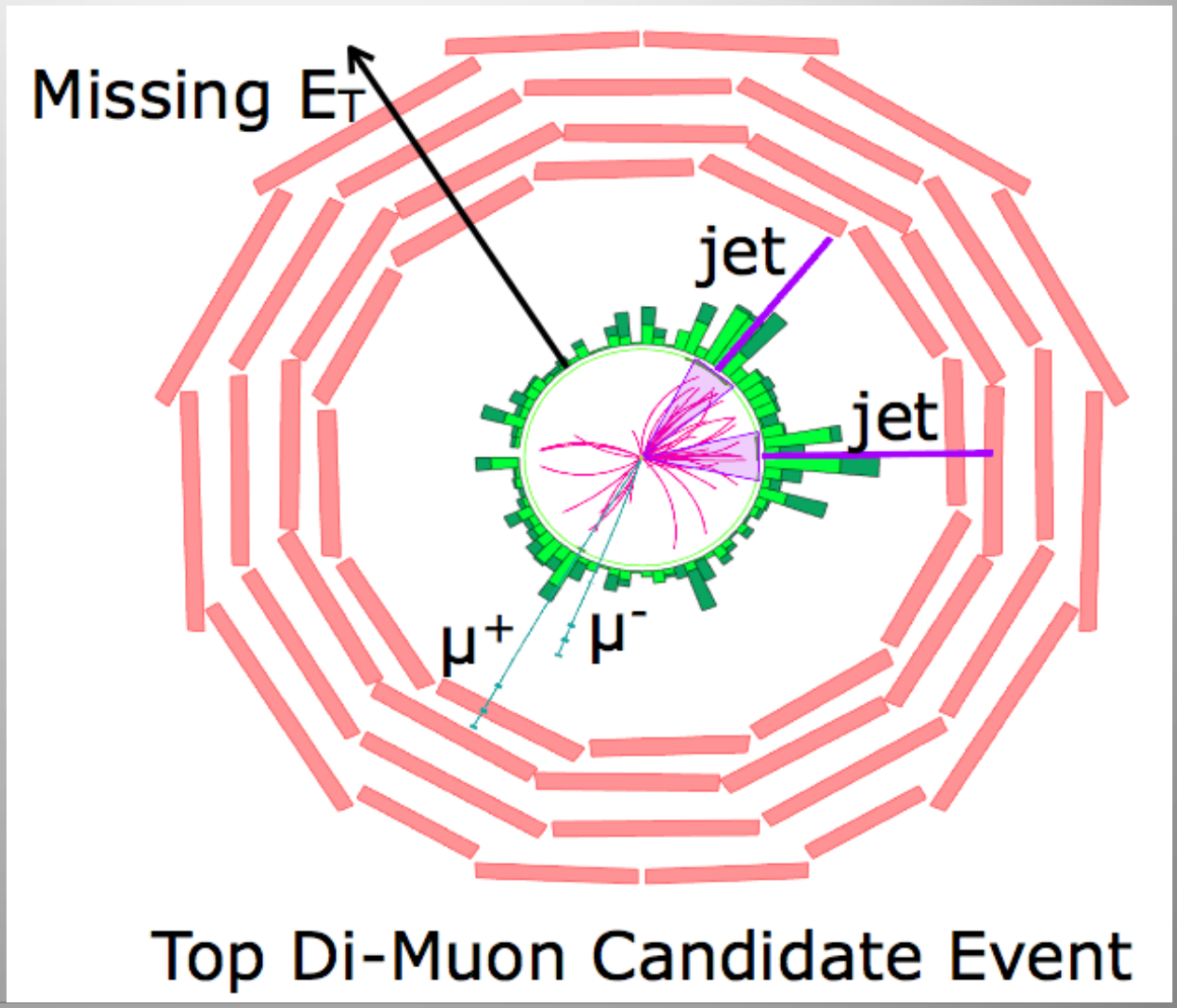


$M_{top} \approx 173$ GeV $\tau \sim 5e10^{-25}$ s $\Gamma^{-1} \approx (1.5\ \text{GeV})^{-1}$

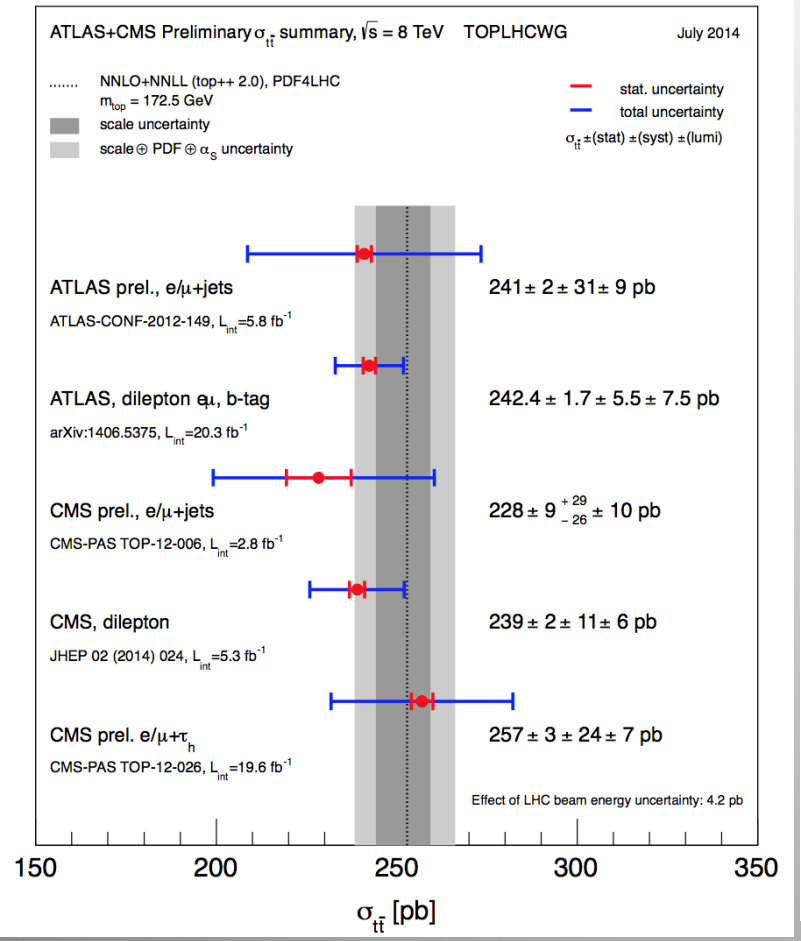
- The heaviest known elementary particle: ~173 GeV
- Coupling to the Higgs ~1 → Special role in EWK symmetry breaking?
- Special sector to searches for new physics

