Elastic and Diffractive Scattering at the LHC

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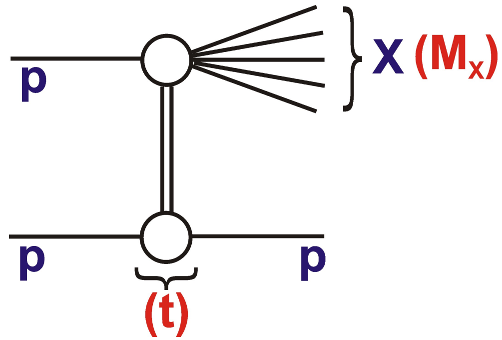
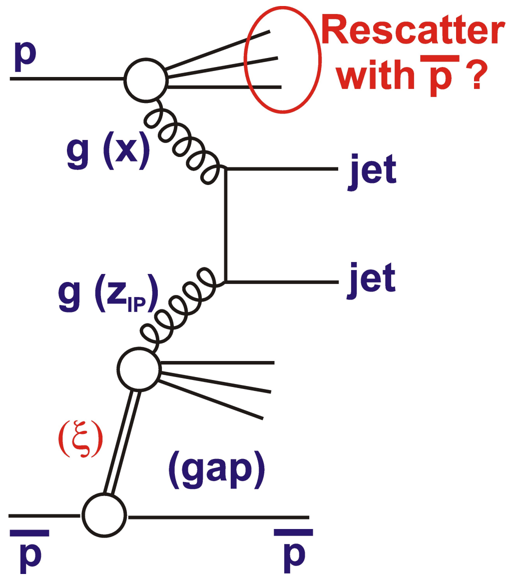
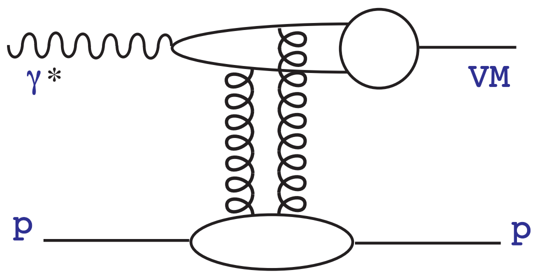
Heidelberg Seminar
8 December 2015

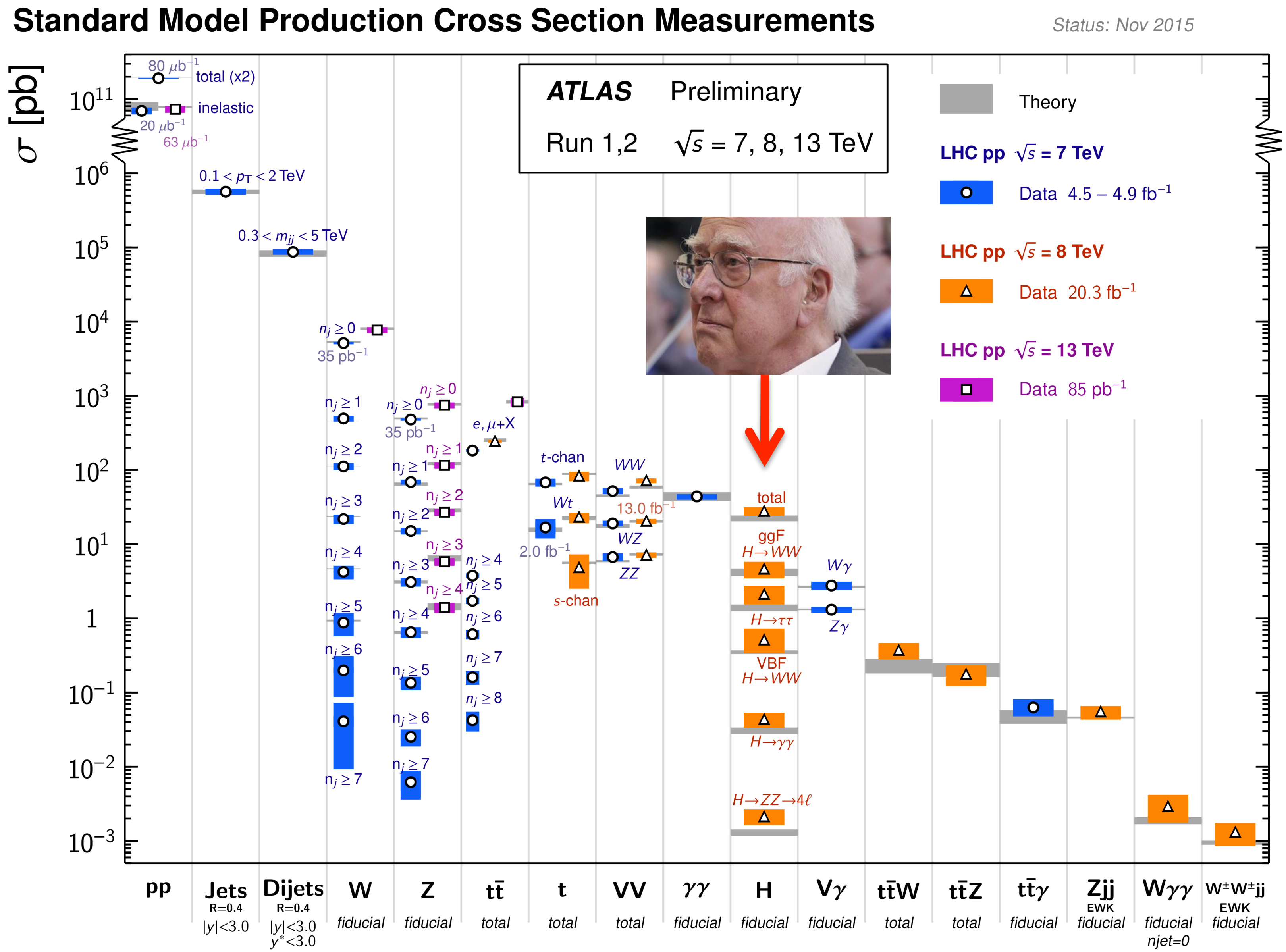
→ Elastic and Total Cross Sections
→ Soft Diffractive Dissociation
→ Hard Diffractive Dissociation
→ Ultra-peripheral Vector Mesons
→ [~~Central Exclusive Production~~]





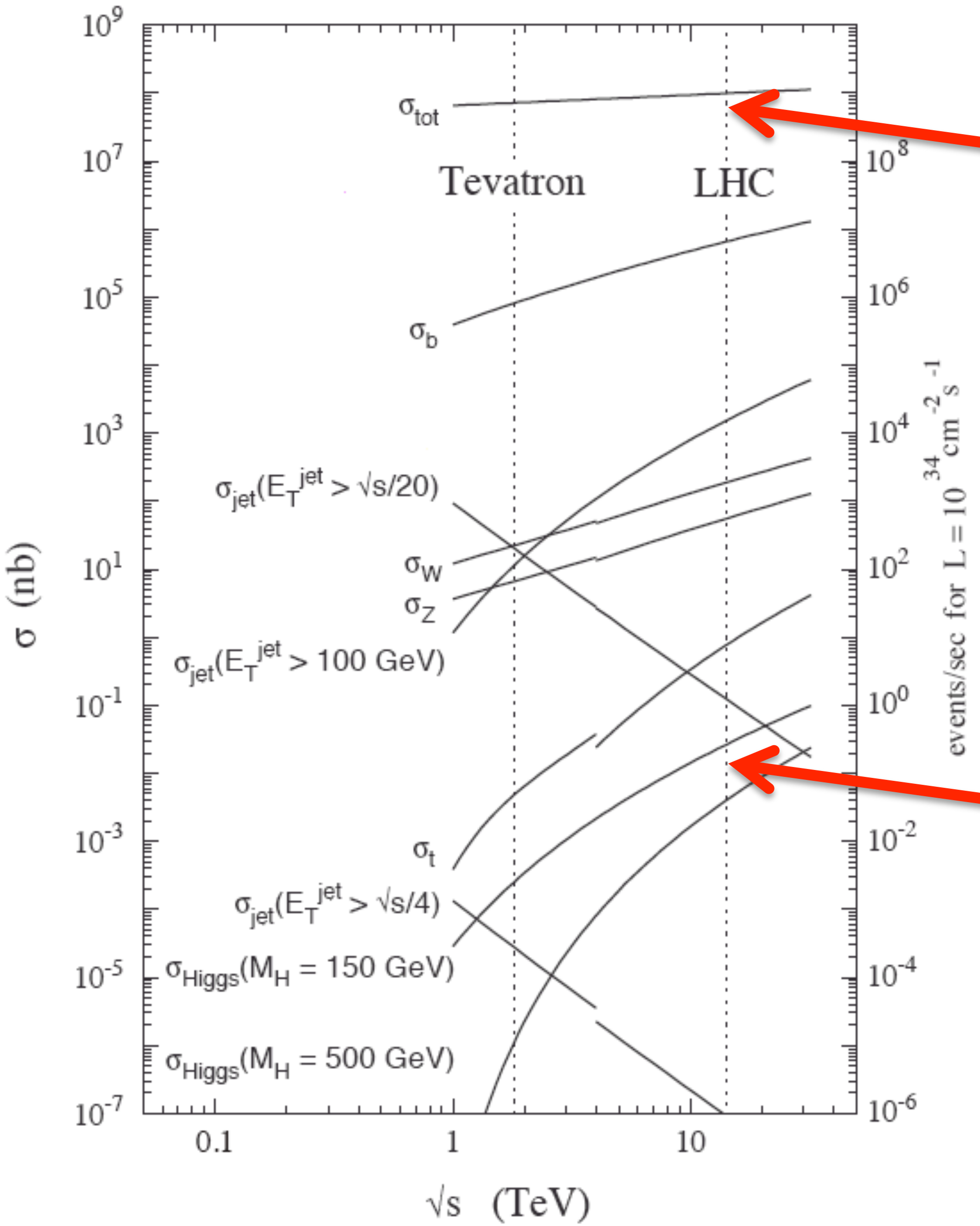


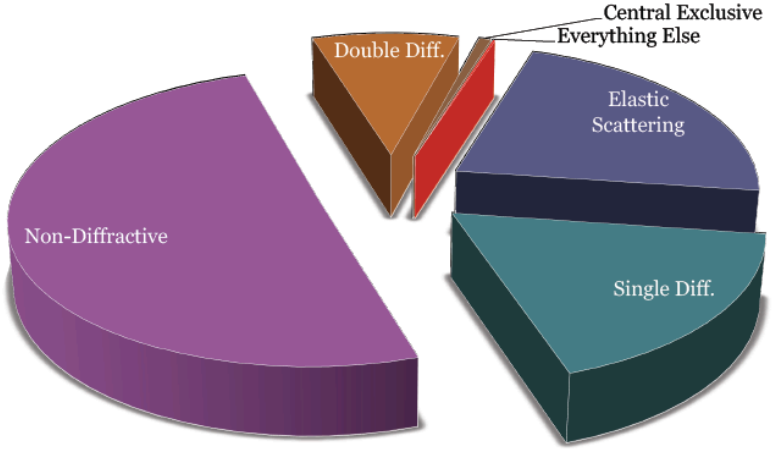
LHC: Exploring the ultra-rare at the Energy Frontier … eg ATLAS

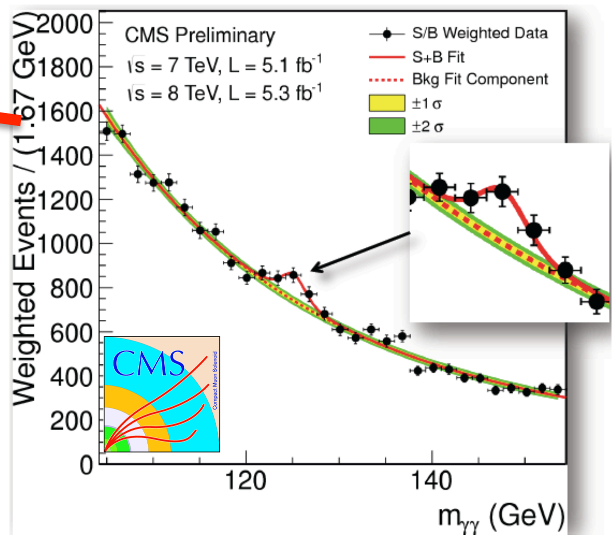


But what usually happens when hadrons Collide?

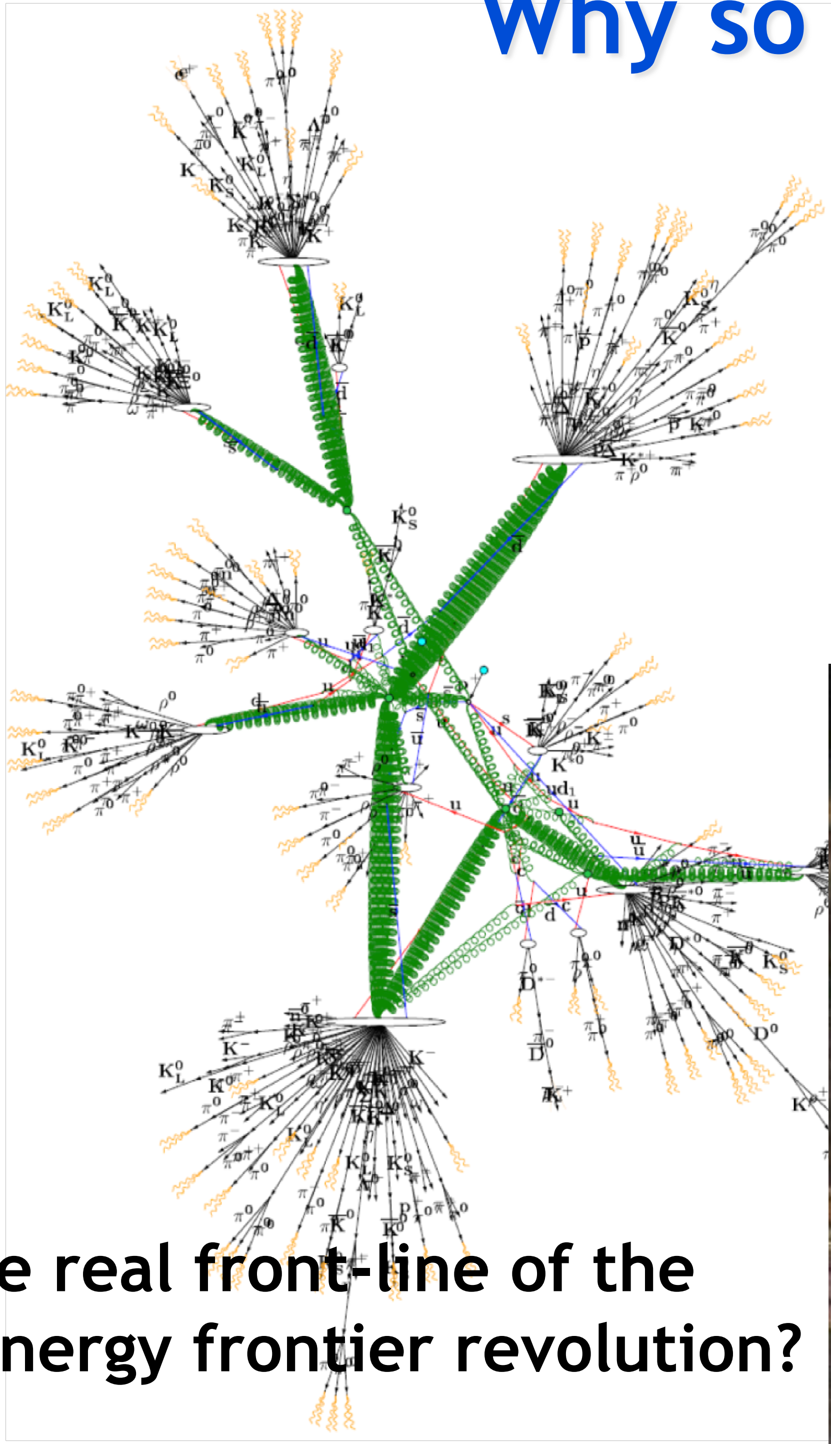
… calculating 10^{-1}/ 10^{0} processes is much harder than 10^{-10} processes ☹







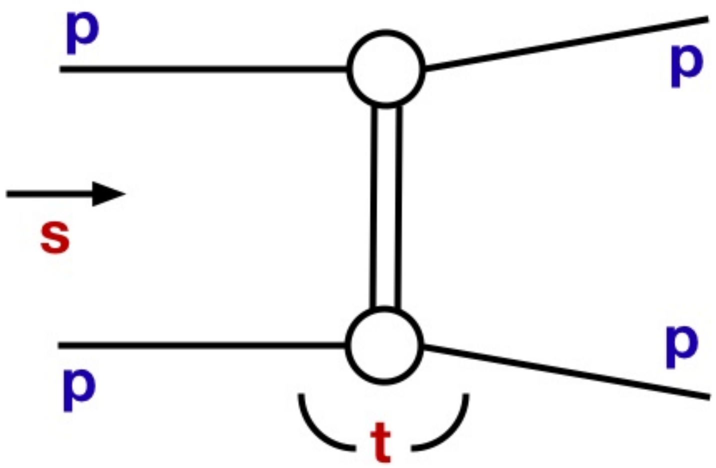
Why so Hard to Calculate?

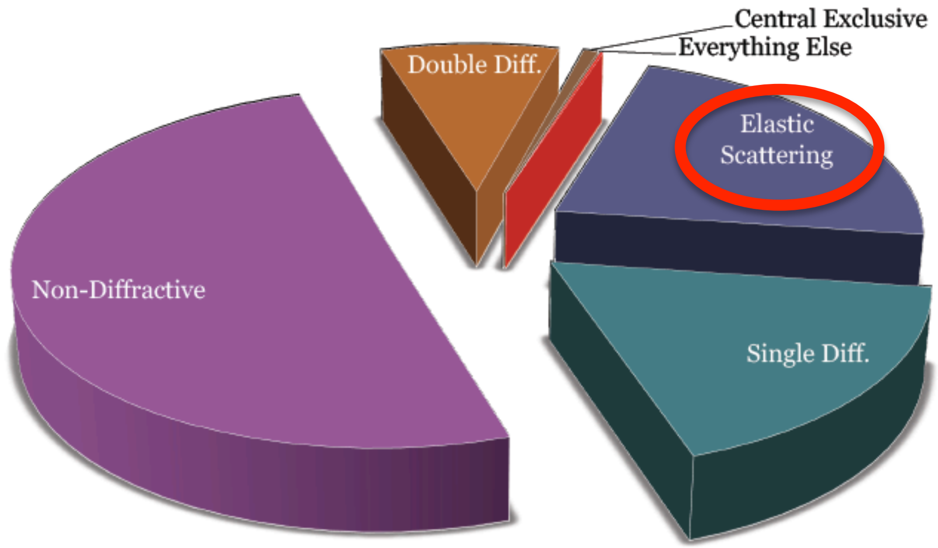


"minimum bias"
pp event in
PYTHIA8
at $\sqrt{s}$=7TeV,
visualised
using MCViz

... the real front-line of the
energy frontier revolution?

Something `Simple': Elastic Scattering

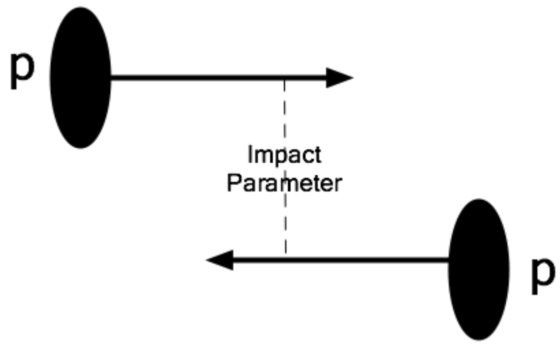




At fixed √s, 1 non –trivial variable
→ squared 4-momentum transfer, t

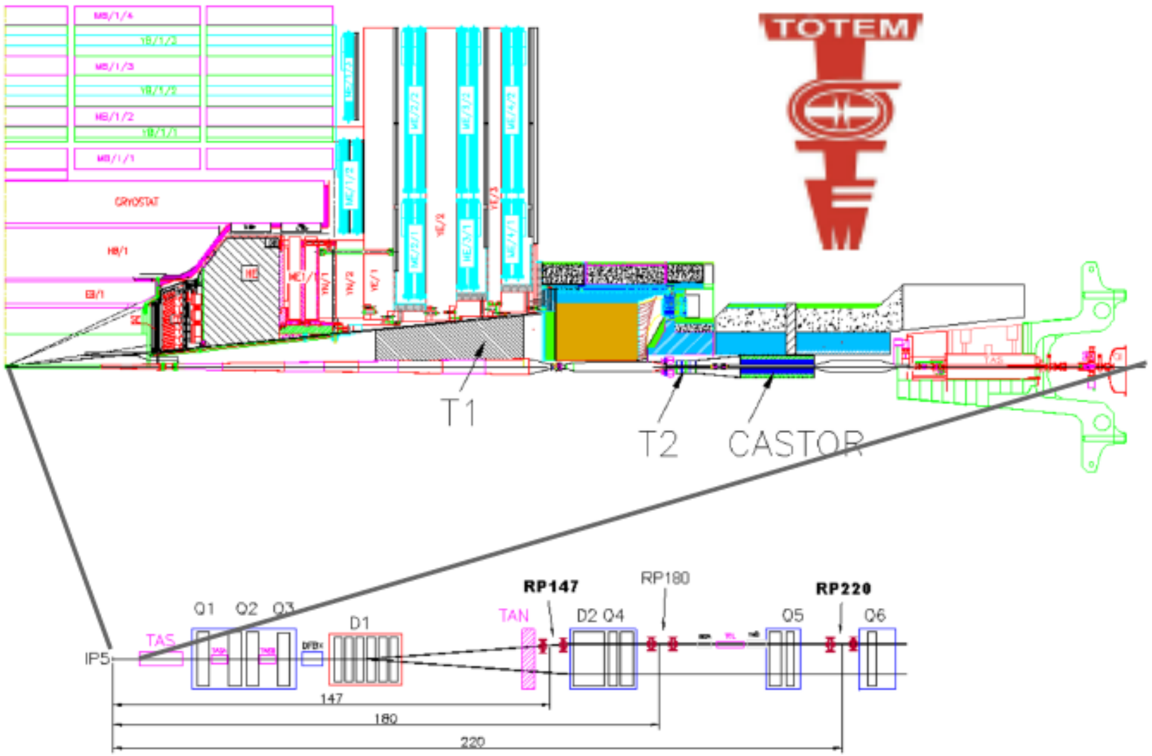
Typically |t| << 1 GeV^2: non-perturbative

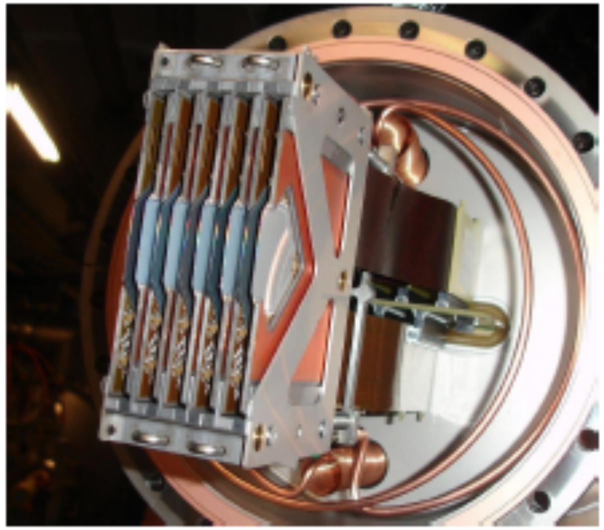
At fixed s: $$\frac{d\sigma}{dt} = \left.\frac{d\sigma}{dt}\right|_{t=0} e^{Bt}$$



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

Forward Proton Spectrometers

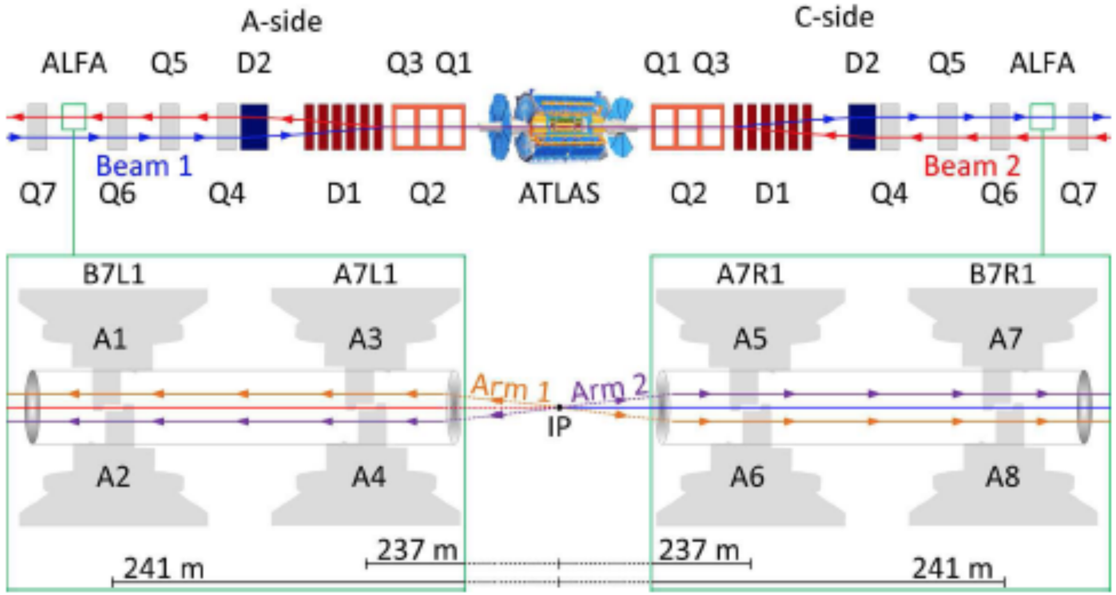




‘Roman pot’ vacuum-sealed insertions to beampipe, well downstream of IP.

