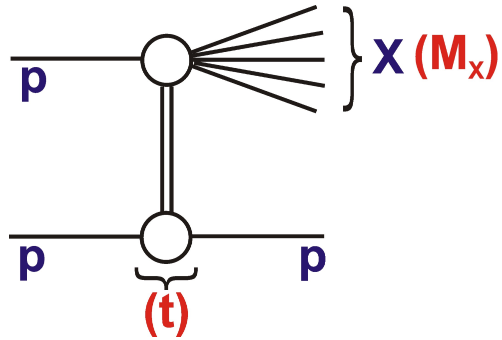
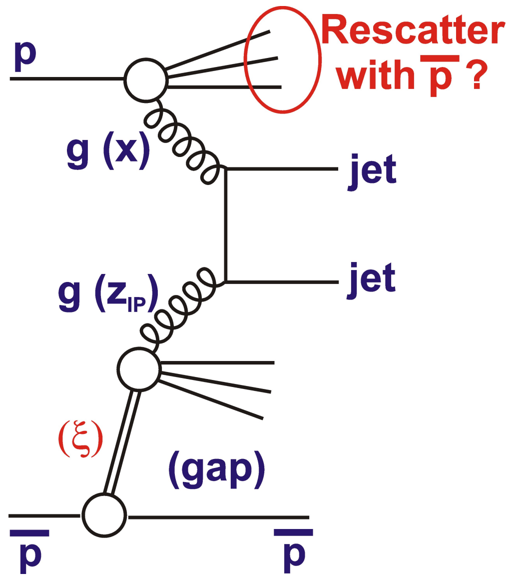
Diffraction at the LHC

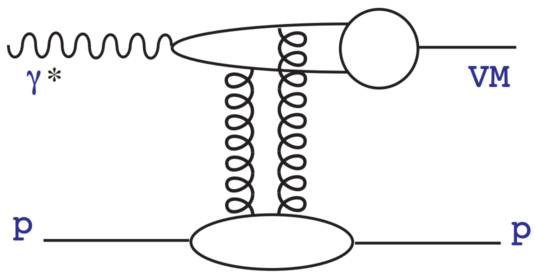
Paul Newman
(University of Birmingham)



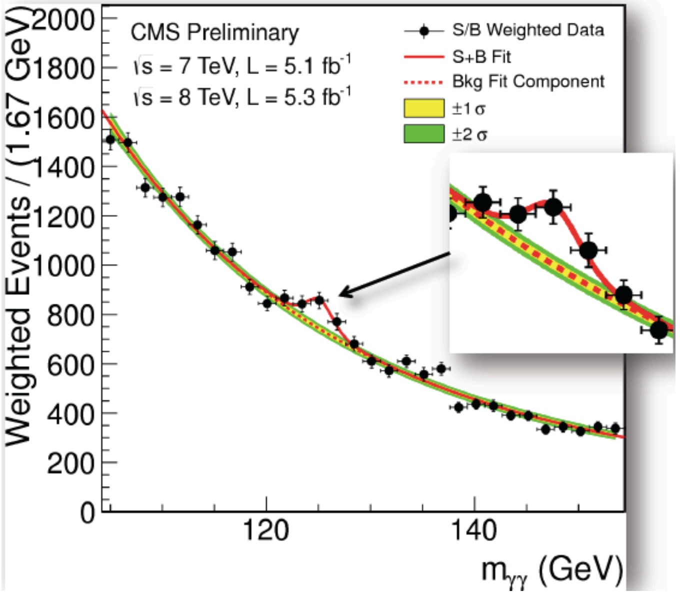


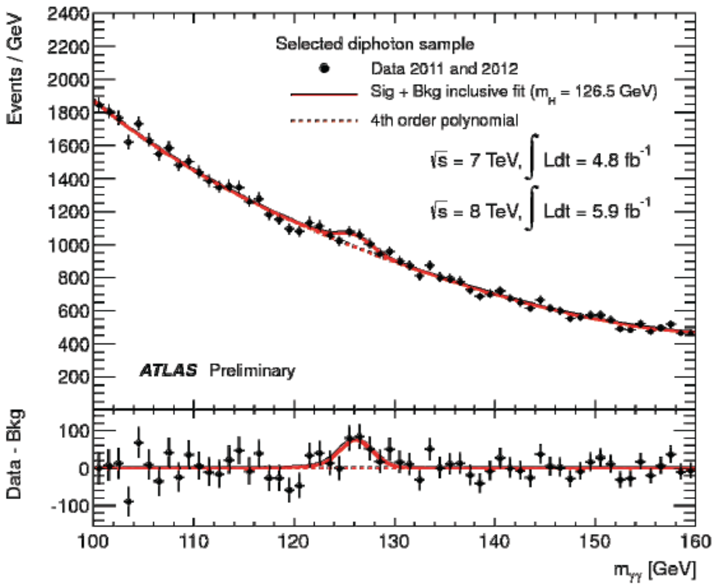
QCD at Cosmic Energies
Paris, 14 May 2013

→ Elastic and Total Cross Sections
→ Soft Diffractive Dissociation
→ Hard Diffractive Dissociation
→ Ultra-peripheral J/Ψ Production
→ [Central Exclusive Production]

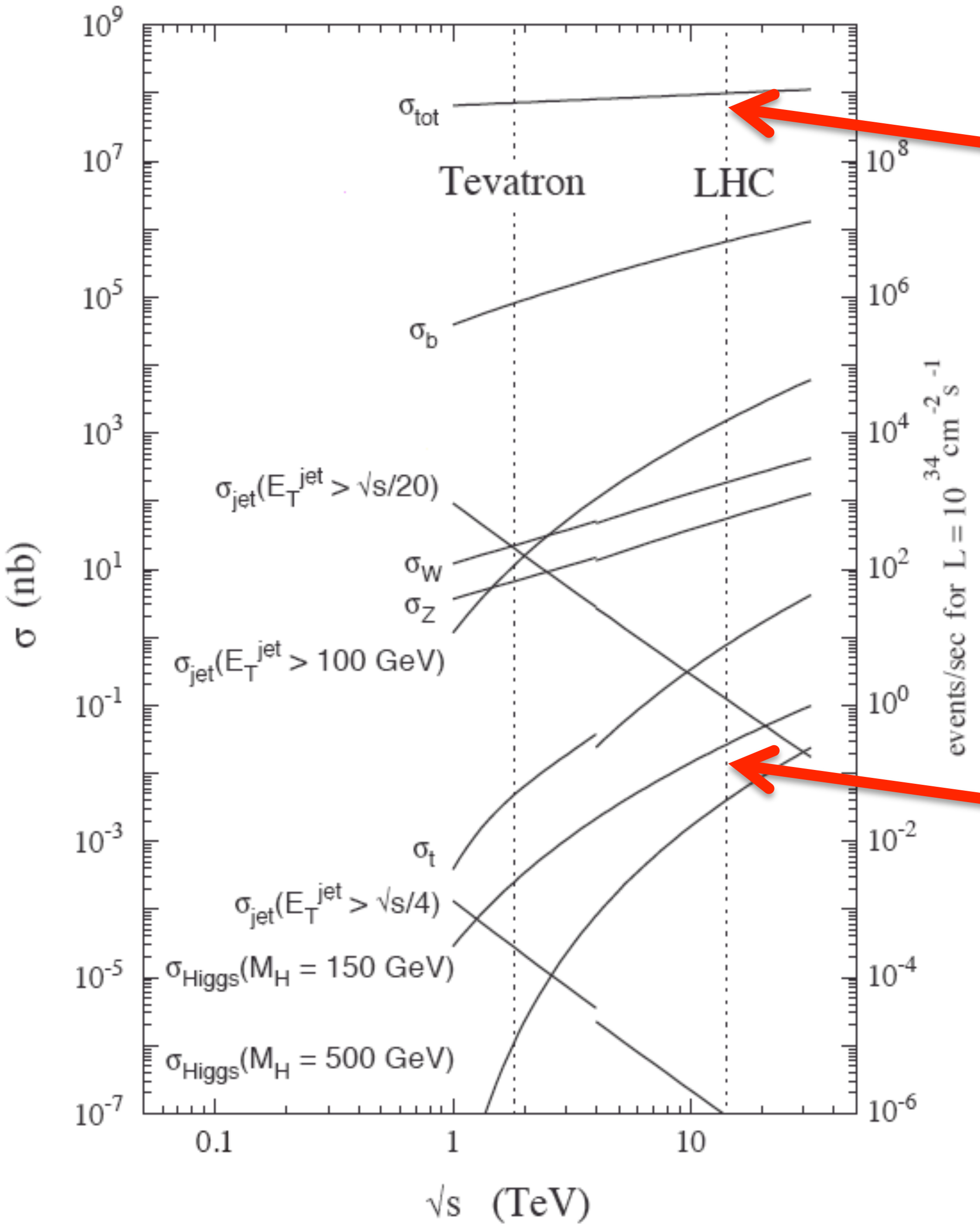


LHC Main achievement so far: Higgs



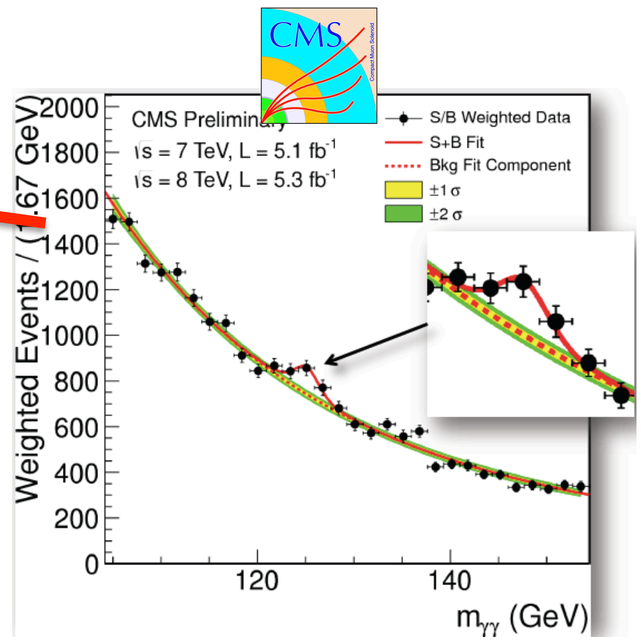


But what usually happens when hadrons Collide?

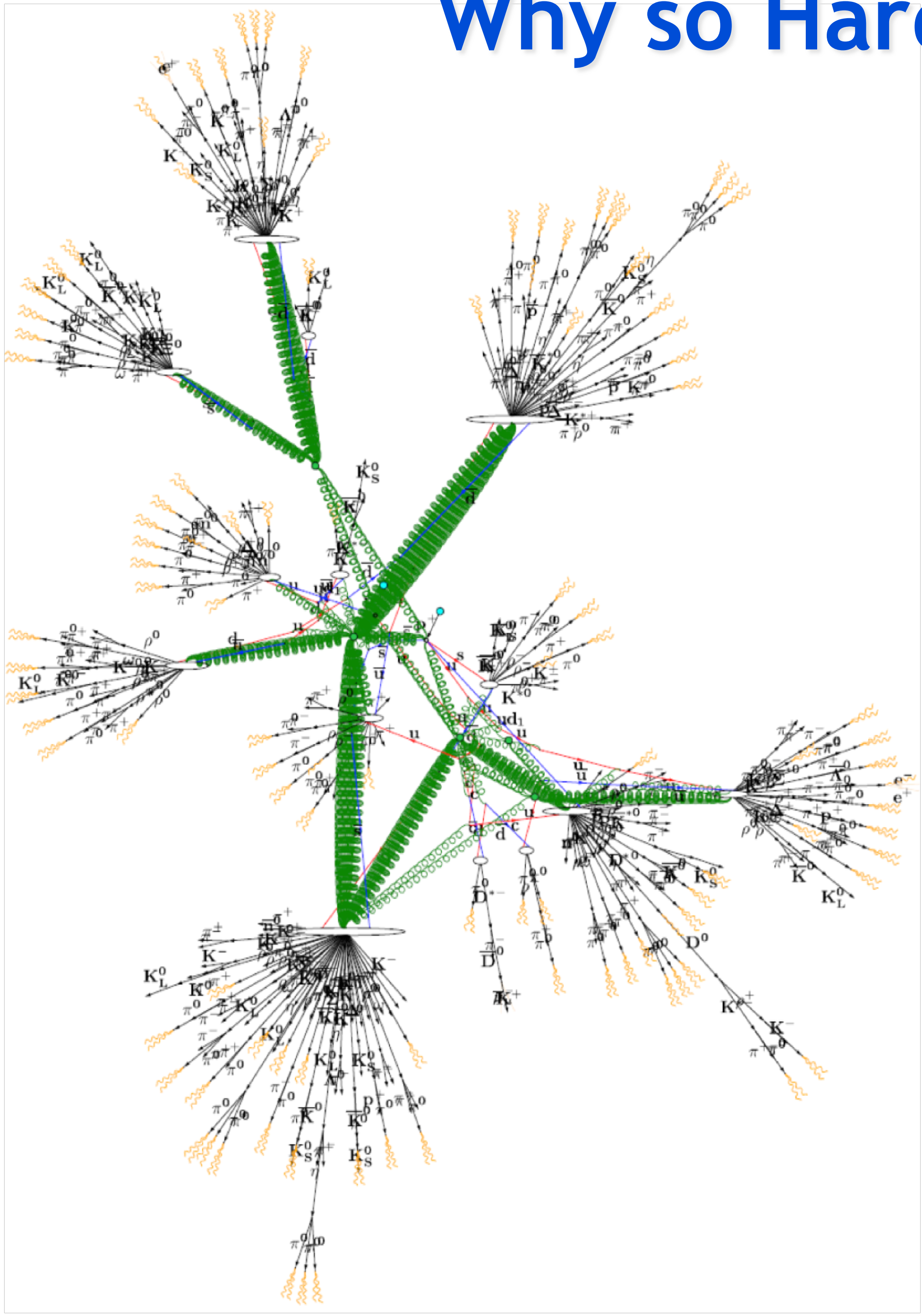


Diffraction is ~50% of total cross-sec.

… calculating 10^{-1}/ 10^{0} processes is much harder than 10^{-10} processes ☹



Why so Hard to Calculate?



“minimum bias” pp event in PYTHIA8 at √s=7TeV, visualised using MCViz

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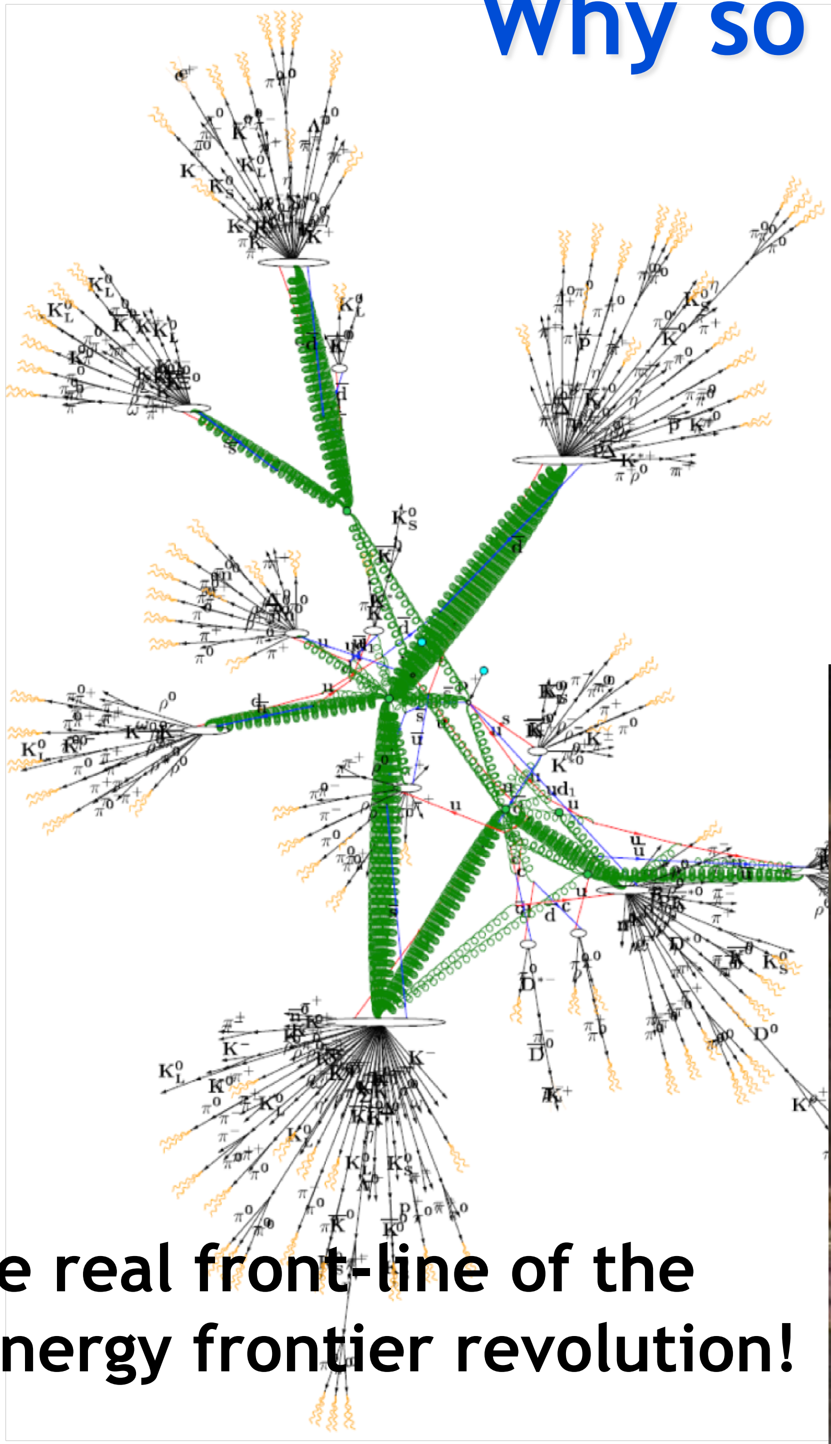
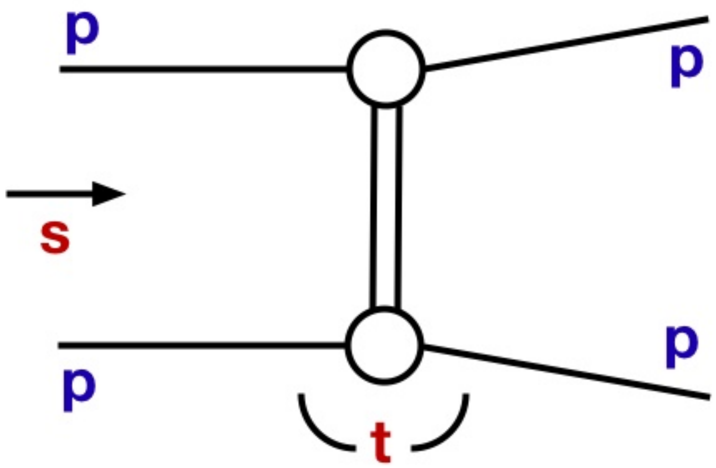
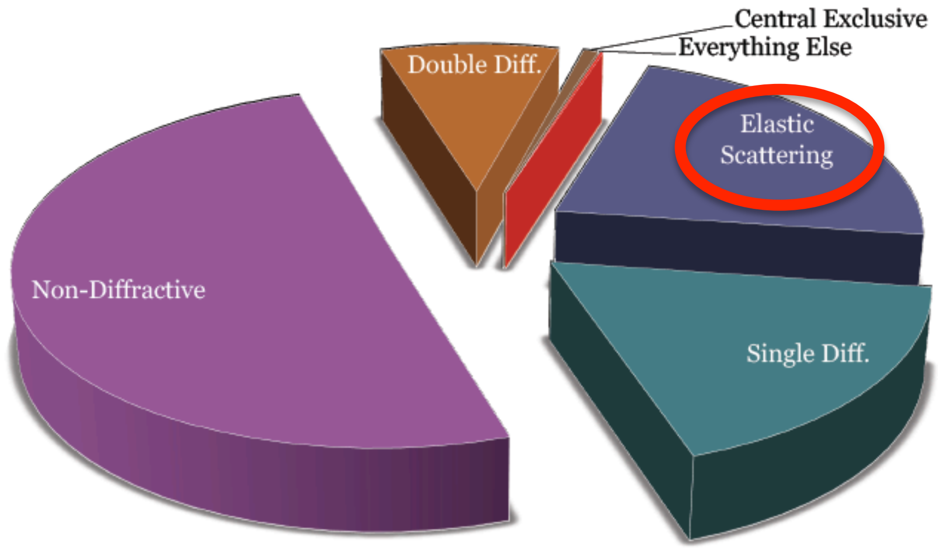


"minimum bias" pp event in PYTHIA8 at $\sqrt{s}$=7TeV, visualised using MCViz

… the real front-line of the energy frontier revolution!

Something `Simple': Elastic Scattering





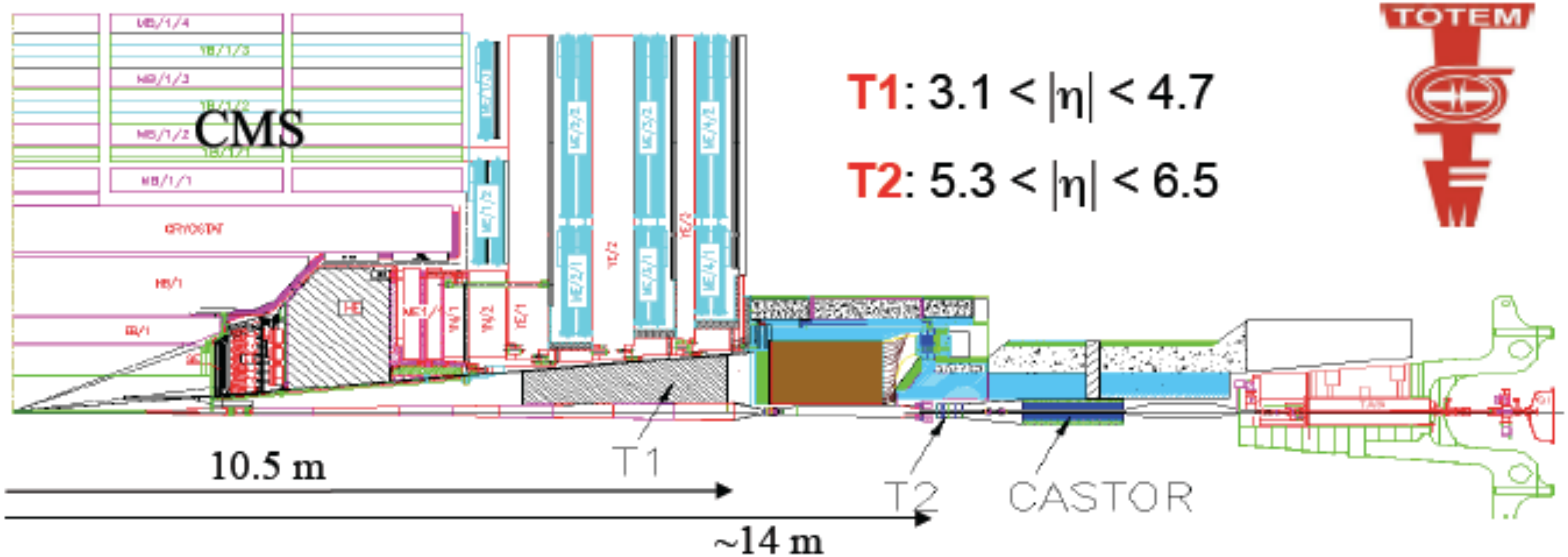
At fixed √s, 1 non –trivial variable (t)

Typically t << 1 GeV^2: non-perturbative

At fixed s: $$\frac{d\sigma}{dt} = \left.\frac{d\sigma}{dt}\right|_{t=0} e^{Bt}$$

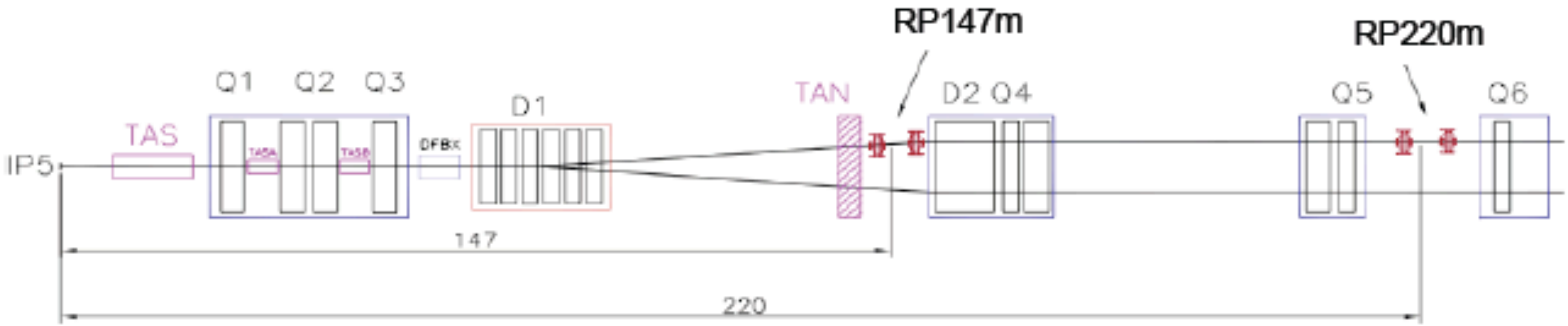
Slope parameter B measures mean impact parameter
(~size of interaction region ~ range of strong force ~1-2fm).

