Recent Experimental Results on Soft (& Semi-hard) Strong Interactions

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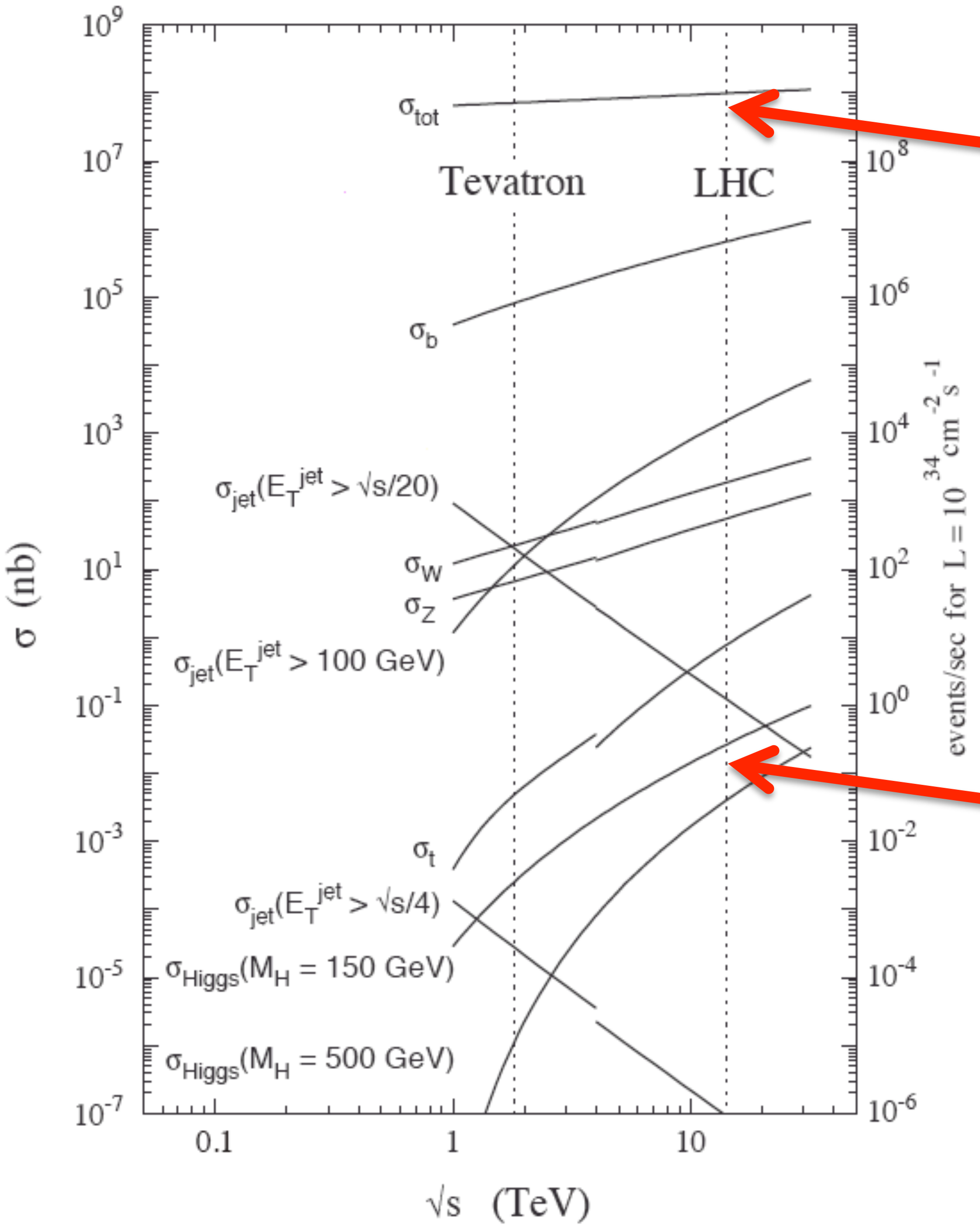
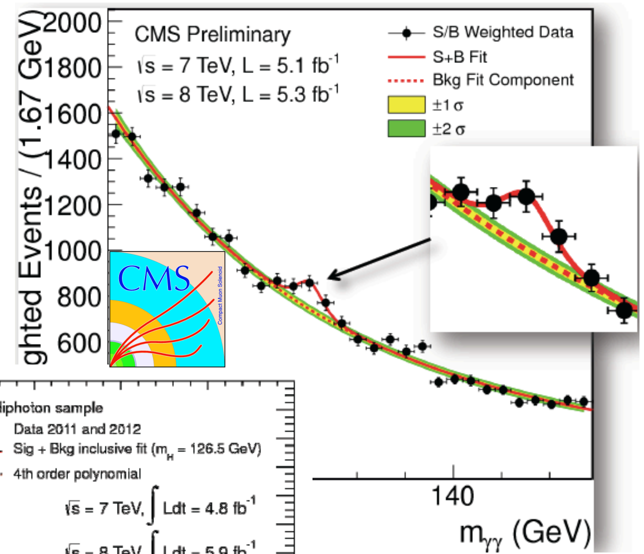
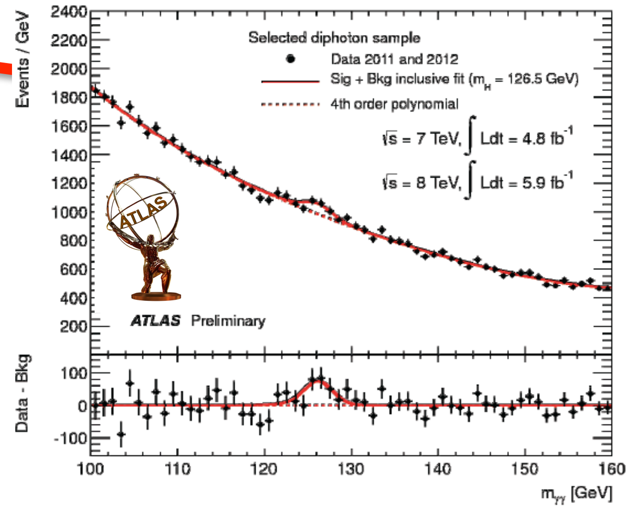
What usually happens when hadron(s) Collide?

This talk…

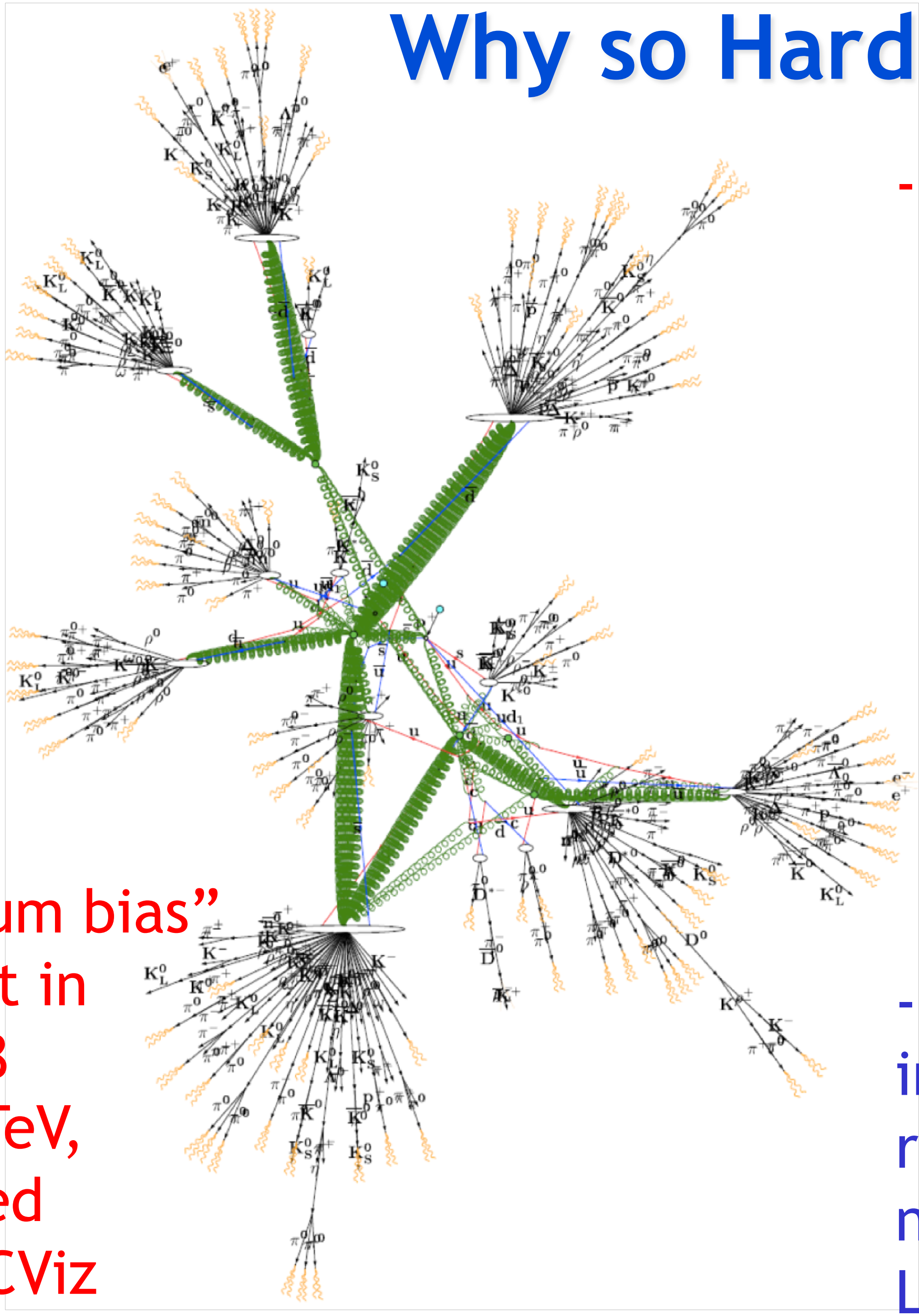
… calculating 10^{-1} processes is much harder than 10^{-10} processes ☹





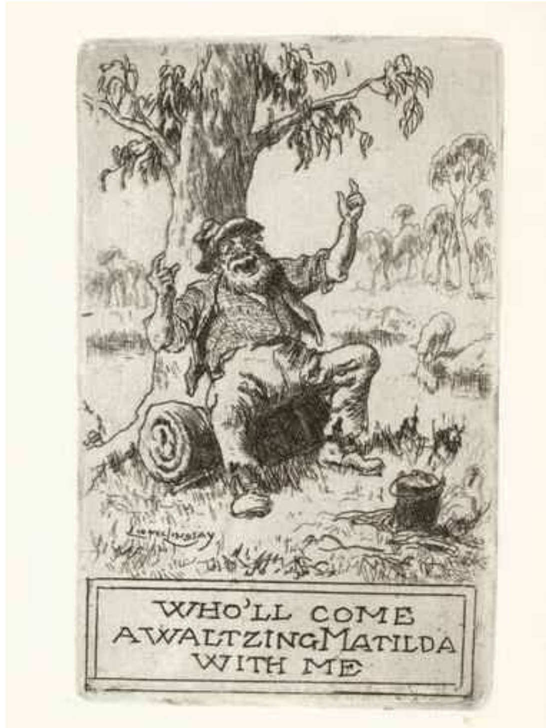


Why so Hard to Calculate?



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

- Front-line territory!



- Constrained by impressively precise recent data and original new observables from LHC, HERA & Tevatron

Why should we Care?

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

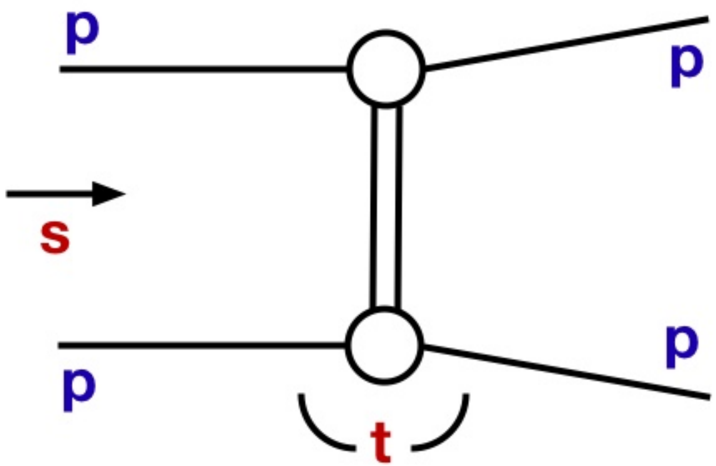
Fundamental questions:

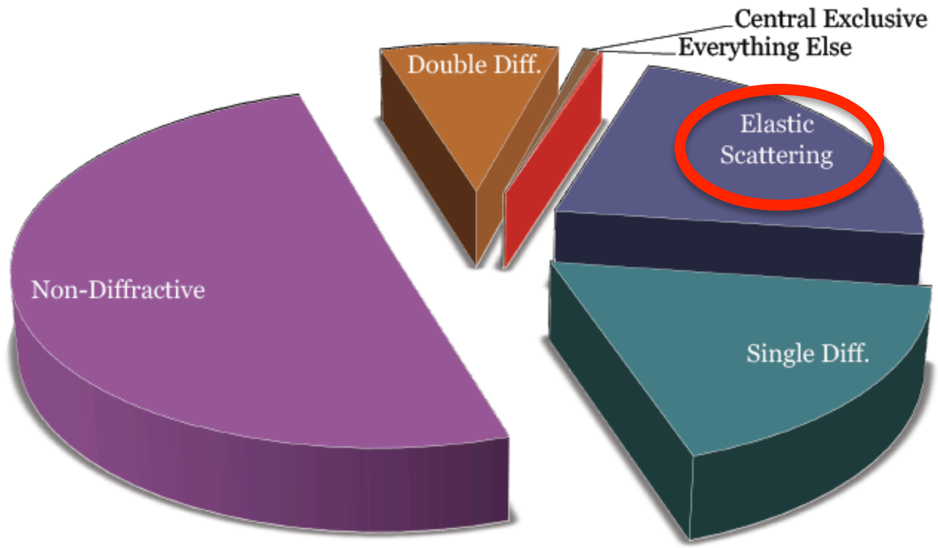
- confinement
- hadronic mass generation,
- non-perturbative degrees of freedom
- strong / weak coupling and Super-gravity
- …

Practical concerns:

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

Something `Simple': Elastic Scattering



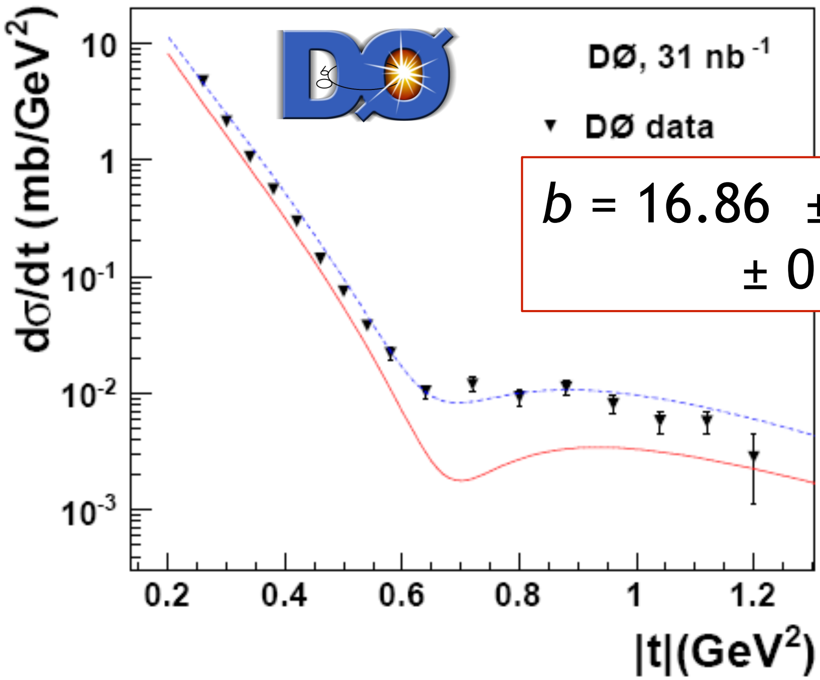


At fixed √s, 1 non –trivial variable (t)

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

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

Slope parameter b `measures' size of interaction region.



