Review of QCD results from CMS

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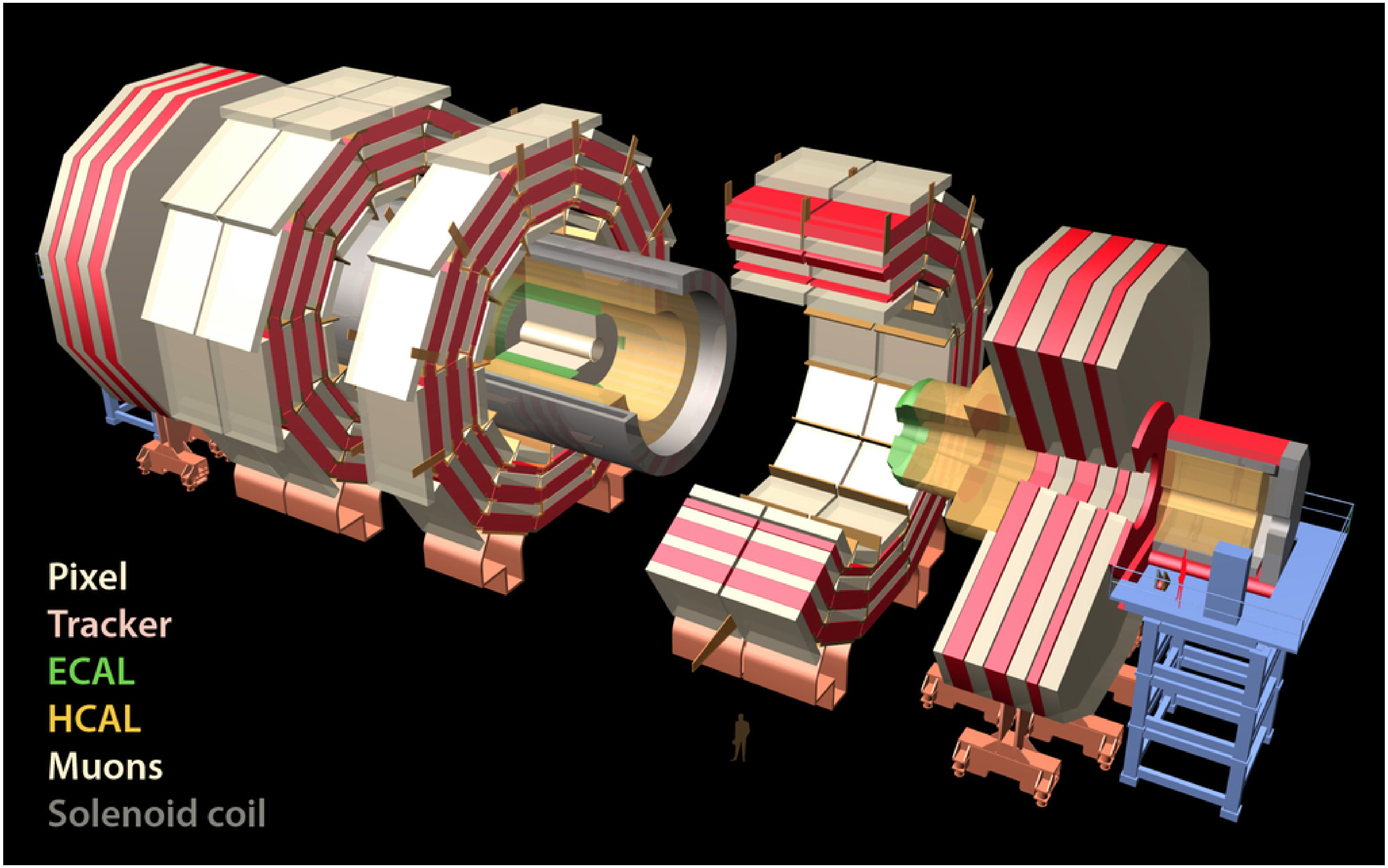
on behalf of the CMS Collaboration

Zimányi 2011 Winter School, Budapest, Hungary
November 28, 2011

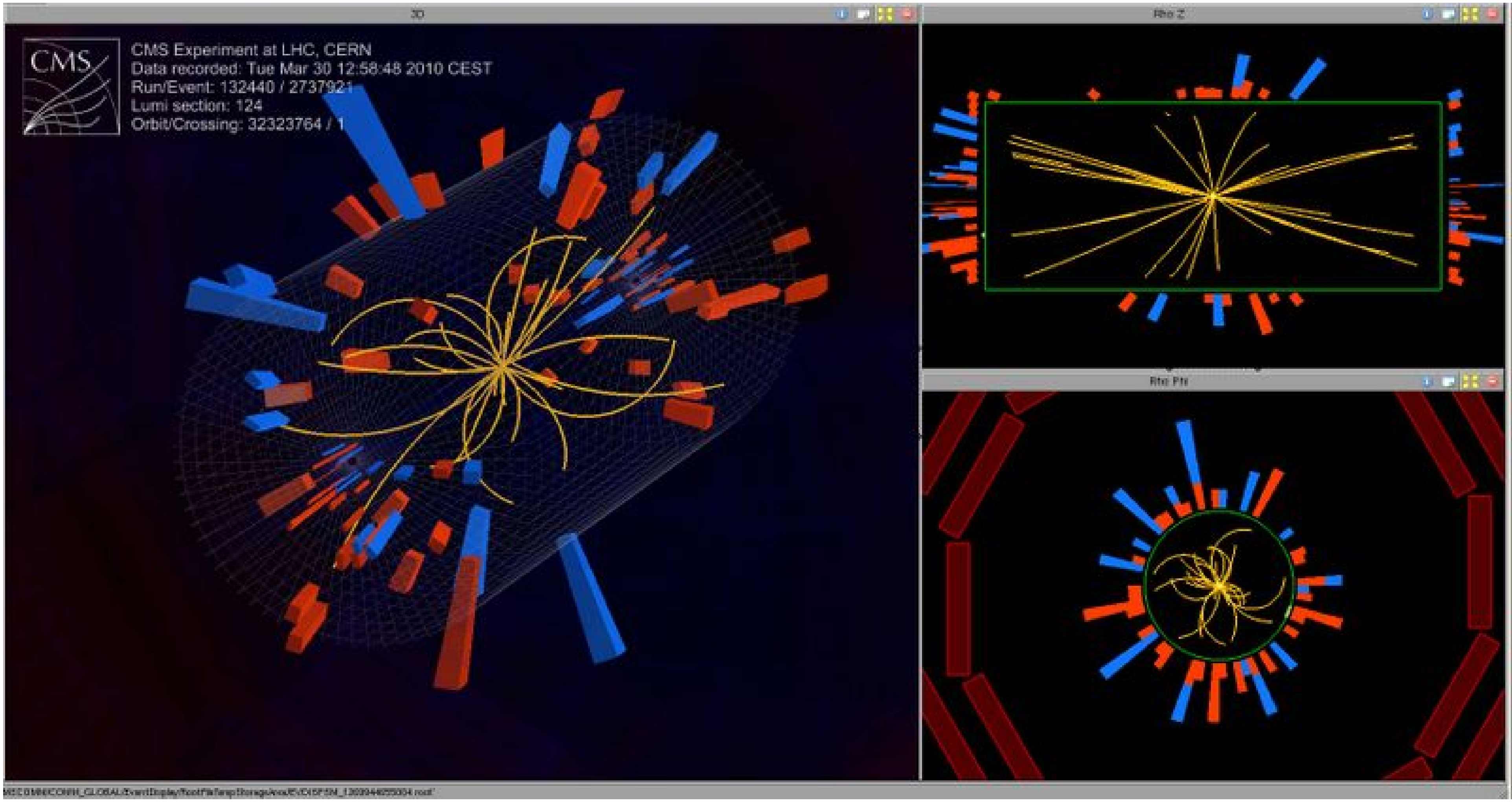
The CMS detector



Silicon tracker (pixels+strips) Lead tungstate crystal ECAL

Hermetic ($|\eta| < 5.2$) HCAL Muon system (RPC, DT, CSC) 3.8 T field

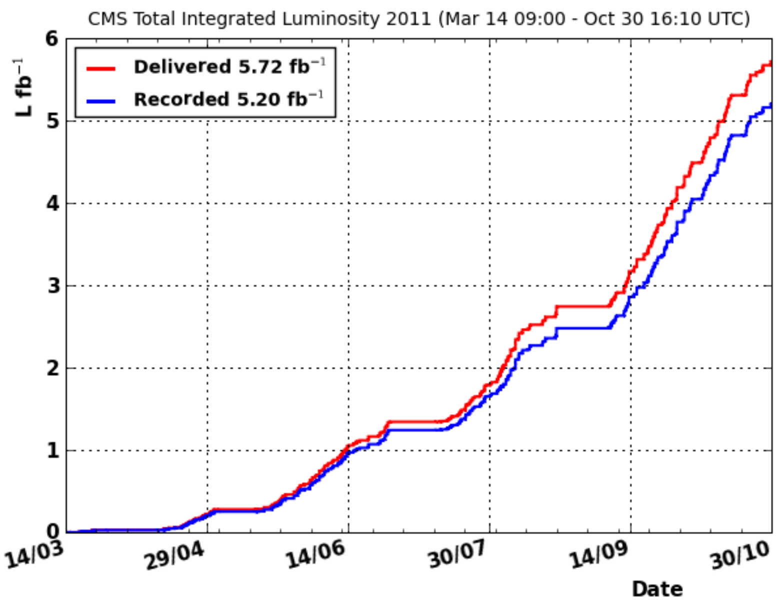
The detector at work

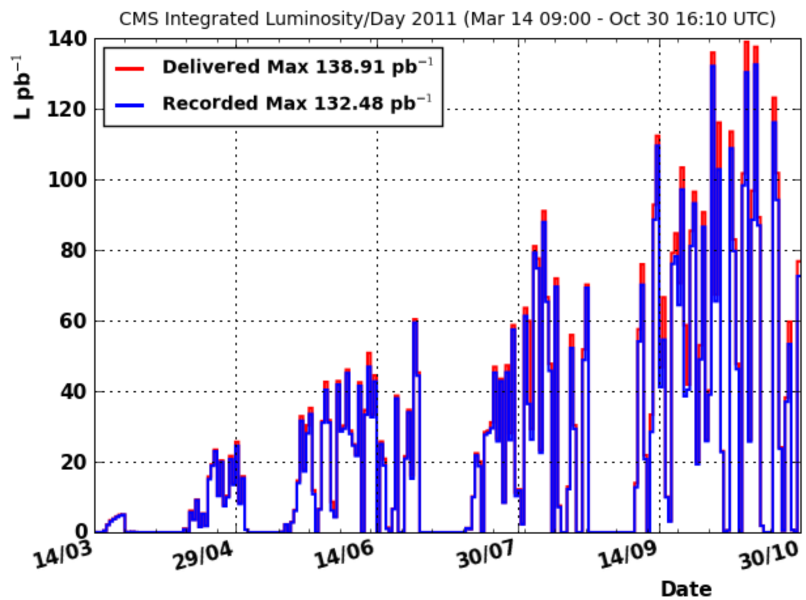


A minimum bias pp event at CMS

2011: $\sqrt{s} = 7$ TeV High pile-up (average at 15)

2011 data – pp mode



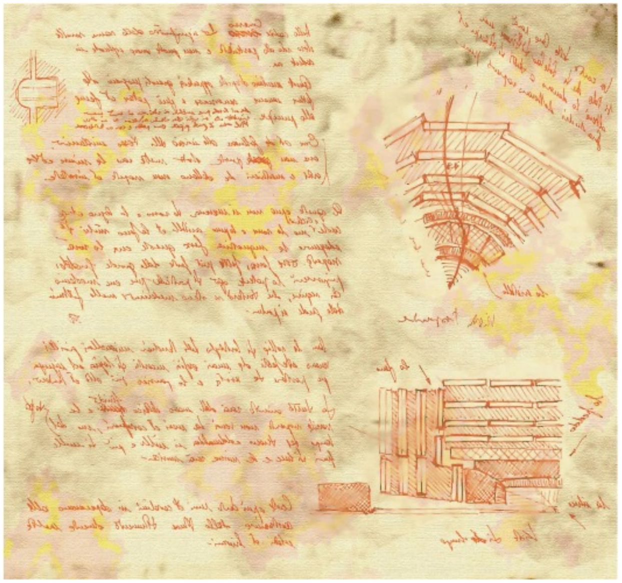


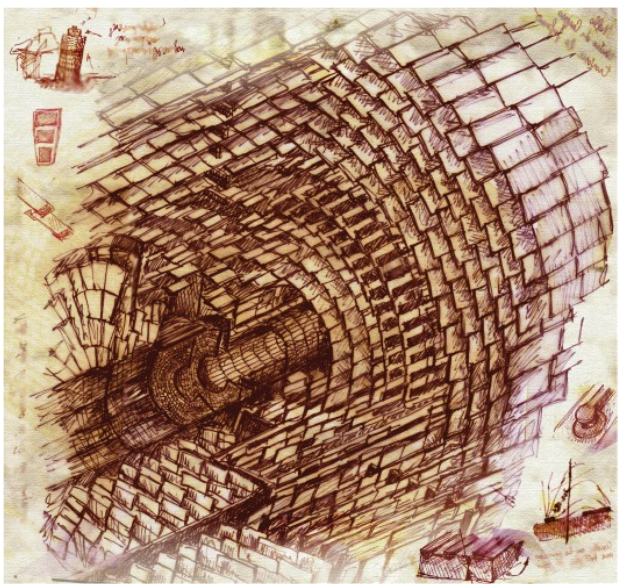
Mode than 5 fb^{-1} collected
More than 100 pb^{-1} per day towards the end

p-Pb test and pilot physics was not possible
Problems with proton injection line (septum)

To be repaired for next year, now running in Pb-Pb mode

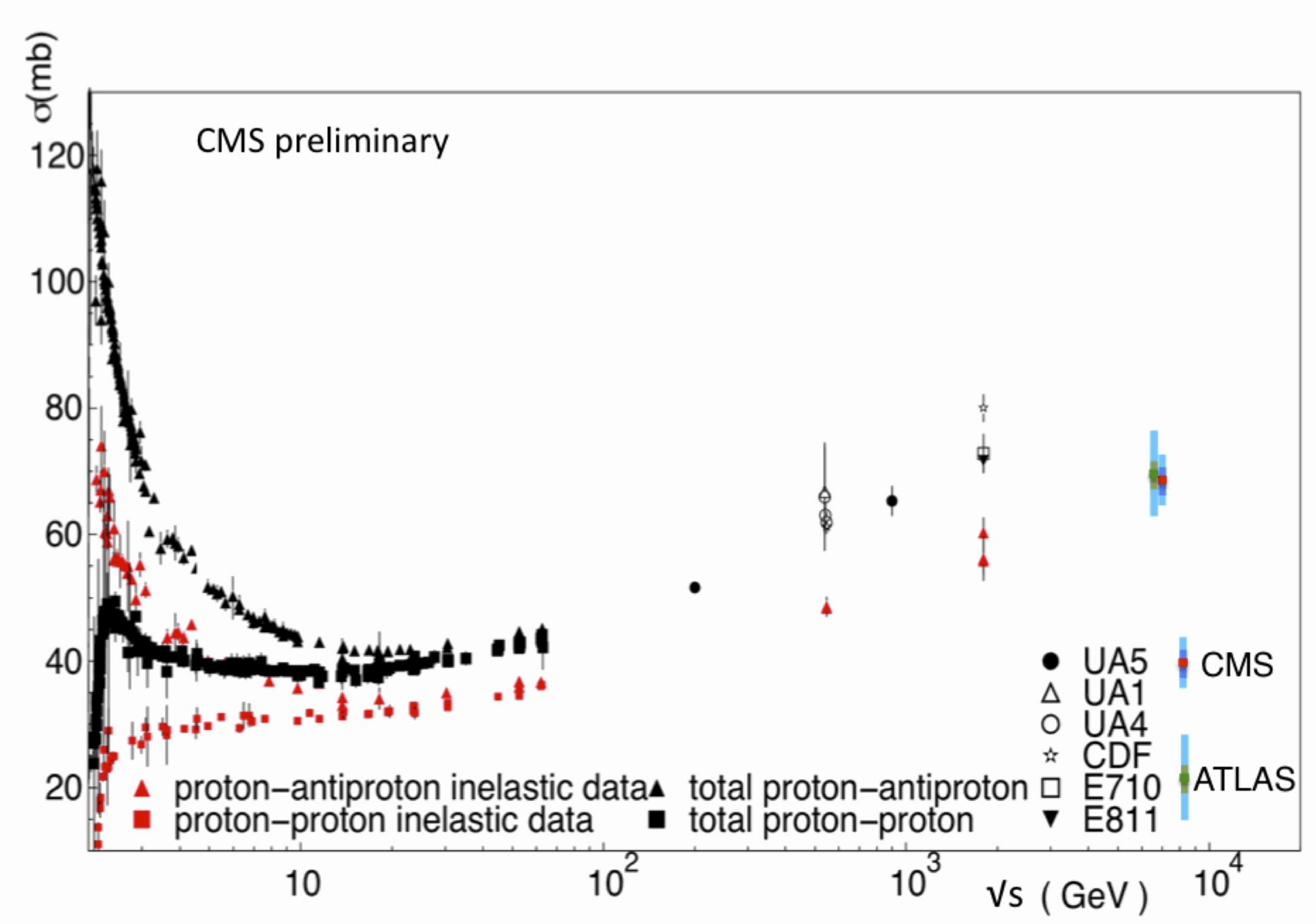
Physics





- Physics topics
  - QCD $\Rightarrow$ this talk
    - Hadrons
    - Jets
    - Photons
  - Forward and diffraction
  - Heavy ions $\Rightarrow$ Anna's talk
  - B physics
  - Electroweak
  - Top
  - Higgs
  - SUSY
  - Exotica

