The first year of the LHC: what we have learned

UK Christmas Theory Workshop, Durham,
Dec 16-17 2010

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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

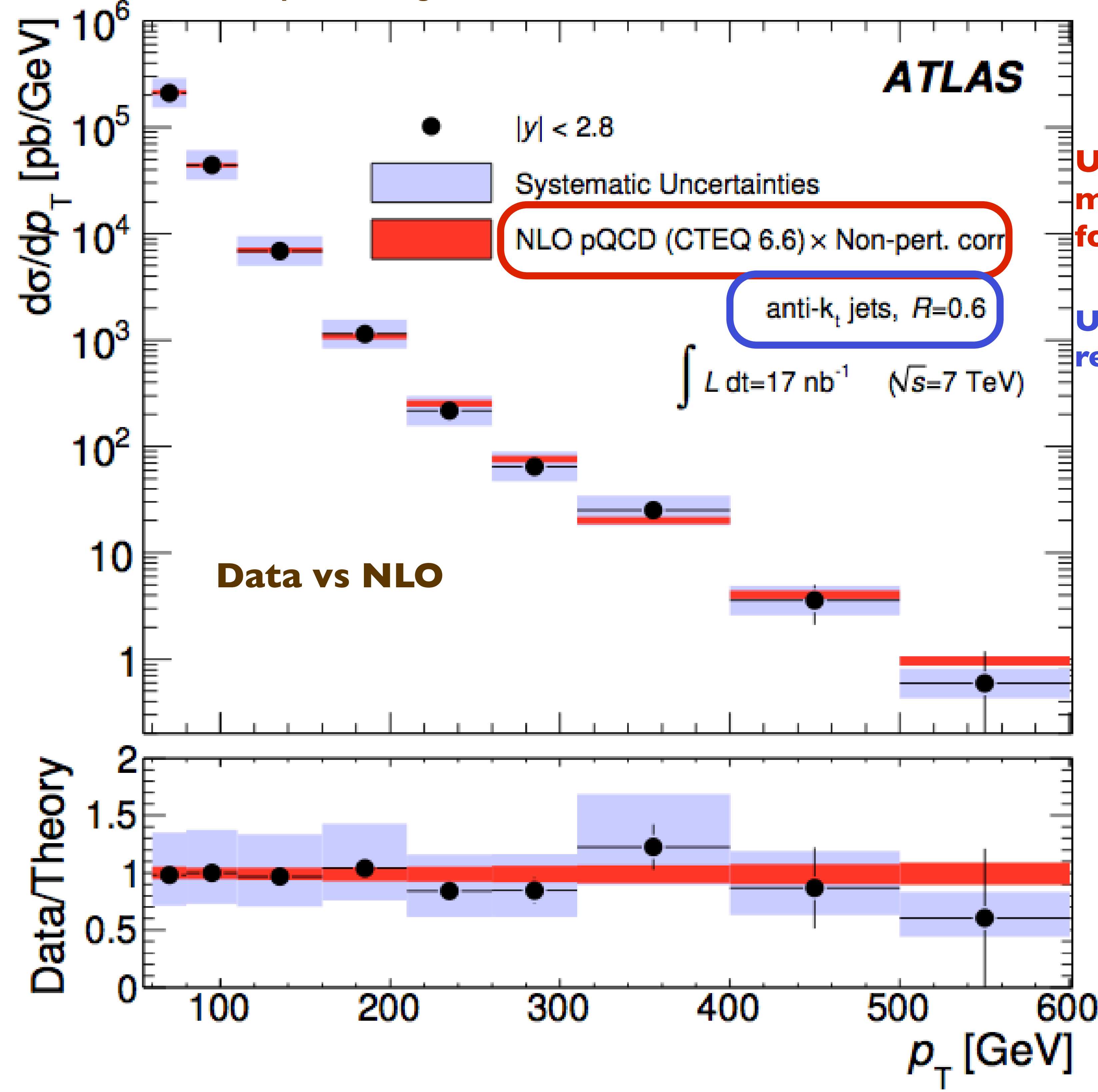
- Final states of the modern "Rutherford" experiment with the proton: test the fundamental nature of quarks

- 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.)

Inclusive jet E_T spectrum

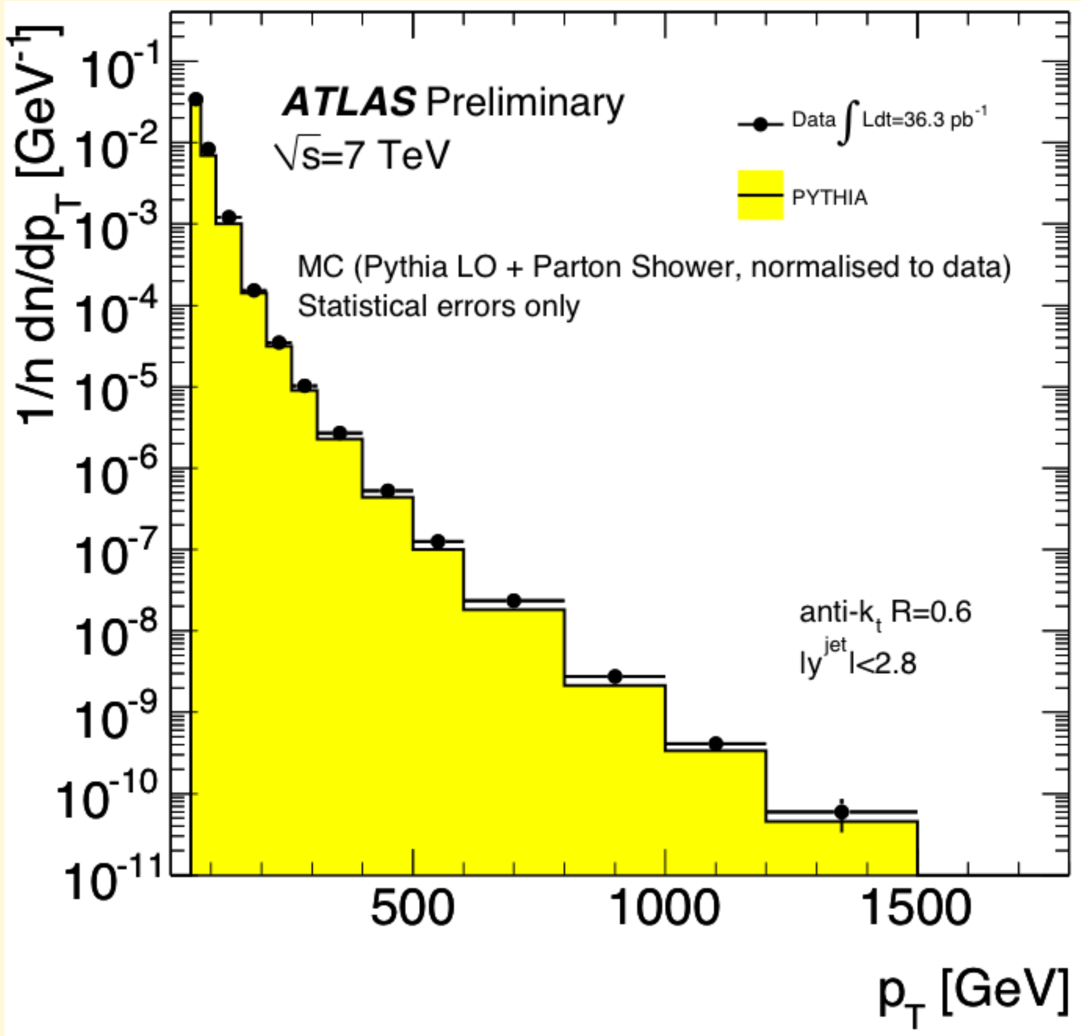
17nb⁻¹, http://arxiv.org/abs/1009.5908

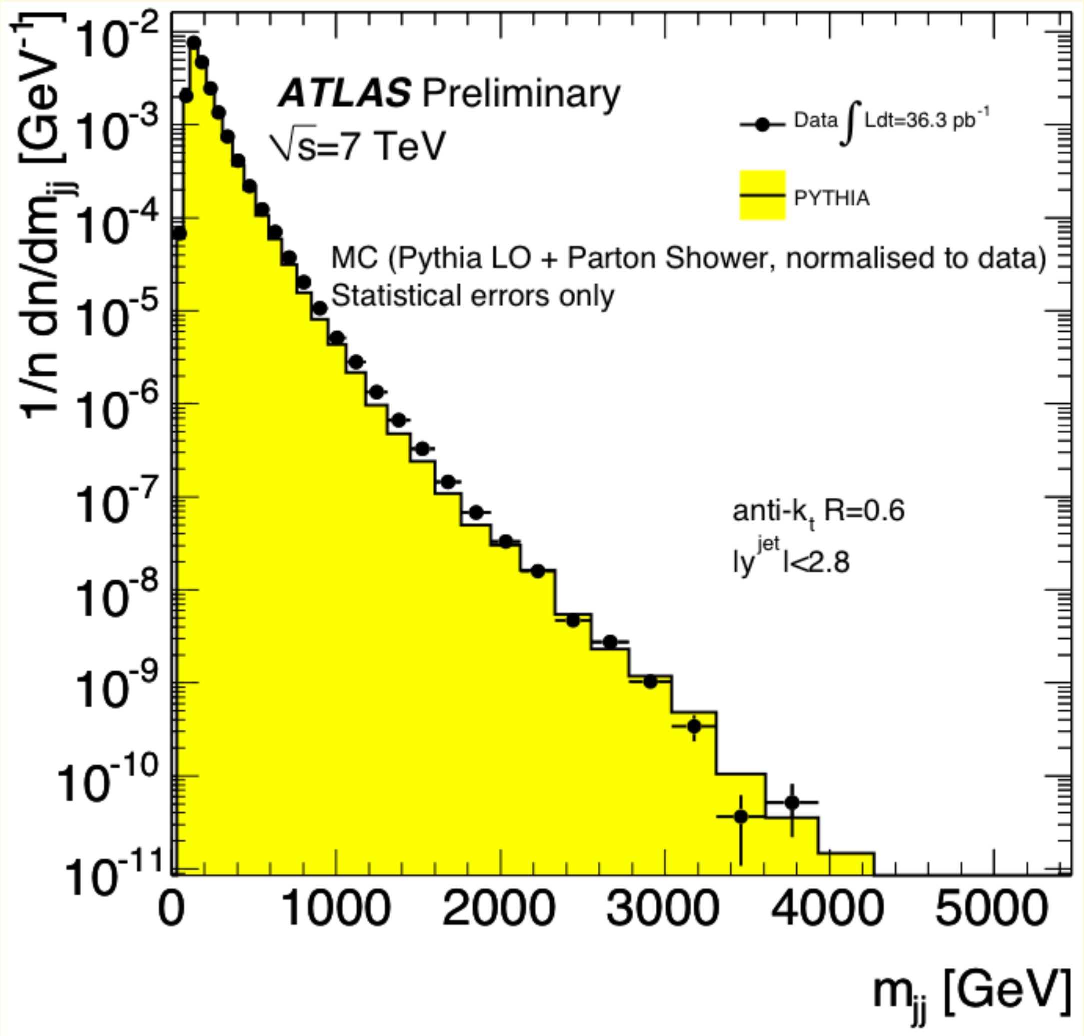


Unfolded cross-section measurement, suitable for comparison with NLO

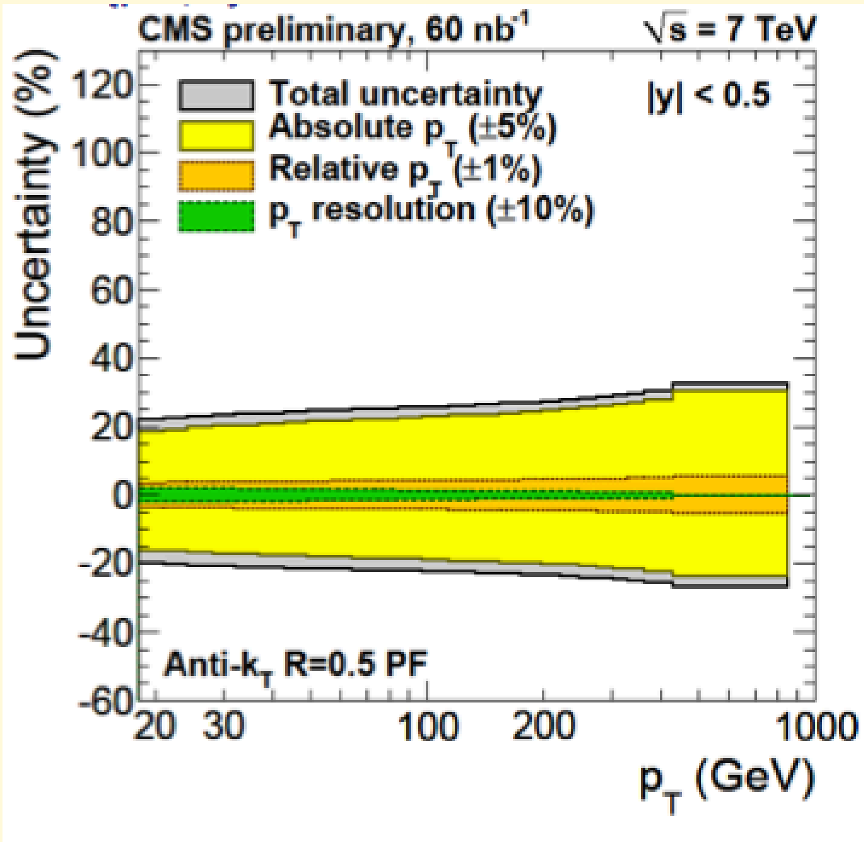
Use of modern jet reconstruction tools

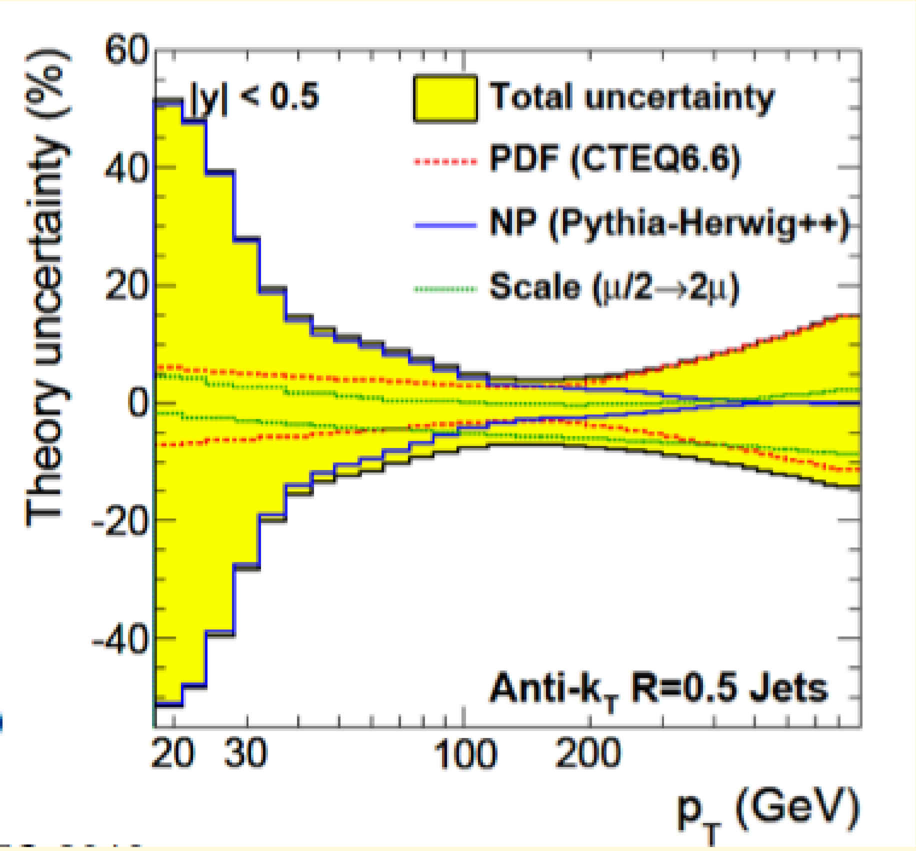
Full 2010 luminosity update:





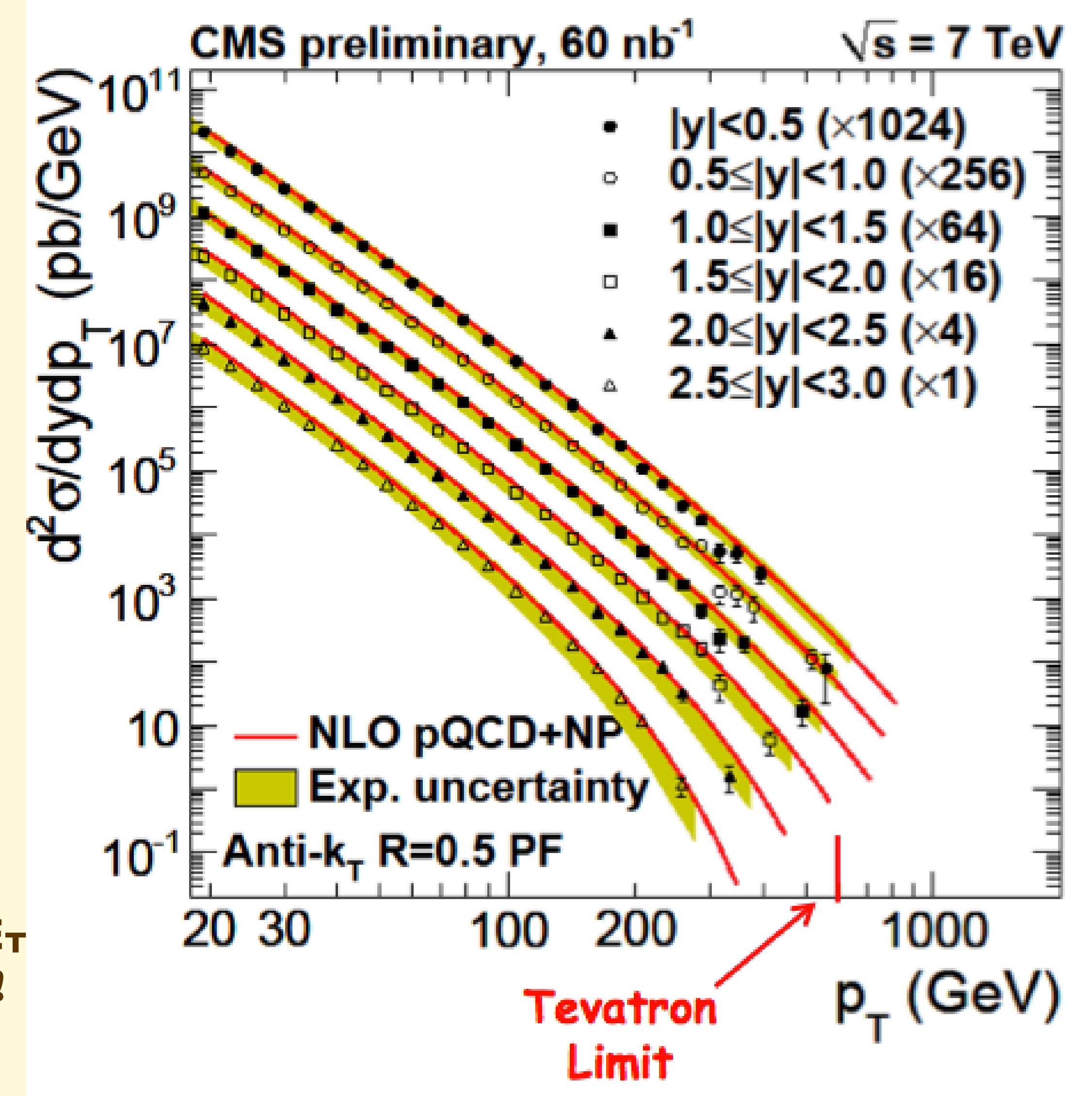
See P. Wells, for the ATLAS collab., 104th LHCC session, http://indico.cern.ch/conferenceDisplay.py?confId=112439





PDF will be dominant source of theoretical systematics at large E_T

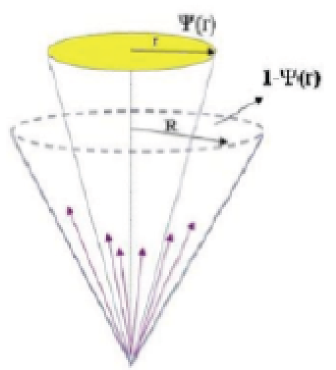
How powerful will be the jet data at large η in reducing this systematics?



Notice reach in E_T down to 20 GeV!!

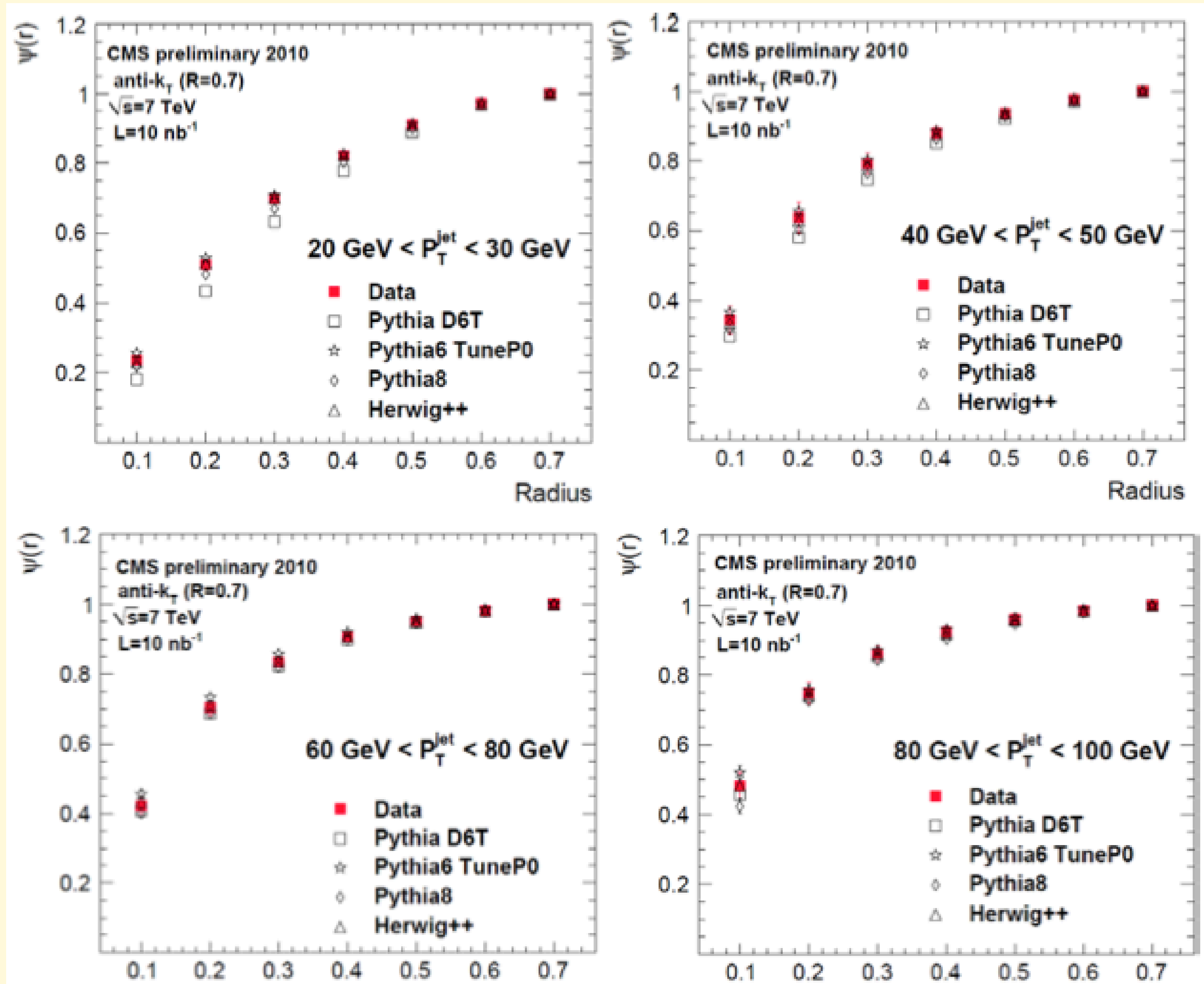
Integrated jet shape

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



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

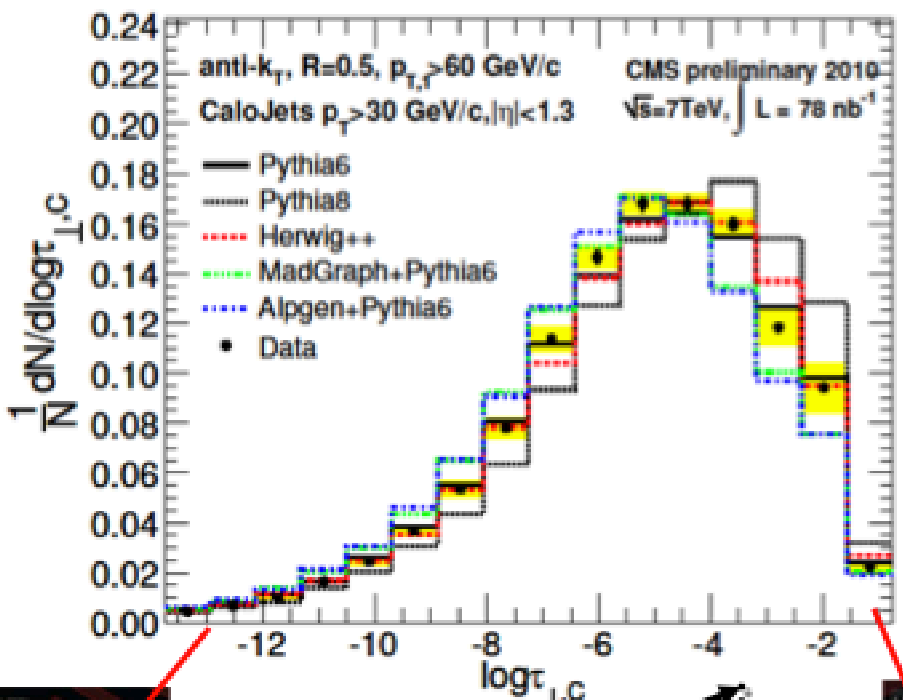


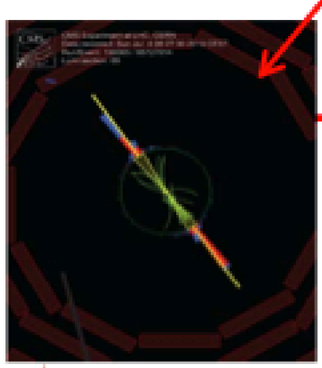
78 nb^{-1} CMS PAS QCD-10-014

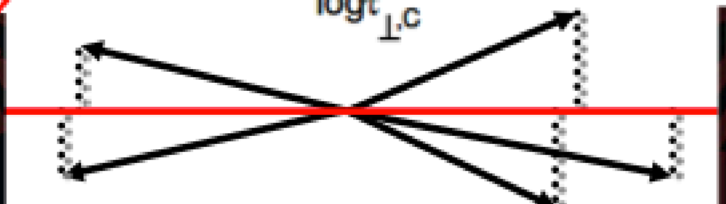
Event Shapes

QCD High PT

- Event shapes provide geometric information about energy flow in hadronic events
- Useful for tuning of MC models for non-perturbative effects
- Robust against experimental uncertainties

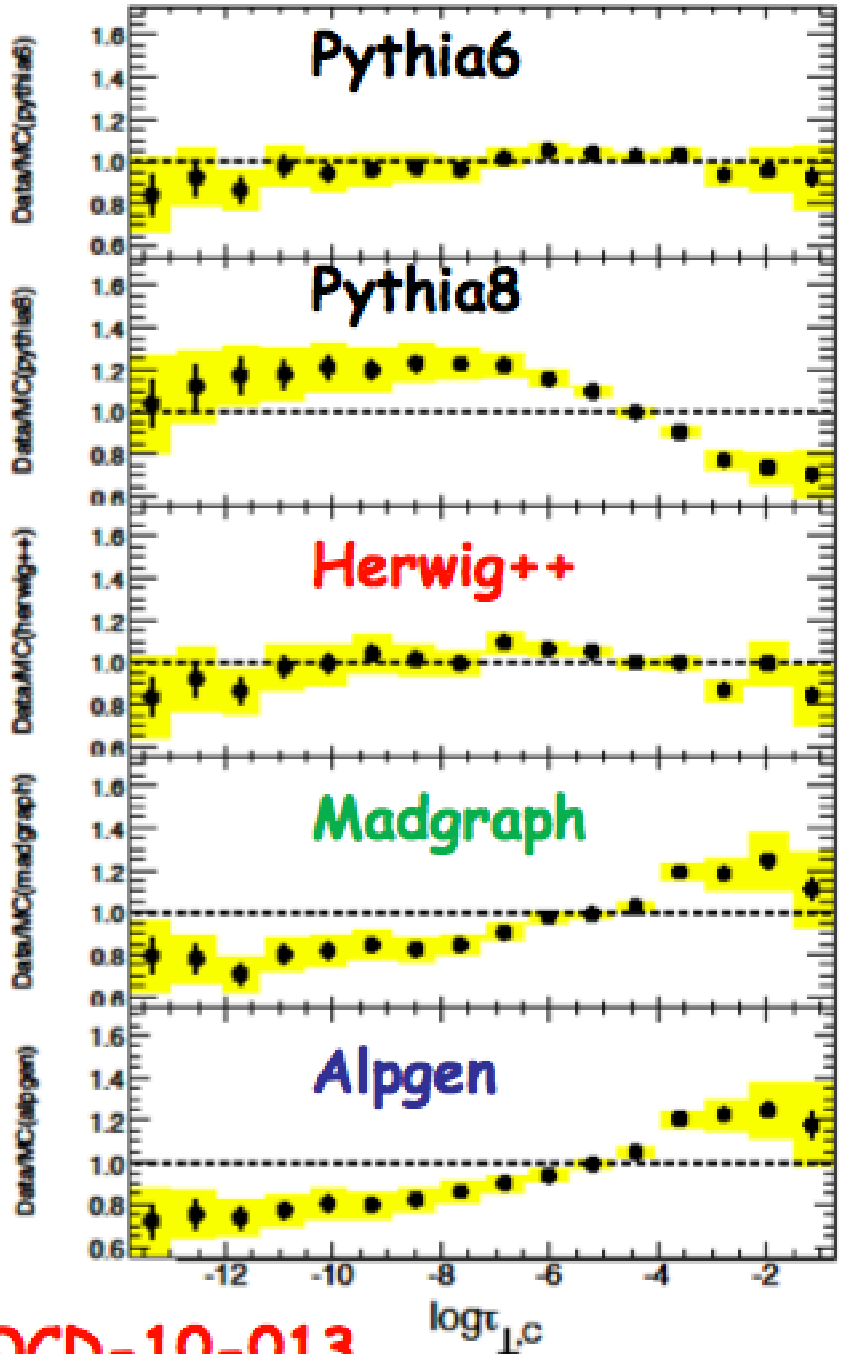






$$T_{\perp,C} \equiv \max_{\vec{n}_T} \frac{\sum_{i\in C} |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_{i\in C} p_{\perp,i}}$$