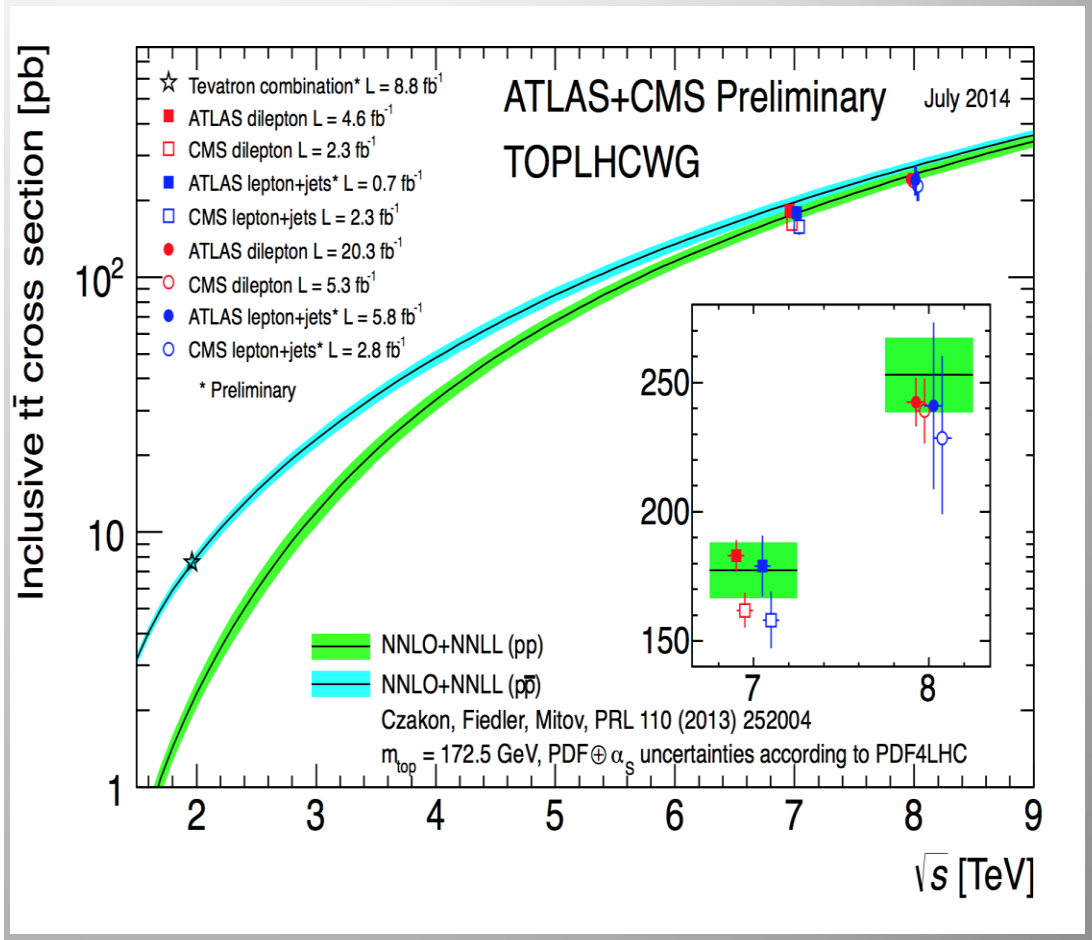
Candidate Event for Top Production





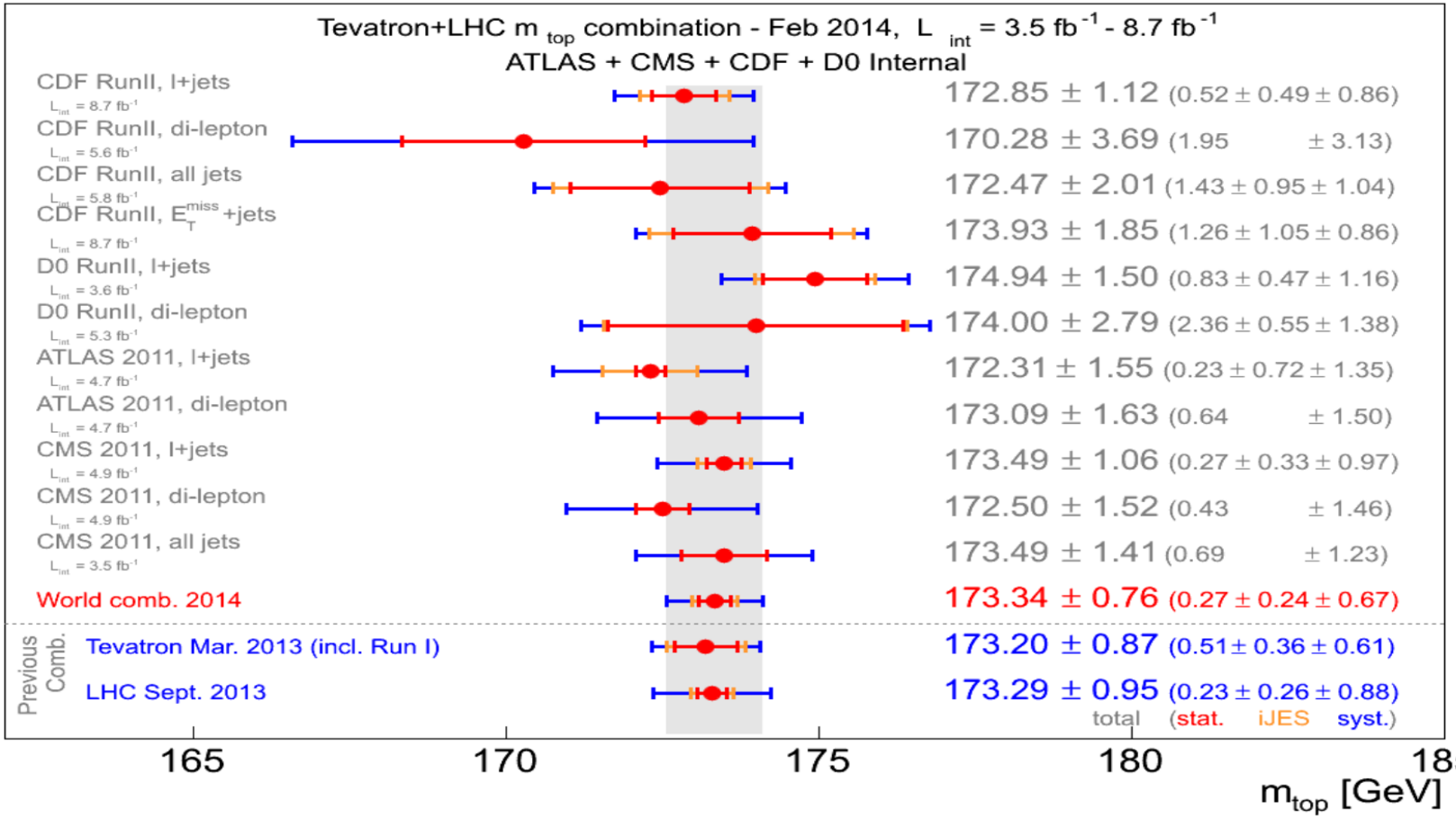
Top Pair Production at 7/8 TeV





ATLAS and CMS have made top anti-top pair cross-section measurements at 7 and 8 TeV, and are in agreement with NLO QCD expectations. Present precision ~ 6%

The Mass of the Top Quark



