Soft (and Hard) QCD Processes in TOTEM

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on behalf of the TOTEM Collaboration

WE-Heraeus Physics School

QCD – Old Challenges and New Opportunities

Bad Honnef, Sept 24–30, 2017

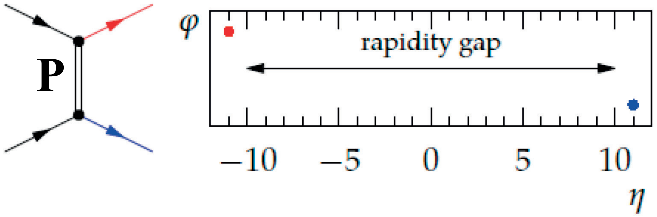
Outline

1. Scope of this presentation: Elastic (and diffractive) pp scattering
2. The TOTEM experiment at the LHC:
   Detector apparatus and measurement principles
3. Elastic cross-section measurements: Overview and highlights
4. Total cross-section measurements
5. In progress: Central-exclusive production of low-mass resonances
6. RP spectrometer upgrades for CT-PPS

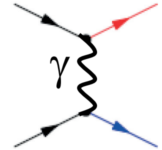
1. Scope: Elastic and Diffractive pp Scattering

Diffractive | **Electromagnetic**

Elastic Scattering (ES), ≈ 25 mb

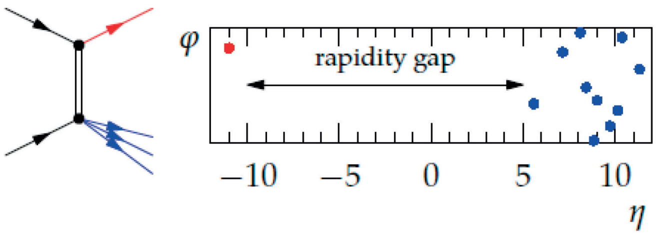


very low momentum transfers
|t| ~ O(10^{-4} GeV^2)



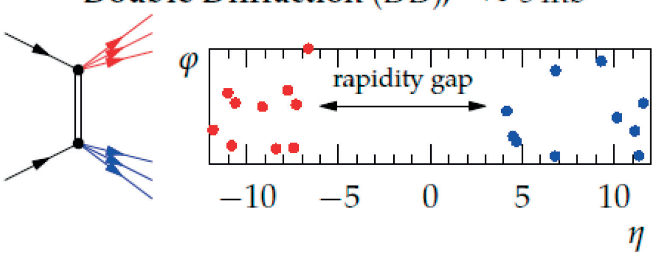
Coulomb scattering

Single Diffraction (SD), ≈ 10 mb



not covered here

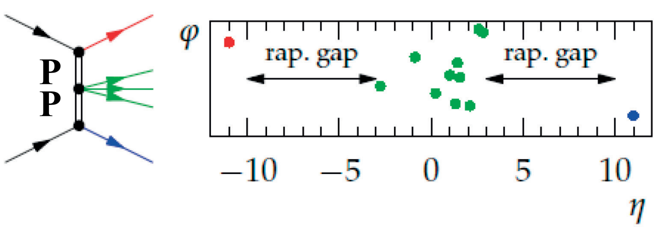
Double Diffraction (DD), ≈ 5 mb



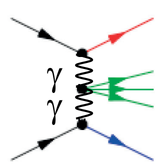
not covered here

Exchange of colourless objects (Pomeron, γ, Odderon?) →
- rapidity gaps
- often surviving forward protons

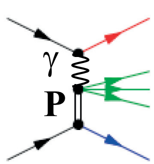
Central Diffraction (CD), ≈ 1 mb



pure QED

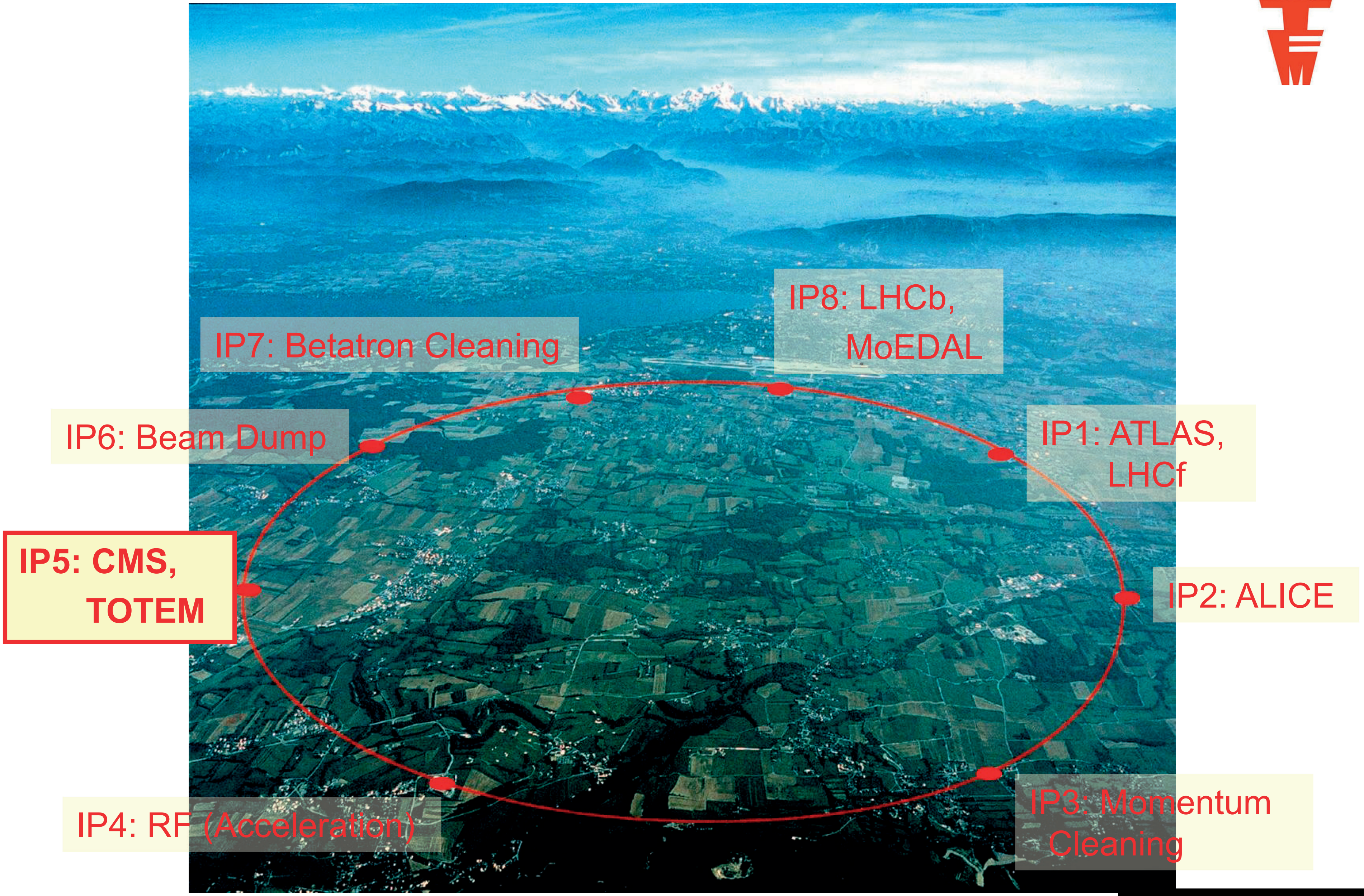


Photoproduction



→ CT-PPS project with CMS

2. The TOTEM Experiment at the LHC



Experimental Setup at IP5 in Run 1

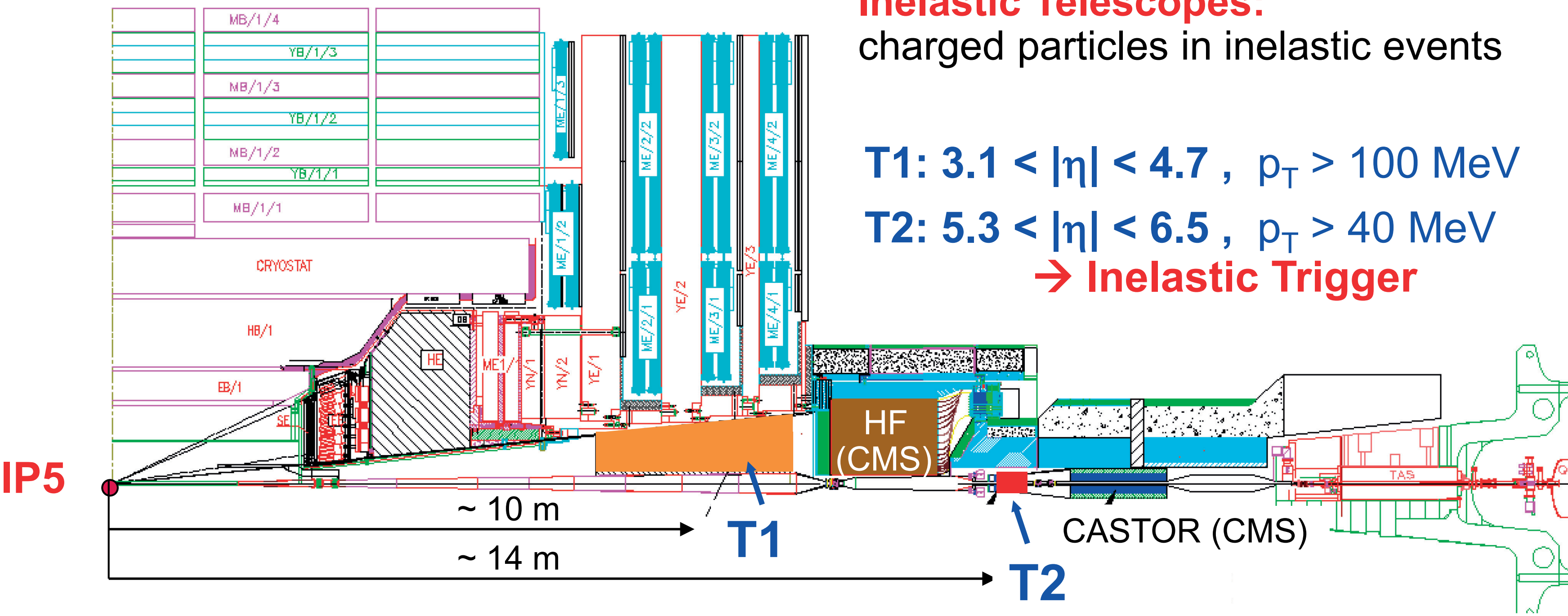
[Ref.: JINST 3 (2008) S08007]

Inelastic Telescopes:
charged particles in inelastic events

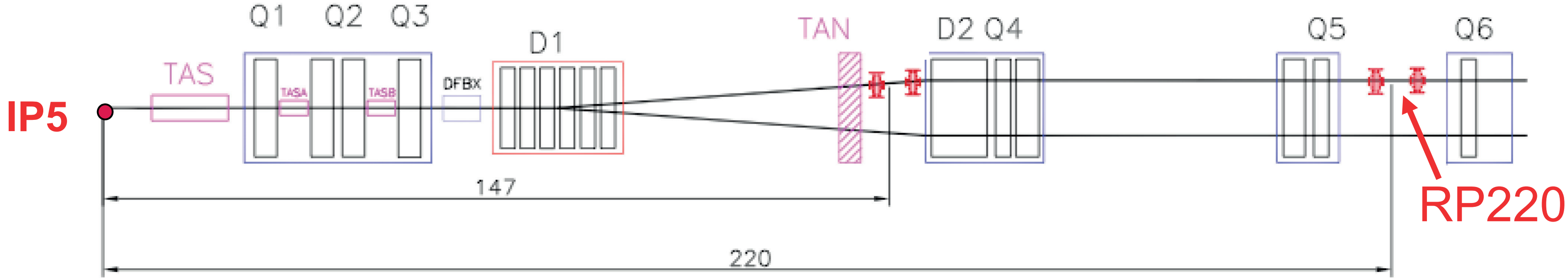
T1: 3.1 < |η| < 4.7 , p_T > 100 MeV

T2: 5.3 < |η| < 6.5 , p_T > 40 MeV

→ Inelastic Trigger



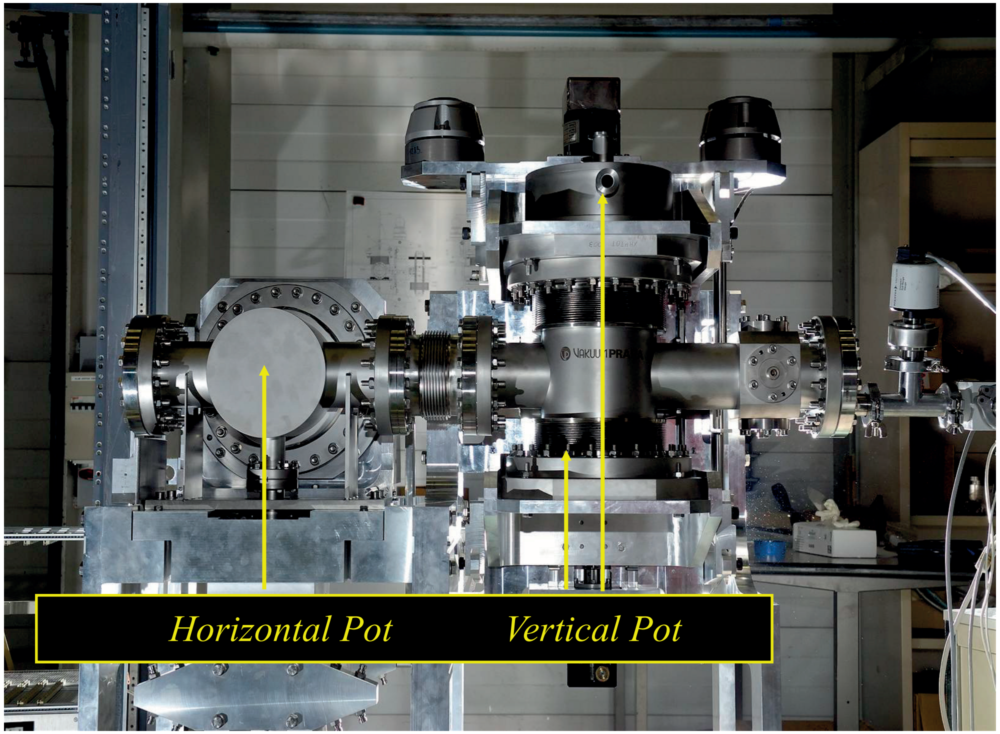
Roman Pots: elastic & diffractive protons close to outgoing beams **→ Proton Trigger**



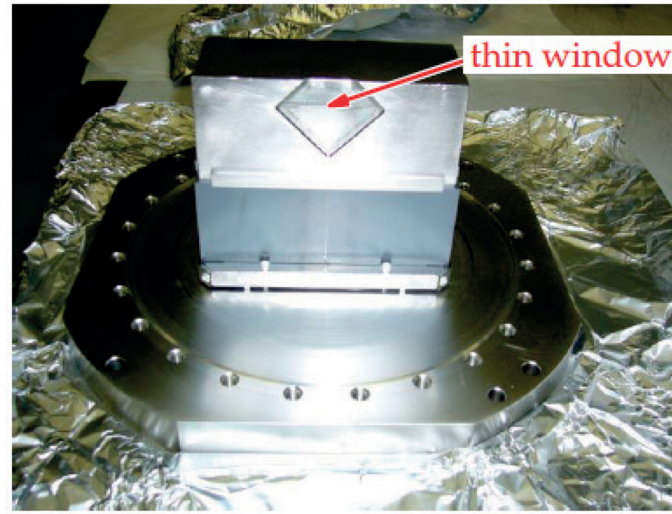
Roman Pots

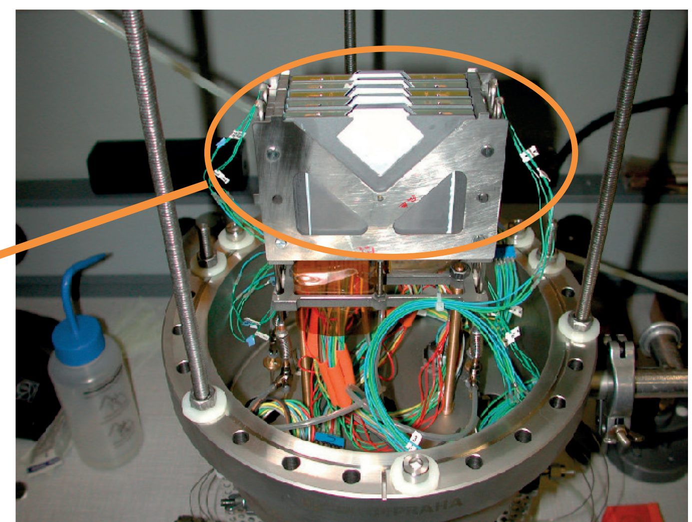
Roman Pot = movable box inside the beam pipe, housing silicon detectors.

