QCD Measurements with the CMS Detector

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LHC Seminar

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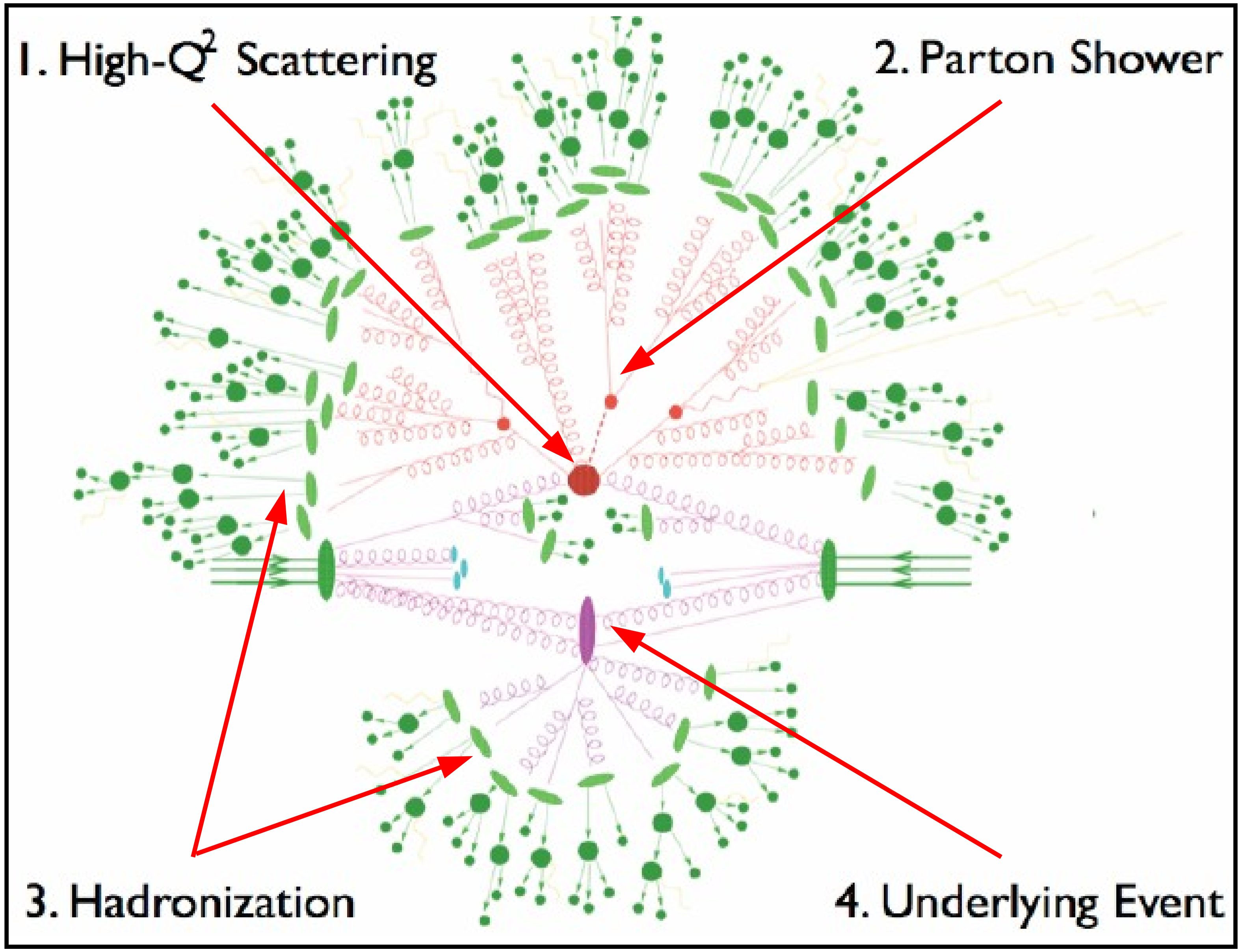
Outline

- **Soft QCD**
  - charged particle spectra and pseudorapidity distributions
  - charged particle multiplicities
  - strange particle production
  - particle correlations
  - underlying event
- **Jet measurements**
  - inclusive jet & dijet production
  - dijet angular distributions & azimuthal decorrelations
  - hadronic event shapes
  - 3j/2j ratio
- **Photon measurements**
  - inclusive photon production
  - di-photon production

Proton-Proton Collisions & QCD



✦ pp collisions reveal multiple aspects of QCD:
- perturbative behavior at the hard scattering scale
- parton showers
- multiple parton interactions
- hadronization
- structure of the proton

✦ QCD is a remarkable theory which deserves to be explored in detail

✦ even more important: before we can claim ANY signal of New Physics, we must understand this immensely complicated environment

QCD at the LHC

❖ **Unique opportunity to explore a large phase space:**
- higher LHC collision energy
- capabilities of the detectors

❖ **Specific areas of interest:**

☑ understand the soft particle production

☑ understand the underlying event activity. Is it universal in the various processes?

☑ do the perturbative calculations describe the data accurately enough?

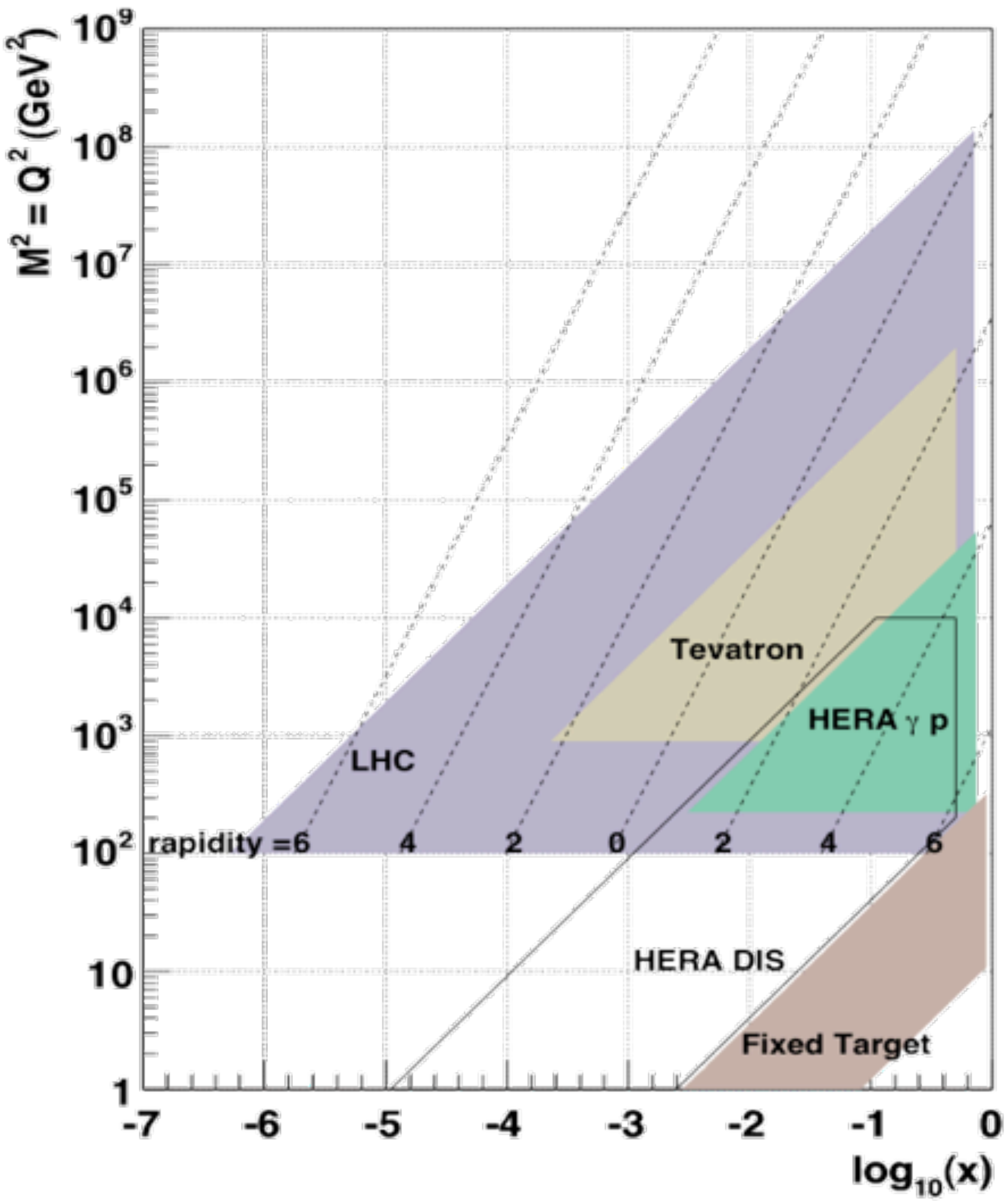
☑ differentiate between the various PDF sets

☑ reduce the uncertainty of the gluon PDF

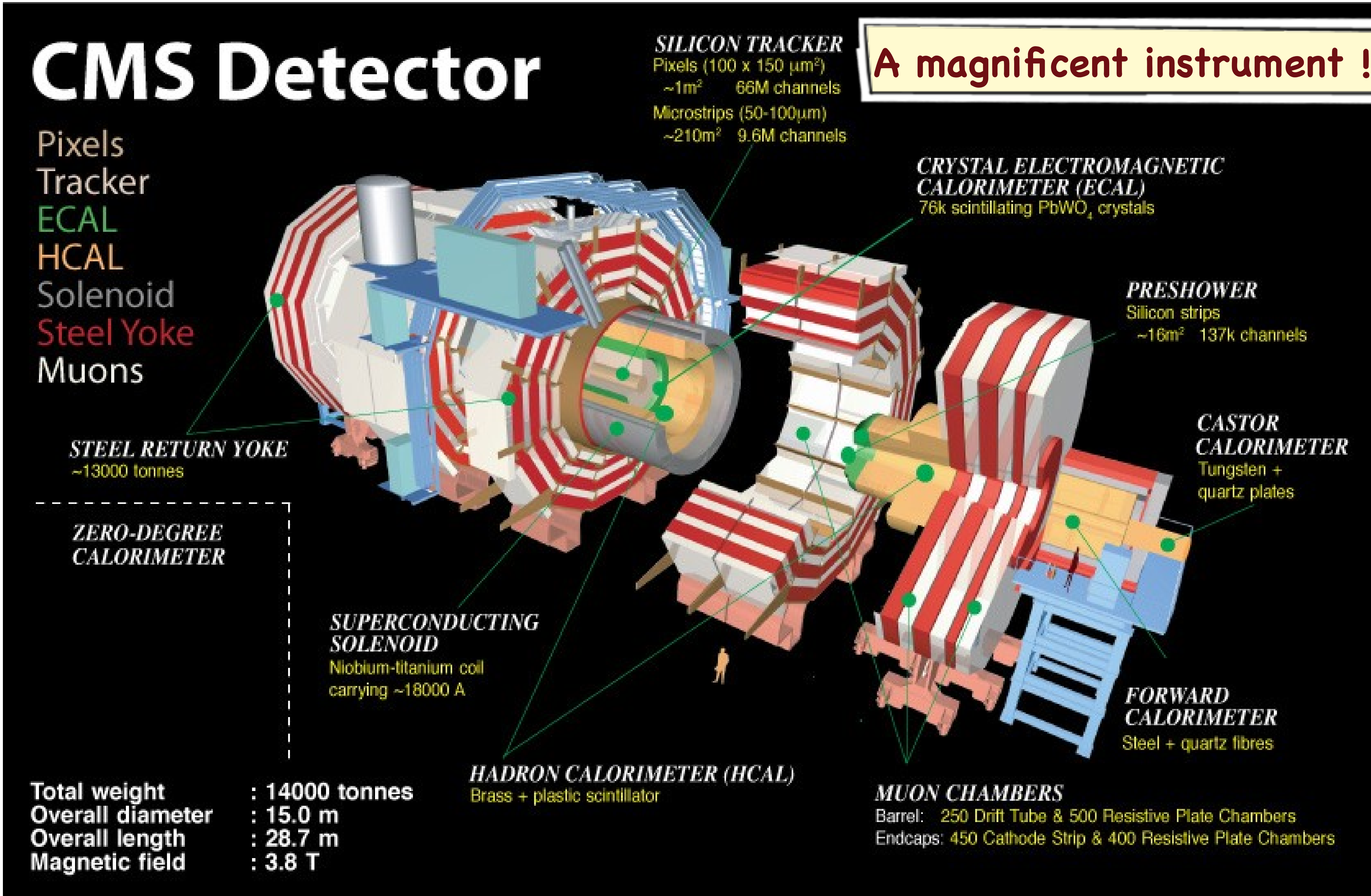
☑ understand the multijet production

☑ improve the Monte-Carlo generators

....



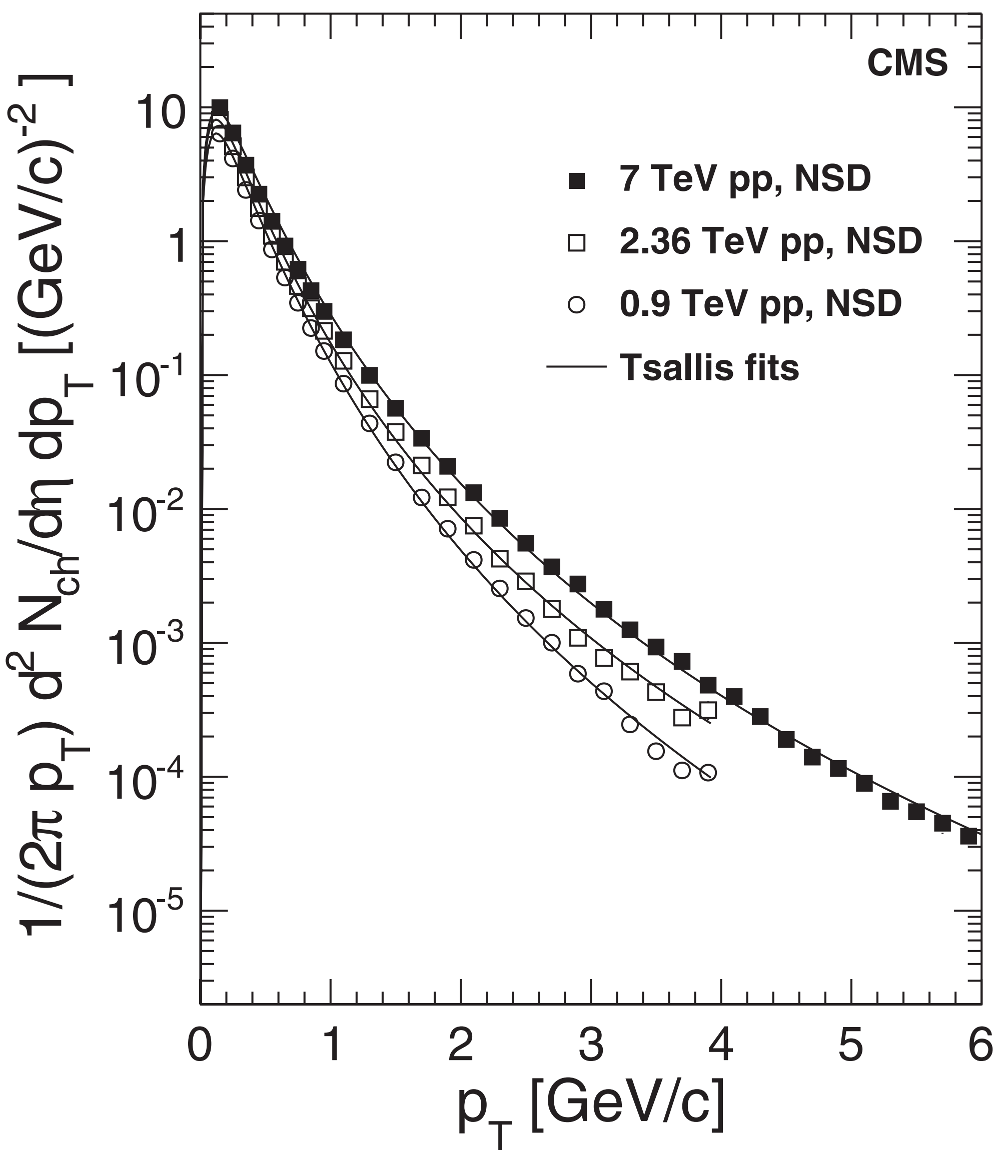
CMS

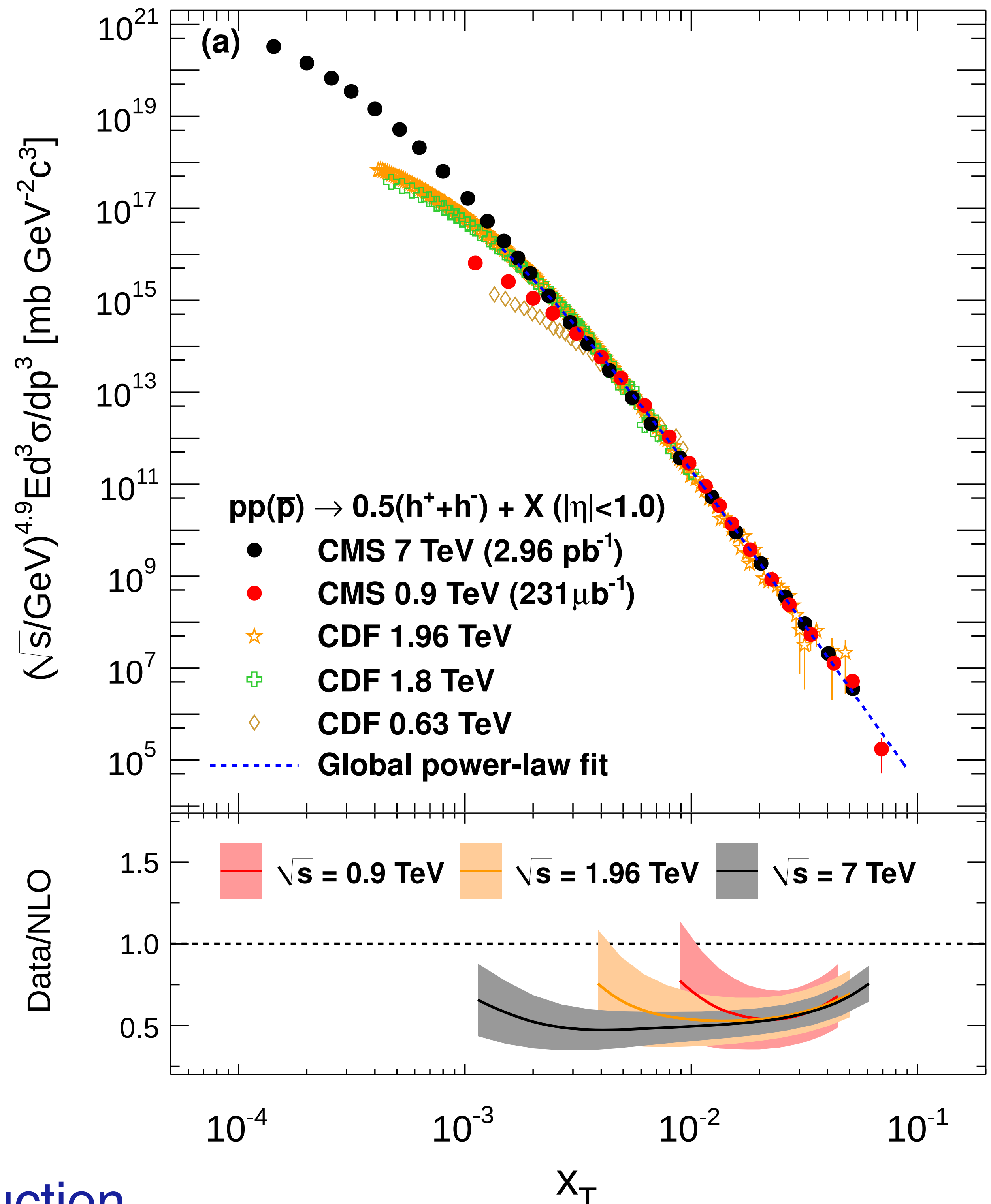


A magnificent instrument !!!

Soft QCD Measurements

Charged Hadron Spectra

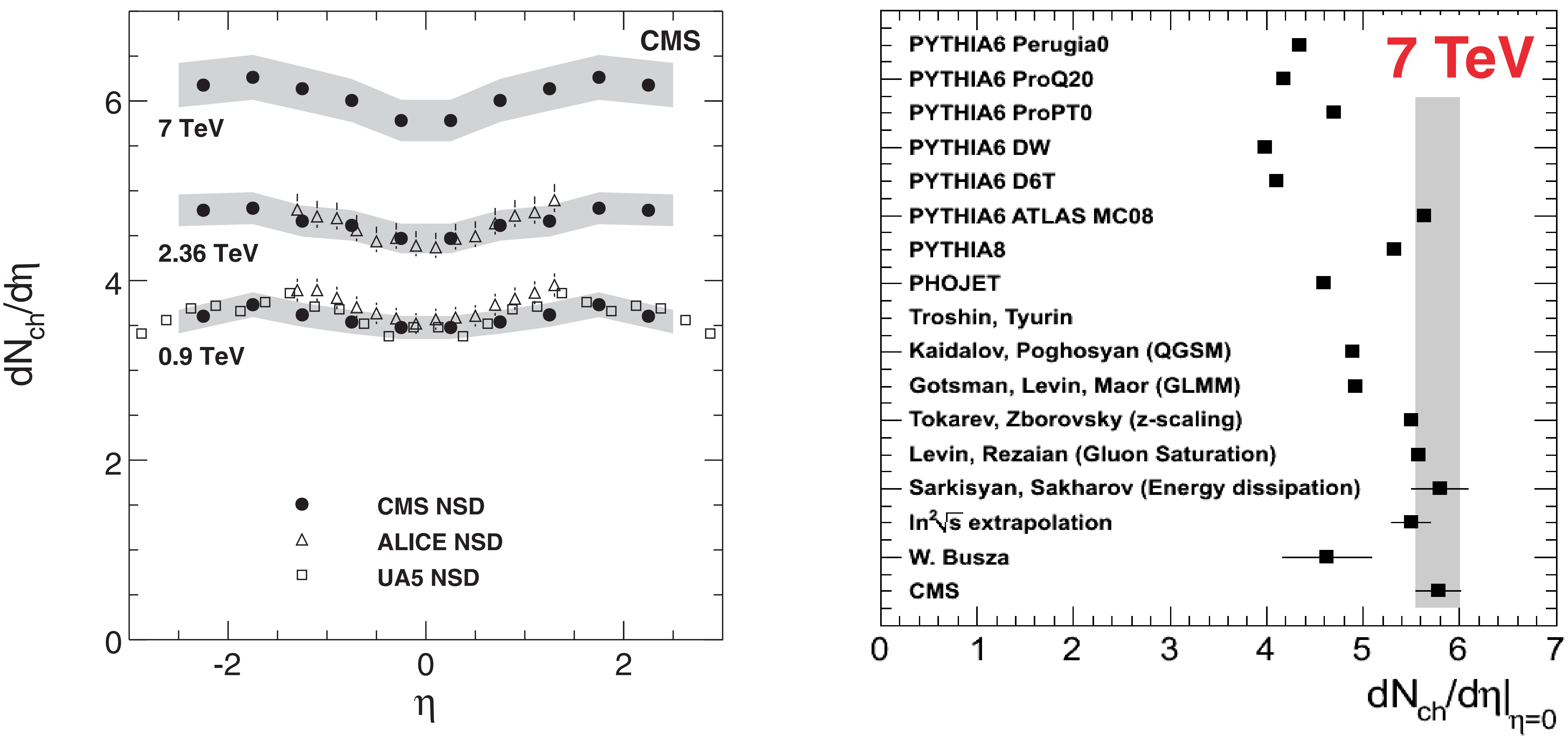




- ✦ p_T spectra described well by Tsallis fits
- ✦ scaling behavior with sqrt(s) at high x_T
- ✦ NLO predictions overestimate particle production

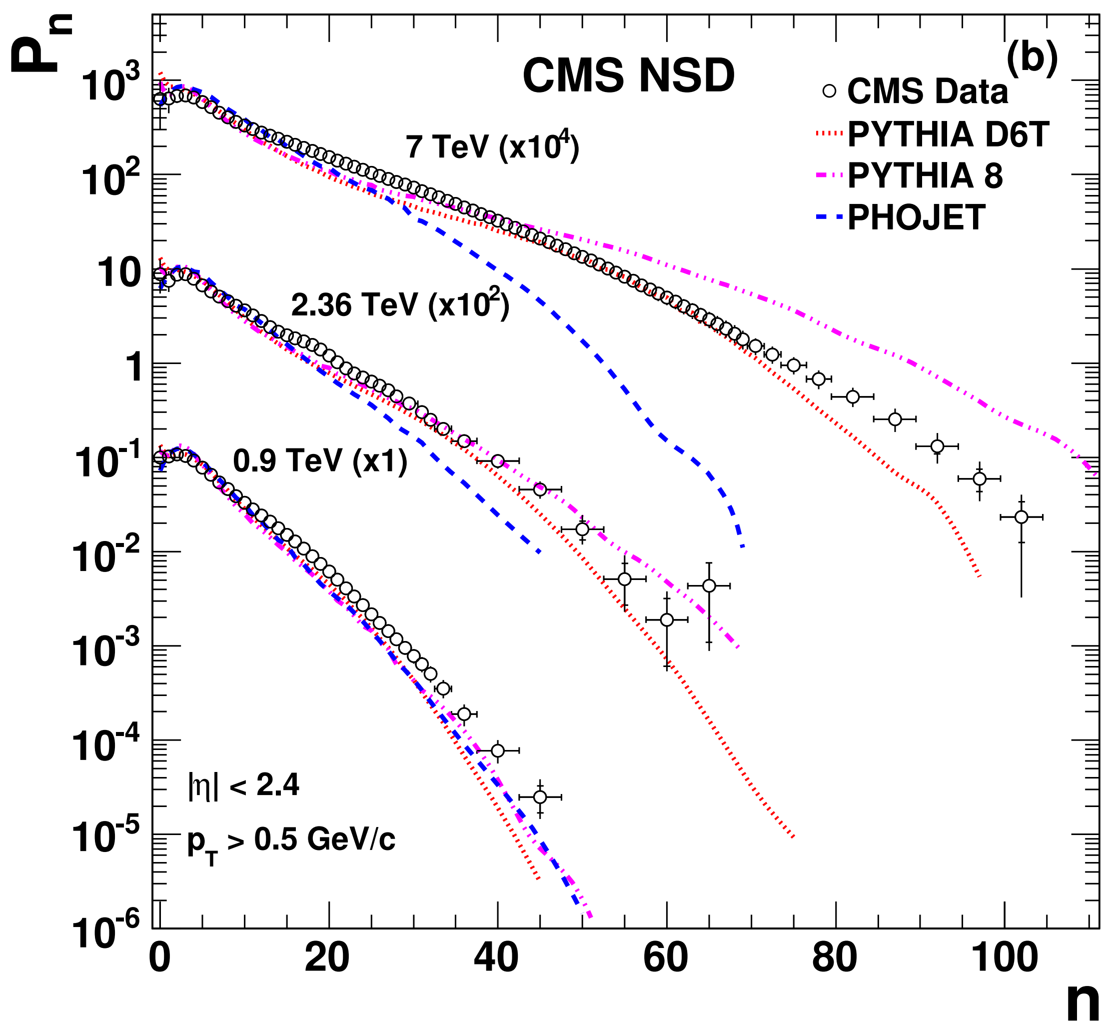
PRL 105 (2010) 022002
JHEP 08 (2011) 086

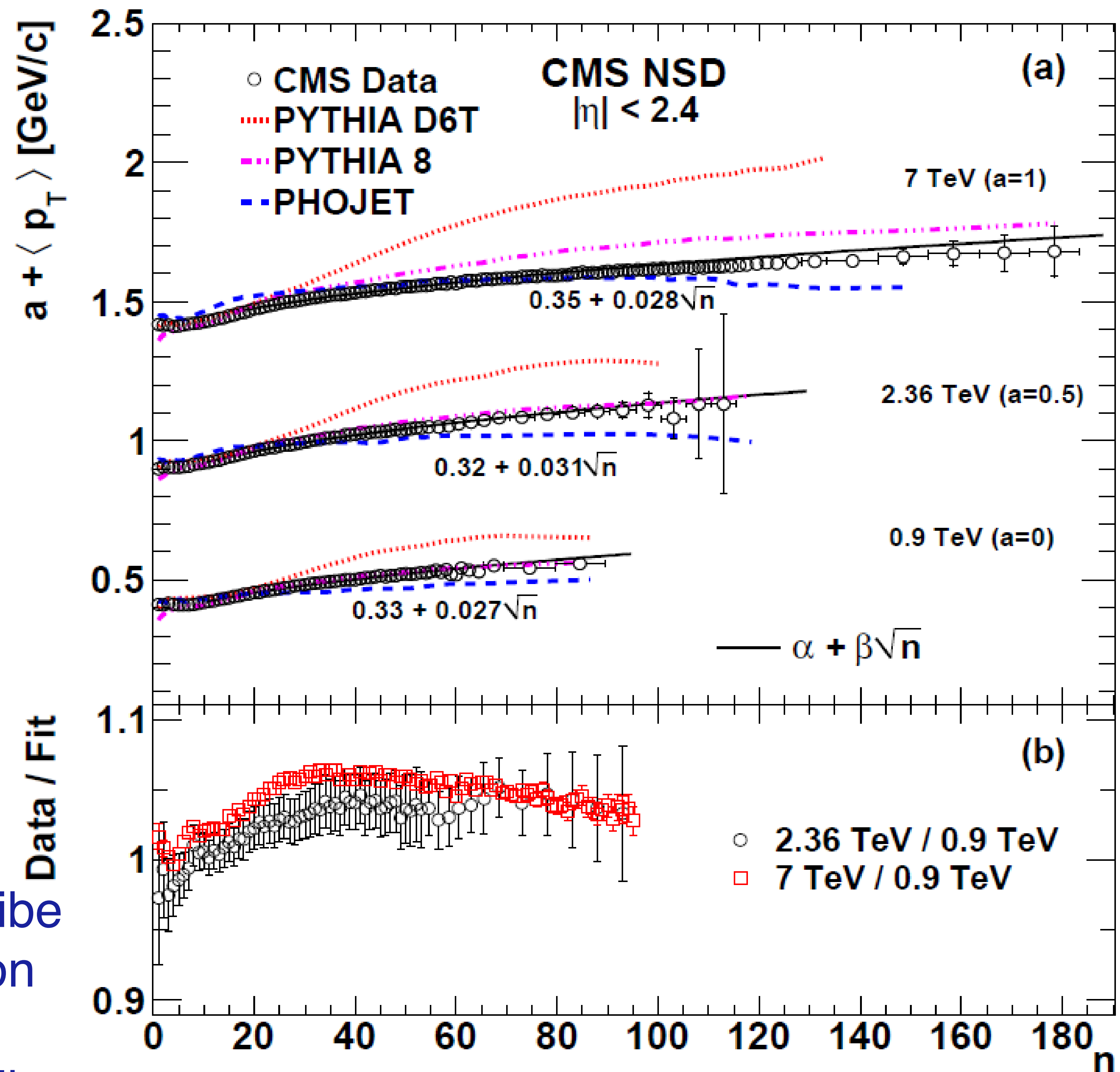
Charged Hadron Pseudorapidity Distributions



- ✦ CMS measurements in agreement with other experiments
- ✦ pre-LHC Monte-Carlo tunes predict lower particle densities
  - ATLAS tune in agreement
- ✦ some analytic models are in reasonable agreement

Charged Hadron Multiplicity

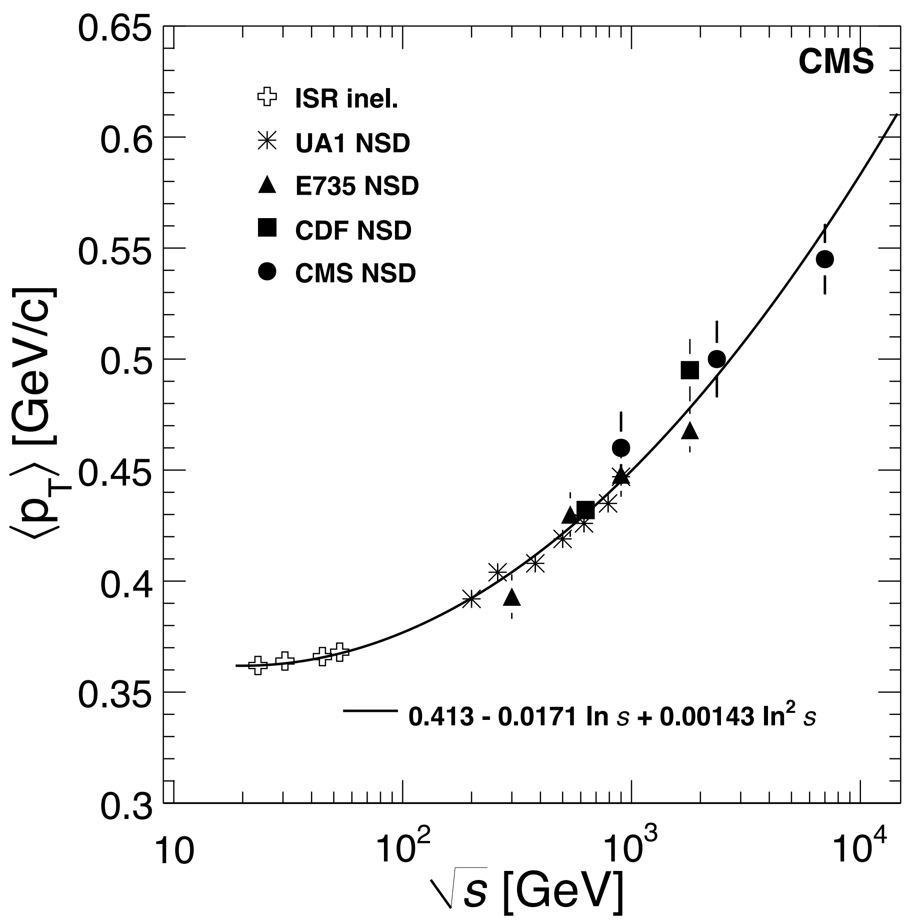


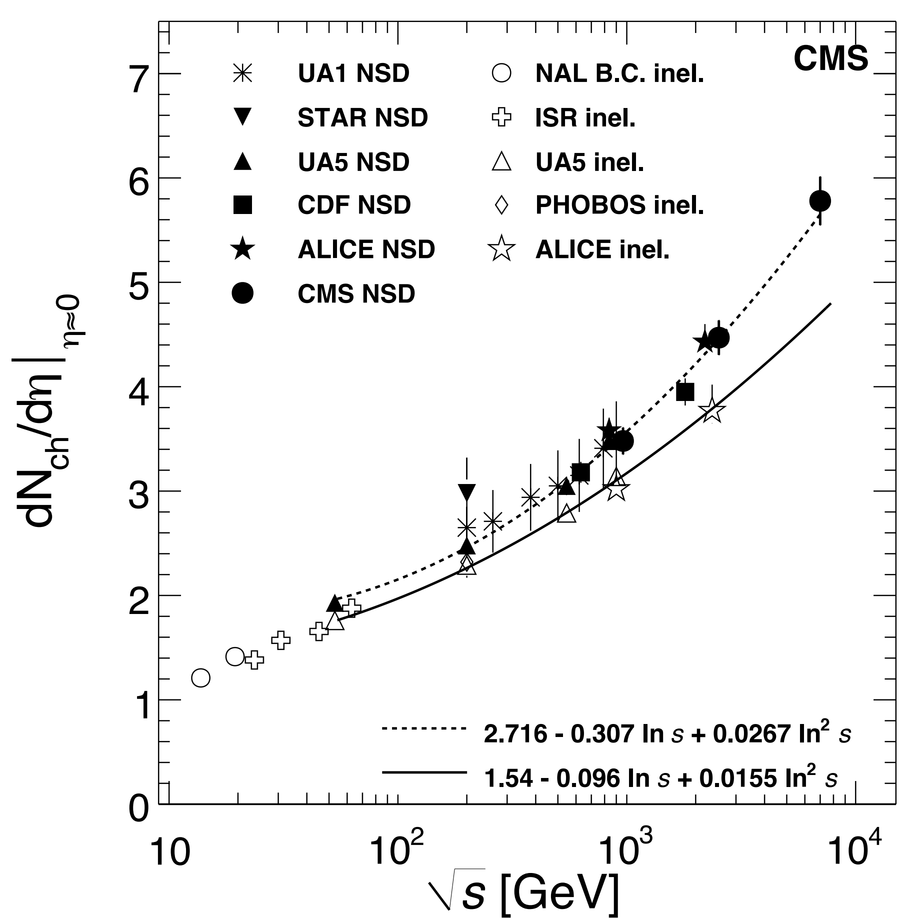


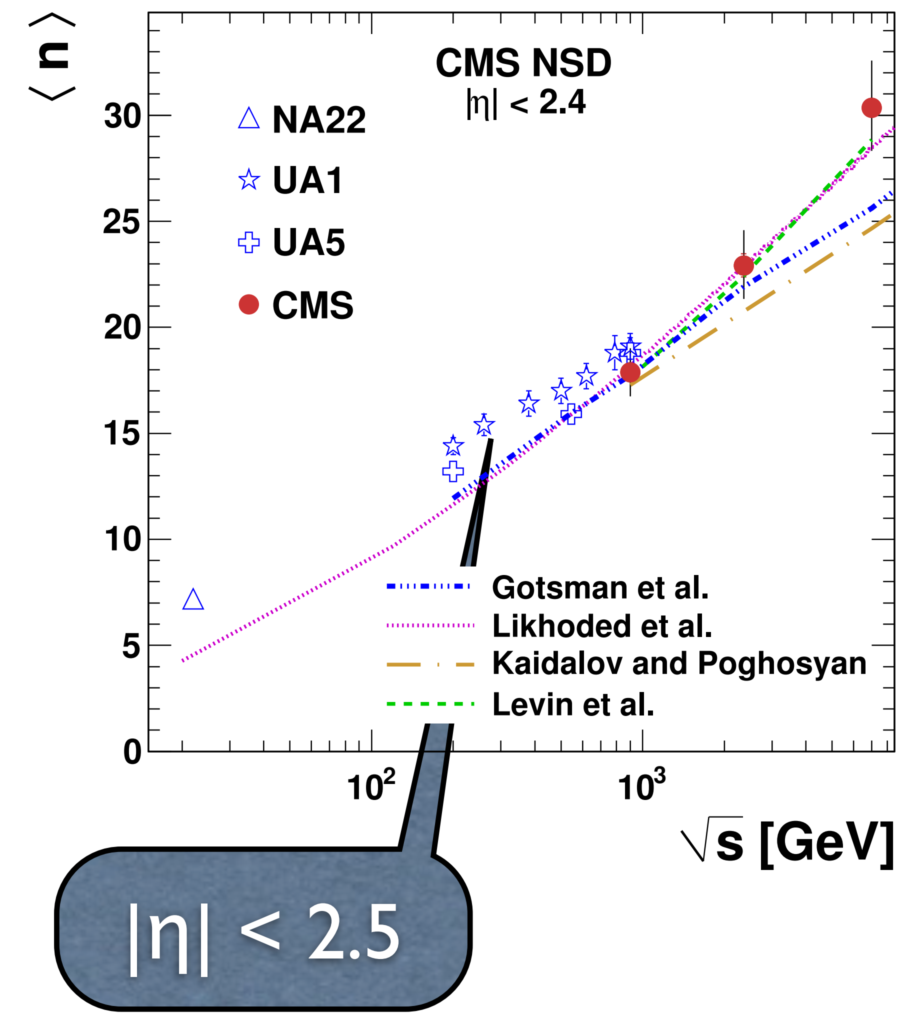
- ✦ no Monte-Carlo generator can describe the multiplicity distributions at all collision energies
- ✦ no Monte-Carlo generator can describe simultaneously the multiplicity and the average p_T