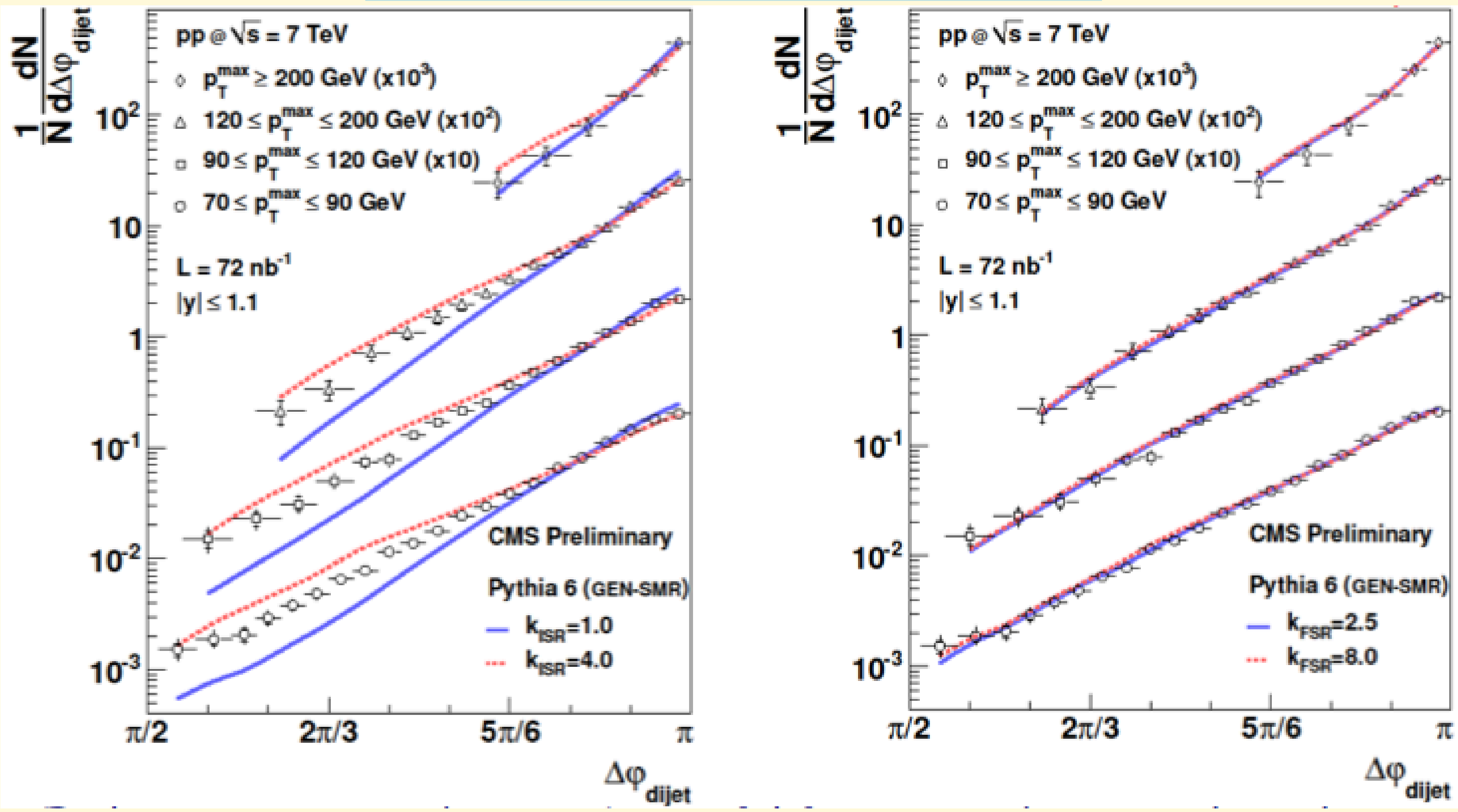
Central transverse thrust



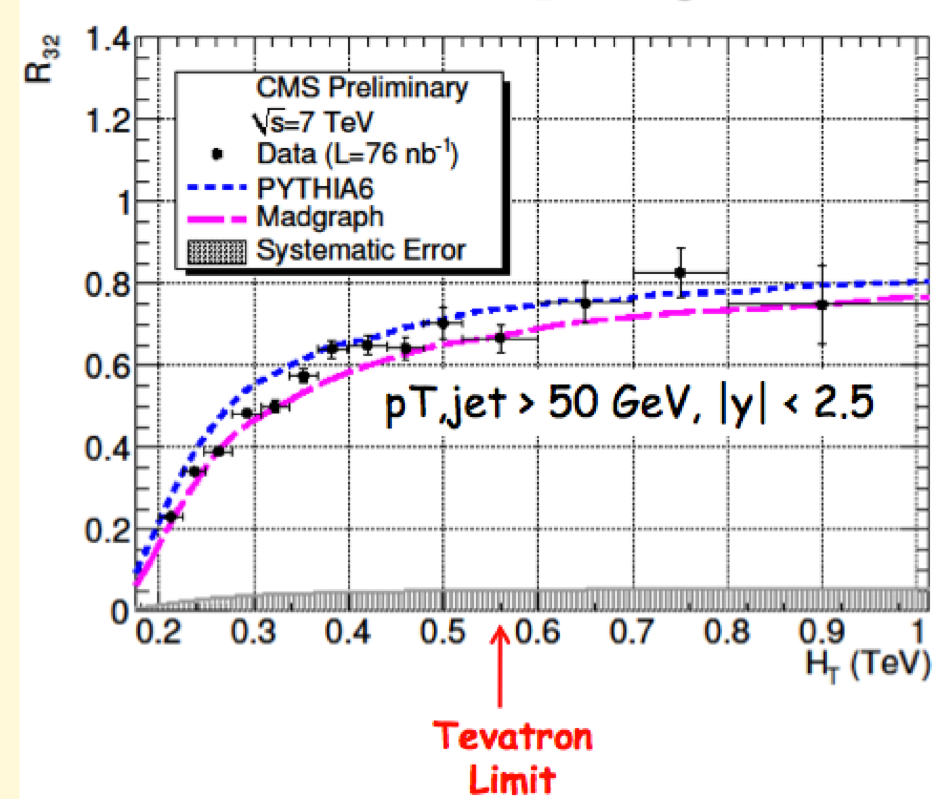
QCD-10-013

Other global properties of jet final states

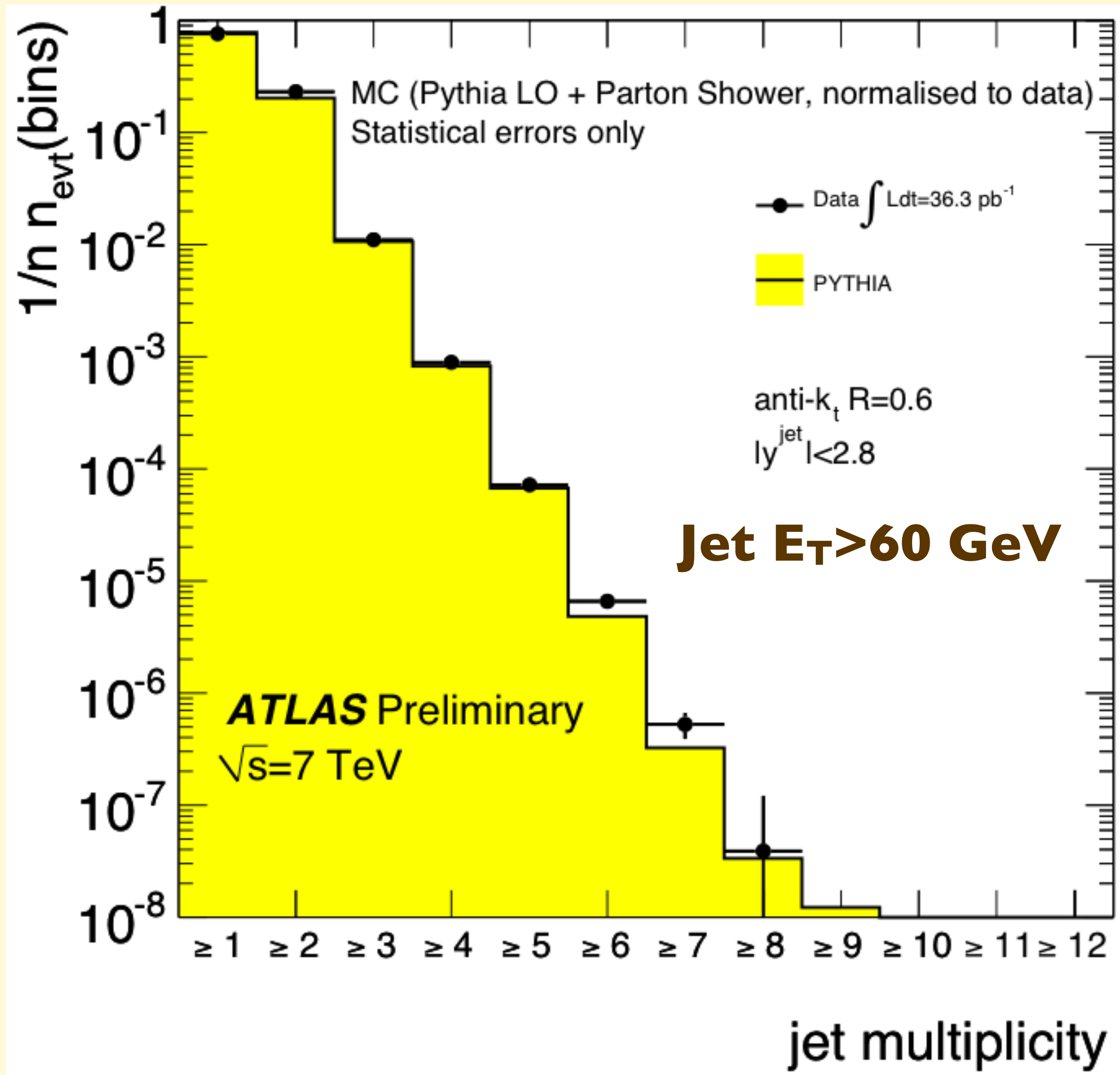
Dijet Angular Decorrelation

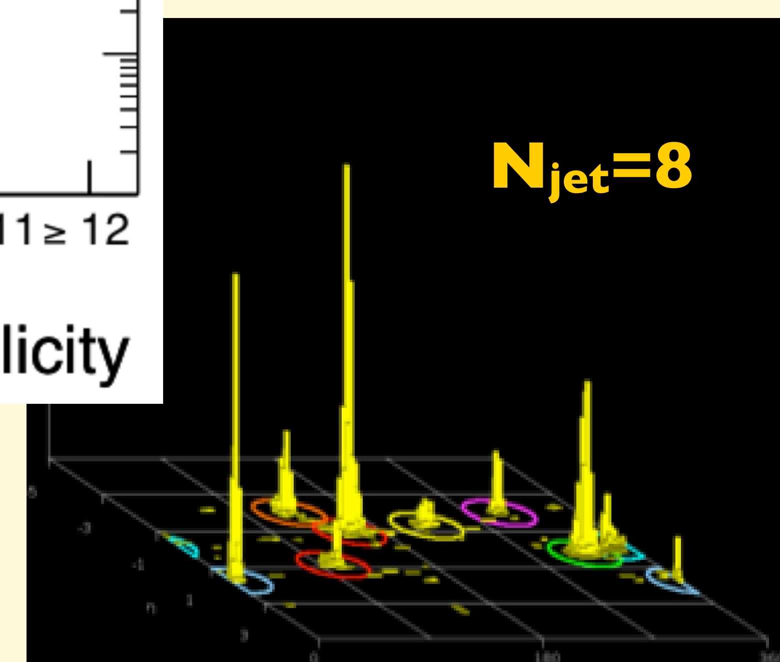


$$R_{32} = \frac{d\sigma_3/dH_T}{d\sigma_2/dH_T}$$



Multijets





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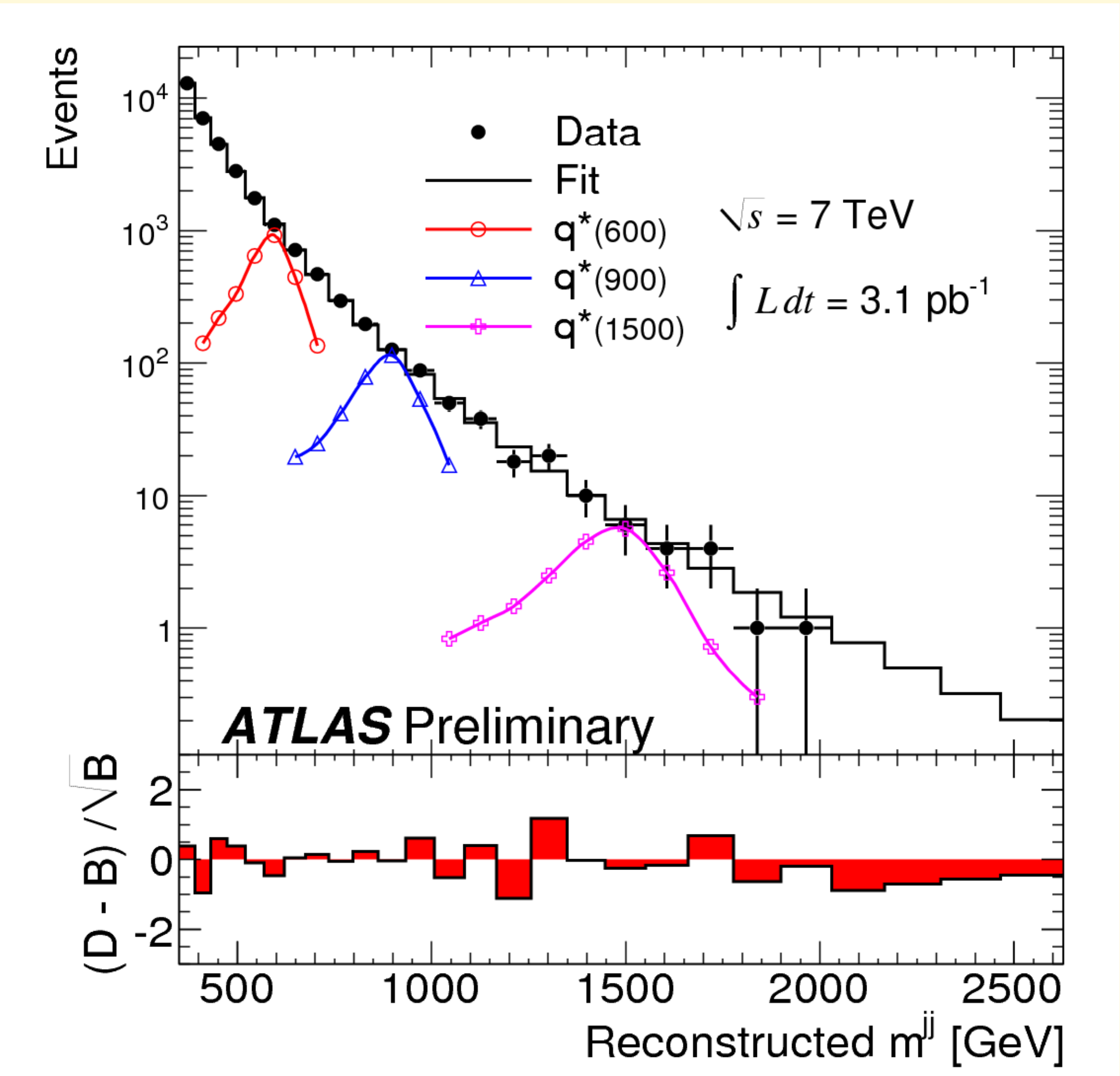
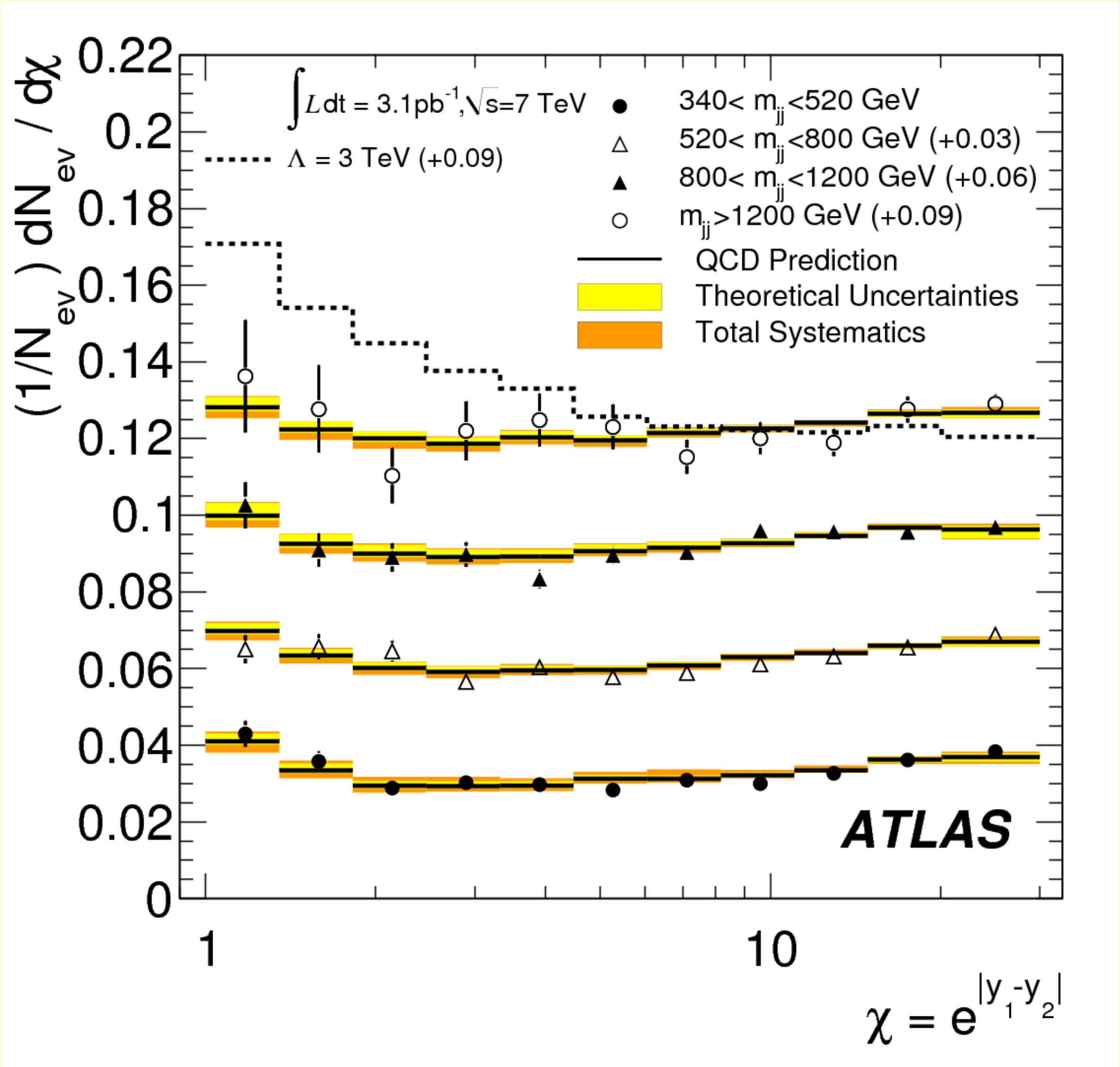
First constraints on new physics



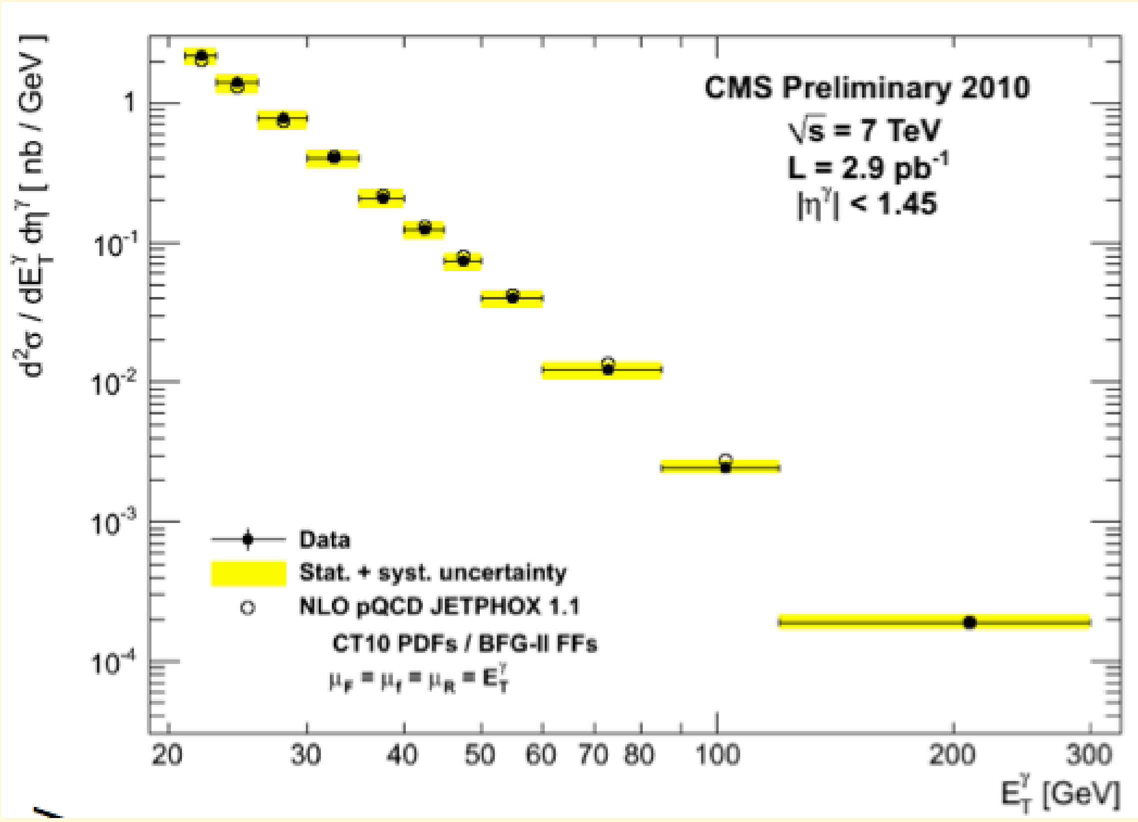


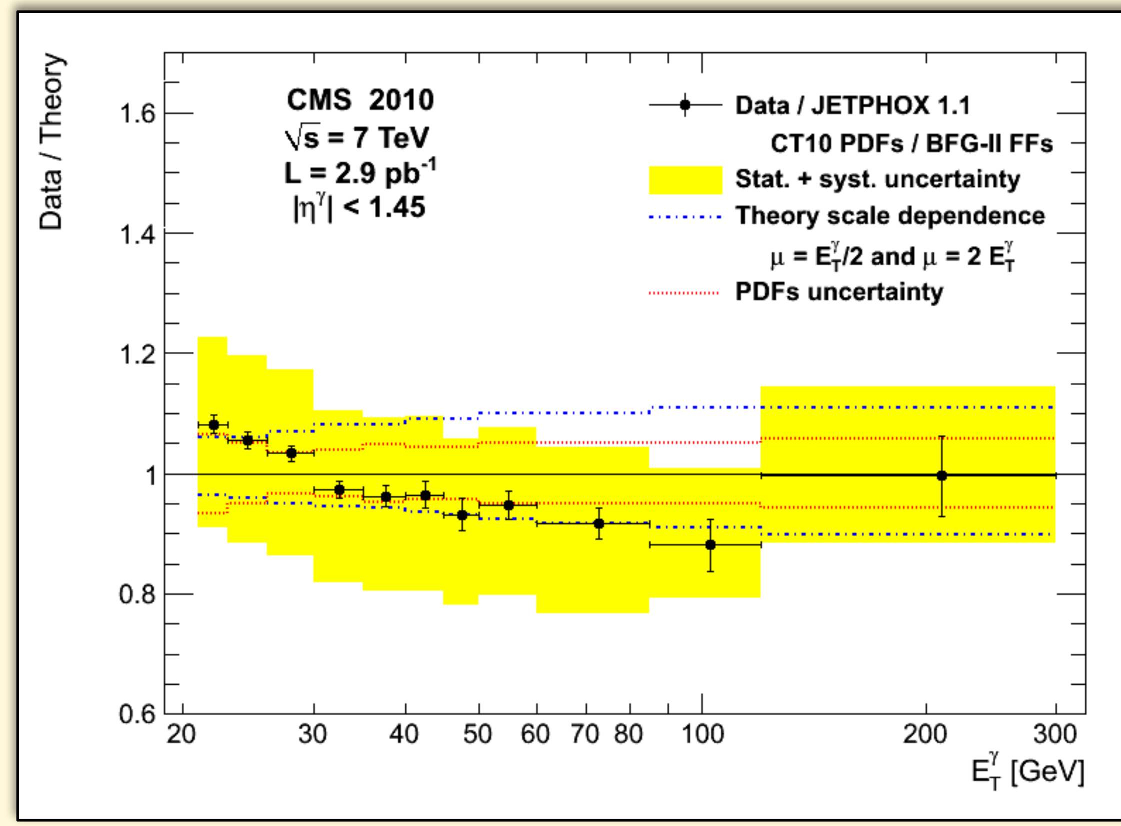
0.50 < m(q*) < 1.53 TeV @ 95% CL

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

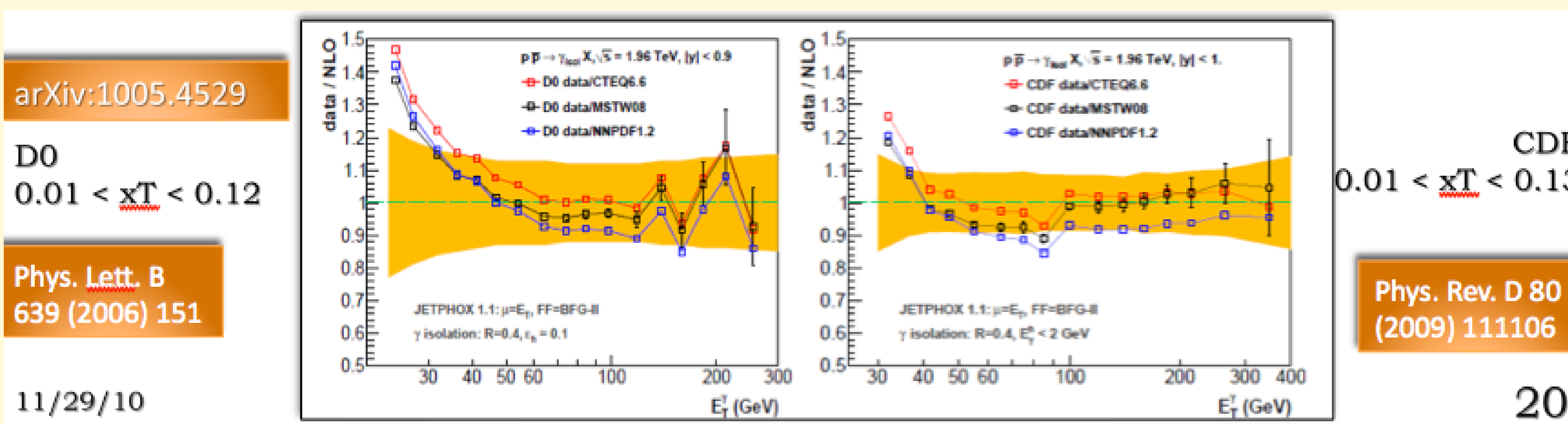
Photons

Prompt photon spectrum, LHC data vs TH



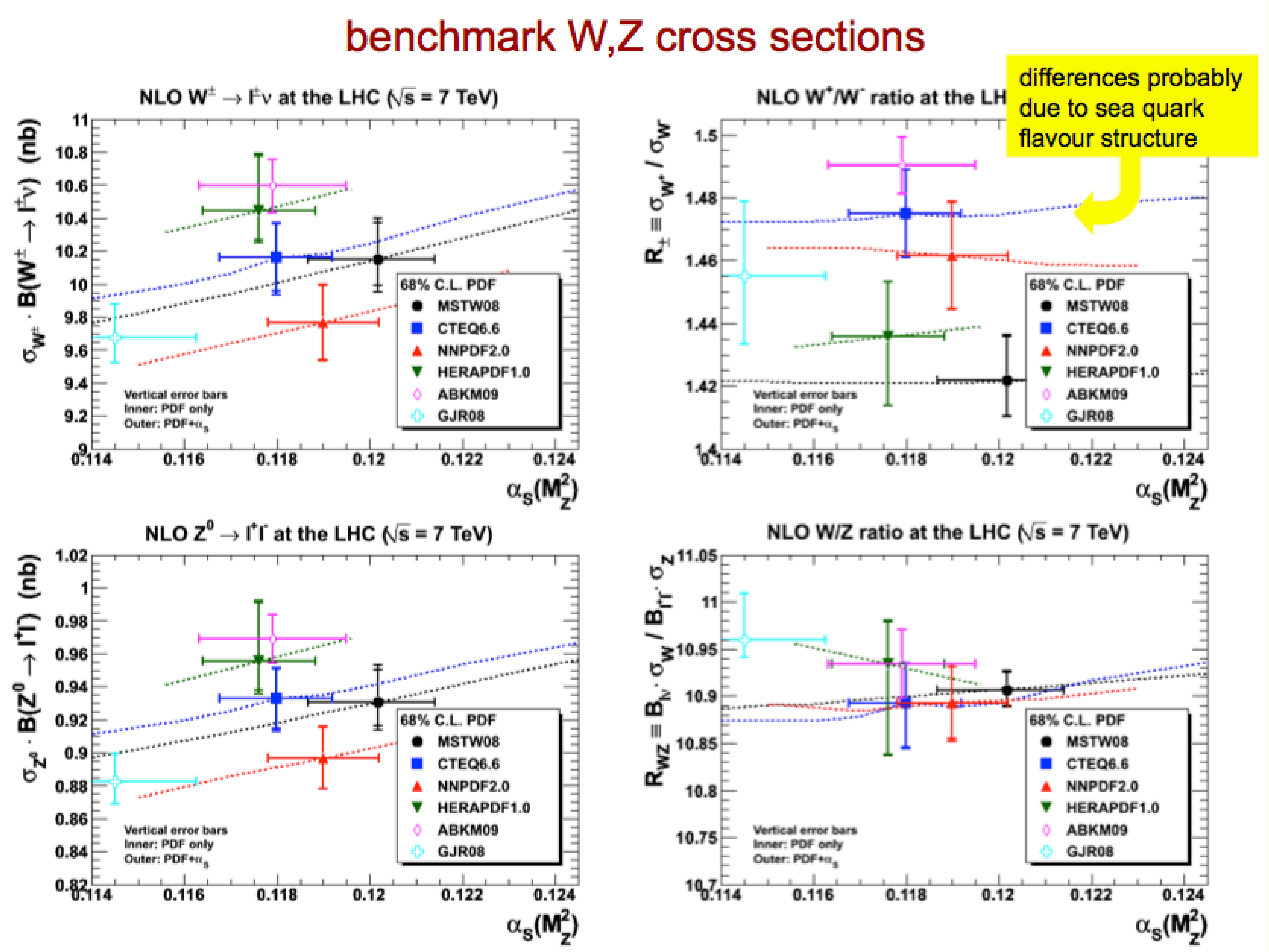


Cfr Tevatron:

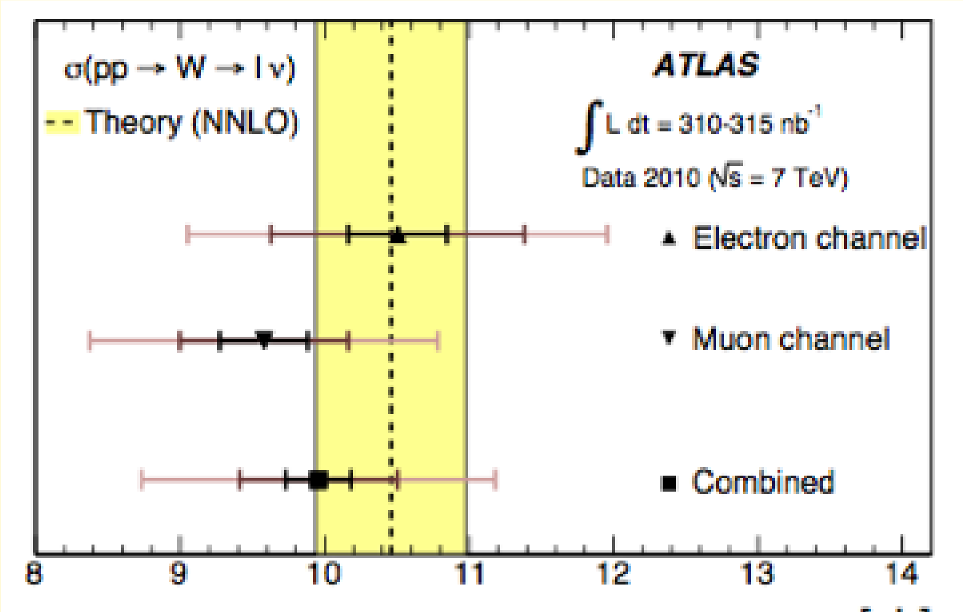


W/Z

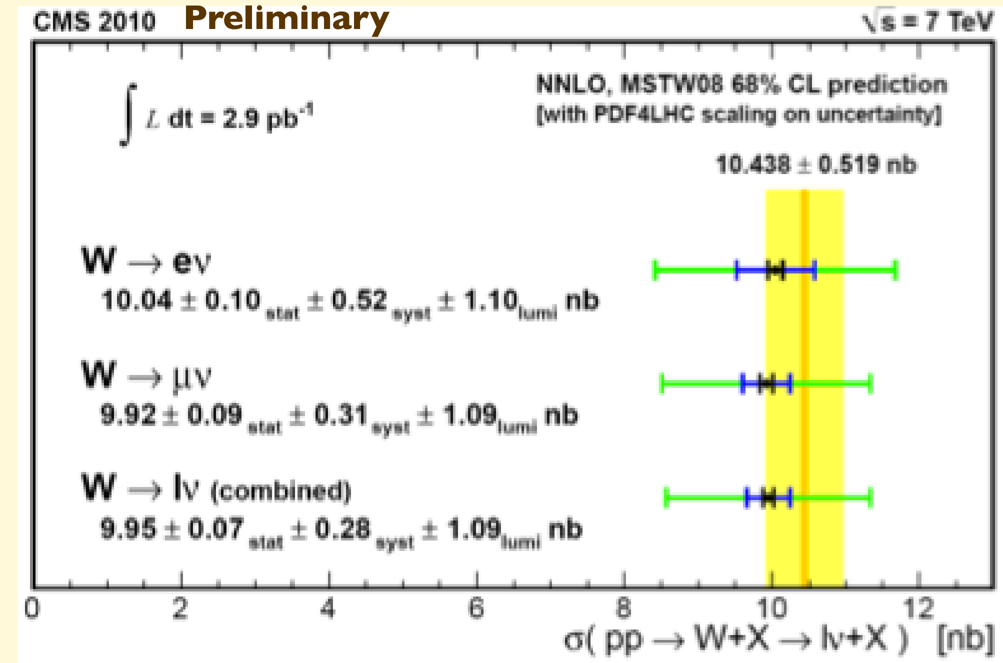
- Primary sources of charged leptons, and missing energy (via neutrinos) =>
  - sources of background to searches of DM-like particles
- Present in the decay chain of almost any heavy object, both in the SM and in BSM scenarios =>
  - probes of new physics
- Inclusive production known in QCD with intrinsic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