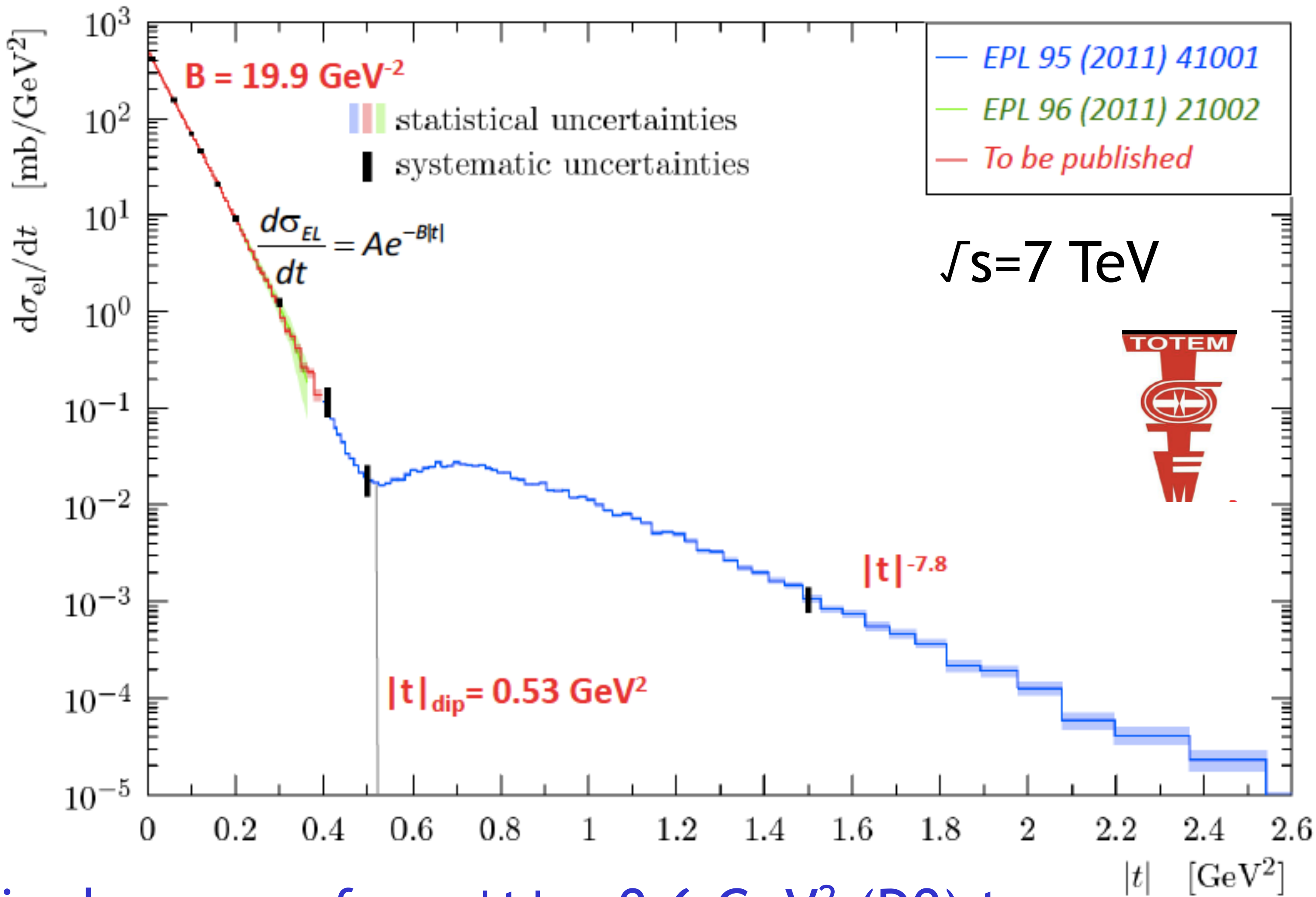
Roman Pots
√s=1.96 TeV

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

Interaction range ~ few fm.

Elastic Cross Section (TOTEM Roman Pots)

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



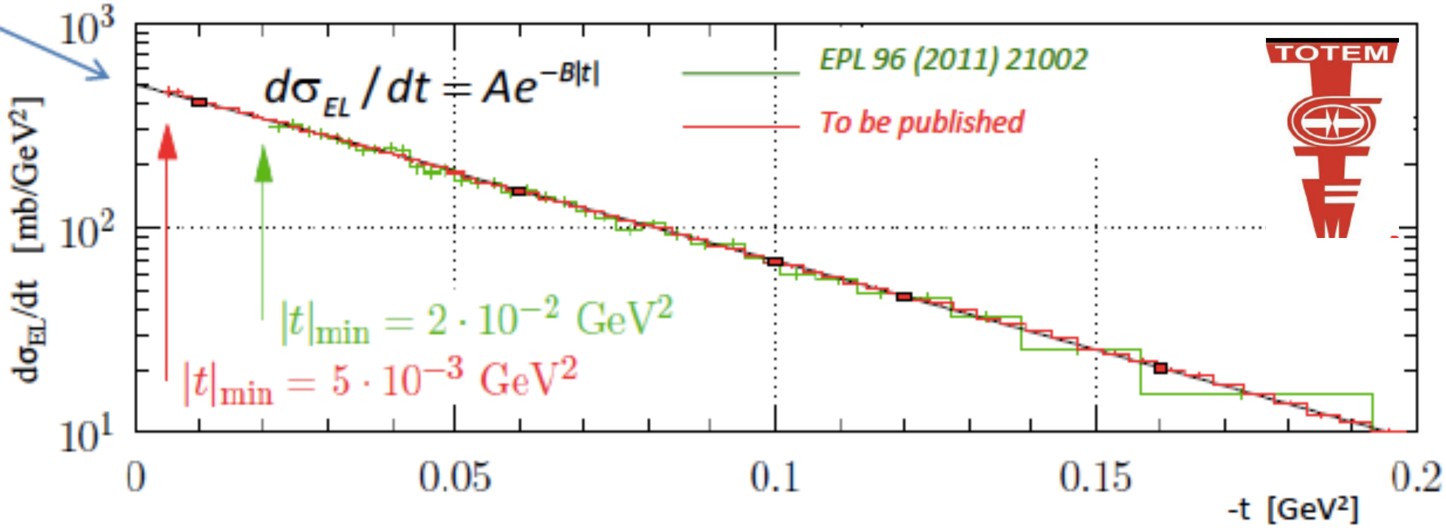
- Position of dip decreases from |t| ~ 0.6 GeV^2 (D0) to 0.53 GeV^2 (TOTEM)
- Slope increases: B = 16.7± 0.2 GeV^{-2} (D0) 19.9±0.3 GeV^{-2} (TOTEM)

… effective size of interacting protons grows with energy

Optical Theorem: Relating elastic & total cross sections

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

$$A = \left.\frac{d\sigma_{EL}}{dt}\right|_{t\to 0}$$



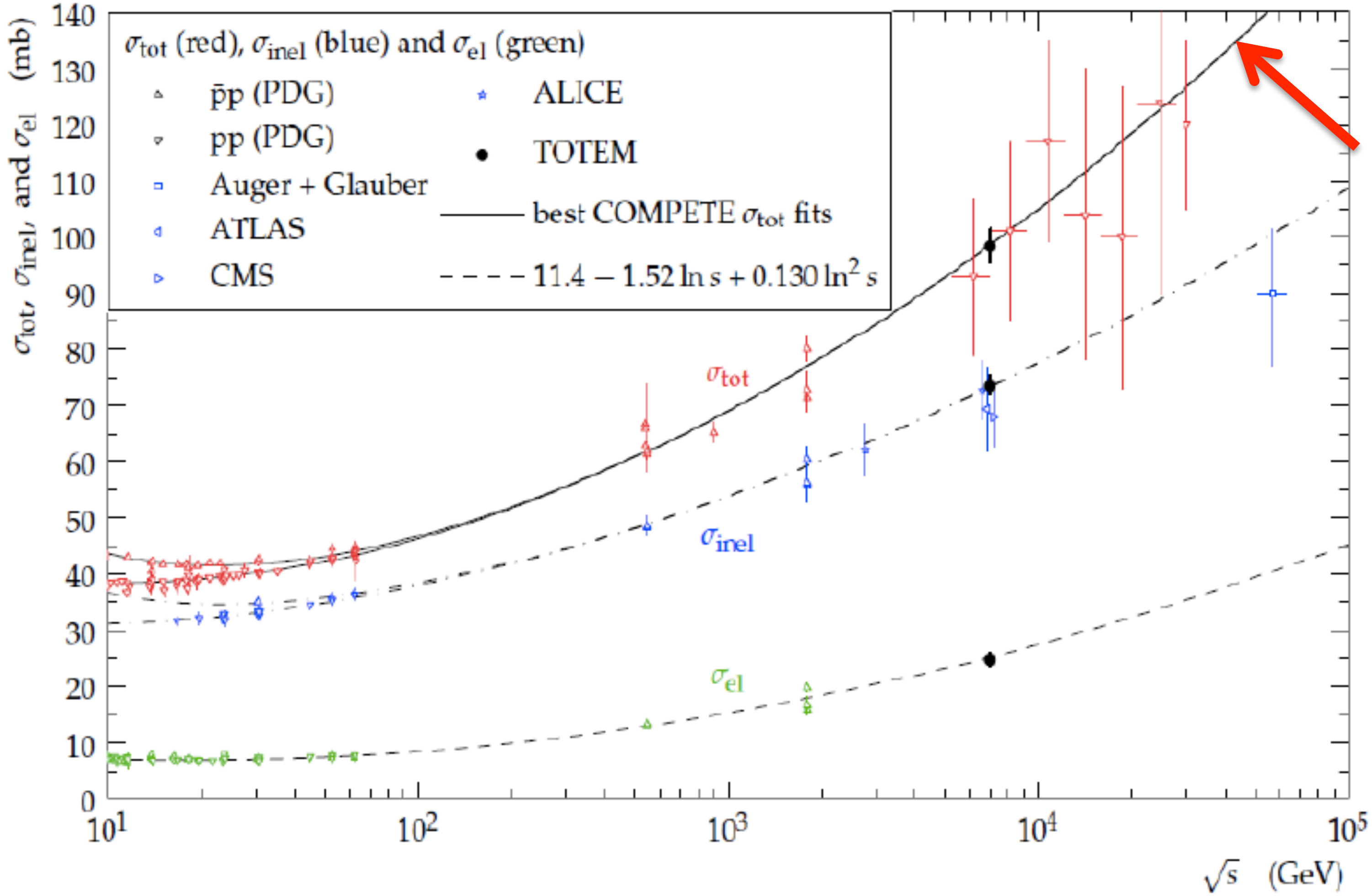
Dedicated run (special optics @ β^* = 90m) → |t| ~ 0.005 GeV^2

- 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

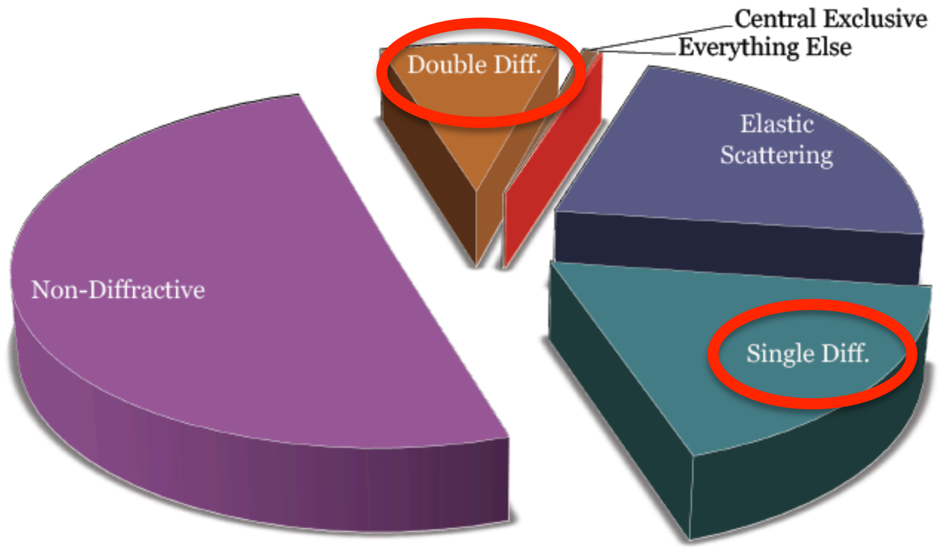
$$\sigma_{el} = \left(24.8 \pm 0.2^{(\mathrm{stat})} \pm 1.2^{(\mathrm{syst})}\right)\mathrm{mb} \qquad \sigma_T = \left(98.3 \pm 0.2^{(\mathrm{stat})} \pm 2.7^{(\mathrm{syst})} \begin{bmatrix} +0.8 \\ -0.2 \end{bmatrix}^{(\mathrm{syst\ from\ }\rho)}\right)\mathrm{mb}$$



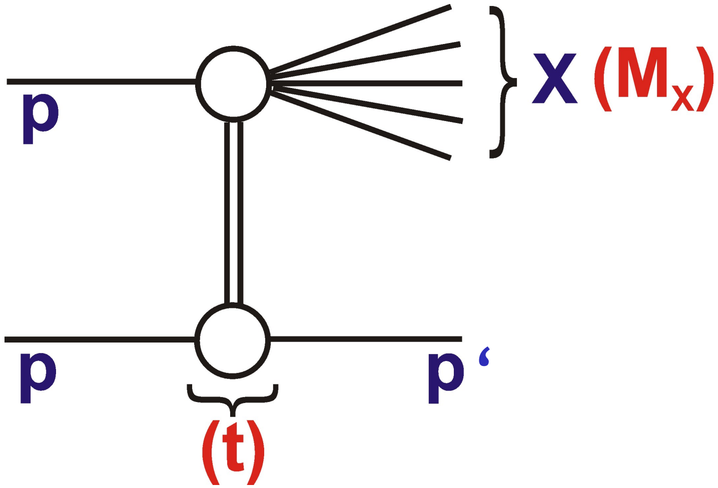
Consistent with fits to previous data (leading $\ln^2 s$ dependence, satisfying Froissart unitarity bound)

Inferred total inelastic cross section consistent with ATLAS, CMS and ALICE min-bias measurements (luminosity monitoring)