The LHC Elastic Cross Section: TOTEM



T1: $3.1 < |\eta| < 4.7$

T2: $5.3 < |\eta| < 6.5$

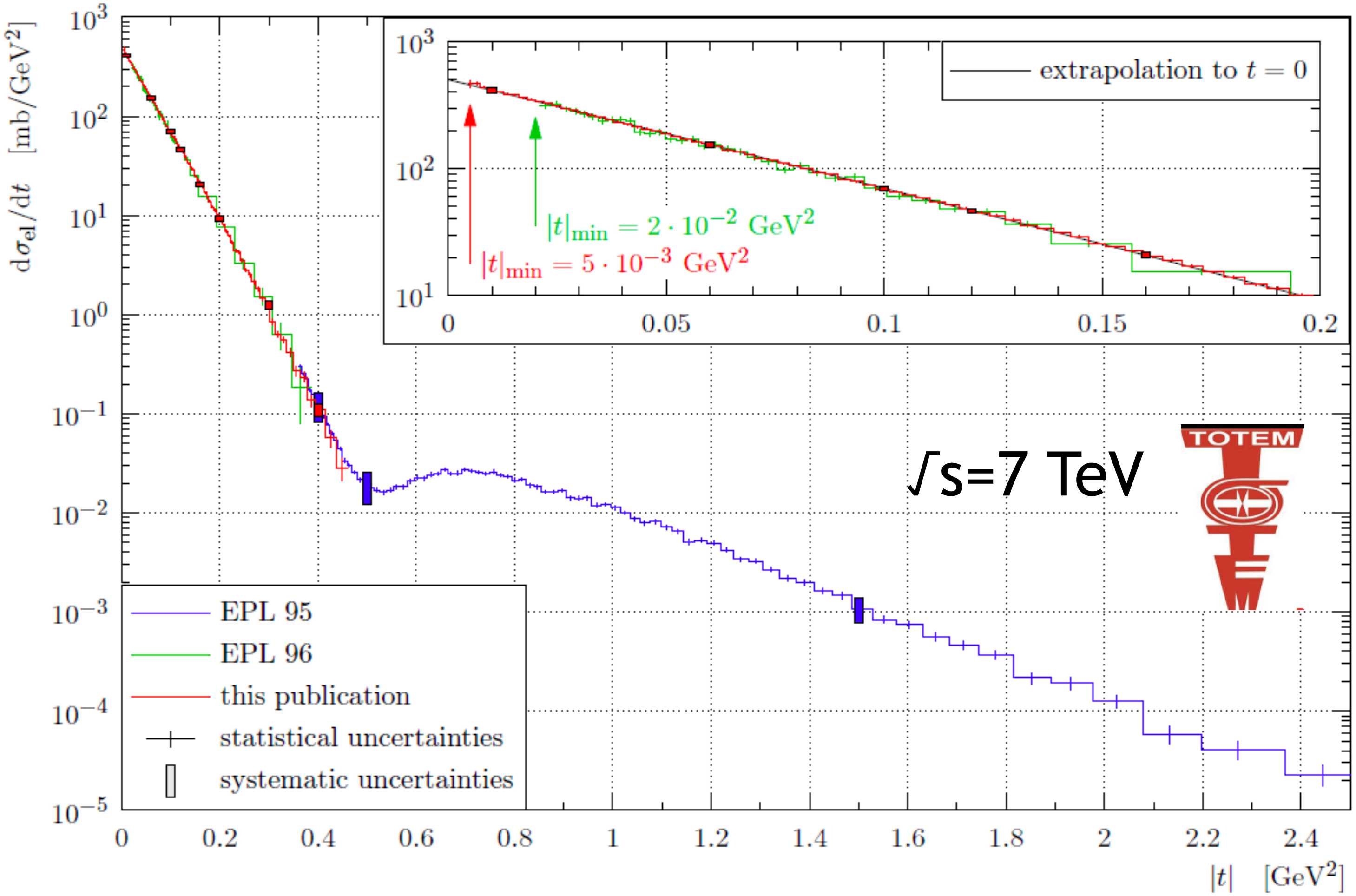


- The most hermetic detector ever?
- Elastic scattering measurement using Roman pots at 220m

Elastic Cross Section (TOTEM Roman Pots)

Precise t dependence of elastic (pp → pp) cross section over wide range of |t| at LHC

$$\frac{d\sigma}{dt} = \left.\frac{d\sigma}{dt}\right|_{t=0} e^{Bt}$$

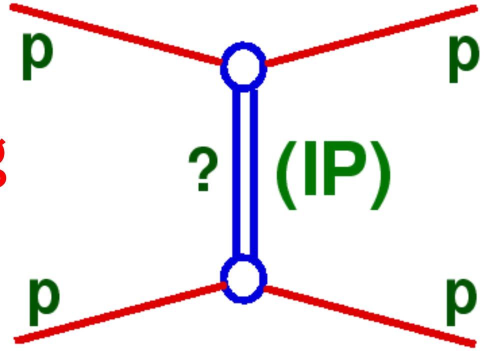


- B increases compared with Tevatron → 19.9±0.3±0.3 GeV^{-2}
- Dip pos'n decreases compared with Tevatron → 0.53±0.01 GeV^2

Mean impact param increases with √s (longer-lived fluctuations)

Vacuum Exchange and the Pomeron

What governs elastic scattering at high energies?



`Historically' … pomeron trajectory

$$\alpha(t) = \alpha(0) + \alpha' t \approx 1.085 + 0.25t$$

$$\frac{d\sigma_{EL}}{dt} \propto \left(\frac{s}{s_0}\right)^{2\alpha(t)-2}$$

Vacuum Exchange and the Pomeron

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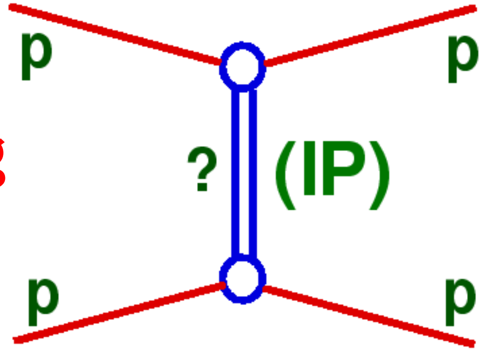

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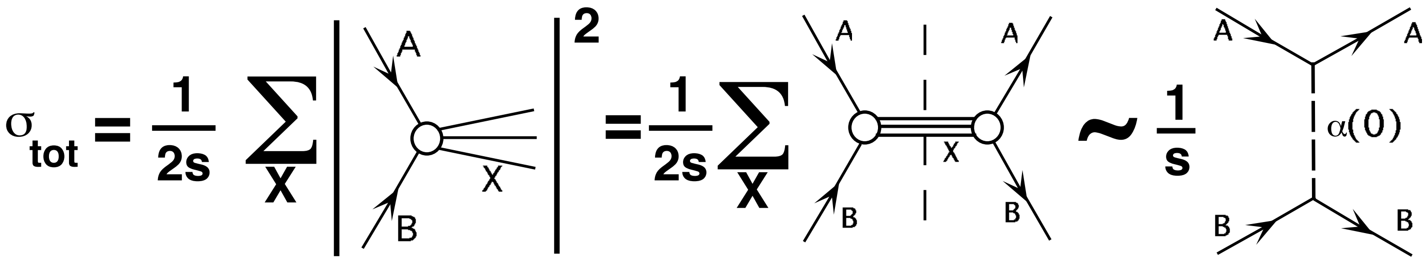
Closely related to total x-sec via optical theorem



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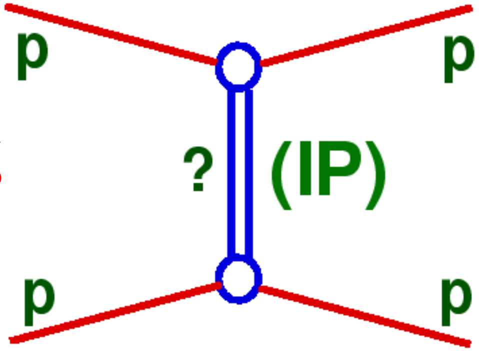
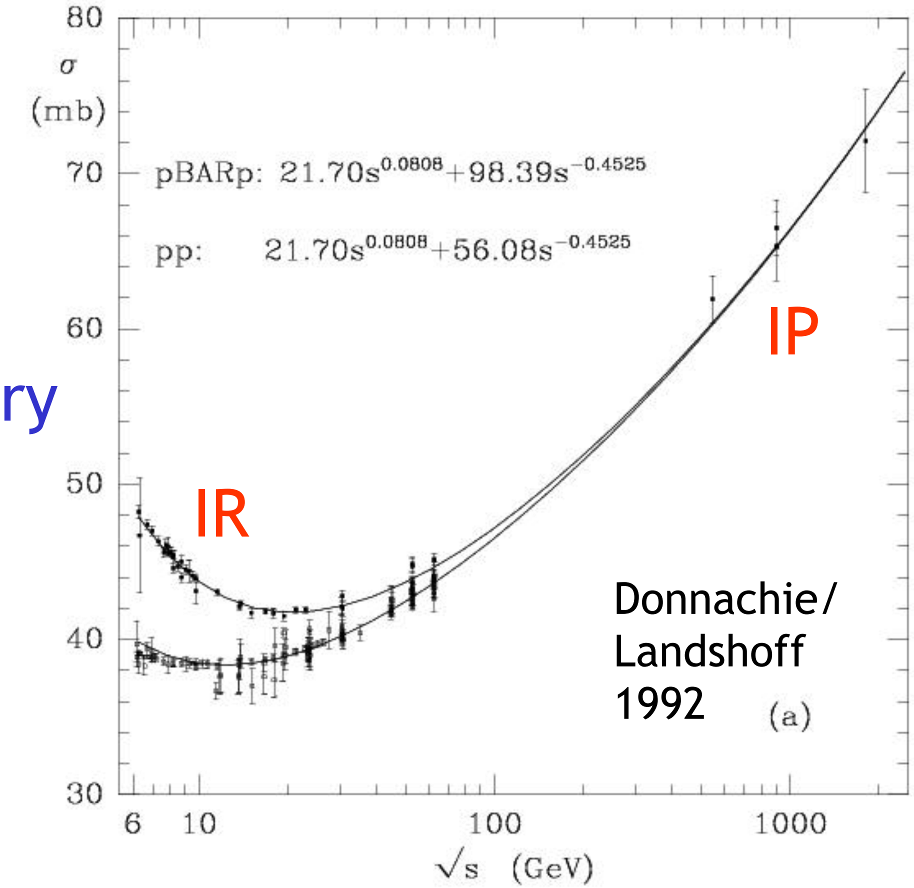


`Historically' … pomeron trajectory

$$\alpha(t) = \alpha(0) + \alpha' t \approx 1.085 + 0.25t$$

$$\frac{d\sigma_{EL}}{dt} \propto \left(\frac{s}{s_0}\right)^{2\alpha(t)-2} \qquad \sigma_{tot} \propto \left(\frac{s}{s_0}\right)^{\alpha(0)-1}$$



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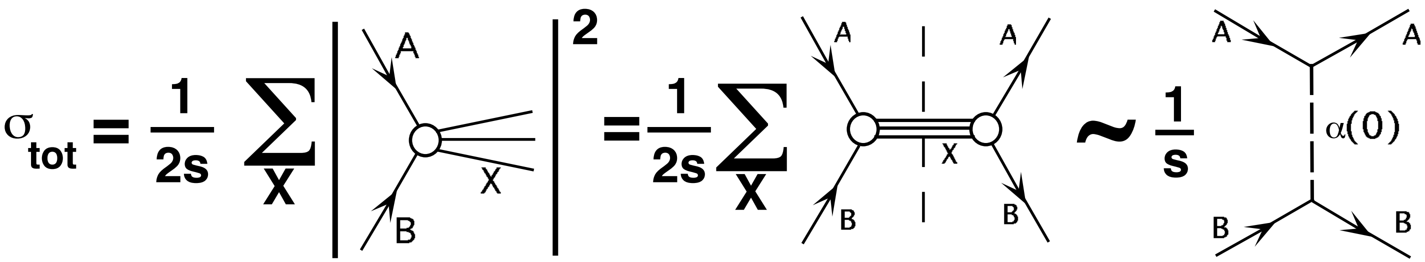
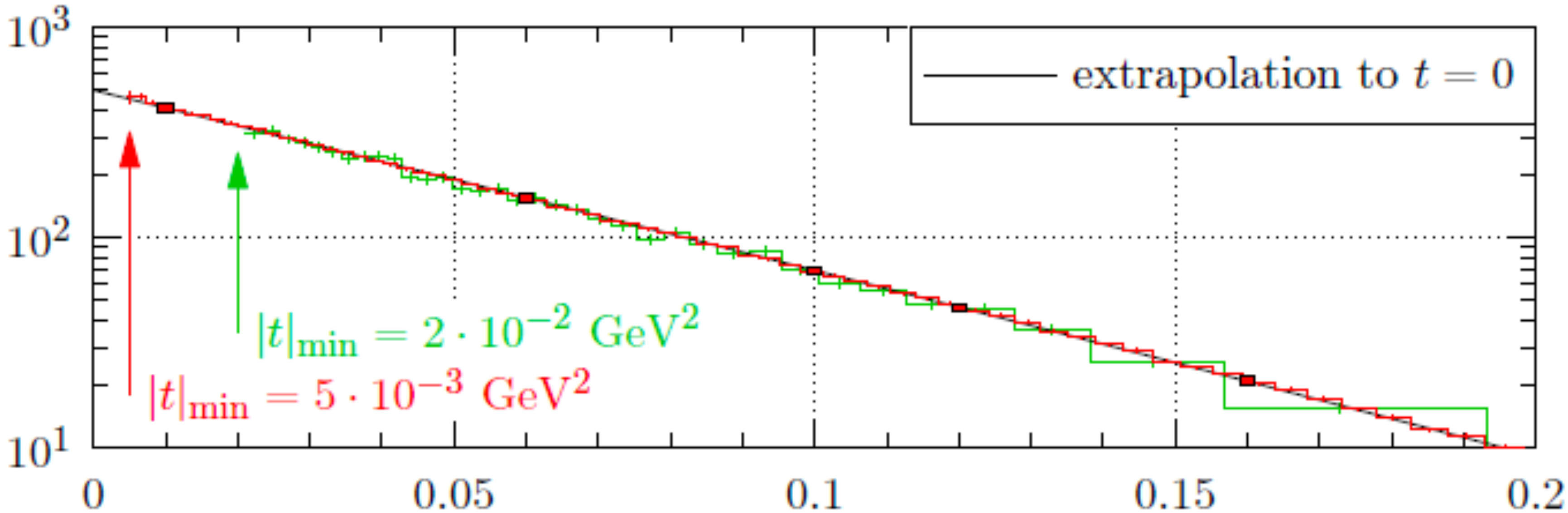


Optical Theorem: Relating elastic & total cross sections

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



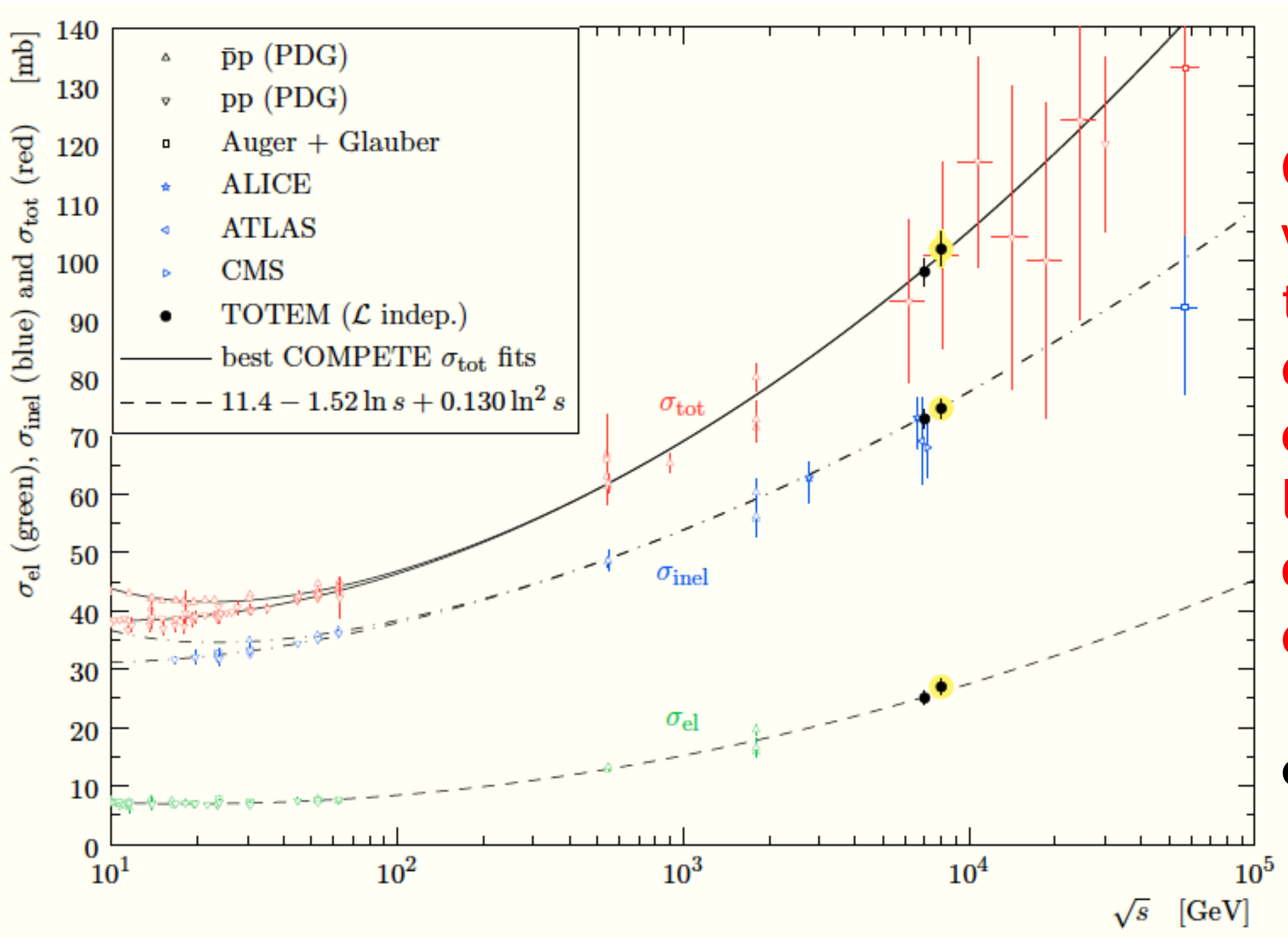
Dedicated run (special optics @ β* = 90m) → |t| ~ 0.005 GeV^2

- 10% extrapolation to t=0
- Luminosity measurement from CMS
- ρ from previous data

… one of four evaluations of σ_{tot} by TOTEM

Totem Total (and Elastic) Cross Section

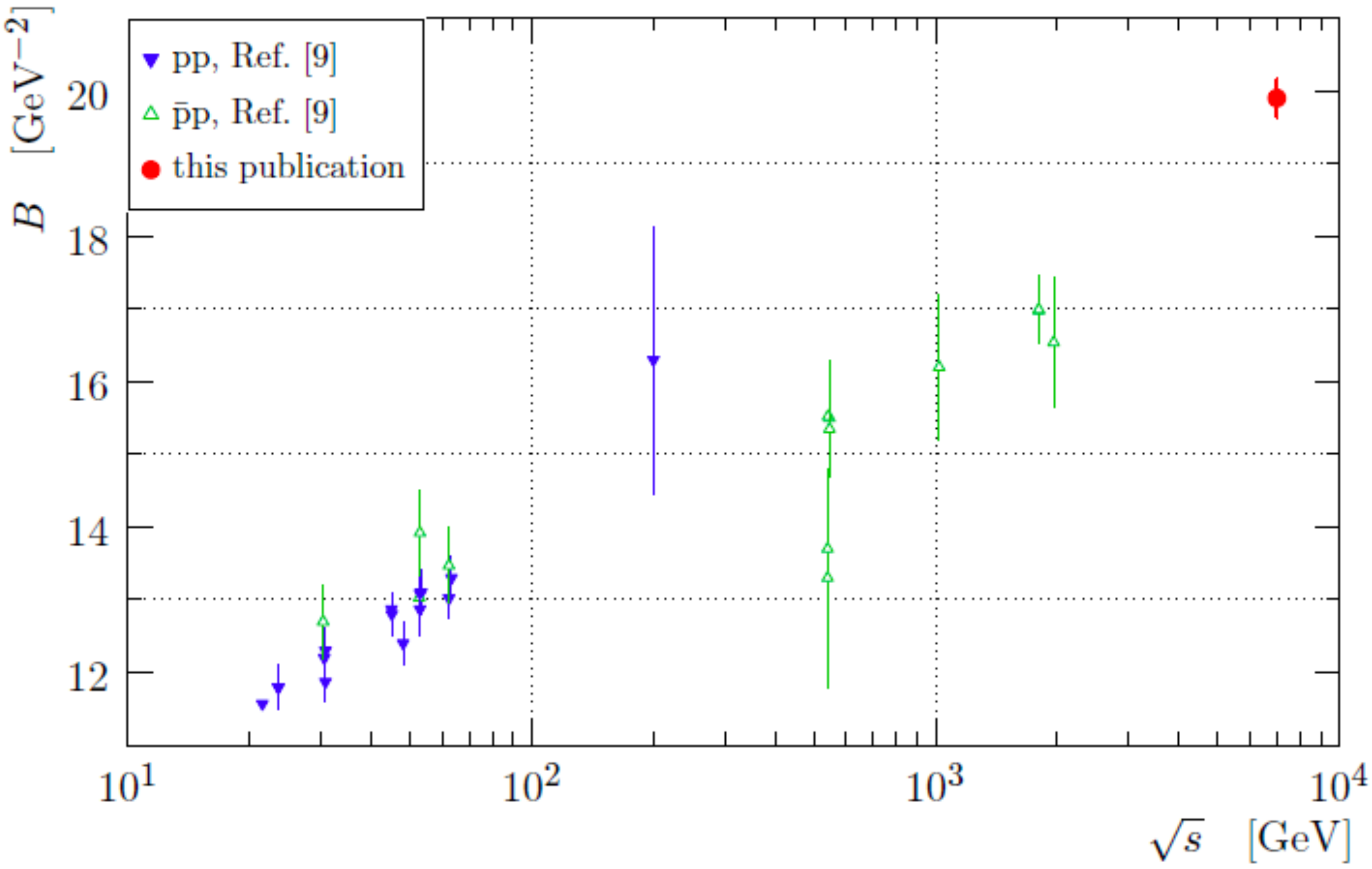
Now published at both √s=7 TeV and √s=8 TeV



Consistent with fits to previous data (with either a logarithmic or power law dependence).