JHEP 01 (2011) 079

Collision-Energy Dependence

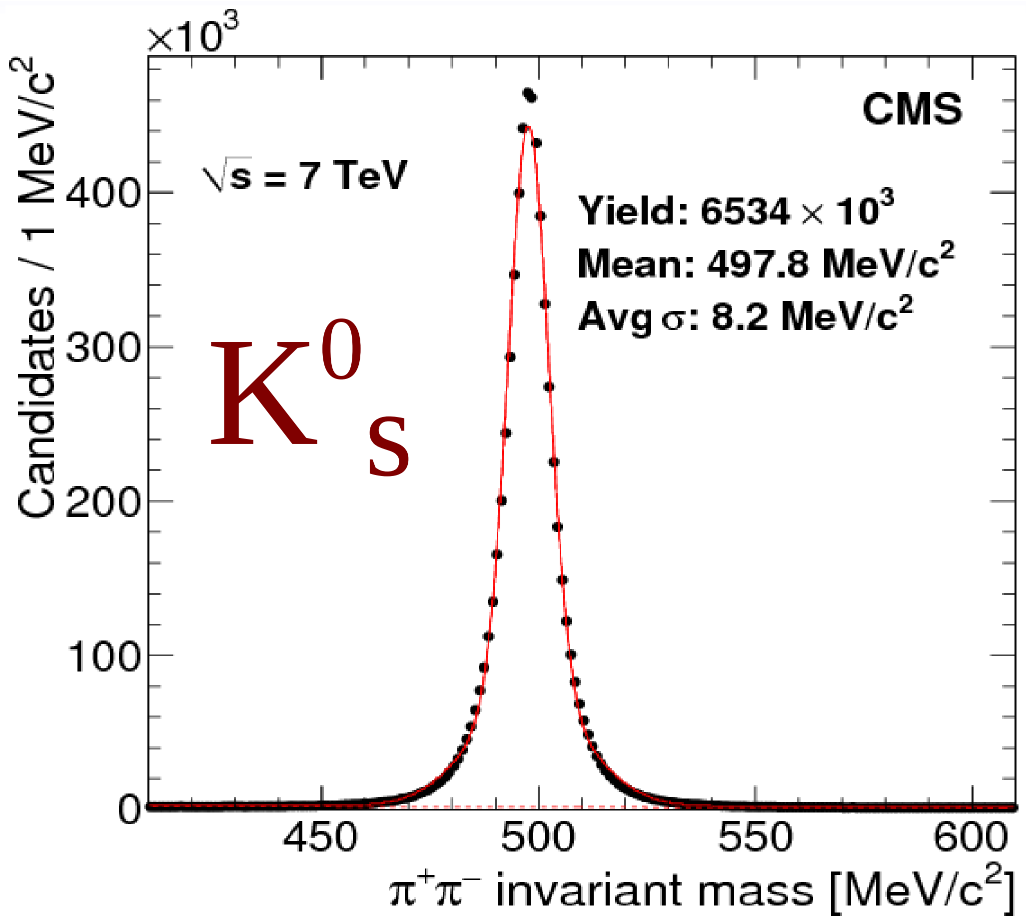


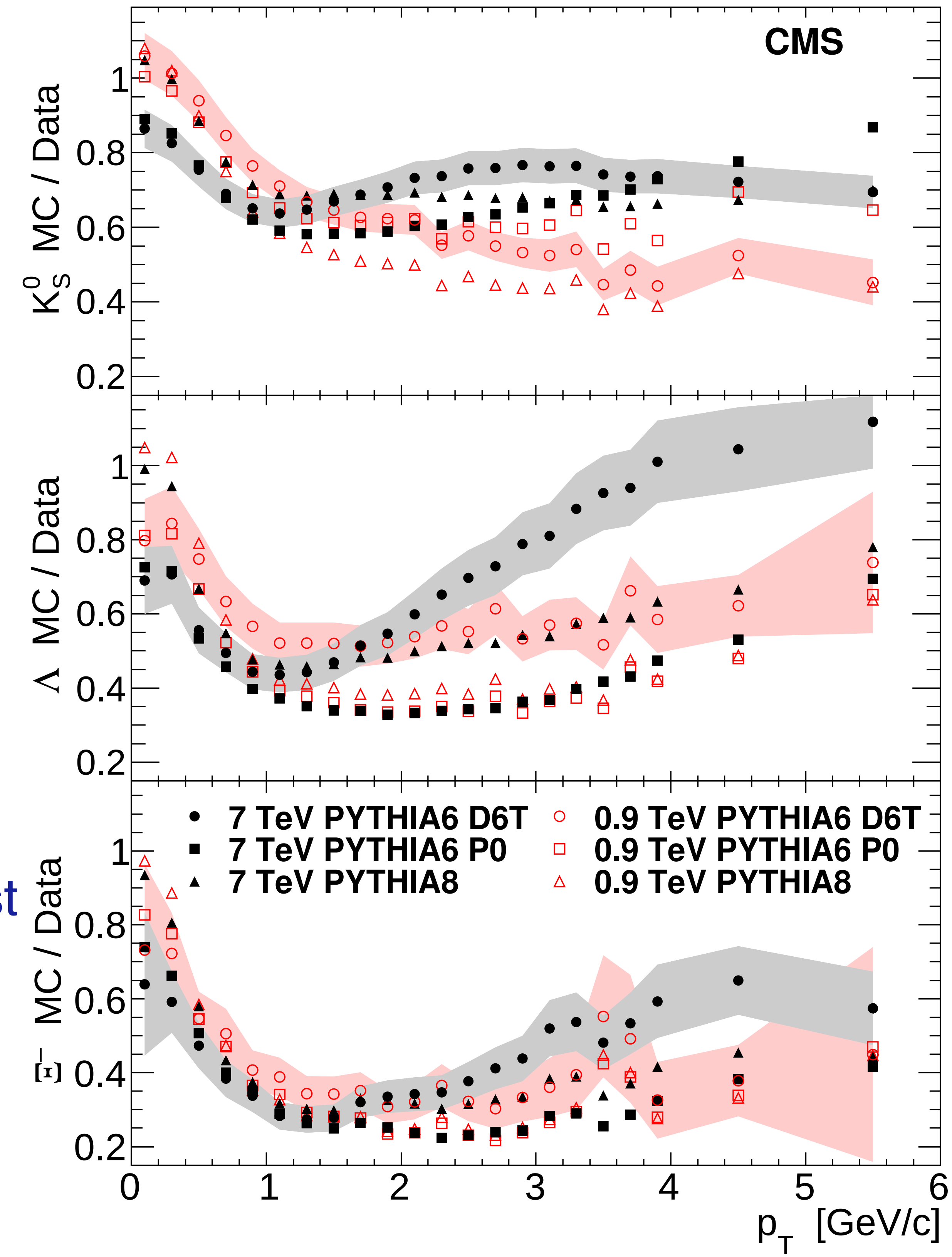




- ✦ CMS measurements in three collision energies: 0.9, 2.36, 7 TeV
- ✦ in agreement with other experiments
- ✦ sharp increase of particle production towards sqrt(s) = 7 TeV

Strange Particle Production

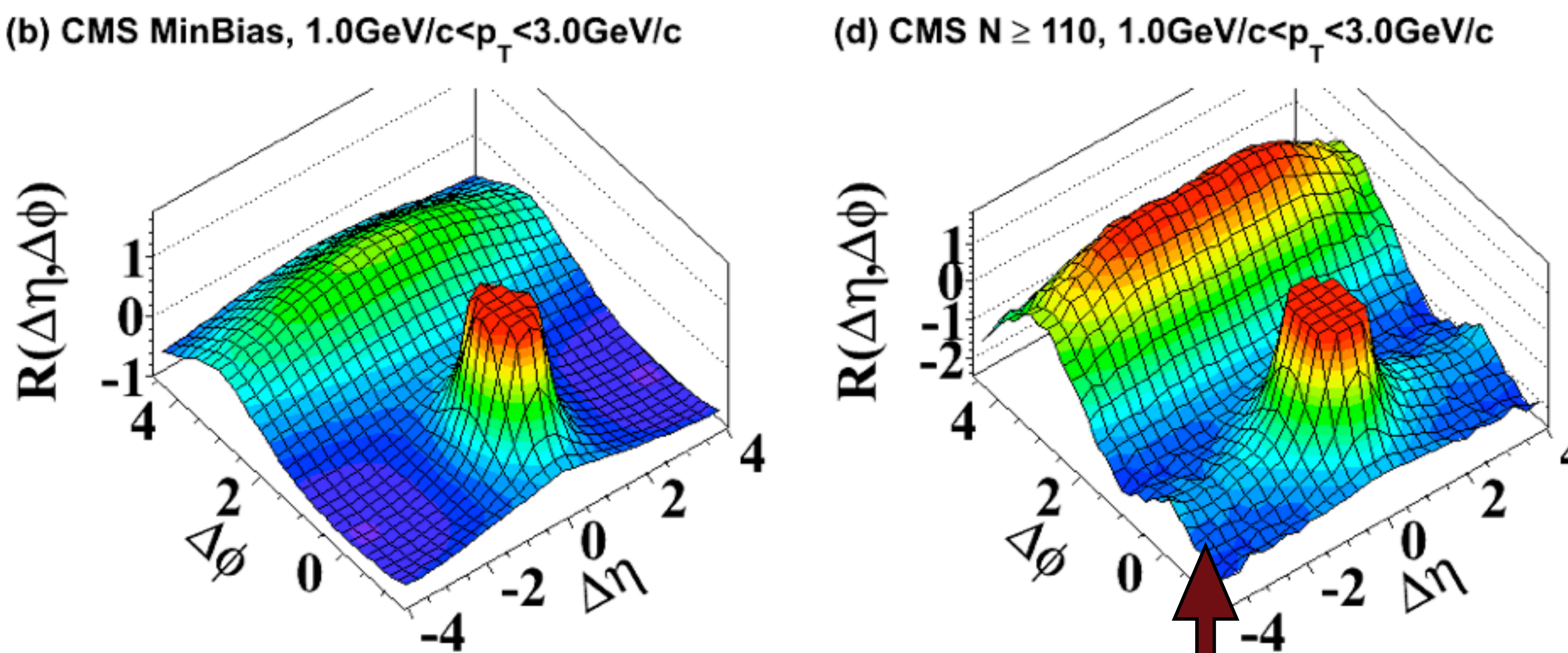




- ✦ strange particle production is a sensitive test of Monte-Carlo tunes
- ✦ significant discrepancies observed between data and pre-LHC tunes of PYTHIA
- ✦ largest deviation for Ξ^- at both collision energies (0.9 & 7 TeV)

JHEP 05 (2011) 064

Particle Correlations

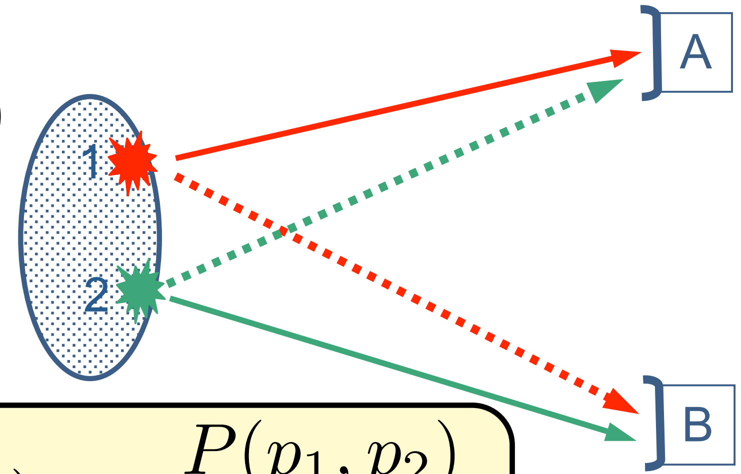


- ✦ two-particle correlations in Δη and Δϕ
- ✦ various regions of interest:
  - particles inside a jet (Δη,Δϕ ~ 0)
  - particles of "back-to-back" jets (Δϕ ~ π)
- ✦ first observation of near-side, long range correlations at high multiplicities
  - not predicted by MC
  - sign of nuclear medium effects?

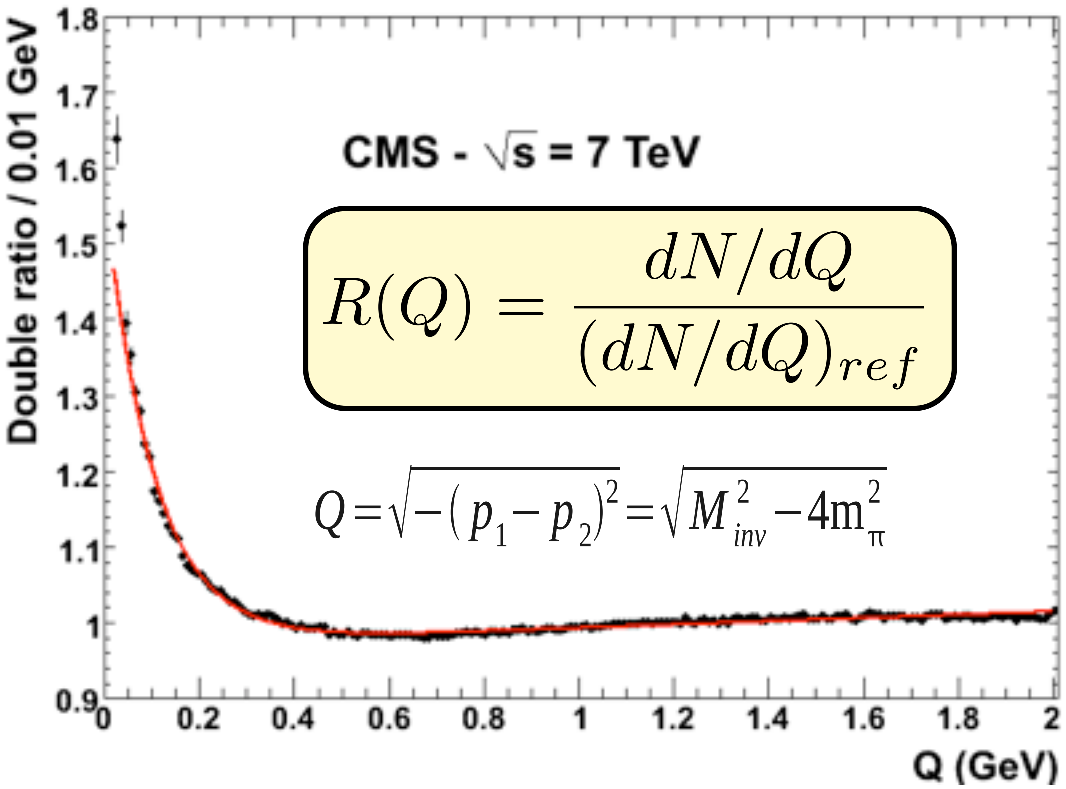
Near-side (Δϕ ~ 0), long range angular correlations at **high multiplicities** and intermediate p_T

JHEP 09 (2010) 091

Bose-Einstein Correlations



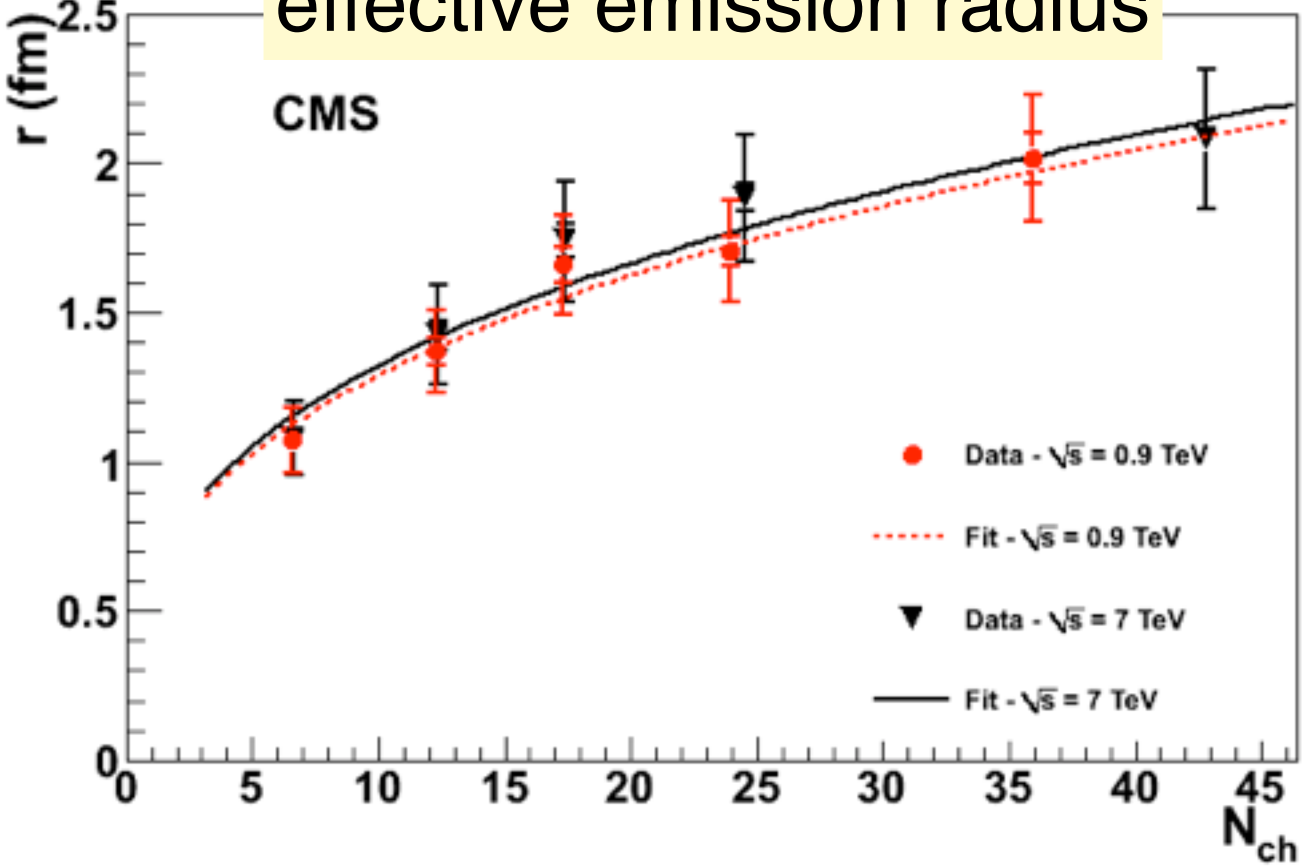
$$R(Q) = \frac{P(p_1, p_2)}{P(p_1)P(p_2)}$$



$$R(Q) = \frac{dN/dQ}{(dN/dQ)_{ref}}$$

$$Q = \sqrt{-(p_1 - p_2)^2} = \sqrt{M_{inv}^2 - 4m_\pi^2}$$

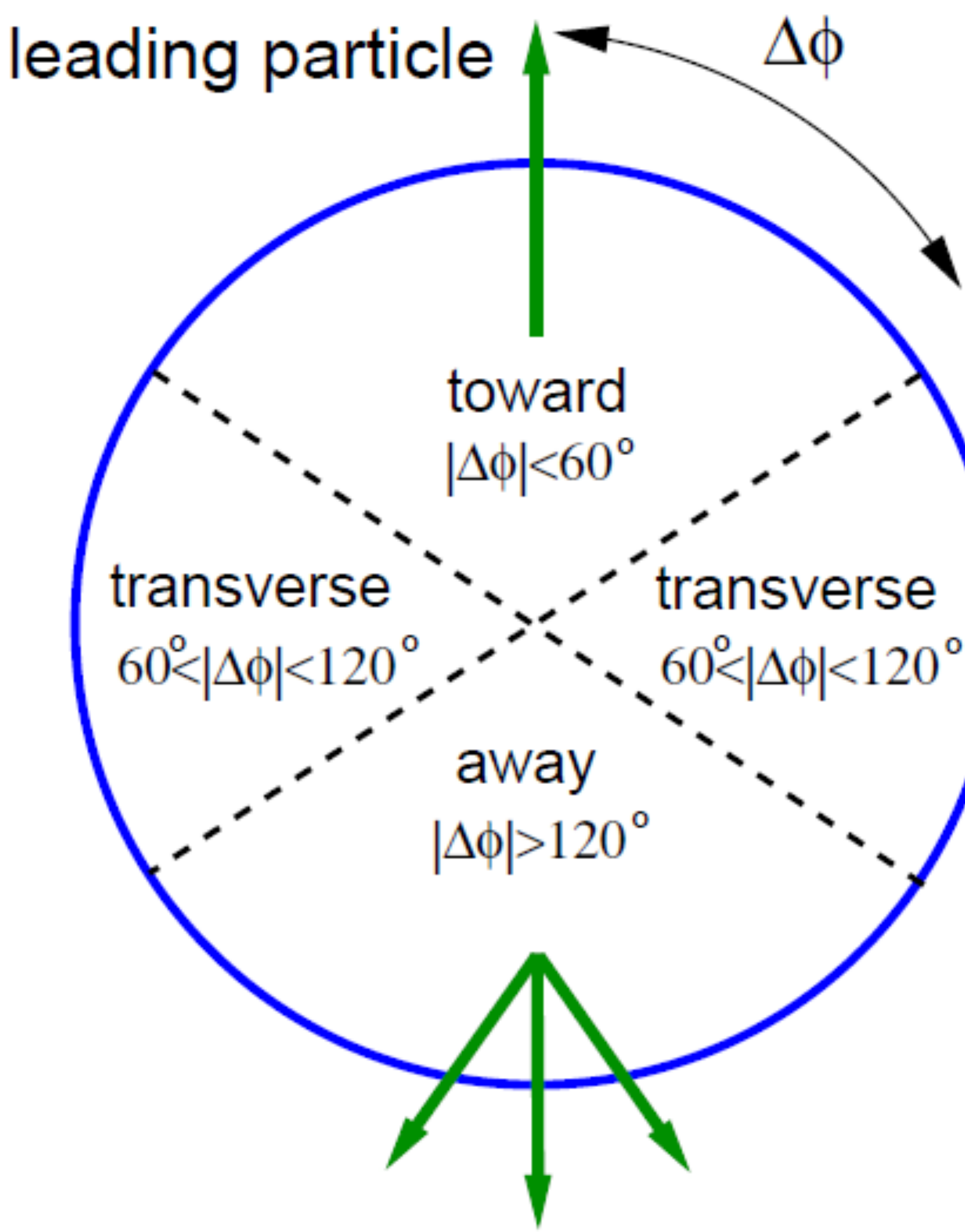
effective emission radius



- ✦ correlations between identical bosons with overlapping wave functions
- ✦ production probability enhancement at low Q
- ✦ provides information about the size of the emitting source
- ✦ ratio to reference sample with no correlations

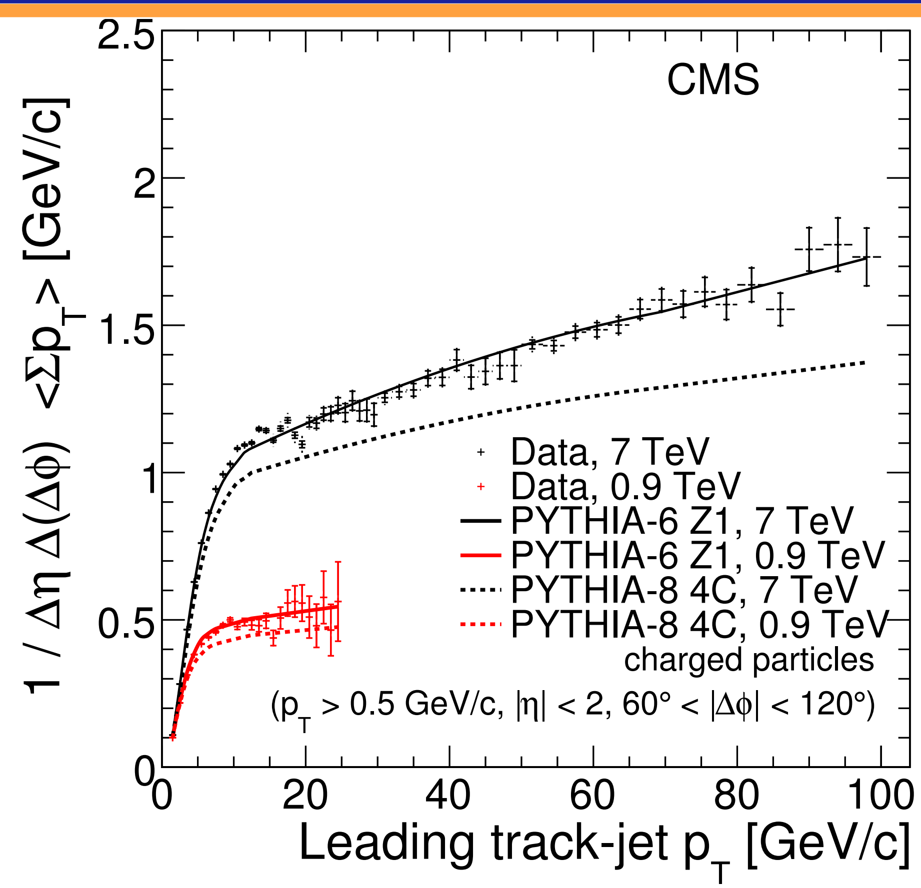
JHEP 05 (2011) 029

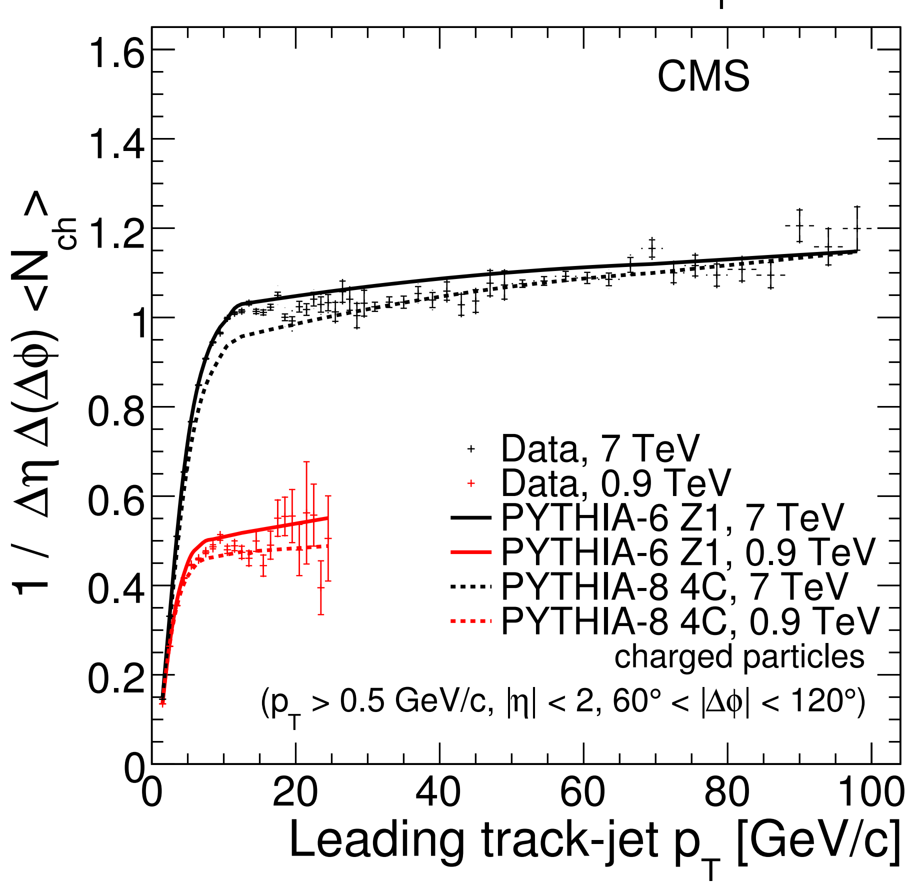
Underlying Event (I)

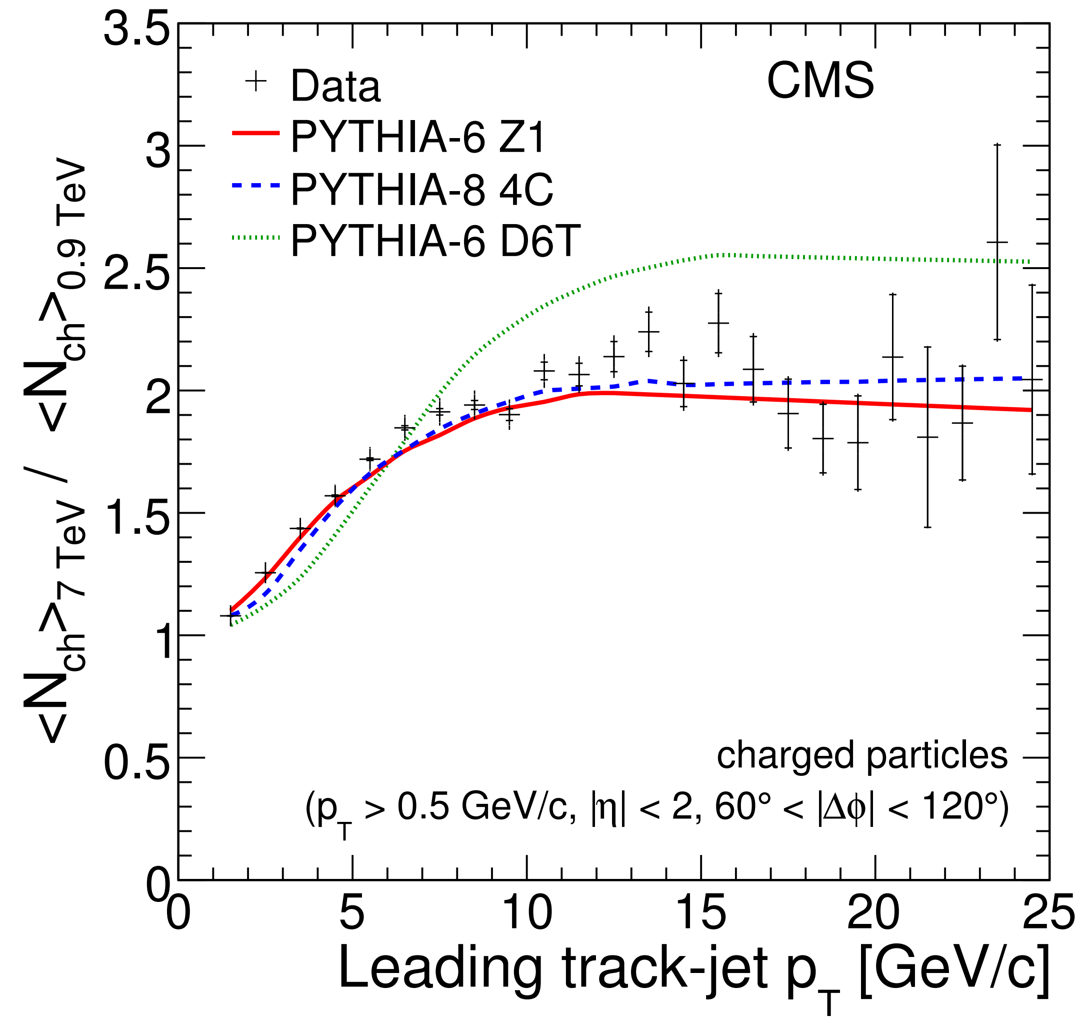


- ✦ the "underlying event" consists of everything else except for the hard interaction
  - multiple parton interactions
  - initial and final state radiation
  - beam remnants
- ✦ the event is divided in three regions
  - ***toward*** (defined by the leading particle / jet)
  - ***away***
  - ***transverse*** (sensitive to UE)
- ✦ two observables quantify the UE activity
  - multiplicity density of charged hadrons
  - scalar sum p_T density of charged hadrons

Underlying Event (II)



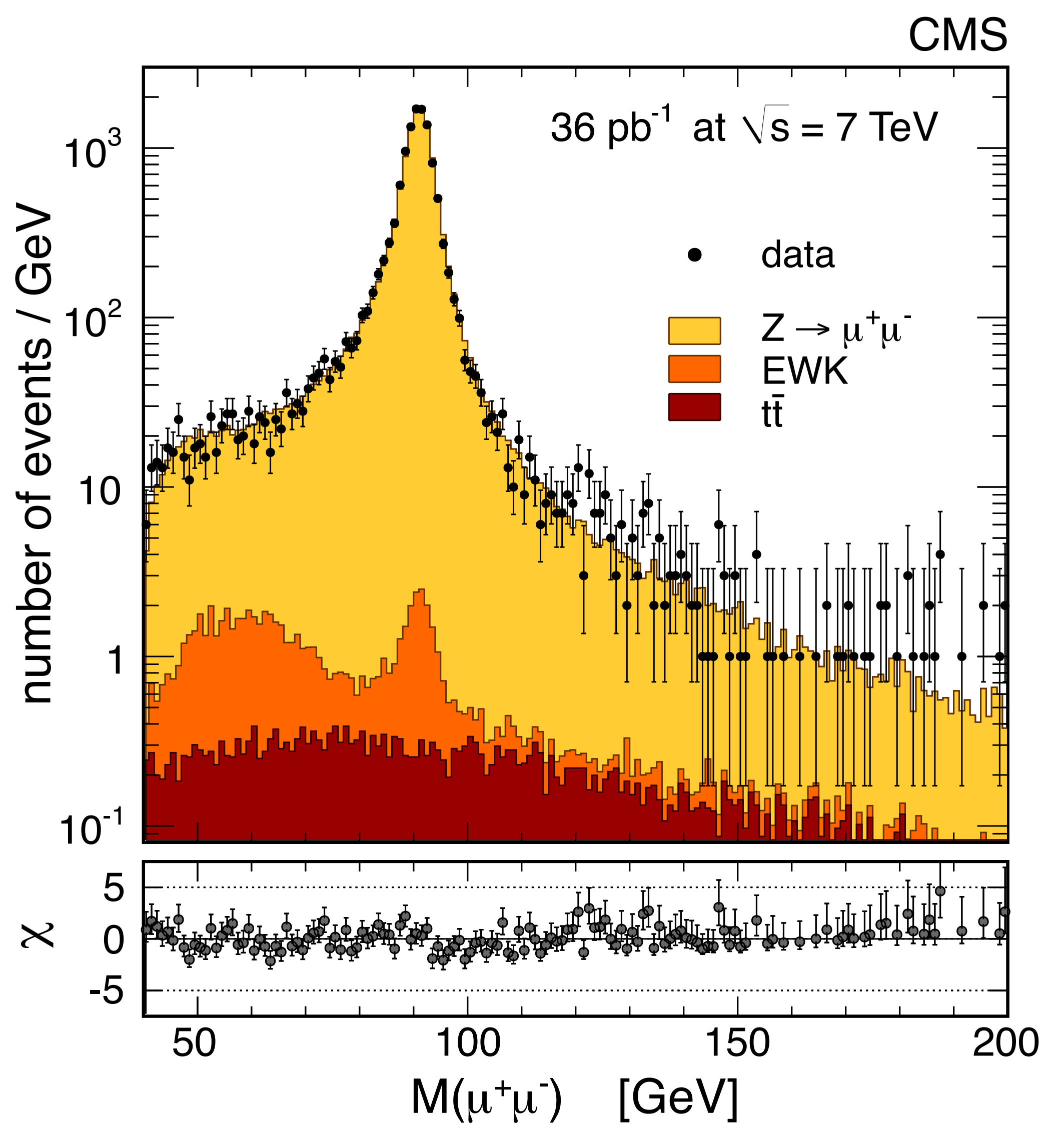


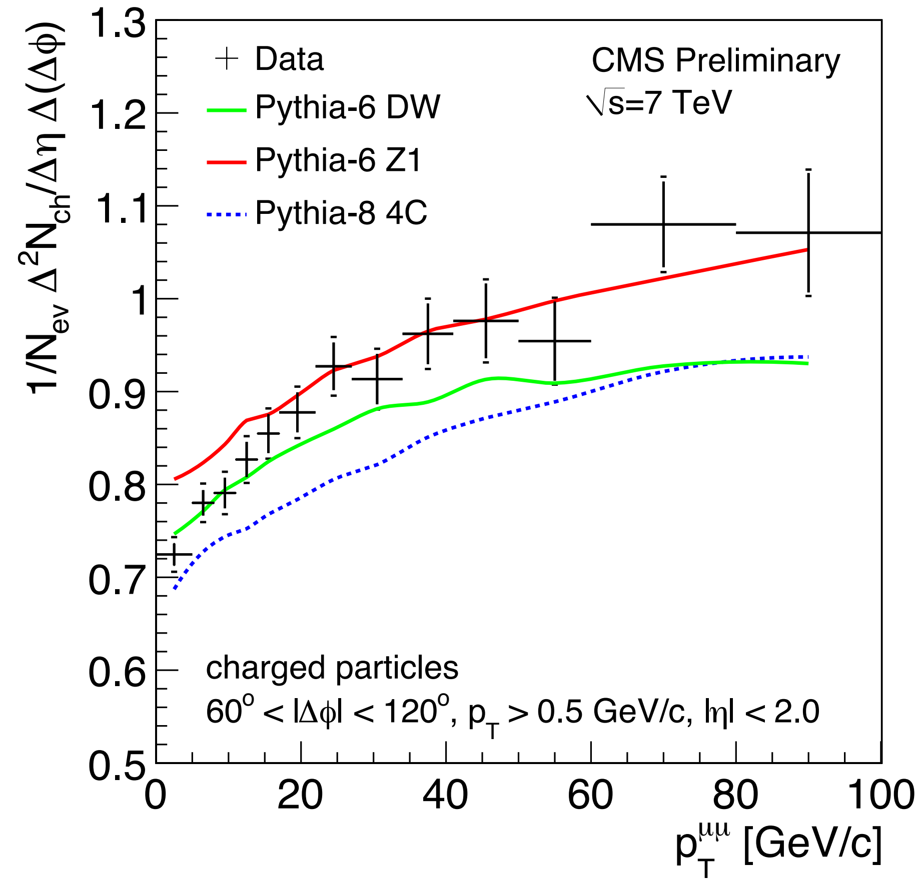


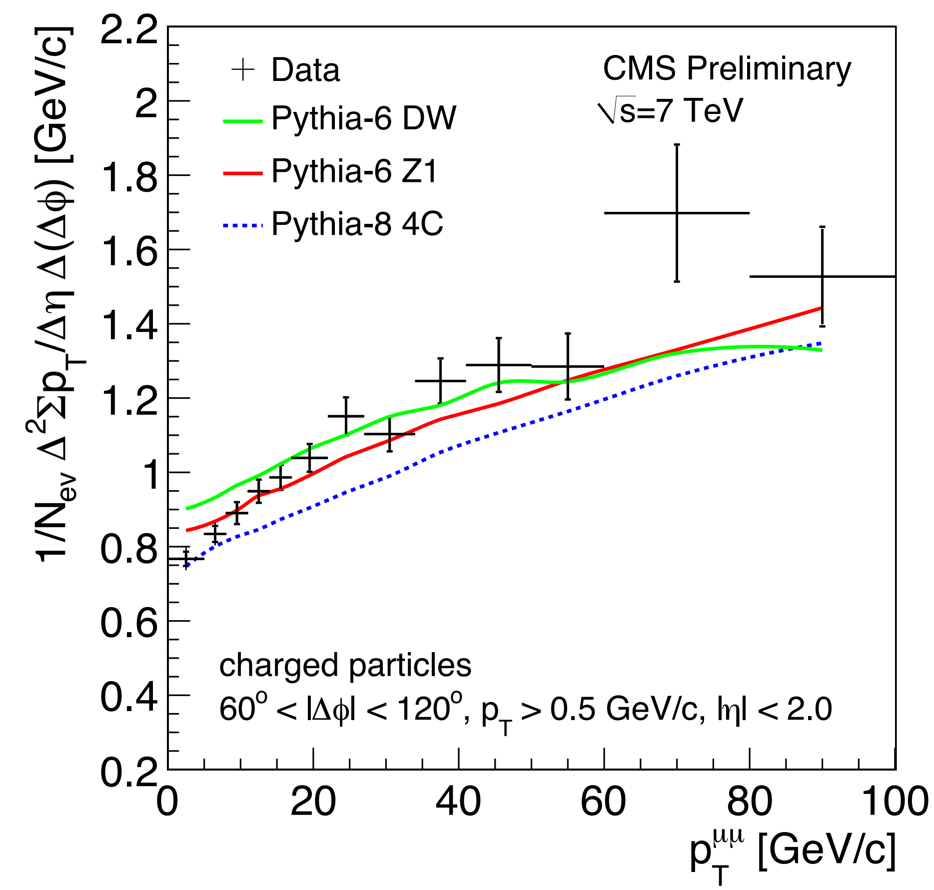
- ✦ the hard scale of the event is defined by the hardest track-jet
- ✦ the UE activity shows a sharp increase up to p_T~10 GeV, followed by a plateau (saturation region)
- ✦ the UE activity increases by a factor ~2 from 0.9 to 7 TeV
- ✦ pre-LHC tunes do not describe the UE, but newer tunes do