Inelastic cross section

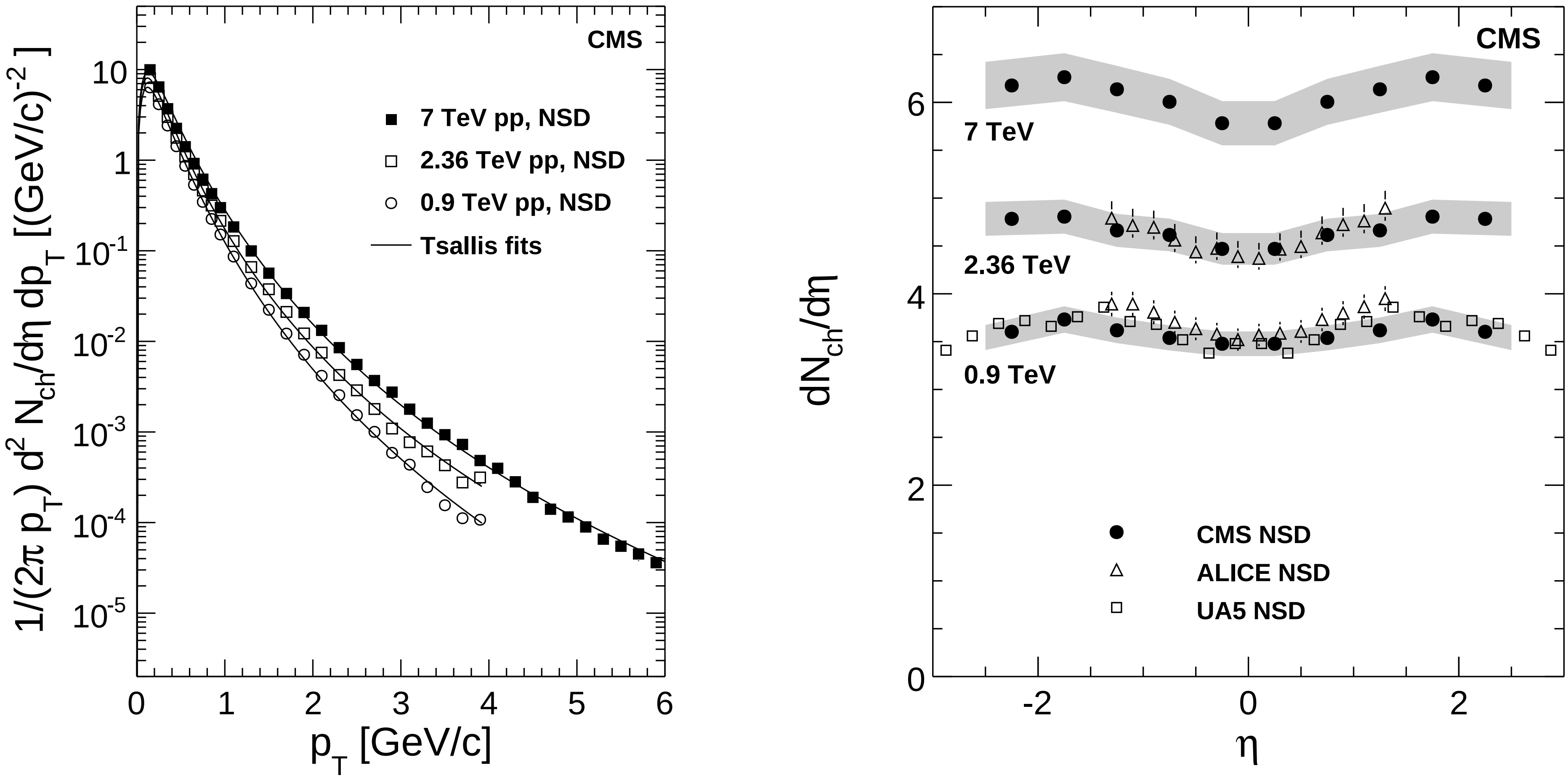


FWD-11-001

$$\sigma_{\text{inel}}(\text{pp}) = 68.0 \pm 2.0(\text{syst}) \pm 2.4(\text{lum}) \pm 4(\text{extrapolation})\text{mb}$$

By vertex counting using pile-up events

Spectra of charged hadrons



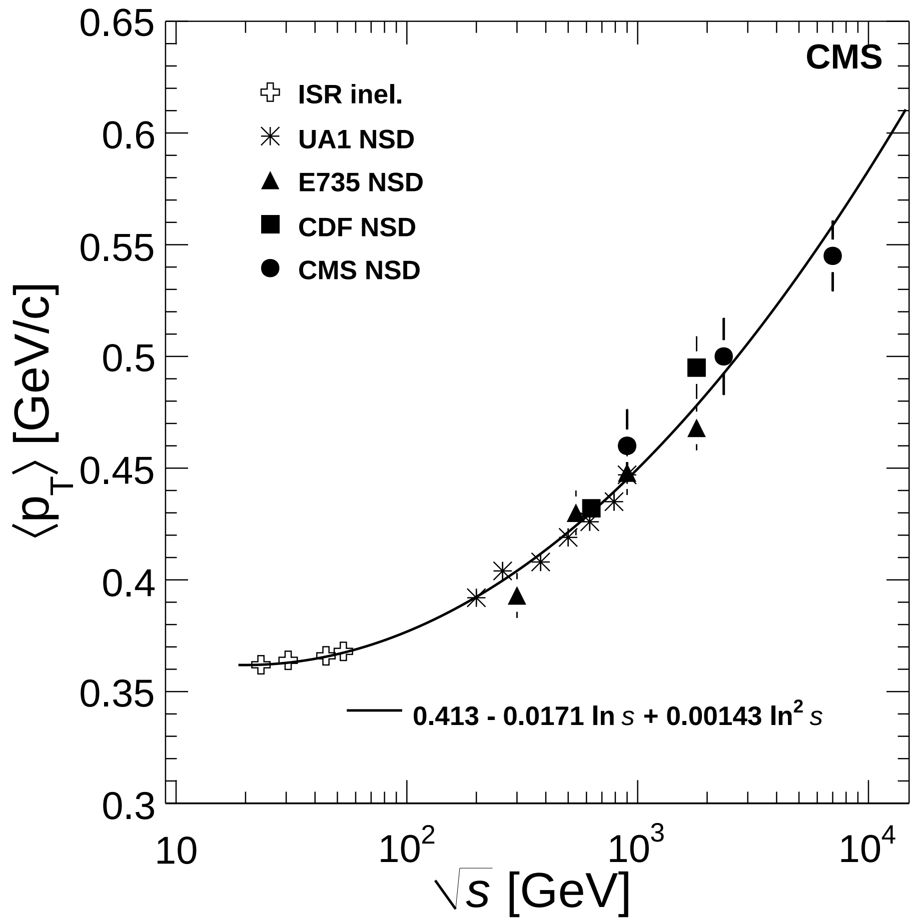
PRL 105 (2010) 022002

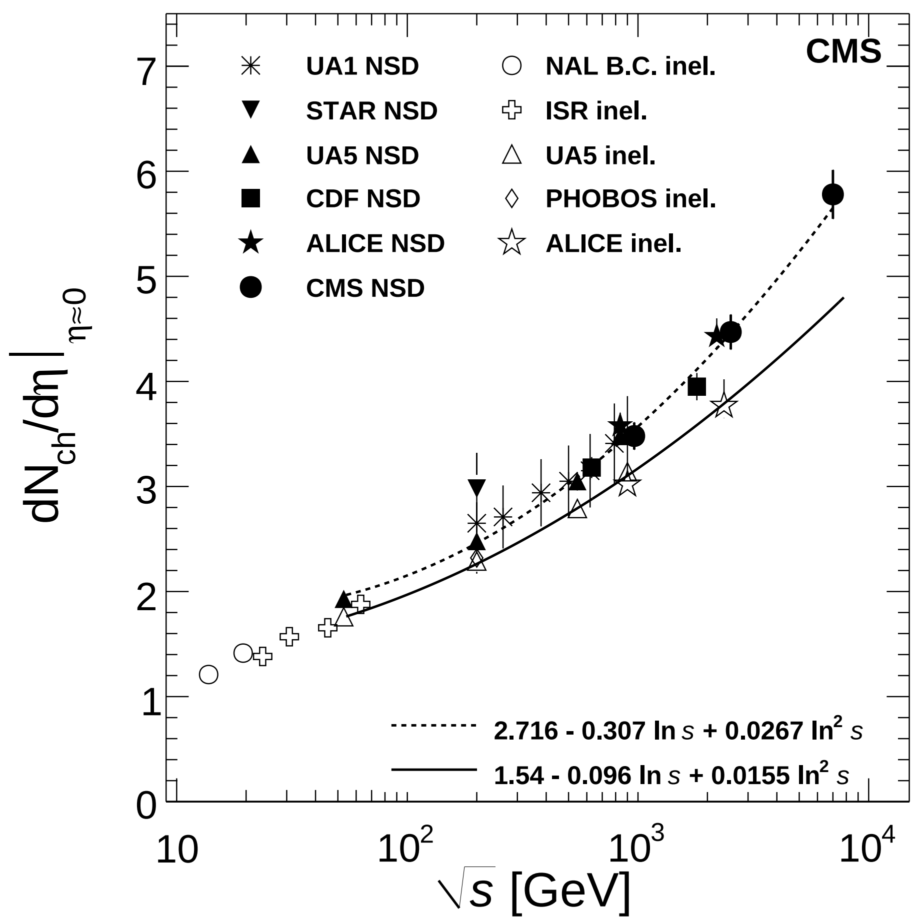
For $dN/d\eta$ combination of three methods