$\alpha_{IP}(0) \sim 1.08$

√s dependence of t Slopes and α'



Fixed s:

$$\frac{d\sigma_{EL}}{dt} \propto \exp(Bt)$$

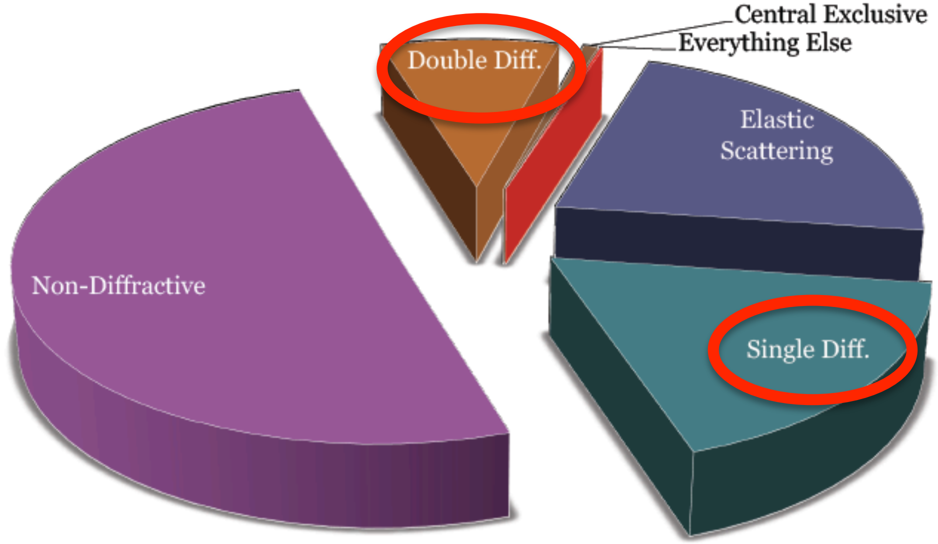
$$B = B_0 + 2\alpha' \ln\left(\frac{s}{s_0}\right)$$

-Comparing lower energy with TOTEM data suggests

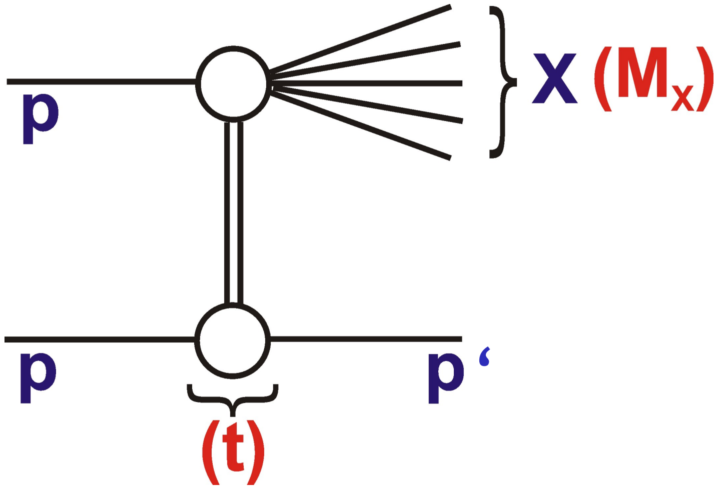
α' larger than 0.25 GeV^{-2}

- There were similar observations at HERA …
- Single pomeron exchange insufficient (absorptive corrections)

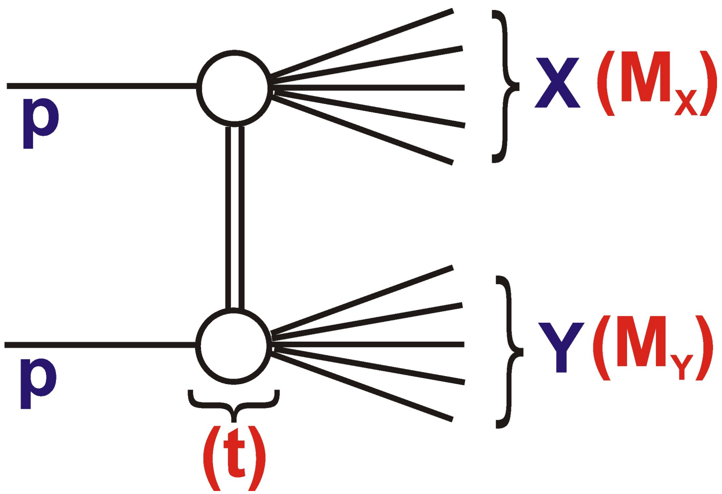
Inelastic Diffraction



Single diffractive dissociation



Double diffractive dissociation



Additional kinematic variables:

$$\xi = \frac{M_X^2}{s} = 1 - \frac{E_p^{/}}{E_p}$$

$$\xi_Y = \frac{M_Y^2}{s}$$

At LHC, M_X, M_Y can be as large as 1 TeV in soft diffractive processes

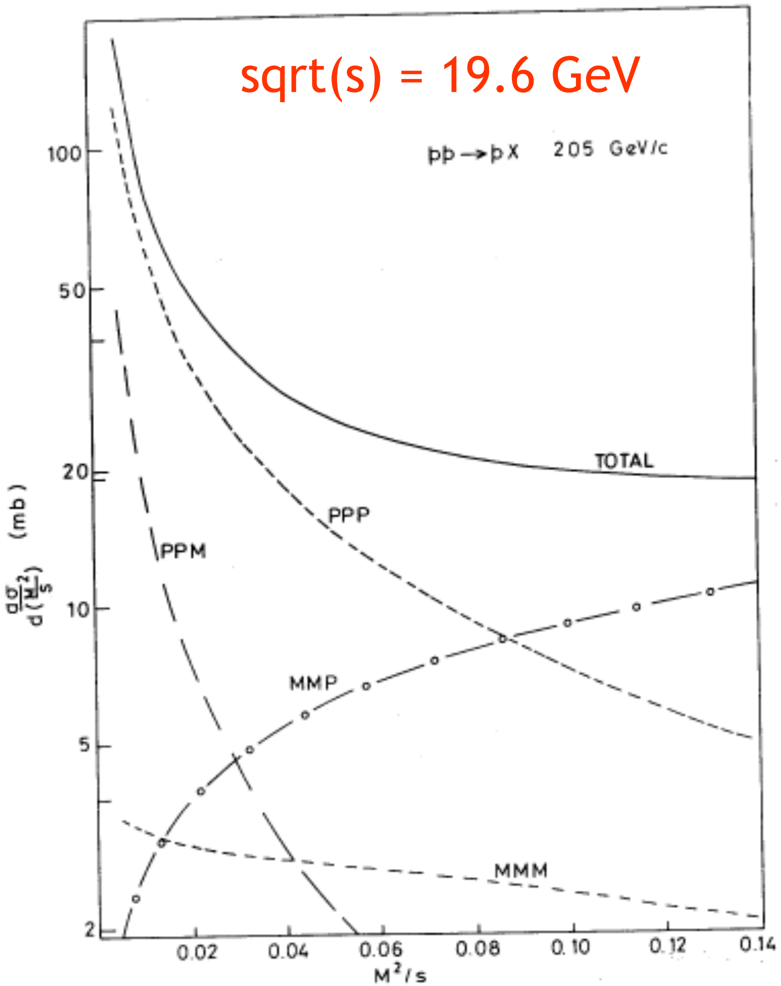
Uncertainties in pre-LHC Predictions

Single dissociation

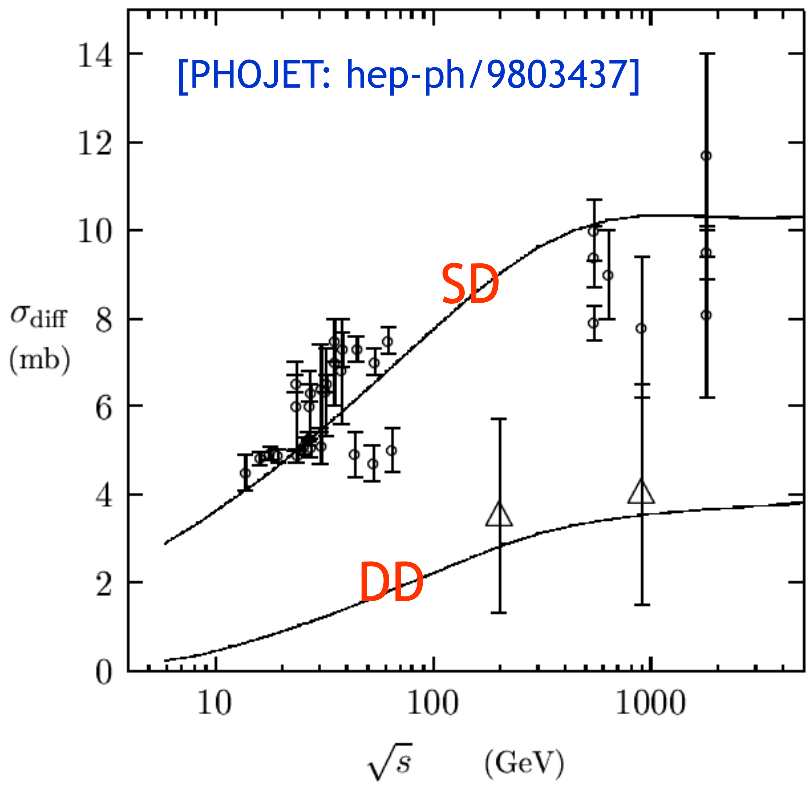
σ = 14mb (PYTHIA8)
σ = 10mb (PHOJET)

Double dissociation

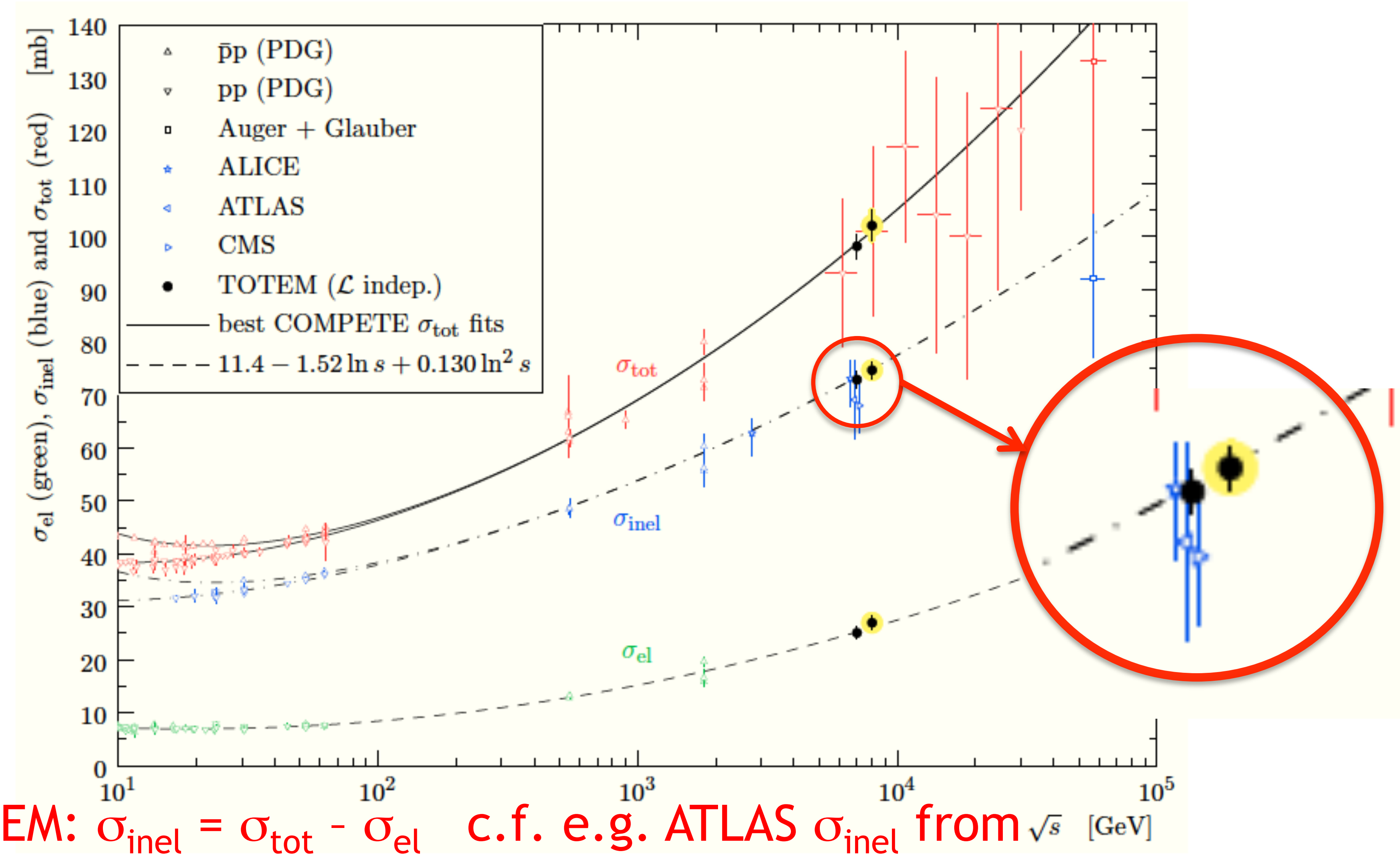
σ = 9mb (PYTHIA8)
σ = 4mb (PHOJET)



Parameterisations based on old low energy data, particularly poor for DD



Total Inelastic Cross Section

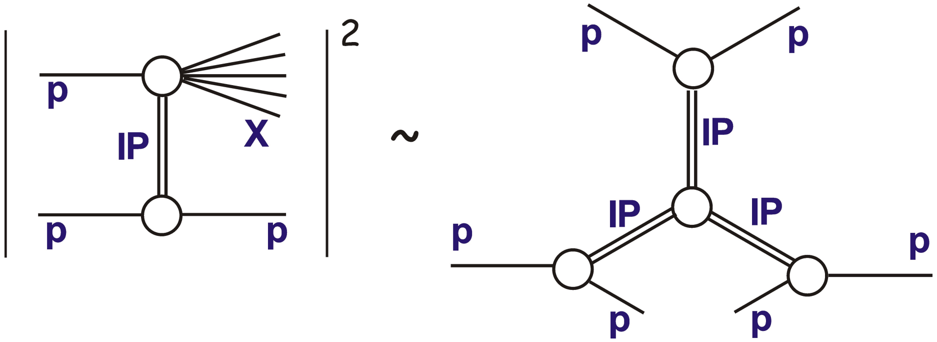


TOTEM: $\sigma_{inel} = \sigma_{tot} - \sigma_{el}$ c.f. e.g. ATLAS σ_{inel} from counting visible events, extrapolating into invisible region (diffraction with $\xi < 5.10^{-6}$, $M_X < 15$ GeV)

→ low mass dissociation underestimated in models?

Soft Diffraction: ξ and Gap-size Dynamics

$$\left[\alpha(t) = \alpha(0) + \alpha' t\right]$$



At fixed s: $\frac{d\sigma}{d\xi\, dt} \propto \left(\frac{1}{\xi}\right)^{2\alpha(t)-\alpha(0)} e^{bt}$

i.e. approximately: $\frac{d\sigma}{d\xi} \propto \frac{1}{\xi}$

Deviations from this behaviour sensitive to $\alpha_{IP}(t)$ and to absorptive corrections → c.f. multi-parton interactions

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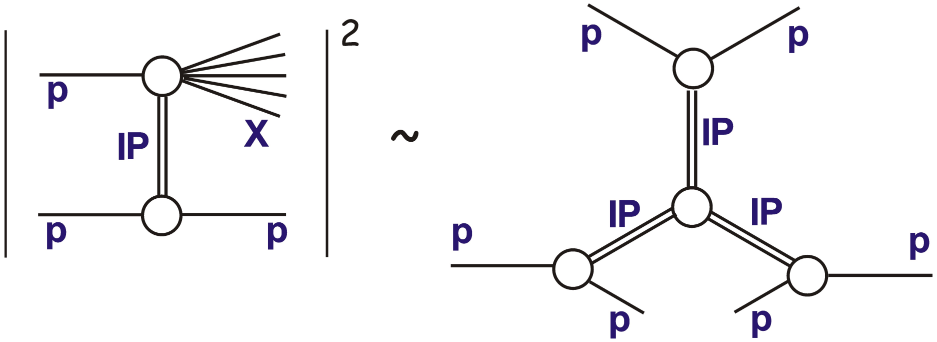

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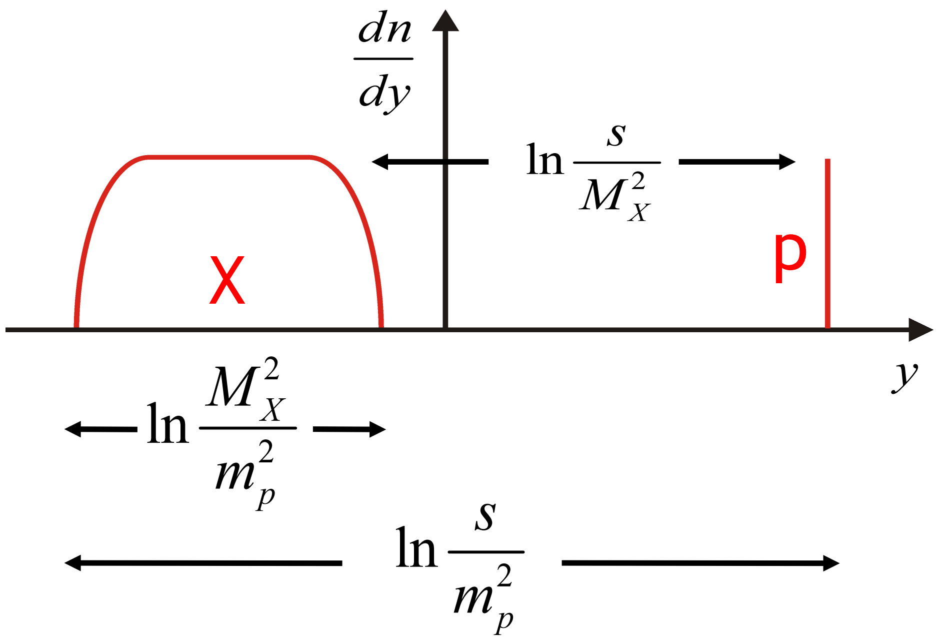


Up to event-by-event hadronisation fluctuations, ξ variable predictable from empty rapidity regions

$$\Delta\eta \approx -\ln \xi$$

… ~ flat gap distributions $$\frac{d\sigma}{d\Delta\eta} \approx \text{const.}$$

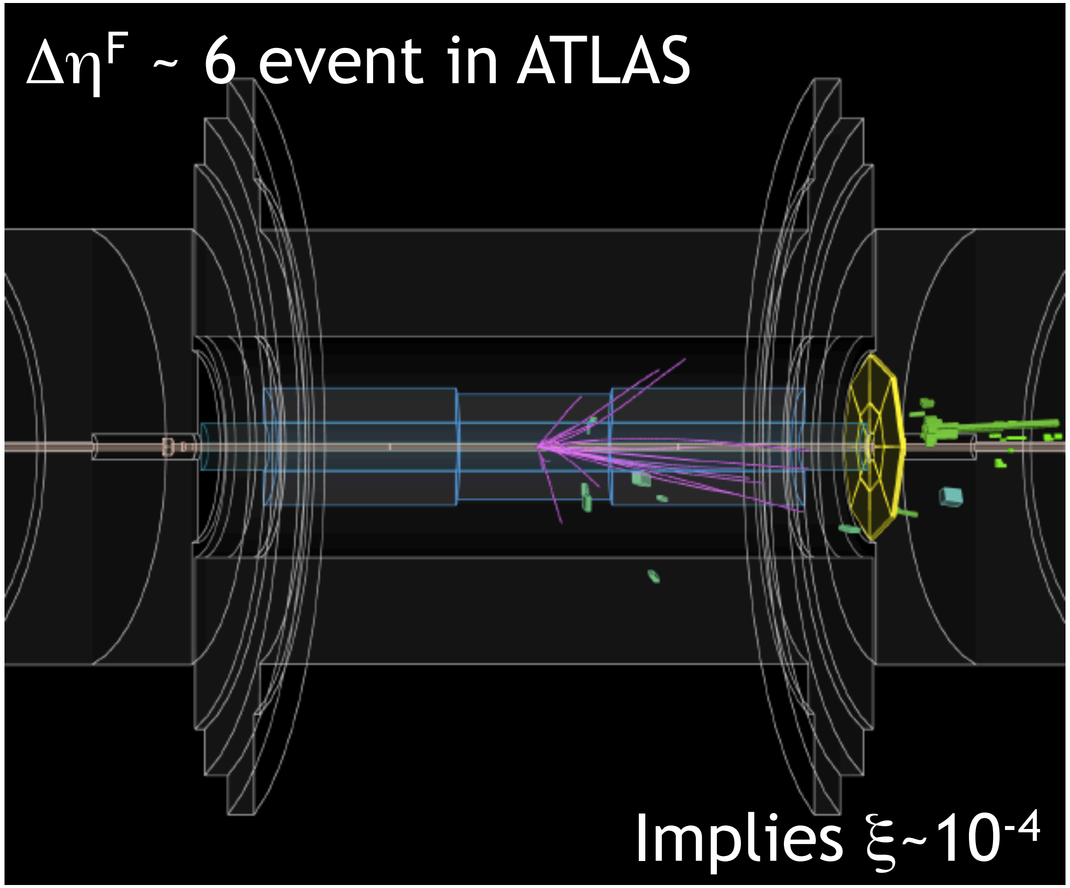
Differential rapidity gap cross-sections

- Cross sections differential in `visible' rapidity gap size $\Delta\eta^F$
- ATLAS: $\Delta\eta^F$ extends from $\eta = \pm 4.9$ to 1st particle with $p_t > 200$ MeV
- CMS: $\Delta\eta^F$ extends from $\eta = \pm 4.7$ to 1st particle with $p_t > 200$ MeV

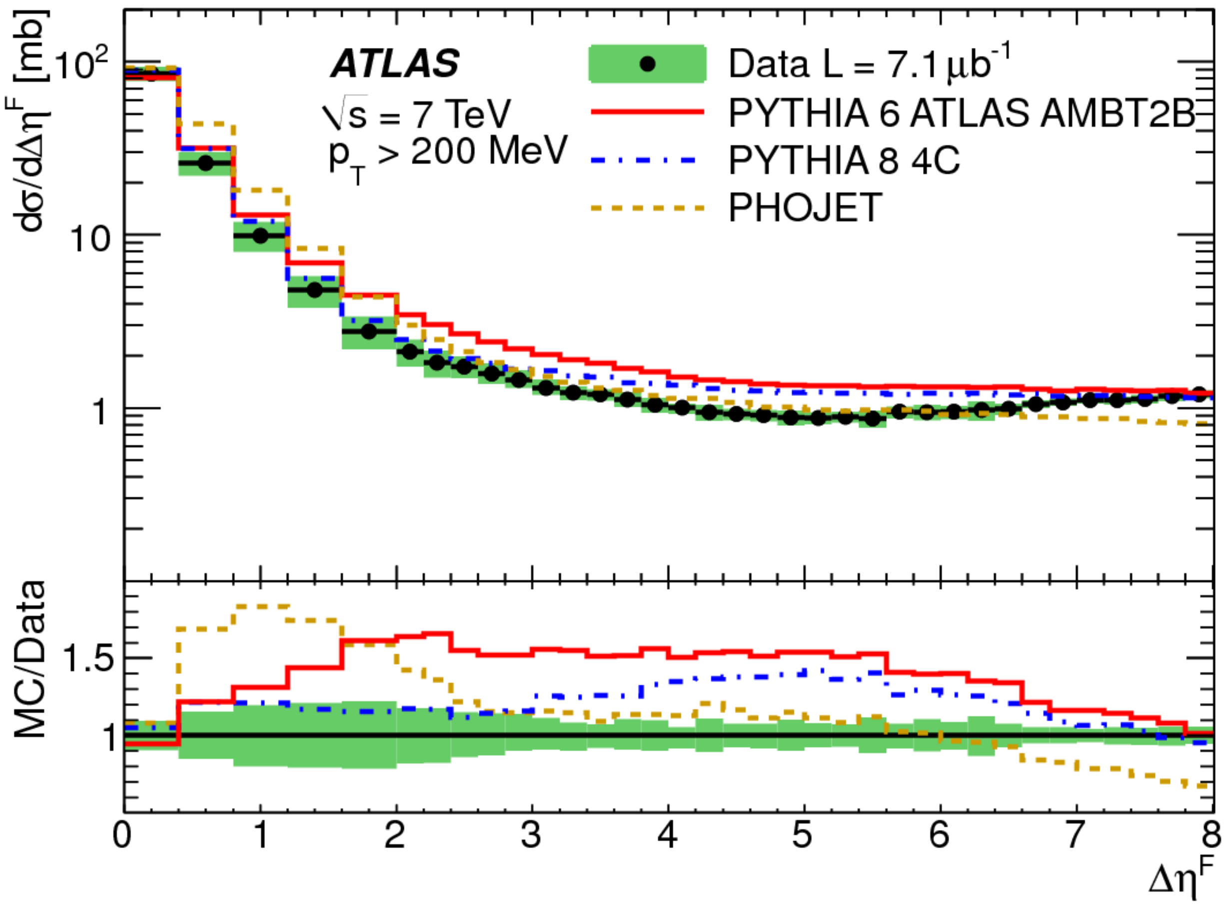
$0 < \Delta\eta^F < 8$ (ATLAS)
$0 < \Delta\eta^F < 8.4$ (CMS)

