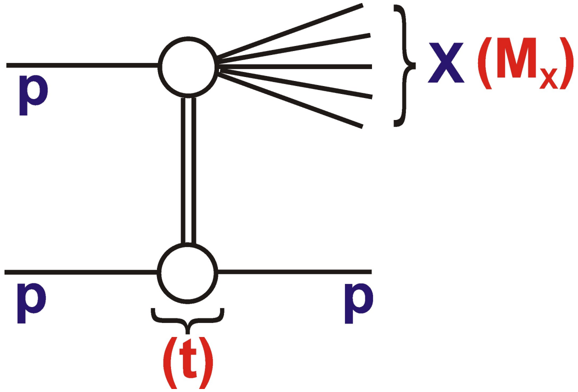
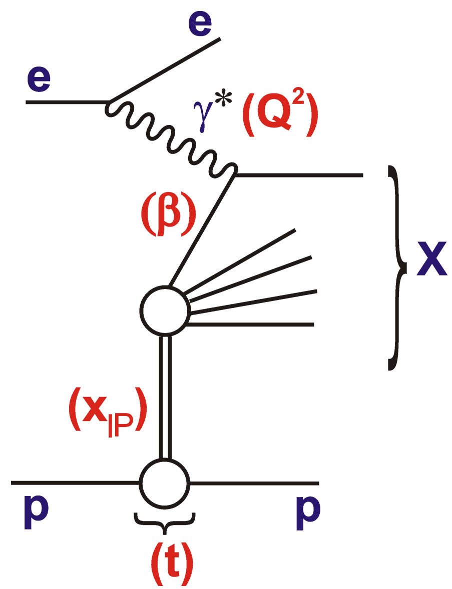
Diffraction and Multi-Parton Interactions: an experimental perspective

Paul Newman (University of Birmingham)



MPI@LHC, DESY
23 November 2011



→ Diffraction and Multi-Parton Interactions
→ Soft diffraction at the LHC
→ Radiation patterns between jets at the LHC
→ Diffractive DIS at HERA → Diffractive Partons
→ Testing the Diffractive Partons at HERA
→ Breaking the Diffractive Partons: γp, pbar-p & pp

Diffraction & Multi-Parton Interactions

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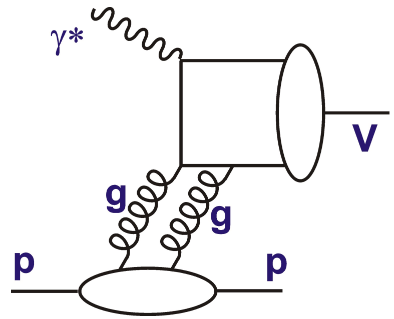
- Trivially, more than 1 parton in t channel



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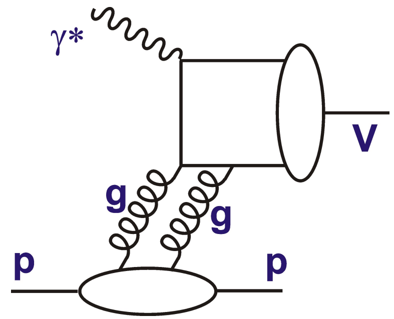
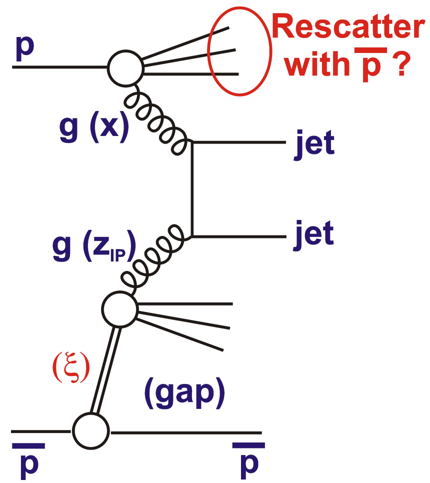
- Gap survival probabilities / absorption:
… multiple interactions with large impact parameters





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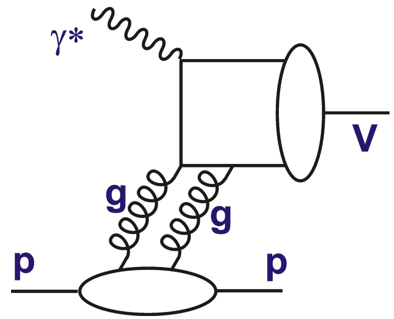

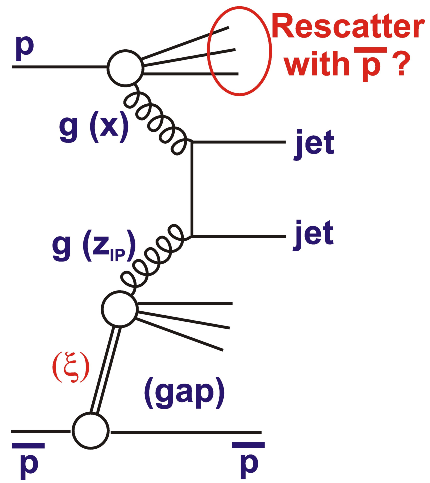

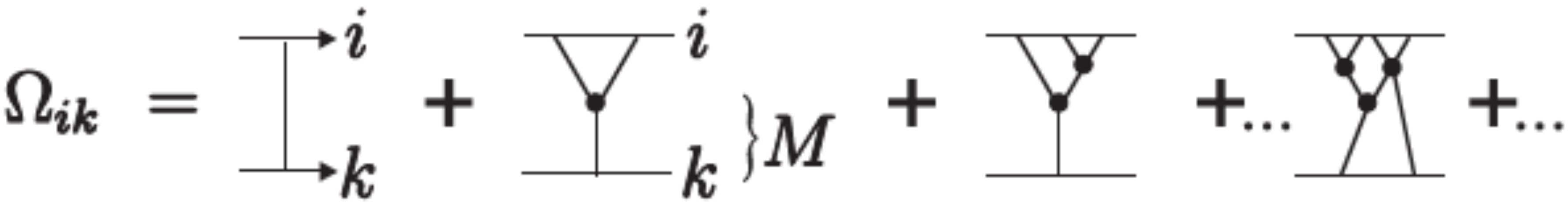

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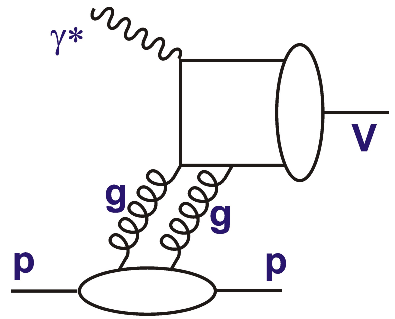

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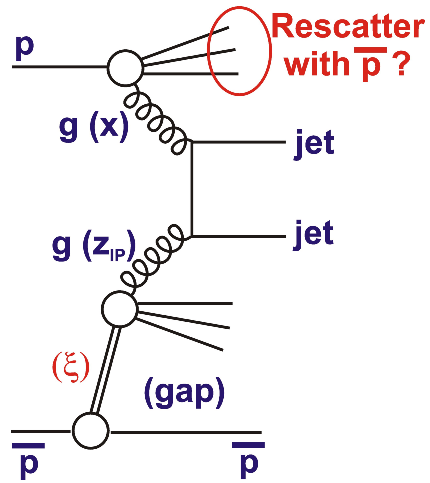

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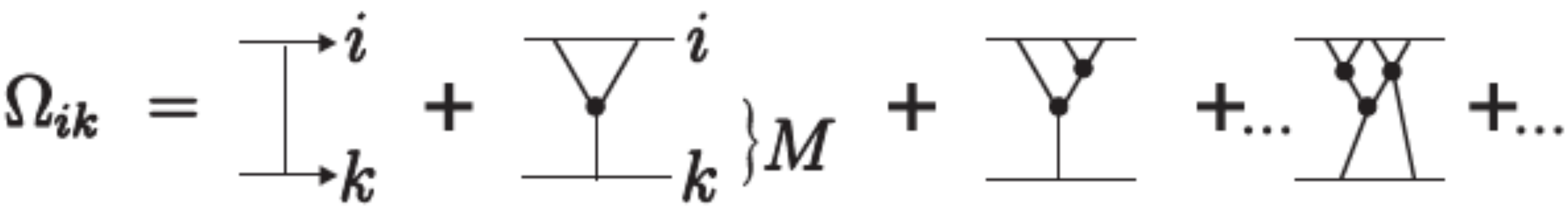
- Less obviously, small rapidity gaps as sensitive probe of hadronisation fluctuations and underlying event



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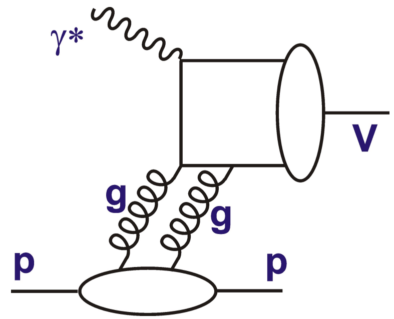

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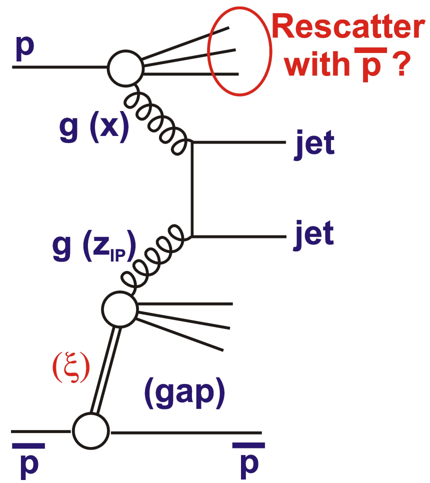

- Absorptive effects due to multiple soft exchanges in minimum bias models

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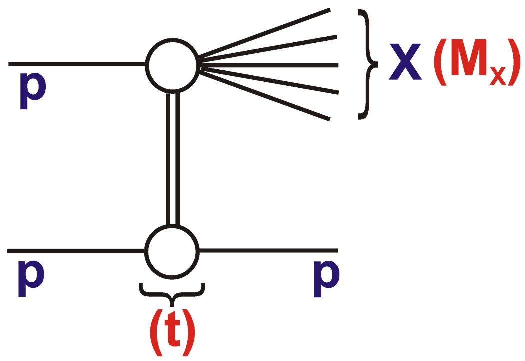
Not covered here

- Elastic scattering in pp / ppbar (see Ken Osterberg)
- Exclusive vector mesons in ep and pp (see Marcella Capua)

Soft Diffraction at the LHC: Processes and Kinematic Variables

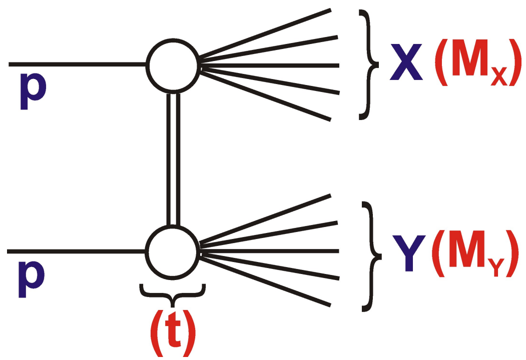
Single diffractive (SD), pp → Xp

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



Double diffractive (DD), pp → XY

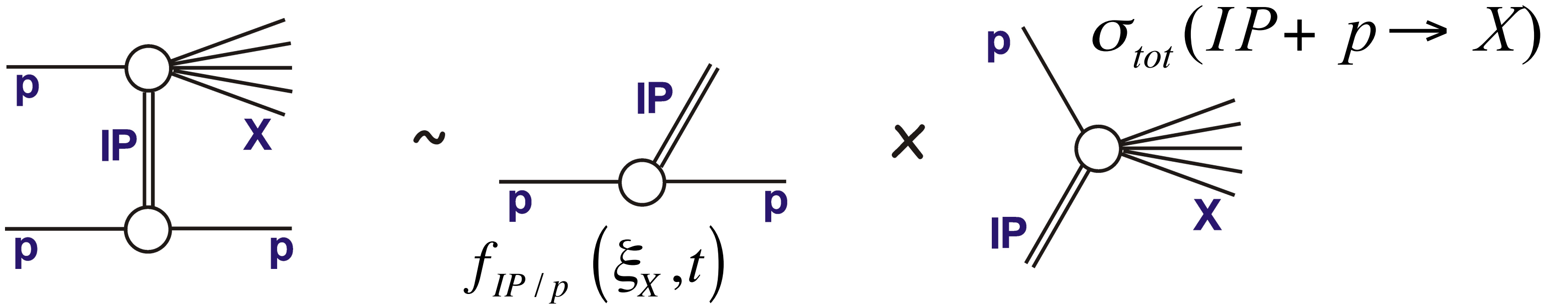
$$\xi_Y = M_Y^2/s$$



- At LHC energies, M_X, M_Y can range from m_p+m_π → ~1 TeV
- Large uncertainties in LHC cross sections, especially DD
- No proton tagged SD data (yet) …
  - … integrate over t
  - … select based on energy flow / rapidity gap topologies

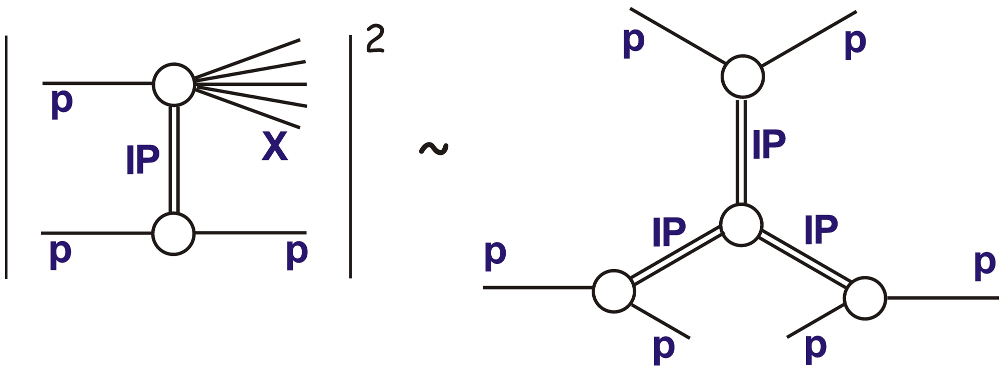
"Standard Model" of Soft Diffraction

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



Optical theorem relates σ_{tot}(IP+p) to elastic IP+p amplitude

Calculate SD cross sections from triple pomeron amplitudes



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

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

i.e approx: $\frac{d\sigma}{d\xi_X} \propto \frac{1}{\xi_X}$

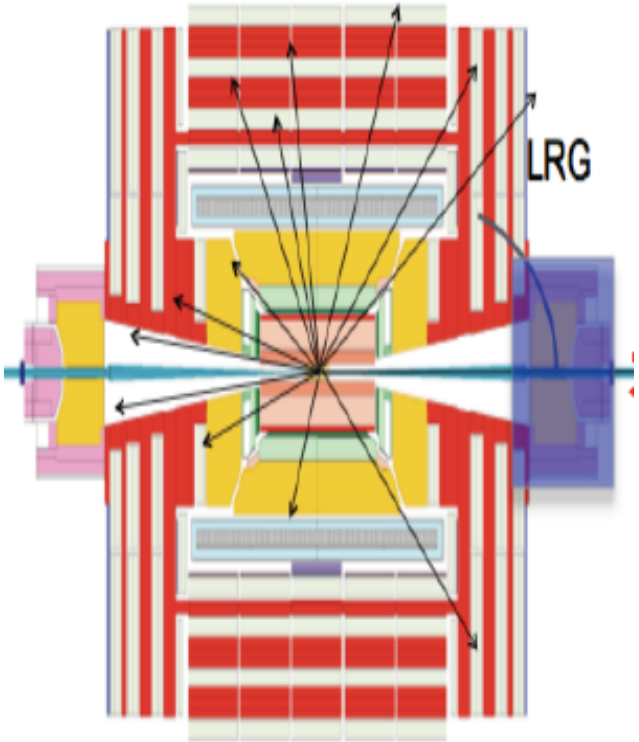
PHOJET, PYTHIA models based on this approach.

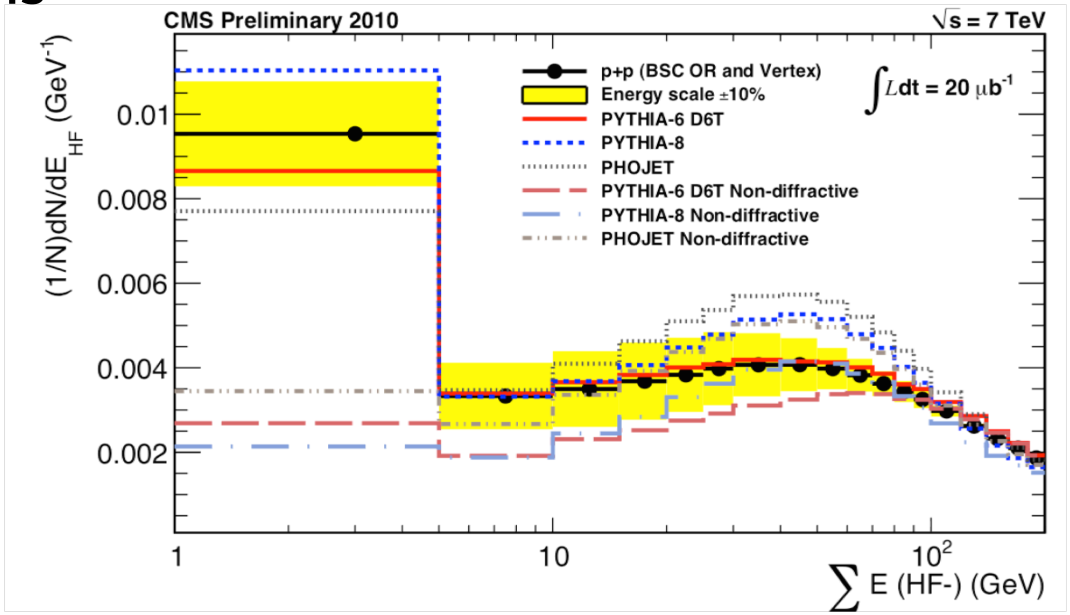
Real life $\alpha(0) \neq 1$ … LHC data sensitive to this

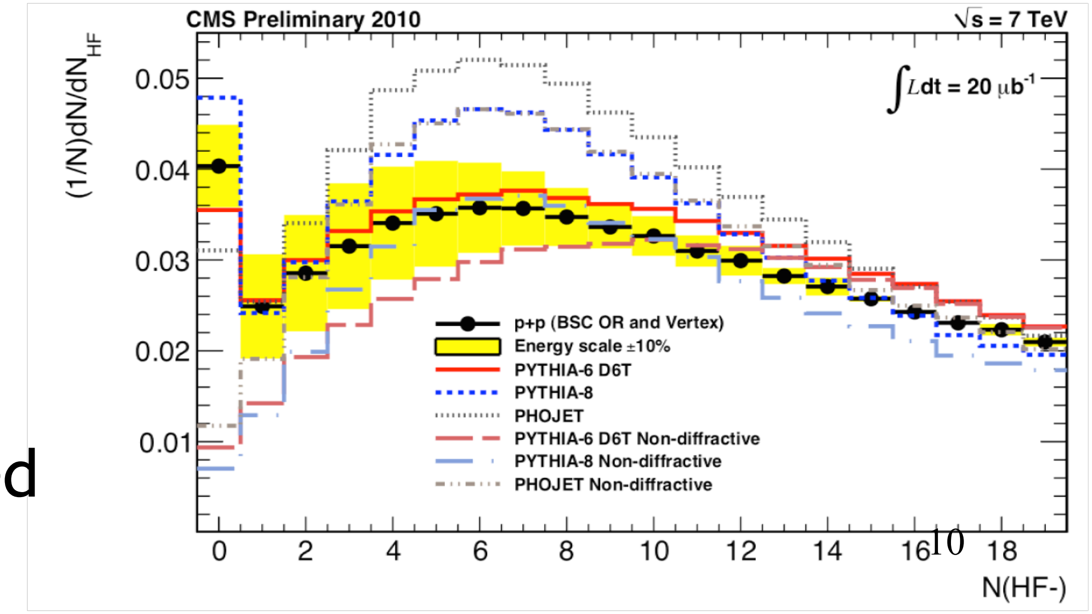
Deviations from triple-pom behaviour from multiple interactions?

CMS: Forward energy flow approach

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

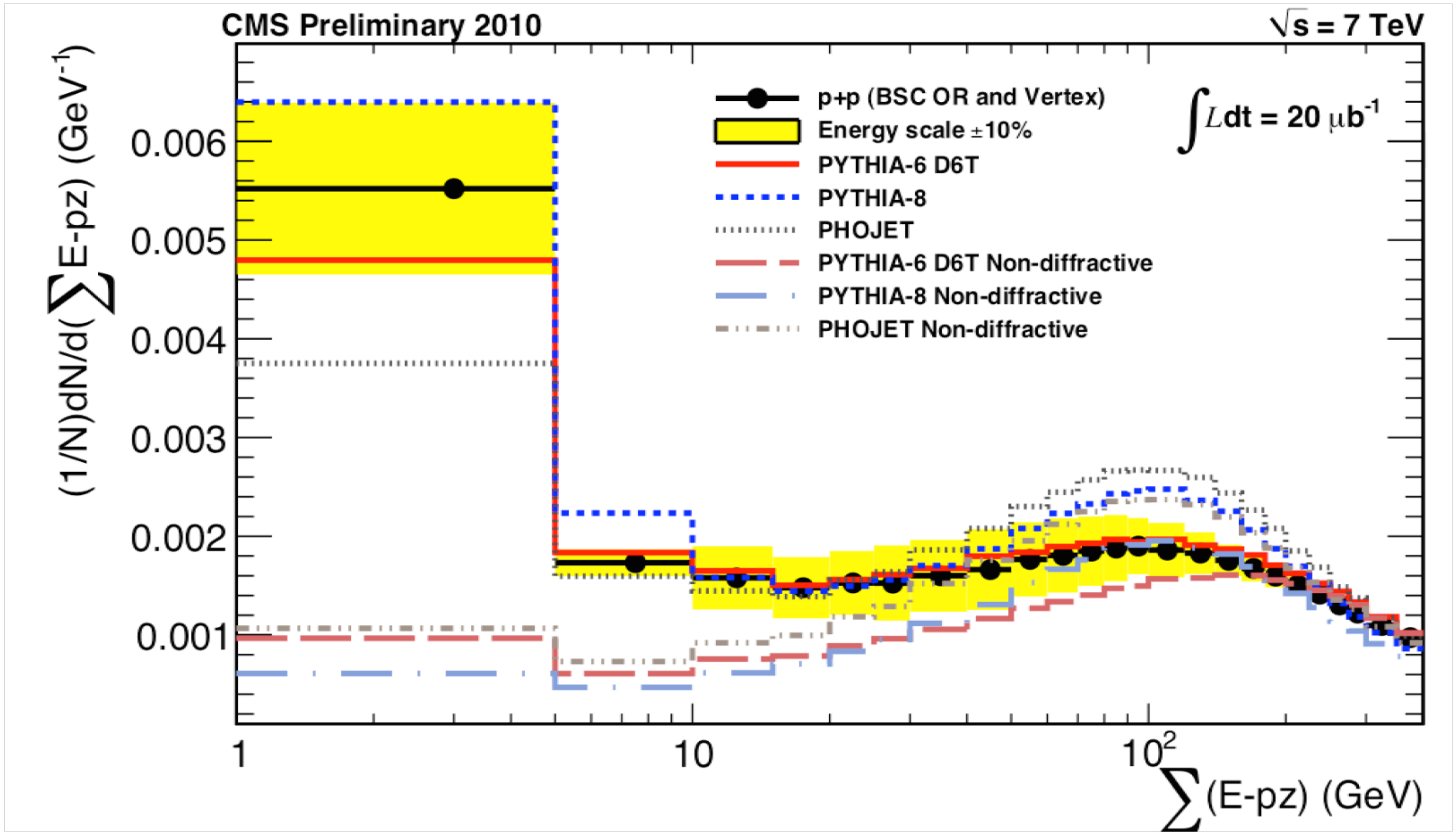






Excess of events with diffractive topology observed at all 3 LHC beam energies

A Promising Variable to Reconstruct ξ_X

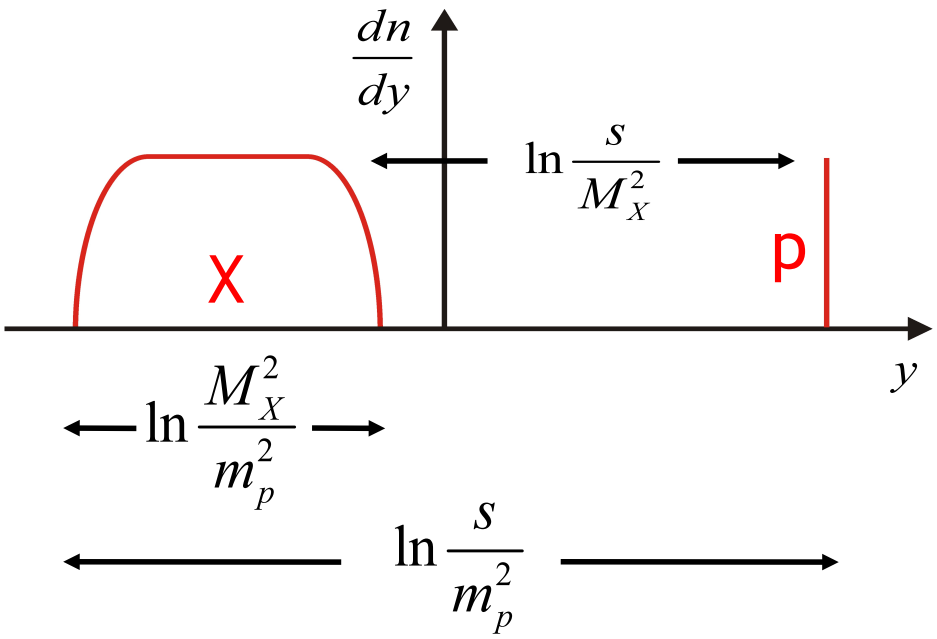


Potentially strong sensitivity to diffractive dynamics

$$\sum_X E - p_z = 2E_p \cdot \xi_X$$ … and lost particles have $E\text{-}p_z \sim 0$