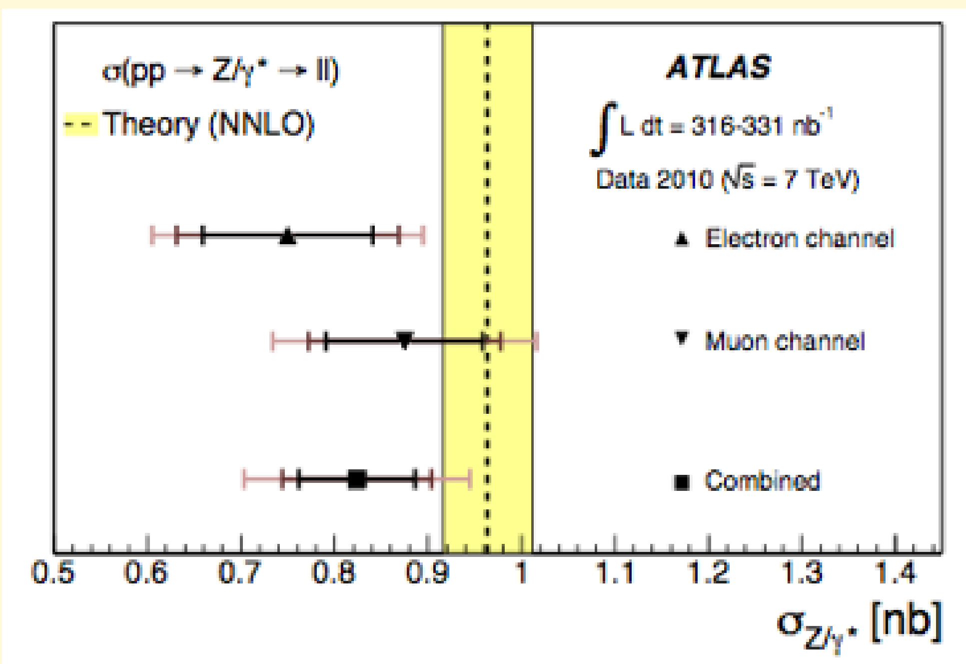


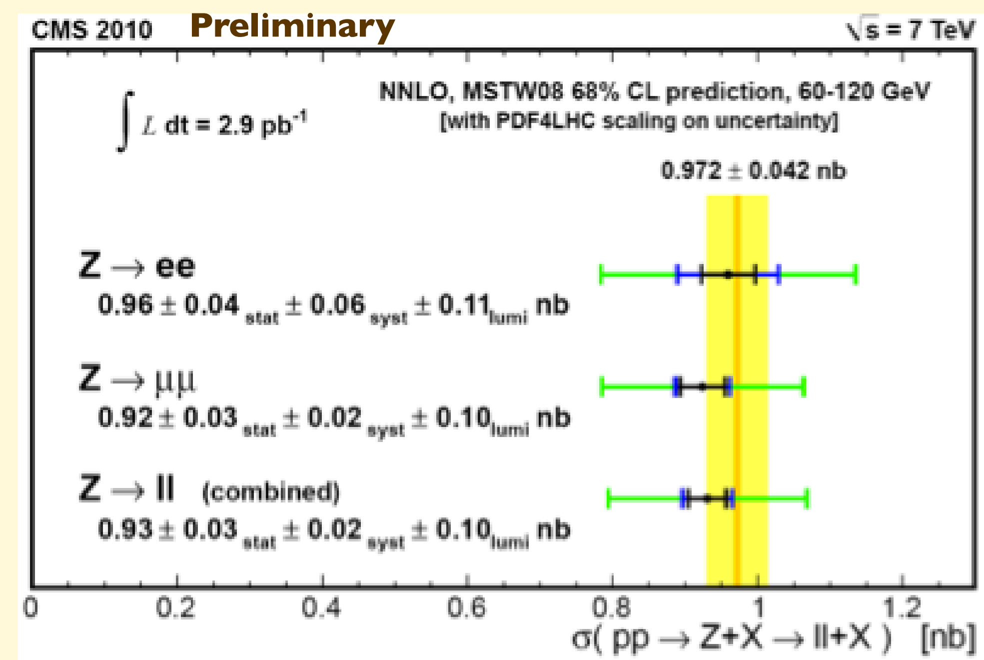
From G. Watt, and W.J. Stirling talk at Trento Workshop “LHC at the LHC”

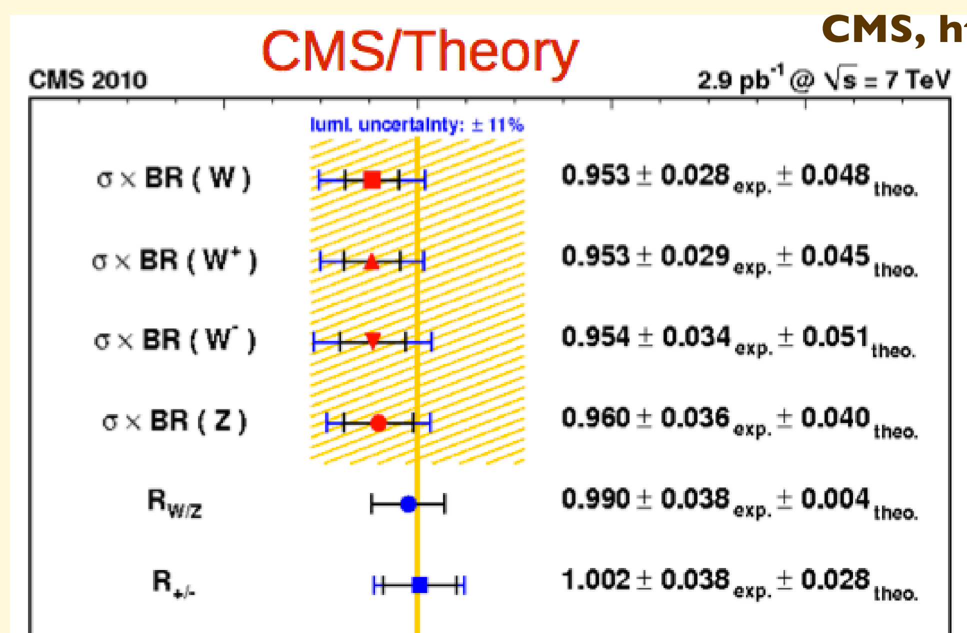


320 nb⁻¹, http://arxiv.org/abs/1010.2130



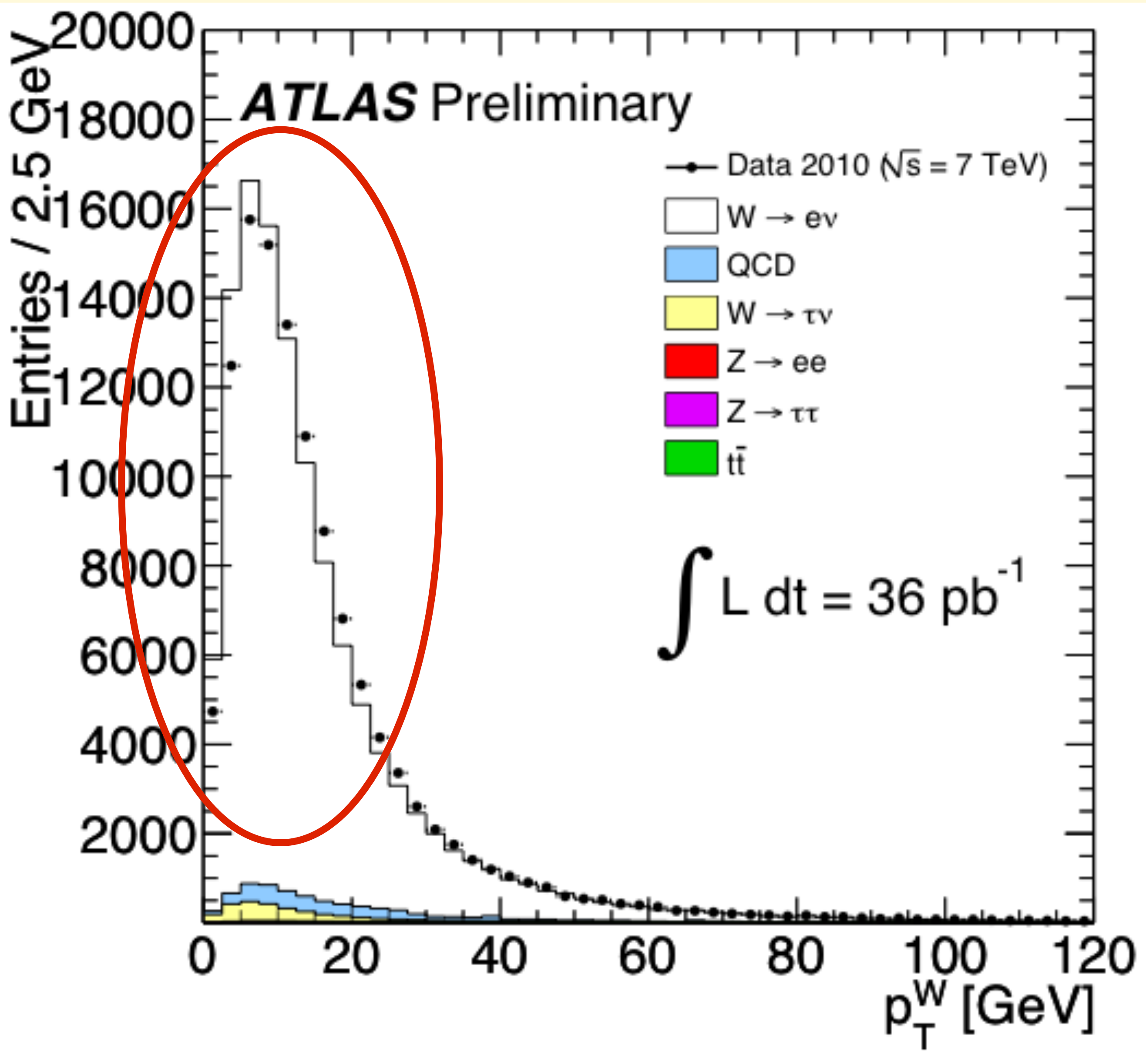


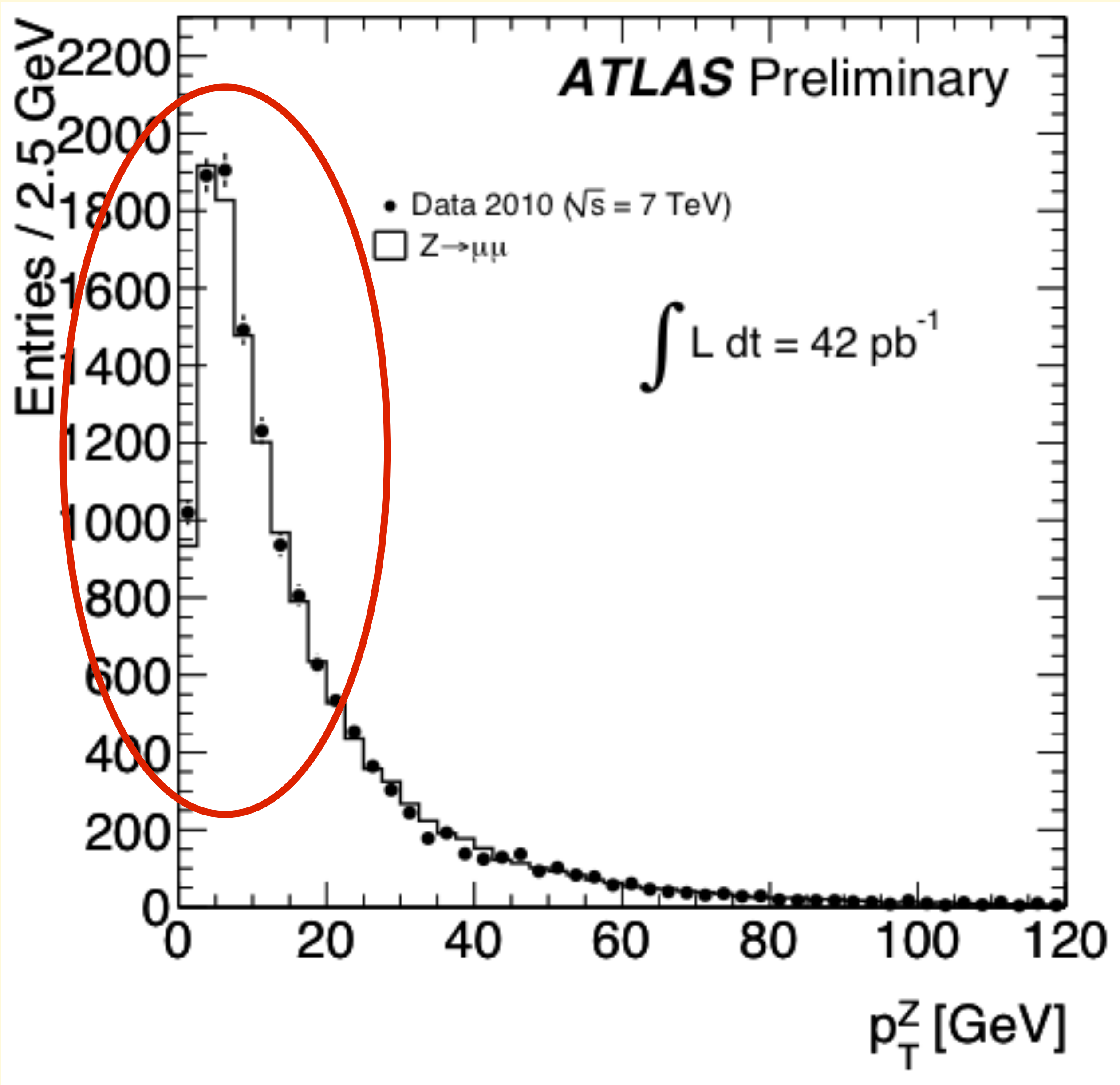




CMS, http://arxiv.org/abs/1012.2466, JHEP

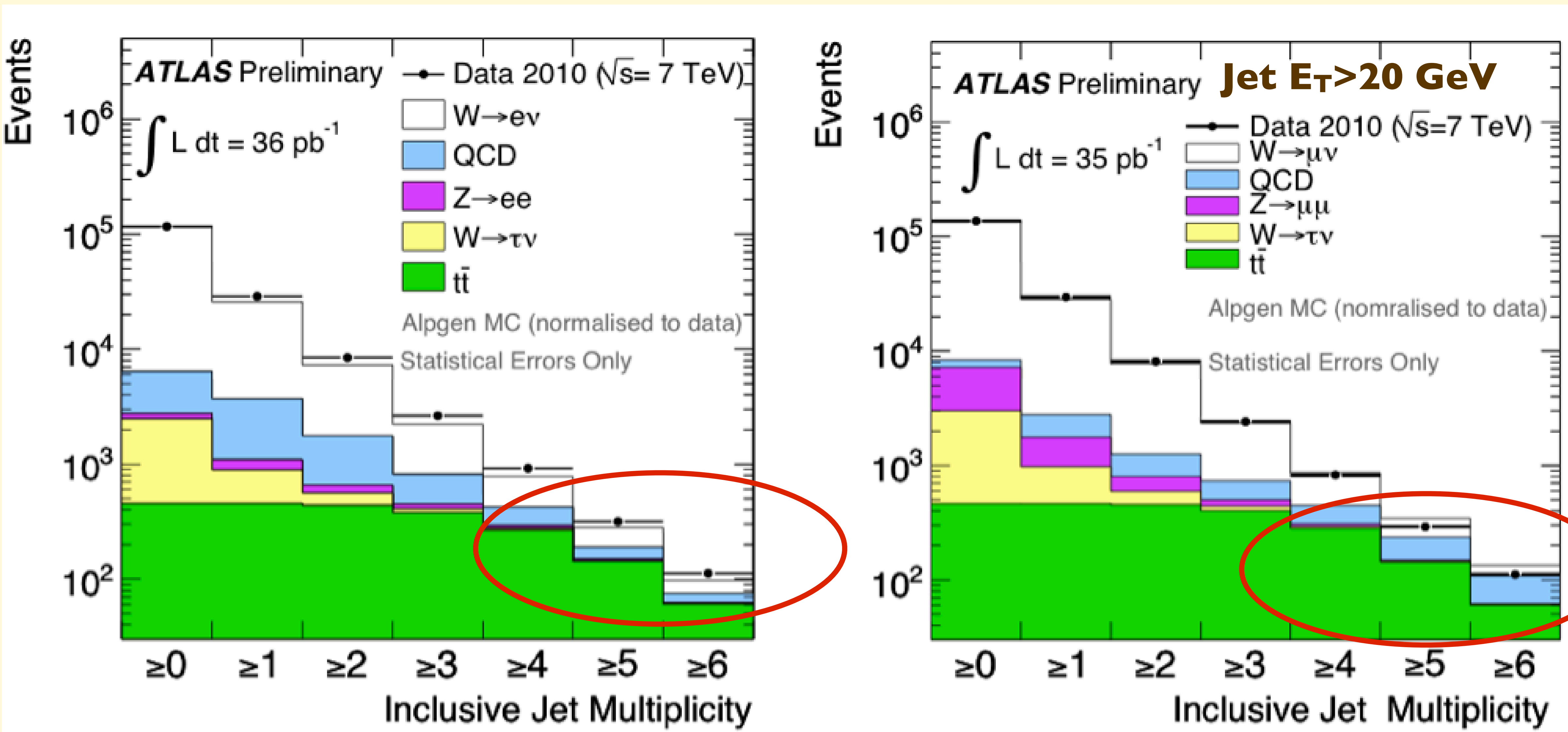
W/Z pt spectra



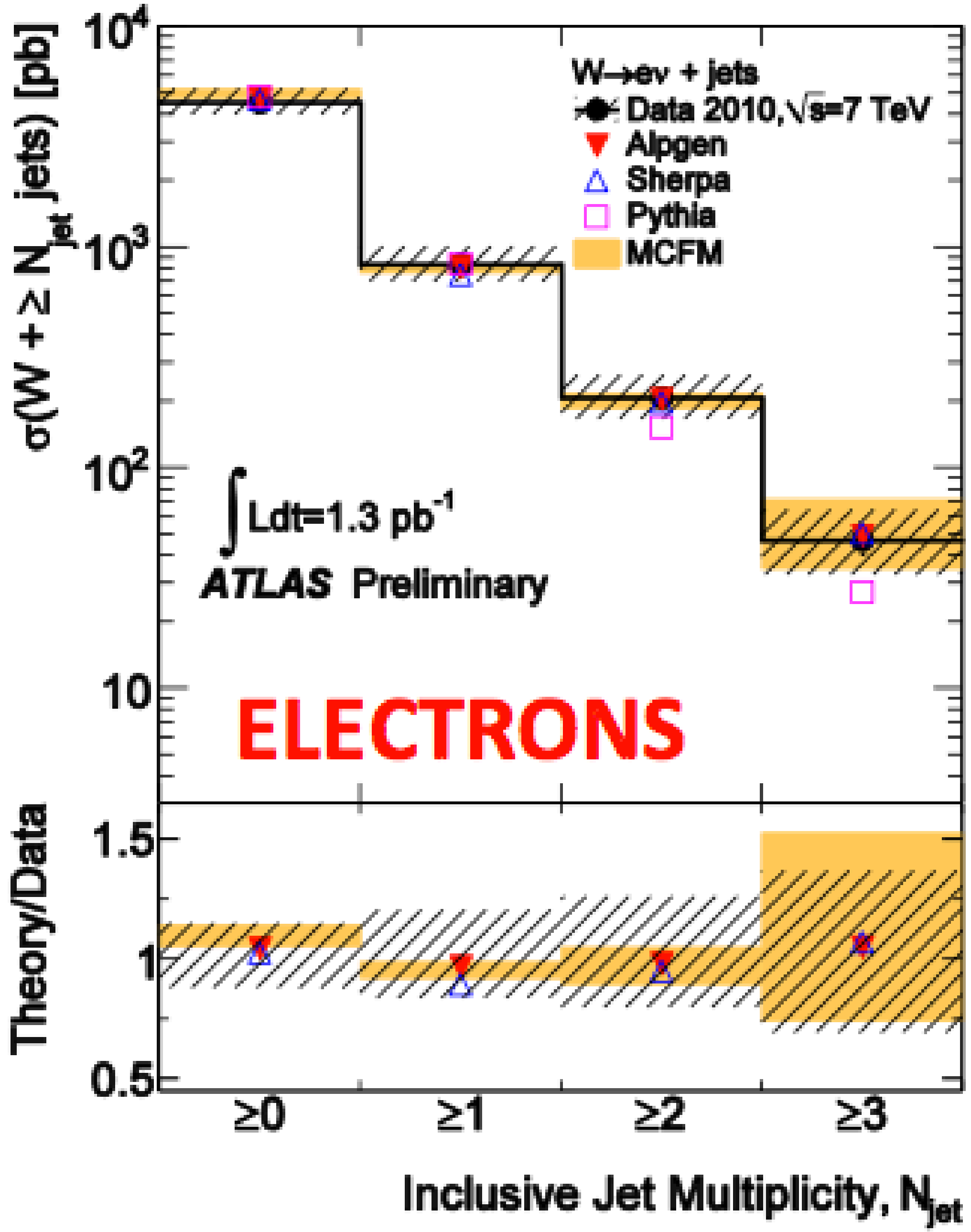


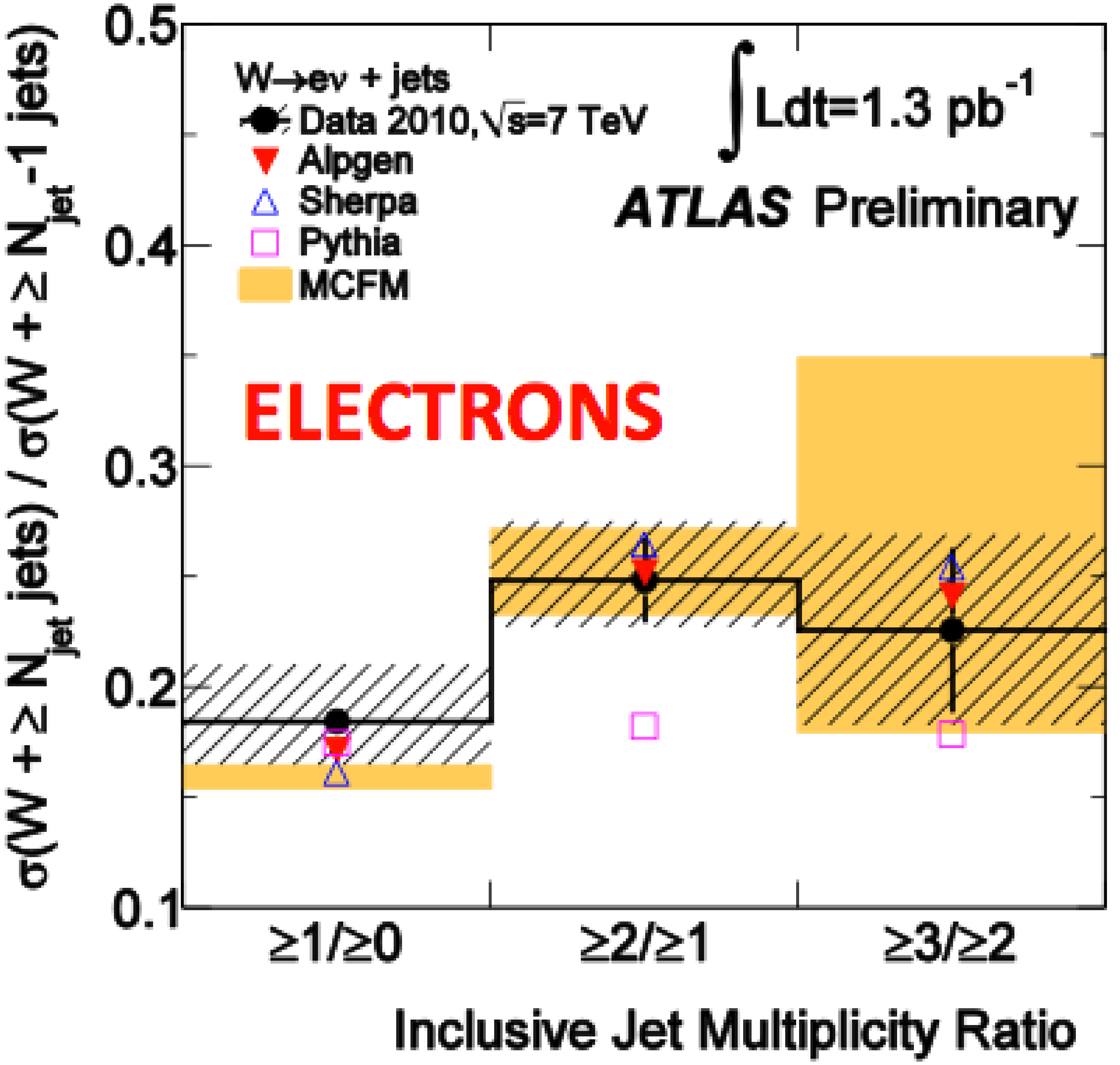
From the perspective of QCD, the modeling of W and Z pt is the same. So the different levels of agreement between data and theory in these two plots suggest that some more tuning of the detector description is required before moving on to quantitative tuning of QCD MCs.

W+jets



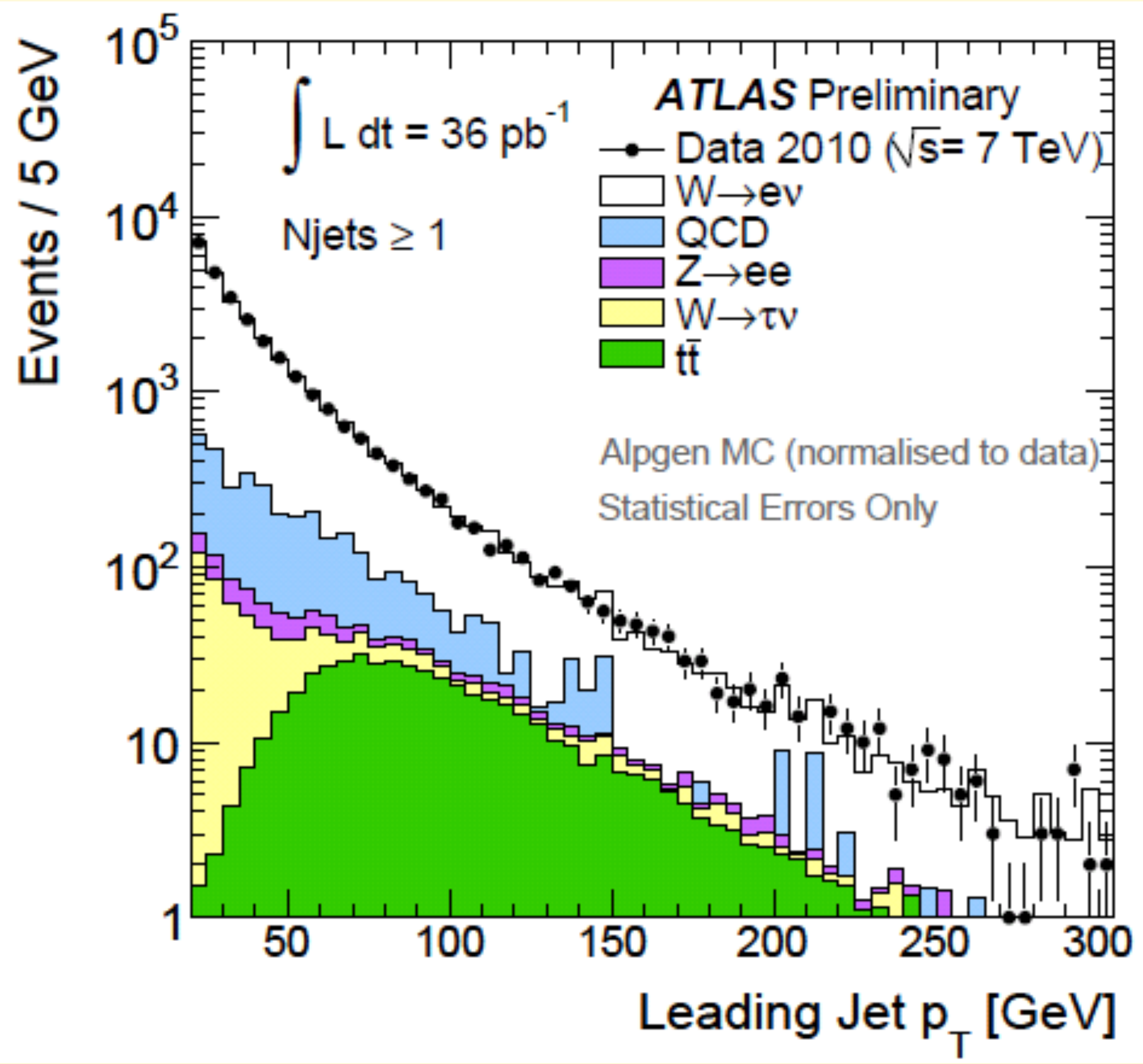
Statistics even out in the e and mu channels at large N_{jet}, making the agreement even more remarkable



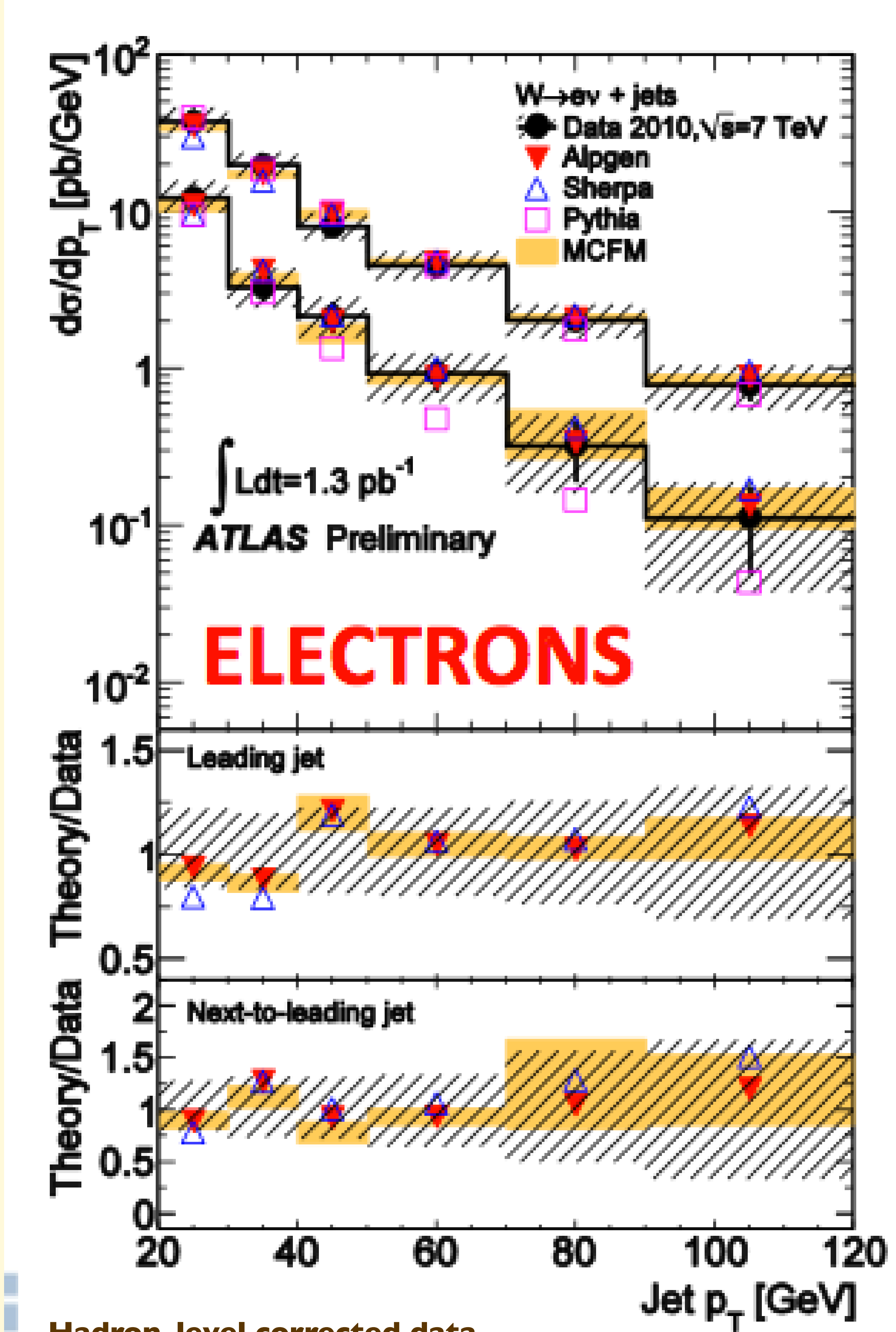


Alexander A. Paramonov (Argonne National Laboratory)
On behalf of the ATLAS collaboration
Conference on LHC First Data
Ann Arbor, December 12-14, 2010