Using Tevatron and LHC combination of the mass measurements

- Combination performed using BLUE

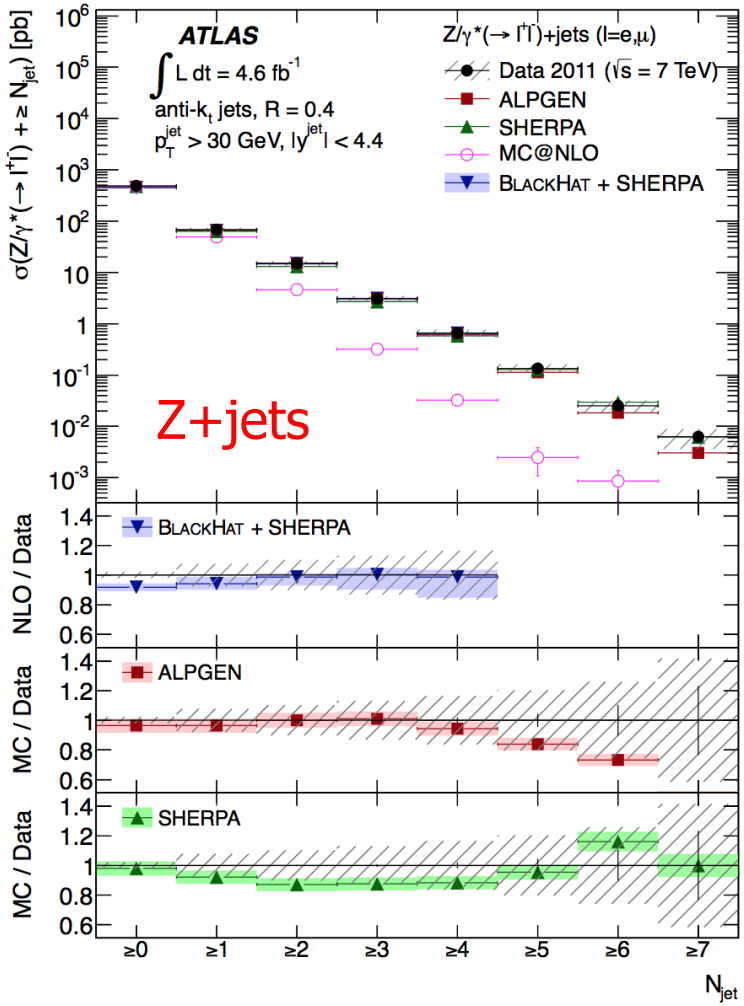
$m_t = 173.34 \pm 0.27\ (\text{stat.}) \pm 0.24\ (\text{iJES}) \pm 0.67\ (\text{syst.})\ \text{GeV}$

$$m_t = 173.34 \pm 0.76\ \text{GeV}$$

The best value on the top mass to date!!