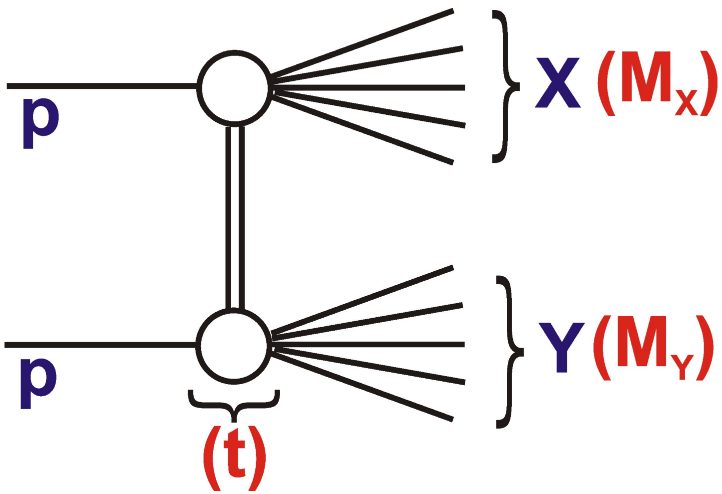
Inelastic Diffraction



Single diffractive dissociation



Double diffractive dissociation

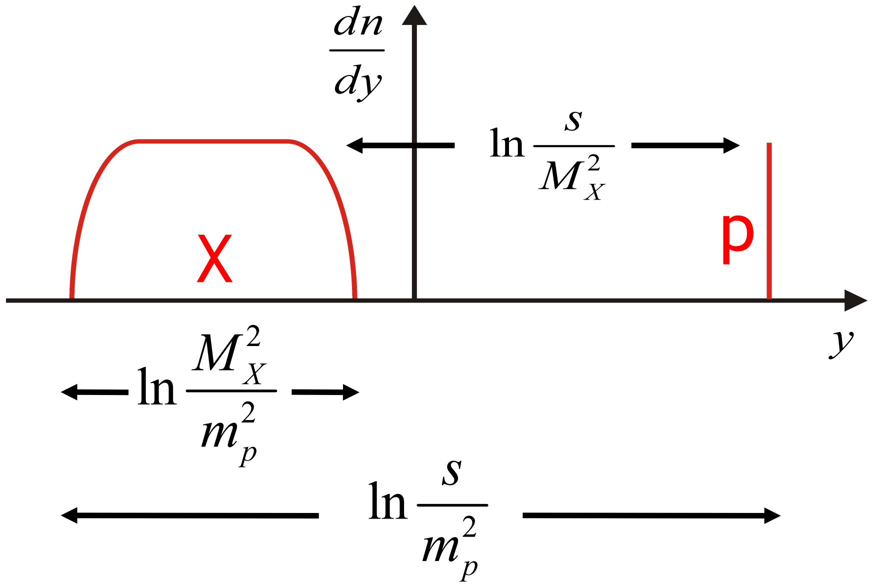


Additional kinematic variable

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

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

ATLAS: Differential gap cross-sections

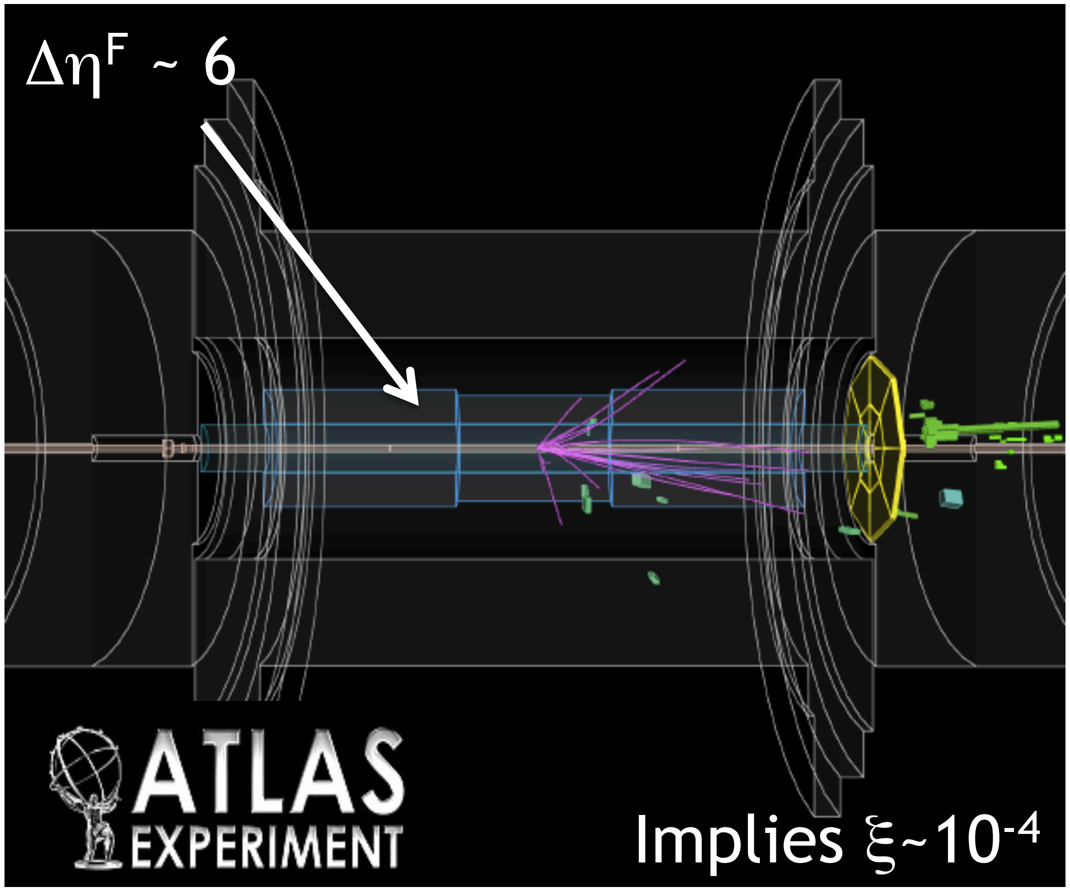


Strong correlation between size of empty rapidity region and kinematics

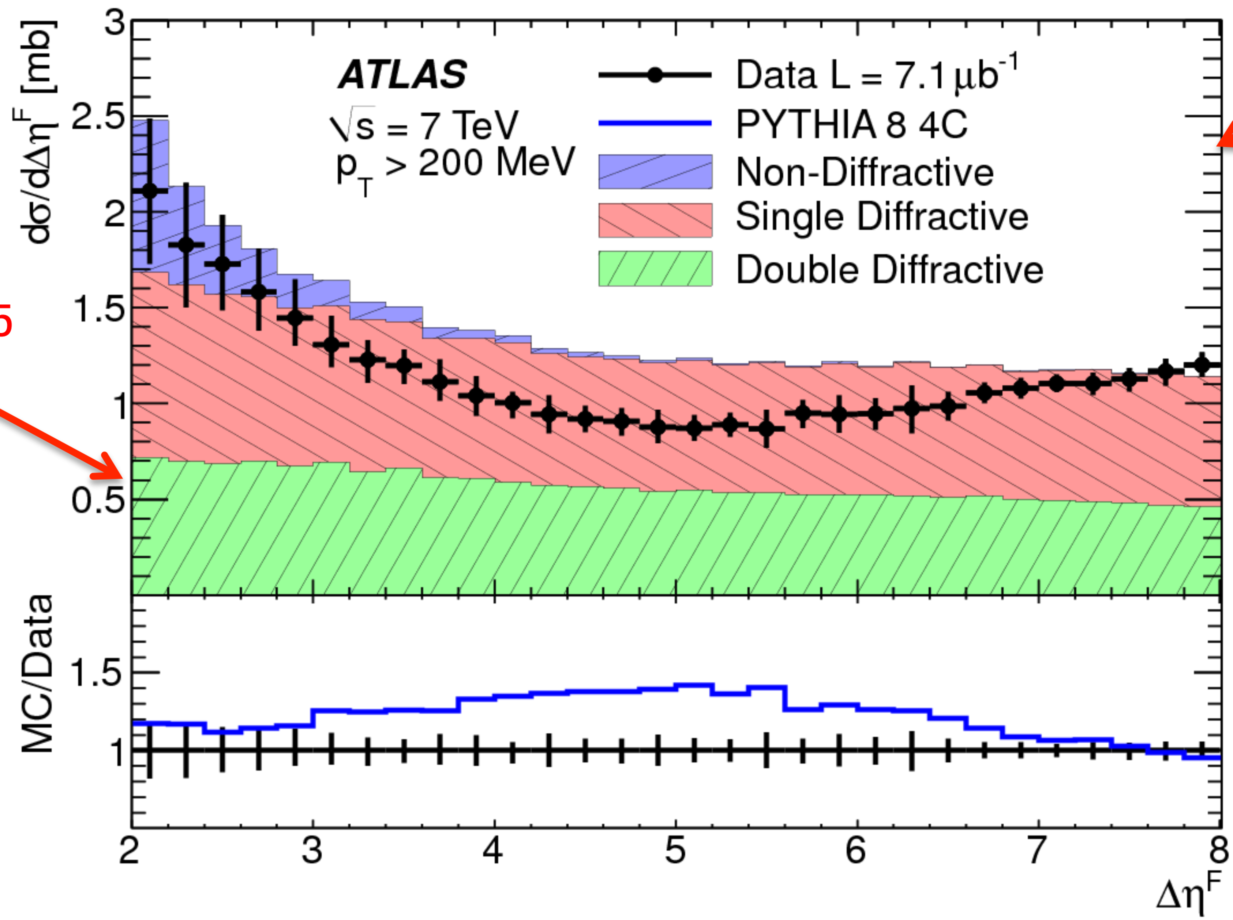
$$\Delta\eta \approx -\ln\xi$$

- Cross sections measured from first $\sqrt{s}$ = 7 TeV LHC run [30 March 2010, 7.1 μb^{-1}, peak lumi 1.1 x 10^{27} cm^{-2} s^{-1}]

- Differential in rapidity gap $\Delta\eta^F$ extending from $\eta = \pm 4.9$ to 1st particle @ p_t > 200 MeV



Large Gaps and Diffractive Dynamics



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

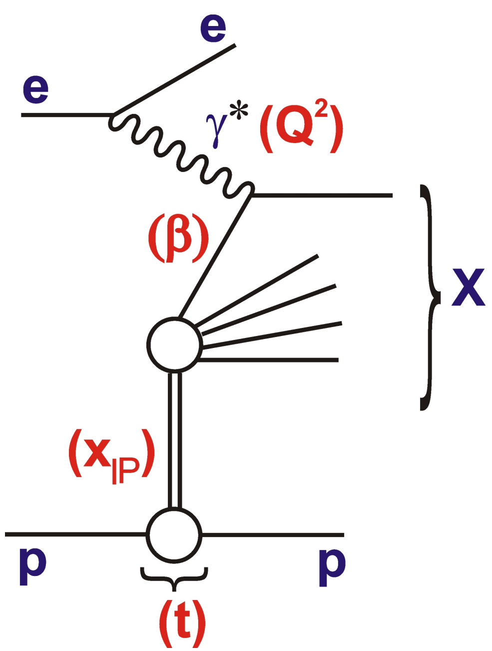
$\xi \sim 10^{-2.5}$

4% precision for large gaps

10~20% as $\Delta\eta^F \rightarrow 0$

- Exponential fall of non-diffractive contribution at small gaps
- Diffractive "plateau": ~ 1 mb per unit of gap size for $\Delta\eta^F > 3$.
- Slow rise with gap size consistent with expectations
- Ample opportunity to improve model details

HERA & Partonic Diffraction

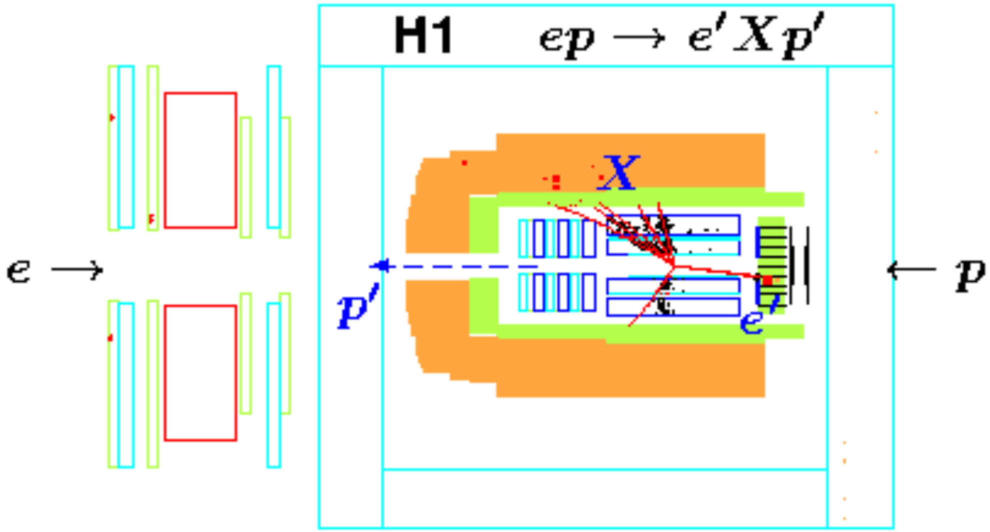


$x_{IP} = \xi = M_X^2/W^2$

= fractional momentum loss of proton
(momentum fraction IP/p)

$\beta = x \ / \ x_{IP}$

(momentum fraction, struck q / IP)

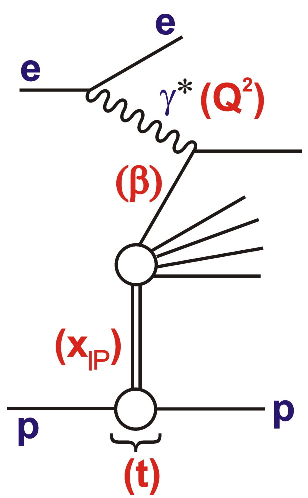


Virtual photon probes partonic structure of diffractive DIS rather like inclusive DIS …

Experimentally identified through rapidity gaps or direct tagging of scattered proton

>100 papers later …

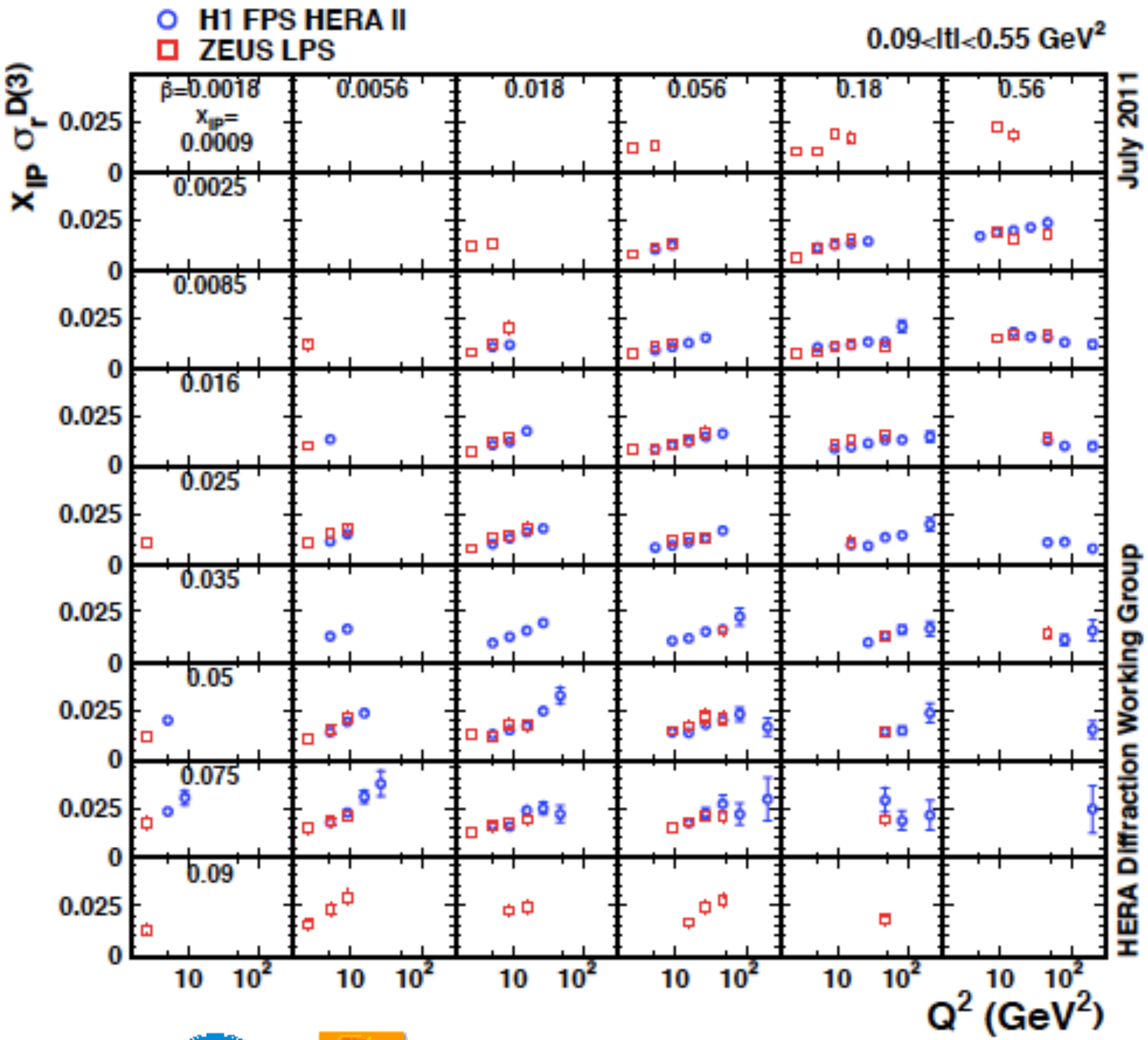
ZEUS v H1 Diffractive DIS



3% precision in rapidity gap method

First combined H1 / ZEUS data (proton tagged)

