Soft QCD, diffraction and forward physics at LHC

LHCP Conference

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Outline

- Introduction: Theory and LHC experiments

- Measurement of pp cross sections:
  - Elastic and total pp cross sections
  - Rates of diffractive processes (rapidity gaps)
- Charged particle multiplicities
- Tests of BFKL dynamics and saturation effects
- Forward energy flow and input to cosmic ray physics

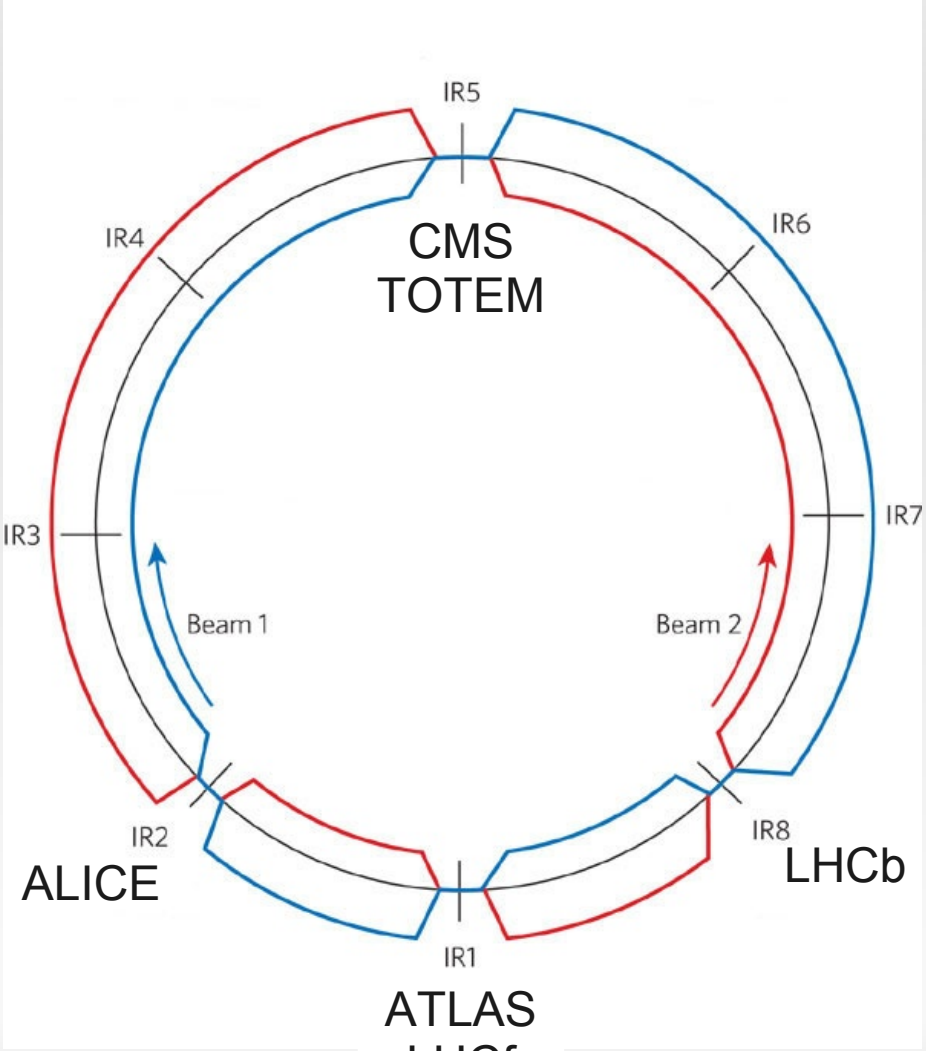
- Conclusion and prospects

Some physics motivations

- Improve our understanding of the strong nuclear interaction:
  - Hard → soft regime transition
  - Mechanism of diffractive processes
  - Mechanism of hadronization and confinement
  - Search for new QCD dynamics (BFKL?)
  - Proton structure

- Valuable input to our experiments
  - Tune Monte Carlo generators for particle physics
  - Input to cosmic ray physics

LHC experiments

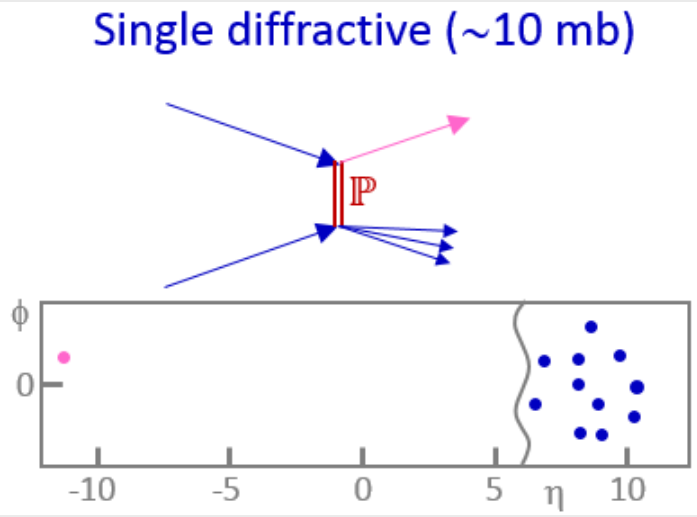


- ATLAS, CMS: General purpose
- ALICE: Heavy ion physics
- LHCb: Beauty physics (forward general purpose detector)
  - Fully instrumented in $2 < \eta < 5$
- TOTEM: pp cross sections and diffraction physics
  - Trackers 10-13 m on both sides of CMS
  - Roman pots 140-200 m both sides
- LHCf: Model cosmic ray showers
  - Two detectors 140 m before and after ATLAS
  - Detects neutral particles at $\eta > 8.6$

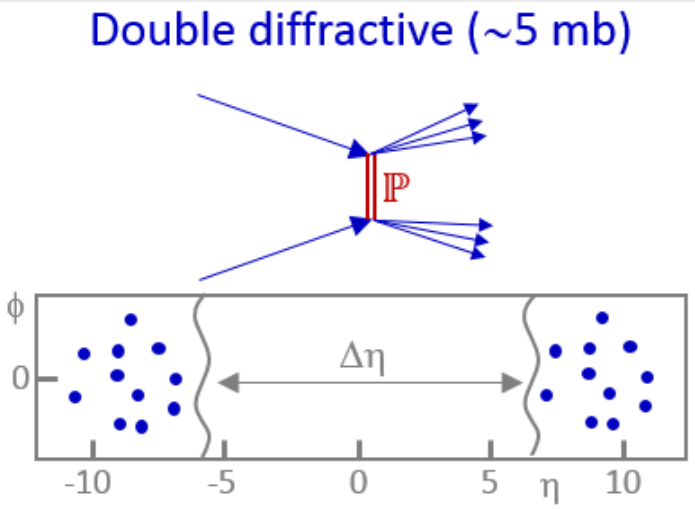
Classification of diffractive events

("Double Pomeron Exchange")

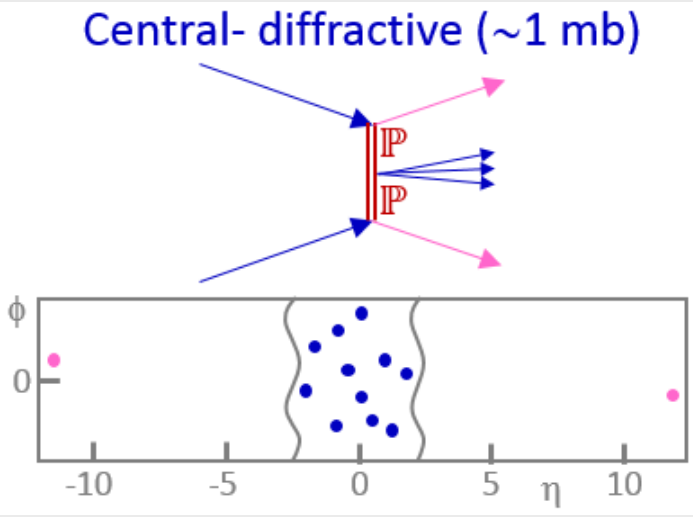
Single diffractive (~10 mb)