W+jets, E_T spectrum

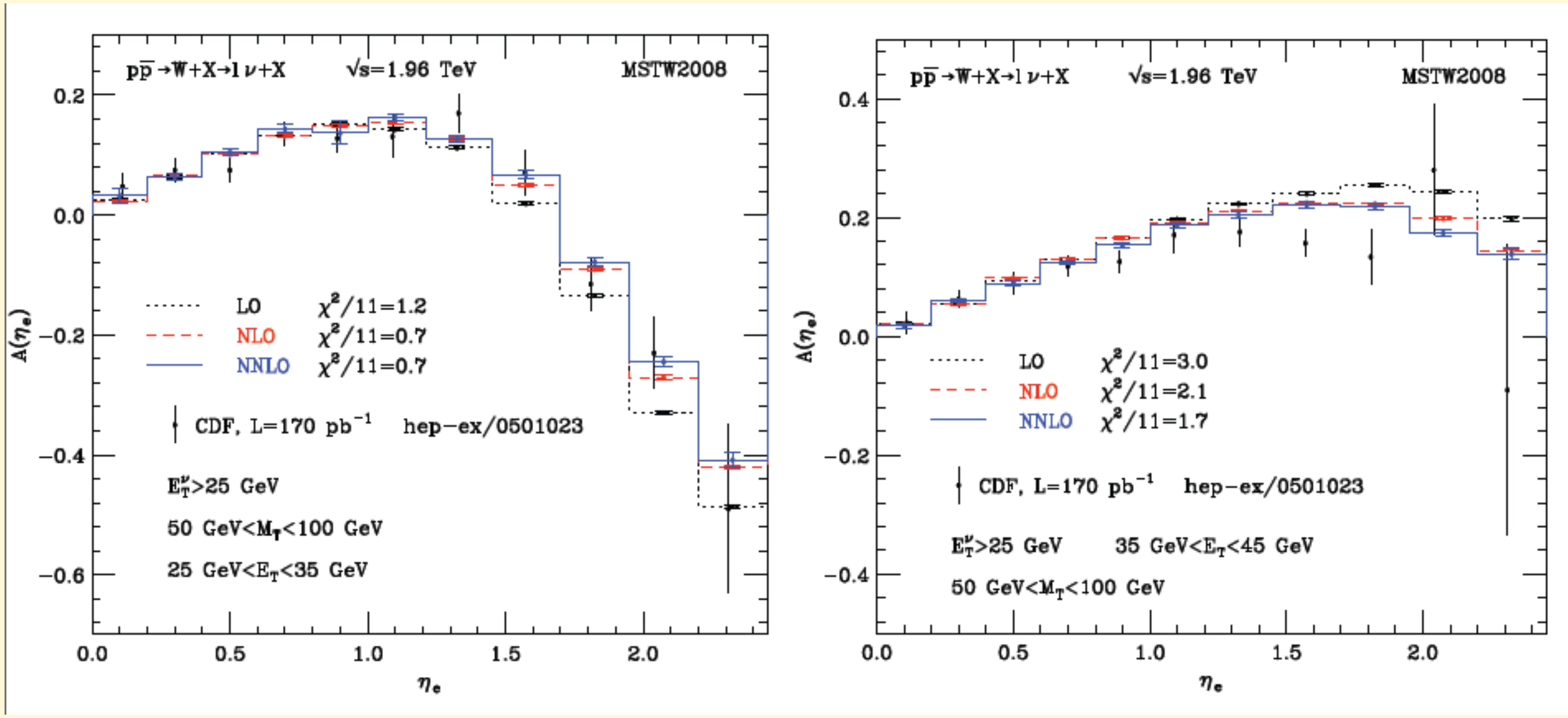


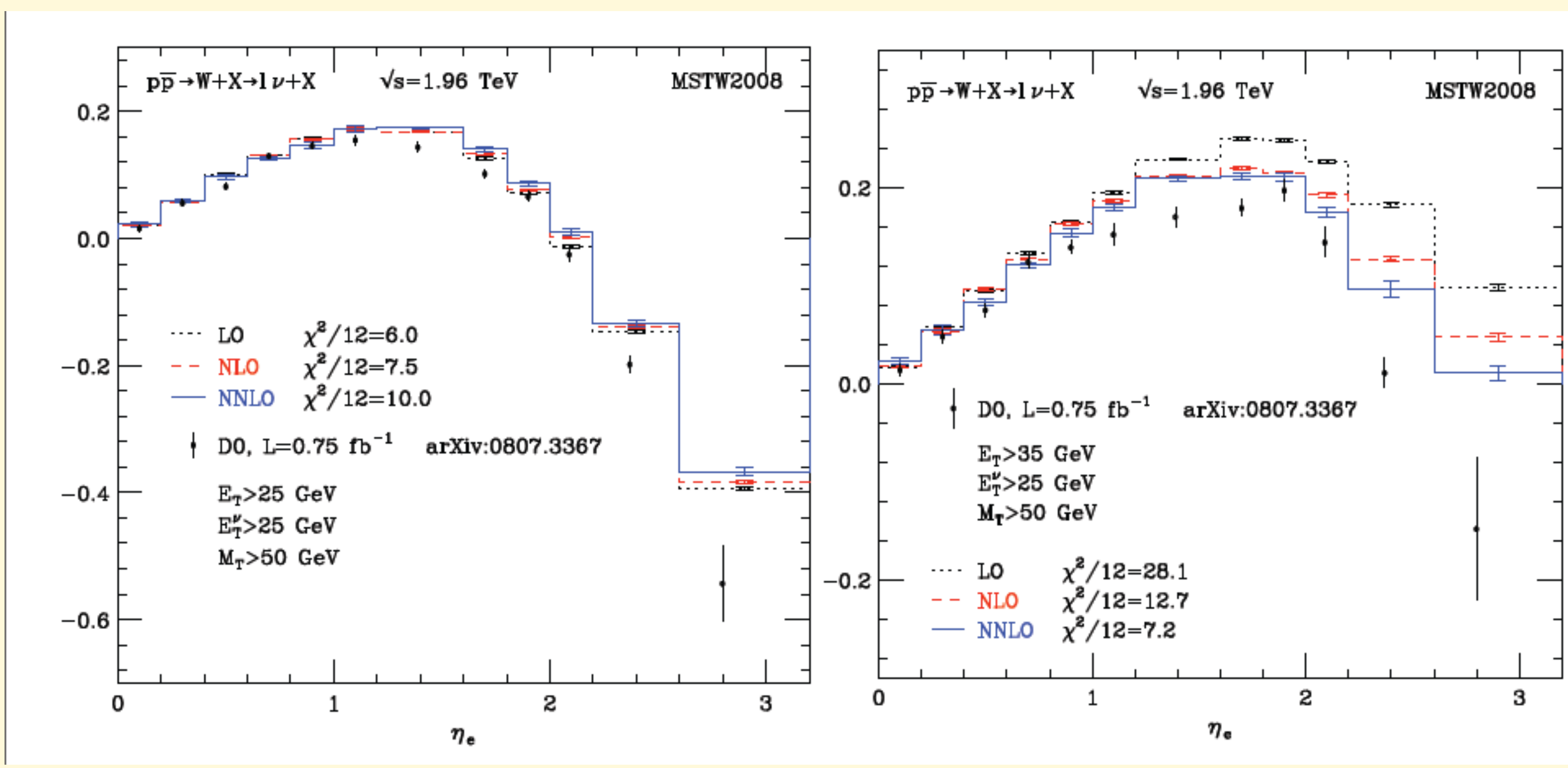
Uncorrected data



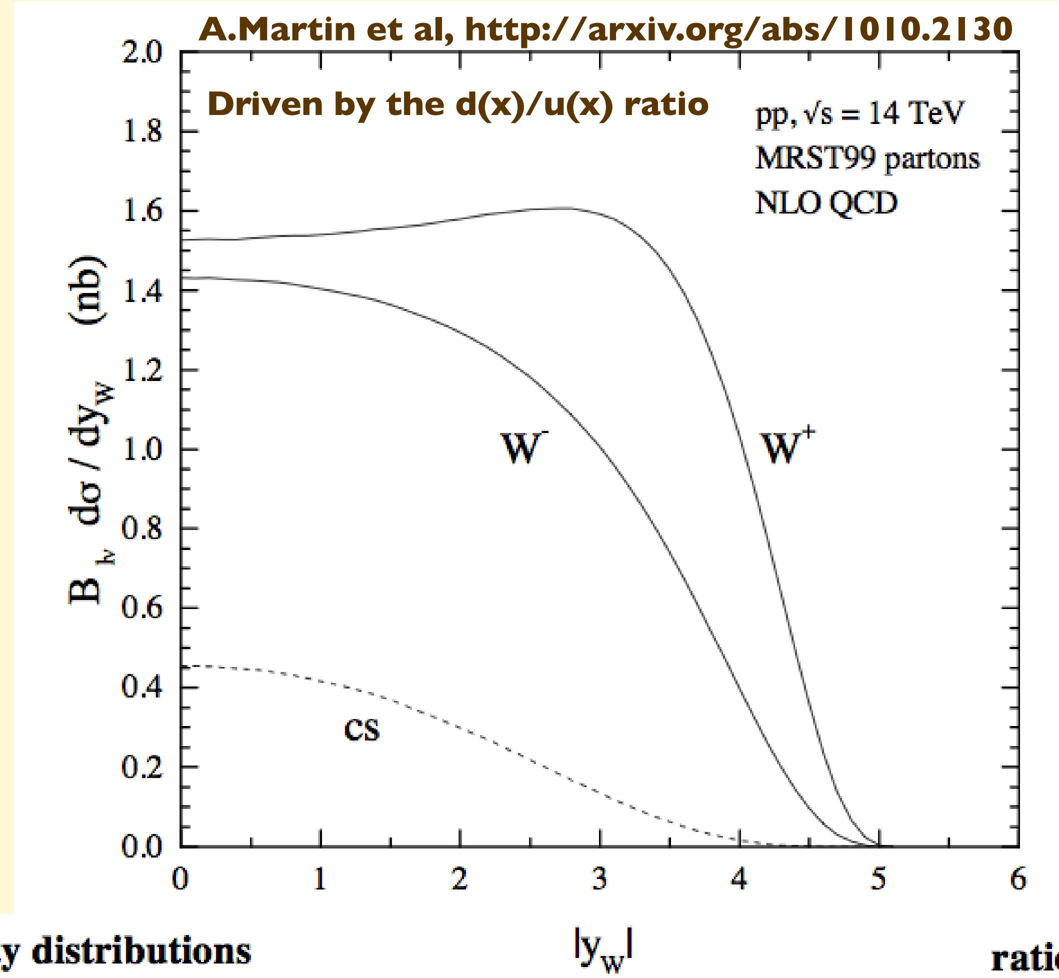
Hadron-level corrected data

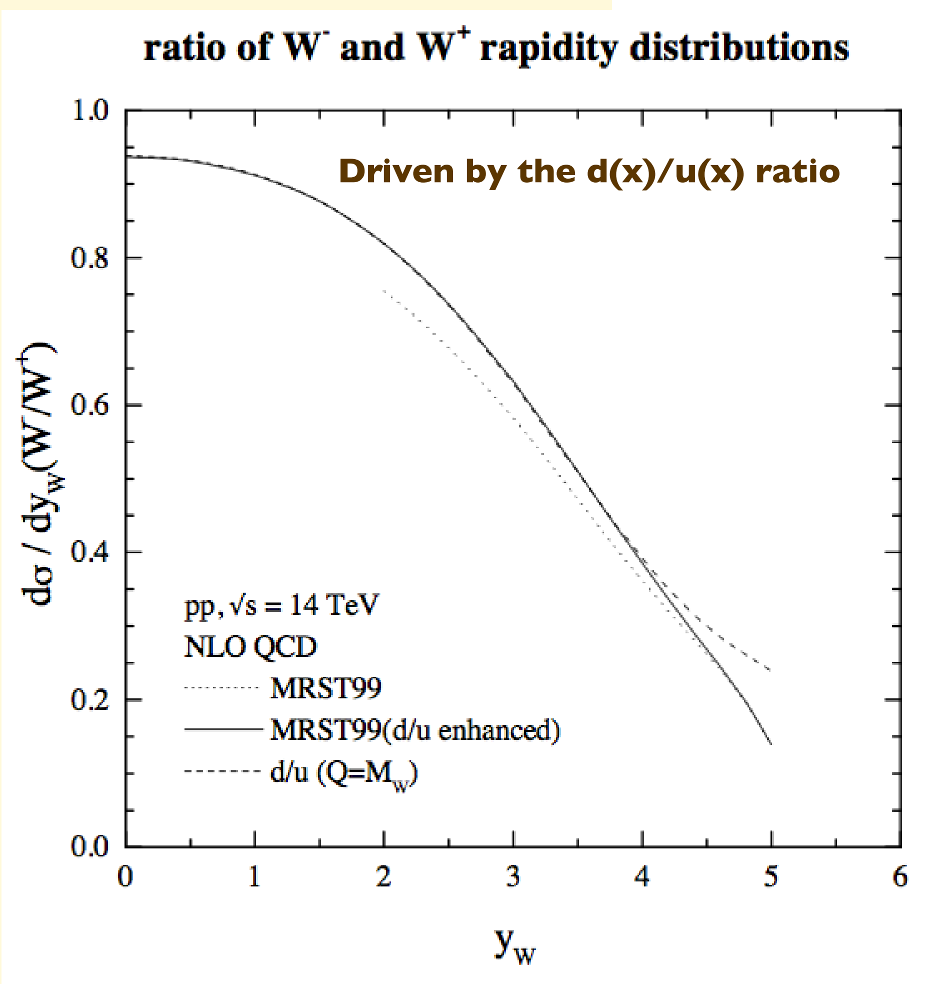
Lepton rapidity charge-asymmetry in W production at the Tevatron

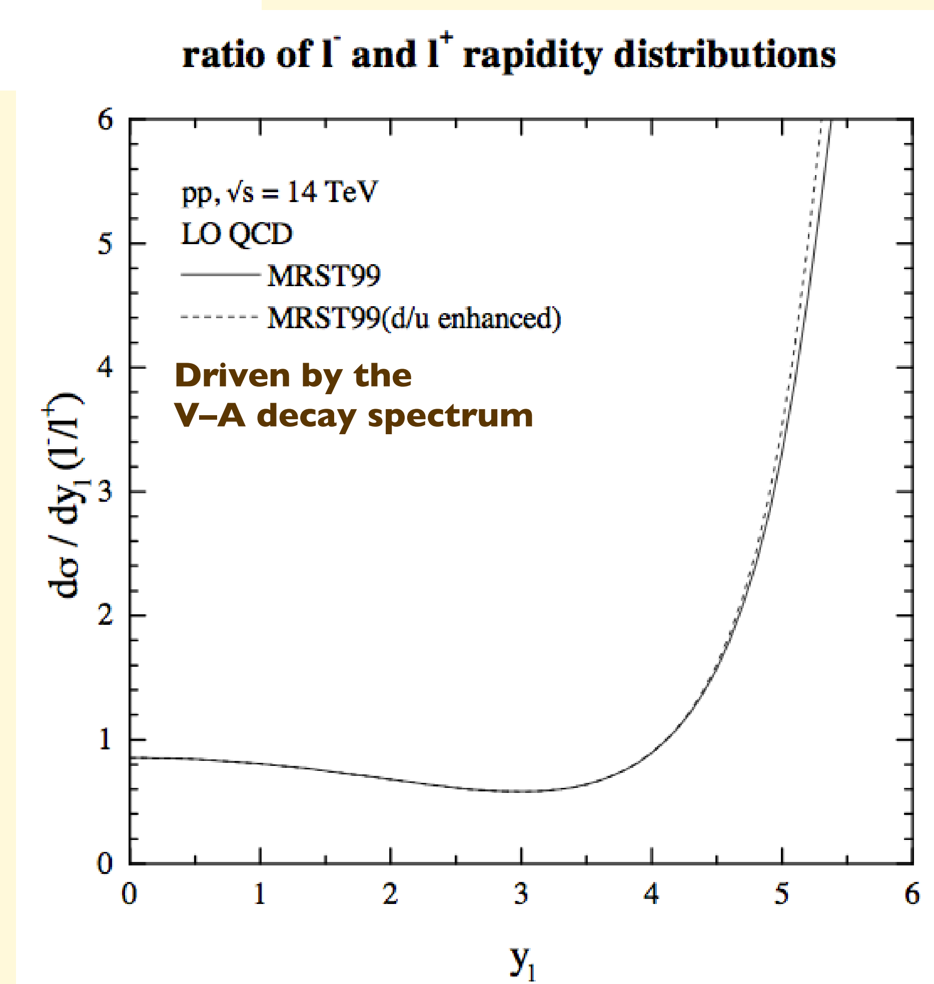




W+ / W– production asymmetries



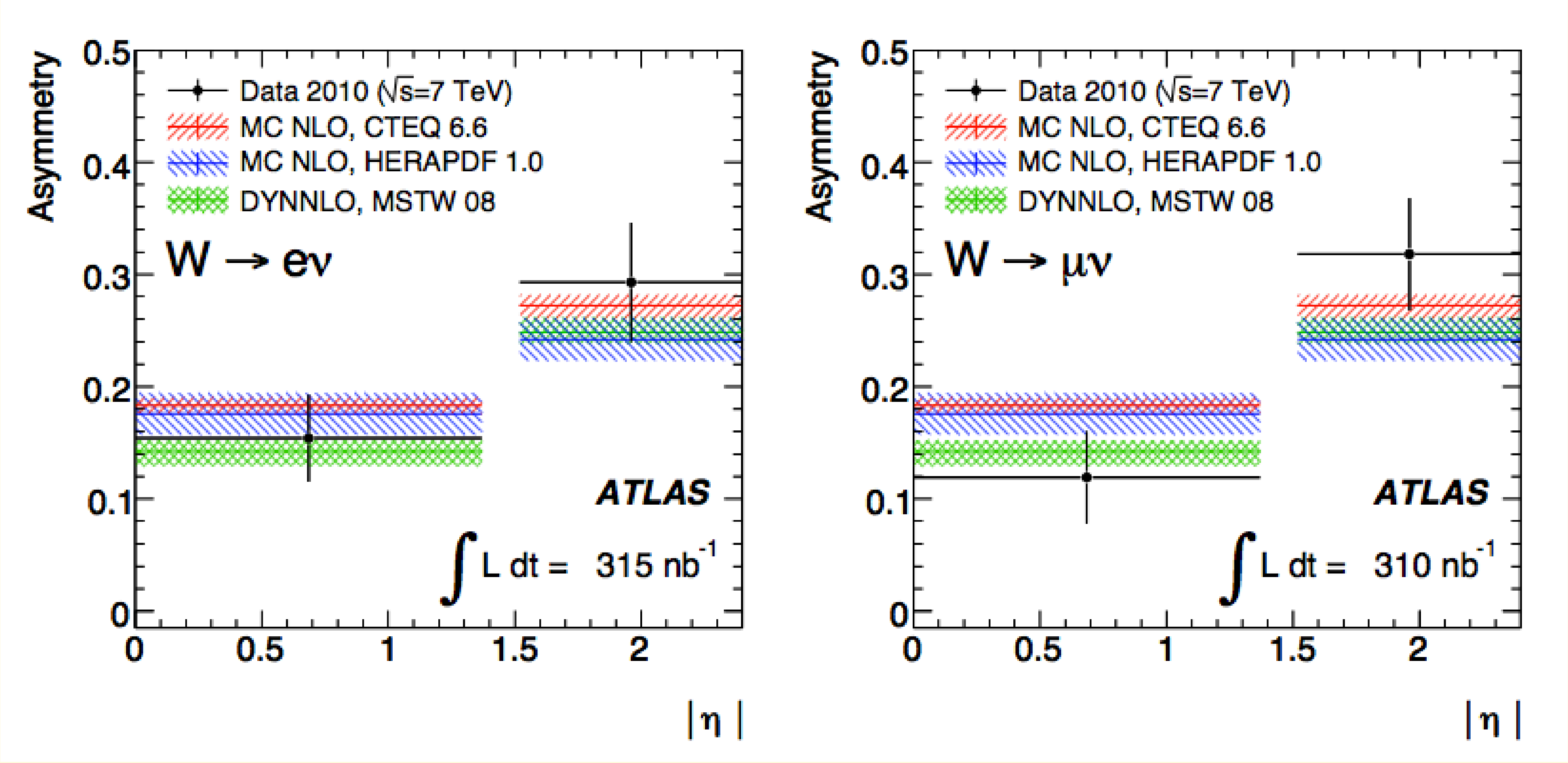




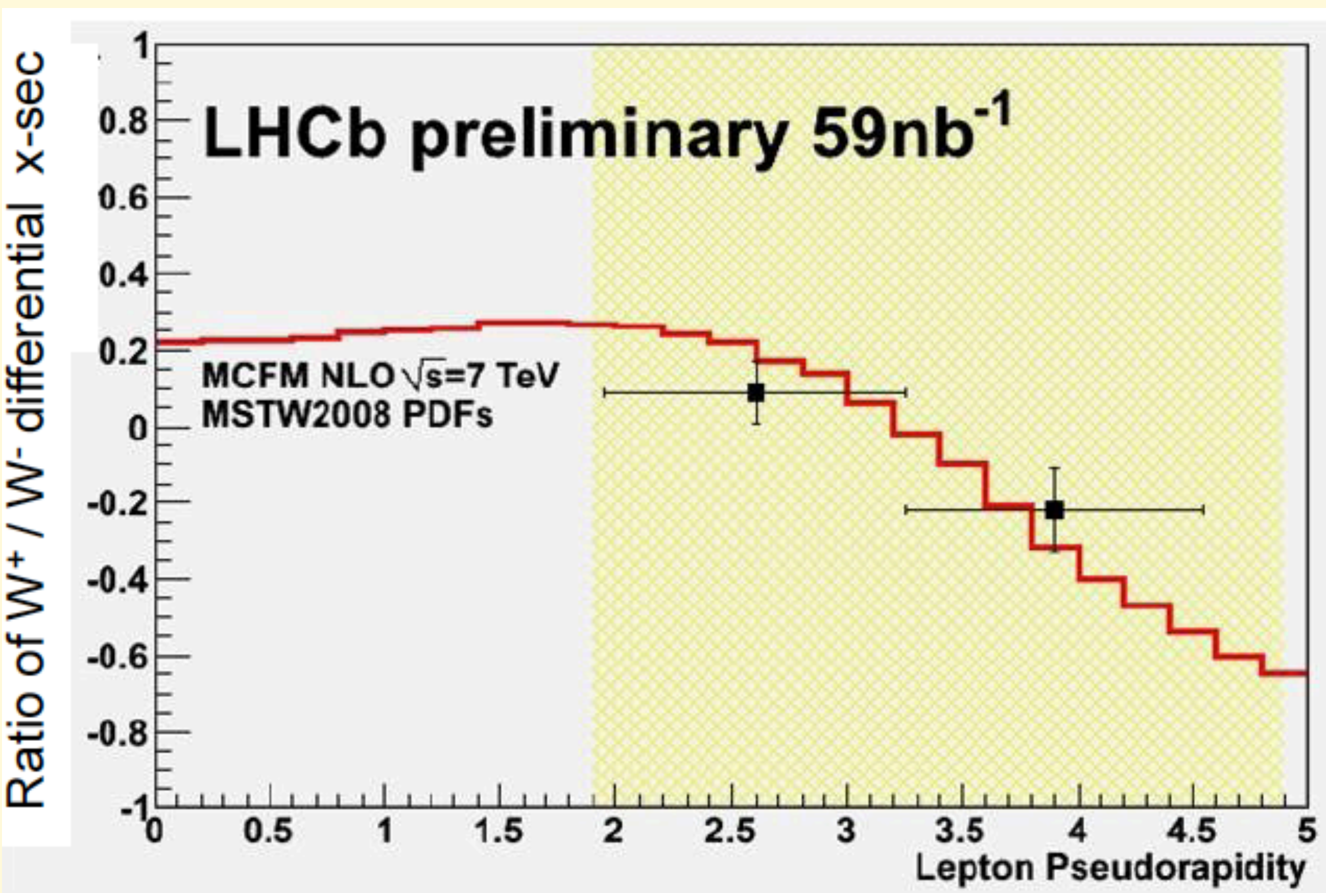
Lepton charge asymmetry at the LHC

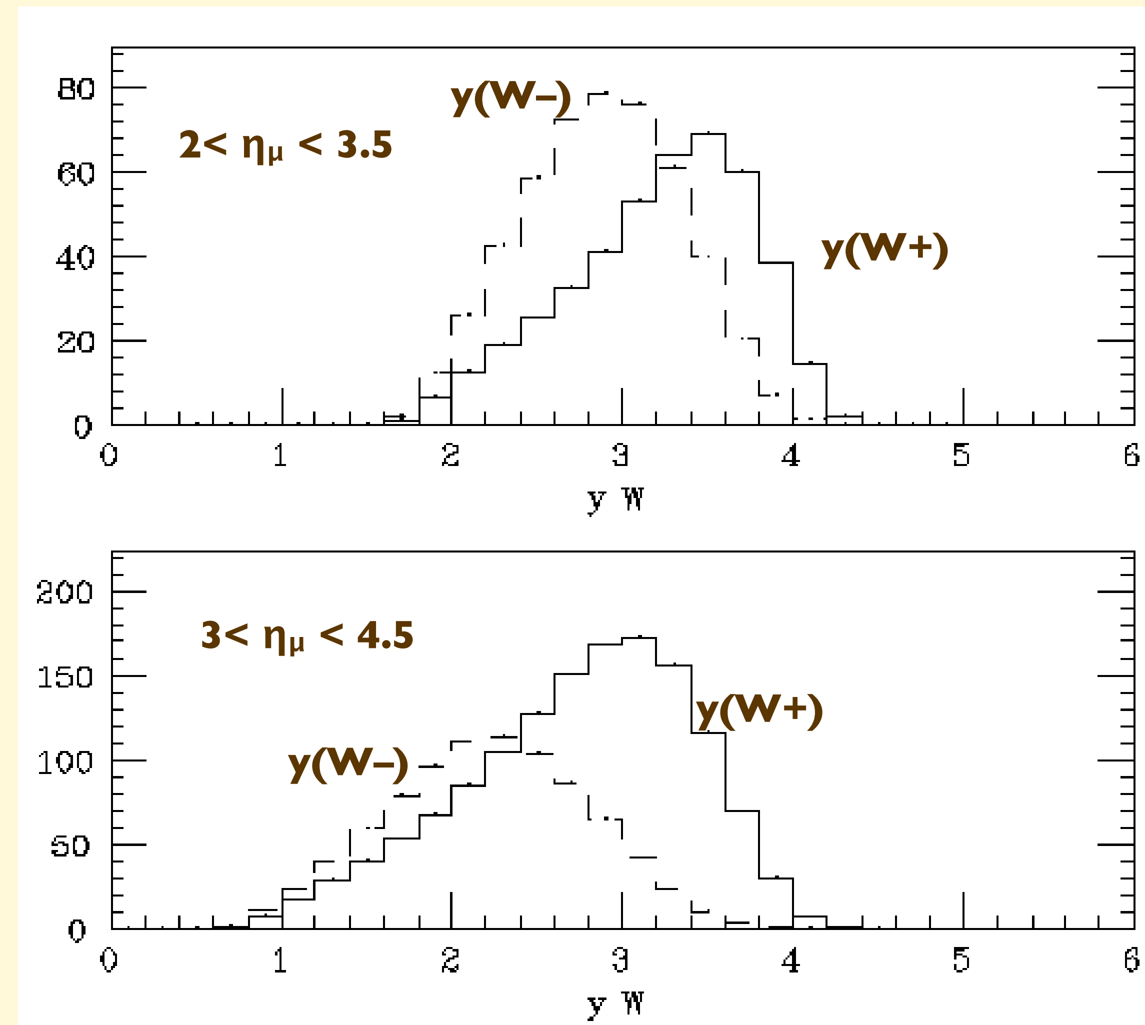
$$A_\ell = \frac{\sigma^{\text{fid}}_{W^+} - \sigma^{\text{fid}}_{W^-}}{\sigma^{\text{fid}}_{W^+} + \sigma^{\text{fid}}_{W^-}}$$

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



EW boson production in the forward region, LHCb

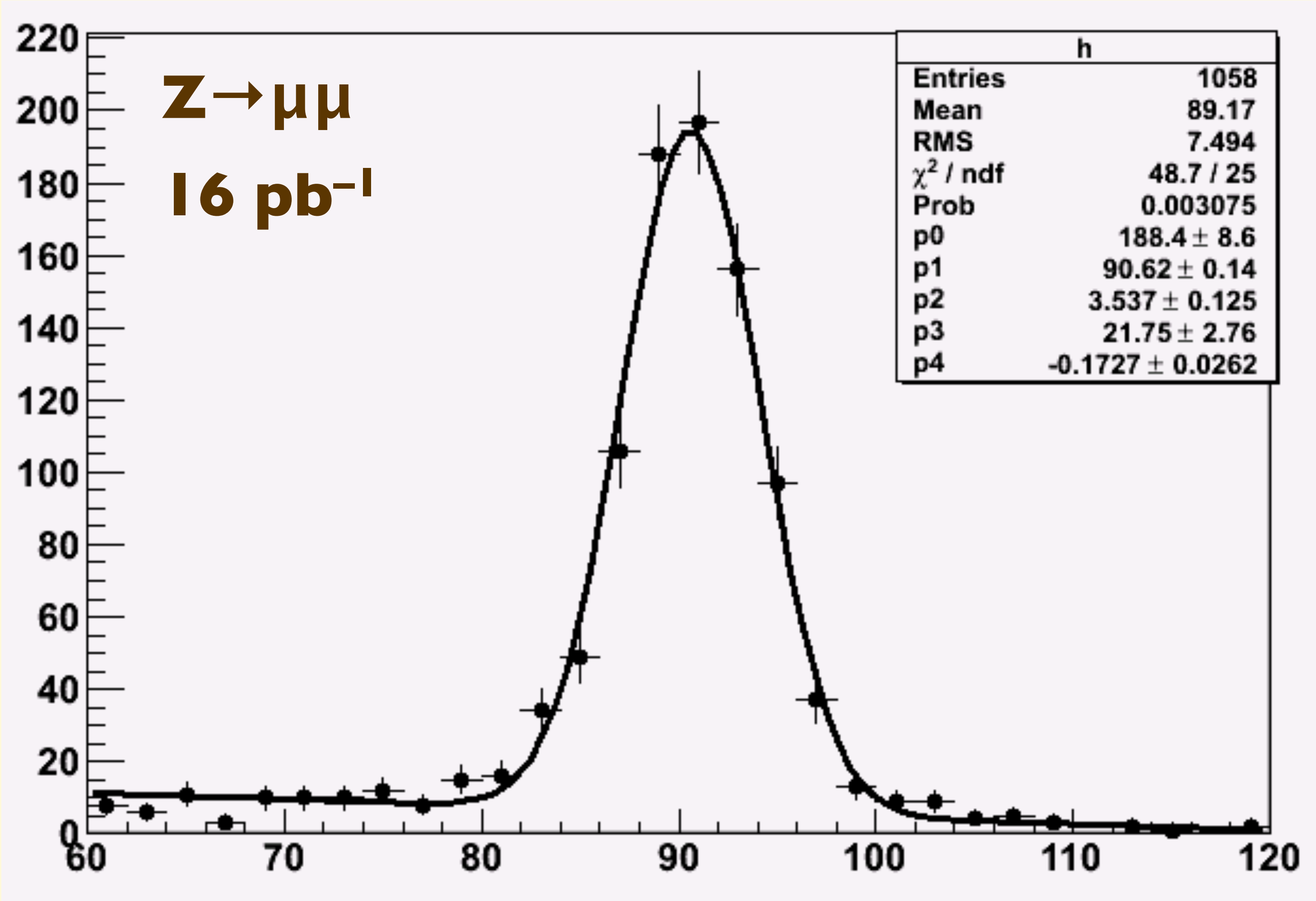




W→μν, charge asymmetry

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

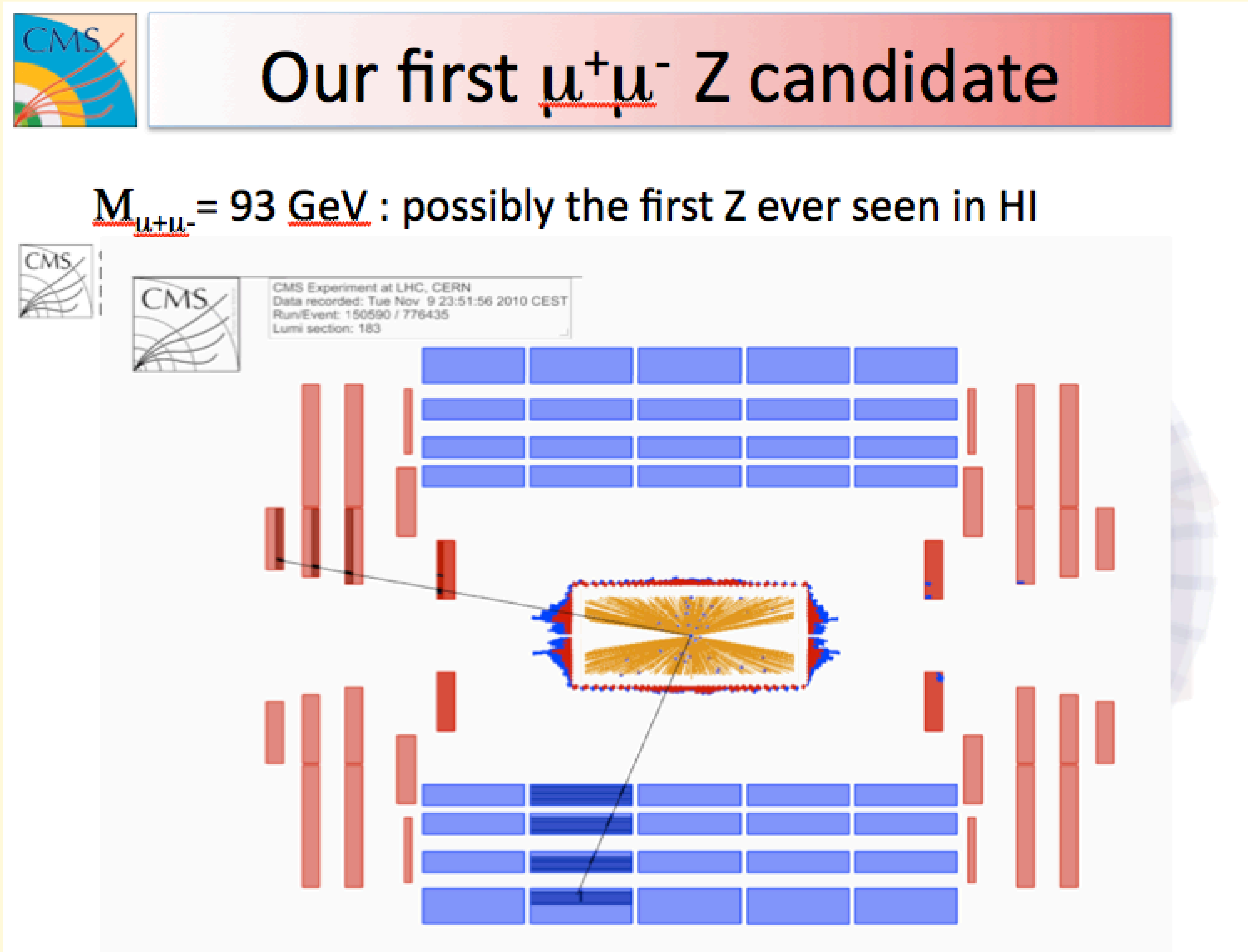
EW boson production in the forward region, LHCb