Full tracks; tracklets with bckg subtraction; hit counting with corr's

Tsallis fits: combination of low-p_T exponential and high-p_T power law

Spectra of charged hadrons – $\sqrt{s}$ dependence



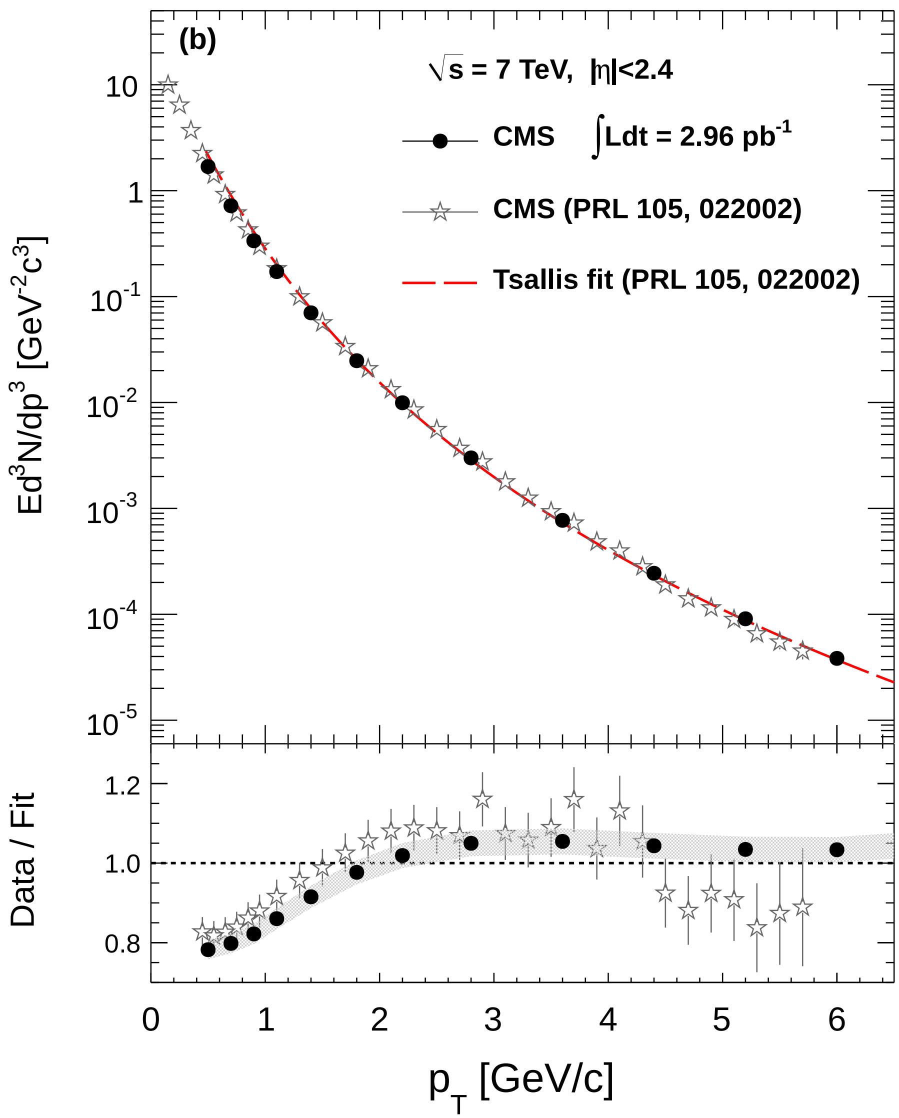


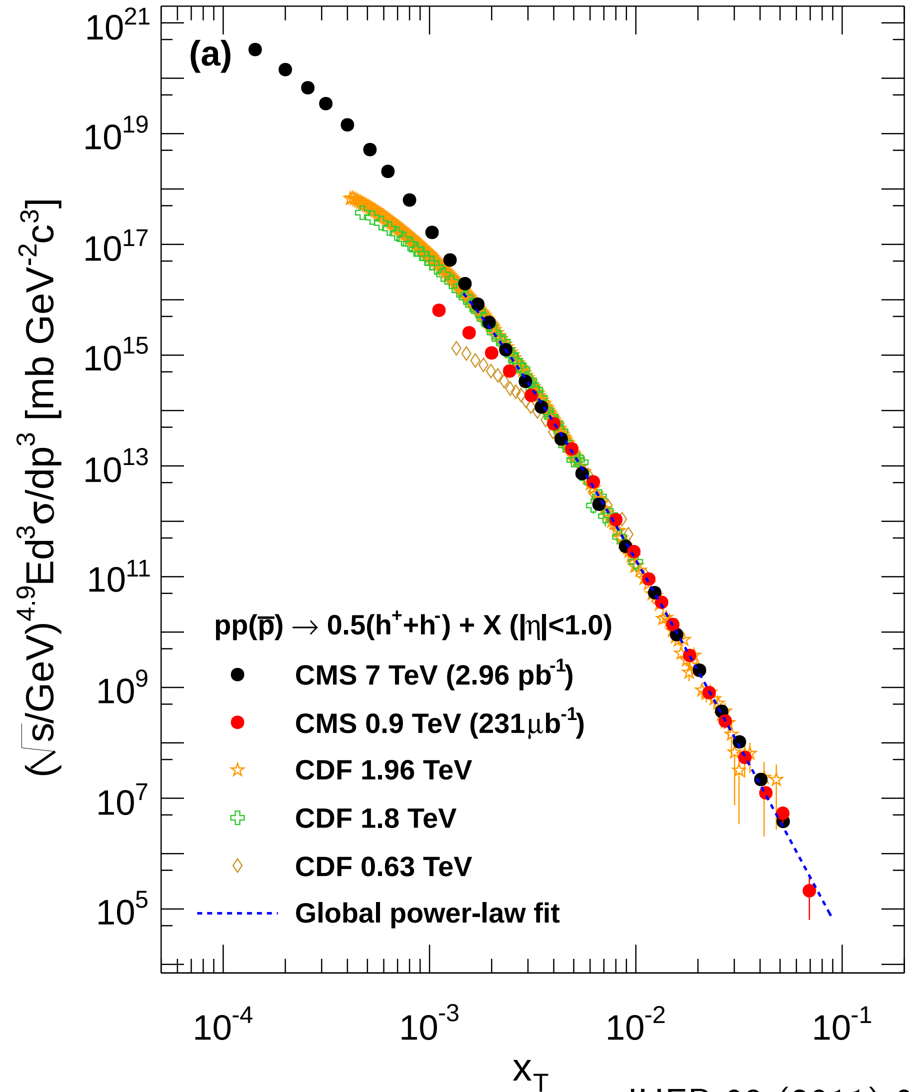
PRL 105 (2010) 022002

Higher $\langle p_T \rangle$, accelerated increase of $dN_{ch}/d\eta$ density

Input for theory

Spectra of charged hadrons – high p_T



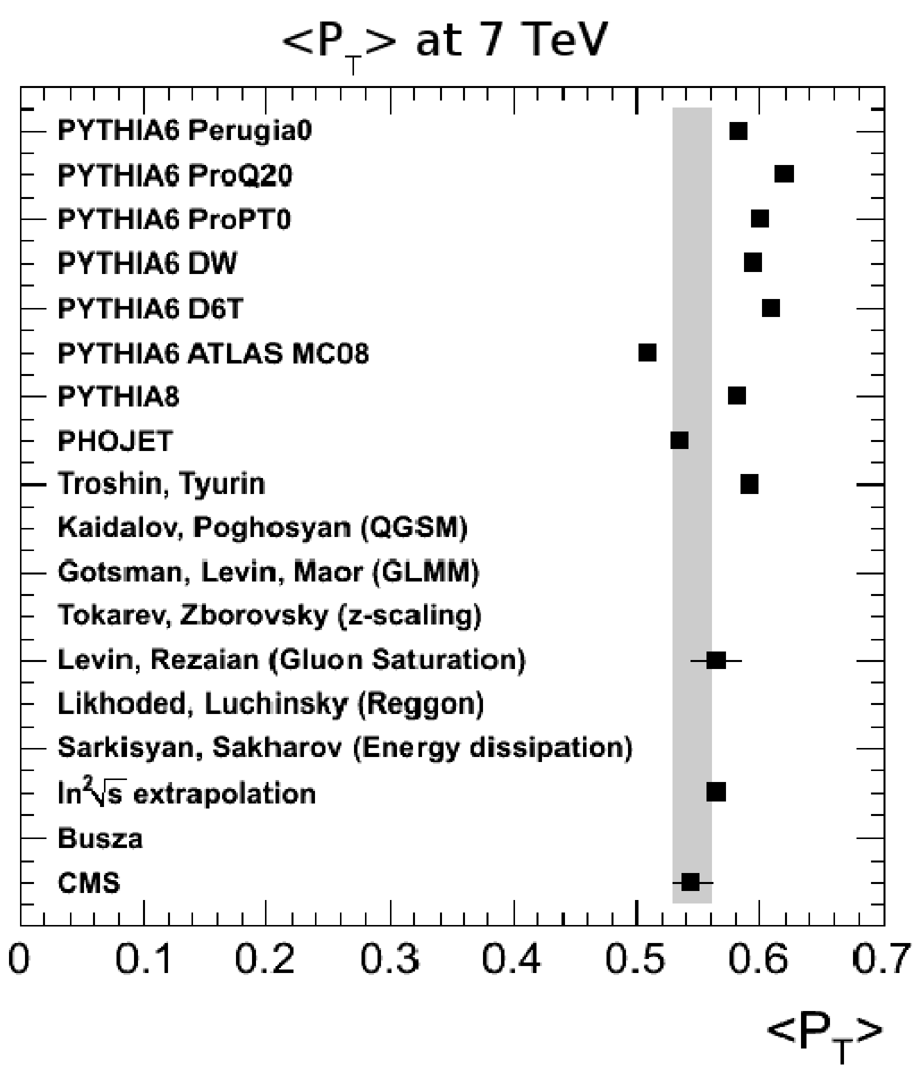


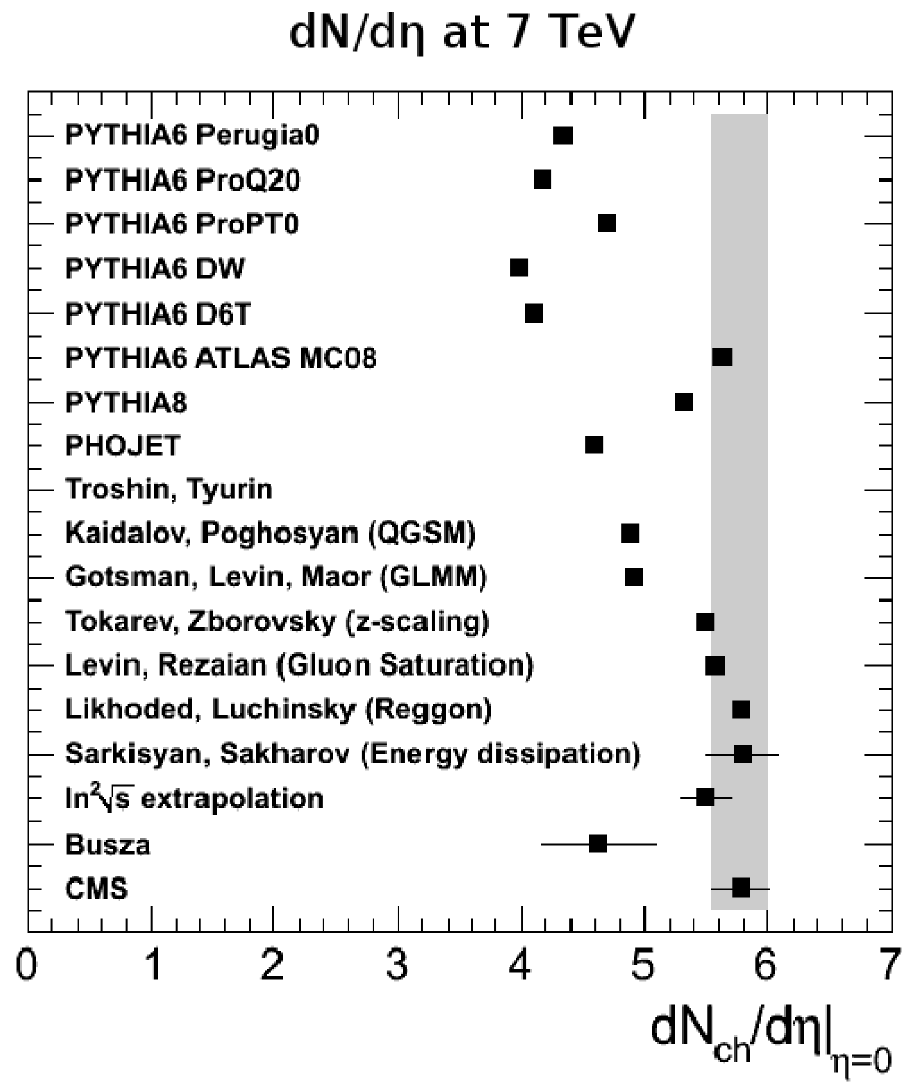
JHEP 08 (2011) 086

Jet triggers used to extend reach, nice match with first results

Power-law trend, flattening and high p_T is not seen, scaling in x_T

Spectra of charged hadrons – models?

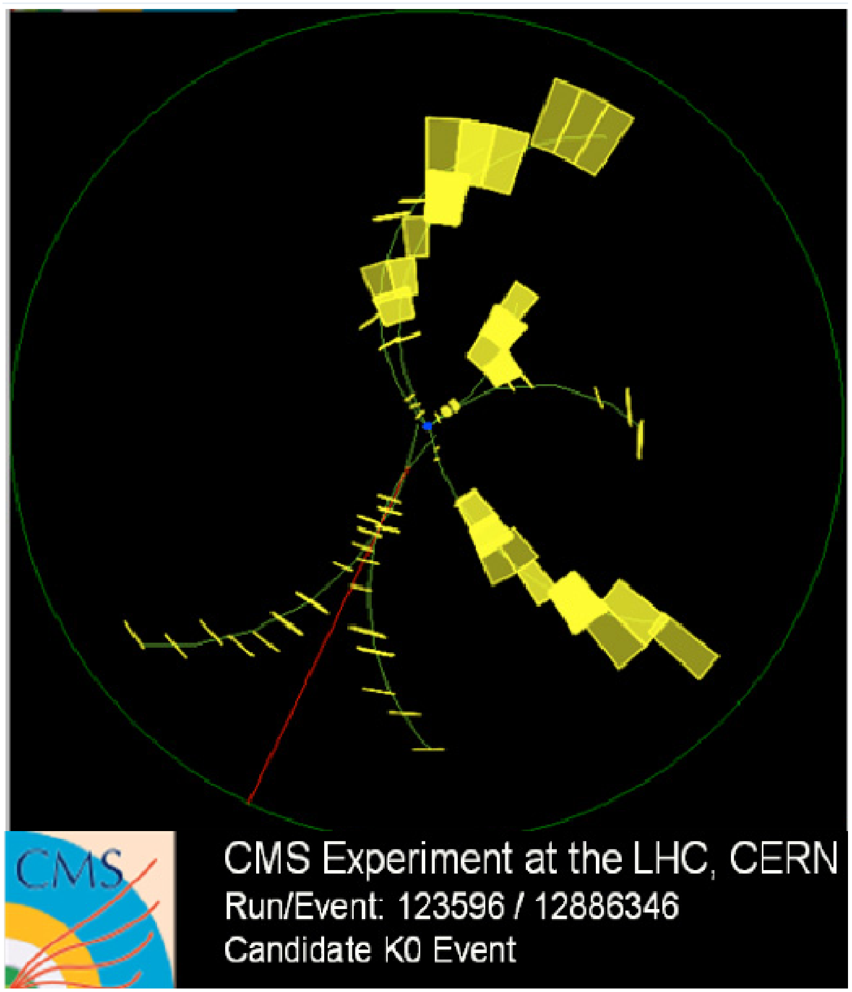




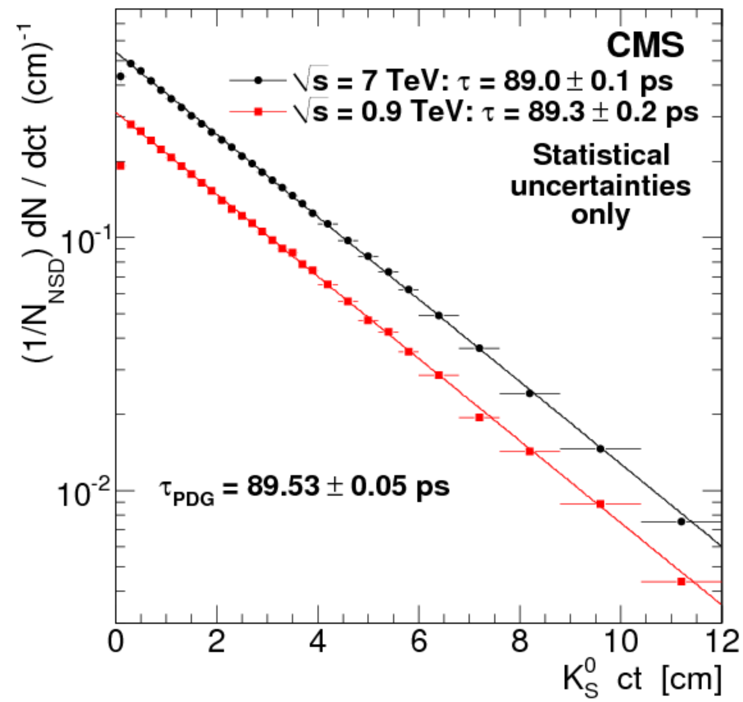
Pre-LHC tunes are usually off

Good agreement with some analytical models (saturation)

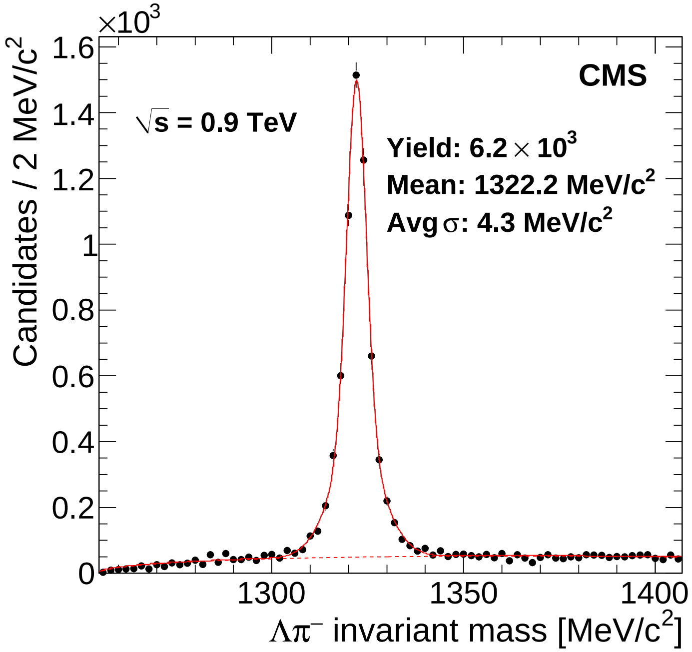
Spectra of strange hadrons

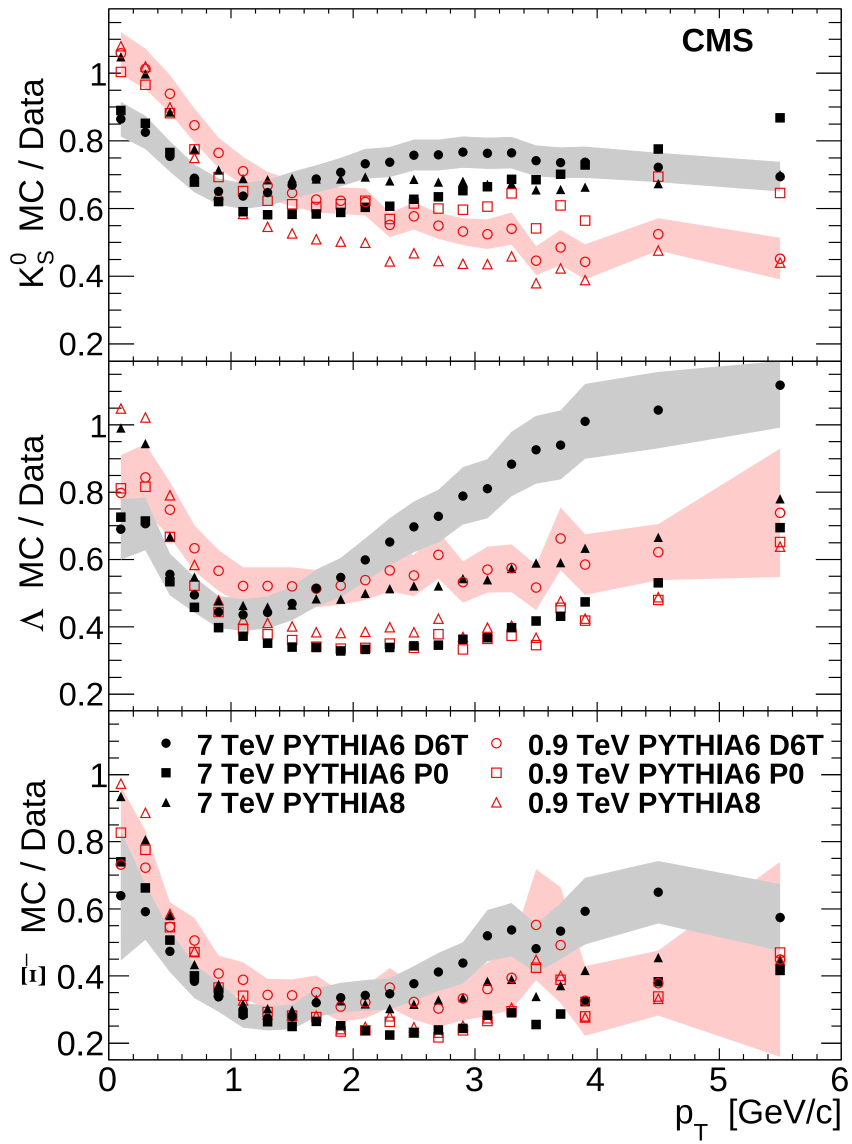


- Analysis
  - Reconstruction with decay topology $K^0_S \to \pi^+\pi^-$, $\Lambda \to p\pi^-$, $\overline{\Lambda} \to \overline{p}\pi^+$, $\Xi^- \to \Lambda\pi^-$, $\overline{\Xi}^+ \to \overline{\Lambda}\pi^+$
  - All results for $|y| < 2.0$
  - Reconstruction efficiencies are validated by lifetime measurements