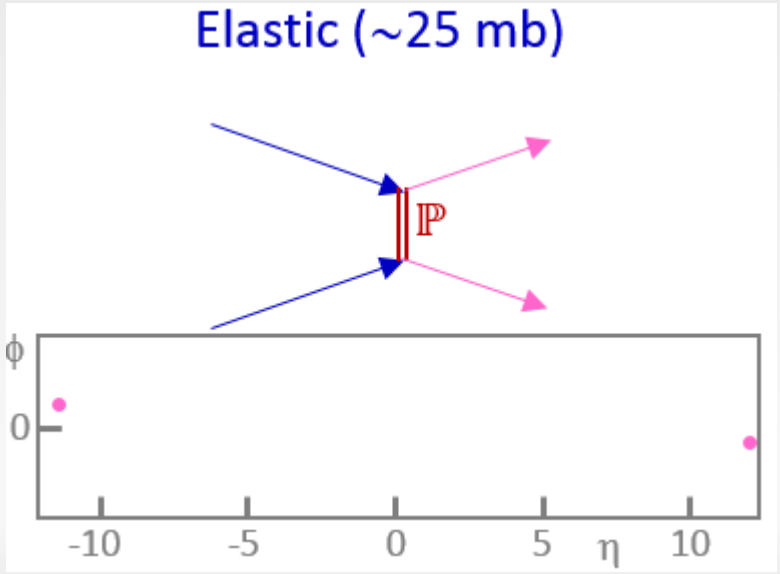
Double diffractive (~5 mb)



Central- diffractive (~1 mb)



Elastic (~25 mb)



- Diffractive and elastic events: ~40% of LHC pp collisions
- Tests QCD at large distance
- Large rapidity gaps are signatures for diffraction

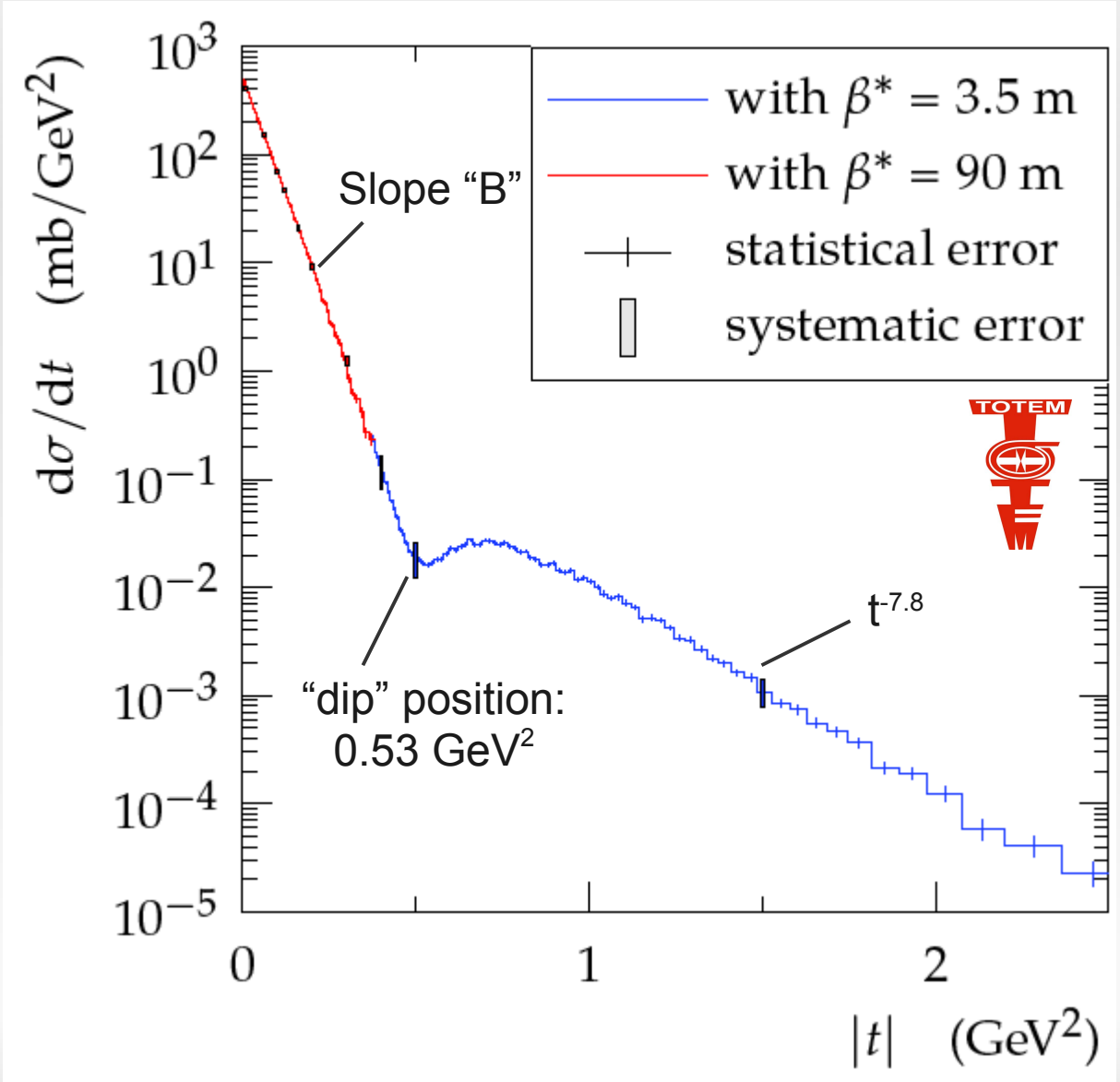
Measurements of elastic and total pp cross sections at LHC

pp elastic cross section

EPL 101 (2013) 21002

EPL 95 (2011) 41001

- An elastic interaction is an exchange of momentum between the two protons
- Measured as a function of “t” : 4-mom transfer squared
- Increasing t = deeper in the proton structure
- B_{7TeV} = (19.89 ± 0.27) GeV^{-2} at t=0

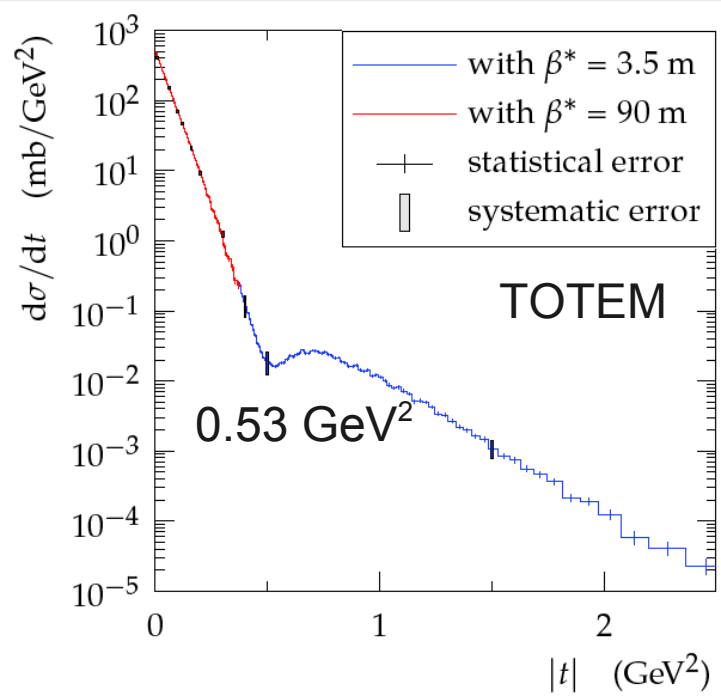


pp elastic cross section

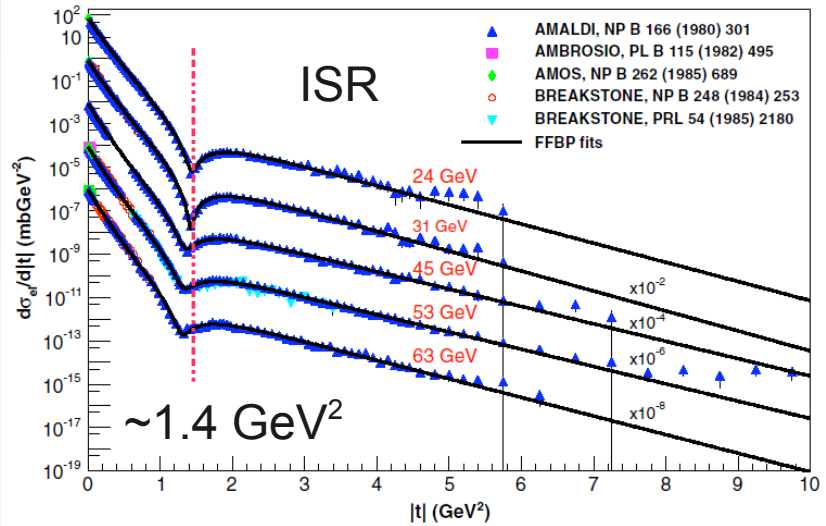
- Last pp elastic cross sections dated back from ISR: 30 years ago
- Old ISR trends confirmed at 100 times higher √s:
  - dip position gets smaller and B gets higher as √s increases