JHEP 09 (2011) 109

Underlying Event in DY Events



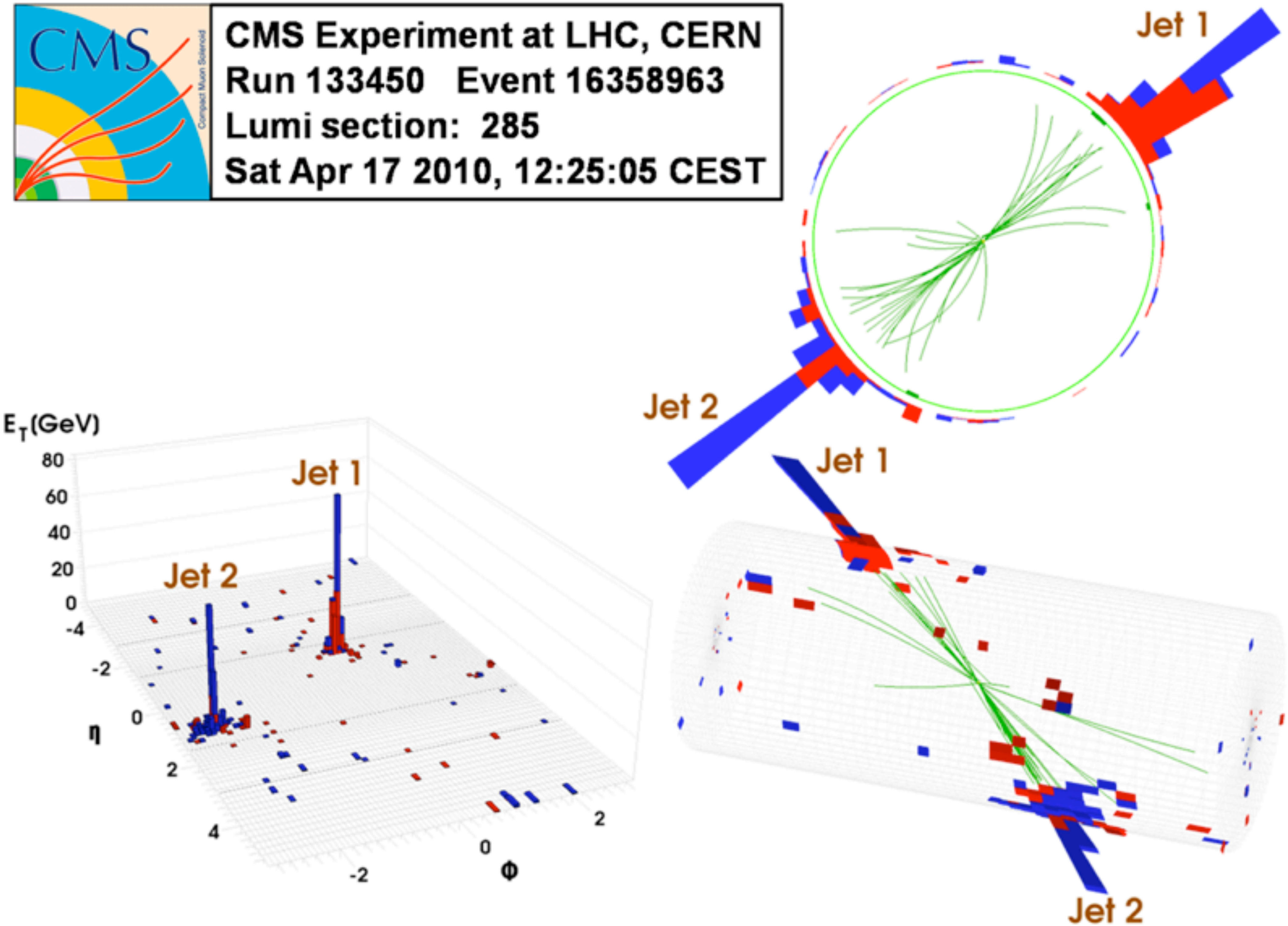




- ✦ UE activity in Drell-Yan events
- ✦ the hard scale of the events is practically defined by the Z pole
- ✦ explore the saturation region
- ✦ newer tunes of Pythia6 describe the data well

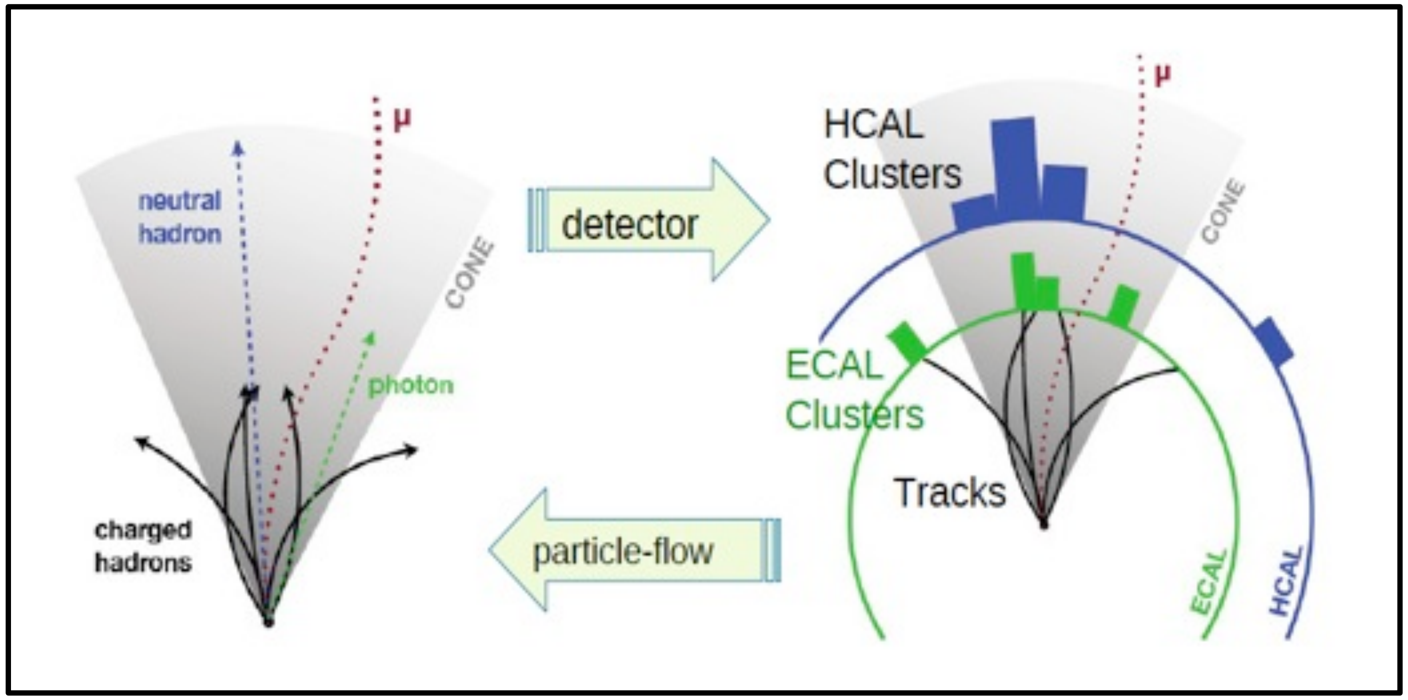
PAS-QCD-10-040

Measurements with Jets

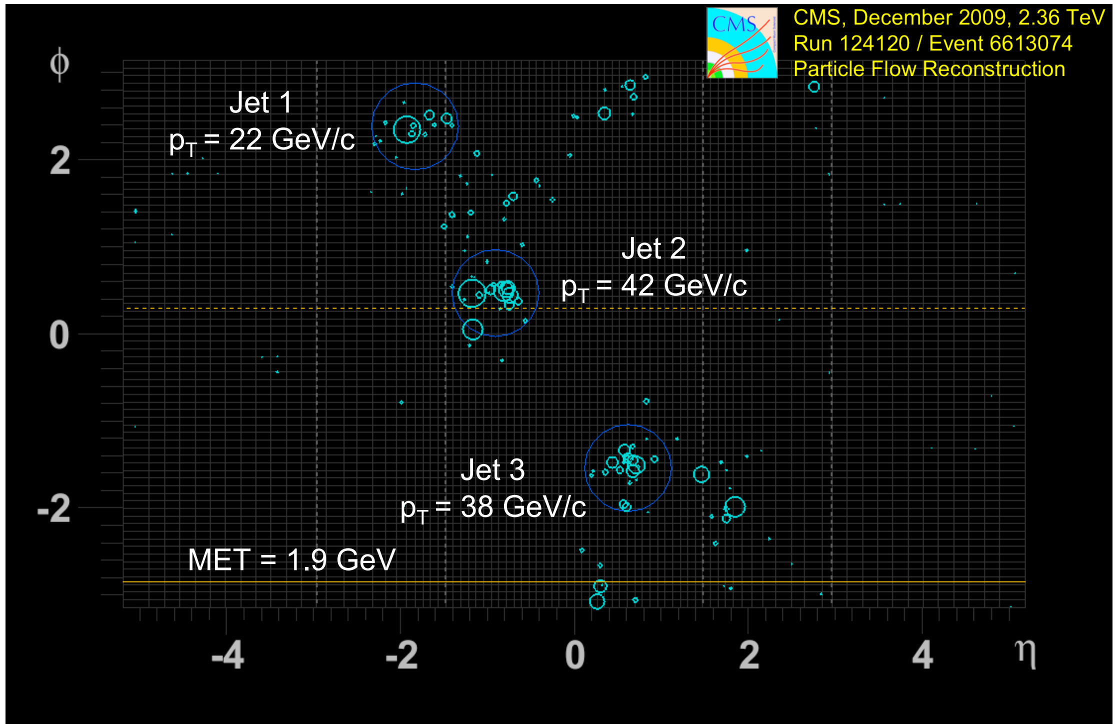

CMS Experiment at LHC, CERN
Run 133450 Event 16358963
Lumi section: 285
Sat Apr 17 2010, 12:25:05 CEST
Jet 1
Jet 2
E_T(GeV)
80
60
40
20
0
-4
-2
0
2
4
η
-2
0
2
Φ
Jet 1
Jet 2
Jet 1
Jet 2

Particle-Flow Reconstruction

✦ **Sophisticated "particle flow" reconstruction algorithm**
- exploits the excellent tracker performance and the fine ECAL granularity

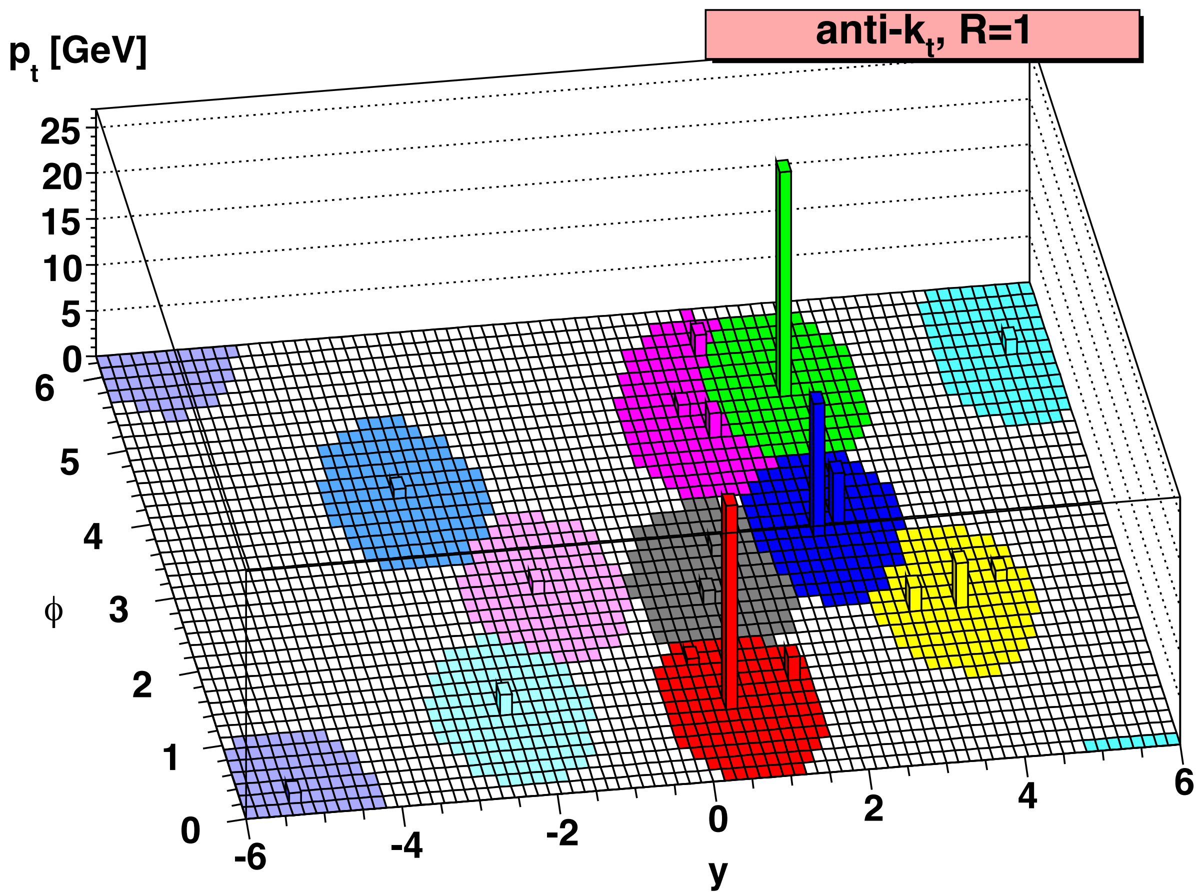


✦ **Reconstructed individual particles according to their detection signature**
- **charged hadrons** (tracks + linked ECAL/HCAL deposits)
- **neutral hadrons** (unlinked HCAL deposits)
- **photons** (unlinked ECAL deposits)
- **electrons** (tracks + linked ECAL deposits with E/p ~ 1)
- **muons** (tracks + muon chamber hits)



Jet Clustering

✦ ***anti-k_T*** **clustering algorithm:**
- sequential recombination (k_T family)
- infrared and collinear safety
- geometrically well defined (circular shape in the y-ϕ plane)
- tends to cluster around the hard energy depositions
- distance parameter R=0.5 (default) & 0.7

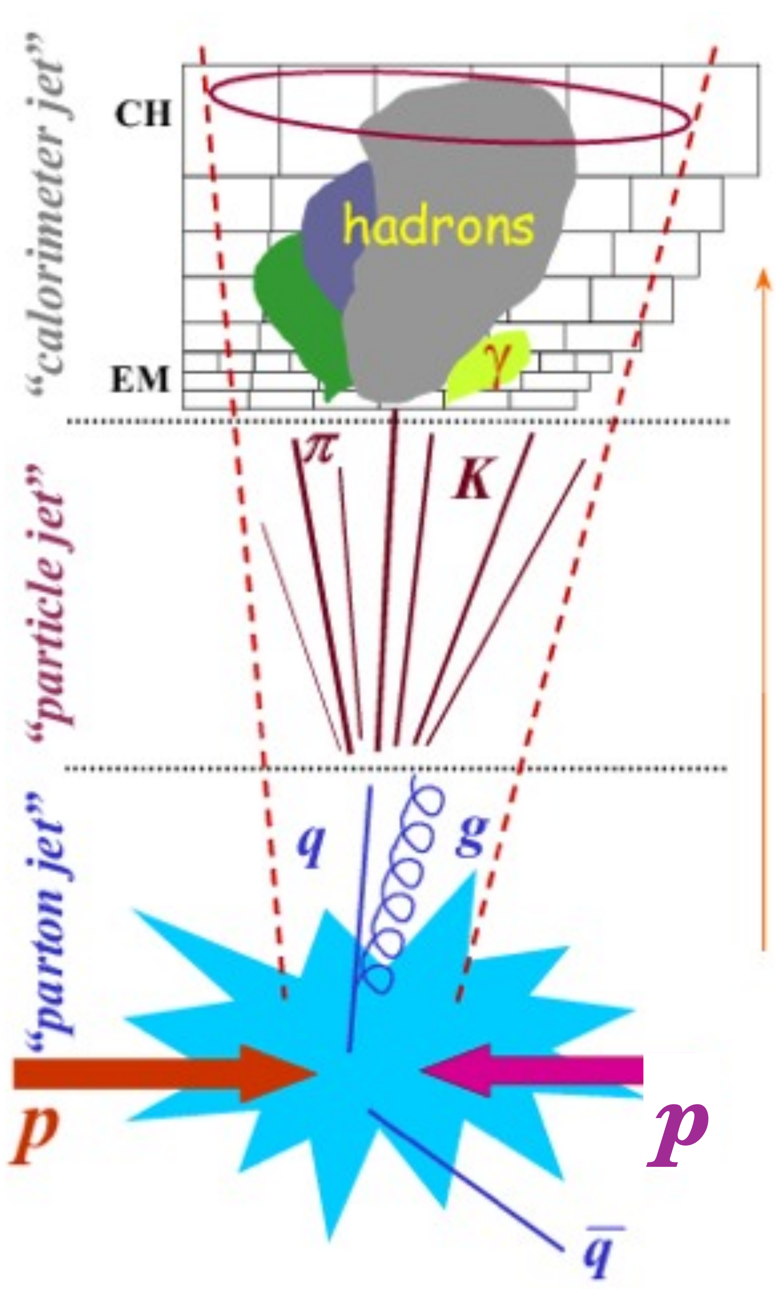


✦ ***"E-scheme"*** **jet reconstruction**
- 4-momentum summation
- massive jets

$$d_{ij} = \min\left(p_{Ti}^{-2}, p_{Tj}^{-2}\right)\frac{\Delta R_{ij}^2}{R^2}$$
$$d_{iB} = p_{Ti}^{-2}$$
$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

✦ **Inputs to the jet clustering algorithm**
- 4-momentum vectors of the reconstructed particles

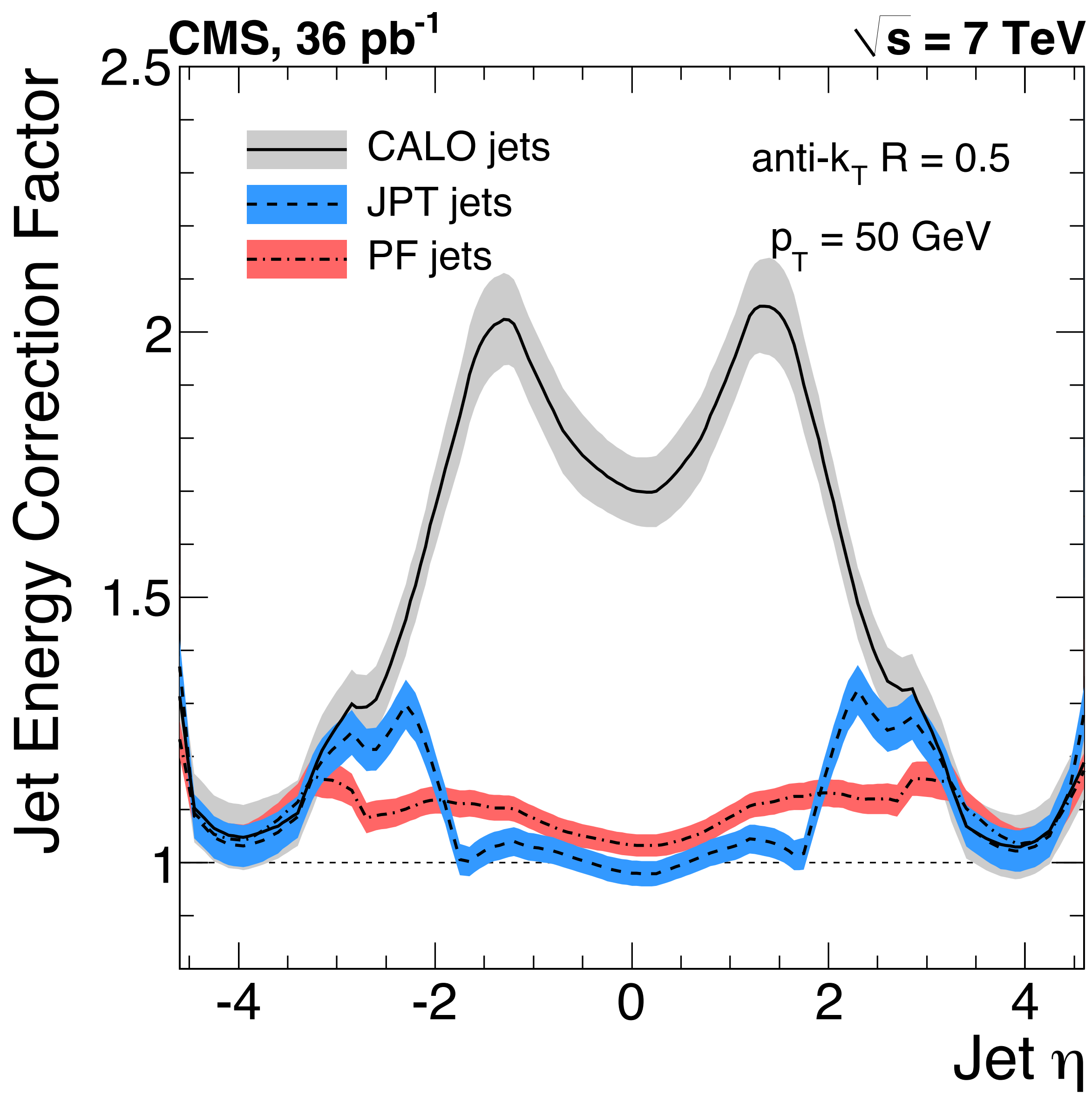
Jet Energy Calibration (overview)

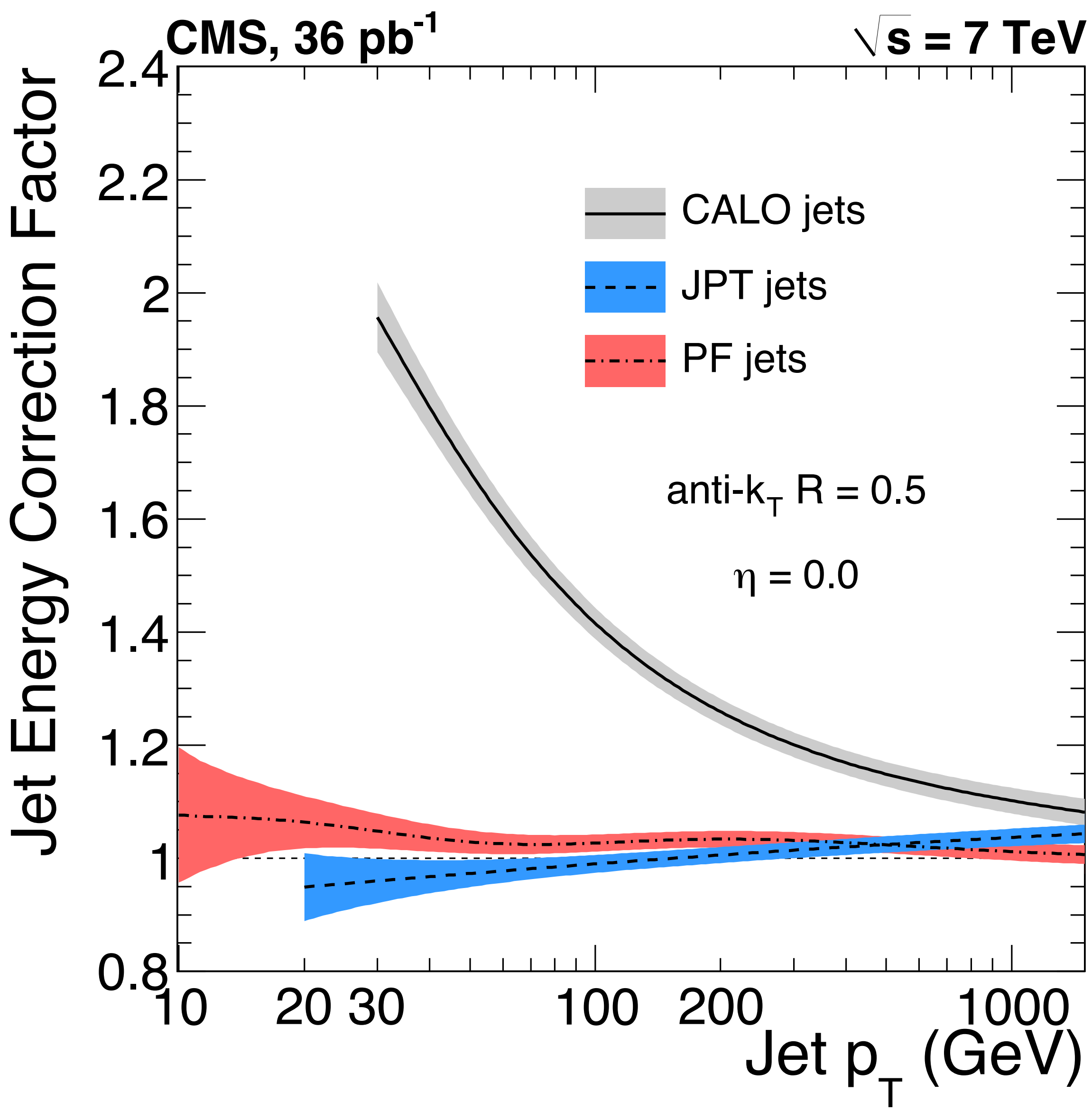


- **Average correction of a detector jet to the particle level**
  - multiplicative factor to the entire jet 4-momentum vector
- **Offset correction to account for noise & pile-up**
- **Calibration based on the MC JEC**
- **Residual correction from in-situ measurements**
  - relative JES vs η from dijet p_T balancing
  - absolute JES vs p_T from γ/Z + jet p_T balance
- **Default JEC refers to the QCD flavor composition**
  - flavor dependence up to 2-3% for PF jets

$$\mathcal{C} = C_{\text{off}}(p_T^{raw}) \cdot C_{\text{MC}}(p'_T, \eta) \cdot C_{\text{rel}}(\eta) \cdot C_{\text{abs}}$$

Jet Energy Calibration

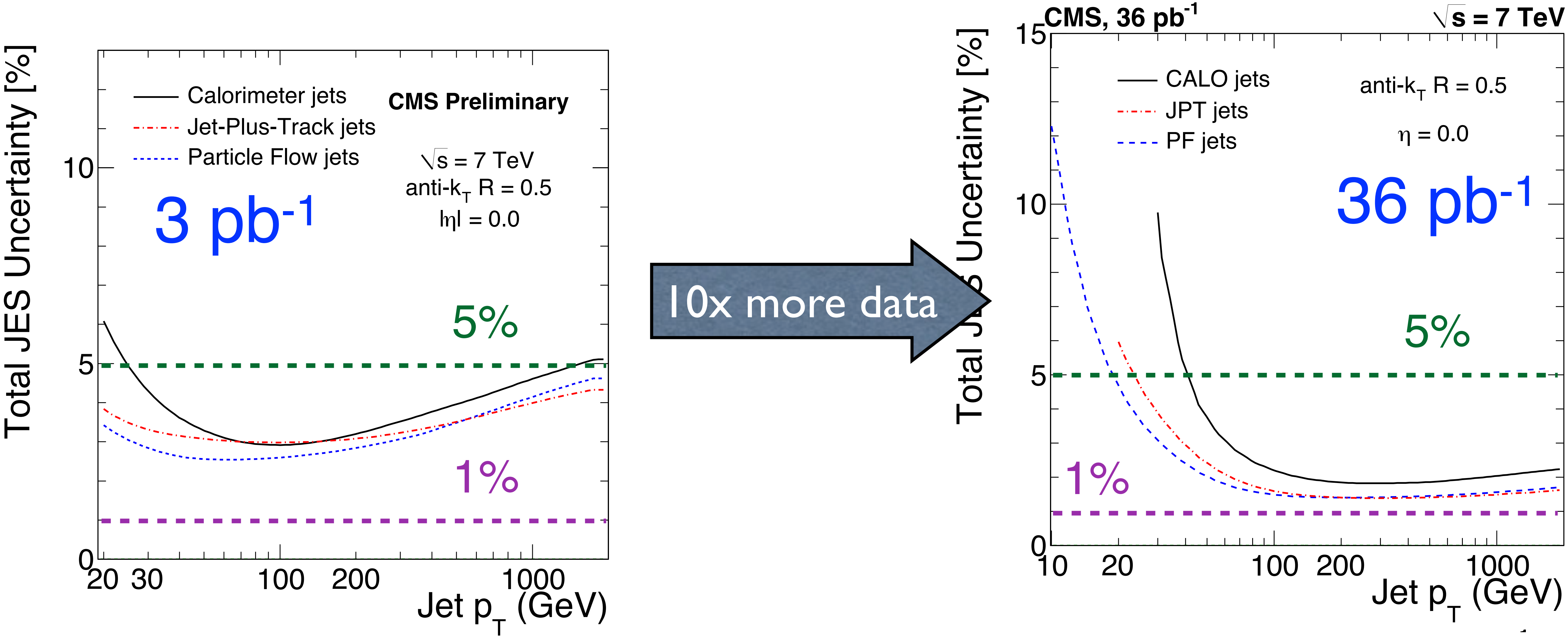




- **Simple calorimetric jets require a large correction factor**
  - non-compensating calorimetric system
- **Particle-flow jets require a small correction factor (< 10%)**
  - huge improvement compared to the calorimetric jet performance

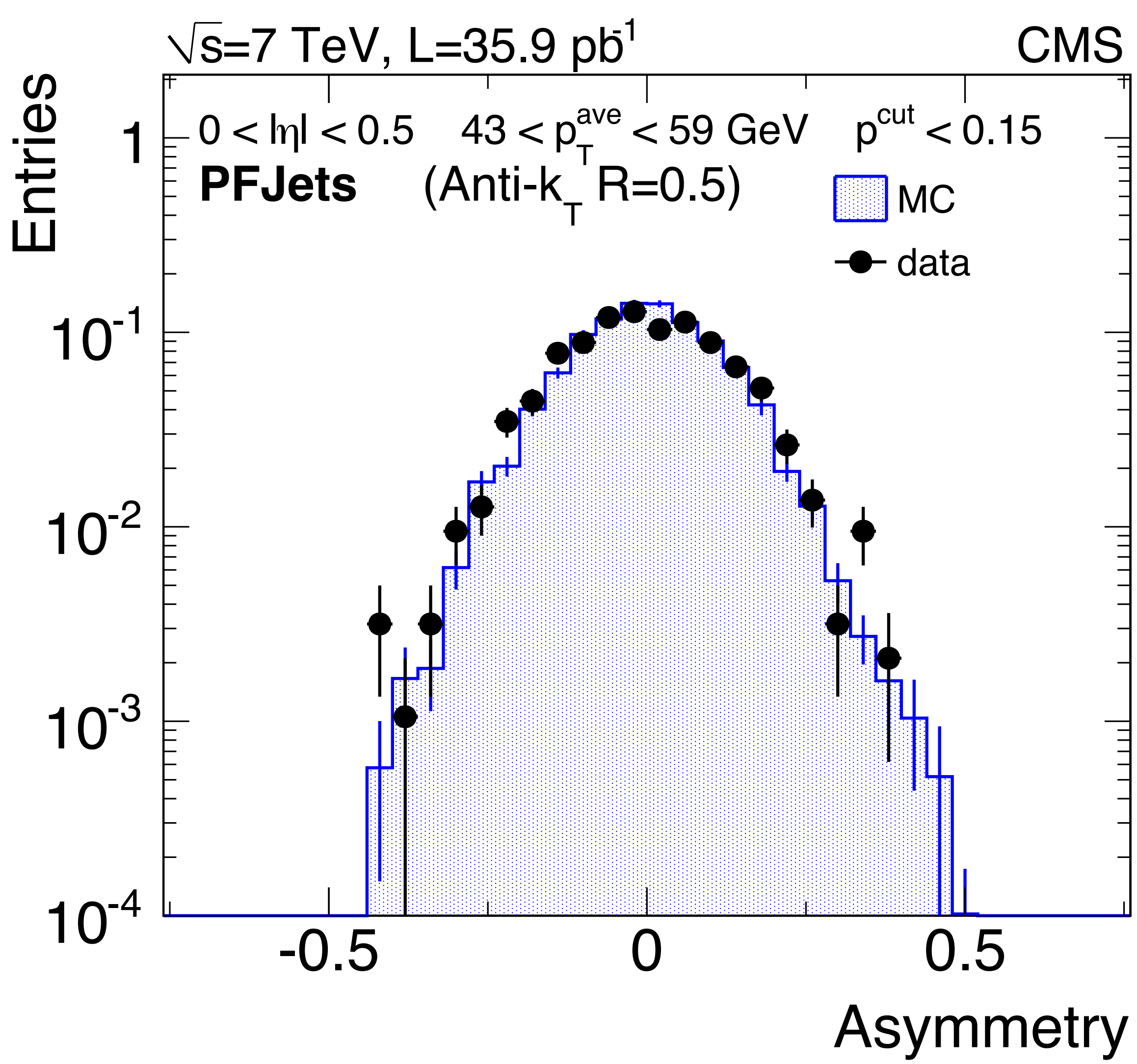
arXiv:1107.4277

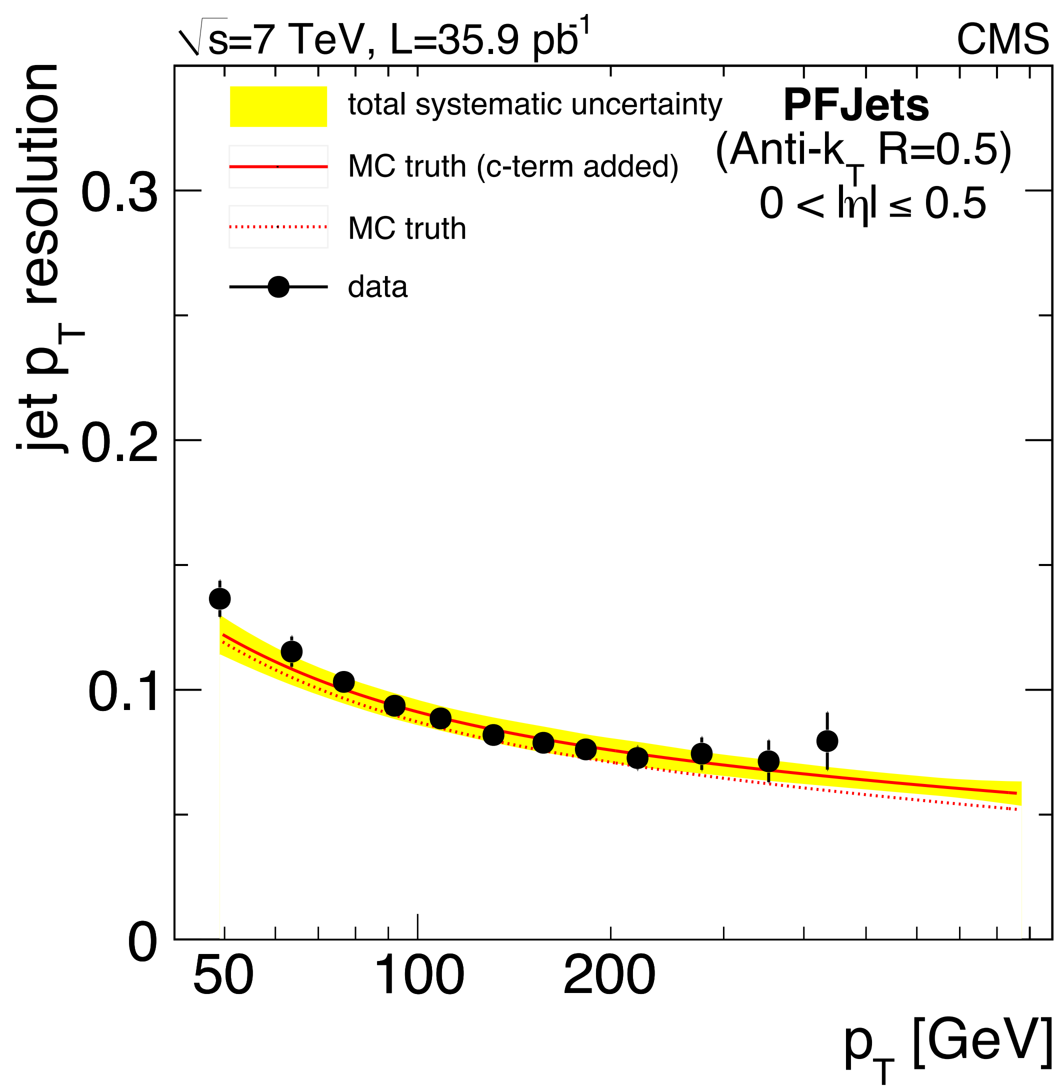
Jet Energy Scale Uncertainty



- **JES uncertainty achieved in 2010: better than 3% for p_T > 30 GeV**
  - significant improvement compared to the estimate with the first 3 pb^{-1}
- **the jet measurements published by CMS use the 3 pb^{-1} JES**
  - the JES derivation is a very time consuming procedure
- **the goal of 1% JES is realistic with the 2011 data**

Jet p_T Resolution





- **Measured in data**
  - **better than 10% for PF jets with p_T > 80 GeV**
  - dijet asymmetry method
  - photon + jet p_T balance
- **Simulated resolution systematically better**
  - by 10-20% (relative) depending on η

arXiv:1107.4277

Inclusive Jet Cross Section

✦ **Double-differential inclusive jet cross section vs jet p_T and y**

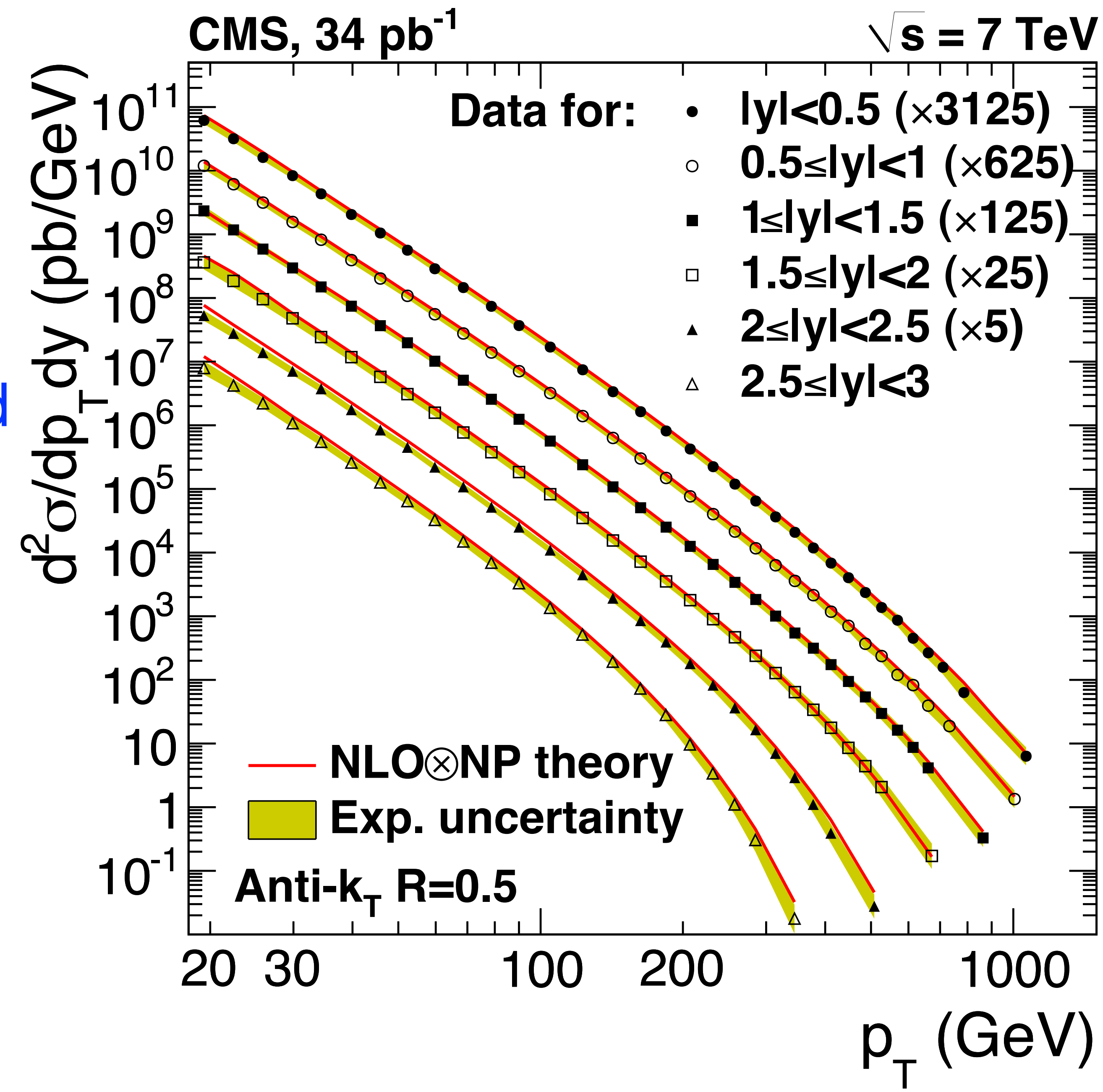
- using anti-k_T PF jets with **R=0.5**
- 34 pb^{-1}
- p_T range from 18 GeV to 1.1 TeV
- 6 rapidity bins, up to |y|=3.0 (the forward region 3.0 < |y| < 5.0 is covered by another, dedicated measurement)

