Introduction to the theory of hadronic collisions, and the physics of the LHC

Part III:

The first year of the LHC: what we have learned

CERN Winter School on Supergravity,

Strings, and Gauge Theory 2011

Jan 24- 28 2011

Michelangelo L. Mangano

TH Unit, Physics Department, CERN

michelangelo.mangano@cern.ch

Introduction

- A year of learning: confirmations, surprises
- Every piece of data has yielded valuable information, nothing wasted, nothing redundant, including the runs at 900 GeV
- Amazing degree of coherence, overall coordination and planning in the execution and delivery of the analyses.
- Remarkable thoroughness of enquiry
- As theorists, we found:
  - Things that should have worked, did work, but still $(\mathrm{syst+stat})_{\mathrm{exp}} > (\mathrm{syst})_{\mathrm{TH}}$
  - Things that may not have worked, did work, and $(\mathrm{syst+stat})_{\mathrm{exp}} \lesssim (\mathrm{syst})_{\mathrm{TH}}$
  - Things that we had no robust prediction for: some of them worked, others didn't ....
  - Things that we had no clue, didn't bother to study and make predictions for, and turned out to be exciting
  - Nothing that should have worked and didn't!

Jets

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

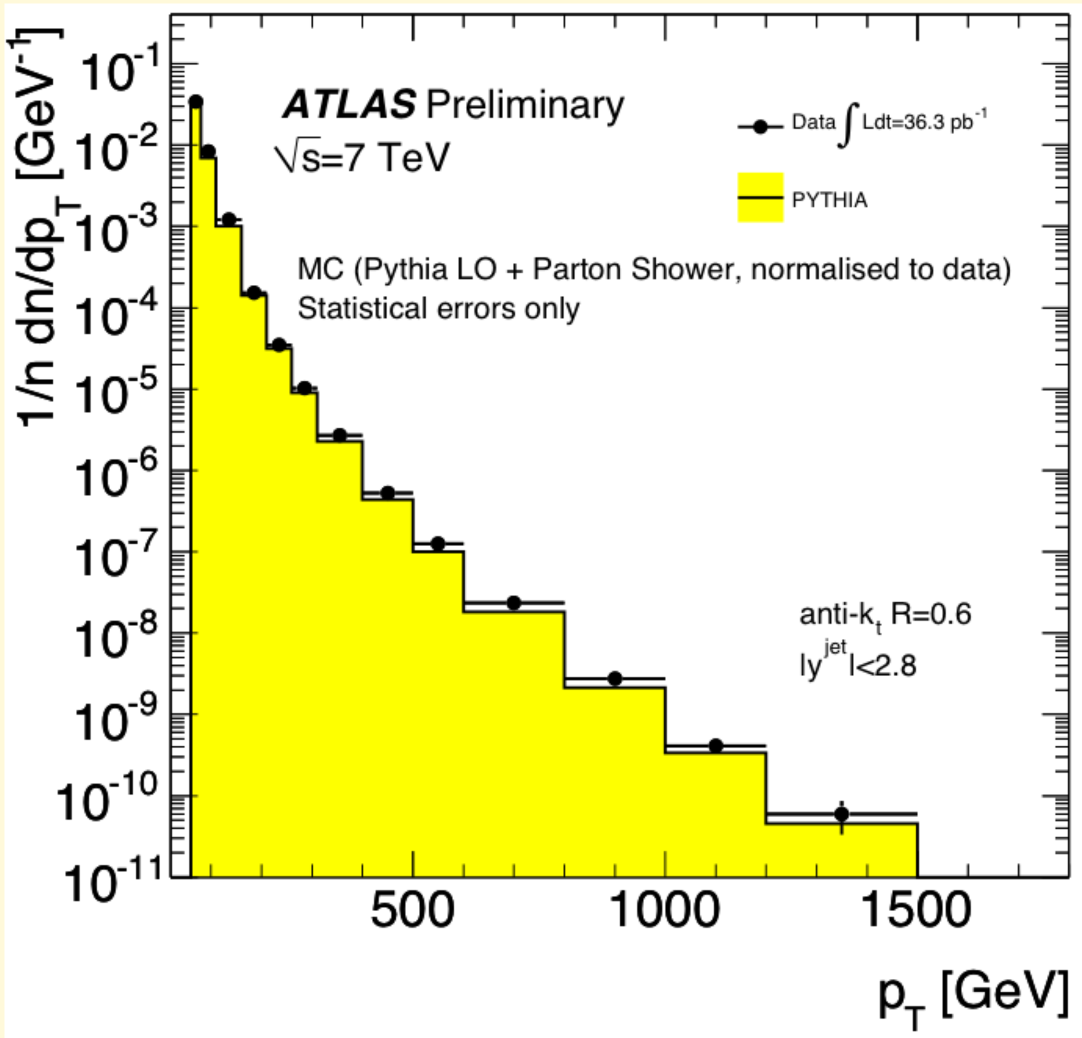
- Key objects for spectroscopy of heavy particles

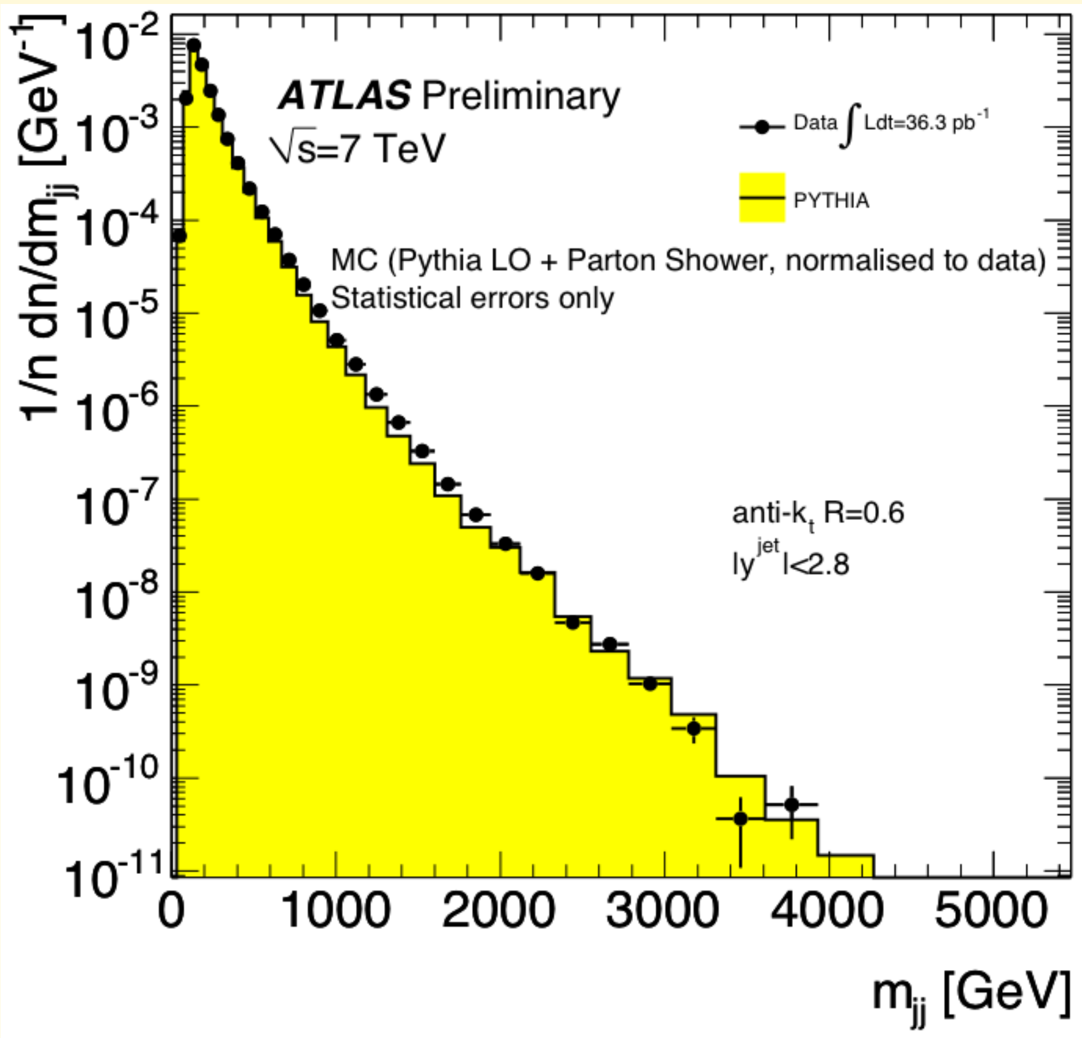
- Final states of the modern "Rutherford" experiment with the proton: test the fundamental nature of quarks

- 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.)

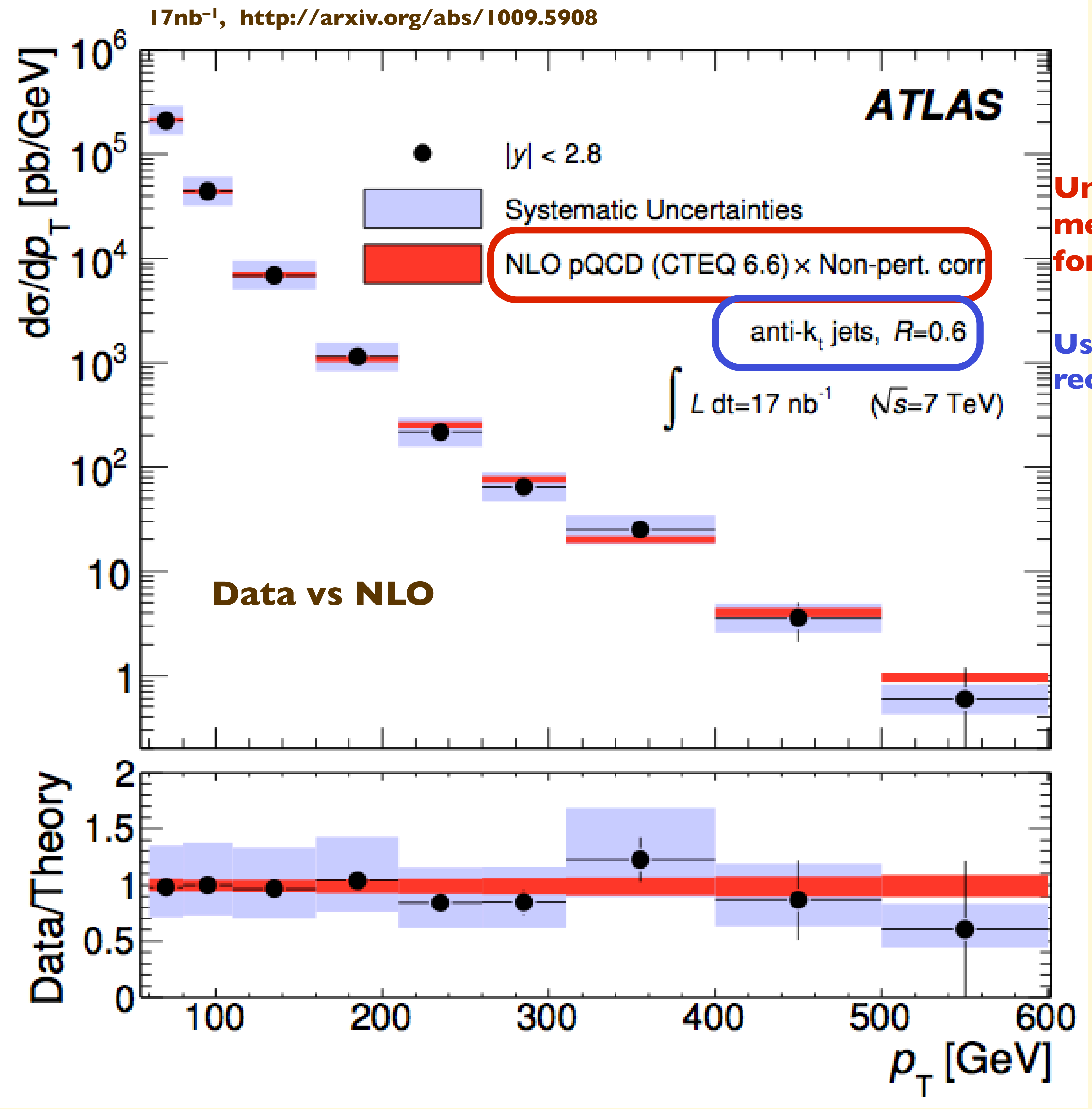
Full 2010 luminosity update:





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

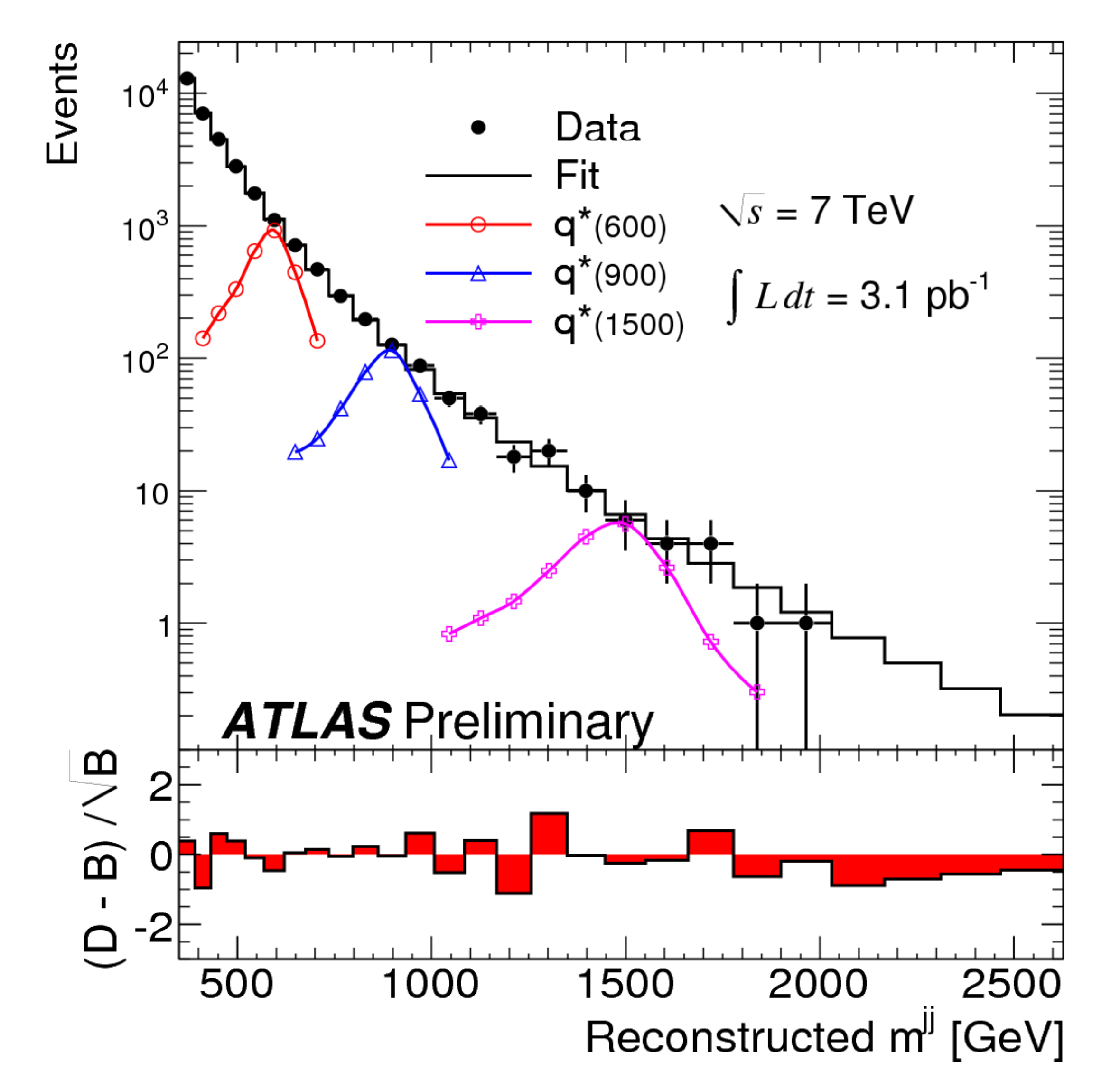
Inclusive jet E_T spectrum

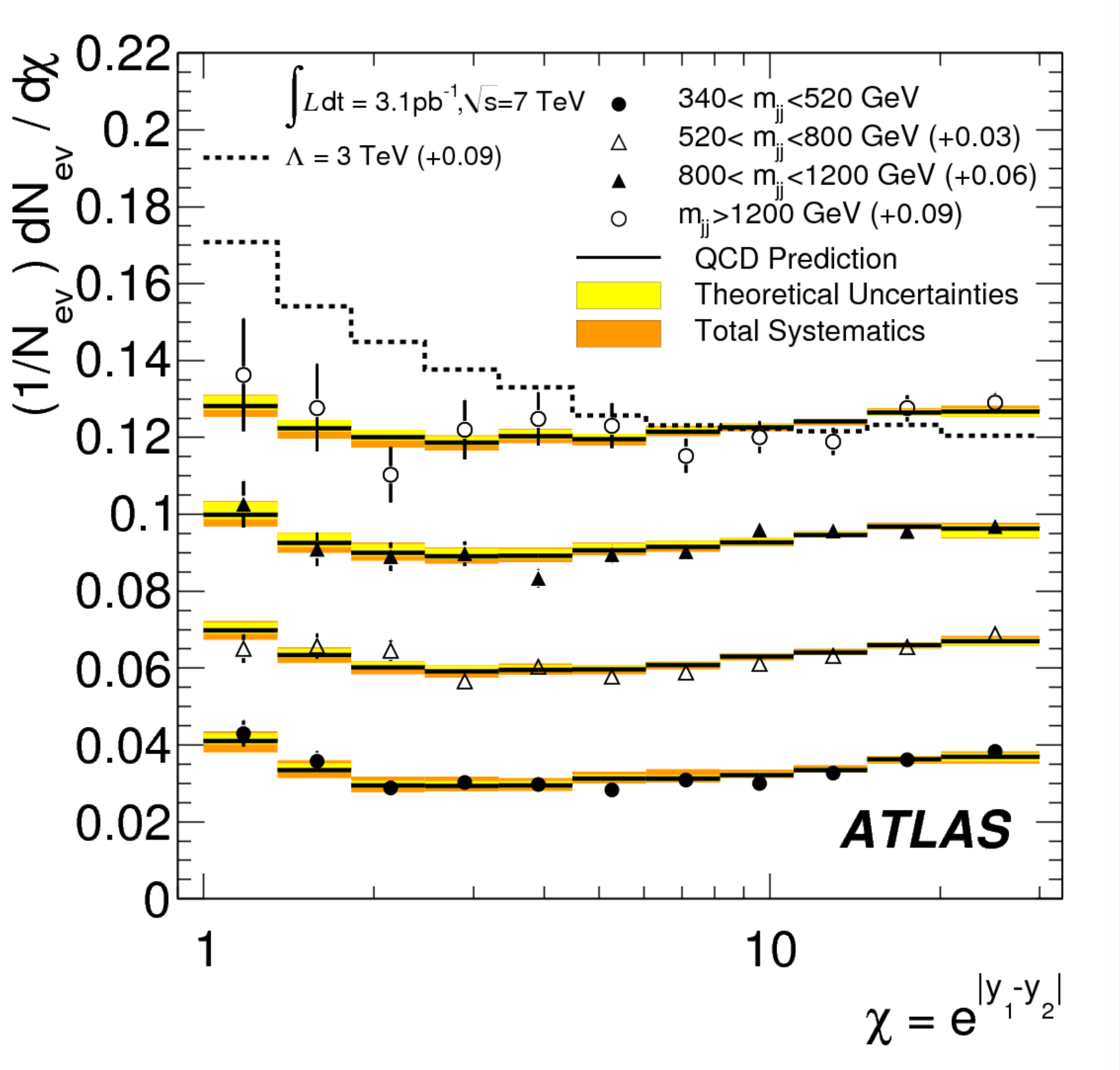


Unfolded cross-section measurement, suitable for comparison with NLO

Use of modern jet reconstruction tools

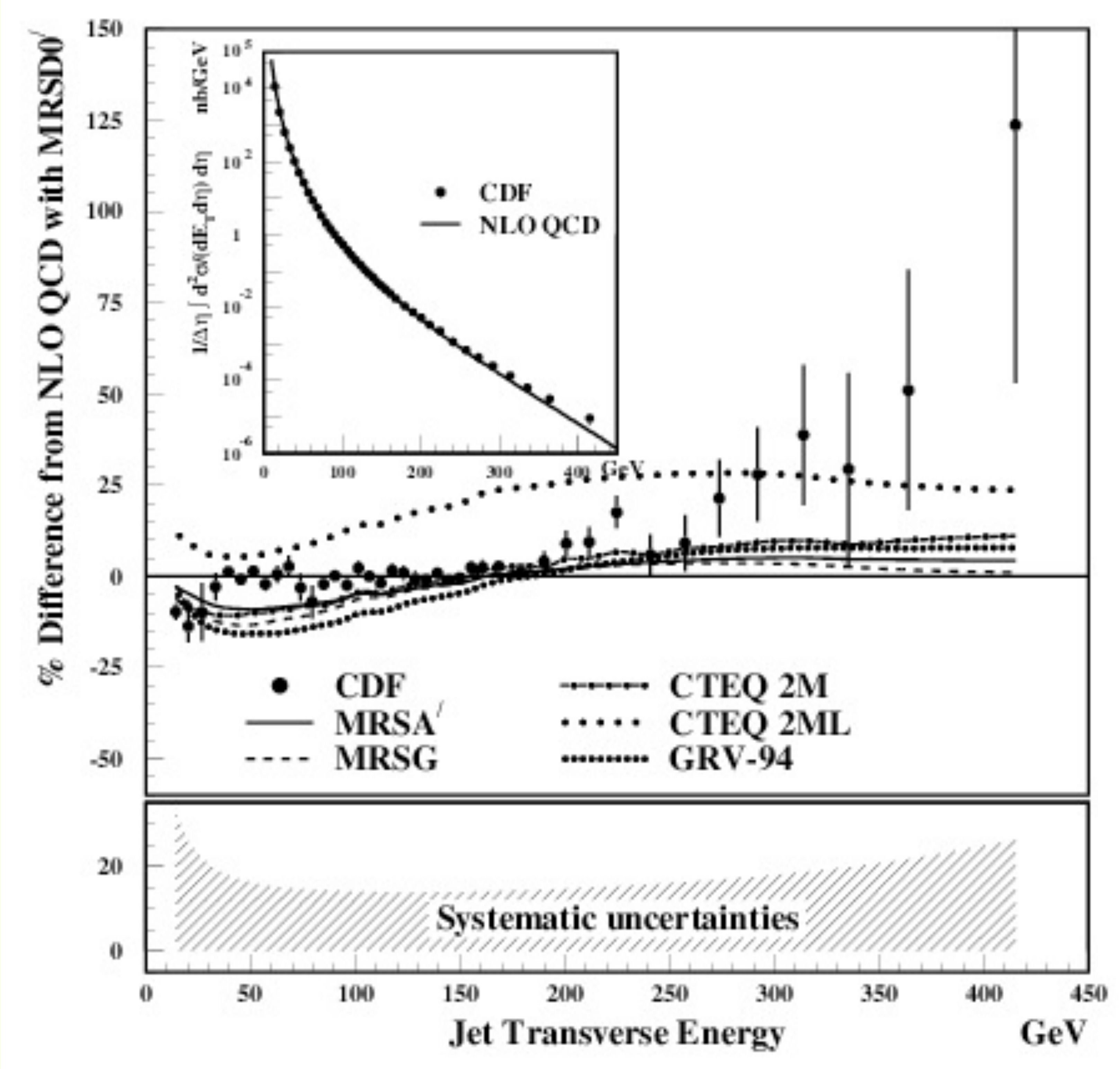
First constraints on new physics





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

Quark contact interactions with scale < 3.4 TeV @ 95% CL


% Difference from NLO QCD with MRSD0′
CDF
NLO QCD
CDF
MRSA′
MRSG
CTEQ 2M
CTEQ 2ML
GRV-94
Systematic uncertainties
Jet Transverse Energy
GeV

Some more jet kinematics ...

Prove as an **exercise** that

$$x_{1,2} = \frac{p_T}{E_{beam}} \cosh y^* \, e^{\pm y_b}$$

where

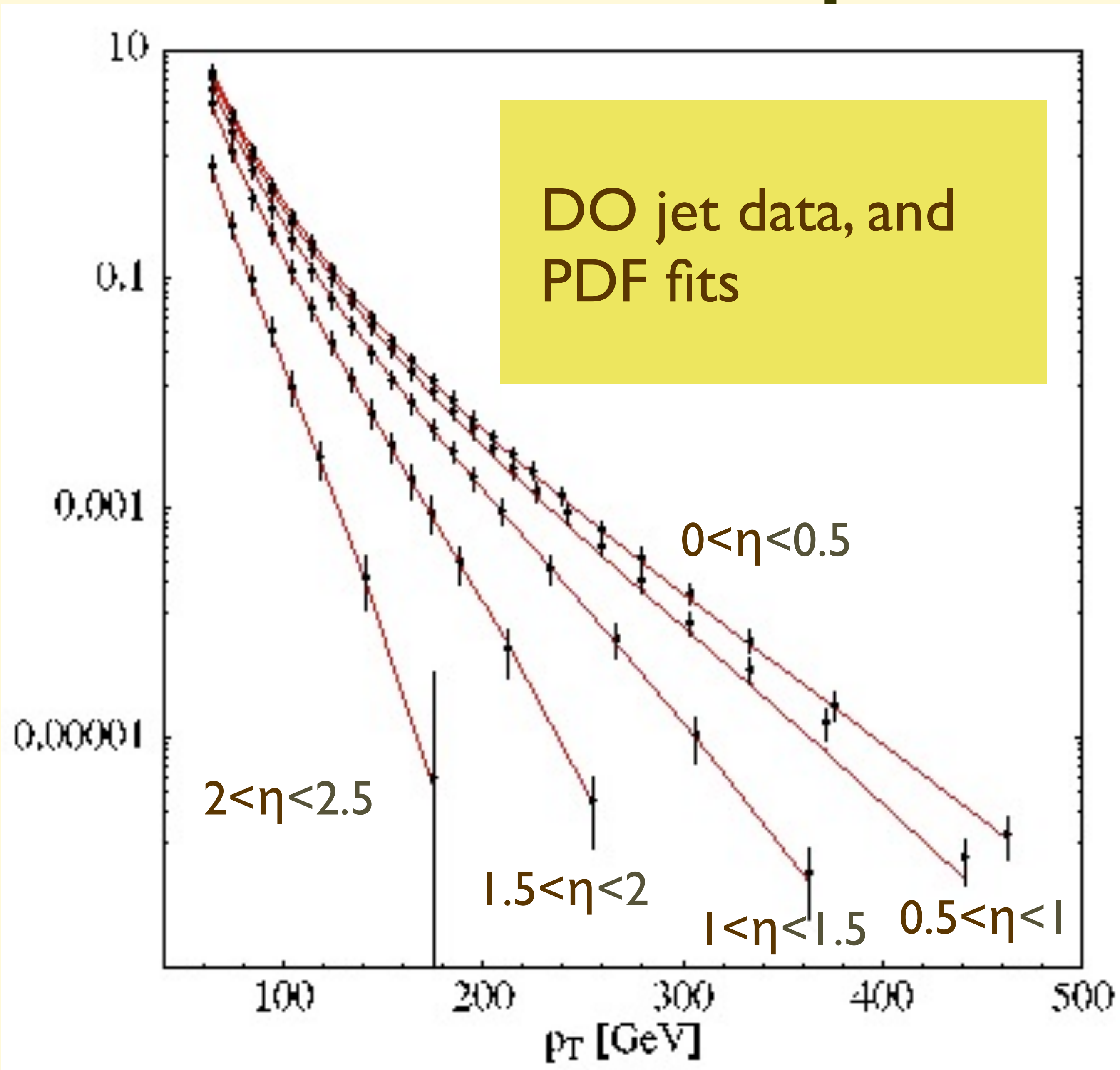
$$y^* = \frac{\eta_1 - \eta_2}{2}, \quad y_b = \frac{\eta_1 + \eta_2}{2}$$