    → ***effective proton radius is increasing with √s***

EPL 101 (2013) 21002
EPL 95 (2011) 41001



ISR data, plot from Phys. Rev D 88, 094019



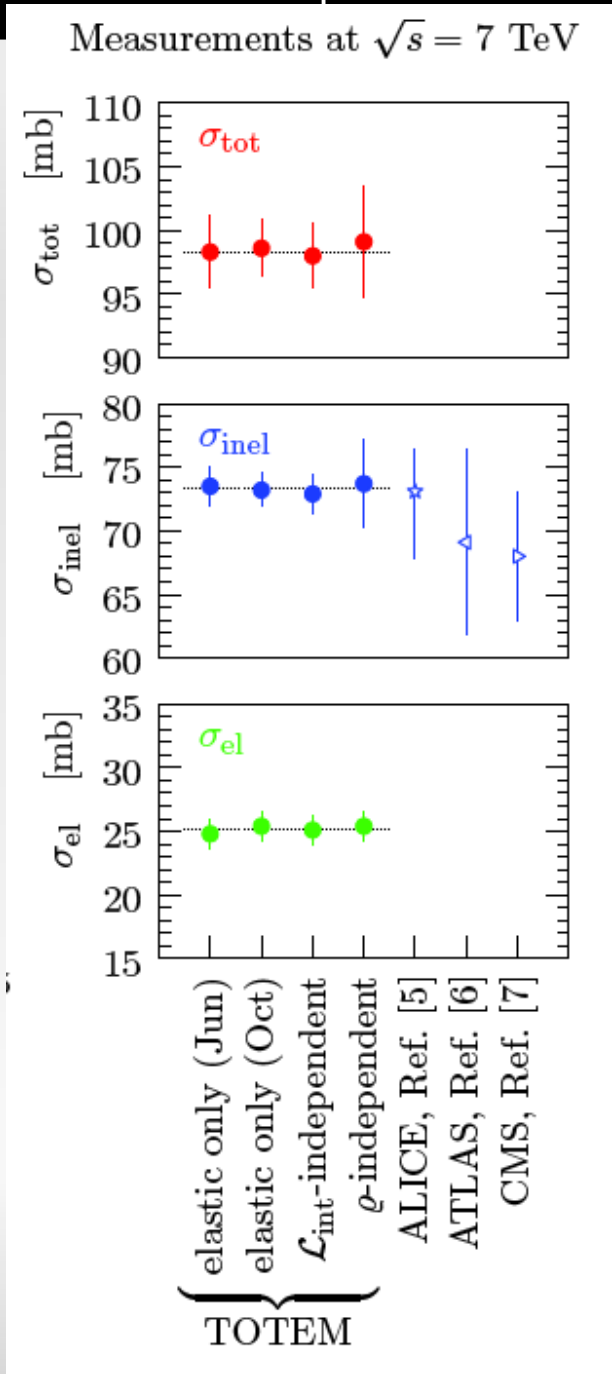
pp total cross section

CERN-PH-EP-2012-353
EPL 101 (2013) 21004

- TOTEM used three methods to get σ_{tot}
  - From elastic measurements at t~0 only, using "optical theorem"

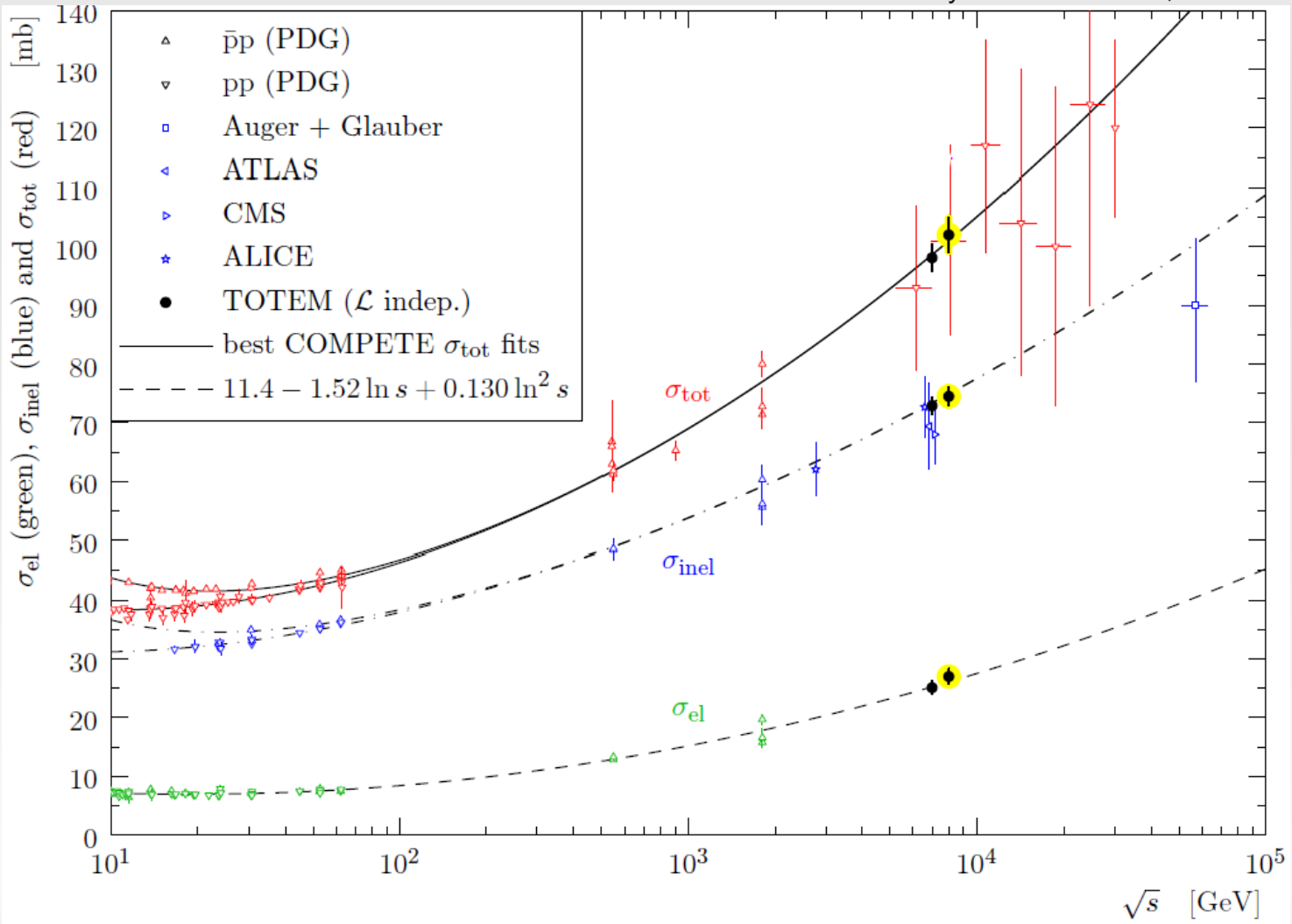
$$\sigma_{\text{tot}}^2 = \frac{16\pi}{1+\rho^2} \frac{\mathrm{d}\sigma_{el}}{\mathrm{d}t}\bigg|_{t=0}$$

  - From both inelastic and elastic measurements, using optical theorem (luminosity-independent)
  - Summing measured inel. and el. contributions ("ρ-independent")
- TOTEM results (lumi-independent):
  - σ_{tot} (7 TeV) = (98.0 ± 2.5) mb
  - σ_{tot} (8 TeV) = (101.7 ± 2.9) mb [Phys. Rev. Lett. 111, 012001]