✦ **Unfolding**

- simple bin-by-bin correction using the ansatz method

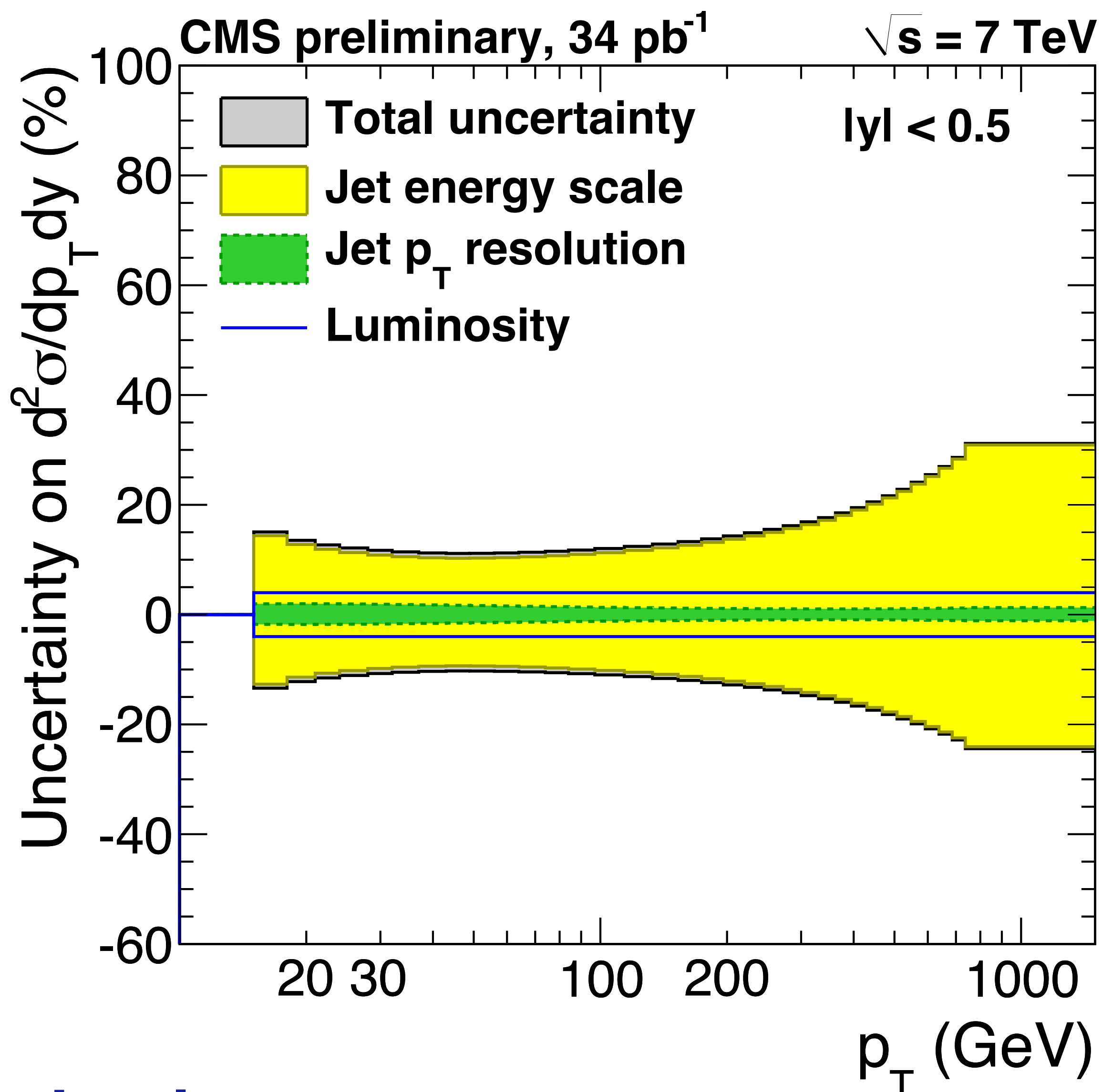
✦ **Theory**

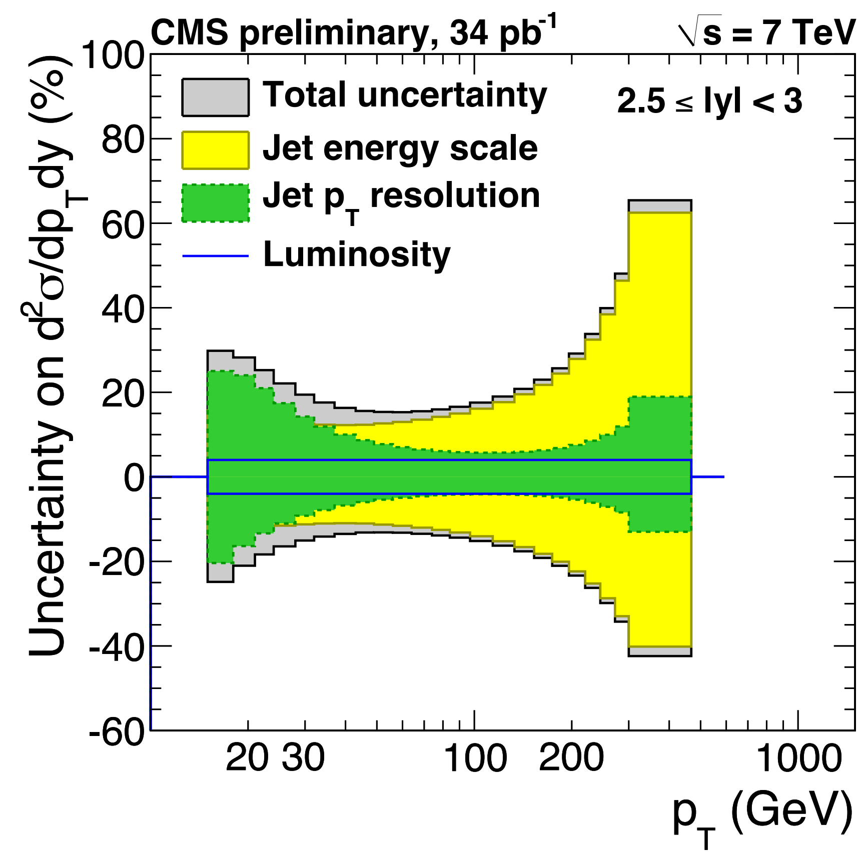
- NLOJet++ (*fastNLO*)

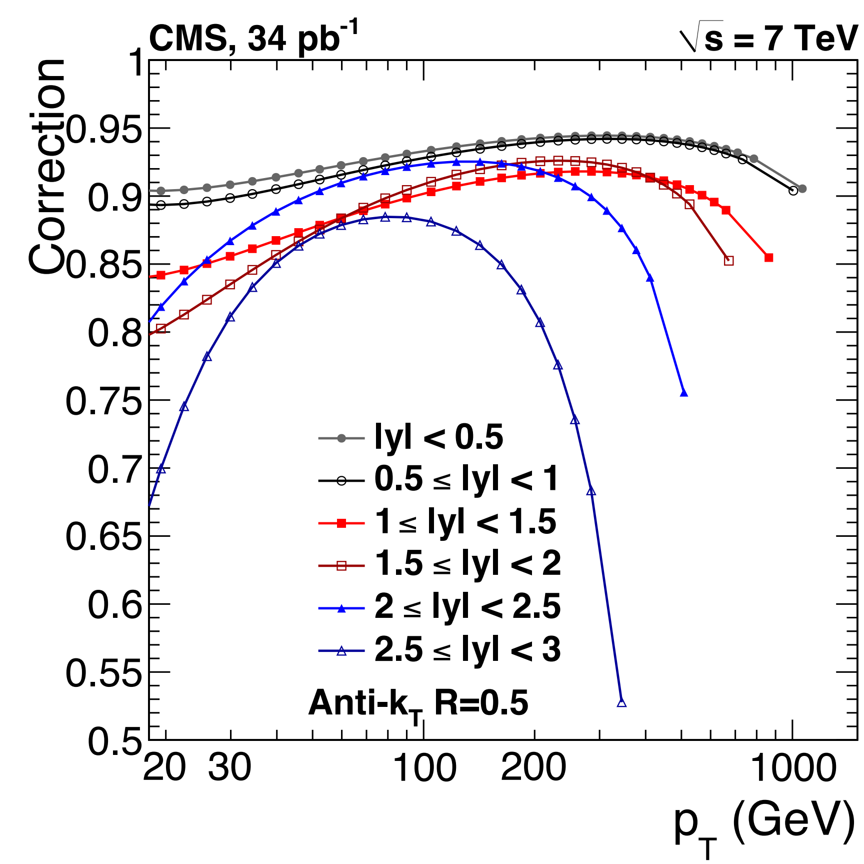


PRL 107 (2011) 132001

Experimental Uncertainties

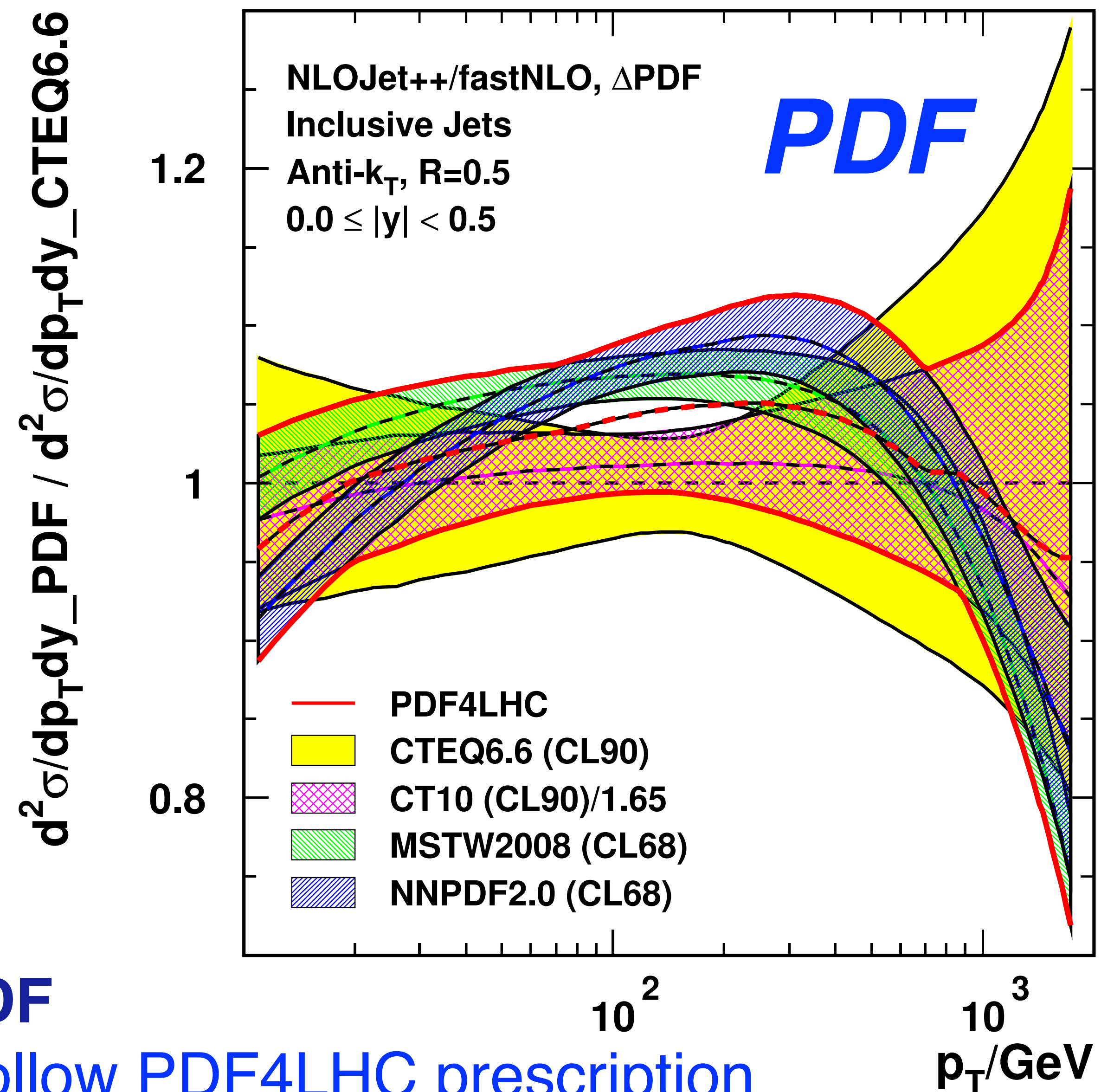


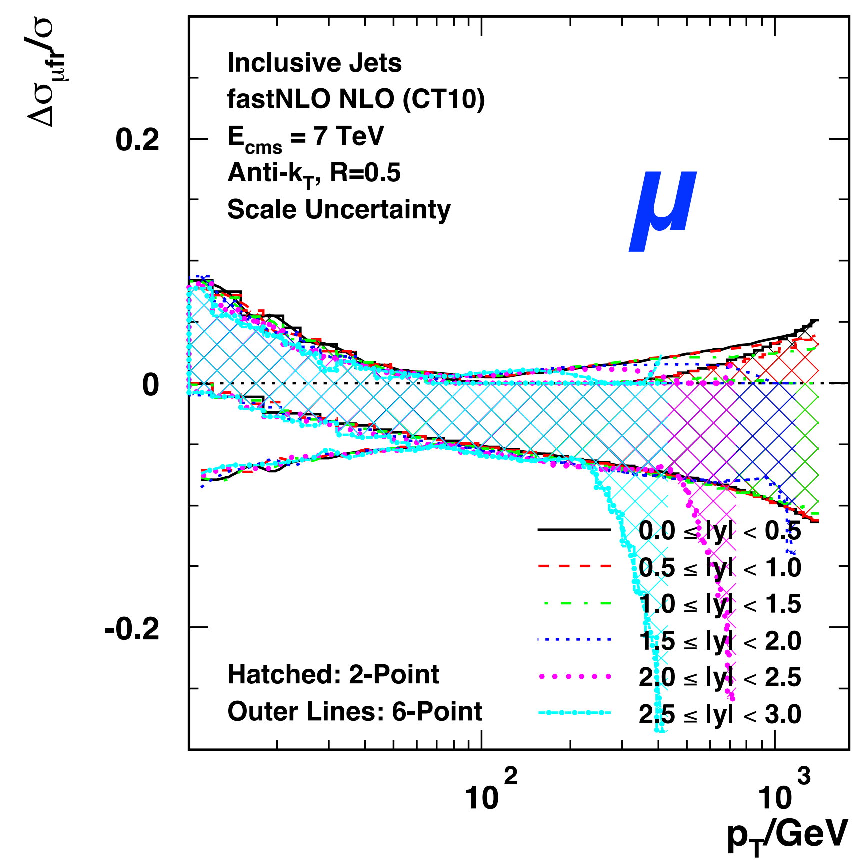


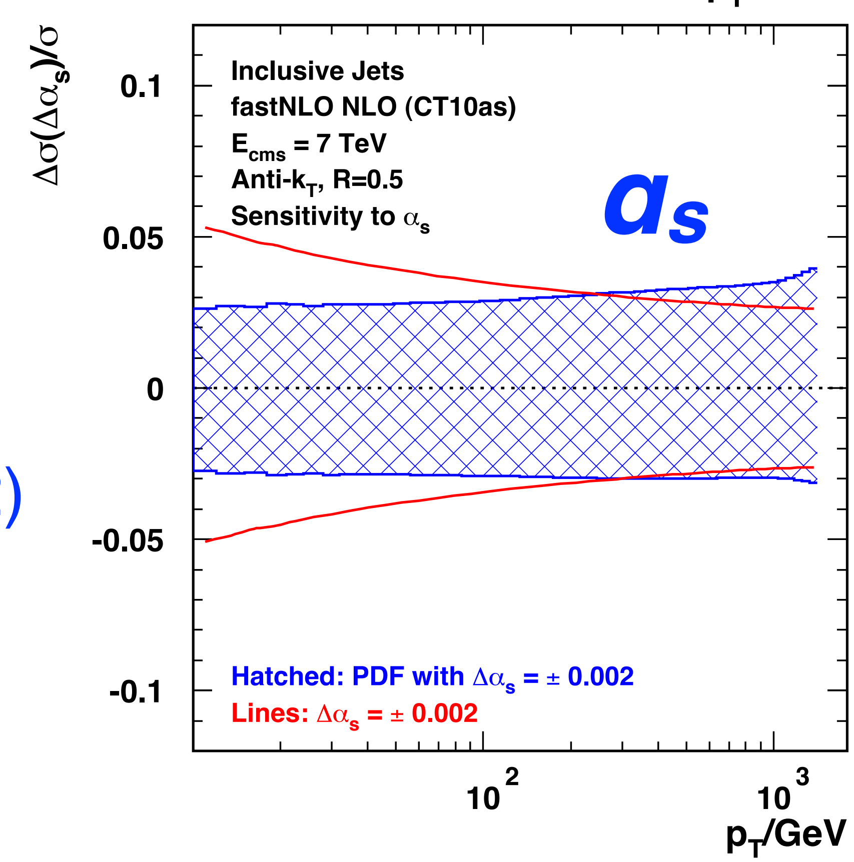


- **JES dominates**
  - falling spectrum: 1% JES uncertainty corresponds to 5-10% cross-section unc.
- **Resolution enters through unsmearing**
  - significant at high rapidity

Theory Uncertainties

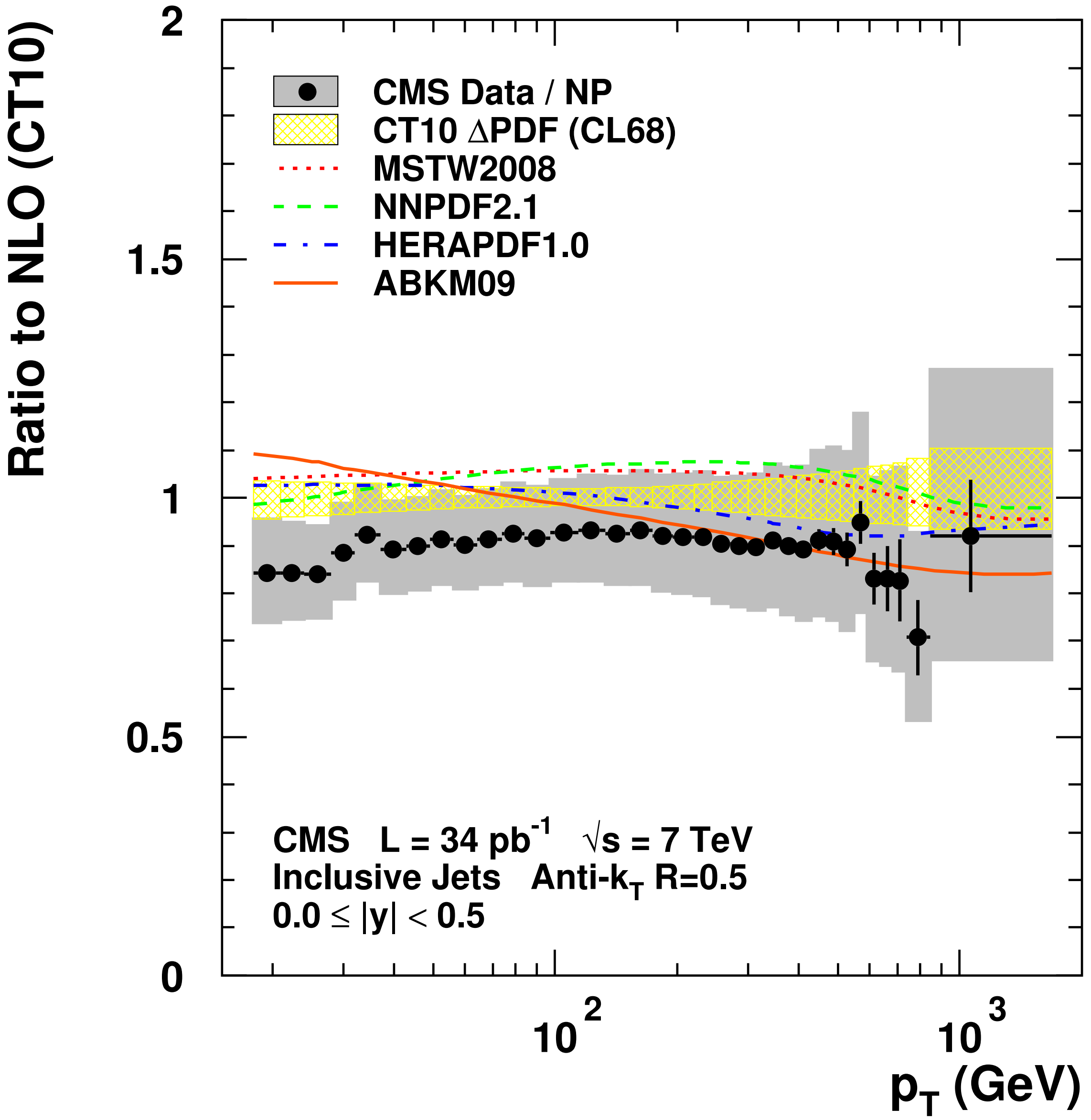


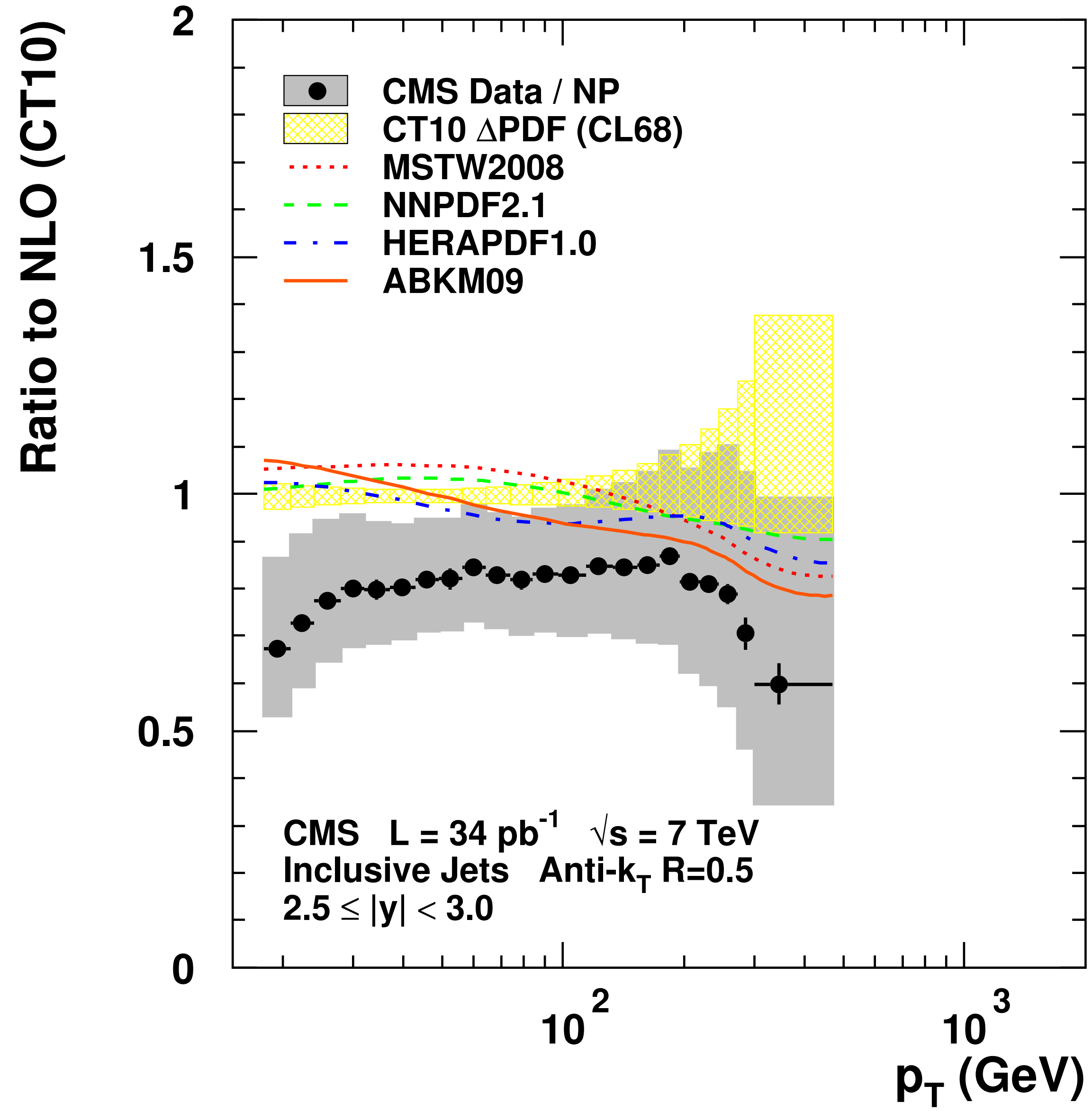




- **PDF**
  - follow PDF4LHC prescription
- **scale ($\mu_R = \mu_F = p_T$)**
  - 6 point variation: (μ_R/p_T, μ_F/p_T) = (0.5, 0.5) ... (1,2)
- **$\Delta\alpha_s$ = ± 0.002 (CT10)**
- **NP correction**
  - estimated with Pythia6 and Herwig++
  - dominant uncertainty at low p_T

PDF Comparisons



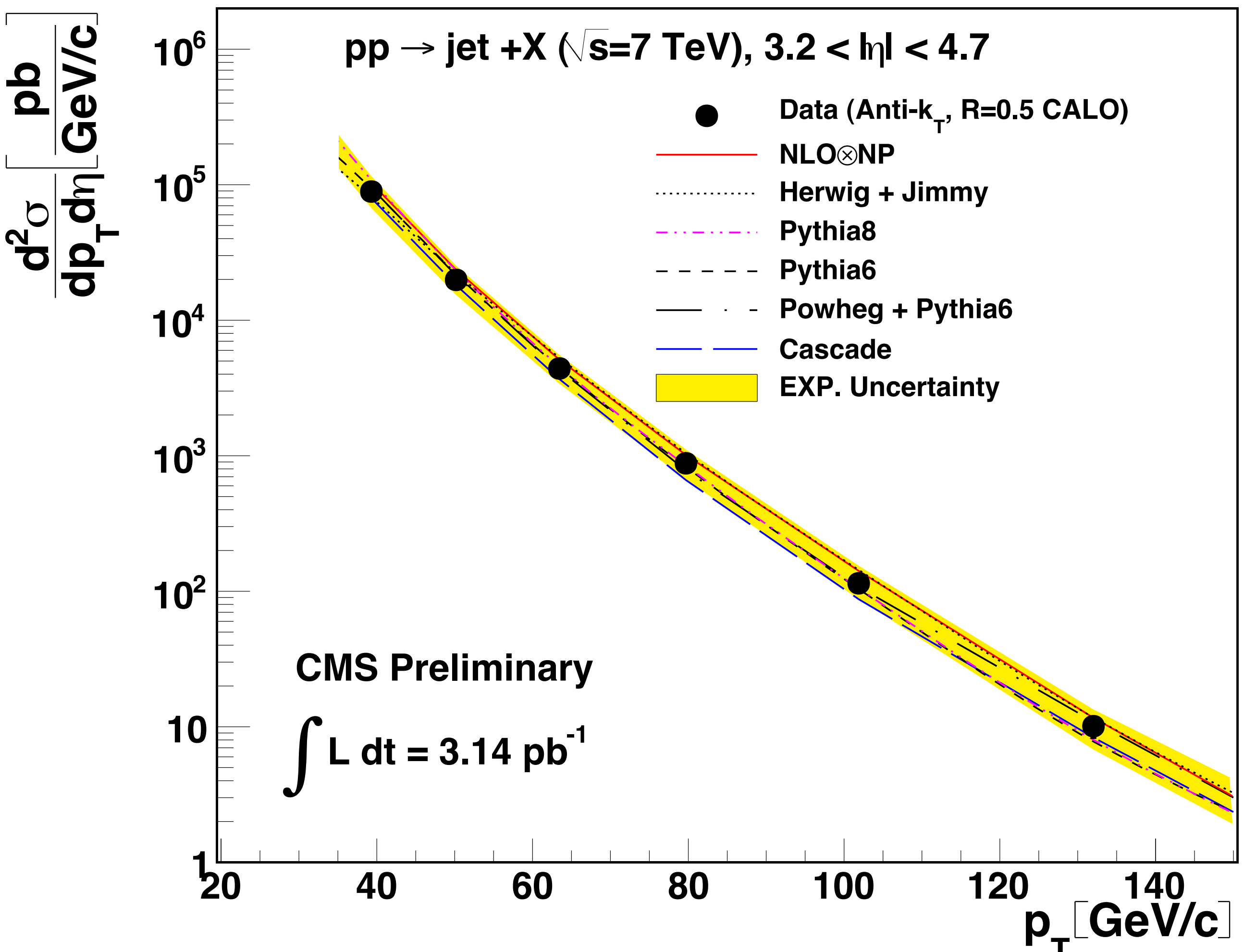


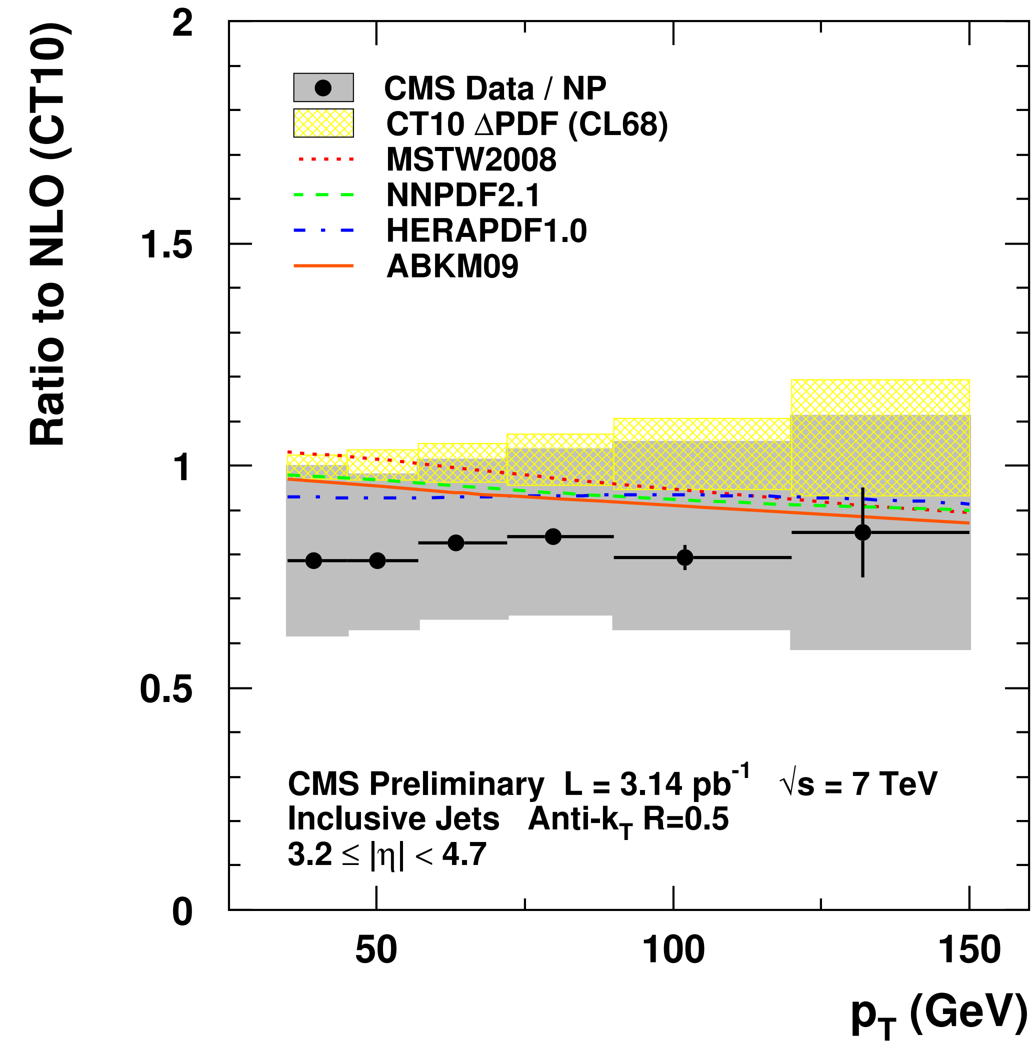
✦ **Comparison with various PDF sets**

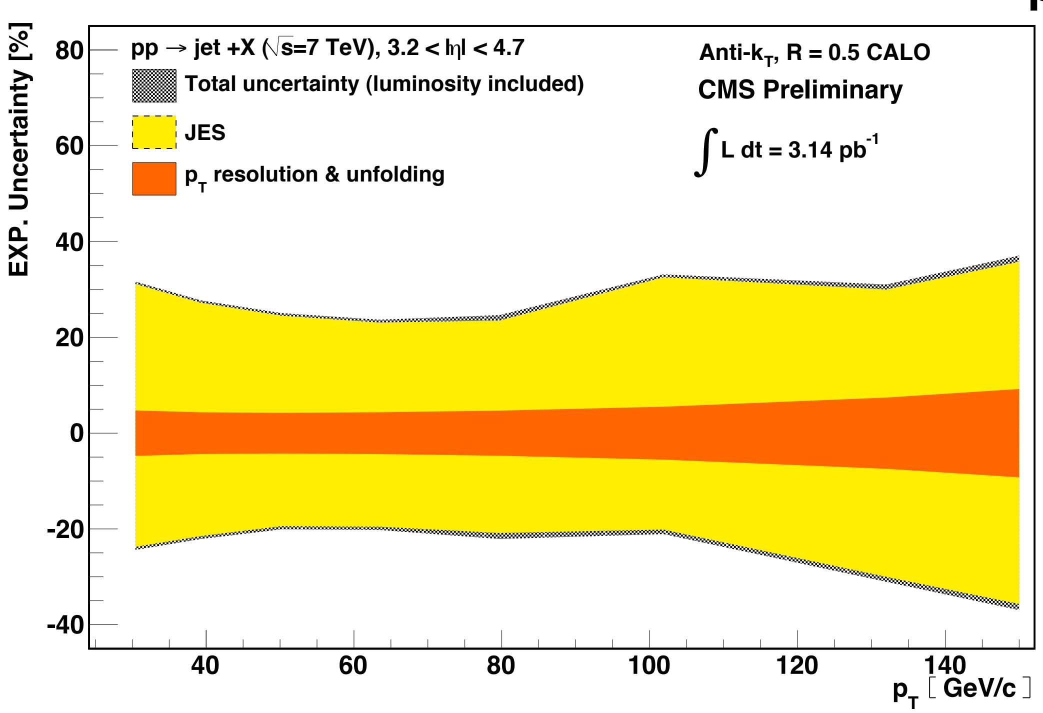
- compatibility with all PDFs in the central rapidity bins
- better agreement at higher jet p_T (> 100 GeV) but NP correction uncertainties large at low p_T
- the agreement slightly worsens in the outer rapidity bins

CMS-NOTE-2011-004

Forward Jets





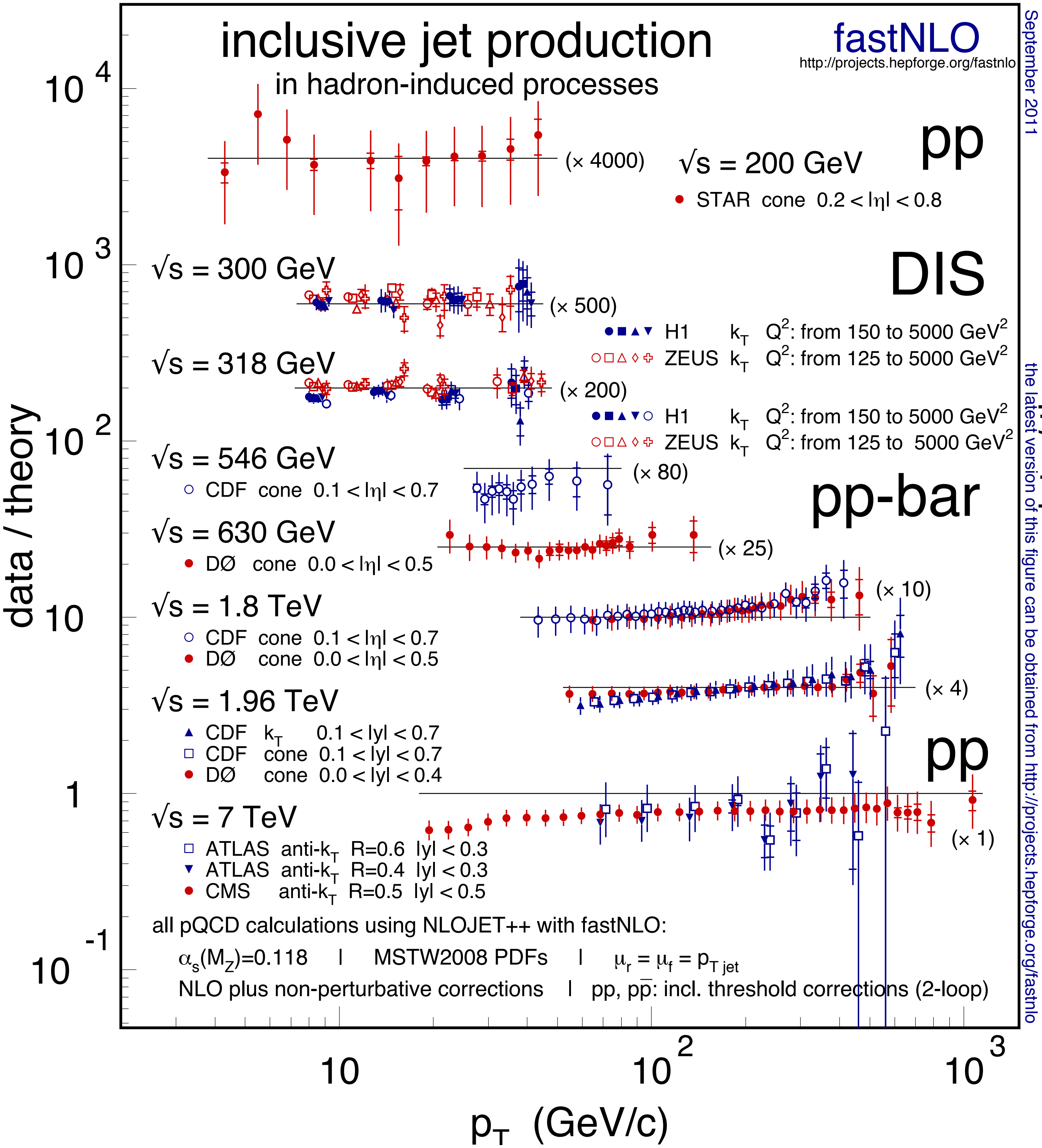


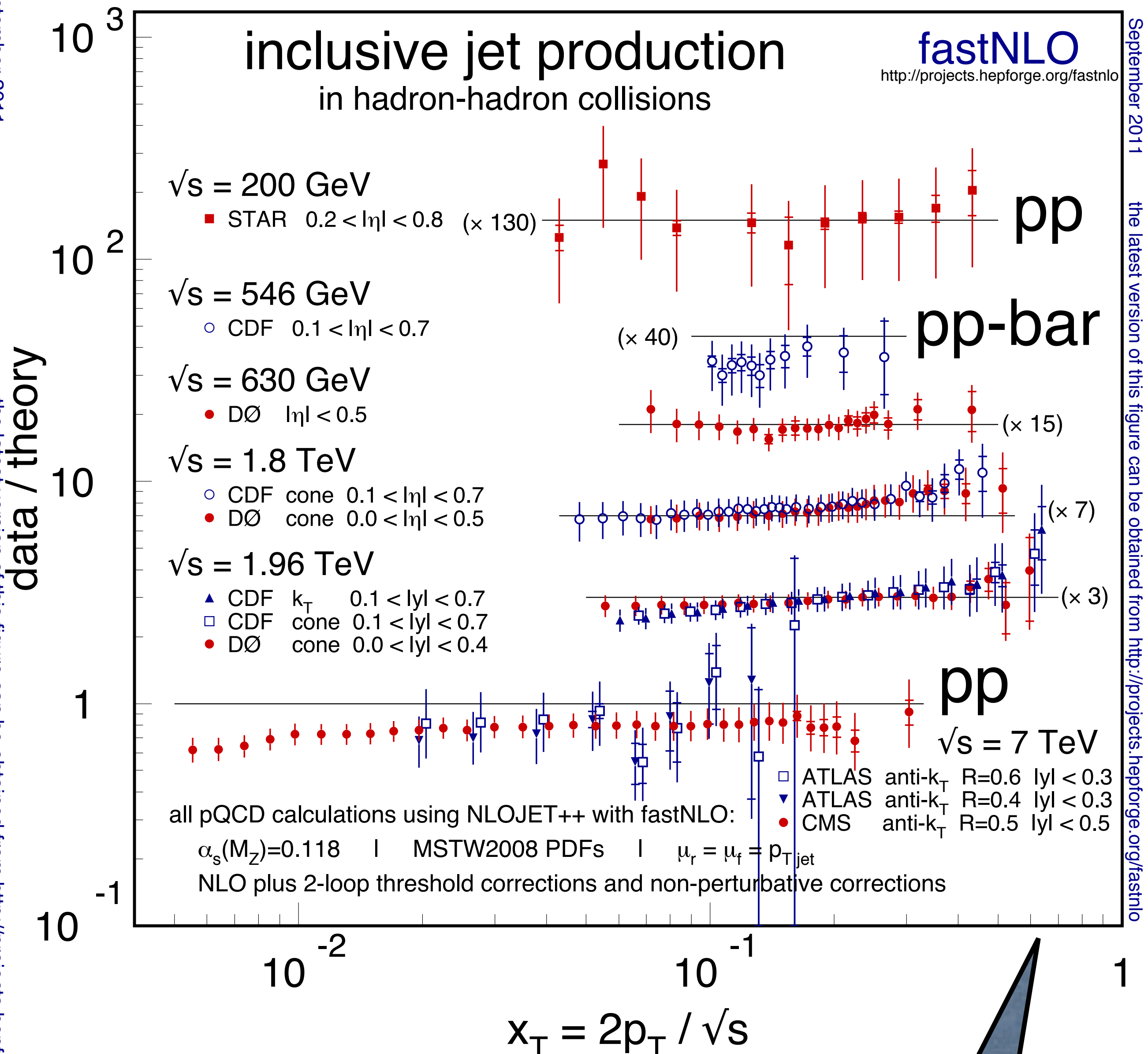
✦ Inclusive forward jet production cross section

- measurement dominated by the JES uncertainty
- good agreement with the MC predictions
- compatible with the NLO prediction

CMS-FWD-10-003

Inclusive Jets: the Big Picture





The 2011 LHC data of $\sim 5\,fb^{-1}$ extend to $x_T \sim 0.6$

arXiv:1109.1310

Dijet Cross Section

✦ **Double-differential inclusive dijet cross section vs dijet invariant mass and |y|$_{max}$**