… corresponding (where diffraction dominates) to
$10^{-6} <\sim \xi <\sim 10^{-2}$ … or
$7 <\sim M_X <\sim 700$ GeV
[SD + low M_Y DD]

Corrected for experimental effects to level of stable hadrons



ATLAS Differential Gap Cross Section

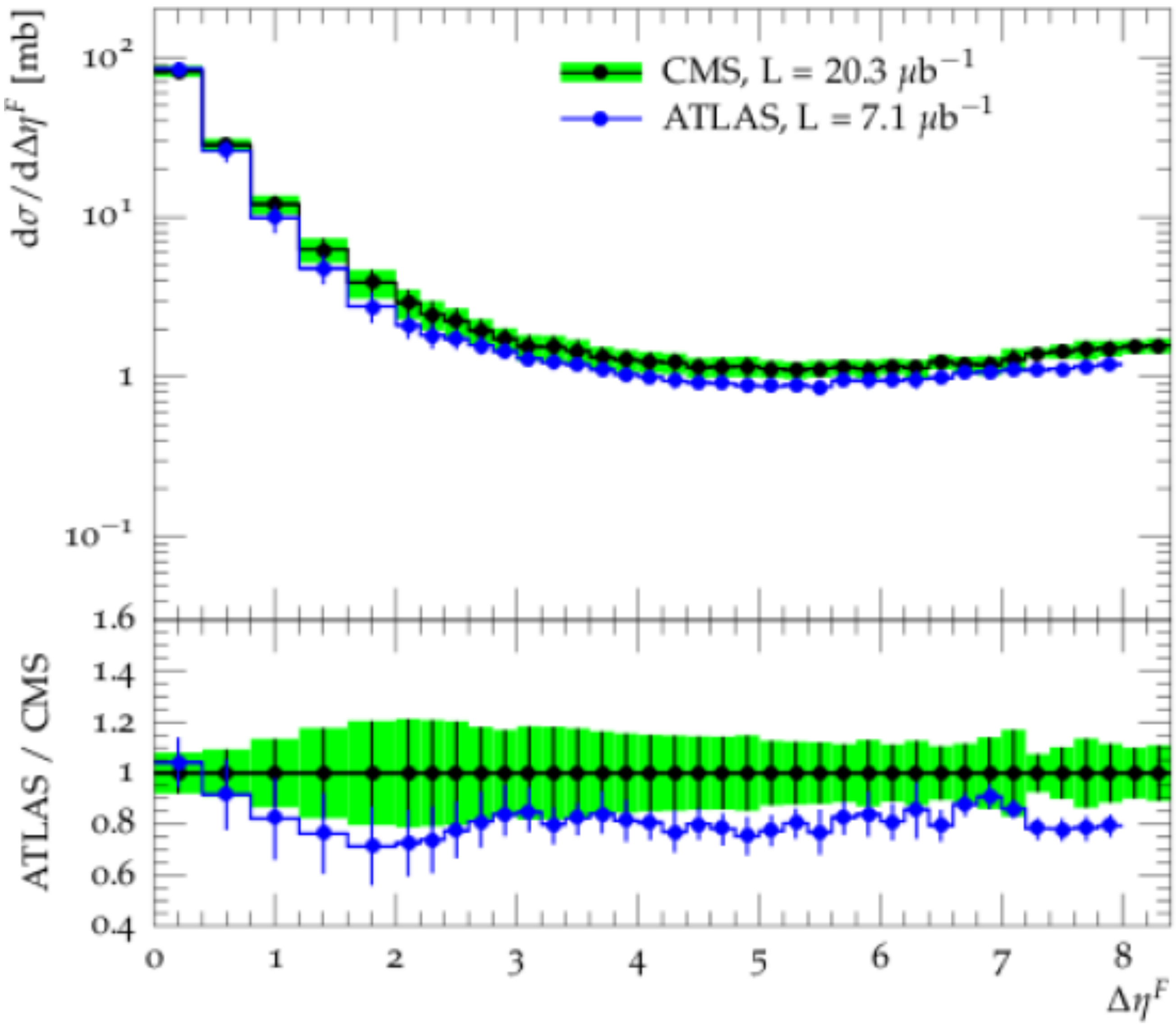


- Precision between ~8% (large gaps) and ~20% ($\Delta\eta^F$ ~ 1.5)
- Large gaps measure x-sec for SD [+ DD with M_Y <~ 7 GeV]
- Small gaps sensitive to hadronisation fluctuations / MPI

… huge uncertainties

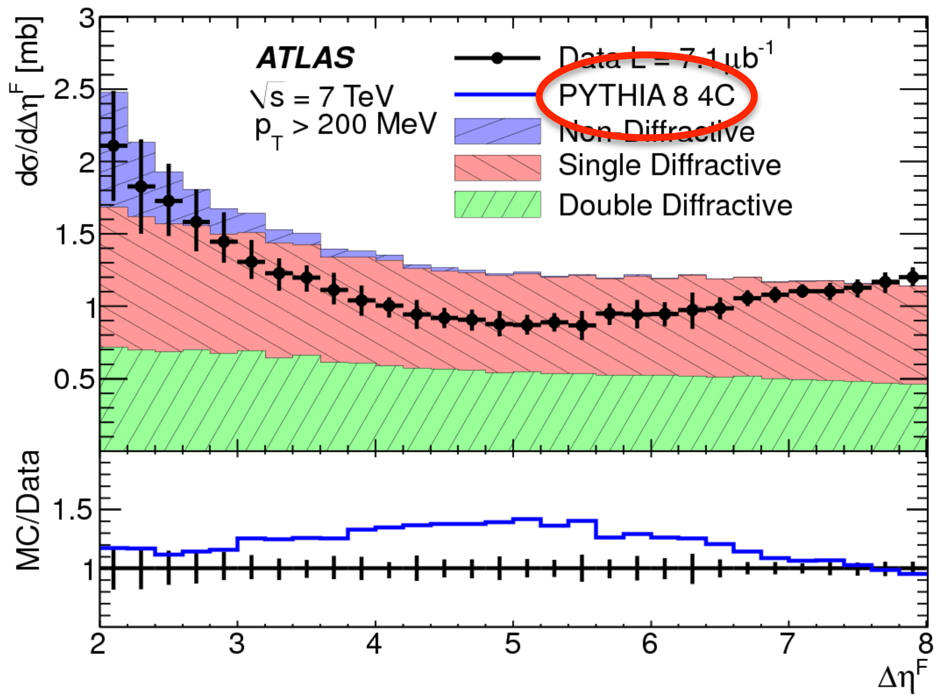
- PYTHIA best at small gaps, PHOJET > 50% high at $\Delta\eta^F$ ~ 1.5

Comparison between CMS and ATLAS

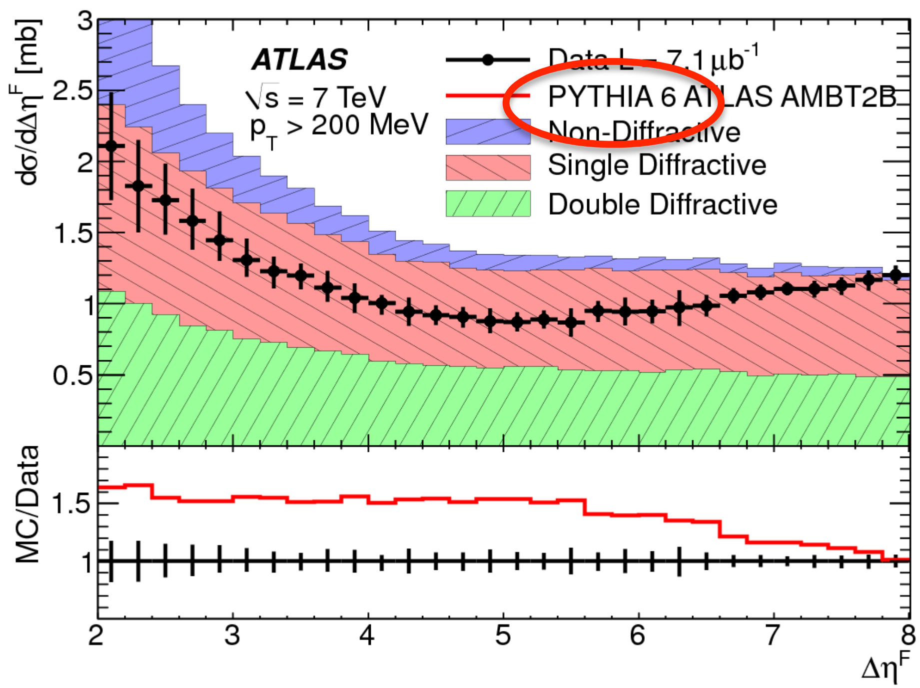


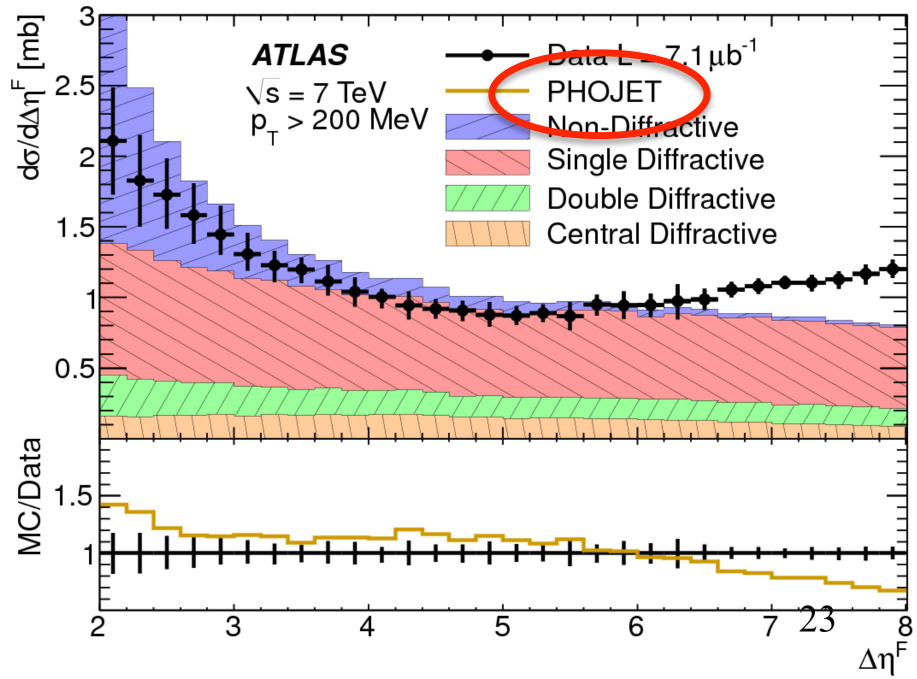
- Cross sections defined slightly differently (start |η| of gap)
- Acceptable agreement within uncertainties …

Large Gaps and Diffractive Dynamics



- Diffractive plateau with ~ 1 mb per unit of gap size for $\Delta\eta^F > 3$ broadly described by models
- PYTHIA high (DD much larger than in PHOJET)
- PHOJET low at high $\Delta\eta^F$





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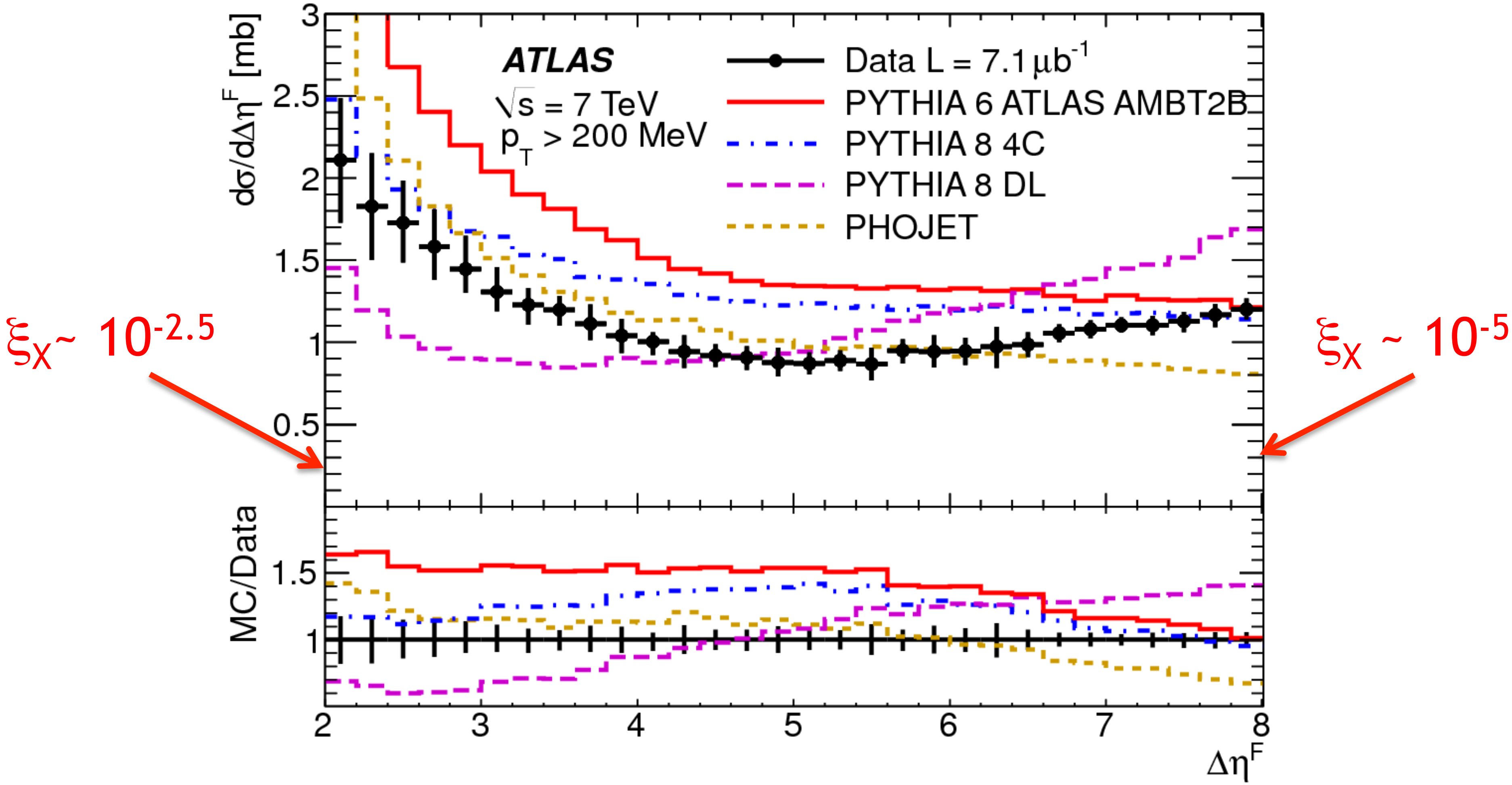
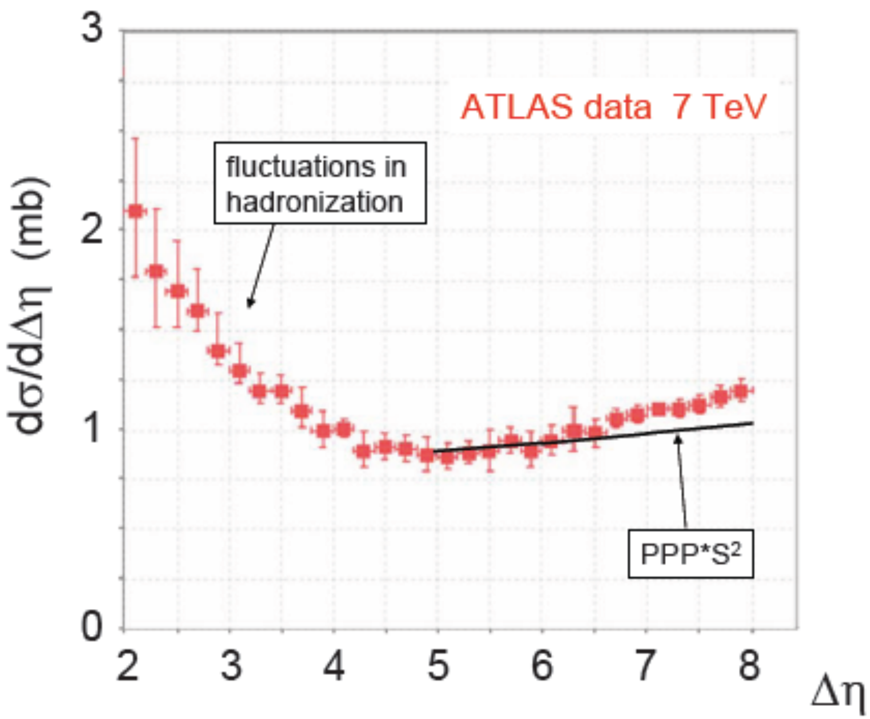
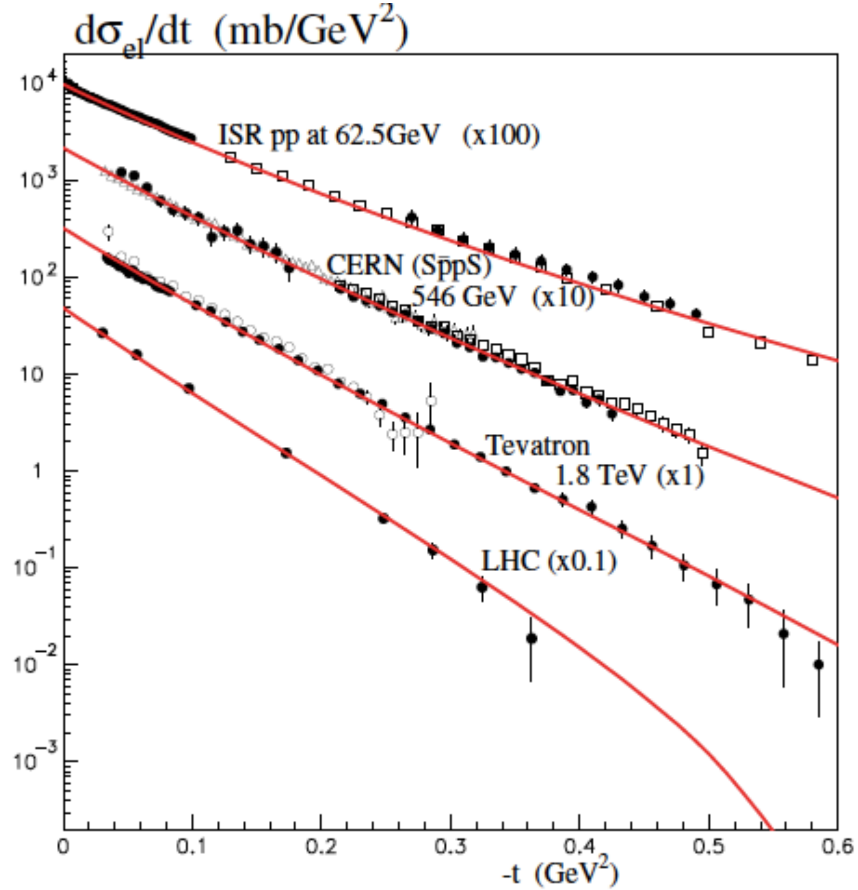


- Default PHOJET, PYTHIA have $\alpha_{IP}(0) = 1$; DL has $\alpha_{IP}(0) = 1.085$
- Fit to large $\Delta\eta^F$ data: $\alpha_{IP}(0) = 1.058 \pm 0.003$ (stat) ± 0.036 (syst)
- CMS find better description with $\alpha_{IP}(0) = 1.080$ than 1.104
- Also sensitive to the MC tune used.

e.g. KMR Model of Soft Diffractive Processes

[arXiv:1201.6298]



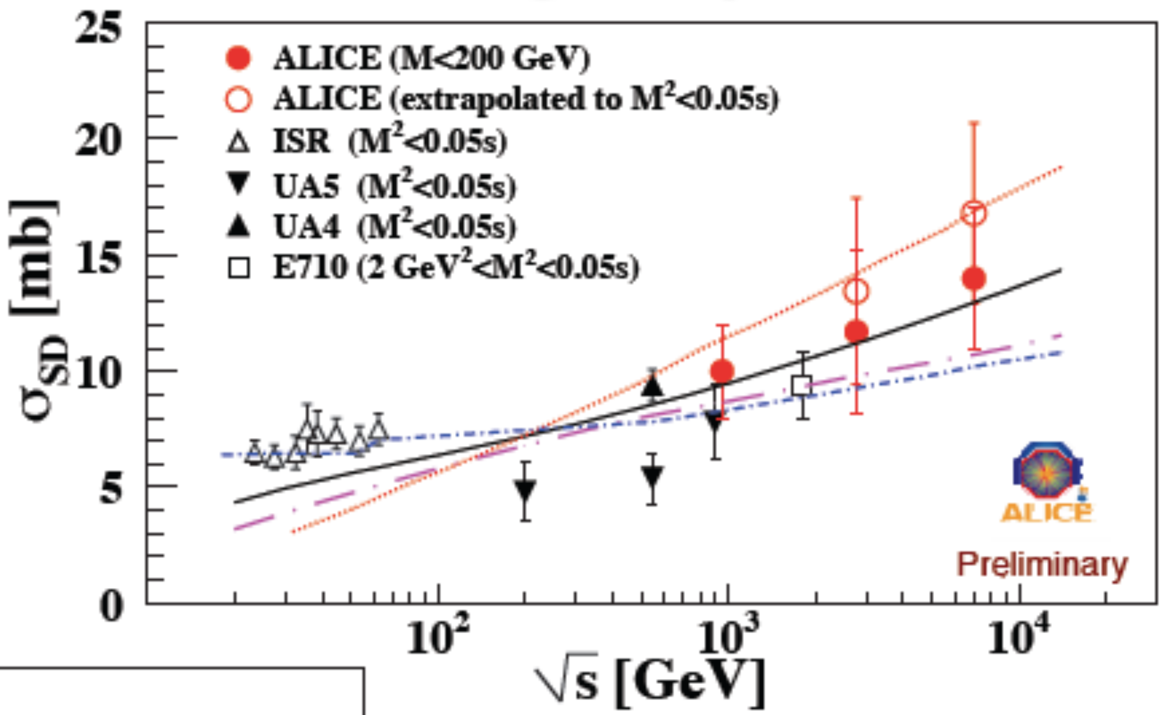


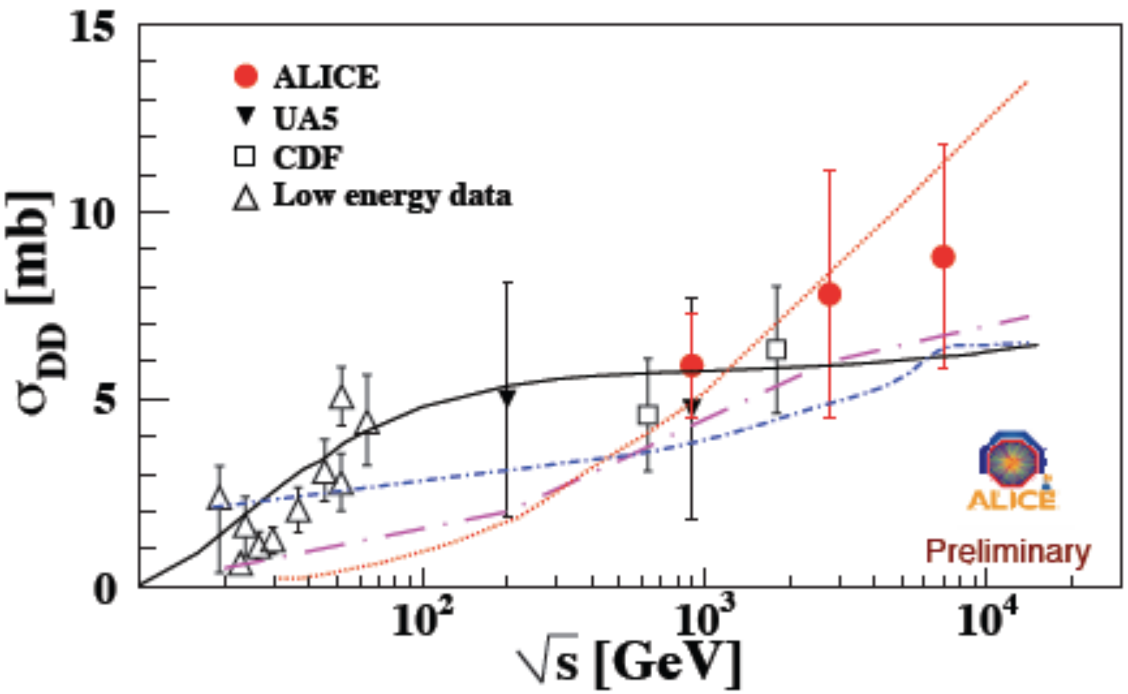
… simultaneous Durham (KMR) description of ATLAS gaps data and elastic cross section data from ISR to Totem based on a single pomeron in a 3-channel eikonal model, with significant absorptive corrections in gaps / dissociation case

