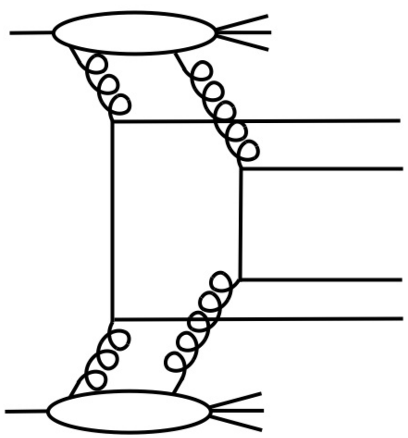
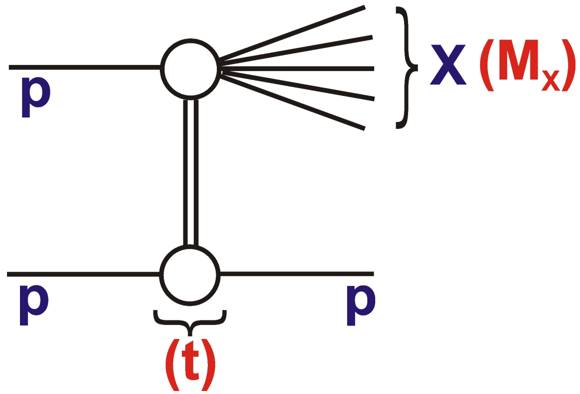
Diffraction and Soft Strong Interactions: Selected New Results from the LHC

Paul Newman (University of Birmingham)

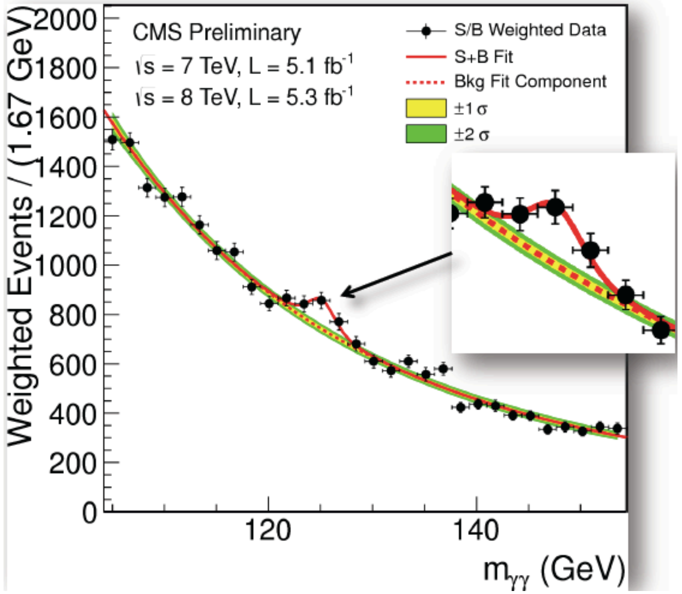


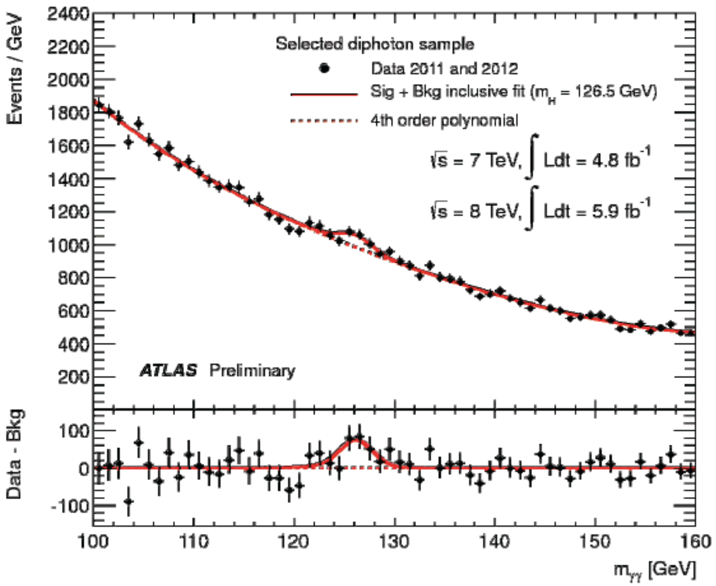


Penn State Seminar
27 February 2013

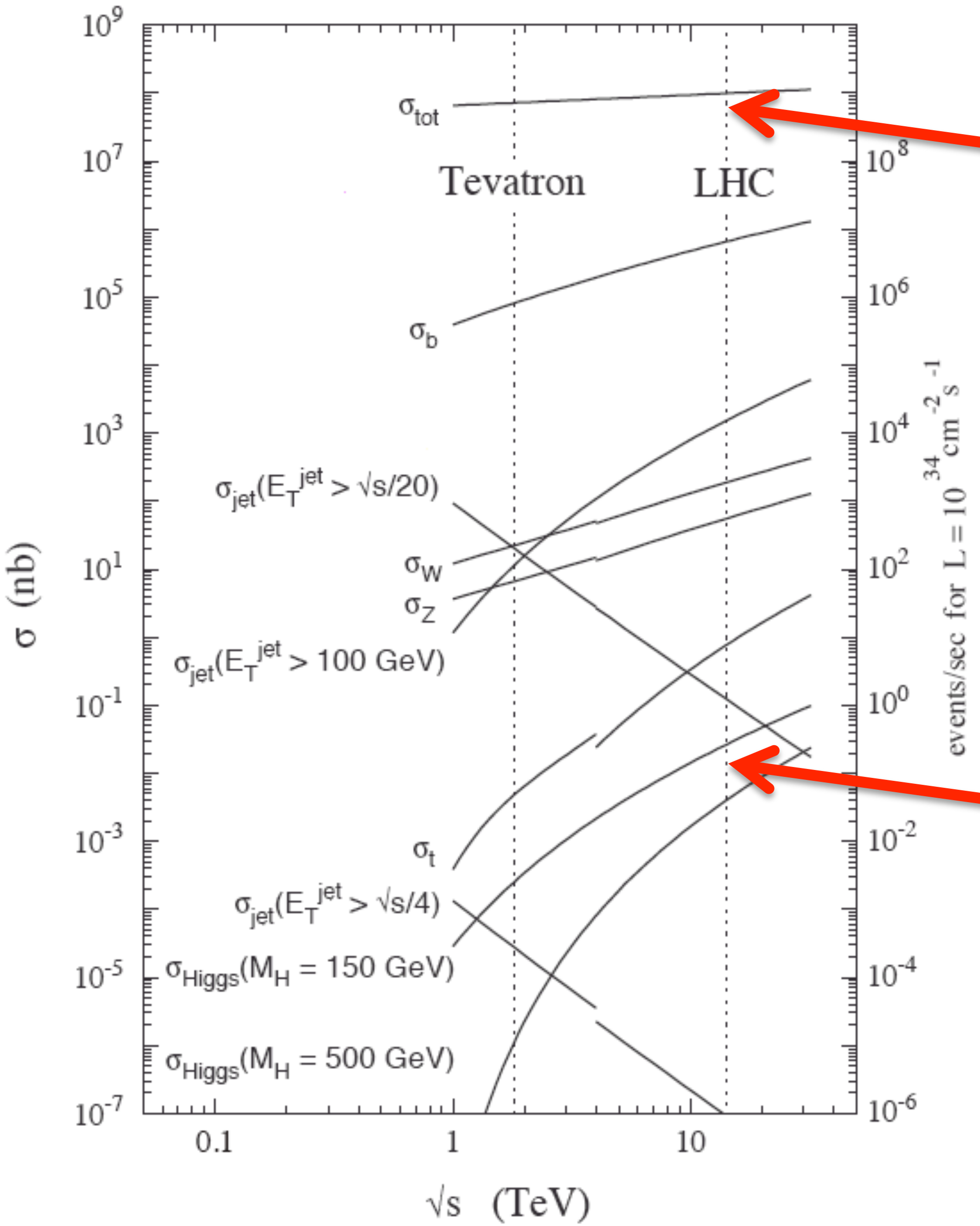
→ Elastic and Total Cross Sections
→ Diffractive dissociation (soft and hard)
→ Underlying event and multiple parton interactions
→ (Very) forward Energy flow and Charged Particle Production

LHC Main achievement so far: Higgs



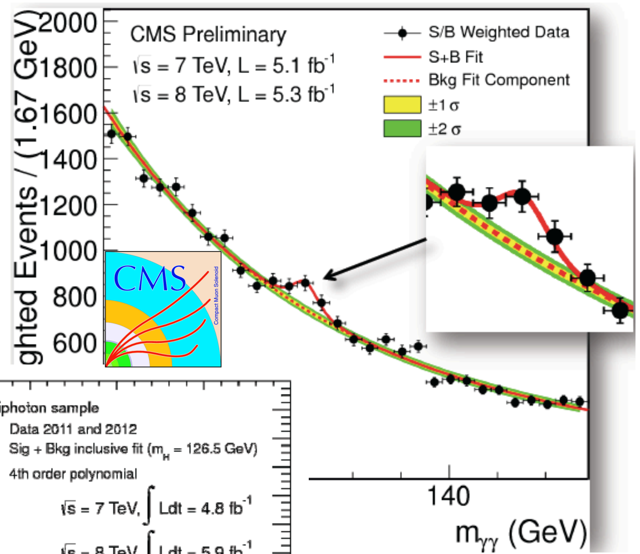


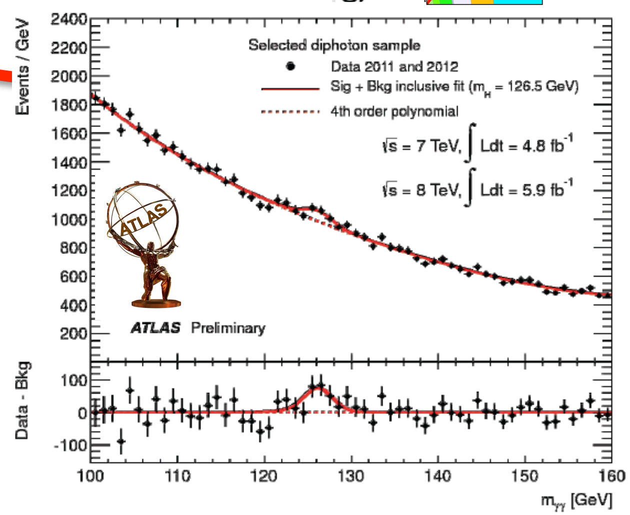
But what usually happens when hadrons Collide?



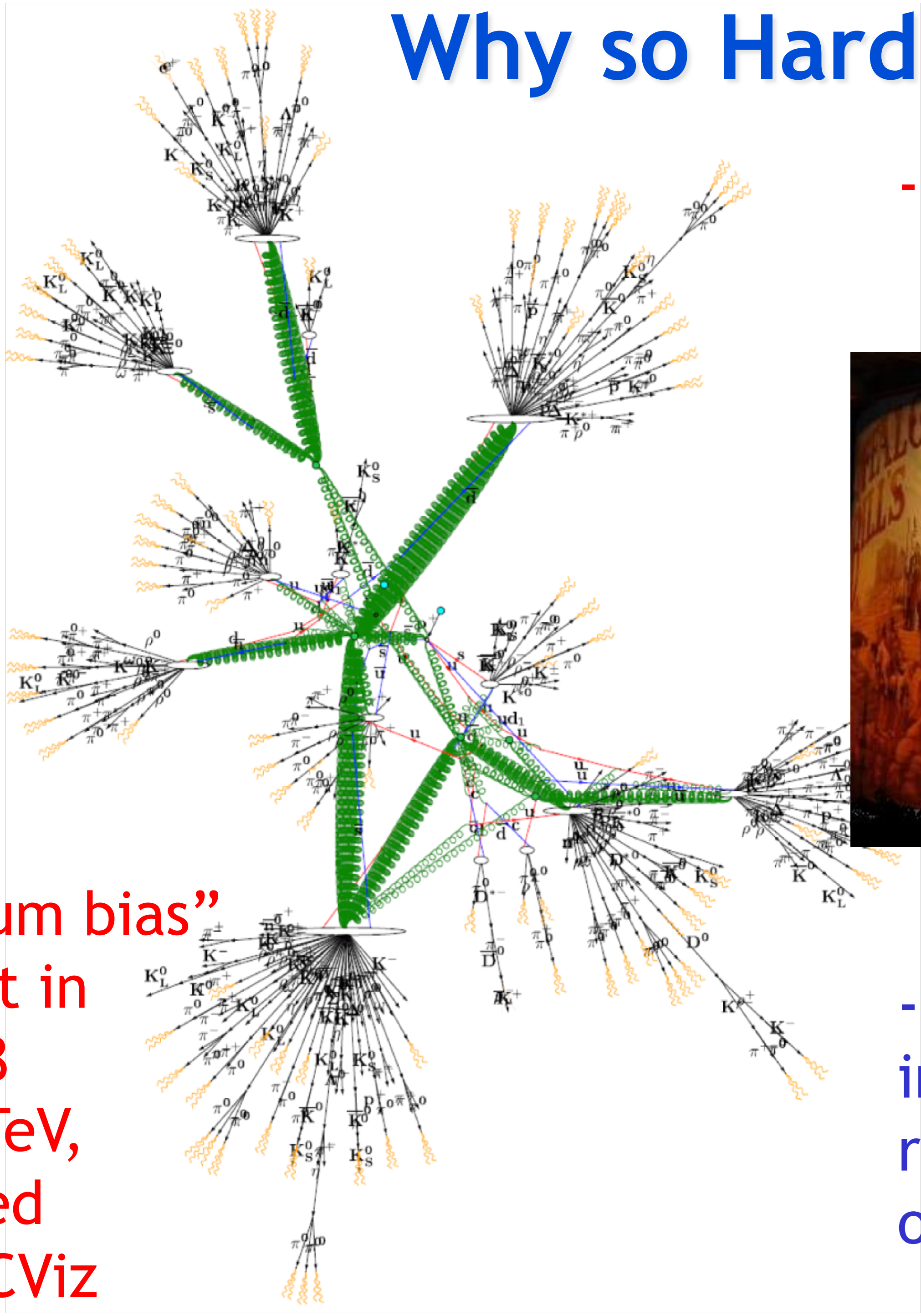
This talk…

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

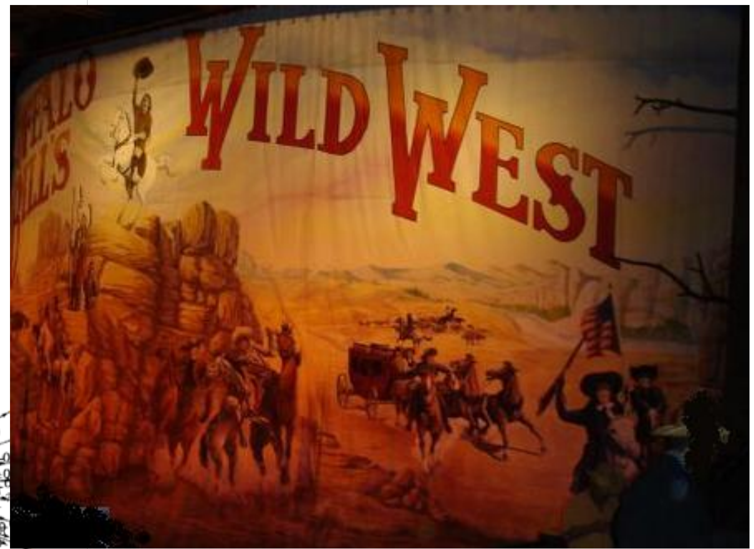




Why so Hard to Calculate?



- Front-line territory!



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

- Constrained by impressively precise recent data and some original new observables

Why should we Care?

Dominant strong interaction processes fundamental to our basic understanding of the Standard Model:

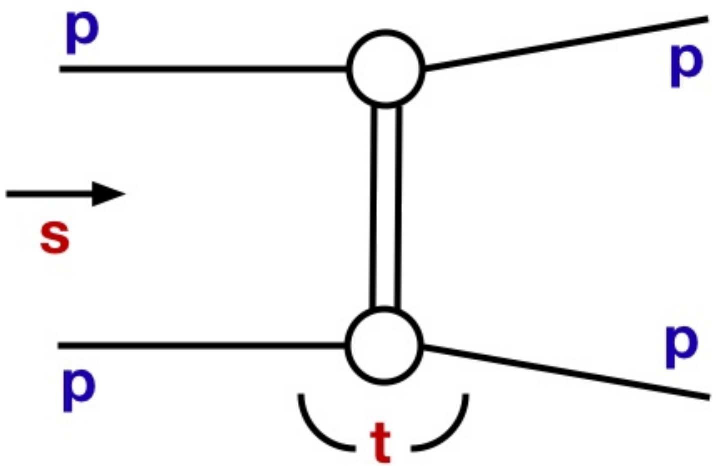
Fundamental questions:

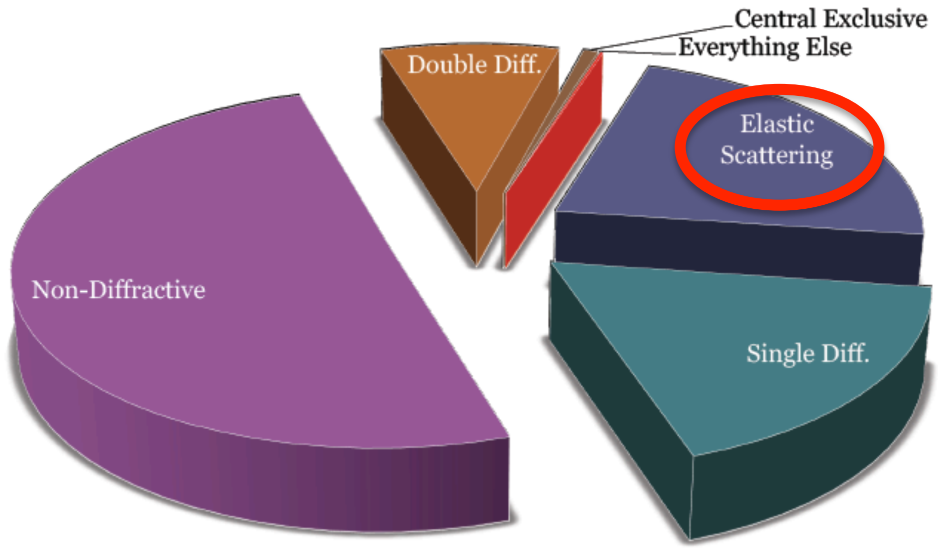
- confinement
- hadronic mass generation,
- non-perturbative degrees of freedom
- strong / weak coupling and Super-gravity
- …

Practical concerns:

- Modelling pile-up at the LHC
- Modelling underlying event at LHC
- Modelling cosmic ray air showers
- …

Something `Simple': Elastic Scattering



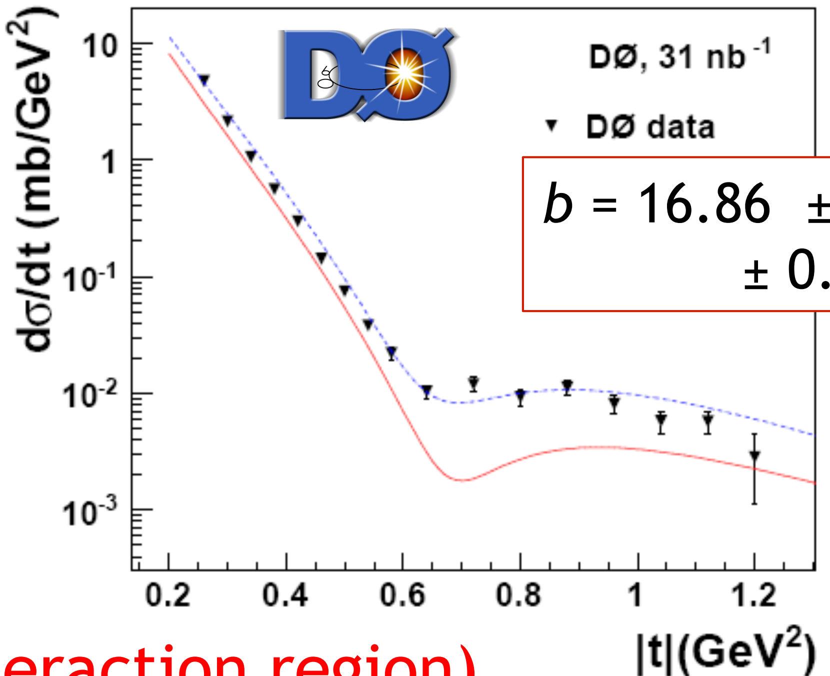


At fixed √s, 1 non –trivial variable (t)

Typically t << 1 GeV²: non-perturbative

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).

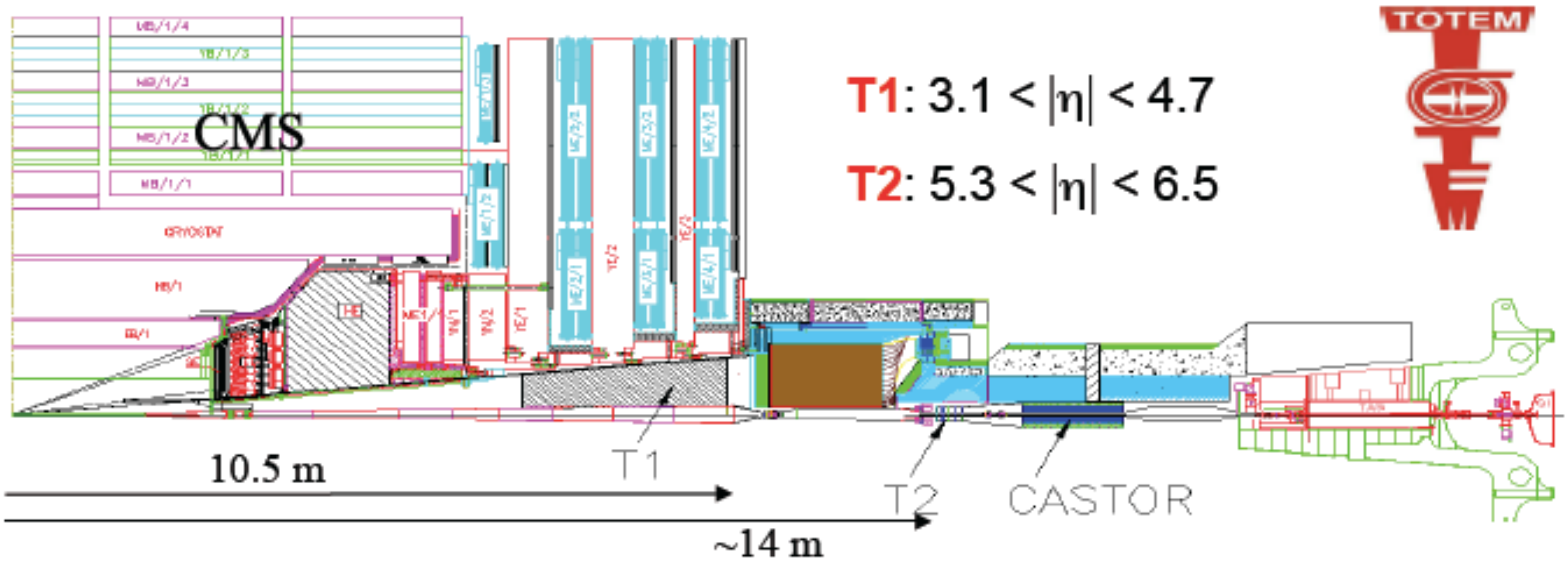


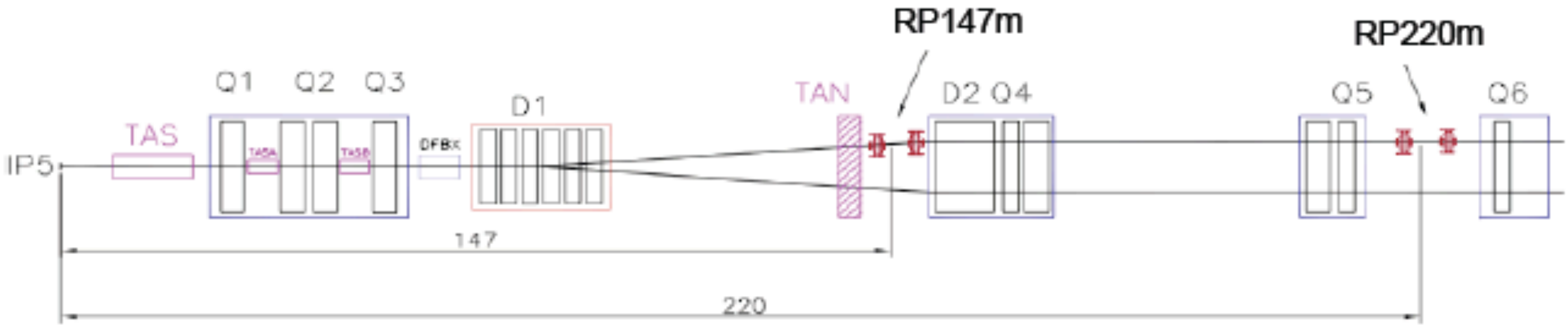
Roman Pots
√s=1.96 TeV

b = 16.86 ± 0.10 (stat) ± 0.20 (sys) GeV^{-2}

Strong force range ~ few fm.

