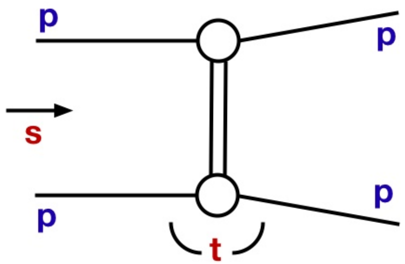
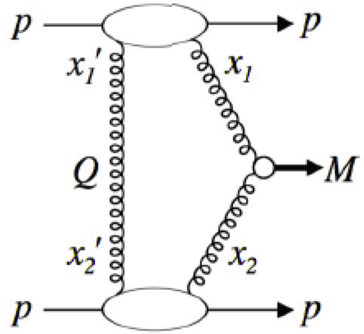
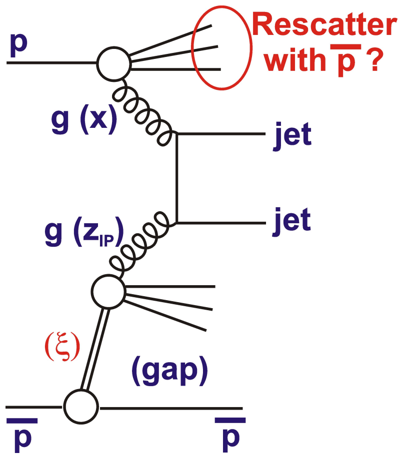
Elastic and Diffractive Scattering at the LHC

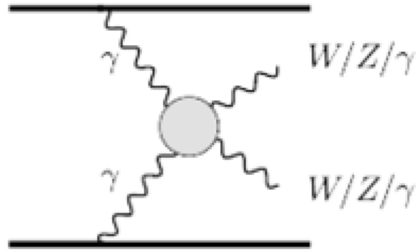
… a review of the story so far and prospects for the future …

Paul Newman
(University of Birmingham)





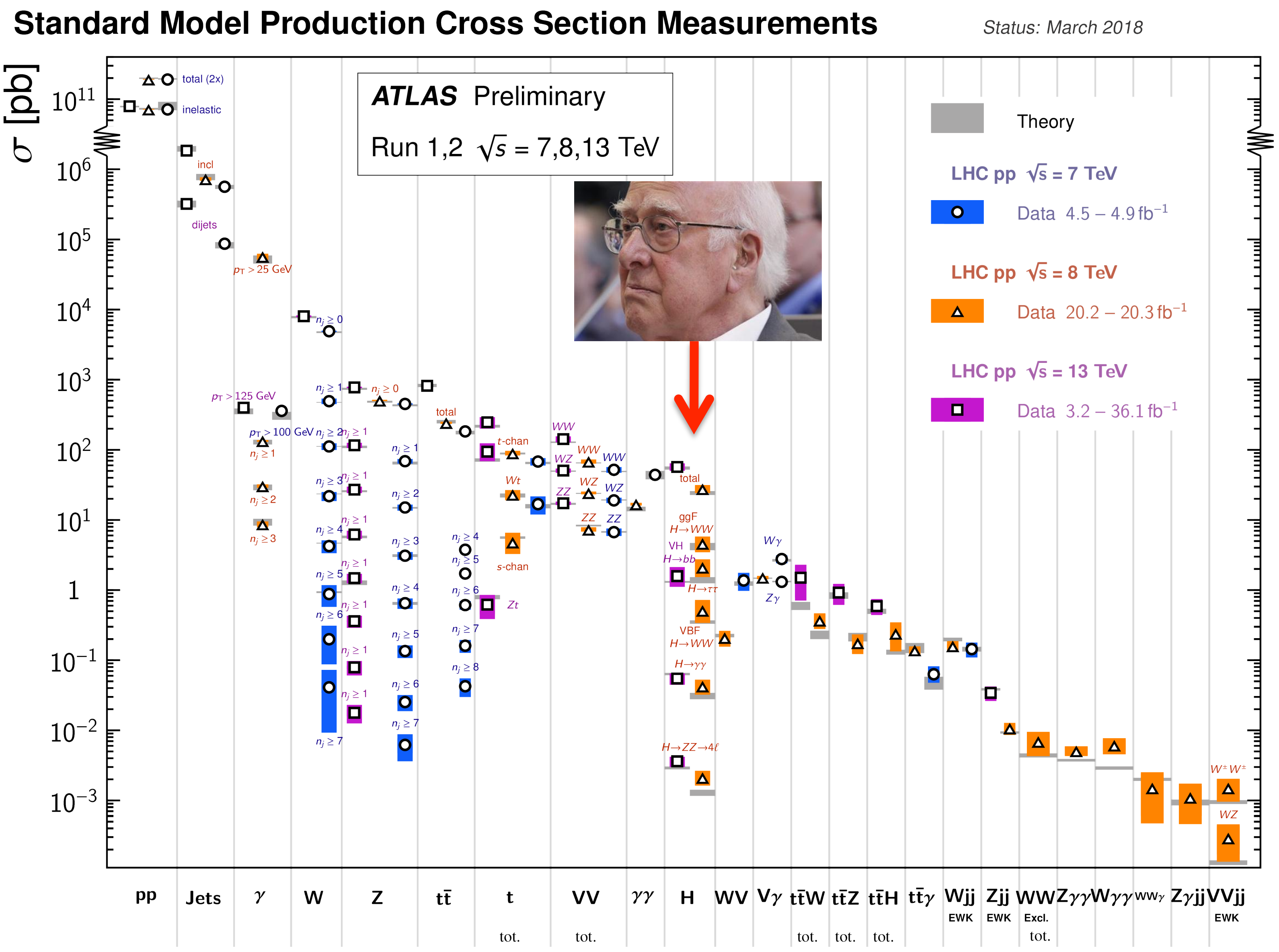




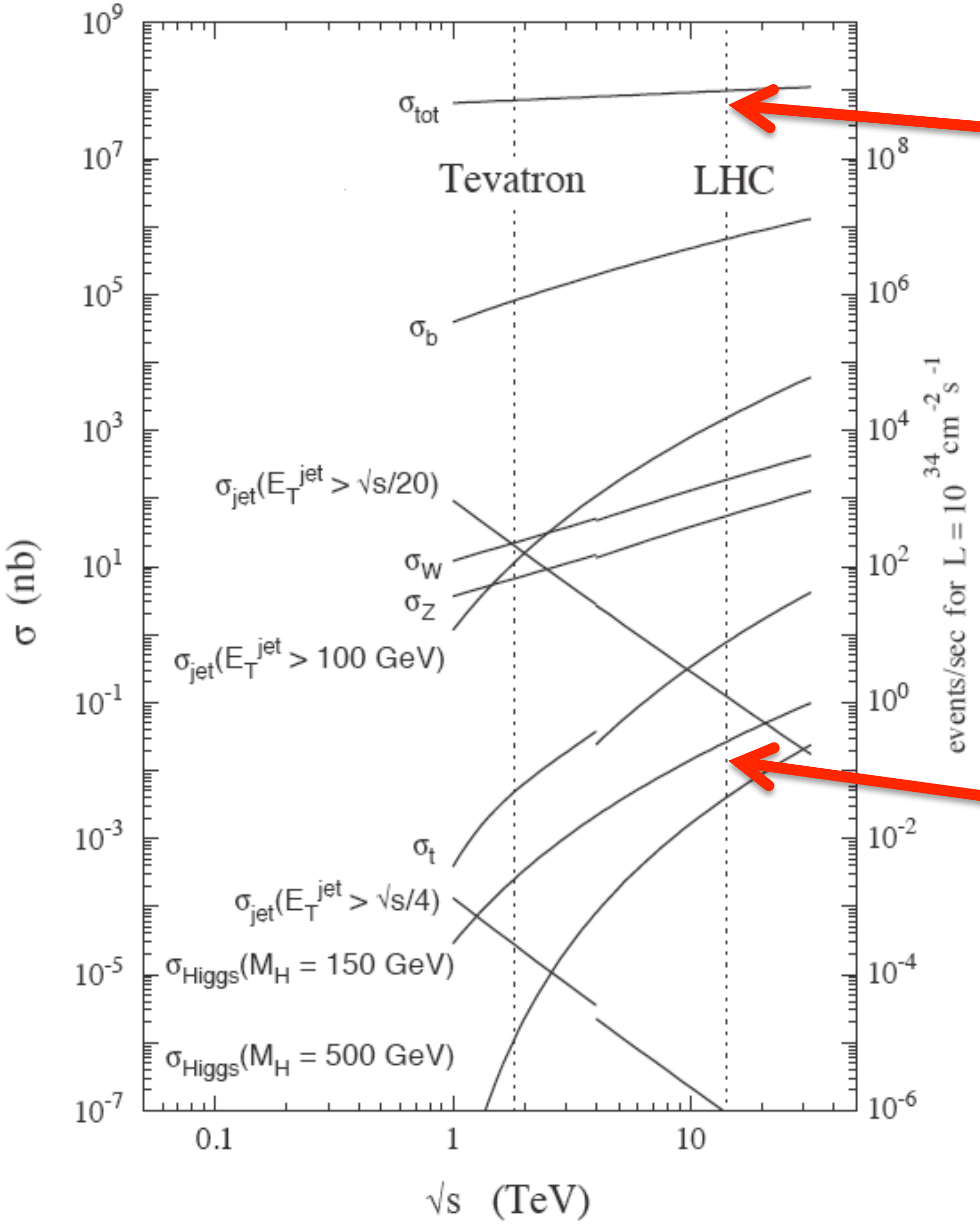
DESY Colloquia,
15-16 May 2018

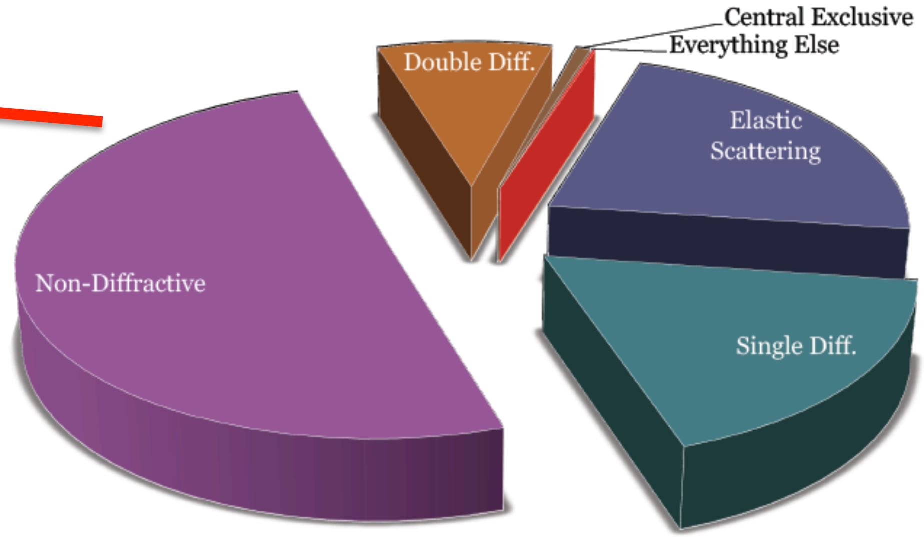
→ Elastic and Total Cross Sections
→ Soft Diffractive Dissociation
→ Hard Diffractive Dissociation
→ [~~Ultra-peripheral Vector Mesons~~]
→ Prospects for Central Exclusive Production

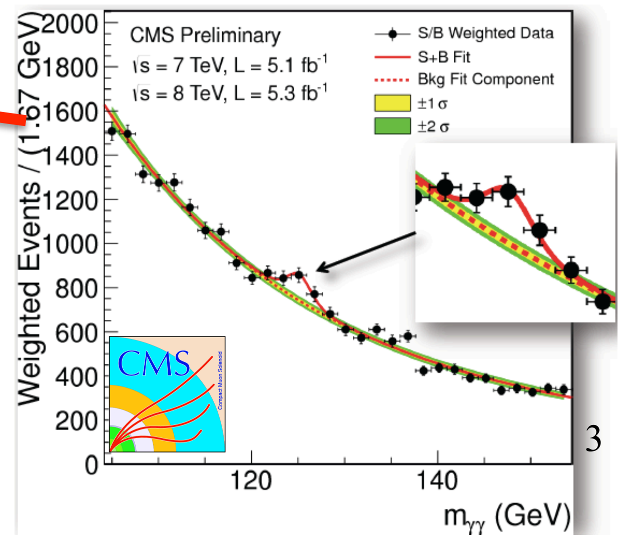
LHC: Exploring the ultra-rare at the Energy Frontier … eg ATLAS



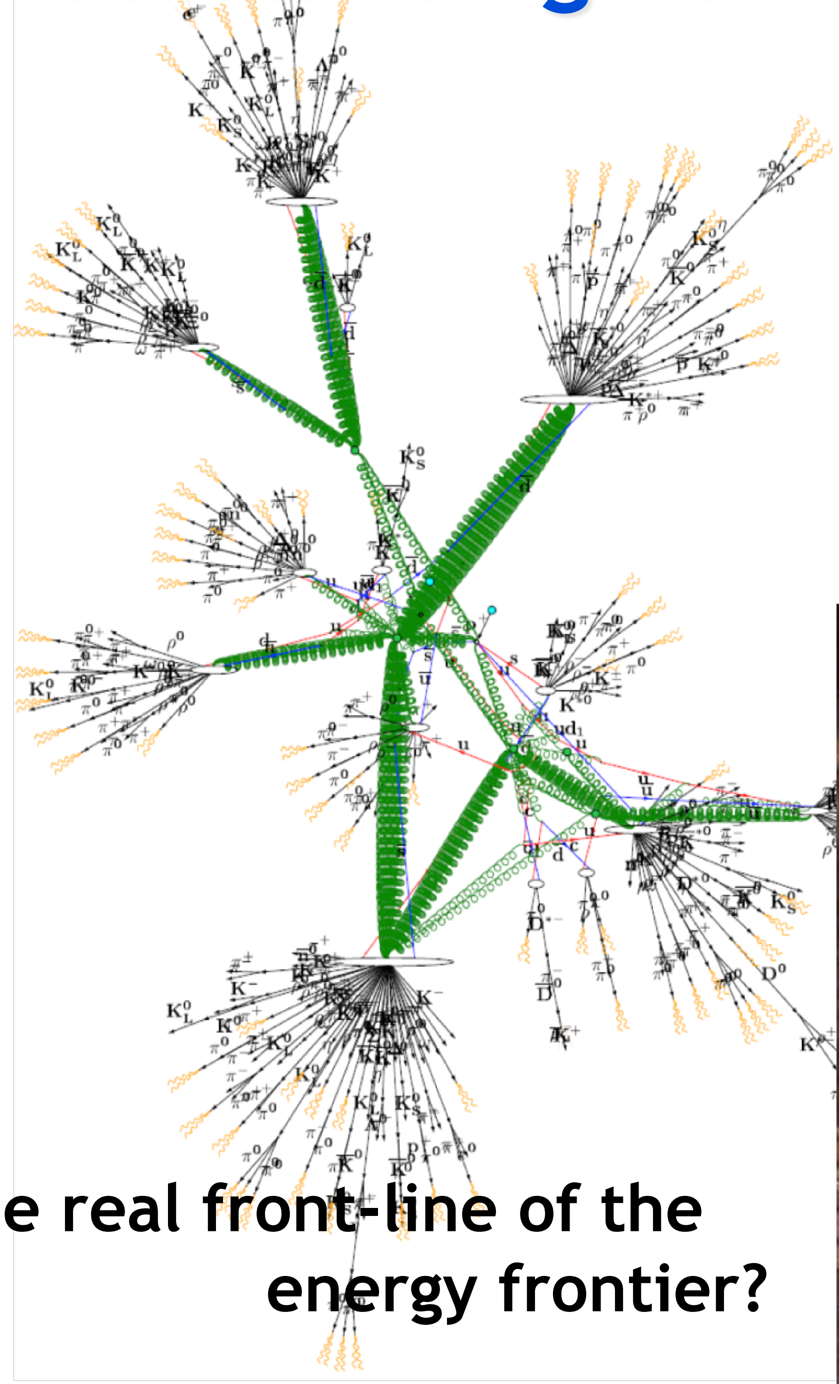
But what usually happens when hadrons collide?







Understanding 10^{-1} Processes is Hard!



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

… the real front-line of the energy frontier?

Why should we Care?

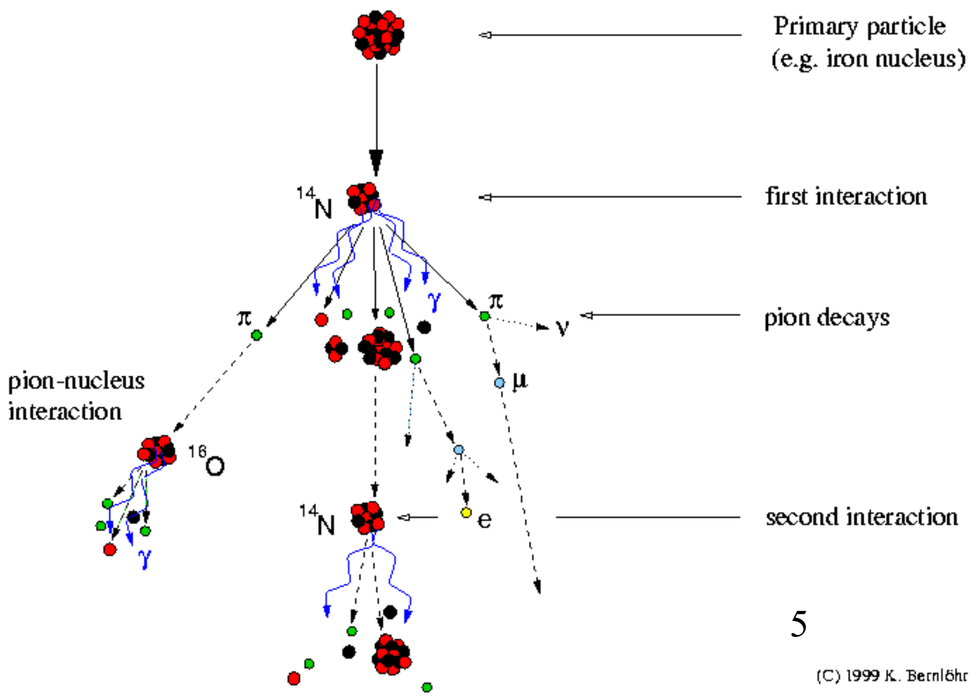
Everyday strong interaction processes intimately linked to our basic understanding of physics:

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
- …

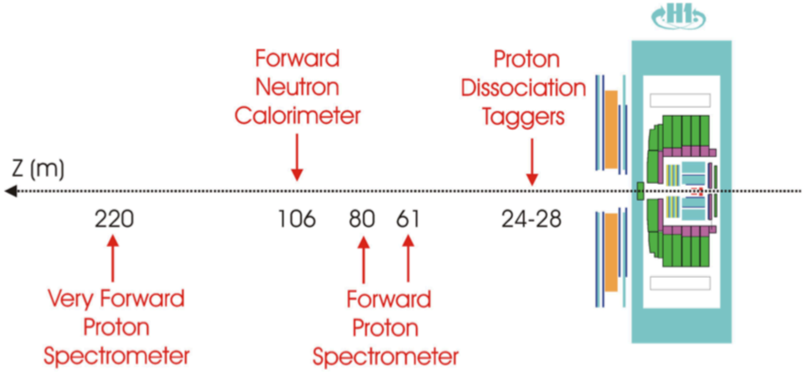


Methods for Diffraction and Elastics

… old slide from diffraction at HERA

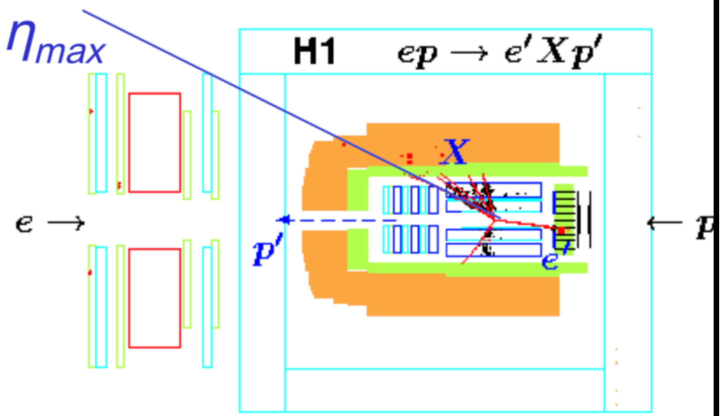
Signatures and Selection Methods

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



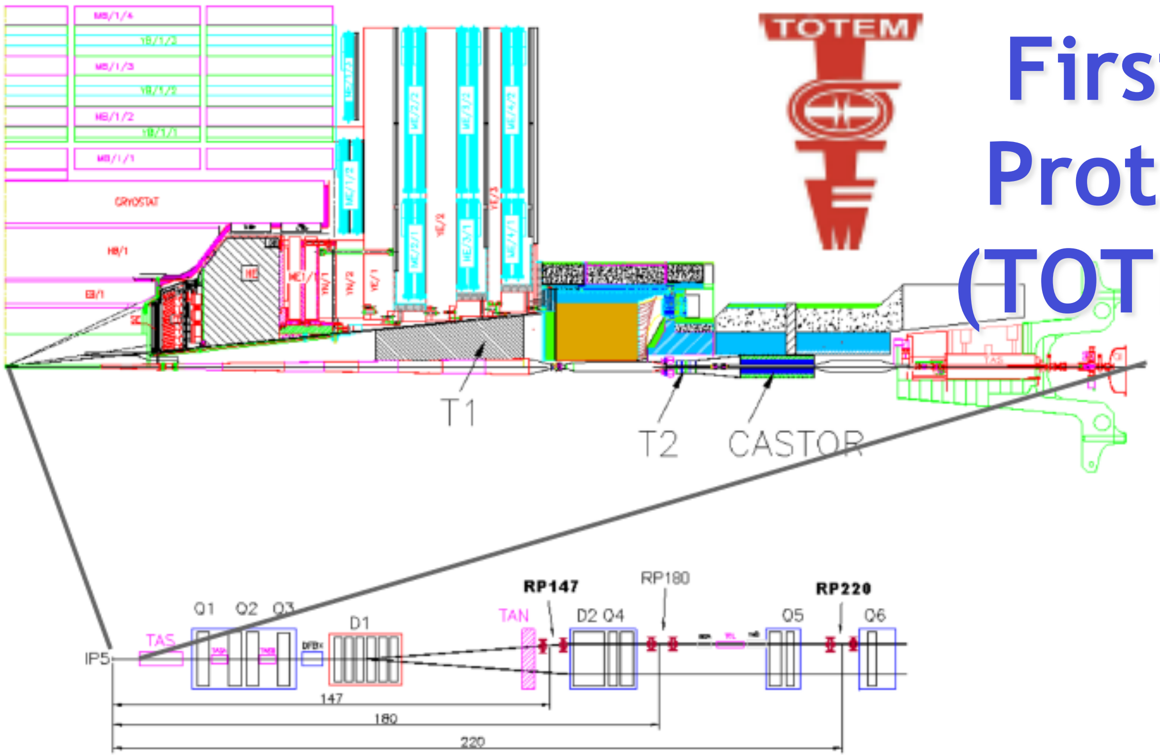
Limited by statistics and p-tagging systematics

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

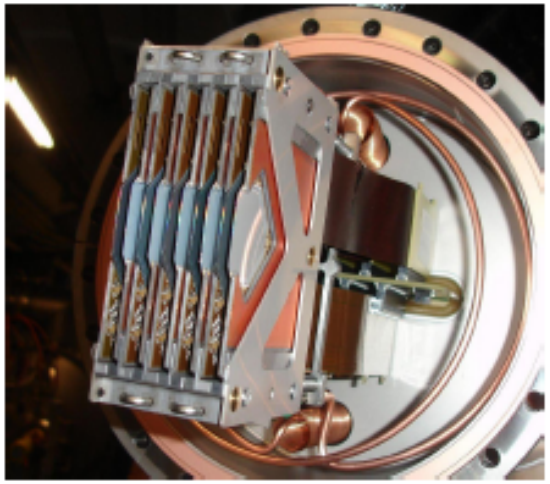


Limited by p-diss systematics

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



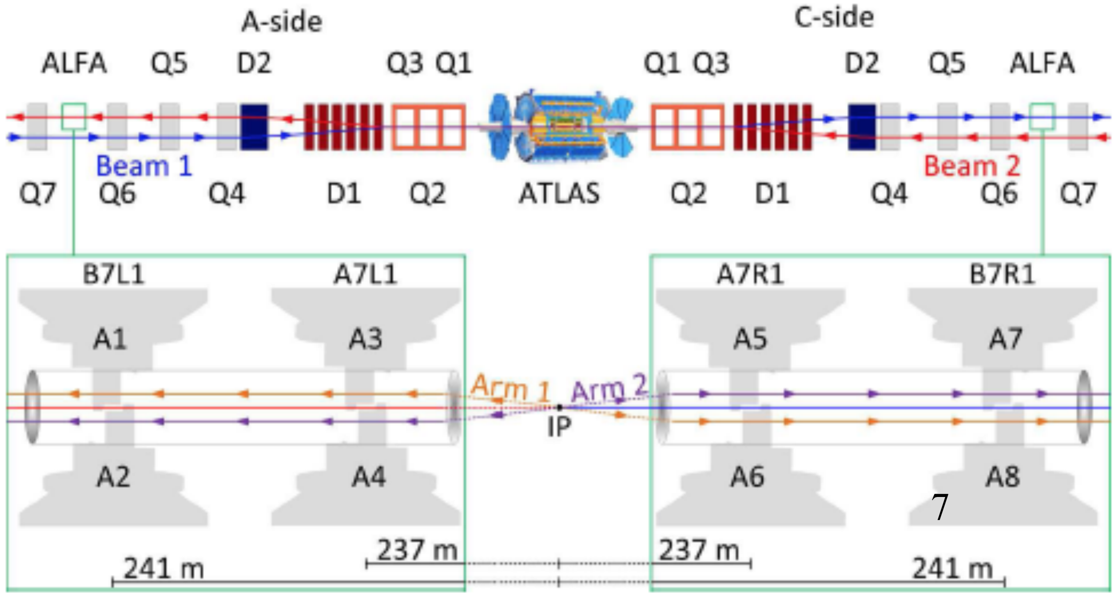
First Generation LHC Proton Spectrometers (TOTEM & ATLAS-ALFA)



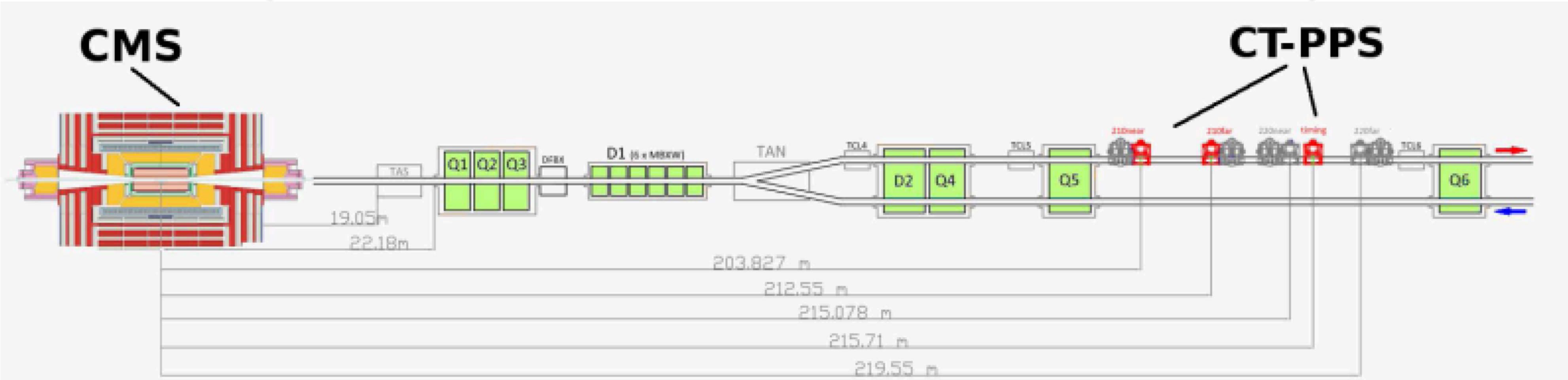
‘Roman pot’ vacuum-sealed insertions to beampipe, well downstream of IP.

→Usually deployed in dedicated (high β*) runs

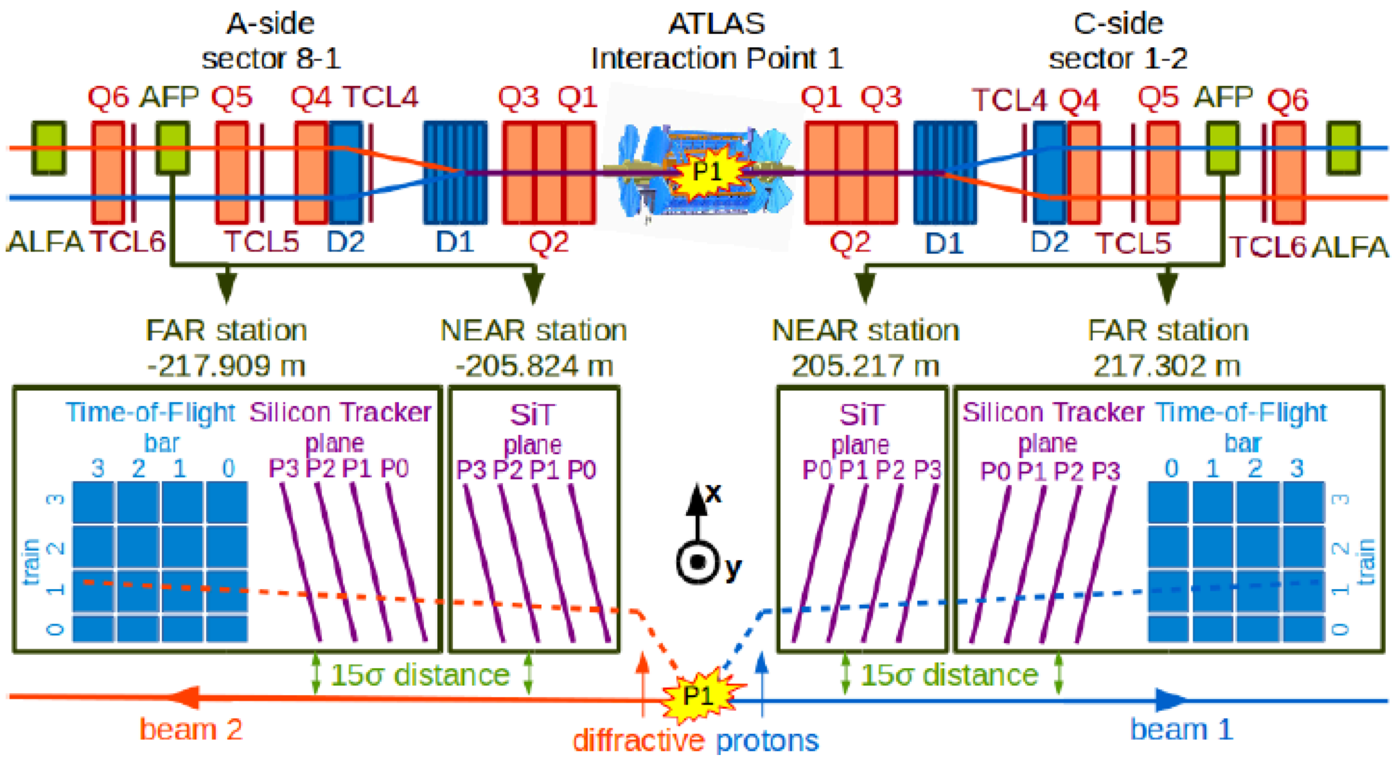
→ Can run independently of ATLAS / CMS or with common DAQ.



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



AFP
@
ATLAS

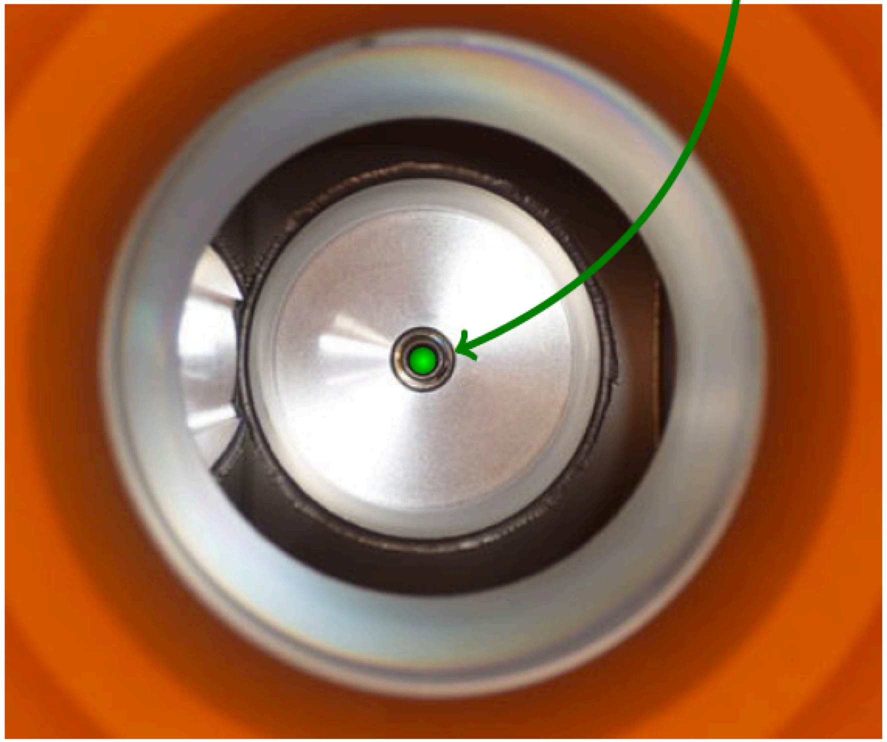


Advantages of Roman Pot Technology

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

Advantages of Roman Pot Technology

LHC beam



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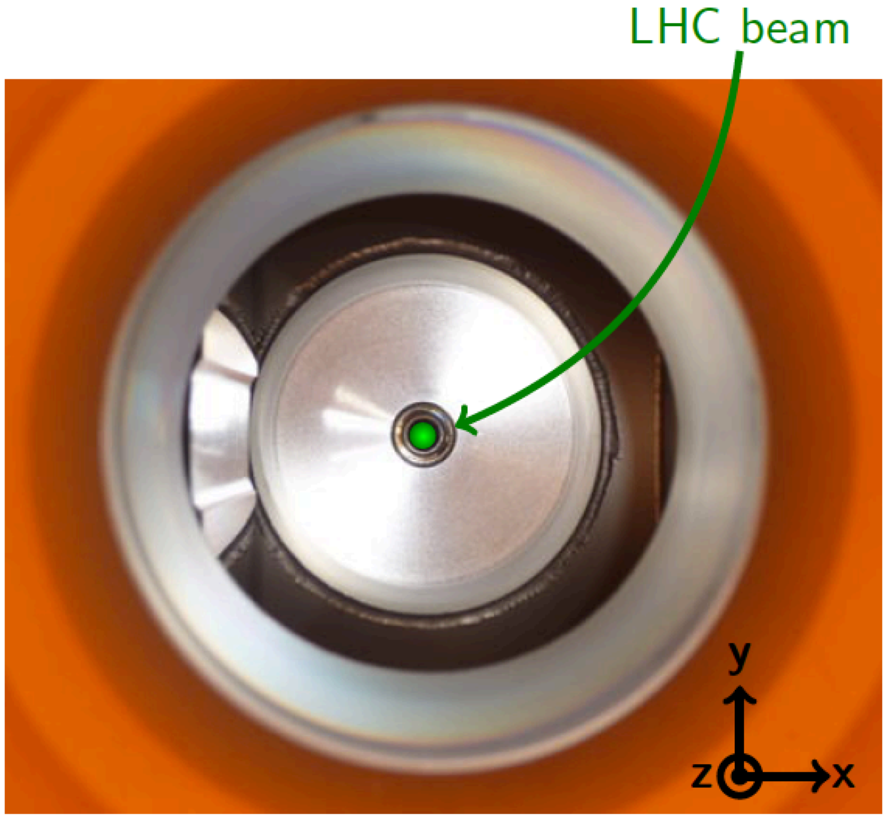

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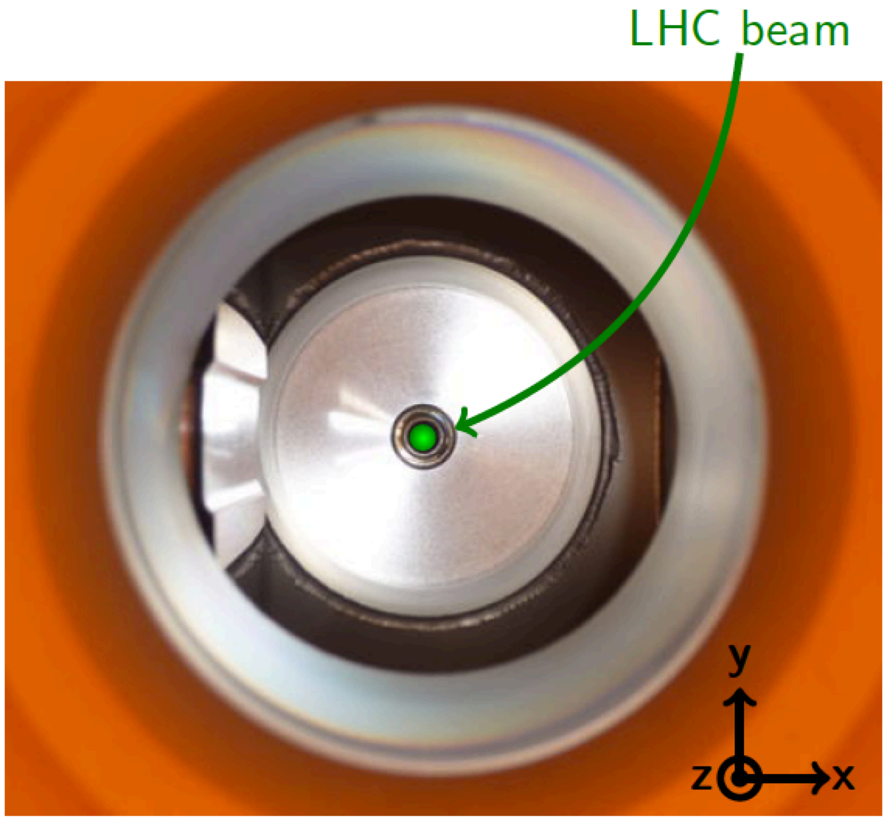

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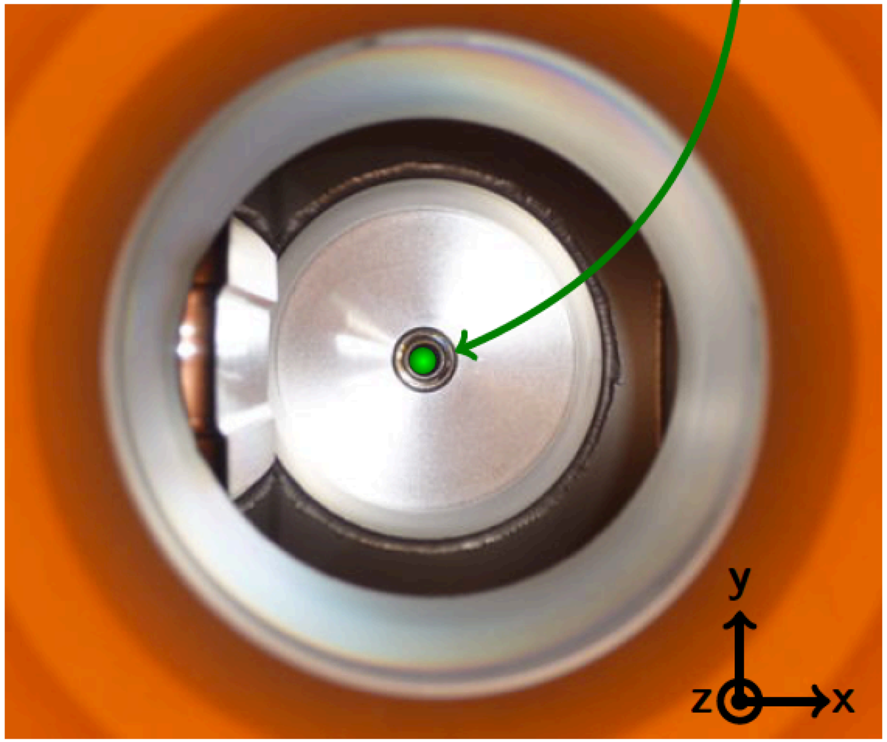

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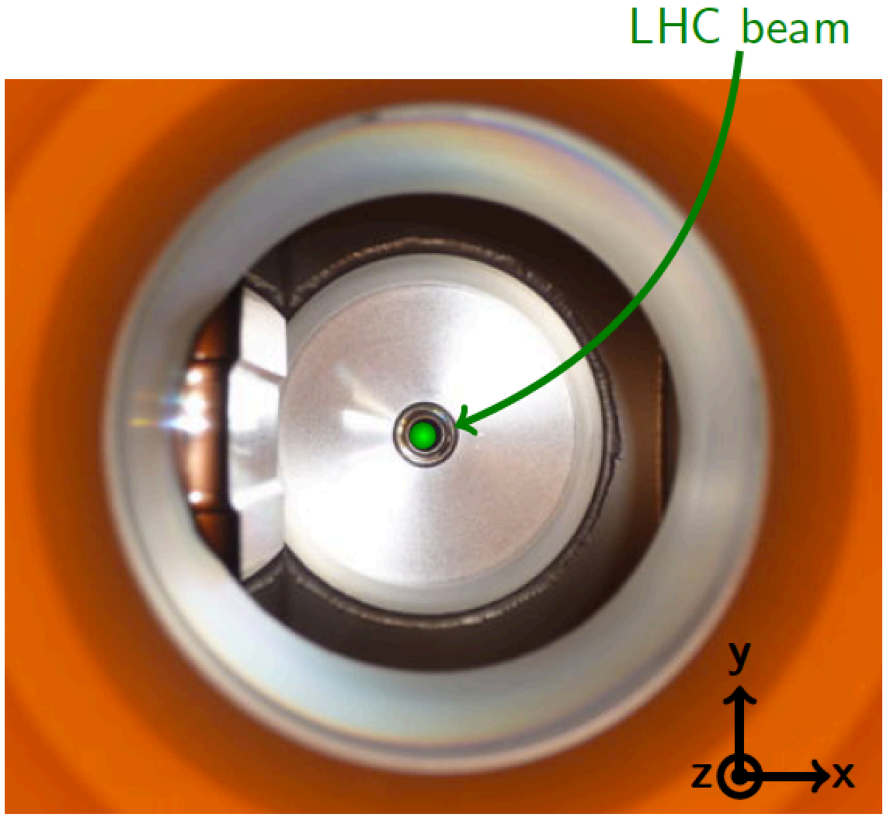

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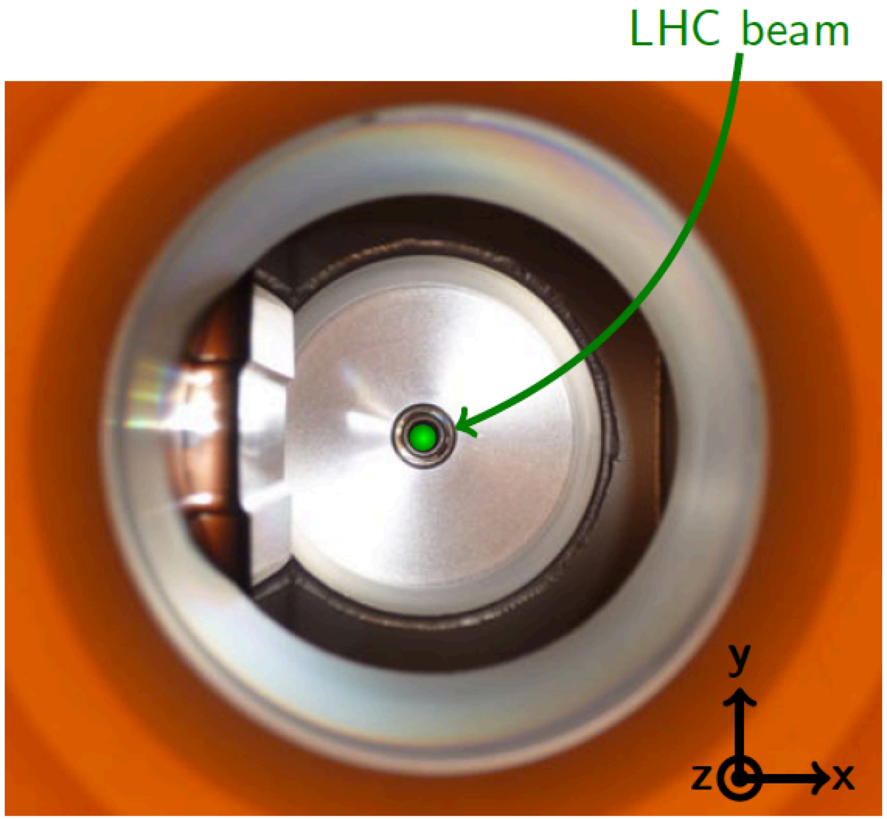

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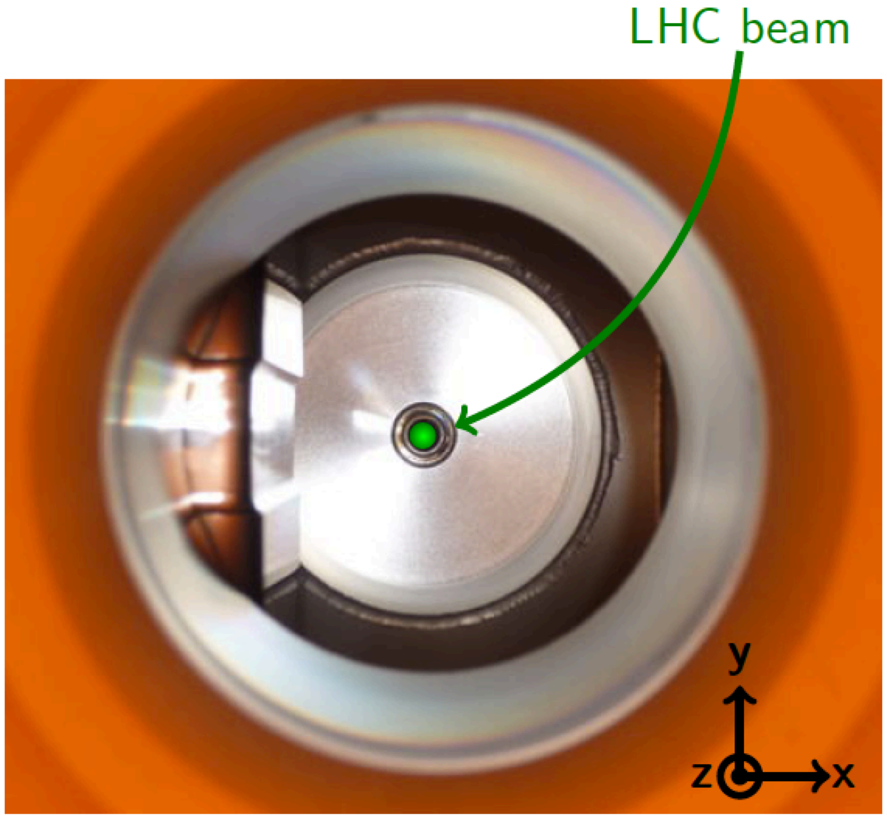
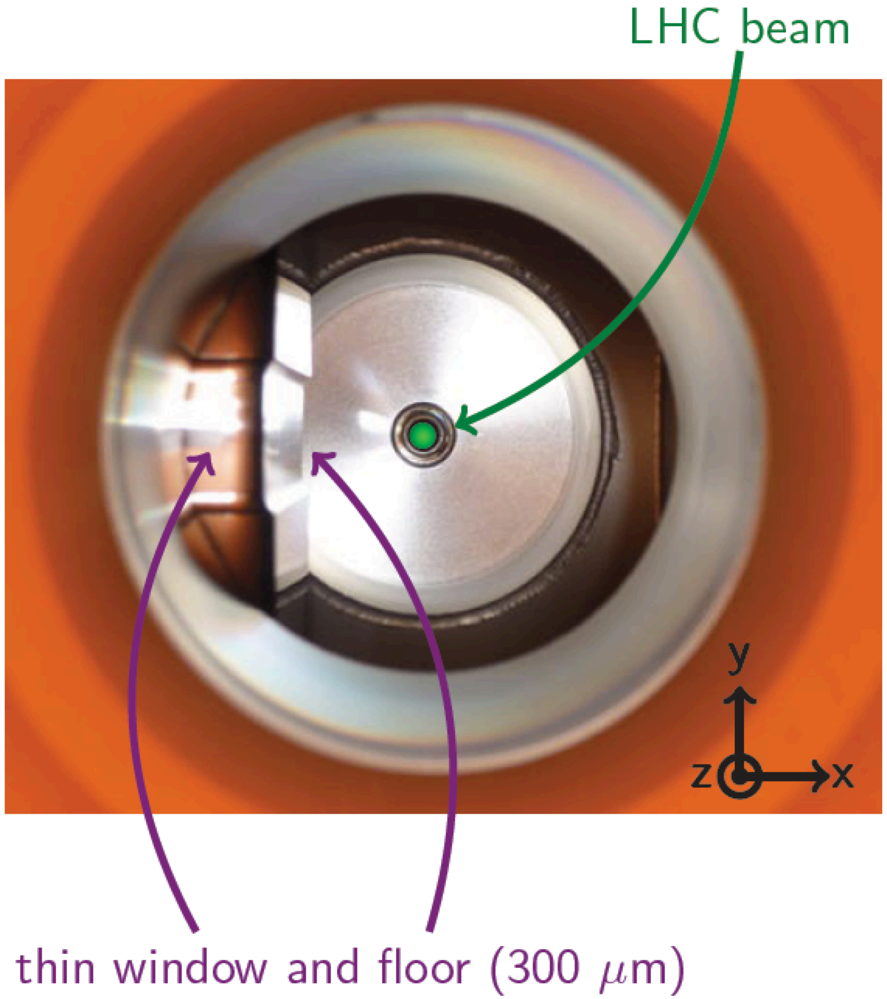
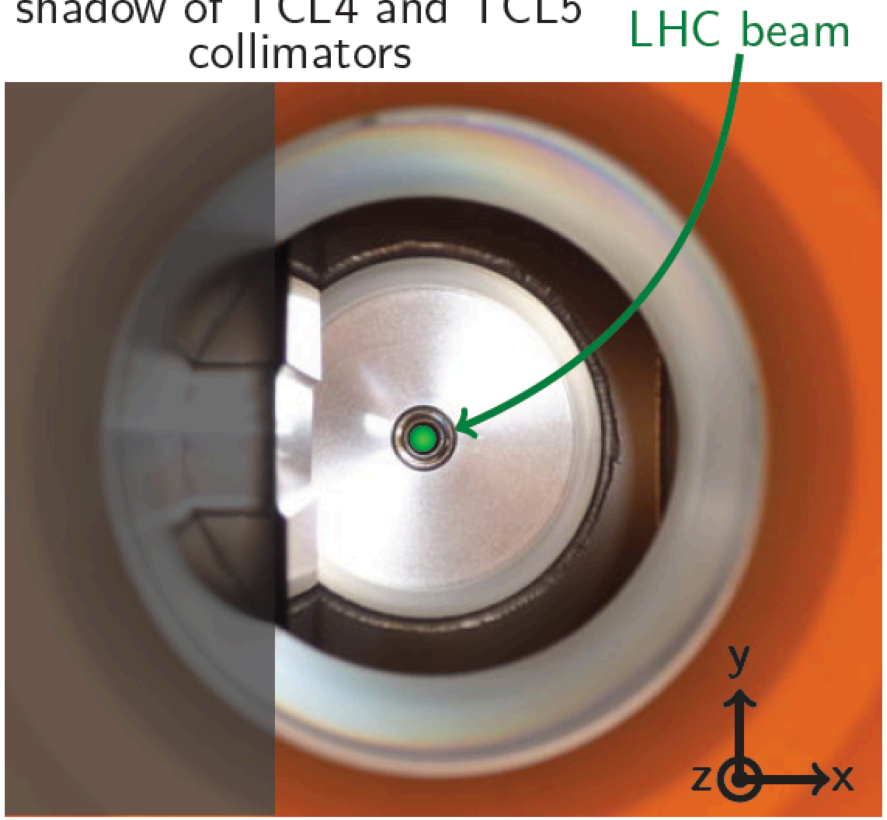



LHC beam
y
z
x
thin window and floor (300 μm)

Advantages of Roman Pot Technology

shadow of TCL4 and TCL5 collimators



thin window and floor (300 μm)

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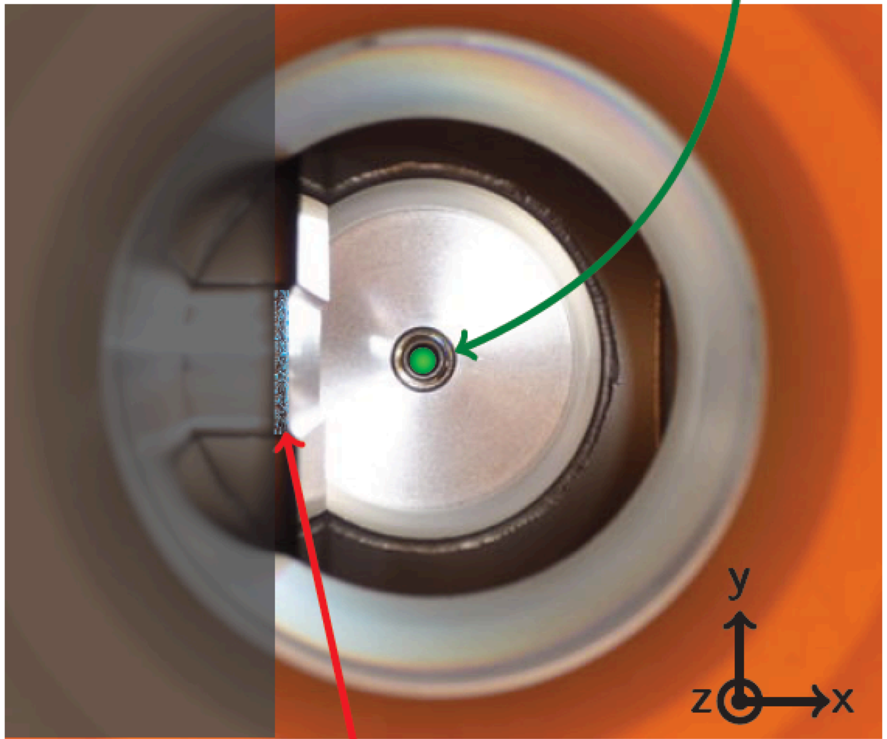
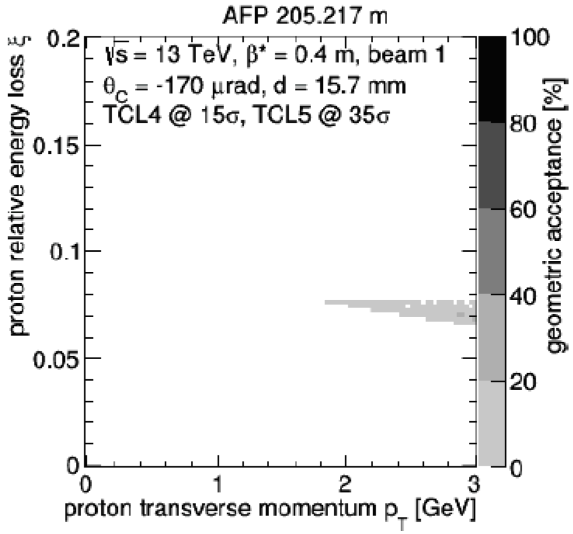


diffractive protons

thin window and floor (300 μm)

Geometric acceptance:



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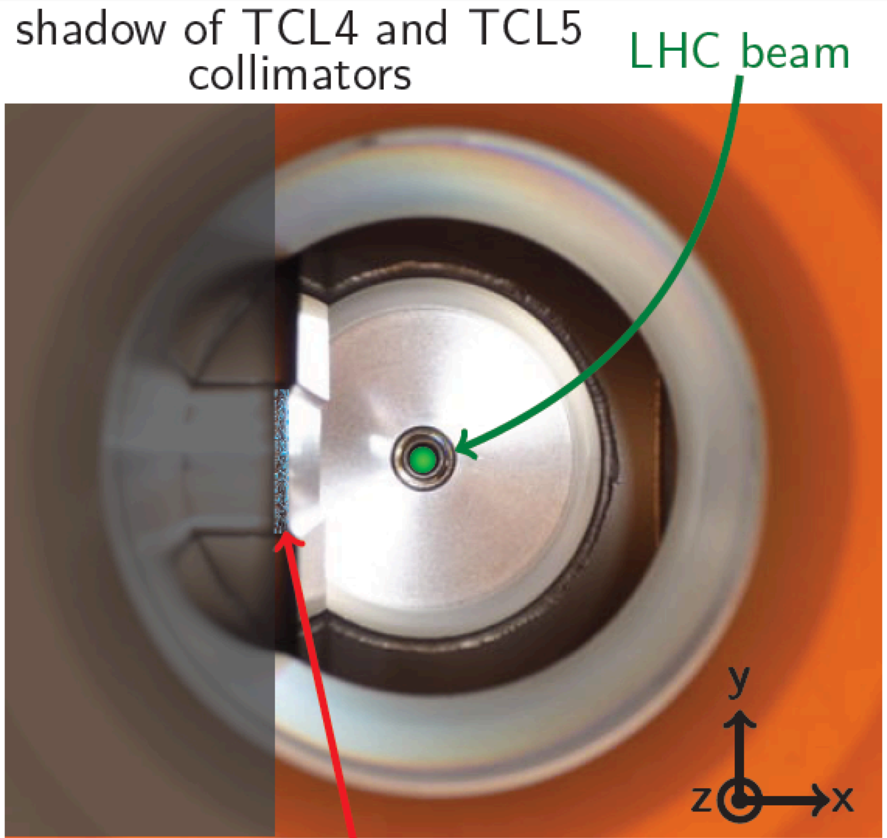

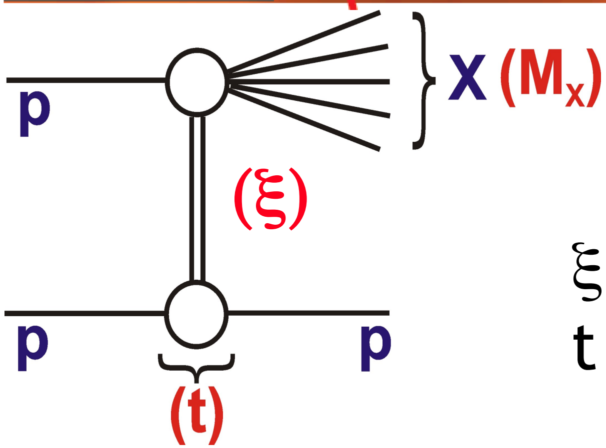

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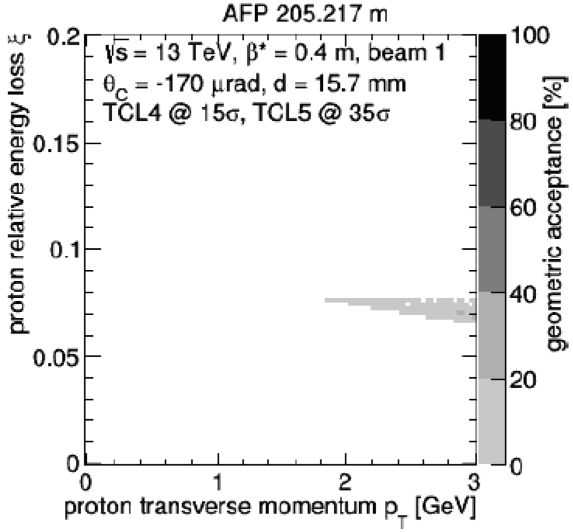

Described here in terms of kinematics of `Single Diffractive Dissociation' (SD)

ξ = fractional proton energy loss

$t = -p_T^2$ of outgoing proton

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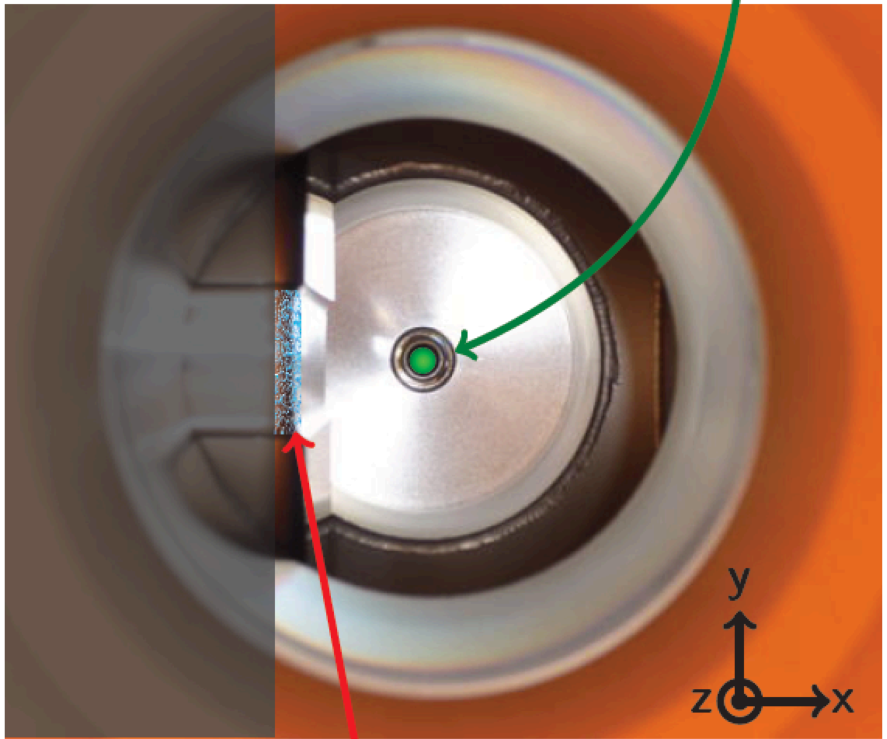
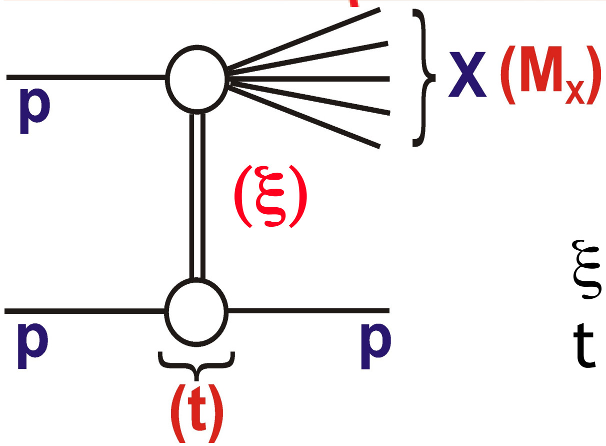
LHC beam





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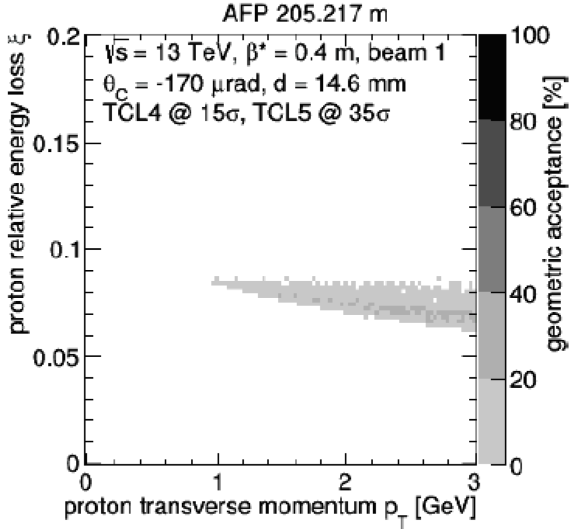

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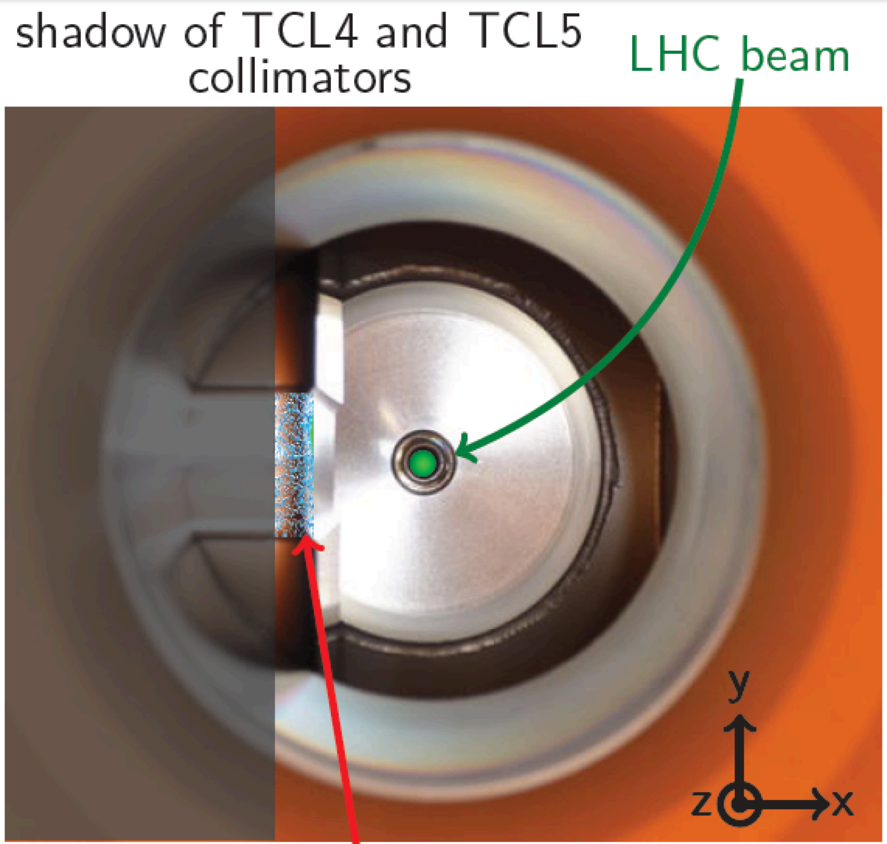

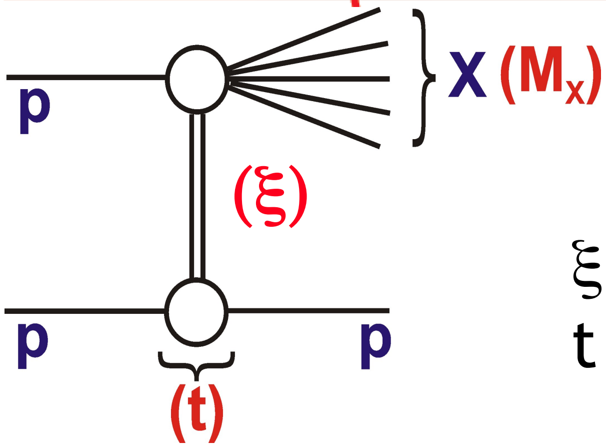

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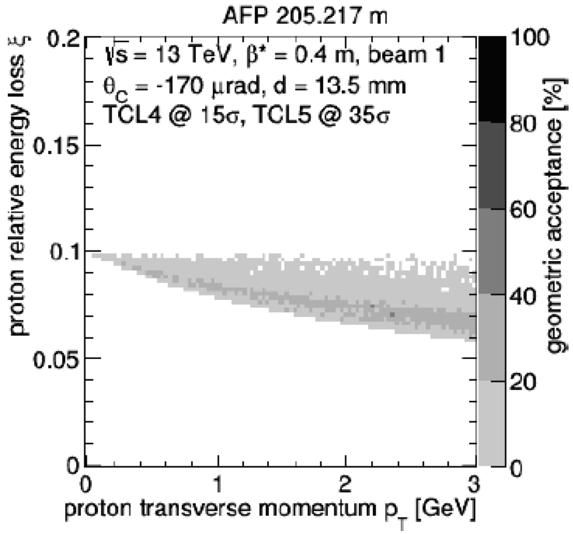

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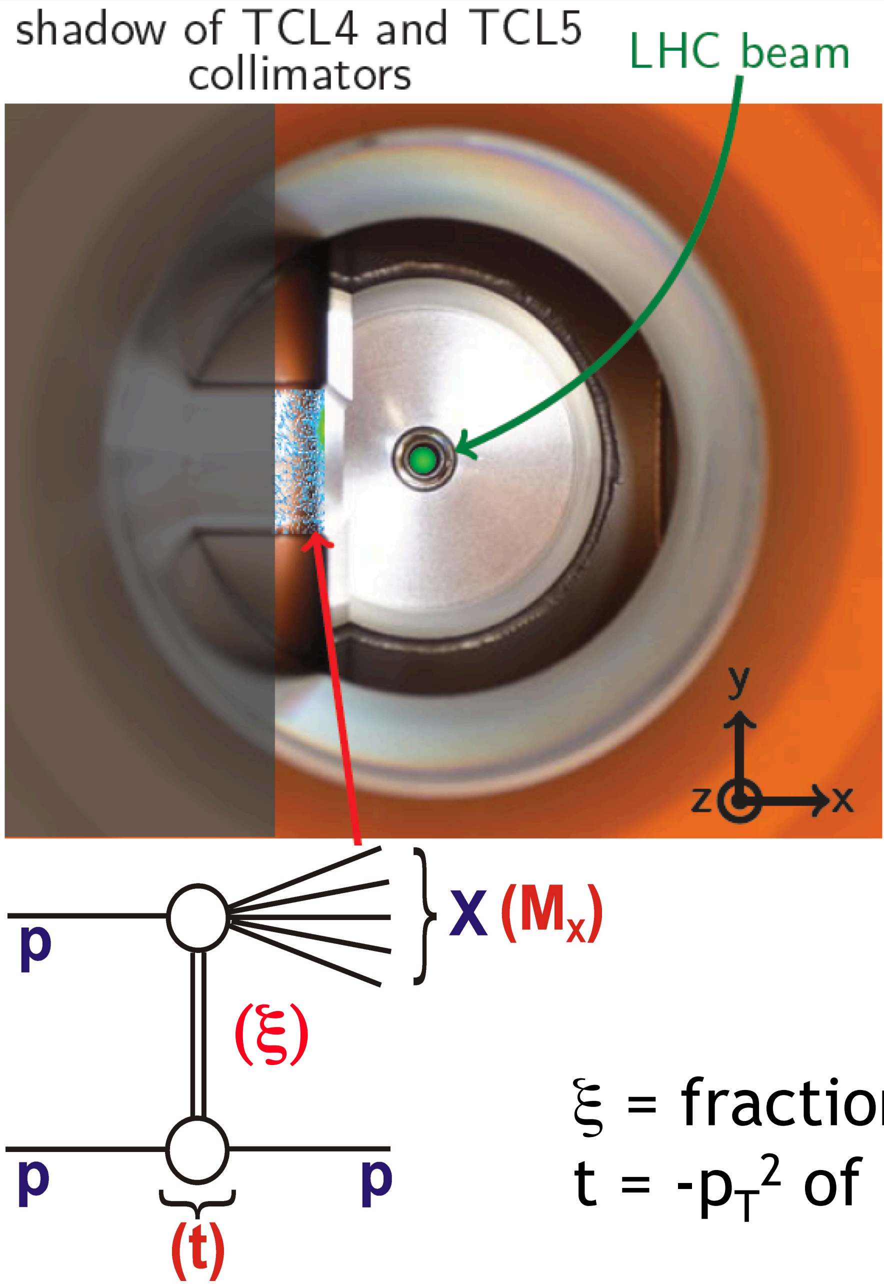

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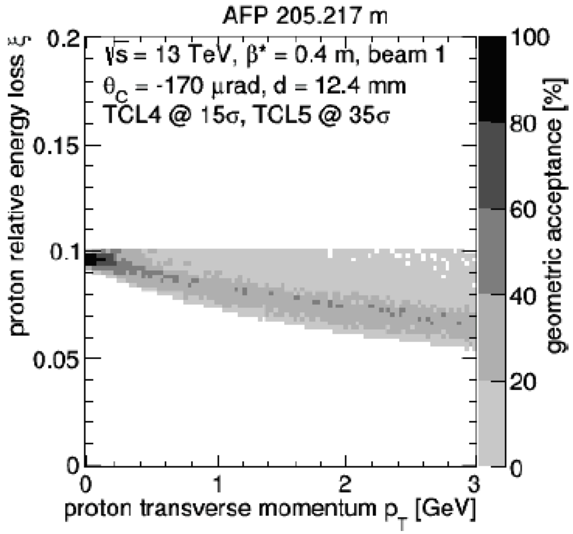

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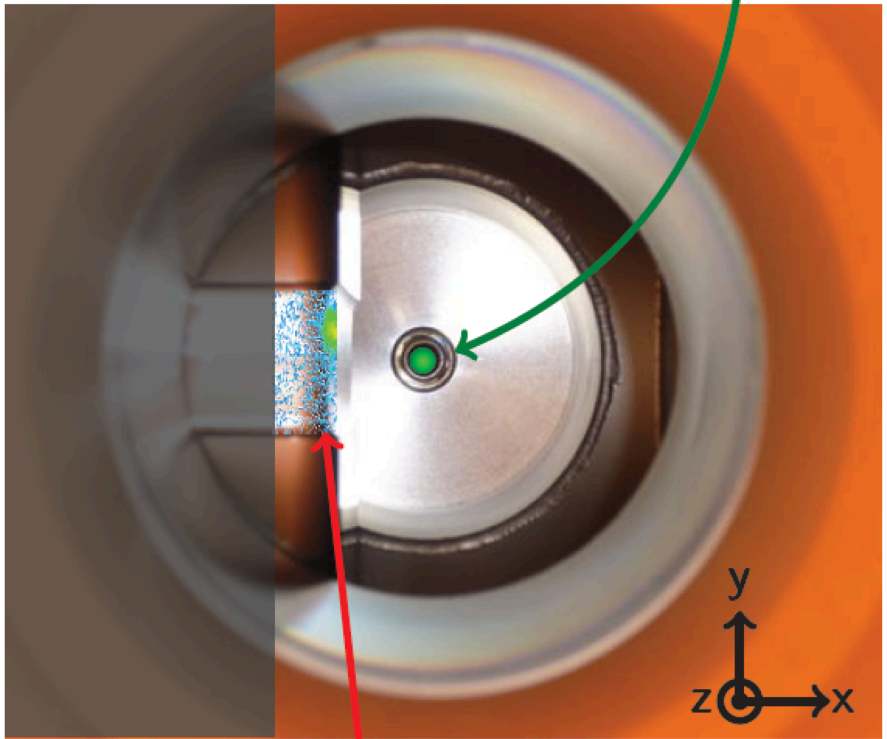

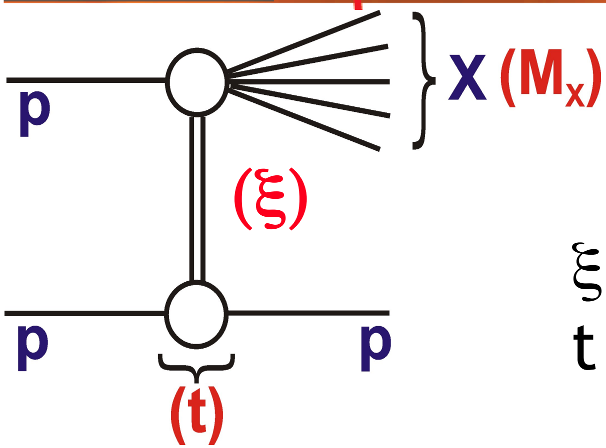

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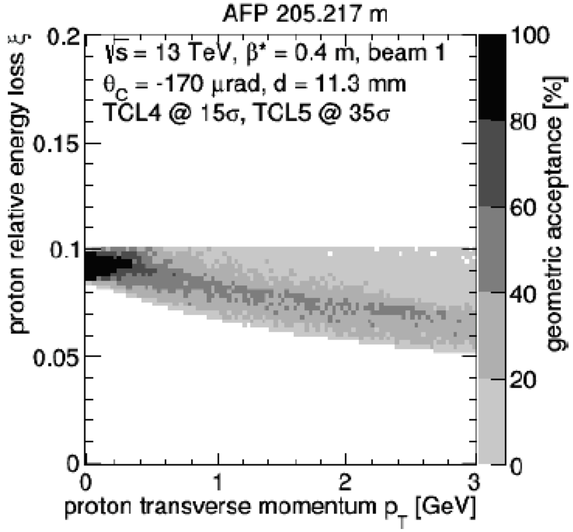

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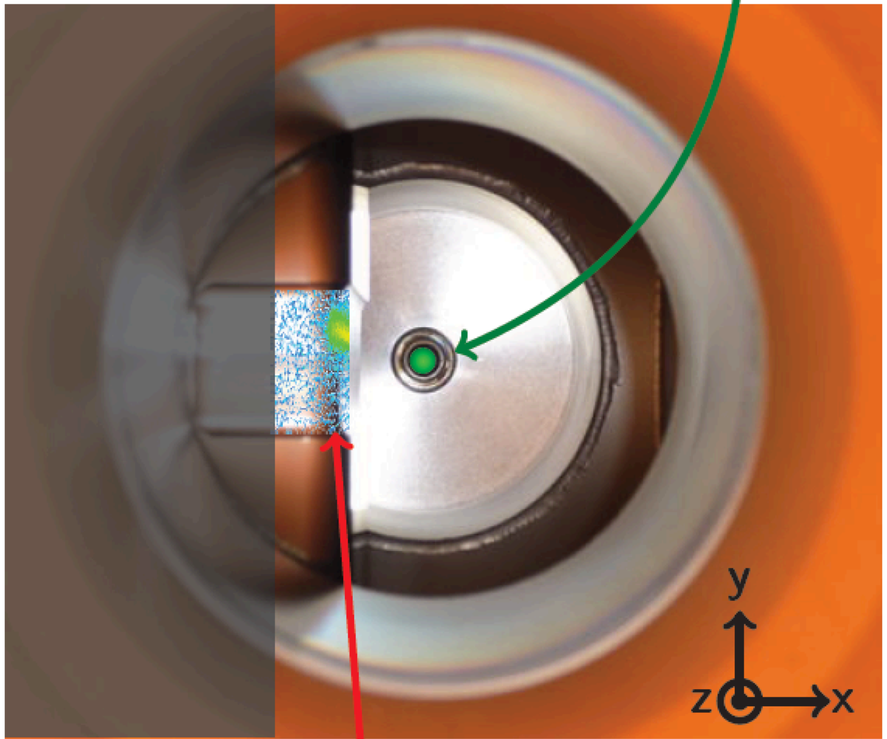

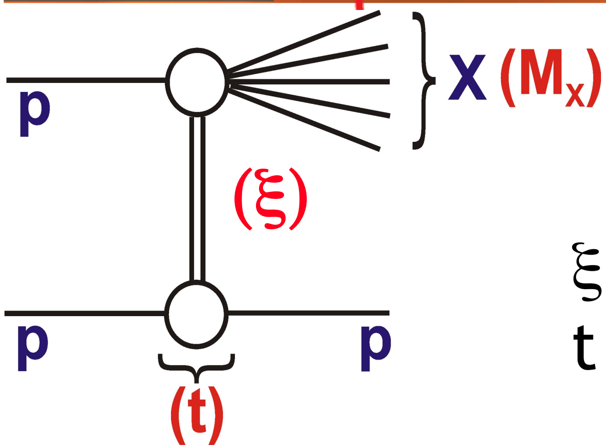

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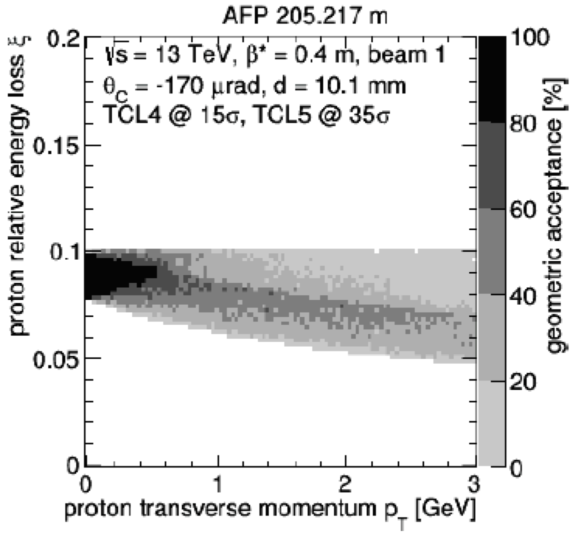

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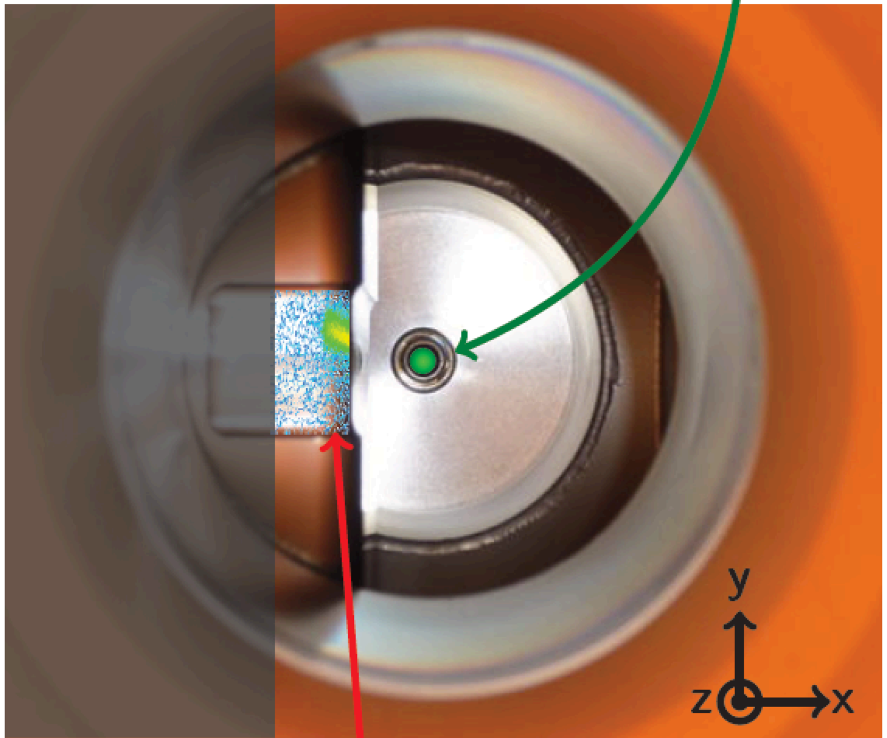

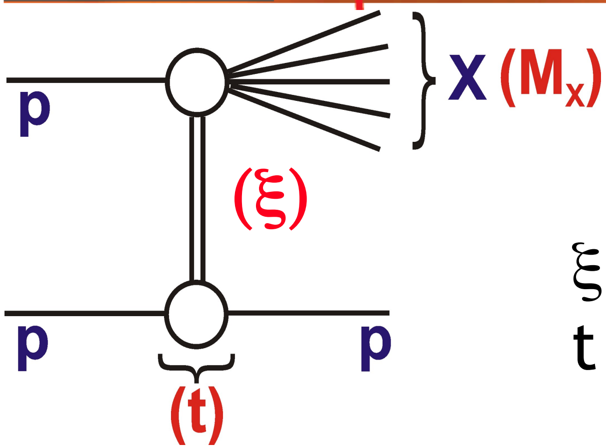

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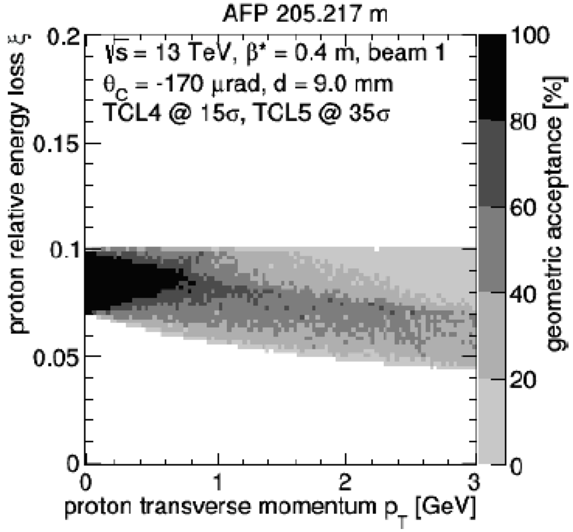

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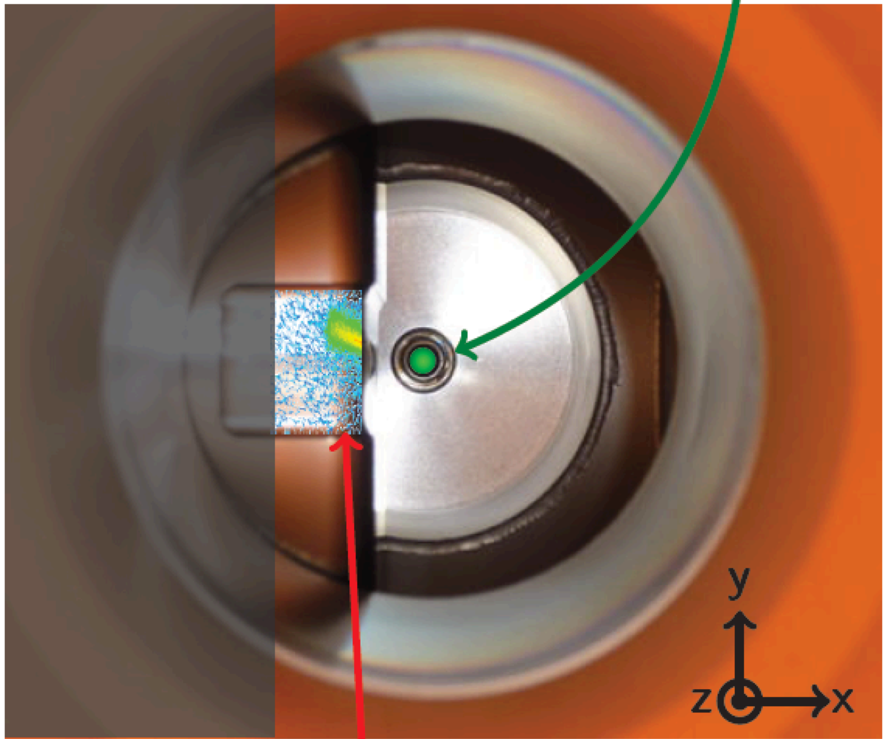

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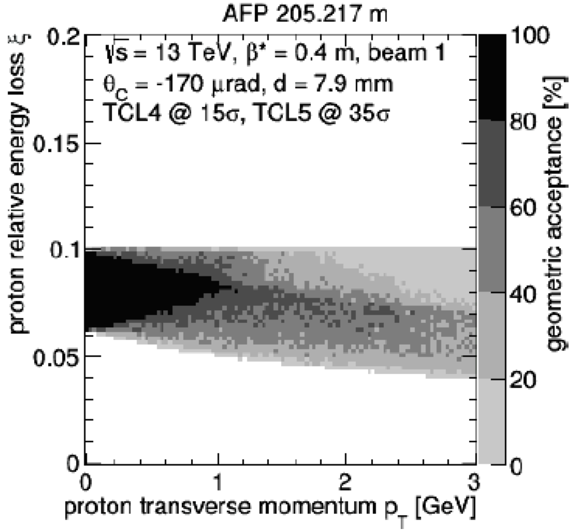

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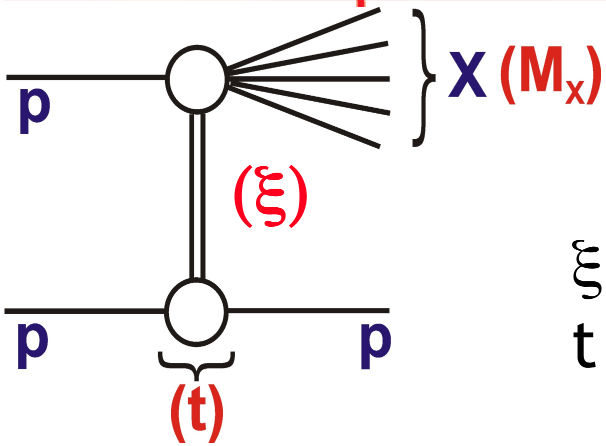

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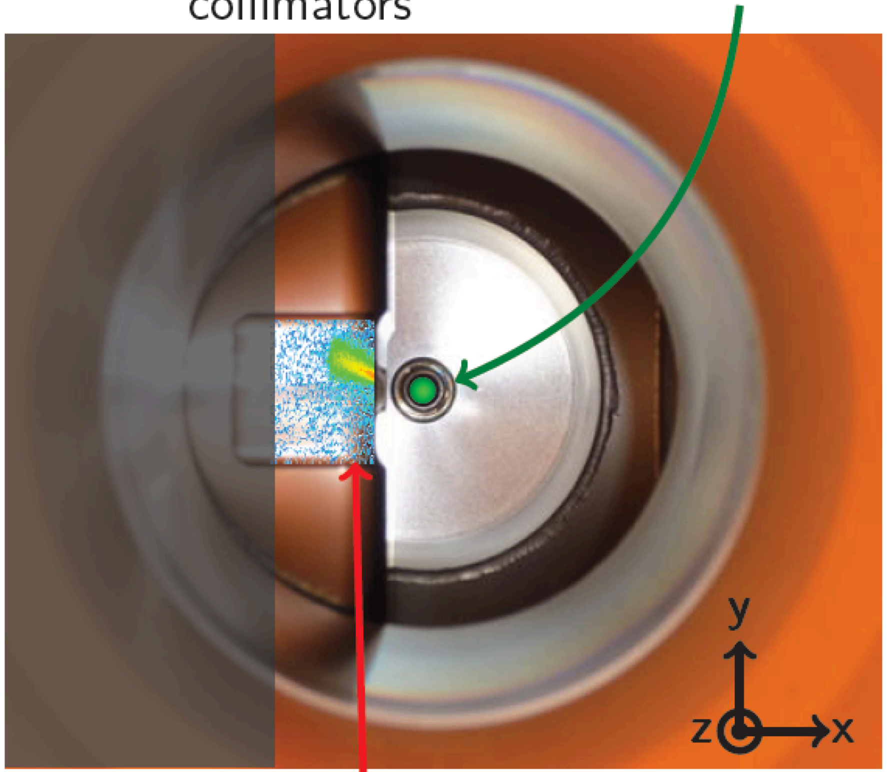

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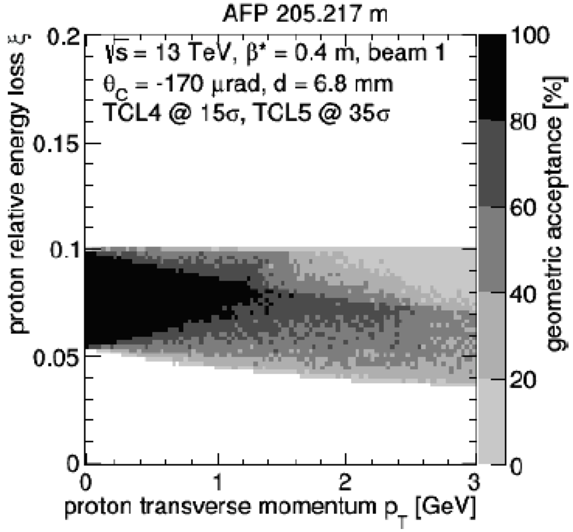

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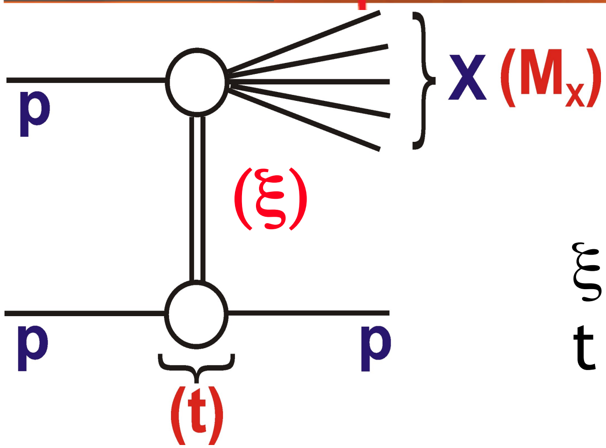

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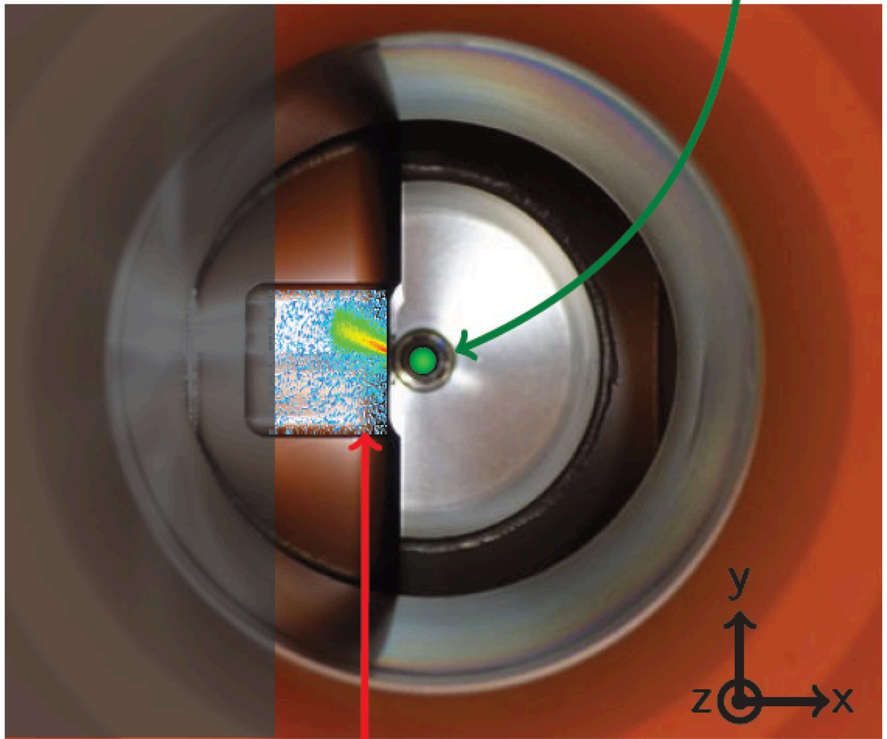

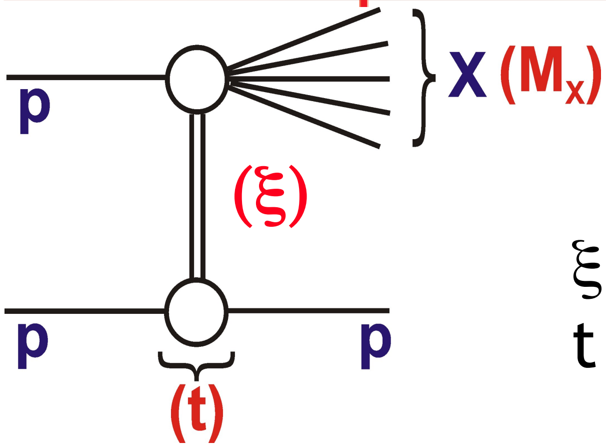

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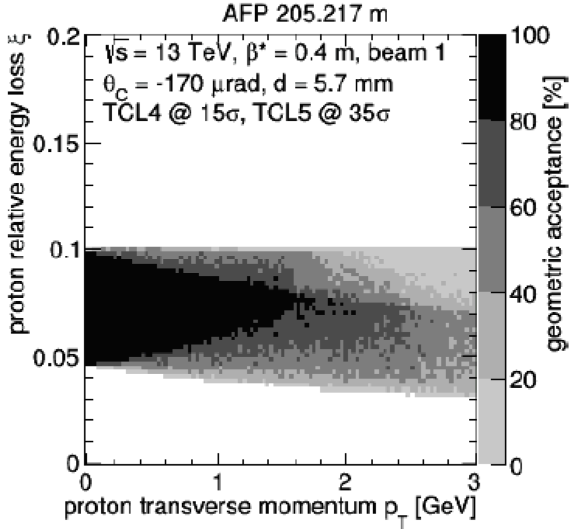

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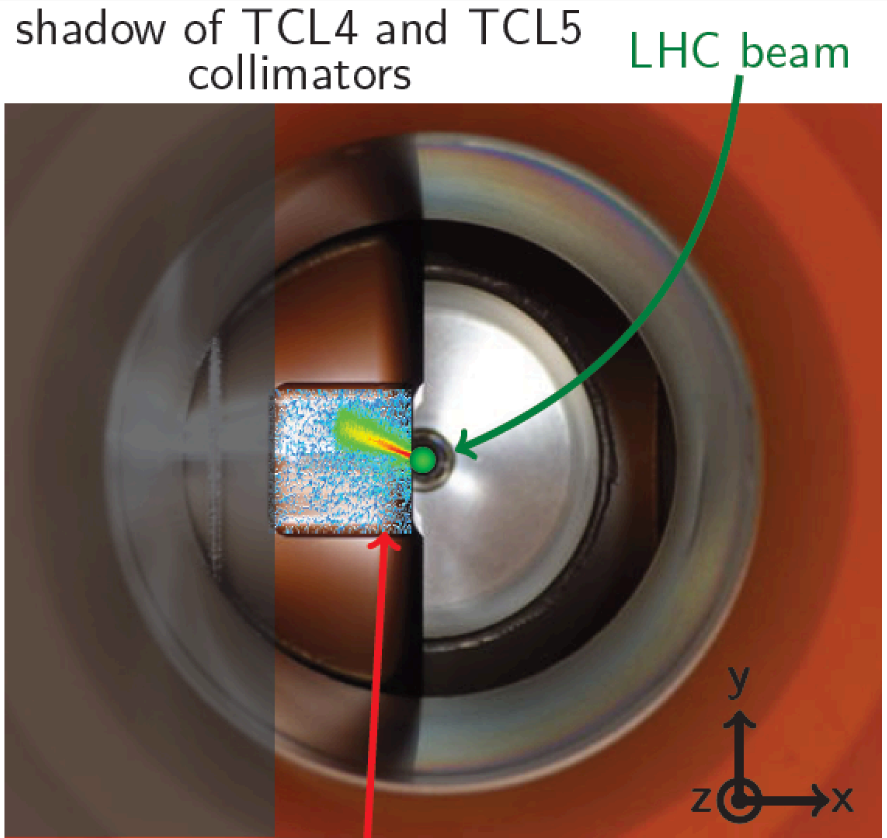

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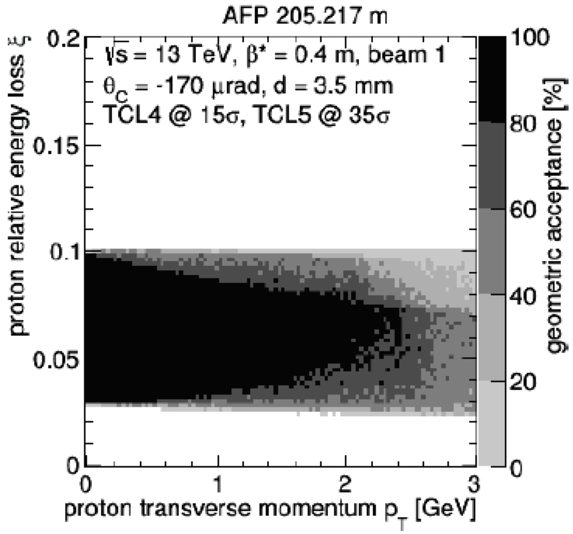

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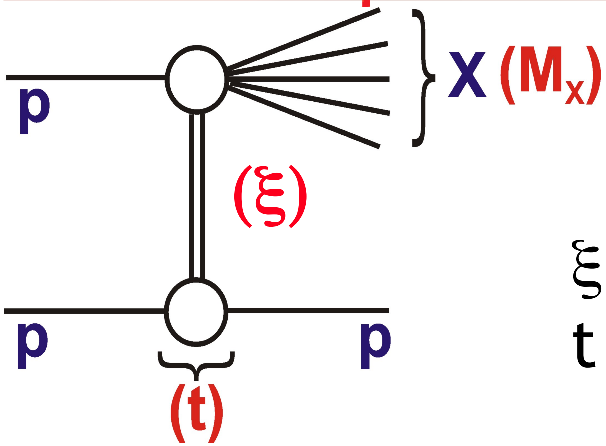

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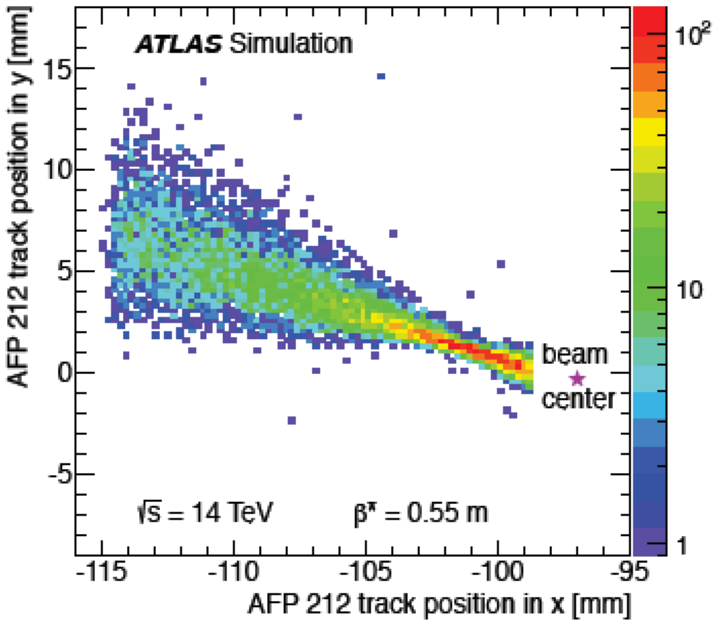
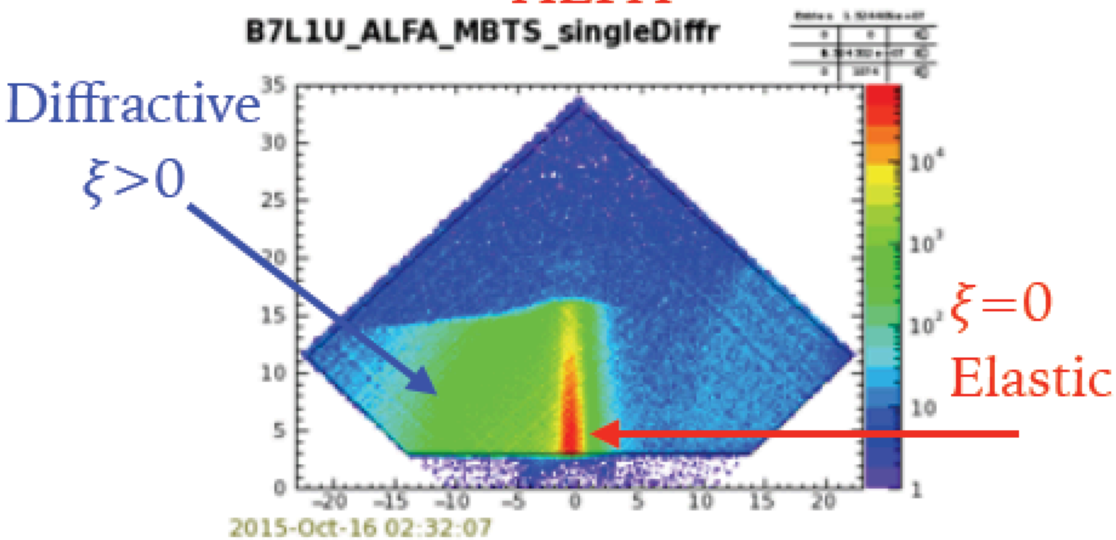
Acceptance Depends on Location and Orientation of Pot (horizontal or vertical) and on beam optics

e.g. complementarity between ATLAS ALFA and AFP

AFP

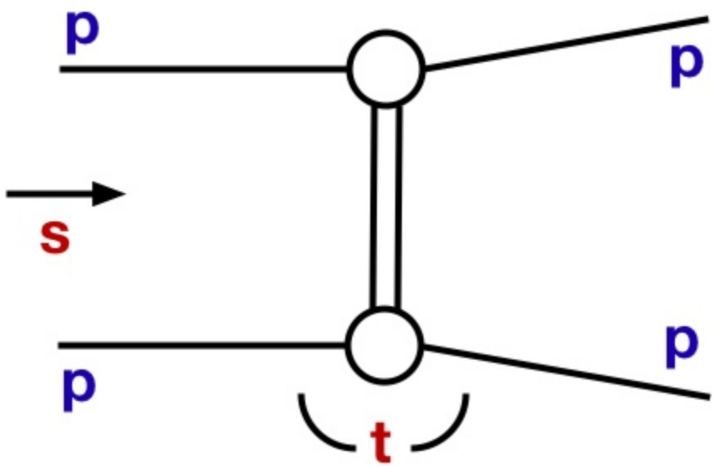


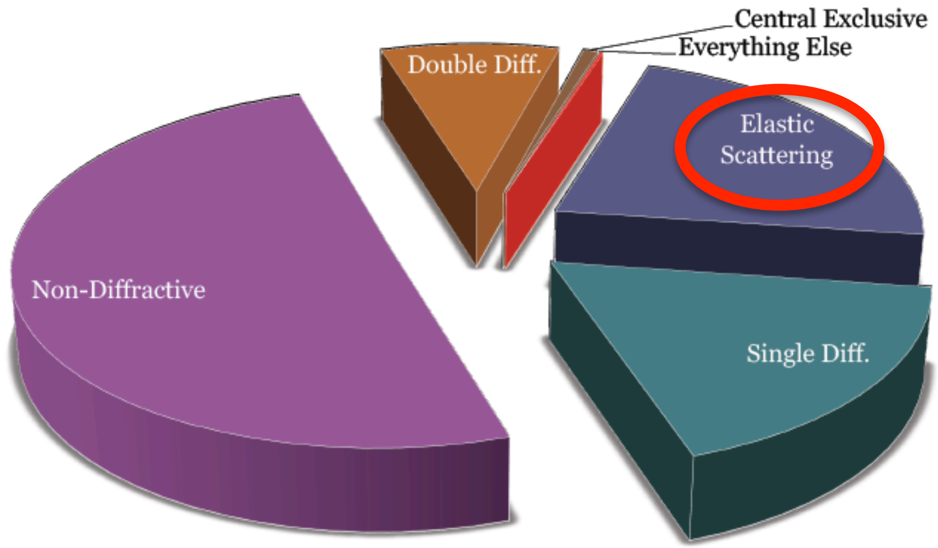
ALFA



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

Start `Simple': Elastic Scattering

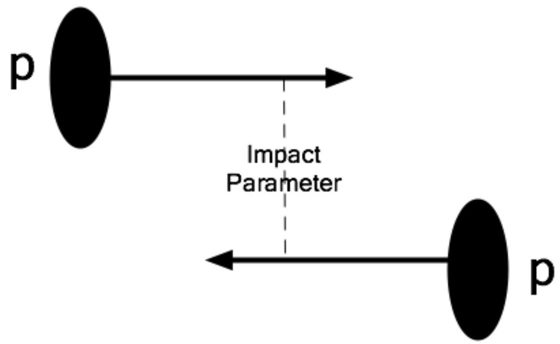




At fixed √s, 1 non –trivial variable
→ squared 4-momentum transfer, t

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

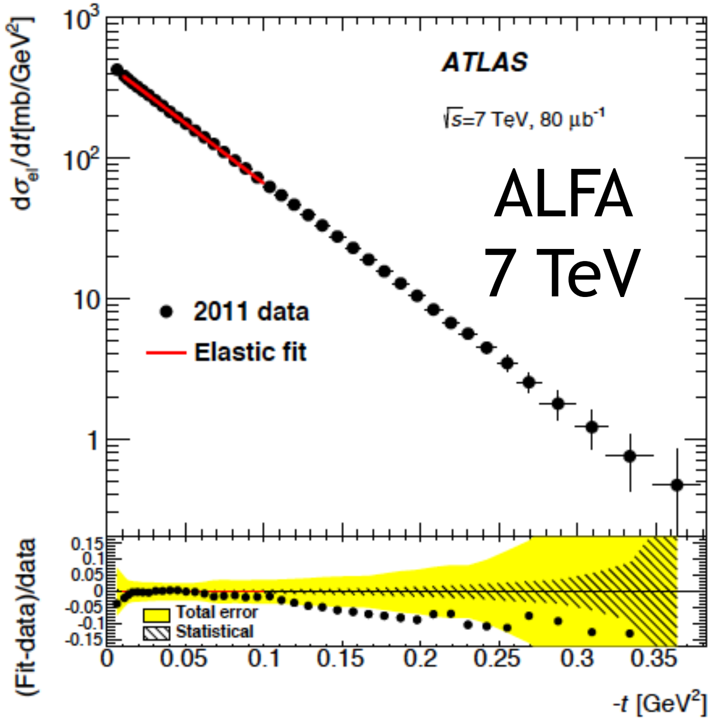
At fixed s: $$\frac{d\sigma}{dt} = \left.\frac{d\sigma}{dt}\right|_{t=0} e^{Bt}$$

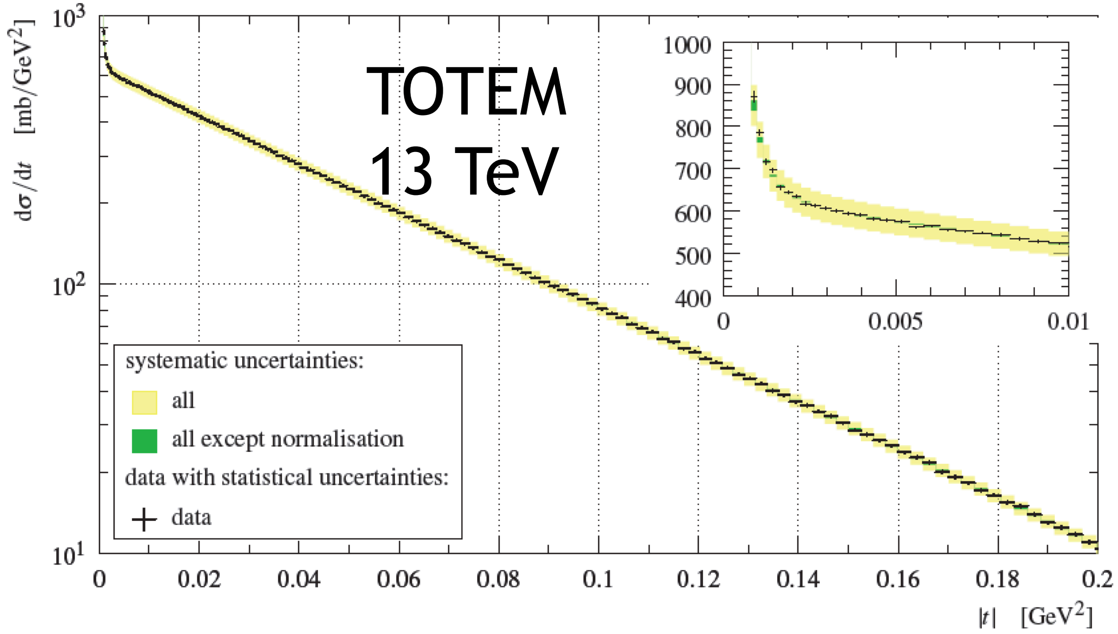


Slope parameter B measures mean impact parameter (~size of interaction region ~ range of strong force ~1-2fm).

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)

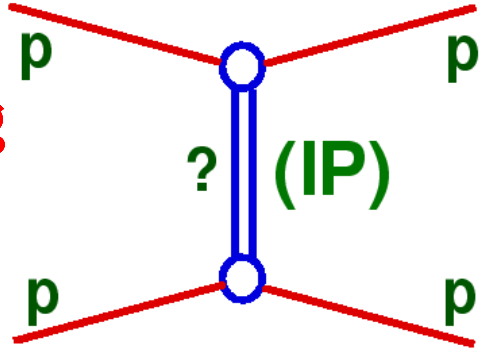
$$\frac{d\sigma}{dt} = \left.\frac{d\sigma}{dt}\right|_{t=0} e^{Bt}$$

e.g. at √s=7 TeV …

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

Underlying Physics of Elastic Scattering

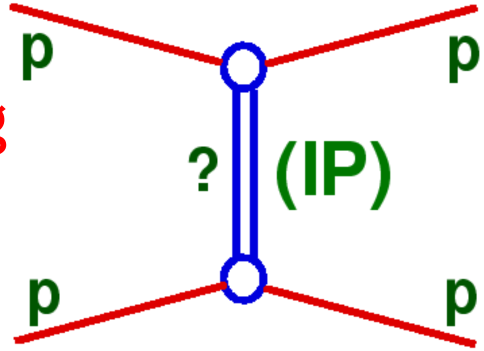
What governs elastic scattering at high energy and modest |t|?



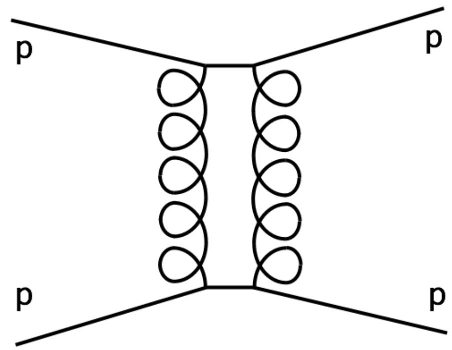
Historically, 'pomeron trajectory'

Underlying Physics of Elastic Scattering

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



Historically, 'pomeron trajectory'



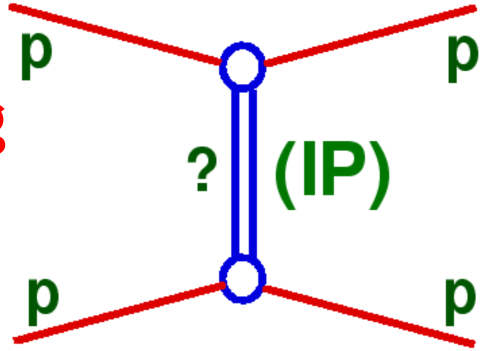
Loosely interpreted in terms of exchange of two gluons in a net colour singlet state

[but beware of partonic language in non-perturbative regime]

Most commonly described in `Regge' phenomenology …

Underlying Physics of Elastic Scattering

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



Historically, ‘pomeron trajectory’

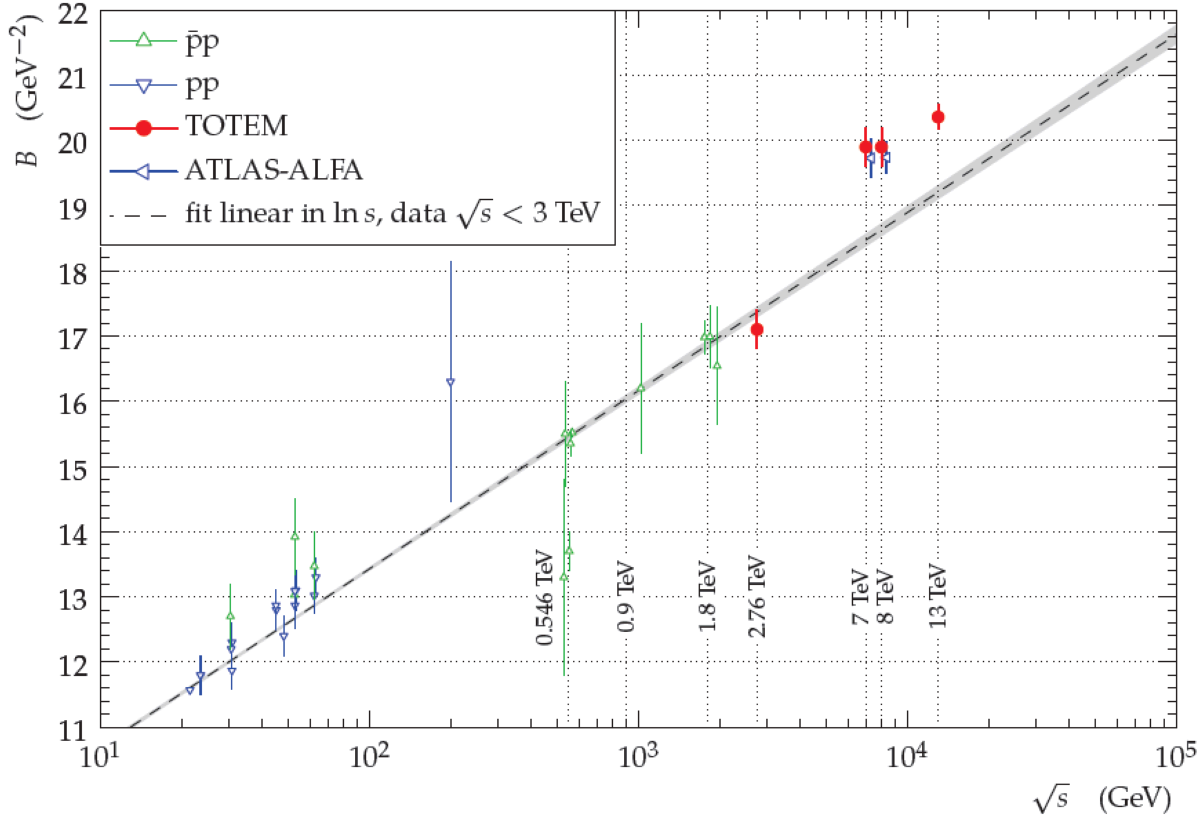
$$\alpha(t) = \alpha(0) + \alpha' t \approx 1.085 + 0.25t$$

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

Slope parameter $B = B_0 + 2\alpha' \ln\left(\frac{s}{s_0}\right)$ grows logarithmically with energy

√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:

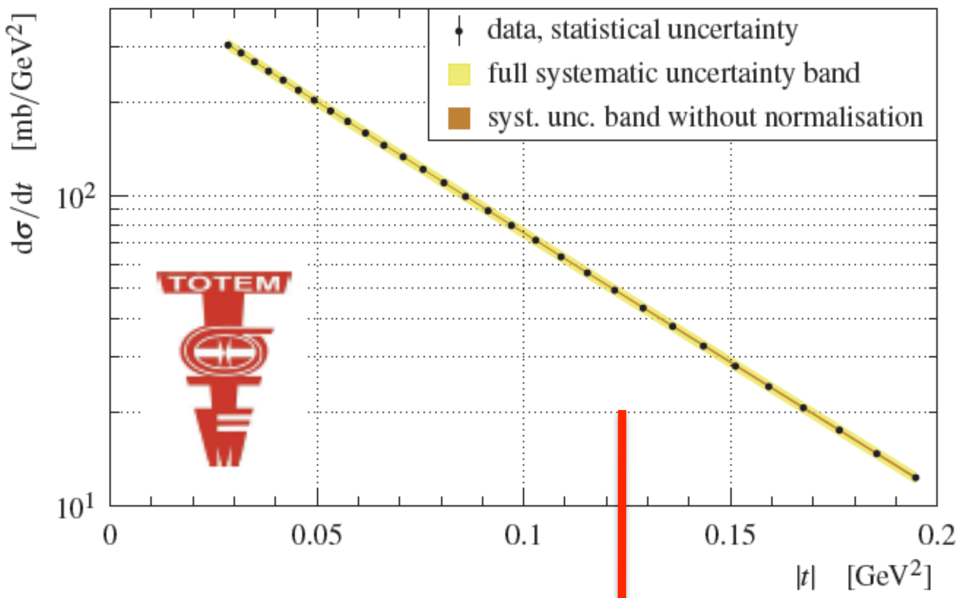
$$\frac{d\sigma_{EL}}{dt} \propto \exp(Bt)$$

`Standard' Pomeron `pole' Regge theory

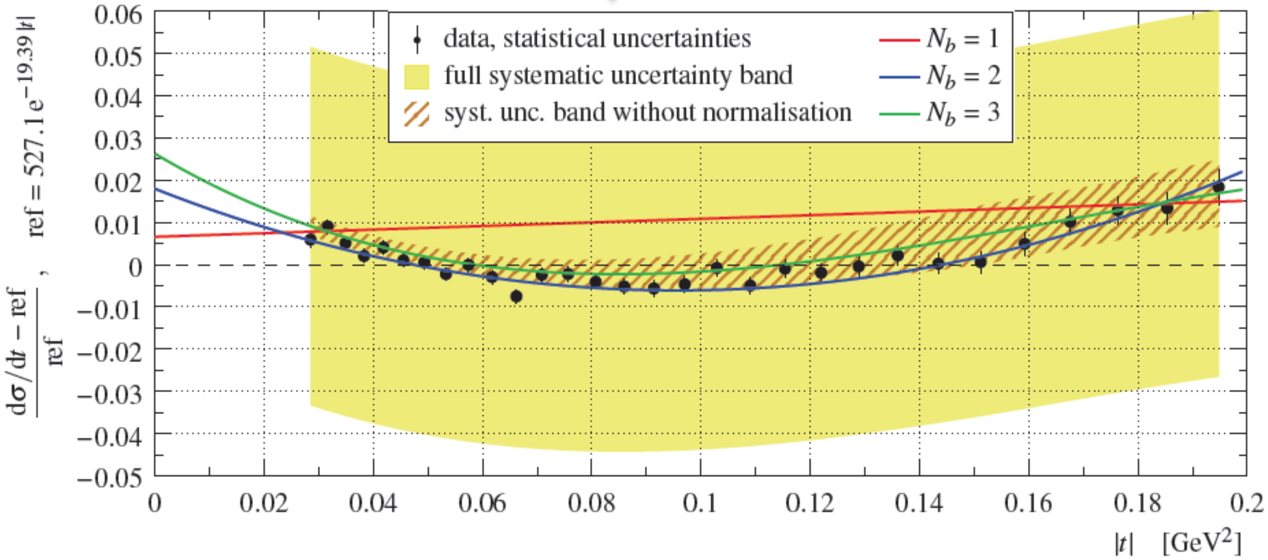
$$B = B_0 + 2\alpha' \ln\left(\frac{s}{s_0}\right)$$

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

Looking in more detail (TOTEM 8 TeV, 13 TeV)



eg 2012 β*=90m 8TeV sample is 7 million events → single exponential slope rejected at 7.2σ level

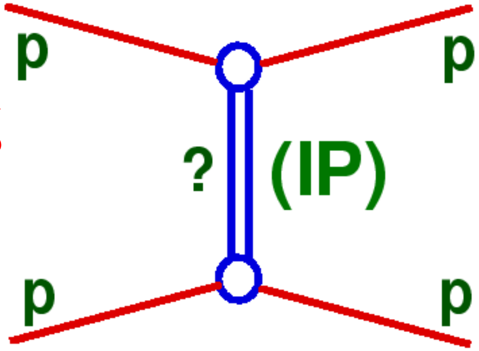


… suggests that low |t| (non-perturbative) elastic scattering via strong interaction is not mediated by a single exchange (like a pomeron Regge Pole).

→Multiple exchanges/ absorptive corrections

From Elastic to Total Cross Sections

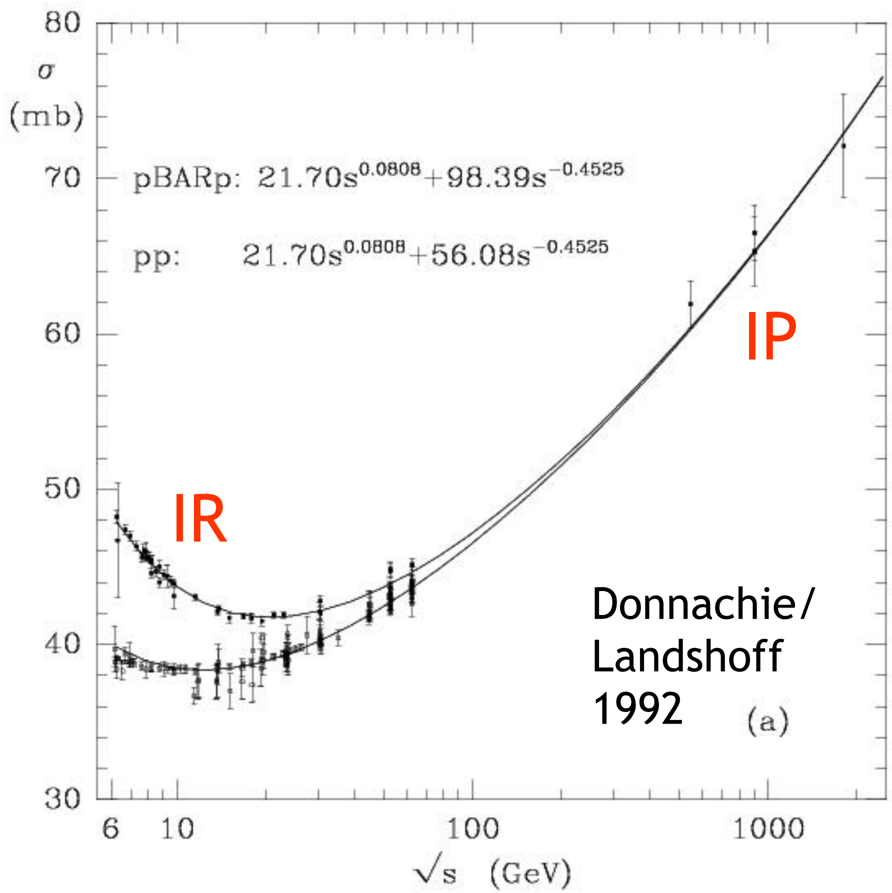
What governs elastic scattering at high energy and modest |t|?



Historically, 'pomeron trajectory'

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

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

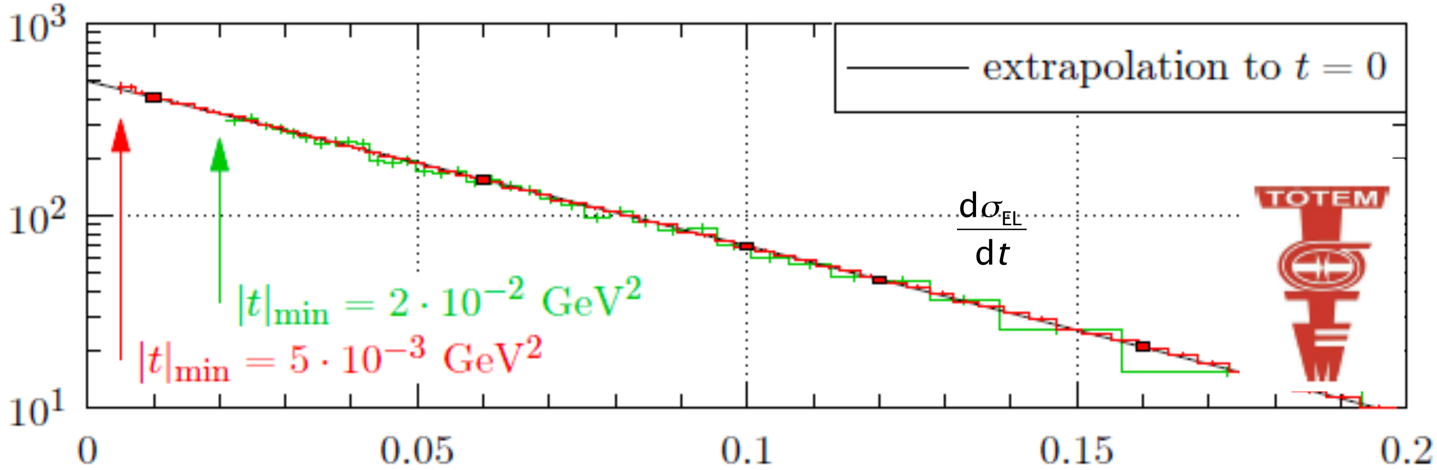


Elastic scattering closely related to total x-sec via optical theorem …

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

Extracting Total X-Section through Optical Theorem

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

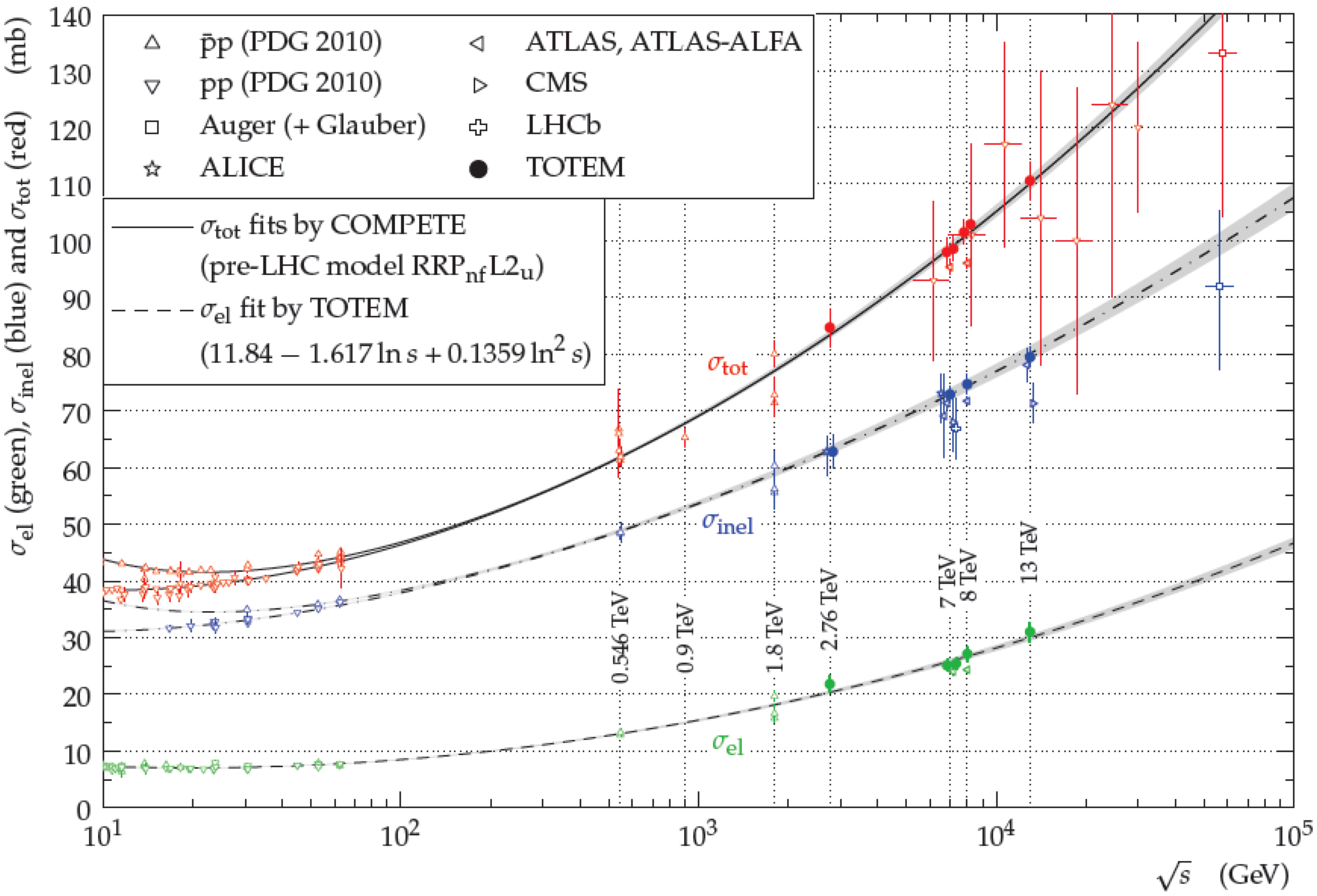


$\left.\frac{d\sigma_{EL}}{dt}\right|_{t=0}$ can be obtained through extrapolation of hadronic part of elastic cross section (~10% extrapolation)

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

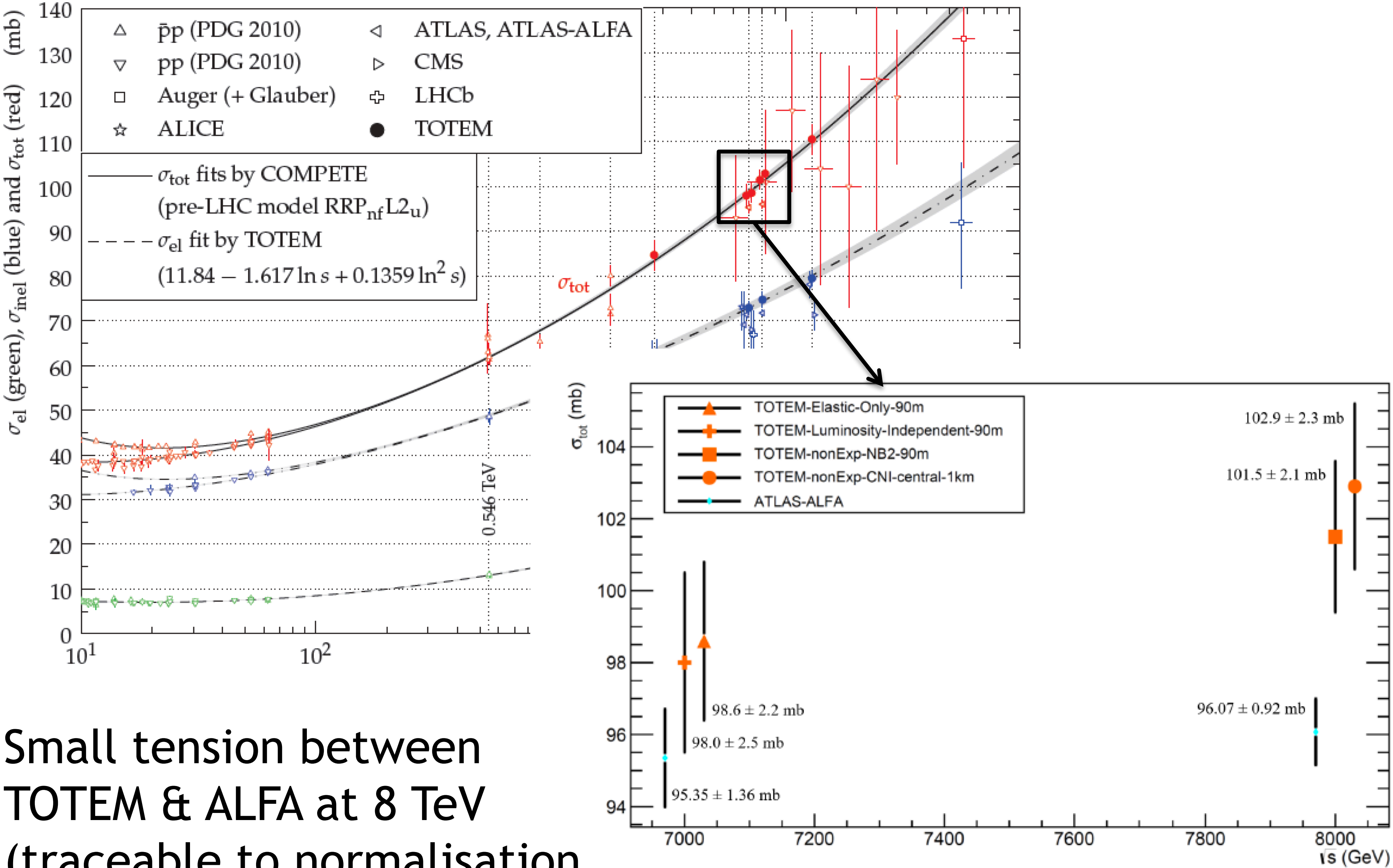
Total (& Elastic) Cross Section versus √s



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

- Now published at both √s=7 TeV and √s=8 TeV by TOTEM and ATLAS-ALFA and at 13 TeV by TOTEM
- Extractions from cosmic ray data extend to √s ~50 TeV !

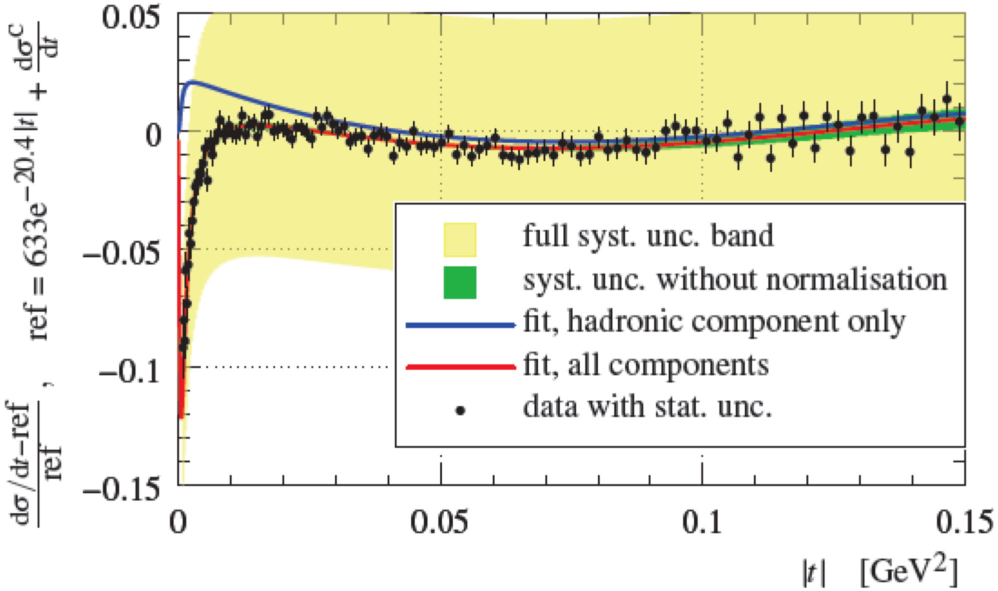
Total (& Elastic) Cross Section versus √s

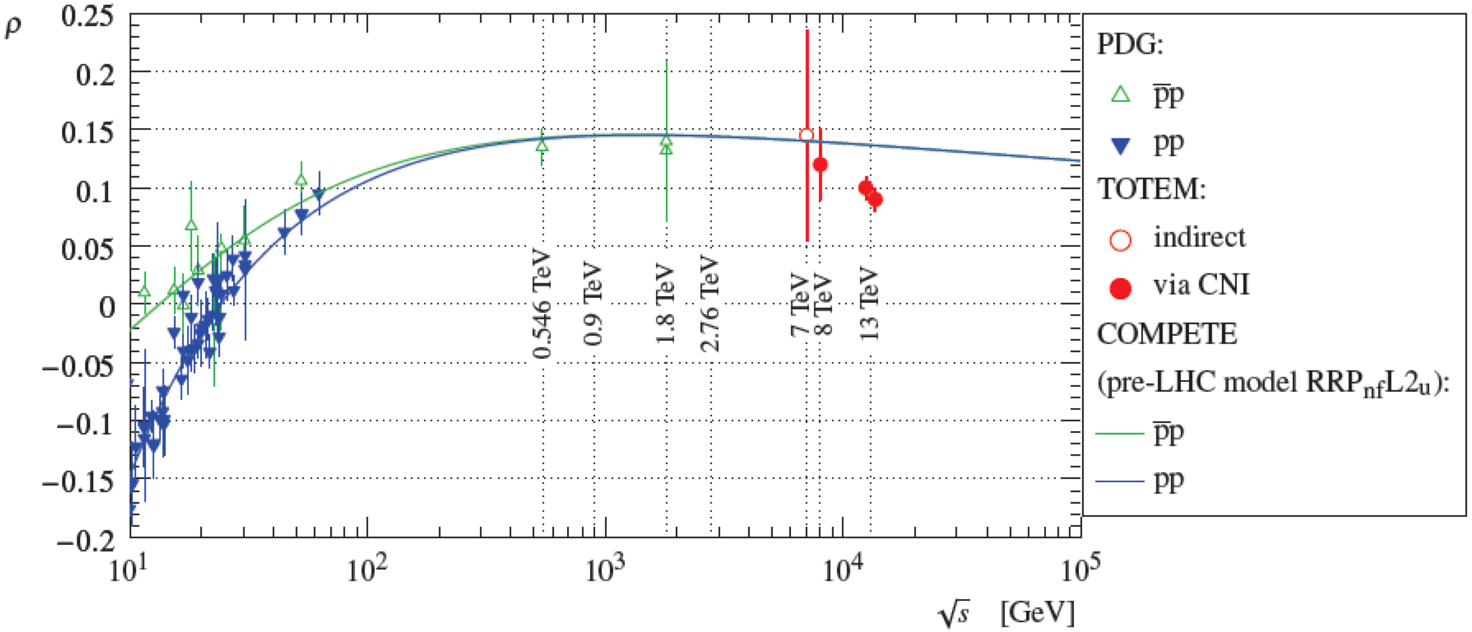


Small tension between TOTEM & ALFA at 8 TeV (traceable to normalisation of elastic data)

First LHC Extraction of ρ Parameter

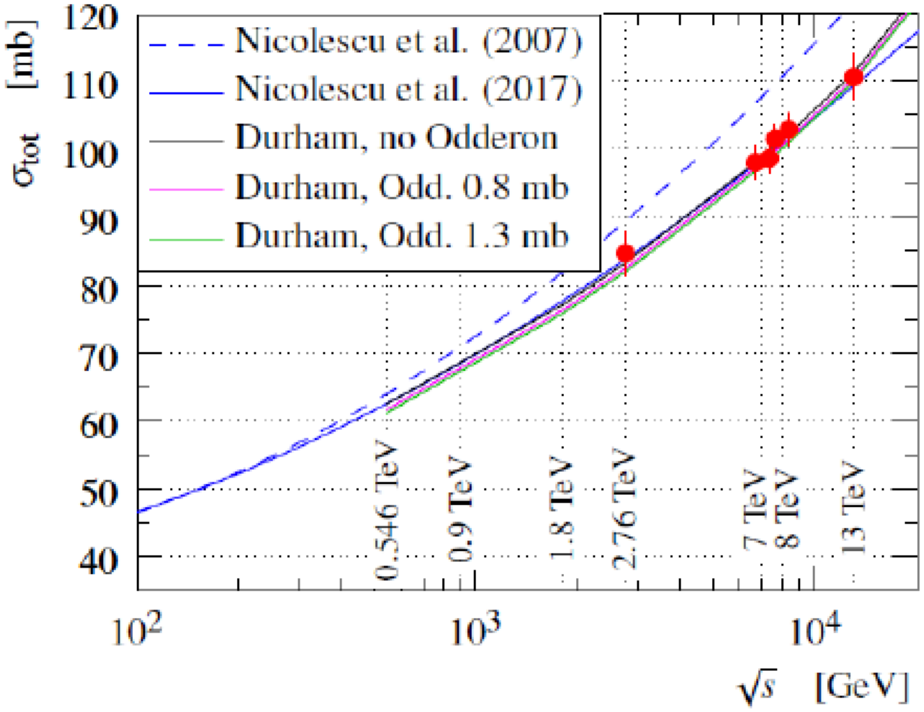
- Interference between Coulomb and Nuclear parts of elastic cross section is sensitive to ρ parameter
- Very high statistics TOTEM sample at 13 TeV ...
- Results are well below `standard' COMPETE extrapolation of pre-LHC data

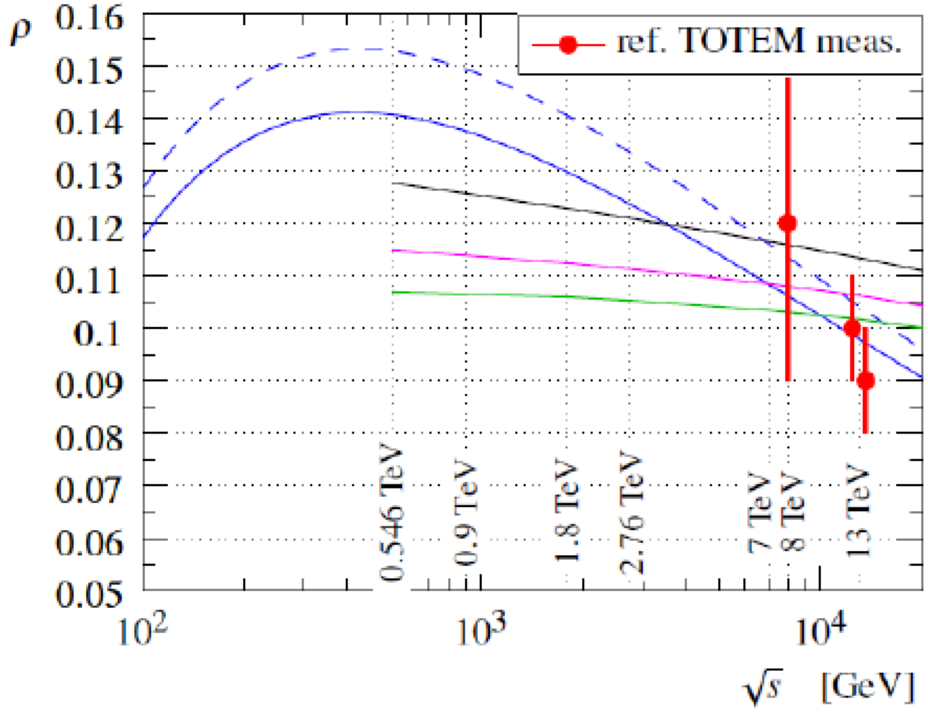




No extrap'ed pre-LHC model describes both ρ and σ_{tot} from 13 TeV TOTEM data.

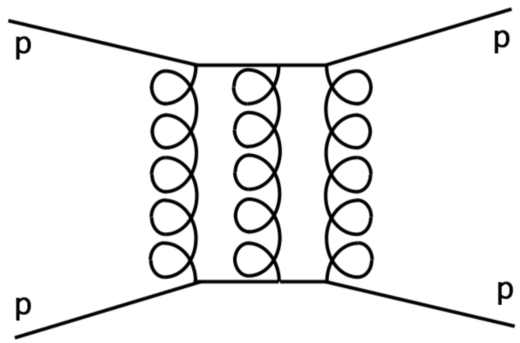
Interpretation as Evidence for Odderon





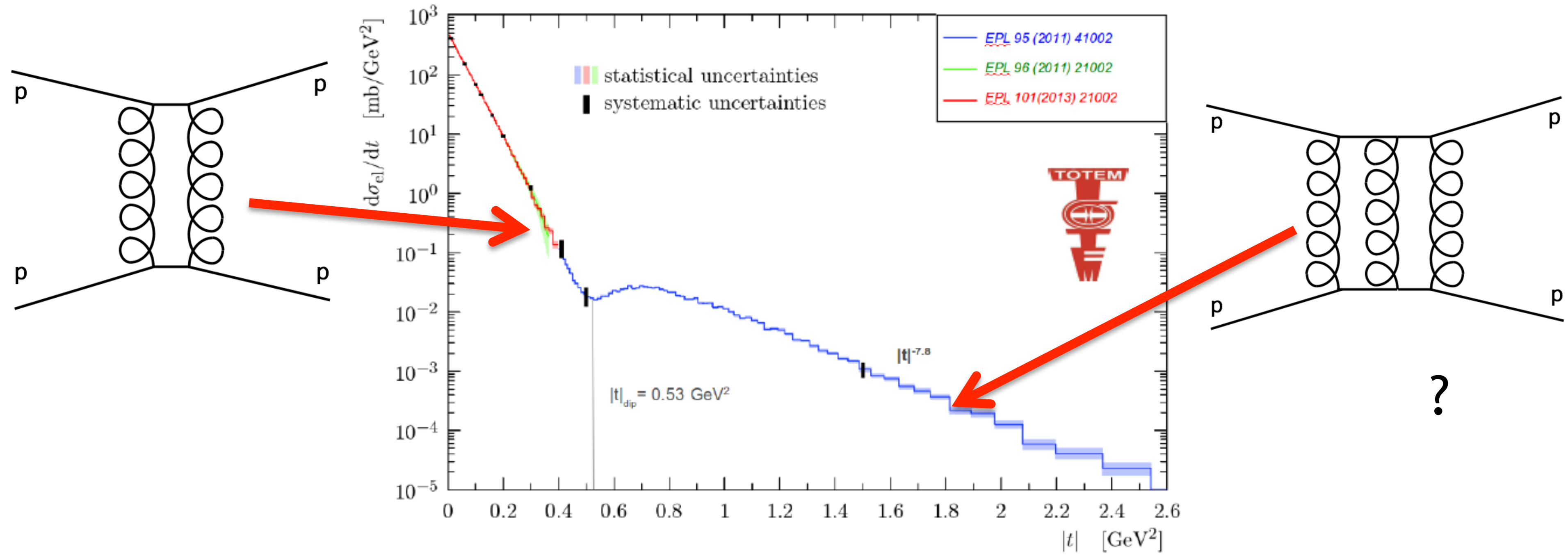
- Introducing a CP-odd contribution to the elastic exchange (i.e. an `odderon' – 3 gluon-based state) is one way of reconciling data

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



→ Detailed studies are ongoing …

Perturbative Odderon in Elastic Scattering at very large|t| ?



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?).
- Evidence for Odderon production, interfering with pomeron to create the dip? … No models describe detail.

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

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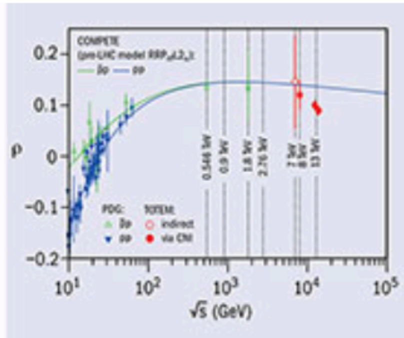
Researchers at the Large Hadron Collider have discovered what could be evidence of a quasiparticle they've been chasing for nearly 50 years.

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.

… maybe …

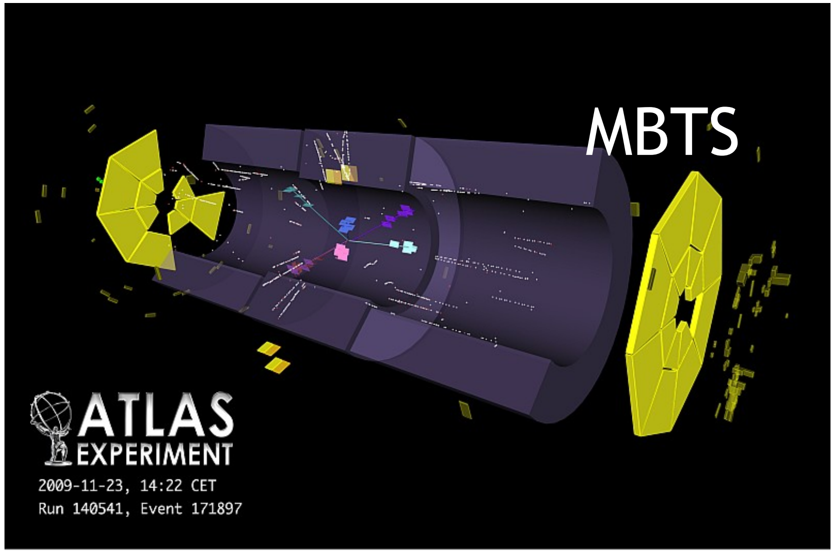
Direct Measurement of Total (Inelastic) Cross Section

- Extraction of total cross section only via elastic measurement and optical theorem requires a more `direct' cross check

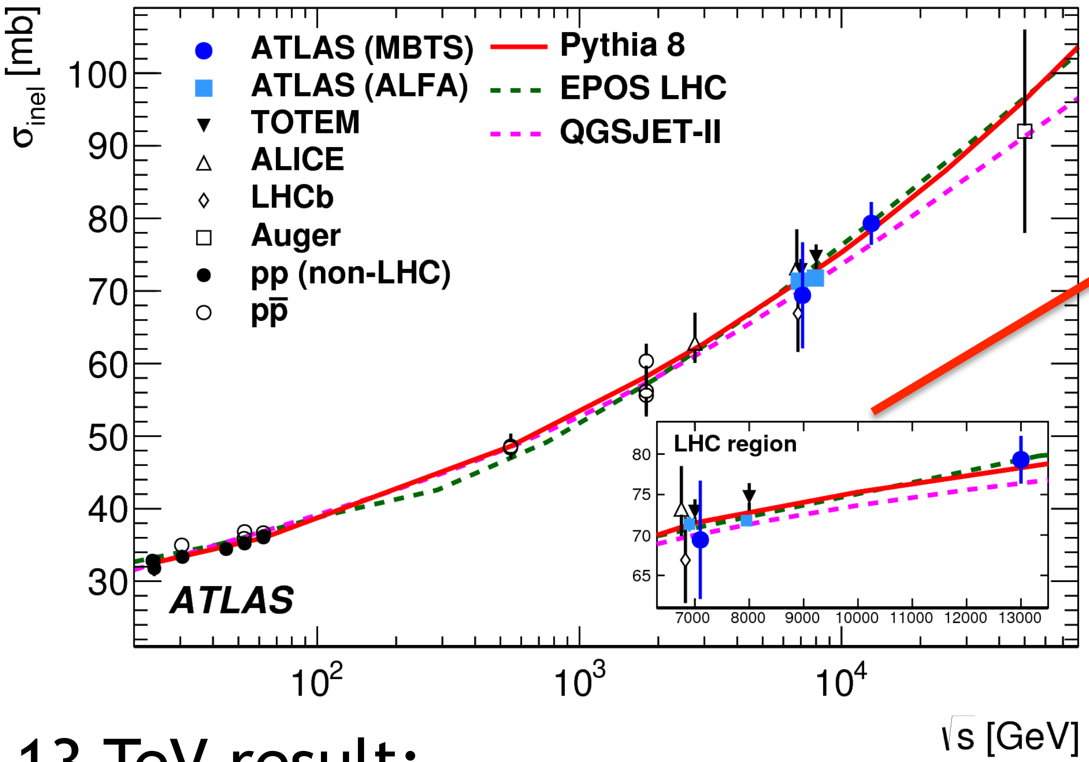
Total inelastic cross section can be measured either from $\sigma_{tot} - \sigma_{el}$ or directly by counting (almost) "all" events with a minimum bias trigger

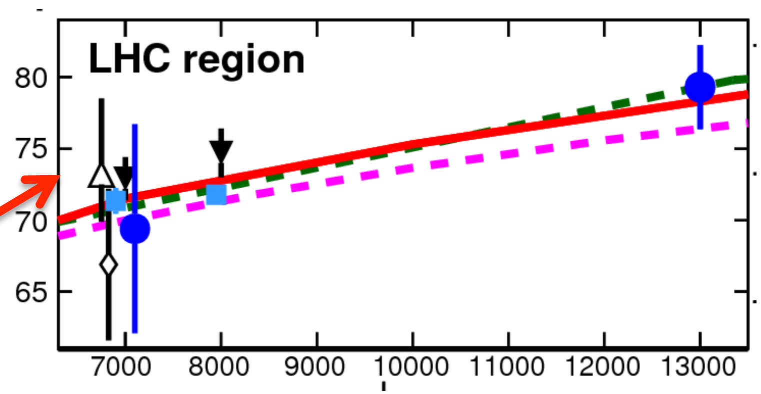
… eg collect events using ATLAS Minimum Bias Trigger Scintillators (MBTS) $z = \pm 3.6$m, $2.1 < |\eta| < 3.8$ see 90-95% of all inelastic events

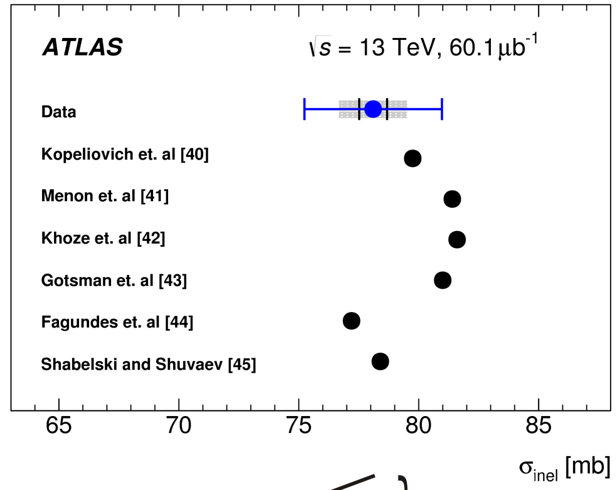
[similar techniques in all main LHC experiments]



Inelastic Cross Section Measurements

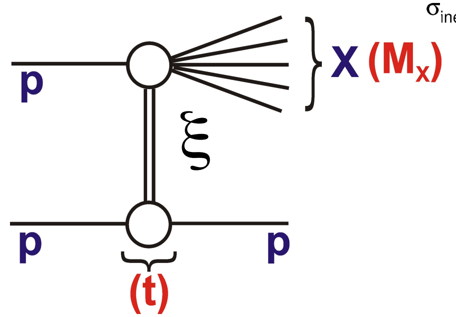






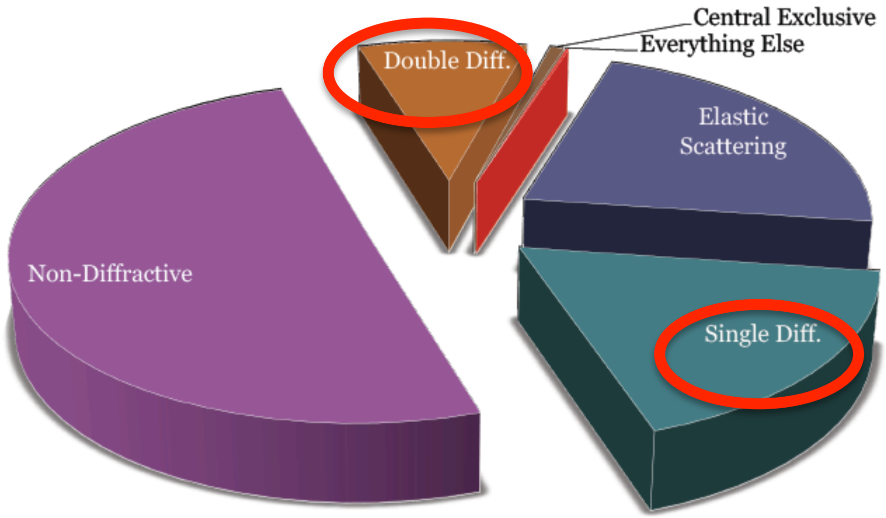
13 TeV result:

σ_{inel} = 79.3 ± 0.6(exp) ± 1.3(lum) ± 2.5(extr) mb

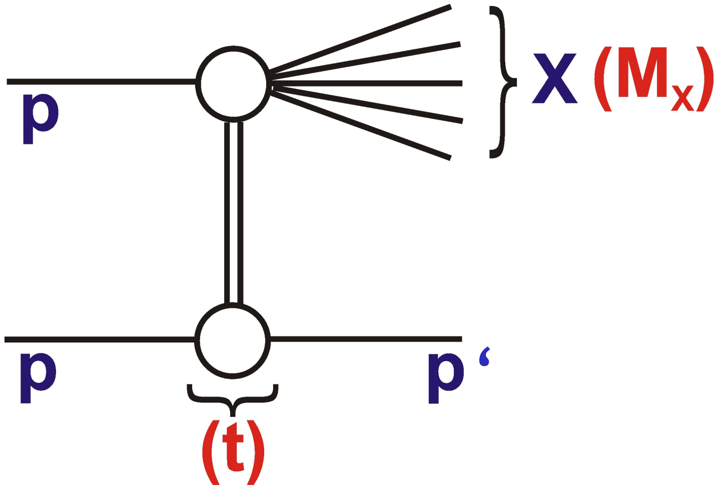


- Direct and indirect results compatible and indirect result in agreement with indicative selection of models
- Comparisons limited by extrapolation to low mass diffractive dissociation (unseen by MBTS for ξ <~ 10^{-6})

Inelastic Diffraction



Single diffractive dissociation

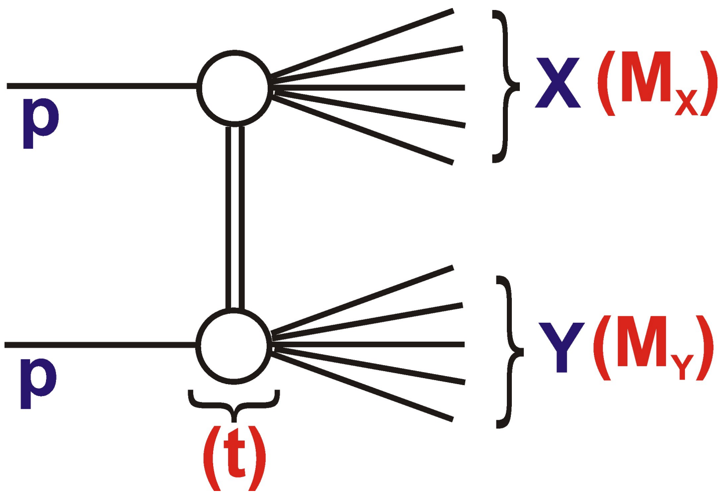


Additional kinematic variables:

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

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

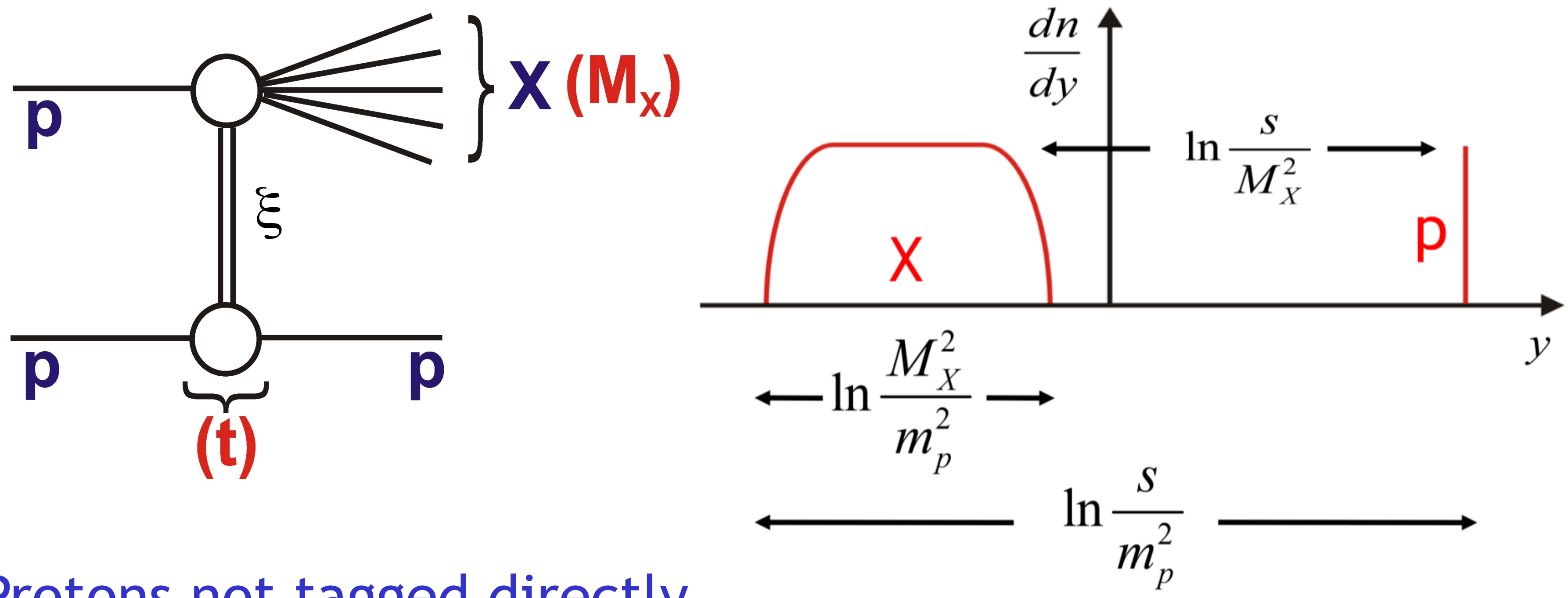
Double diffractive dissociation



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

… very poorly predicted pre-LHC

Diffractive Channels:
& Rapidity Gap Kinematics



- Protons not tagged directly

- ξ variable strongly correlated with empty rapidity regions

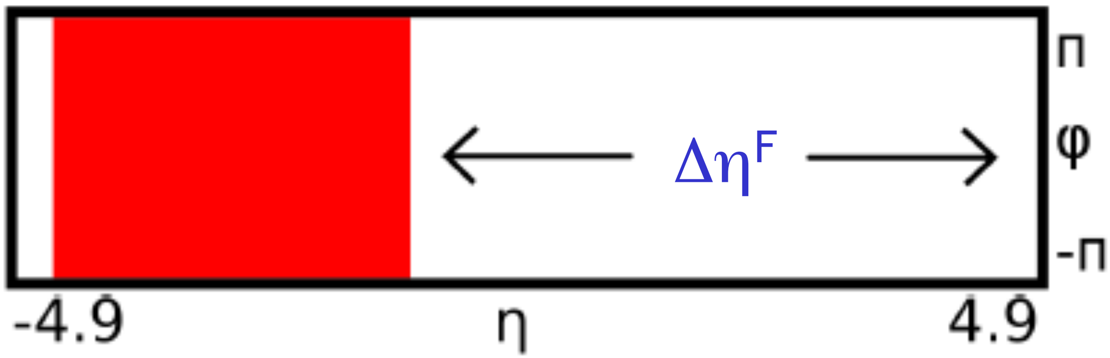
$$\Delta\eta \approx -\ln\xi$$

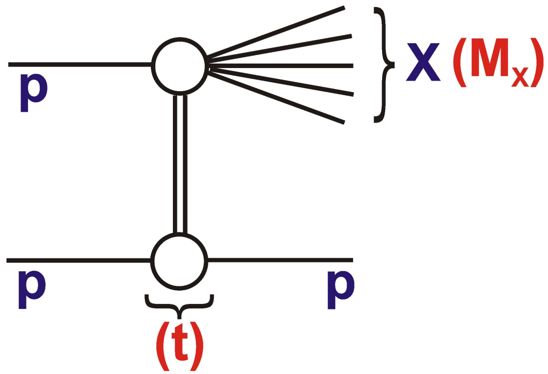
… exploited in all SD measurements to be shown

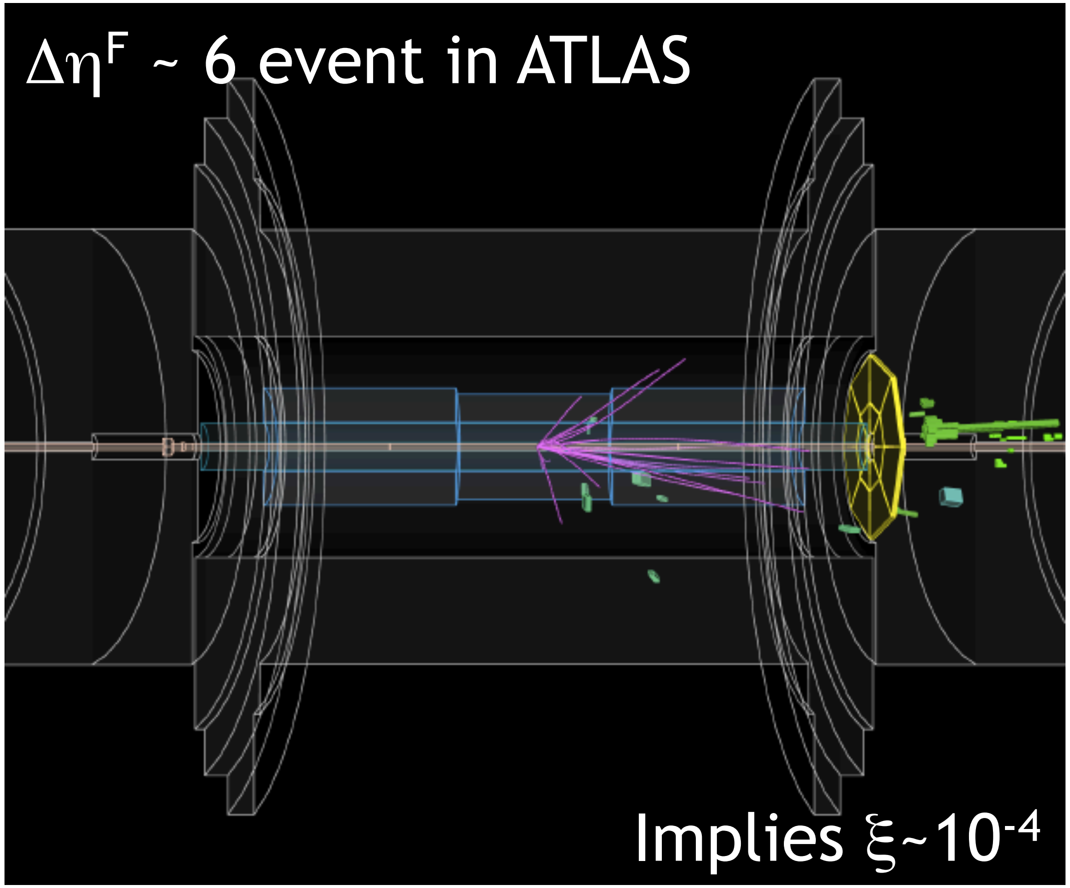
- Correlation limited by hadronisation fluctuations

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 $|\eta| > 4.9$

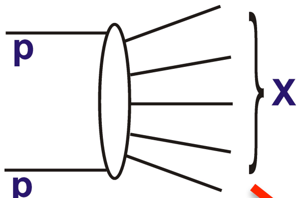
… large $\Delta\eta^F$ sensitive to SD + low M_Y DD

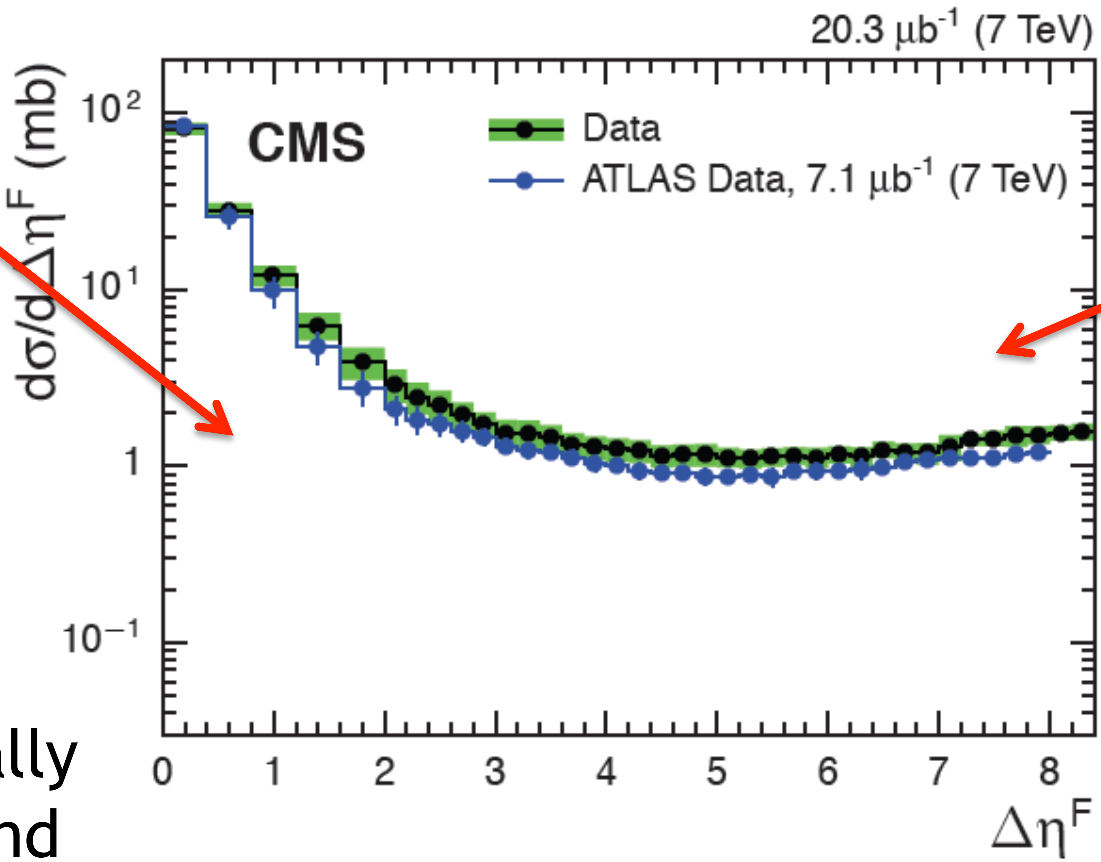
CMS and ATLAS Rapidity Gap Data

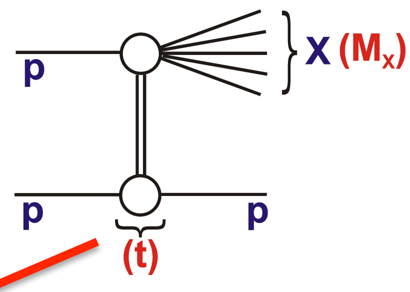
Using very early LHC runs at 7 TeV (avoiding pile-up) …

ATLAS: $\Delta\eta^F$ extends from $\eta = \pm 4.9$ to 1st particle with $p_t > 200$ MeV

- CMS: $\Delta\eta^F$ extends from $\eta = \pm 4.7$ to 1st particle with $p_t > 200$ MeV





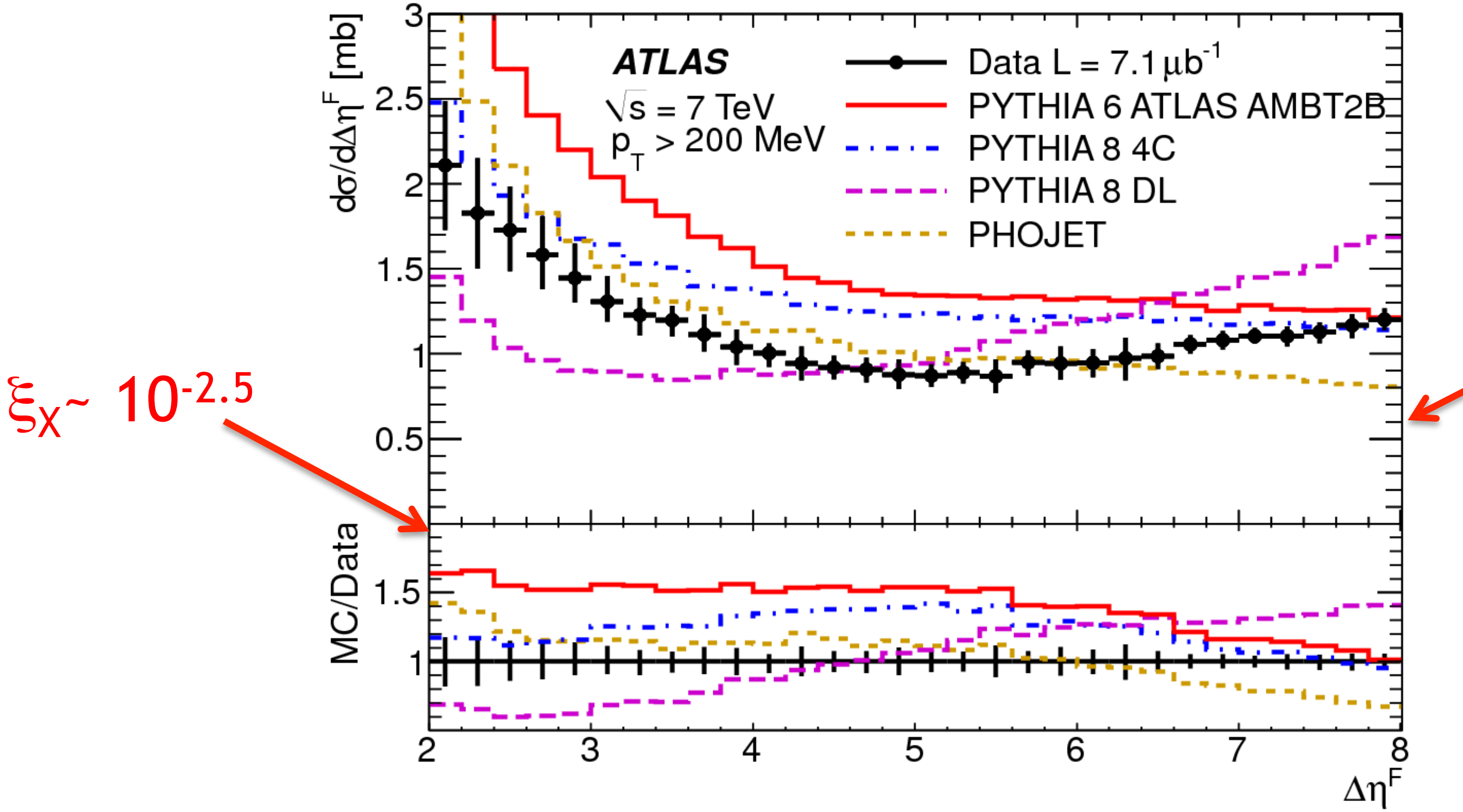


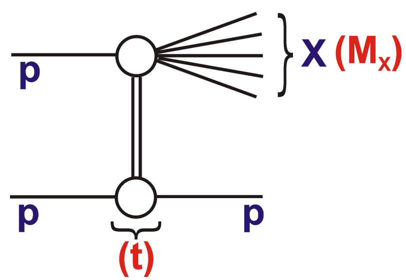
Small gaps dominated by non-diffractive processes … exponentially suppressed and sensitive to hadronisation fluctuations / underlying event

Large gaps dominated by diffractive processes … characteristic plateau

Roughly 1mb per unit gap size

Large Gap Region compared with Models

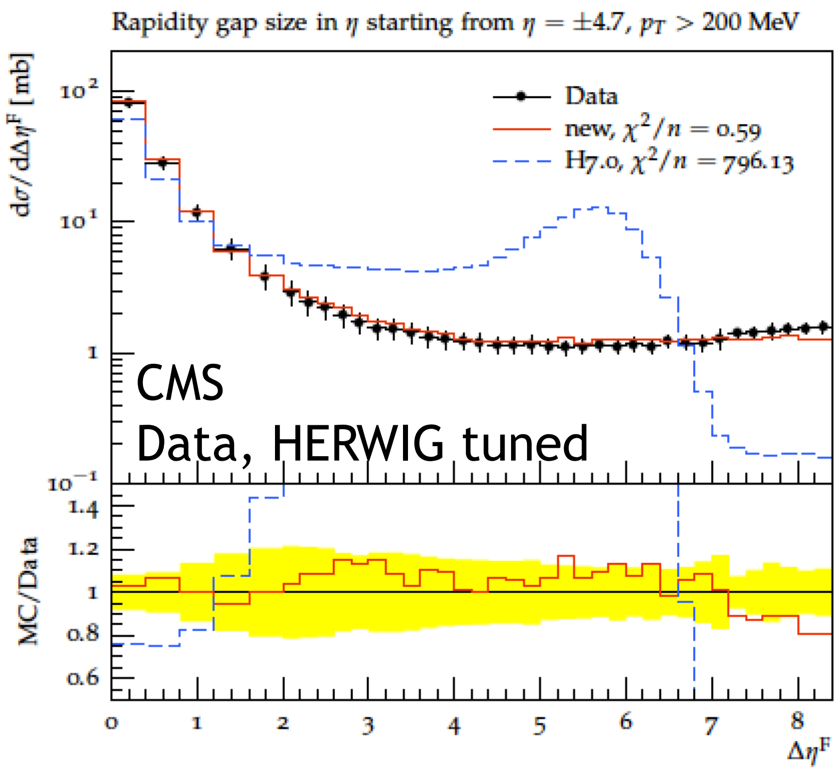




- Most models take `triple Regge' approach: $\frac{d\sigma}{d\xi\, dt} \propto \left(\frac{1}{\xi}\right)^{2\alpha(t)-\alpha(0)} e^{bt}$

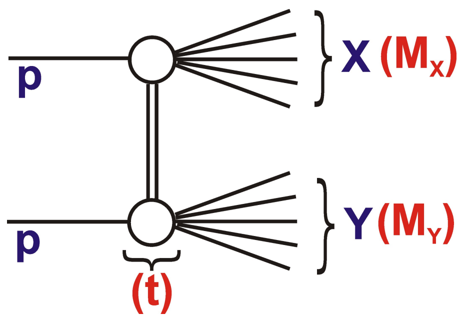
- Large differences between models due to assumptions on total diffractive cross sections, α(t) and fragmentation modelling,
- Fit to large $\Delta\eta^F$ data: $\alpha_{IP}(0)$ = 1.058 ± 0.003 (stat) ± 0.036 (syst)

Tuning Monte Carlo Models

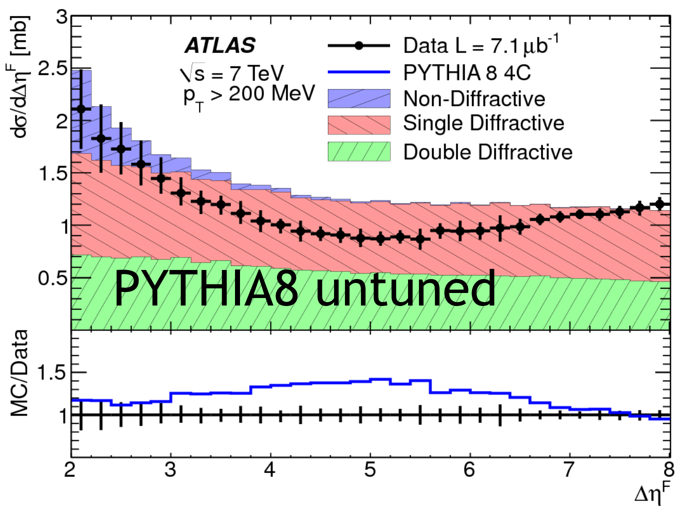


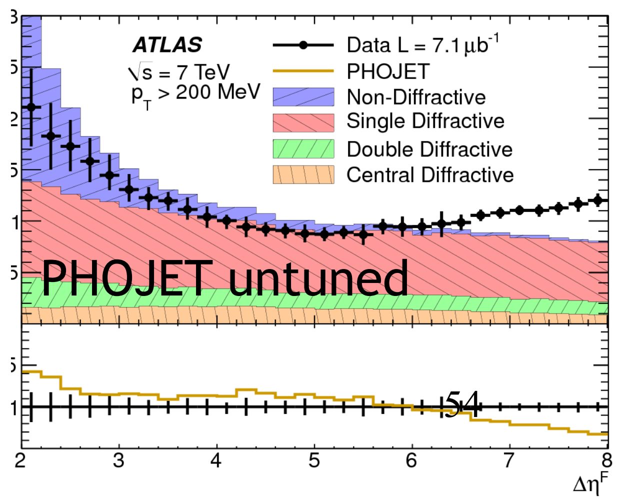
Successful description in HERWIG7 (cluster hadronisation + soft multiple interactions, tuned to CMS data)

Main remaining question: how big are DD and ND contributions??

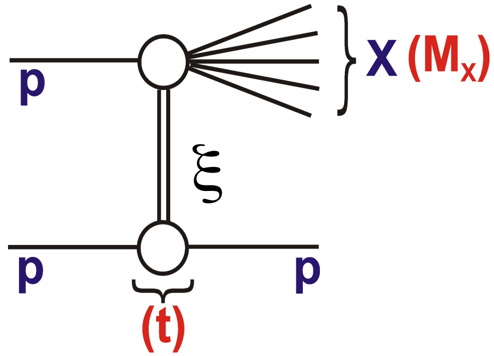


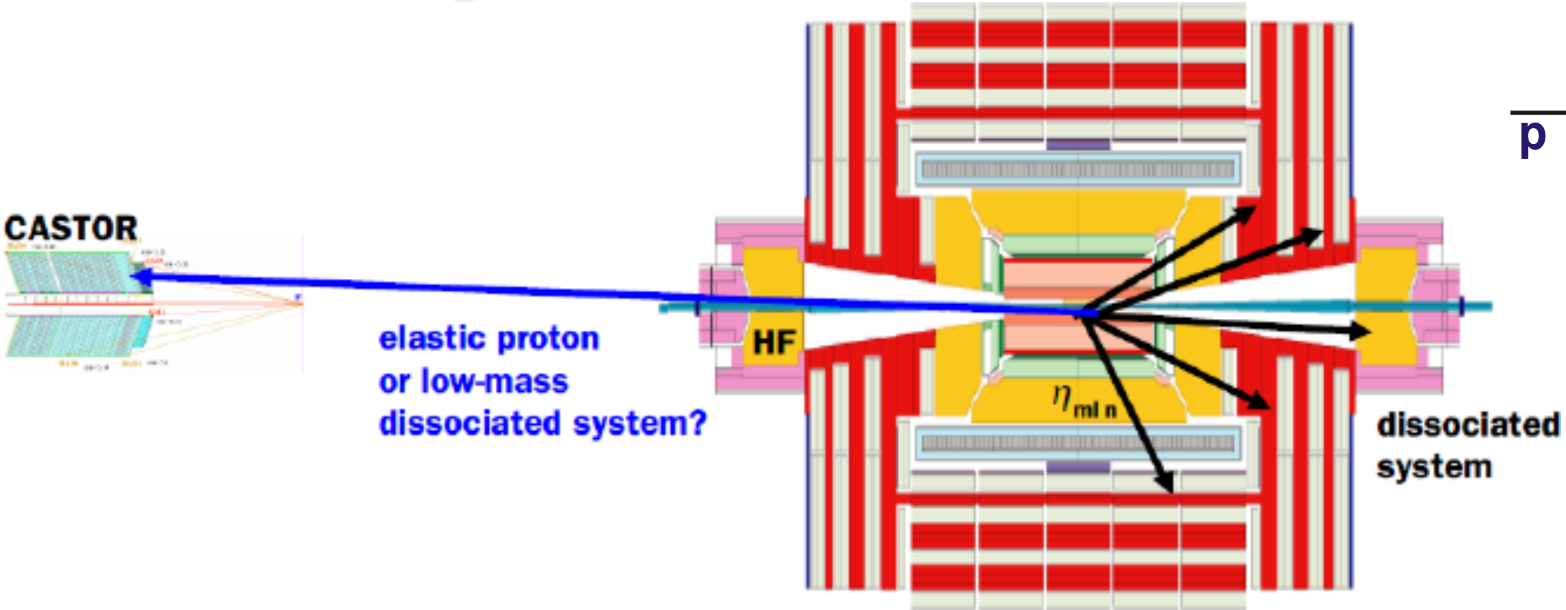
- Further significant progress will require proton tagging to unfold SD from DD and ND





SD Cross Sections with Direct ξ Measurement





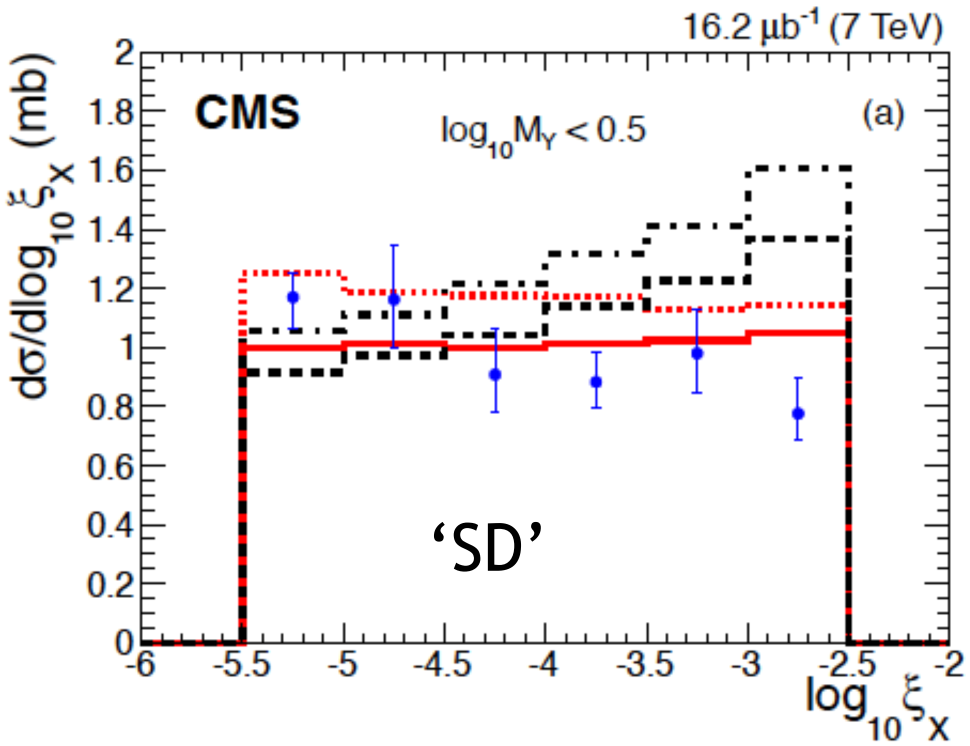
- Use forward calorimeter (CASTOR) tag to help distinguish SD from DD (sensitive to much lower M_Y than central detector).

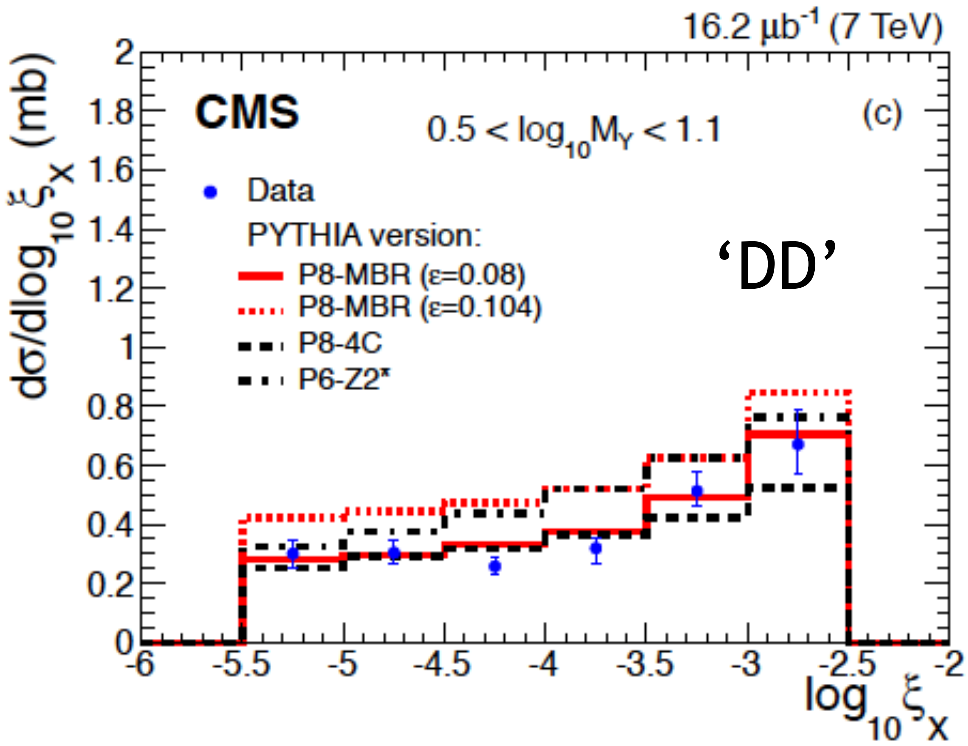
- Directly reconstruct ξ using particle flow algorithm and cunning kinematics.

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

- Larger uncertainties, but more directly related to dynamics.

CMS Direct ξ Measurement



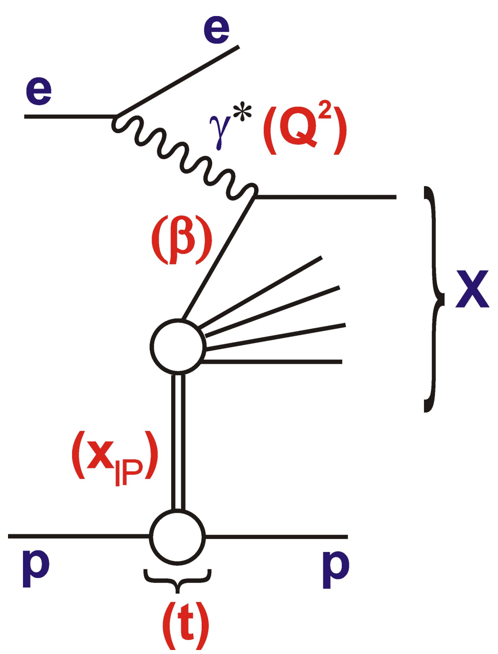


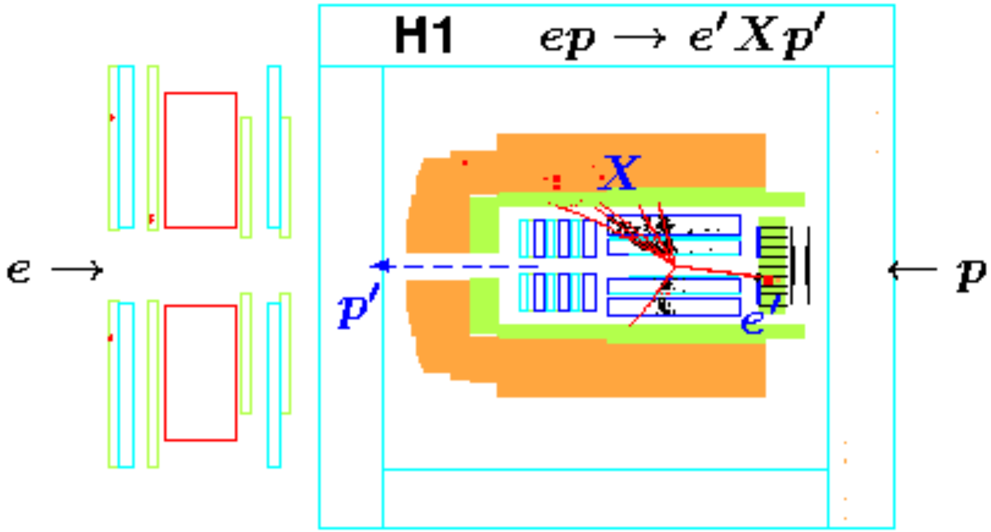
- SD data (small DD admixture M_Y <~ 3 GeV) compatible with PYTHIA8 with $\alpha_{IP}(0)$ = 1.08 or 1.104

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

… precision still limited by SD / DD unfolding → need p tags!

Diffraction at the Parton Level



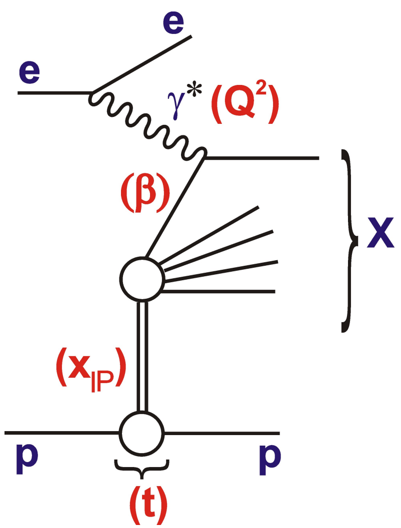


HERA ep Collider:

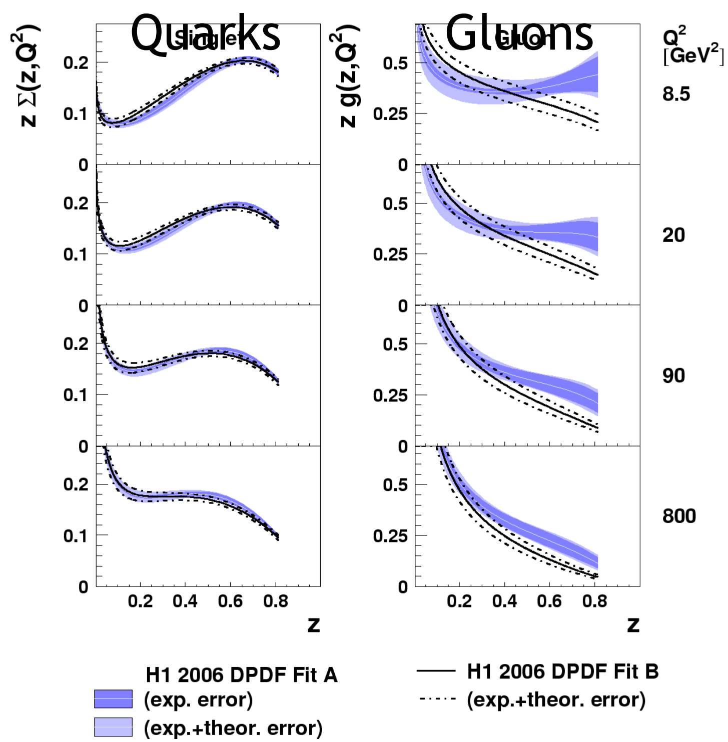
Virtual photon probes pomeron partonic structure rather like inclusive DIS …

>100 papers later …

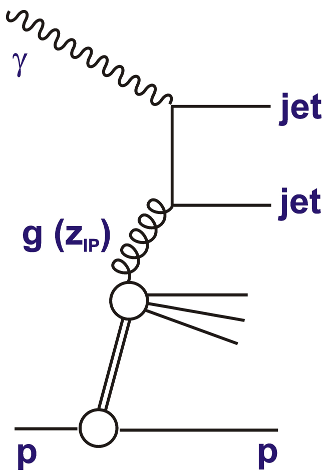
Hard Diffraction: Structure of Vacuum Exchange

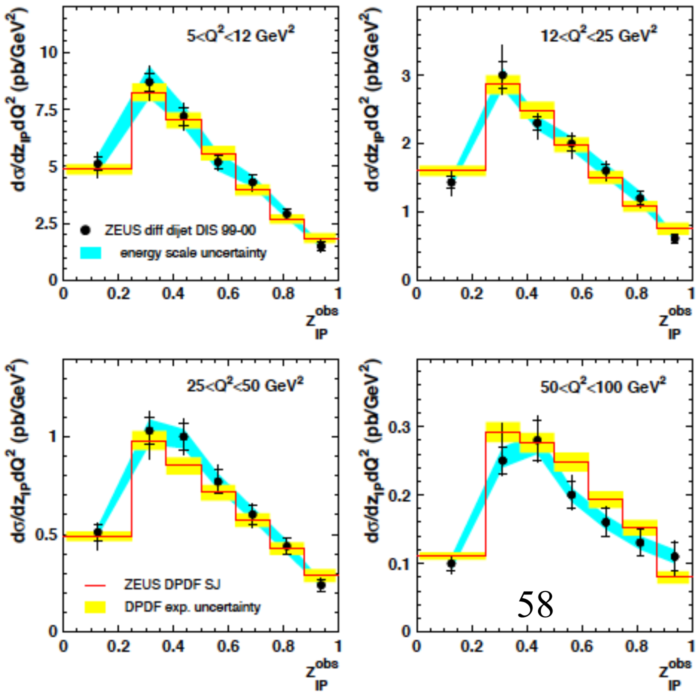


Diffractive DIS at HERA → Diffractive parton densities (DPDFs) dominated by gluon, which extends to large momentum fractions



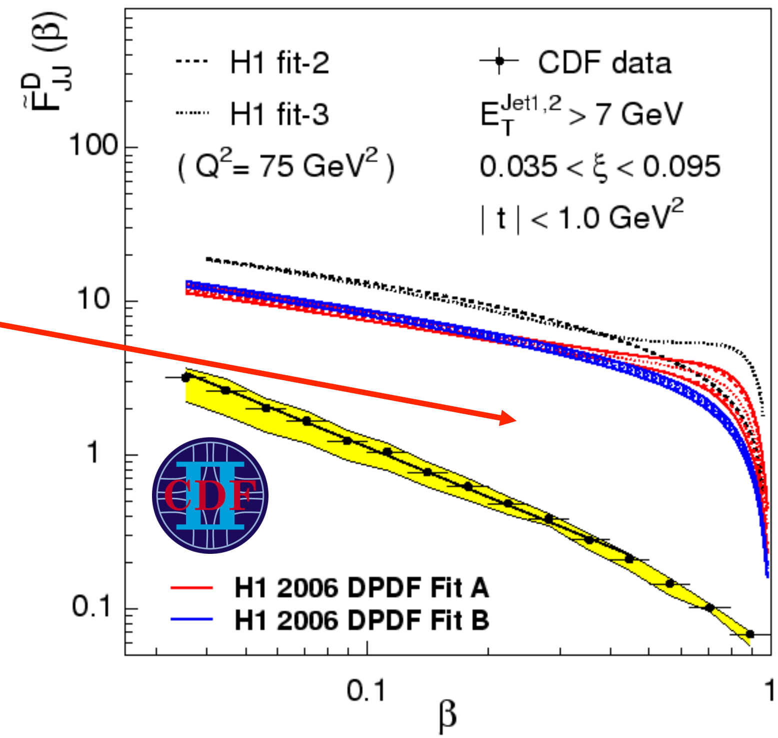
… NLO predictions based on HERA DPDFs give impressive description of all HERA 'hard' diffractive data, eg jet production …





→ DPDFs used in many models in pp

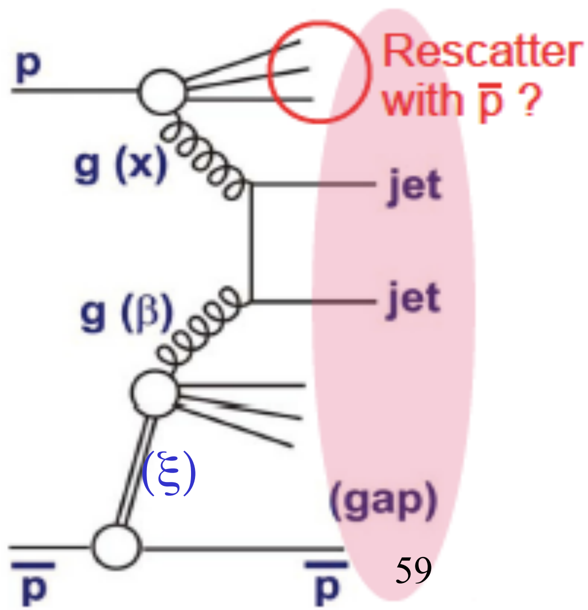
… but in pp(bar)



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

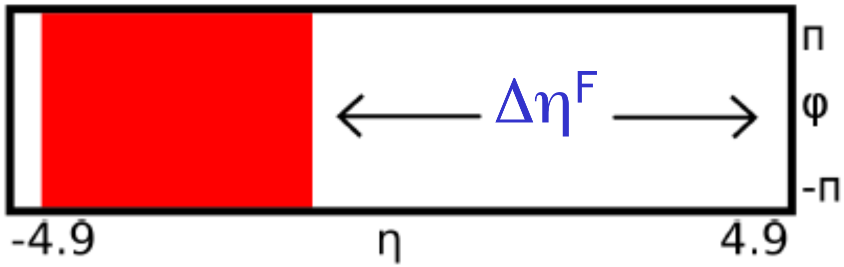
CMS data suggest similar effect [Phys Rev D87 (2013) 012006]

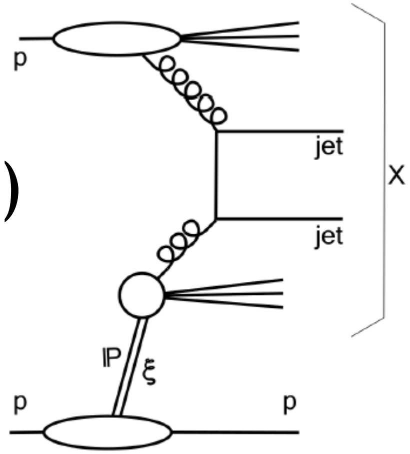
… rescattering (absorptive corrections / related to MPI …) breaks factorisation … `rapidity gap survival probability' ~ 0.1



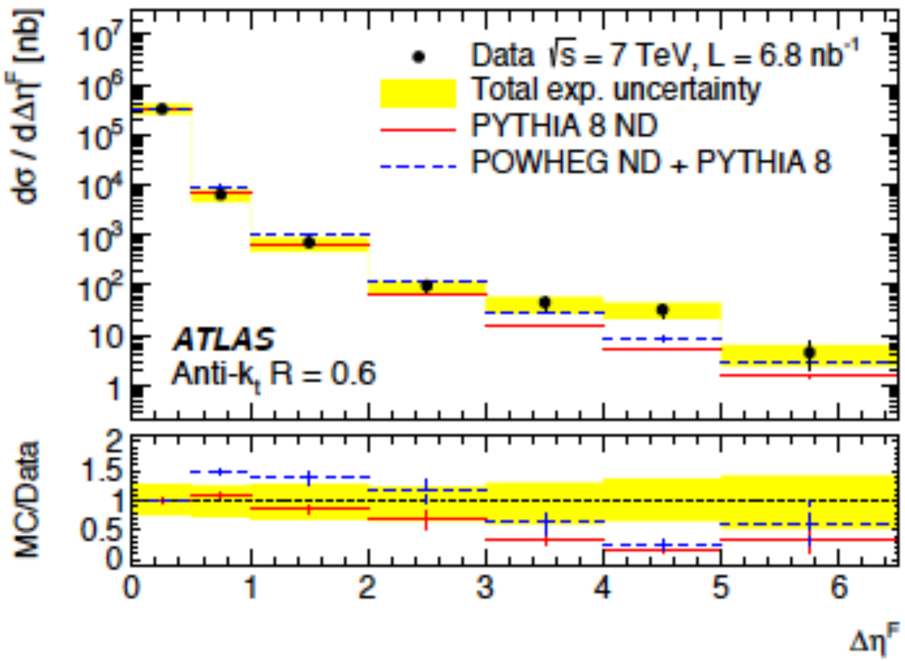
LHC hard diffraction sensitive to both DPDFs and gap survival probability →
Here: First results from LHC:
… dijets with large rapidity gaps …

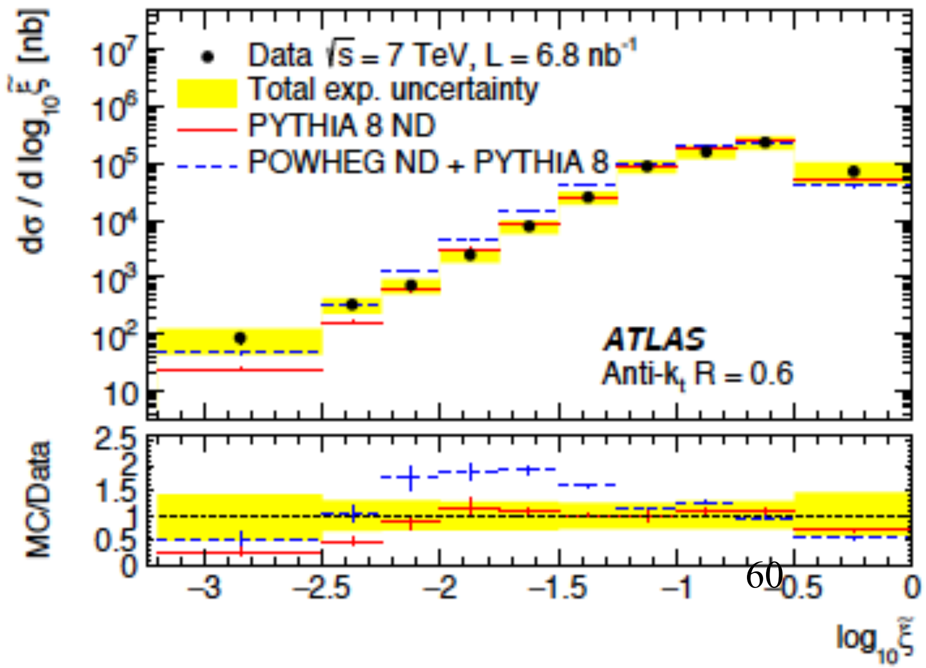
Diffractive Dijets (p_T>20 GeV) from ATLAS





- 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 …





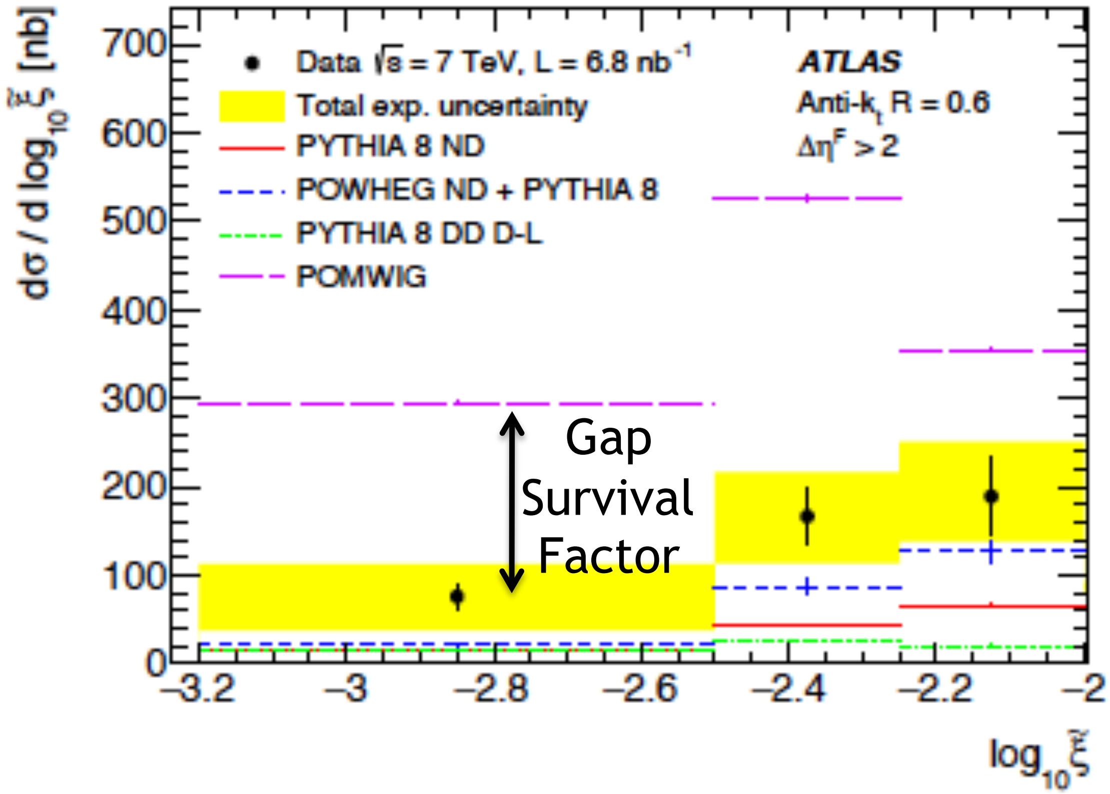
Evidence for Diffractive Contribution

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

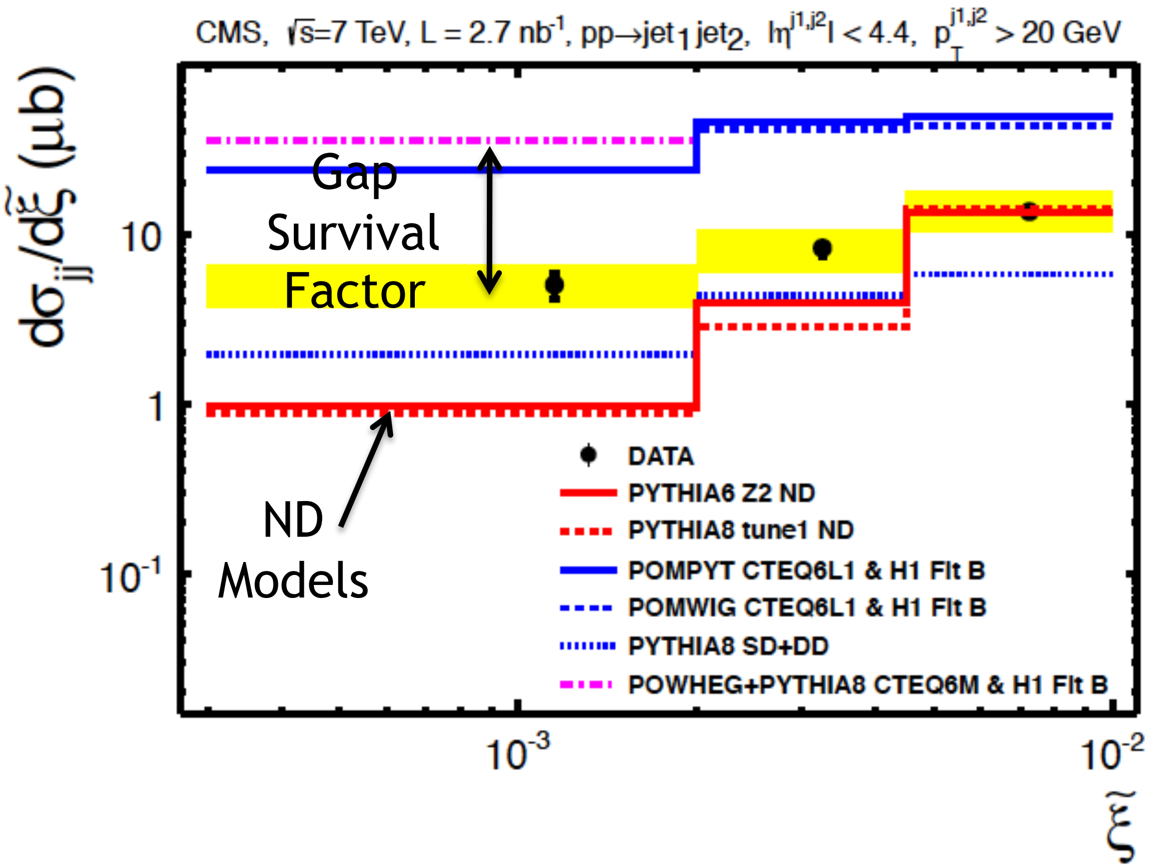
→ Comparison of smallest ξ with DPDF-based model (POMWIG) leads to rapidity gap survival probability estimate …

- 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

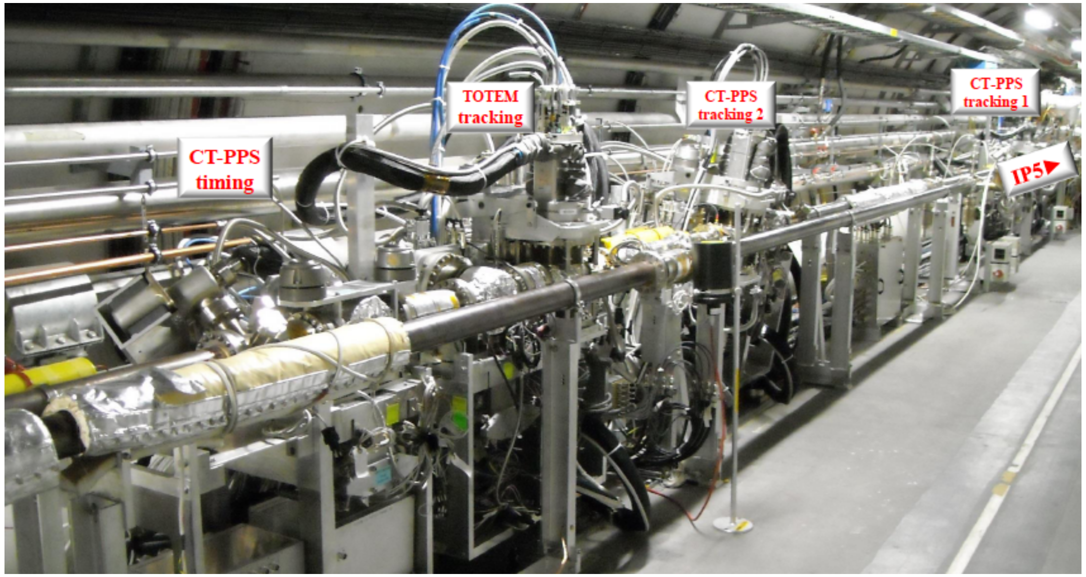
→ Gap survival probability estimate $S^2 = 0.08 \pm 0.04$ (based on NLO POWHEG)

… 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

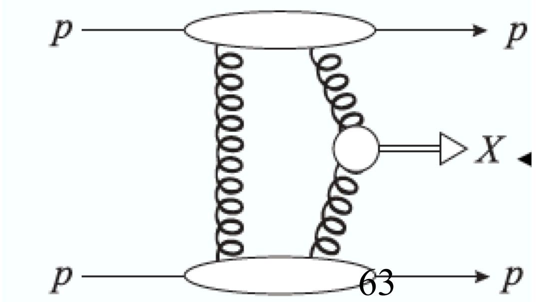


Future LHC diffractive Physics based on CT-PPS (CMS/TOTEM) & AFP (ATLAS)
- Will operate in Run 2 and very likely Run 3 (and possibly be upgraded for HL-LHC)

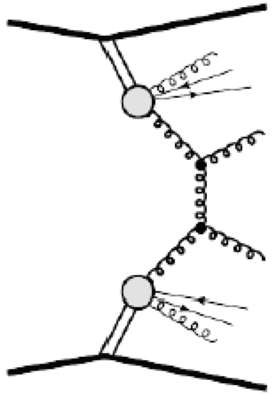
- Precision (fairly) radiation hard silicon pixel spatial detectors
- Time of Flight detectors with ~ 25ps timing precision from Cerenkov light in diamond (CT-PPS) and quartz (AFP)

→ Operate in normal LHC runnning conditions

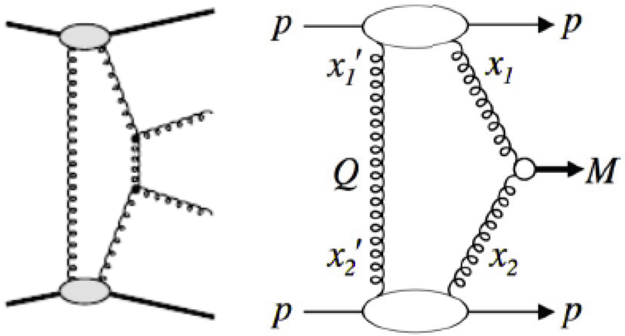
→ Optimised for double proton-tagged processes, where vertex can be located to ~1mm from proton ToF, suppressing pile-up



Newly Accessed Physics with Double Tags

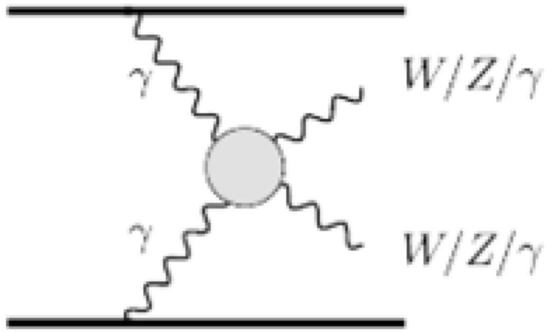


- <u>Inclusive central production</u>
pomeron-pomeron hard scattering with jets, heavy flavour, W, Z signatures



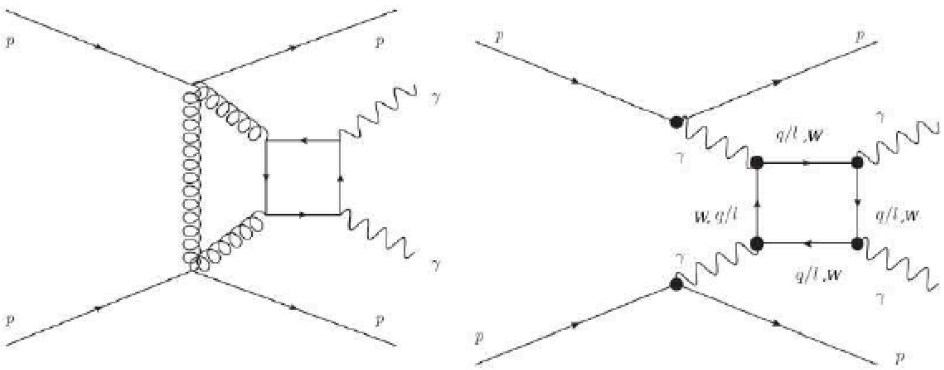
- <u>Central Exclusive QCD Production</u>
of dijets, γ-jet and other strongly produced high mass systems

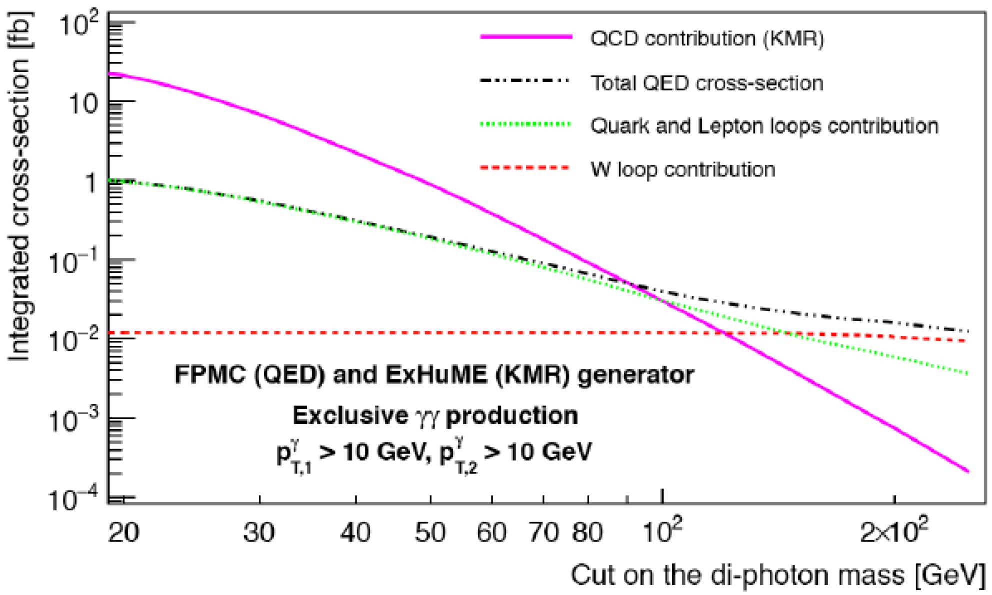
- <u>Two photon physics</u> → exclusive dileptons, dibosons & anomalous multiple gauge couplings, exclusive t-tbar?...



- <u>Searches for new heavy particles</u>
heavy Higgs recurrencies, pair produced BSM states, axions, vector-like fermions ...)

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





In general …

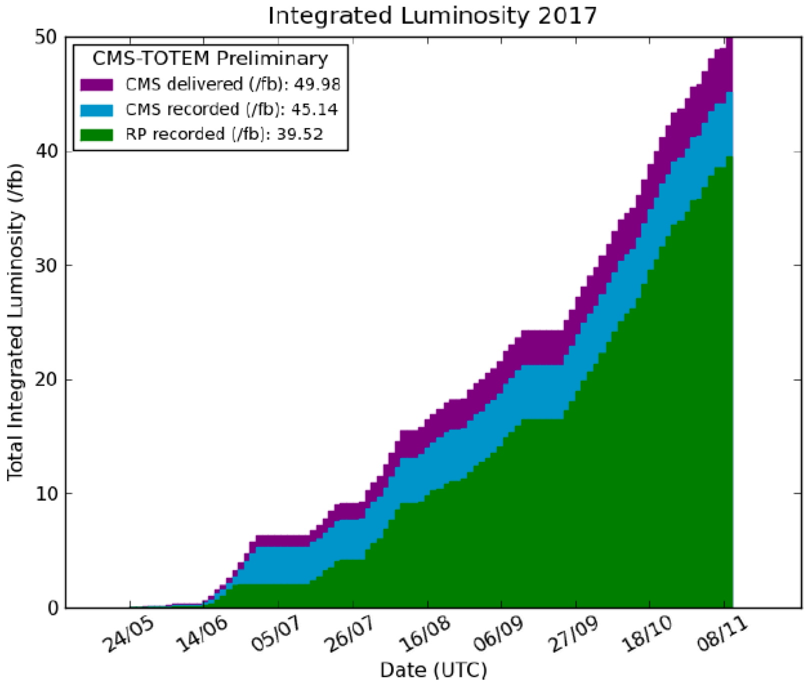
- QCD production dominates at low central system masses

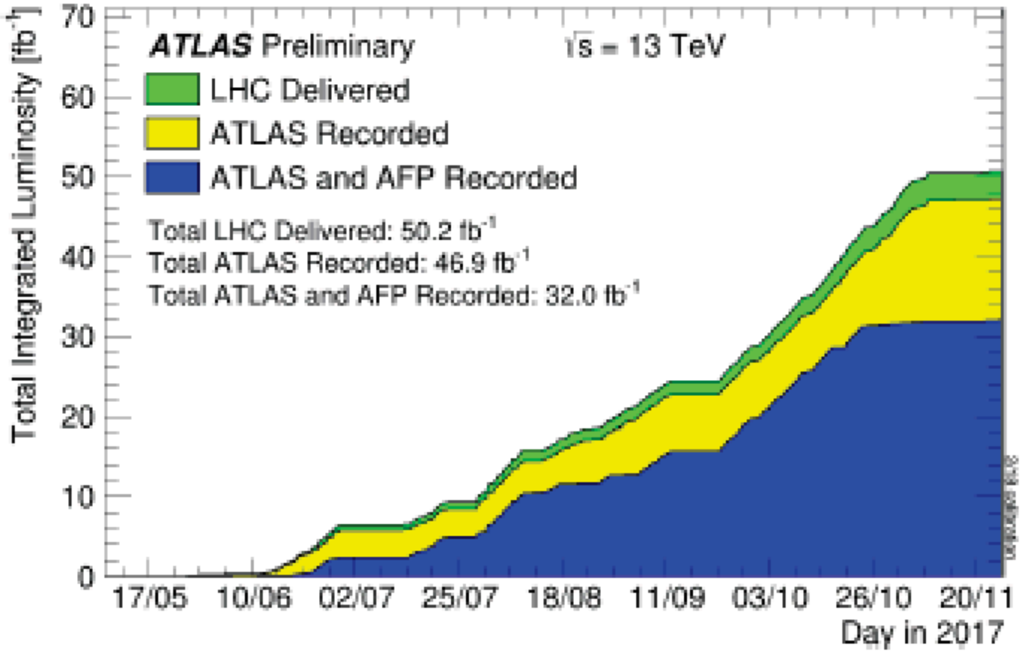
- QED production (light-by-light) takes over at larger central system masses

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

Data Collected to Date

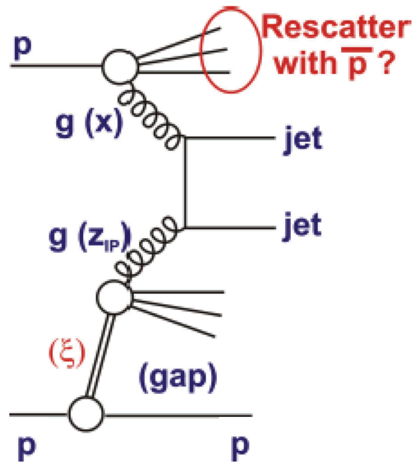
- CT-PPS fully installed from 2016, AFP from 2017



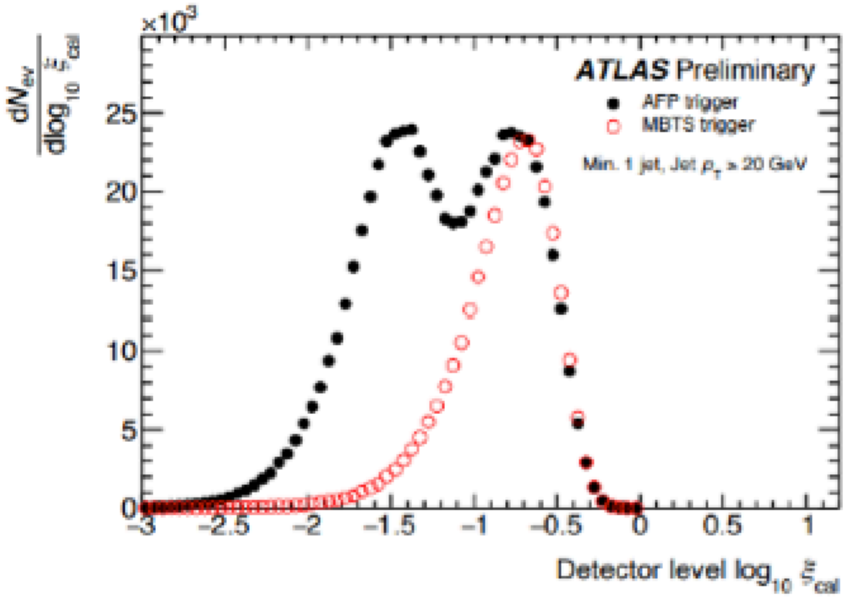


- 39 fb^{-1} accumulated by CT-PPS in 2017, 32 fb^{-1} by AFP.
  - → Transformational lumi compared with all previous Roman pot data
  - → Commissioning and data understanding ongoing
  - → First results obtained (with single tags so far)

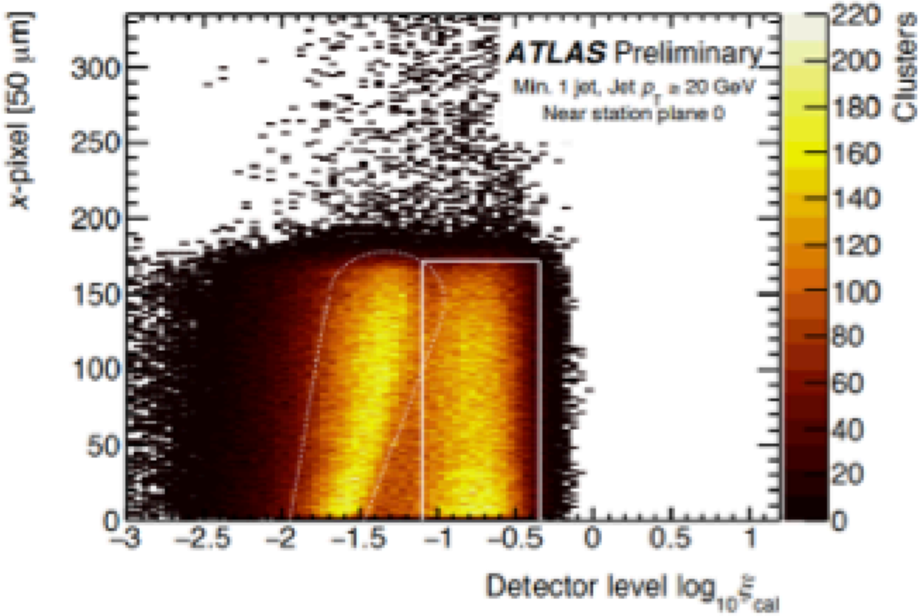
AFP Observation of Single Diffractive Dijet Signal



- 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

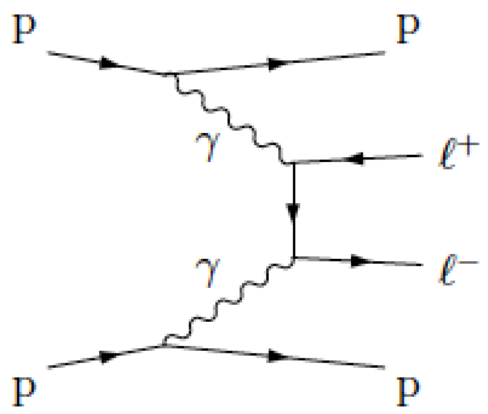


Low x data exhibit expected x-y correlation in AFP pixels and correlation between pixel x position and ξ_{Cal}

→ Clear diffractive signature

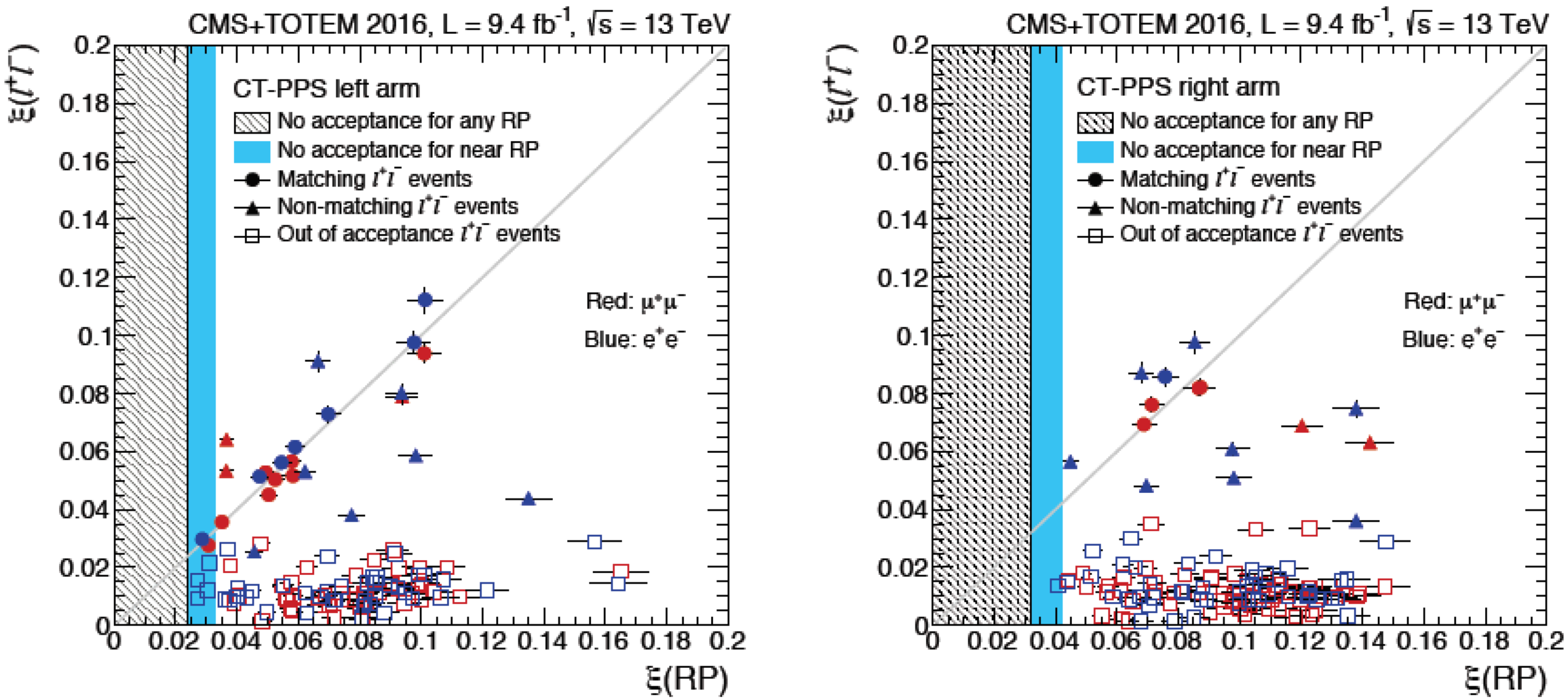
First High Lumi Study @ CT-PPS (9.4 fb^{-1})

$\gamma\gamma \rightarrow$ 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 …

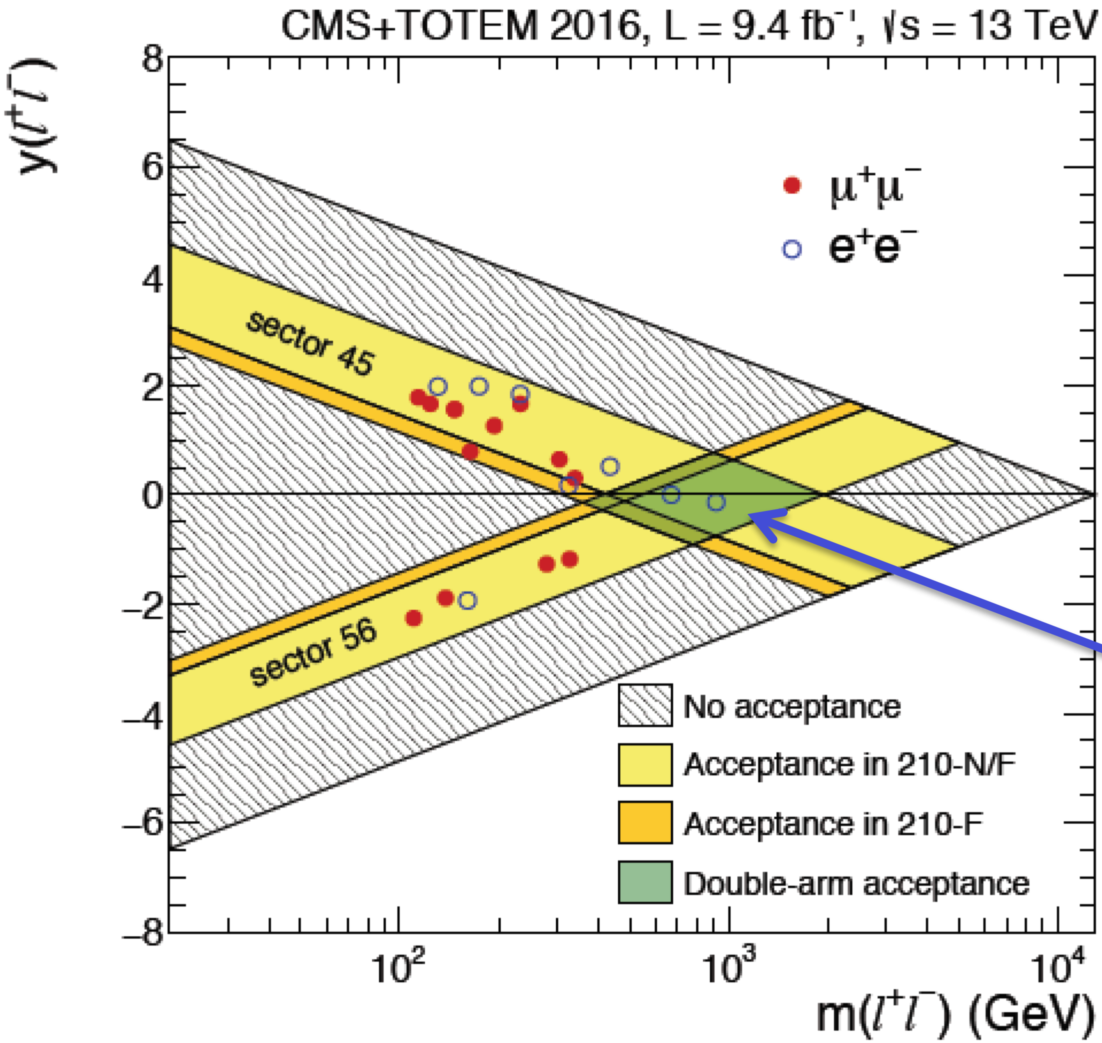
12 $\mu\mu$ events match in ξ (1.5±0.5 background)
8 ee events match in ξ (2.4±0.5 background)

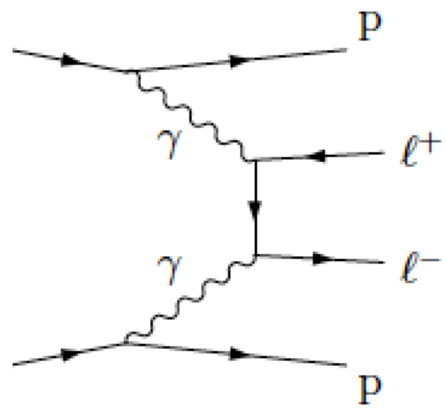


5.1σ signal

[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($\mu\mu$) = 342 GeV

Summary

Precise elastic & total cross section data

- Surprises in energy dependences
- Evidence for odderon? Low-x effects?

Soft Diffractive (Single)-Dissociation data

- Soft pomeron with intercept as expected works well
- Only `rapidity gap' method so far
- Proton tagging required for DD/ND suppression

First Hard Diffractive Dissociation Data

- Limited by control over ND gap fluctuations and low M_Y DD
- Rapidity gap survival probability larger than expected?
- Further progress requires proton tagging

At the start of a revolution based on high lumi Roman pots

- Uncharted QCD territory in exclusive central production
- Rare / exotic EW physics and searches with tagged protons