Detectors can approach the beam centre to < 1mm when the beams are stable.



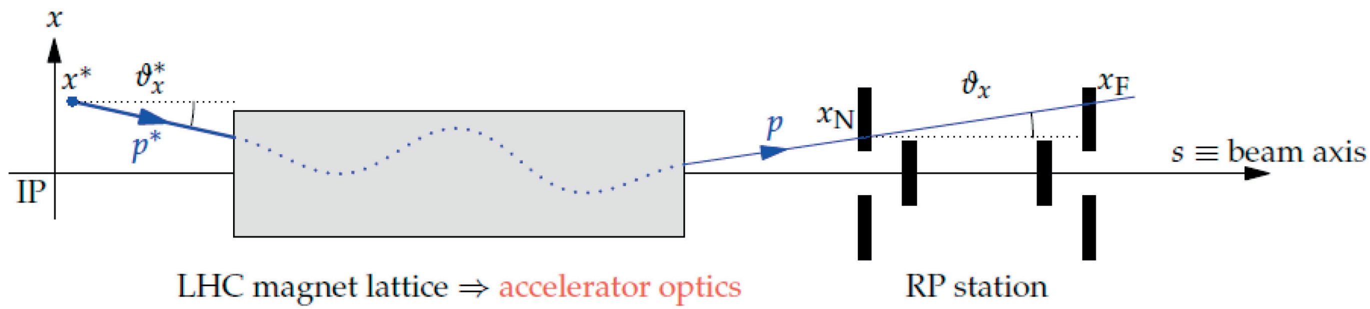
Detector housing





Stack of 10 silicon strip detectors (5 pairs back to back)

Proton Transport and Reconstruction via 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

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

Values at IP5 to be reconstructed

Product of all lattice element matrices

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

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

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 = inversion of transport equation

Excellent beam optics understanding needed.

TOTEM method: optics calibration using proton tracks [New J. Phys. 16 (2014) 103041]

LHC Optics and TOTEM Running Scenario

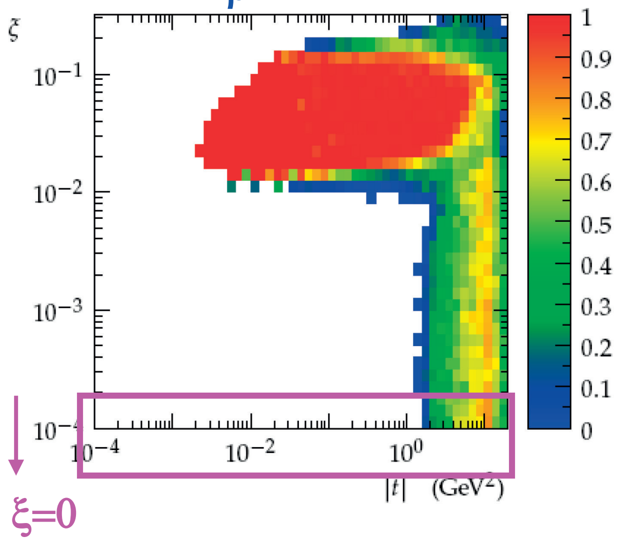
Acceptance for elastic and diffractive protons:

$t \approx -p^2\,\Theta^{*\,2}$: four-momentum transfer squared; $\xi = \Delta p/p$: fractional momentum loss

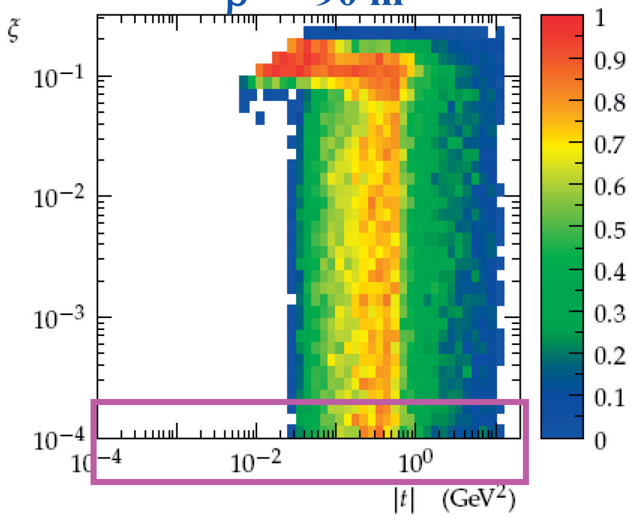
Some typical examples:

$> 10^{33}$ cm^{-2} s^{-1} ← $\mathcal{L} \propto \frac{1}{\beta^*}$ — $\sim 10^{27}$ cm^{-2} s^{-1}

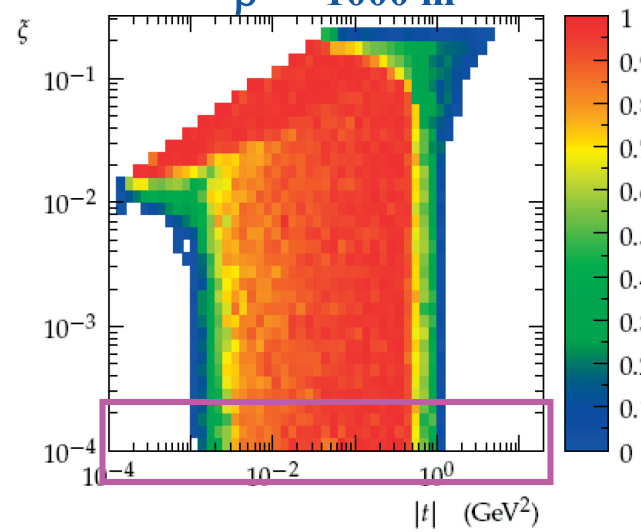
β* = 0.55 m



β* = 90 m



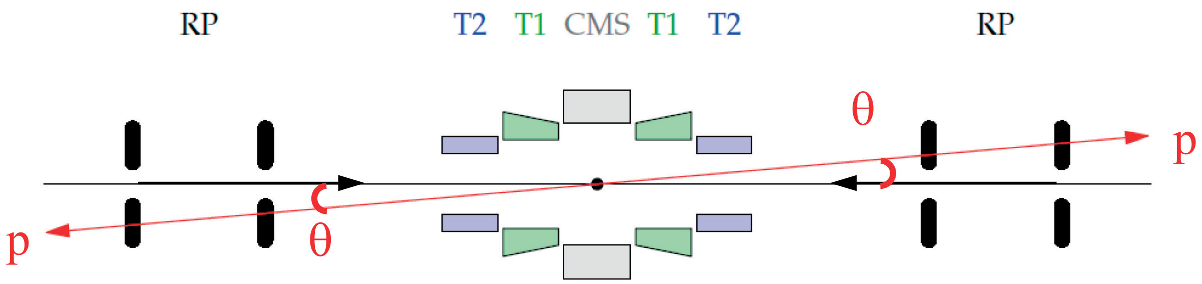
β* = 1000 m



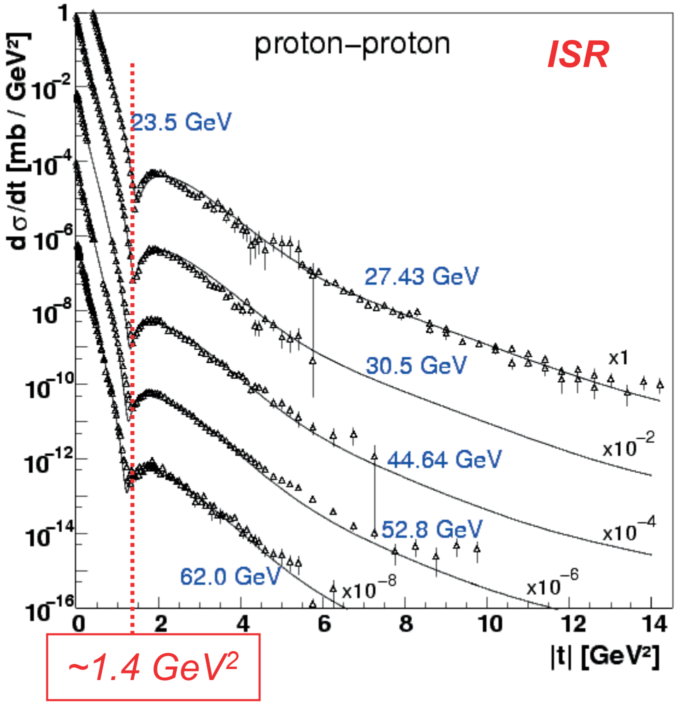
Elastic scattering: special case for ξ = 0

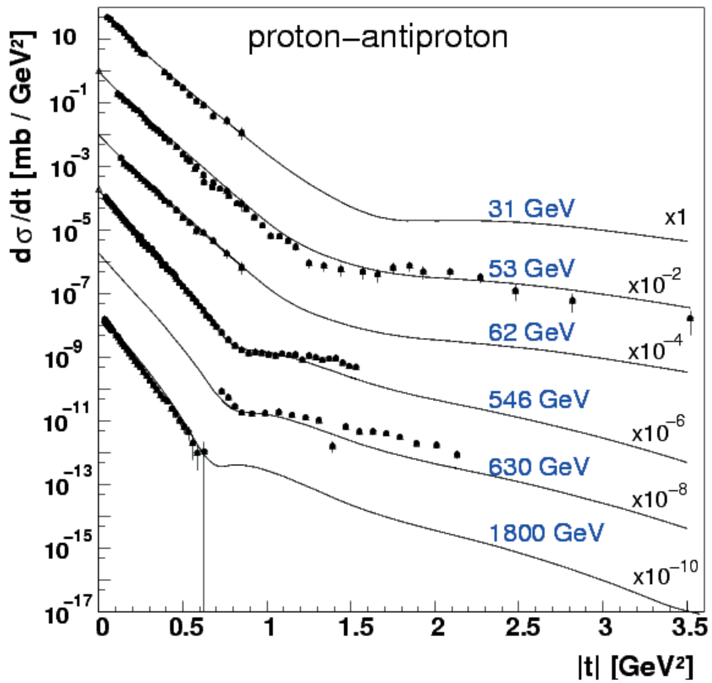
|t| > O(1 GeV^2) — **|t| > O(10^{-2} GeV^2)** — **|t| > few 10^{-4} GeV^2**

3. Elastic Cross-Section Measurements

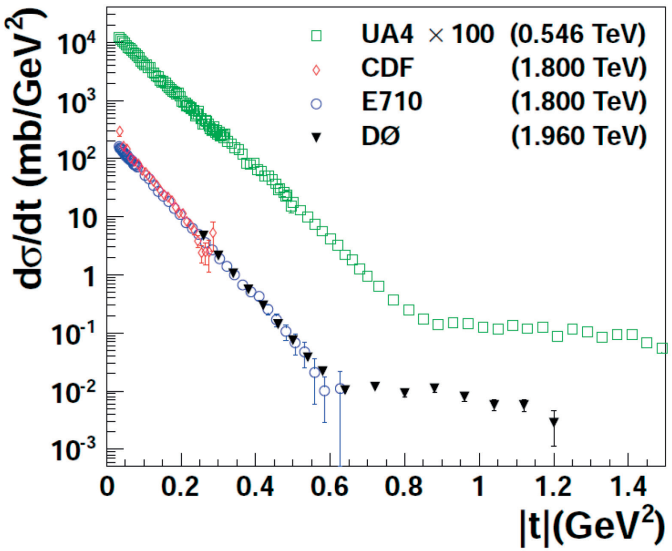


Elastic scattering – from ISR to Tevatron: Old Trends





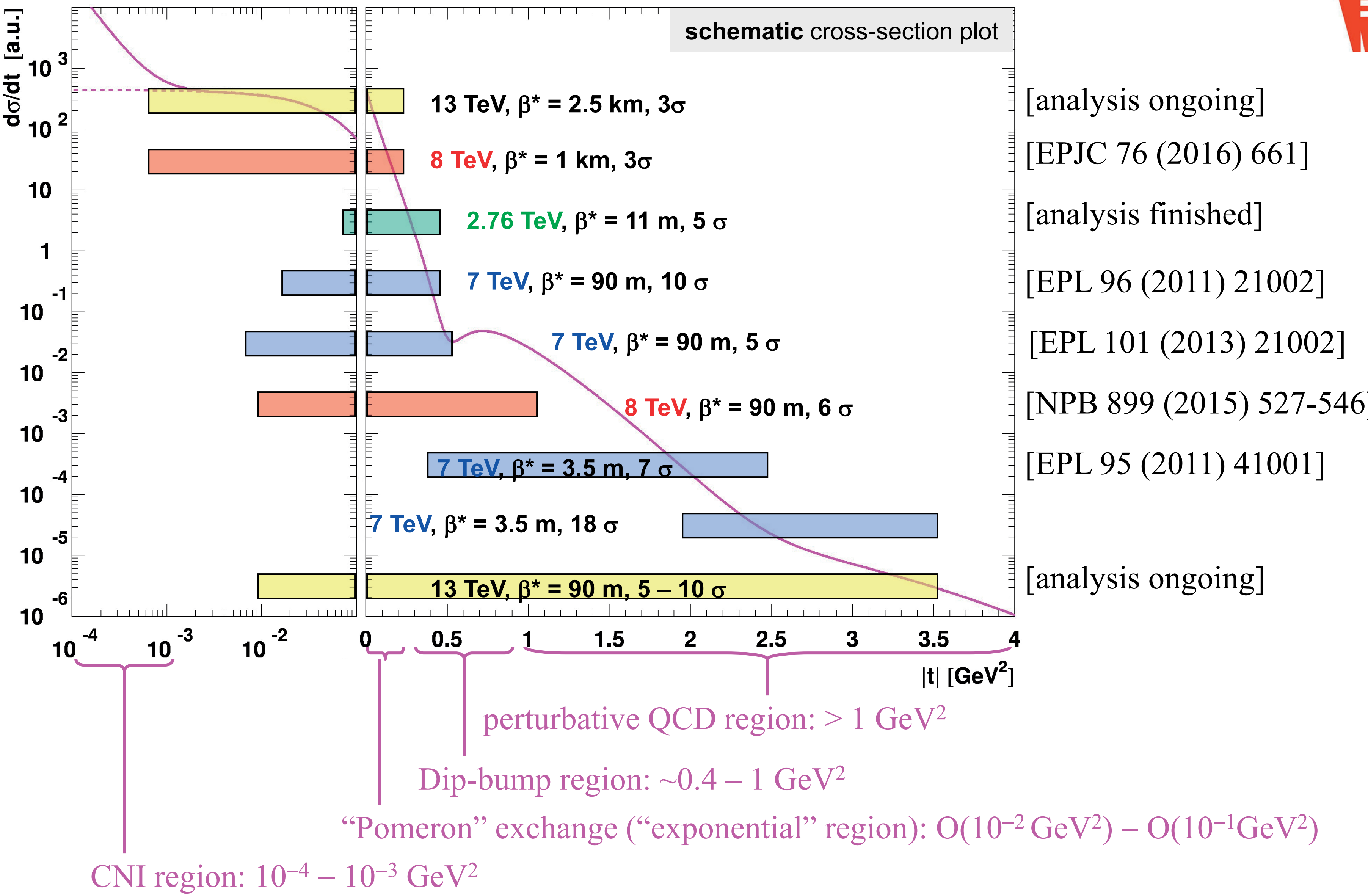
$|t| \approx p^2\ \theta^2$



- *Minimum in pp, shoulder in $\bar{p}p$*
  → *different mix of processes (e.g. Odderon contribution)*
- *Minimum / shoulder moves to lower |t| with increasing s*
  → *interaction region grows (as also seen from σ_{tot})*
- *Exponential slope at low |t| increases with energy*

