# Forward Physics at the LHC

**Workshop on Forward Physics at RHIC**

RIKEN-BNL Res. Center, 31st July 2012

**David d'Enterria**

**CERN**

# Overview

(0) Intro. Forward detectors at the LHC

(1) Elastic, inelastic & total x-sections.

(2) Diffractive scattering.

(3) Double Pomeron Exchange & central-exclusive.

(4) Photon-photon collisions.

(5) Low-x QCD.

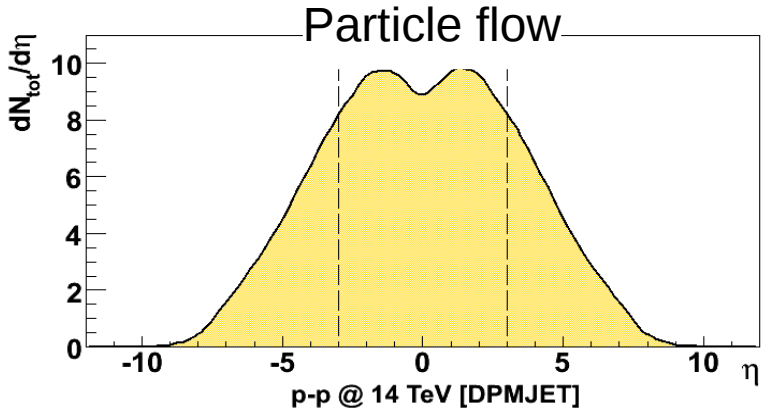
(6) Beam remnants (UHE cosmic-rays).

# LHC experiments: ($p_T$,η) acceptance

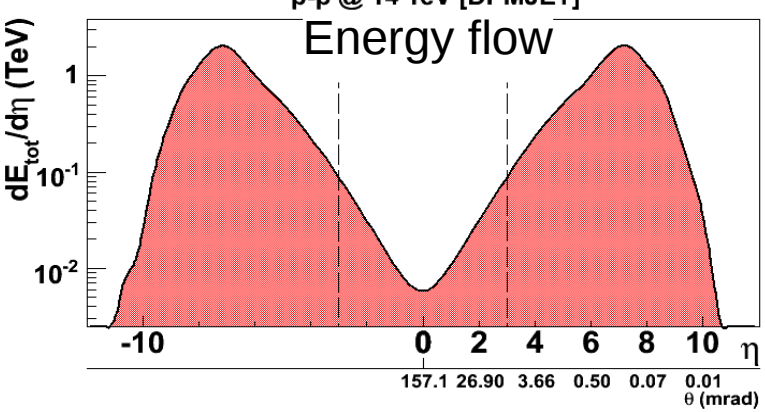
- Particle production at the LHC over $\Delta y = 2 \cdot y_{beam} = 2 \cdot \ln(\sqrt{s})/m_p \sim 20$ units

p-p @ 14 TeV

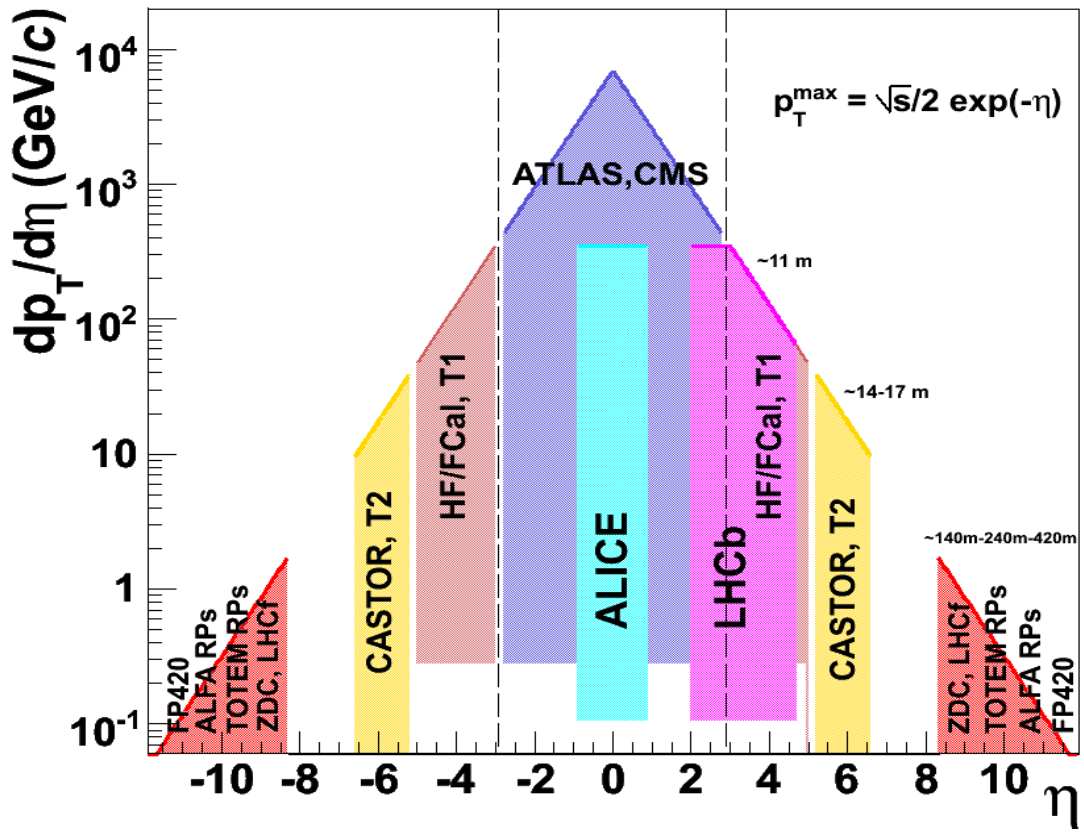
Particle flow




Energy flow




DdE, arXiv:0708.0551



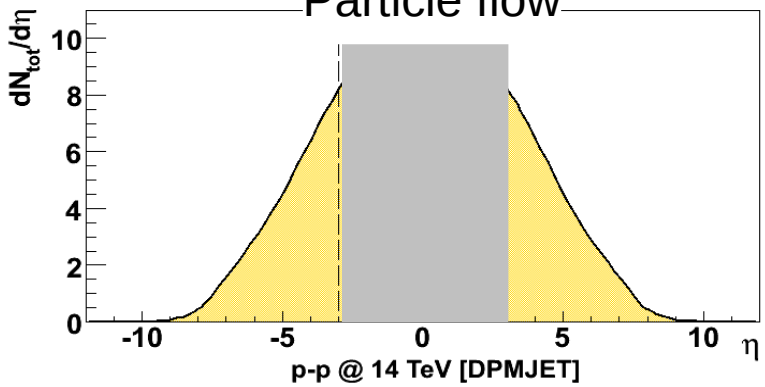

- Most of phase-space covered (1st time in a collider)

# LHC experiments: Forward

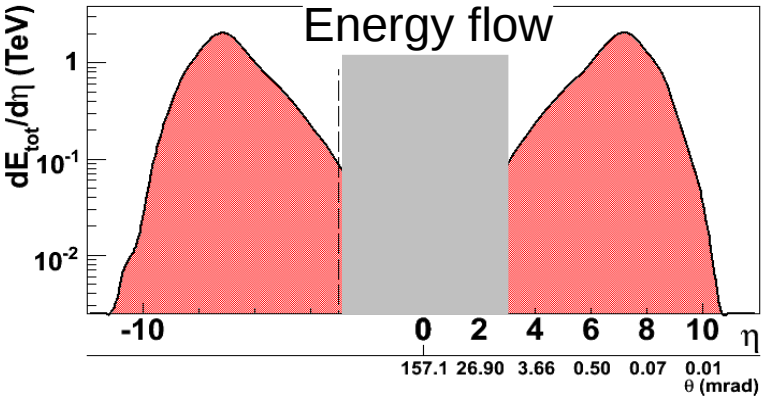
- Convention (arbitrary): Forward ≡ |η|>3

p-p @ 14 TeV

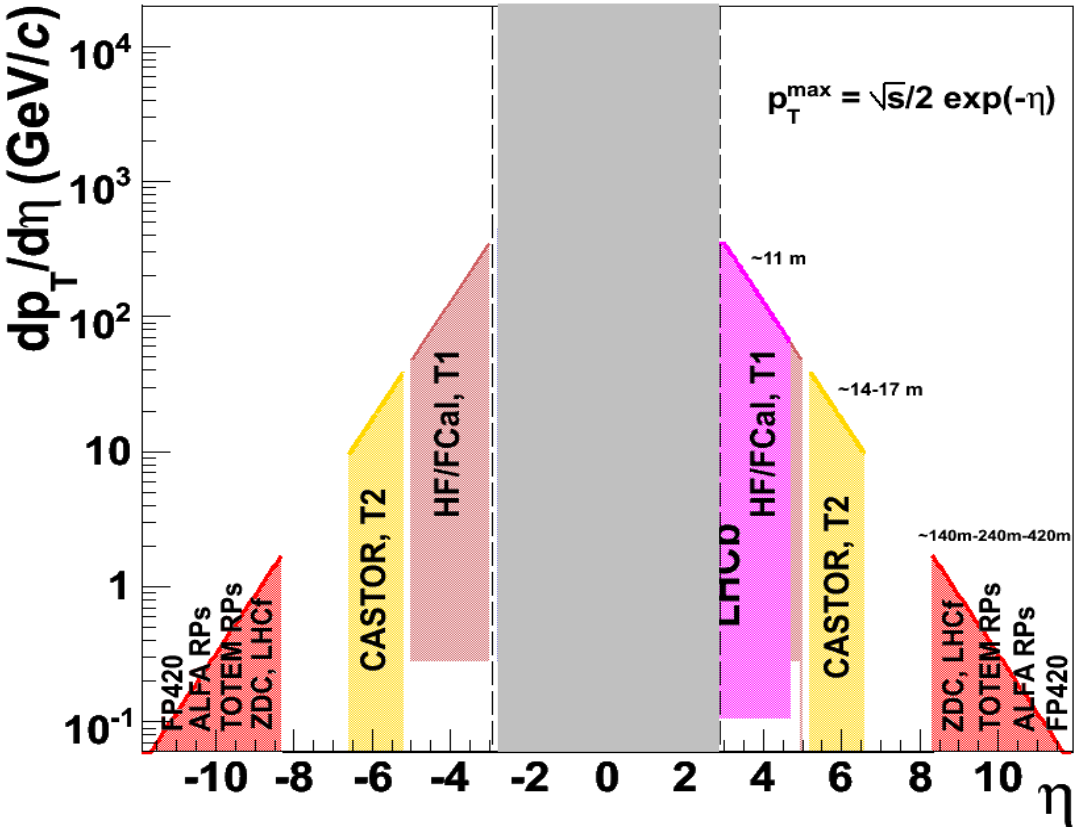
Particle flow




Energy flow




DdE, arXiv:0708.0551



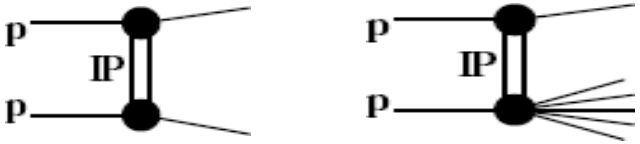

- Disclaimer: Results shown today are for proton-proton at 7 TeV (few forward Pb-Pb results expected for QM'12)

# Forward physics: why ?

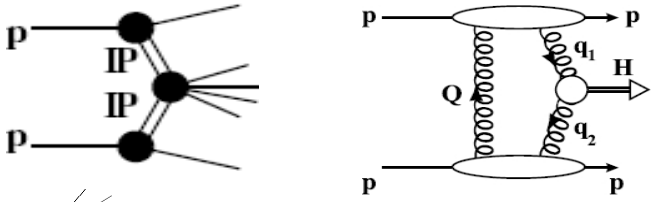
- Many interesting (mostly color-singlet exchange) scattering processes at the LHC are characterized by forward particle production:

**QCD:**

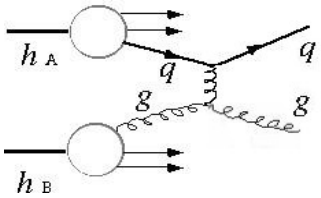
Elastic & diffractive:

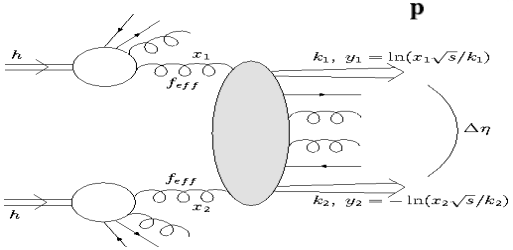



Double-pomeron, central exclusive:



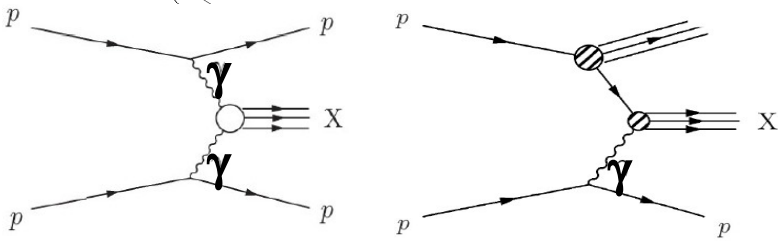

Low-x QCD:



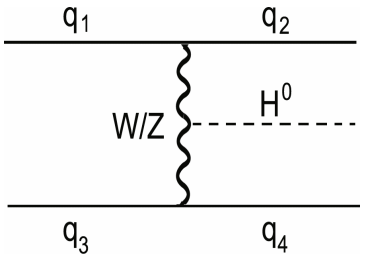




**Electro-weak**

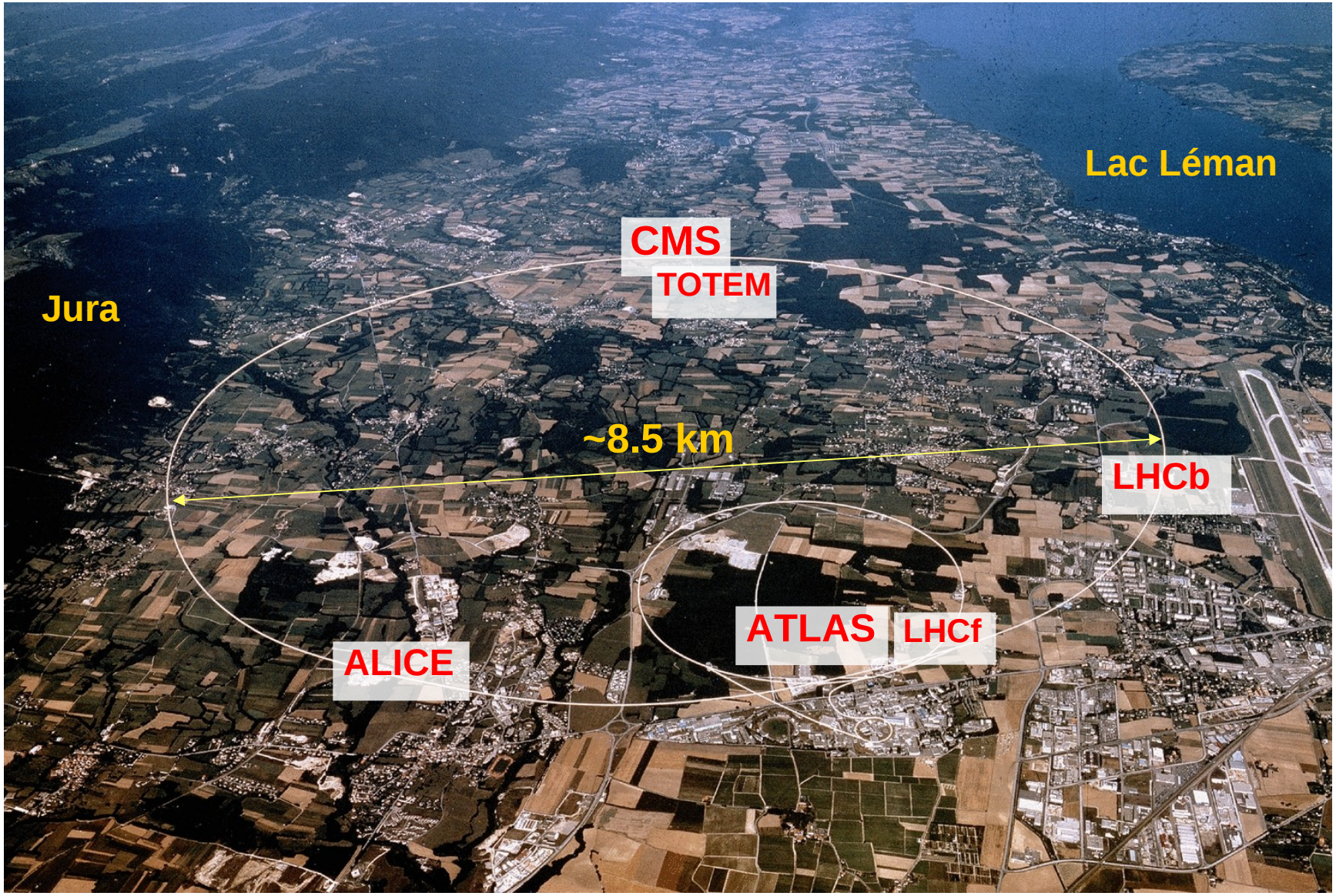
two-photon, photon-hadron:




Vector-Boson-Fusion:

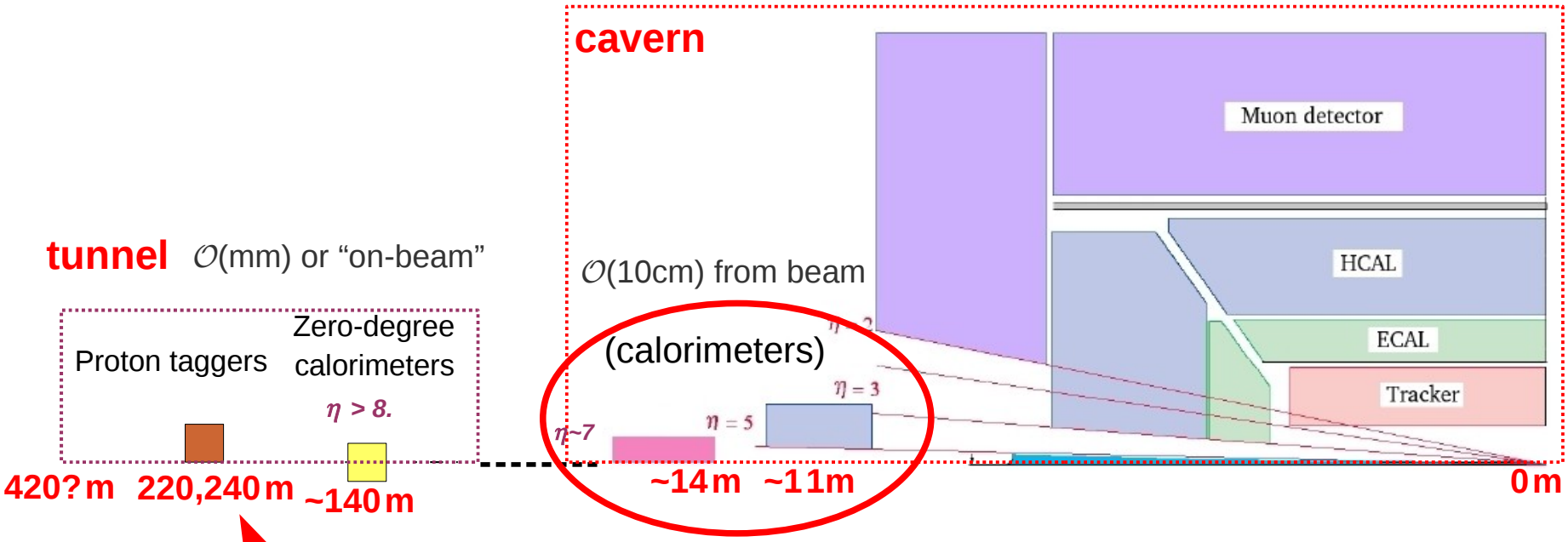


# Forward LHC detectors: where ?

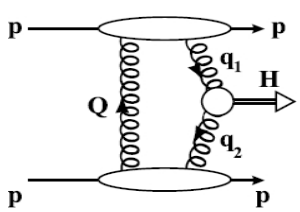


# Forward detectors: Atlas & CMS

- Near-beam detectors beyond $|\eta| = \ln \tan(\theta/2) > 3$

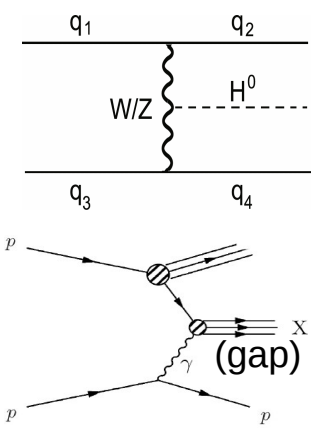



**1)** p,n tagging devices



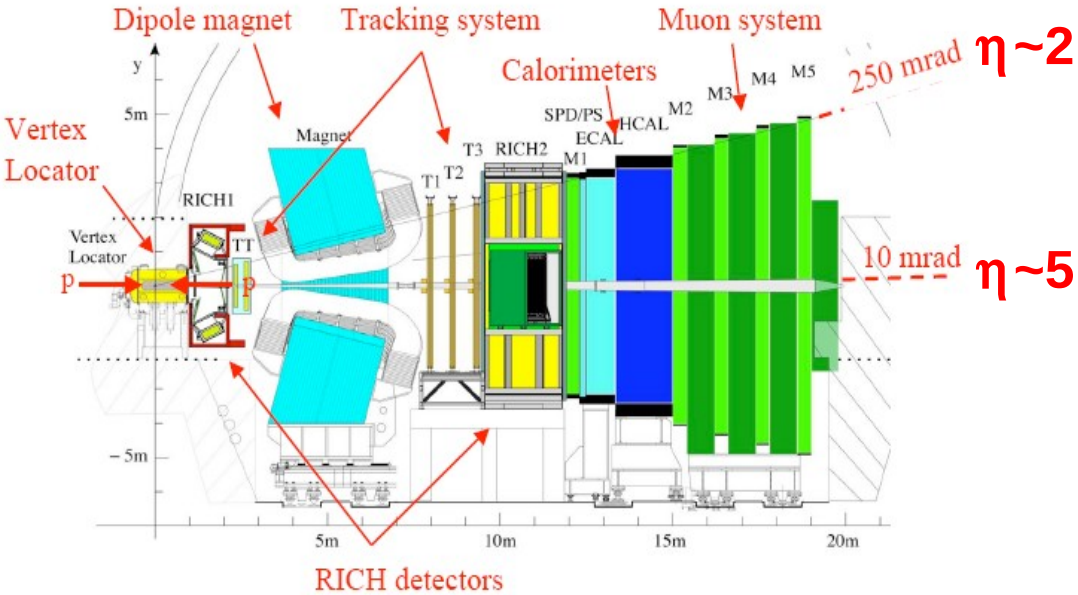

**2)** Direct particle measurements: fwd. jets, ...

**3)** Hadron "vetoing" devices: rapidity gaps



# Forward detectors: LHCb & ALICE

- Full LHCb ! Single-arm fwd detector optimized for heavy-flavor reco:




- Particle ID (e, γ, muons, hadron ID), secondary vertexing, ...

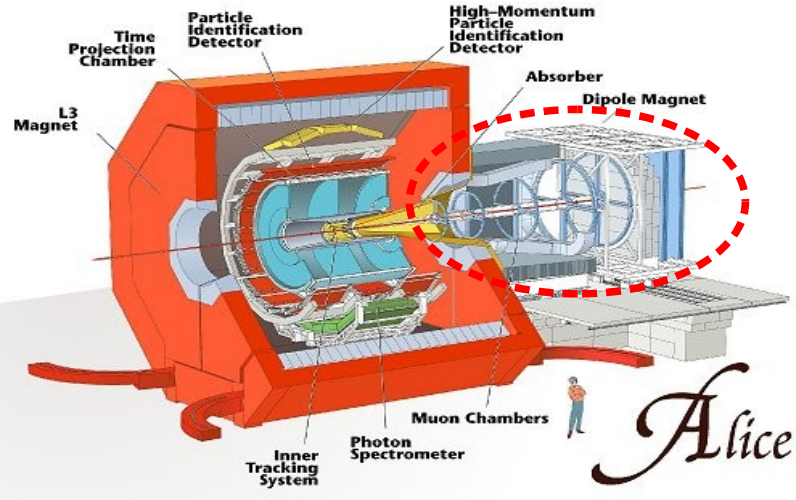
- Although so far only few QCD analyses available ...

