The first year of the LHC: what we have learned

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- 2012: continue full year with similar luminosity, after Xmas break.

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- Nothing that should have worked and didn't!

Jets

- Fundamental manifestation of quarks/gluons emerging from hard production and decay processes

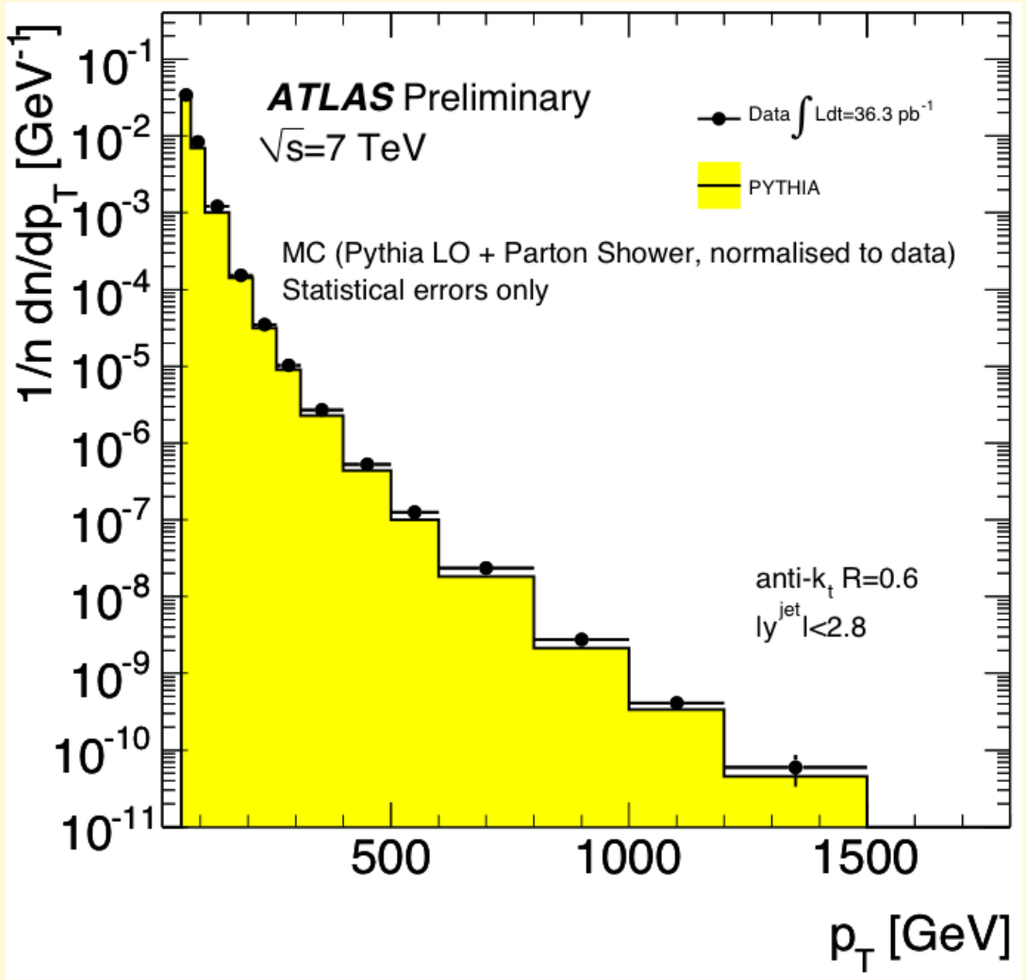
- Key objects for spectroscopy of heavy particles

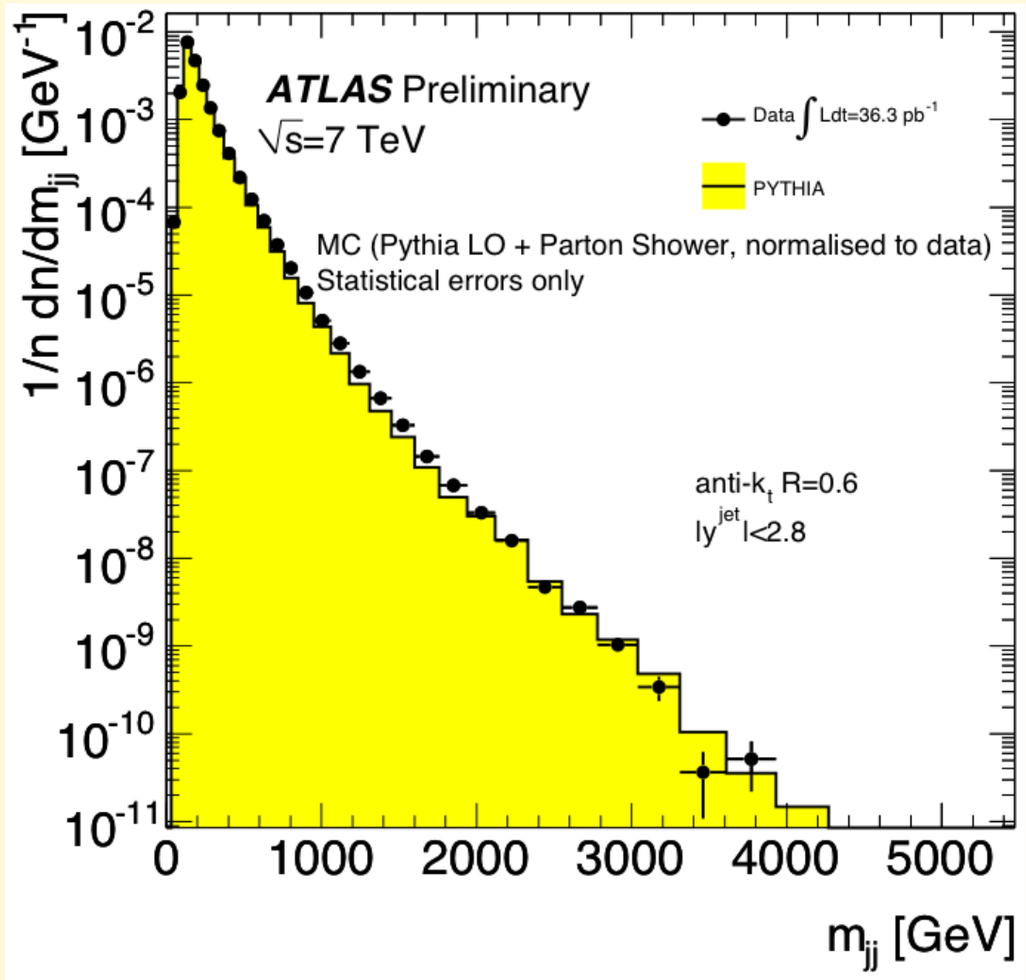
- Final states of the modern "Rutherford" experiment with the proton: test the fundamental nature of quarks

- Inclusive production of jets from generic QCD interactions known to next-to-leading-order (NLO) accuracy

- test of the accuracy of the perturbative QCD framework (factorization theorem, parton densities, etc.)

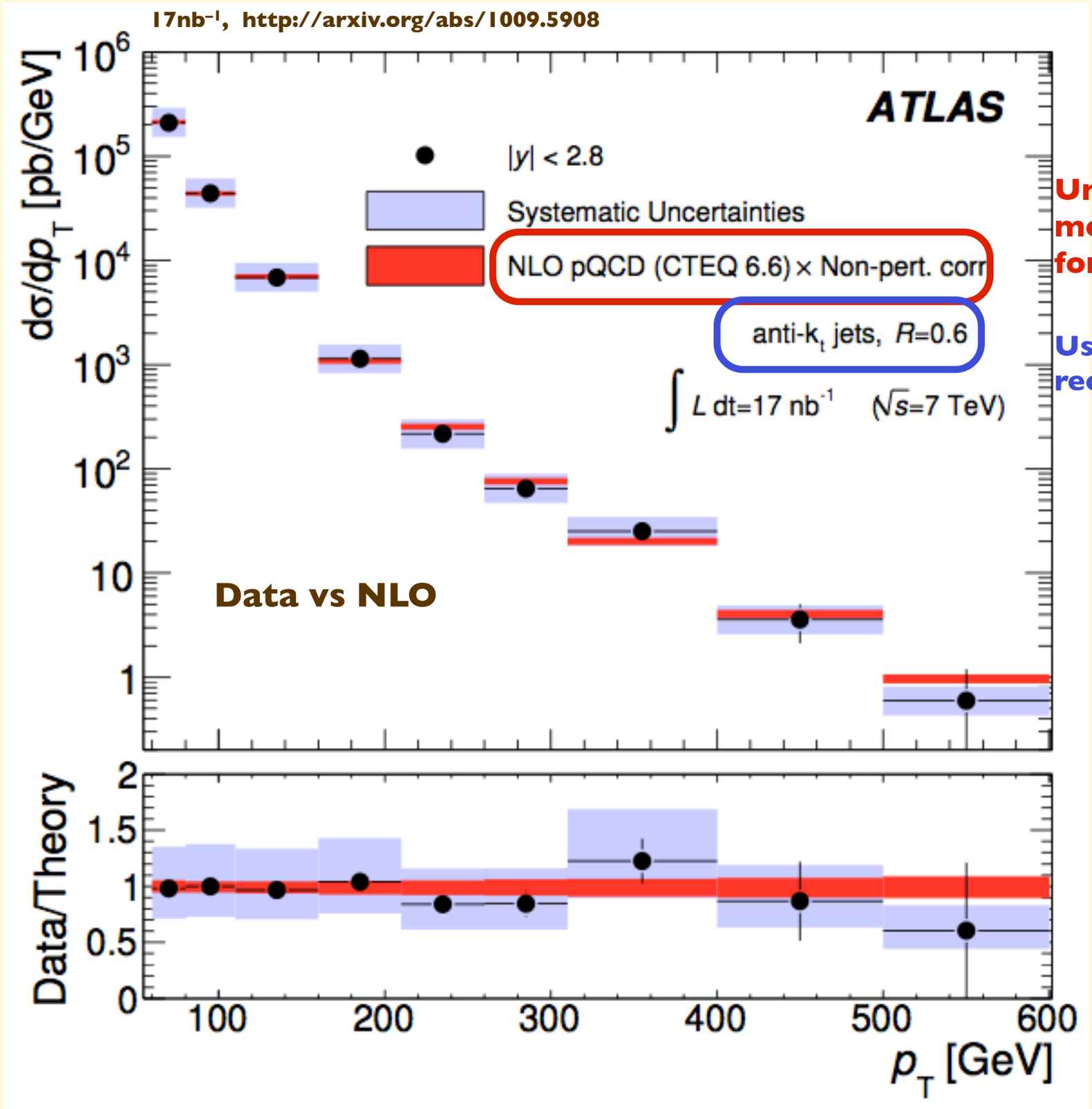
Inclusive transverse-energy and dijet invariant mass spectra:





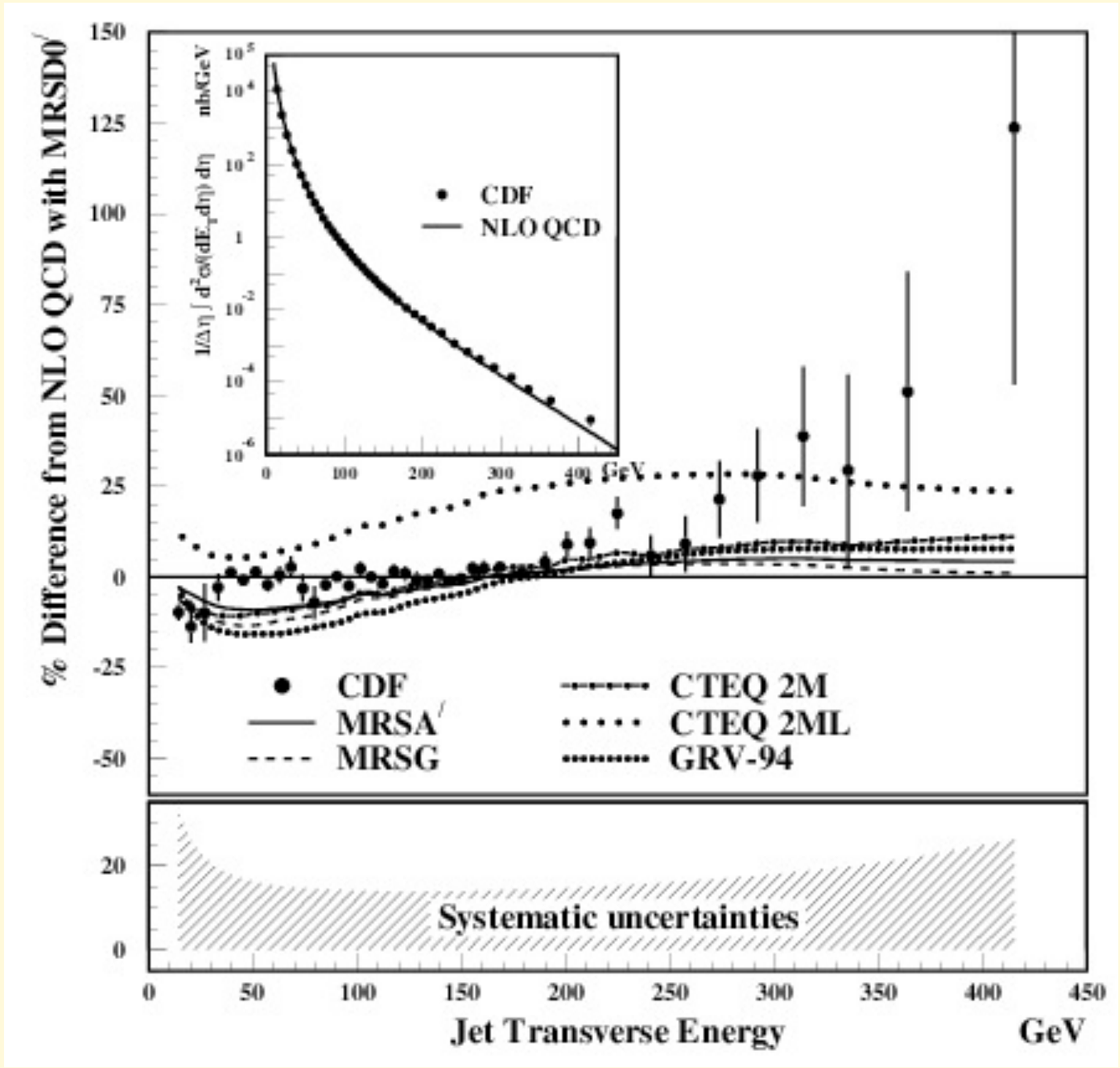
See P. Wells, for the ATLAS collab., 104th LHCC session, http://indico.cern.ch/conferenceDisplay.py?confId=112439

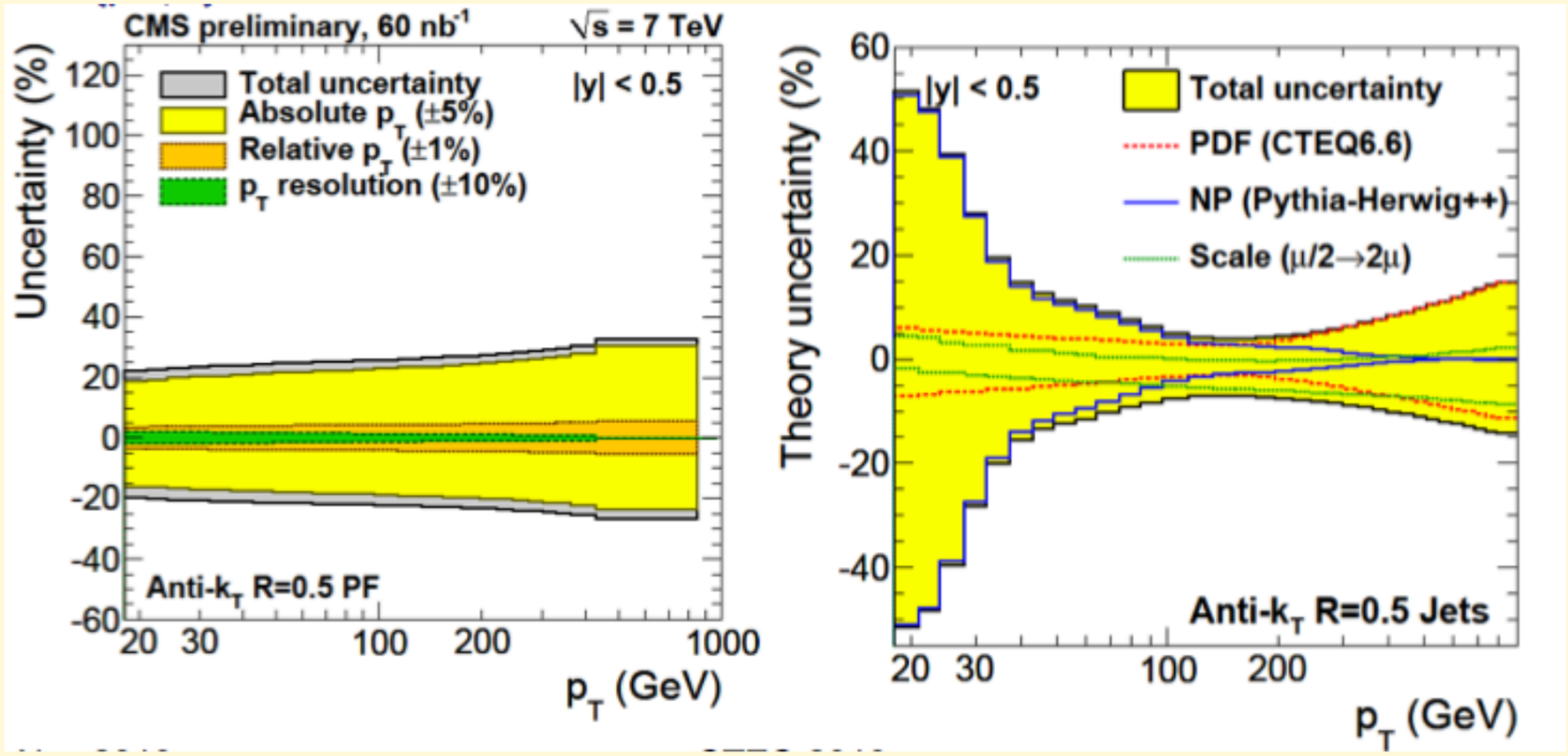
Inclusive jet E_T spectrum



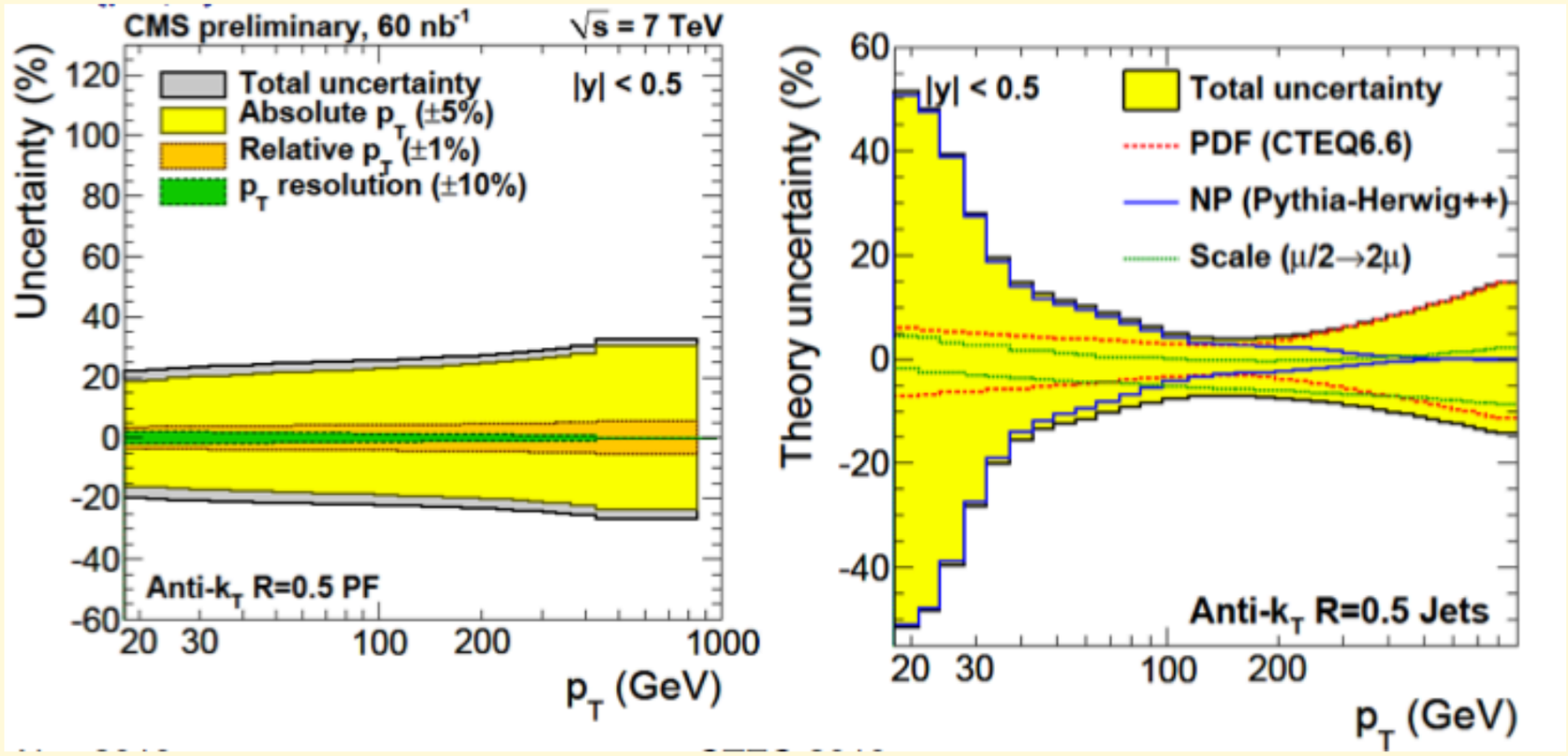
Unfolded cross-section measurement, suitable for comparison with NLO

Use of modern jet reconstruction tools


% Difference from NLO QCD with MRSD0′
150
125
100
75
50
25
0
-25
-50
1/Δη ∫ d²σ/(dE_T dη) dη nb/GeV
10⁵
10⁴
10²
1
10⁻²
10⁻⁴
10⁻⁶
0
100
200
300
400 GeV
CDF
NLO QCD
CDF
MRSA′
MRSG
CTEQ 2M
CTEQ 2ML
GRV-94
20
0
Systematic uncertainties
0
50
100
150
200
250
300
350
400
450
Jet Transverse Energy
GeV



PDF will be dominant source of theoretical systematics at large E_T



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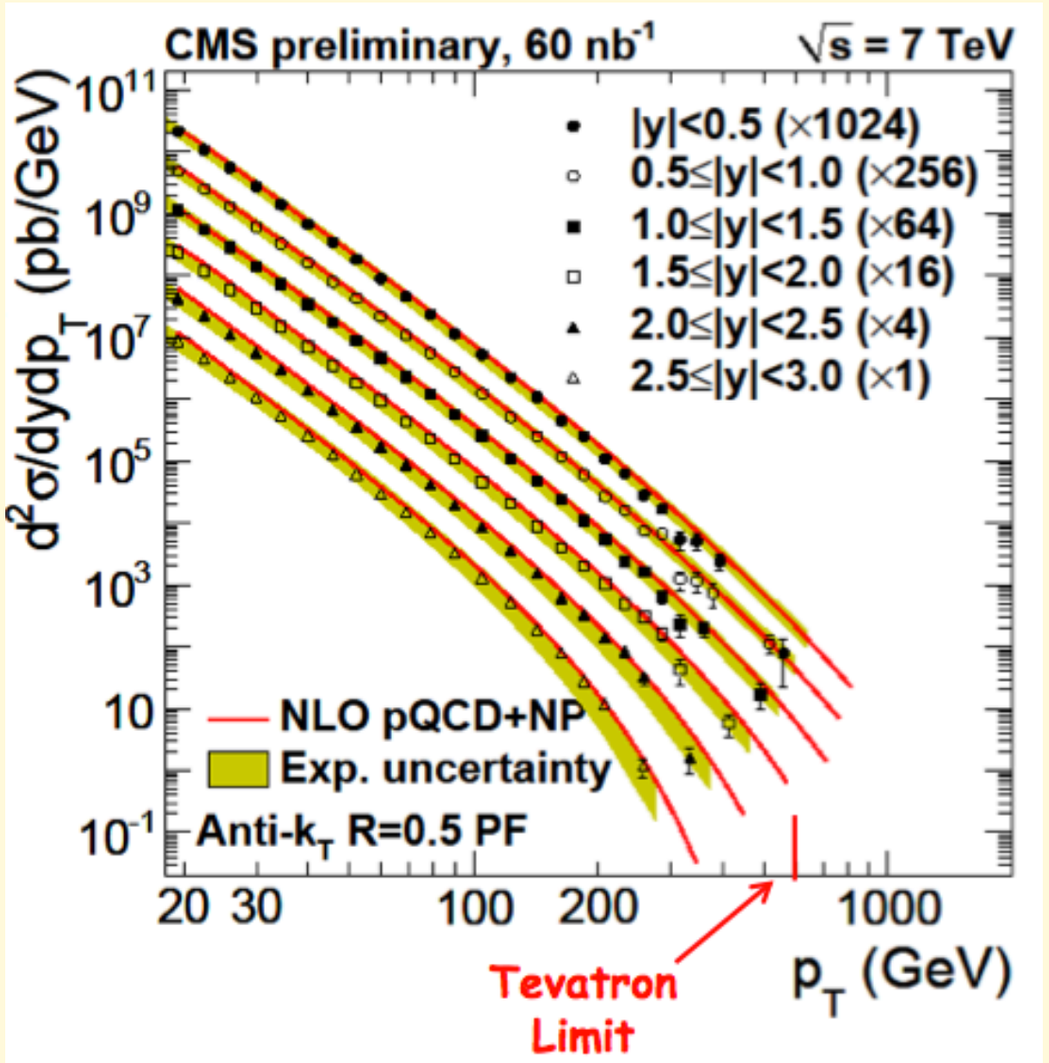
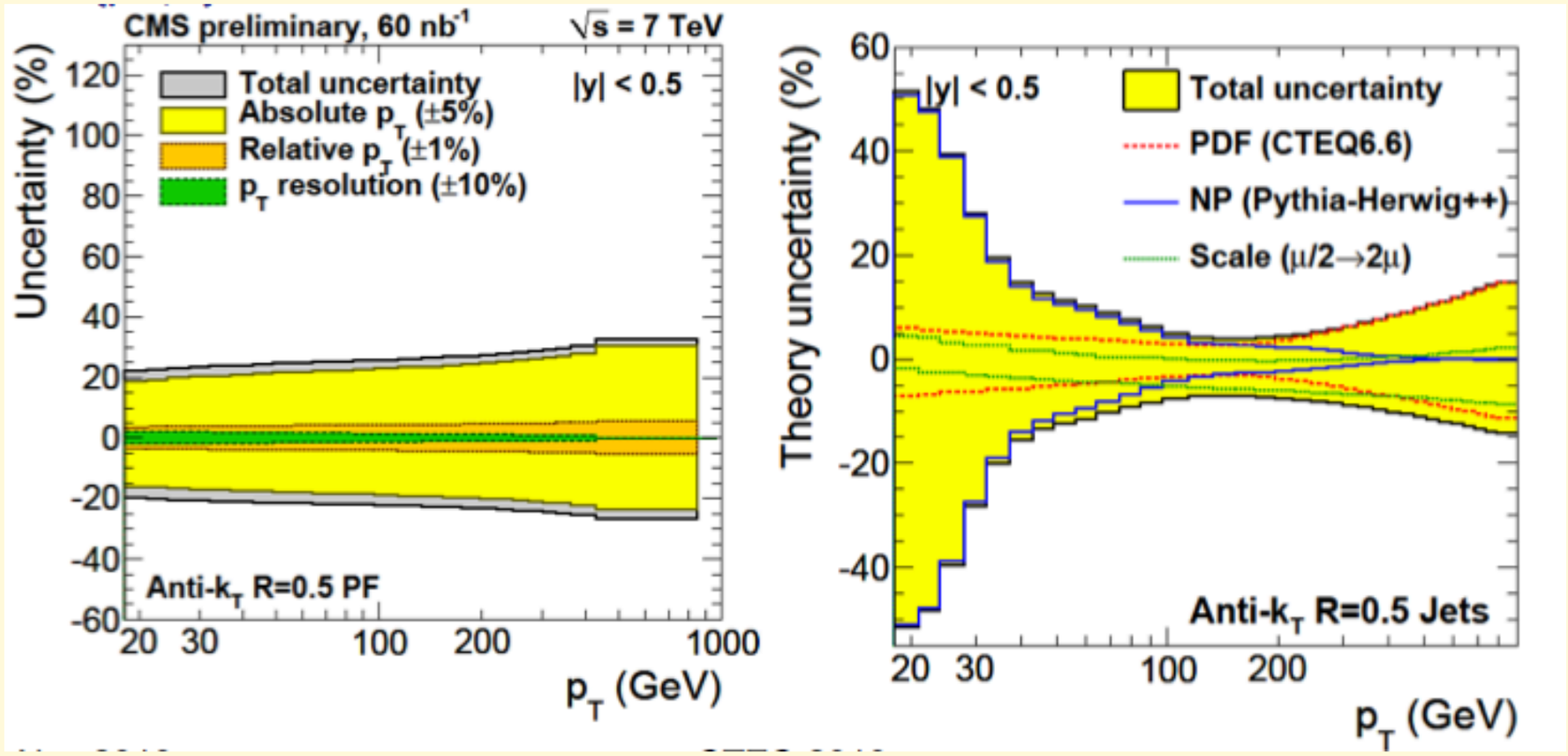
How powerful will be the jet data at large η in reducing this systematics?





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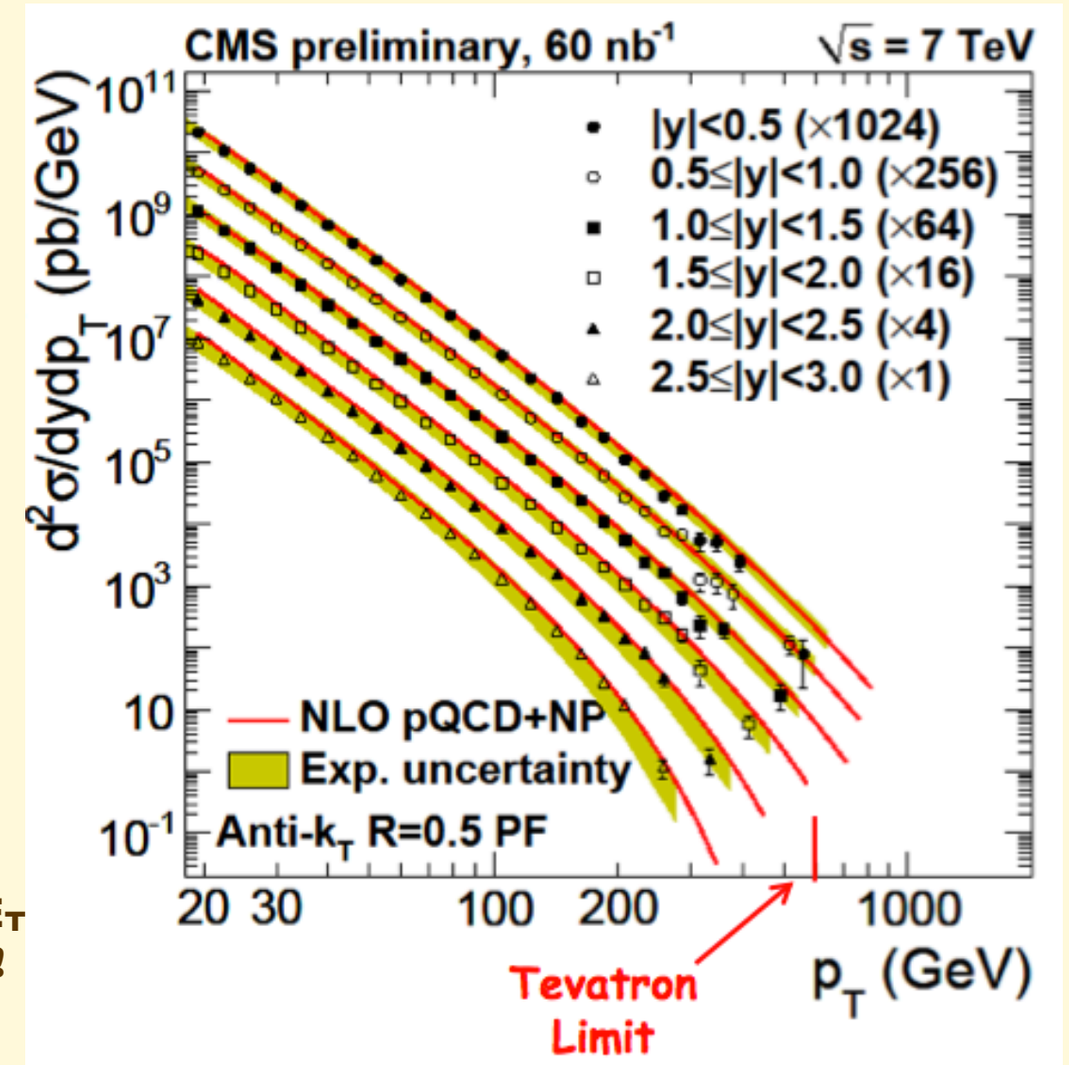
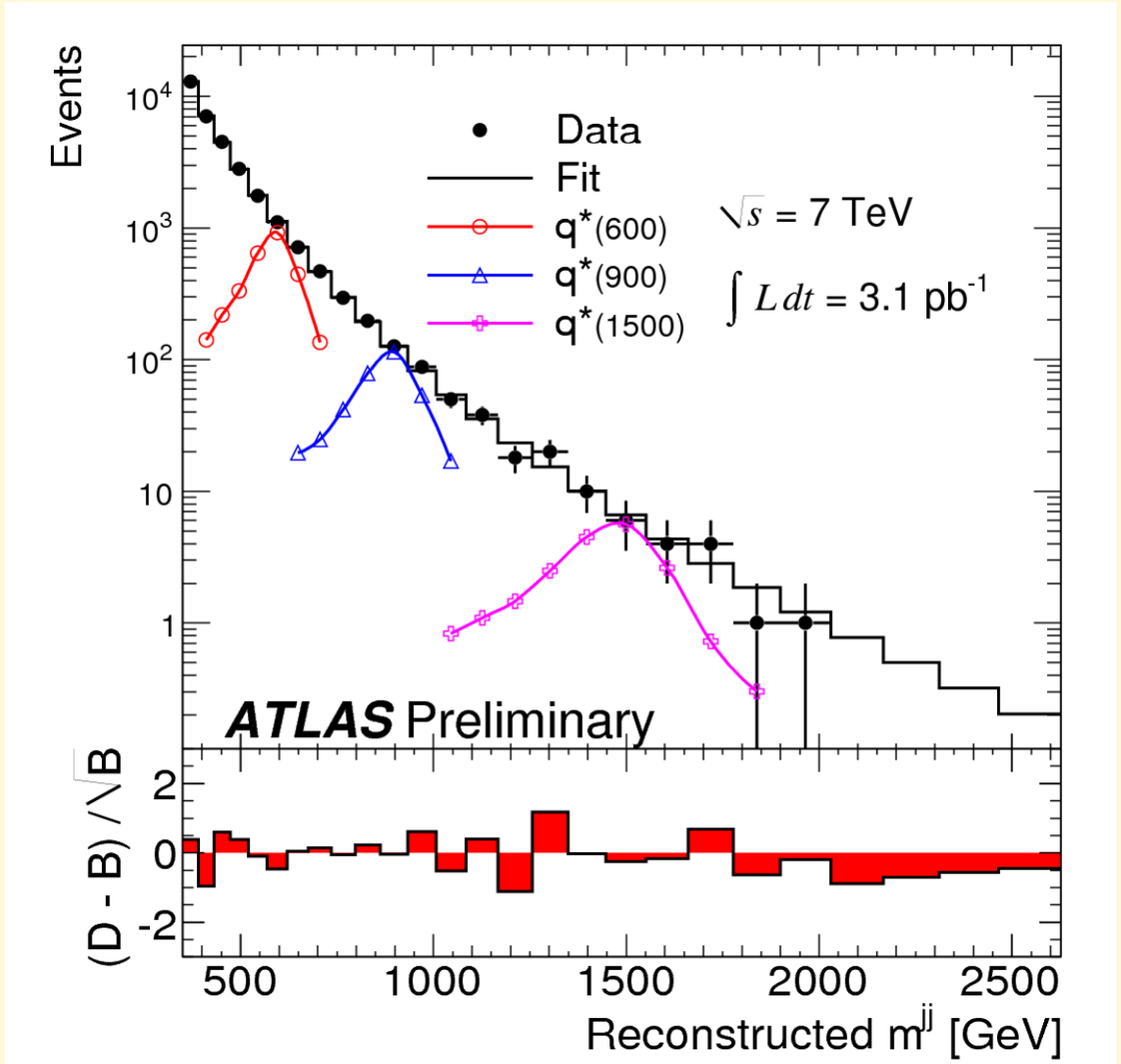


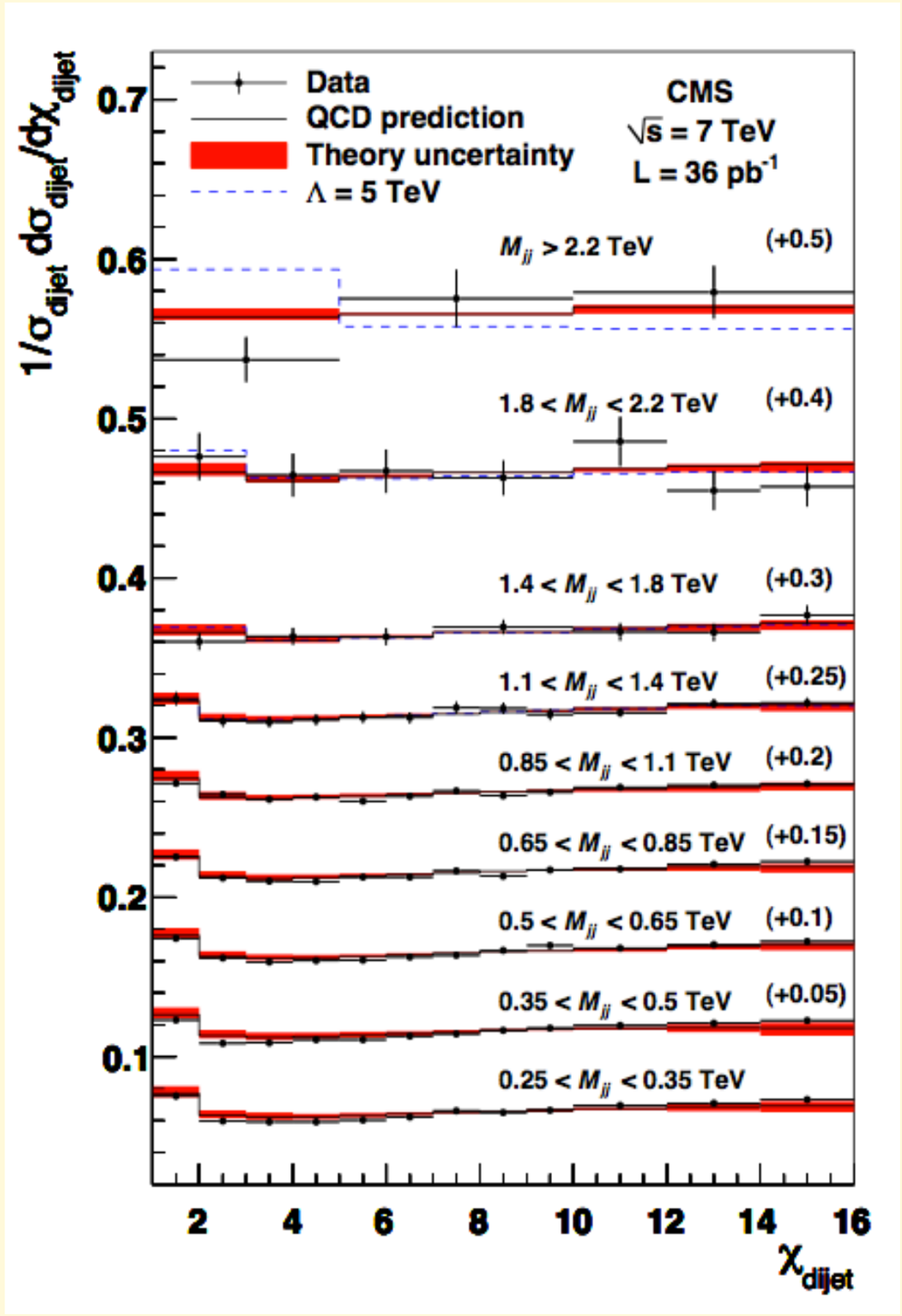
Notice reach in E_T down to 20 GeV!!

