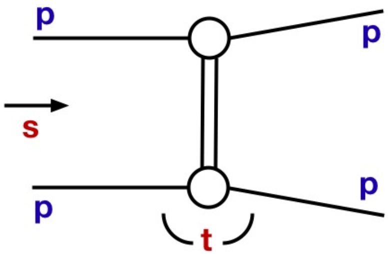
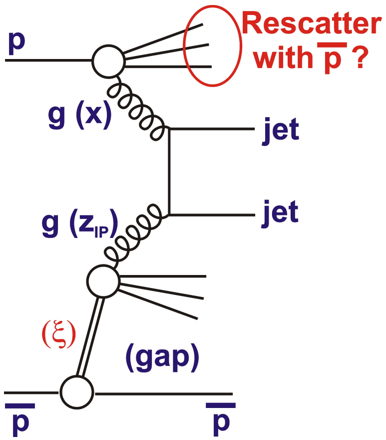
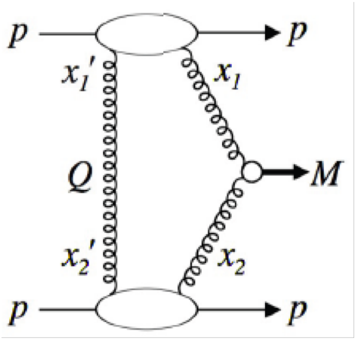
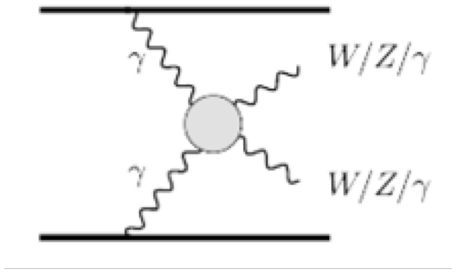
Elastic and Diffractive Scattering at the LHC

… a review of the story so far and prospects for the future …









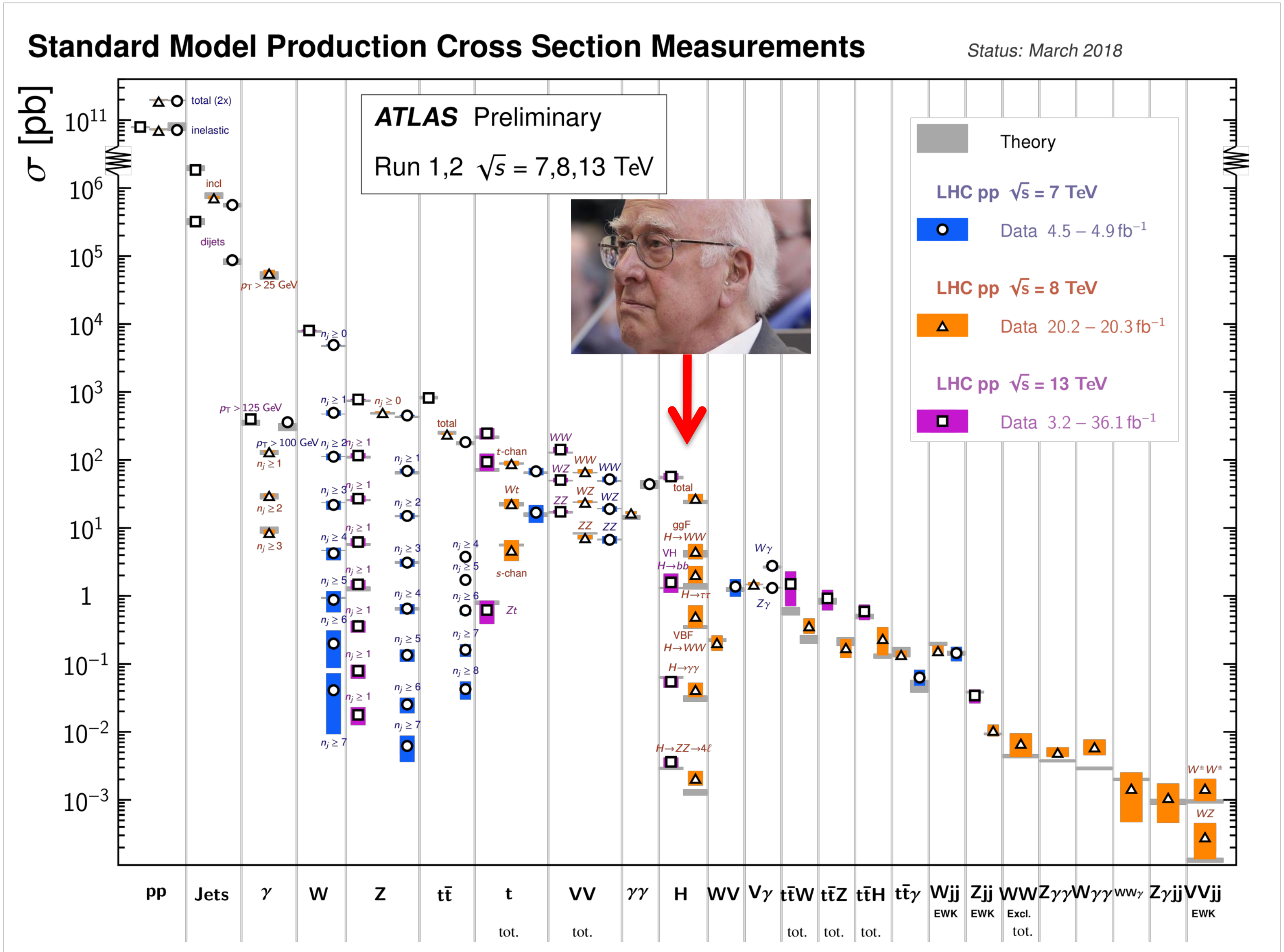
Paul Newman
(University of Birmingham)

Saclay seminar,
28 January 2019

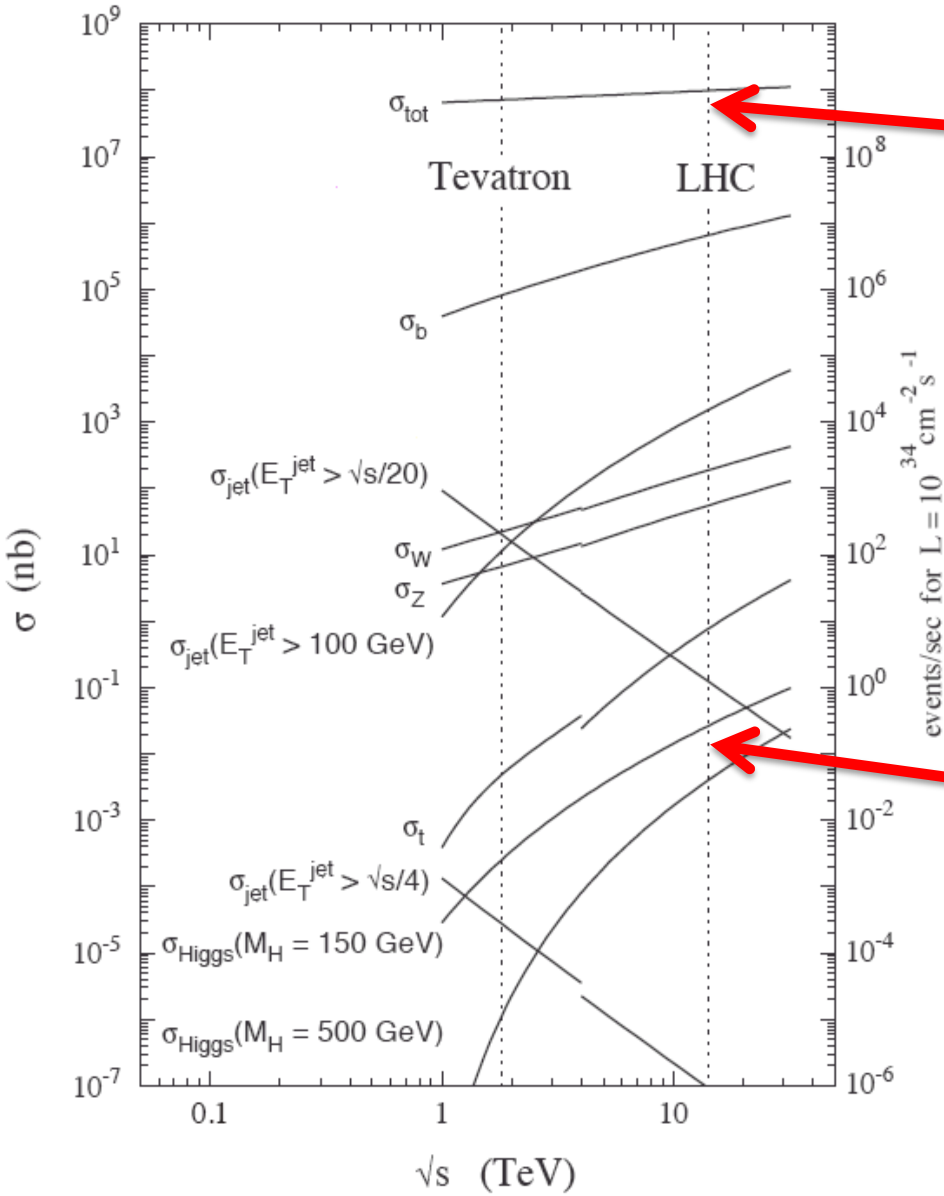
→ Elastic and Total Cross Sections
→ Soft Diffractive Dissociation
→ Hard Diffractive Dissociation
→ [~~Ultra-peripheral Vector Mesons~~]
→ Prospects for Central Exclusive Production

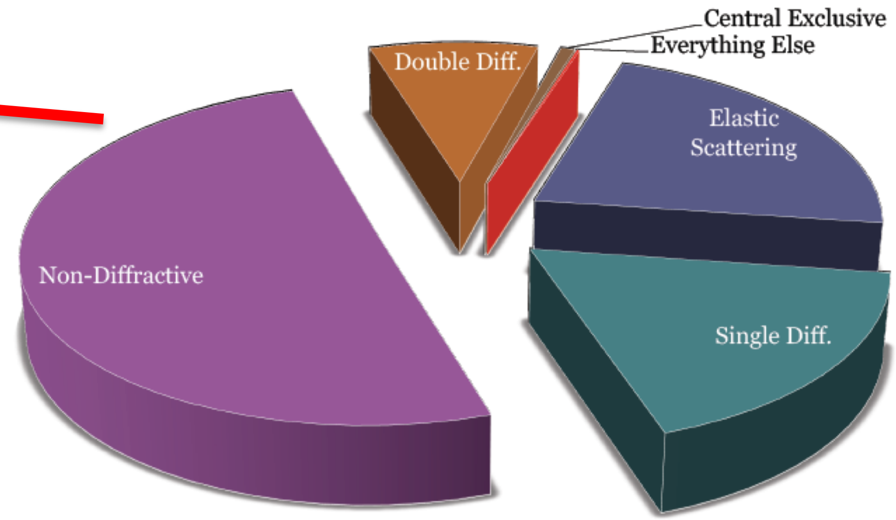
MIND THE GAP

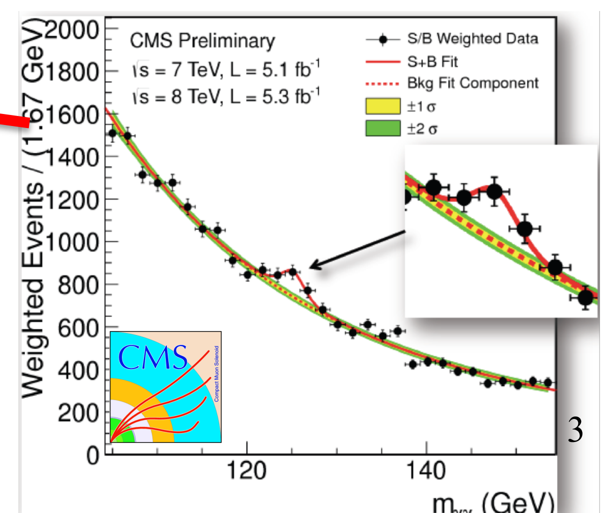
LHC: Exploring the ultra-rare at the Energy Frontier



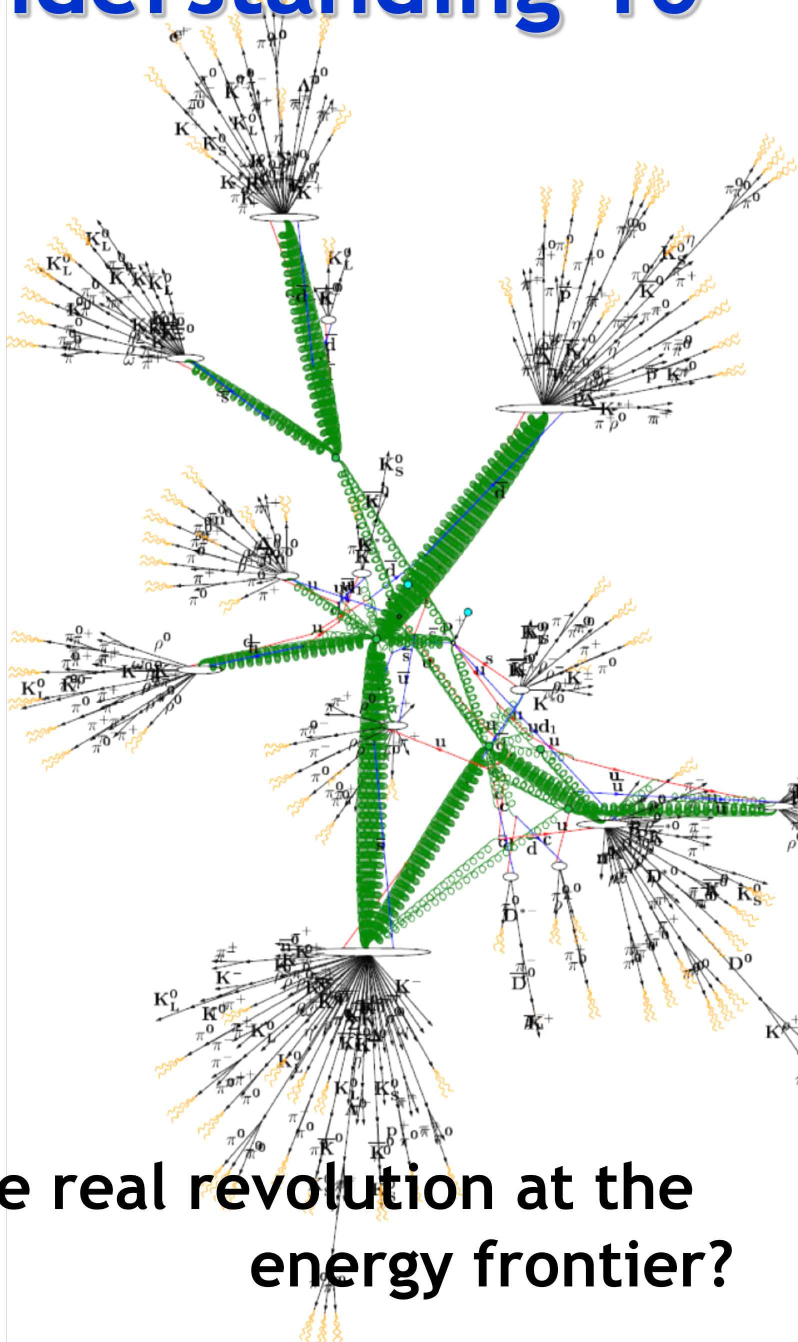
But what usually happens when hadrons collide at large $\sqrt{s}$?







Understanding 10^{-1} Processes is Hard!

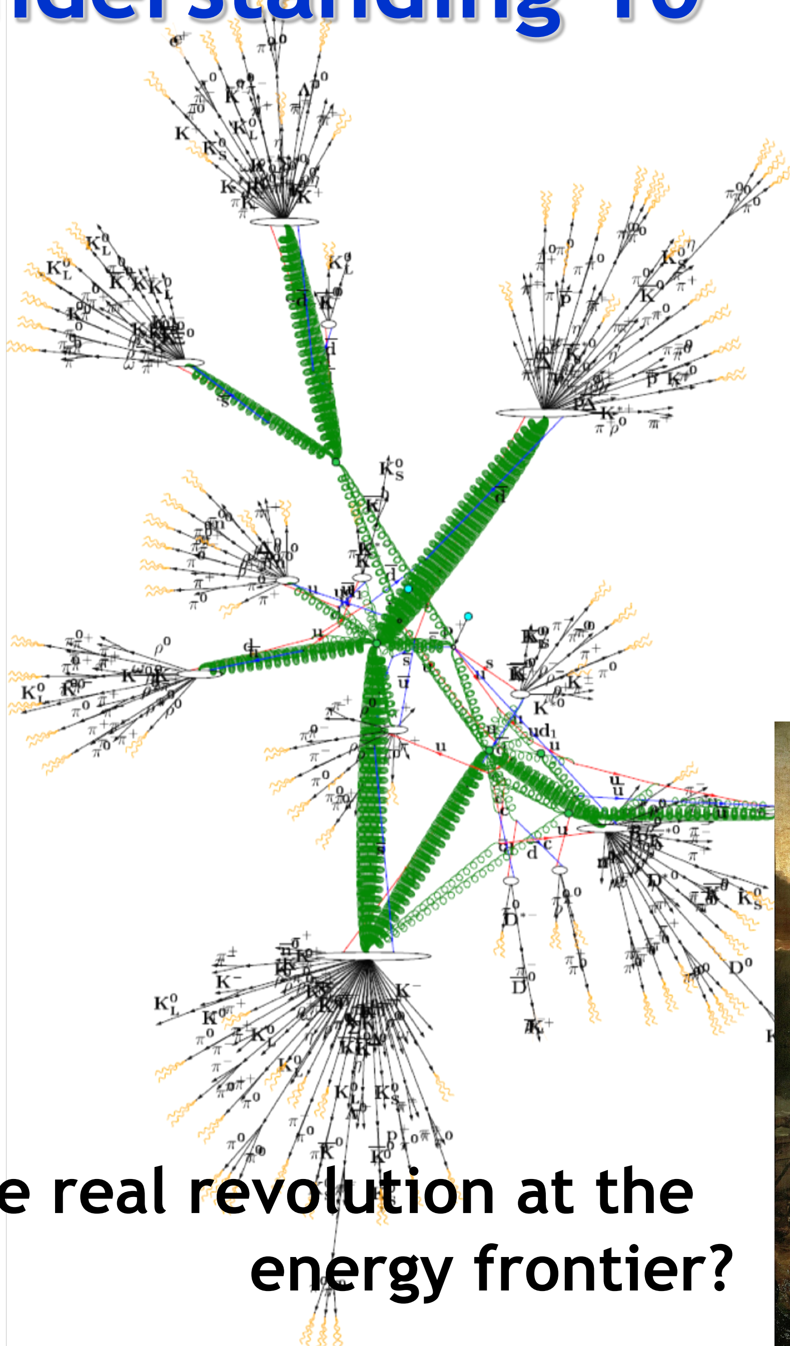


"minimum bias" pp event in PYTHIA8 at $\sqrt{s}$=7 TeV, visualised using MCViz

Eugène DELACROIX: La Liberté guidant le peuple

… the real revolution at the energy frontier?

Understanding 10^{-1} Processes is Hard!



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

Théodore Géricault
Le Radeau de la Méduse

... the real revolution at the energy frontier?

Why should we Care?

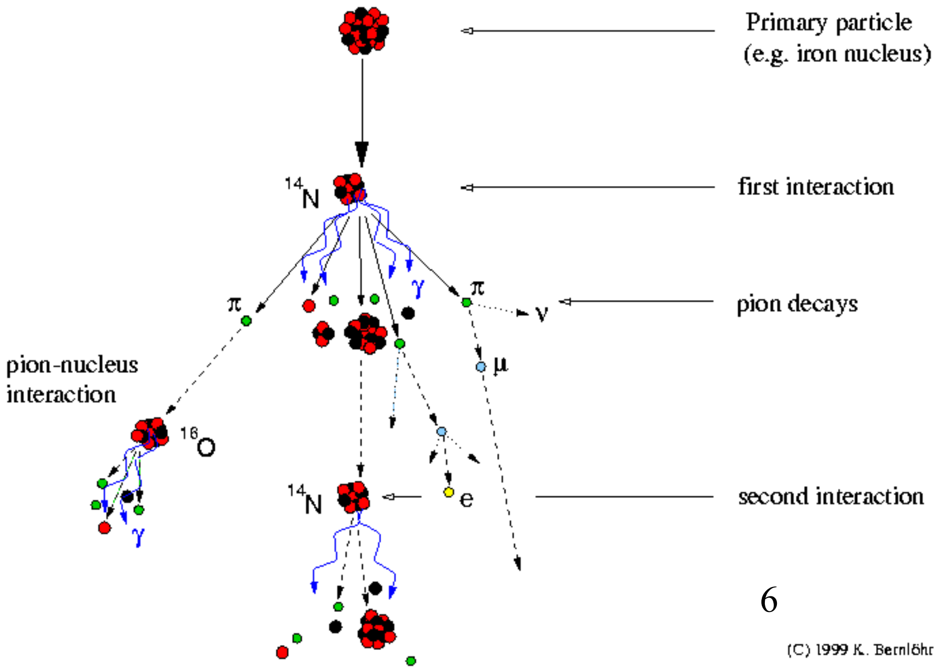
Everyday strong interaction processes intimately linked to our basic understanding of physics:

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
- Luminosity monitoring
- Modelling cosmic ray air showers
- ...

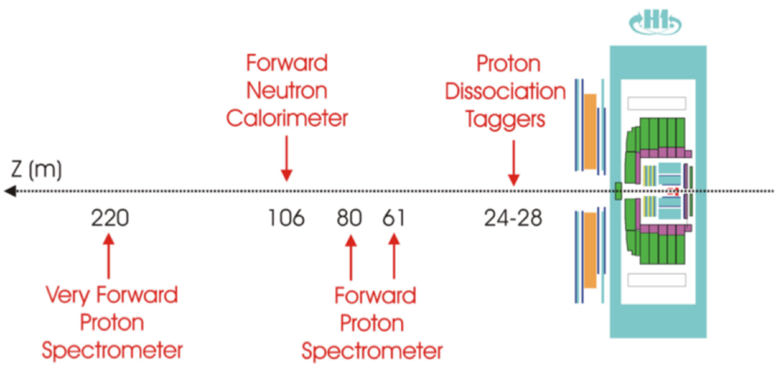


Methods for Diffraction and Elastics

… old slide from diffraction at HERA

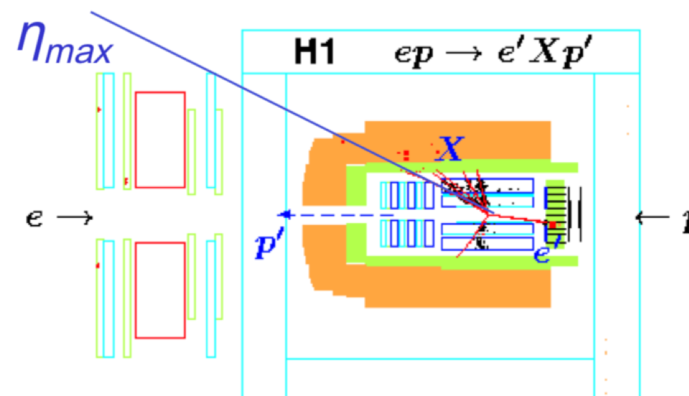
Signatures and Selection Methods

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



Limited by statistics and p-tagging systematics

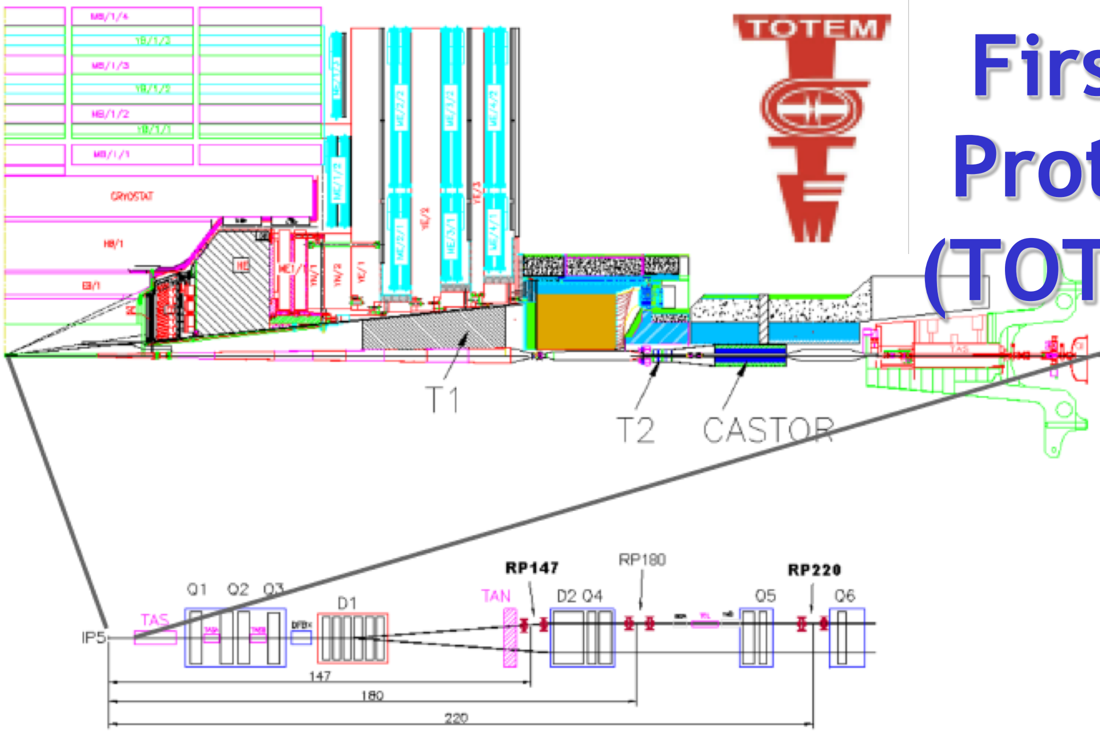
\`Large Rapidity Gap' **(LRG)** adjacent to outgoing (untagged) proton

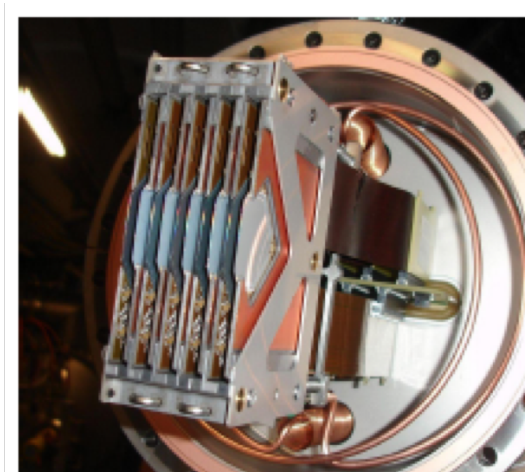


Limited by p-diss systematics

Partially still true for LHC (but proton tagging technology got better and rapidity gaps got harder to identify)

First Generation LHC Proton Spectrometers (TOTEM & ATLAS-ALFA)

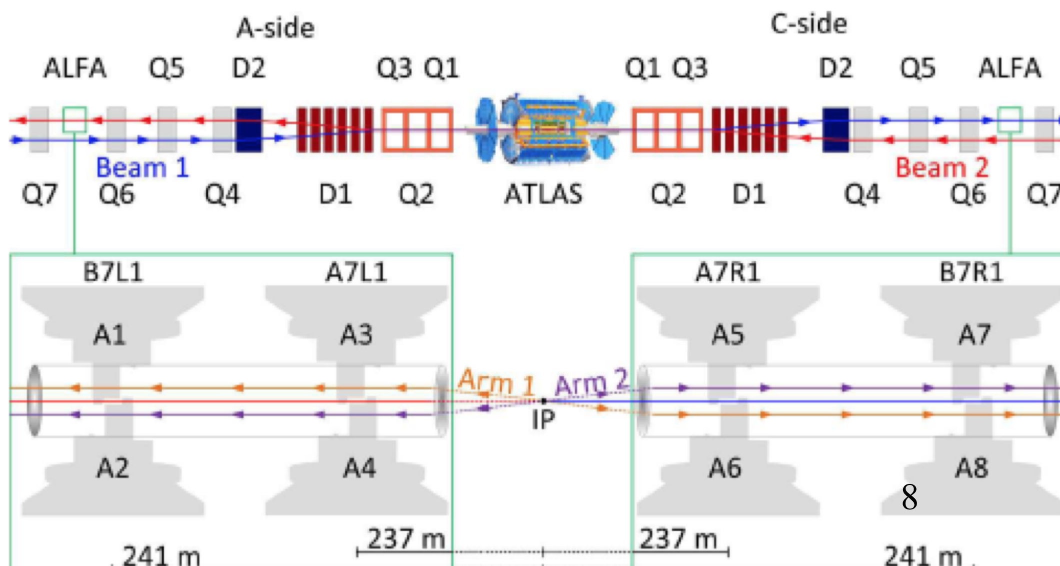




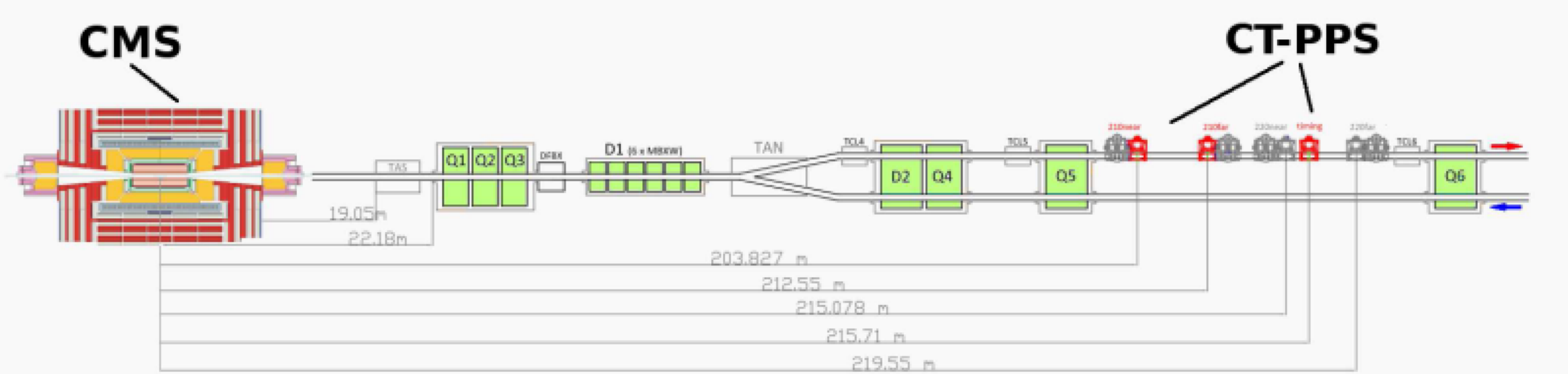
‘Roman pot’ vacuum-sealed insertions to beampipe, well downstream of IP.

→Usually deployed in dedicated (high β*) runs

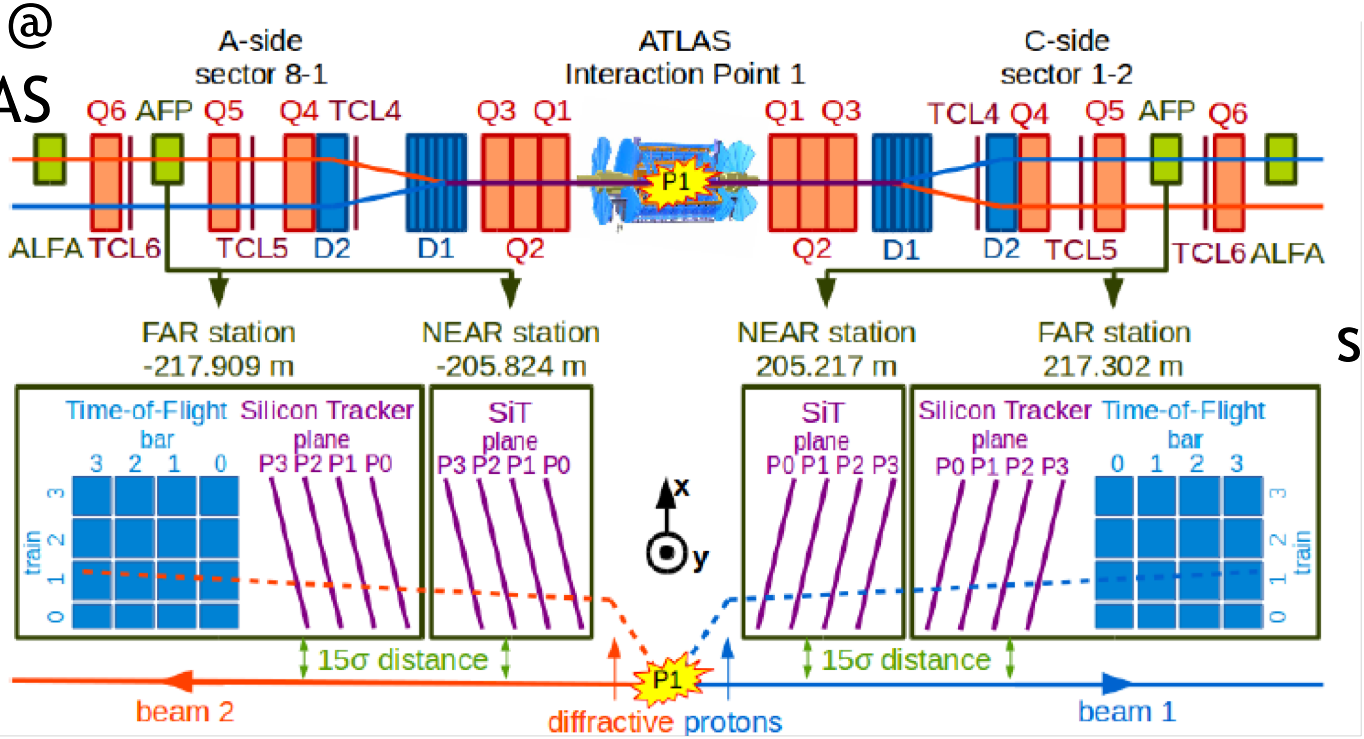
→ Can run independently of ATLAS / CMS or with common DAQ.



Second Generation LHC Proton Spectrometers (CT-PPS at CMS and AFP at ALFA)

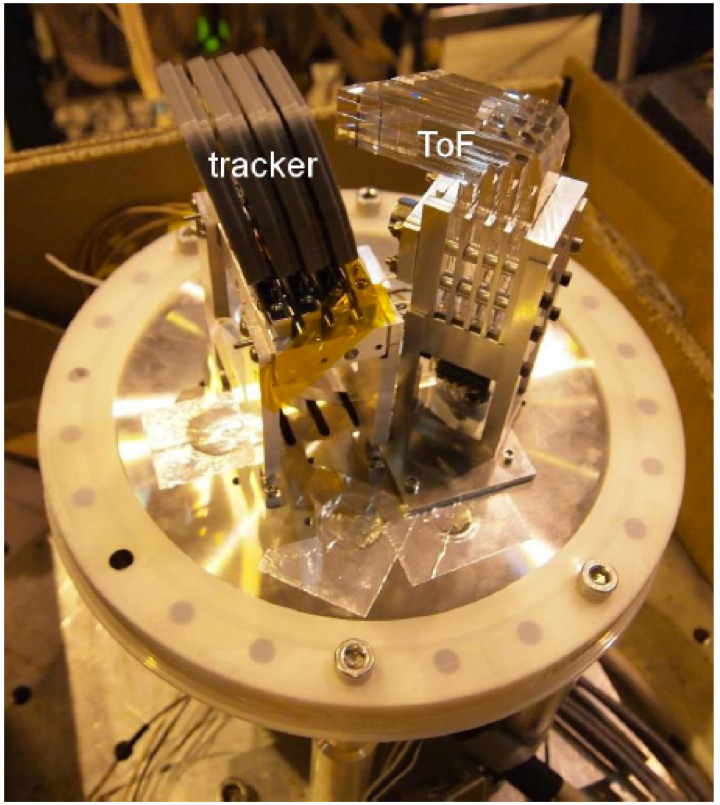


AFP @ ATLAS



Designed to operate in standard high luminosity runnning.

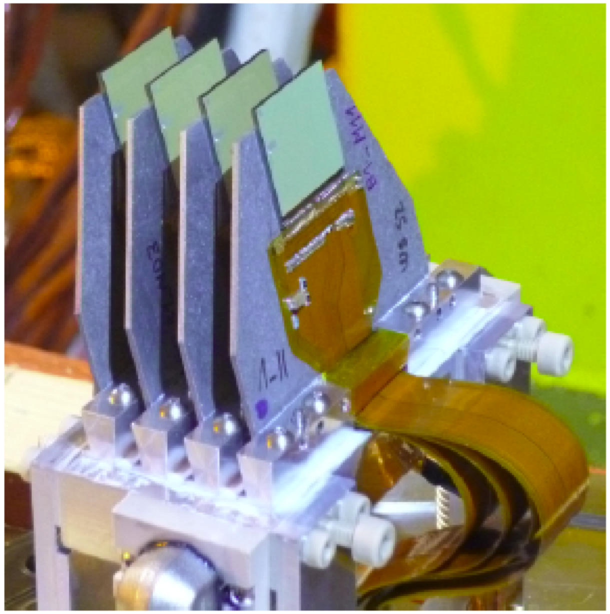
AFP Detectors

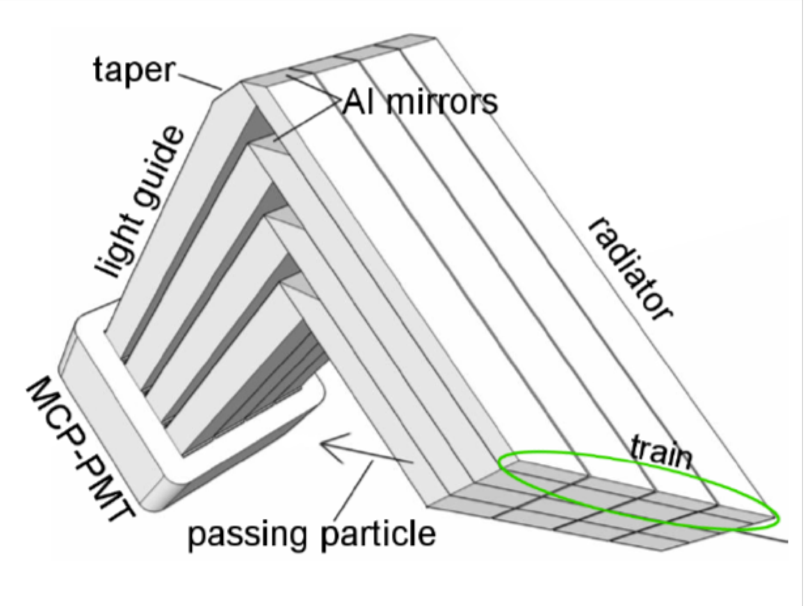


Tracking: four slim-edge 3D pixel sensor planes per station (IBL)

- Pixel sizes 50x250 μm
- 14^o tilt improves x resolution (hence ξ)
  → δx = 6 μm, δy = 30 μm
- Trigger capability

Timing: 4x4 quartz bars at Cerenkov angle to beam. Light detected in PMTs
→ resolution 25ps demonstrated

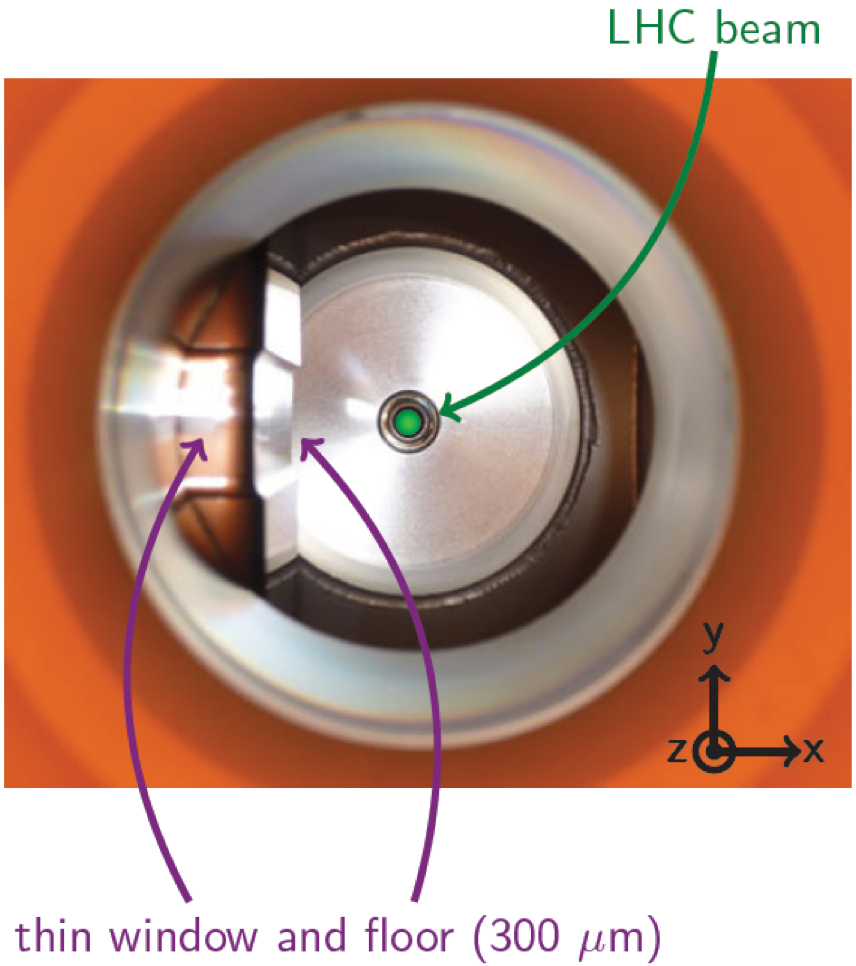




Advantages of Roman Pot Technology

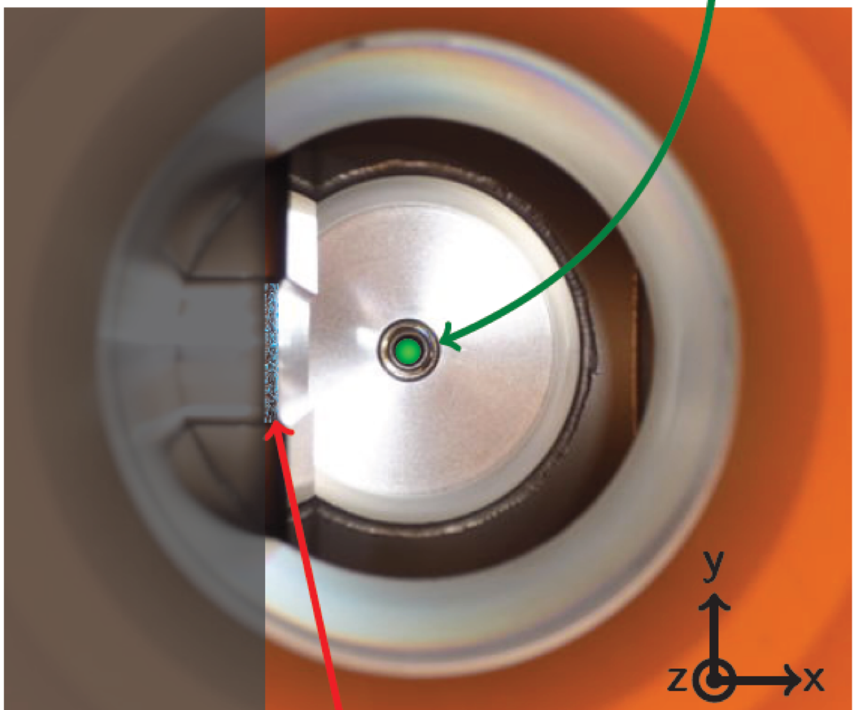
[a nice illustration, from AFP, with thanks to Maciej Trzebinski]

Advantages of Roman Pot Technology



shadow of TCL4 and TCL5 collimators

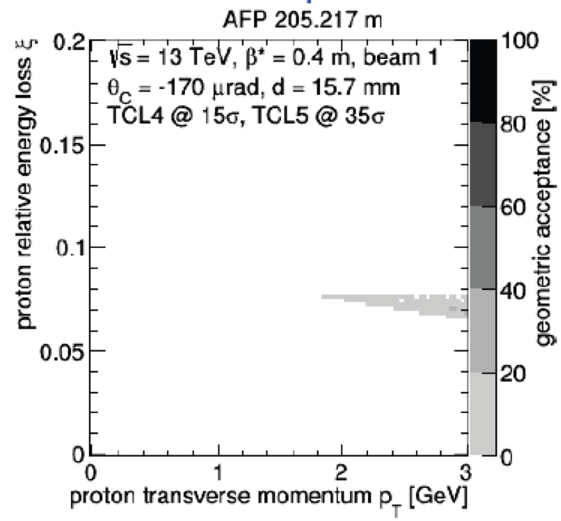
LHC beam



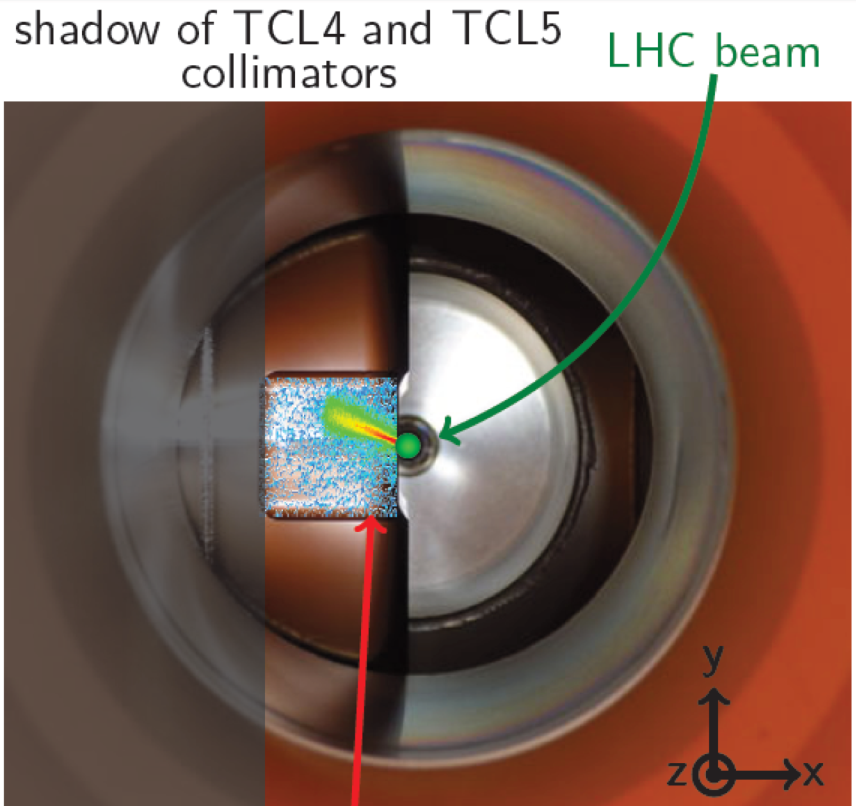
diffractive protons

thin window and floor (300 μm)

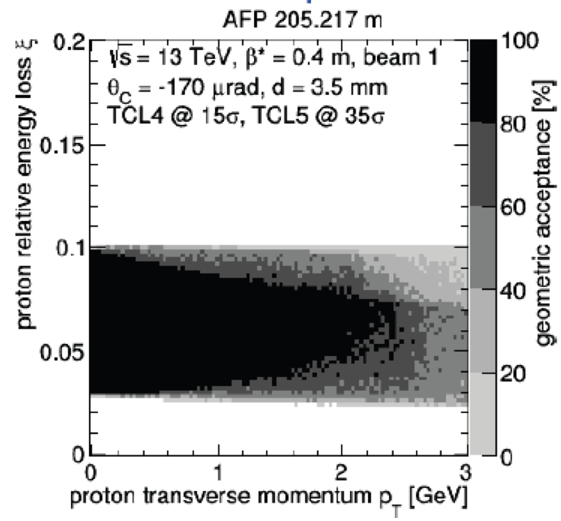
Geometric acceptance:



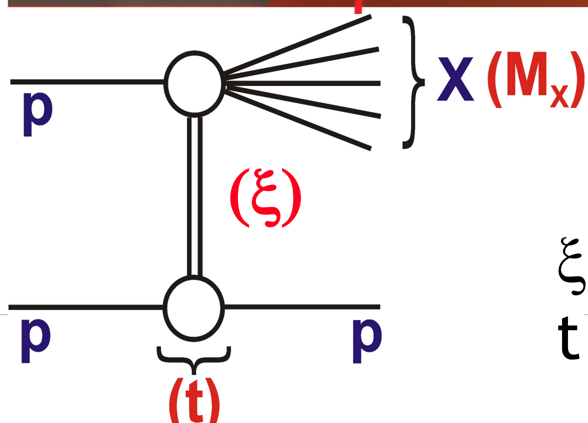
Advantages of Roman Pot Technology



Geometric acceptance:



Described here in terms of kinematics of `Single Diffractive Dissociation' (SD)

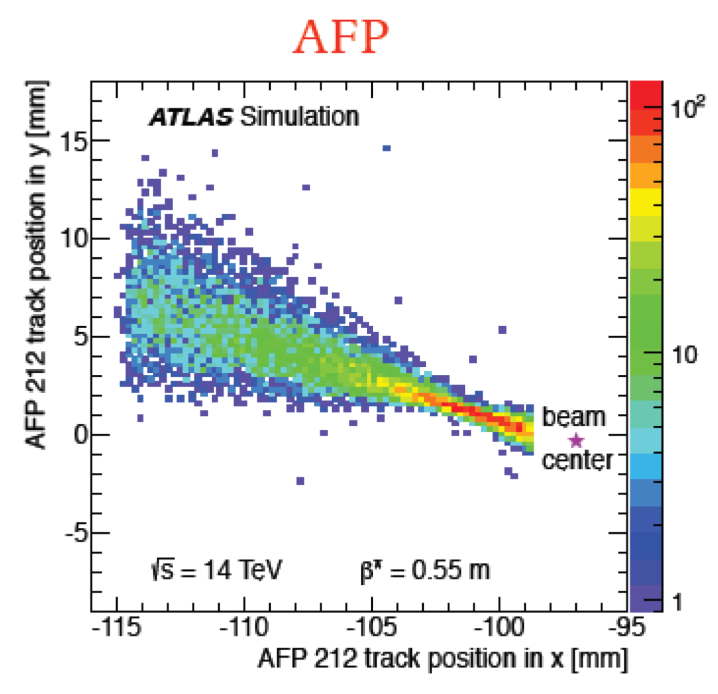


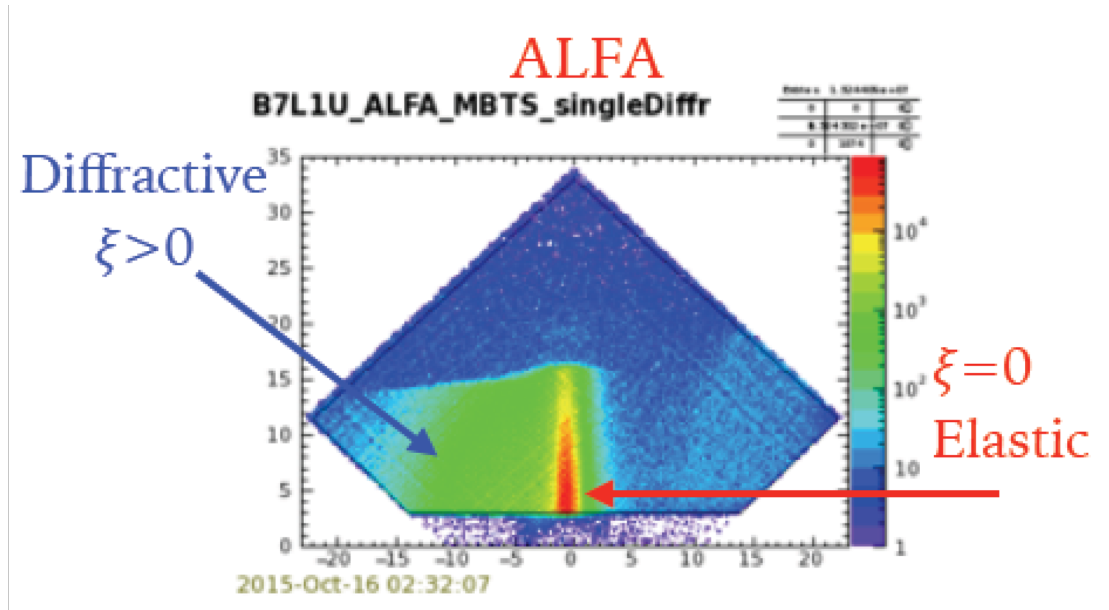
ξ = fractional proton energy loss

$t = -p_T^2$ of outgoing proton

Acceptance Depends on Location and Orientation of Pot (horizontal or vertical) and on beam optics

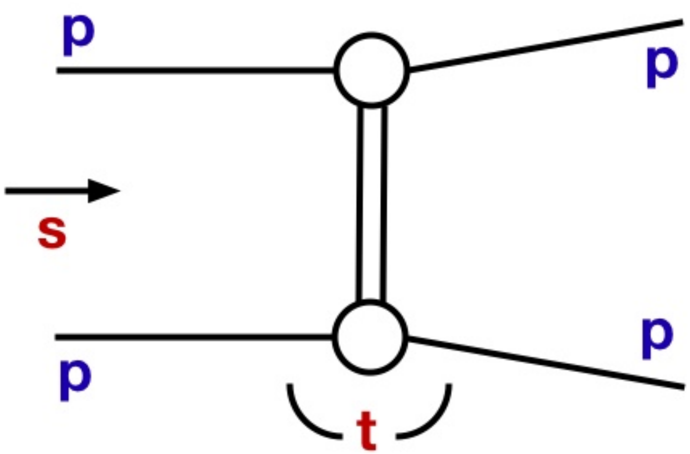
e.g. complementarity between ATLAS ALFA and AFP

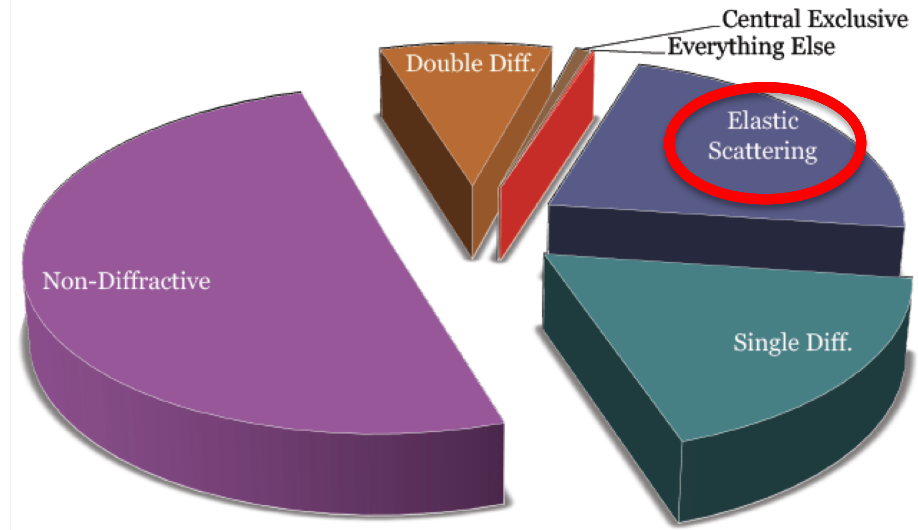




- ALFA is optimised for Elastic scattering
- AFP acceptance for Inelastic diffraction with ξ >~ 0.02

Start `Simple': Elastic Scattering

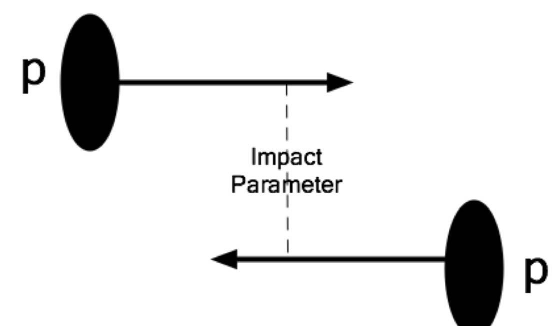




At fixed √s, 1 non –trivial variable
→ squared 4-momentum transfer, t

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

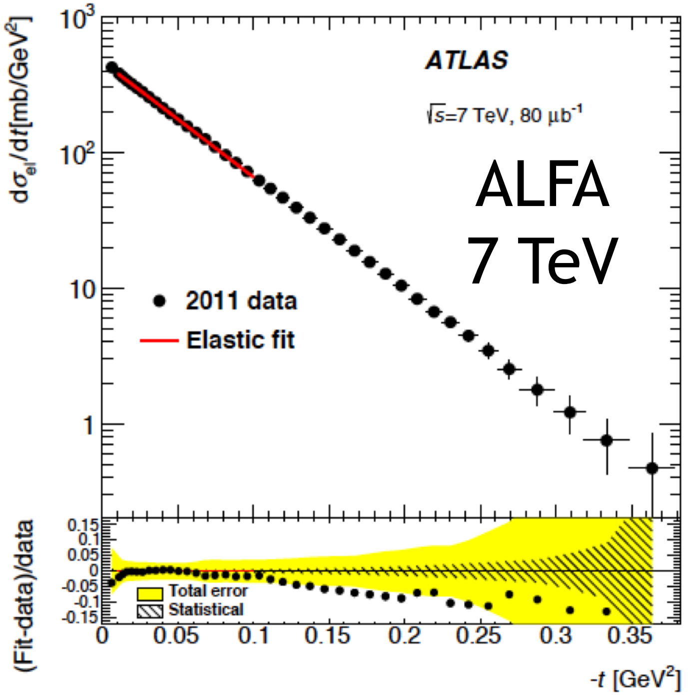
At fixed s: $$\frac{d\sigma}{dt} = \left.\frac{d\sigma}{dt}\right|_{t=0} e^{Bt}$$

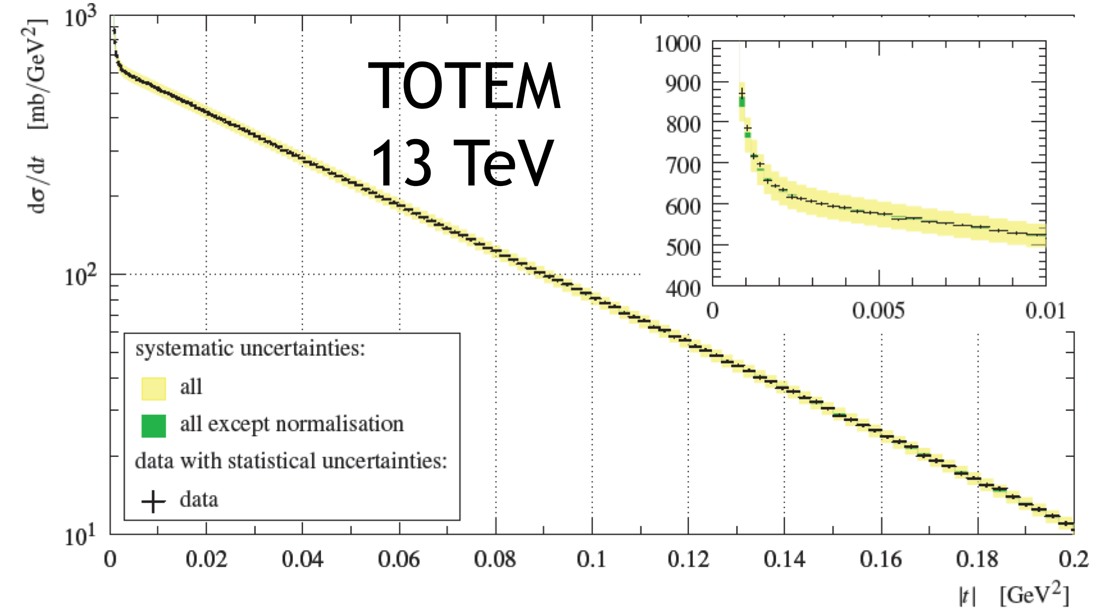


Slope parameter B measures mean impact parameter (~size of interaction region ~ range of strong force ~1-2fm).

Example Elastic Scattering Data

Precise t dependence over ‘bulk’ range of |t|at LHC





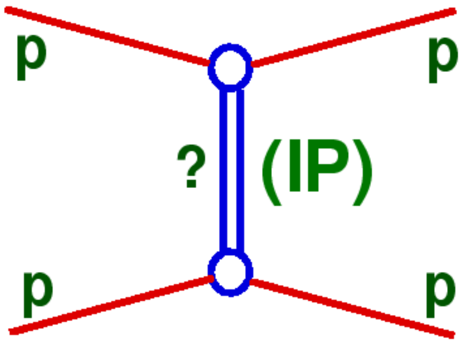
`Standard’ exponential fit, excluding lowest |t| (influence of Coulomb, rather than hadronic, scattering) and largest |t|(various pQCD effects)

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

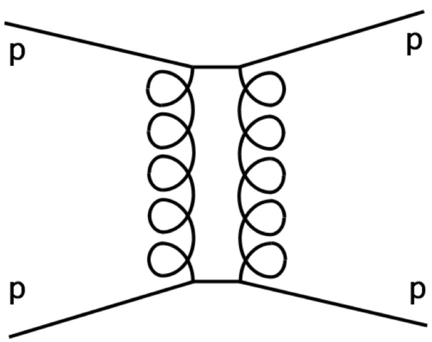
e.g. at √s=7 TeV …

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

Universal Exchange Picture of Elastic and Diffractive Scattering



- Historically, Regge phenomenology offers unified picture in terms of trajectory exchanges
- `Pomeron' exchange dominates for sufficiently large $\sqrt{s}$.



- Loosely interpreted as exchange of two gluons in net colour singlet state [but beware partonic language in non-perturbative regime]

For **elastic scattering** at fixed t:

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

Pomeron trajectory:

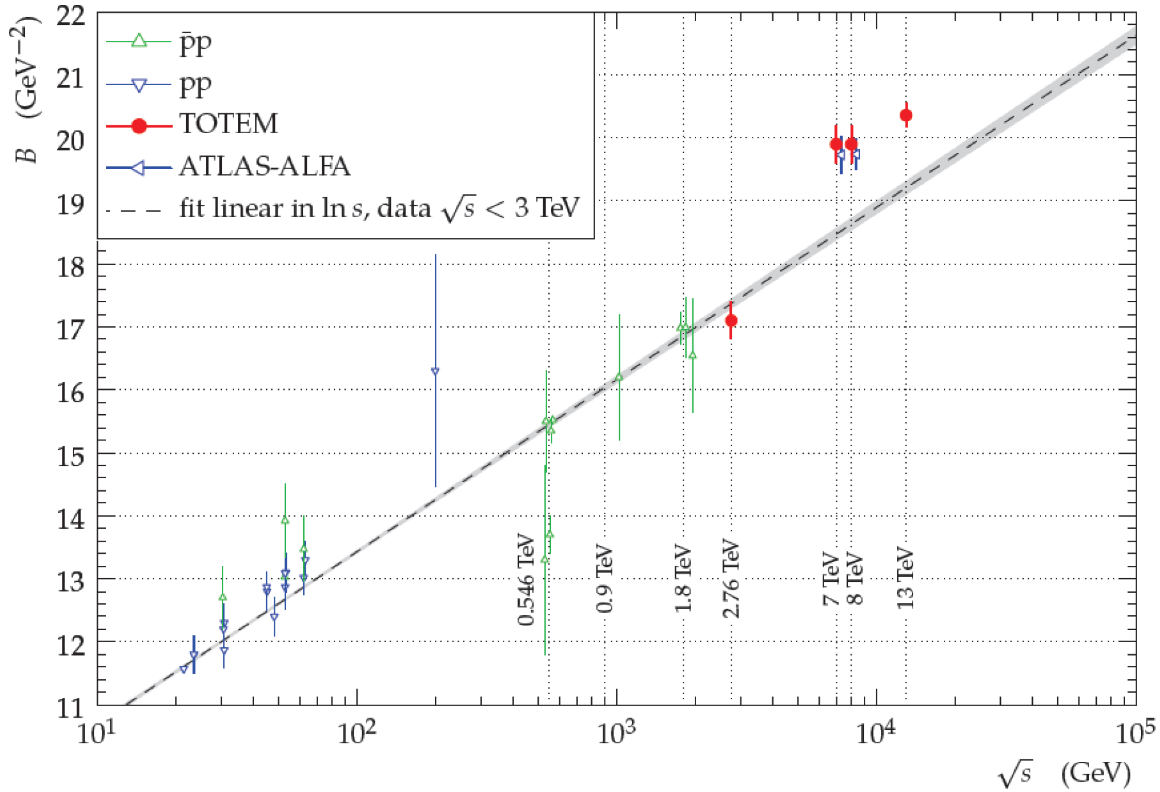
$$\alpha(t) = \alpha(0) + \alpha' t \approx 1.085 + 0.25t$$

… Leads to slope parameter growing logarithmically with energy

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

√s dependence of t Slopes

- B increases with √s … 'shrinkage' of forward elastic peak → Increase of mean impact parameter / effective proton size as longer-lived fluctuations develop larger transverse size.



From fits at fixed s:

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

`Standard' Pomeron `pole' Regge theory

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

- Growth seems faster than `standard' α' ~ 0.25 GeV^{-2} → Single pomeron exchange insufficient (absorptive corrections / different physics)

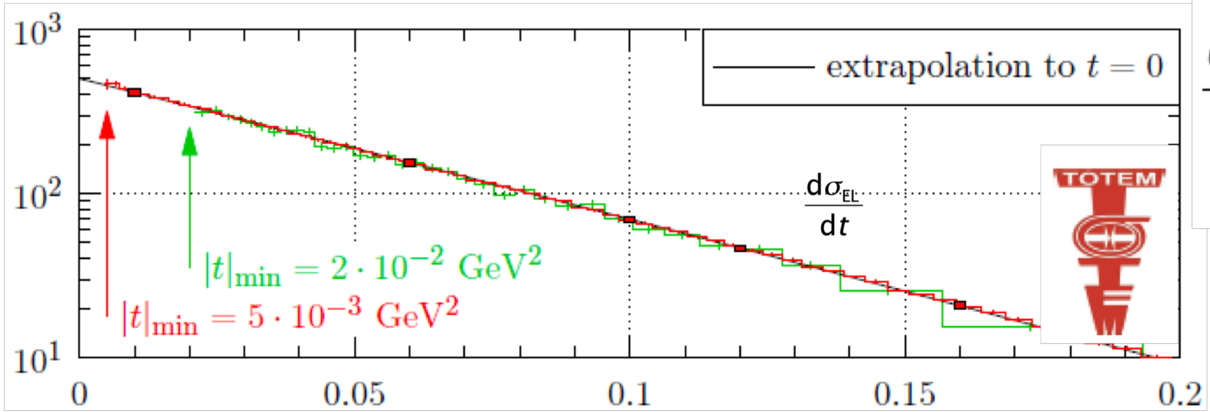
From Elastic to Total Cross Sections

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

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

e.g in Regge language, leads to $\sigma_{tot} \propto \left(\frac{s}{s_0}\right)^{\alpha(0)-1}$

Asymptotically (Froissart bound) limited to $\ln^2 s$ dependence

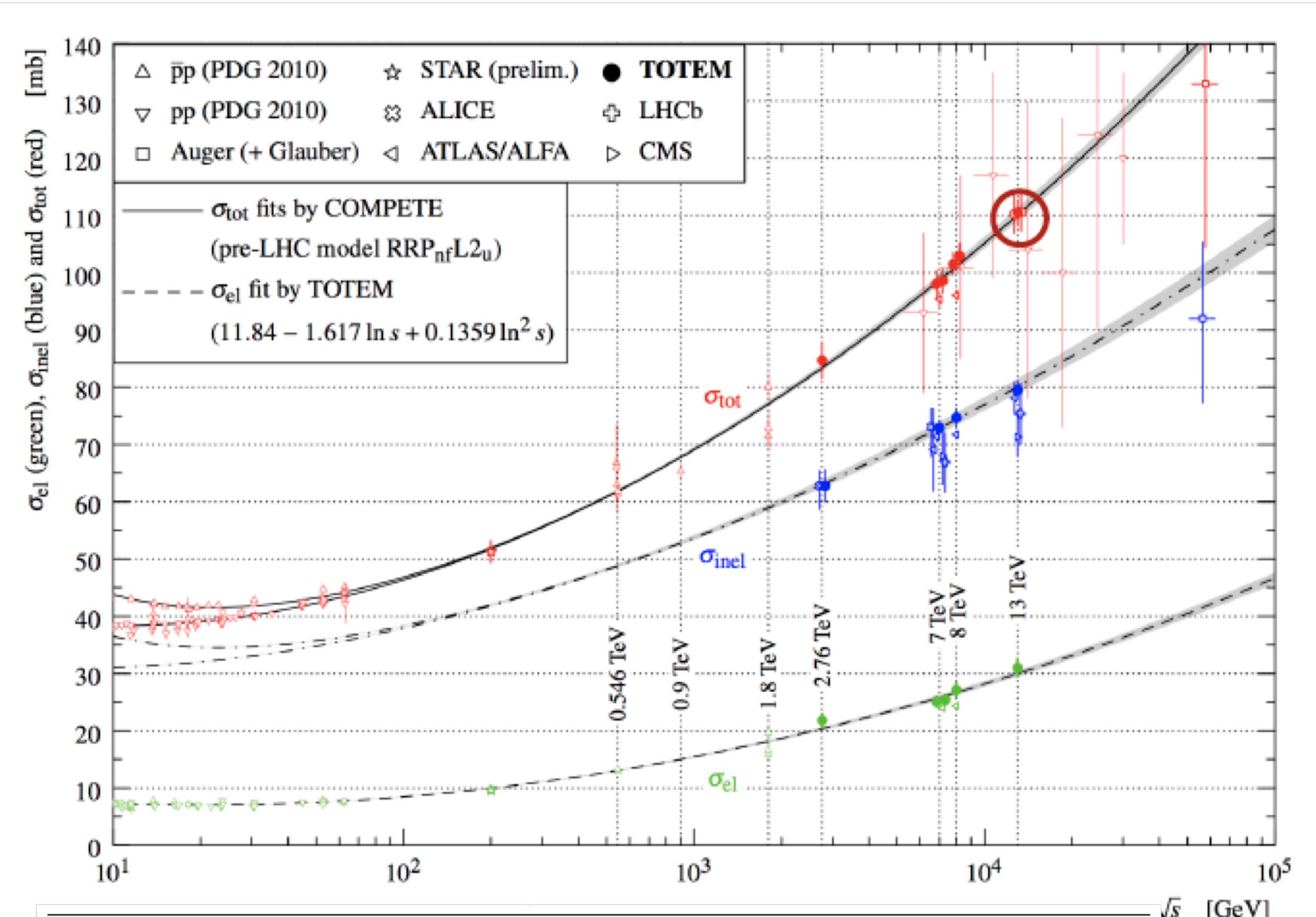


$\left.\frac{d\sigma_{EL}}{dt}\right|_{t=0}$ obtained through extrapolation of hadronic part of elastic cross section (~10% extrapolation)

ρ ~ 0.14 = Real / Imaginary part of hadronic amplitude at t=0

- Most recent / sophisticated treatment exploits Coulomb-Nuclear interference and fits to full t range and simultaneously extracts σ_{tot} and ρ … see later

Total (& Elastic) Cross Section versus √s



data	method	ρ	σ_{tot} [mb]
$\beta^* = 90\,\text{m}$	Ref. [6]	-	110.6 ± 3.4
$\beta^* = 2500\,\text{m}$	approach 1	0.09 ± 0.01	111.8 ± 3.2
	approach 2	0.09 ± 0.01	111.3 ± 3.2
	approach 3	$0.08(5) \pm 0.01$	110.3 ± 3.5
	approach 3 (single fit)	0.10 ± 0.01	109.3 ± 3.5
$\beta^* = 90$ and $2500\,\text{m}$	Ref. [6] $\oplus$ approach 3		110.5 ± 2.4

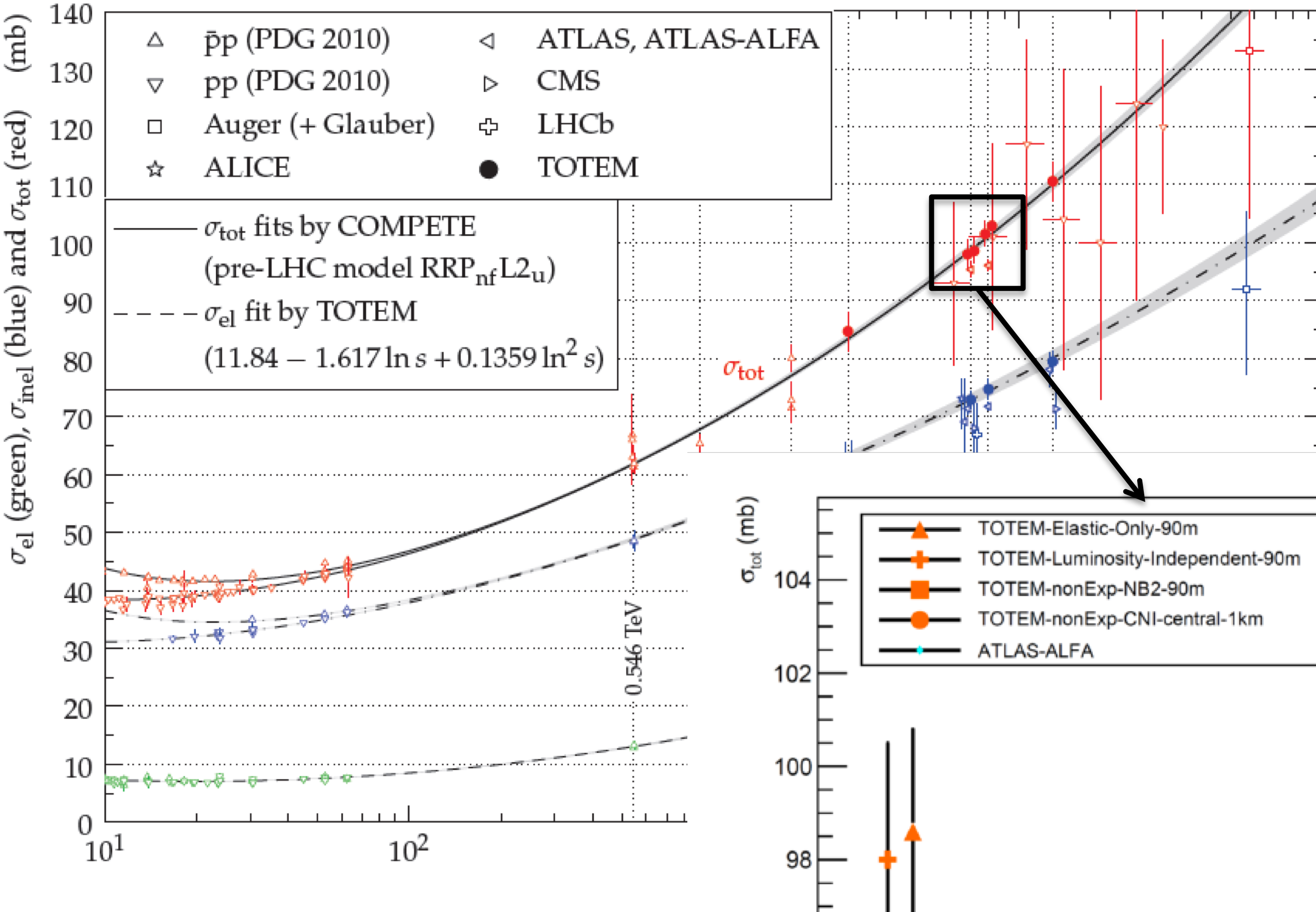
[TOTEM 13 TeV]

Multiple TOTEM Extractions at $\sqrt{s} = 13$ TeV → 2.5% precision

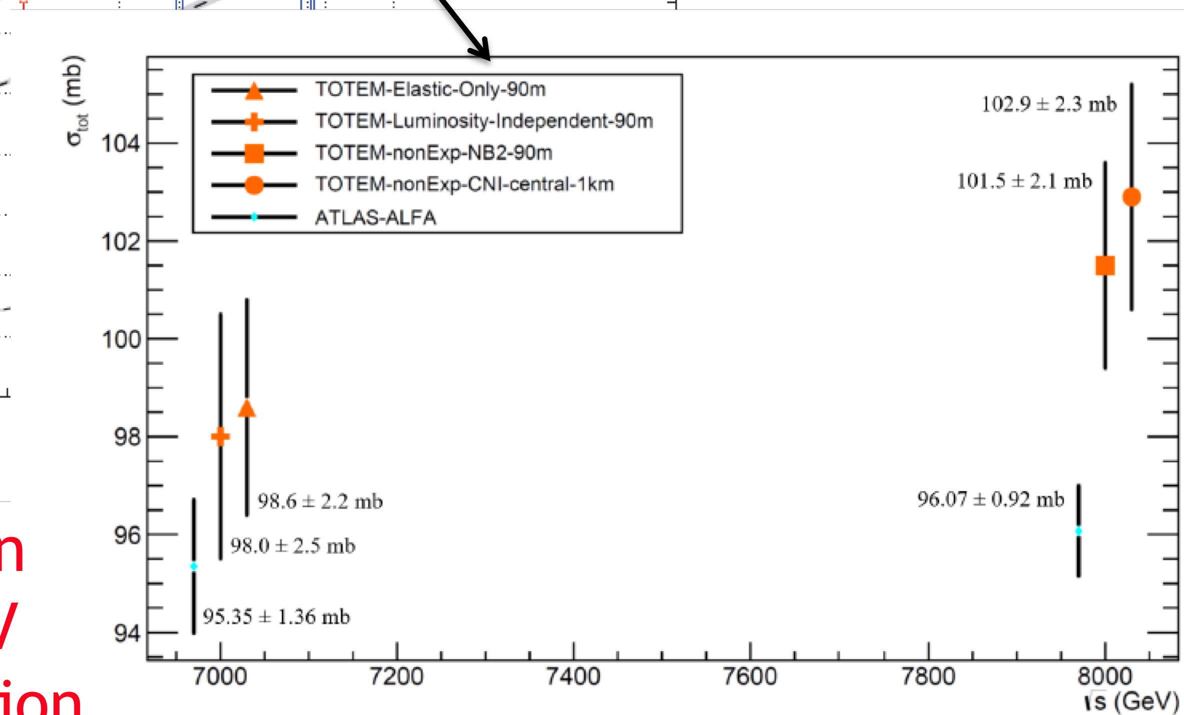
Cosmic ray data extend to 50 TeV!

Broadly consistent with fits to low energy data (with either logarithmic or power law behaviour)

Total (& Elastic) Cross Section versus √s



ATLAS-ALFA:
1% measurement
at 8TeV

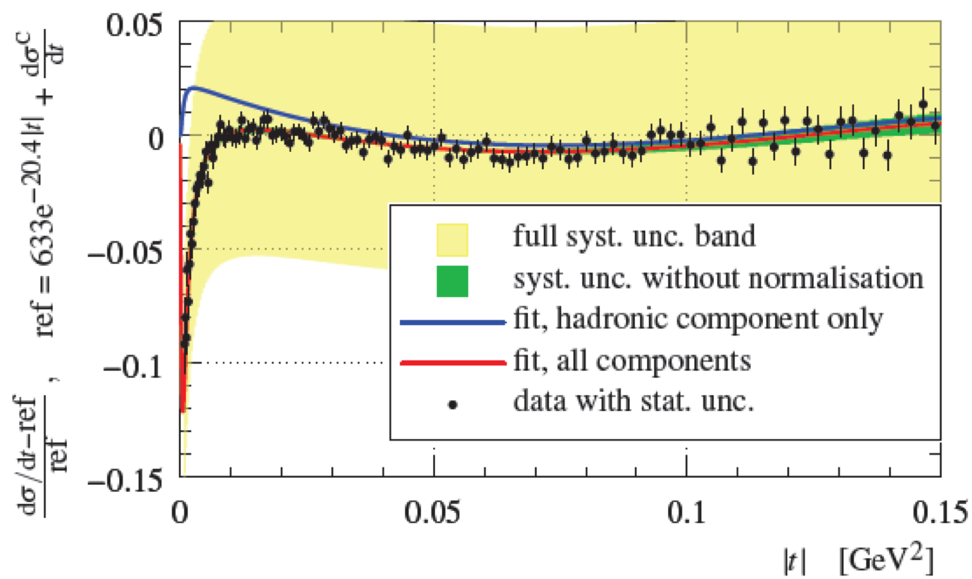


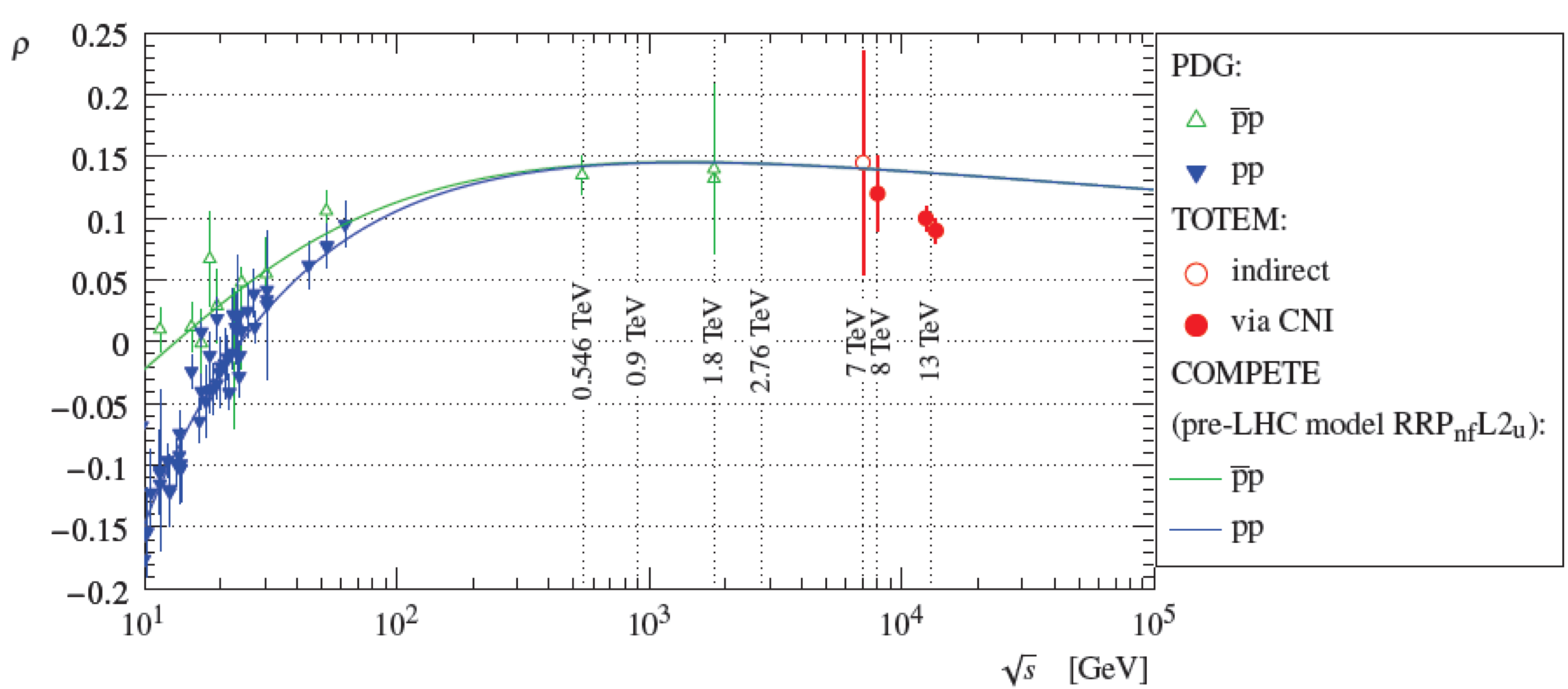
Small tension between
TOTEM & ALFA at 8 TeV
(traceable to normalisation
of elastic data)

First LHC Extraction of ρ Parameter

- Interference between Coulomb and Nuclear parts of elastic cross section is sensitive to ρ parameter
- Very high statistics TOTEM sample at 13 TeV ...

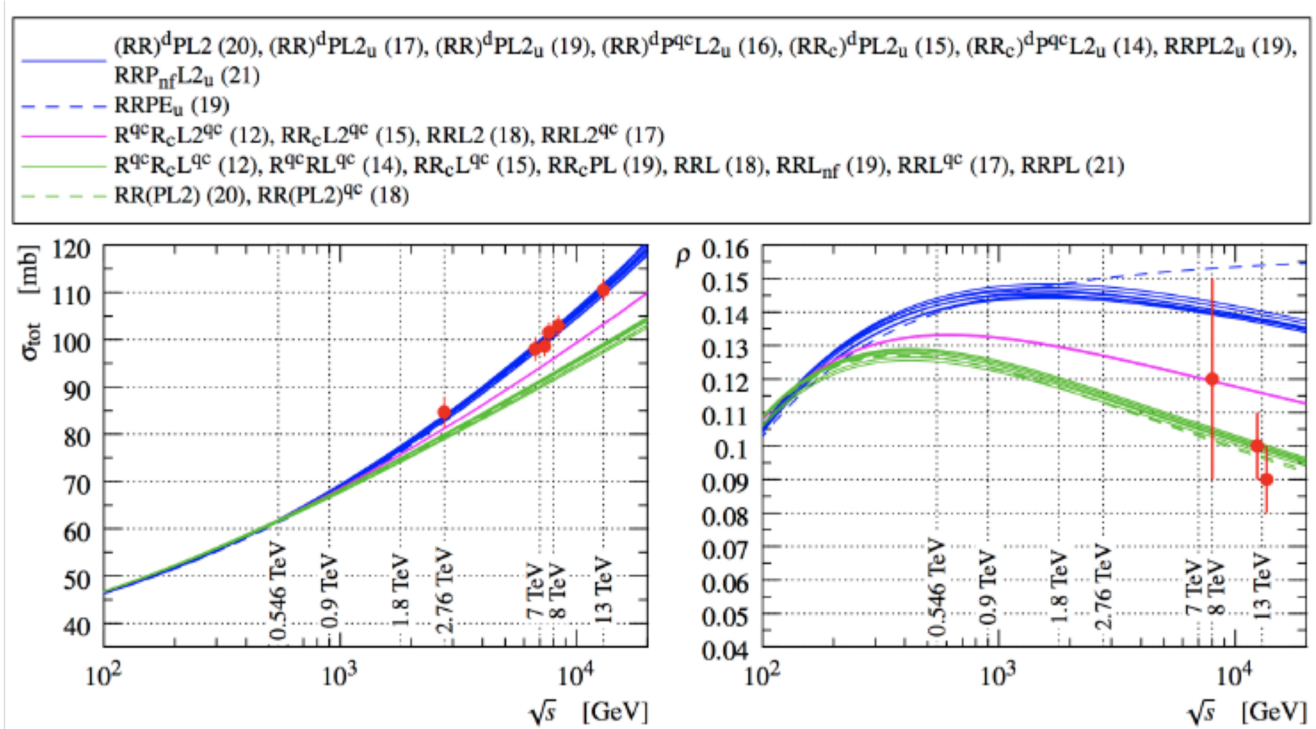
→ First LHC measurements of ρ





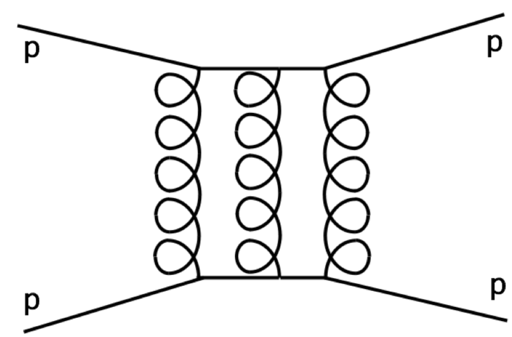
Interpretation as Evidence for Odderon

- No extrapolated pre-LHC model describes both ρ and σ_{tot} from 13 TeV TOTEM data (multiple models studied in `COMPETE' framework).



- Introducing a CP-odd contribution to the elastic exchange (i.e. an `odderon' – 3 gluon-based state) is one way of reconciling data

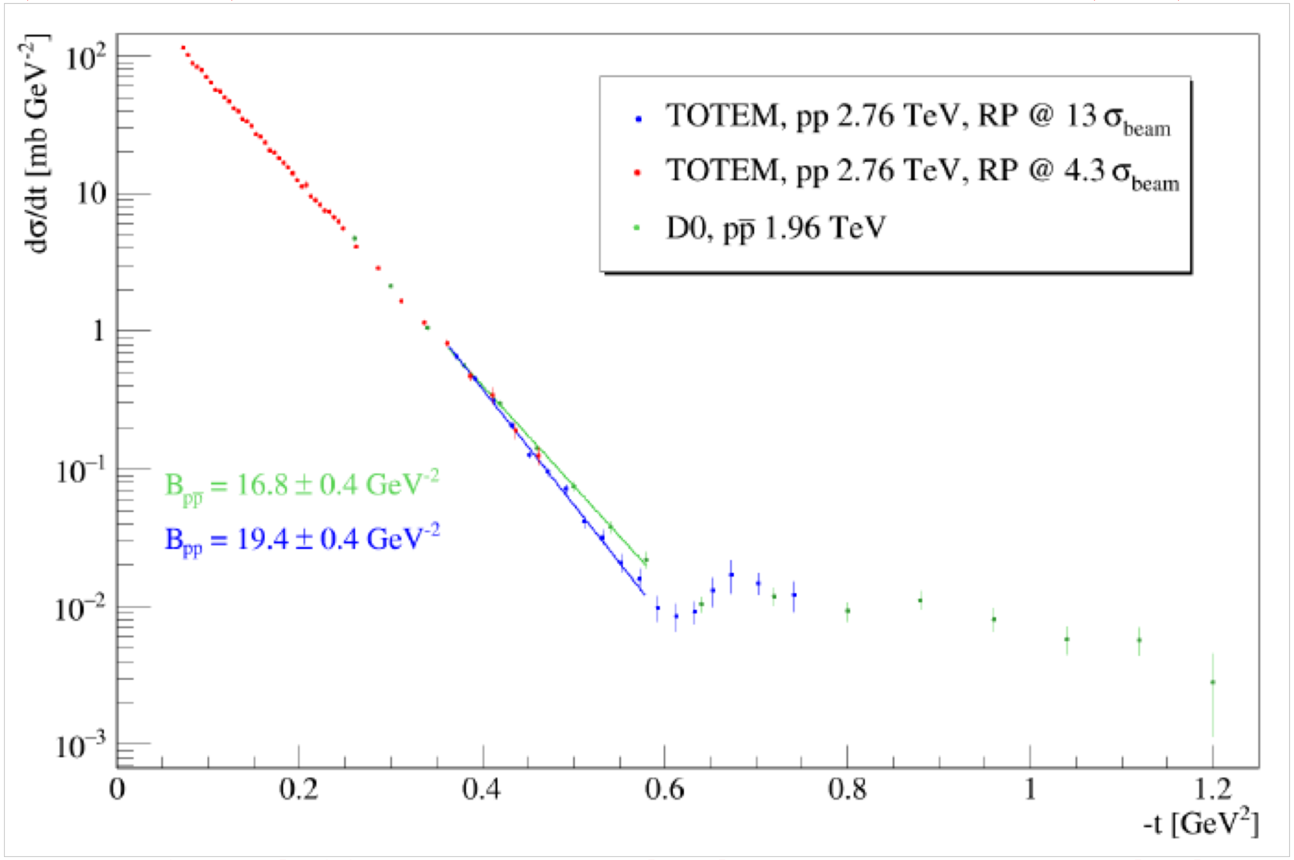
- Slow-down of growth of σ_{tot} beyond LHC range (influencing ρ via dispersion relations) is another



→ Detailed studies are ongoing …

Odderons and pp versus ppbar

- CP-odd odderon exchange should contribute oppositely in pp (eg LHC) and ppbar (eg Tevatron) cases.
- LHC (TOTEM) data at 2.76 TeV v Tevatron (D0) at 1.96 TeV



- Evidence for difference in behaviour around the 'diffractive dip' … 'smoking gun' for odderon if conclusive …

Did TOTEM Discover the Odderon?

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

TOTEM-2017-002
16 December 2017

CERN-EP-2017-335
19 December 2017

First determination of the ρ parameter at $\sqrt{s} = 13$ TeV – probing the existence of a colourless three-gluon bound state

The TOTEM Collaboration

MailOnline Science & Tech

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Experiments at the Large Hadron Collider uncover possible evidence of elusive 'odderon' that physicists have sought after for decades

- Physicists have been looking for subatomic quasiparticle, 'odderon' since 1970s
- It involves collisions in which an odd number of gluons are exchanged
- While it hasn't been seen in earlier experiments, technology is now more precise

By CHEYENNE MACDONALD FOR DAILYMAIL.COM
PUBLISHED: 00:46, 2 February 2018 | **UPDATED:** 00:46, 2 February 2018

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Researchers at the Large Hadron Collider have discovered what could be evidence of a quasiparticle they've been chasing for nearly 50 years.

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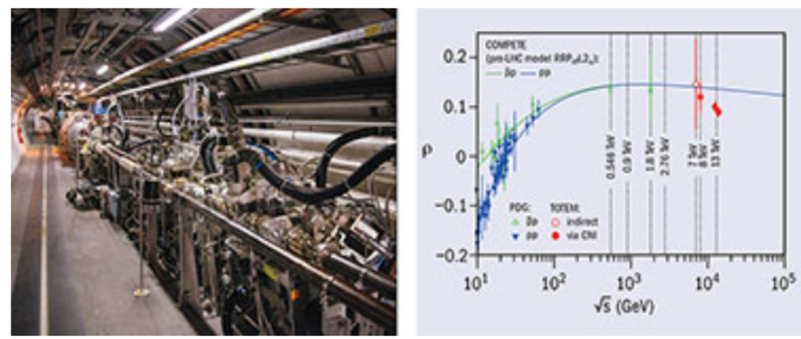
"All my wifi problems gone gone gone. A perfect home wifi solution […]"

CERN COURIER

Mar 23, 2018

Oddball antics in proton–proton collisions



Figure

The TOTEM collaboration at CERN has uncovered possible evidence for a subatomic three-gluon compound called an odderon, first predicted in 1973. The result derives from precise measurements of the probability of proton–proton collisions at high energies, and has implications for our understanding of data produced by the LHC and future colliders.

Did TOTEM Discover the Odderon?

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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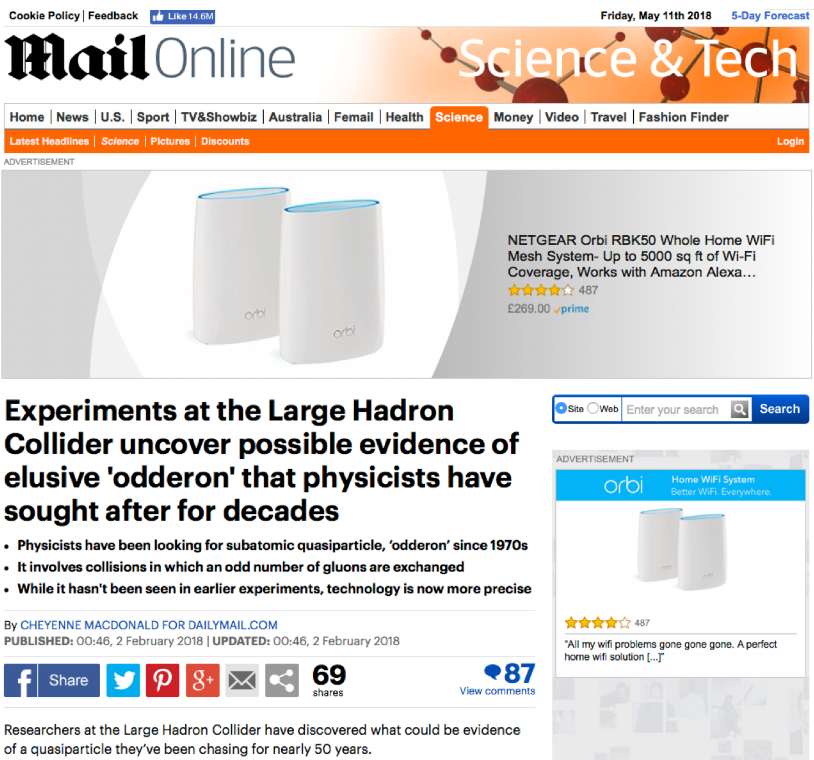

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Overjoyed: A jubilant Nigel Farage in London early today celebrating the stunning victory for the Leave campaign

WE'RE OUT!

After 43 years UK freed from shackles of EU

PM in crisis as voters reject Project Fear

Leave surge sends pound to a 31-year low

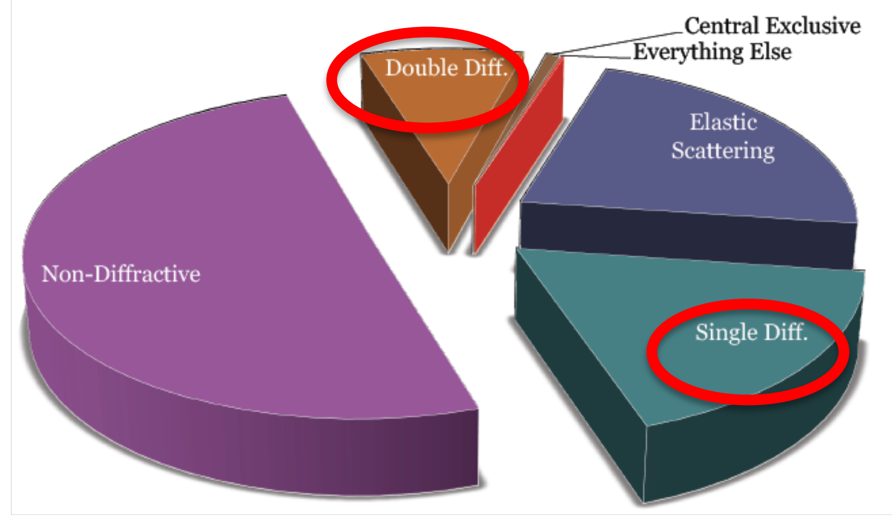
By James Slack, Daniel Martin and Jason Groves

A HUGE revolt by Middle England last night gave a stunning victory to Brexit.

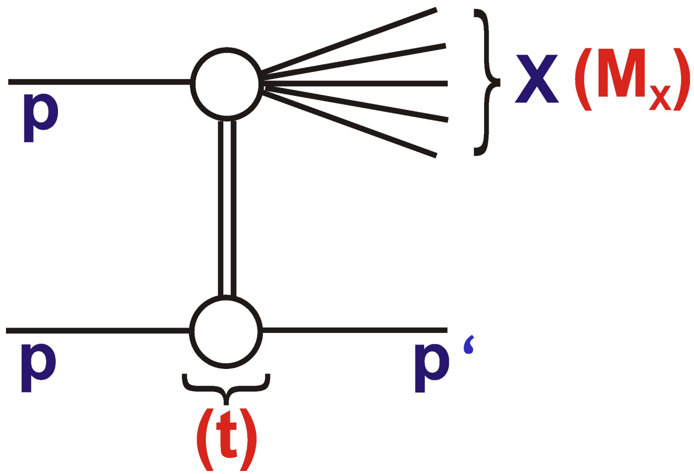
Turn to Page 2

[Should you believe anything you read in the Daily Mail?]

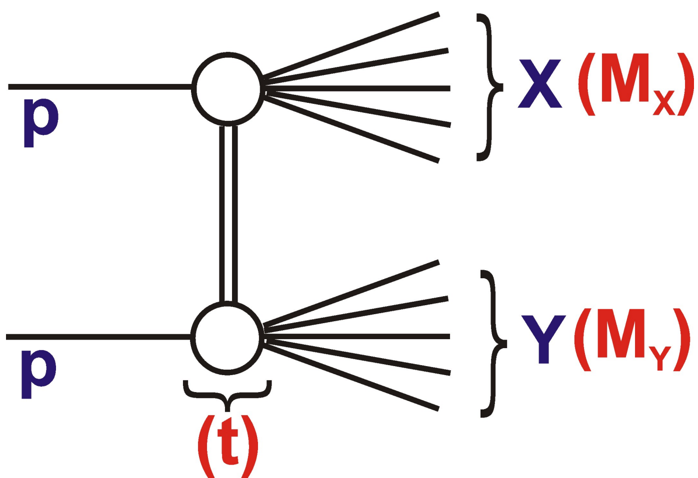
Inelastic Diffraction



Single diffractive dissociation



Double diffractive dissociation



Additional kinematic variables:

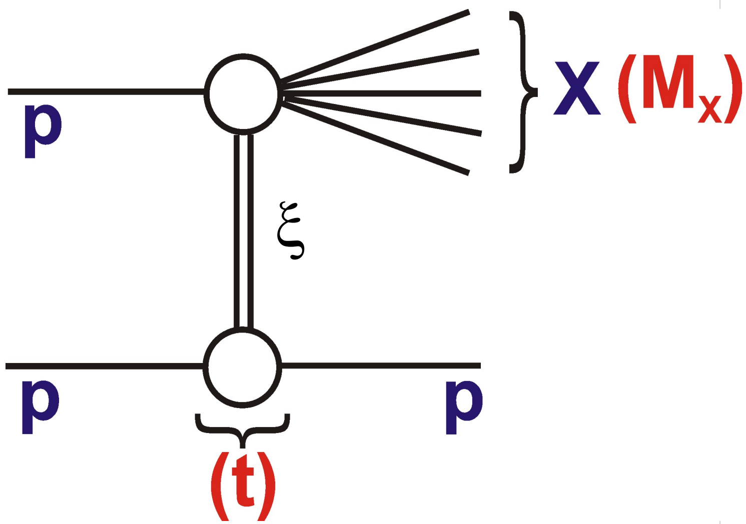
$$\xi = \frac{M_X^2}{s} = 1 - \frac{E_p'}{E_p}$$

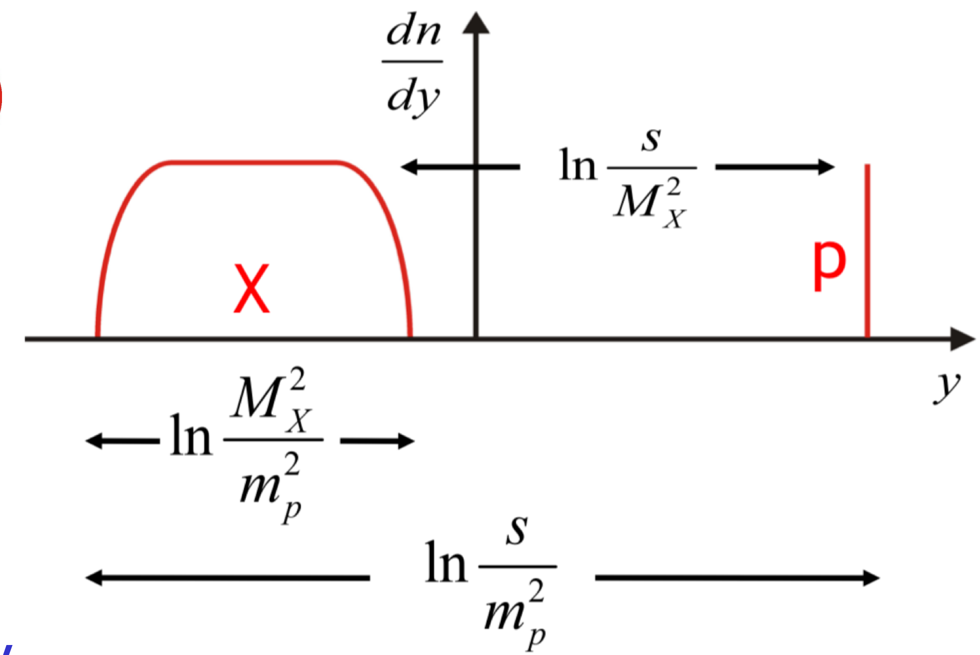
$$\xi_Y = \frac{M_Y^2}{s}$$

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

… very poorly predicted pre-LHC

Diffractive Channels:
& Rapidity Gap Kinematics





- Protons not tagged directly

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

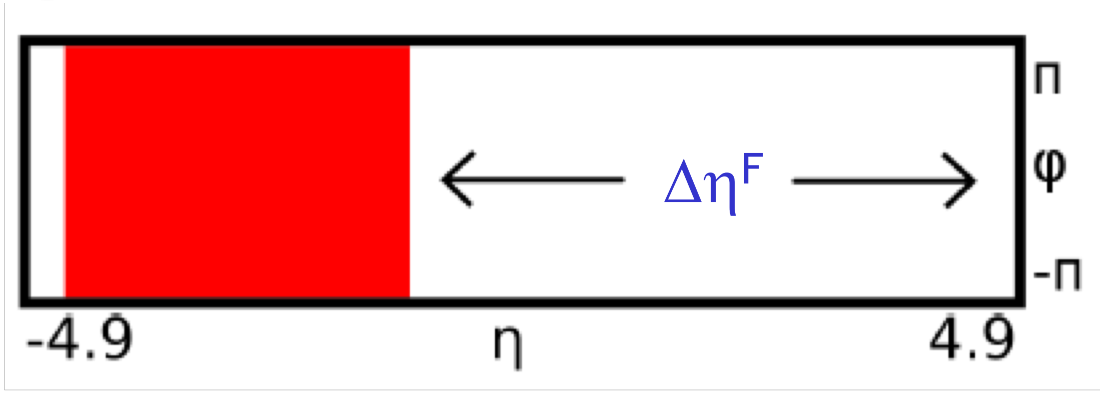
- $\xi = {}^{M_X^2}/_{s}$ is strongly correlated with empty rapidity regions

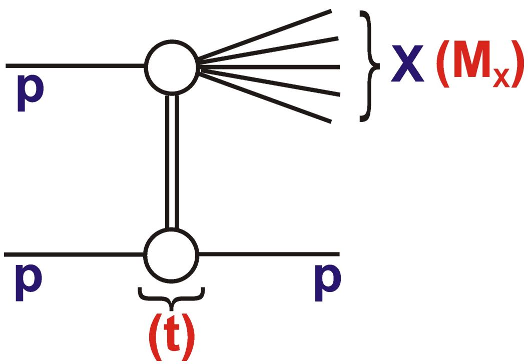
… exploited in all SD measurements to be shown

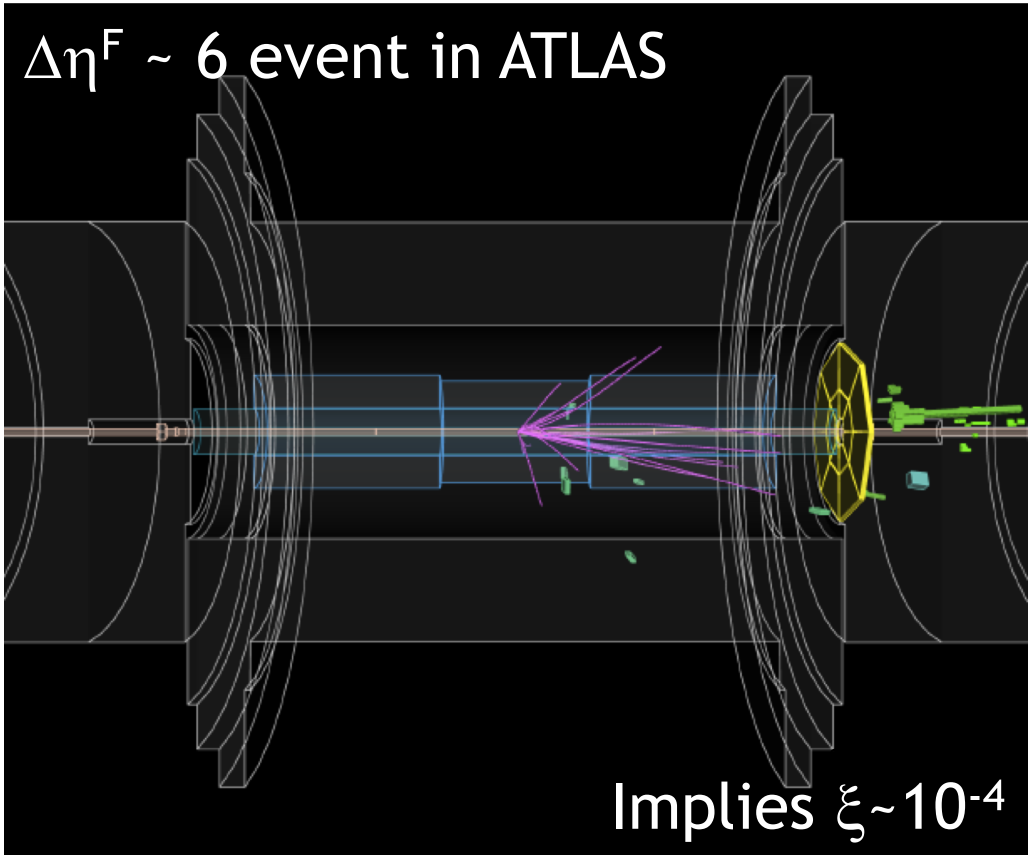
- Correlation limited by hadronisation fluctuations

Rapidity gap cross-sections

Method developed by ATLAS to measure hadron Level cross section as a function of $\Delta\eta^F$: forward or backward rapidity gap extending to limit of instrumented range: i.e. including $\eta = \pm 4.9$







… no statement on $|\eta| > 4.9$

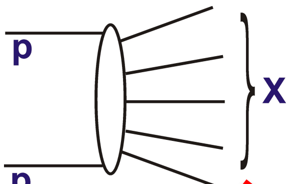
… large $\Delta\eta^F$ sensitive to SD + low M_Y DD

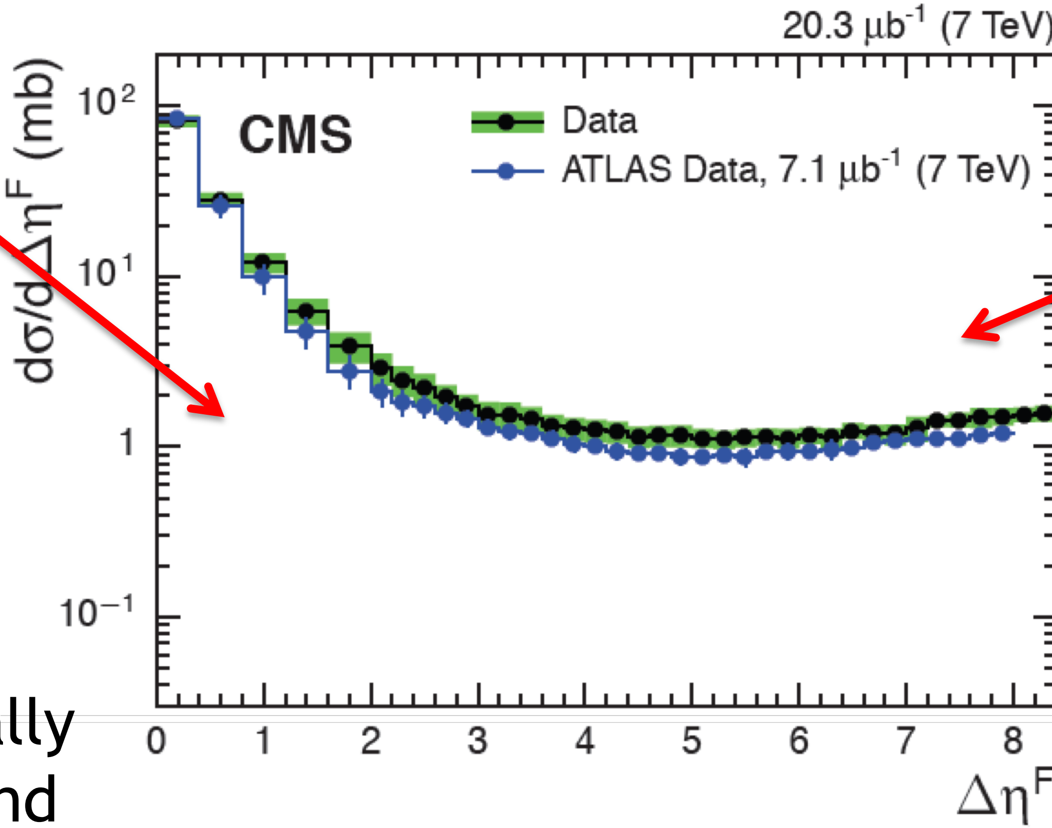
CMS and ATLAS Rapidity Gap Data

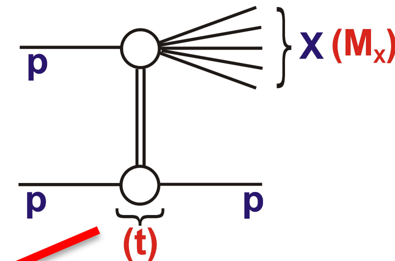
Using very early LHC runs at 7 TeV (avoiding pile-up) …

ATLAS: $\Delta\eta^F$ extends from $\eta = \pm4.9$ to 1st particle with $p_t > 200$ MeV

- CMS: $\Delta\eta^F$ extends from $\eta = \pm4.7$ to 1st particle with $p_t > 200$ MeV







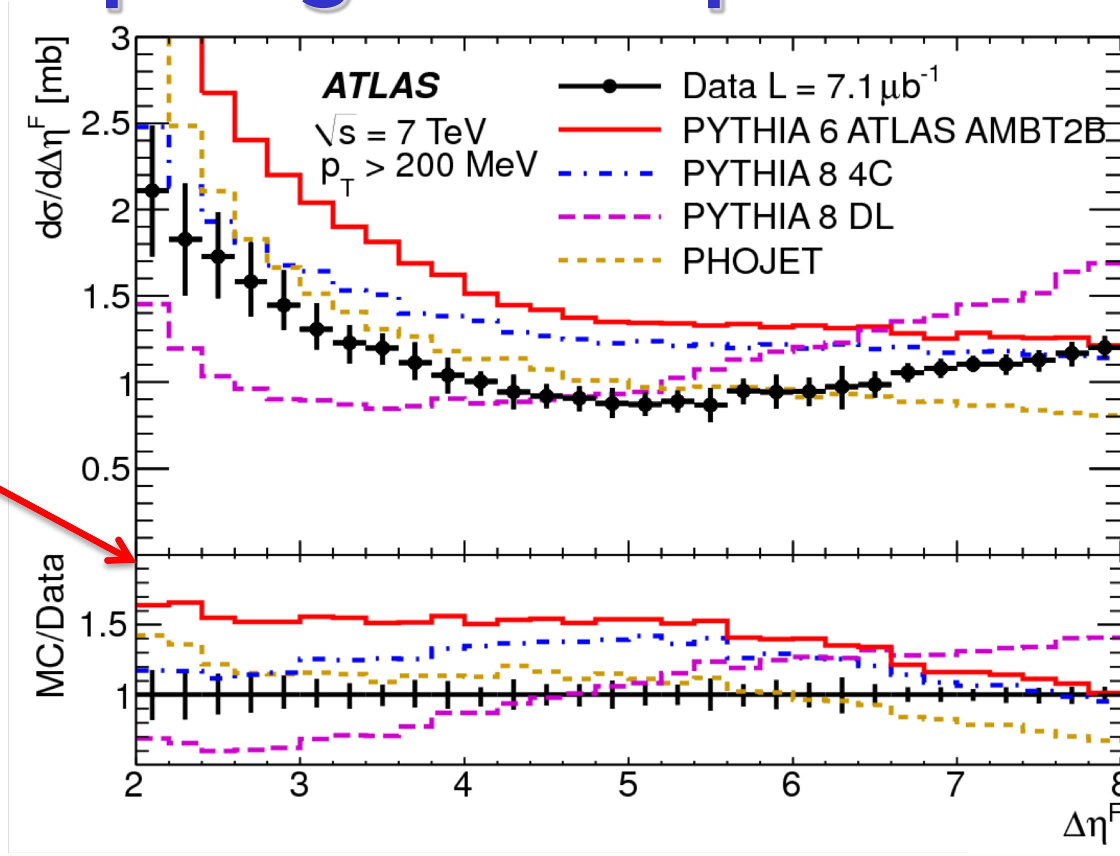
Small gaps dominated by non-diffractive processes … exponentially suppressed and sensitive to hadronisation fluctuations / underlying event

Large gaps dominated by diffractive processes … characteristic plateau

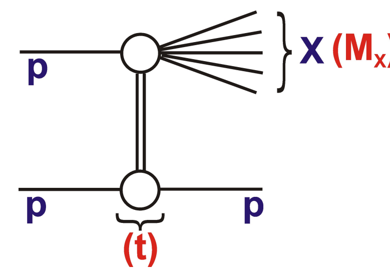
Roughly 1mb per unit gap size

Large Gap Region compared with Models

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



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

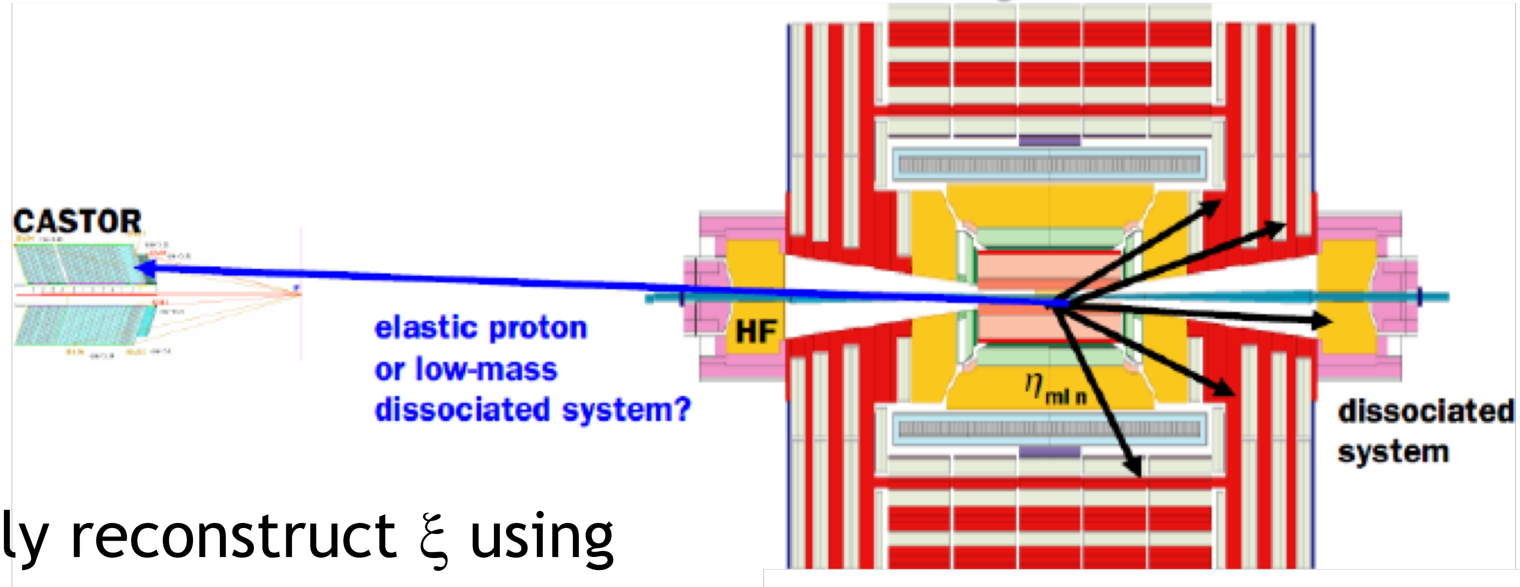


- Most models take `triple Regge' approach: $\dfrac{d\sigma}{d\xi\, dt} \propto \left(\dfrac{1}{\xi}\right)^{2\alpha(t)-\alpha(0)} e^{bt}$

- Large differences between models due to assumptions on total diffractive cross sections, $\alpha(t)$ and fragmentation modelling.

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

SD Cross Section with Direct ξ Measurement

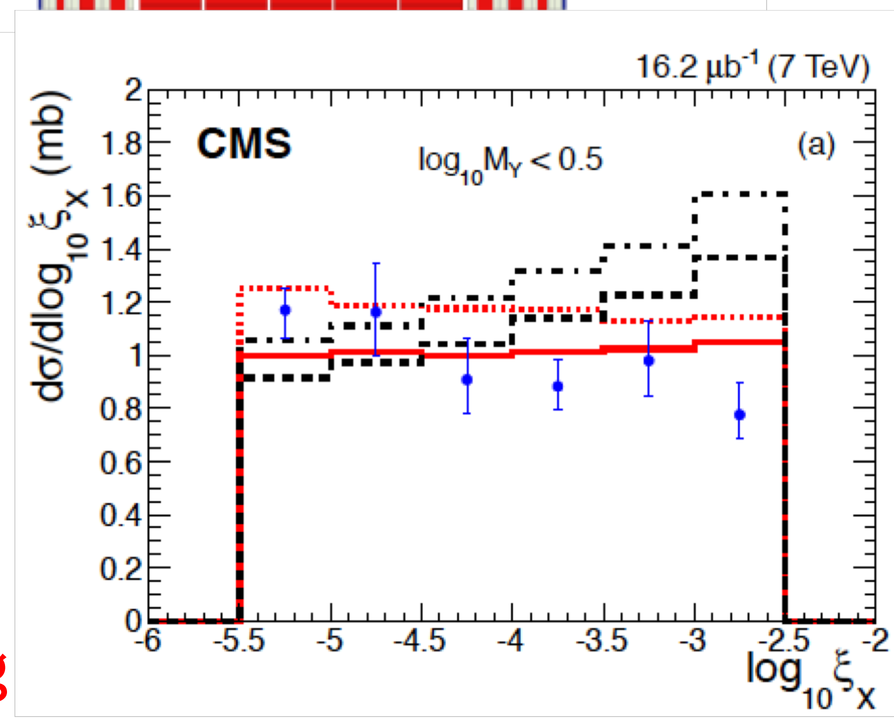


- Directly reconstruct ξ using particle flow algorithm and cunning kinematics.

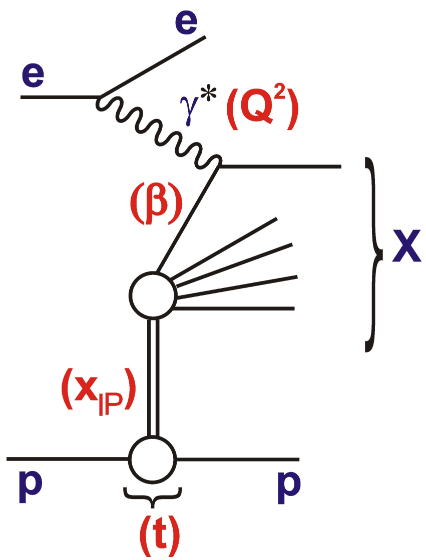
$$\tilde{\xi}^{\pm} = \frac{\sum (E^i \pm p_z^i)}{\sqrt{s}} \simeq \frac{M_X^2}{s}$$

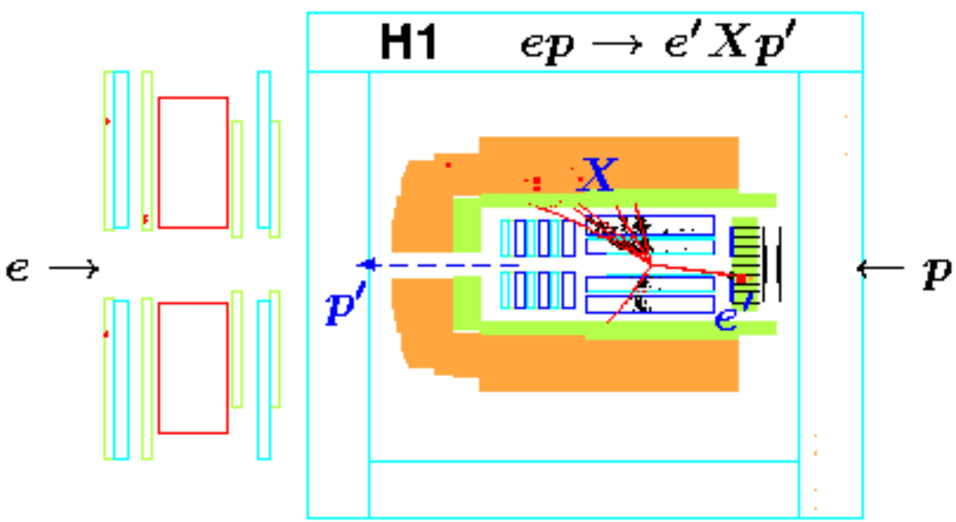
- Compatible with $\alpha_{IP}(0) = 1.08$

- Precision limited by unfolding SD and DD → Need proton tagging



Inelastic Diffraction at the Parton Level



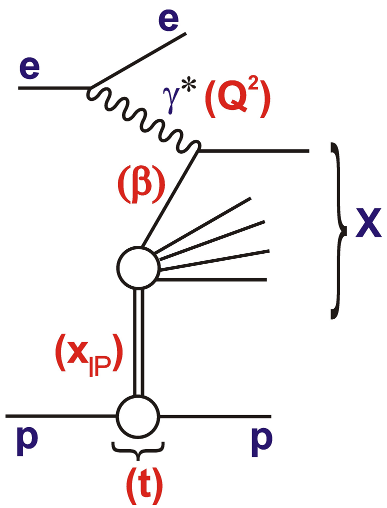


HERA ep Collider:

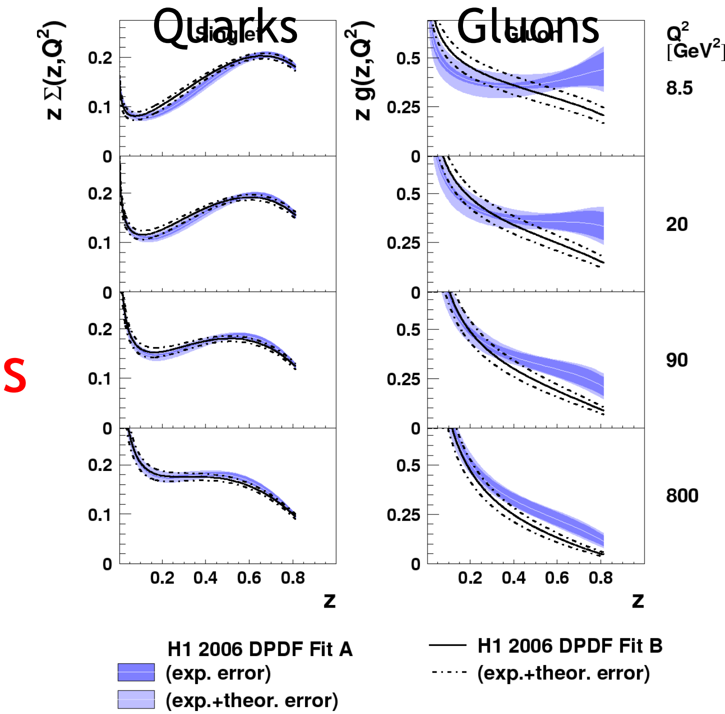
Virtual photon probes pomeron partonic structure rather like inclusive DIS …

>100 papers later …

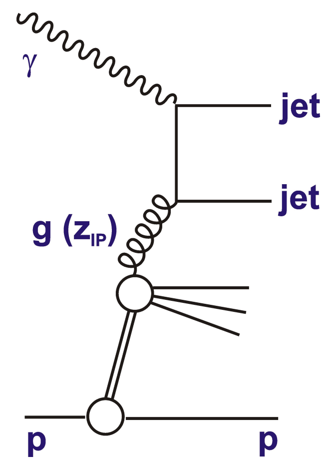
Hard Diffraction: Structure of Vacuum Exchange

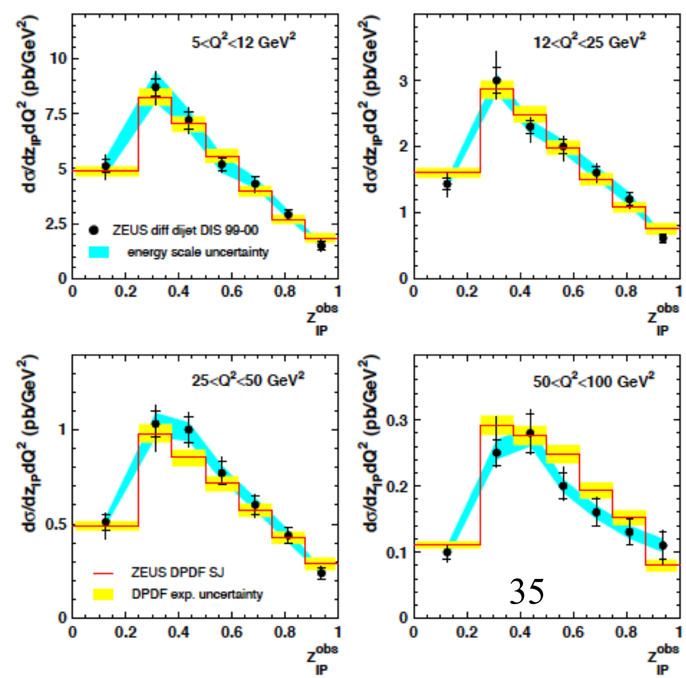


Diffractive DIS at HERA → Diffractive parton densities (DPDFs) dominated by gluon, which extends to large momentum fractions



… NLO predictions based on HERA DPDFs give impressive description of all HERA 'hard' diffractive data, eg jet production …

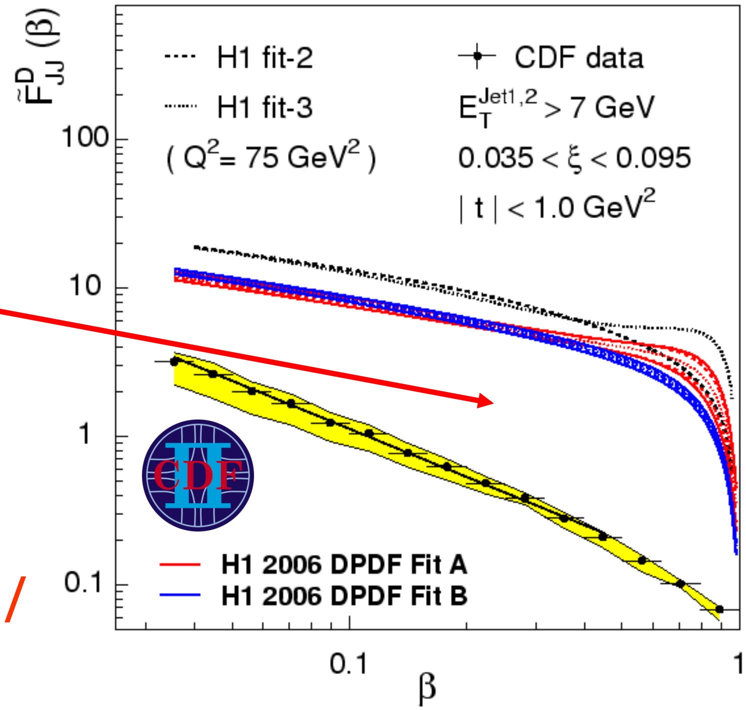




→ DPDFs used in many models in pp

… but in pp(bar)

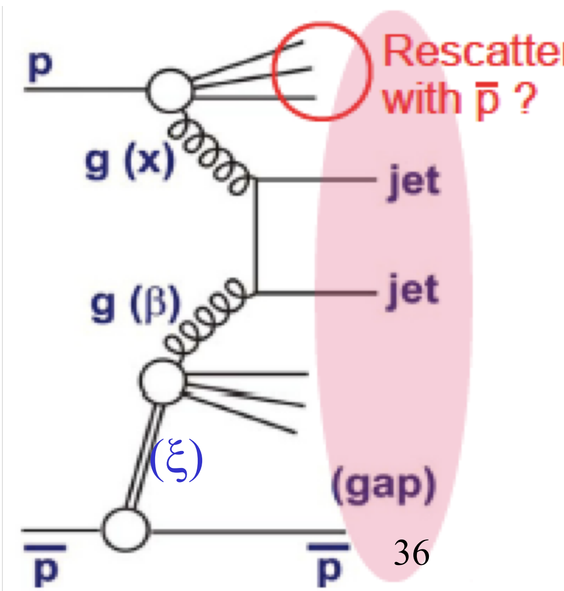
Spectacular failure in comparison of Tevatron proton-tagged diffractive dijets with HERA DPDFs [PRL 84 (2000) 5043]



… rescattering (absorptive corrections / related to Multi Parton Interactions …) breaks factorisation …

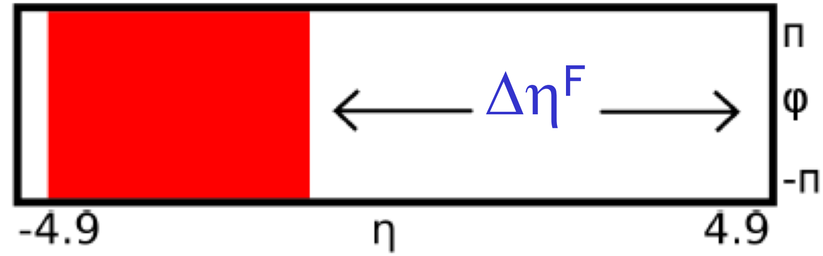
`*rapidity gap survival probability*' ~ 0.1

Gap survival probability needs to be understood to interpret all LHC hard diffraction data.

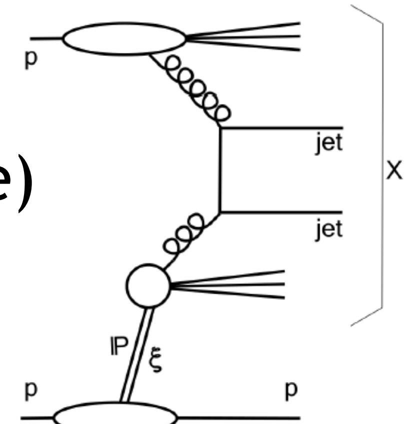


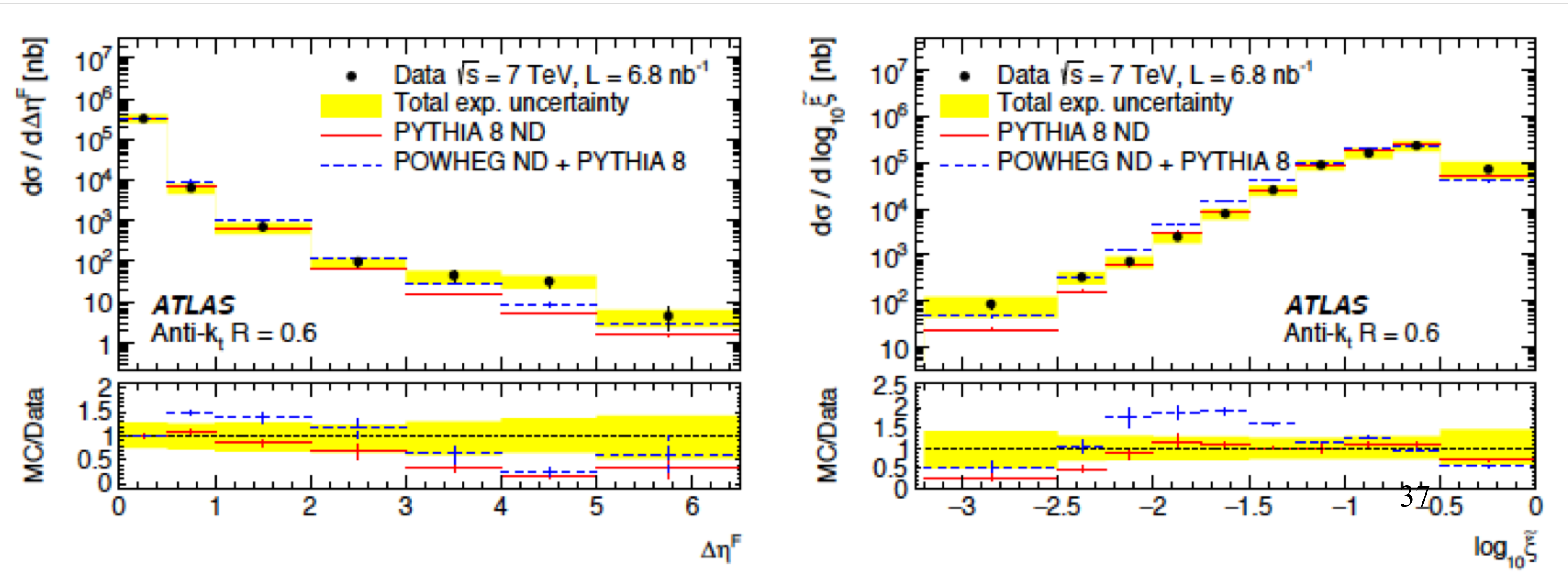
Here: First results from LHC:
… dijets with large rapidity gaps …

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 …





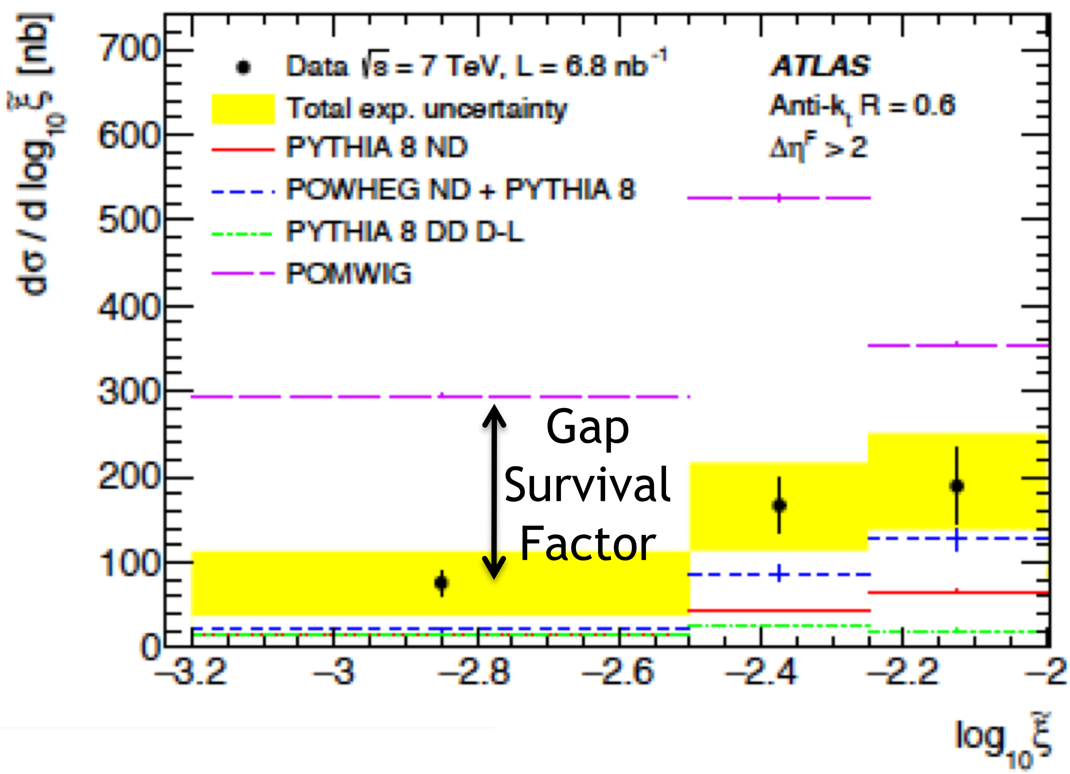
Evidence for Diffractive Contribution

Focusing on small ξ, whist simultaneously requiring large gap size ($\Delta\eta_F$ > 2) gives best sensitivity to diffractive component

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

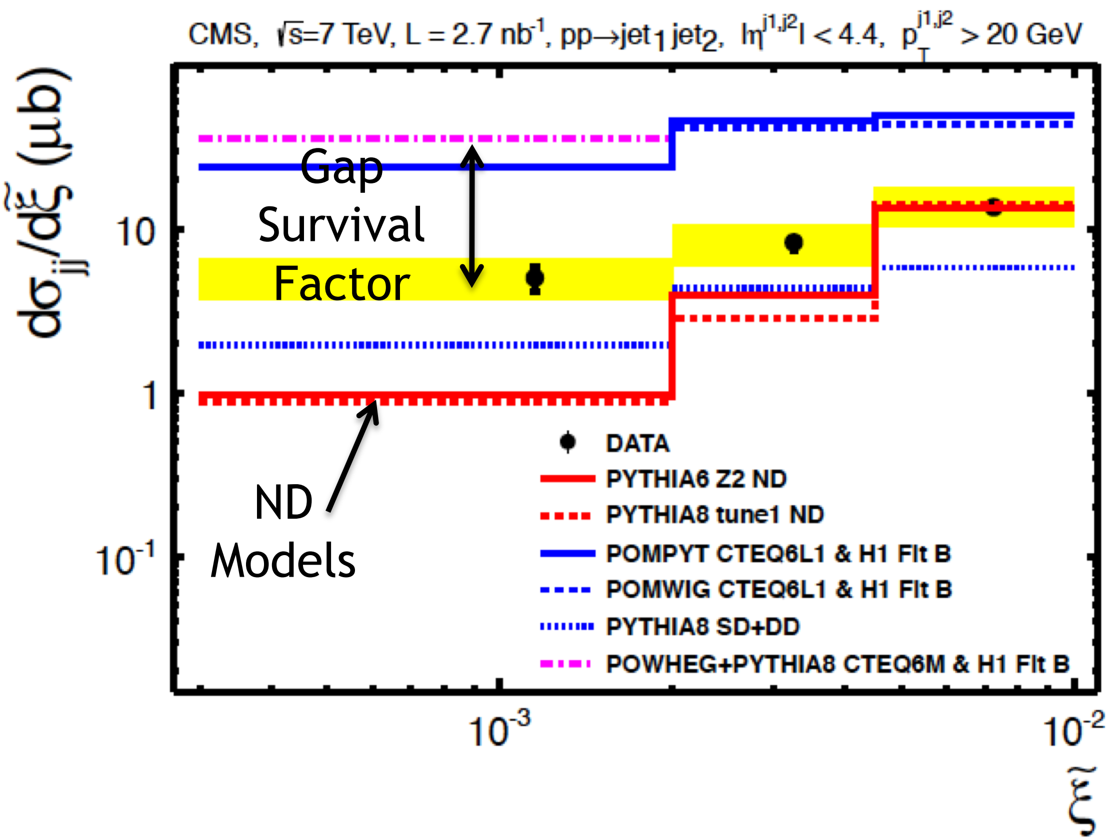
→ Comparison of smallest ξ with DPDF-based model (POMWIG) leads to rapidity gap survival probability estimate …

- Model dependence not investigated in detail
- In context of POMWIG, using anti-k_T with R=0.6:



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

Similar CMS Analysis



- Comparison of 1st bin v diffractive DPDF models

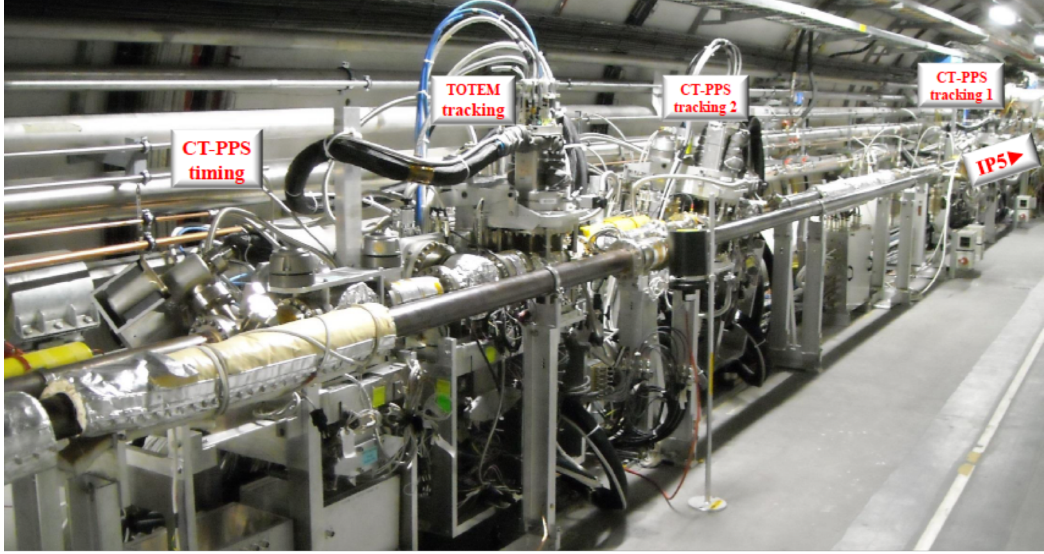
→ Gap survival probability estimate $S^2 = 0.08 \pm 0.04$ (based on NLO POWHEG)

… 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

New Generation of Roman Pots

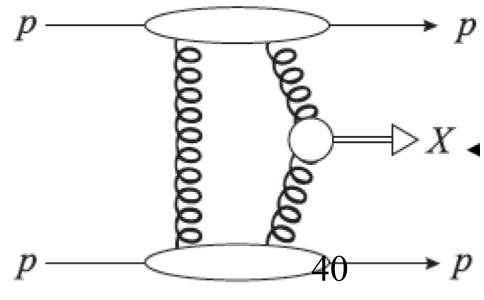


Future LHC diffractive Physics based on CT-PPS (CMS/TOTEM) & AFP (ATLAS)
- Operated in Run 2 and will remain in Run 3 (and possibly be upgraded for HL-LHC)

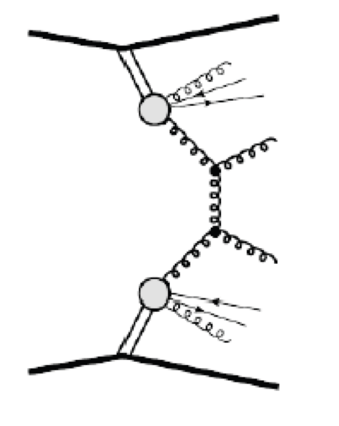
- Precision (fairly) radiation hard silicon pixel spatial detectors
- Time of Flight detectors with ~ 25ps timing precision from Cerenkov light in diamond (CT-PPS) and quartz (AFP)

→ Operate in normal LHC runnning conditions

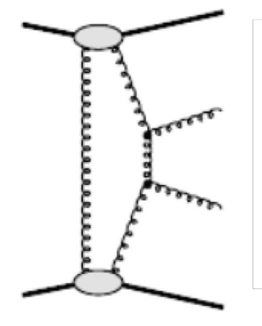
→ Optimised for double proton-tagged processes, where vertex can be located to ~1mm from proton ToF, suppressing pile-up

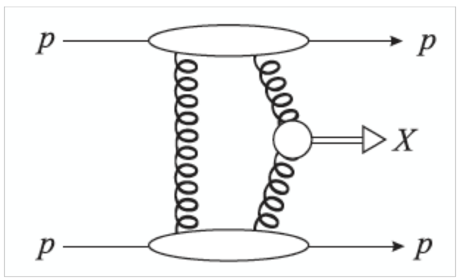


Newly Accessed Physics with Double Tags



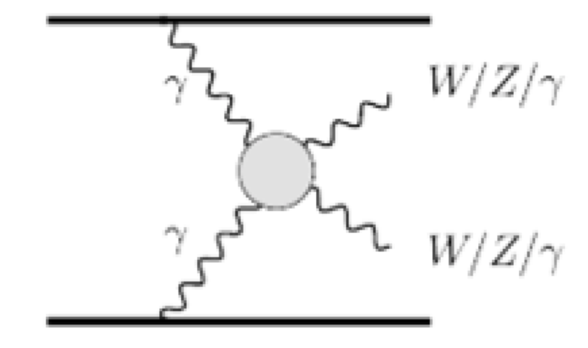
- **Inclusive central production**
  pomeron-pomeron hard scattering with jets, heavy flavour, W, Z signatures





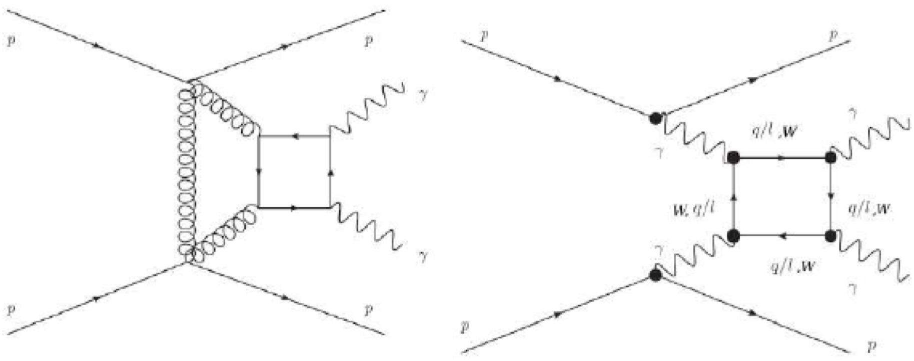
- **Central Exclusive QCD Production**
  of dijets, γ-jet and other strongly produced high mass systems

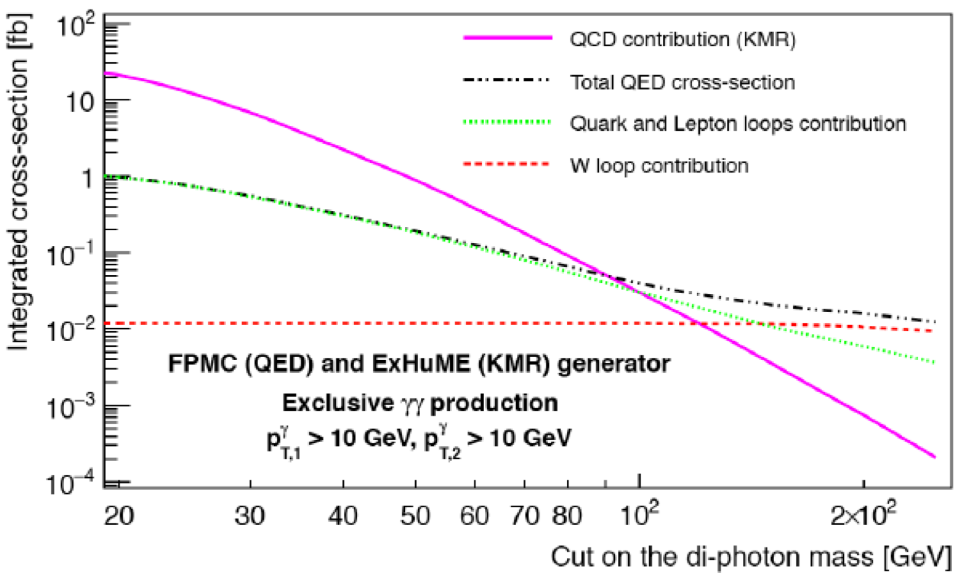
- **Two photon physics** → exclusive dileptons, dibosons & anomalous multiple gauge couplings, exclusive t-tbar?...