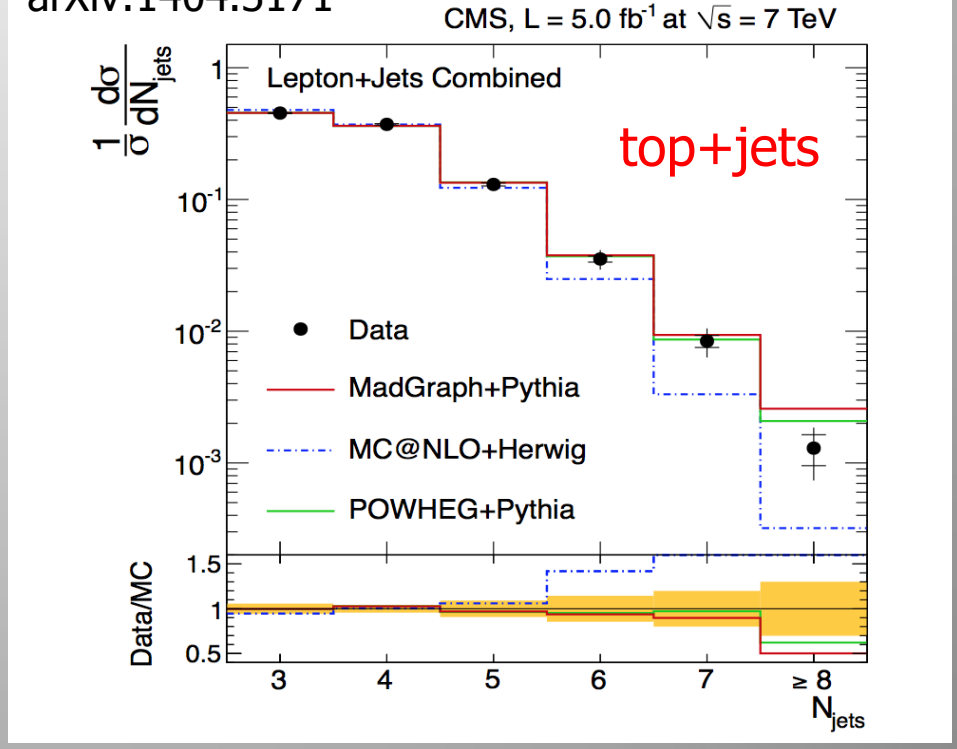
Vector Boson+Jets and Top+Jets

arXiv:1304.7098



High statistics and precision at the LHC allows for W/Z+jets and top+jets studies

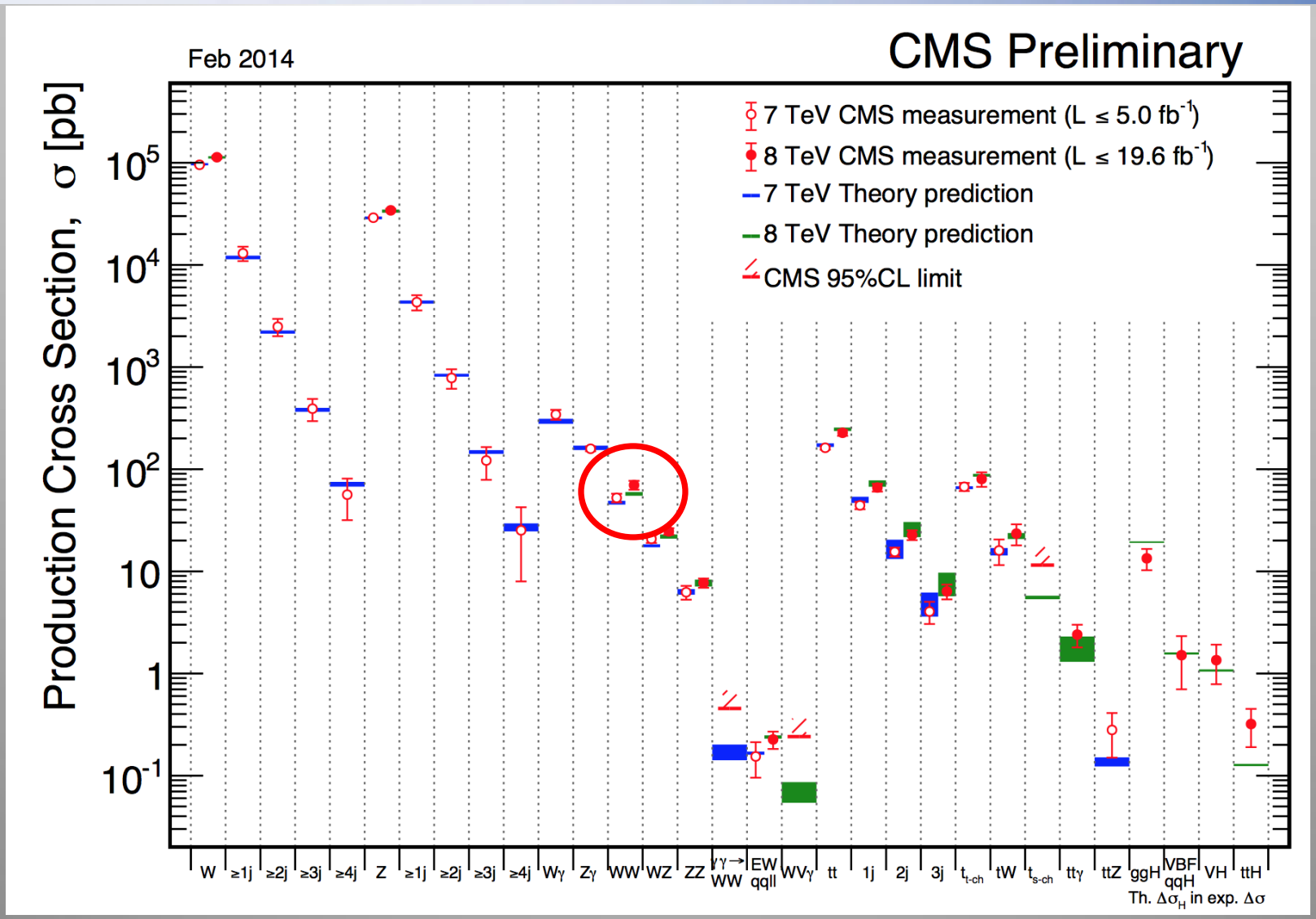
arXiv:1404.3171



Good description by theory for both processes

Important backgrounds for searches, eg for SUSY searches

Summary: Cross Sections at 7/8 TeV



Measurements in good agreement with the Standard Model predictions

Anomalous WW Production?