Total SD, DD Cross Secs Using Gaps: ALICE

ALICE: Integrated SD, DD cross secs at three √s based on gap rates and topologies [extrapolation into lowest ξ regions]

- σ(SD) with ξ < 0.05
- σ(DD) with gap Δη > 3

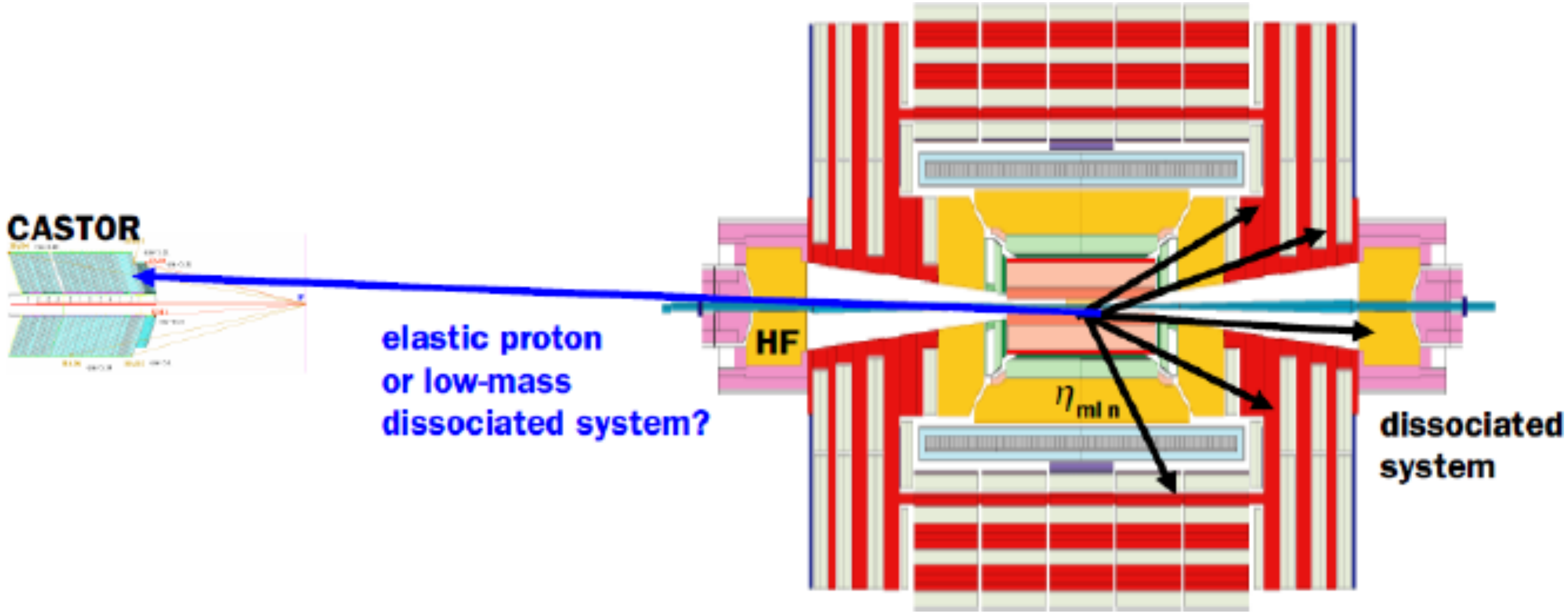




- Good agreement with SPS data and wide range of model predictions.

- **New data in restricted ξ ranges (CMS, TOTEM)**

New CMS Data: Direct ξ Measurement



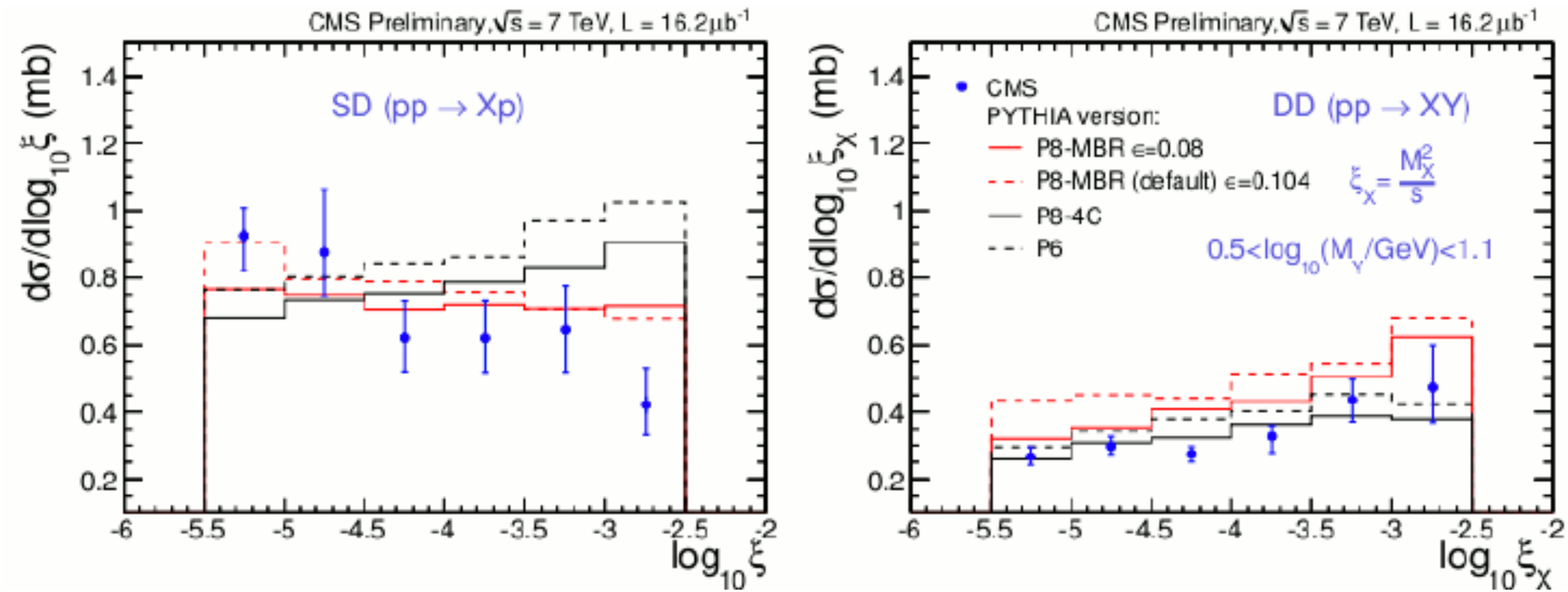
- Use forward calorimeter (CASTOR) tag to help distinguish SD from DD (sensitive to much lower M_Y than central detector).

- Directly reconstruct ξ using particle flow algorithm and cunning kinematics.

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

- Larger uncertainties, but more directly related to dynamics.

New CMS Measurement

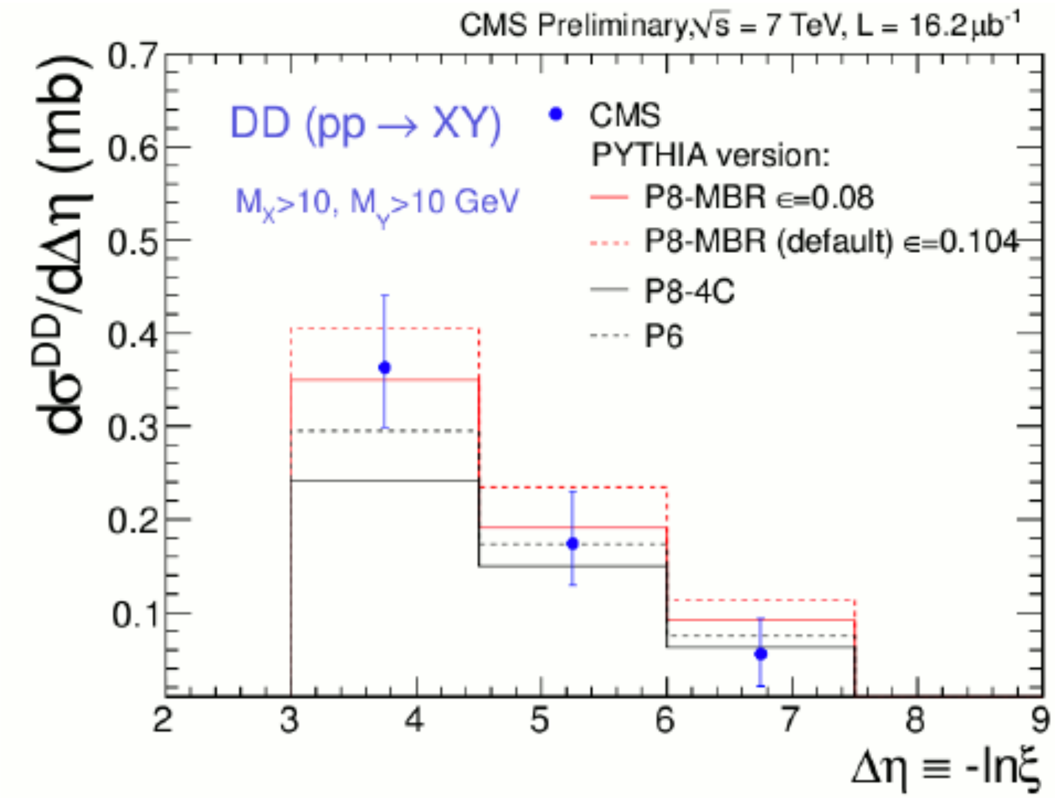


- SD data (small low M_Y DD subtraction) compatible with PYTHIA8 with $\alpha_{IP}(0) = 1.08$ or 1.104

- Precise DD data ($3.2 < M_Y < 12$ GeV) prefer $\alpha_{IP}(0) = 1.08$

- Data also sensitive to PYTHIA version and tune

New CMS Measurement

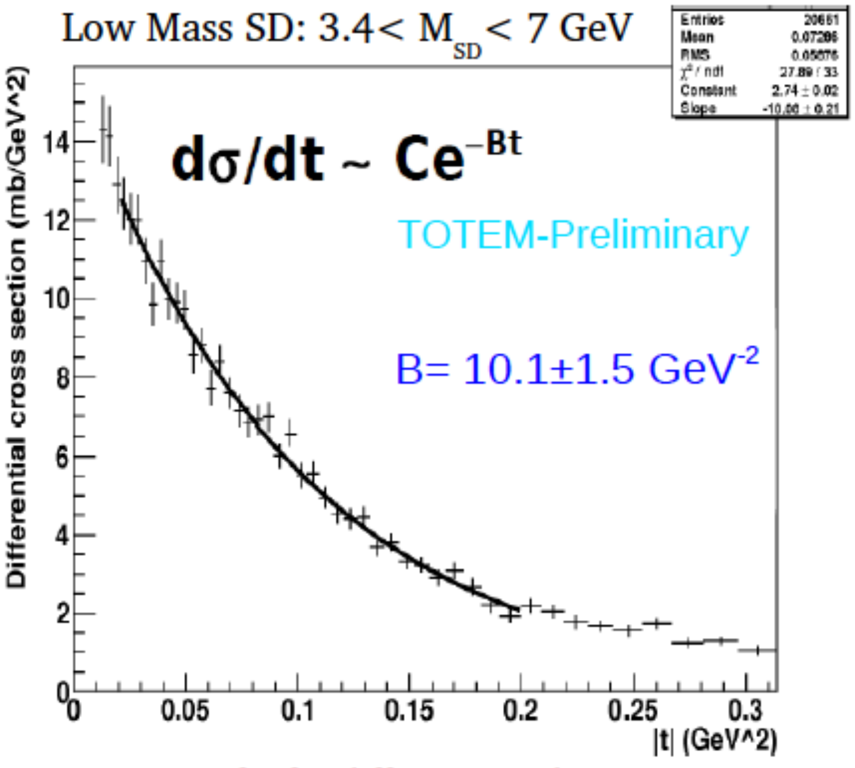


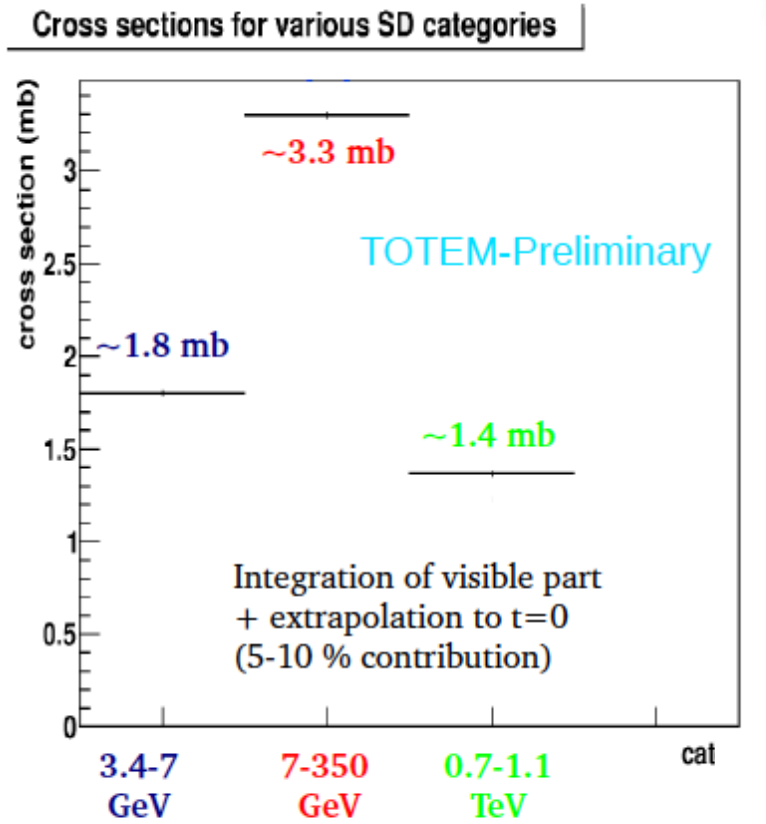
- Data with central gap ($\Delta\eta$ > 3, within CMS acceptance) constrain DD cross section at large M_X (>10 GeV) and M_Y (>10 GeV)

- Again compatible with PYTHIA8 with $\alpha_{IP}(0)$ = 1.08 or 1.104

… increasingly detailed SD and DD data → challenging theory

New TOTEM Data: Proton Tagged SD





- Mass regions inferred from gap sizes, but proton-tagged:

… first LHC measurement of t slope of single dissociation …

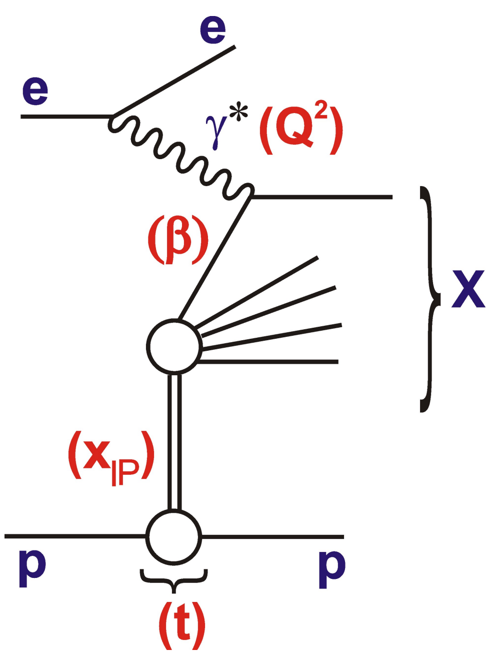
~½ of elastic slope at low M_X, as in lower energy pp data

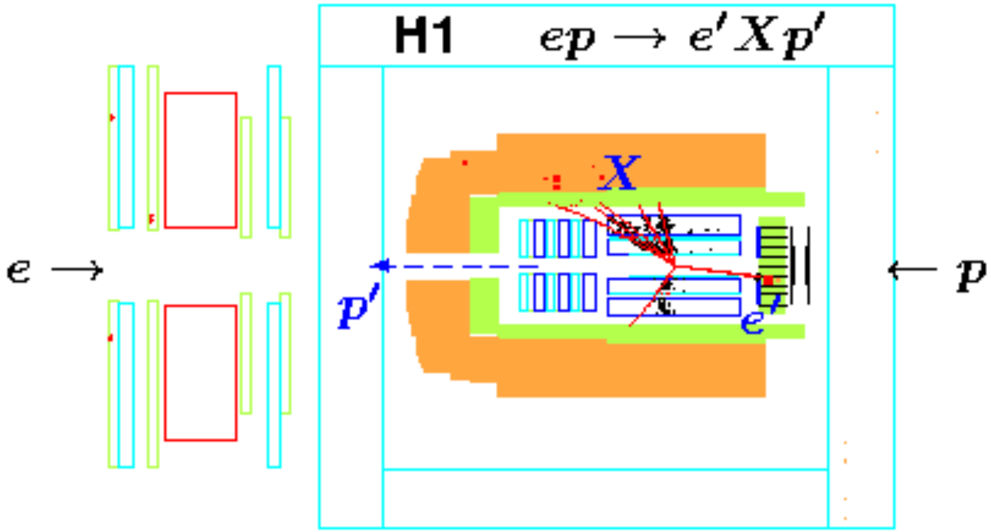
B then falls with increasing M_X

… cross sections measured in three wide M_X ranges

Lots of SD cross section at M_Y < 3.4 GeV

Diffraction at the Parton Level



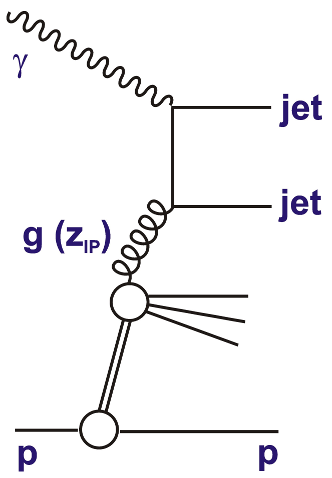


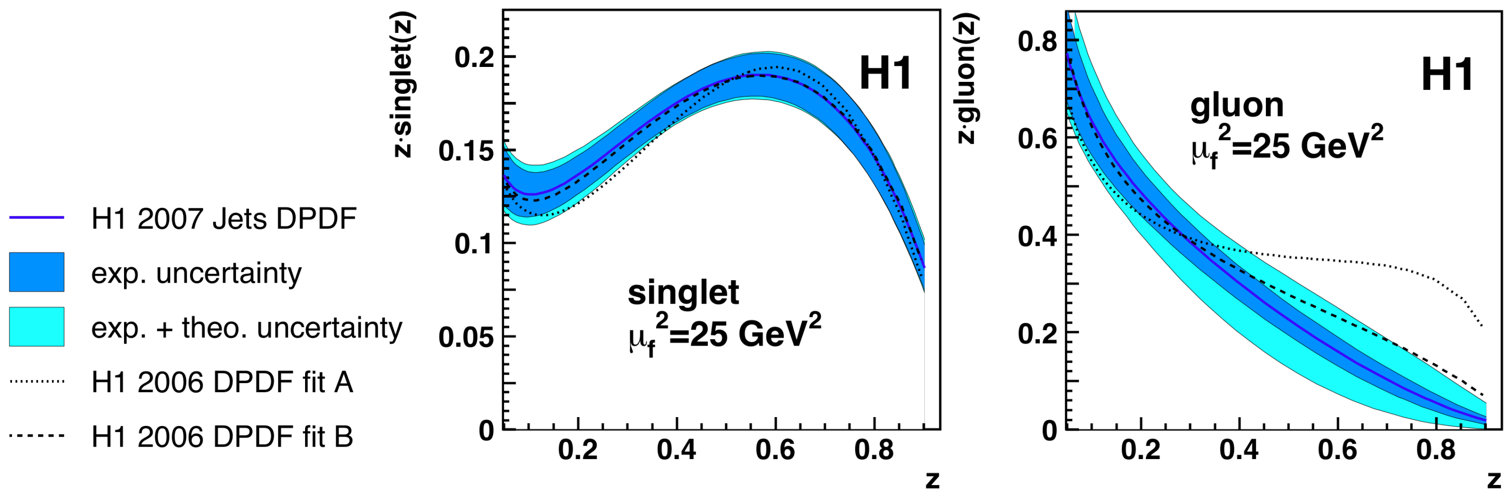
HERA ep Collider:

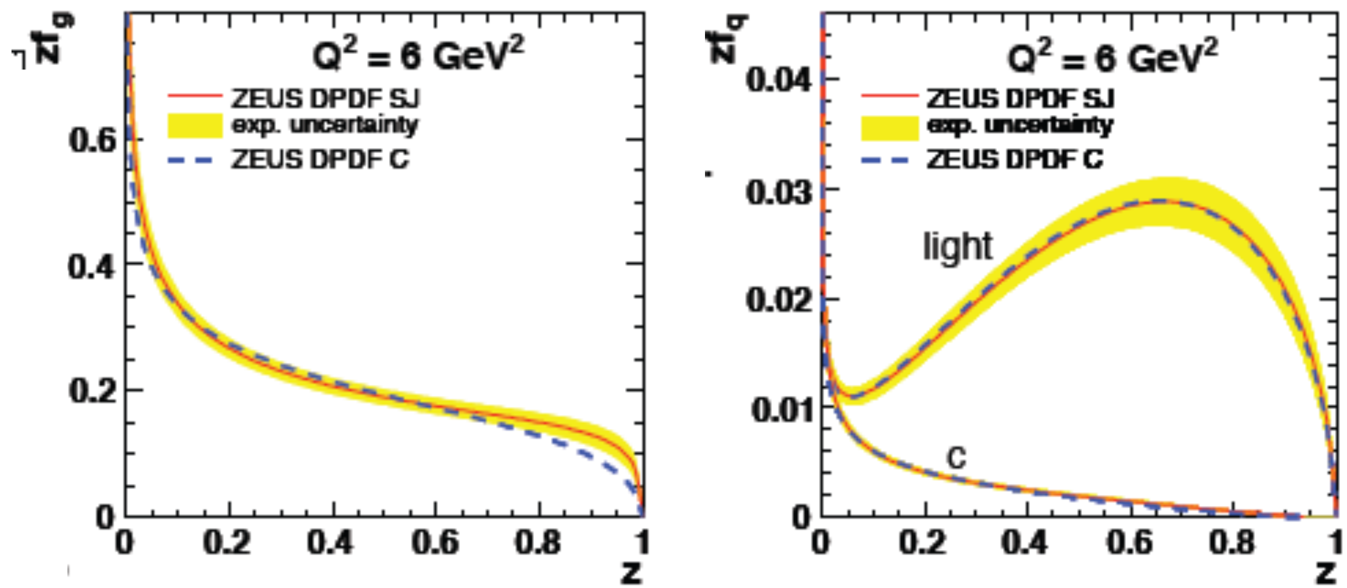
Virtual photon probes pomeron partonic structure rather like inclusive DIS …

>100 papers later …

Diffractive Parton Densities (DPDFs)