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

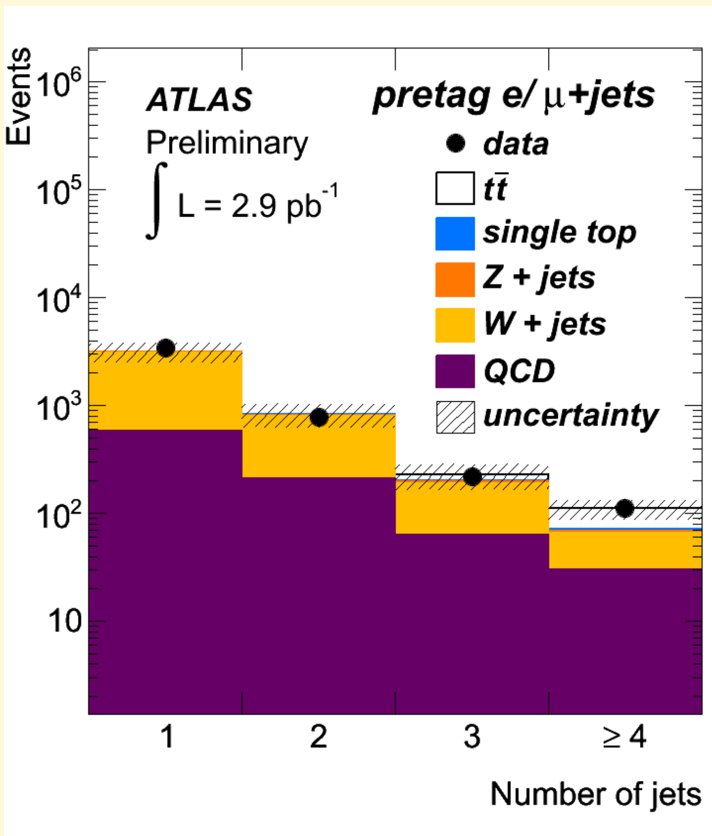
See S.Stone, for the LHCb collab., 104th LHCC session, http://indico.cern.ch/conferenceDisplay.py?confId=112439

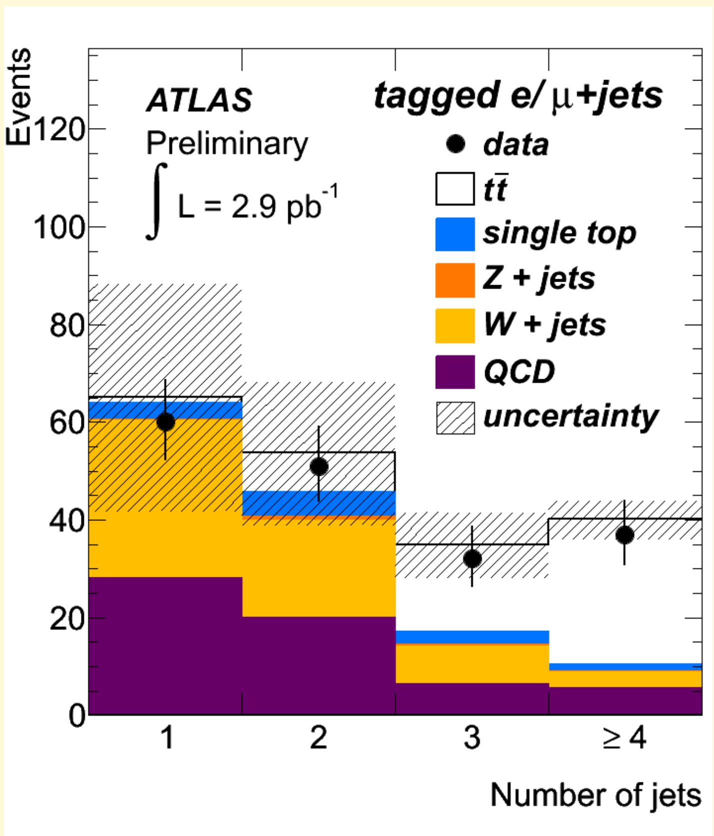
EW boson production in Pb Pb collisions, CMS

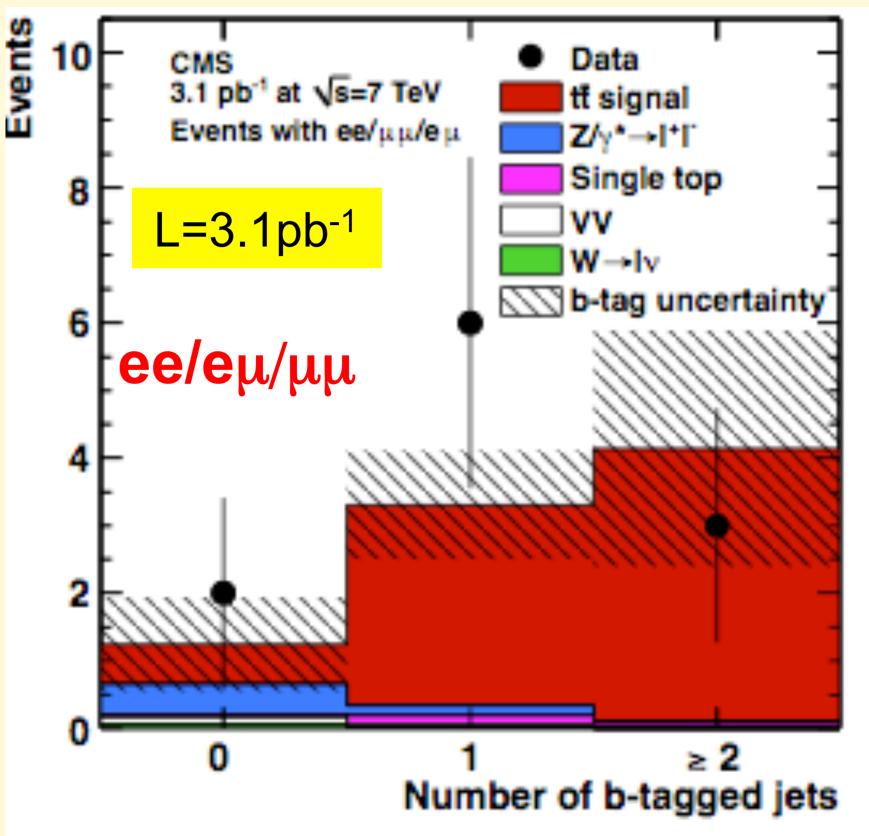


Heavy quarks

Top

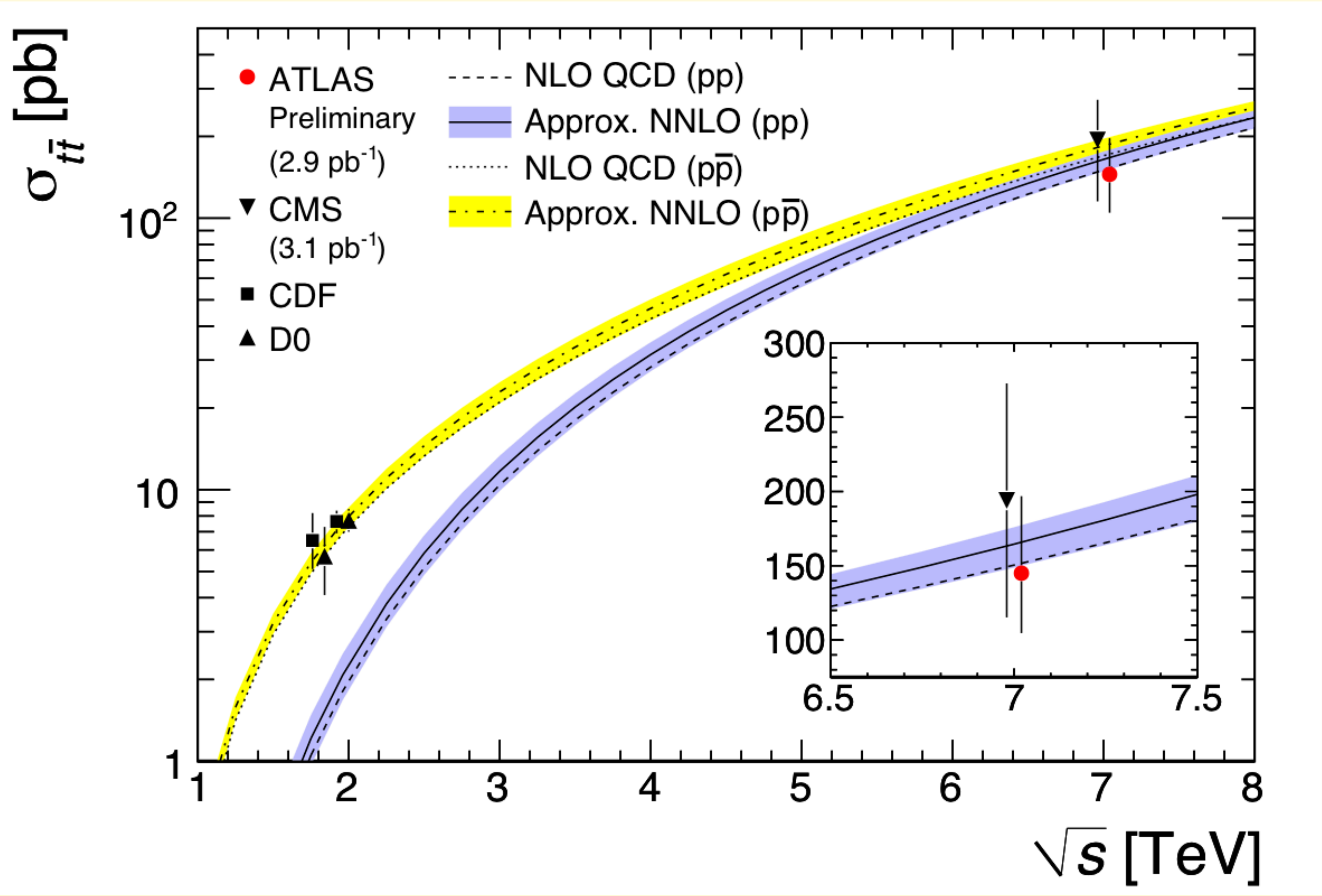






1 e or μ with p_T>20 GeV, E_T^{miss}>20 GeV, E_T^{miss}+$m_T(W)$>60 GeV
N_{jets} with p_T>25 GeV, with no b-tag requirement or at least one b-tag
Signal defined to have 4 or more jets, and at least 1 b-tag

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



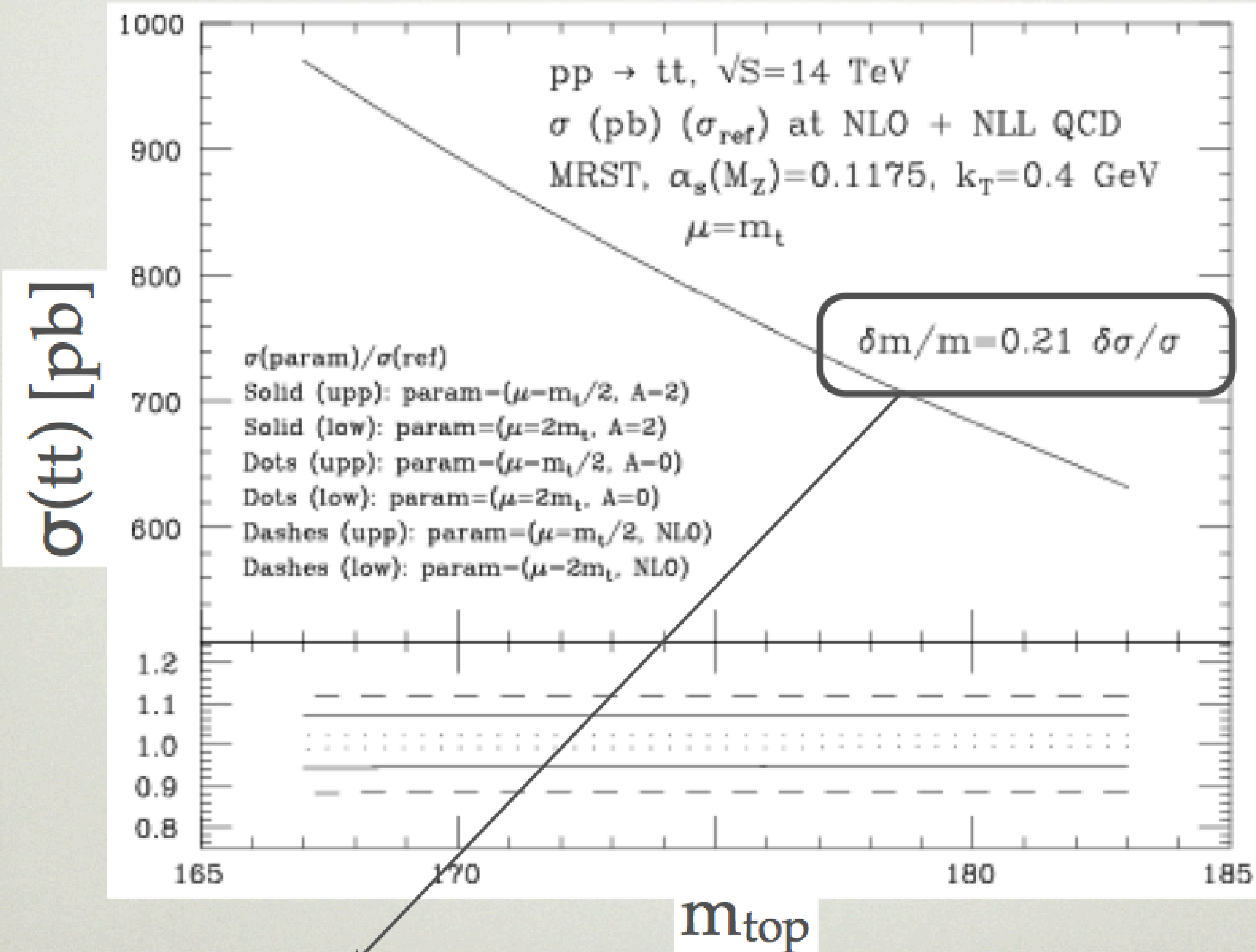
[1] ATLAS (lepton+b+≥3 jets and dileptons+≥2jets): $\sigma_{ATLAS} = 145 \pm 31 {}^{+42}_{-27}$ pb

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

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

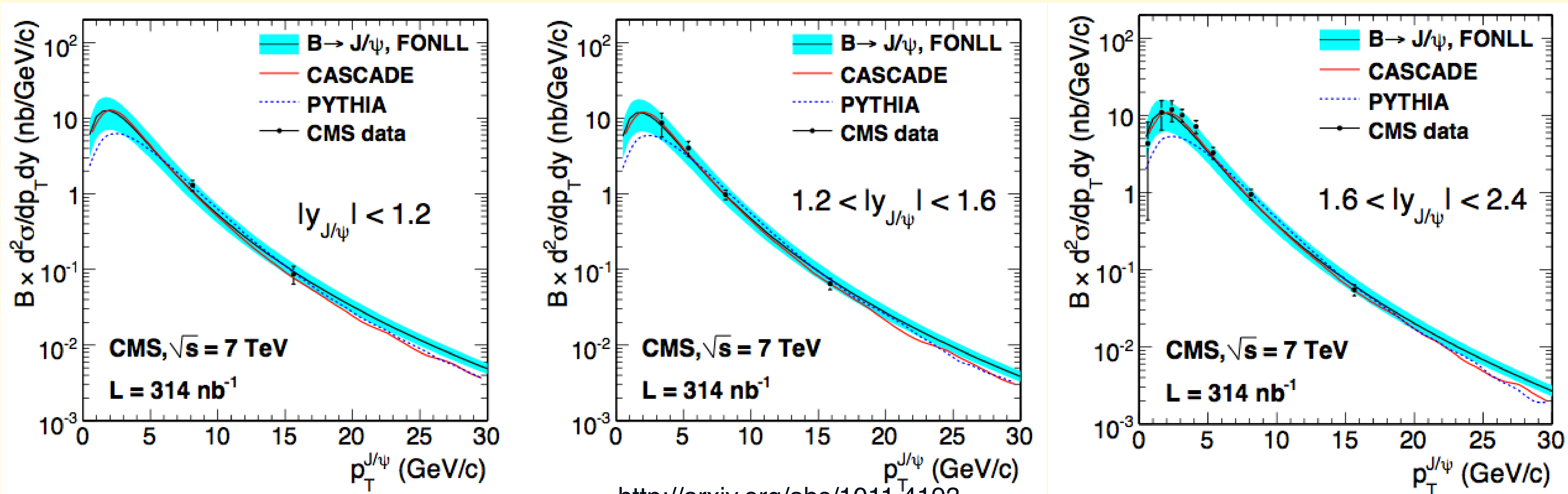
[1] **See P. Wells, for the ATLAS collab., 104th LHCC session, http://indico.cern.ch/conferenceDisplay.py?confId=112439**

[2] **arXiv:1010.5994**

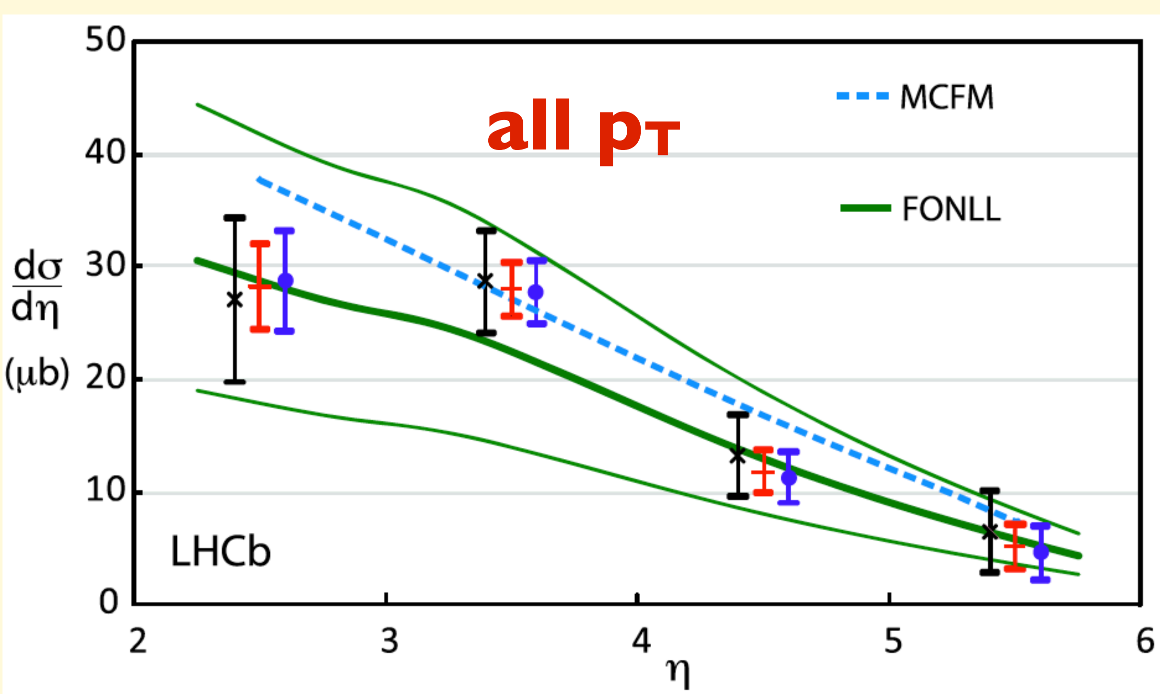


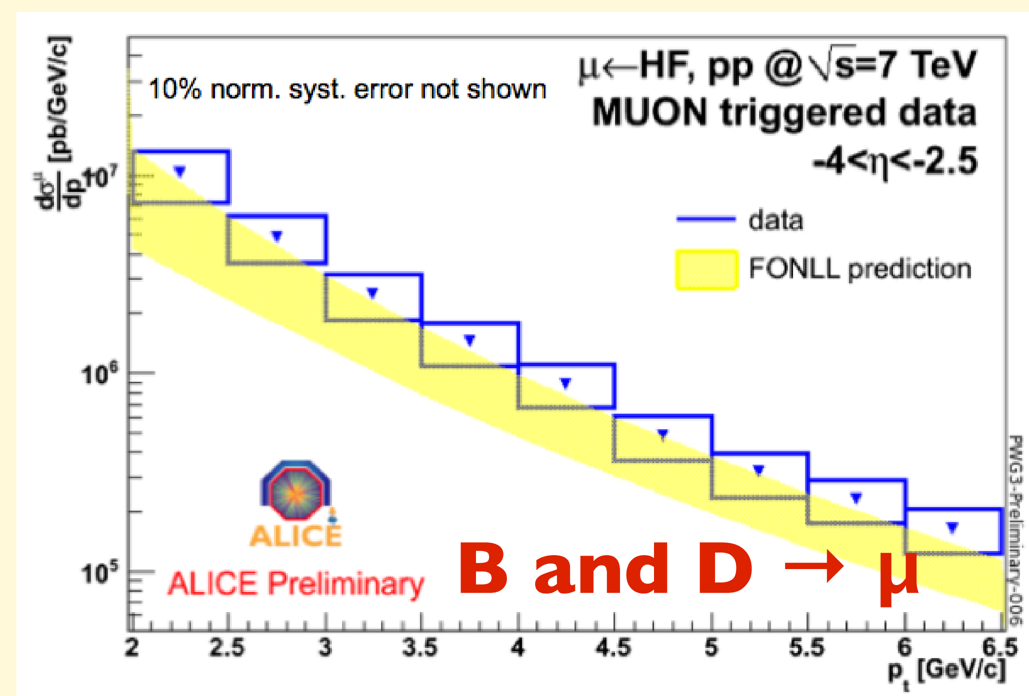
$\Delta\sigma/\sigma = \pm 5\% \Leftrightarrow \Delta m/m = \pm 1\% \lesssim 2$ GeV, comparable to Δm_{direct}

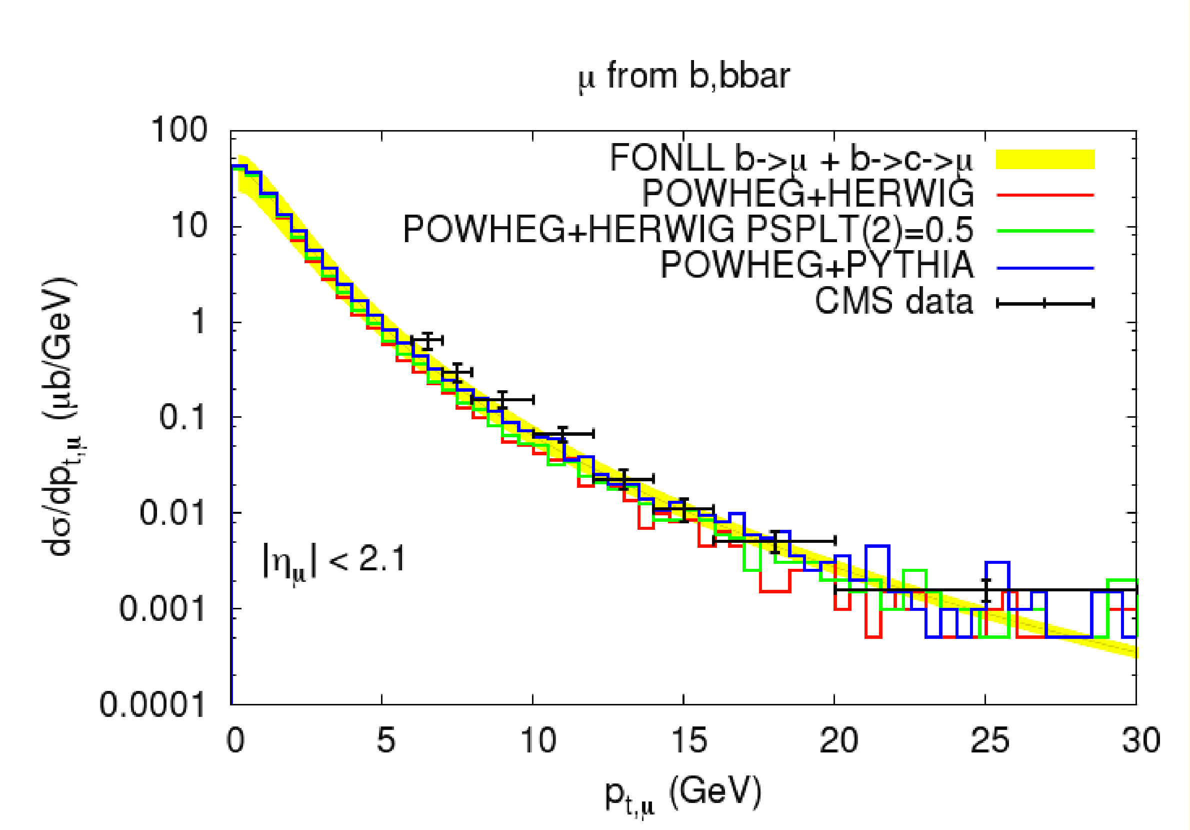
Open Q: by and large good agreement of data and NLO

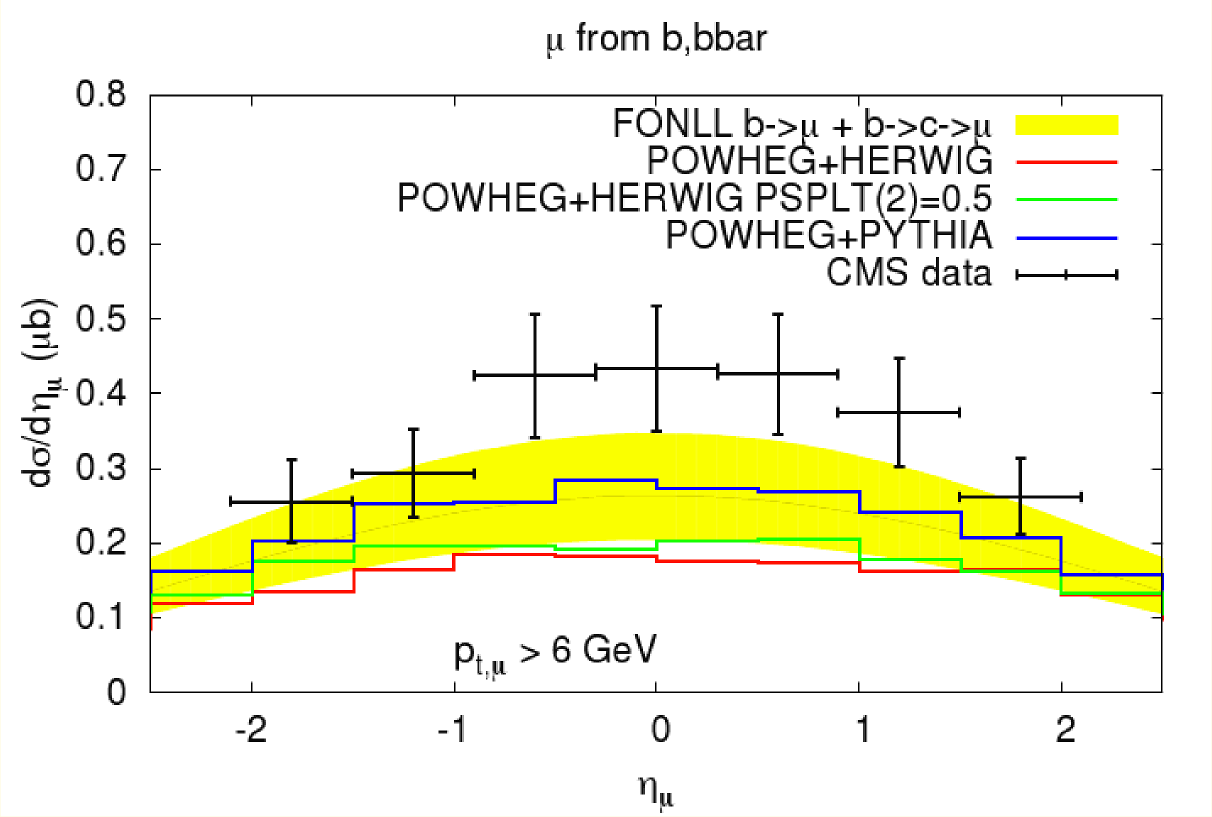


http://arxiv.org/abs/1011.4193






μ from b,bbar
FONLL b->μ + b->c->μ
POWHEG+HERWIG
POWHEG+HERWIG PSPLT(2)=0.5
POWHEG+PYTHIA
CMS data
dσ/dp$_{t,\mu}$ (μb/GeV)
|η$_\mu$| < 2.1
p$_{t,\mu}$ (GeV)