pp cross section: Summary

CERN-PH-EP-2012-354
Phys. Rev. Lett. 111, 012001

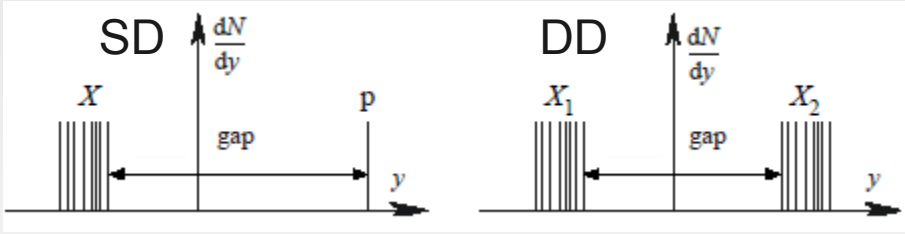


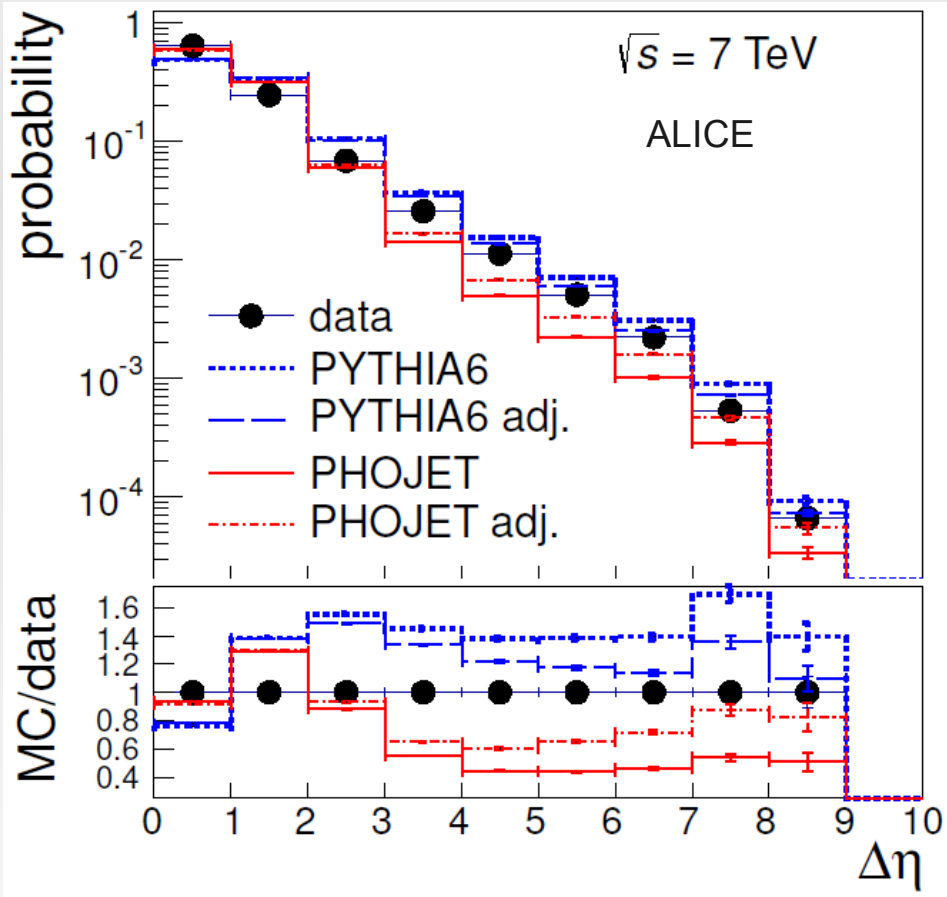
Rates of diffractive processes

Rates of diffractive processes

Eur. Phys. J C (2013) 73:2456

- Measurement made at low luminosity and low beam current
- Events triggered with any hit in ALICE detector (which covers an eta interval of 8.8 units)
- Infer SD and DD rates from rapidity gap distributions



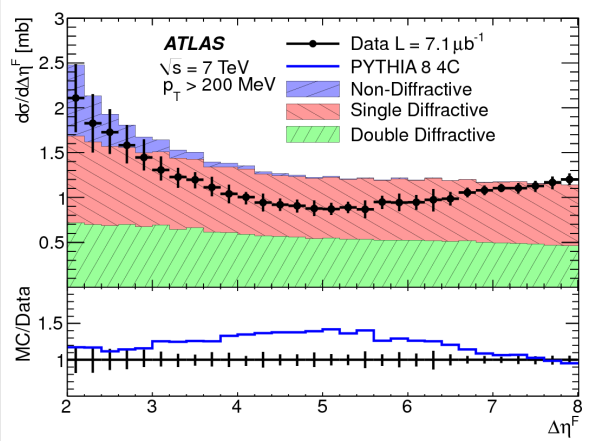


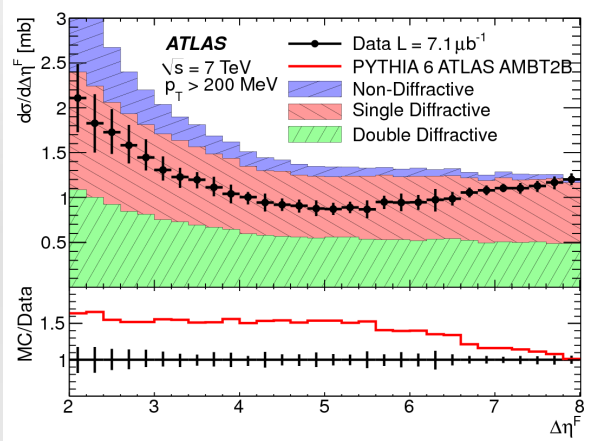
- DD events defined as events with $\Delta\eta > 3$ and $M_x < 200$ GeV

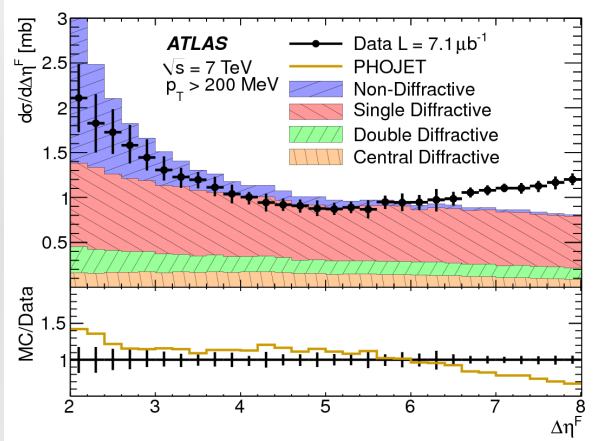
- $\sigma_{SD}/\sigma_{inel} = 0.21\pm0.03, 0.20^{+0.07}_{-0.08}, 0.20^{+0.04}_{-0.07}$ at $\sqrt{s}$ = 0.9, 2.76 and 7 TeV
- $\sigma_{DD}/\sigma_{inel} = 0.11\pm0.03, 0.12\pm0.05, 0.12^{+0.05}_{-0.04}$ at $\sqrt{s}$ = 0.9, 2.76 and 7 TeV

Diffractive processes at ATLAS

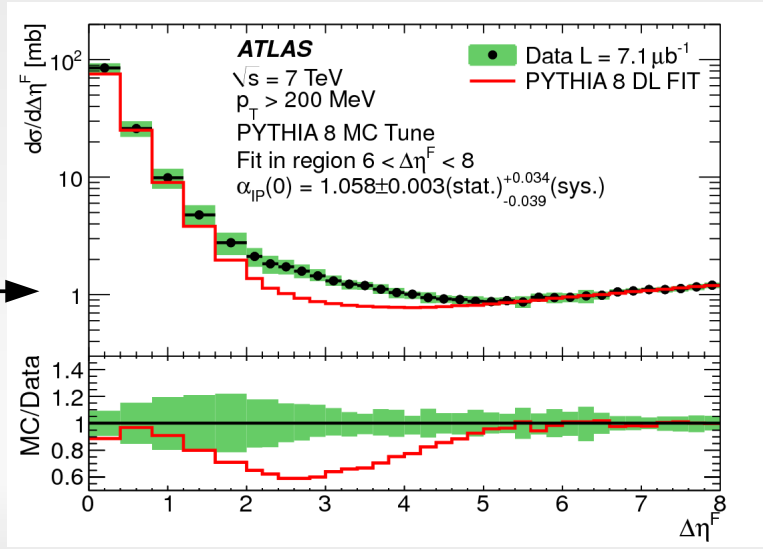
Eur.Phys.J. C (2012) 72:1926







- Forward rapidity gaps defined as larger $\Delta\eta^F$ region on detector edge ($\eta = \pm 4.9$) devoid of p_T>200 MeV particles
- Measured $d\sigma/d\Delta\eta^F \sim 1$ mb for $\Delta\eta^F > 3$
- Default PHOJET and PYTHIA do not describe the rise of the cross section observed at $\Delta\eta^F > 5$
  - Rise interpreted from a triple Pomeron contribution with a Pomeron intercept $\alpha_P(0) > 1$
  - Slope very sensitive to the precise value of $\alpha_P(0)$



Other related diffraction measurements at LHC:
- CMS: PAS FSQ-12-005
- TOTEM: Phys. Rev. Lett. 111 (2013) 262001

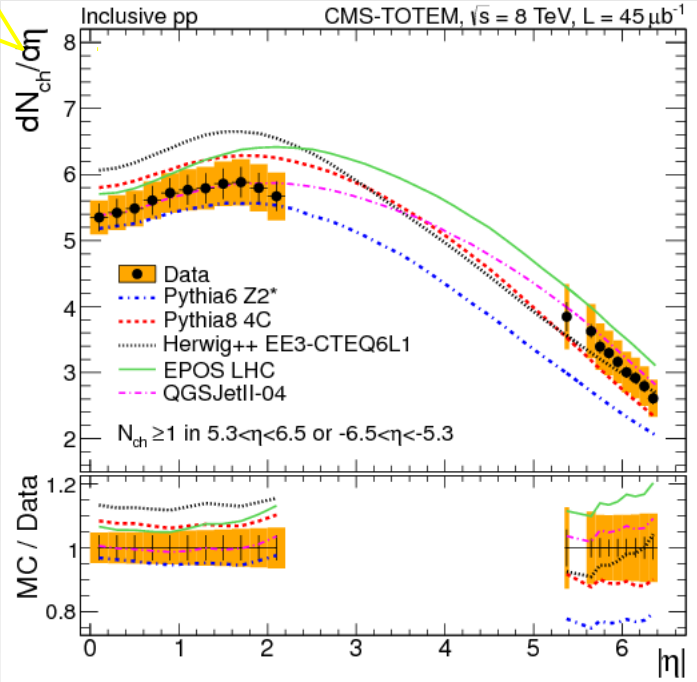
Measurements of charged particle multiplicities at LHC