So far uncorrected for experimental effects

Alternative Approach: Rapidity Gaps



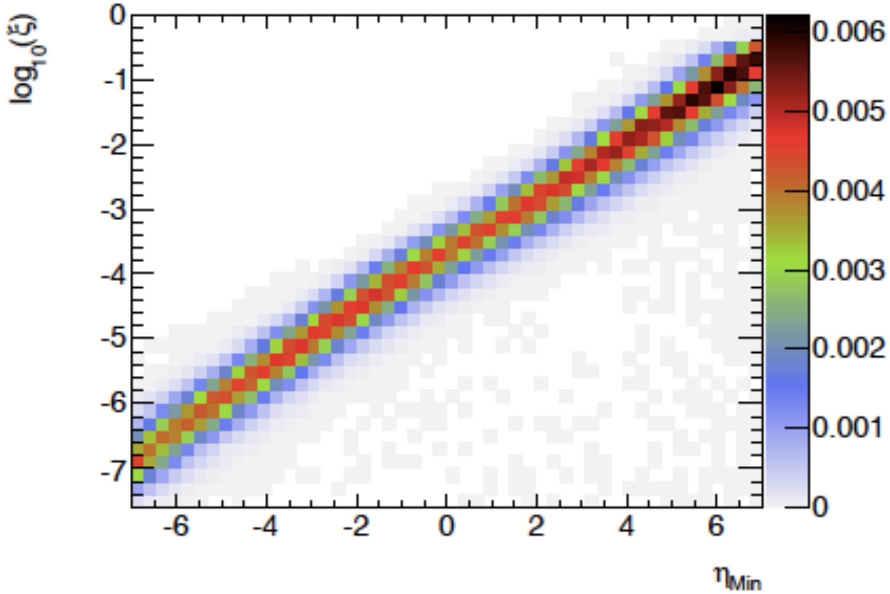
Up to event-by-event hadronisation fluctuations, ξ variables are predictable from empty rapidity regions

→Large rapidity gaps

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

and ~ flat gap distributions

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



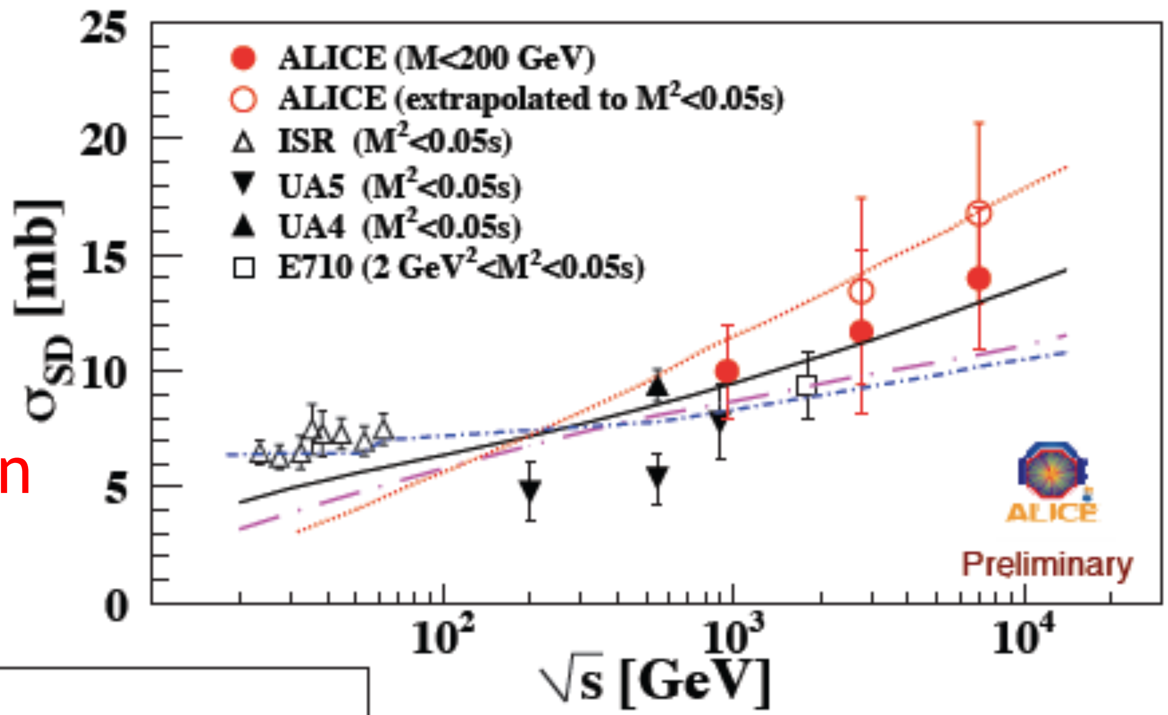
LHC coverage (|η| < 4.9) gives sensitivity with large gap to:

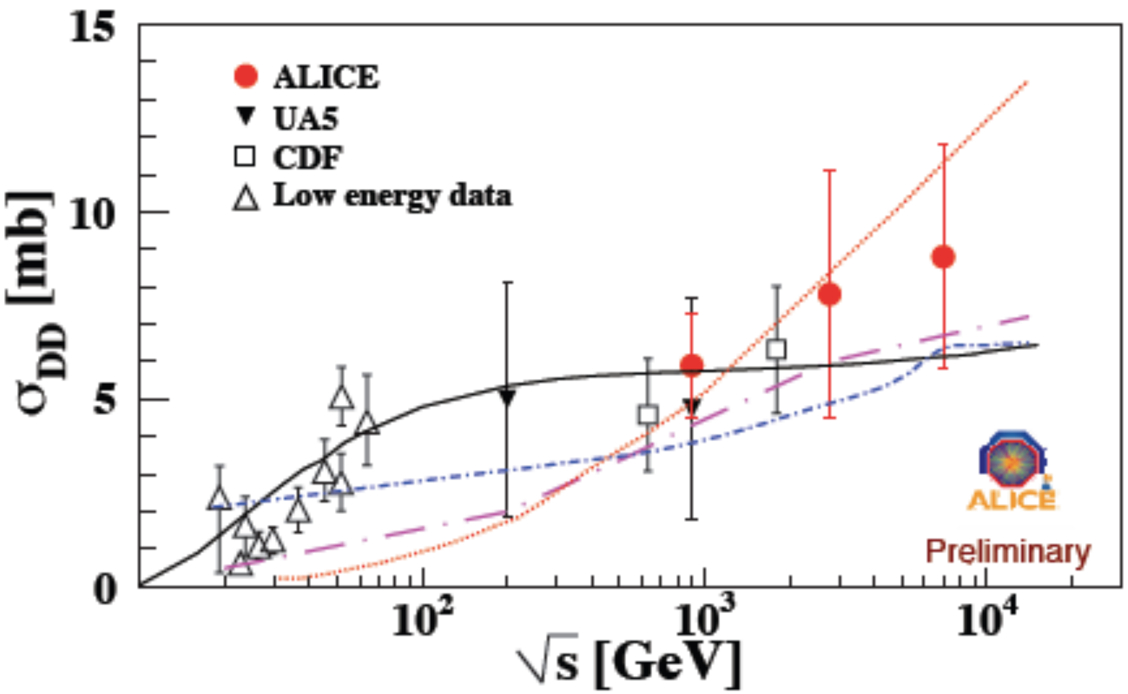
$10^{-6} <\sim \xi <\sim 10^{-2}$

(equivalently 7 <~ M_X <~ 700 GeV)

ALICE: Total SD and DD Cross Sections

ALICE: Unfold integrated SD and DD cross sections at all three CMS energies based on 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

ATLAS: Differential gap x-sections

NEW!

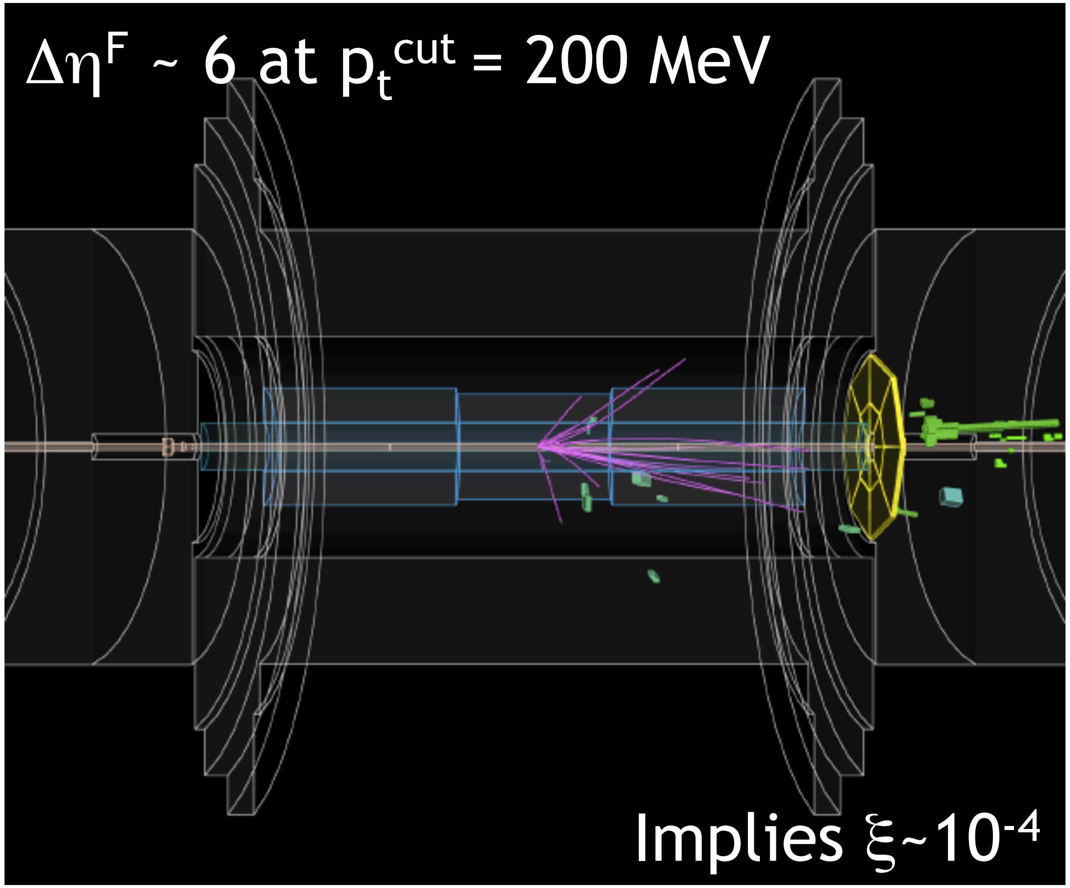
- Cross sections measured from first $\sqrt{s}$ = 7 TeV LHC run
- Differential in rapidity gap size $\Delta\eta^F$
- $\Delta\eta^F$ extends from $\eta = \pm 4.9$ to first particle with $p_t > p_t^{cut}$

[Larger of gaps at $\pm\eta$ taken]

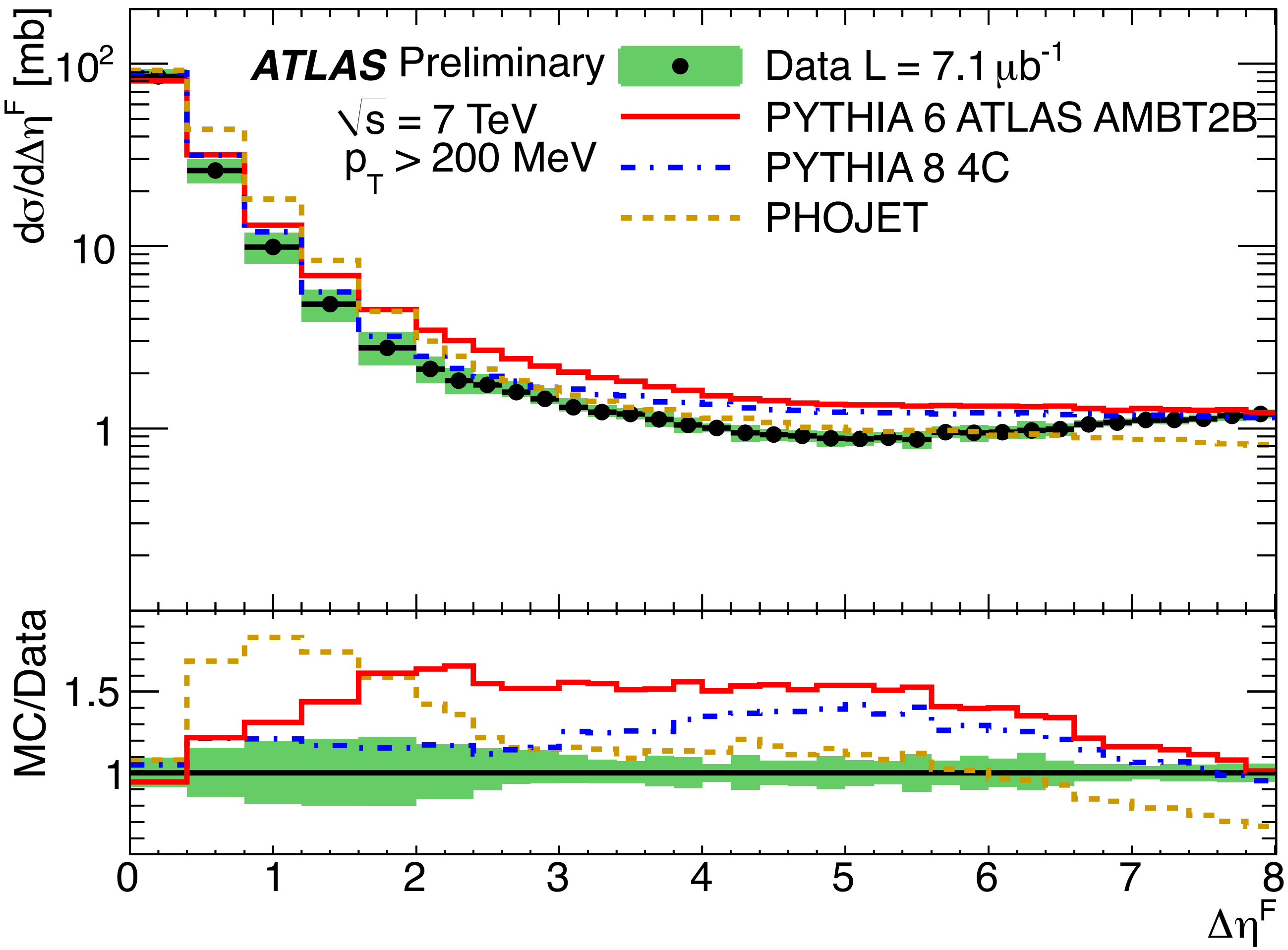
$200 \text{ MeV} < p_t^{cut} < 800 \text{ MeV}$

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

Corrected for experimental effects to level of stable hadron

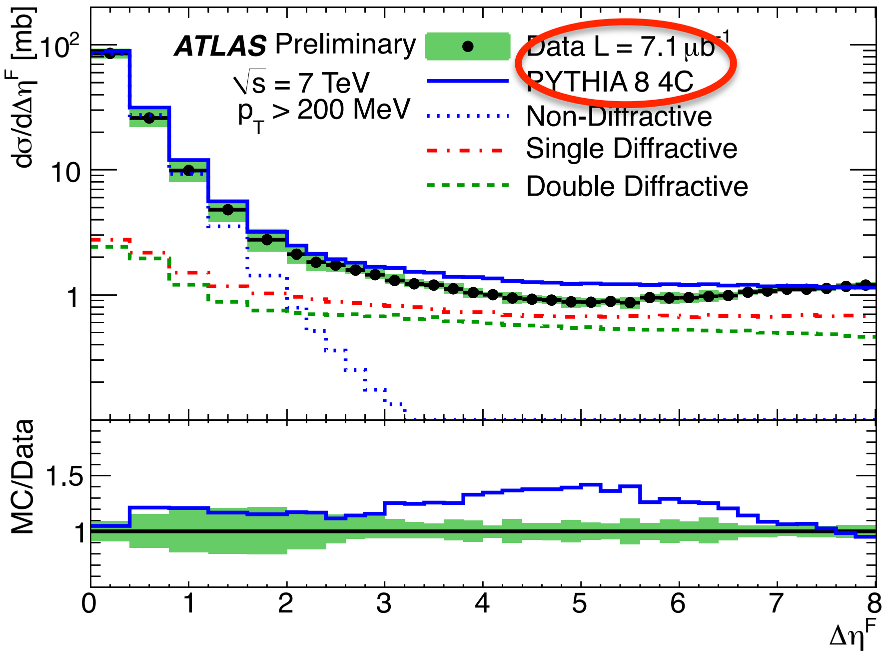


ATLAS Differential Gap Cross Section

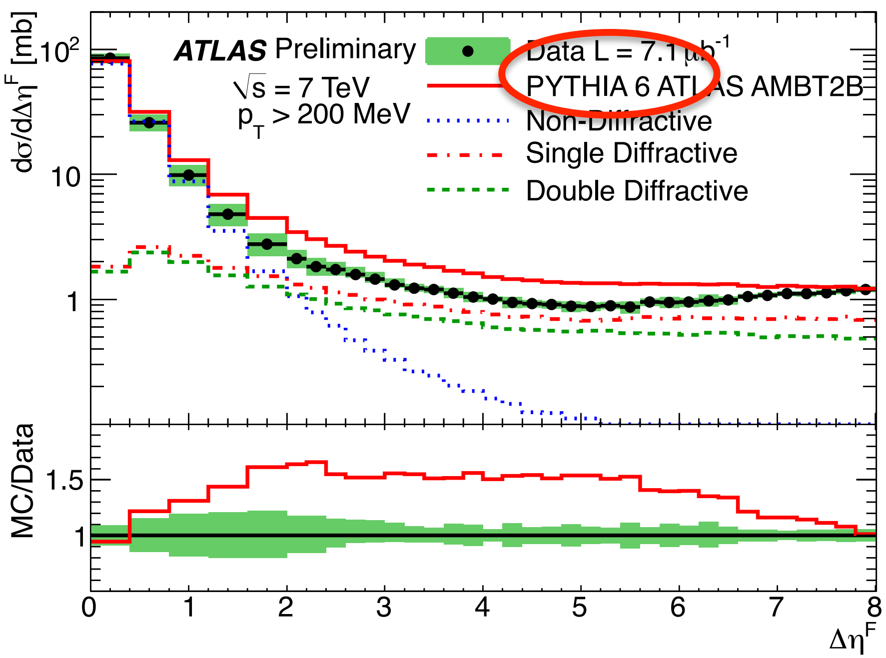


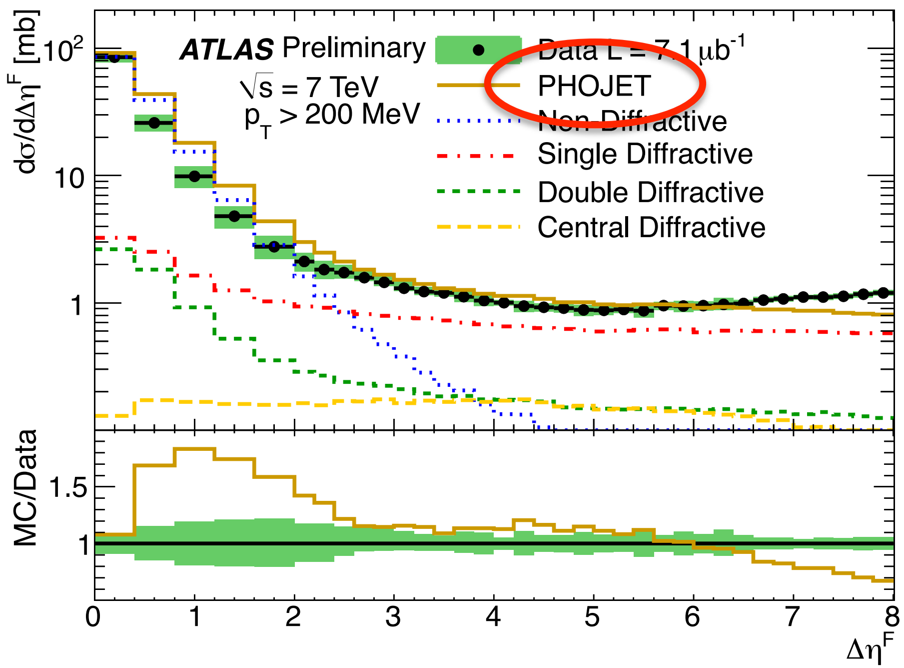
- Precision between ~8% (large gaps) and ~20% ($\Delta\eta^F$ ~ 1.5)
- Small gaps sensitive to hadronisation fluctuations / MPI
- Large gaps measure x-sec for SD [+ DD with M_Y <~ 7 GeV]