Precise determination of soft and hard dynamics



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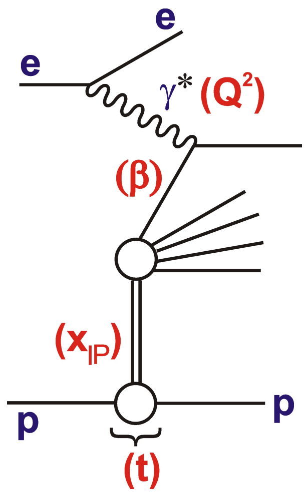

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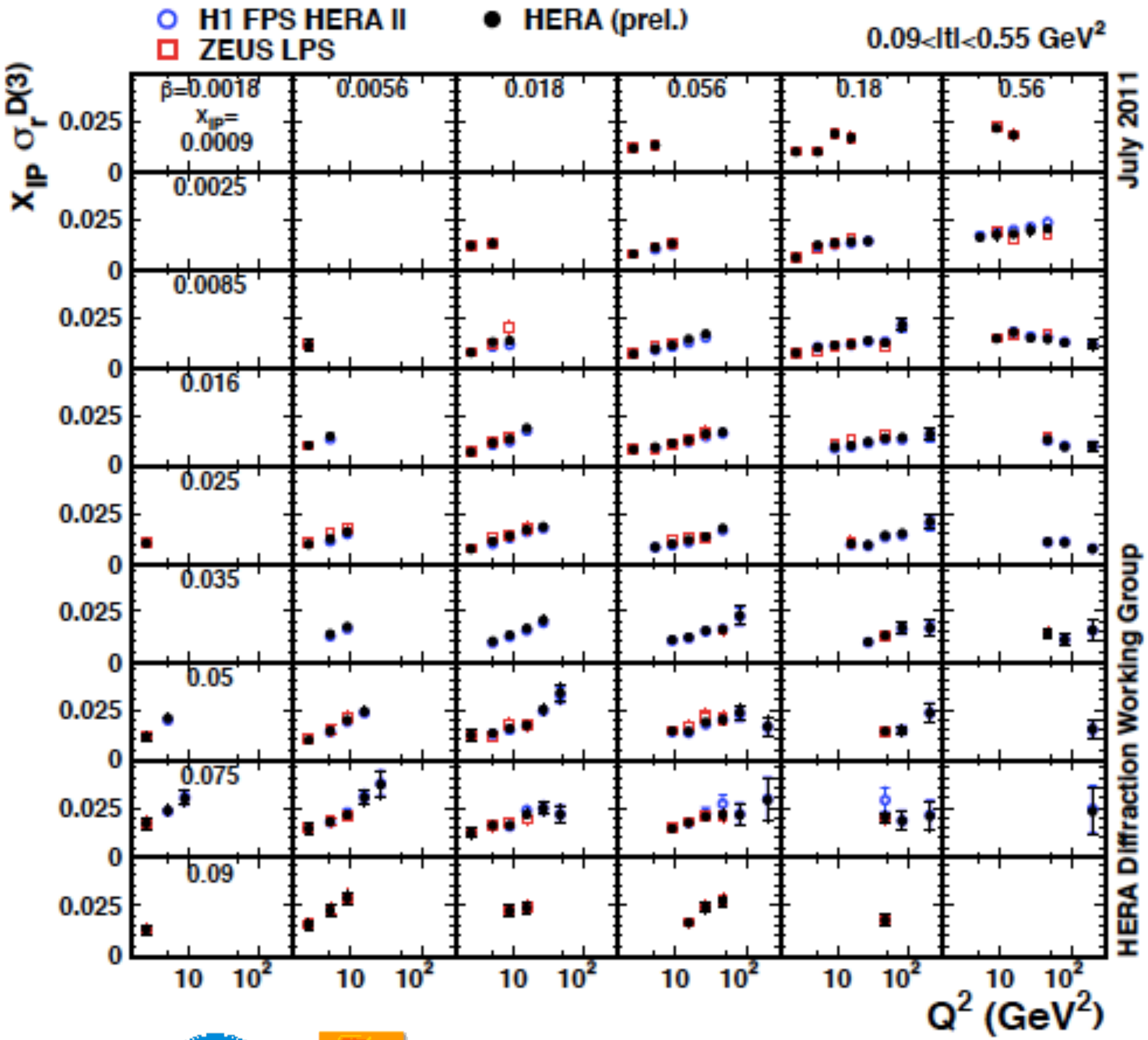

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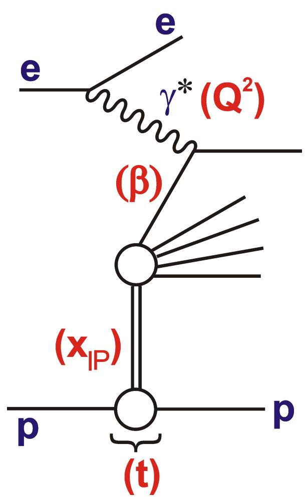

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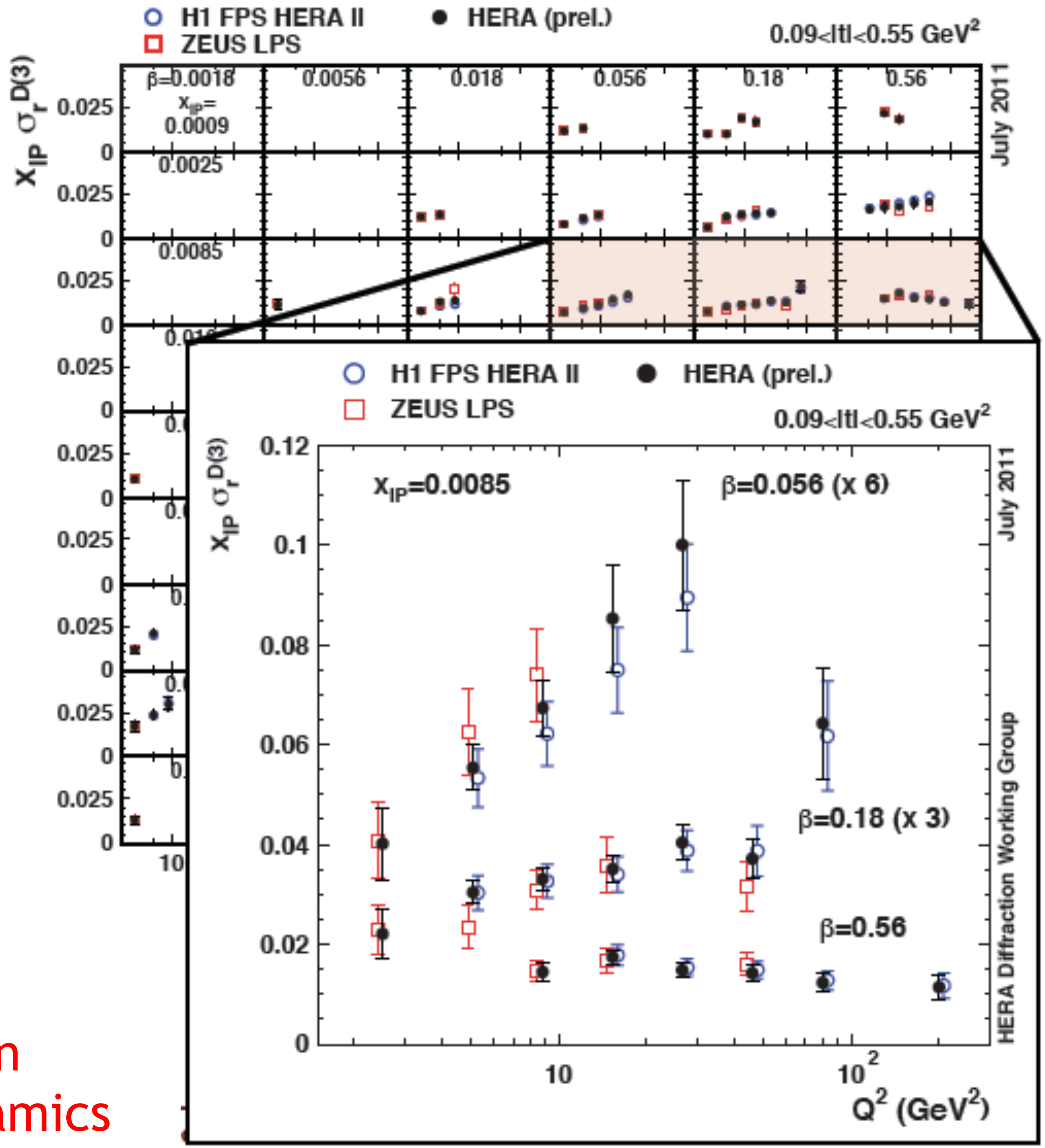
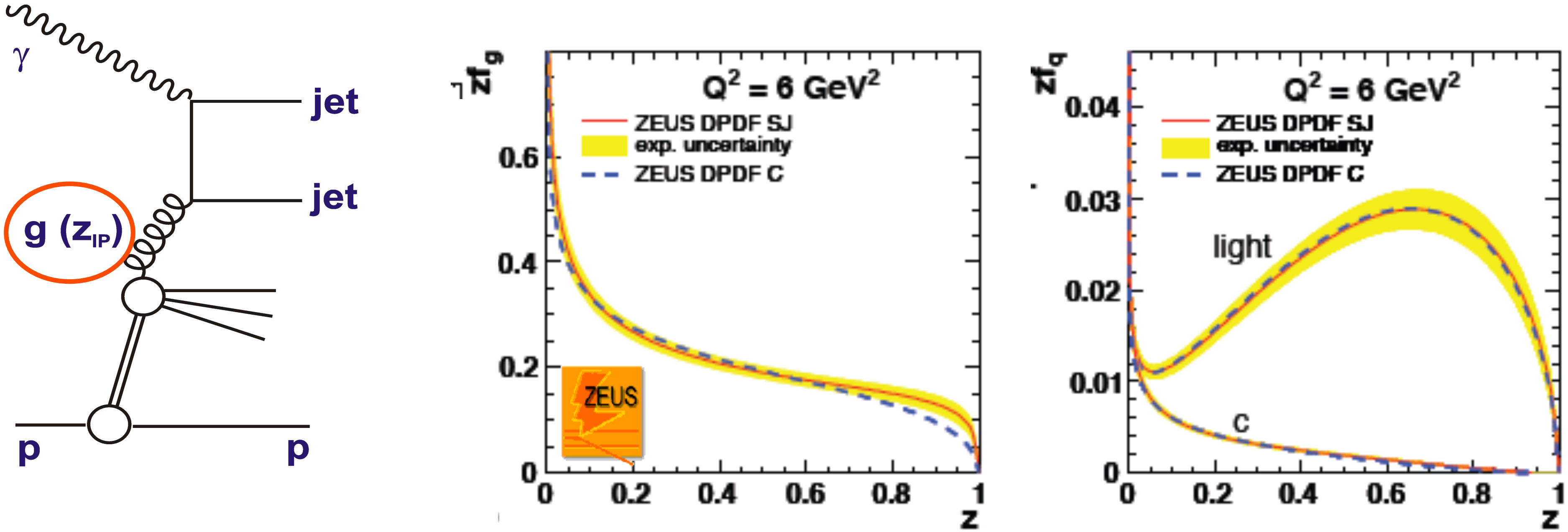


Diffractive Parton Densities (DPDFs)



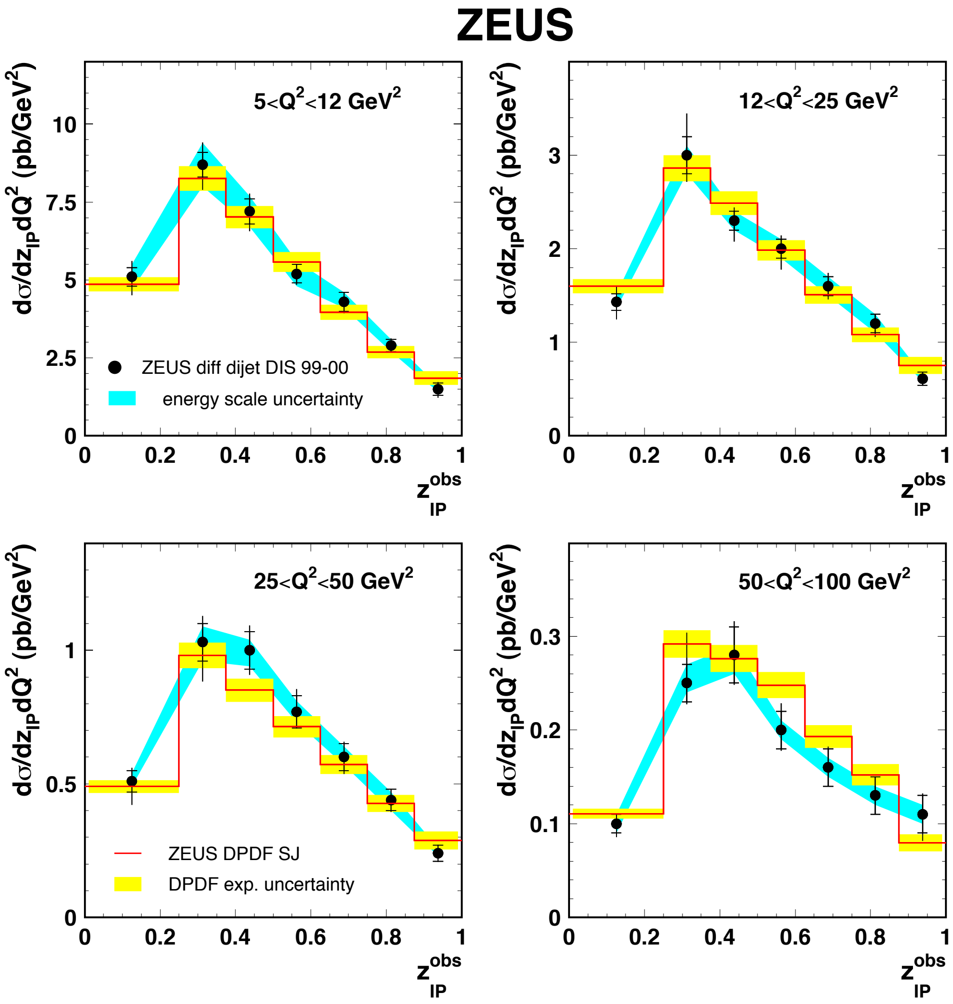
- DPDFs obtained through NLO DGLAP QCD fits to data.