First constraints on new physics



Exclude 0.50 < m(q*) < 1.53 TeV @ 95% CL

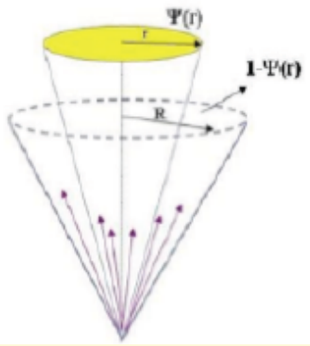
$$\chi = \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$



Exclude quark contact interactions with scale < 5 TeV @ 95% CL

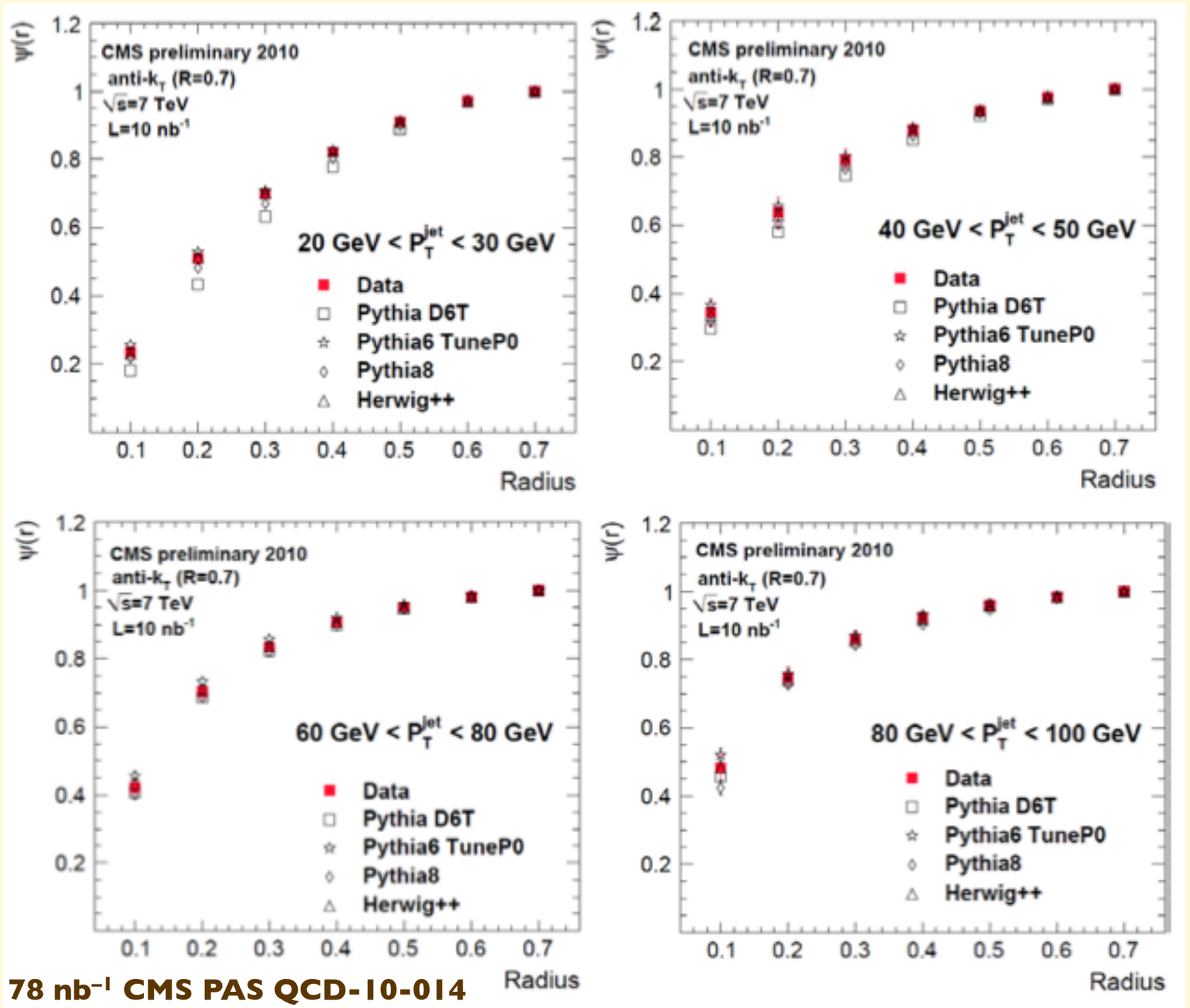
Integrated jet shape

$$\Psi(r)=\frac{1}{N_{jets}}\sum_{jets}\frac{P_T(0,r)}{P_T^{jet}(0,R)}$$



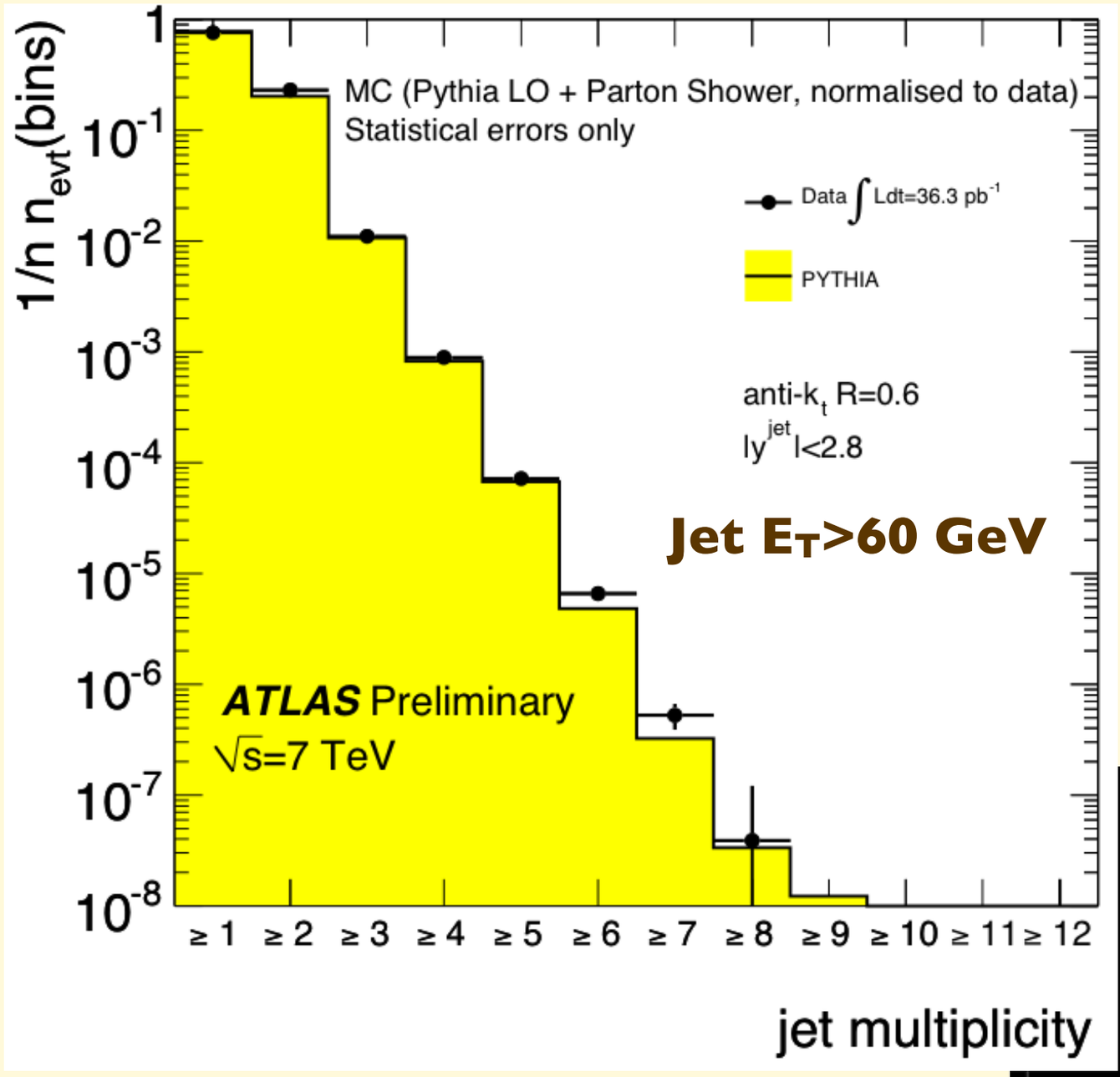
Probes modeling of shower evolution, with implications for:

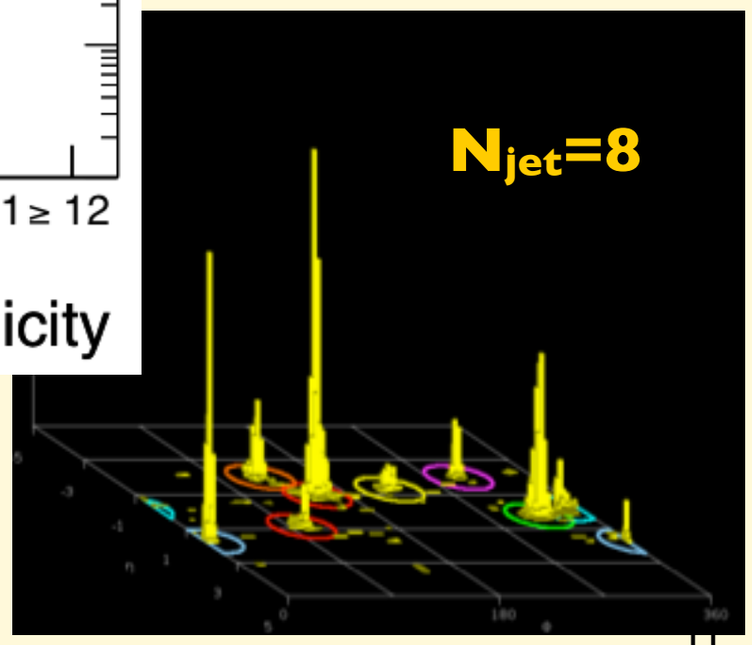
- precision QCD studies (e.g. jet E_T spectrum, data vs NLO)
- jet spectroscopy (e.g. top mass determination)
- multiparton matrix-elements/shower matching
- pt W



78 nb^{-1} CMS PAS QCD-10-014

Multijets





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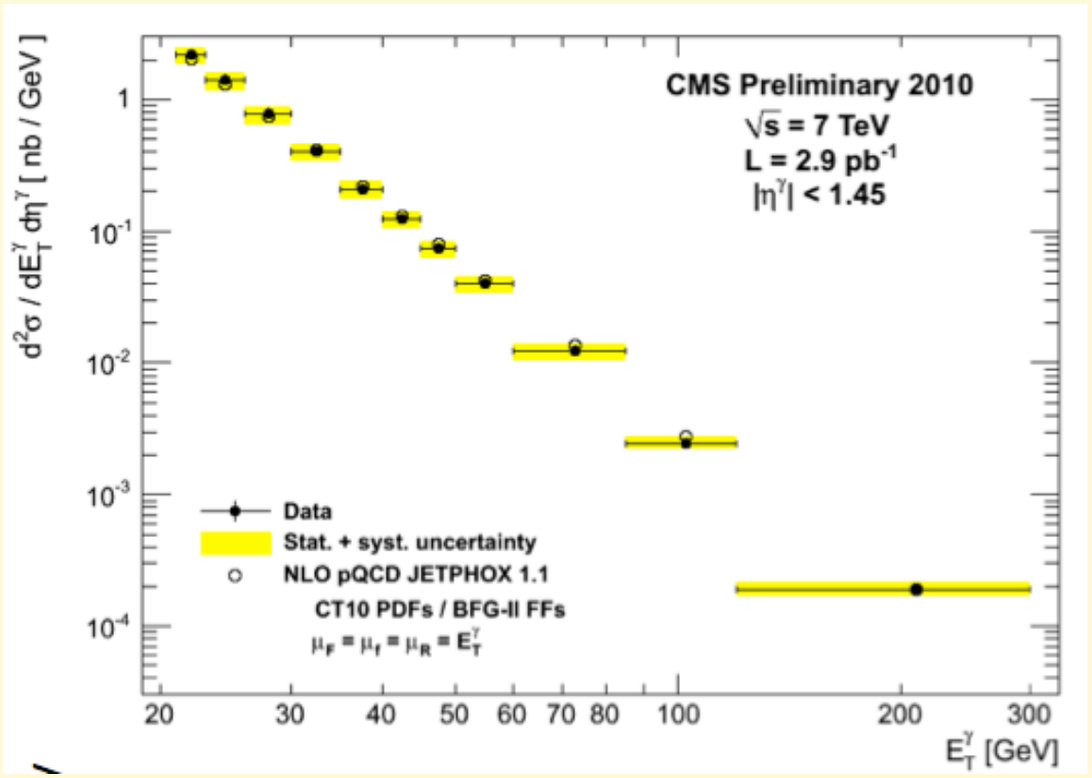
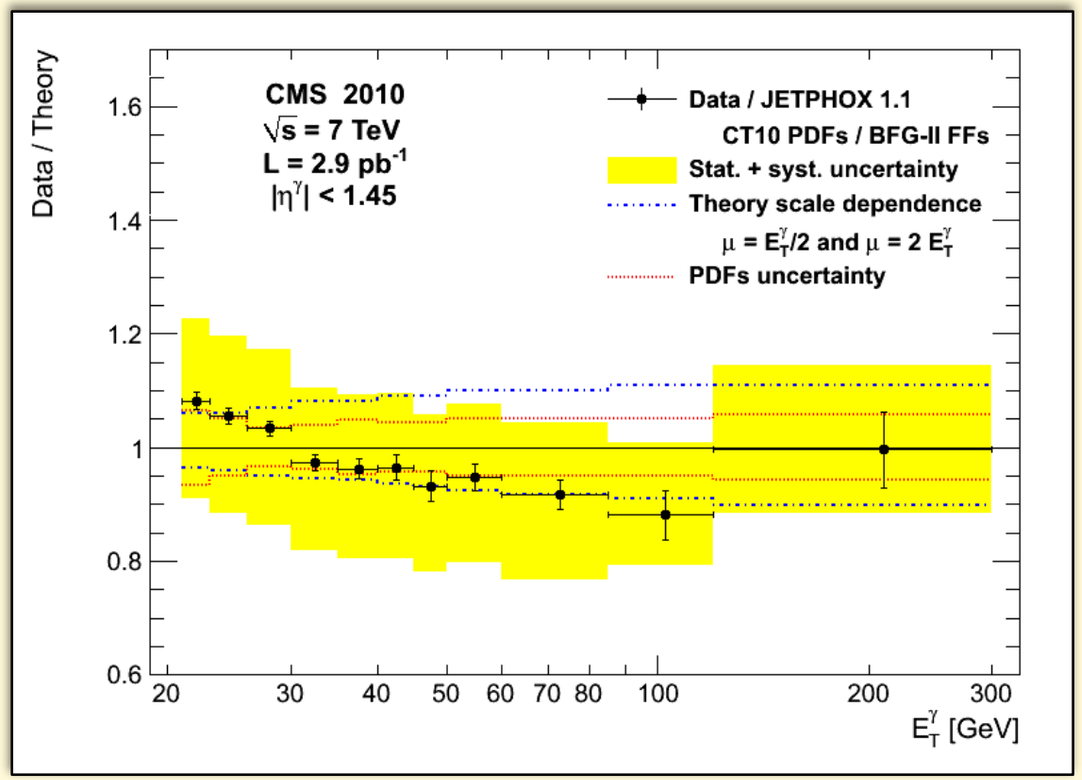
Photons

Prompt photon spectrum, LHC data vs TH



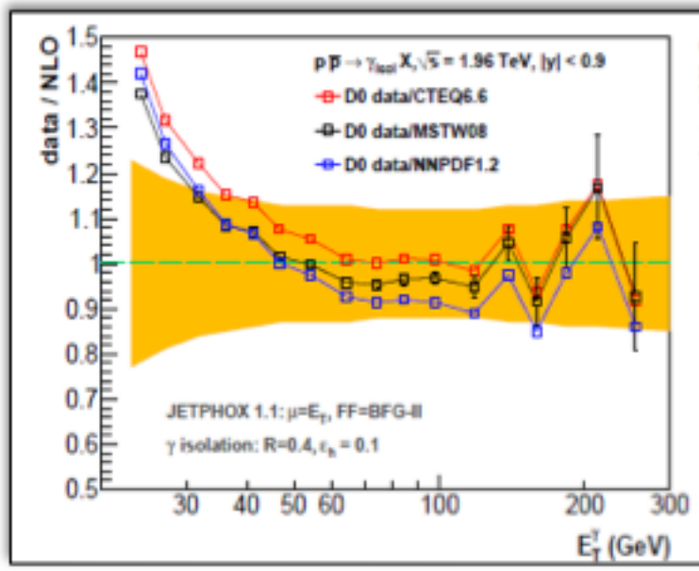


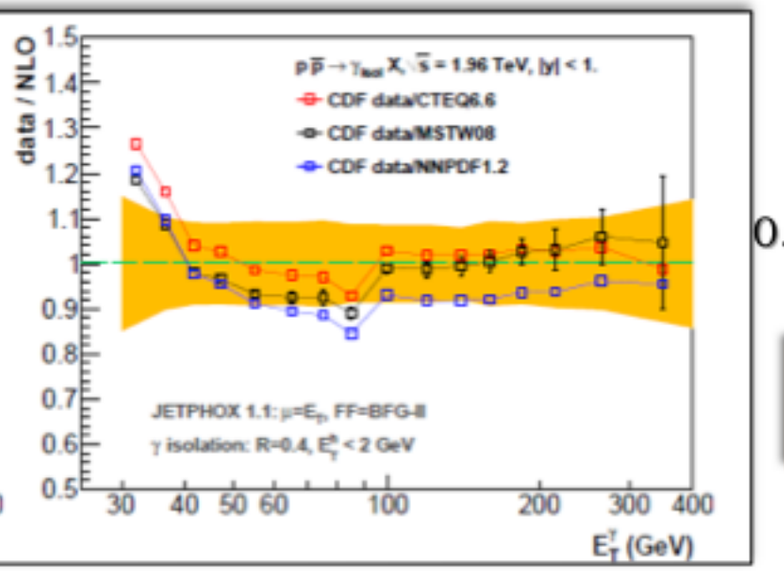
Cfr Tevatron:

arXiv:1005.4529

D0
0.01 < xT < 0.12

Phys. Lett. B
639 (2006) 151





CDF
0.01 < xT < 0.13

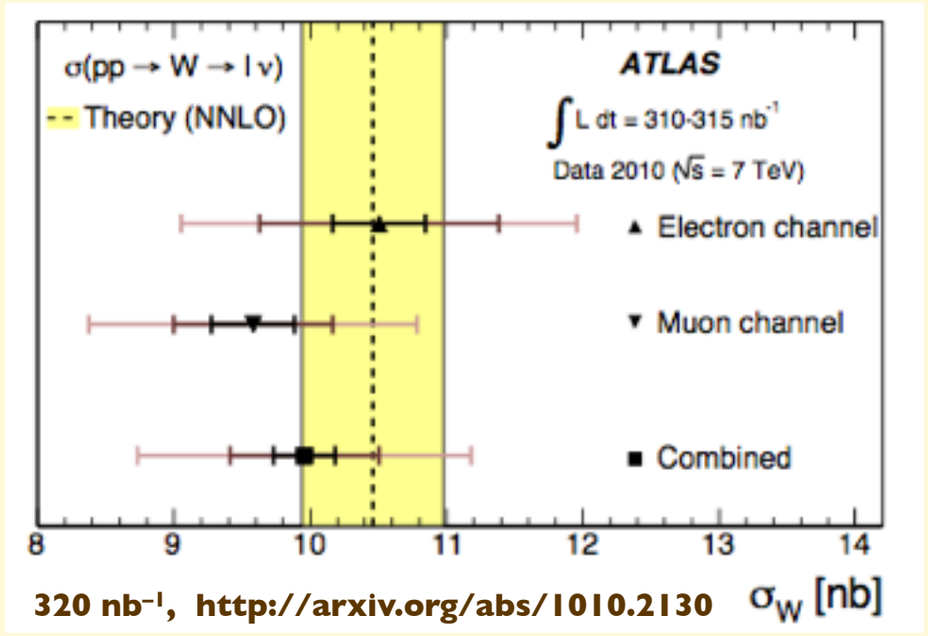
Phys. Rev. D 80
(2009) 111106

11/29/10

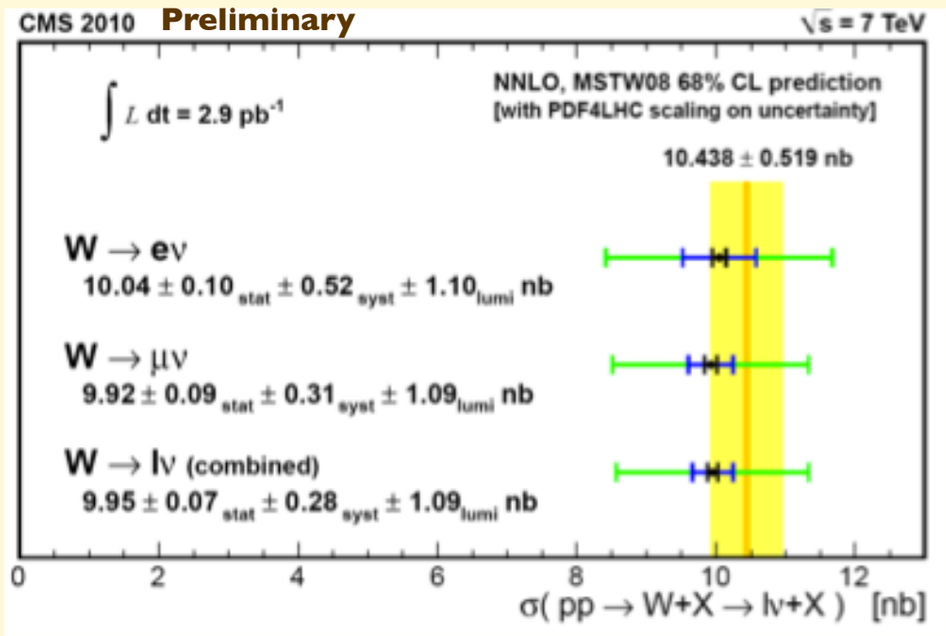
20

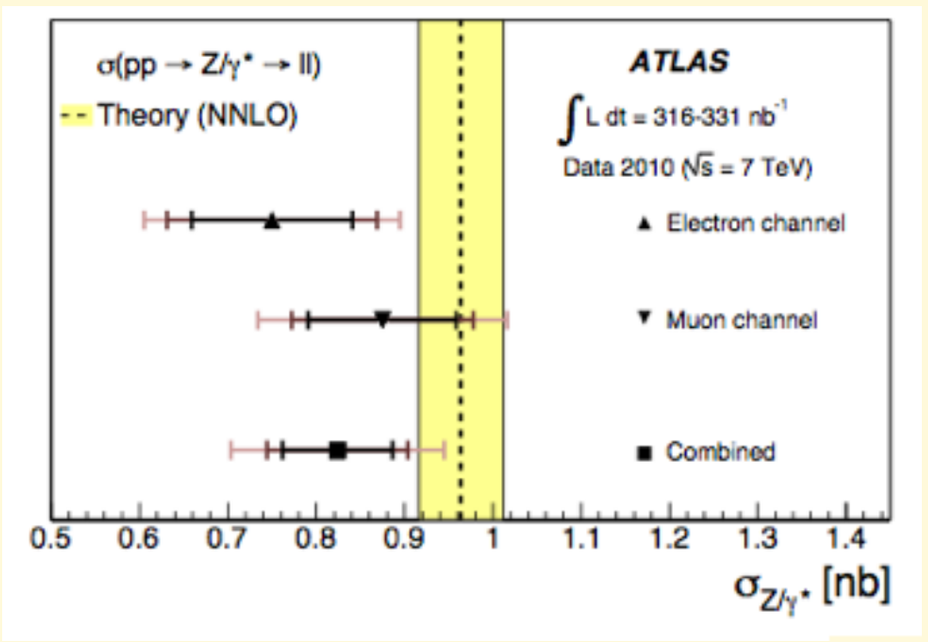
W/Z

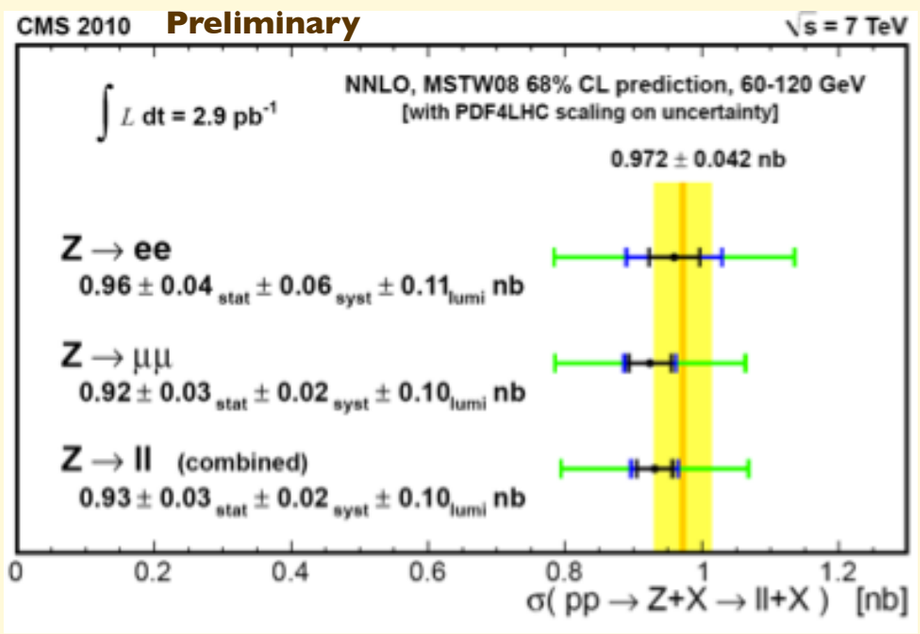
- Primary sources of charged leptons, and missing energy (via neutrinos) =>
  - sources of background to searches of DM-like particles
- Present in the decay chain of almost any heavy object, both in the SM and in BSM scenarios =>
  - probes of new physics
- Inclusive production known in QCD with intrinsic accuracy at the level of ±2% (NNLO).
- Additional uncertainty from input parameters, such as:
  - α_S
  - PDF
- The most accurate prediction of QCD, and thus one of the most sensitive probes of the proton structure



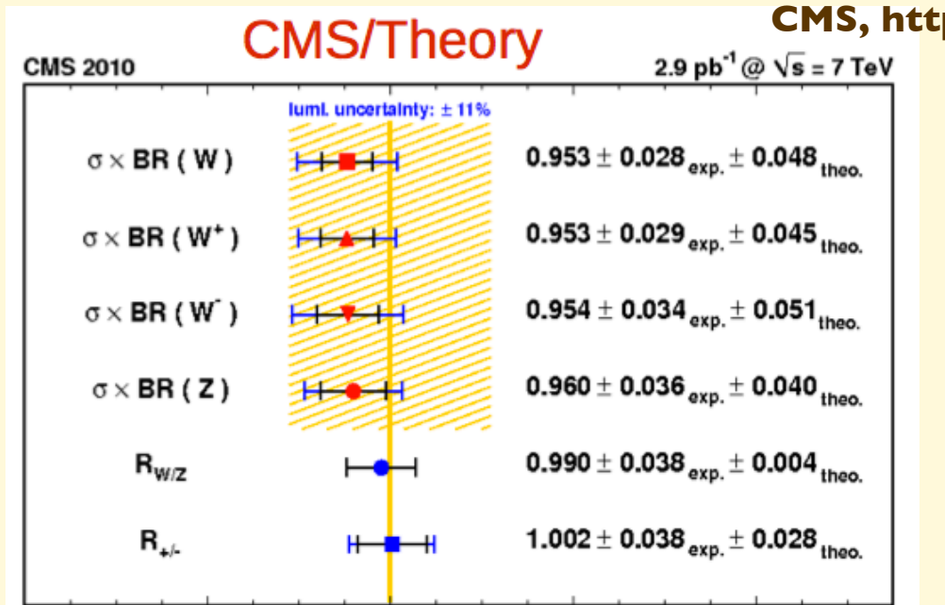
320 nb⁻¹, http://arxiv.org/abs/1010.2130