Small Gaps and Hadronisation

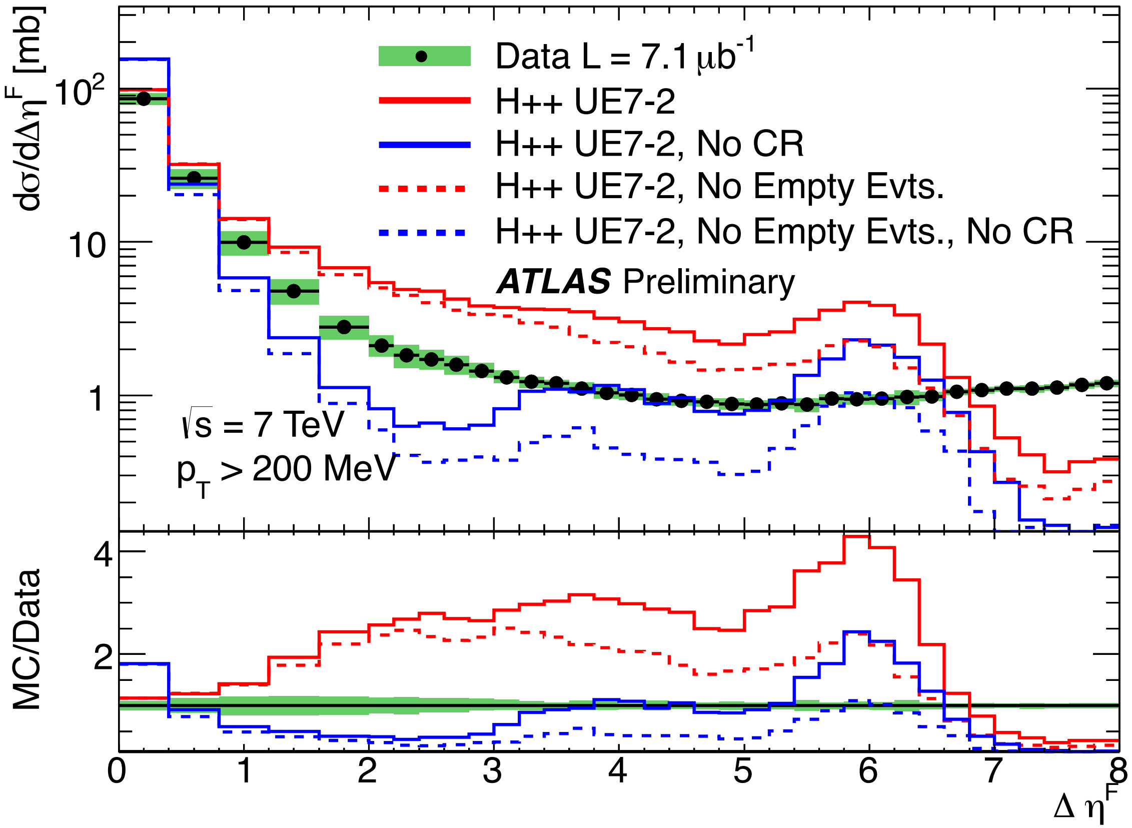


- Big variation between MCs in small non-zero gap production via ND → fluctuations / UE
- PYTHIA8 best at small gaps
- PHOJET > 50% high at $\Delta\eta^F \sim 1.5$





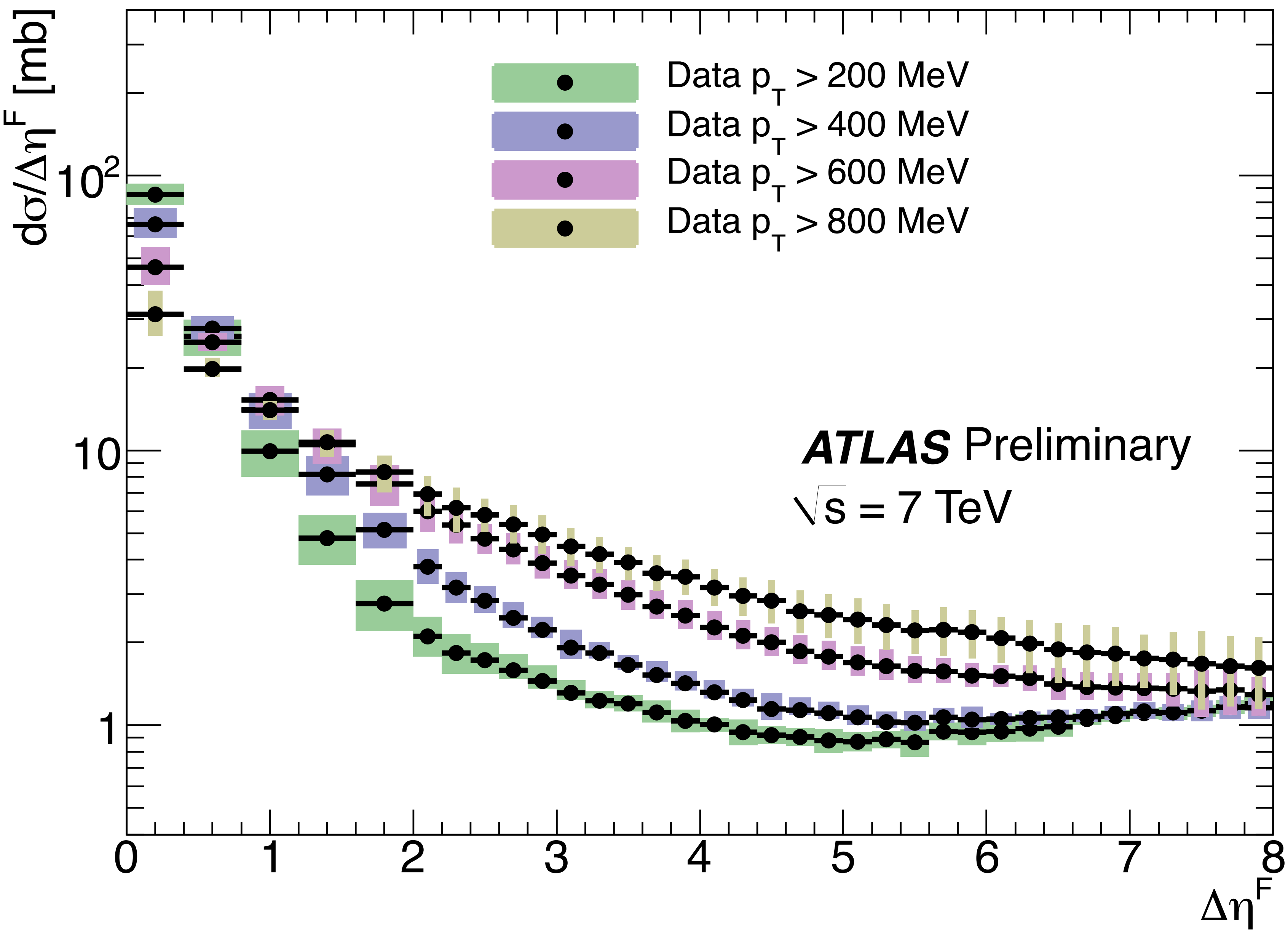
Cluster Fragmentation: HERWIG++



- 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 $\Delta\eta^F = 6$

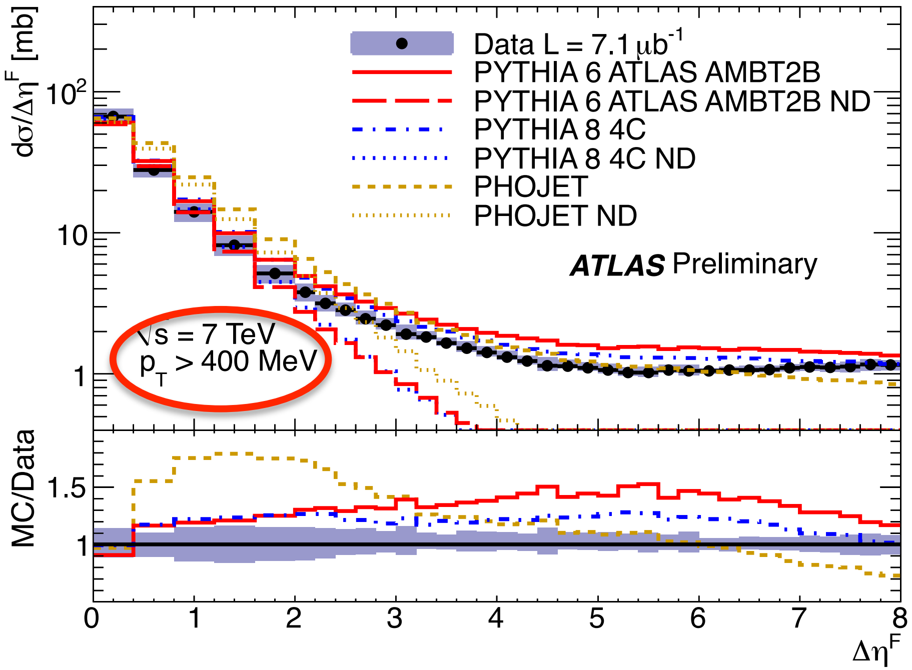
- Effect not killed by removing colour reconnection or events with zero soft or semi-hard scatters in eikonal model

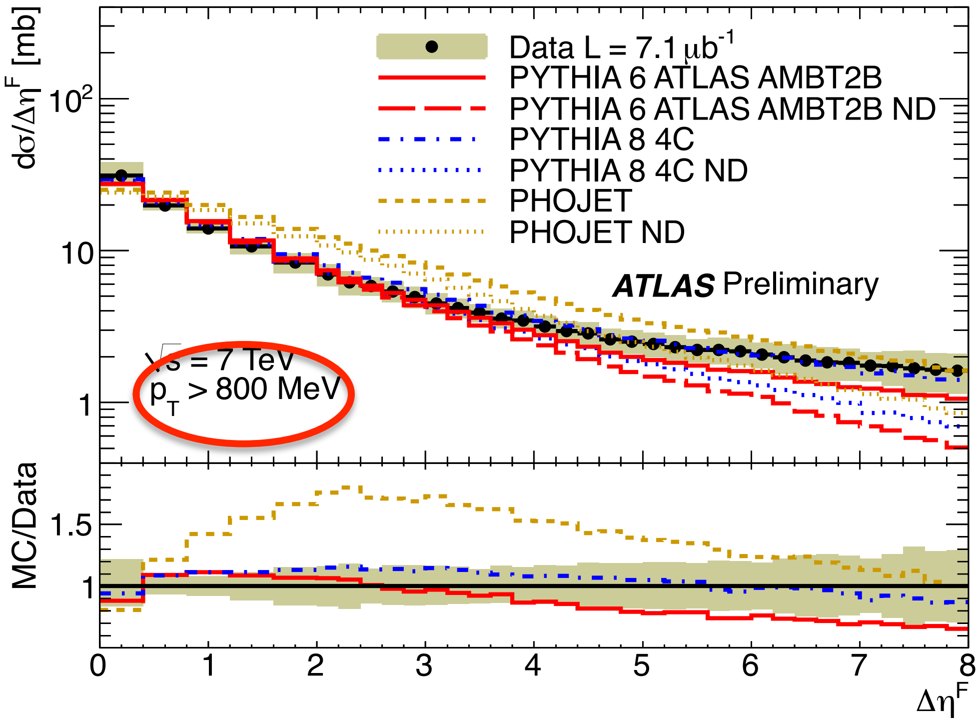
Increasing the pt cut defining gaps



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

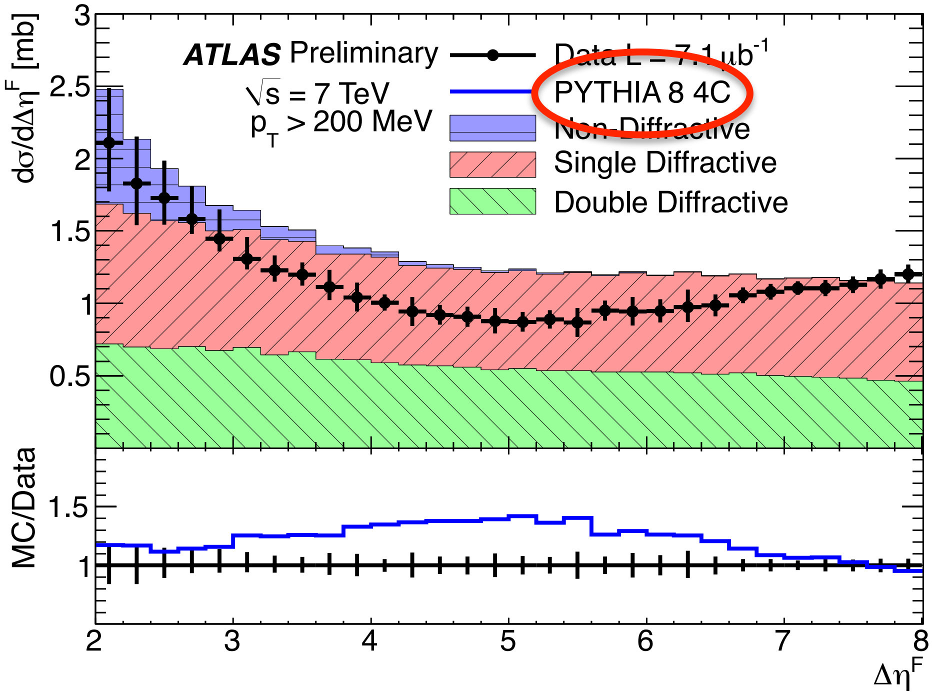




- Switching to p_t^{cut} = 400 MeV doesn't change qualitative picture

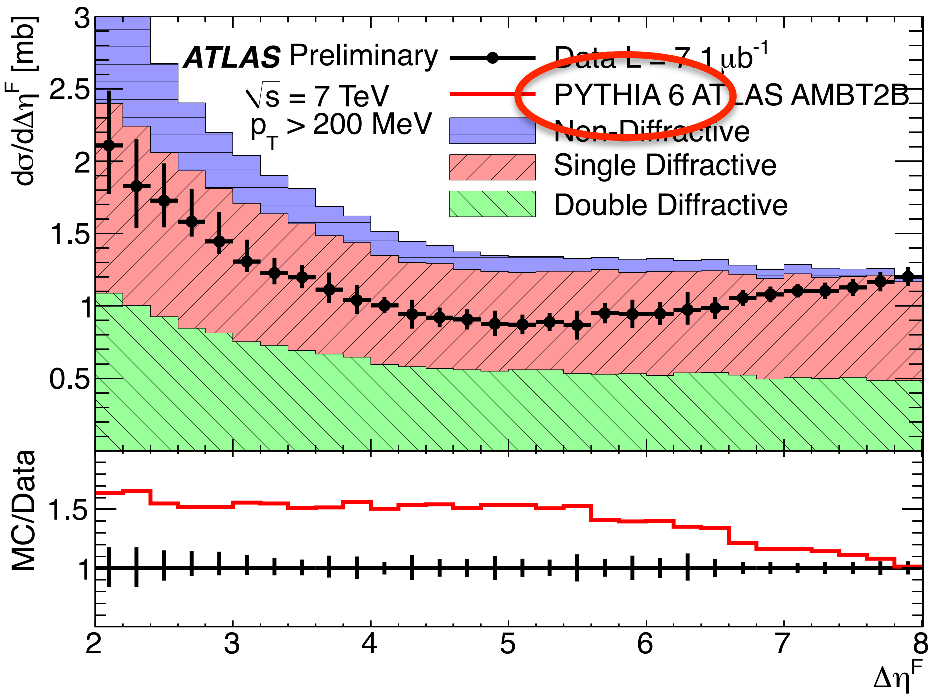
- Diffractive / non-diffractive processes barely distinguished at p_t^{cut} = 800 MeV

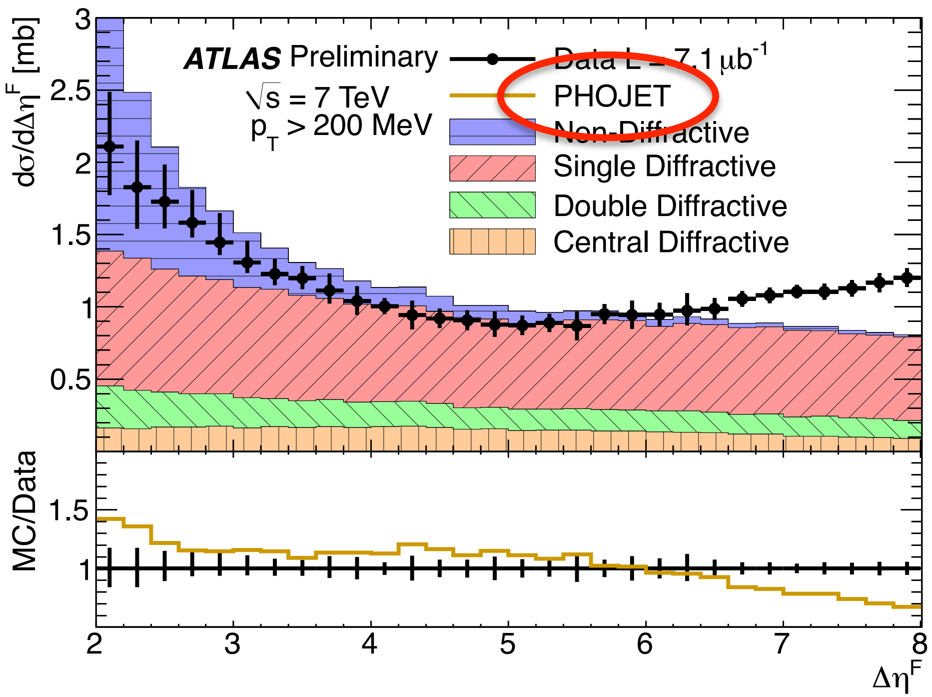
Large Gaps and Diffractive Dynamics



-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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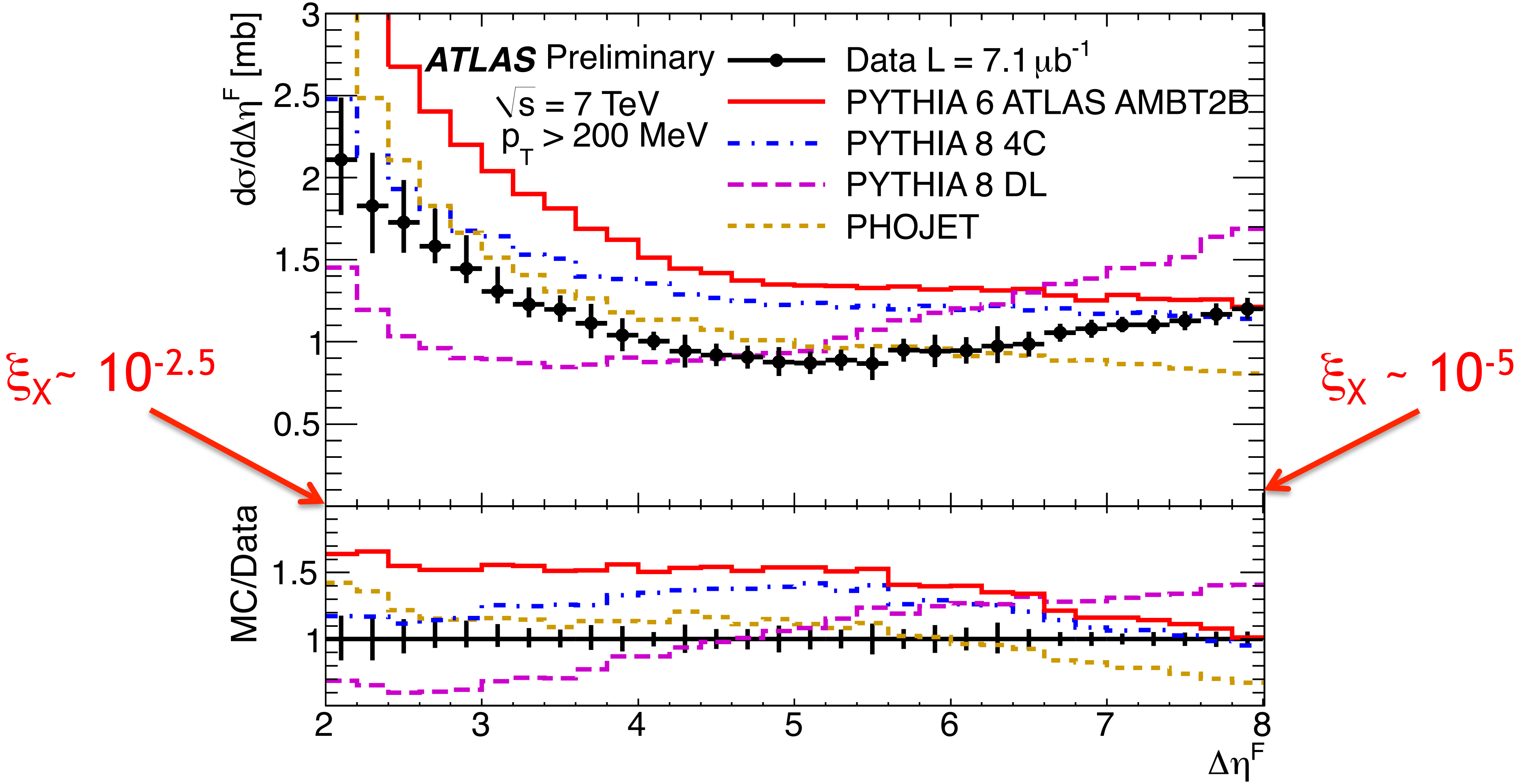


Default PHOJET and PYTHIA models have $\alpha_{IP}(0)$ = 1

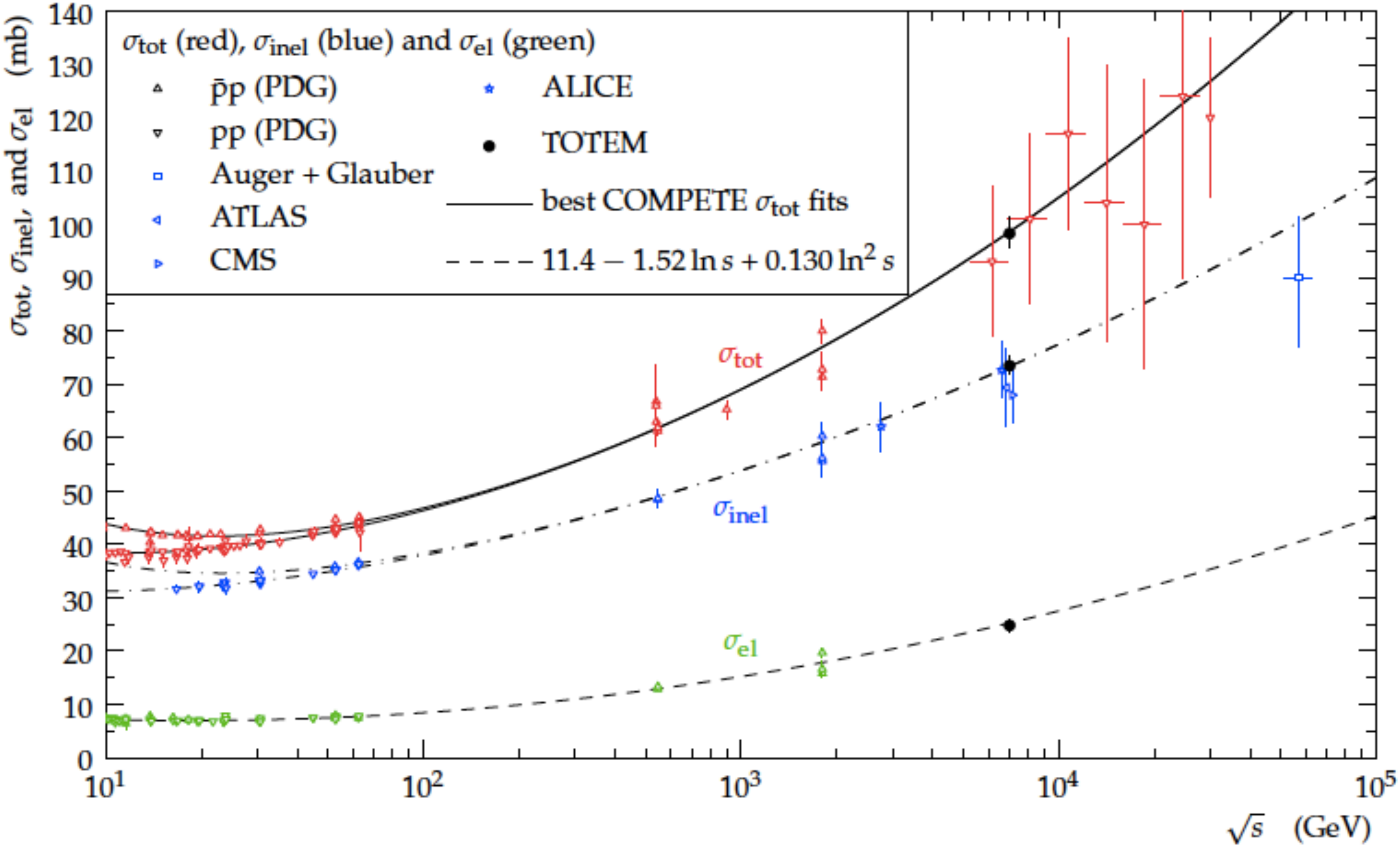
Donnachie-Landshoff flux has $\alpha_{IP}(0)$ = 1.085

