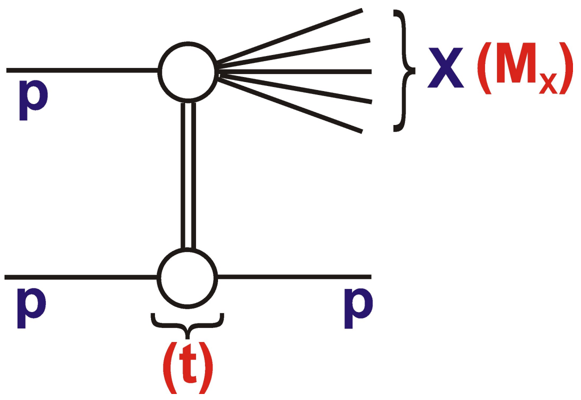
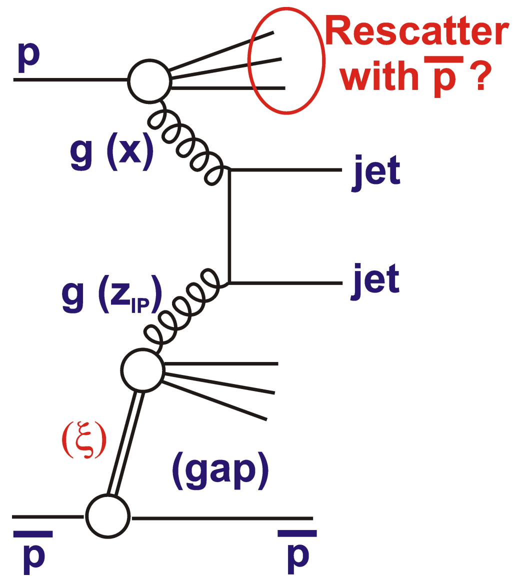
Diffractive Processes and the LHC

Paul Newman (University of Birmingham)



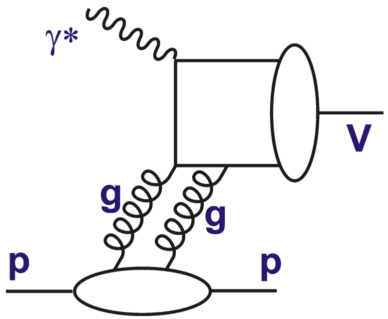
MPI@LHC, Tel Aviv
16 October 2012



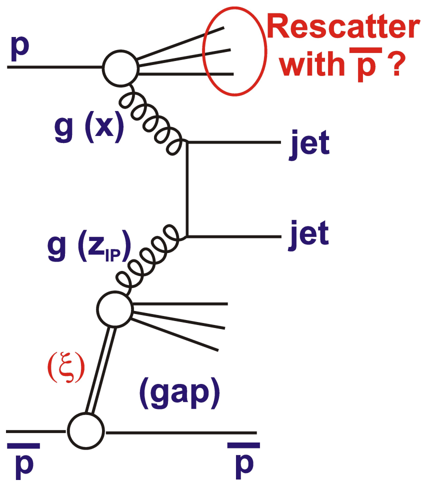
→ Diffraction and Multi-Parton Interactions
→ Elastic, Total and Dissociative LHC Cross Sections
→ Large Rapidity Gaps and hadronisation fluctuations
→ First LHC measurements of Hard Scattering in Single Dissoc^n
→ Central Production

Diffraction & Multi-Parton Interactions

- Trivially, more than 1 parton in t channel

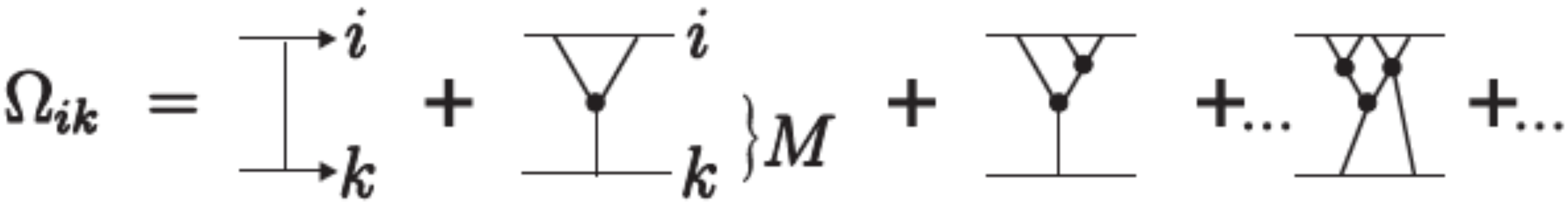


- Gap survival probabilities / absorption
Must be due to multiple interactions
… but with large impact parameters



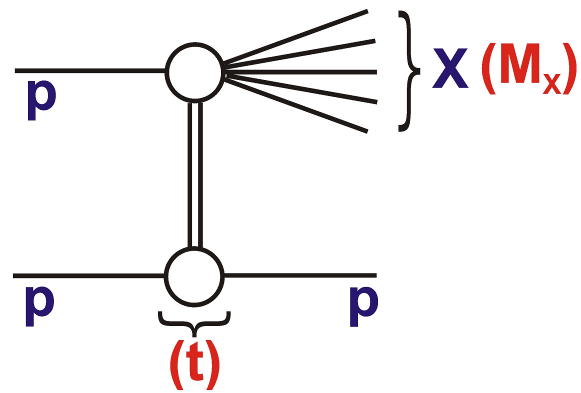
- Absorptive effects due to multiple soft exchanges in minimum bias models

- Less obviously, small (but non-zero) rapidity gaps as a complementary probe of underlying event modelling

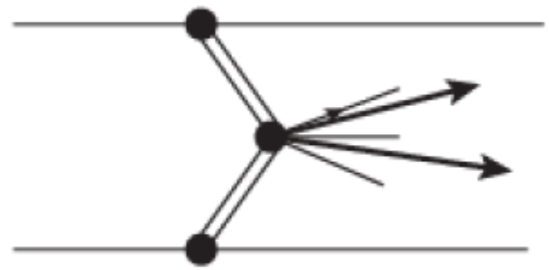


What I won't talk about ...

MPI studies (e.g. transverse region to jets ...) within diffractively produced systems in single dissociation / central production processes

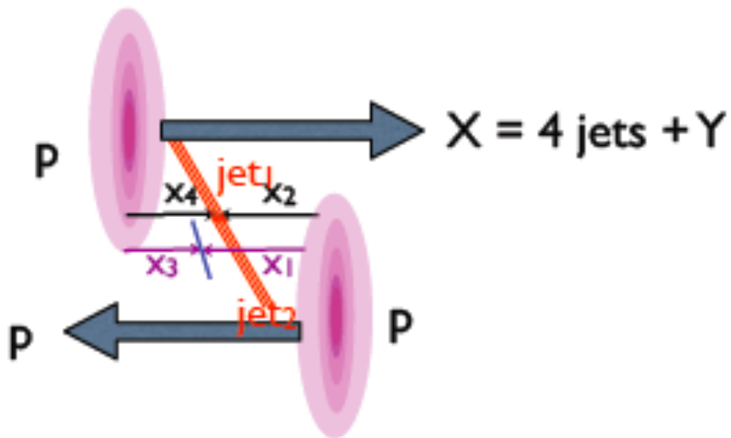


- Test our understanding of MPI with complementary (IP-p, IP-IP) initial states



- Test our understanding of diffractive production mechanism ...

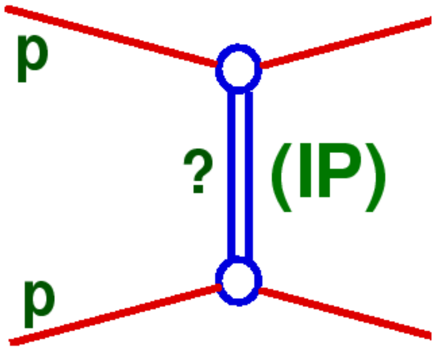
- Uncorrelated 2+2 jet production: If $x_1 + x_2 \sim \xi$, gaps close to gap, probe of hard diffractive exchange



- (Maybe?) build a link MPI → gap survival experimentally?

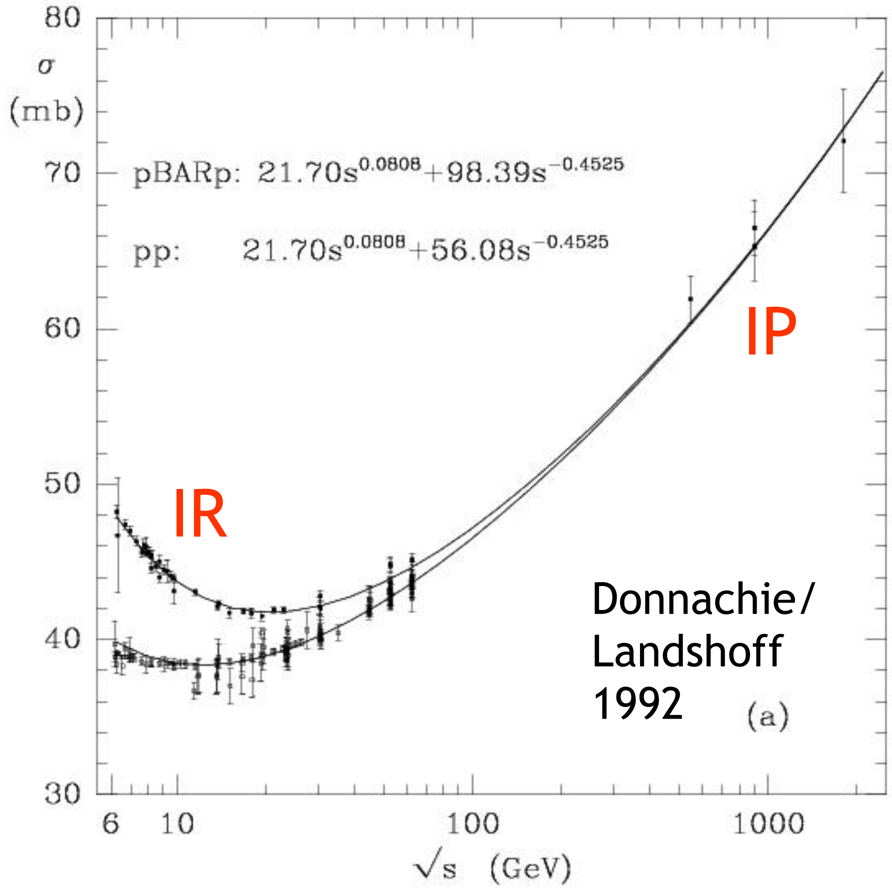
Diffraction, Vacuum Exchange and the Pomeron

What governs elastic scattering at high energies?



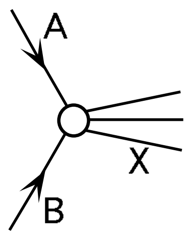
$$\frac{d\sigma_{EL}}{dt} \propto \left(\frac{s}{s_0}\right)^{2\alpha(t)-2} \qquad \sigma_{tot} \propto \left(\frac{s}{s_0}\right)^{\alpha(0)-1}$$

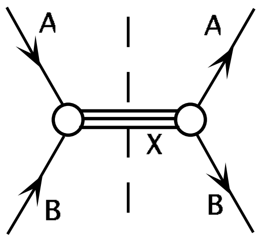
$$\alpha(t) = \alpha(0) + \alpha' t \approx 1.085 + 0.25t$$

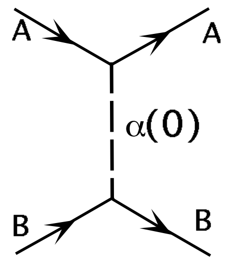


Closely related to total x-sec via optical theorem

$$\sigma_{tot} = \frac{1}{2s} \sum_X \Big| \quad \Big|^2 = \frac{1}{2s} \sum_X \quad \sim \frac{1}{s}$$

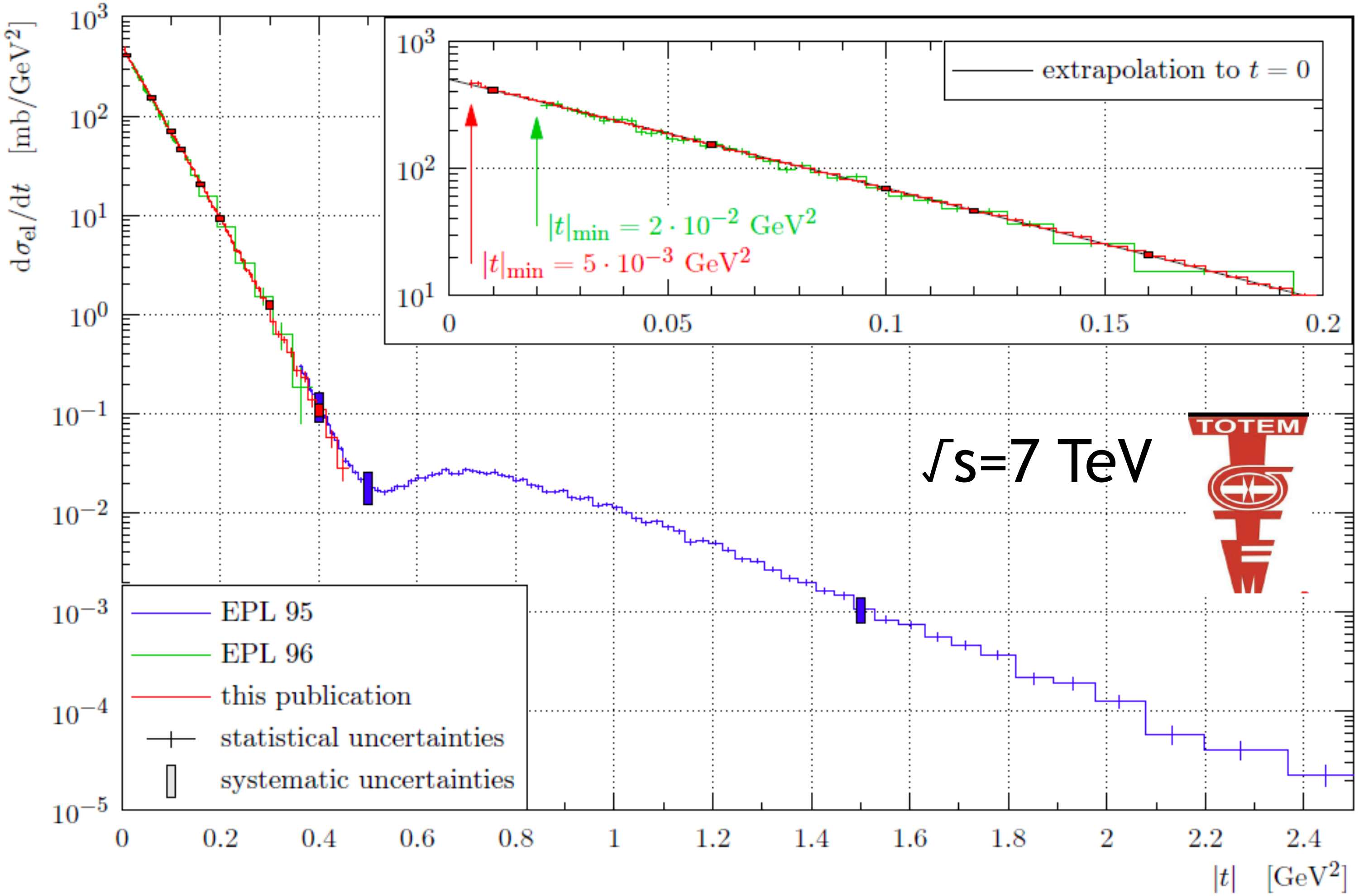






Elastic Cross Section (TOTEM Roman Pots)

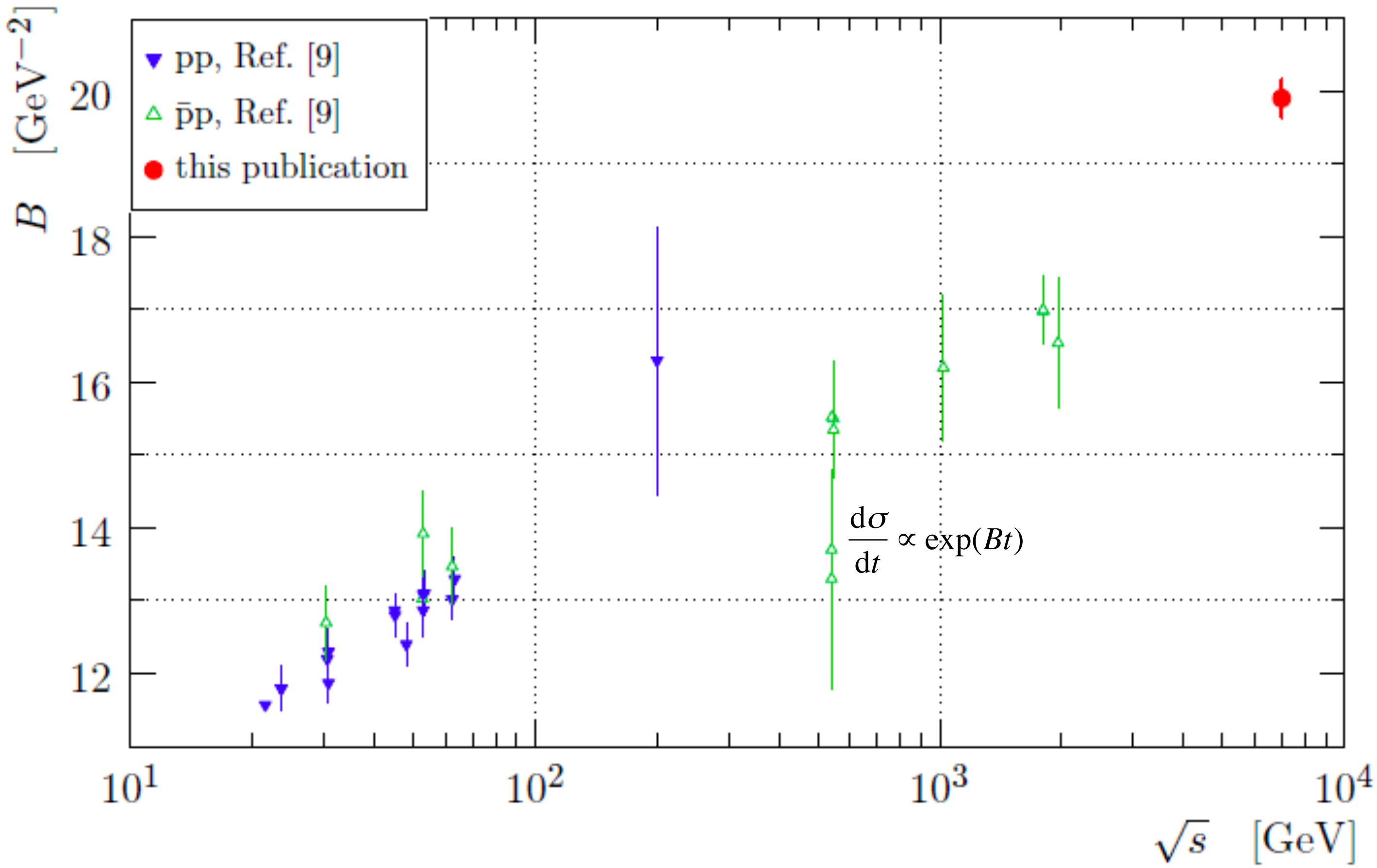
Precise t dependence of elastic (pp → pp) cross section over wide range of |t| at LHC



- Position of dip decreases from |t| ~ 0.6 GeV^2 (Tevatron) to 0.53 GeV^2 (TOTEM)

… proton transverse size increasing with √s

√s dependence of t Slopes and α’



Fixed s:

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

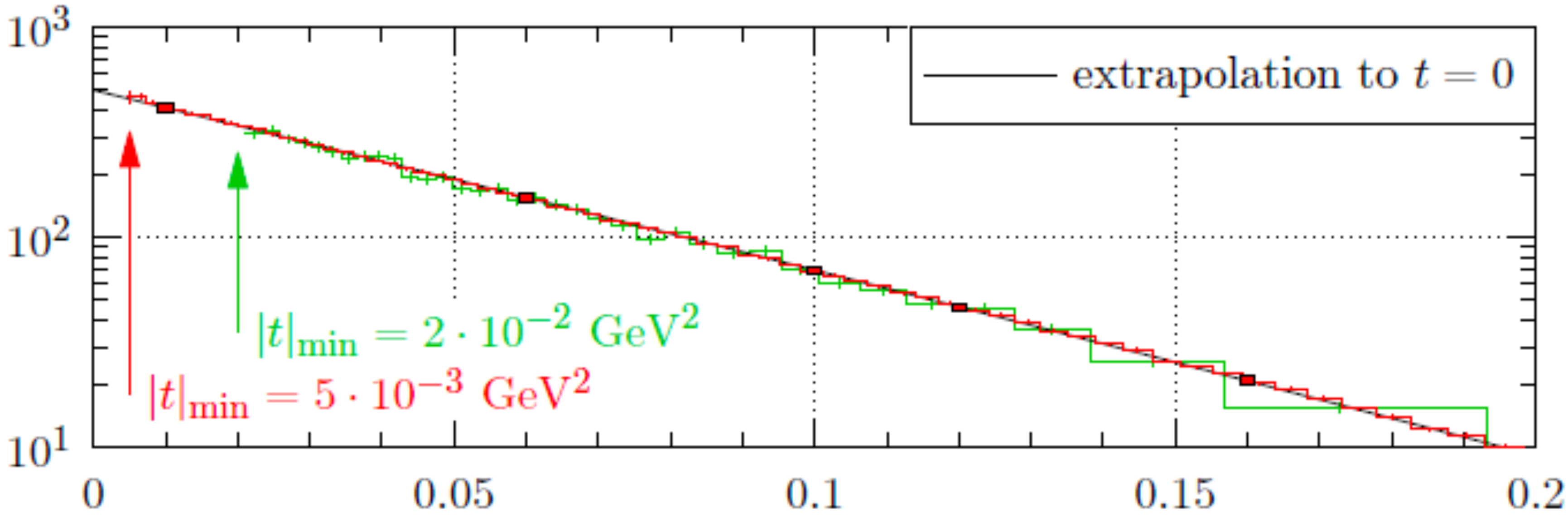
$$B = B_0 + 2\alpha' \ln\left(\frac{s}{s_0}\right)$$

- B = 16.7± 0.2 GeV^{-2} (D0) → 19.9±0.3 GeV^{-2} (TOTEM)

… suggests α’ significantly larger than 0.25 GeV^{-2}
… c.f. HERA measurements where α’ less than 0.25 GeV^{-2}