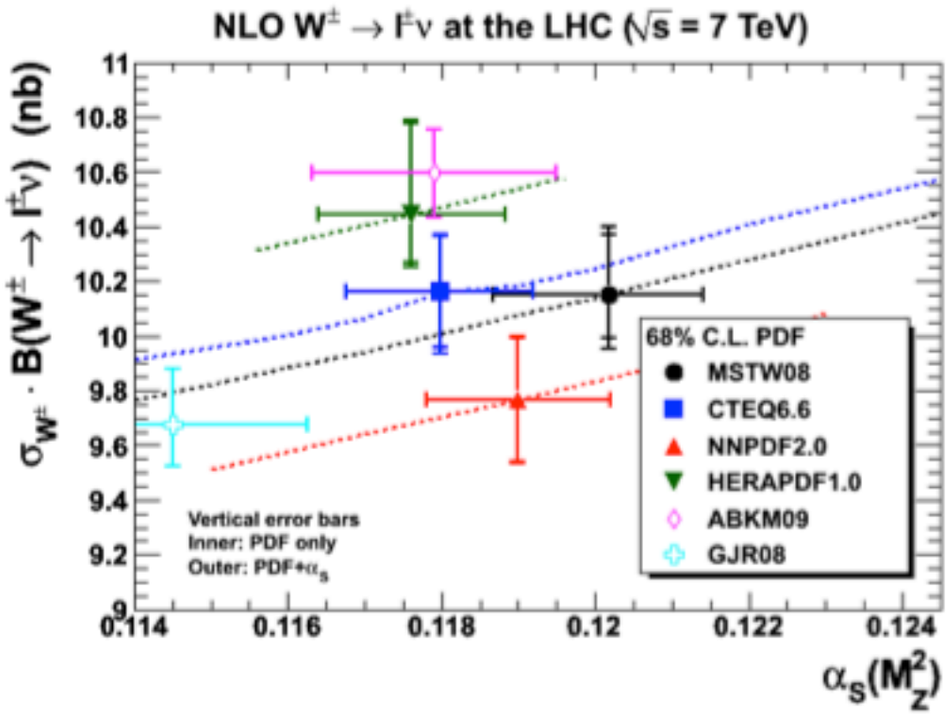


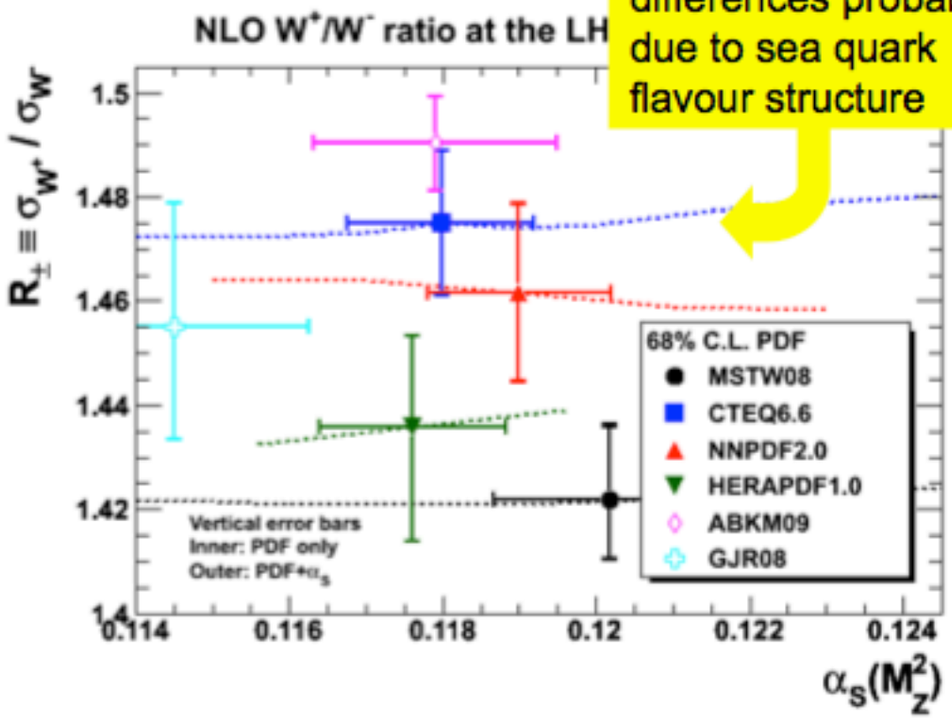


CMS, http://arxiv.org/abs/1012.2466, JHEP

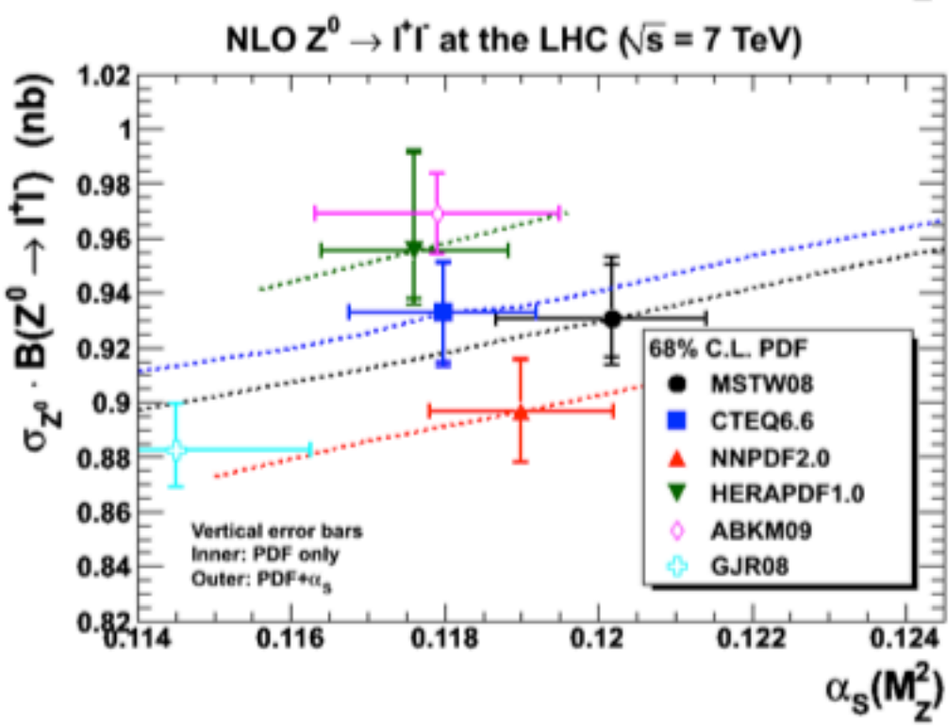


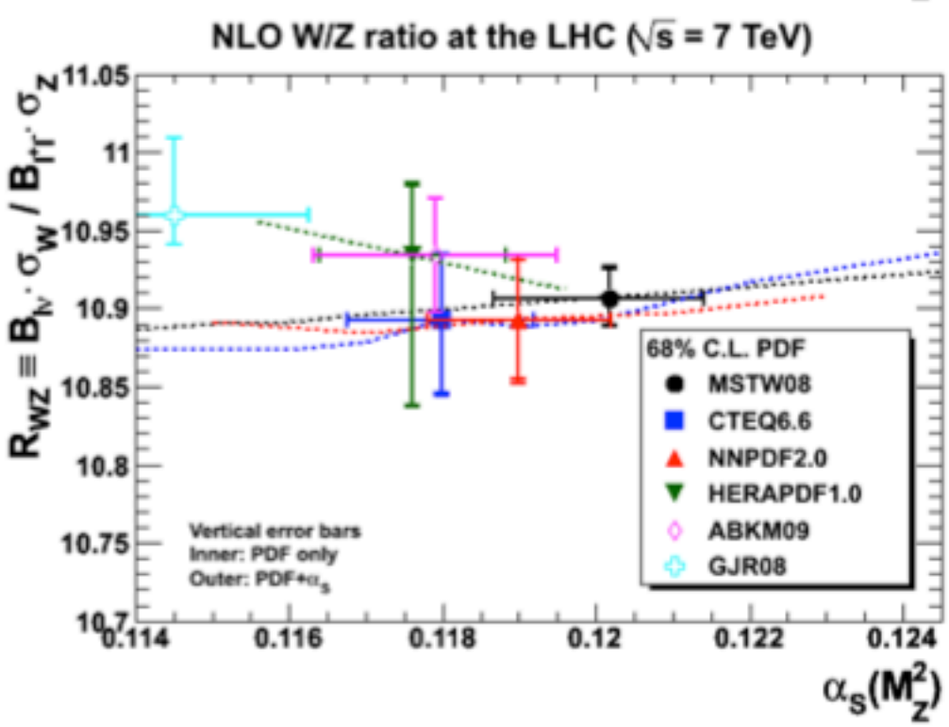
benchmark W,Z cross sections





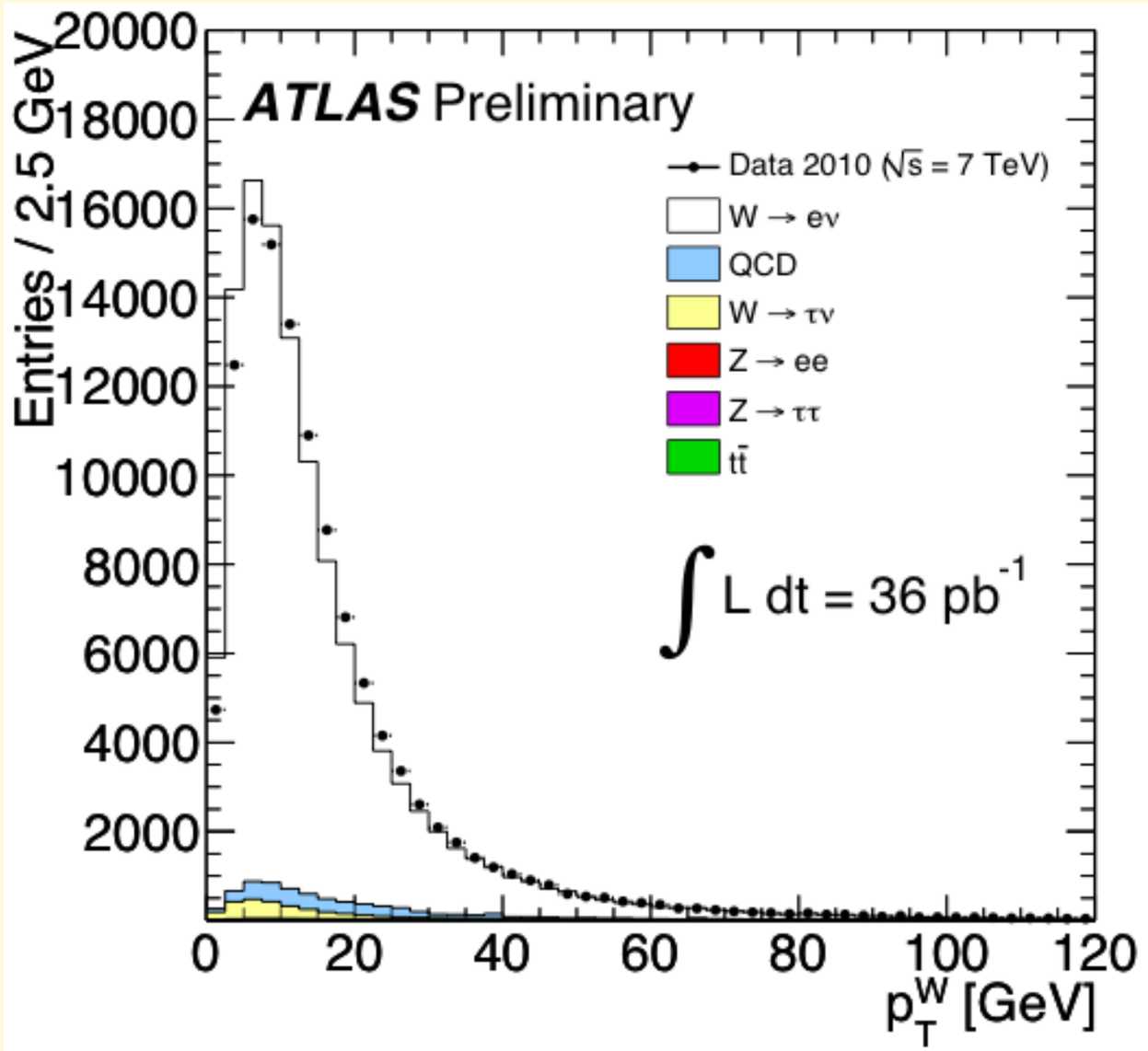
differences probably due to sea quark flavour structure

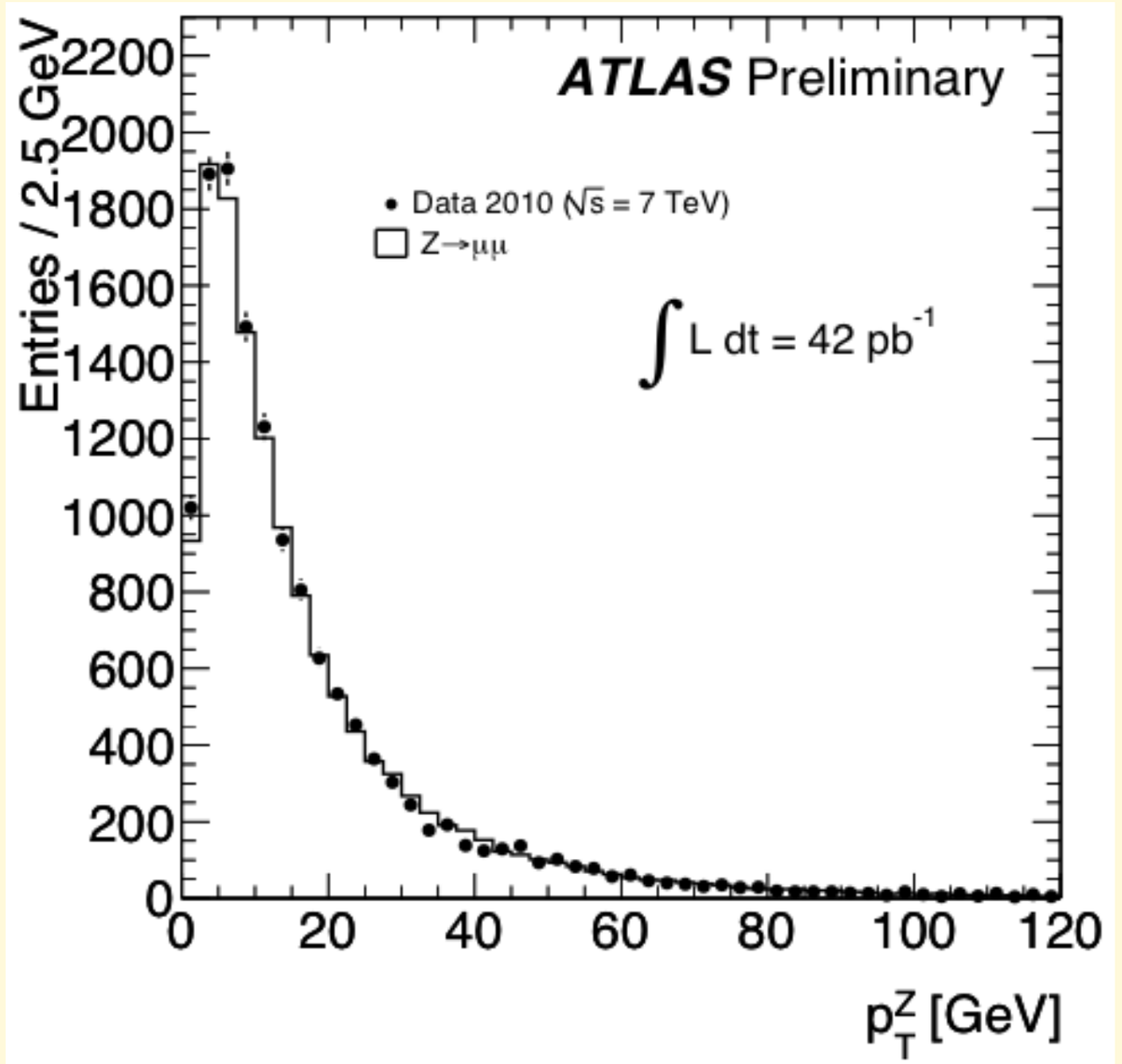




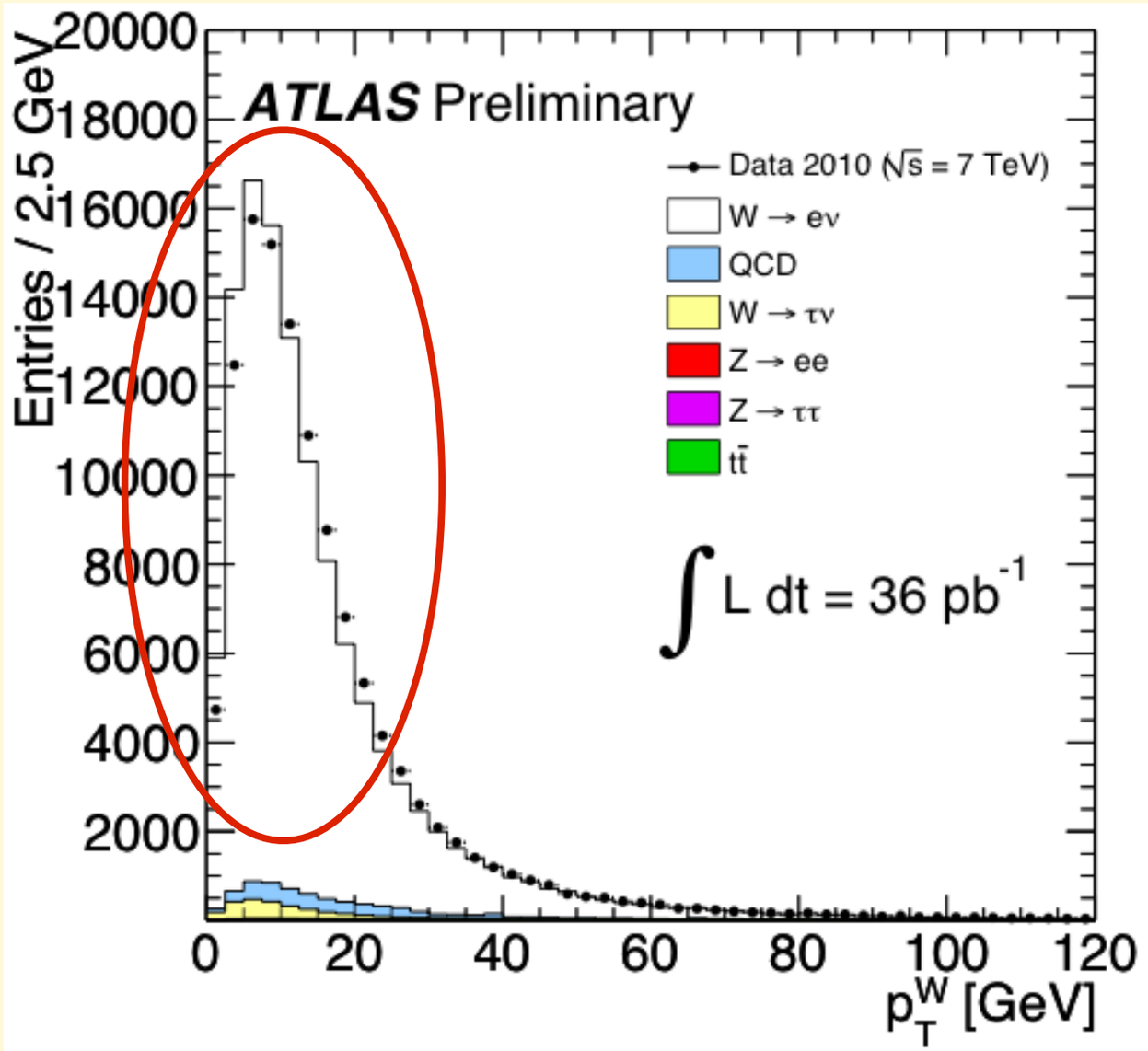
From G. Watt, and W.J. Stirling talk at Trento Workshop "LHC at the LHC"

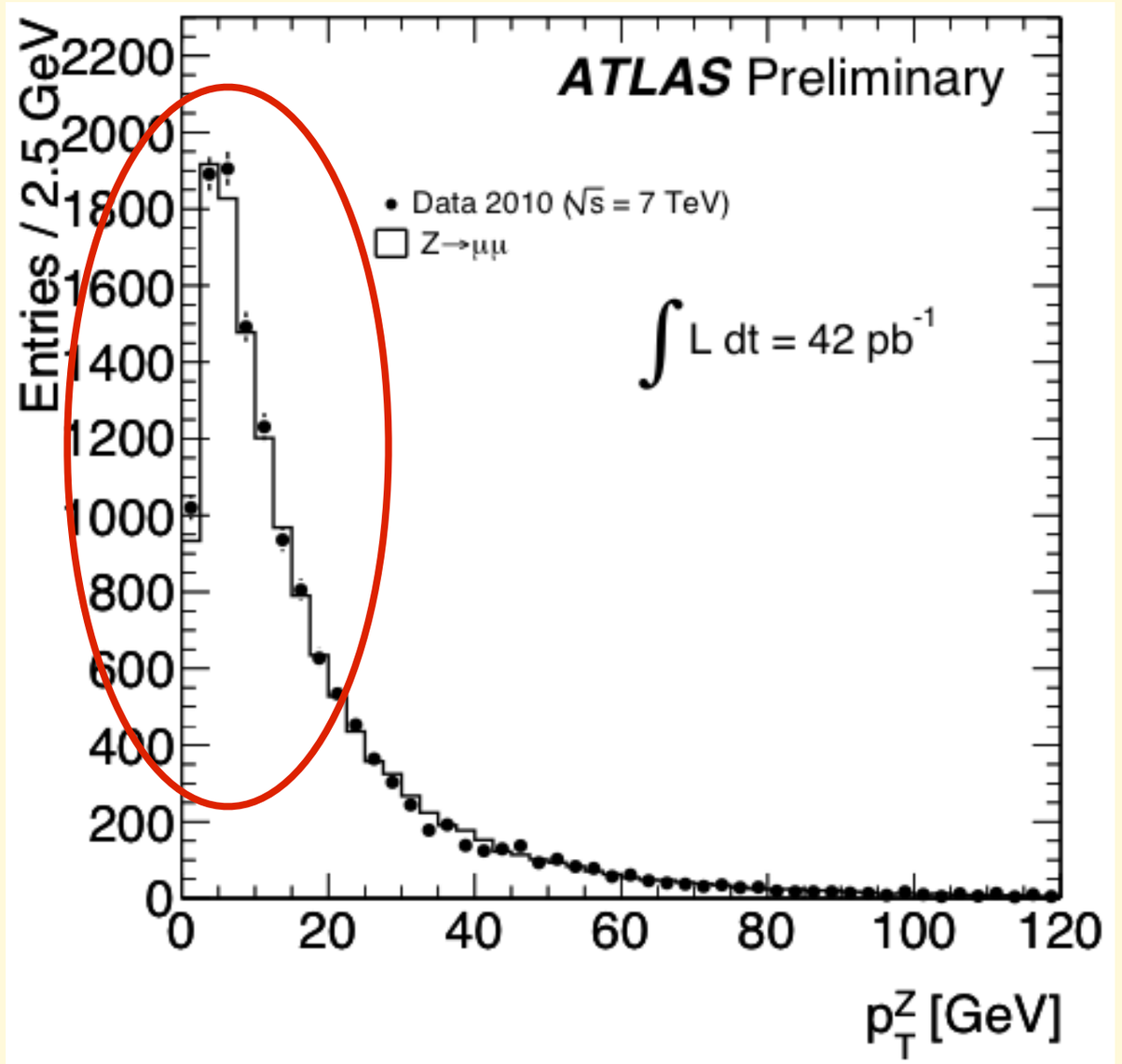
W/Z pt spectra





W/Z pt spectra

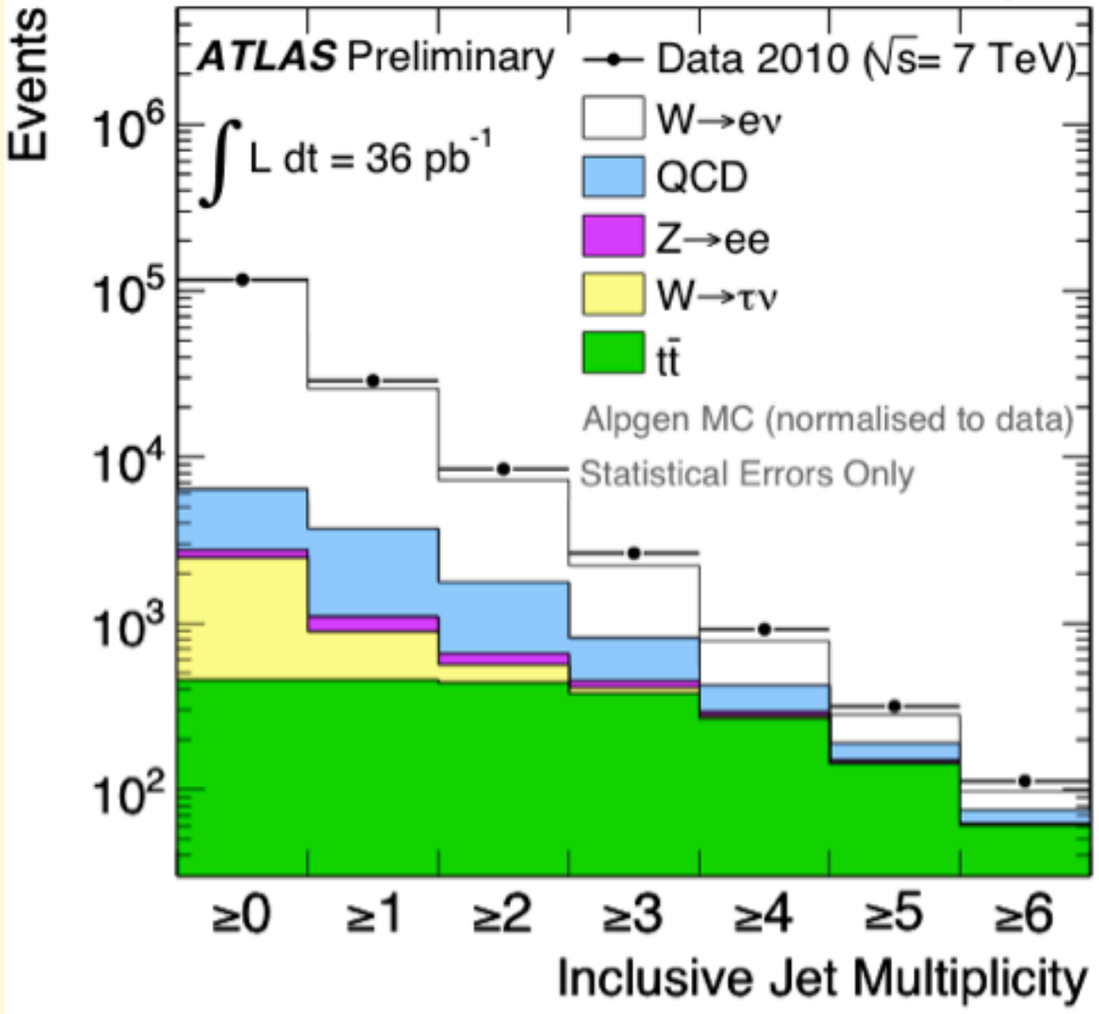


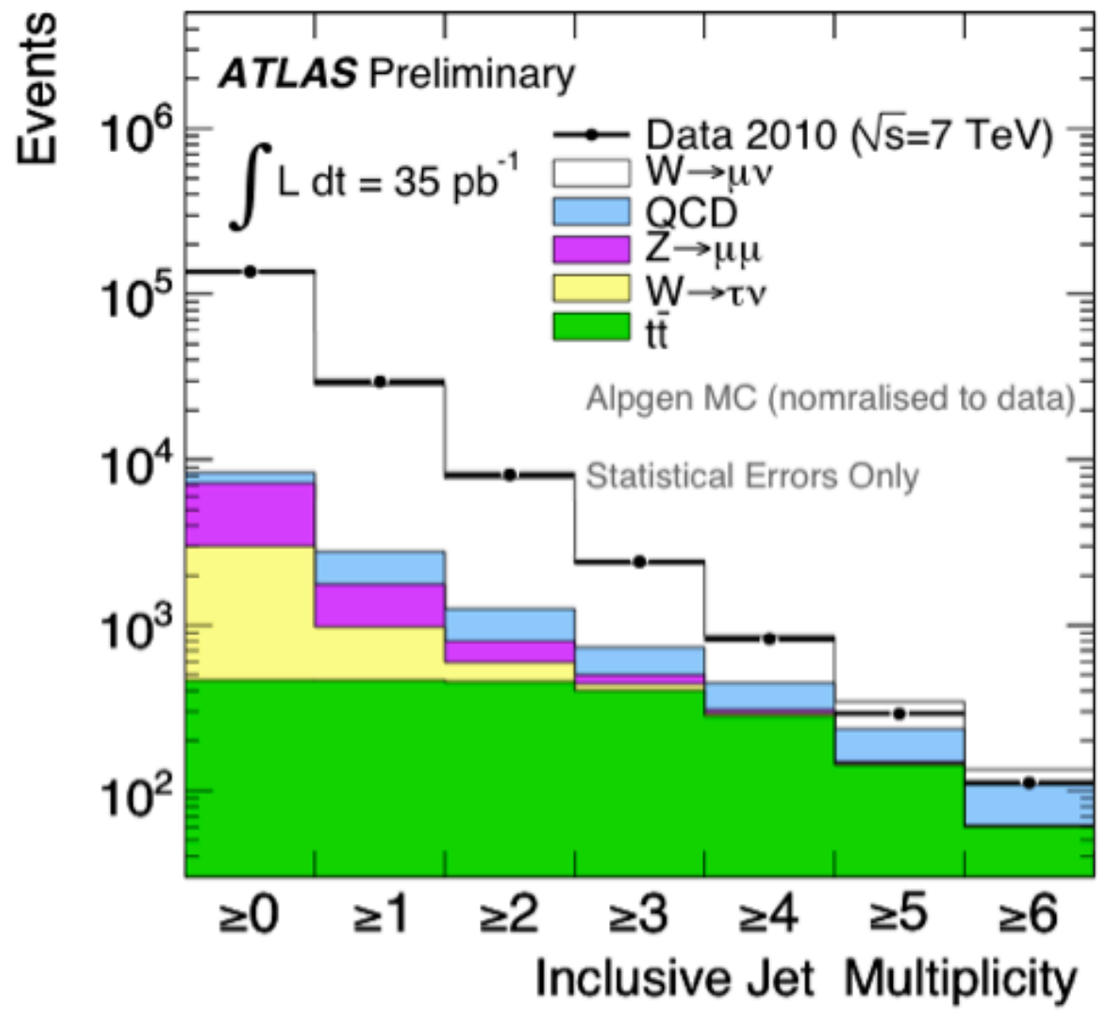


From the perspective of QCD, the modeling of W and Z pt is the same. So the different levels of agreement between data and theory in these two plots suggest that some more tuning of the detector description is required before moving on to quantitative tuning of QCD MCs.

W+jets

Jet E_T>20 GeV

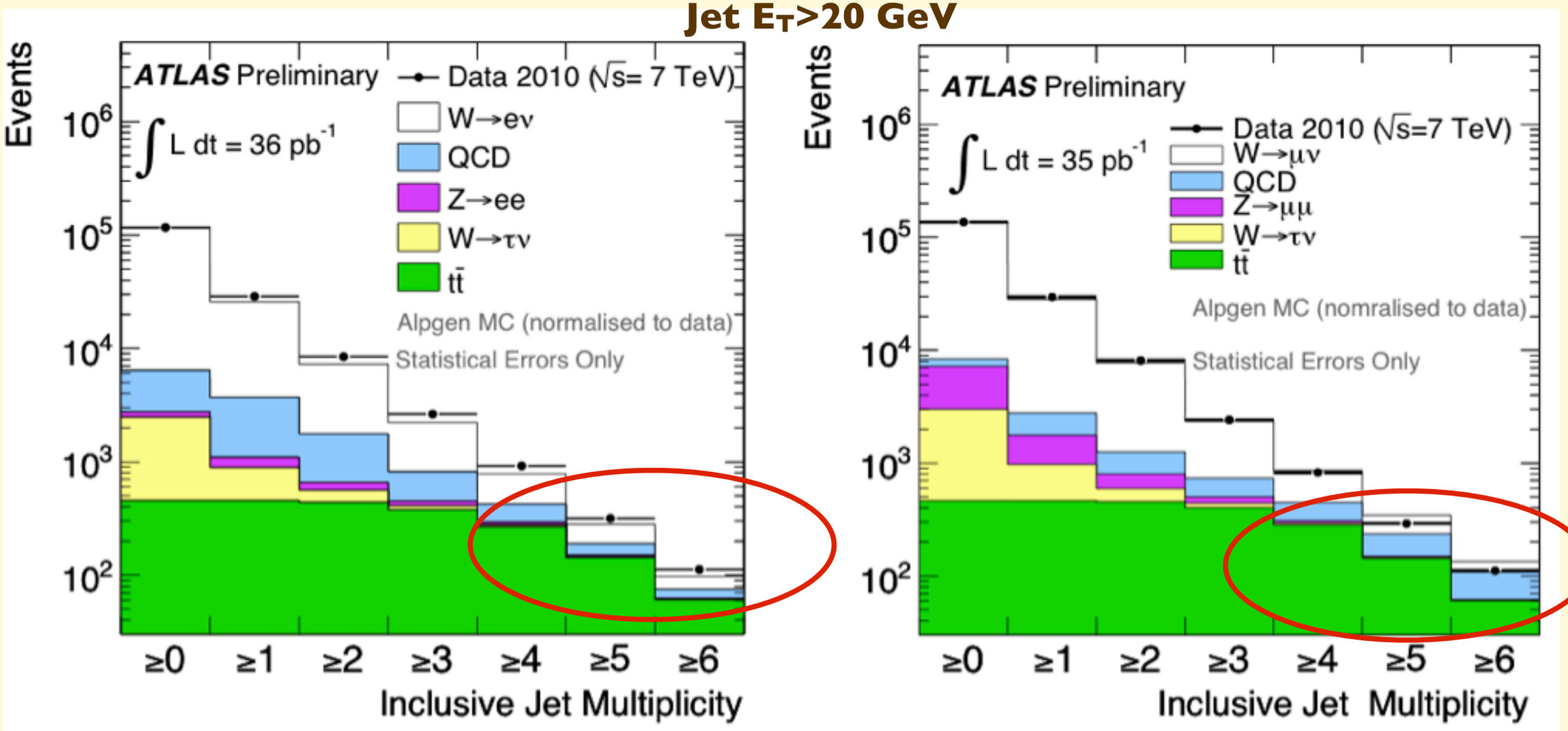




Bodes well for reliability of SM backgrounds estimates to SUSY searches in jets+MET!

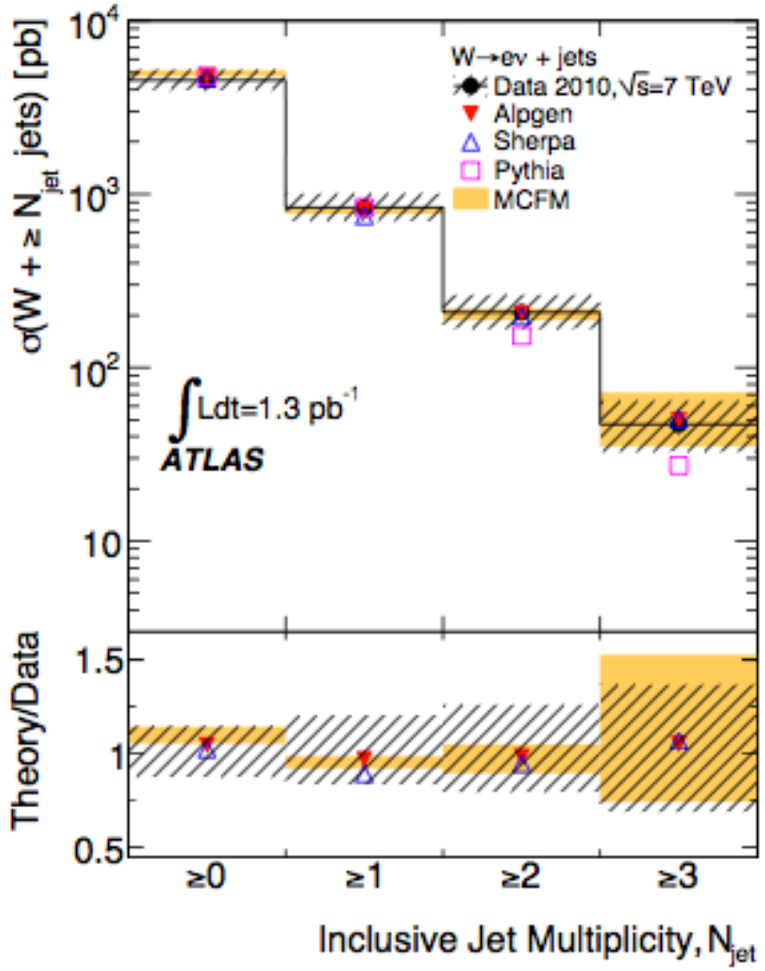
W+jets

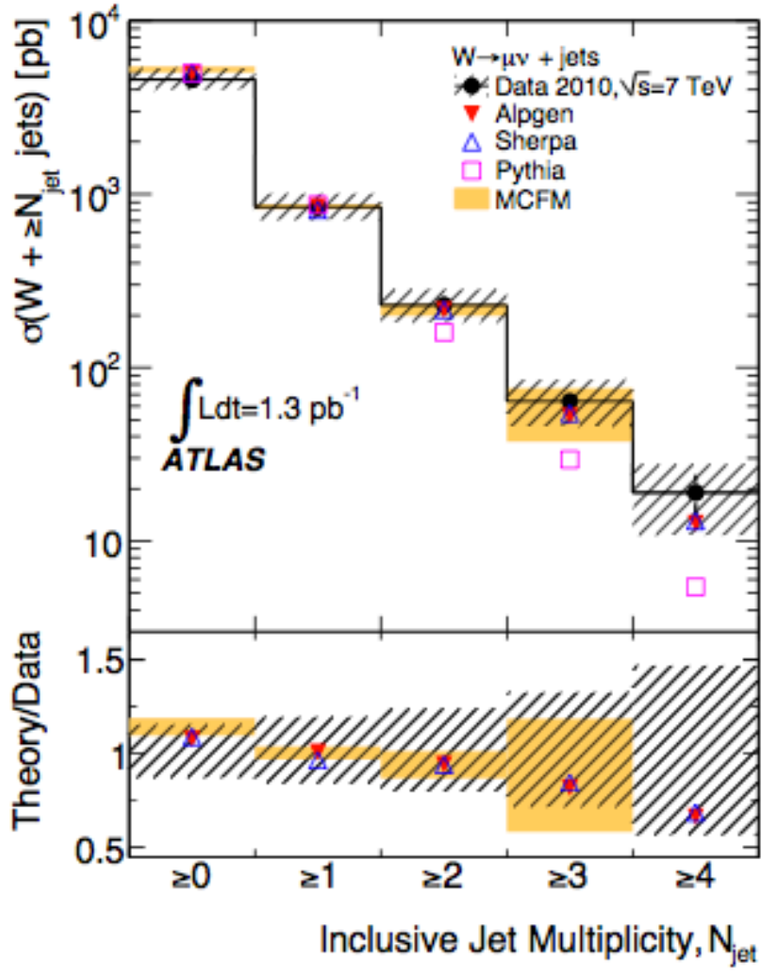
Jet E_T>20 GeV

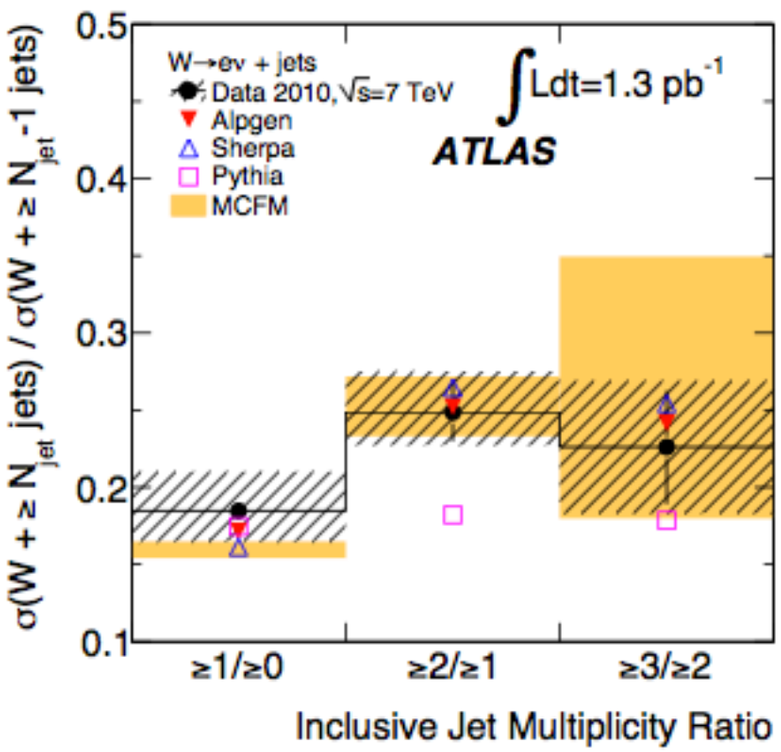


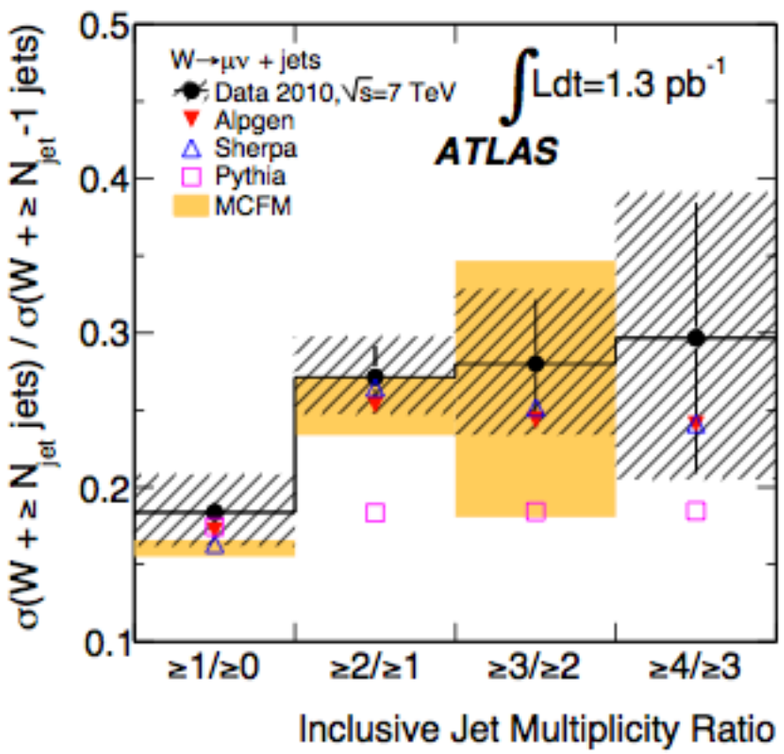
Statistics even out in the e and mu channels at large N_{jet}, making the agreement even more remarkable

Bodes well for reliability of SM backgrounds estimates to SUSY searches in jets+MET!





