Diffraction at TOTEM and CMS

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Colloquia INFN Firenze

Outlook

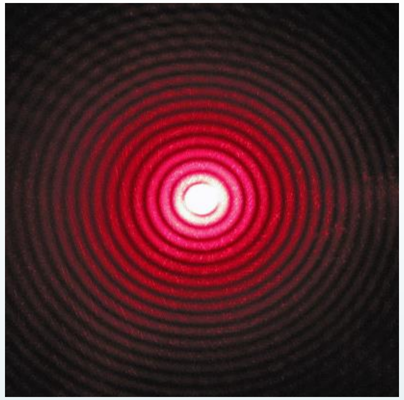
- What is diffraction at the LHC
- Why we study diffraction at the LHC
- How we measure diffraction in CMS/TOTEM
- How we can exploit diffraction
- Which results
- Future plans

Disclaimer: I don't mean to be exhaustive on any of the items above

Diffraction: from optics to HEP

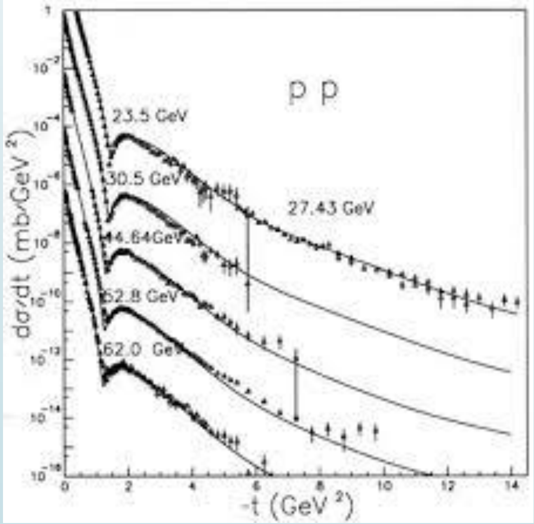
- Diffraction in optics occurs when a beam of light meets/hits an obstacle whose dimensions are comparable to its wavelength
- The intensity pattern of diffracted light is characterized by a sharp forward peak (+secondary maxima)

$$I(\theta) \sim I_0(1 - Bk^2\theta^2)$$



- In hadron scattering we may imagine that hadron interaction and propagation is given by the absorption of the wave functions caused by many inelastic channels open at high energy
- Actually some (diffractive) hadronic processes show similar behavior in the differential cross section

$$\frac{d\sigma}{dt} = \left.\frac{d\sigma}{dt}\right|_{t=0} e^{-B|t|} \sim \left.\frac{d\sigma}{dt}\right|_{t=0} (1\text{-}B|t|)$$



With $t = -2|p|^2(1-\cos\theta)$ (Mandelstam invariant)

Defining Diffraction in HEP

- An interaction in which no quantum numbers (but those of the vacuum) are exchanged

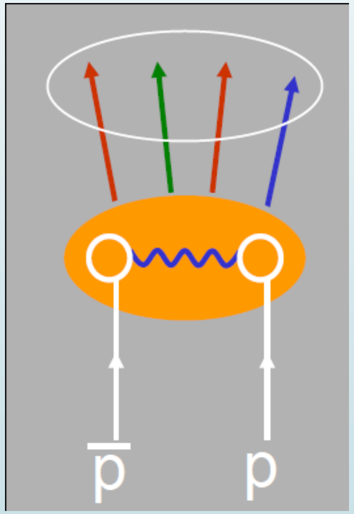
OR

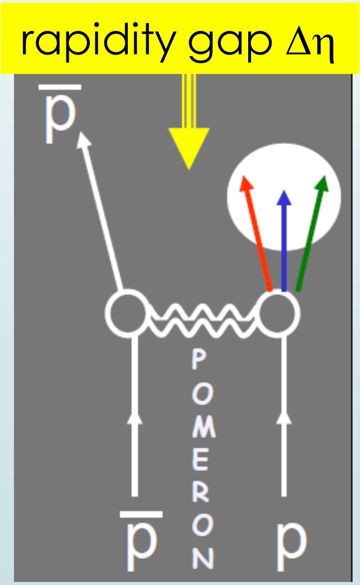
- An interaction characterized by a final state with non exponentially suppressed rapidity gaps

Non Diffractive processes

- color exchange
- gaps exponentially suppressed

$$\frac{d\sigma}{d\Delta\eta} \sim e^{-\Delta\eta}$$





Diffractive processes

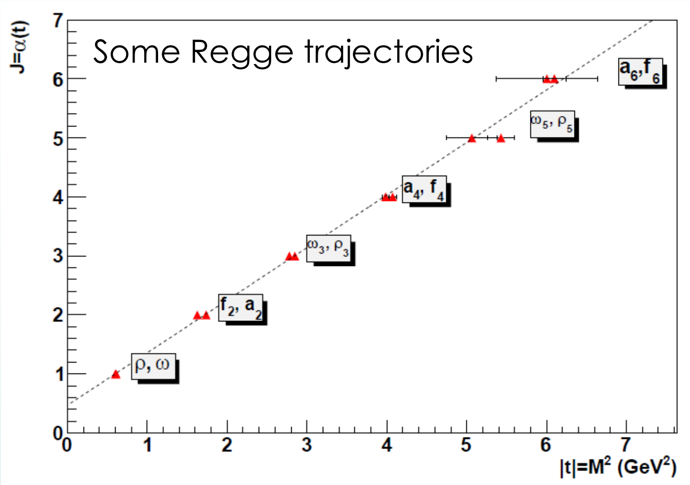
- colorless exchange
- large gap signature

$$\frac{d\sigma}{d\Delta\eta} \sim \text{const}$$

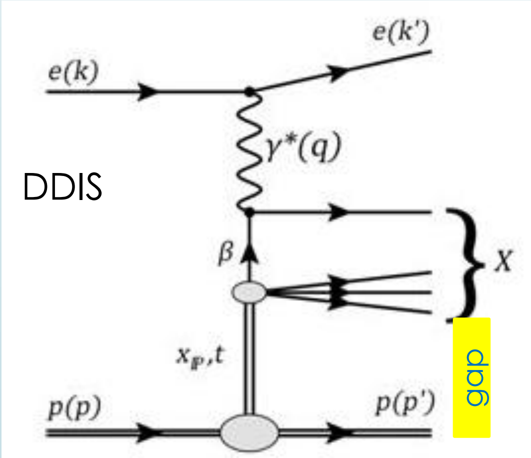
Pseudorapidity: $\eta = -\ln(\tan(\theta/2))$

Theoretical frame (just a sketch) – (1)

- Most of diffractive processes are soft processes, pQCD can't be used
- Historically diffraction is described by means of the Regge theory techniques
  - hadron-hadron interactions are described by the exchange of a whole set of particles usually referred to as a reggeon
  - The reggeon with the quantum numbers of the vacuum is called **Pomeron**



- Nevertheless diffraction can occur also in hard processes, as proved by HERA in DDIS (*diffractive deep inelastic scattering*) studies
  - This opened the doors to the interpretation of the Pomeron in QCD terms. The simplest **Pomeron** is seen as a **colorless couple of gluons**



Theoretical frame (just a sketch) – (2)

- The optical theorem that comes from the Unitarity of S matrix

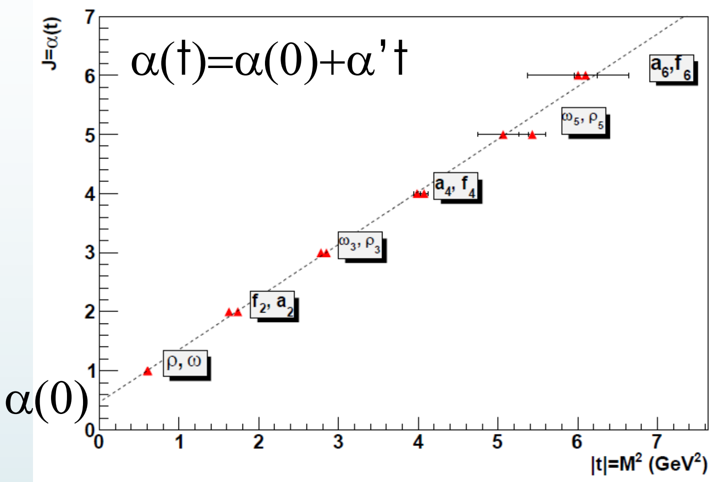
$$\sigma_{\text{tot}} = \frac{1}{s}\Im(A_{\text{el}}(t=0))$$

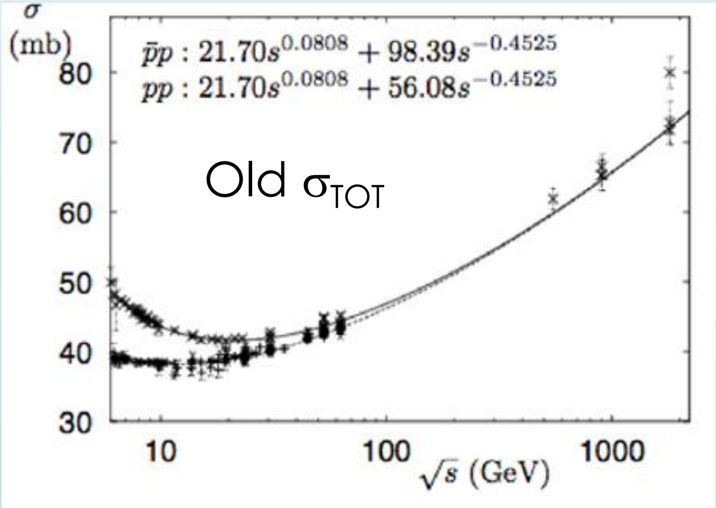
- In the Regge theory $\sigma_{\text{tot}} \sim \sum_i A_i s^{\alpha_i(0)-1}$

- Typically $\alpha(0)\sim0.5$. To account for a rising of σ_{TOT} with s a trajectory with $\alpha(0)>1$ is needed
- The Pomeron trajectory is introduced with $\alpha(0)_{\text{Pomeron}}>\sim1$ and only one "particle"
- The elastic scattering distribution is expected to show a broad exponential peak that shrinks with the energy

$$\frac{d\sigma_{\text{el}}}{dt} \sim s^{2\alpha(0)-2} e^{-2\alpha'|t|\ln s}$$

- The shrinkage is actually seen in data





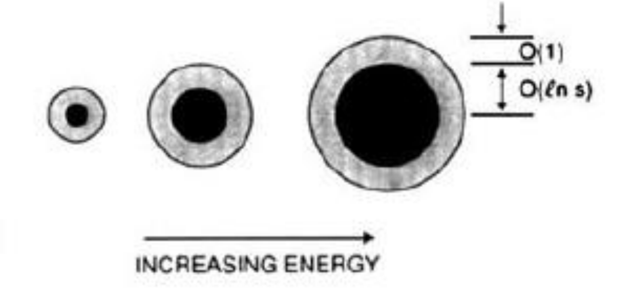
Theoretical frame (just a sketch) – (3)

- Regge theory was developed in the 60's
- Since then many models have been developed to better describe the experimental results
    - t-channel models, based on the Regge framework
    - s-channel models, based on the eikonal description

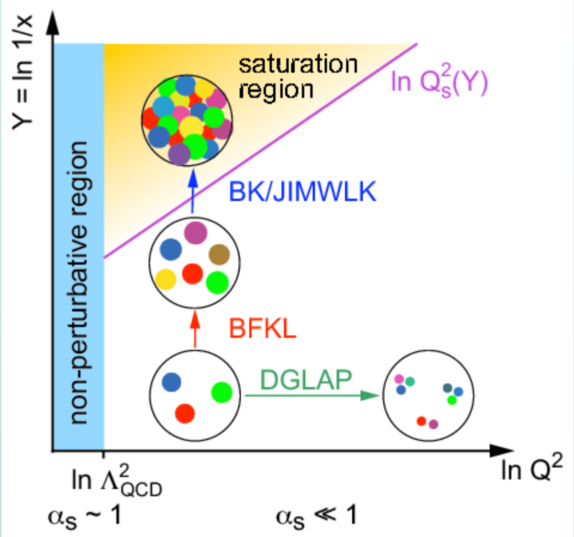
$$\sigma_{\mathrm{el}} = \int \mathrm{d}^2 b \, |\Gamma(s,b)|^2 = \int \mathrm{d}^2 b \, |1 - e^{-\Omega(s,b)}|^2,$$

$$\sigma_{\mathrm{tot}} = 2 \int \mathrm{d}^2 b \, \Re(\Gamma(s,b)) = \int \mathrm{d}^2 b \, \Re\left(1 - e^{-\Omega(s,b)}\right)$$

Impact picture model



    - QCD inspired models
- Pomeron in QCD
    - As a gluon ladder (DGLAP and BFKL)



Diffraction at HERA: DDIS – (1)

$$\frac{d^2\sigma}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left\{1 - y + \frac{y^2}{2[1+R(x,Q^2)]}\right\}F_2(x,Q^2)$$

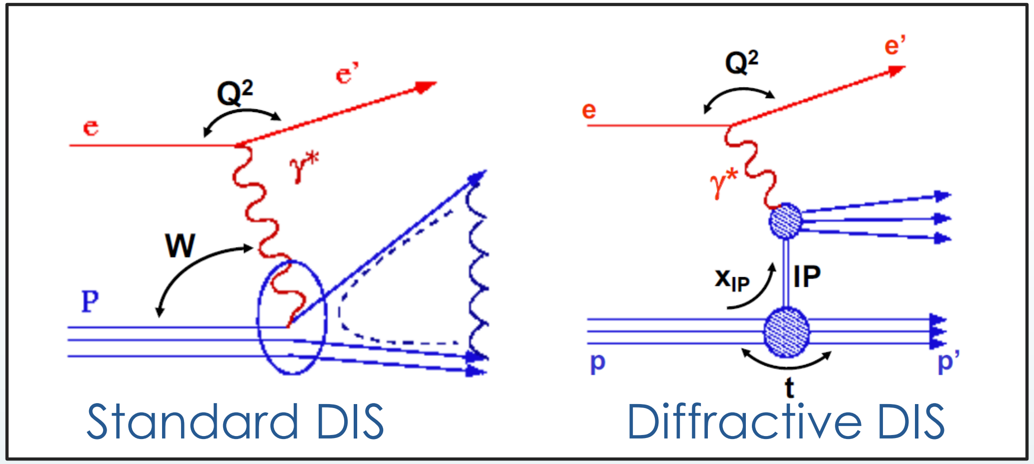
DIS probes the structure function F_2 of the proton

$$\frac{d^4\sigma}{d\beta dQ^2 dx_{IP} dt} = \frac{4\pi\alpha^2}{\beta Q^4}\left\{1 - y + \frac{y^2}{2(1+R^{D(4)})}\right\}F_2^{D(4)}(\beta,Q^2,x_{IP},t)$$

$$\downarrow$$

$$F_2^{D(4)} \approx f_{IP}(x_{IP},t)\, F_2^{IP}(\beta,Q^2)$$

DDIS probes the “structure function” F_2^P of the Pomeron



Standard DIS

Diffractive DIS

x=fraction of the proton momentum carried by the struck quark
x_P = fraction of proton momentum taken by the Pomeron
$\beta = x/x_P$

Comparing the structure functions of proton and Pomeron
- the Pomeron is not a “normal” hadron
- the Pomeron is mainly done of gluons

Diffraction at HERA: DDIS – (2)

Hard scattering factorization occurs both in DIS and in DDIS

$$F_2^D \sim f_{i/p}^D \otimes \widehat{\sigma}_i$$

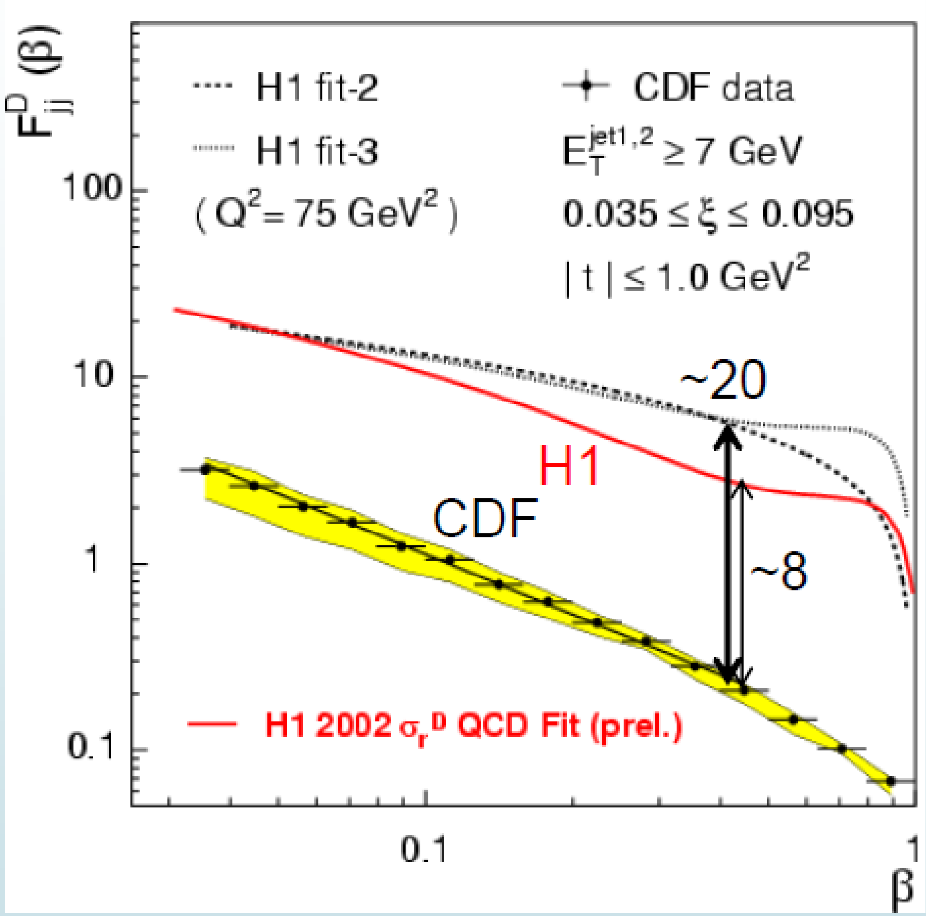
universal partonic cross section

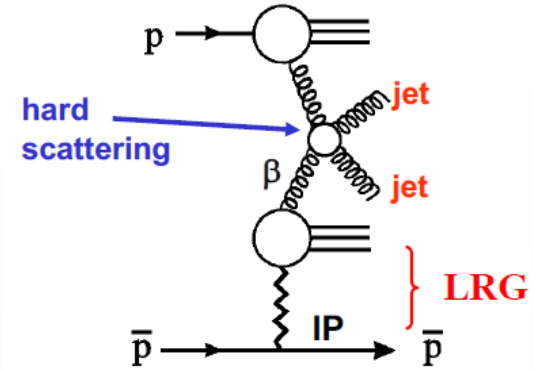
diffractive parton distribution function: evolves according to DGLAP

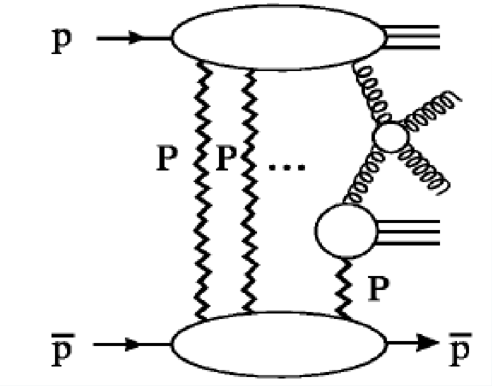
$f_{i/p}^D(z,Q^2,x_{IP},t)$: probability to find, with probe of resolution Q^2, in a proton, parton *i* with momentum fraction z, under the condition that proton remains intact, and emerges with small energy loss, x_{IP} and momentum transfer *t* – diffractive PDFs are a feature of the proton

- DPDFs can be seen as a new type of PDFs which apply when the vacuum quantum numbers are exchanged
- **Hard scattering factorization has been seen at HERA in diffractive DIS** (studying e.g. dijets events)