The Elastic Cross Section at the LHC: TOTEM

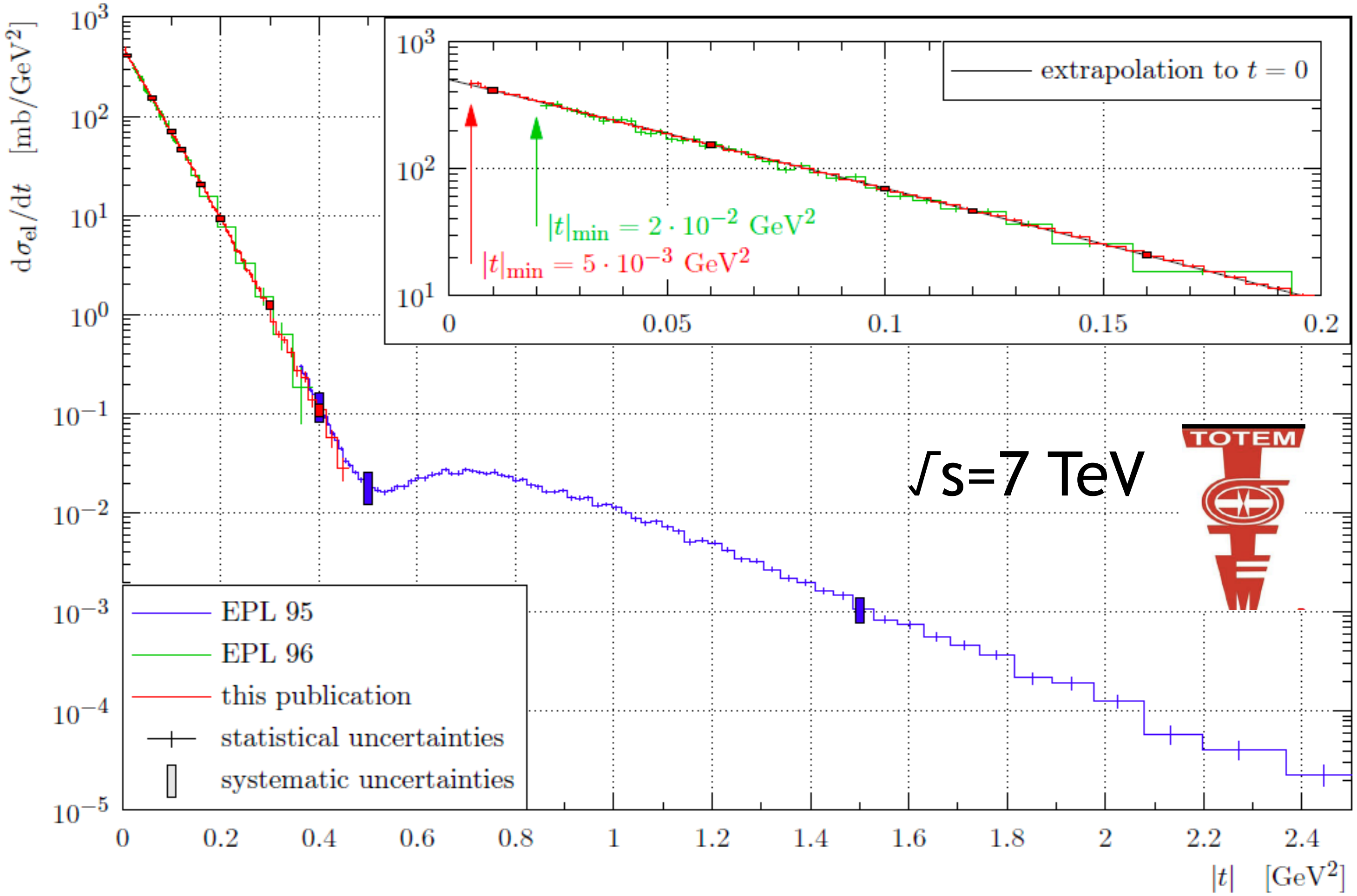




- The most hermetic detector ever?
- Elastic scattering measurement using Roman pots at 220m

Elastic Cross Section (TOTEM Roman Pots)

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

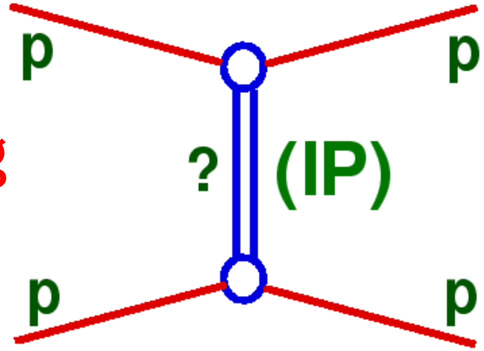


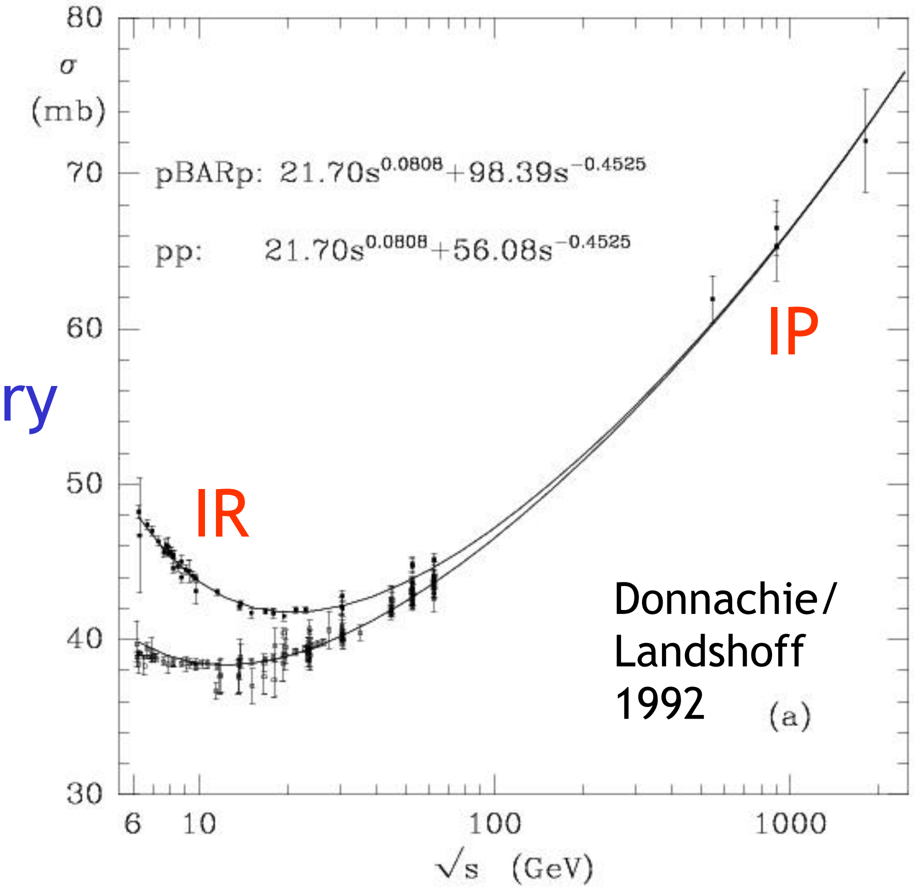
- B increases: 16.7± 0.2 GeV^{-2} (D0) → 19.9±0.3 GeV^{-2} (TOTEM)
- Position of dip decreases from |t| ~ 0.6 GeV^2 (Tevatron) to 0.53 GeV^2 (TOTEM) →

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

Vacuum Exchange and the Pomeron

What governs elastic scattering at high energies?



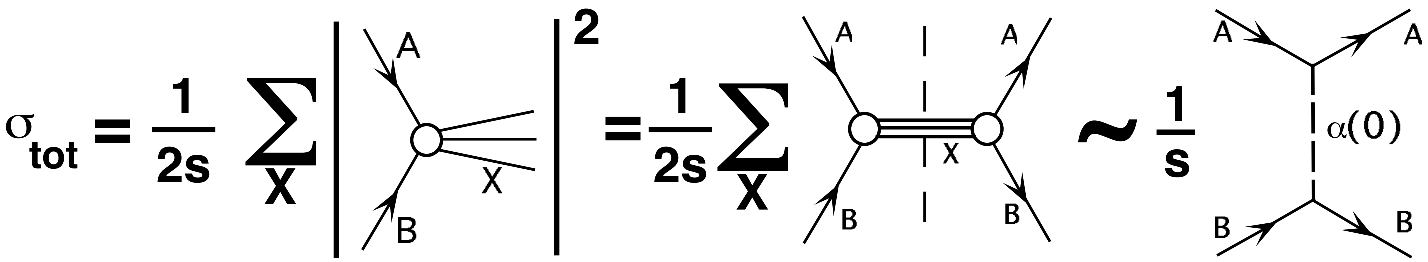


\`Historically' … pomeron trajectory

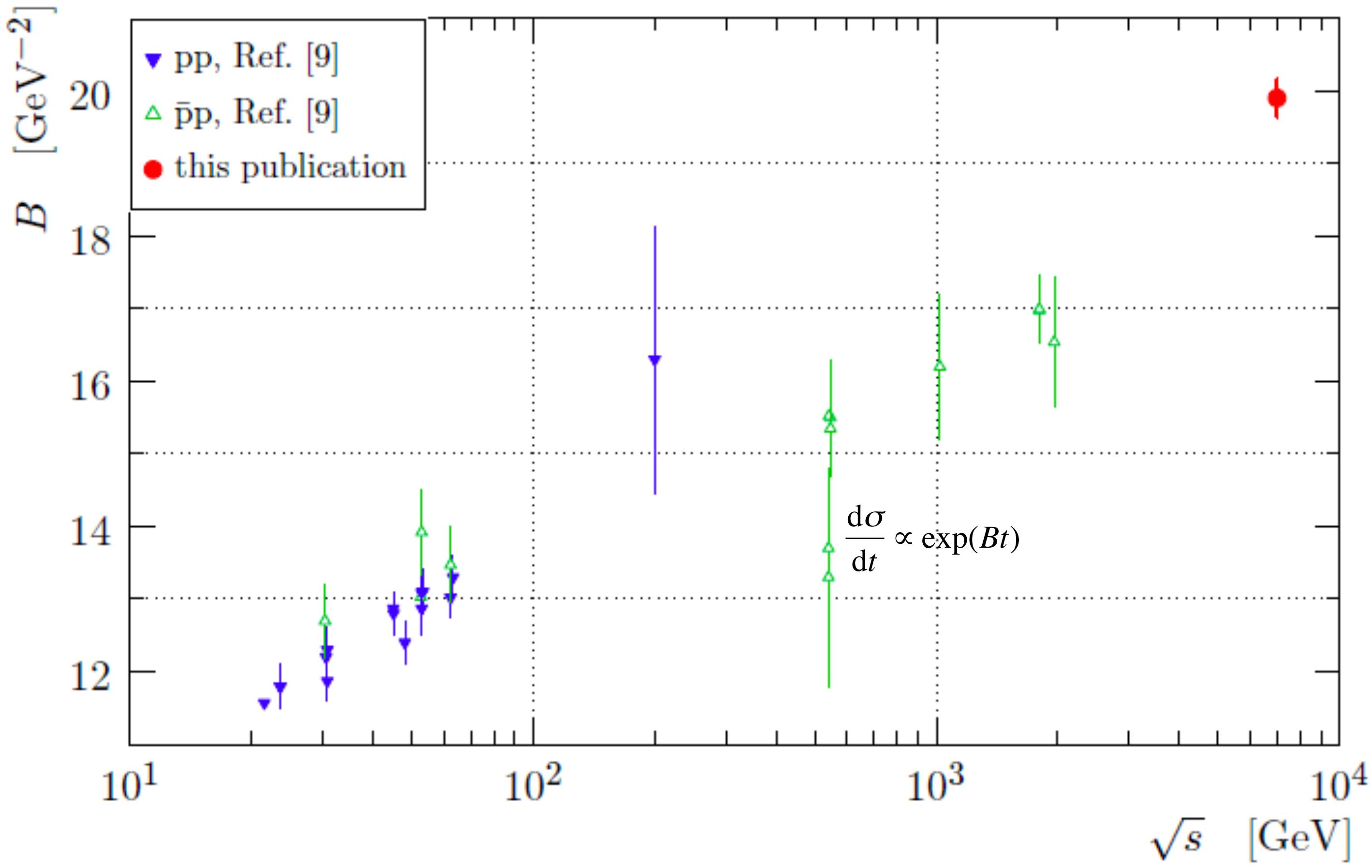
$$\alpha(t) = \alpha(0) + \alpha' t \approx 1.085 + 0.25t$$

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

Closely related to total x-sec via optical theorem



√s dependence of t Slopes and α'



Fixed s:

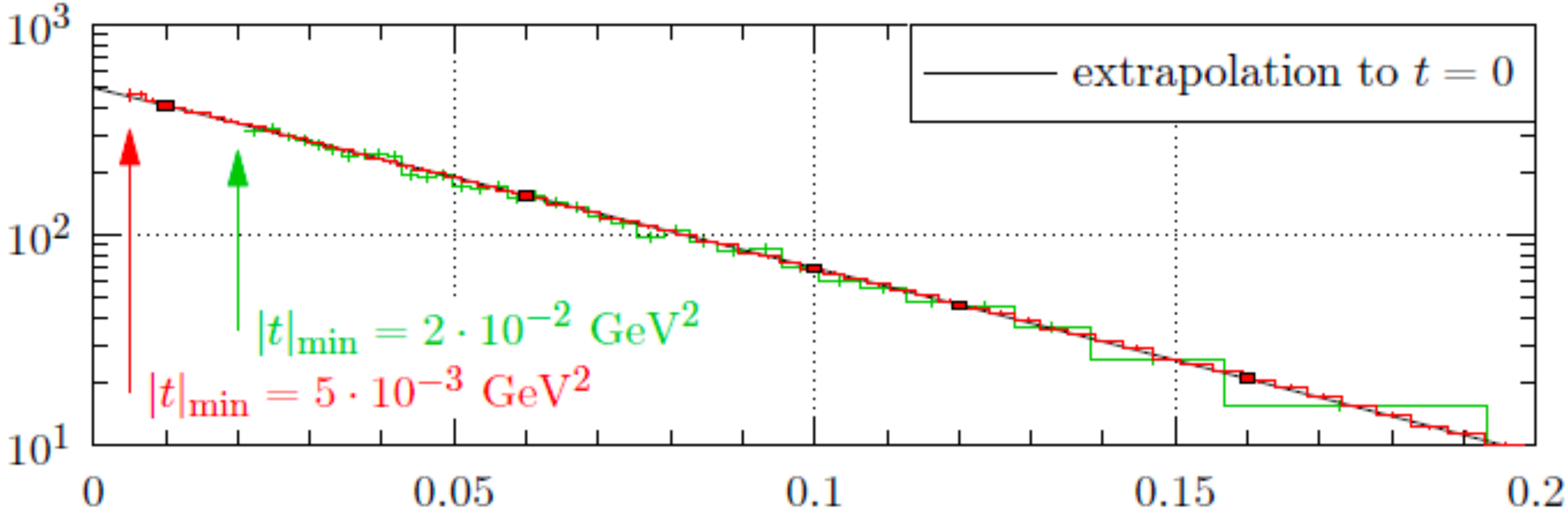
$$\frac{d\sigma_{EL}}{dt} \propto \exp(Bt)$$

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

- Comparing Tevatron and TOTEM results suggests α' significantly larger than the generally assumed value of 0.25 GeV^{-2}
- There were similar observations at HERA …
- Single pomeron exchange insufficient (`absorptive corrections')

Optical Theorem: Relating elastic & total cross sections

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



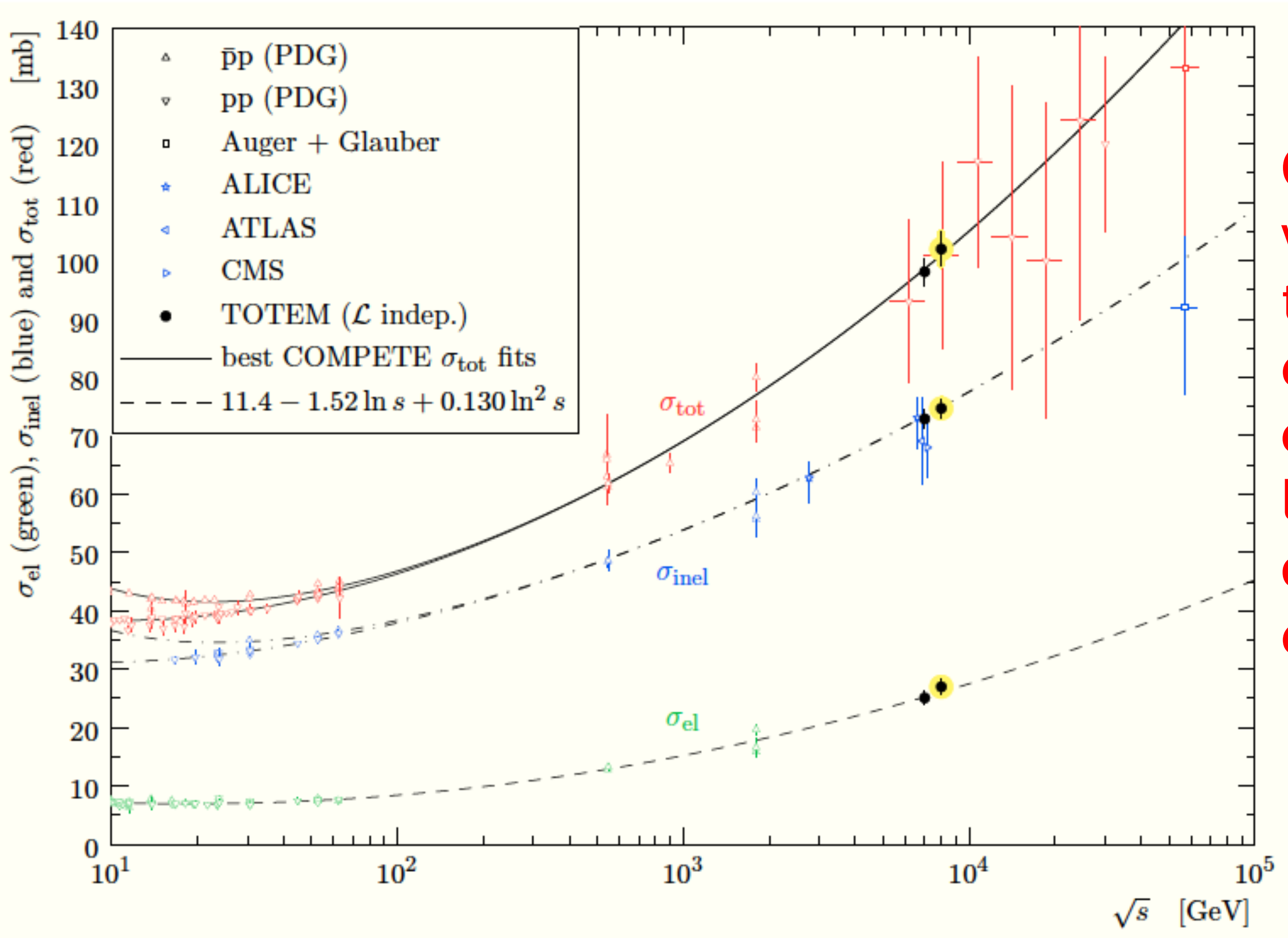
Dedicated run (special optics @ β* = 90m) → |t| ~ 0.005 GeV^2

- 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

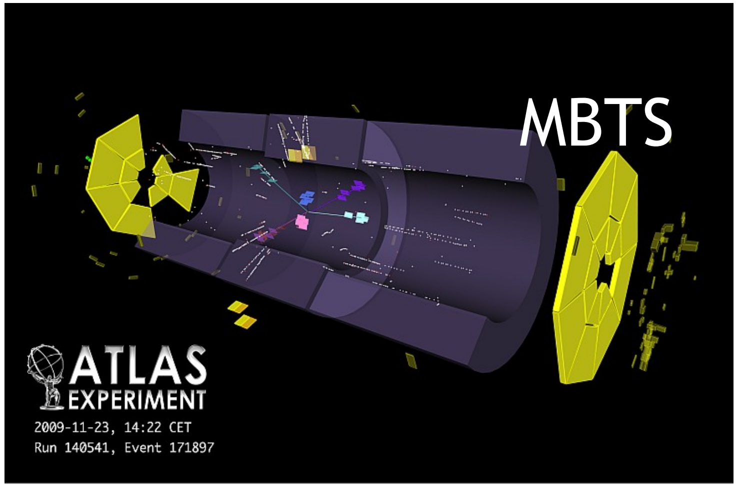
Now published at both √s=7 TeV and √s=8 TeV

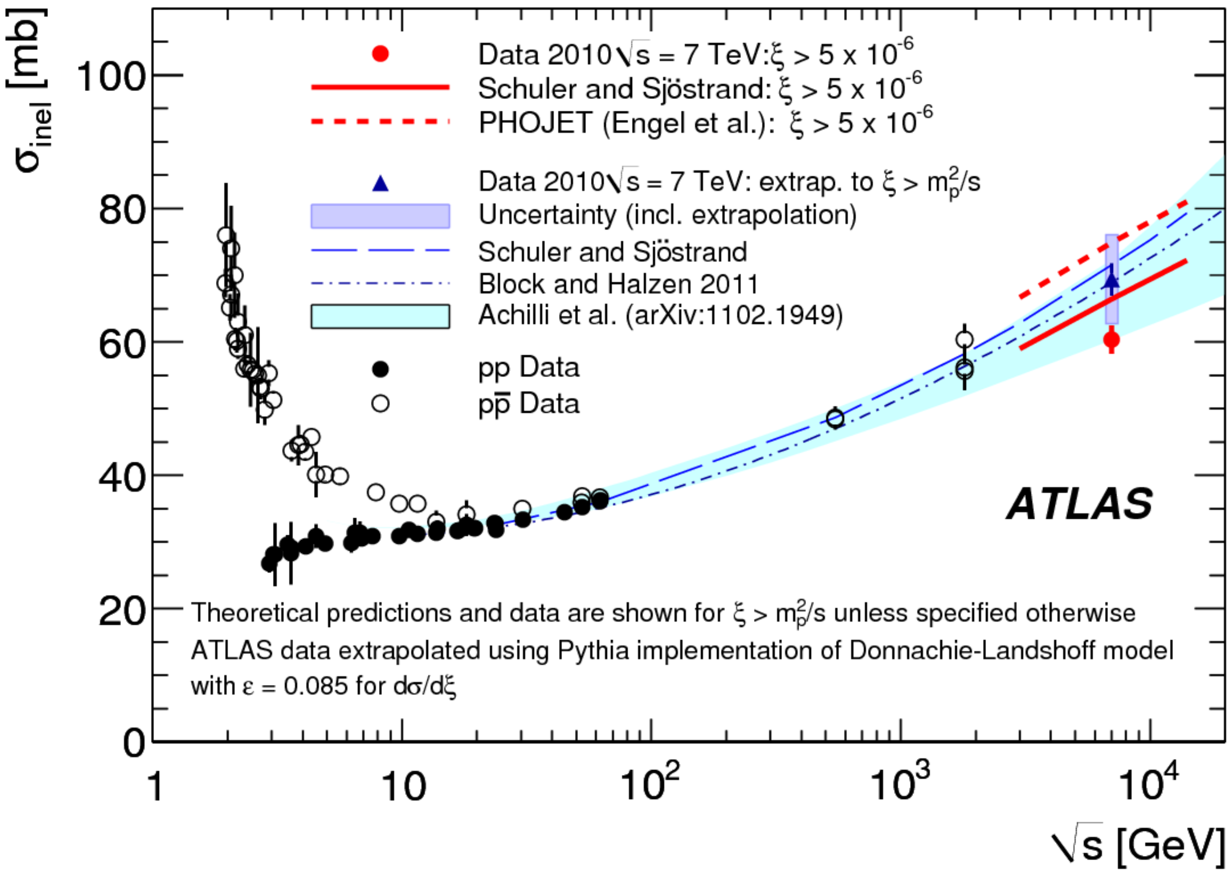


Consistent with fits to previous data (with either a logarithmic or power law dependence).

Total Inelastic pp Cross Section (ATLAS)

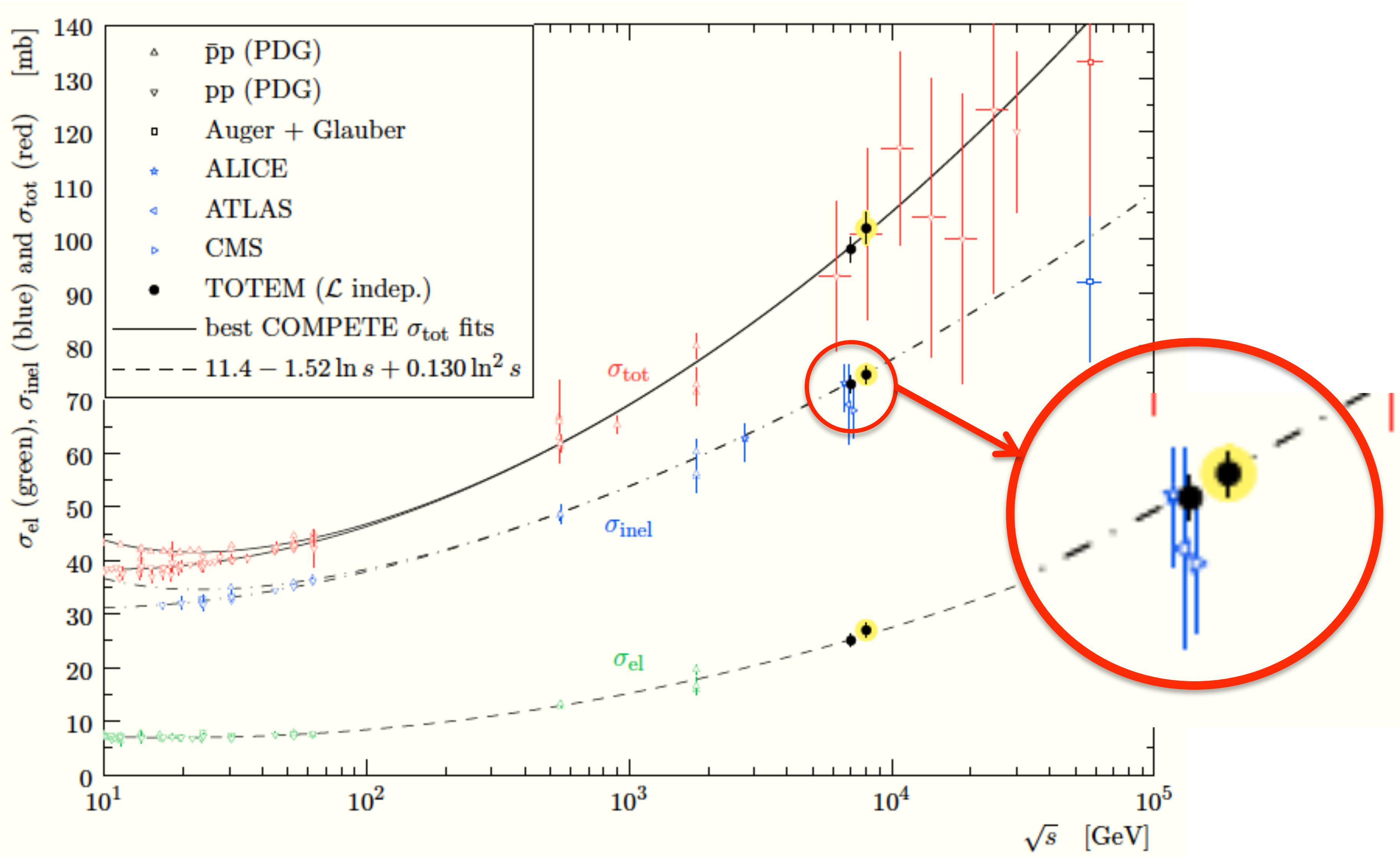
- Using MBTS trigger ($2.1 < |\eta| < 3.8$), miss only elastic (pp → pp) and low mass diffraction (pp → pX etc)





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

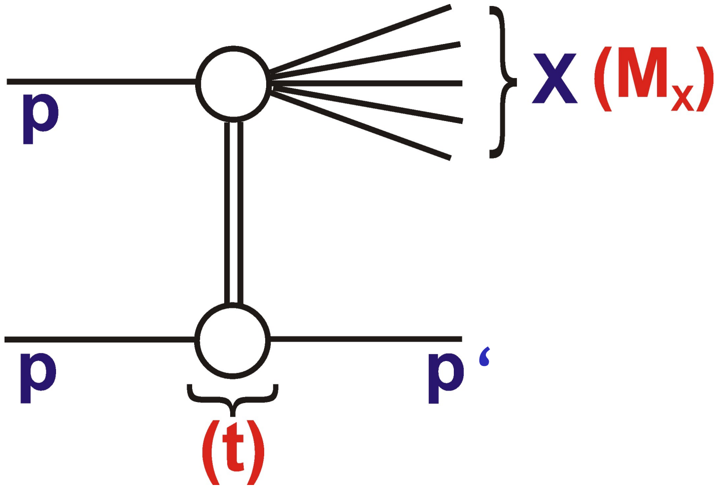
Comparison with Indirect TOTEM Data



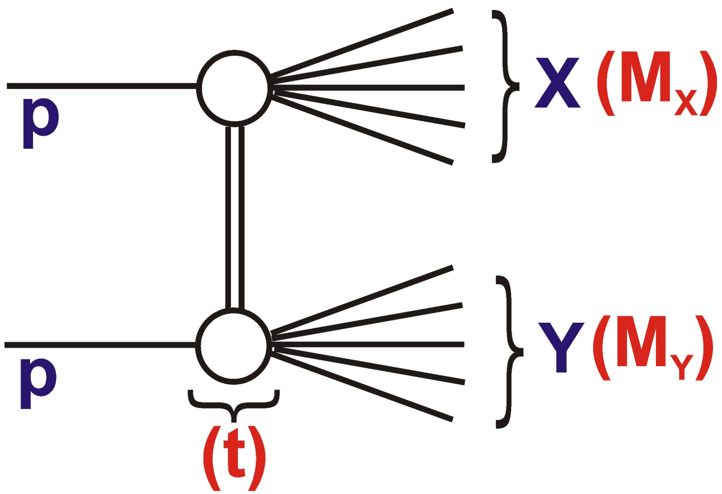
Central Value of extrapolated ATLAS result within large (model dependence) errors of TOTEM, but central value somewhat lower … need improved modelling of low mass dissociation ...