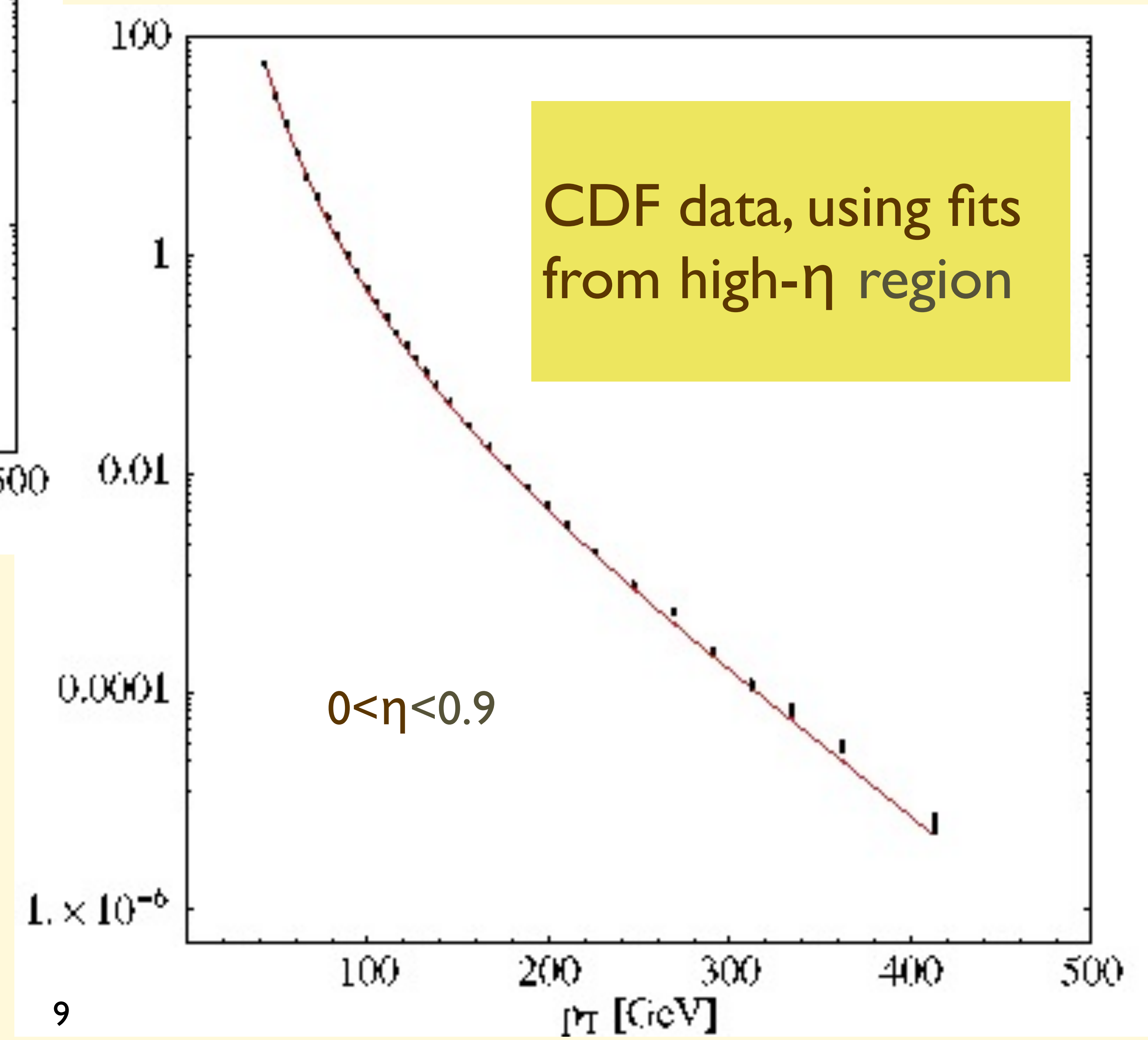
We can therefore reach large values of x either by selecting large invariant mass events:

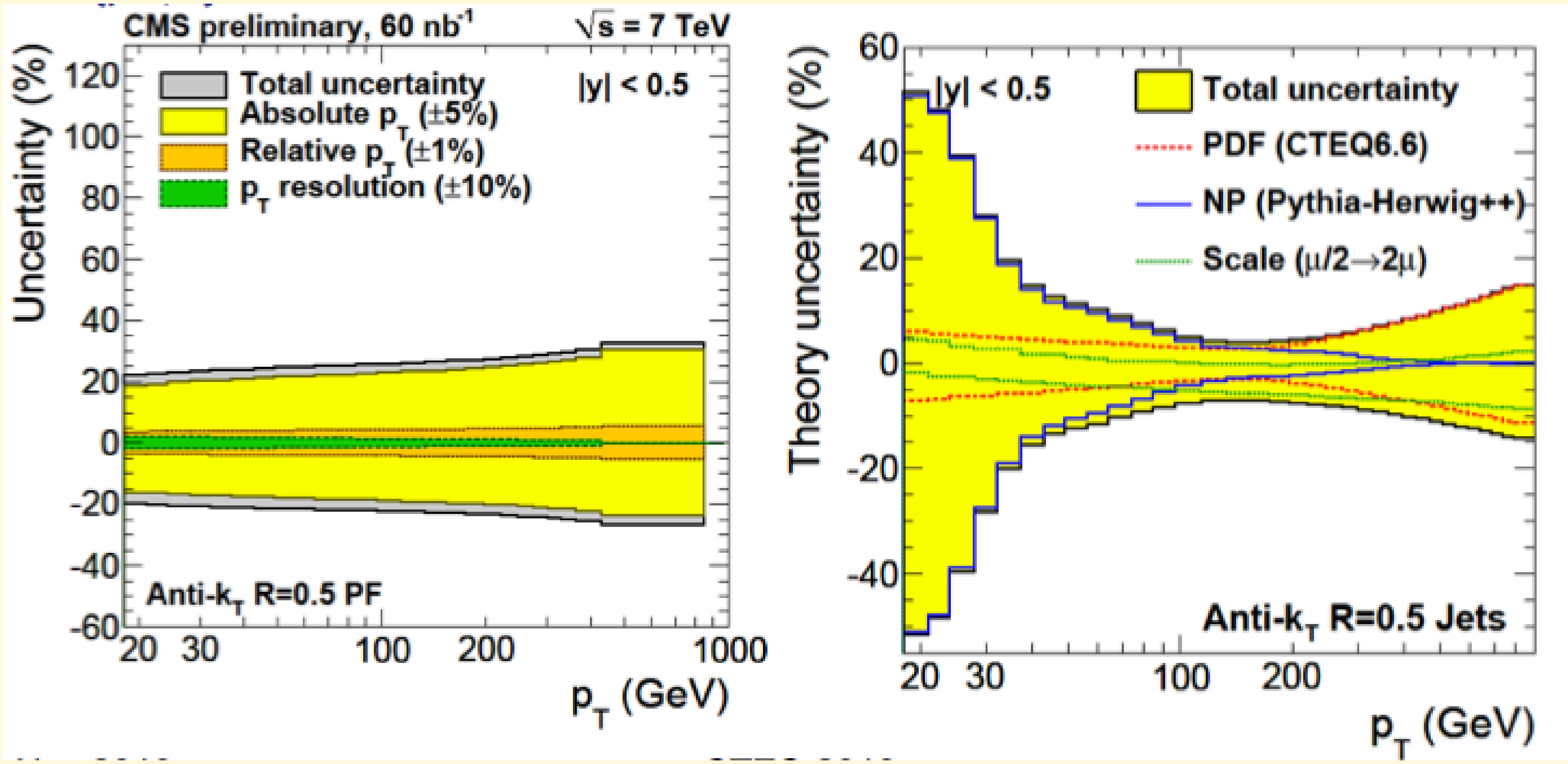
$$\frac{p_T}{E_{beam}} \cosh y^* \equiv \sqrt{\tau} \to 1$$

or by selecting low-mass events, but with large boosts (y_b large) in either positive of negative directions. In this case, we probe large-x with events where possible new physics is absent, thus setting consistent constraints on the behaviour of the cross-section in the high-mass region, which could hide new phenomena.

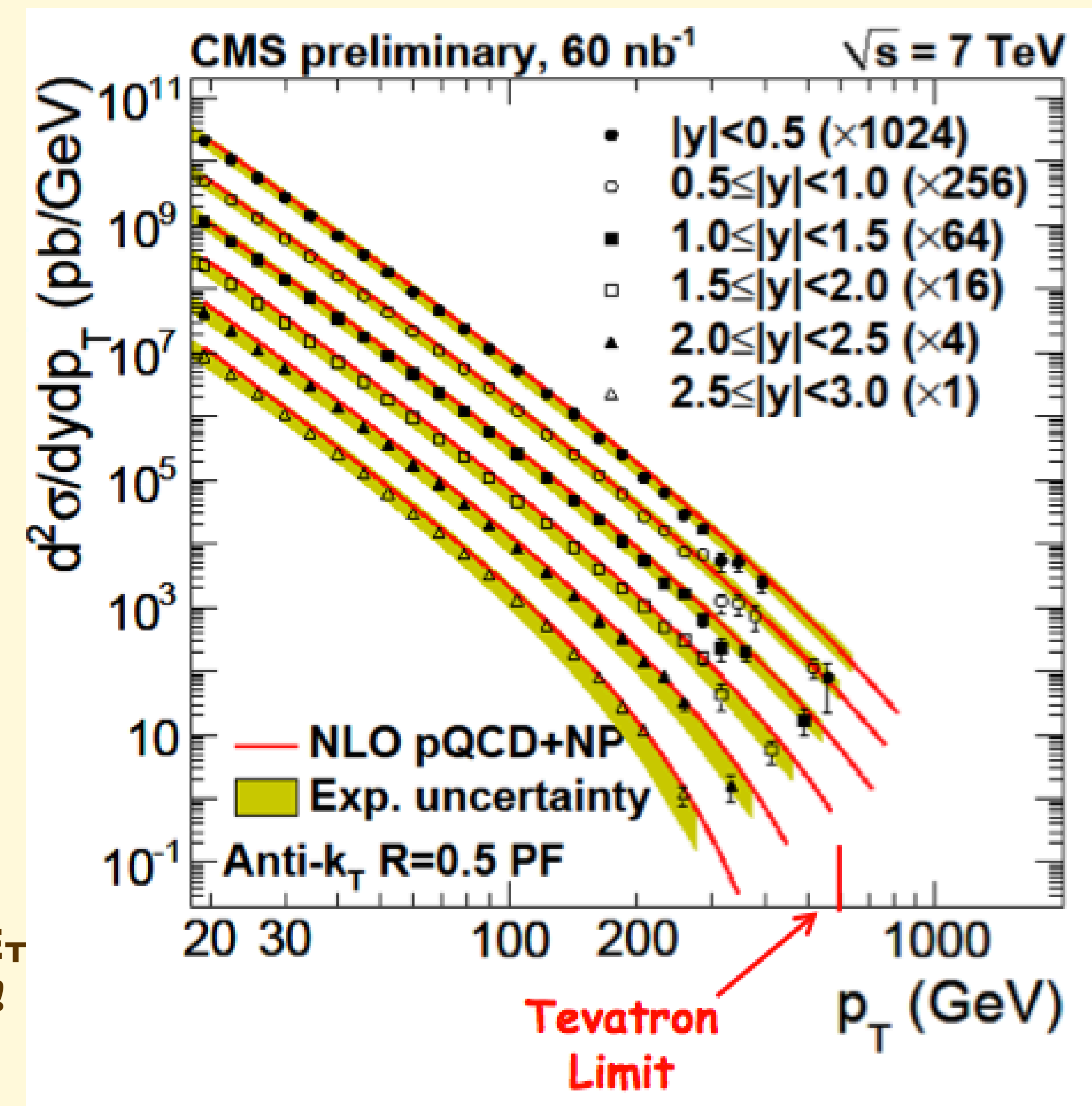
Example, at the Tevatron







PDF will be dominant source of theoretical systematics at large E_T

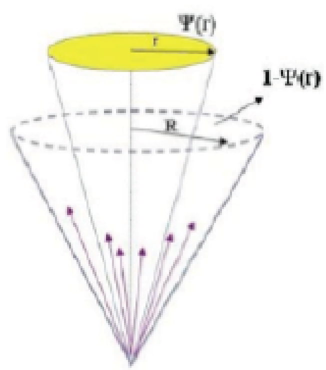


How powerful will be the jet data at large η in reducing this systematics?

Notice reach in E_T down to 20 GeV!!

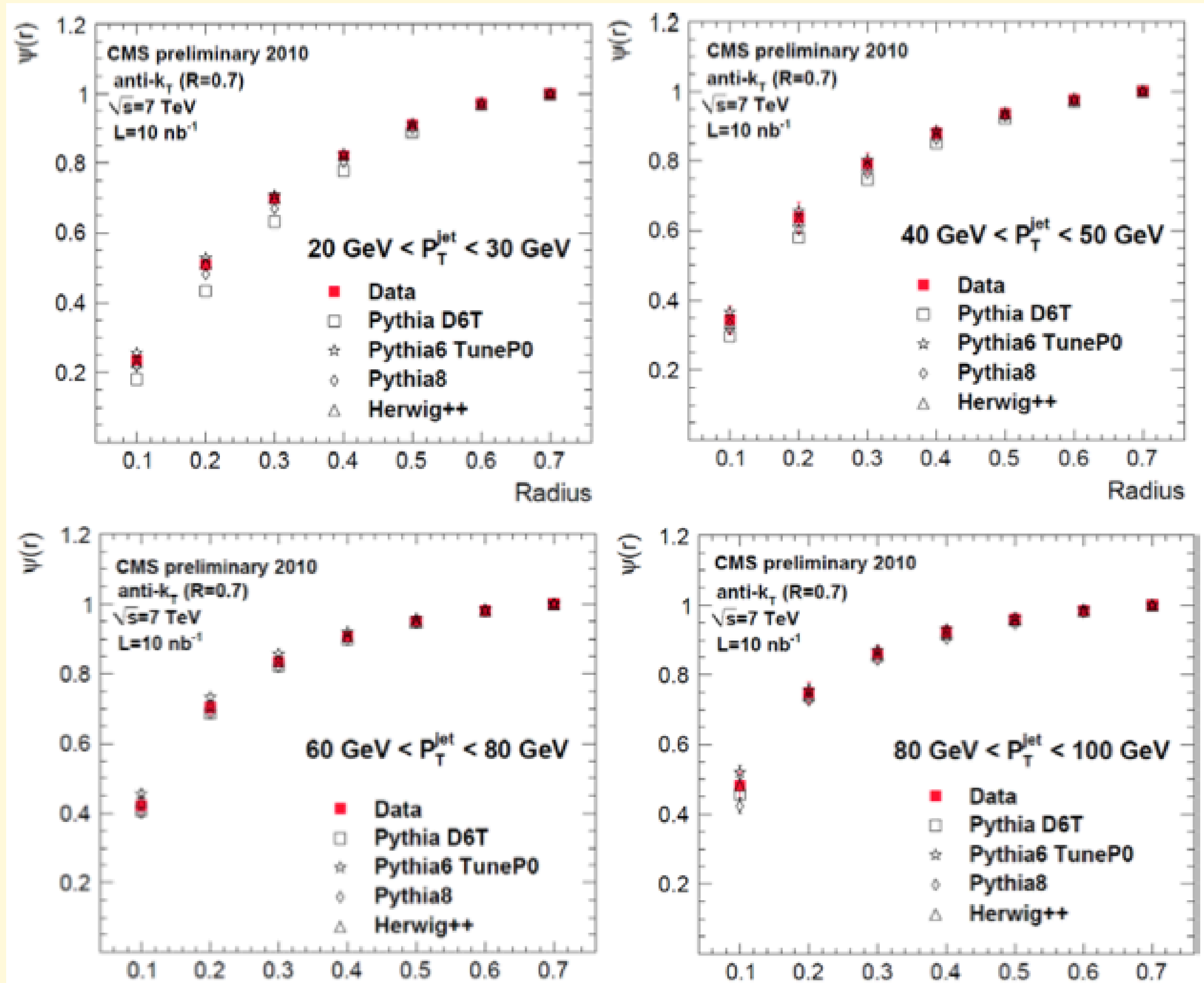
Integrated jet shape

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



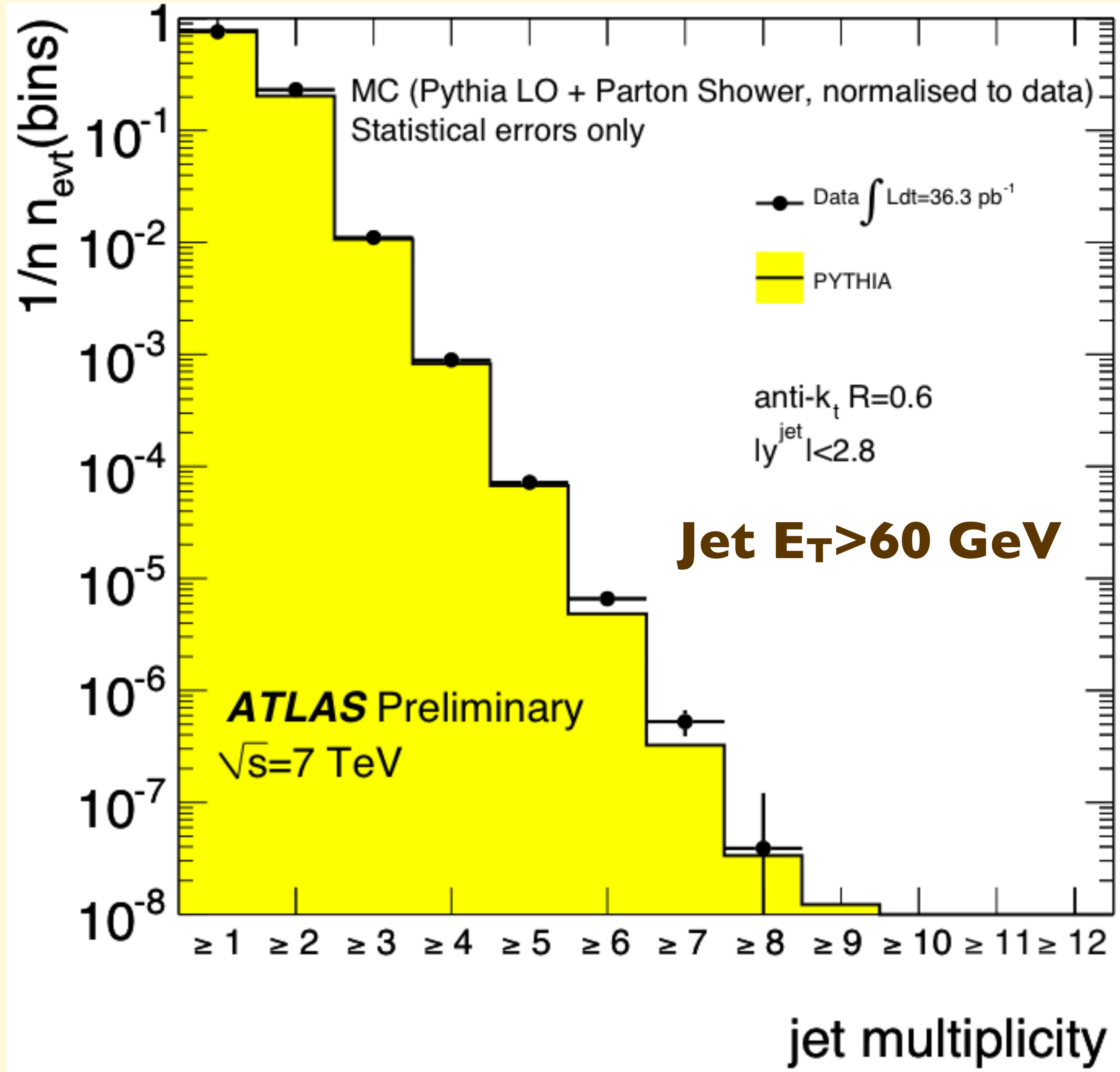
Probes modeling of shower evolution, with implications for:

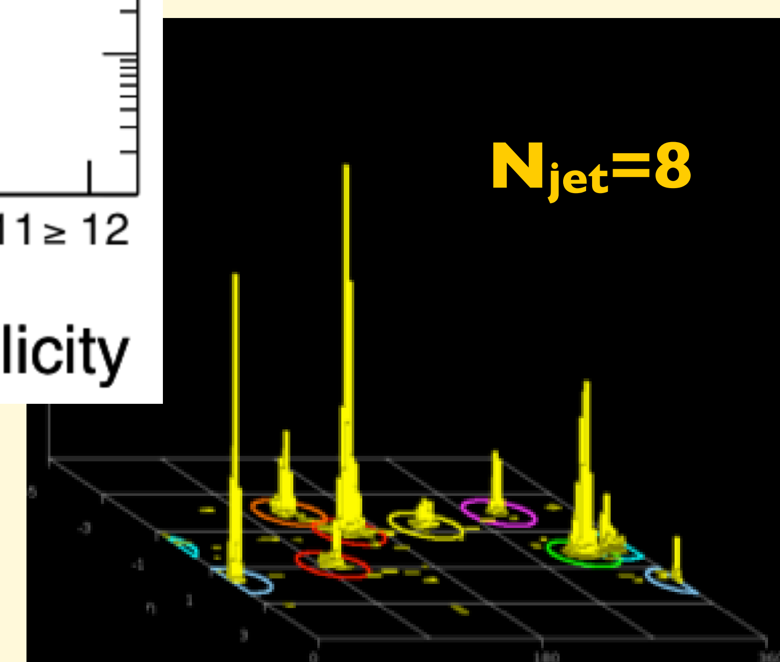
- precision QCD studies (e.g. jet E_T spectrum, data vs NLO)
- jet spectroscopy (e.g. top mass determination)
- multiparton matrix-elements/shower matching
- pt W



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

Multijets

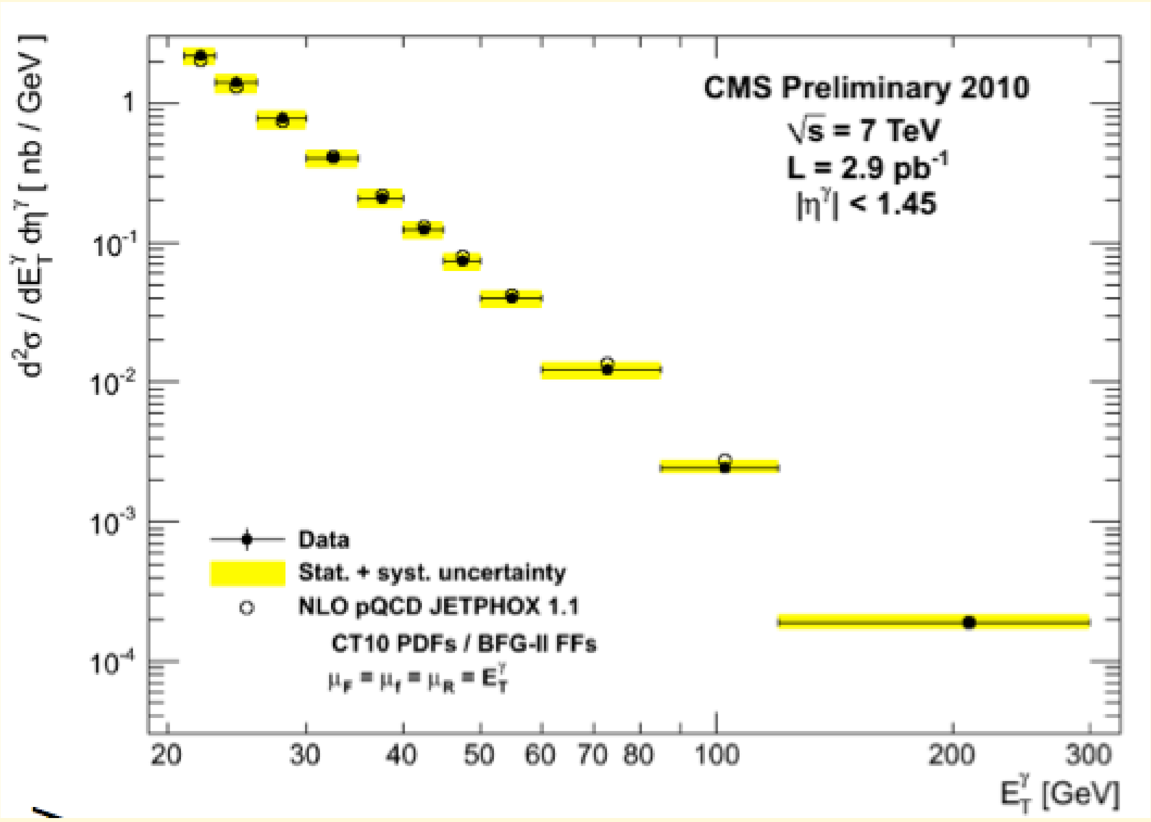


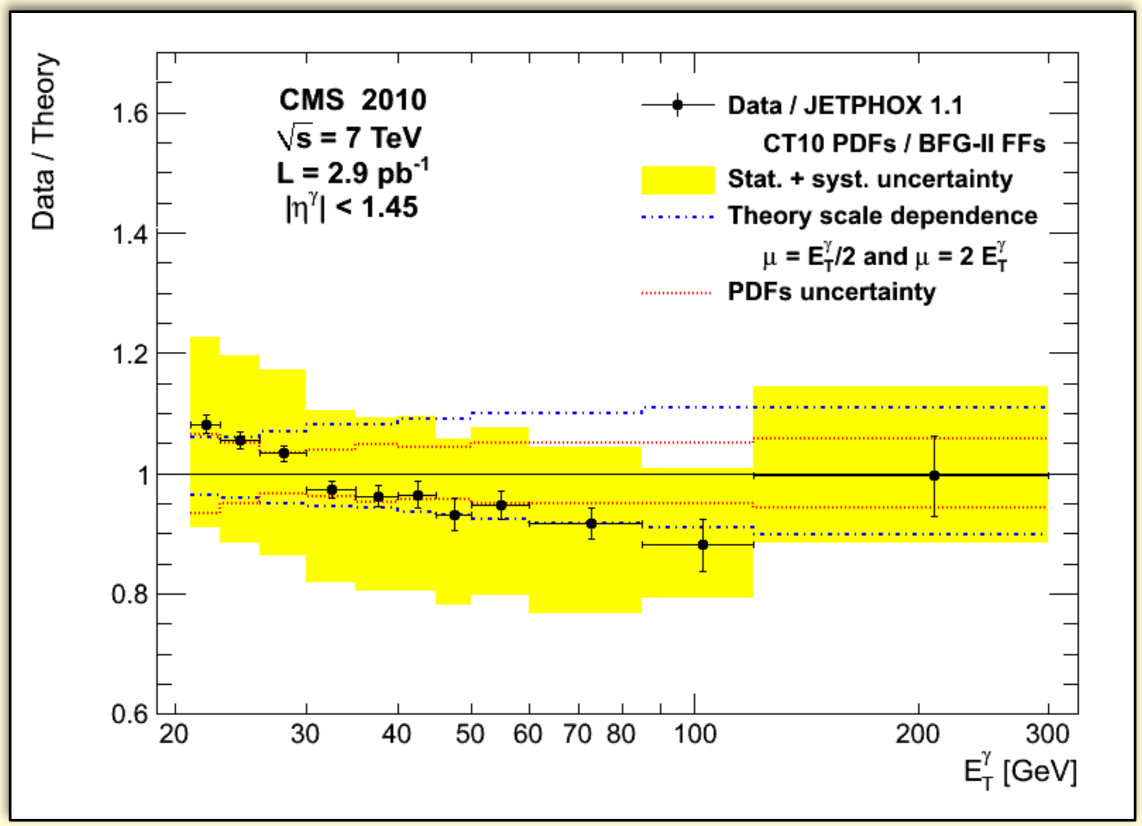


See P. Wells, for the ATLAS collab., 104th LHCC session, http://indico.cern.ch/conferenceDisplay.py?confId=112439