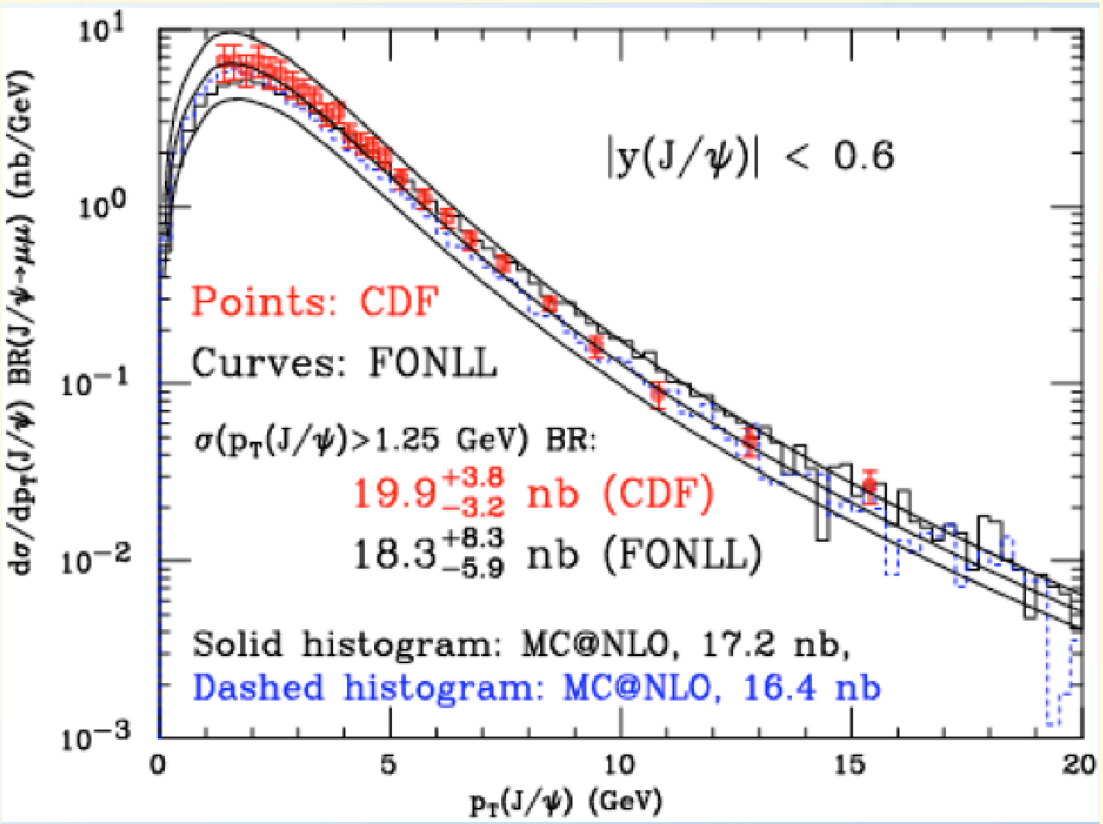

μ from b,bbar
FONLL b->μ + b->c->μ
POWHEG+HERWIG
POWHEG+HERWIG PSPLT(2)=0.5
POWHEG+PYTHIA
CMS data
dσ/dη$_\mu$ (μb)
p$_{t,\mu}$ > 6 GeV
η$_\mu$

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

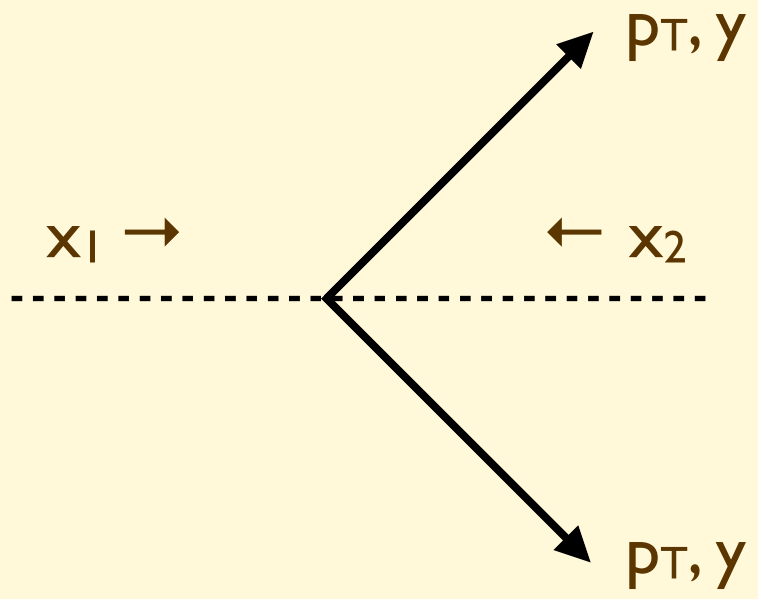


The dynamical regime of the LHC is theoretically more challenging

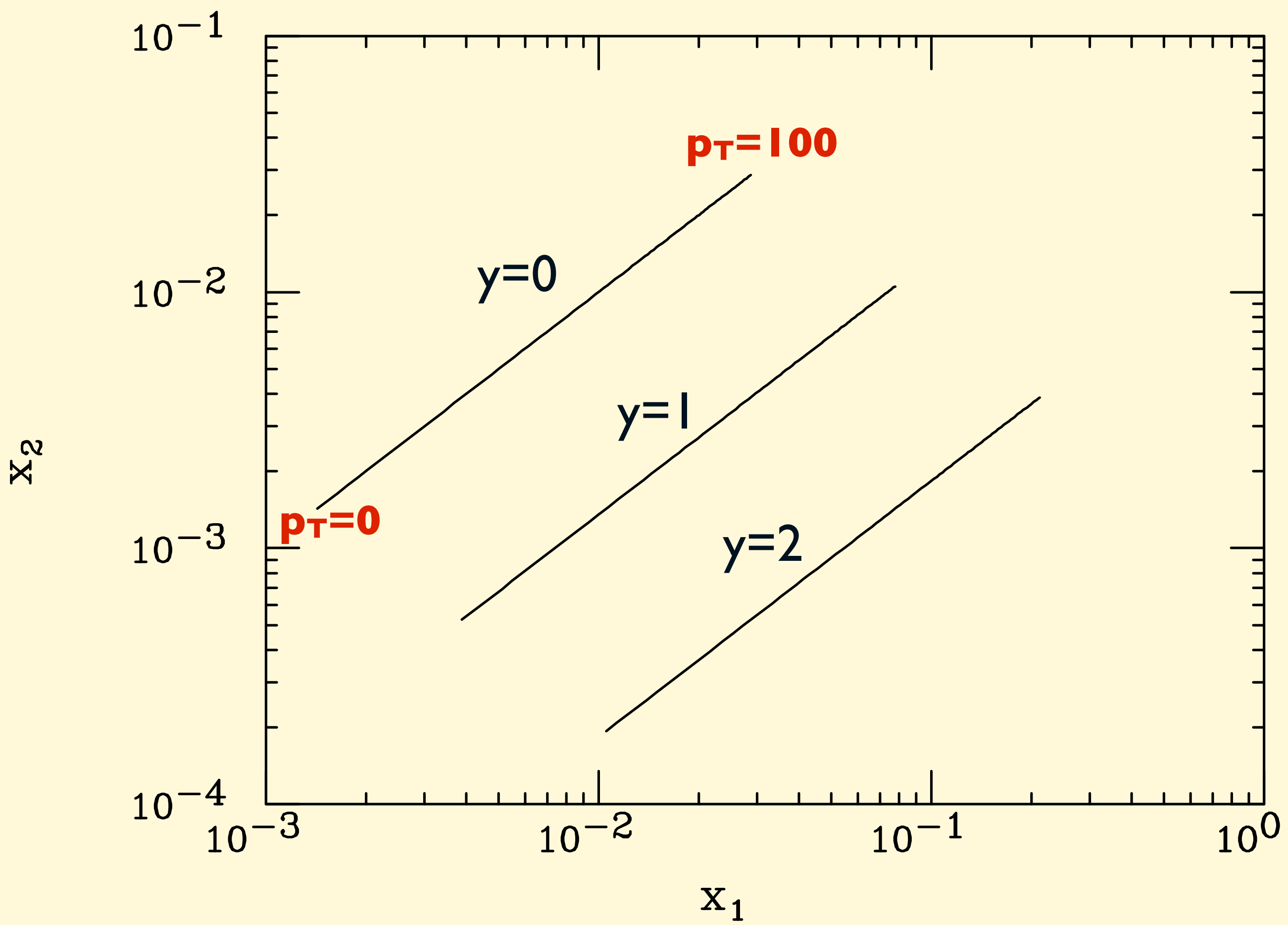
- large S => small x
- large rapidity (ALICE, LHCb)
  - o access to even smaller x
  - o small pt, sensitivity to higher-twist effects

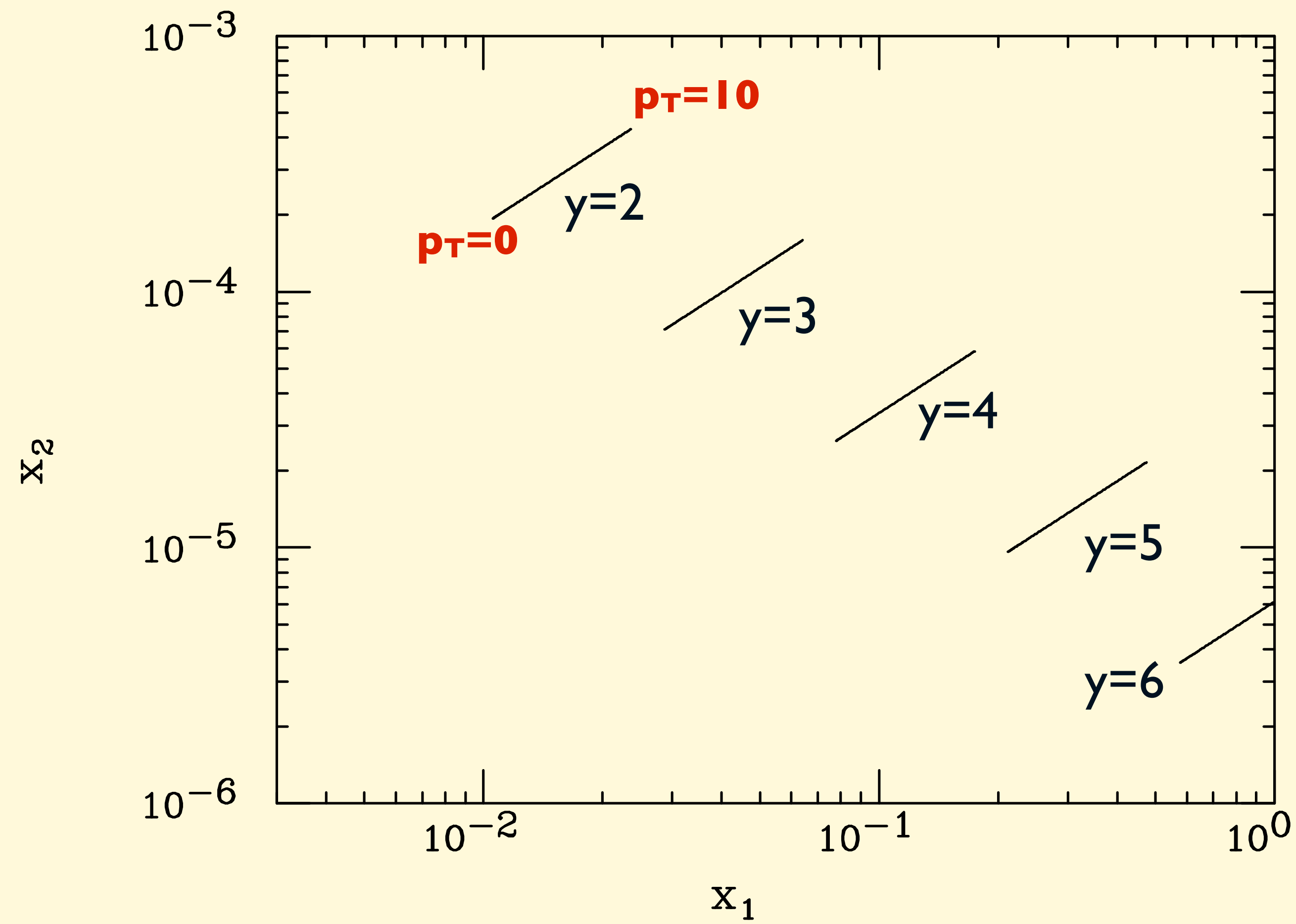
Nason, Dawson, Ellis
Collins, R.K.Ellis
Ball, Ellis
Catani Ciafaloni Hautmann
....

Kinematic reach

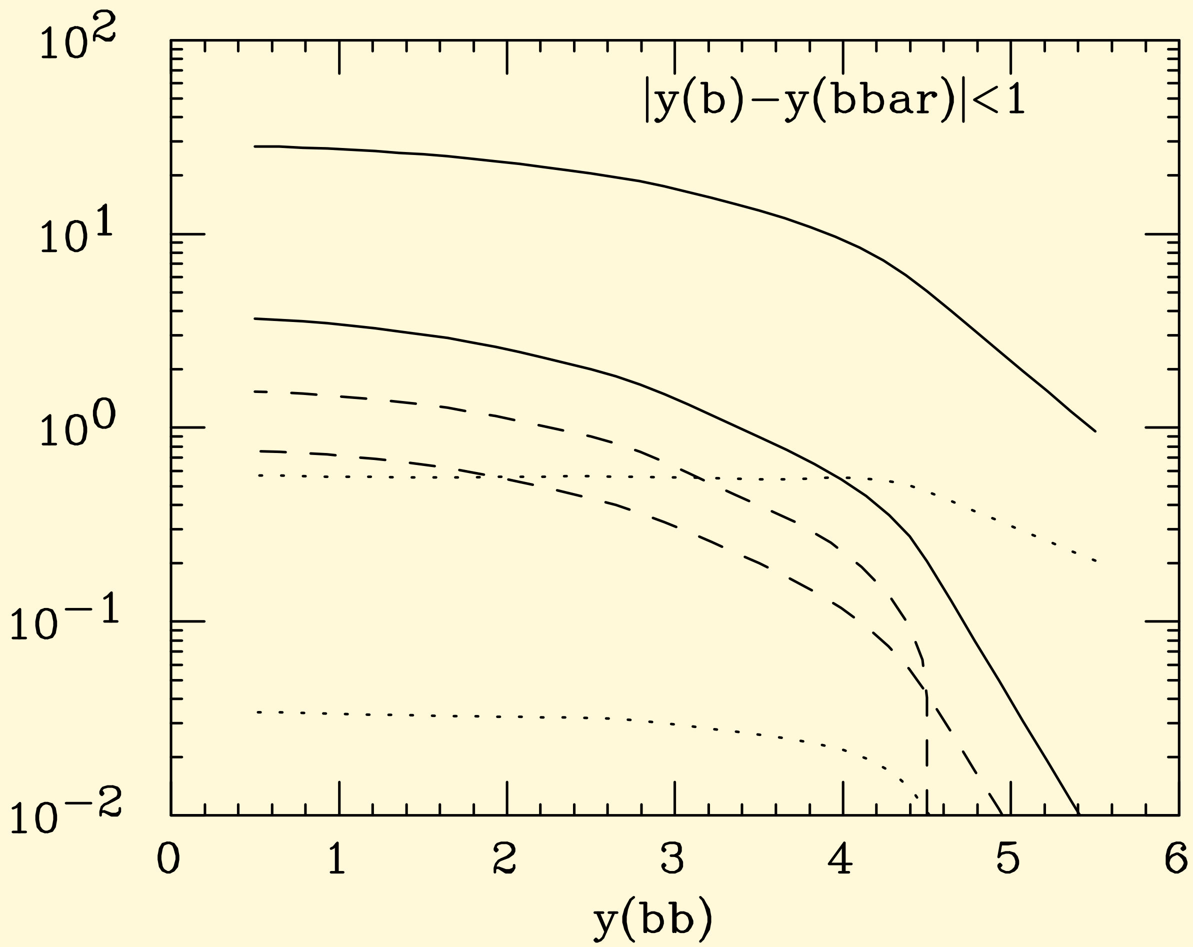


$$x_{1,2} = \frac{m_T}{E_b}\, e^{\pm y}$$





Initial state composition:



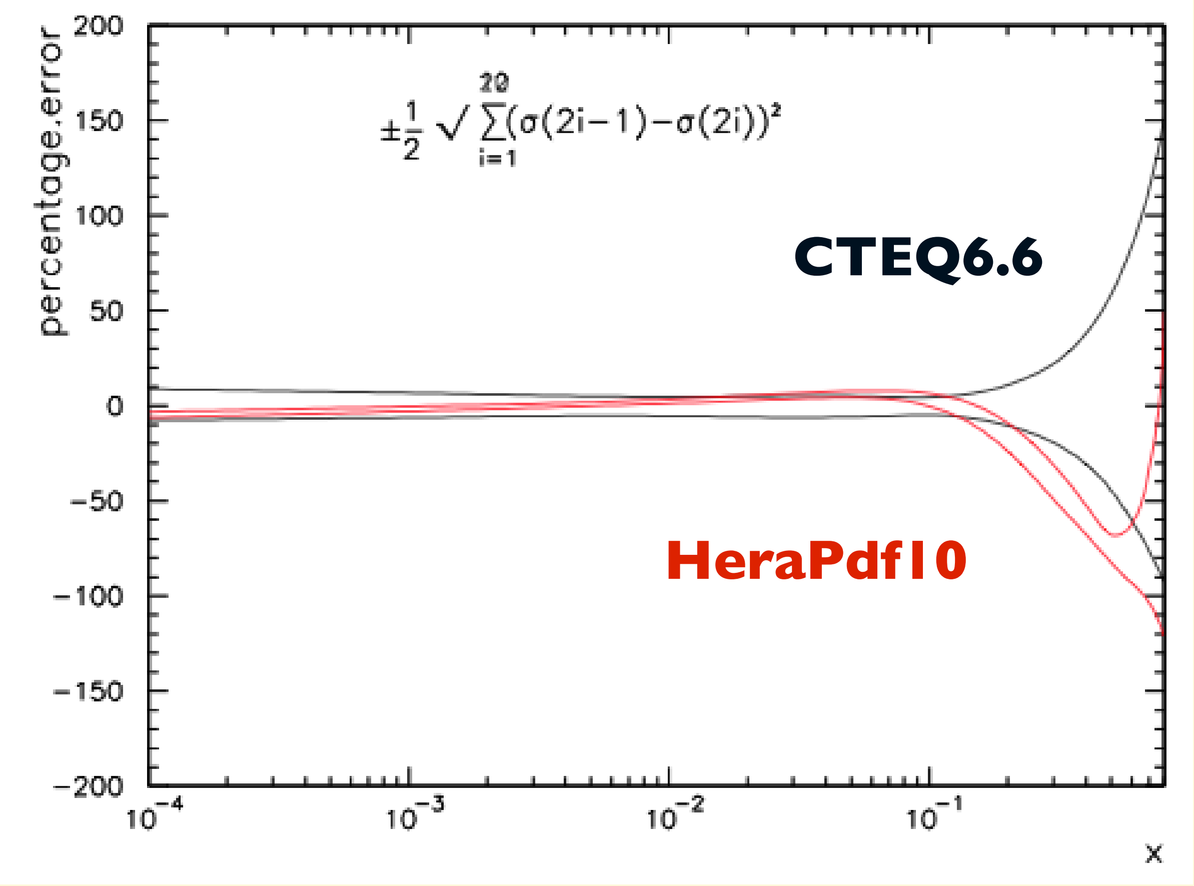
gg

qg

qqbar

Upper curves: $p_T>0$

Lower curves: $p_T>12$ GeV



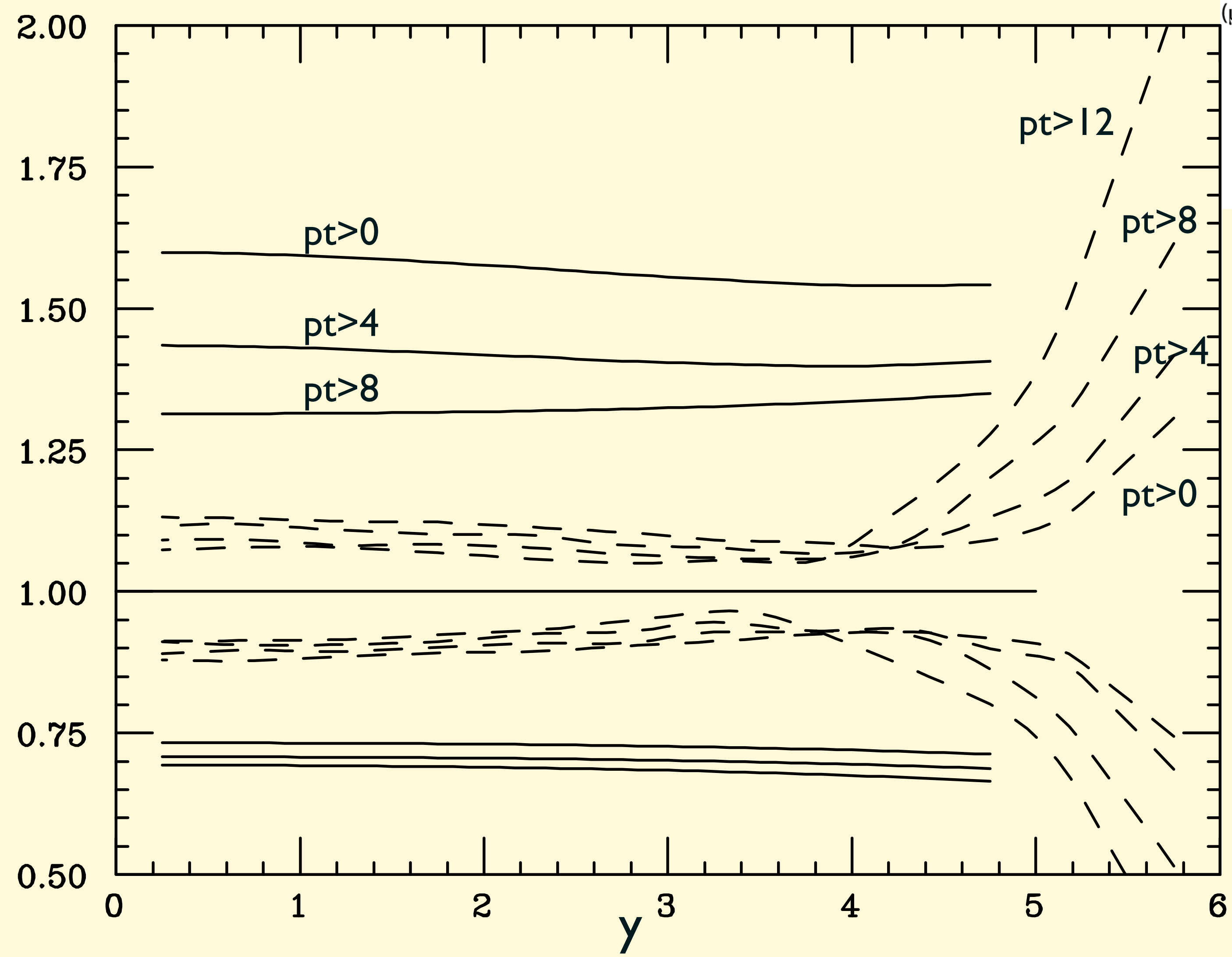
Dominated by gg initial state, possibly sensitive to gluon PDF

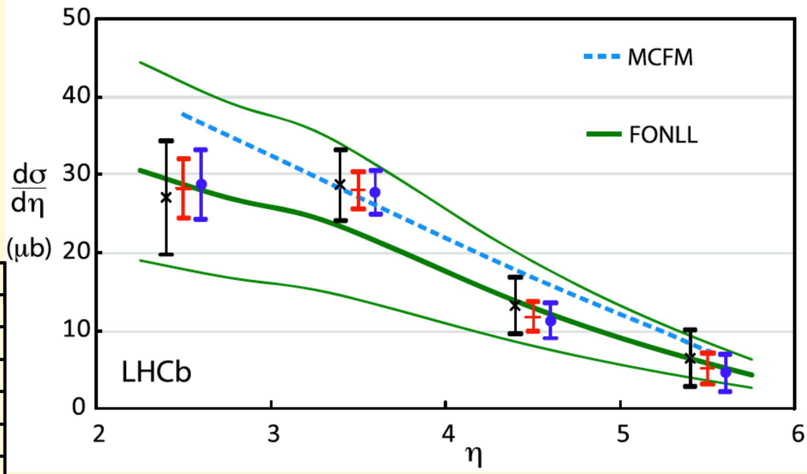
Scale vs PDF systematics

Solid lines: scale/mass systematics

$$\frac{\frac{d\sigma}{dy}(\mu_R^{max}, \mu_F^{max}, m_b^{max})}{\frac{d\sigma}{dy}(\mu_R^0, \mu_F^0, m_b^0)}$$

$$\frac{\frac{d\sigma}{dy}(\mu_R^{min}, \mu_F^{min}, m_b^{min})}{\frac{d\sigma}{dy}(\mu_R^0, \mu_F^0, m_b^0)}$$



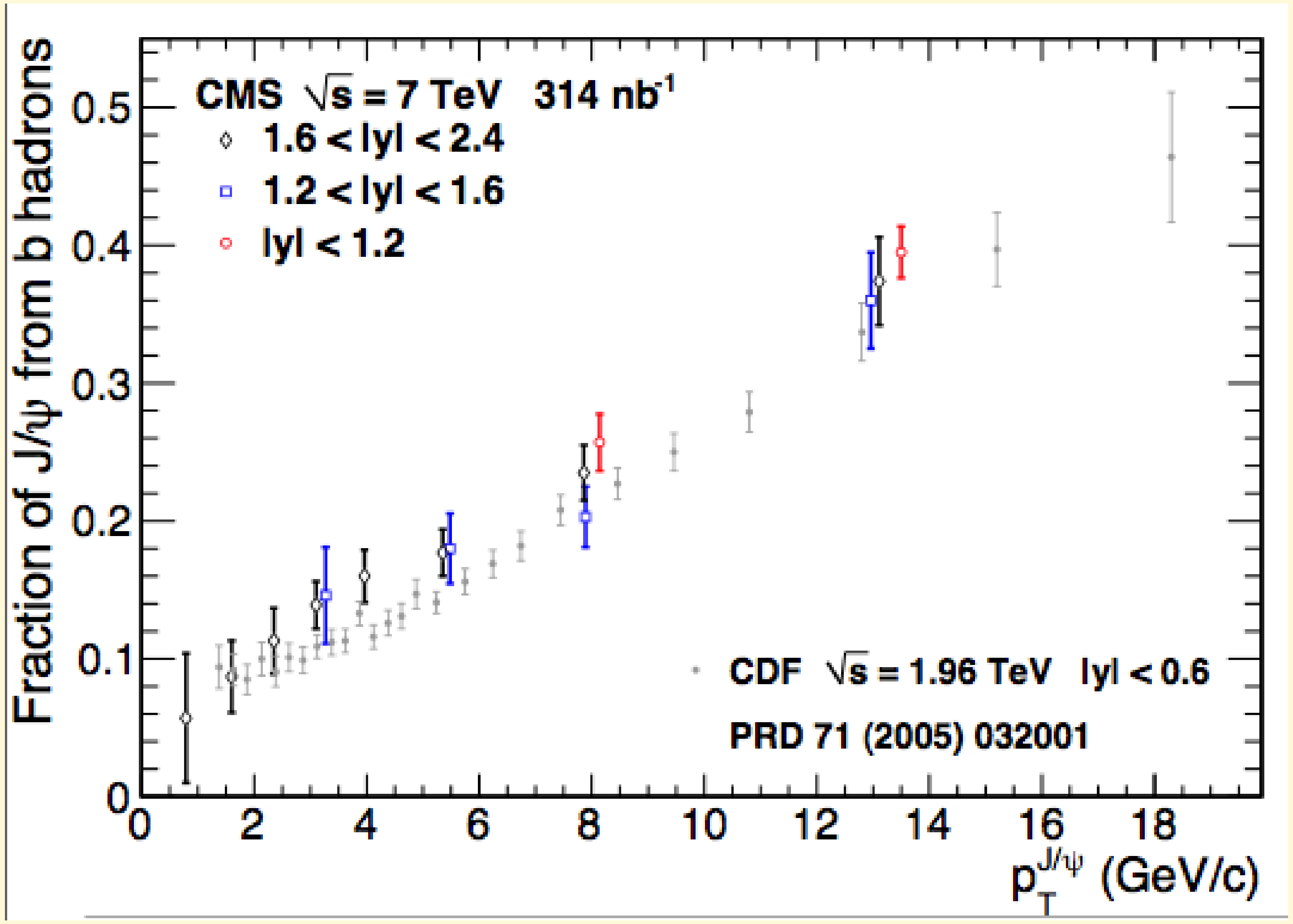


Dashed lines: PDF systematics (CTEQ6.6)

$\mu_{\mathbf{F,R}}^{\mathbf{max,min,0}}, \mathbf{m_b^{max,min,0}}$ parameter values at **maximum, minimum and central** values of the cross-section

- great stability of the y distribution vs scale/mass variations
- scale systematics fully correlated in y, so **y shape is robust**
- scale dependence at the ±30% level dominates over mass-dependence for $p_T \gtrsim m_b$
- PDF systematics affects the shape of the y distribution well beyond the effects of scale variations, once y>4 => **PDF sensitivity**

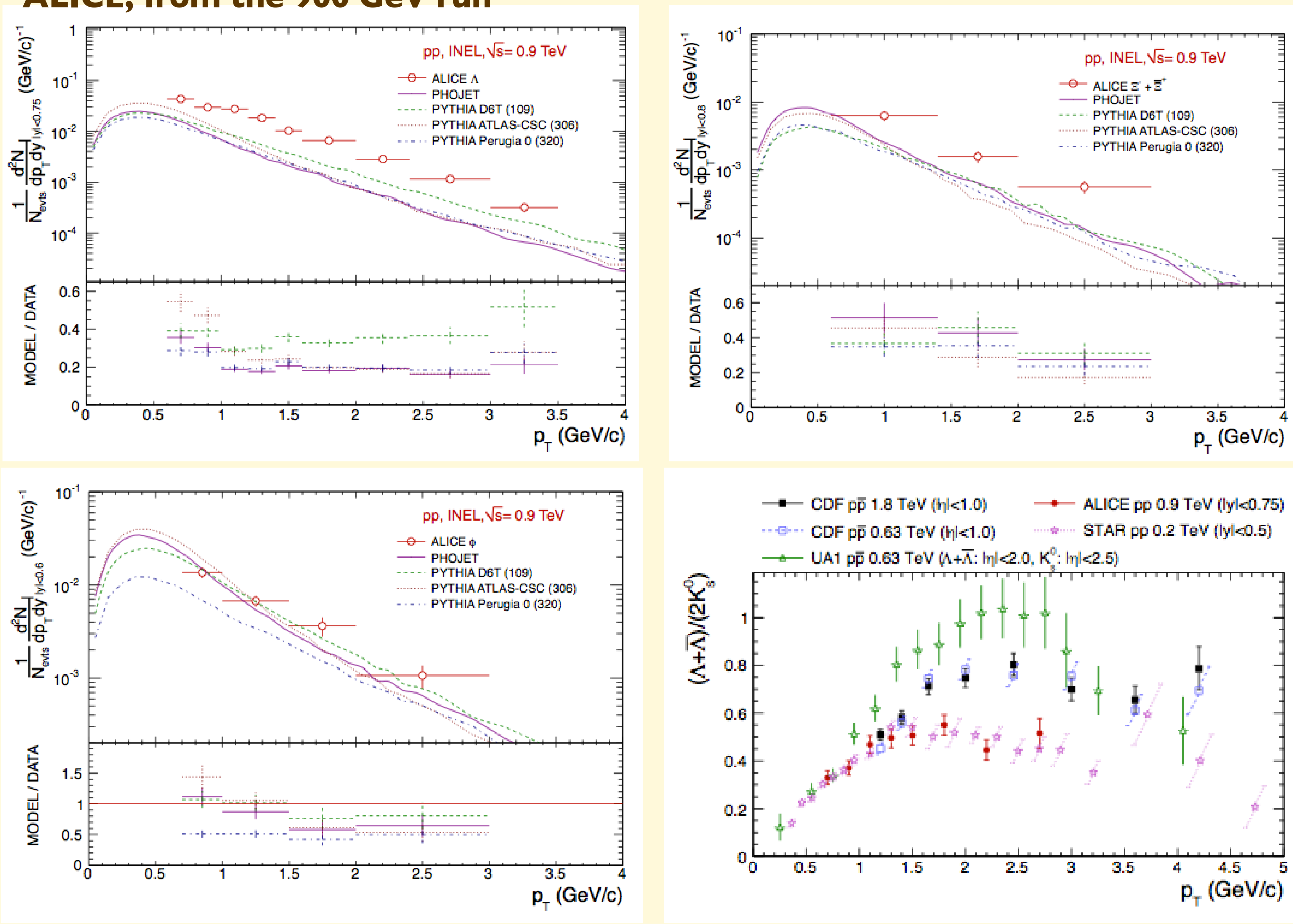
J/psi production: fraction of prompt and b-decay