Data exhibit slope in between these models at large $\Delta\eta^F_{21}$

Full interpretation pending …

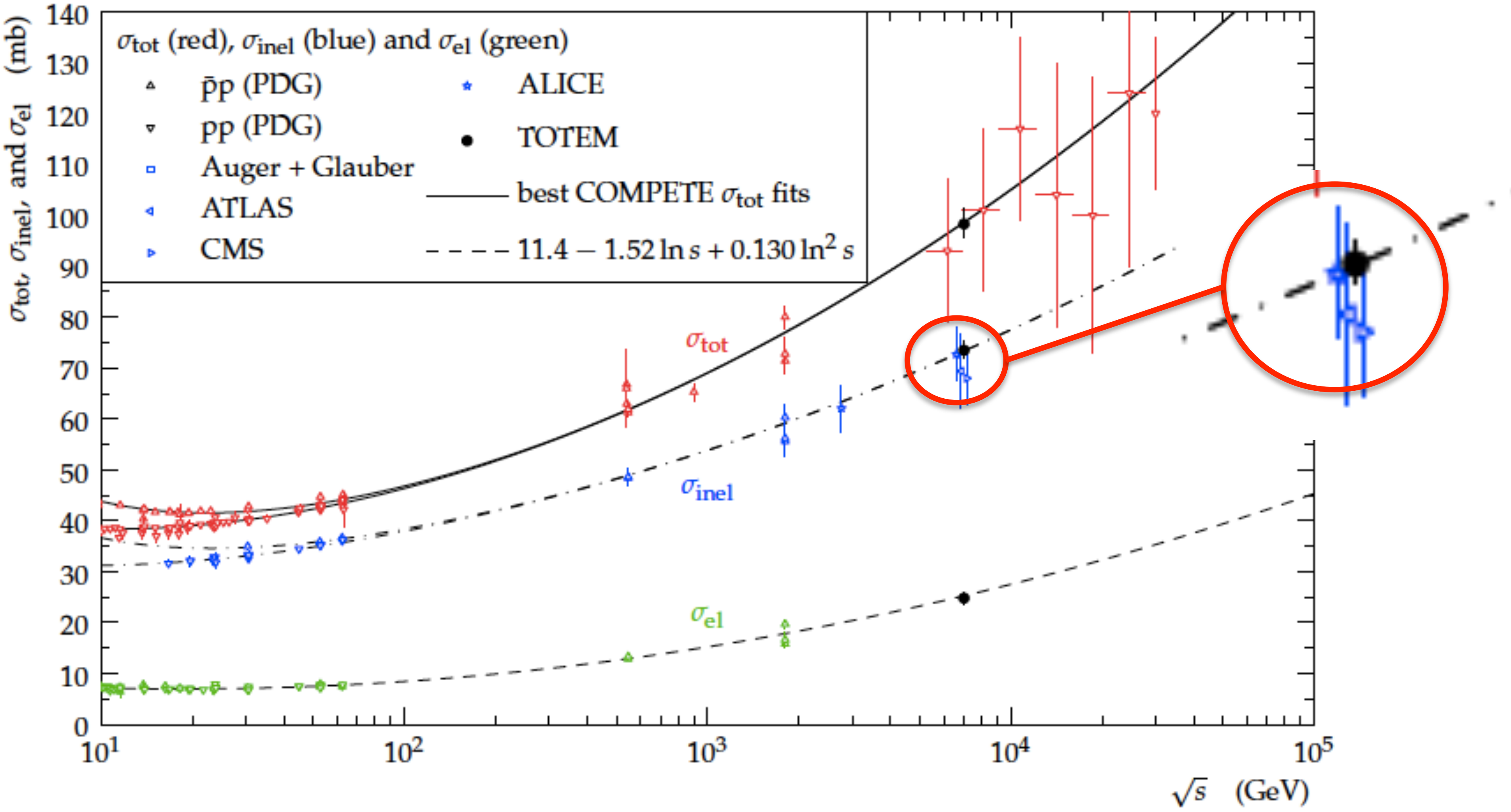
Total Inelastic pp Cross Section

- Full current picture on total cross section (from TOTEM)

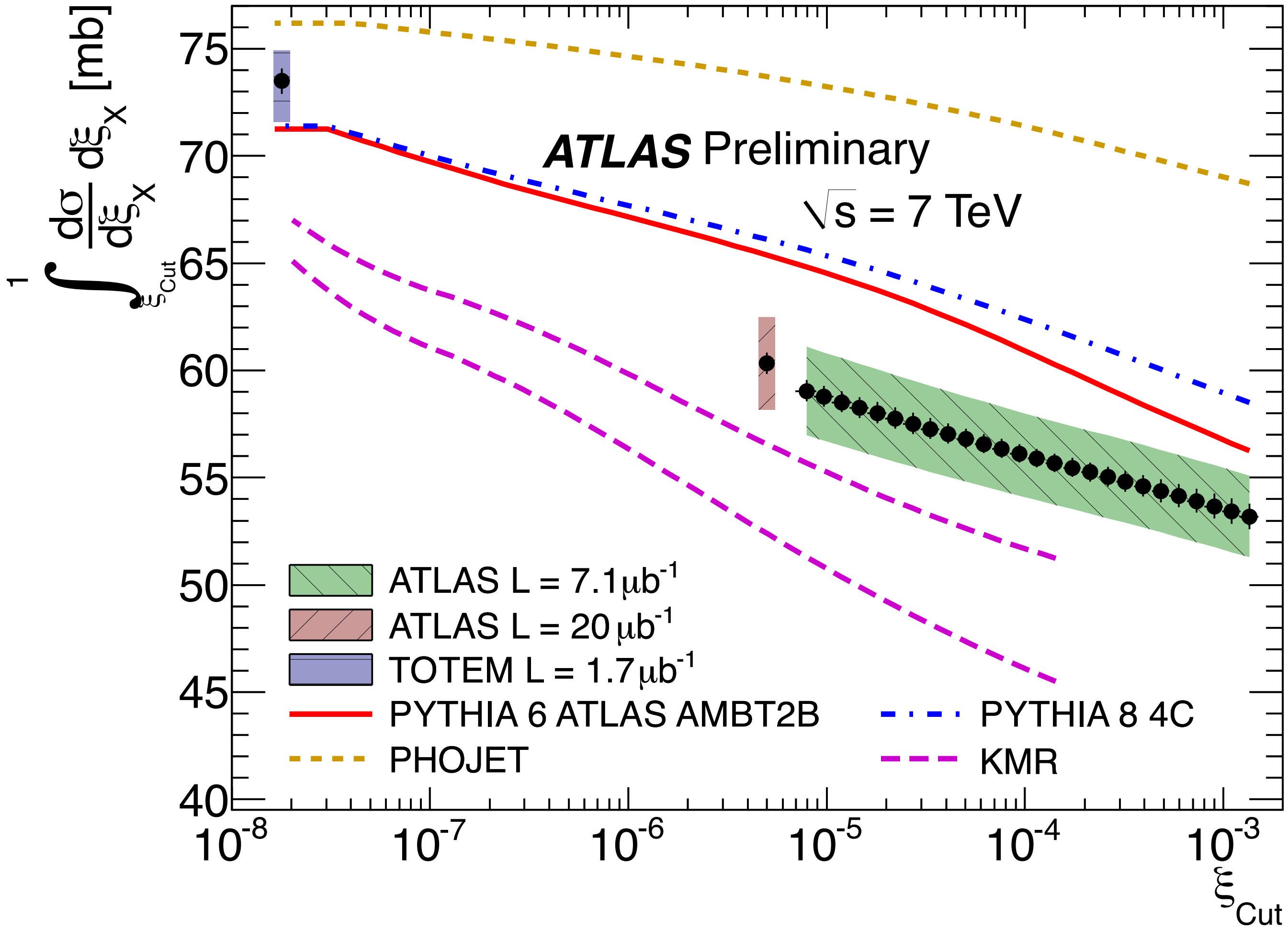


Total Inelastic pp Cross Section

- Full current picture on total cross section (from TOTEM)
- ATLAS and CMS central values lower than TOTEM after extrap'n into region of very low ξ (extrapolation error is dominant)



Uncertainties in Low ξ Extrapolations

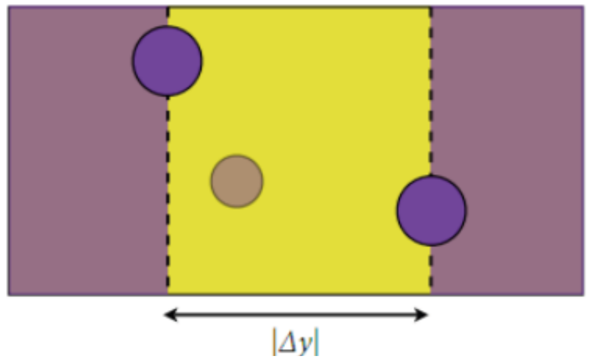


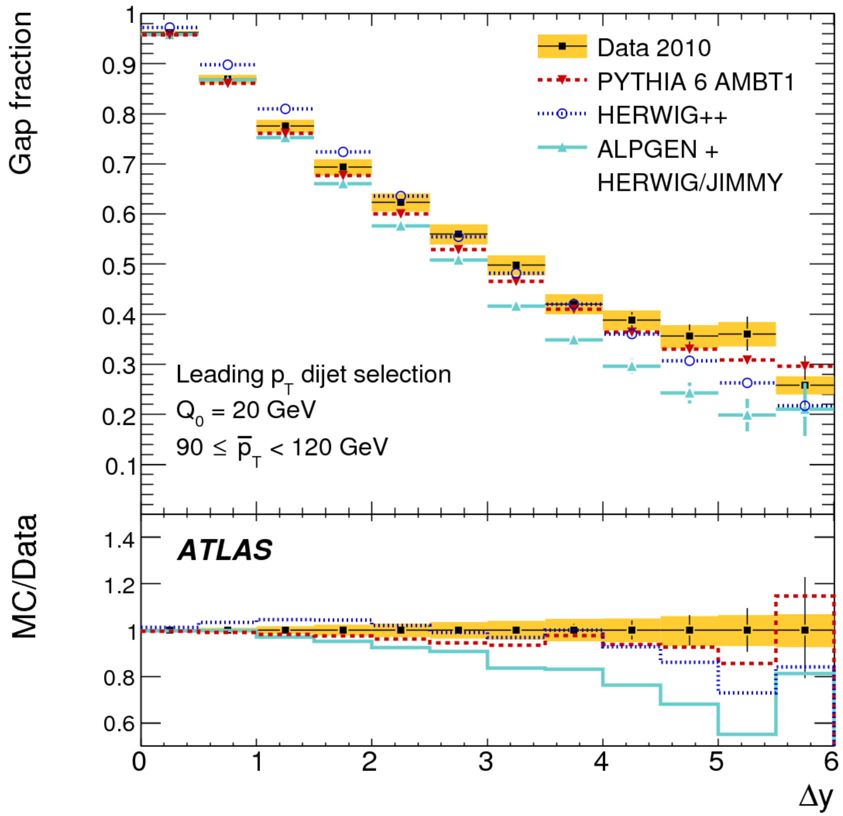
- Integrating gap cross section up to some max $\Delta\eta^F$ (equivalently min ξ_X) and comparing with TOTEM indicates that small ξ_X region underestimated in PHOJET and PYTHIA:
- 14 mb with $\xi < 10^{-5}$, compared to 6 (3) mb in PYTHIA (PHOJET)

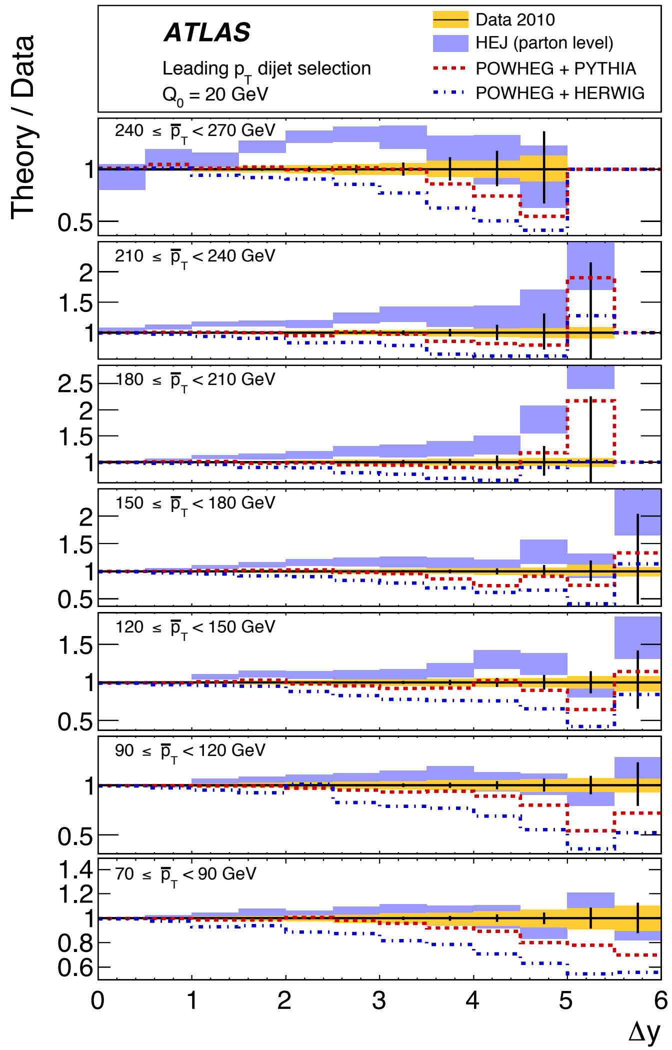
Dijets with Vetoes

Similar approach to harder physics: gaps between jets-type topology, but with typically E_T < 20 GeV in intermediate region

(JHEP 09 (2011) 053)



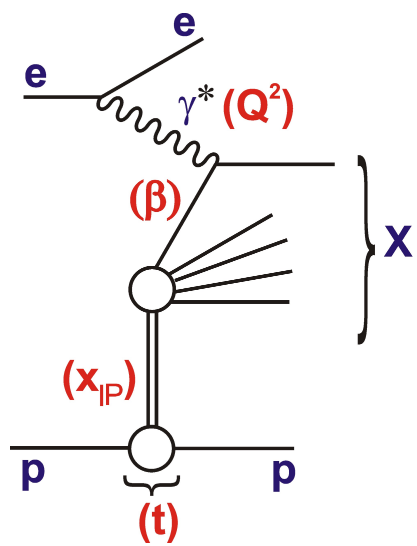


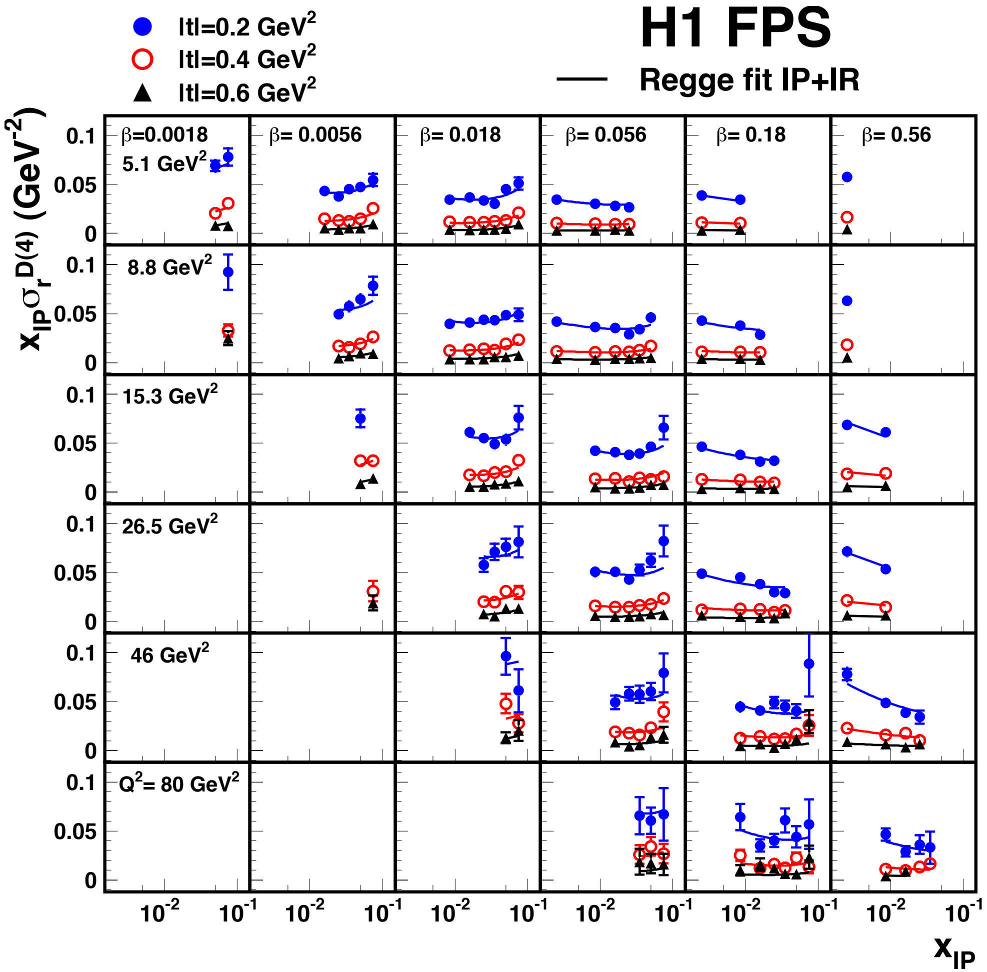


Hard Diffraction at HERA

Inclusive data as 'reduced' x-sec …

$$\sigma_r^{D(4)}(\beta, Q^2, x_{IP}, t) = F_2^{D(4)} - \frac{y^2}{Y_+} F_L^{D(4)} \sim F_2^{D(4)}$$





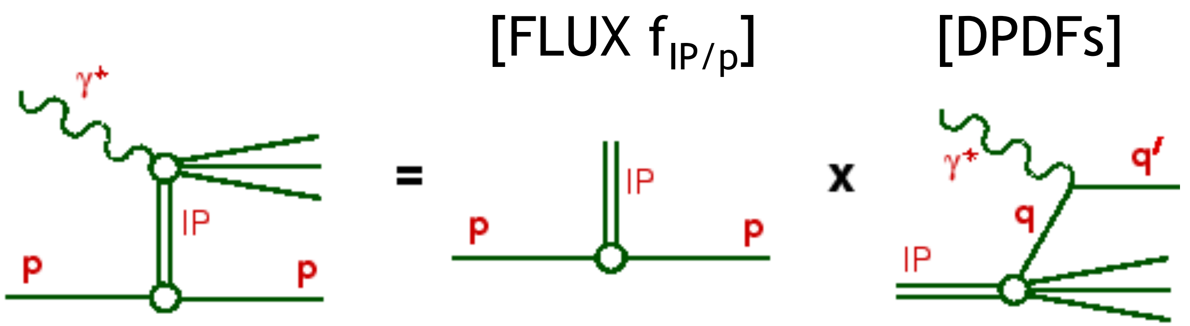
Most recent developments from tagging intact protons

Final H1 HERA-II FPS data
→ Roman pots at 60-80m
($156\ pb^{-1}$ = 20 x HERA-I)

4D structure function, 3 t bins

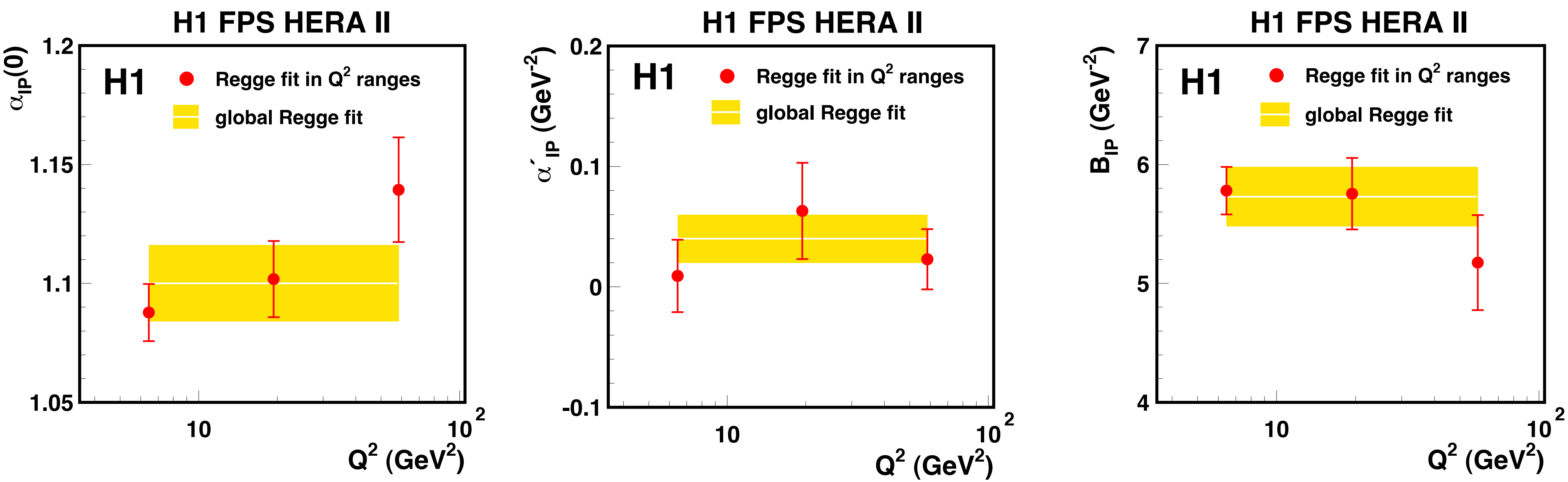
Final VFPS data still to come…

Factorisation and Pomeron Trajectory



$$f_{IP/p}(x_{IP},t) = \frac{e^{B_{IP}t}}{x_{IP}^{2\alpha_{IP}(t)-1}}$$

$$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP}t$$



No evidence for Q^2 or β dependence of $\alpha_{IP}(t)$ or t slope

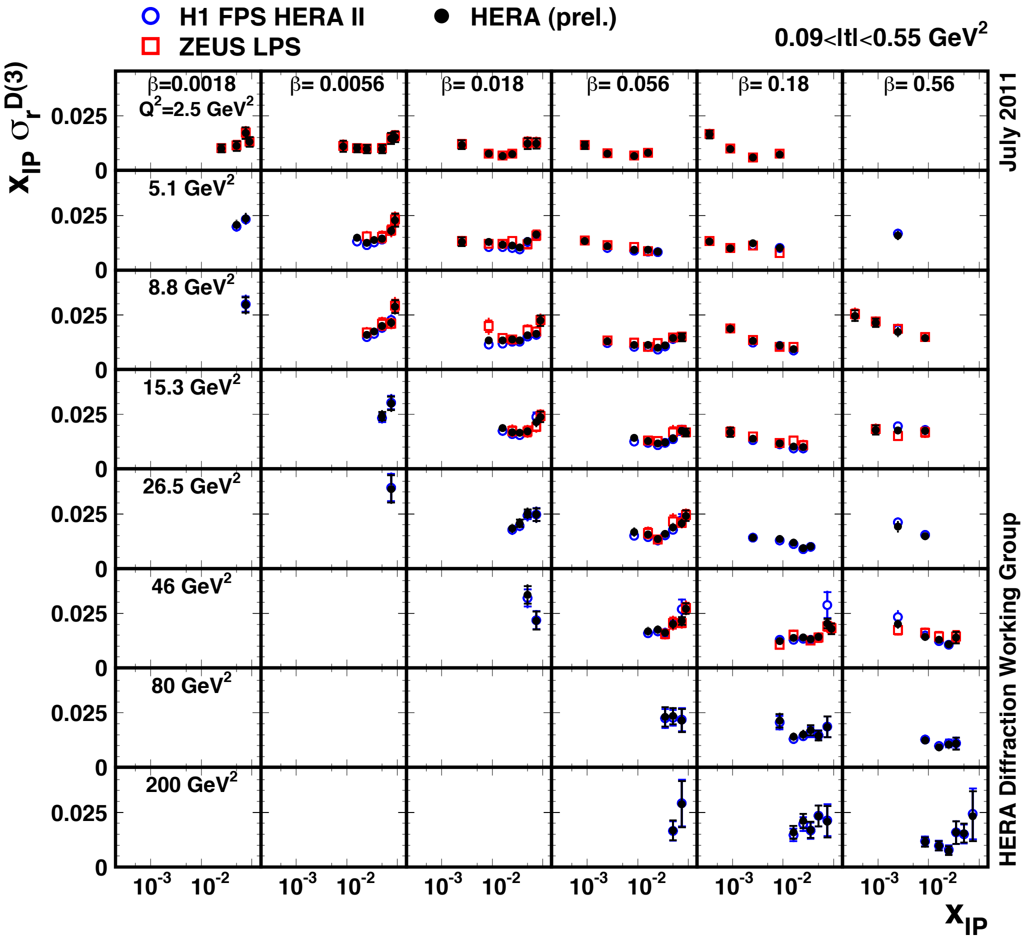
$\alpha_{IP}(0)$ consistent with soft IP → Dominantly soft exchange