From HERA to Tevatron: factorization breaking





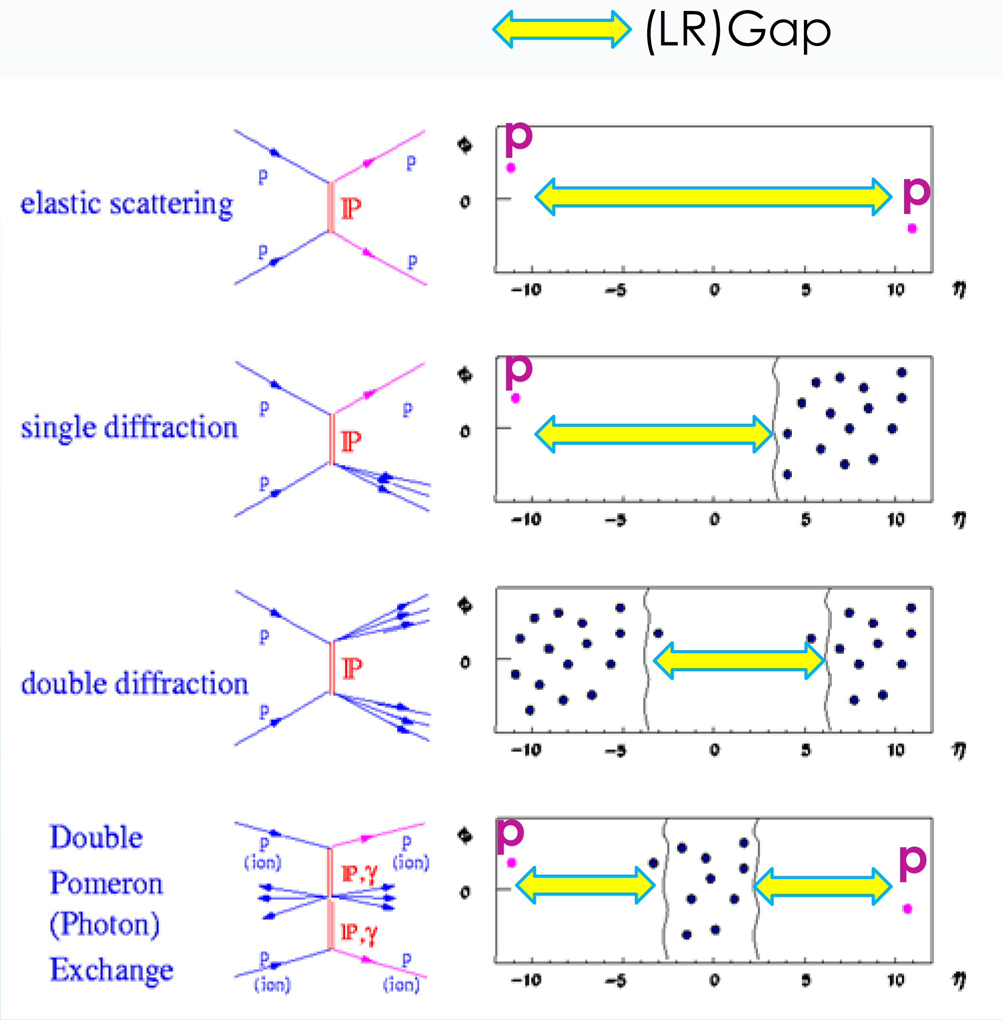


- All hard-diffraction processes at Tevatron Run 1 at $\sqrt{s}$=1.8TeV are **suppressed by a factor ~8** wrt the predictions based on HERA PDFs
- Violation of factorisation understood in terms of (soft) **rescattering corrections** of the spectator partons (MPI)
- MPI lower the probability of the rapidity gap to form. A **rapidity gap survival probability S^2** can be introduced
- **S^2 at the LHC?** S^2 ~5% in most models but, anyway, S^2 is difficult to predict and difficult to measure…

Why studying diffraction at the LHC

- In proton-proton scattering at the LHC energies ~40% of the total cross section is made of diffractive processes
- Elastic scattering and soft diffractive processes can shed new light on the soft hadron-hadron interactions
- Performing SM precision measurements and searching for new physics require a deep understanding of the Underlying Event
- Hard diffraction provides an important test of QCD and probes the low-x structure of the proton
- Low-x → high gluon density → saturation
- Central exclusive production (CEP) $pp \to pXp$ is a powerful “tool” to study rare processes because of the kinematics and quantum number constraints
- Total and elastic cross sections, forward multiplicity and energy flow can help understanding the development of air-showers in Cosmic Ray physics

Diffractive processes at the LHC



σ approx.

- ~30 mb
- ~10 mb
- ~5 mb
- ~0.5 mb

Diffractive cross sections account for ~**40-45%** of the total proton-proton cross section at the LHC energies.

Large rapidity gaps are present.

At least one interacting **proton survives** in most of the diffractive processes.

Experimental keys to diffraction:

- **measuring gaps**
- **detect forward protons**

How to measure diffraction with CMS and TOTEM

- CMS and TOTEM share the same interaction point at the LHC
- CMS coverage: $|\eta| < \sim 5$ with calorimeters ($|\eta| < \sim 2.5$ also with tracker)
- TOTEM coverage $\sim 3 < |\eta| < \sim 6.5$ with trackers + forward proton detectors ($|\eta| \sim 10$)
- **CMS+TOTEM = an almost 4π acceptance detector**

But CMS and TOTEM are two different collaborations…

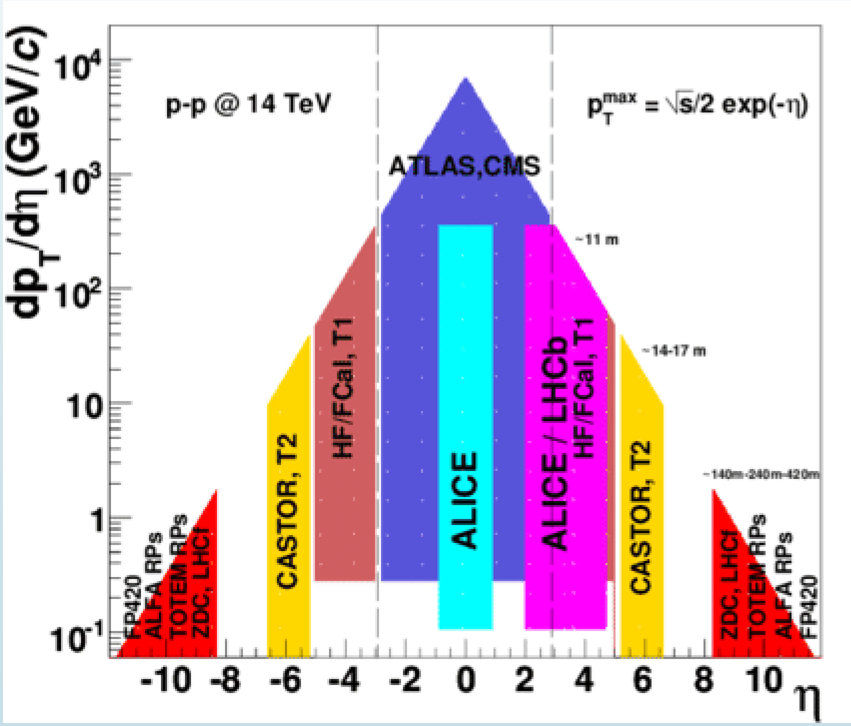
- **CMS** measured diffraction with **LRG strategy**
- **TOTEM** measured diffraction with proton taggers and forward trackers in special **low luminosity** runs

Then

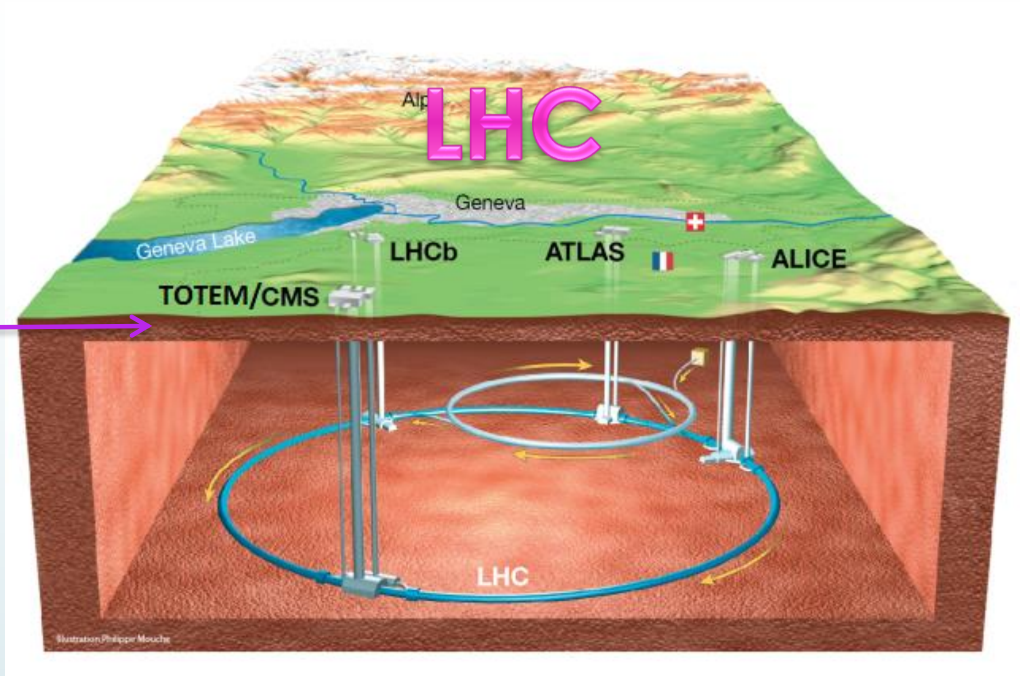
- CMS and TOTEM made common measurements in low luminosity runs (merging data a posteriori)

Finally

- CMS and TOTEM merged efforts and built a **Precision Proton Spectrometer** (**CT-PPS**) to measure the protons also in **high luminosity runs** with common DAQ



The experimental apparatus

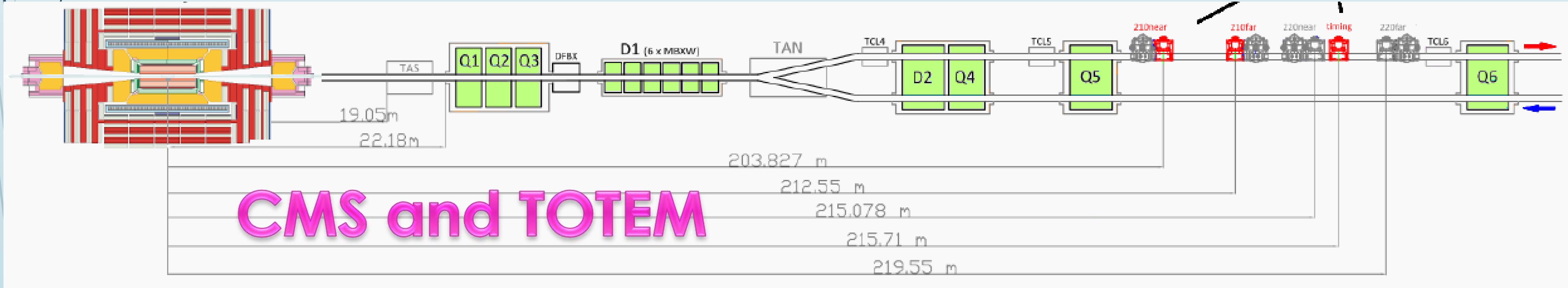


The operating conditions of the LHC (running scenarios) are of the utmost importance for diffraction studies

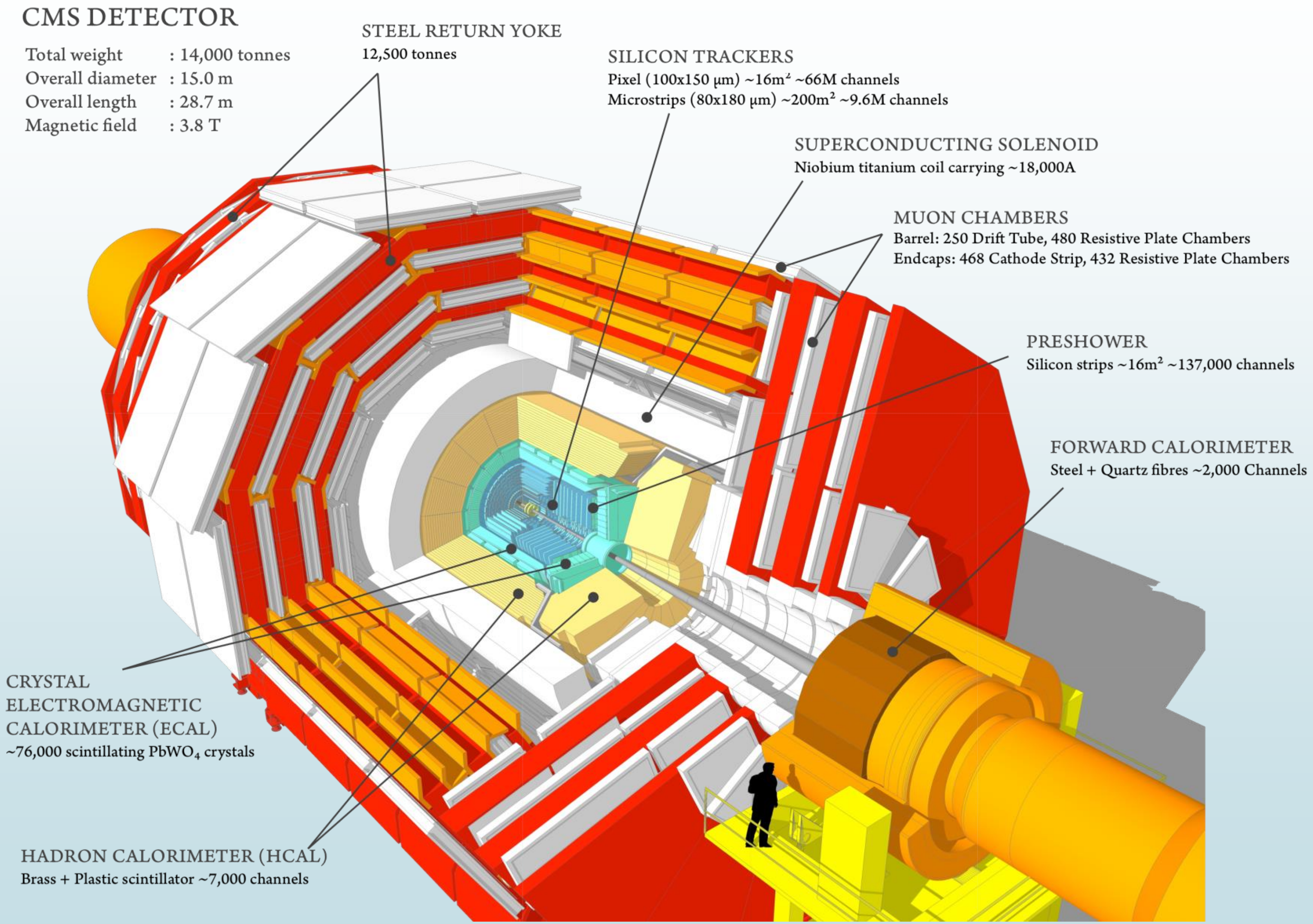
CMS and TOTEM experiments share the Interaction Point 5 at the LHC

Central Detector

Roman Pots



The CMS central detectors



CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
Silicon strips ~16m² ~137,000 channels

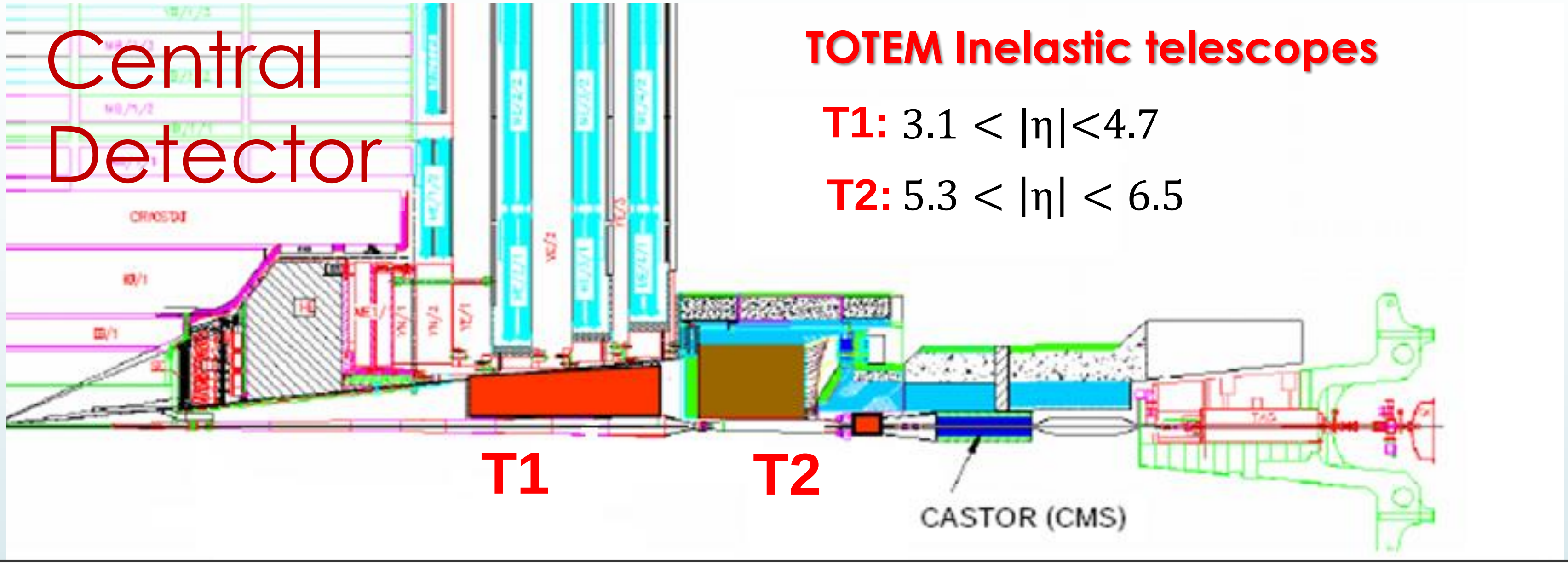
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

TOTEM and CMS Very Forward Detectors

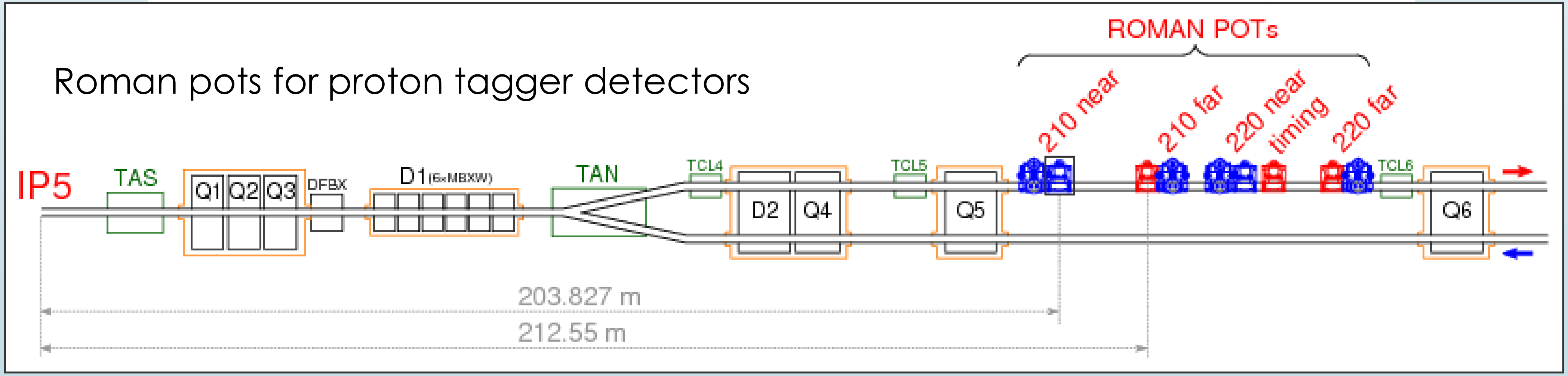
- TOTEM inelastic telescopes and CMS/TOTEM proton tagging detectors



TOTEM Inelastic telescopes

T1: $3.1 < |\eta| < 4.7$

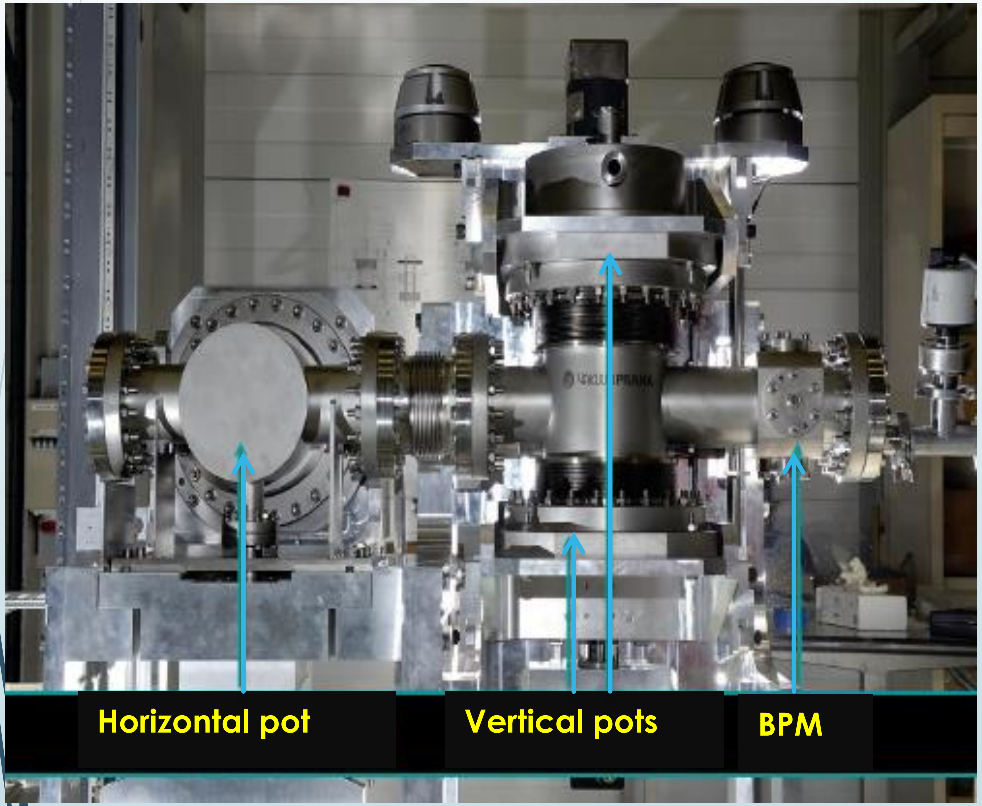
T2: $5.3 < |\eta| < 6.5$



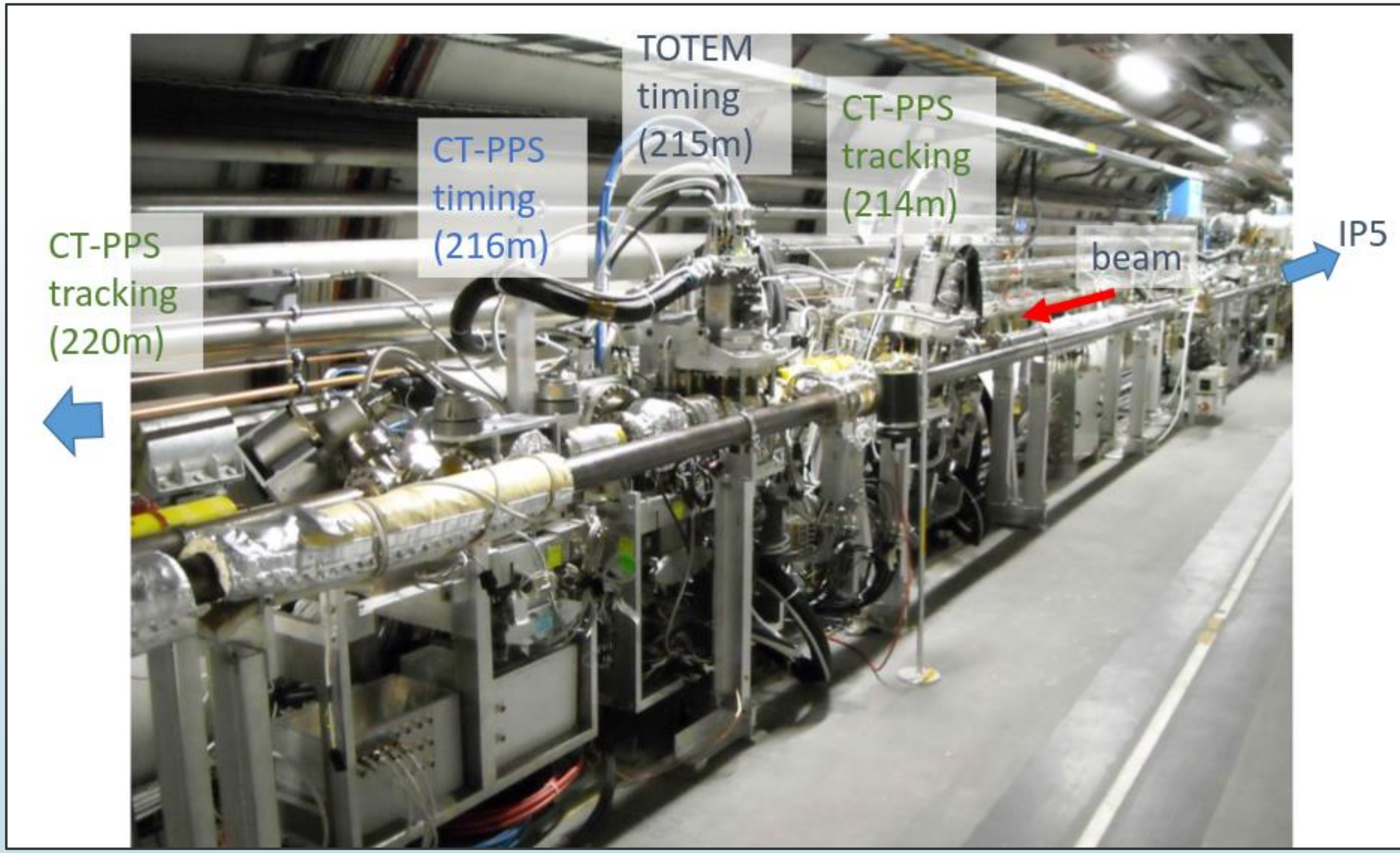
Roman pots for proton tagger detectors

The Roman Pot devices

A RP station



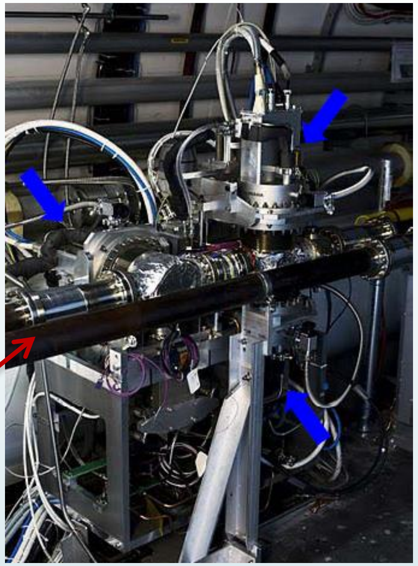
Layout inside the LHC tunnel

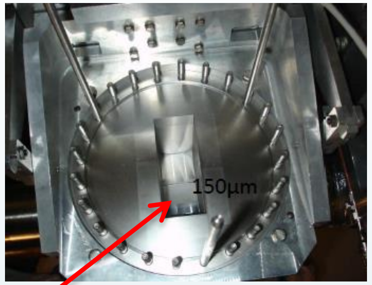


Roman Pots: detectors near the beam

Roman Pot unit
with
motor system
(step size: 5 µm)

LHC beam-pipe

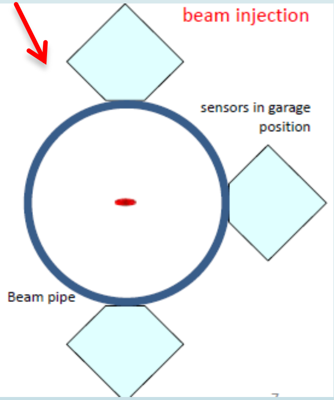




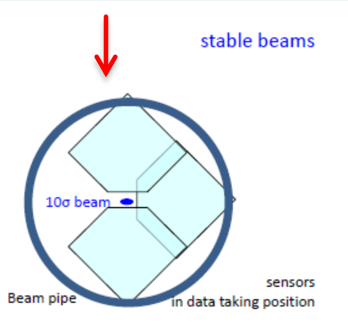
Separation
of high LHC vacuum
from detector vacuum

Secondary vacuum ~ 20mbar
Temp : -25 ^{0}C

Roman Pot
parking position



Roman Pot
data taking position



Typical beam size:
540 µm / 850 µm in low lumi
~100 µm in high lumi

Different detector configurations

Low luminosity runs

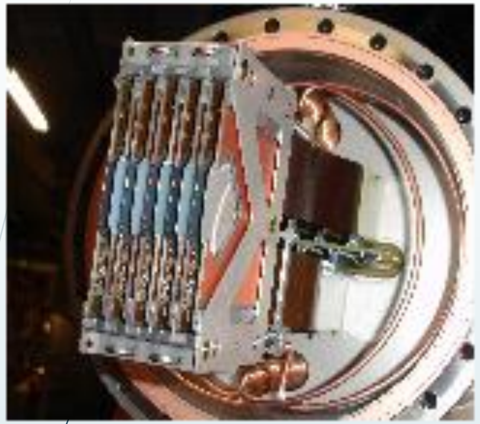
- Si strips in vertical (elastic scattering)
- Si strips in horizontal (alignment)

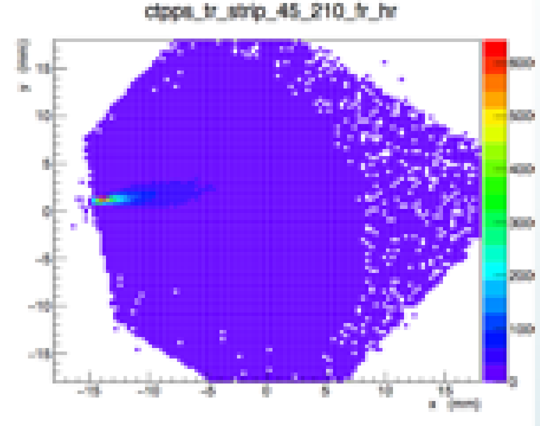
High luminosity runs

- Si strips in vertical (alignment)
- 3D pixels in horizontal (diffraction)
- Timing dets in horizontal (diffraction)

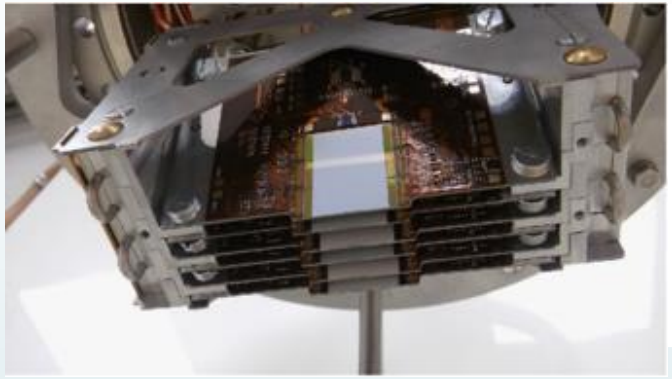
Tracking detectors

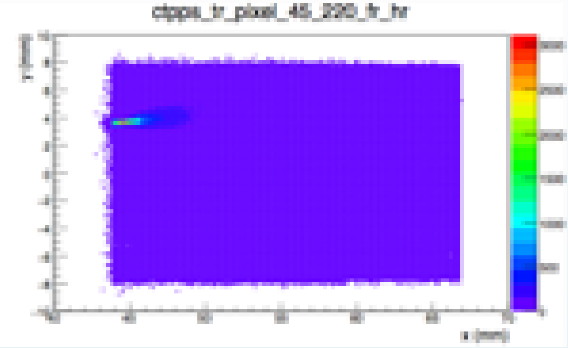
- Silicon strips





Silicon pixels

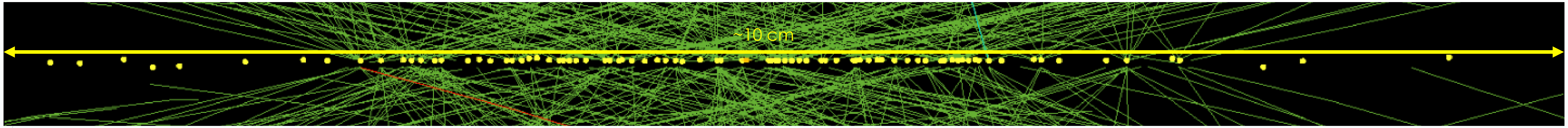




- 10 planes per station of "edgeless" silicon strip detectors (5 'u' + 5 'v')
- pitch: 66 μm; track resolution: ~12 μm
- designed for **low-luminosity** running (TOTEM)

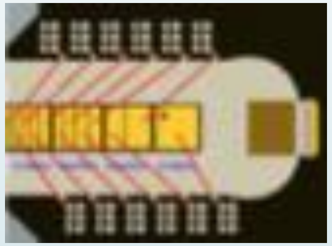
- 6 planes per station of "slim-edge" silicon pixel detectors with 3D technology (tilted by ~18°)
- pixel size: 100 μm × 150 μm; track resolution ~20 μm
- designed for **high-luminosity** running (PPS) ⟹ multi-track capability

Timing detectors



- TOF measurement to reduce background from pileup (uncorrelated proton tracks)
  - Ideally, desired resolution $\sigma_t \approx 20$ ps $\Longrightarrow$ $\sigma_z \approx 4$ mm

Diamond sensors



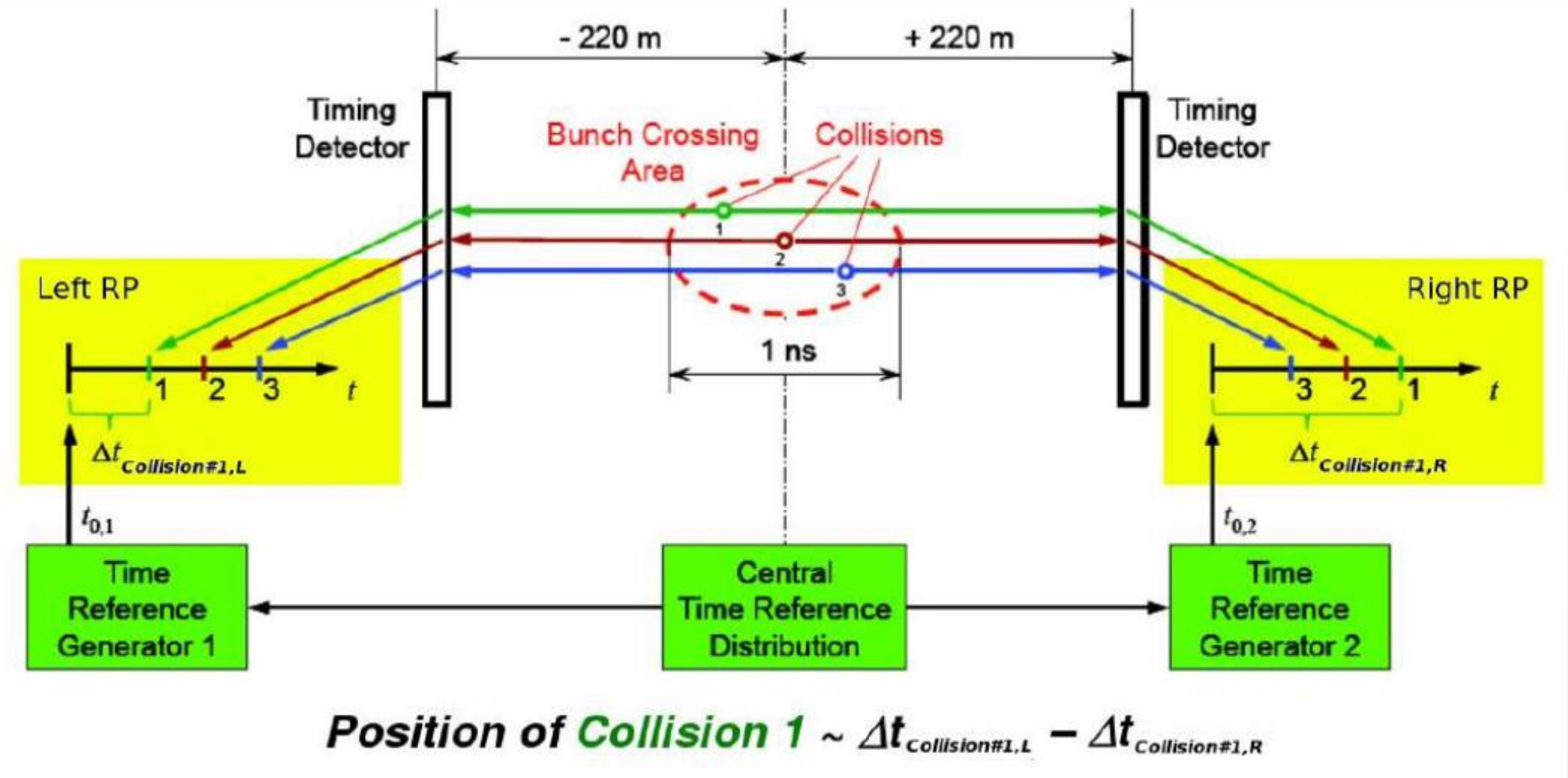
- 4 planes (3 in 2017) of CVD diamond sensors
- macro-pixels of varying size
- single-plane resolution target: ~80 ps
- 2+2 double-diamond layers in 2018 (larger signal expected ⟹ faster rise time)
- radiation hard

Ultra-Fast Silicon Detectors

- 1 plane (in 2017) of UFSD, based on LGAD technology
- single-plane resolution in test beam: ~30 ps
- R&D to improve radiation hardness

- Common readout electronics

More on timing measurement

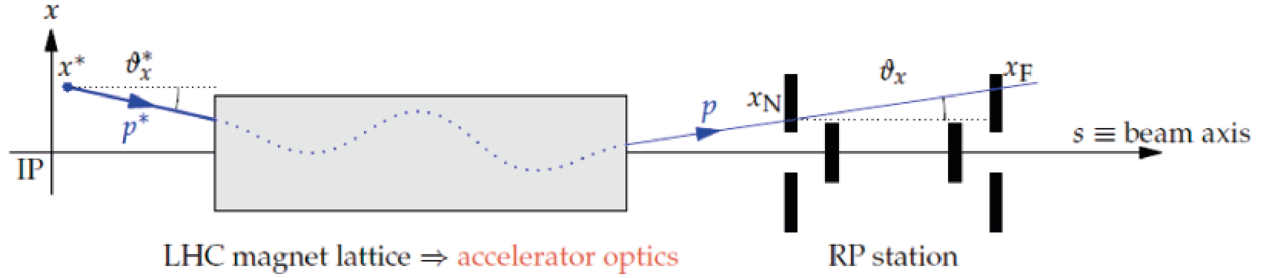


Position of Collision 1 $\sim \Delta t_{Collision\#1,L} - \Delta t_{Collision\#1,R}$

The only way to associate the protons arrived in the RP to the vertex reconstructed by CMS is to measure the **TOF difference between the left and the right protons.**

- Vertex reconstructed by using the optics and tracking information is not precise enough.
- $Z = c\,\Delta T/2$ → 20 ps time resolution/Arm makes possible the longitudinal vertex reconstruction with less than 5 mm uncertainty

Proton reconstruction and beam optics



- (x^*, y^*): vertex position
- (θ_x^*, θ_y^*): emission angle: $t \approx -p^2(\theta_x^{*2} + \theta_y^{*2})$
- $\xi = \Delta p/p$: momentum loss (elastic case: $\xi = 0$)

Measured in RP

$$\begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \\ \Delta p/p \end{pmatrix}_{RP} = \underbrace{\begin{pmatrix} v_x & L_x & 0 & 0 & D_x \\ v'_x & L'_x & 0 & 0 & D'_x \\ 0 & 0 & v_y & L_y & 0 \\ 0 & 0 & v'_y & L'_y & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}}_{\text{Product of all lattice element matrices}} \begin{pmatrix} x^* \\ \Theta_x^* \\ y^* \\ \Theta_y^* \\ \Delta p/p \end{pmatrix}_{IP5}$$

Values at IP5 to be reconstructed

$$x_{RP} = L_x \Theta_x^* + v_x x^* + D_x \xi$$

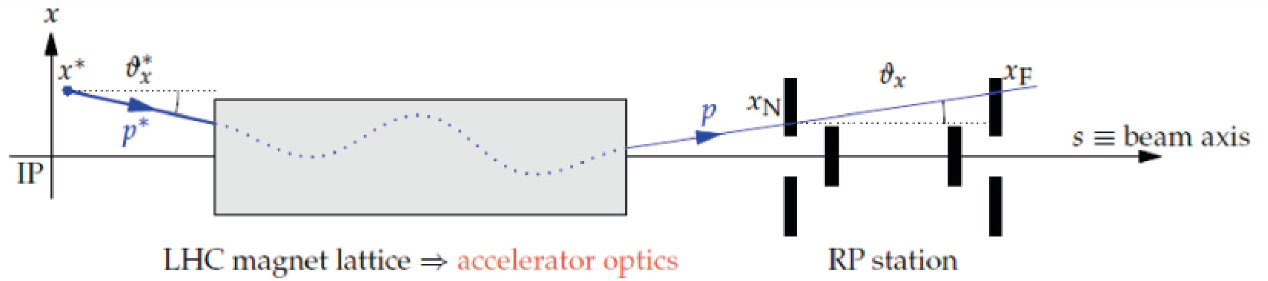
$$y_{RP} = L_y \Theta_y^* + v_y y^*$$

- L_x, L_y: effective lengths (sensitivity to scattering angle)
- v_x, v_y: magnifications (sensitivity to vertex position)
- D_x : dispersion (sensitivity to momentum loss); $D_y \sim 0$:

Reconstruction of proton kinematics inverting the transport equation

Excellent beam optics understanding needed [New J. Phys. 16 (2014) 103041]

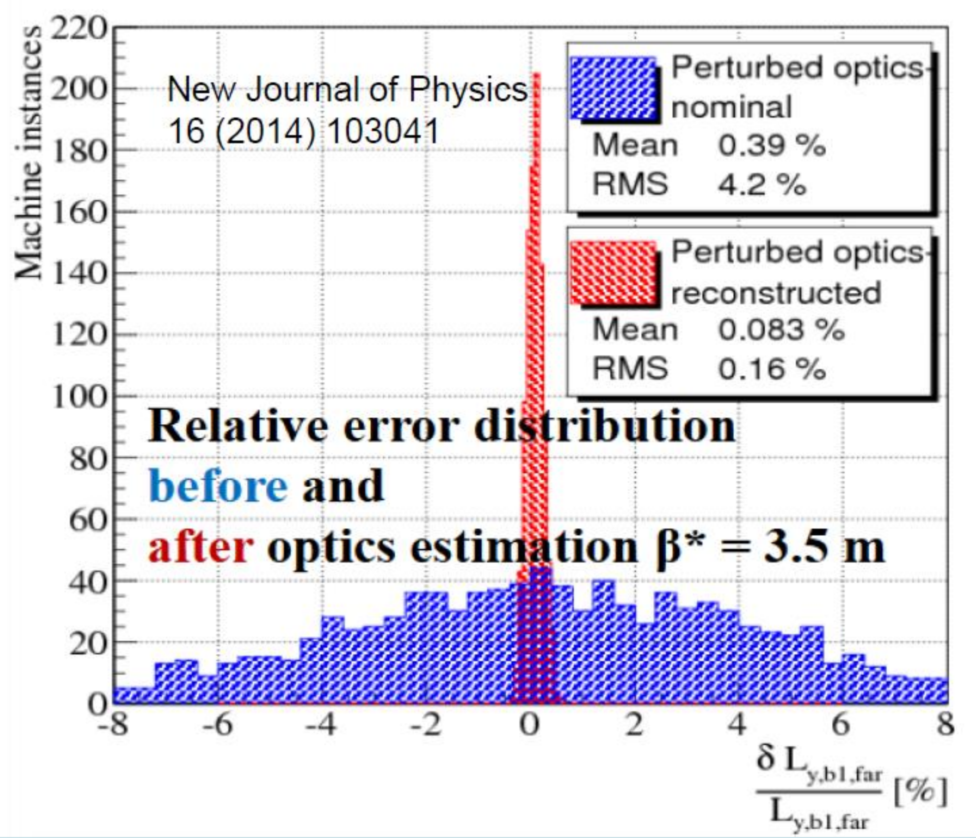
Optics parameters from data



Machine imperfections alter the optics:

- **Strength conversion error, σ(B)/B ≈ 10^{-3}**
- **Beam momentum offset, σ(p)/p ≈ 10^{-3}**
- Magnet rotations, σ(ϕ) ≈ 1 mrad
- Magnetic field harmonics, σ(B)/B ≈ 10^{-4}
- Power converter errors, σ(I)/I ≈ 10^{-4}
- Magnet positions Δx, Δy ≈ 100 µm

$$t(v_x, L_x, L_y, \ldots, p) = -p^2 \cdot \left(\Theta_x^{*2} + \Theta_y^{*2}\right)$$

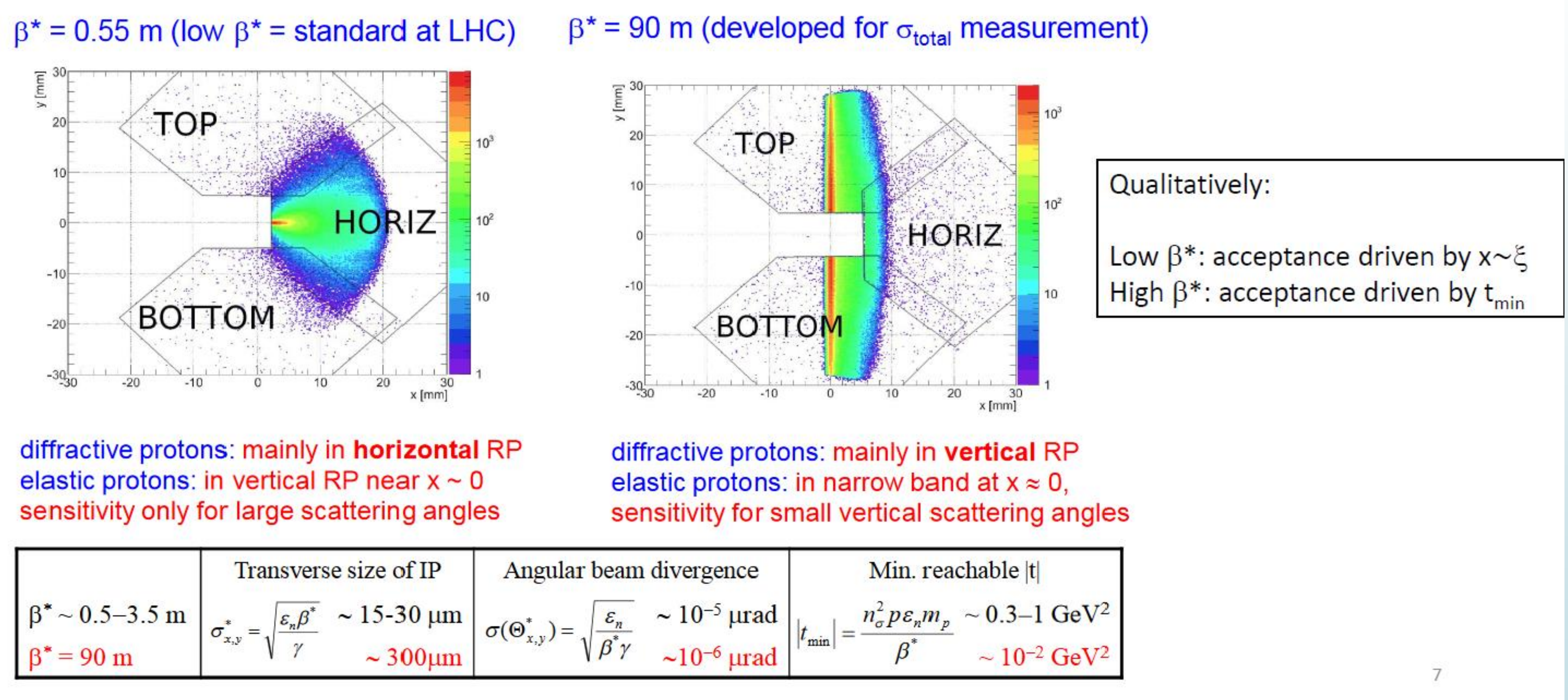


New Journal of Physics 16 (2014) 103041

Relative error distribution before and after optics estimation β* = 3.5 m

Low and high luminosity optics

Low luminosity → high β*
High luminosity → low β*



β* = 0.55 m (low β* = standard at LHC)

β* = 90 m (developed for σ_{total} measurement)

diffractive protons: mainly in **horizontal** RP
elastic protons: in vertical RP near x ~ 0
sensitivity only for large scattering angles

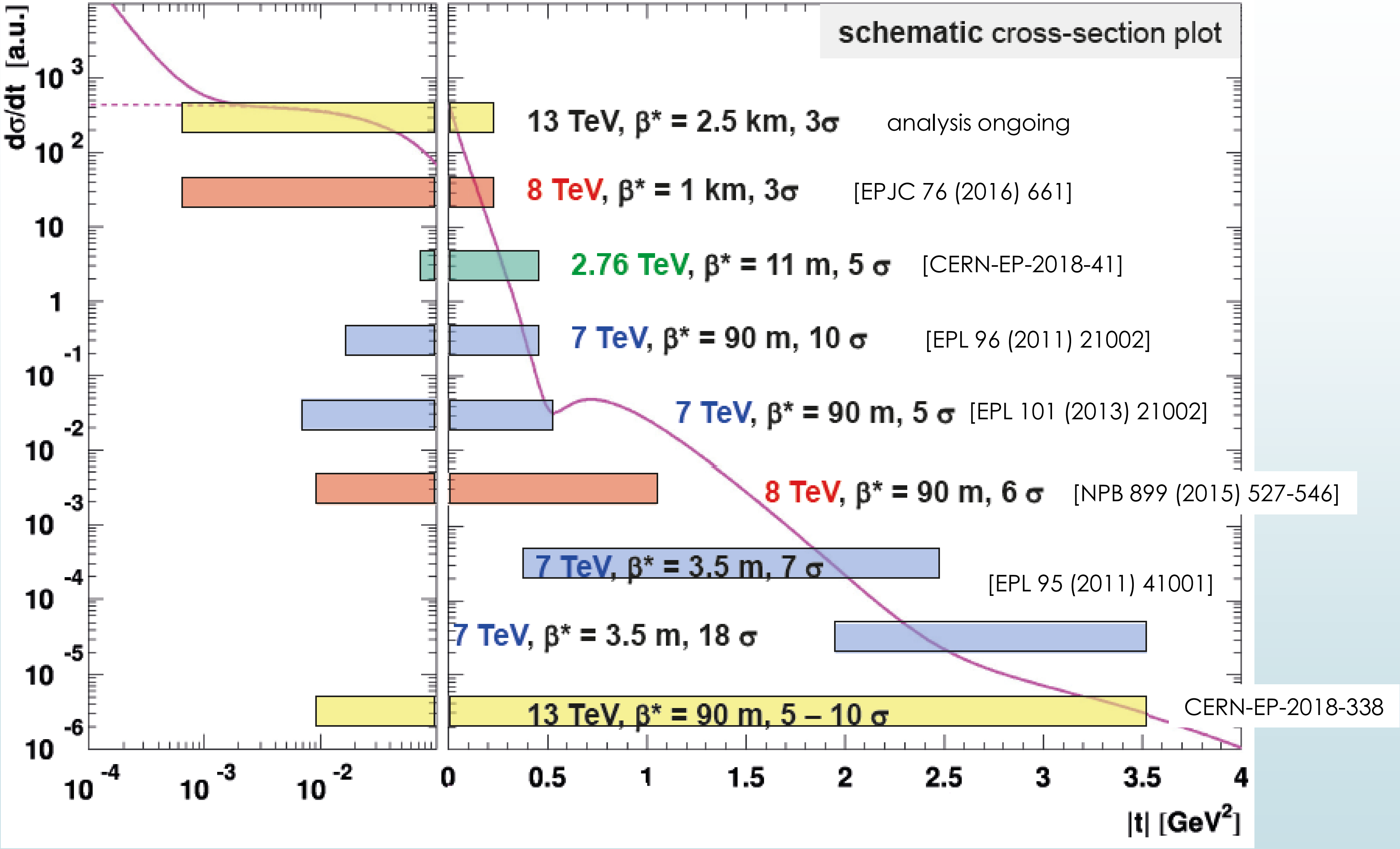
diffractive protons: mainly in **vertical** RP
elastic protons: in narrow band at x ≈ 0,
sensitivity for small vertical scattering angles

Qualitatively:

Low β*: acceptance driven by x~ξ
High β*: acceptance driven by t_{min}

	Transverse size of IP	Angular beam divergence	Min. reachable |t|
β* ~ 0.5–3.5 m	$\sigma^*_{x,y} = \sqrt{\frac{\varepsilon_n \beta^*}{\gamma}}$ ~ 15-30 µm	$\sigma(\Theta^*_{x,y}) = \sqrt{\frac{\varepsilon_n}{\beta^* \gamma}}$ ~ 10^{-5} µrad	$\|t_{min}\| = \frac{n_\sigma^2 p \varepsilon_n m_p}{\beta^*}$ ~ 0.3–1 GeV²
β* = 90 m	~ 300µm	~10^{-6} µrad	~ 10^{-2} GeV²

Elastic scattering: data sets vs t ranges



13 TeV, β* = 2.5 km, 3σ analysis ongoing

8 TeV, β* = 1 km, 3σ [EPJC 76 (2016) 661]

2.76 TeV, β* = 11 m, 5 σ [CERN-EP-2018-41]

7 TeV, β* = 90 m, 10 σ [EPL 96 (2011) 21002]

7 TeV, β* = 90 m, 5 σ [EPL 101 (2013) 21002]

8 TeV, β* = 90 m, 6 σ [NPB 899 (2015) 527-546]

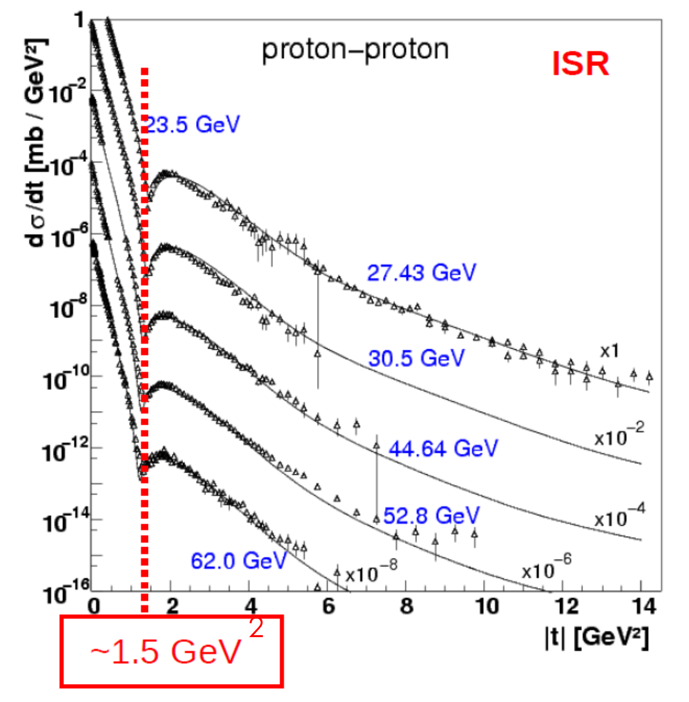
7 TeV, β* = 3.5 m, 7 σ

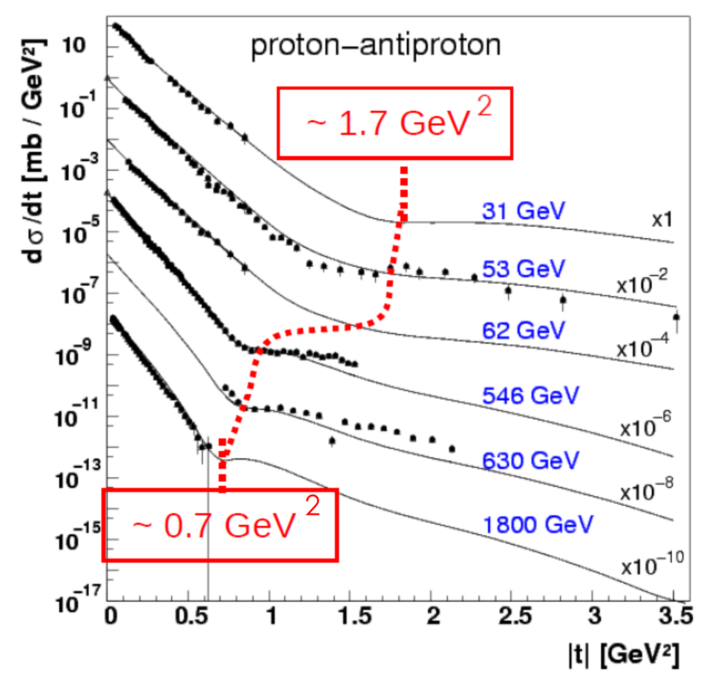
[EPL 95 (2011) 41001]

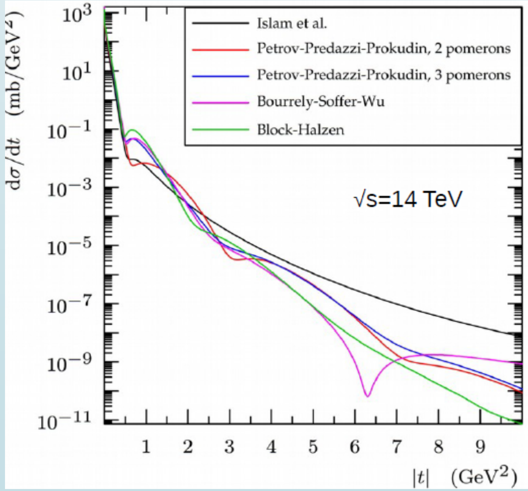
7 TeV, β* = 3.5 m, 18 σ

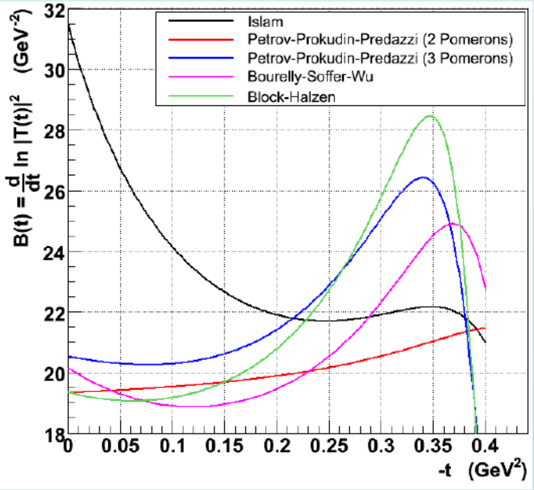
13 TeV, β* = 90 m, 5 – 10 σ CERN-EP-2018-338

Elastic scattering: dσ/dt before LHC









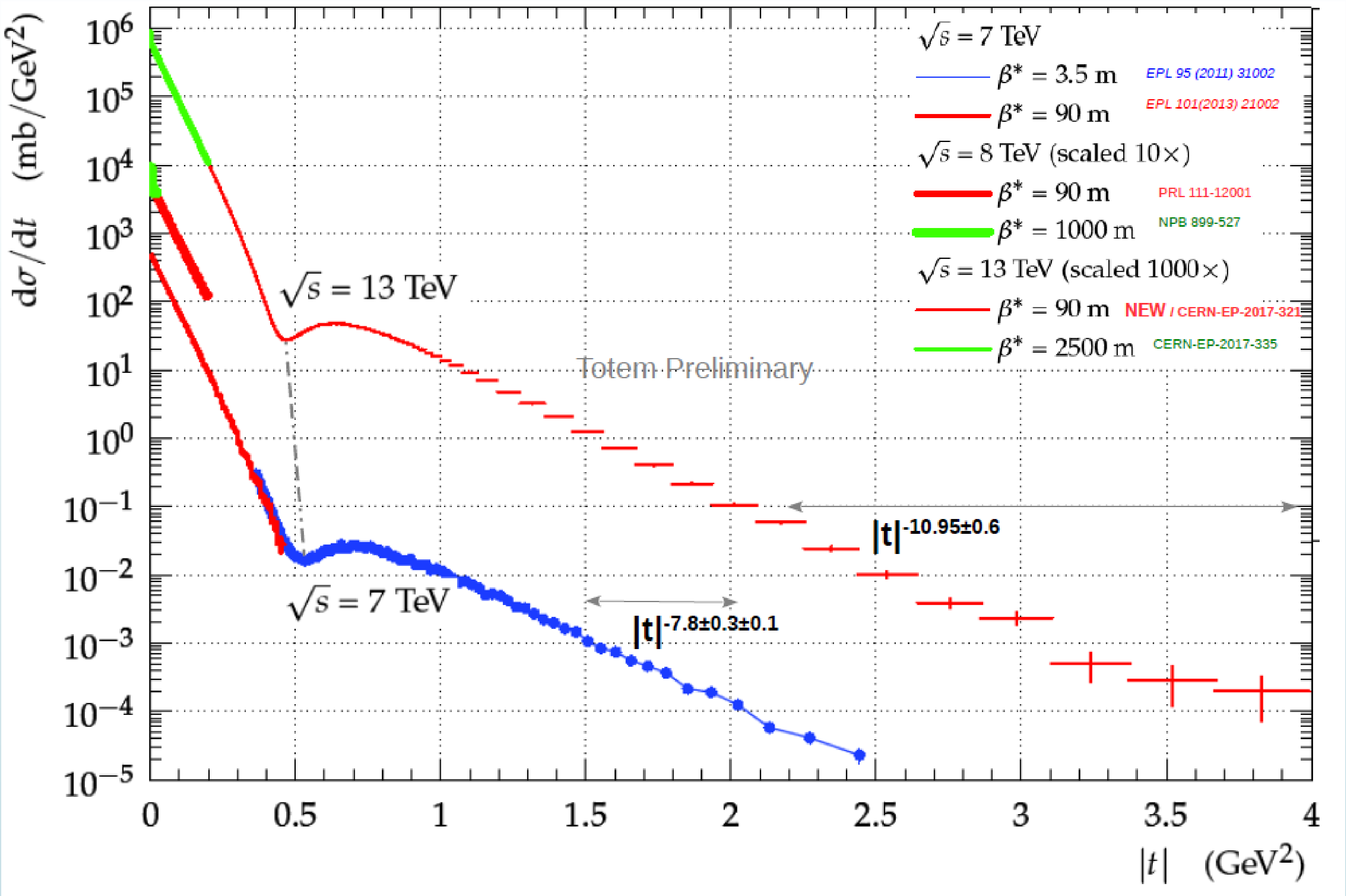
Some open questions for LHC energies

- What happens to the dip?
- Any secondary maxima/structures at large t?
- What happens to the forward peak slope B(t)?
- Can we measure ρ?

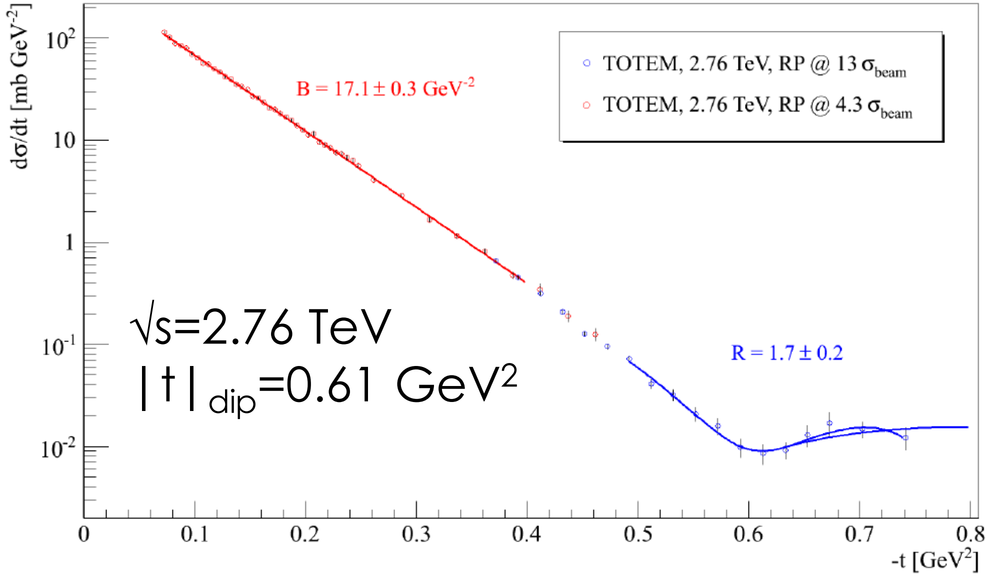
$$\rho = \frac{\Re A^H(t=0)}{\Im A^H(t=0)}$$

Elastic scattering: dσ/dt at LHC

- No structures at high t
- Dip still there
- Shrinkage of the forward peak continues

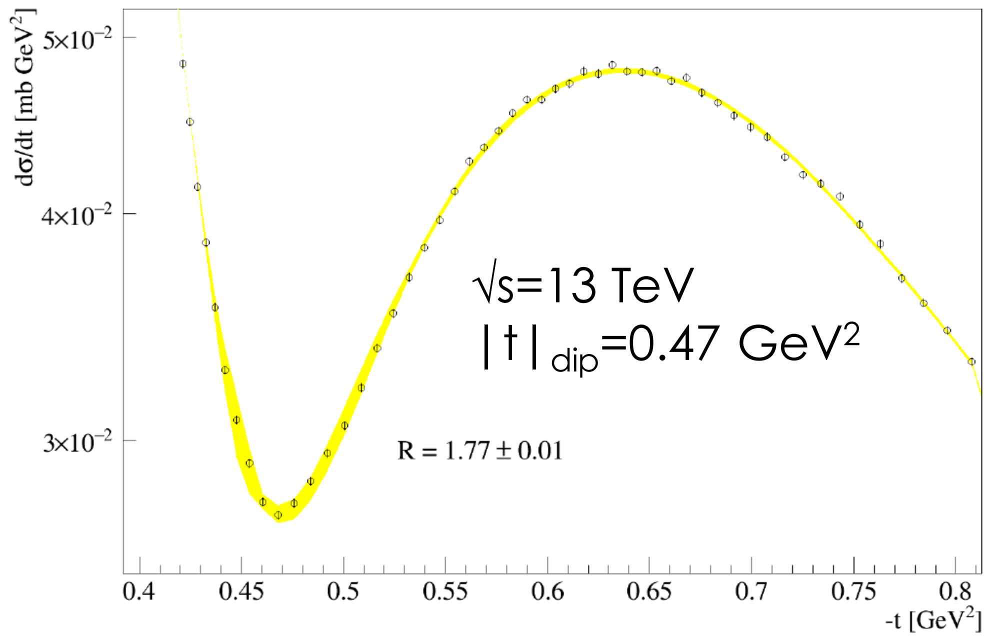


Elastic scattering: dip at LHC



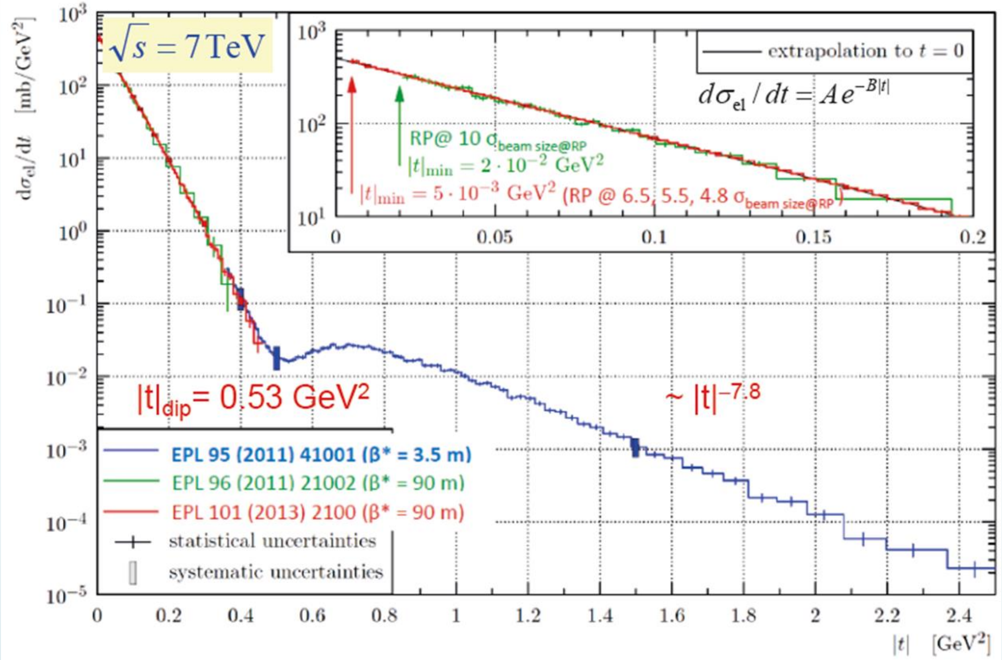
√s=2.76 TeV

$|t|_{dip}$=0.61 GeV²



√s=13 TeV

$|t|_{dip}$=0.47 GeV²



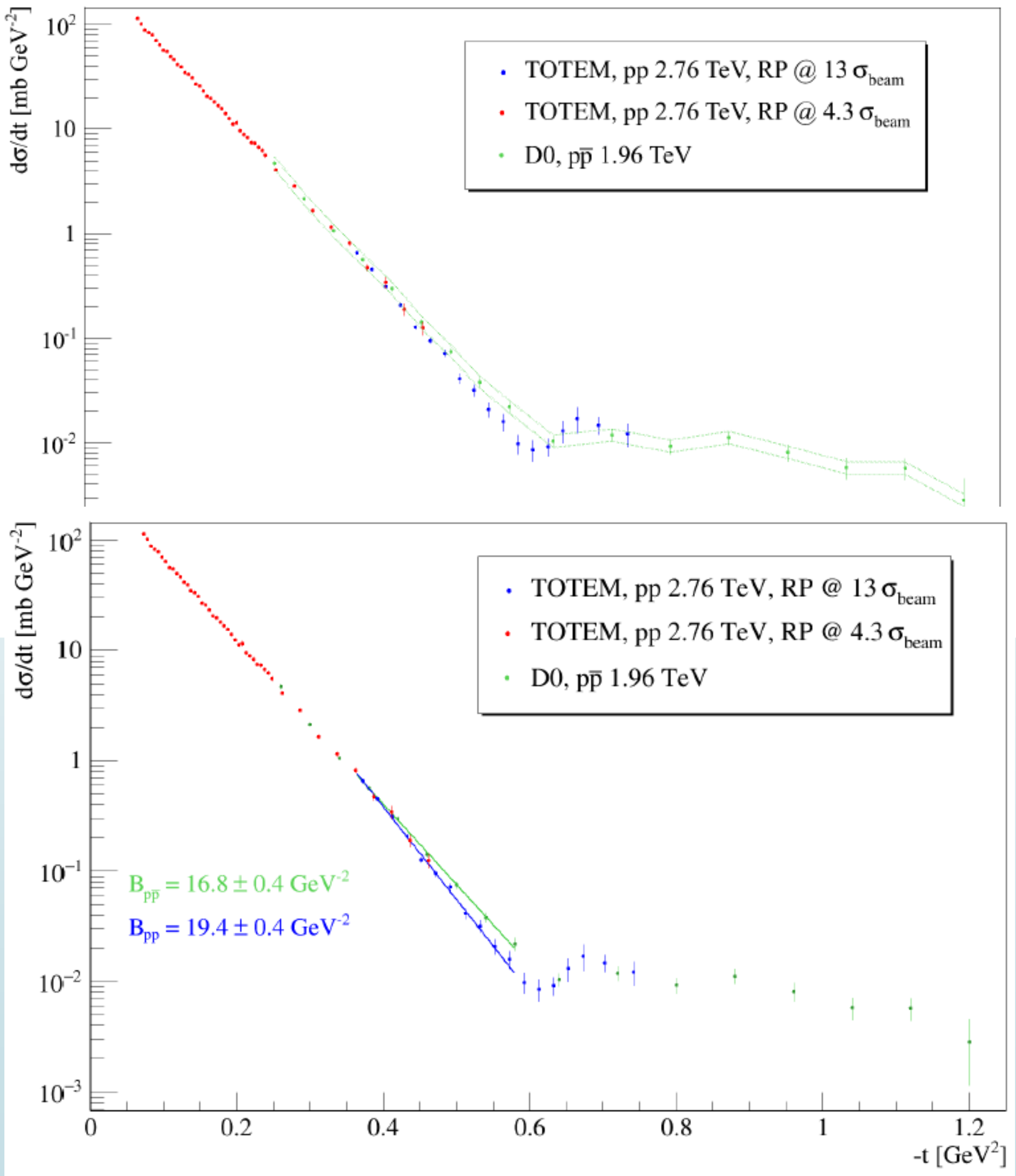
$|t|_{dip}$= 0.53 GeV²

~ $|t|^{-7.8}$

- The dip position decreases with energy
- Bump/dip ratio measured at different energies

Elastic scattering: LHC vs Tevatron

- The measurement of TOTEM at 2.76 TeV can be compared with D0's at 1.96 TeV
- First comparison of pp and ppbar data at TeV energies
- Ratio bump/dip
  - R=1.7±0.2 in pp
  - R=1.0±0.1 in ppbar



Such a difference in R in pp and ppbar scattering can be interpreted as the existence of the **Odderon** (the $J=1^{--}$ counterpart of the Pomeron).

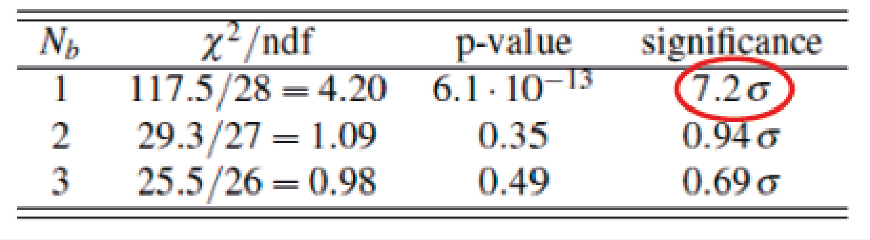
The Odderon is described in QCD as the exchange of a colorless 3-gluon bound state in the t-channel.

The comparison of TOTEM and D0 is still a work in progress …

Elastic scattering at low t

- Usually called the "exponential region"
- Peak is fitted with a polynomial exponential

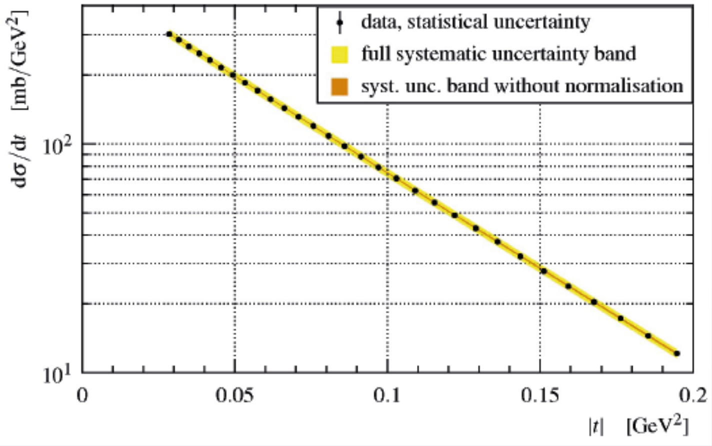
$$d\sigma_{el}/dt = A * exp\left(\sum_{i=1}^{N_b} b_i t^i\right)$$



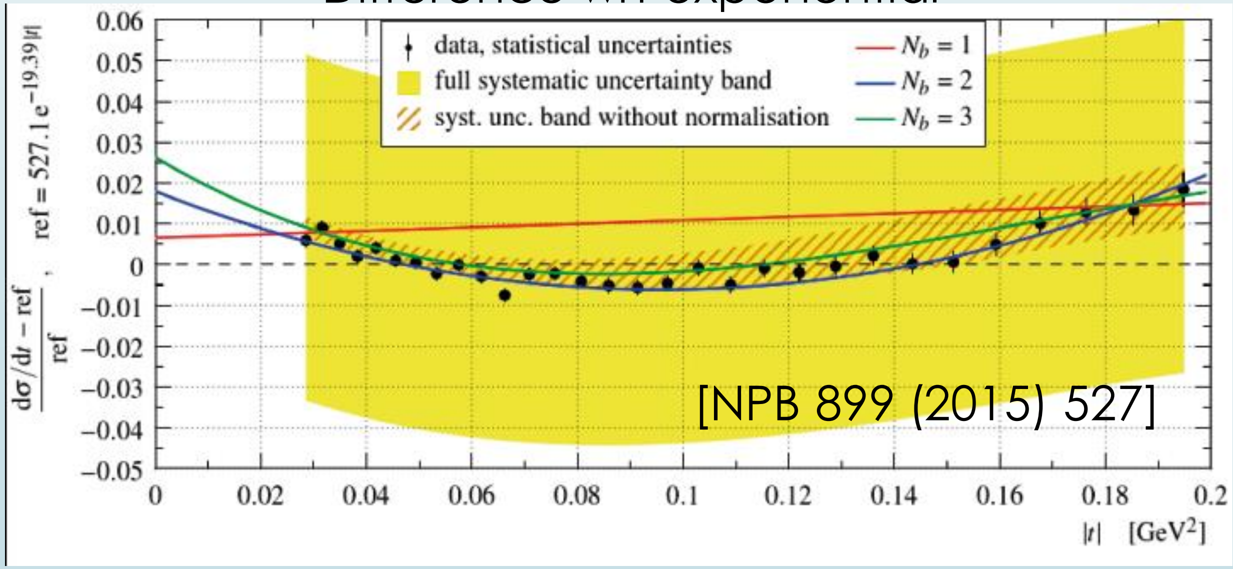
N_b	χ^2/ndf	p-value	significance
1	$117.5/28 = 4.20$	$6.1 \cdot 10^{-13}$	$7.2\,\sigma$
2	$29.3/27 = 1.09$	0.35	$0.94\,\sigma$
3	$25.5/26 = 0.98$	0.49	$0.69\,\sigma$

- Non-exponentiality already seen at the ISR
- Simple exponential ruled out with a significance of 7.2 σ
- Differences of the order of ~1%. Very high statistics and very good control of systematics.

The peak at "first glance"



Difference wrt exponential

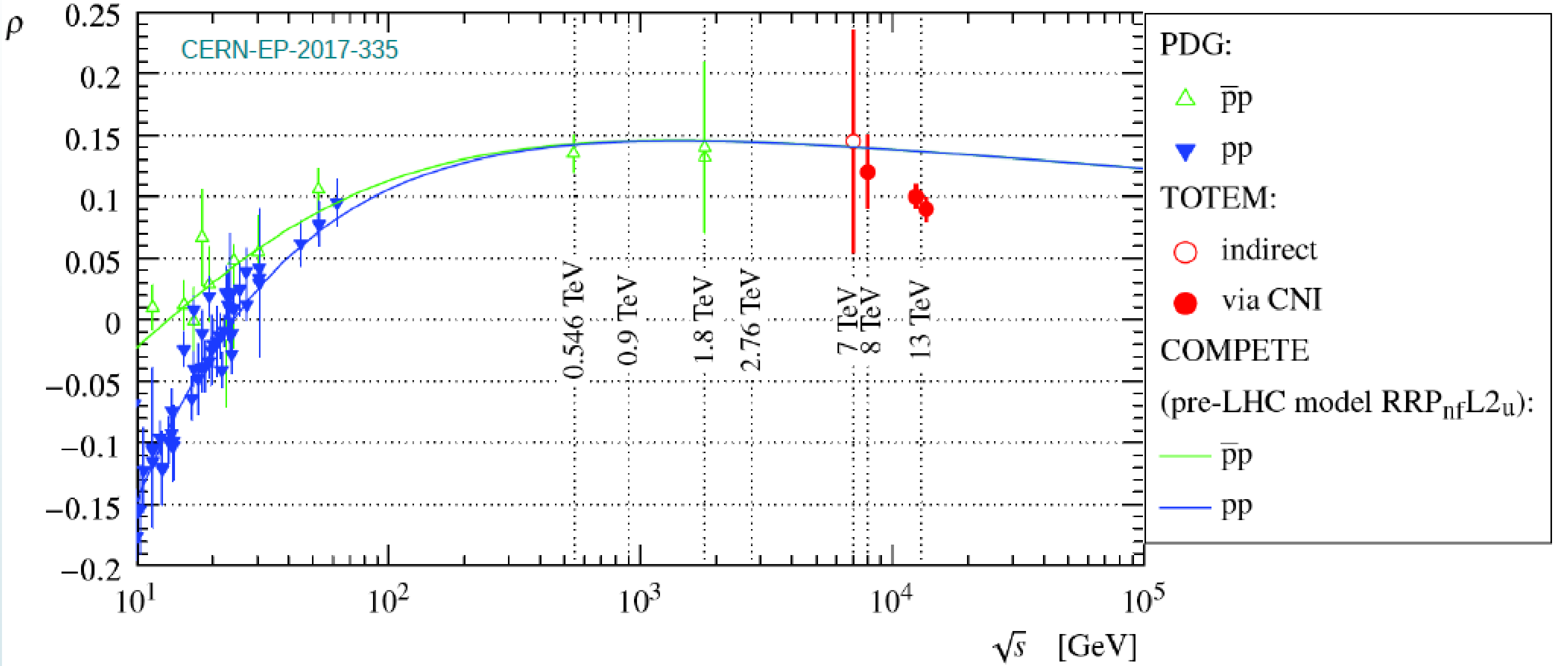


[NPB 899 (2015) 527]

Elastic scattering: Coulomb interference and measurement of ρ

$$\rho = \frac{\Re A^H(t=0)}{\Im A^H(t=0)}$$

- Totem direct measurement at 8 and 13 TeV
- Indirect measurement done at 7 TeV
- First pp measurements of ρ since ISR era
- Expected results at 900 GeV



Direct measurement done fitting the amplitude from CNI (Coulomb Nuclear Interference).

The new measurements are clearly below predictions

Total pp cross section: analysis methods

From Optical theorem

$$\sigma^2_{\text{tot}} \propto \left[\Im A_{\text{el,N}}(t=0)\right]^2 \propto \frac{1}{1+\rho^2}\left|A_{\text{el,N}}(t=0)\right|^2 = \frac{16\pi}{1+\rho^2}\frac{d\sigma_{el}}{dt}\Big|_{t=0} \quad \text{with} \quad \rho = \frac{\Re A_{\text{el,N}}}{\Im A_{\text{el,N}}}\Big|_{t=0}$$

$$L\sigma_{\text{tot}} = N_{\text{el}} + N_{\text{inel}}$$

N_{inel} (from T1,T2 telescopes)

N_{el} (from RomanPots detectors)

L independent

$$\boxed{\sigma_{tot} = \frac{16\pi}{(1+\rho^2)}\frac{(dN_{el}/dt)_{t=0}}{(N_{el}+N_{inel})}}$$

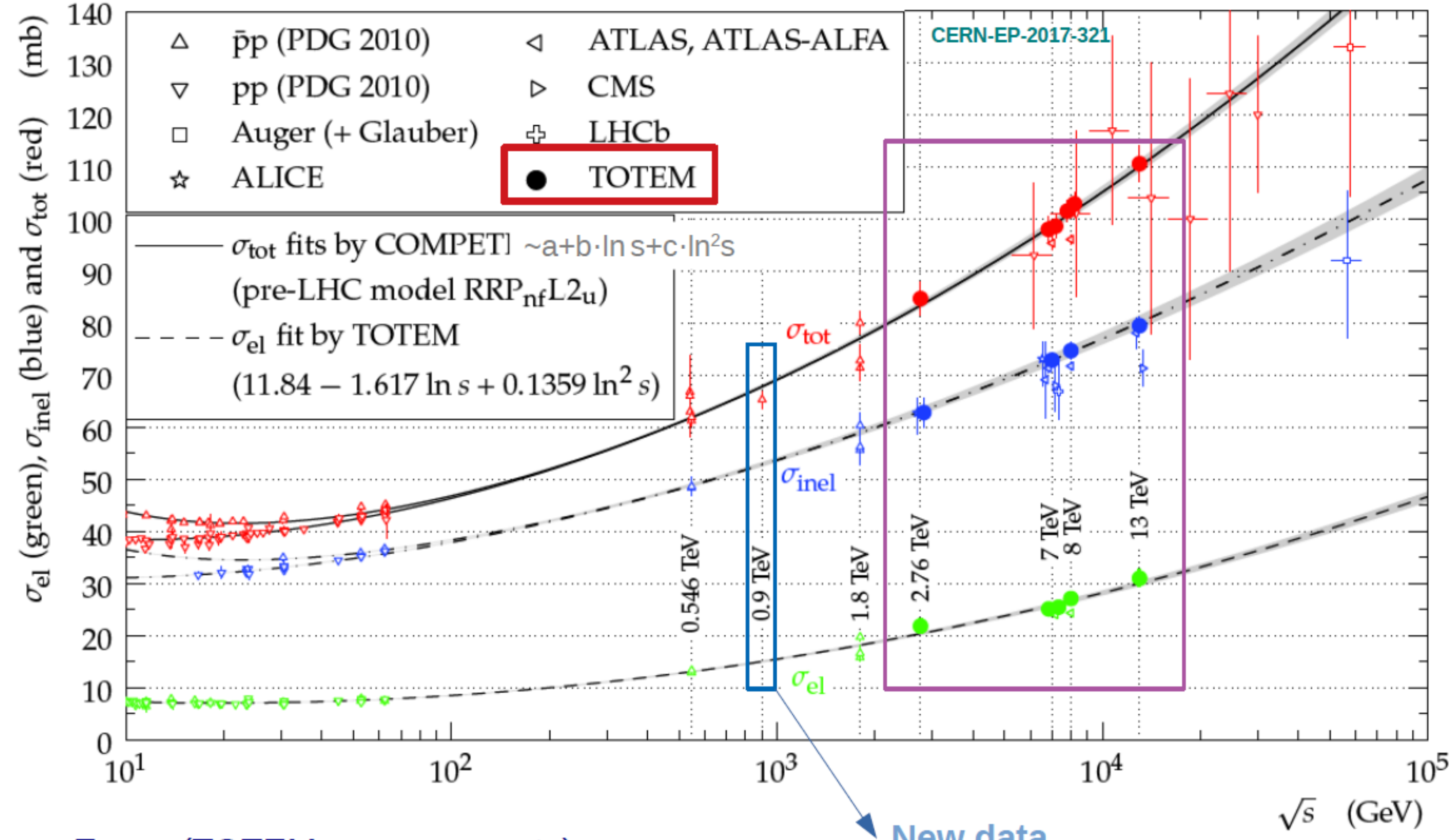
L dependent
Elastic Only

$$\boxed{\sigma^2_{tot} = \frac{16\pi}{(1+\rho^2)}\frac{1}{\mathcal{L}}\left(\frac{dN_{el}}{dt}\right)_{t=0}}$$

ρ independent

$$\boxed{\sigma_{tot} = \sigma_{el} + \sigma_{inel}}$$

Total cross section: results



New data available!

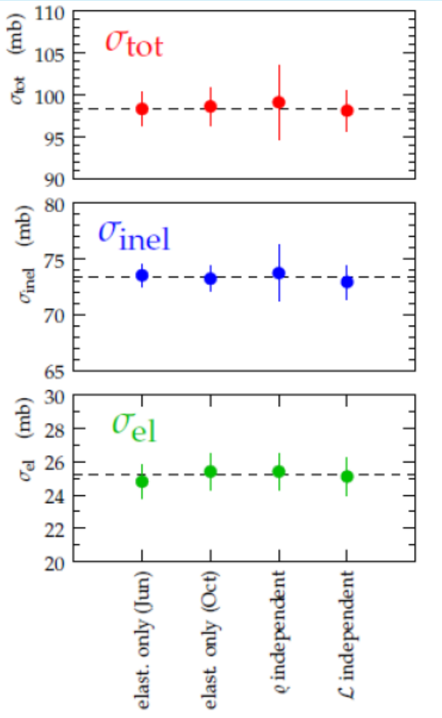
Errors (TOTEM measurements)

σ_{TOT} ~ 2-3 %

σ_{INEL} ~ 2 %

σ_{EL} ~ 2-4 %

Consistency of different methods



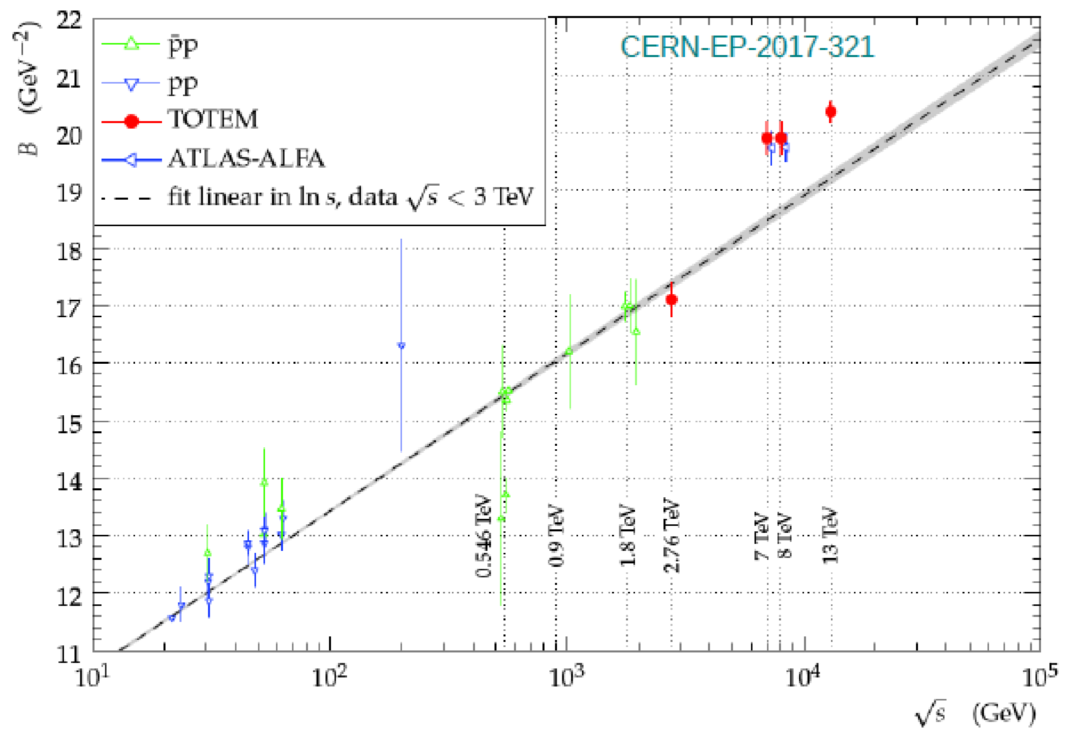
7 TeV, several methods
Same beam conditions

Total pp cross section: measurements

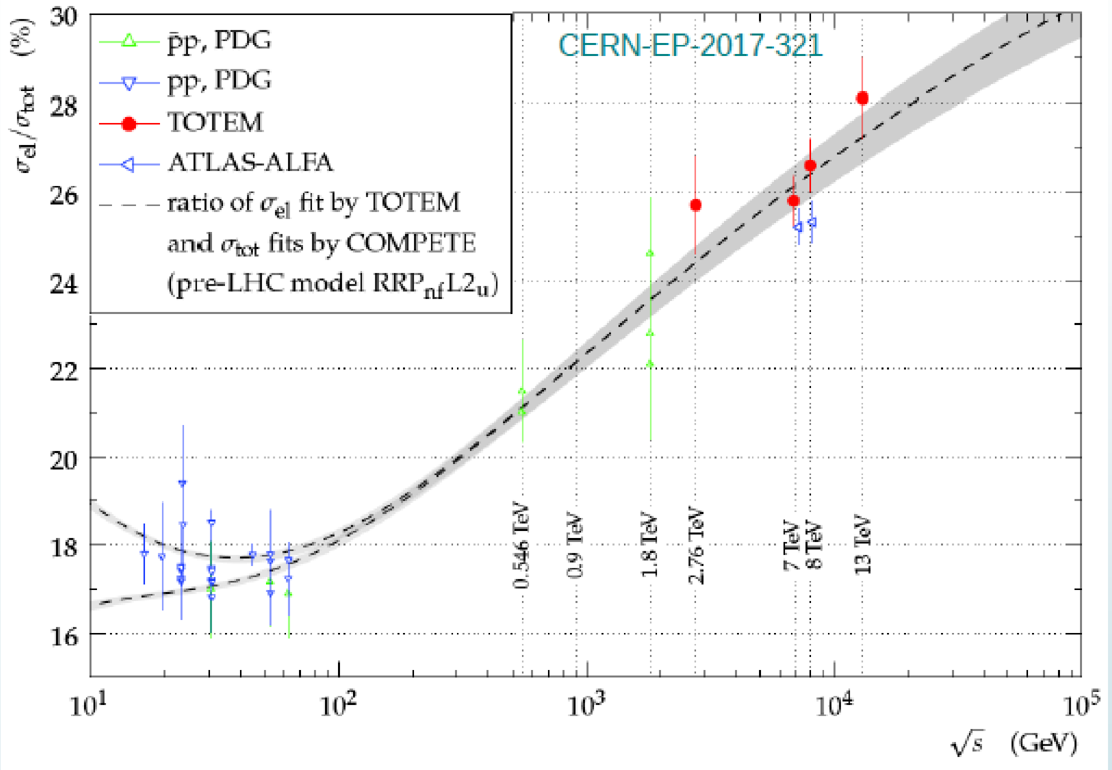
- 2.76 TeV
  - Luminosity independent **σ_{tot} = (84.7 ±3.3) mb** using ρ = 0.145 [COMPETE]
- 7 TeV
  - Luminosity independent **σ_{tot} = (98.0 ± 2.5) mb** using ρ = 0.14[COMPETE]
  - ρ independent **σ_{tot} = (99.1 ± 4.3) mb**
  - From elastic scattering only
    - **σ_{tot} = (98.3 ± 2.8) mb**
    - **σ_{tot} = (98.6 ± 2.2) mb**
- 8 TeV
  - Luminosity independent **σ_{tot} = (101.7 ± 2.9) mb**
- 13 TeV
  - Luminosity independent **σ_{tot} = (110.6 ± 3.4) mb**

Total cross section: some implications

Forward peak slope B



σ_{el}/σ_{tot}

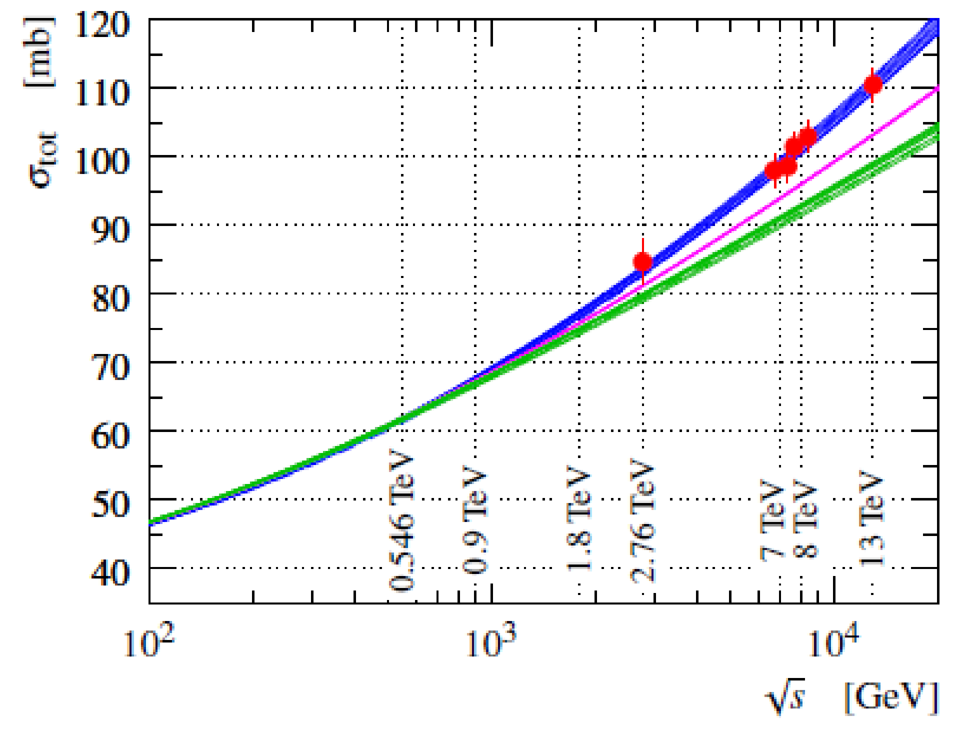


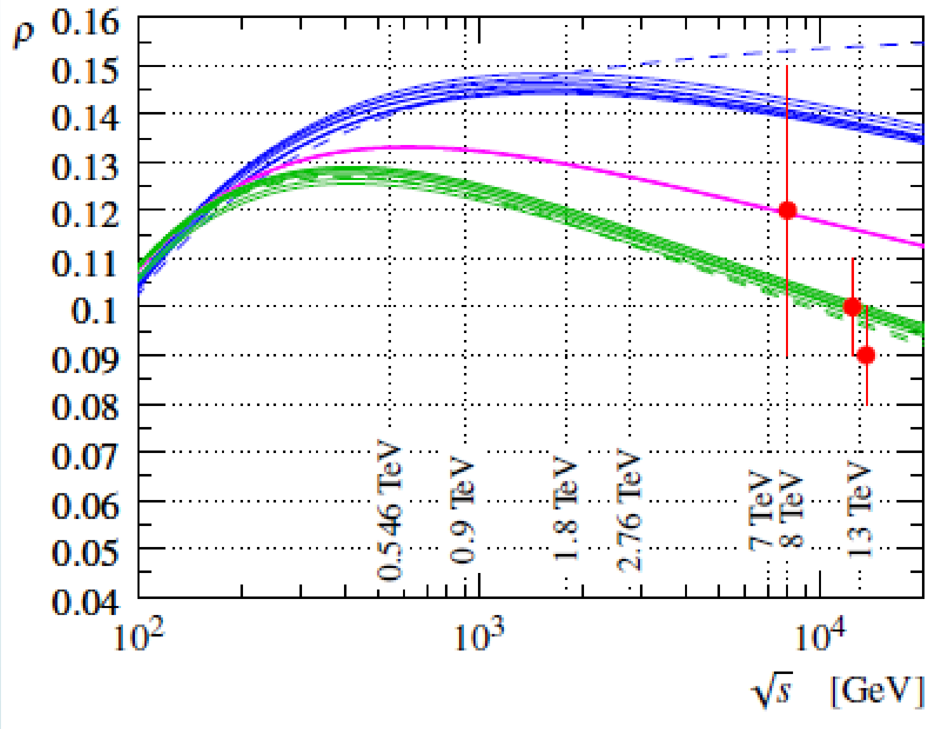
- Forward peak shrinkage speeds up

- confirmation of the increase of elastic cross section vs total ratio with energy

Total cross section and ρ: implications

- The COMPETE collaboration fitted 256 models with all existing data





None of the considered models is compatible with both sets of measurements

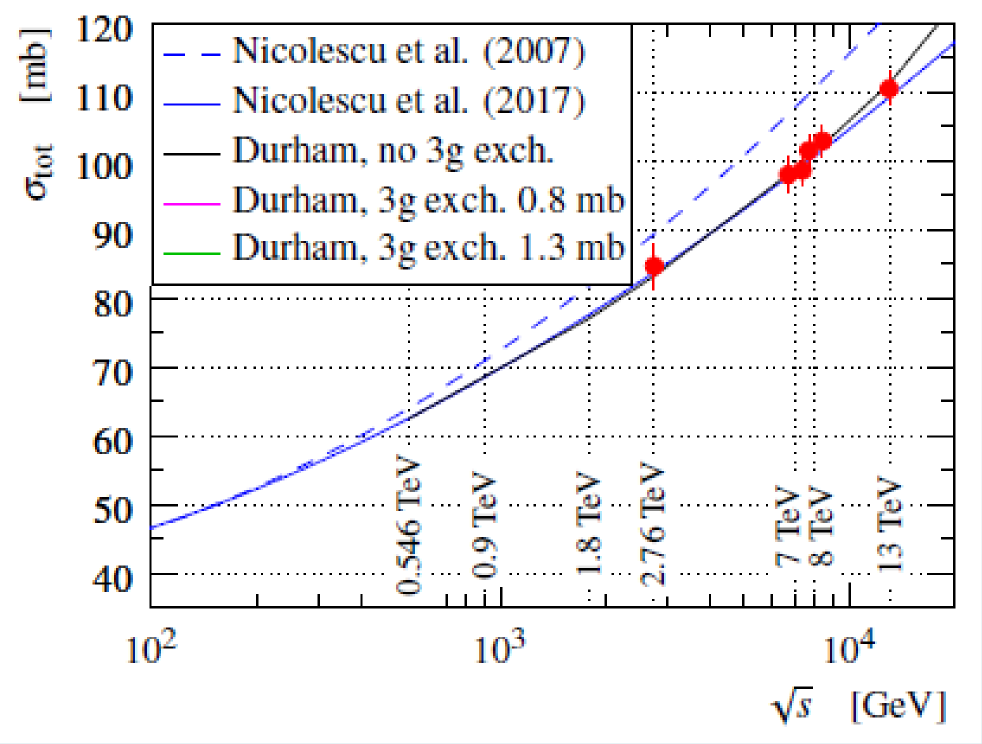
It can be shown from basic principles that a relation such as $\rho \propto \sim d\sigma_{tot}/ds$ holds

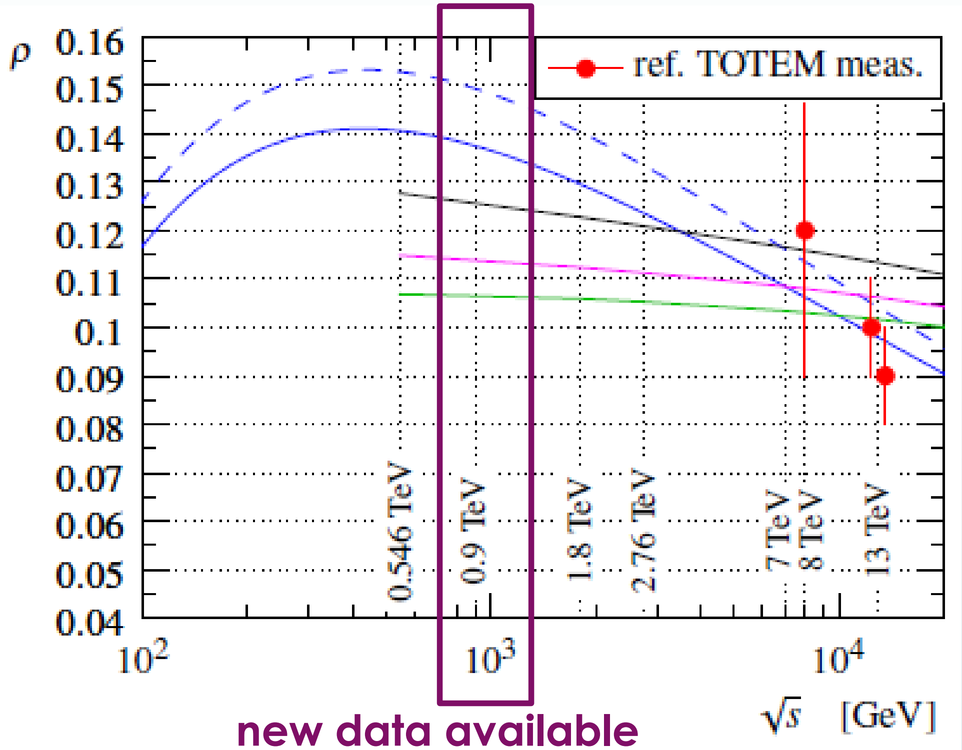
Therefore it may be that the increase rate of σ_{tot} is going to slow down at higher energies

OR ... see next slide ...

Total cross section and ρ: implications

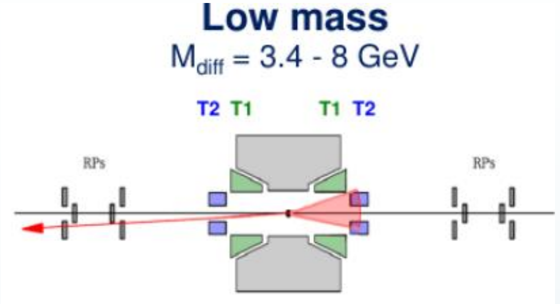
- ... there's a need of the exchange of an odd-signature object

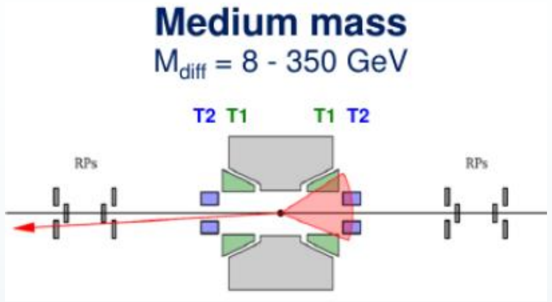


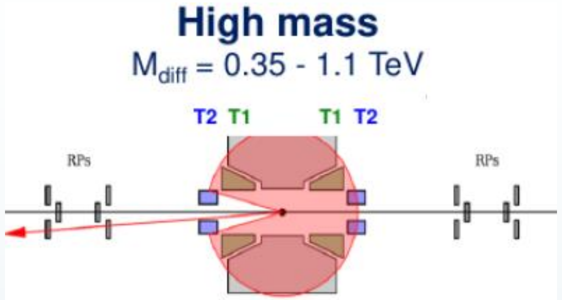


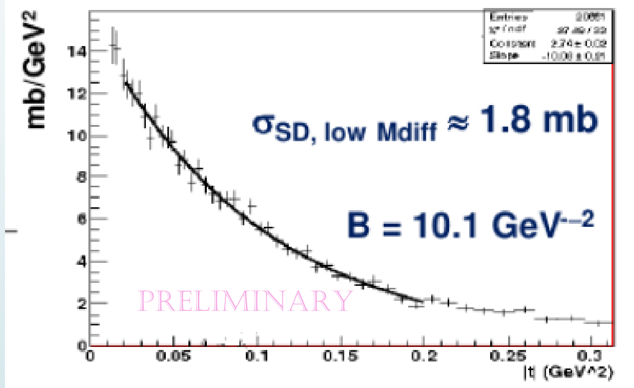
Such an object, a Reggeon usually referred to as **Odderon**, which can be seen as a colourless bound state of three gluons with quantum numbers $J^{PC} = 1^{--}$

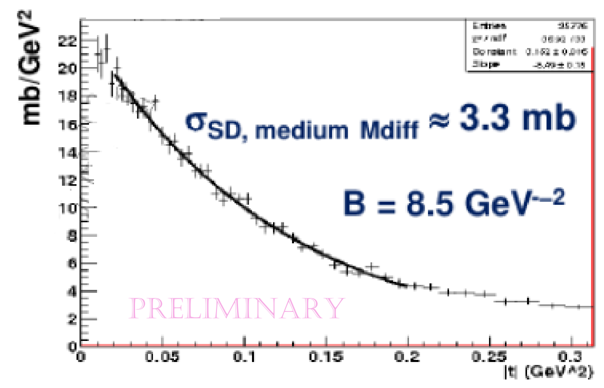
Single diffraction (preliminary)

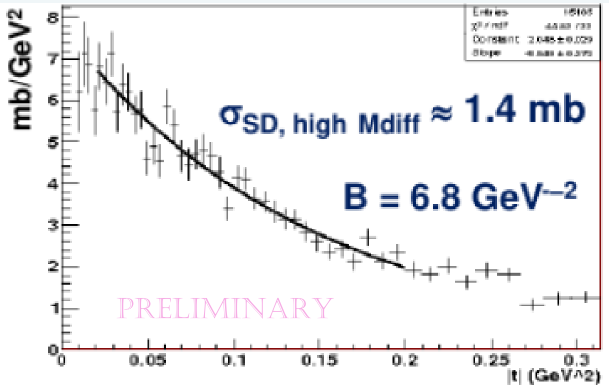












Estimated uncertainties: ΔB~15%, Δσ~20%

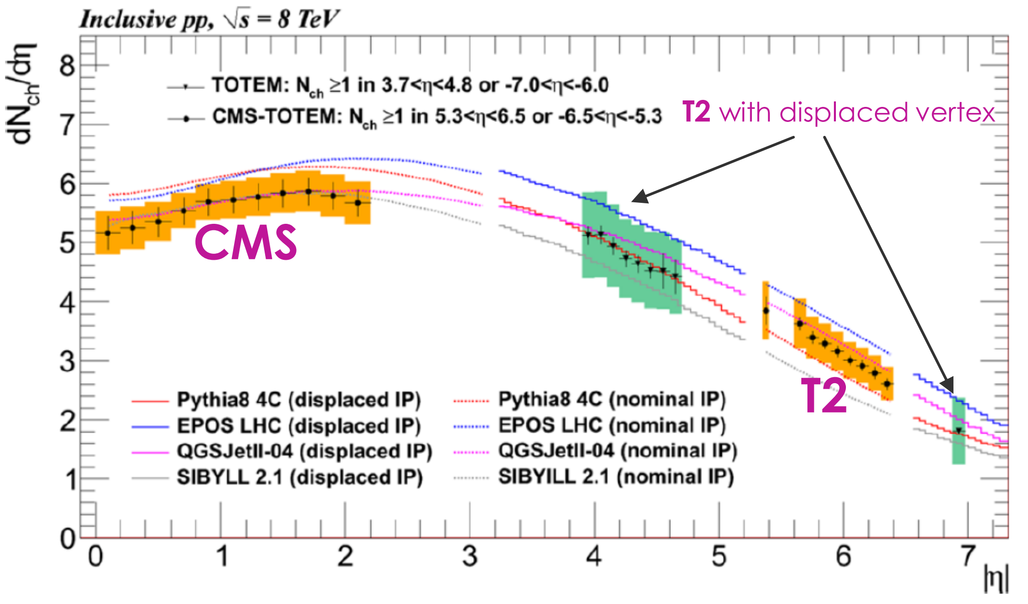
σ_{SD} = 6.5 ± 1.3 mb in the range 3.4 GeV < M_{diff} < 1.1 TeV

Preliminary results. Not all corrections included

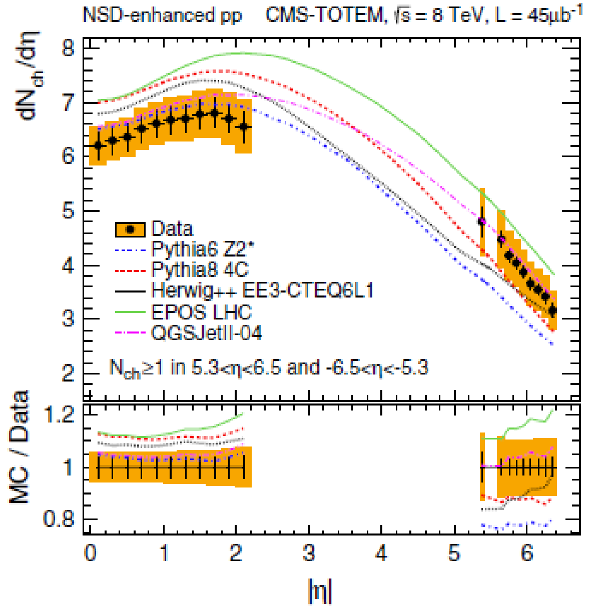
Charged-particle pseudorapidity density

- **MC tuning** in the forward region
- Valuable information for **Cosmic Ray** physics simulations
- Measurements done with T2 and CMS central detector

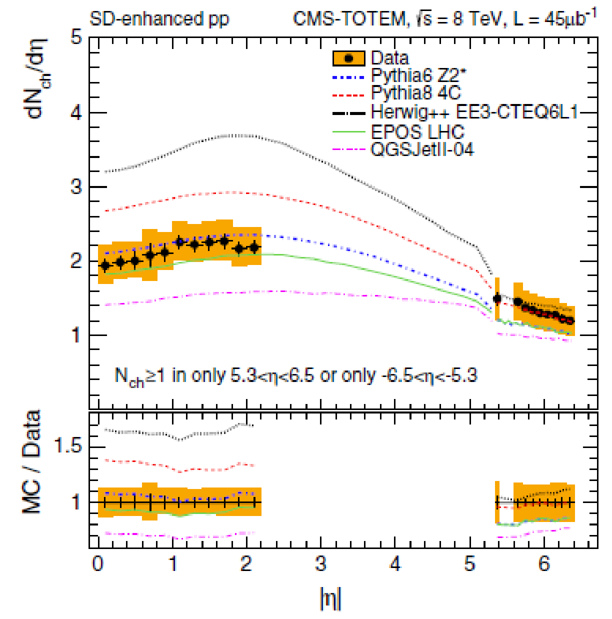
Inclusive dataset



None of the MC generators can consistently describe data



NSD-enhanced



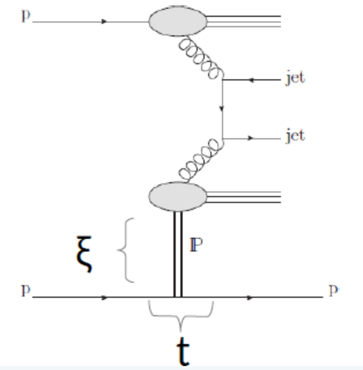
SD-enhanced

CMS-PAS-FSQ-12-033

Hard diffraction: di-jet production (1)

First CMS-TOTEM measurement with tagged protons from low-pileup data at √s=8TeV

- Dijets in central CMS, scattered proton in Roman Pots
- Background from inclusive dijets, in coincidence with random RP track from pileup or beam-background proton
- Matching: compare ξ calculated from protons and from jets

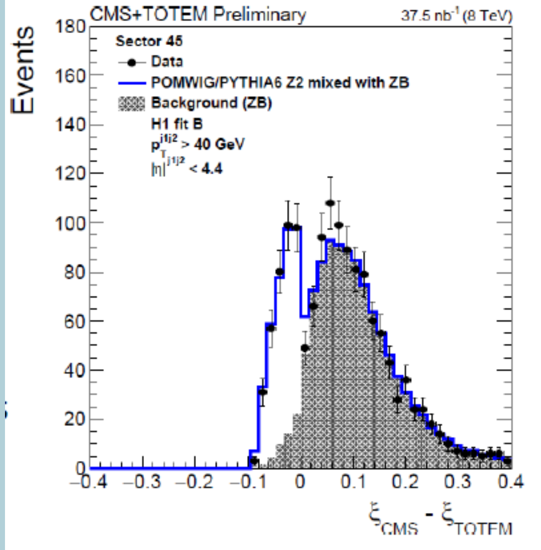


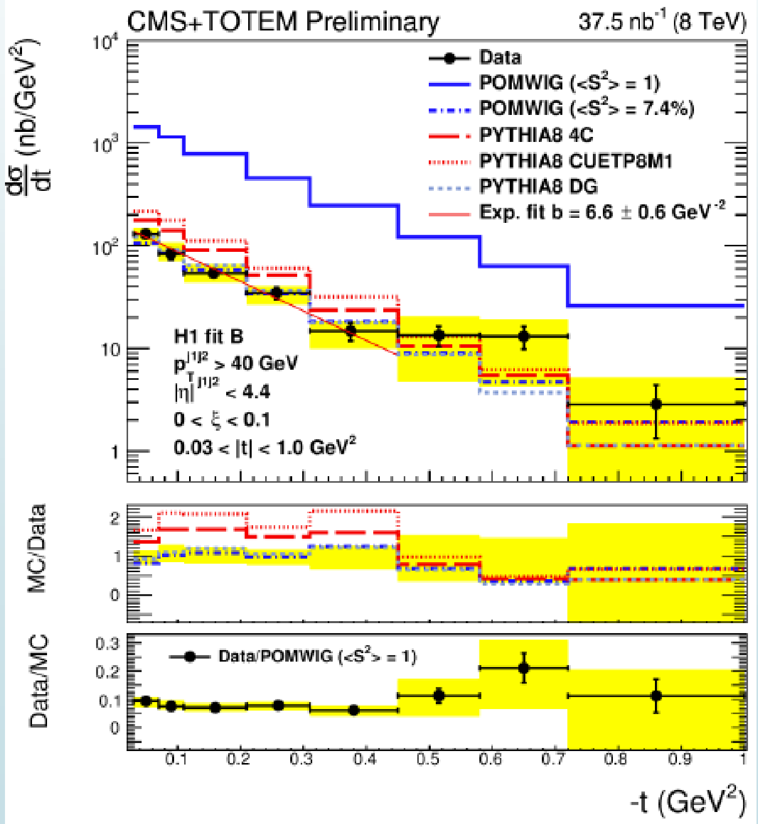
Event selection

$$\xi^{\pm}_{\rm CMS} = \frac{\sum \left(E^i \pm p_z^i\right)}{\sqrt{s}}$$

$$\xi_{\rm CMS} - \xi_{\rm TOTEM} < 0$$

$$p_T > 40\ {\rm GeV},\ |\eta| < 4.4,\ \xi < 0.1$$
$$0.03 < |t| < 1\ {\rm GeV}^2$$





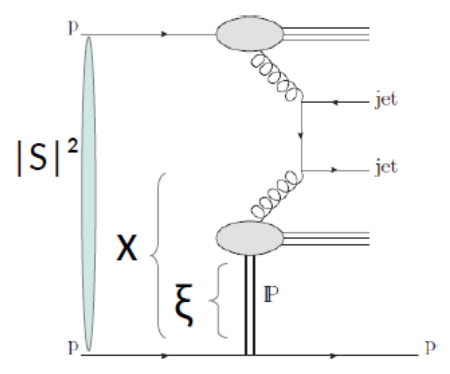
$$\sigma_{\rm jj}^{\rm pX} = 21.7 \pm 0.9\,({\rm stat})\,^{+3.0}_{-3.3}\,({\rm syst}) \pm 0.9\,({\rm lumi})\,{\rm nb}$$