Charged particle multiplicities

NEW

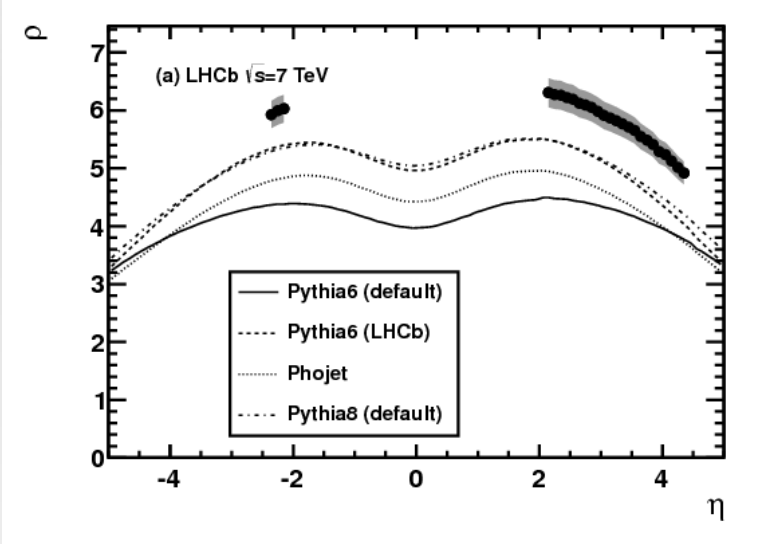
8 TeV

Arxiv 1405.0722
CERN-PH-EP-2014-063



7 TeV

Eur.Phys.J.C72 (2012)



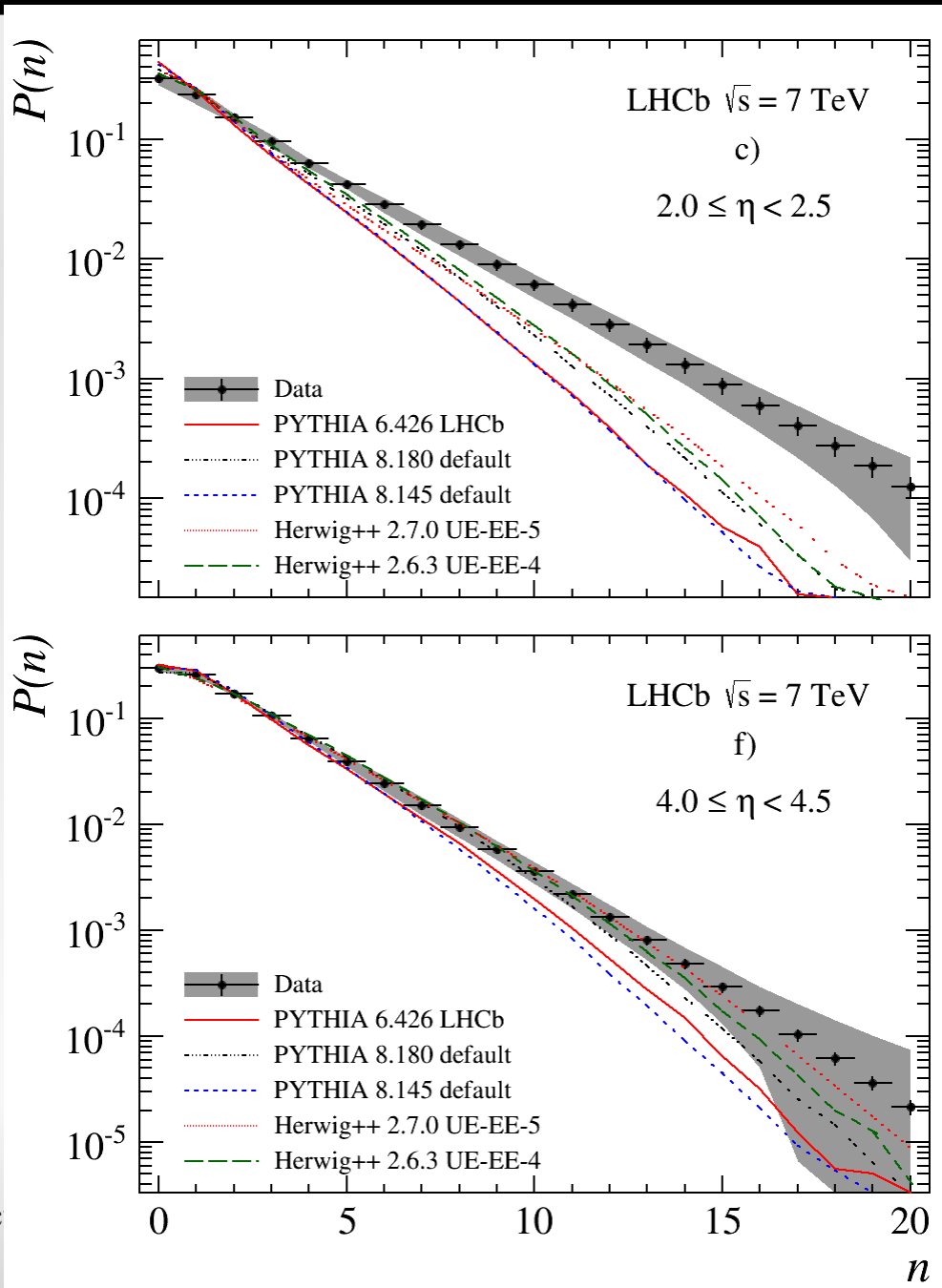
- CMS, TOTEM and LHCb together filled the pseudorapidity region from 0 to 6.5

  → Invaluable input for the tuning of Monte Carlo generators

Charged particle multiplicities

ArXiv:1402.4430
Eur. Phys. J. C (2014) 74:2888

- LHCb also recently published the distributions of the number of charged particles in several pseudorapidity regions
- All tested MC generators underestimate the number of events with high charge multiplicity
- Details in Phil Ilten's talk

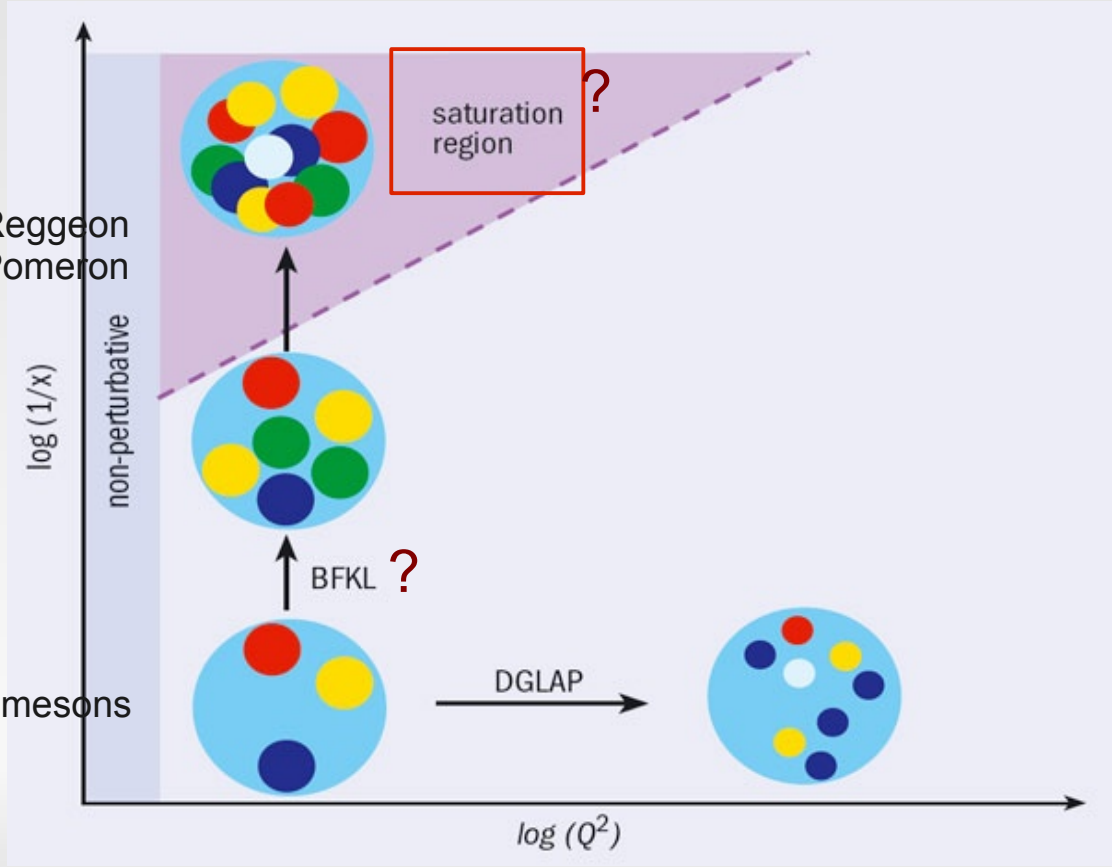


See also ch. particle multiplicity measurements at ATLAS:
- JHEP 1207 (2012) 019
- New J. Phys. 13 (2011) 053033