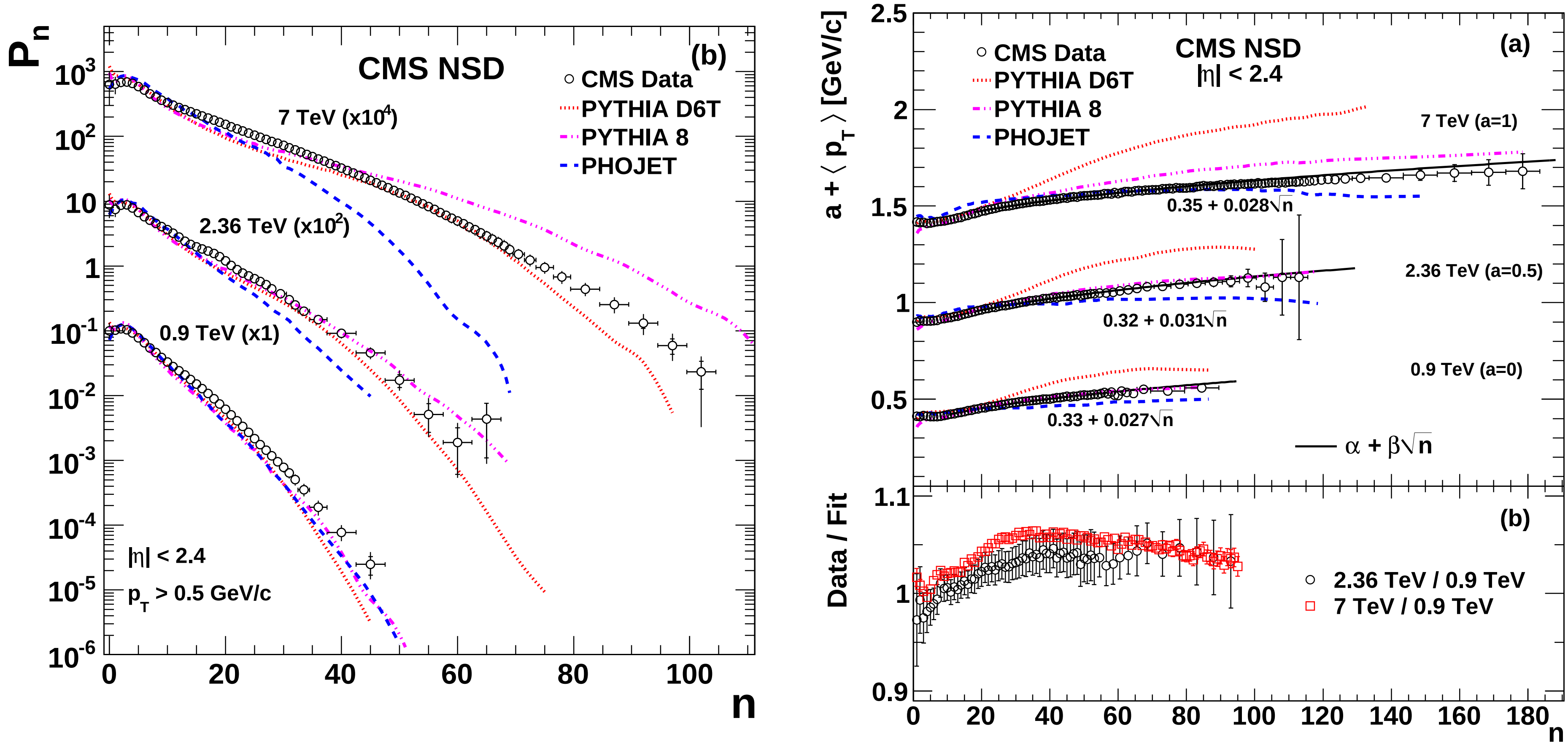
Spectra of strange hadrons – models?





- Strangeness
  - Significantly more strangeness is seen in data than in MC
  - Factor 3 for Ξ at 7 TeV
  - Discrepancy grows with increasing mass and $\sqrt{s}$
  - $\langle p_T \rangle$ is much better described

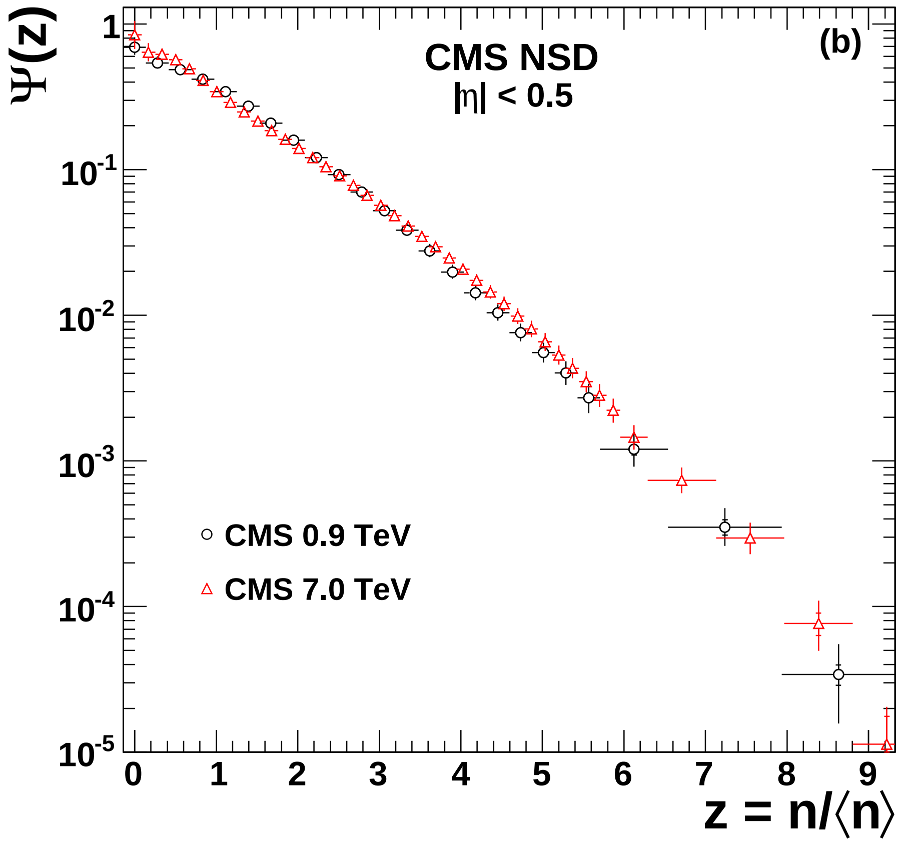
Event-by-event multiplicity

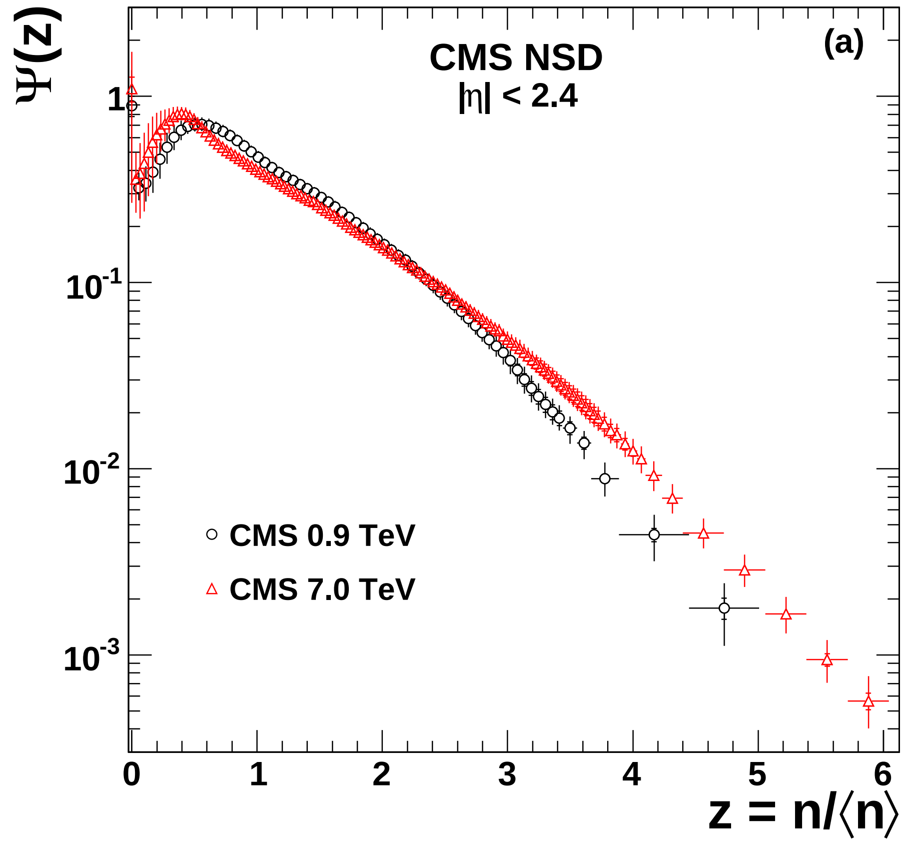


JHEP 01 (2011) 079

- Models
  - With varying success, no model gets everything right at 7 TeV
  - Pythia8 matches the total multiplicity,
    but predicts too many high p_T particles at large η

Event-by-event multiplicity

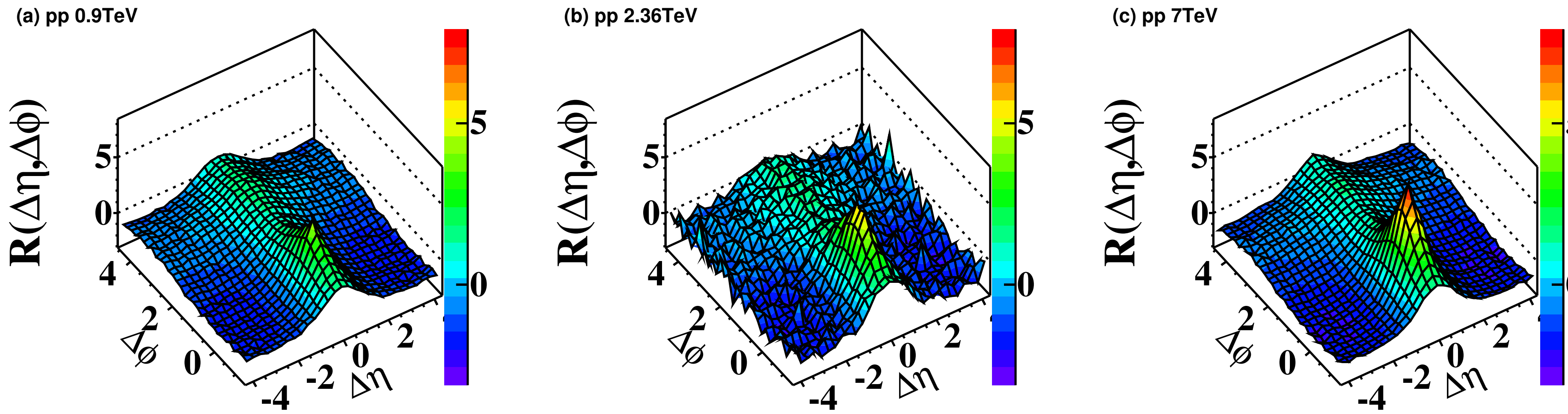




JHEP 01 (2011) 079

- KNO scaling
  - $\Psi(z) = \langle n \rangle P_n$ was shown to be independent of $\sqrt{s}$
  - True for $|\eta| < 0.4$, but it is violated for $|\eta| < 2.4$

Hadron correlations – angular – data

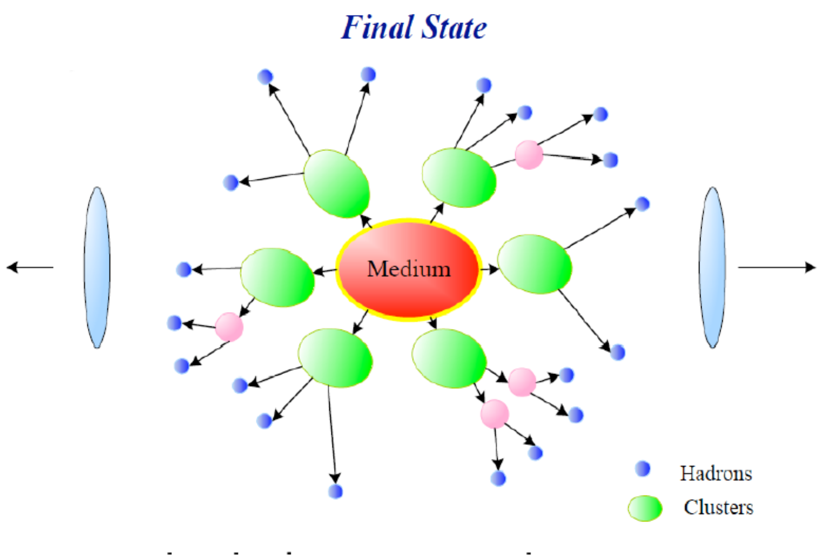


JHEP 09 (2010) 091

- Analysis
  - Particles tend to be produced correlated, in clusters
  - Extensive studies exist at lower energies
  - Count the number of track pairs in $(\Delta\eta, \Delta\phi)$ bins
    signal and background (mixed events with similar z_{vtx} and multiplicity N)
  - Look at the ratio
    $R(\Delta\eta, \Delta\phi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\phi)}{B_N(\Delta\eta,\Delta\phi)} - 1\right)\right\rangle_N$

Gaussian in $\Delta\eta$, broader at large $\Delta\phi$

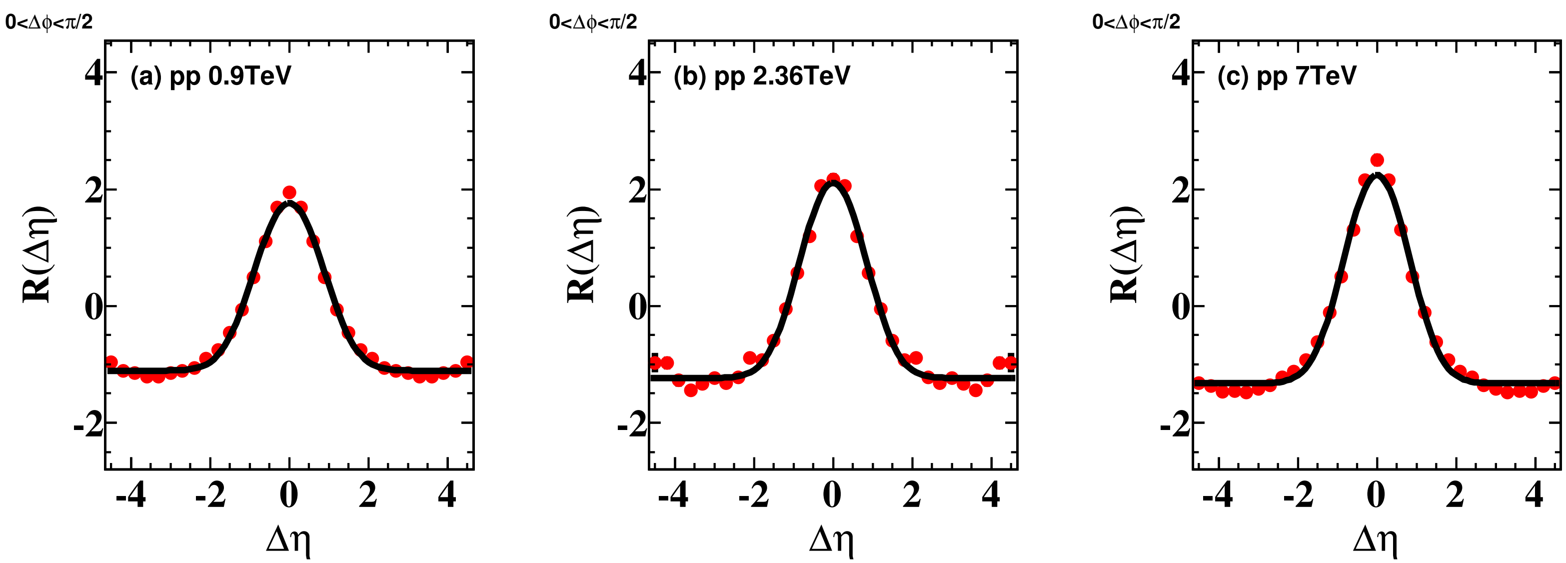
Hadron correlations – angular – a simple model