Optical Theorem: Relating elastic & total cross sections

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



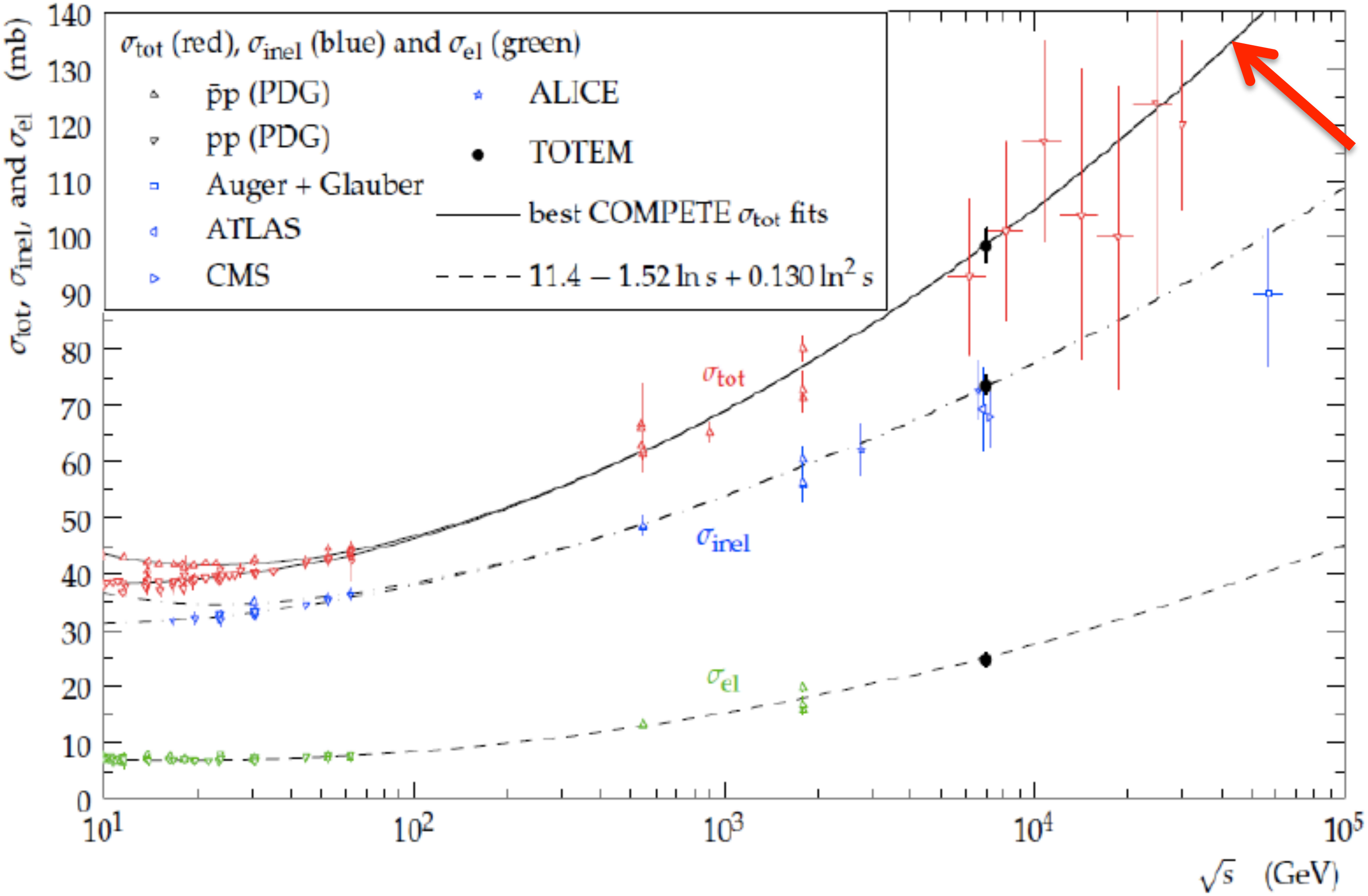
Dedicated run (special optics @ β* = 90m) → |t| ~ 0.005 GeV^2

- 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

$$\sigma_{el} = \left(24.8 \pm 0.2^{(stat)} \pm 1.2^{(syst)}\right) \mathrm{mb} \quad \sigma_T = \left(98.3 \pm 0.2^{(stat)} \pm 2.7^{(syst)} \left[{}^{+0.8}_{-0.2}\right]^{(syst\ from\ \rho)}\right) \mathrm{mb}$$

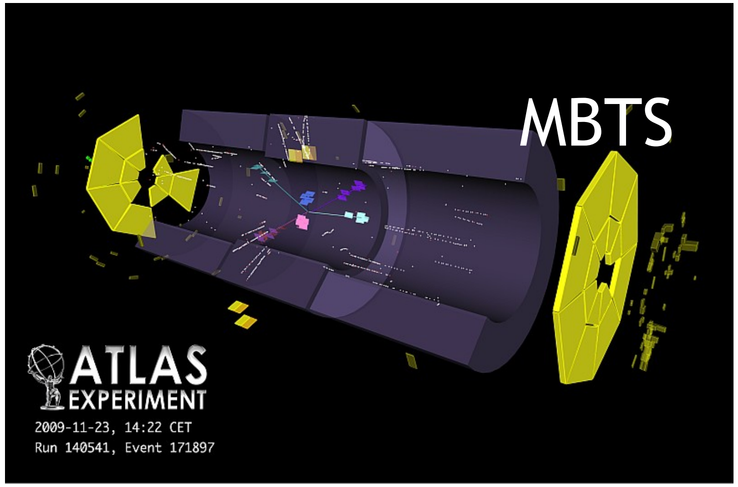


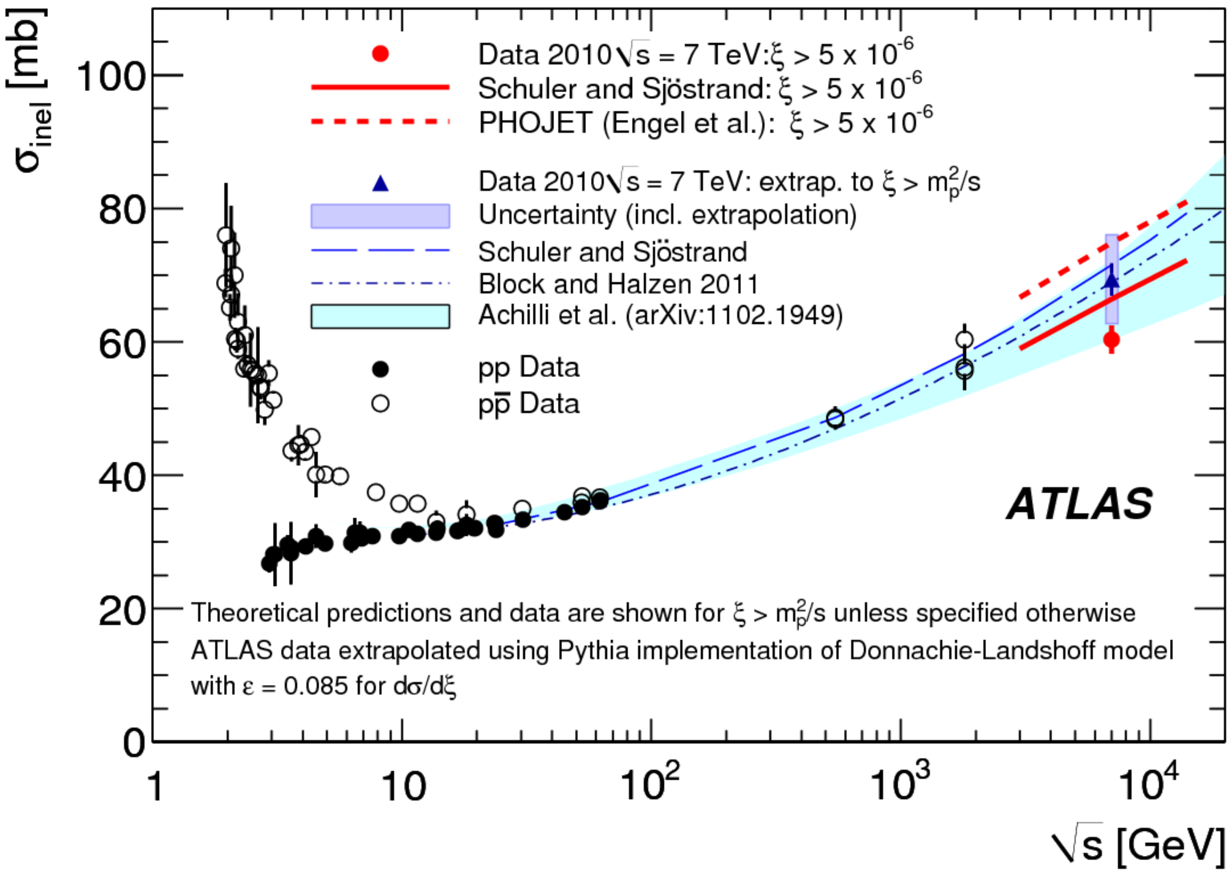
Consistent with fits to previous data (leading $\ln^2 s$ dependence, saturating Froissart unitarity bound)

Inferred total inelastic cross section consistent with ATLAS, CMS and ALICE min-bias measurements …

Total Inelastic pp Cross Section (ATLAS)

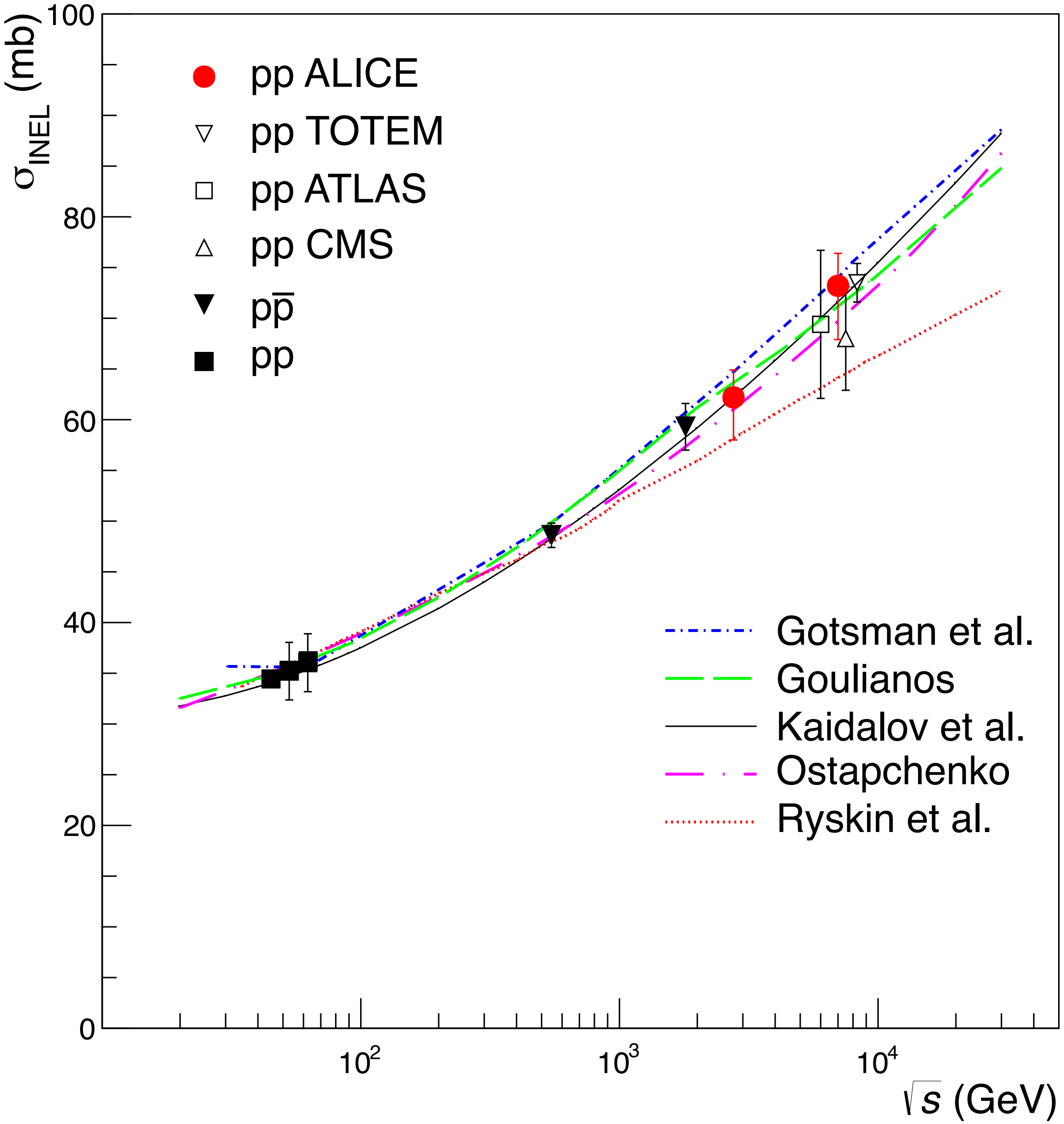
- Using MBTS trigger ($2.1 < |\eta| < 3.8$), miss only elastic ($pp \rightarrow pp$) and low mass diffraction ($pp \rightarrow pX$ etc)





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

Total Inelastic pp Cross Section (ALICE)



New result from ALICE [with corrected Tel Aviv curve hot off the press]

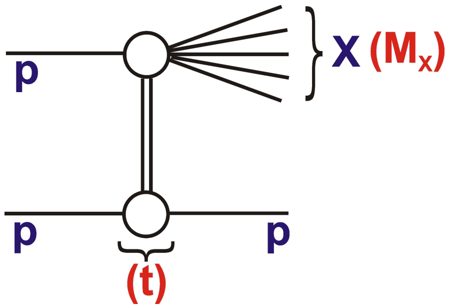
ALICE agrees well with Totem. Other direct measurements with low ξ extrapolations (ATLAS, CMS) have central values lieing somewhat lower.

… low mass diffraction has large uncertainties!

Independent results soon from ALFA @ ATLAS

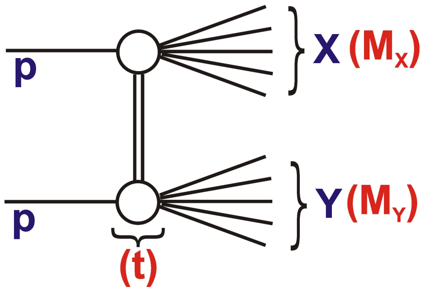
Inelastic Diffraction

Single dissociation (SD), pp → Xp

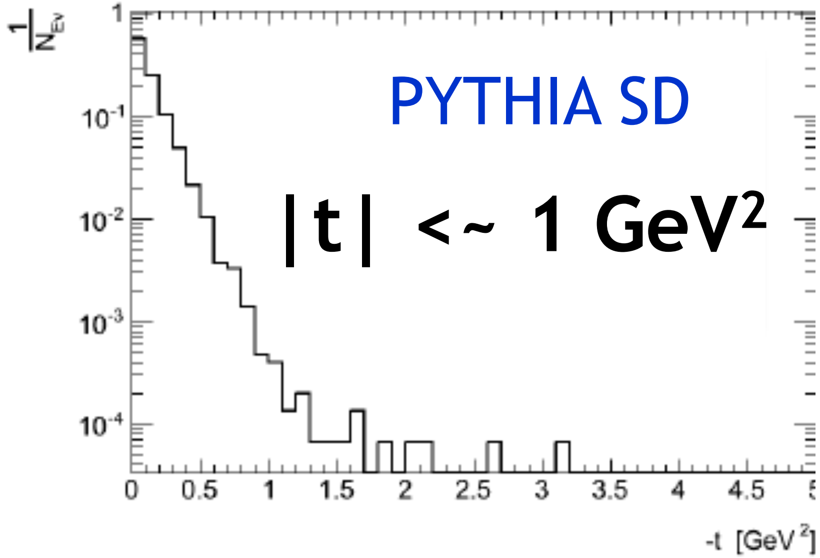


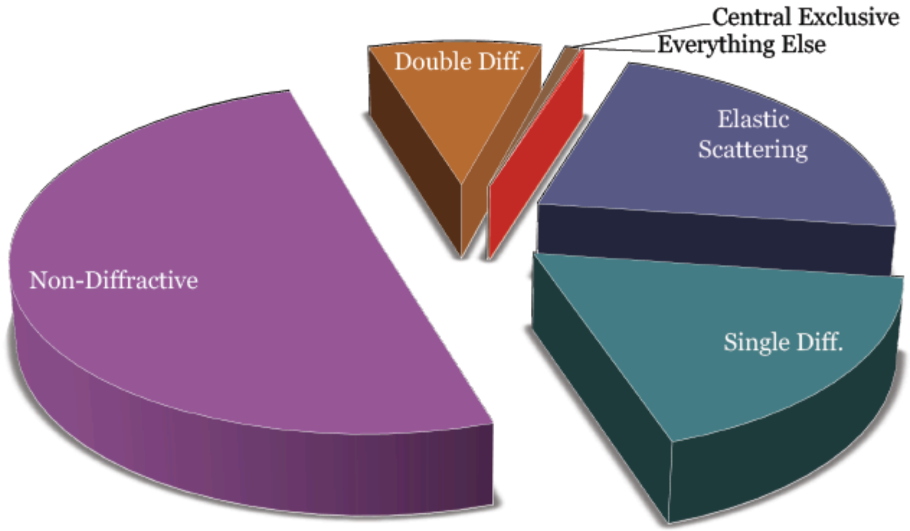
$$\xi = M_X^2/s$$

Double dissociation (DD), pp → XY



$$\xi_Y = M_Y^2/s$$





-At LHC energies, M_X, M_Y can range from $m_p + m_\pi$ → ~1 TeV

- Diffractive channels together account for ~ half of total LHC cross section

Uncertainties in pre-LHC Predictions

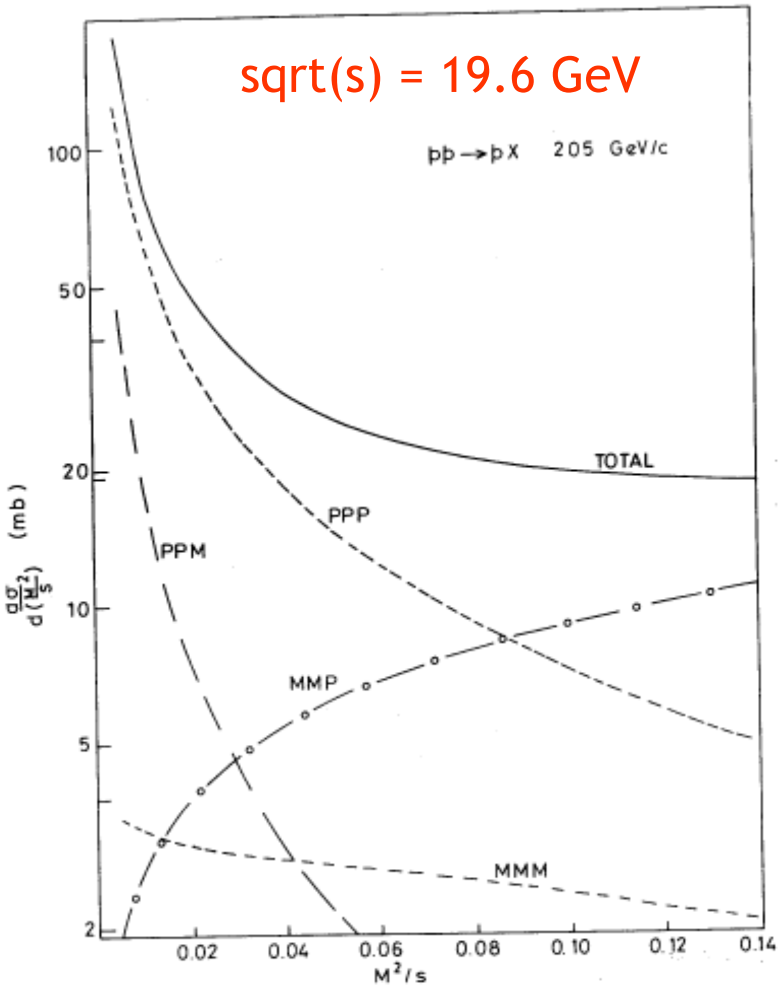
Single dissociation

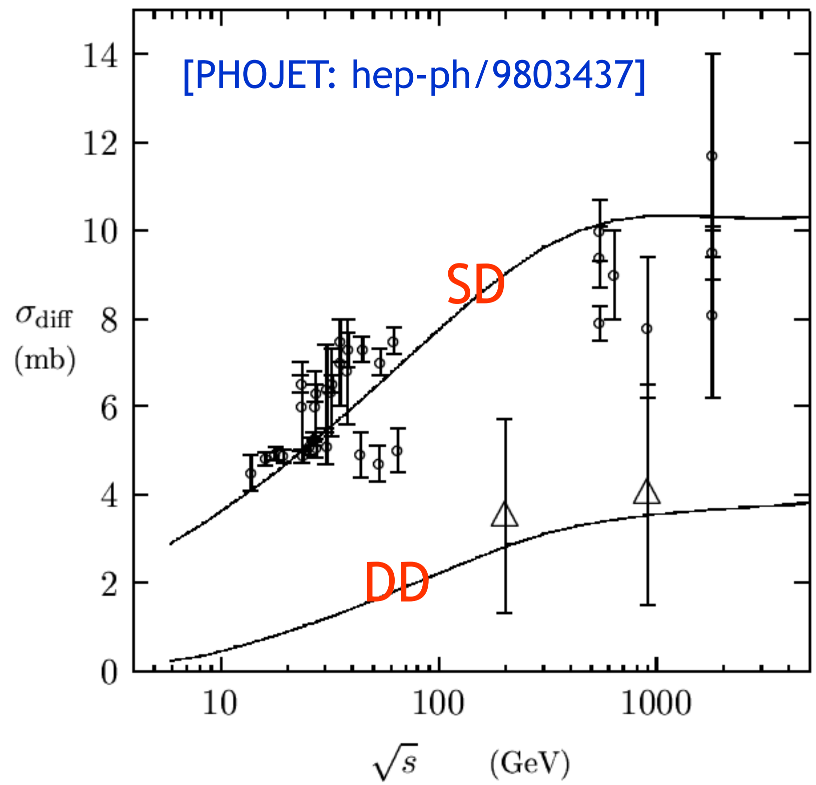
σ = 14mb (PYTHIA8)
σ = 10mb (PHOJET)

Double dissociation

σ = 9mb (PYTHIA8)
σ = 4mb (PHOJET)

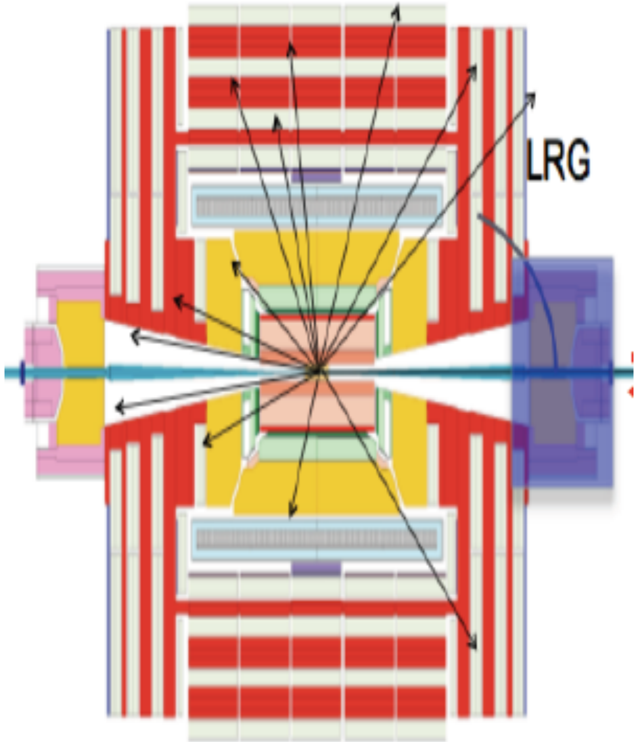
Parameterisations based on old low energy data, particularly poor for DD