Photons

Prompt photon spectrum, LHC data vs TH



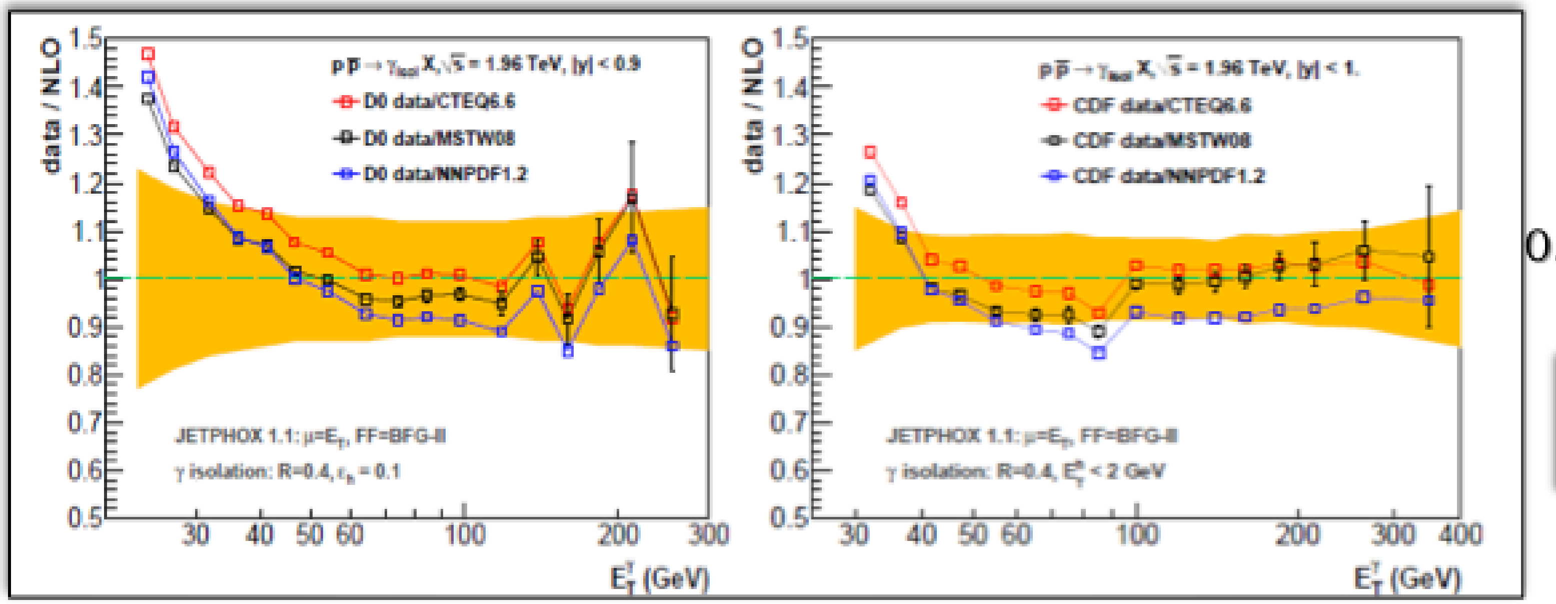


Cfr Tevatron:

arXiv:1005.4529

D0
0.01 < xT < 0.12

Phys. Lett. B
639 (2006) 151



CDF
0.01 < xT < 0.13

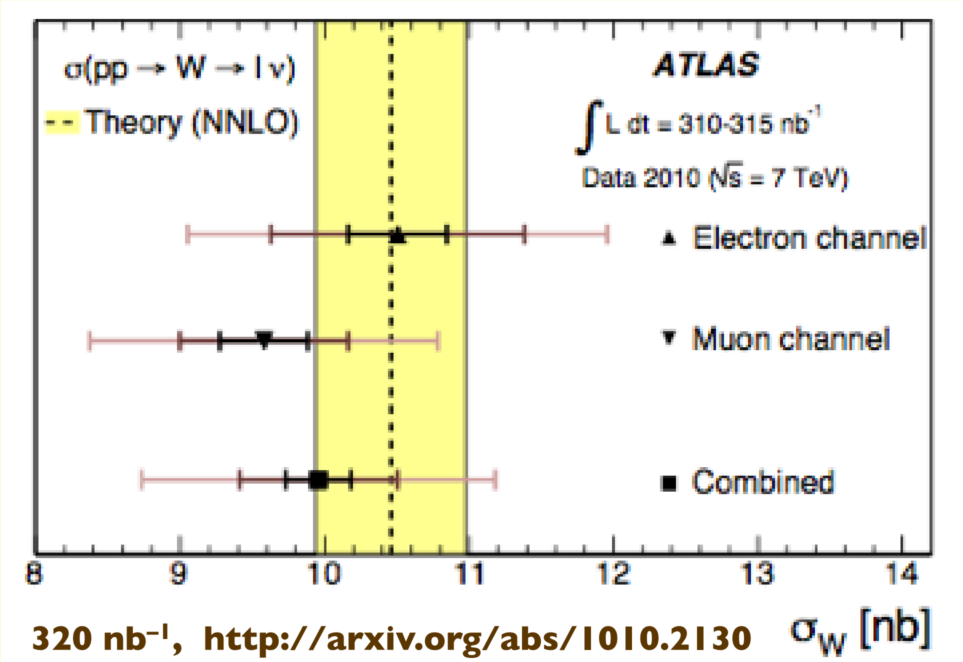
Phys. Rev. D 80
(2009) 111106

11/29/10

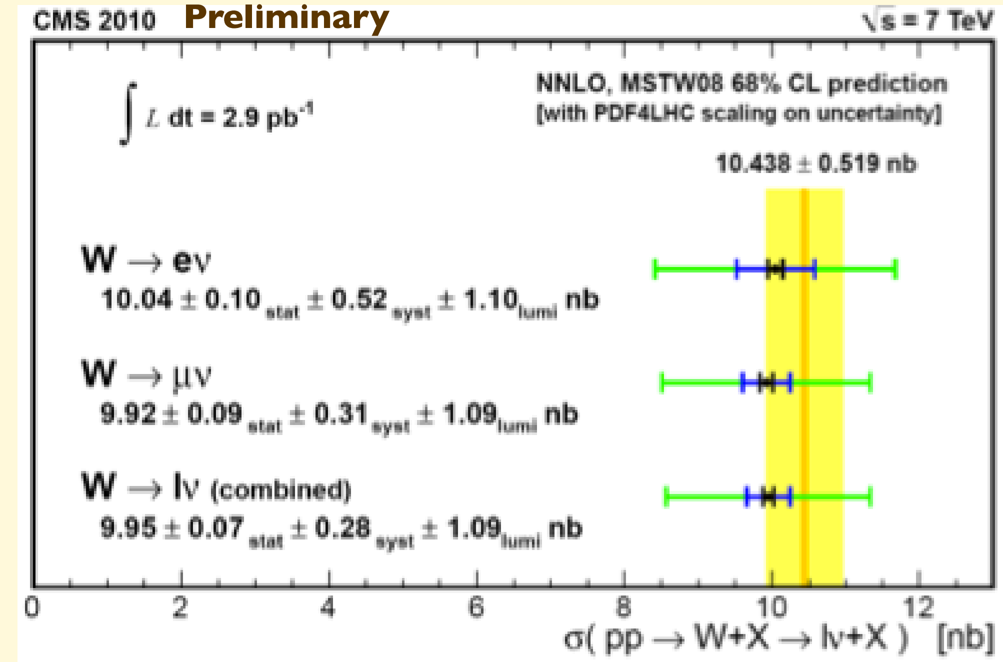
20

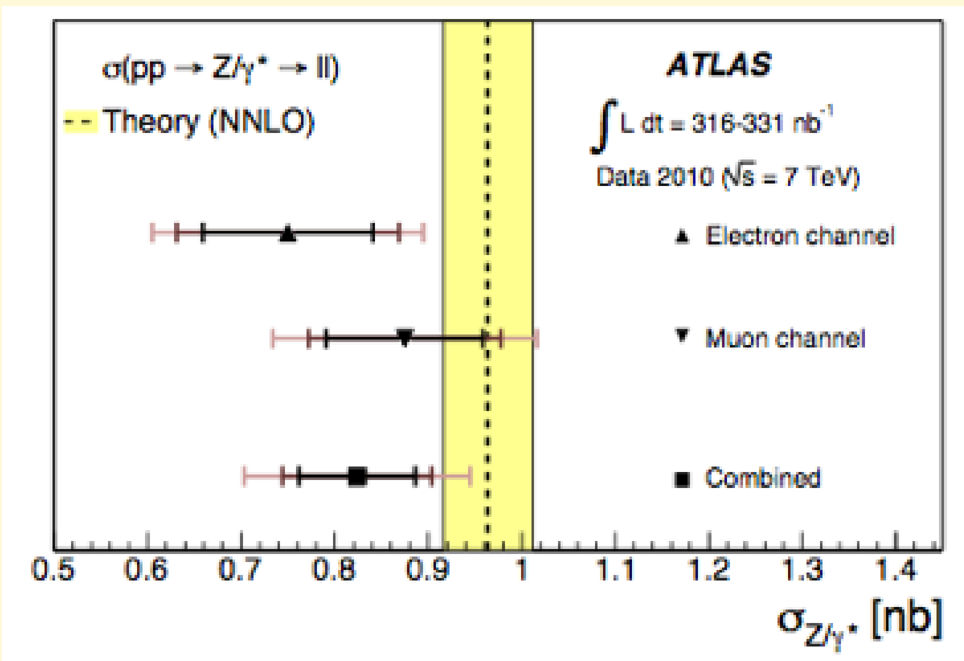
W/Z

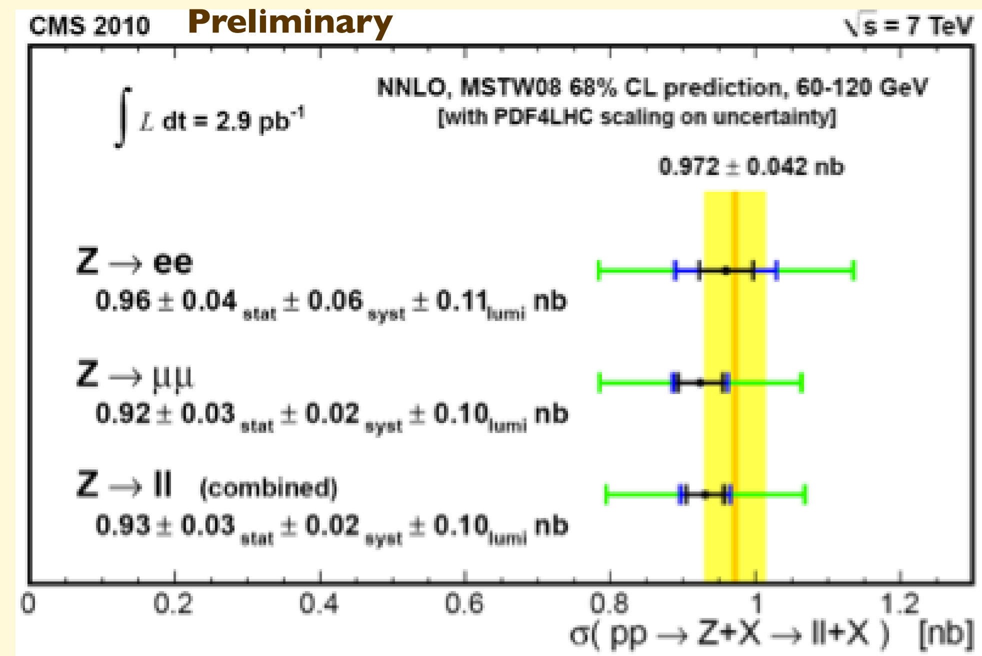
- Primary sources of charged leptons, and missing energy (via neutrinos) =>
  - sources of background to searches of DM-like particles
- Present in the decay chain of almost any heavy object, both in the SM and in BSM scenarios =>
  - probes of new physics
- Inclusive production known in QCD with intrinsic 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



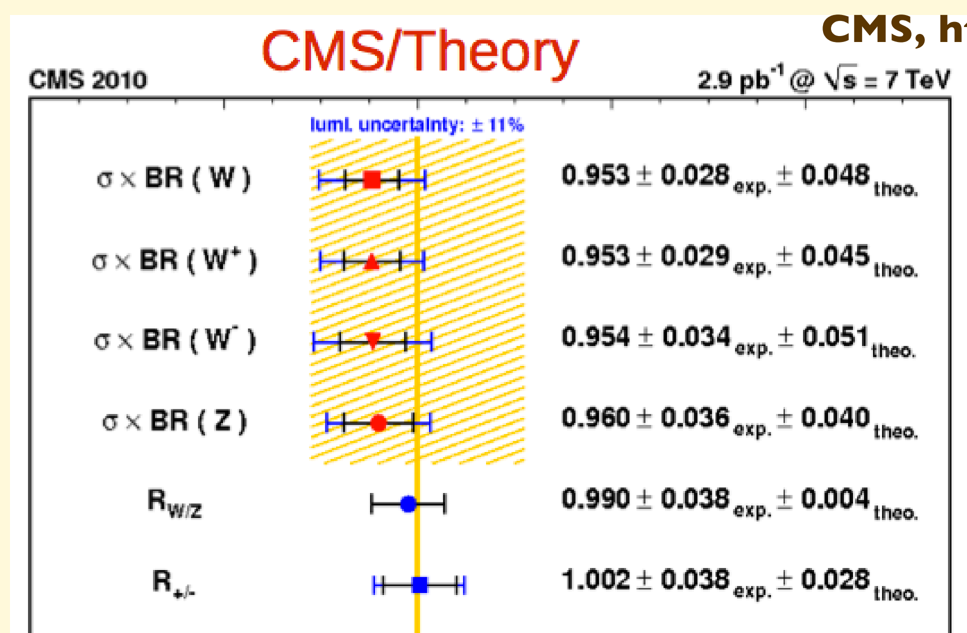
320 nb⁻¹, http://arxiv.org/abs/1010.2130

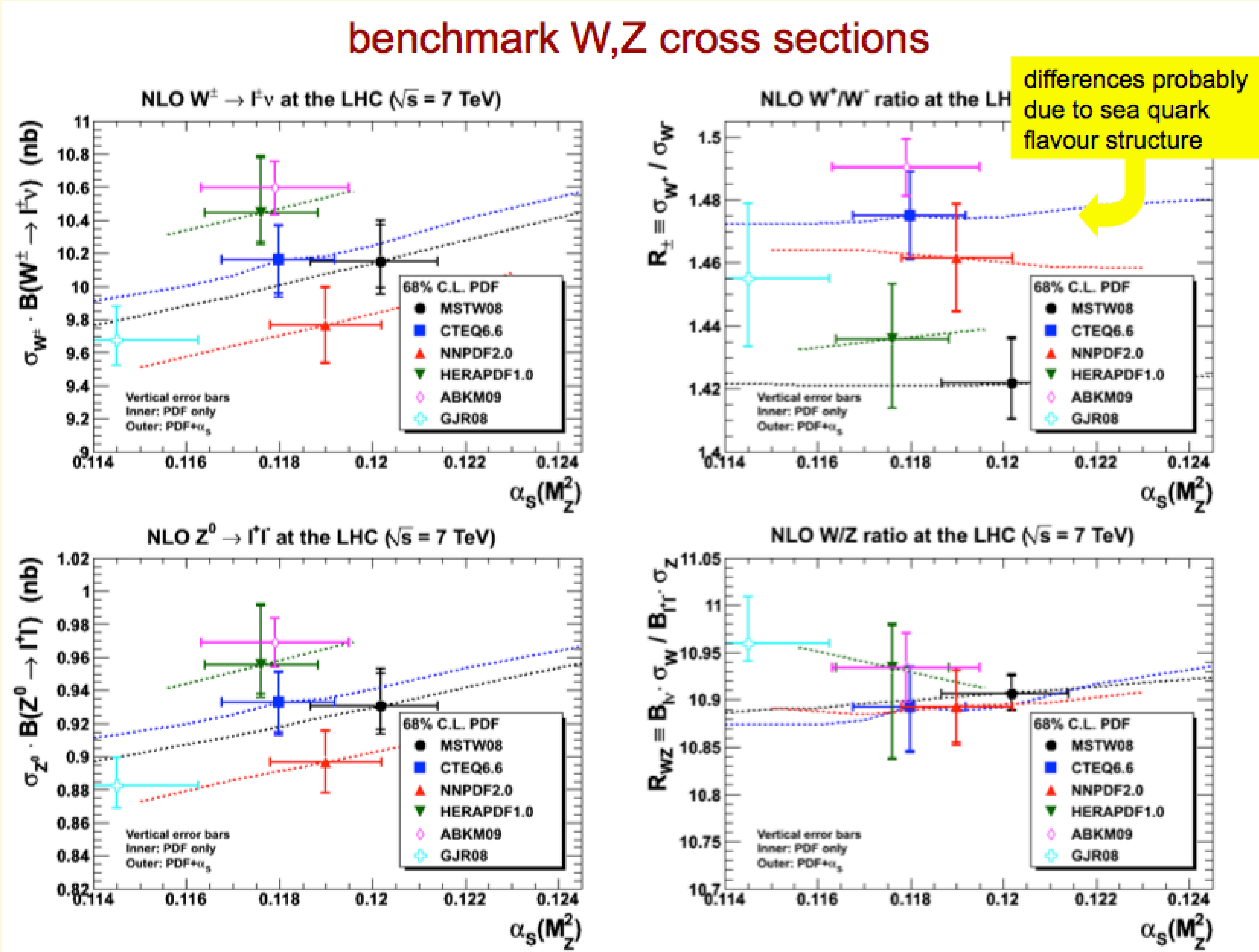






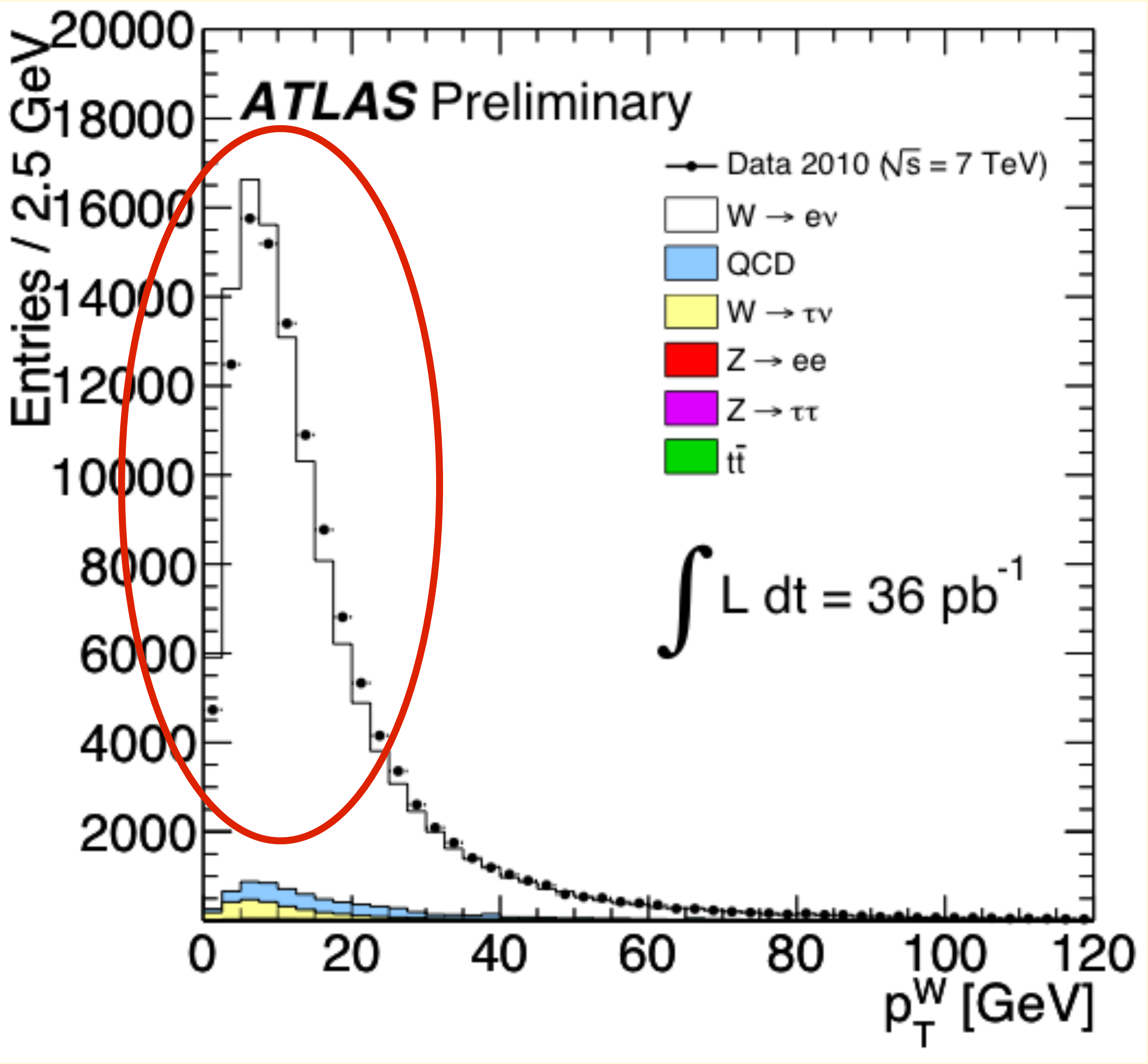
CMS, http://arxiv.org/abs/1012.2466, JHEP

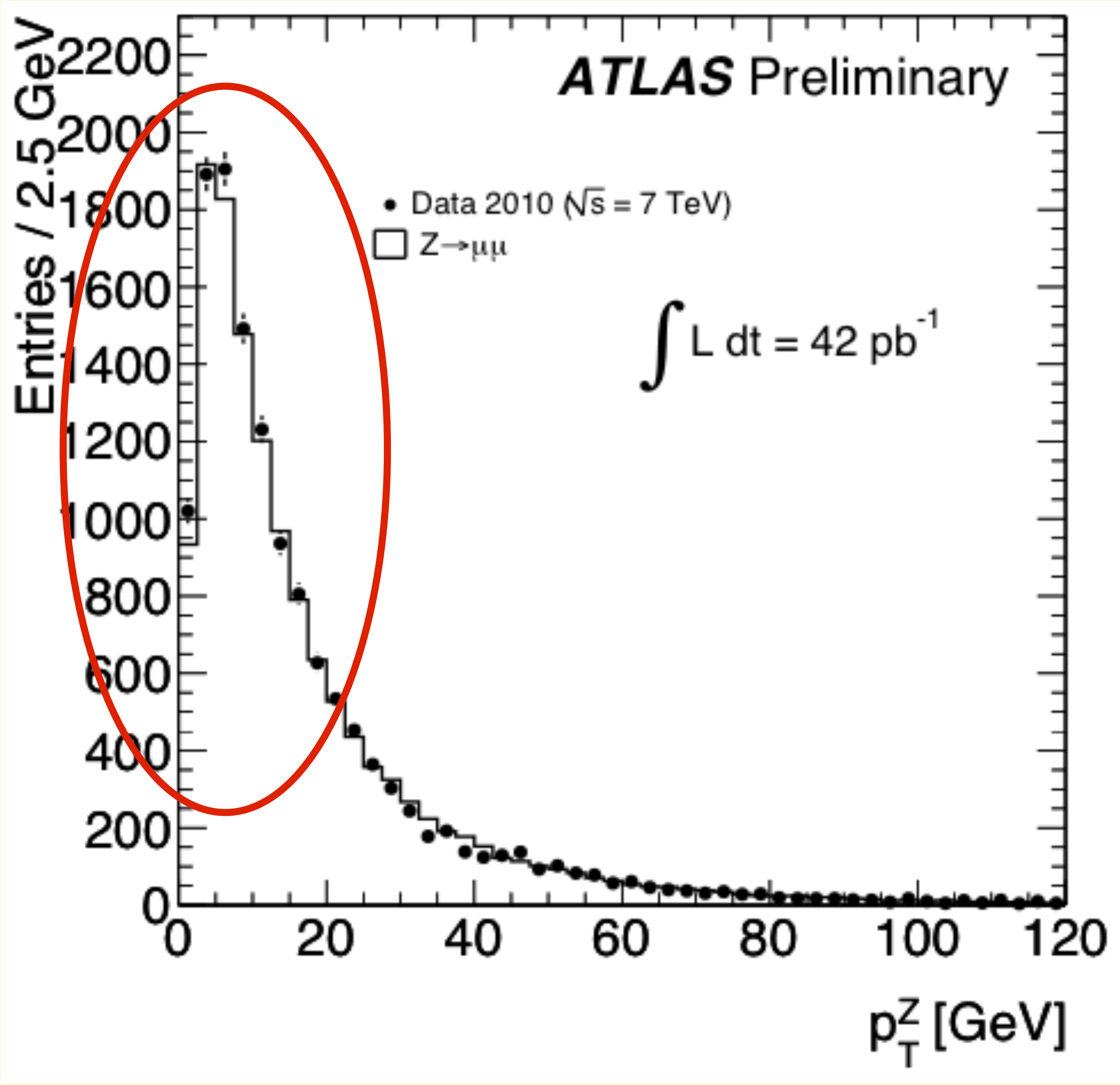




From G. Watt, and W.J. Stirling talk at Trento Workshop "LHC at the LHC"

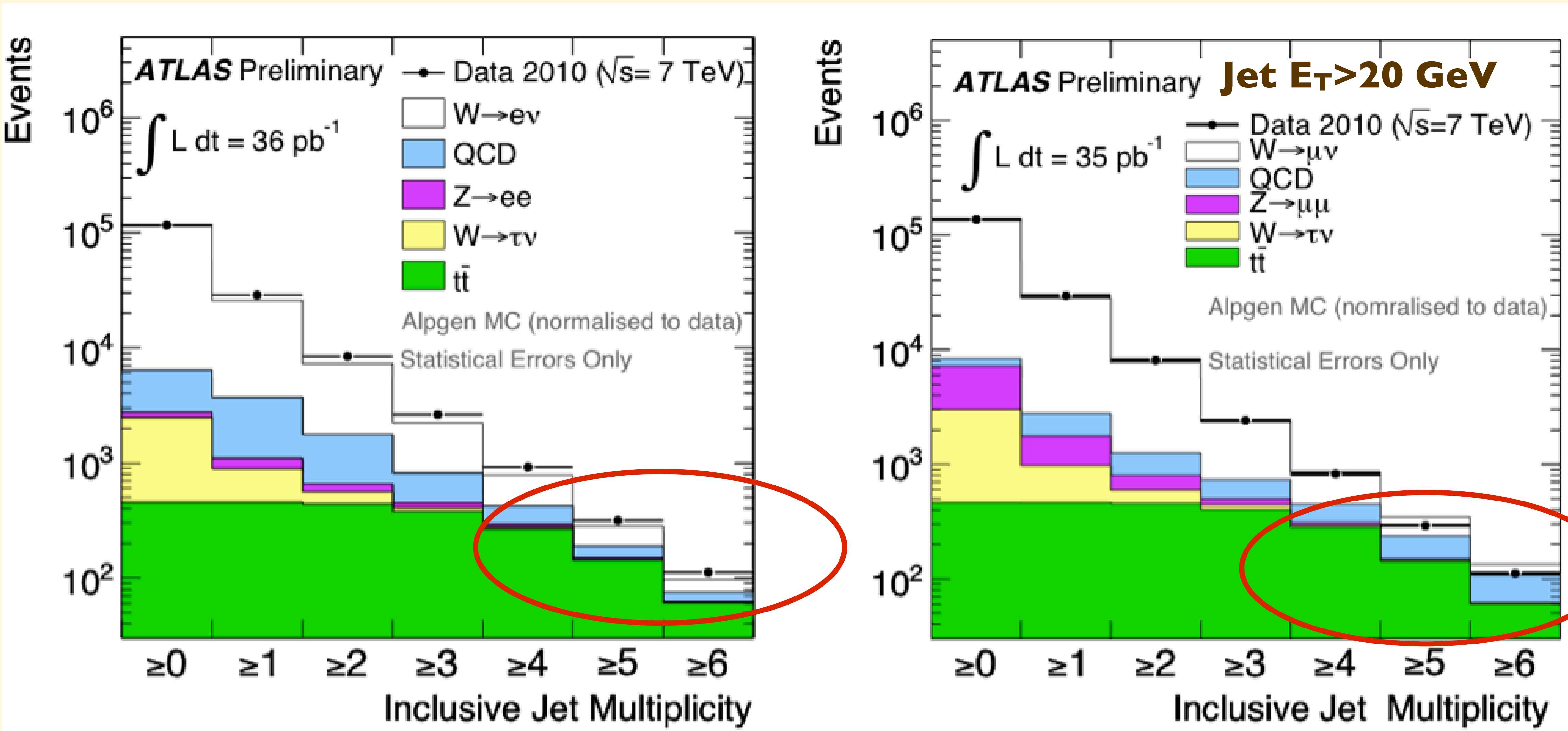
W/Z pt spectra



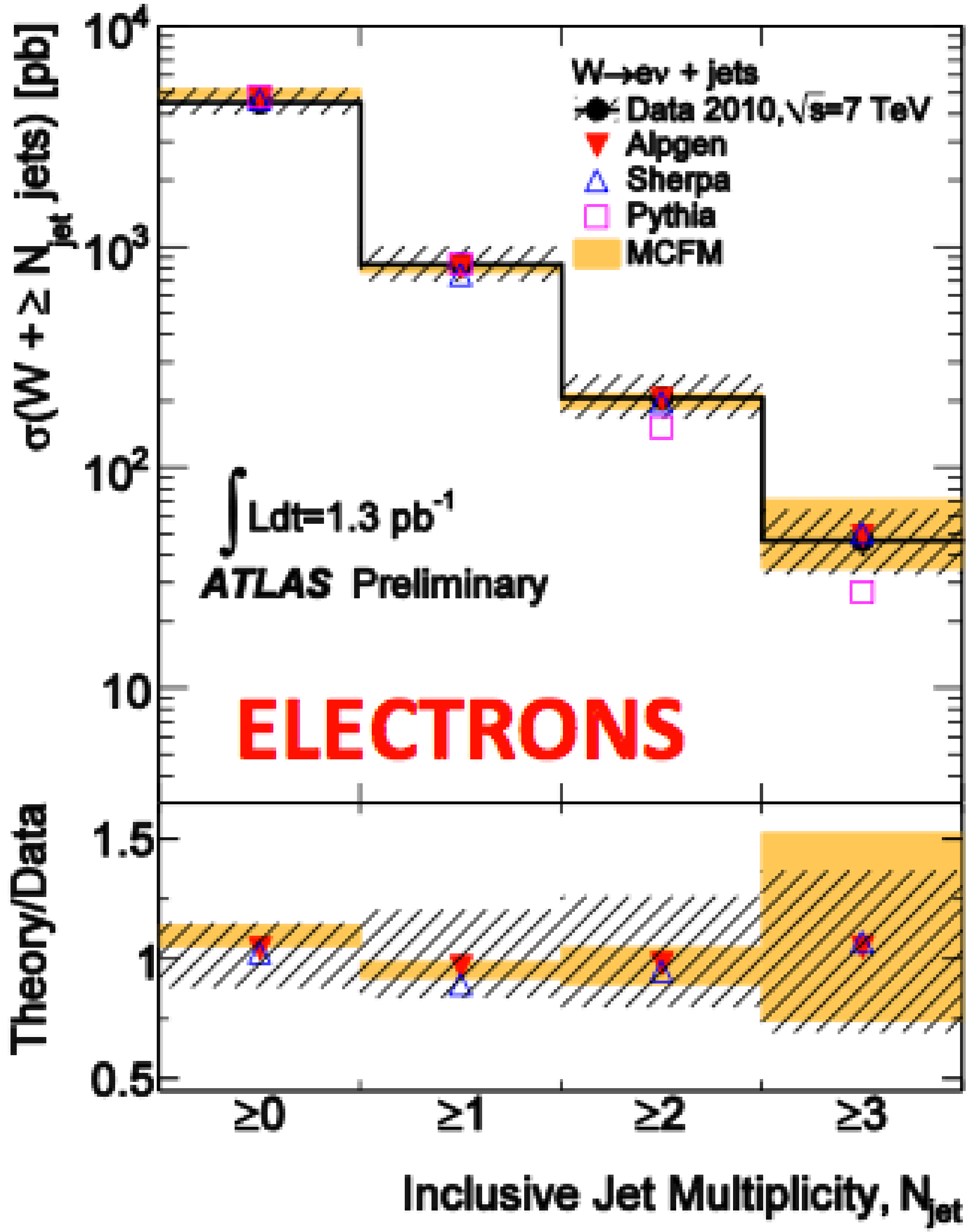


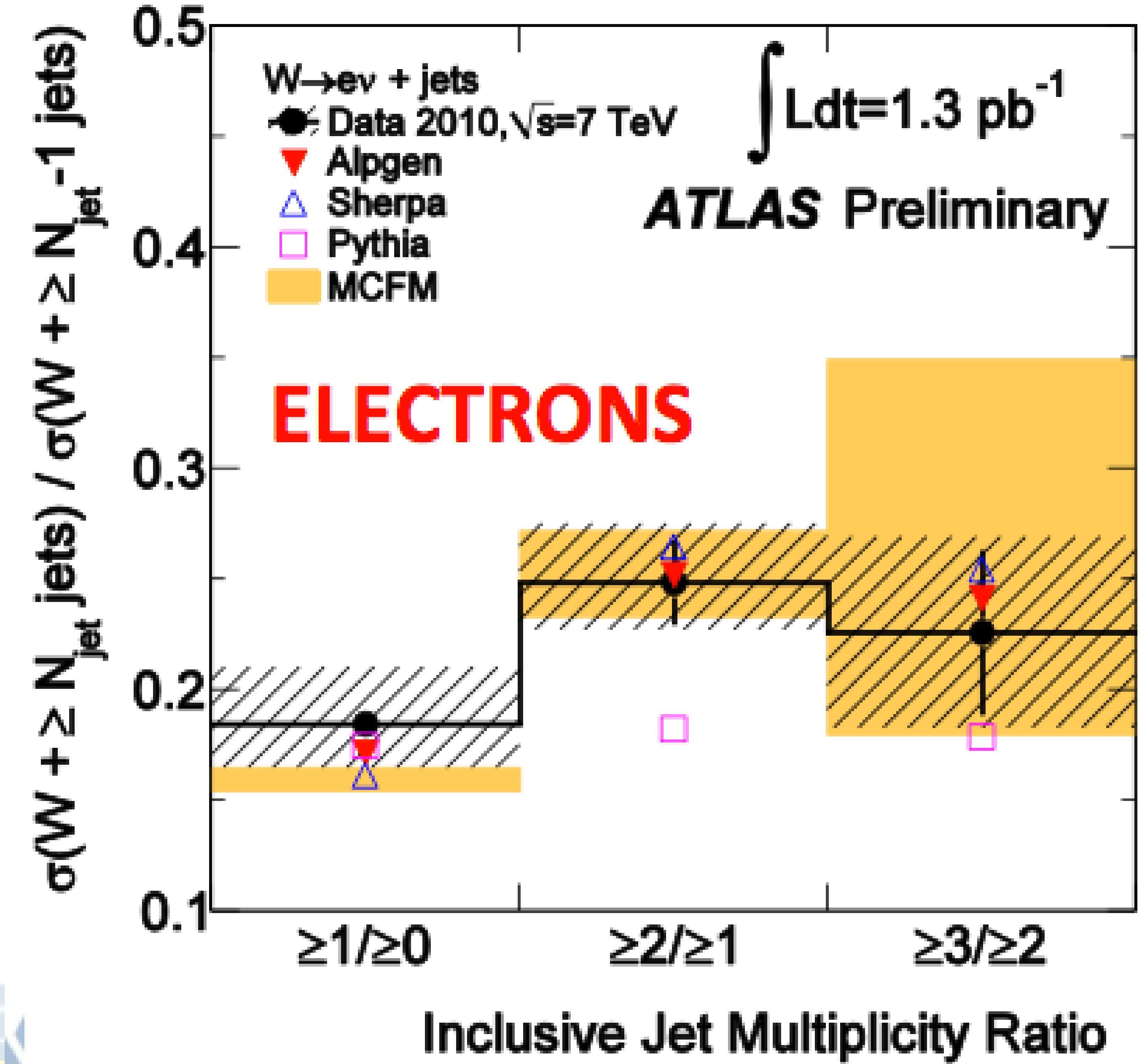
From the perspective of QCD, the modeling of W and Z pt is the same. So the different levels of agreement between data and theory in these two plots suggest that some more tuning of the detector description is required before moving on to quantitative tuning of QCD MCs.