- Forward muon spectrometer:

  $2.5 < \eta < 4$

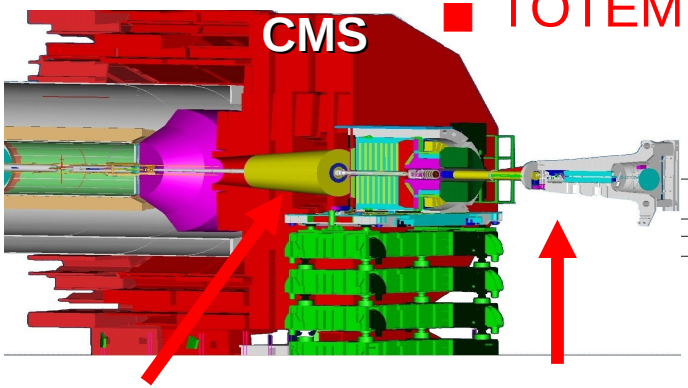
  ZDCs also at ±7m,±100m

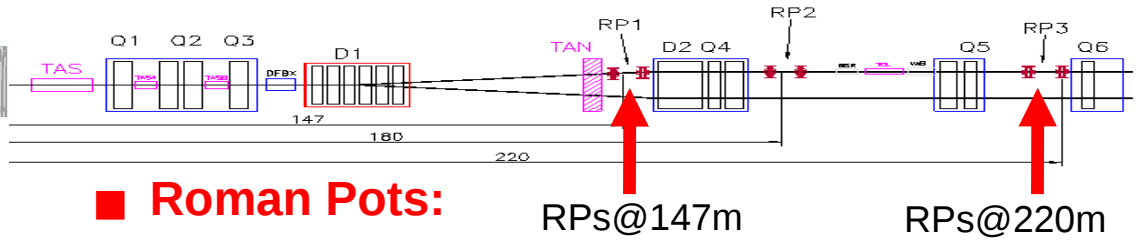
  $4.8 < |\eta| < 5.7$



# Forward detectors: TOTEM & LHCf

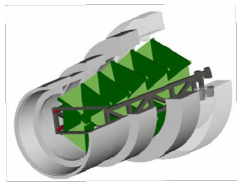
- TOTEM and LHCf: dedicated very-forward experiments

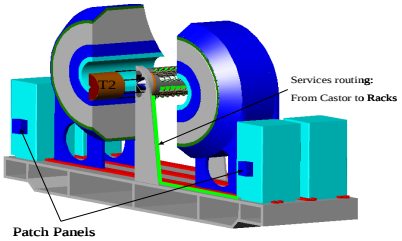


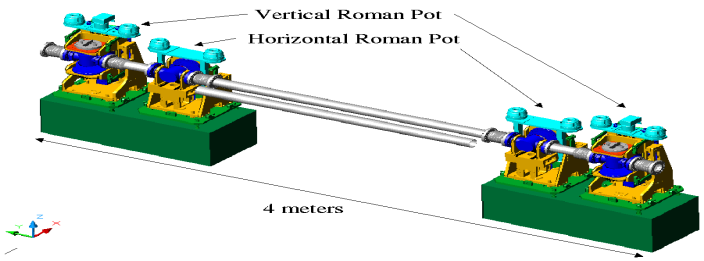



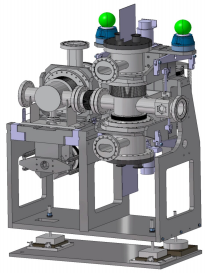

- **Roman Pots:**

- **T1,T2** (±10m,±13m in CMS IP):

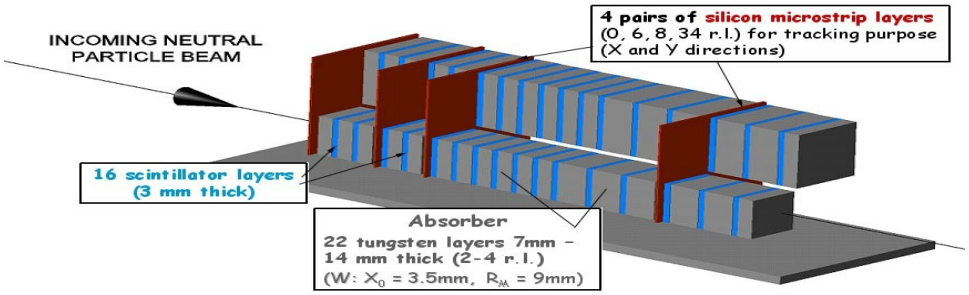




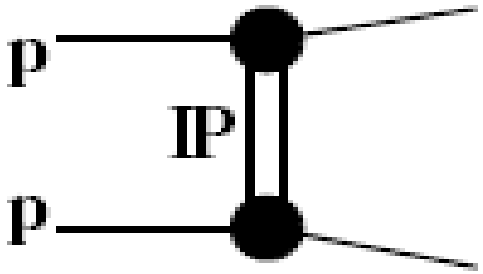



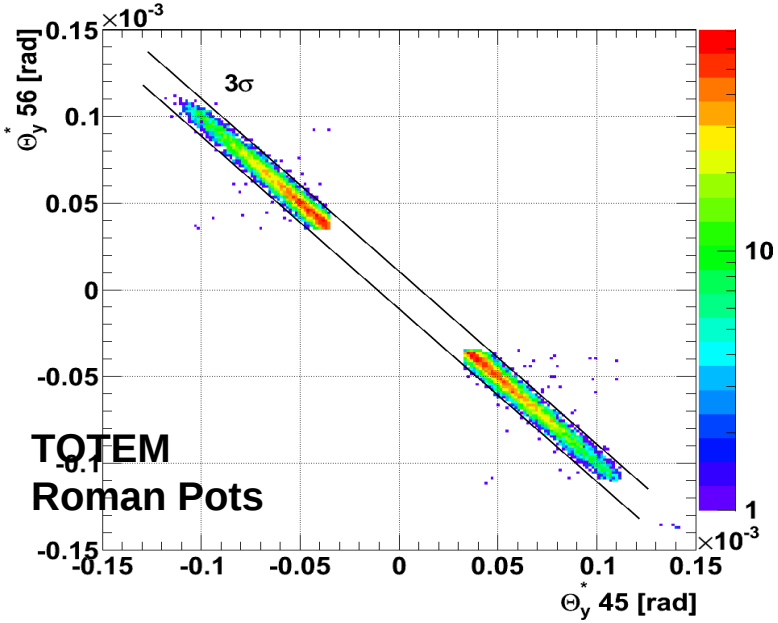



- **LHCf** (±140m in ATLAS tunnel):



# Elastic, inelastic & total cross sections



# p-p collisions at the LHC

- Hadrons are extended composite objects: Even at asymptotically large c.m. energies, ~40% of hadronic interactions are not "point-like":

pQCD

(1) Perturbative parton-parton collisions

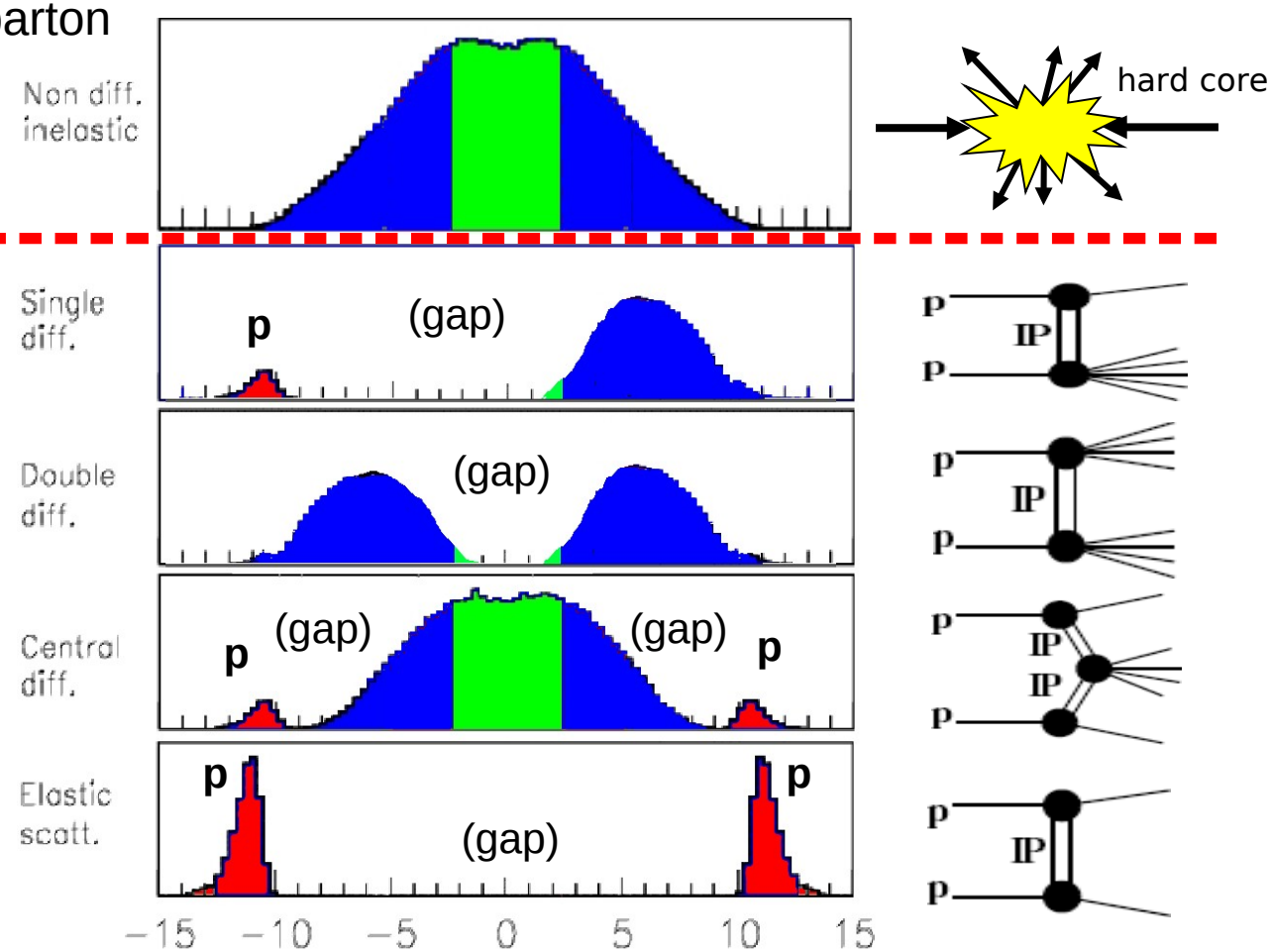
~60%

Regge-Gribov

(2) Diffractive, elastic

~40%

- 1 or 2 protons "intact" + 1 or 2 rapidity gaps:
- No colour flux.
- Colourless exchange with vacuum $J^{PC}=0^{++}$ quantum-numbers: |Pomeron = 2-gluons in colour-singlet state.



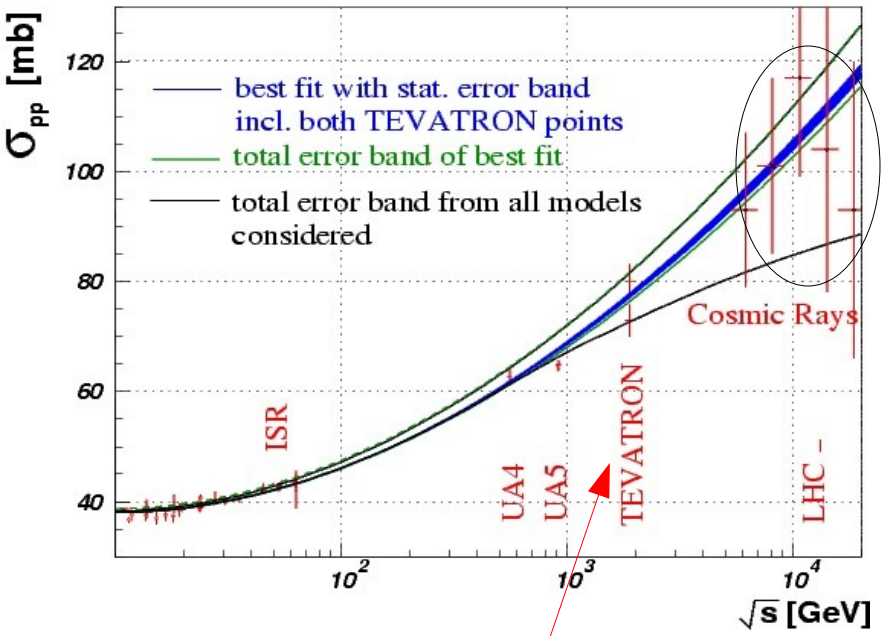

- pQCD (~60 mb) + elastic (~25 mb) + diffractive (~15mb) ~ 100 mb at the LHC.

# Total & elastic p-p cross sections

- Non-computable from QCD Lagrangian (maybe lattice ?), but constrained by fundamental QM relations: Froisart bound, optical theorem, dispersion relations.

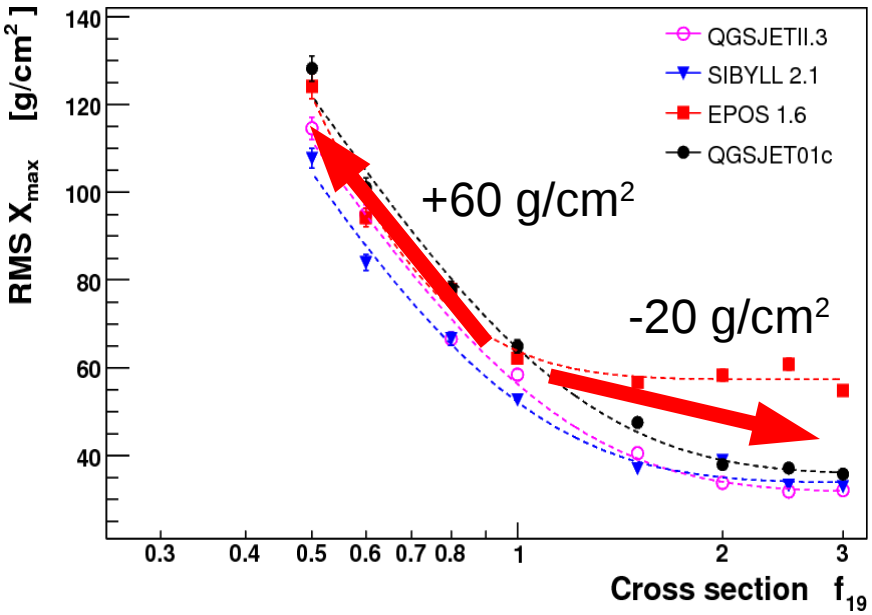
- LHC p-p x-section predictions:

$\sigma_{tot}$(LHC) = 90-120 mb $^{+10}_{-20}$ %.




- Pre-LHC model uncertainties driven by E710–CDF 2.6σ disagreement

- Impact on cosmic-ray MCs: Uncertainties of $\sigma_{inel}(E_{lab}\sim10^{19}$ eV) change by factor of ~2 the air-shower maximum fluctuations:




R.Ulrich, R.Engel,M.Unger, PRD83 (2011) 05426

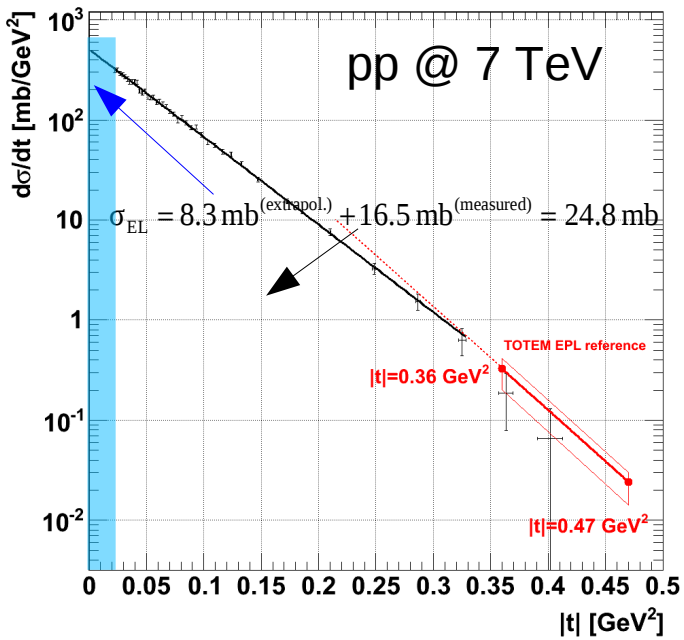
# Total & elastic cross sections (TOTEM)

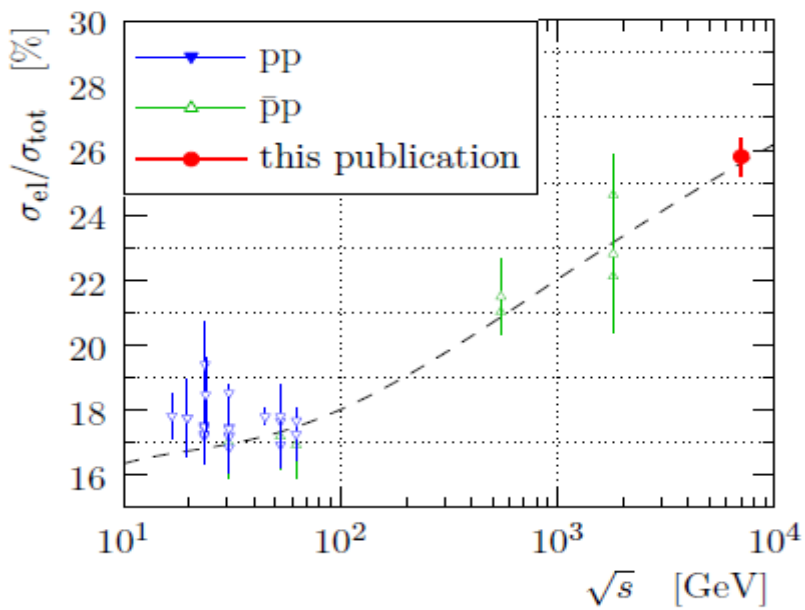
- 3 methods used to measure total x-section:
  - (1) Measure $(dN/dt)_{t=0}$ , Lumi (CMS)
    + $\rho_{theor}$ (COMPETE), optical theorem:
  - (2) Measure $N_{el}$, $N_{inel}$, Lumi (TOTEM) :
  - (3) Measure $(dN/dt)_{t=0}$ , $N_{el}$, $N_{inel}$ :

$$\sigma_{TOT}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \left.\frac{d\sigma_{EL}}{dt}\right|_{t=0}$$

$$\sigma_{tot} = \sigma_{el} + \sigma_{inel}$$

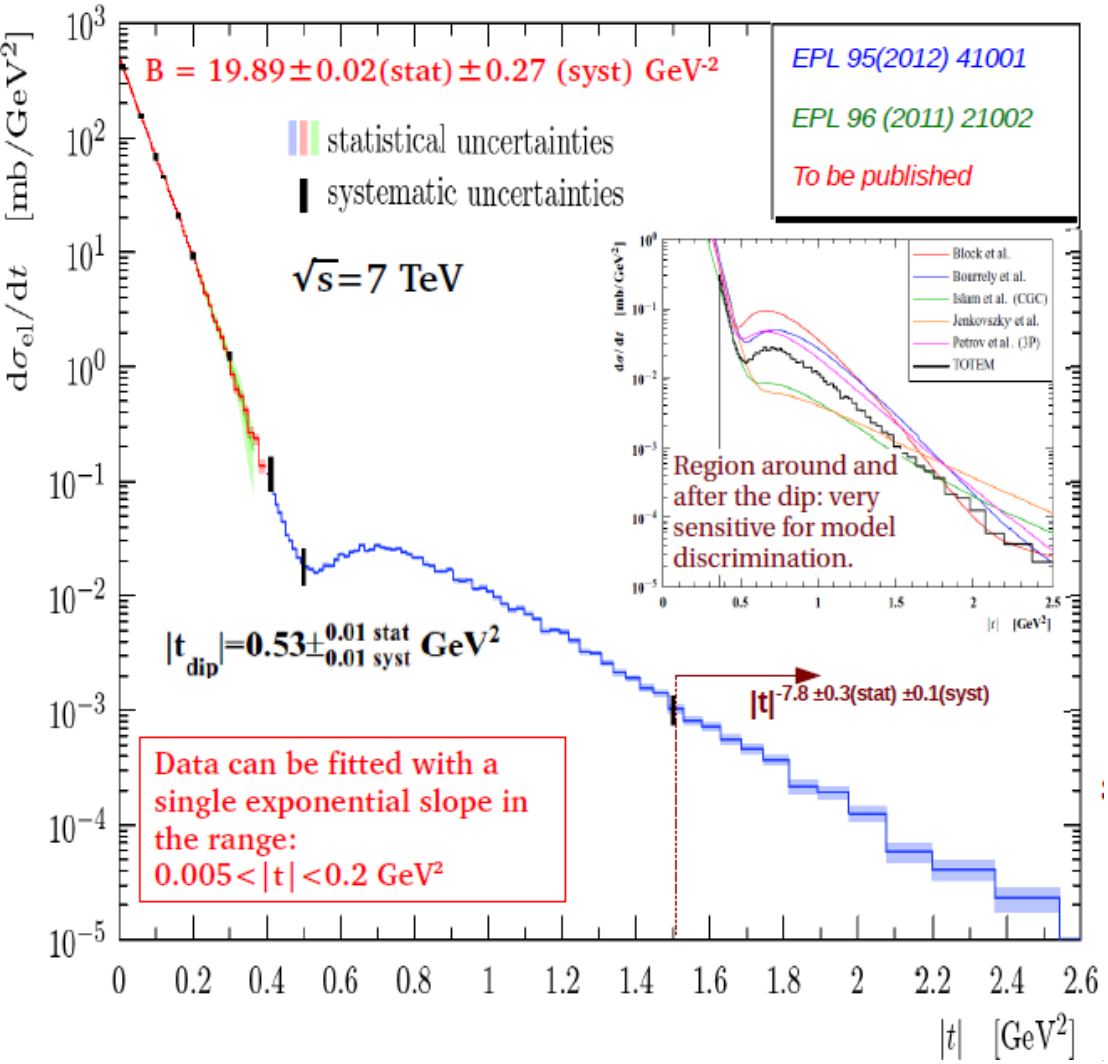
$$\sigma_{tot} = \frac{16\pi}{(1+\rho^2)} \frac{(dN_{el}/dt)_{t=0}}{(N_{el}+N_{inel})}$$

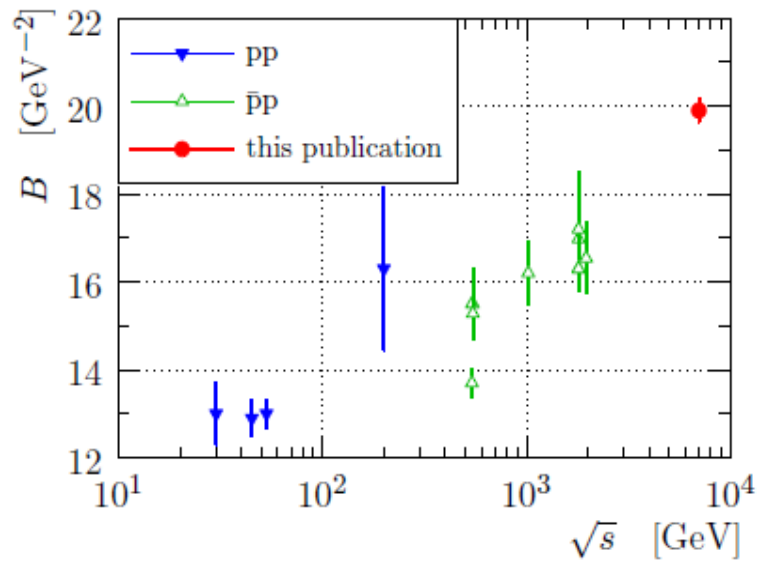



- All methods yield: $\sigma_{tot}$ ~ 98 mb, $\sigma_{el}$ ~ 25 mb at 7 TeV. Increase of $\sigma_{el}/\sigma_{tot}$

# Differential elastic scattering (TOTEM)

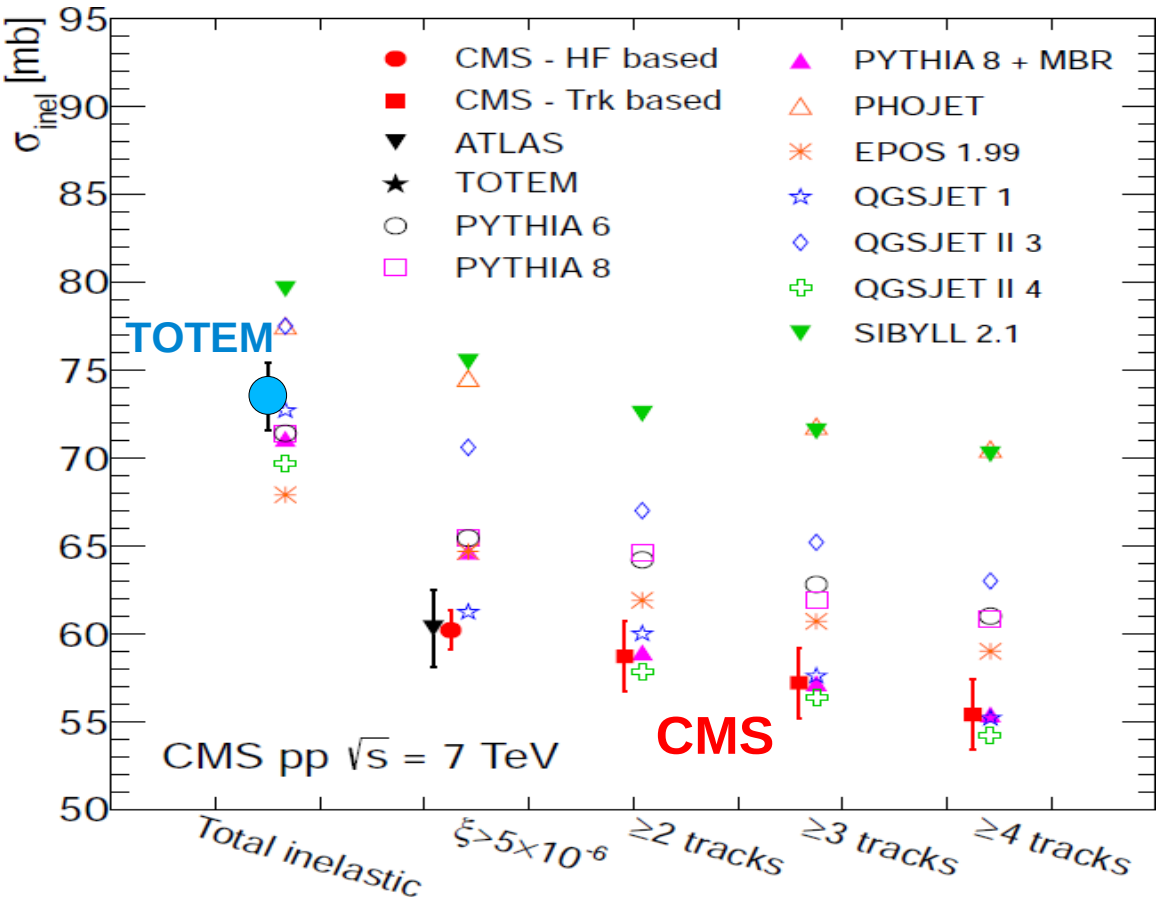



- TOTEM has confirmed :
  - Decrease of inverse expo slope
  - Shrinkage of diffraction peak
  - Decrease of dip t-position
- But so far only partial quantitative agreement with model predictions.