Di-boson production: This should not be a problem for theory, no?

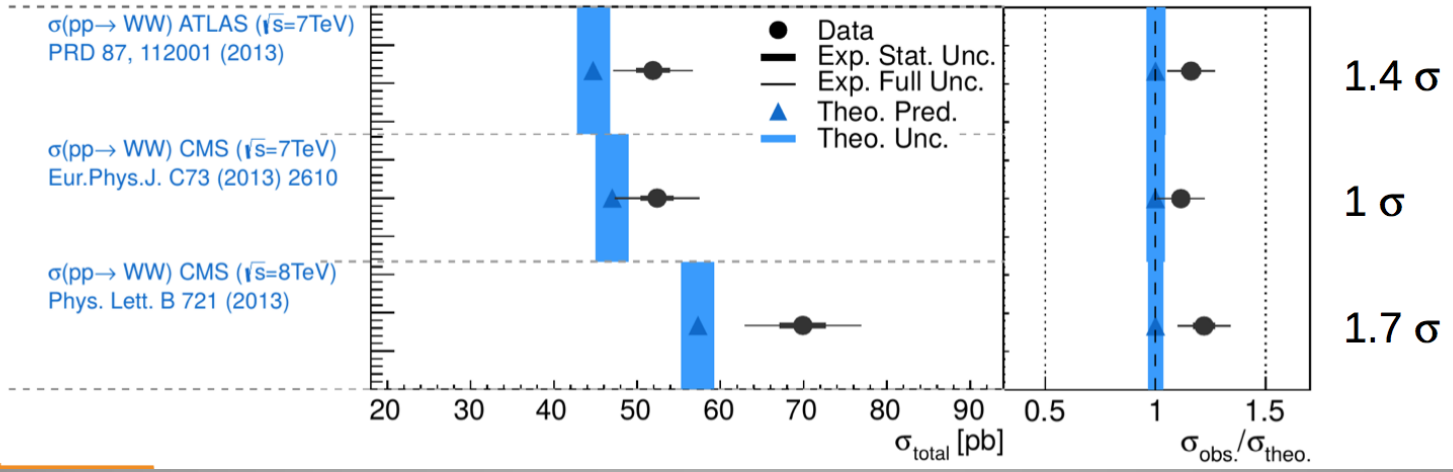
Standard Model prediction: $58.7^{+1.0}_{-1.1}$ (PDF) $^{+3.1}_{-2.7}$ (total) pb

Contributions neglected in this SM prediction

- $q\bar{q} \rightarrow WW$ (NLO → NNLO+NNLL k-factor) + 1.6 pb
- $gg \rightarrow WW$ (LO → NNLO+NNLL k-factor) + 1.4 up to +2.8 pb

- Electroweak corrections – 0.5 pb
- yy-induced WW + 0.5 pb
- Vector boson scattering + 0.5 pb
- Double parton interaction + 0.04 pb

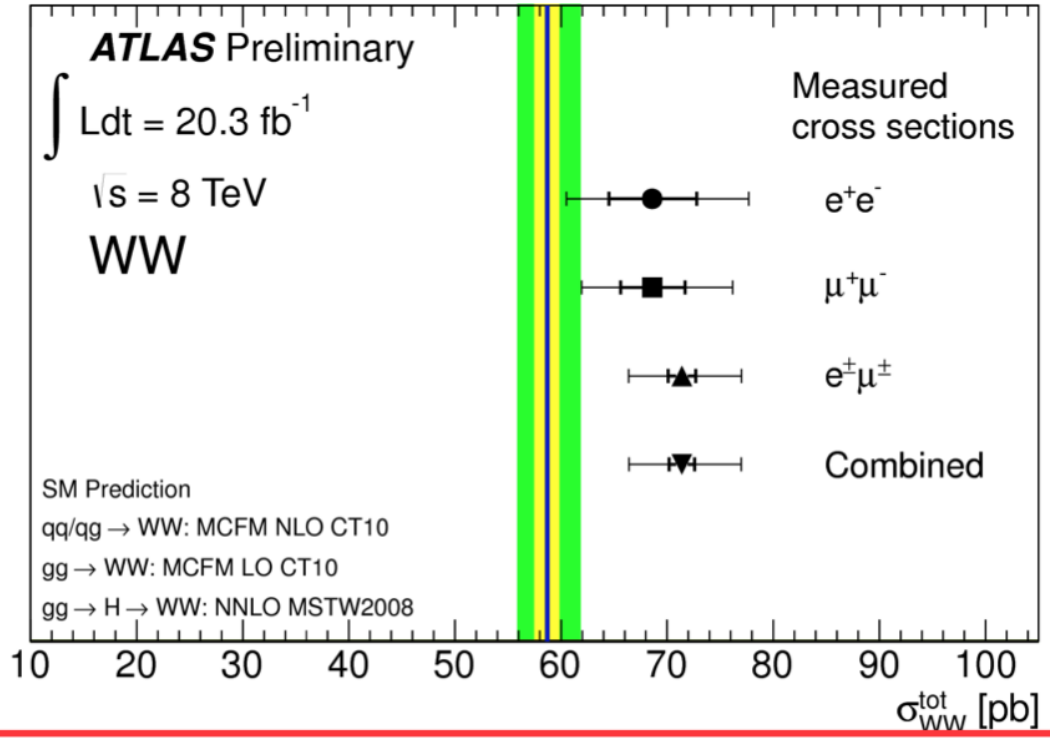
Total sum of: + 3.5 to 4.9 pb



Bizar: all measurements so far gave a systematically higher value!
Less the case for ZZ and WZ as far as we can see...