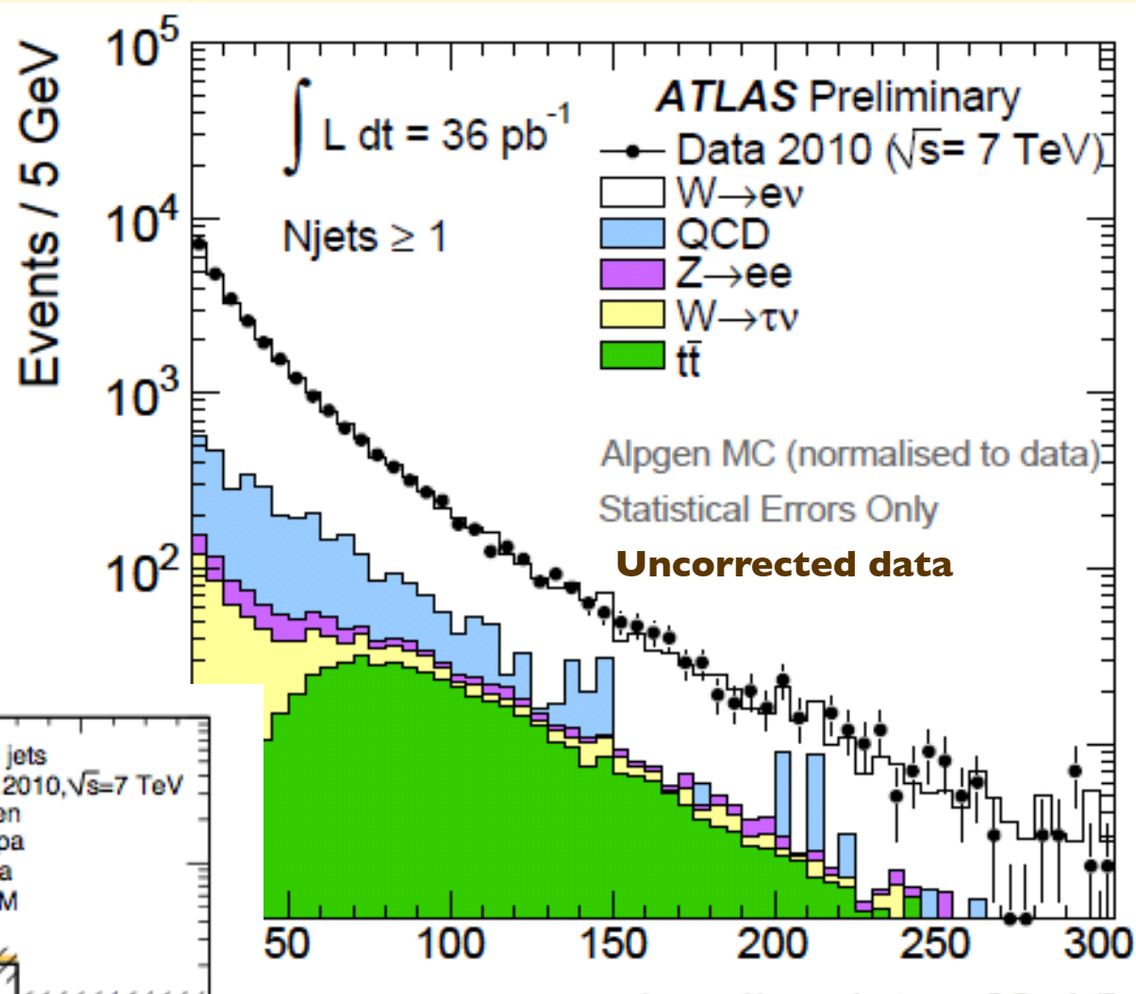




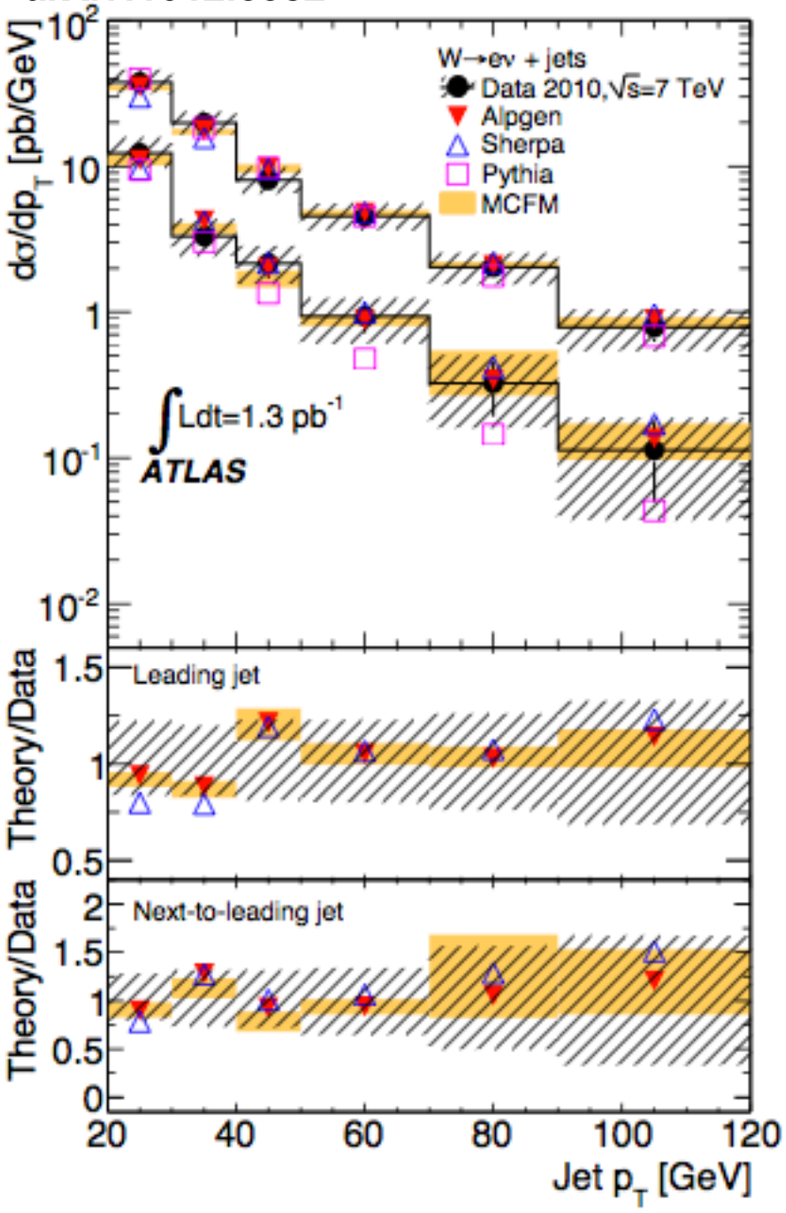
arXiv:1012.5382

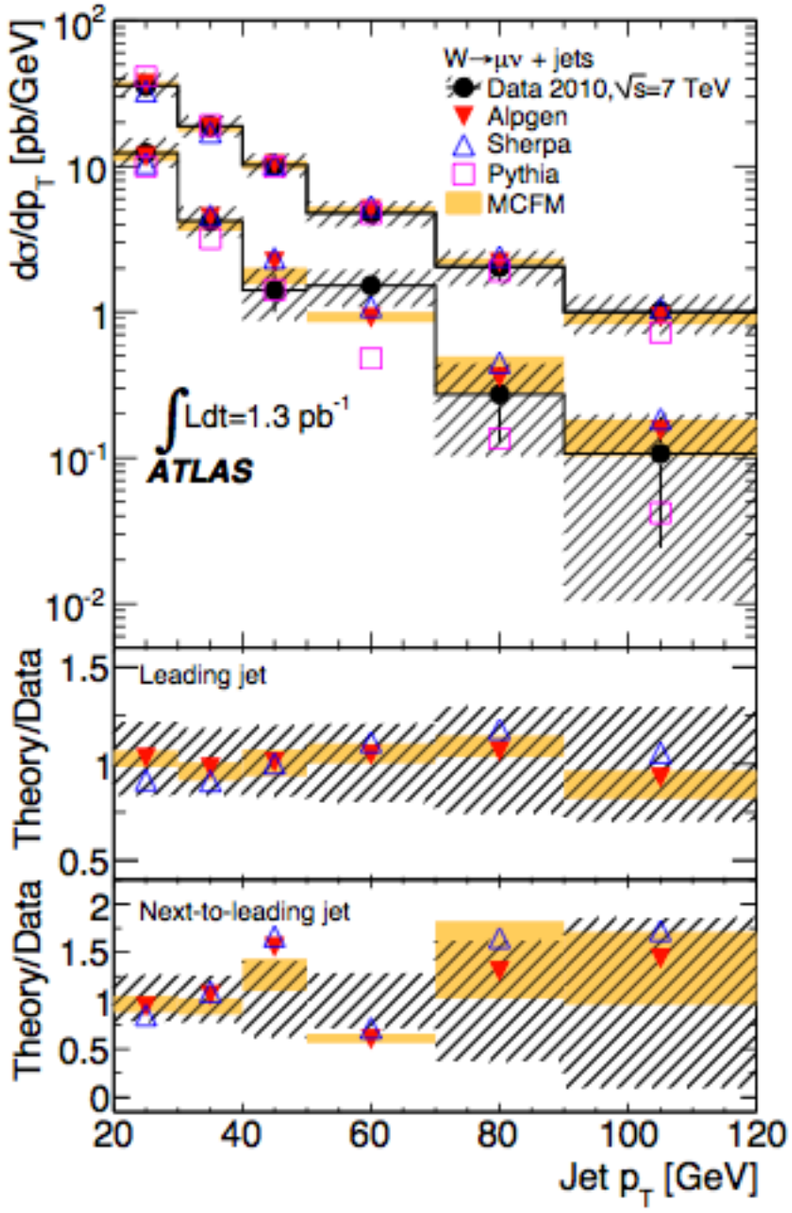
W+jets, E_T spectrum

Uncorrected data

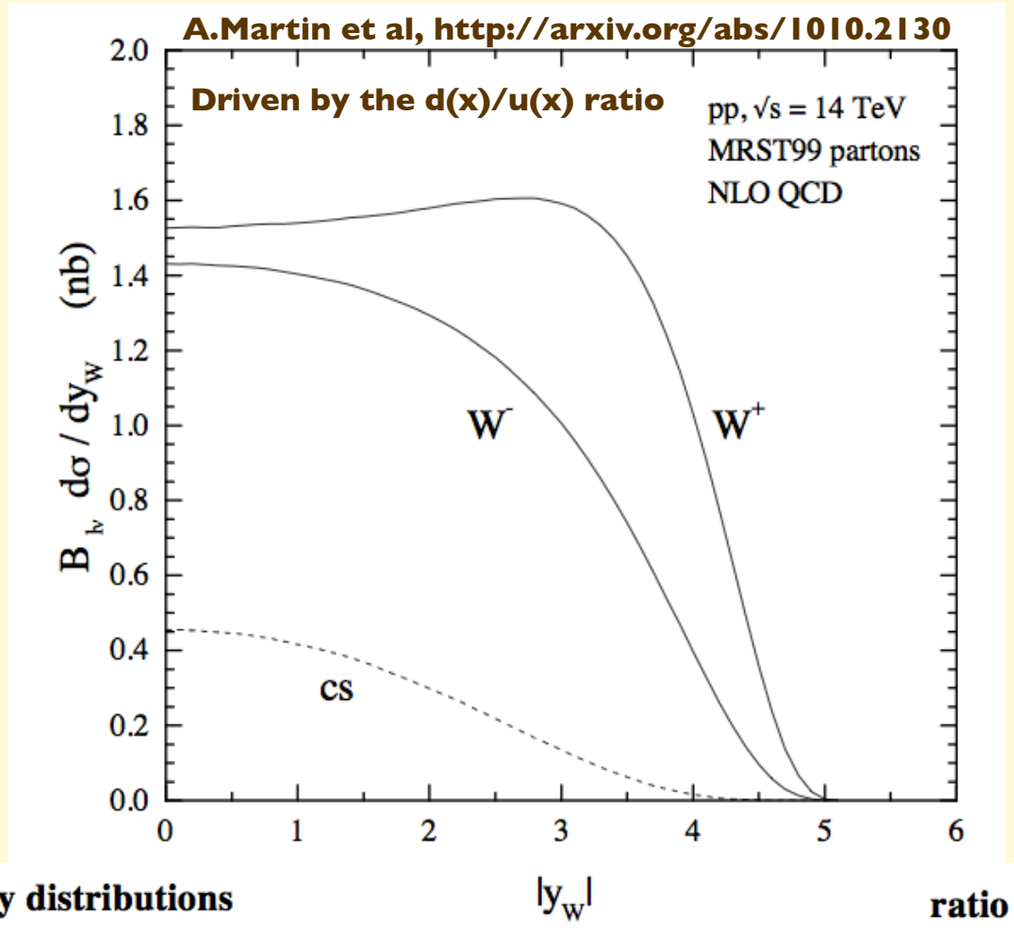


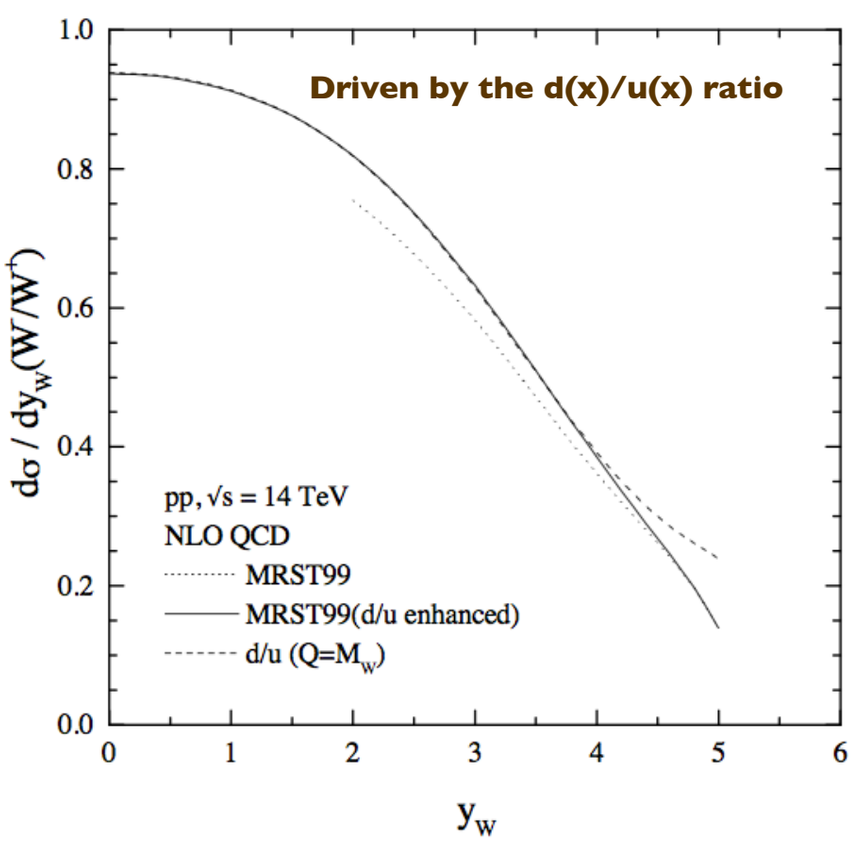
Hadron-level corrected data
arXiv:1012.5382

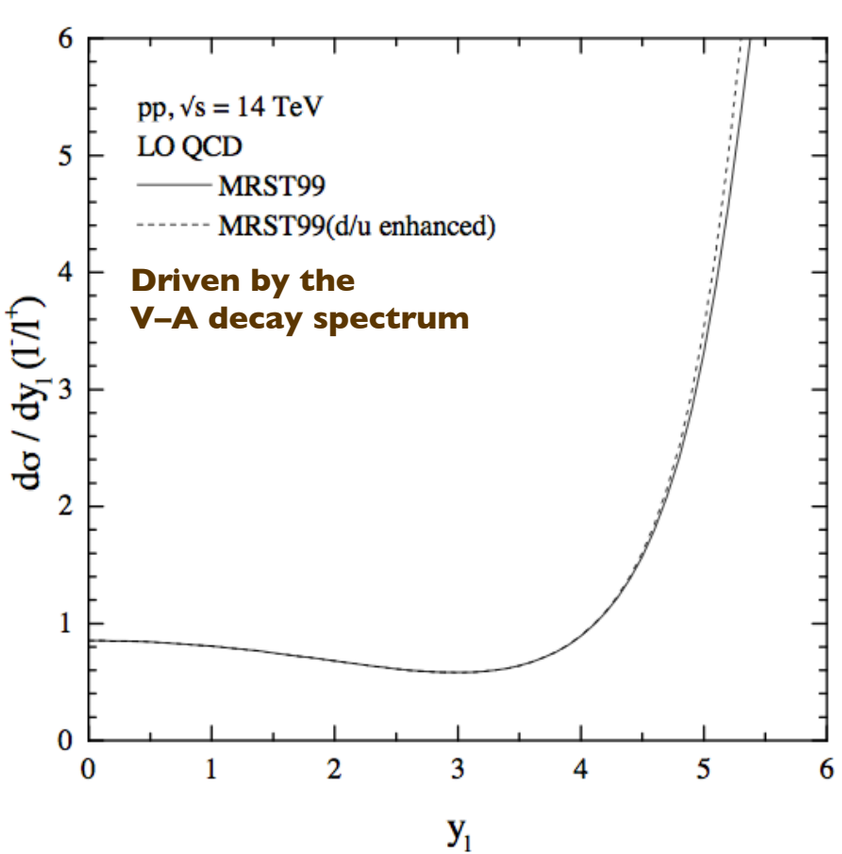




W+ / W– production asymmetries





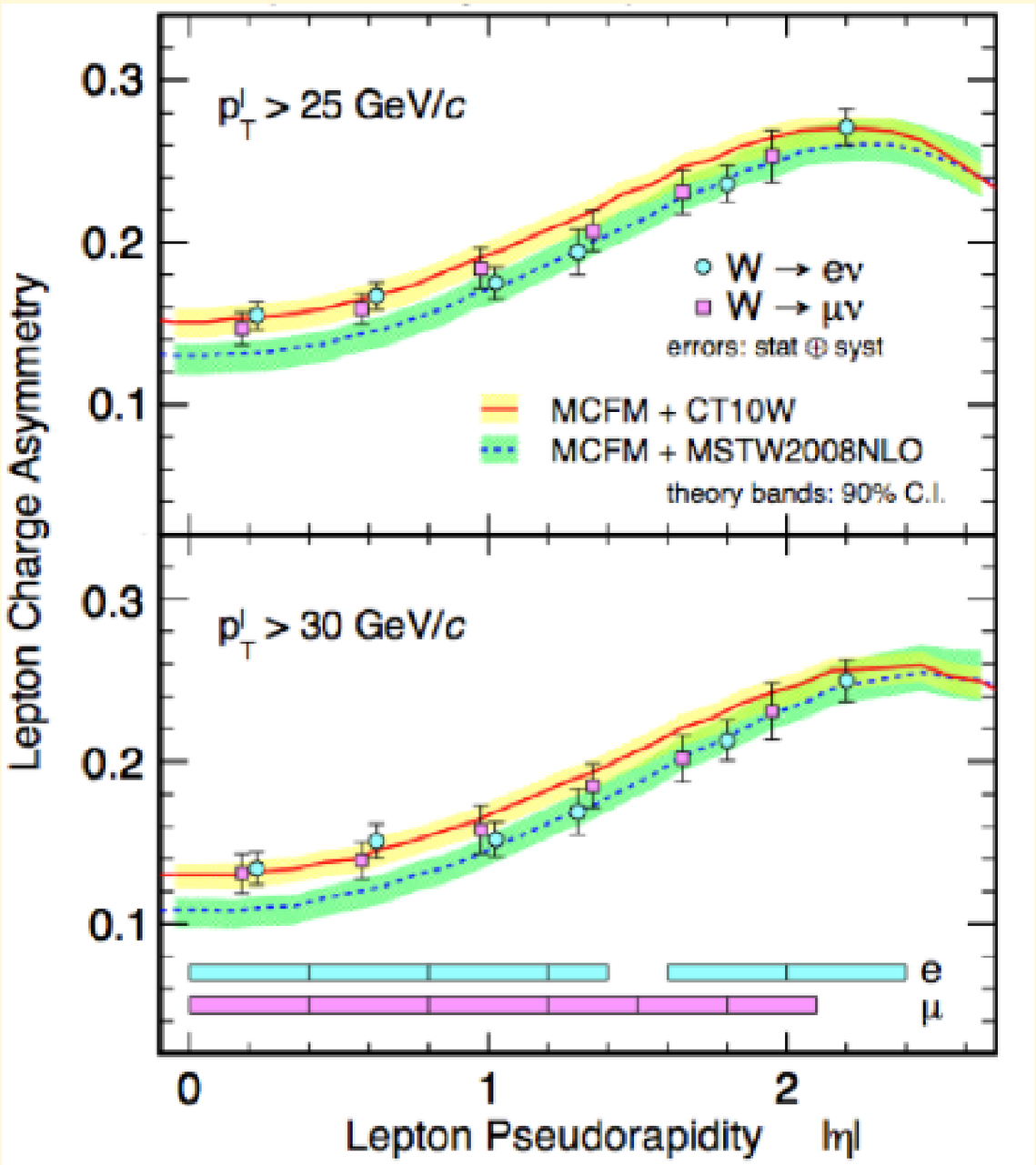


Lepton charge asymmetry at the LHC

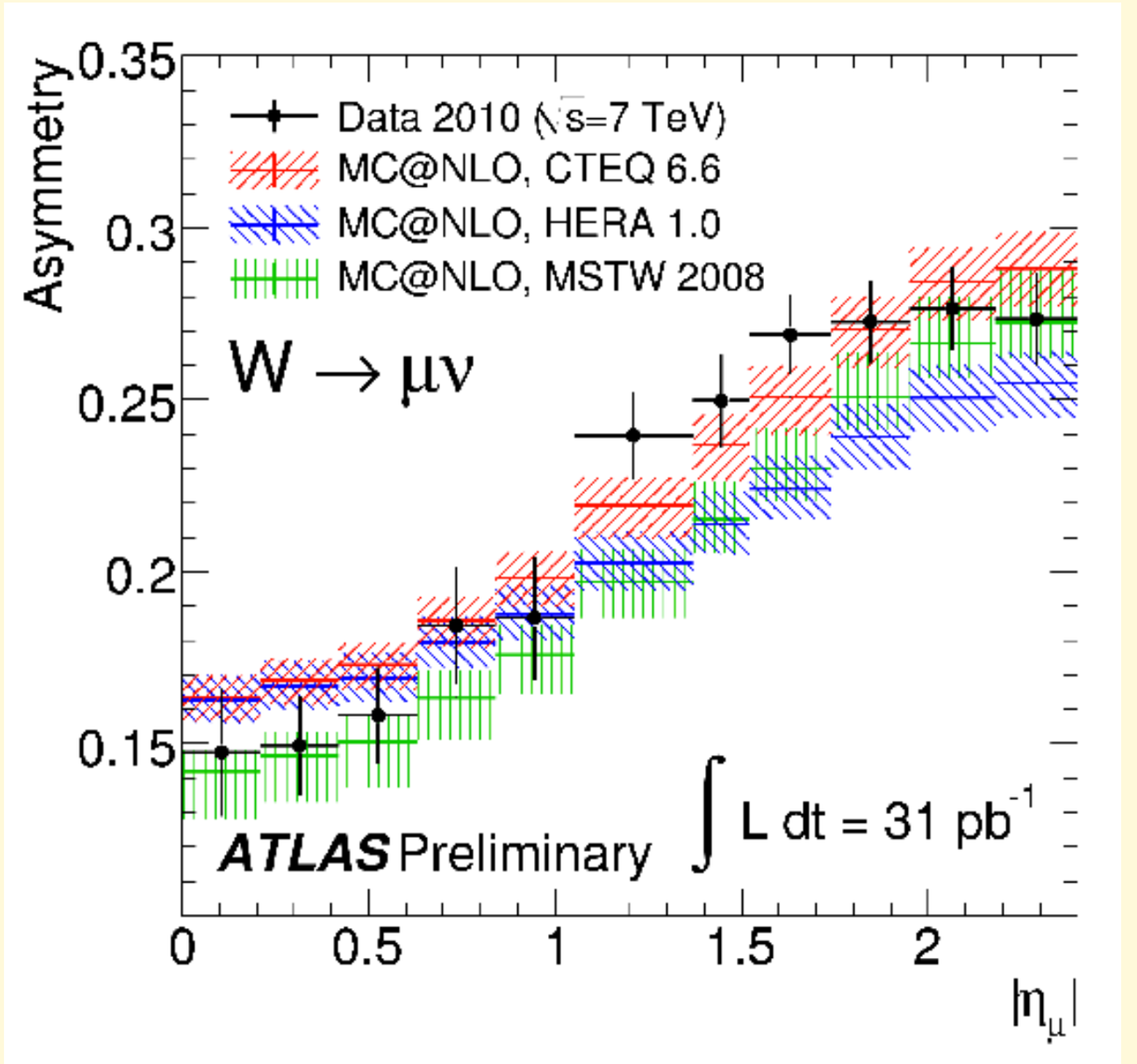
$$A_\ell = \frac{\sigma^{\text{fid}}_{W^+} - \sigma^{\text{fid}}_{W^-}}{\sigma^{\text{fid}}_{W^+} + \sigma^{\text{fid}}_{W^-}}$$

CMS preliminary 36 pb^{-1} at $\sqrt{s}$ = 7 TeV

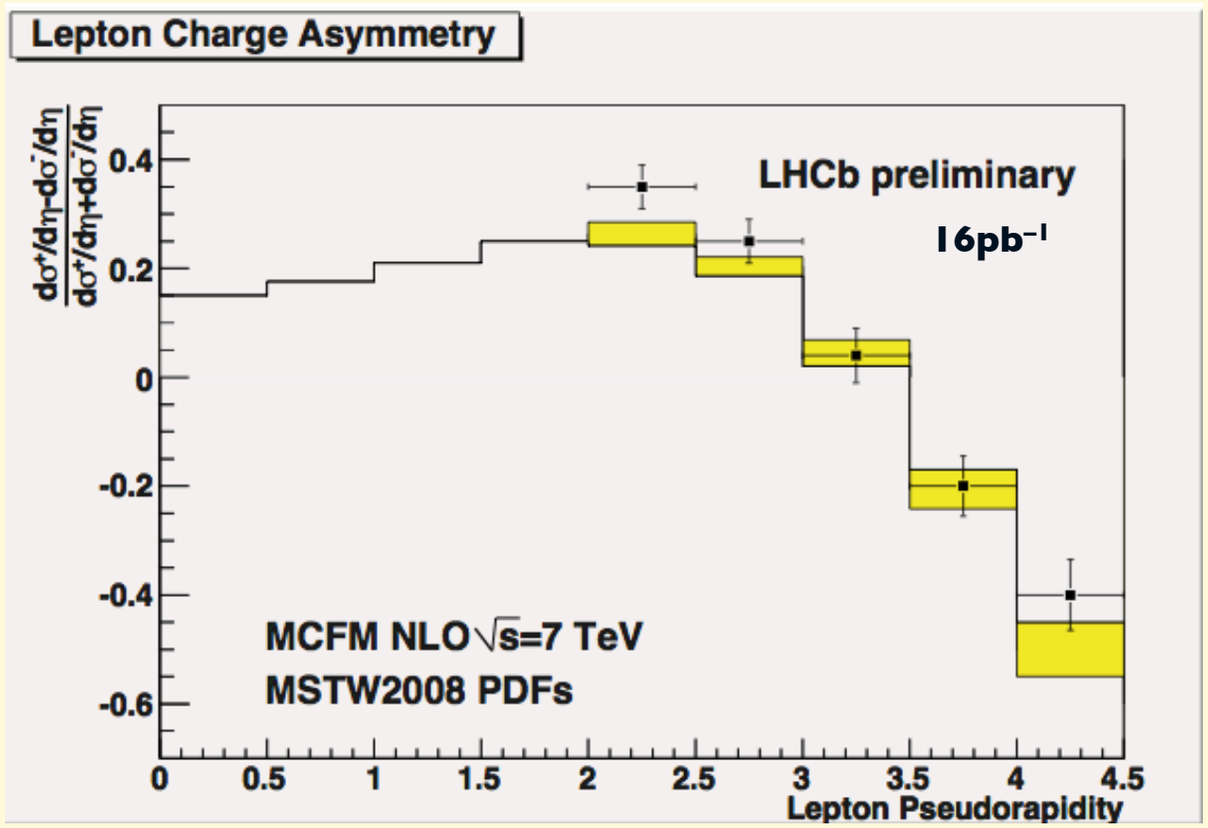
CMS PAS EWK-10-006

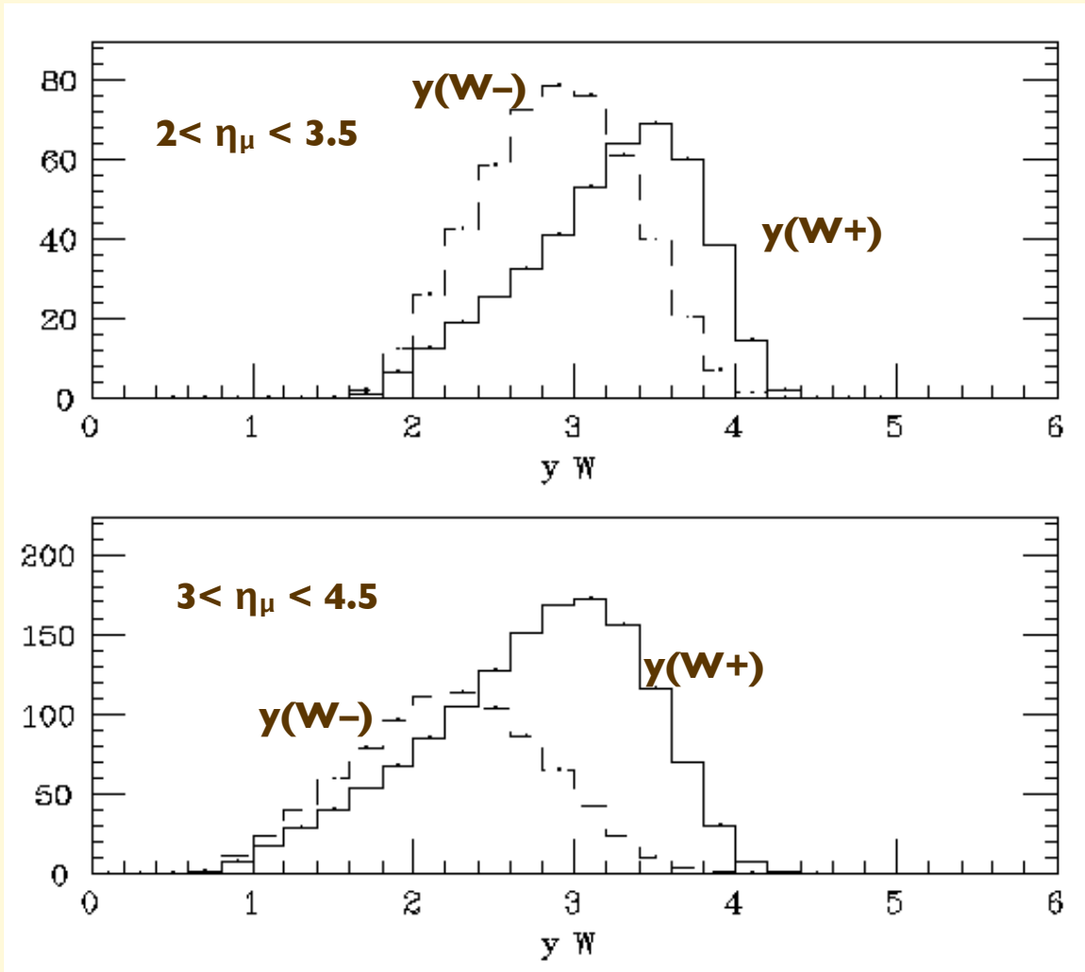


ATLAS preliminary, 31pb^{-1}, LaThuile '11



EW boson production in the forward region, LHCb

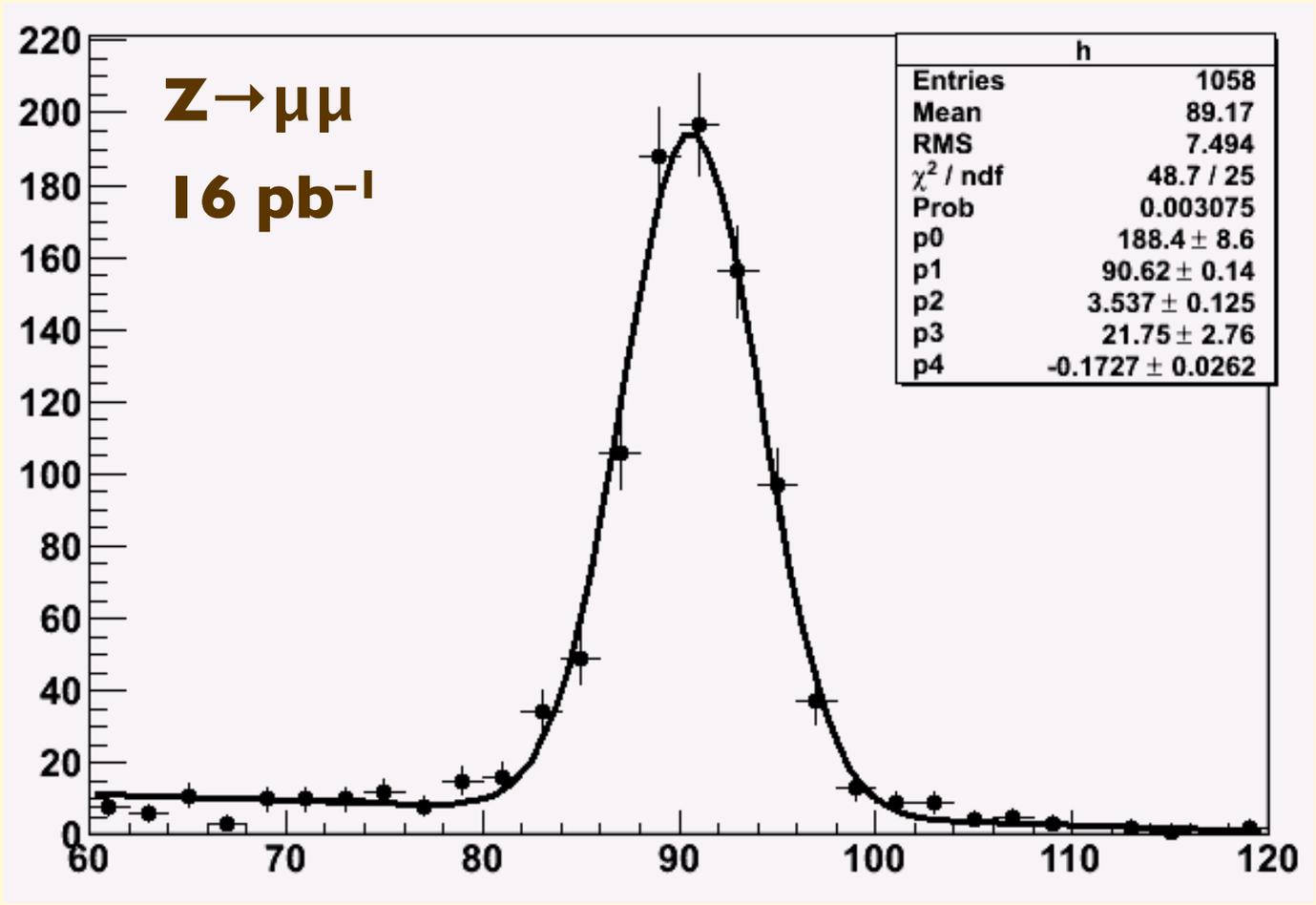




W→μν, charge asymmetry

See S.Stone, for the LHCb collab., 104th LHCC session, http://indico.cern.ch/conferenceDisplay.py?confId=112439