W+jets



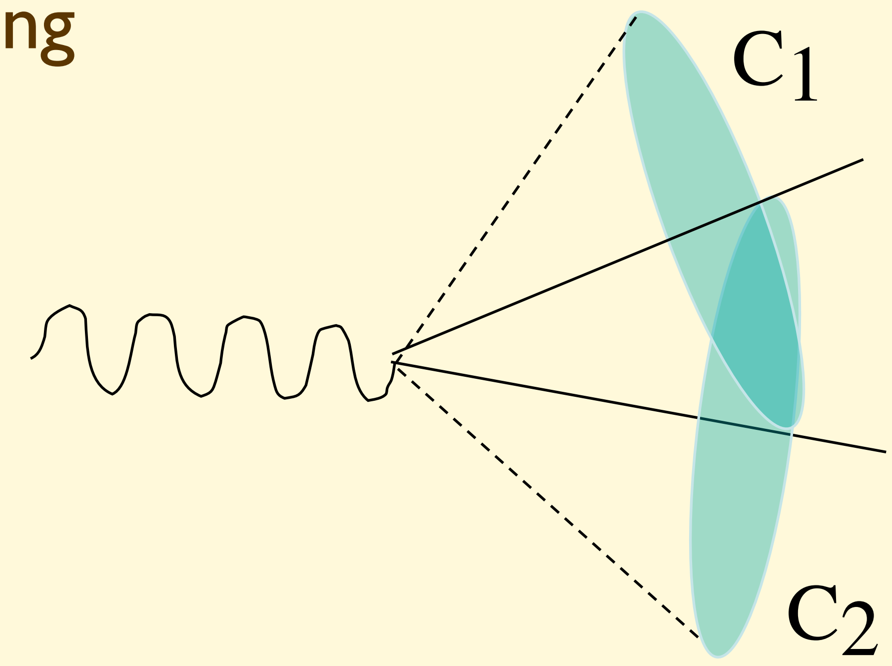
Statistics even out in the e and mu channels at large N_{jet}, making the agreement even more remarkable


W→eν + jets
Data 2010,√s=7 TeV
Alpgen
Sherpa
Pythia
MCFM
∫Ldt=1.3 pb-1
ATLAS Preliminary
ELECTRONS
σ(W + ≥ Njet jets) [pb]
Theory/Data
≥0
≥1
≥2
≥3
Inclusive Jet Multiplicity, Njet


W→eν + jets
Data 2010,√s=7 TeV
Alpgen
Sherpa
Pythia
MCFM
∫Ldt=1.3 pb-1
ATLAS Preliminary
ELECTRONS
σ(W + ≥ Njet jets) / σ(W + ≥ Njet-1 jets)
≥1/≥0
≥2/≥1
≥3/≥2
Inclusive Jet Multiplicity Ratio

Main limitation of shower approach:

Because of angular ordering



no emission outside $C_1 \oplus C_2$:

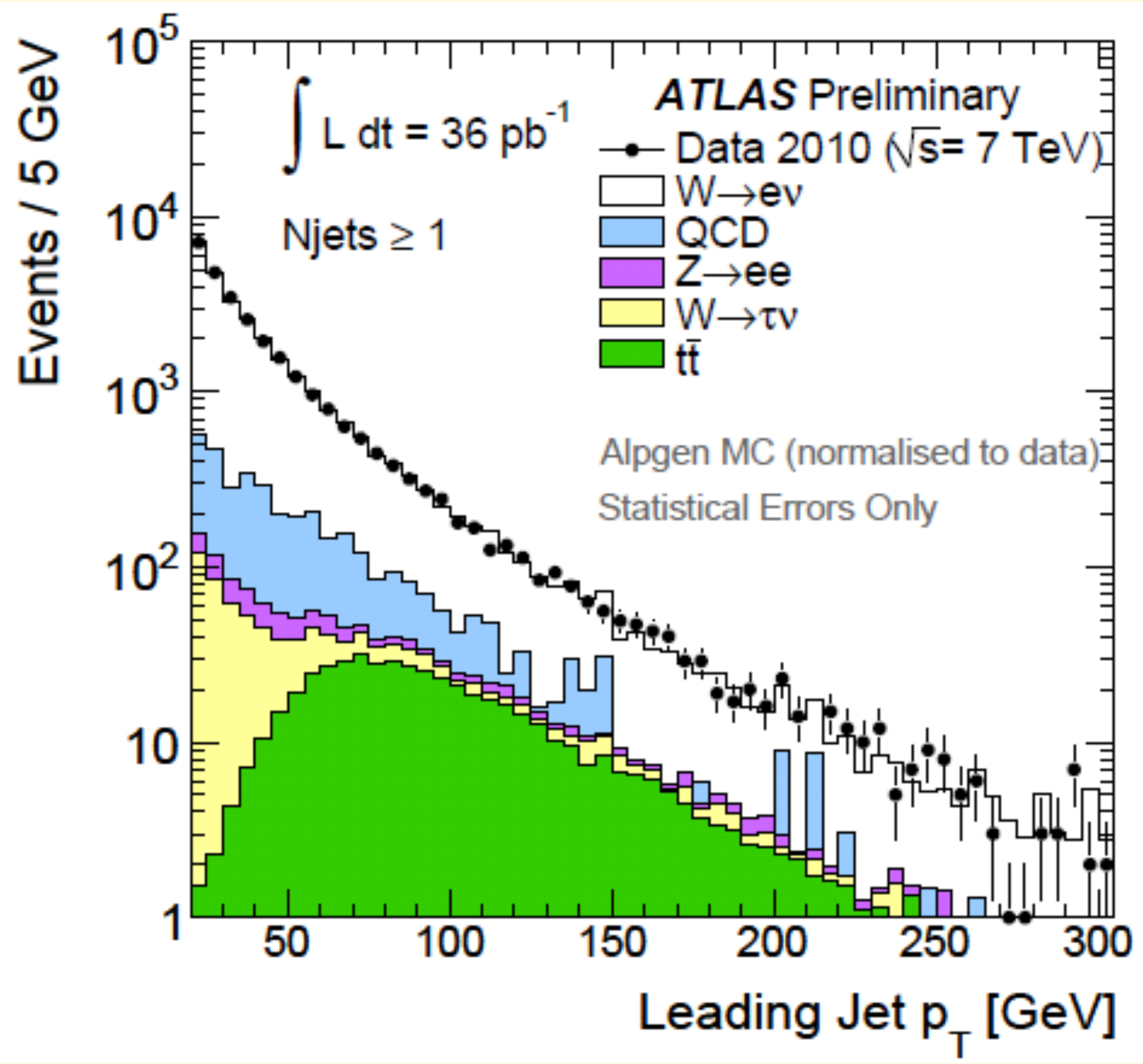
- lack of hard, large-angle emission
- poor description of multijet events

incoherent emission inside $C_1 \oplus C_2$:

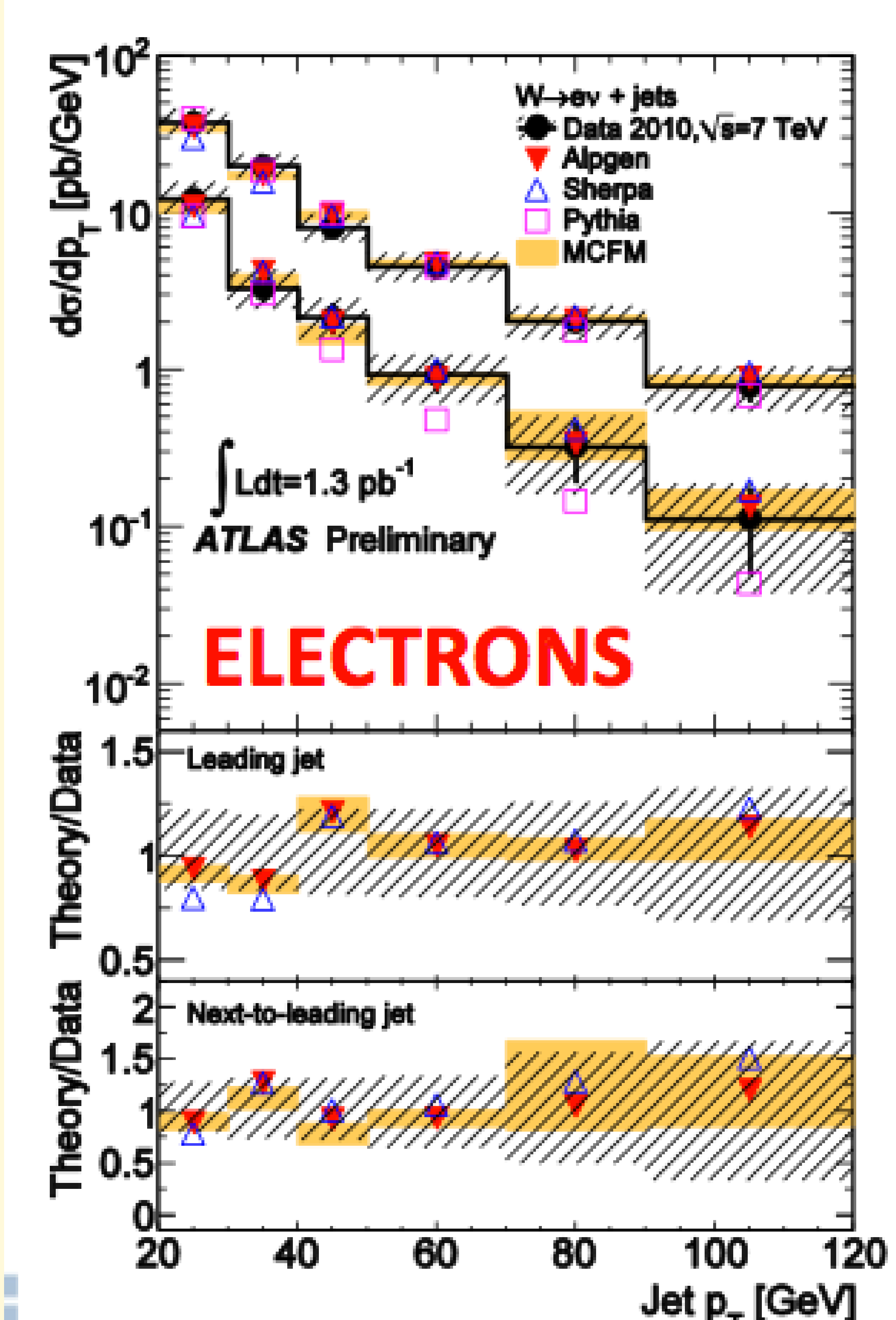
- loss of accuracy for intrajet radiation

The soft-gluon approximation used in the shower MCs is appropriate to describe the evolution of individual jets, and to connect the perturbative hard process to the full hadronic final state, but the emission of hard radiation, as in the case of multijet final states, must be calculated using exact matrix elements