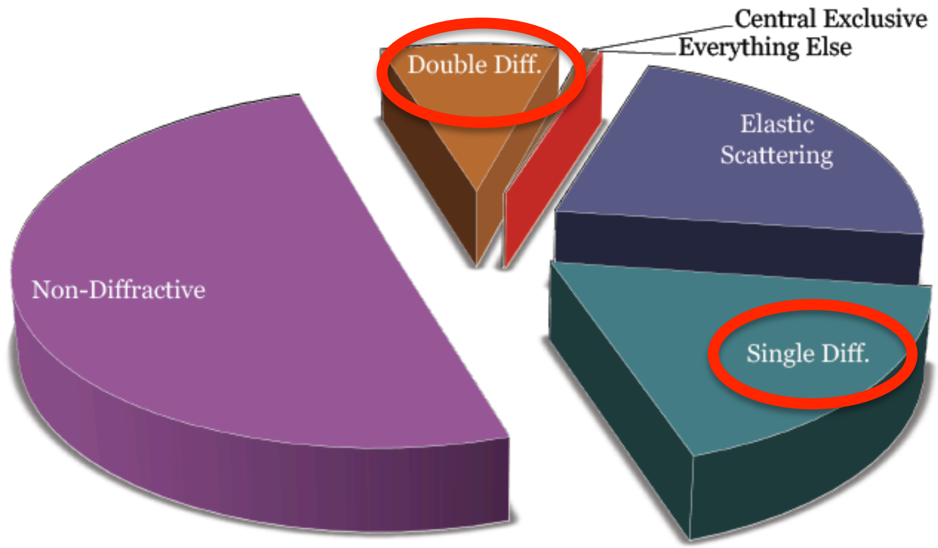
Inelastic Diffraction

Single diffractive dissociation



Double diffractive dissociation





Additional kinematic variable

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

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

Uncertainties in pre-LHC Predictions

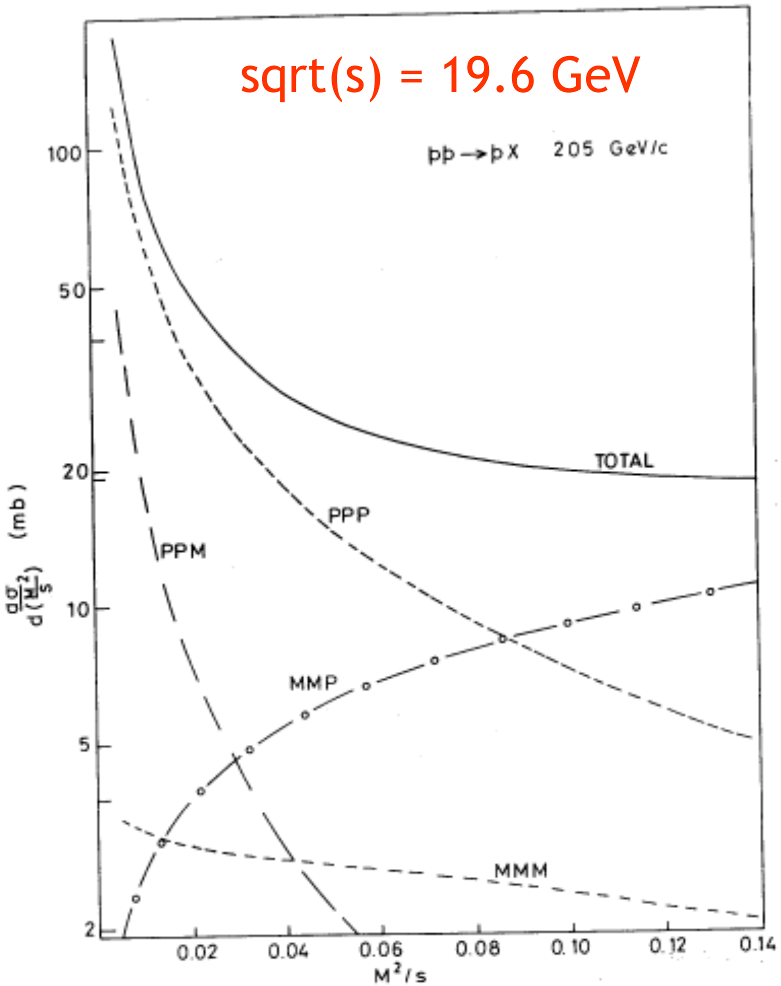
Single dissociation

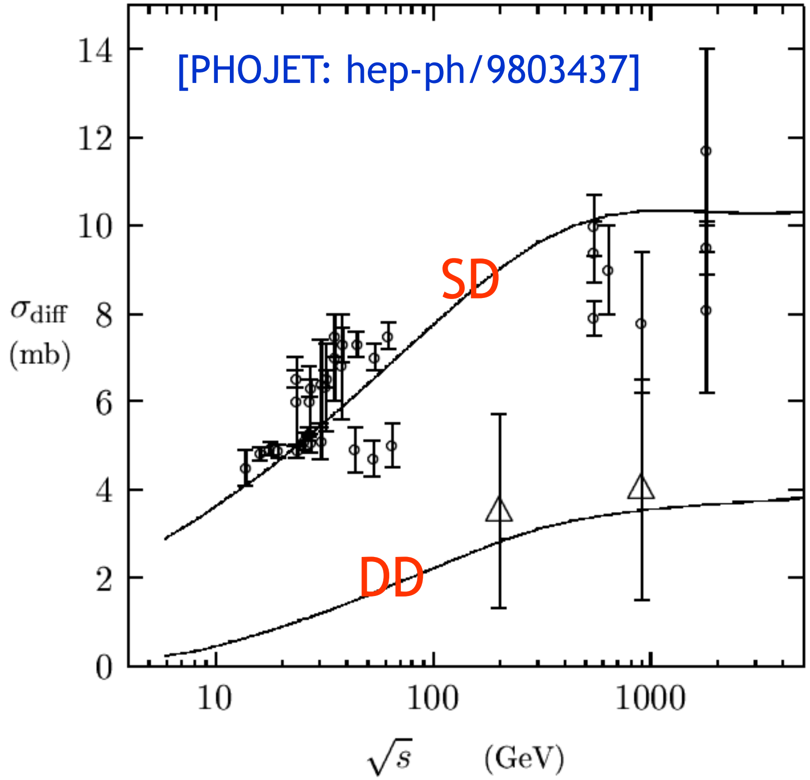
σ = 14mb (PYTHIA8)
σ = 10mb (PHOJET)

Double dissociation

σ = 9mb (PYTHIA8)
σ = 4mb (PHOJET)

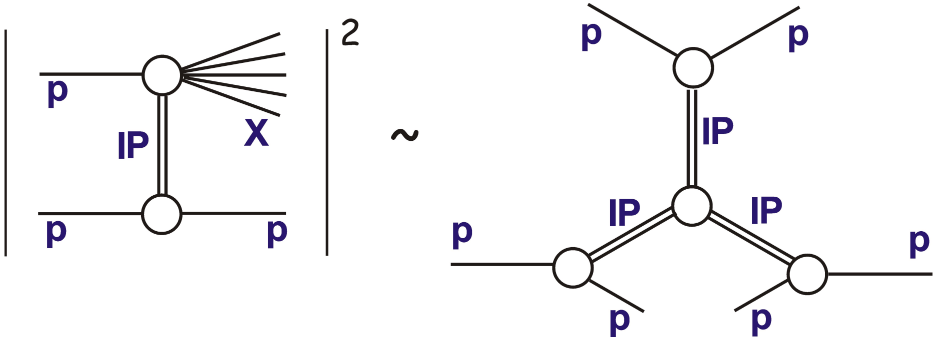
Parameterisations based on old low energy data, particularly poor for DD





"Standard Model" of Soft Diffraction

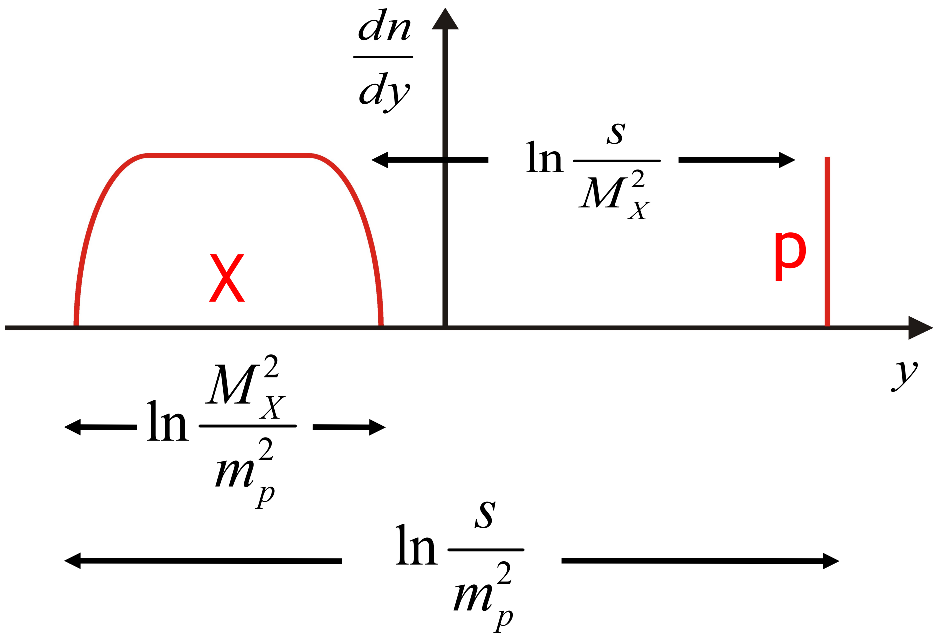
$$\left[\alpha(t) = \alpha(0) + \alpha'\, t\right]$$



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

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

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

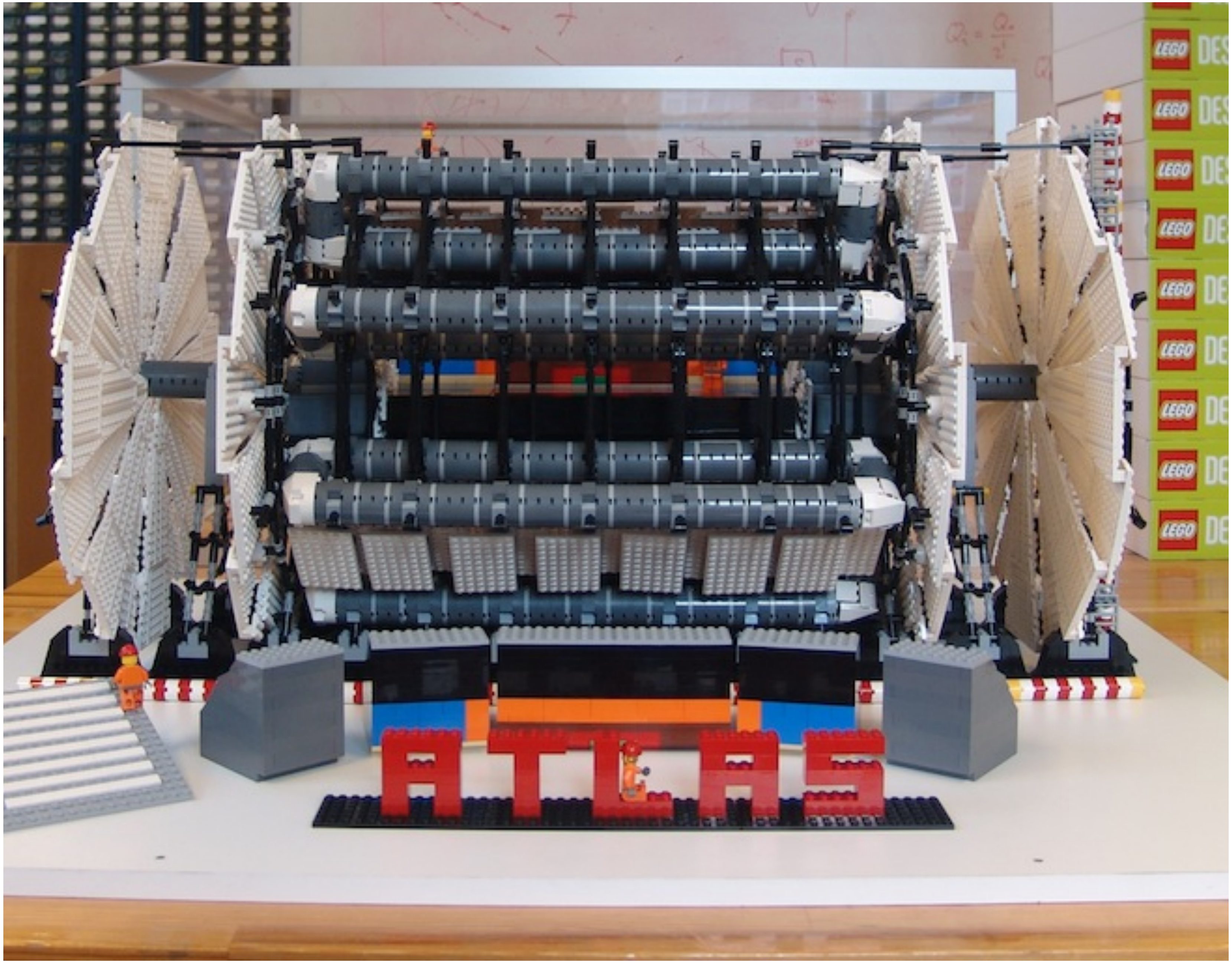


Up to event-by-event hadronisation fluctuations, ξ variable predictable from empty rapidity regions

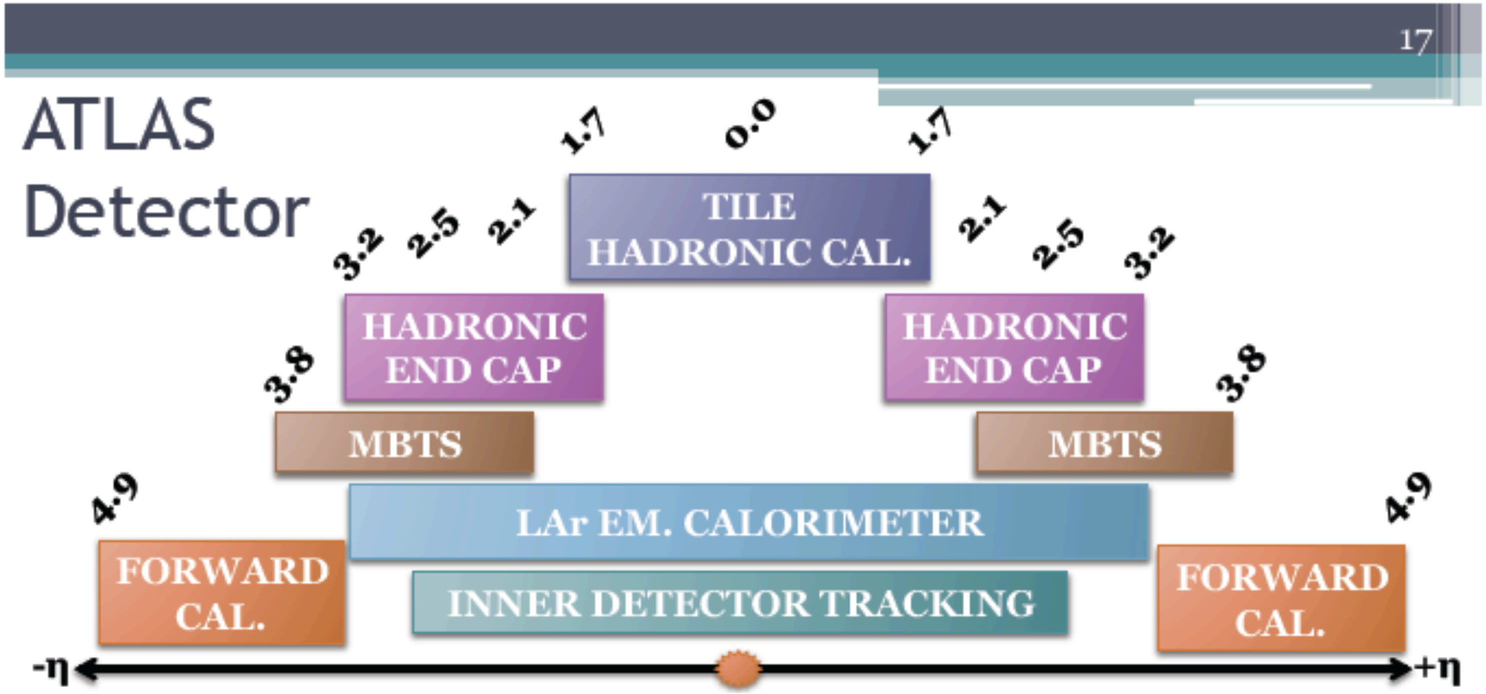
$$\Delta\eta \approx -\ln \xi$$

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

ATLAS Detector



ATLAS Acceptance



Data obtained using full calorimeter coverge (|η| < 4.9) and inner tracking detector (|η| < 2.5)

MBTS scintillators provide almost unbiased trigger

Detector is sensitive to particle production with p_T >~ 200 MeV

Differential rapidity gap cross-sections

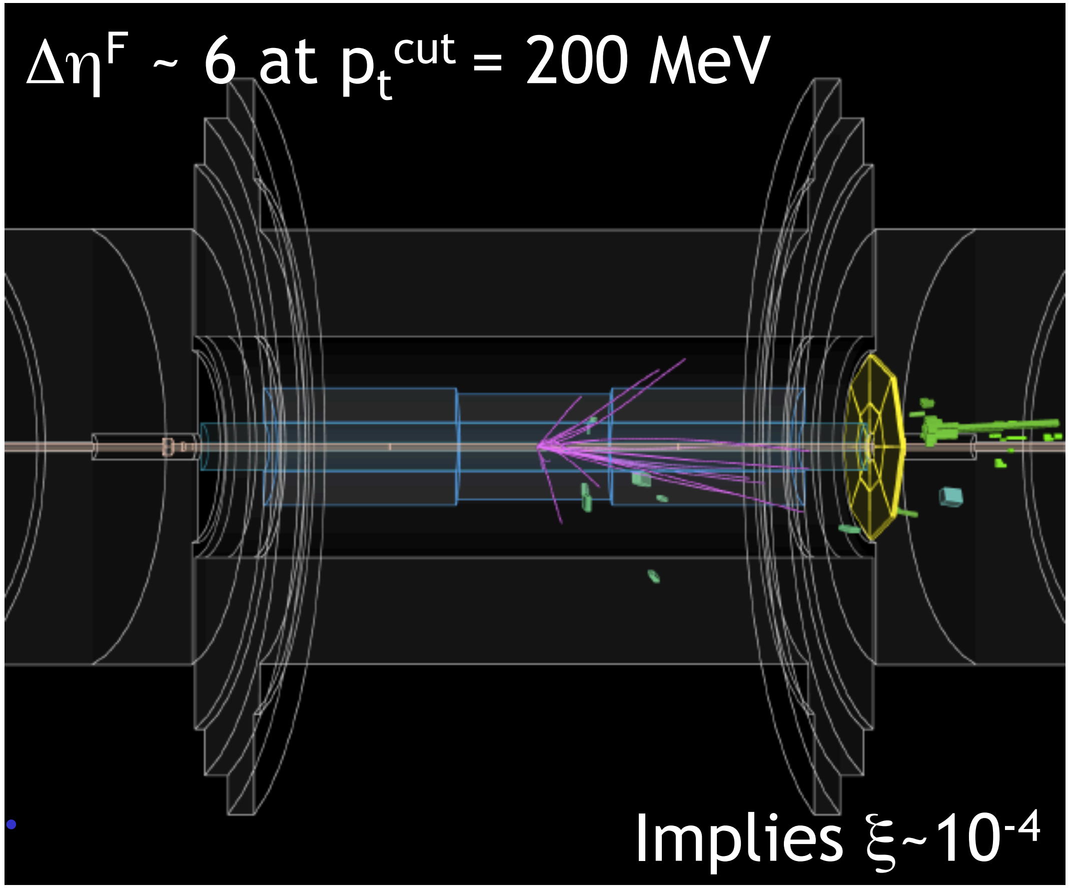
- Cross sections differential in `visible' rapidity gap size $\Delta\eta^F$
- $\Delta\eta^F$ extends from $\eta = \pm 4.9$ to first particle with $p_t > p_t^{cut}$

200 MeV < p_t^{cut} < 800 MeV
0 < $\Delta\eta^F$ < 8

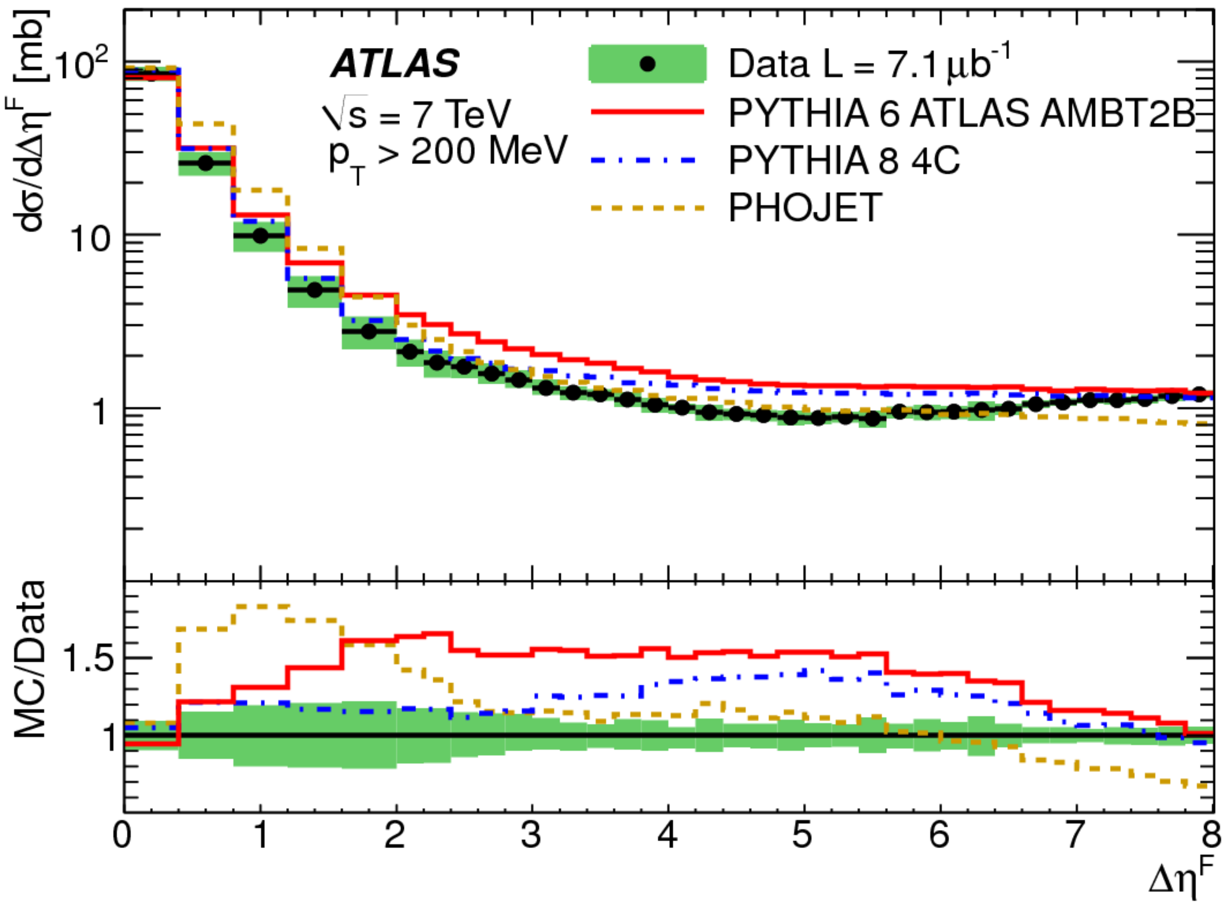
… corresponding (where diffraction dominates) to
$10^{-6} <\sim \xi <\sim 10^{-2}$ … or
$7 <\sim M_x <\sim 700$ GeV

Corrected for experimental effects to level of stable hadrons

p_t^{cut} = 200 MeV results follow …



Differential Rapidity Gap Cross Section

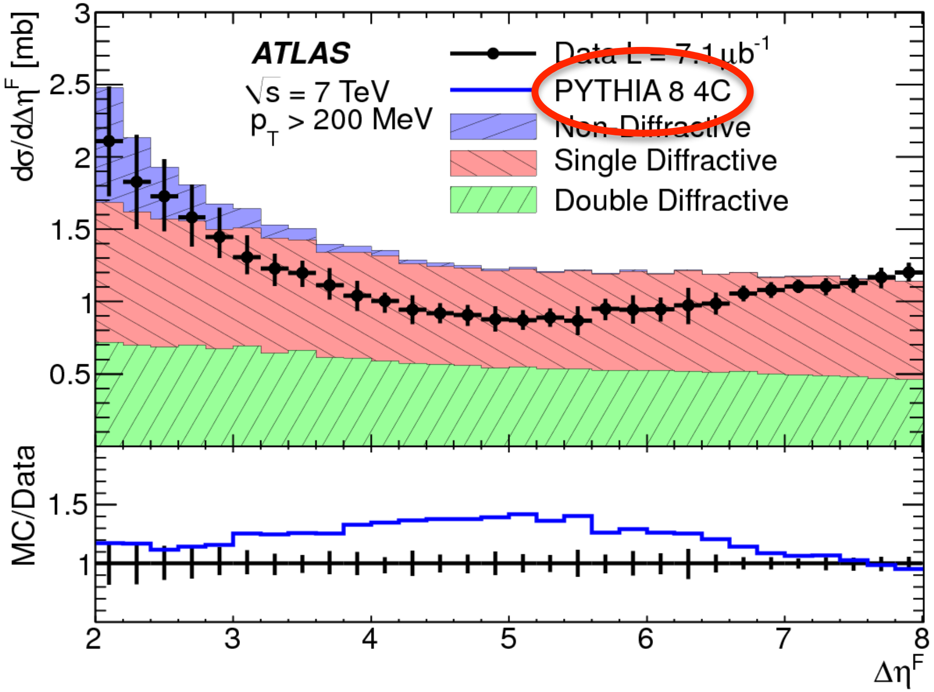


- Precision between ~8% (large gaps) and ~20% ($\Delta\eta^F$ ~ 1.5)
- Large gaps measure x-sec for SD [+ DD with M_Y <~ 7 GeV]
- Small gaps sensitive to hadronisation fluctuations / MPI

  … huge uncertainties

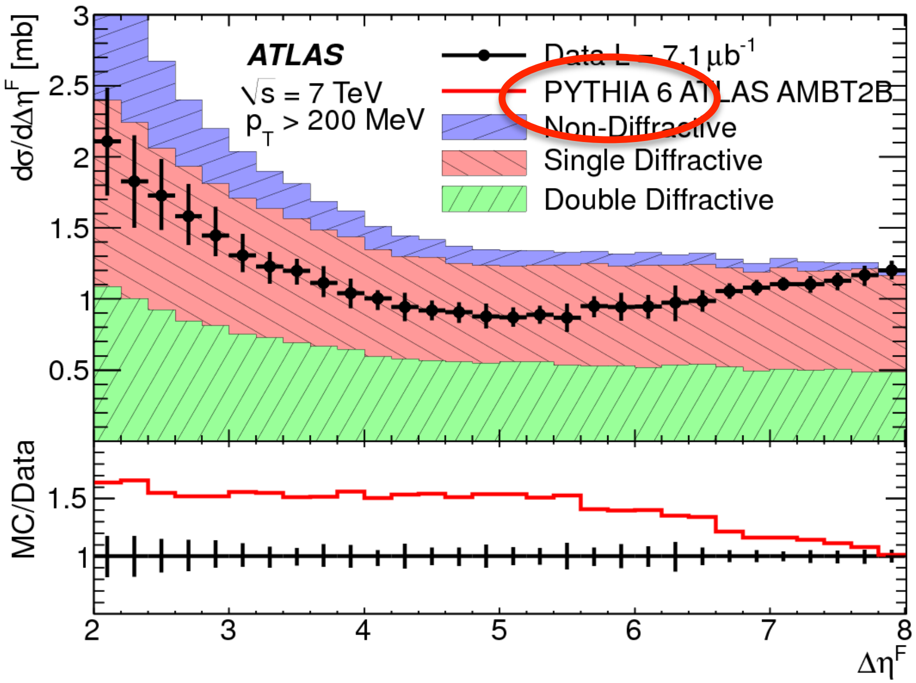
- PYTHIA best at small gaps, PHOJET > 50% high at $\Delta\eta^F$ ~ 1.5