EW boson production in the forward region, LHCb

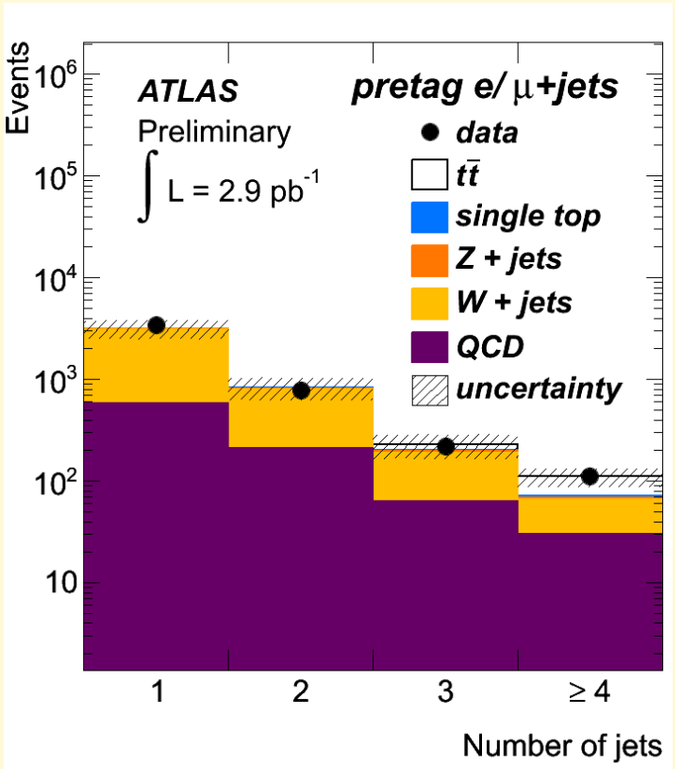


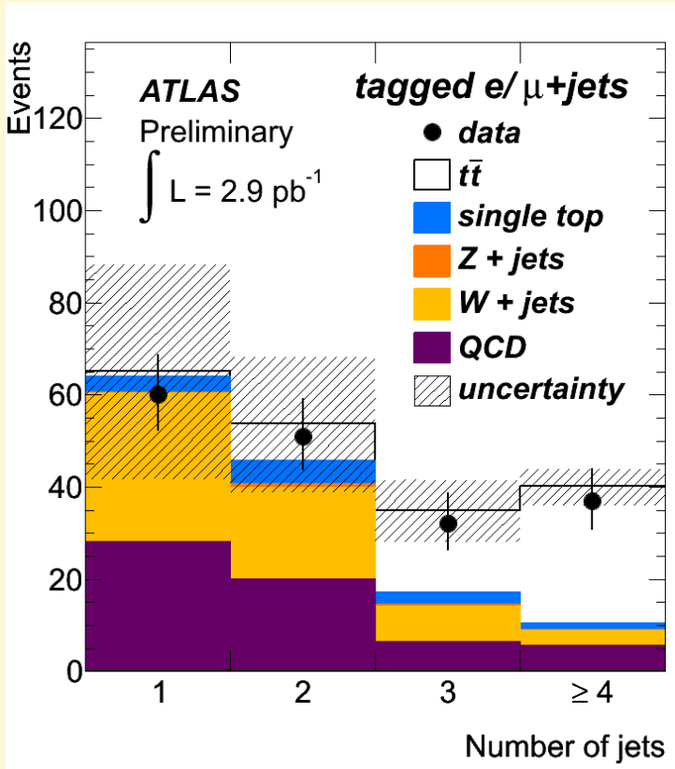
These observations open the way for many interesting new measurements, from PDF constraints, to a determination of A_{FB} and $\sin^2\theta_W$

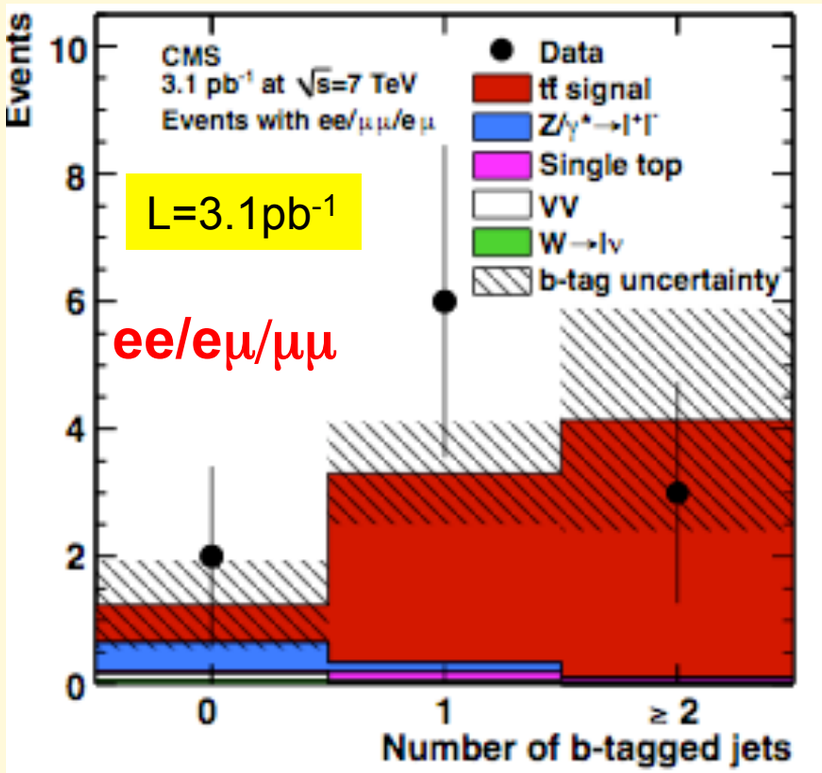
See S.Stone, for the LHCb collab., 104th LHCC session, http://indico.cern.ch/conferenceDisplay.py?confId=112439

Heavy quarks

Top





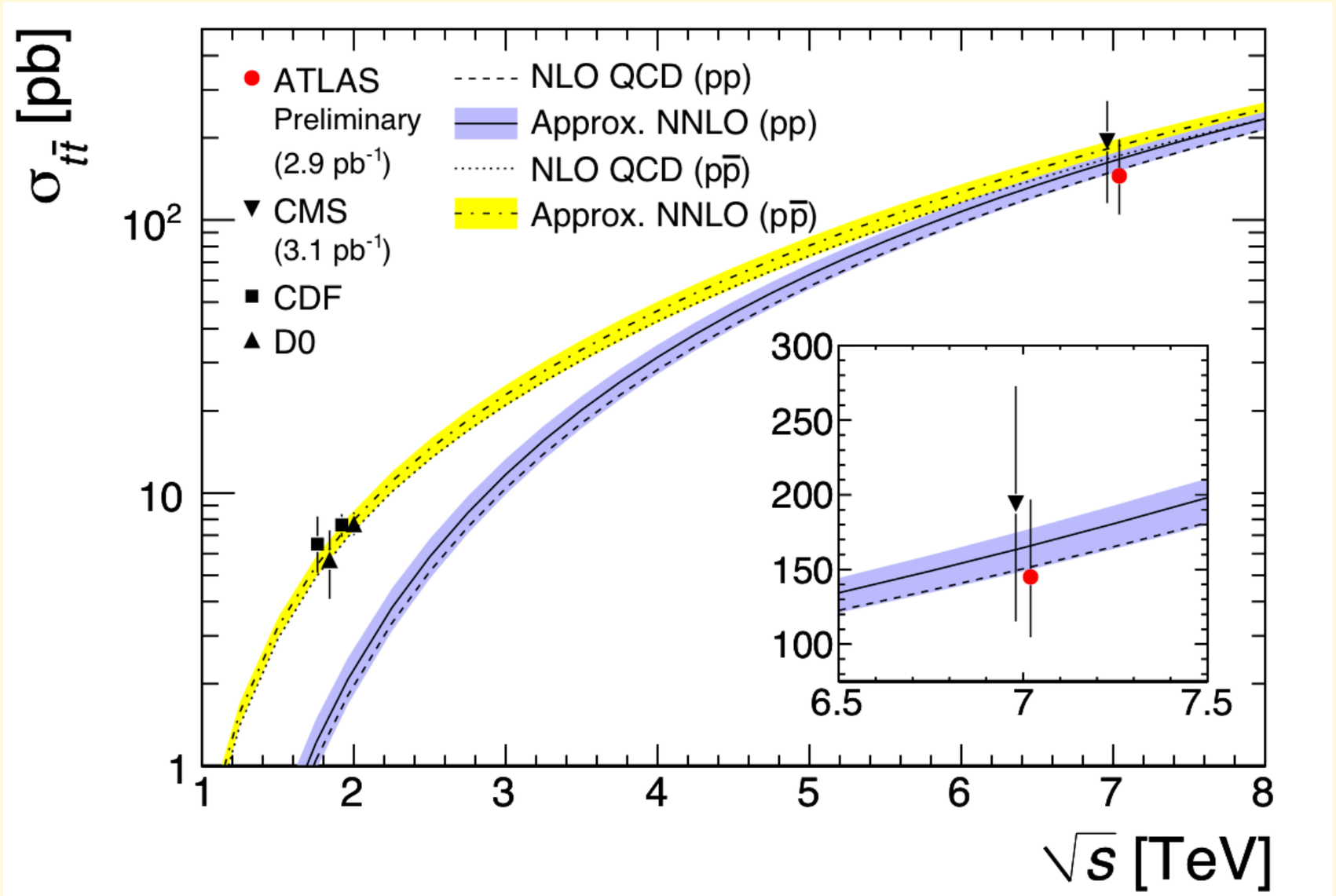


1 e or μ with p_T>20 GeV, E_T^{miss}>20 GeV, $E_T^{miss}+m_T(W)$>60 GeV

N_{jets} with p_T>25 GeV, with no b-tag requirement or at least one b-tag

Signal defined to have 4 or more jets, and at least 1 b-tag

See P. Wells, for the ATLAS collab., 104th LHCC session, http://indico.cern.ch/conferenceDisplay.py?confId=112439



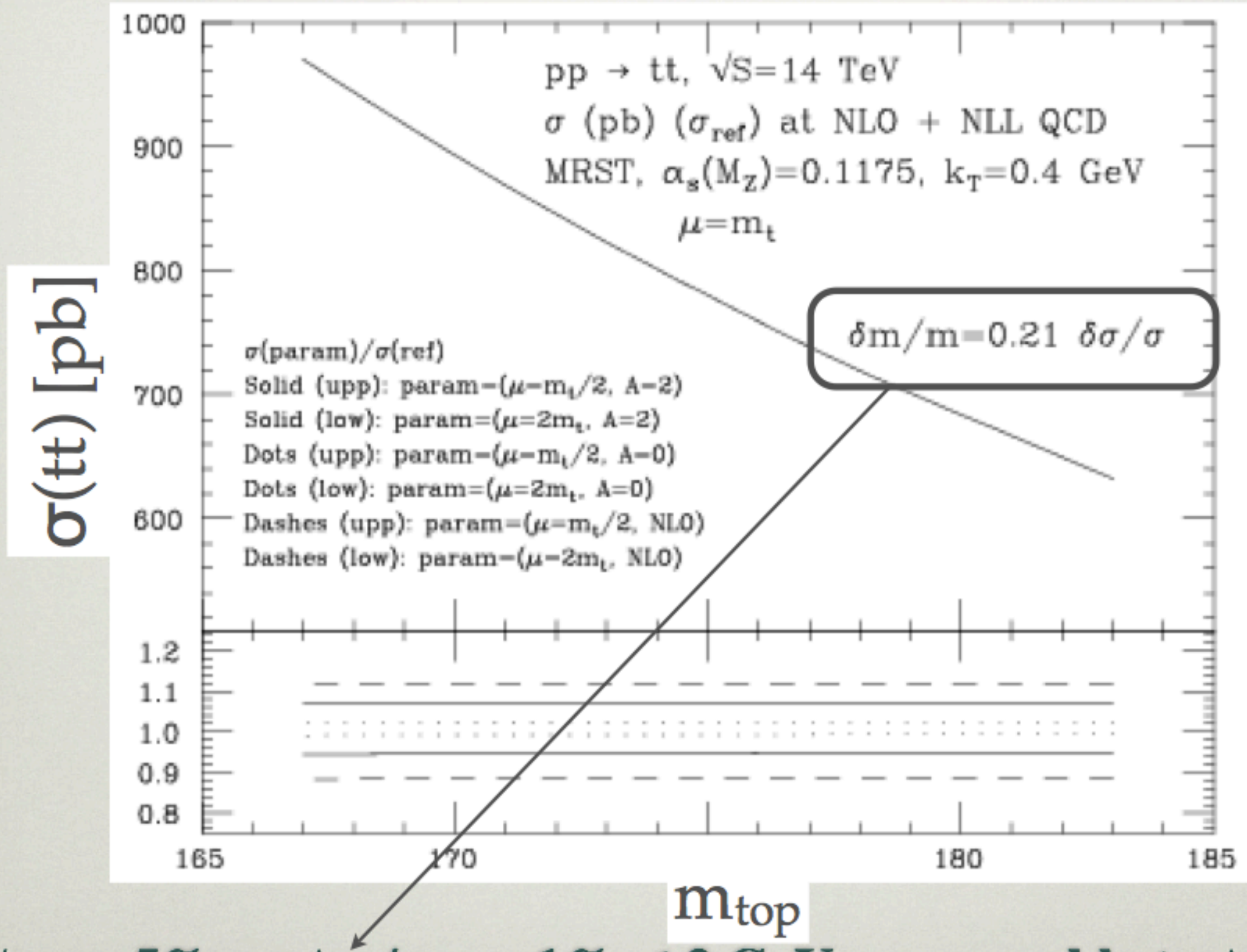
(1) ATLAS (lepton+b+≥3 jets and dileptons+≥2jets): $\sigma_{ATLAS} = 145 \pm 31 \,^{+42}_{-27}$ pb

(2) CMS (dileptons+≥2jets): $\sigma_{CMS} = 194 \pm 72_{stat} \pm 24_{syst} \pm 21_{lum}$

$\sigma_{TH} = 167 \,^{+13}_{-10}$ pb

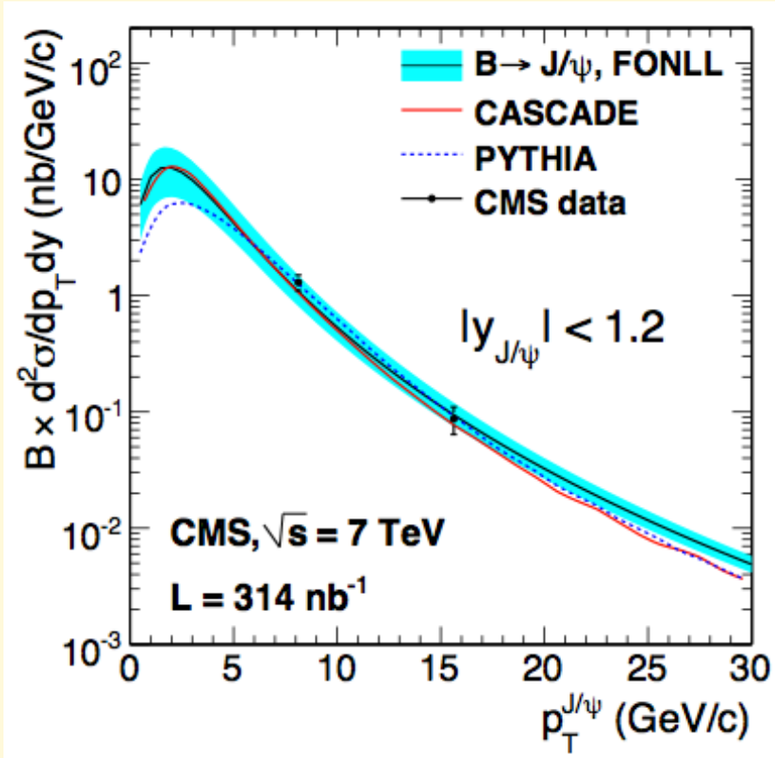
(1) **See P. Wells, for the ATLAS collab., 104th LHCC session, http://indico.cern.ch/conferenceDisplay.py?confId=112439**

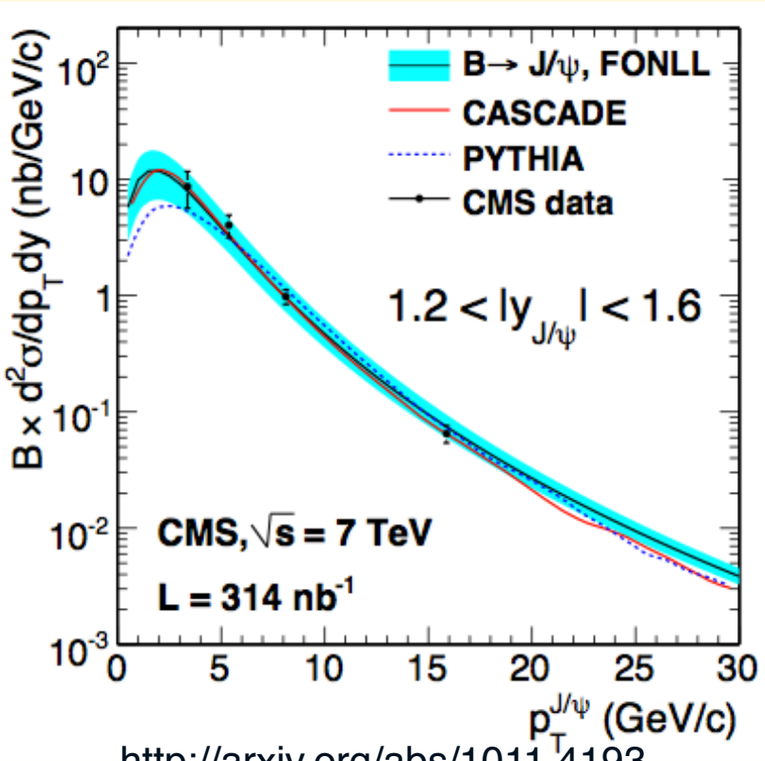
(2) **arXiv:1010.5994**

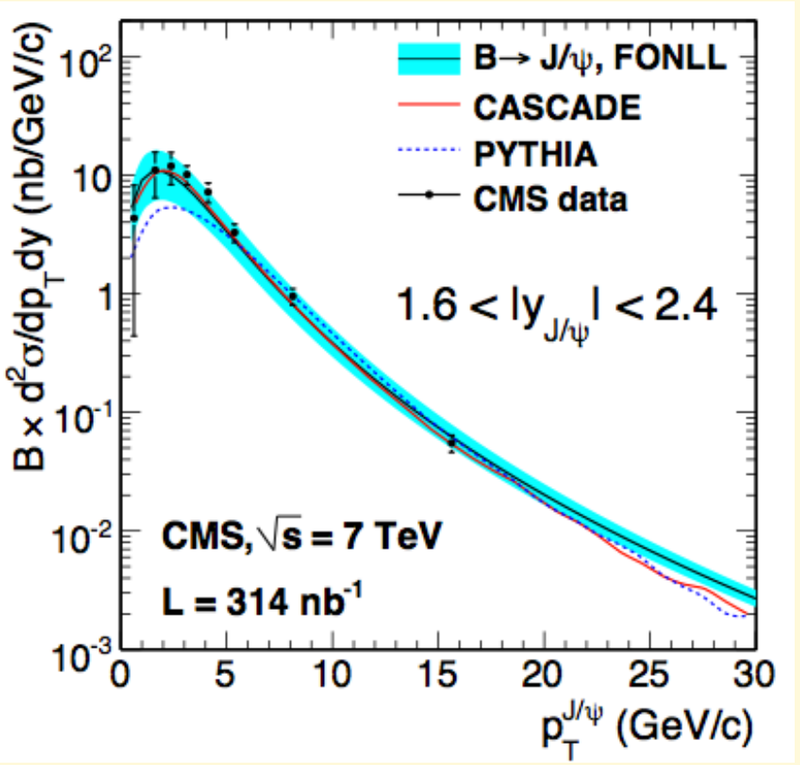


$\Delta\sigma/\sigma = \pm 5\% \Leftrightarrow \Delta m/m = \pm 1\% \lesssim 2$ GeV, comparable to Δm_{direct}

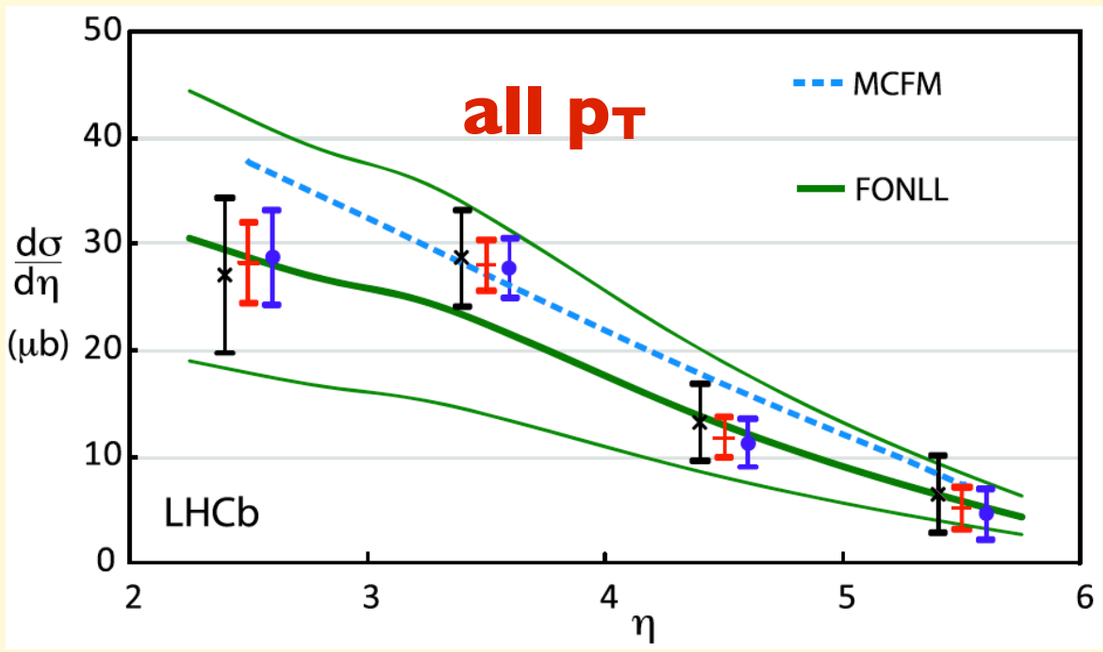
Open Q: by and large good agreement of data and NLO

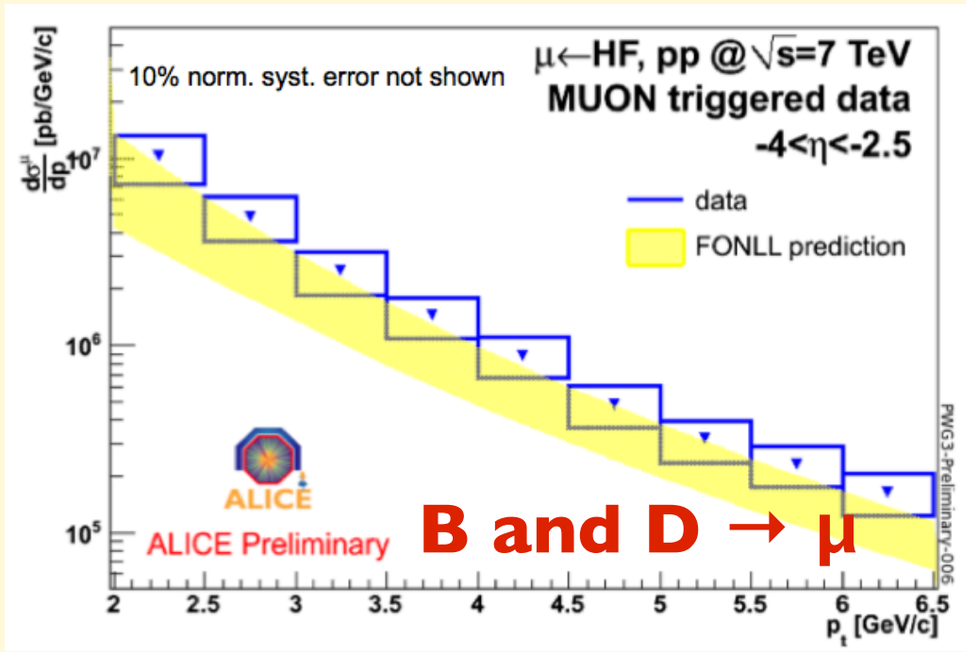






http://arxiv.org/abs/1011.4193



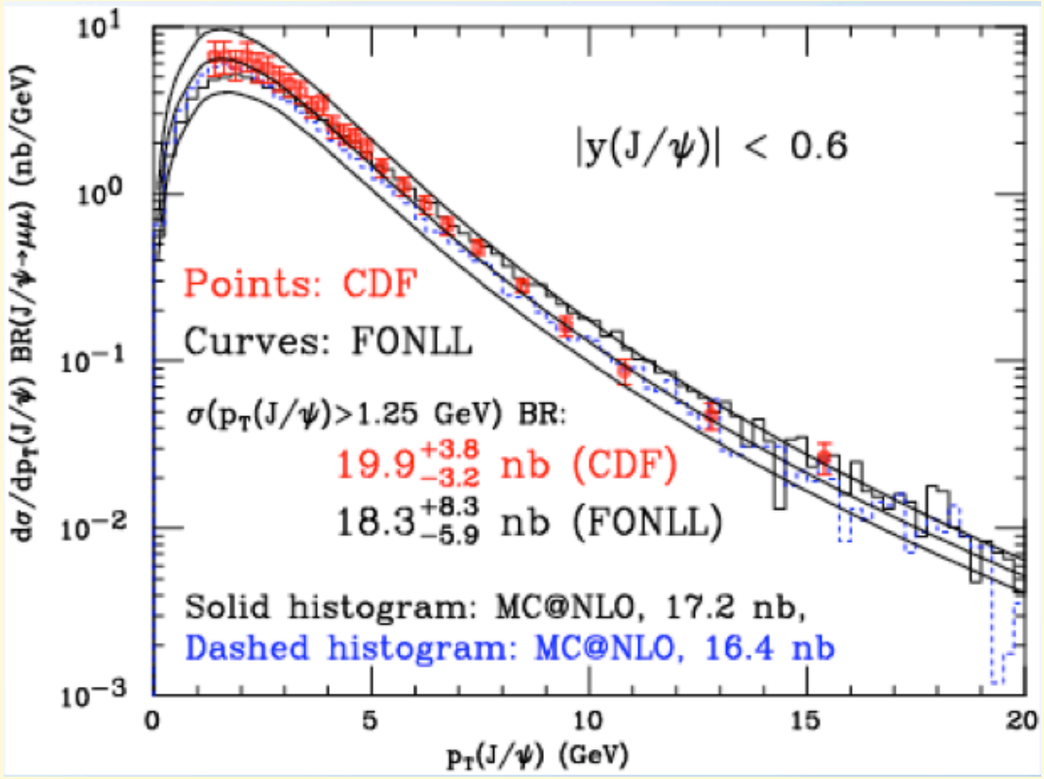


This agreement is one of the most significant results from LHC-2010

Why is it not trivial?

It took a while to establish consistency between Tevatron data and pQCD

hep-ph/0411020

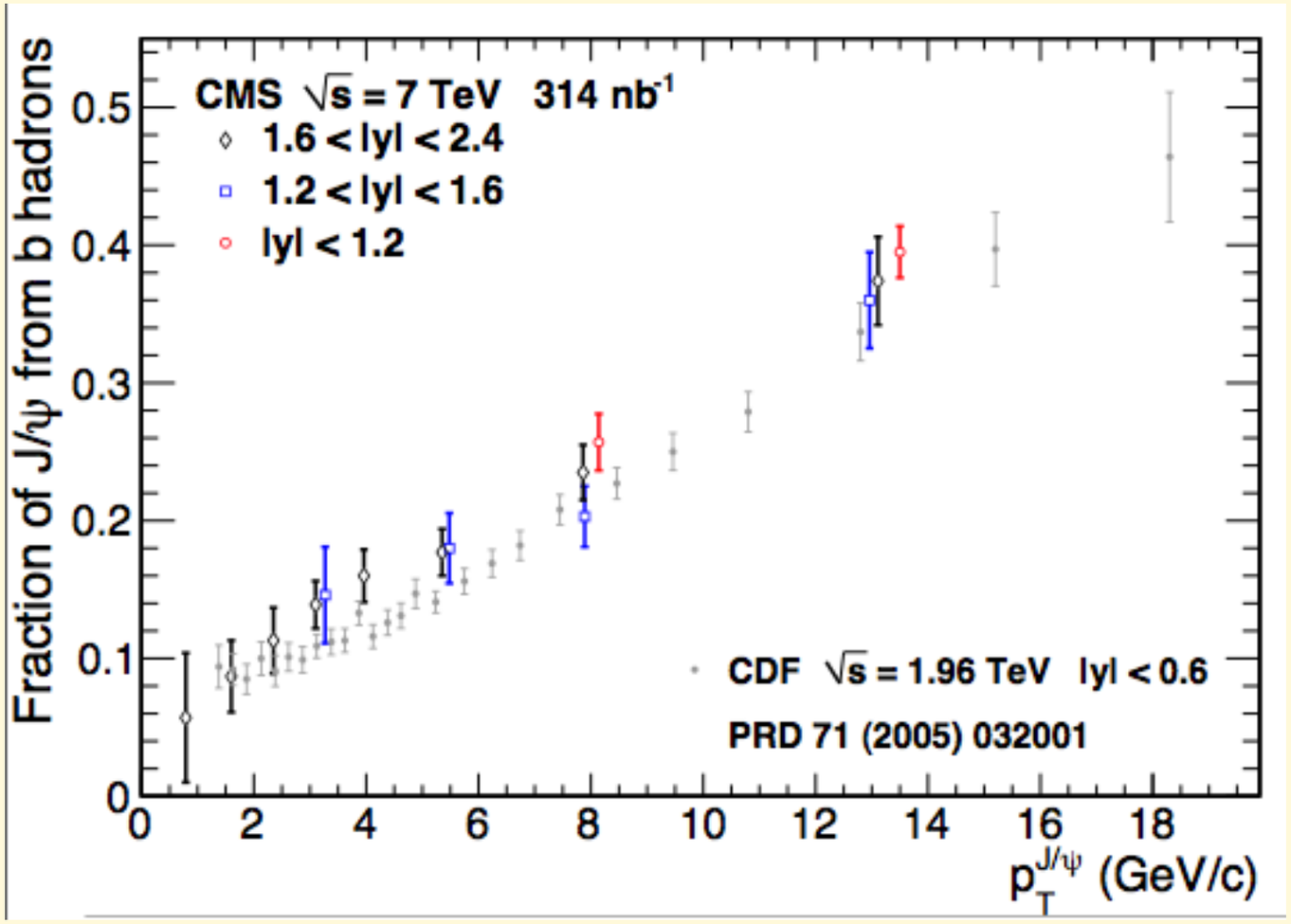


The dynamical regime of the LHC is theoretically more challenging

- large S => small x
- large rapidity (ALICE, LHCb)
  - o access to even smaller x
  - o small pt, sensitivity to higher-twist effects

Nason, Dawson, Ellis
Collins, R.K.Ellis
Ball, Ellis
Catani Ciafaloni Hautmann
....

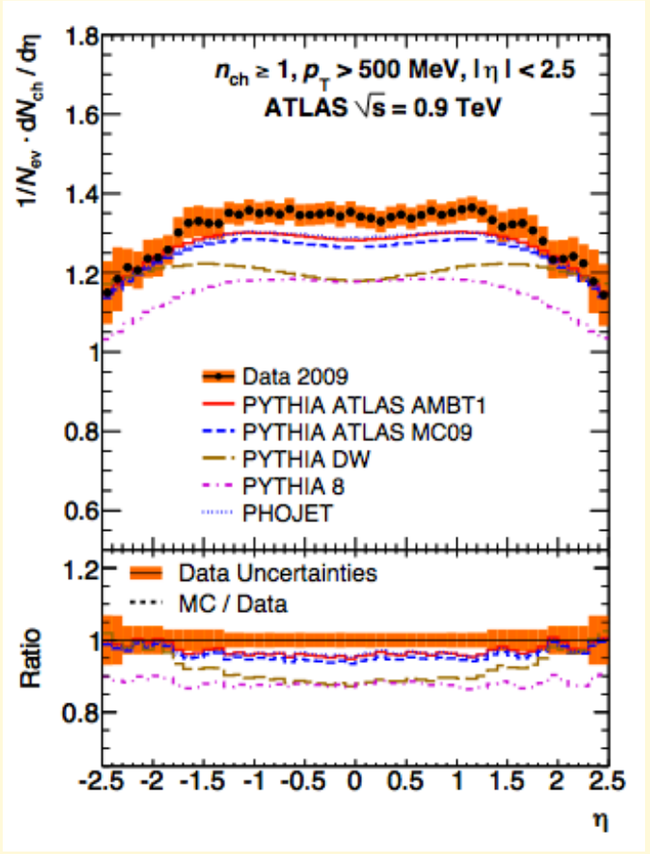
J/psi production: fraction of prompt and b-decay

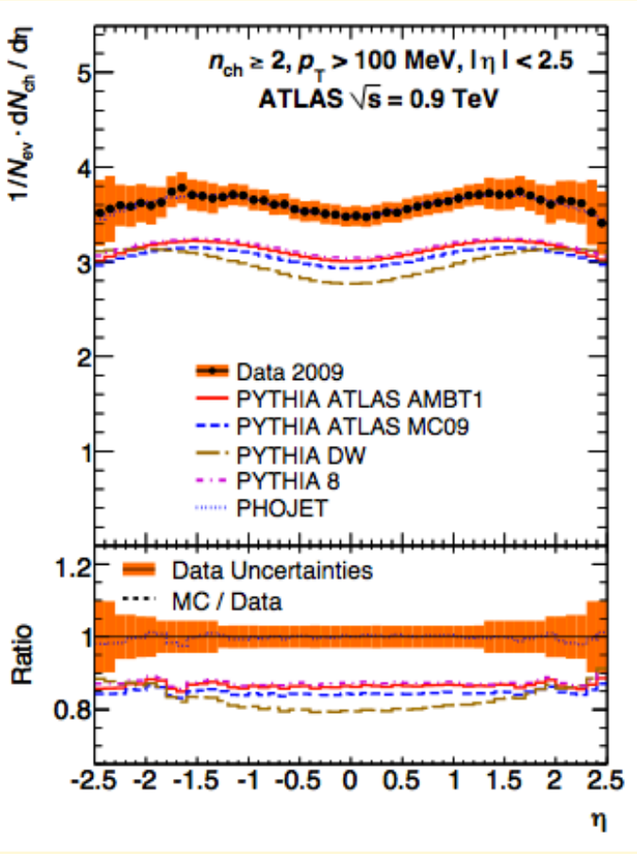


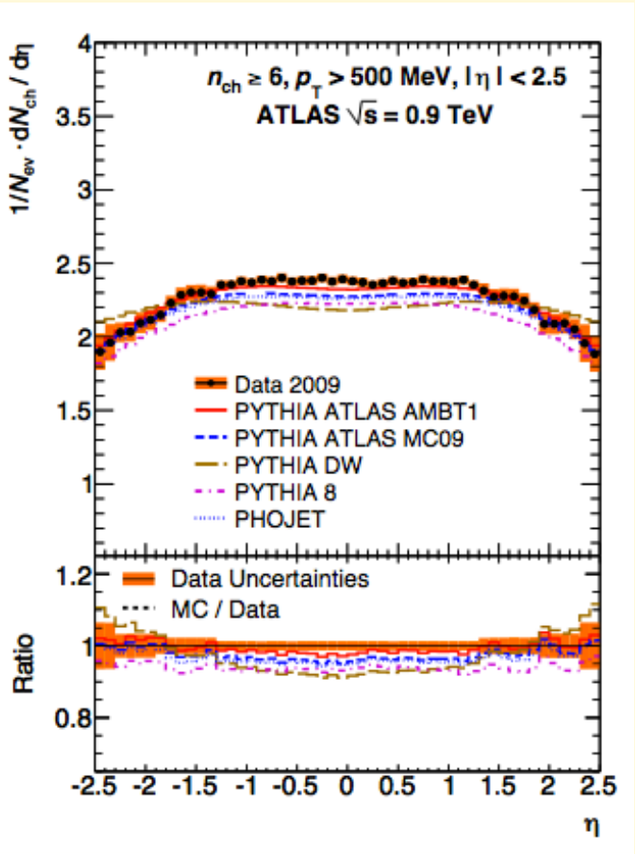
General properties of inclusive final states, a few examples