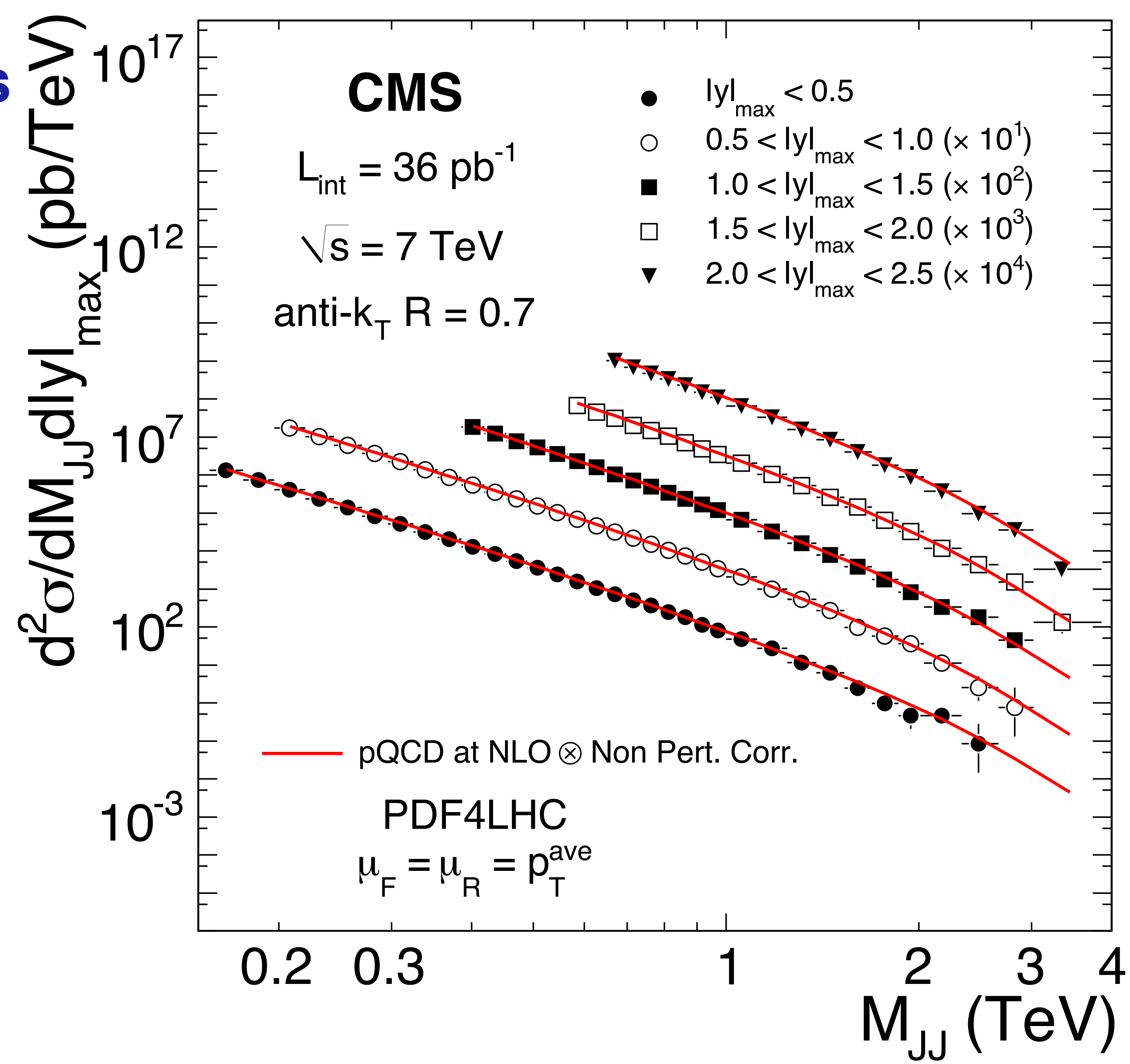
- using anti-k_T PF jets with **R=0.7**
- 36 pb^{-1}
- $p_{T,1}$ > 60 GeV, $p_{T,2}$ > 30 GeV
- mass range from 0.16 to 3.5 TeV
- 5 bins of $|y|_{max}$, up to 2.5

✦ **Unfolding**

- simple bin-by-bin correction using MC smearing

✦ **Theory**

- NLOJet++ (*fastNLO*)



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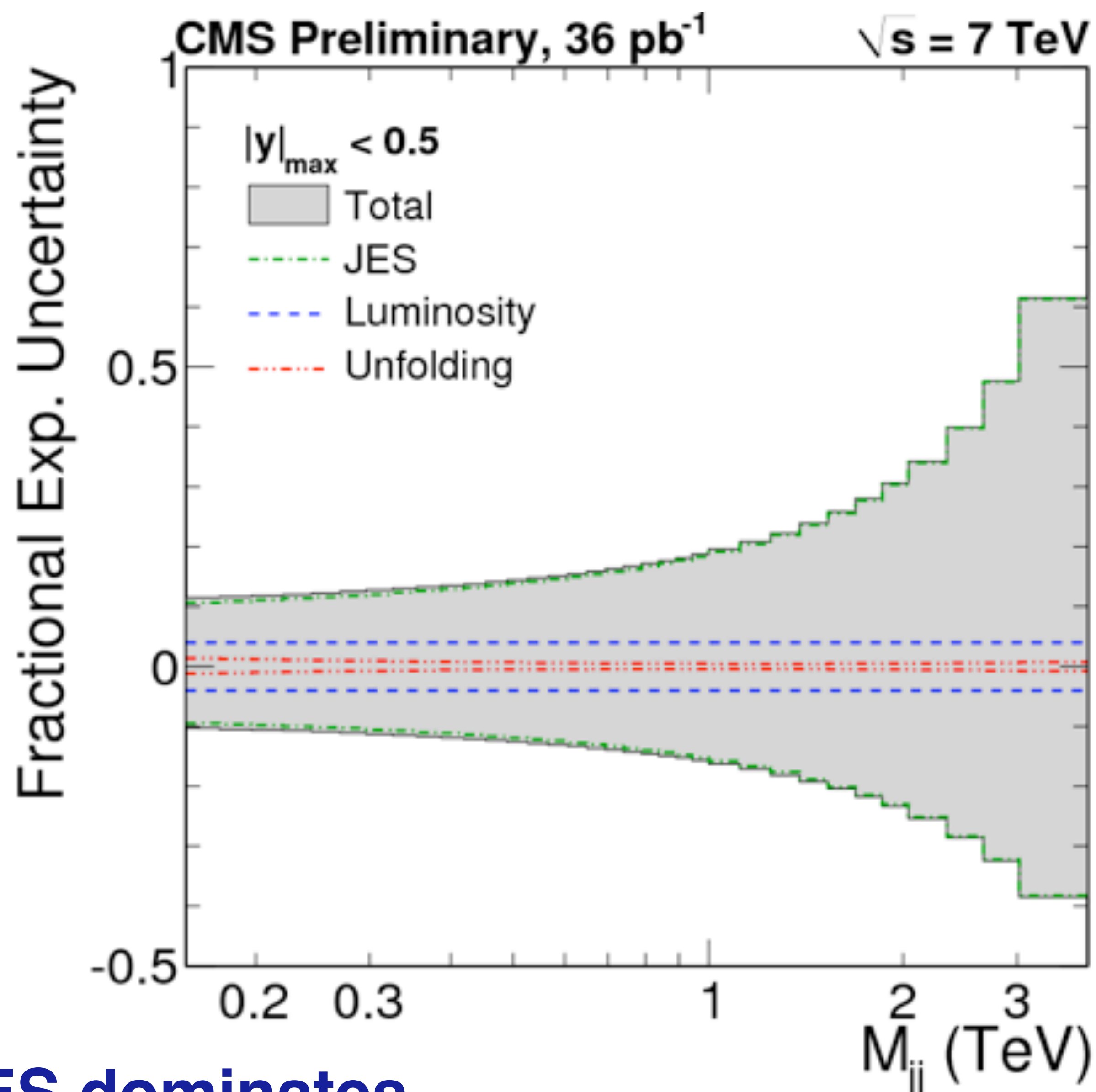
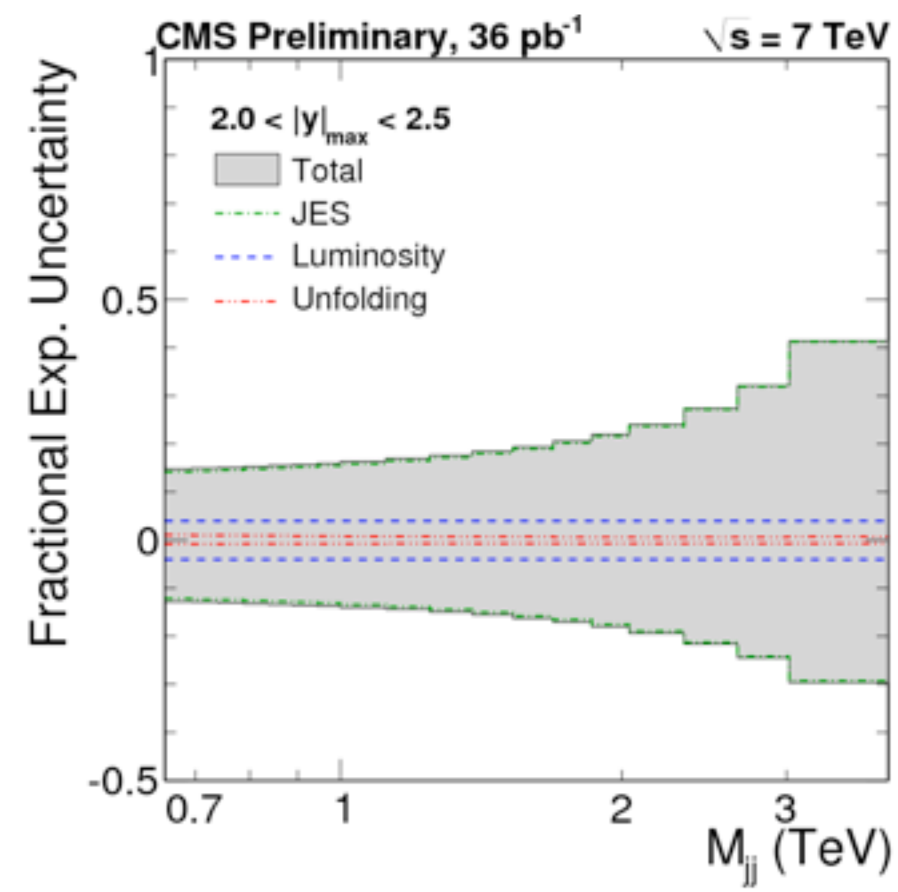
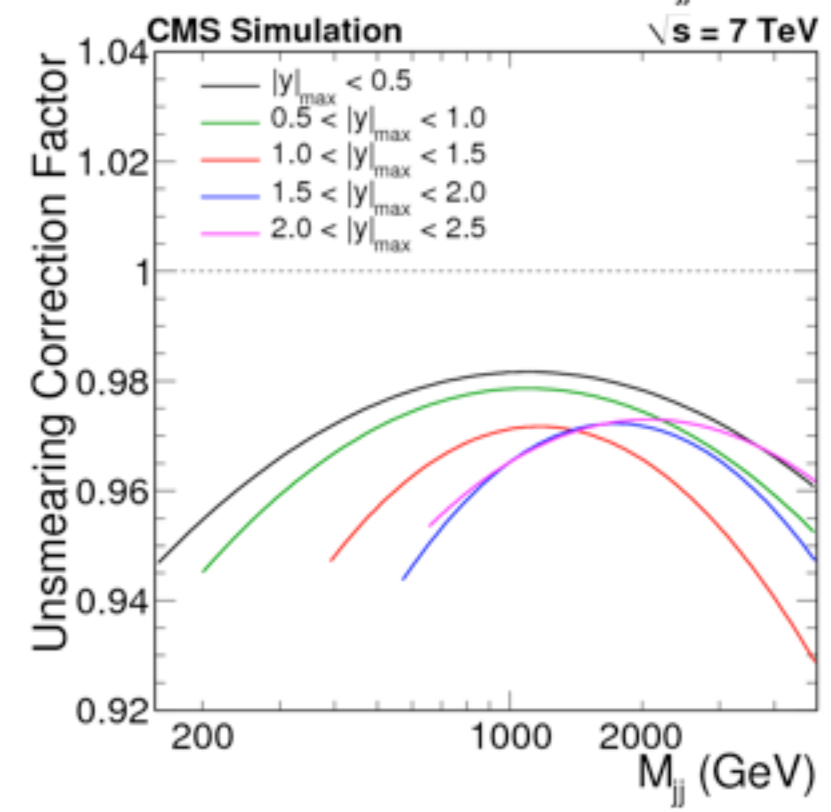
Experimental Uncertainties

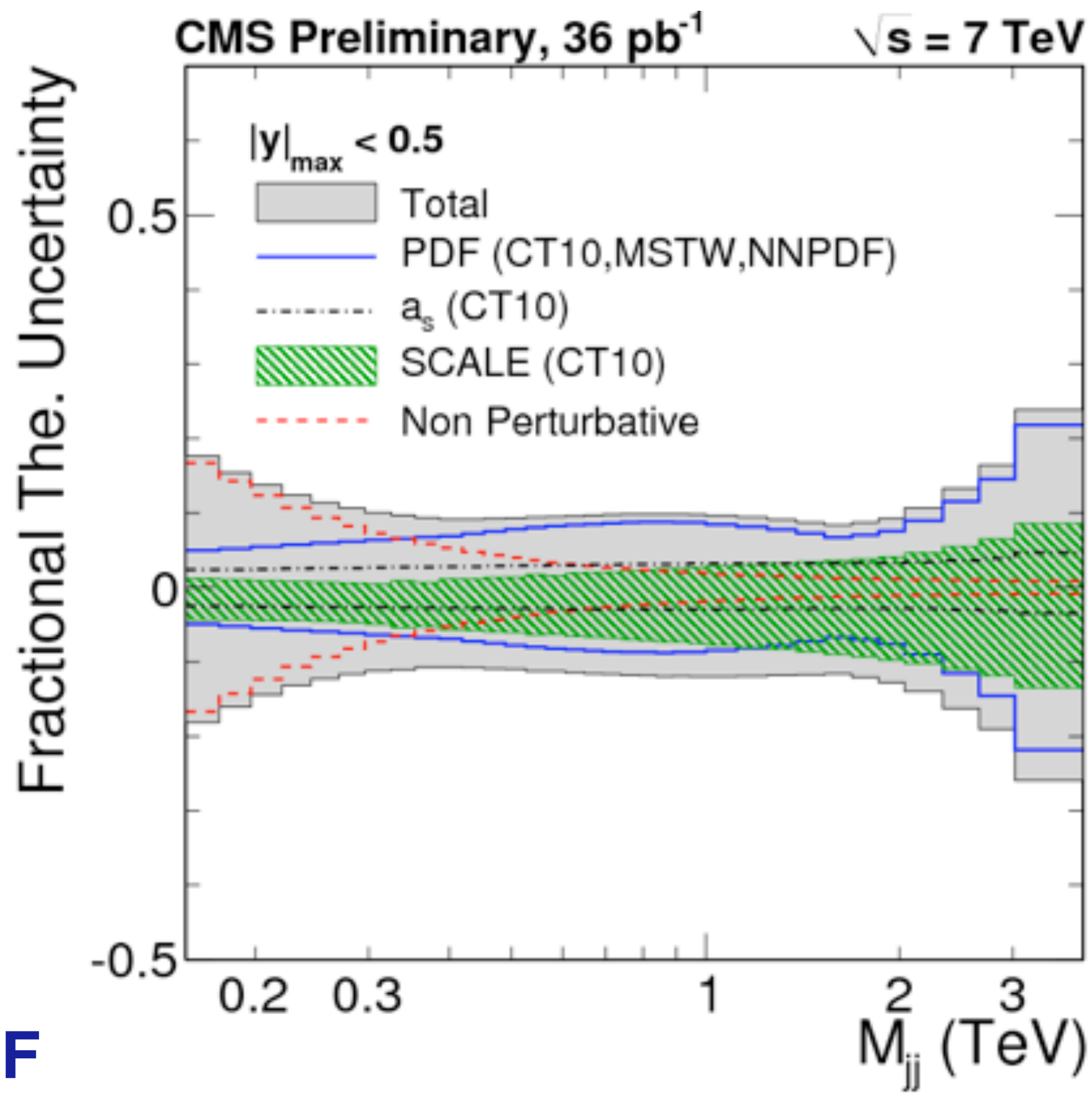


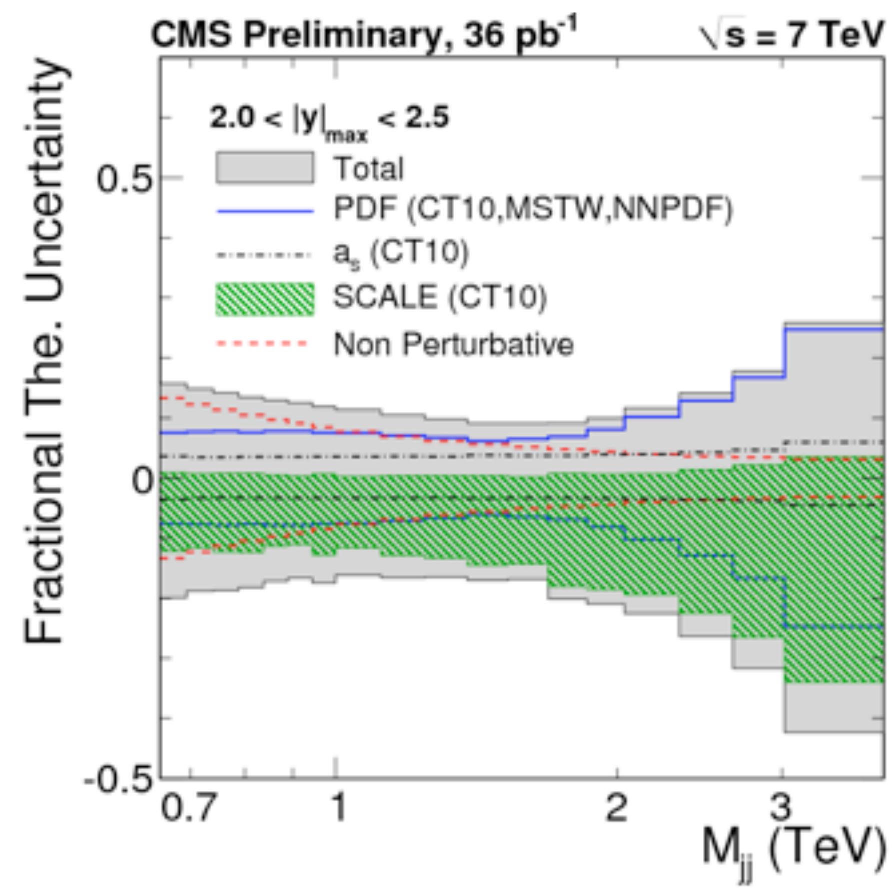


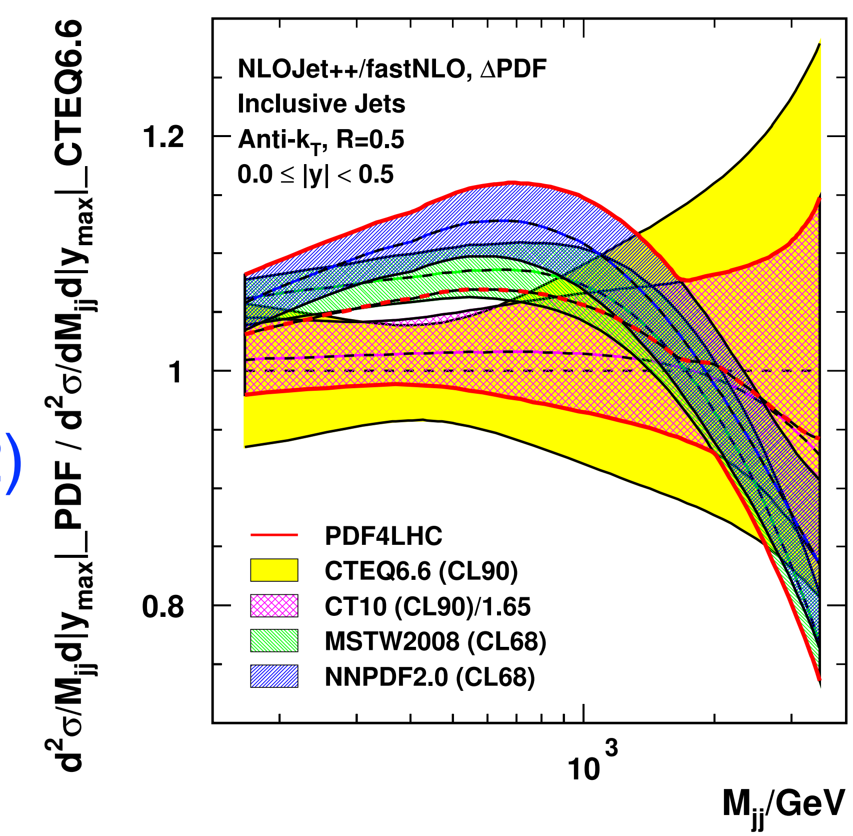


- **JES dominates**
  - falling spectrum: 1% JES uncertainty corresponds to 5-10% cross-section unc.
- **Resolution enters through unsmearing**
  - up to 2-3%

Theory Uncertainties

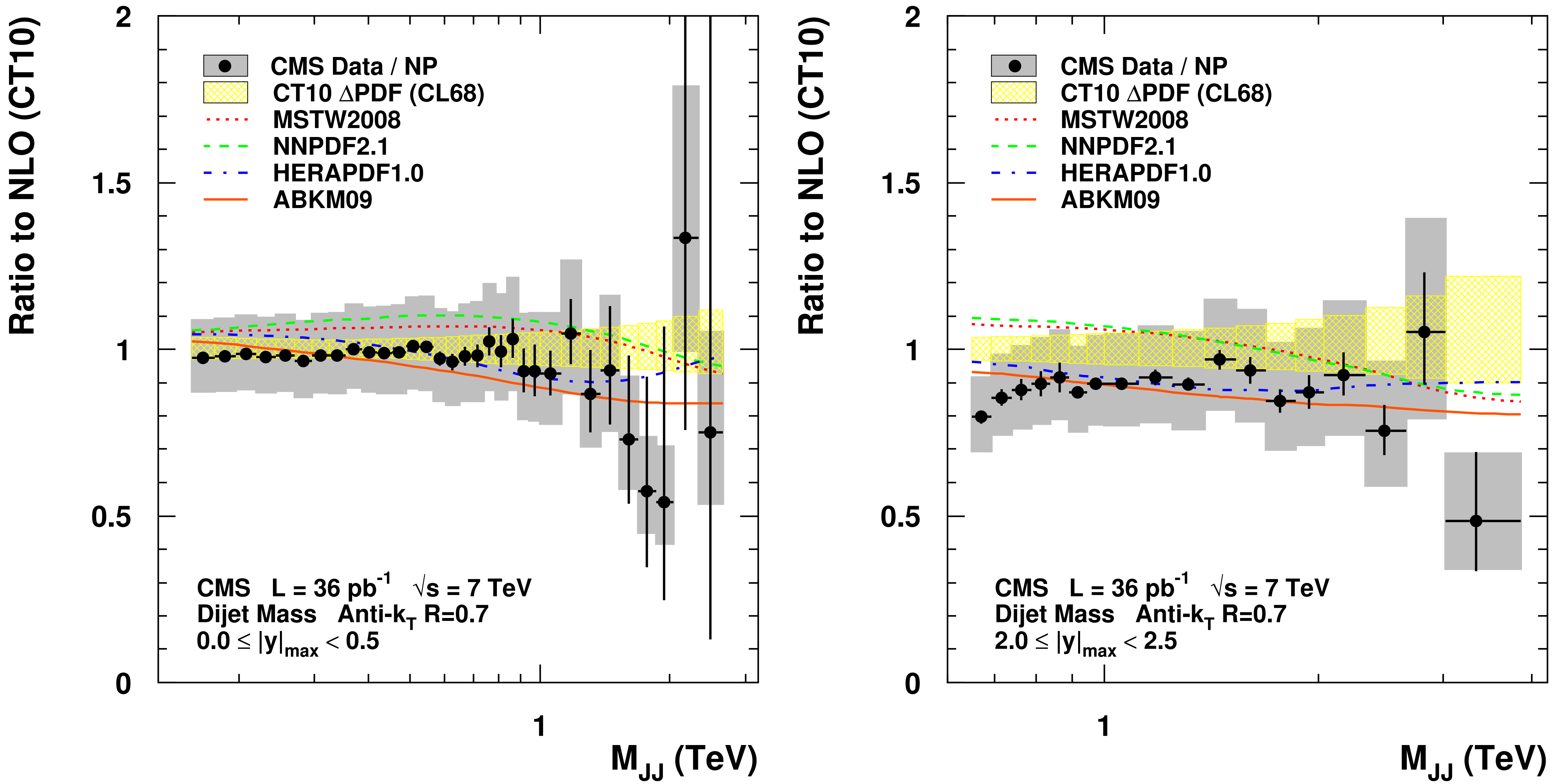






- **PDF**
  - follow PDF4LHC prescription
- **scale ($\mu_R = \mu_F = \langle p_T \rangle$)**
  - 6 point variation: $(\mu_R/\langle p_T \rangle, \mu_F/\langle p_T \rangle) = (0.5, 0.5) \ldots (1,2)$
- **$\Delta\alpha_s = \pm 0.002$ (CT10)**
- **NP correction**
  - estimated with Pythia6 and Herwig++
  - dominant uncertainty at low masses

PDF Comparisons



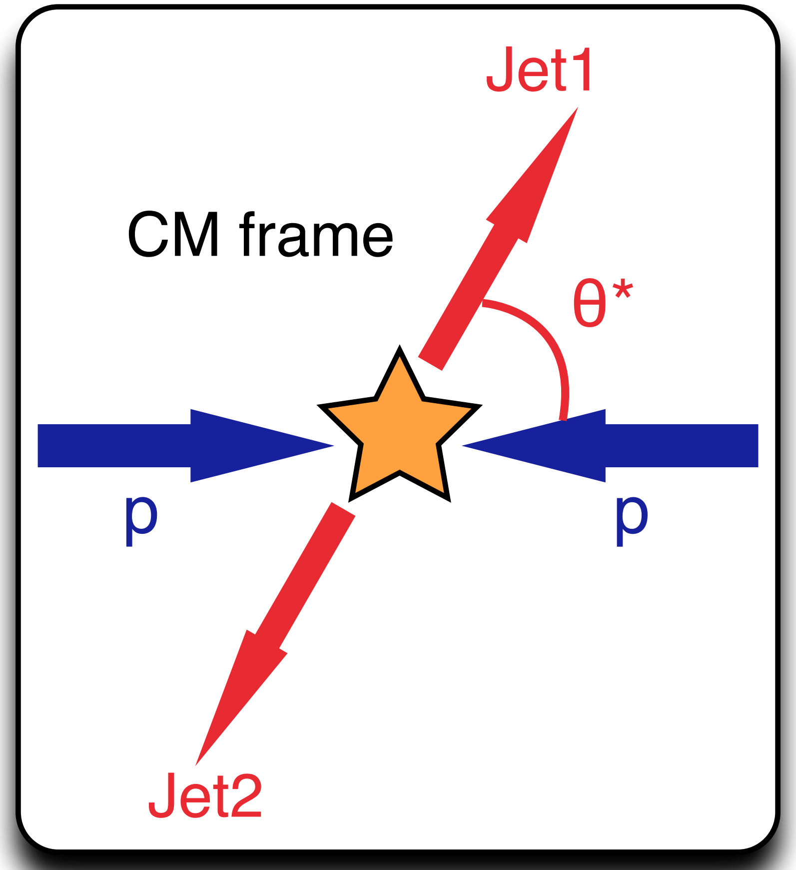
✦ **Comparison to various PDF sets**

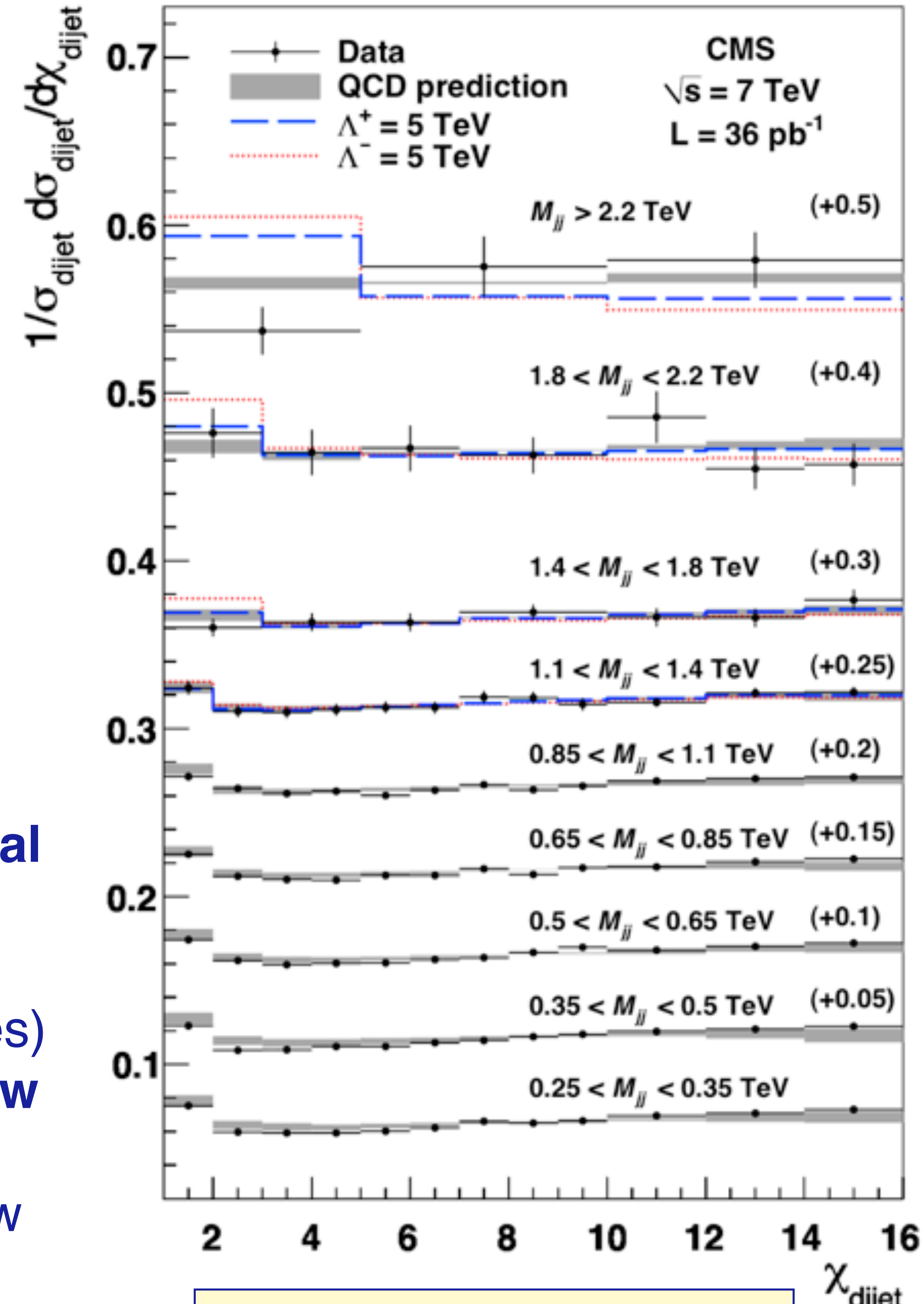
- good agreement with all PDFs in the central rapidity bins
- agreement with CT10, MSTW2008, NNPDF2.1 worsens in the outer rapidity bins but improves for HERAPDF1.0 and ABKM09

CMS-NOTE-2011-004

Dijet Angular Distributions

$$\chi = e^{|y_1 - y_2|} \approx \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$





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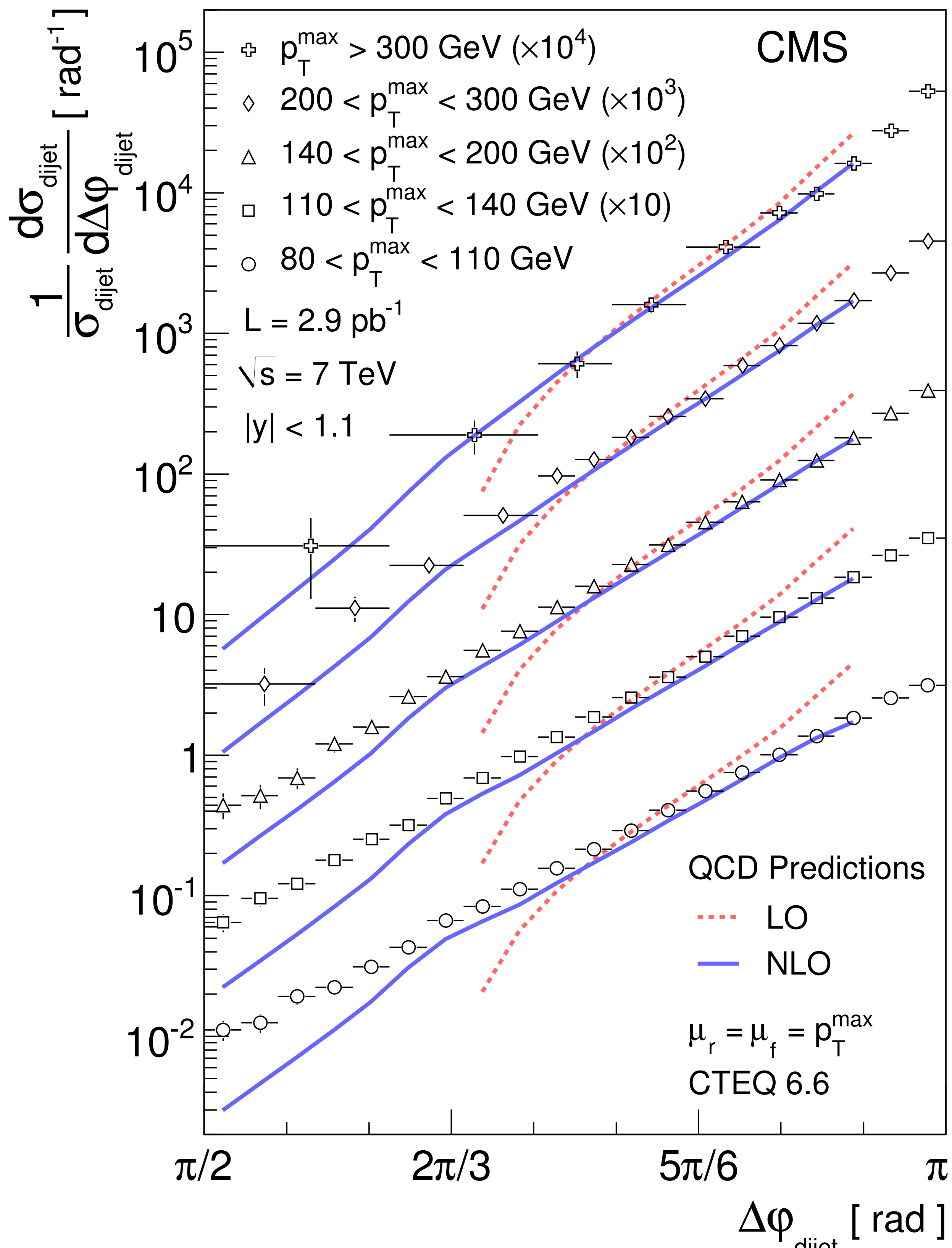
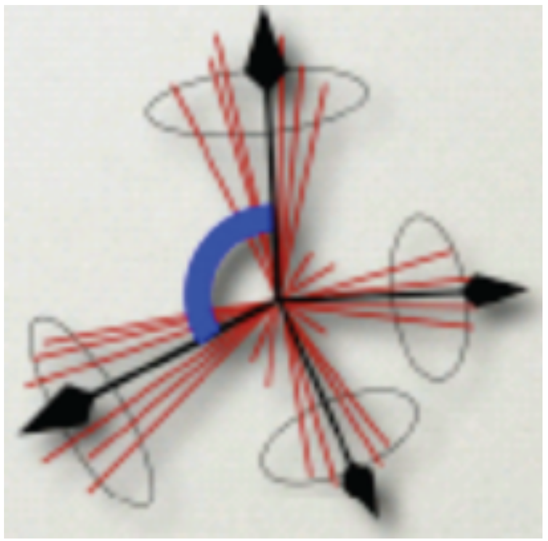
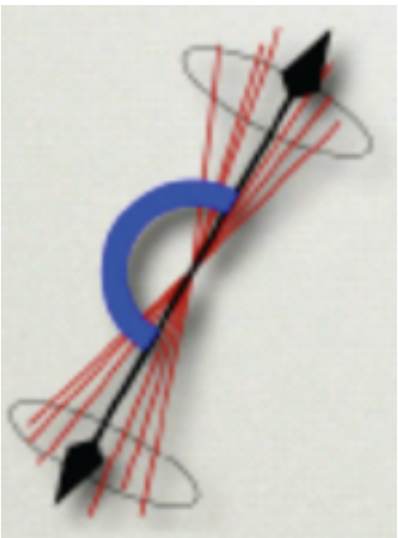
- ✦ **The dijet angular distributions give additional insight to the QCD dynamics**
  - parton-parton scattering in QCD is *t-channel* dominated (Rutherford scattering at small angles)
- ✦ **Stringent test of pQCD and sensitivity to New Physics**
  - contact interactions or resonances would show deviation from QCD at large scattering angles

Dijet Δϕ Distributions (vs NLO)





$$\Delta\phi \sim \frac{\pi}{2}$$



$$\Delta\phi \sim \pi$$

- ✦ **Normalized dijet cross section, as a function of Δϕ**
  - indirect probe of multijet topologies, without explicit reconstruction of additional jets
- ✦ **pQCD @ NLO is necessary to describe the azimuthal decorrelation**