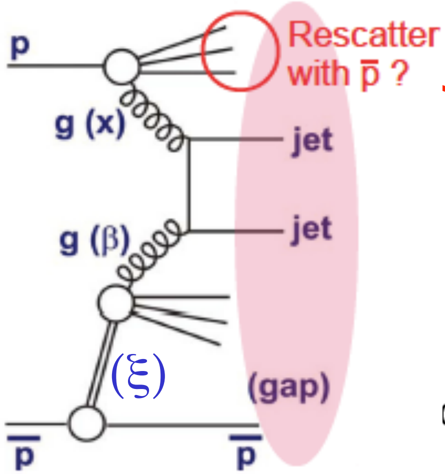


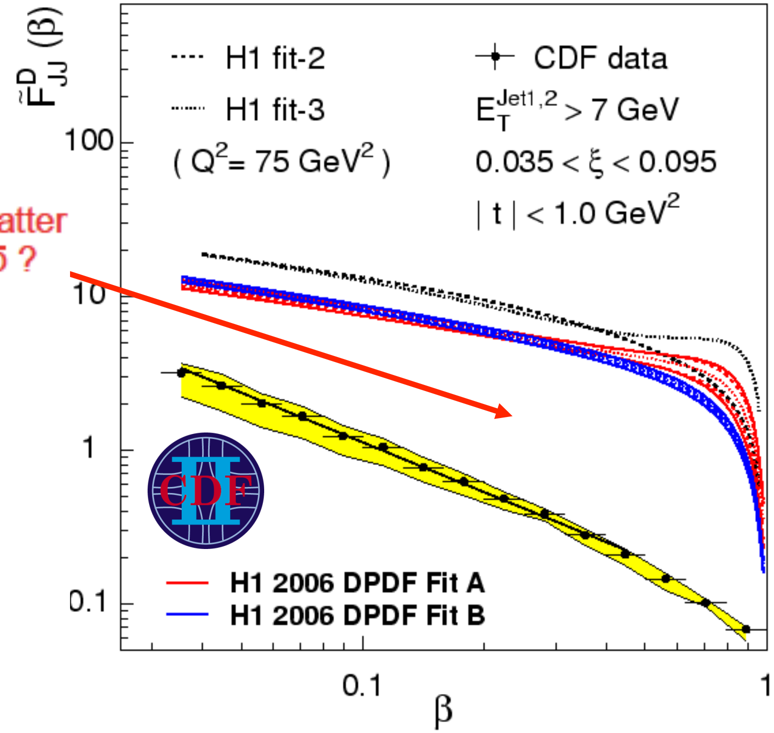
NLO DPDFs lead to impressive descriptions of all hard diffractive DIS data

DPDFs dominated by a gluon density which extends to large z

… but in pp(bar)

Spectacular failure in **comparison of Tevatron proton-tagged diffractive dijets with HERA DPDFs**
… `rapidity gap survival probability' ~ 0.1





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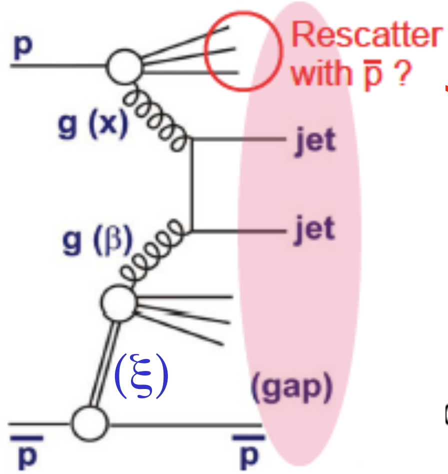
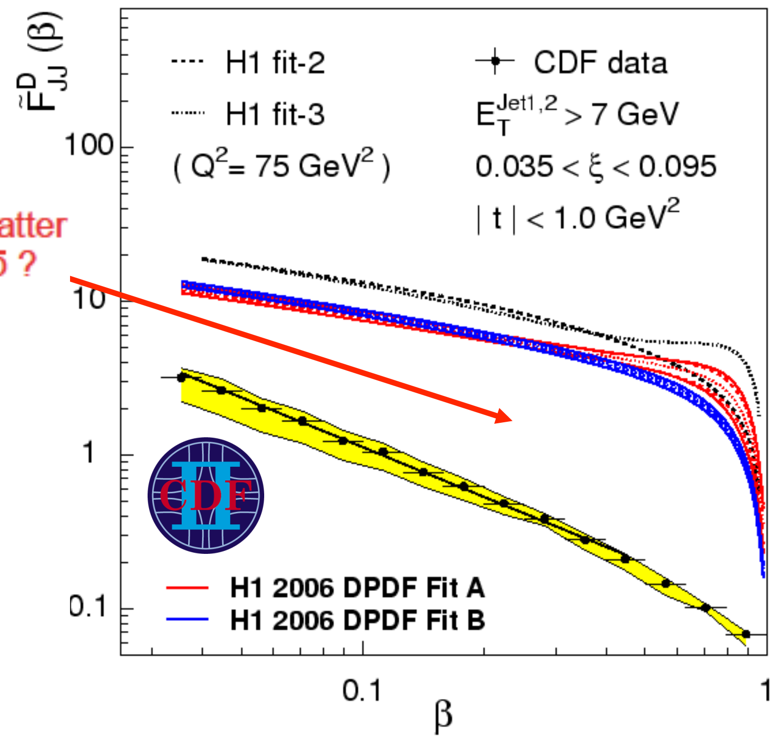
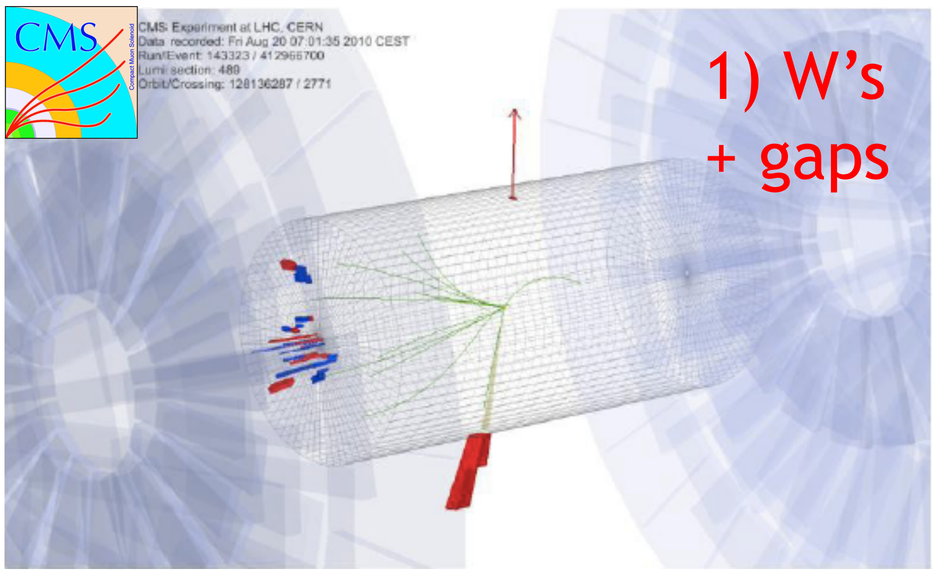
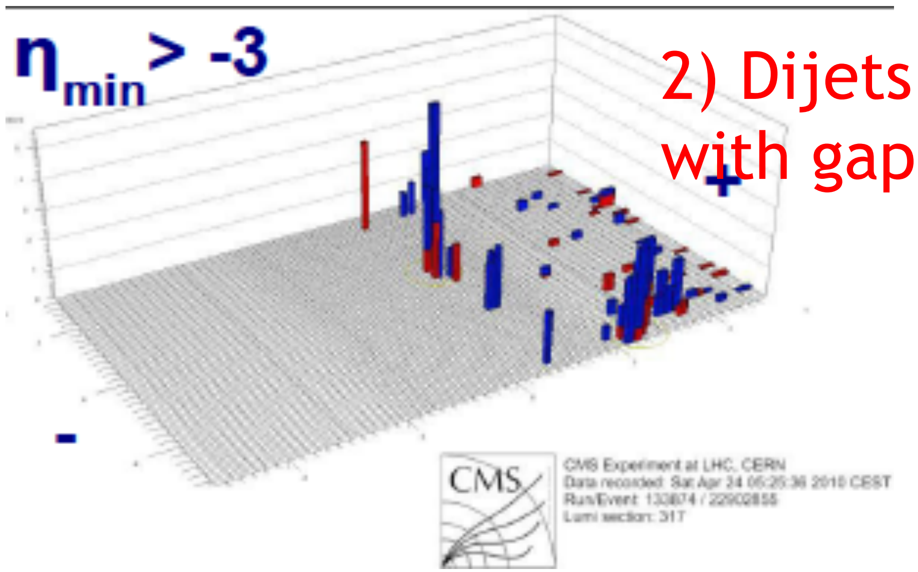




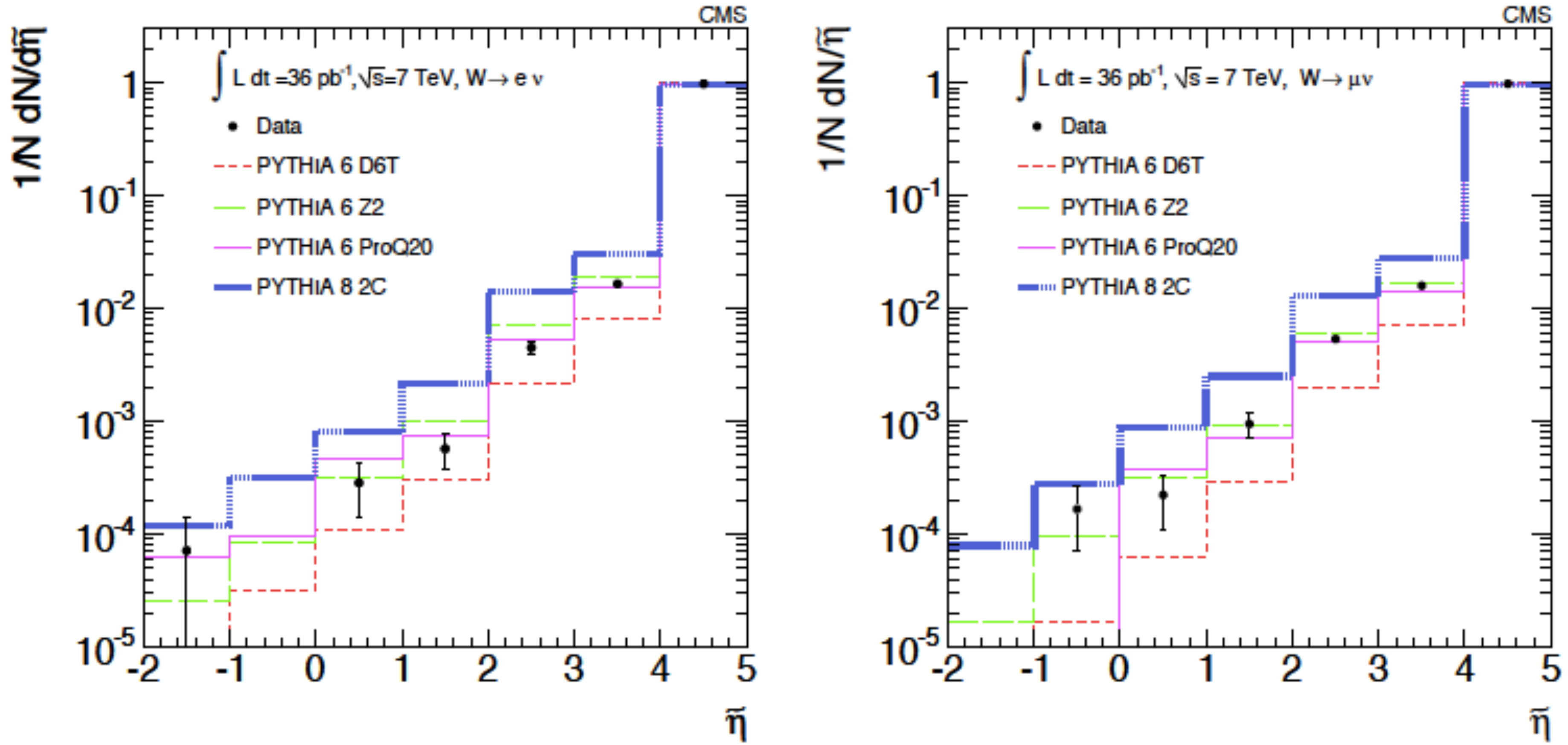
CMS: First Hard diffraction data from LHC …





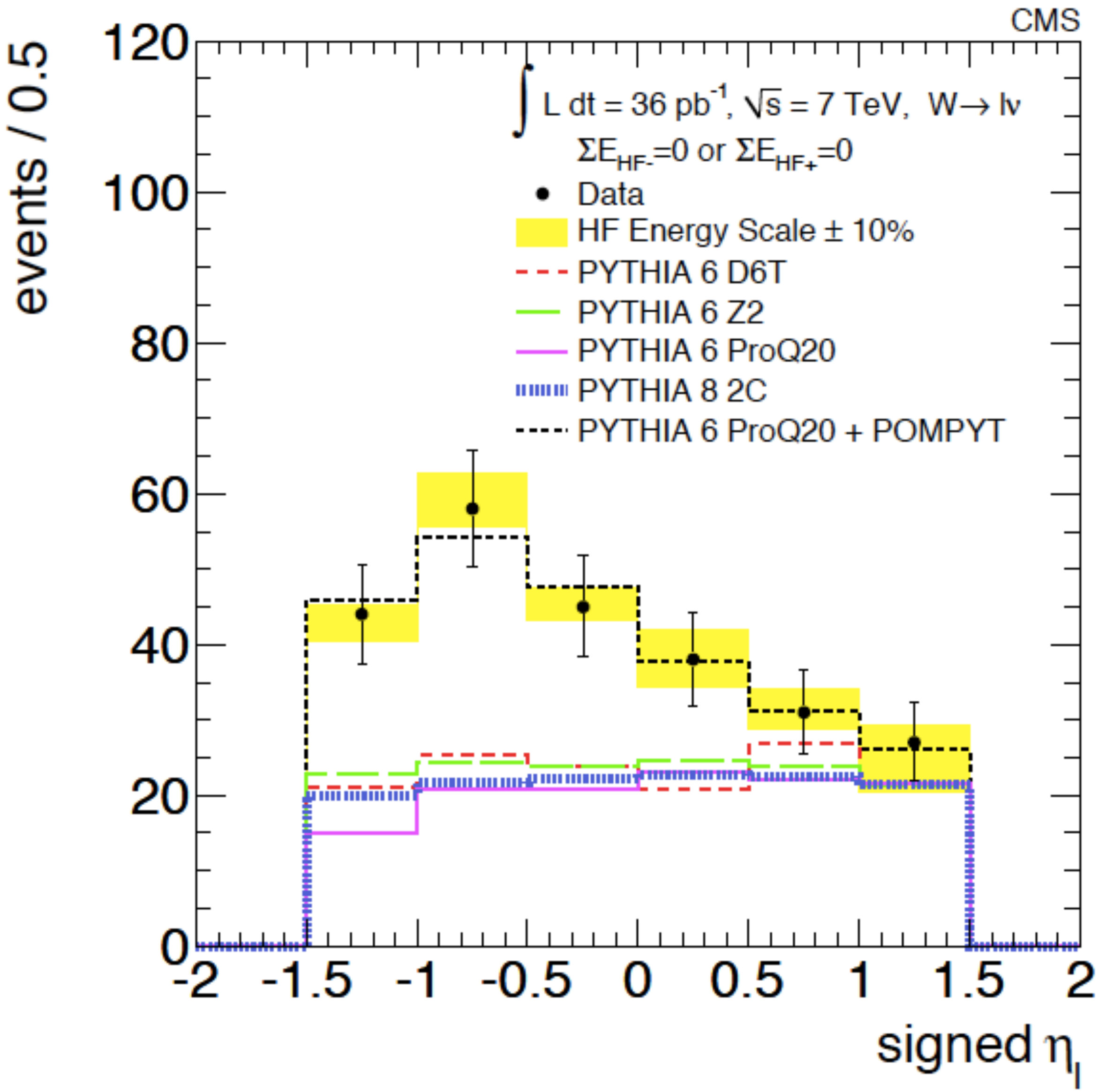
W and Z events with gaps at CMS

After pile-up corrections, ~1% of W and Z events exhibit no activity above noise thresholds over range $3 < \pm\eta < 4.9$ … interpretation complicated by non-diffractive hadronisation fluctuations …



$\tilde{\eta}$ (= 4.9 – Δη) end-point of gap - starting at acceptance limit

Gap-Lepton η Correlation for W bosons

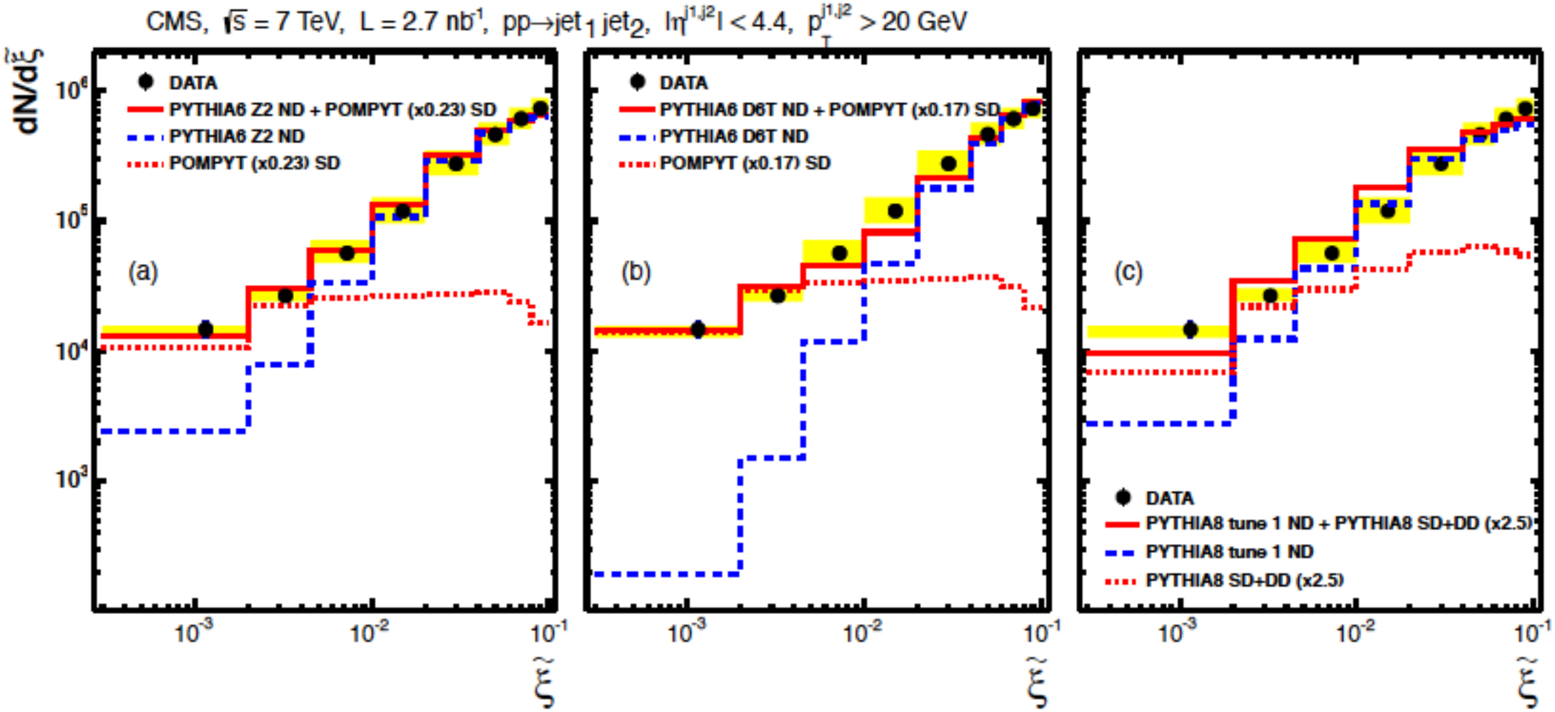


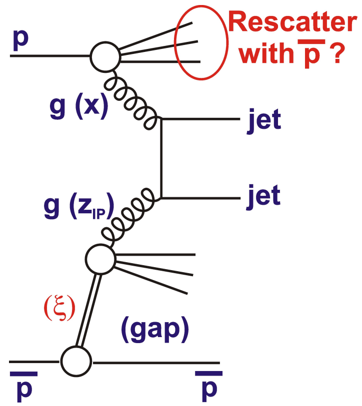
Lepton pseudorapidity with + sign if lepton in same hemisphere as gap, else – sign.

Fit to combination of PYTHIA and POMPYT hard diffraction model suggests significant (~50%) diffractive contribution

Surprisingly large?… Interpretation in terms of cross section or gap survival pending …

CMS Dijets with Low ξ





Uncorrected data prior to rapidity gap selection

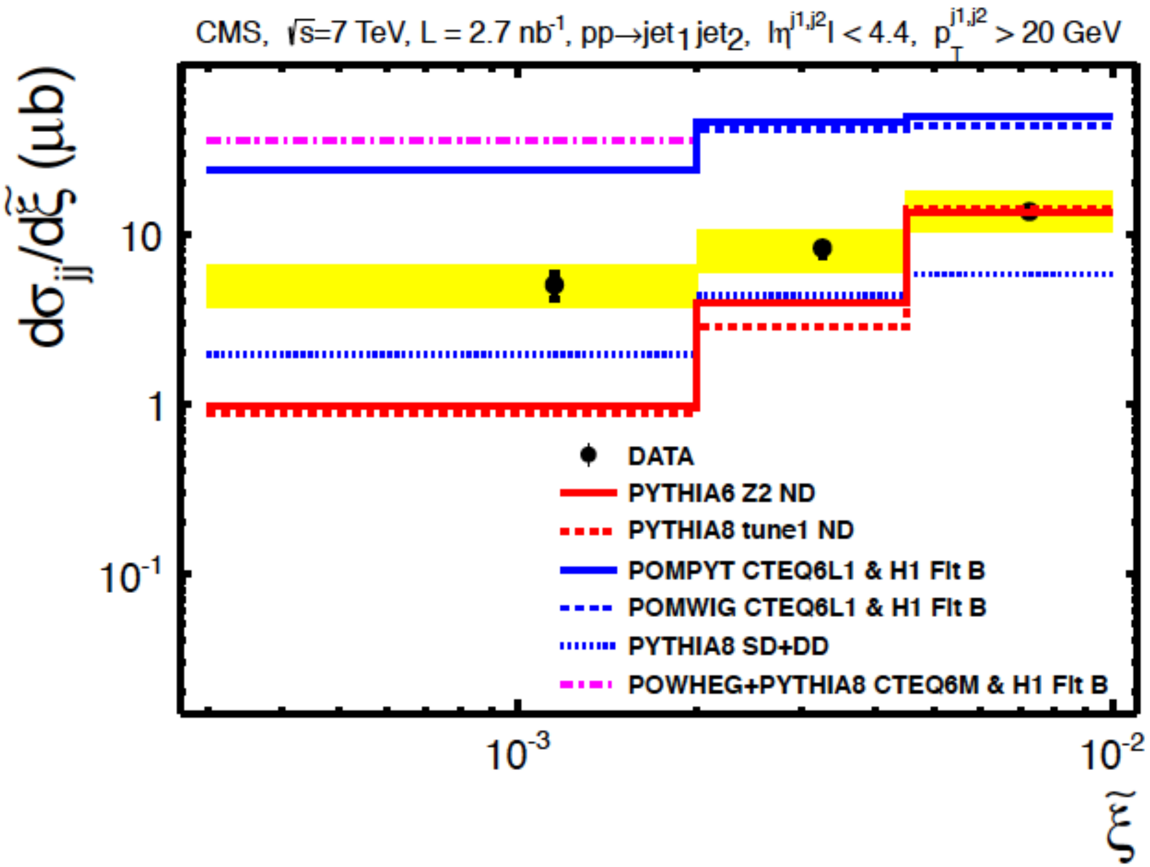
-Diffractive signal required at low ξ (Data > PYTHIA ND)

-Fit linear combination of PYTHIA (ND) and POMPYT / PYTHIA8-SD+DD (DPDF-based diffractive models)

→ Best description from PYTHIA6 with POMPYT x 0.23

→ PYTHIA8, SD/DD contribution has to be multiplied by a factor ~2.5 and still gives inferior description

Corrected Differential Cross Section



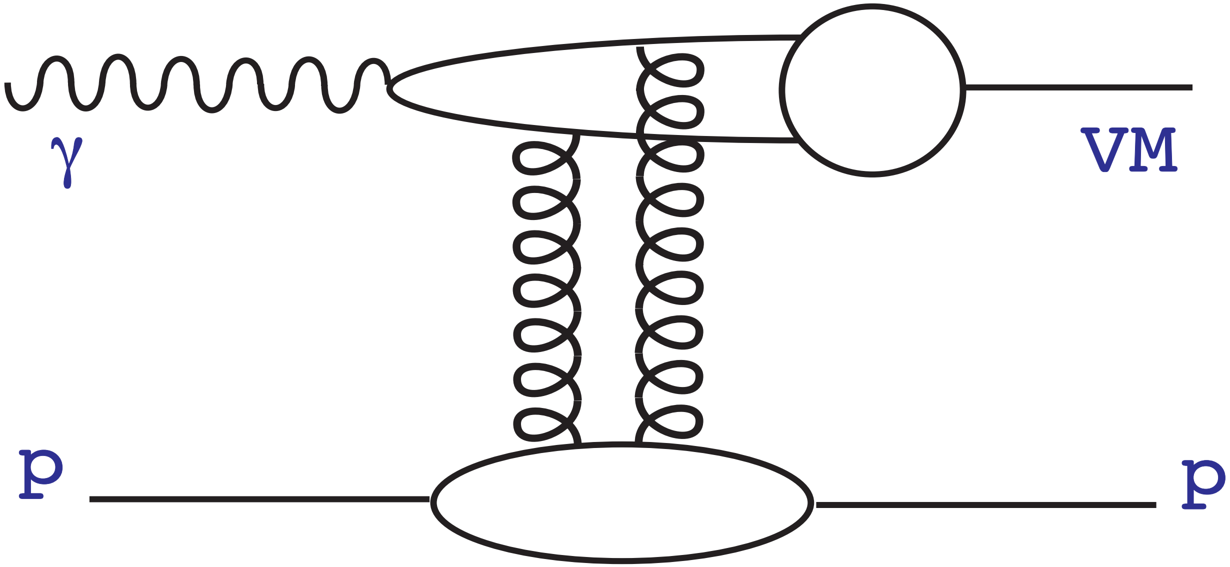
- Comparison of 1st bin v diffractive DPDF models

→ Gap survival probability estimate 0.08 ± 0.04 (based on NLO POWHEG)
… comparable to Tevatron, but different x range
… larger than expected?