Elastic Scattering Cross-Section Measurements

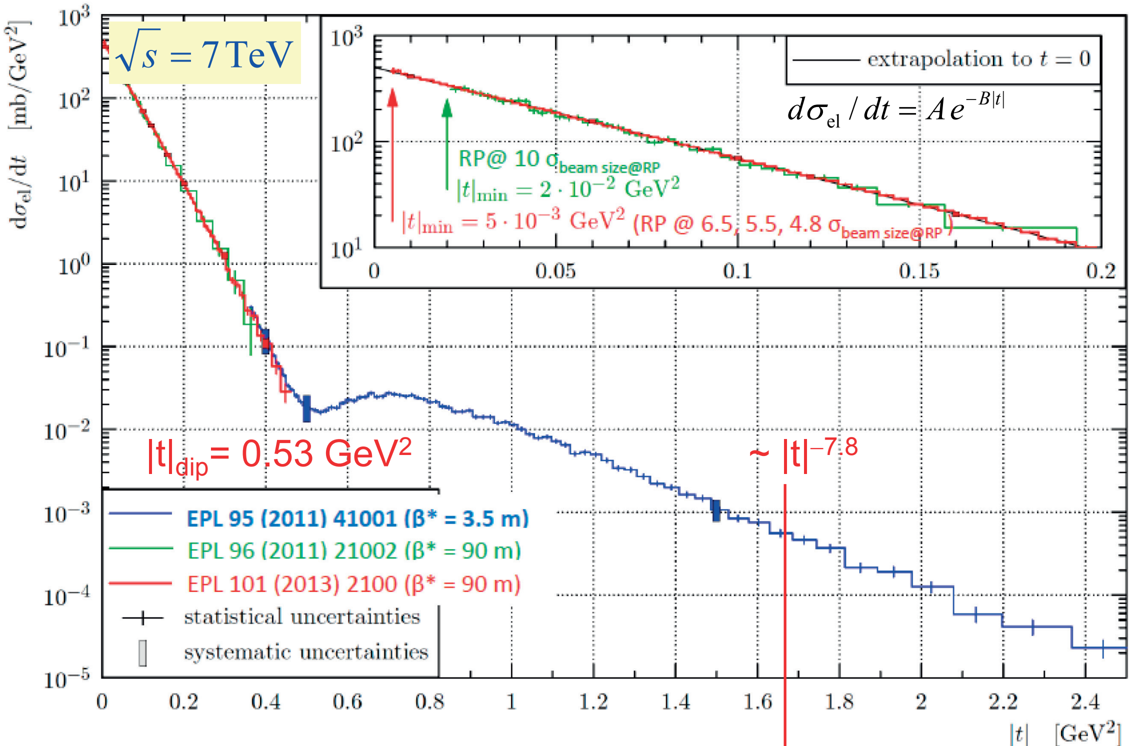
Data sets at different energies covering a wide |t| range

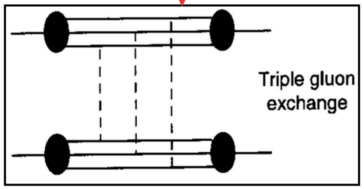


Elastic Scattering: the Dip and beyond (1)

The 7 TeV Measurements

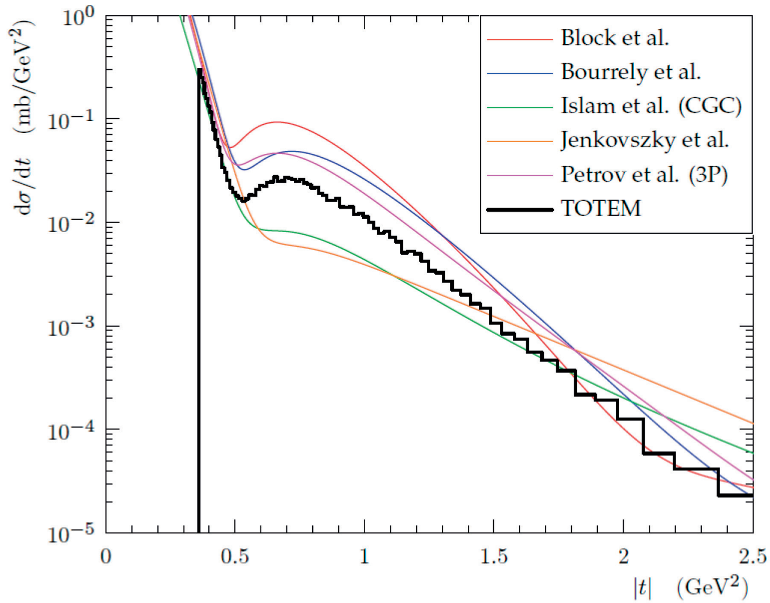
(3 data sets at different optics and RP distances to cover max. t-range)





pQCD (e.g. Donnachie-Landshoff): ~ $|t|^{-8}$

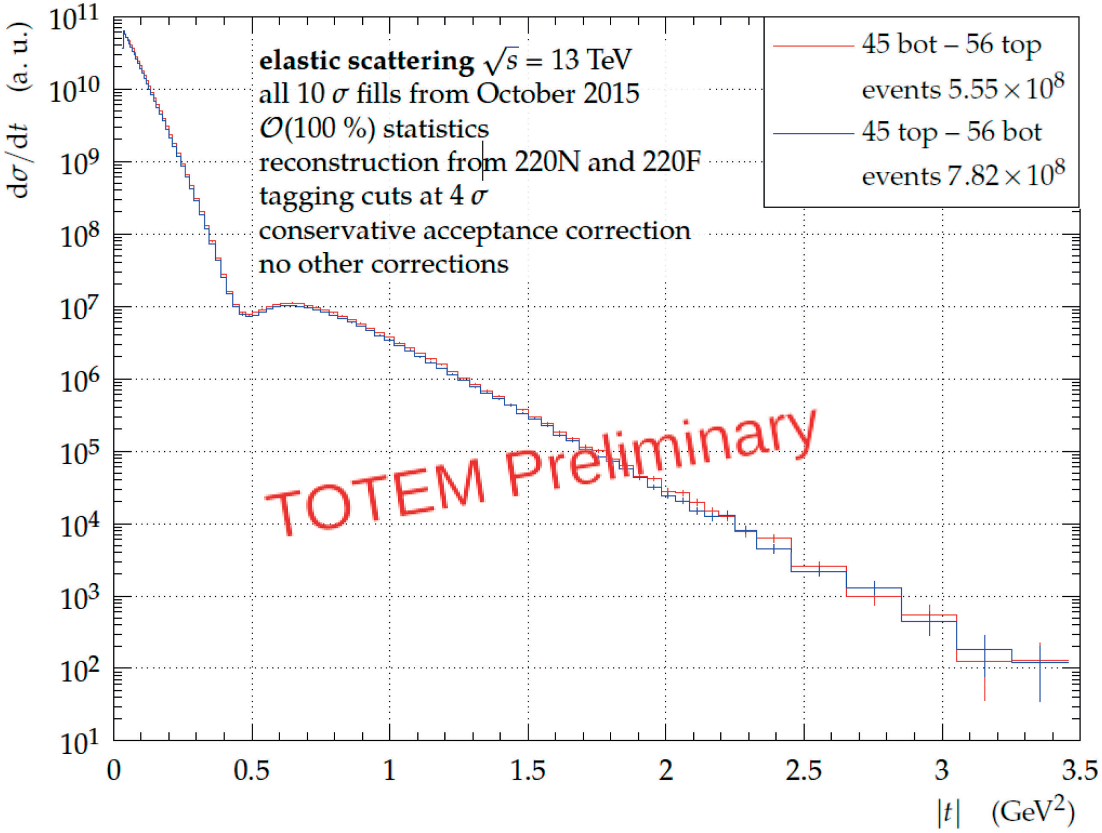
Comparison with 7 TeV Predictions



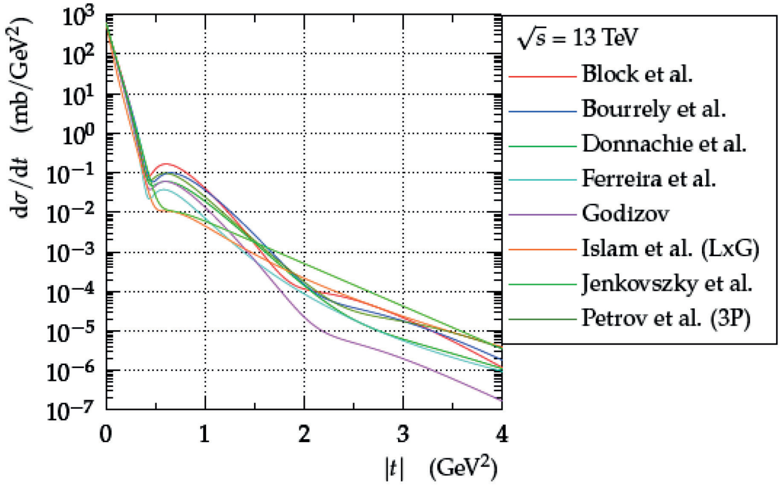
At the time of the first publication:
No model described the TOTEM data.

Elastic Scattering: the Dip and beyond (2)

The 13 TeV Measurement @ $\beta^* = 90$ m (preliminary)



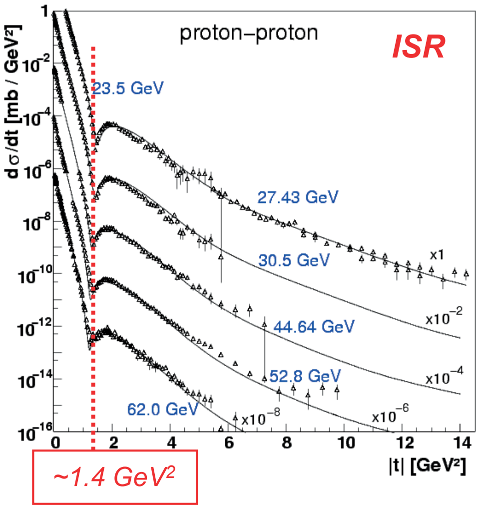
model predictions:

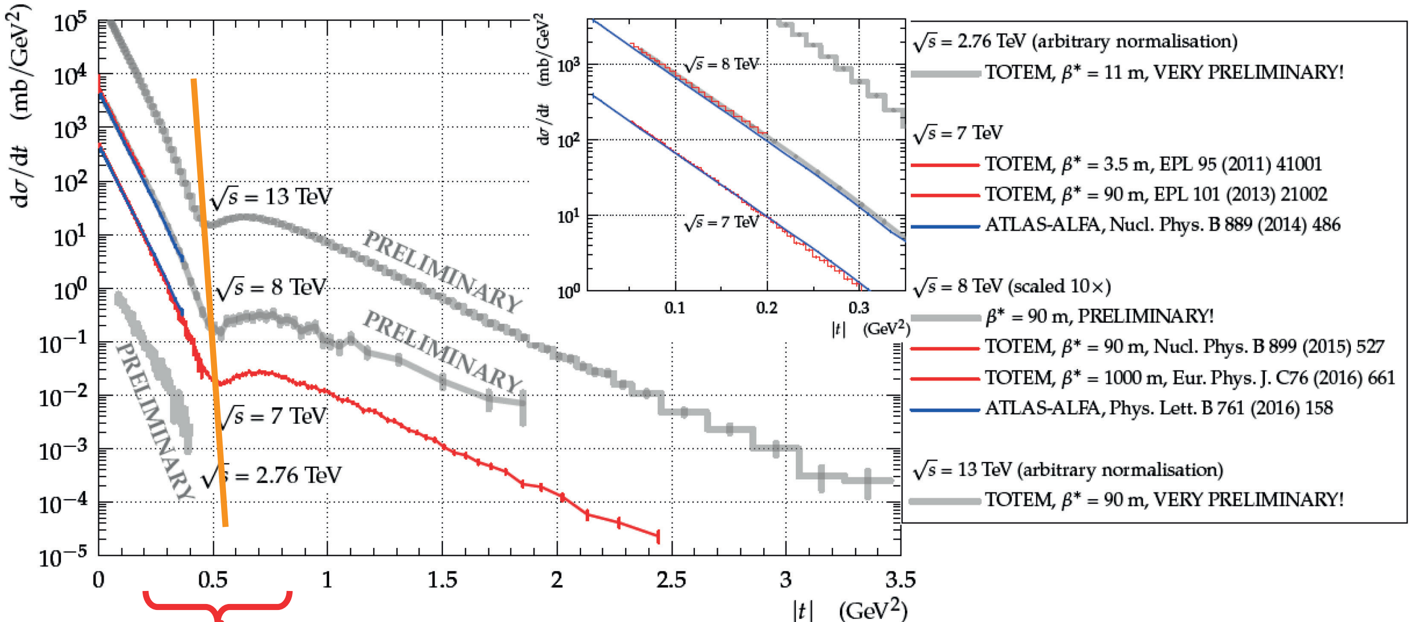


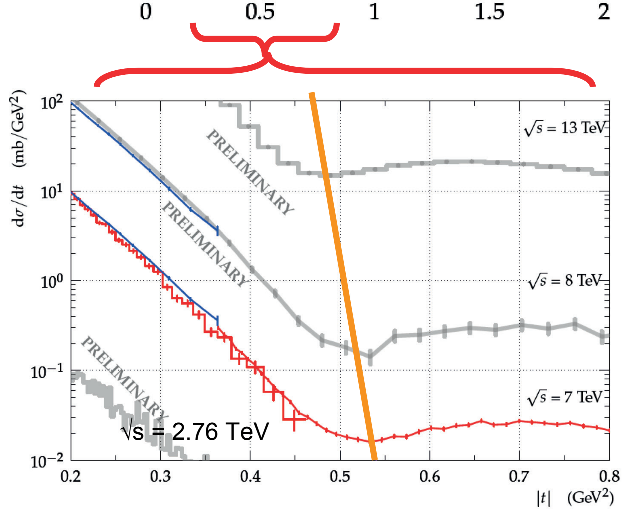
data: no structure at large |t|
→ rules out most models

Elastic Scattering: the Dip and beyond (3)

Dip position: moves to lower |t| with increasing energy





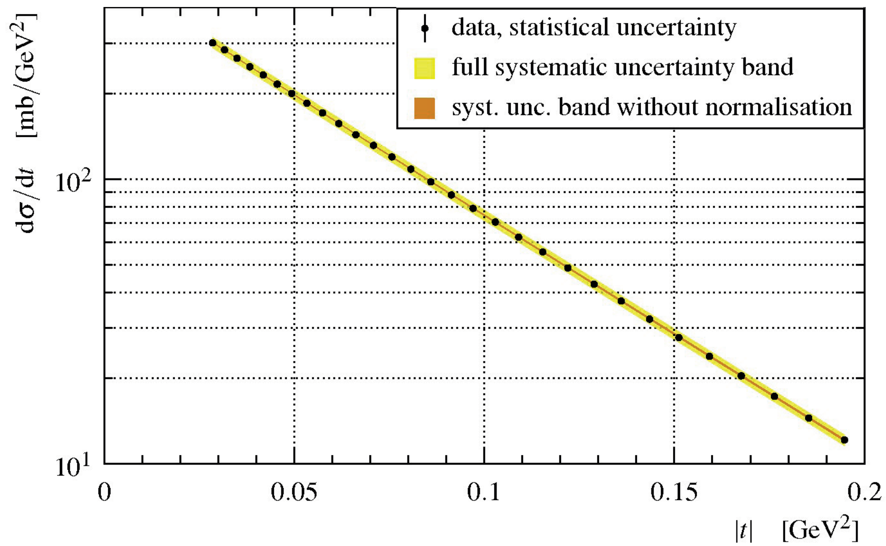


New measurement @ 2.76 TeV, β* = 11m:
very limited t-range (0.08 – 0.4 GeV²) → dip not reached

Elastic Scattering: The "Exponential" Region at low |t| (1)

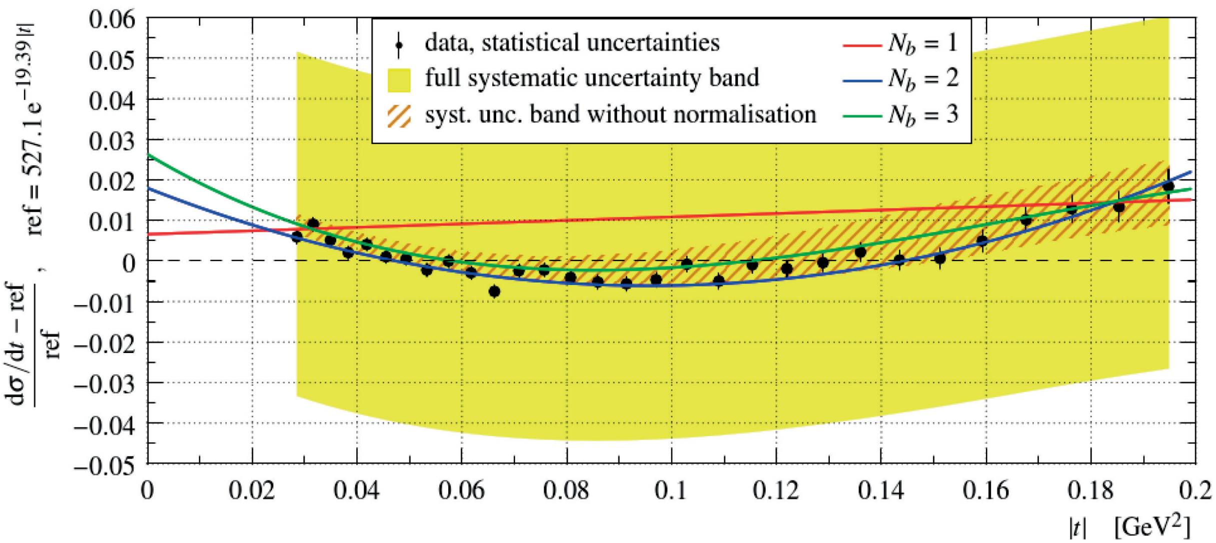
Is it really exponential?