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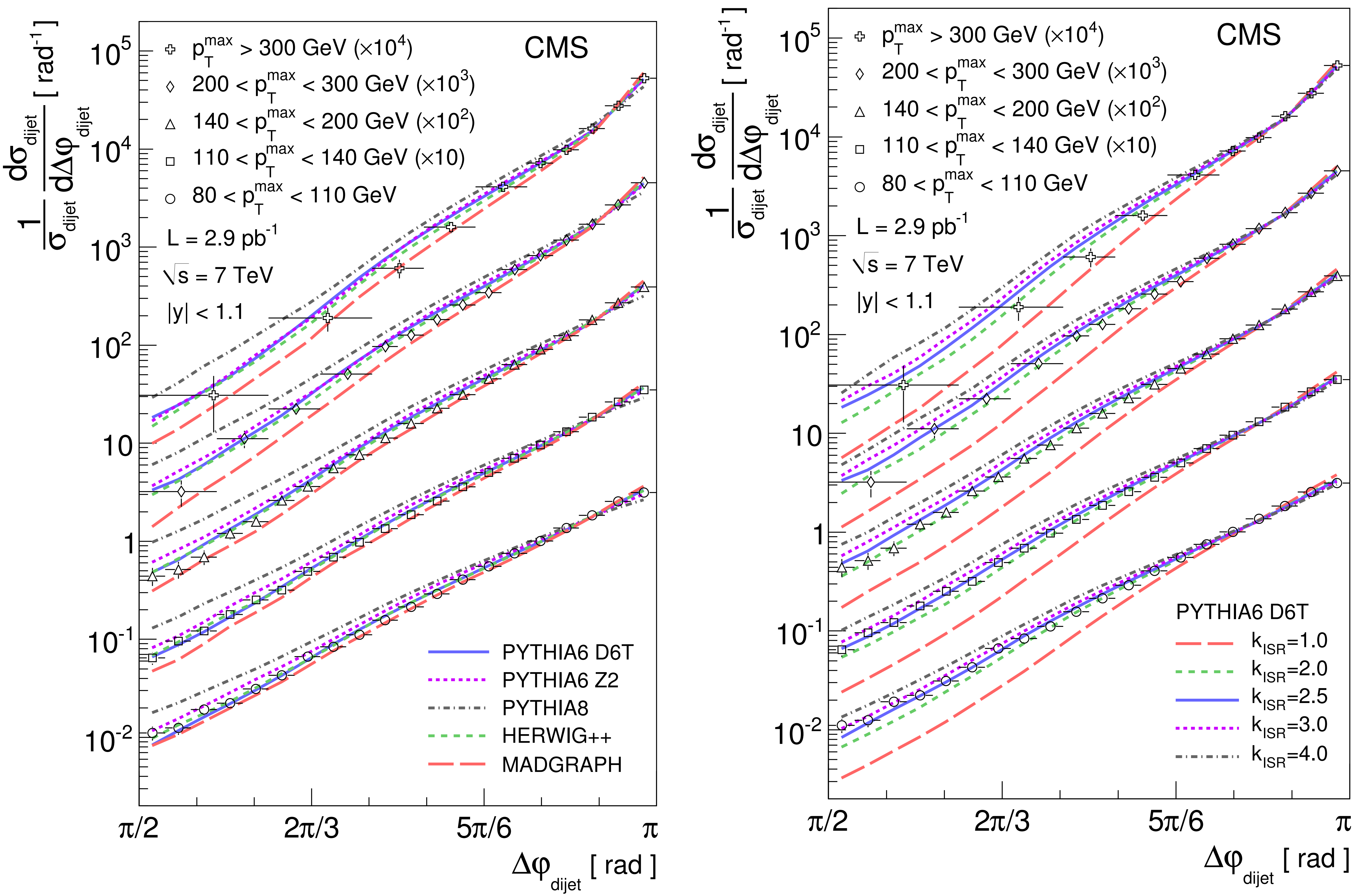
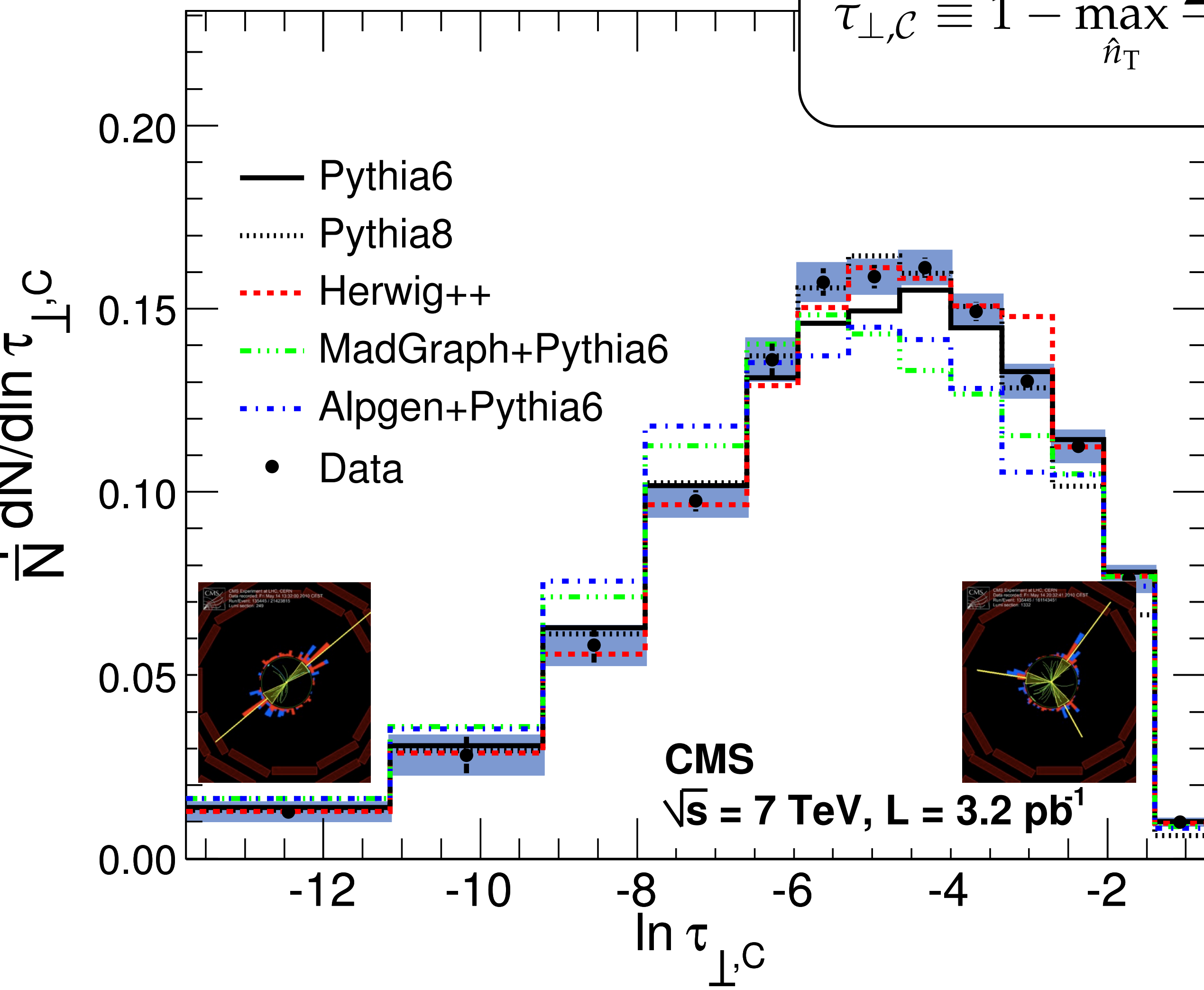
Dijet Δφ Distributions (vs MC generators)

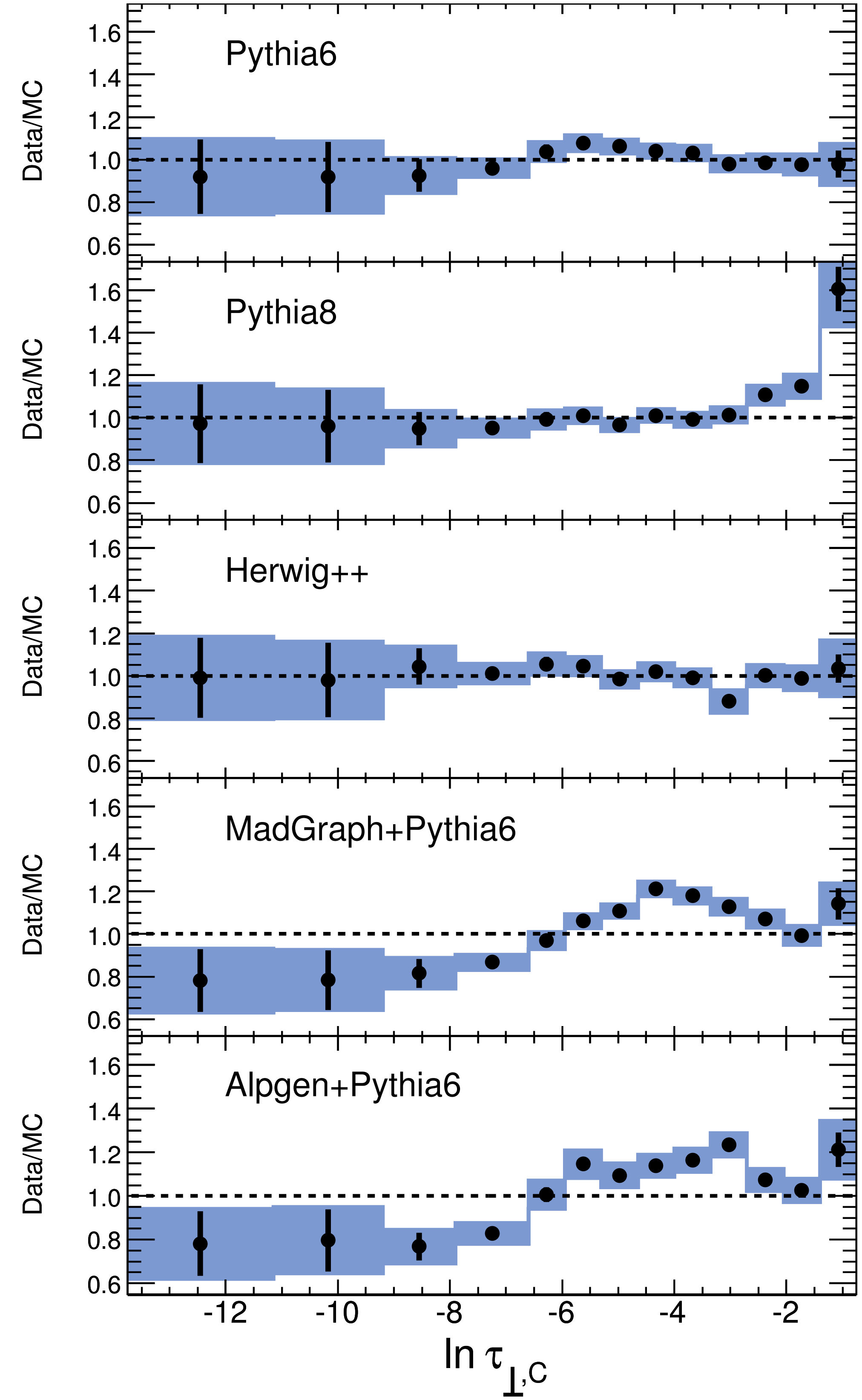


Hadronic Event Shapes

Central Transverse Thrust

$$\tau_{\perp,\mathcal{C}} \equiv 1 - \max_{\hat{n}_\mathrm{T}} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \hat{n}_\mathrm{T}|}{\sum_i p_{\perp,i}}$$





- ✦ **Event-shape variables**
  - central transverse thrust
  - measured in bins of the leading jet p_T
  - probe QCD radiative processes
  - sensitive to 2j and 3j topologies
- ✦ **Sensitive to the MC generator modeling**

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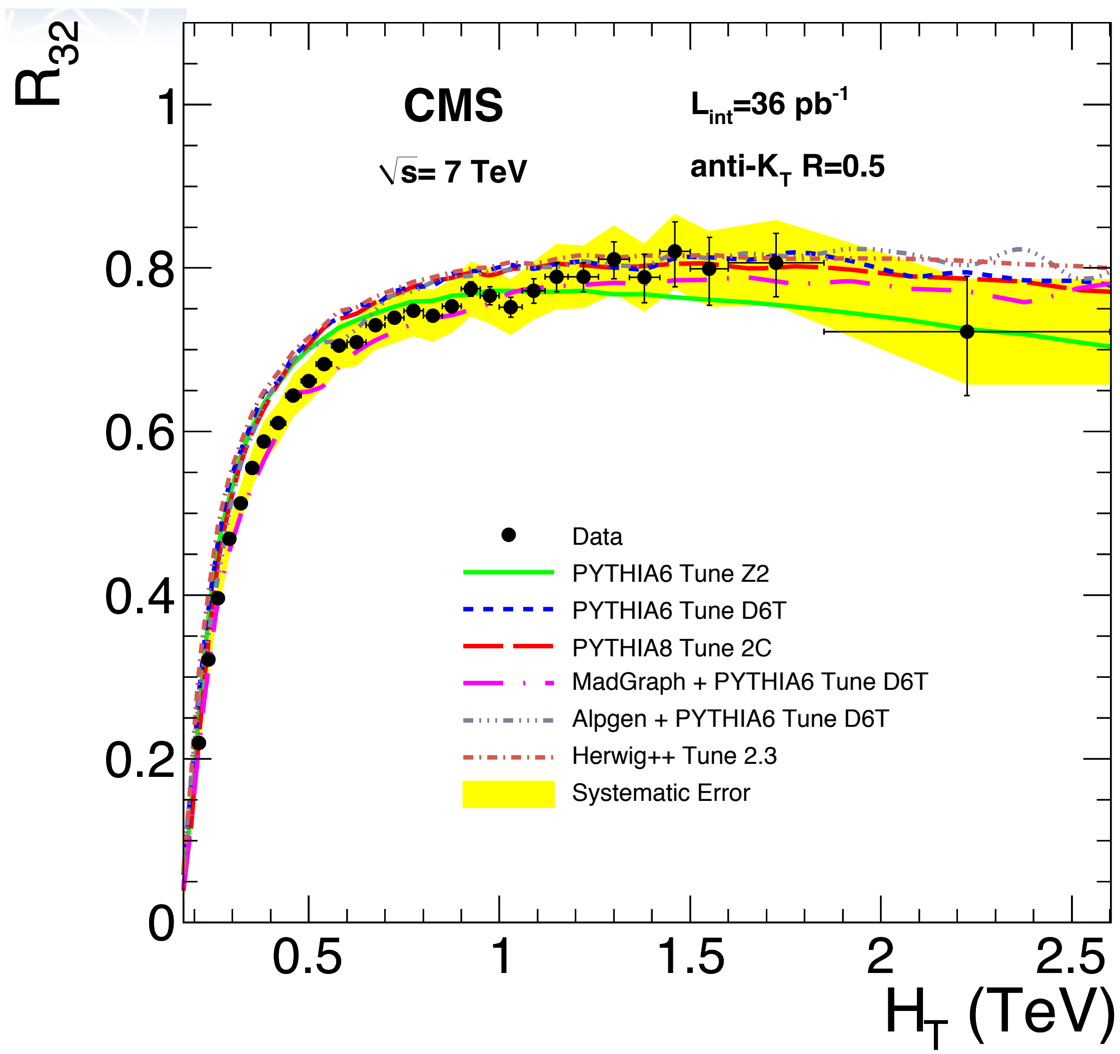
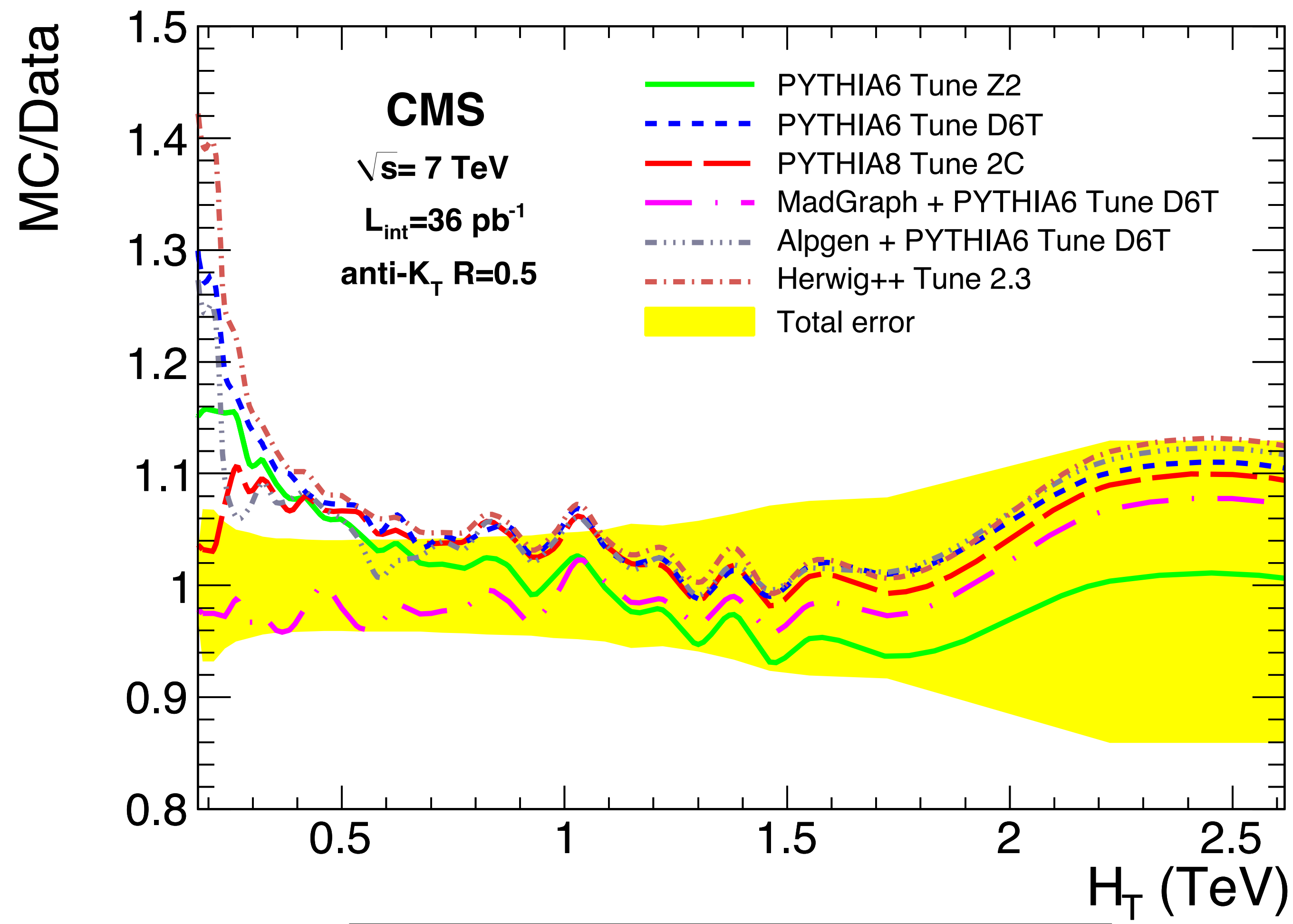
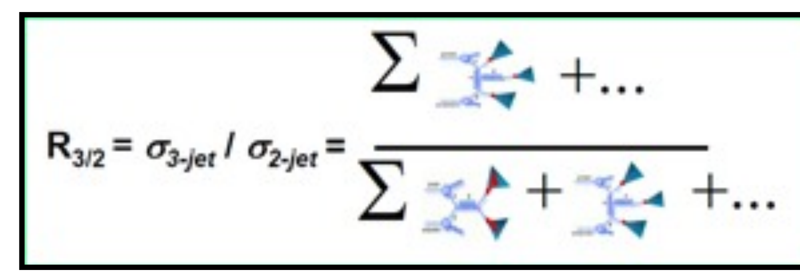
3j/2j Cross-Section Ratio







- **Ratio of cross sections (3j/2j), vs H_T**
  - insensitive to many experimental uncertainties
  - the NLO calculation for the given setup is affected by large scale uncertainties
  - can be used for the α_S measurement (in a different setup)
- **Comparison to QCD MC generators**
  - all generators agree for $H_T > 0.7$ TeV with some deviation at low values
  - the ME predictions are sensitive to the choice of the jet p_T matching threshold

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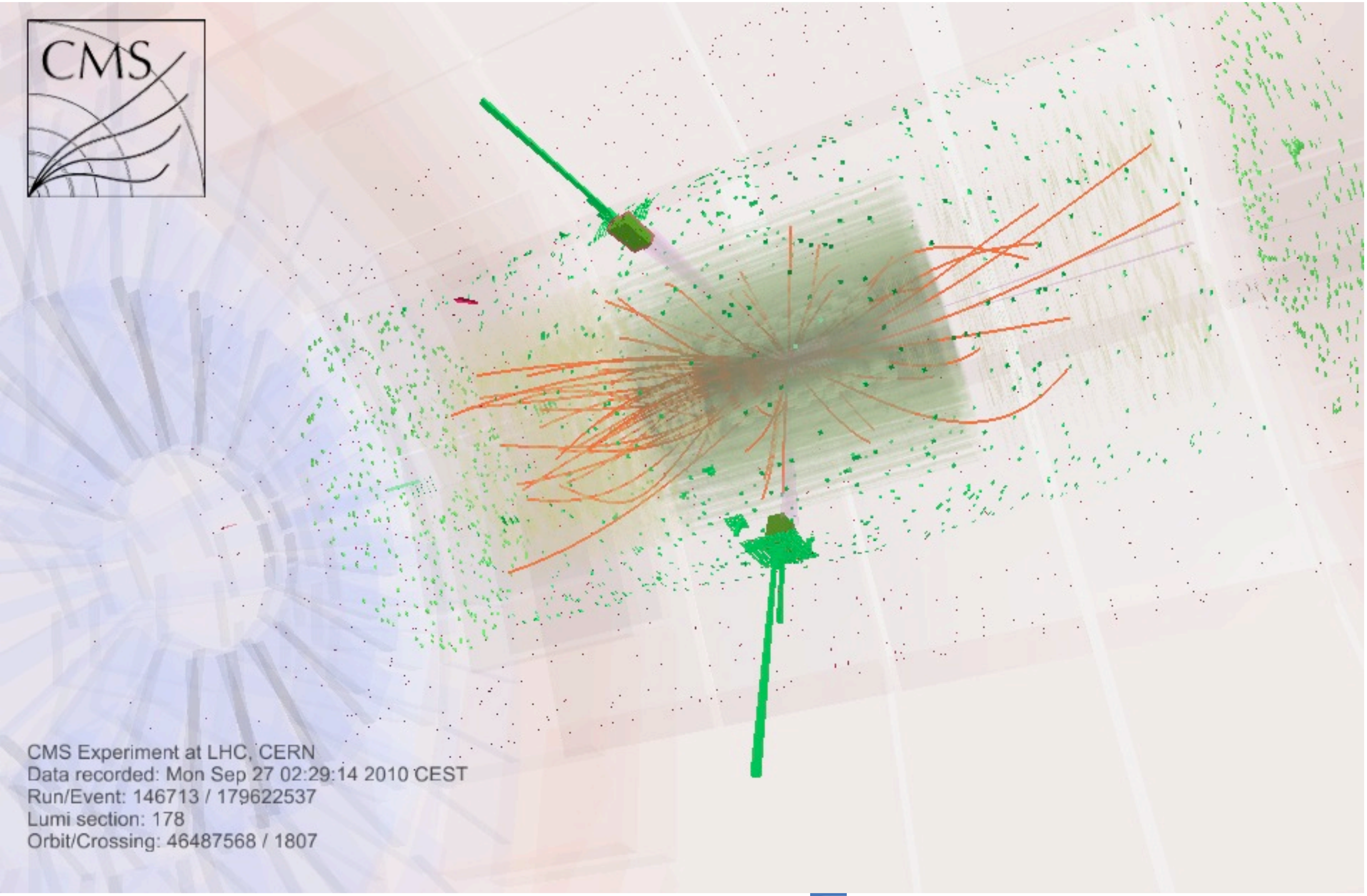
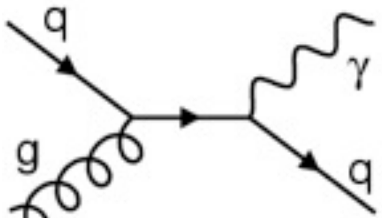
Measurements with Photons

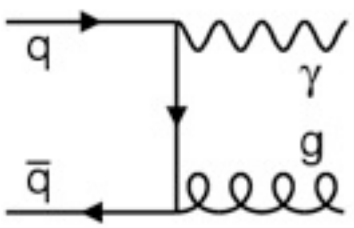

CMS
CMS Experiment at LHC, CERN
Data recorded: Mon Sep 27 02:29:14 2010 CEST
Run/Event: 146713 / 179622537
Lumi section: 178
Orbit/Crossing: 46487568 / 1807

Direct Photon Production

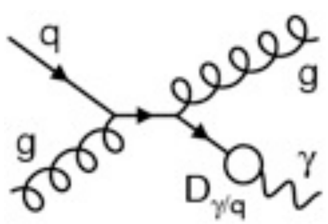
Compton

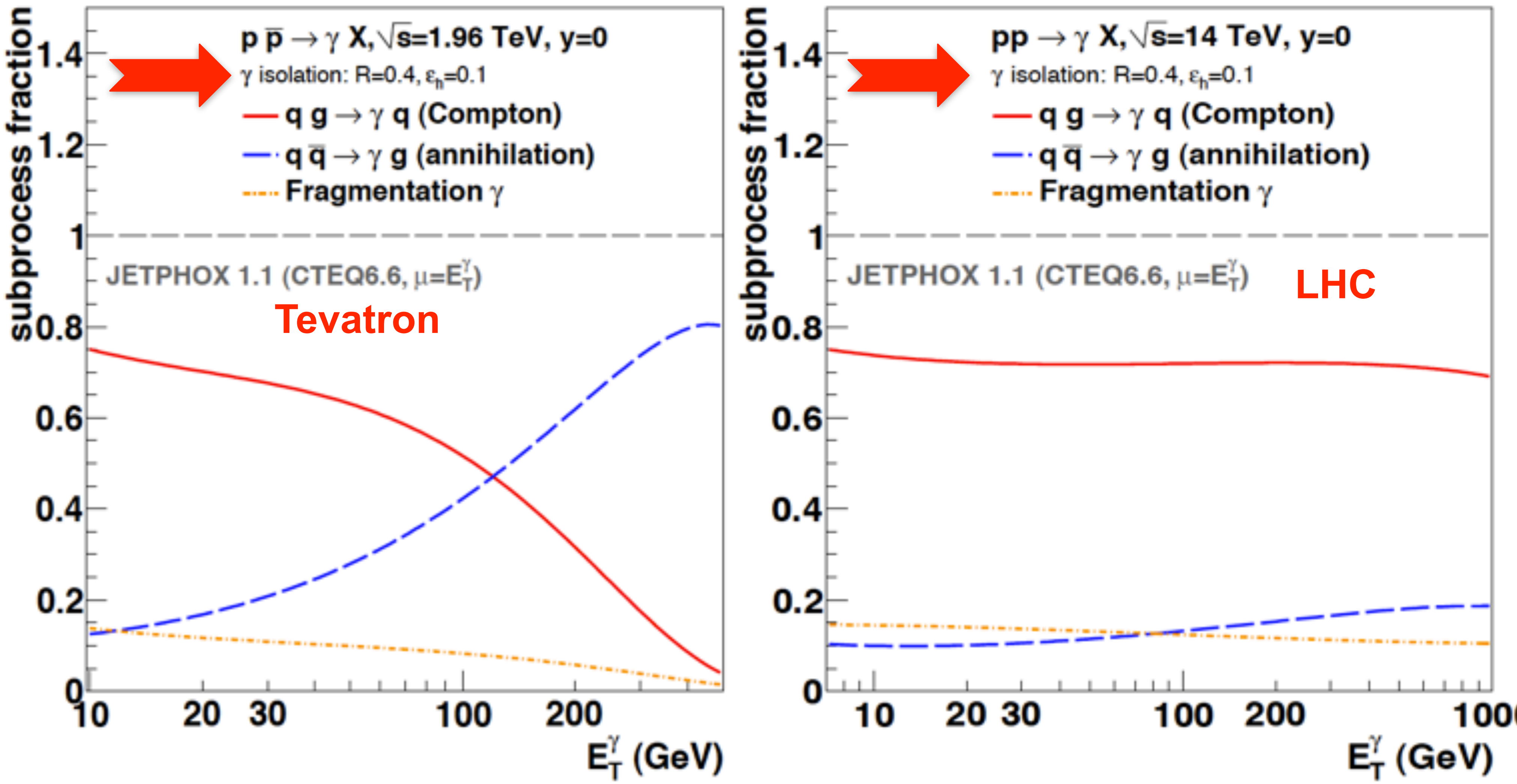


Annihilation



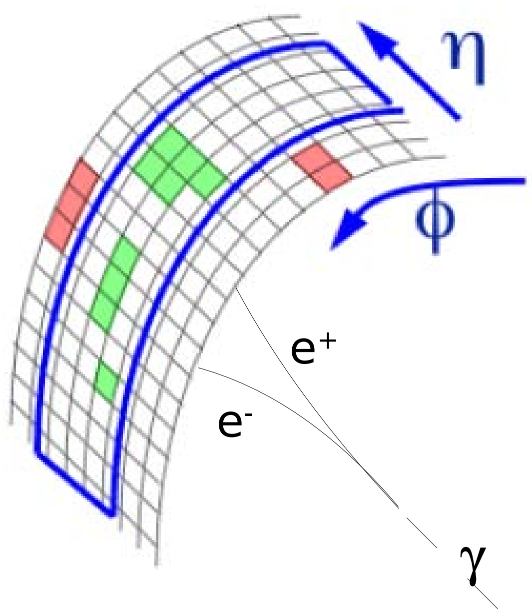
Fragmentation



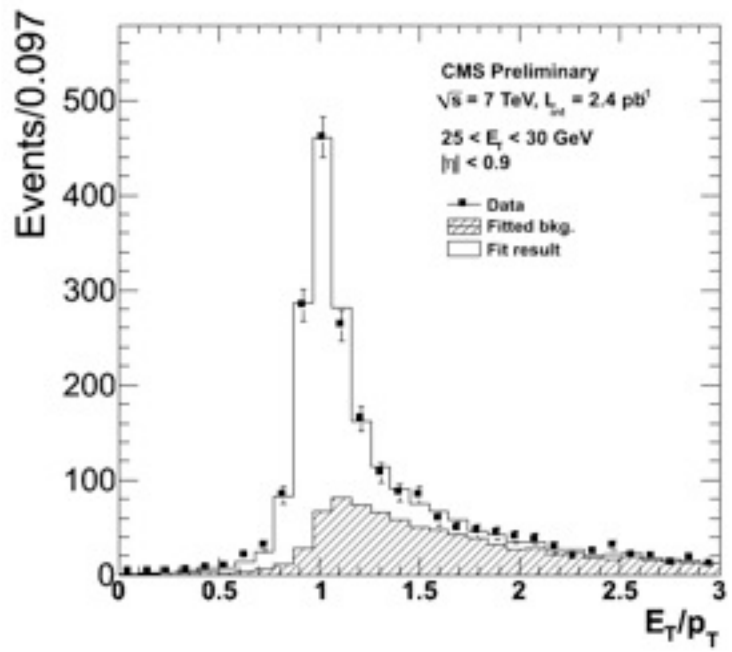


- **Production mechanisms**
  - quark-gluon Compton scattering (dominant at LHC)
  - quark-antiquark annihilation
  - fragmentation of colored partons (greatly suppressed by isolation requirements)
- **Test of pQCD**
  - NLO calculations
  - sensitive to gluon PDF

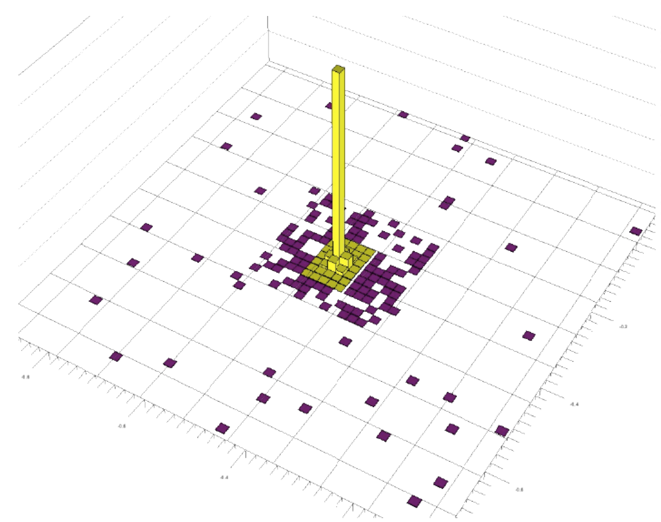
Photon Signal Extraction

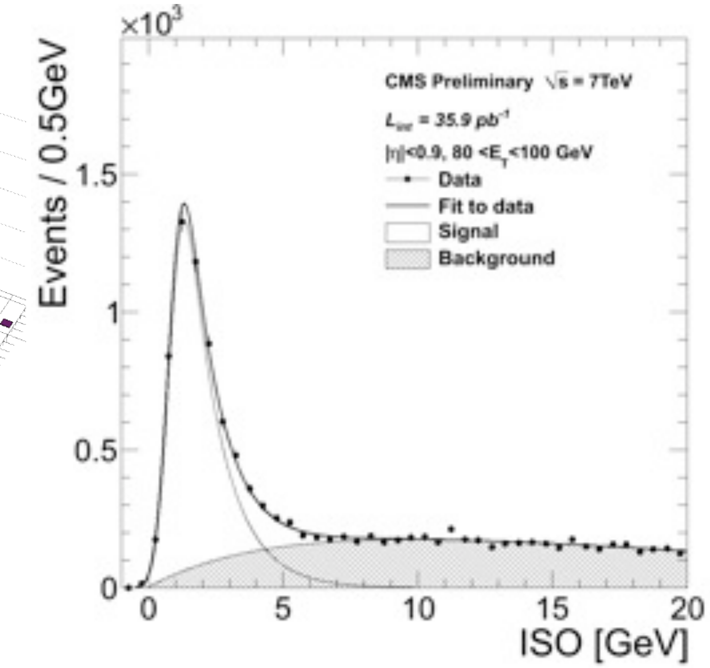


Conversion



Combined Isolation Template





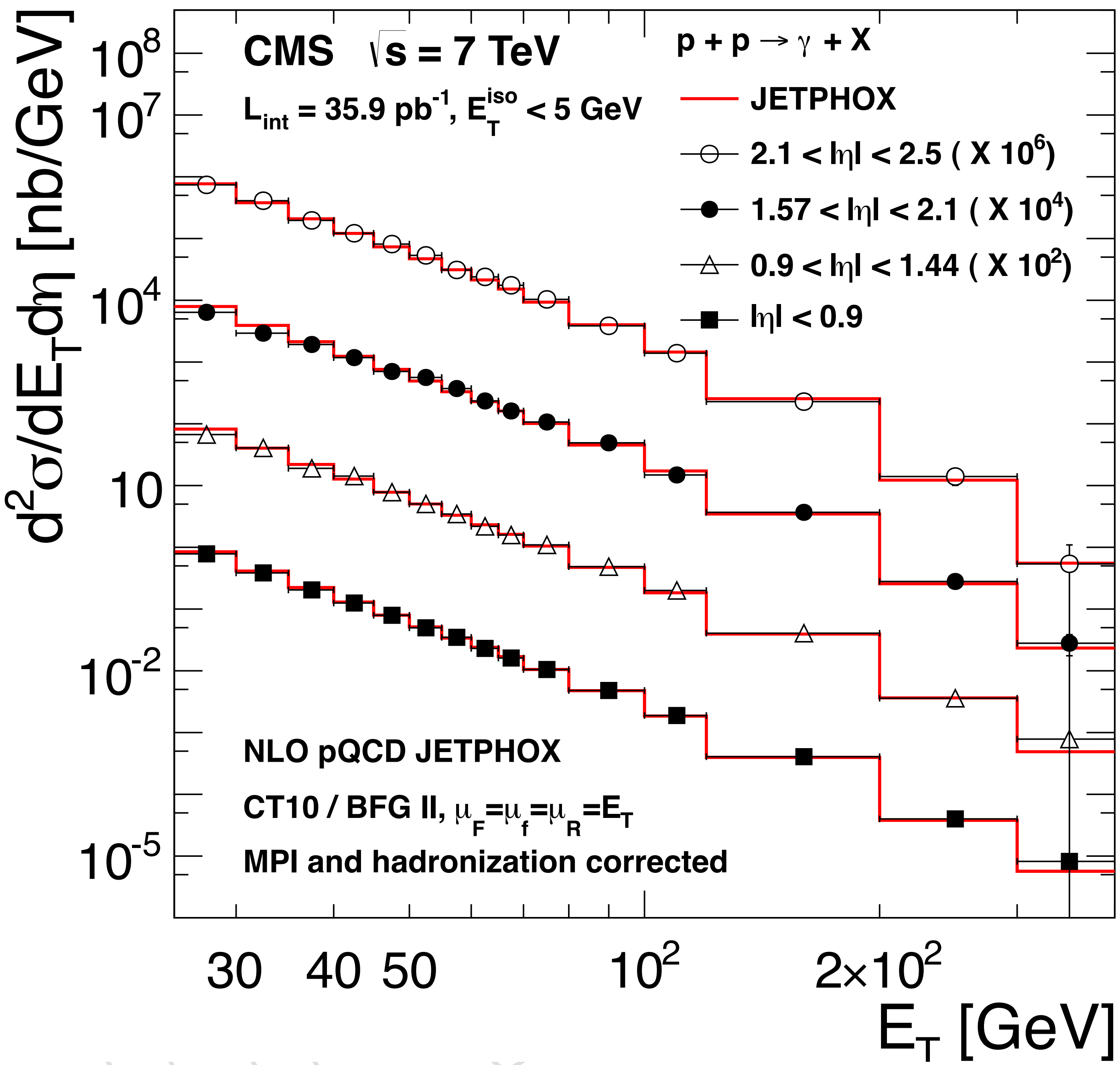
✦ **Reconstruction**

- photon candidates based on identification & isolation preselection criteria
- quality requirements on the converted photon candidates

✦ **Signal yield**

- photon candidates contaminated by decays of energetic neutral mesons
- signal extracted statistically
- conversion template ($E_{T,ECAL}/p_{T,trk}$ variable)
- isolation template ($ISO = ISO_{TRK}+ISO_{ECAL}+ISO_{HCAL}$ variable)

Isolated Prompt Photon Cross Section



✦ **Differential isolated prompt photon cross section**

- combination of conversion and isolation template methods
- measurement from 25 GeV to 400 GeV in E_T and up to |η| = 2.5
- bin-by-bin unfolding

✦ **Theory prediction**

- isolation: E_T < 5 GeV in R < 0.4
- JETPHOX
- CT10 PDF & BFG II fragmentation functions
- $\mu_R = \mu_F = \mu_f = E_T$
- NP correction = 0.975

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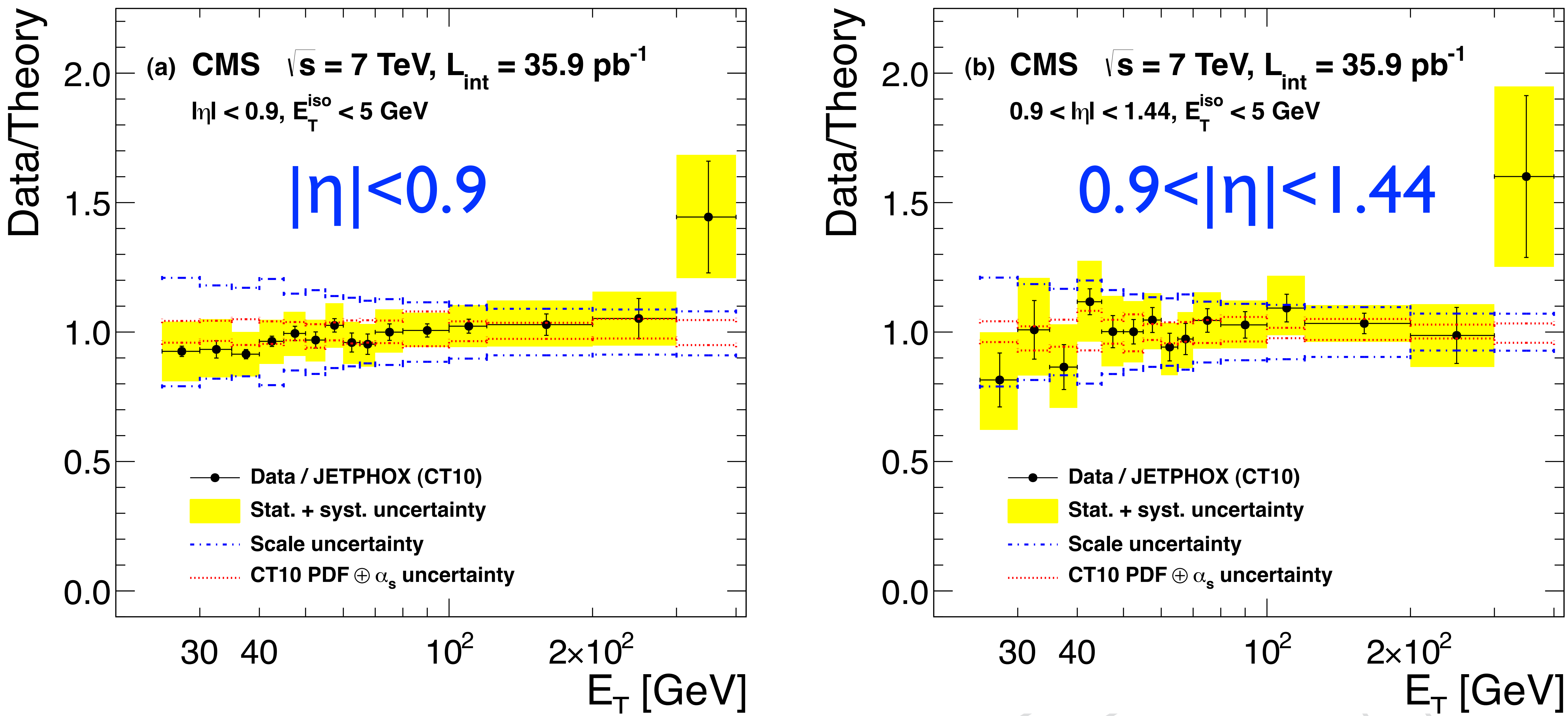
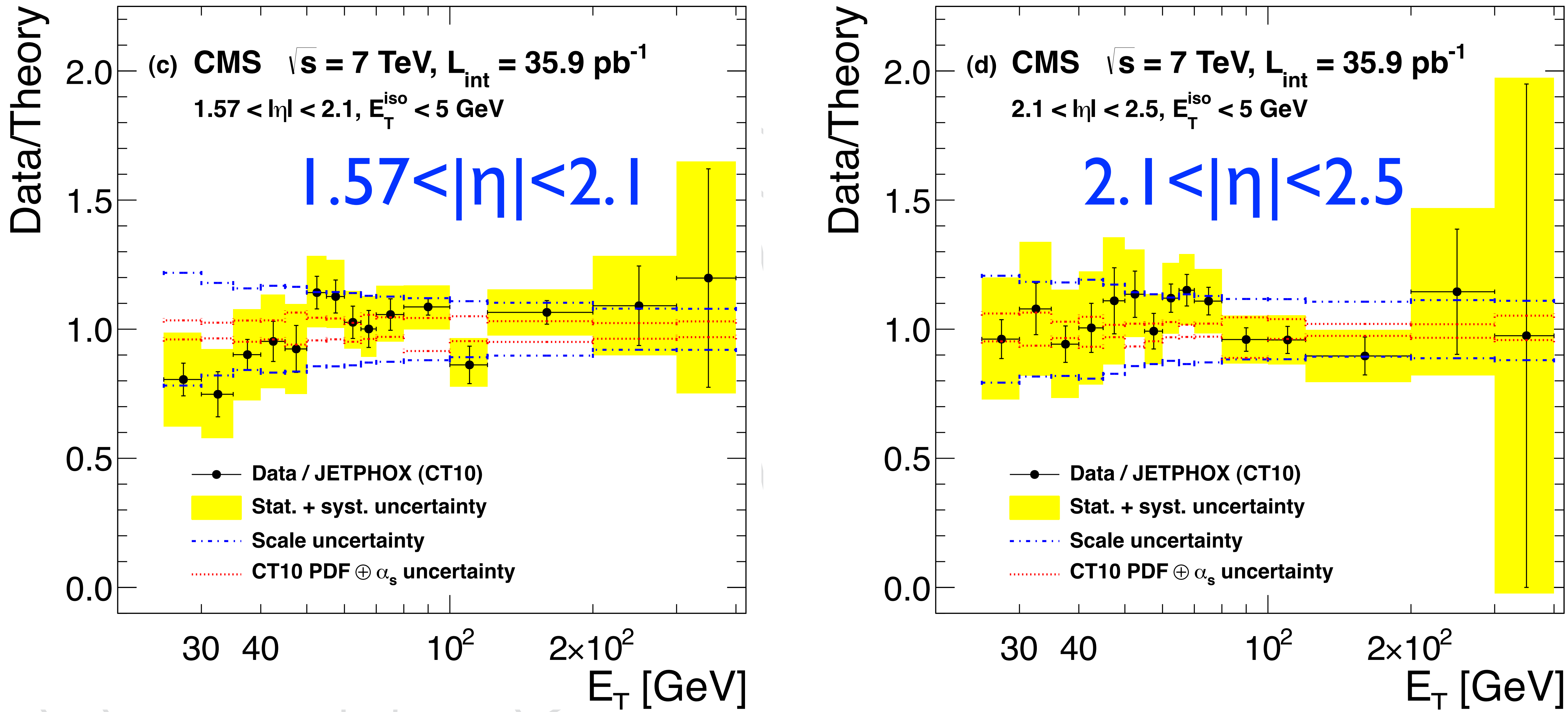
Comparison to Theory (I)