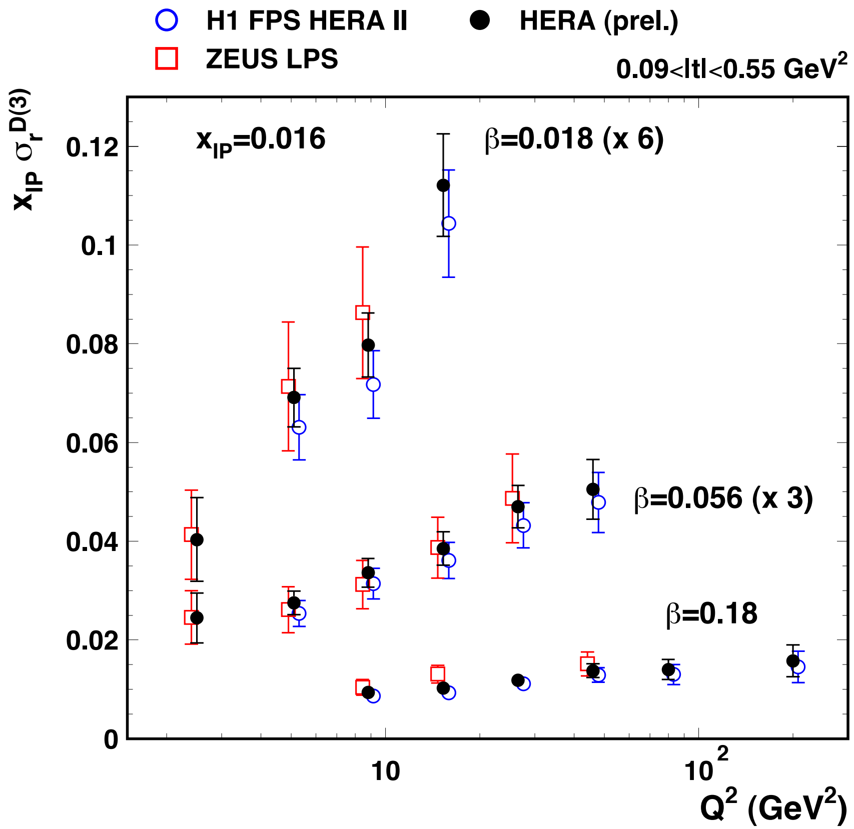
α_{IP}' smaller than soft IP → Absorptive effects?...

First H1-ZEUS Combined Diffractive Data

Proton tagged data in region of mutual acceptance:

H1/ZEUS norm: = 0.91 ± 0.01 (stat) ± 0.03 (syst) ± 0.08 (norm)

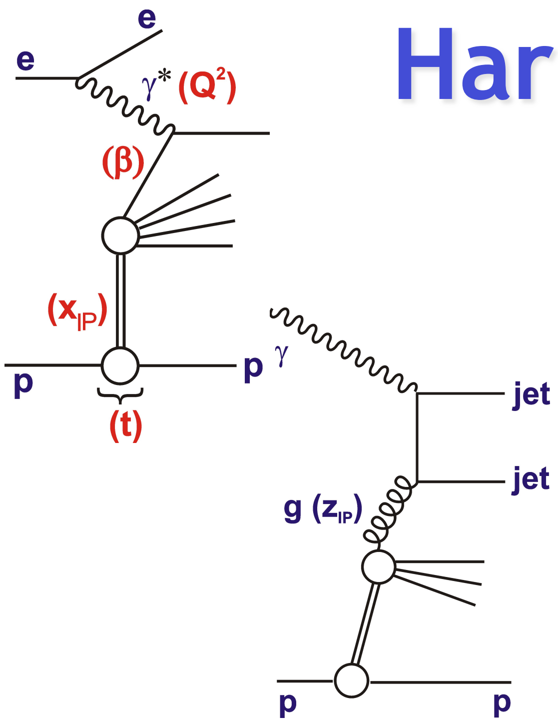


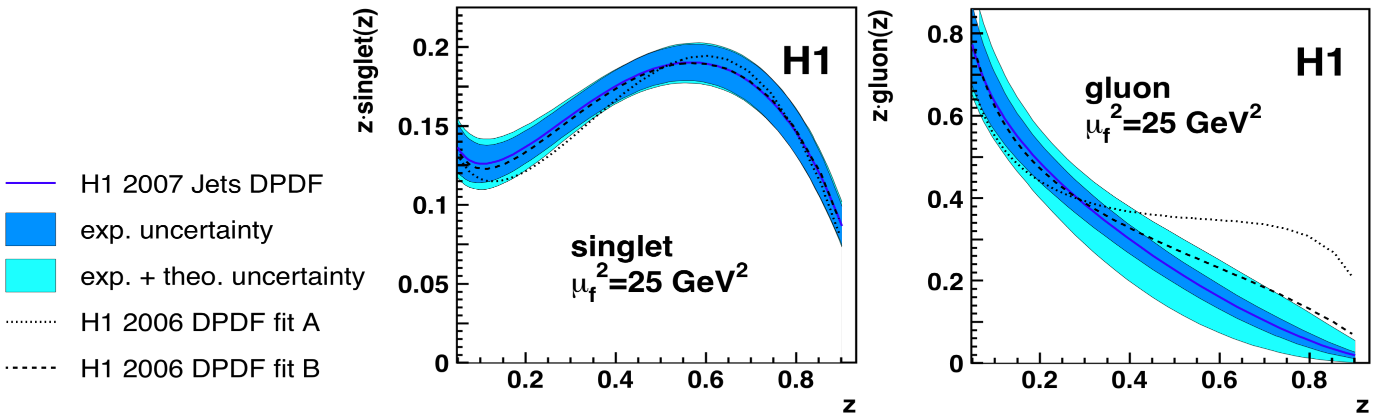


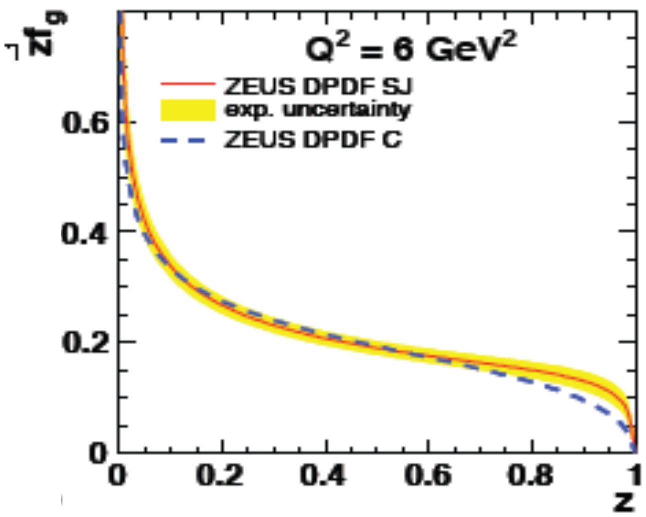
Improvements beyond the statistical → cross-calibration of systematics

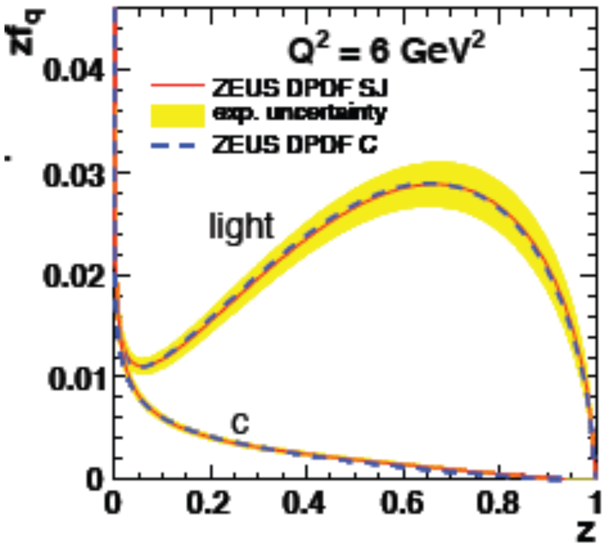
More to follow …

Hard Processes: Diffractive PDFs





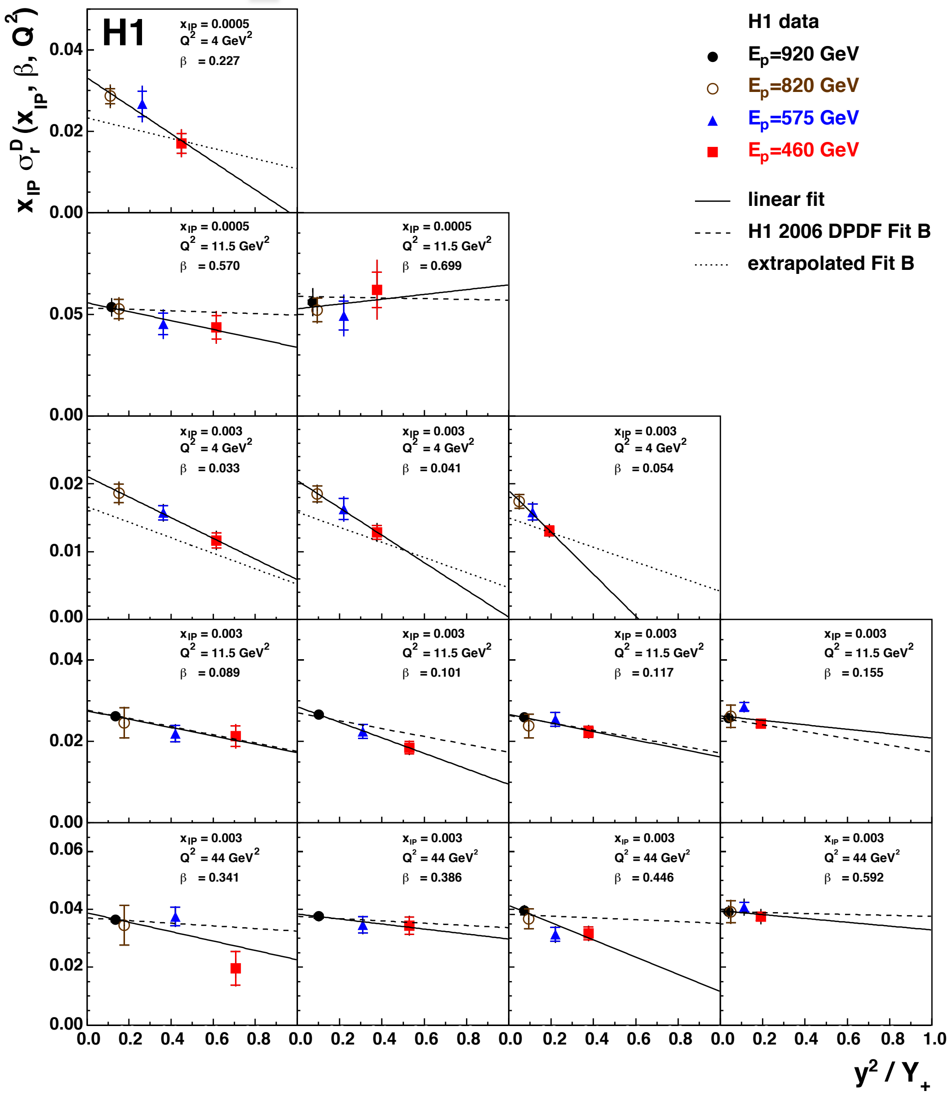




Lead to impressive descriptions of all hard diffractive DIS data

DPDFs dominated by a gluon density which extends to large z

Testing the DPDFs: First F_L^D Measurement



$$\sigma_r^{D(3)}\left(\beta,\, Q^2,\, x_{IP},\, \sqrt{s}\right) = F_2^{D(3)} - \frac{y^2}{Y_+} F_L^{D(3)}$$

Investigate role of longitudinally polarised photons in bulk of diffractive DIS

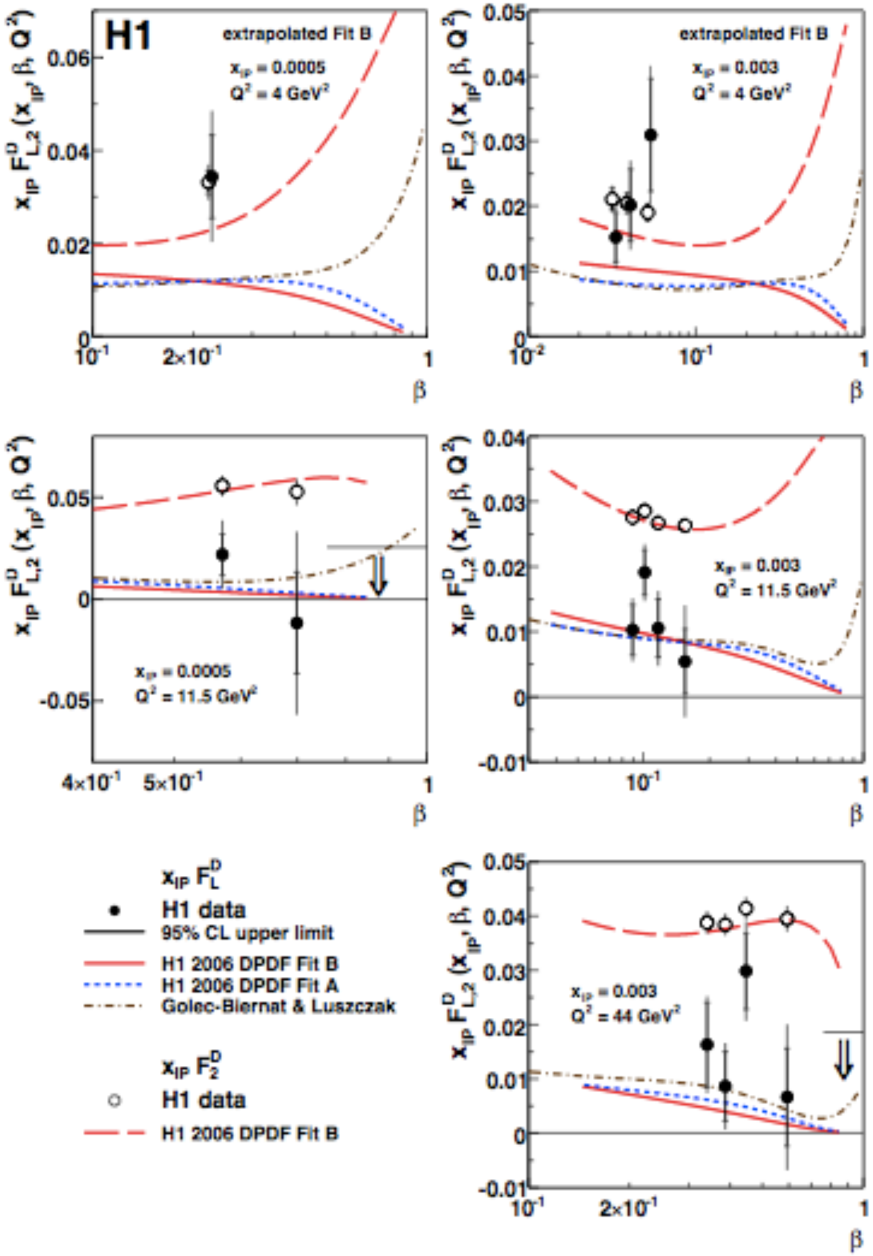
Novel test of diffractive gluon density

… F_L^D sensitivity @ highest y ($E_e \rightarrow$ 3.4 GeV)
… vary $E_p \rightarrow$ change y at fixed β, x_{IP}, Q^2

Large Rapidity Gap data

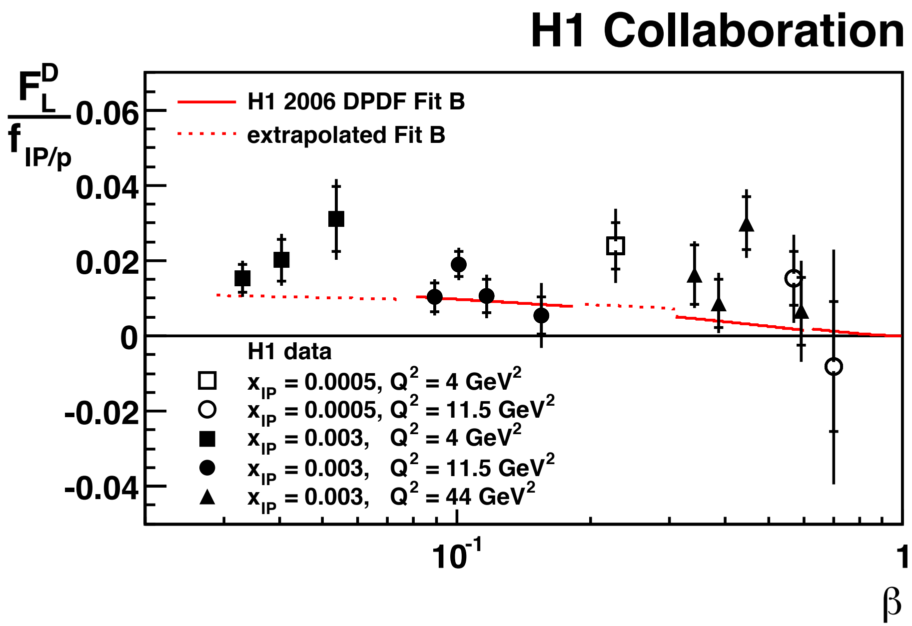
… 11pb^{-1} @ 575 GeV, 6pb^{-1} @ 460 GeV, in addition to 820 GeV, 920 GeV data

F_L^D Measurement



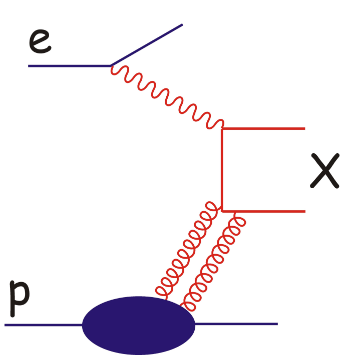
- F_L^D shown to be several σ from zero over wide β range

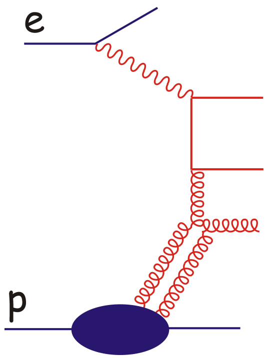
- Compatible with all predictions based on NLO DGLAP fits to σ_r^D, including model with large higher twist F_L^D component as β → 1



Forward Jets in Diff DIS

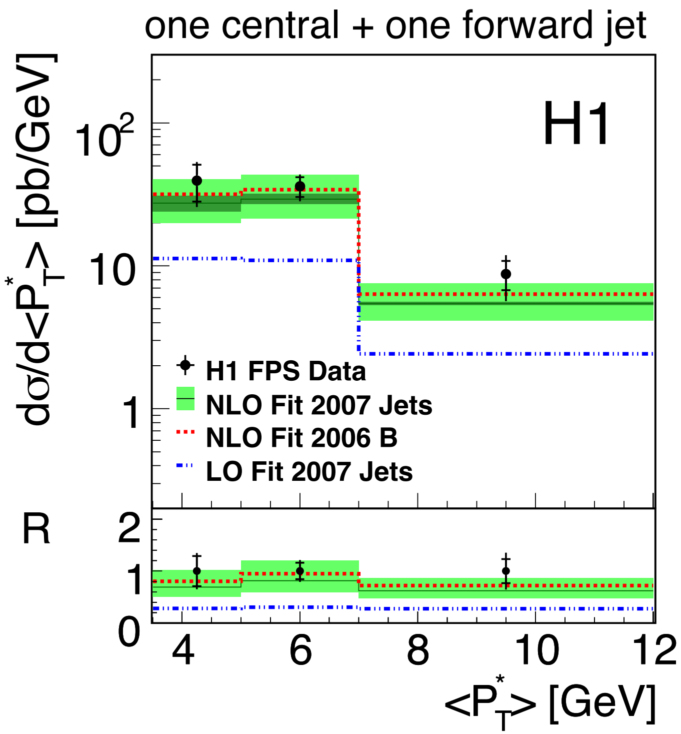
New analysis with FPS proton tag … extends x_{IP} and η_{jet} ranges … search for 'hard' pQCD-calculable contributions … exclusive 2/3 jets with DGLAP p_t ordering broken?