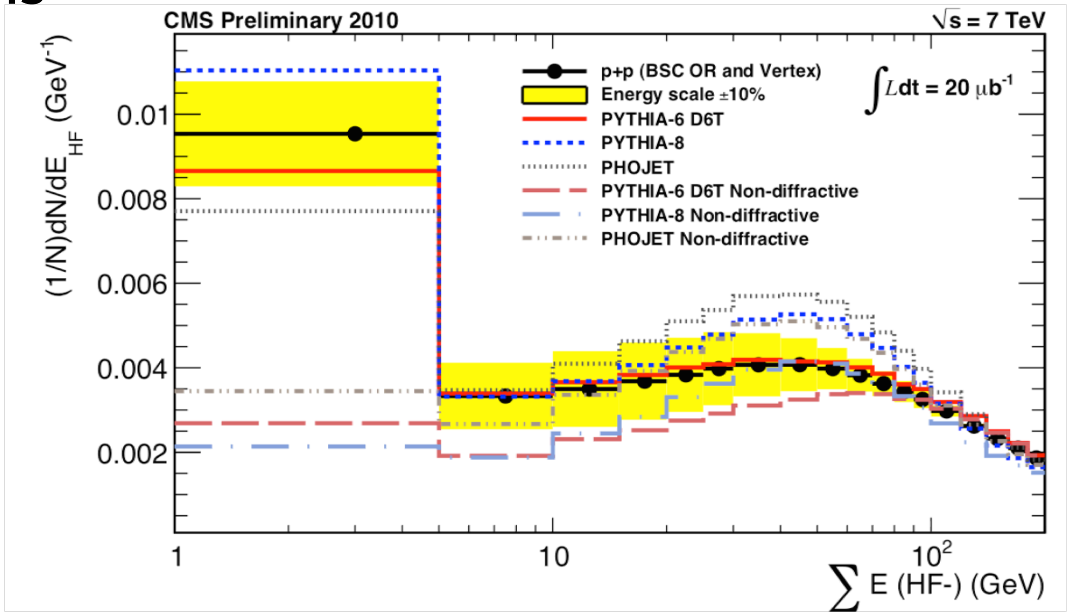


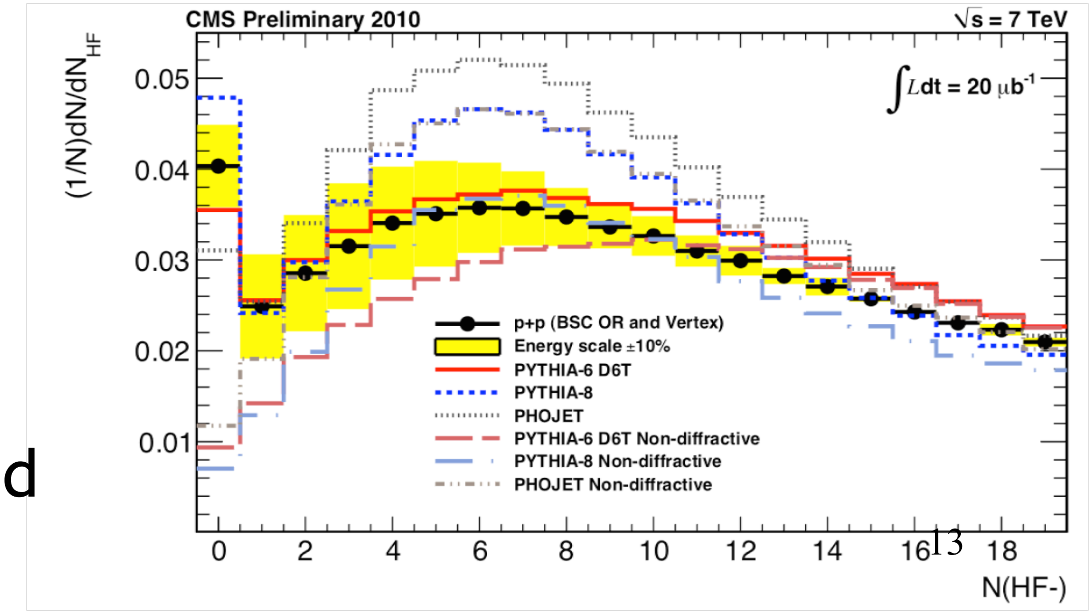


CMS: First Direct LHC Dissoc^{n} Observation

Inclusive min-bias distributions of forward HCAL activity ($2.9 < |\eta| < 5.2$)



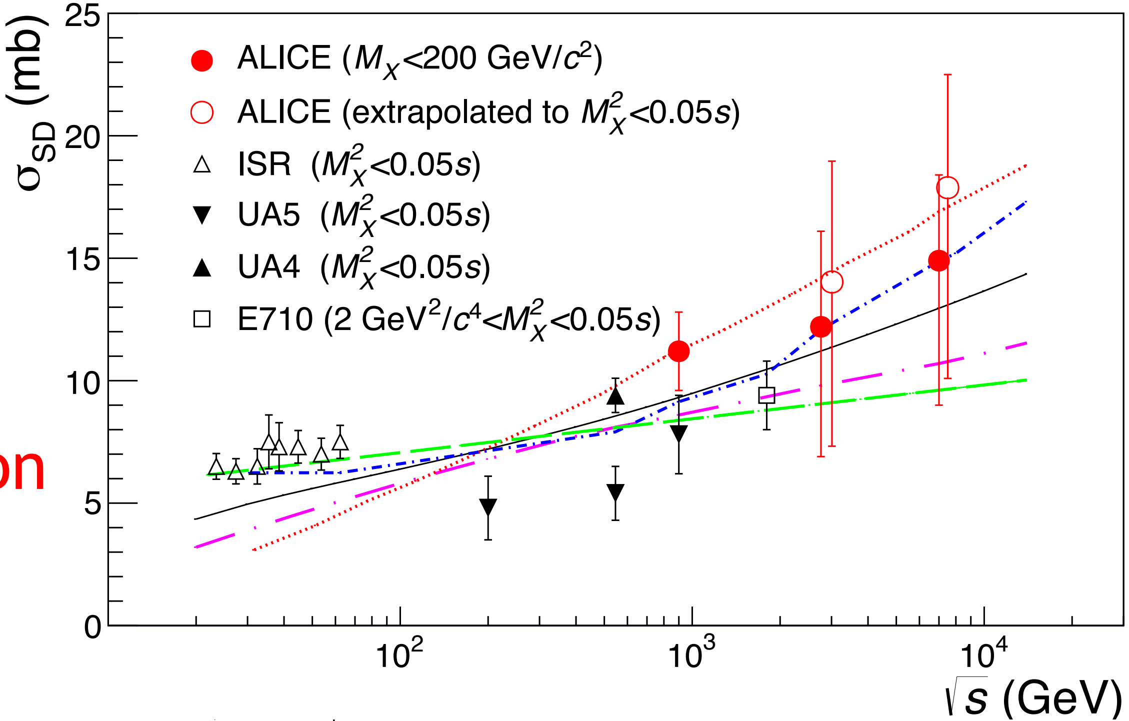


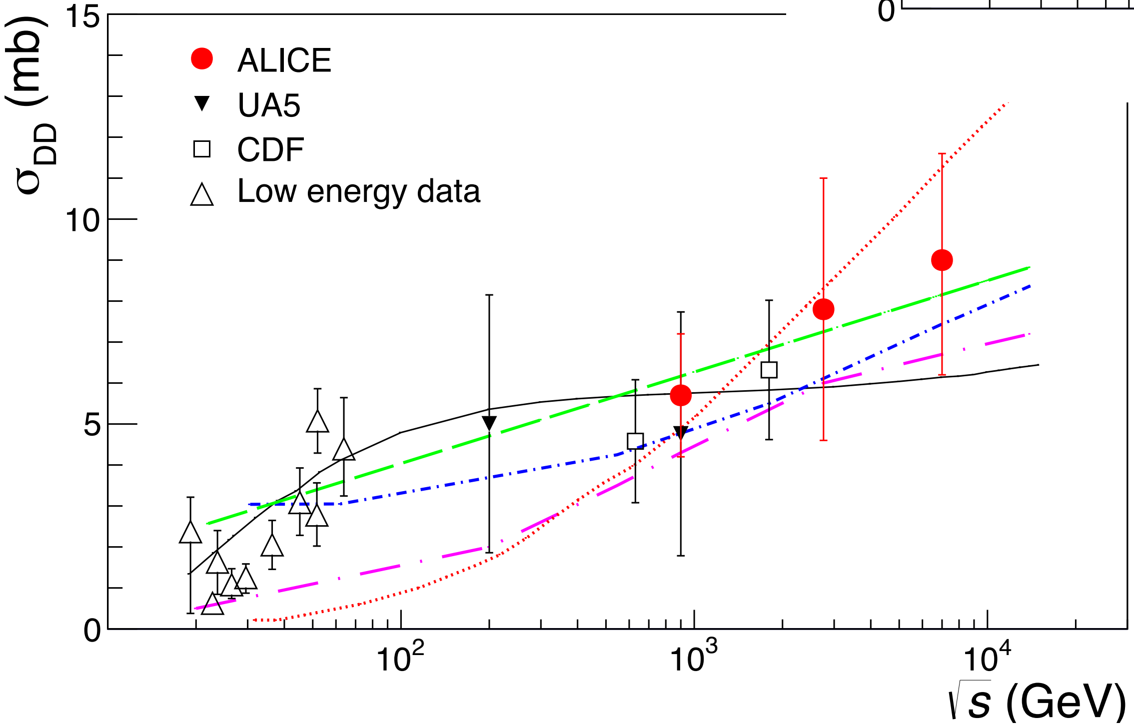


Excess of events with diffractive topology observed at all 3 LHC beam energies

ALICE: Total SD and DD Cross Sections

ALICE: Unfold integrated SD and DD cross sections at all three CMS energies based on rapidity gap rates and topologies. [implies some extrapolation into lowest ξ regions]



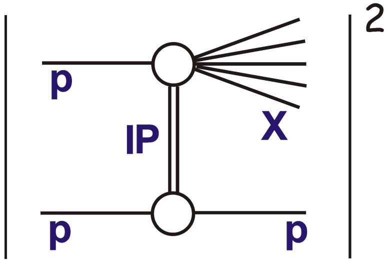


σ(SD) with ξ < 0.05

σ(DD) with gap Δη > 3

Good agreement with SPS data and wide range of model predictions

"Standard Model" of Soft Diffraction



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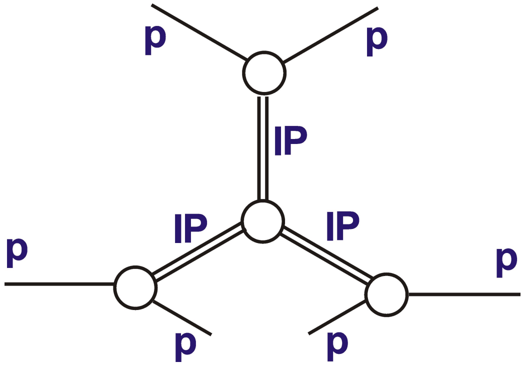


At fixed s:

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

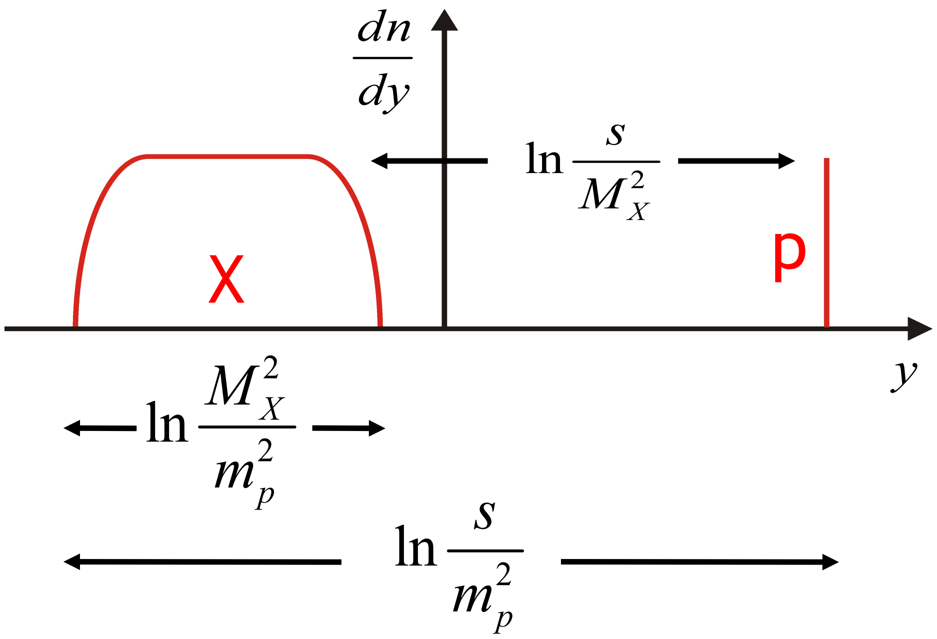
$$\left[\alpha(t) = \alpha(0) + \alpha' t\right]$$

i.e $\frac{d\sigma}{d\xi} \propto \frac{1}{\xi}$ to first approximation

Deviations from this behaviour sensitive to $\alpha_{IP}(t)$

… also sensitive to absorptive corrections → multiple soft exchanges in different configurations)

Rapidity Gap approach



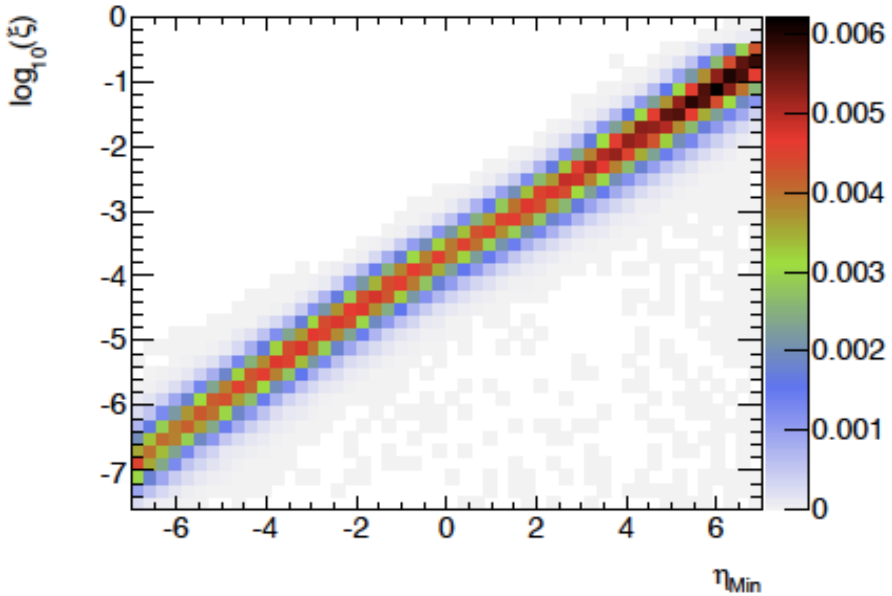
Up to event-by-event hadronisation fluctuations, ξ variables are predictable from empty rapidity regions

→Large rapidity gaps

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

and ~ flat gap distributions

$$\frac{d\,\sigma}{d\,\Delta\eta} \approx \text{const.}$$



LHC coverage (|η| < 4.9) gives sensitivity with large gap to:

$10^{-6} <\sim \xi <\sim 10^{-2}$

(equivalently 7 <~ M_X <~ 700 GeV)

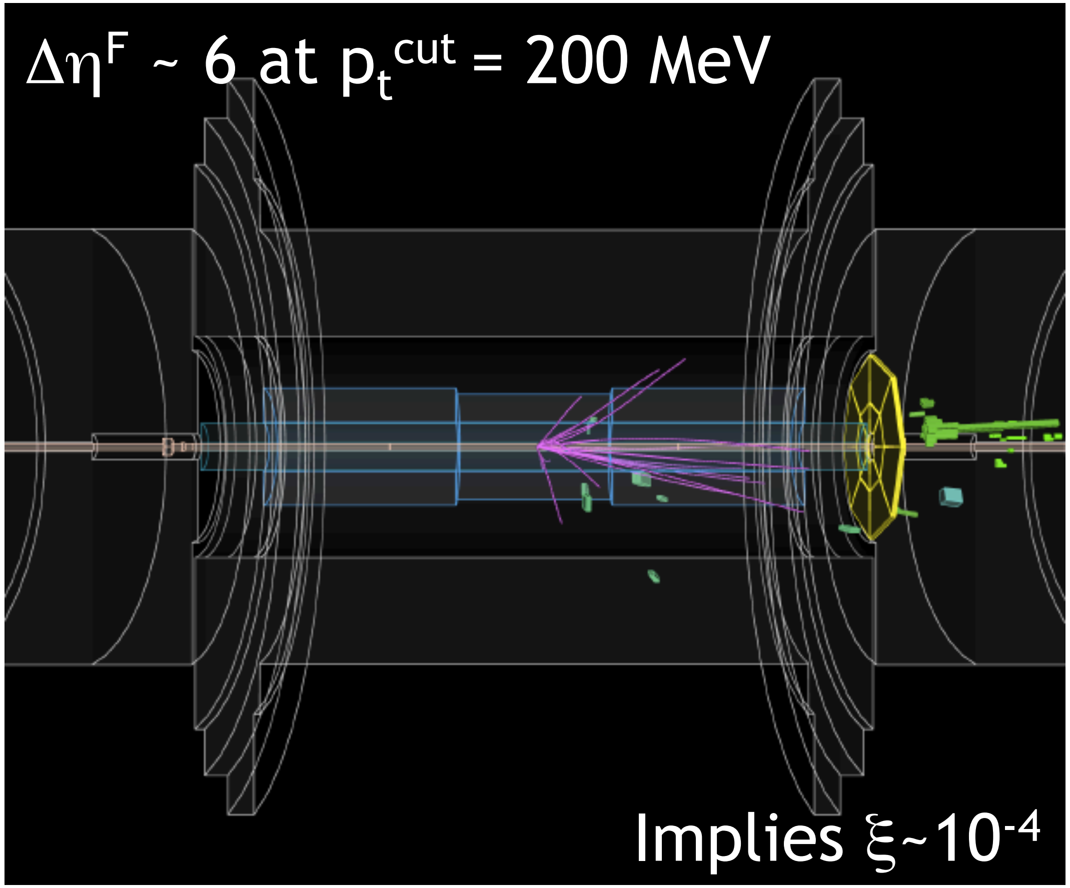
ATLAS: Differential gap cross-sections

- Cross sections measured from first $\sqrt{s}$ = 7 TeV LHC run
- Differential in rapidity gap size $\Delta\eta^F$
- $\Delta\eta^F$ extends from $\eta = \pm 4.9$ to first particle with $p_t > p_t^{cut}$

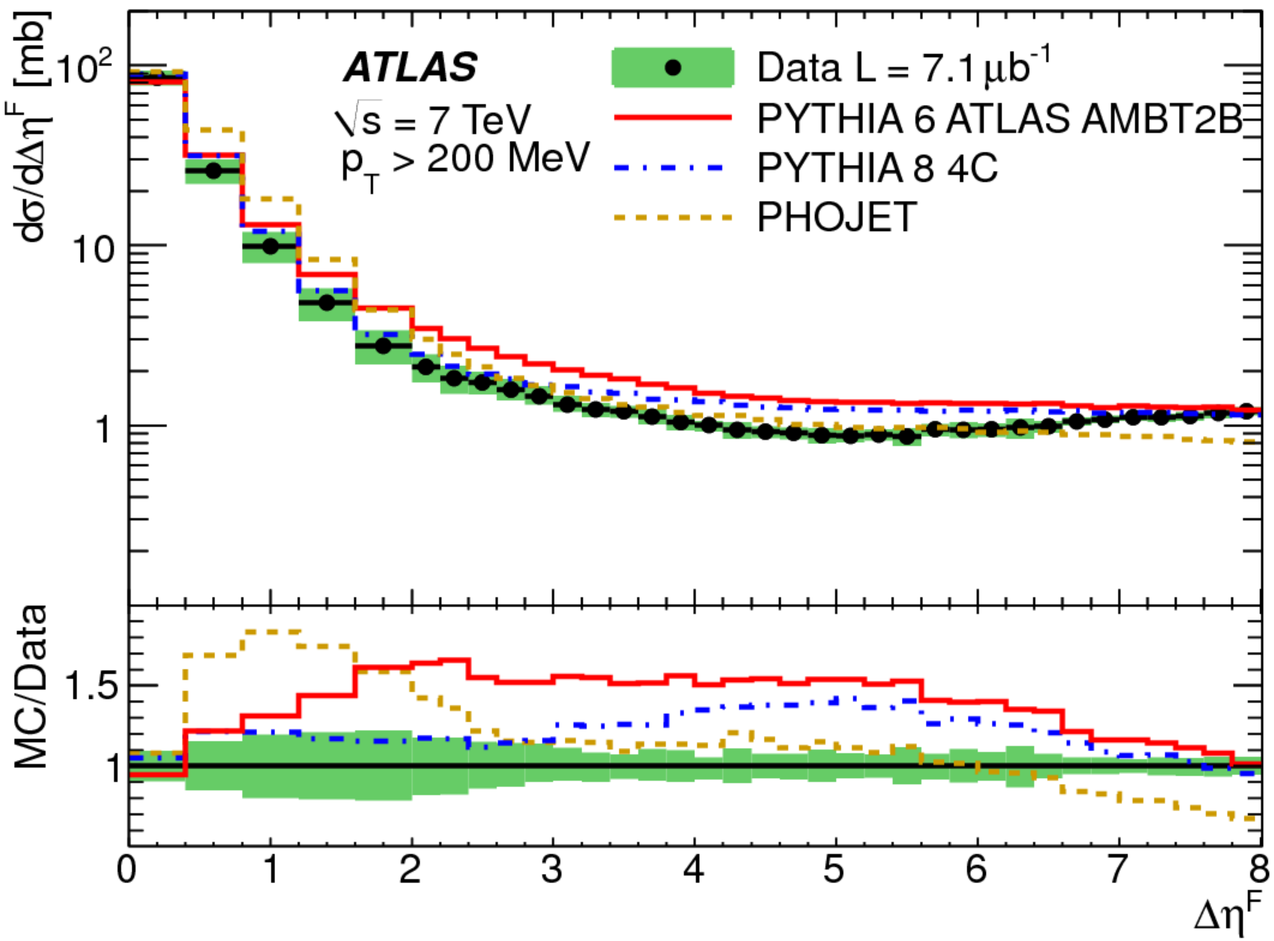
200 MeV < p_t^{cut} < 800 MeV

$0 < \Delta\eta^F < 8$

Corrected for experimental effects to level of stable hadrons



ATLAS Differential Gap Cross Section

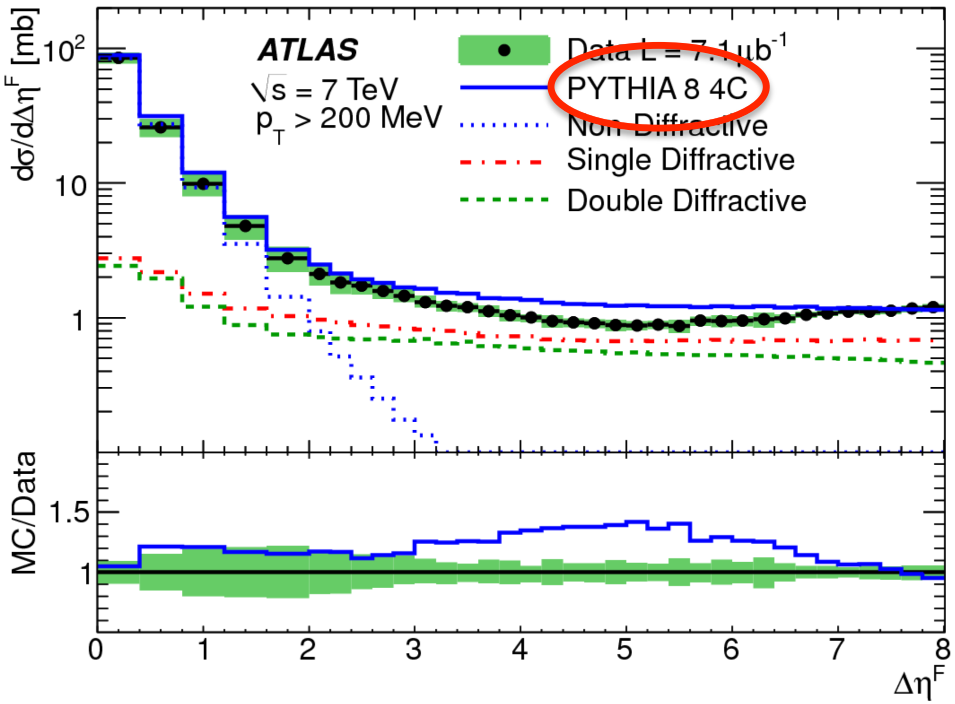


- Precision between ~8% (large gaps) and ~20% ($\Delta\eta^F$ ~ 1.5)
- Small gaps sensitive to hadronisation fluctuations / MPI