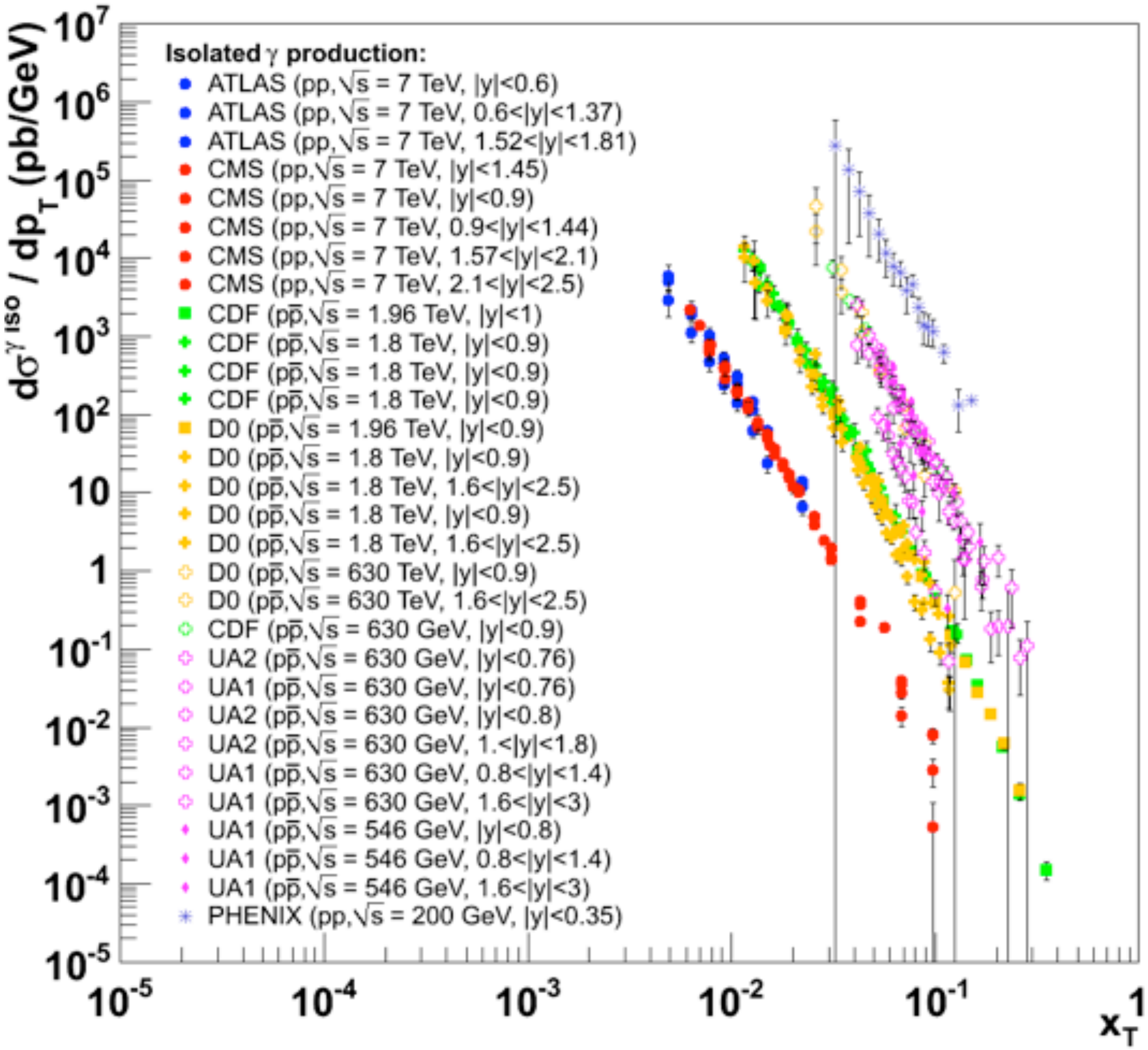
- **Good agreement with the theory**
  - scale uncertainty dominates the theoretical prediction
- **Overestimated cross section at low E_T**
  - different trend than the one observed at Tevatron

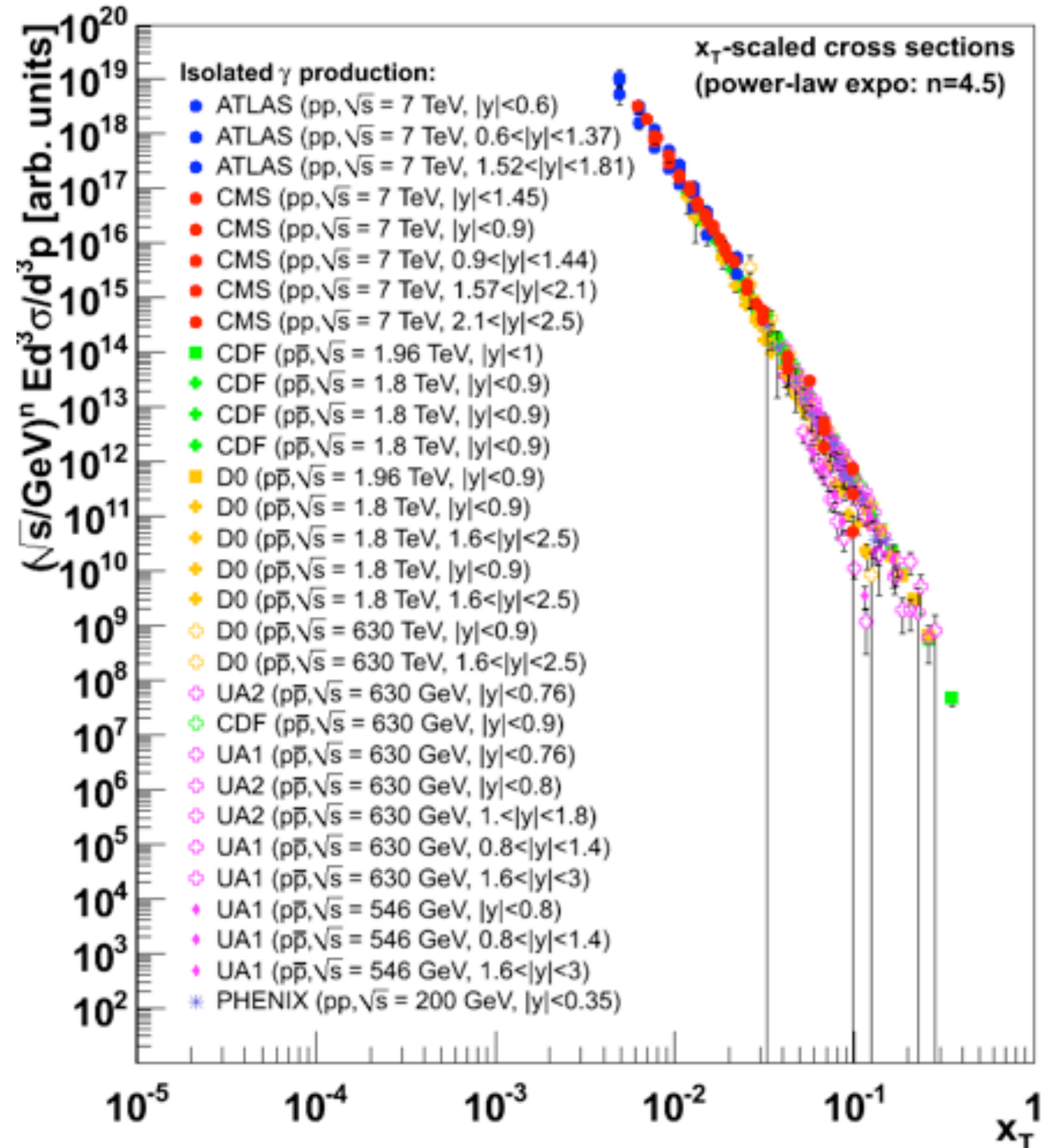
Comparison to Theory (II)



- ✦ **Good agreement with the theory**
  - scale uncertainty dominates the theoretical prediction
- ✦ **Overestimated cross section at low E_T**
  - different trend than the one observed at Tevatron

Isolated Prompt Photons: the Big Picture

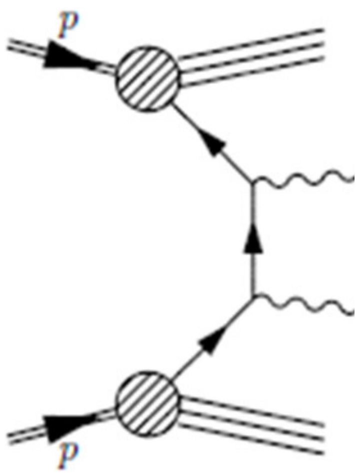




There exists a large number of photon measurements that could be used to constrain directly the gluon PDF

Di-photon Production

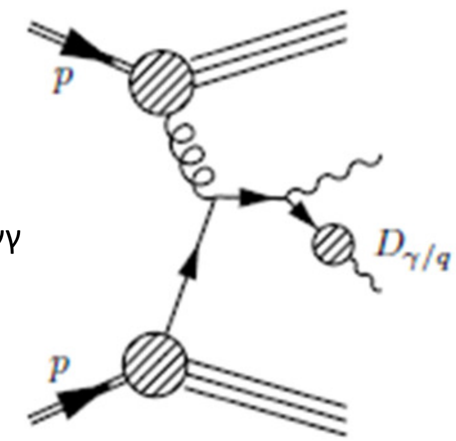
Direct Born



26 pb @ NLO

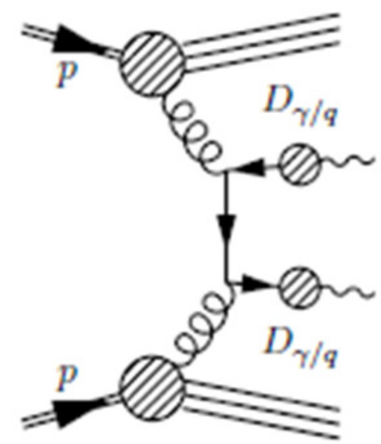
One Fragmentation

$\mu_{frag} = m_{\gamma\gamma}$



10 pb @ NLO

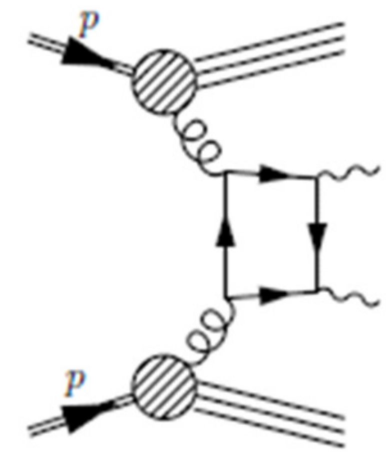
Two Fragmention



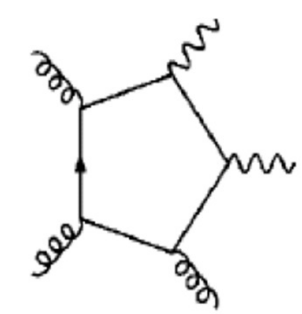
0.5 pb @ NLO

DIPHOX

Direct Box



15 pb @ NLO

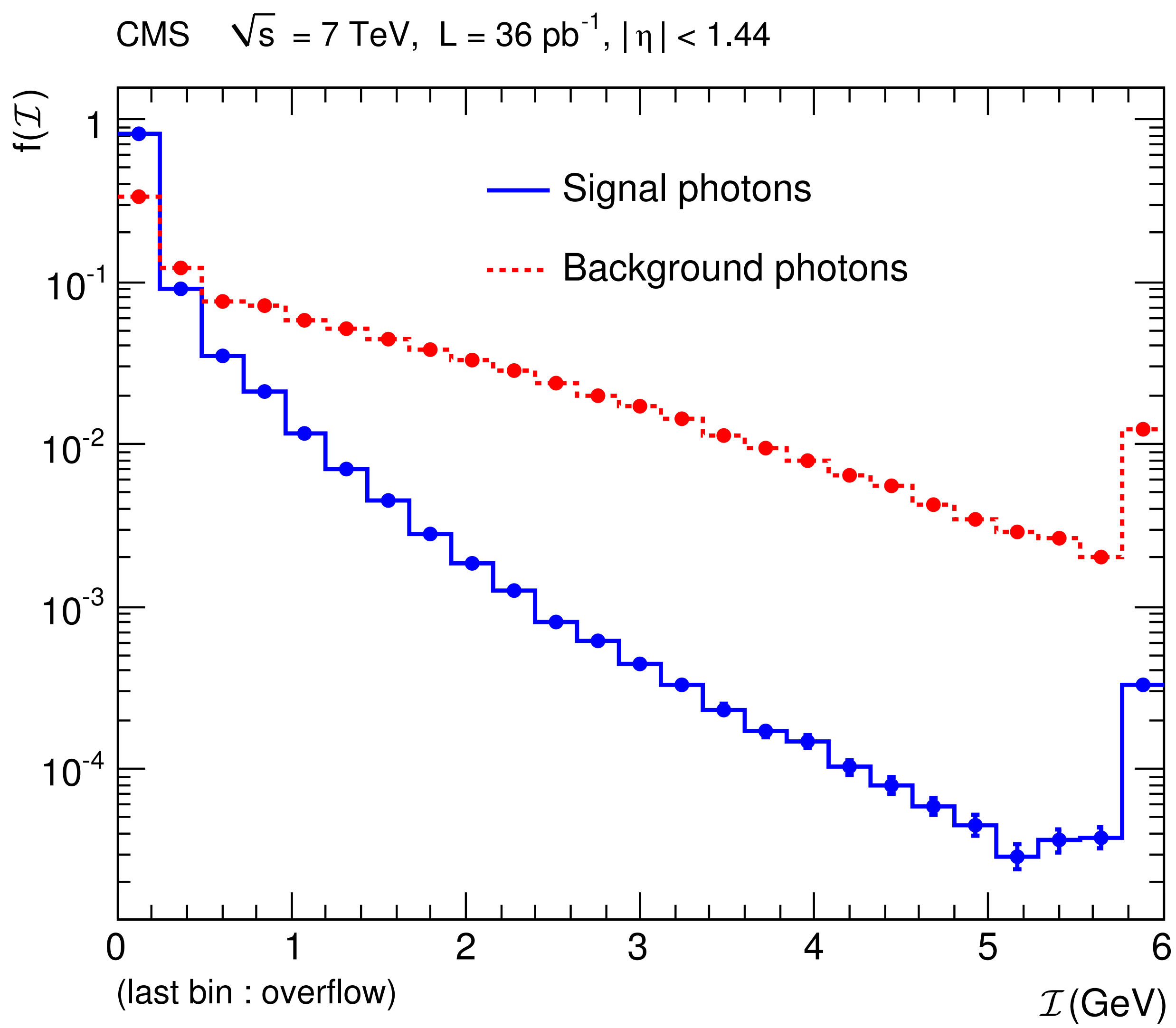


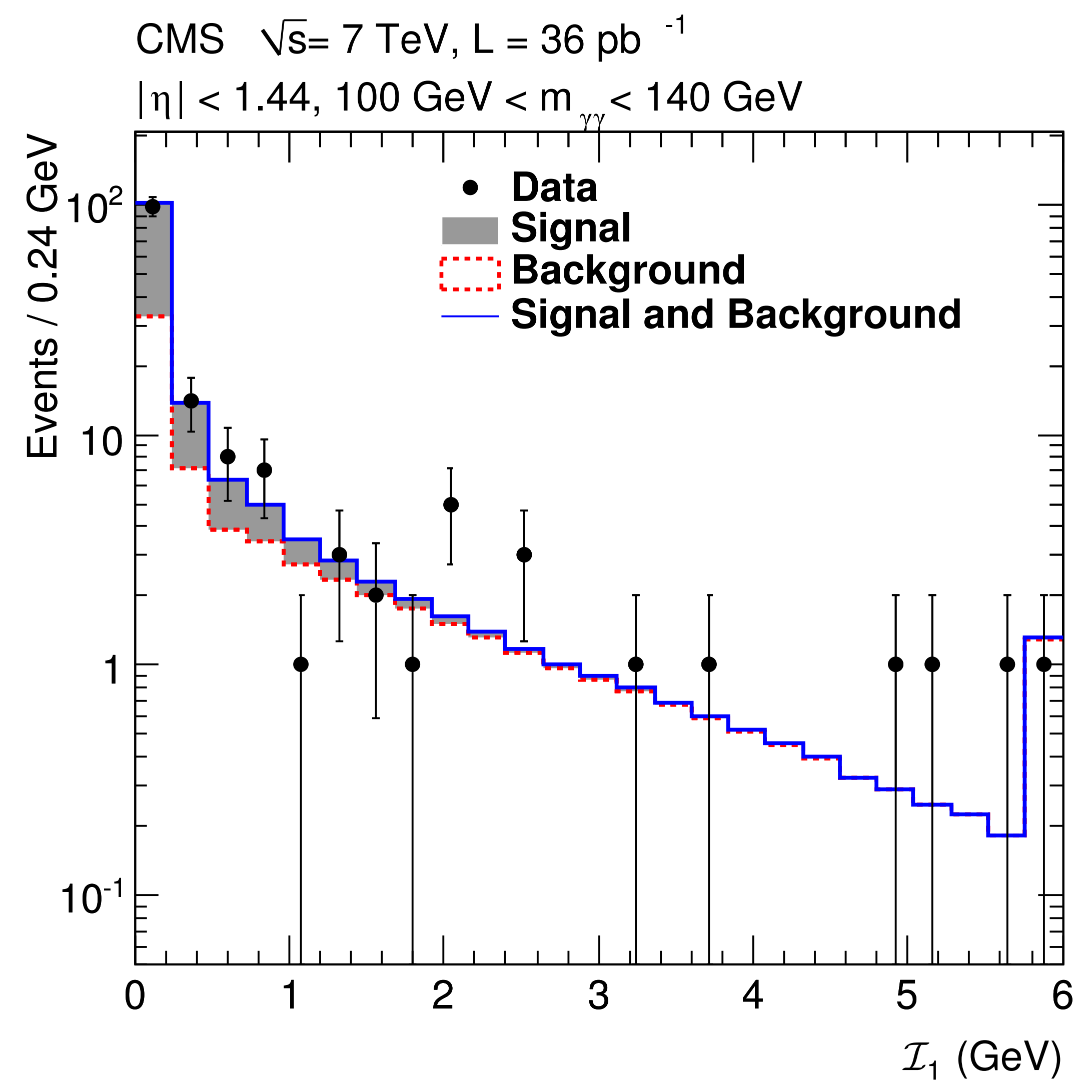
GAMMA2MC

The sub-process cross sections refer to the CMS measurement acceptance

- **Probing pQCD**
  - NLO calculations
  - PDF
- **Irreducible background for the H→γγ search**

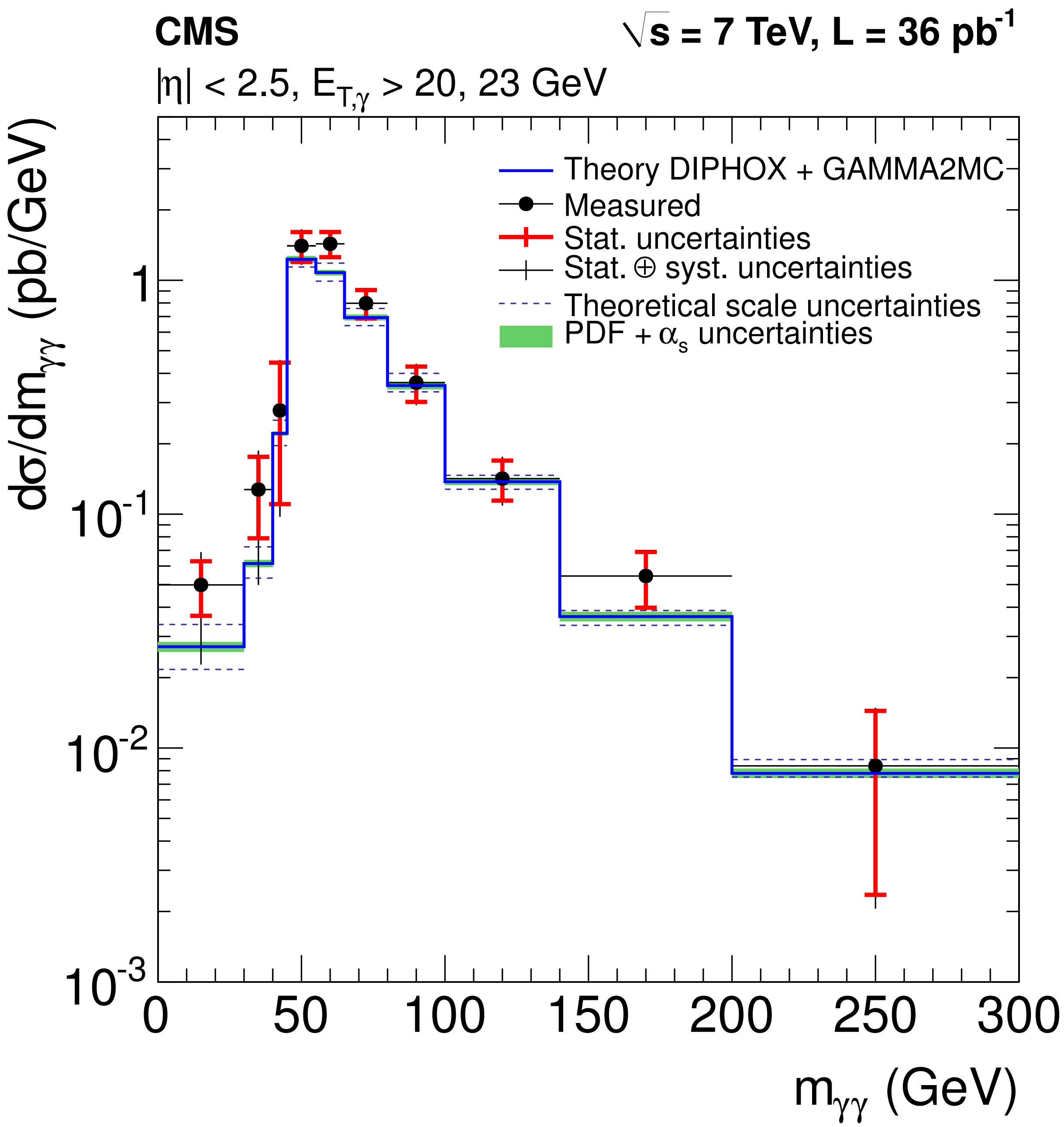
Di-photon Signal Extraction

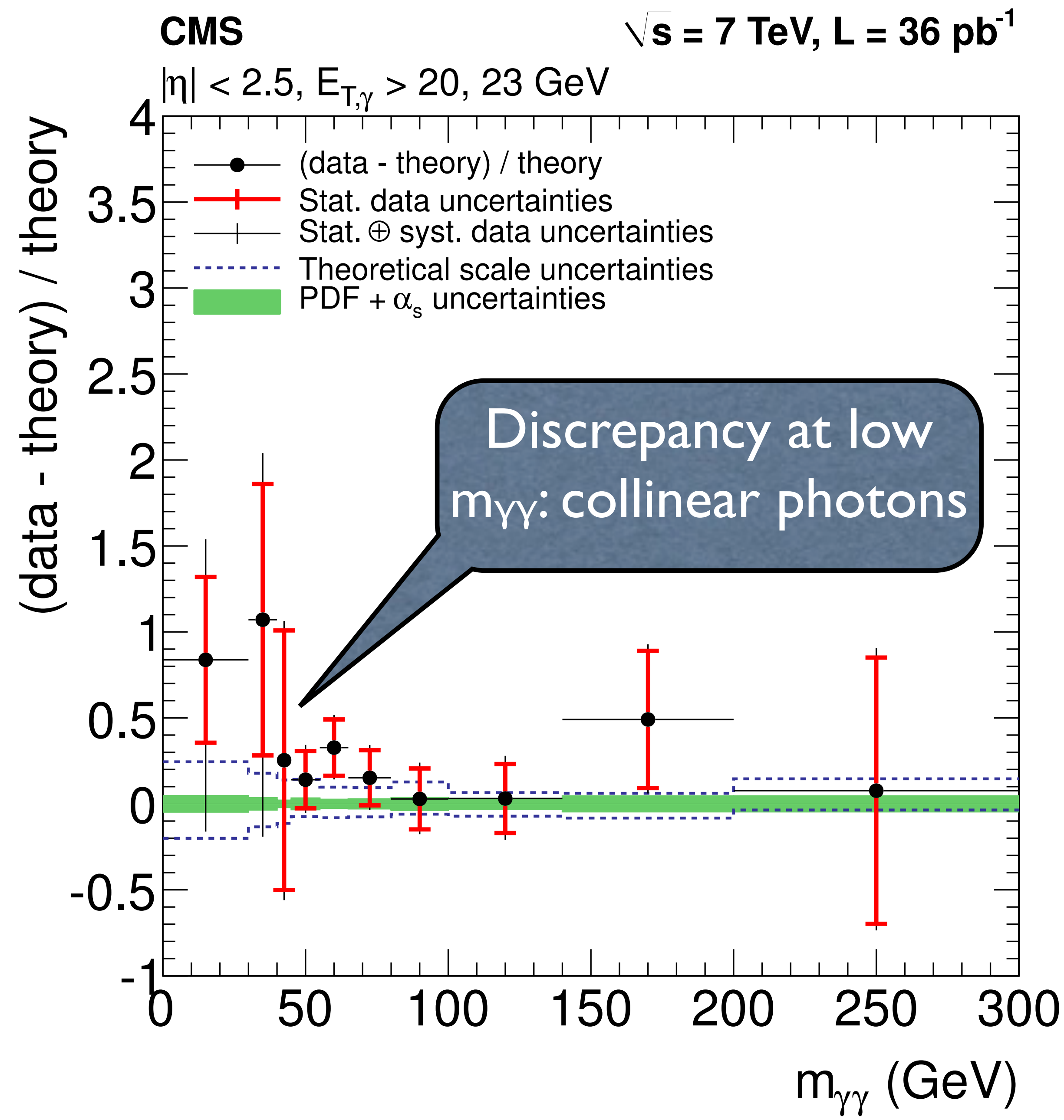




- **Reconstruction**
  - photon candidates based on identification & isolation preselection criteria
  - $E_{T,1} > 23$ GeV, $E_{T,2} > 20$ GeV, $R_{\gamma\gamma} > 0.45$ in η-φ,
- **Signal yield**
  - signal extracted statistically
  - ECAL isolation template

Di-photon Cross Section (vs $m_{\gamma\gamma}$)





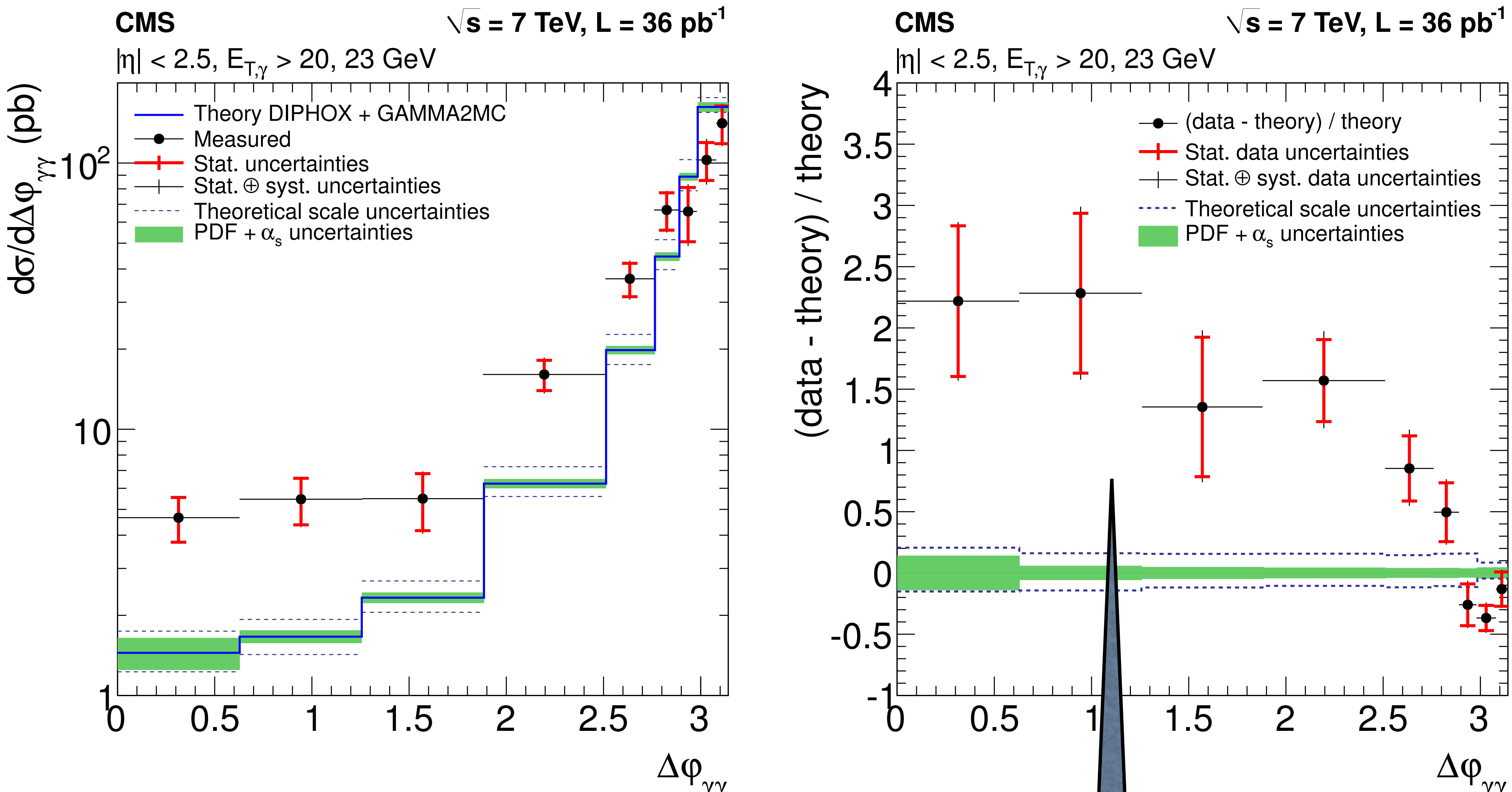
- **Differential isolated prompt photon cross section**
  - response matrix inversion unfolding
- **Theory prediction**
  - isolation: $E_T < 5$ GeV in $R < 0.4$
  - NP correction = 0.953

PDF4LHC

$\mu_R = \mu_F = \mu_f = m_{\gamma\gamma}$

arXiv:1110.6461

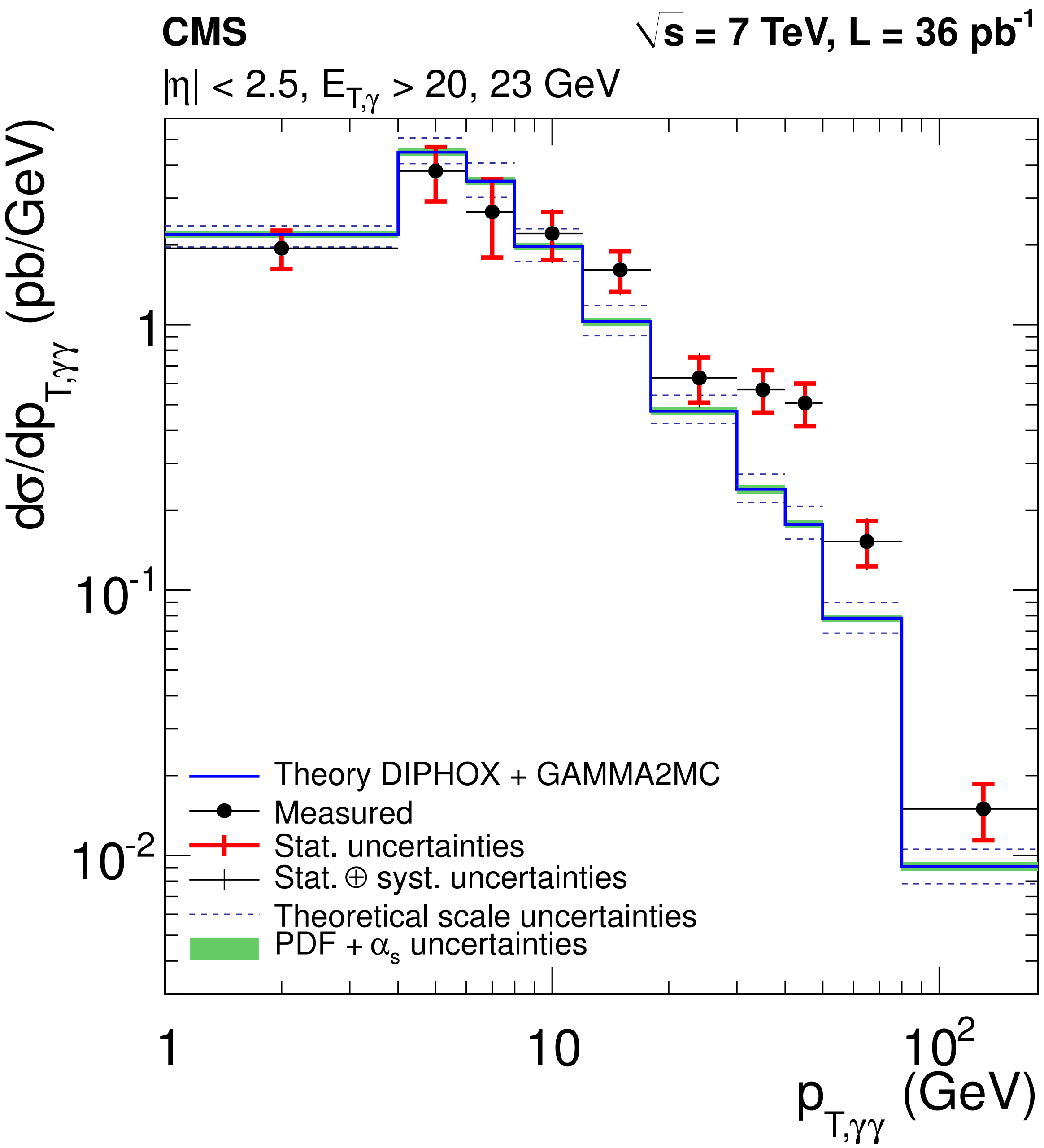
Di-photon Cross Section (vs $\Delta\phi_{\gamma\gamma}$)

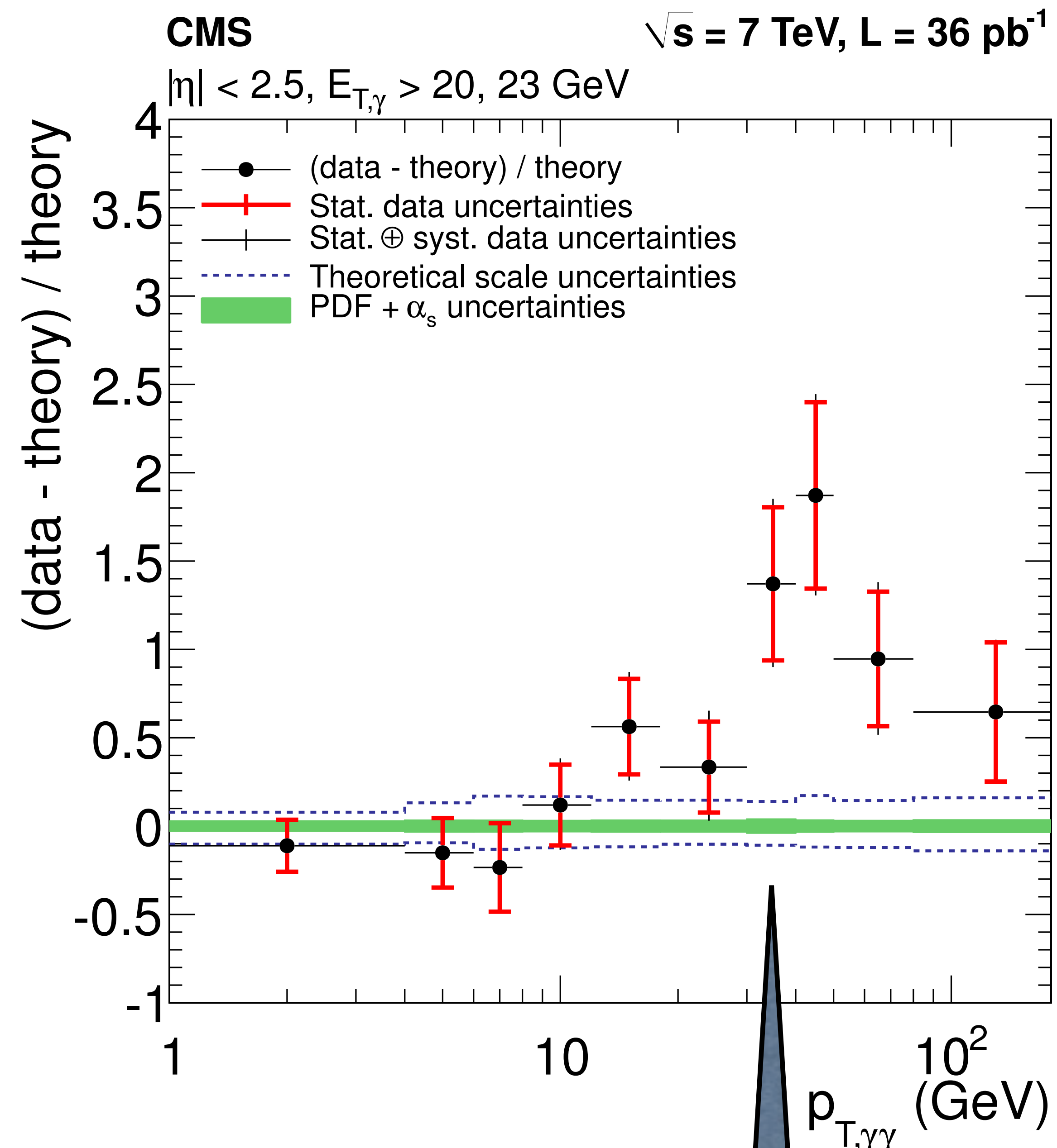


- **Differential isolated prompt photon cross section**
  - response matrix inversion unfolding
- **Theory prediction**
  - isolation: $E_T < 5$ GeV in $R < 0.4$
  - NP correction = 0.953

Discrepancy at low $\Delta\varphi_{\gamma\gamma}$: collinear photons

Di-photon Cross Section (vs $p_{T,\gamma\gamma}$)

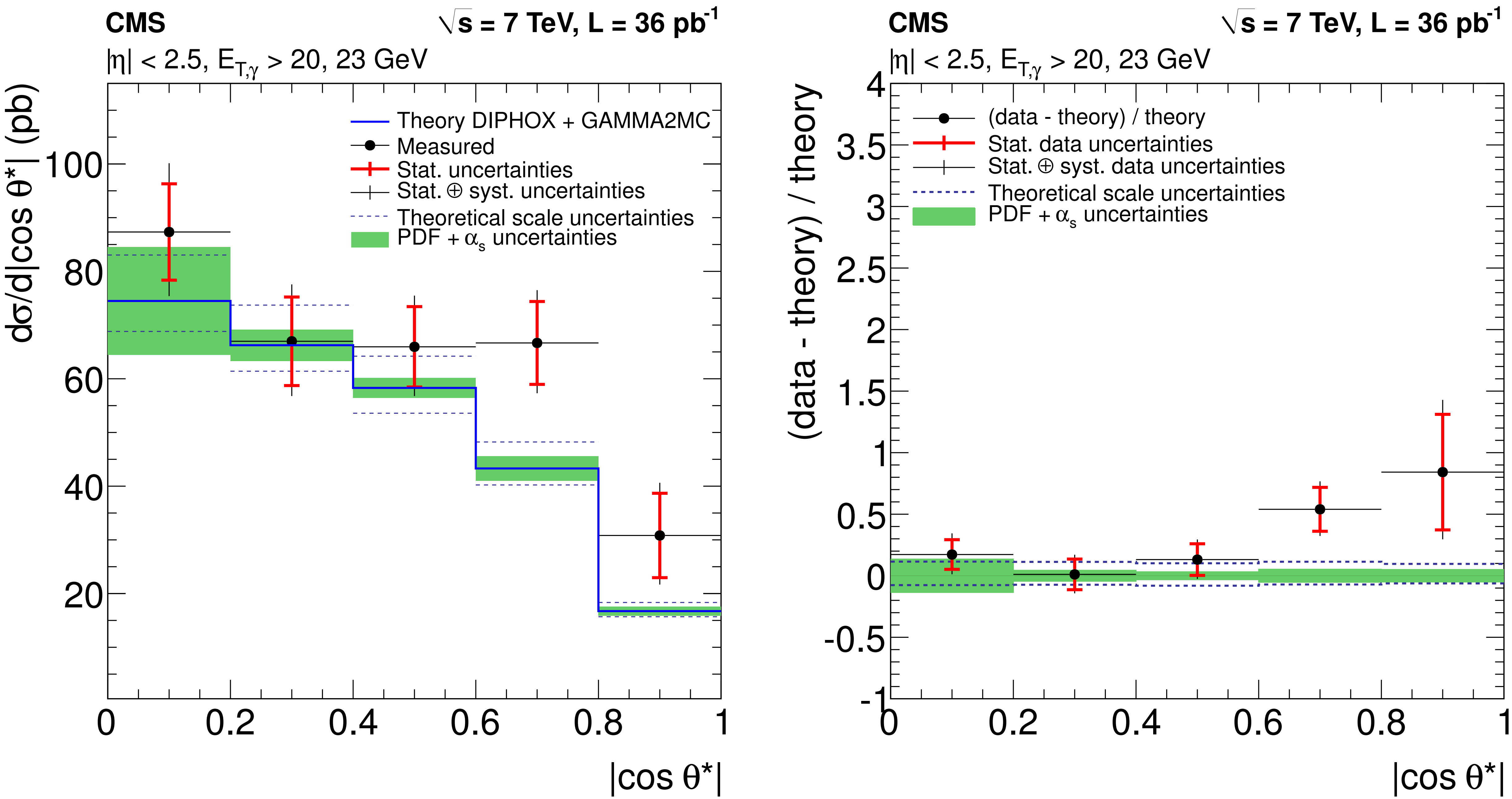




- **Differential isolated prompt photon cross section**
  - response matrix inversion unfolding
- **Theory prediction**
  - isolation: $E_T < 5$ GeV in $R < 0.4$
  - NP correction = 0.953

Discrepancy at high $p_{T,\gamma\gamma}$: collinear photons

Di-photon Cross Section (vs cosθ*)



- **Differential isolated prompt photon cross section**
  - response matrix inversion unfolding
- **Theory prediction**
  - isolation: $E_T < 5$ GeV in $R < 0.4$
  - NP correction = 0.953

Ongoing Measurements

(1) Photon + jets differential cross sections
(2) Photon + jet angular distribution
(3) Di-photon + jets
(4) Jet cross-sections, reaching jet $p_T > 2$ TeV ($x_T \sim 0.6$)
(5) Three-jet production rate vs invariant mass
(6) Measurement (?) of alpha_s with the R_{32}
(7) Three-jet and Four-jet properties
(8) Jet structure and substructure
(9) Color coherence
....