W+jets, E_T spectrum

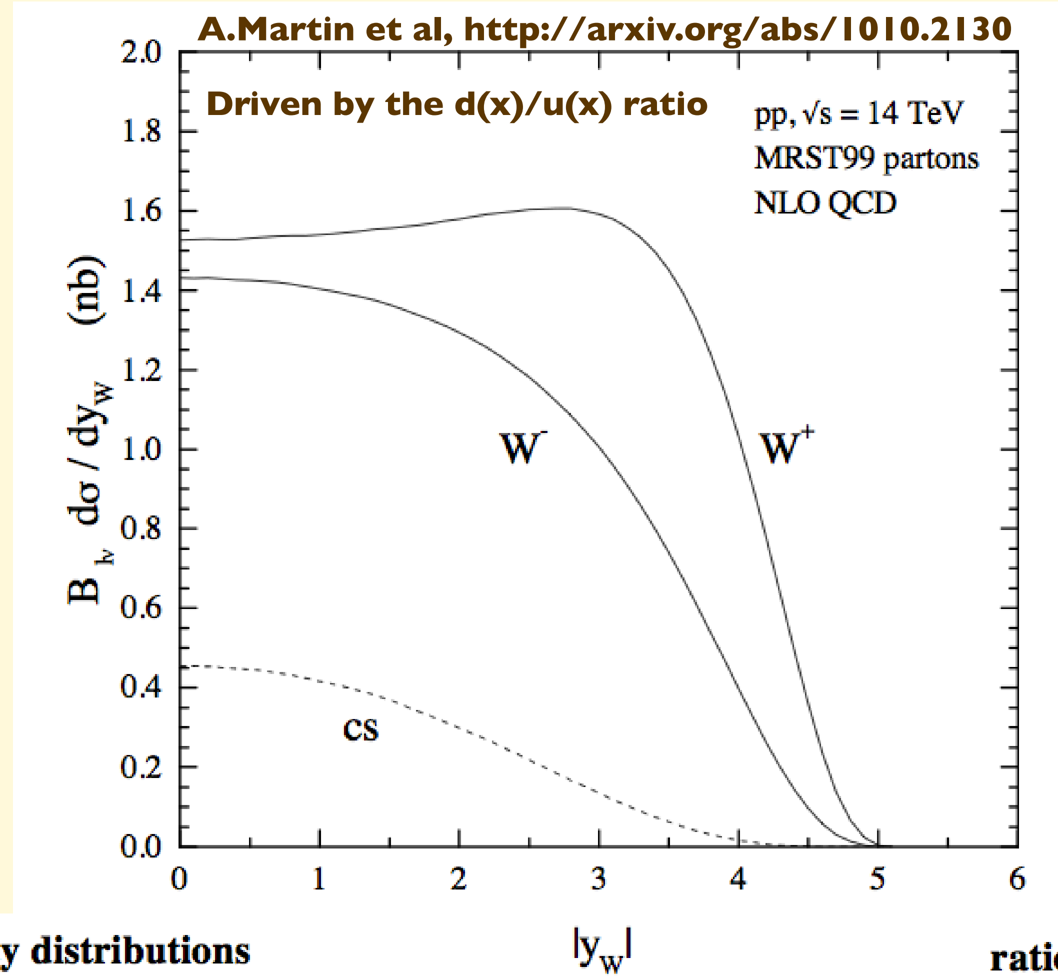


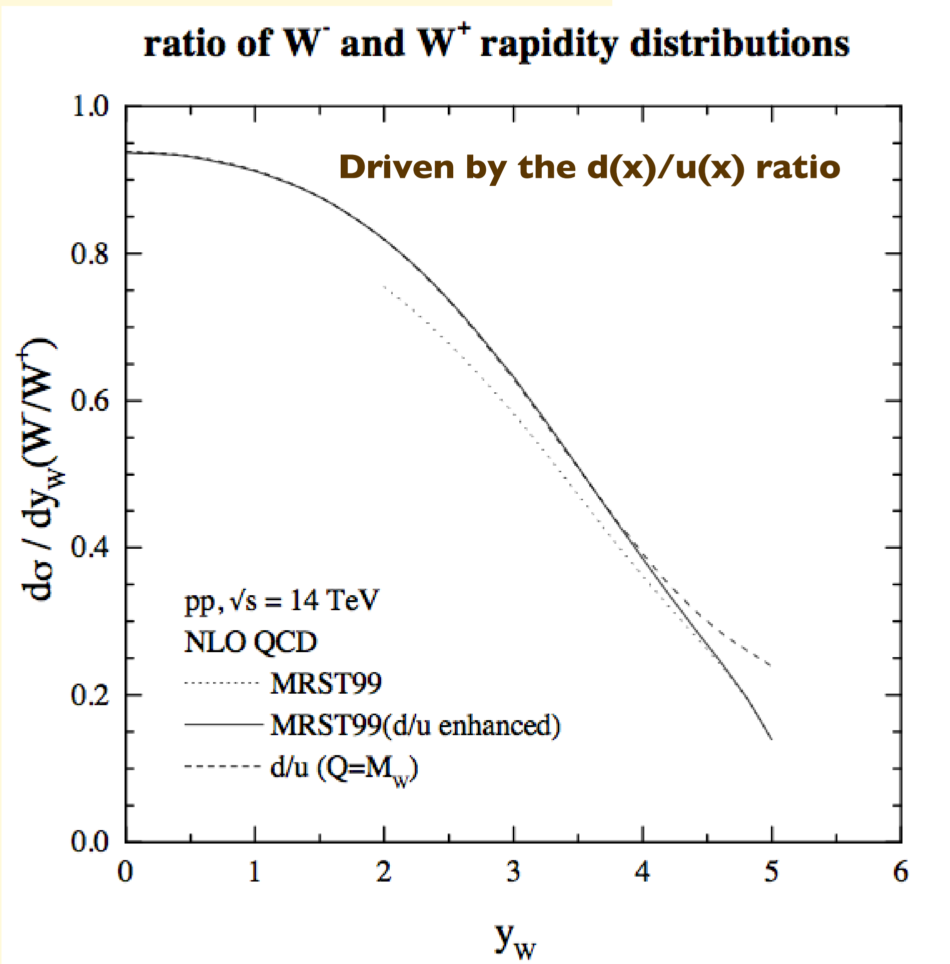
Uncorrected data

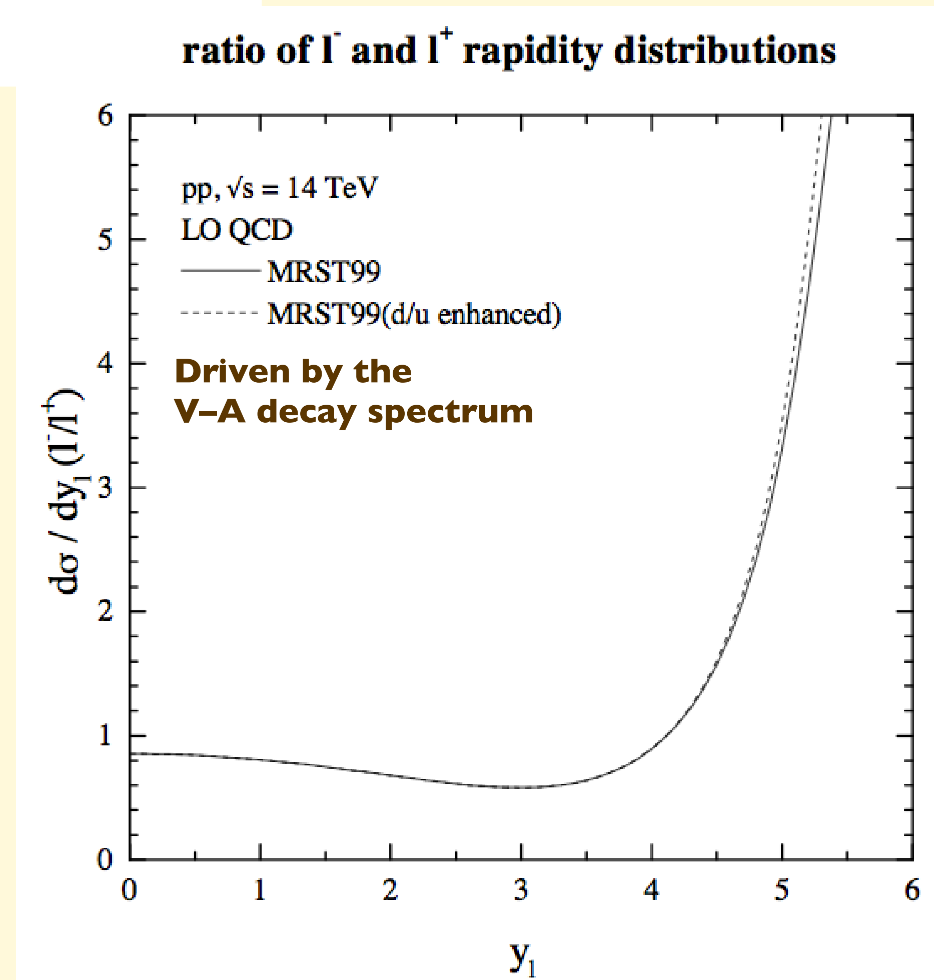


Hadron-level corrected data

W+ / W– production asymmetries



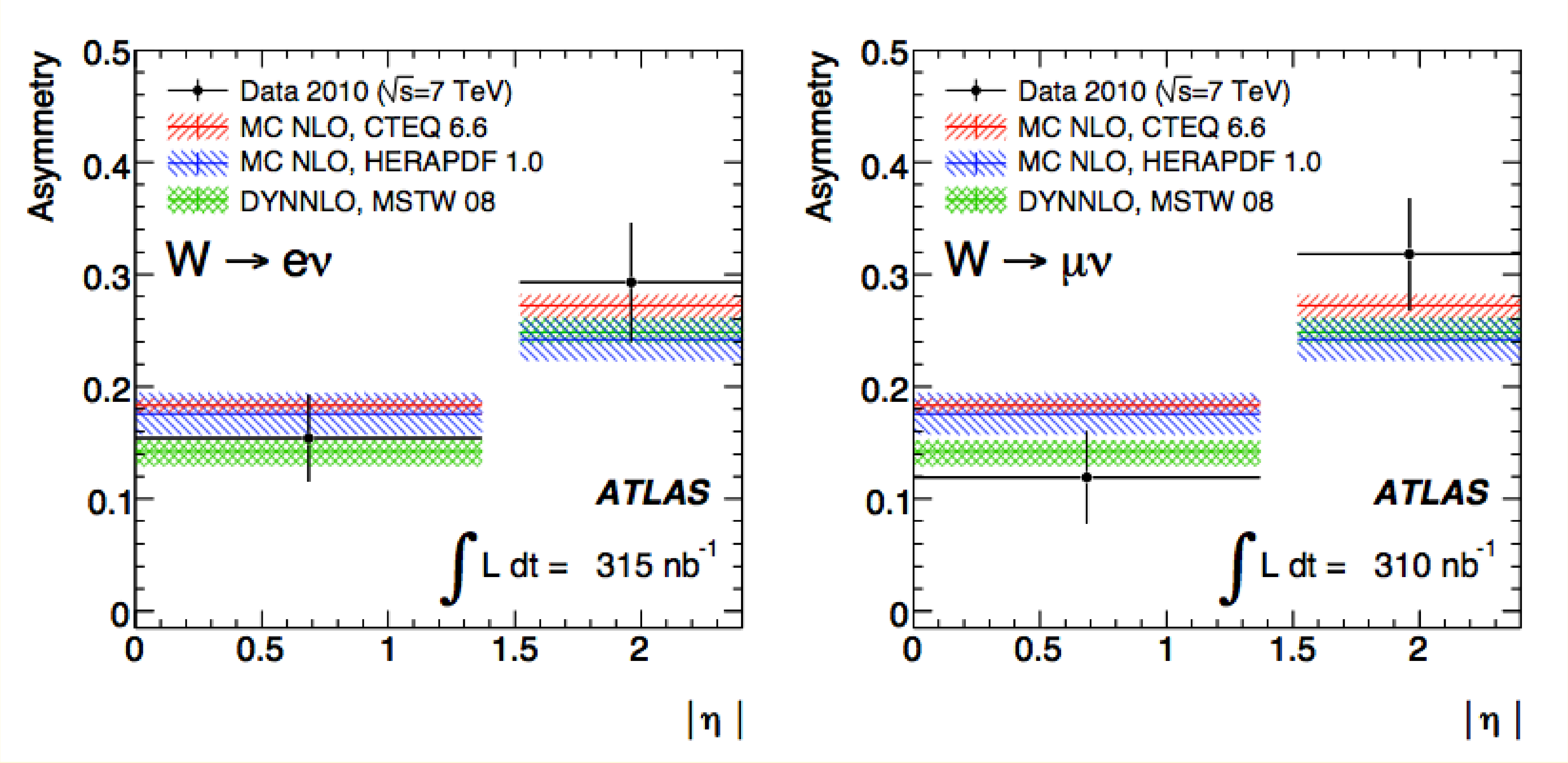




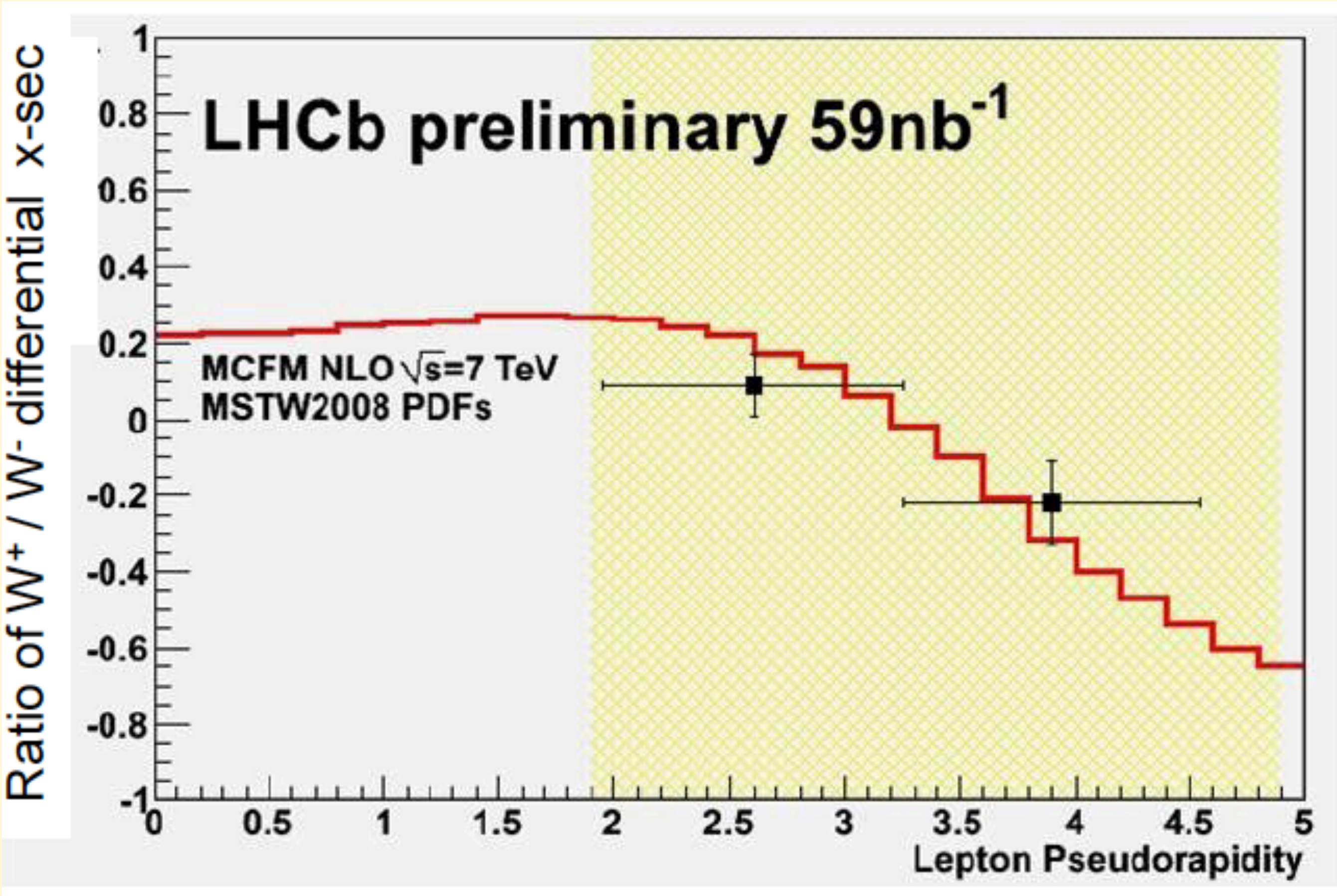
Lepton charge asymmetry at the LHC

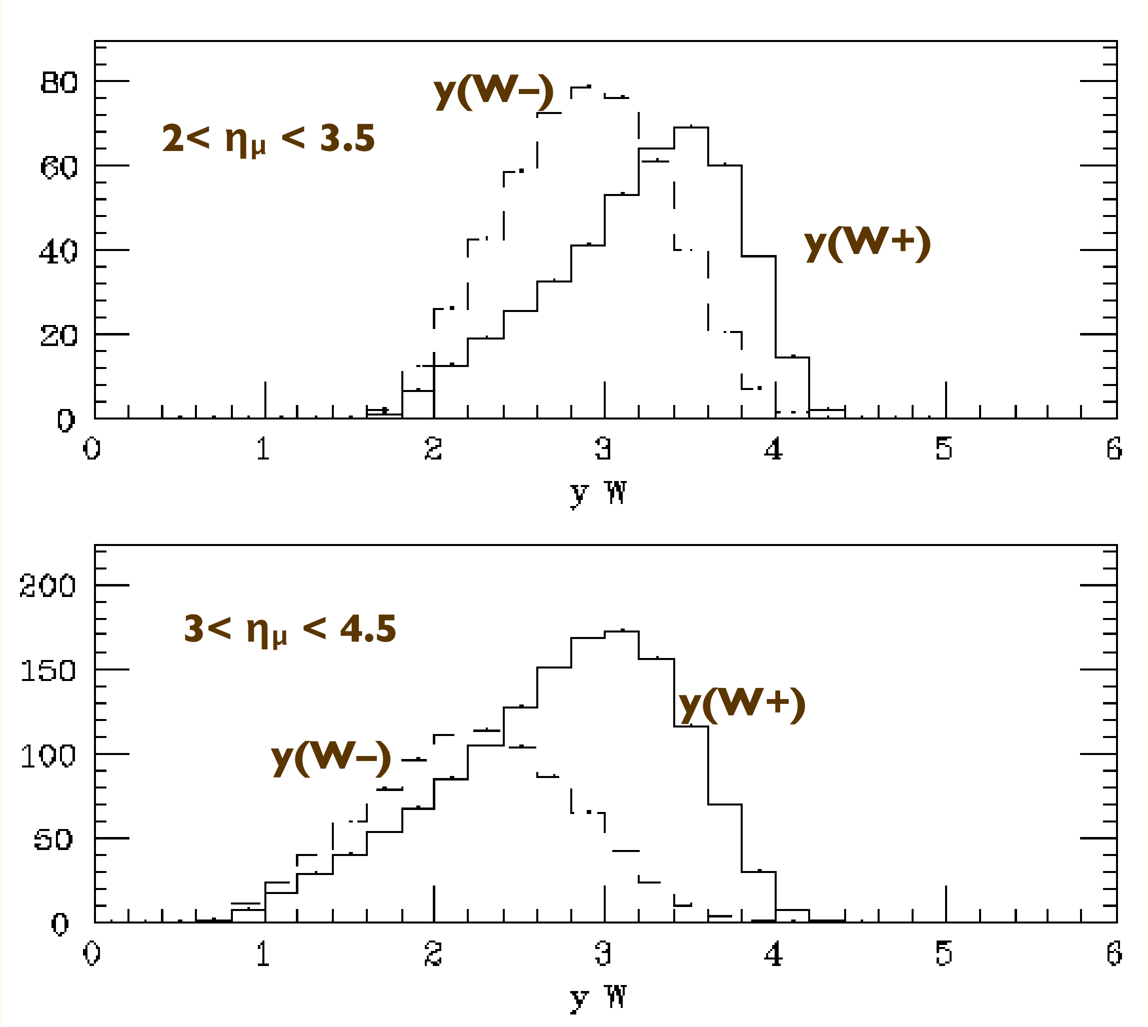
$$A_\ell = \frac{\sigma^{\rm fid}_{W^+} - \sigma^{\rm fid}_{W^-}}{\sigma^{\rm fid}_{W^+} + \sigma^{\rm fid}_{W^-}}$$

320 nb^{-1}, http://arxiv.org/abs/1010.2130



EW boson production in the forward region, LHCb

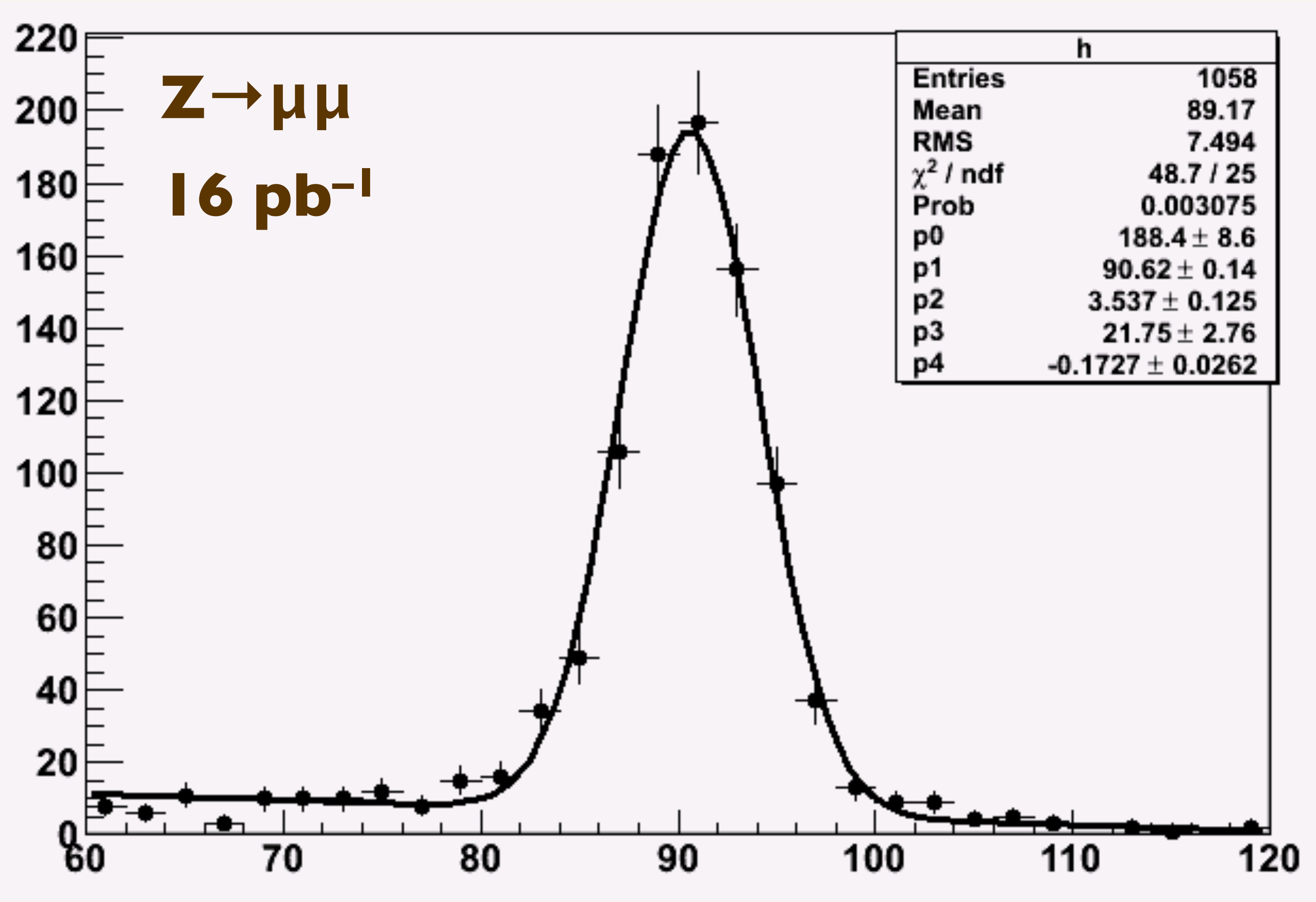




W→μν, charge asymmetry

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



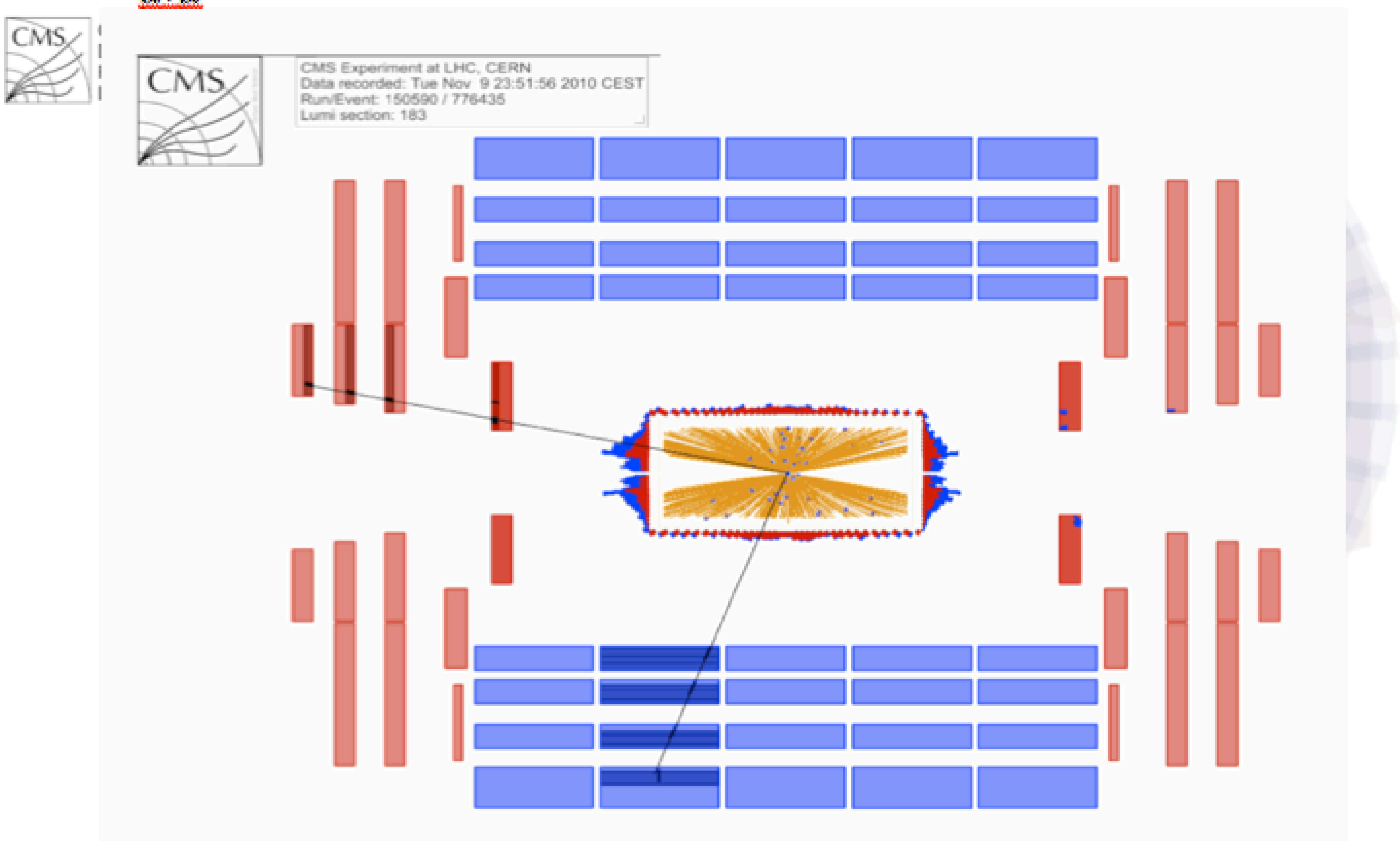
These observations open the way for many interesting new measurements, from PDF constraints, to a determination of A_{FB} and $\sin^2\theta_W$

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

EW boson production in Pb Pb collisions, CMS

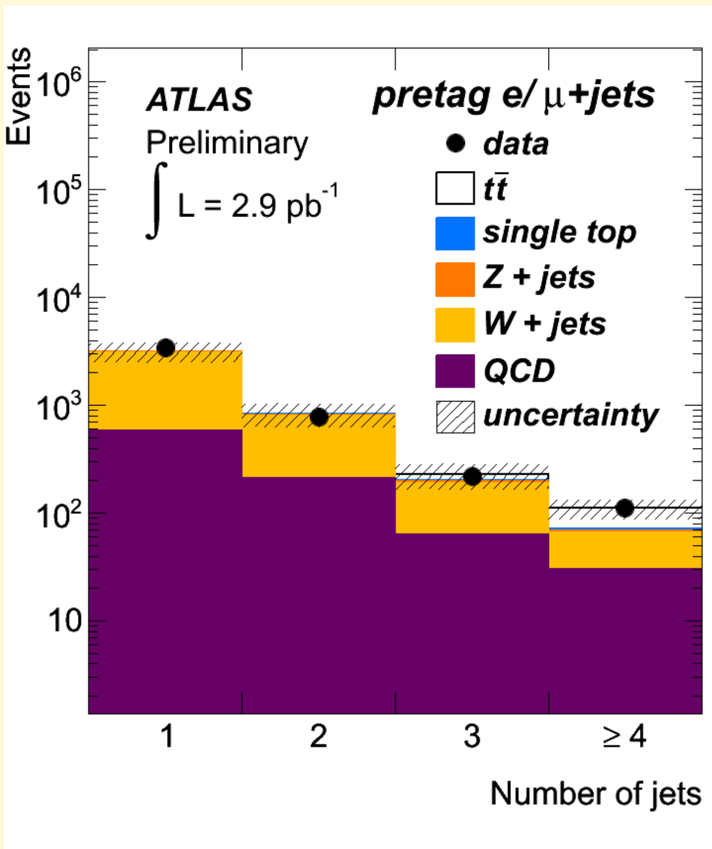
Our first $\mu^+\mu^-$ Z candidate

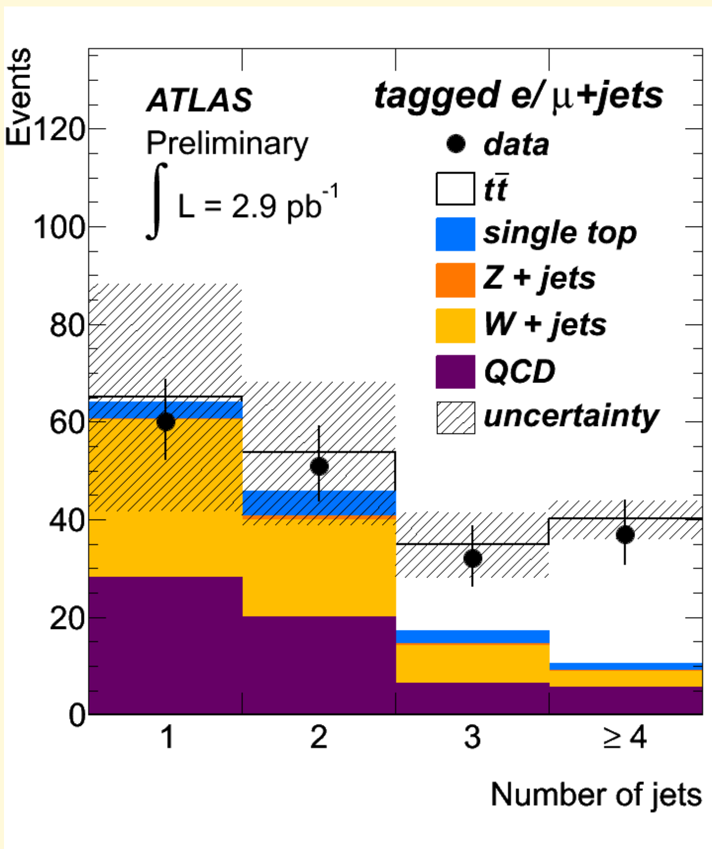
$M_{\mu+\mu-}$ = 93 GeV : possibly the first Z ever seen in HI

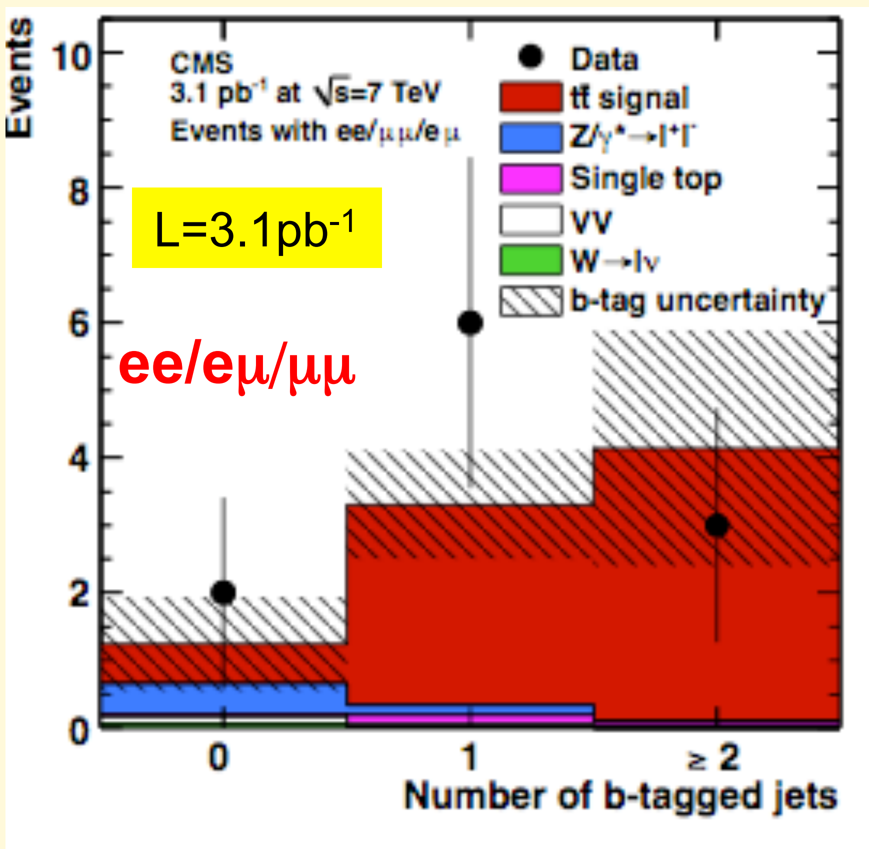


Heavy quarks

Top

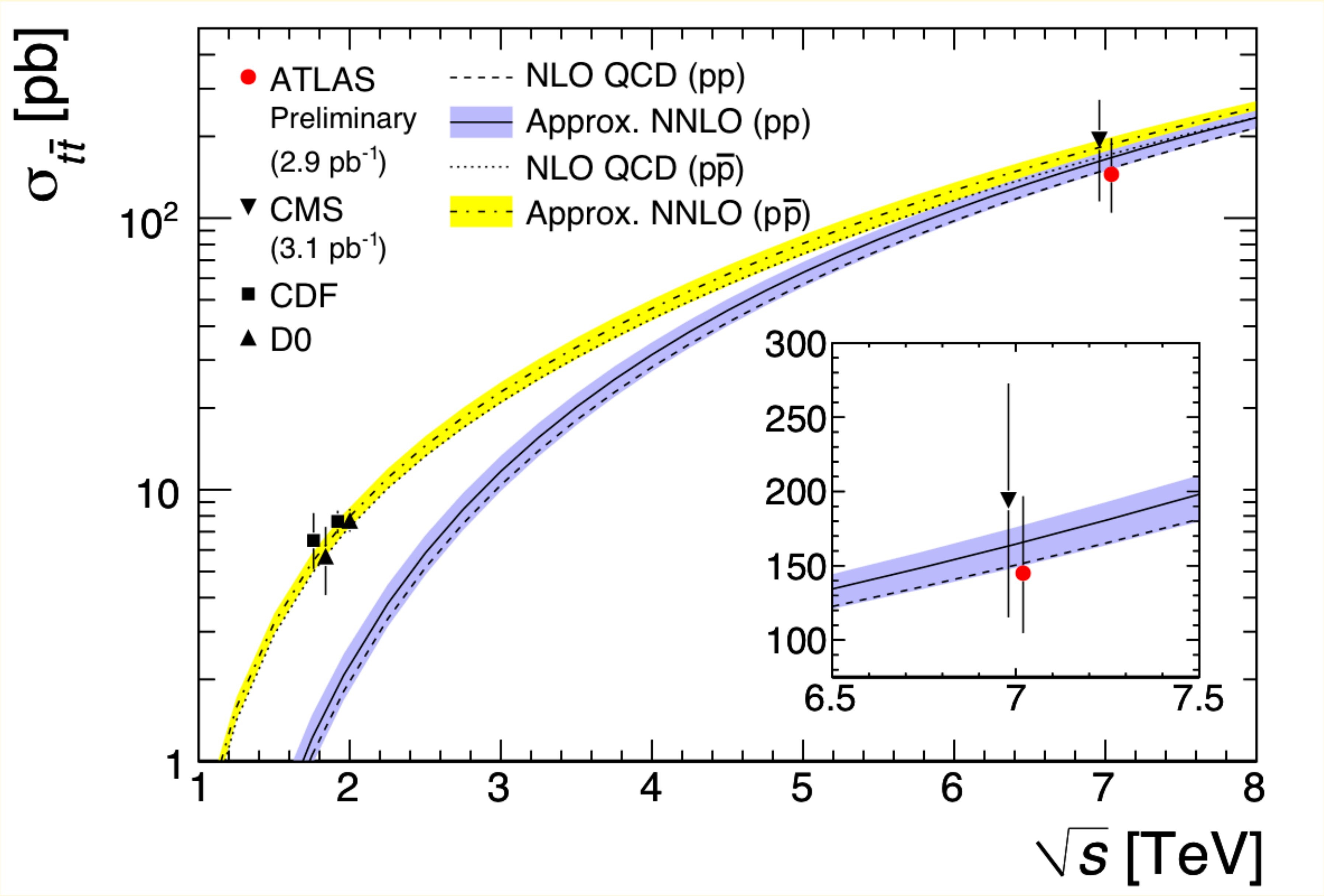






1 e or μ with p_T>20 GeV, E_T^{miss}>20 GeV, $E_T^{miss}+m_T(W)$>60 GeV
N_{jets} with p_T>25 GeV, with no b-tag requirement or at least one b-tag
Signal defined to have 4 or more jets, and at least 1 b-tag

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



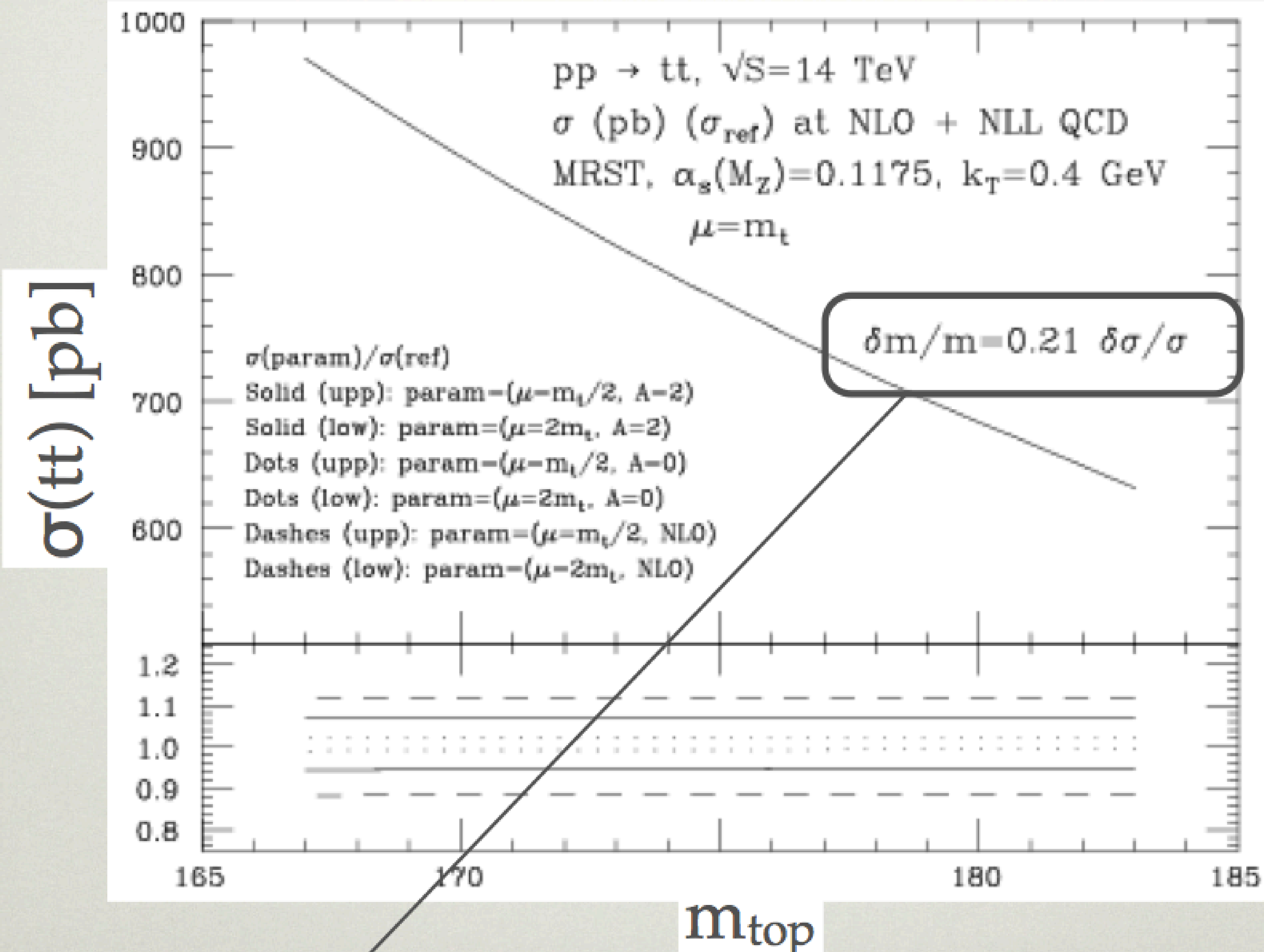
[(1)] ATLAS (lepton+b+≥3 jets and dileptons+≥2jets): $\sigma_{ATLAS} = 145 \pm 31 \begin{array}{c} +42 \\ -27 \end{array}$ pb

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

$$\sigma_{TH} = 167 \begin{array}{c} +13 \\ -10 \end{array} \text{ pb}$$

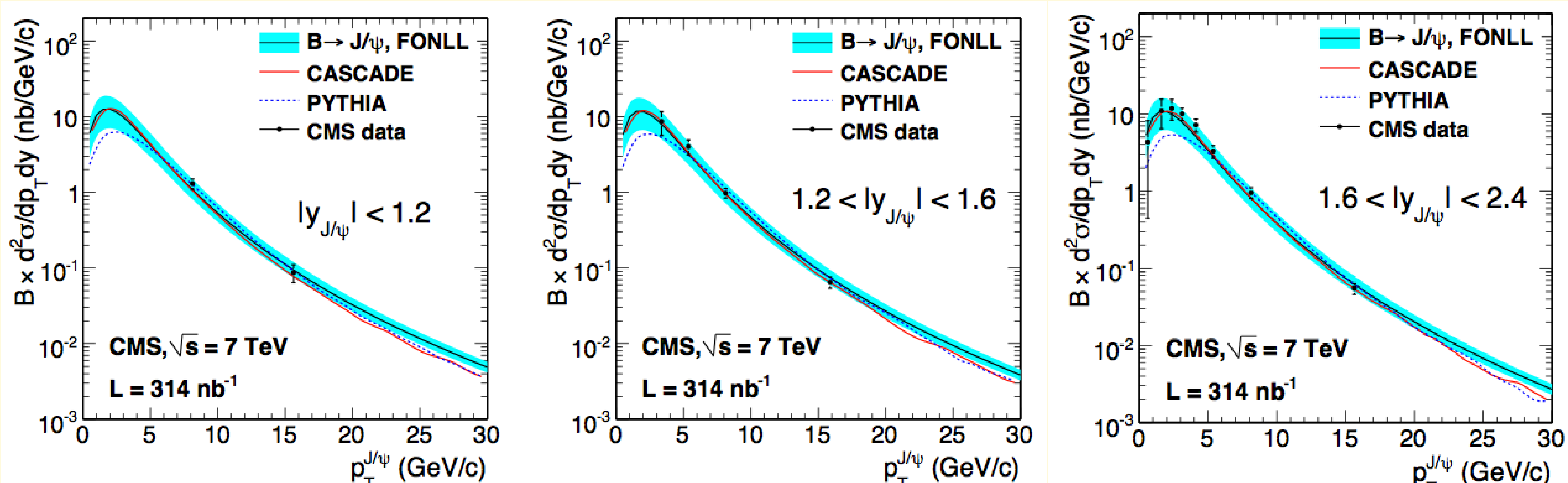
[(1)] **See P. Wells, for the ATLAS collab., 104th LHCC session, http://indico.cern.ch/conferenceDisplay.py?confId=112439**