Data set with 7 M events ($\sqrt{s}$ = 8 TeV, β^* = 90 m):
0.027 GeV^2 < |t| < 0.2 GeV^2 ,
i.e. Coulomb effects negligible



Quite exponential at the first glance, but a closer look reveals …

Relative deviation from exponential: $\dfrac{d\sigma/dt - \text{ref}}{\text{ref}}$



$$\frac{d\sigma}{dt}(t) = \left.\frac{d\sigma}{dt}\right|_{t=0} \exp\left(\sum_{i=1}^{N_b} b_i\, t^i\right) ,$$

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

Pure exponential form (N_b = 1) excluded at 7.2 σ significance.
[NPB 899 (2015) 527]

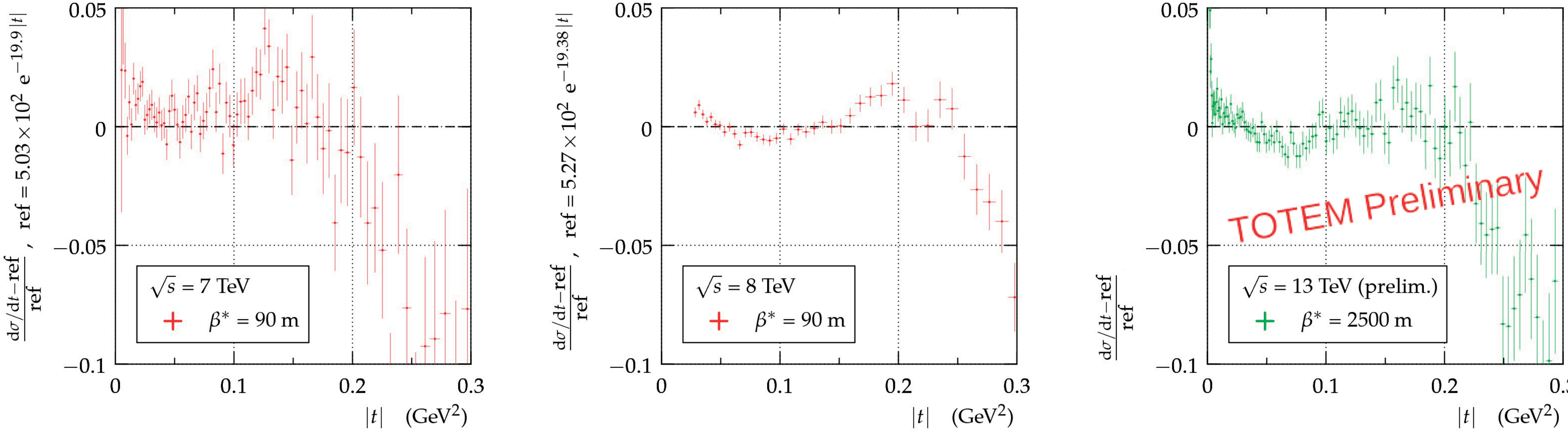
... a percent-level deviation only visible with very high statistics.

Elastic Scattering: The "Exponential" Region at low |t| (2)

Non-exponentiality at $|t| < 0.2$ GeV^2: similar pattern observed also at $\sqrt{s}$ = 7 and 13 TeV

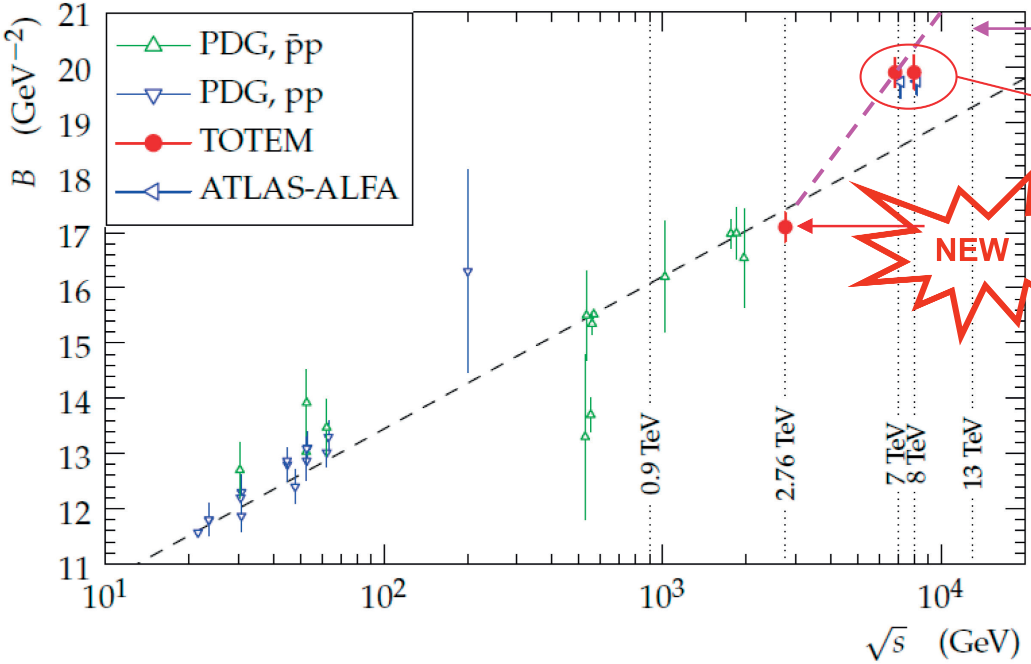
$\frac{d\sigma/dt - \text{ref}}{\text{ref}}$ where ref = fixed exponential function $A\, e^{-B|t|}$

7 TeV **8 TeV** **13 TeV**



Elastic Scattering: The "Exponential" Region at low |t| (3)

Increase of elastic slope $B = \left[\frac{d}{dt}\ln\left(\frac{d\sigma}{dt}\right)\right]\Big|_{t=0}$ with √s :

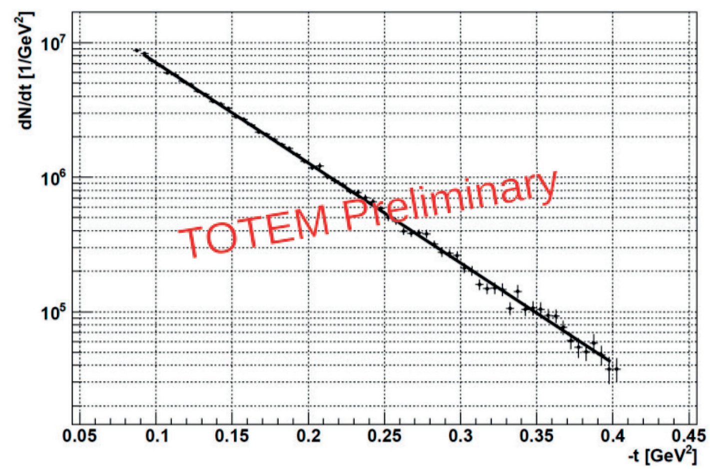


waiting for the 13 TeV point !

compatibility TOTEM - ALFA

TOTEM measurement @ √s = 2.76 TeV:

$B = 17.10 \pm 0.26$ GeV^{-2} ($d\sigma_{el}/dt \propto e^{-B|t|}$)



Dependence of B on fit range included in error bar

Up to ~ 3 TeV: compatible with simple Regge model:

$$\frac{d\sigma}{dt} \propto s^{2[\alpha(t)-1]}, \quad \alpha(t) = \alpha_0 + \alpha' t \quad \Rightarrow B = B_0 + 2\alpha' \ln s$$

Higher energies: multi-Pomeron exchanges: B ∝ ln s → (ln s)^2 [A. Donnachie, P.V. Landshoff: PRD 85 (2012) 094024]

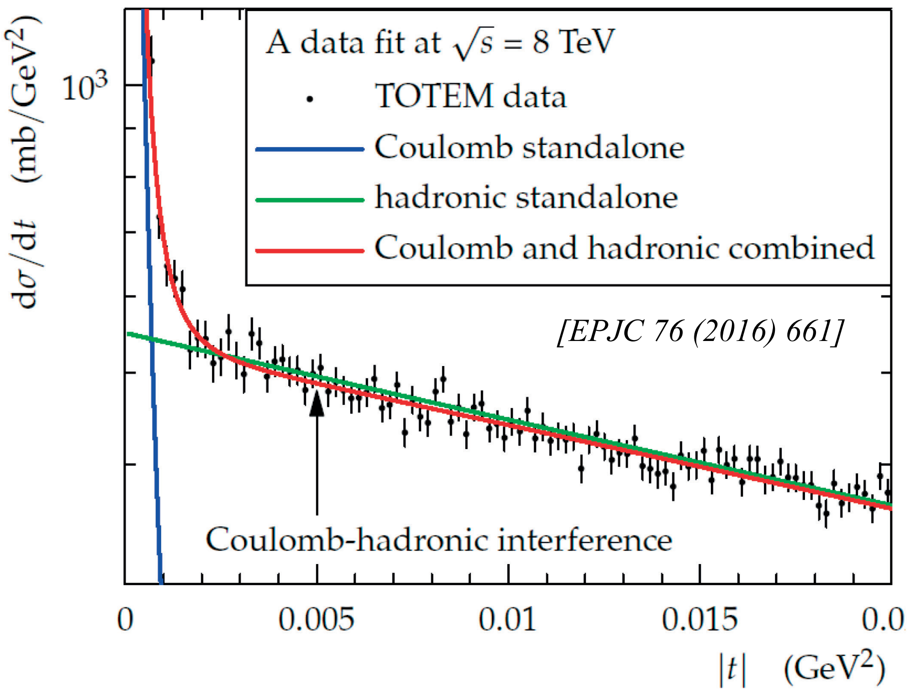
Intermediate energy point between 3 and 4 TeV would be helpful.

Elastic Scattering: Coulomb-Nuclear Interference Region (1)

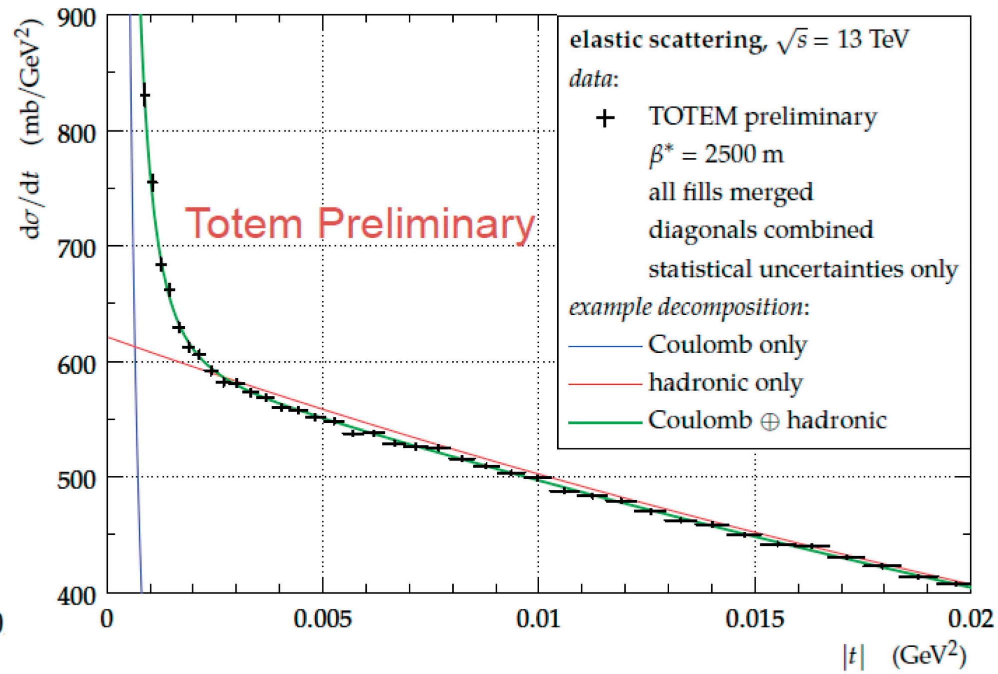
Measure elastic scattering at |t| as low as 6 x 10^{-4} GeV^2:

- optics specially developed for measurements at very low |t|
- RP approach to 3 σ from the beam centre

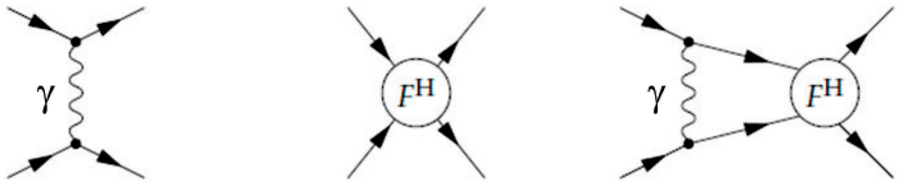
√s = 8 TeV, β* = 1000 m



√s = 13 TeV, β* = 2500 m



Elastic Scattering: Coulomb-Nuclear Interference Region (2)



$$F^{C+H} = F^C + F^H e^{i\alpha\Psi}$$

$$F^C = \frac{\alpha s}{t}\mathcal{F}^2(t)$$

- Modulus constrained by measurement in nucl. region: $d\sigma/dt \cong A\, e^{-B(t)\,|t|}$
  $B(t) = b_0 + b_1\, t + \ldots$
- Phase $\arg(F^H)$: very little guidance by data

Simplified West-Yennie (SWY) formula (standard in the past):

- constant slope $B(t) = b_0$ → already excluded by 90m data at higher |t| → SWY incompatible with data !
- constant hadronic phase $\arg(F^H) = p_0$
- $\Psi(t)$ acts as real interference phase

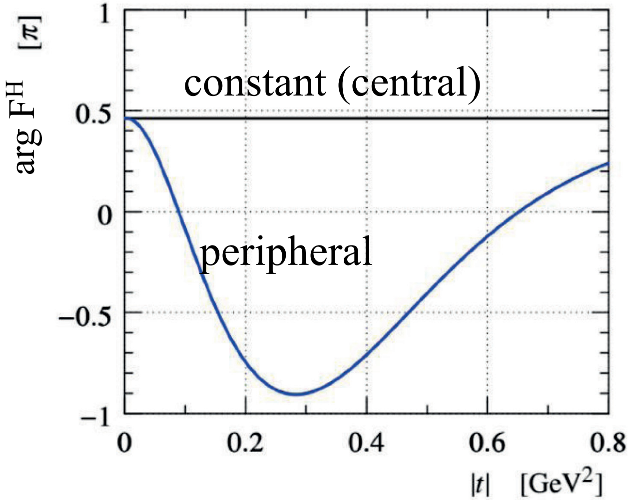
Cahn or Kundrát-Lokajíček (KL) formula:

- any slope $B(t)$
- any hadronic phase $\arg(F^H)$: to be chosen as input
- complex $\Psi(t)$!

Elastic Scattering: Coulomb-Nuclear Interference Region (3)

Choice of hadronic phase arg $F^H(t)$ controls the behaviour in impact-parameter space (b)

Phase examples:

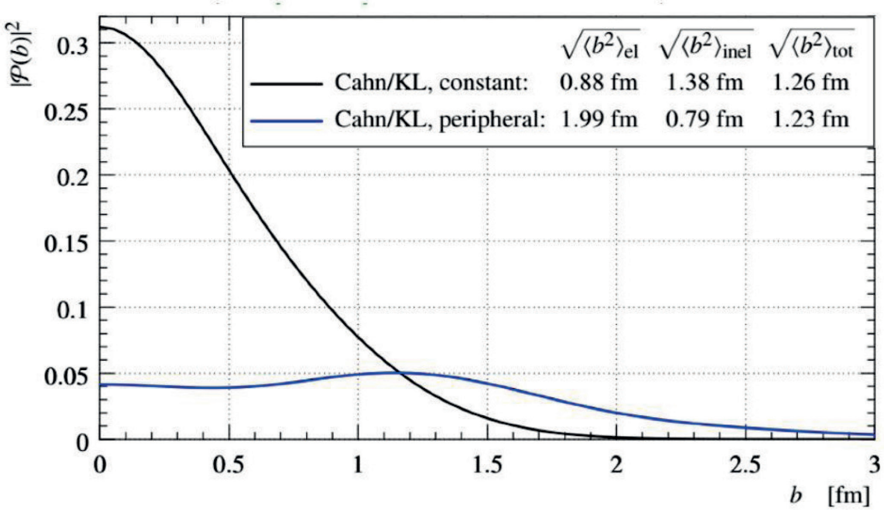


$$\arg F(t) = p_0$$

$$\arg F(t) = p_0 + \zeta_1 \left|\frac{t}{t_0}\right|^{\kappa} \exp(\nu t) \quad (t_0 = 1\,\mathrm{GeV}^2)$$

$$\rho = \frac{\Re F^H(0)}{\Im F^H(0)} = \cot \arg F^H(0) = \cot p_0$$ in both cases.

Impact parameter distributions:



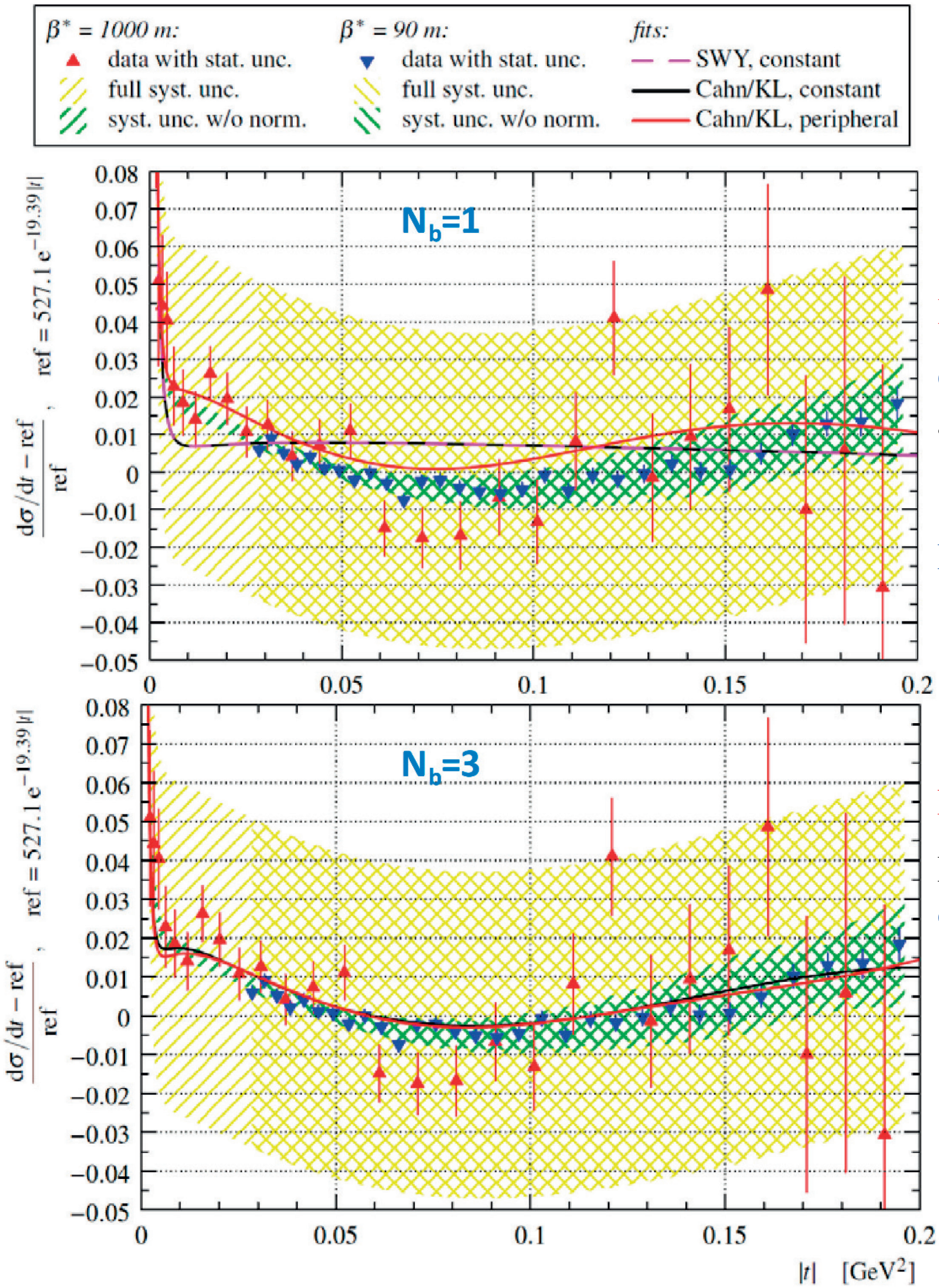
constant (central): most commonly used:
$\langle|b|\rangle_{el} < \langle|b|\rangle_{inel}$

peripheral:
$\langle|b|\rangle_{el} > \langle|b|\rangle_{inel}$

[EPJC 76 (2016) 661]

TOTEM 8 TeV data compatible with both phases (same result for ρ: 0.12 ± 0.03)
→ elastic pp scattering not necessarily central

Elastic Scattering: Coulomb-Nuclear Interference Region (4)



Purely exponential hadronic amplitude (N_b=1)

Central phase excluded (with SWY, Cahn & KL) → application of SWY formula excluded too

($\rho = 0.05$ with very bad fit)

Peripheral phase not explicitly excluded by data

($\rho = 0.10$)

Non-exponential hadronic amplitude (N_b=3)

Both central & peripheral phase compatible with data → centrality not a necessary description for elastic scattering

Same result $\rho = 0.12 \pm 0.03$
for central and peripheral phase

Elastic Scattering: Coulomb-Nuclear Interference Region (5)

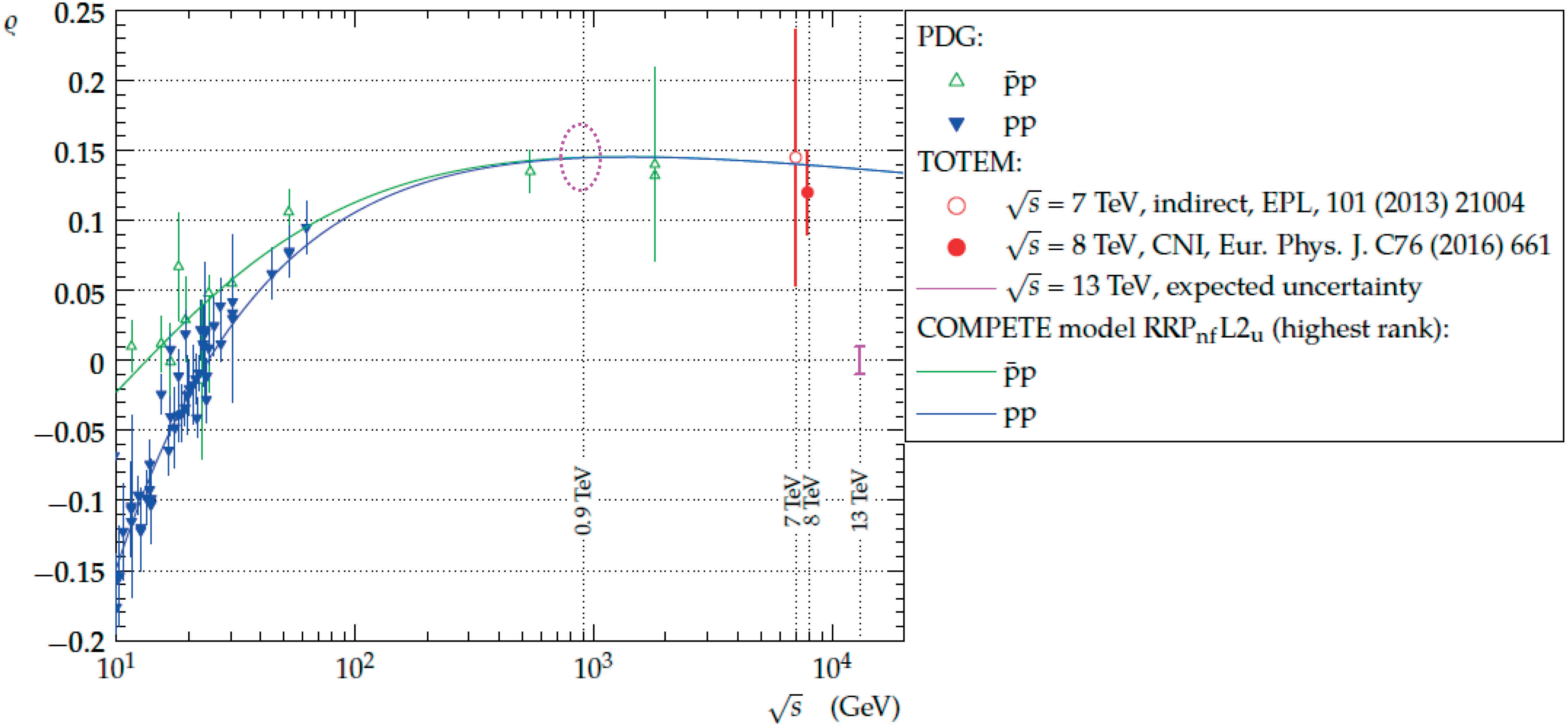
TOTEM

$$\rho = \frac{\Re F^H(0)}{\Im F^H(0)} = \cot \arg F^H(0)$$

- via dispersion relation: prediction of σ_{tot} at higher energies:

$$\rho(s) = \frac{\pi}{2\sigma_{tot}(s)} \frac{d\sigma_{tot}}{d\ln s} \quad \text{(first order)}$$

- sensitive to presence of Odderon [Nicolescu, Gauron]:
  would decrease ρ at 13 TeV: $\Delta\rho \approx -0.04$ (data uncertainty: $\sigma(\rho) \approx 0.01$!)



No pp measurements between ISR and 7 TeV → TOTEM request for 2017: special run @ $\sqrt{s}$ = 900 GeV

4. Total pp Cross-Section

Total Cross-Section: Methods and Results

7 TeV

elastic observables only: (with optical theorem)

$$\sigma_{tot}^2 = \frac{16\pi}{1+\varrho^2} \frac{1}{\mathcal{L}} \left.\frac{dN_{el}}{dt}\right|_0$$

(ρ=0.14 [COMPETE extrapolation])

June 2011: σ_{tot} = (98.3 ± 2.8) mb [EPL 96 (2011) 21002]

Oct. 2011: σ_{tot} = (98.6 ± 2.2) mb [EPL 101 (2013) 21002]

different beam intensities !

σ_{tot}

ϱ independent: (without optical theorem)

$$\sigma_{tot} = \frac{1}{\mathcal{L}}(N_{el} + N_{inel})$$

σ_{tot} = (99.1 ± 4.3) mb

luminosity independent: (with optical th.)

$$\sigma_{tot} = \frac{16\pi}{1+\varrho^2} \frac{dN_{el}/dt|_0}{N_{el} + N_{inel}}$$

σ_{tot} = (98.0 ± 2.5) mb

8 TeV

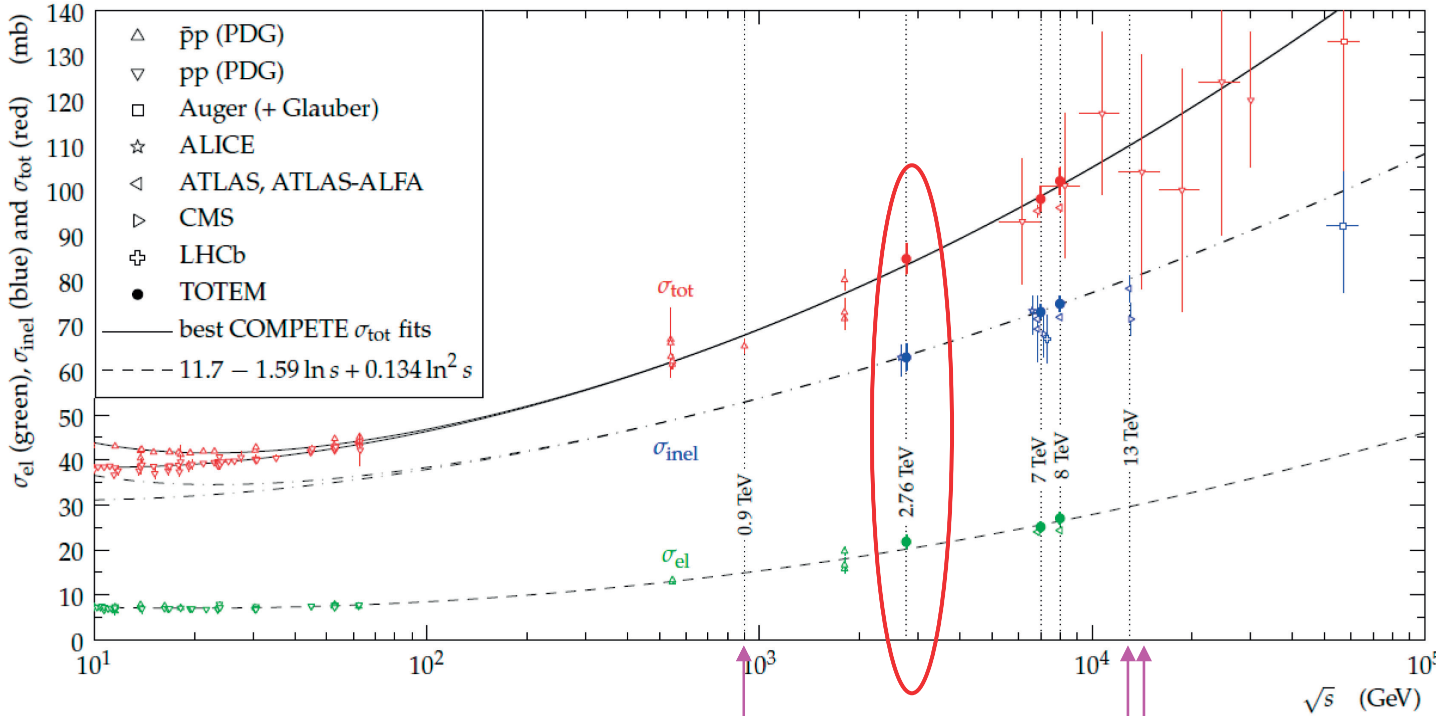
- Luminosity-independent (β* = 90 m): σ_{tot} = (101.7 ± 2.9) mb [PRL 111(2013) 012001]
- Combining β* = 90 m & 1 km data: Improved extrapolation of hadronic amplitude to t = 0 (Coulomb interference measured) & simultaneous ρ determination: [EPJC 76 (2016) 661]
  σ_{tot} = (102.9 ± 2.3) mb (assuming central hadronic phase)
  σ_{tot} = (103.0 ± 2.3) mb (assuming peripheral hadronic phase)

2.76 TeV

[preliminary]

Luminosity-independent: σ_{tot} = (84.7 ± 3.3) mb using ρ = 0.145 [COMPETE]

pp Cross-Section Measurements



New TOTEM result
@ √s = 2.76 TeV

σ_{tot} = 84.7 ± 3.3 mb

σ_{inel} = 62.8 ± 2.9 mb

σ_{el} = 21.8 ± 1.4 mb

ALICE @ √s = 2.76 TeV:

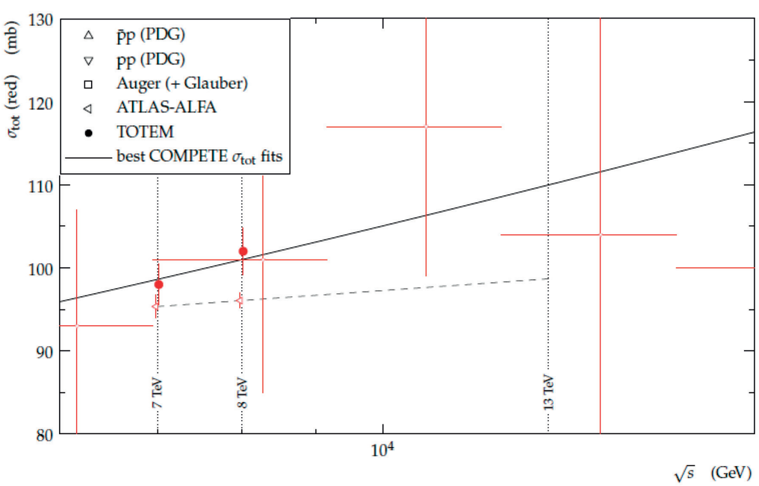
$\sigma_{inel} = 62.8\ ^{+2.4}_{-4.0} \pm 1.2$ mb