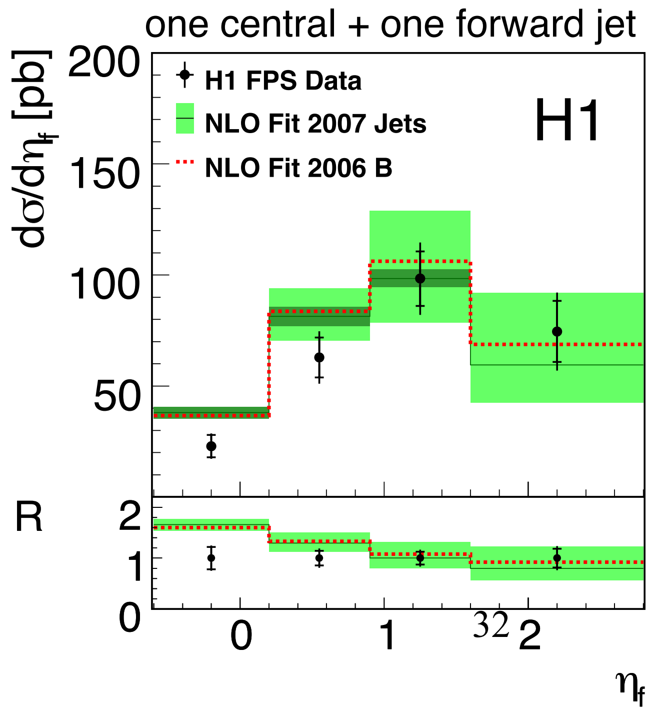




p_t > 3.5 GeV, m_{jj} > 12 GeV
Forward jet: 1 < η_{fwd} < 2.8
Central jet -1 < η_{cen} < η_{fwd}

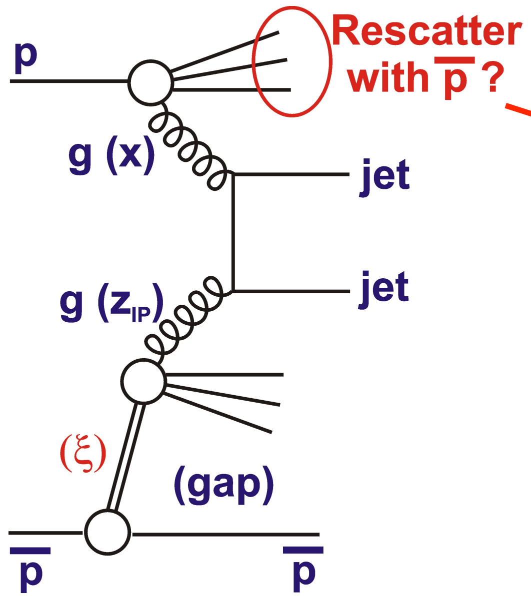
… No evidence for configurations beyond those predicted from NLO DGLAP & DPDFs

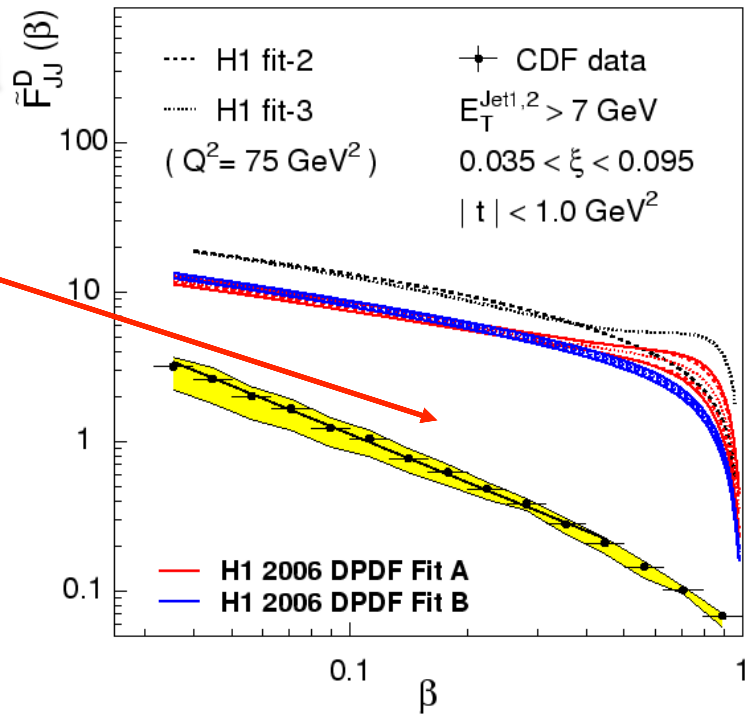




Predicting Tevatron Data

Tevatron effective DPDFs from dijets show strong factor^n breaking compared with HERA DPDFs … `gap survival' factor $S^2 \sim 0.1$





… usually explained by multiple interactions / absorption

• Rapidity gap survival probabilities should in principle be calculable using multiple (~~parton~~?) interaction models

• However (in contrast to most MPI models) impact parameters are usually small (governed by t) → Challenging!

Currently described by soft phenomenology (Durham, Tel Aviv)

Hard Diffraction: Tevatron

Most recent paper from CDF: Phys Rev D82 (2010) 112004:
Using Roman pot proton taggers …
Diffraction with $0.03 < \xi < 0.1$, $|t| < 1$ GeV^2 accounts for

- 1.00 ± 0.05 (stat.) ± 0.10 (syst.) % of W production
- 0.88 ± 0.21 (stat.) ± 0.08 (syst.) % of Z production

at the Tevatron (suggests small gap survival probability)

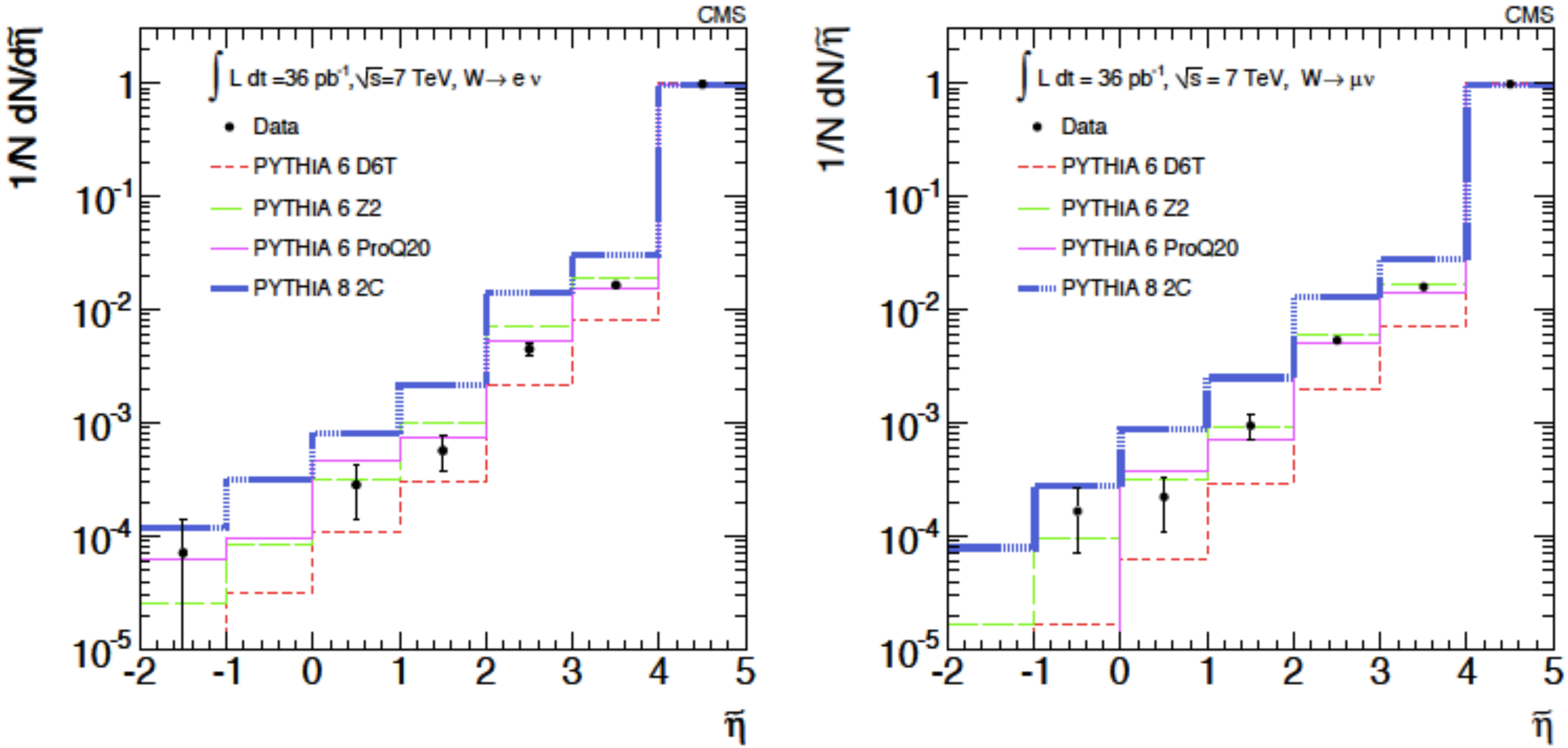
Comparable with lots of other diffractive processes measured using large rapidity gap approach …

Hard component	Fraction (R) %
Dijet	0.75 ± 0.10
W	1.15 ± 0.55
b	0.62 ± 0.25
J/ψ	1.45 V 0.25

Universal suppression relative to factorised predictions?

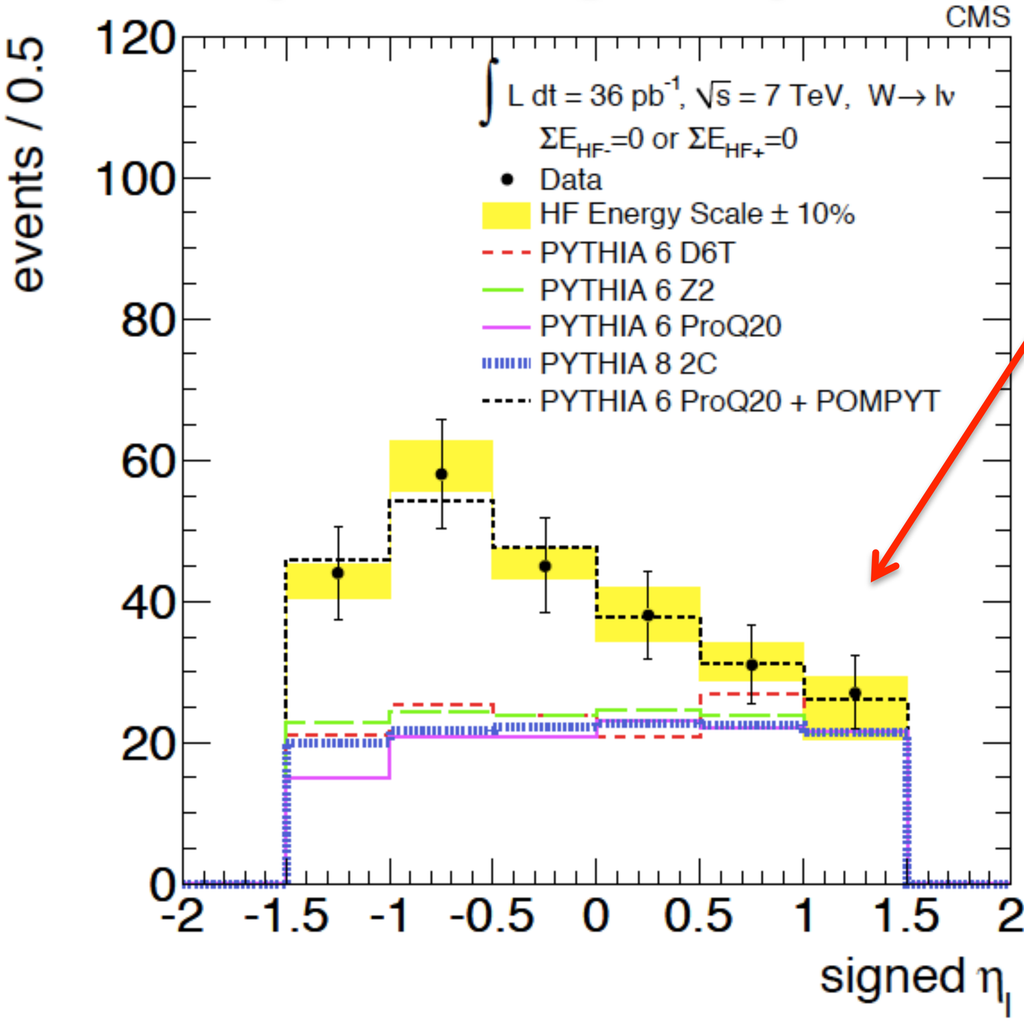
W and Z events with gaps at CMS

After pile-up corrections, ~1% of W and Z events exhibit no activity above noise thresholds over range $3 < \pm\eta < 4.9$ … interpretation not yet clear …



$\tilde{\eta}$ (= 4.9 – $\Delta\eta$) 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

Extraction of (limits on?) gap survival probabilities at the LHC from diffractive W/Z and jet production eagerly awaited … survival may be small (~3% according to phenomenology)

Summary

Soft diffractive processes at the LHC

- Precision data emerging
- Small non-zero gaps sensitive to had^n / MPI
- Large gaps sensitive to diffractive dynamics
- Detailed tests of soft MC models → tunes
- Compare v TOTEM → insight on low mass diffraction

Diffractive Deep Inelastic Scattering

- First H1-ZEUS combinations
- Novel diffractive factorisation tests – DPDFs work
- No big gap survival effects

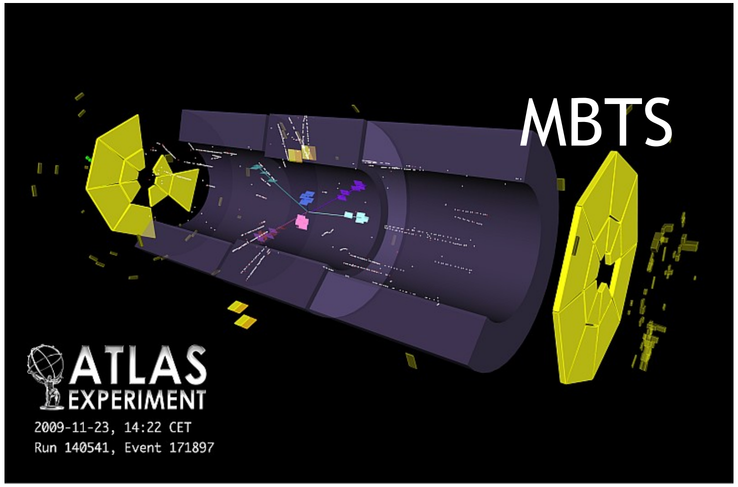
Hard Diffraction at the Tevatron and the LHC

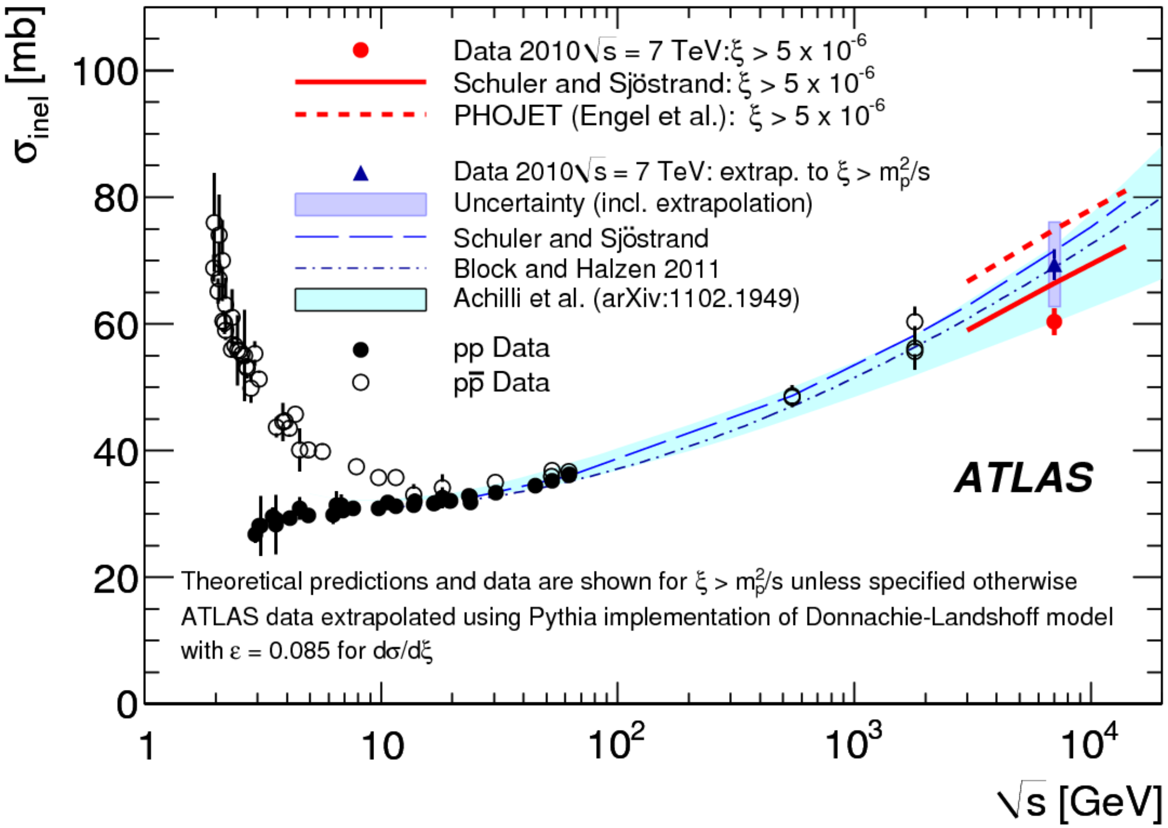
- Big gap destruction effects (~90%) at Tevatron
- First results with W/Z at the LHC … survival probability?..

Back-ups

Total Inelastic pp Cross Section

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



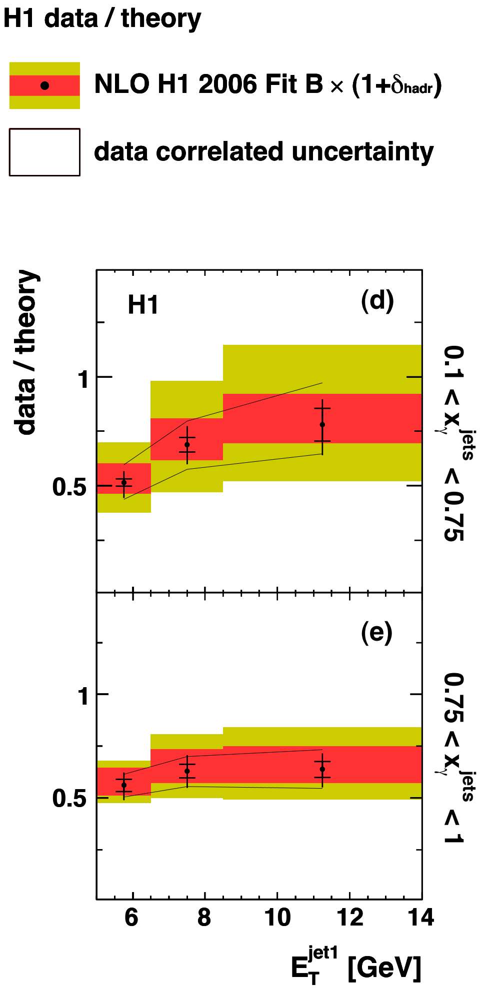


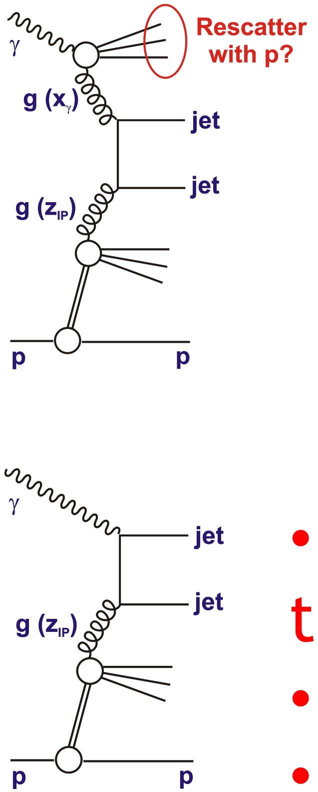
- After 5-10% extrapolation, obtain total inelastic cross section at $\sqrt{s}$ = 7 TeV

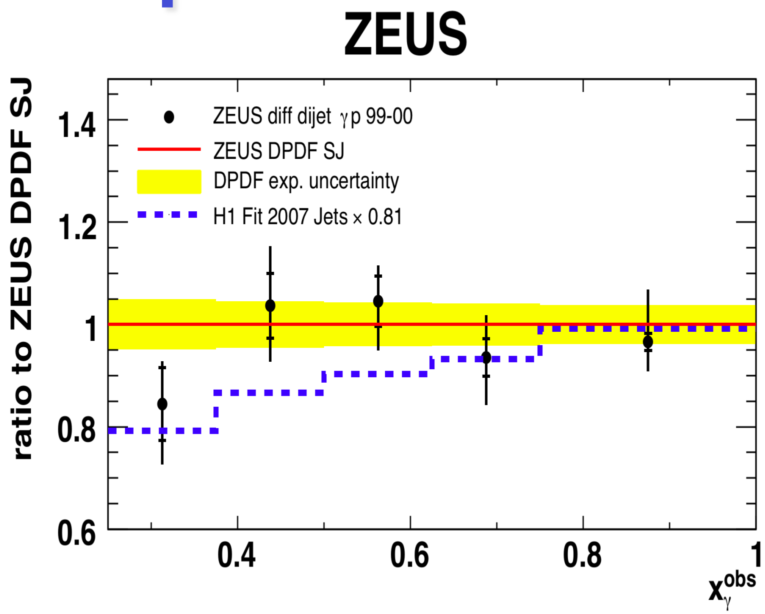
- … dominated by 3.4% luminosity error

- PYTHIA & (especially) PHOJET lie above data

Rapidity Gap Survival Probability in Diffractive Dijet Photoproduction



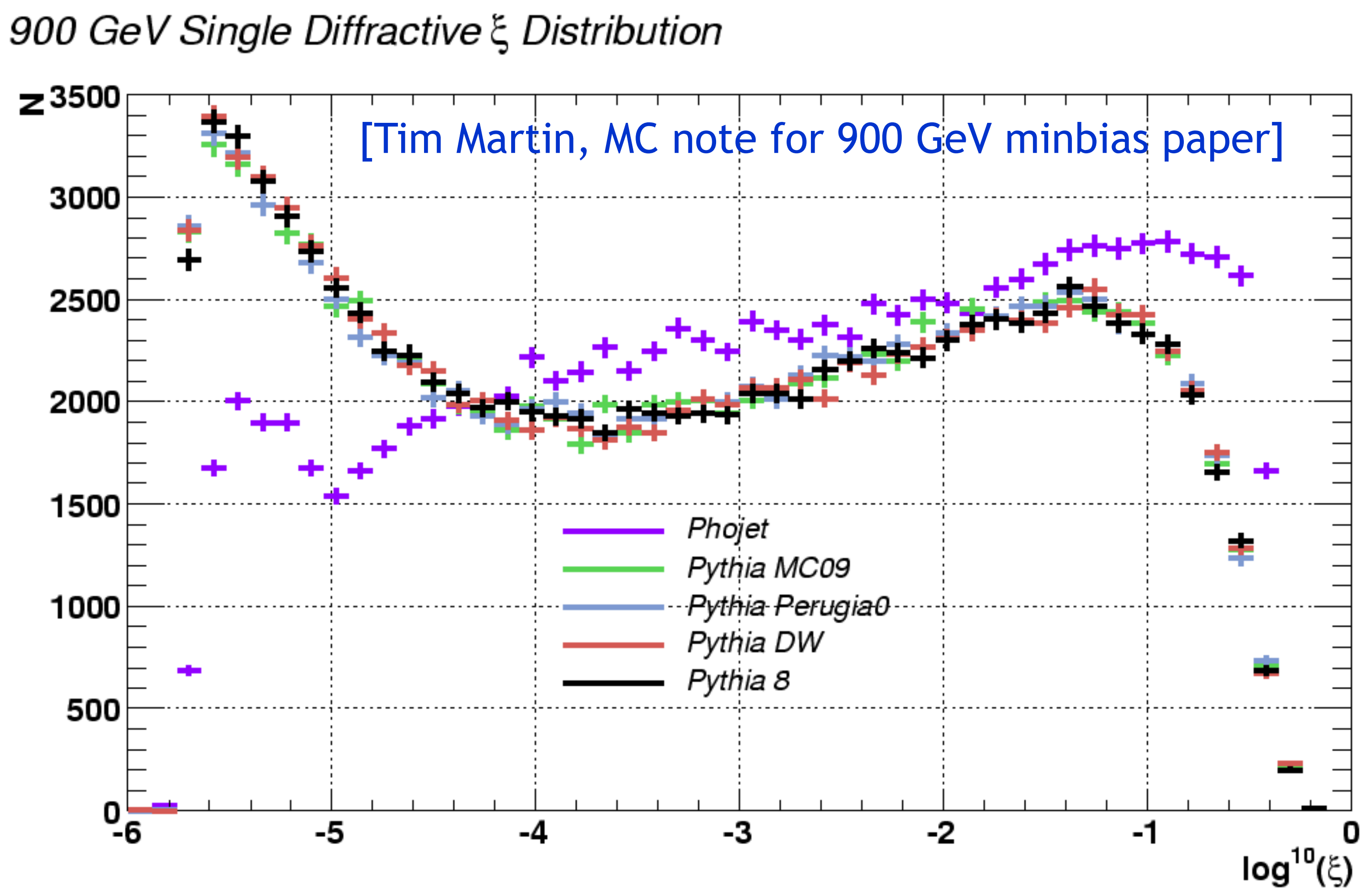




- Suppression relative to NLO smaller than expected
- No significant effect in ZEUS data
- Gap survival unexpectedly has little dependence on x_γ
- Hint of a dependence on jet E_T?