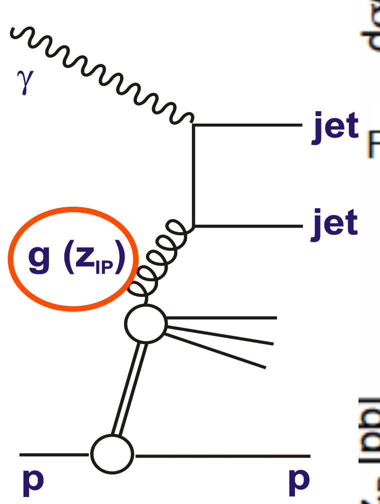
- Quark density to ~5%, gluon from scaling violations to ~ 10%

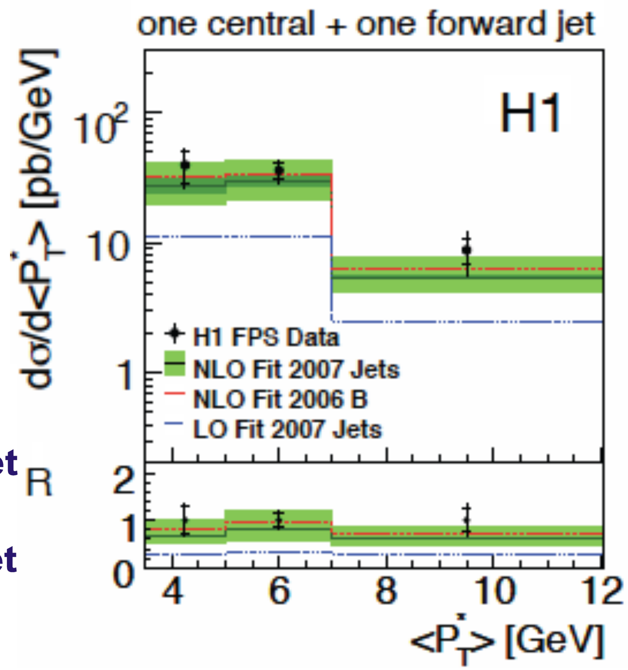
- Diffractive scattering dominantly gluons (~70% of exchanged momentum, extending to large momentum fractions z)

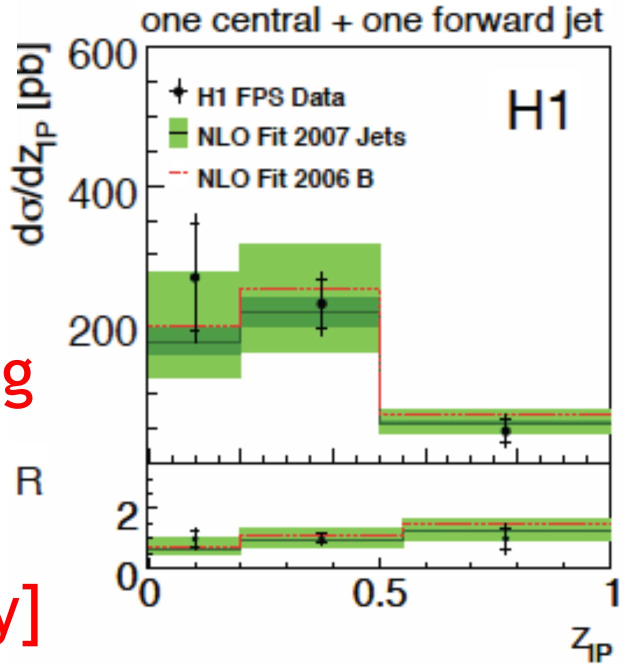
- Impressive descriptions of all hard diffractive DIS data

DPDFs and Diffractive DIS Final States







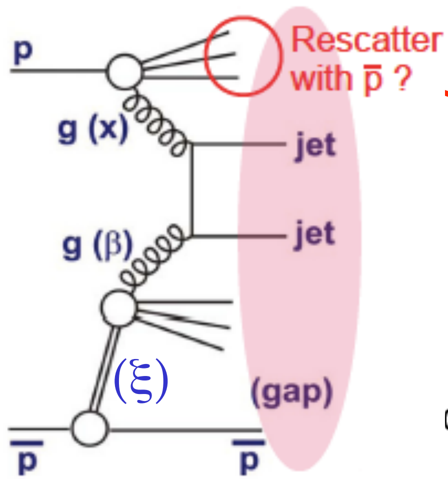


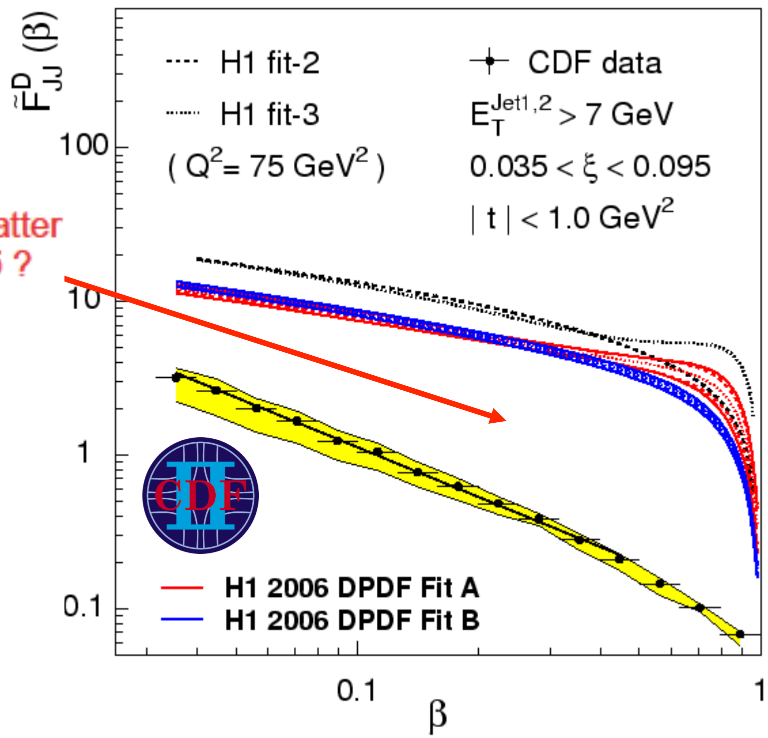
-Successful comparisons in all cases, including configurations where DGLAP questionable

[precision limited by theory scale uncertainty]

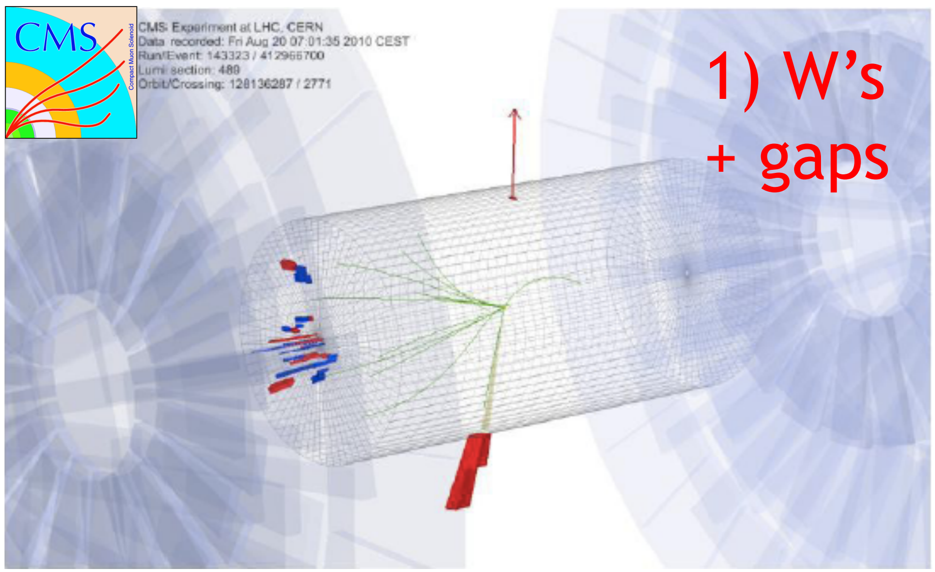
… meanwhile in pp(bar)

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





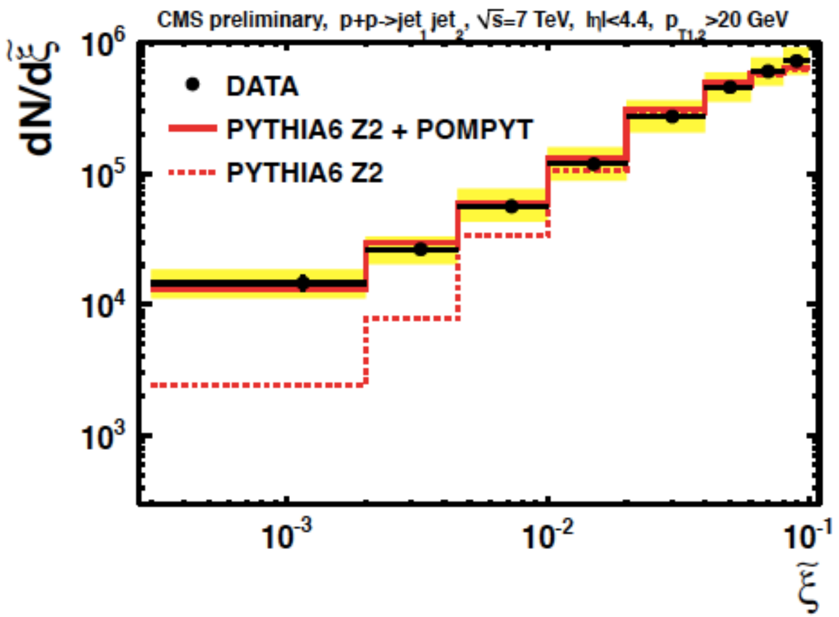
1st Hard diffraction signals at LHC (rap. gap selection)

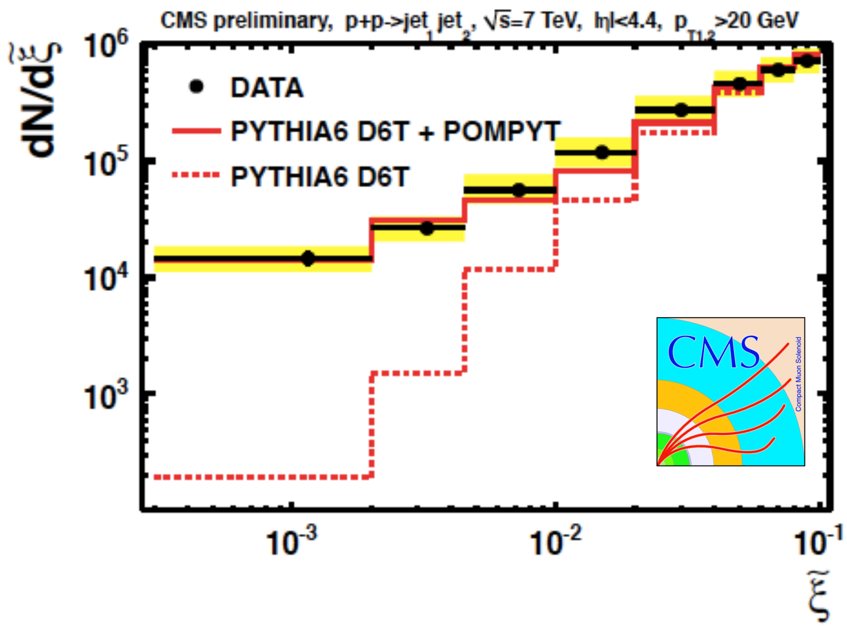


2) Dijets with ξ reconstructed from full observed final state

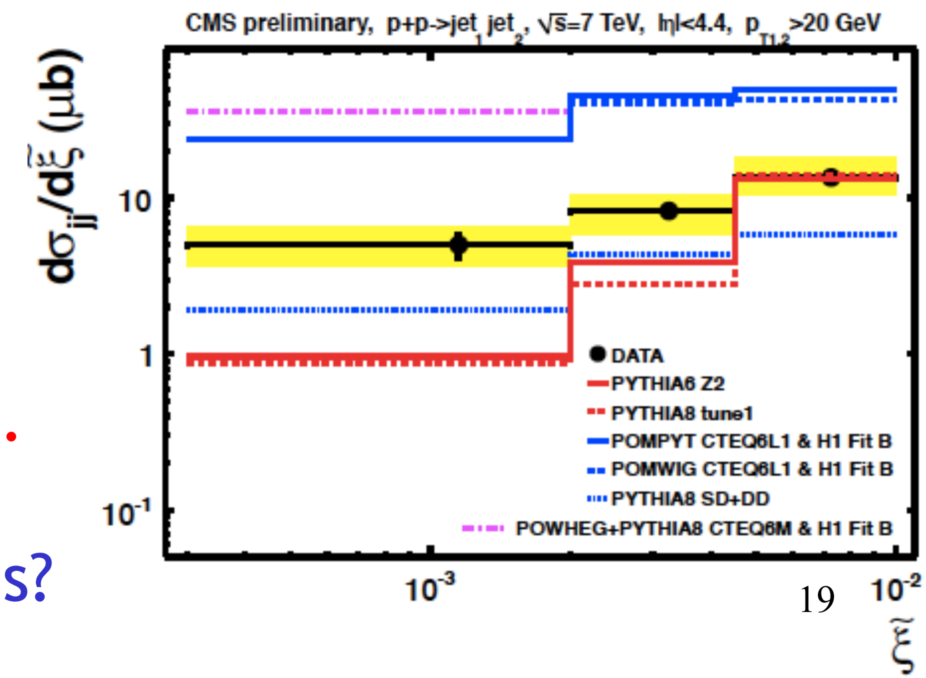
$$\tilde{\xi}^{\pm} = \frac{\sum (E^i \pm p_z^i)}{\sqrt{s}} \simeq \frac{M_X^2}{s}$$

CMS Diffractive Dijets





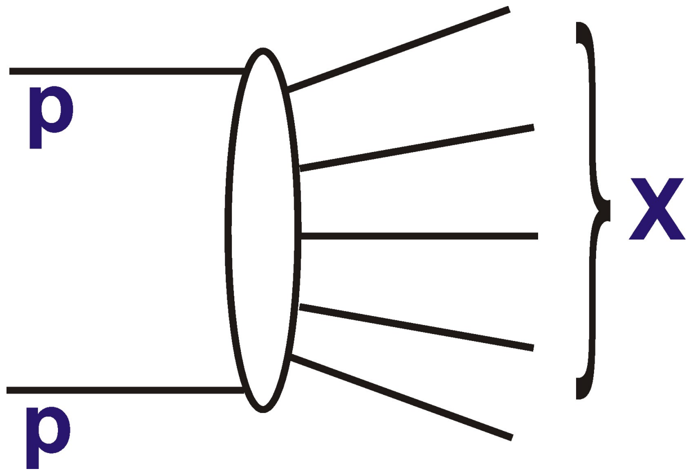
Cross section measured after applying rapidity gap cuts.

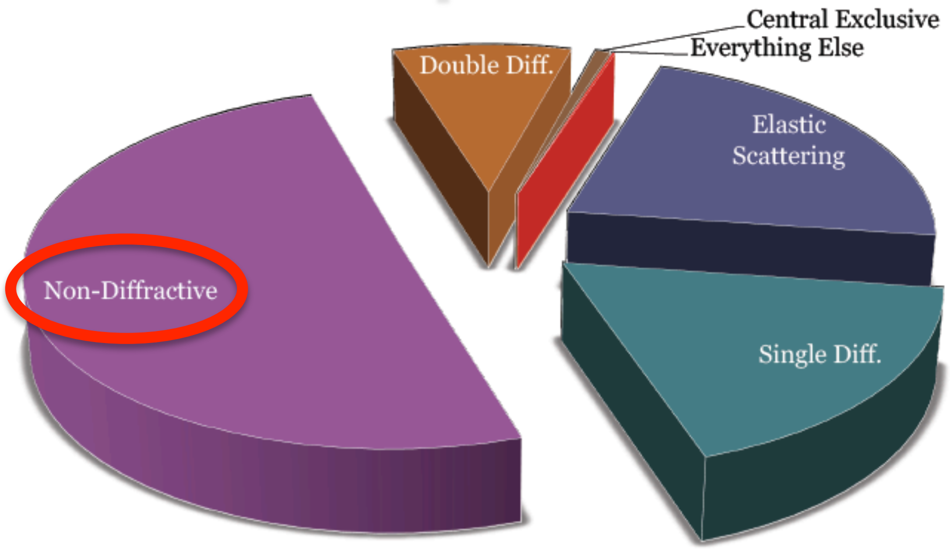


Gap survival probability from NLO MC = 0.08±0.04
(surprisingly) similar to Tevatron.