[(2)] **arXiv:1010.5994**

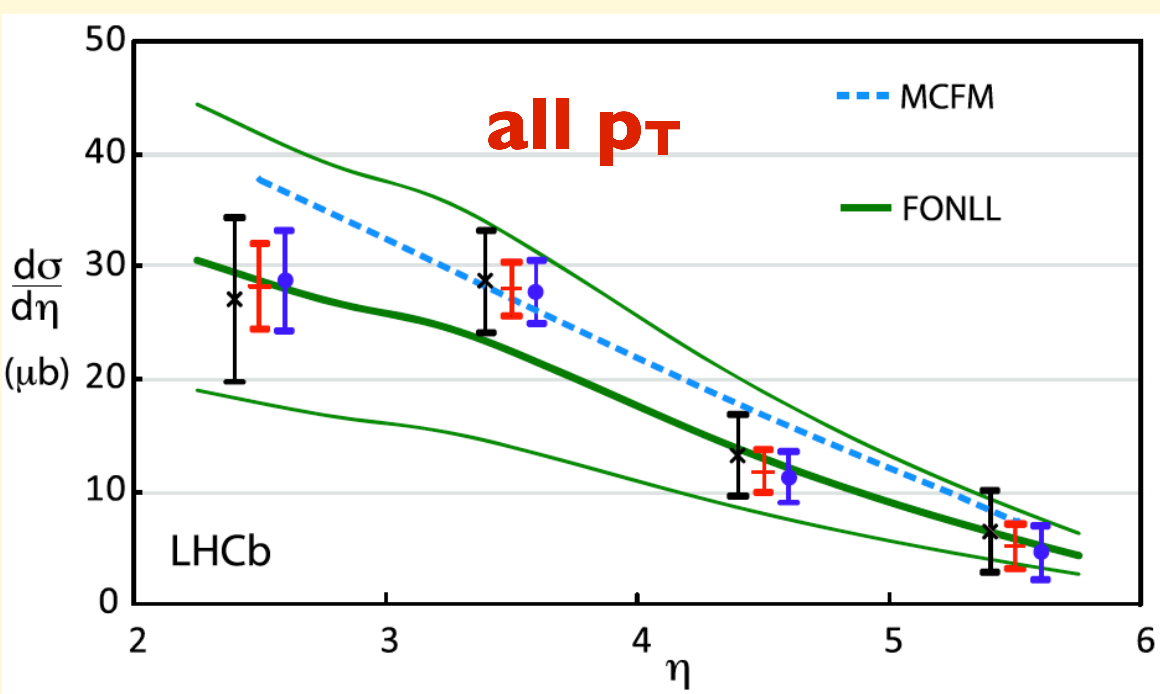


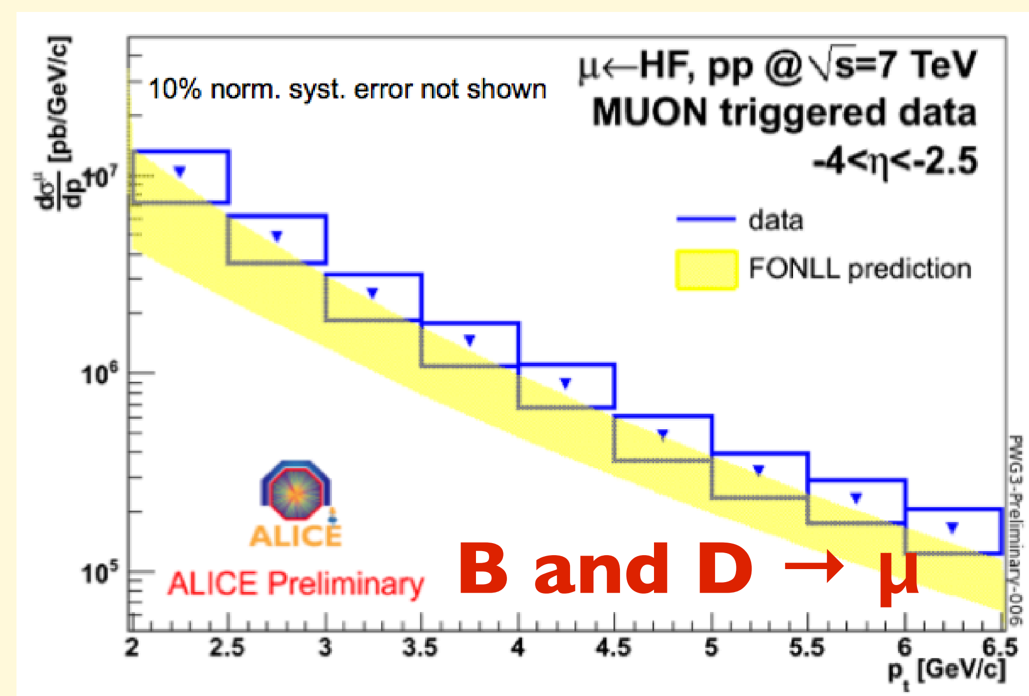
$\Delta\sigma/\sigma = \pm 5\% \Leftrightarrow \Delta m/m = \pm 1\% \lesssim 2$ GeV, comparable to Δm_{direct}

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



http://arxiv.org/abs/1011.4193



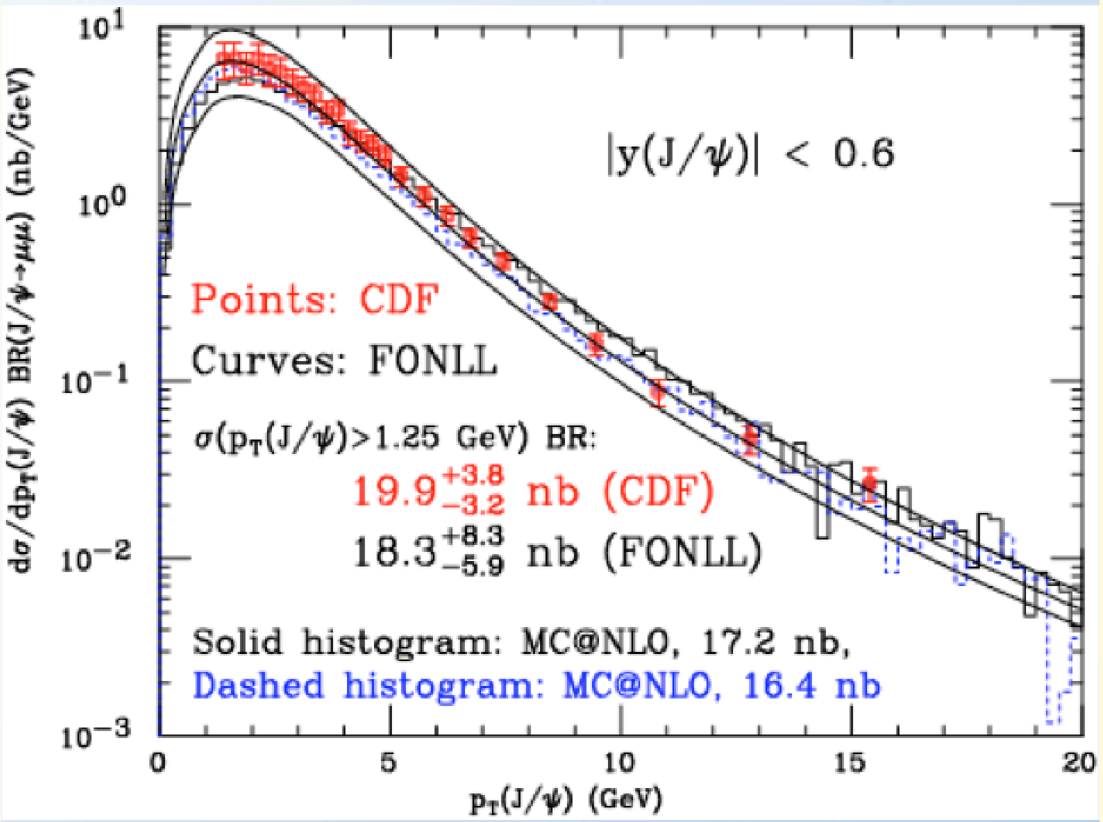


This agreement is one of the most significant results from LHC-2010

Why is it not trivial?

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

hep-ph/0411020

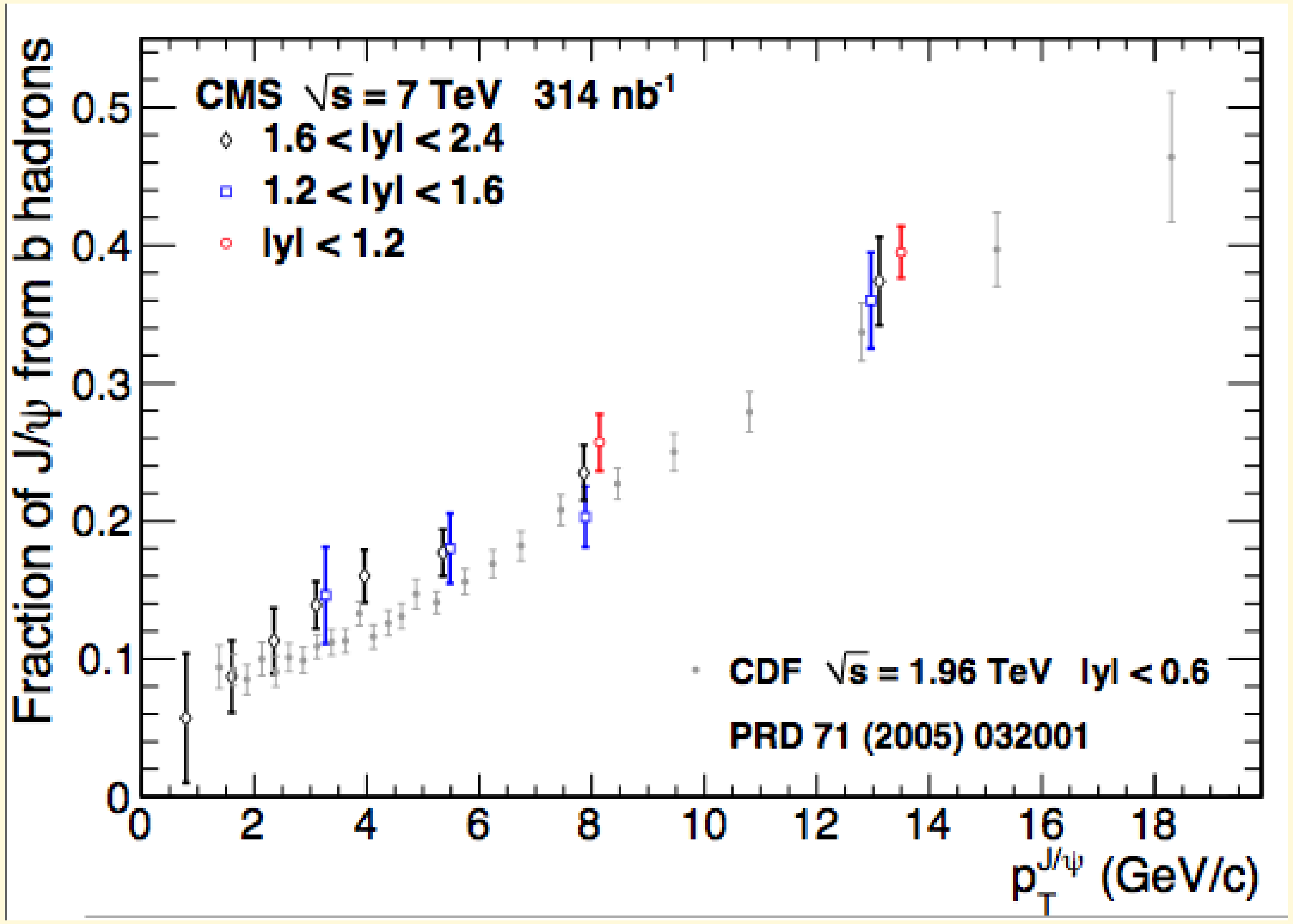


The dynamical regime of the LHC is theoretically more challenging

- 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
....

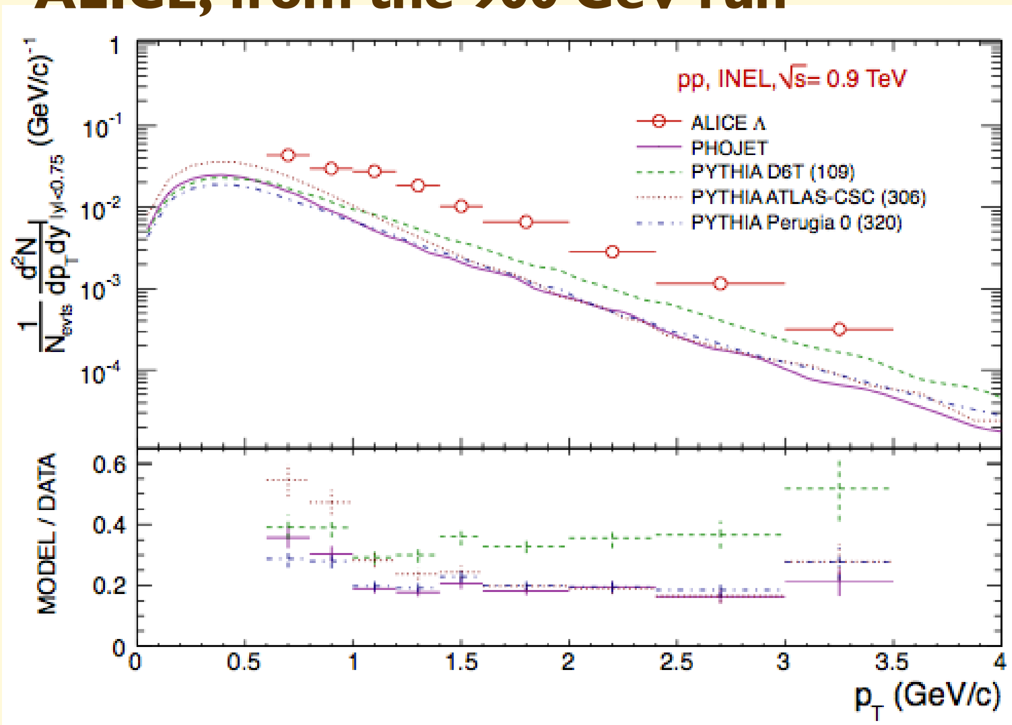
J/psi production: fraction of prompt and b-decay

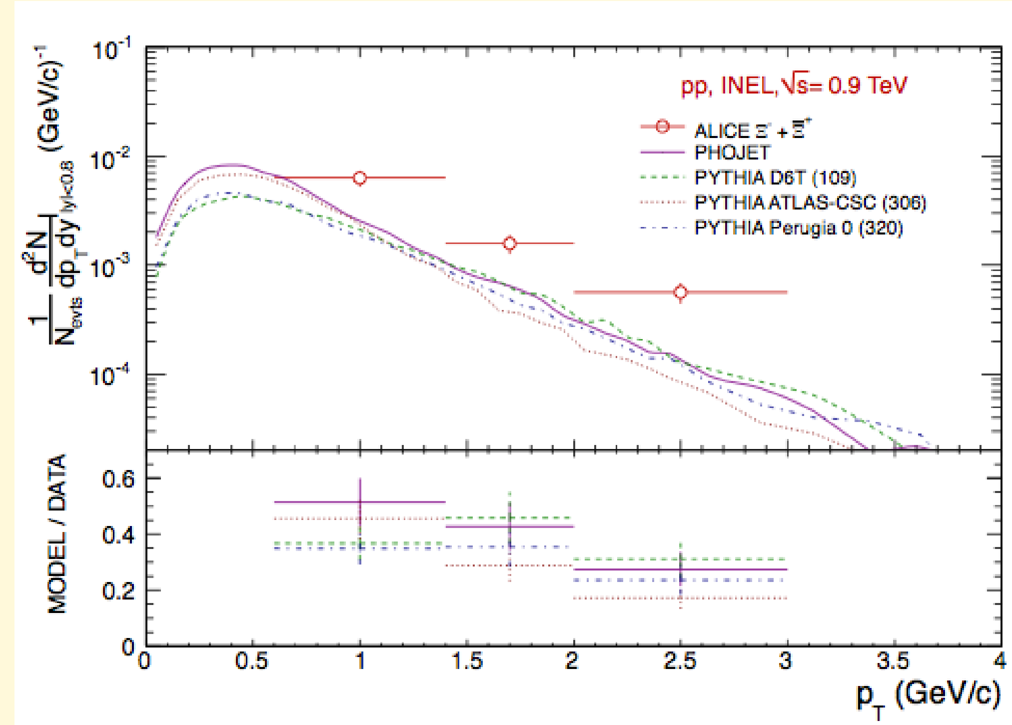


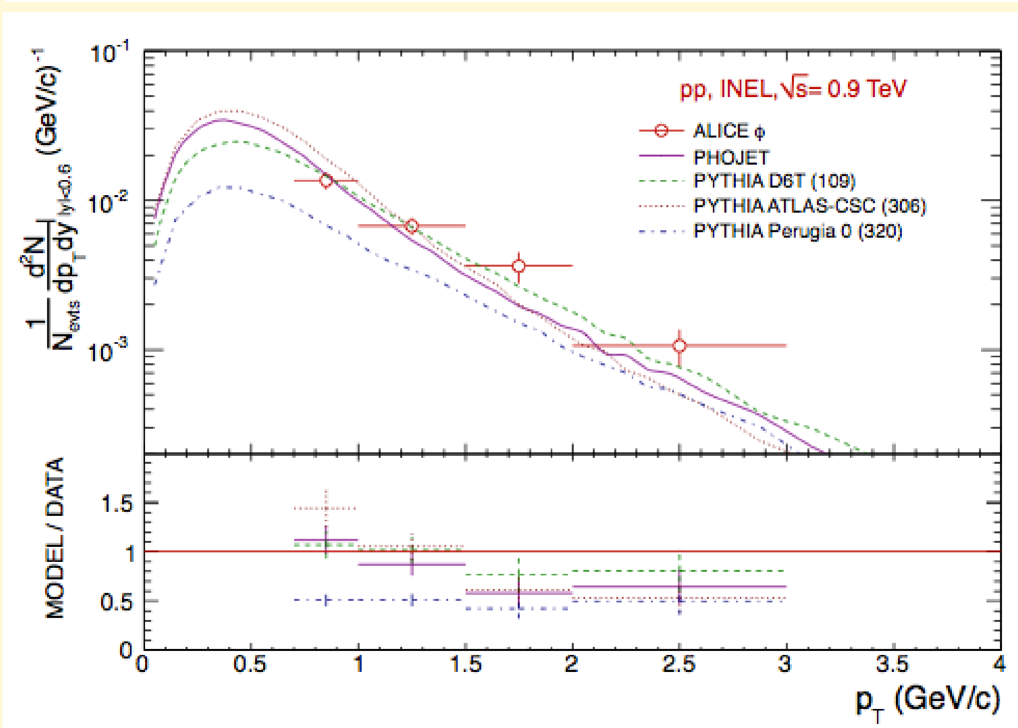
General properties of inclusive final states, a few examples

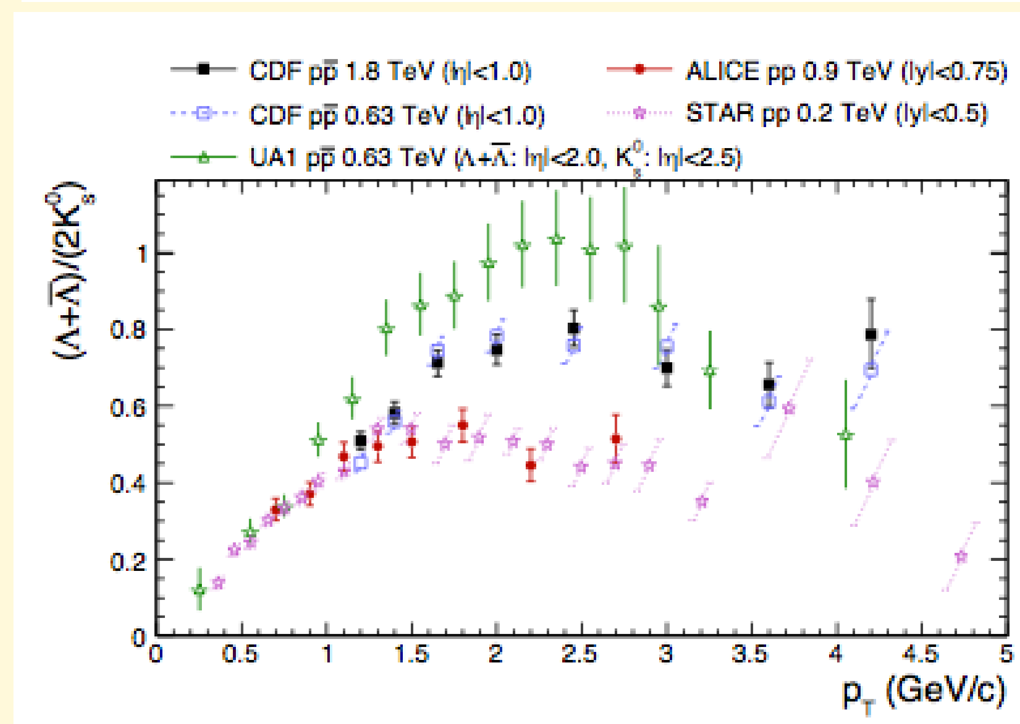
Strange particle production

ALICE, from the 900 GeV run





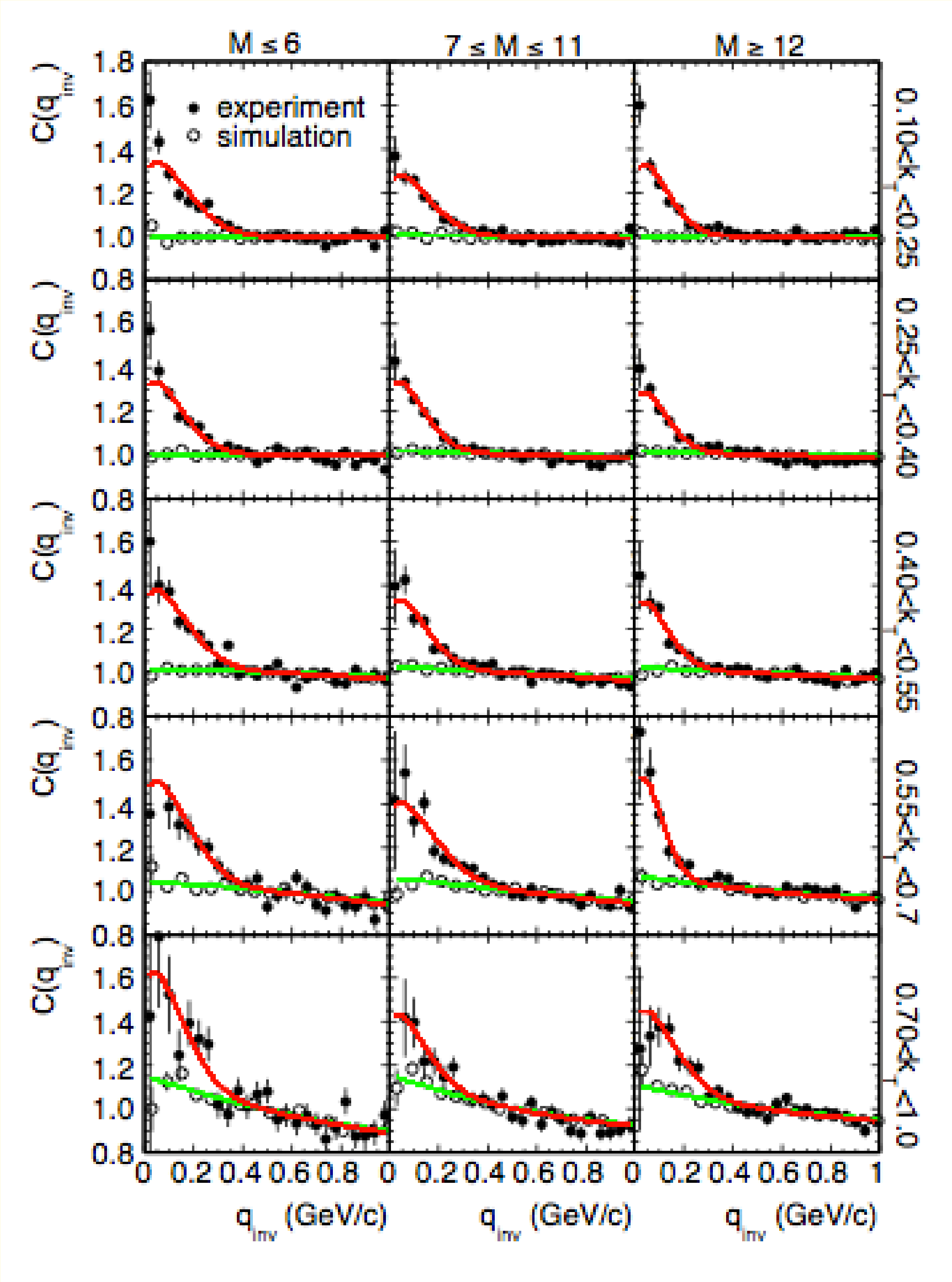




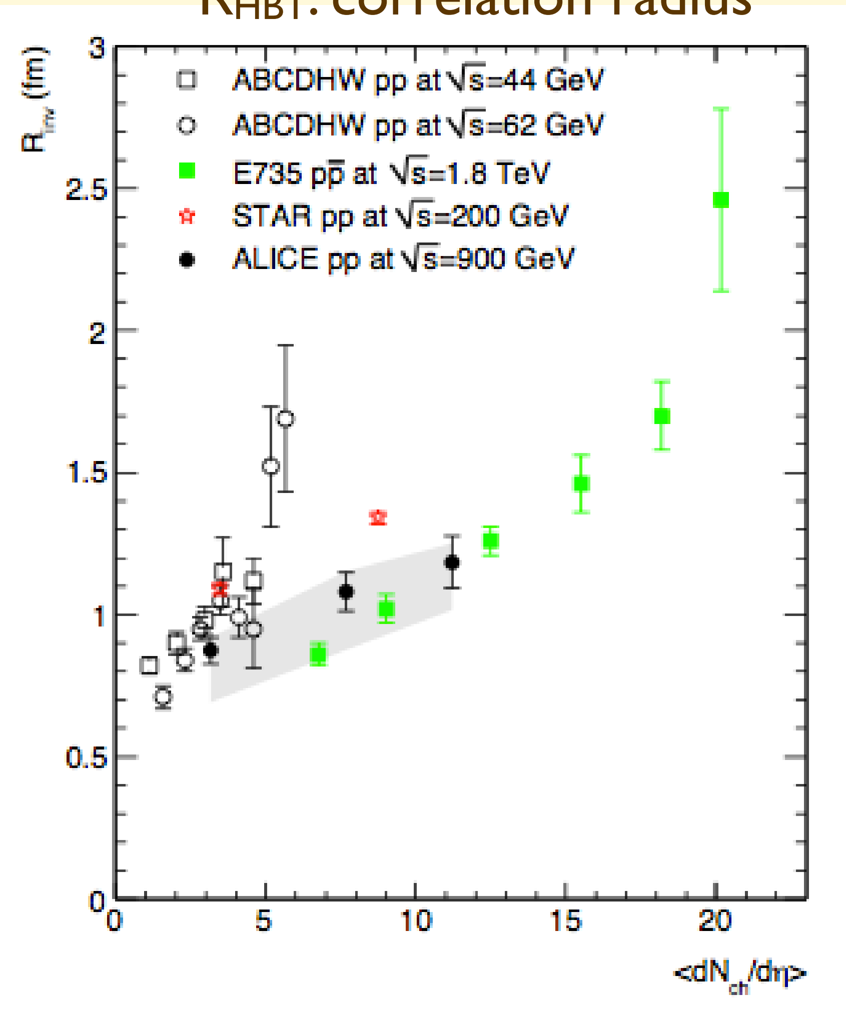
Very important benchmark for strangeness production studies in Pb-Pb, needs further clarification!