→Usually deployed in dedicated (high β*) runs

→ Can run independently of ATLAS / CMS or with common DAQ.

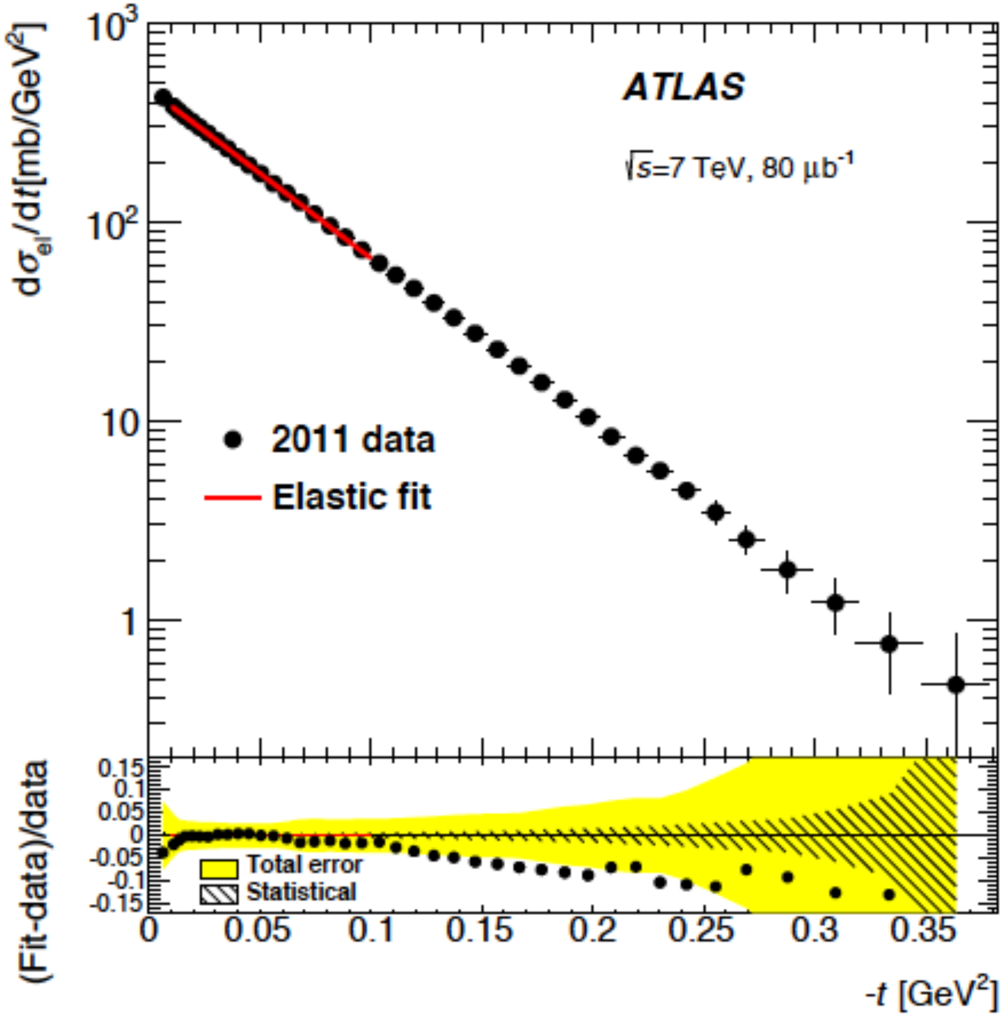


Elastic Scattering at √s=7 TeV

Precise t dependence of elastic (pp → pp) cross section over 'bulk' range of |t| at LHC

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

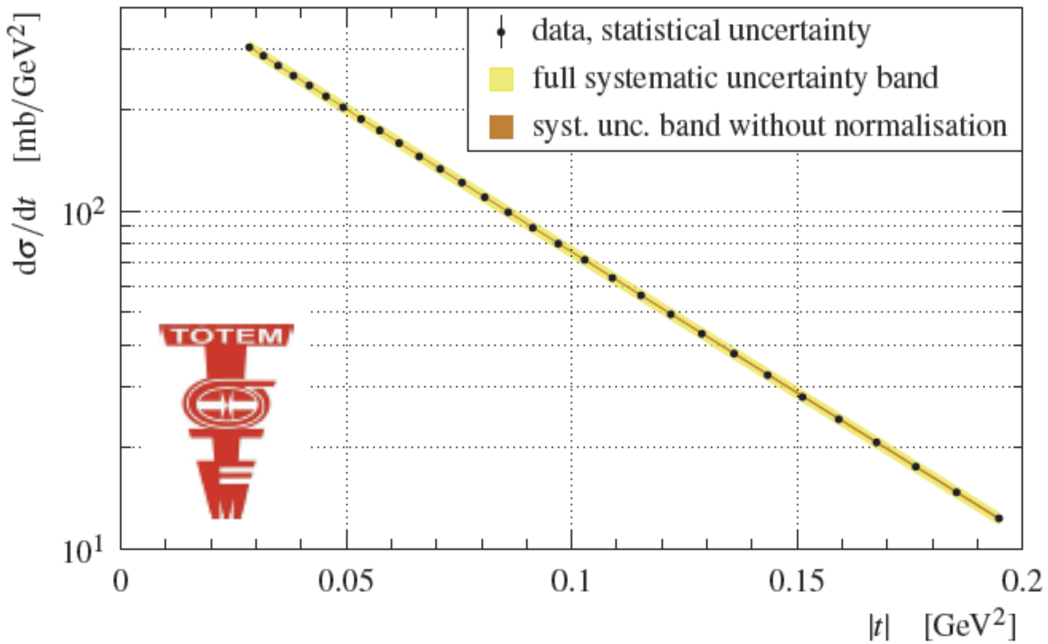
B=19.89±0.27 GeV^{-2} (TOTEM)
B=19.73±0.24 GeV^{-2} (ALFA)



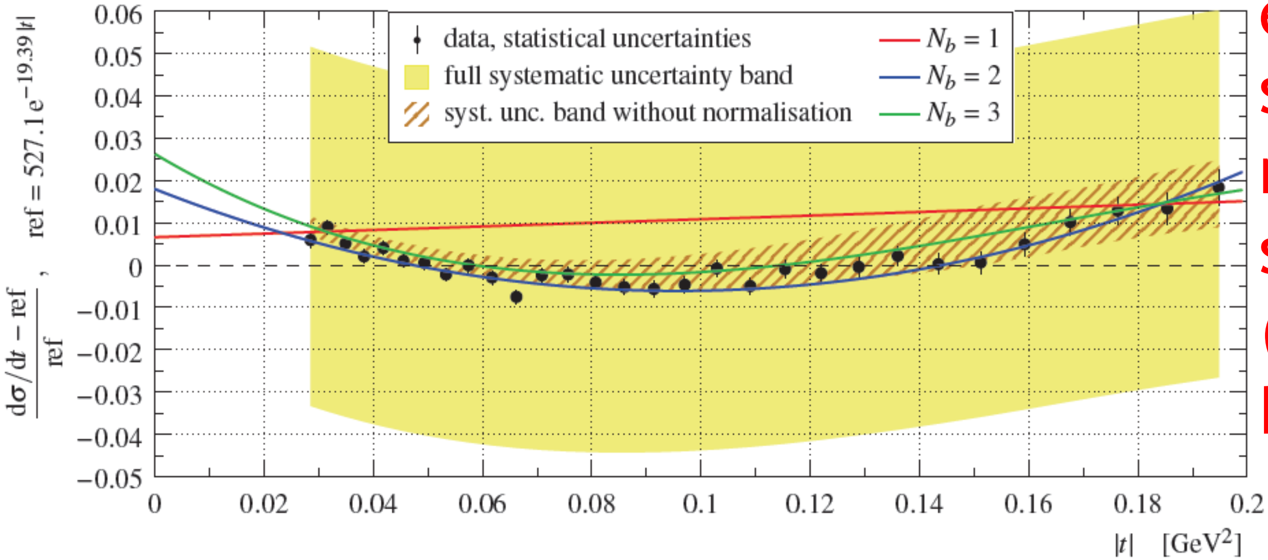
[excluding lowest |t| →
Influence of Coulomb (rather than hadronic) scattering]

- B increases compared with Tevatron ("shrinkage" with energy)
… i.e. mean impact parameter increases with √s
(longer-lived fluctuations developing larger transverse size)

Elastic Scattering at √s=8 TeV



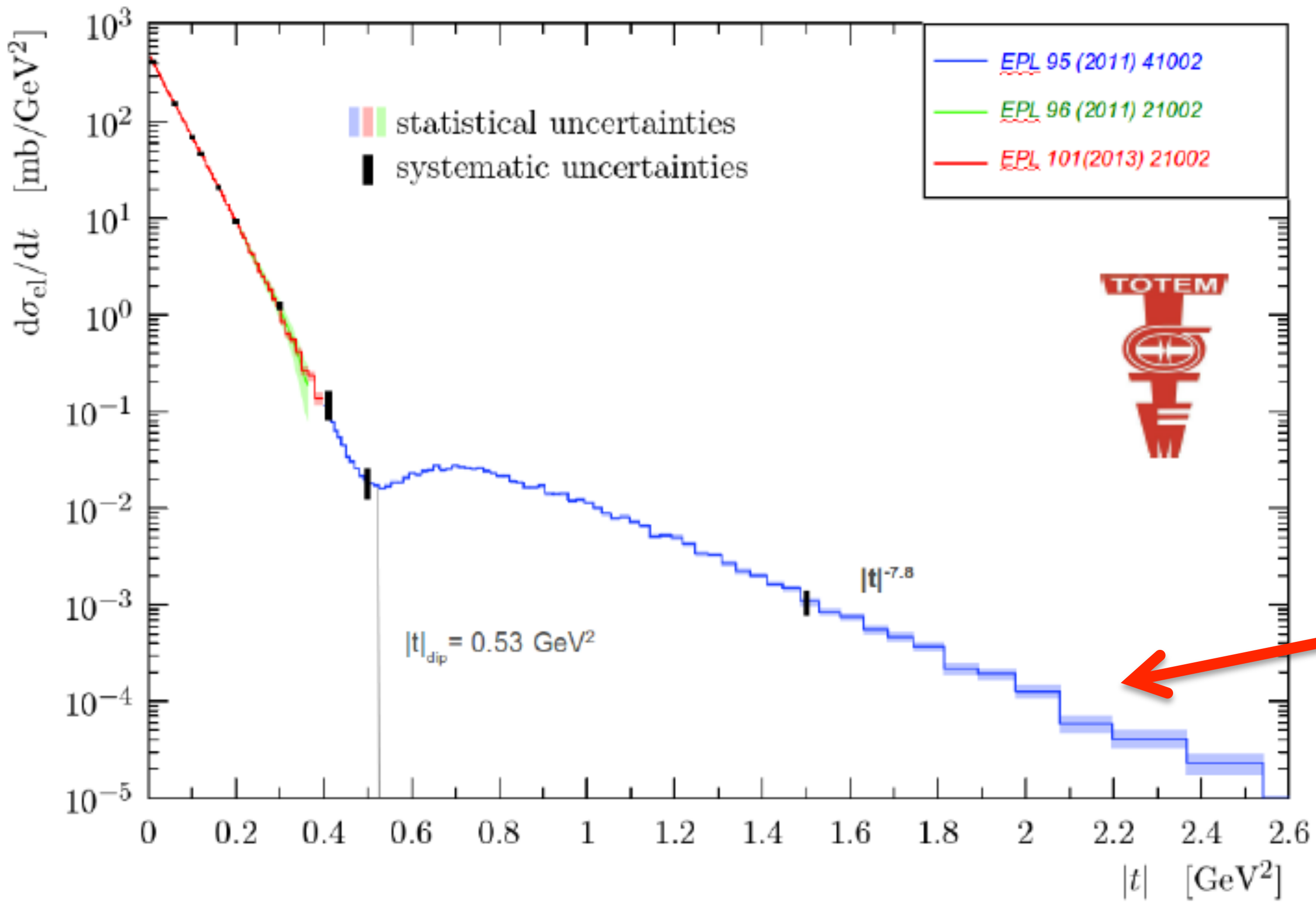
7 Million events (β^*=90m, 2012) … single exponential slope rejected at 7.2σ level

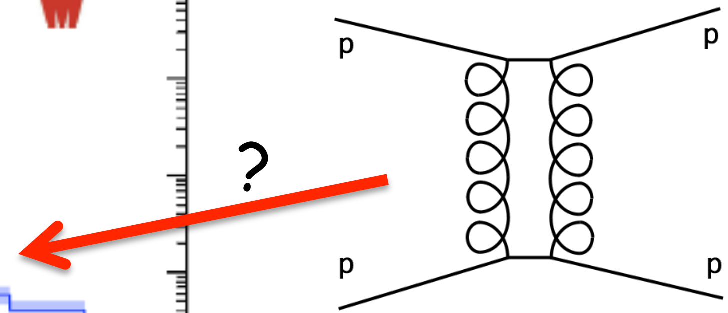


… implies that low |t| (non-perturbative) elastic scattering via strong interaction is not mediated by a single exchange (like a pomeron Regge Pole).

→Multiple exchanges/ absorptive corrections

Elastic Scattering at perturbative |t|

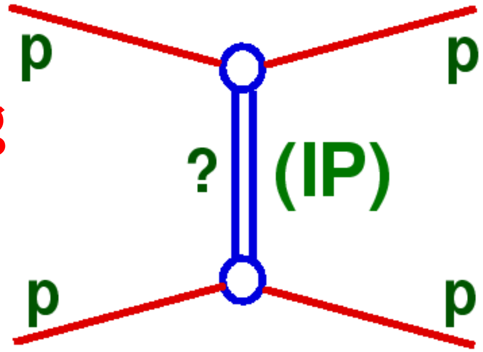


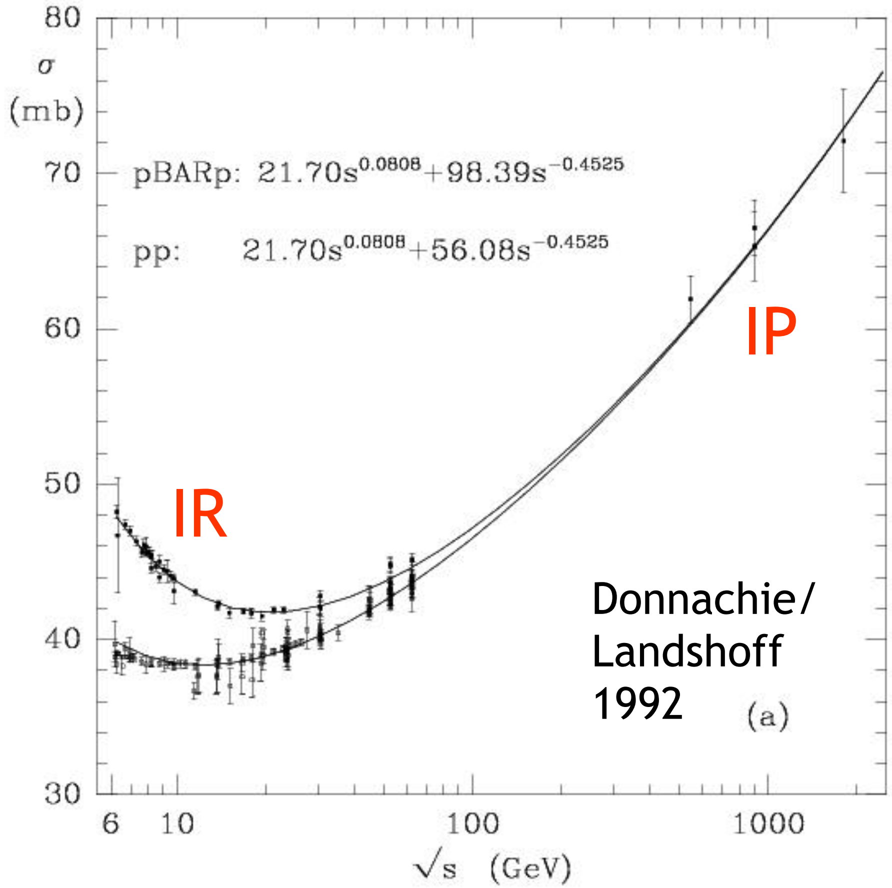


- Dip pos'n decreases compared with Tevatron → shrinkage
- Larger |t| perturbative region consistent with power law ~t^{-8}
- No evidence for further secondary structure … suggests a single perturbative mechanism (2 or 3 g?). No models describe detail.
- 2015, already ~10^9 events, extending to |t| ~ 3.5 GeV^2

Vacuum Exchange, Elastic & Total Xsecs

What governs elastic scattering at high energy and small |t|?





Historically, 'pomeron trajectory'

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

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

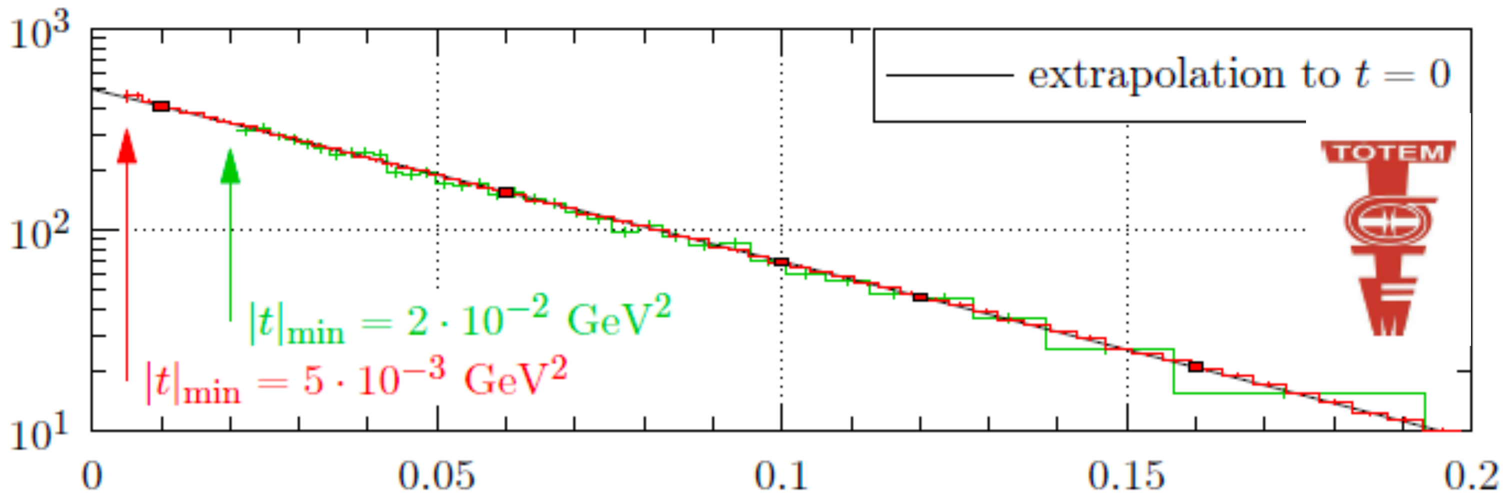
Elastic scattering closely related to total x-sec via optical theorem …

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

Optical Theorem: Relating elastic & total cross sections

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

[ρ~0.1 = phase of Coulomb-Nuclear interference at t=0]