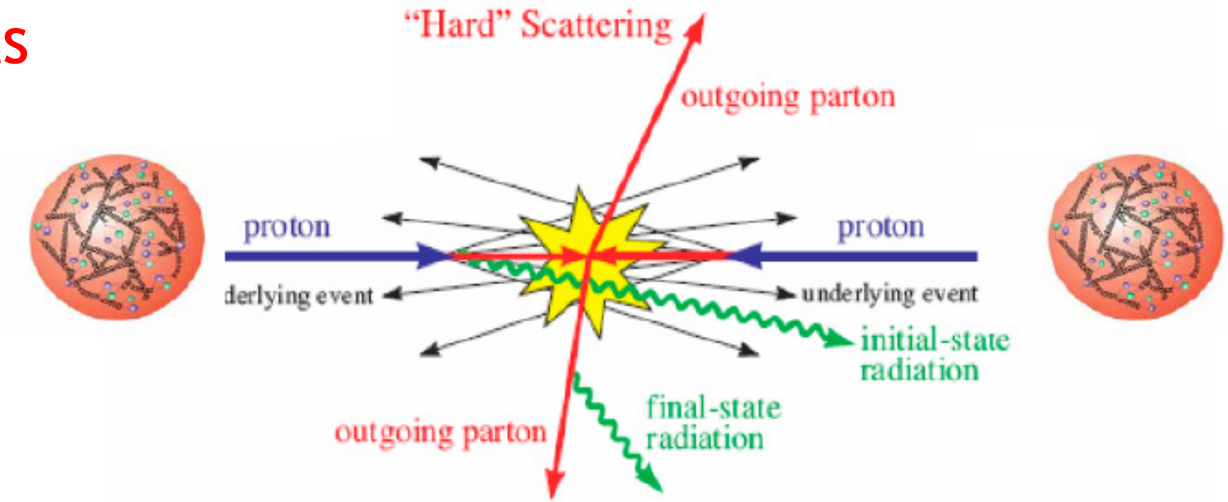
- Non-diffractive gap fluctuations?
- Proton-tagged data will clarify

The rest: non-diffractive processes





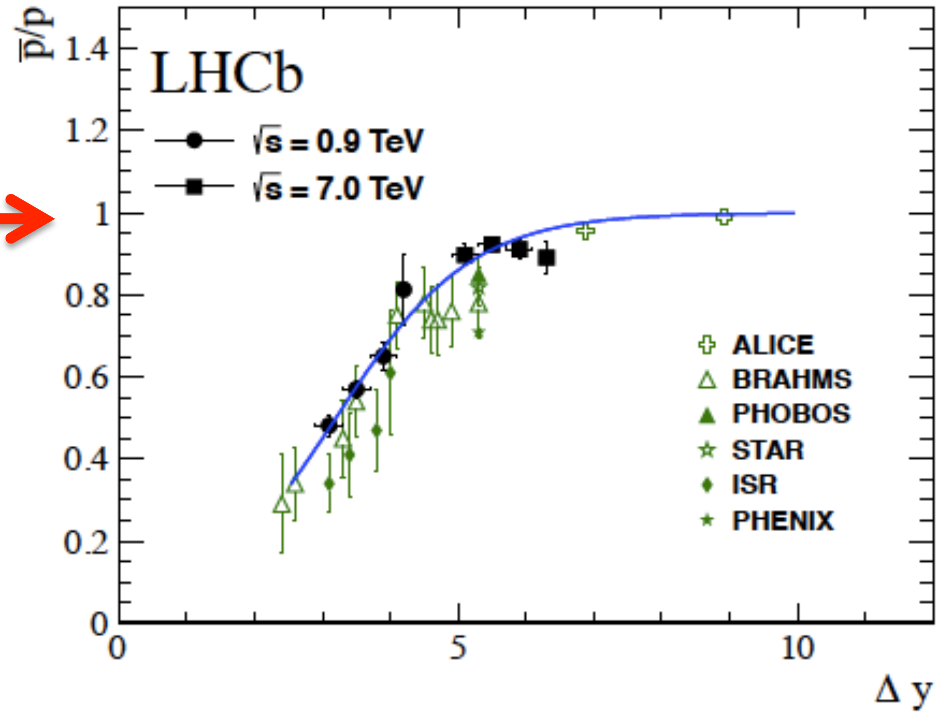
Complicated!... and non-perturbative aspects not ignorable even for hard scattering studies



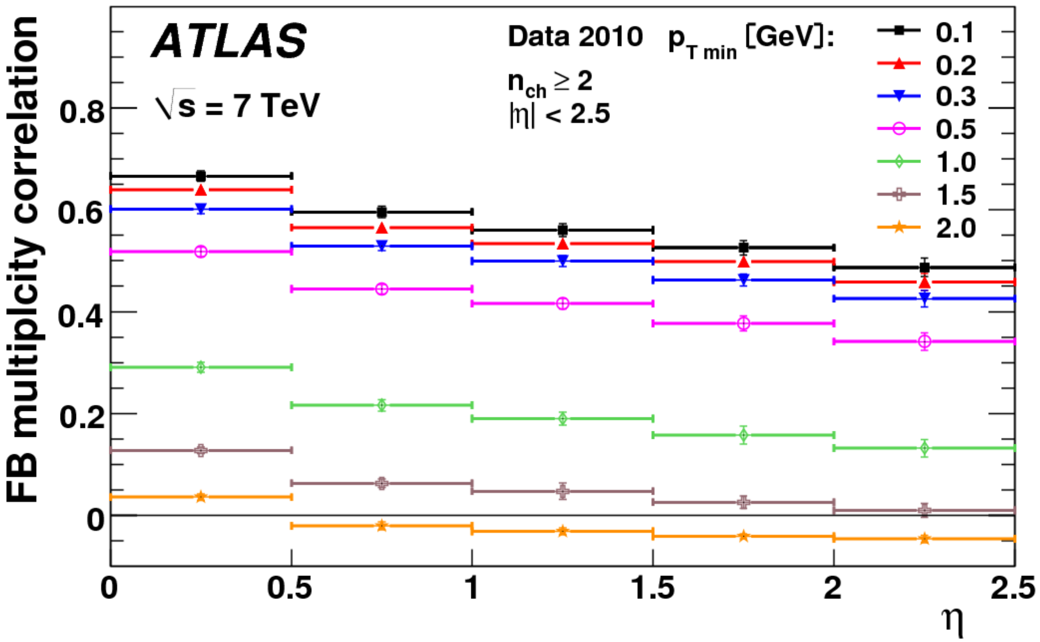
Significant progress in understanding the "underlying event": originating from beam remnants and multiple soft and hard scatterings

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

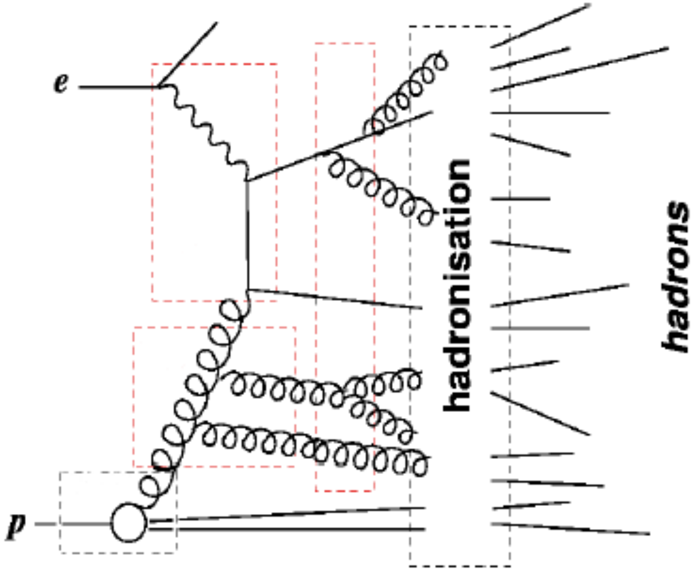


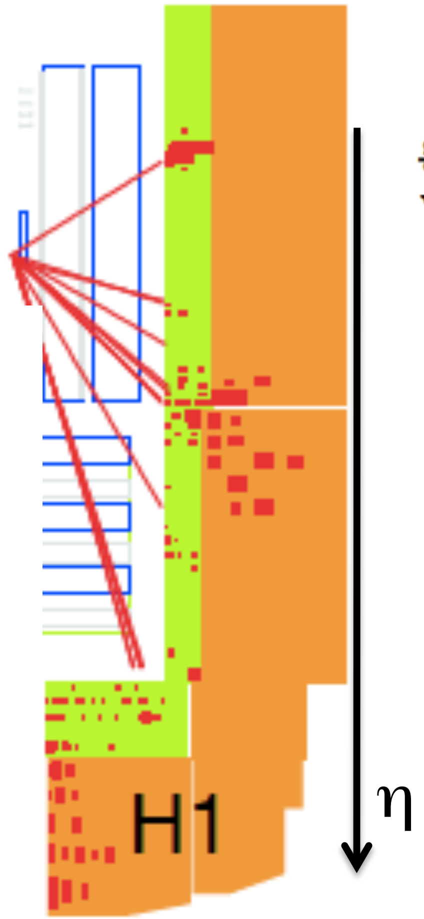
Colour connections lead to forward-backward multiplicity correlation > 0.5 between $\eta = \pm 2.5$ for low p_T particles

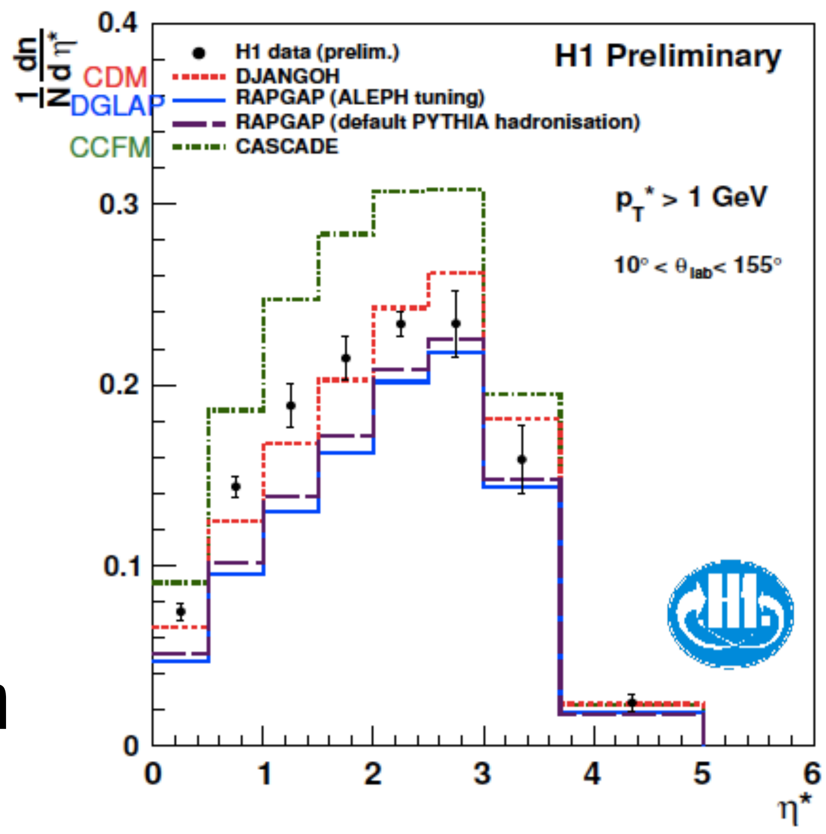
Where does the Energy / Particles Go?

- Studies of particle production and energy flow using many novel observables
- Also which types of particles are produced (not covered here).

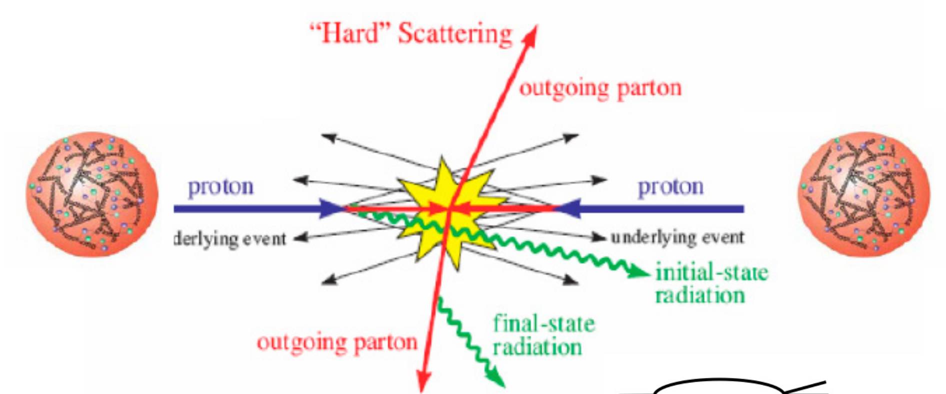
- Data often ahead of phenomenology, even after tuning …

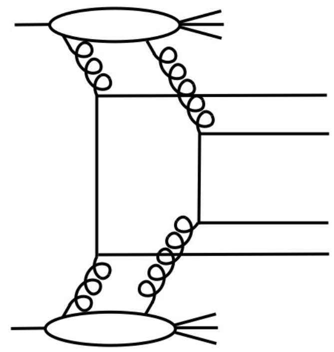




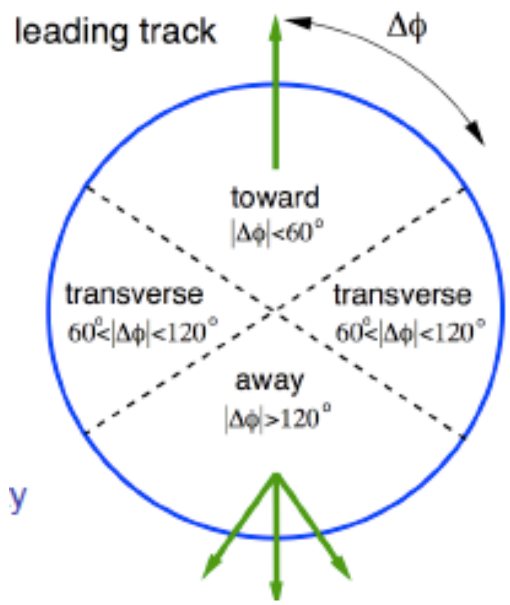


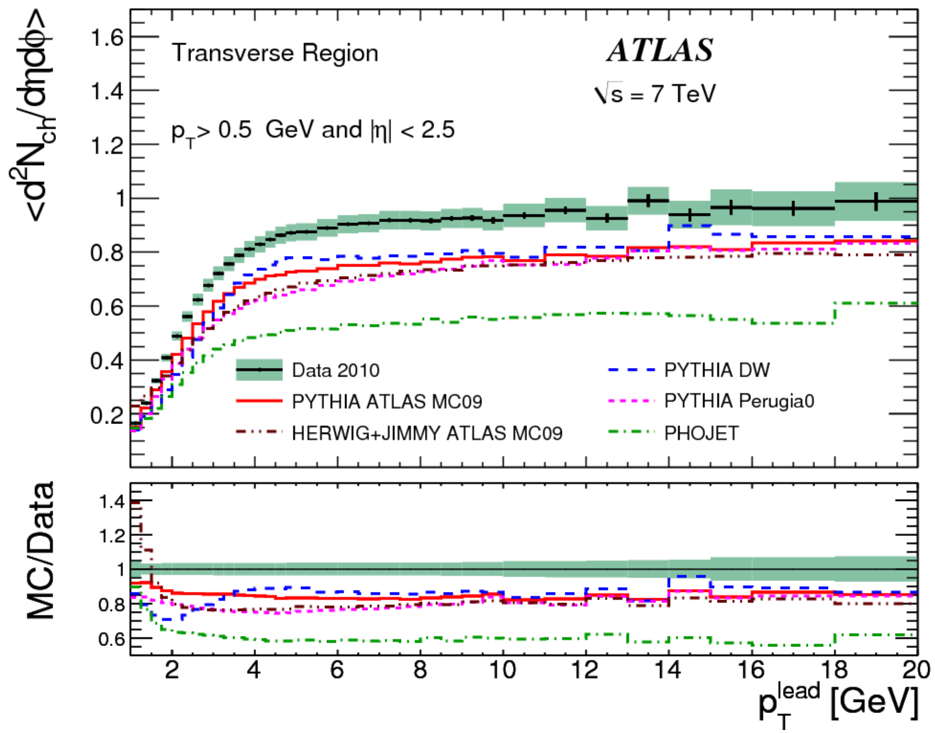
Underlying Event / Multi-parton Scattering