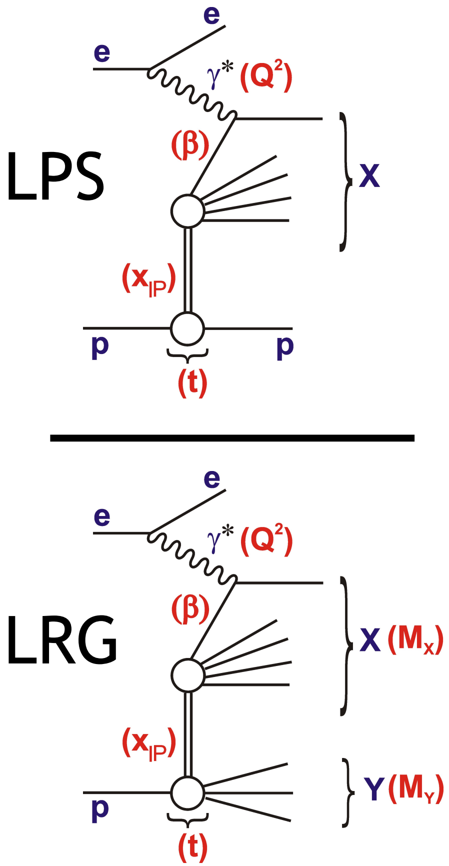
Can be reproduced with more sophisticated treatment of point-like (anomalous) component of photon structure (KKMR)

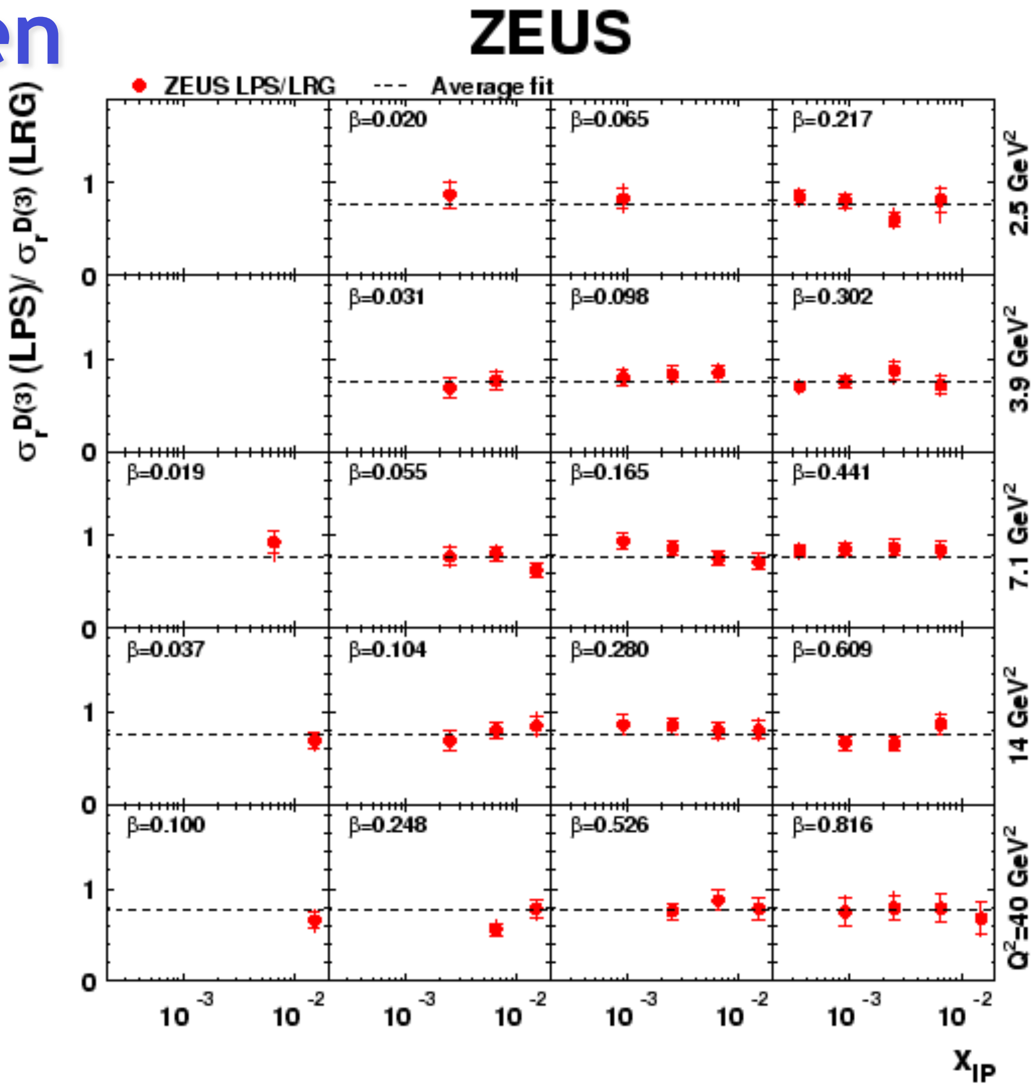
Comparison between Cross Sections



- Big difference between PHOJET and PYTHIA cross sections at small and large ξ
- Different tunes of PYTHIA6 and PYTHIA8 are very similar

Comparisons between Methods





- LRG selections contain typically 20% p diss
- No significant dependence on any variable
- **… well controlled, precise measurements**

Refined gap Survival Model (KKMR)

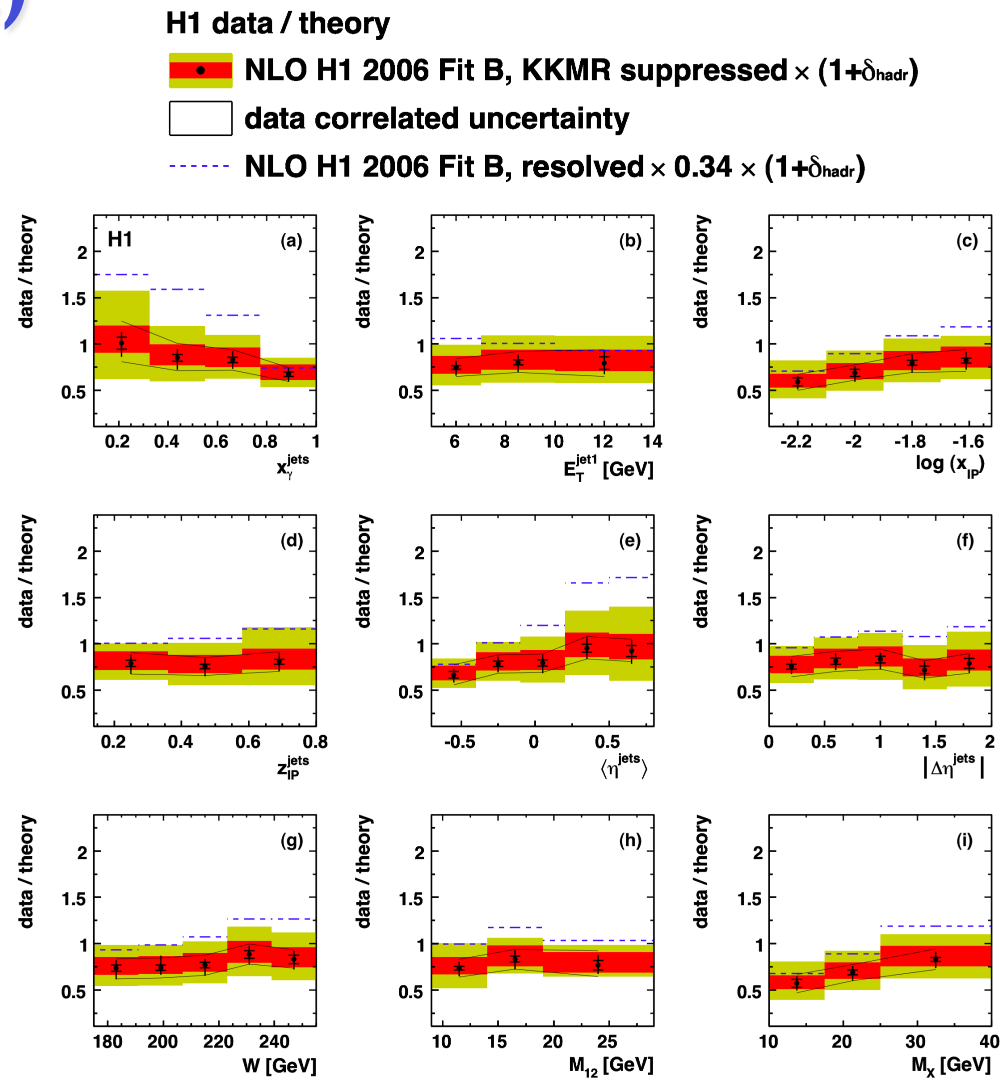
[hep-ph/0911.3716]

Direct contribution remains unsuppressed

Suppression factor 0.34 applies to Hadron-like (VMD) part of photon structure only (low $x_\gamma < 0.1$)

Point-like (anomalous) part of photon structure has less suppression (~0.7-0.8)

Smaller gap destruction effects with some E_T dependence



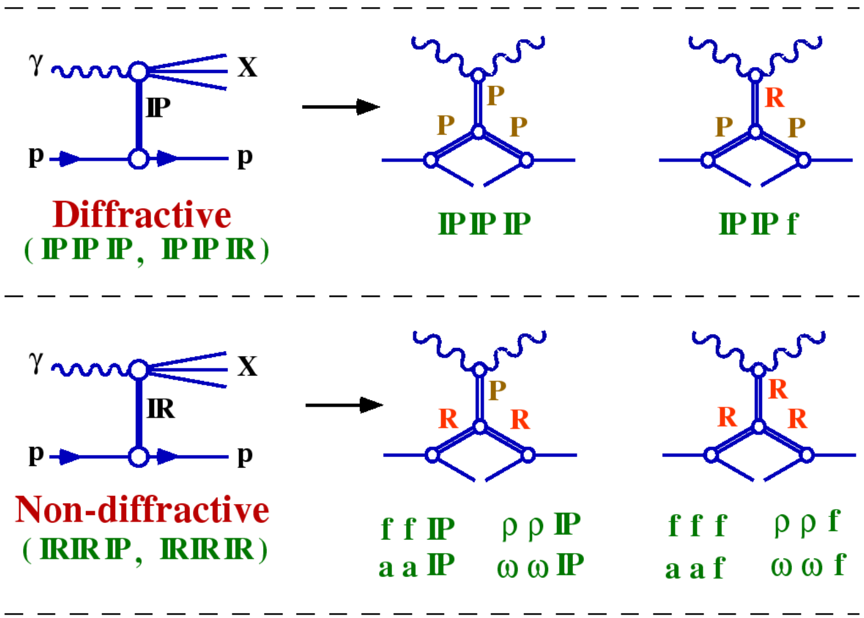
Fair agreement with both H1 and ZEUS data …

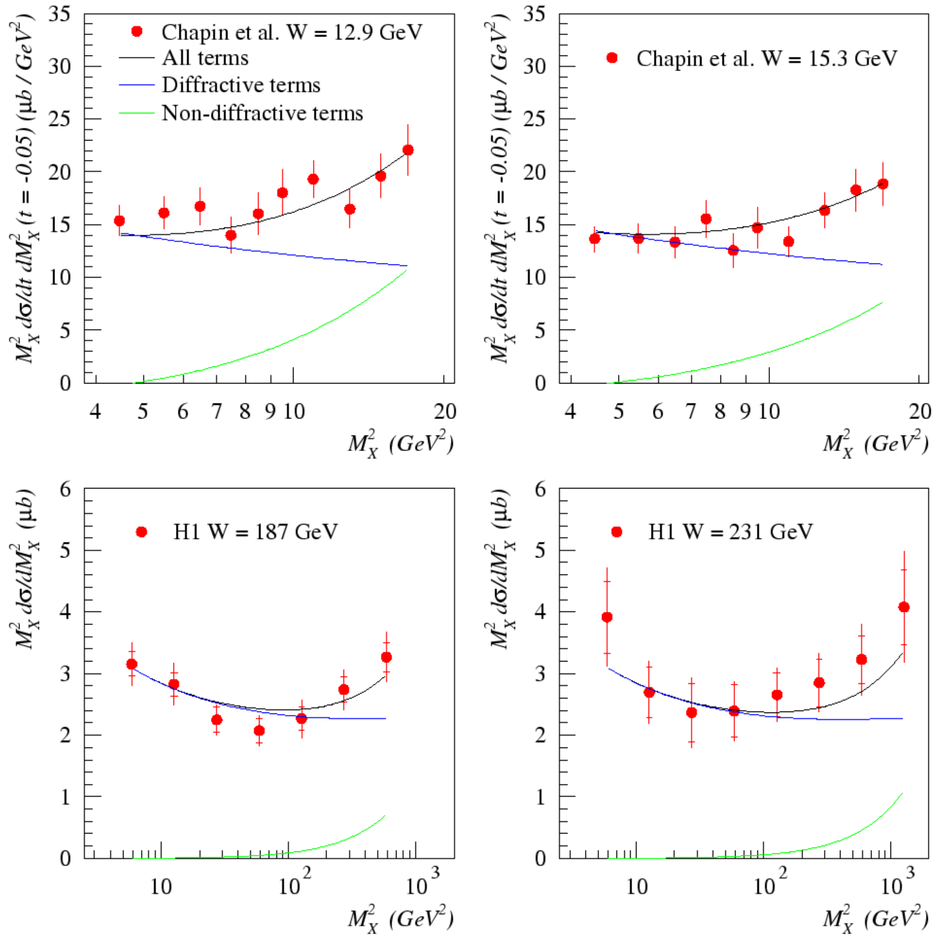
Soft Photoproduction SD Cross Section

Triple pomeron →

$$\frac{d\sigma}{dt\,dM_X^2} = \frac{1}{16\pi}\, g_{3IP}(t)\, \beta_{pIP}(t)^2\, \beta_{\gamma\, IP}(0)\, s^{2\alpha(t)-2}\, M_X^{2[\alpha(0)-2\alpha(t)]}$$

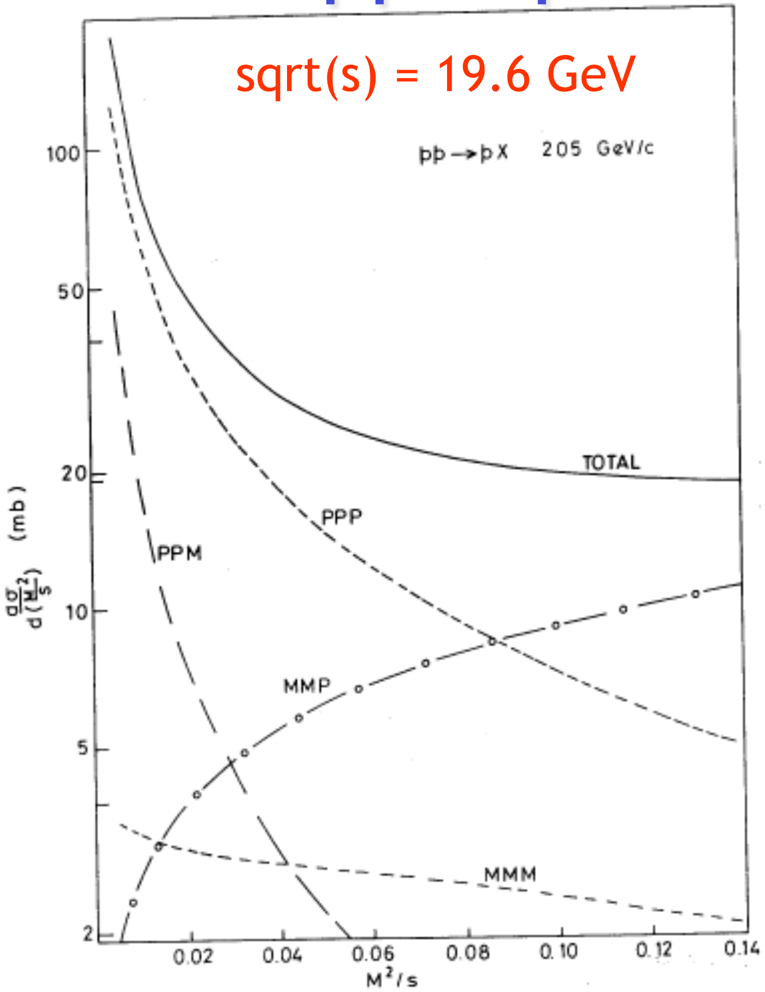
Complication: Triple Regge diagrams can have non-pomeron as well as pomeron contributions





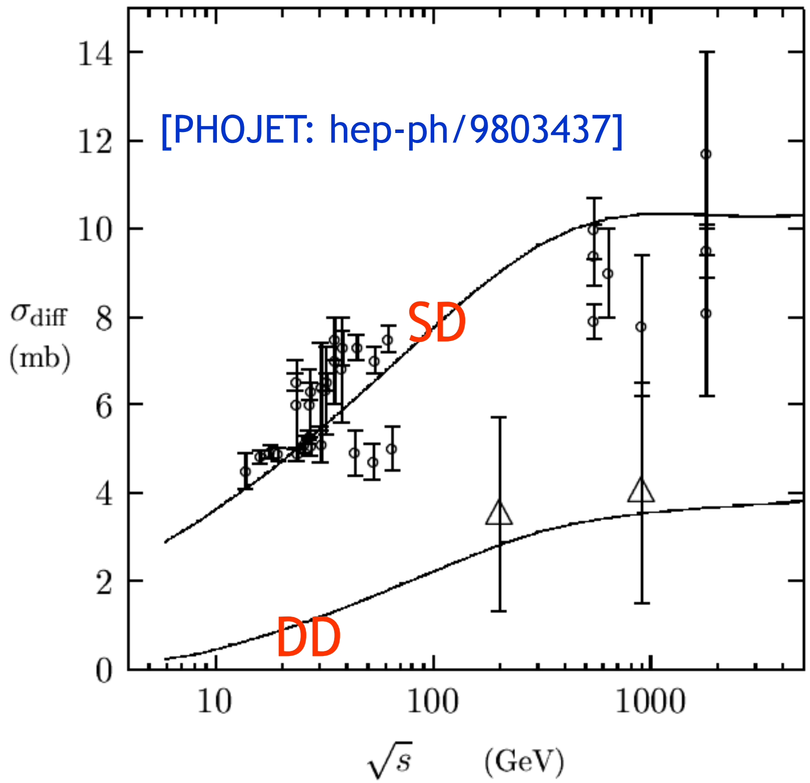
- Example fit to H1 and fixed target $\gamma p \rightarrow Xp$ data shows non-diffractive contributions present at small s and large x_{IP}.

Sub-Leading Terms and pp→ pX



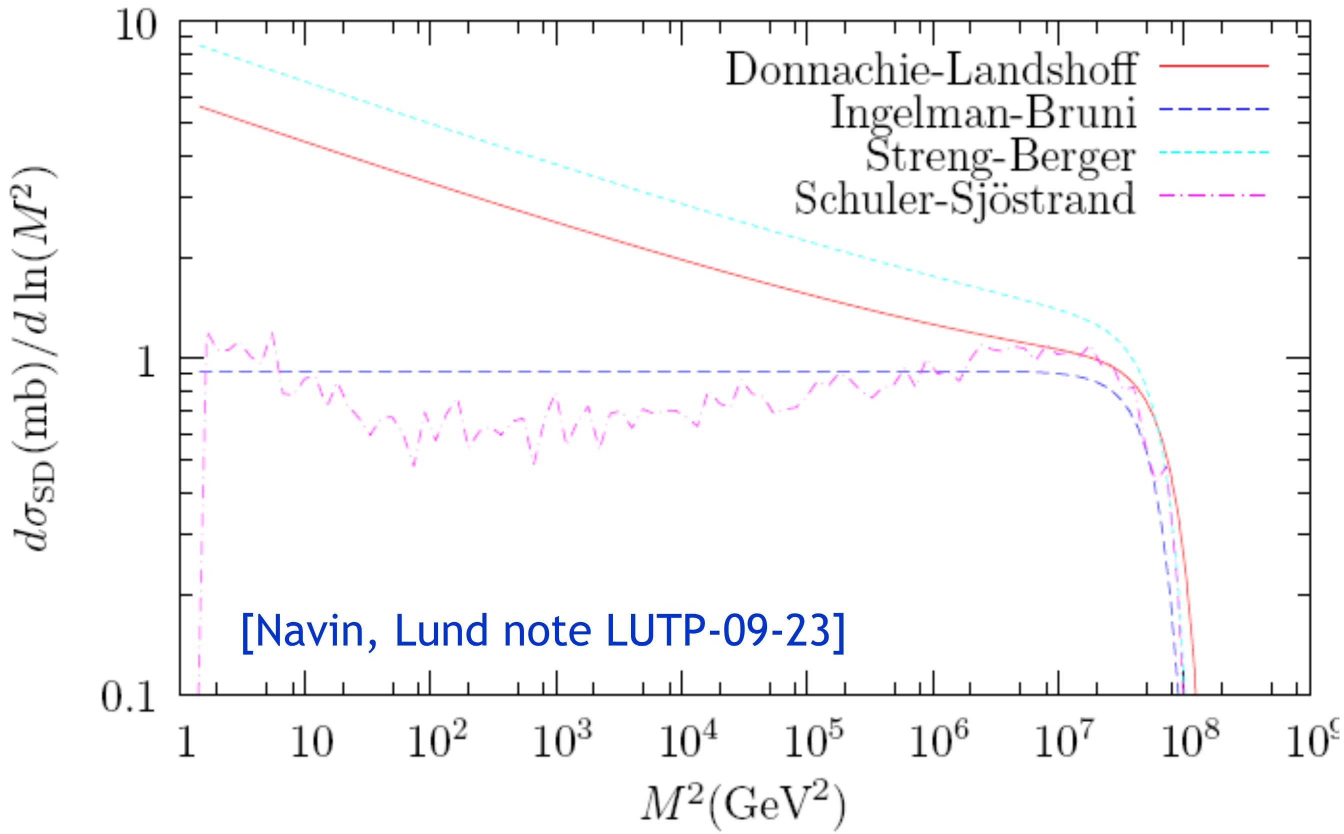
Ancient (ISR) triple Regge phenomenology of pp → pX

Roberts & Roy: NP B77 (1974) 240
Field & Fox: NP B80 (1974) 367



- Sub-leading terms suppressed like 1/sqrt(s) or stronger … negligible at LHC,
- Perhaps influence assumed 3IP coupling in MC models?