Rapidity and multiplicity spectra

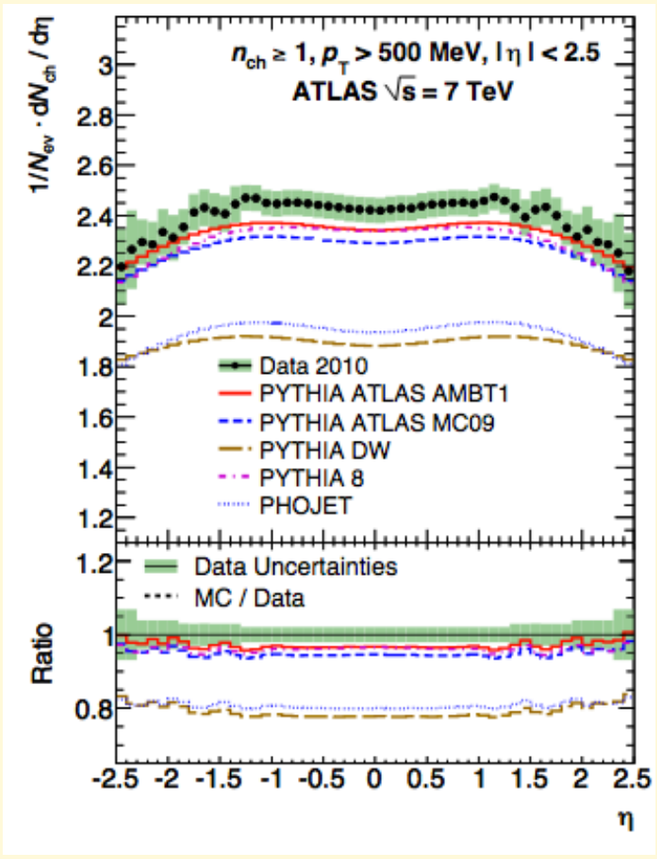
900 GeV

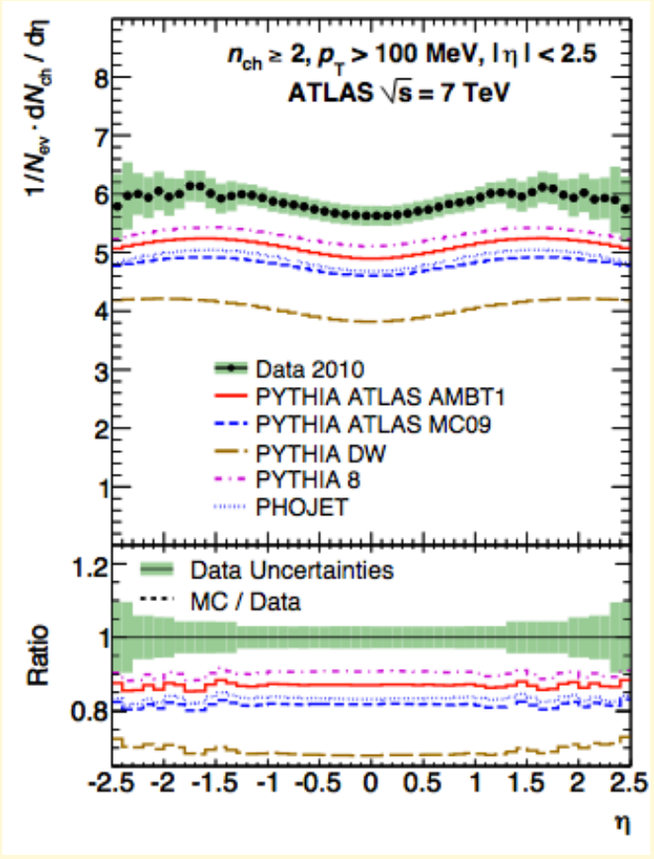


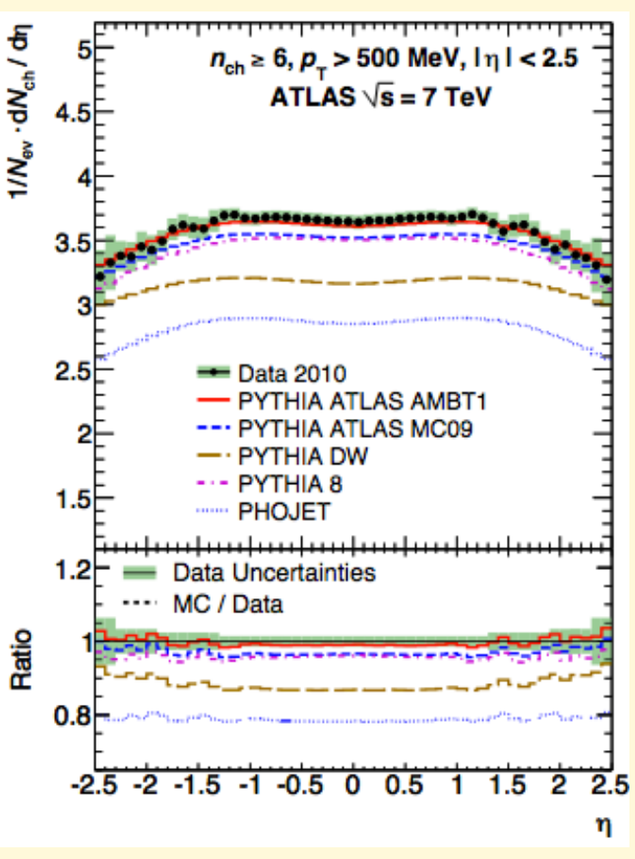




7 TeV



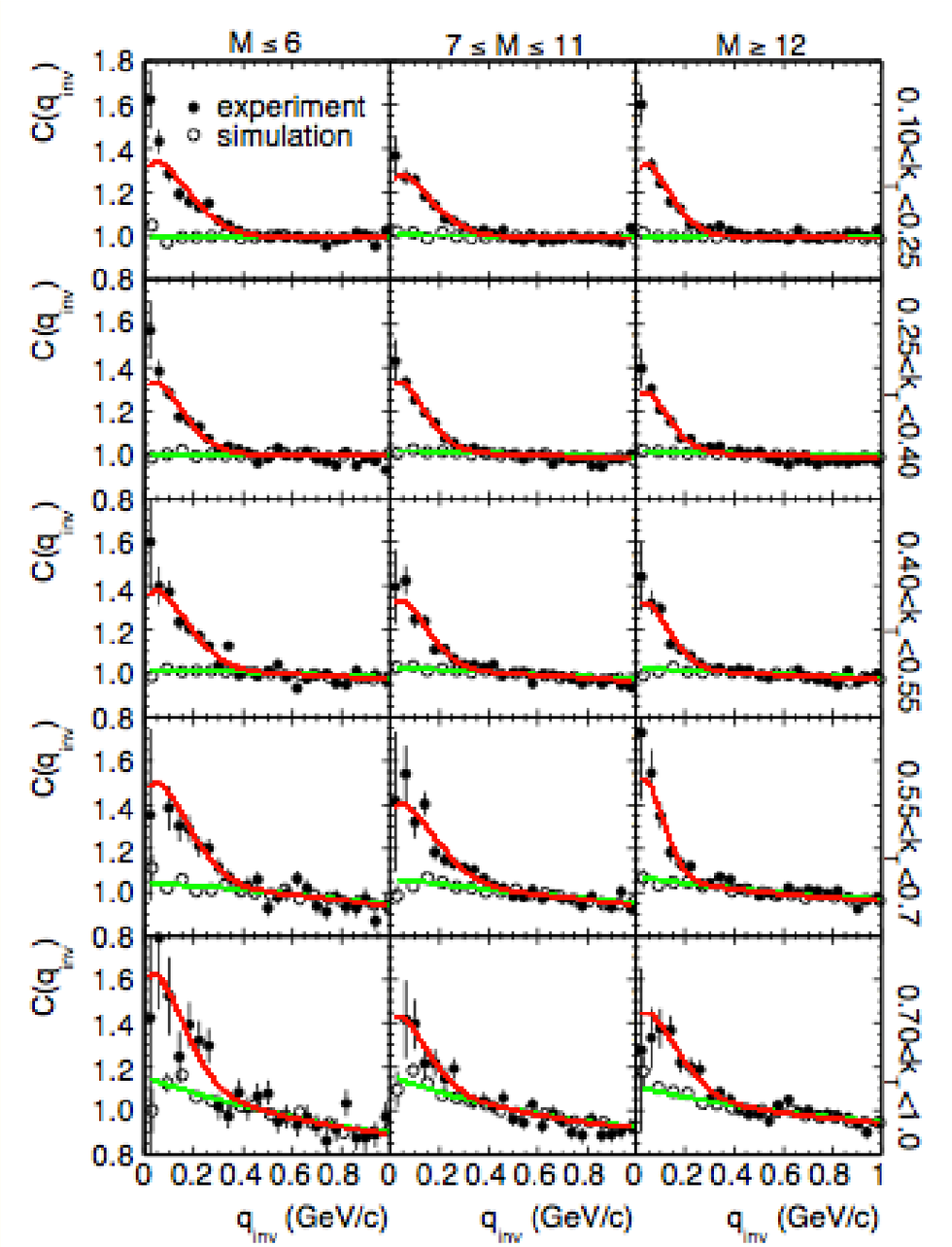




ATLAS, http://arxiv.org/abs/1012.5104

Bose-Einstein correlations

ALICE, from the 900 GeV run



$q_{inv} = |\mathbf{q_1} - \mathbf{q_2}|$ in rest frame

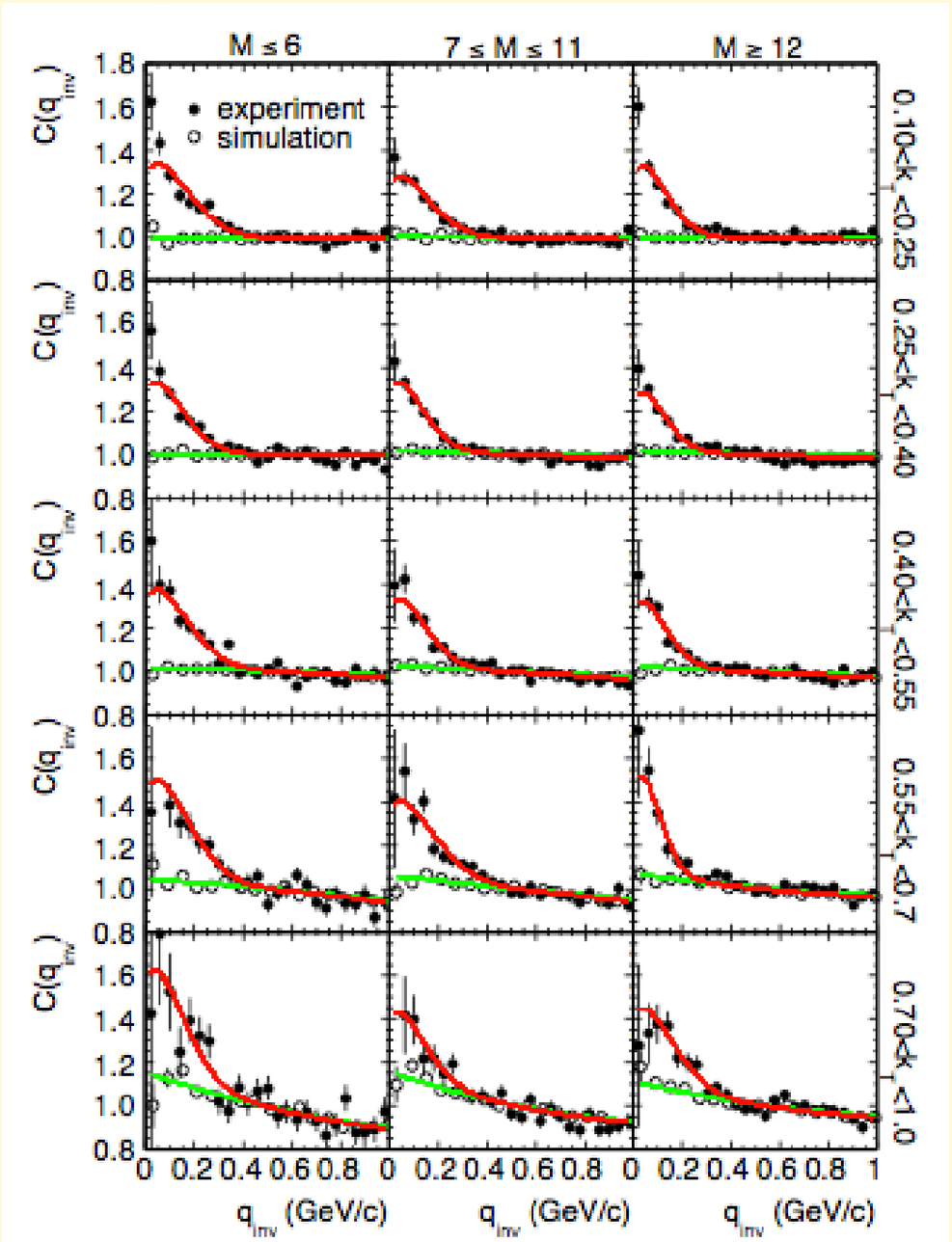
C(q)= A(q)/B(q), where:

A(q)=$\pi^{\pm}\pi^{\pm}$ correlation function

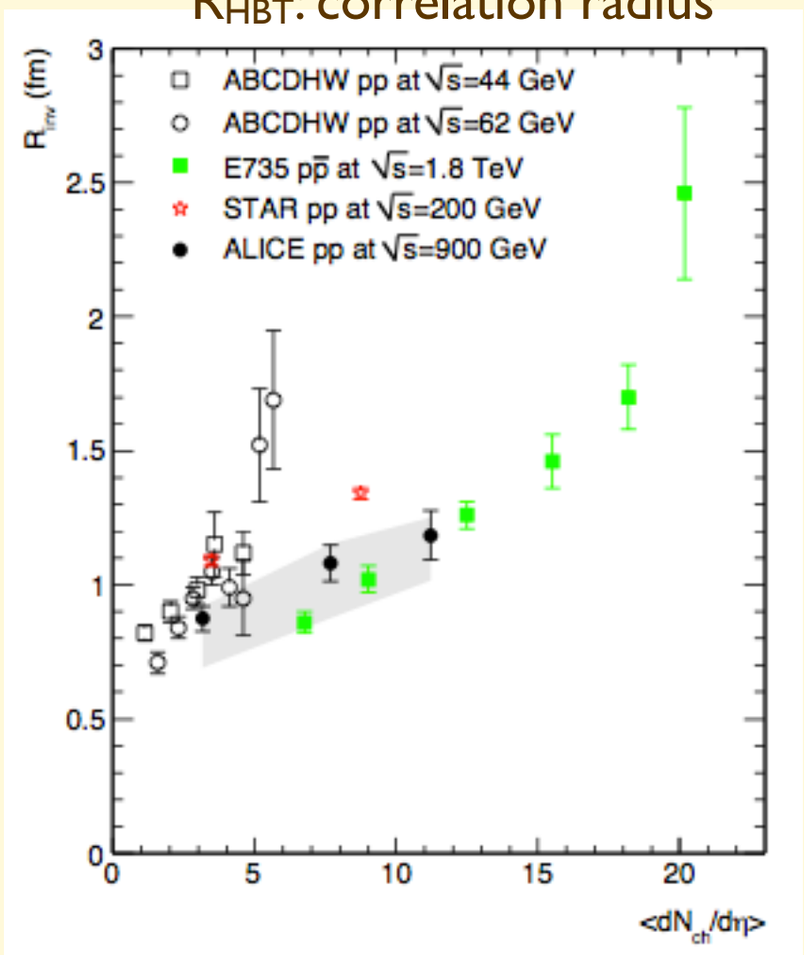
B(q)=$\pi^{\pm}\pi^{\pm}$ c.f., with particles from different events

Bose-Einstein correlations

ALICE, from the 900 GeV run



R_{HBT}: correlation radius



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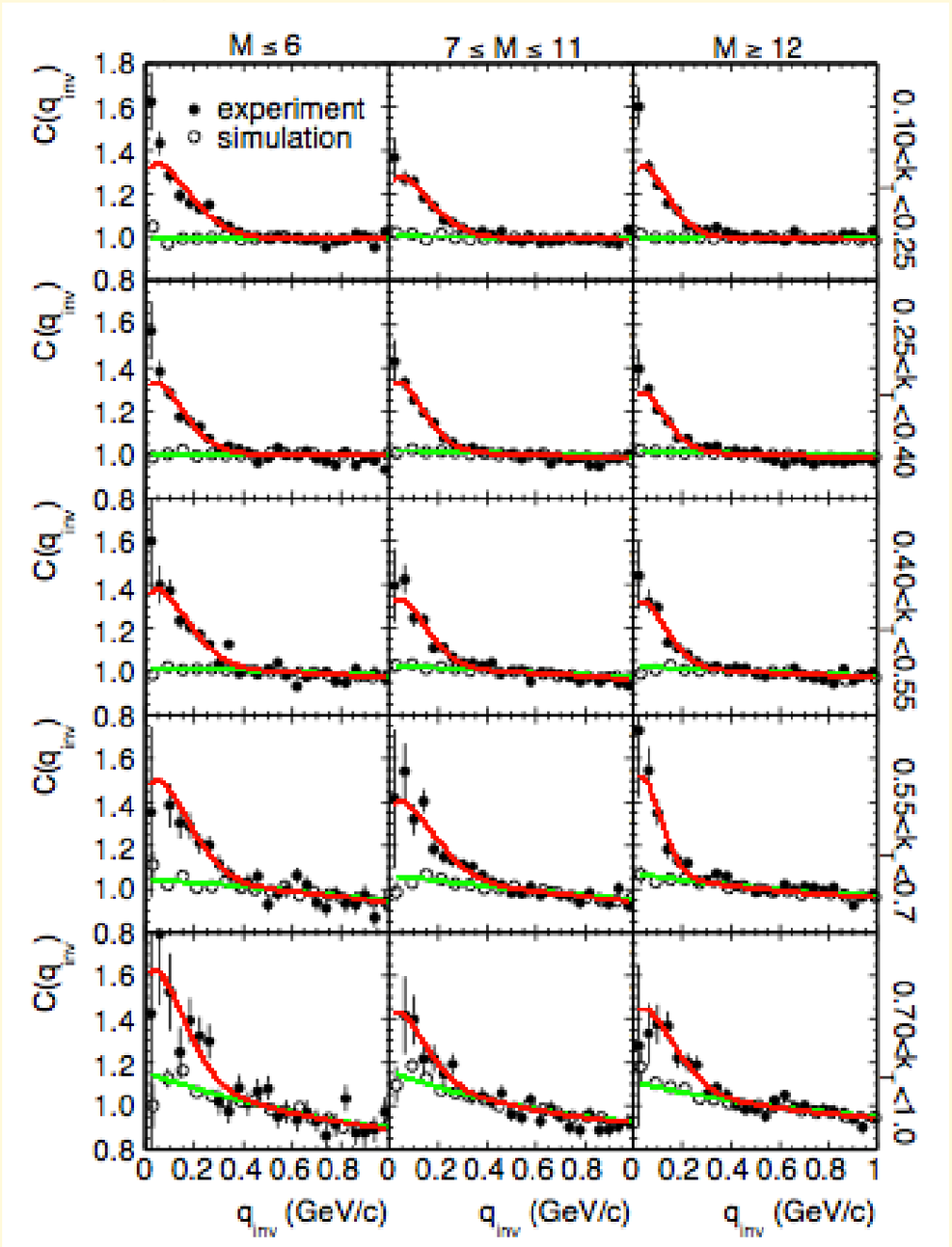

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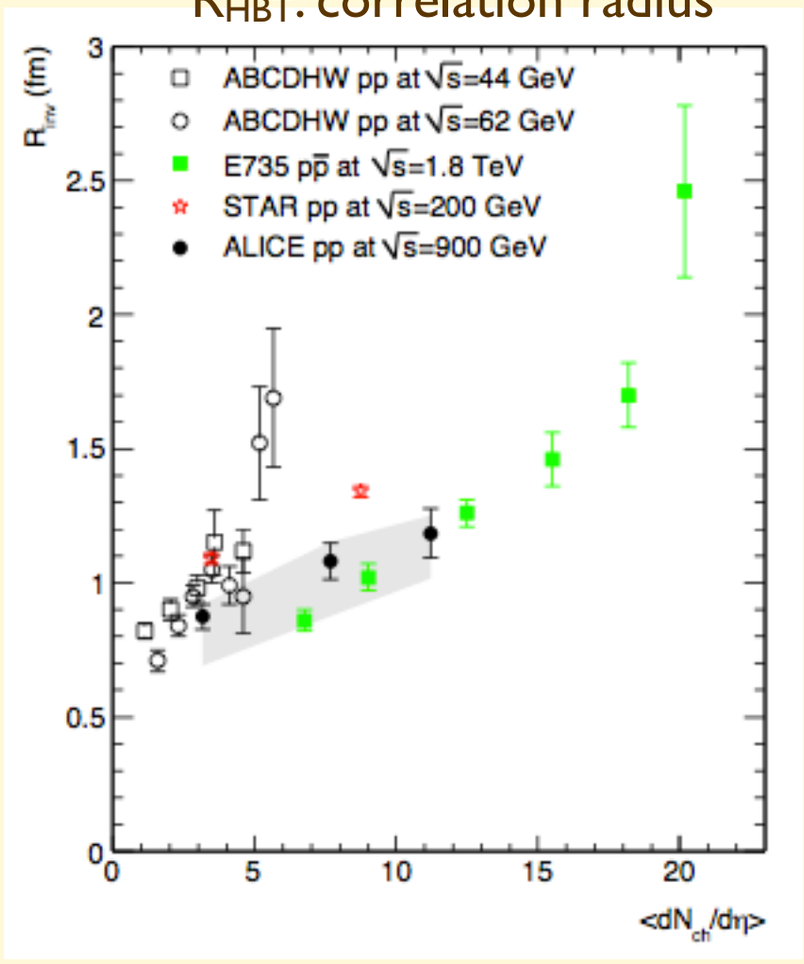
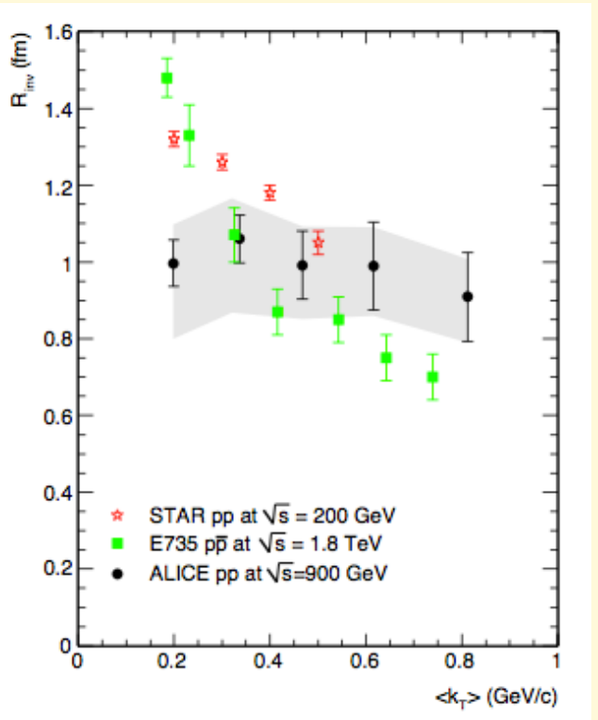
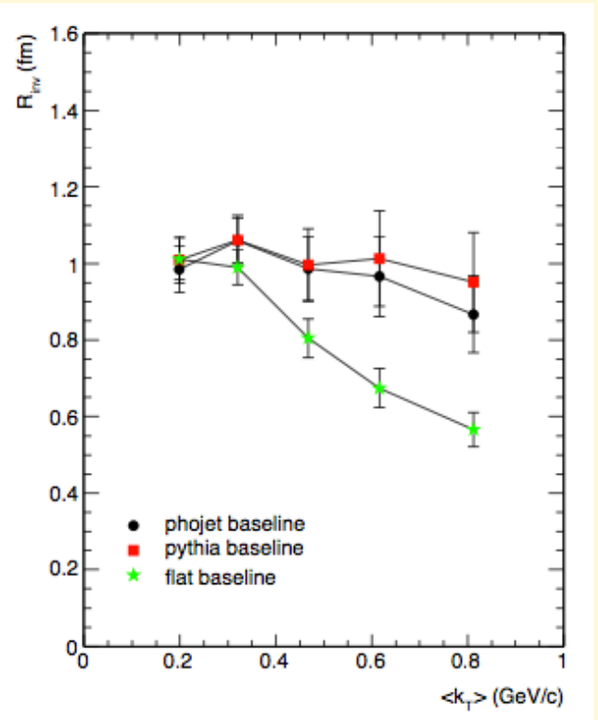
R_{HBT}: correlation radius

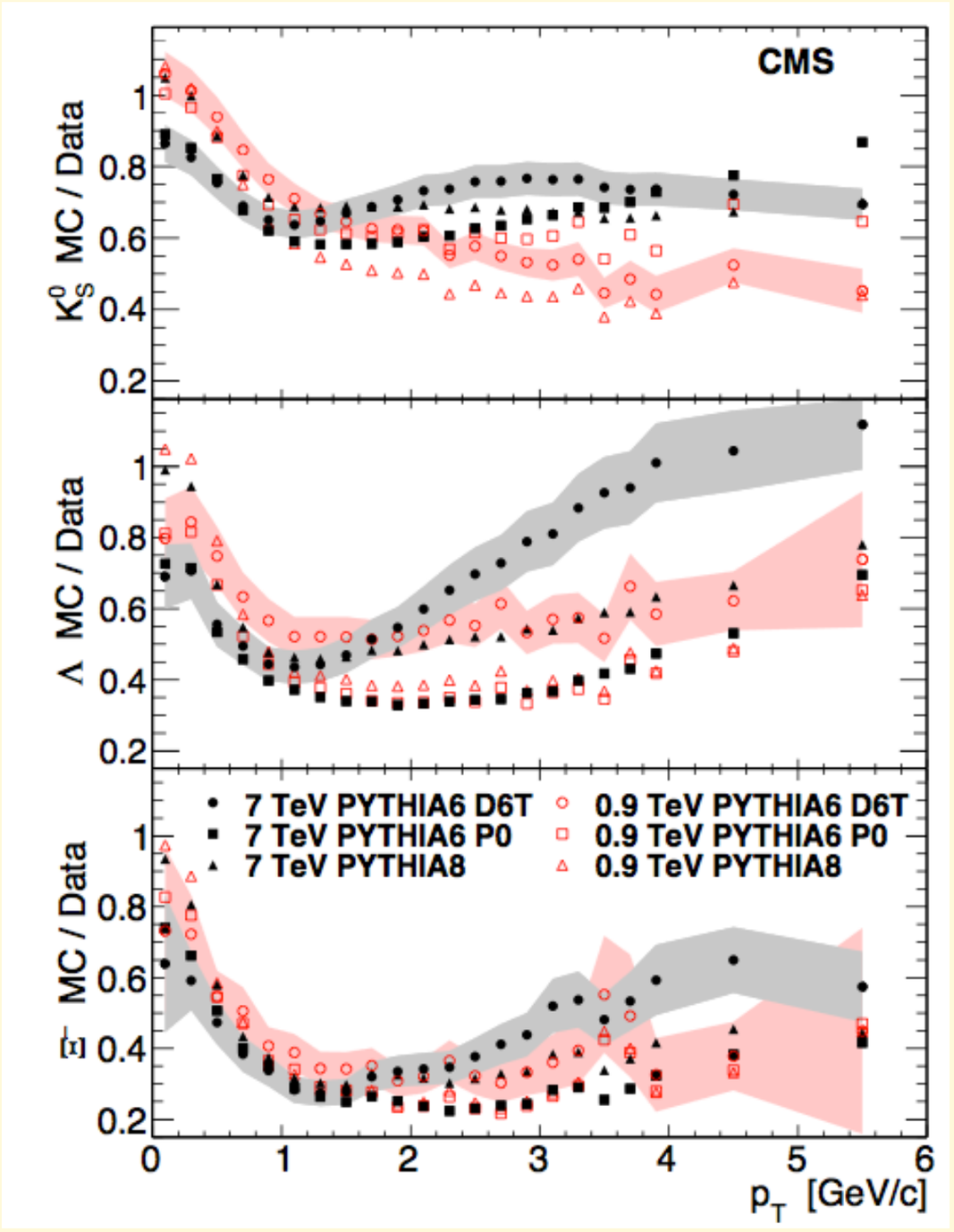


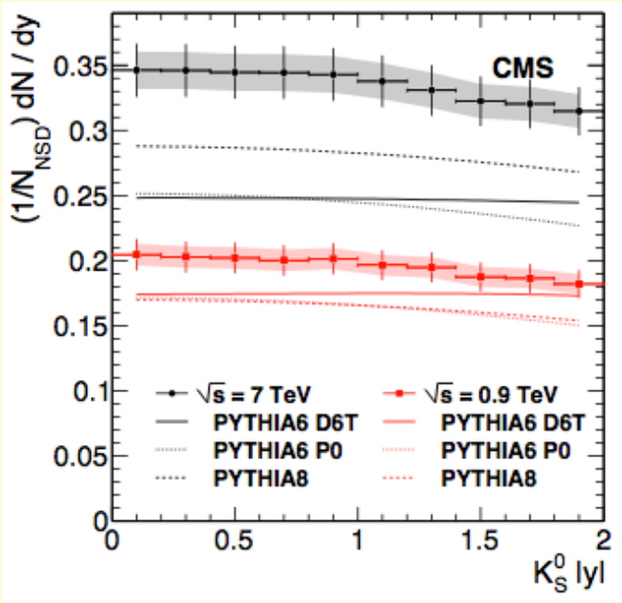


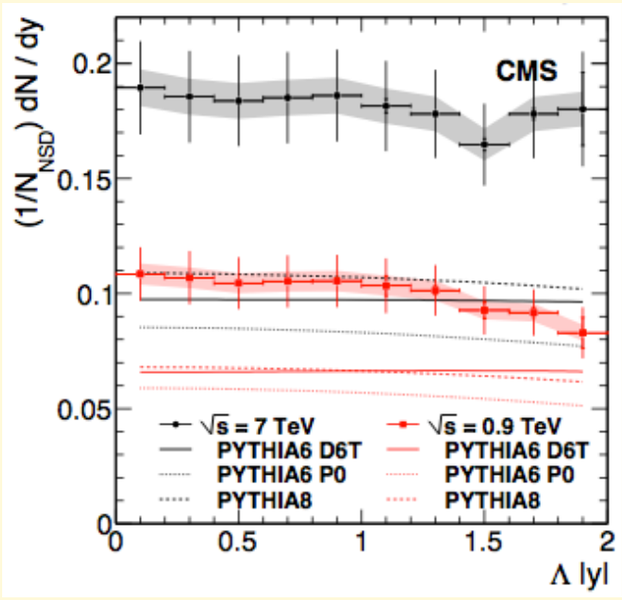


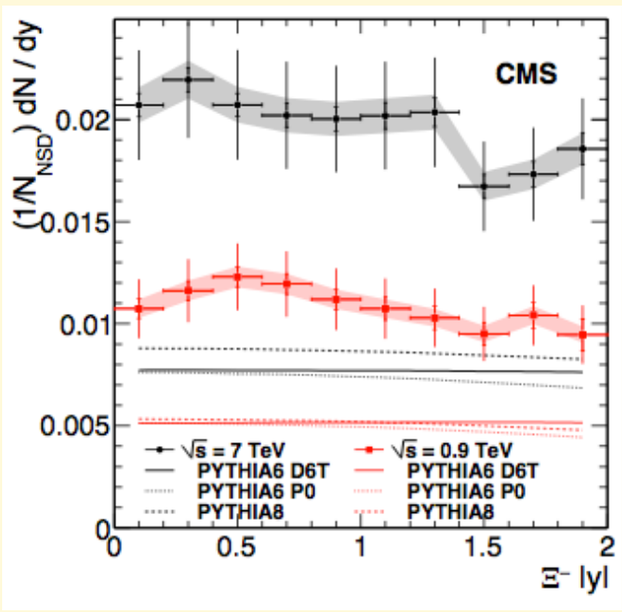
Strange particle production

CMS, CERN-PH-EP-2010-094 ; CMS-QCD-10-007-003





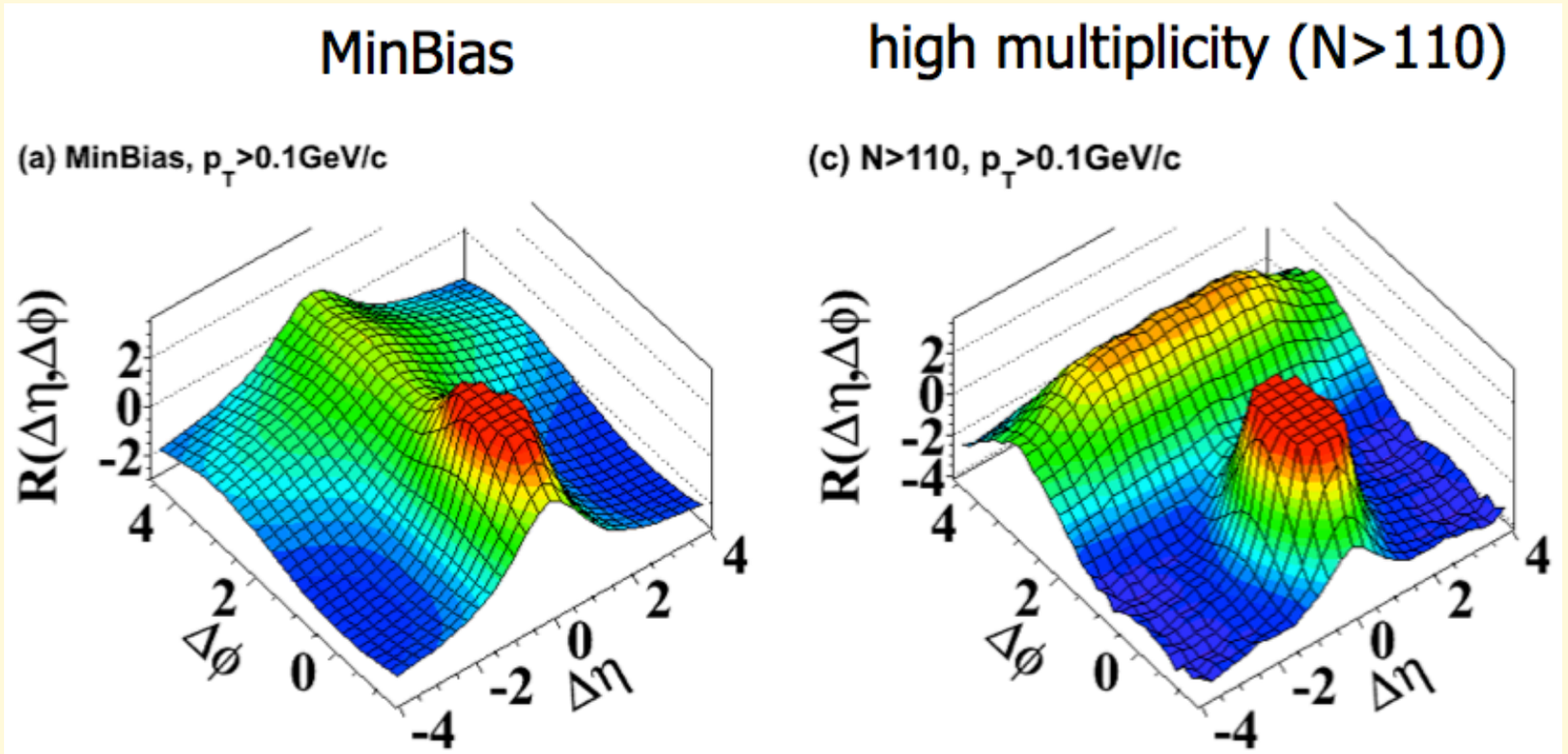


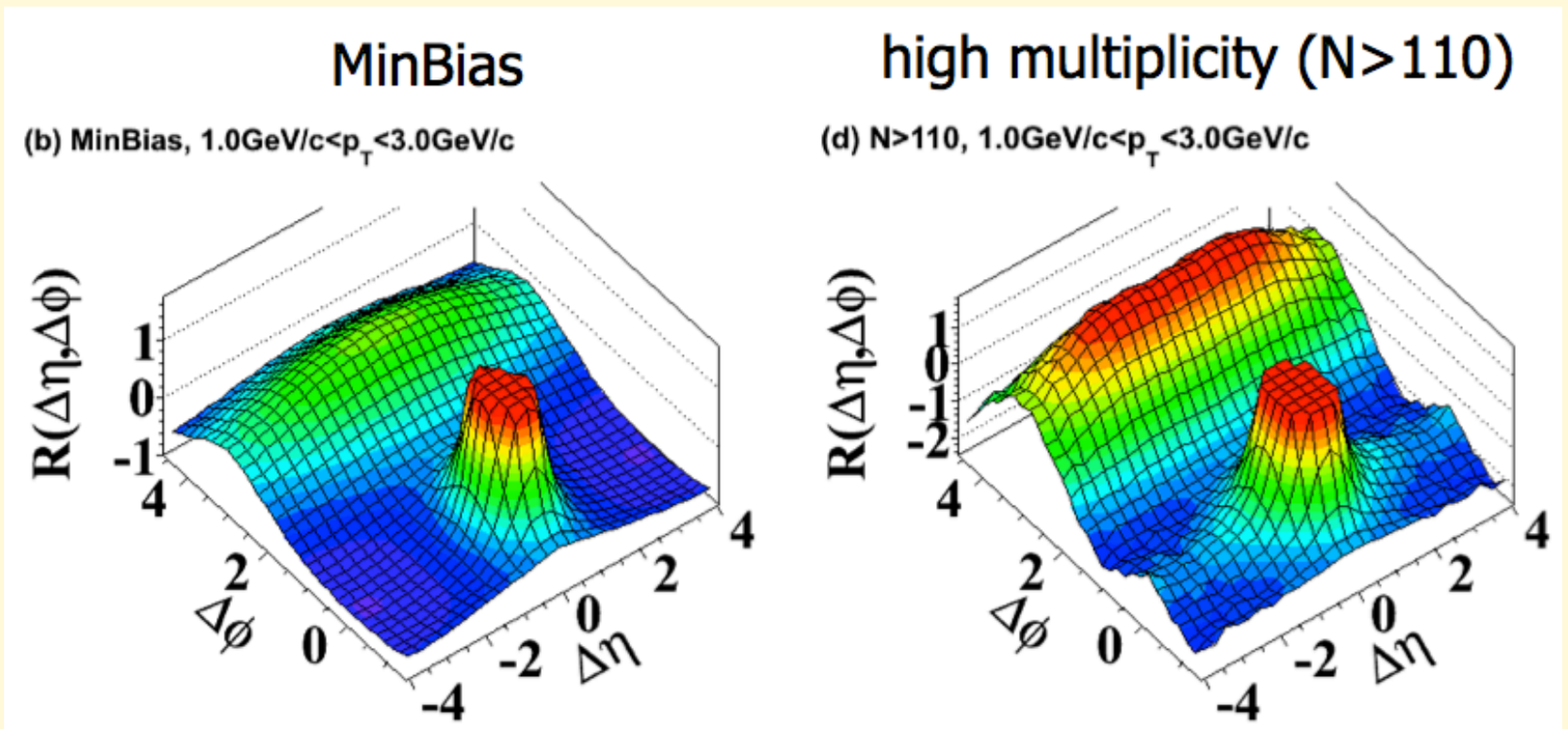


Very important benchmark for strangeness production studies in Pb-Pb, needs further clarification!