- Region transverse to hard scattering plane particularly sensitive to multiple (parton) int's.
- Pre-LHC MC models predicted too little transverse activity and jettiness in $\Delta\phi \sim 180^o$ away region …

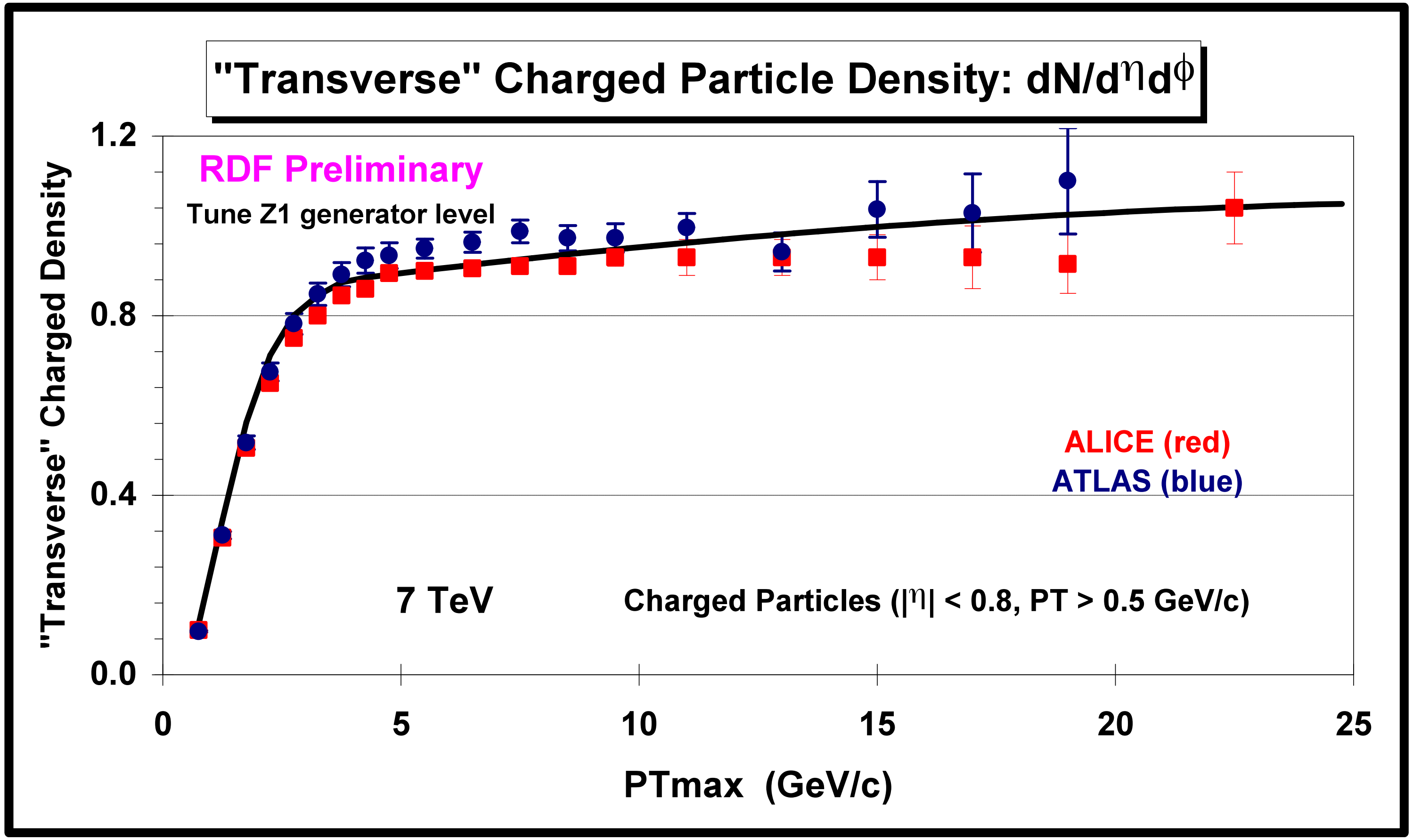




Tuning the Underlying Event

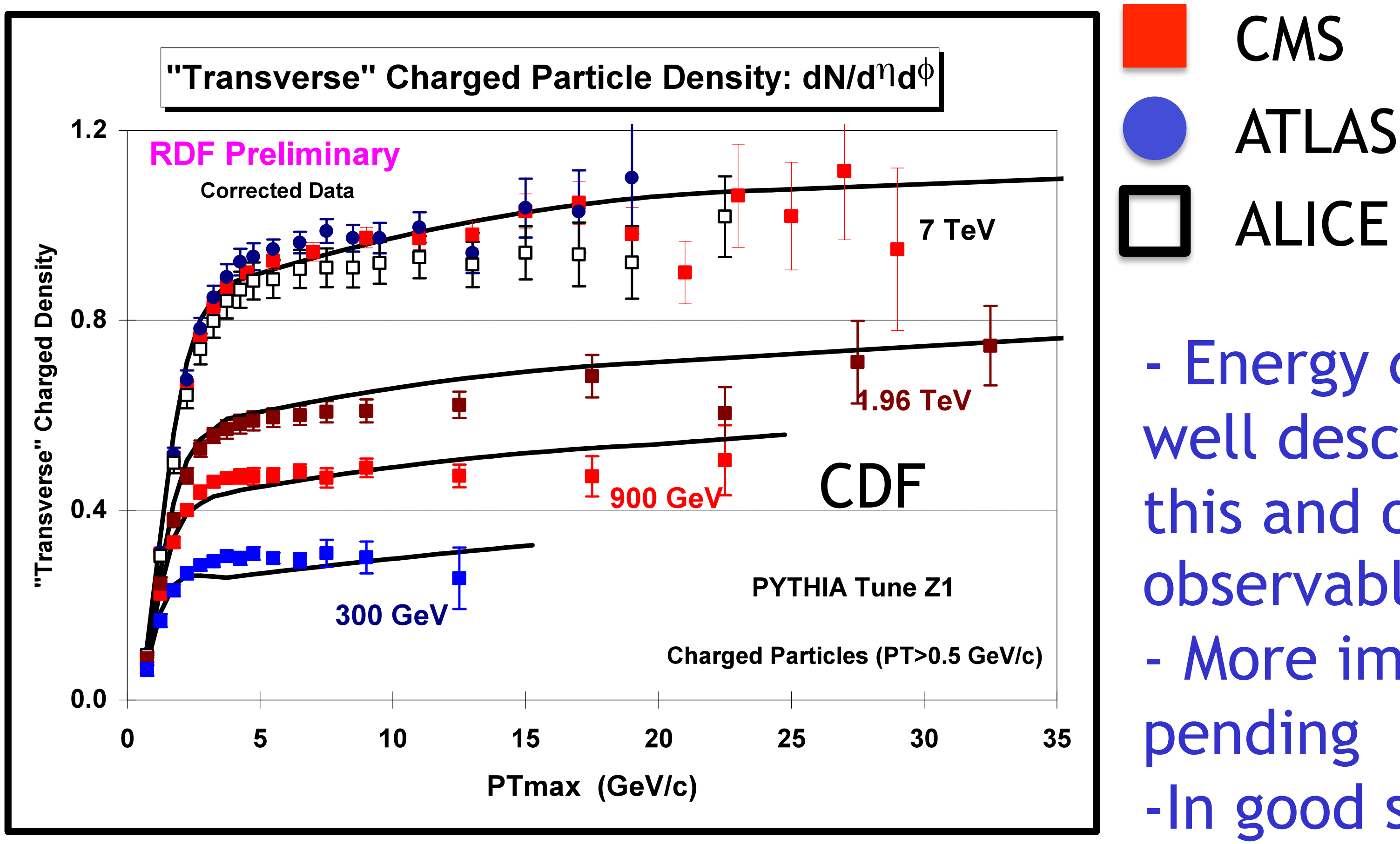
e.g. Tune Z1 of PYTHIA6 (ATLAS AMBT1 → Rick Field)
Principle changes are in energy dependence, PYTHIA version (p_T instead of virtuality ordered parton showers), PDFs (CTeQ5L), MPI p_T cut off and energy dependence

Example illustration …

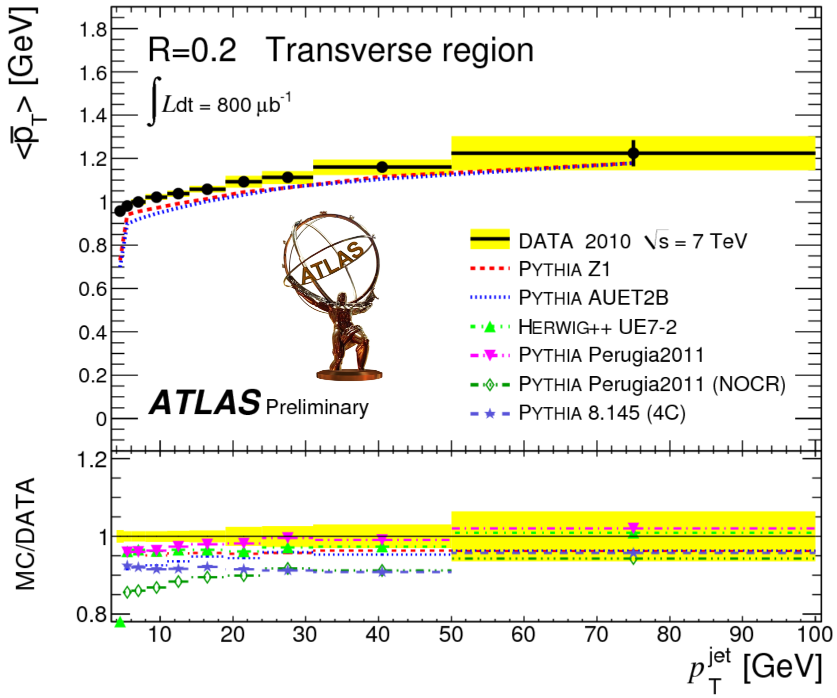


Energy Dependence of Z1 Tune

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

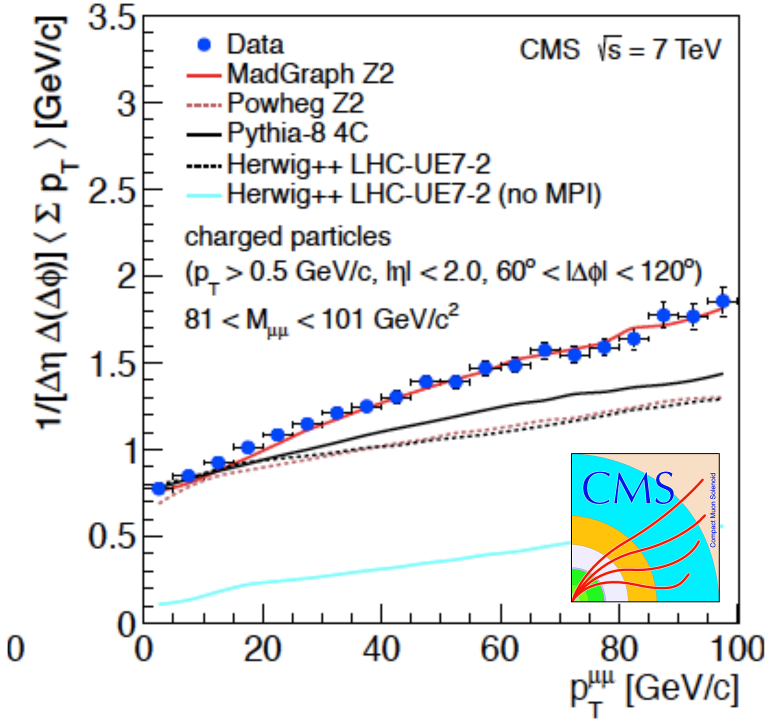


Asking the Underlying Event Question Differently: Higher p_T of towards region tag

Towards region determined by leading "track-jet" …

Extending to much higher pt

Z1 description remains good



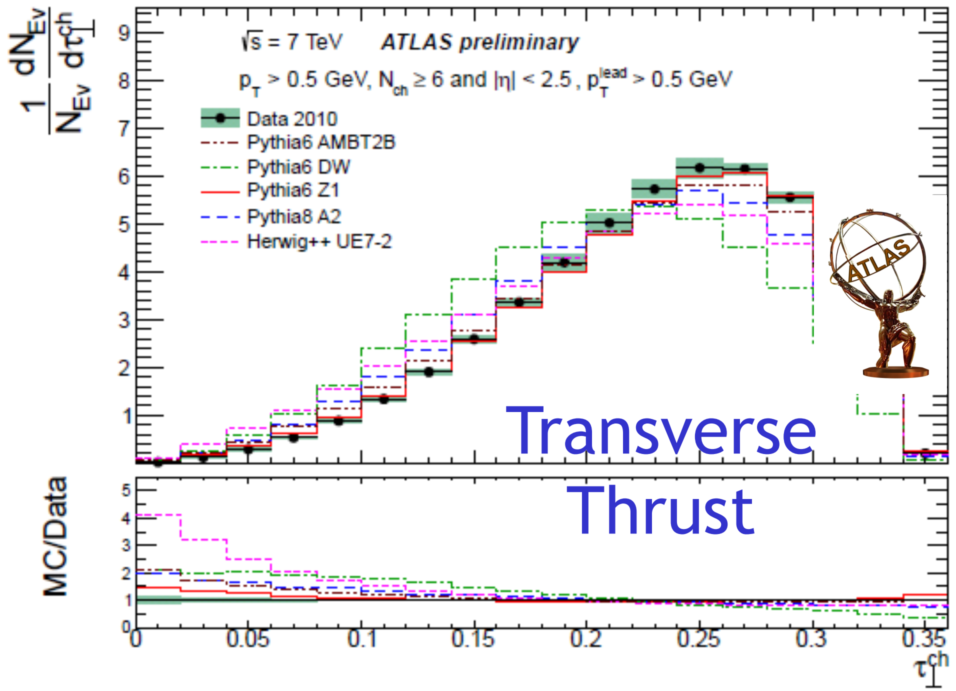
Towards region determined by $\mu^+\mu^-$ direction in Drell-Yan events