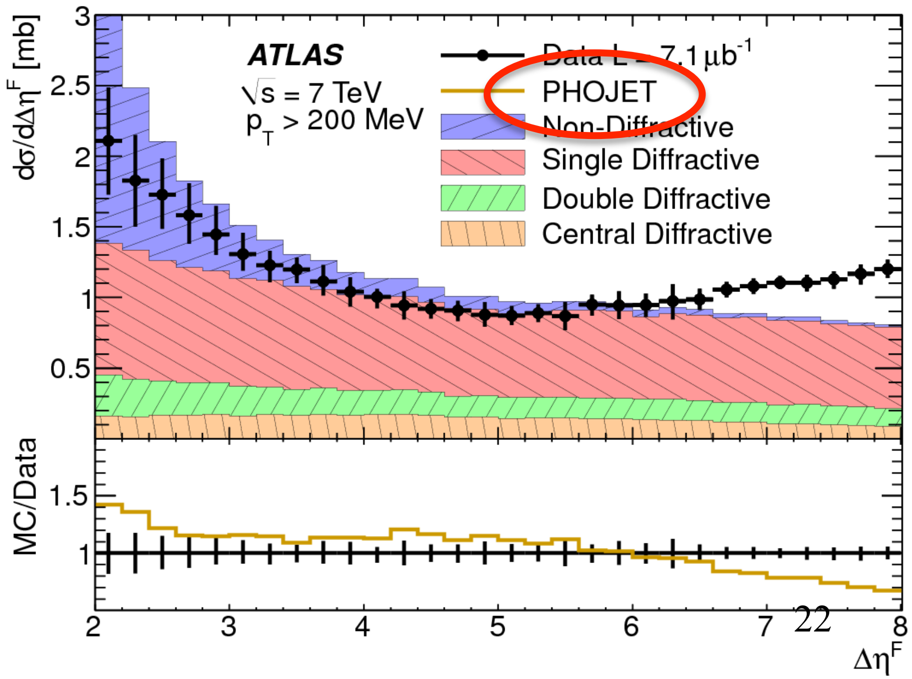
Large Gaps and Diffractive Dynamics



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

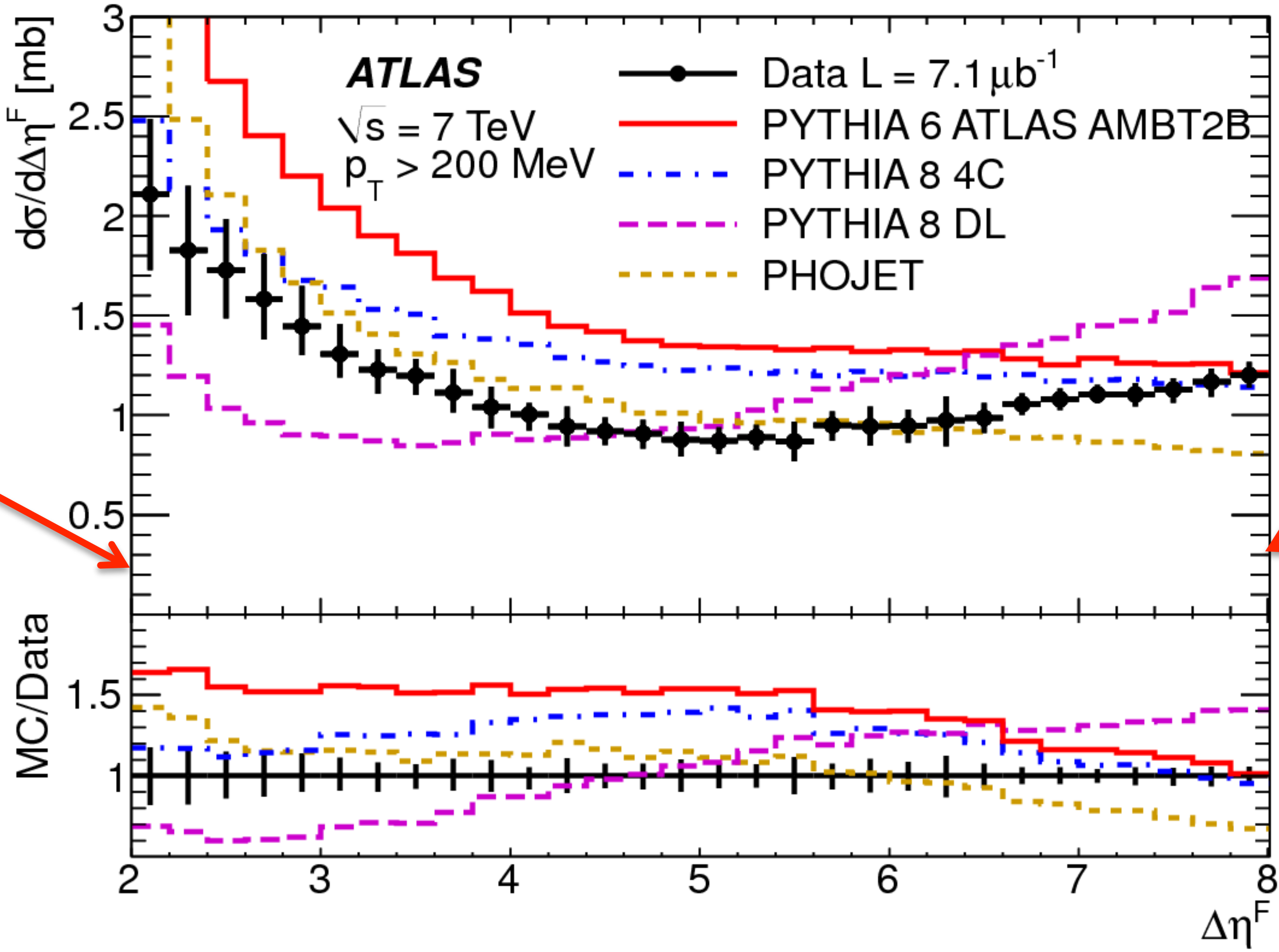
- PYTHIA high (DD much larger than in PHOJET)
- PHOJET low at high $\Delta\eta^F$





Large Gaps and Diffractive Dynamics

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



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

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

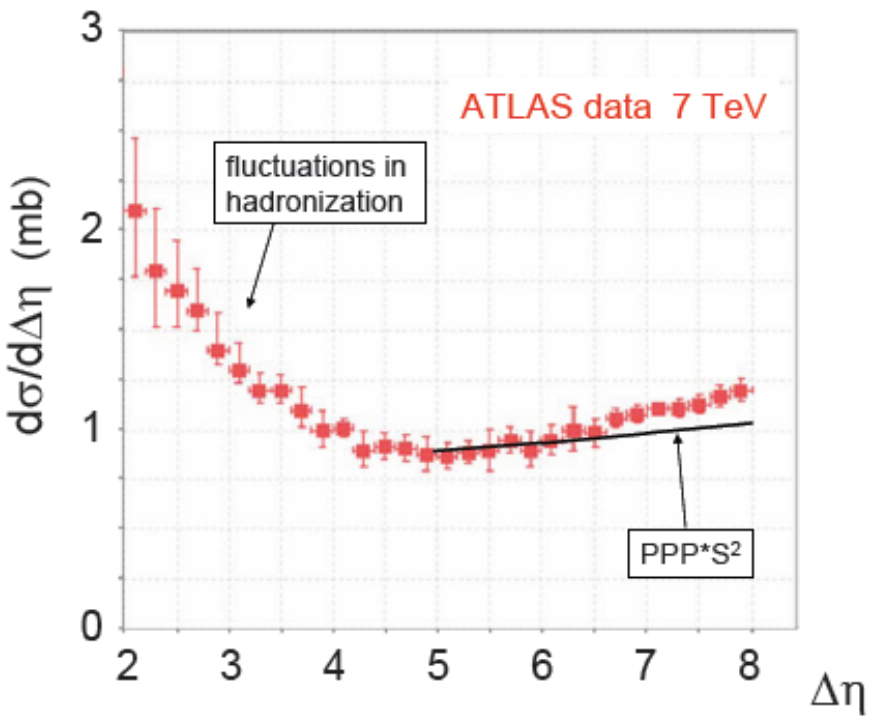
Donnachie-Landshoff flux has $\alpha_{IP}(0) = 1.085$

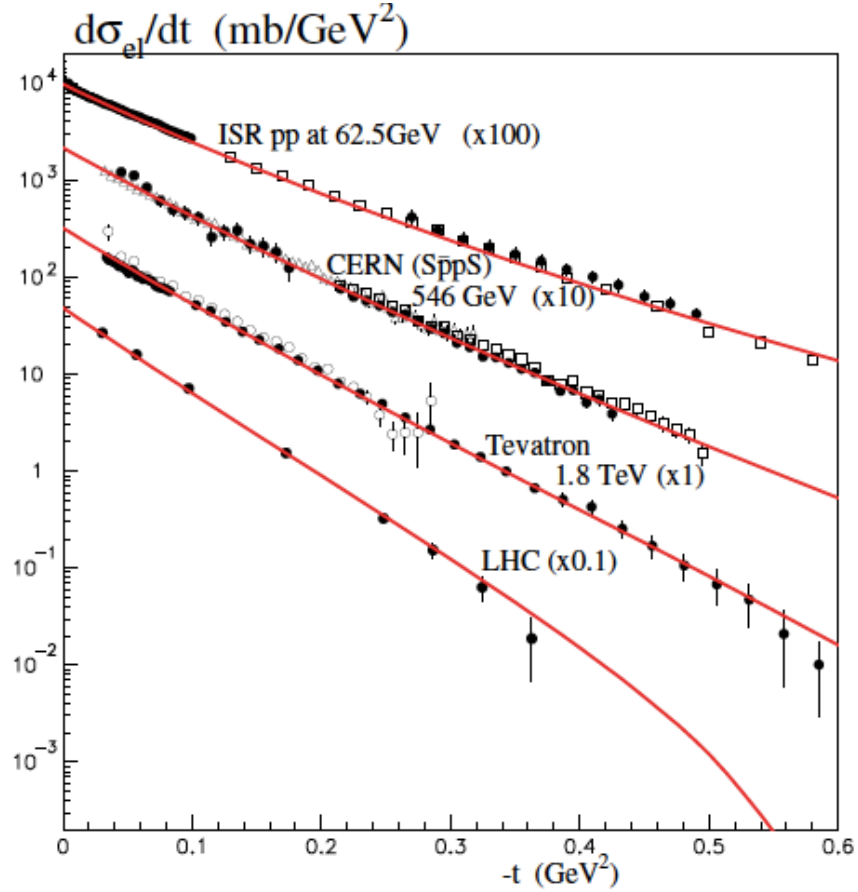
Fit to large $\Delta\eta^F$ region: $\alpha_{IP}(0) = 1.058 \pm 0.003$ (stat) ± 0.036 (syst)

[Absorptive corrections neglected in all cases]

Durham Model of all Soft Diffractive Processes

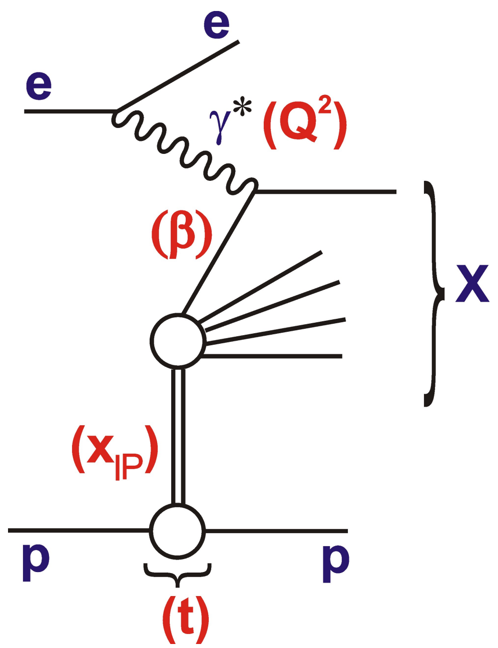
[arXiv:1201.6298]

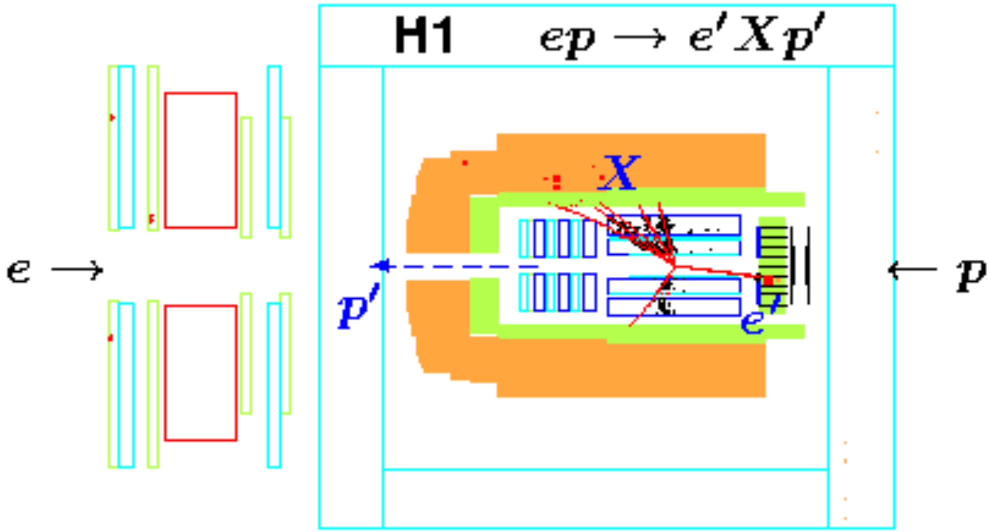




… simultaneous Durham (KMR) description of ATLAS gaps data and elastic cross section data from ISR to Totem based on a single pomeron in a 3-channel eikonal model, with <u>significant absorptive corrections in gaps / dissociation case</u>

Diffraction at the Parton Level



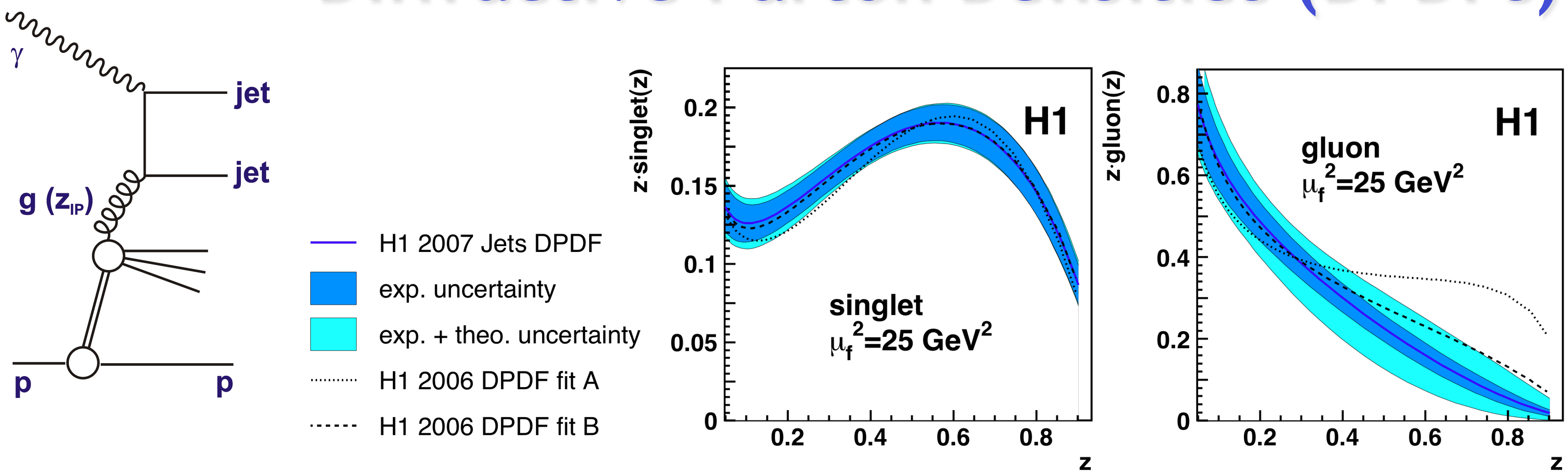


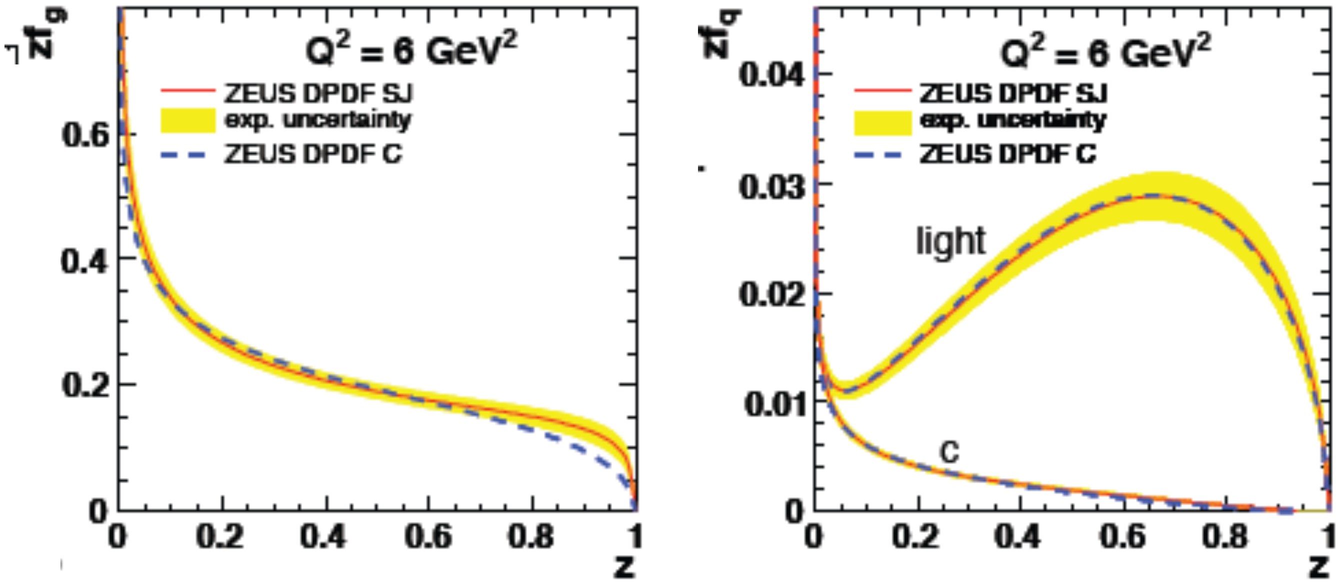
HERA ep Collider:

Virtual photon probes pomeron partonic structure rather like inclusive DIS …

>100 papers later …

Diffractive Parton Densities (DPDFs)



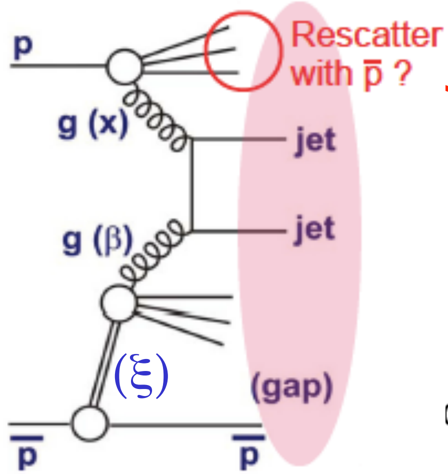


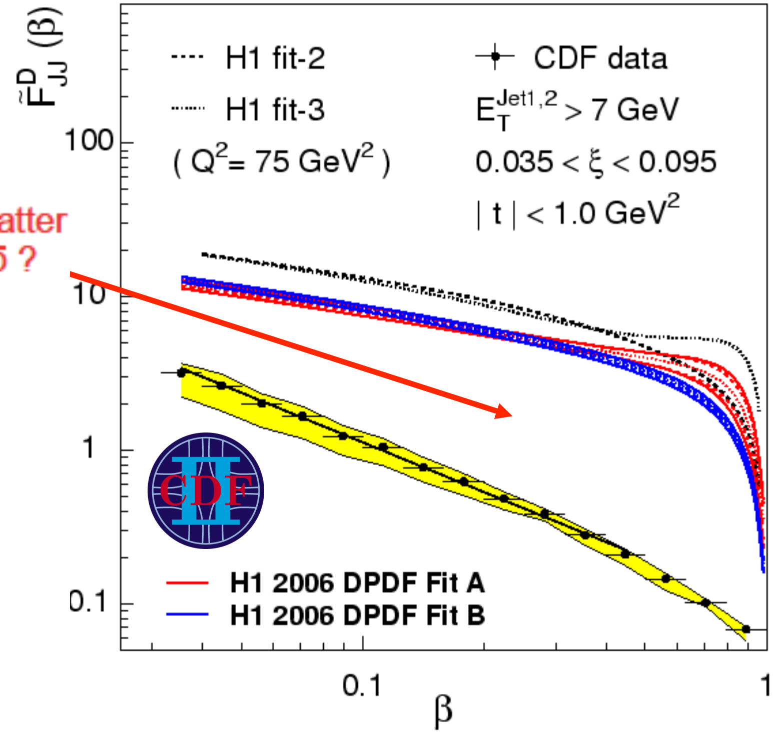
NLO DPDFs lead to impressive descriptions of all hard diffractive DIS data

DPDFs dominated by a gluon density which extends to large z

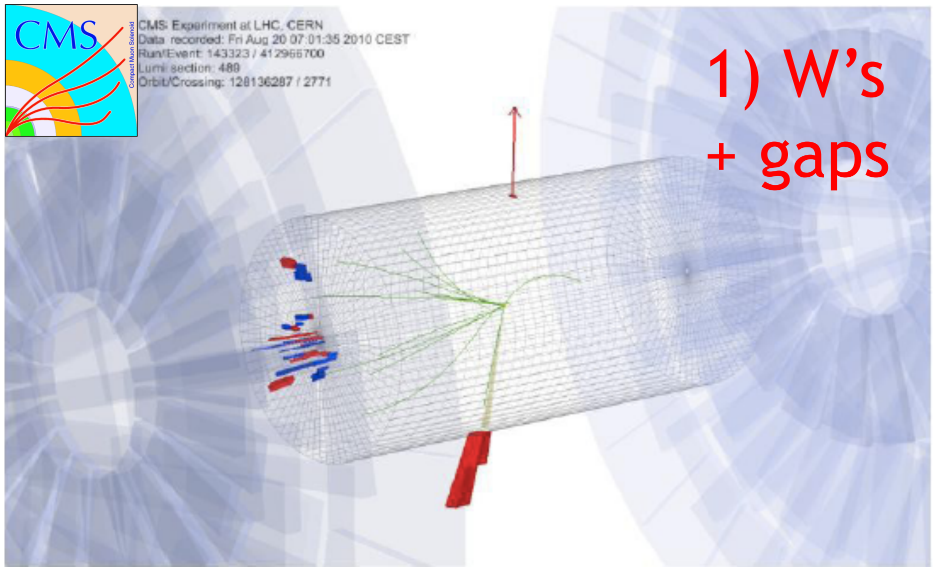
… but in pp(bar)

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





1st Hard diffraction data from LHC …

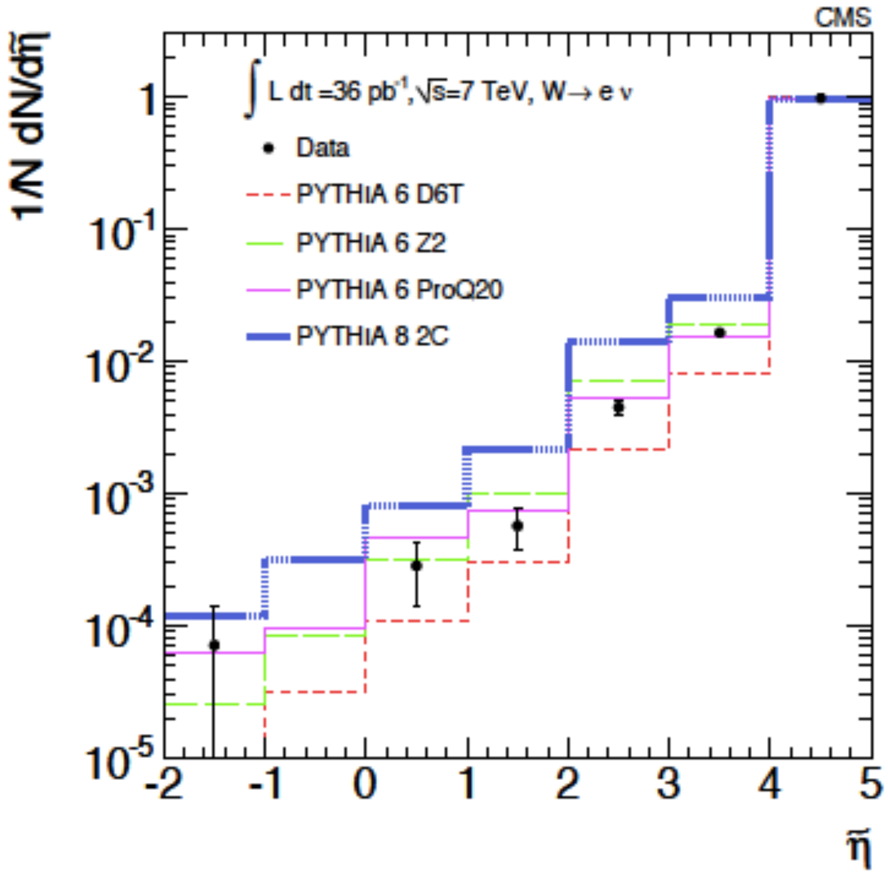


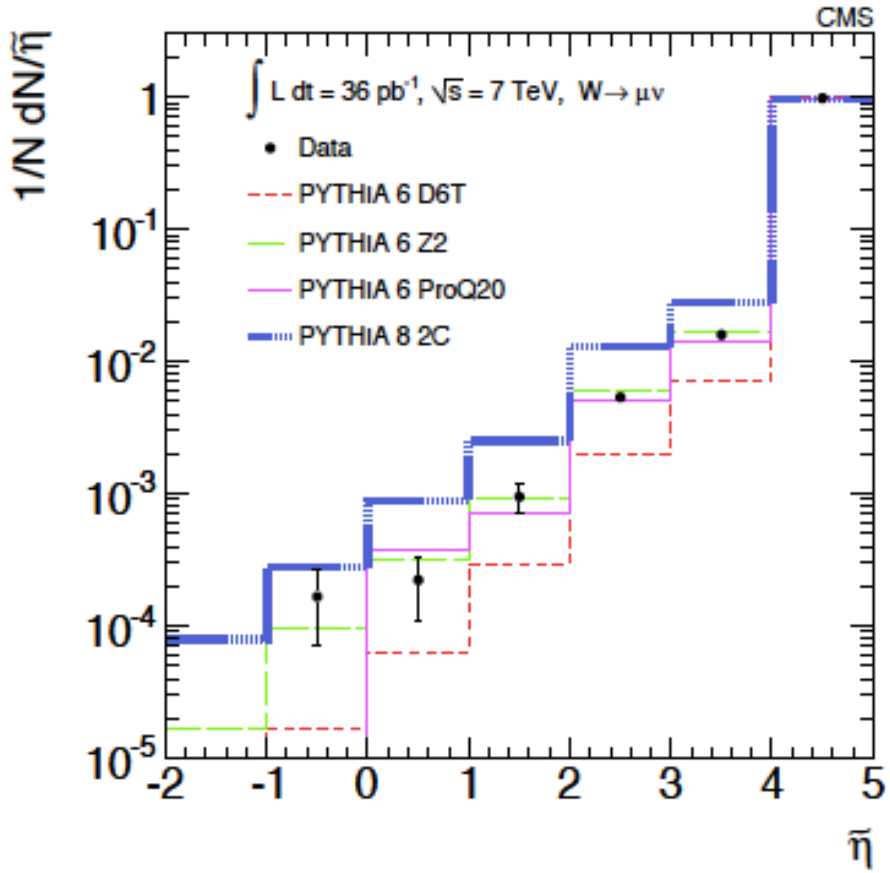
2) Dijets with ξ reconstructed from full observed final state