Anomalous WW Production?

What was missing until now was the ATLAS 8 TeV result



ATLAS-CONF-2014-033

$$\sigma_{WW}^{\text{tot}} = 71.4\ ^{+1.2}_{-1.2}(\text{stat})\ ^{+5.0}_{-4.4}(\text{syst})\ ^{+2.2}_{-2.1}(\text{lumi})\ \text{pb}$$

Standard Model prediction: $58.7^{+1.0}_{-1.1}$ (PDF) $^{+3.1}_{-2.7}$ (total) pb

Important: how well do we control the theory? Now NLO, Higgs included

New Physics in WW Cross Sections?

Both these phenomenology papers appeared on June 3rd …

'Stop' that ambulance! New physics at the LHC?

arXiv:1406.0858

Jong Soo Kim,[a] Krzysztof Rolbiecki,[a] Kazuki Sakurai,[b] and Jamie Tattersall[c]

Natural SUSY in Plain Sight

arXiv:1406.0848

David Curtin, Patrick Meade, Pin-Ju Tien

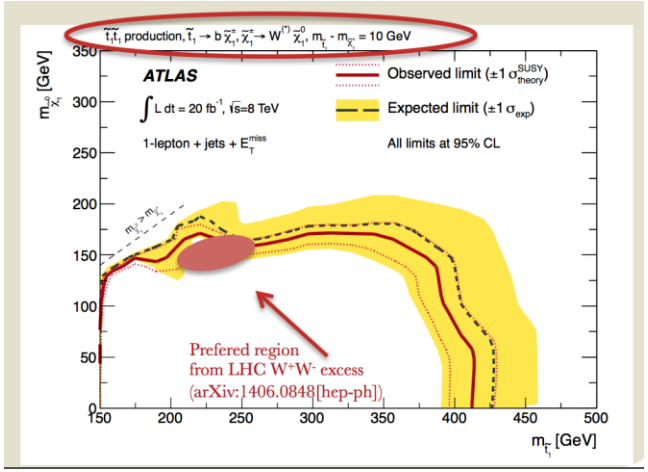
Interpretation in the two papers (Overall analyses of WW, and available SUSY searches):

→ Stop pair production -- with m_{stop} ~ 200 GeV– plus decay to chargino leading to the WW excess

$$\tilde{t}_1 \to \tilde{\chi}_1^{\pm}\, b \to \tilde{\chi}_1^0\, W^{\pm(*)}\, b \to \tilde{\chi}_1^0\, \ell^{\pm}\, \nu\, b$$

$$m_{\tilde{t}_1} = 212^{+35}_{-35}\ \text{GeV},$$
$$m_{\tilde{\chi}_1^0} = 150^{+30}_{-20}\ \text{GeV}.$$

- Tests in other channels?
  ATLAS already excluded this point?
- WW excess at 13 TeV?

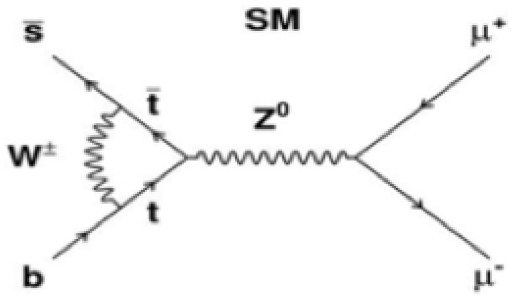


Da Costa ICHEP14

My take:

- Need to have a careful look at QCD corrections, effects of the jet veto…
- Need other measurements eg WW→lνjj, WW+0/1/2 jets…

Precision Measurements: $B_{s(d)} \rightarrow \mu\mu$



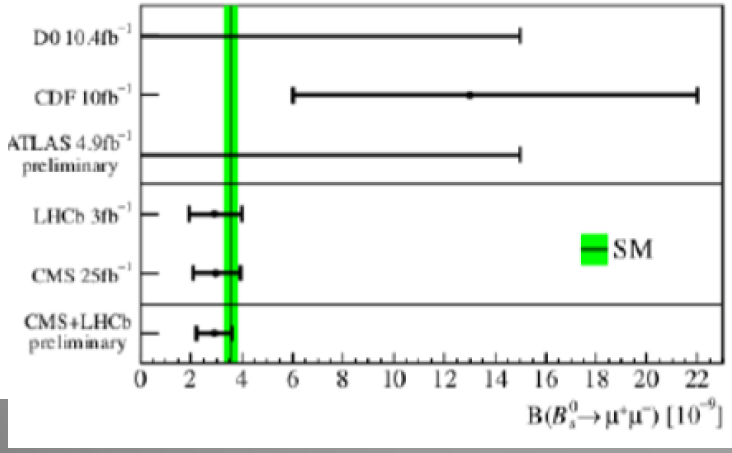
- A B_s particle is a particle consisting of a beauty-quark and strangeness-quark, with a mass of ~ 10 GeV
- Three B_s particles in a million will decay into two muons. This decay has been chased since 30 years.
- New physics modifies these Standard Models predictions

$$\mathrm{BR}(B_s \rightarrow \mu^+\mu^-) = 3.56 \pm 0.29 \times 10^{-9}$$

Observation:

$$\mathrm{BR}(B_s \rightarrow \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