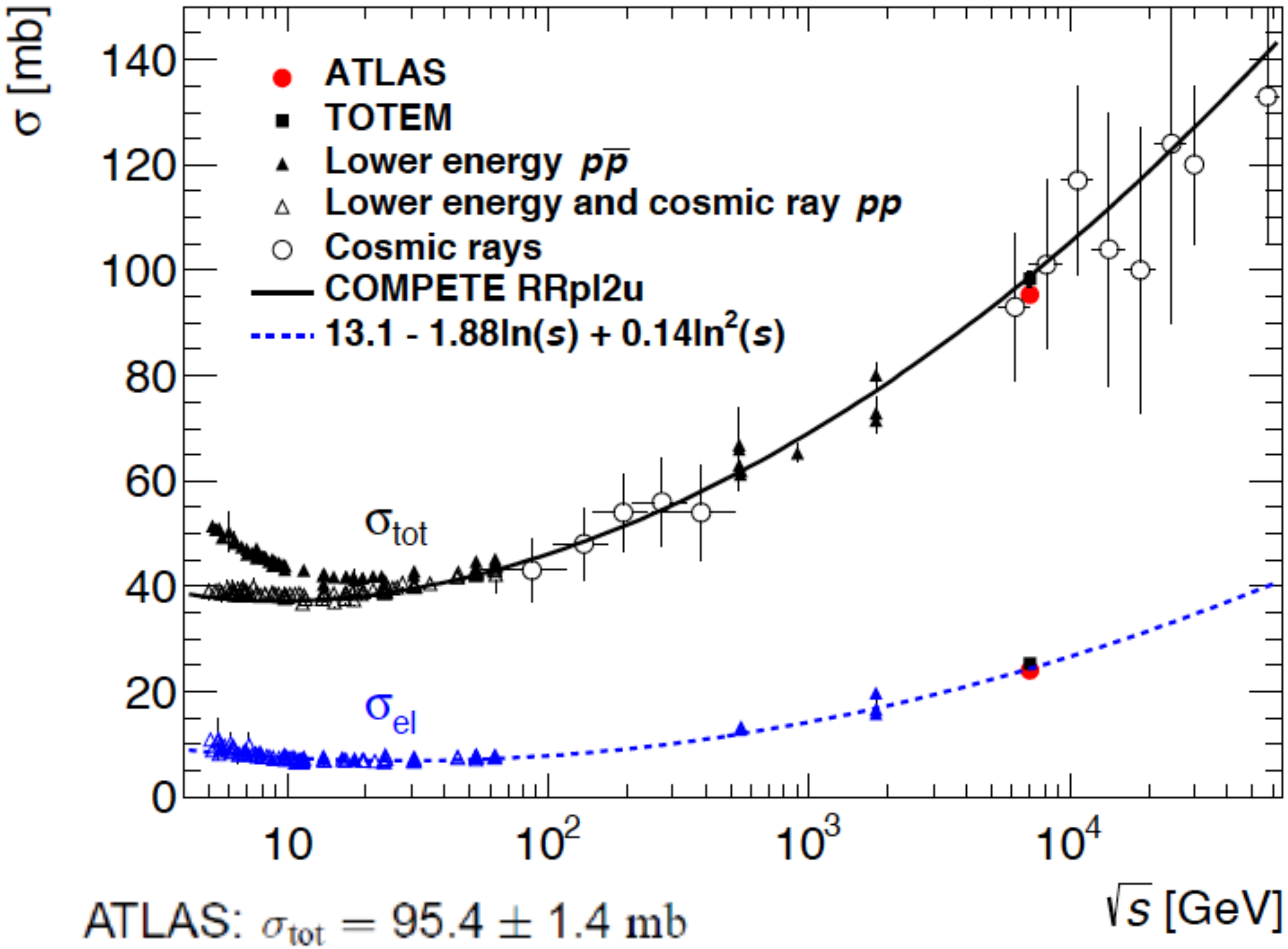


~ 10% extrapolation to t=0

- Luminosity measurement from Van der Meer scans
- ρ from previous data

… one of several related evaluations of σ_{tot} …

Total (and Elastic) Cross Section



ATLAS: $\sigma_{\text{tot}} = 95.4 \pm 1.4$ mb

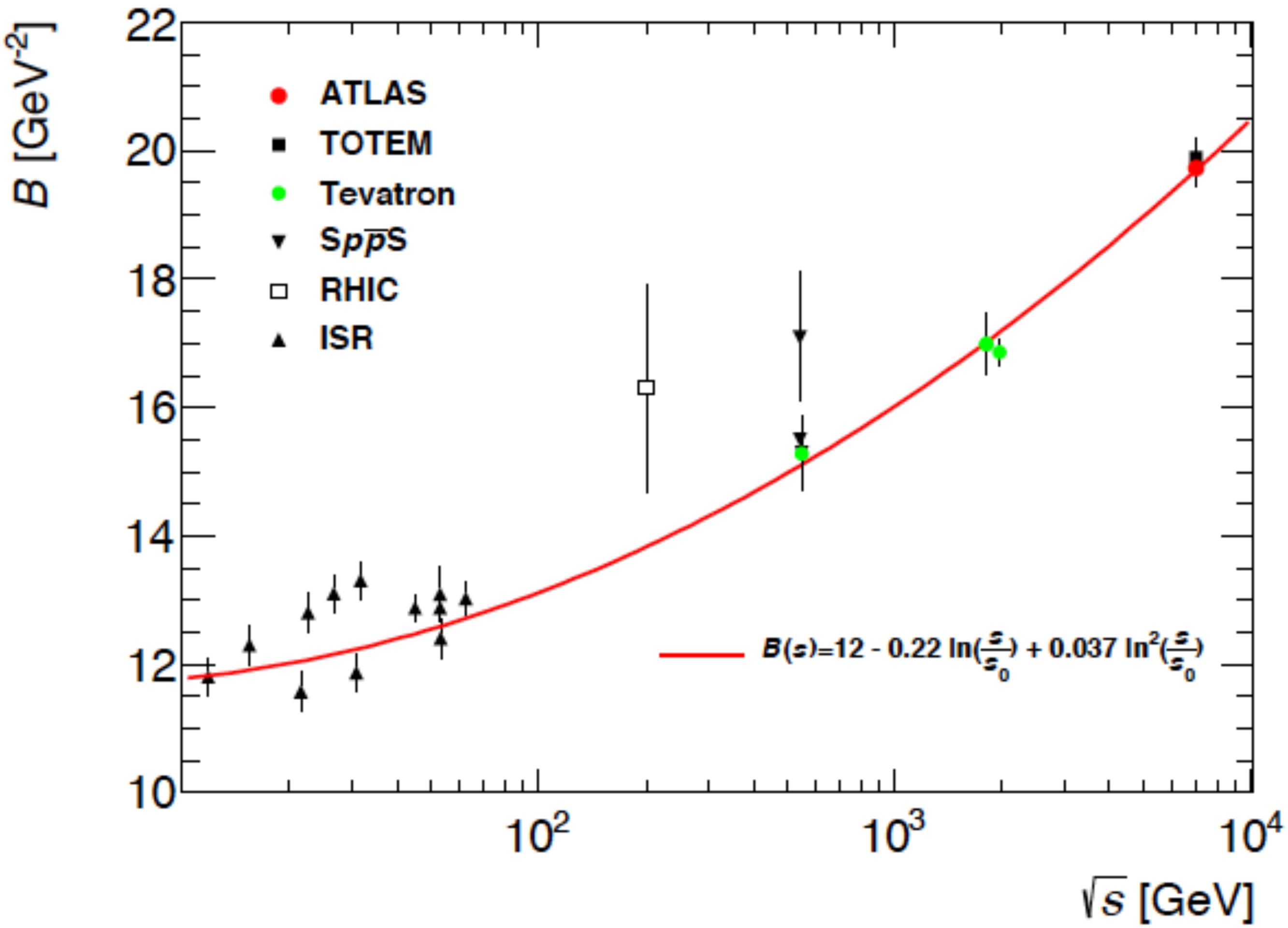
TOTEM: $\sigma_{\text{tot}} = 98.6 \pm 2.2$ mb

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

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

- Now published at both $\sqrt{s}$=7 TeV and $\sqrt{s}$=8 TeV by TOTEM
- Extractions from cosmic ray data extend to $\sqrt{s}$ ~50 TeV !

√s dependence of t Slopes and α_{IP}'



Fixed s:

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

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

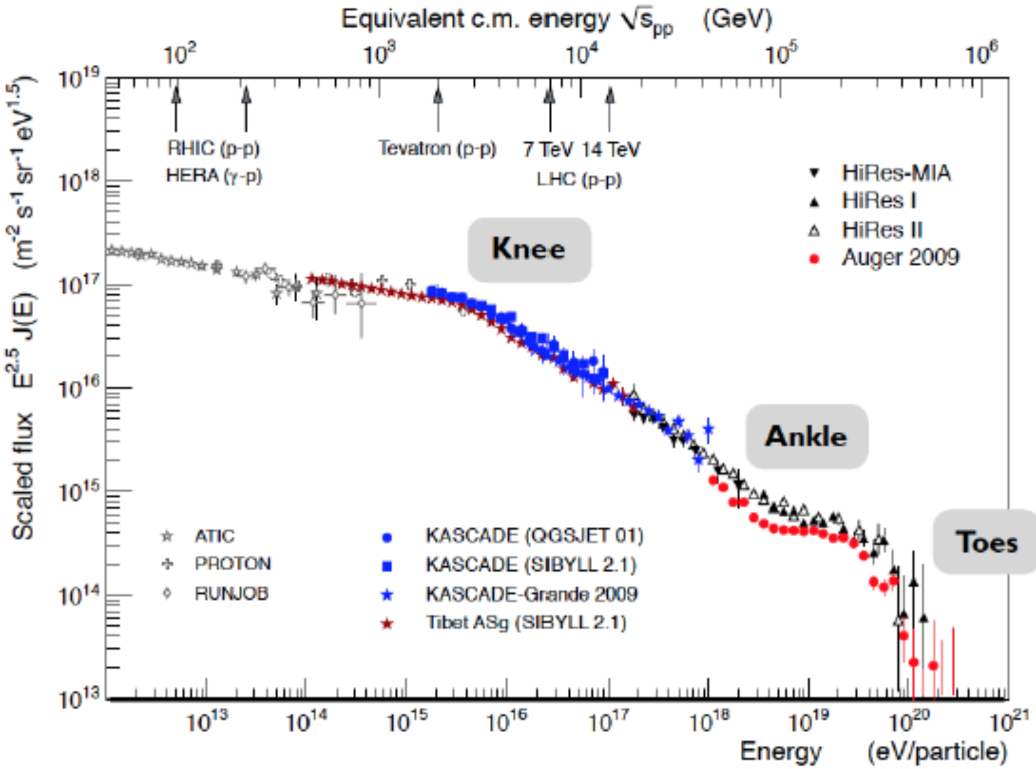
- Comparing lower energy with LHC data suggests

α' larger than 0.25 GeV^{-2}

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

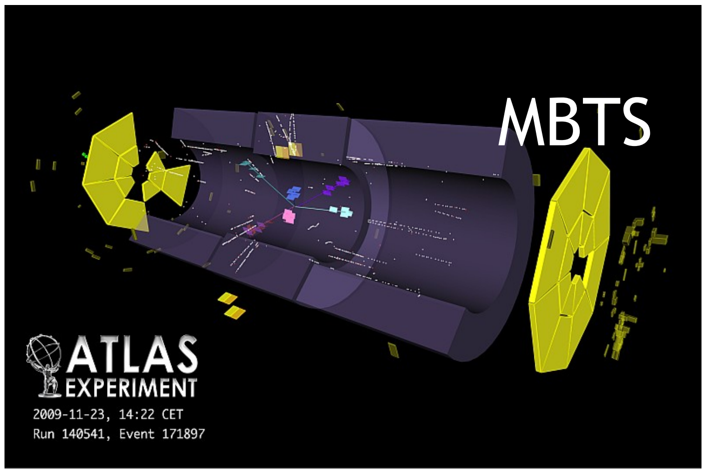
Total Inelastic Cross Section

- Crucial quantity for understanding cosmic ray air showers
- Important ingredient for modelling pile-up (and lumi) at LHC

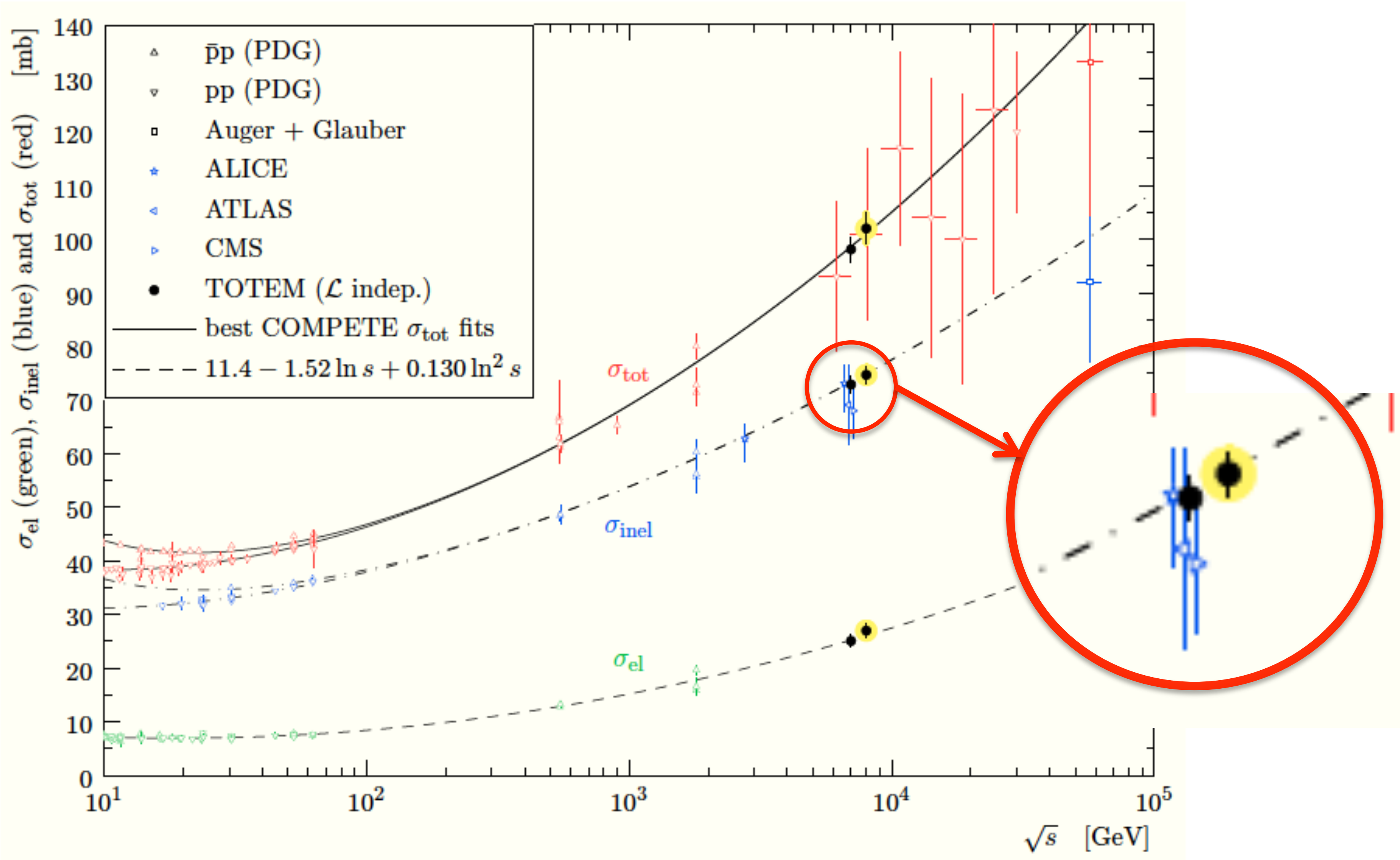


Can be measured either from σ_{tot} - σ_{el} or directly by counting (almost) “all” events with a minimum bias trigger

… eg ATLAS Minimum Bias Trigger Scintillators (MBTS) see 90-95% of all inelastic events



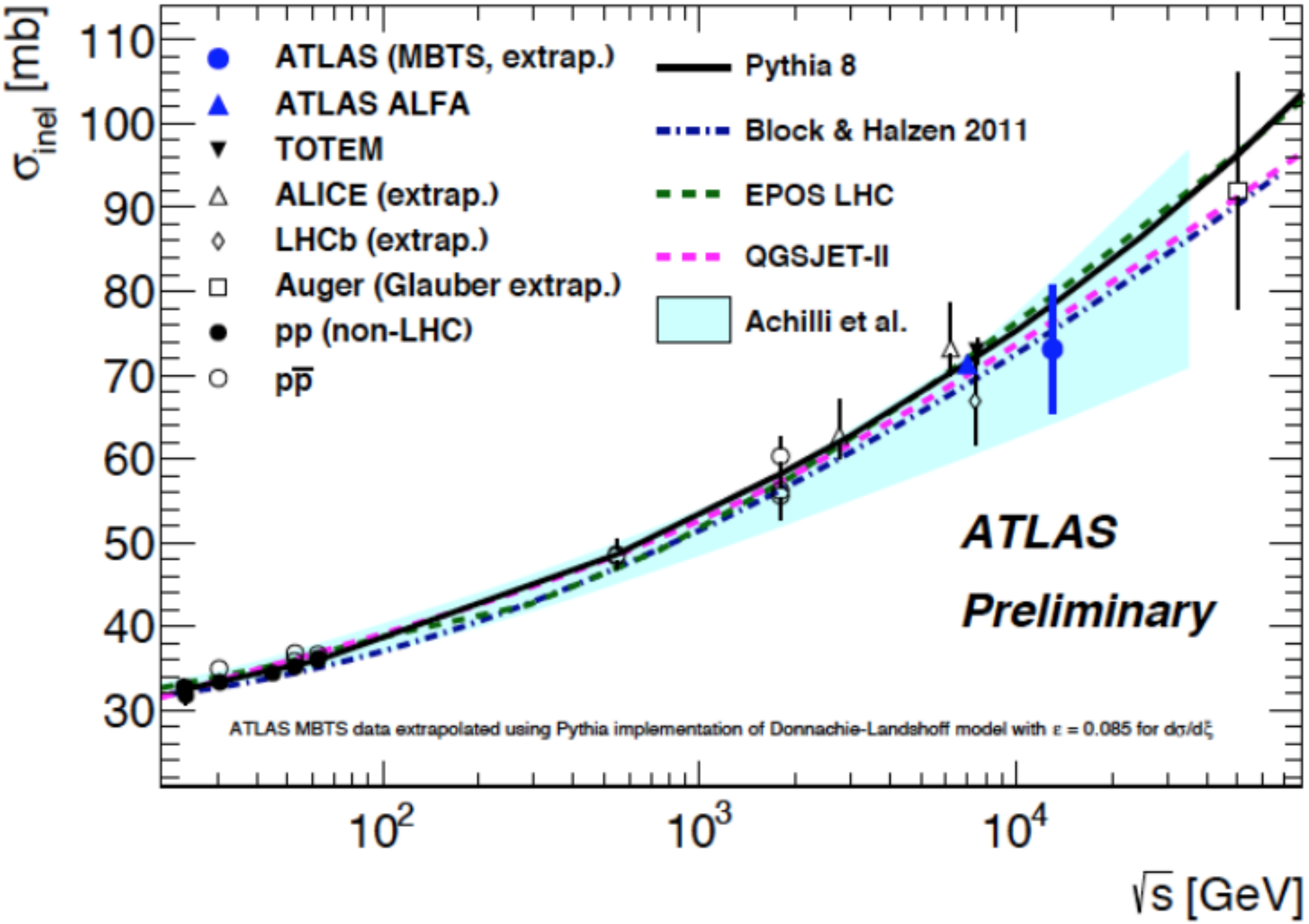
Total Inelastic Cross Section



TOTEM: $\sigma_{inel} = \sigma_{tot} - \sigma_{el}$ c.f. e.g. ATLAS σ_{inel} from counting visible events, extrapolating into invisible region

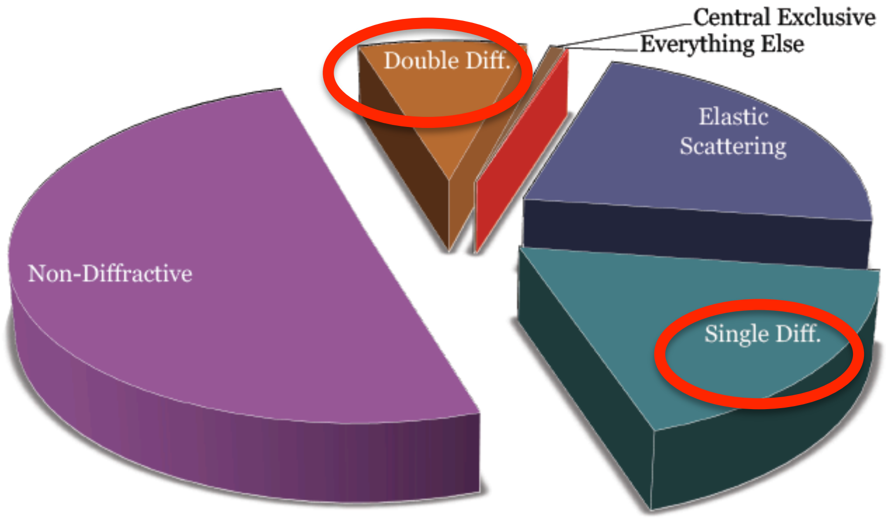
… good agreement – direct measurements tend to be lower?...