Searches for signs of BFKL dynamics and saturation effects

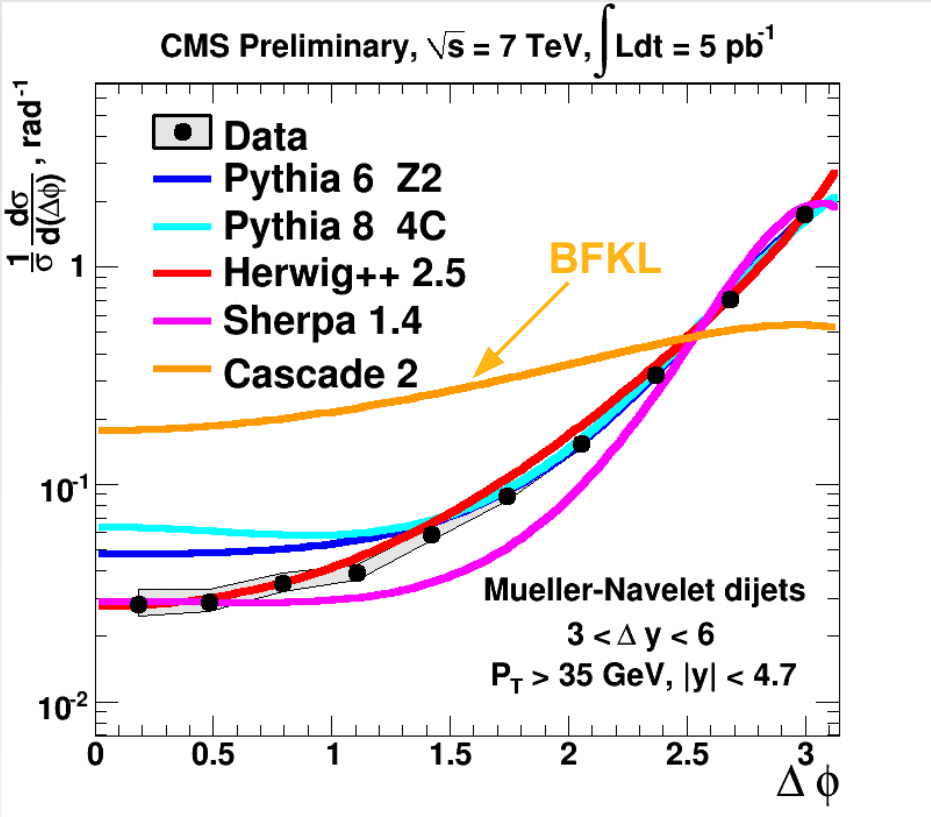
BFKL: QCD dynamics at low x?

- Balitsky-Fadin-Kuraev-Lipatov dynamics:
  - Theoretically derived from QCD, QFT
  - Predicts the rise of the pp cross section at high √s
  - Hints exist, but clear experimental evidence still awaited



Large-rapidity-distance jets

CMS PAS FSQ-12-002

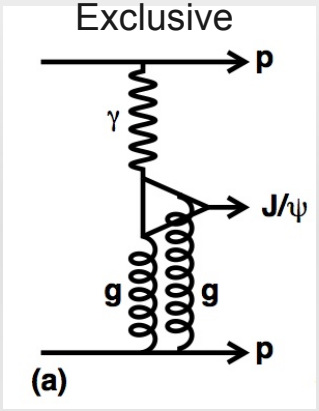


- BFKL predicts a decreased azimuthal correlation between jets separated by large rapidity gaps
- CMS showed ΔΦ distributions for dijets with Δy > 3 and pT > 35 GeV
- No evidence for BFKL dynamics found
- Such searches will become more sensitive at higher c.m. energies

Other related large-rapidity-distance jets measurement at CMS:
- CMS: PAS FSQ-12-008

Exclusive J/Ψ and Ψ(2s) productions

J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002

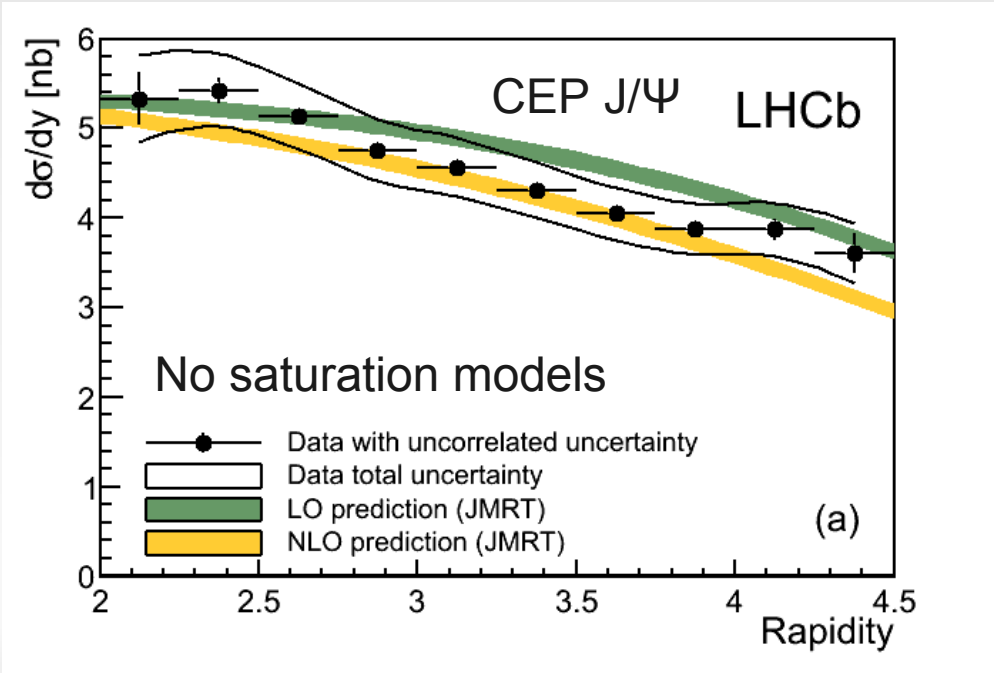


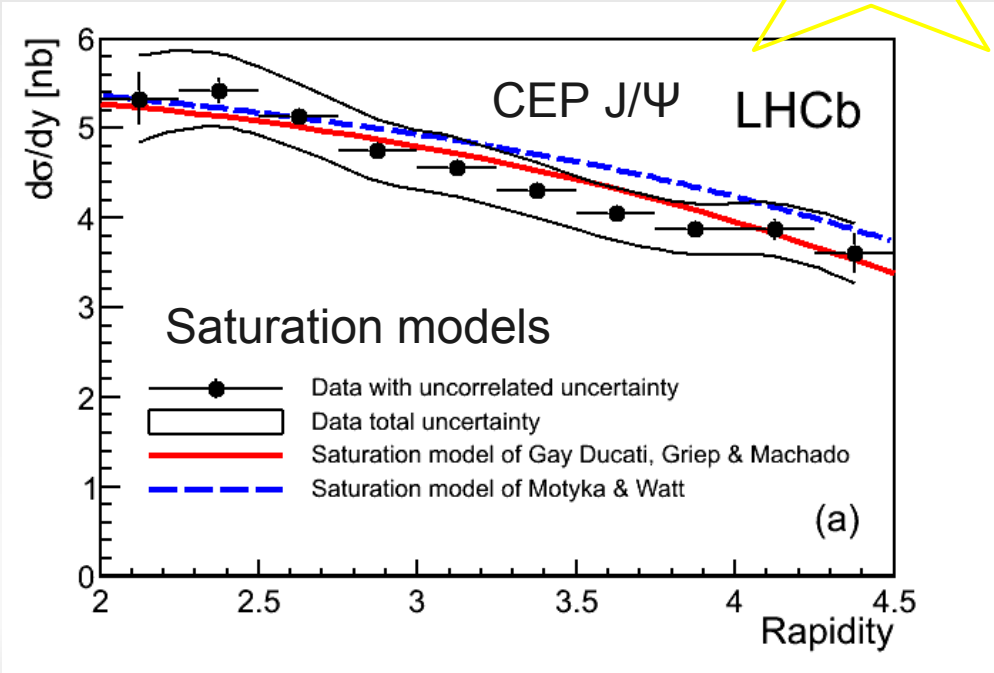
- Probe x down to 5.10^{-6} at LHCb

  → sensitive to saturation effects?