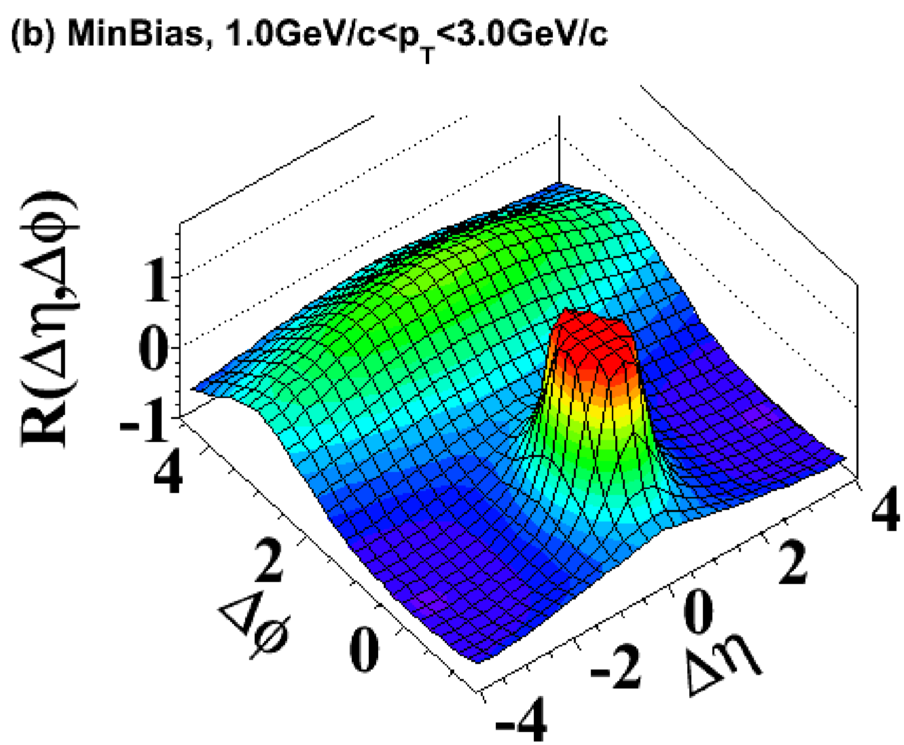
- Independent cluster model
  - Clusters are produced independently
  - They decay isotropically into hadrons
  - Only two parameters:
    cluster size K_{eff}, cluster width δ

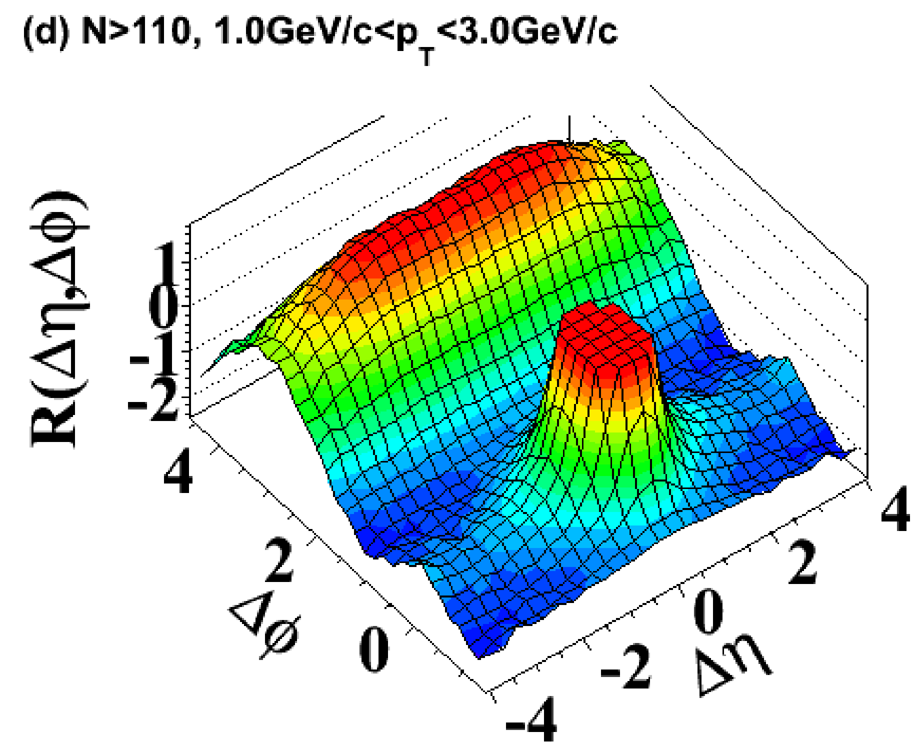
$$R(\Delta\eta) = (K_{eff} - 1)\left[\frac{\Gamma(\Delta\eta)}{B(\Delta\eta)} - 1\right]$$

$$\Gamma(\Delta\eta) \propto \exp\left[-\frac{(\Delta\eta^2)}{4\delta^2}\right]$$



Hadron correlations – multiplicity dependence



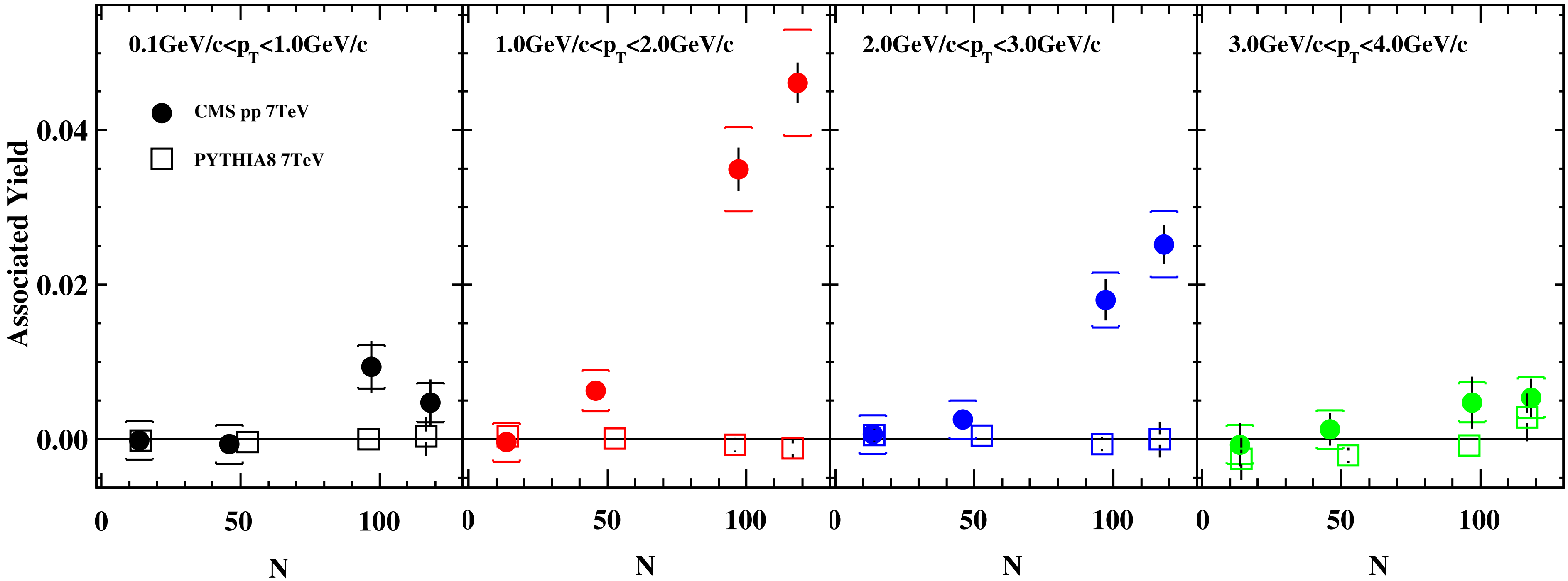


JHEP 09 (2010) 091

Pronounced new structure at large $\Delta\eta$ at $\Delta\phi \approx 0$

Effect is maximal in the $1 < p_T < 3$ GeV/c range

Hadron correlations – multiplicity dependence



JHEP 09 (2010) 091

Associated yield for the near-side of the correlation function integrated over the region of $2.0 < |\Delta\eta| < 4.8$

Origin of the effect? Likely QCD

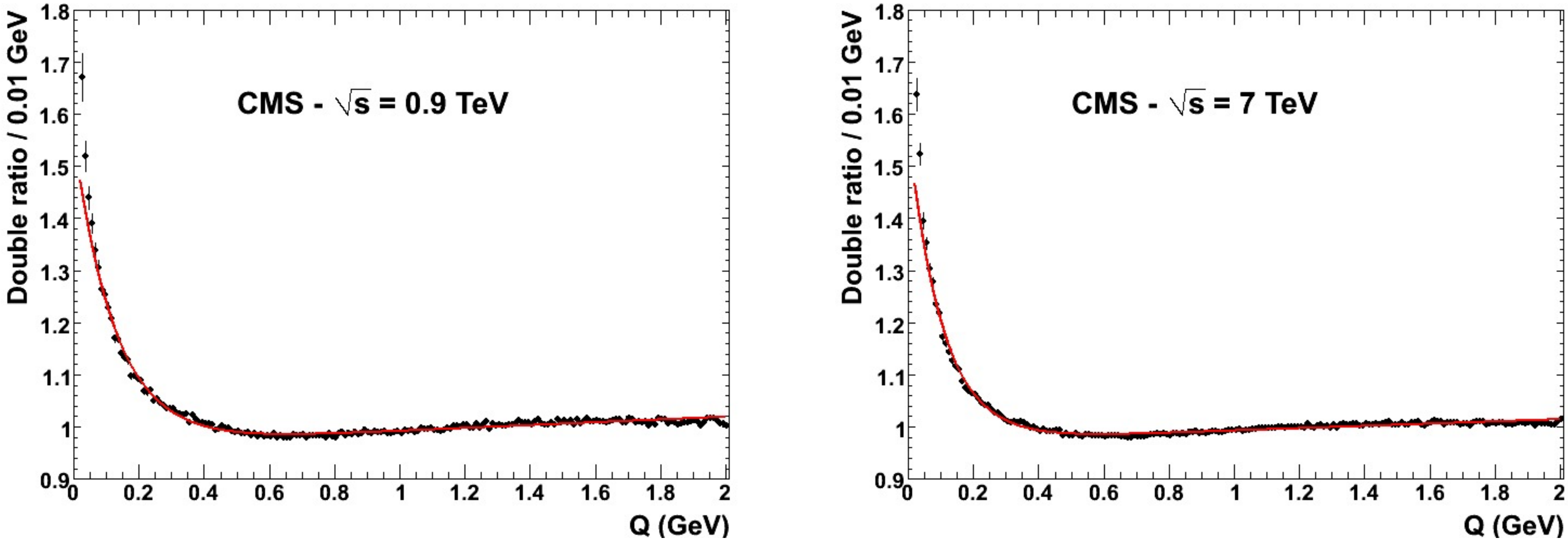
Hadron correlations – Bose-Einstein

- Analysis
  - Correlation between identical bosons
  - The size of the correlated emission region can be inferred
  - What to measure? Difference of four-vectors, $Q = \sqrt{-(p_1 - p_2)^2}$
  - Parametrization
    $R(Q) = C\,[1 + \lambda\Omega(Qr)]\,(1 + \delta Q)$
    effective radius r, strength λ, long range correlation δ
    $\Omega(Qr)$ is the Fourier transform of the emission region

- Uncorrelated background distributions?
  - pairs from same event
    opposite charge; opposite charge with one track $\mathbf{p}$ inverted; same charge with $\mathbf{p}$ inverted; same charge with $\mathbf{p}$ rotated in the transverse plane
  - pairs from different events
    random; similar $dN/d\eta$; similar total invariant mass of charged particles

Combined reference sample was used

Hadron correlations – Bose-Einstein

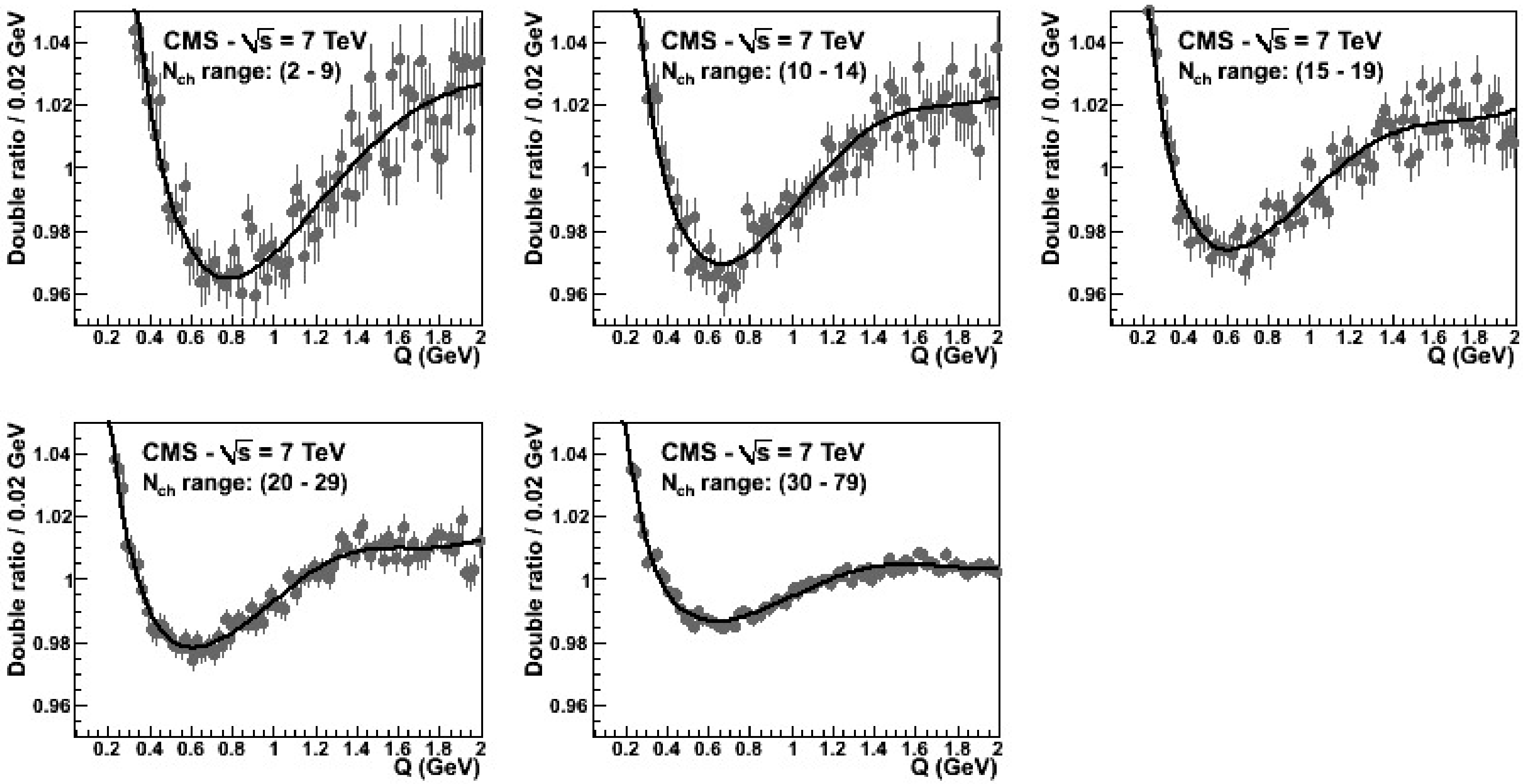


JHEP 05 (2011) 029

Ratio of signal and uncorrelated background distributions
Combined reference sample is used
Extracted radii in the 1.5 – 2 fm range, $\lambda \approx 0.62$