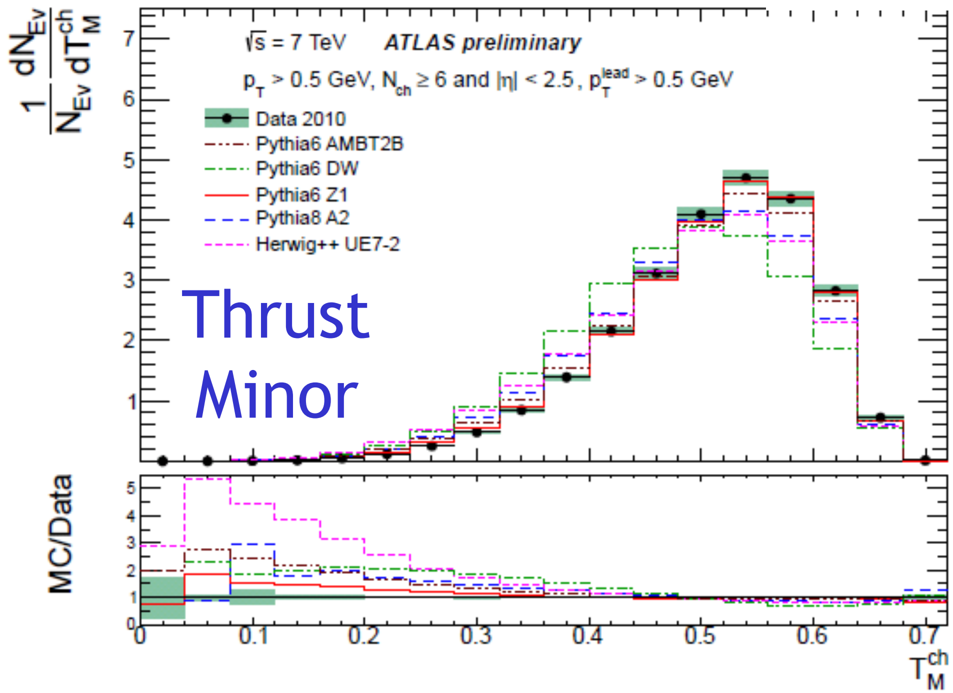
Madgraph (+Pythia) Z2 is slight update of Z1 → again successful

Many further similar examples

Complementary Ways of Characterising Events: Global Event Shapes

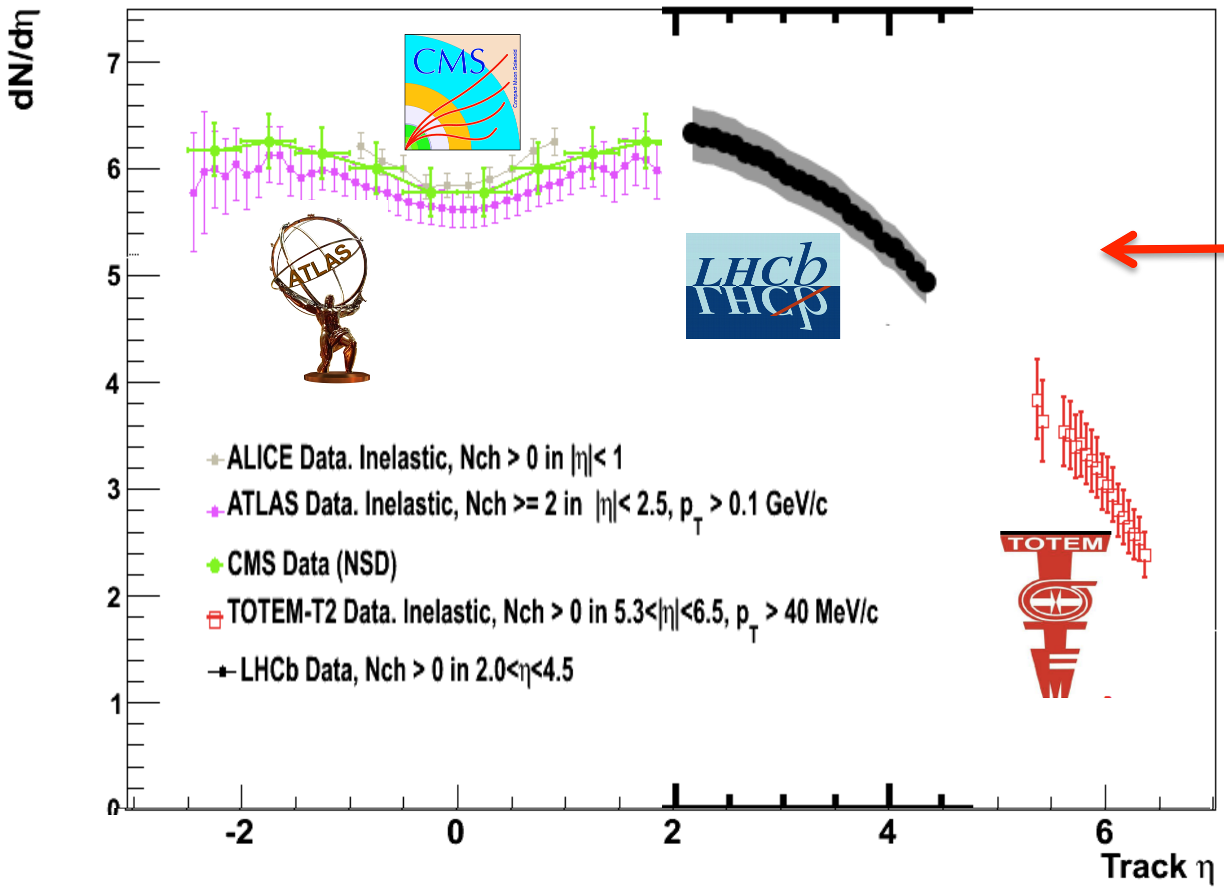
- Transverse thrust
- Thrust minor,
- Transverse Sphericity





also well described by Z1 tune …

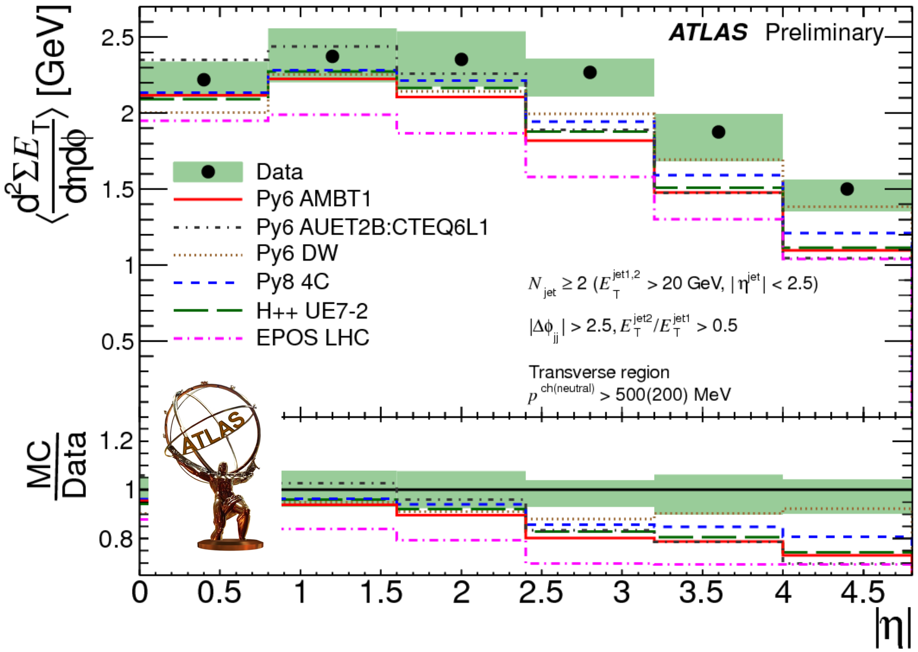
High Rapidity Coverage at LHC



Charged particle multiplicity measurements

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

Measurements in the Forward Region



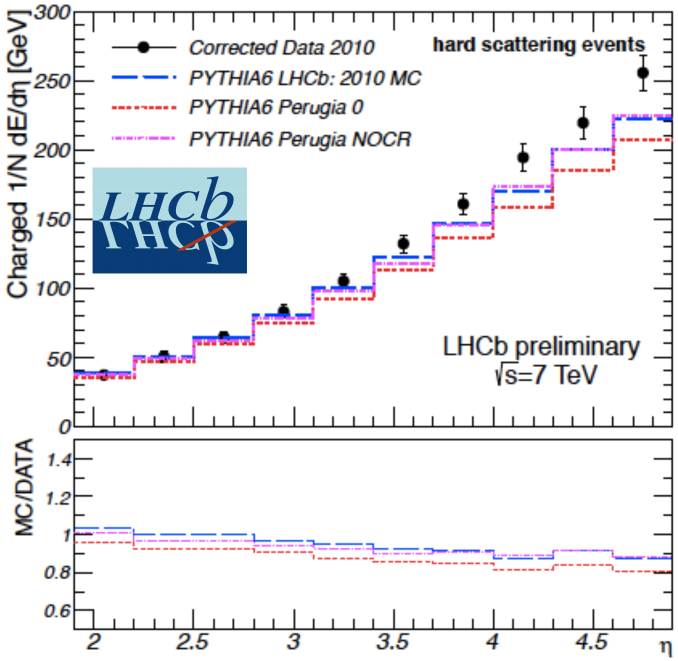
Transverse Energy Flow

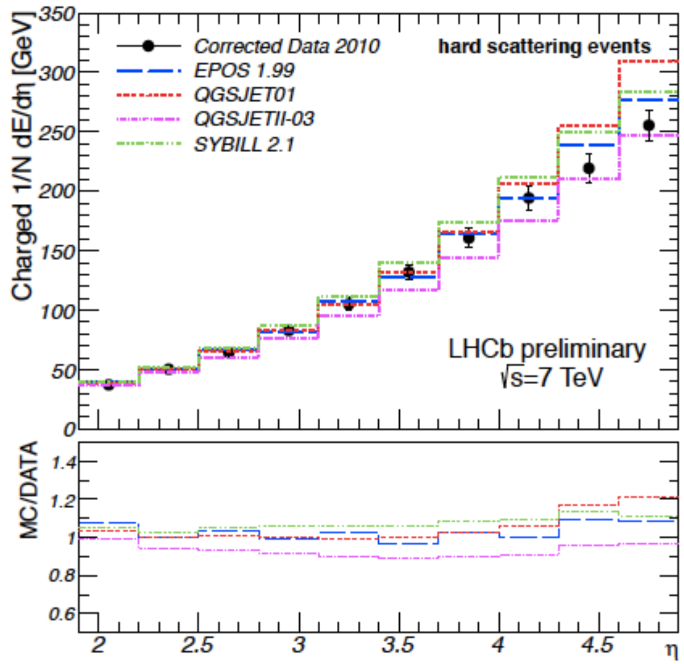
- Insufficient energy at large rapidity ($|\eta| < 4.8$) in standard MC models
- Sensitive to low x gluon PDF, underlying event and parton cascade dynamics

Energy Carried by Charged Particles

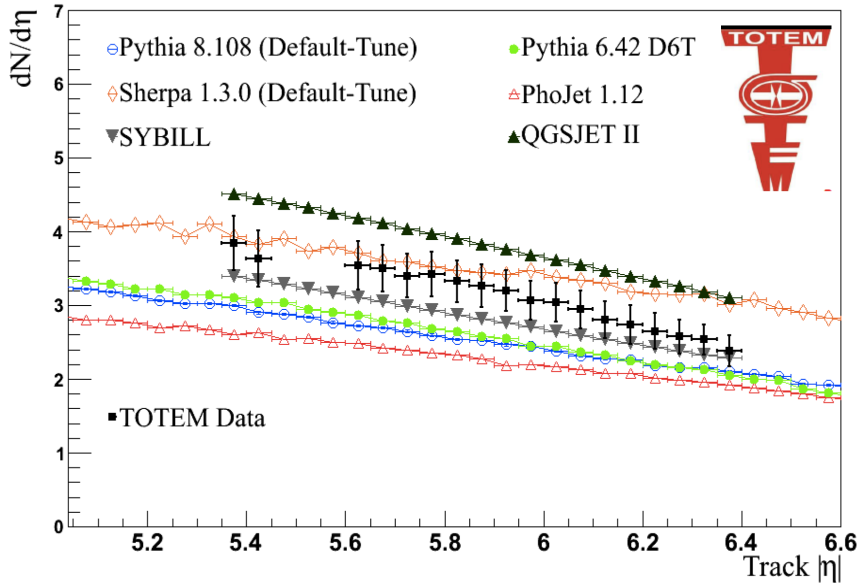
($2 < \eta < 4.8$)

- Dedicated cosmic air shower models better?





Measurements in Very Forward Region

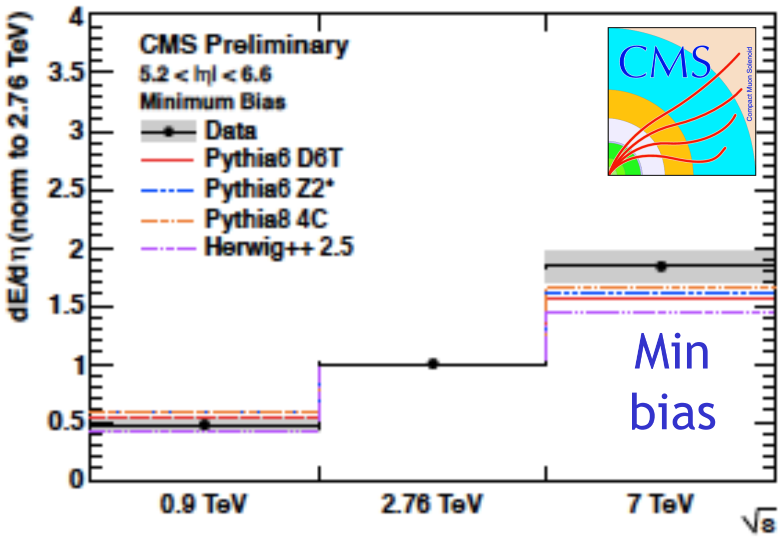


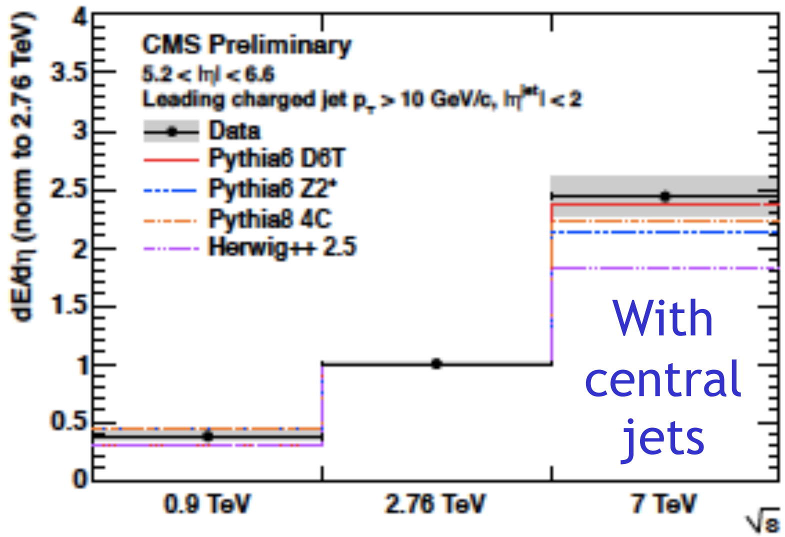
Charged Particle Multiplicity
$(5.4 < \eta < 6.4)$

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

… "challenging"

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

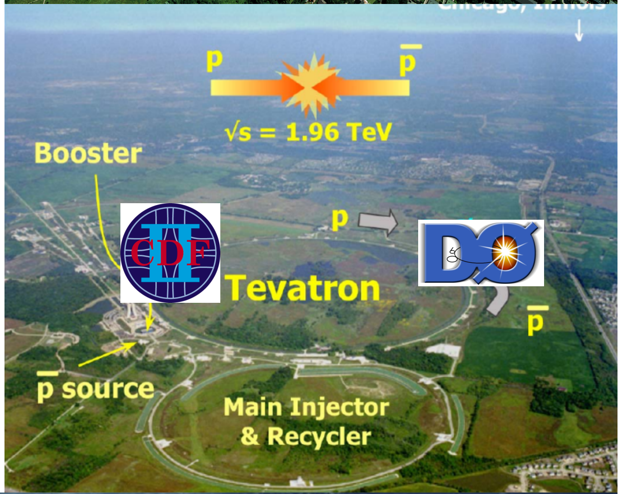




To summarise …

New (types of) data from LHC, together with what we are still learning at HERA and the Tevatron → growth spurt in measurements sensitive to soft and semi-hard strong interactions:

- Diffraction, underlying event, energy and particle flow featured here
- Correspondingly fast model development → reliable tools
- Essential for full understanding at TeV scale



Apologies for many excellent omitted results

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… and many more

To summarise …