Total, Elastic and Inelastic Cross-Section Measurements in TOTEM

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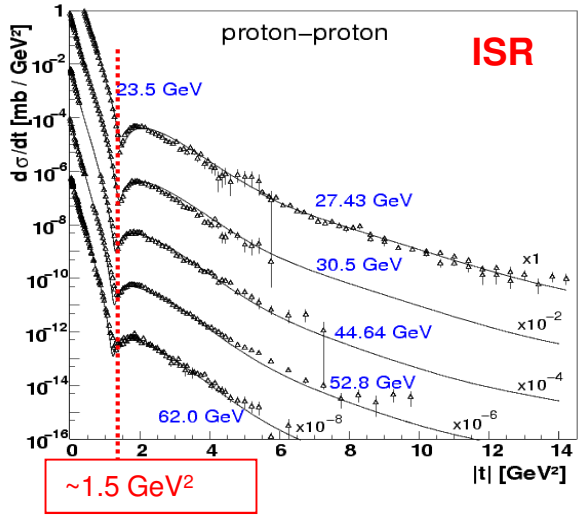
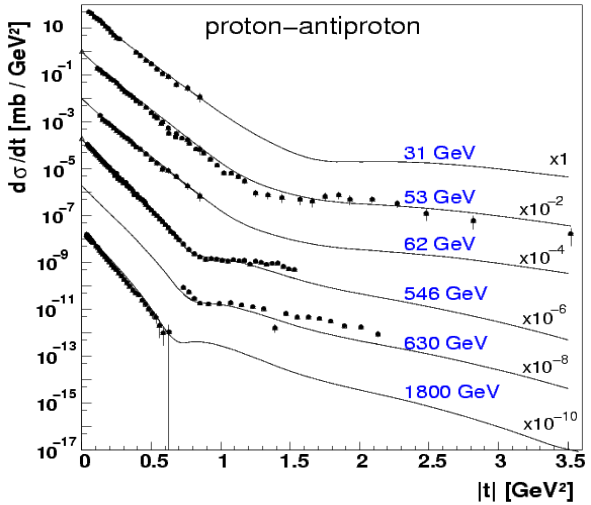
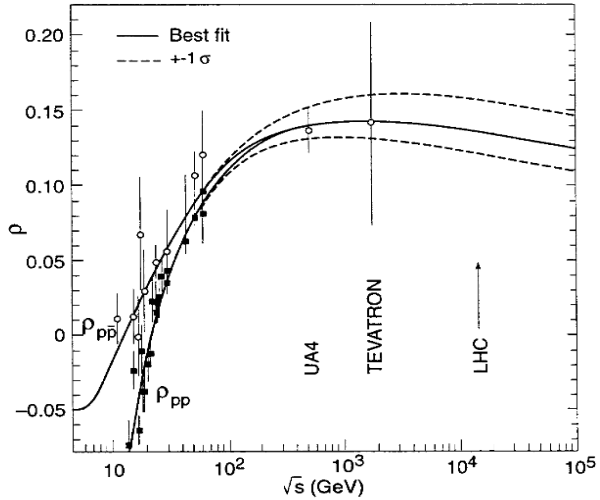
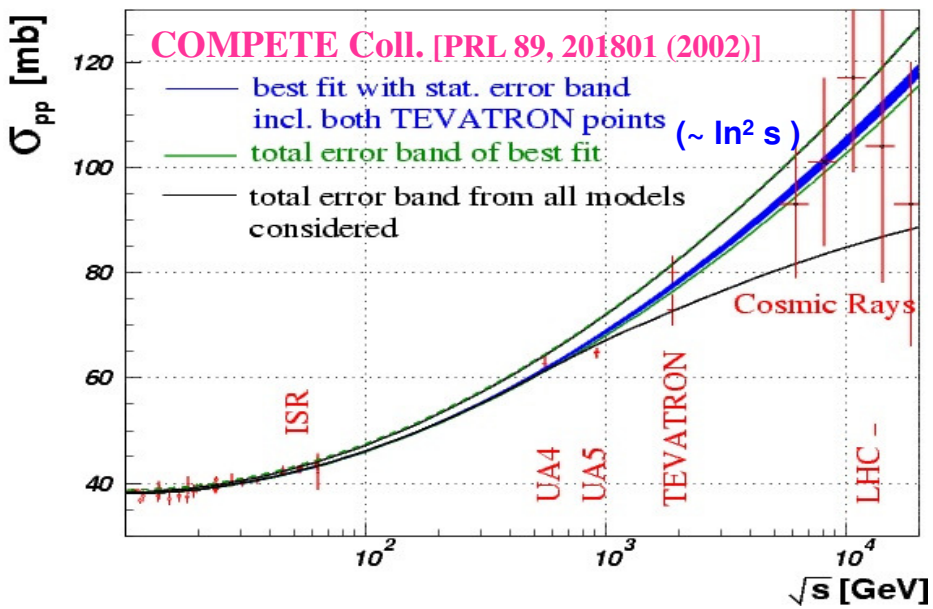
Cross-Section Measurements: from ISR to Tevatron