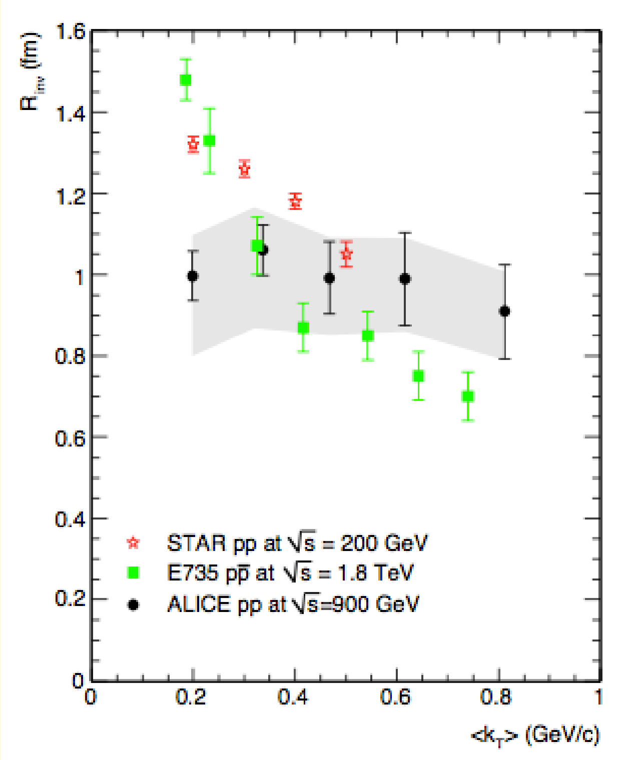
Bose-Einstein correlations

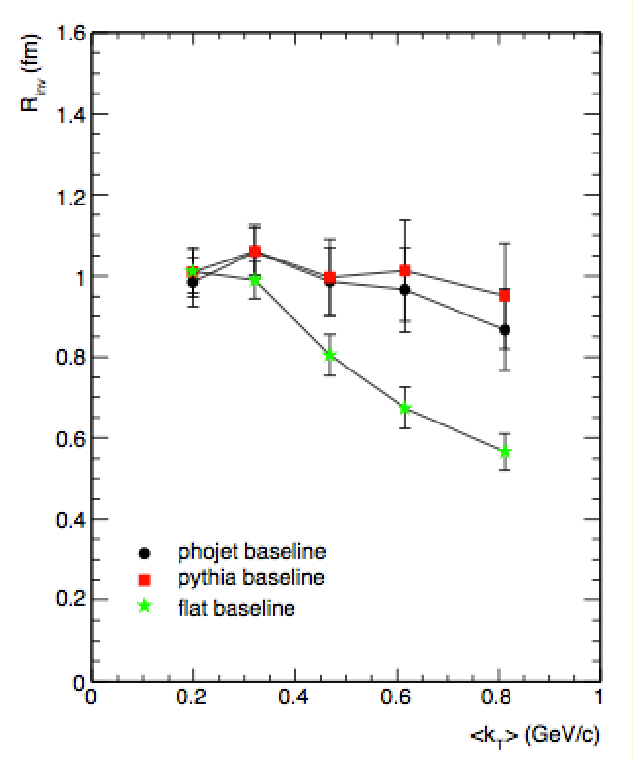
ALICE, from the 900 GeV run



R_{HBT}: correlation radius







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

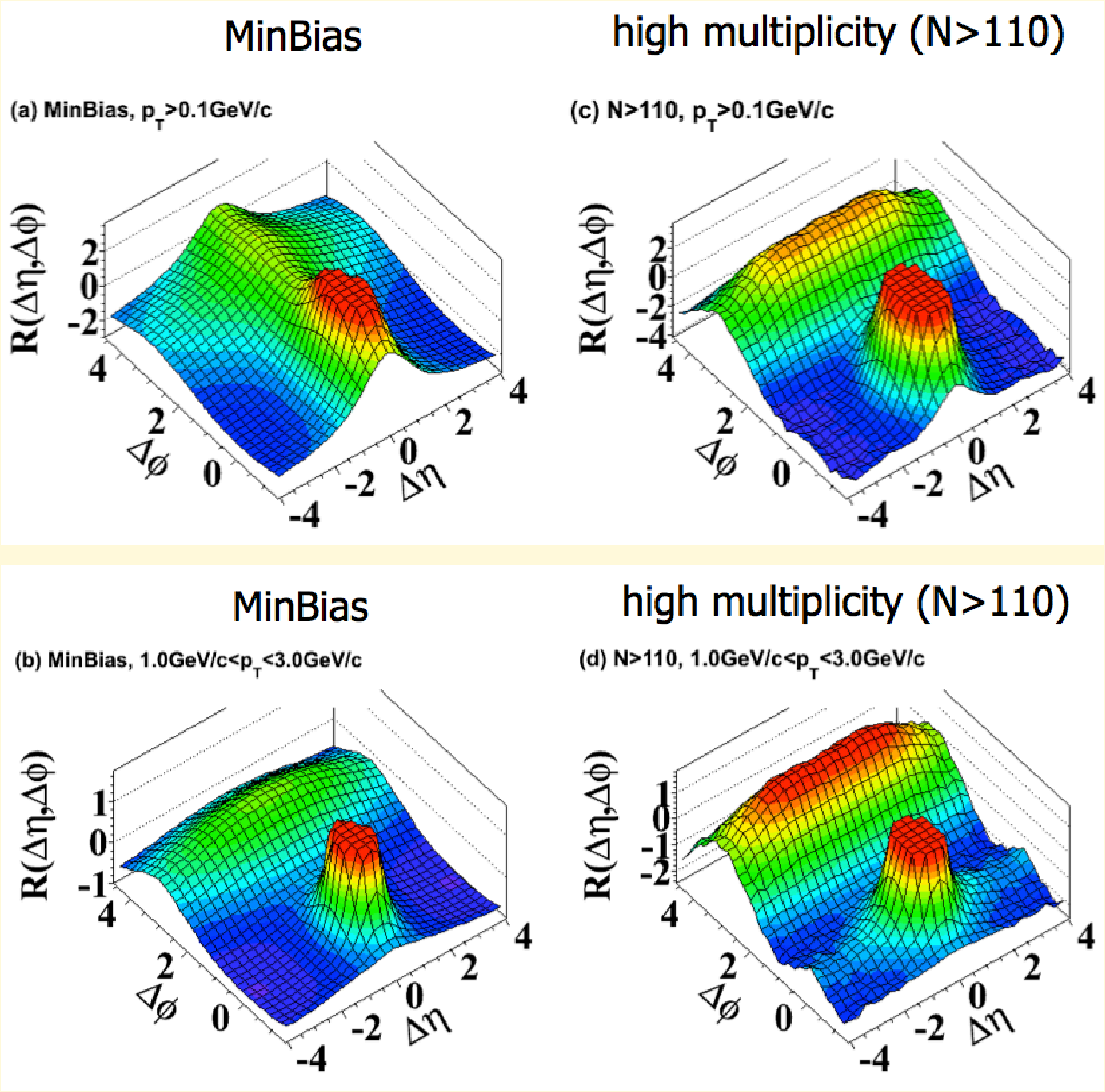
C(q)= A(q)/B(q), where:

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

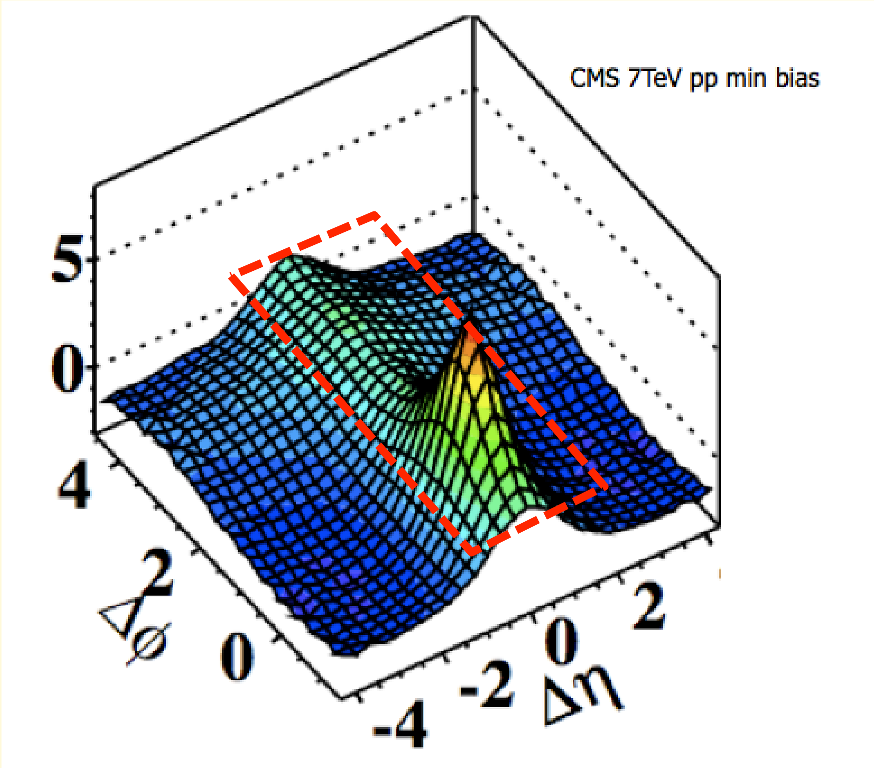
B(q)=$\pi^{\pm}\pi^{\pm}$ c.f., with particles from different events

CMS's "ridge" in high-multiplicity events

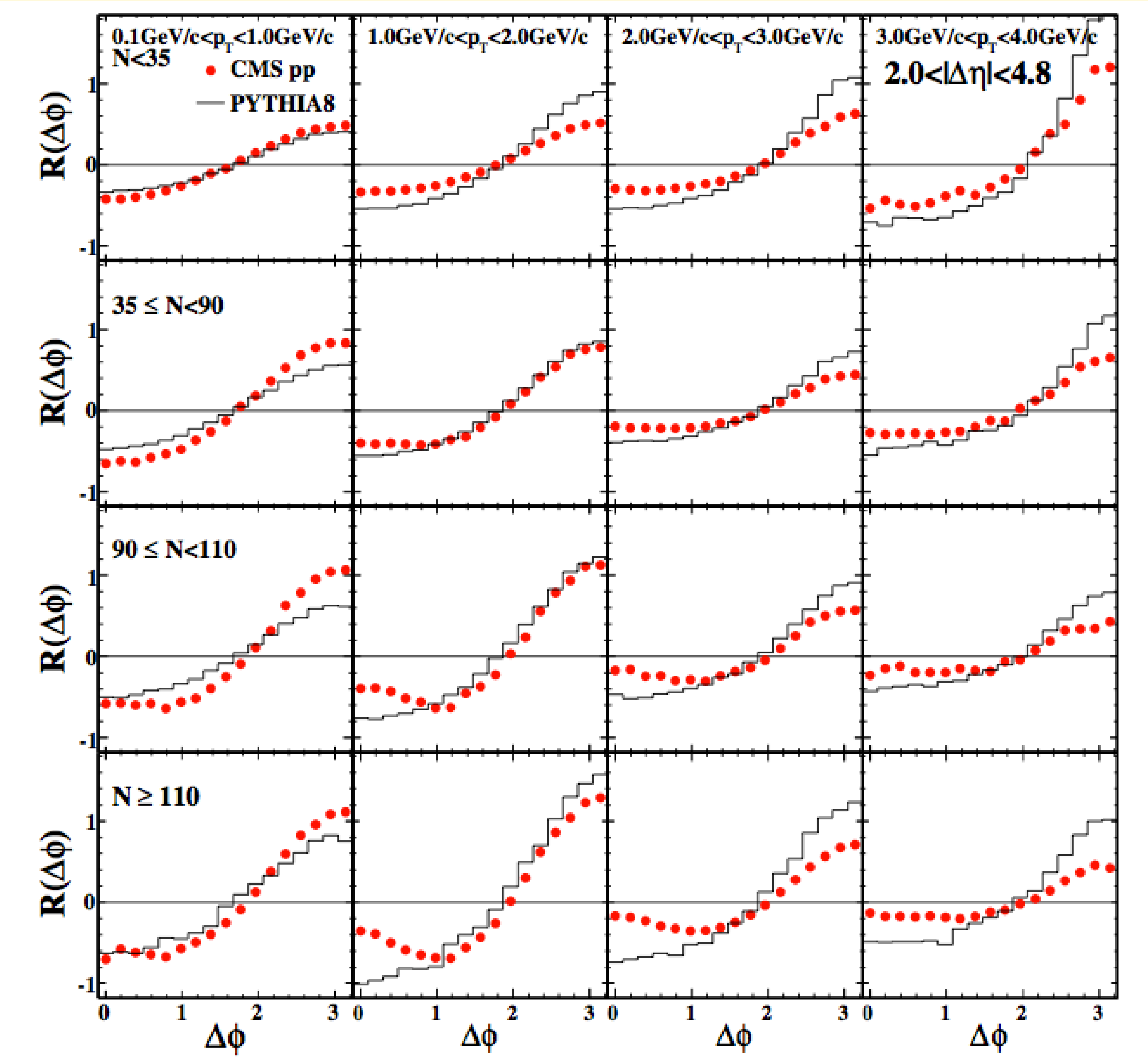
2-particle correlation function $$S_N(\Delta\eta,\Delta\varphi)=\frac{1}{N(N-1)}\frac{d^2N^{signal}}{d\Delta\eta d\Delta\varphi}$$



CMS's "ridge" in high-multiplicity events

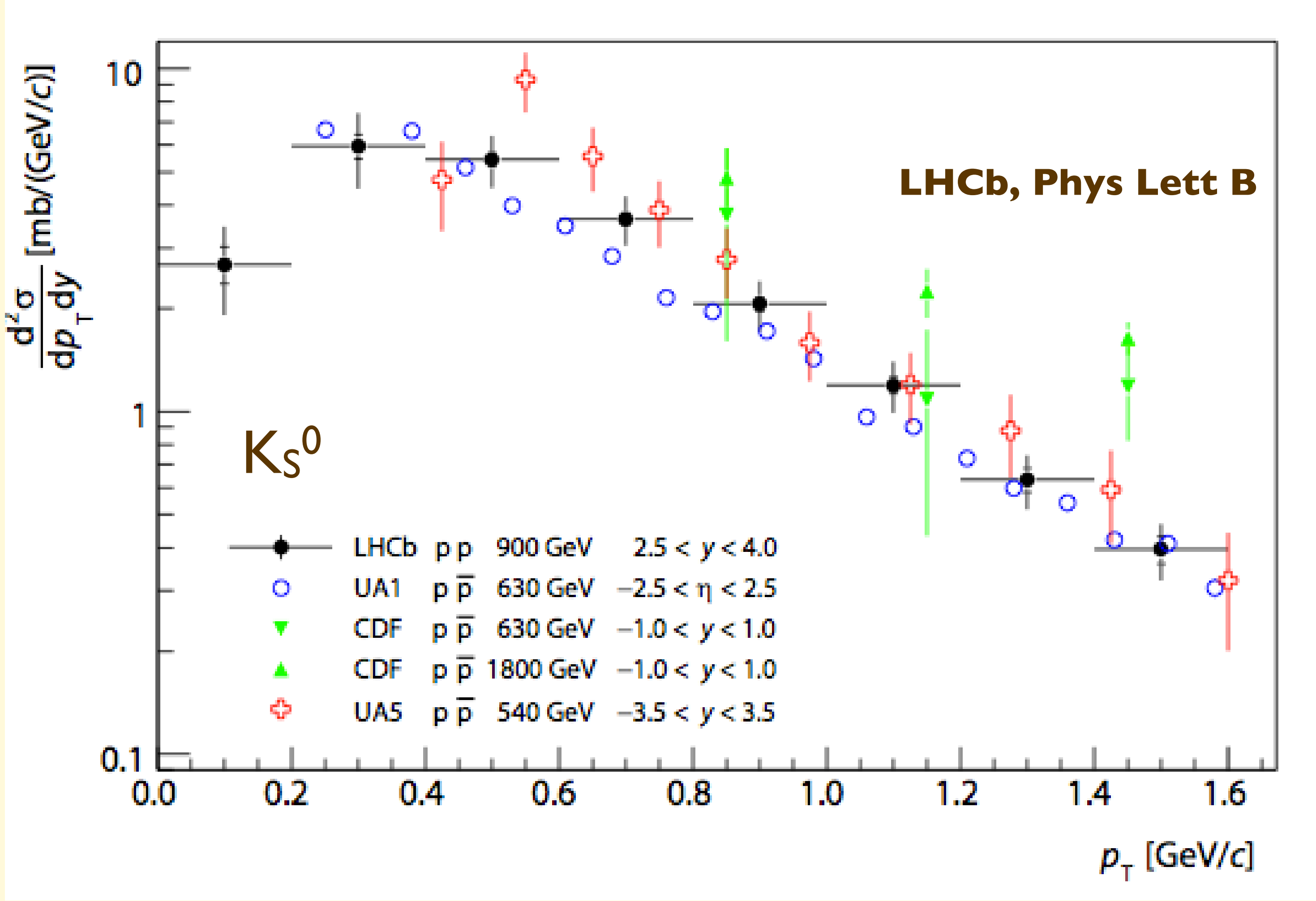


Integrating in eta, outside of the jet region:



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)

Strange particle production

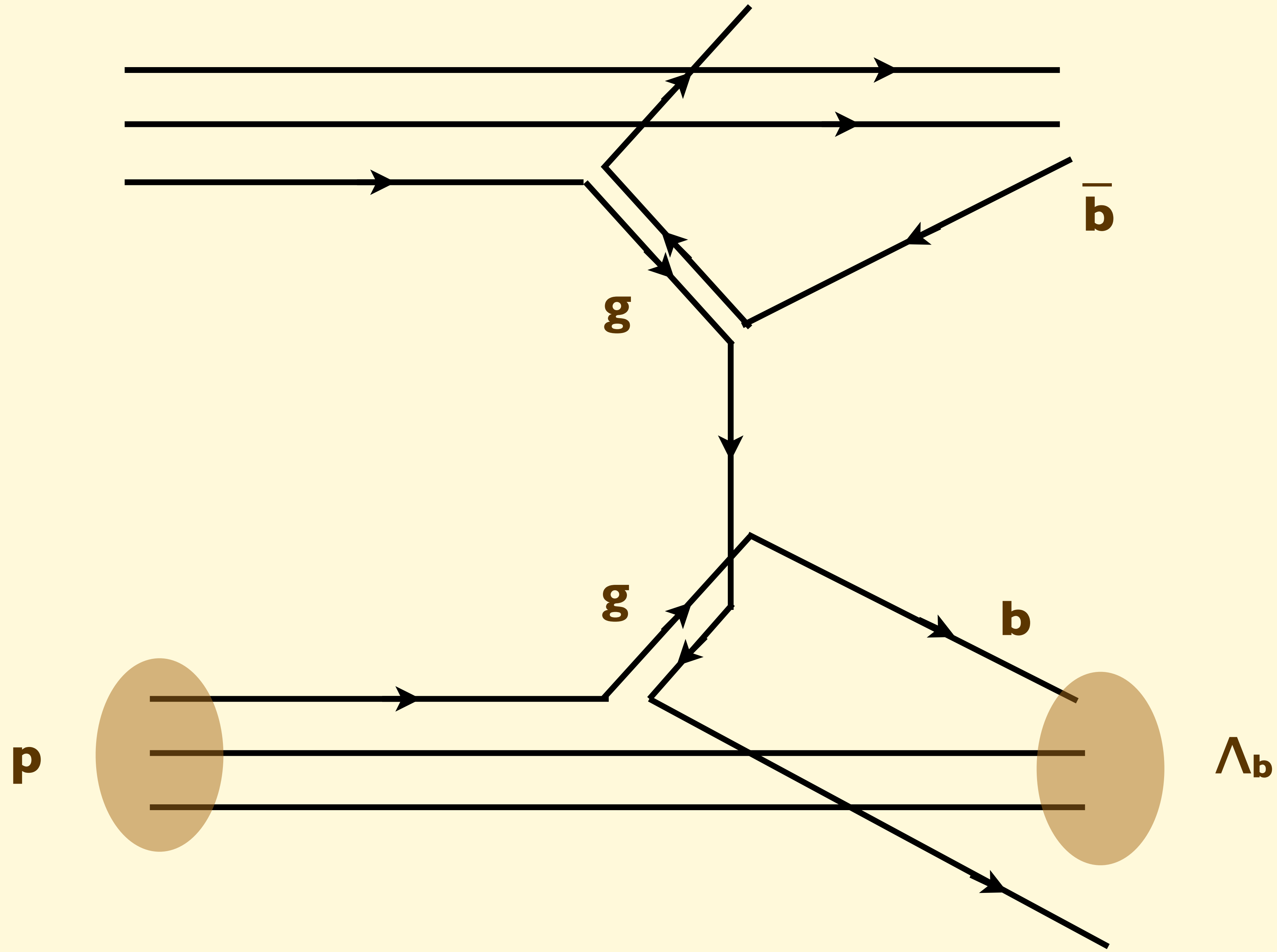


Other non-pQCD issues of relevance to pQCD physics

$b \rightarrow H_b$ 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

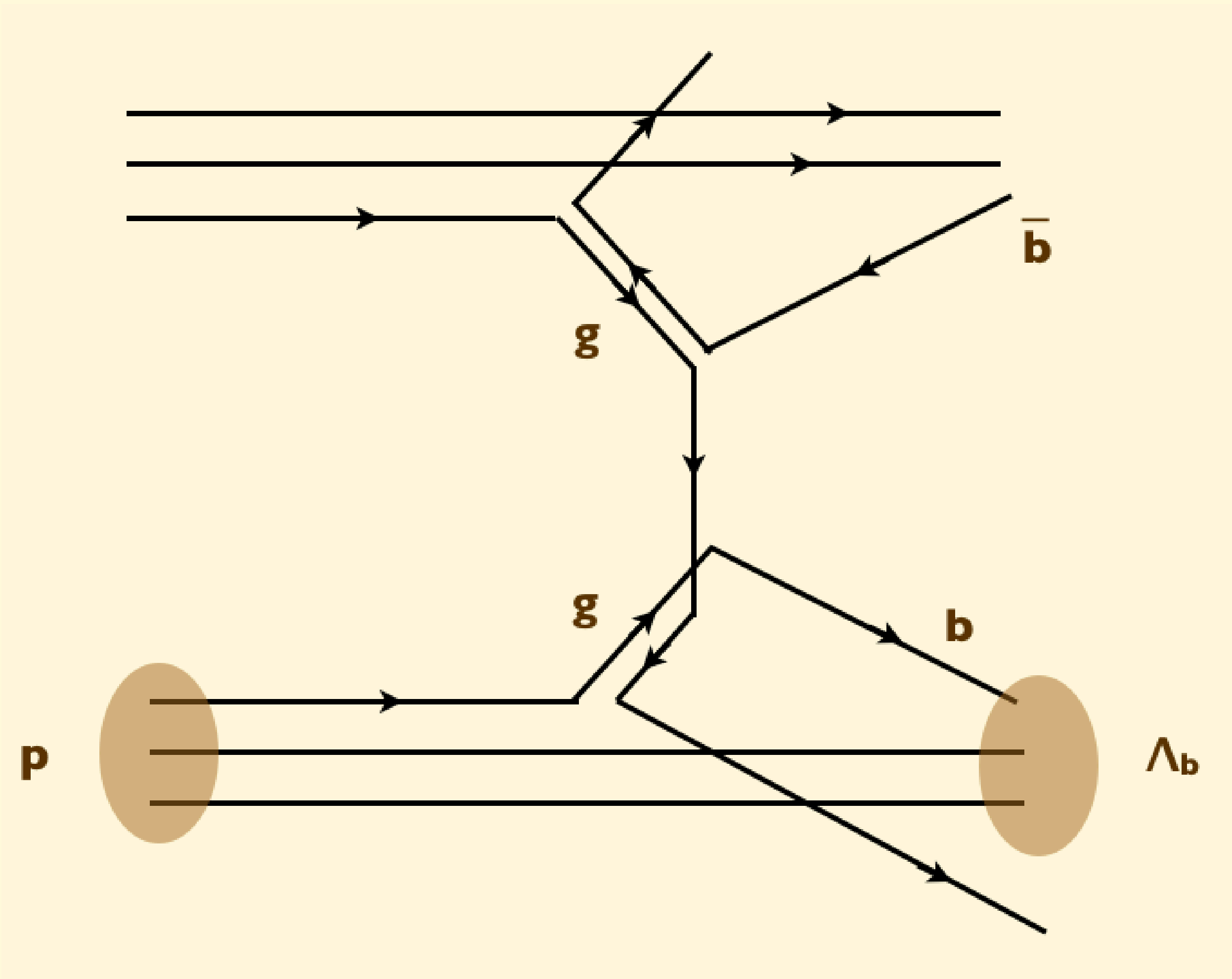
- **Needs clarification!**
- **To the least it points to — not unexpected — deviations from factorization**
- **In view of the CP non-invariance of the initial state, and of the forward kinematics of LHCb, each individual fraction will have to be measured very accurately**



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

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

Example



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

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

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

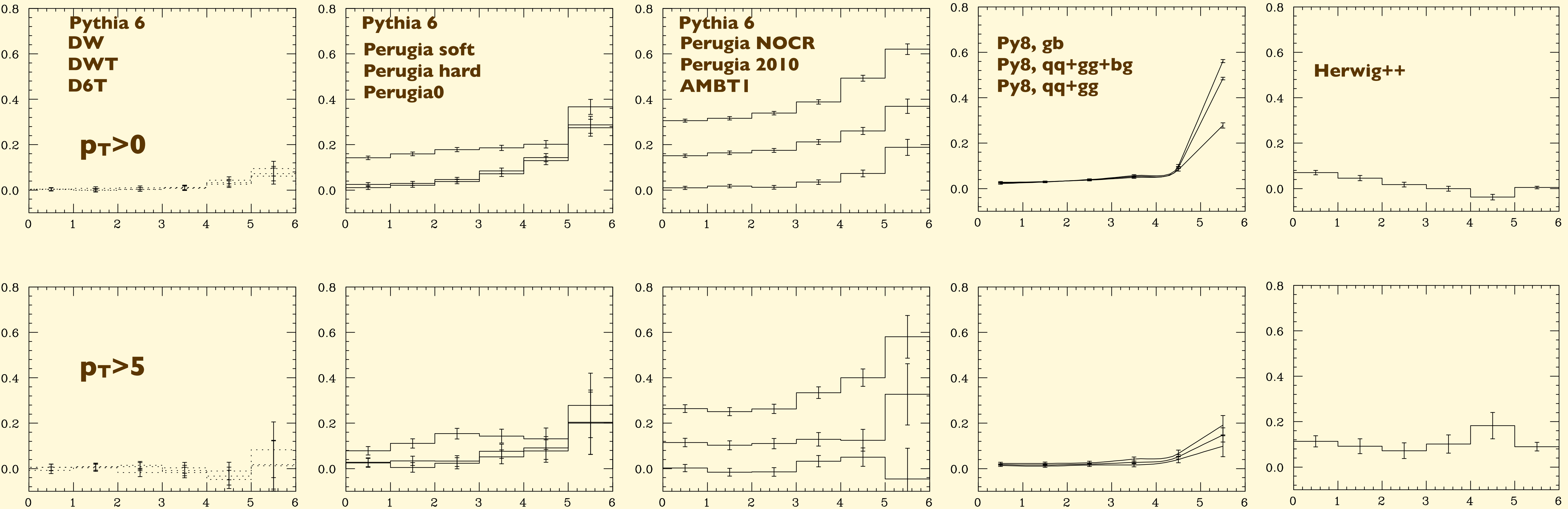
$$A(y) = \frac{dN(\Lambda_b)/dy - dN(\bar{\Lambda}_b)/dy}{dN(\Lambda_b)/dy + dN(\bar{\Lambda}_b)/dy}$$

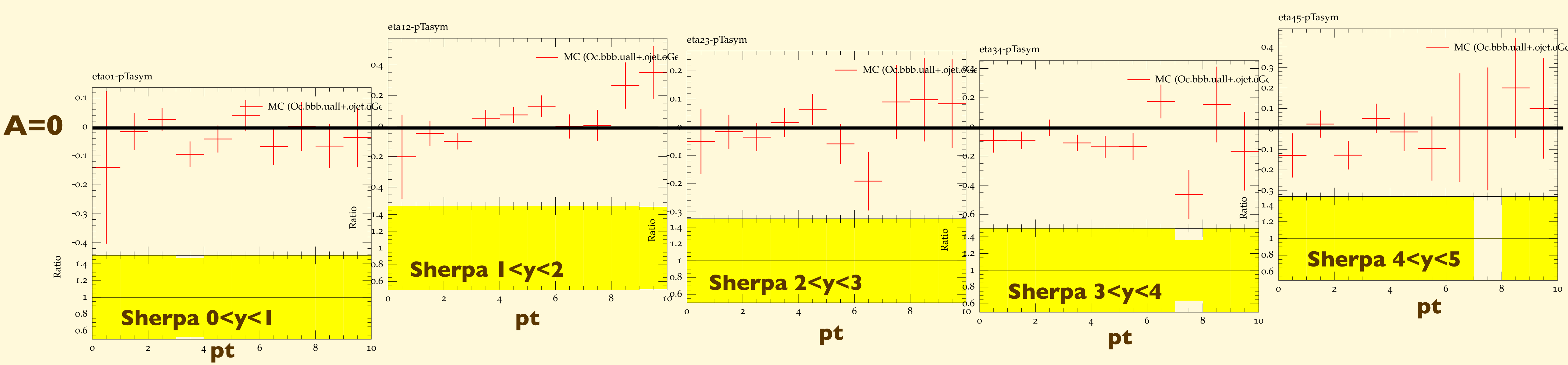
If A(y)≠0 ⇒ N(B)≠N(Bbar) ⇒ apparent CP violation!