General properties of inclusive final states, a few examples

Strange particle production

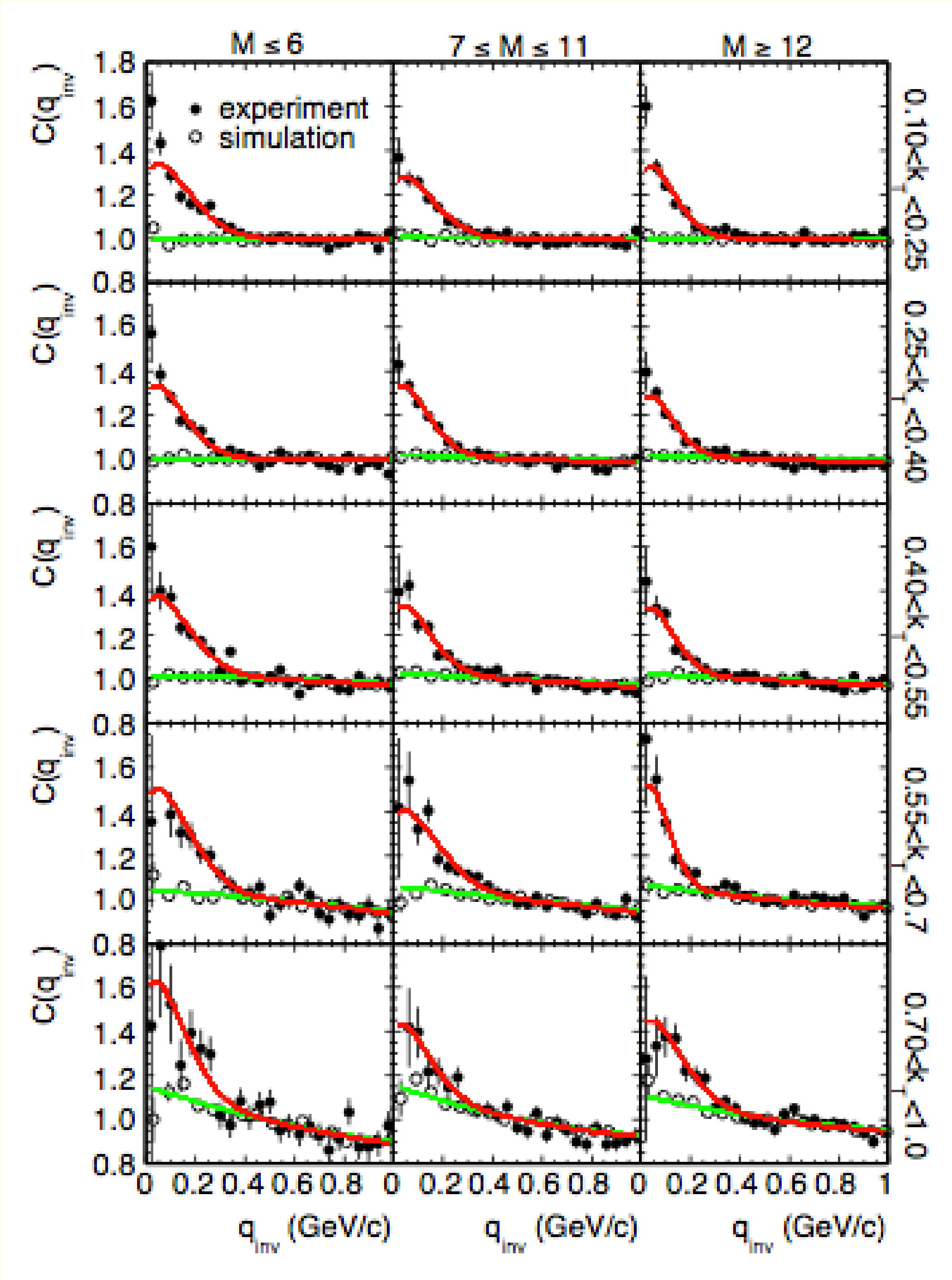
ALICE, from the 900 GeV run



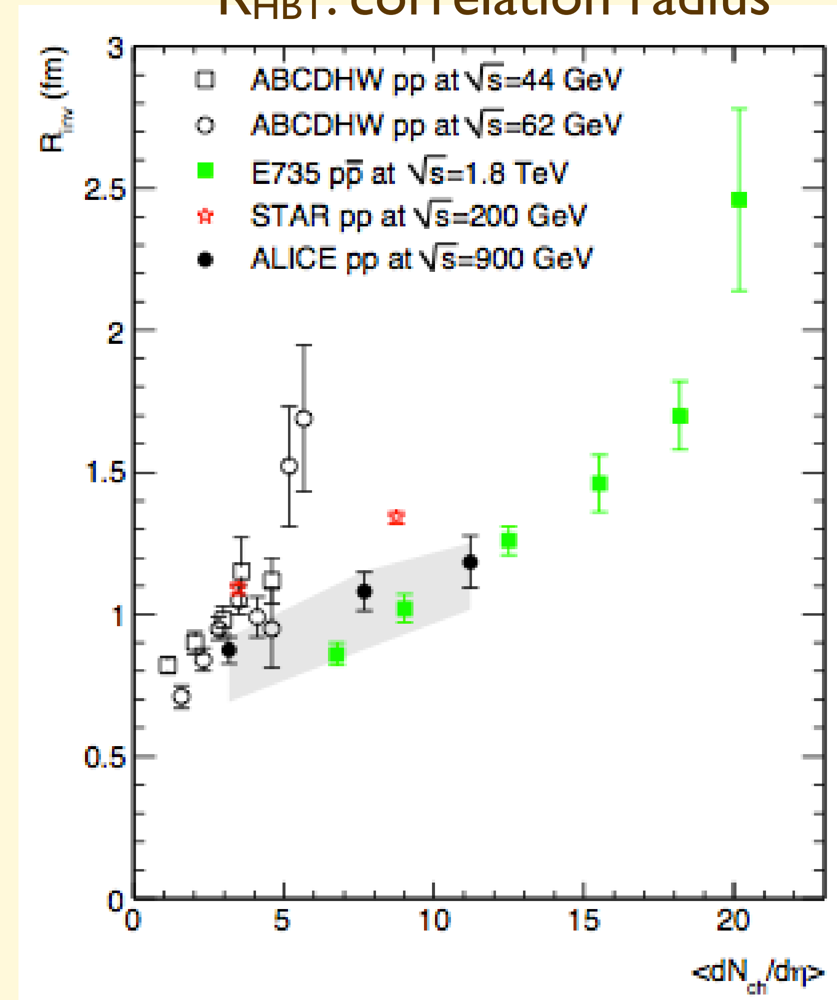
Very important benchmark for strangeness production studies in Pb-Pb, needs further clarification!

Bose-Einstein correlations

ALICE, from the 900 GeV run



R_{HBT}: correlation radius

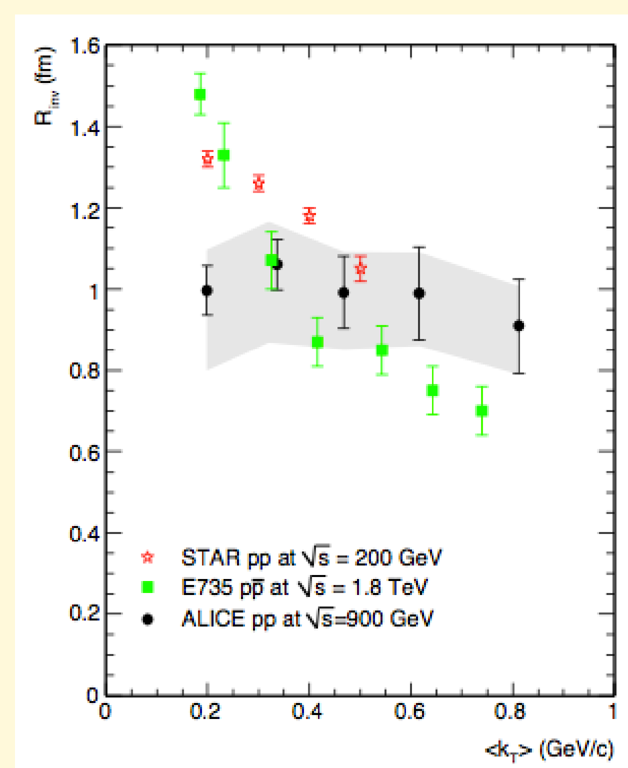


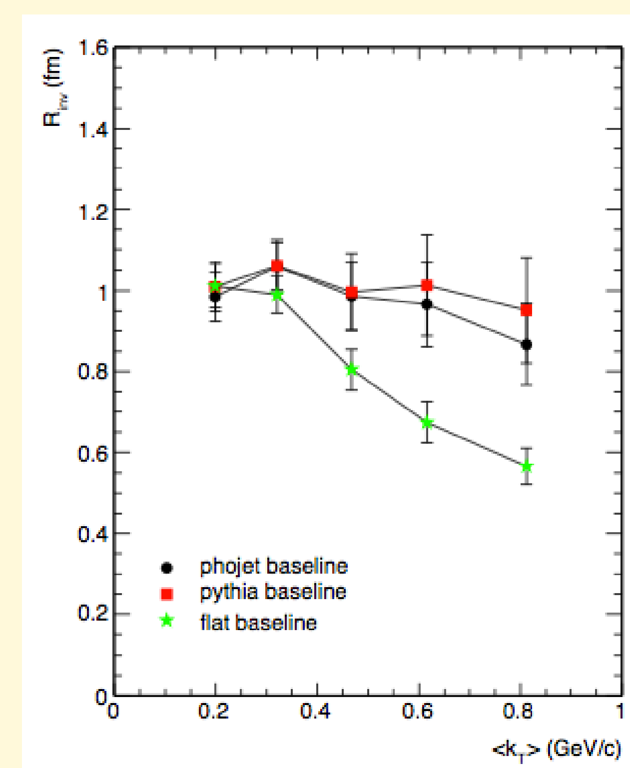
q_{inv} = $|\mathbf{q_1} - \mathbf{q_2}|$ in rest frame

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

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

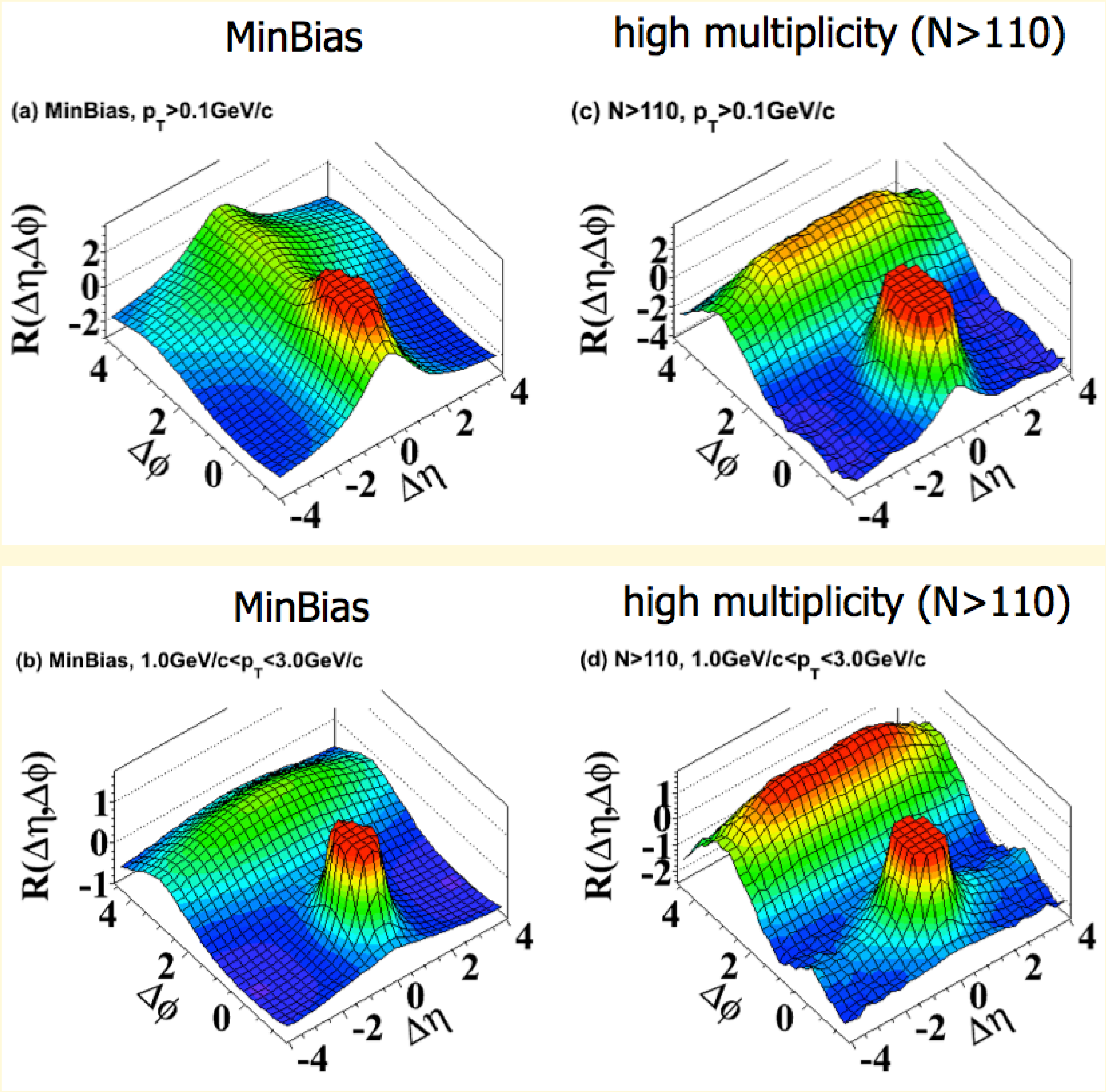
B(q)=$\pi^{\pm}\pi^{\pm}$ c.f., with particles from different events



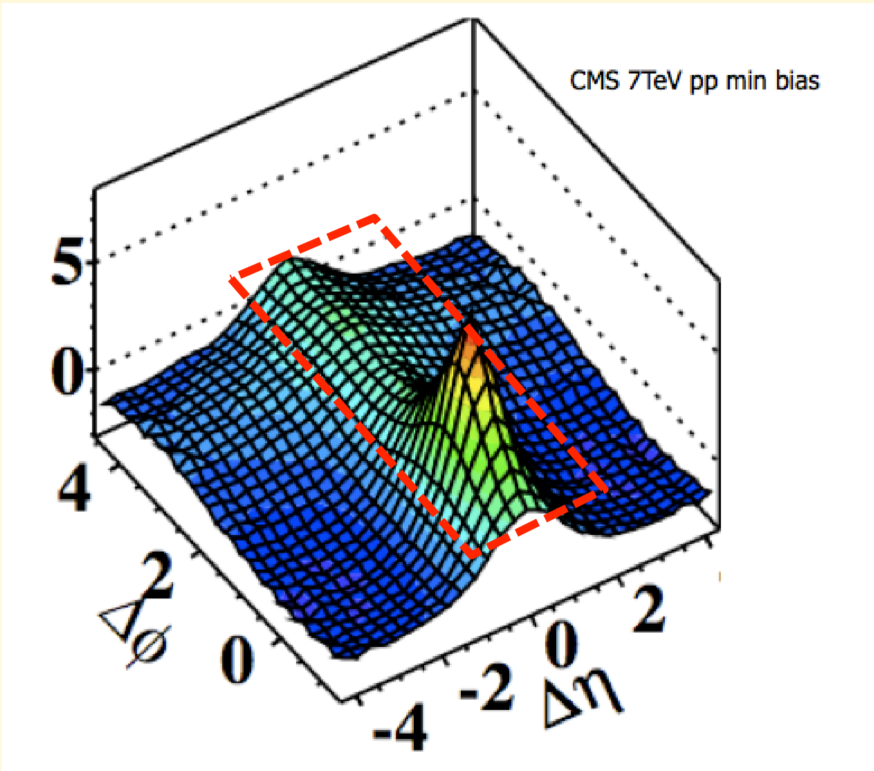


CMS's "ridge" in high-multiplicity events

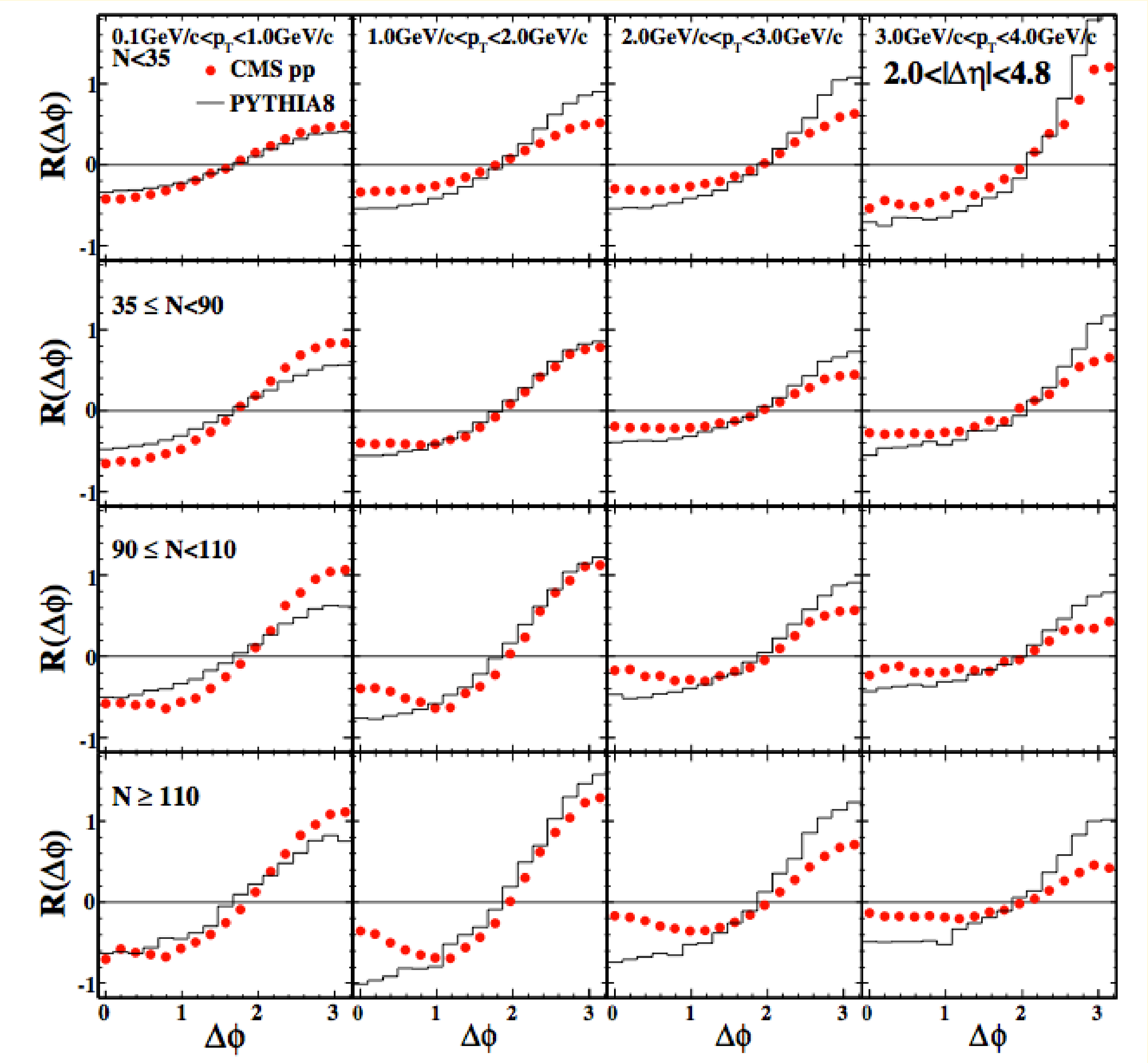
2-particle correlation function $S_N(\Delta\eta,\Delta\varphi) = \frac{1}{N(N-1)} \frac{d^2 N^{signal}}{d\Delta\eta d\Delta\varphi}$



CMS's "ridge" in high-multiplicity events

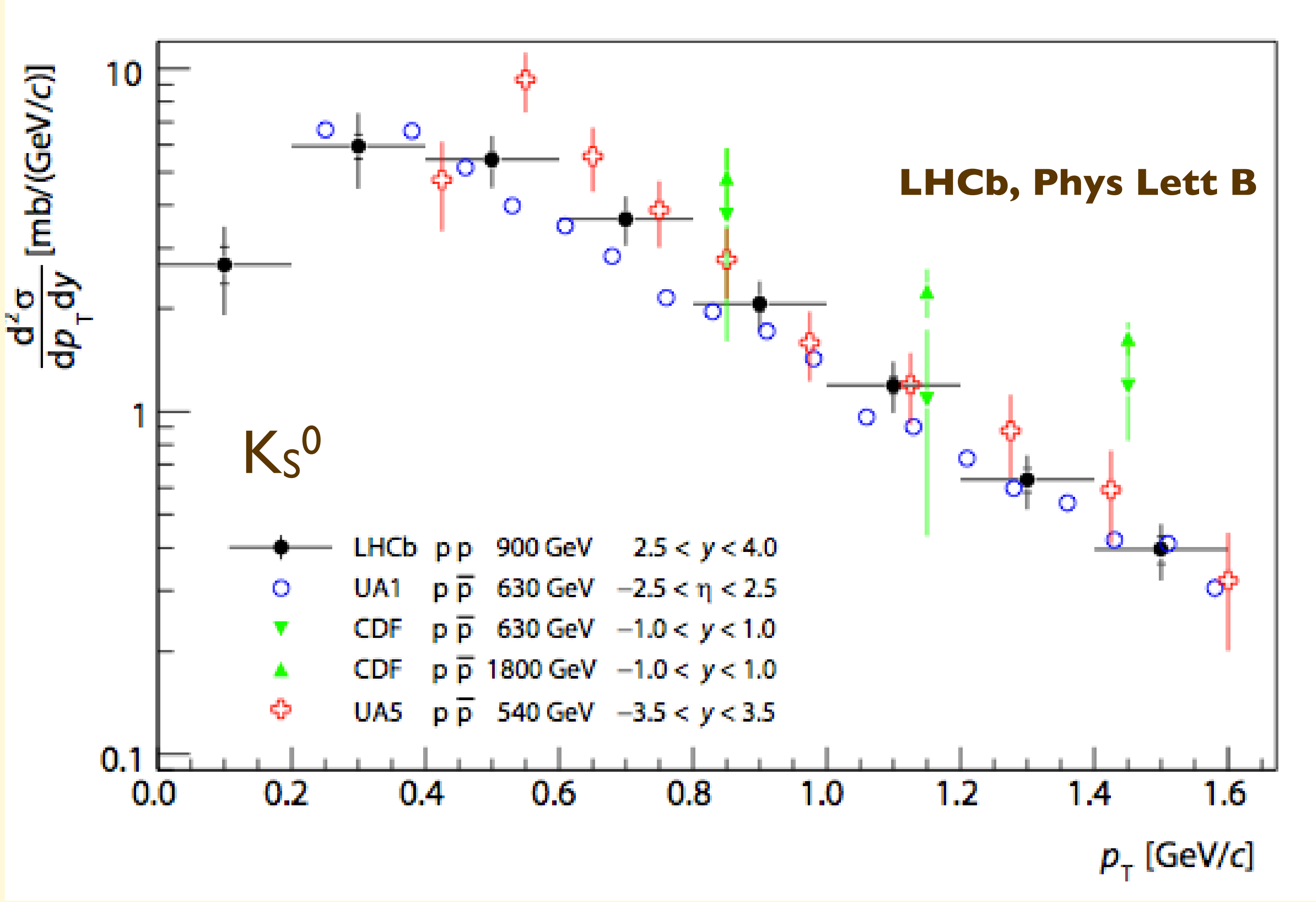


Integrating in eta, outside of the jet region:



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

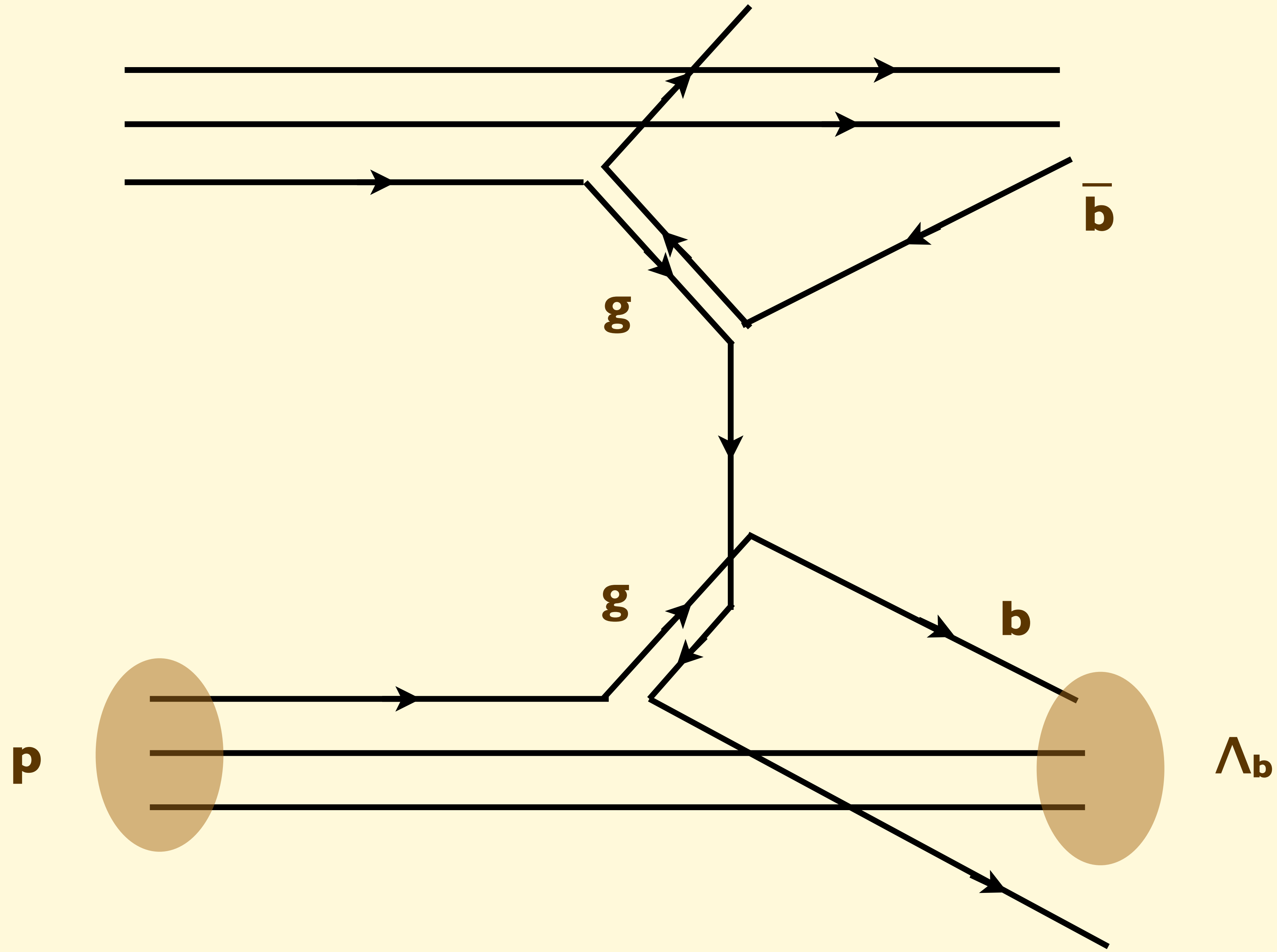


Other non-pQCD issues of relevance to pQCD physics

$b \to H_b$ 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

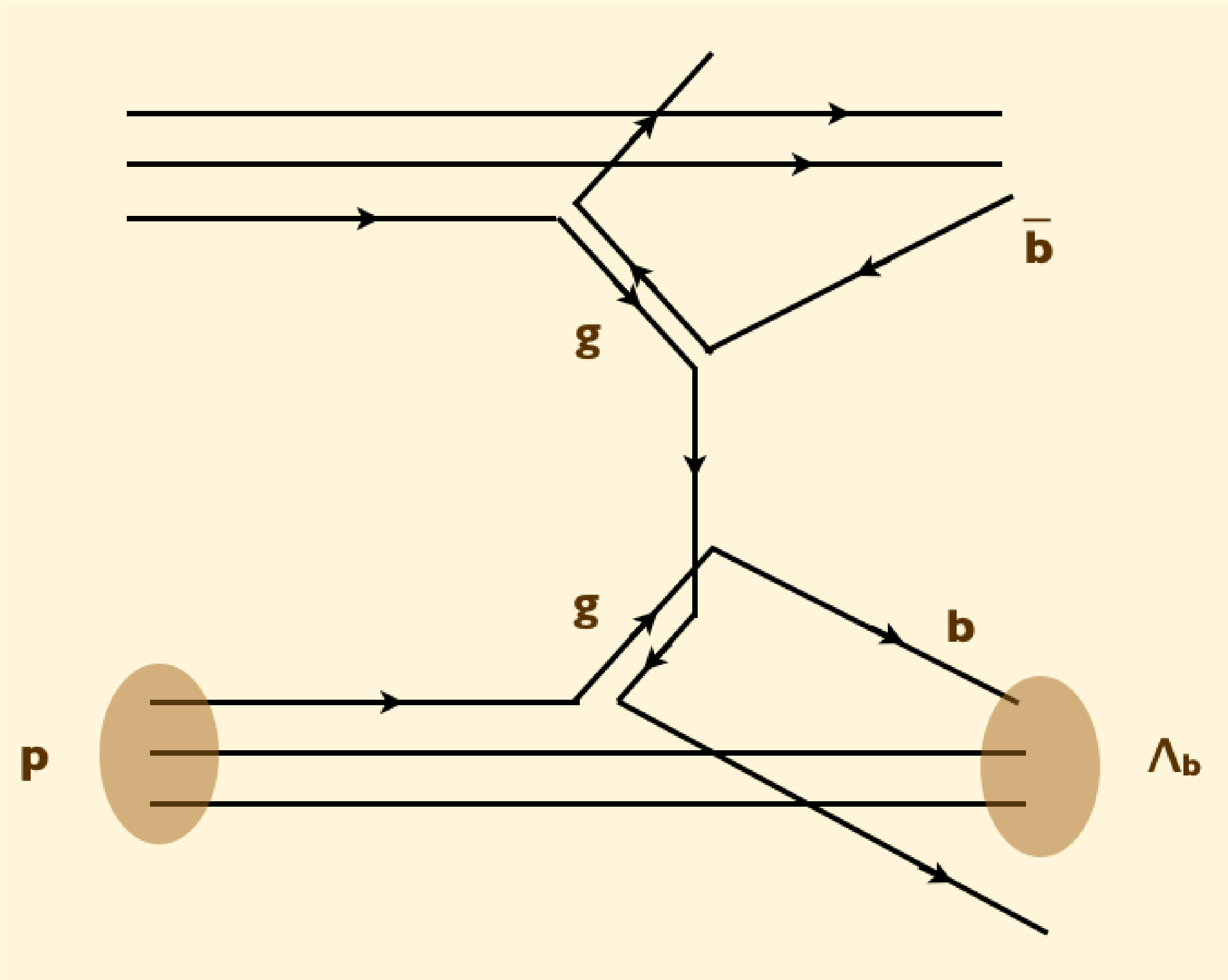
- **Needs clarification!**
- **To the least it points to — not unexpected — deviations from factorization**
- **In view of the CP non-invariance of the initial state, and of the forward kinematics of LHCb, each individual fraction will have to be measured very accurately**



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

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

Example



gg → $\bar{b}$ Λ_b

gg ↛ b $\bar{\Lambda}_b$

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

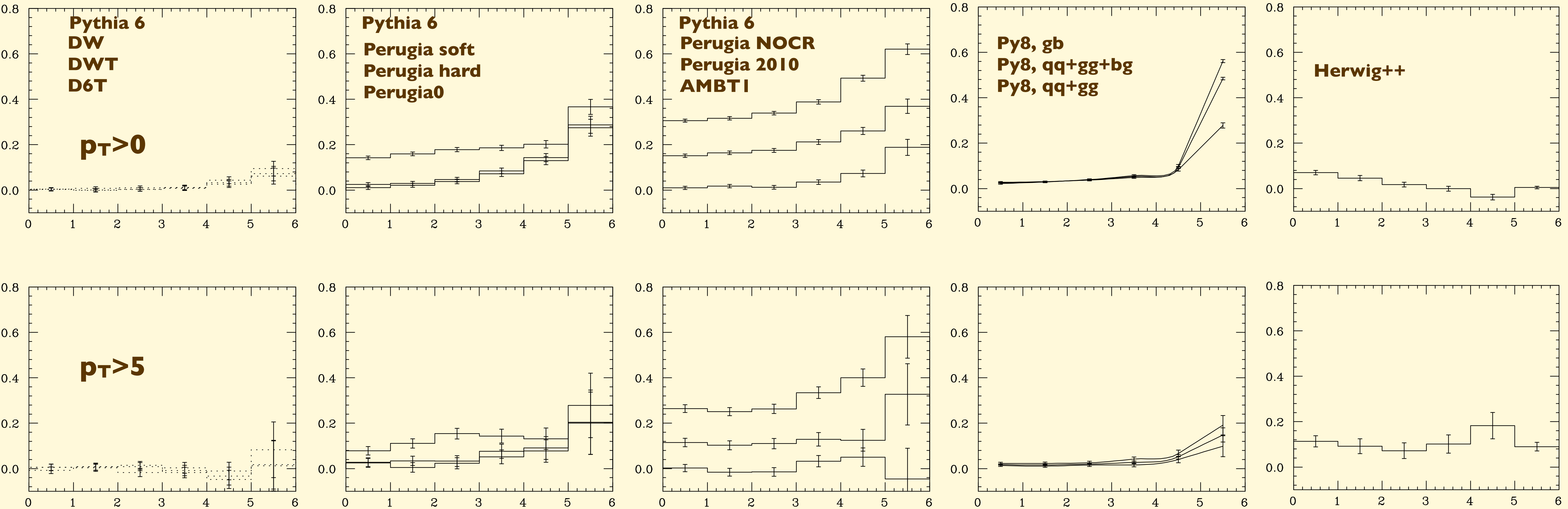
$$A(y) = \frac{dN(\Lambda_b)/dy - dN(\bar{\Lambda}_b)/dy}{dN(\Lambda_b)/dy + dN(\bar{\Lambda}_b)/dy}$$

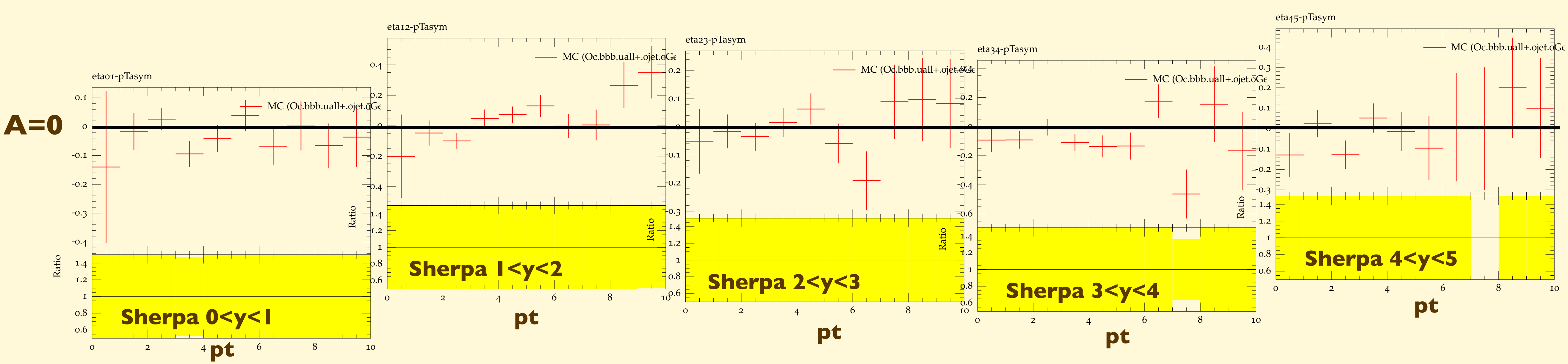
If A(y)≠0 ⇒ N(B)≠N(Bbar) ⇒ apparent CP violation!