CMS-BPH-13-007 arXiv:1211.2674



Results from LHCb +CMS experiments combined

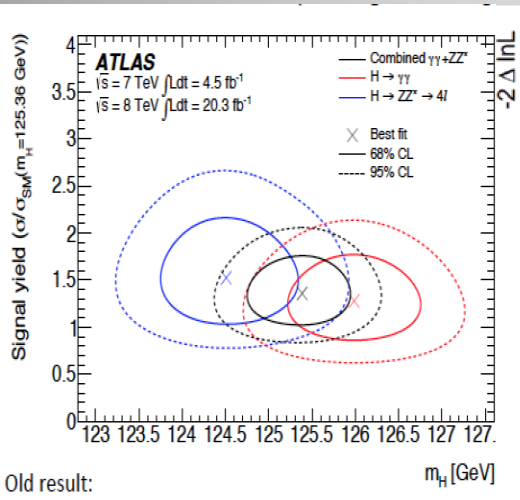
But no sign of New Physics here…☹

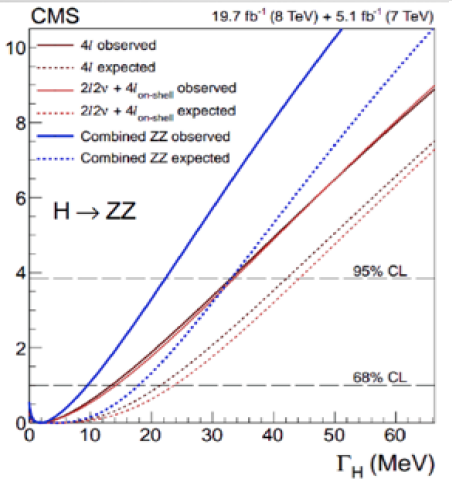
Higgs!

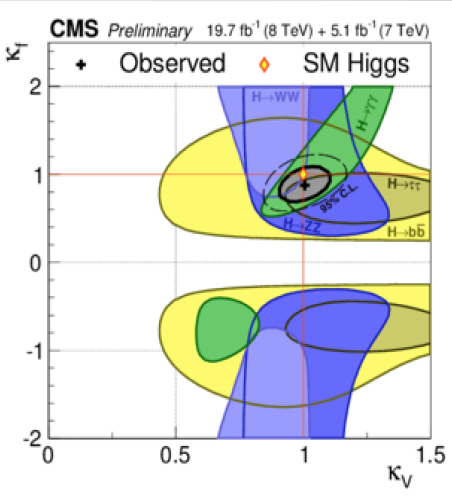
We discovered a Higgs particle!

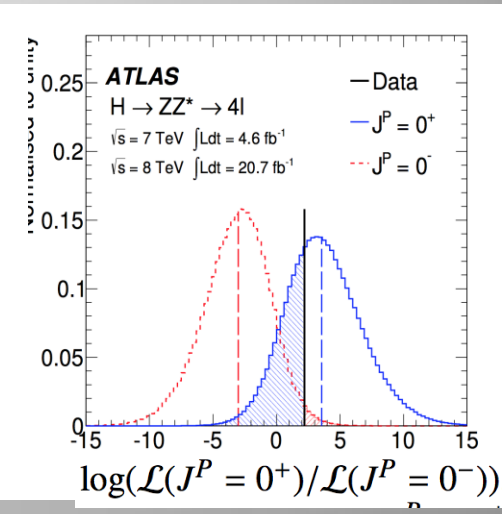
Brief Higgs Summary

We know already a lot on this Brand New Higgs Particle!!









Mass =
A: 125.4 ±0.4 GeV
C: 125.0 ±0.3 GeV

Width =
A: < 24 MeV
C: < 22 MeV
(95%CL)

Couplings are within 20% of the SM values

Spin =
0^+ preferred over 0^-,1,2

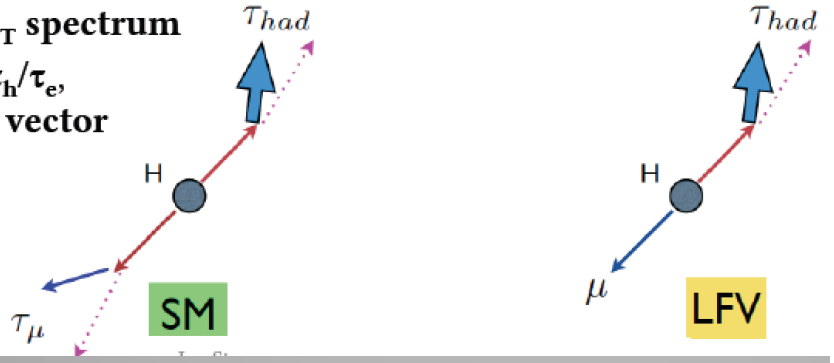
SM-like behaviour for most properties, but we look of course for anomalies, i.e. unexpected decay modes or couplings, multi-higgs production…