ALICE coll., EPJC 73 (2013) 2456

900 GeV: planned for 2017

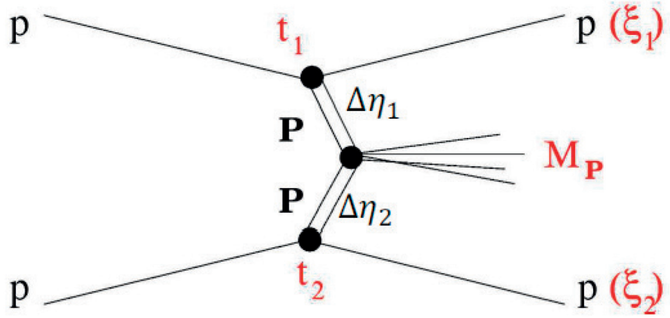
14 TeV: foreseen for LHC Run 3

13 TeV: analysis in progress

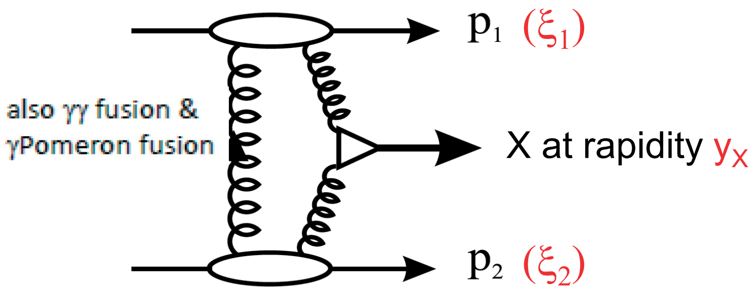


8 TeV: tension with ATLAS-ALFA due to normalisation
(elastic slopes compatible)

5. Central Production of Low-Mass Resonances (with CMS)

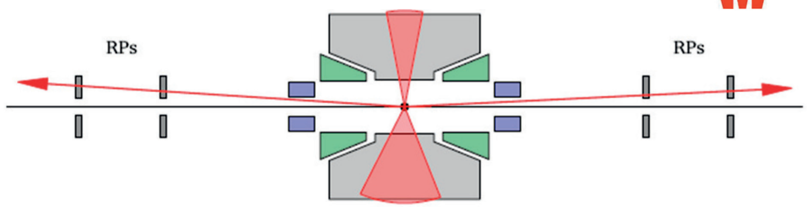


Central Exclusive Production: General Principle



$$M_X^2 = \xi_1 \xi_2 s$$

$$y_X = \frac{1}{2} \ln \frac{\xi_1}{\xi_2}$$



- Exchange of colour singlets with vacuum quantum numbers
  → selection rules for system X: $J^{PC} = 0^{++}, 2^{++}, \ldots$ (for **PP** exchange)

- Tagging with double-arm proton detection compared to rapidity-gap based tag:
  - no contamination by proton-dissociation events with particles only in uninstrumented regions
  - Prediction of rapidity gap from proton ξ: $\Delta\eta_{1,2} = -\ln \xi_{1,2}$
  - But: mass reach and luminosity depending on optics

- Event selection via comparison of central system (CMS) with proton kinematics (TOTEM):
  M(pp) =? M(central), p_T(pp) =? p_T(central), vertex(pp) =? vertex(central)

Examples:

- Studies of low-mass glueball candidates
- Exclusive $\chi_{c1,2,3}$ and J/Ψ production
- Search for missing mass signals

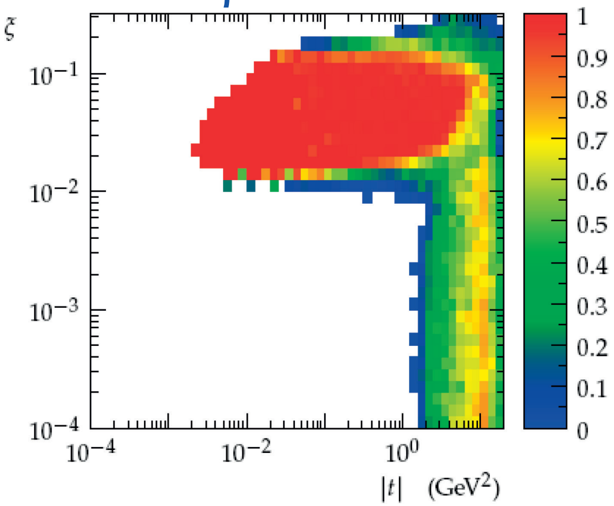
LHC Optics and Diffractive Acceptance

Acceptance for elastic and diffractive protons:

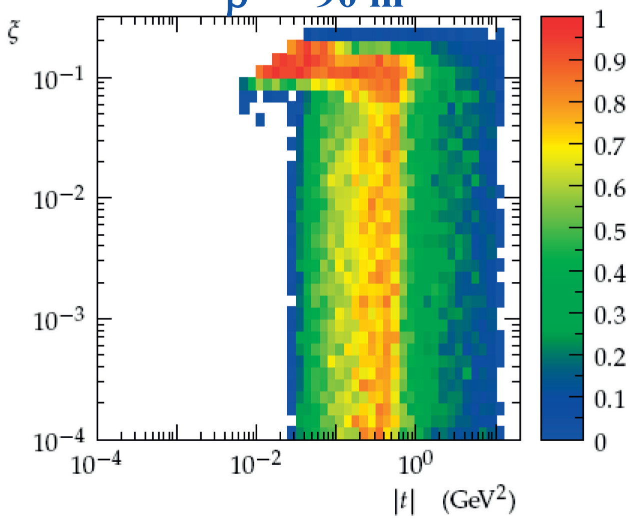
$t \approx -p^2\,\Theta^{*2}$: four-momentum transfer squared; $\xi = \Delta p/p$: fractional momentum loss

$> 10^{33}$ cm^{-2} s^{-1} ← $\mathcal{L} \propto \dfrac{1}{\beta^*}$ → $\sim 10^{27}$ cm^{-2} s^{-1}

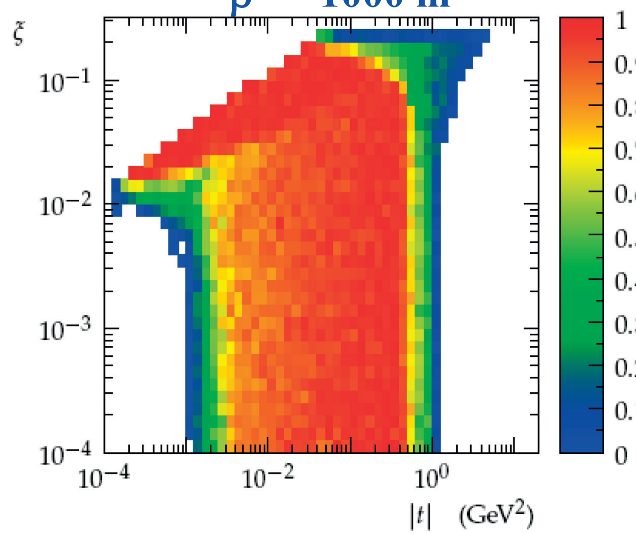
β* = 0.55 m



β* = 90 m



β* = 1000 m



Diffraction:
$\xi > \sim 0.01$
$M > \sim 300$ GeV

→ CT-PPS project

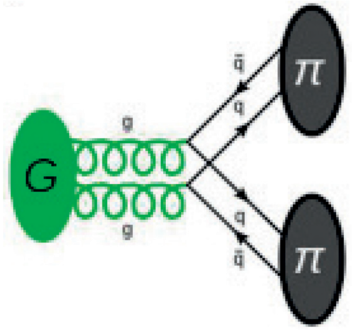
Diffraction:
all ξ if $|t| > \sim 10^{-2}$ GeV^2
all M

→ low-mass studies @ 90 m!

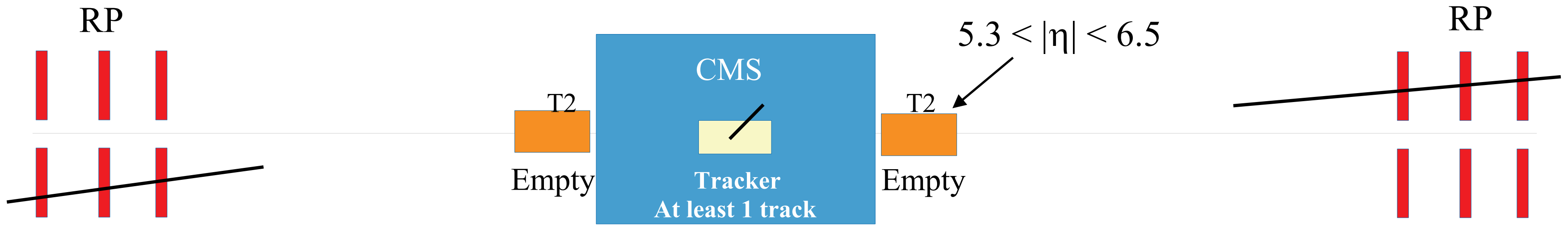
Lumi too low for diffraction

Central Exclusive Production of Low-Mass Resonances, Search for Glueball Candidates

- Pomeron ~ colourless gluon pair/ladder → Pomeron fusion likely to produce glueballs
- CEP with gluons of $x \sim 10^{-3} - 10^{-4}$ → pure gluon pair gives $M_X \sim 1 - 4$ GeV
- Lattice QCD: lightest glueball has $J^{PC} = 0^{++}$; next one 2^{++}.
- $0^{++}(2^{++})$ glueball candidates: **f_0 (f_2) resonances in 1.3 – 1.8 GeV (> 2 GeV) mass range:** recently favoured candidates: **$f_0(1370)$, $f_0(1500)$, $f_0(1710)$ and $f_J(2220)$**



- Strategy:
  - determine σ_{CEP} of glueball candidates
  - characterize their decays and branching ratios: $\pi^+\pi^-$, K^+K^-, $\rho^0\rho^0$, $\Phi\Phi$, ...
  - with more statistics: spin-parity analysis
- CMS+TOTEM advantages:
  - Good reconstruction of charged-particle-only events using new, dedicated low-pT tracking
  - Good particle ID (dE/dx) 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 at 13 TeV in 2015: **$L = 0.4$ pb^{-1}** at $\beta^* = 90$ m with dedicated low mass CEP trigger



Low-Mass Resonance CEP: Background Rejection (p_T Balance)

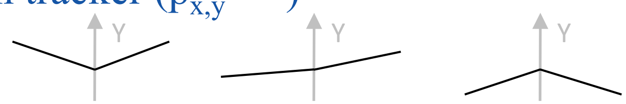
$pp \rightarrow p + \pi^+\pi^- + p$ candidates

M resol. via proton ξ not good enough at small M

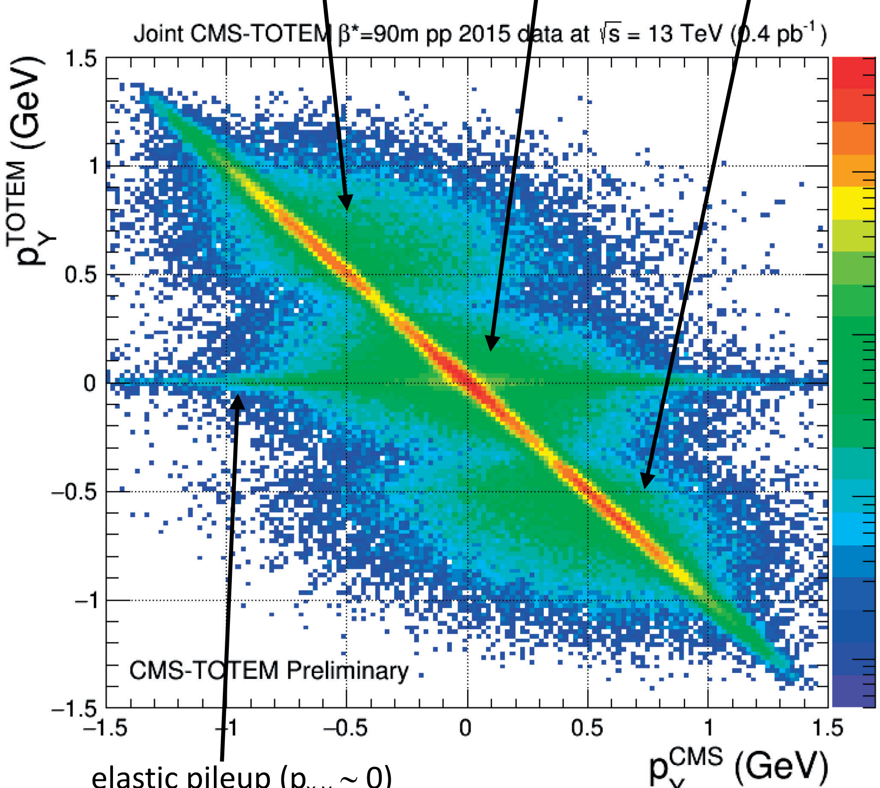
but:

Transverse momentum sum of protons ($p_{x,y}^{TOTEM}$) vs. transverse momentum sum of charged particles in tracker ($p_{x,y}^{CMS}$)

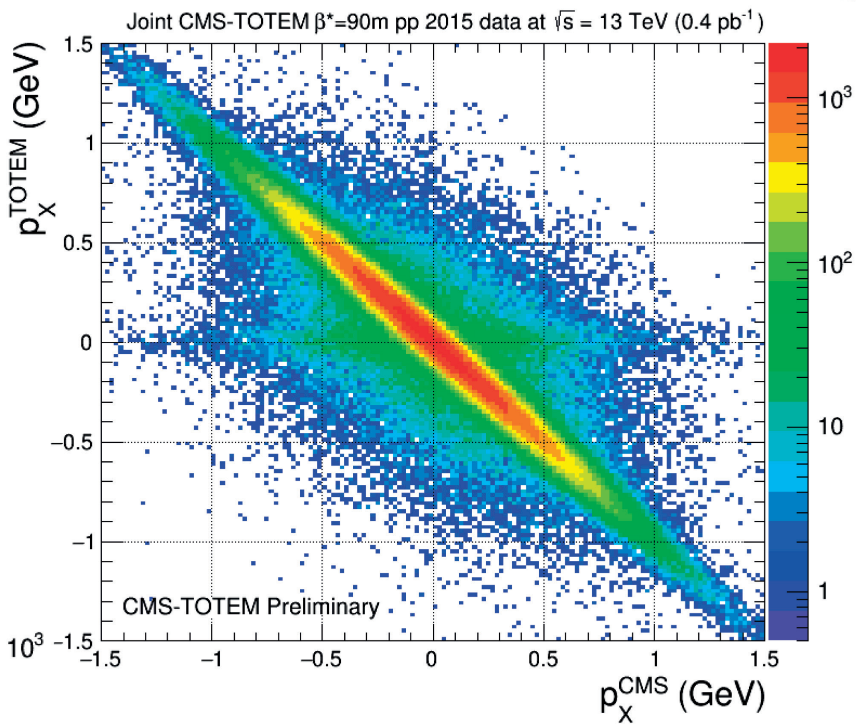
Different proton configurations

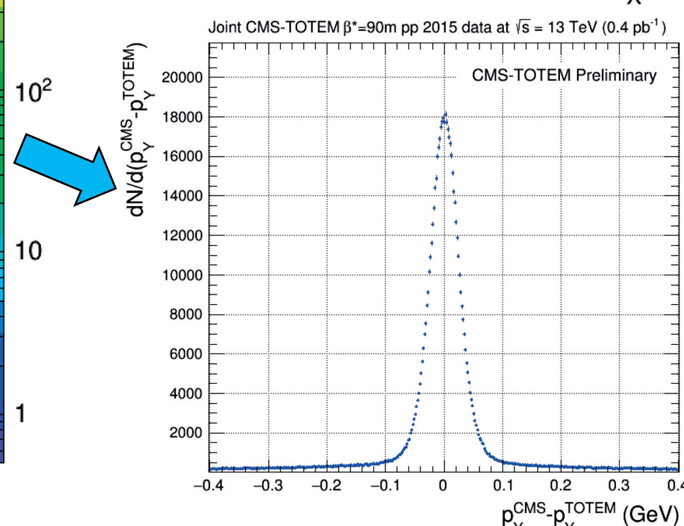


top-top diagonal bottom-bottom



elastic pileup ($p_{x,y} \sim 0$)





2 σ cuts → Very pure exclusive sample selected !!