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

W and Z events with gaps at CMS

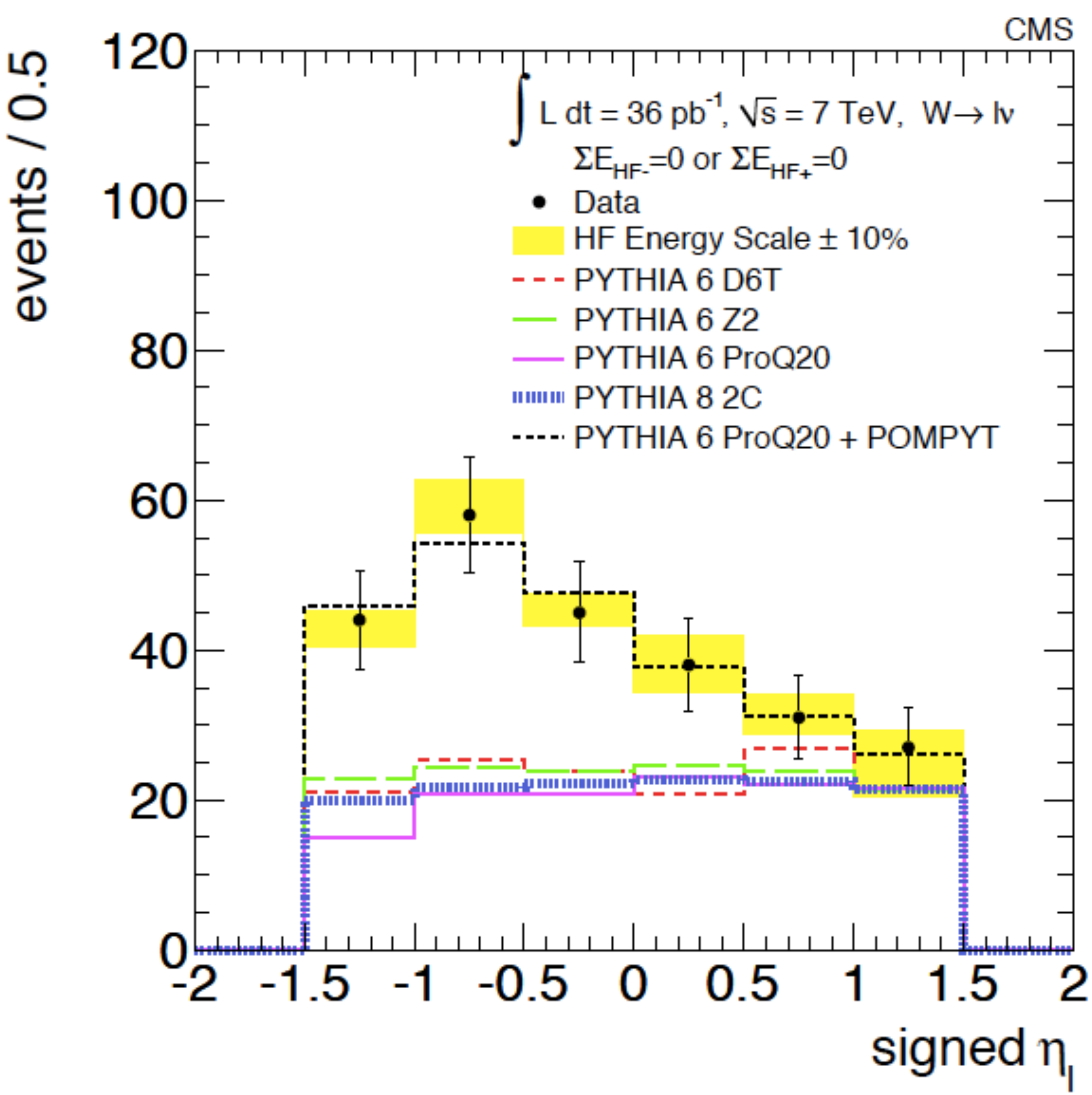
After pile-up corrections, ~1% of W and Z events exhibit no activity above noise thresholds over range $3 < \pm\eta < 4.9$ … interpretation complicated by non-diffractive hadronisation fluctuations …





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

Gap-Lepton η Correlation for W bosons

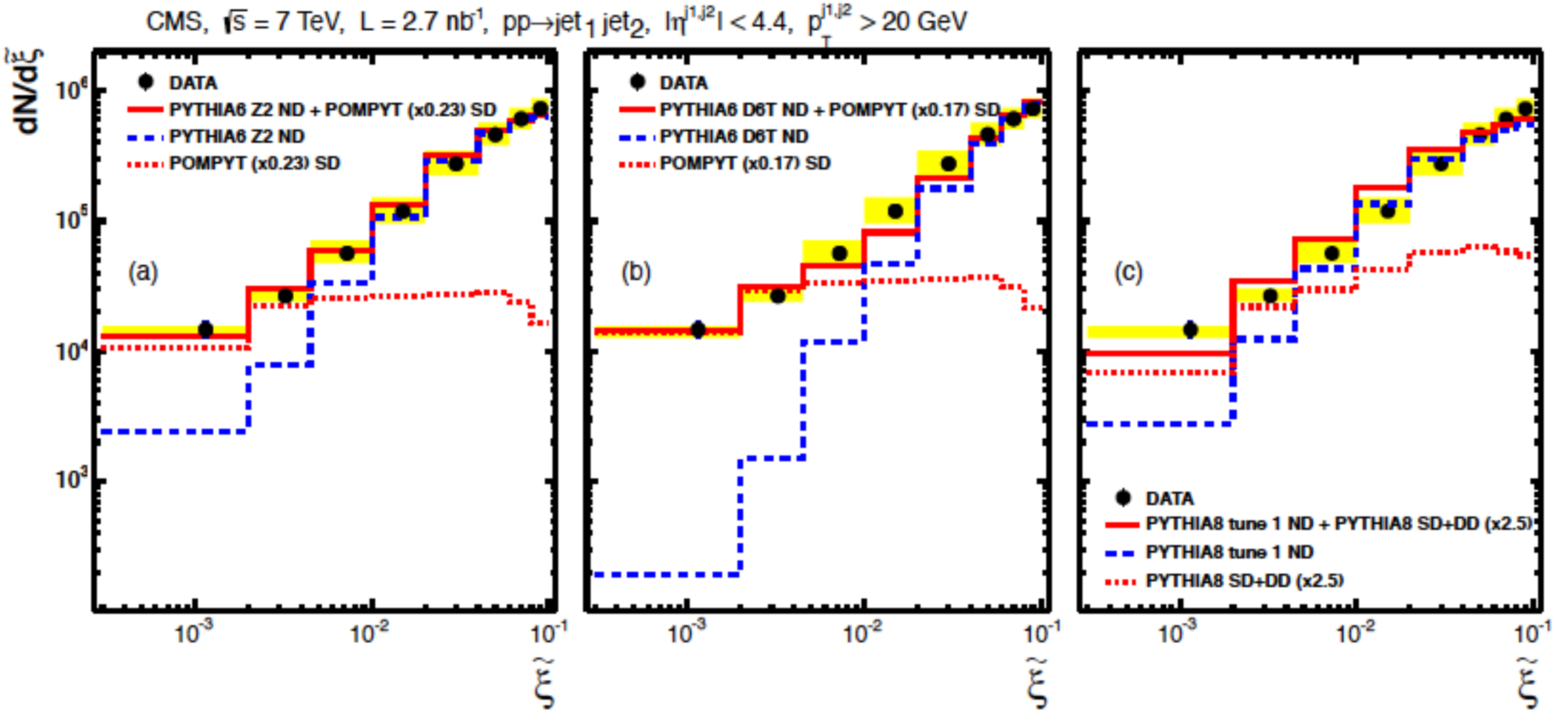


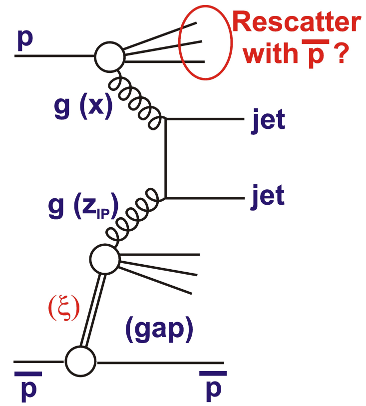
Lepton pseudorapidity with + sign if lepton in same hemisphere as gap, else – sign.

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

Surprisingly large?... No statement yet on cross section or gap survival probability

CMS Dijets with Low ξ





Uncorrected data prior to rapidity gap selection

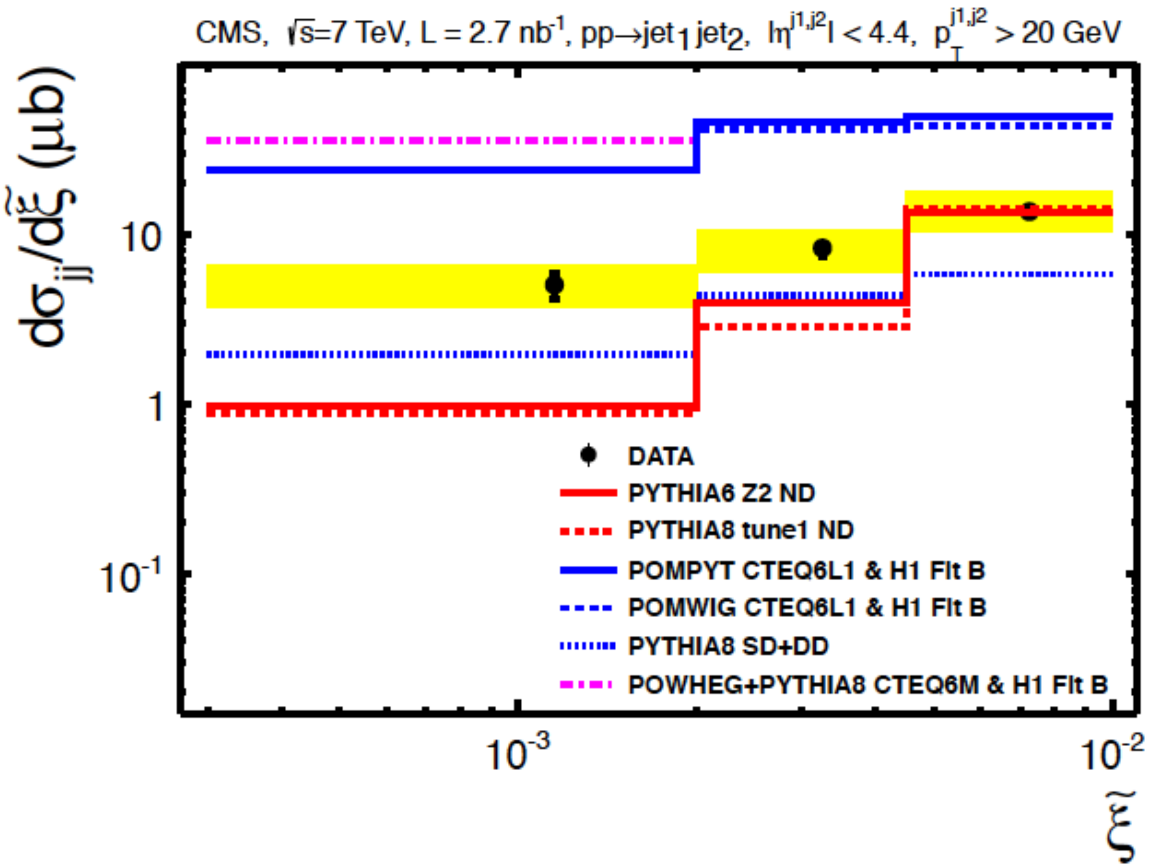
-Diffractive signal required at low ξ (Data > PYTHIA ND)

-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

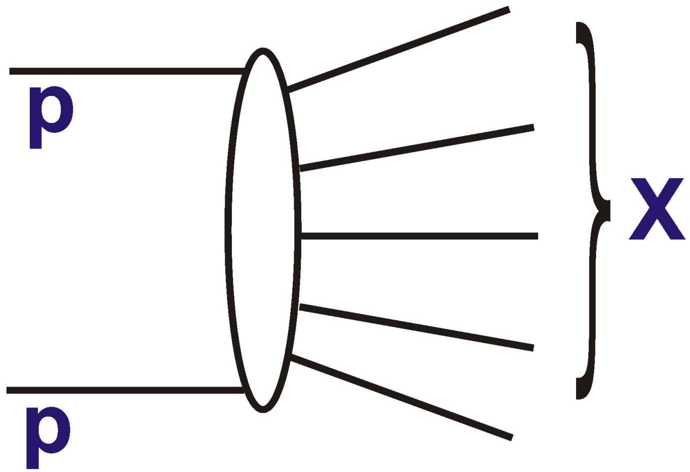


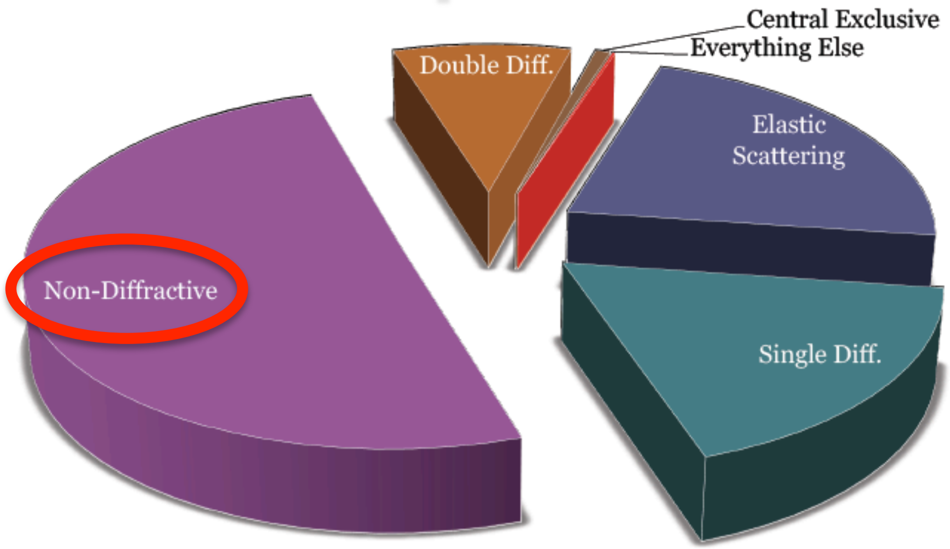
- Comparison of 1st bin v diffractive DPDF models

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

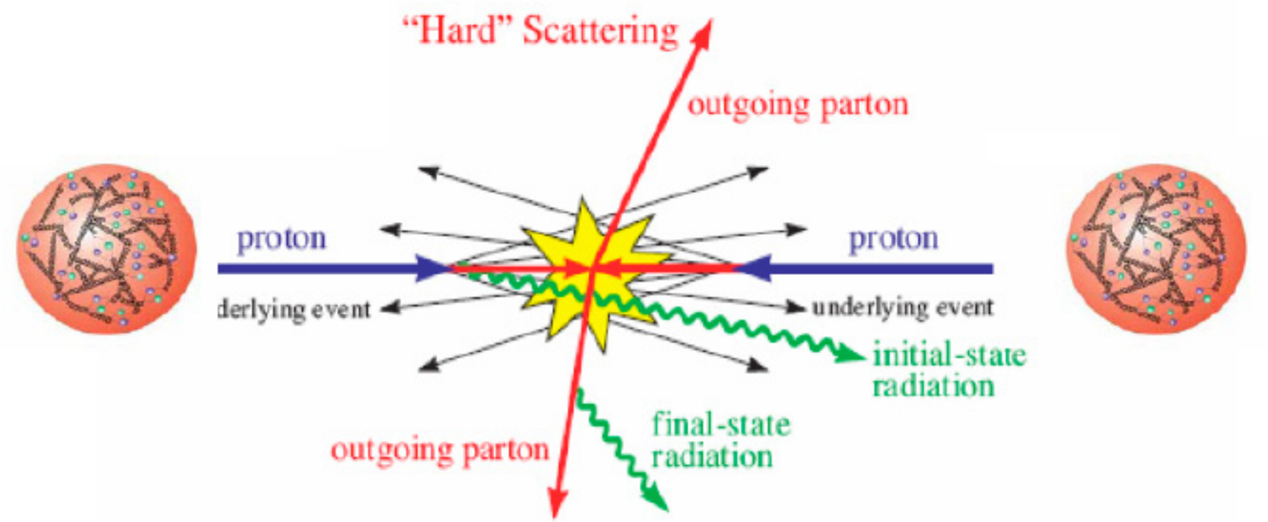
Proton tagged data will help a lot, by removing complications from Double dissociation and non-diffractive events with large gap fluct's)

The rest: non-diffractive processes

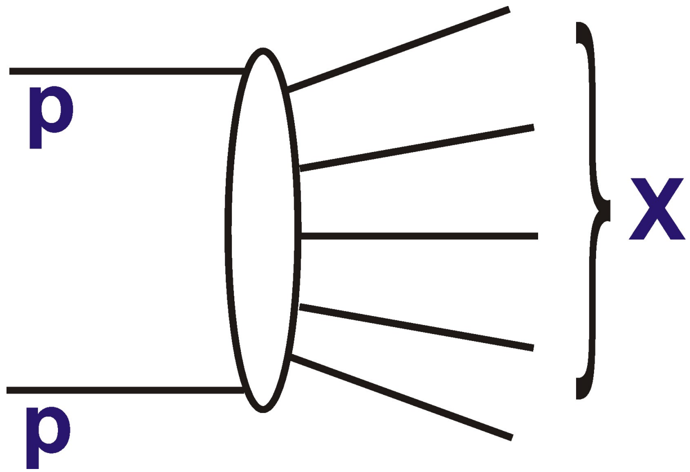


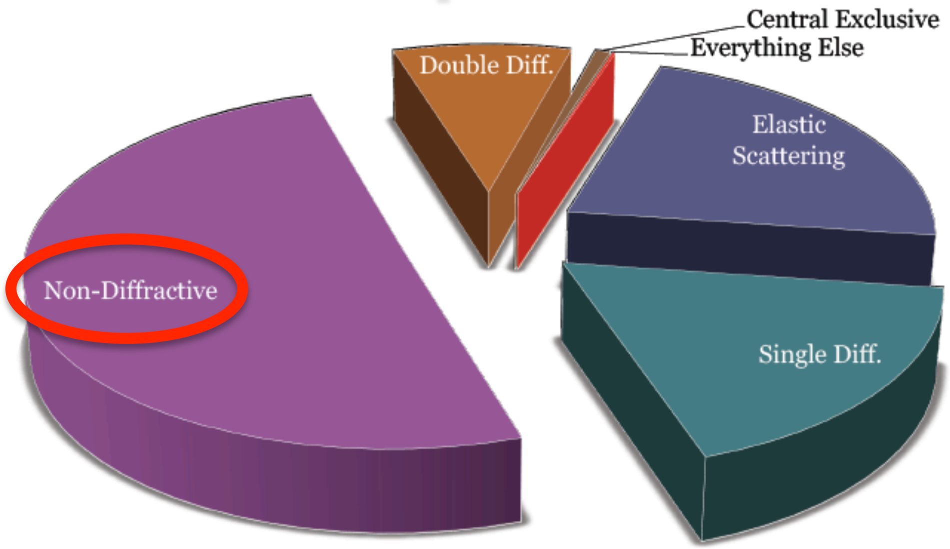


Complicated!... and
non-perturbative aspects not ignorable
even for hard scattering studies



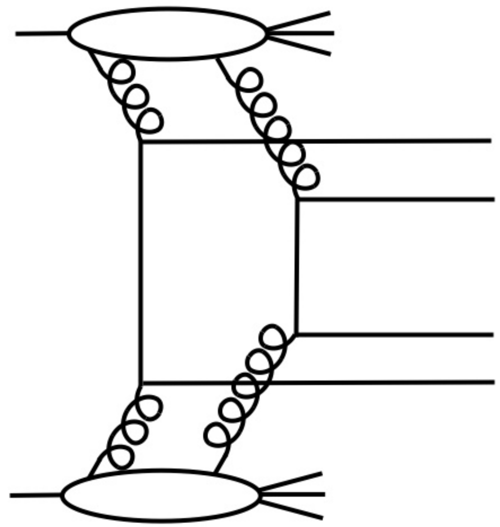
The rest: non-diffractive processes





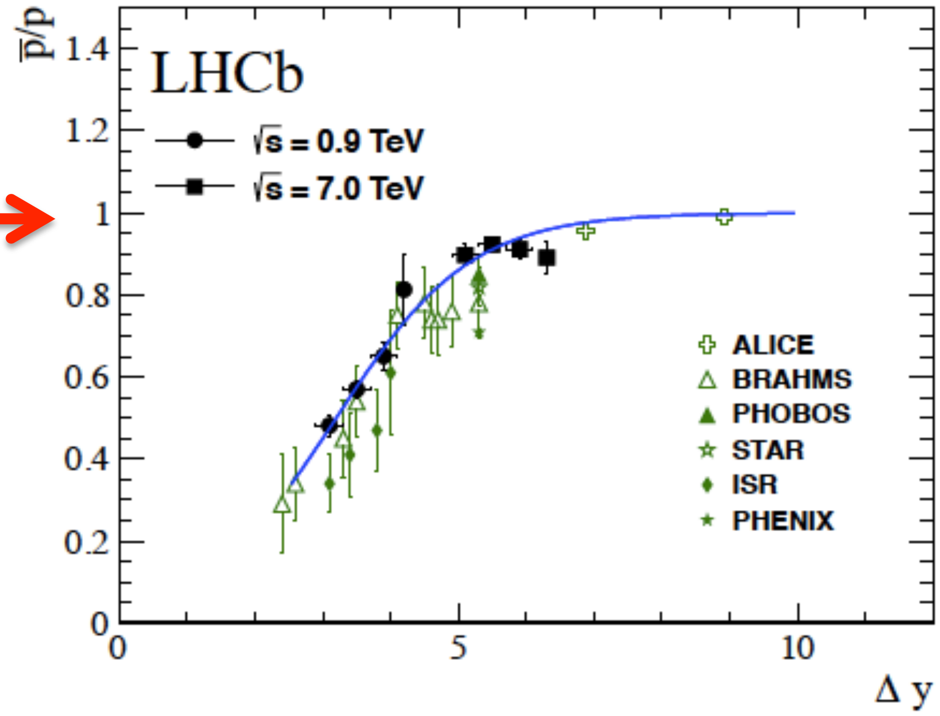
Complicated!… and
non-perturbative aspects not ignorable
even for hard scattering studies

Significant progress in understanding the "underlying event": originating from beam remnants and
multiple parton interactions

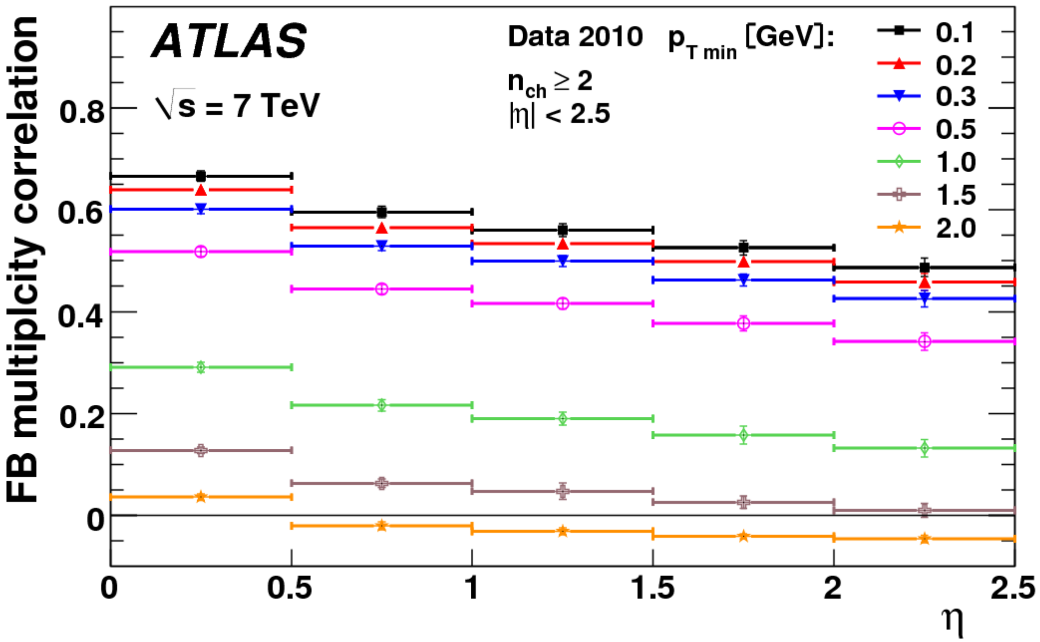


Complexity! Correlations & Transport

Baryon number transport over $\Delta y \rightarrow 5$ rapidity units from beam particle