Inelastic Cross Section at √s = 13 TeV

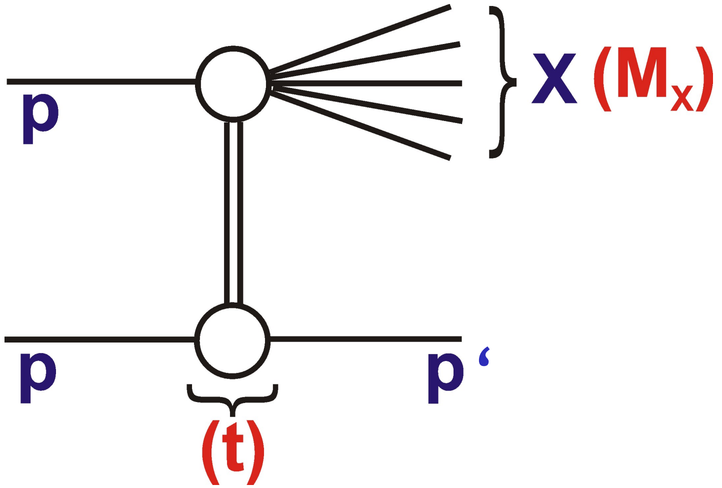


Uncertainty almost entirely from luminosity … will decrease …

Inelastic Diffraction



Single diffractive dissociation

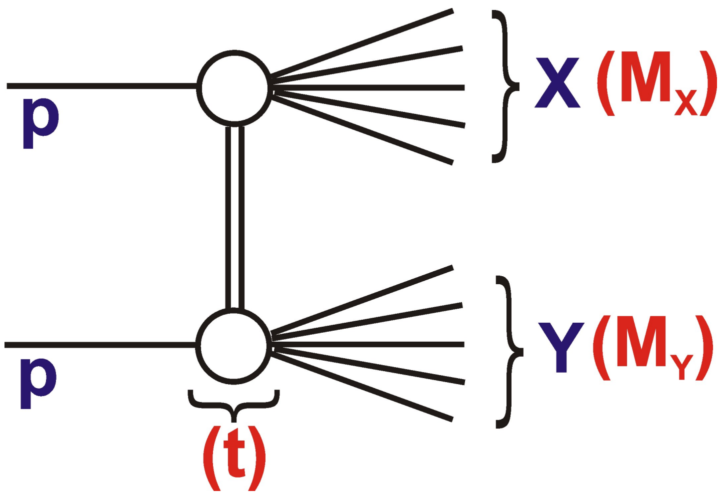


Additional kinematic variables:

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

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

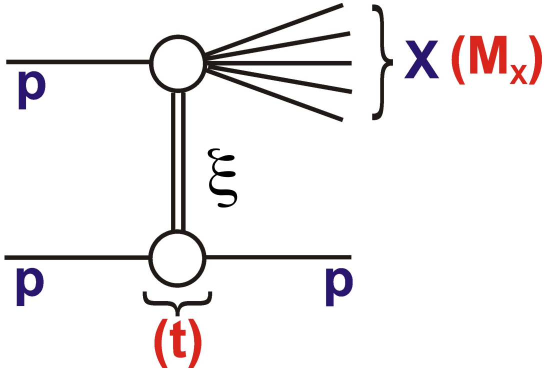
Double diffractive dissociation



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

… very poorly predicted pre-LHC

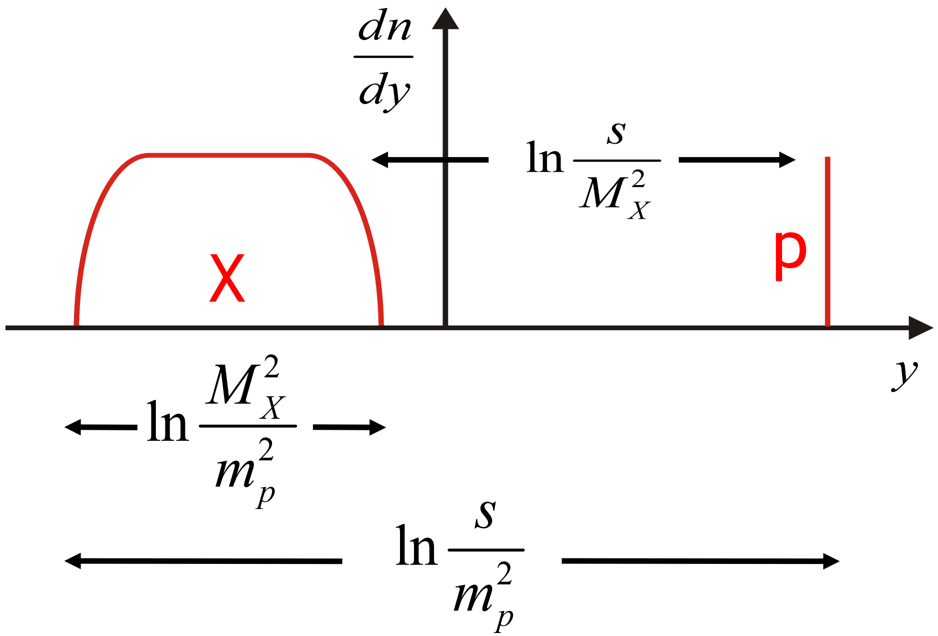
Soft Diffraction: ξ and Gap-size Dynamics



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

i.e. approx: $$\frac{d\sigma}{d\xi} \propto \frac{1}{\xi}$$ $$[\alpha(t) = \alpha(0) + \alpha' t]$$

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



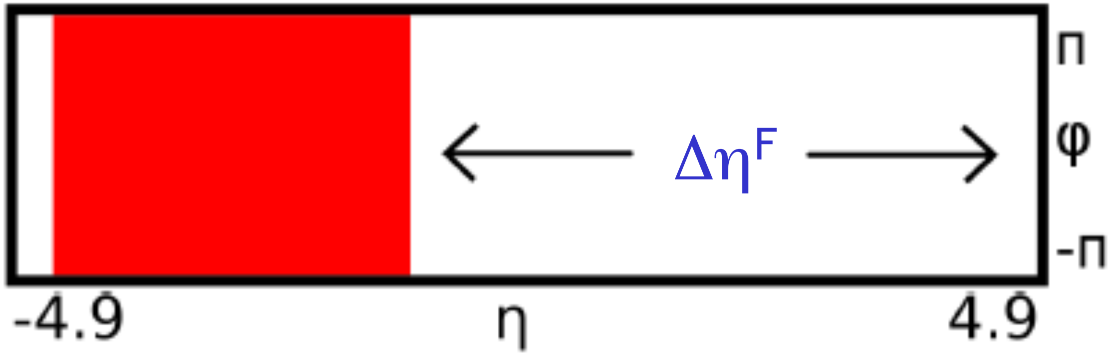
Up to event-by-event hadronisation fluctuations, ξ variable predictable from empty rapidity regions

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

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

Differential rapidity gap cross-sections

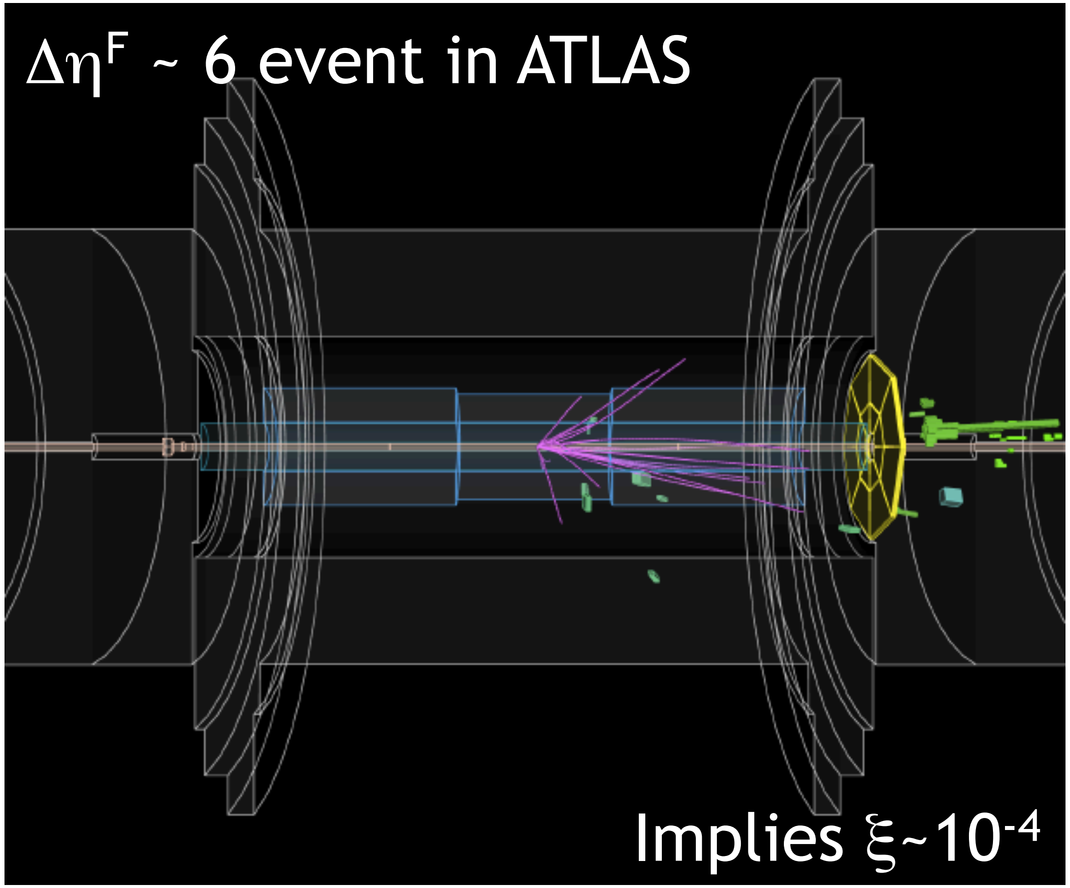
Inclusive cross sections differential in size of empty rapidity region within η range to which central detectors are sensitive



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

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

… no statement on $\eta >\sim 4.9$

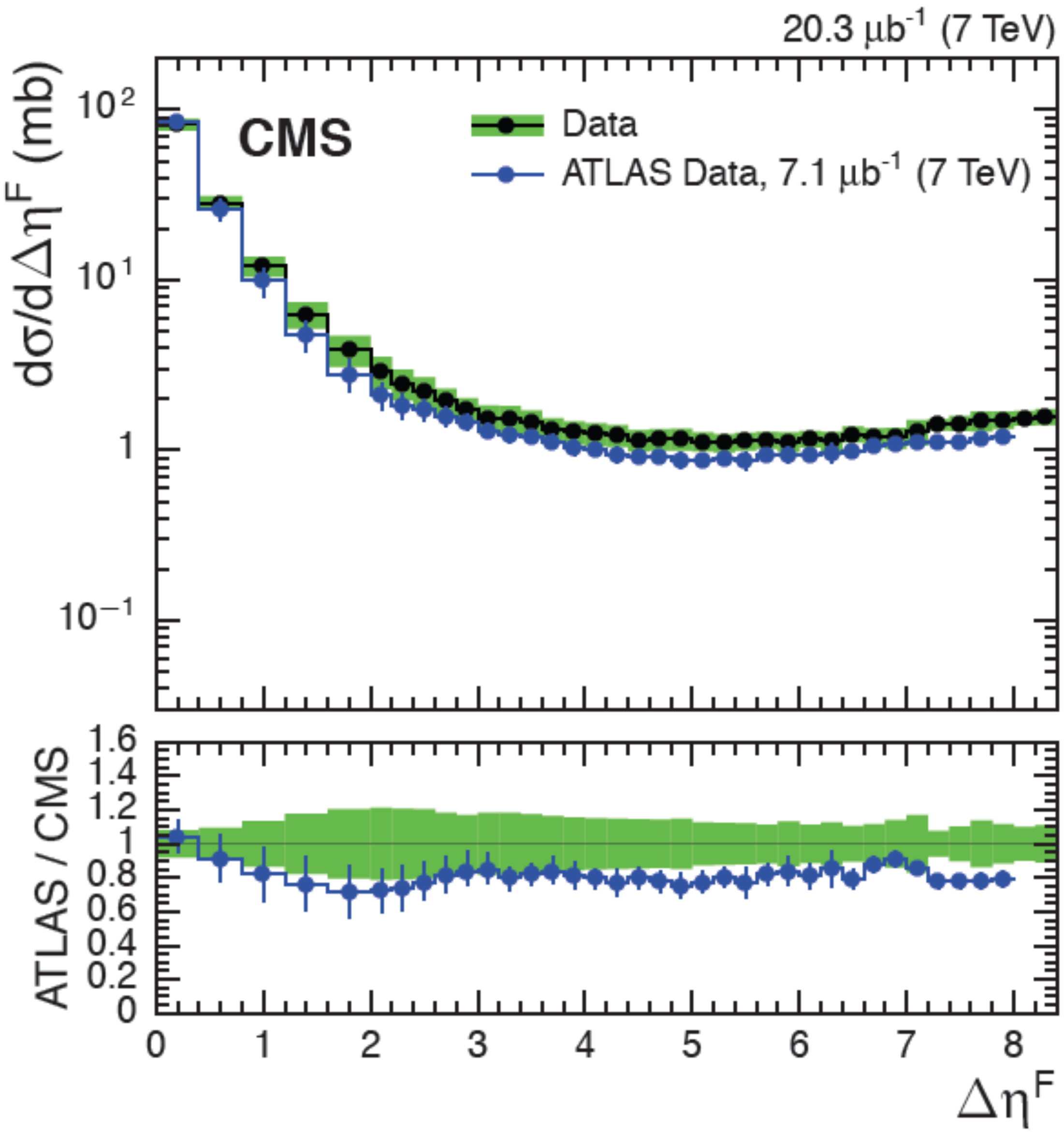


Comparison between CMS and ATLAS

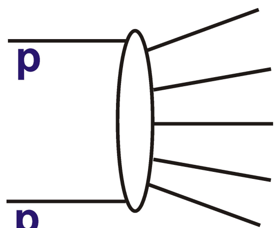
Using first ever LHC run at 7TeV (avoiding pile-up)

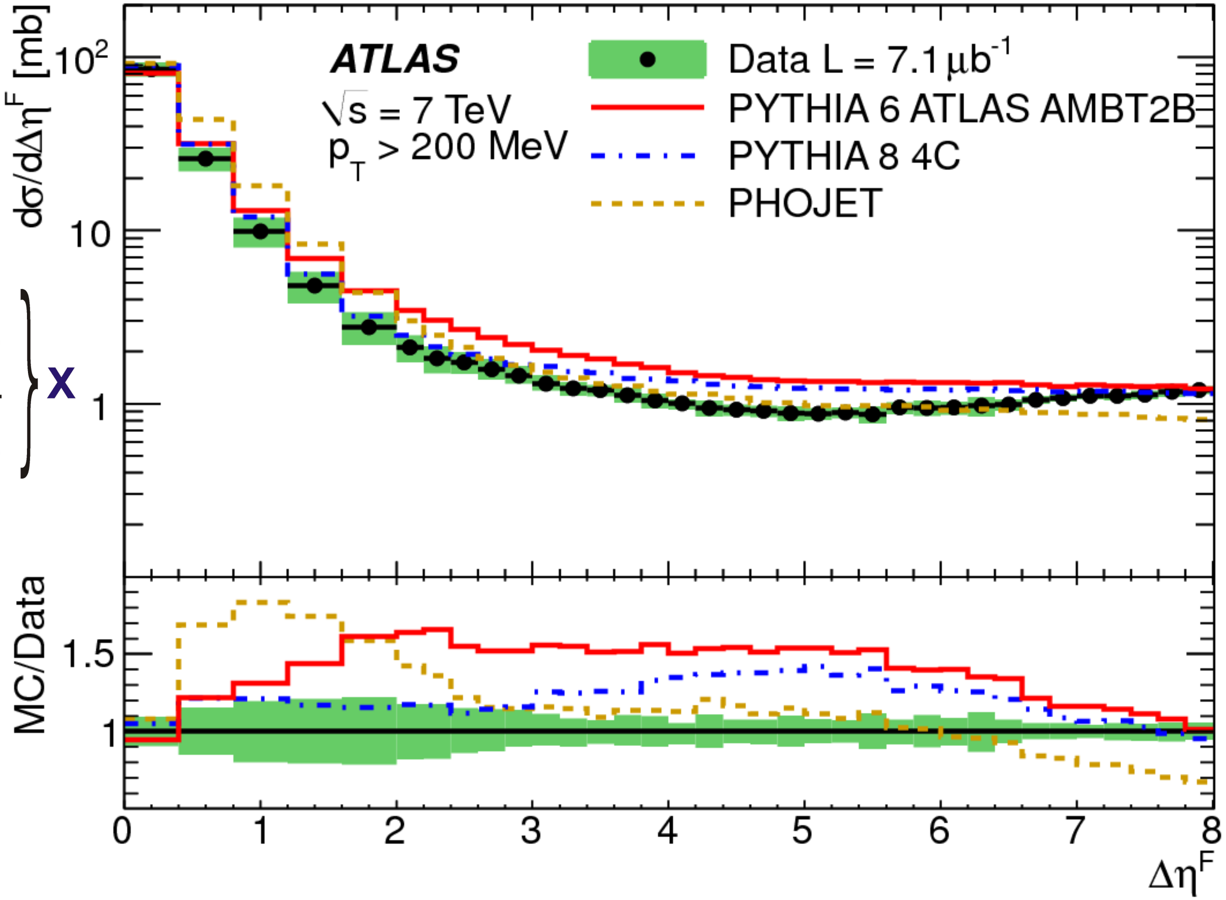
- Agreement on overall characteristics

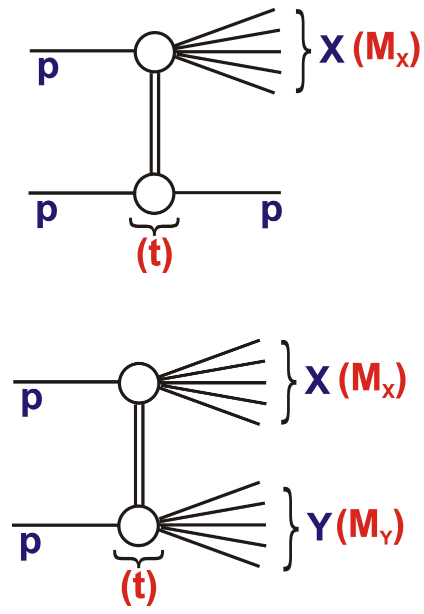
- Cross sections defined slightly differently
- ATLAS: $\Delta\eta^F$ extends from η= ±4.9 to 1st particle with p_t>200 MeV
- CMS: $\Delta\eta^F$ extends
-from η= ±4.7 to 1st
-particle with p_t>200 MeV



ATLAS Differential Gap Cross Section



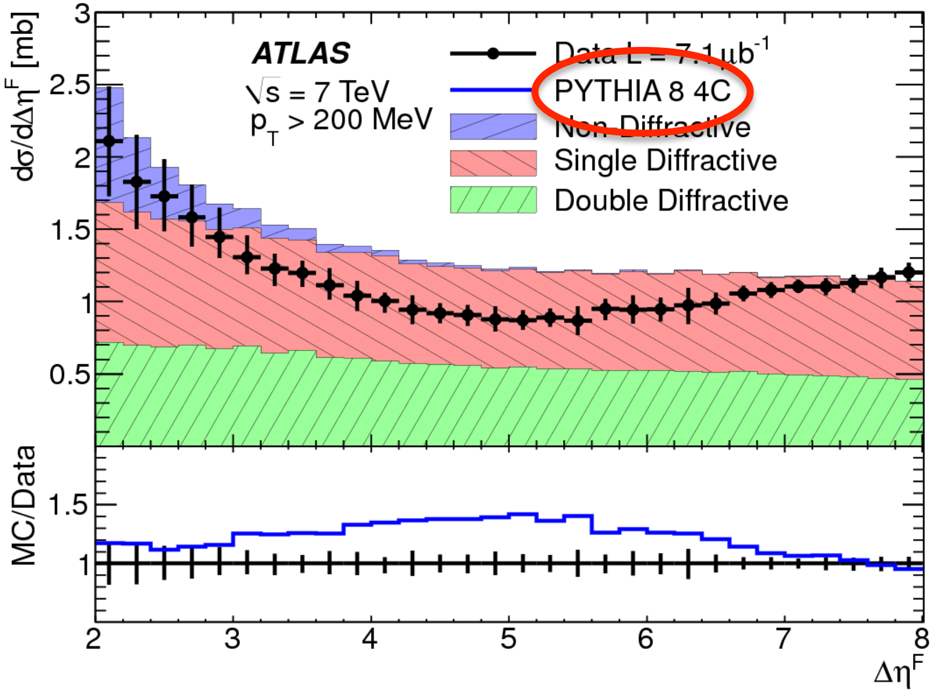




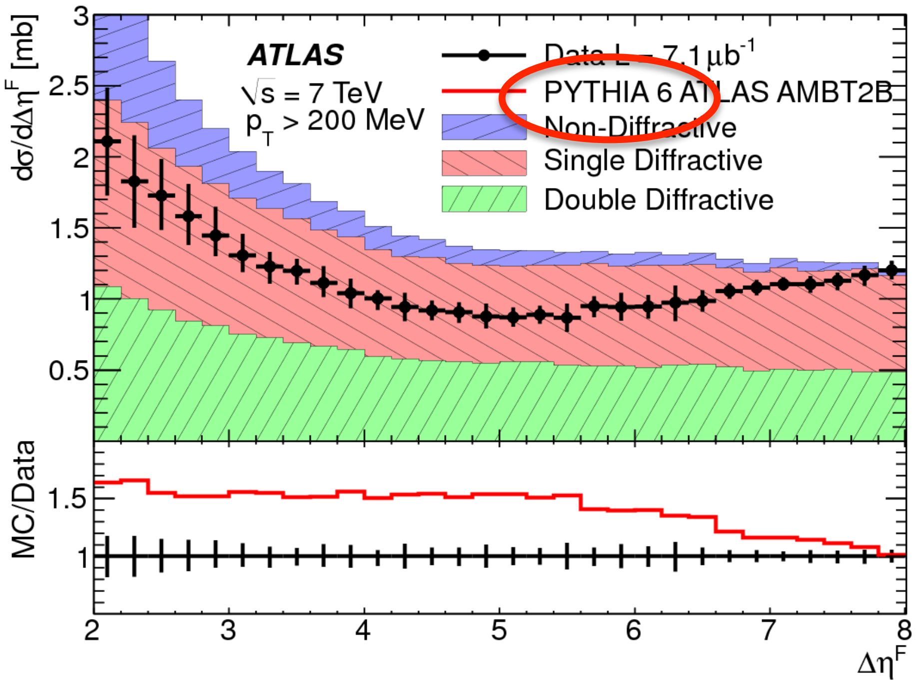
- Precision between ~8% (large gaps) and ~20% ($\Delta\eta^F$ ~ 1.5)
- Large gaps measure x-sec for SD [+ DD with M_Y <~ 7 GeV]
- Small gaps sensitive to hadronisation fluctuations / MPI

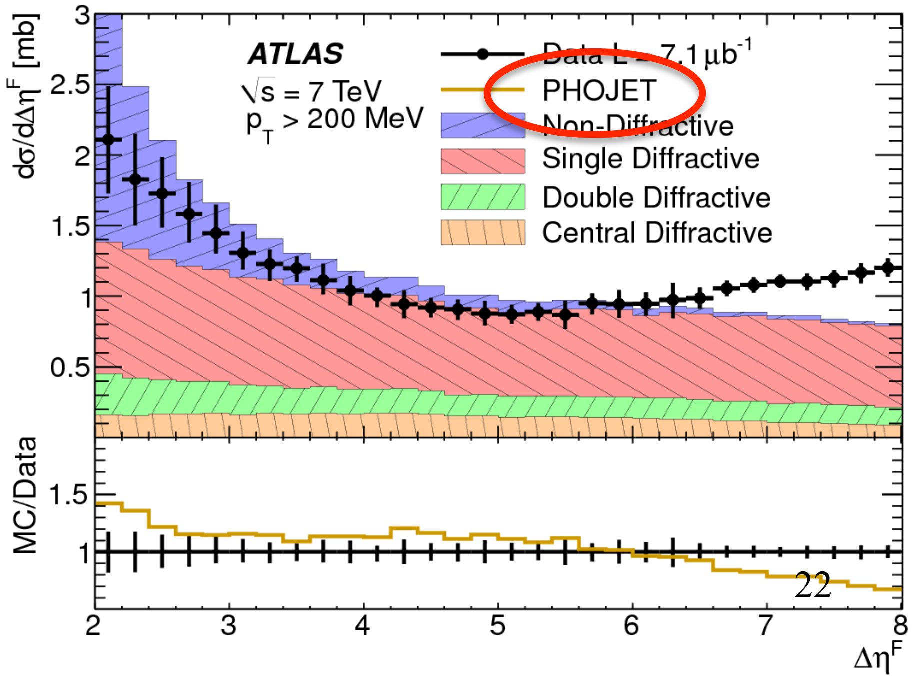
  ... huge uncertainties
- PYTHIA best at small gaps, PHOJET > 50% high at $\Delta\eta^F$ ~ 1.5

Large Gaps and Diffractive Dynamics



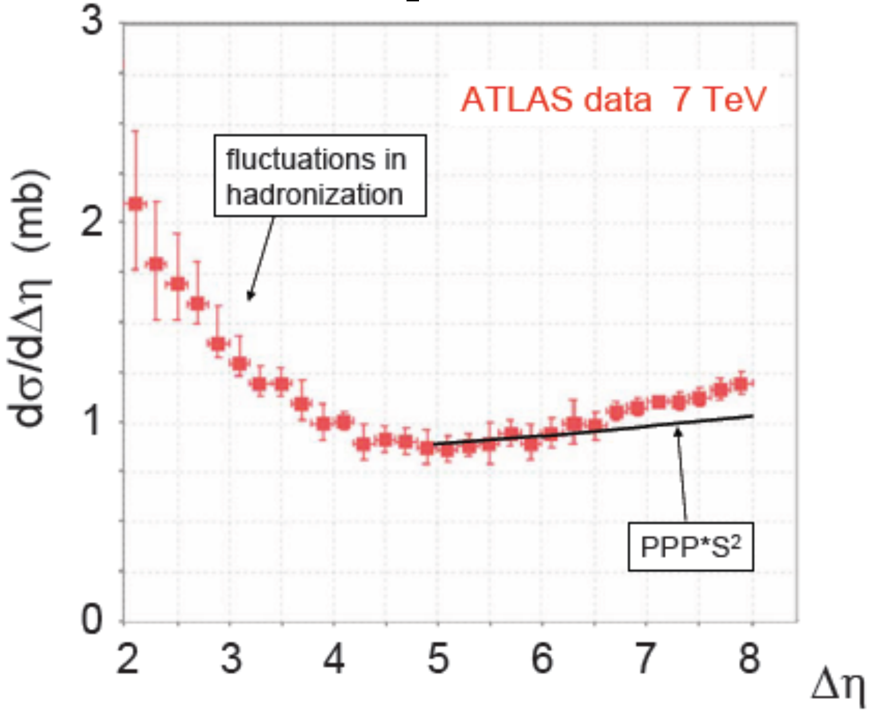
- Diffractive plateau with ~ 1 mb per unit of gap size for $\Delta\eta^F > 3$
- Broadly described by models
- $\alpha_{IP}(0) = 1.058 \pm 0.036$ (ATLAS)
- Further significant progress will require proton tagging to unfold SD from DD and ND

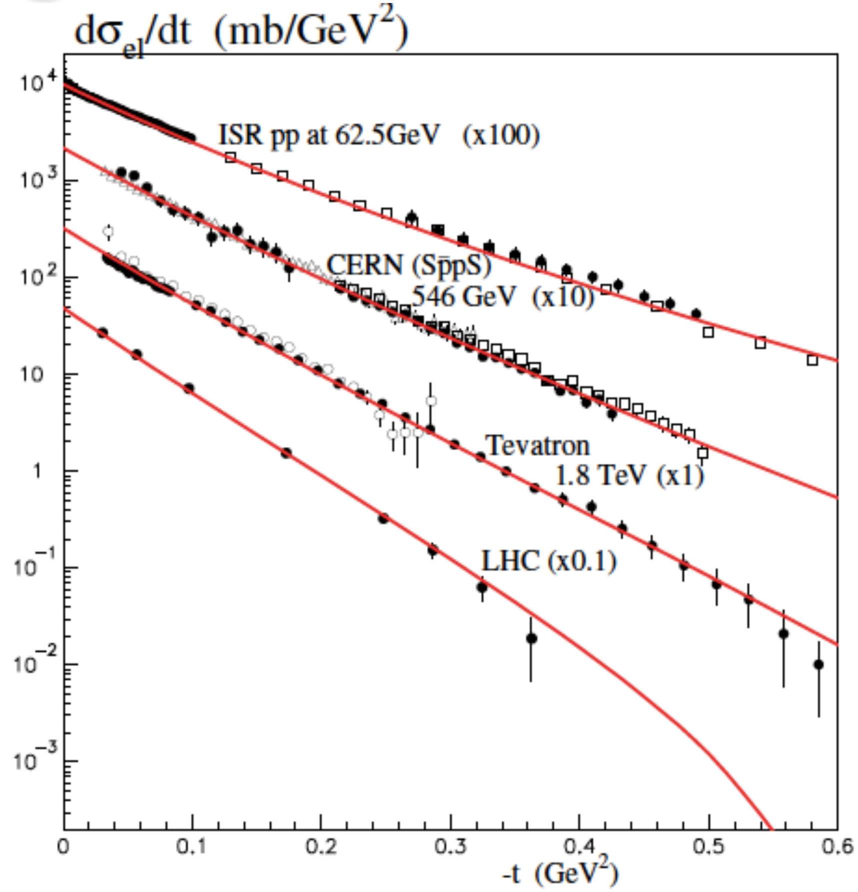




Simultaneous Modelling of soft SD and EL?