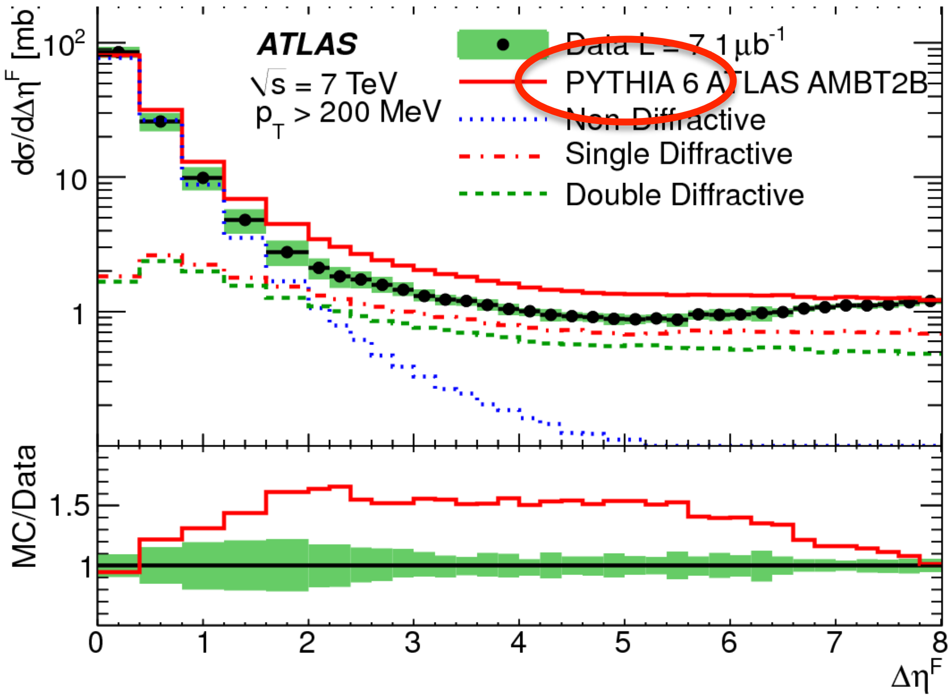
… huge uncertainties …

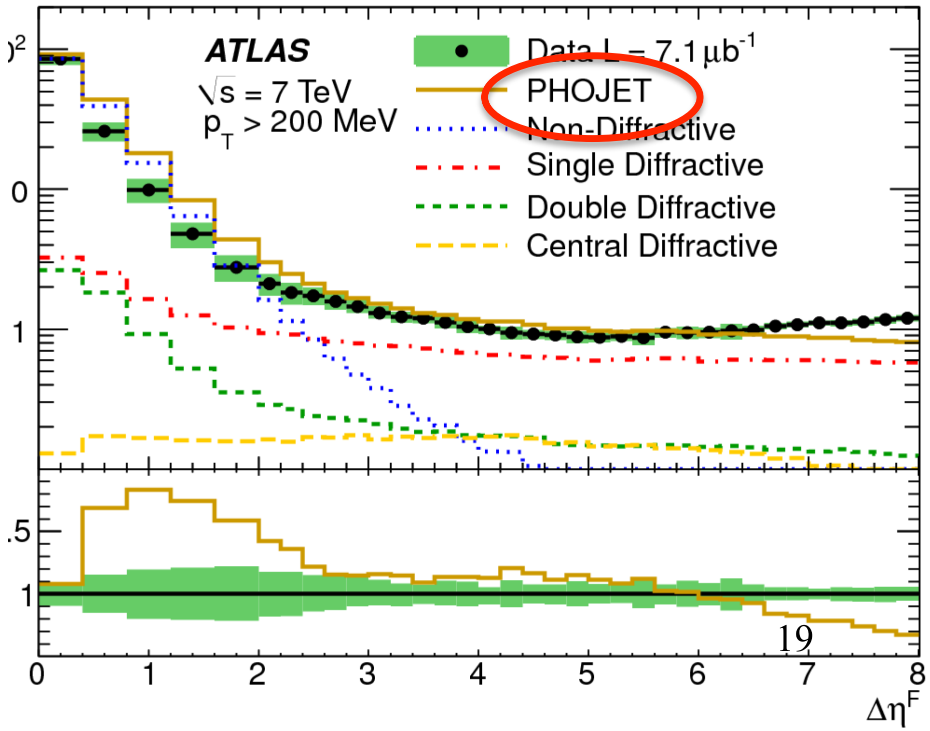
- Large gaps measure x-sec for SD [+ DD with M_Y <~ 7 GeV]

Small Gaps and Hadronisation

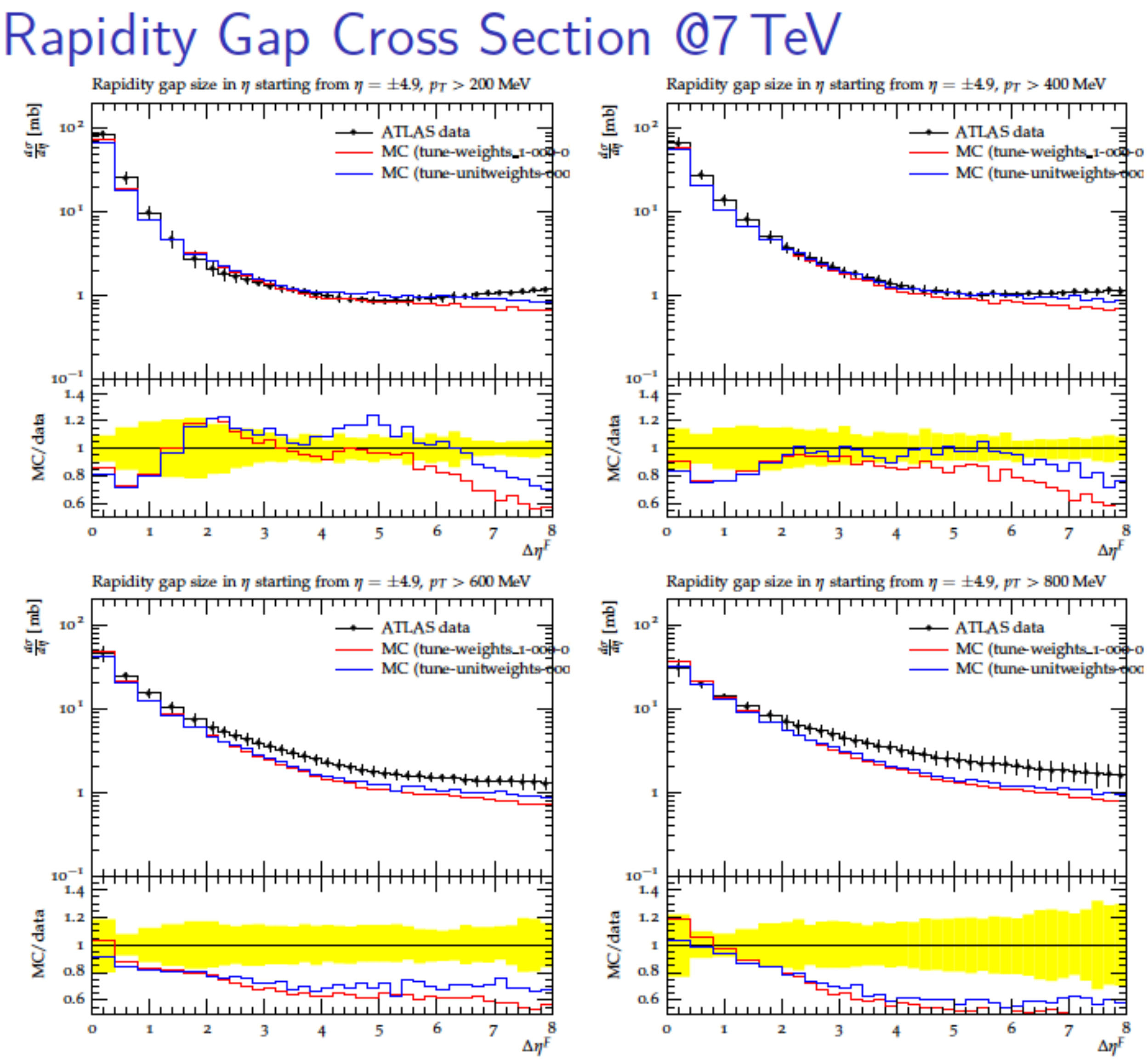


- Big variation between MCs in small non-zero gap production via ND → fluctuations / UE
- PYTHIA8 best at small gaps
- PHOJET > 50% high at $\Delta\eta^F \sim 1.5$
- See also higher p_T cut data





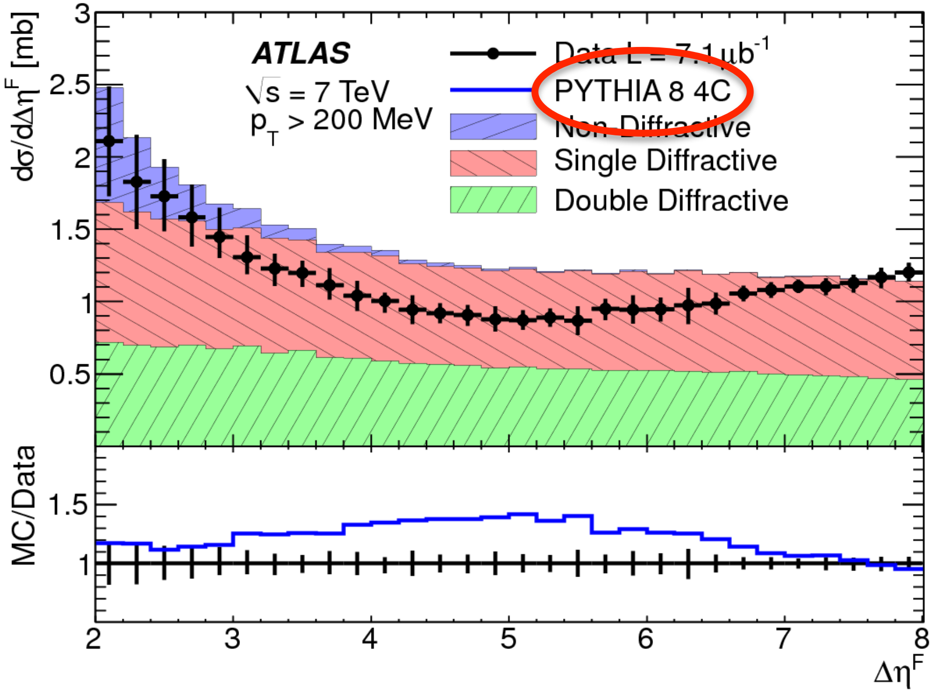
SHRiMPS (MB in SHERPA): sneak preview



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

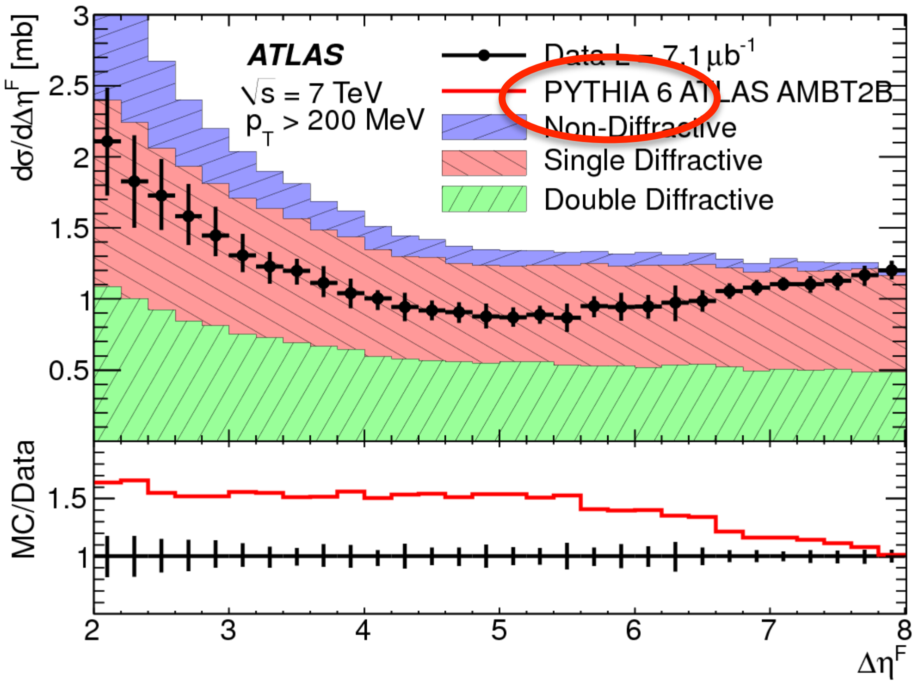
Impressive (but still not perfect) description!

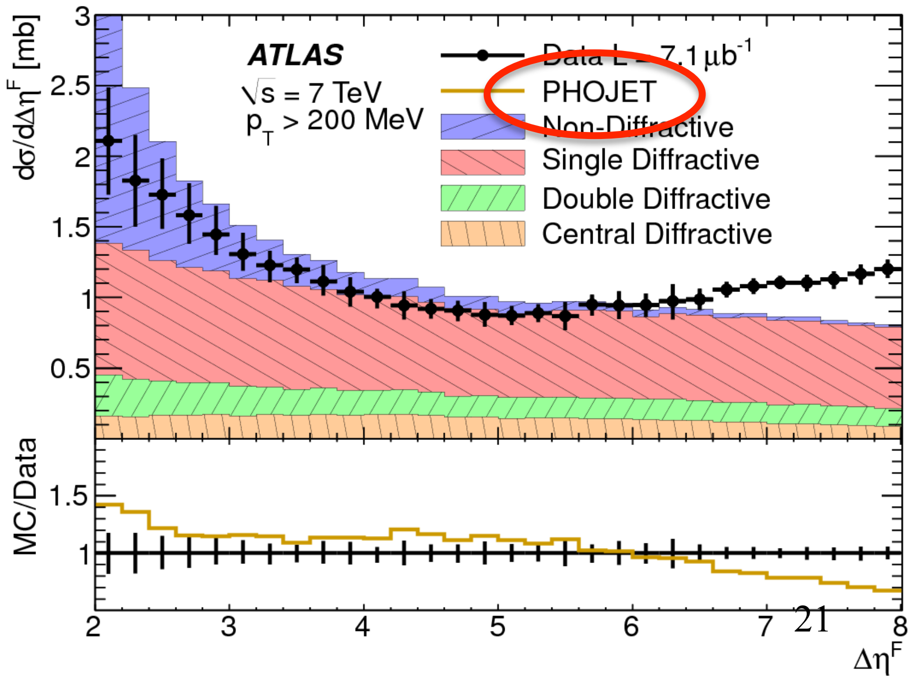
Large Gaps and Diffractive Dynamics



-Diffractive plateau with ~ 1 mb per unit of gap size for $\Delta\eta^F > 3$ broadly described by models

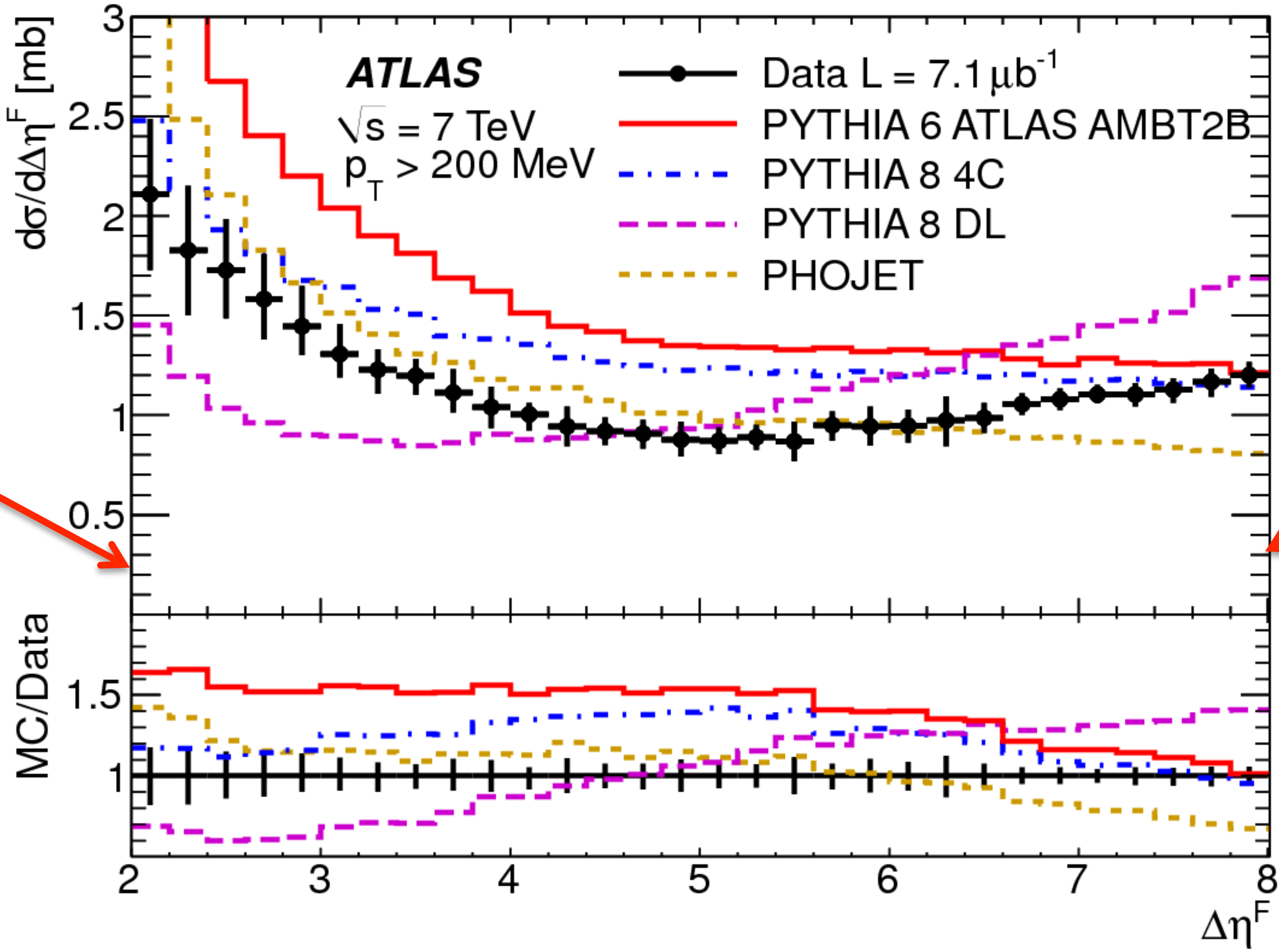
- PYTHIA high (DD much larger than in PHOJET)
- PHOJET low at high $\Delta\eta^F$





Large Gaps and Diffractive Dynamics

$\xi_X \sim 10^{-2.5}$



$\xi_X \sim 10^{-5}$

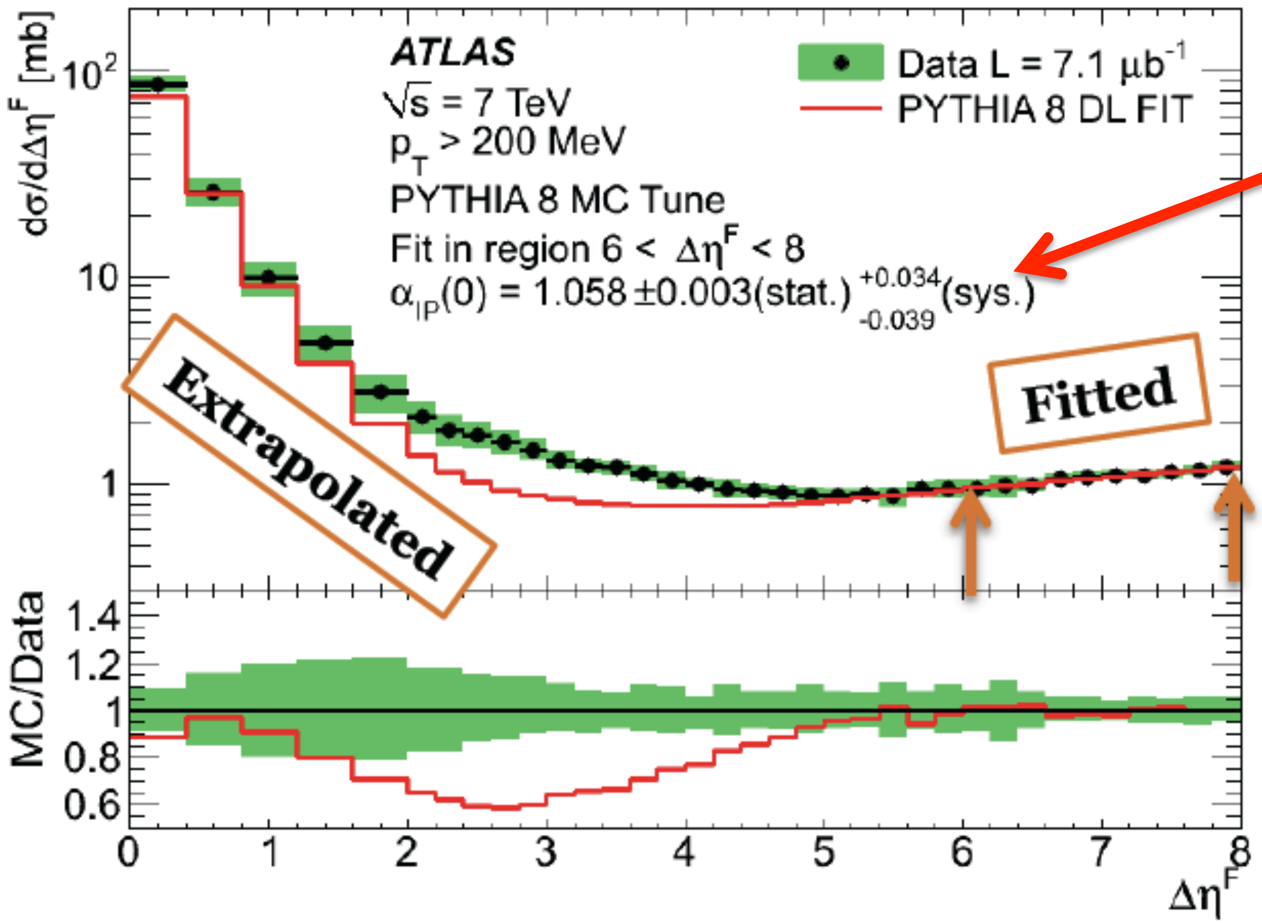
Default PHOJET and PYTHIA models have $\alpha_{IP}(0) = 1$