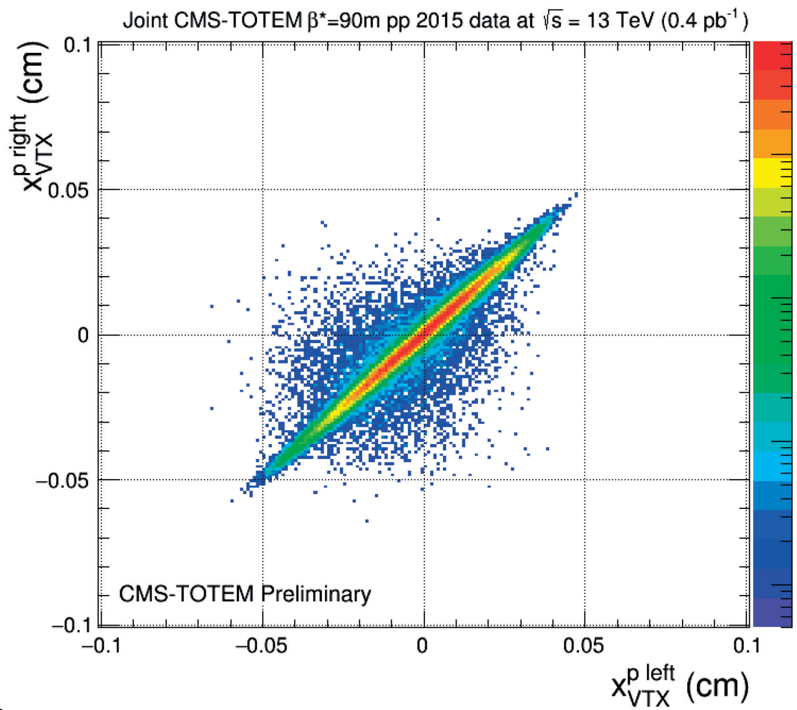
Low-Mass Resonance CEP: Background Rejection (Vertex Cuts)

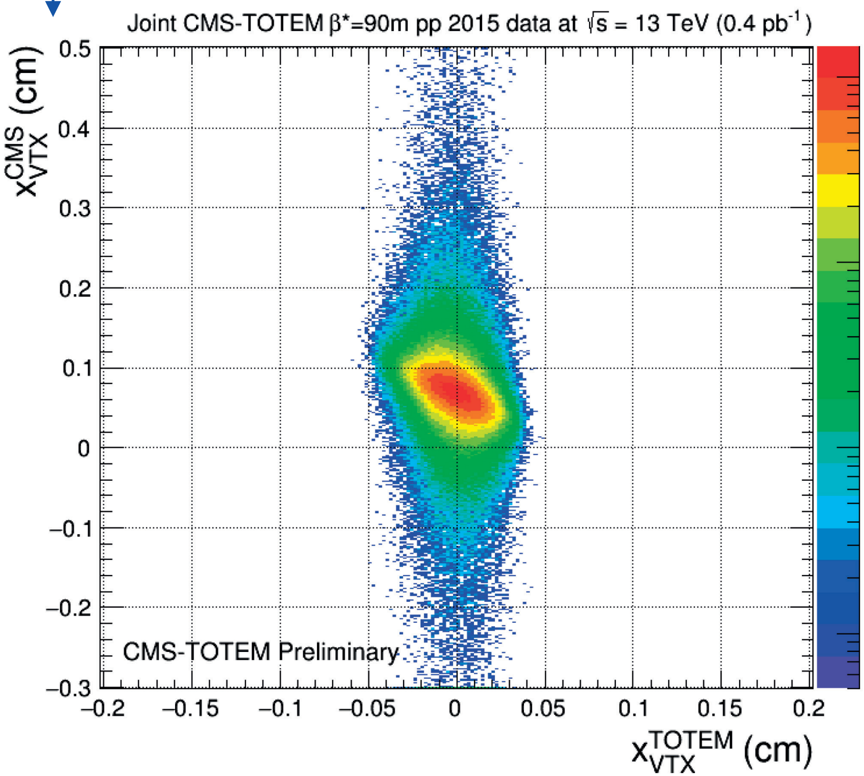
$pp \to p + \pi^+\pi^- + p$ candidates

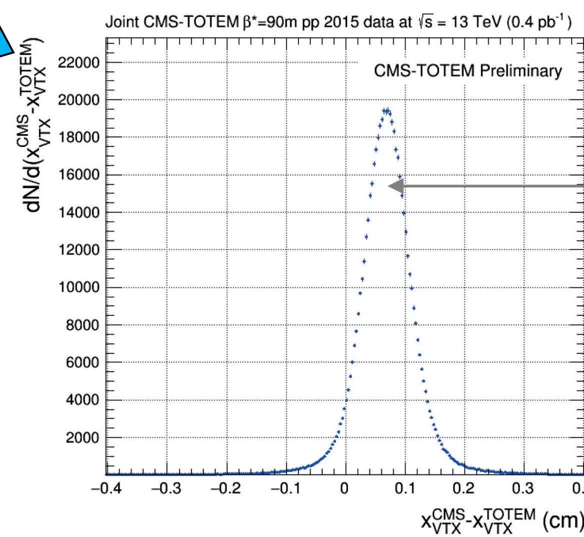
Horizontal vertex position:

- proton left ($x_{VTX}^{p\ left}$) vs. right ($x_{VTX}^{p\ right}$) →
- from CMS tracks (x_{VTX}^{CMS}) vs. both protons (x_{VTX}^{TOTEM})

no sensitivity to proton y_{VTX} due to LHC optics !







Offset due to different CMS & TOTEM reference frames

Physics results coming soon.

Next Step:
Longitudinal Vertex Reconstruction by ToF Measurement

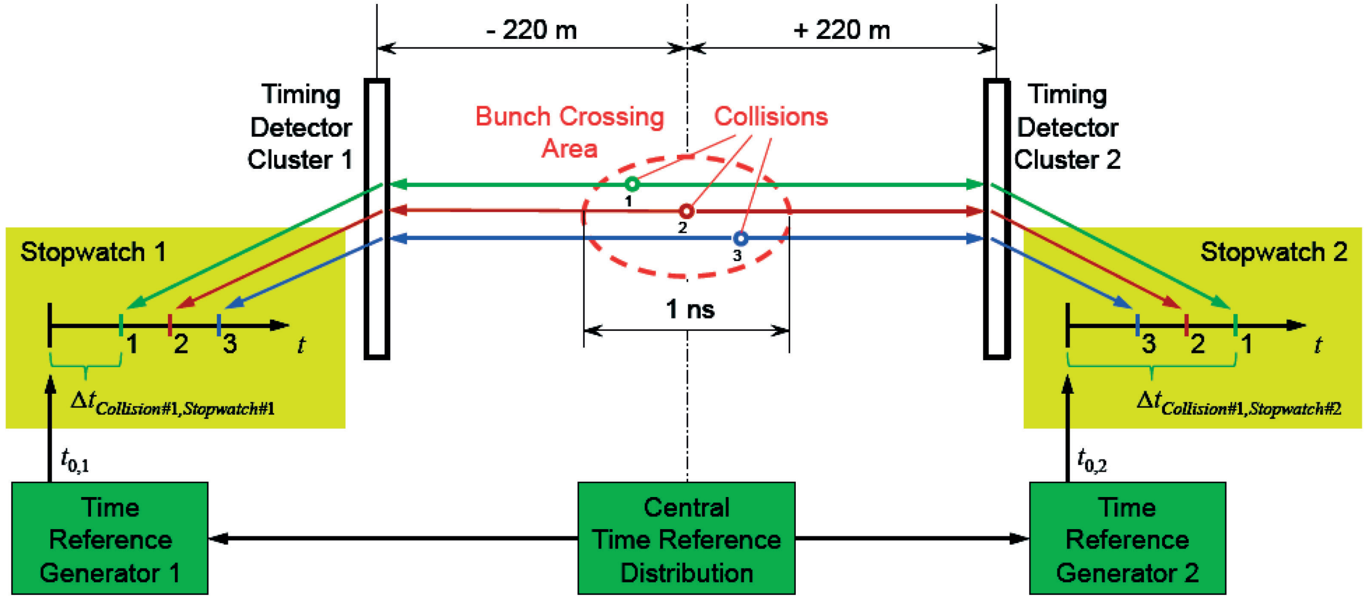
Next run requested for 2018 with more statistics (e.g. for spin-parity analysis):

higher luminosity → higher pileup (μ ~ 1 instead of ~0.1 in 2015)

Pileup = multiple events in 1 bunch collision !

- CMS tracker can separate multiple vertices longitudinally,
- leading proton tracks have angles in μrad range → insufficient vertex precision

→ for double-arm events (CD) reconstruct vertex from time-of-flight difference

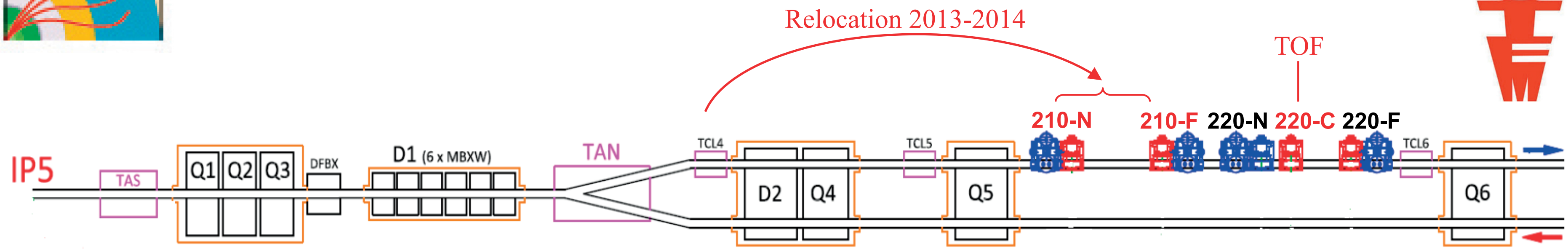


$$\text{Position of Collision 1} \sim \Delta t_{Collision\#1,Stopwatch\#1} - \Delta t_{Collision\#1,Stopwatch\#2}$$

Diamond detectors ($\sigma(t)$ ~ 80 ps per plane) and Ultrafast Silicon timing detectors ($\sigma(t)$ ~ 35 ps per plane) already operating in Roman Rots used for CT-PPS project.

This winter: installation in Roman Pots for 90 m run.

6. RP Spectrometer Upgrades for CT-PPS



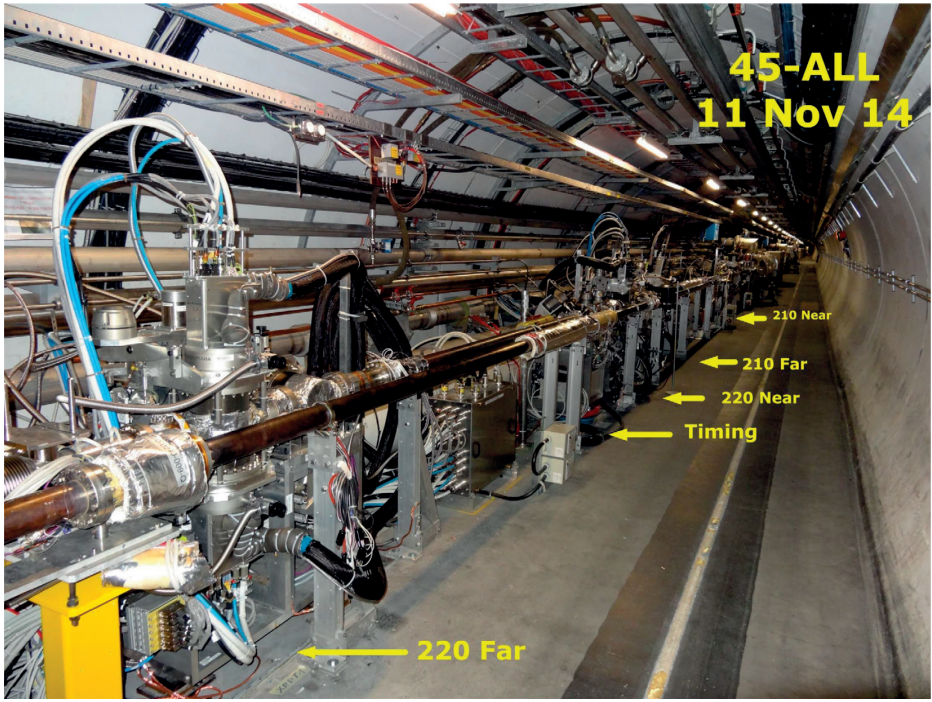
Upgrades for operation at high luminosities
within the CMS-TOTEM Precision Proton Spectrometer (CT-PPS) project for running in all standard LHC fills at low β*

- Addition of a new pot on each side for **time-of-flight (TOF) detectors** (now: **diamonds and ultra-fast silicon**)

→ Total system: 26 Roman Pots

- Gradual replacement of (dying) silicon strip detectors with new **3D pixel detectors**
- RF shields for high-lumi tracking pots
  → impedance reduction

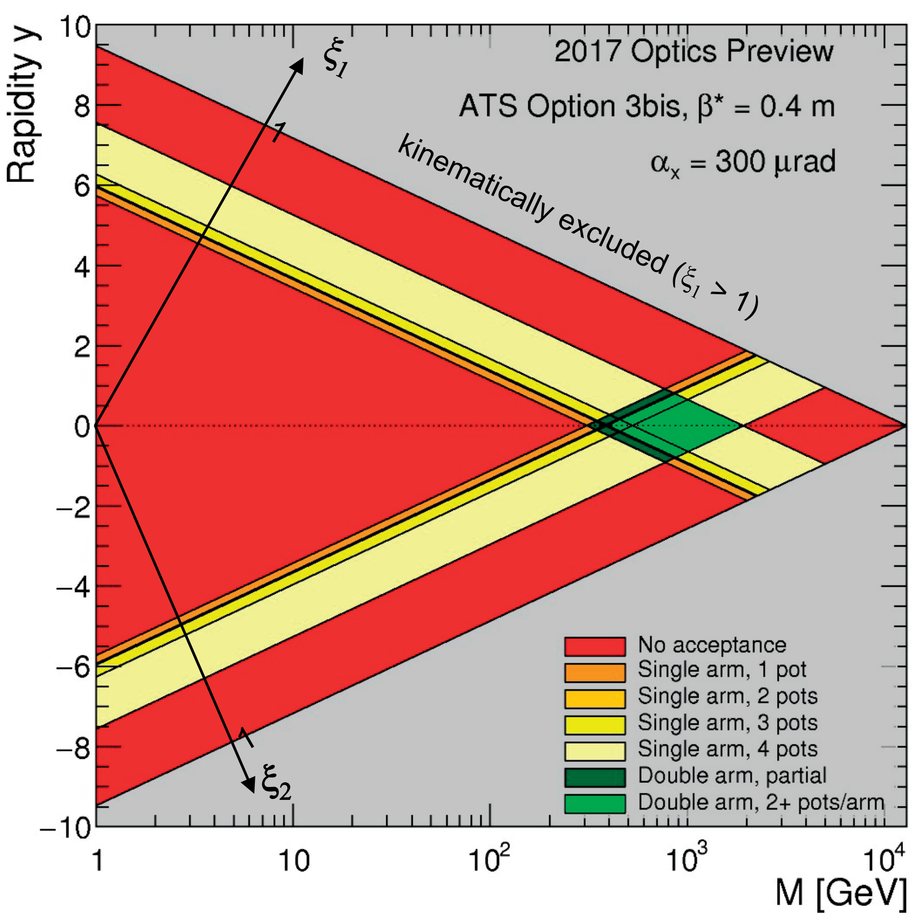
→ Study central production of masses > 300 GeV

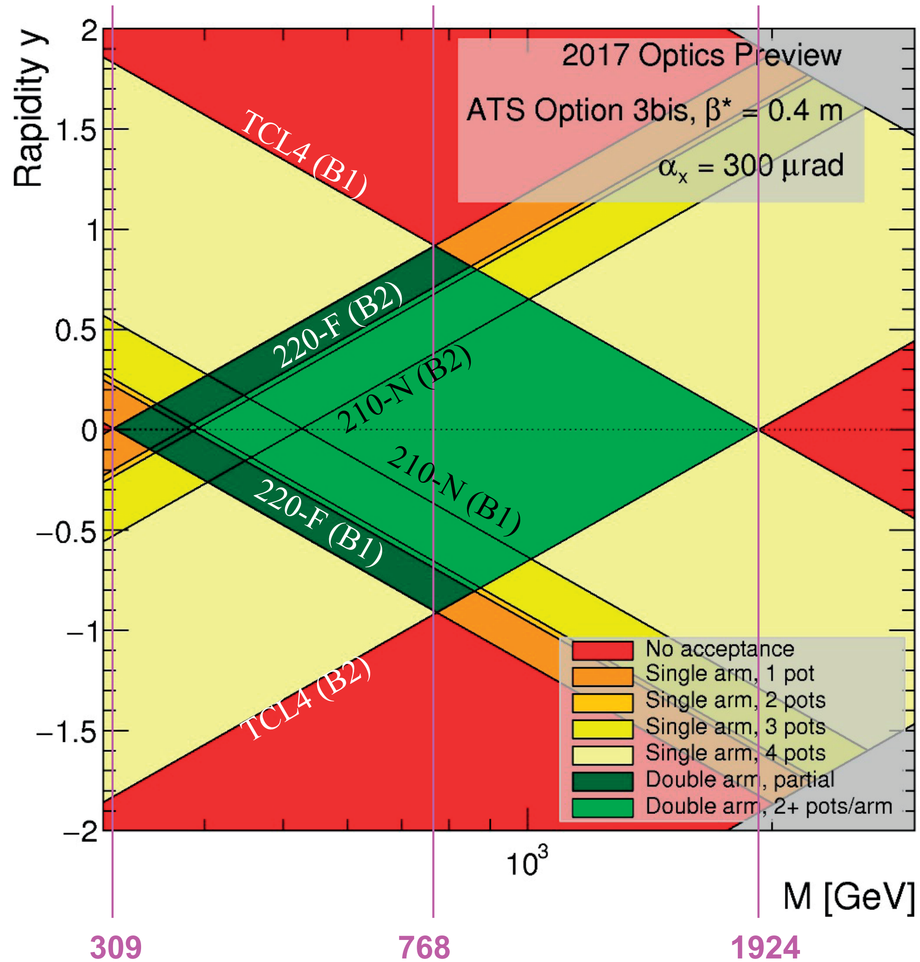


Operation since 2016, first results coming.