PYTHIA8 Pomeron Flux Models



- Default Schuler & Sjostrand flux and more standard(?) Donnachie & Landshoff show significantly different ξ dependences when viewed over huge ξ range at LHC

- Not enough to vary σ(SD), σ(DD) when assessing diffractive cross section model uncertainties @ LHC

PHOJET Implementation

- Cross section based on triple pomeron model with standard pomeron $\alpha(0) = 1.08$
- Sharp cut at steerable large ξ [default ~0.4?]
- No low ξ enhancement

PYTHIA Implementation

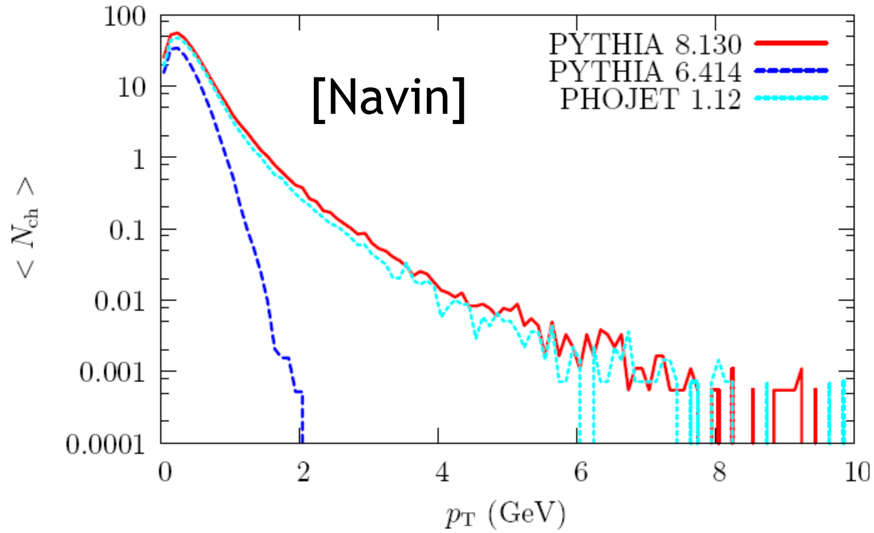
- Triple pomeron model. By default $\alpha(0) = 1$ (!)
- Fudge factors applied to suppress large ξ, give a low ξ enhancement and prevent X and Y systems overlapping in DD

$$\frac{d\sigma_{sd(AX)}(s)}{dt\, dM^2} = \frac{g_{3\mathbb{P}}}{16\pi} \beta^2_{A\mathbb{P}} \beta_{B\mathbb{P}} \frac{1}{M^2} \exp(B_{sd(AX)} t) F_{sd}$$

$$F_{sd} = \left(1 - \frac{M^2}{s}\right) \left(1 + \frac{c_{res} M^2_{res}}{M^2_{res} + M^2}\right)$$

- Exactly the same default in PYTHIA8, but now with 3 other parameterisations available

Hard Diffraction in MCs

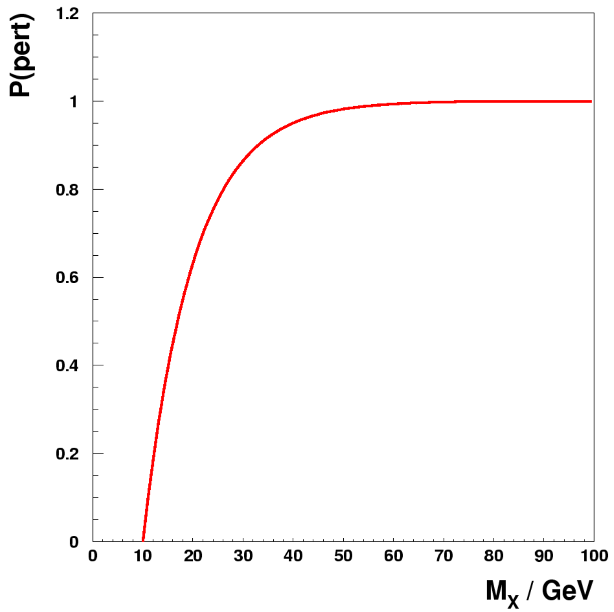


PHOJET

- Fairly standard IP flux
- Two components (soft / hard)
- Divided at p_T = 3 GeV
- (Old) CKMT model of DPDFs

PYTHIA8

- Choice of (old) IP fluxes
- Two component (soft / hard)
- Divided according to smooth turn-on
- Hard component dominates at LHC
- Choice of modern DPDFs for hard part



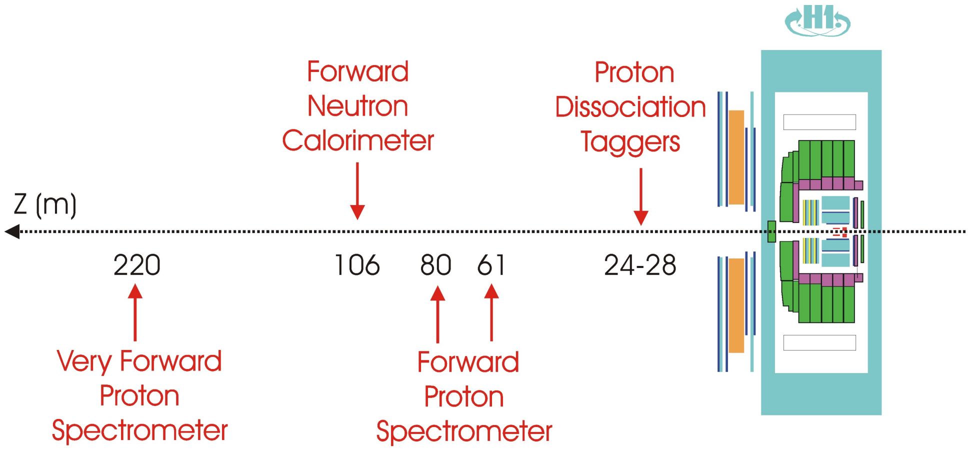
RAPGAP / POMWIG

- Hard component only
- Consistent use of flux and DPDFs from fits to HERA data

None contain models of MI induced Rapidity Gap Destruction ☹

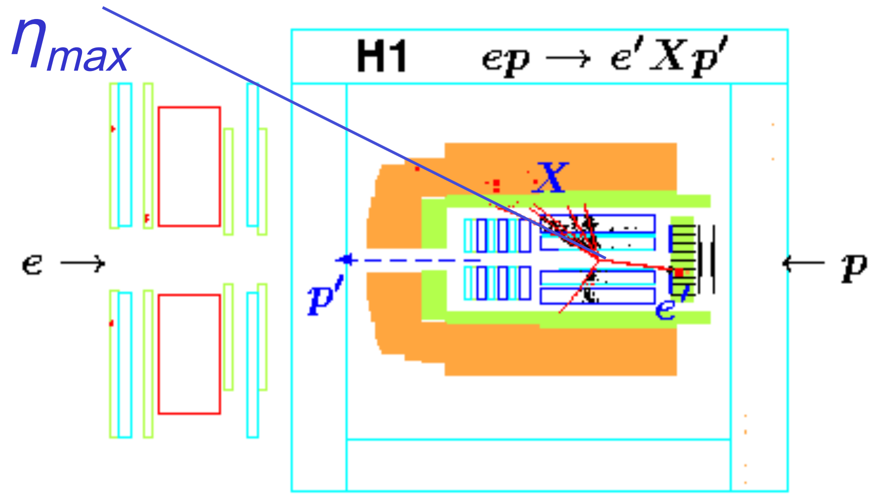
Signatures and Selection Methods

Scattered proton in Leading Proton Spectrometers **(LPS)**



Limited by statistics and p-tagging systematics

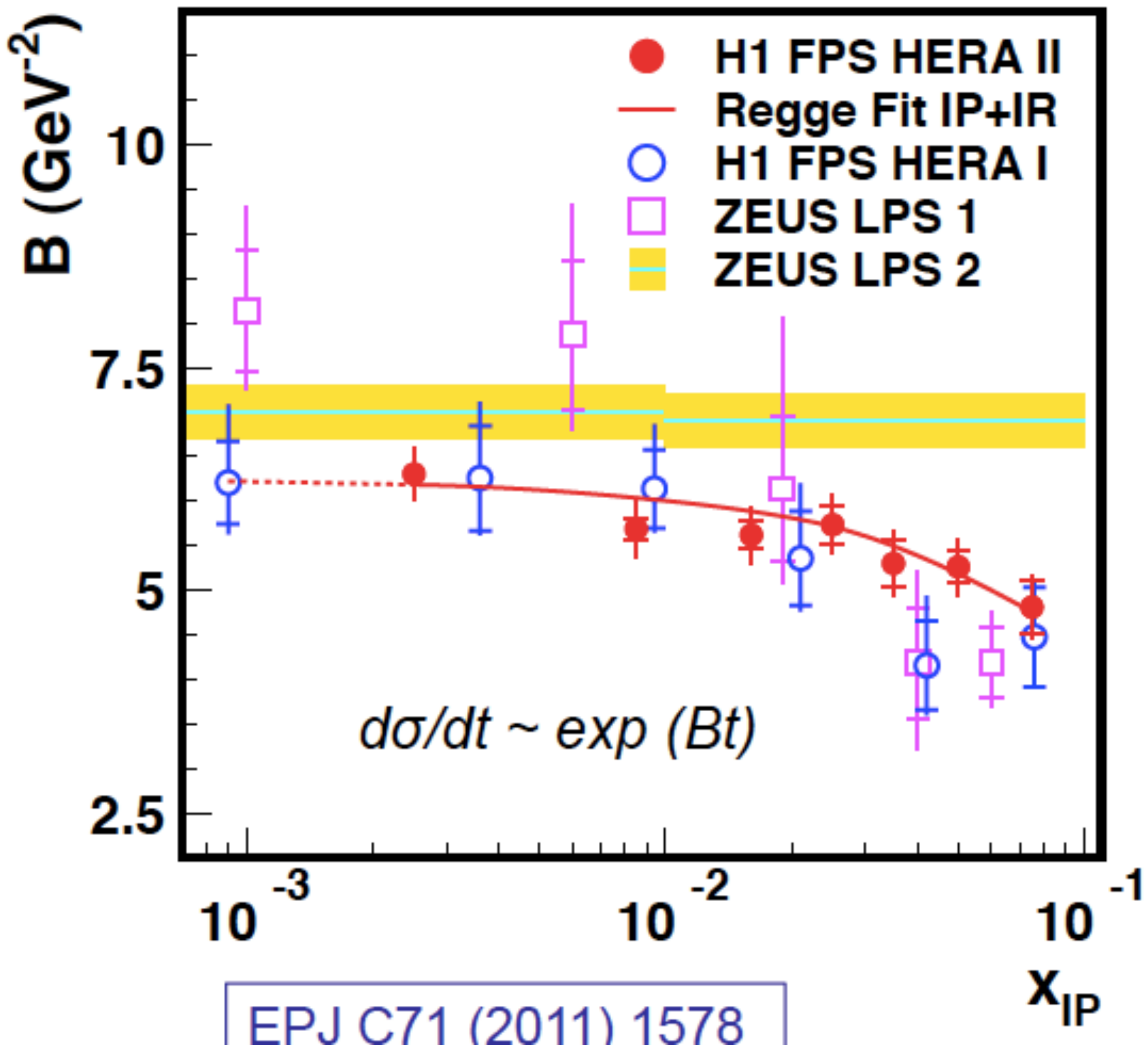
`Large Rapidity Gap' **(LRG)** adjacent to outgoing (untagged) proton



Limited by p-diss systematics

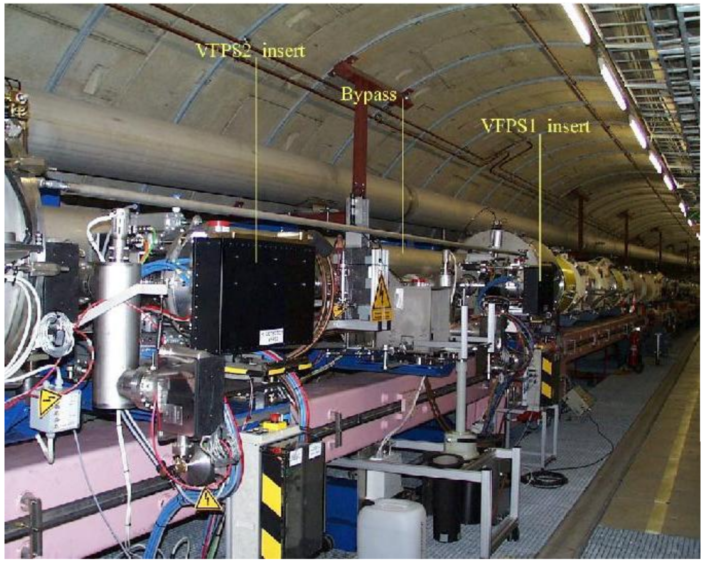
- The 2 methods have very different systematics
- Both experiments also have Zero Degree Calorimeters for forward neutron measurements

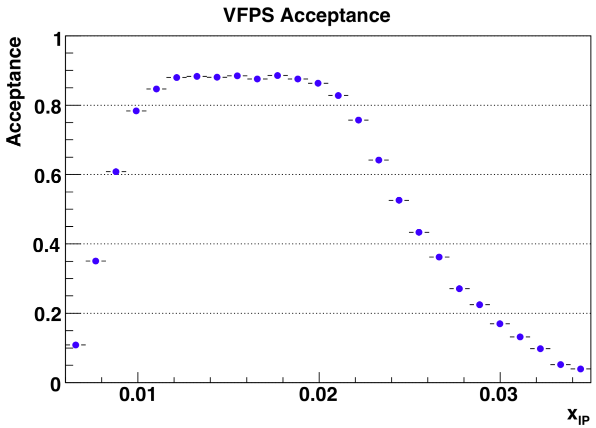
H1 FPS at HERA-II

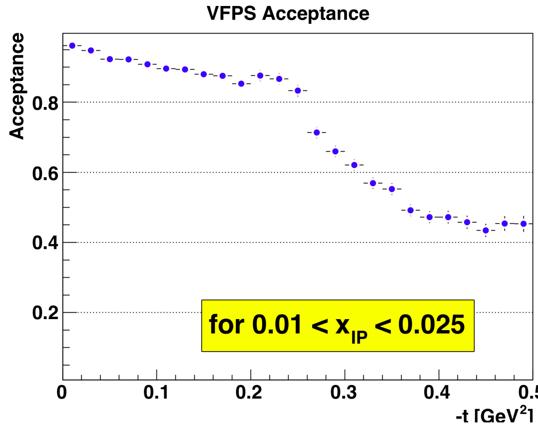


Sub-leading exchanges

First Physics Results from H1 VFPS

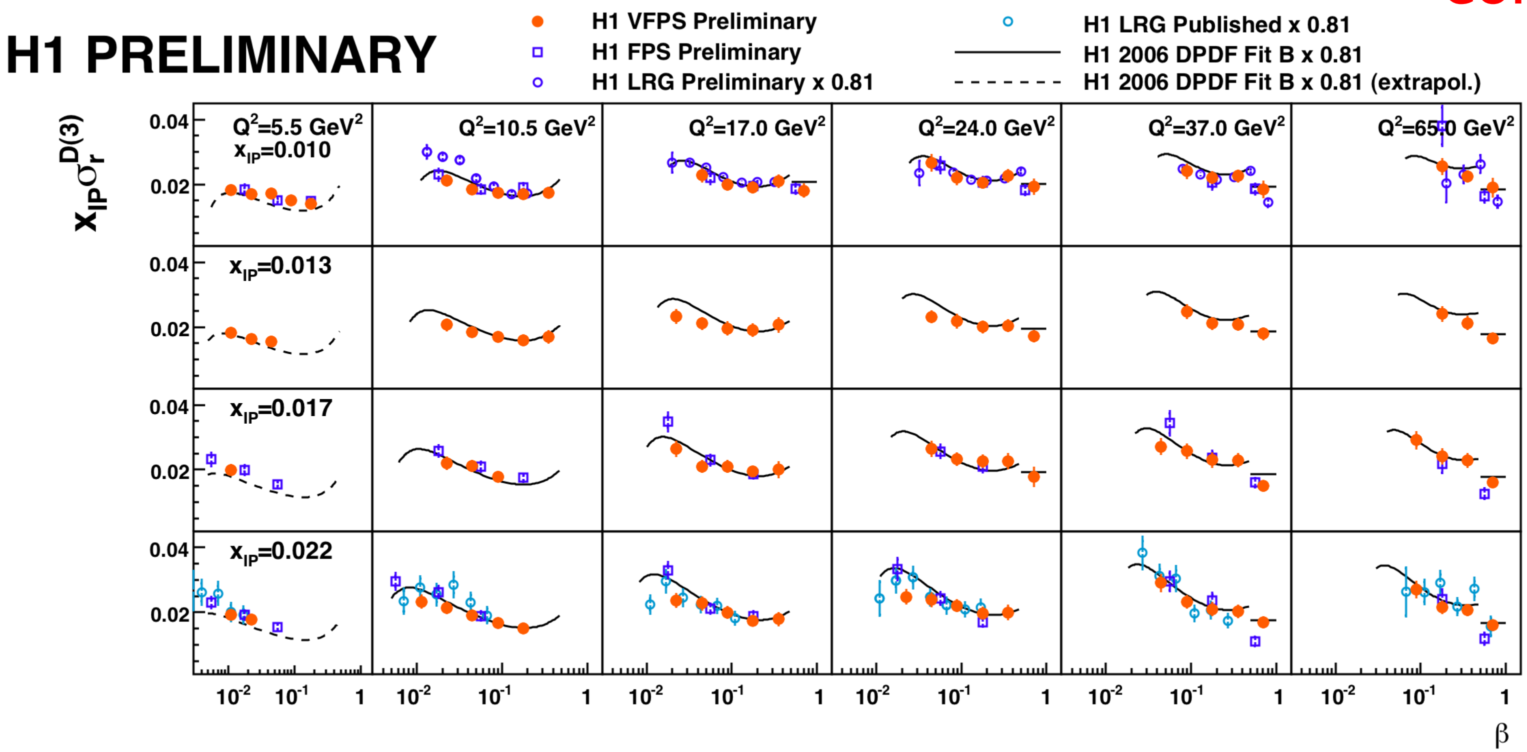






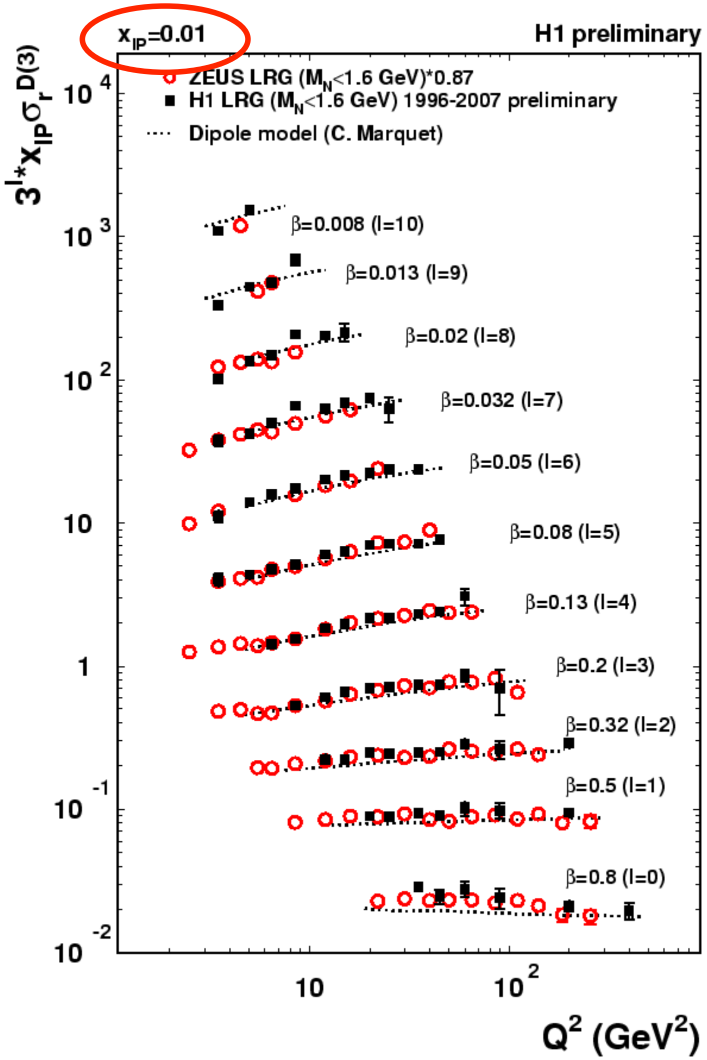
>90% acceptance over wide region - complementary x_{IP} range to LRG

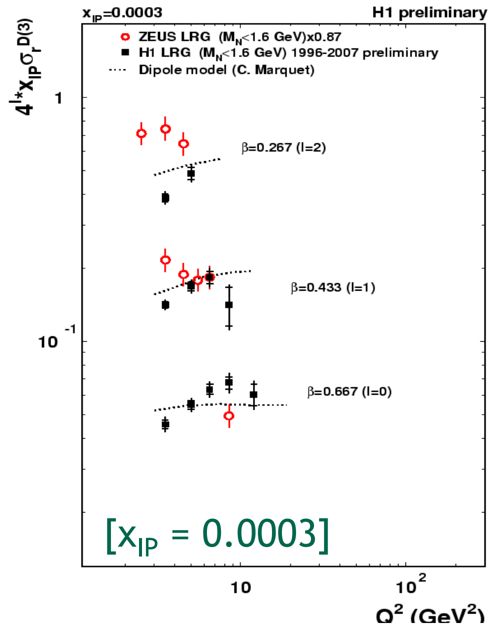
95pb-1

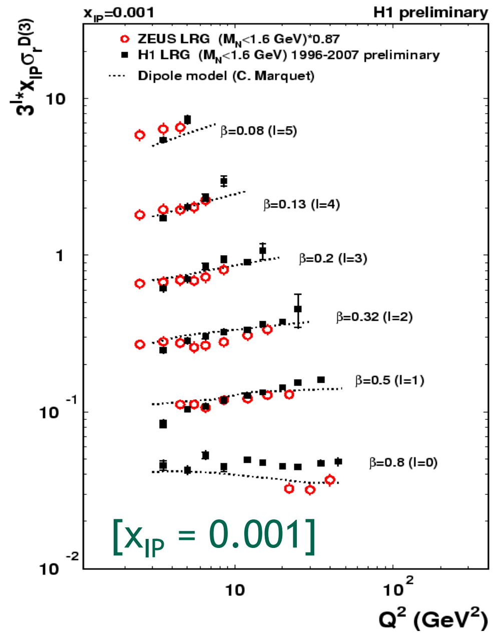


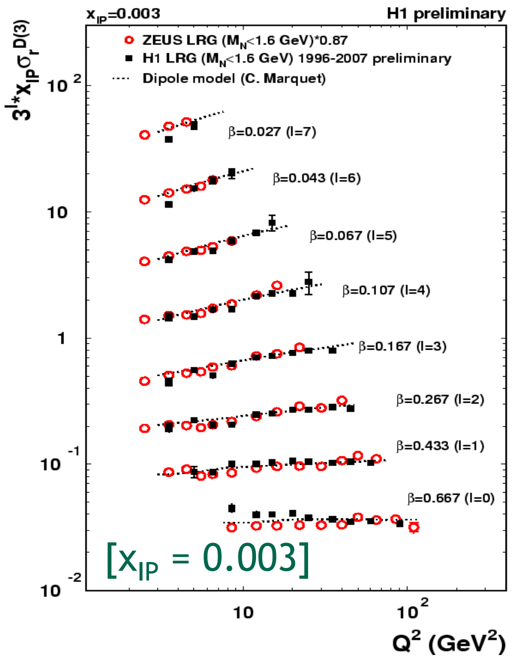
First precise data recently released …

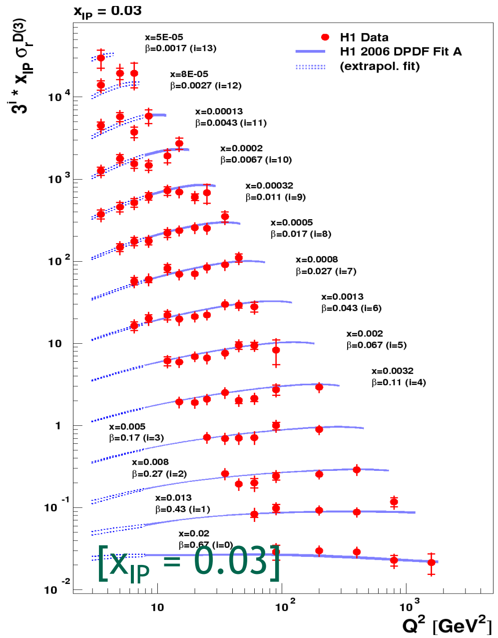
ZEUS v H1 LRG Data











- New H1 data with 370 pb^{-1}
- Few % point-to-point precision over wide kinematic range
- ~13% difference between H1 and ZEUS within norm^{n} errors