Exponential function is favored, $\Omega(Qr) = e^{-Qr}$

Hadron correlations – Bose-Einstein



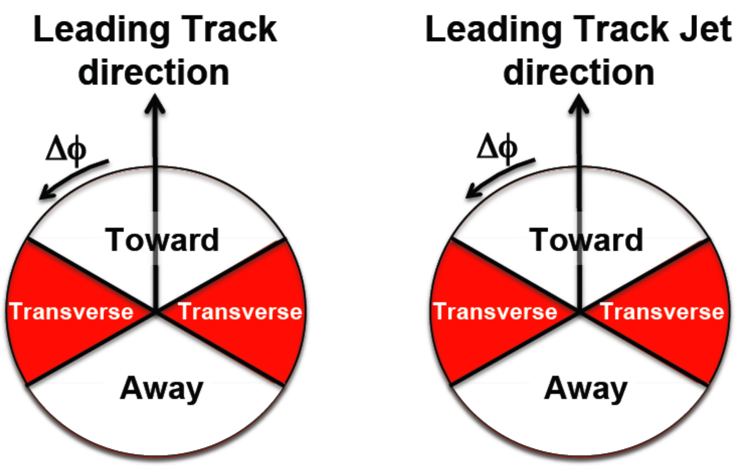
JHEP 05 (2011) 029

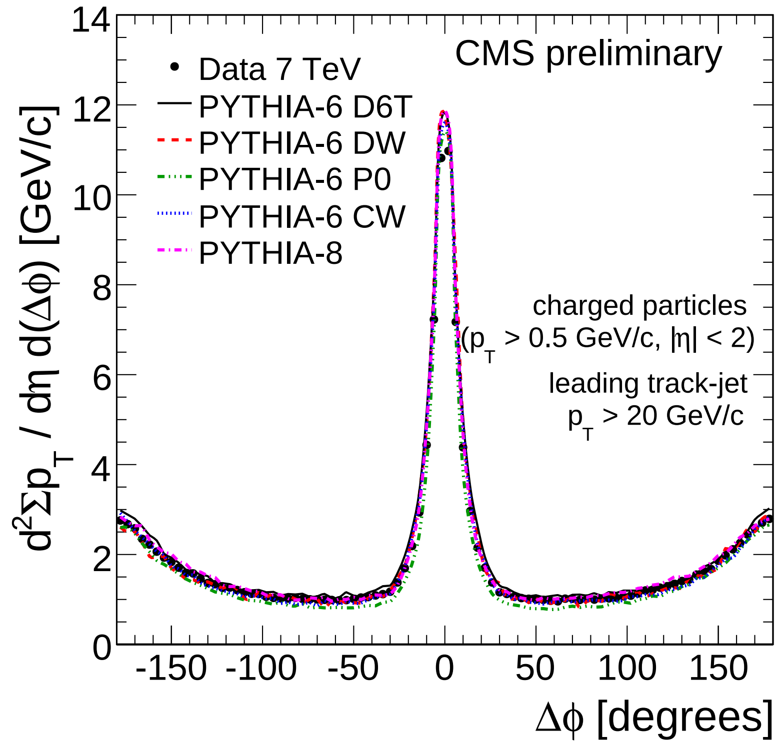
Dip?

Fit with a parameterization describing the time evolution of the source by means of a one-sided asymmetric Levy distribution

T. Csörgő et al, PLB 663 (2008) 214

Underlying event



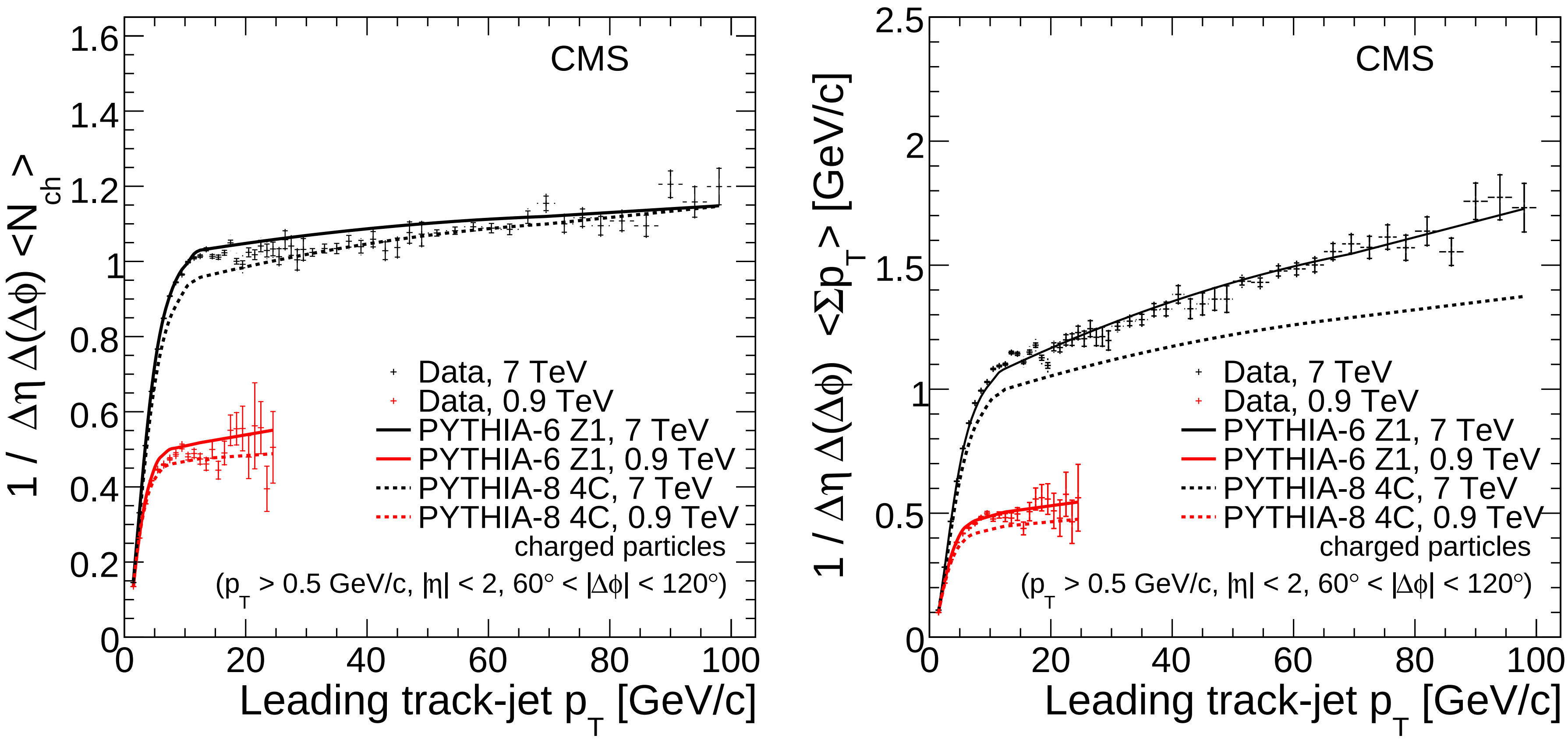


Look at particle production wrt to a high energy object (track or jet), mostly in transverse direction

Important field for MC tuning, understanding of the interaction process

Sensitive to new effects, e.g. multi-parton interactions

Underlying event



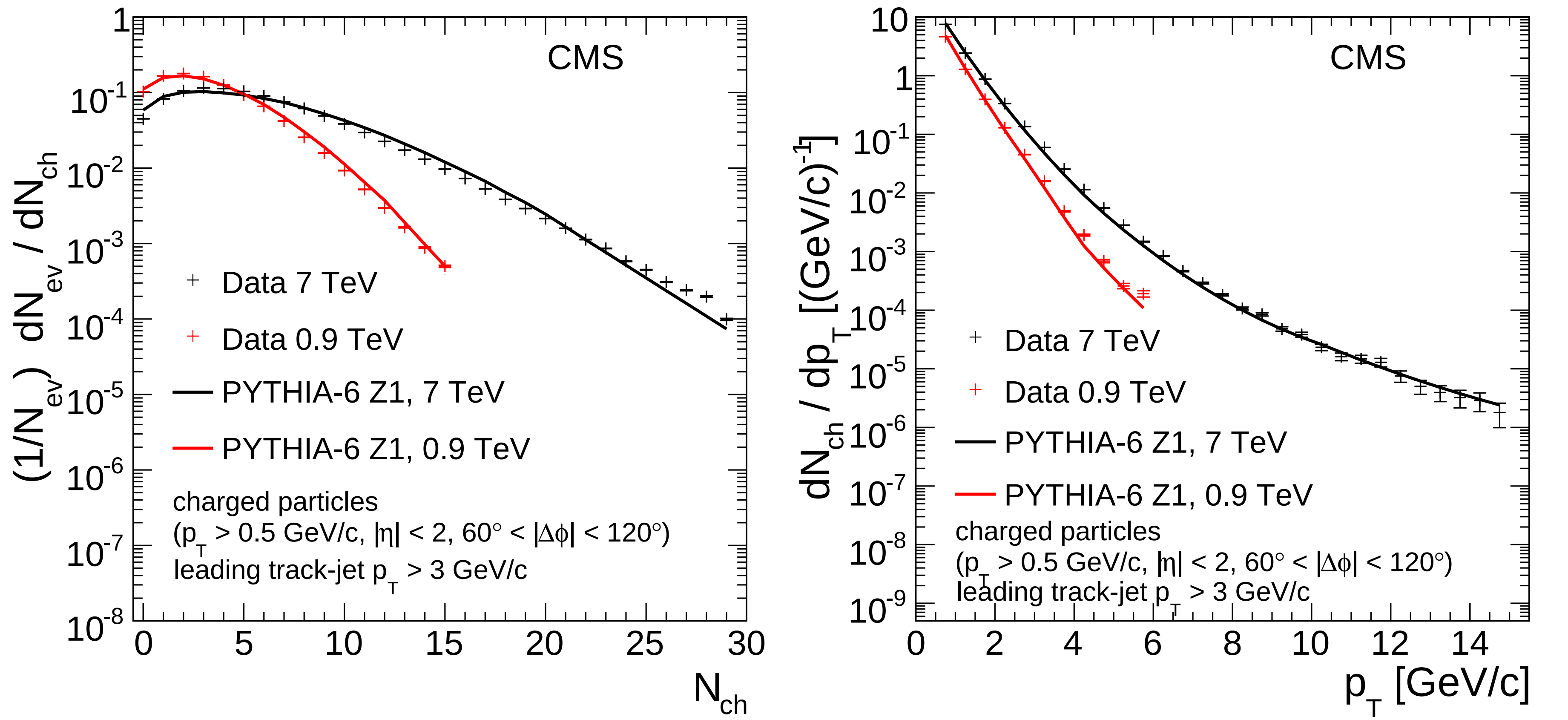
JHEP 09 (2011) 109

Particle densities, sum of p_T in the transverse region

The hard scale of the event is defined by the hardest track-jet

UE activity shows a sharp increase up to p_T of 10 GeV

Underlying event



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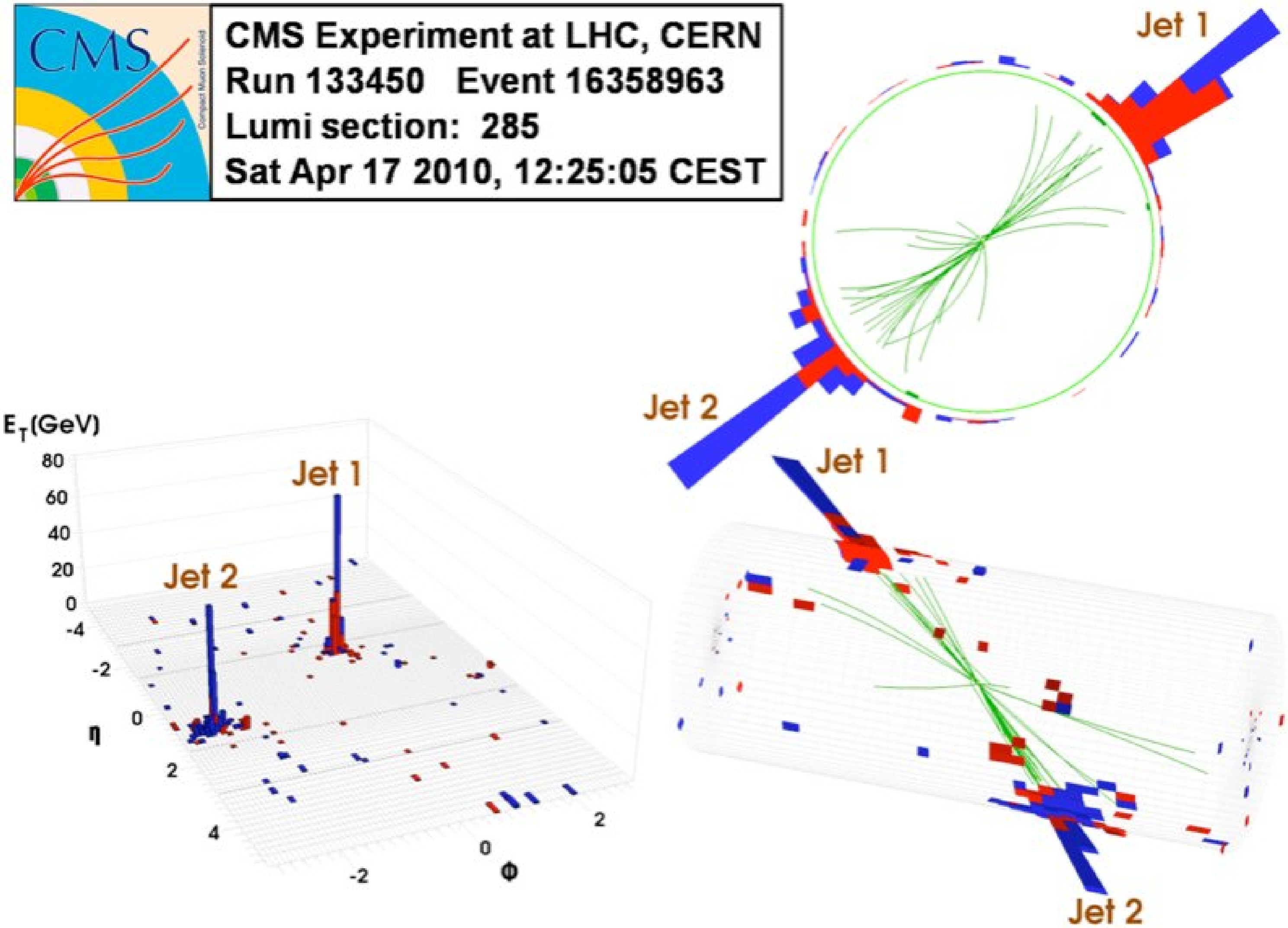
Other event properties