# p-p inelastic x-sections (Atlas, CMS, TOTEM)

- Visible inel. x-section $\sigma_{ATLAS,CMS}$ ~ 60 mb mostly overestimated by MCs:

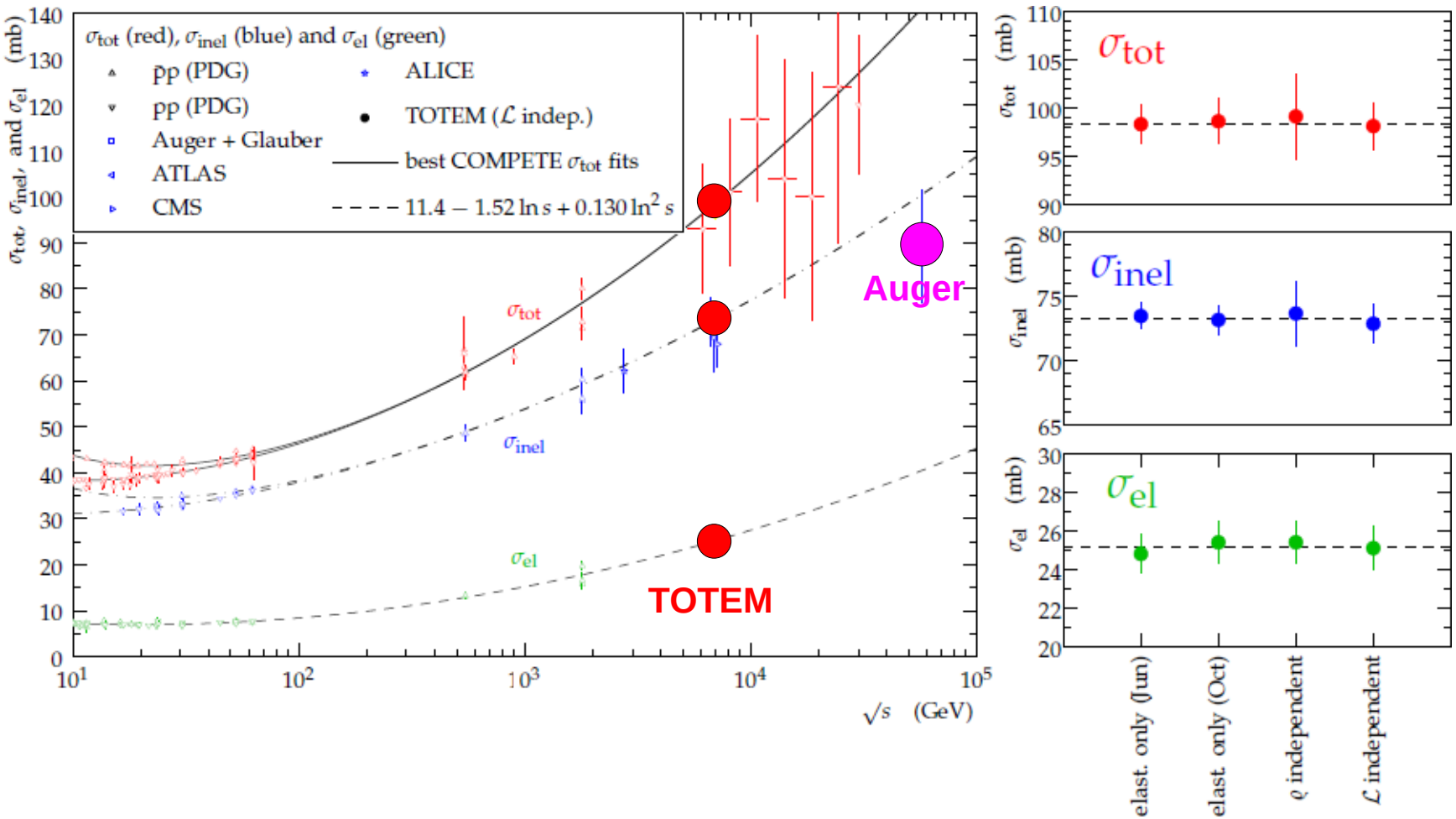



CMS 7-TeV preliminary
PAS-FWD-11-001

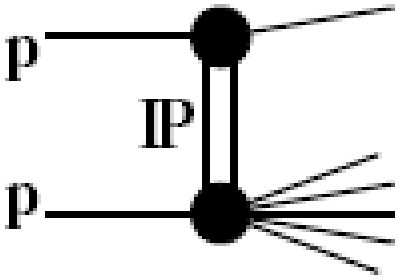
- Most models over-/under-estimate high-/low-mass diffraction.
- Increasingly unbiased evt. selection best reproduced by QGSJET01,-II-4

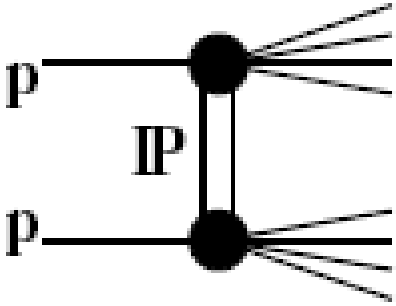
# p-p total/elastic/inel. x-sections (TOTEM)

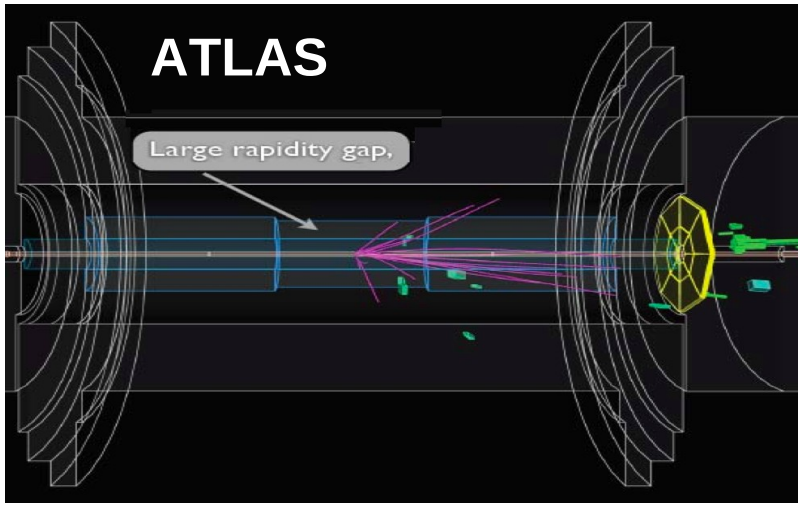
- TOTEM $\sigma_{tot}$~ 98 mb falls right on top of COMPETE fit prediction (which goes in between E710–CDF at 1.8 TeV ...)



# Diffractive scattering



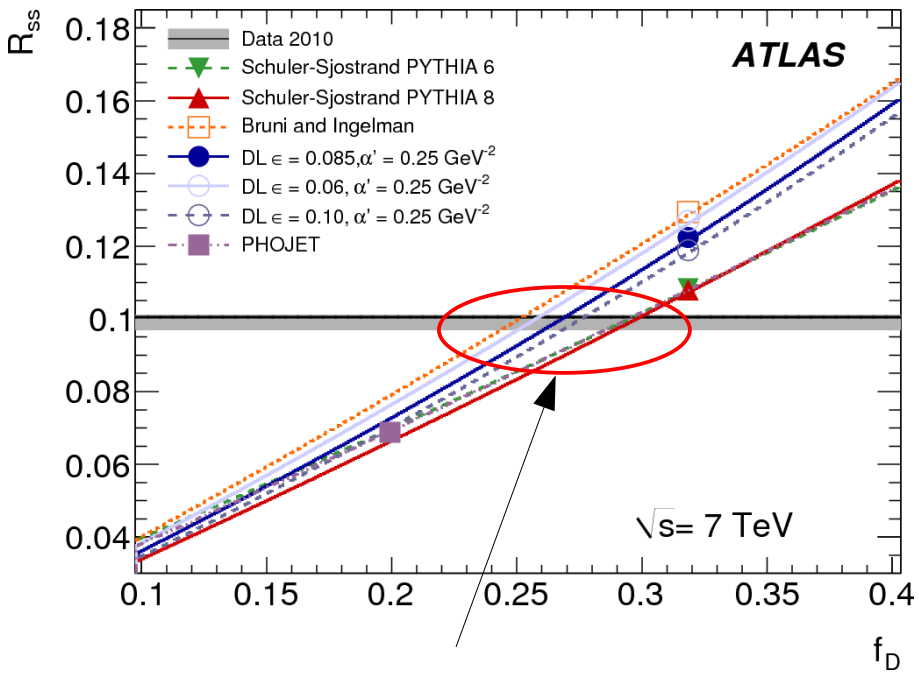



# Soft diffraction (ATLAS)

- Inclusive diffractive x-section measurement:

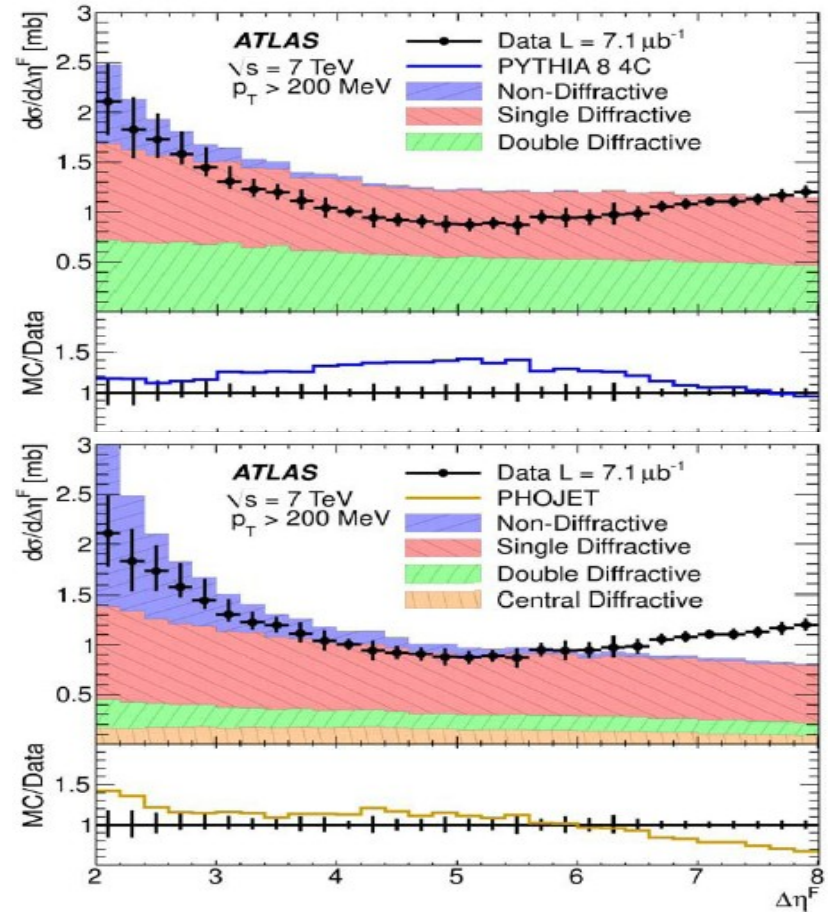
Ratios of single/double-side triggers




$R_{SS}$ =10.0±0.4% → $f_D$~25-30%

$\sigma_{diff}$~17-21 mb depending on models

- x-section vs. rap-gap:



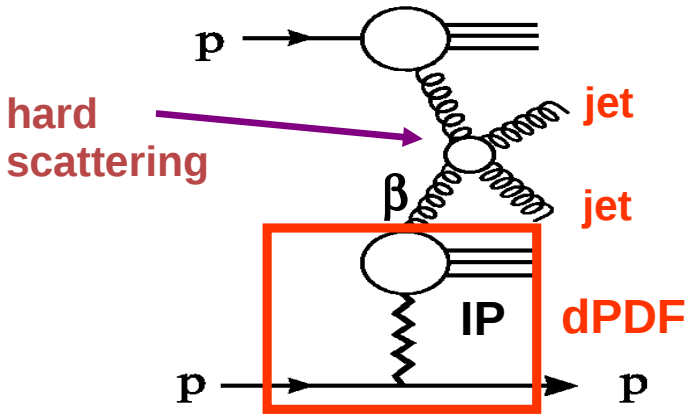

- PHOJET better at large $\Delta\eta_F$ (flat contribution from diffraction)
- PYTHIA (no DPE) better at smaller $\Delta\eta_F$

Non-diffraction dominant (expo decrease)

# Hard diffraction

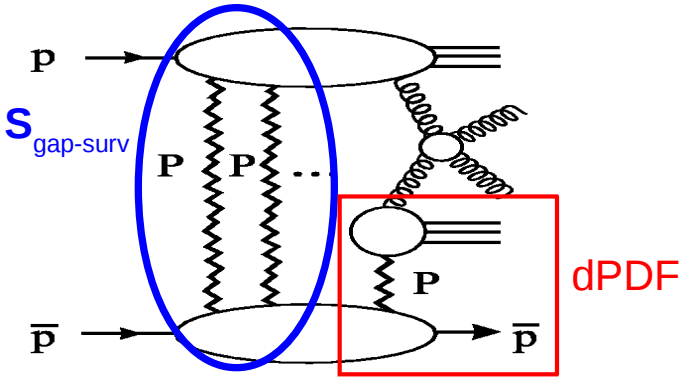
- Hard diffraction calculable using QCD factorization theorem:

$$\sigma_{\text{hard-diffractive}} = \text{dPDF} \otimes \sigma_{\text{parton-parton}} \otimes S_{\text{gap-survival}}$$

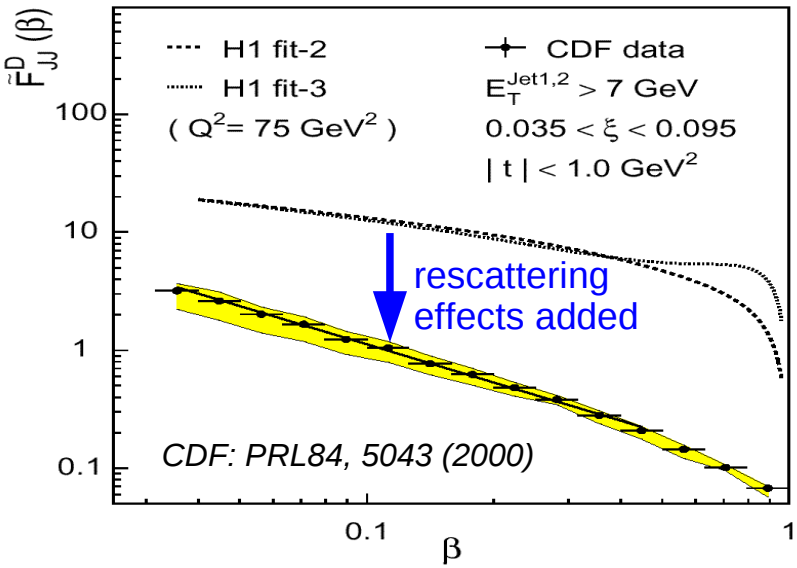



Diffractive PDFs: probability to find a parton of given *x* under condition that proton stays intact (measured at HERA).

- Gap survival S: probability to fill rapidity gap with hadrons from extra rescatterings




$p\bar{p} \to p\ jj\ X$

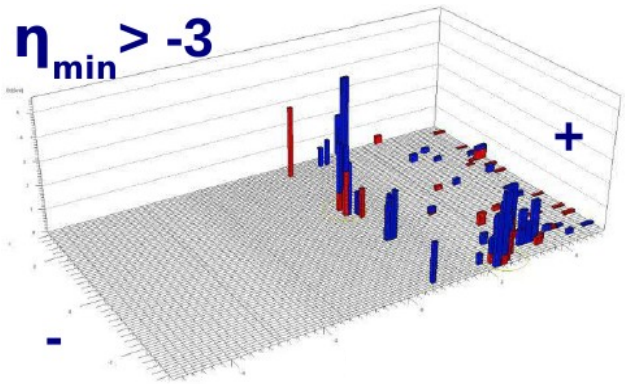



$S_{\text{gap-surv.}}$~10% at Tevatron

# Diffractive dijets (CMS)

CMS-FWD-10-004

- Observation of diffractive dijet production:




2 jets (anti-$k_T$, R=0.5) with $p_T$>20 GeV and |η|<4.4

Dijet distribution binned as a function of:

$$\tilde{\xi}^{\pm} = \frac{\sum (E^i \pm p_z^i)}{\sqrt{s}} \simeq \frac{M_X^2}{s}$$

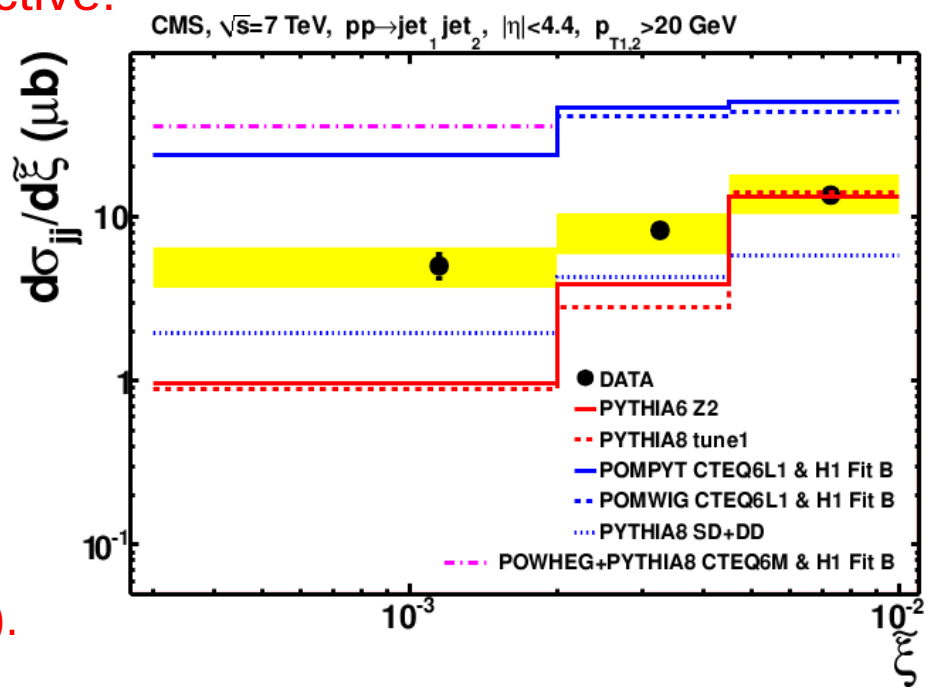
= proton fractional momentum loss in SD events

ξ reconstructed from all other particles in event.

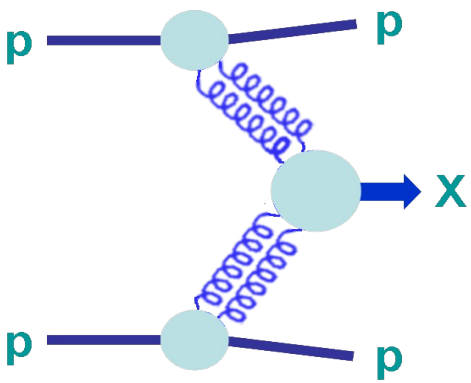
- Low-ξ region predominantly diffractive:

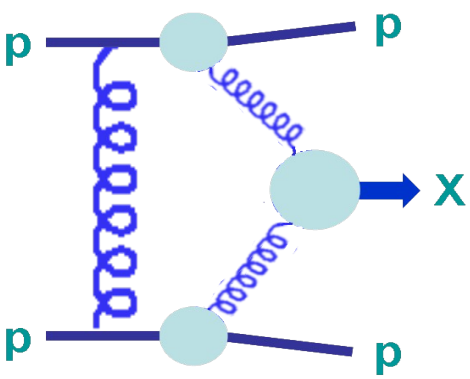
$$\frac{d\sigma_{jj}}{d\tilde{\xi}} = \frac{N_{jj}^i}{L \cdot \epsilon \cdot A^i \cdot \Delta\tilde{\xi}^i}$$

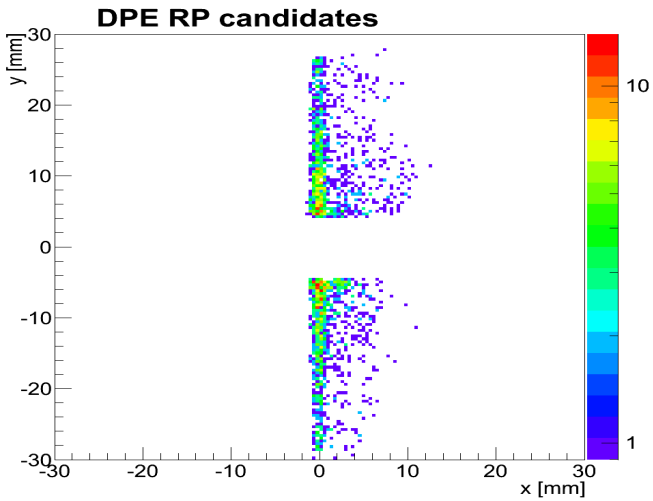
- Excess of events in low-ξ region wrt. non-diffractive MCs.
- Diffractive MCs x5 above data in lowest-ξ bin interpreted in terms of rap-gap survival probability:
  S=0.12±0.05 (LO), 0.08 ±0.04 (NLO).

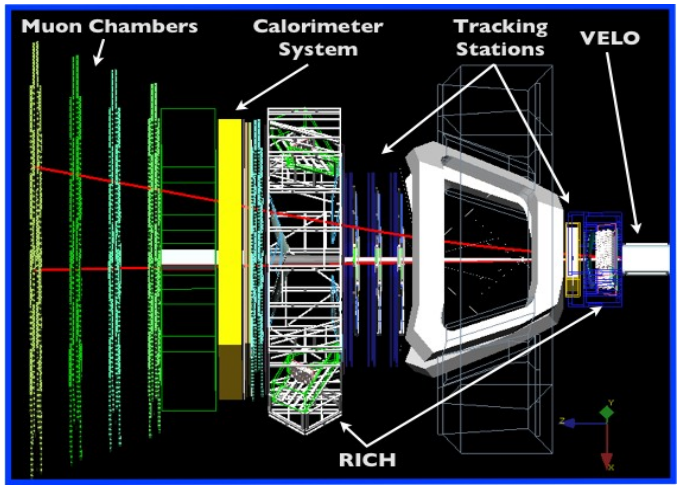


# Double-pomeron & central-exclusive



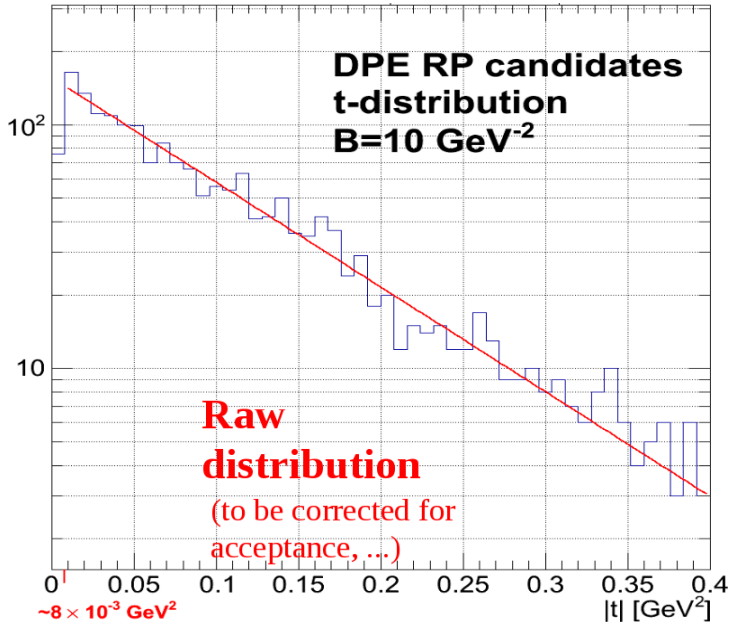



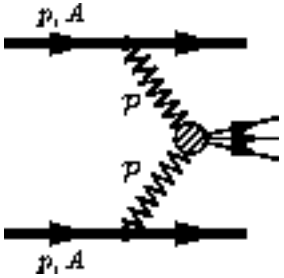
# Double pomeron exchange (TOTEM, ALICE)

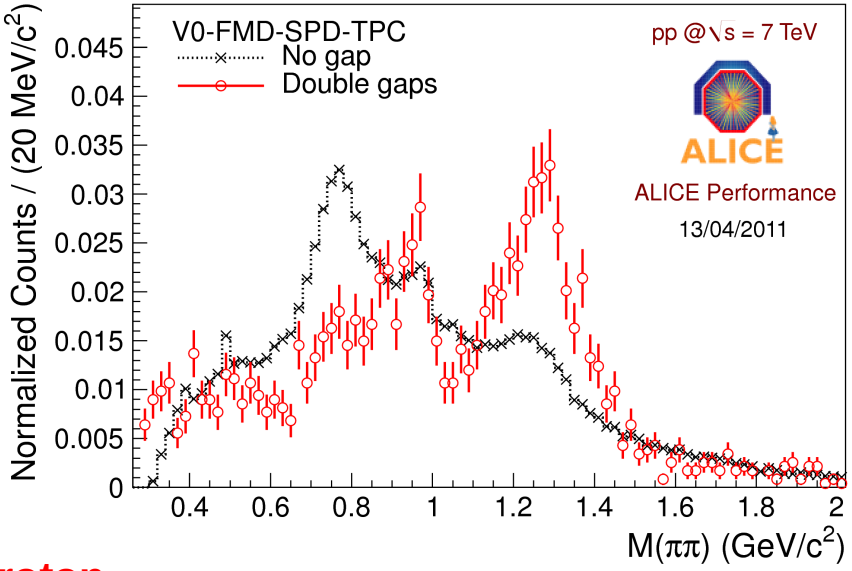
- First attempts at measuring the inclusive DPE x-section:

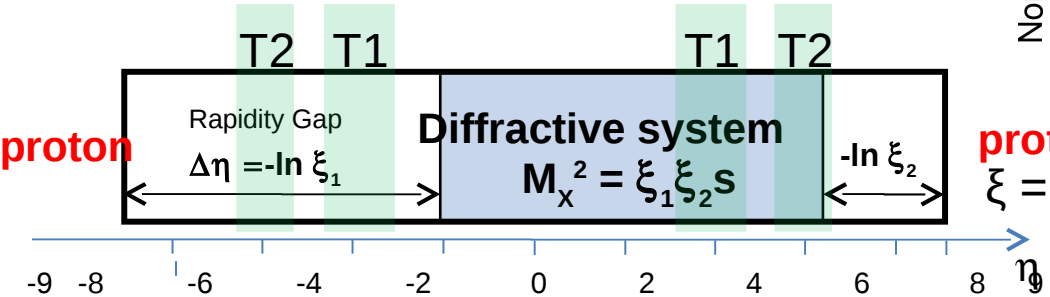



- Enhanced $f_0(980)$ & $f_2(1270)$ production in double-gap events ($\Delta\eta_{gaps}$ = 3, 4):