- Dominant uncertainty: theor. model of inel. bkg (J/Ψ ana)

2014





Input to cosmic ray physics

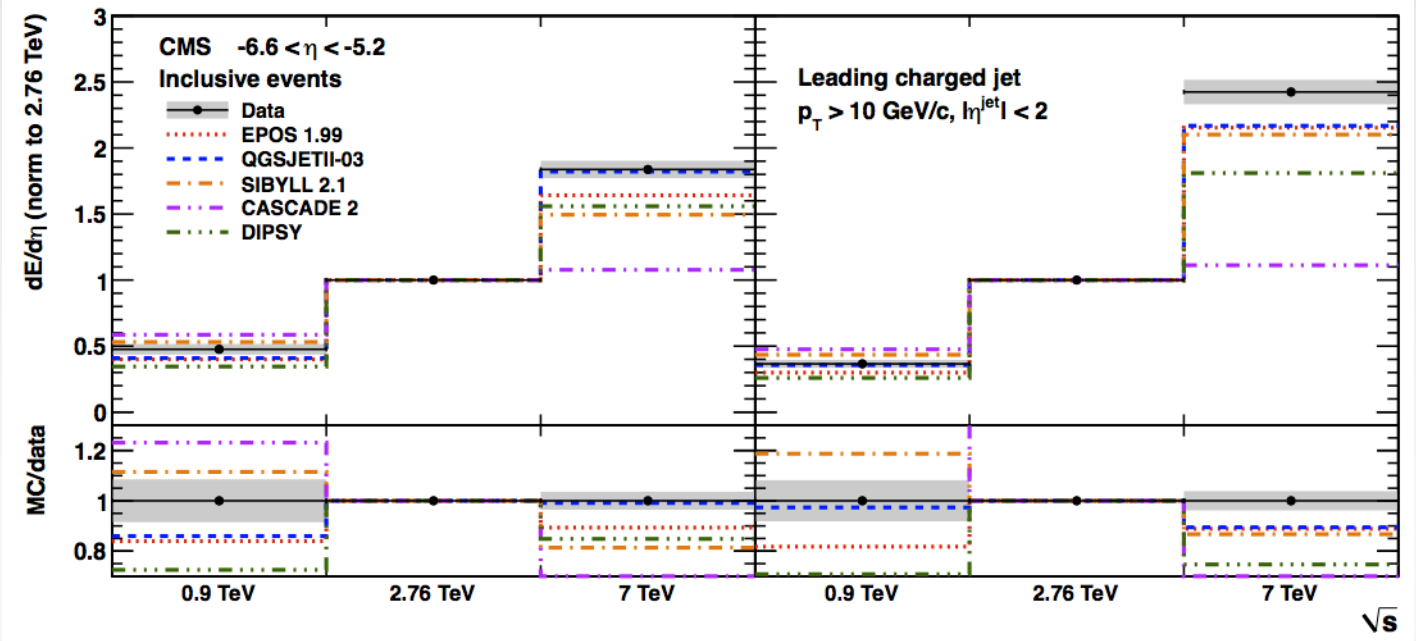
Forward Energy Flow

JHEP 04 (2013) 072

- Measured by CMS in -6.6 < η < -5.2 at different event hard scales
  - Hard scale controlled by leading central jet p_T
- Study made on ND event samples at √s = 0.9, 2.76 and 7 TeV
- EF dependence on hard scale driven by Multi-Parton Interaction
  - Cf Pietro Antonioli's talk for details about MPI

Models used in cosmic ray physics (EPOS, QGSJET, SIBYLL) show good agreement with CMS energy flow data within 10-20%

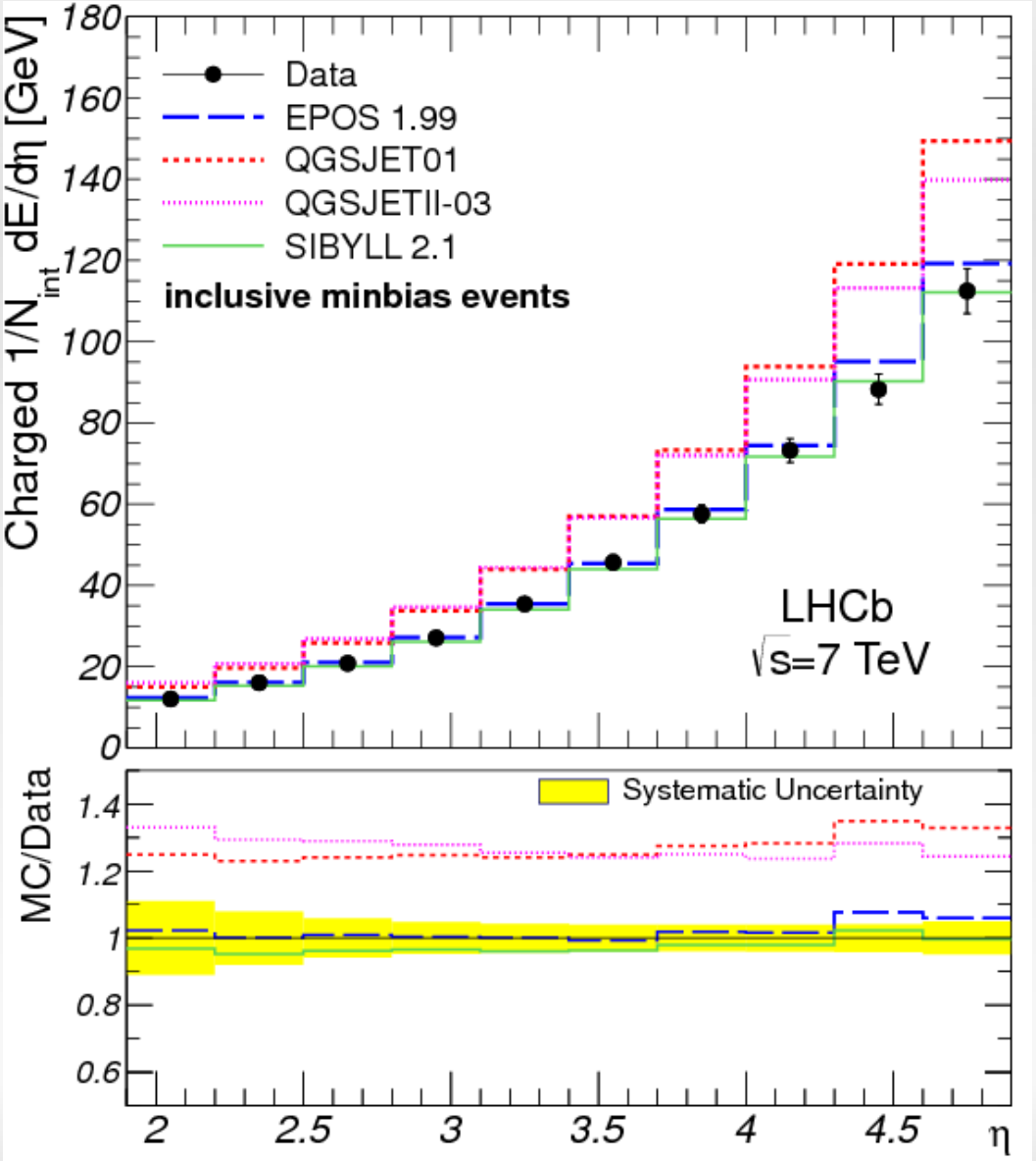
Older EF measurement at CMS (in 3.15 <|η| < 4.9):
- JHEP 11 (2011) 148



Forward Energy Flow

Eur. Phys. J. C (2013) 73:2421

- LHCb also published a measurement of forward energy flow at 7 TeV
  - $1.9 < \eta < 4.9$
  - Nicely complements CMS rapidity coverage
- Good general agreement between HEP tuned generators, cosmic ray models and data
- But none of the models are able to perfectly describe all results