Proton tagged data required for substantial further progress

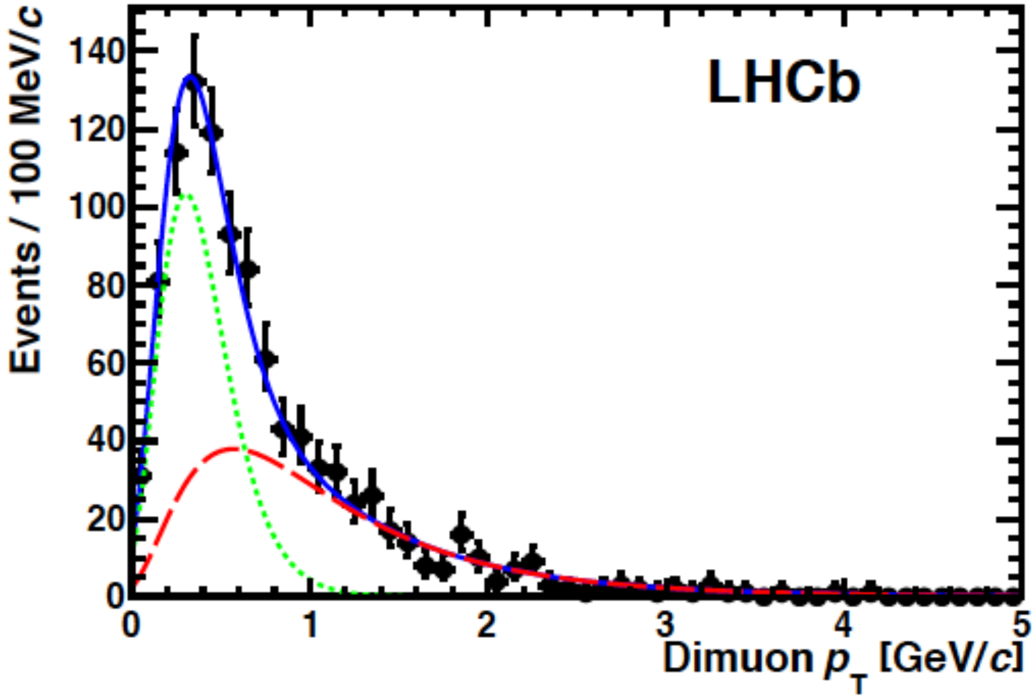
→ removing complications from double dissociation and non-diffractive events with large gap fluctuations

Ultraperipheral J/Ψ Photoproduction, the Low x Gluon Density and Saturation



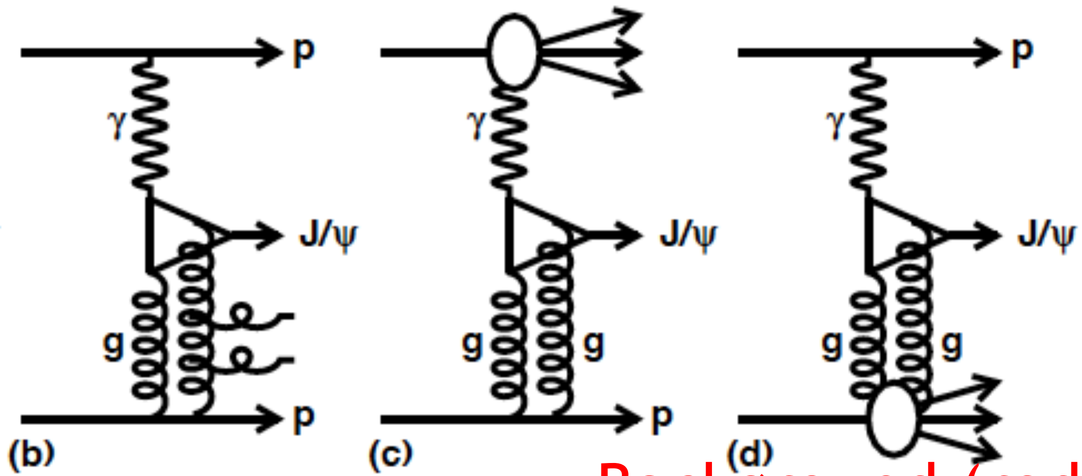
- LHC protons as a source of photons: VM photoproduction …
- Experimentally very simple
- Fairly well understood theoretically
- Sensitivity to square of gluon density at lowest order
- $x \sim M_{\Psi}^2 / W^2$ can be small → saturation / non-linear regime
- Can vary impact parameter (target blackness) with t

Exclusive J/Ψ Production in pp at LHCb

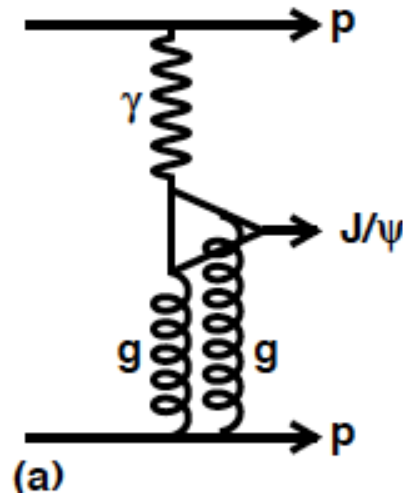


Coherent signal extracted by fitting t distribution (10% uncertainty claimed … needs further study?)

Signal (green)

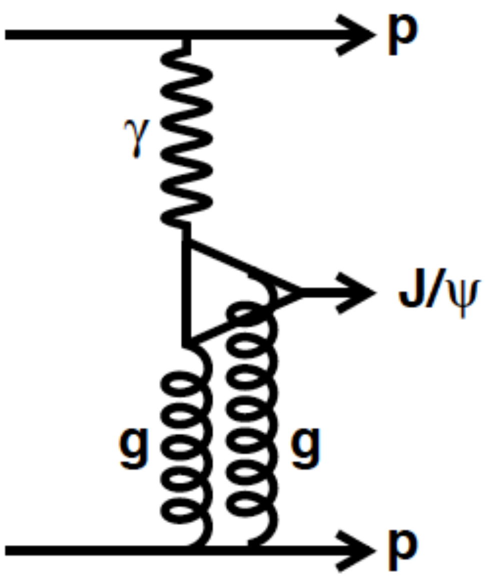


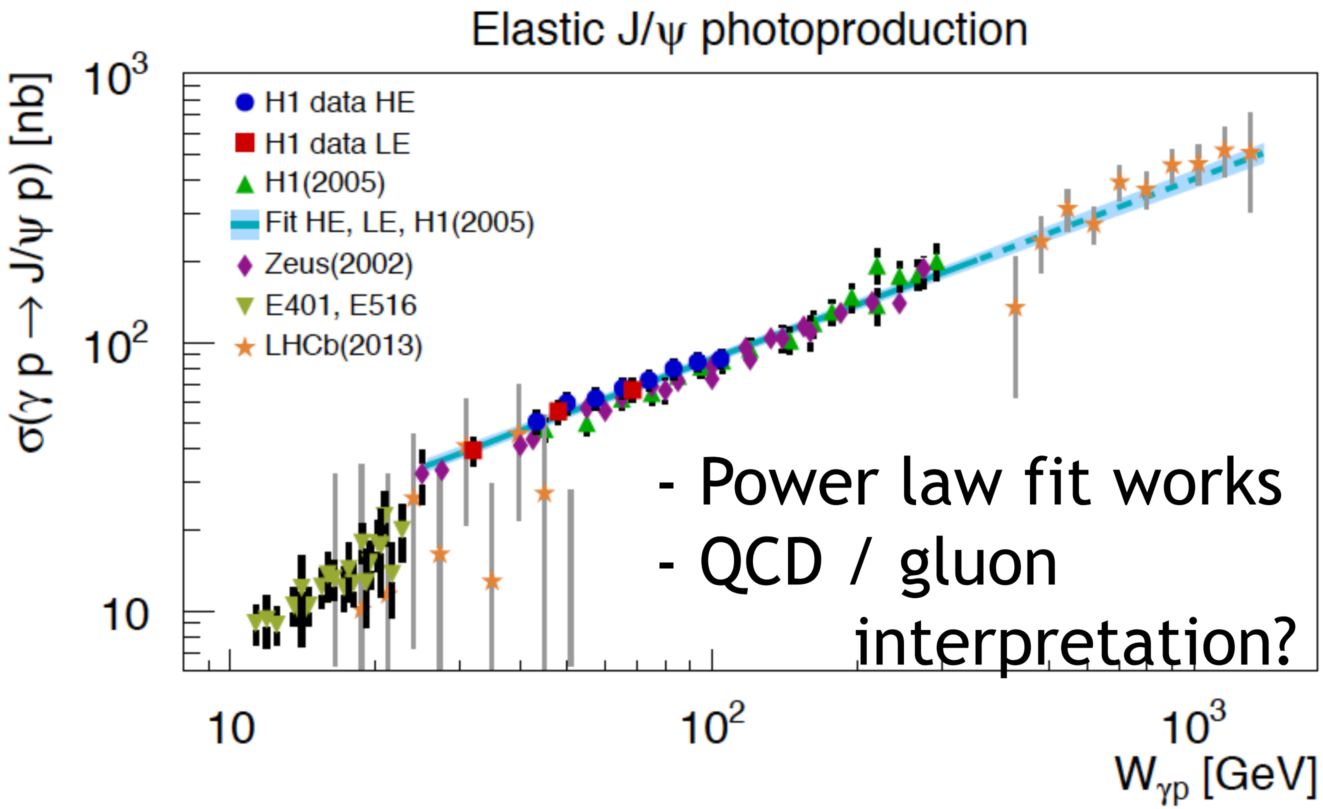
Background (red)



Ultra-peripheral Production at the LHC

Ambiguity on whether forward J/Y is produced by high energy photon and low energy gluons or vice versa
… dealt with on a statistical basis
Very interesting kinematic range, and more data to follow (hopefully including t depdences)





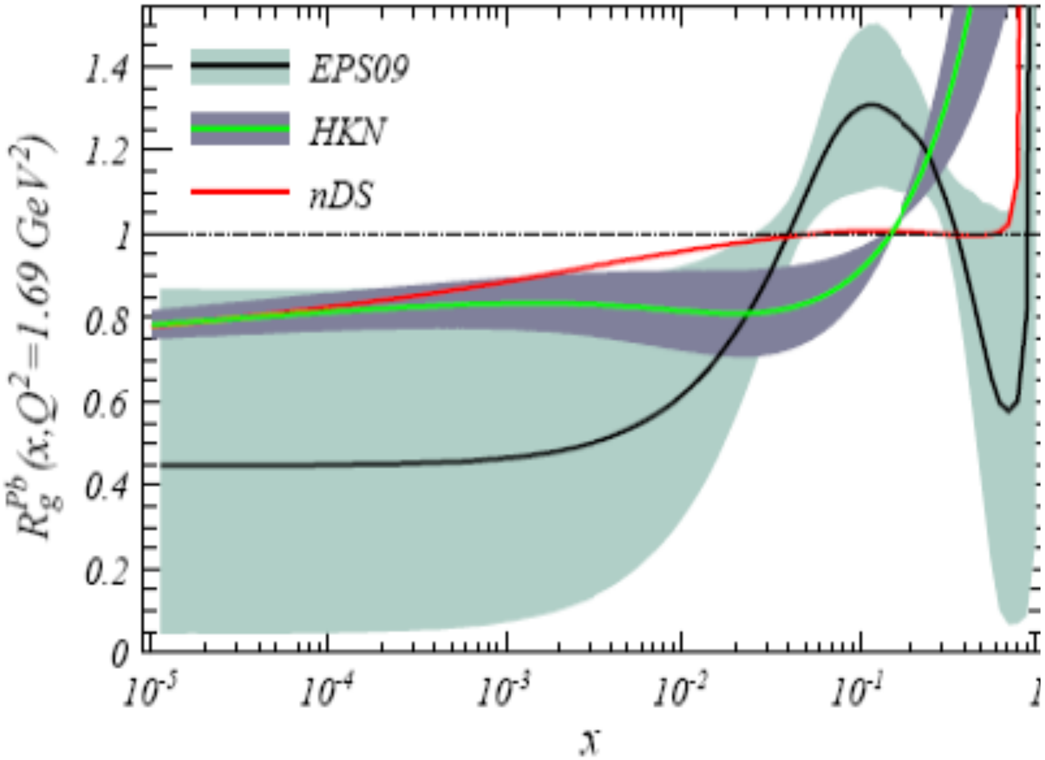
- Power law fit works
- QCD / gluon interpretation?

arXiv:1301.7084

… and in AA or pA:

Huge uncertainties in
Nuclear gluon density,
especially at low x …

Nuclear gluon shadowing factor vs x



e.g. arXiv:0909.1254

The J/ψ Way to Nuclear Structure

A. Caldwell [1], and H. Kowalski [2]

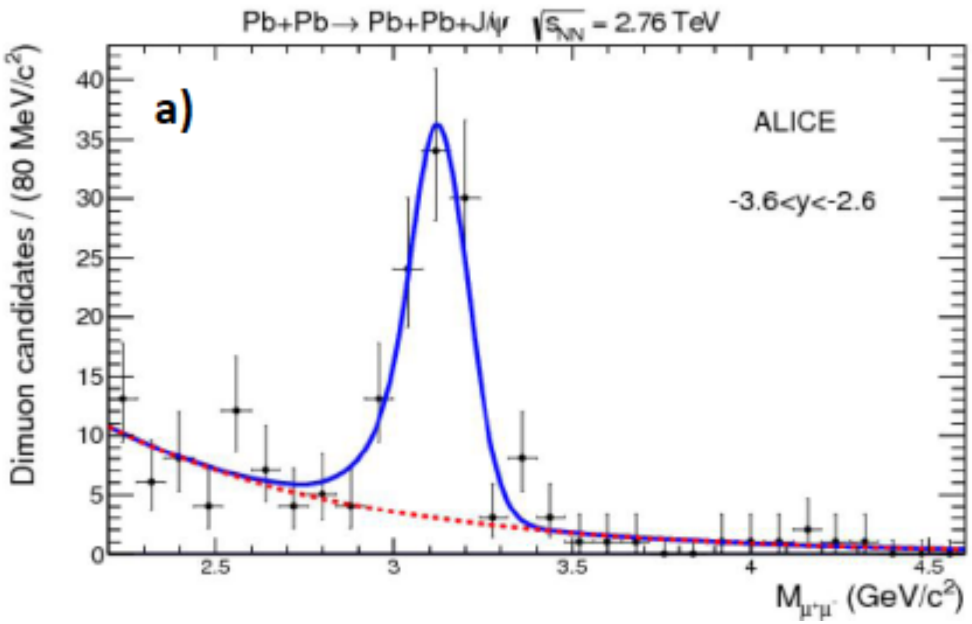
[1] *Max Planck Institute for Physics, München*

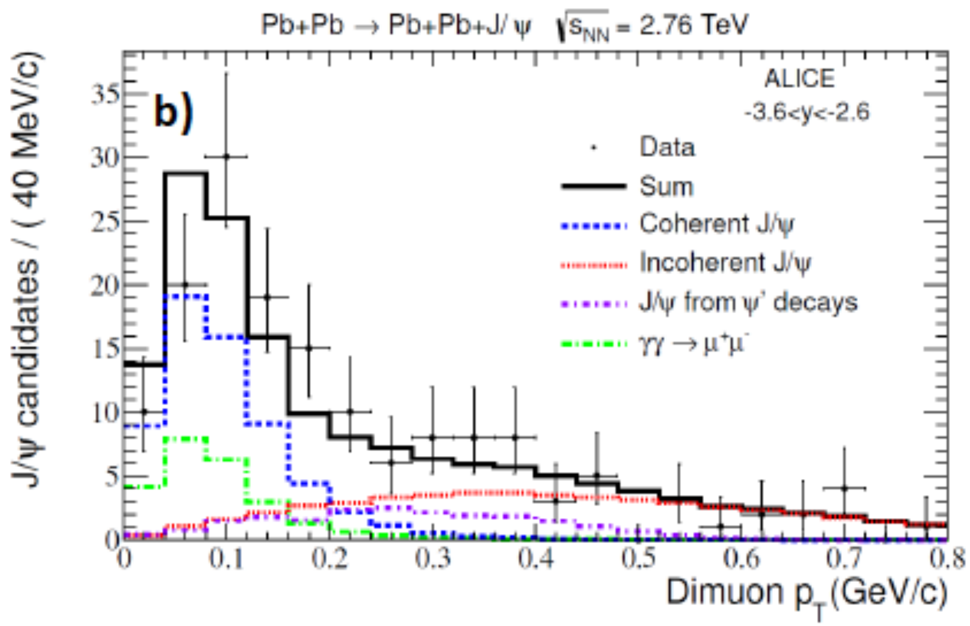
[2] *Deutsches Elektronen-Synchrotron DESY, D-22607 Hamburg, Germany*

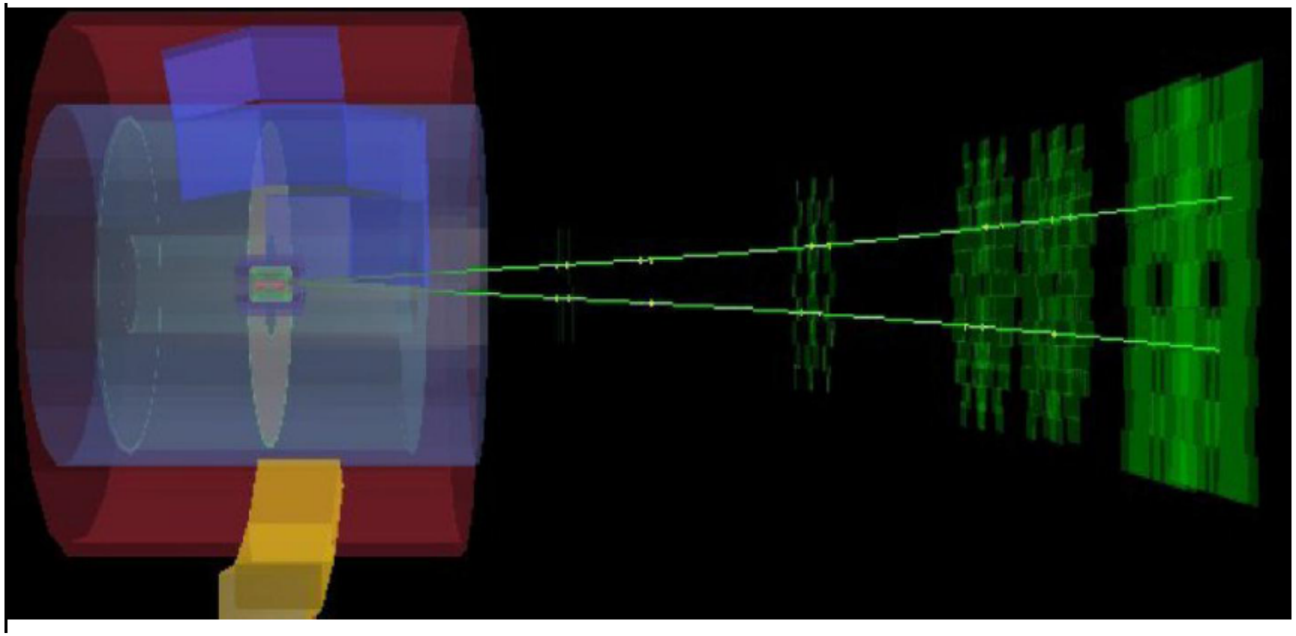
Abstract

We propose to investigate the properties of nuclear matter by measuring the elastic scattering of J/ψ on nuclei with high precision. The J/ψ mesons are produced from the photons emitted in high energy electron-proton or electron-nucleus scattering in the low-x region. The measurement could be performed at the future ENC, EIC or LHeC facilities.