$J^{PC} = (0,2)^{++}$



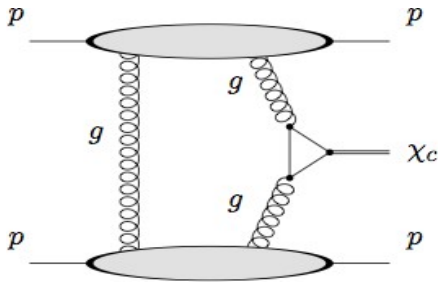

$\xi = \Delta p/p$

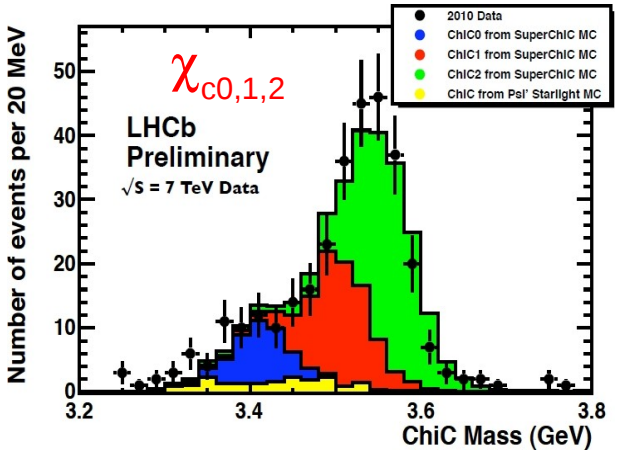
# Central exclusive production (LHCb, CMS)

CMS PAS-FWD-11-004

- Exclusive $\chi_c$ production:

LHCb-CONF-2011-022

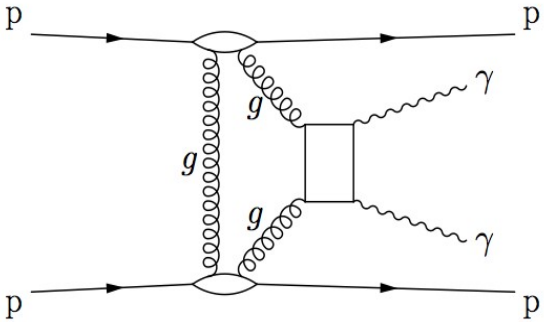



$\chi_c \to J/\Psi\ \gamma$ + nothing else in event

| | $\sigma(pp \to pp(J/\psi + \gamma))$ LHCb (pb) | SuperCHIC prediction (pb) |
|---|---|---|
| $\chi_{c0}$ | $9.3 \pm 4.5$ | 14 |
| $\chi_{c1}$ | $16.4 \pm 7.1$ | 10 |
| $\chi_{c2}$ | $28 \pm 12.3$ | 3 |

- Exclusive $\gamma\gamma$ production:

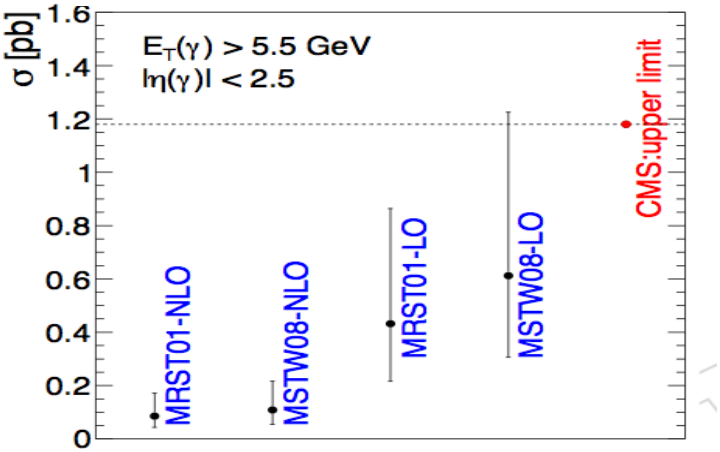



Just 2 EM showers (nothing else to $|\eta| = 5.2$)

No $\gamma\gamma$ candidates found.

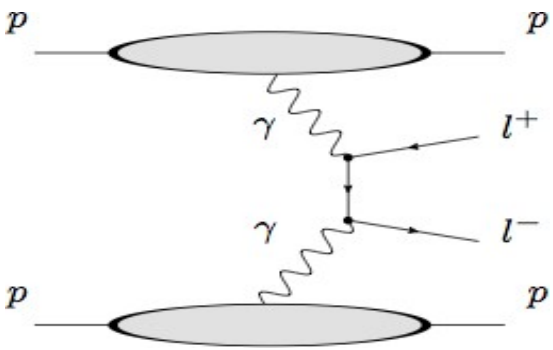
Upper limit x-section:

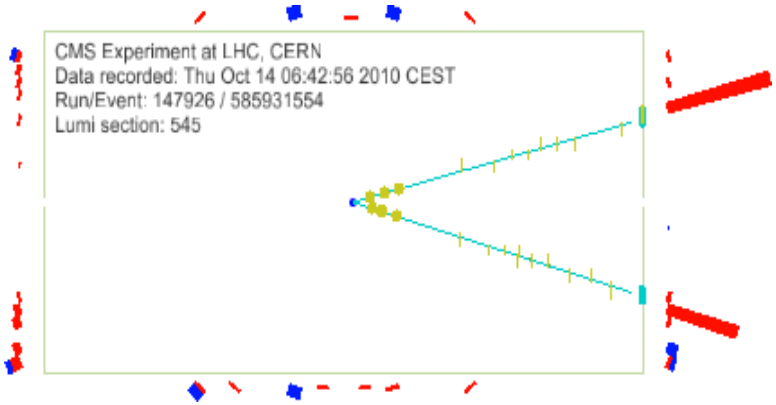
$$\sigma^{E_T(\gamma)>5.5\,\mathrm{GeV},\,|\eta(\gamma)|<2.5}_{\text{exclusive }\gamma\gamma\text{ production}} < 1.30\ \mathrm{pb}$$




☞ Important constraints for gap-survival probability for CEP Higgs.

# Photon-photon collisions

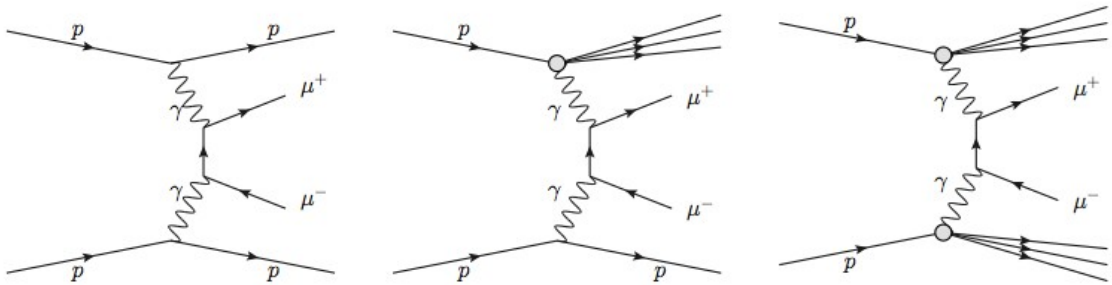


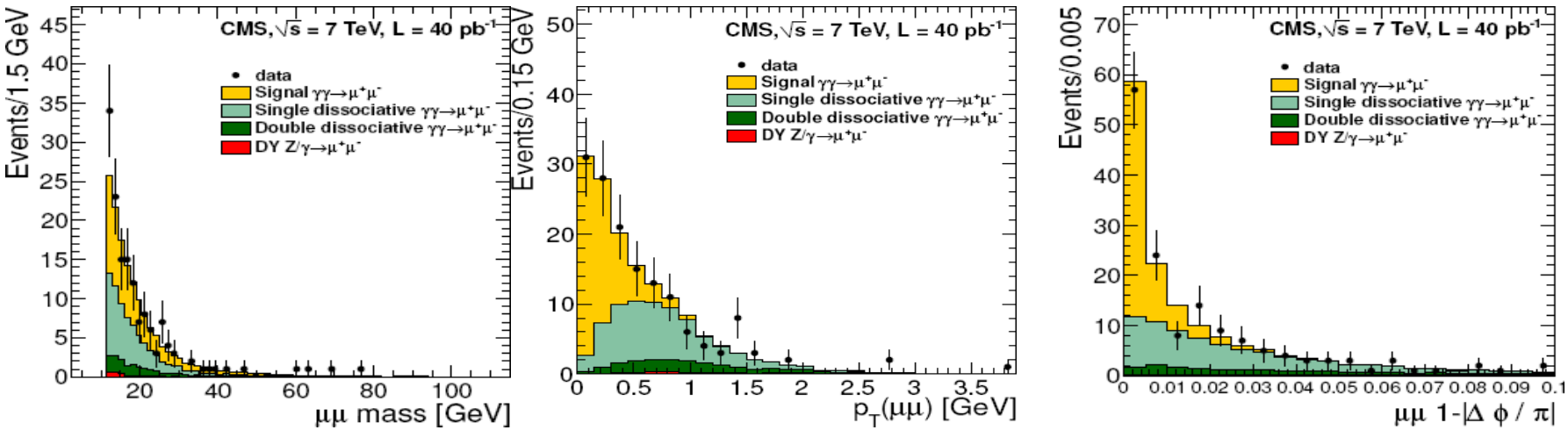
# Exclusive γ-γ dimuon production (CMS)

JHEP 01 (2012) 052

- Exclusive dimuons observed in $m_{\mu\mu}$ ~ 11 – 80 GeV (above Υ):




Just 2 muons,
$E_T$ > 5.5 GeV, |η| < 2.1,
nothing else to |η| = 5.2

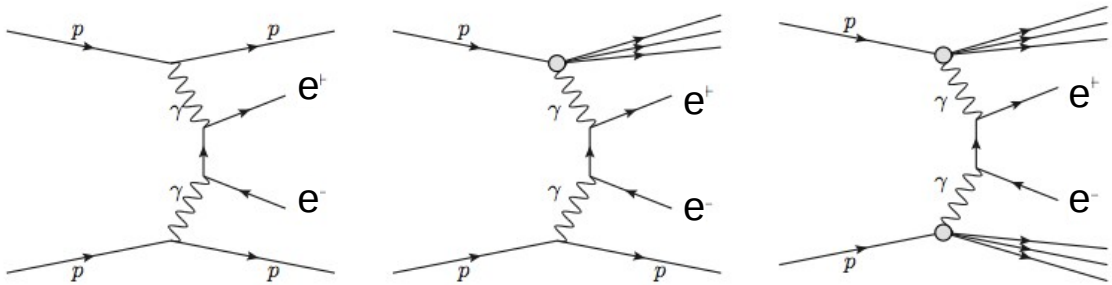



- Pair-$p_T$ very small (peak at ~50 MeV/c). Muons are ~back to back.
- Agreement with LPAIR (QED): pp → γ γ → μμ

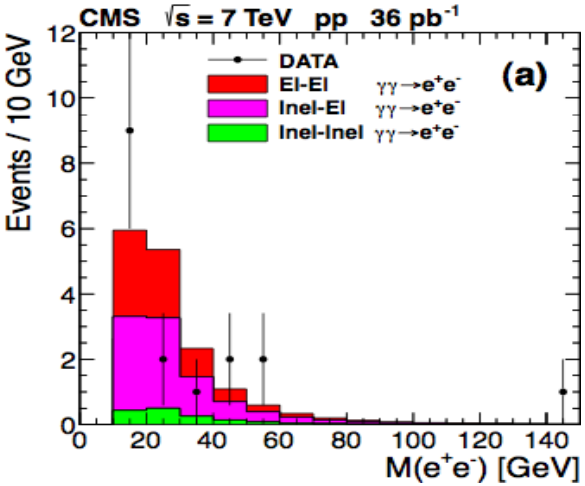
# Exclusive γ-γ dielectron production (CMS)

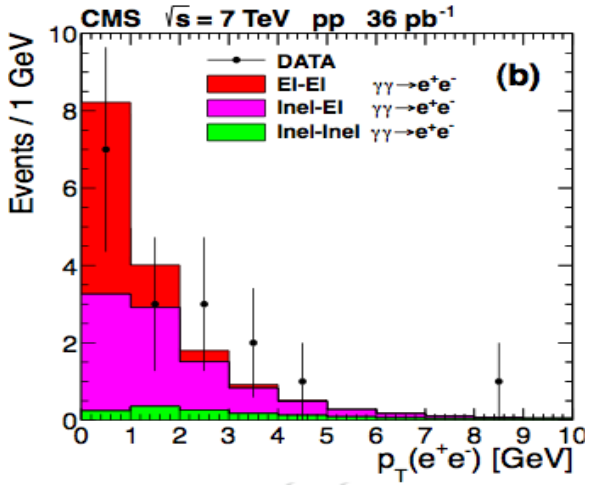
CMS PAS-FWD-11-004

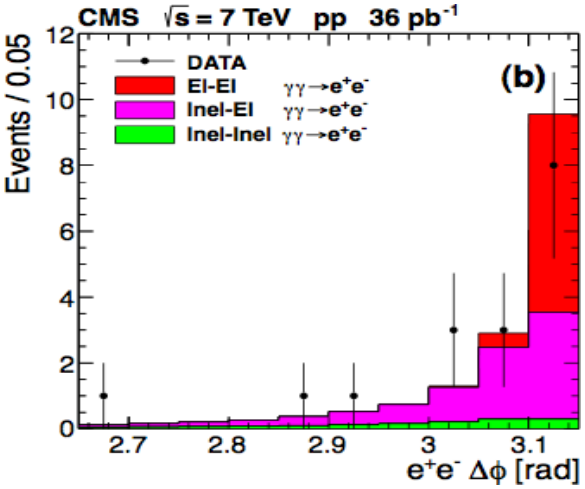
- Exclusive dielectrons observed in $m_{ee}$ ~ 11 – 140 GeV (above Y):




Just 2 EM showers,
$E_T$ > 5.5 GeV, |η| < 2.1,
nothing else to |η| = 5.2

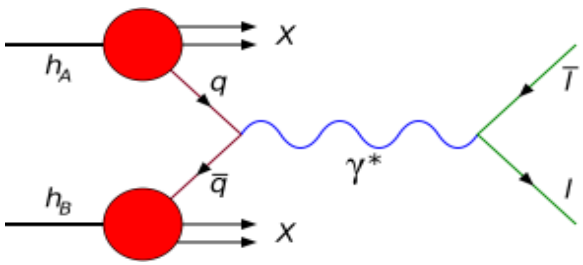


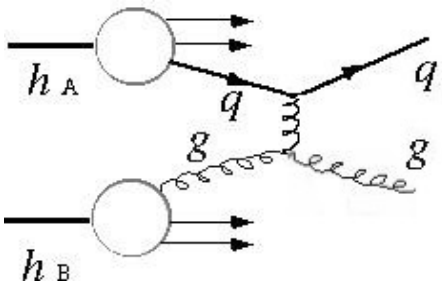



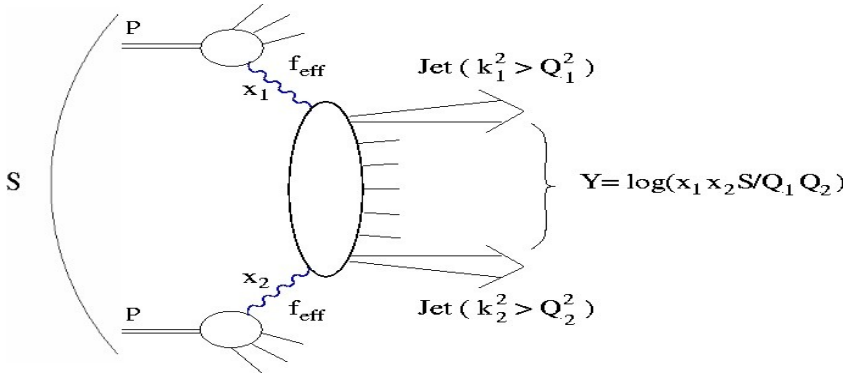




- Pair-$p_T$ very small (peak at ~200 MeV/c). Electrons ~back to back.
- Agreement with LPAIR (QED): pp → γ γ → ee

# Low-x QCD

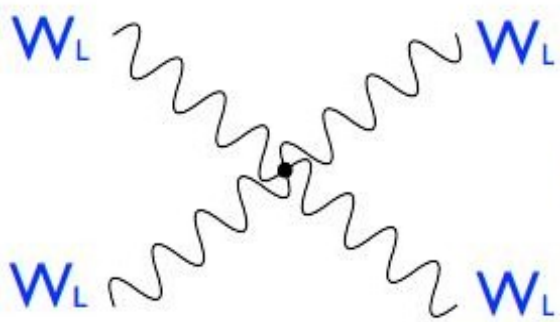

$h_A$
$h_B$
$x$
$x$
$q$
$\bar{q}$
$\gamma^*$
$\bar{l}$
$l$


$h_A$
$h_B$
$q$
$q$
$g$
$g$

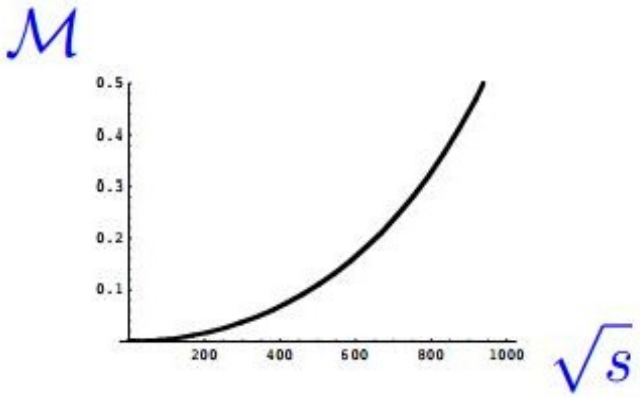

P
P
S
$f_{eff}$
$f_{eff}$
$x_1$
$x_2$
Jet ( $k_1^2 > Q_1^2$ )
Jet ( $k_2^2 > Q_2^2$ )
$Y = \log(x_1 x_2 S/Q_1 Q_2)$

# Unitarity of electroweak cross sections

- SM without a Higgs: longitudinal W-W scattering explodes at ~1 TeV



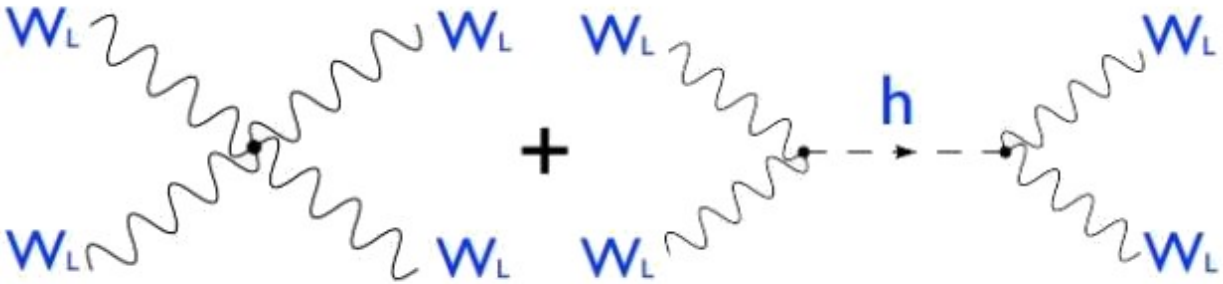

$$\propto \frac{s}{v^2}$$

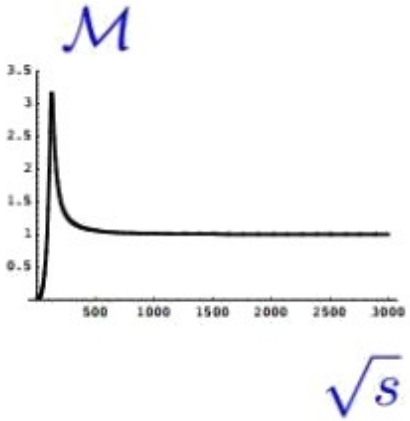



[A.Pomarol, ICHEP'12]

Unitarity is lost at high-energies

- Higgs boson restores finiteness of W-W cross sections:



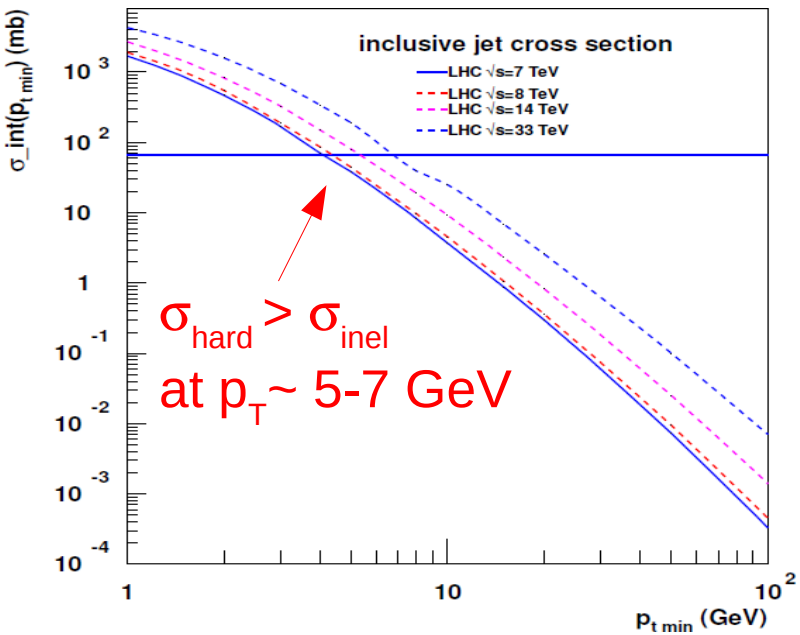



# Unitarity of pQCD cross sections

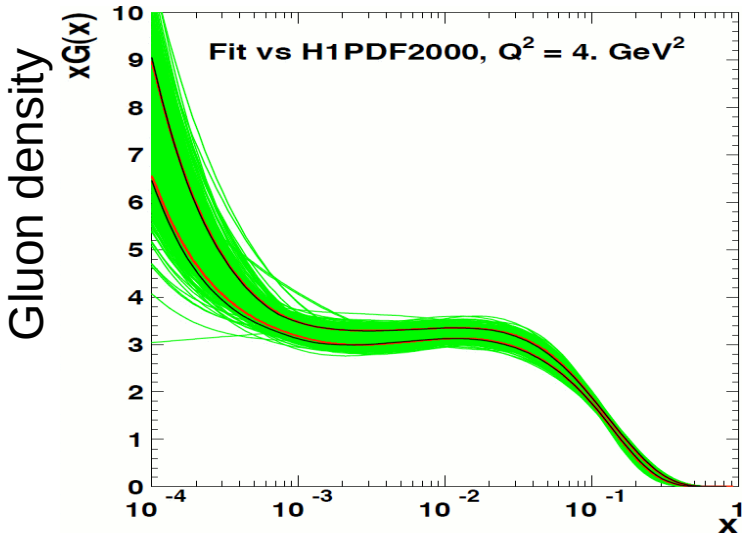
- pQCD (mini)jet production x-section is bigger than total inel p-p x-section for $p_{Tmin}$ ~ 5-7 GeV at the LHC !

$$\sigma_{\rm hard}(p_{\perp\rm min}) = \int_{p^2_{\perp\rm min}}^{s/4} \frac{{\rm d}\sigma}{{\rm d}p^2_\perp}\,{\rm d}p^2_\perp$$

... Why this happens ?




- Very high gluon densities at small-x:



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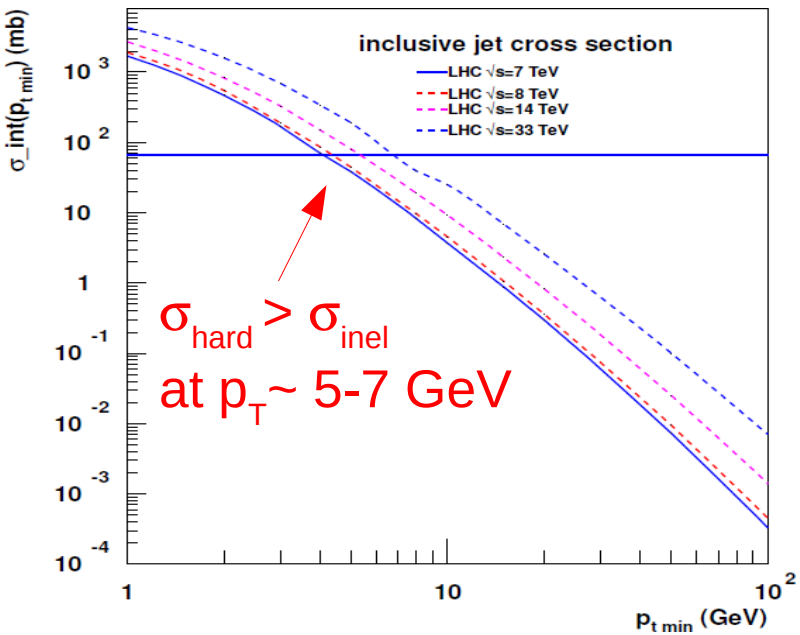
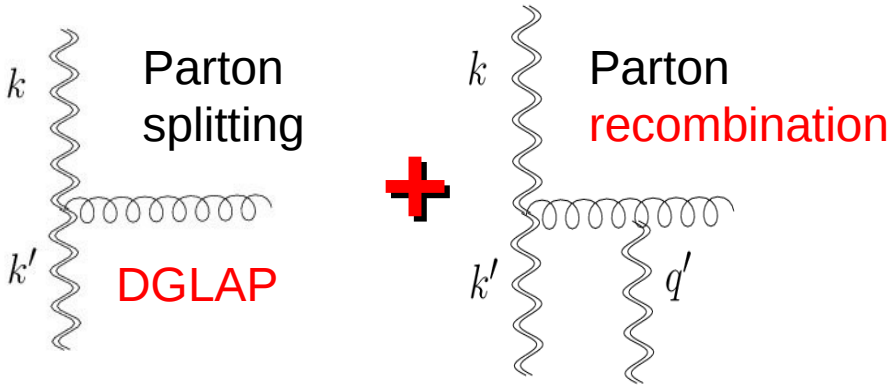
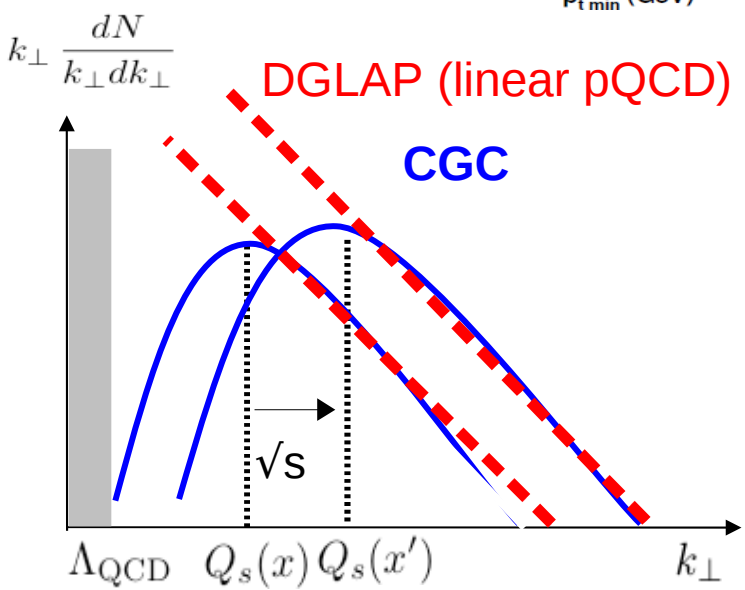



- Very high gluon densities at small-x.
- Solution: Gluon saturation
  - Add non-linear QCD evolution eqs.