Donnachie-Landshoff flux has $\alpha_{IP}(0) = 1.085$

Data exhibit slope in between these models at large $\Delta\eta^F$

[No absorptive corrections in either case]

$\alpha(0)$ extraction & a crude PYTHIA8 tuning



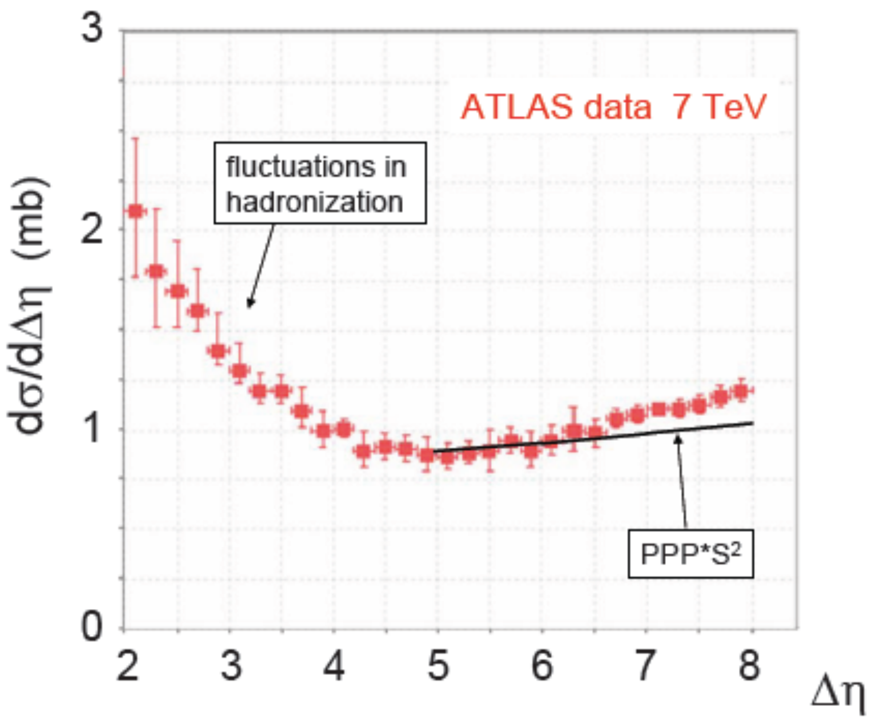
$\alpha(0)$ uncertainty heavily dominated by model dependence of hadronisation

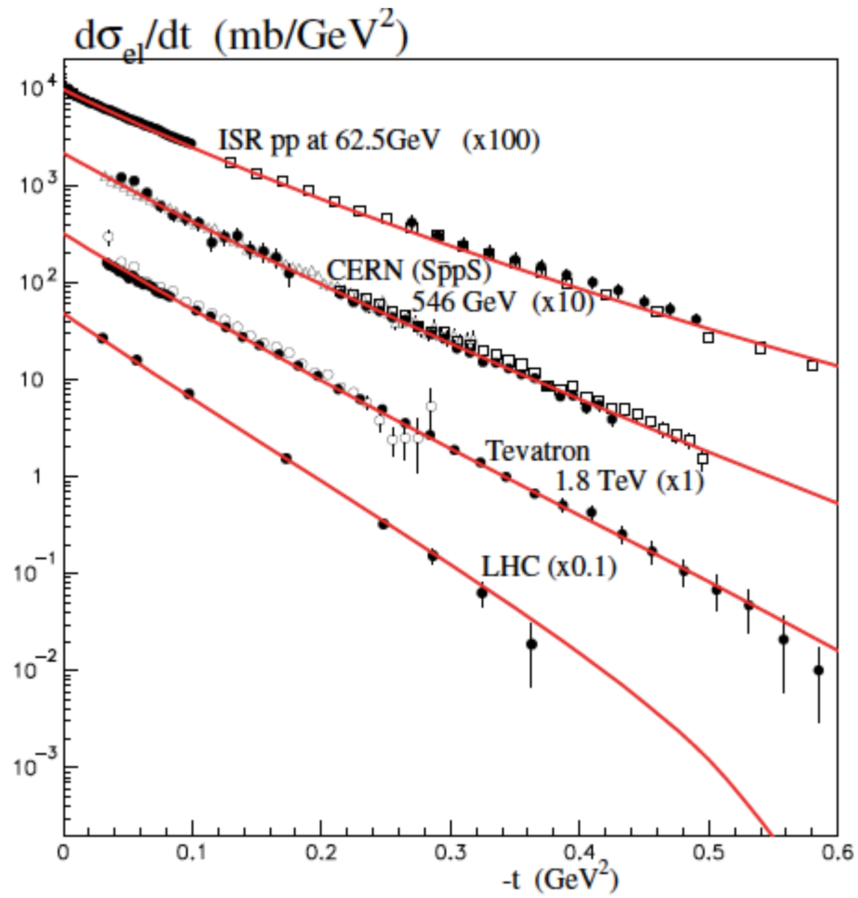
Only other input to extrapolation is overall fraction of diffractive events from total inelastic cross section paper.

→ describes small gaps well, but not transition between non-diffractive and diffractive regions

KMR Model of all Soft Diffractive Processes

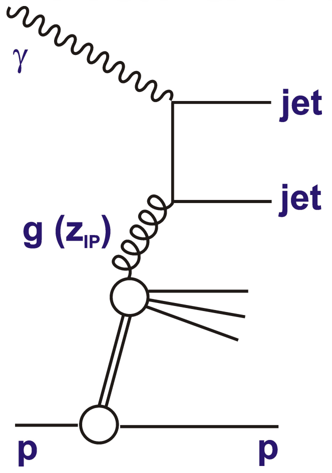
arXiv:1201.6298

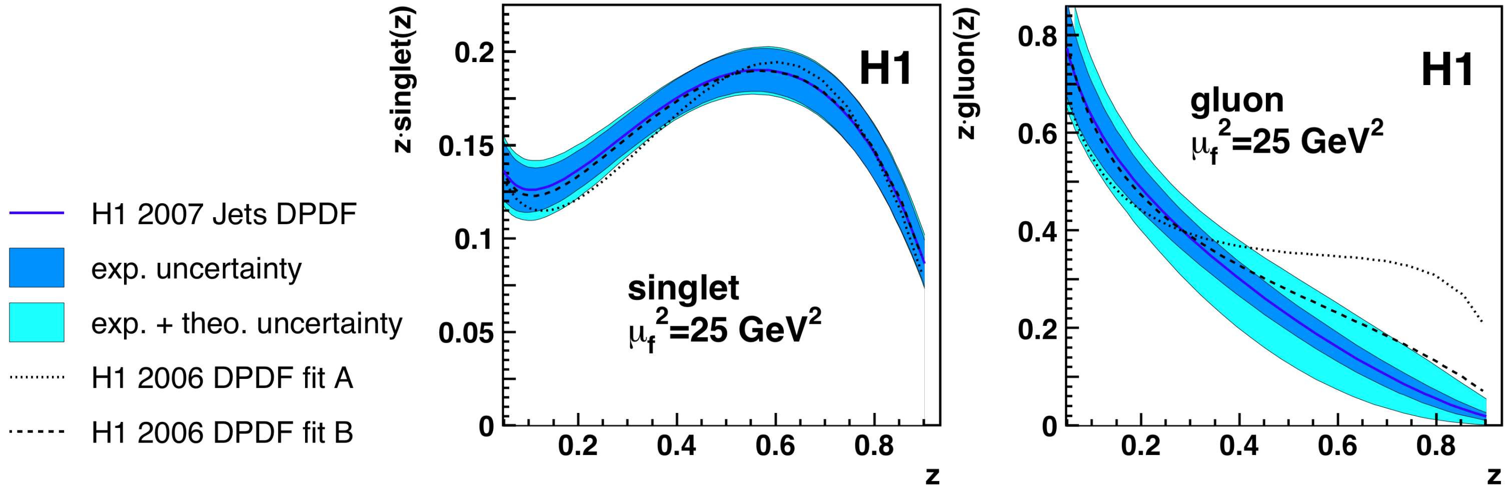


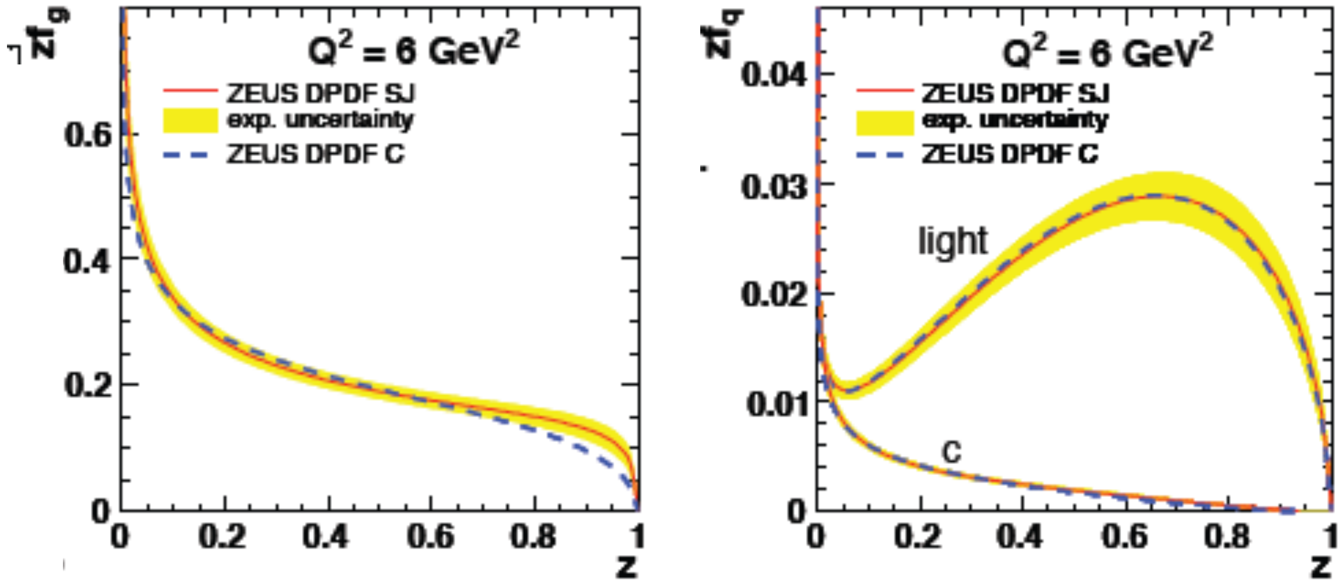


… simultaneous Durham (KMR) description of ATLAS gaps data and elastic cross section data from ISR to Totem based on a single pomeron in a 3-channel eikonal model, with <u>significant absorptive corrections in gaps / dissociation case</u>

Hard Processes in Diffraction: DPDFs @ HERA







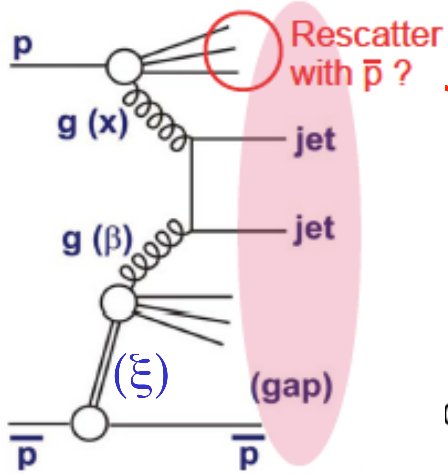
NLO DPDFs lead to impressive descriptions of all hard diffractive DIS data

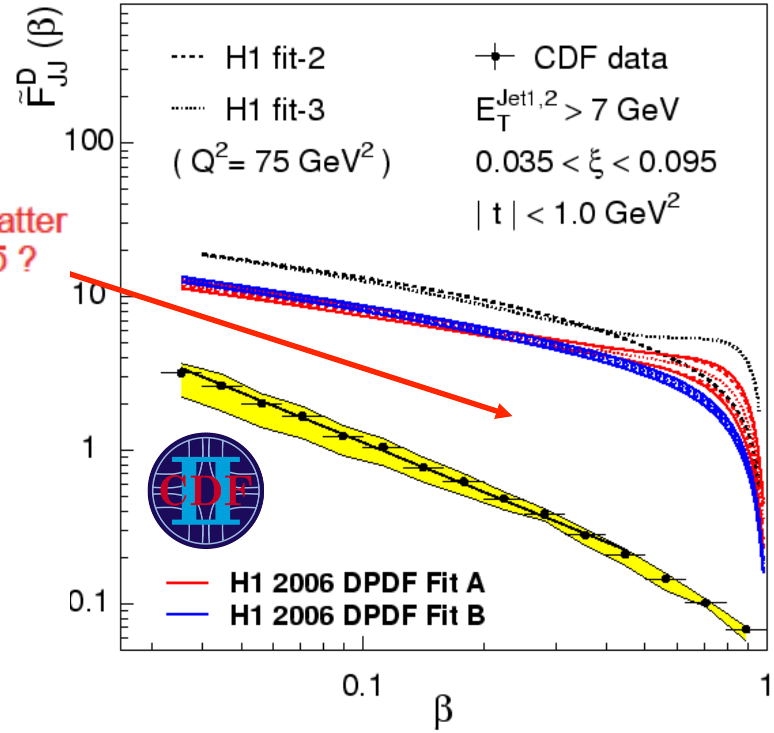
DPDFs dominated by a gluon density which extends to large z

… but in pp(bar)

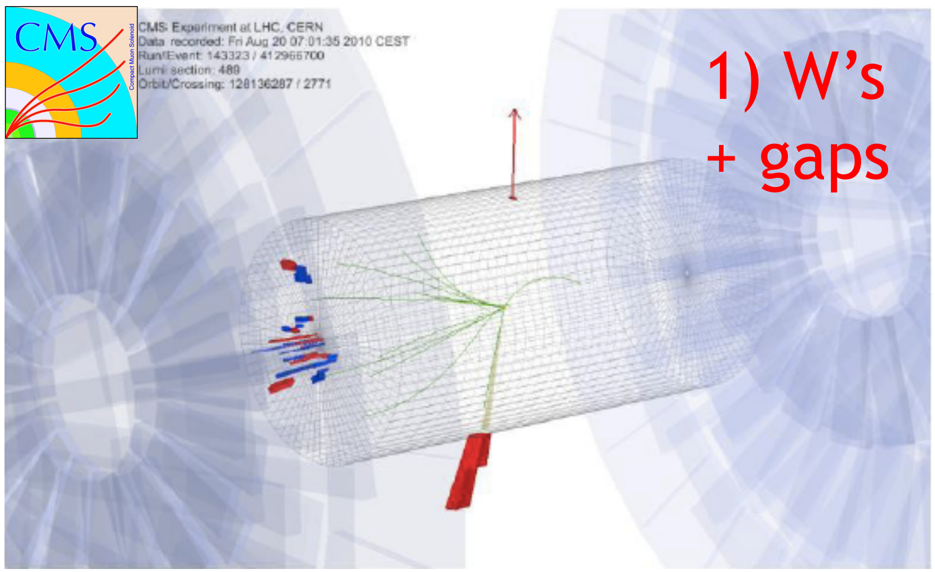
Spectacular failure in **comparison of Tevatron proton-tagged diffractive dijets with HERA DPDFs**

… `rapidity gap survival probability' ~ 0.1





1st Hard diffraction data from LHC …

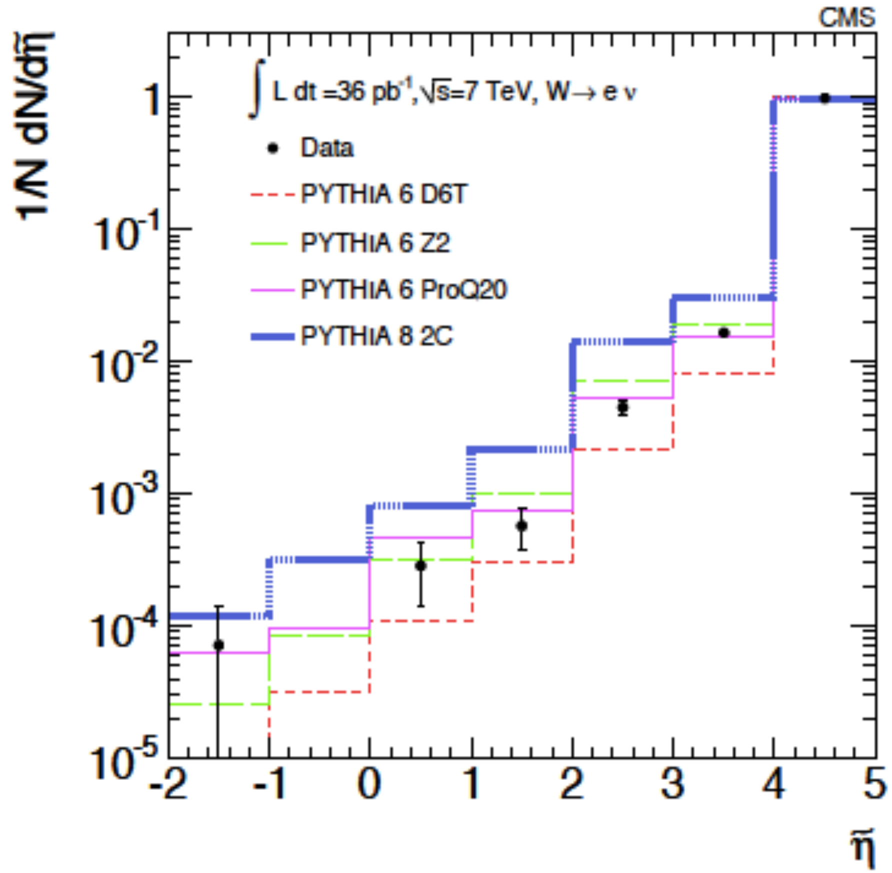


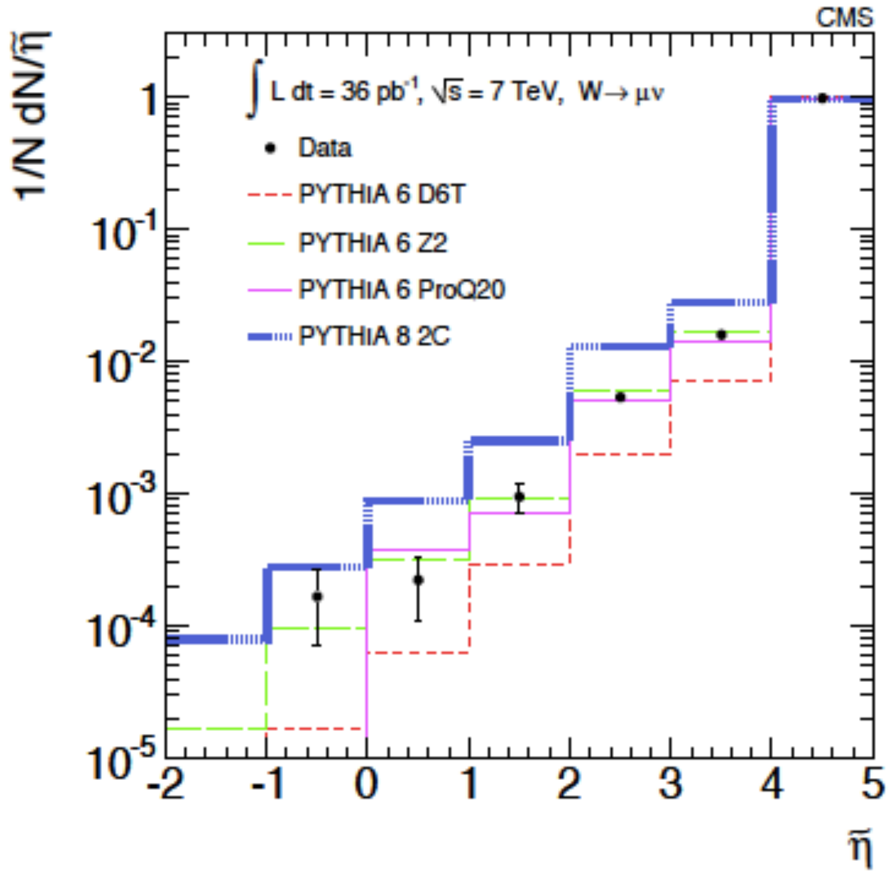
2) Dijets with ξ reconstructed from full observed final state

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

W and Z events with gaps at CMS

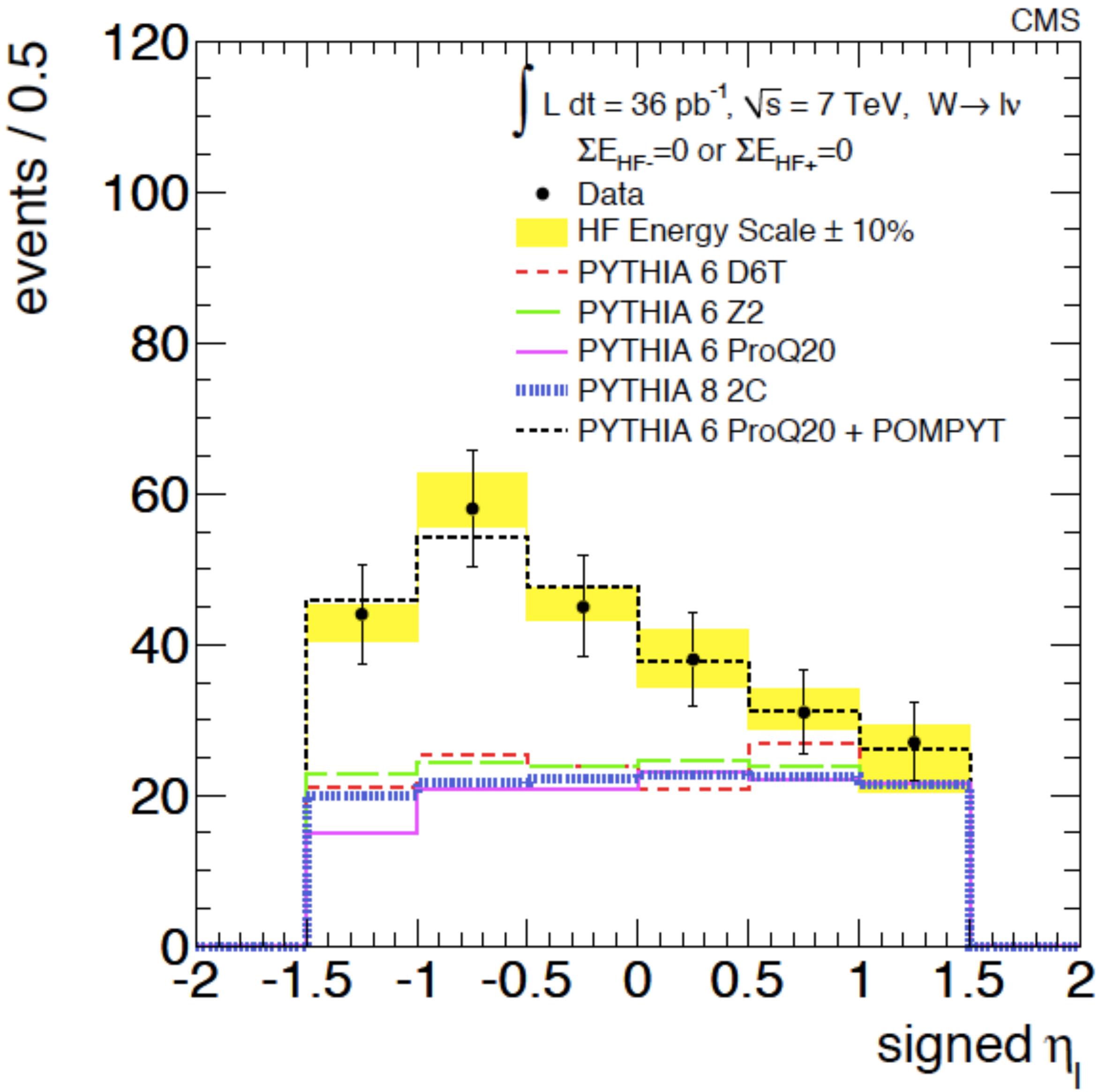
After pile-up corrections, ~1% of W and Z events exhibit no activity above noise thresholds over range 3 < ±η < 4.9 … interpretation complicated by non-diffractive hadronisation fluctuations …