New Pythia tunes based on these and previous data

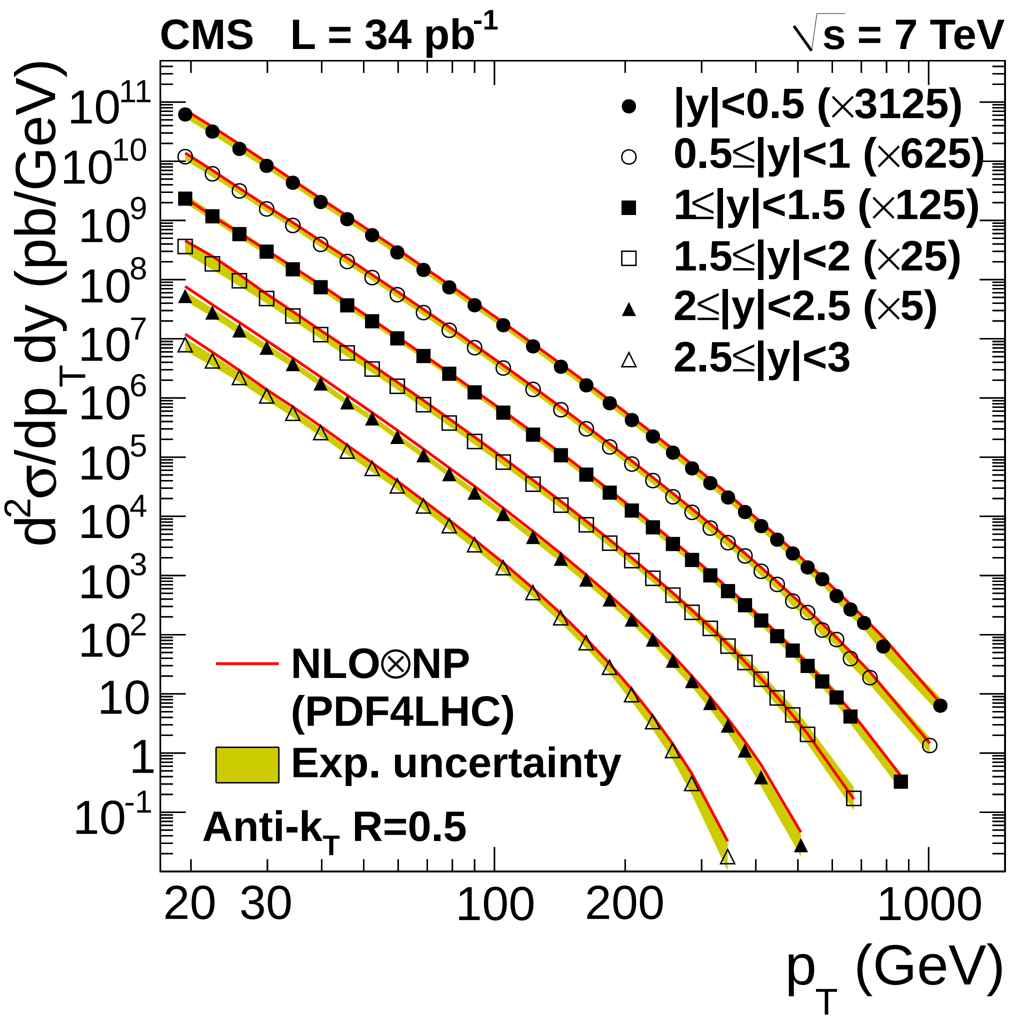
Jets



Sophisticated reco (particle flow)

Jet clustering, energy calibration, scale, resolution, uncertainties

Inclusive jet cross section

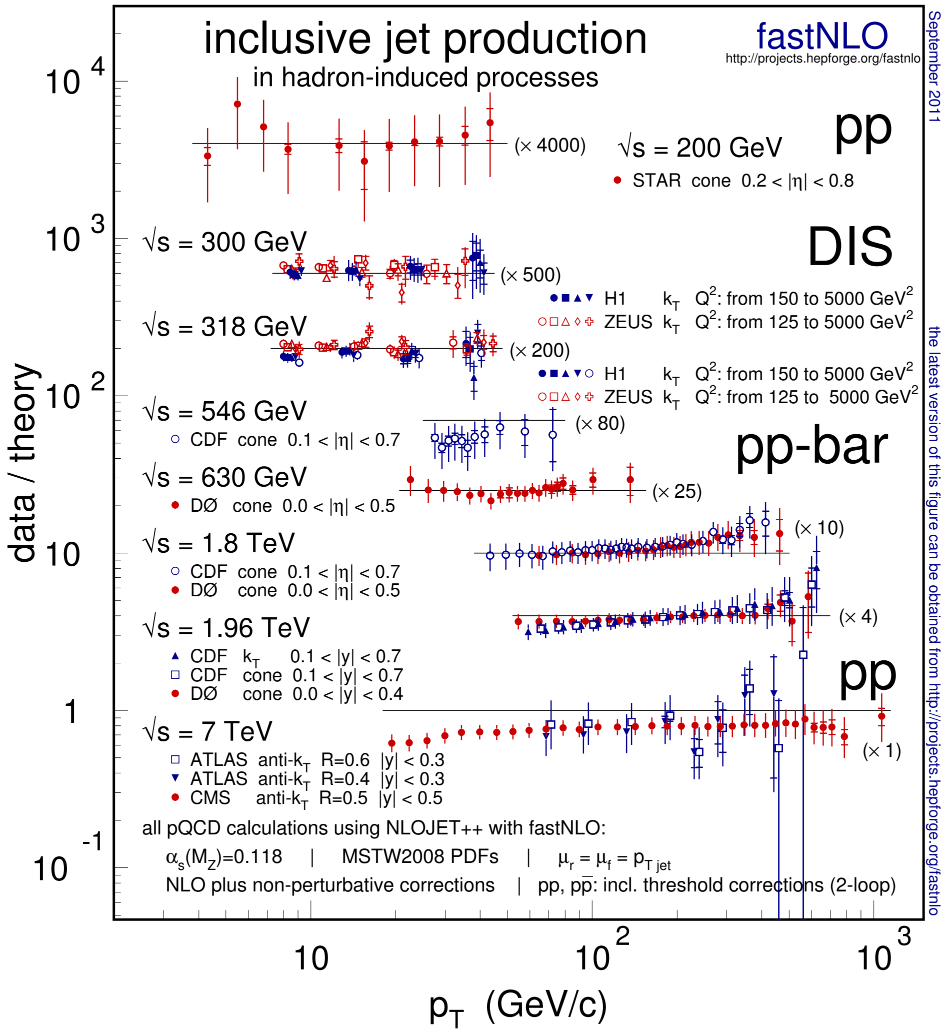


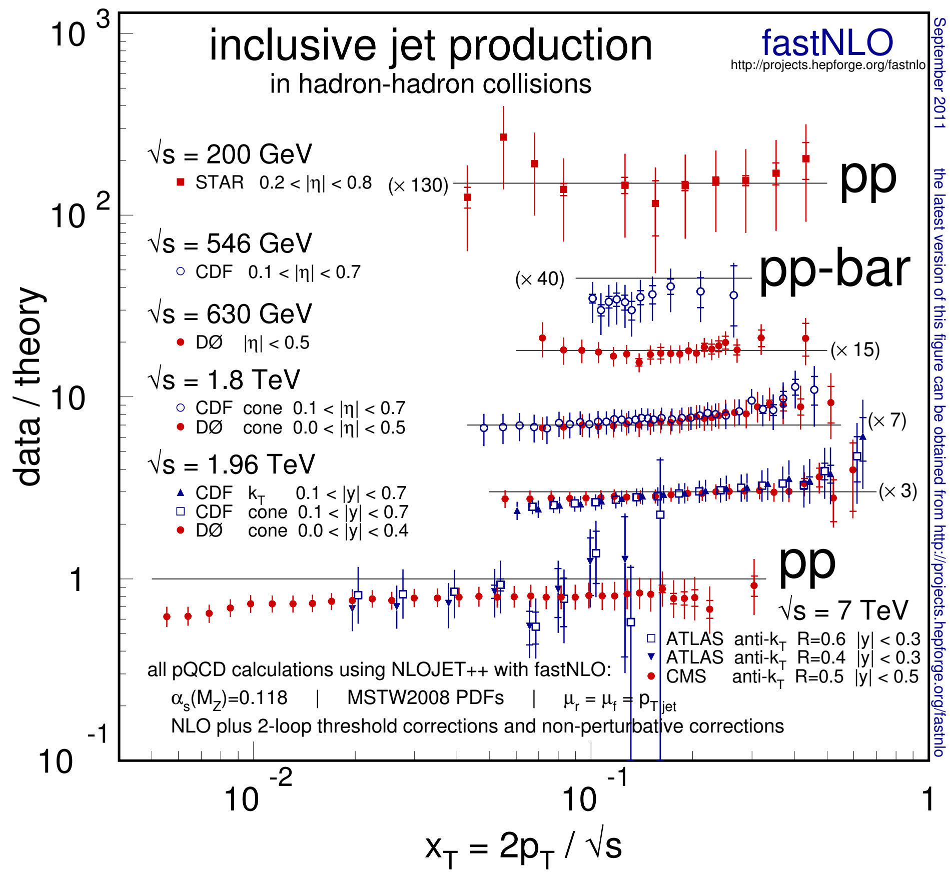
- Analysis
  - Anti-k_T particle flow jets with R $= 0.5$
  - Inclusive jet spectra are in good agreement with NLO theory
  - Extending below 20 GeV thanks to novel reco algo
  - Extending up to $|y| < 3.0$; there are results in the forward region

PRL 107 (2011) 132001

More to come with this year's data

Inclusive jets

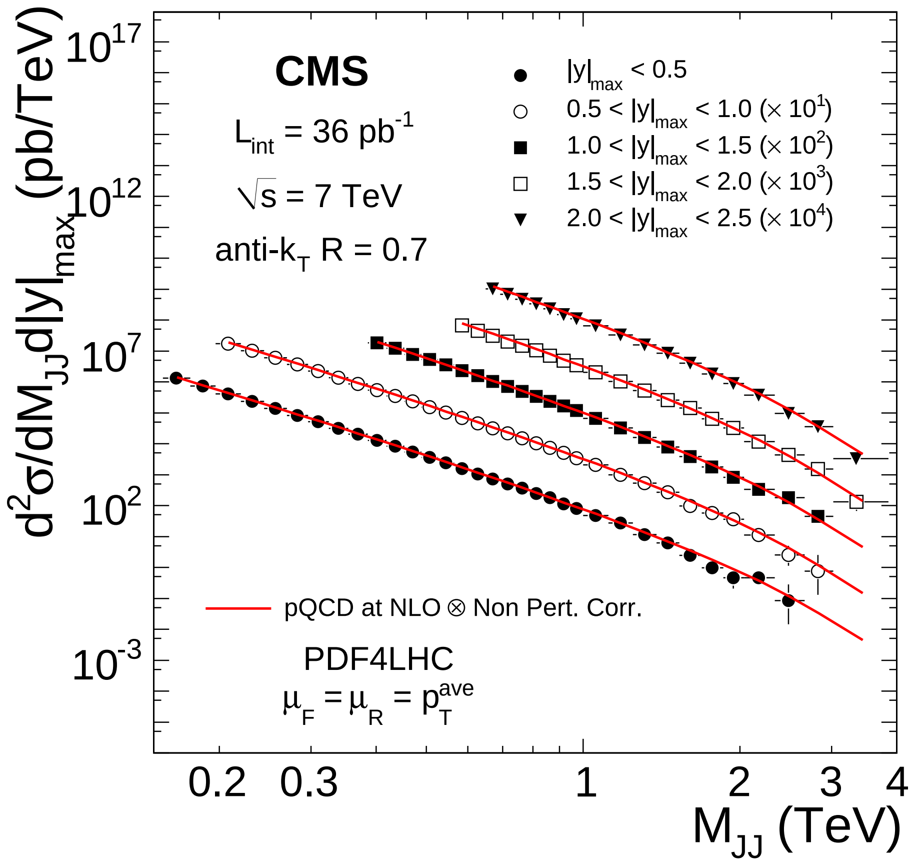




arXiv:1109.1310

The big picture

Dijets cross section

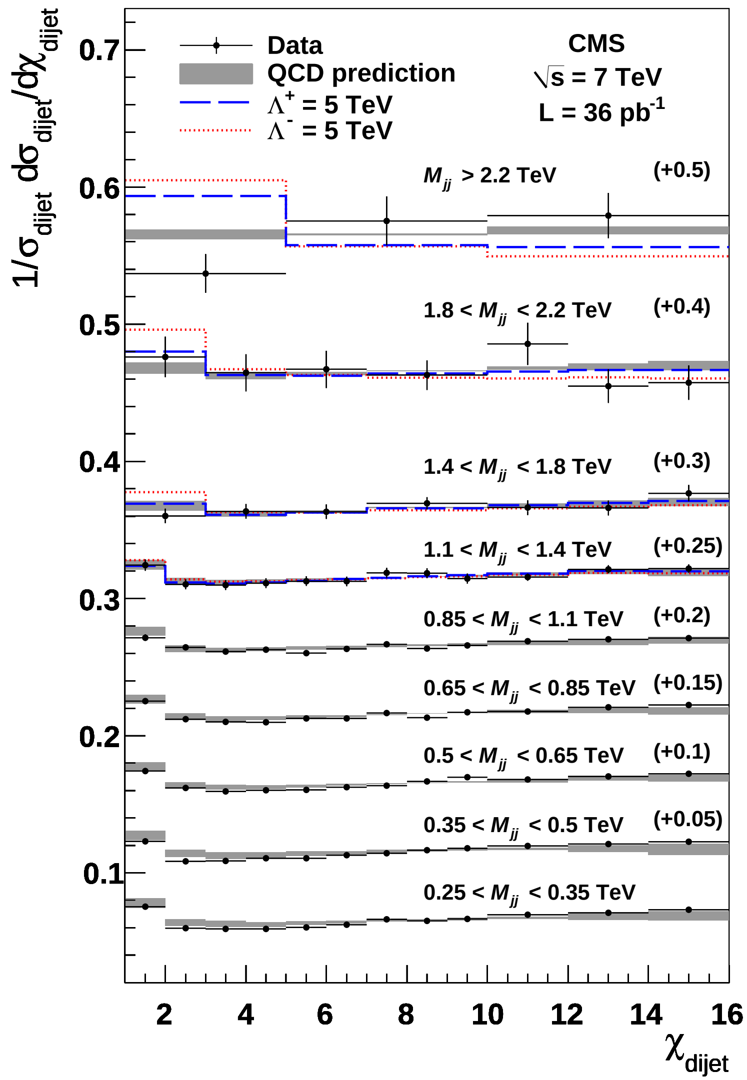


PLB 700 (2011) 187

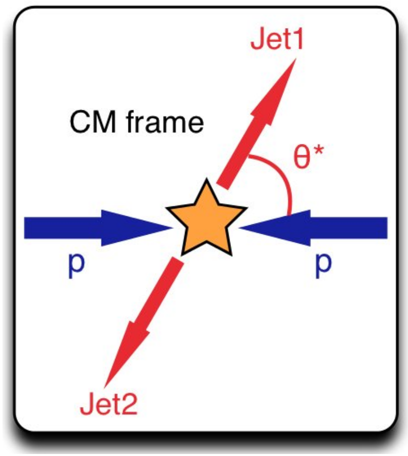
- Analysis
  - Anti-k_T particle flow jets with R $=$ 0.7
  - Again good agreement with NLO theory
  - Mass range from 0.16 to 3.5 TeV
  - Extending up to $|y|_{max} < 3.0$