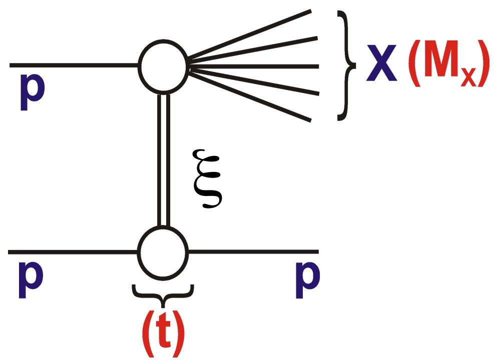
[Khoze, Martin, Ryskin, arXiv:1201.6298]

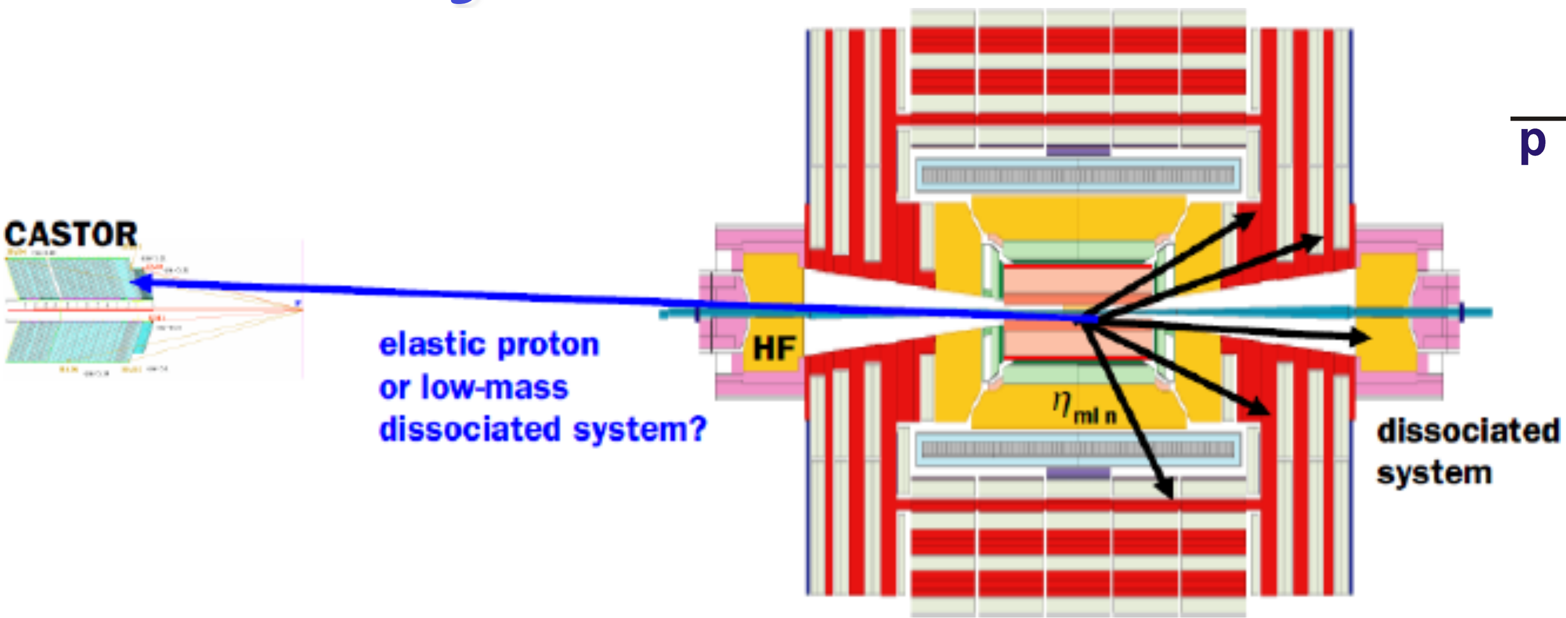




… simultaneous Durham (KMR) description of ATLAS gaps data and elastic cross section data from ISR to Totem based on a single pomeron in a 3-channel eikonal model, with significant absorptive corrections in gaps / dissociation case

SD Cross Sections with Direct ξ Measurement





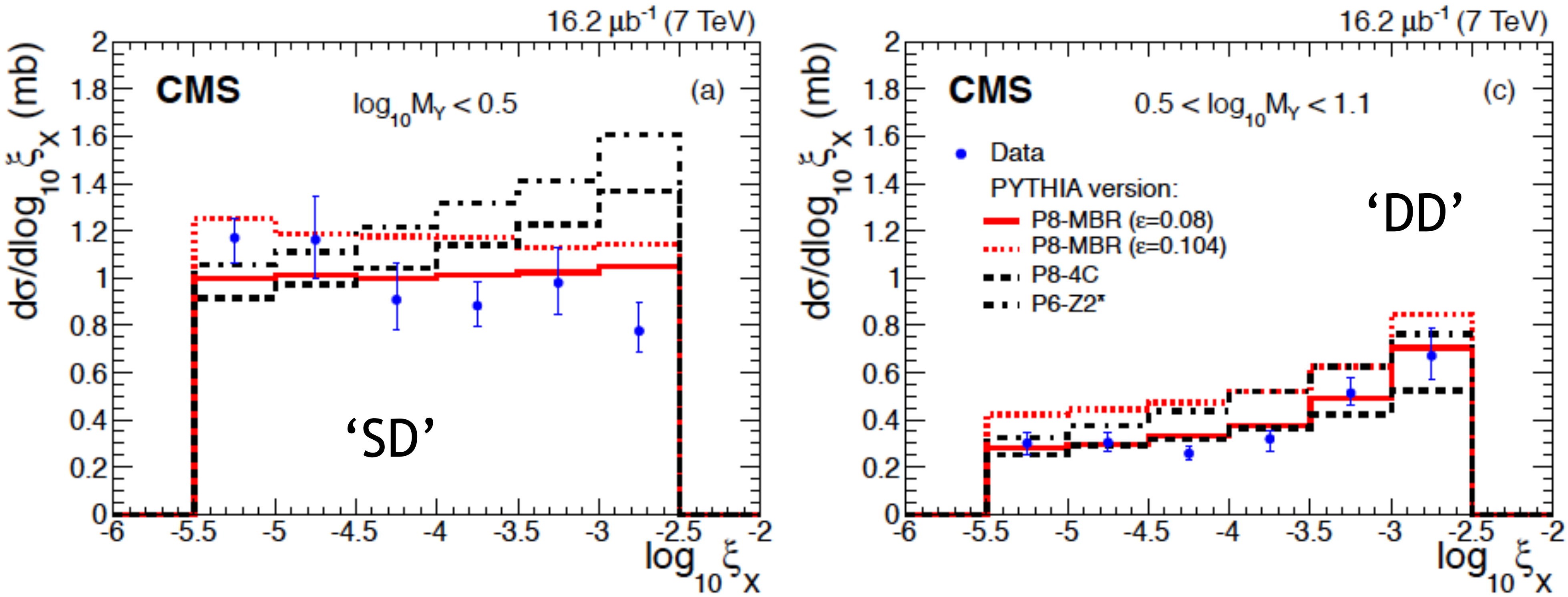
- Use forward calorimeter (CASTOR) tag to help distinguish SD from DD (sensitive to much lower M_Y than central detector).

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

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

- Larger uncertainties, but more directly related to dynamics.

CMS Direct ξ Measurement

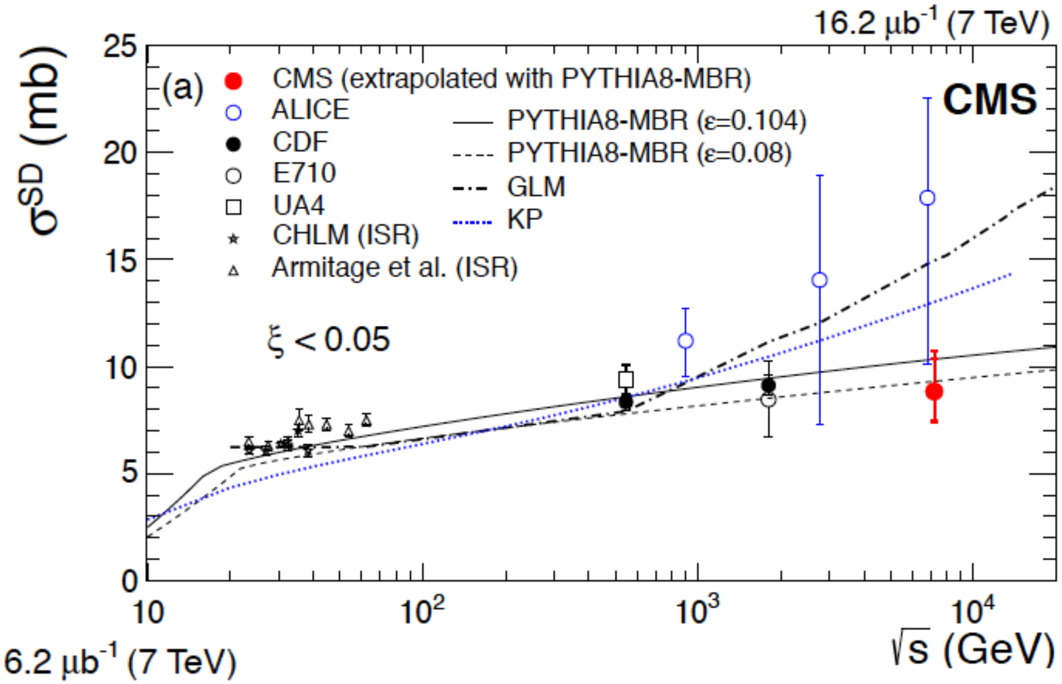


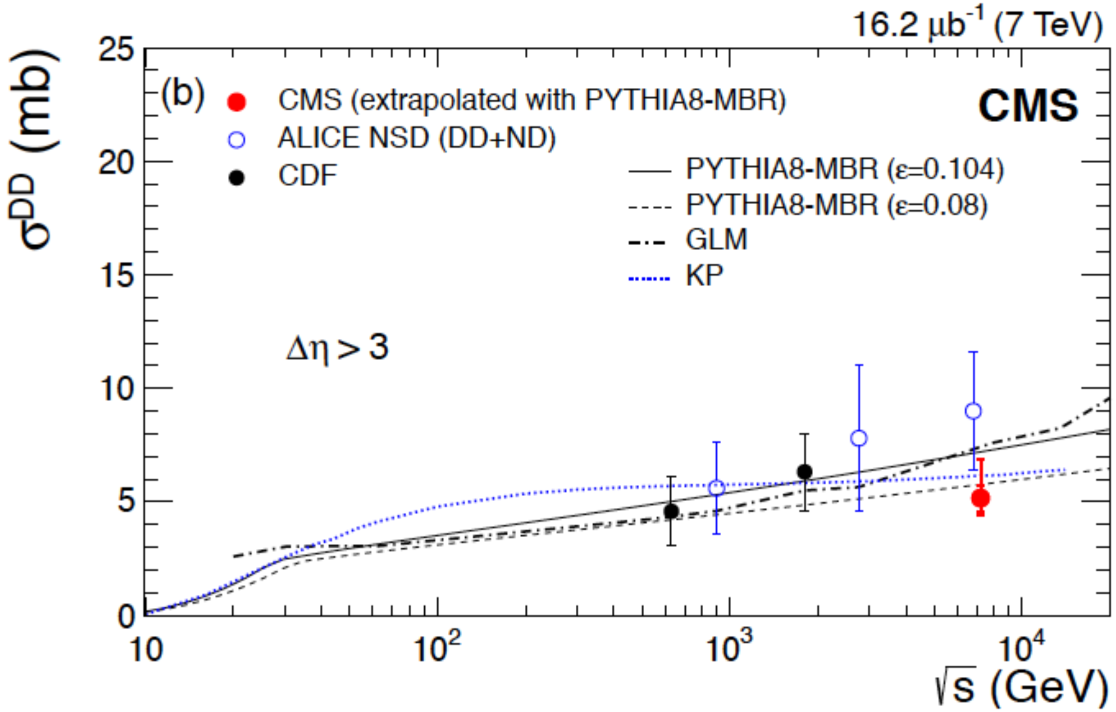
- SD data (small low M_Y DD admixture) compatible with PYTHIA8 with $\alpha_{IP}(0) = 1.08$ or 1.104

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

Total SD, DD Cross Secs as Function of √s

CMS: integration over ξ
ALICE: Integrated SD, DD cross secs at three √s based on gap rates and topologies
… Extrapolations into lowest and highest ξ regions

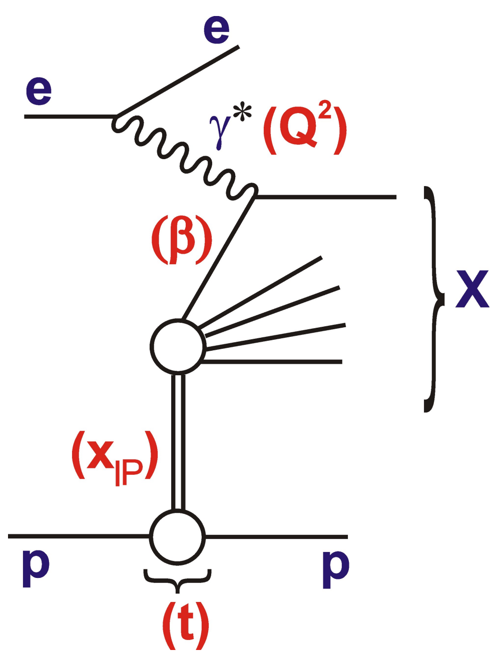


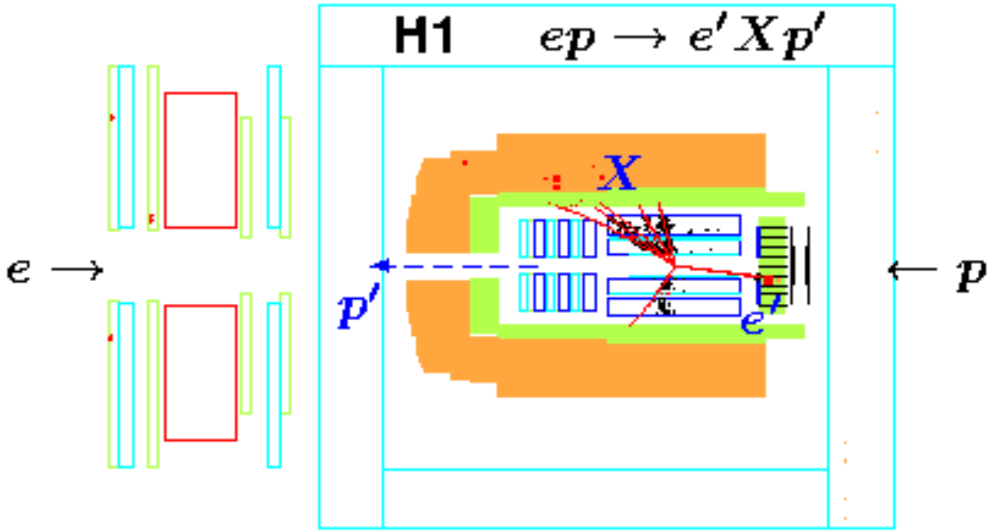


– σ(SD) with ξ < 0.05
– σ(DD) with gap Δη > 3

- Good agreement with SPS data and predictions with modest rise with energy → smallish $\alpha_{IP}(0)$

Diffraction at the Parton Level



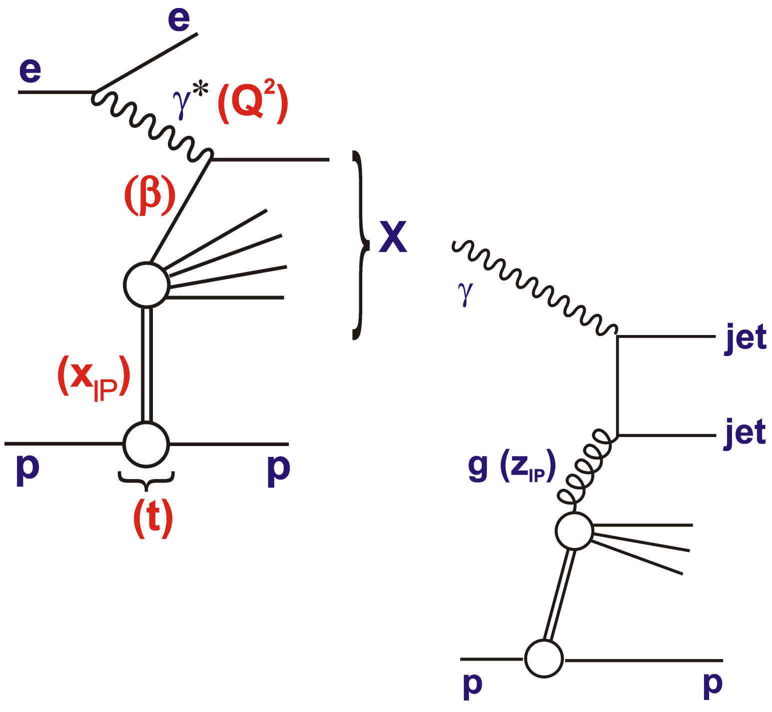


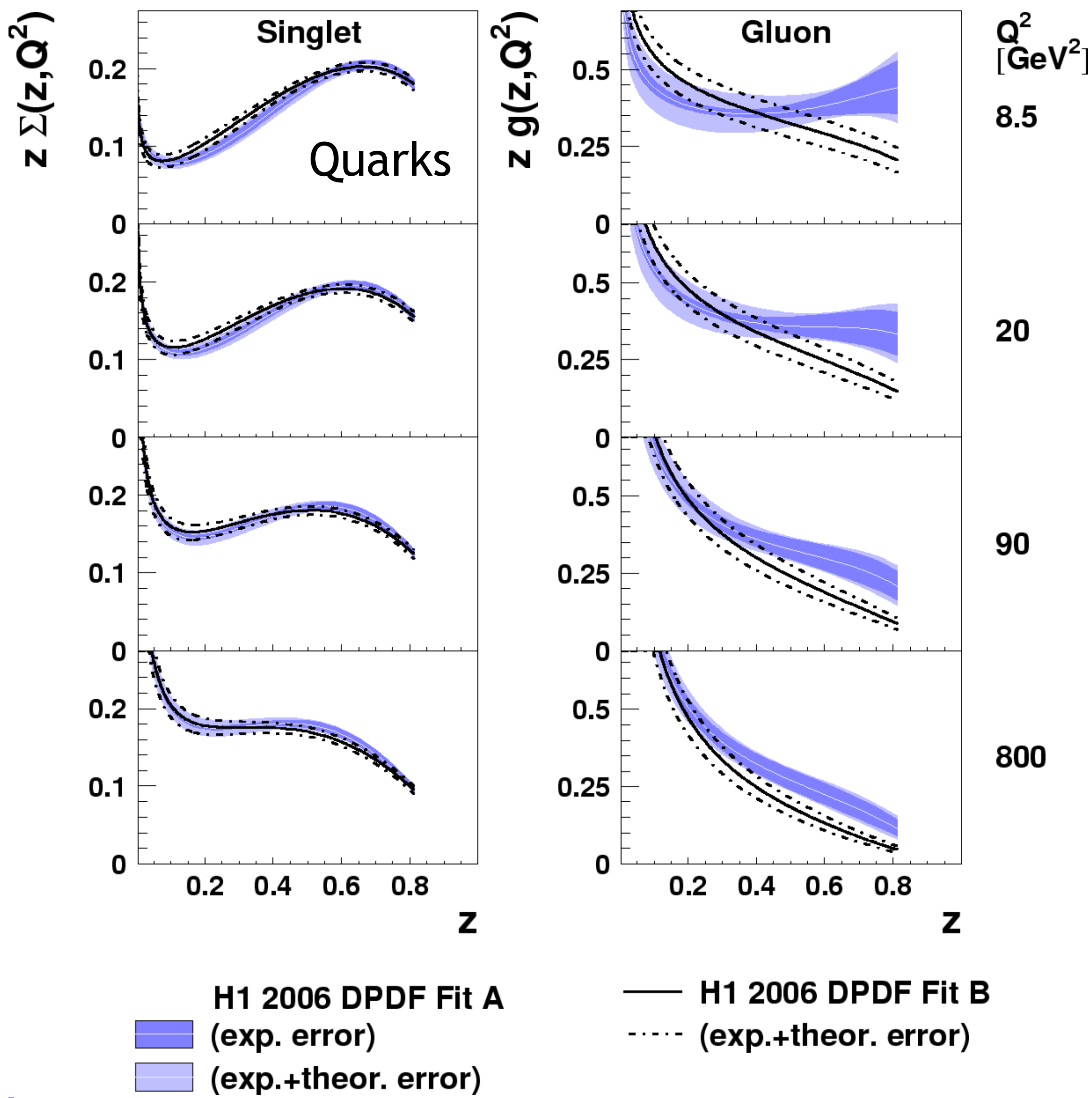
HERA ep Collider:

Virtual photon probes pomeron partonic structure rather like inclusive DIS …

>100 papers later …

Diffractive Parton Densities (DPDFs)





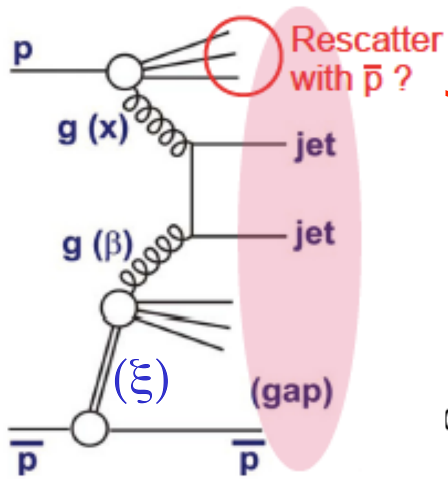
HERA DPDFs dominated by gluon, which extends to large momentum fractions

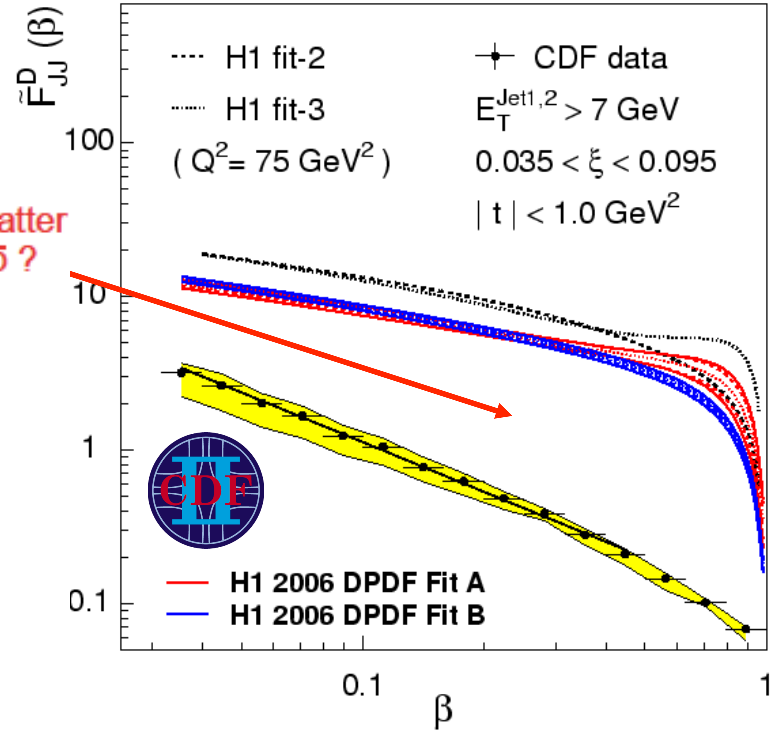
… NLO DPDFs lead to impressive description of all HERA 'hard' diffractive data

… but in pp(bar)

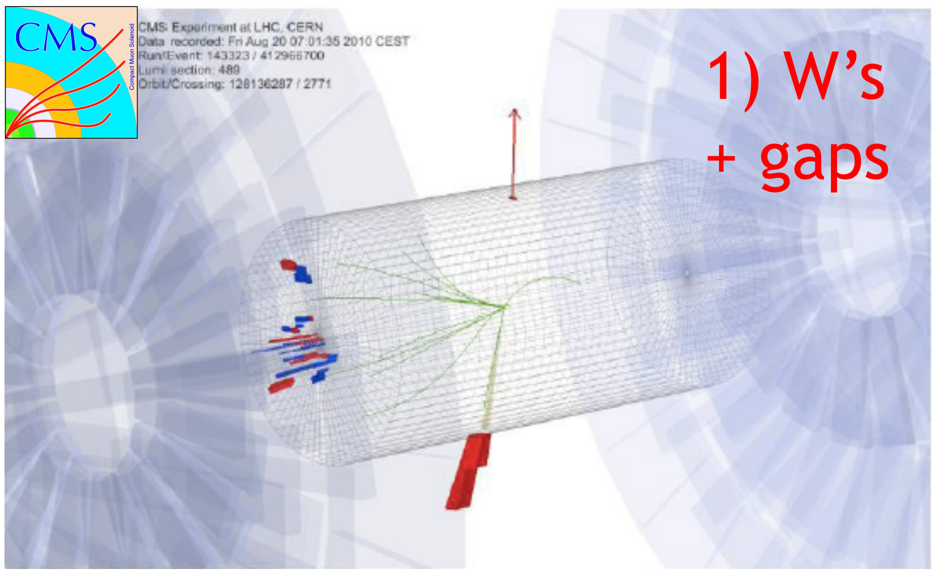
Spectacular failure in **comparison of Tevatron proton-tagged diffractive dijets with HERA DPDFs**

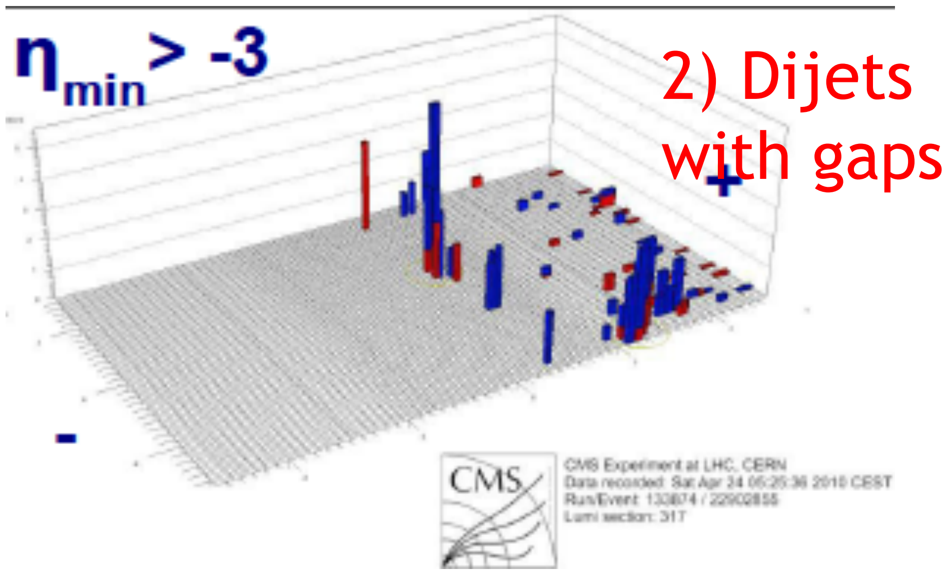
… `rapidity gap survival probability' ~ 0.1



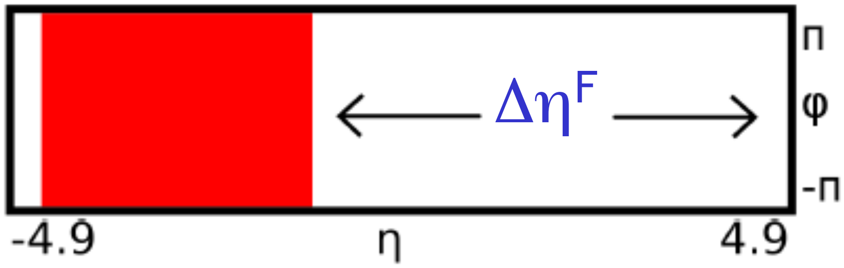


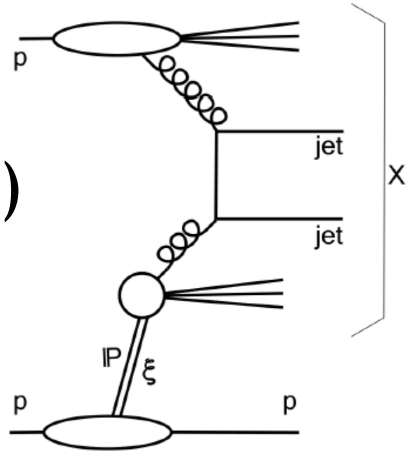
First Hard diffraction studies from LHC …



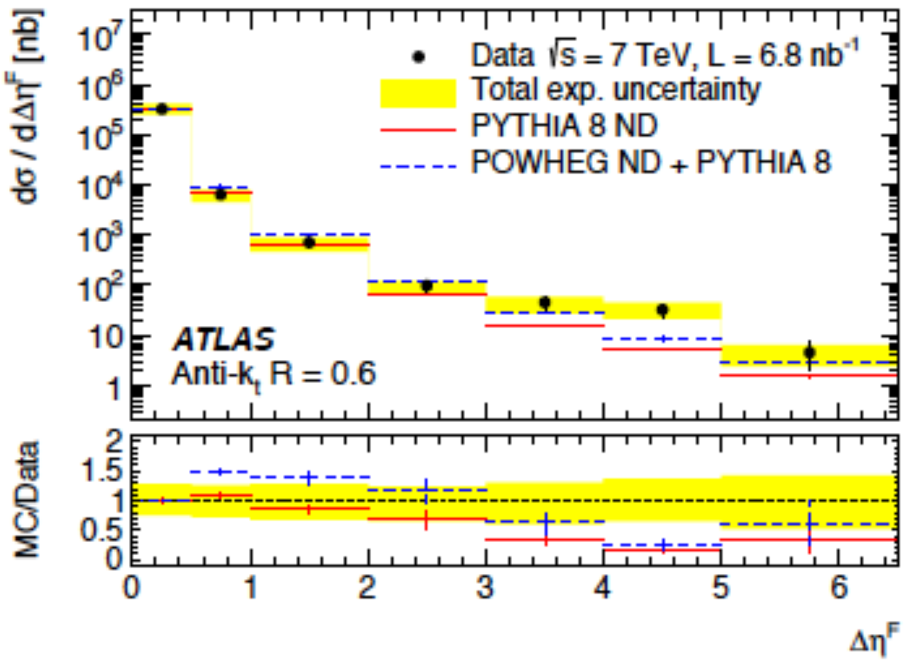


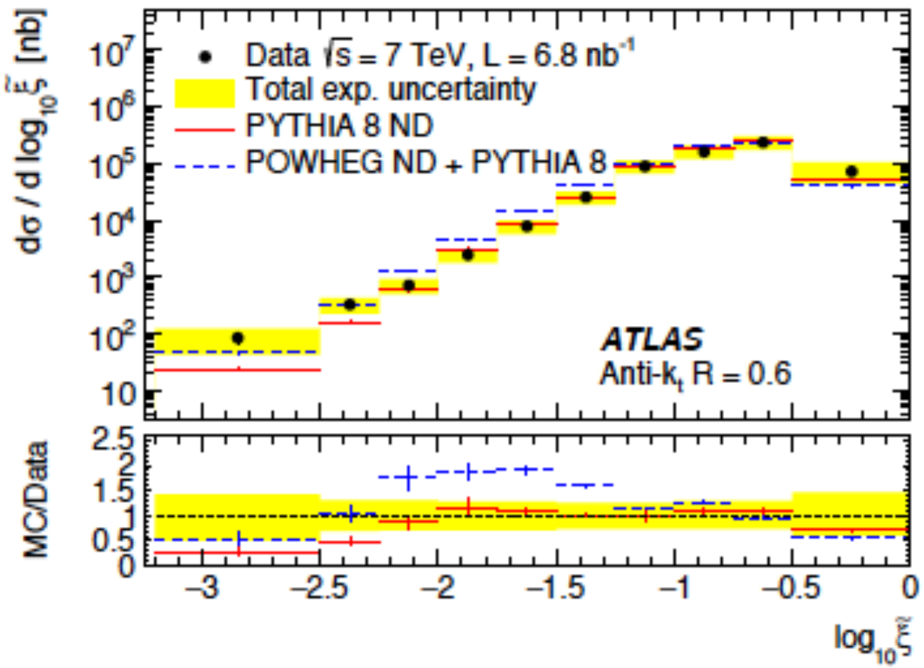
New Diffractive Dijets (p_T>20 GeV) from ATLAS





- Kinematic suppression of large gaps → no clear diffractive plateau (unlike minimum bias case)
- ND models matched to small gap sizes give contributions compatible with data up to largest $\Delta\eta_F$ and smallest ξ … no clear diff signal …





New Diffractive Dijets from ATLAS

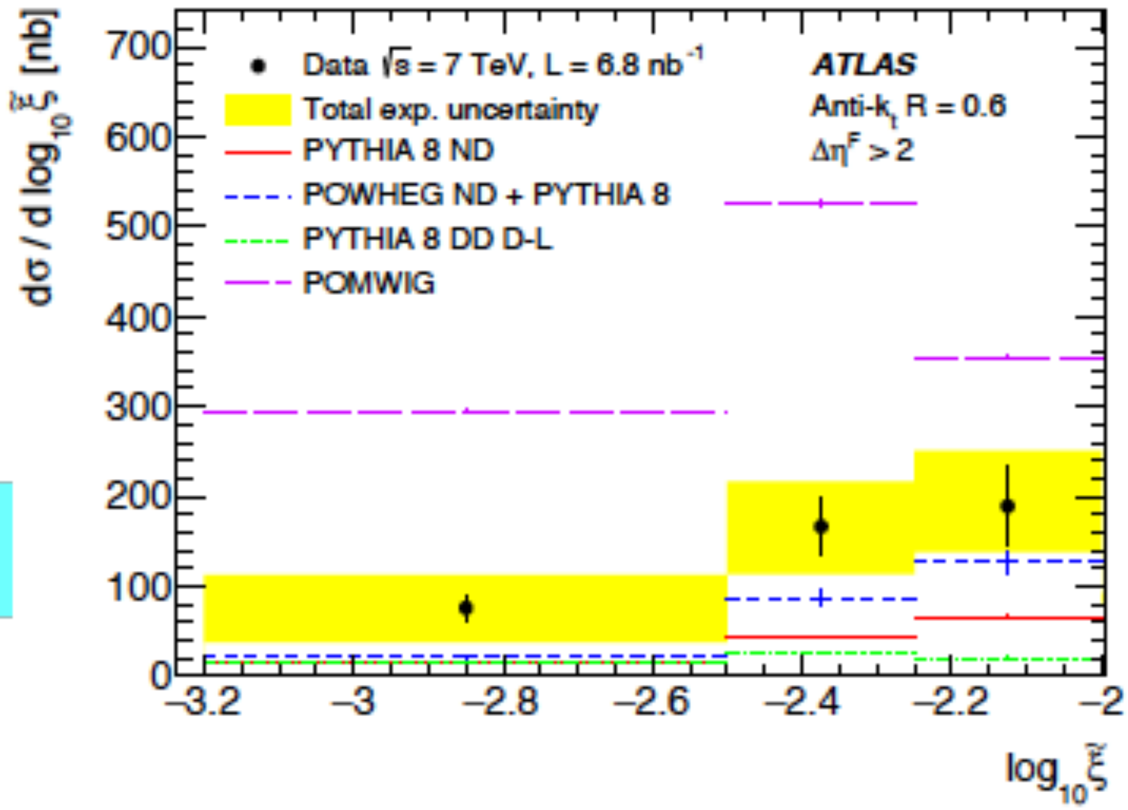
Looking at small ξ, whist simultaneously requiring large gap size ($\Delta\eta_F$ > 2) gves best sensitivity to diffractive component

→ Models with no SD jets below data by factor >~3

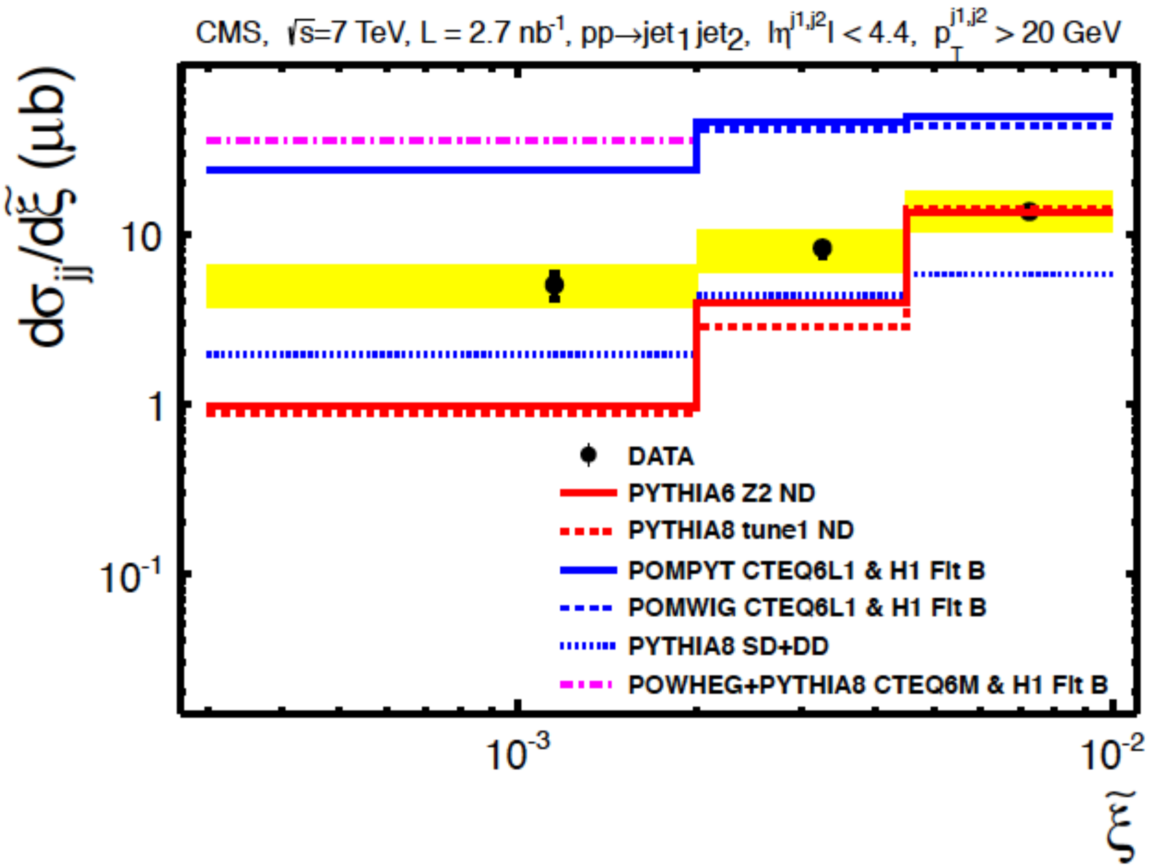
→ Comparison of smallest ξ with DPDF based model (POMWIG) leads to rapidity gap survival probability estimate …

$S^2 = 0.16 \pm 0.04(\text{stat}) \pm 0.08(\text{syst.})$

(using anti-k_T R=0.6)



CMS Diffractive Jet Cross Section



- Comparison of 1st bin v diffractive DPDF models

→ Gap survival probability estimate $S^2 = 0.08 \pm 0.04$ (based on NLO POWHEG)

… LHC results for S^2 comparable to Tevatron, but different x range

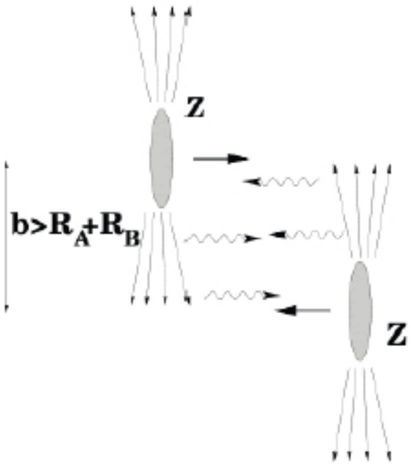
… larger than expected?