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

Exploiting Gap-Lepton η Correlation

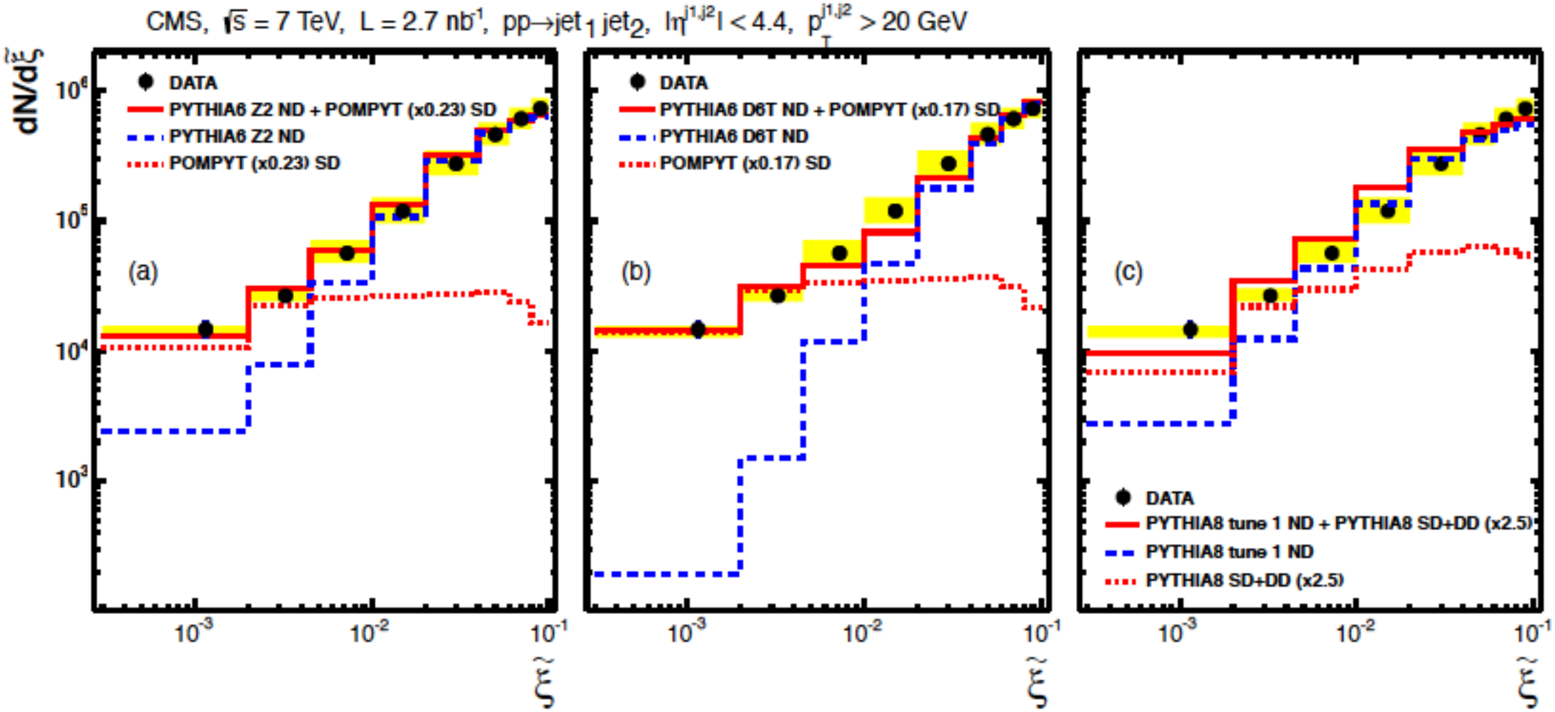


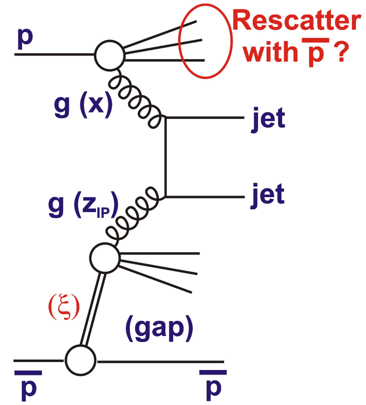
Lepton pseudorapidity with + sign if lepton in same hemisphere as gap, else – sign.

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

Surprisingly large?...

CMS Dijets with Low E±p_z





Uncorrected data prior to rapidity gap selection

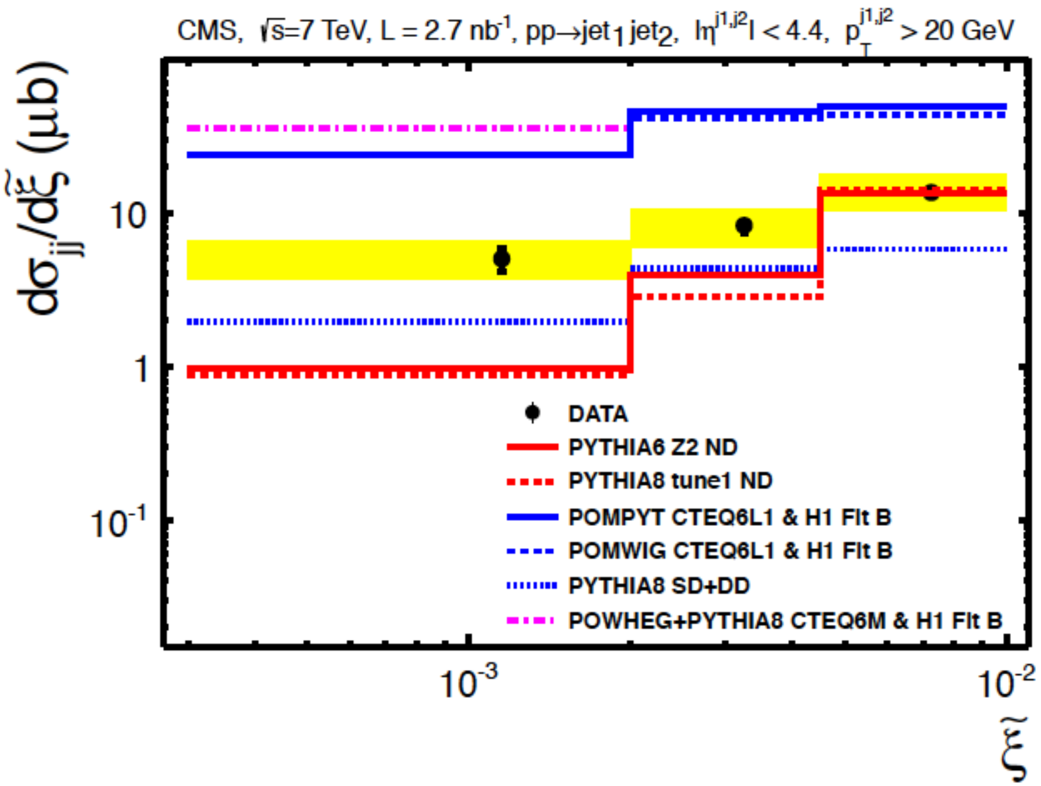
-Diffractive signal required at low ξ (Data > PYTHIA ND)

-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



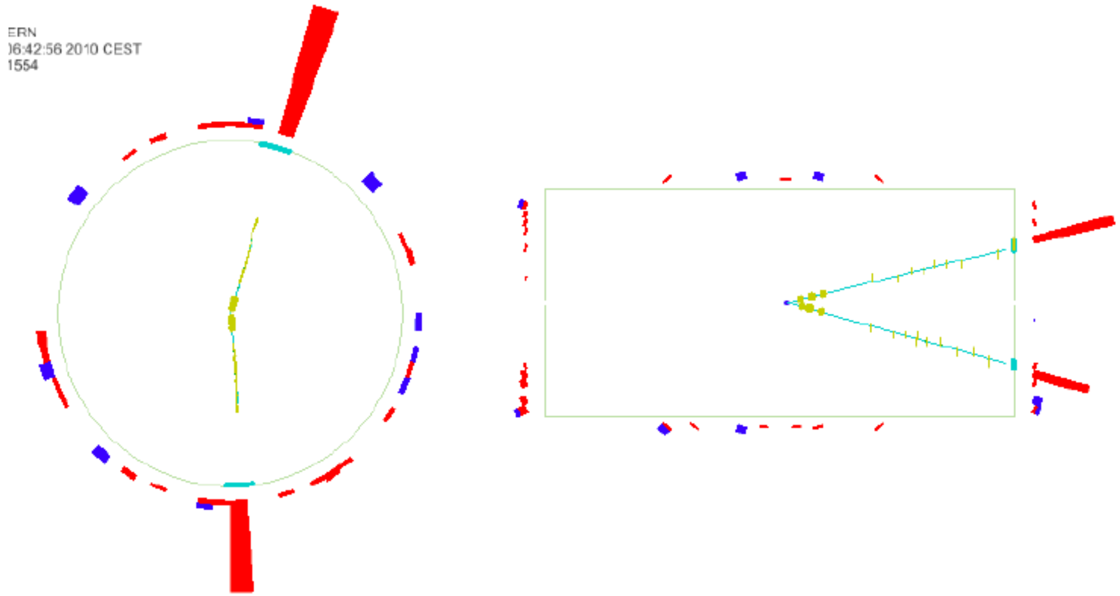
- Comparison of 1st bin v diffractive DPDF models (POMPYT, POMWIG) shows factor ~ 0.21 ± 0.07 required
… but double dissociation included in data, but not (or less) in models

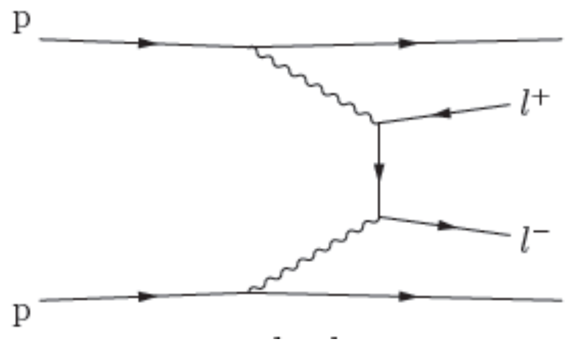
→ Gap survival probability estimate 0.12 ± 0.05 (LO)
→ Gap survival probability estimate 0.08 ± 0.04 (NLO - POWHEG)
… comparable to Tevatron, but different x range
… larger than expected?

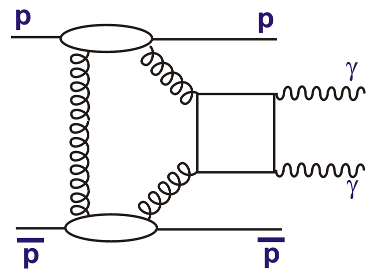
- PYTHIA 8 diffraction model too low by factor ~ 2

Proton tagged data will help a lot (DD, ND large gap fluct's)

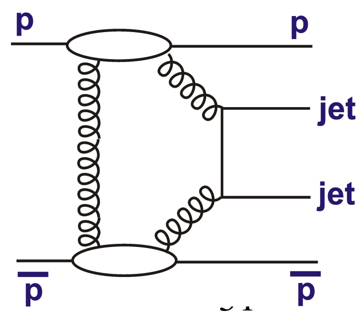
Quick word on Central (Excl) Production







- 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 …

Summary

Precise LHC soft diffractive, elastic, total cross section data

- Broadly described by single pomeron with intercept as expected, but α_{IP}' larger than thought?
- Simultaneous description of all data requires better understanding of absorptive corrections / shadowing.
- Low mass diffractive dissociation remains problematic

First data on diffractive hard scattering

- Suggestion of surprisingly large gap survival probability?
- Need improved understanding of hadronisation fluctuations leading to large gaps in non-diff data
- Proton tagging can by-pass this issue

Future directions include MPI in diffraction, lots more hard processes including central production

[Thanks to O. Kepka, T. Martin, O. Villalobos-Baille, K. Zapp and many others]

Total Inelastic pp Cross Section

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

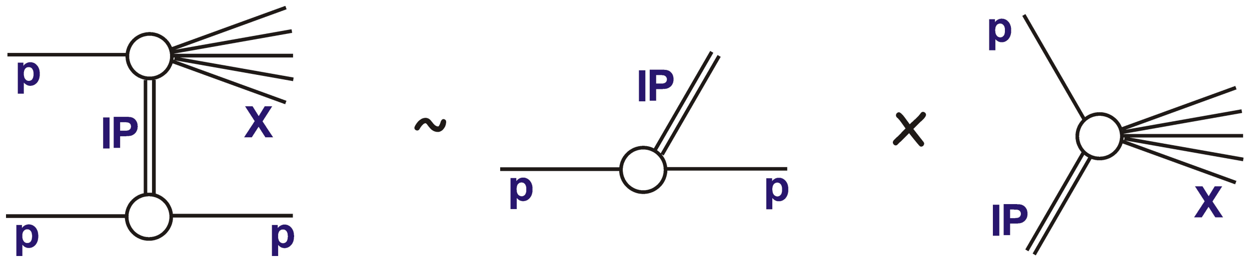
Using luminosity from CMS: $$\frac{d\sigma_{EL}}{dt} = \frac{1}{L} \cdot \frac{dN_{EL}}{dt}$$

ρ from COMPETE fit: $$\rho = 0.14^{+0.01}_{-0.08}$$

$$\sigma_{TOT} = \sqrt{19.20\,\mathrm{mb\,GeV}^2 \cdot \left.\frac{d\sigma_{EL}}{dt}\right|_{t=0}}$$

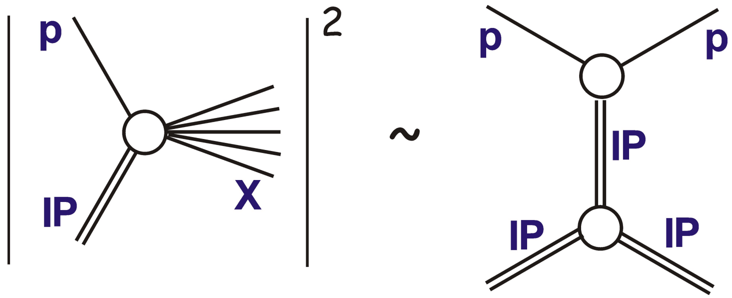
Generalised Optical Theorem

1) Factorise SD into a pomeron (IP) flux and a total p+IP cross section

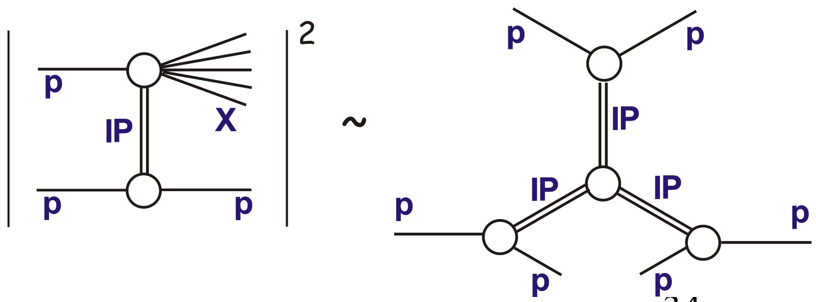


$$f_{IP/p}(\xi, t) \qquad \sigma_{tot}(IP + p \rightarrow X)$$

2) Similarly to total pp cross section, relate total p+IP cross section to forward elastic amplitude via optical theorem

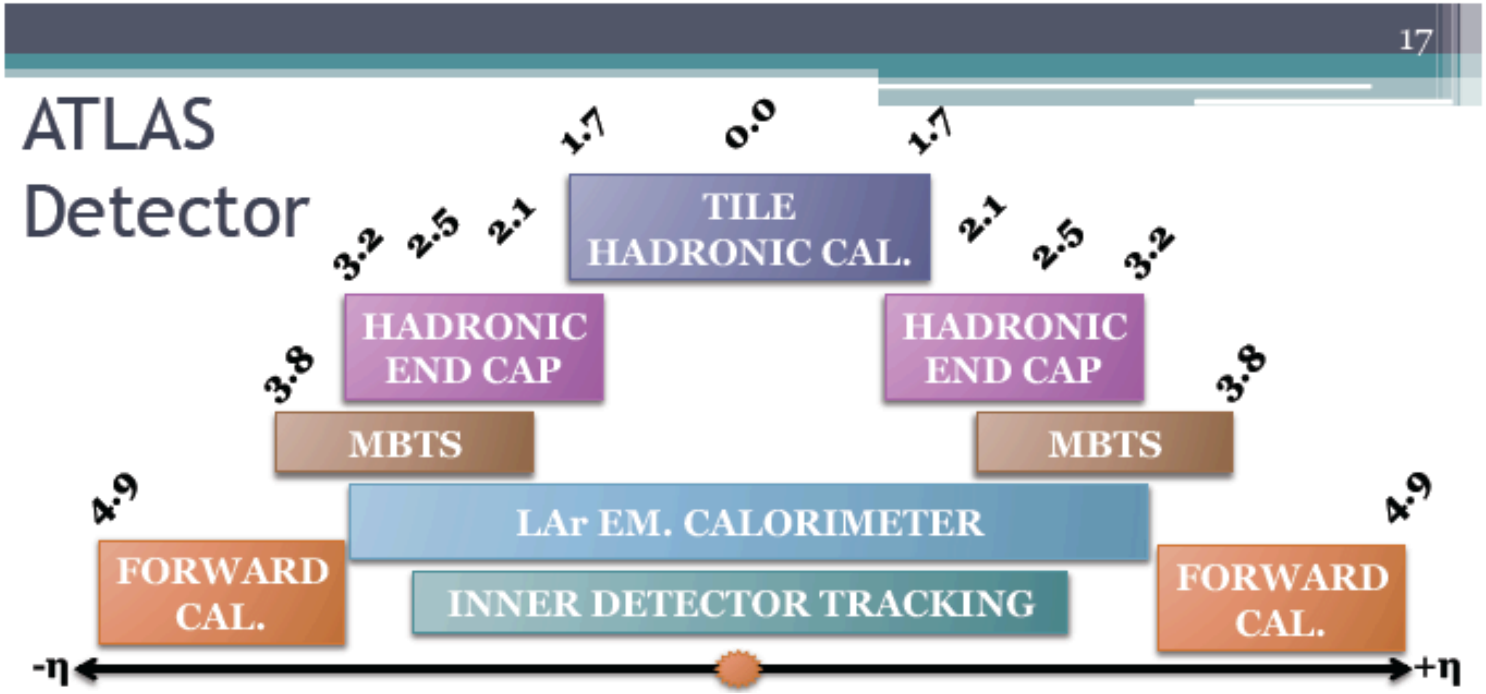


3) Calculate SD cross sections from triple pomeron amplitudes



[similar treatment for DD]

ATLAS Acceptance



Rapidity gaps identified using full range of calorimetry ($|\eta| < 4.9$) and inner tracking detector ($|\eta| < 2.5$)

Detector is sensitive to particle production with $p_T > 200$ MeV … Measurements defined by this requirement

Higher p_T cuts also applied to investigate dependence

ATLAS Measurement

Uses only the first ever physics run at $\sqrt{s}$ = 7 TeV.