More to come with this year's data

Dijet angular distributions



PRL 106 (2011) 201804

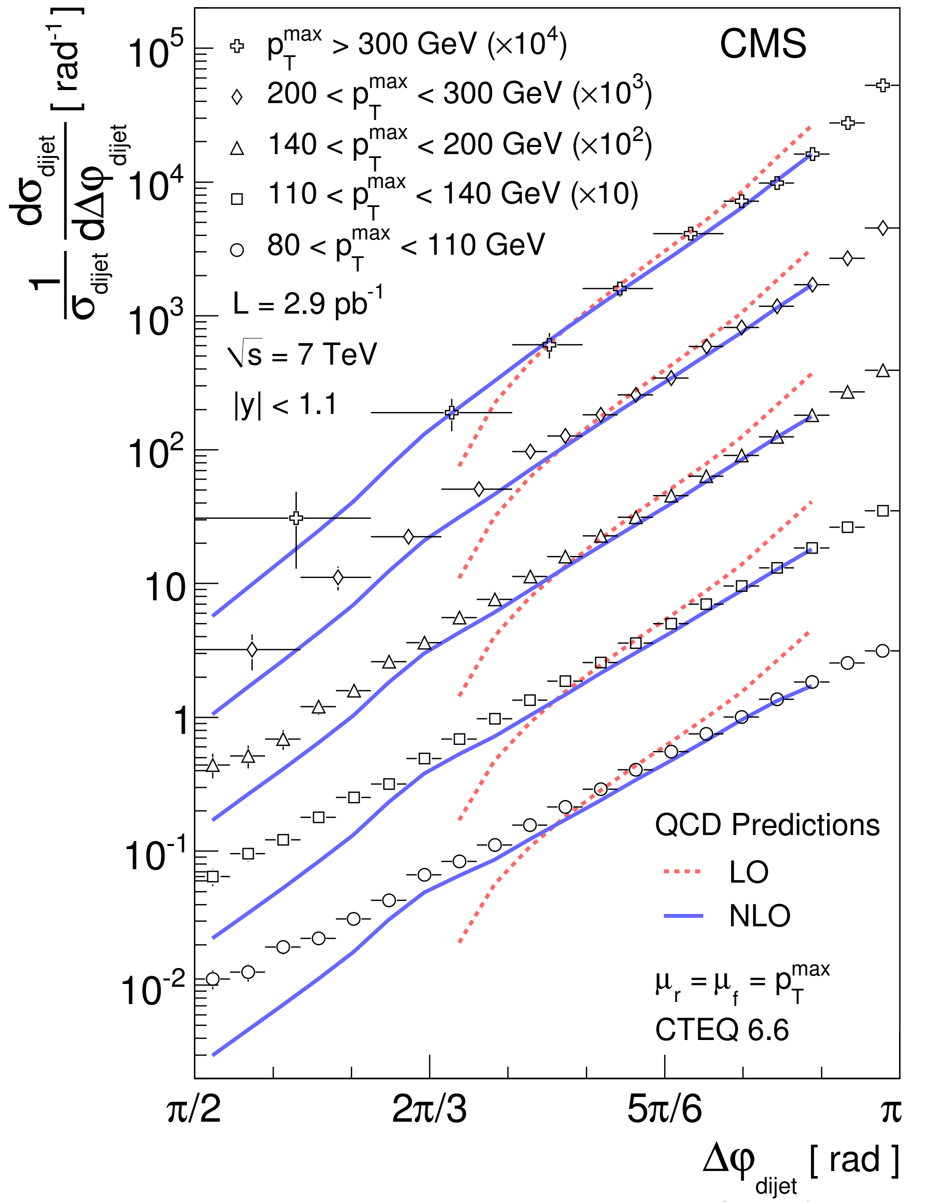


$$\chi = e^{y_1 - y_2} \approx \frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}$$

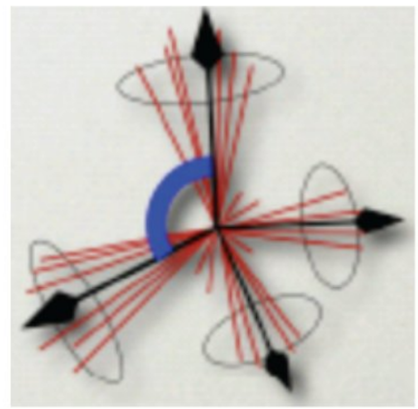
- Why important?
  - Gives additional insight to the QCD dynamics
  - Stringent test of perturbative QCD and sensitivity to new physics

Very good agreement

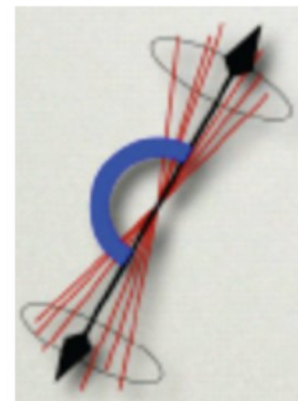
Dijet $\Delta\phi$ distributions



PRL 106 (2011) 122003



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

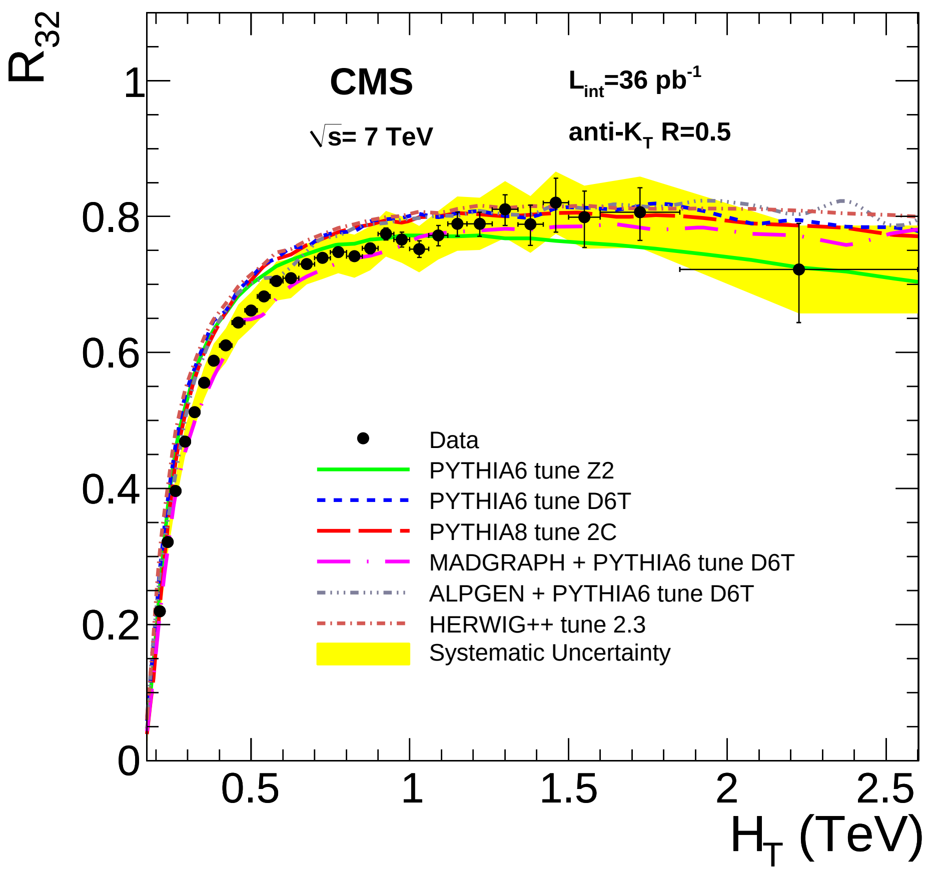


$$\Delta\phi \sim \pi$$

- Why important?
  - Indirect probe of multijet topologies
  - NLO is necessary to describe azimuthal decorrelation

Good agreement

3-jet/2-jet cross-section ratio

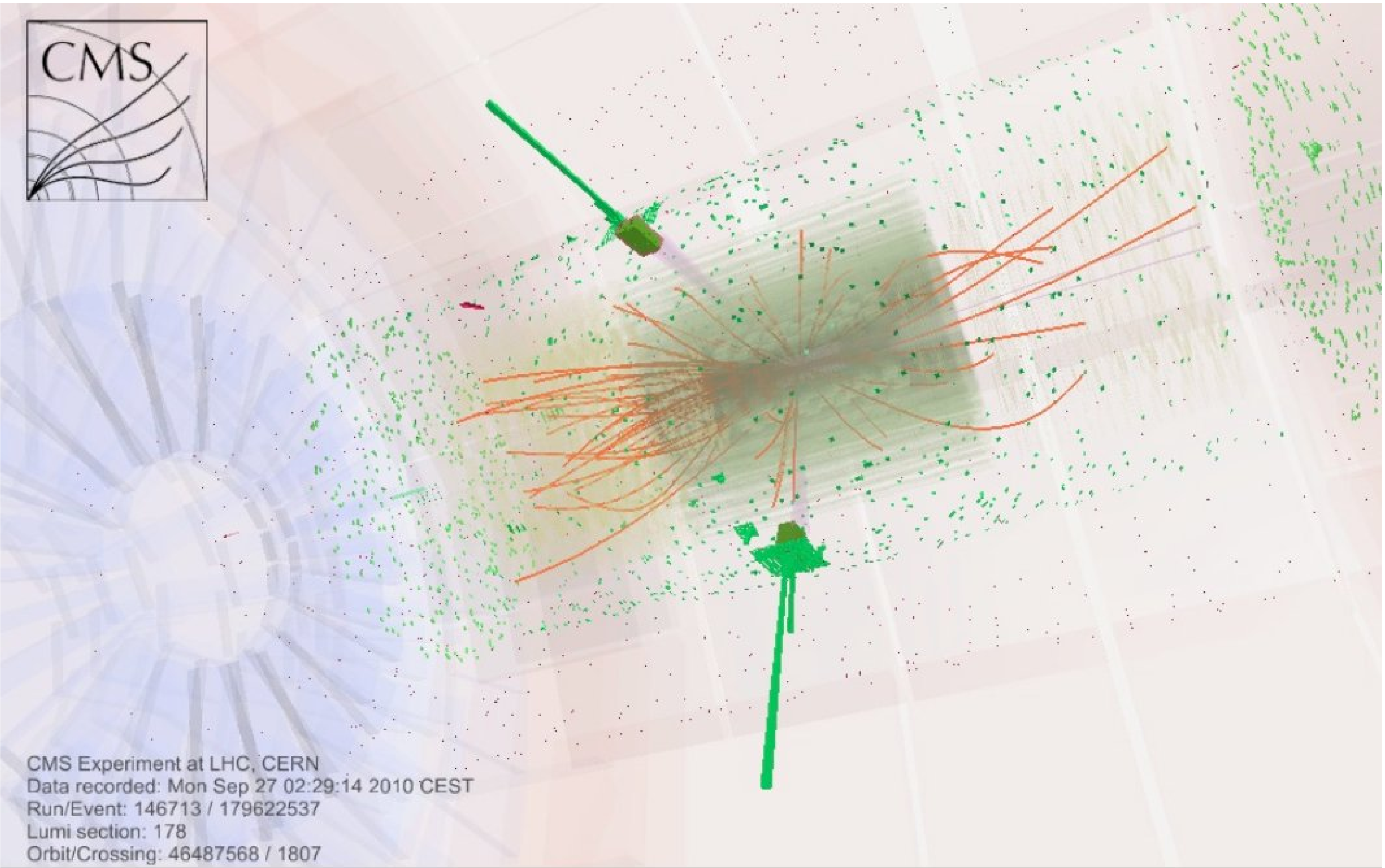


PLB 702 (2011) 336

- Why important?
  - Ratio of cross sections as function of scalar sum (H_T)
  - Not sensitive to many experimental uncertainties
  - Could be used for measurement of α_s

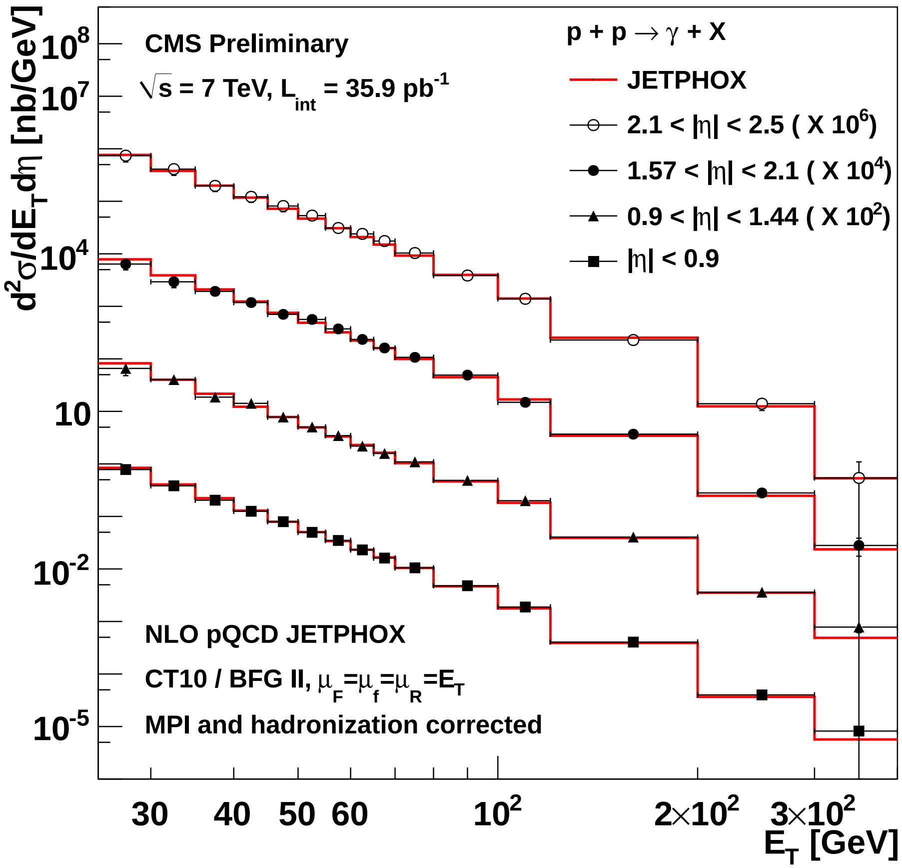
All generators agree for $H_T > 0.7$ TeV

Photons



Several sources: qg Compton, $q\bar{q}$ annihilation, fragmentation
Isolation and conversion templates; statistical signal extraction

Isolated prompt photons



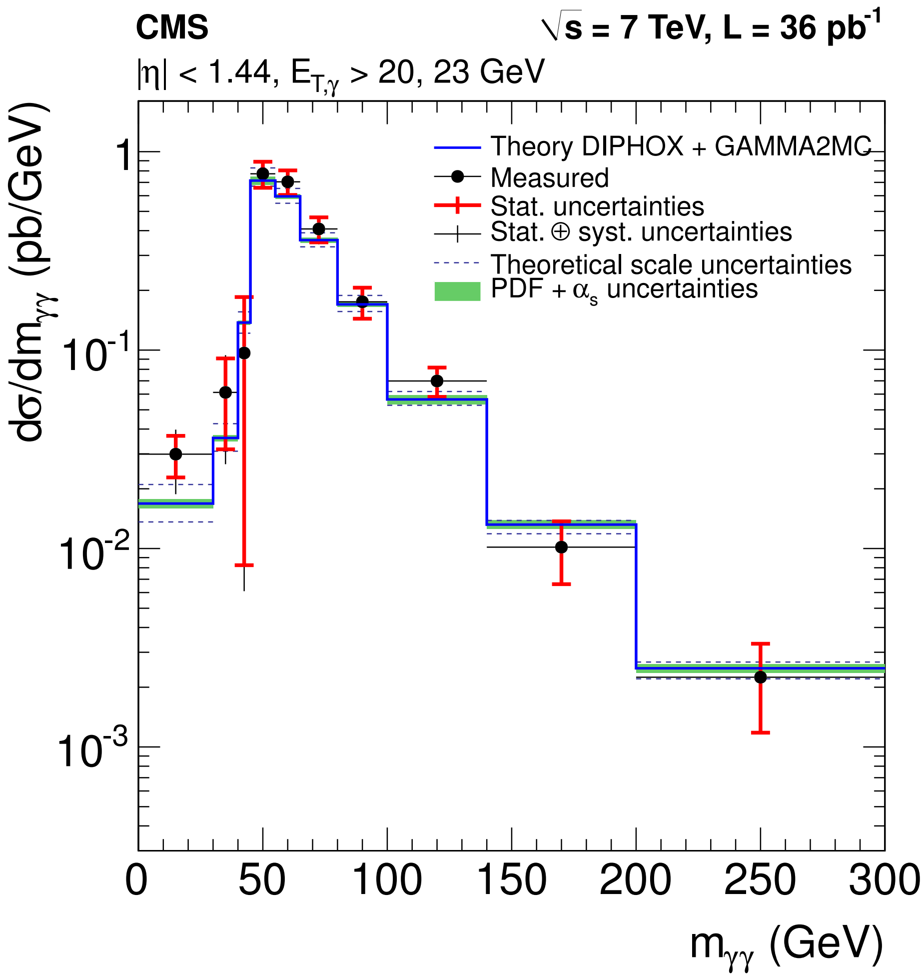
PRD 84 (2011) 052011

- Analysis
  - Combination of conversion and isolation template methods
  - From 25 to 400 GeV
  - Cross section is slightly overestimated at low E_T

Good agreement with theory

Large number of photon measurements, could be used soon to constrain the gluon PDF

Diphotons



arXiv:1110.6461

- Why important?
  - Probing perturbative QCD, NLO calculations and PDF
  - Irreducible background for Higgs search ($H \to \gamma\gamma$)

Discrepancy at low $m_{\gamma\gamma}$, due to collinear photons

Summary

- CMS QCD
  - Rich physics (19 journal publications and several preliminary results)
  - Good match of data and theory
  - Precision measurements based on 2011 data will follow
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsQCD