Forward Physics: An Experimental Perspective

Prof Paul Newman
(University of Birmingham)

H1, ATLAS, LHeC, ePIC experiments

(please call me Paul)
Email: p.r.newman@bham.ac.uk

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Saariselkä, Finland
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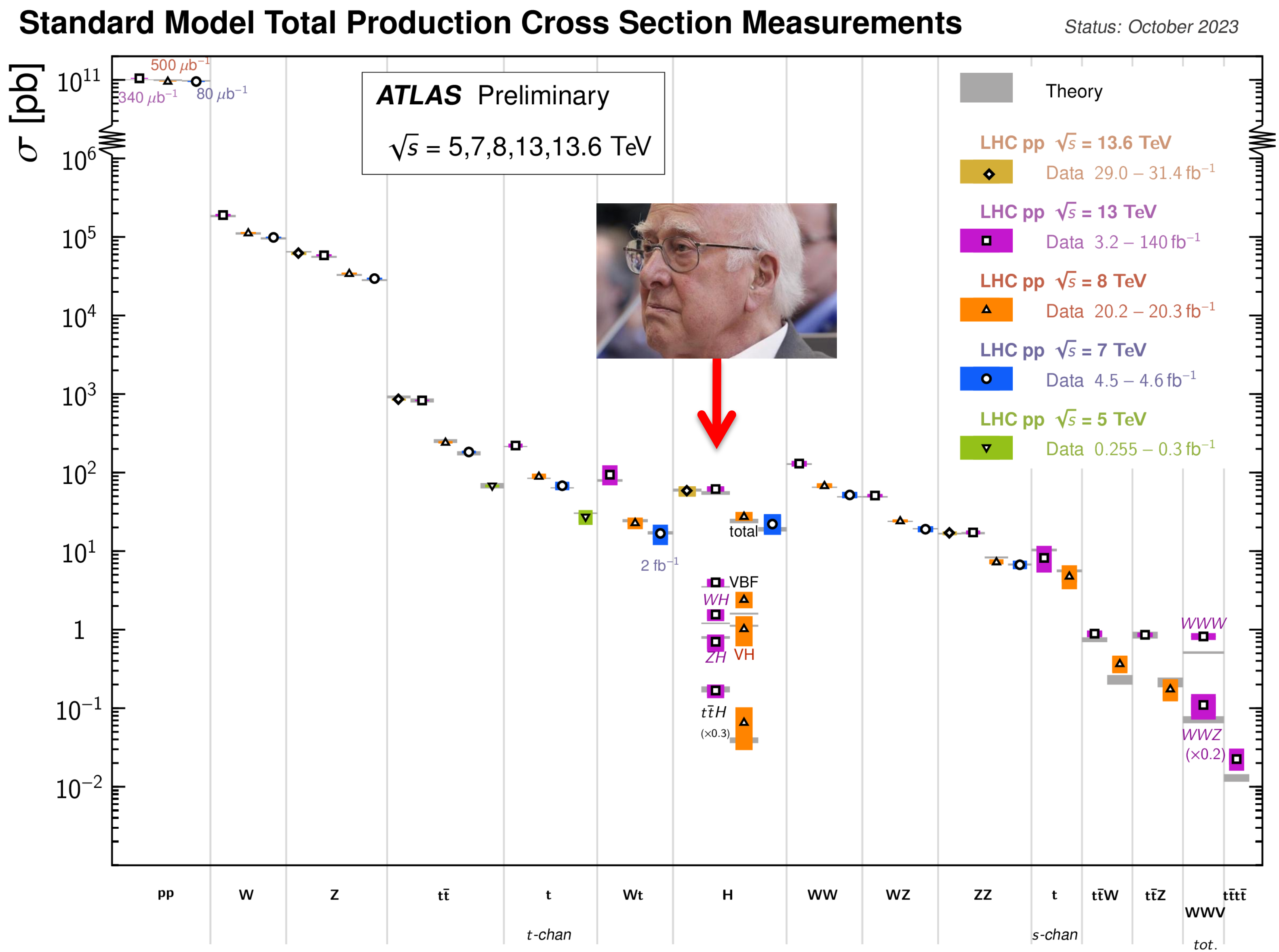
Lecture 2: Soft Forward Physics & Diffraction in proton-proton Collisions

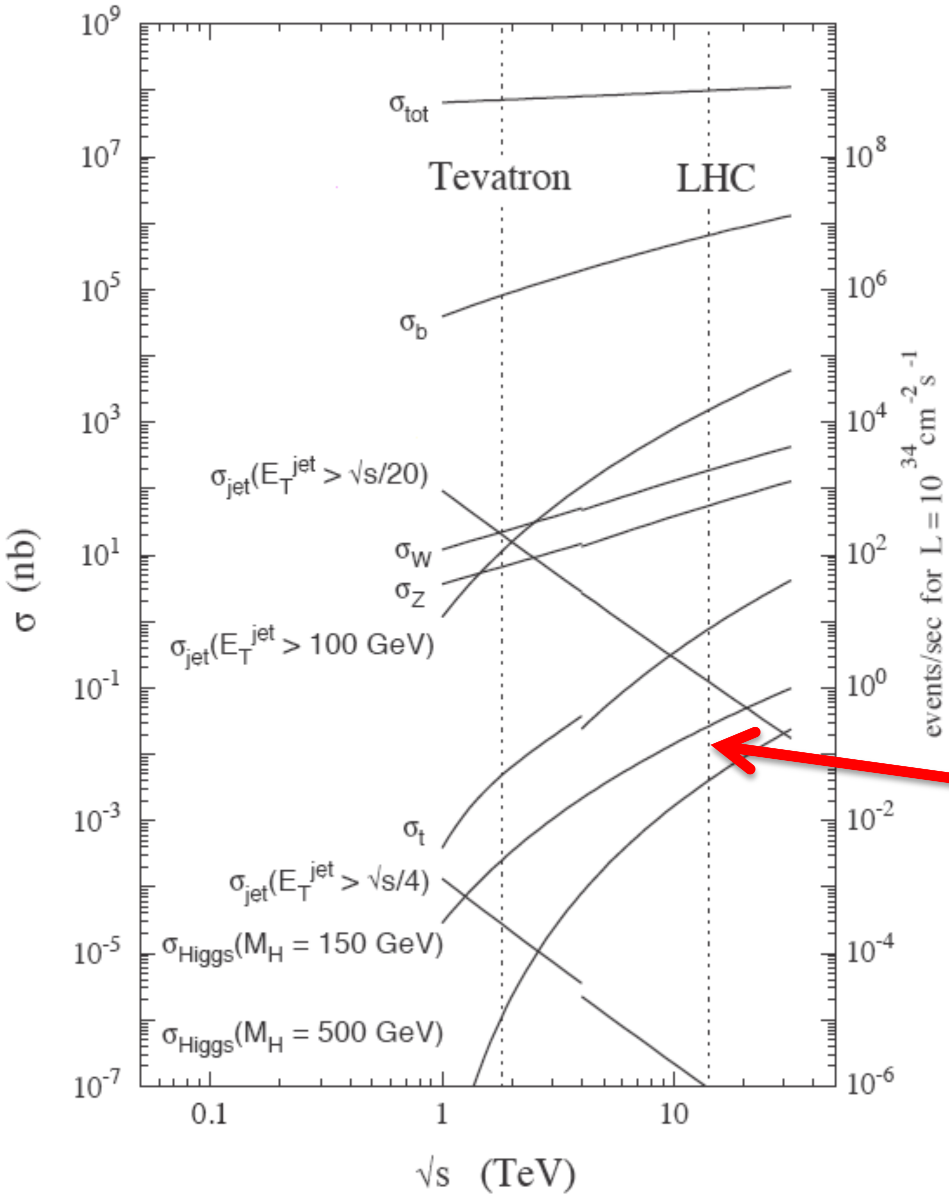
Lecture 2

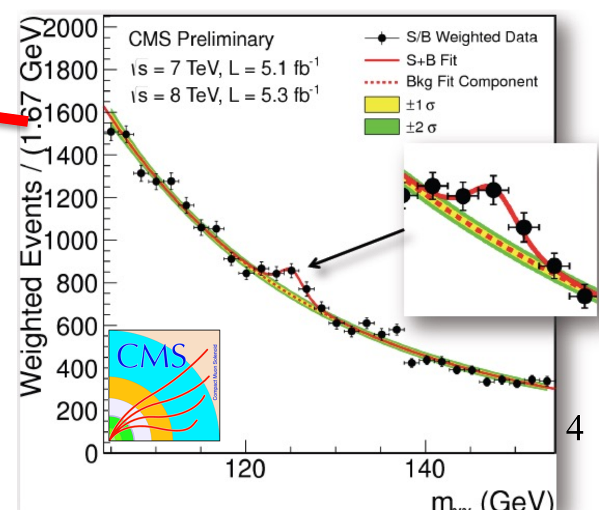
- Minimum Bias LHC Data → Features of Non-Diffractive Data
- Experimental methods for processes with intact protons
- Elastic scattering at the LHC
- Single Diffractive dissociation at the LHC

LHC: Exploring the ultra-rare at the Energy Frontier



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





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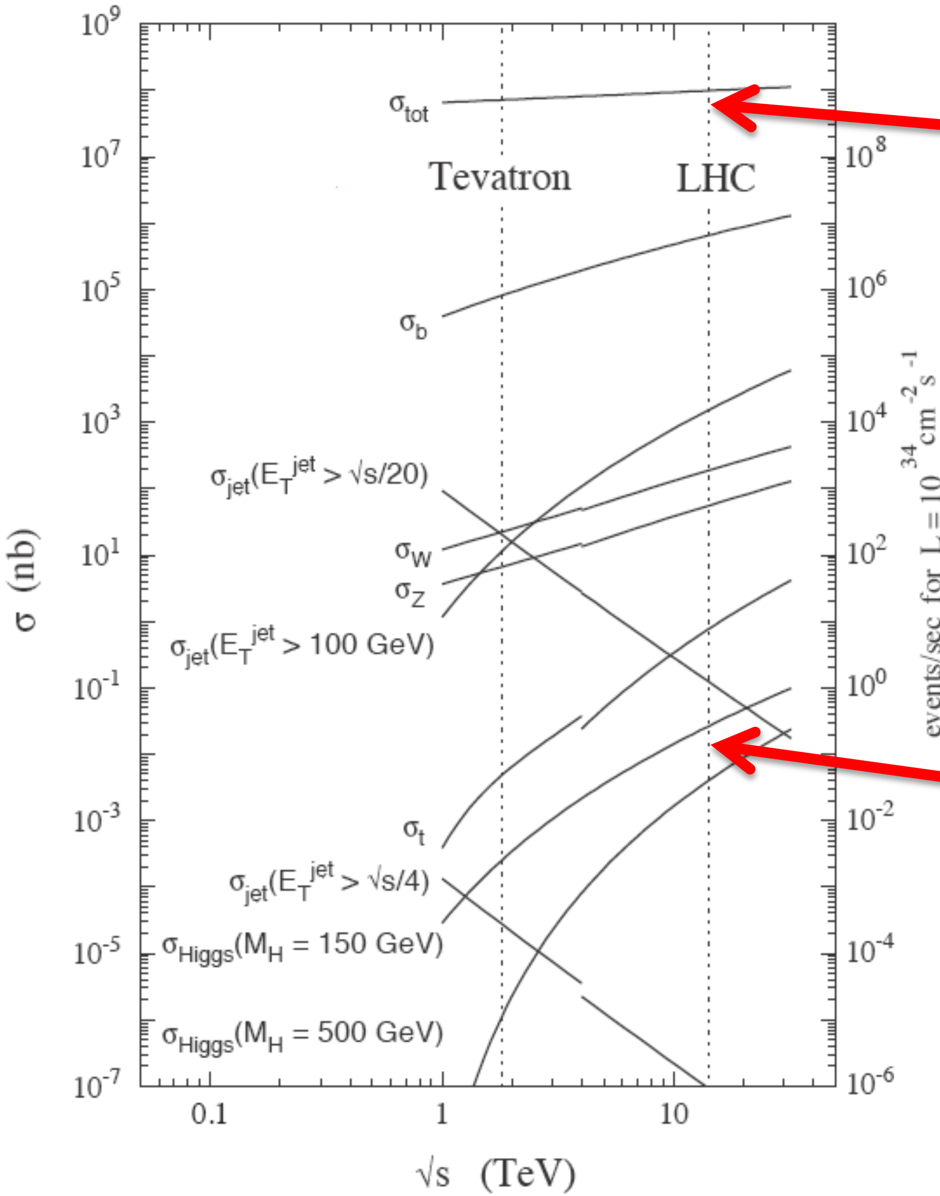
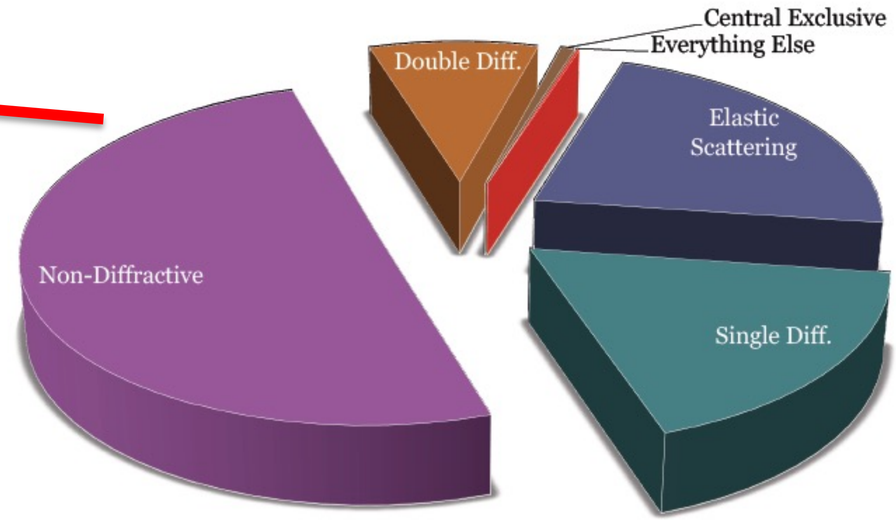
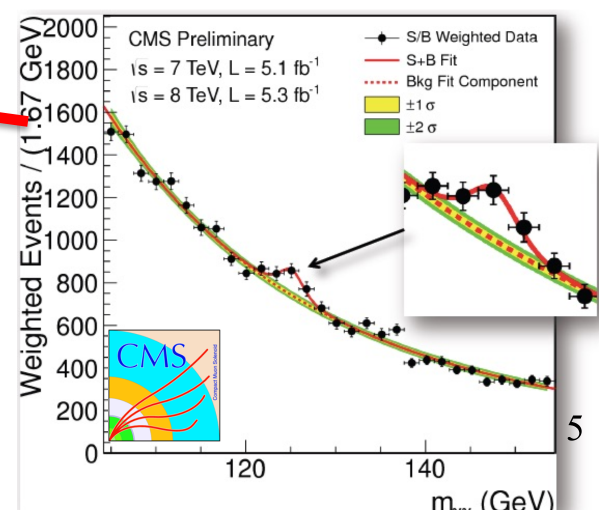
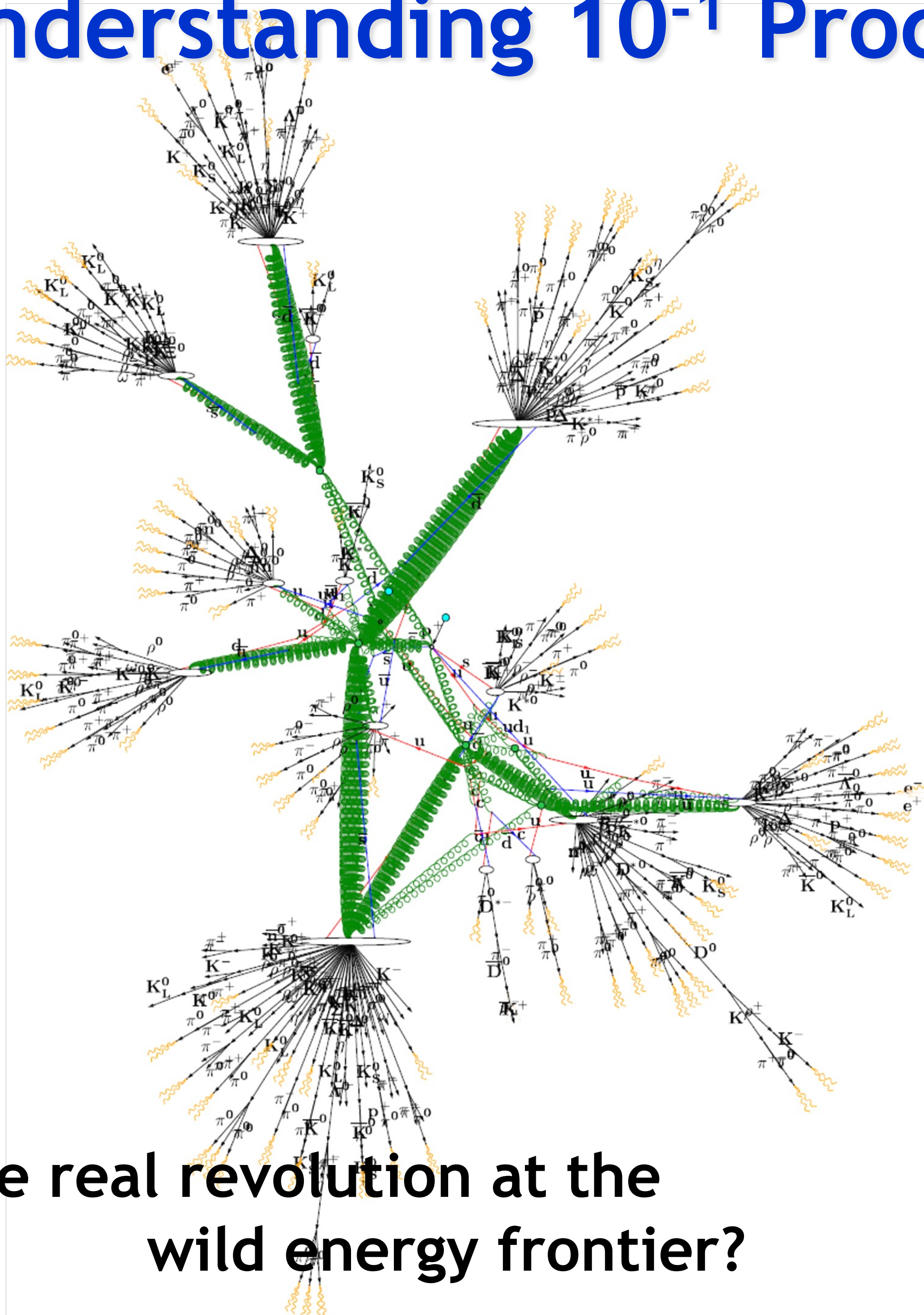






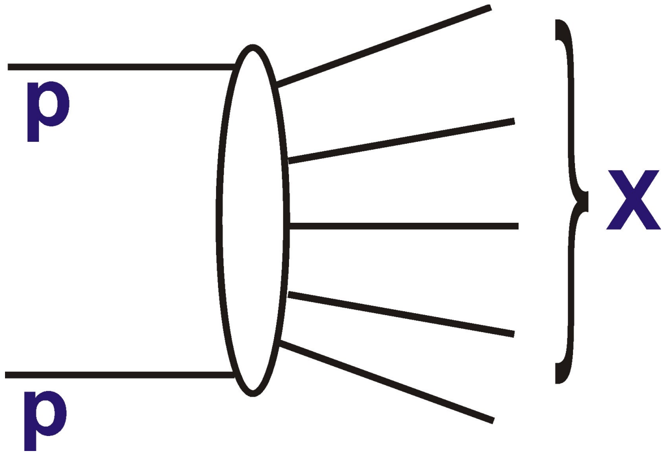
Understanding 10^{-1} Processes is Hard!

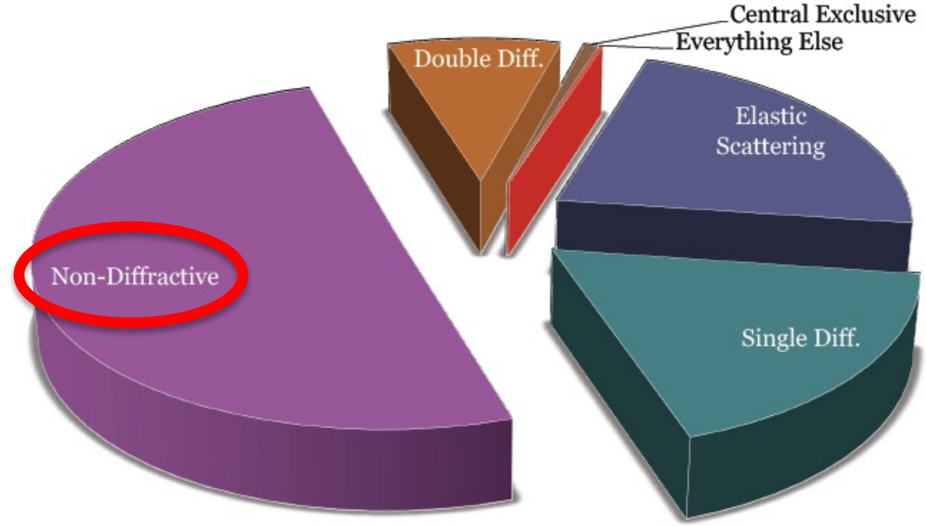


“minimum bias” pp event in PYTHIA8 at $\sqrt{s}$=7 TeV, visualised using MCViz

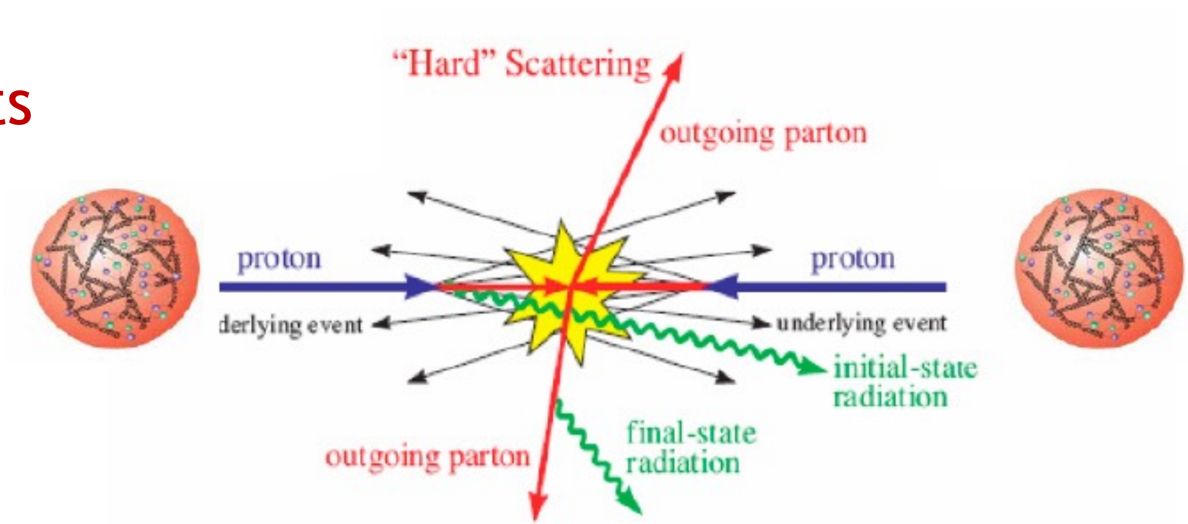
… the real revolution at the wild energy frontier?

The bulk: soft non-diffractive processes



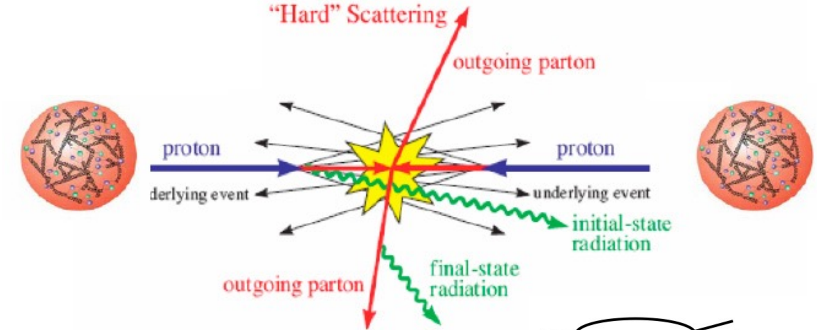


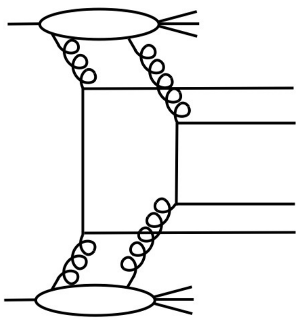
Complicated! … and non-perturbative aspects not ignorable even for hard scatterings …



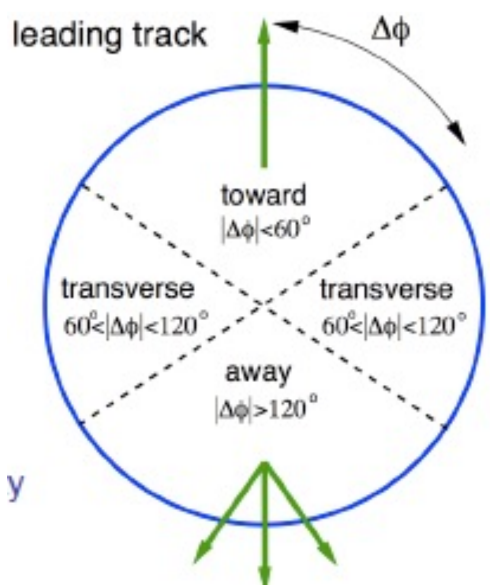
The "underlying event": originates from beam remnants and multiple soft and hard scatterings

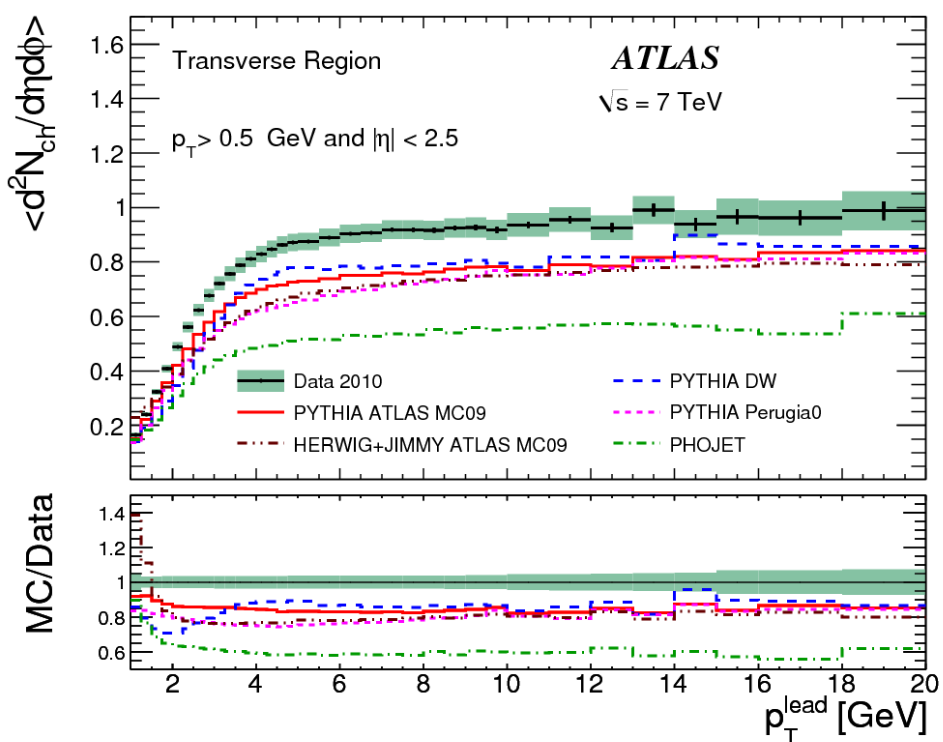
Evidence for Underlying Event / Multi-parton Scattering



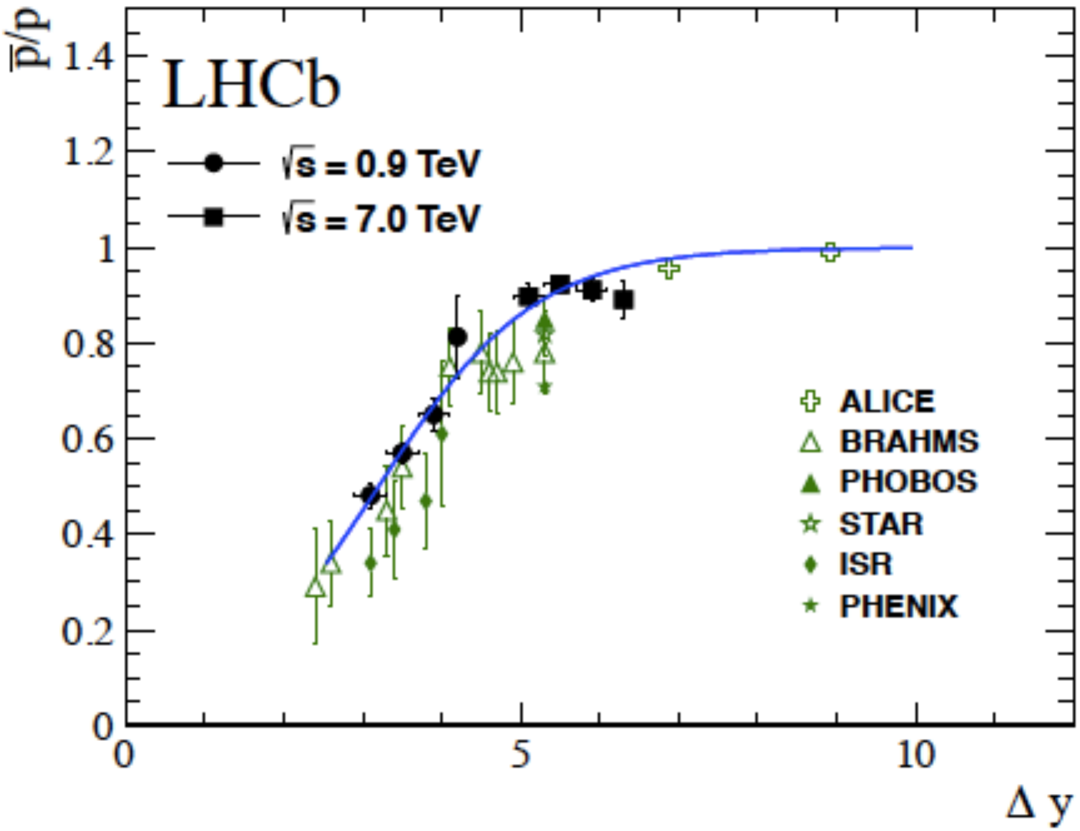


- Region transverse to hard scattering plane particularly sensitive to multiple (parton) interactions.
- Pre-LHC MC models predicted too little transverse activity and jettiness in $\Delta\phi \sim 180^o$ away region …





Complex Dynamics!
e.g. Baryon Number Transport

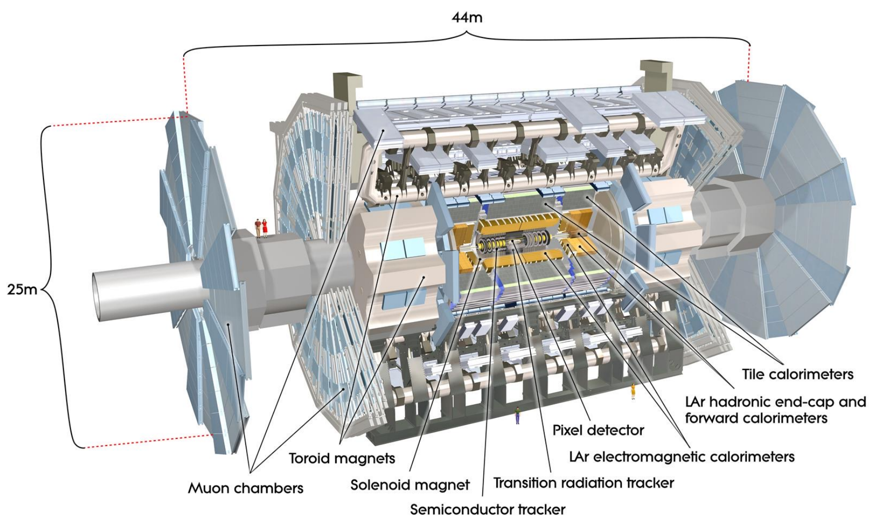


- $\bar{p}/p$ ratio must be close to 1 in central region
- Decreases at large |y| (or $|\eta|$) due to baryon number +1 beam particles
- Baryon number transport over Δy → 5 rapidity units from beam particle

Rapidity Coverage at LHC

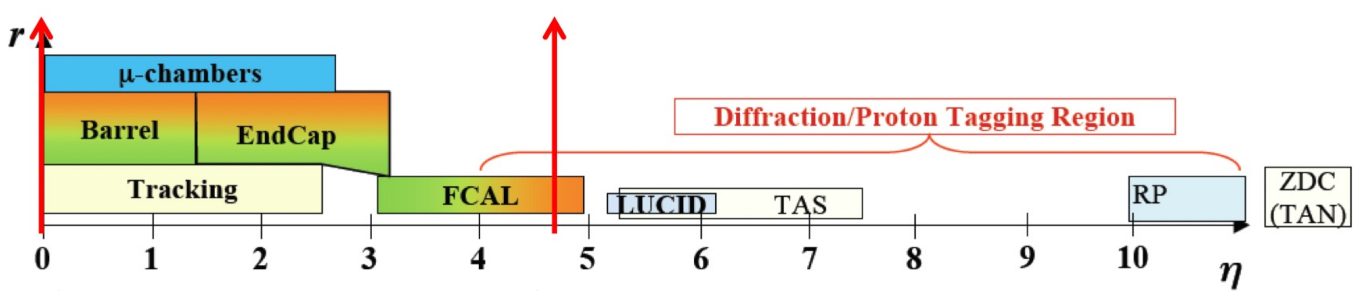
- System with centre of mass energy $\sqrt{s}$ hadronises over (pseudo)-rapidity region $\Delta y \sim \ln \frac{s}{m_p^2}$ with roughly constant particle production per unit (pseudo)-rapidity in the central region, tailing off towards the beam particles

- Forward (large $|y|$) region in principle sensitive to low x physics, parton cascade dynamics and underlying event



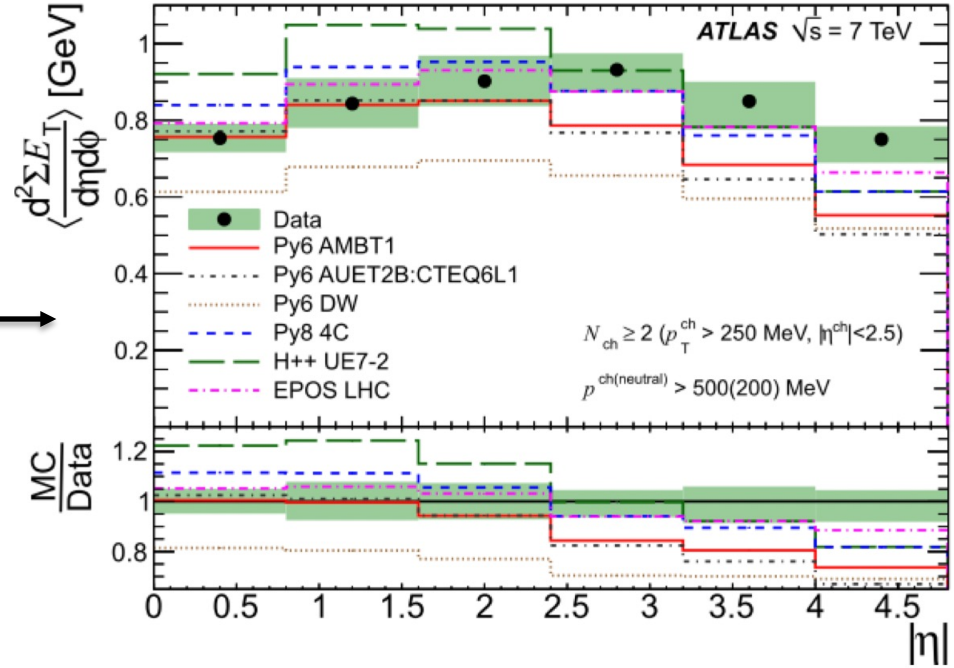
- Main LHC experiments are focused on central region, but there is also forward instrumentation …

- ‘Central’ ATLAS and CMS give information up to $|y| \sim 4.5 - 5.0$

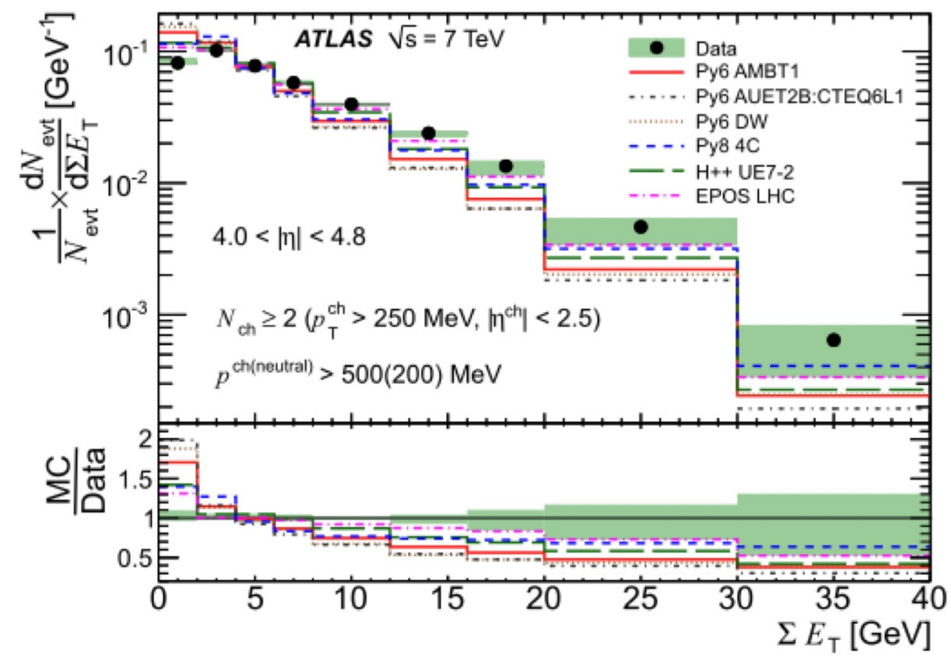


Example Data from main Detectors

Transverse Energy Flow versus |η| up to |η|= 4.8)



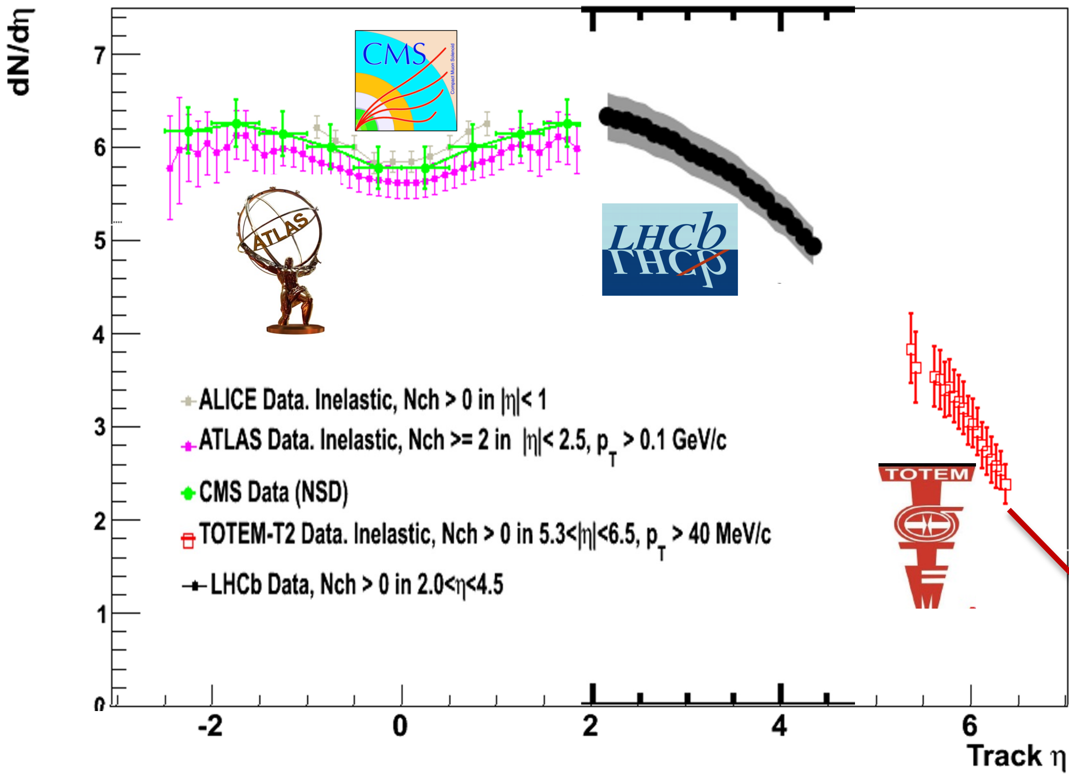
Total transverse energy with 4.0 < |η| < 4.8

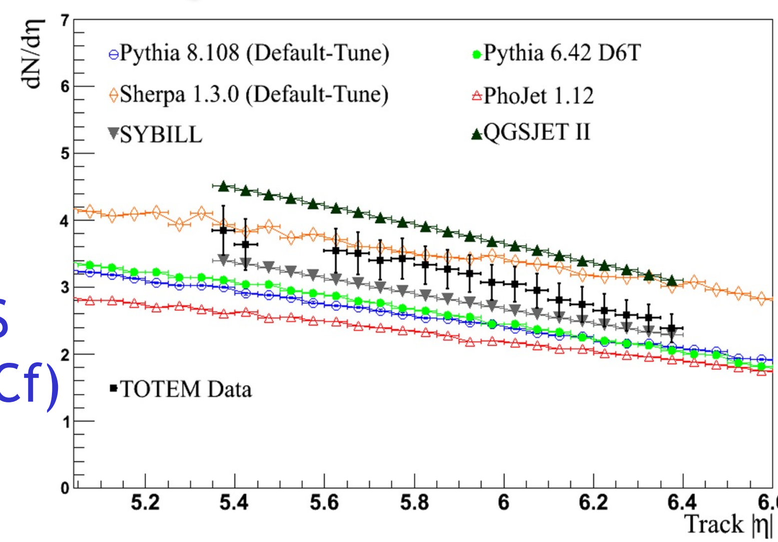


- No Monte Carlo models describe all features 'out of the box'
- Testing ground for models (mainly a tuning exercise) as used in eg cosmic ray air showers
- Complicated (rich!) physics, but hard to extract information about underlying QCD dynamics

The Really Very Forward Region

Charged particle multiplicity measurements beyond the rapidity plateau



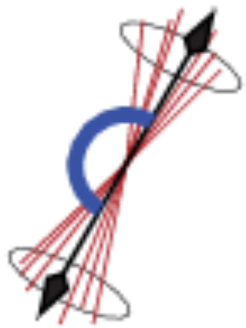


- Very Forward tracking provided by LHCb and TOTEM T2 telescope (5.3 < |η| < 6.5) show changed behaviour towards beam

- Similarly calorimeters: ATLAS LUCID, CMS CASTOR and dedicated fwd experiments (LHCf)

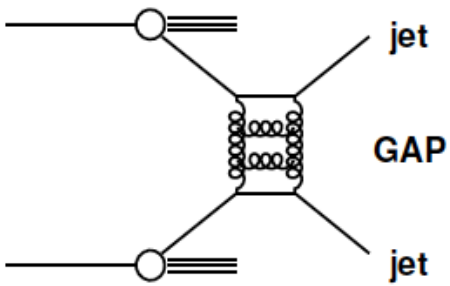
- More for model tuning than deep insights

Dedicated low-x observables in LHC Physics



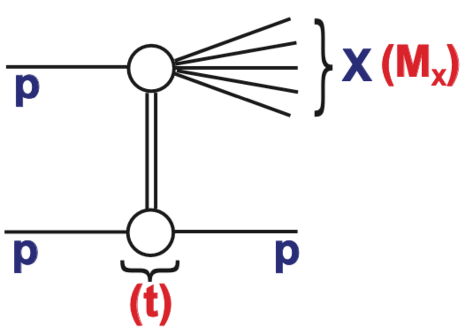
Example observables from early LHC stuies:

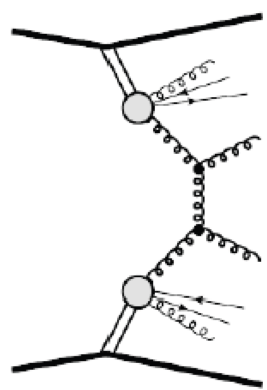
- Azimuth decorrelations between jets
- Gaps between jets
- ...

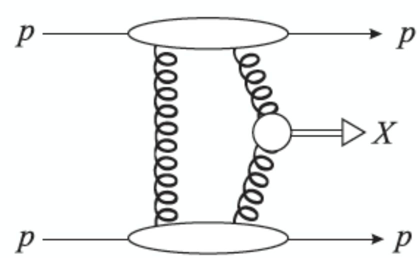


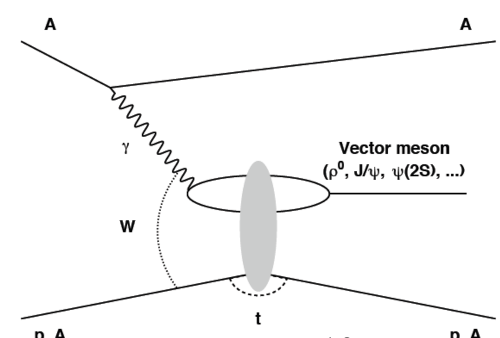
Strongly interacting colour-singlet exchanges

- Elastic scattering (later today)
- Diffractive dissociation (later today)
- Central inclusive production (elsewhere)
- Central exclusive production (elsewhere)
- Ultra-peripheral collisions (next lecture)

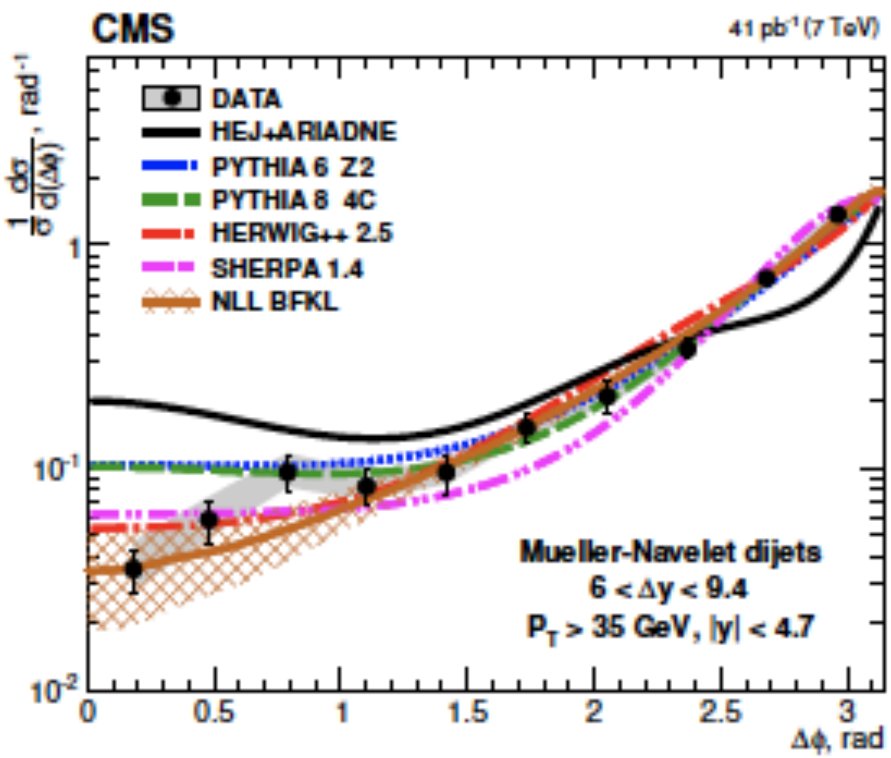








Azimuthal Decorrelations between Mueller-Navelet jets



- Choice of Forward-Backward highest E_T jets with comparable energy suppresses phase-space for DGLAP evolution and offers chance to search for BFKL evolution

- Sensitivity enhanced at large azimuthal decorrelation due to multiple emissions

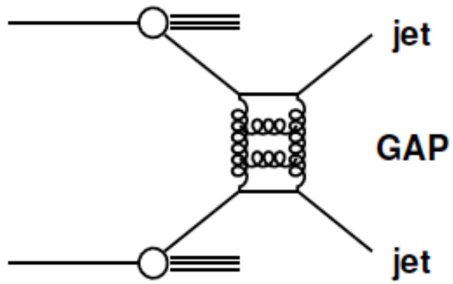
… Jets separated by up to $\Delta y = 9.4$ units!

- LL BFKL model (HEJ) overestimates decorrelations
- Analytic NLL BFKL calculation agrees well with data

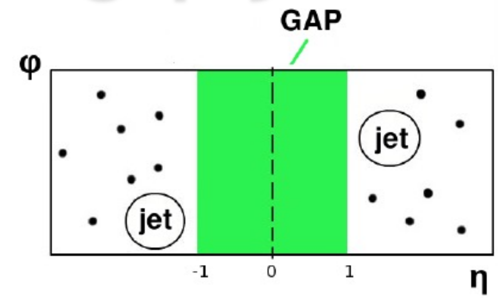
BUT

- DGLAP-based models with tuning also describe data

→ This is typical despite increasingly sophisticated observables

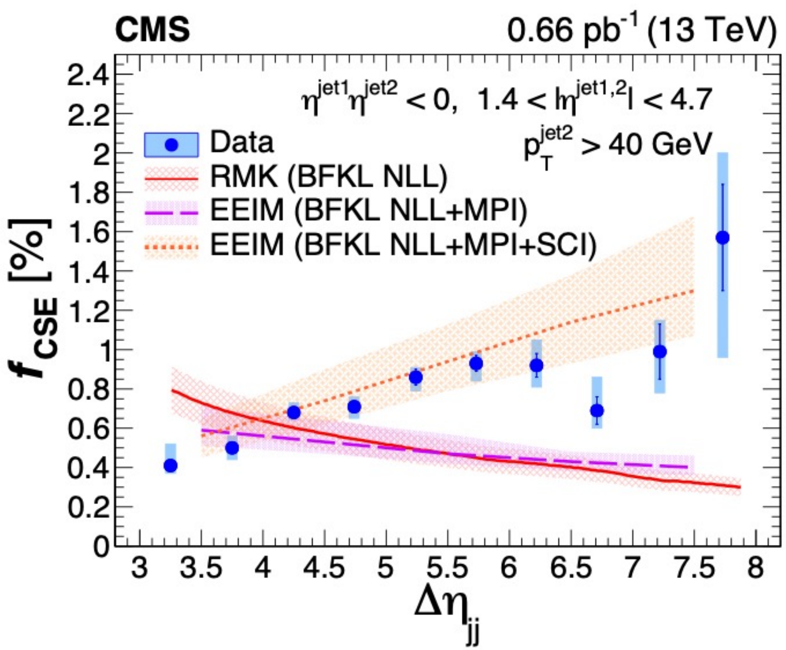


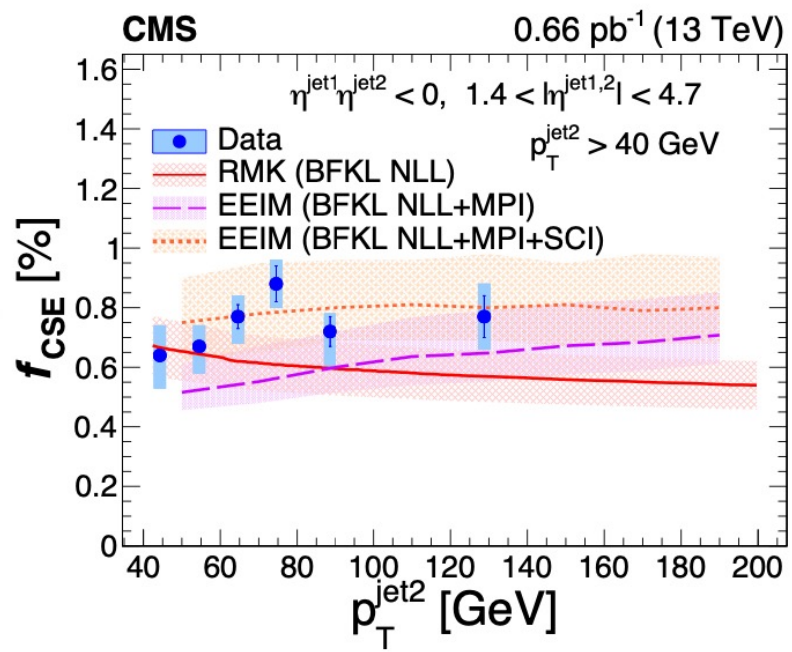
LHC Searches for BFKL Pomeron: Jet-gap-jet events



- Gaps between jets are classic signature for BFKL dynamics ('BFKL pomeron exchange')

- Complicated by rapidity gap survival / infrared safety and pile-up
- Typical observable: fraction f_{CSE} of dijet events with gap versus size of gap



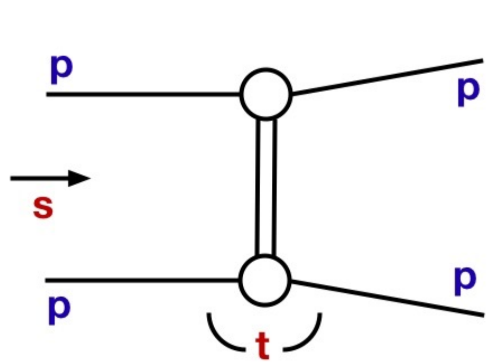


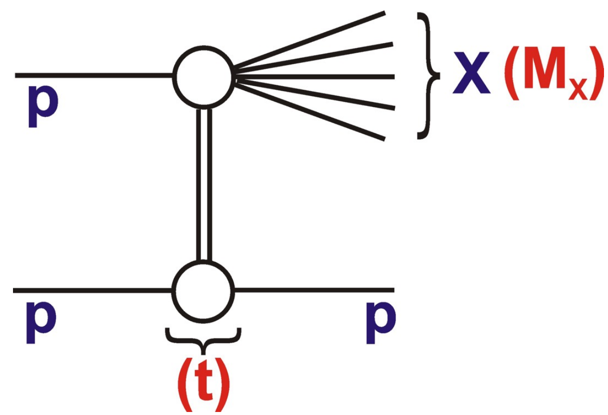
- Not describable with standard MC. Broad agreement with BFKL models.

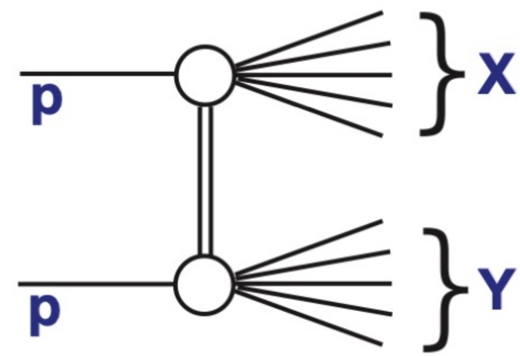
Elastic and Diffractive Processes in Proton-Proton Collisions

[See also Valery Khoze lectures on 'High Energy soft QCD & Diffraction']

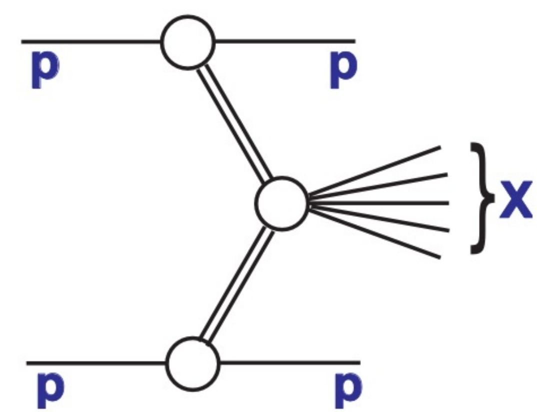
We are concerned with processes where no net quantum numbers are exchanged and the protons either stay intact or `dissociate'







- There are also more complex topologies



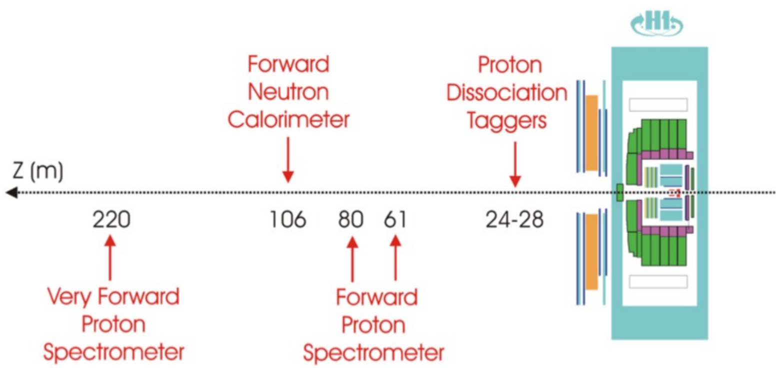
- Experimental signatures:
  - … intact protons scattered through very small angles
  - … large regions with no particle production ('rapidity gaps')

Methods for Diffraction and Elastics

… old slide from diffraction at HERA

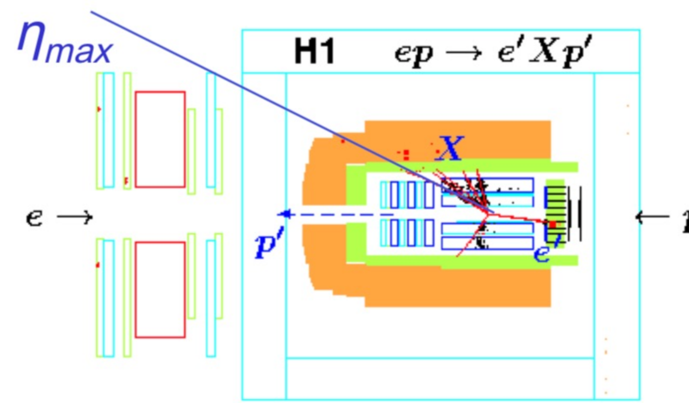
Signatures and Selection Methods

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



Limited by statistics and p-tagging systematics

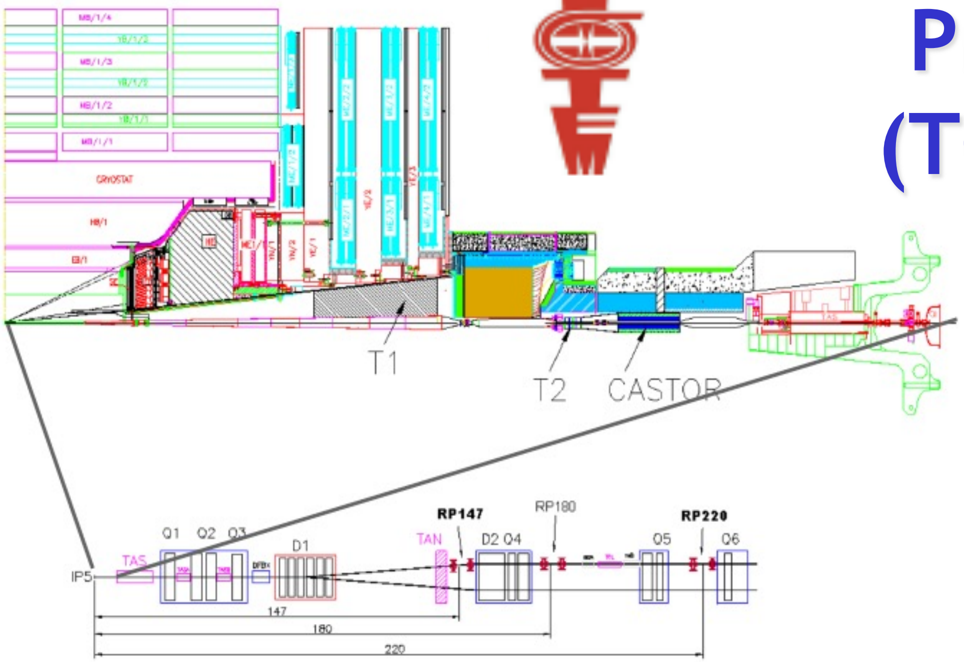
`Large Rapidity Gap' **(LRG)** adjacent to outgoing (untagged) proton

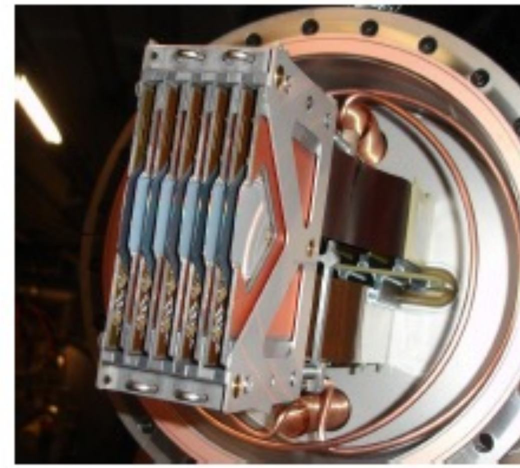


Limited by p-diss systematics

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

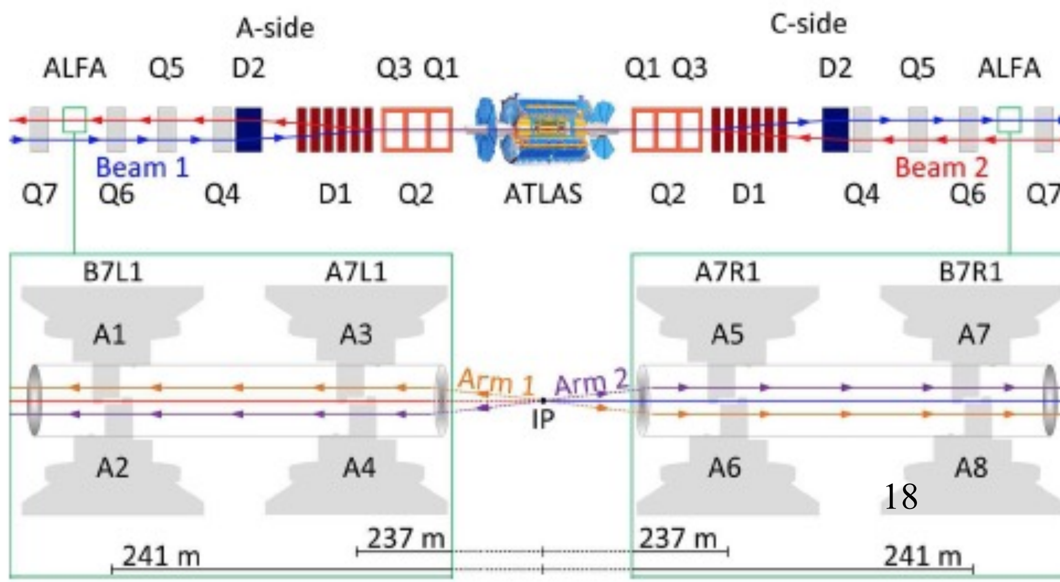
First Generation LHC Proton Spectrometers (TOTEM & ATLAS-ALFA)



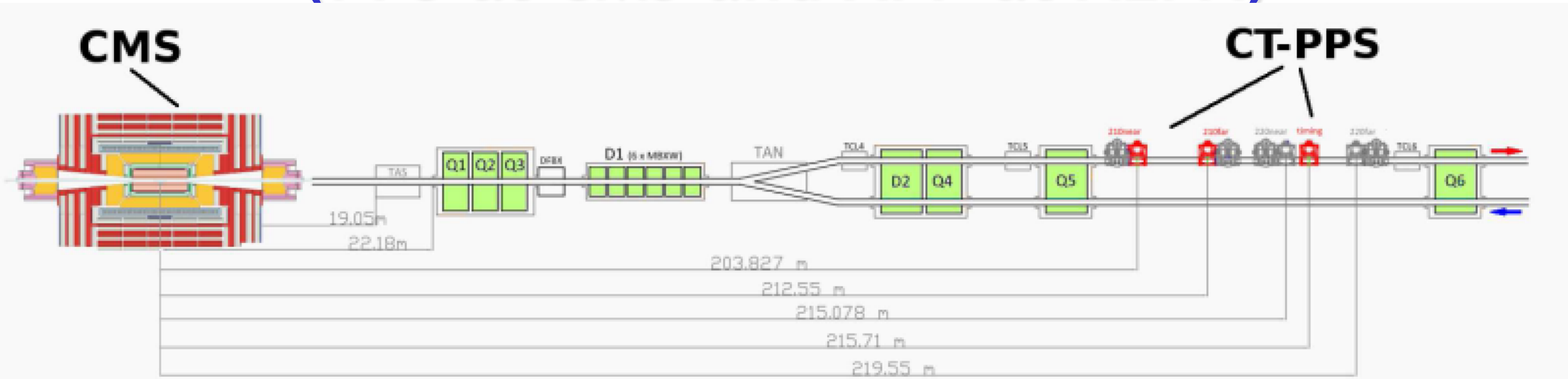


‘Roman pot’ vacuum-sealed insertions to beampipe, well downstream of IP.

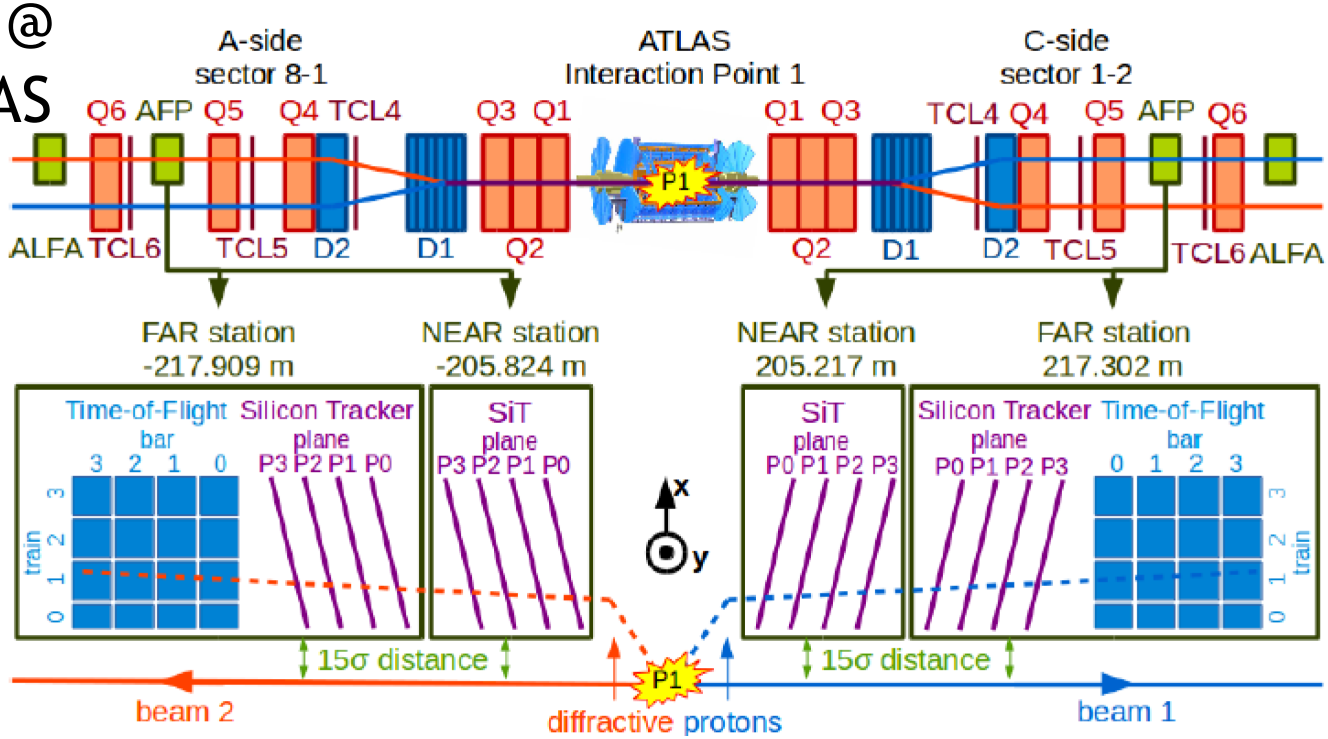
Not very radiation-hard → deployed in dedicated (high β^*, low luminosity) LHC runs



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



AFP @ ATLAS



Radiation-hard detectors, designed to operate in standard high luminosity runnning.

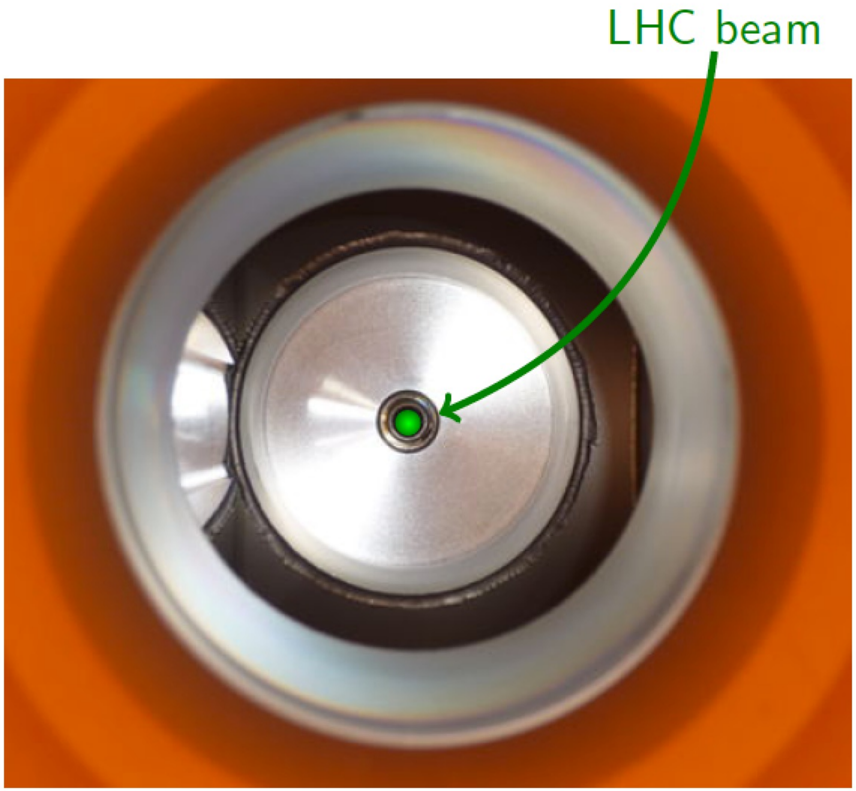
Principle of Roman Pot Detectors

Advantages of Roman Pot Technology

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

Principle of Roman Pot Detectors

Advantages of Roman Pot Technology



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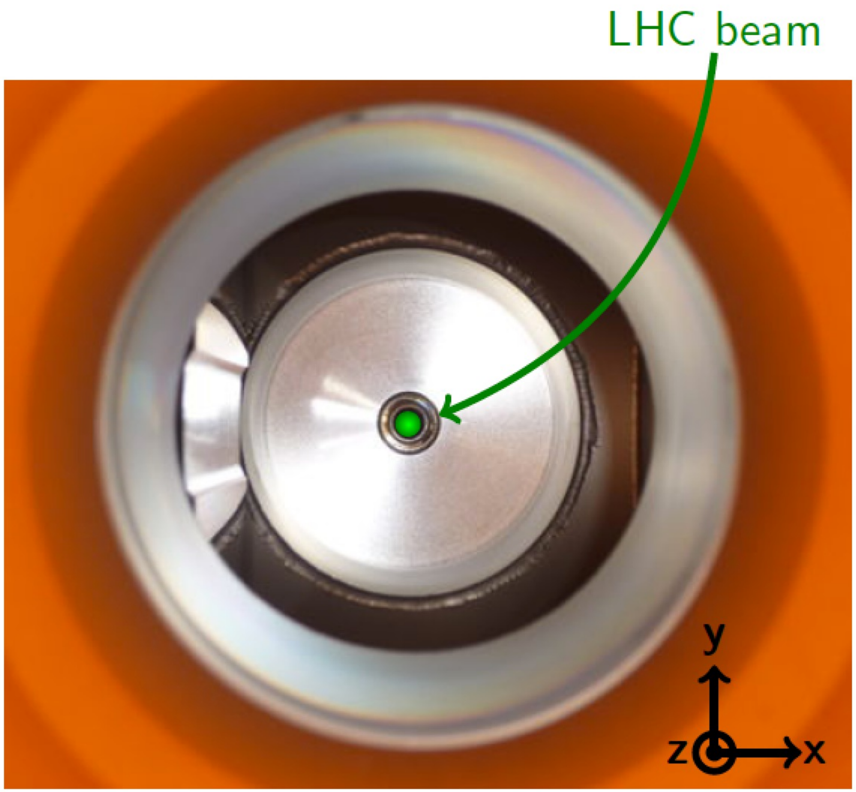

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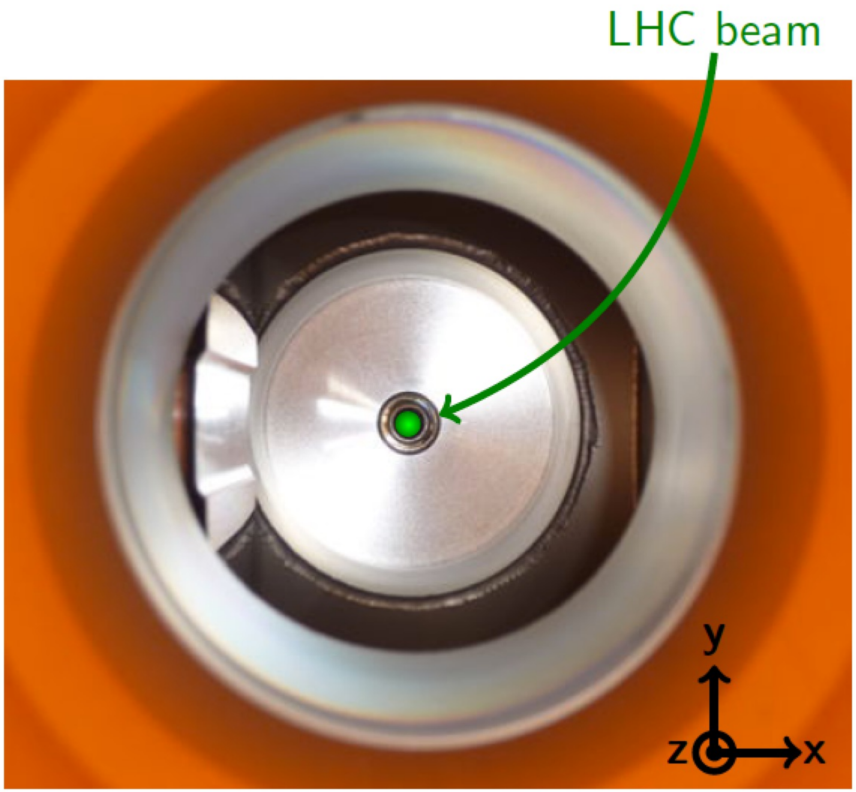

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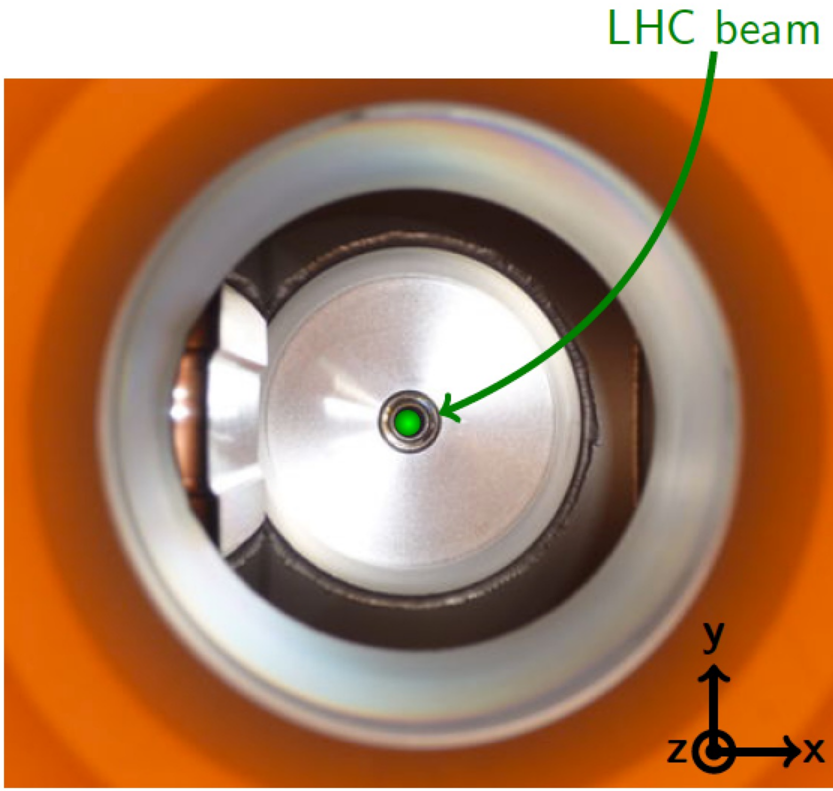

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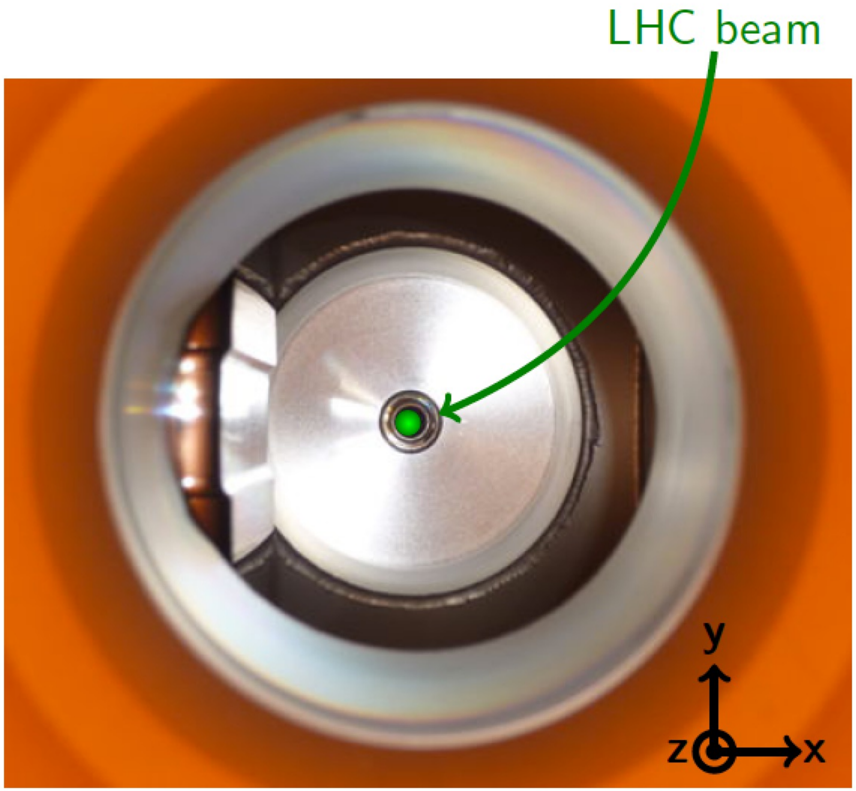

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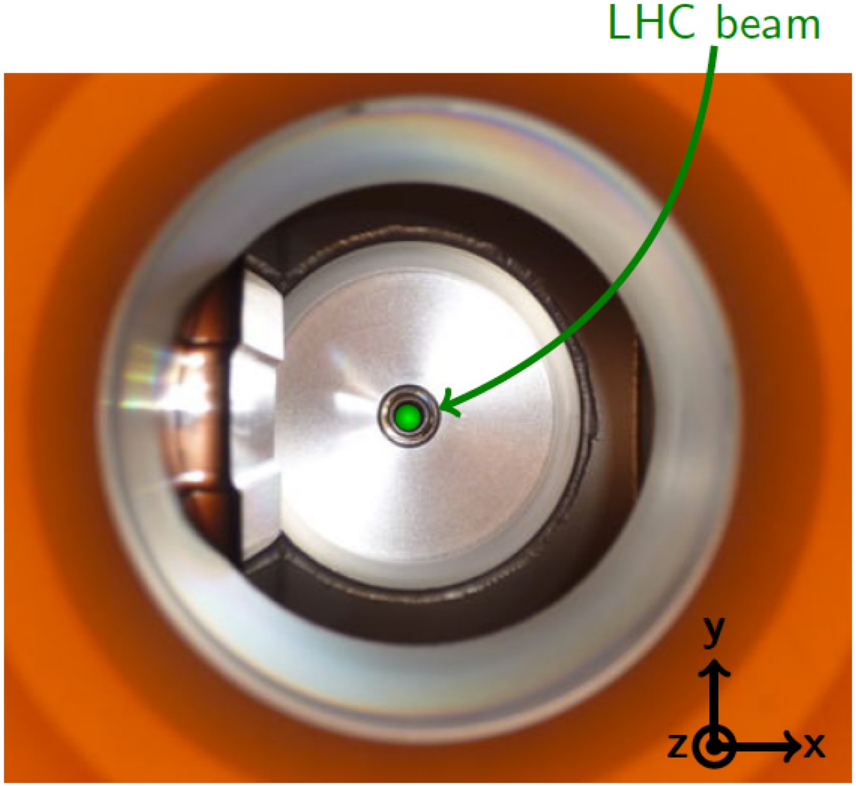

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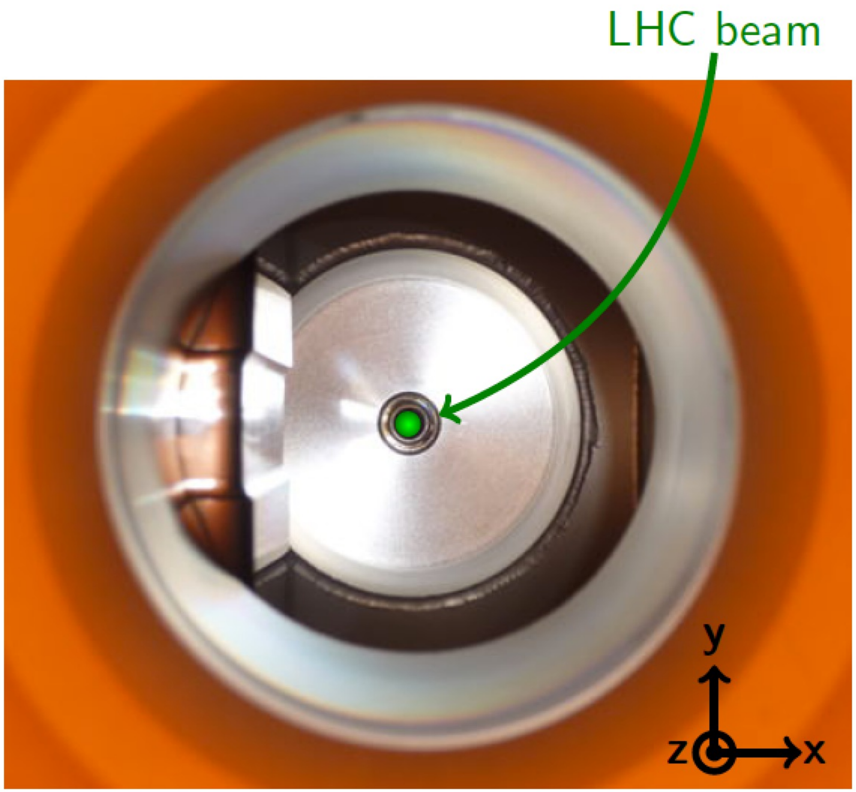

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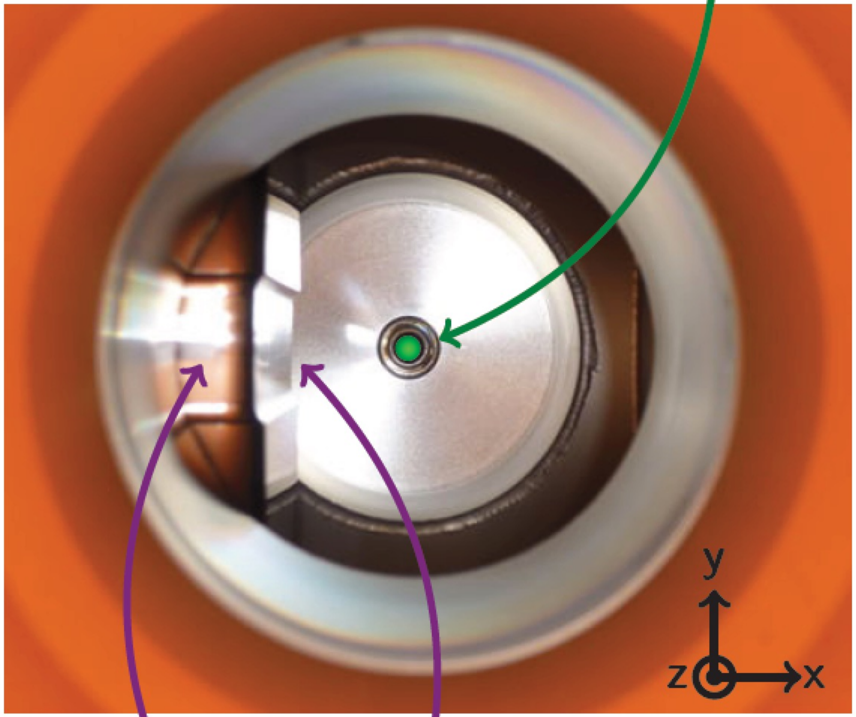
LHC beam



thin window and floor (300 μm)

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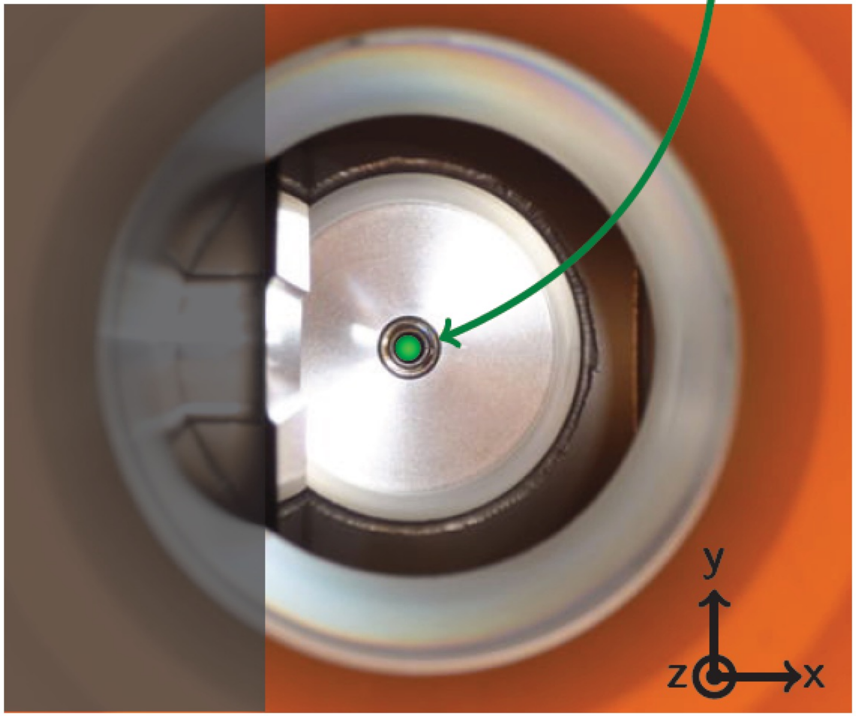
Advantages of Roman Pot Technology

shadow of TCL4 and TCL5 collimators

LHC beam



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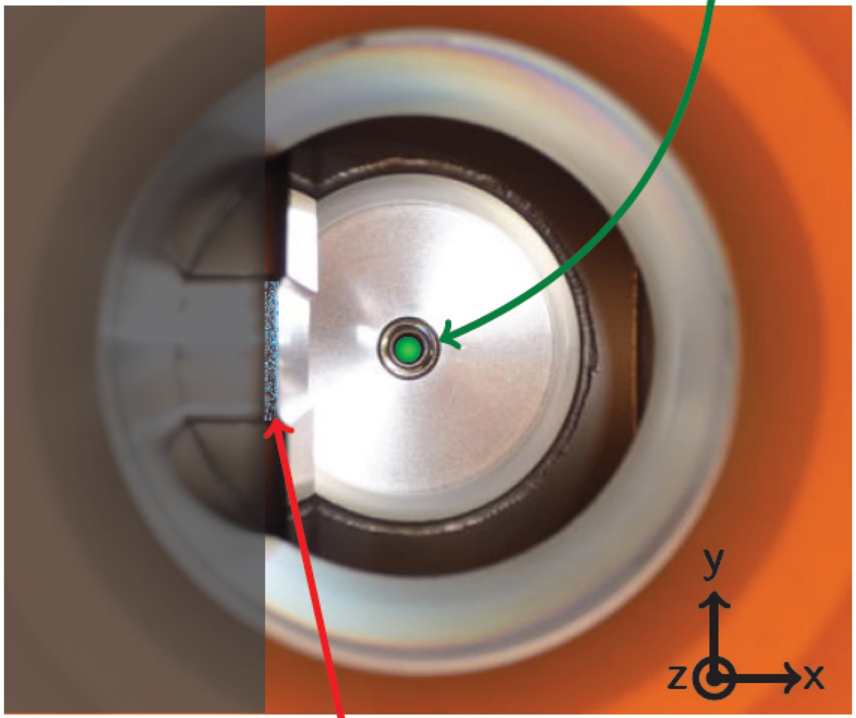
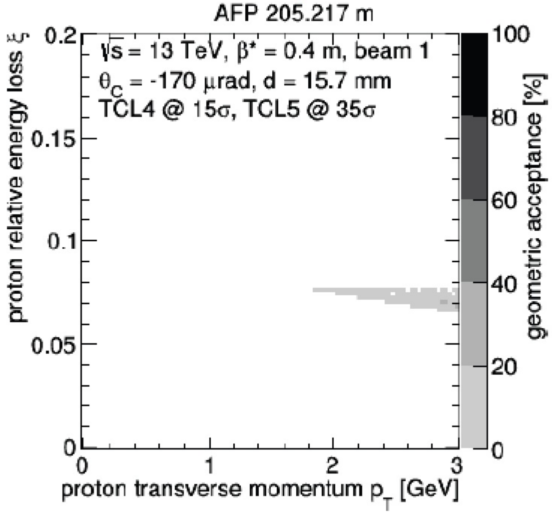


diffractive protons

thin window and floor (300 μm)

Geometric acceptance:



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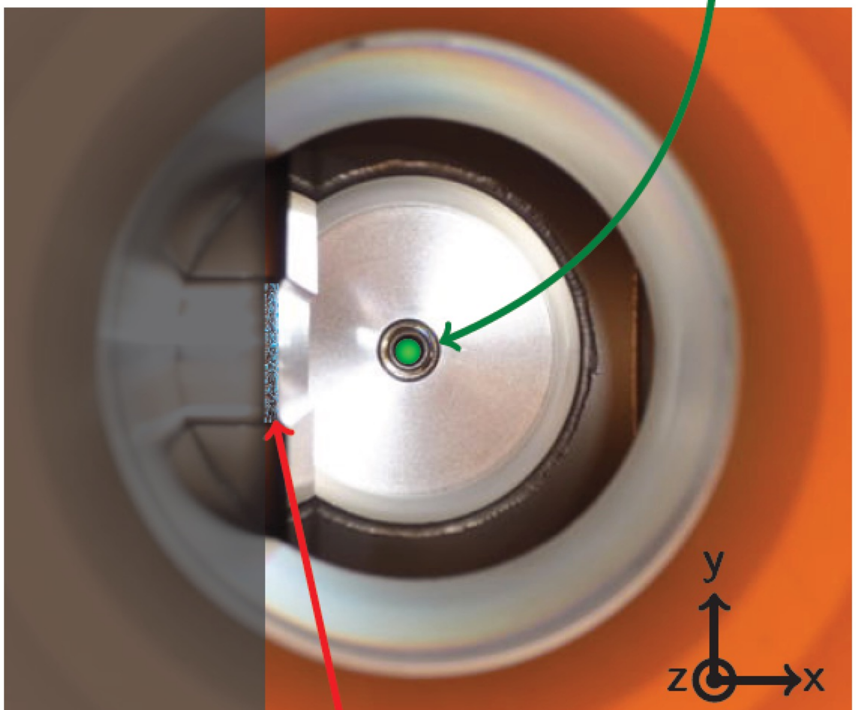

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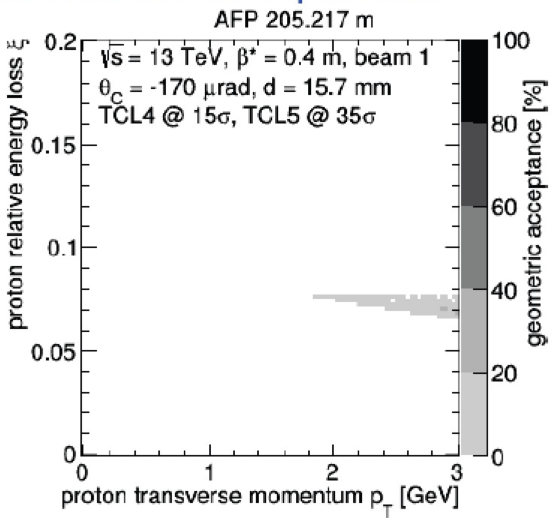
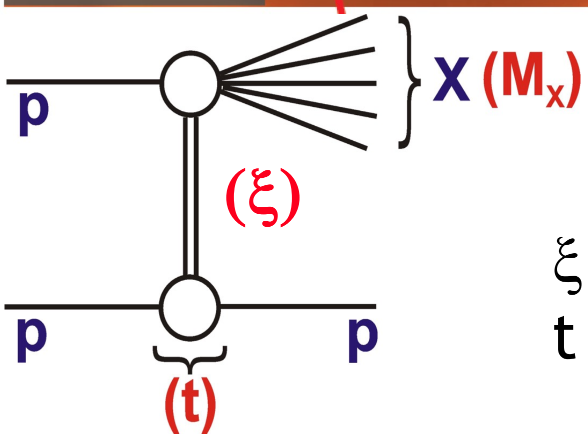


Described here in terms of kinematics of `Single Diffractive Dissociation' (SD)



ξ = fractional proton energy loss

$t = -p_T^2$ of outgoing proton

4/21

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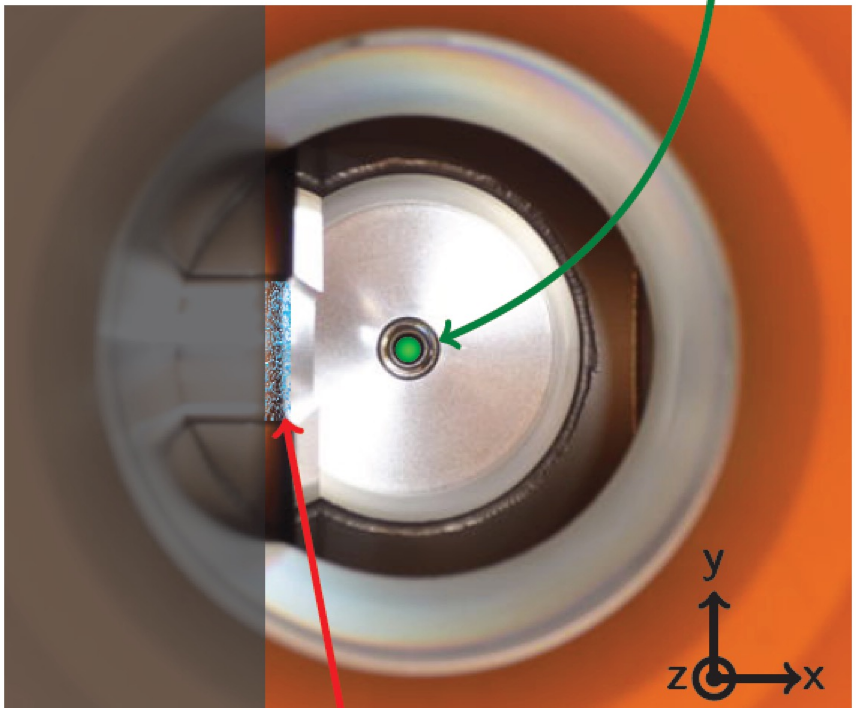
LHC beam



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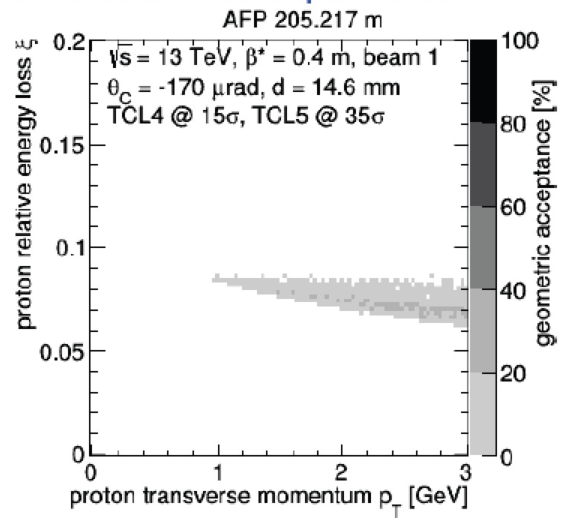

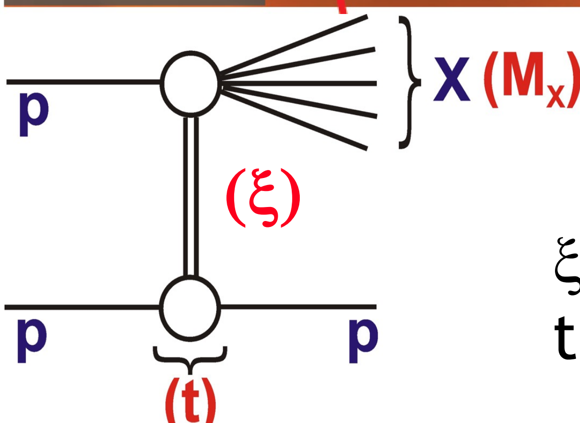

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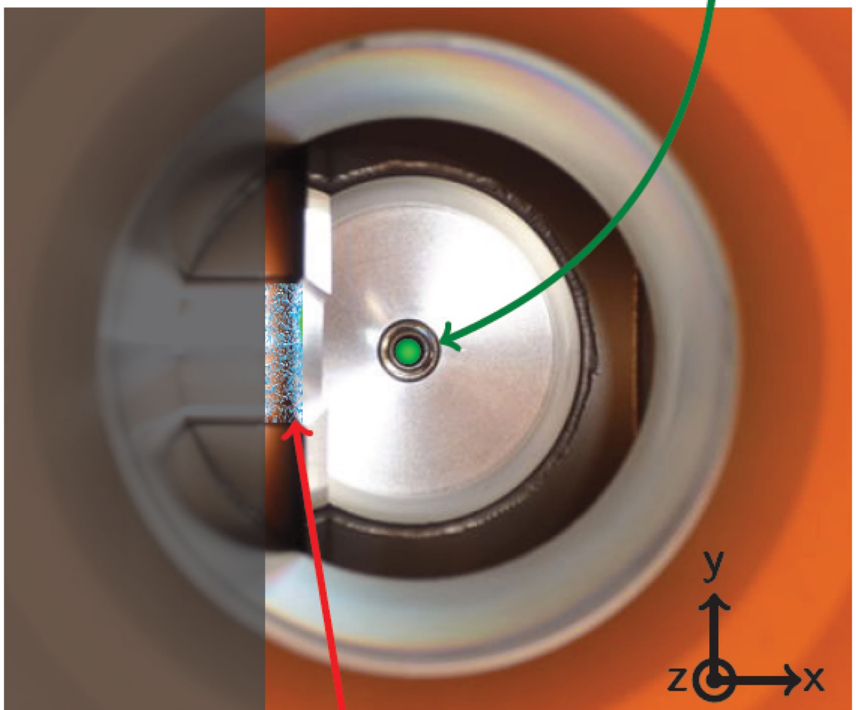
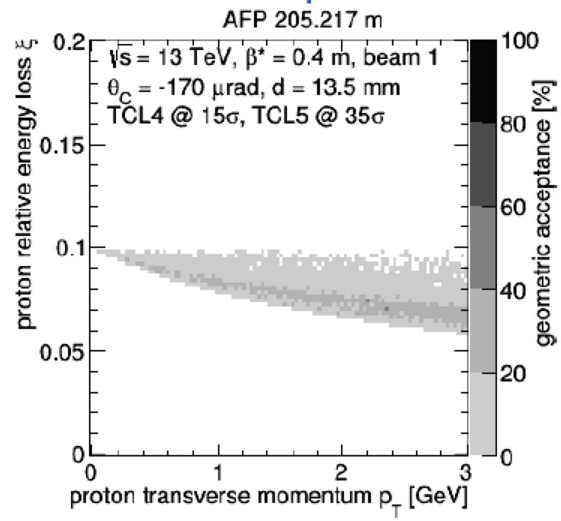
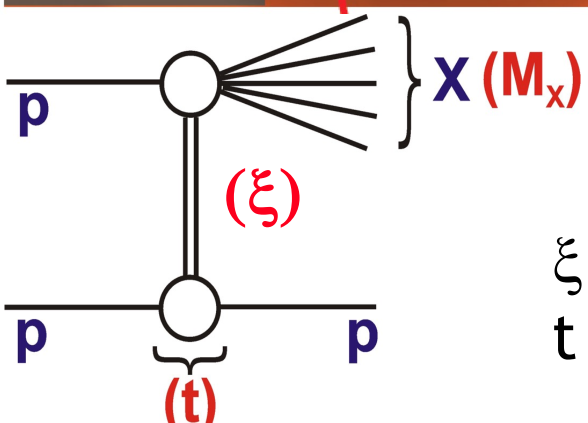
Advantages of Roman Pot Technology



Geometric acceptance:





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ξ = fractional proton energy loss

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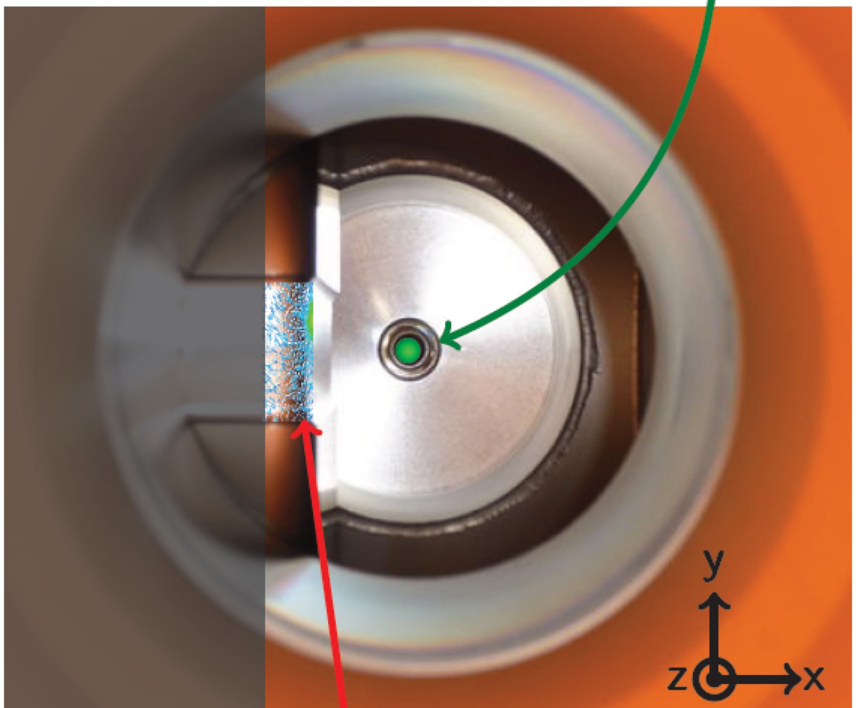

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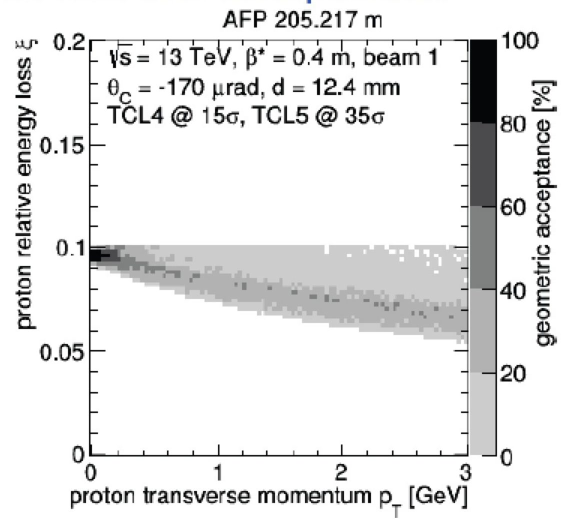

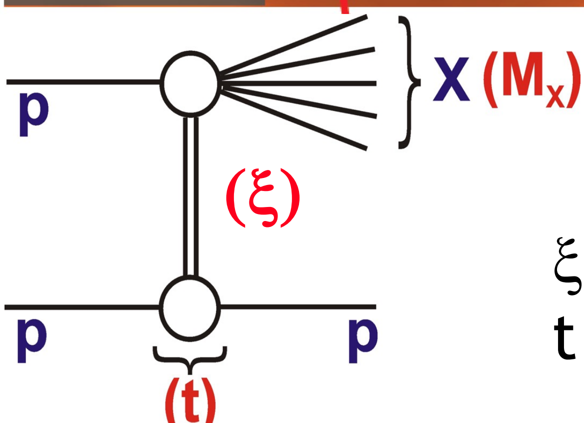

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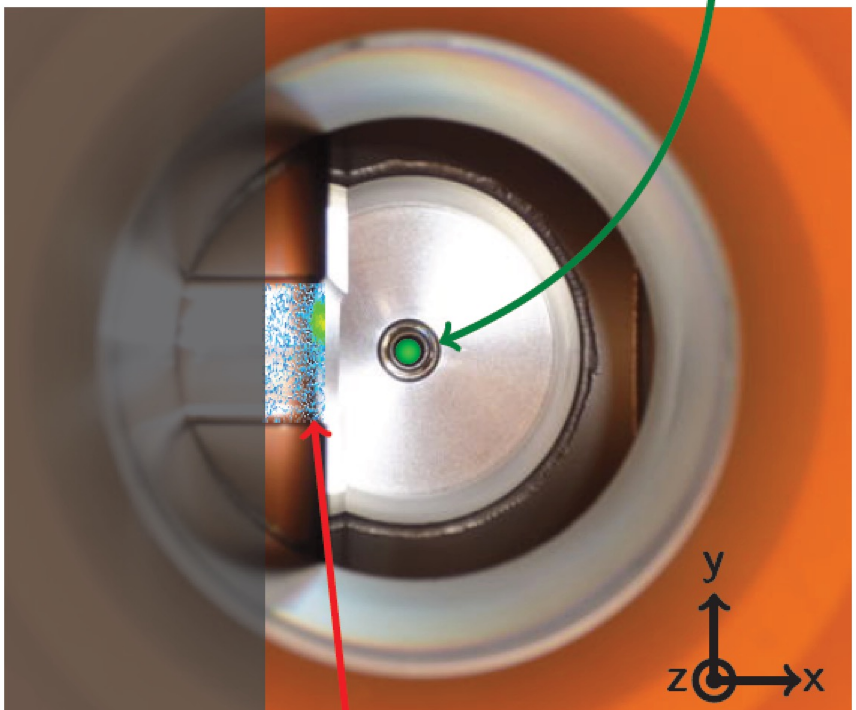

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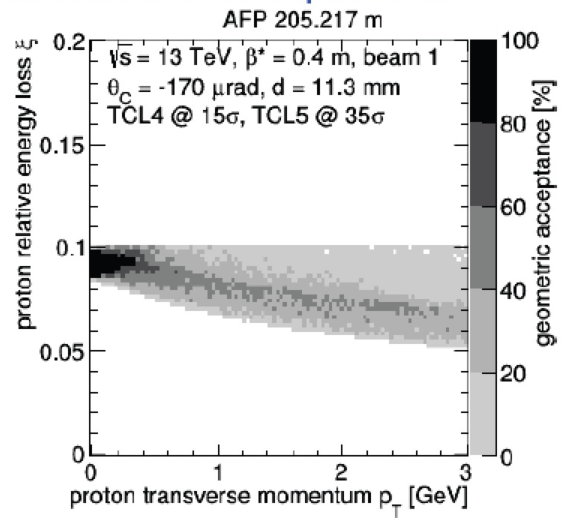

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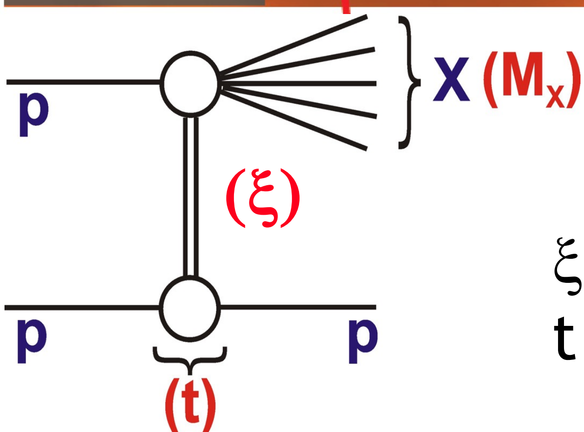

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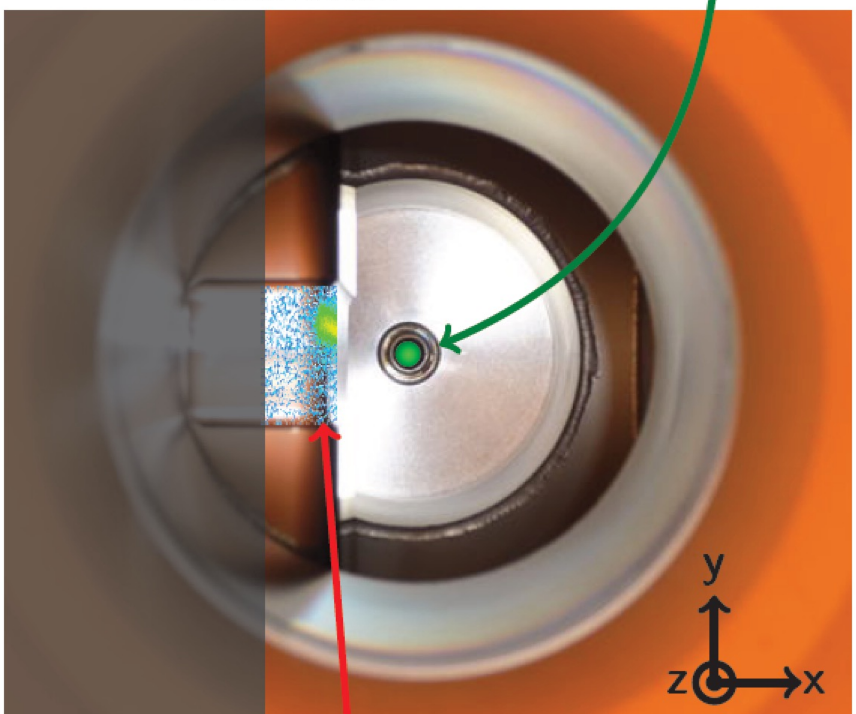

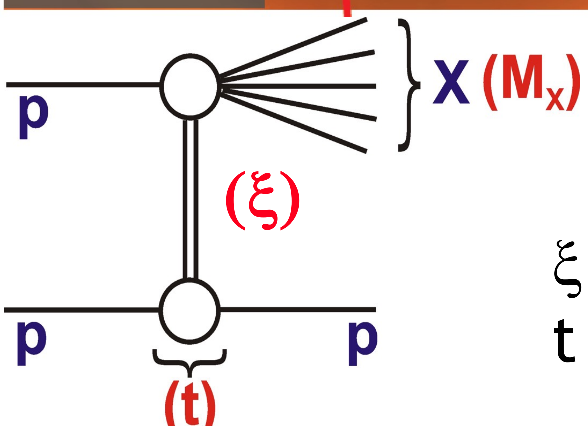

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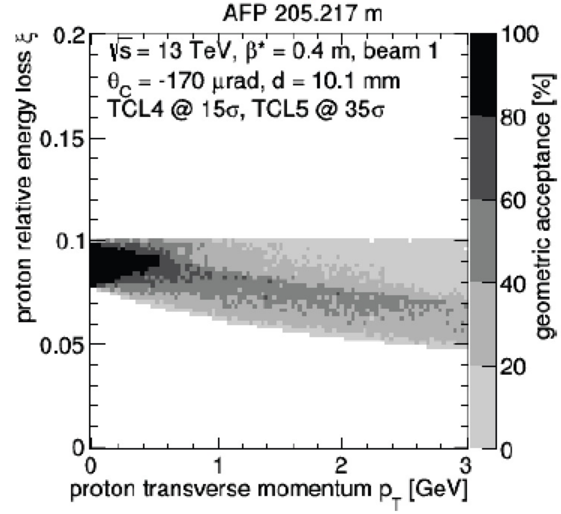

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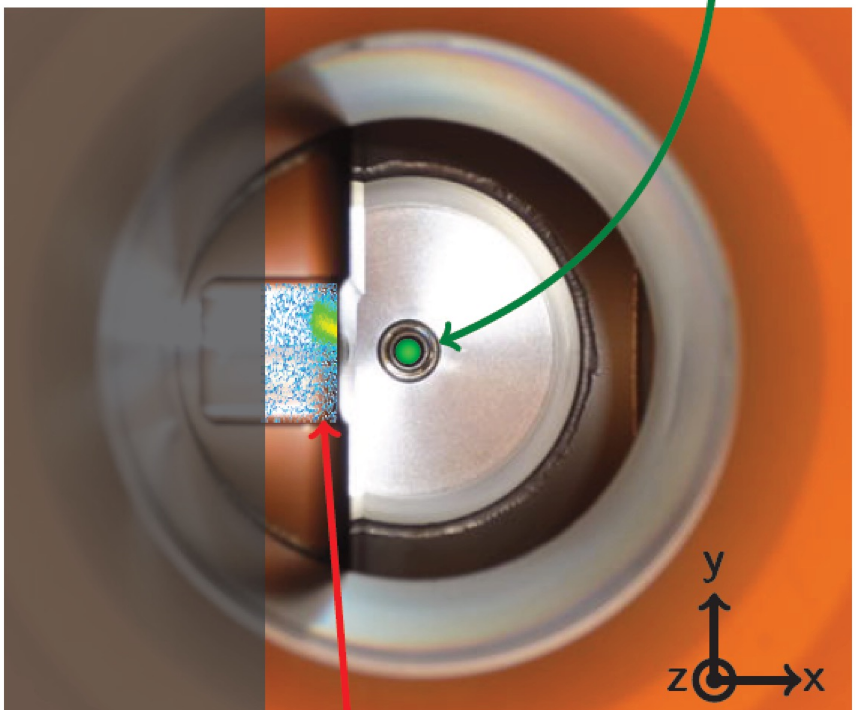

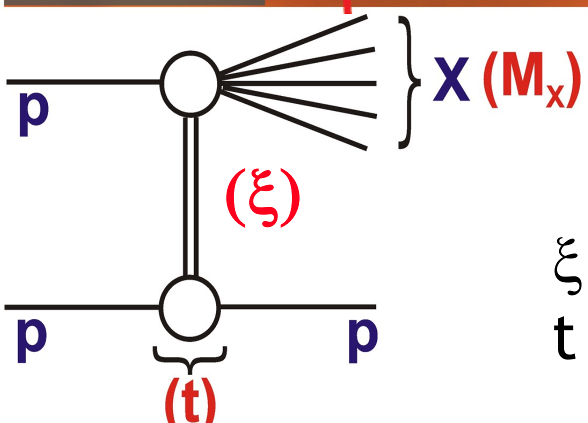

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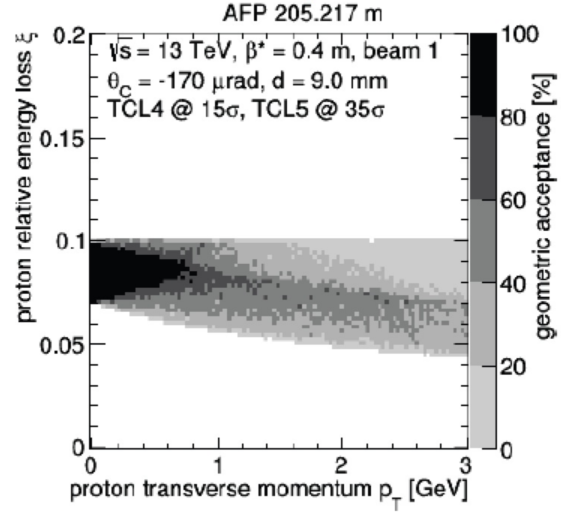

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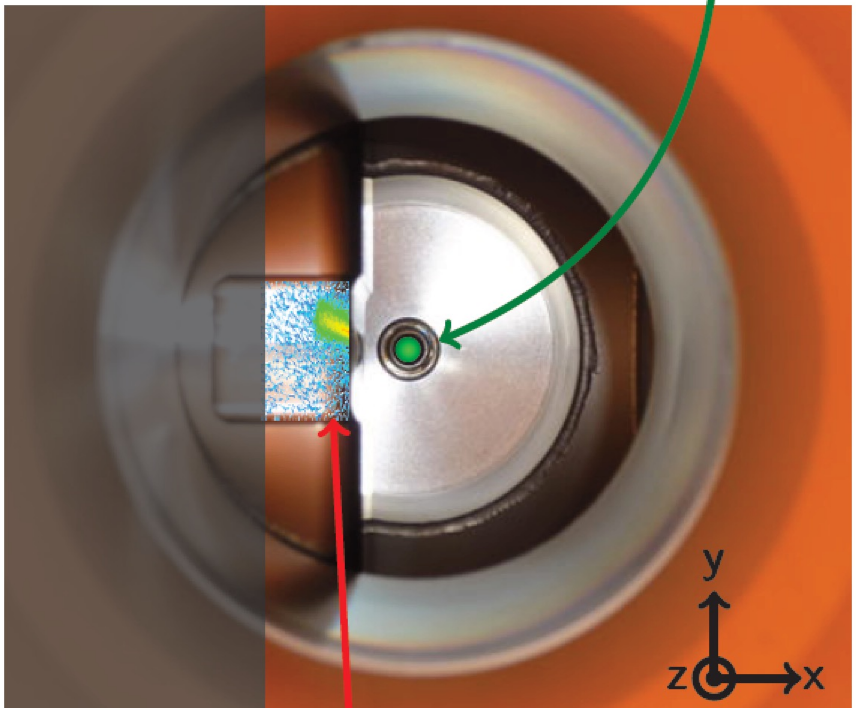

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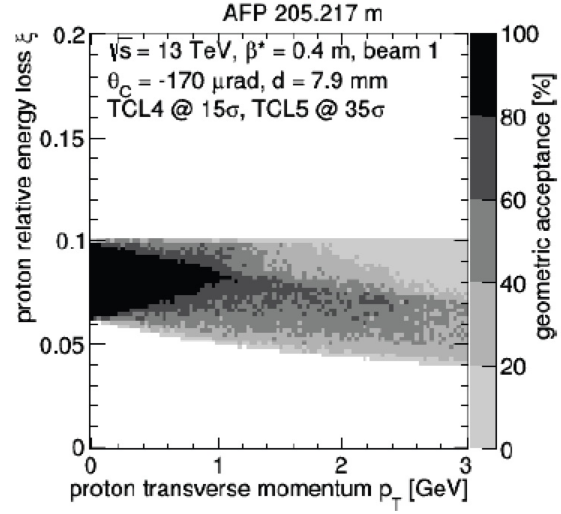

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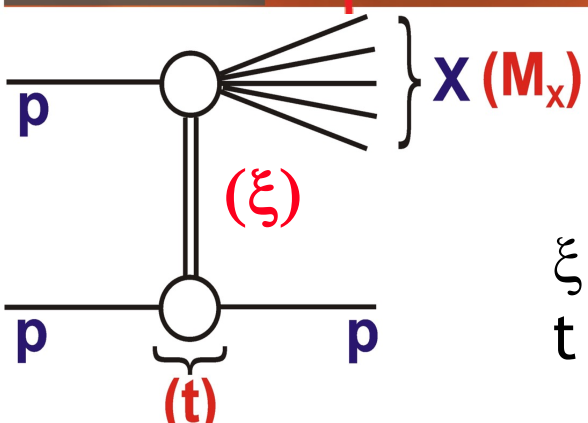

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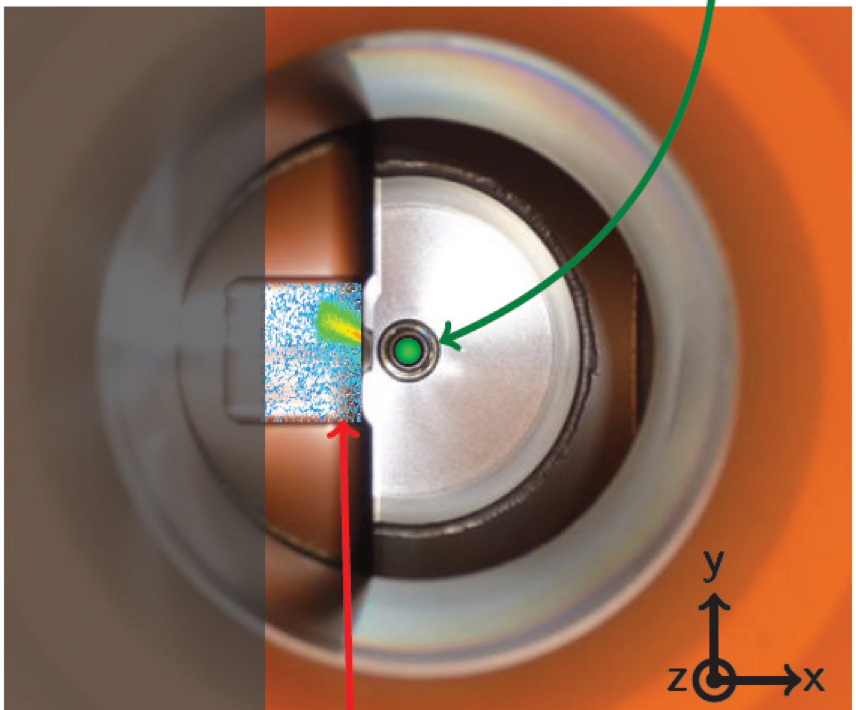

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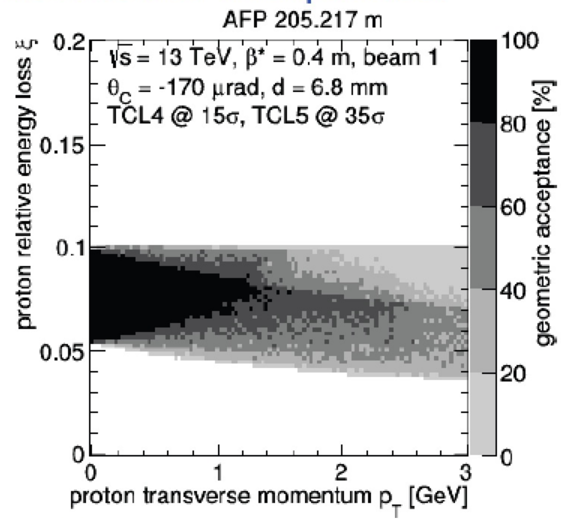

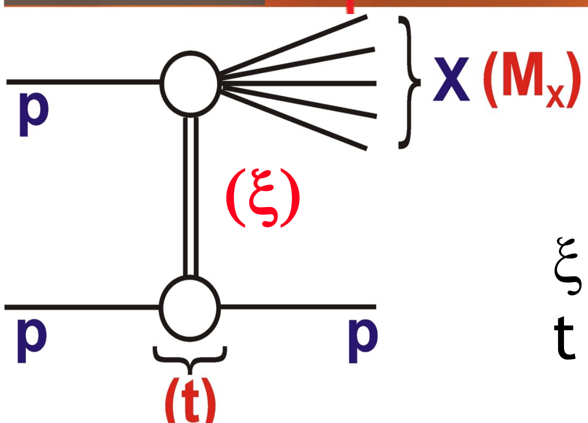

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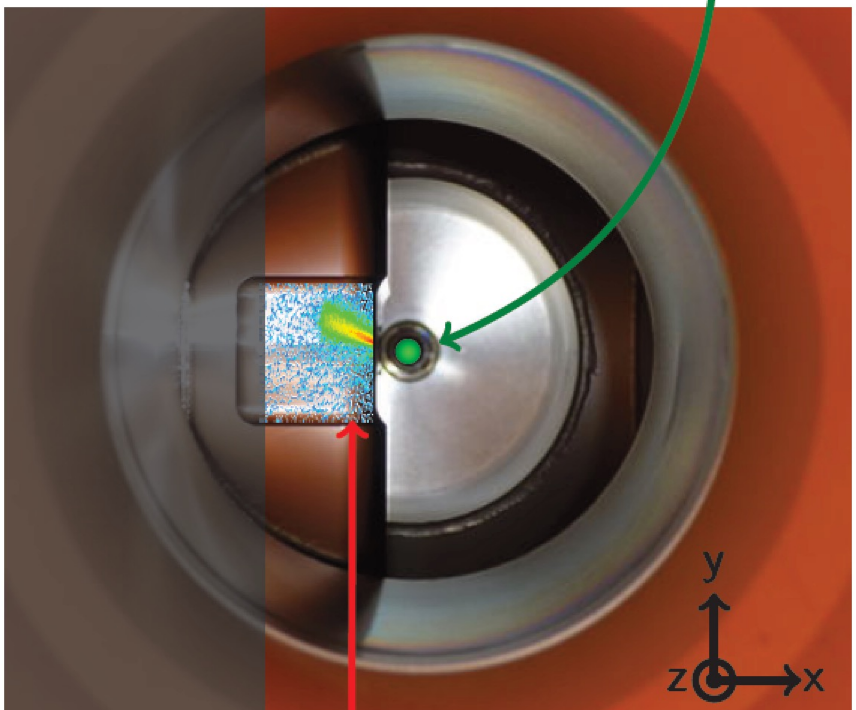

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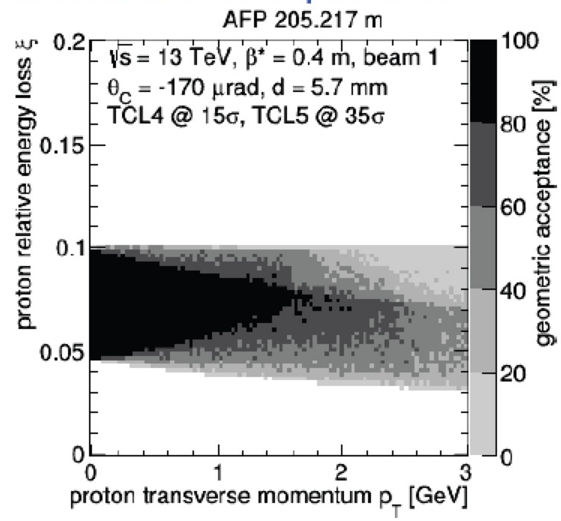

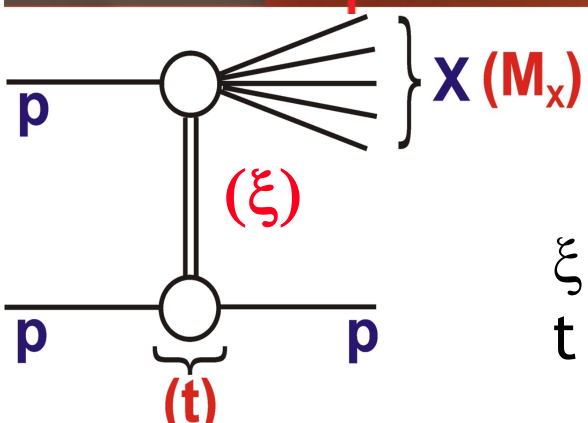

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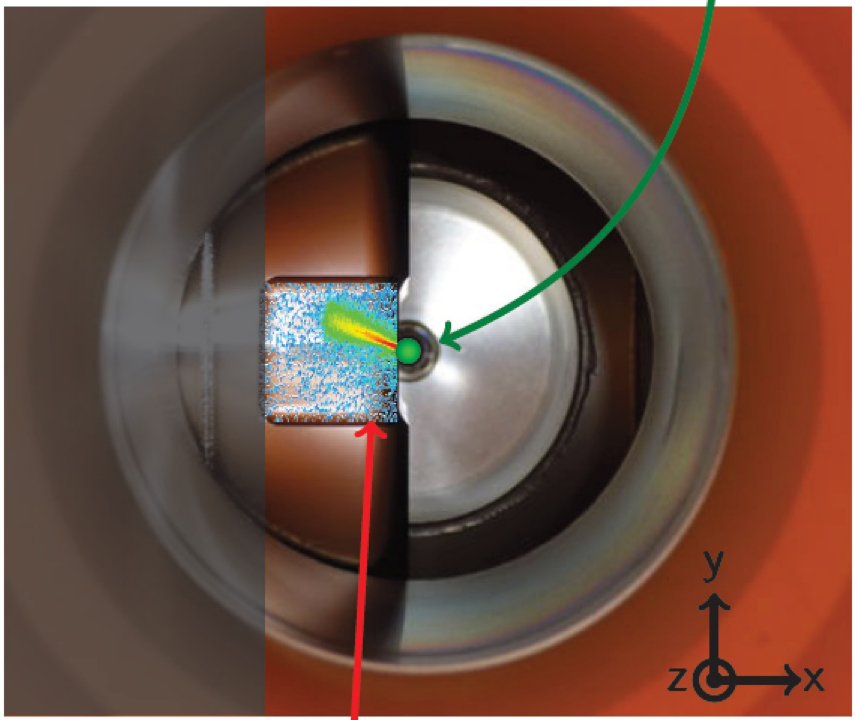

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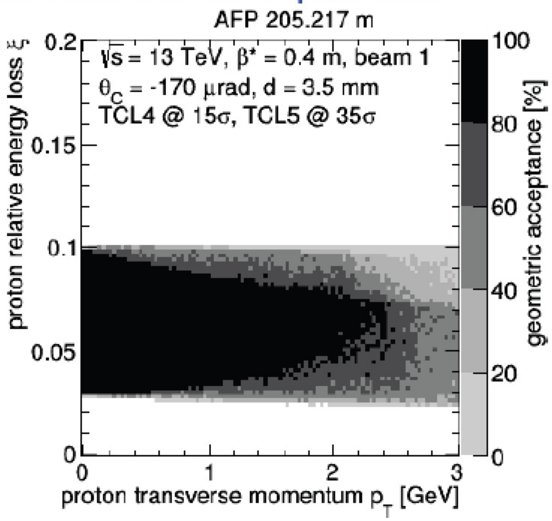

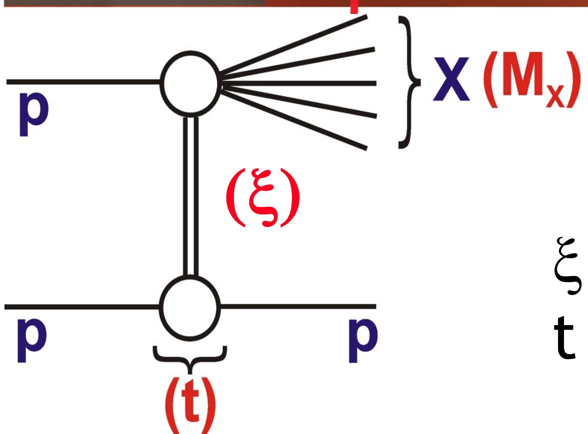

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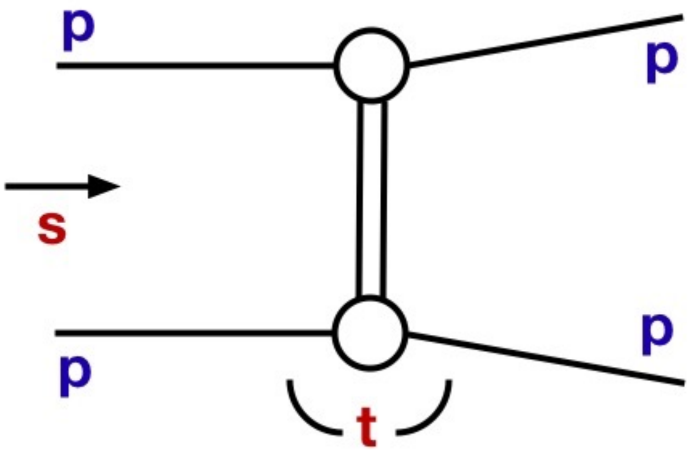
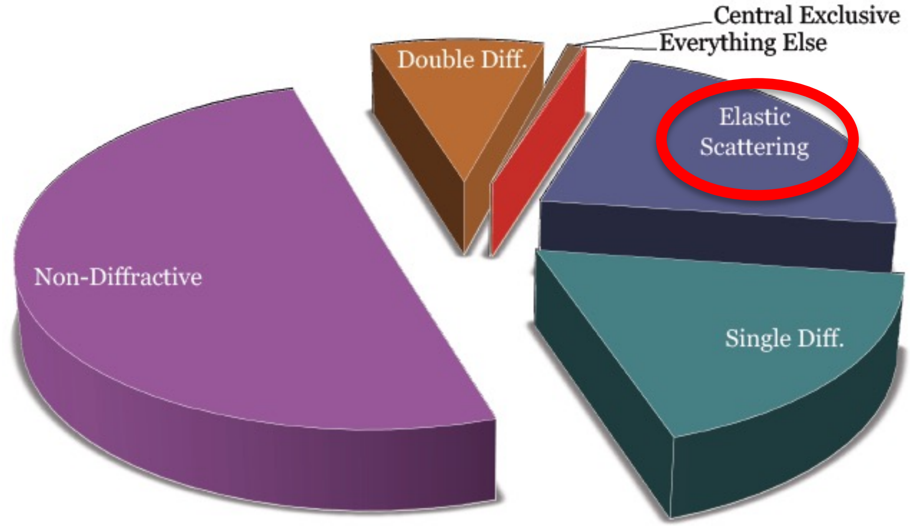
Start `Simple': Elastic Scattering

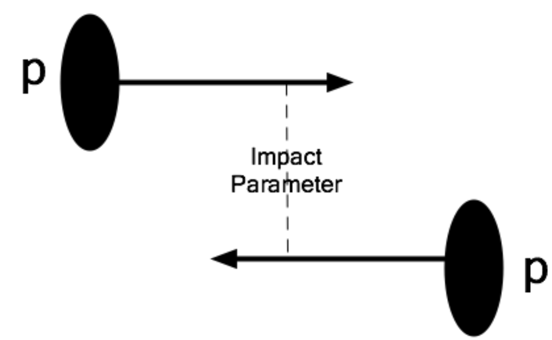




At fixed $\sqrt{s}$, 1 non-trivial variable
→ squared 4-momentum transfer, t

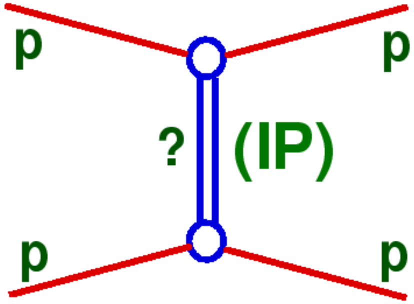
Typically |t| << 1 GeV^2: non-perturbative

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

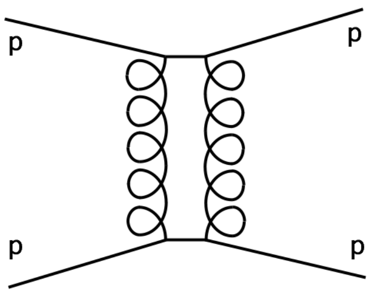


Slope parameter B measures mean impact parameter (~size of interaction region ~ range of strong force ~1-2fm).

Universal Exchange Picture of Elastic and Diffractive Scattering



- Regge asymptotics offers unified picture in terms of trajectory exchanges
- Soft `Pomeron' dominates for sufficiently large $\sqrt{s}$.
- Non-perturbative object, but in Perturbative limits, loosely interpreted as exchange of two gluons in net colour singlet state, and ultimately BFKL pomeron



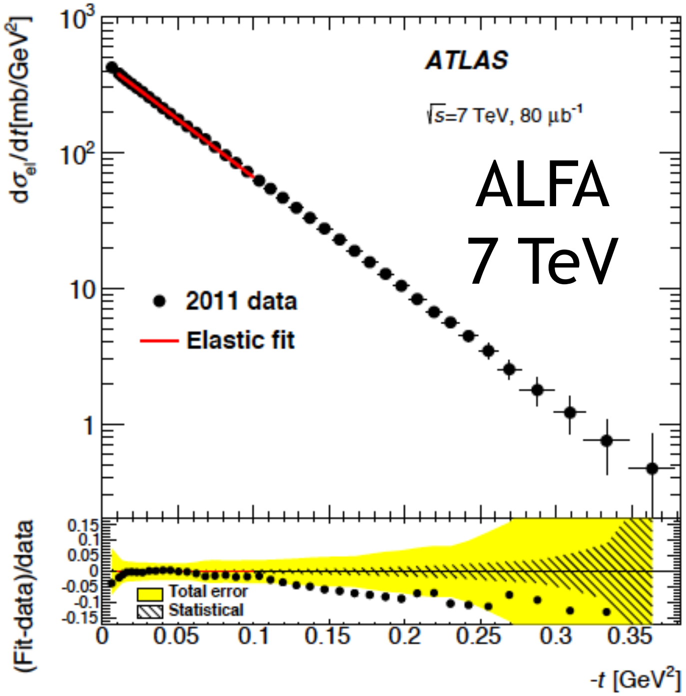
SOFT Pomeron trajectory: $\alpha(t) = \alpha(0) + \alpha' t \approx 1.085 + 0.25t$

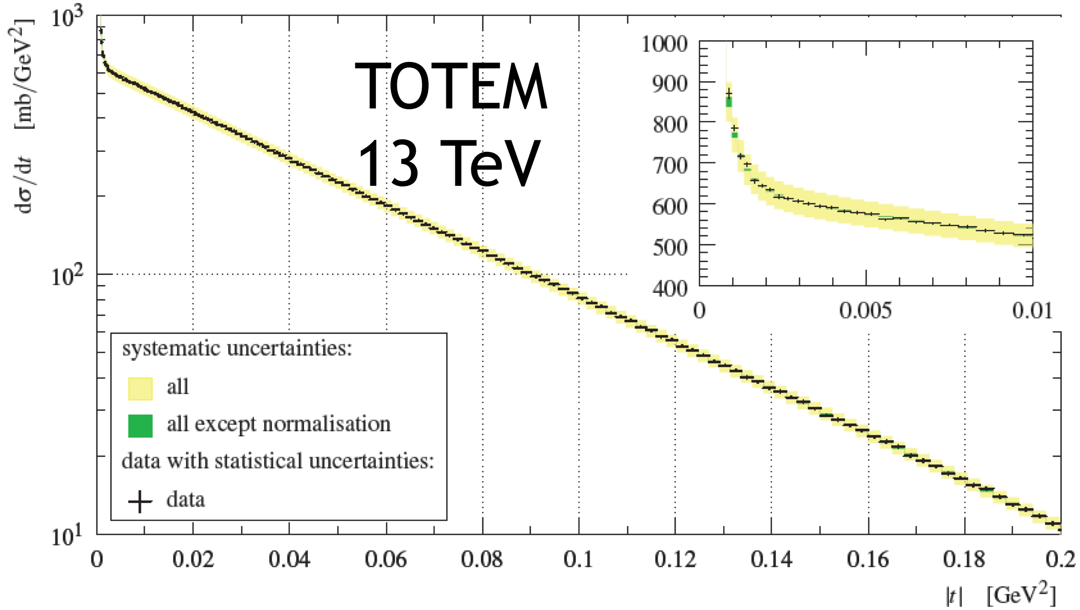
For <u>**elastic scattering**</u>: $$\frac{d\,\sigma_{EL}}{d\,t} = \left(\frac{s}{s_0}\right)^{2\alpha(t)-2} e^{Bt}$$

... Leads to slope parameter growing logarithmically with energy $$B = B_0 + 2\alpha' \ln\left(\frac{s}{s_0}\right)$$

Example Elastic Scattering Data

Precise t dependence over low |t| range at LHC …





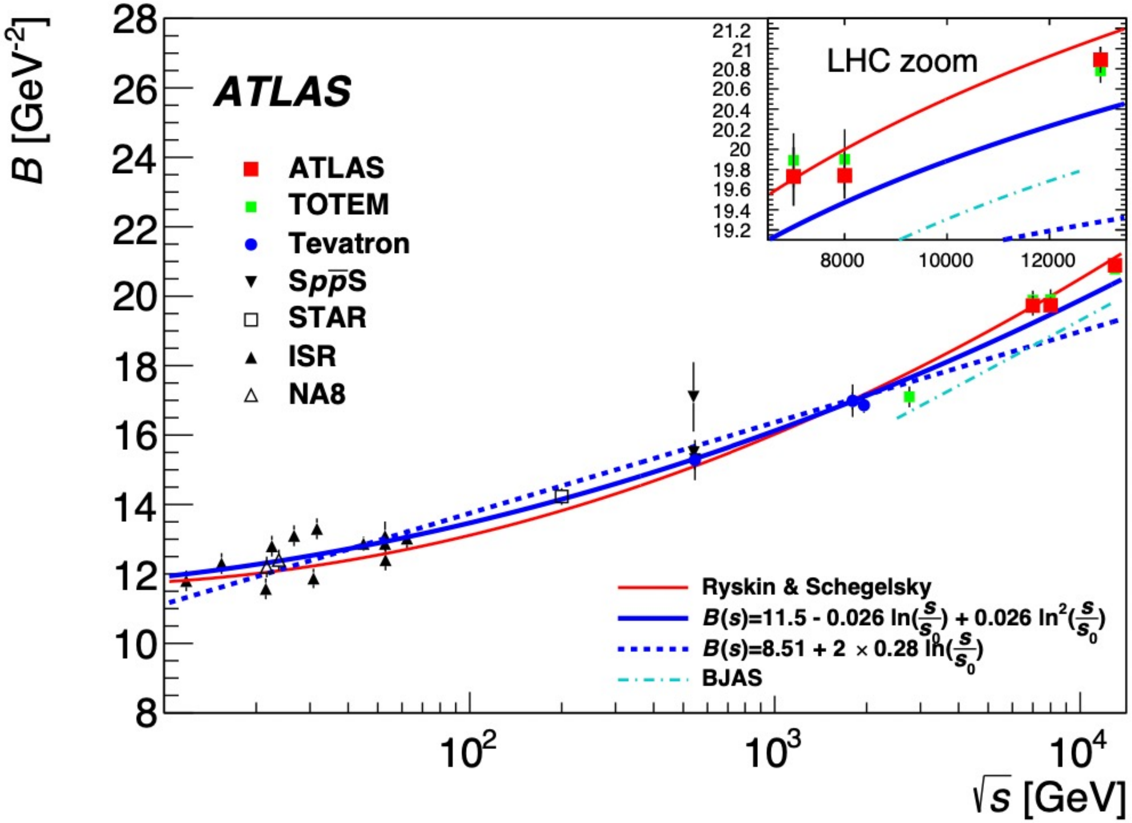
`Standard' exponential fit, excluding lowest |t| (influence of Coulomb scattering) and largest |t|(deviations, perhaps due to pQCD effects)

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

e.g. at √s=13 TeV … B=21.14 ± 0.2413 GeV^{-2} (ALFA)

√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

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

- ATLAS and TOTEM agree well

- Growth at LHC seems faster than `standard' α' ~ 0.25 GeV^{-2}
- Parameterisations with ln^2 term or more complex dependences better

… Single pomeron exchange insufficient (multi-IP / absorptive corrections)

From Elastic to Total Cross Sections

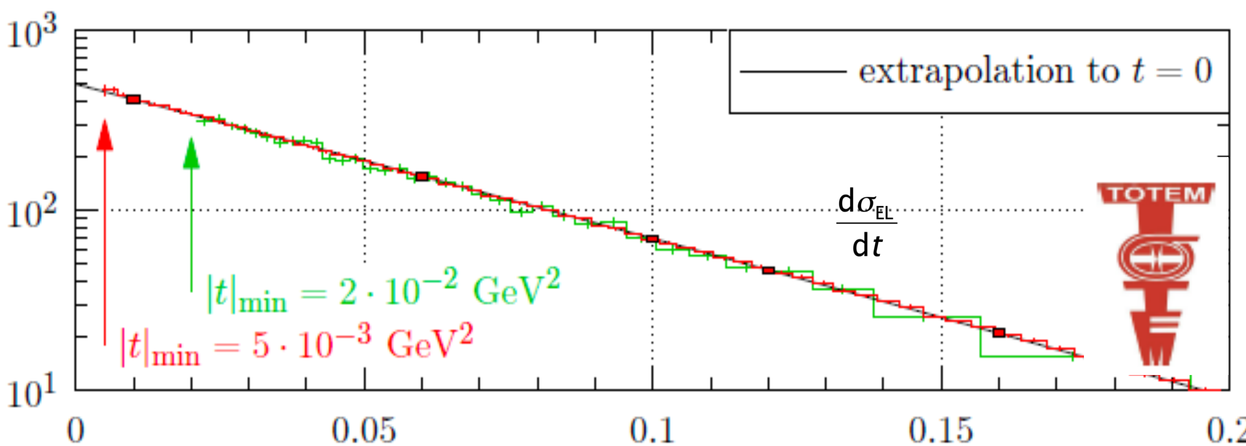
Elastic amplitude closely related to total x-sec via optical theorem …

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

[ρ ~ 0.1 = Real / Imaginary part of hadronic amplitude at t=0]

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

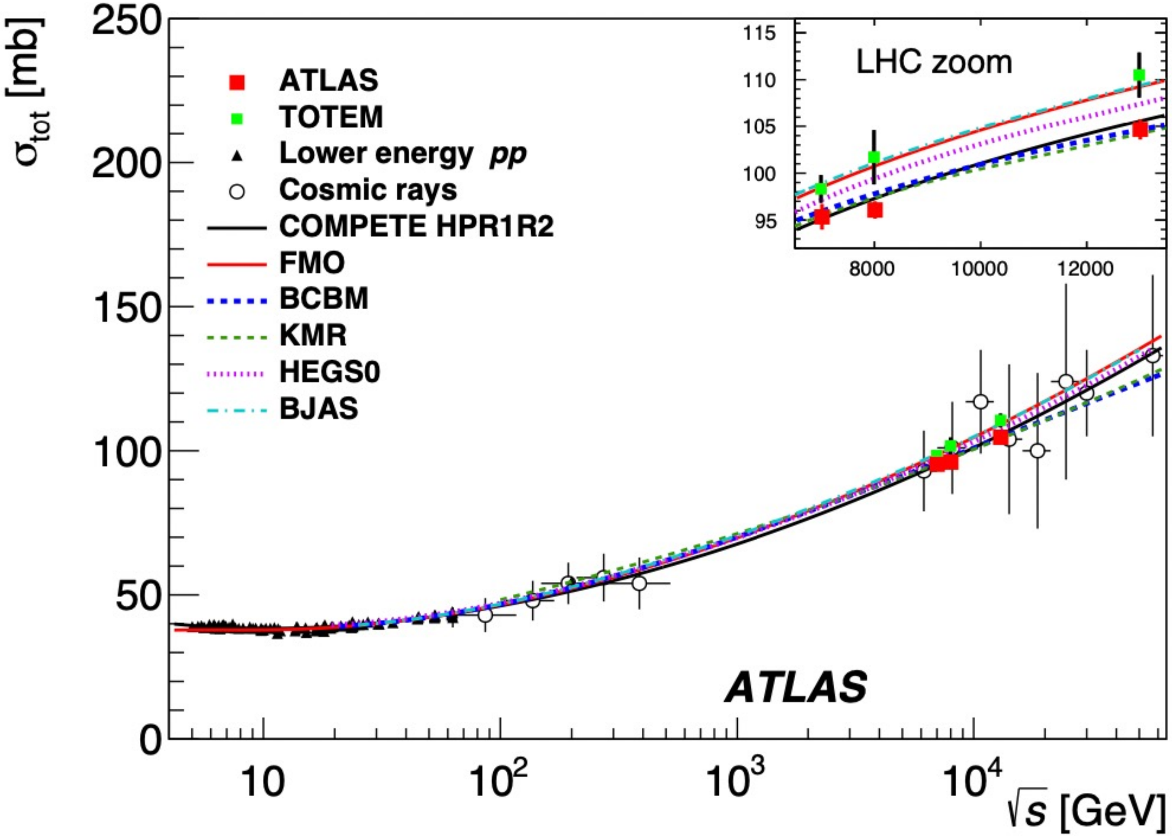
[But beware: Asymptotically (Froissart bound) limited to $\ln^2 s$ dependence]



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

More sophisticated treatment exploits Coulomb-Nuclear interference and fit full t range, simultaneously extracting σ_{tot} and ρ … see later

Total Cross Section versus √s



- Growth is slower than Regge pole power-law prediction.

- e.g. COMPETE prediction based on fits to lower energy data with multi-IP exchanges, leading to ln s and ln^2 s terms

- Systematic differences between ALFA and TOTEM arise from normalisations of elastic data.

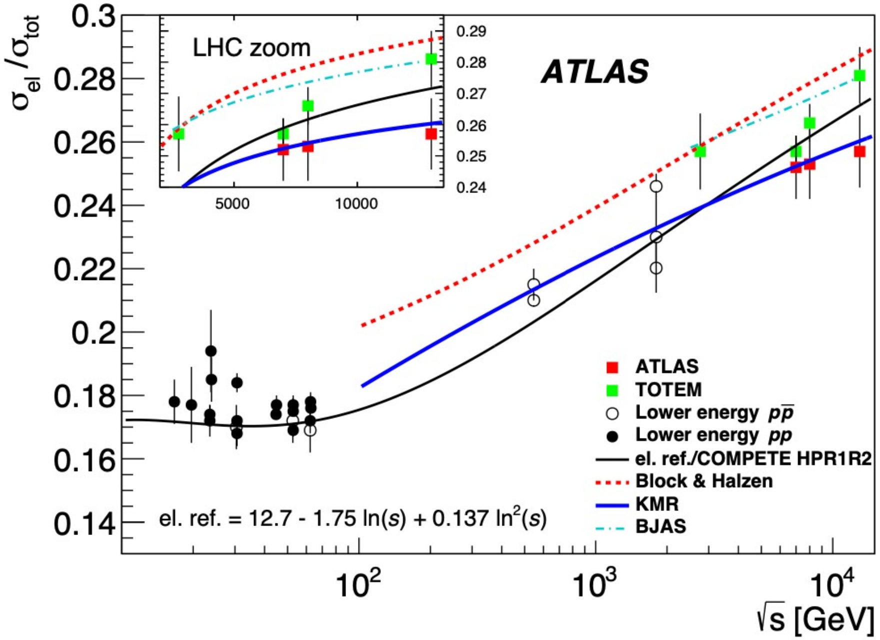
Cosmic ray data extend to 50 TeV!

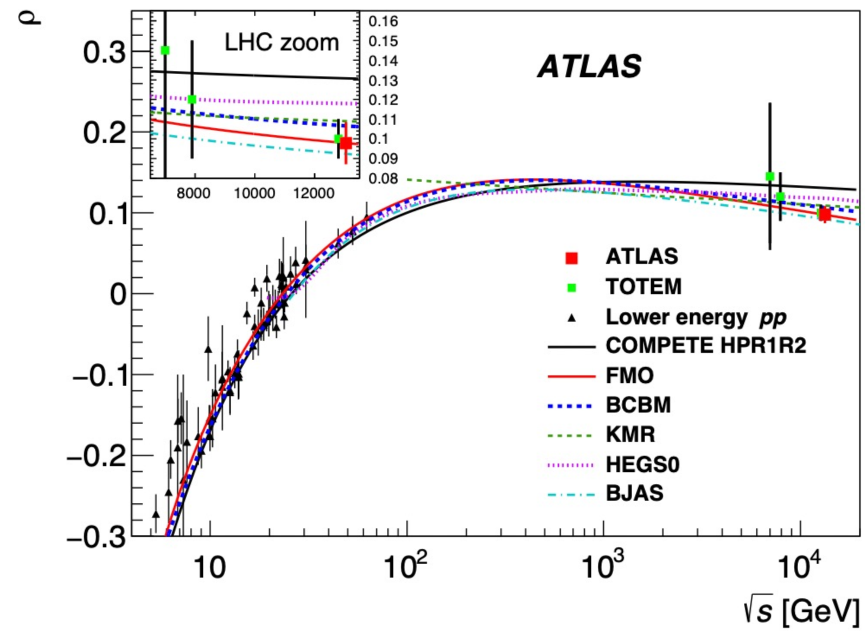
data	method	ρ	σ_{tot} [mb]
$\beta^* = 90$m	Ref. [6]	-	110.6 ± 3.4
$\beta^* = 2500$m	approach 1	0.09 ± 0.01	111.8 ± 3.2
	approach 2	0.09 ± 0.01	111.3 ± 3.2
	approach 3	$0.08(5) \pm 0.01$	110.3 ± 3.5
	approach 3 (single fit)	0.10 ± 0.01	109.3 ± 3.5
$\beta^* = 90$ and 2500m	Ref. [6] $\oplus$ approach 3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

[TOTEM 13 TeV]

c.f. ALFA 13 TeV: $\sigma_{tot} = 104.7 \pm 1.1$mb.

Some Low-x Implications of Elastics

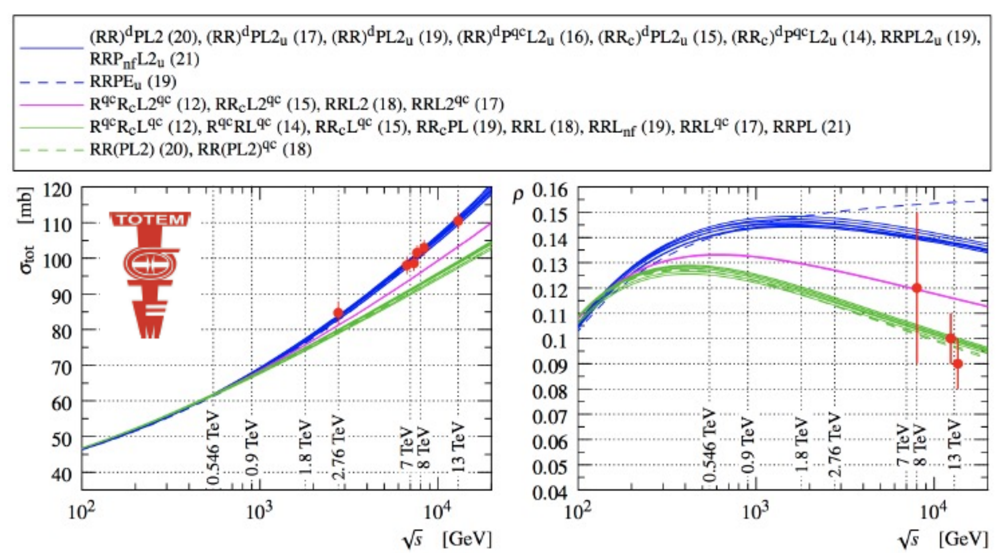




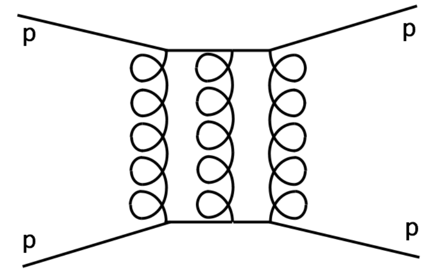
- Ratio of elastic to total cross section grows with $\sqrt{s}$ … related to low-x parton density growth
- Reaches ~0.26 at LHC.

c.f. Black disk limit is 0.5

- ρ parameter precisely extracted.
- TOTEM interpret failure of models to simultaneously describe ρ and σ_{tot} as evidence for C- odderon exchange

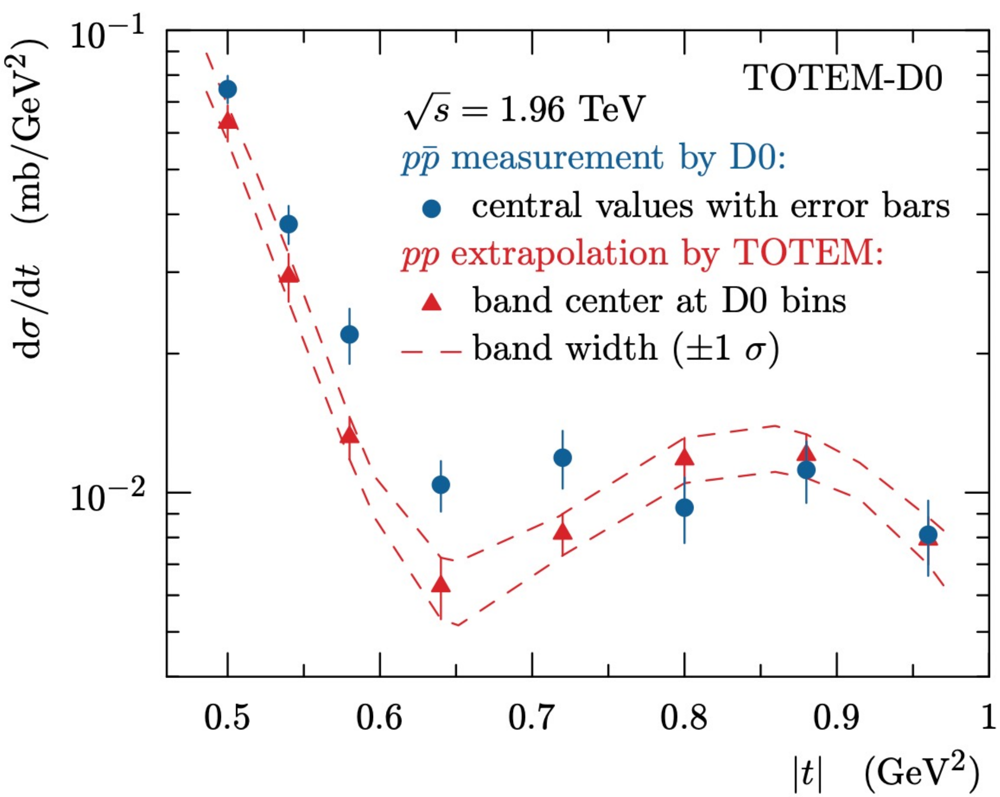


Odderons and pp versus ppbar



- CP-odd odderon exchange would contribute oppositely in pp (eg LHC) and ppbar (eg Tevatron) as $s \to \infty$.
→ smoking gun signature …

LHC (TOTEM) elastic scattering data extending to large |t| ('diffractive dip') extrapolated from 2.76 TeV v Tevatron (D0) at 1.96 TeV

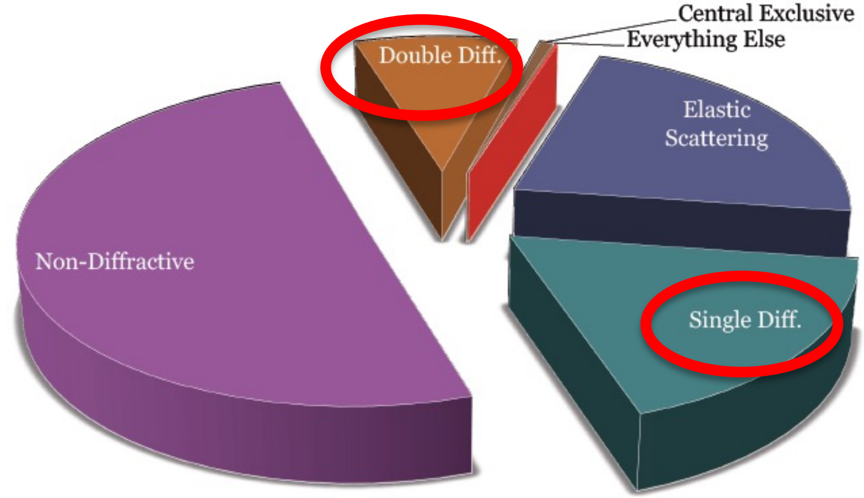


- Difference between pp and ppbar at >3σ level

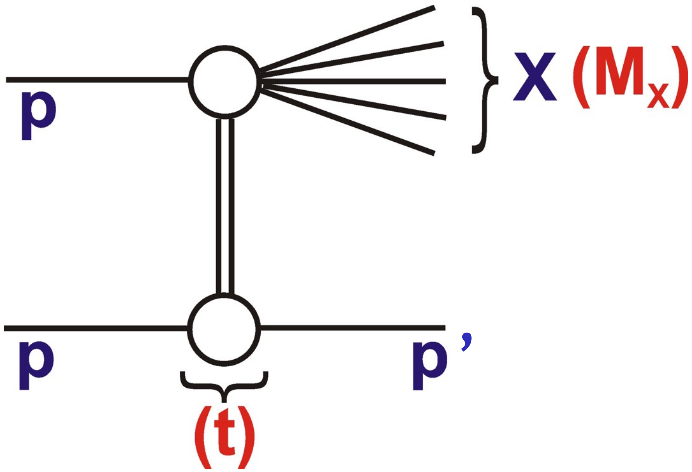
- Together with TOTEM σ_{tot} and ρ results (also > 3σ), presented as an Odderon discovery

- See Valery Khoze lectures for a full discussion

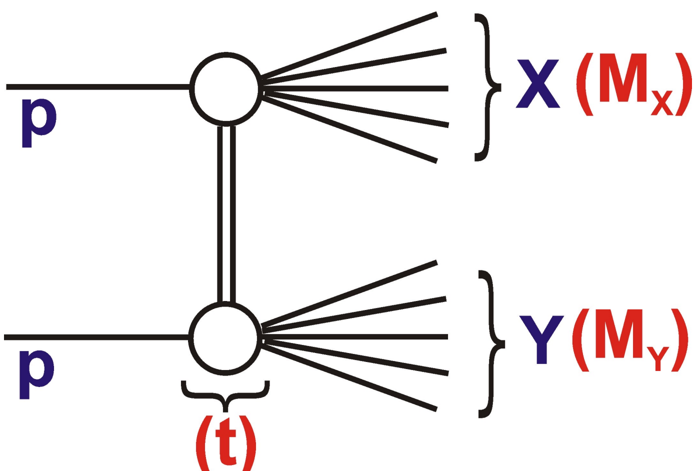
Inelastic Diffraction



Single diffractive dissociation



Double diffractive dissociation



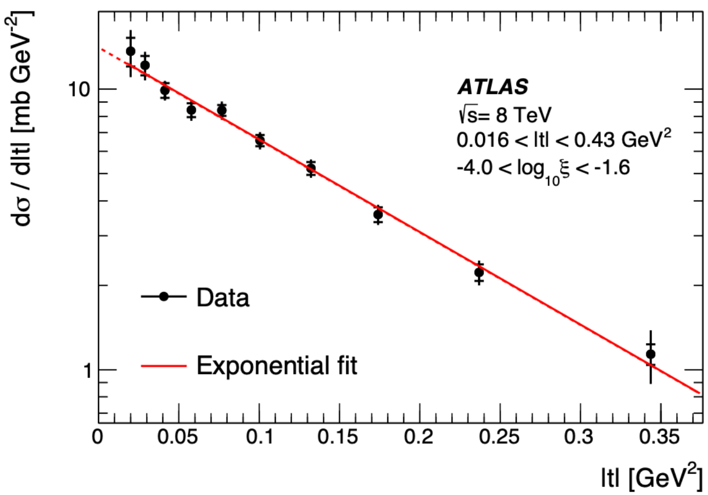
Additional kinematic variables:

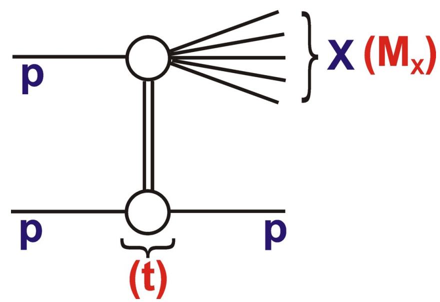
$$\xi = \frac{M_X^2}{s} = 1 - \frac{E_p'}{E_p}$$

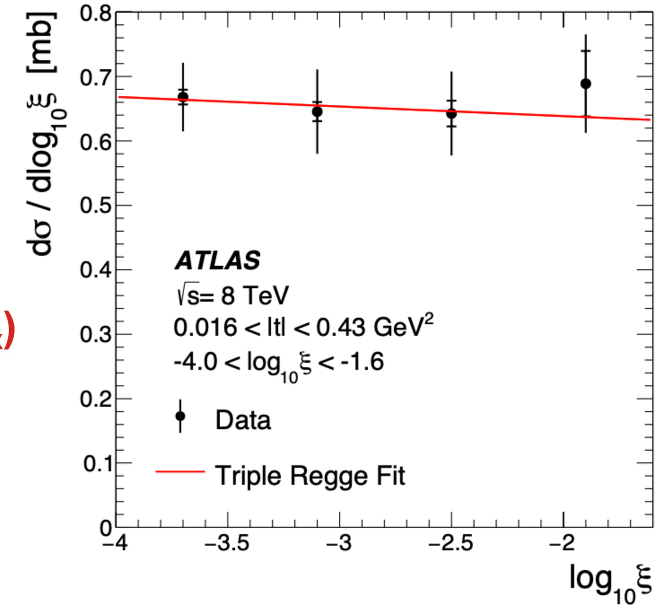
$$\xi_Y = \frac{M_Y^2}{s}$$

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

Proton-tagged Single Diffraction (ALFA)







- Only one published measurement [pp→pX with $\xi = M_X^2/s$]

- Interpreted in Regge theory ('Triple Regge') …
At fixed s, with the same universal pomeron as that describing elastic cross sections …

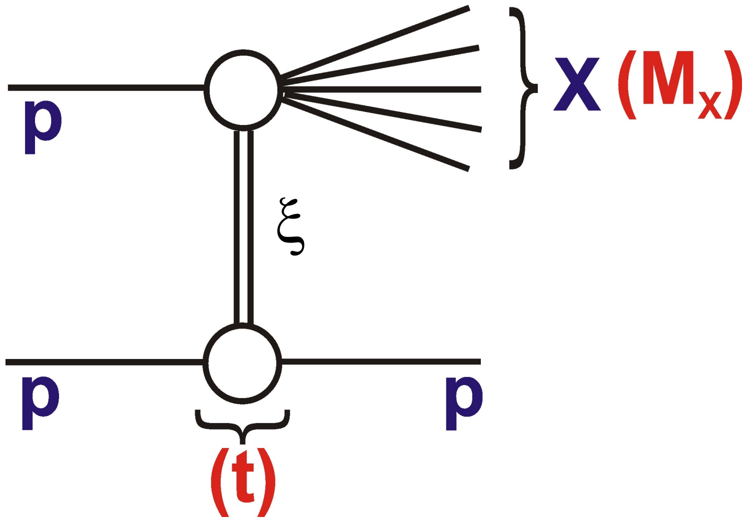
$$\frac{d\sigma}{d\xi\, dt} \propto \left(\frac{1}{\xi}\right)^{2\alpha(t)-\alpha(0)} e^{bt}$$

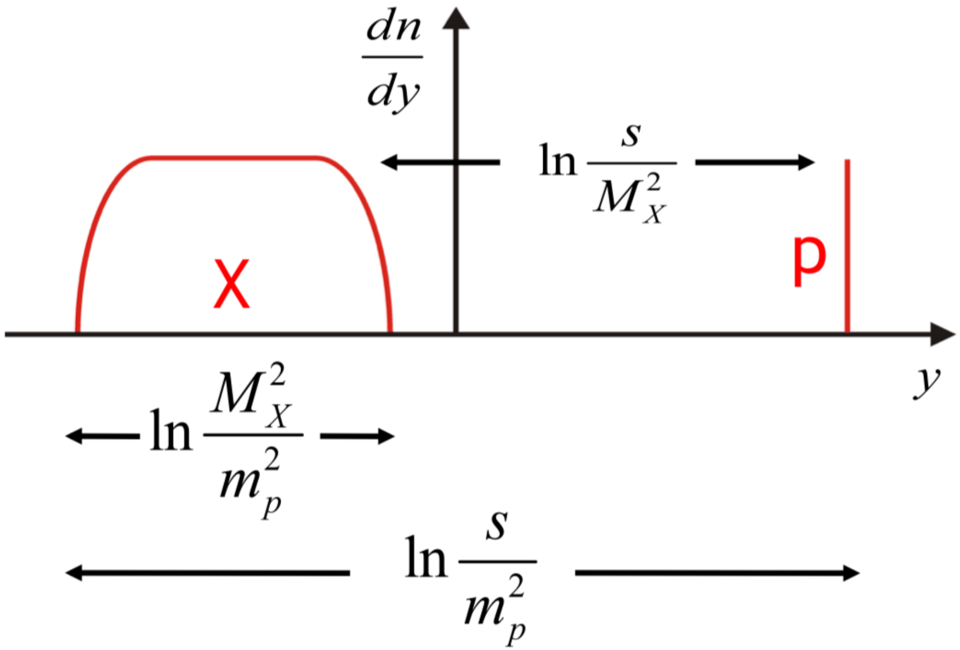
- Fitting the data yields consistent results with soft pomeron, but with large uncertainties

$$\alpha(0) = 1.07 \pm 0.02\ (\text{stat.}) \pm 0.06\ (\text{syst.}) \pm 0.06\ (\alpha')$$

$$B = 7.65 \pm 0.26(\text{stat.}) \pm 0.22(\text{syst.})\ \text{GeV}^{-2}$$

Diffractive Channels:
& Rapidity Gap Kinematics





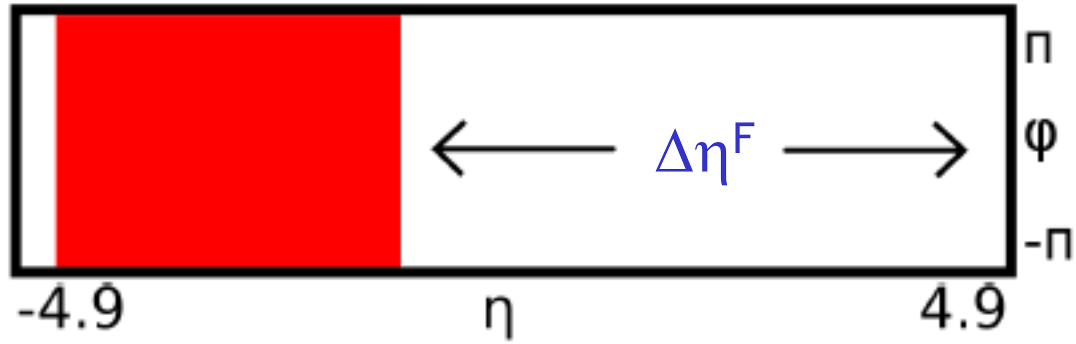
- $\xi = {M_X^2}/{s}$ is strongly correlated with $\Delta\eta \approx -\ln\xi$ empty rapidity regions

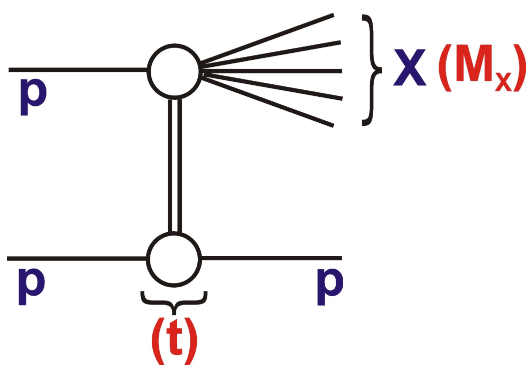
… exploited in SD measurements

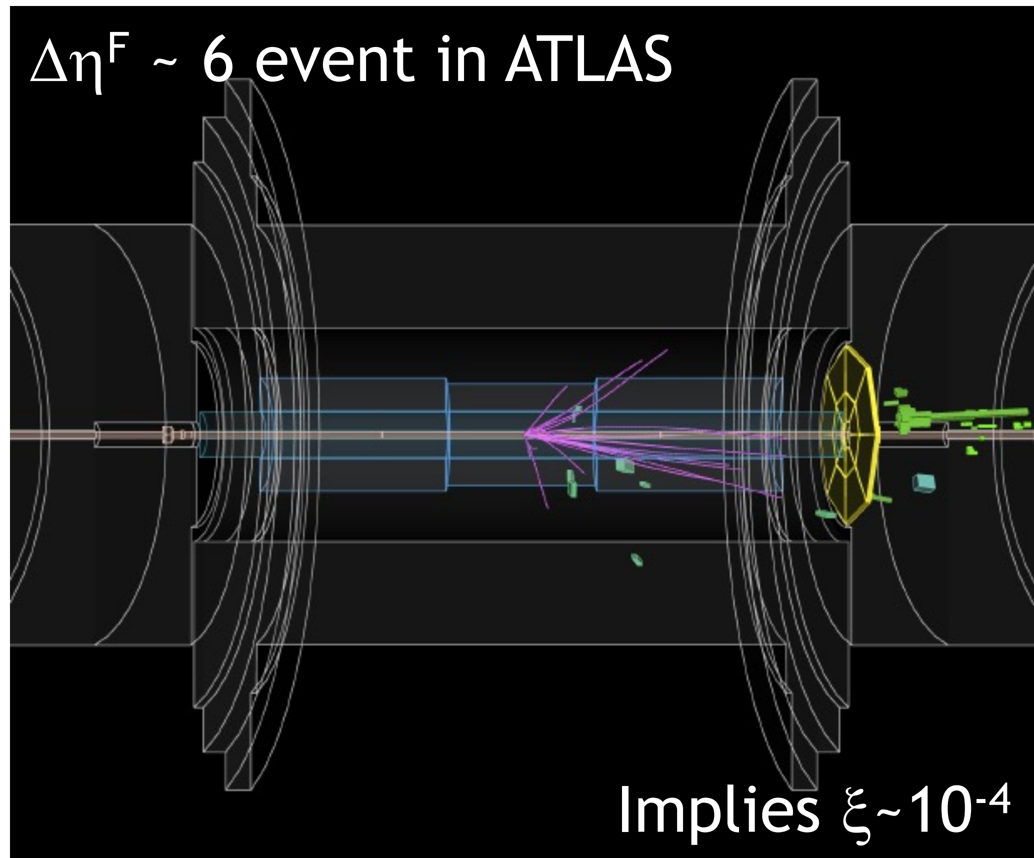
[Correlation limited by hadronisation fluctuations]

Rapidity gap cross-sections

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







… no statement on $|\eta| > 4.9$

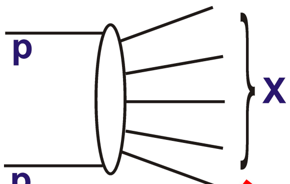
… large $\Delta\eta^F$ sensitive to SD + low M_Y DD

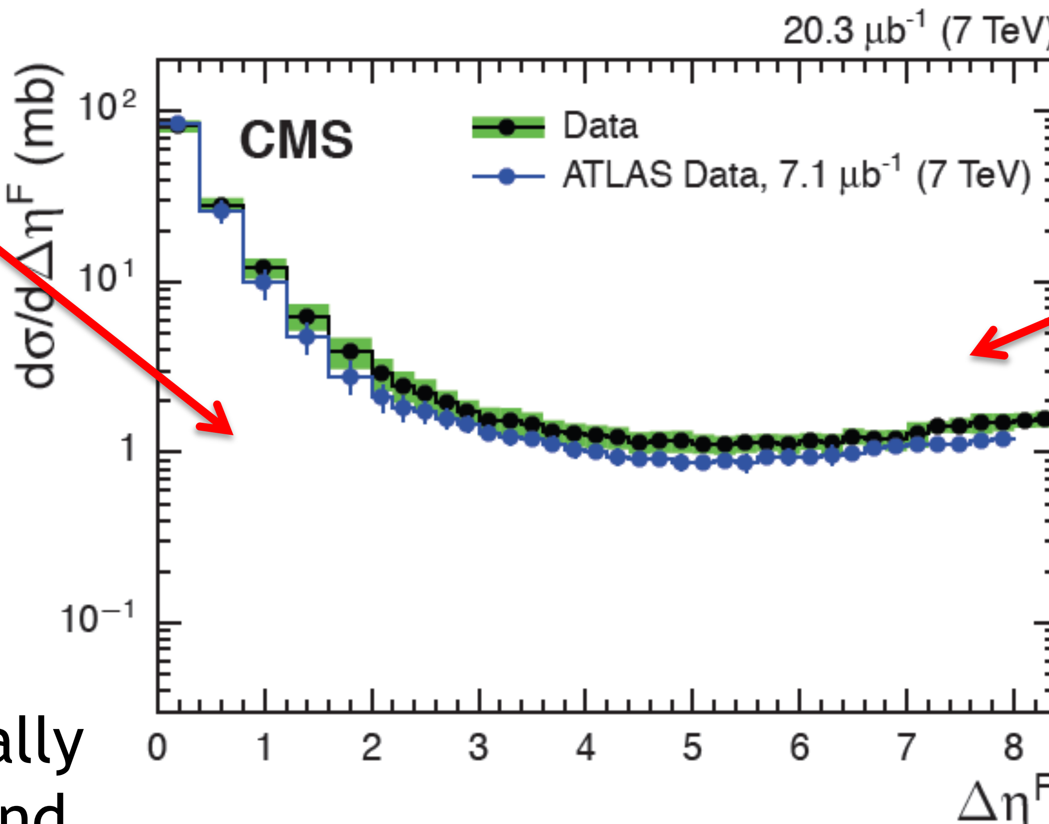
CMS and ATLAS Rapidity Gap Data

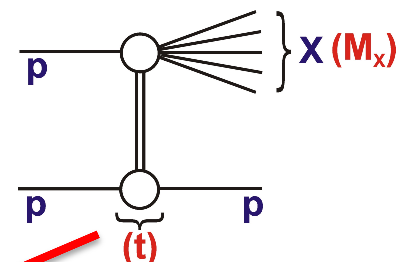
- Using very early LHC runs at 7 TeV (avoiding pile-up) …

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







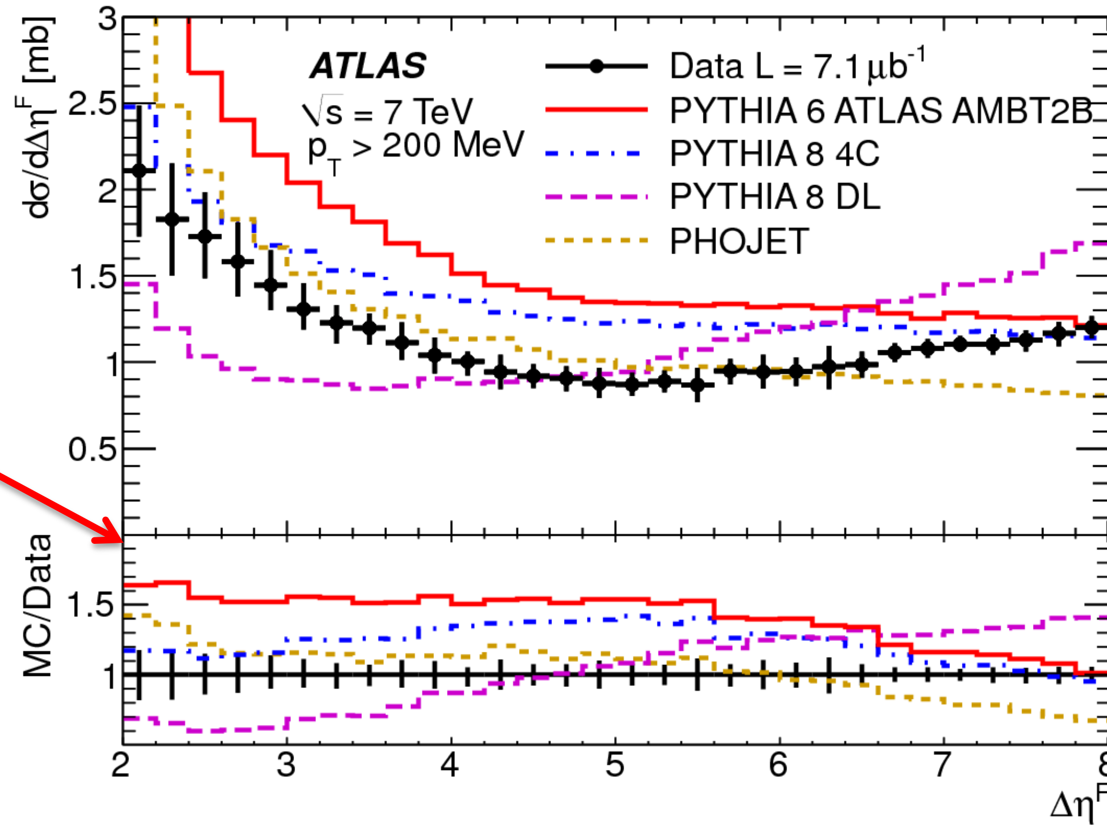
Small gaps dominated by non-diffractive processes … exponentially suppressed and sensitive to hadronisation fluctuations / underlying event

Large gaps dominated by diffractive processes … characteristic plateau

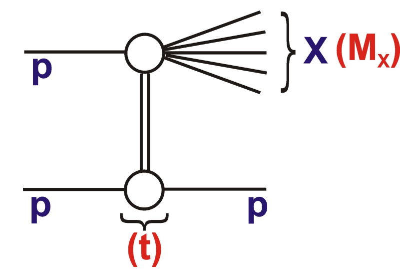
Roughly 1mb per unit gap size

Large Gap Region compared with Models

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



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



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

- Fit to large $\Delta\eta^F$ data using $\Delta\eta \sim -\ln\xi$ relation and $\frac{d\sigma}{d\xi\, dt} \propto \left(\frac{1}{\xi}\right)^{2\alpha(t)-\alpha(0)} e^{bt}$

  $\alpha_{IP}(0) = 1.058 \pm 0.003\ (\text{stat}) \pm 0.036\ (\text{syst})$

… still consistent with soft pomeron …

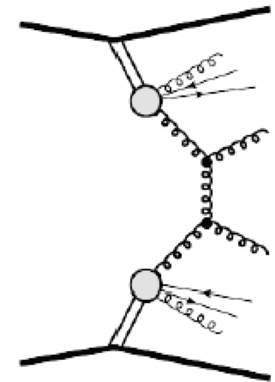
Current and Future Diffraction at LHC

- Most of the ongoing diffractive programme involves Roman Pot tagging in normal high luminosity running conditions

→ Studies with double proton tags (pp→ppX)

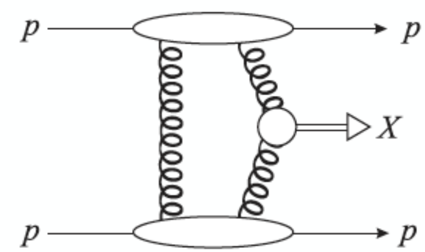
- **Inclusive central production**

pomeron-pomeron hard scattering with jets, HF, W, Z signatures



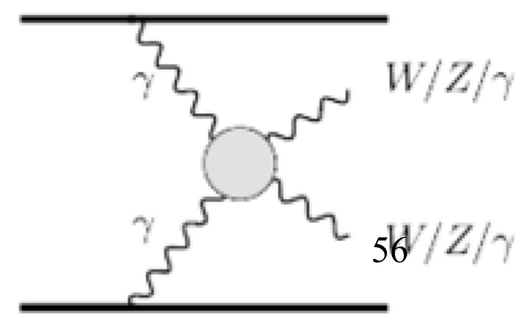
- **Central Exclusive QCD Production**

of dijets, γ-jet and other strongly produced high mass systems … Higgs?...

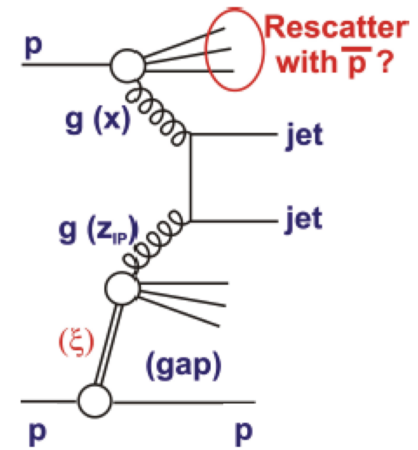


- **Two photon physics** → exclusive dileptons, dibosons & anomalous multiple gauge couplings …

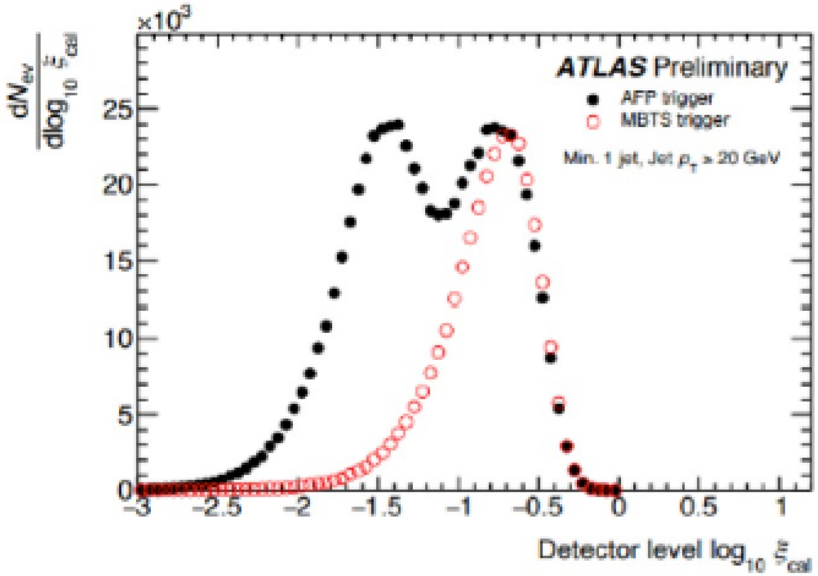
[Dominates at large masses]



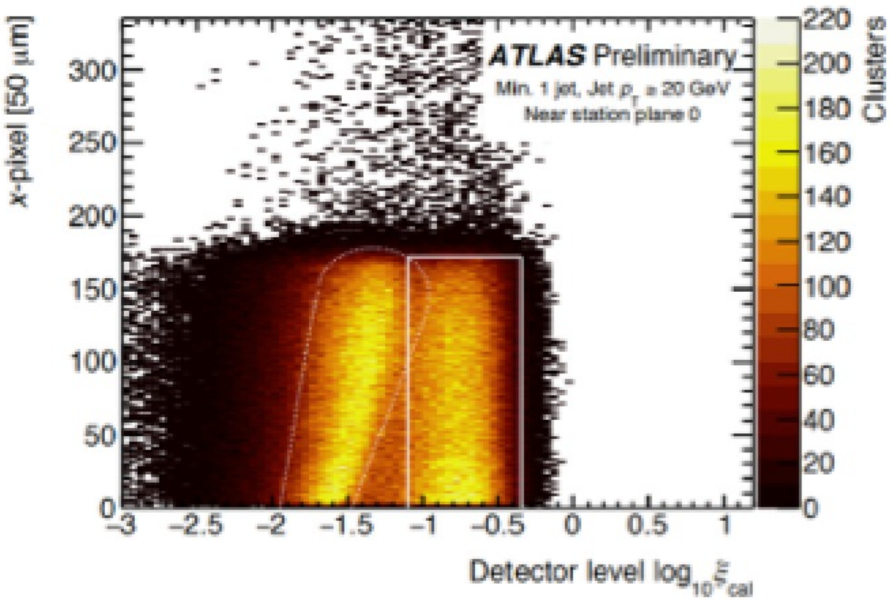
AFP Observation of Single Diffractive Dijet Signal



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



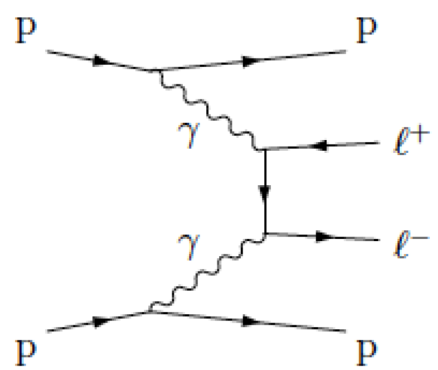
- Strong enhancement in low ξ_{Cal} diffractive region for AFP-triggered data over MBTS data + common pile-up contribution



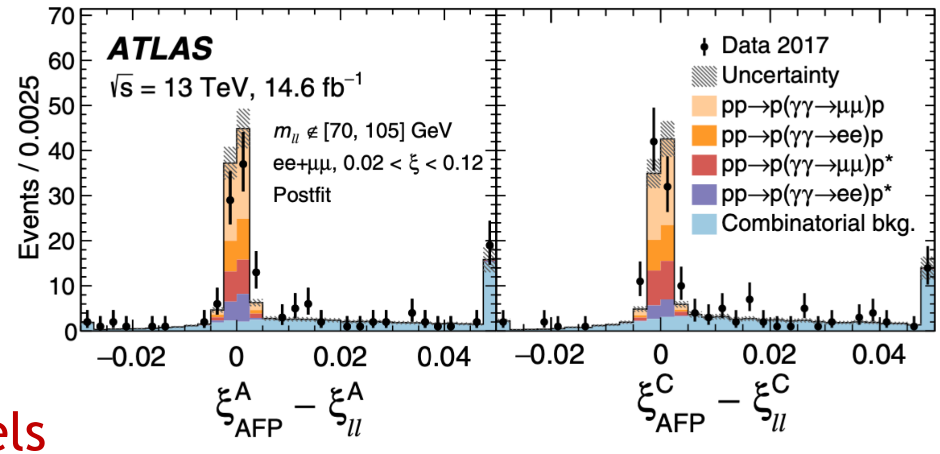
Low ξ data exhibit expected x-y correlation in AFP pixels and correlation between pixel x position and ξ_{Cal}

→ Clear diffractive signature

First Publications on γγ Process



Correlation between x measured
In Roman Pots v Central Detectors



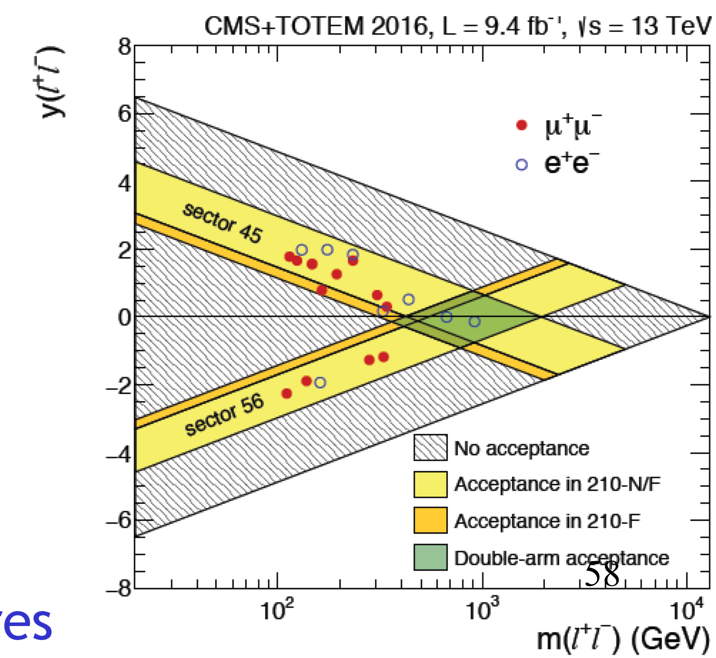
- 5σ observations by CMS-PPS and ATLAS-AFP in ee and μμ channels

- Dilepton masses → TeV scale

- First (ATLAS) cross-section measurements consistent with calculations

$\sigma_{\text{HERWIG+LPAIR}} \times S_{\text{surv}}$	$\sigma^{\text{fid.}}_{ee+p}$ (fb)	$\sigma^{\text{fid.}}_{\mu\mu+p}$ (fb)
$S_{\text{surv}} = 1$	15.5 ± 1.2	13.5 ± 1.1
S_{surv} using Refs. [33,34]	10.9 ± 0.8	9.4 ± 0.7
SUPERCHIC 4 [97]	12.2 ± 0.9	10.4 ± 0.7
Measurement	11.0 ± 2.9	7.2 ± 1.8

Di-lepton rapidity versus mass



→ See Valery and Christophe's lectures

Summary

- Bulk data at LHC is a laboratory for soft strong interactions
  - Rich phenomenology of non-diffractive processes, but hard to extract underlying dynamics
  - Gaps between jets provide some evidence for BFKL
  - Elastic and diffractive data broadly as expected from soft-Pomeron Regge predictions, but with need for multi-pomeron exchanges.
  - Not yet at black disk limit, but σ_{EL}/σ_{TOT} within factor ~2

Next Lecture

- Diffraction at the parton level → Diffractive DIS and Ultra-peripheral LHC Collisions

- Prospects with Future ep Colliders