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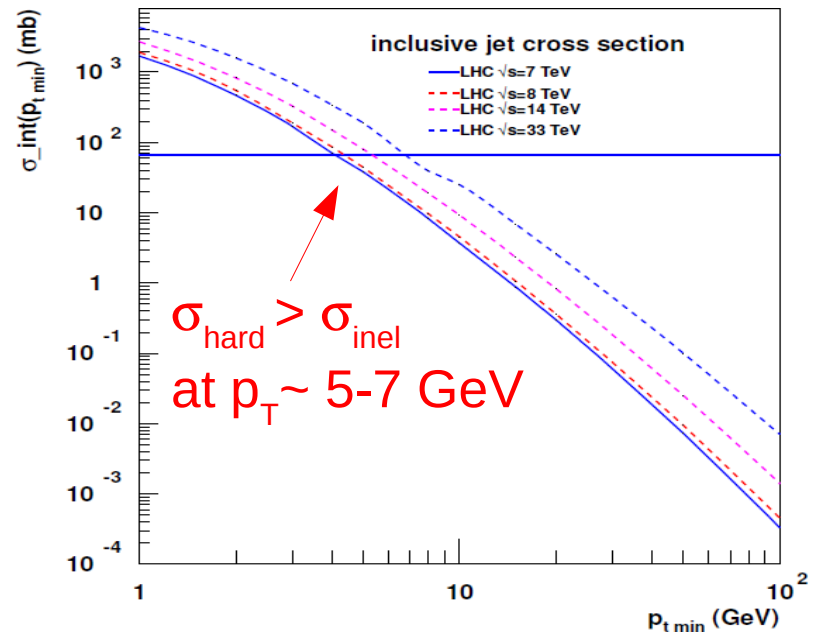
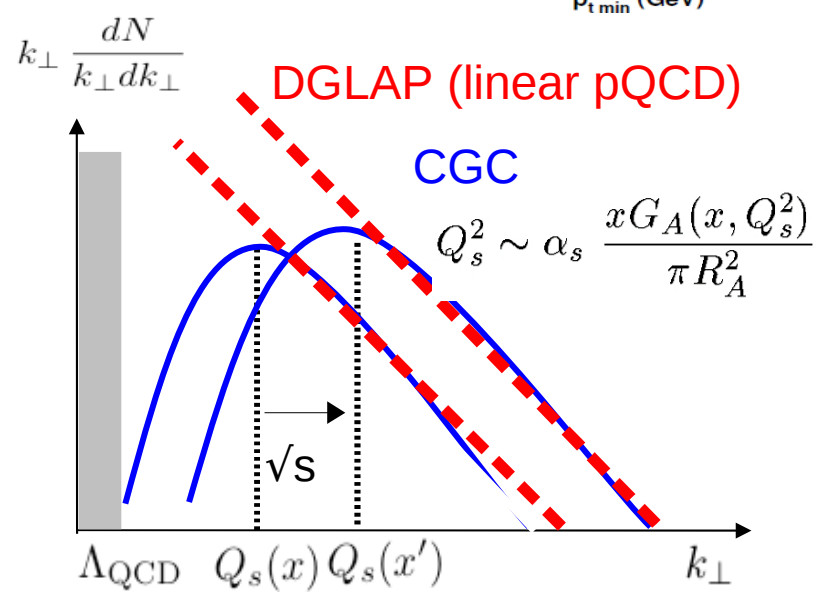



- Very high gluon densities at small-x.
- Solution: Gluon saturation
  - Add non-linear QCD evolution eqs.

collinear factorization assumptions (leading-twist, incoherent parton scatt.) invalid around "saturation scale" $Q_s$

New effective theory: CGC
New evolution equations: JIMWLK



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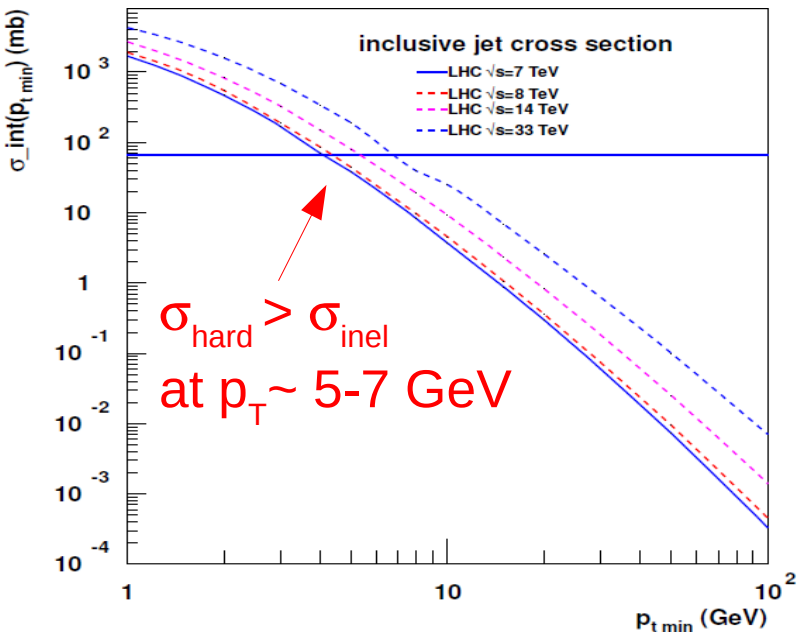
... Why this happens ?

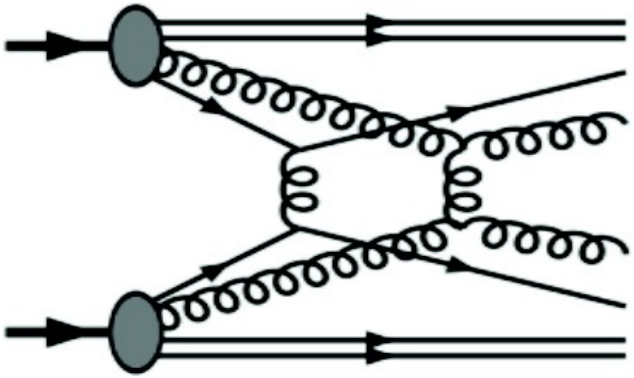



- Very high gluon densities at small-x.
- Solution: Gluon saturation
  - Multi-parton interactions

Interpret ...

$$\langle n \rangle = \frac{\sigma_{\rm hard}(p_{\perp\rm min})}{\sigma_{\rm inel}}$$

= average number of parton–parton scatterings above $p_{\perp\rm min}$ in an event

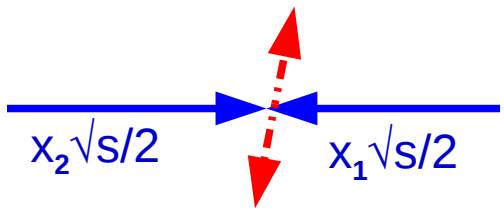


Most collider MCs (PYTHIA, HERWIG) follow this approach

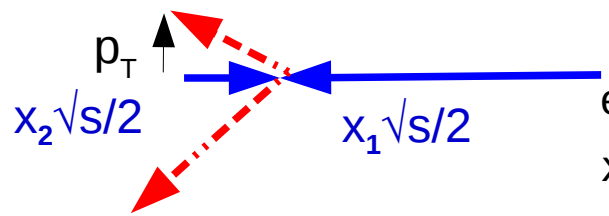
# Small-$x$ ⇒ Forward rapidities

- 2 → 2 parton kinematics:

**y = 0**: $x_1 \sim x_2 \sim x_T = 2p_T/\sqrt{s}$




$$x_{1,2}^{2\to 2} = \frac{p_T}{\sqrt{s}}\left(e^{\pm y} + e^{\pm y'}\right) \Rightarrow x_2^{min} = \frac{x_T\, e^{-\eta}}{2 - x_T\, e^{\eta}}$$




e.g. LHC, $p_T$ = 10 GeV/c

$x_T \sim 10^{-3}$ ($\eta \sim 6$): $x_{min} \sim 10^{-6}$

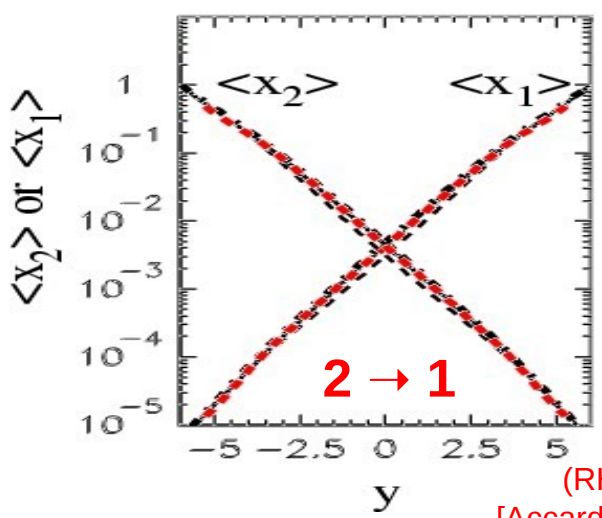
- 2 → 1 (gluon fusion) CGC kinematics: much lower $x$ reached ($x_2 = x_2^{min}$)

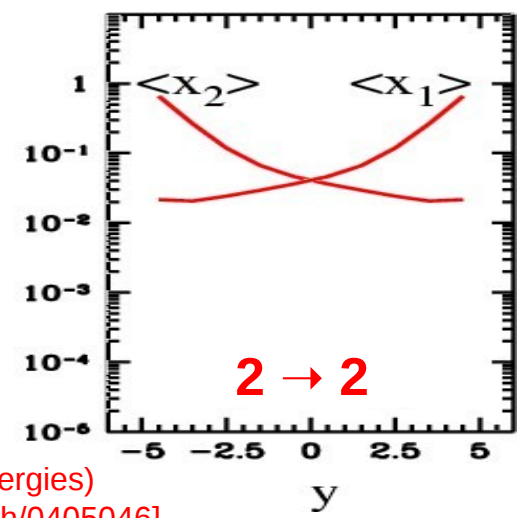
$$x_{1,2}^{2\to 1} = \frac{p_T}{\sqrt{s}}\left(e^{\pm y}\right)$$

Every 2-units of y, $x_2$ decreases by ~10

CGC: $x(y=4) \sim 10^{-4}$

DGLAP: $x(y=4) \sim 10^{-2}$

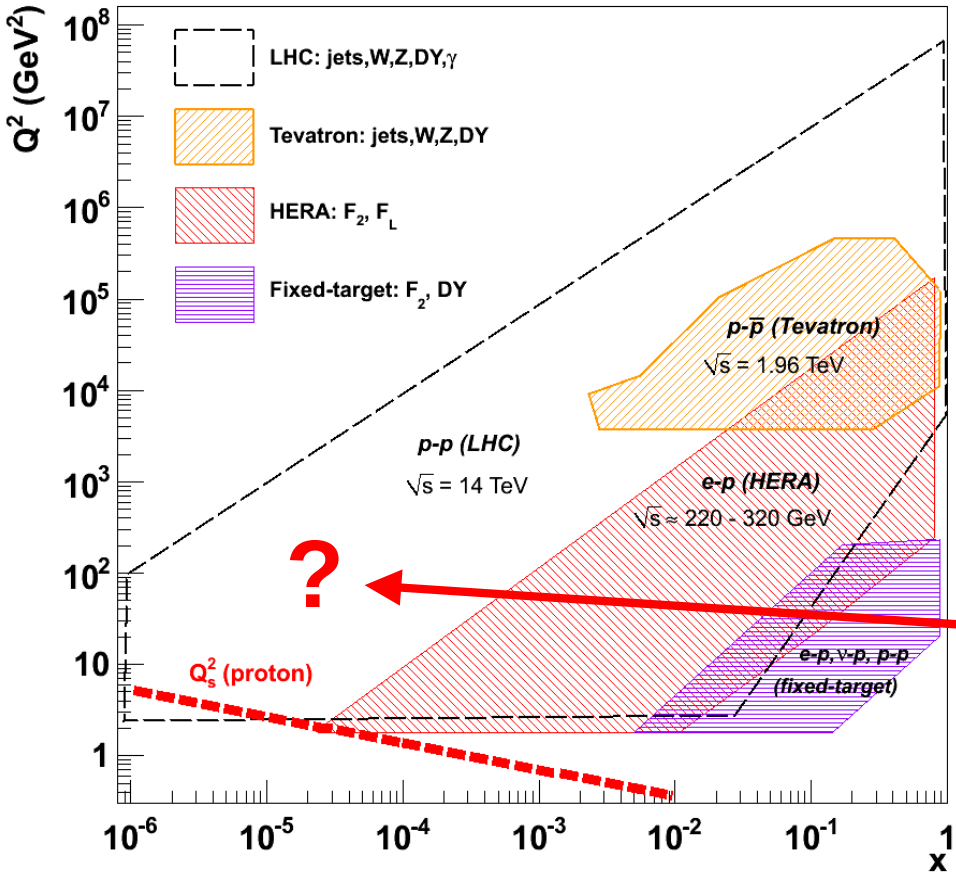



(RHIC energies)
[Accardi,nucl-th/0405046]

# Low-*x* studies in p-p at forward η

- At y=0, $x=2p_T/\sqrt{s}\sim10^{-3}$ (probed at HERA,Tevatron). Go fwd. for $x<10^{-4}$
- Very large pQCD cross-sections:




$p(p_1)+p(p_2)\to \text{jet}+\gamma+\text{X}$ Prompt γ

$p(p_1)+p(p_2)\to l\bar{l}+\text{X}$ Drell-Yan

$p(p_1)+p(p_2)\to \text{jet}_1+\text{jet}_2+\text{X}$ Jets

$p(p_1)+p(p_2)\to \text{Q}+\bar{\text{Q}}+\text{X}$ Heavy-Q

$p(p_1)+p(p_2)\to W/Z+\text{X}$ W,Z

Forward rapidities:

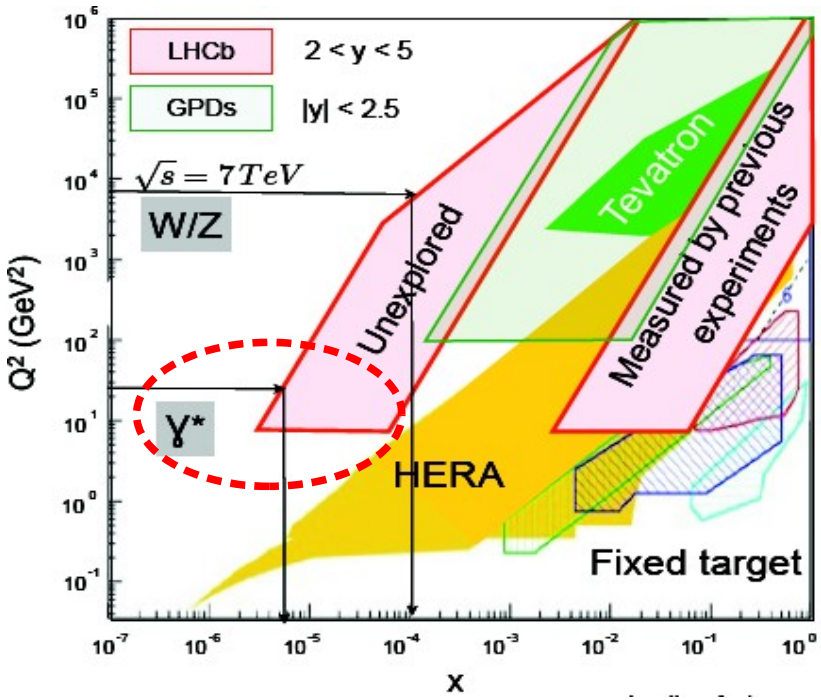
(e.g. y~5, M~2.5 GeV)

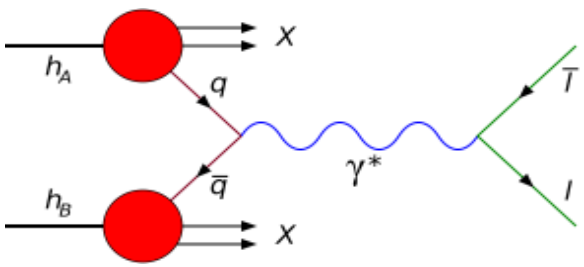
x down to $10^{-6}$ !

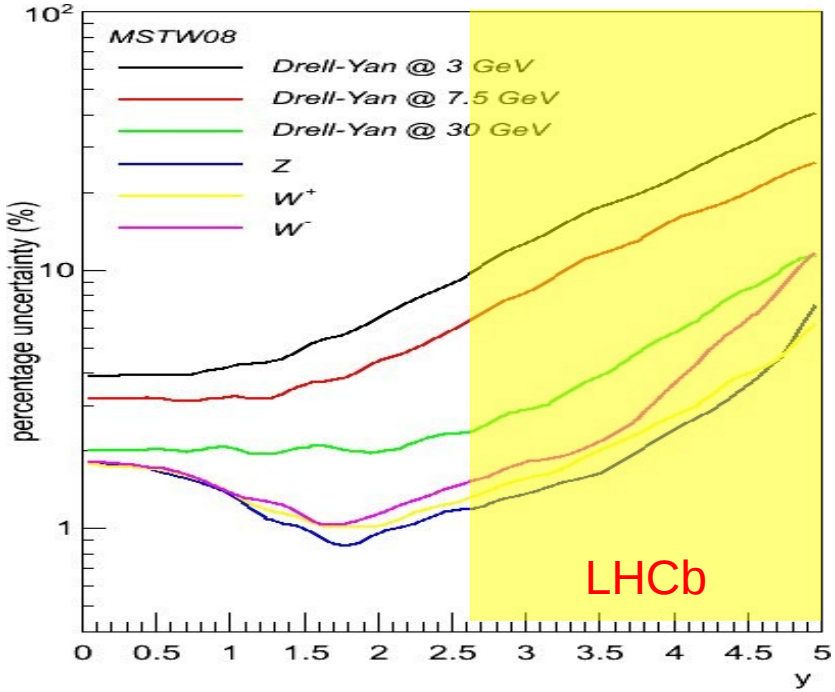
- But barely touching sat. momentum: $Q_s^2\sim 0.6$ GeV$^2$ (y=0), 3 GeV$^2$ (y=5)

# Forward Drell-Yan at 2.5 < η < 5 (LHCb)

- Forward DY sensitive to PDFs at $x \sim 10^{-5}, Q^2 = m_{ll}^2$ :



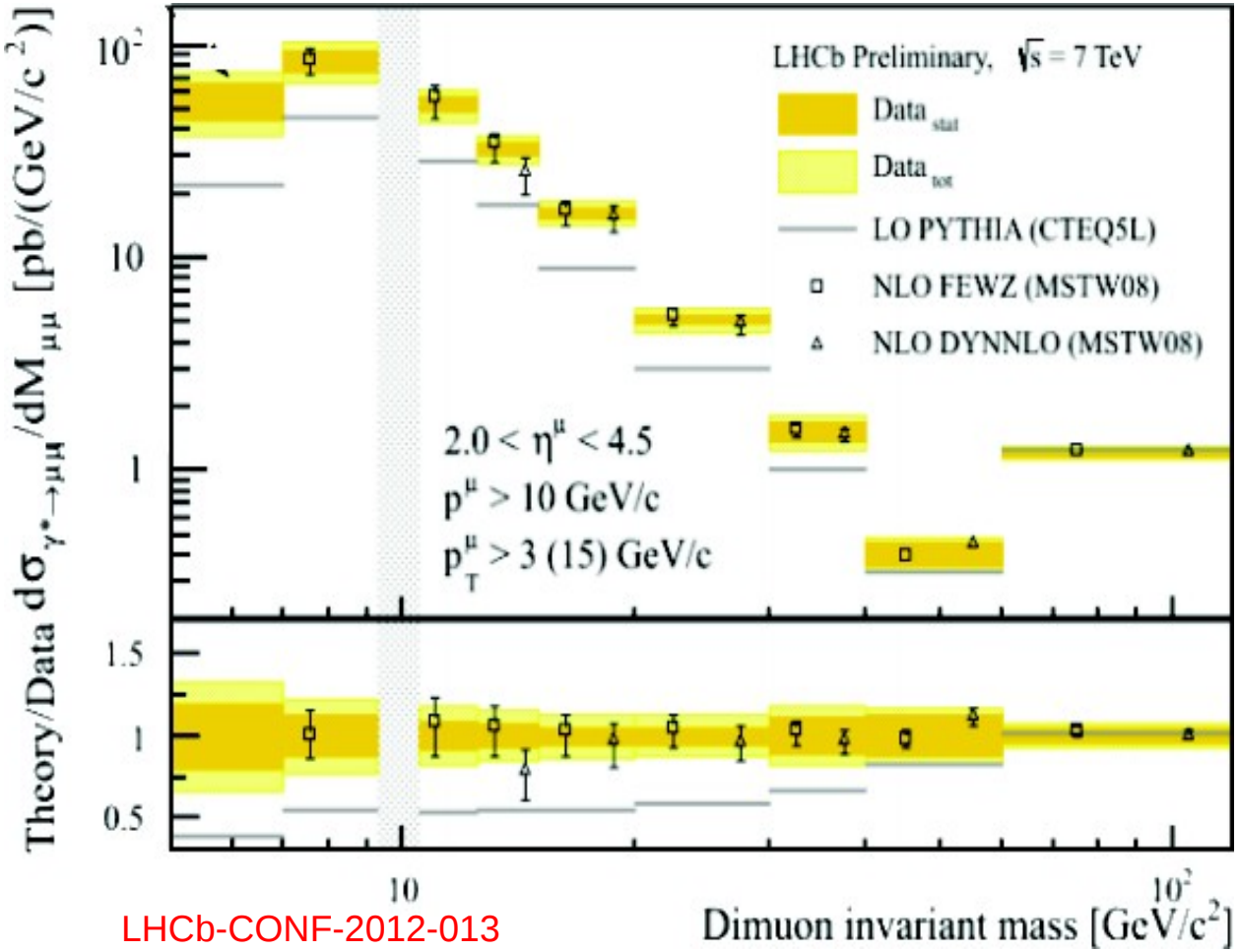




- ~30% PDF uncertainties for low-mass DY NLO x-sections at rapidities y~5:

(parton saturation effects ?)

# Forward Drell-Yan at 2.5 < η < 5 (LHCb)

- Forward DY x-section vs $m_{\mu\mu}$ well reproduced by NLO (DGLAP PDFs) from $m_{\mu\mu}$ = 5 – 120 GeV:




LHCb-CONF-2012-013

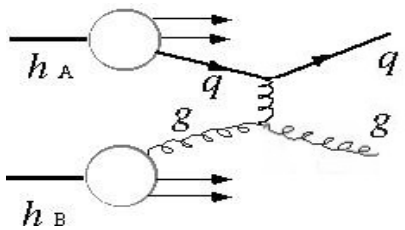
muons must have:
p > 10 GeV
$p_T$ > 3 GeV
2 < η < 4.5

(Υ mass excluded)

How well do the data compare to gluon-saturation predictions ?