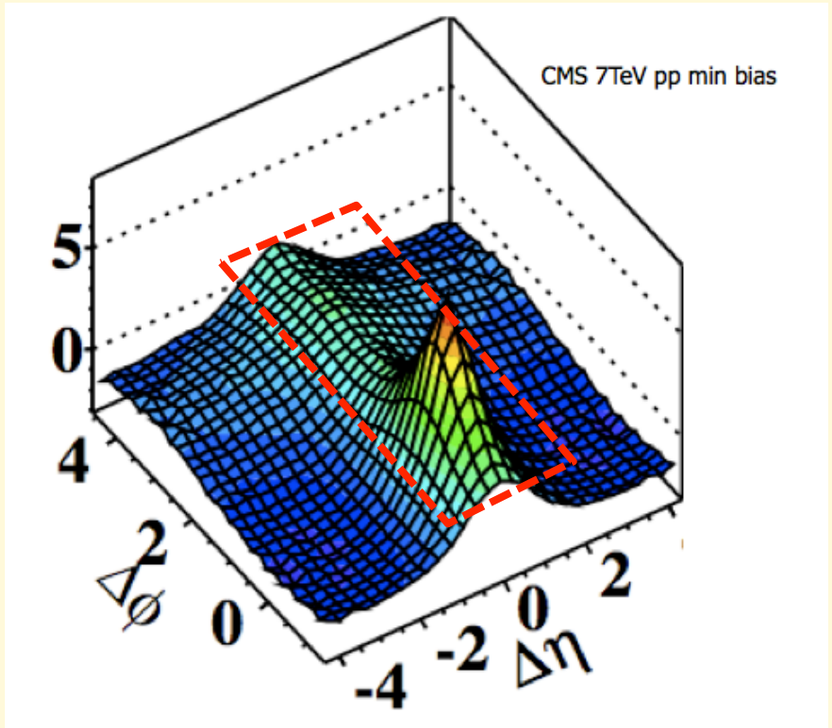
CMS's "ridge" in high-multiplicity events

2-particle correlation function $$S_N(\Delta\eta,\Delta\varphi) = \frac{1}{N(N-1)}\frac{d^2N^{signal}}{d\Delta\eta d\Delta\varphi}$$

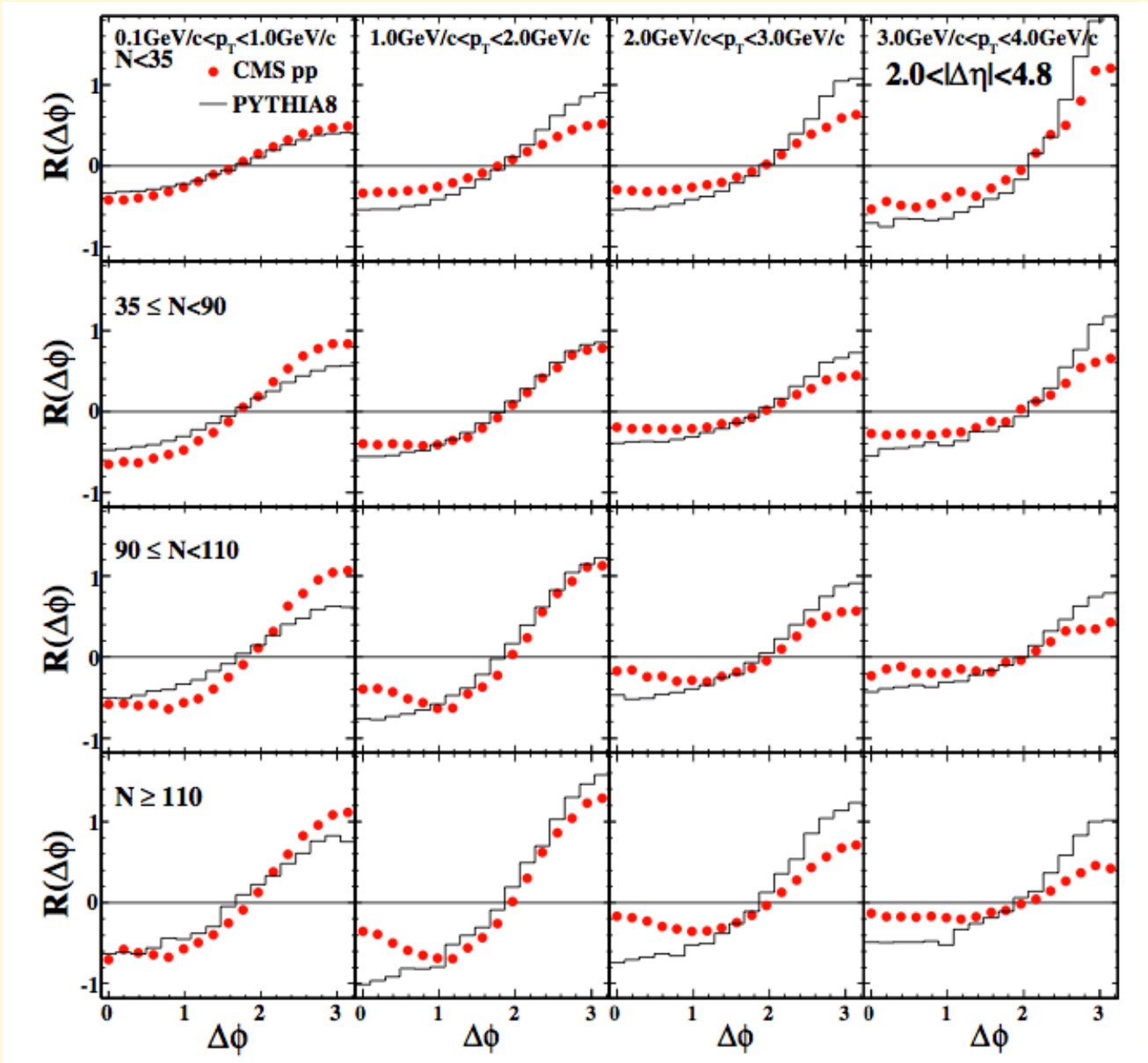




CMS's "ridge" in high-multiplicity events



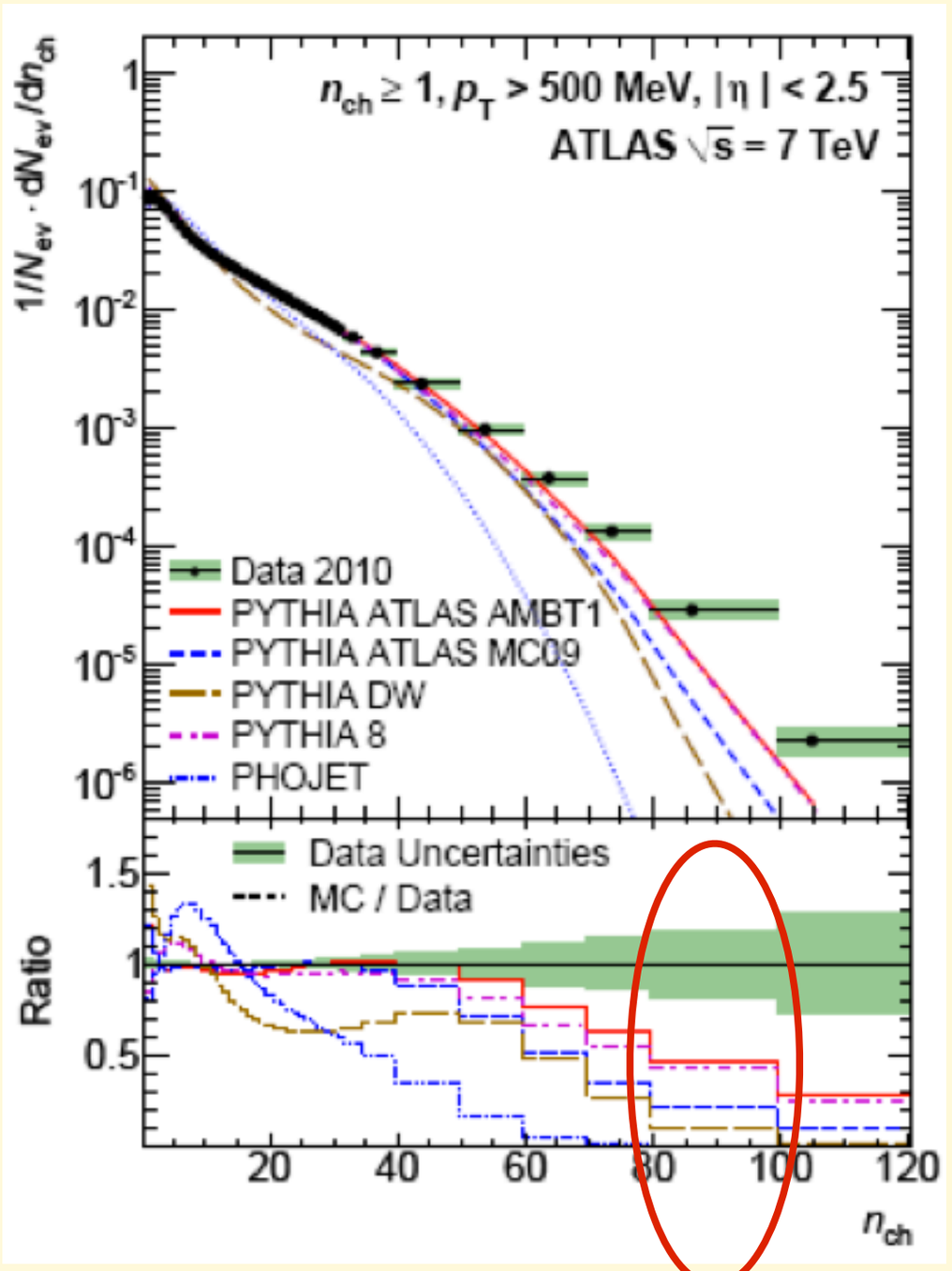
Integrating in eta, outside of the jet region:

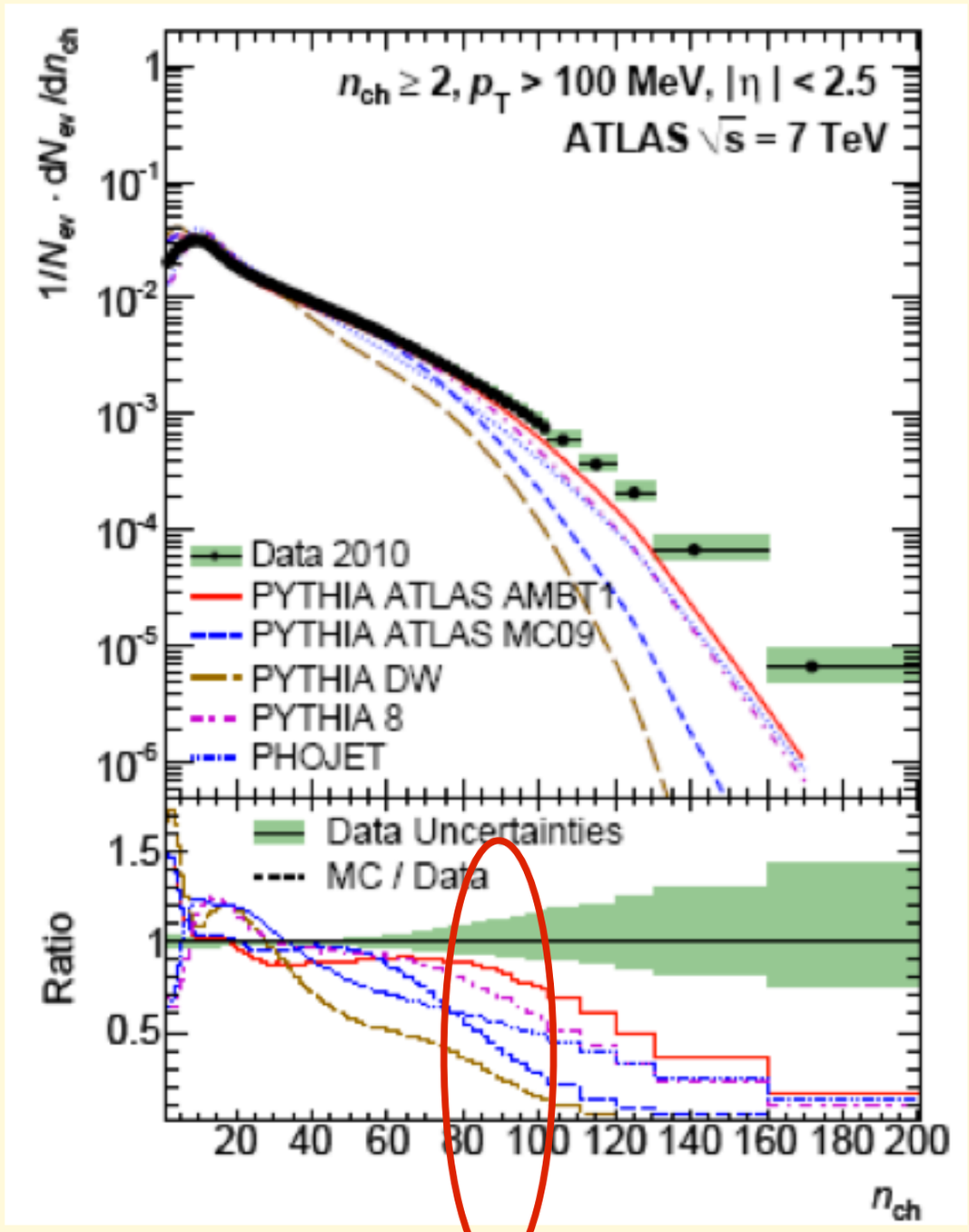


Many of us tried, but failed to explain this observation using pQCD (we thought it was a colour coherence effect, which only full matrix-element calculations can describe accurately)

More on large multiplicity final states

ATLAS, http://arxiv.org/pdf/1012.5104v2





Need a detailed characterization of the structure of large-multiplicity final states:
- are they dominated by 2-jets back to back?
- are they dominated by many soft jets (e.g. multiple semi-hard collisions)
- do they look "fireball"-like (spherically symmetric)?

More on large multiplicity final states

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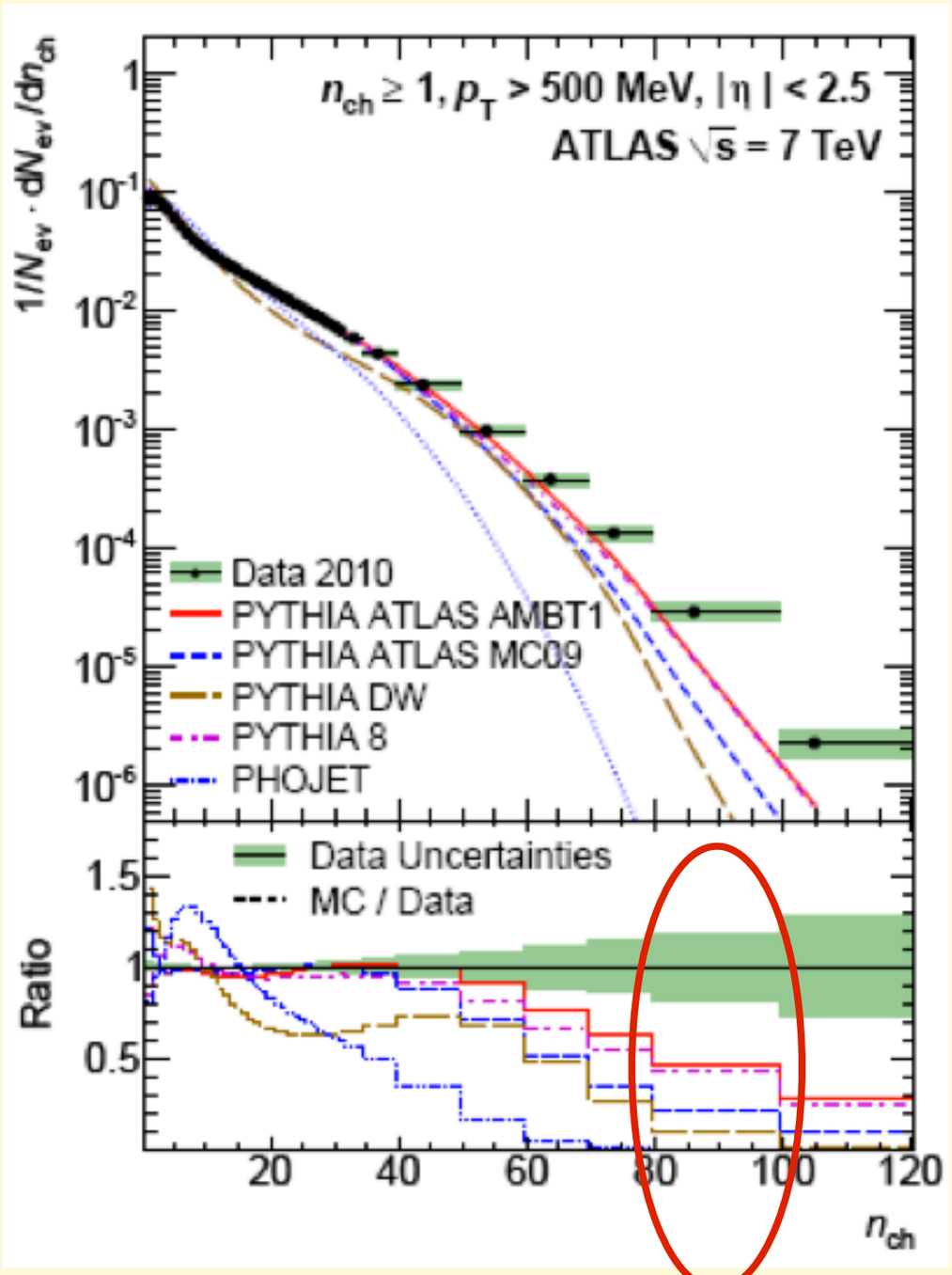

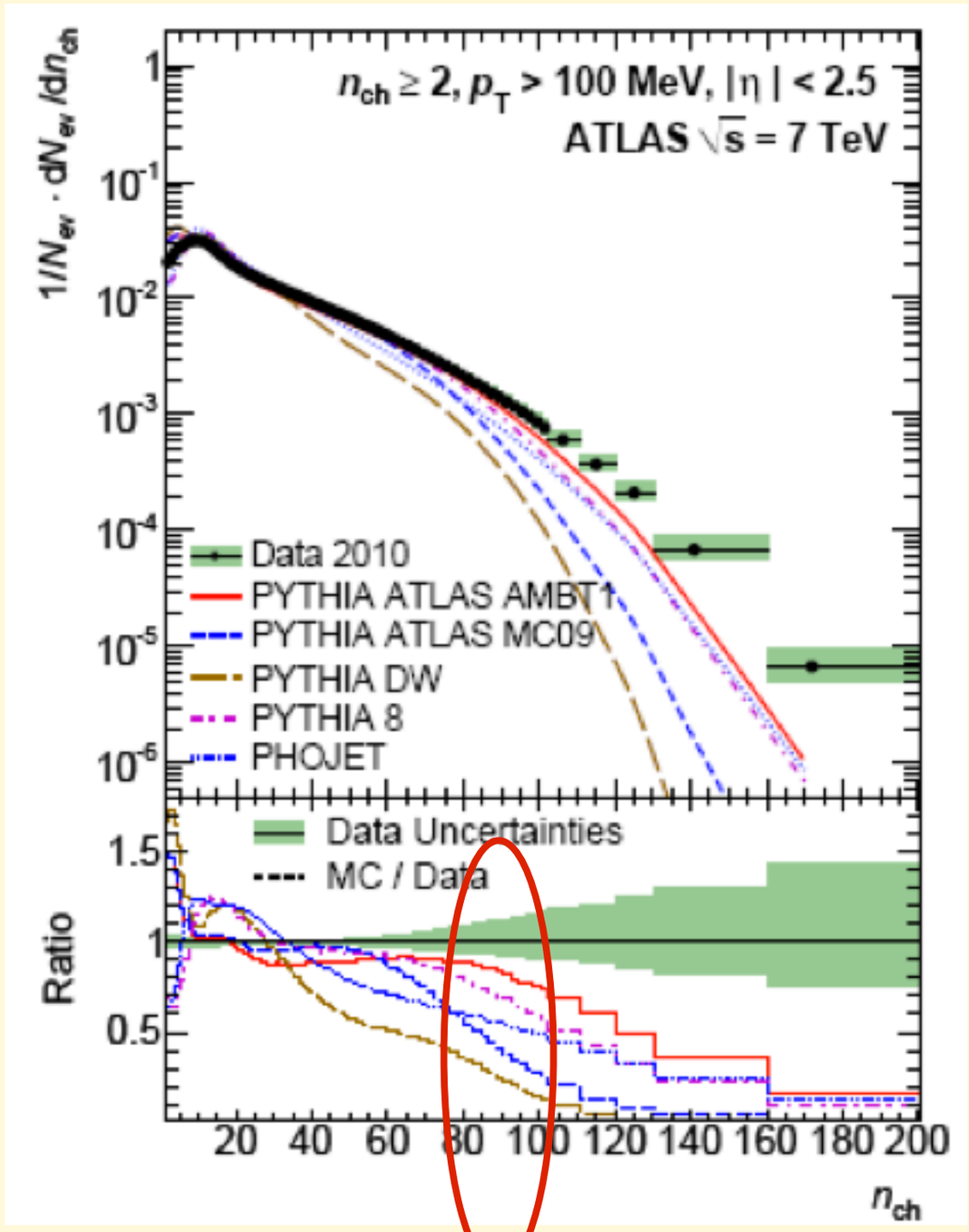

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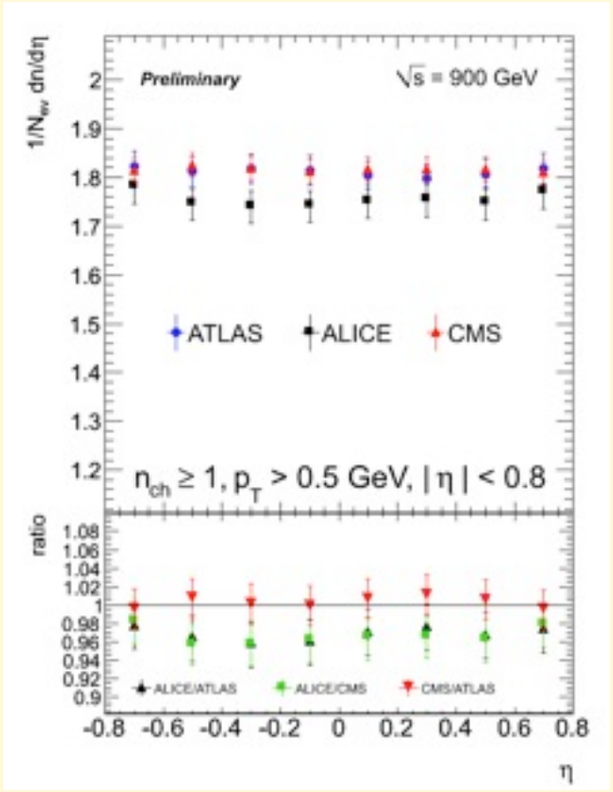
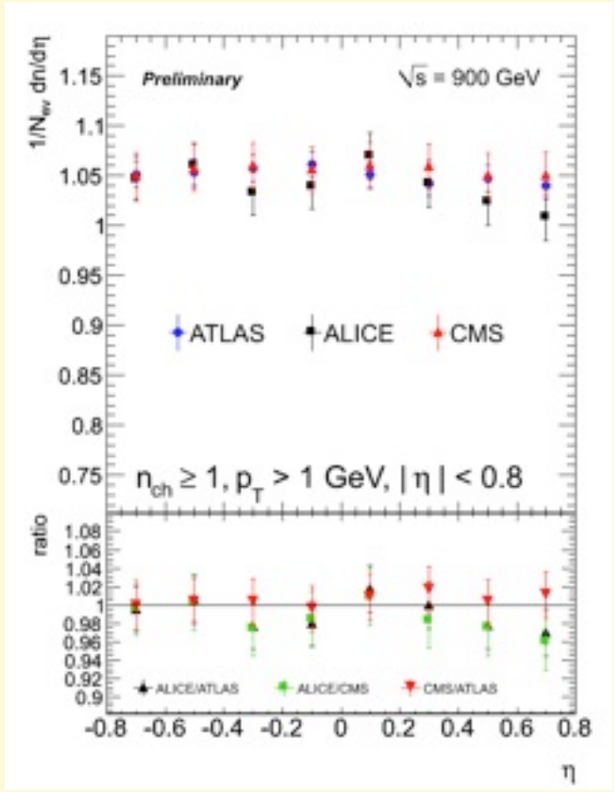
- are they dominated by 2-jets back to back?
- are they dominated by many soft jets (e.g. multiple semi-hard collisions)
- do they look "fireball"-like (spherically symmetric)?

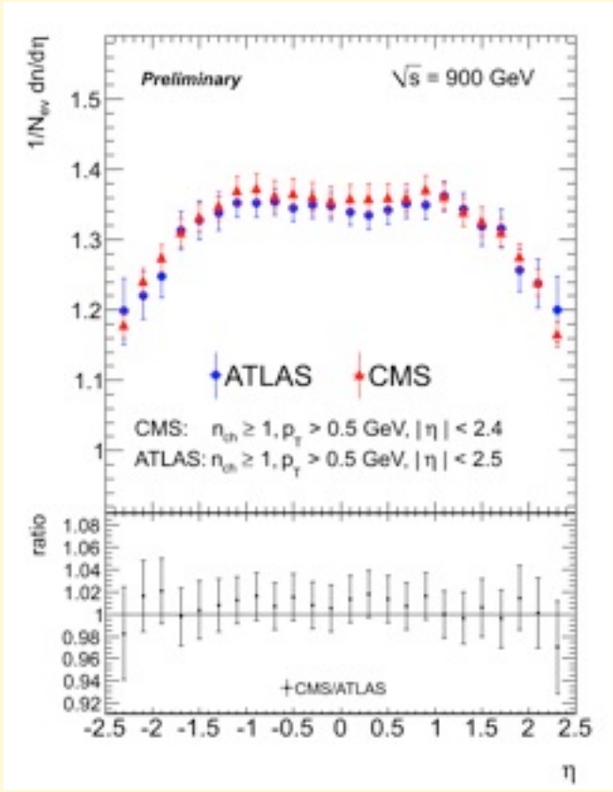
Are we staring at something *fundamental*, or is this just QCD chemistry?

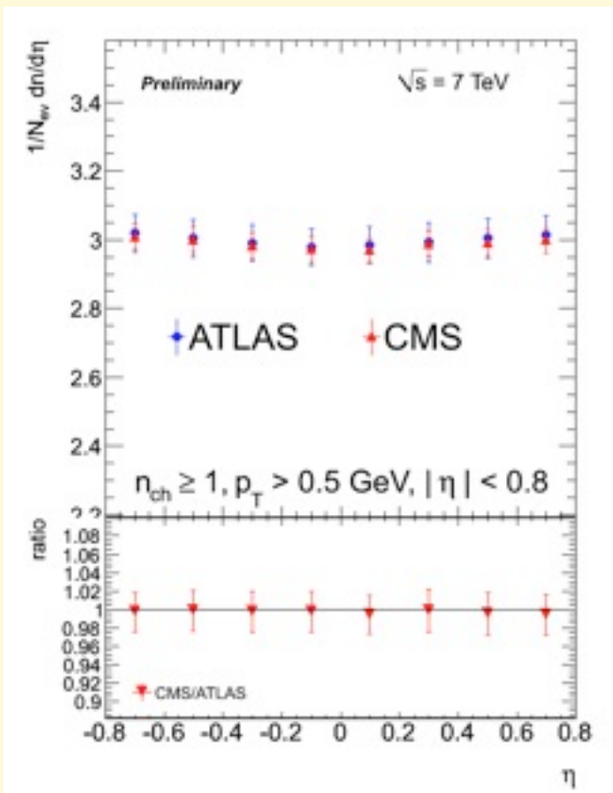
The "minimum bias common plots": the first example of comparison/ combination of the results of several LHC experiments

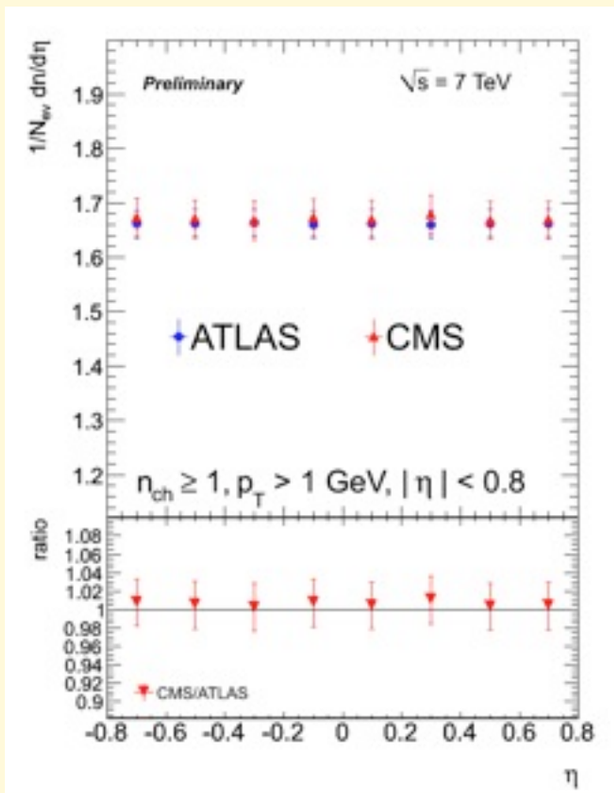
LHC working group on Minimum bias and underlying event

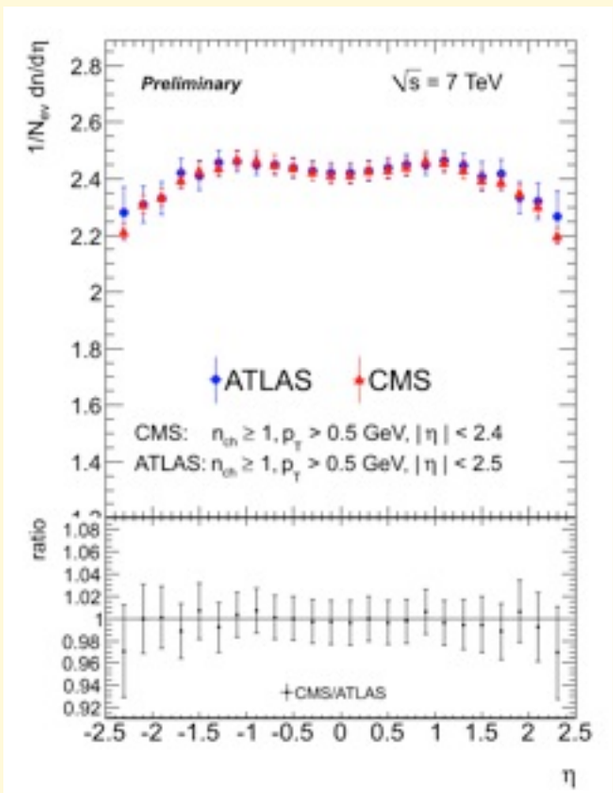










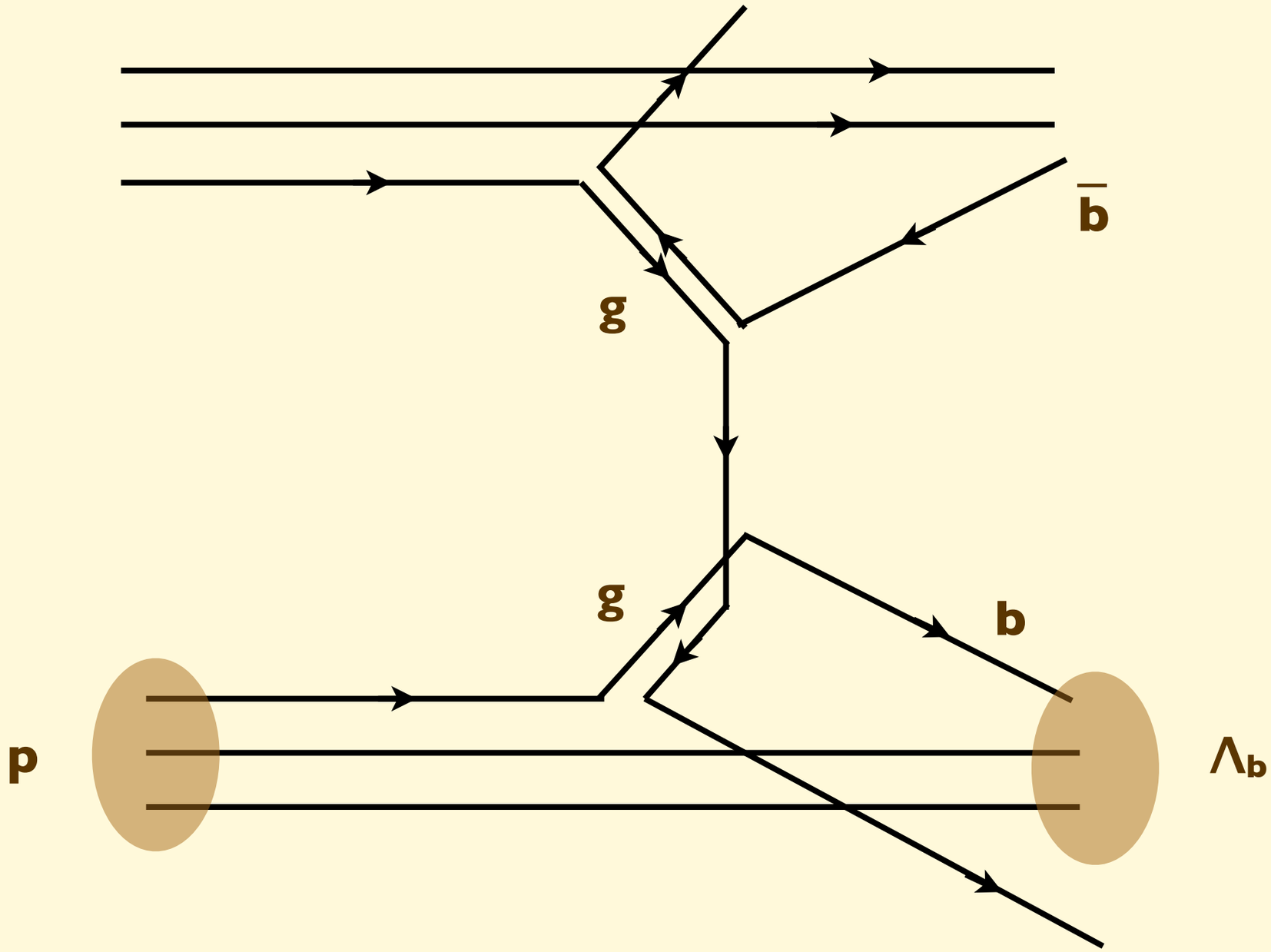


Other non-pQCD issues of relevance to pQCD physics

$b \to H_b$ fragmentation fractions:

Species	Z^o fraction (%)	Tevatron fraction (%)
B^-	40.3±0.9	33.3±3.0
B^0	40.3±0.9	33.3±3.0
B_s	10.4±0.9	12.1±1.5
Λ_b	9.1±1.5	21.4±6.8

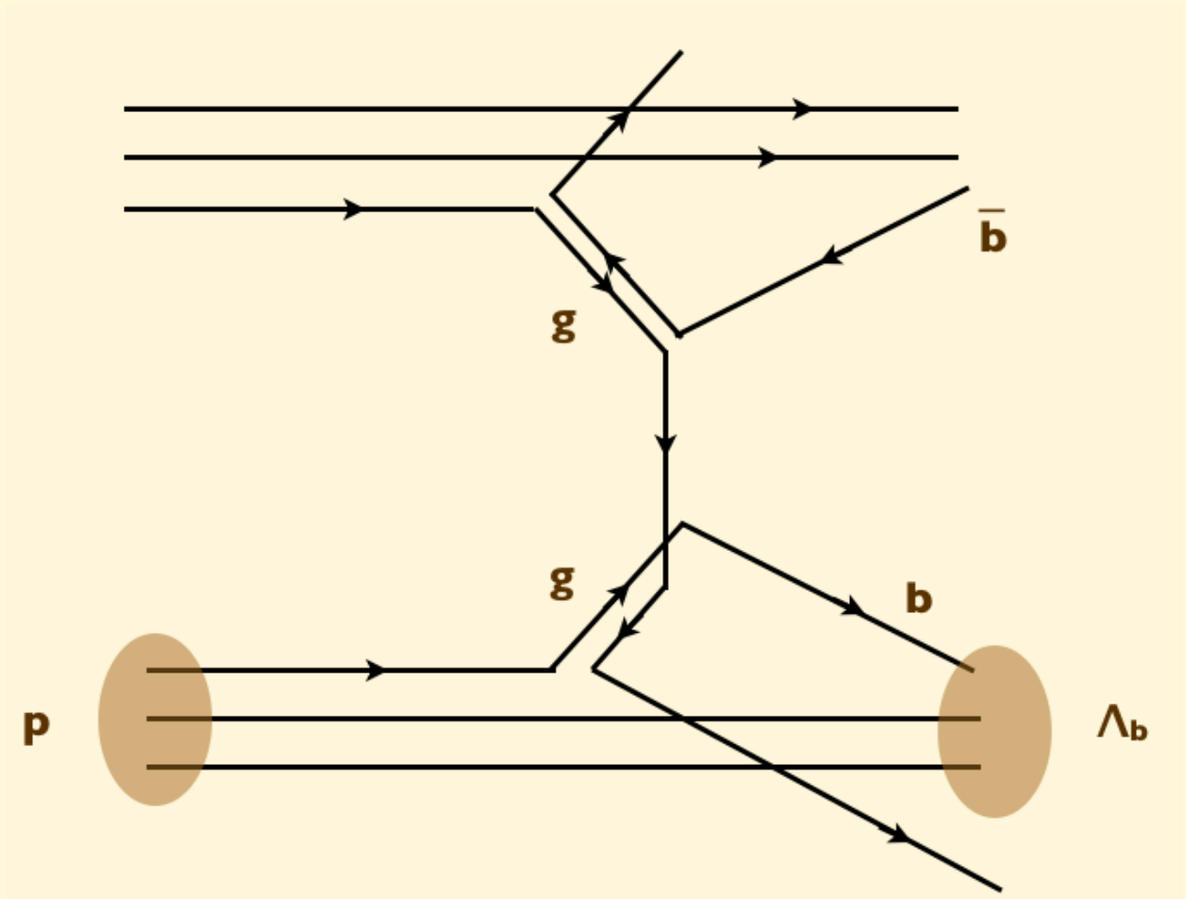
- **Needs clarification!**
- **To the least it points to — not unexpected — deviations from factorization**
- **In view of the CP non-invariance of the initial state, and of the forward kinematics of LHCb, each individual fraction will have to be measured very accurately**



$gg \rightarrow \overline{b}\,\Lambda_b$

$gg \not\rightarrow b\,\overline{\Lambda}_b$

Example



$$gg \rightarrow \overline{b}\,\Lambda_b$$

$$gg \not\rightarrow b\,\overline{\Lambda}_b$$

$$\frac{N(B^0)}{N(\bar{B}^0)} = \frac{1 - f(b \rightarrow \Lambda_b)}{1 - f(\bar{b} \rightarrow \bar{\Lambda}_b)}$$

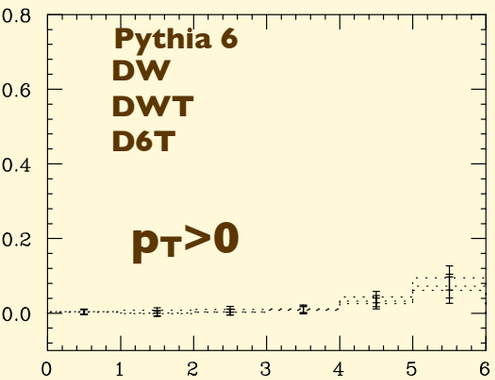
$$A(y) = \frac{dN(\Lambda_b)/dy - dN(\bar{\Lambda}_b)/dy}{dN(\Lambda_b)/dy + dN(\bar{\Lambda}_b)/dy}$$

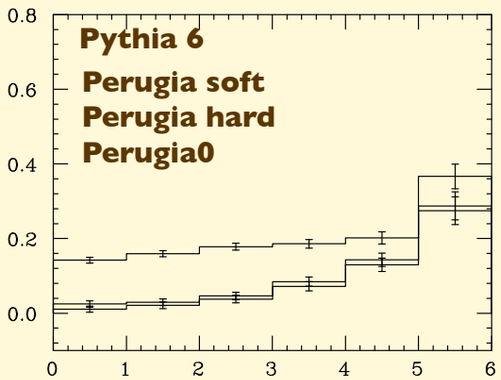
If A(y)≠0 ⇒ N(B)≠N(Bbar) ⇒ apparent CP violation!