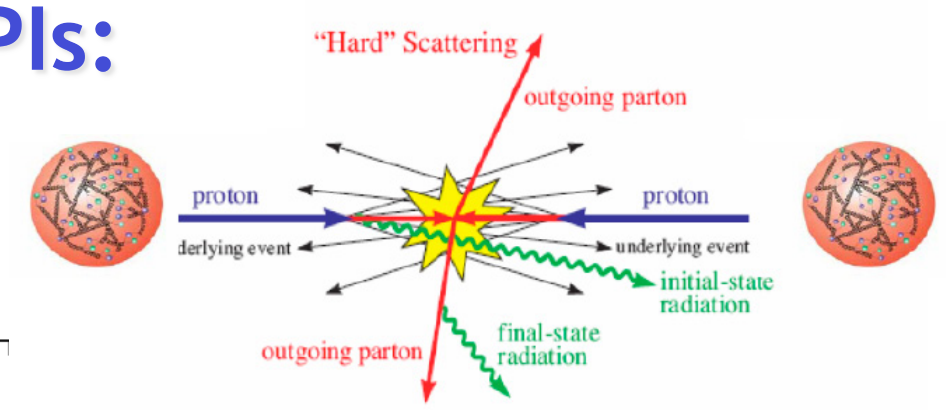


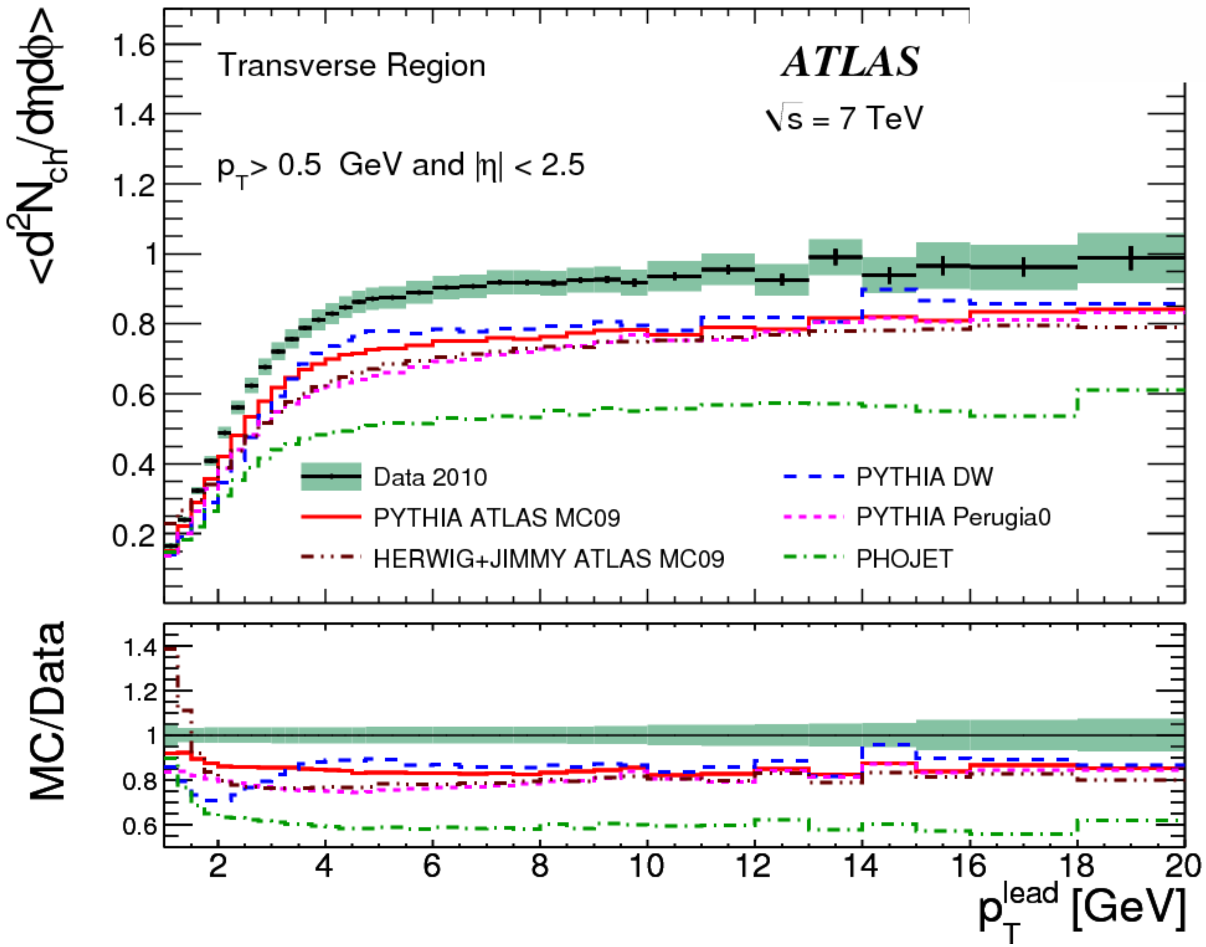
Normalised covariance between distributions at $\pm\eta$ relative to mean of each

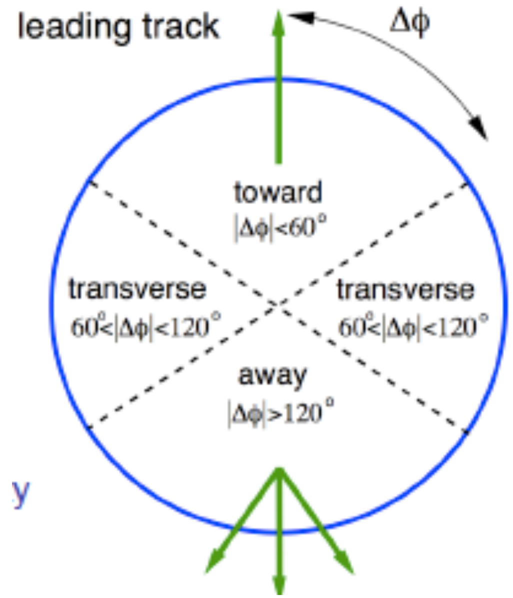


Colour connections lead to forward-backward multiplicity correlation > 0.5 between $\eta = \pm 2.5$ for low p_T particles

Underlying Event and MPIs: The Bad Old Days … (2011)







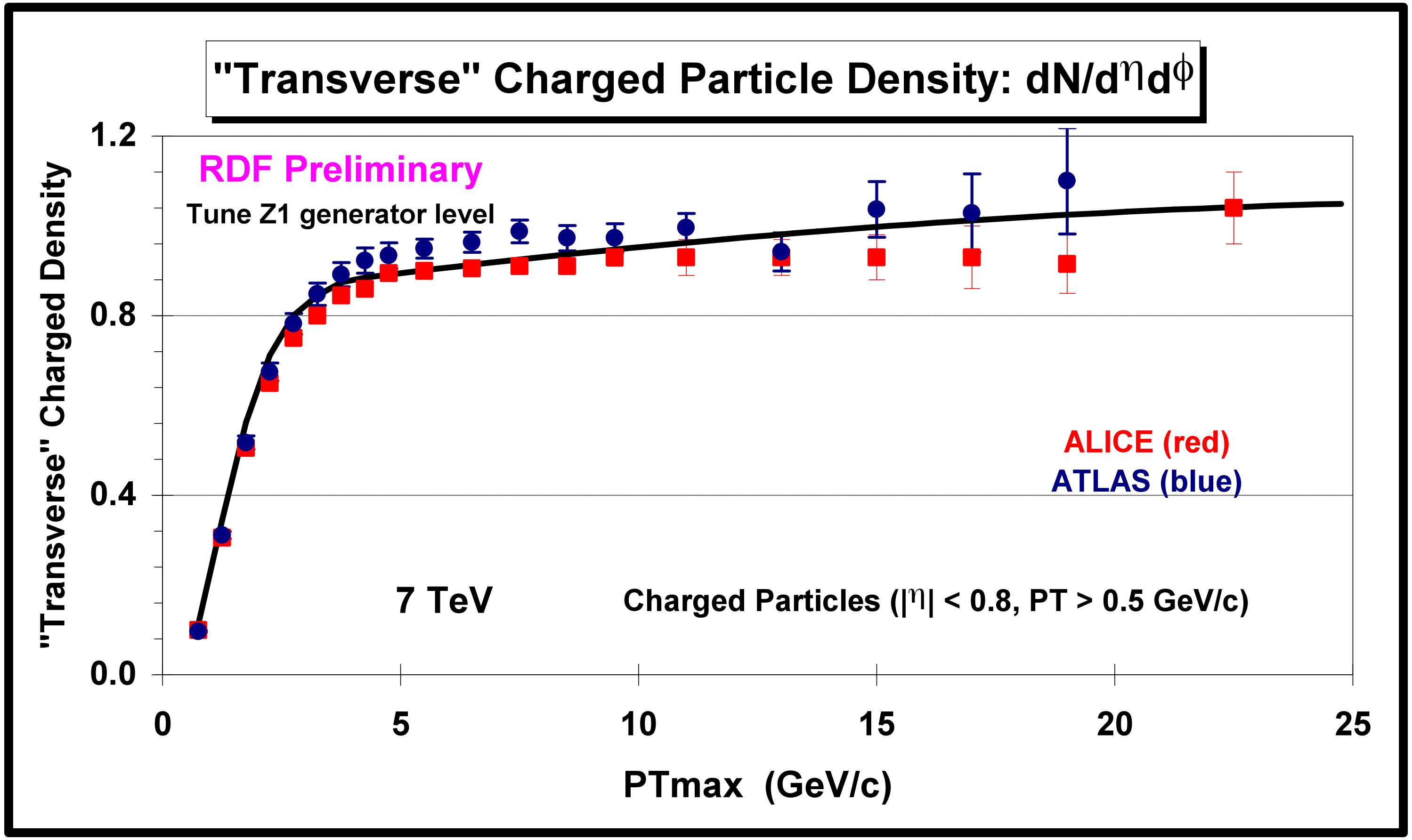
The earliest LHC data quickly showed up our lack of understanding of multi-parton scattering & underlying event

Tuning the Underlying Event

e.g. Tune Z1 of PYTHIA6 (ATLAS AMBT1 → Rick Field)

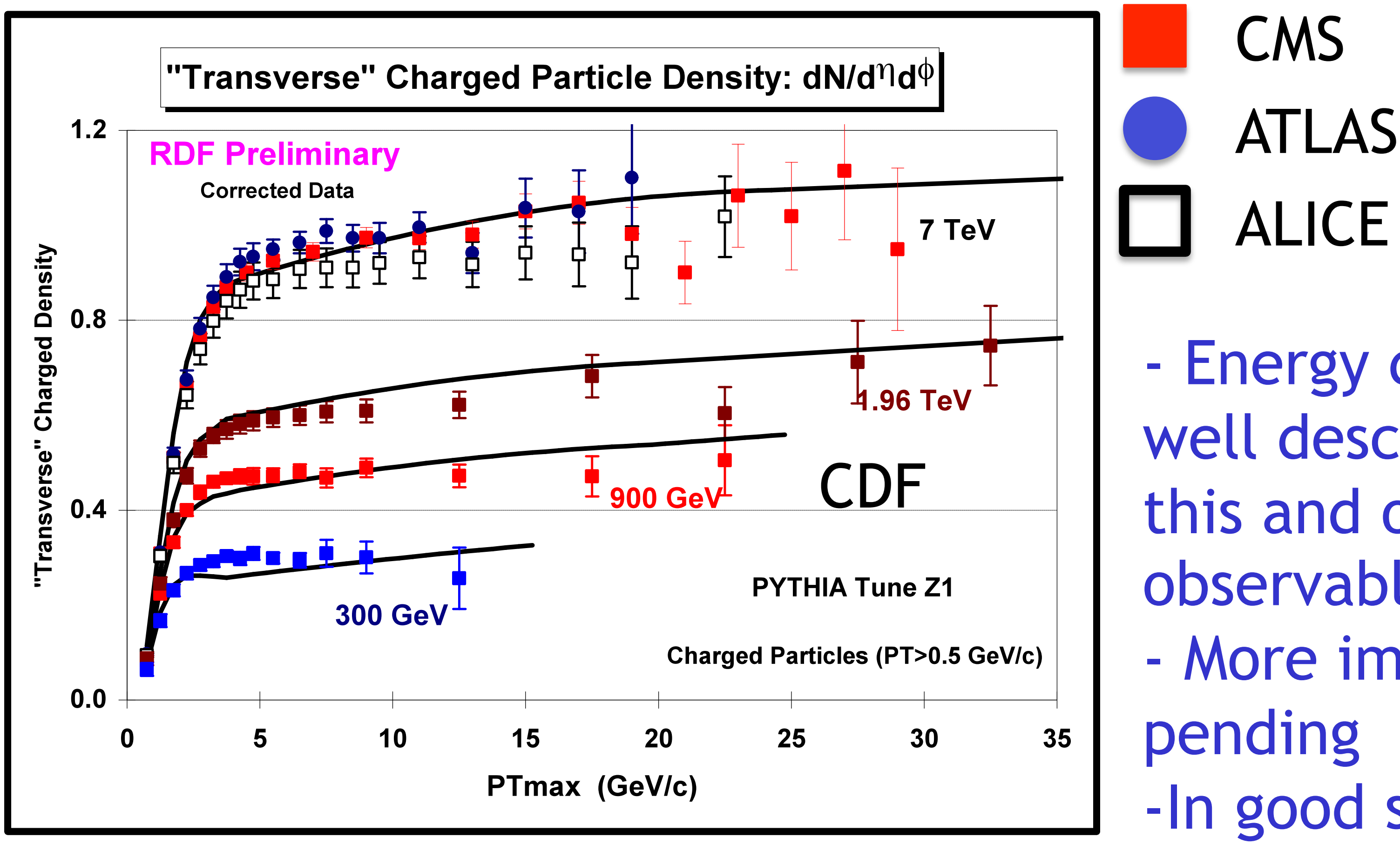
Principle changes are in energy dependence, PYTHIA version (p_T instead of virtuality ordered parton showers), PDFs (CTeQ5L), MPI p_T cut off and energy dependence

Example illustration …



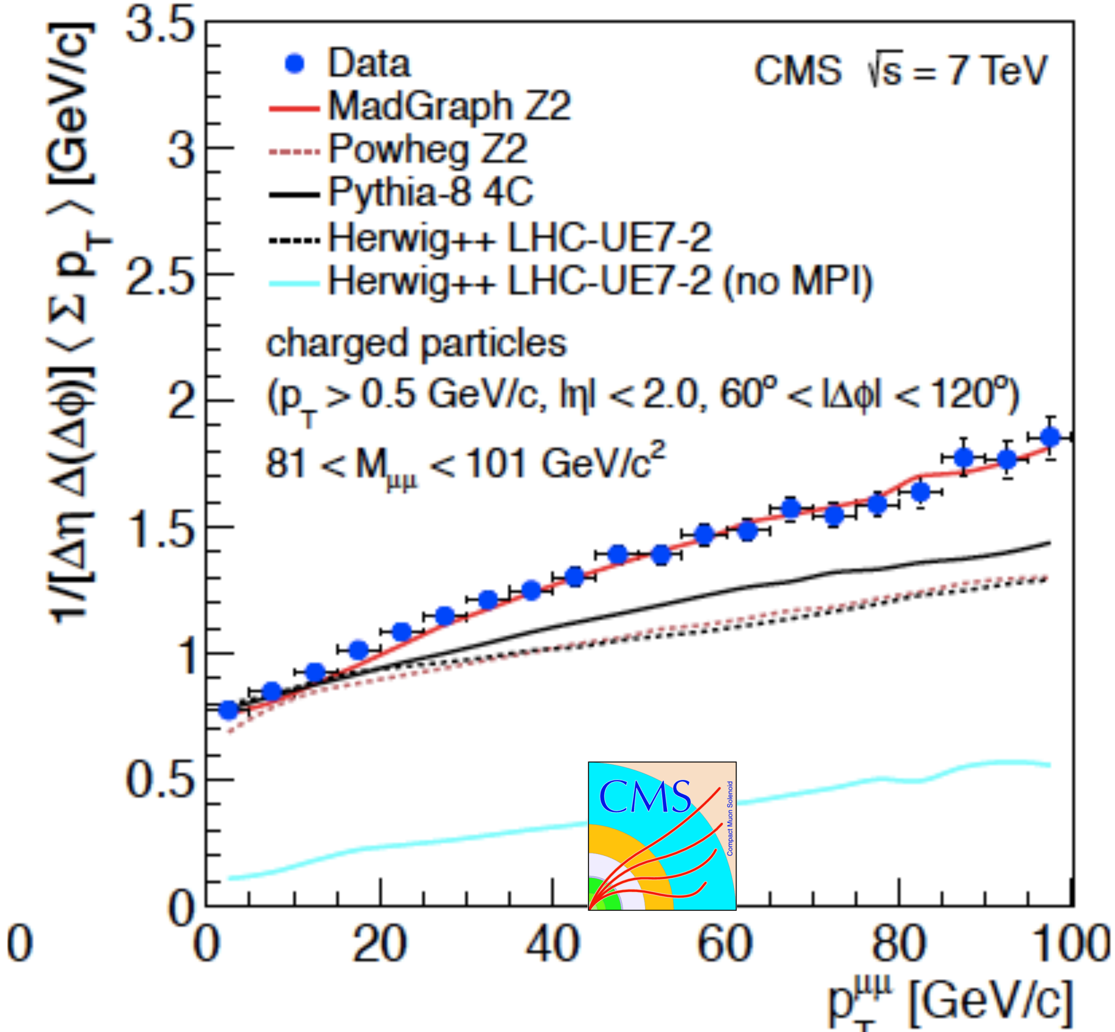
Energy Dependence of Z1 Tune

Simultaneous description of CDF data from Tevatron energy scan (300 GeV, 900 GeV, 1.96 TeV) & LHC(900 GeV, 7 TeV, 8 TeV)



- Energy dependence well described for this and other observables
- More improvements pending
-In good shape for 13 TeV data

Underlying Event in Dedicated Samples with Hard Proceses:

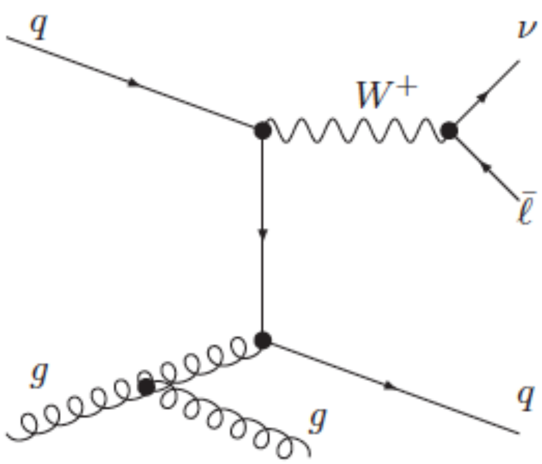


Towards region determined by $\mu^+\mu^-$ direction in Drell-Yan events … much higher p_T of `towards region' tag

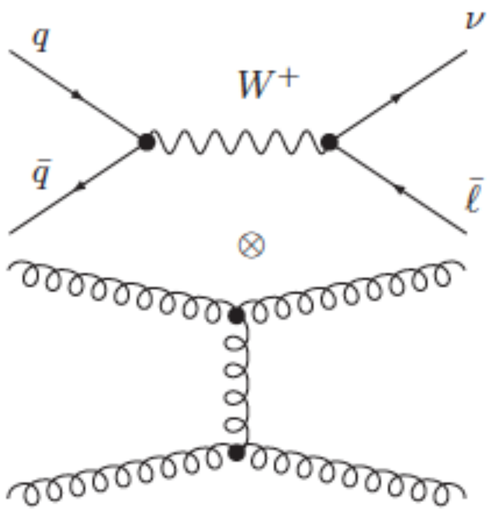
Madgraph (+Pythia) Z2 is slight update of Z1 → again successful

Many further similar examples

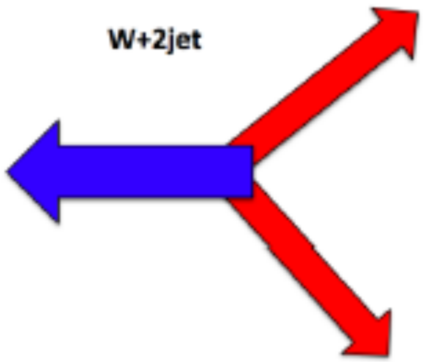
Double Parton Interactions in W + dijet Events (ATLAS)



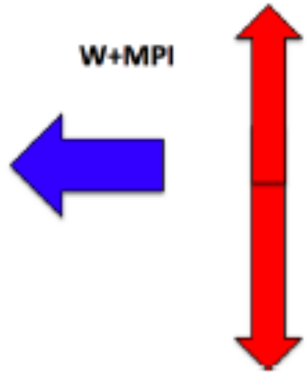
Single Hard Process



Double Parton Interaction

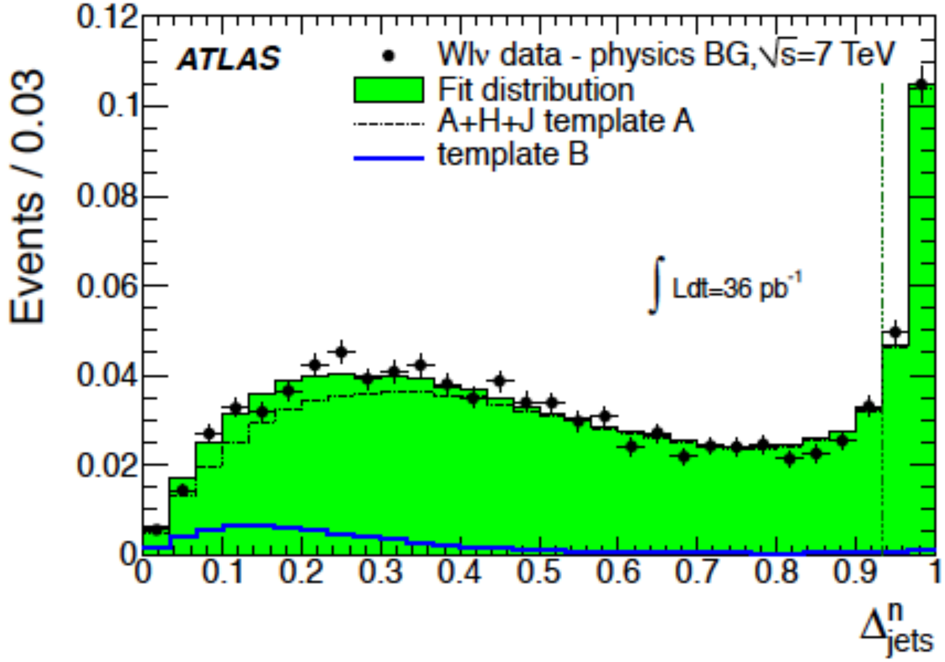


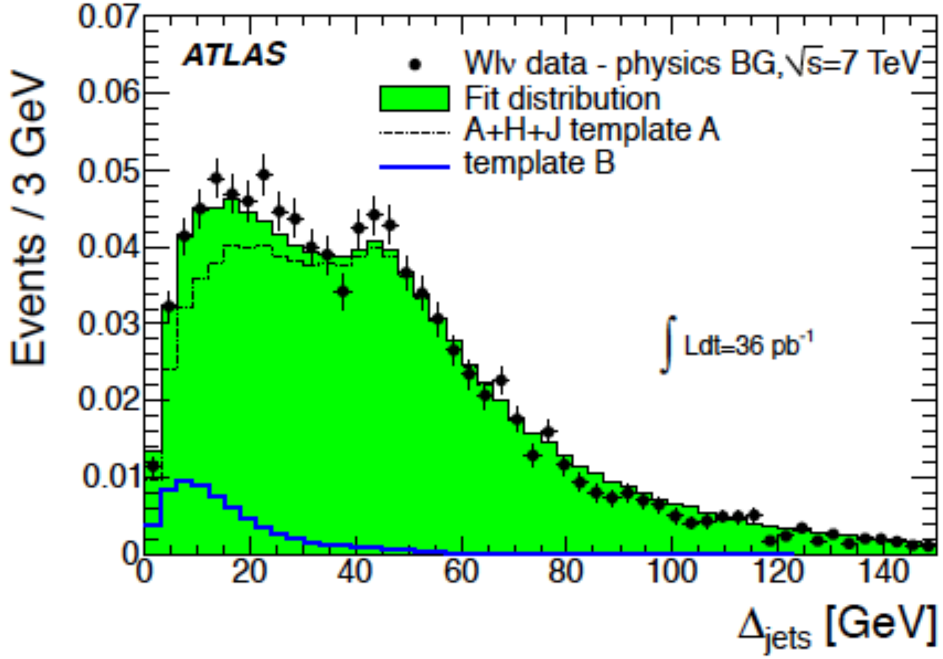
Distinguish using topology in transverse plane.



Double Parton Interactions in Wjj Events

$$\Delta^{\mathrm{n}}_{\mathrm{jets}} = \frac{|\vec{p}_{\mathrm{T}}^{\,J_1} + \vec{p}_{\mathrm{T}}^{\,J_2}|}{|\vec{p}_{\mathrm{T}}^{\,J_1}| + |\vec{p}_{\mathrm{T}}^{\,J_2}|} \qquad \Delta_{\mathrm{jets}} = |\vec{p}_{\mathrm{T}}^{\,J_1} + \vec{p}_{\mathrm{T}}^{\,J_2}|$$





Fit normalised (or unnormalised) transverse momentum balance between jets after background subtraction to linear combination of two templates:

A (single hard process, ALPGEN+HERWIG+JIMMY with MPI off)

B (double parton interactions, standard dijet data)

Double Parton Interactions in Wjj Events

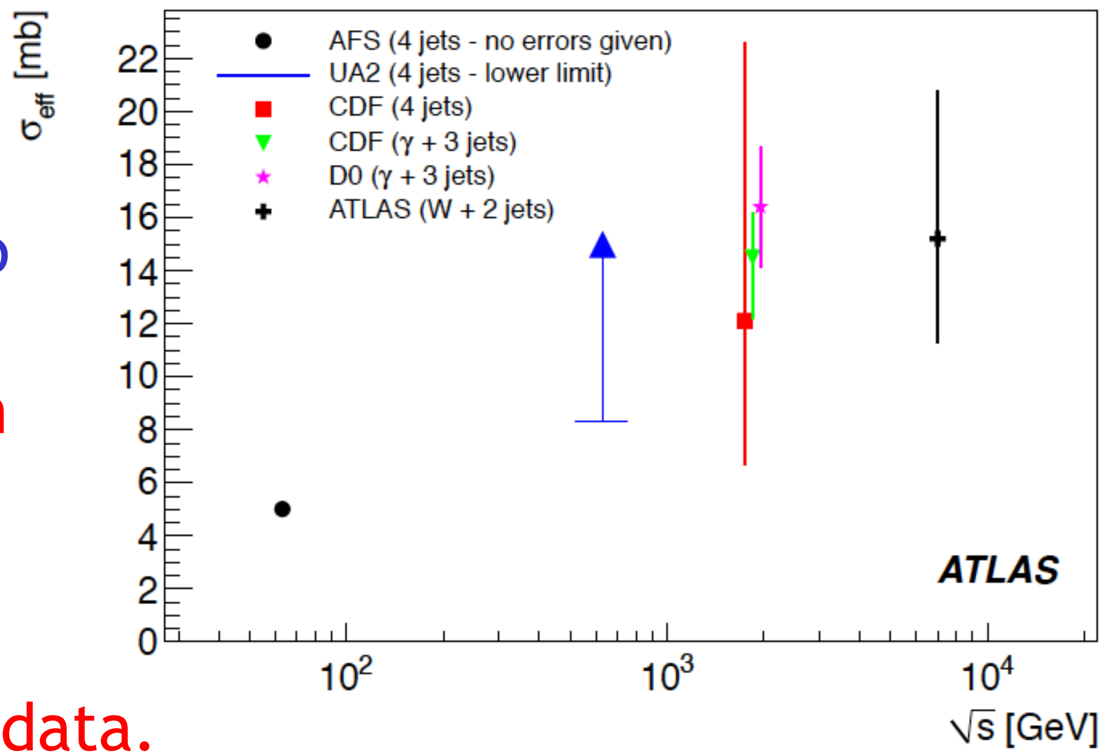
Fraction of Double Parton Interaction events in this sample: $f_{DP} = 0.076 \pm 0.013\ (\text{stat}) \pm 0.018\ (\text{sys})$

Interpret in terms of effective area for double parton interactions σ_{eff} ...

$$\sigma_{\mathrm{eff}} = \frac{1}{f_{\mathrm{DP}}^{(\mathrm{D})}} \cdot \frac{N_{W_{0\mathrm{j}}}}{N_{W+2\mathrm{j}}} \cdot \frac{N_{2\mathrm{j}}}{\mathcal{L}_{2\mathrm{j}}}$$

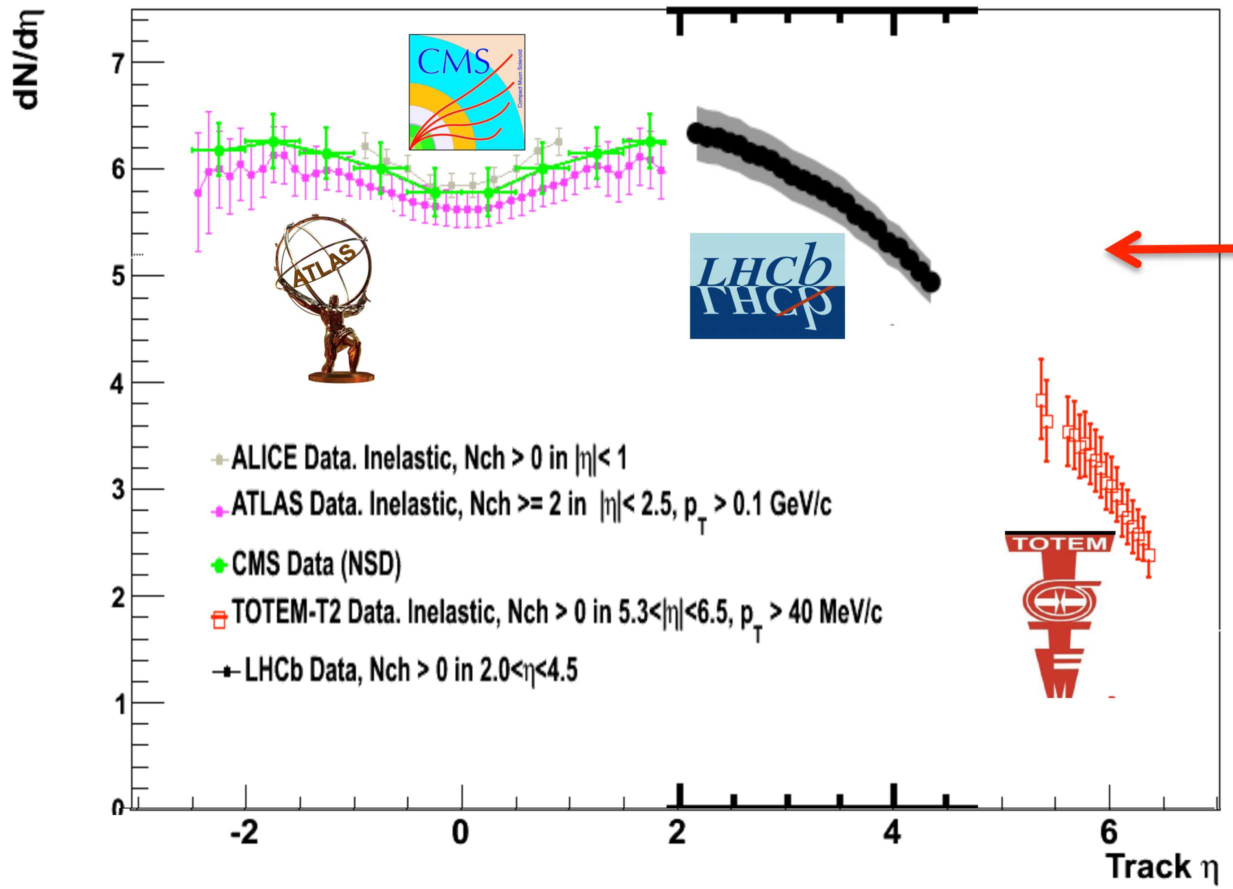
$= 15 \pm 3(\text{stat}) +5/-3(\text{sys})$ mb

... Significantly smaller than inelastic cross section or black disk geometry



... Consistent with previous data.