- **Searches for new heavy particles**
  heavy Higgs recurrencies, pair produced BSM states, axions, vector-like fermions ...)

e.g. Exclusive $\gamma\gamma$ Production





In general …

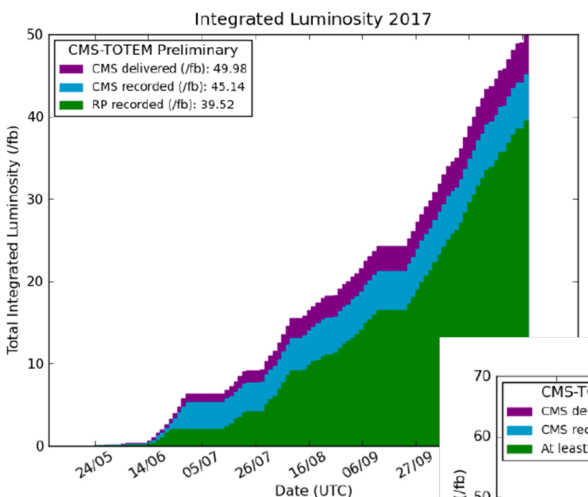
- QCD production dominates at low central system masses

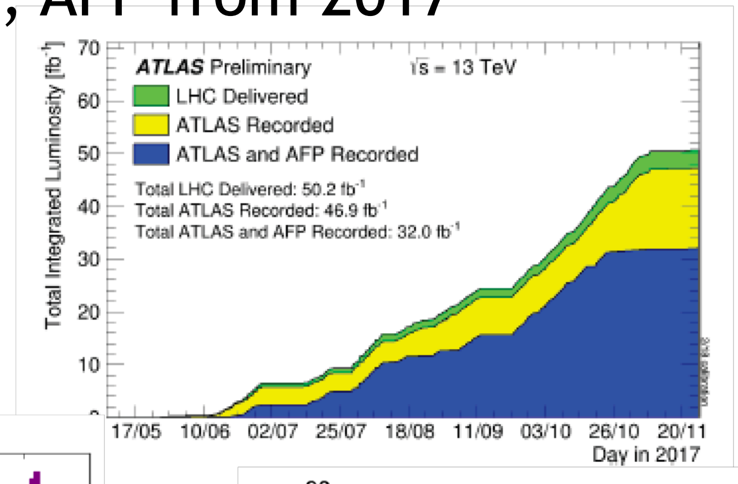
- QED production (light-by-light) takes over at larger central system masses

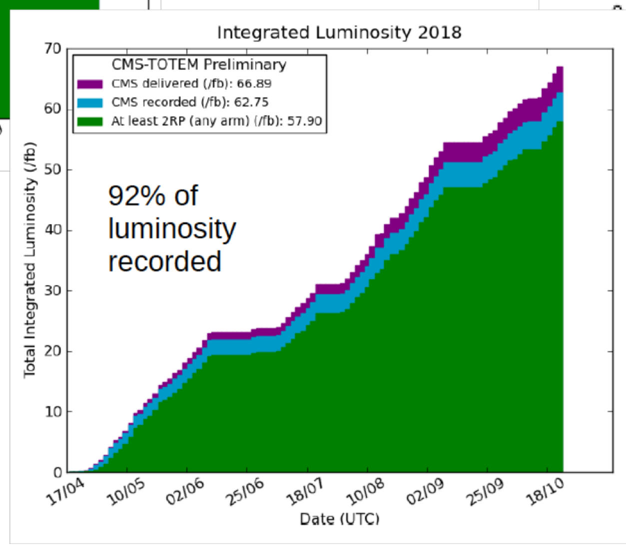
- ZZ, WW, $\gamma\gamma$ final states … Competitive sensitivity to anomalous quartic gauge couplings in large mass region

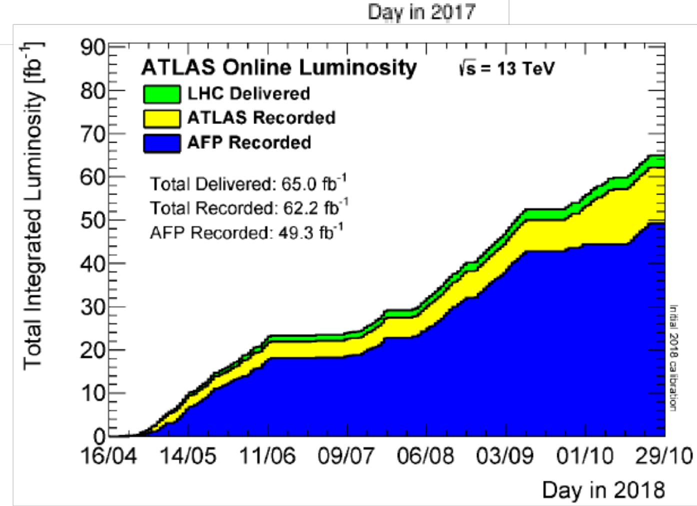
Data Collected to Date

- CT-PPS fully installed from 2016, AFP from 2017



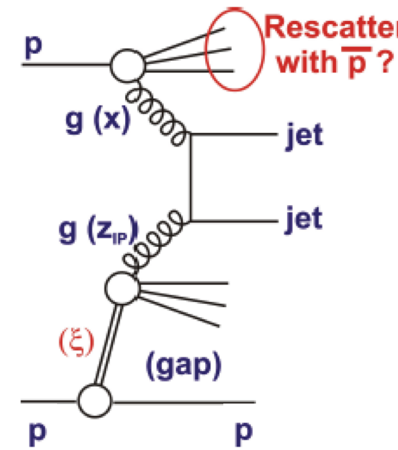




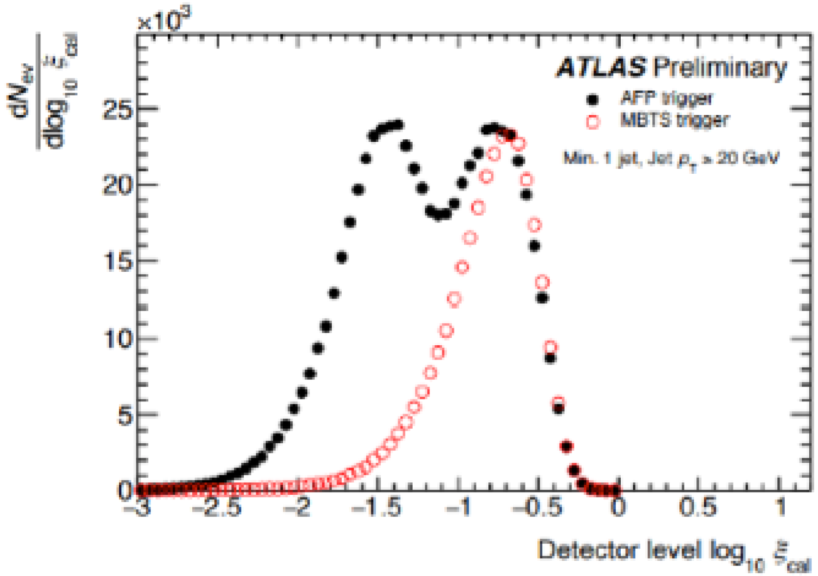


- Total of 110 fb^{-1} accumulated by CT-PPS, 81 fb^{-1} by AFP.
  → Transformational lumi compared with previous Roman potS
    → Commissioning and data understanding ongoing
    → First results obtained (with single tags so far)

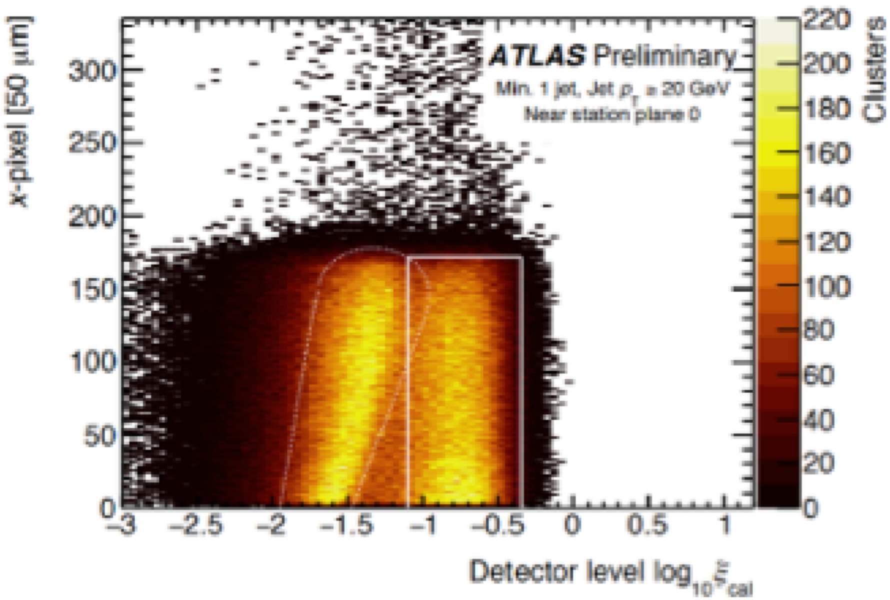
AFP Observation of Single Diffractive Dijet Signal



- Single proton tagged sample with ξ measured in main ATLAS calorimeter



- Strong enhancement in low ξ_{Cal} diffractive region for AFP-triggered data over MBTS data + common pile-up contribution

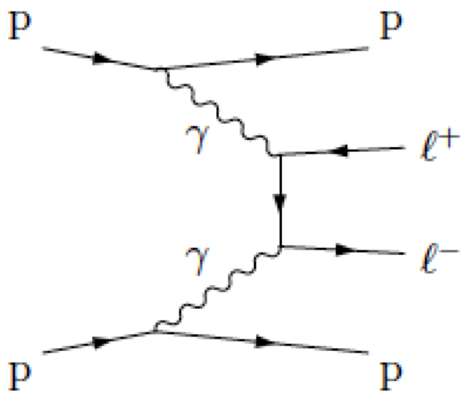


Low ξ data exhibit expected x-y correlation in AFP pixels and correlation between pixel x position and ξ_{Cal}

→ Clear diffractive signature

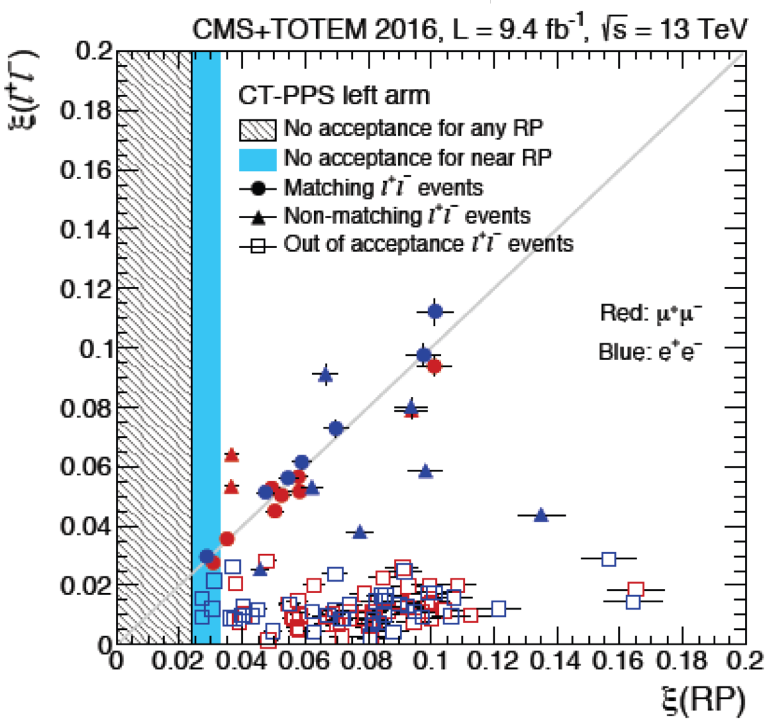
First High Lumi Study @ CT-PPS (9.4 fb^{-1})

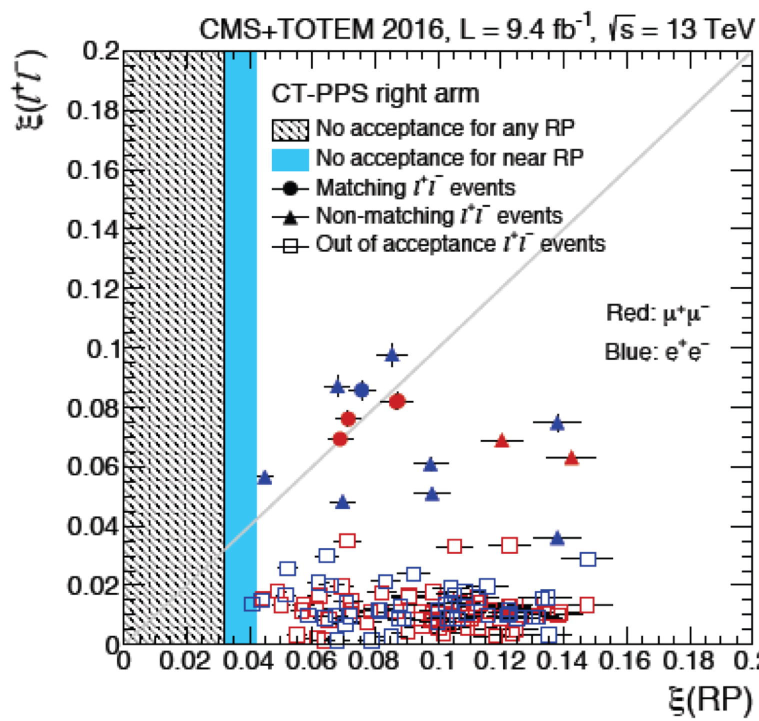
$\gamma\gamma \rightarrow$ ee or $\mu\mu$



- Single proton tagged (so far)
- Dileptons required to be back to back
- Study correlation between ξ from proton and from l^+l^- pair …

12 $\mu\mu$ events match in ξ (1.5±0.5 background)
8 ee events match in ξ (2.4±0.5 background)

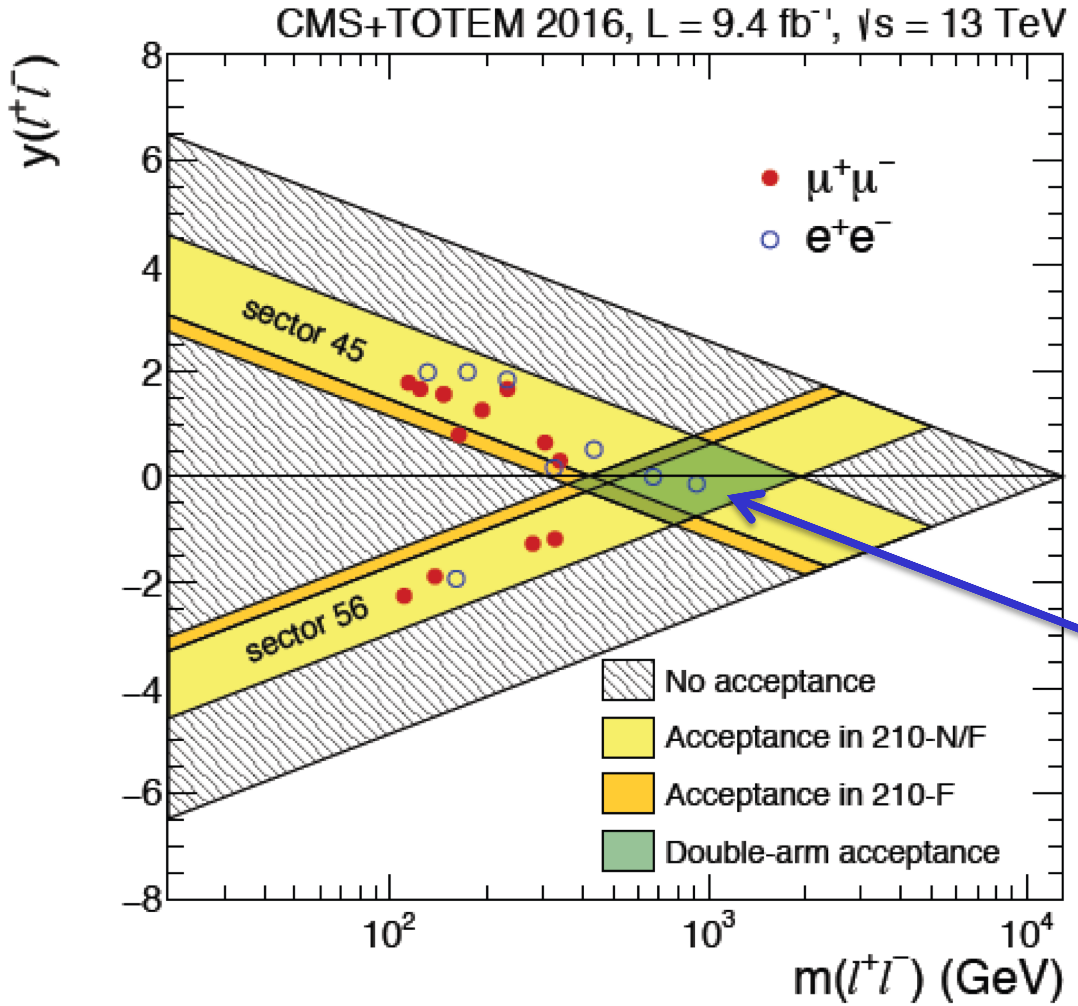


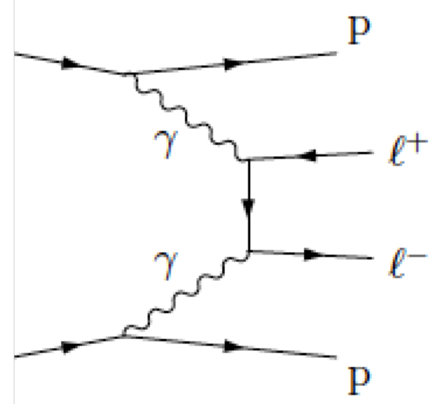


5.1σ signal

[arXiv: 1803.04496]

Kinematics of Candidate Events





Potential region for double tagging: 350GeV <~ m(ll) <~ 2TeV

- 2 electron events were in double tag acceptance, but only one proton seen due to inefficiencies
- Highest mass events: m(ee) = 917 GeV and m(μμ) = 342 GeV

Summary

Precise elastic & total cross section data

- Surprises in energy dependences
- Multi-exchanges / absorption play a role
- Evidence for odderon under discussion

Diffractive dissociation data

- Soft pomeron with intercept as expected works well
- Limited by control over ND gap fluctuations and low M_Y DD
- Rapidity gap survival probability larger than expected?
- Rapidity gap method: further progress requires proton tagging

Undergoing revolution based on high lumi Roman pots

- First results from single tagged samples and <10% of run2 lumi
- Uncharted QCD territory in exclusive central production
- Rare / exotic EW physics and searches with tagged protons