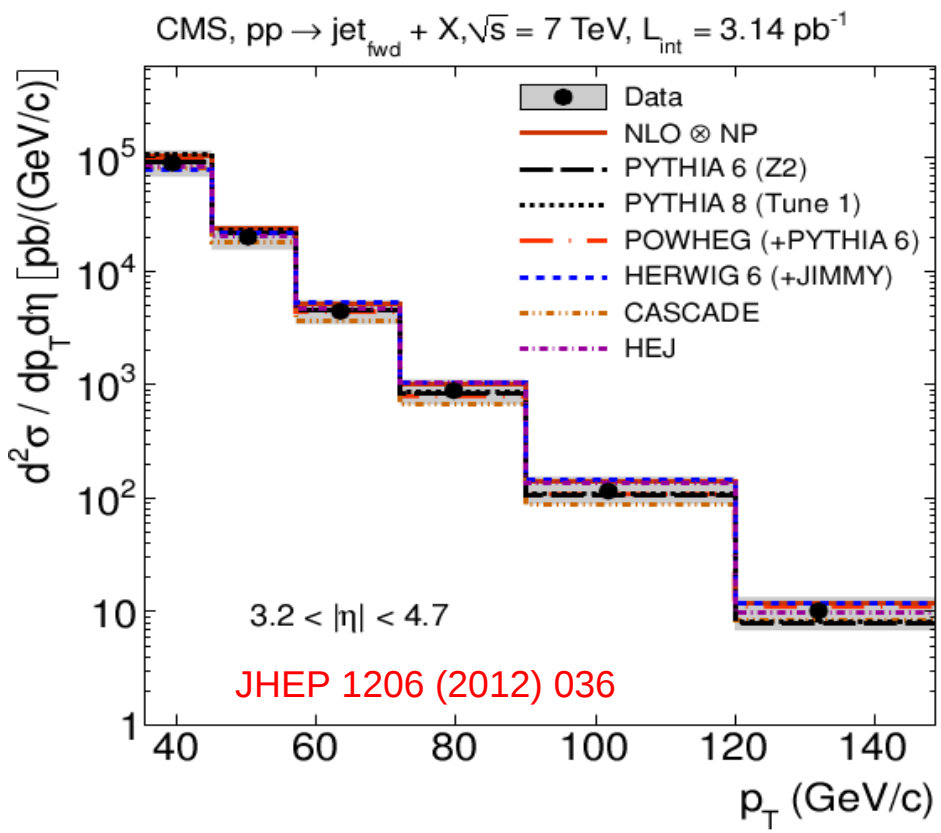
# Forward jets at 3 < |η|< 5 (CMS)

- Forward jets ($E_T$ ~30-140 GeV) sensitive to low-x (and high-x) PDFs:

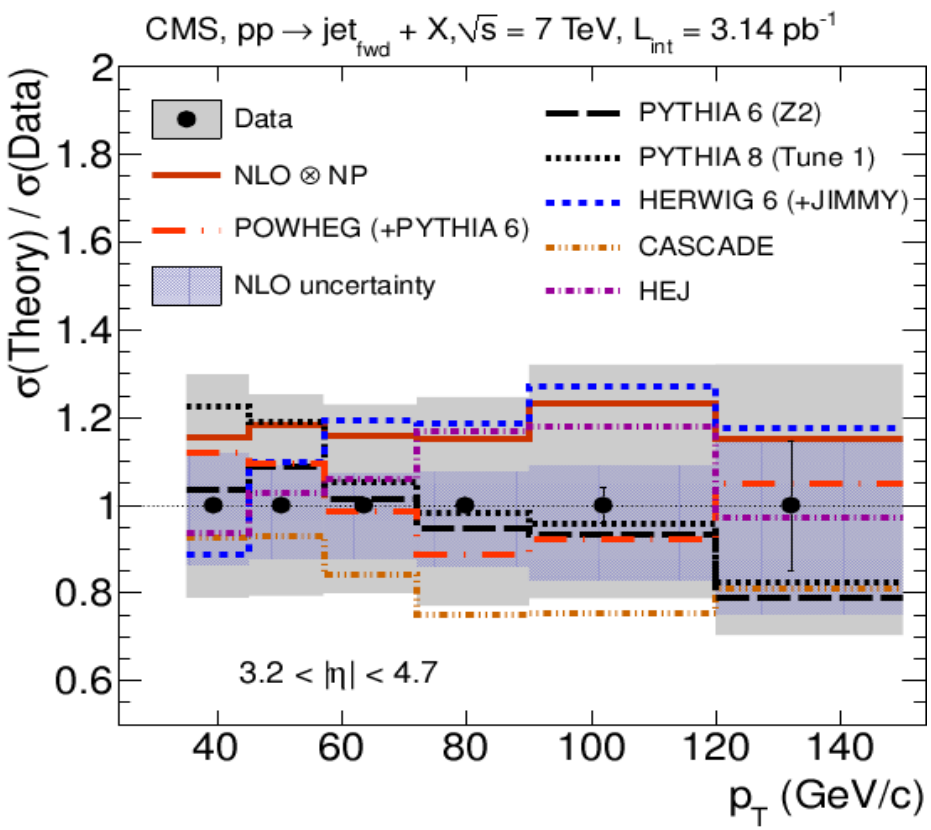



Jets in HF (3<|η|<5) probe: $x_2 \sim 10^{-4}$, $x_1 \sim 0.2$

- Spectrum reproduced by NLO, parton-showers and "BFKL"-MCs:

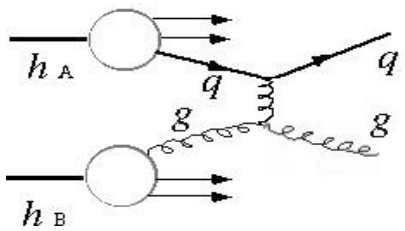



JHEP 1206 (2012) 036



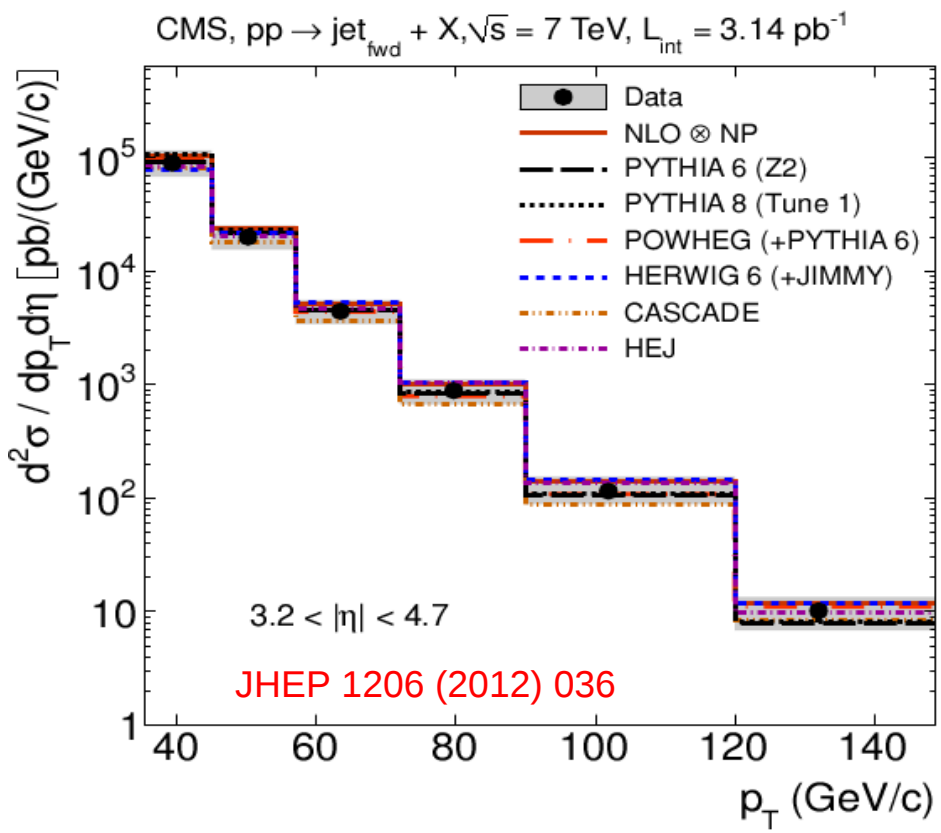
# Forward jets at 3 < |η|< 5 (CMS)

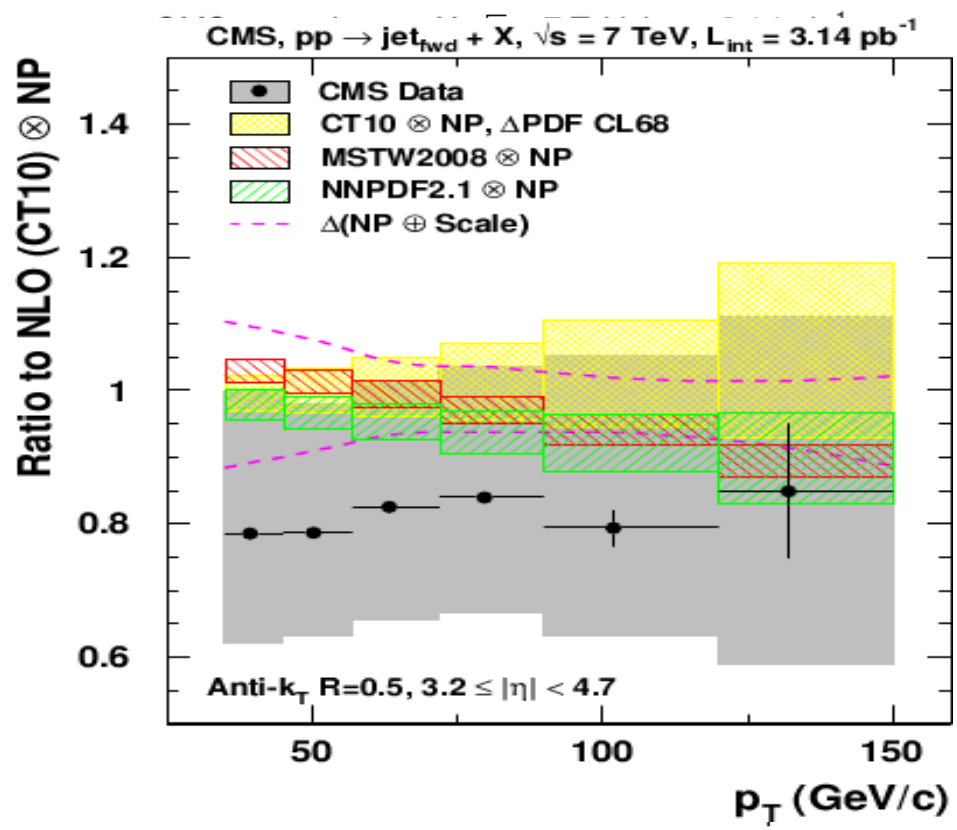
- Forward jets ($E_T$ ~30-140 GeV) sensitive to low-x (and high-x) PDFs:




Jets in HF (3<|η|<5) probe: $x_2 \sim 10^{-4}$, $x_1 \sim 0.2$

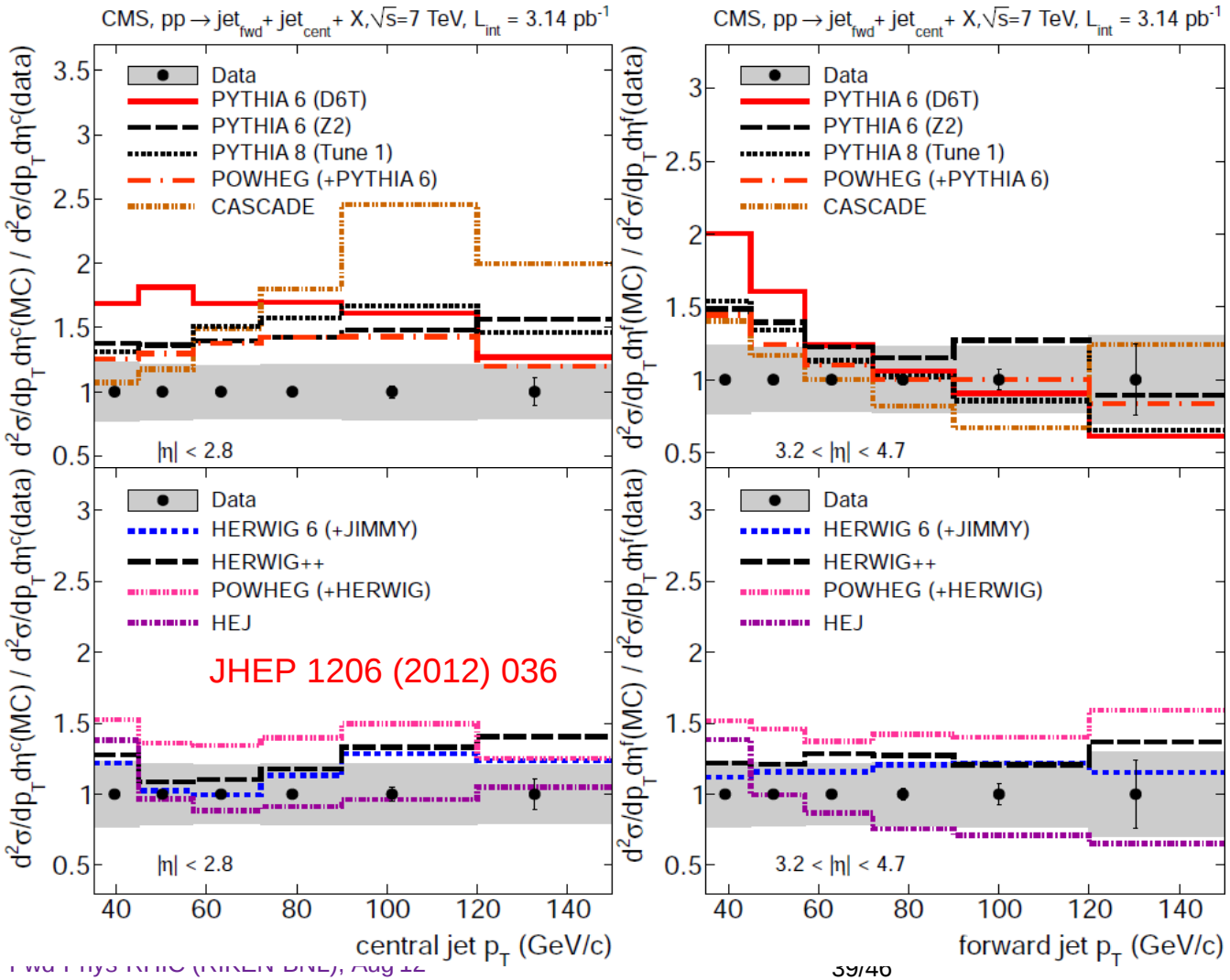
- Although NLO PDFs tend to be +20% above central data:

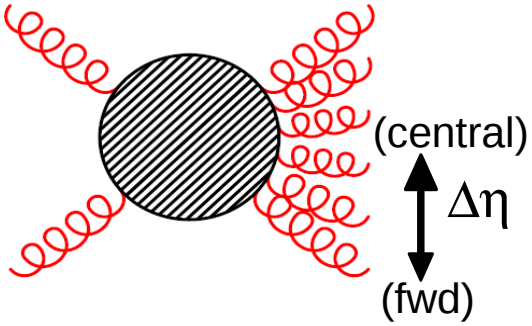


# Forward-central dijets (CMS)

- Fwd-cent. dijets with large $\Delta\eta$ separations probe BFKL-type dynamics.
- Ratios model/data for fwd and central jets $p_T$ spectra:



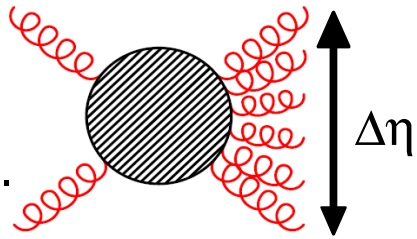

- PYTHIA & NLO overpredict jet spectra specially at low $p_T$

- HERWIG & models w/ wide-angle radiation (HEJ) show better agreement, but CASCADE (DGLAP+ BFKL) also overshoots.

# “Dijet K-factor” vs rapidity separation

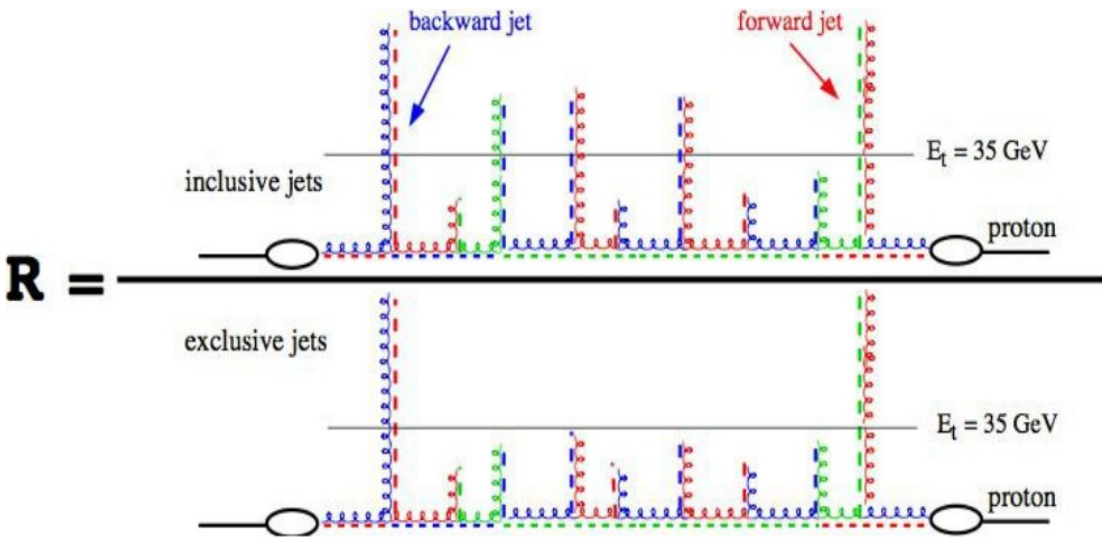
- Reconstruct x-sections pair of jets with $p_T$ > 35 GeV over -4.7 < y < 4.7

(1) Inclusive sample: all events with at least 2 jets.
(2) Exclusive sample: exactly 2 jets per event.
(3) “Muller-Navelet” sample: incl. with most fwd-bckwd jets.




- Compute x-sections as a function of Δy between the jets, take ratios:

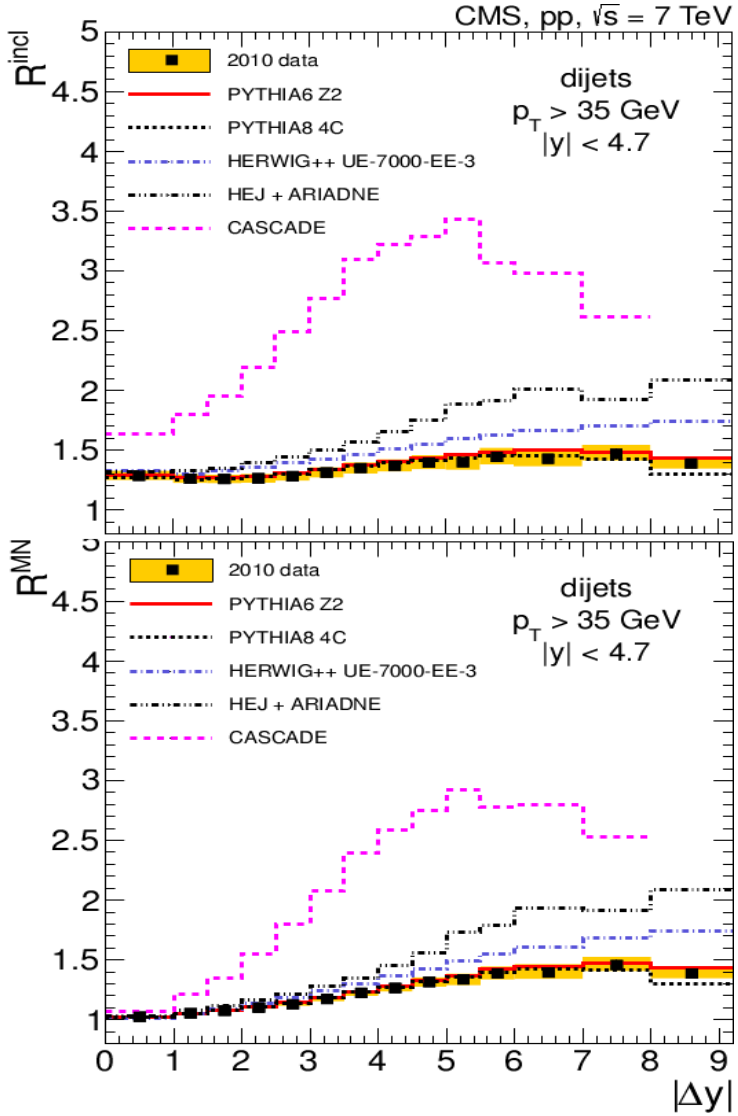
$$R_{incl} = \frac{\sigma_{incl}(\text{dijet})}{\sigma_{excl}(\text{dijet})}, R_{MN} = \frac{\sigma_{MN}(\text{dijet})}{\sigma_{excl}(\text{dijet})}$$




BFKL expectation:
Increased Δy phase space ⇒
Increased rad. probability ⇒
R(Δy) rises with Δy
(up to kinematical limit)

# "Dijet K-factor" vs Δy separation (CMS)

- Ratios of x-sections as a function of Δy between the jets:



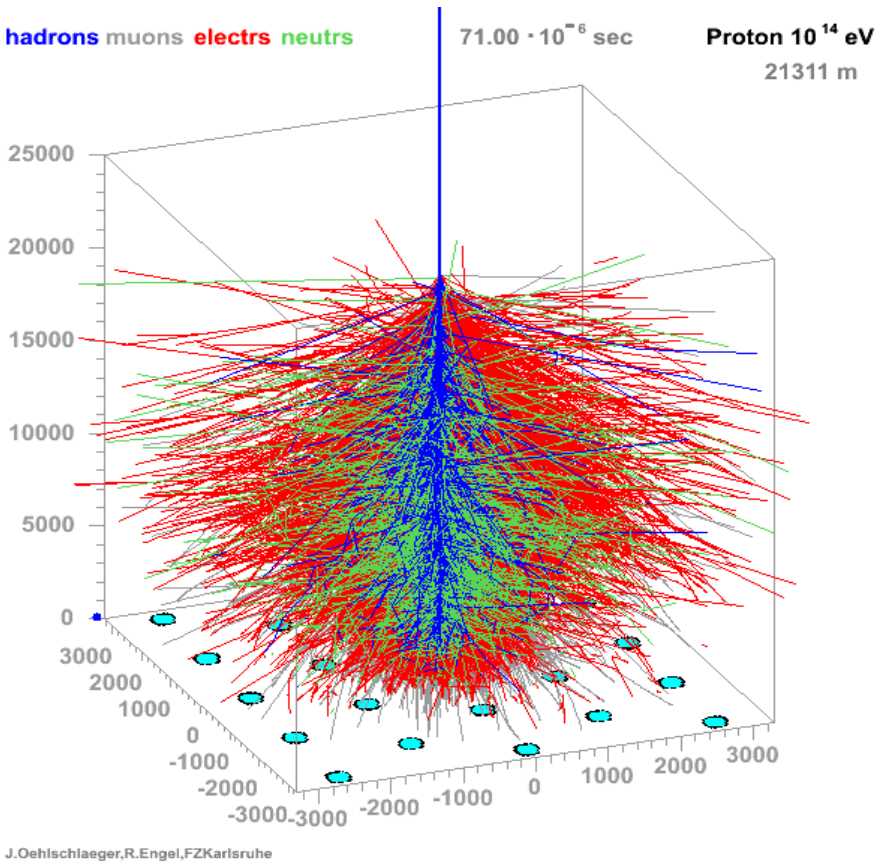

- R rises with |Δy| as expected (drop close to kinematic limit):
  σ(incl.) = 1.2 – 1.4 σ(excl.)
  σ(MN) = 1 – 1.4 σ(excl.)

- PYTHIA: very good agreement w/ data
- HERWIG++ predicts higher R at medium and large Δy.

- HEJ+ARIADNE & CASCADE (BFKL-motivated generators) predict much faster rise of R ...

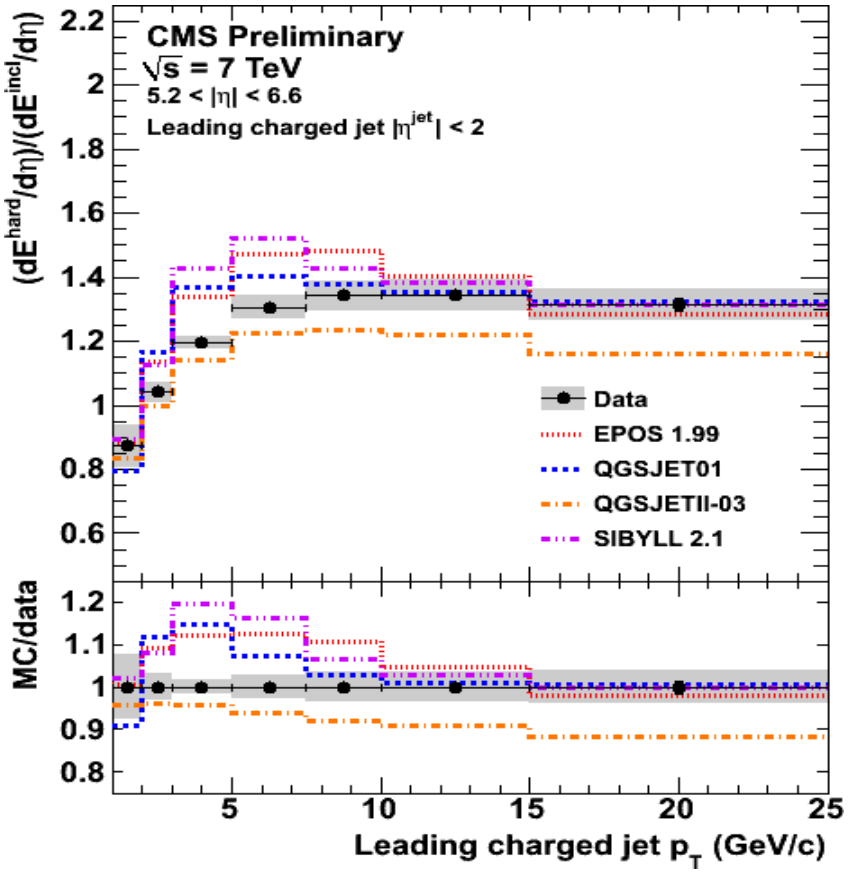
- Is $p_T$ > 35 GeV too high for searches of non-DGLAP dynamics ?