And many others, which are not classified as “QCD” in the CMS organization:

- Z,W + jets production
- Z + jet angular distributions
- heavy flavor production
- forward physics

Summary

✦ Understanding QCD is essential for the LHC physics

✦ CMS has performed a large number of competing QCD measurements with the 2010 data (19 journal publications and several preliminary results)

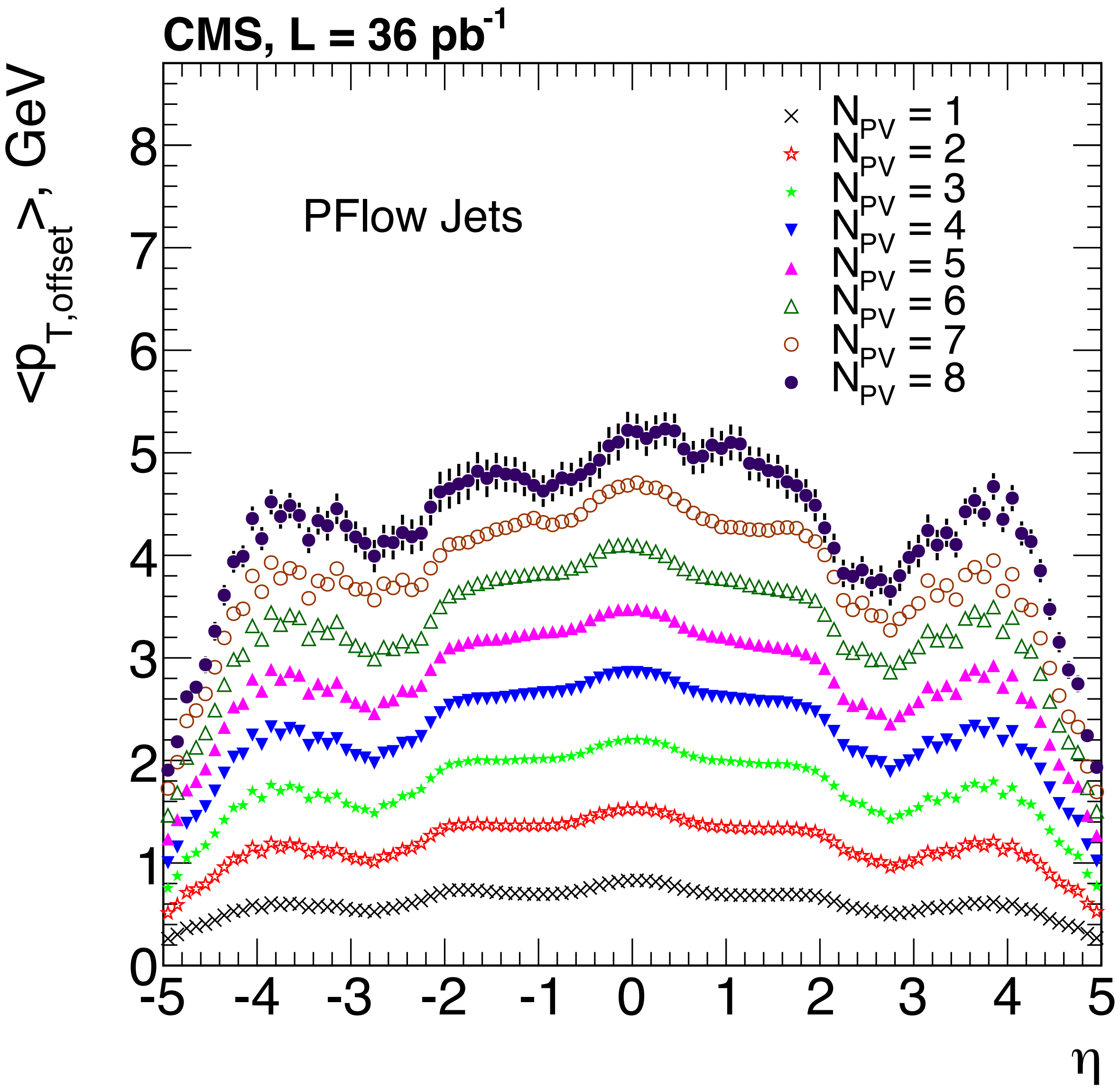
✦ **Overall, data and theoretical predictions are compatible**
- data are described well by pQCD @ NLO in the TeV scale
- but still limited by the experimental systematic uncertainties

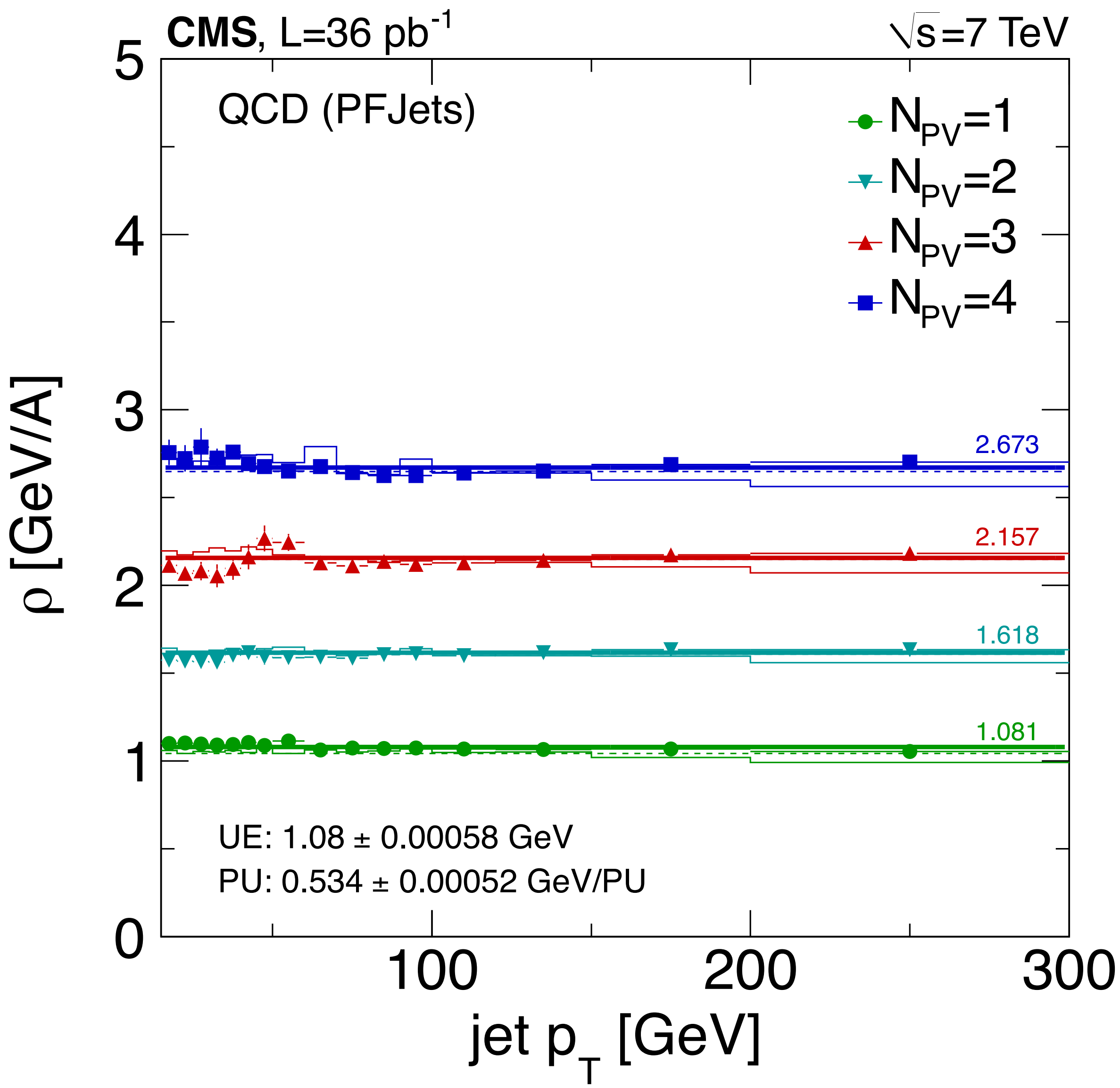
✦ QCD Monte-Carlo generators are in satisfactory agreement with the data
- pre-LHC tunes clearly fail to describe the data
- first LHC tunes in the right direction but there is room for improvement
- MC tuning requires a global fit of as many measurements as possible

✦ Further QCD studies are being pursued with the 2011 data
- the 2010 studies were only the prelude to the precision measurements to follow

Backup

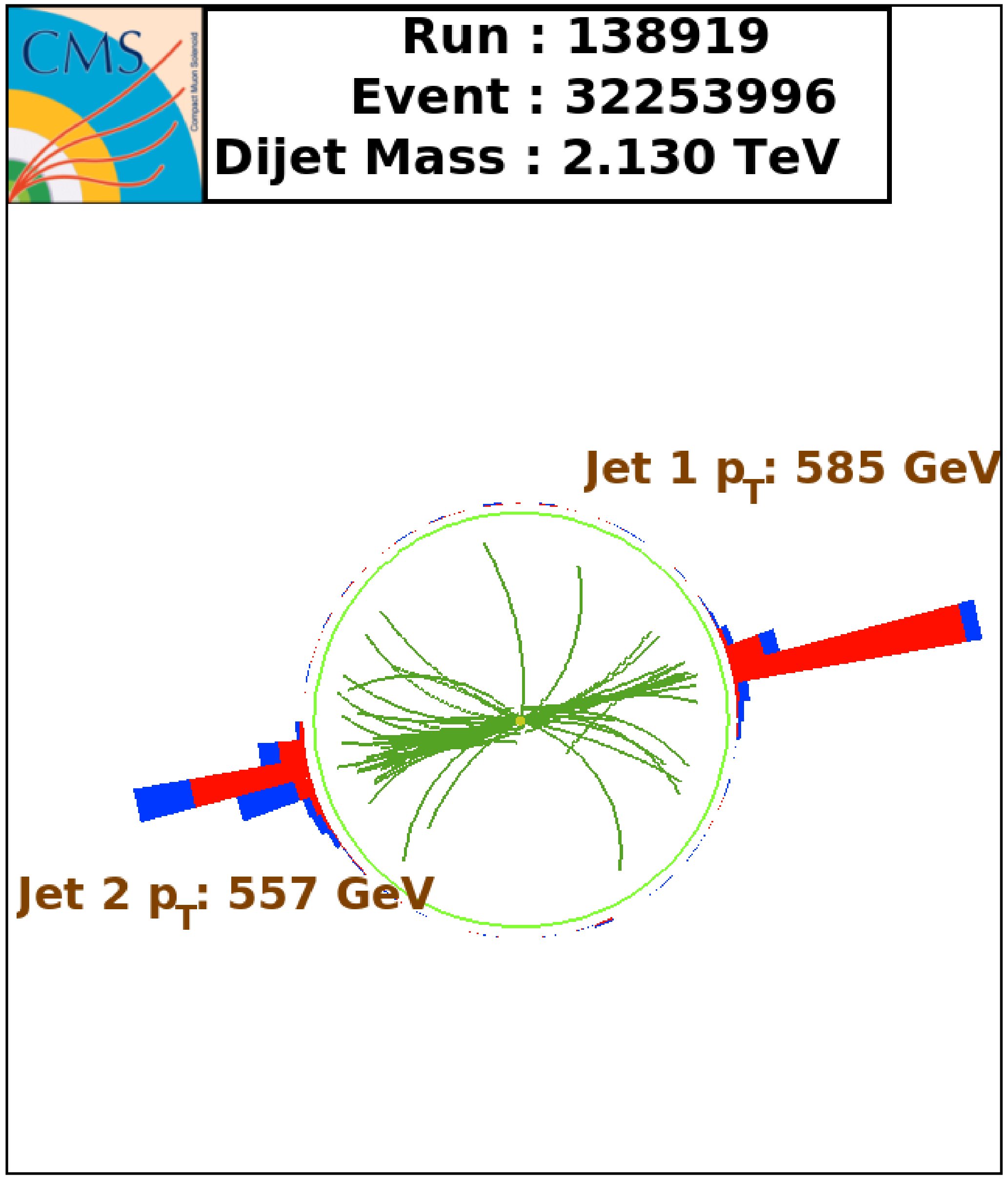
Jet Energy Calibration (offset)

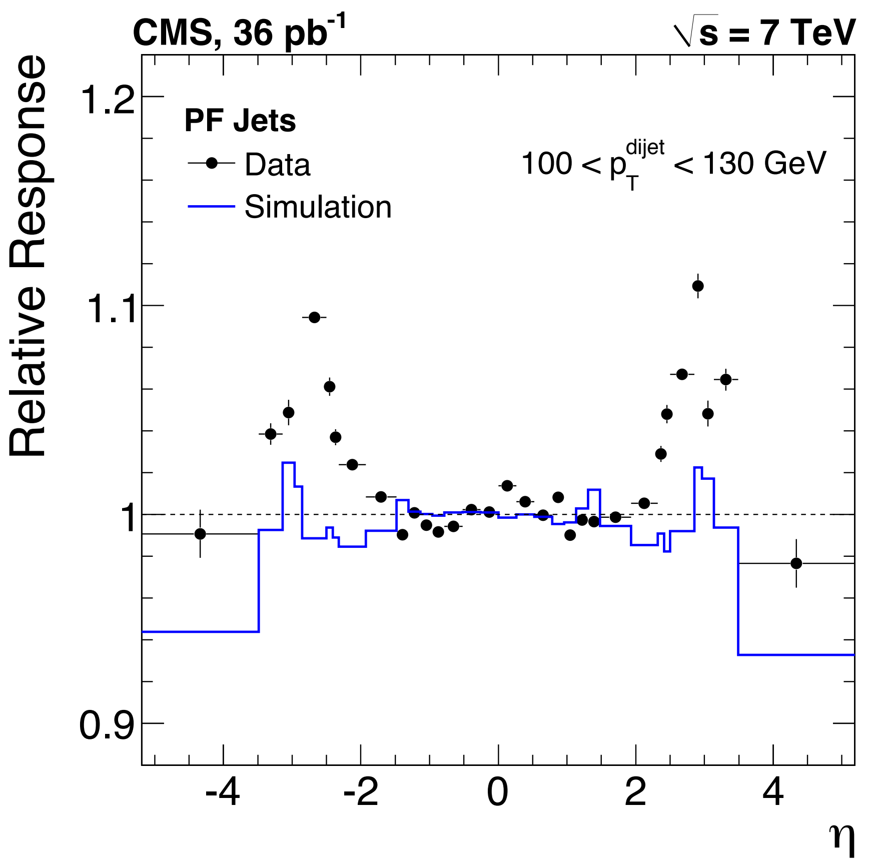


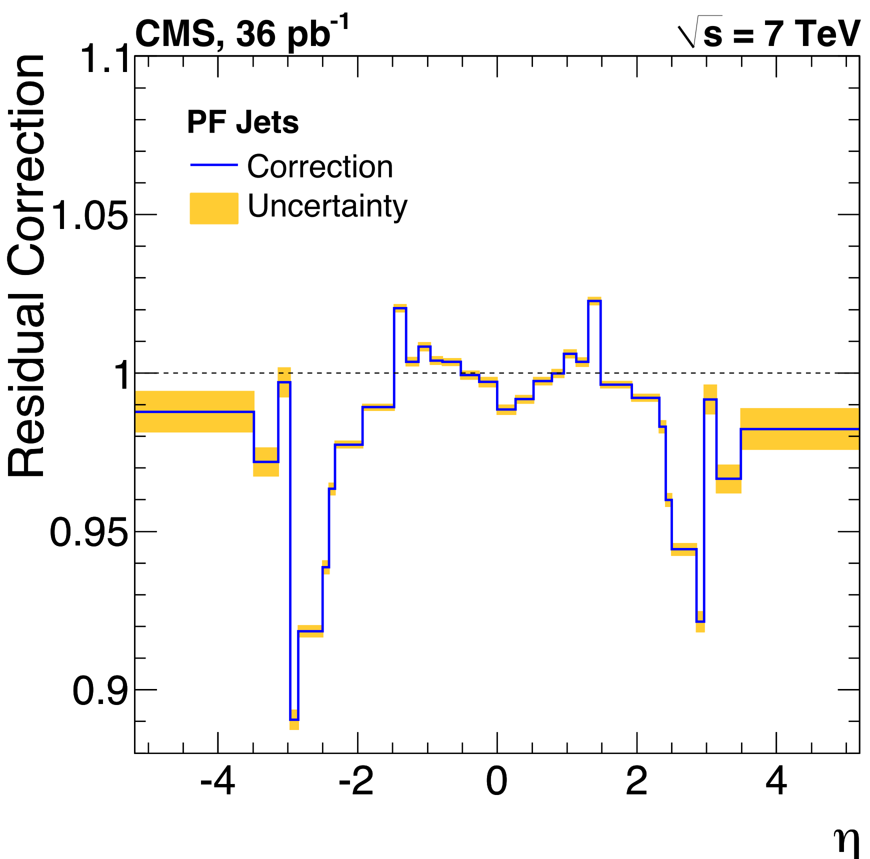


$$C_{\text{hybrid}}(p_T^{raw}, \eta, A_j, \rho) = 1 - \frac{(\rho - \langle \rho_{\text{UE}} \rangle) \cdot \beta(\eta) \cdot A_j}{p_T^{raw}}$$

Jet Energy Calibration (vs η)

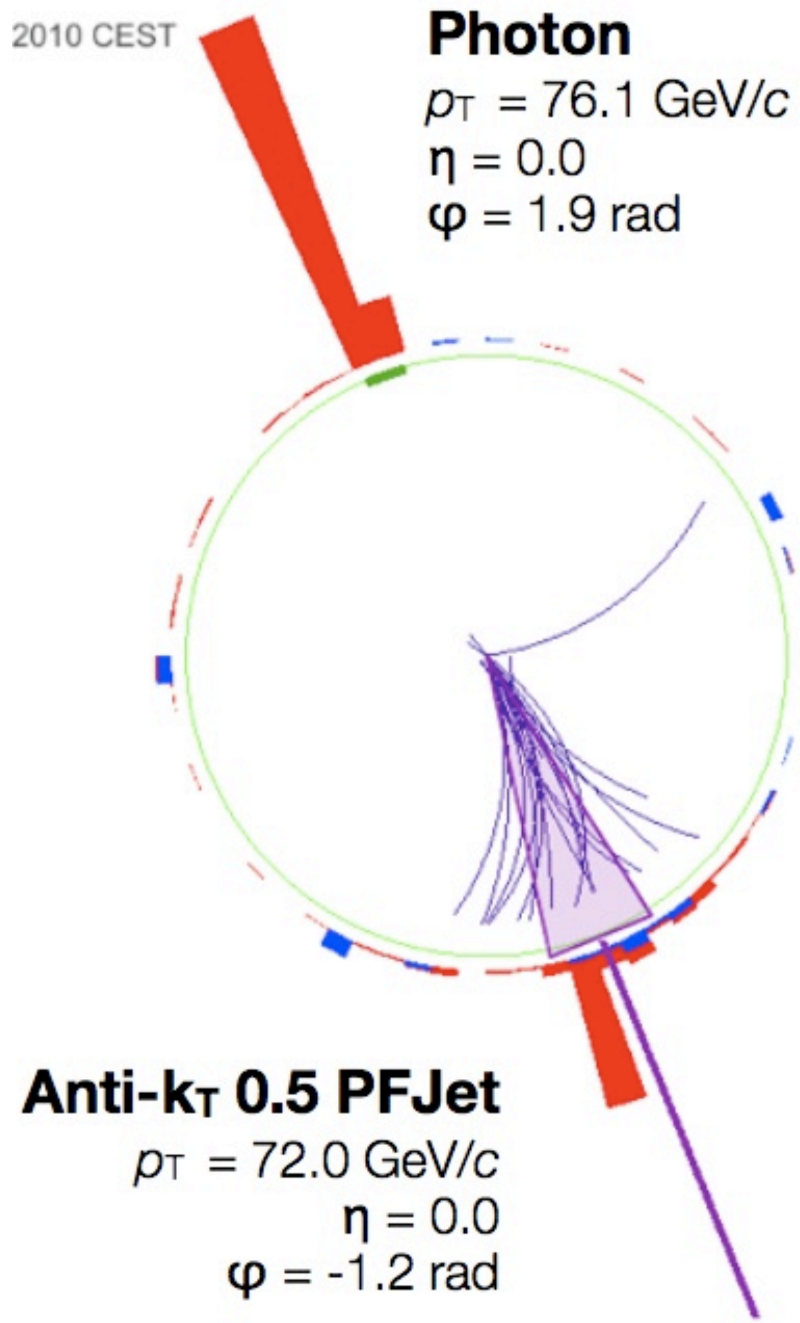


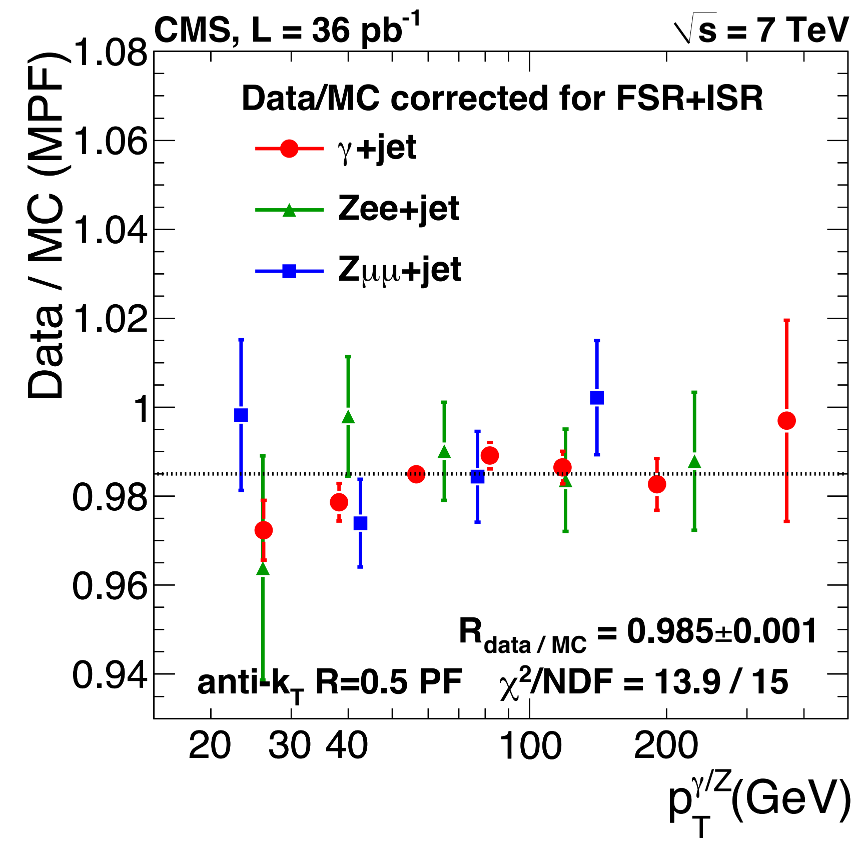


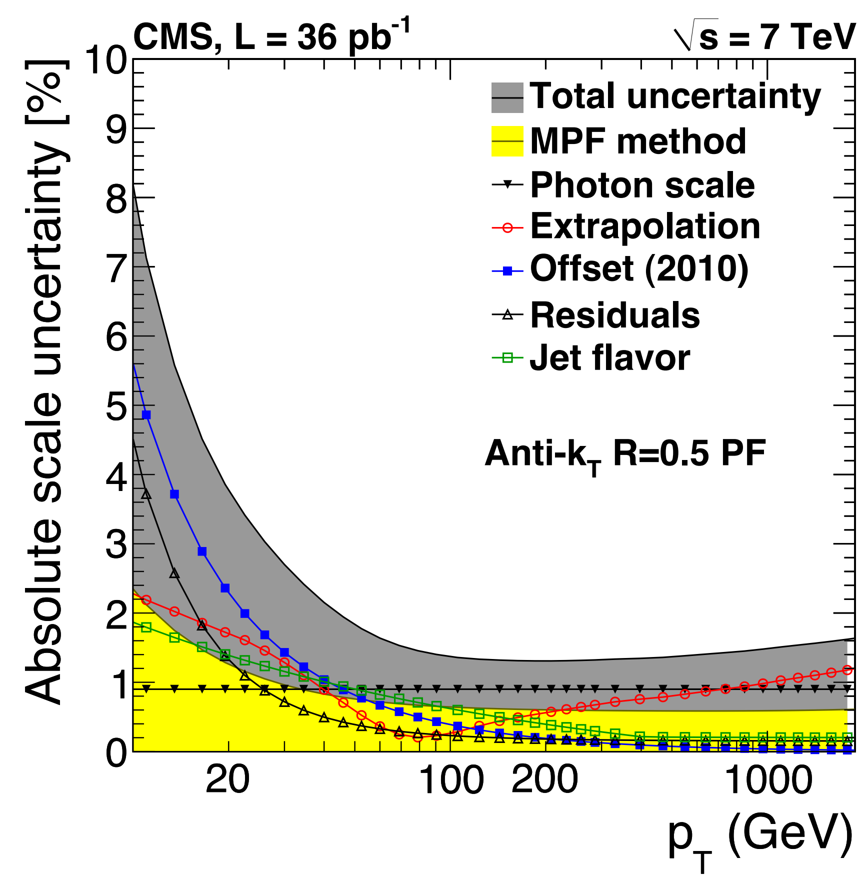


Exploiting the dijet p_T balancing

Jet Energy Calibration (vs p_T)

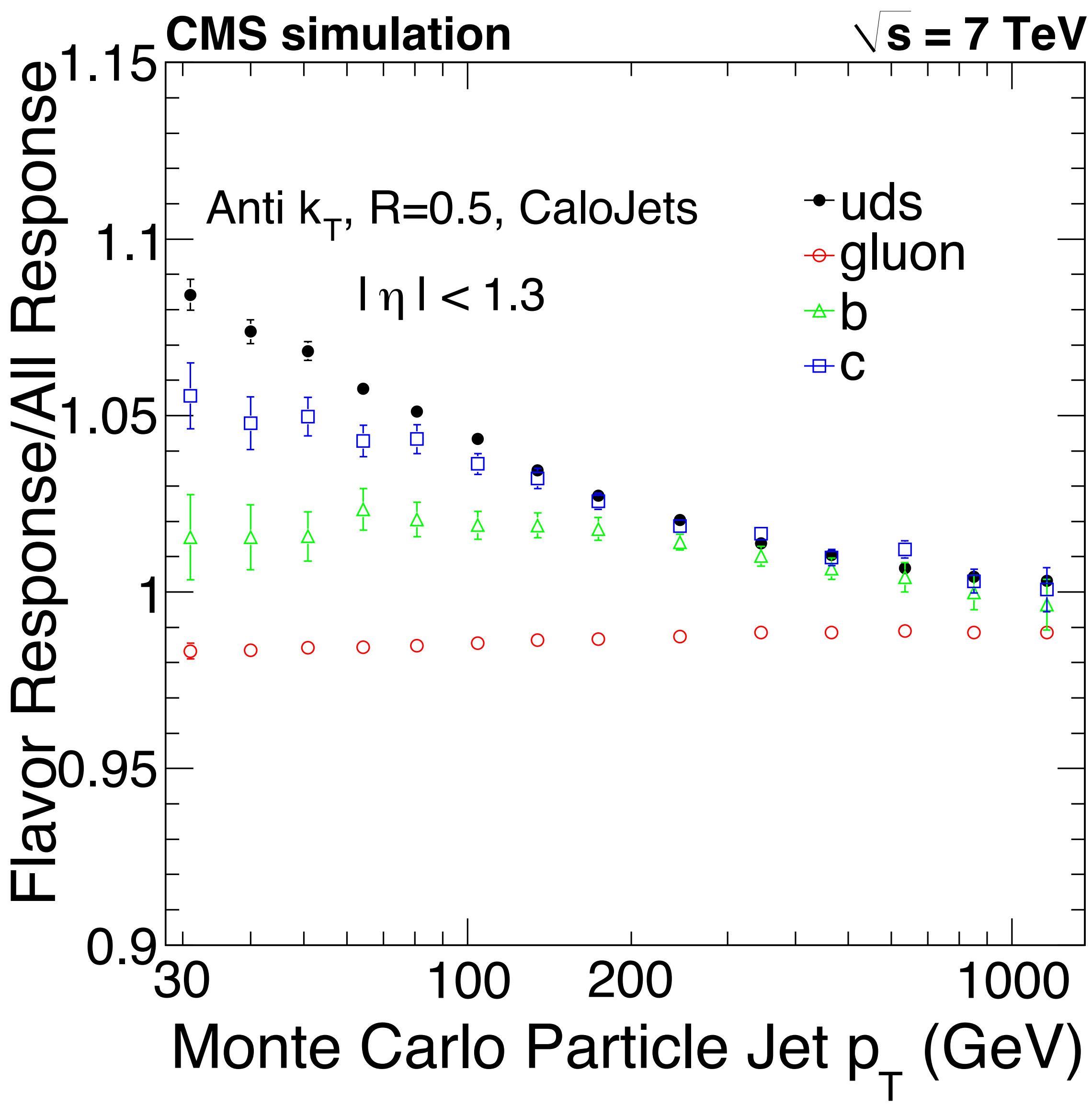


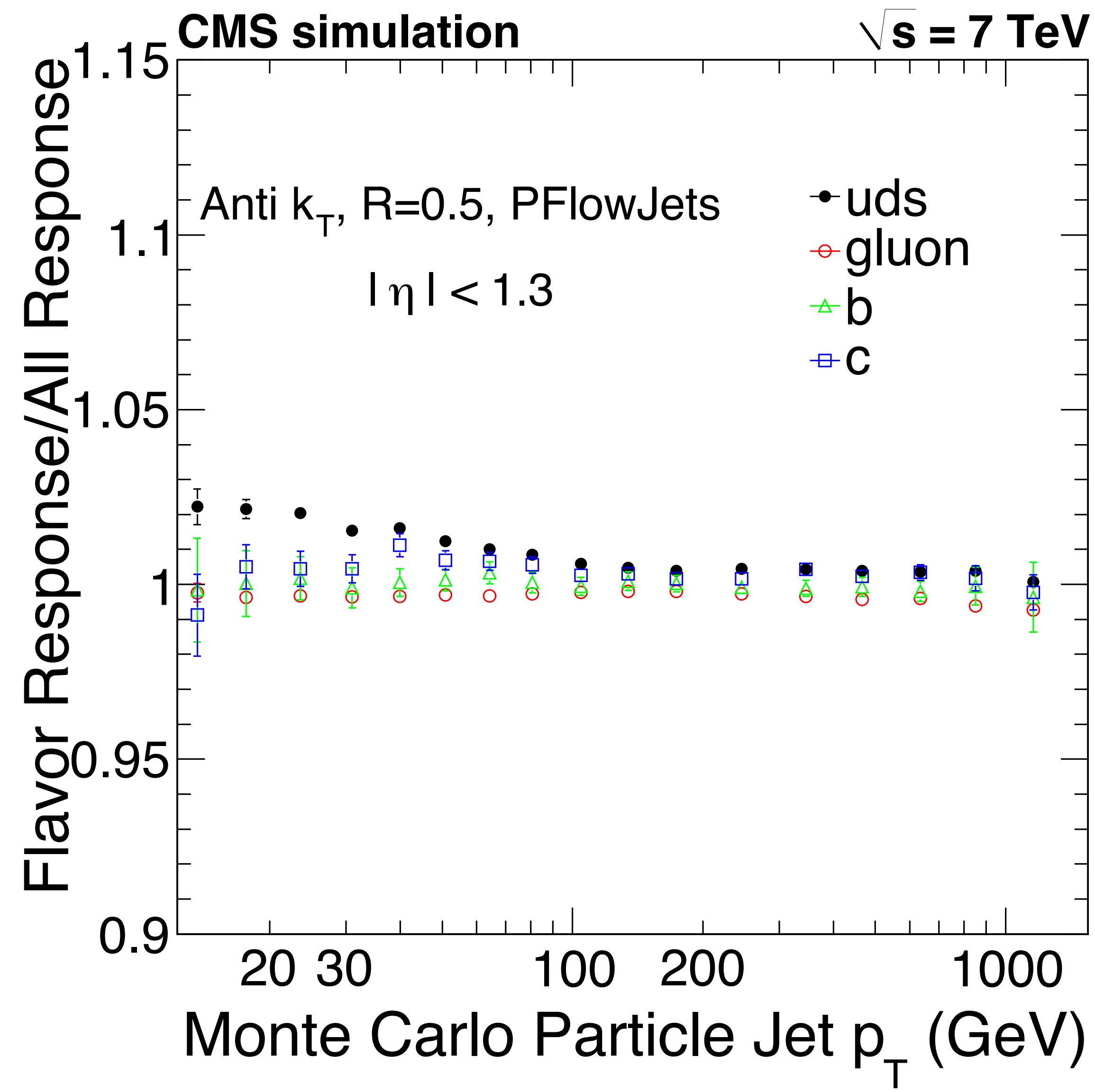




Exploiting the photon/Z+jet p_T balancing

Jet Energy Calibration (flavor dependence)



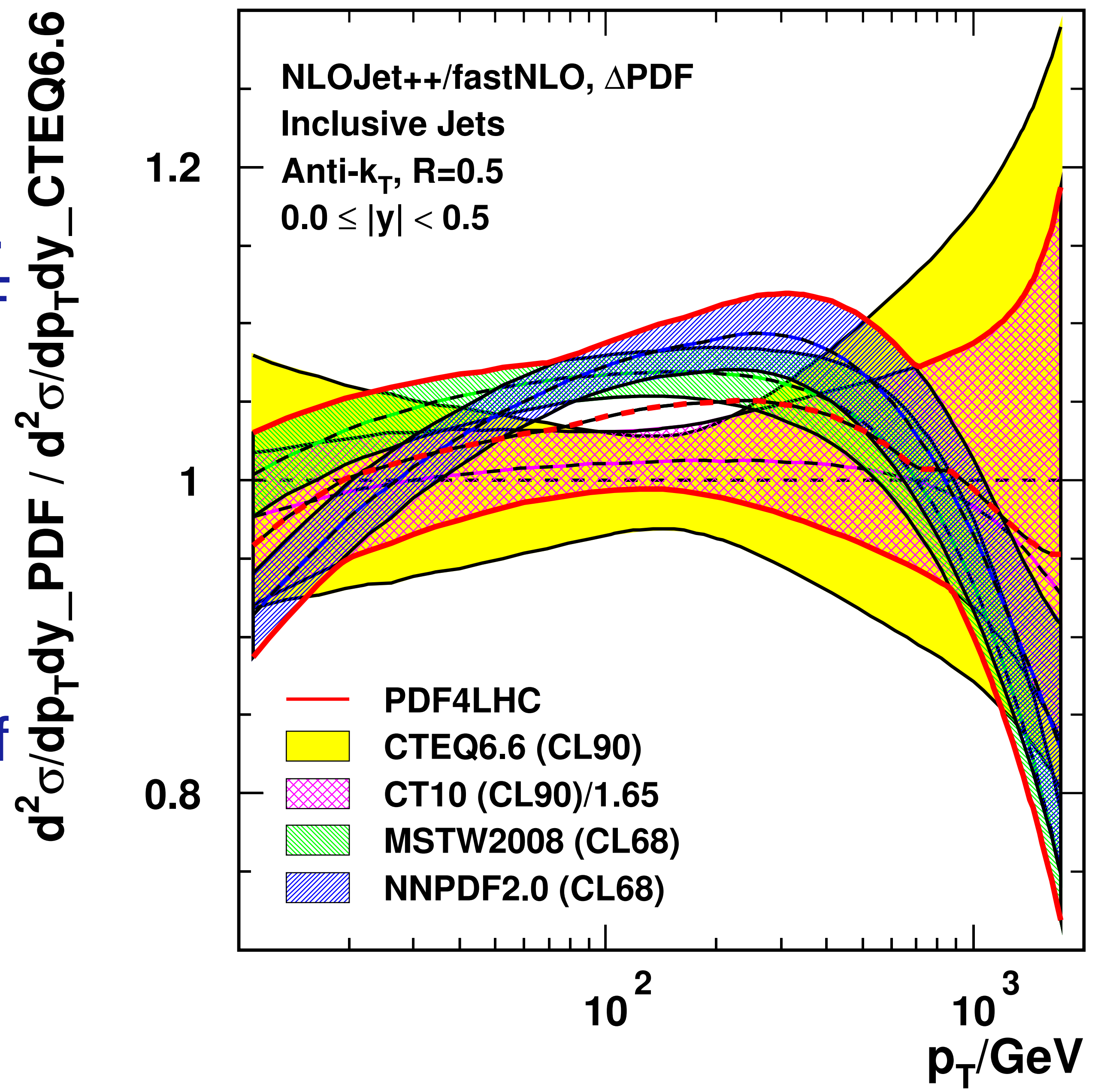


The PF jet reconstruction has reduced the flavor dependence to less than 2% for $p_T > 30$ GeV

The PDF4LHC Prescription

✦ **The PDF4LHC prescription describes the way to combine the various PDFs:**
- compute the observable of interest (e.g. inclusive jet cross section) with each PDF set
- construct the 1-sigma (68% CL) band from each PDF set
- at every point, define the global envelope from the 1-sigma bands
- the PDF4LHC prediction is the center of the global envelope

✦ **The PDF4LHC prescription is meant for a check of the overall compatibility between data and theory predictions**



Hadronic Event Shapes

90 < $p_{T,max}$ < 125 GeV | 125 < $p_{T,max}$ < 200 GeV | $p_{T,max}$ > 200 GeV