Exclusive J/Ψ Production in AA at ALICE



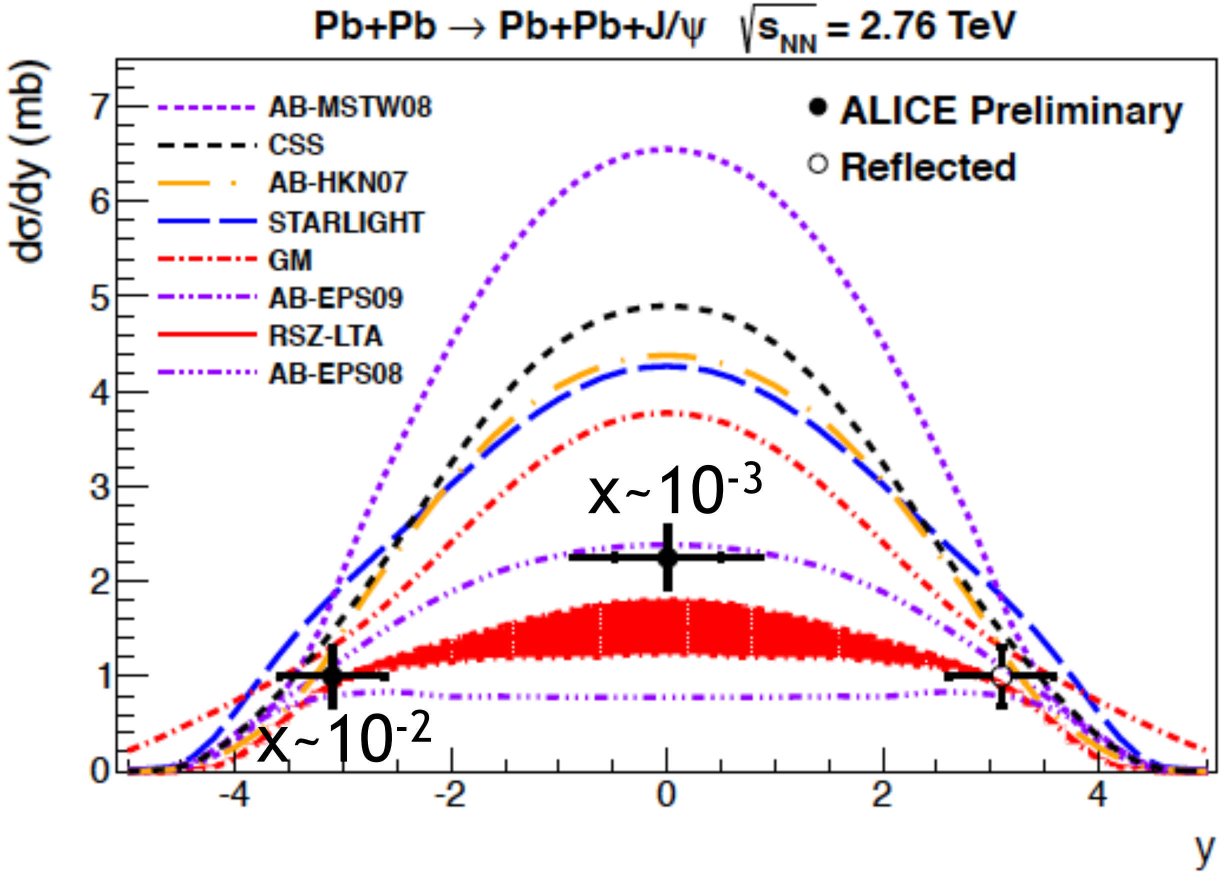


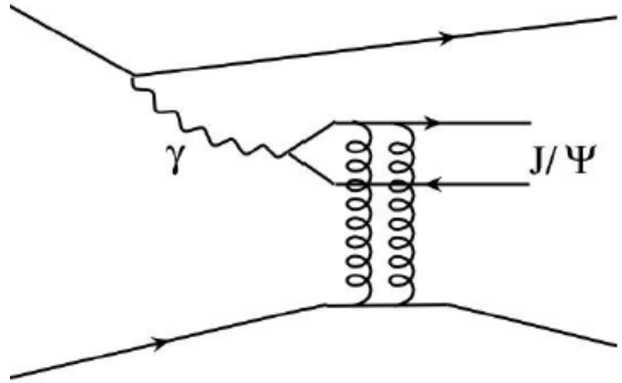


Separating out coherent part again a complicated issue

Phys Lett B718 (2013) 1273
ALI-PREL-43382

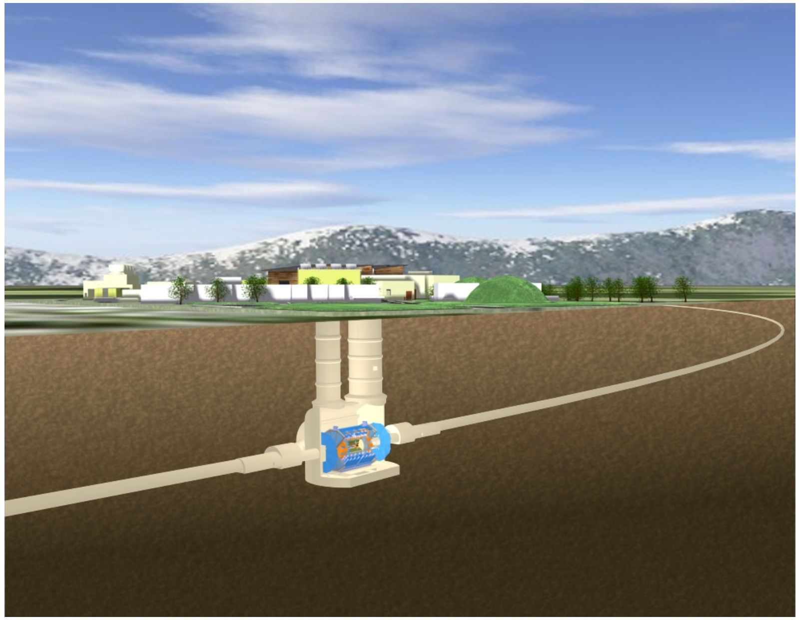
Exclusive J/Y Production in AA at ALICE





- Apparently good discrimination (best agreement with EPS09 shadowing model).
- x values surprisingly large (forward production heavily dominated by high x gluon and low energy photon).
- pA forward data expected to reach x ~ 10^{-5}

Summary



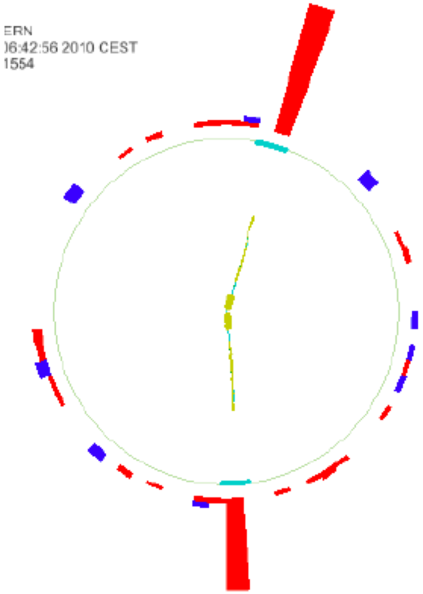
Precise elastic & total cross section data
- Broadly in line with expectations
- Pomeron slope α' non-universal

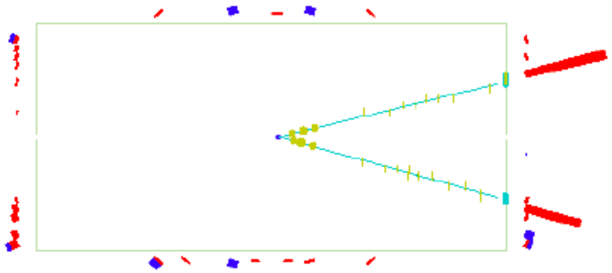
Increasingly Detailed Soft Diffractive Dissociation data
- Soft pomeron with intercept as expected works for soft dissociation
- Lowest M_X, M_Y not well understood
- `Global fits' needed to interpret

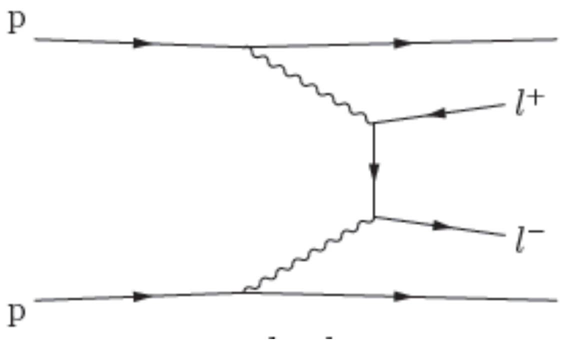
First Hard Diffractive Dissociation Data
- Limited by control over ND gap fluctuations and low M_Y DD
- Proton-tagged data required to understand rapidity gap survival

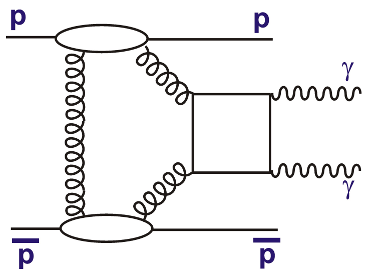
Impressive Ultra-peripheral J/Ψ Data
- New high W region maps well onto HERA
- Interpretation in terms of low x gluon density?

Quick word on Central (Excl) Production



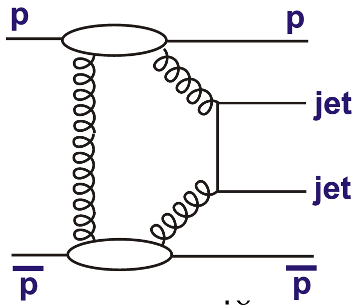






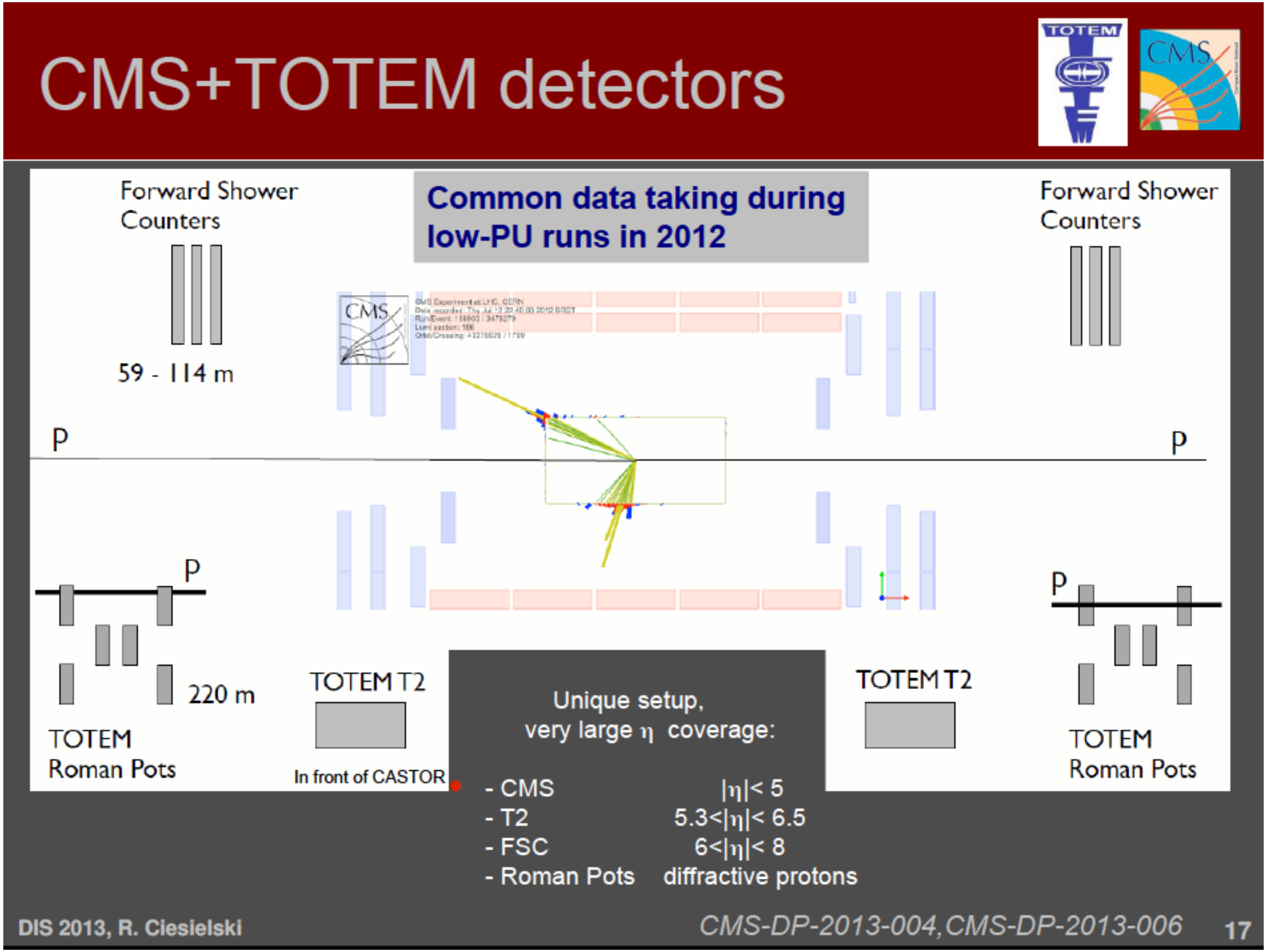
- First results from CMS on e^+e^- and $\mu^+\mu^-$ are consistent with QED prediction.

- No signal for $\gamma\gamma$, jet-jet or other strongly produced central systems so far

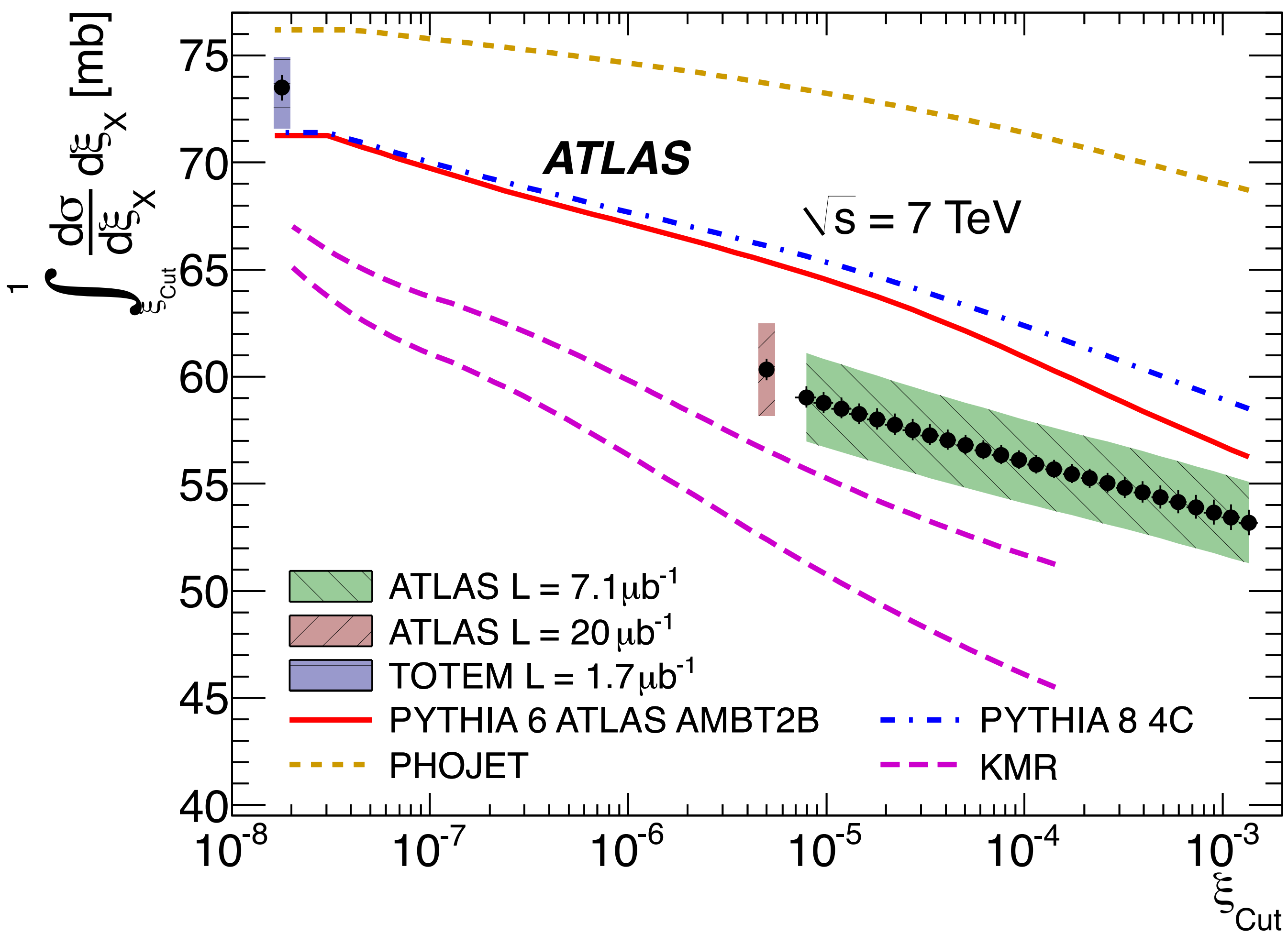


… but watch this space …

Double tagged events with central dijets



Investigating Low Mass Extrapolations

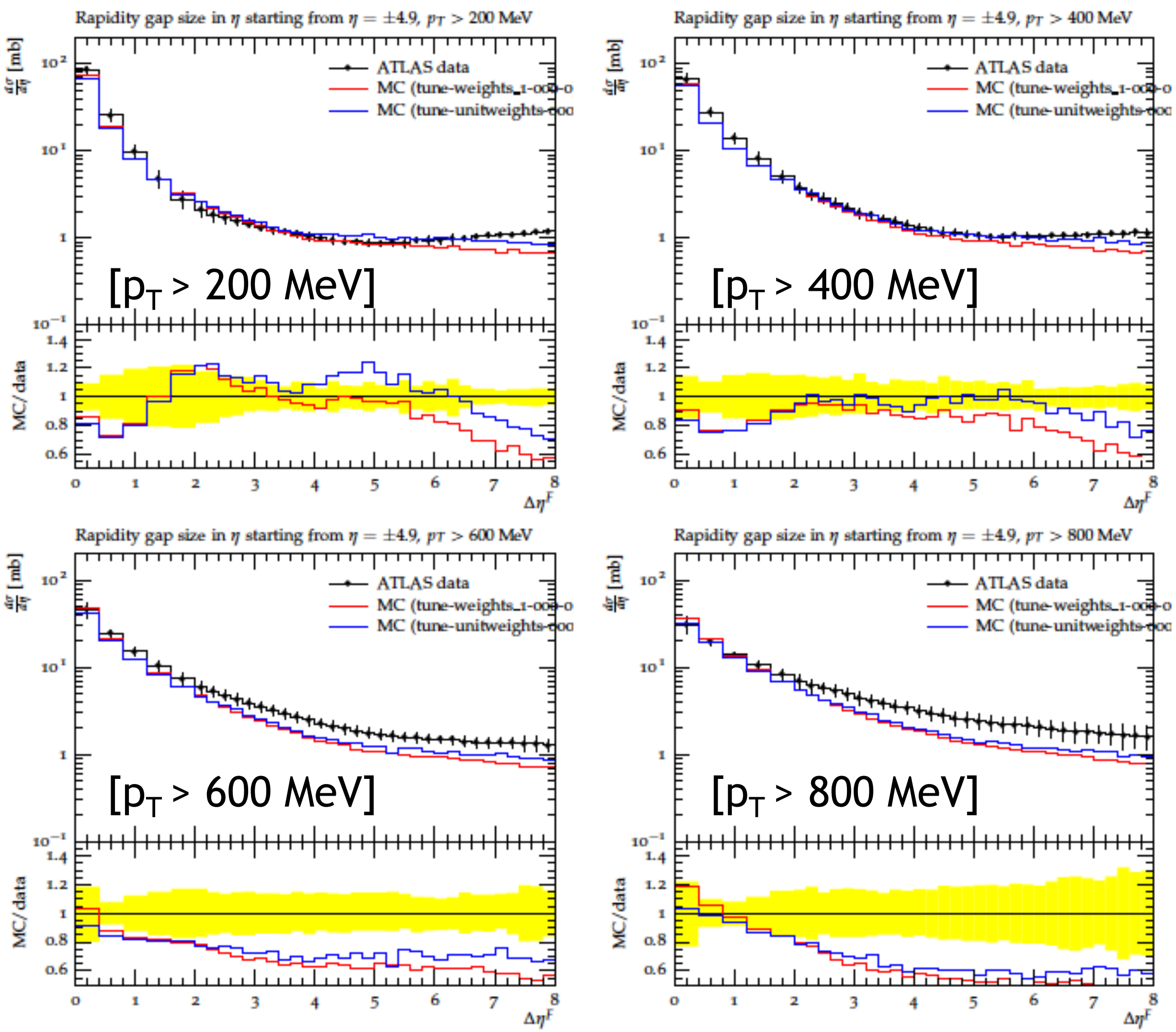


[Inelastic cross section excluding diffractive channels with $\xi < \xi_{cut}$]

- Integrating ATLAS gap cross section up to some max $\Delta\eta^F$ (equivalently min ξ_X) and comparing with TOTEM indicates that small ξ_X region underestimated in PHOJET and PYTHIA:
- 14 mb with $\xi < 10^{-5}$, compared to 6 (3) mb in PYTHIA (PHOJET)

SHRiMPS (MB in SHERPA) Preliminary

Rapidity Gap Cross Section @7 TeV

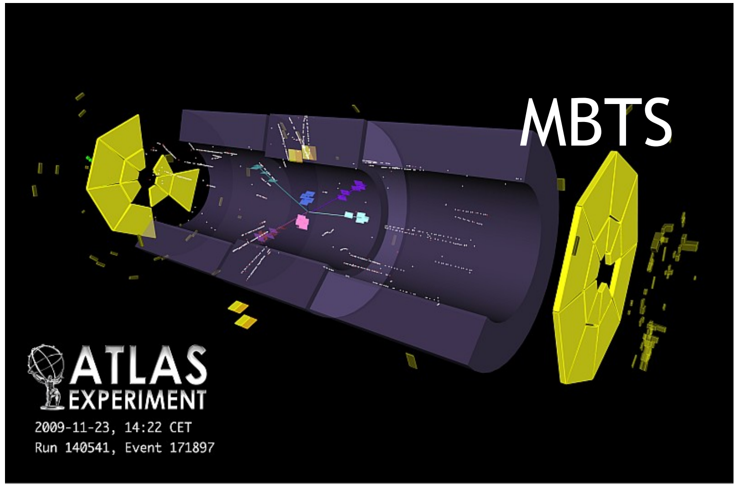


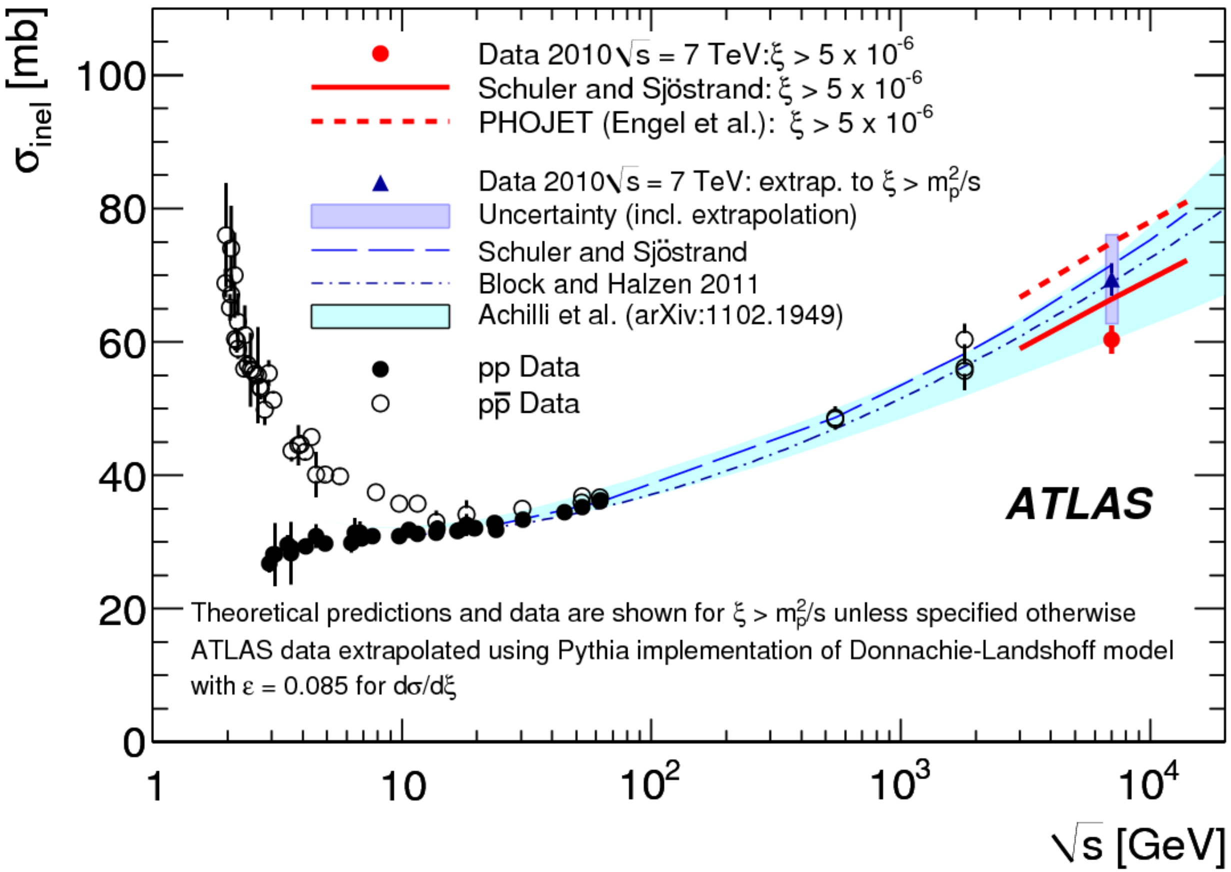
These distributions are complementary to particle spectra / correlations and dedicated underlying event measurements and should be described by any model that aims to provide a `complete' minimum bias description

Impressive (but still not perfect) description …

Total Inelastic pp Cross Section (e.g. ATLAS)

- Using MBTS trigger (2.1 < |η| < 3.8), miss only elastic (pp → pp) and lowest mass diffraction (pp → pX etc)





- Unextrapolated result below PYTHIA and PHOJET defaults
- 5-15% extrapolation yields total inelastic cross section
- Extrapolation includes large uncertainty on low mass dissociation