Modeling

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

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

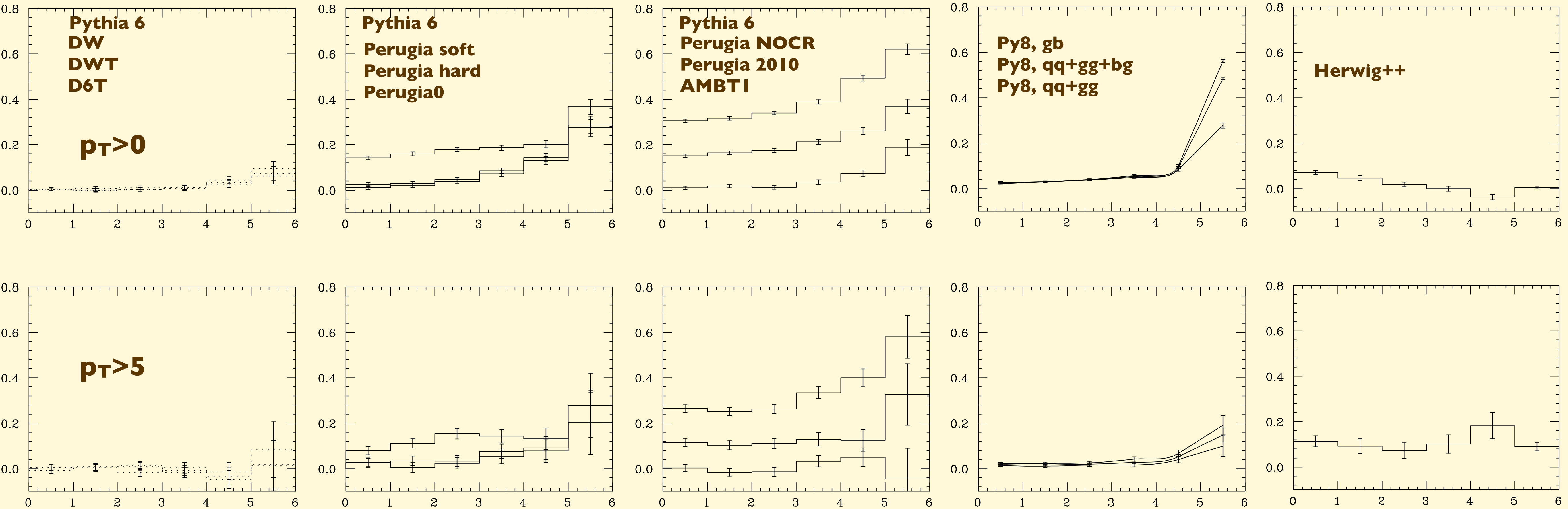




Modeling

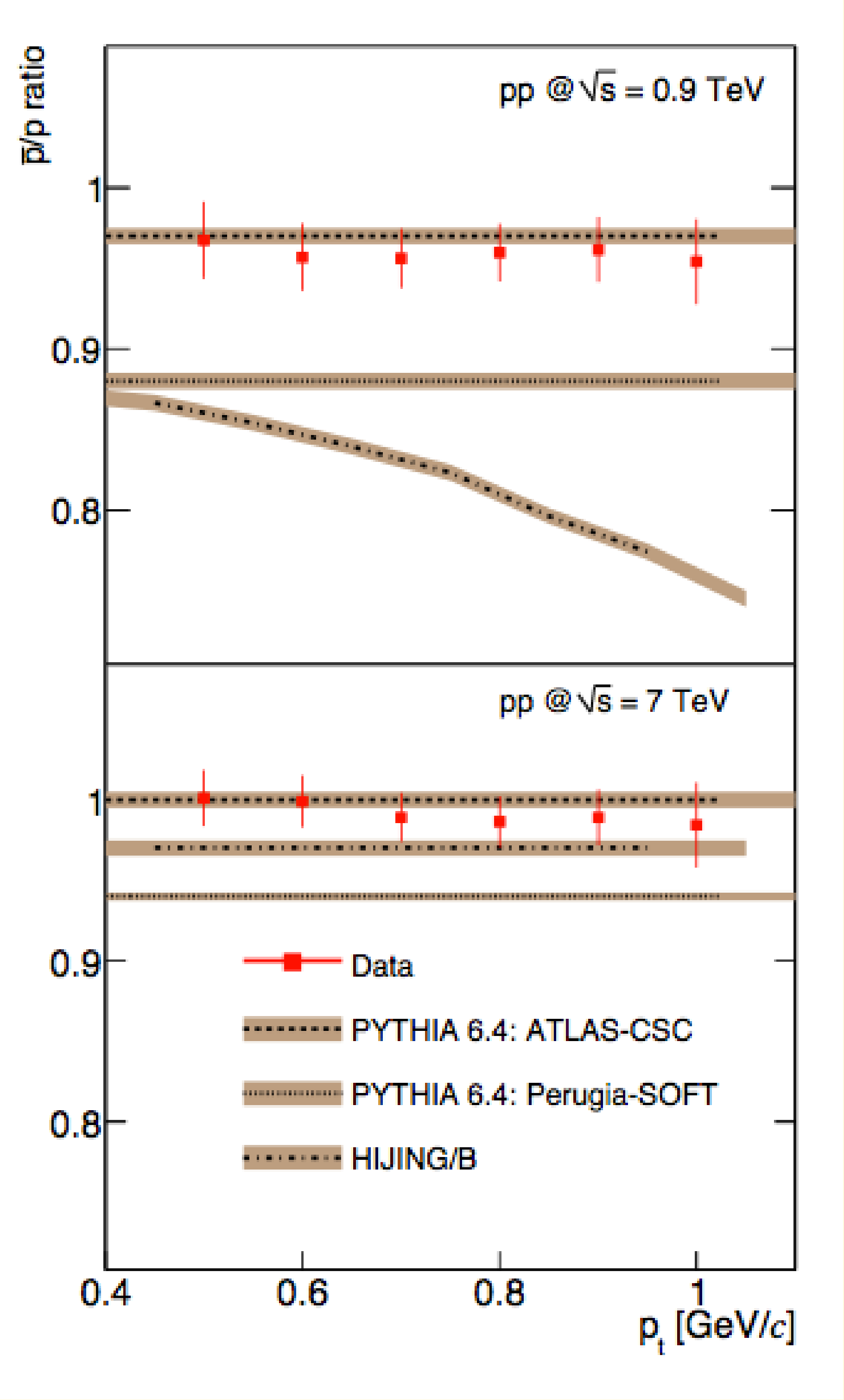
Thanks to P.Skands, T.Sjostrand, D.Grellsheid, J.Winter for providing these predictions

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



- **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!**

Pbar / P ratio

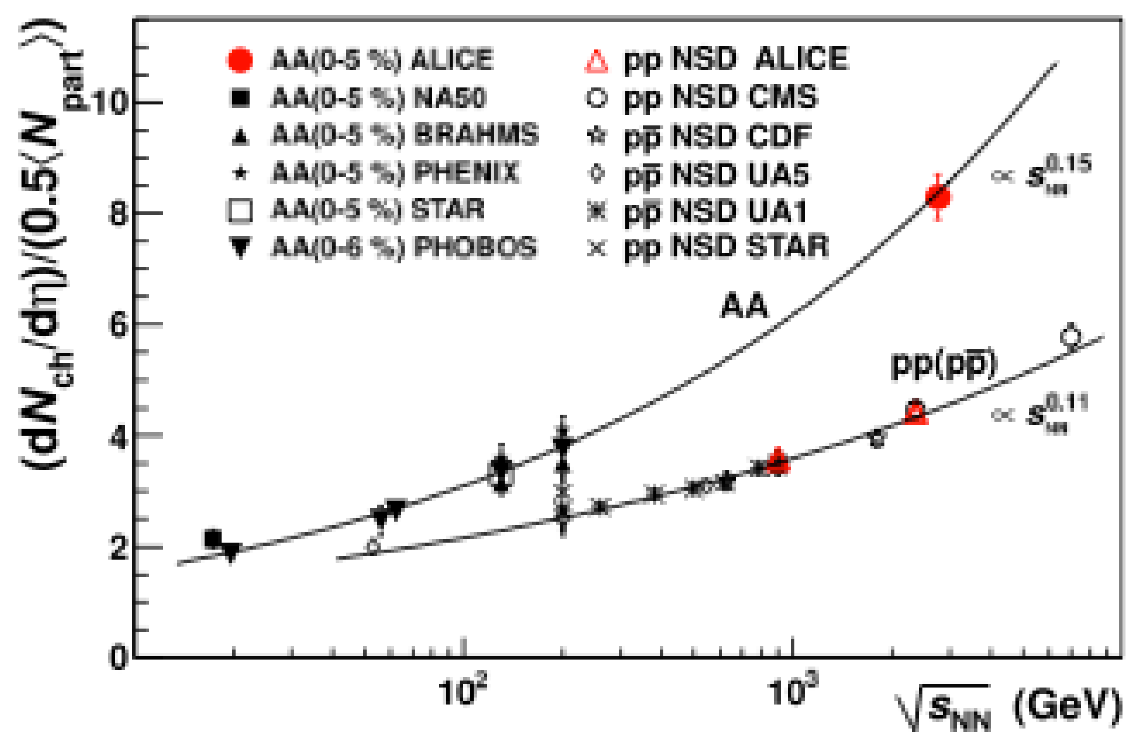


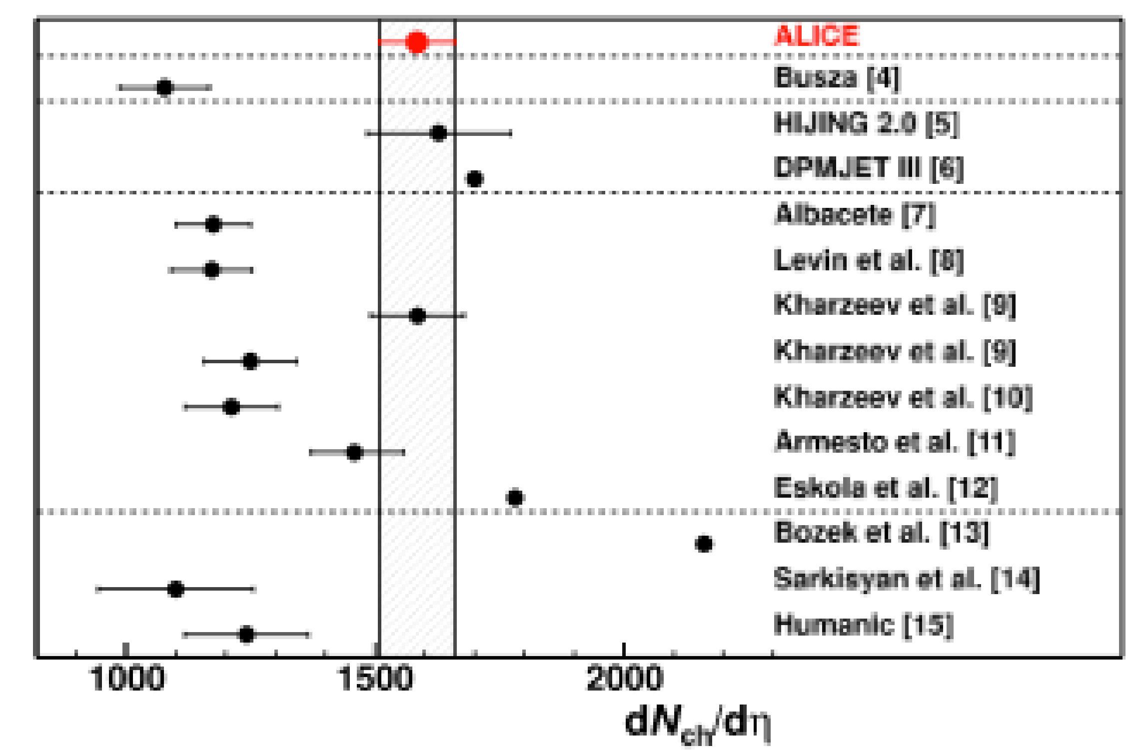
ALICE http://arxiv.org/abs/1006.5432

A first look at Pb-Pb collisions

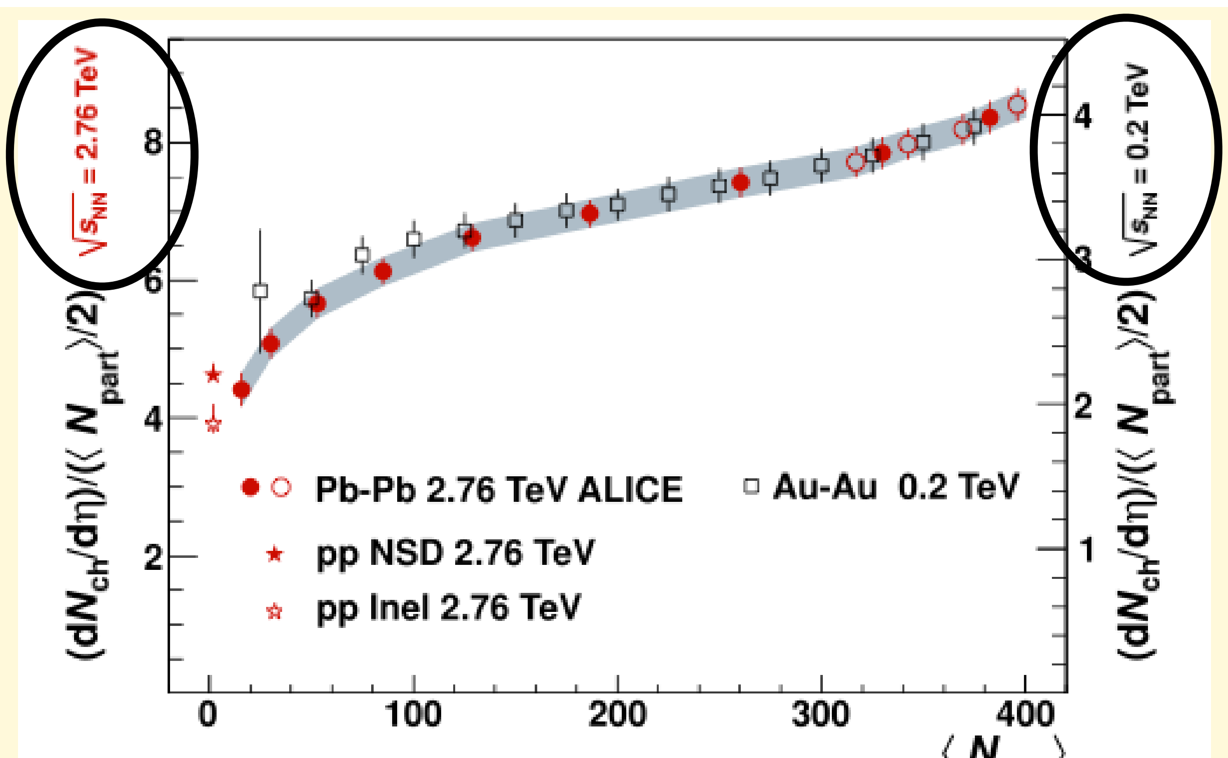
- $\sqrt{S_{NN}}$ = 2.76 TeV => 14 times larger than any previous heavy ion experiment (RHIC)

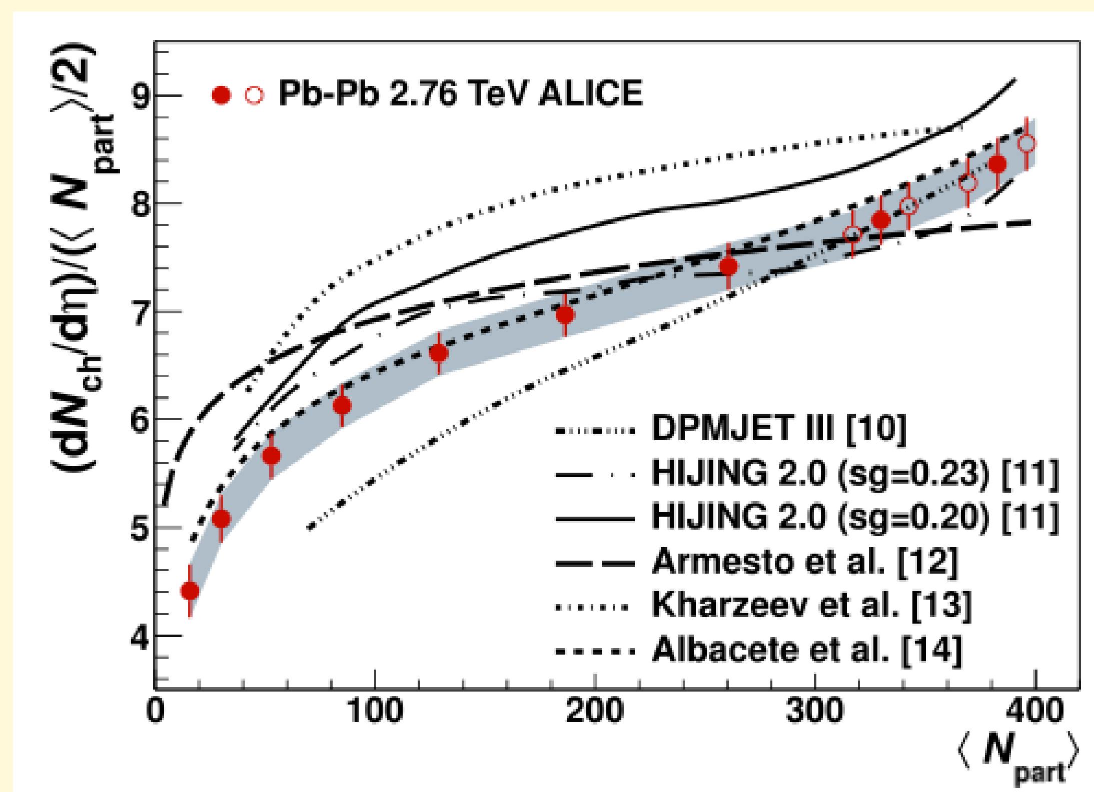
$dN_{ch}/d\eta$ (0-10% centrality) = 1584 ± 4 (stat.) ± 76 (sys.)





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





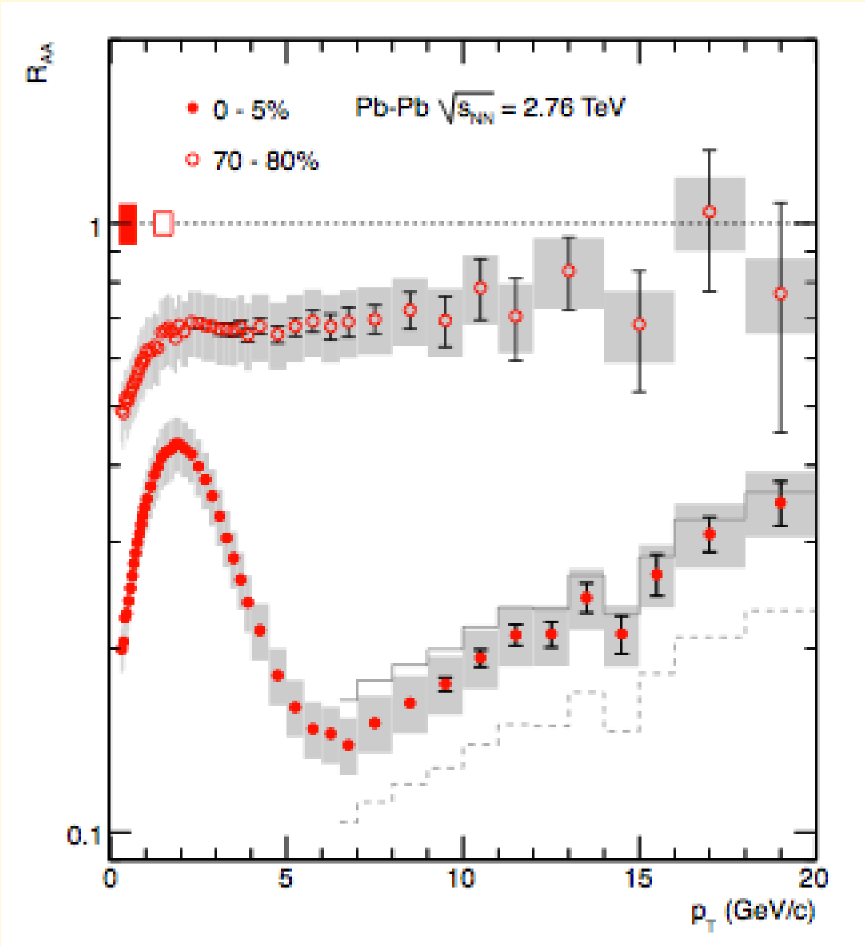
ALICE, http://arxiv.org/abs/1012.1657

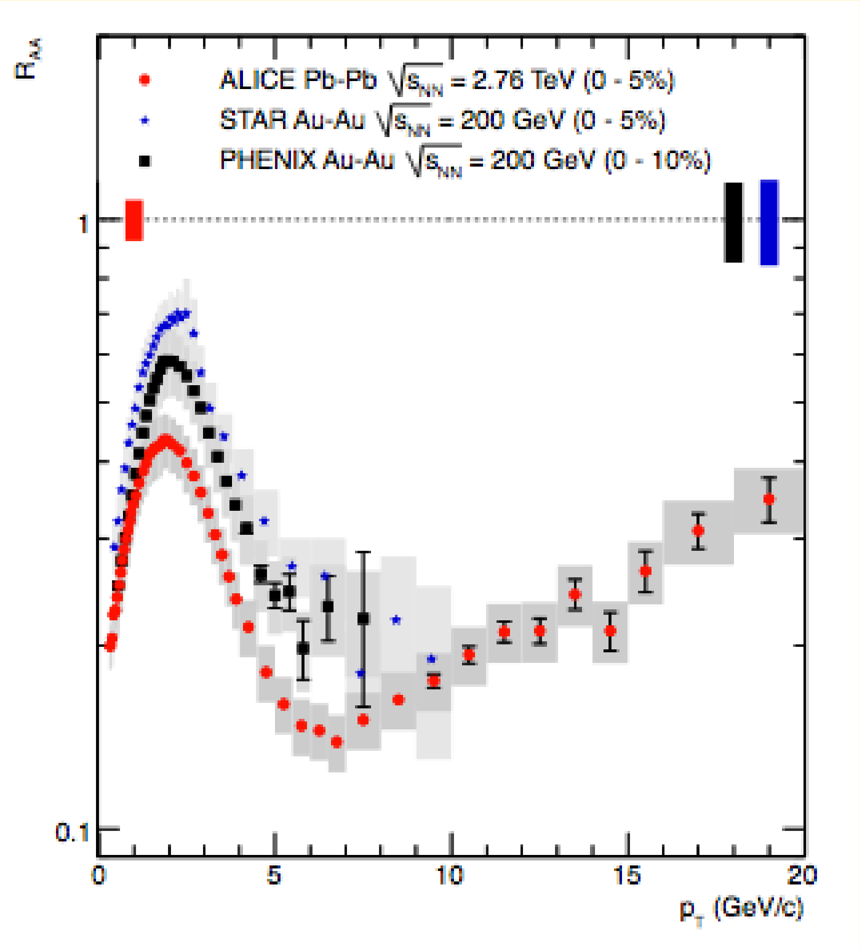
Modeling heavily depends on description of gluon saturation

More on Pb-Pb collisions ....

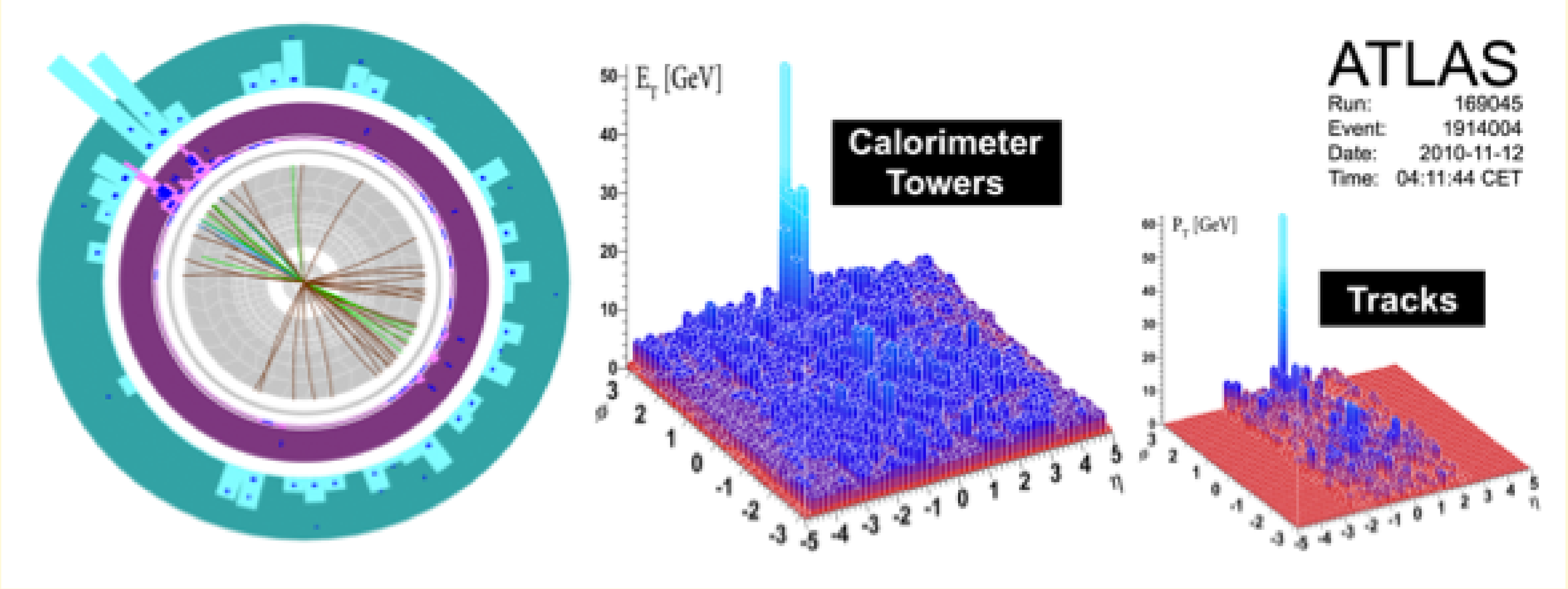
R_{AA}: momentum loss of fast particles moving through the medium

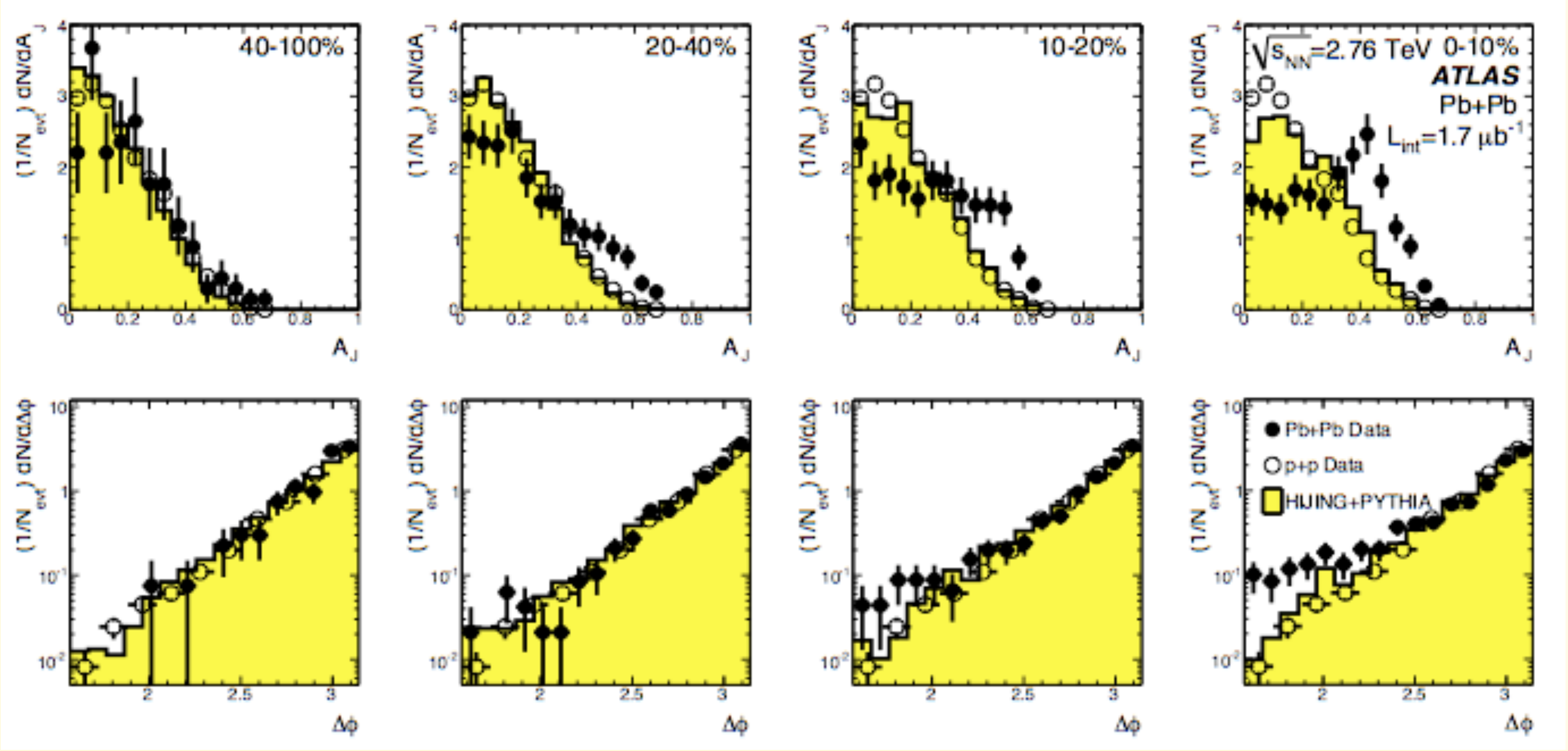
$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle\, (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$





More on Pb-Pb collisions ....





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

Momentum spectrum of cosmic ray muons