30th March 2010, from 13.24 to 16.38

7 minutes shorter than `Lord of the Rings: Return of the King'

Pile-up occurs in less than 1 event in 1000

Integrated luminosity of 7.1 μb^{-1}

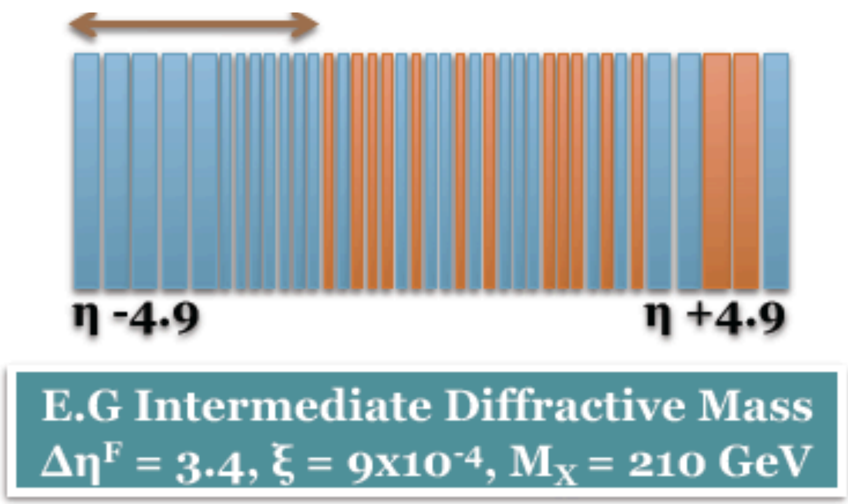
Peak instantaneous luminosity of 1.1 x 10^{27} cm^{-2} s^{-1} ☺

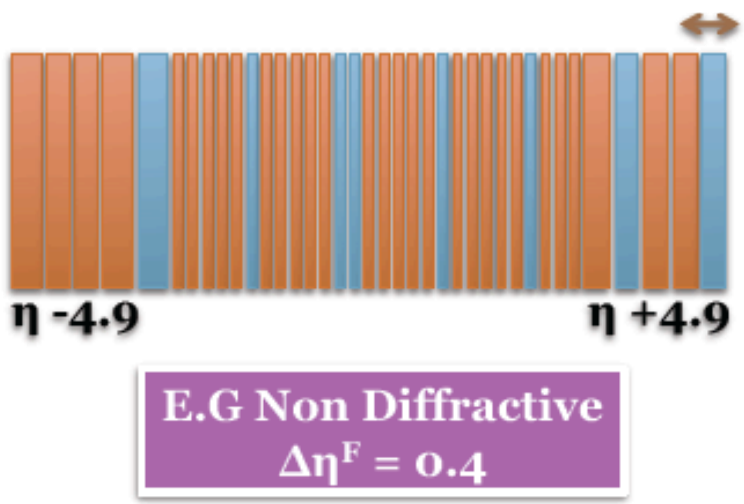
Gap Finding Algorithm / Observable

Divide detector into rings of width usually $\Delta\eta$ = 0.2

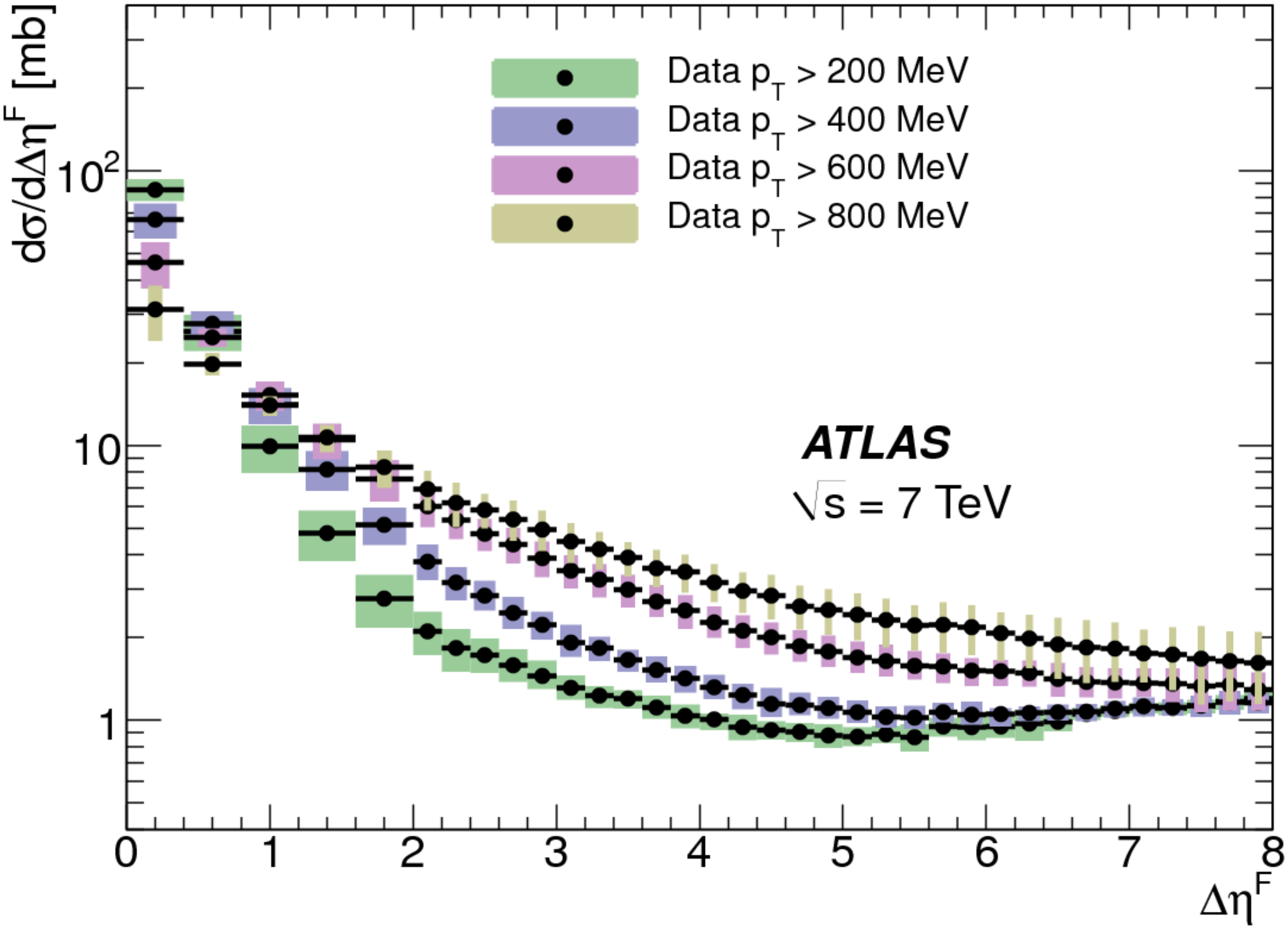
Decide whether there are particles with pT above threshold (usually 200 MeV) in each ring

Define $\Delta\eta^F$ = larger continuous run of empty rings extending to limit of acceptance in forward or backward direction



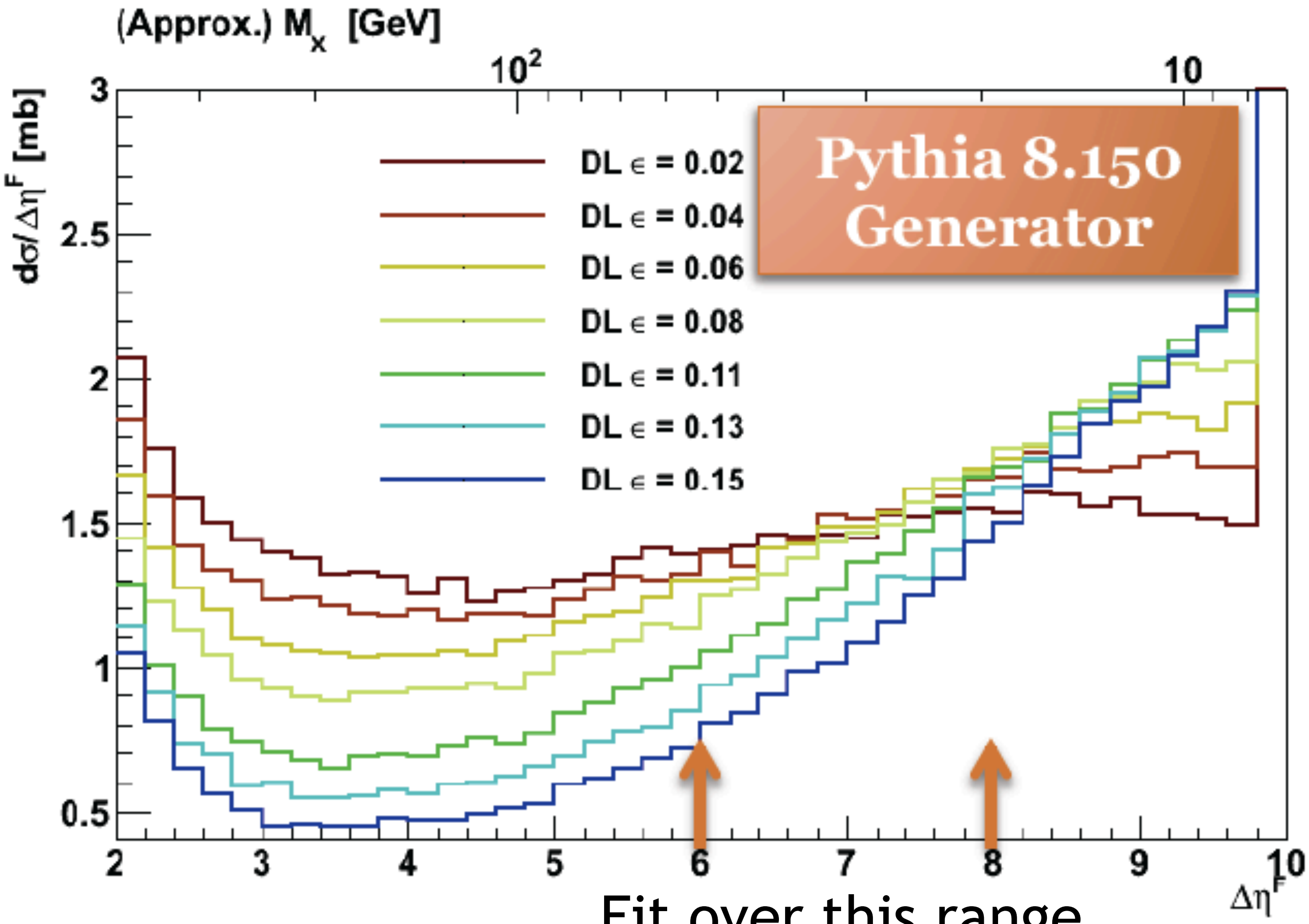


Increasing the pt cut defining gaps



Sensitivity to Pomeron Intercept

Extract $\alpha_{IP}(0) = 1 + \varepsilon$ by optimising description by PYTHIA8 as ε varies in a region where ND contributions are negligible



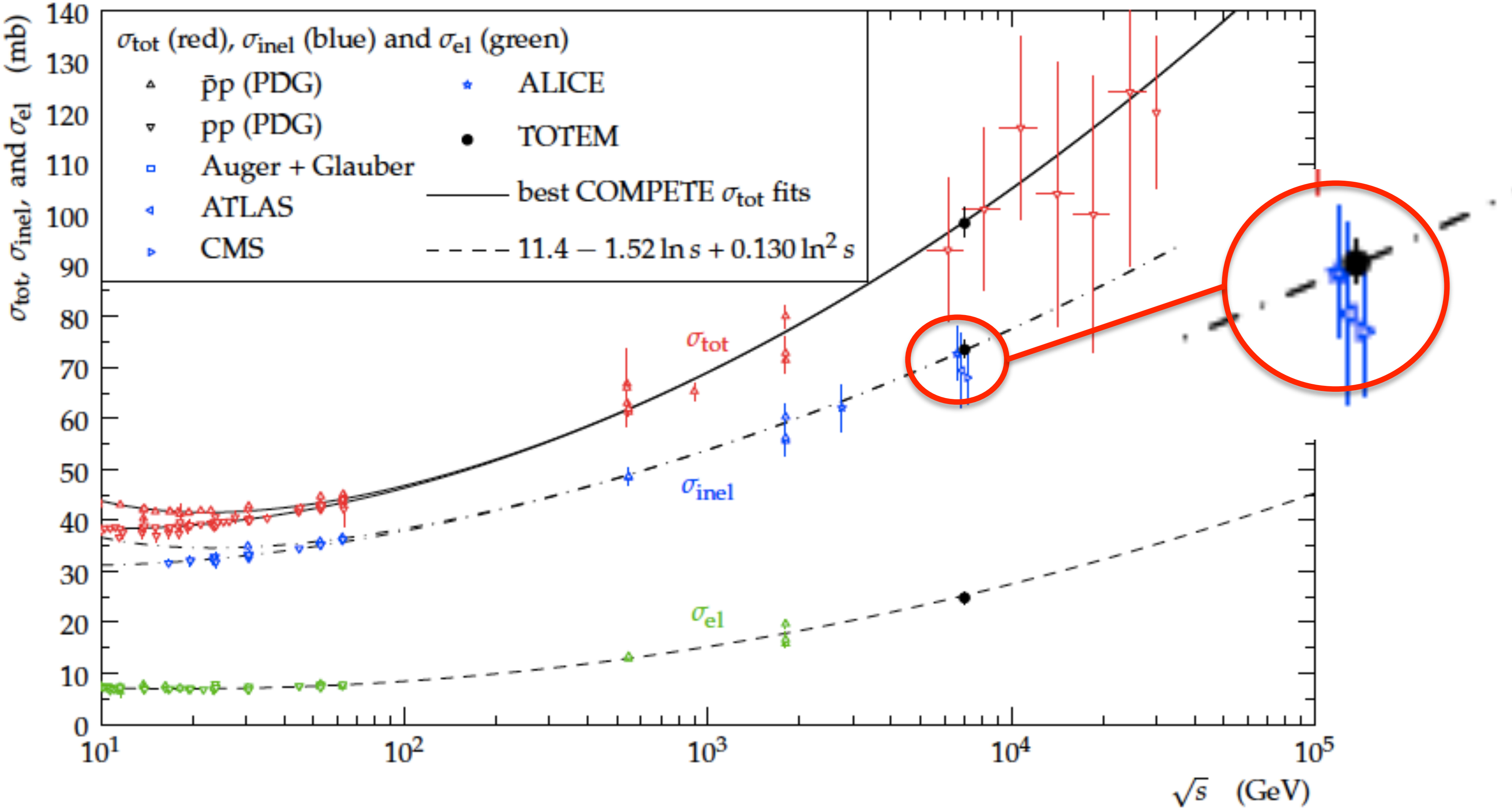
Fit over this range

Totem **Inelastic Cross-Section**

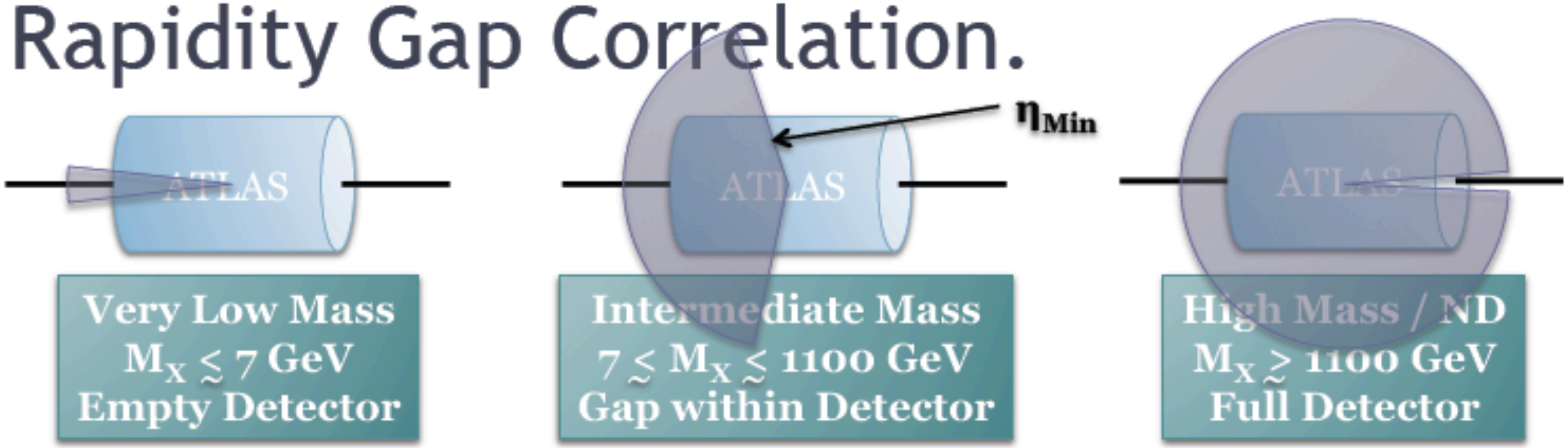
$$\sigma_{inel} = \sigma_{tot} - \sigma_{el} = \left(73.5 \pm 0.6^{(stat)} \left[{}^{+1.8}_{-1.3}\right]^{(syst)}\right) \text{ mb}$$

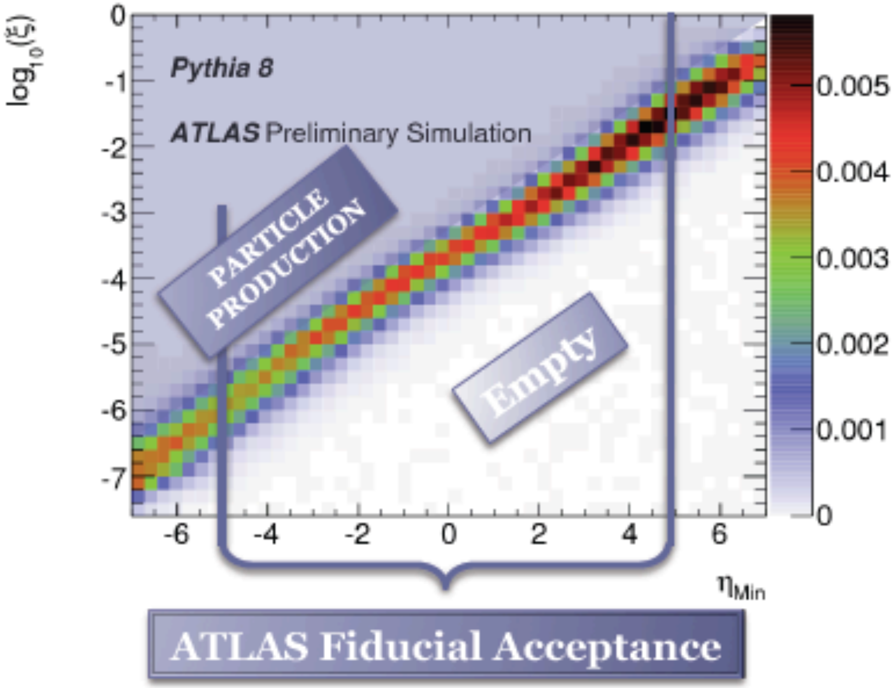
σ_{inel} (CMS) $= (68.0 \pm 2.0^{(syst)} \pm 2.4^{(lumi)} \pm 4.0^{(extrap)})$ mb
σ_{inel} (ATLAS) $= (69.4 \pm 2.4^{(exp)} \pm 6.9^{(extrap)})$ mb
σ_{inel} (ALICE) $= (72.7 \pm 1.1^{(mod)} \pm 5.1^{(lumi)})$ mb

ATLAS, CMS extrapolations to low ξ yield lower σ(inel) than Totem?



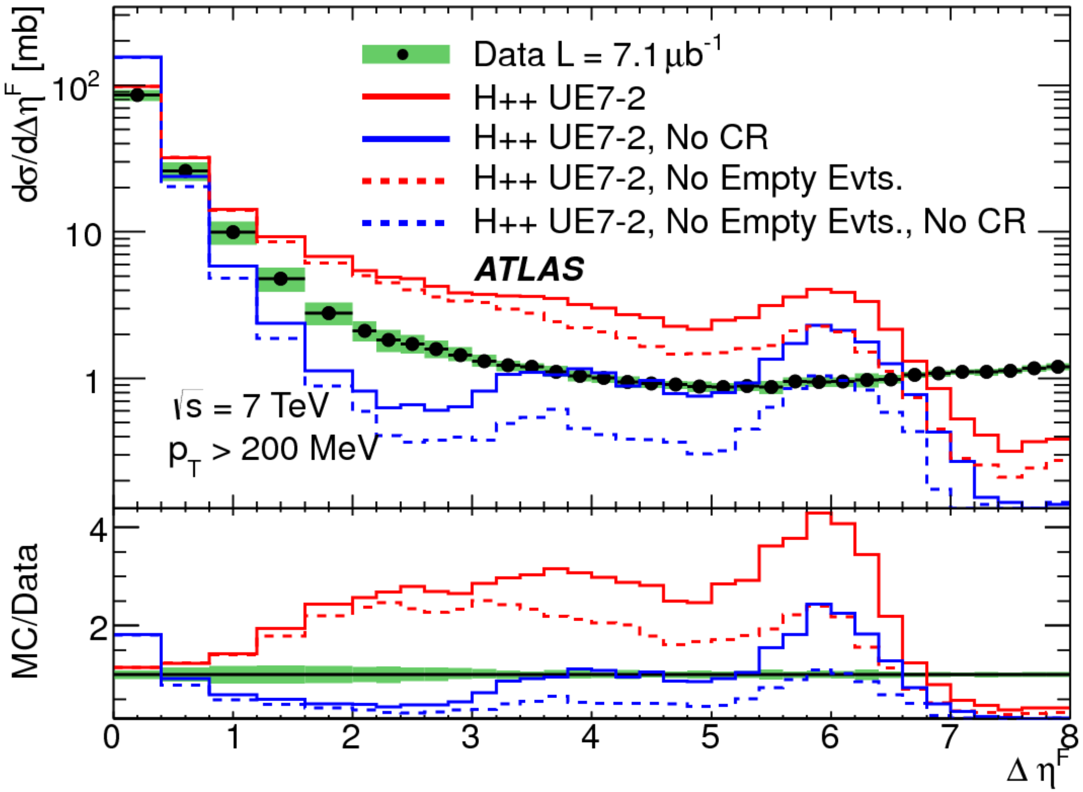
Rapidity Gap Correlation.





- **Rapidity interval** of **final state kinematically linked** to size of **diffractive mass**.
- **Linear relation** between **η of edge of diffractive system** and **ln(M_X)**, smeared out slightly by **hadronisation effects**.

Cluster Fragmentation: HERWIG++

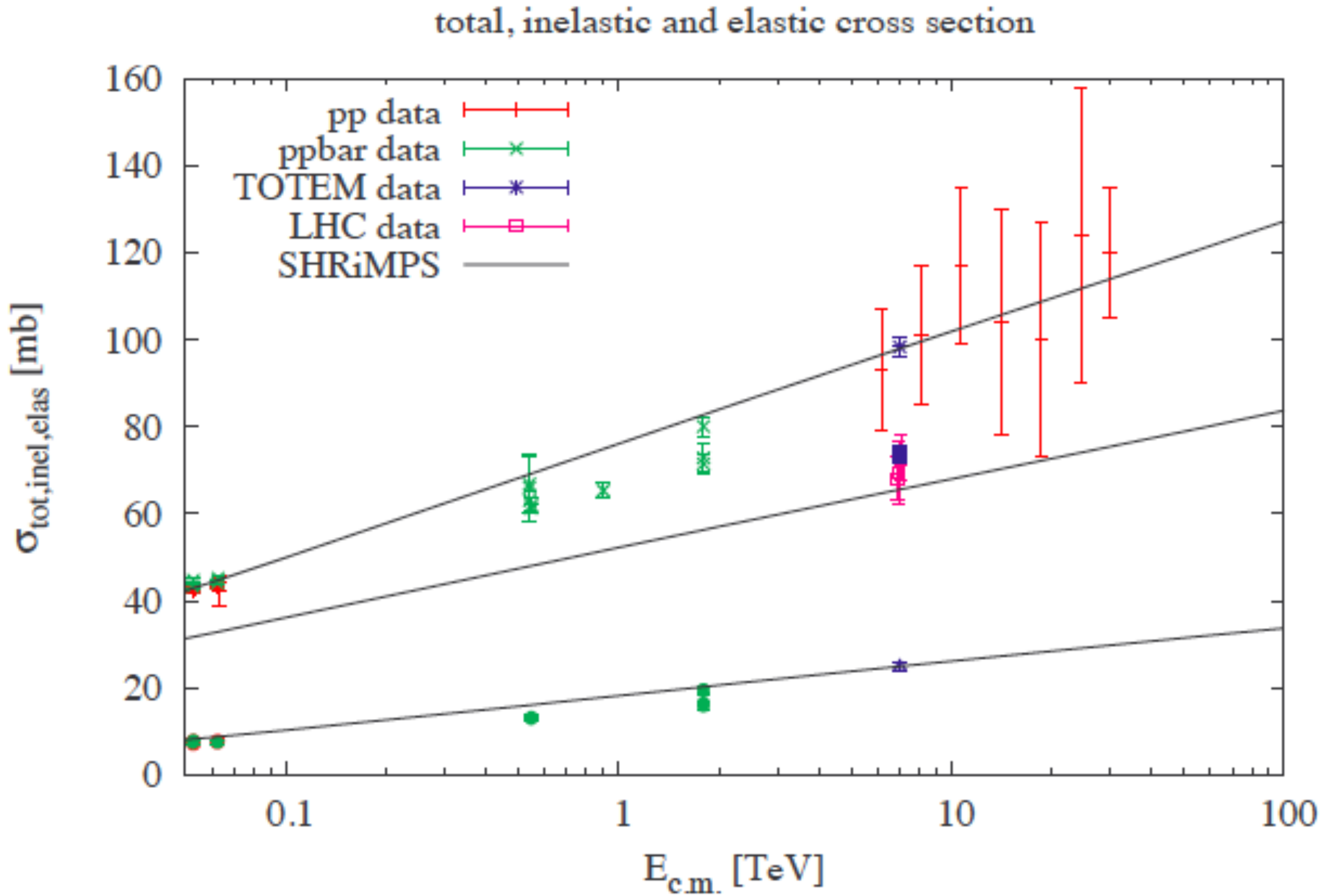


Some Investigations / Progress since, But still not Fully solved and Remains a challenge

- HERWIG++ with underlying event tune UE7-2 contains no explicit model of diffraction, but produces large gaps at higher than measured rate and a "bump" near $\Delta\eta^F = 6$

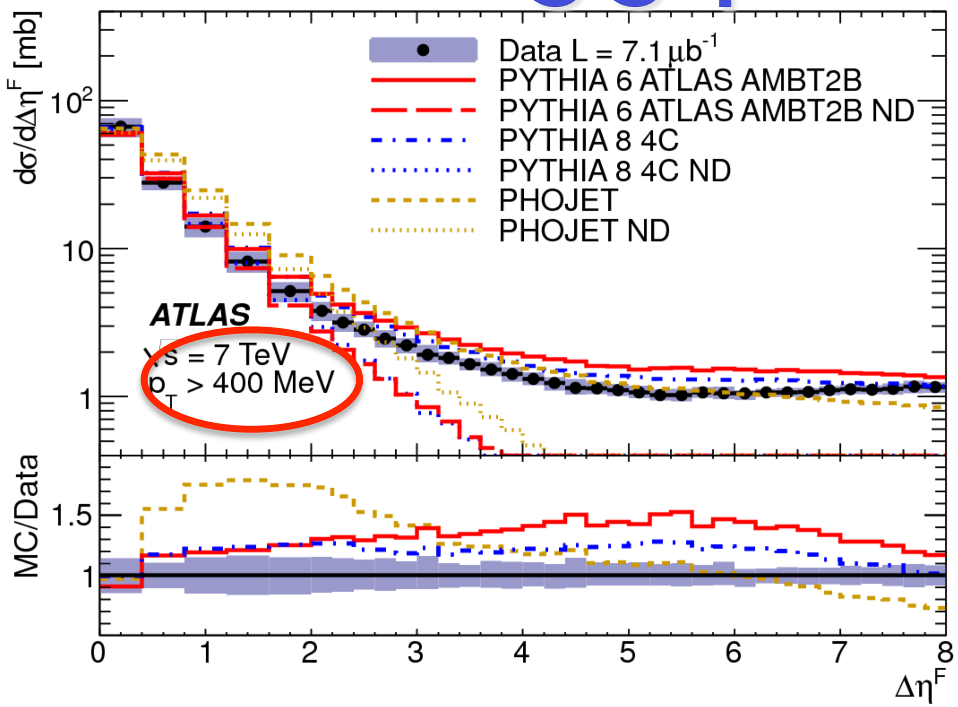
- Effect not killed by removing colour reconnection or events with zero soft or semi-hard scatters in eikonal model

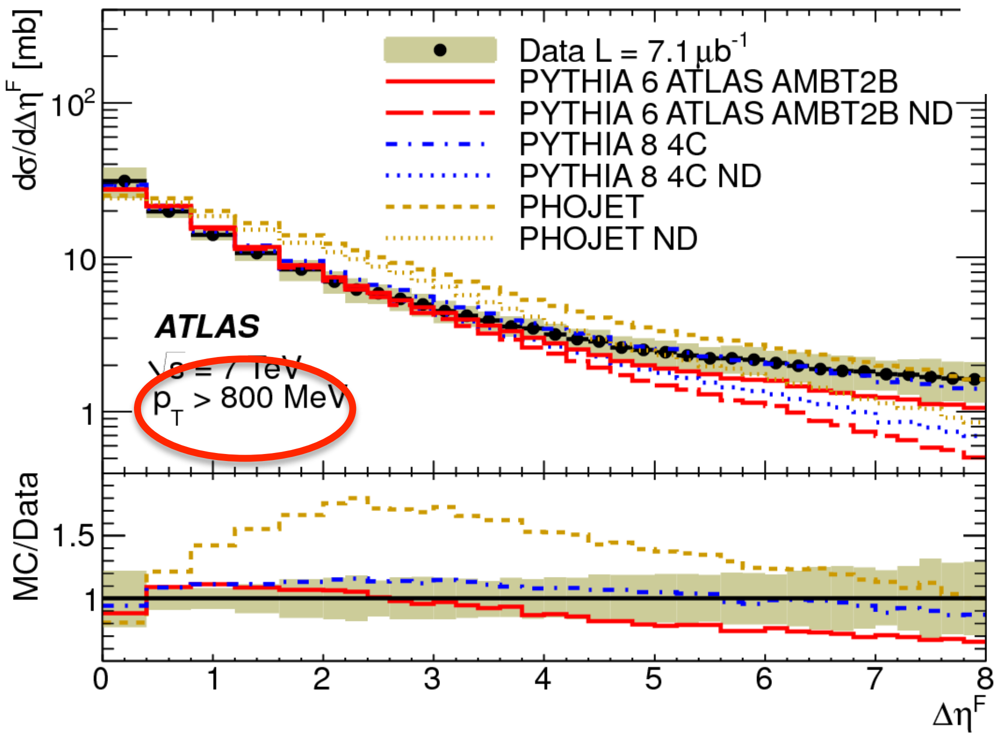
SHRiMPS (MB in SHERPA): sneak preview



Increasing the pt cut defining gaps

As p_t^{cut} increases, data shift to larger $\Delta\eta^F$ in a manner sensitive to hadronisation fluctuations and underlying event

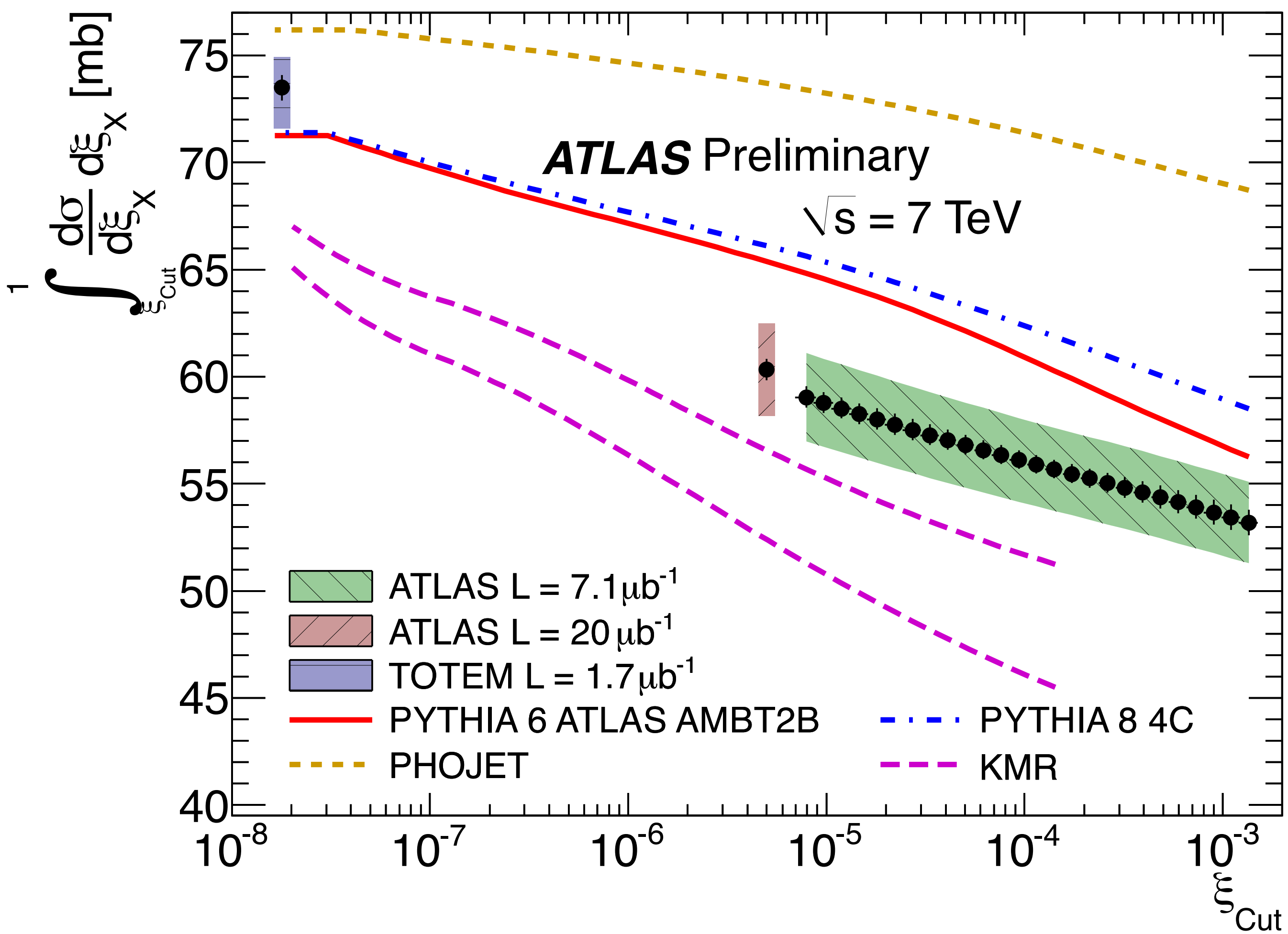




- Switching to p_t^{cut} = 400 MeV doesn't change qualitative picture

- Diffractive / non-diffractive processes barely distinguished at p_t^{cut} = 800 MeV

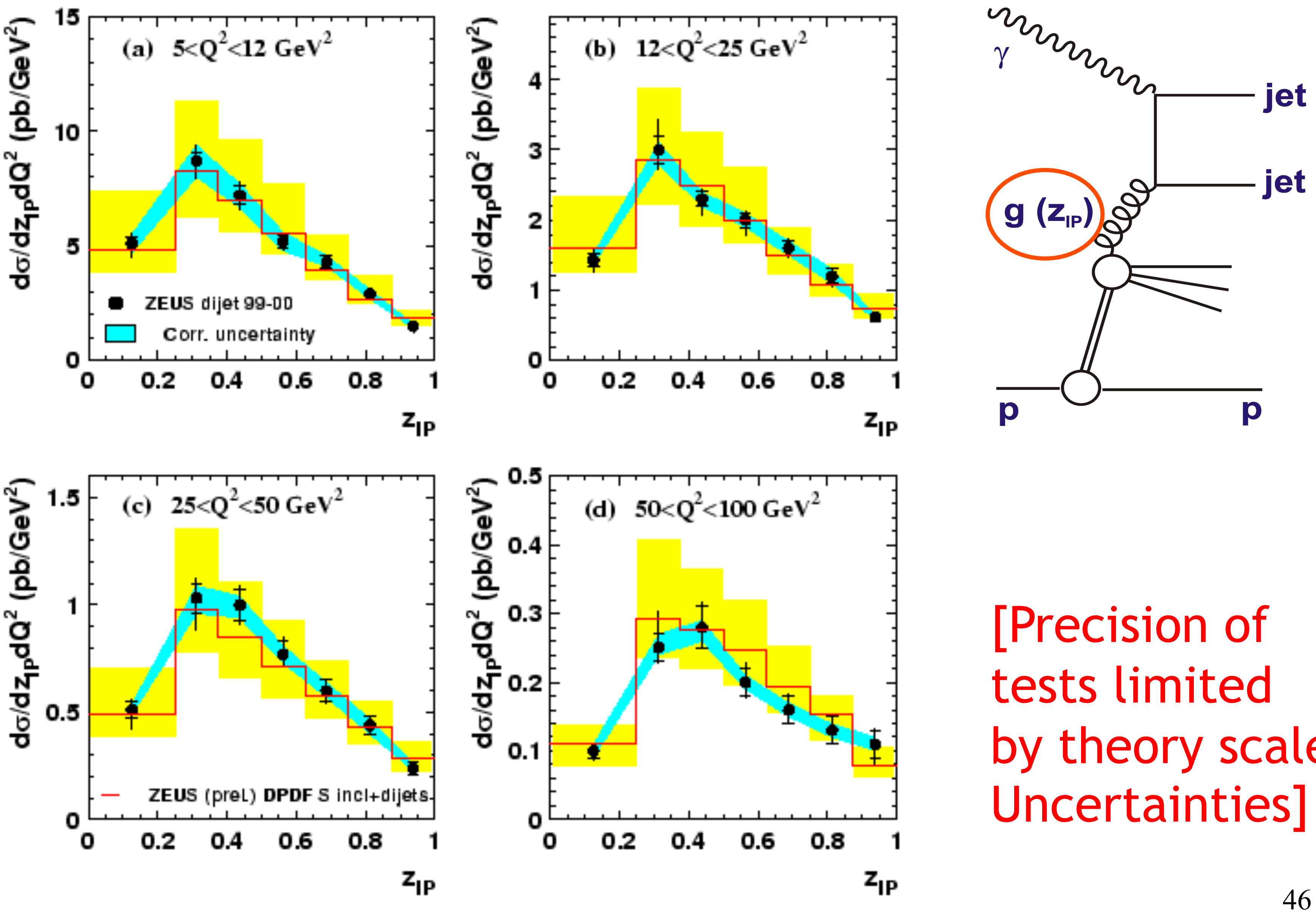
Investigating the Low ξ Extrapolations



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

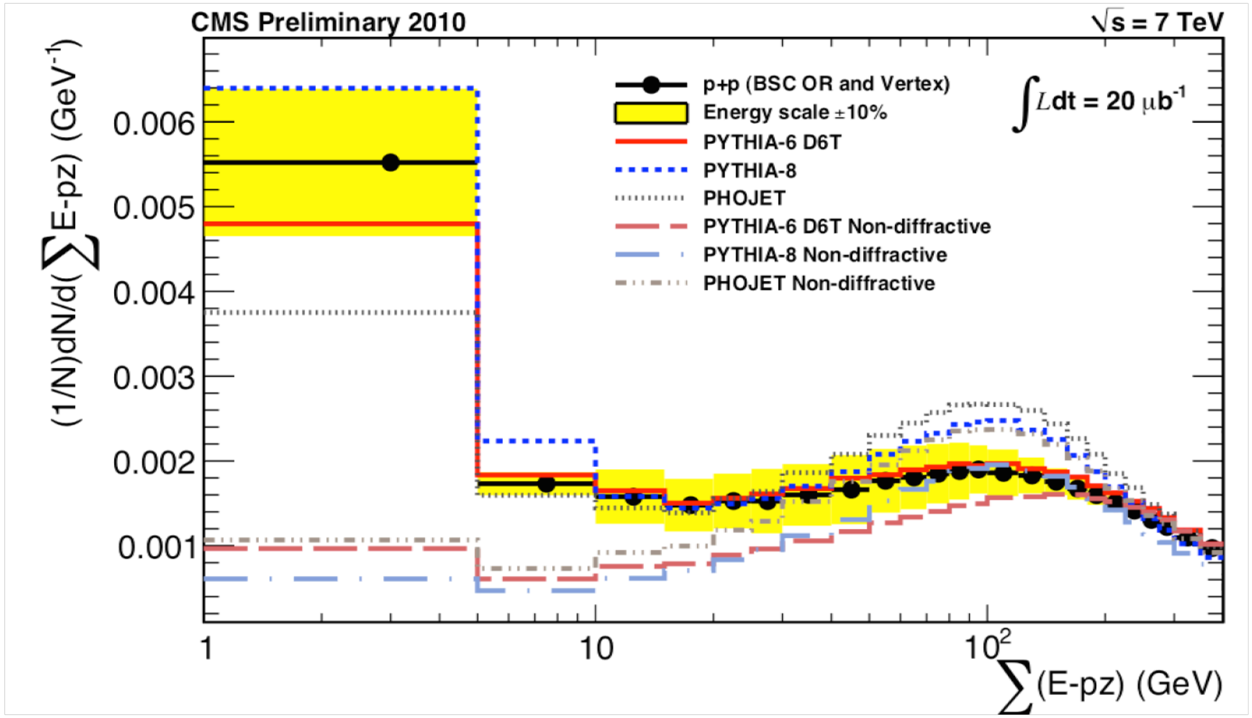
- Integrating ATLAS gap cross section up to some max $\Delta\eta^F$ (equivalently min ξ_X) and comparing with TOTEM indicates that small ξ_X region underestimated in PHOJET and PYTHIA:
- 14 mb with $\xi < 10^{-5}$, compared to 6 (3) mb in PYTHIA (PHOJET)

Example of DPDFs Predicting Diffractive DIS



[Precision of tests limited by theory scale Uncertainties]

A Promising Variable to Reconstruct ξ_X in Hard Diffractive Processes



$$\sum_X E - p_z \approx 2E_p \cdot \xi_X$$

for dissociation system in +z direction

… and lost particles have E-p_z ~ 0

$$\tilde{\xi}^+ = C\frac{\sum (E^i + p_z^i)}{\sqrt{s}}$$

Define for dissociation system in the -z direction (and E+pz for +z dissociation).

… well correlated with ξ at low ξ

Small Gaps & Hadronisation Fluctuations

Eur. Phys. J. C (2010) 69: 85–93
DOI 10.1140/epjc/s10052-010-1392-5

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Diffraction and correlations at the LHC: definitions and observables

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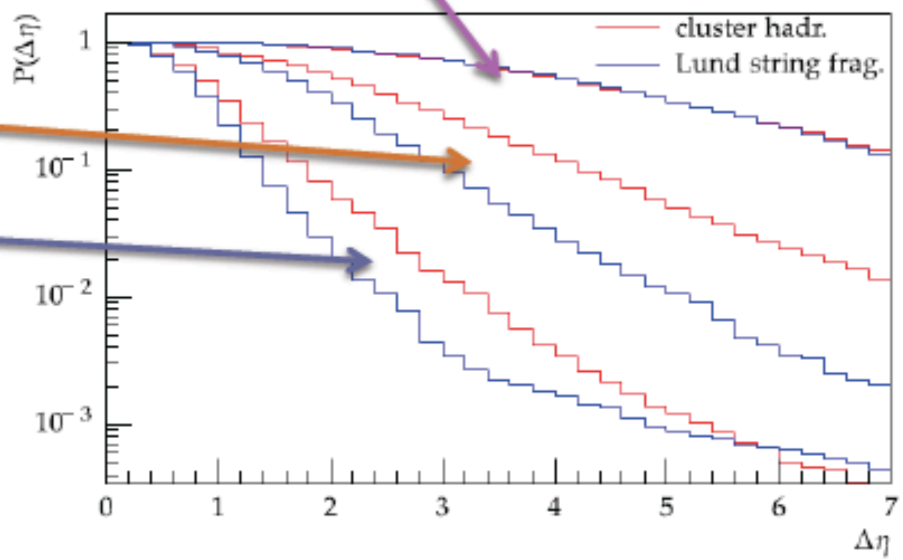
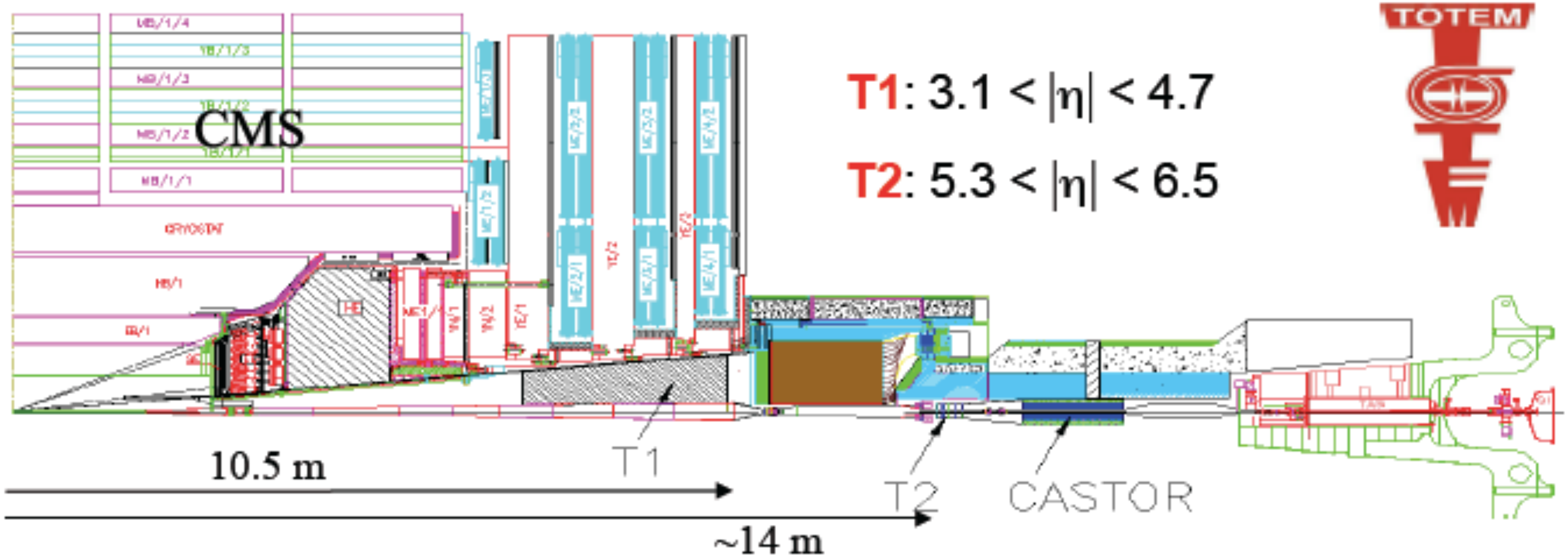


Fig. 4 Probability for finding a rapidity gap (definition 'all') larger than $\Delta\eta$ in an inclusive QCD event for different threshold $p_\perp$. From top to bottom the thresholds are $p_{\perp,\mathrm{cut}} = 1.0, 0.5, 0.1$ GeV. Note that the lines for cluster and string hadronisation lie on top of each other for $p_{\perp,\mathrm{cut}} = 1.0$ GeV. No trigger condition was required, $\sqrt{s} = 7$ TeV

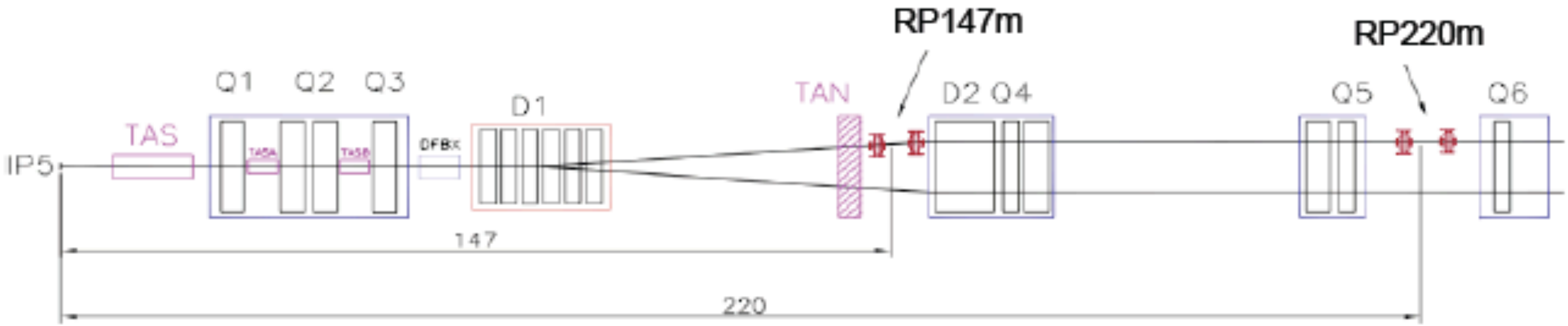
Very large uncertainties in probability for hadronisation fluctuations in non-diffractive events to produce large gaps

TOTEM and the Elastic Cross Section



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

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



- With CMS, the most hermetic detector ever?
- Elastic scattering measurement using Roman pots at 220m