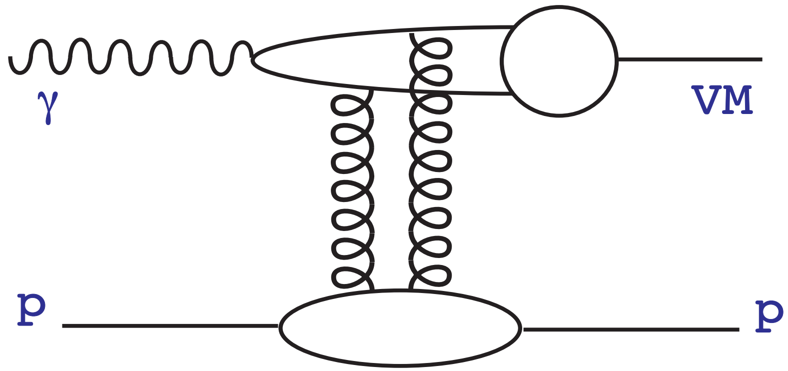
Proton tagged data required for substantial further progress

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

Ultraperipheral J/Ψ Photoproduction, & the Low x Gluon Density of the Proton

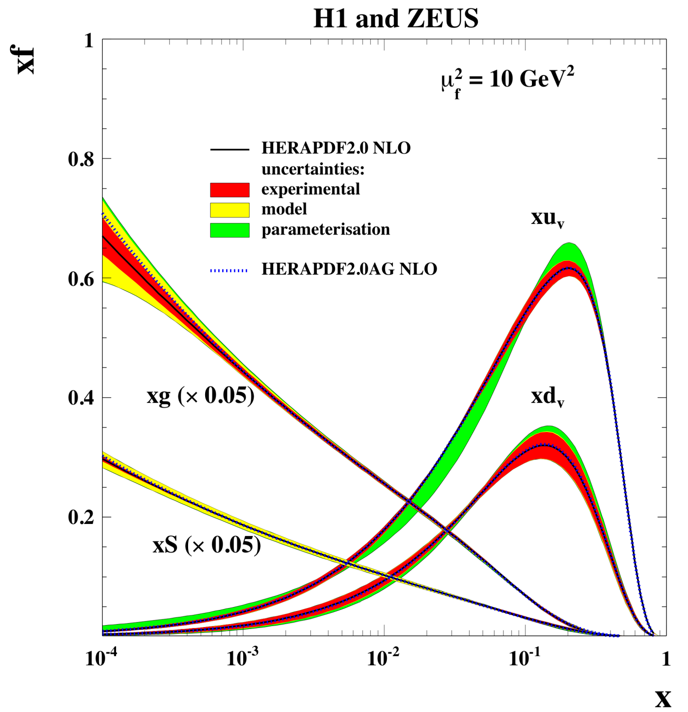
… LHC's "near misses"



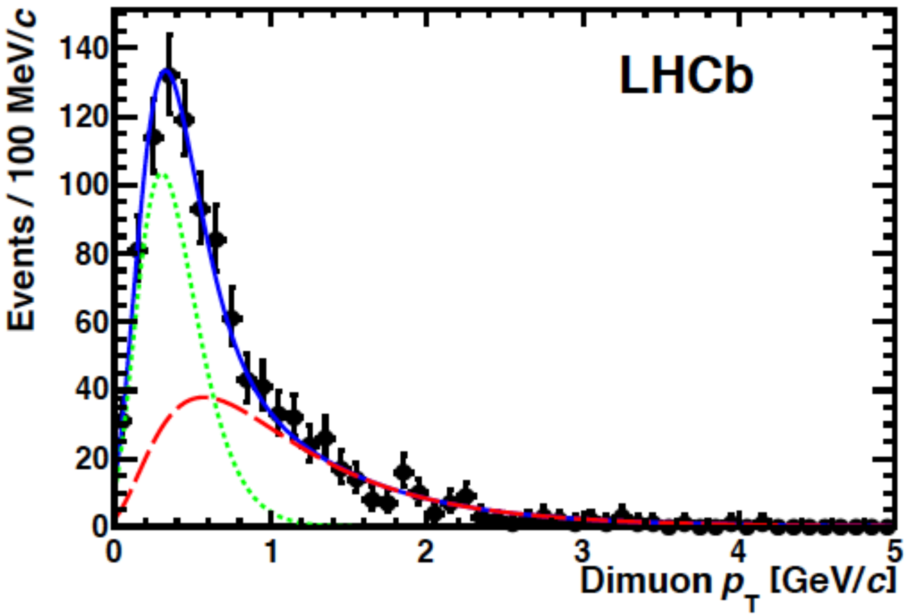


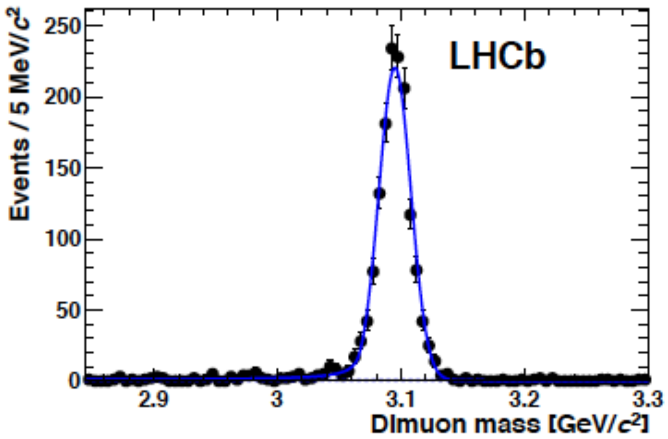
- LHC protons / ions as source of photons VM photoproduction …
- Experimentally very simple
- Sensitivity to square of gluon density at lowest order

$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi\ p)\Big|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x,\bar{Q}^2)\right]^2 \left(1+\frac{Q^2}{M_{J/\psi}^2}\right)$$



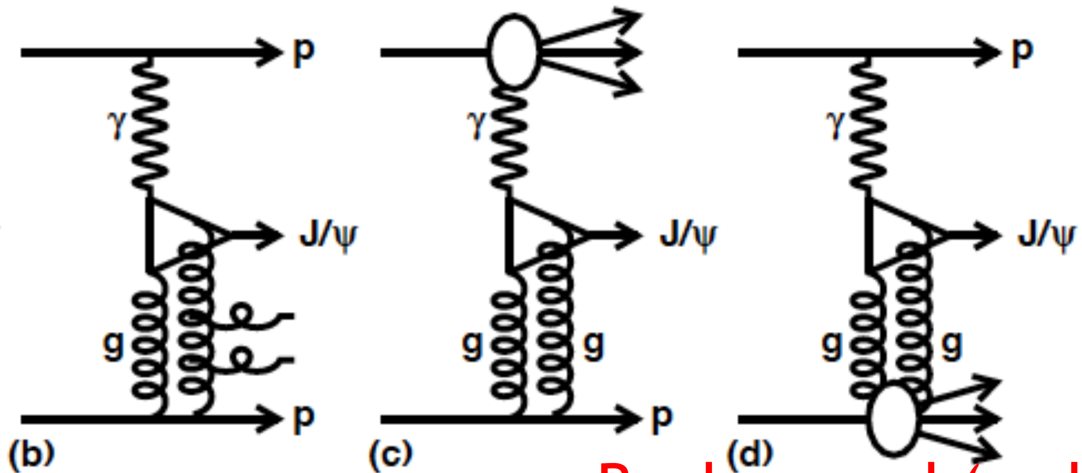
Exclusive J/Ψ Production in pp at LHCb

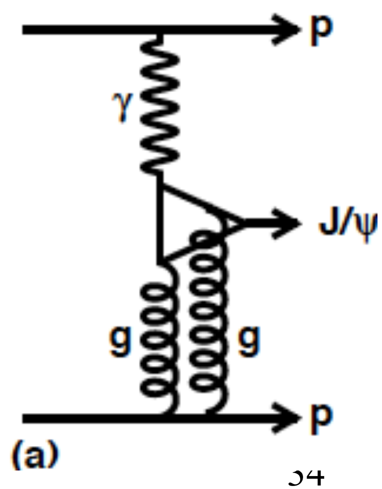




Coherent signal extracted by fitting t (~p_T^2) distribution …

[uncertainties hard to evaluate]





Background (red) Signal (green)

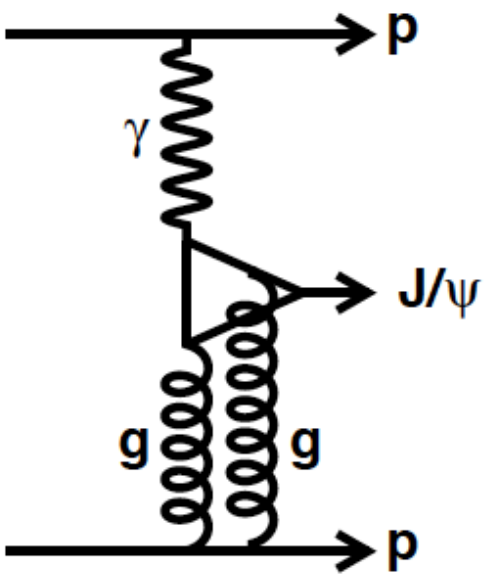
Ultra-peripheral J/Ψ in pp at LHCb

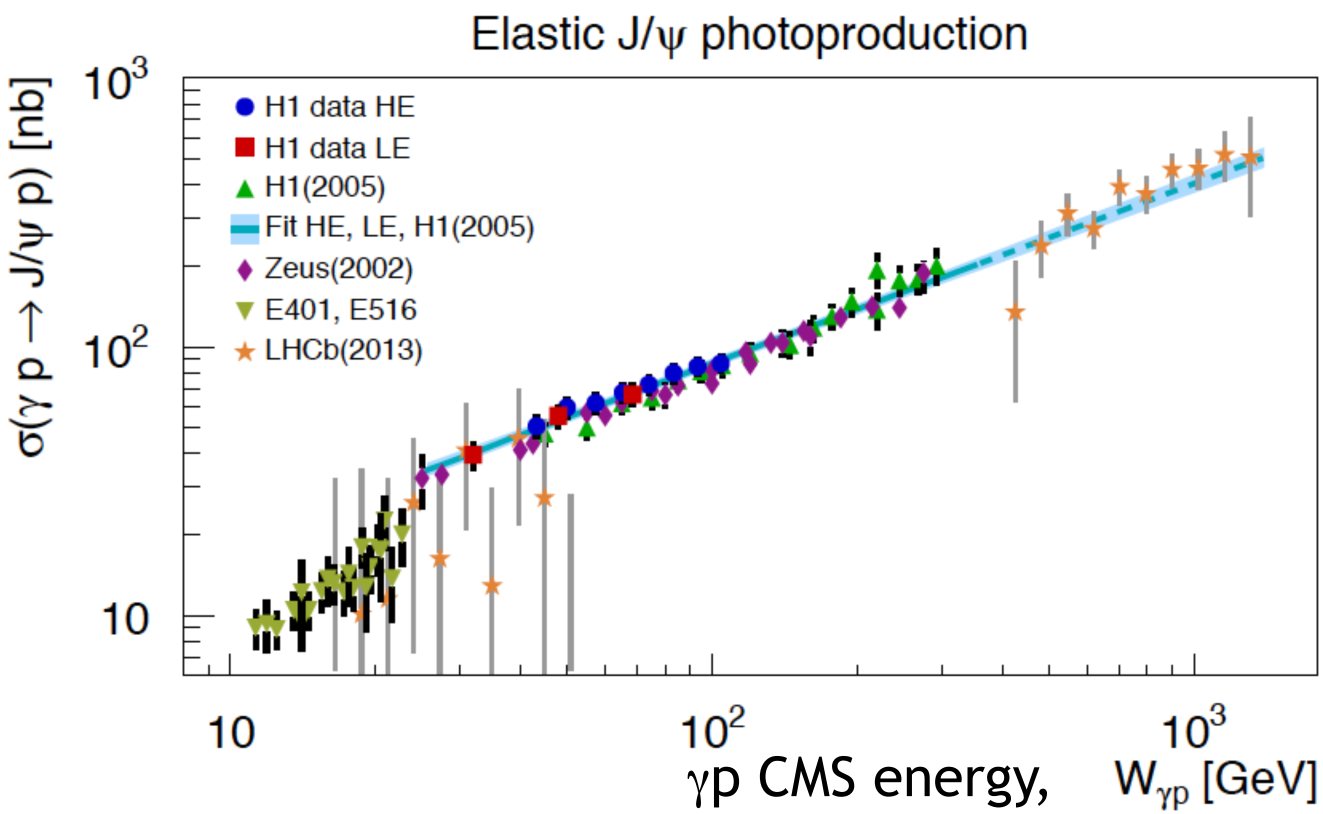
Ambiguity on whether forward J/Ψ is produced by high energy photon and low energy gluons or vice versa

… dealt with on a statistical basis

Very interesting kinematic range …

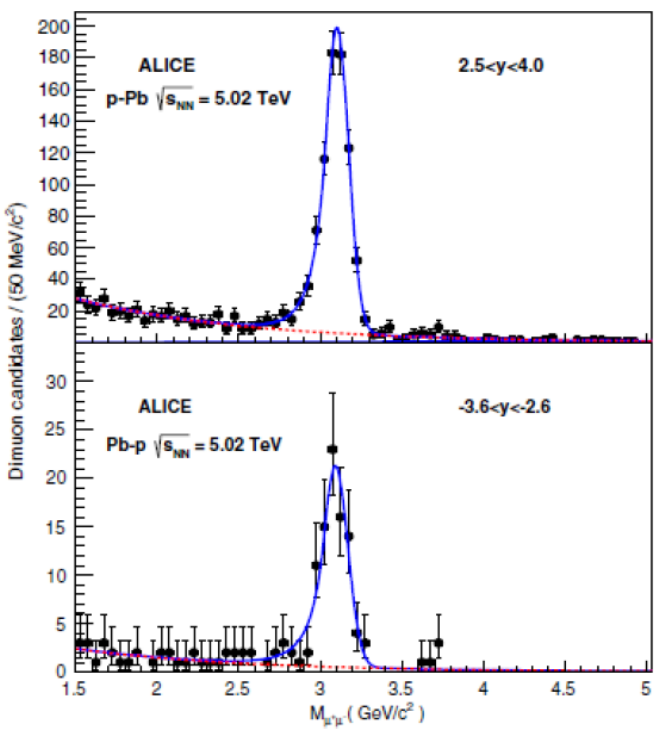
… HERA power law dependence persists to large W / low x

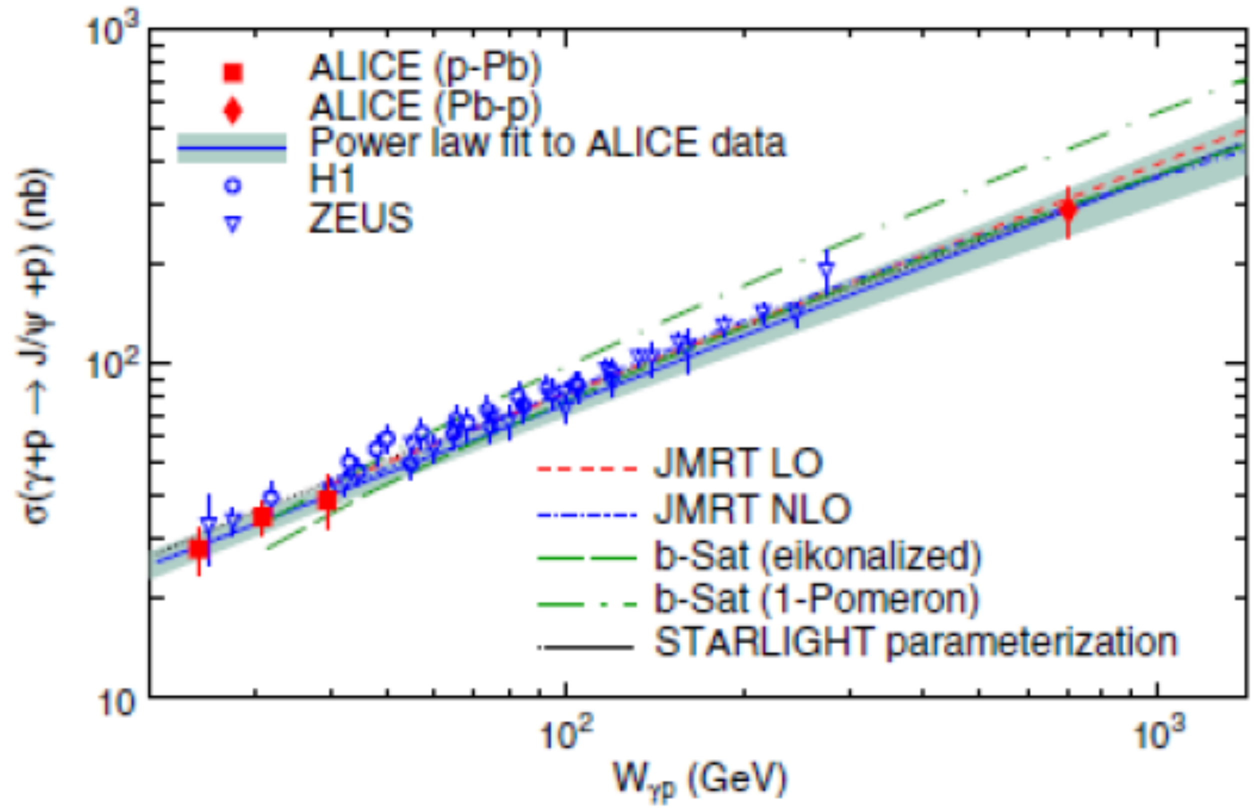




Ultra-peripheral J/Ψ in pPb at ALICE

Pb ion provides prolific source of photons (~Z^2) …
… removes ambiguity → γp 95% of the time, γPb only 5%



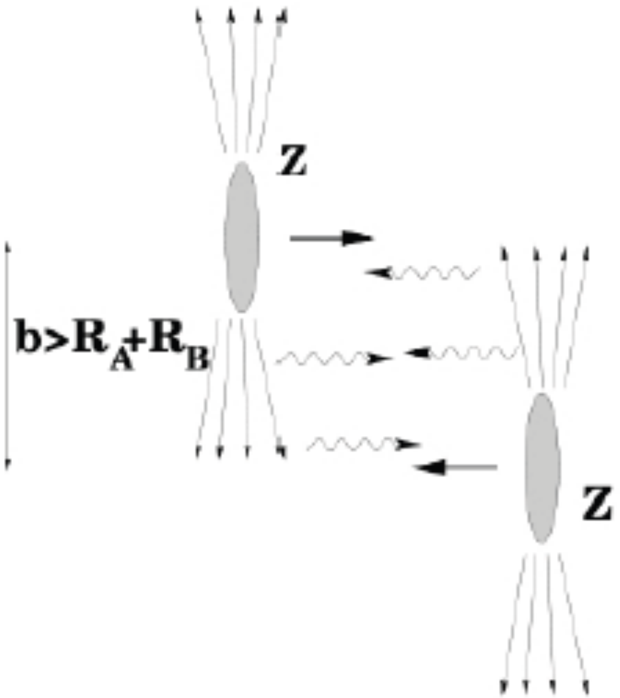


Compatible with power law (= monatomic low x gluon) up to W~700 GeV

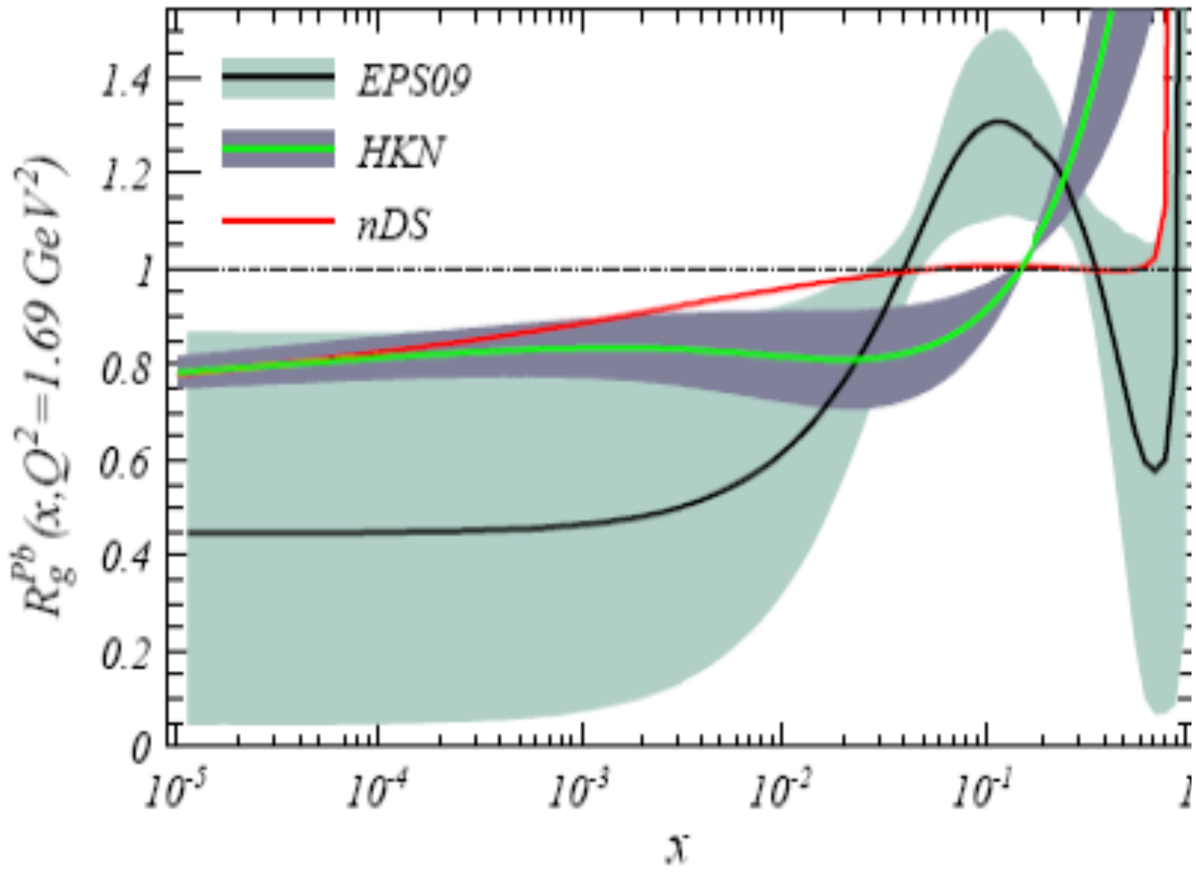
… and in PbPb

Using γPb collisions to probe the nuclear gluon density

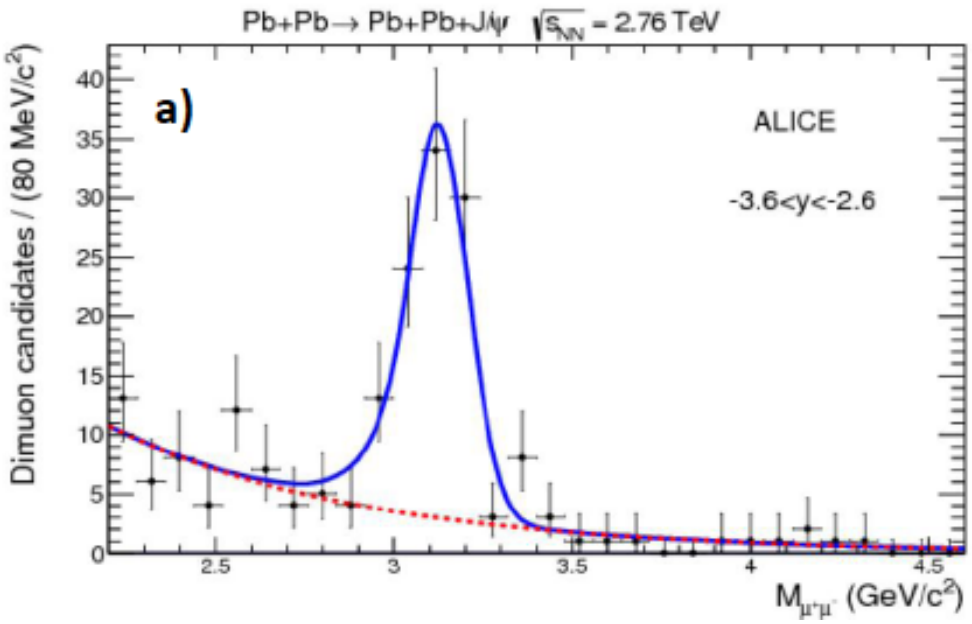
… almost completely unknown, especially at low x …