CT-PPS Mass-Rapidity Acceptance

Central Exclusive Production with: $M^2 = \xi_1 \, \xi_2 \, s$ $y = \frac{1}{2} \ln \frac{\xi_1}{\xi_2}$





Summary / Outlook

1. Elastic Scattering + Total Cross-Section:
   - 13 TeV analysis (including ρ) in an advanced state
   - 900 GeV measurement planned for end 2017
   - In LHC Run 3: 14 TeV

2. Single Diffraction Analysis at 7 TeV ongoing

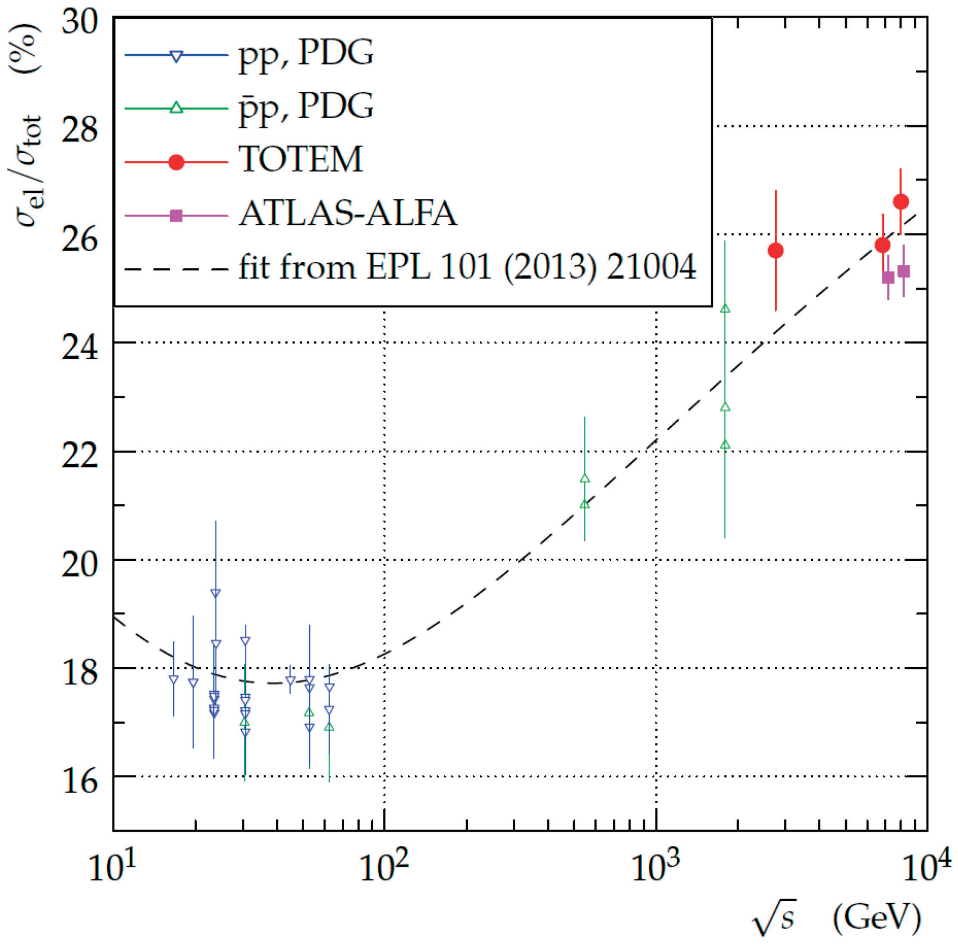
3. Low Mass Resonances & Glueball Search with CMS:
   - analysis of 13 TeV data from 2015 in an advanced state
   - new data set at higher lumi to be requested for 2018

4. CT-PPS Project (with CMS) for production of high masses in operation since 2016
   - 15 fb^{-1} in 2016
   - 13 fb^{-1} so far in 2017
   - first results expected soon

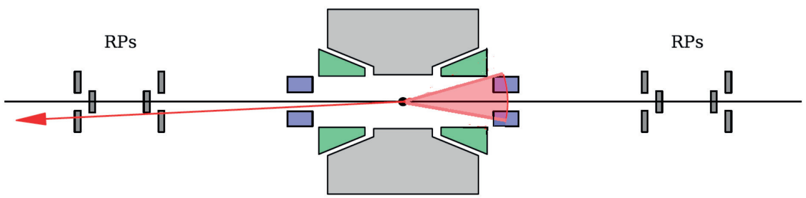
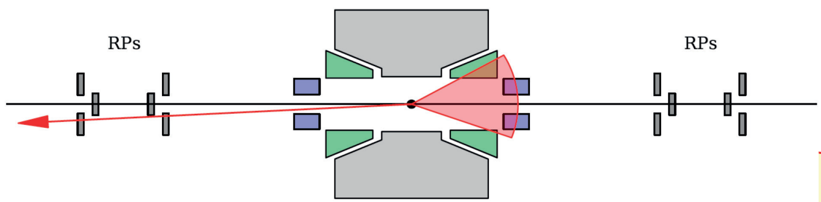
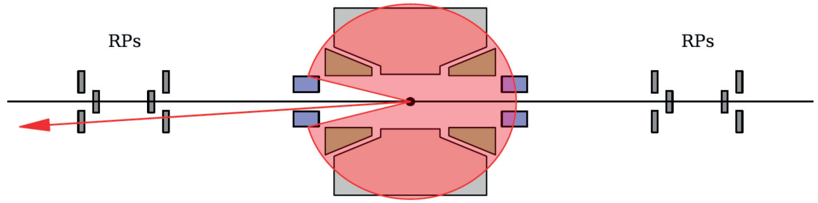
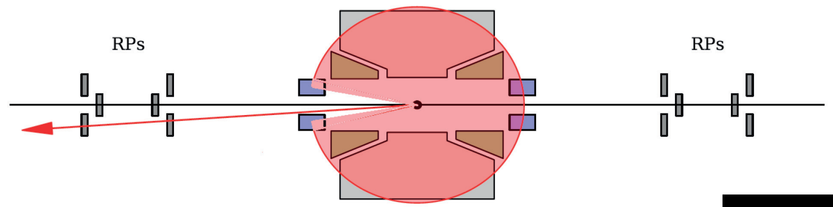
The End

Addendum

Elastic / Total Cross-Section Ratio

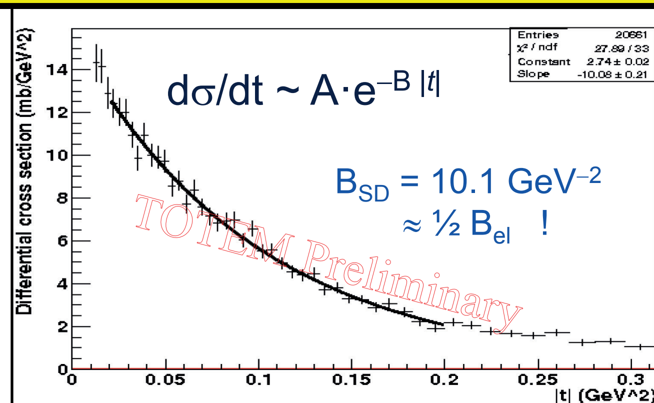


SD Topologies for Different Mass Ranges

M = 3.4 – 7 GeV	$2 \times 10^{-7} < \xi < 1 \times 10^{-6}$	proton & opposite T2 
M = 7 – 350 GeV	$1 \times 10^{-6} < \xi < 2.5 \times 10^{-3}$	proton & opposite T1 + T2 
M = 0.35 – 1.1 TeV	$2.5 \times 10^{-3} < \xi < 2.5 \times 10^{-2}$	proton & opposite T2 (+ T1) & same side T1 
M > 1.1 TeV	$\xi > 2.5 \times 10^{-2}$	proton & opposite T2 (+ T1) & same side T2 (+ T1) 

$$\Delta\eta = -\ln\frac{M^2}{s}$$

SD for Different Mass Ranges (7 TeV Data)

<table>
<tr><td>M =
3.4 – 7 GeV</td><td>$2 \times 10^{-7} < \xi < 1 \times 10^{-6}$</td><td>
</td></tr>
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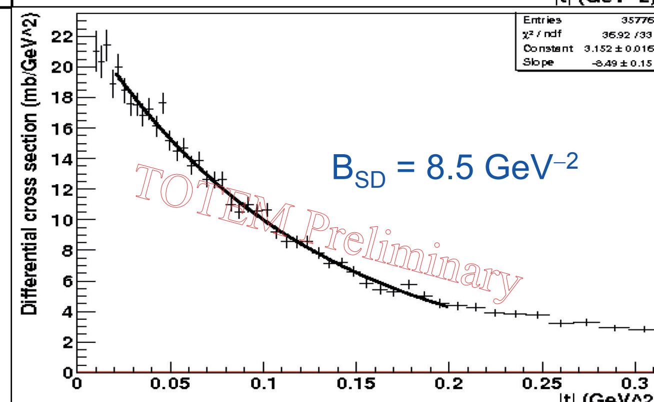
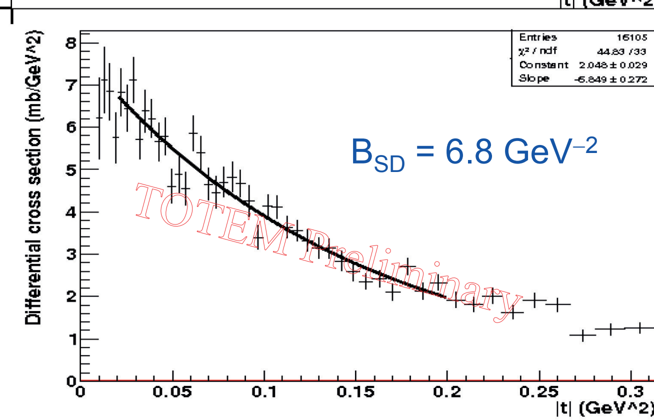
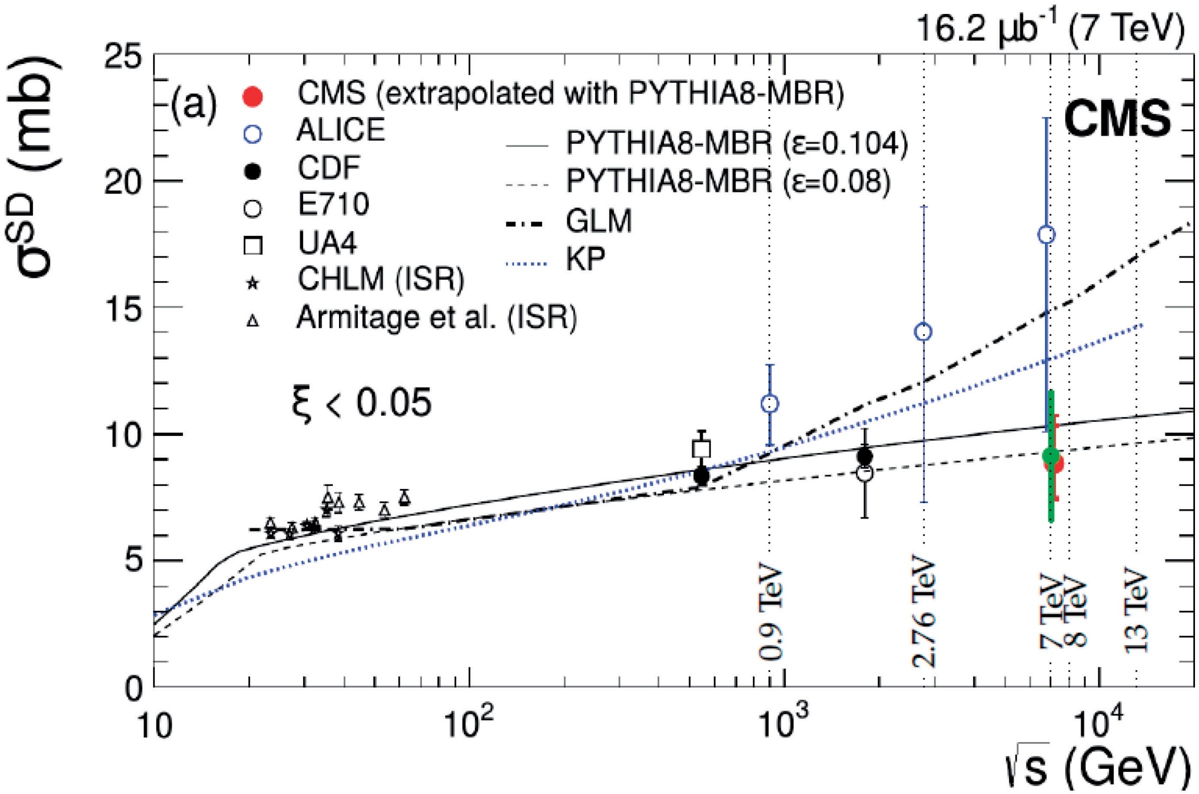
7 – 350 GeV</td><td>$1 \times 10^{-6} < \xi < 2.5 \times 10^{-3}$</td><td>
</td></tr>
<tr><td>M =
0.35 – 1.1 TeV</td><td>$2.5 \times 10^{-3} < \xi < 2.5 \times 10^{-2}$</td><td>
</td></tr>
<tr><td>M > 1.1 TeV</td><td>$\xi > 2.5 \times 10^{-2}$</td><td>in progress</td></tr>
</table>

Work in progress !

estimated uncertainty:
$\delta B/B \sim 15\ \%$

Single Diffraction: Integrated Cross-Section

- original plot from [arXiv:1503.08689], ALICE data [EPJ C73 (2013) 2456]



- green: compilation from TOTEM data, $\sqrt{s}$ = 7 TeV, $\xi \lesssim 0.022$
  - previous slide, $3.4 < M_X < 1100$ GeV: (6.5 ± 1.3) mb
  - [EPL 101 (2013) 21003], $M_X < 3.4$ GeV (SD dominated): (2.62 ± 2.17) mb
  - $\sigma_{SD} \approx (9.1 \pm 2.9)$ mb

[slide stolen from J. Kaspar]

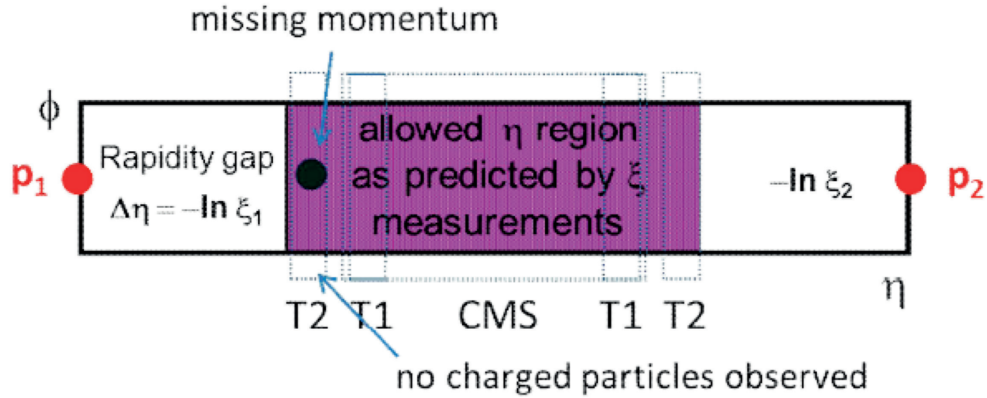
Missing mass & momentum events

new physics that escaped standard searches

(e.g. due to special Pomeron coupling)?

preliminary search for such events performed on existing data samples (0.05 pb^{-1}):

- several topologies investigated for violations of predicted rapidity gap (no signal found)



with $p_{central}$ (particle flow) ≠ p_{pp} & $M_{central}$ (particle flow + $p_{missing}$) ≤ M_{pp} events with $p_{missing}$ in the instrumented region (& requiring $|\eta| > 6.5$ to be forbidden by $\xi_{1,2}$ measurements)

- search for missing mass in $150 < M_{missing} < 600$ GeV at 13 TeV
  some candidates with missing mass up to 400 GeV found but
  limited statistics doesn't allow accurate modeling of background