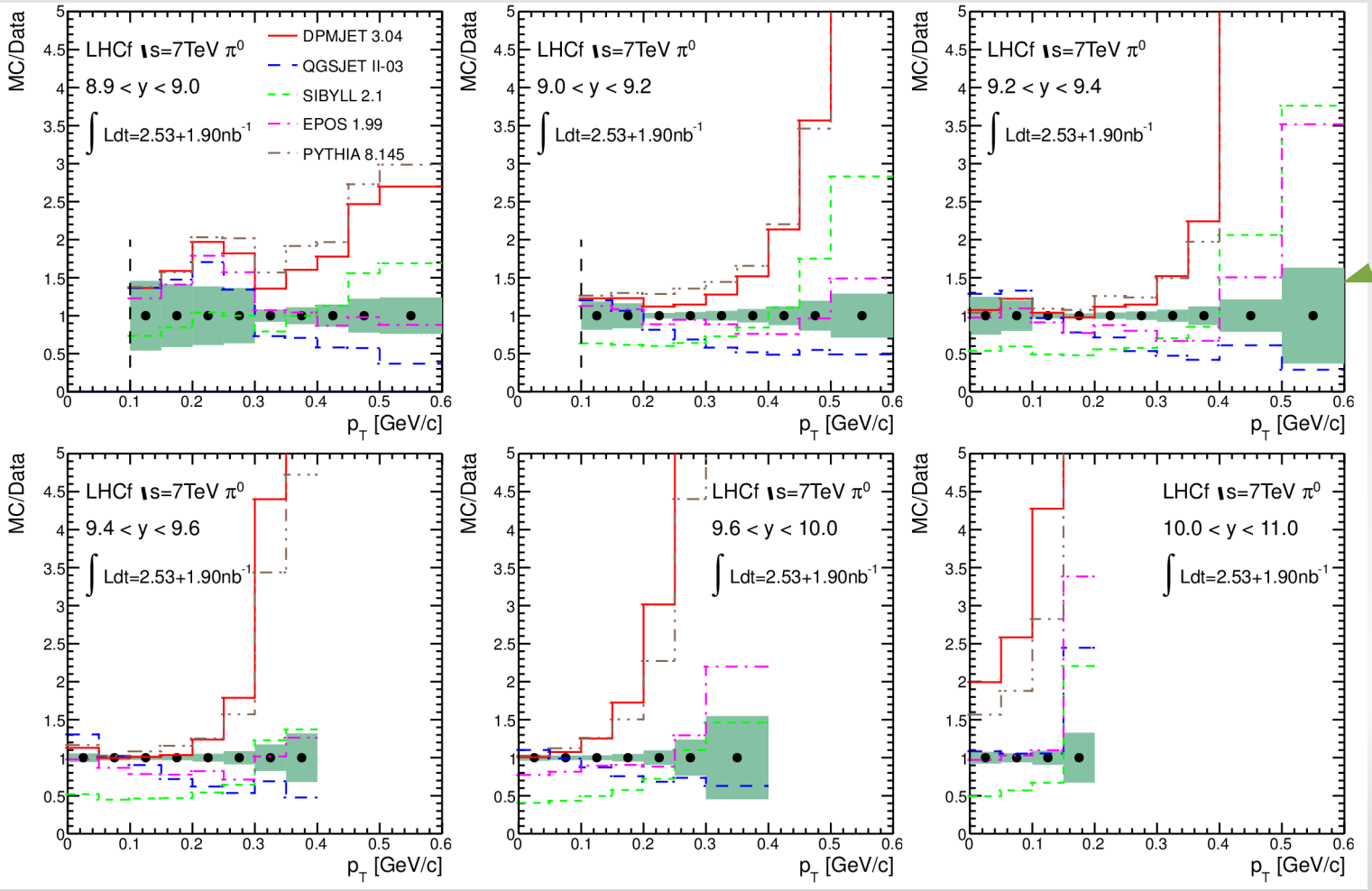


LHCf measurements

Phys. Rev. D 86, 092001 (2012)

- LHCf published zero degree π^0 p_T spectra
- Some deviations are observed with predictions, especially above 200 MeV
- Among the hadronic interaction models tested, EPOS 1.99 shows best overall agreement with data

Ratio of predicted p_T spectra over data:



Total uncertainties

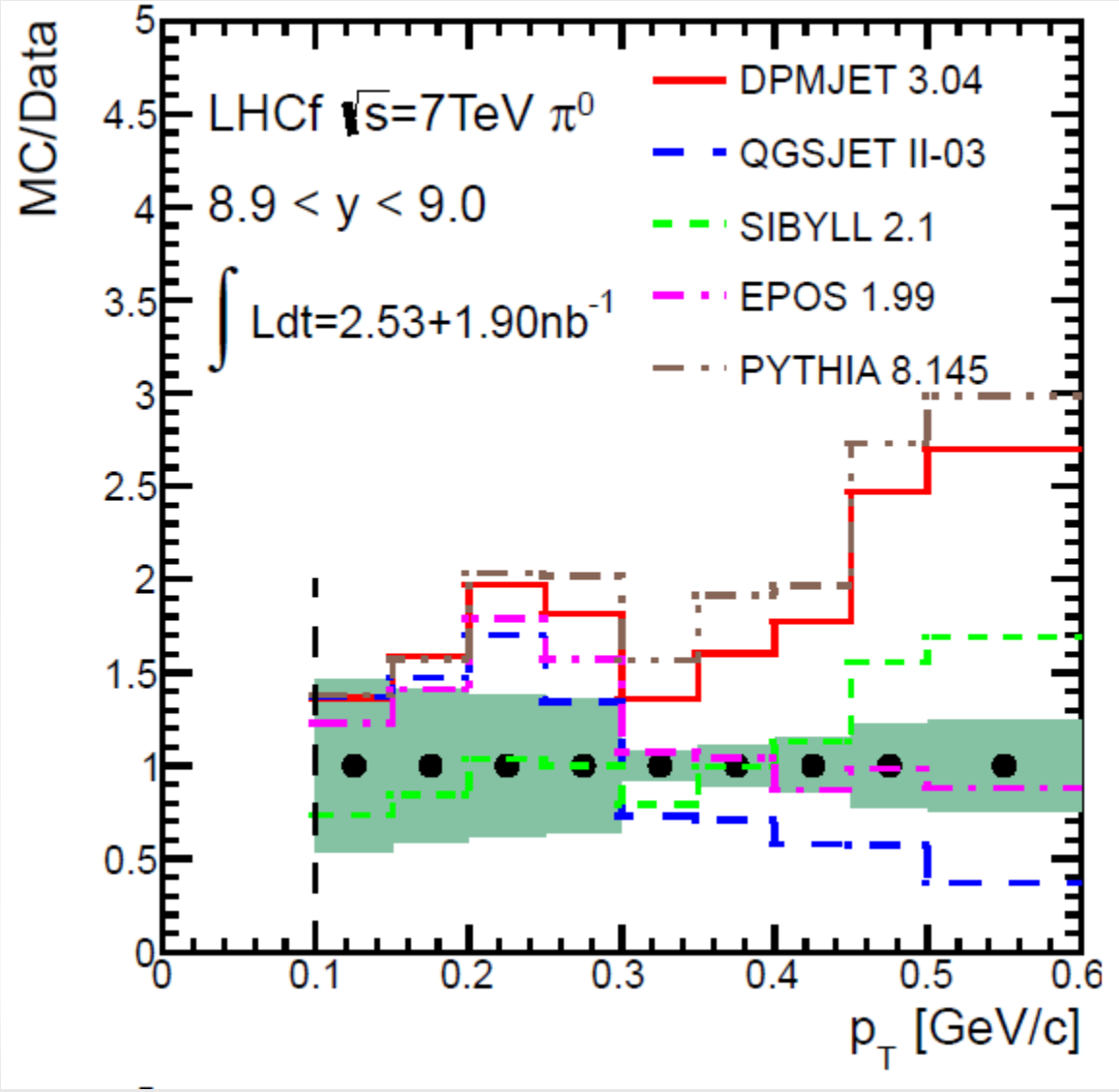
Other related LHCf measurements:

- Phys. Lett. B 715, 298-303 (2012)
- Phys. Lett. B 703 128-134 (2011)
- See Gaku Mitsuka's talk for details about LHCf

LHCf measurements

Phys. Rev. D 86, 092001 (2012)

Ratio of predicted π^0 p_T spectra over data (8.9 < y < 9.0):



Conclusion and prospects

- LHC 1 has had a very rich forward and diffraction physics program
  - Elastic, inelastic, diffractive pp cross sections, particle flows measured
  - Great input for the non perturbative QCD models
- BKFL dynamics still not isolated at LHC
- Saturation effects not seen yet
- Upgrade proposals are numerous and promising
  - CMS+TOTEM : add timing capacities to fight the higher pile-up
  - LHCf: Upgrade to a radiation hard detector
  - LHCb: add High Rapidity Shower Counters to extend diffractive and Central Exclusive Physics program
  - ATLAS: New Forward Protons detectors (AFP) to identify protons in diffractive processes