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

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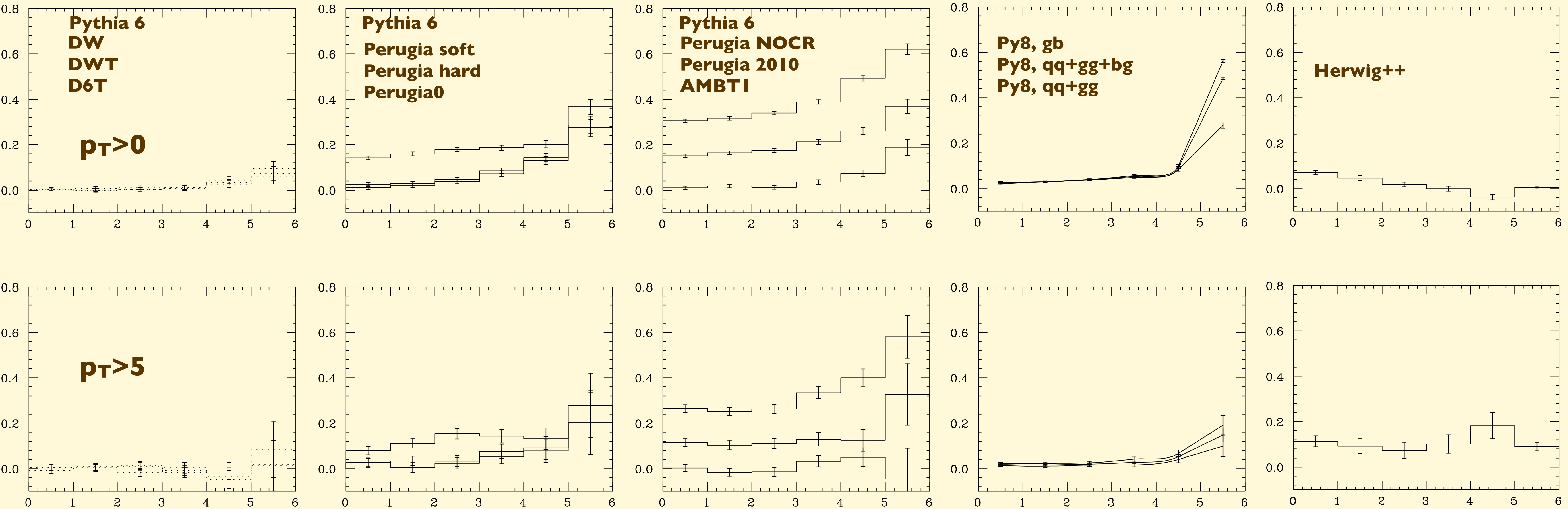
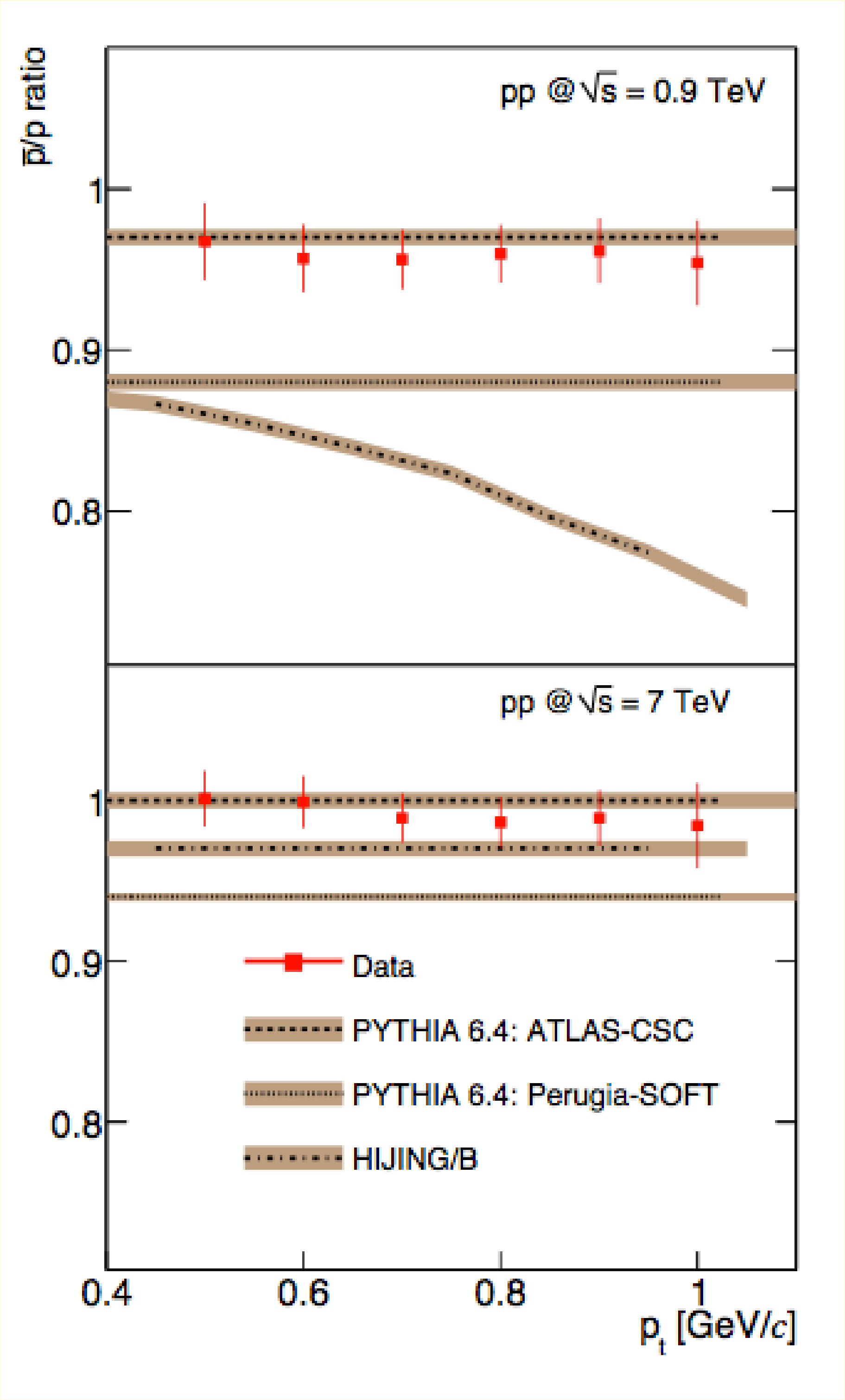


- **Very broad range of "predictions", no robust benchmark**
- **Strong dependence on modeling of perturbative part: more/less gluon radiation will reduce/increase the color-coupling of the b with the proton diquark fragment**
- **Expect correlation with the modeling of strange and charmed baryons**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

Pbar / P ratio

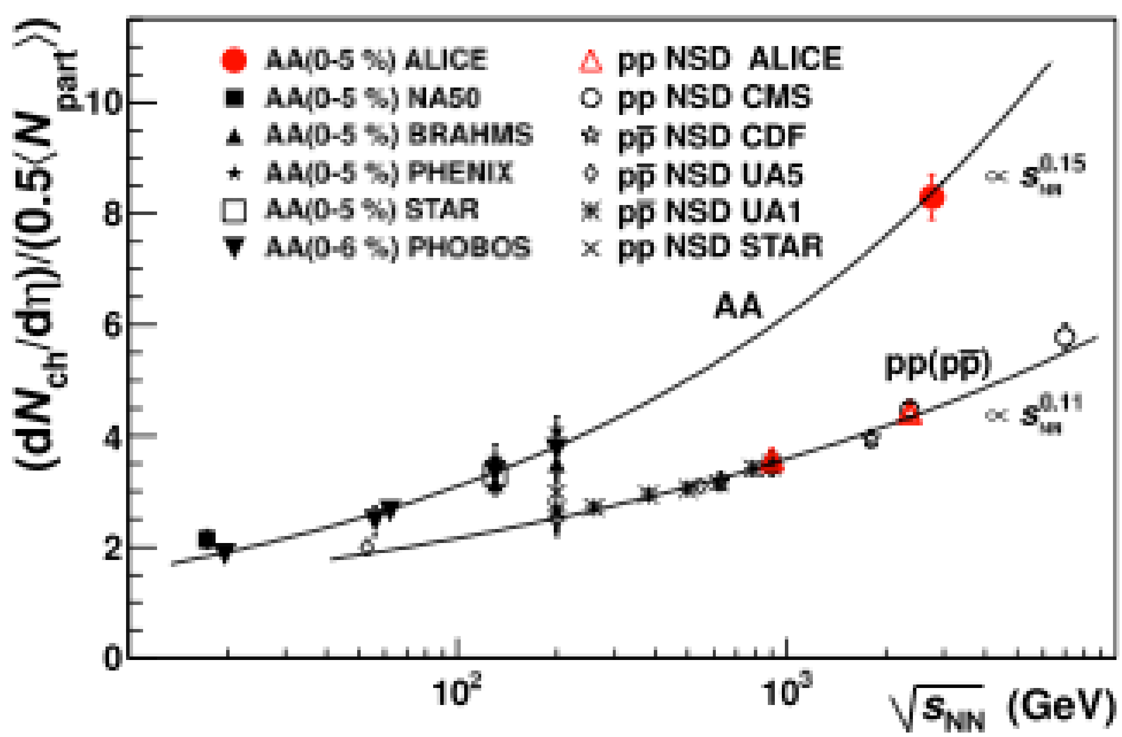


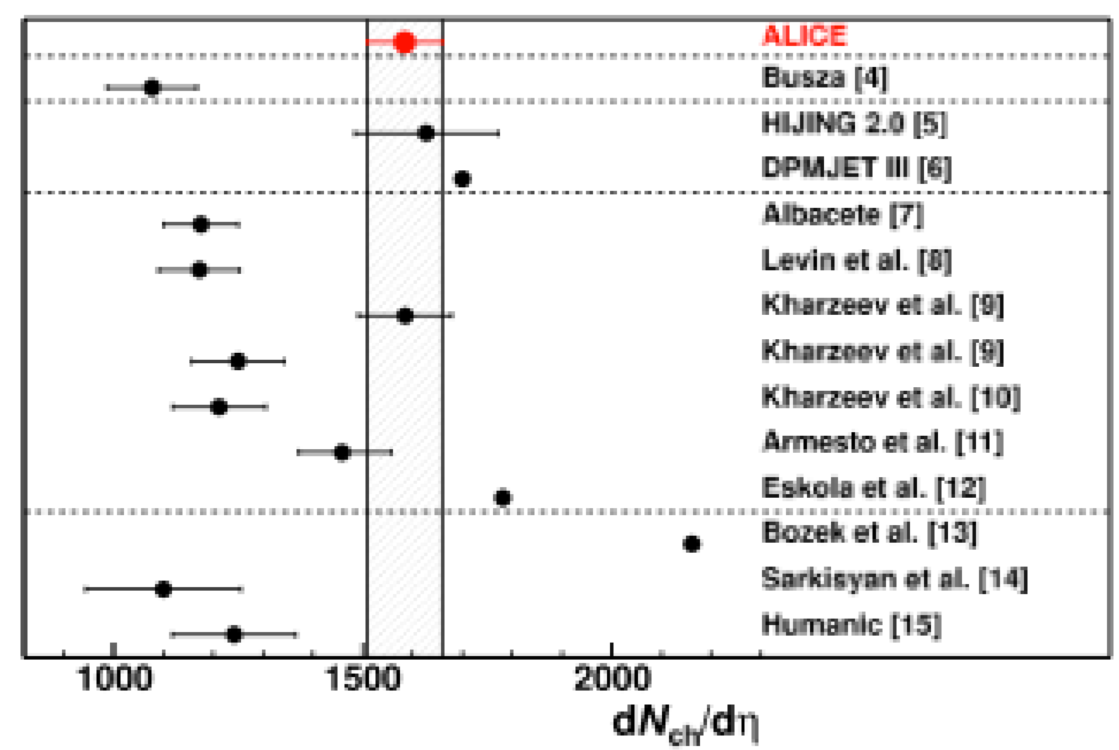
ALICE http://arxiv.org/abs/1006.5432

A first look at Pb-Pb collisions

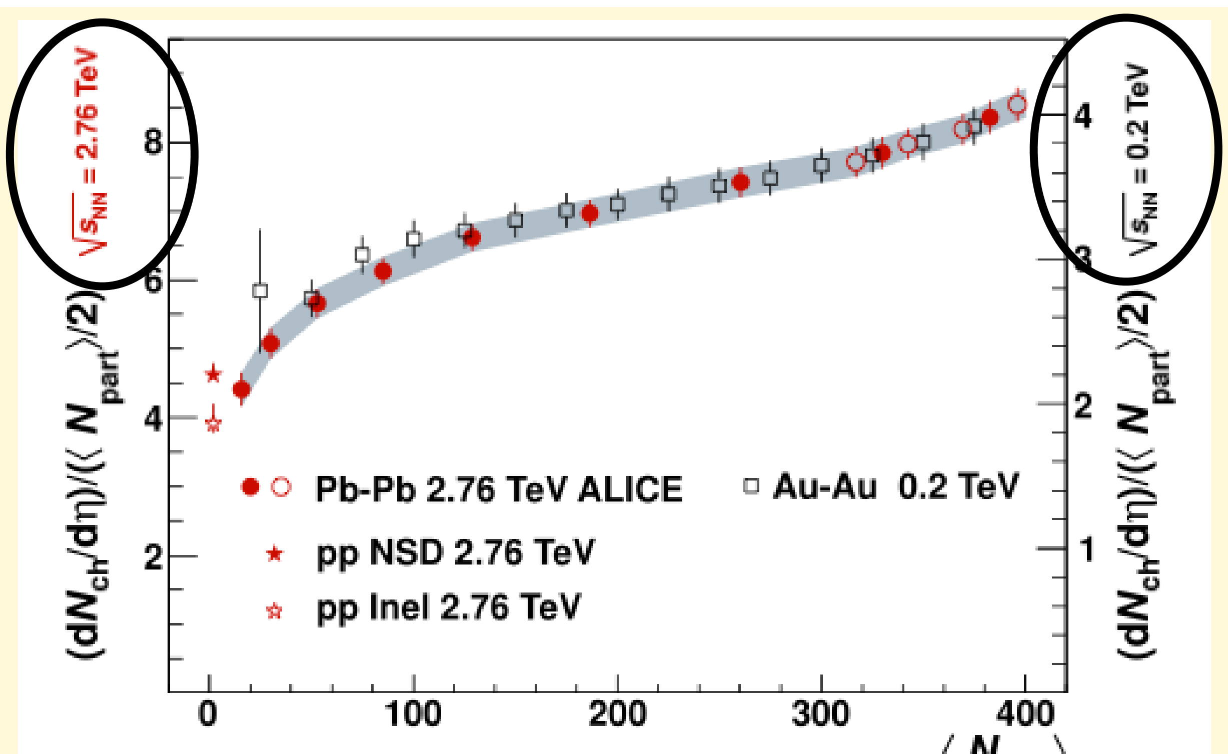
- $\sqrt{S_{NN}}$ = 2.76 TeV => 14 times larger than any previous heavy ion experiment (RHIC)

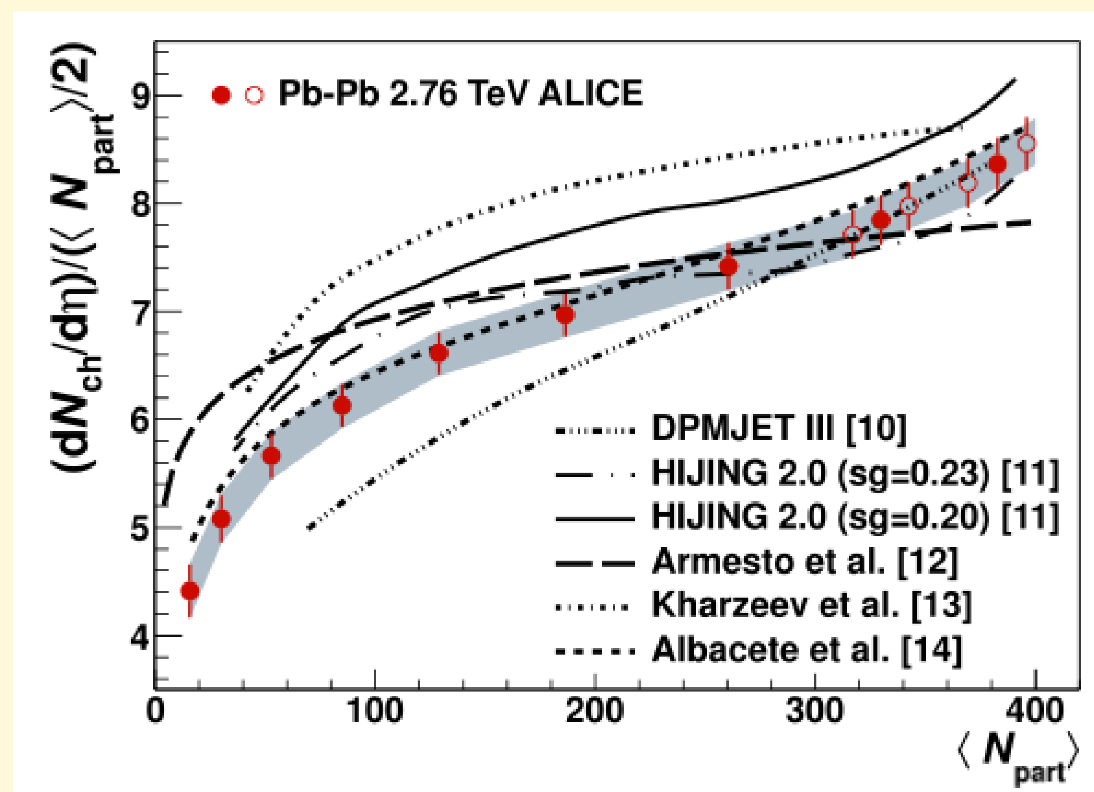
$dN_{ch}/d\eta$ (0-10% centrality) = 1584 ± 4 (stat.) ± 76 (sys.)





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





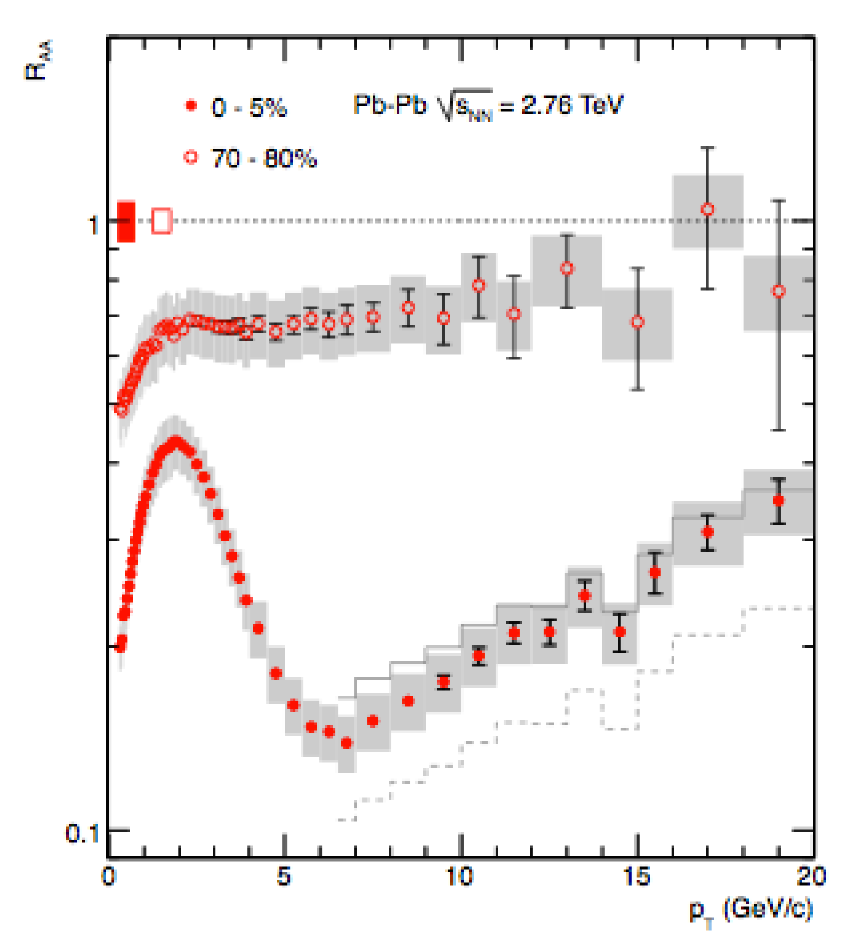
ALICE, http://arxiv.org/abs/1012.1657

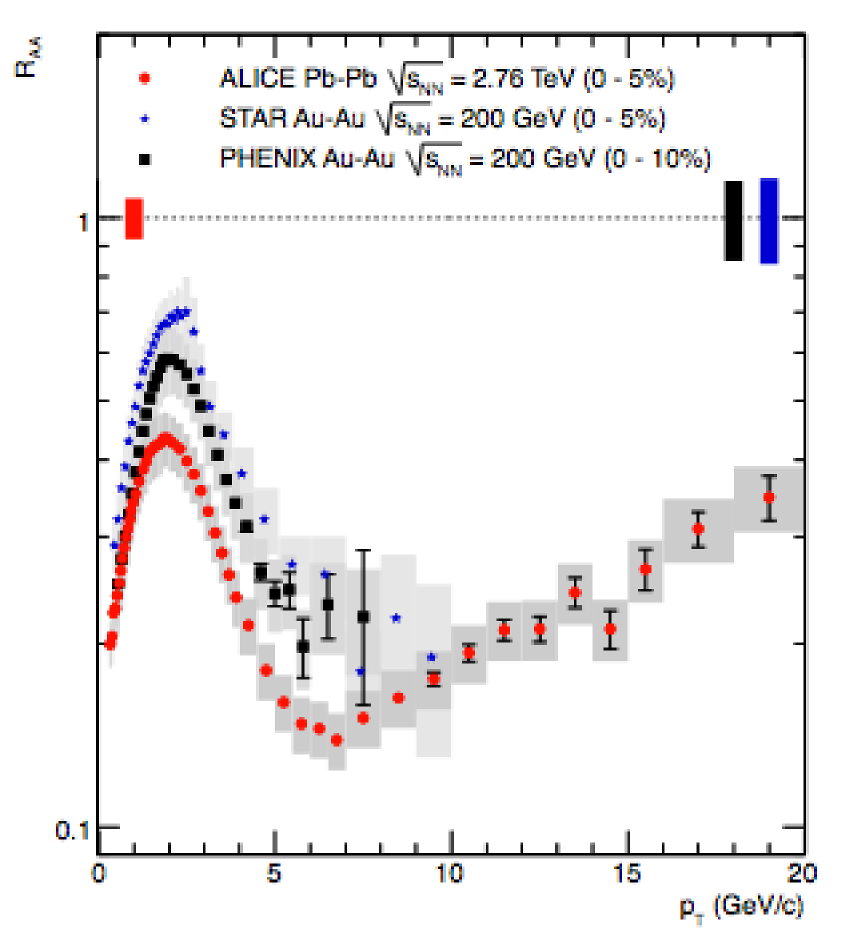
Modeling heavily depends on description of gluon saturation

More on Pb-Pb collisions ....

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

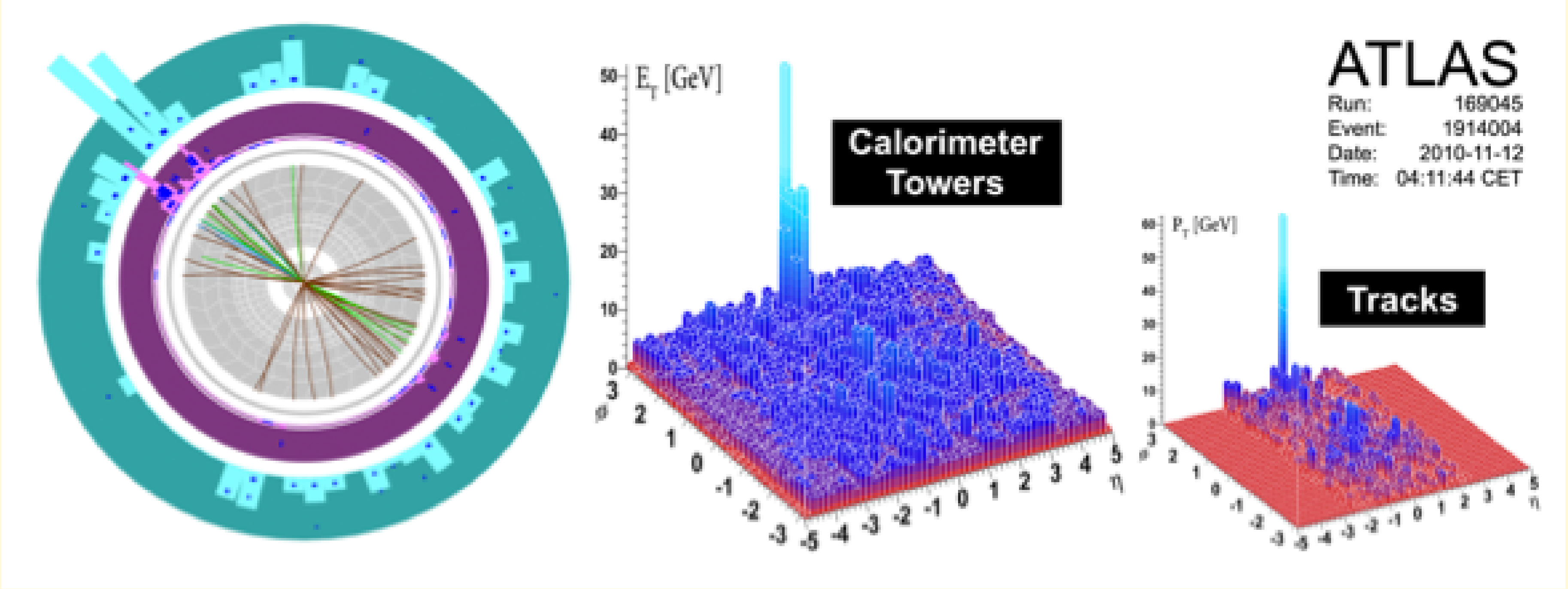
$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta\, dp_T}{\langle N_{coll}\rangle\, (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta\, dp_T}$$

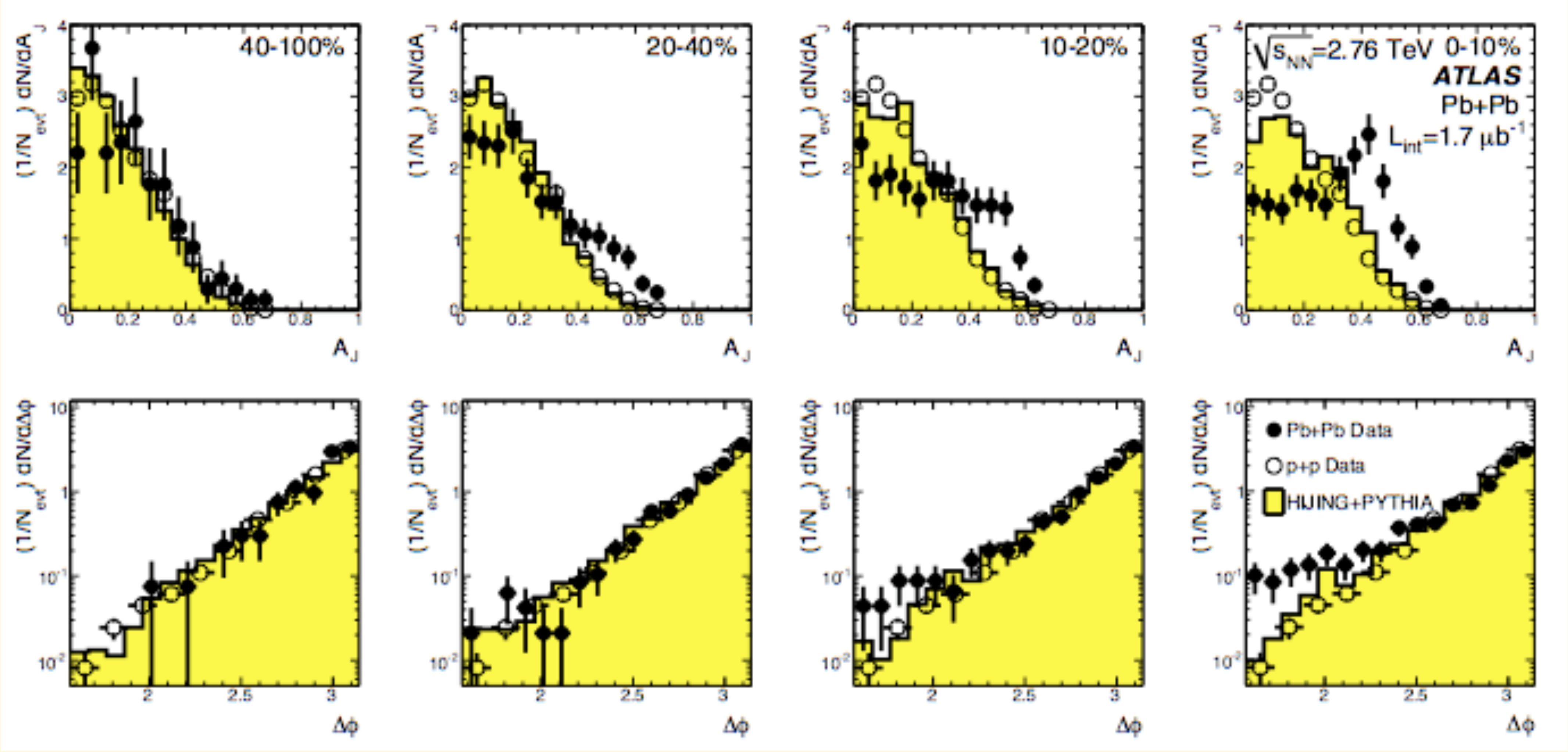




ALICE, http://arxiv.org/abs/1012.1004

More on Pb-Pb collisions ....





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

Momentum spectrum of cosmic ray muons