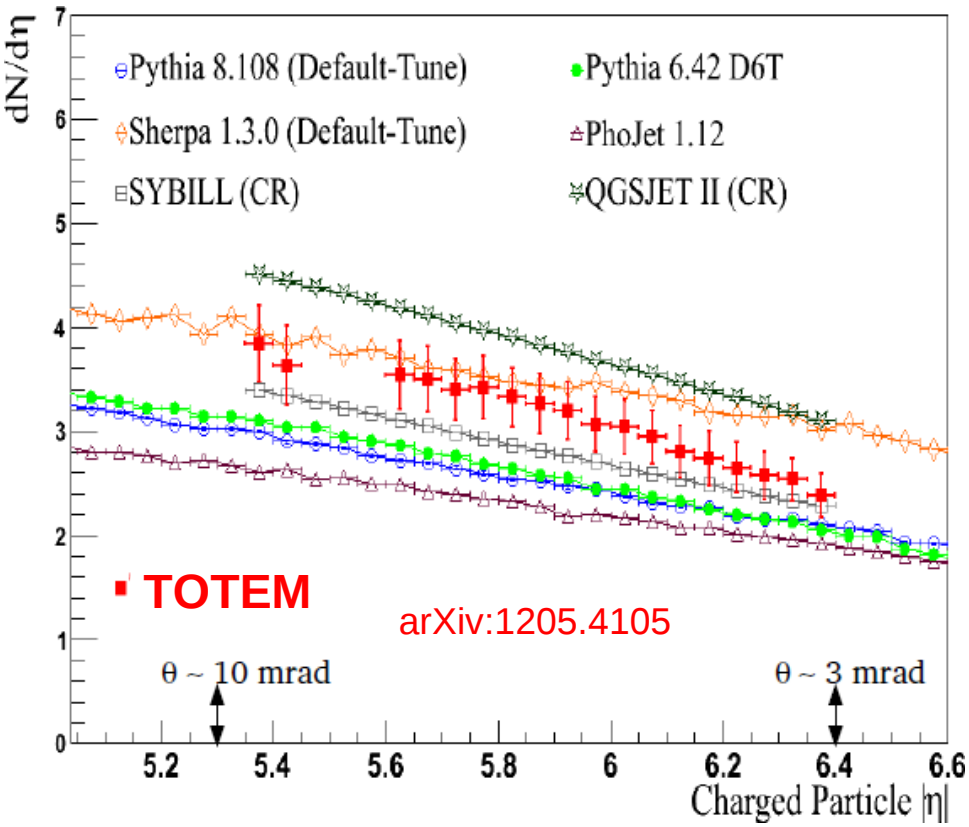
# Hadronic collisions & UHECR



# Forward hadrons at |η| = 5.2 – 6.6 (CMS,TOTEM)

- Important influence on cosmic-ray EAS development:
  - Modeling of multi-parton interactions & beam-remnants



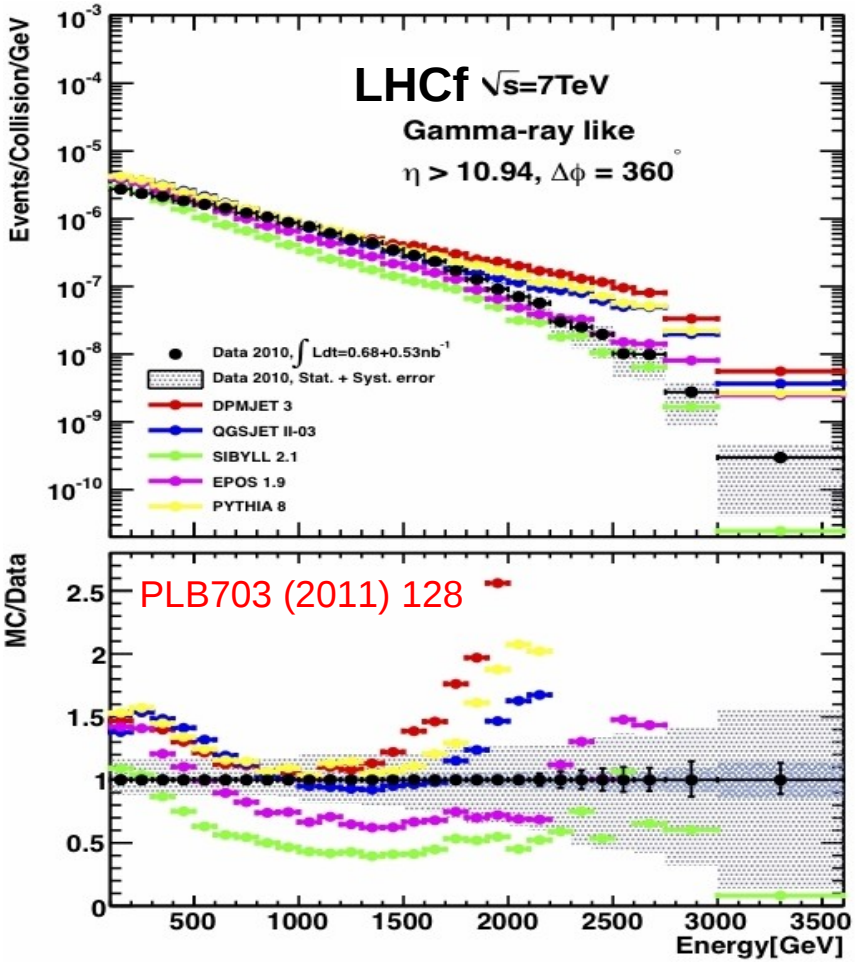




- Good CMS-data vs. CR-model agreement for energy density.
- Collider-MCs do not reproduce well the slope of TOTEM particle density. CR-models better.

(gluon saturation predictions?)

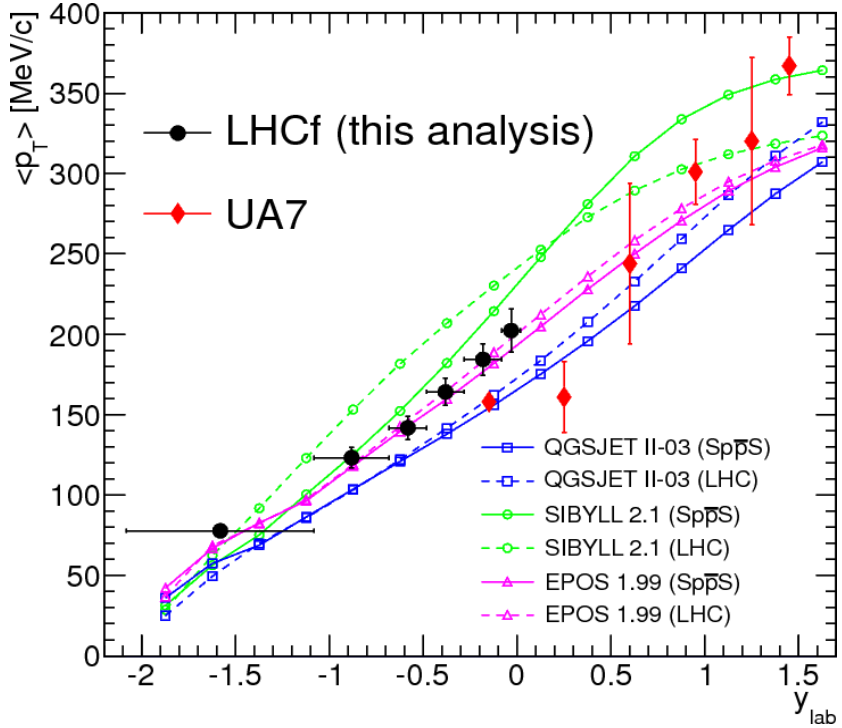
# Very forward hadrons at |η| ~ 8. - 11. (LHCf)

- Important influence on cosmic-ray EAS development:
  - leading baryon (inelasticity) & had-to-e.m. energy transfer ($\pi^0 \rightarrow \gamma\gamma$)




- > ±50% data-model differences for zero degree photon showers.

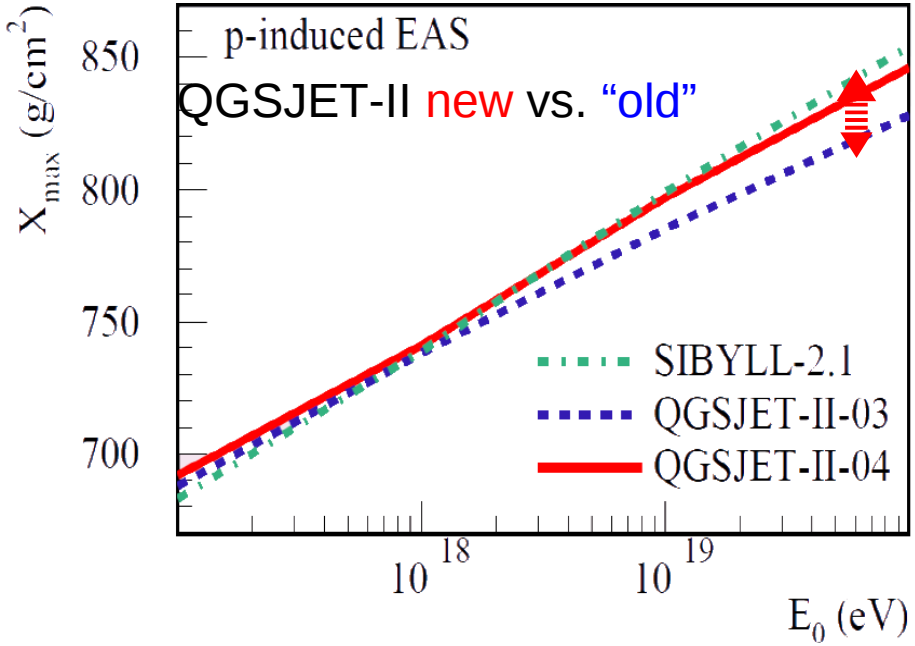
arXiv:1205.4578

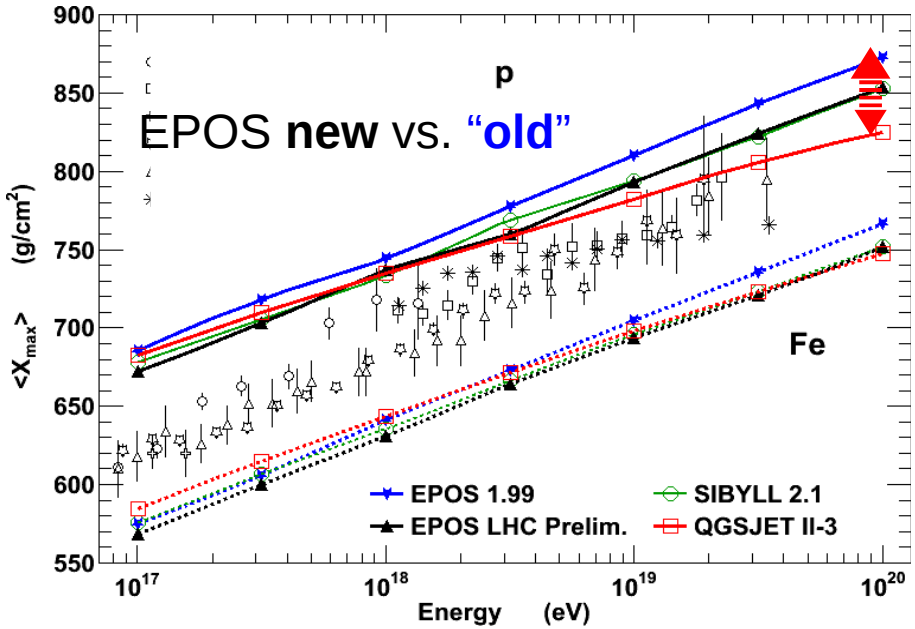



- Mean $p_T$ of zero-degree pions is sqrt(s)-independent. EPOS shows the best overall agreement

# Impact on cosmic-ray composition at ~$10^{20}$ eV

- CR hadronic MCs based on Regge-Gribov Field Theory (extended to pQCD regime via "cut Pomerons") retuned to describe new LHC data:

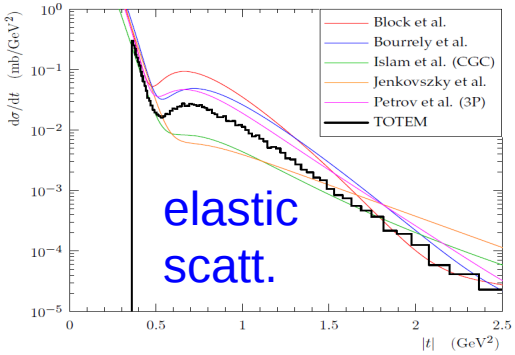


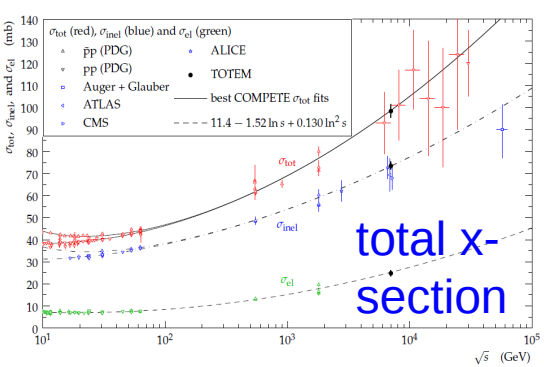



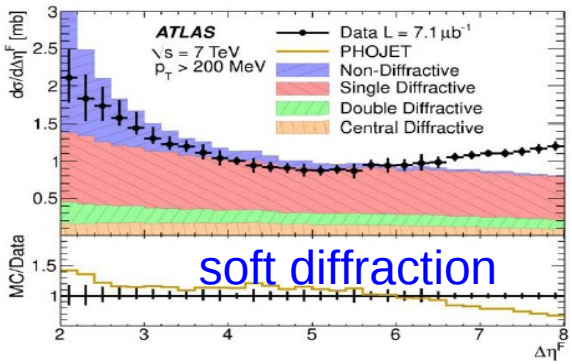

- Consequences:
  - EPOS & QGSJET-II predictions similar now to (older) SIBYLL: change in <$X_{max}$> (reduced uncertainty ~60 g/cm$^2$ to ~10 g/cm$^2$).
  - Composition of CRs closer now to proton (rather than Fe) for all MCs.

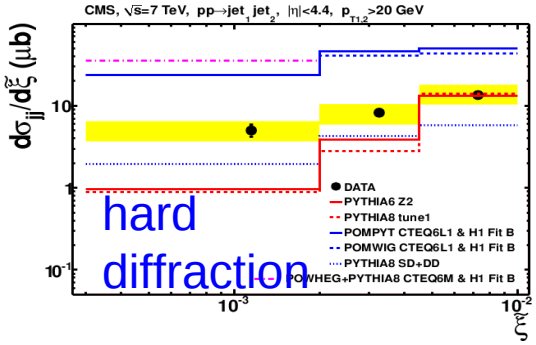
# Summary

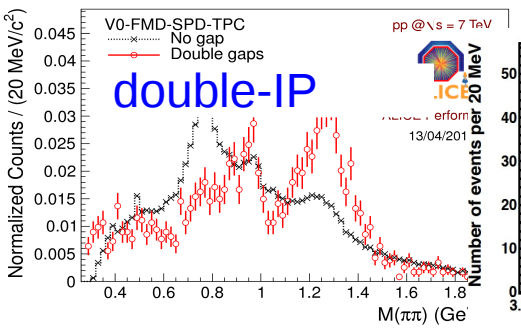
- The LHC is providing a wealth of new forward data open to study !

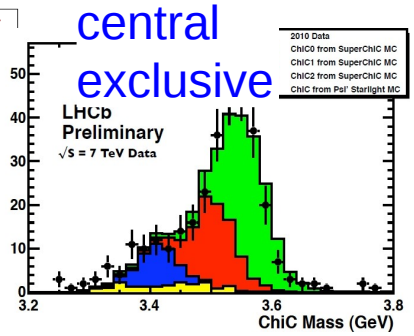


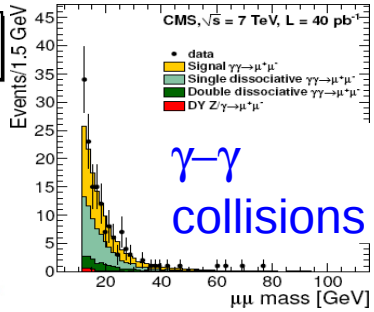



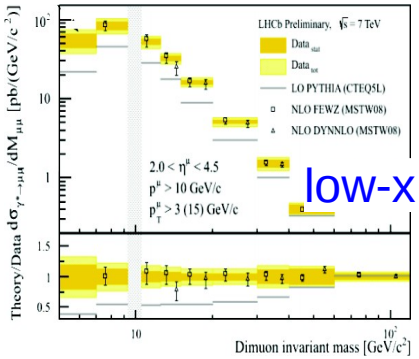



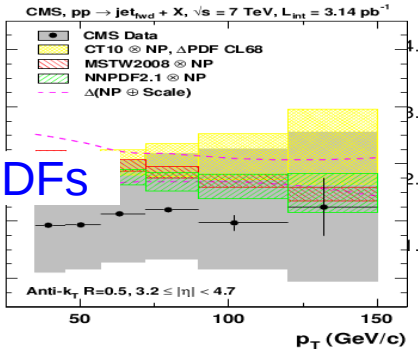



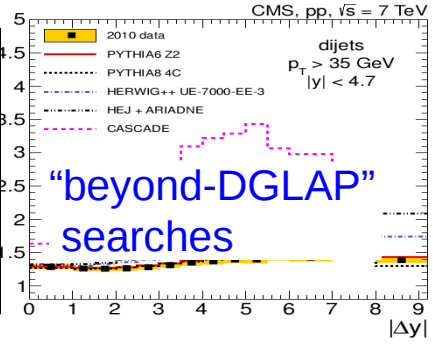



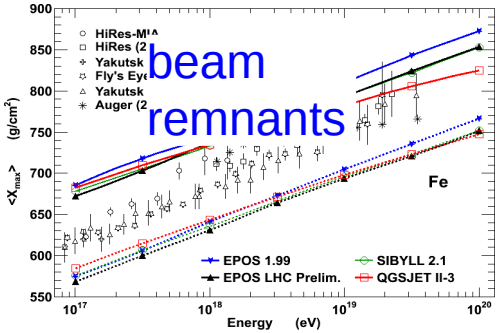



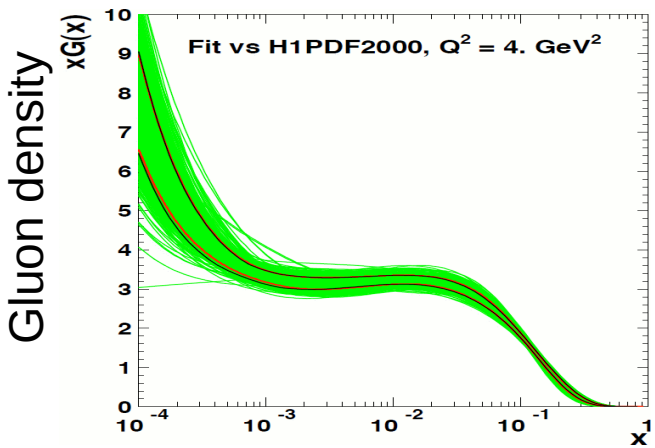

- Exciting experimental/theoretical QCD physics for the years to come!

# Backup slides

# Low-x dynamics

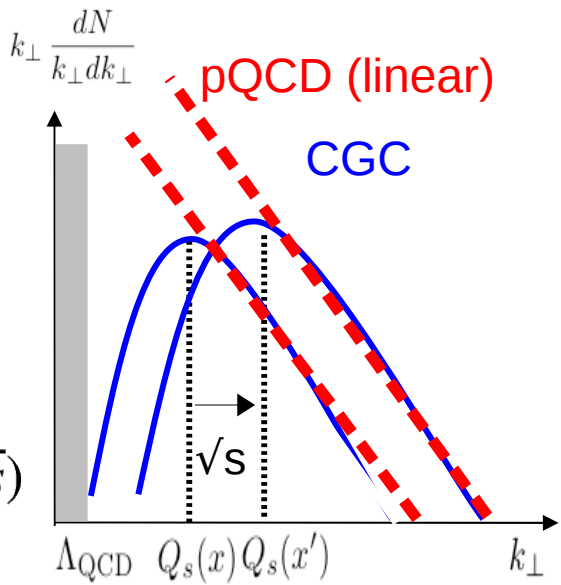
- Gluons start to overlap at "saturation scale"

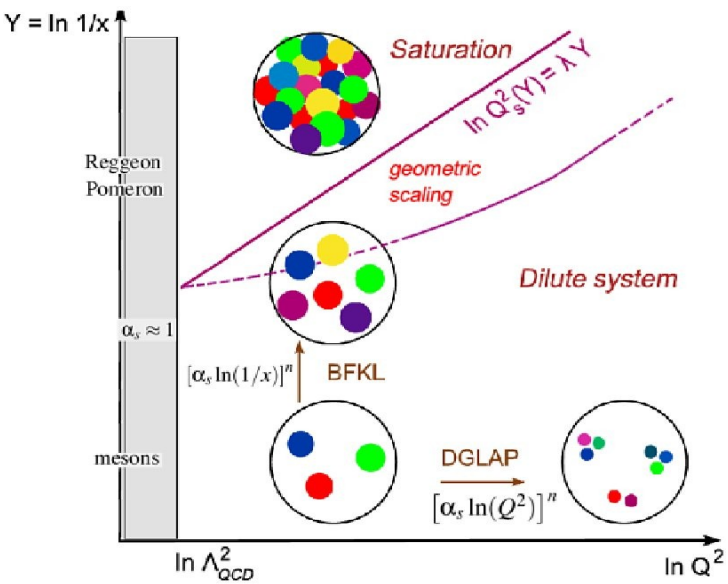
$$Q_s^2 \sim \alpha_s \frac{xG_A(x,Q_s^2)}{\pi R_A^2}$$



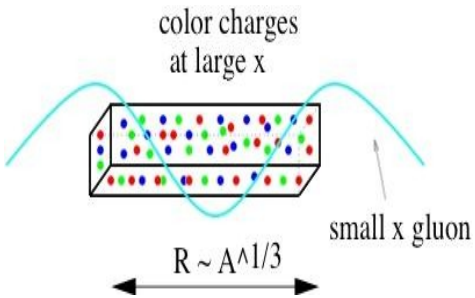

- Asymptotic pQCD g-g x-section peaks at $p_T \sim Q_s(\sqrt{s}) \sim 1\text{-}4$ GeV

$$Q^2_{\rm sat} \propto \log(1/x) \propto \log(\sqrt{s})$$




- Hadrons ~ "Color Glass Condensate" below $Q_s$
- Saturation effects enhanced in nuclei:

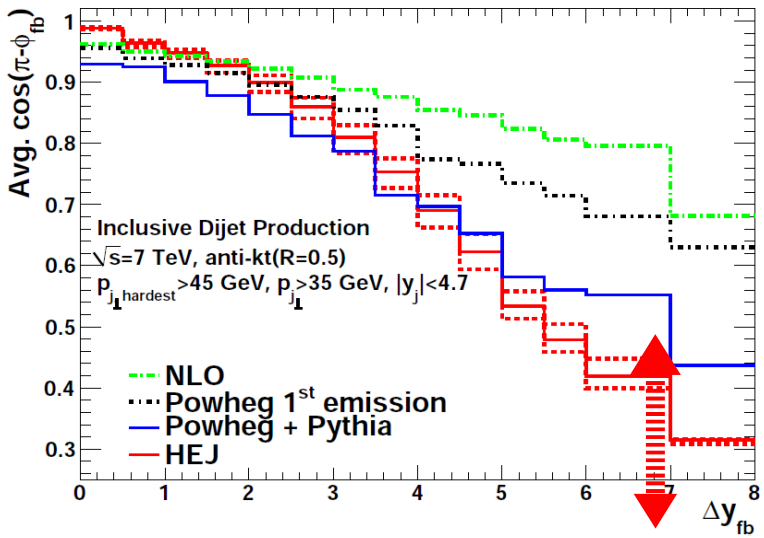



Large # of partons per transverse area

$$Q_s^2 \sim A^{1/3} \sim 6$$

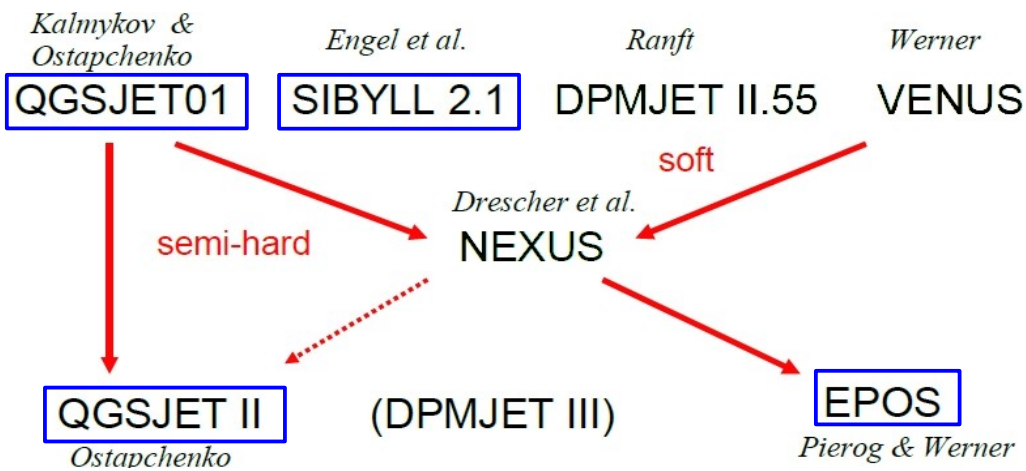
# Beyond DGLAP dynamics at the LHC ?

- Fwd-cent. dijets or dijets+central-veto (p-p at 7 TeV) with large $\Delta\eta$ separations access BFKL-type topologies

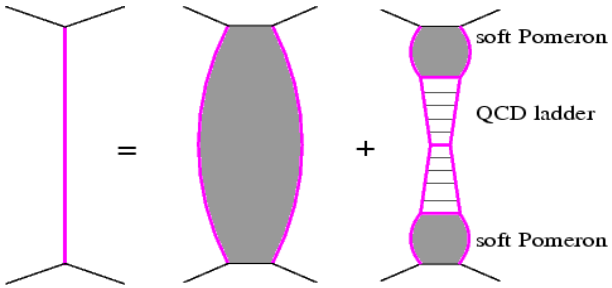



- New observables (Mueller-Navelet dijets) to be studied soon.