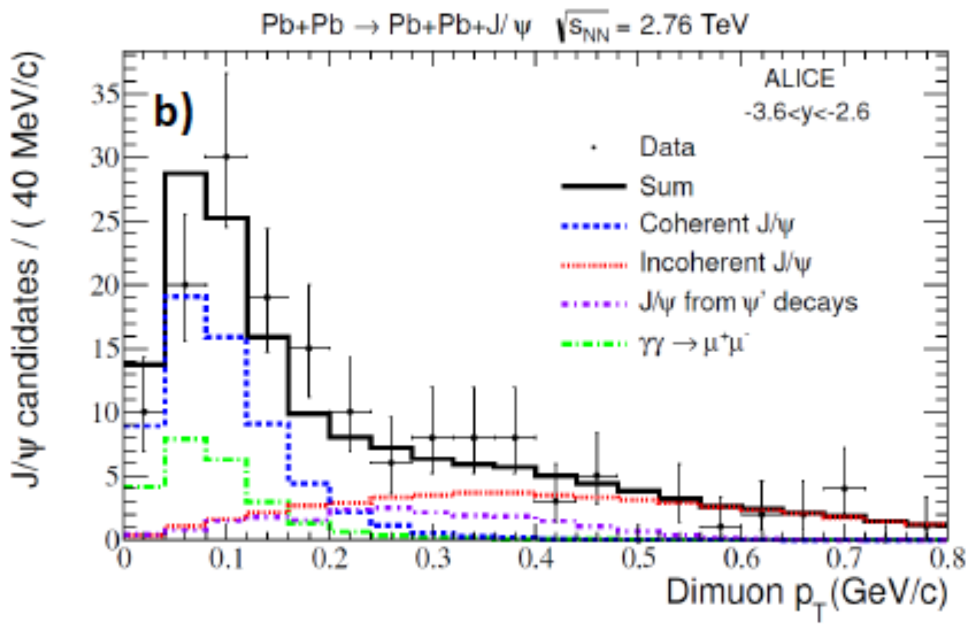


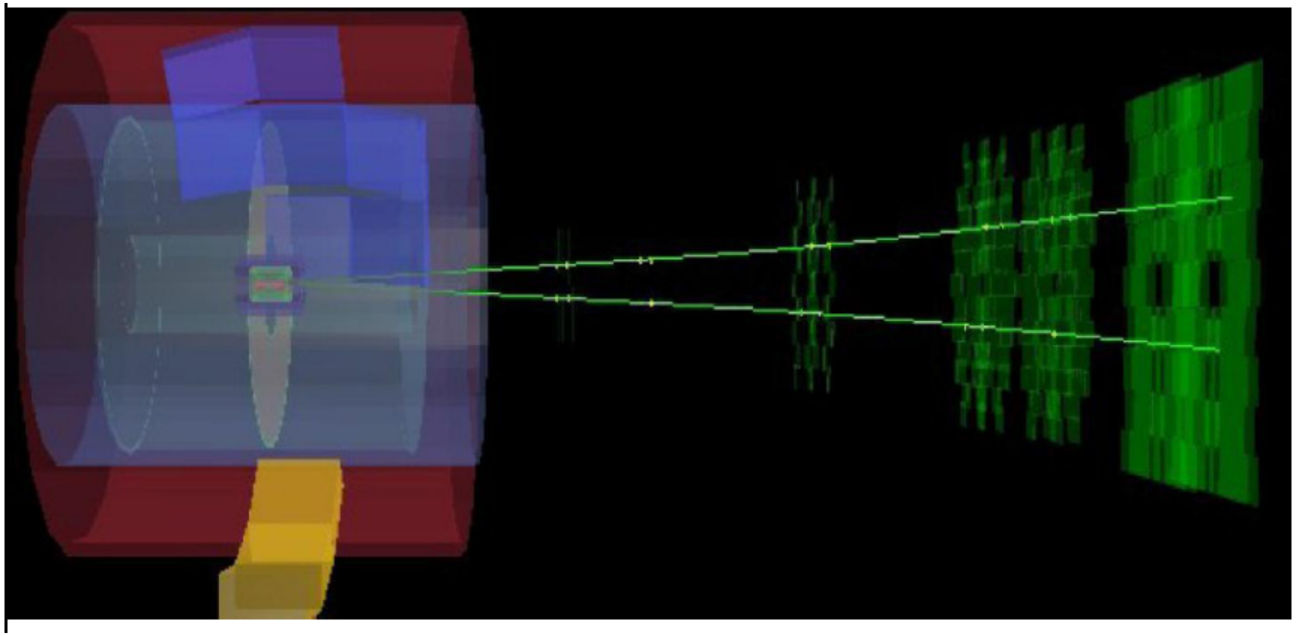
Nuclear gluon shadowing factor vs x



Exclusive J/Ψ Production in AA at ALICE



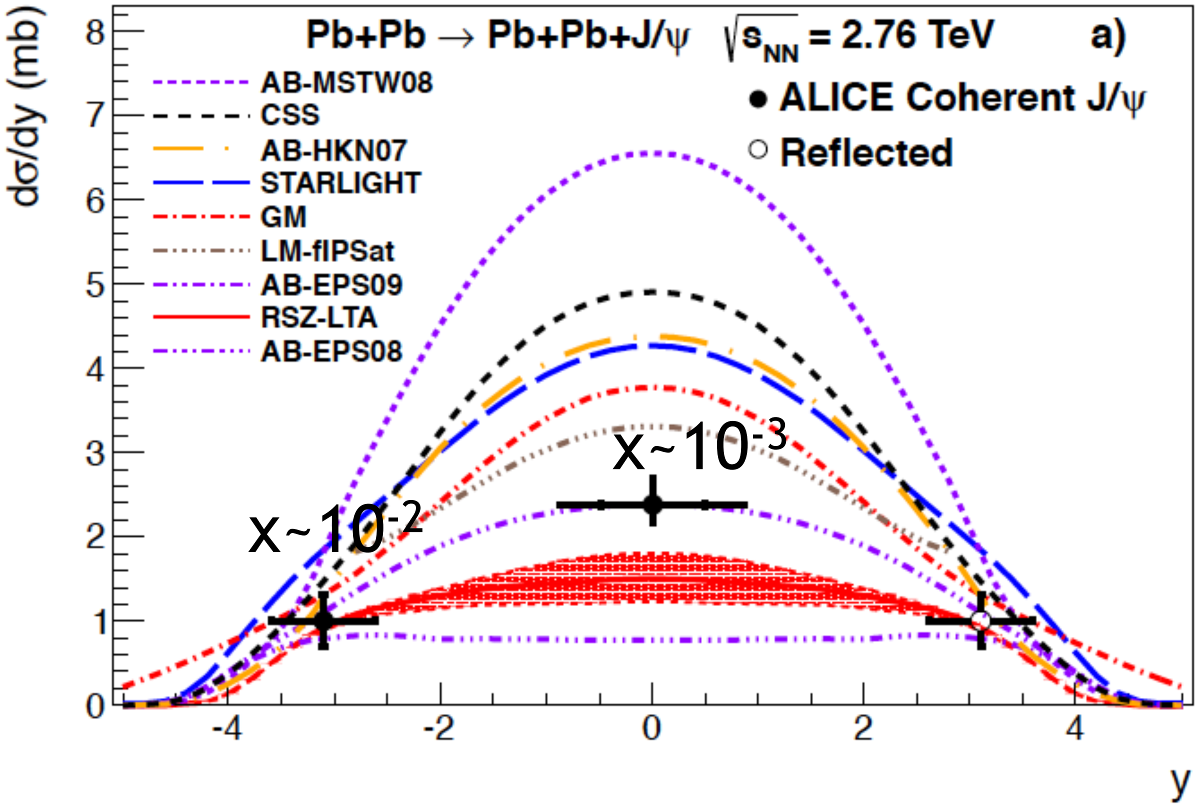


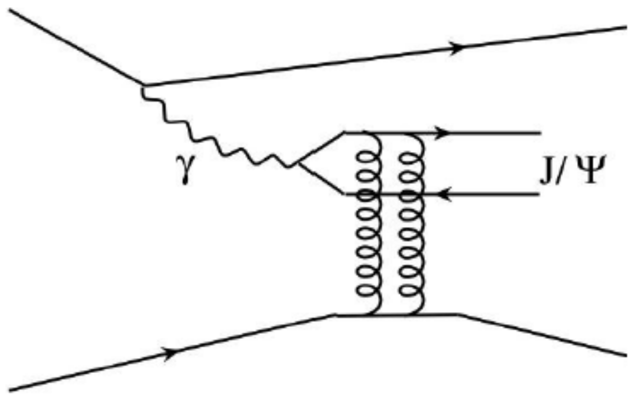


Beautifully clean signature

Separating out coherent part again a complicated issue

Exclusive J/Ψ Production in AA at ALICE

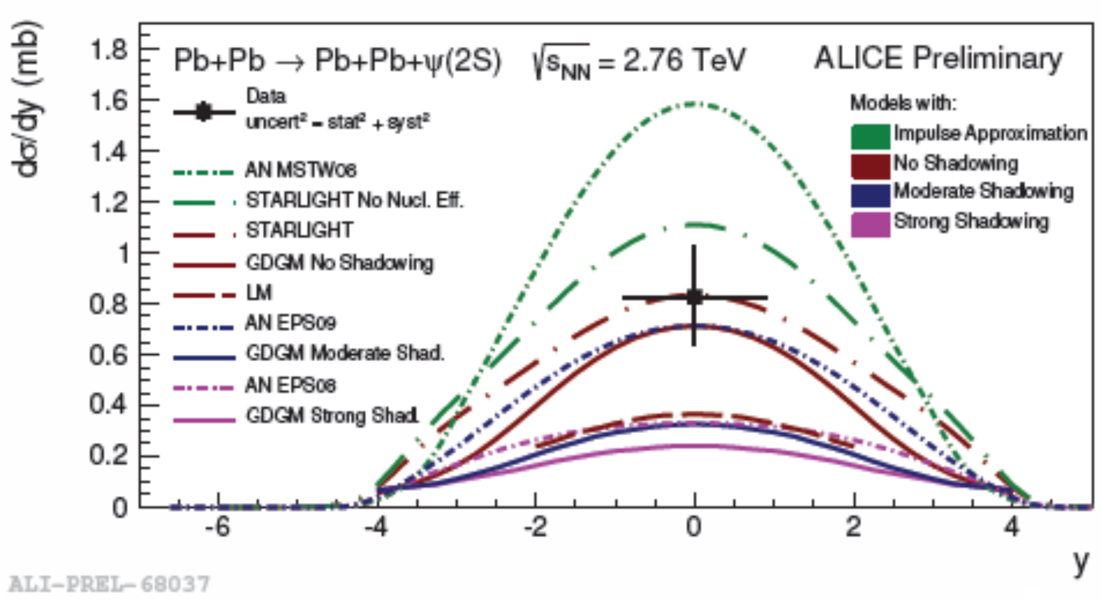




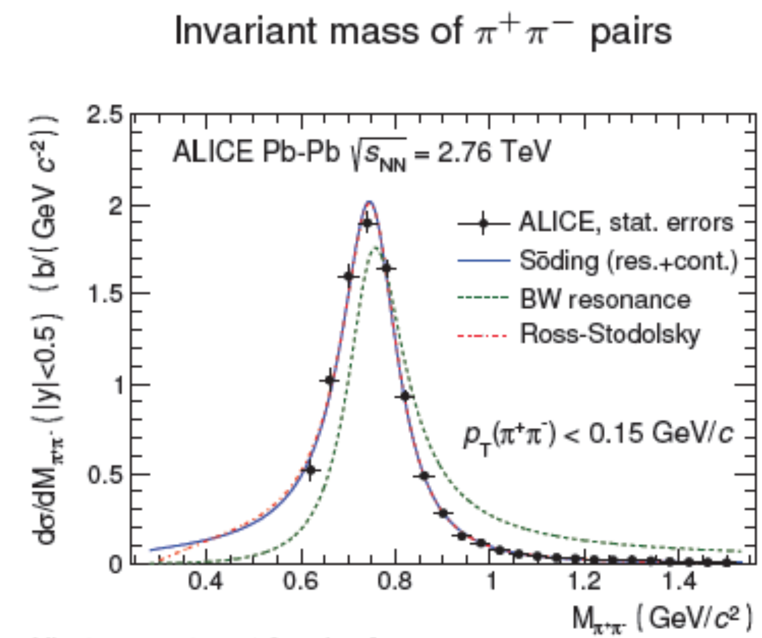
-Remarkable discrimination (best agreement with EPS09 model which incorporates nuclear shadowing).

- x values relatively large (forward production dominated by high x gluon and low energy photon).

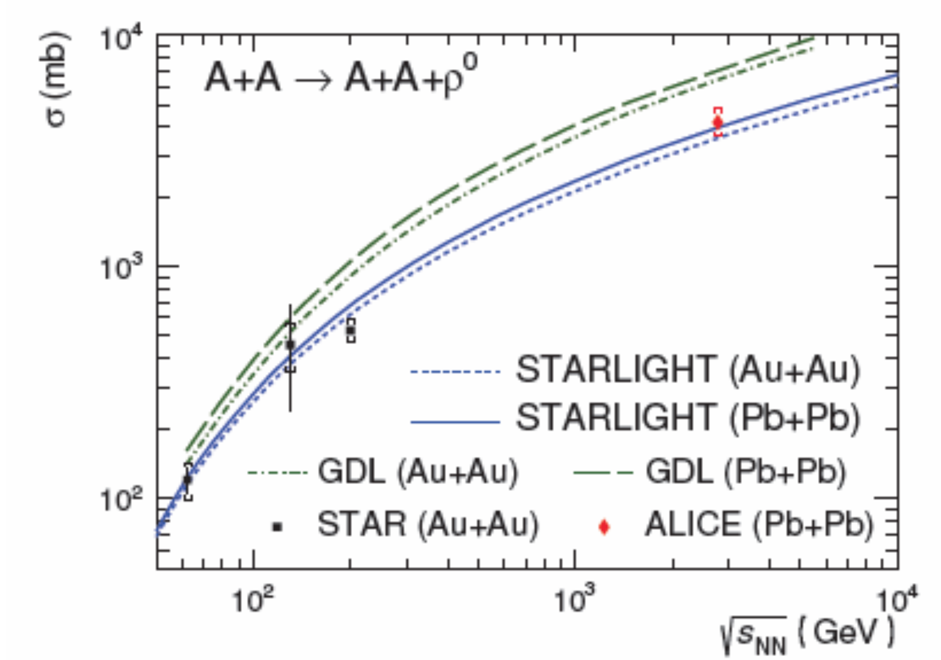
Other Vector Mesons in AA at ALICE



Qualitatively similar picture emerging from Ψ(2S) and ρ mesons



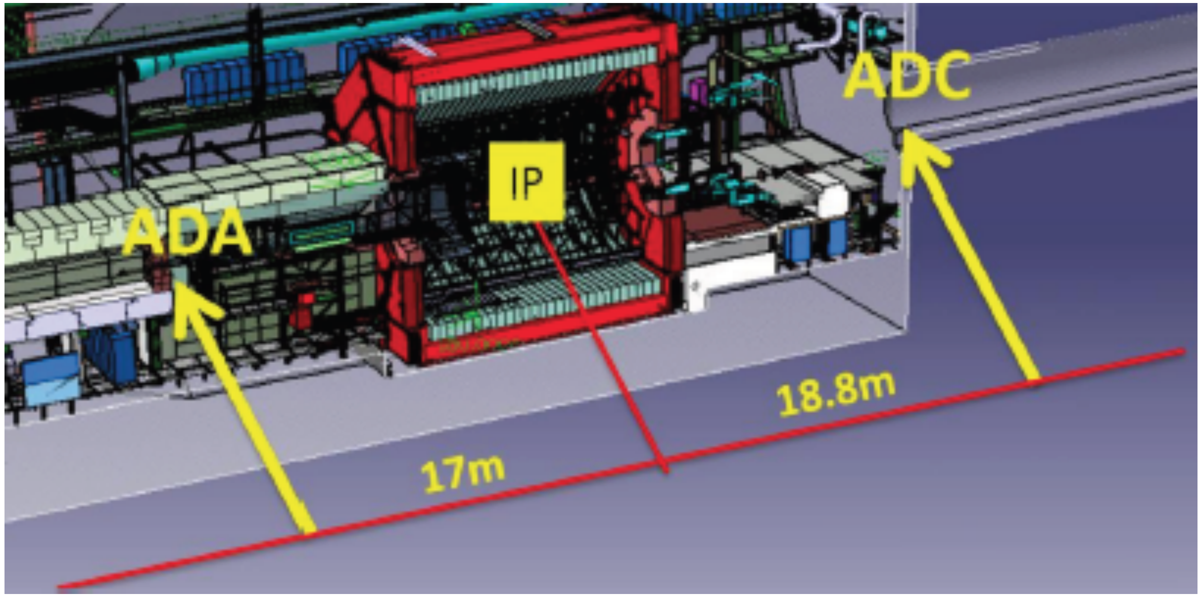
arXiv:1503.09177v1 [nucl-ex]



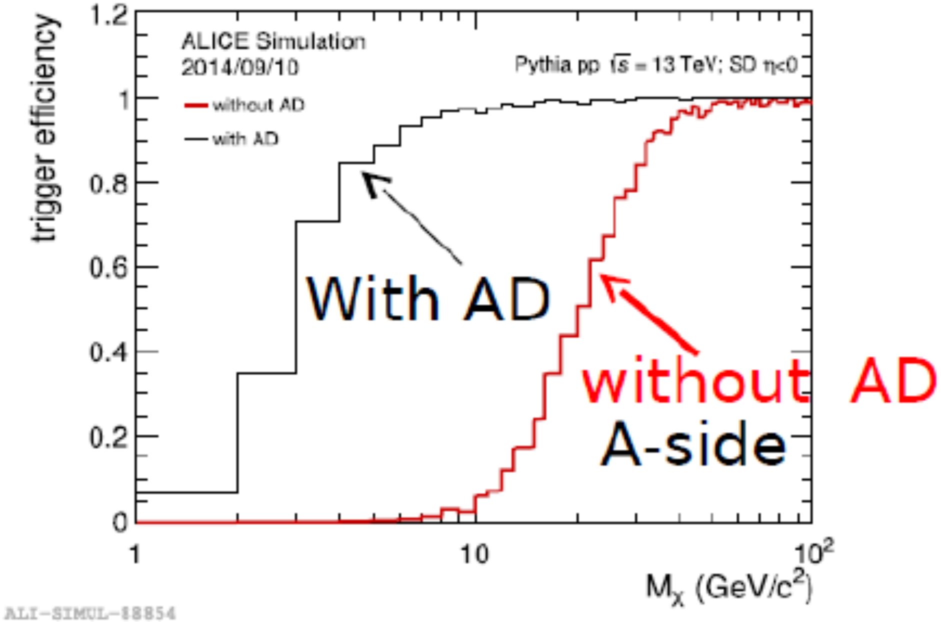
arXiv:1503.09177v1 [nucl-ex]

Future Prospects: Short Term

Forward scintilators
implemented at ALICE
→ Trigger on low ξ SD
→ Veto DD in gap
based analyses



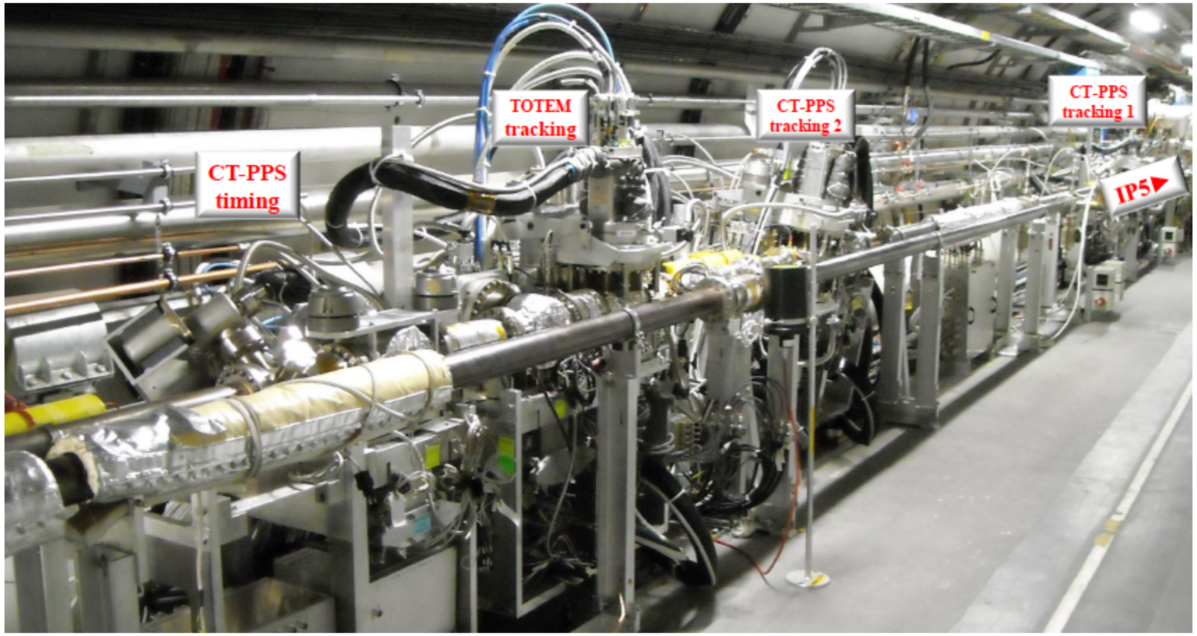
$4.8 < \eta < 6.3$



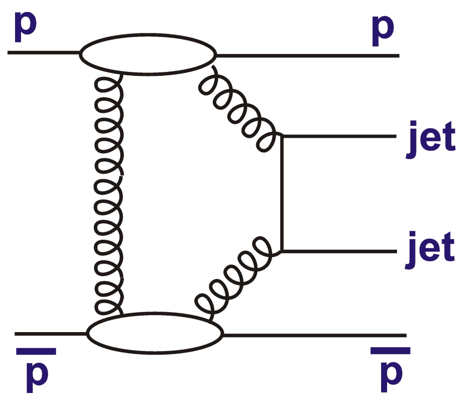
… expect improved precision for ultra-peripheral vector mesons and single diffraction

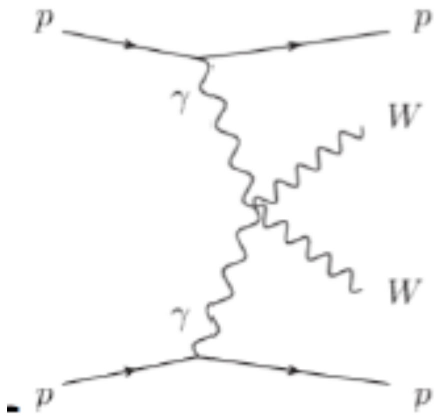
Future Prospects: Longer Term

New Roman pots at CMS-TOTEM (CT-PPS) and ATLAS (AFP) with ~10ps timing detectors allow pile-up suppression by time-of-flight



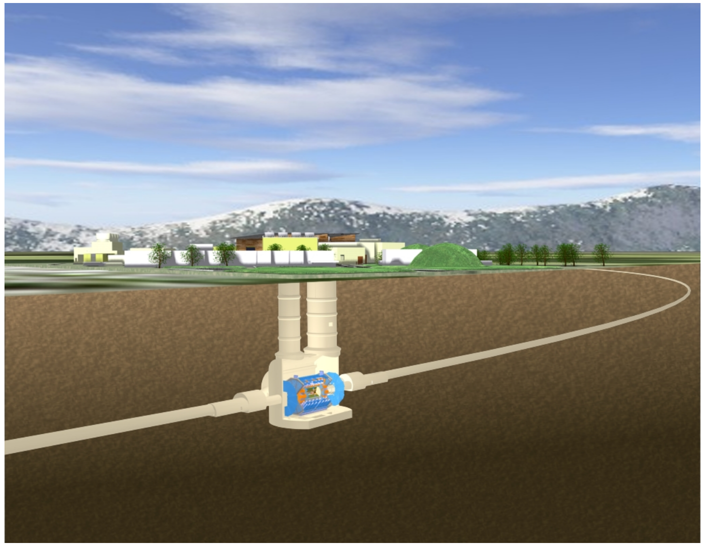
… installation to begin Winter 2015-16





New era of studying ~100fb^{-1} double proton-tagged samples with sensitivity to EW processes and searches (eg quartic gauge couplings) as well as to rare diffractive processes (eg exclusive dijet production)

Summary



Precise elastic & total cross section data
- Broadly in line with expectations
- More to come in large|t| elastics

Increasingly Detailed Soft Diffractive (Single)-Dissociation data
- Soft pomeron with intercept as expected works for soft dissociation
- `Global fits' needed to fully interpret
- Proton tagging required for DD/ND supression

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

Impressive Ultra-peripheral J/Ψ and Other VM Data
- New high W region maps well onto HERA
- No evidence for change in behaviour of low x gluon density