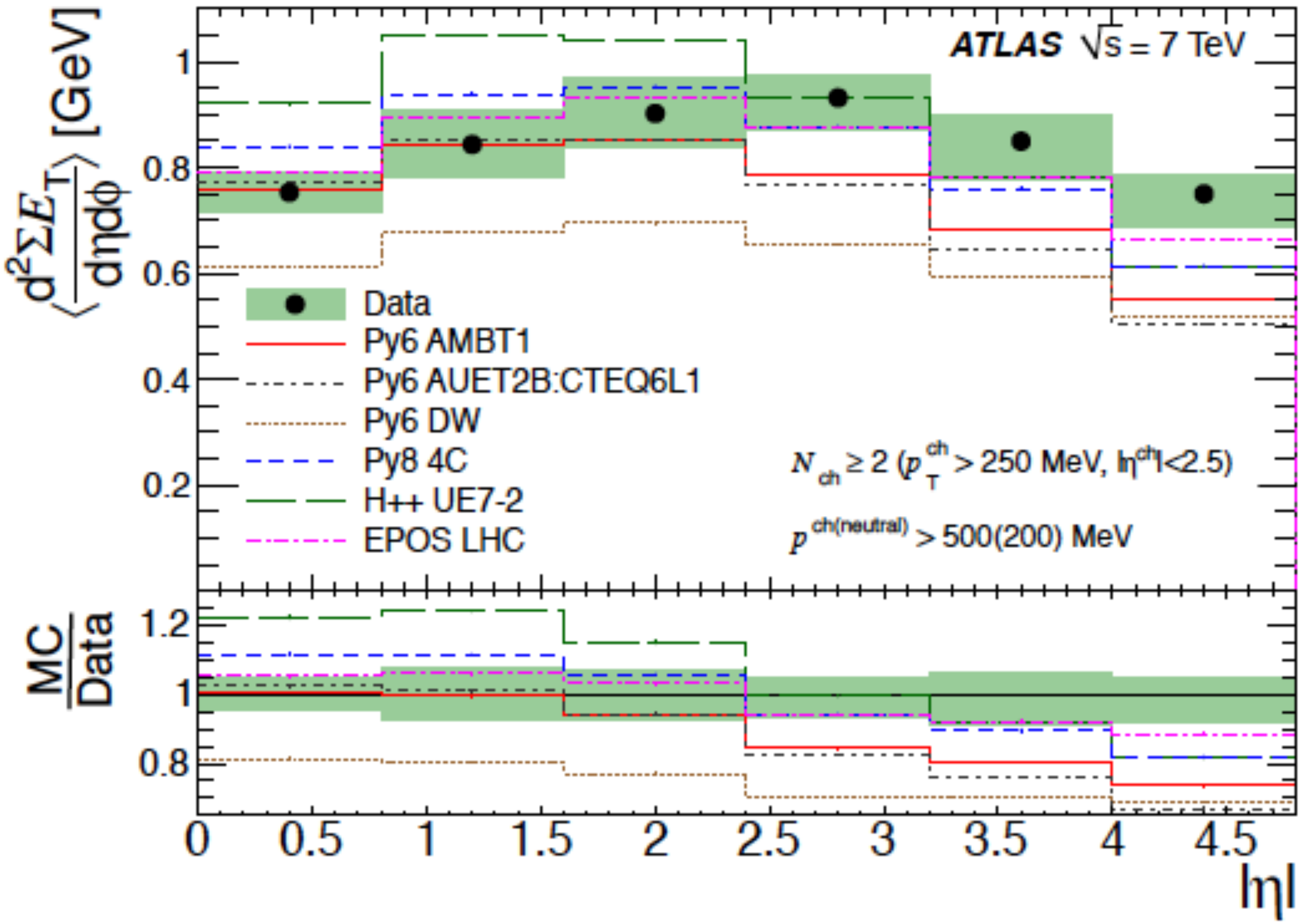
High Rapidity Coverage at LHC



Charged particle multiplicity measurements

-Forward tracking coverage provided by LHCb and TOTEM T2 telescope ($5.3 < |\eta| < 6.5$) - way beyond rapidity plateau!
- ATLAS, CMS calorimeters → $|\eta| \sim 5$
- Also ATLAS LUCID and CMS CASTOR ($5.2 < |\eta| < 6.6$)
- Many complementary measurements possible

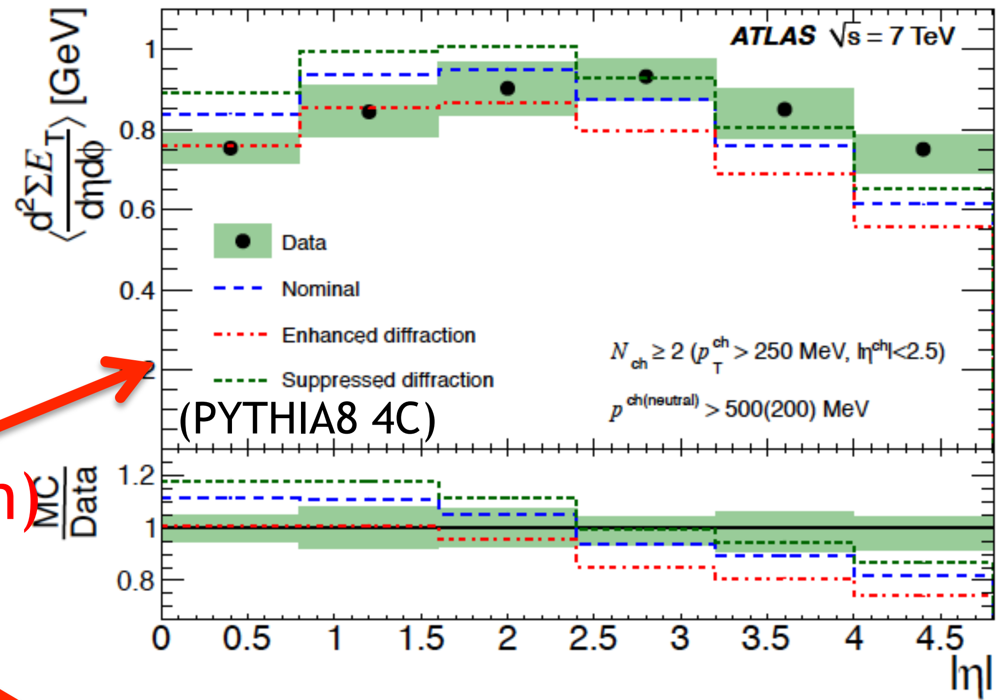
Transverse Energy Density (minbias)



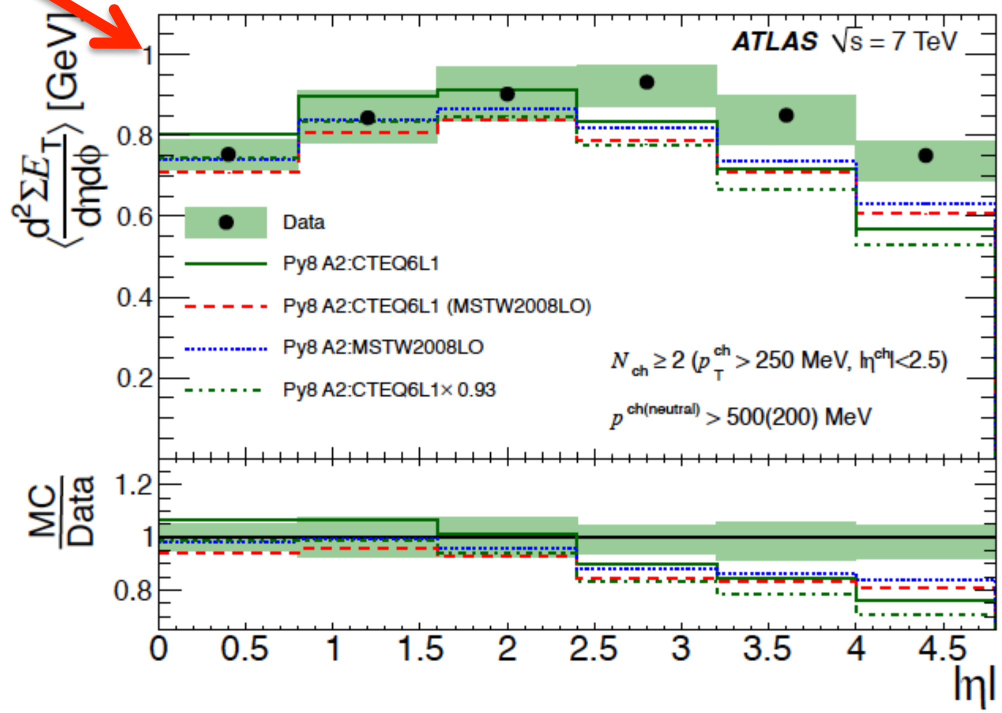
- Several models do acceptable job in central region
- All models low for forward energy flow (emerging LHC theme)
- Dedicated forward heavy ion / cosmic air shower model, EPOS, among best descriptions

Origin of Disrepancy?

Sensitive to role of diffraction (±50% variation in normalisation)



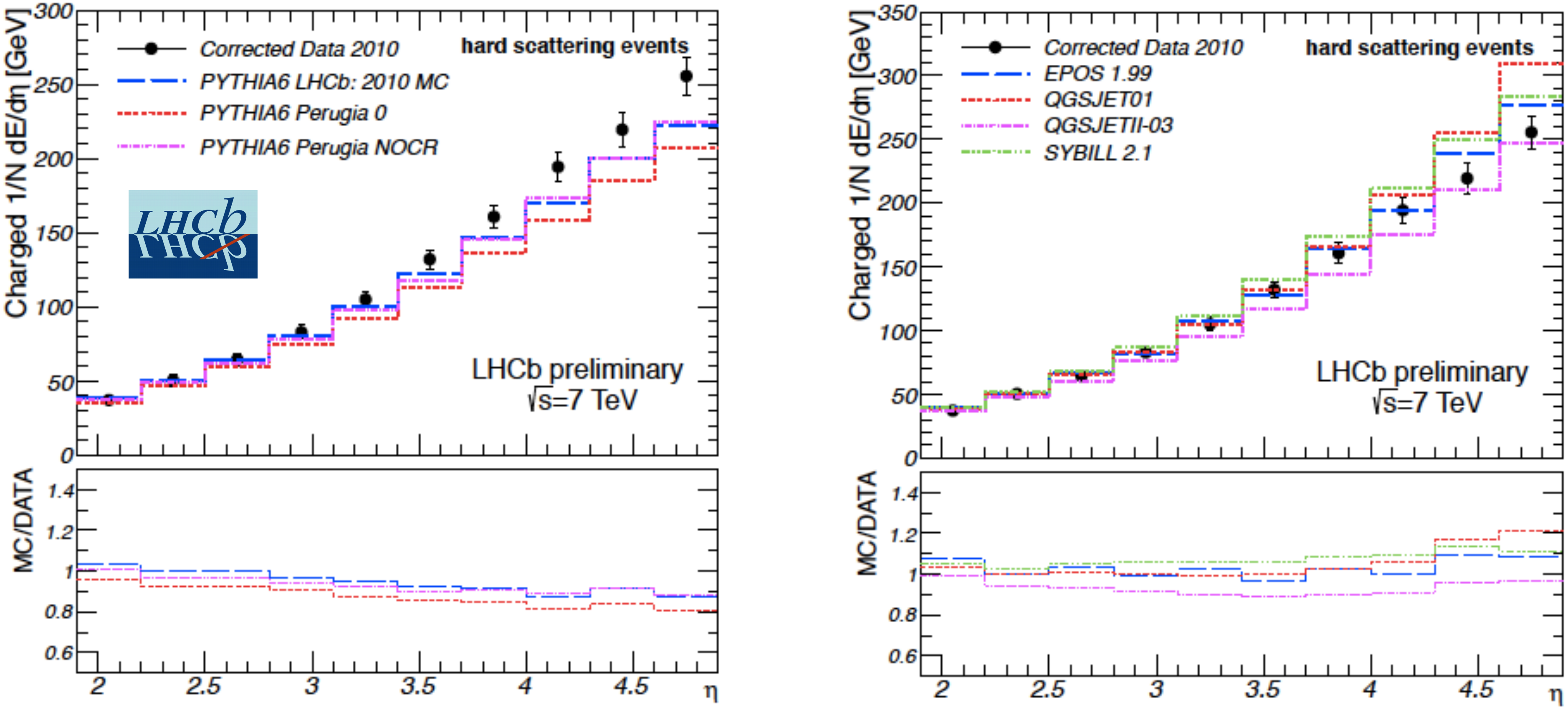
and to PDFs (especially low x gluon)



… as well as parton cascade dynamics and the underlying event.

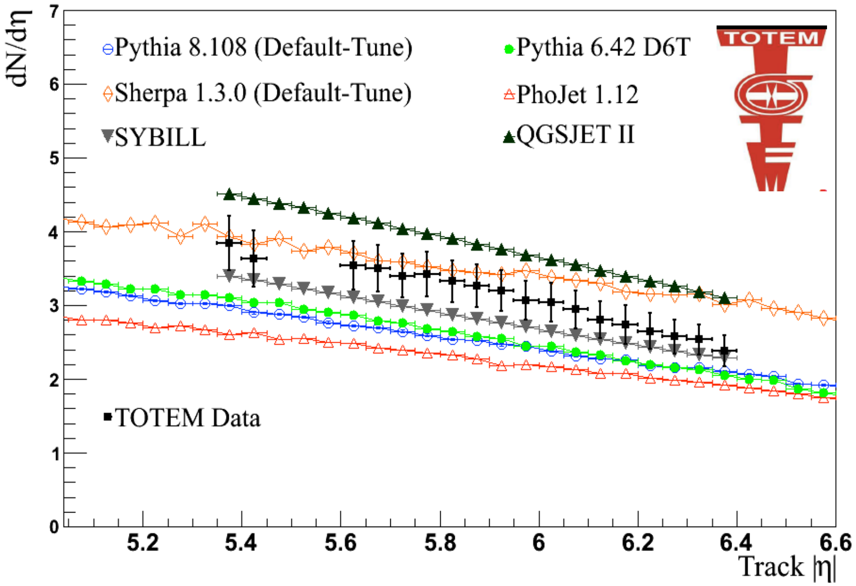
Description not completely solved by variations in any of these.

Energy Carried by Charged Particles (2 < η < 4.8 at LHCb)



- Dedicated cosmic air shower models again better?

Measurements in Very Forward Region

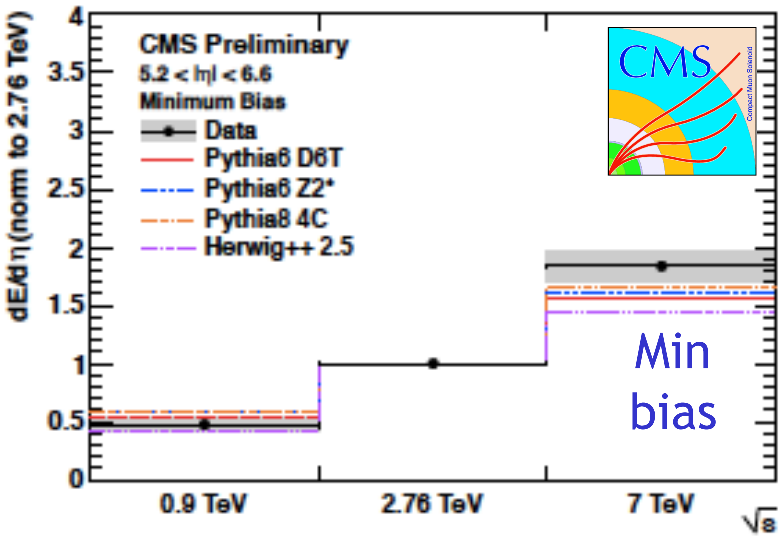


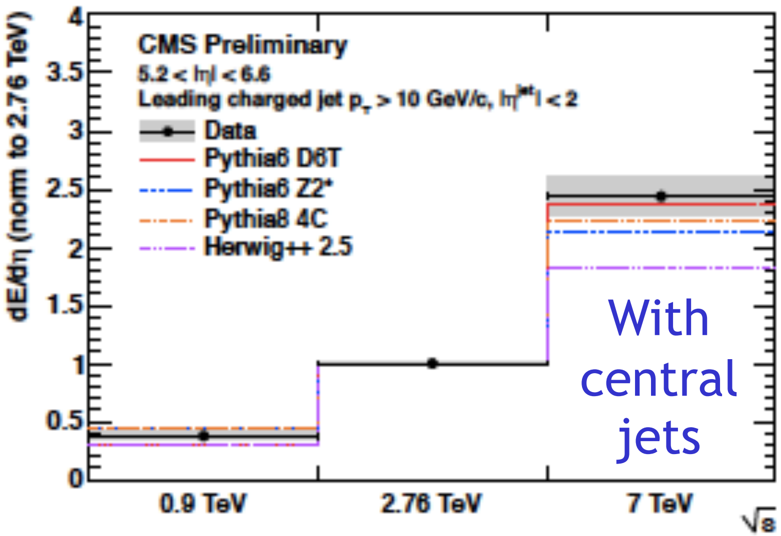
Charged Particle Multiplicity ($5.4 < \eta < 6.4$)

- Standard MC approaches again low, cosmic shower models better?
- Forward energy density grows fast with √s especially for central hard scattering processes

… "challenging"

Forward energy density ($5.2 < \eta < 6.6$)

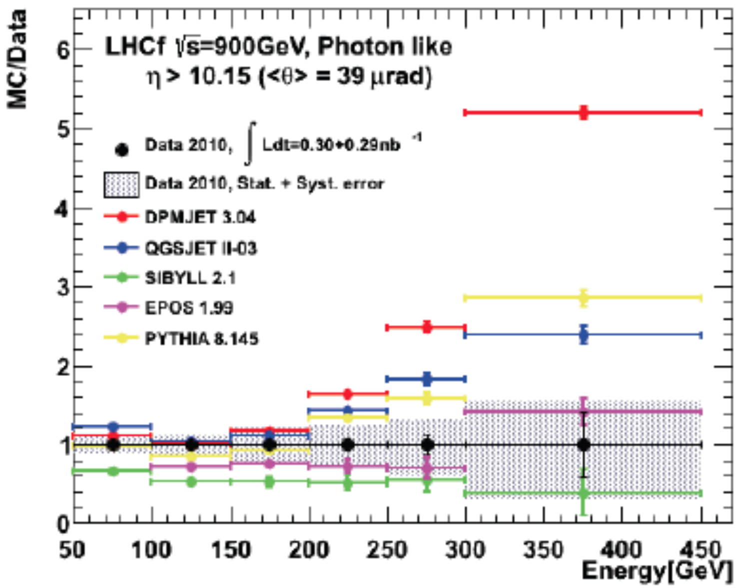


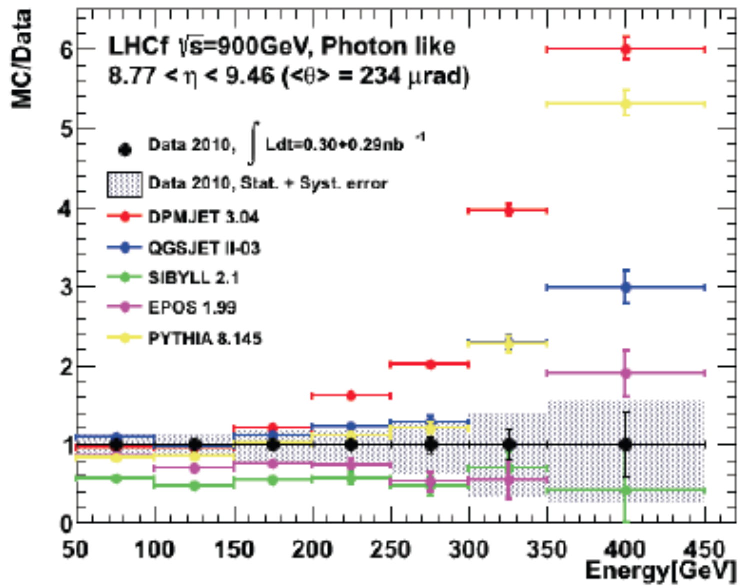


… in fact it goes even Further: LHCf

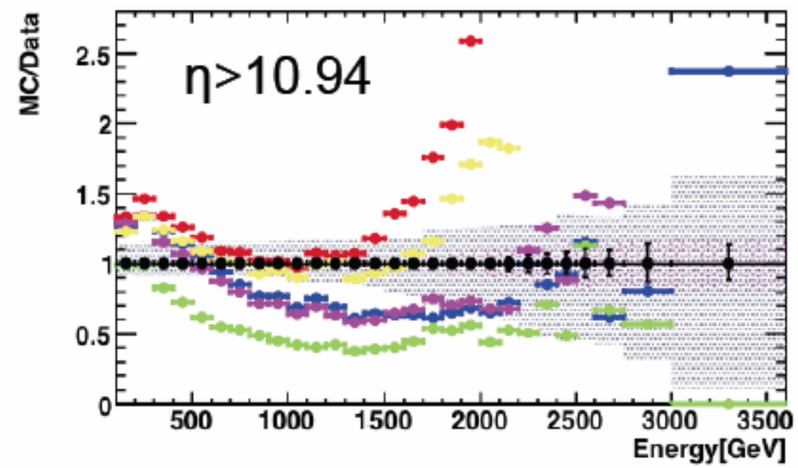
[Zero angle calorimeter detecting photons 140m from ATLAS]

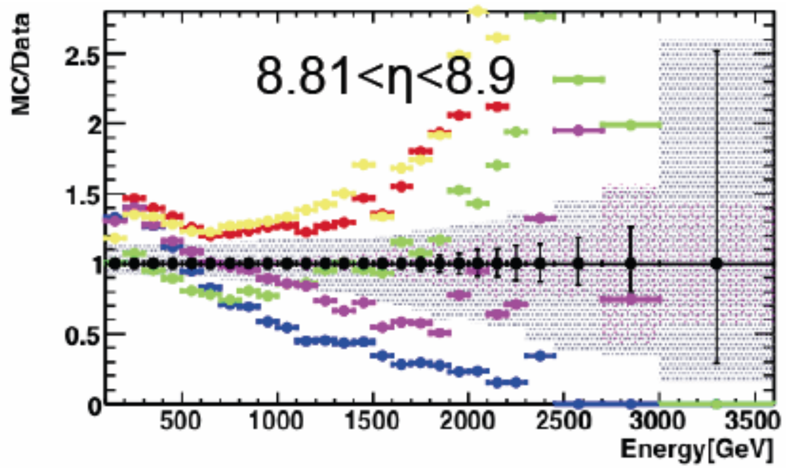
900GeV



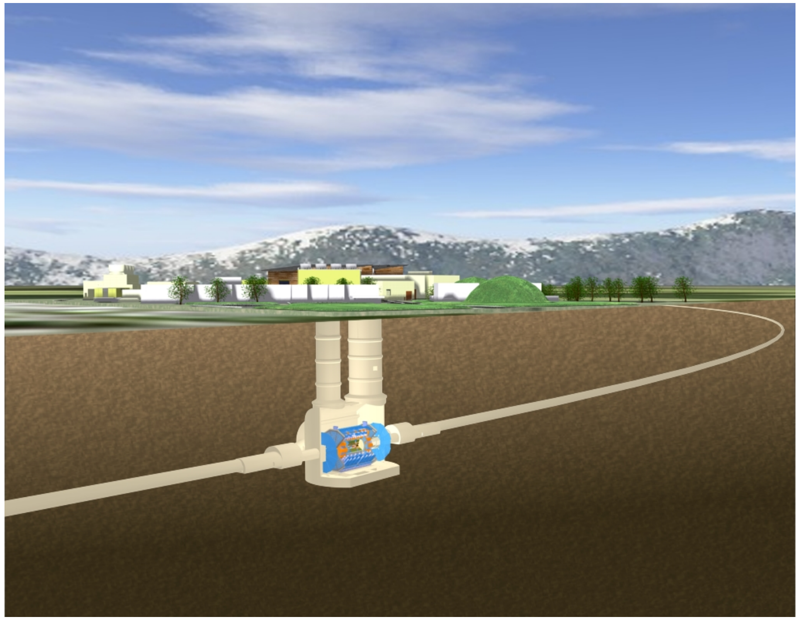


7TeV





Summary



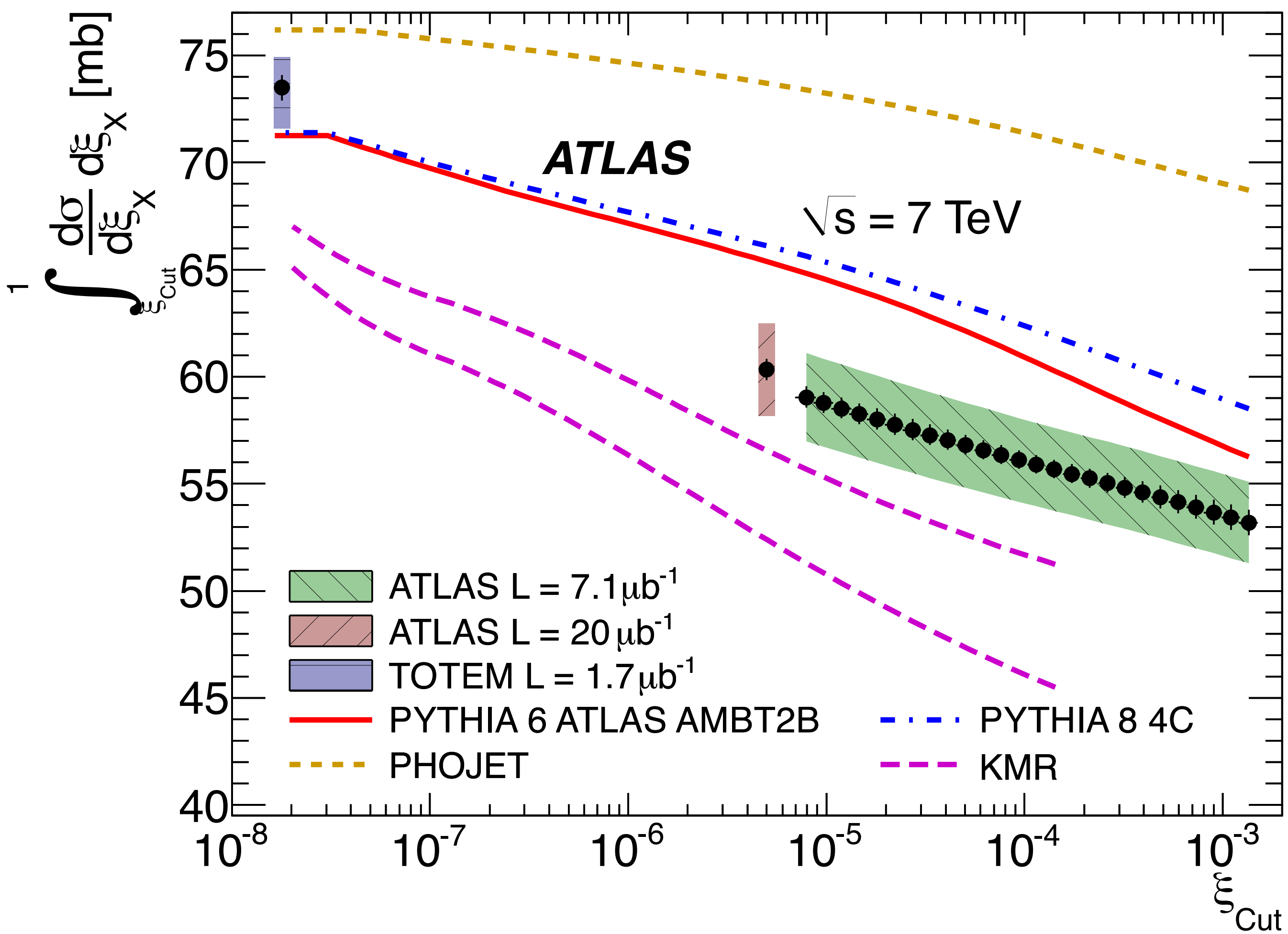
Precise elastic & total cross section data
- Broadly in line with expectations
- Pomeron slope α' non-universal?