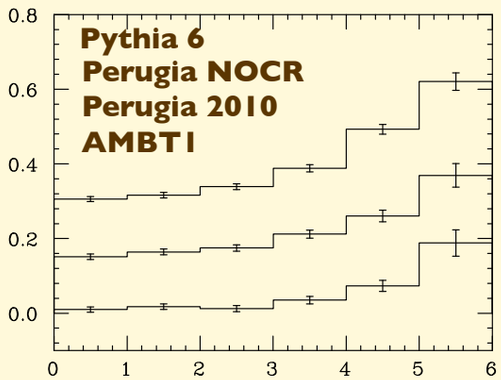
Modeling

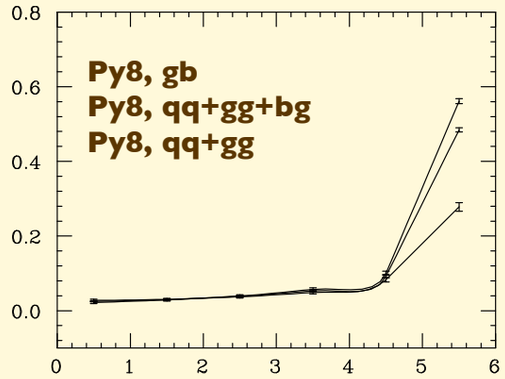
Thanks to P.Skands, T.Sjostrand, D.Grellsheid, J.Winter for providing these predictions

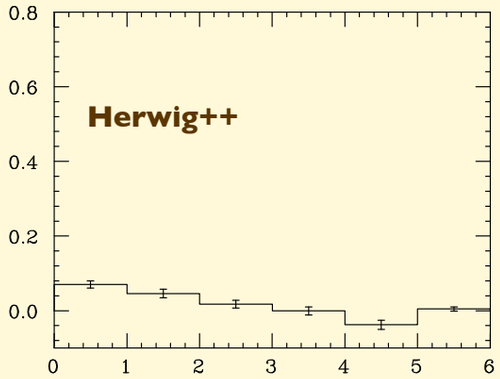
A(y) predictions from various MC codes and tunings:

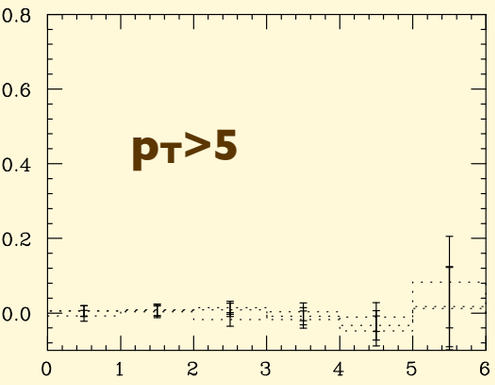


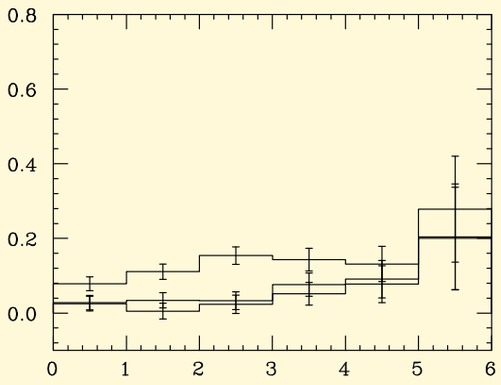


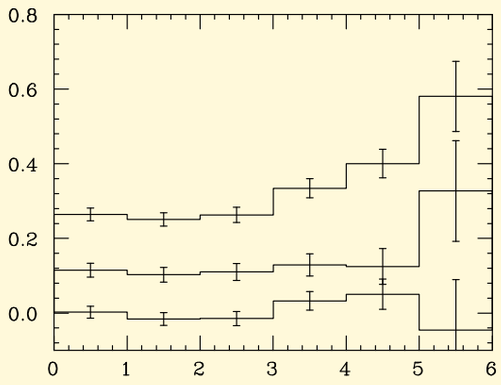


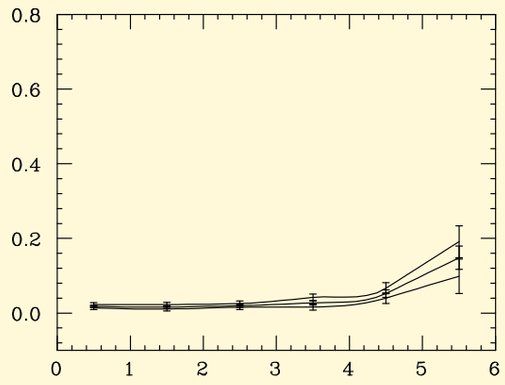


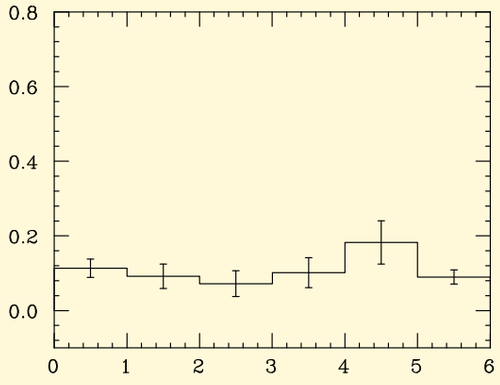




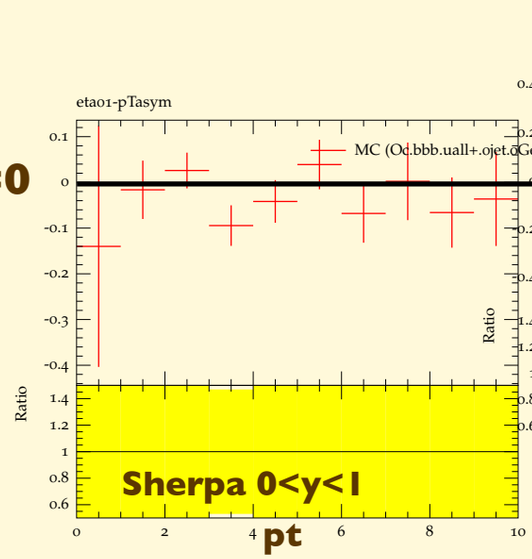


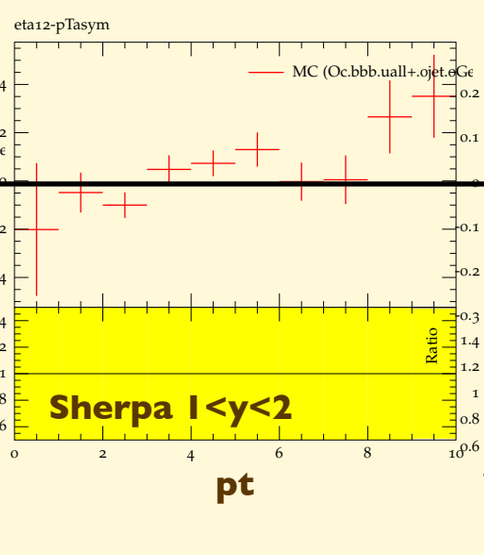


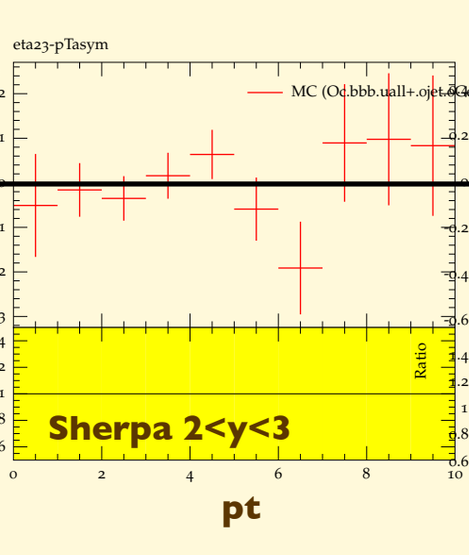


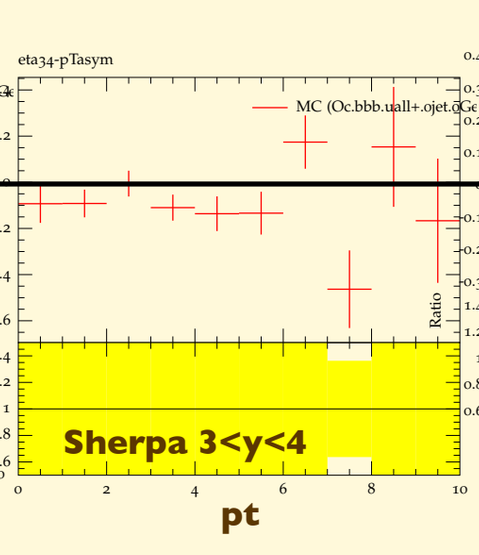


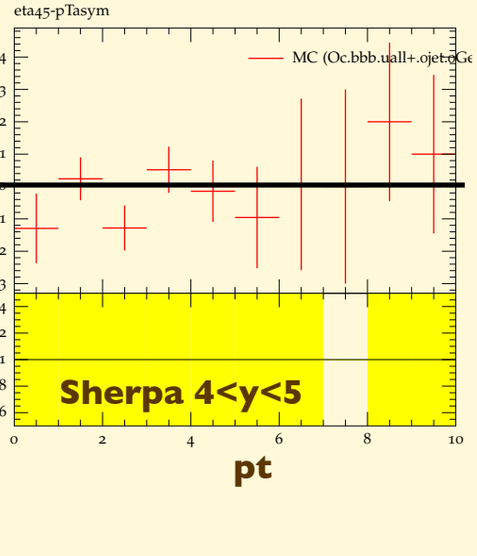
A=0











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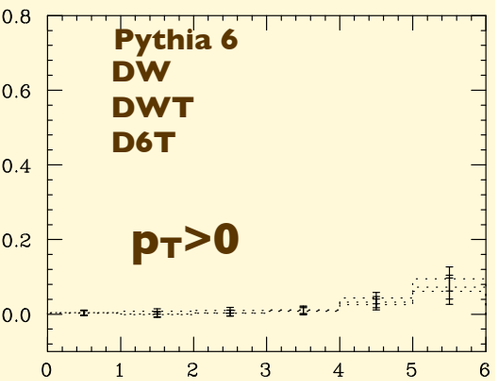
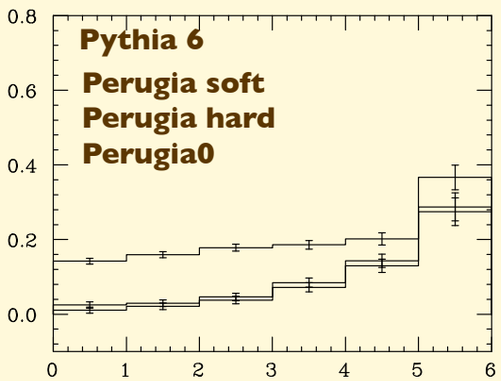
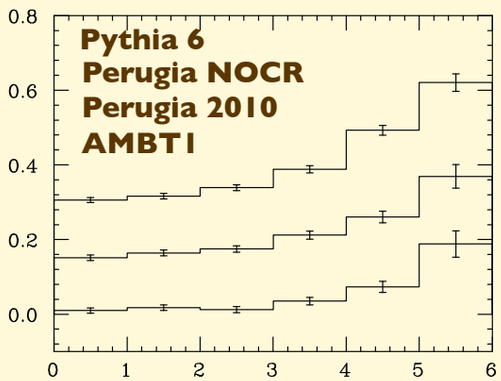
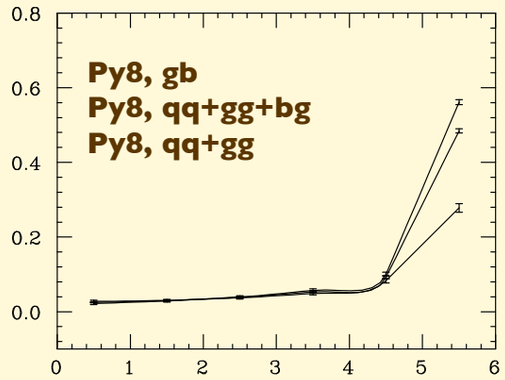
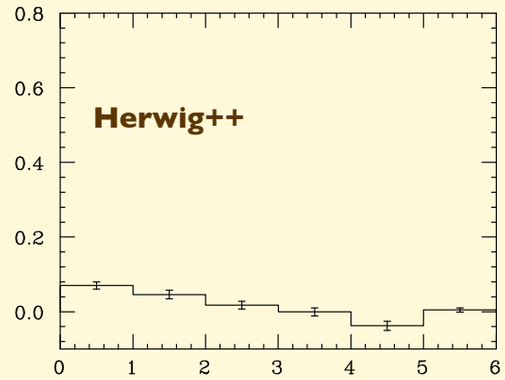
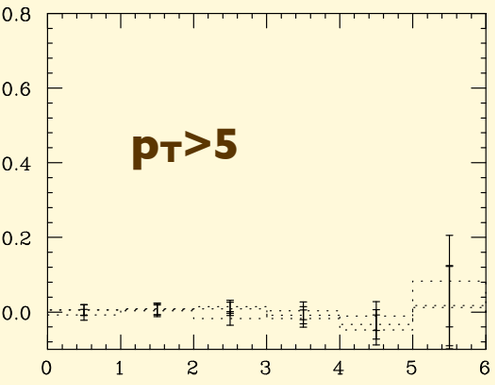


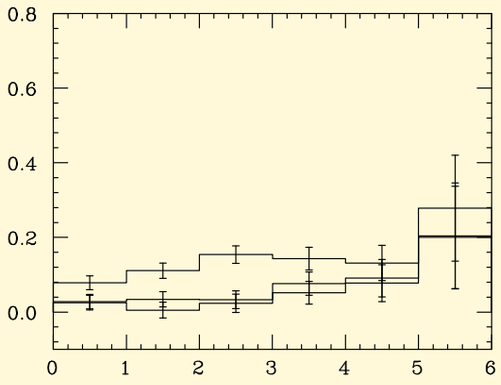


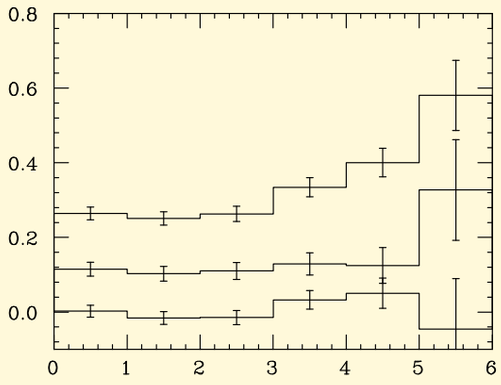


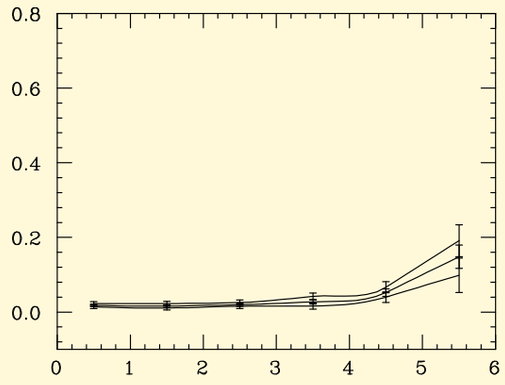


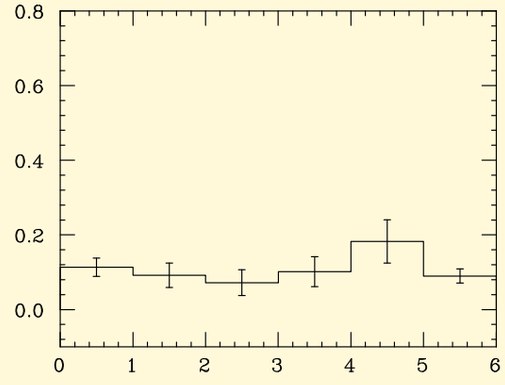










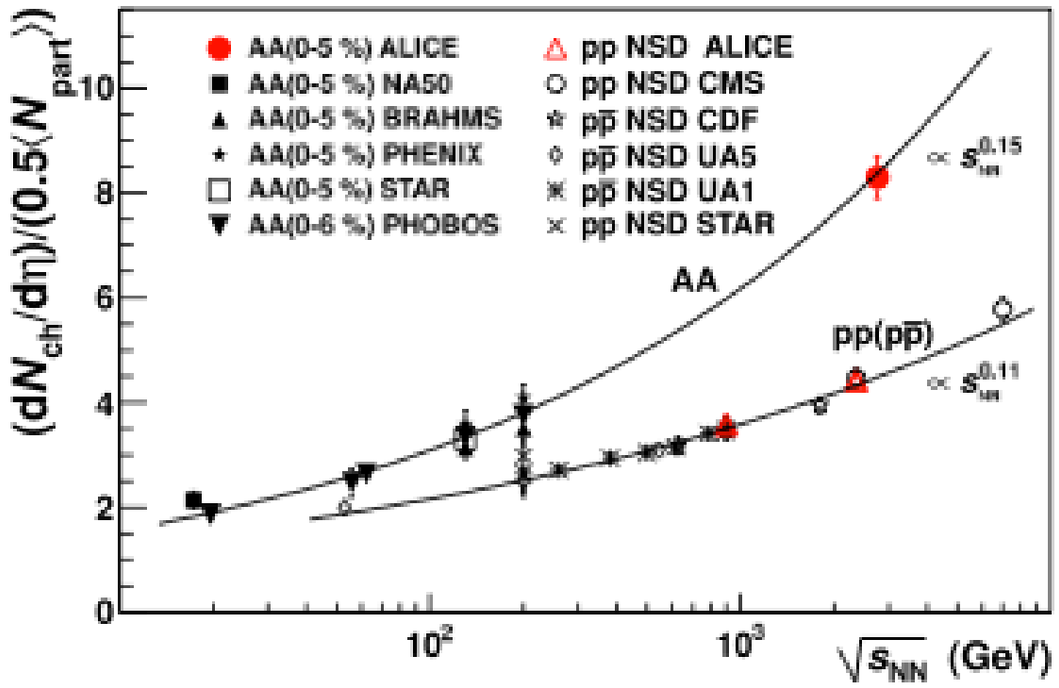


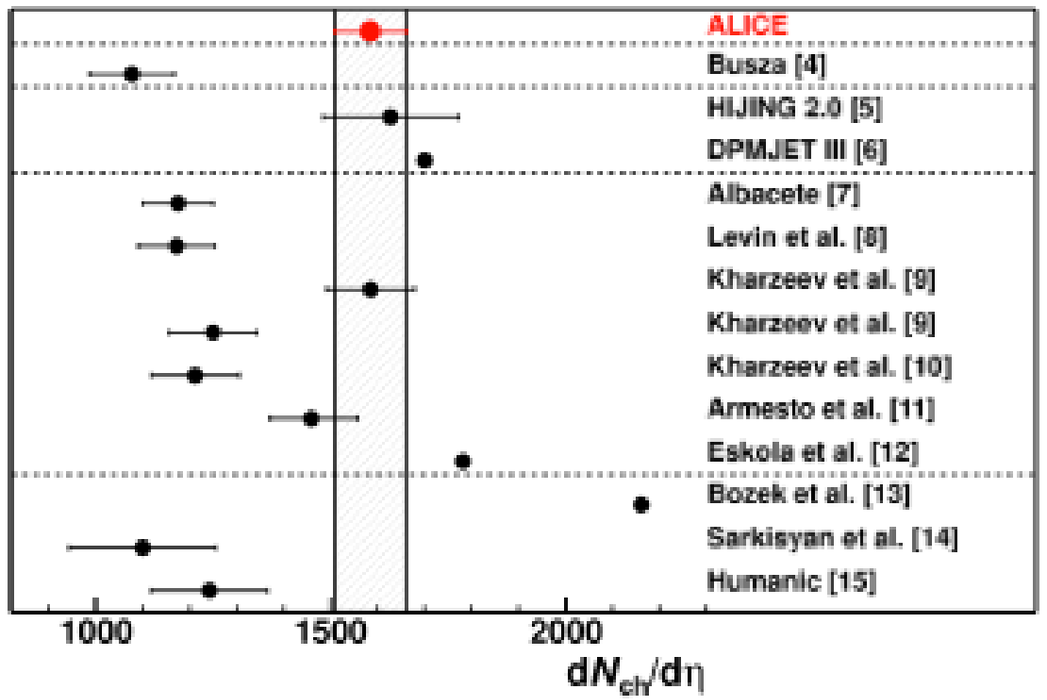
- **Very broad range of "predictions", no robust benchmark**
- **Strong dependence on modeling of perturbative part: more/less gluon radiation will reduce/increase the color-coupling of the b with the proton diquark fragment**
- **Expect correlation with the modeling of strange and charmed baryons**
- **Looking forward to LHCb data!**

A first look at Pb-Pb collisions

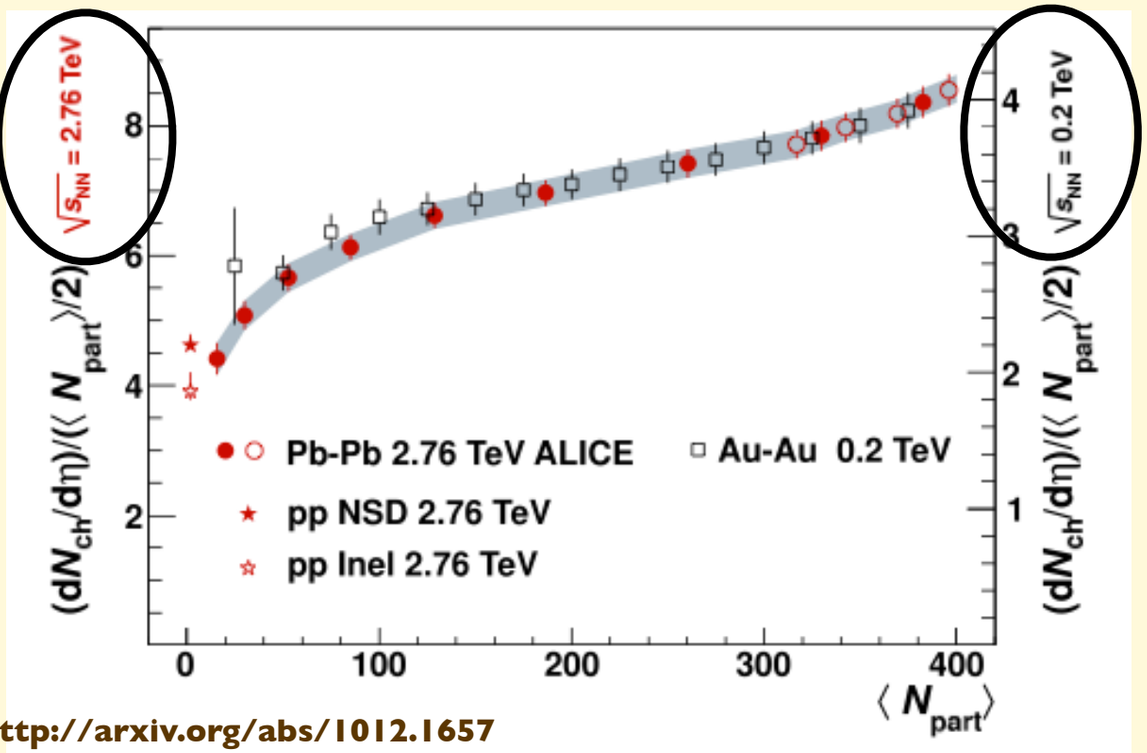
- $\sqrt{s_{NN}}$ = 2.76 TeV => 14 times larger than any previous heavy ion experiment (RHIC)

$dN_{ch}/d\eta$ (0-10% centrality) = 1584 ± 4 (stat.) ± 76 (sys.)

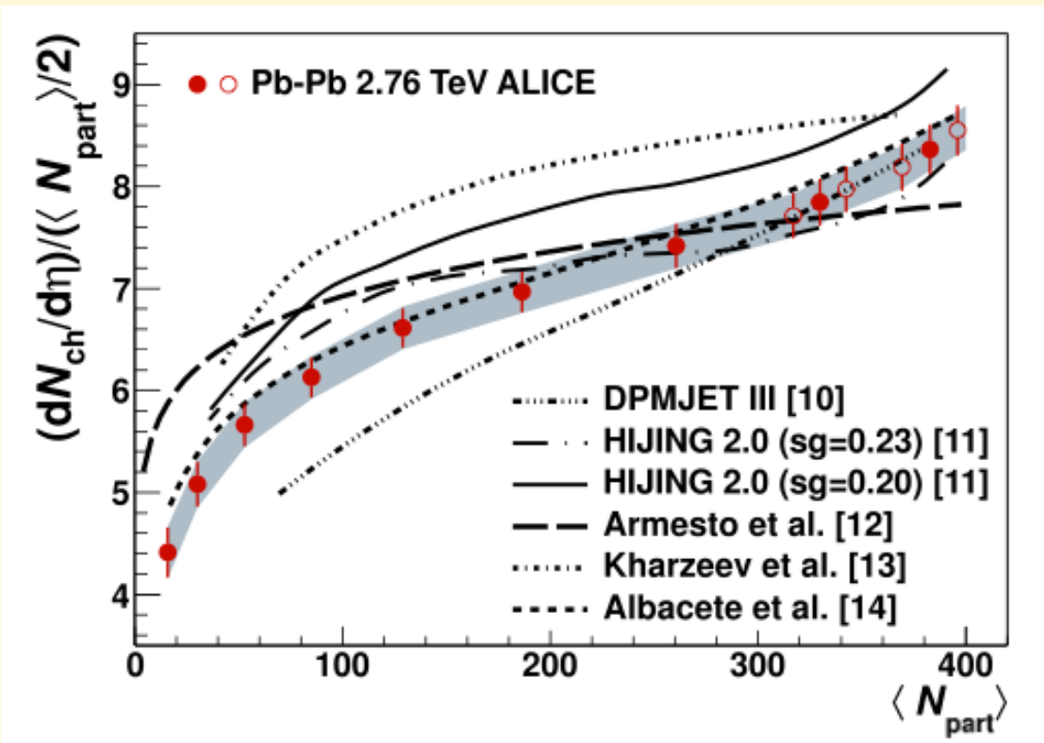




ALICE, http://arxiv.org/abs/1011.3916



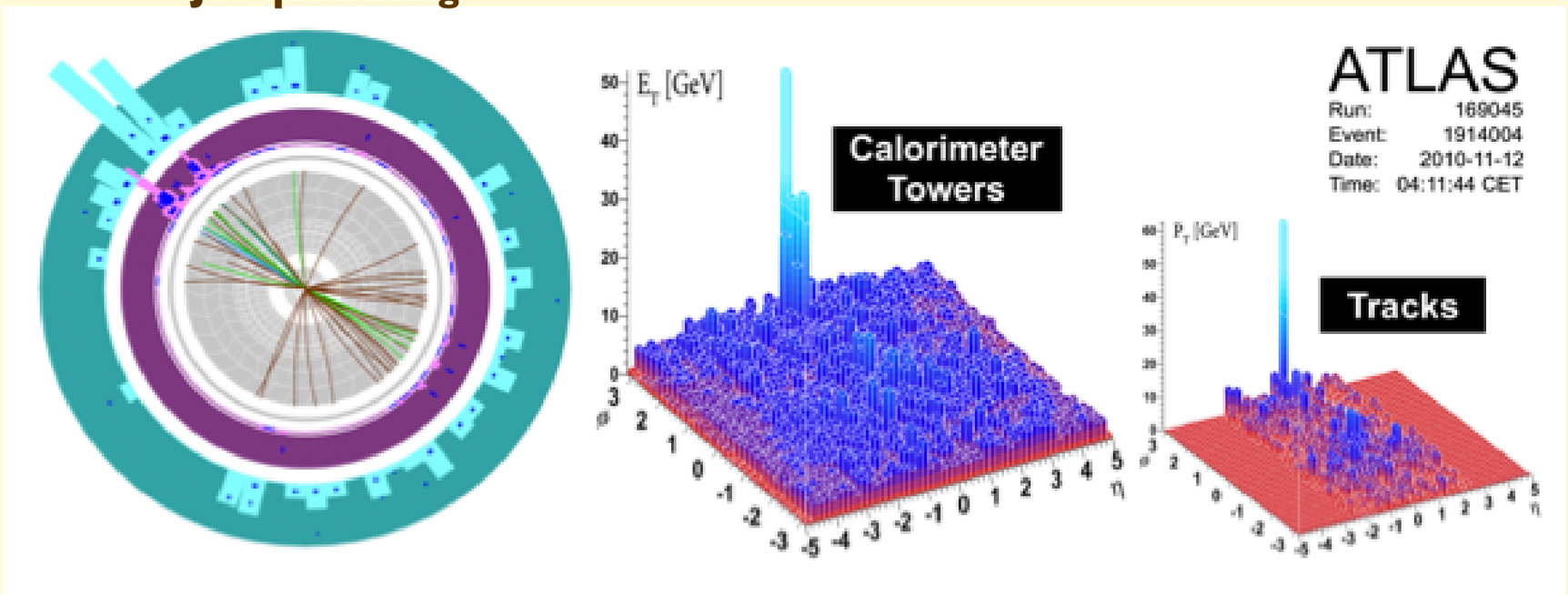
ALICE, http://arxiv.org/abs/1012.1657



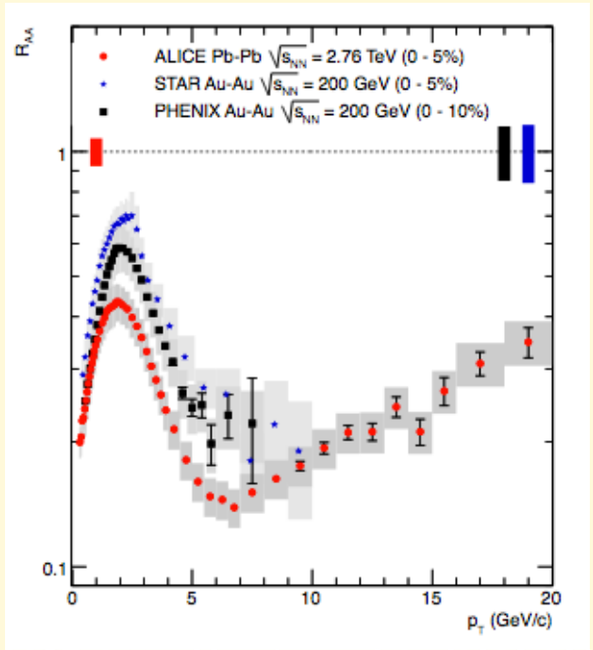
Modeling heavily depends on description of gluon saturation

Hard probes in Pb-Pb collisions ....

Jet quenching

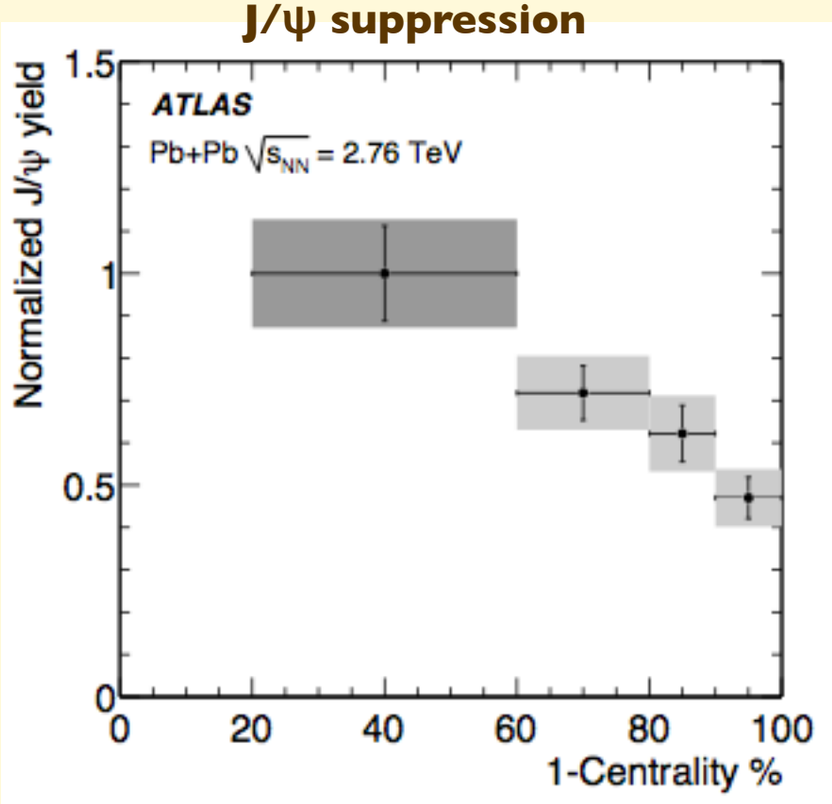


ATLAS, http://arxiv.org/abs/1011.6182

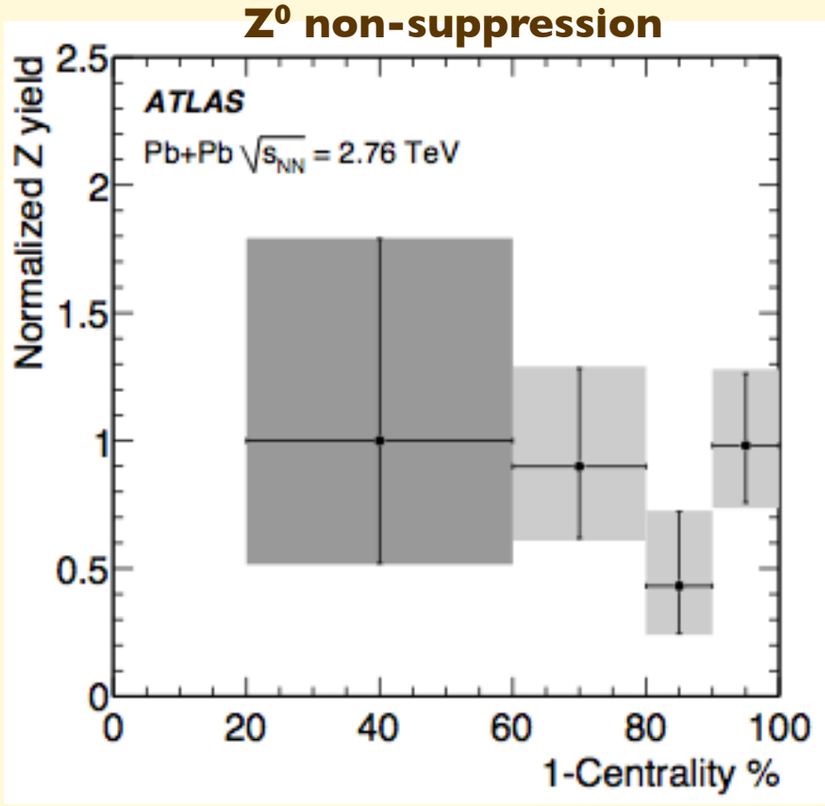


ALICE, http://arxiv.org/abs/1012.1004

J/ψ suppression



Z^0 non-suppression



ATLAS, http://arxiv.org/abs/1012.5419

Once these phenomena will have been properly quantified, using higher statistics, more probes, etc, where do we go from here?

What are the future open questions/challenges for an HI programme?

What is the long-term future of the field, beyond the approved HI LHC programme?

Momentum spectrum of cosmic ray muons