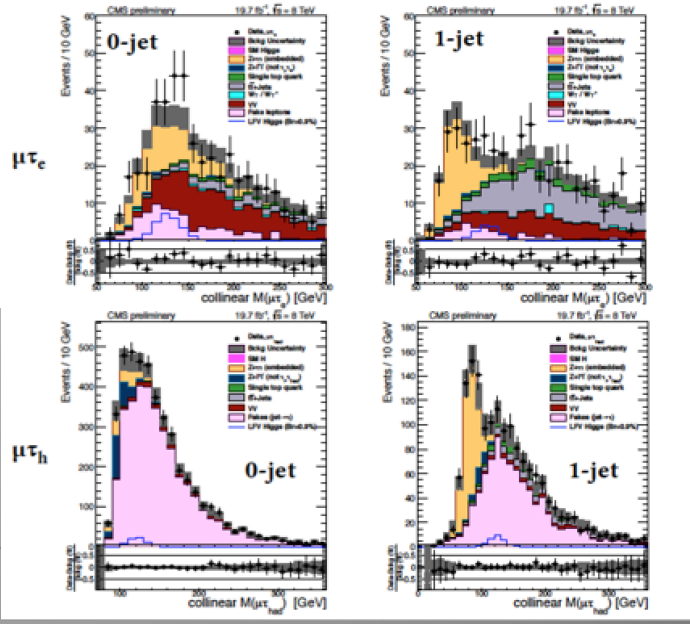
Search for LFV Decays: H →μτ

CMS-PAS-HIG-14-005

- Previous best limits on B(H⟶μτ) <~ 10% from reinterpretation of LHC H⟶ττ searches and from τ⟶μγ arXiv:1209.1397
  - **Can do better with first dedicated search**
- Consider hadronic (τ_h) and electron (τ_e) tau decays
- Same basic event selection and jet categories as SM H⟶ττ analysis (0-jet, 1-jet, VBF-tag)
- Differences in kinematics
  - **Harder muon p_T spectrum**
  - **Δϕ between μ, τ_h/τ_e, missing energy vector**

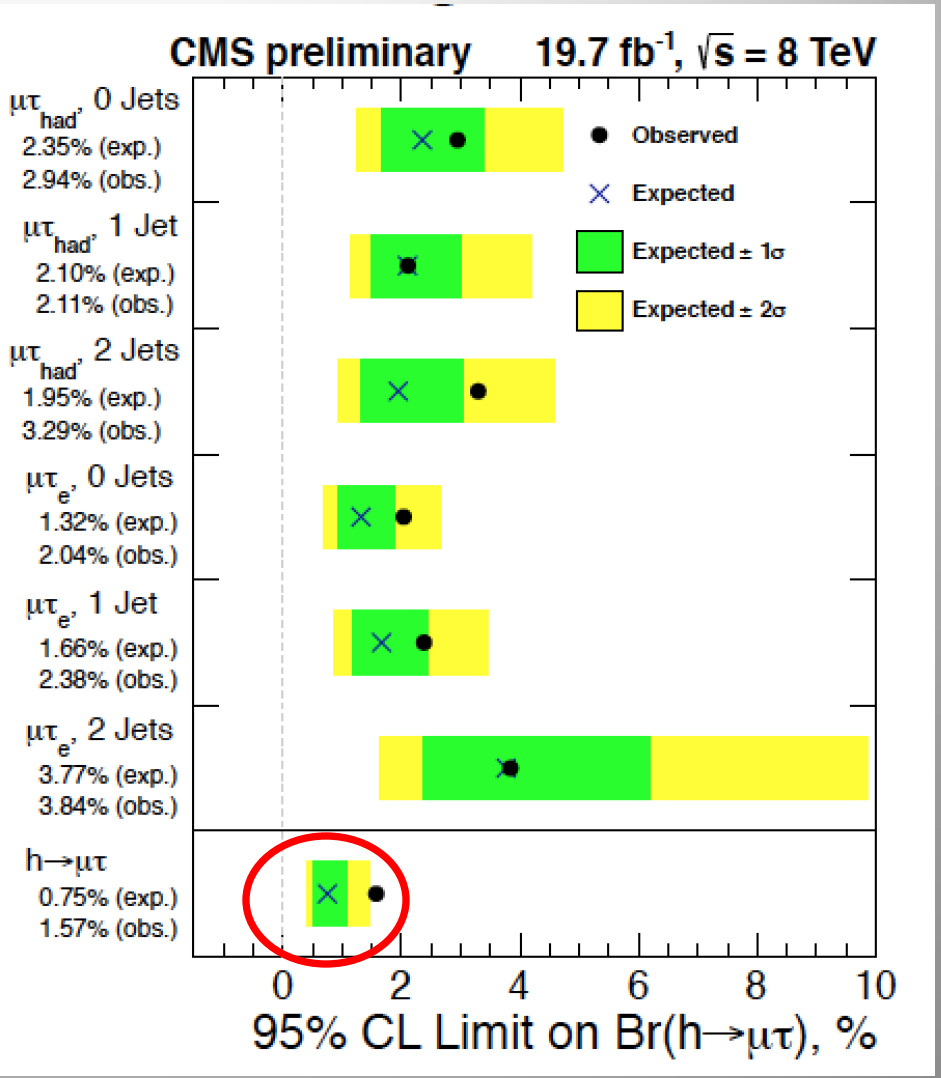
On public demand from our theory friends ☺





Search for LFV Decays: H →μτ

- Comparable sensitivity from all channels
- Observed limit 1.57% (exp. 0.75%)
- **Large improvement of previous limits**
- **Background-only p-value of 0.007 (2.46σ)**
  - Best-fit $B(H\to\mu\tau) = 0.89^{+0.40}_{-0.37}\%$



Mild excess giving a 2.5σ effect… To be watched!!!

Summary

- Run-I delivered many measurements of Standard Model processes, eg on the top quark, EWK and in QCD. Some features of multi-particle production are not understood.
- Electroweak measurements show agreement with the data in general. Some effect in WW production?
- The LHC is a top-factory. Very detailed study of the top quarks ongoing. No surprises yet!
- A prime target of the LHC was the discovery of “a” or “the” Higgs particle. Particle found/Mission accomplished! ☺
- The new particle has properties compatible with a Higgs, but surprises are still possible. This will be one of the topics for the coming run.

But where is everybody else? → Lecture III