Developing Diffractive Diss'n data
- Soft pomeron with intercept as expected works for soft dissociation
- Low mass region not understood
- Proton-tagged data required to understand rapidity gap survival probabilities

Increasingly Sophisticated Multi-Parton Interaction Data
- Would be nice to understand this beyond a MC tuning exercise
- Interpretation / universality of σ_{eff}?

Unprecedented Information at Very Forward Rapidities
- Deficiencies in modelling forward region in all models
- Cosmic Ray air shower models appear to fare best

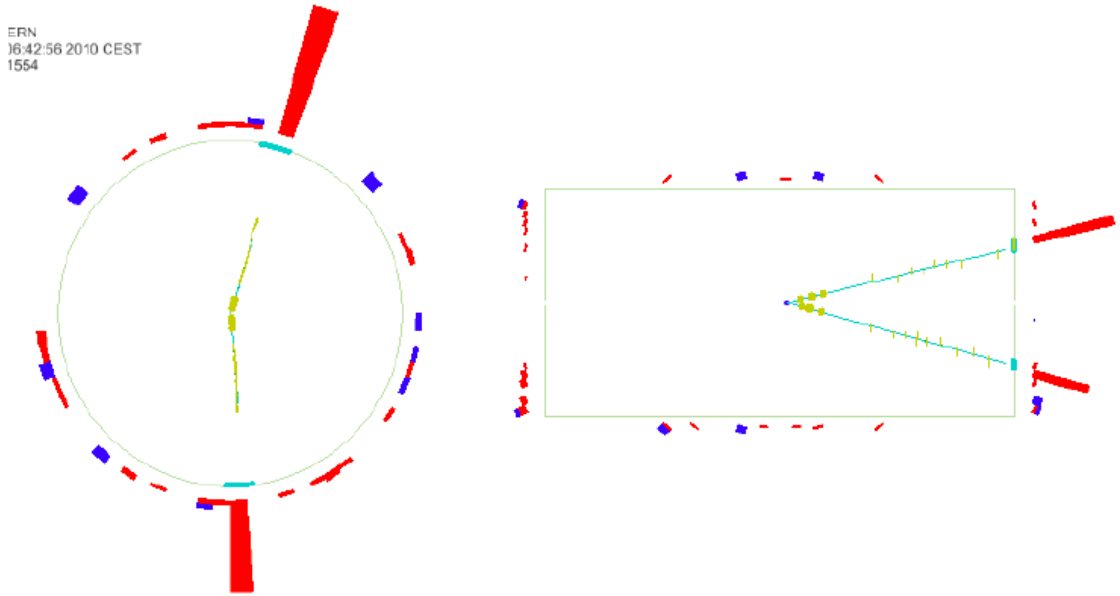
Investigating Low Mass Extrapolations

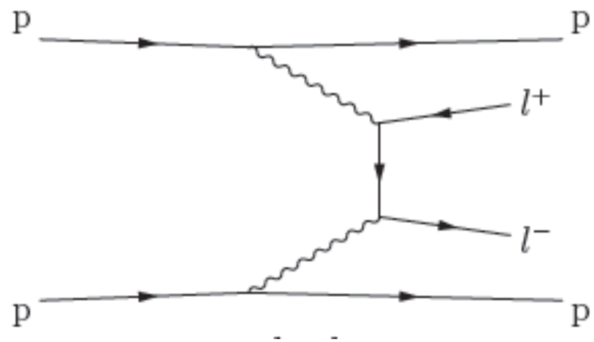


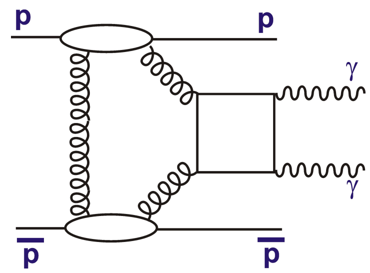
[Inelastic cross section excluding diffractive channels with $\xi < \xi_{cut}$]

- 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)

Quick word on Central (Excl) Production

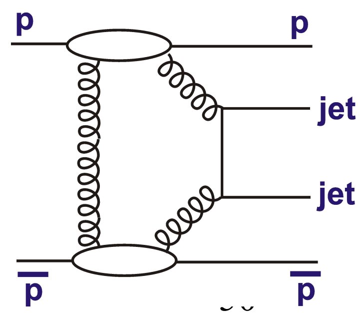






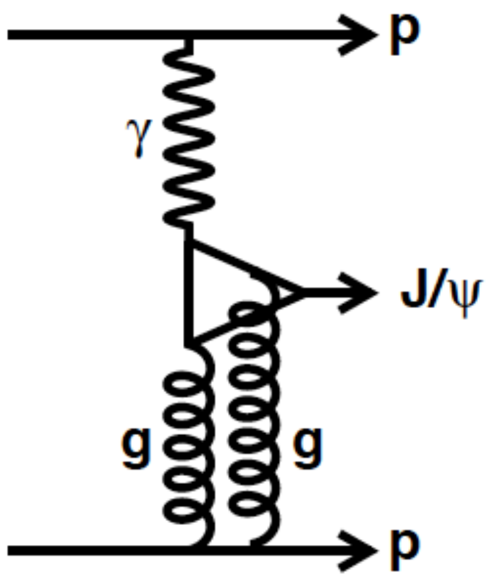
- First results from CMS on e^+e^- and $\mu^+\mu^-$ are consistent with QED prediction.

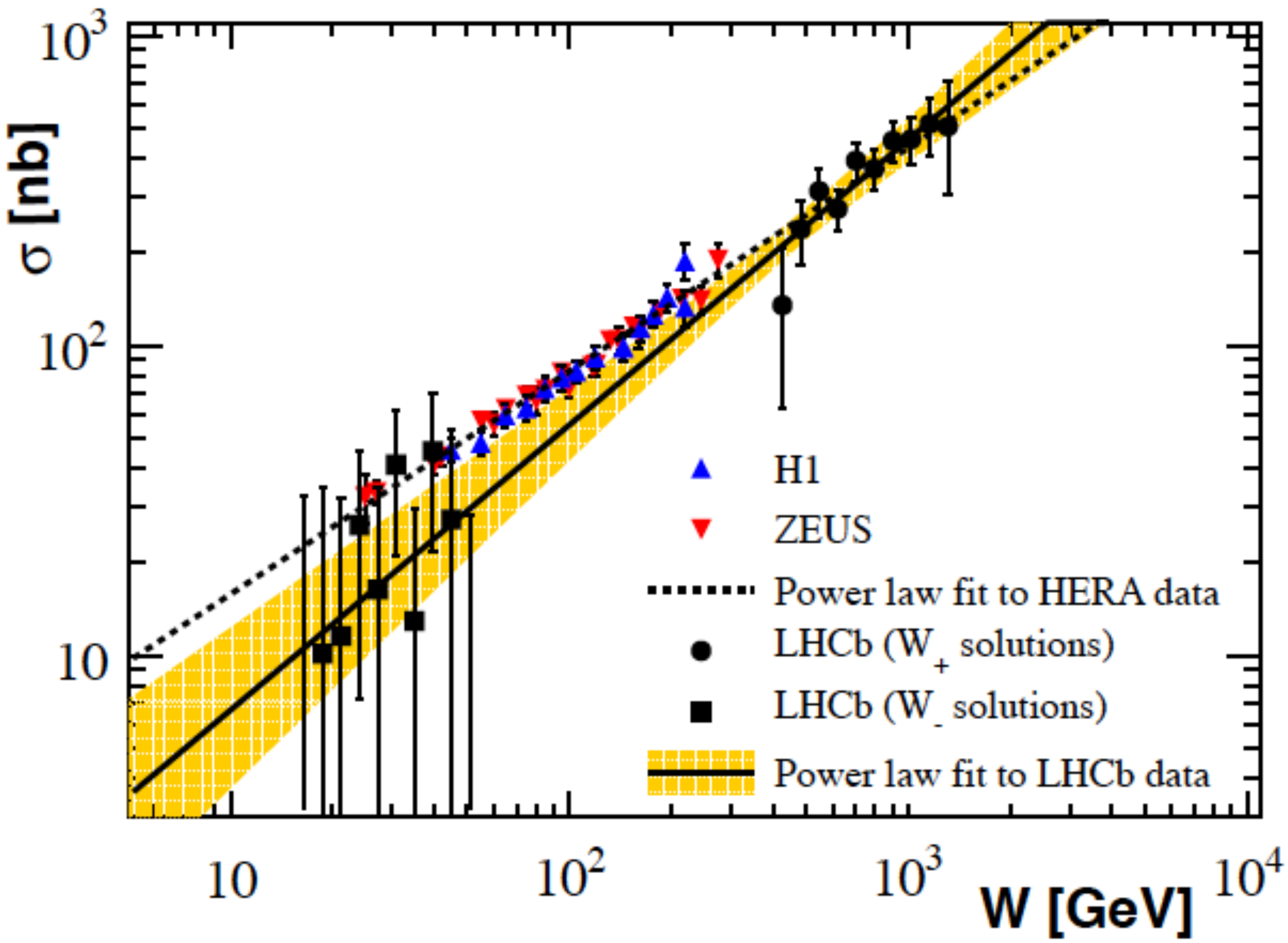
- No signal for $\gamma\gamma$, jet-jet or other strongly produced central systems so far



… but watch this space …

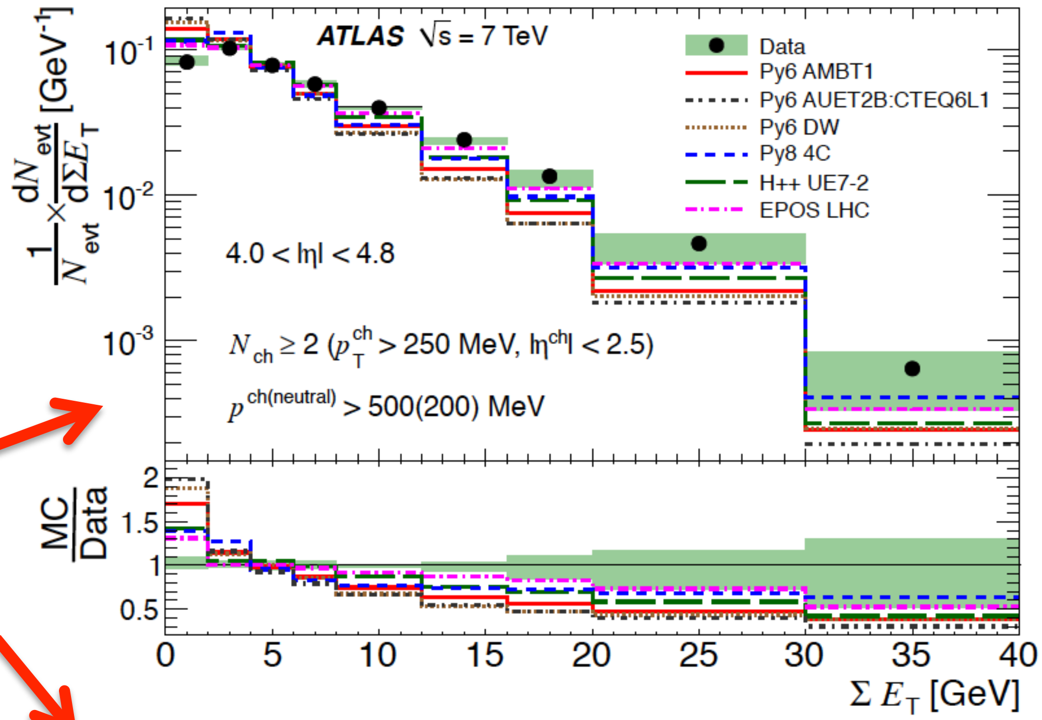
Photoproduction in Ultra-peripheral



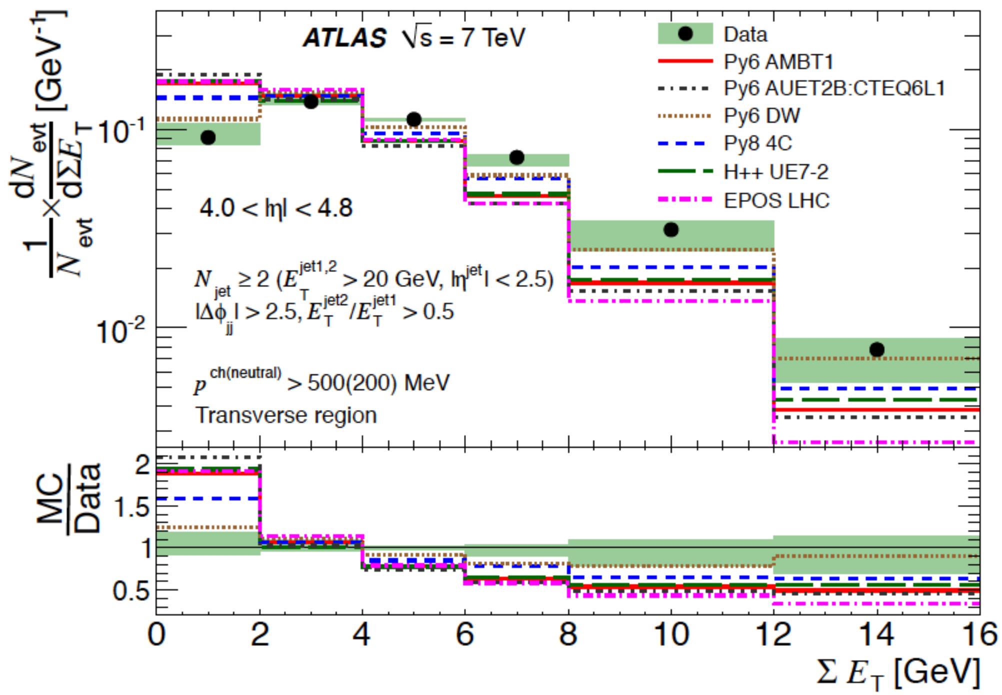


Total Forward (4.0 < |η| < 4.8) Transverse Energy

Min Bias



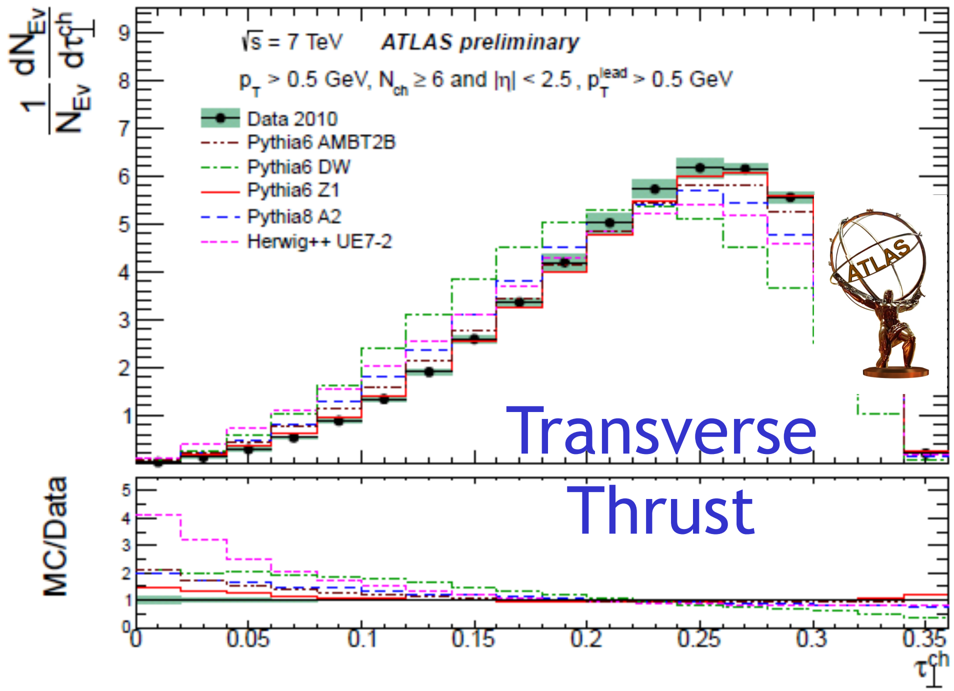
UE in Dijets

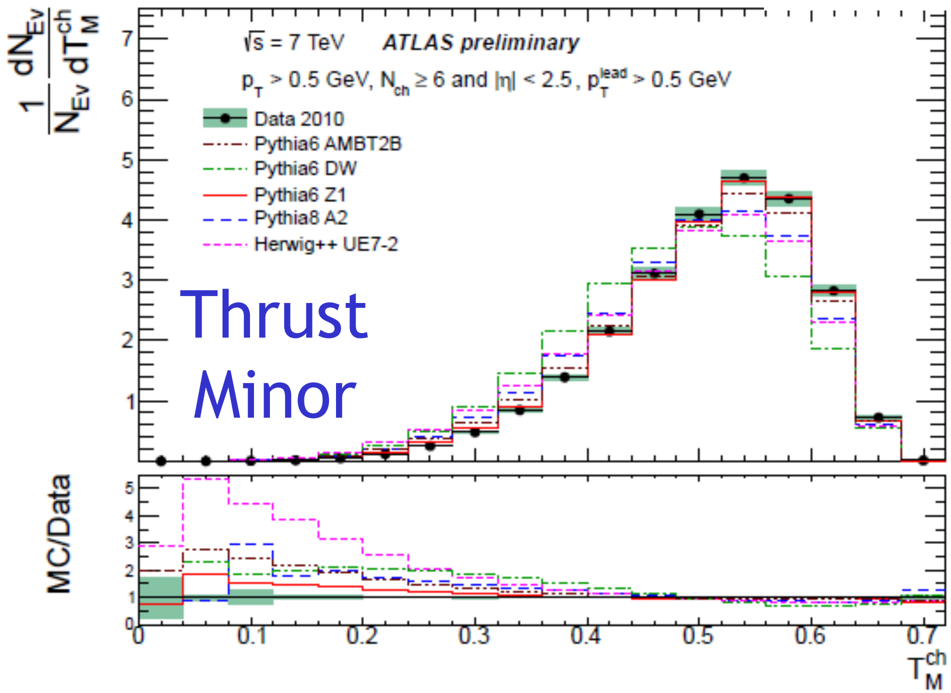


Models all tend to overestimate the low E_T contribution and underestimate the high E_T contribution in most forward region.

Complementary Ways of Characterising Events: Global Event Shapes

- Transverse thrust
- Thrust minor,
- Transverse Sphericity





also well described by Z1 tune …

(Forward) Transverse Energy Flow

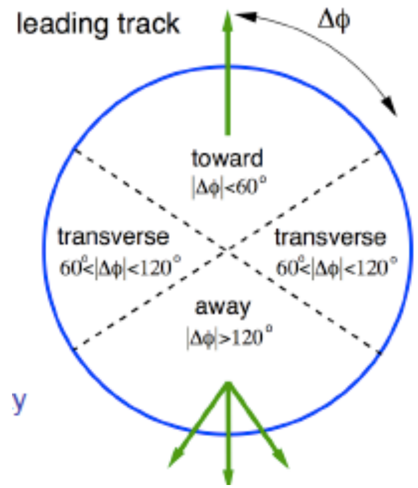
Mean E_T in $|\eta|$ ranges: $$\frac{1}{N_{evt}} \frac{dN_{evt}}{d\,\Sigma E_T}$$

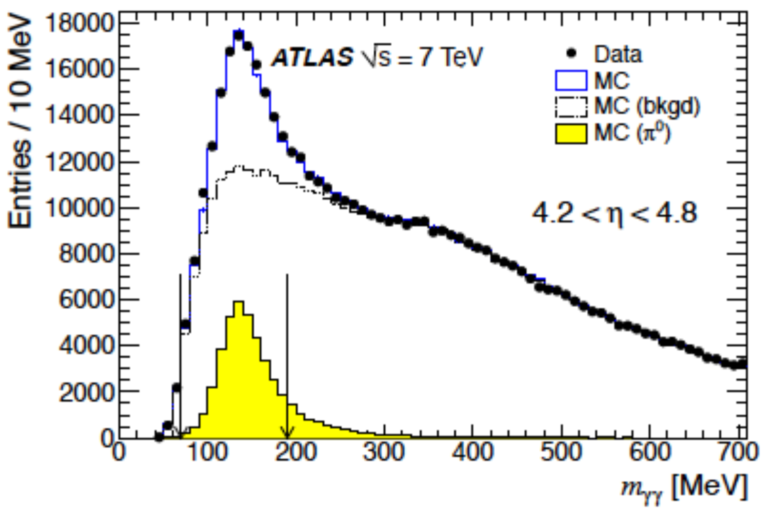
Mean E_T Density: $$\frac{1}{N_{evt}} \frac{d\,\Sigma E_T}{d\eta\, d\phi}$$

$|\eta| < 4.8$, pT > 500 MeV (charged), pT > 200 MeV (neutrals)

1) For all ϕ in minbias events and

2) For transverse region in events with central dijets (E_T^{jet} > 20 GeV) → underlying event in hard process)

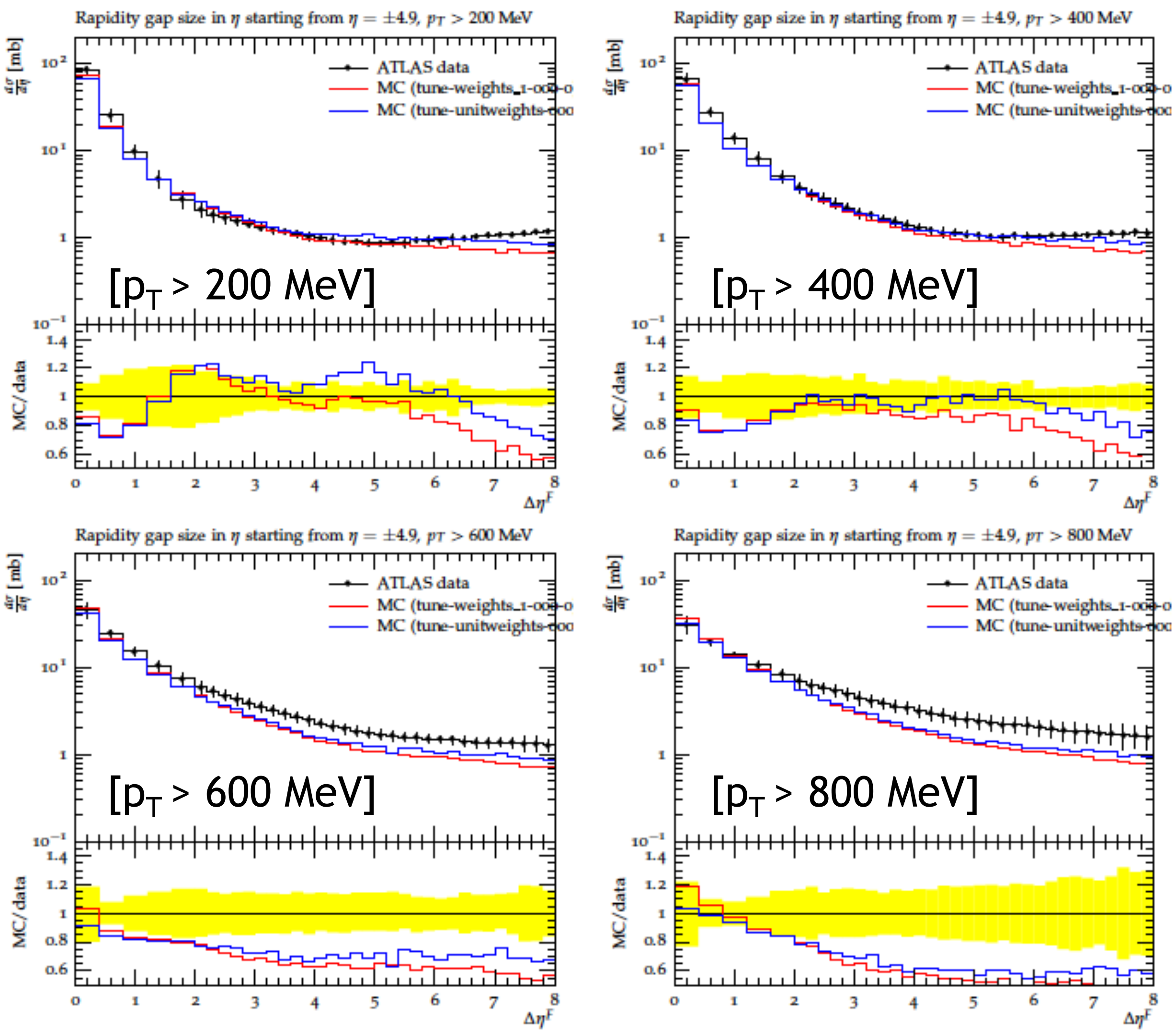




Forward calorimeter calibration based on $\pi^0 \rightarrow \gamma\gamma$ studies

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 ...