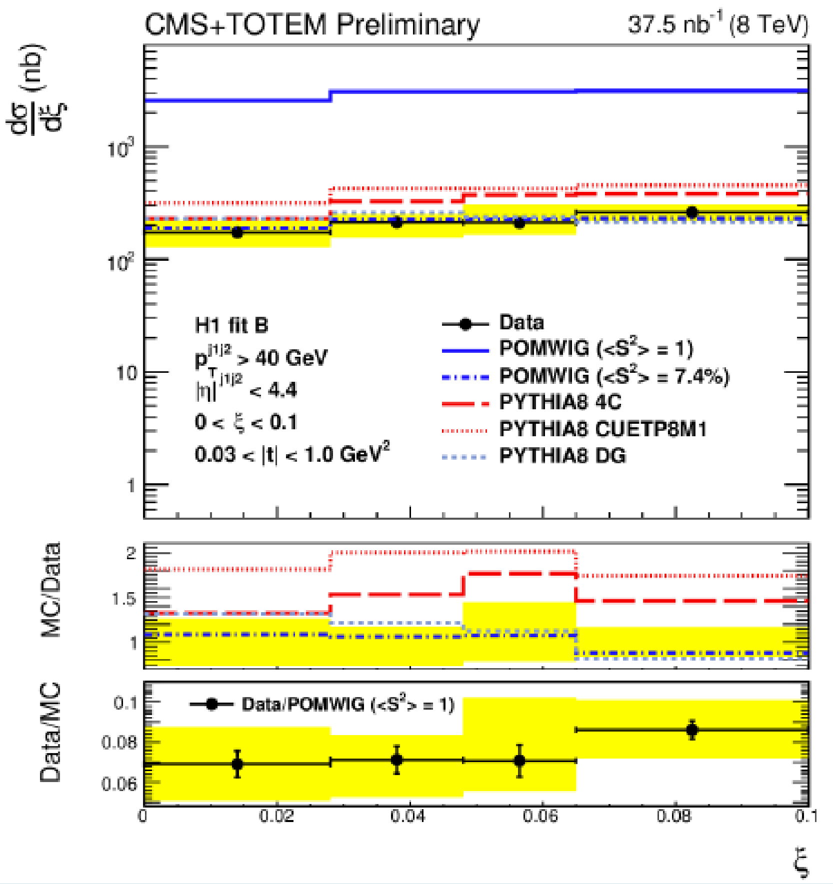
$$d\sigma/dt \propto \exp^{-b|t|} \quad b = 6.6 \pm 0.6\,({\rm stat})\,^{+1.0}_{-0.8}\,({\rm syst})\,{\rm GeV}^{-2}$$

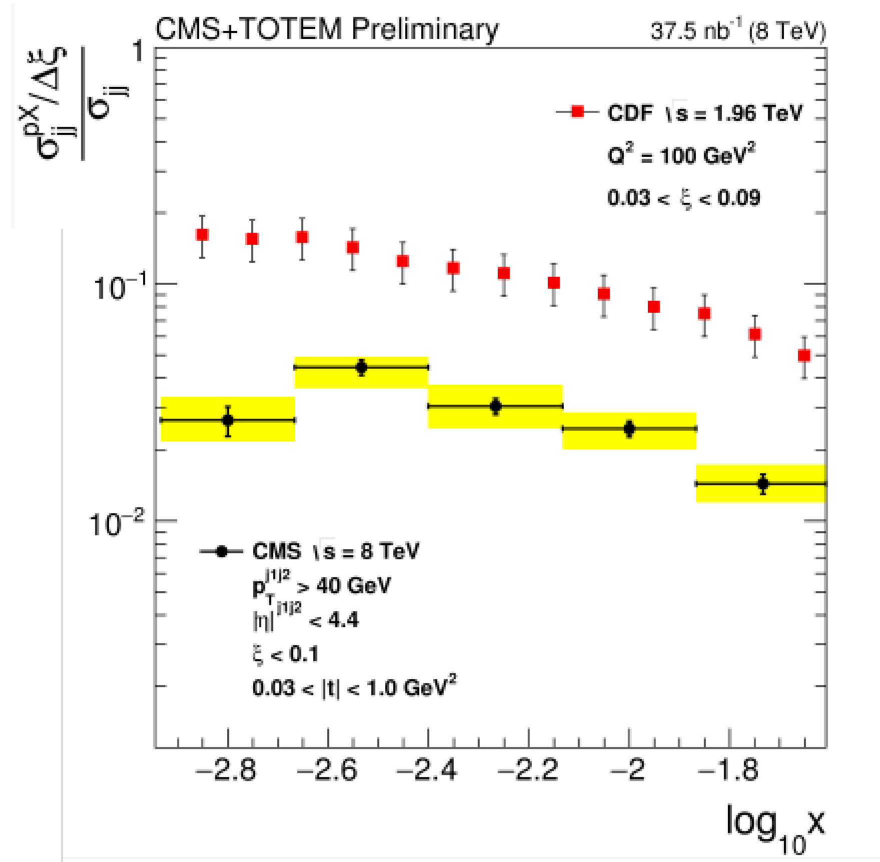
Hard diffraction: di-jet production (2)

- Cross section as a function of ξ
- Ratio of diffractive to inclusive dijets as a function of x

$$x^{\pm} = \frac{\sum_{\text{jets}} \left(E^{\text{jet}} \pm p_z^{\text{jet}}\right)}{\sqrt{s}}$$



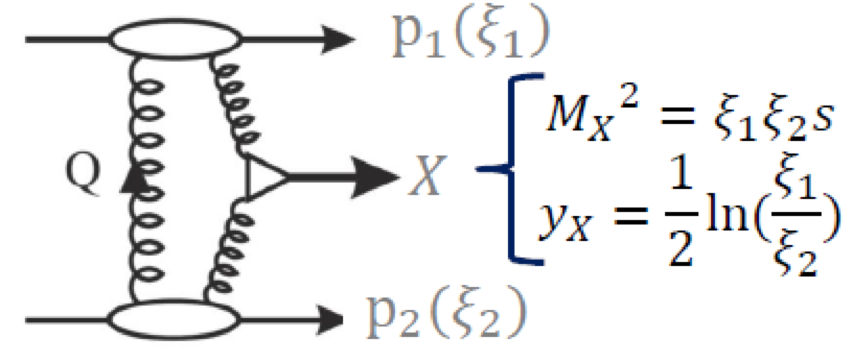




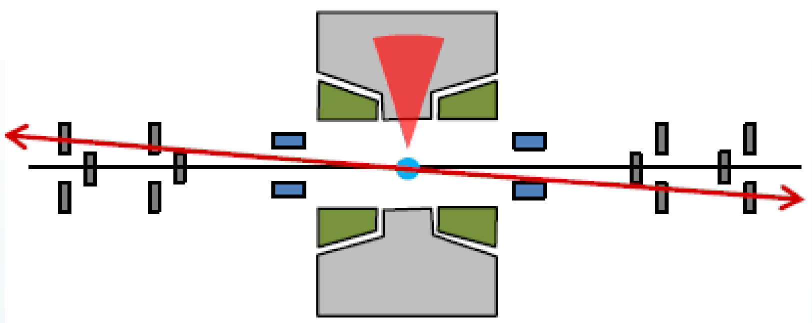
Pythia 8 DG with Dynamic Gap model based on MPI shows good agreement with data

Comparison with CDF results: factor of ~3 suppression wrt to 1.96 TeV, larger contributions from rescattering processes

Central Exclusive Production (with CMS)



$$\begin{cases} M_X{}^2 = \xi_1 \xi_2 s \\ y_X = \frac{1}{2}\ln\left(\frac{\xi_1}{\xi_2}\right) \end{cases}$$



- CMS and TOTEM work together to performs CEP studies
- CMS-TOTEM Trigger information are exchanged and data can be merged offline
- Central exclusivity can be verified via rapidity gaps and forward proton tagging

- selection rules for system X:
  - $J^{PC} = 0^{++}, 2^{++}, \ldots$ (**PP**, gg)
  - $J^{PC} = 1^{--}$ (γ**P**)

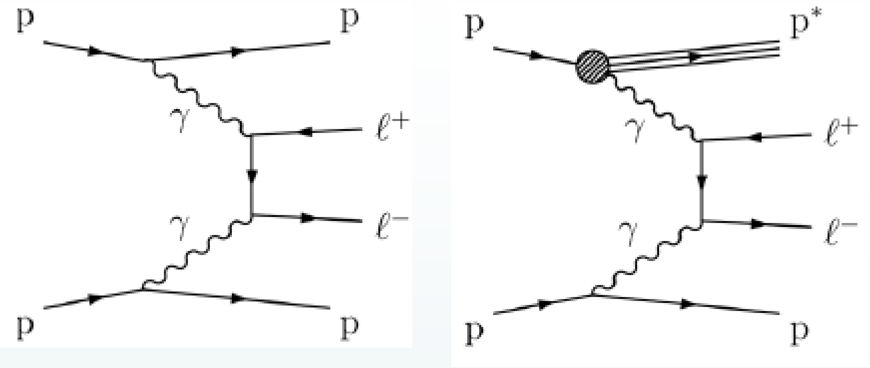
Central Exclusive Production (with CMS)

Low mass resonances and glueballs

- At low ($x \sim 10^{-3} - 10^{-4}$) LHC becomes (a sort of) gluon-gluon collider and CEP is ideal for **glueball production**
  - CEP with $M_X \sim 1 - 4$ GeV produced very purely from gg
- $0^{++}(2^{++})$ glueball candidates: **f_0 (f_2) resonances in 1.3 -1.8 GeV(> 2 GeV) mass range**
- Strategy:
  - determine σ_{CEP} of glueball candidates
  - characterize their decays: $\pi^+\pi^-$, K^+K^-, $\rho^0\rho^0$…
- CMS+TOTEM advantages:
  - Good reconstruction of charged-particle-only events using dedicated low pT tracking
  - Good particle ID and mass resolution ($\sigma(M) \sim 30$ MeV) using CMS tracker
  - RP protons from TOTEM to assure exclusivity ($p_{T,RP} \sim p_{T,tracker}$, $vtx_{RP} \sim vtx_{tracker}$)
- CMS+TOTEM 2015: $L = 0.4\ pb^{-1}$ of high β^* with dedicated low mass CEP trigger

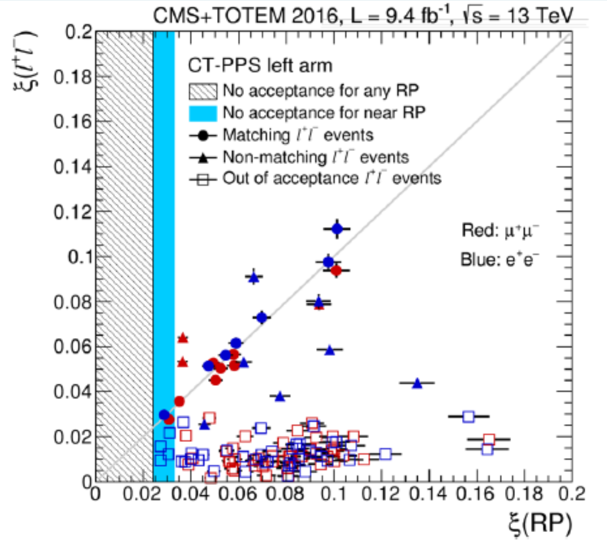
Exclusive $\gamma\gamma \to l^+l^-$ with PPS (1)

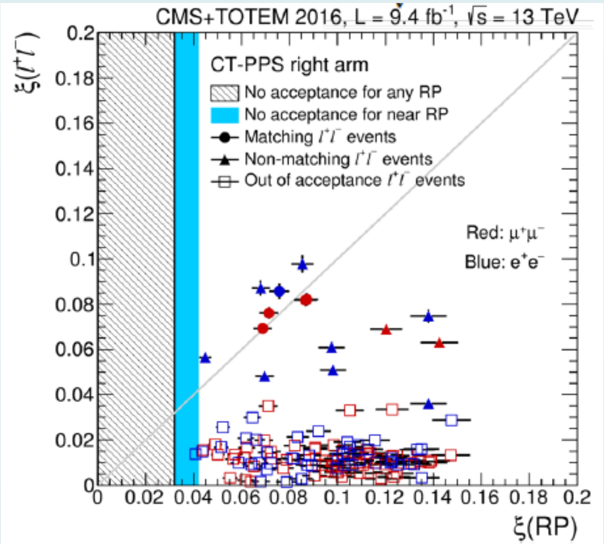
PPS took data as a subdetector of CMS in 2016, 2017 and 2018 high-luminosity runs.
Open the possibility of studying rare processes.



- Initial analysis of “standard candle” process: $\gamma\gamma \to l^+l^-$
- Only 1 proton required, to increase acceptance at lower masses,
- Background from real di-leptons, in coincidence with random RP tracks from pileup or beam-background protons
- **Matching required** – compare ξ calculated from protons and from dileptons

$$\xi(\mu\mu) = \frac{1}{\sqrt{s}} \times \left(p_T(\mu_1)e^{\pm\eta(\mu_1)} + p_T(\mu_2)e^{\pm\eta(\mu_2)}\right),$$



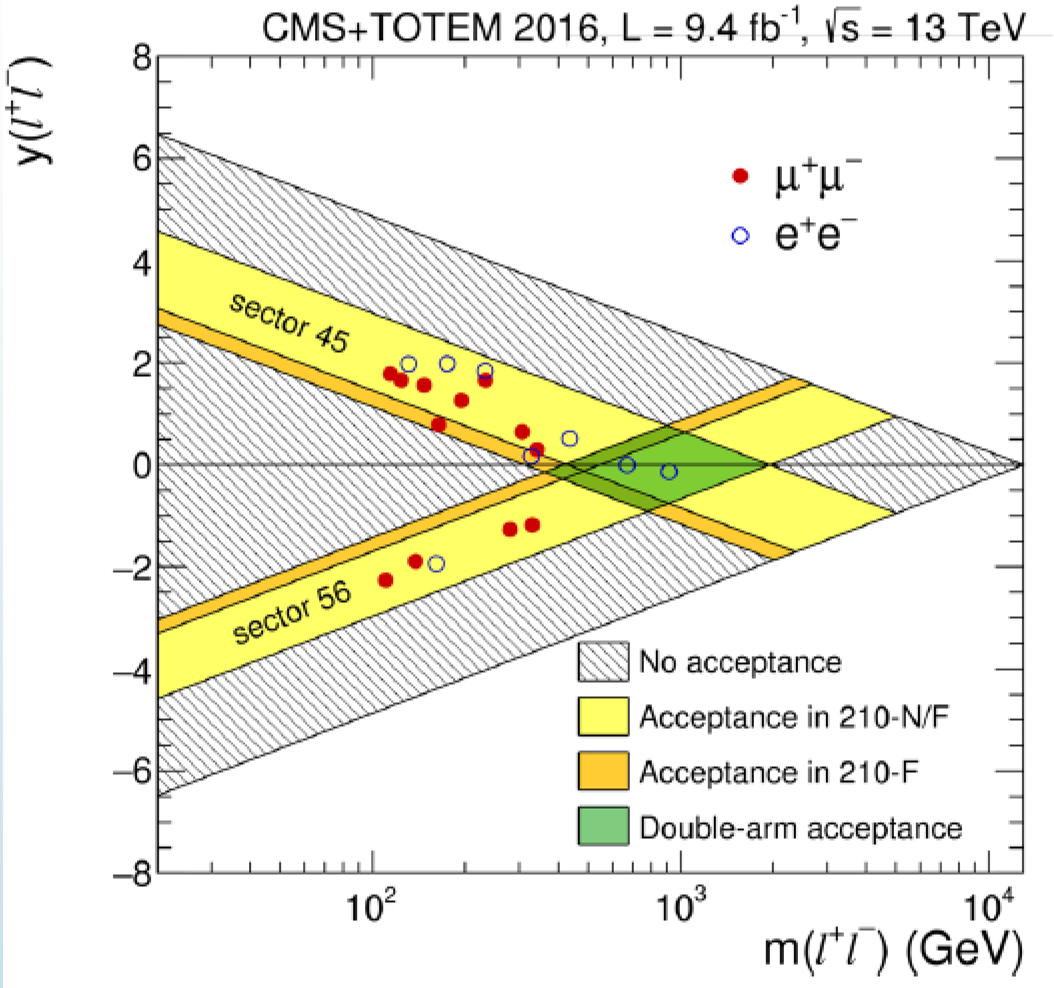


- Observed: 12 μ+μ- and 8 e+e- events with matching kinematics (20 in total)
- Background estimate: 1.49 ± 0.07 (stat.) ± 0.53 (syst.) μ+μ- events 2.36 ± 0.09 (stat.) ± 0.47 (syst.) e+e- events
- Combined significance: **5.1σ**

Exclusive $\gamma\gamma \rightarrow l^+l^-$ with PPS (2)

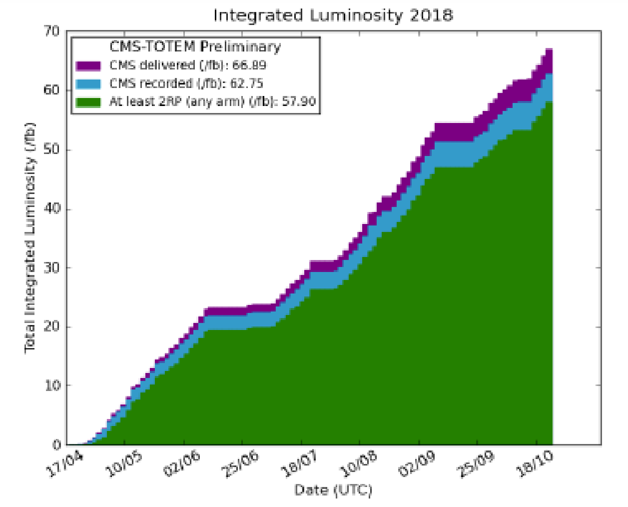
- Event properties:
  - Dilepton mass-rapidity distributions consistent with acceptance for single arm events
  - No double tagged candidates, consistent with Standard Model expectations
  - Mass spectrum from 110 GeV to >900 GeV

Proton-tagged γγ collisions at the EW scale!

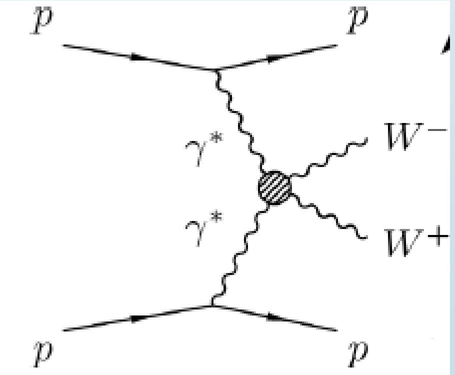


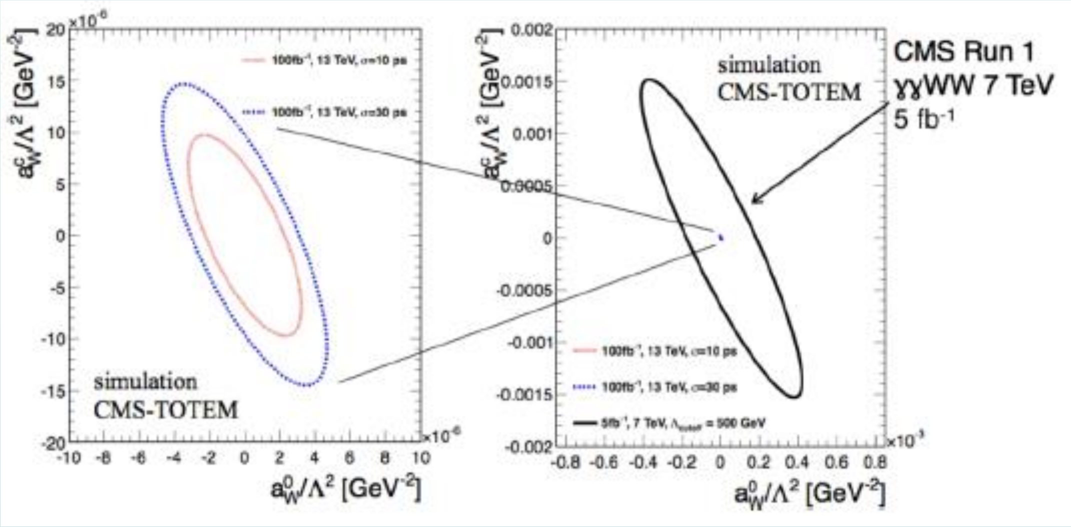
PPS in 2017-2018: data taking and physics prospects

- Si-strip tracking replaced with 3D Si-pixel tracking operation with fast diamond tracking detectors
- About 100/fb of data with RP inserted so far



High-mass/low cross section BSM, electroweak, and QCD & top physics with forward protons, such as gauge boson pair production (WW, ZZ, Zγ, γγ), searches for **anomalous couplings**, new resonances,...





Summary

- High energy diffraction measurements are of the utmost importance to **understand QCD**, especially when soft interactions are involved
- The measurements at the **LHC complete a long series of measurements** done since the beginning of HEP at hadron colliders and sheds new light on questions that were left open, while some still are
- Diffraction can also be used as a tool to select a very clean environment and to allow the measurement of **rare processes**
- Studying **diffraction is a challenge** not only for theorists but also for experimentalists, since dedicated detectors need to be built and operated in very *unfriendly* conditions

Thank you!

Some references

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Aknowledgements

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