# Reggeon-Field-Theory hadronic MCs

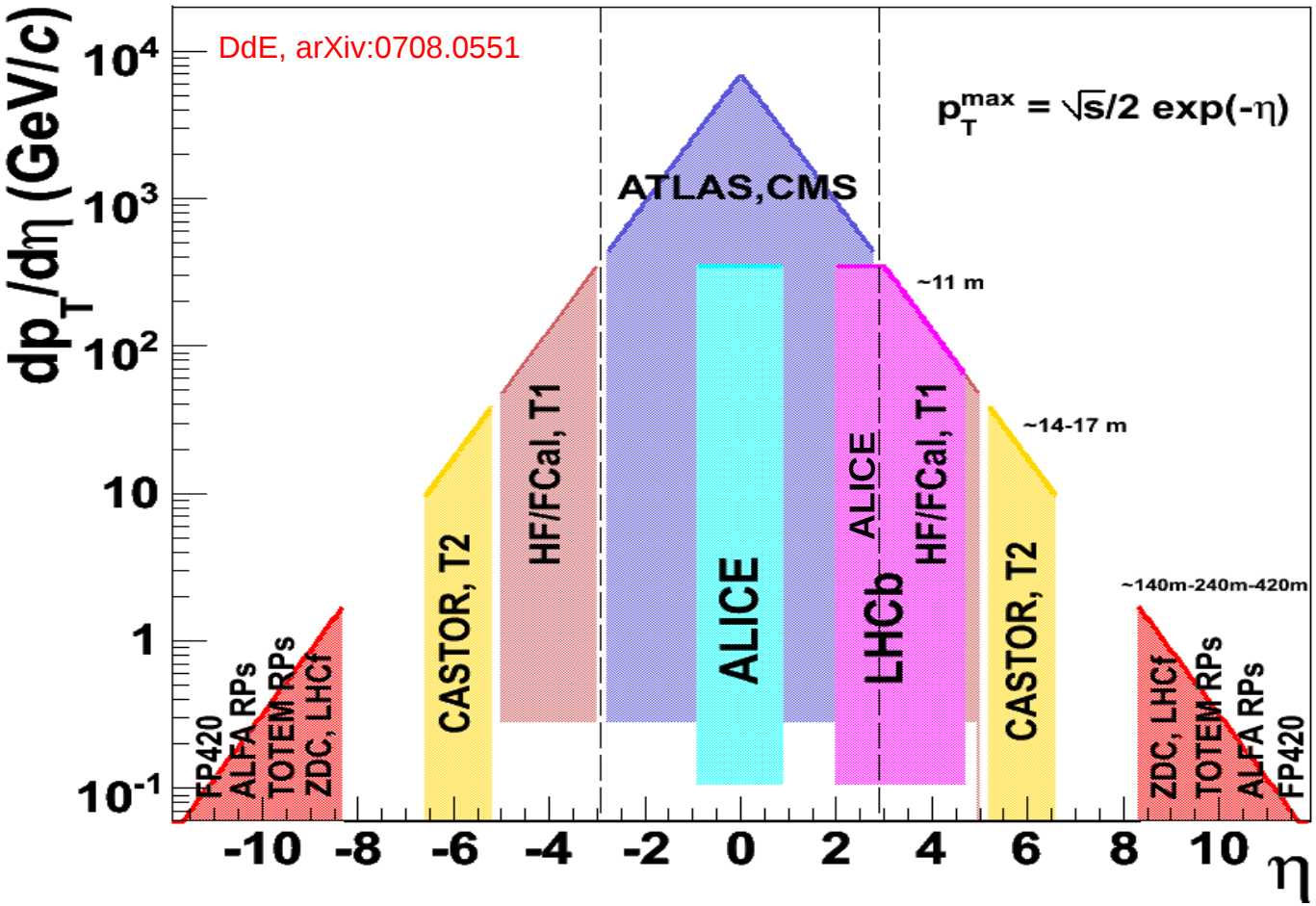



- Soft interactions via Reggeons & Pomerons:
  elastic, diffractive & soft-inelastic scatts. described




- Perturbative interactions via
  "cut (hard) Pomerons" (≅ LO pQCD)
- Semi-hard dynamics built-in:
  - eikonal (multi)parton ladders (p-A, A-A possible)
  - gluon saturation (via enhanced |P diags)
- Non-perturbative ingredients:
  - string fagmentation (Lund model)
  - beam-remnants
- Model parameters:
  - Tuned with accelerator data.
  - $O(20)$ much less than in std collider MCs

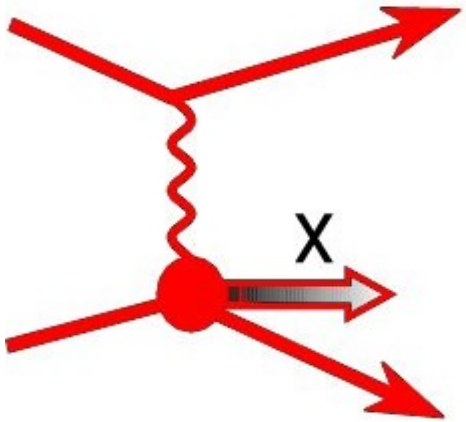
# LHC experiments: ($p_T$,η) acceptance

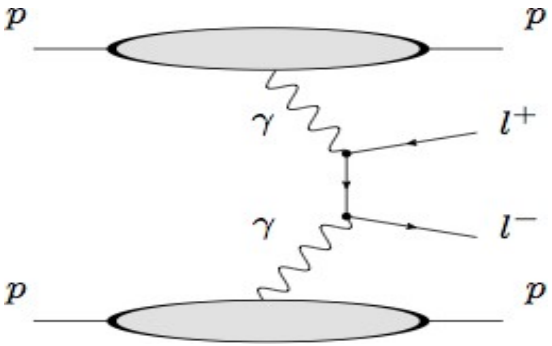


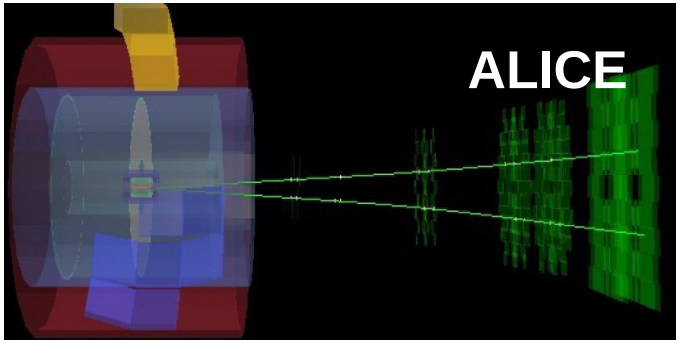

- Detectors cover ~all phase-space (1st time in a collider) !:

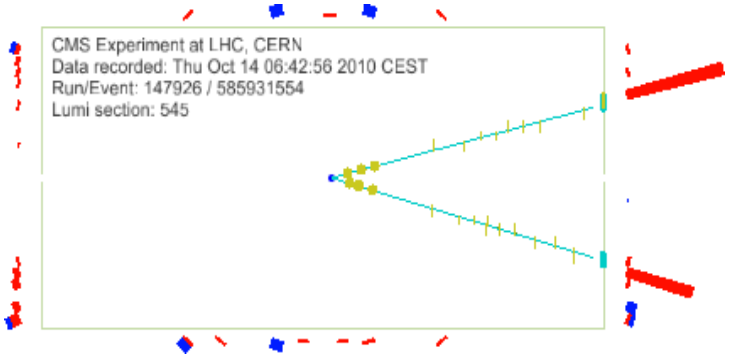
  $0 < p_T < (\sqrt{s}/2)e^{-\eta}$ , $\Delta\eta \sim 2\times\ln(\sqrt{s})/m_p \sim 20$

# Photon-induced collisions



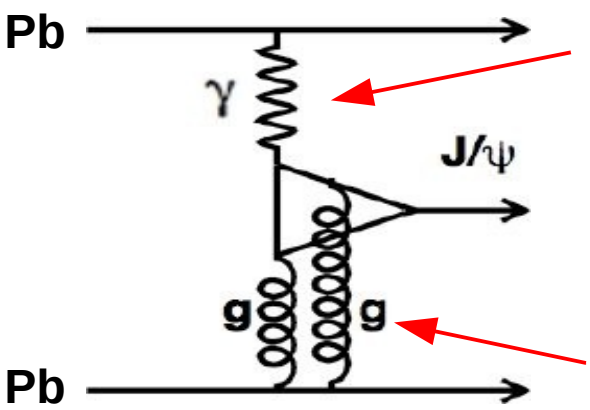



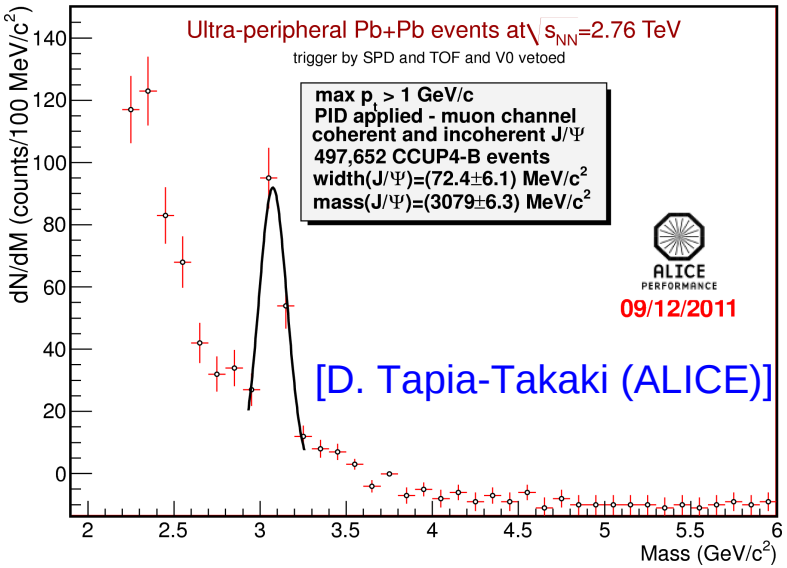
# γ-A and γ-γ collisions (LHC)

- Observation of exclusive PbPb → Pb J/Ψ Pb photoproduction:



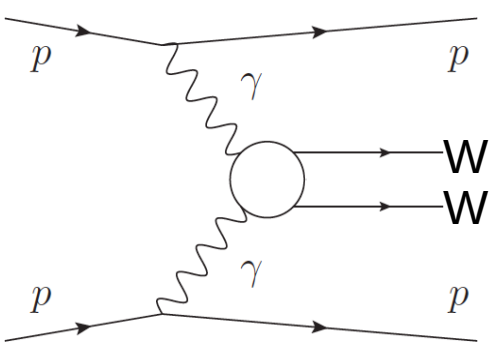

Pb photon fluxes enhanced by $Z^2$~7000 !

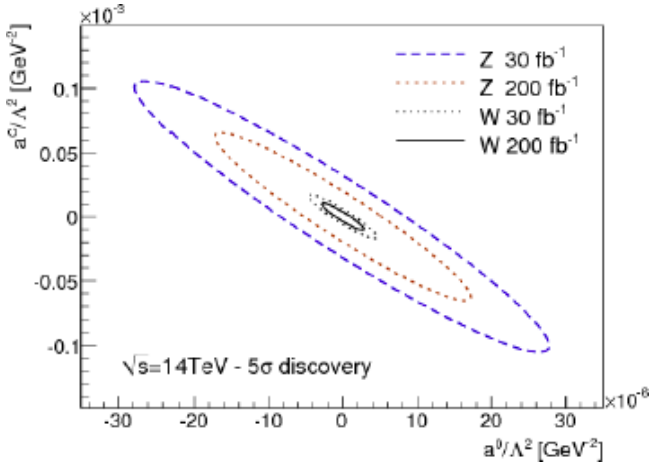
Very sensitive to badly unknown nuclear $xG(x,Q^2)$ !



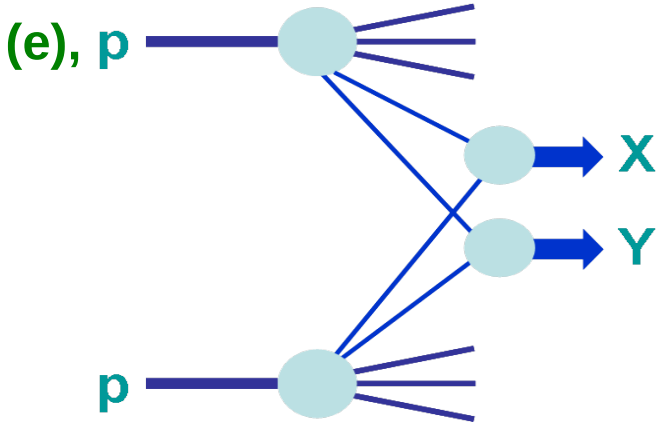

[D. Tapia-Takaki (ALICE)]

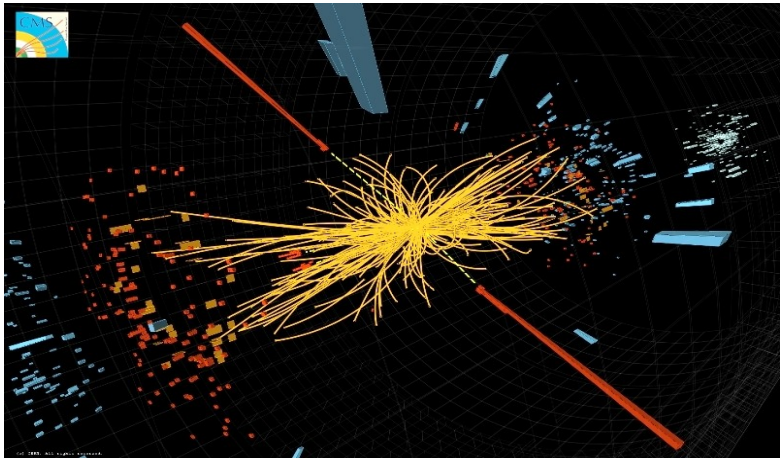
- Study of pp → pWWp: $10^4$ times larger sensitivity to anomalous QGC



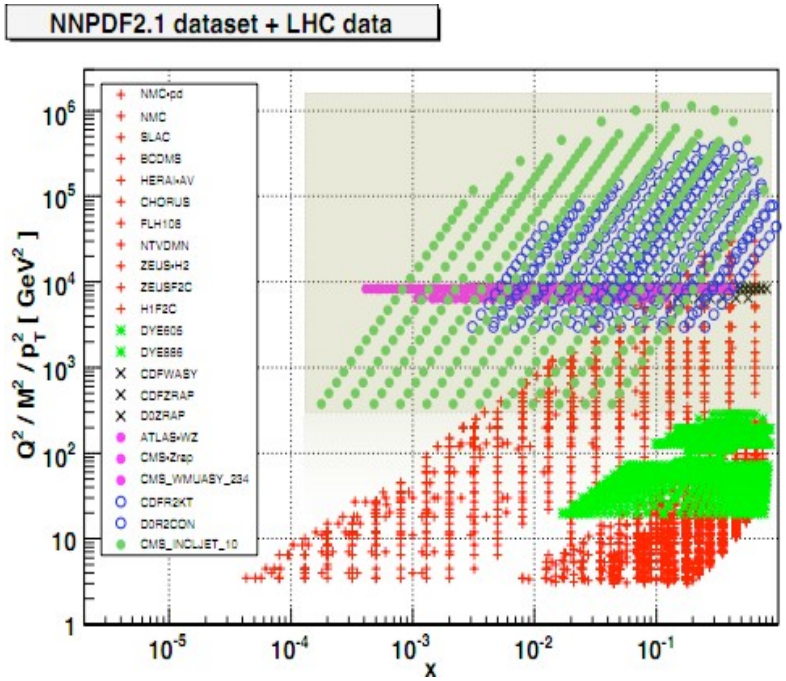
# Hard parton-parton scatterings



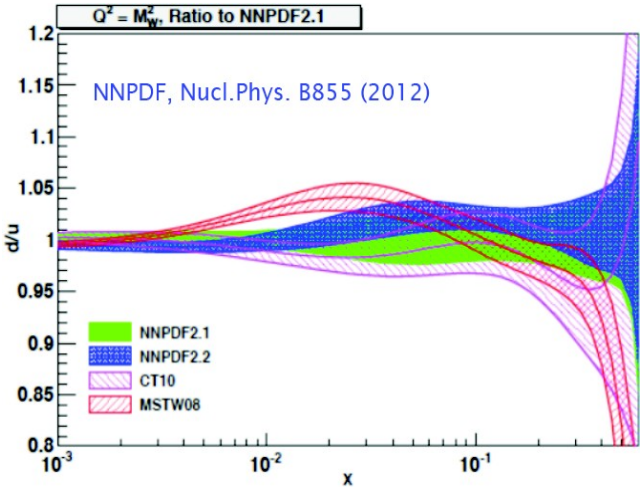



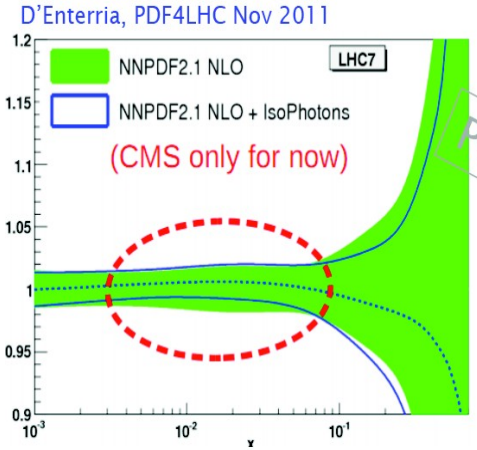
# Parton distribution functions (LHC)

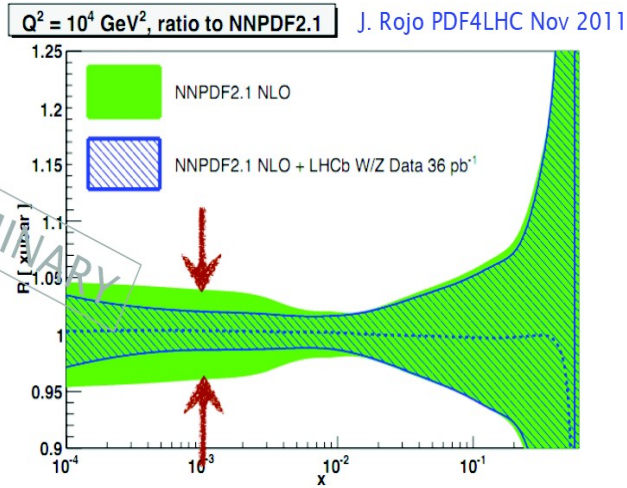
- Lots of new <u>data</u> !
  - Medium & large-x gluon:
    precision jets, prompt γ, top pairs.
  - Light-flavors at medium & small x:
    low-mass DY, Z vs y, W asymm.
  - Strangeness & heavy-flavors:
    W+c for s; Z,γ+c for charm; Z+b for bottom.




- New fast reweighting techniques (NNPDF2.1) for NLO PDFs:



# What's the physics “forward” ?

- Non-perturbative limit of QCD:

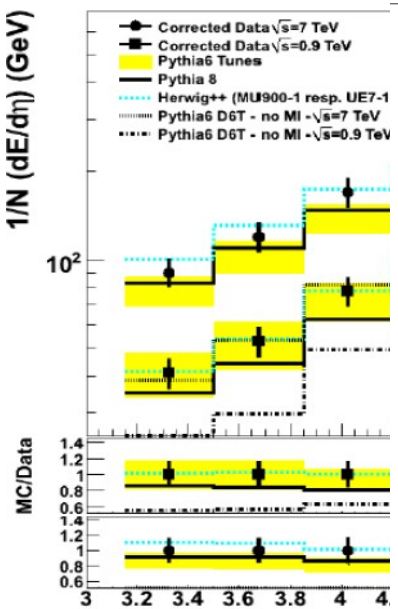
  elastic, soft diffractive p-p scattering (Regge-Gribov)

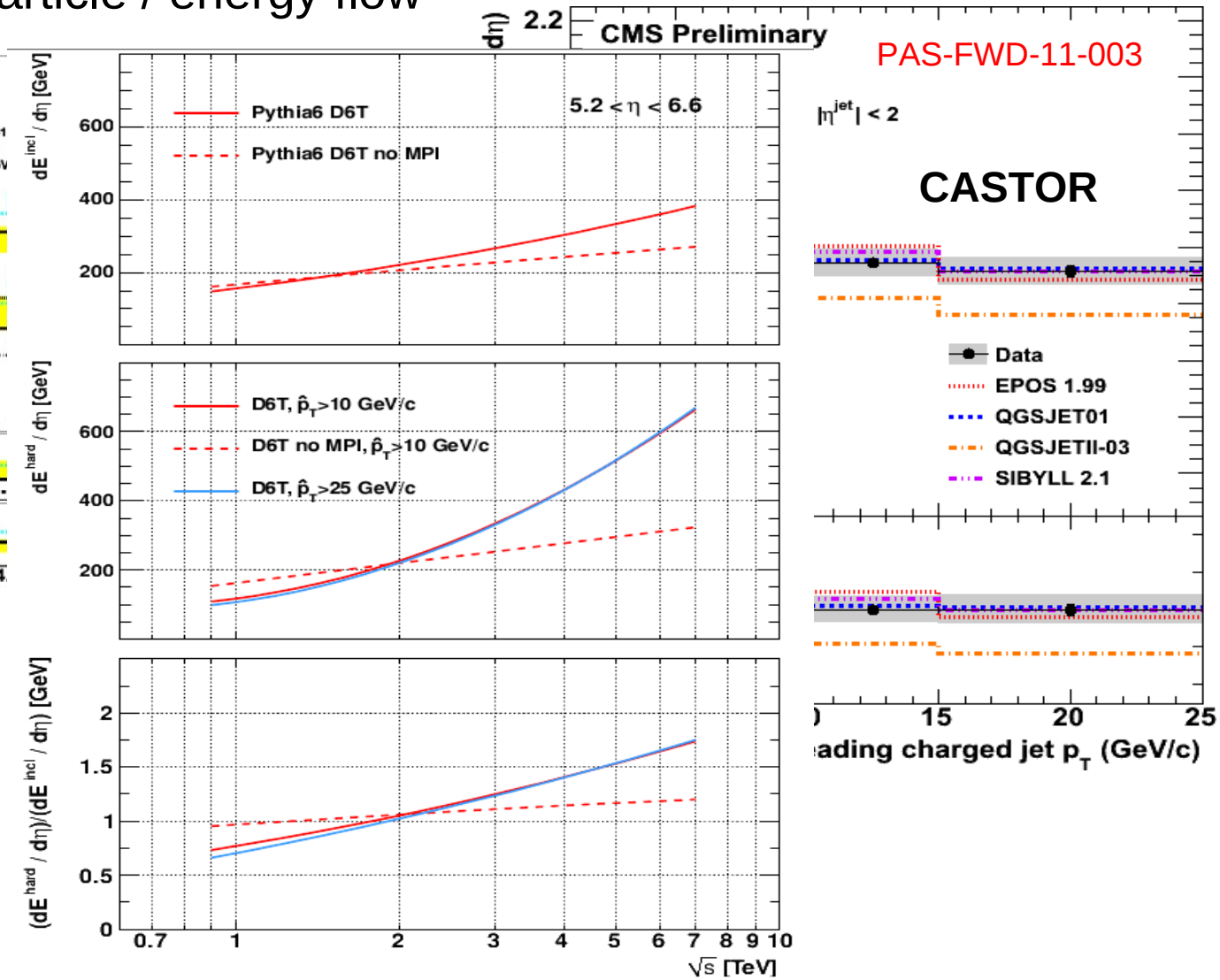
- High-energy (low-x) limit of QCD:

  gluon saturation, multi-parton interactions (Color-Glass condensate)

# Multi-parton interactions (Atlas/CMS)

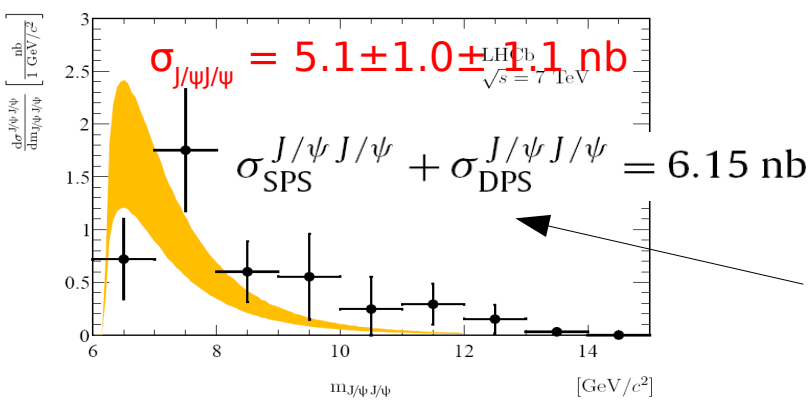
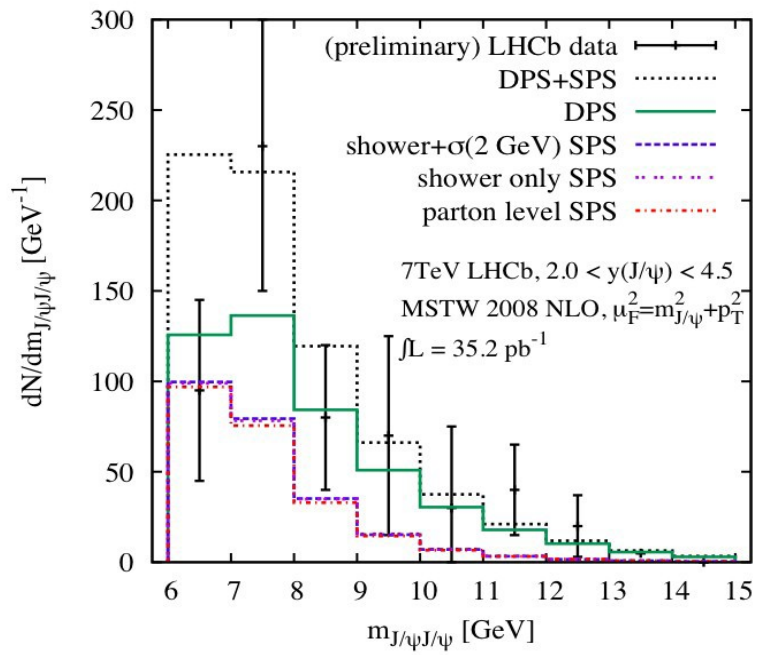
- Forward particle / energy flow




- Forward particle production clearly require MPIs

# Double Parton Scattering (LHCb)

- MPI needed but yet no clear-cut proof of double hard parton-parton scattering.
- Maybe first hint on double J/Ψ prod. ?

J.Gaunt,C.Kom,A.Kulesza,W.Stirli
arXiv:1110.1174