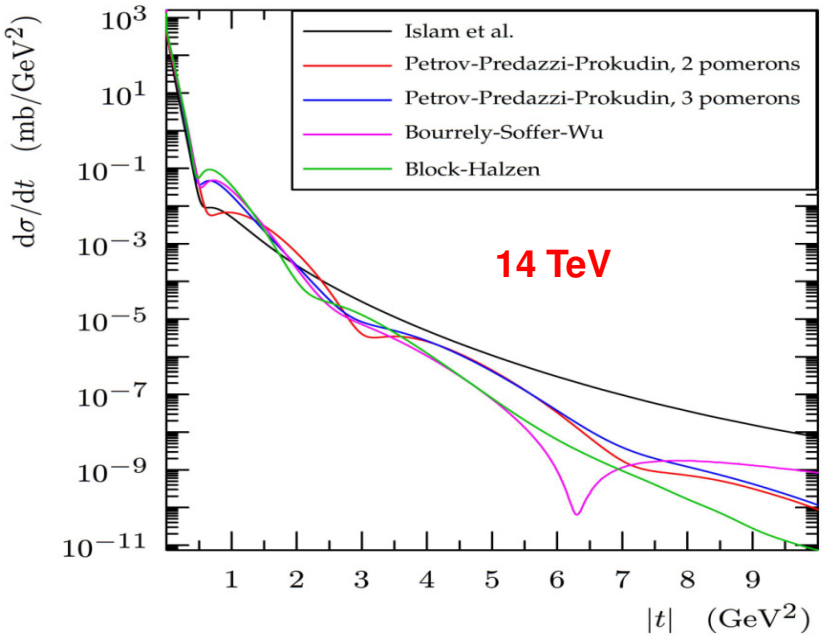






Importance of performing σ_T and $d\sigma_{el}/dt$ measurements @ LHC with adequate resolution, allowing to distinguish among different models predictions and to check known features at higher energies





Three Methods for σ_T Measurement

Optical Theorem: $\sigma_T = \frac{8\pi}{p\sqrt{s}} \mathrm{Im}\, F(s,t)|_{t=0}$

$$\rightarrow \quad \mathcal{L}\sigma_T^2 = \frac{16\pi}{1+\rho^2} \times \left.\frac{dN_{el}}{dt}\right|_{t=0} \qquad \left(\rho = \left.\frac{\mathrm{Re}\ F}{\mathrm{Im}\ F}\right|_{t=0}\right)$$

$\rho = 0.140 \pm 0.007$ (from Compete)

1) Elastic Scattering + Inelastic Scattering + $\mathcal{L}$:

no dependence on ρ

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

2) Elastic Scattering + $\mathcal{L}$ + Optical Th.:

no dependence on N_{inel}

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

3) Elastic Scattering + Inelastic Scattering + Optical Th.:

$\mathcal{L}$-independent

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

σ_T

Proper tracking acceptance in very forward region required: elastically scattered p detection <u>mandatory</u>

TOTEM Detector Setup @ IP5 of LHC

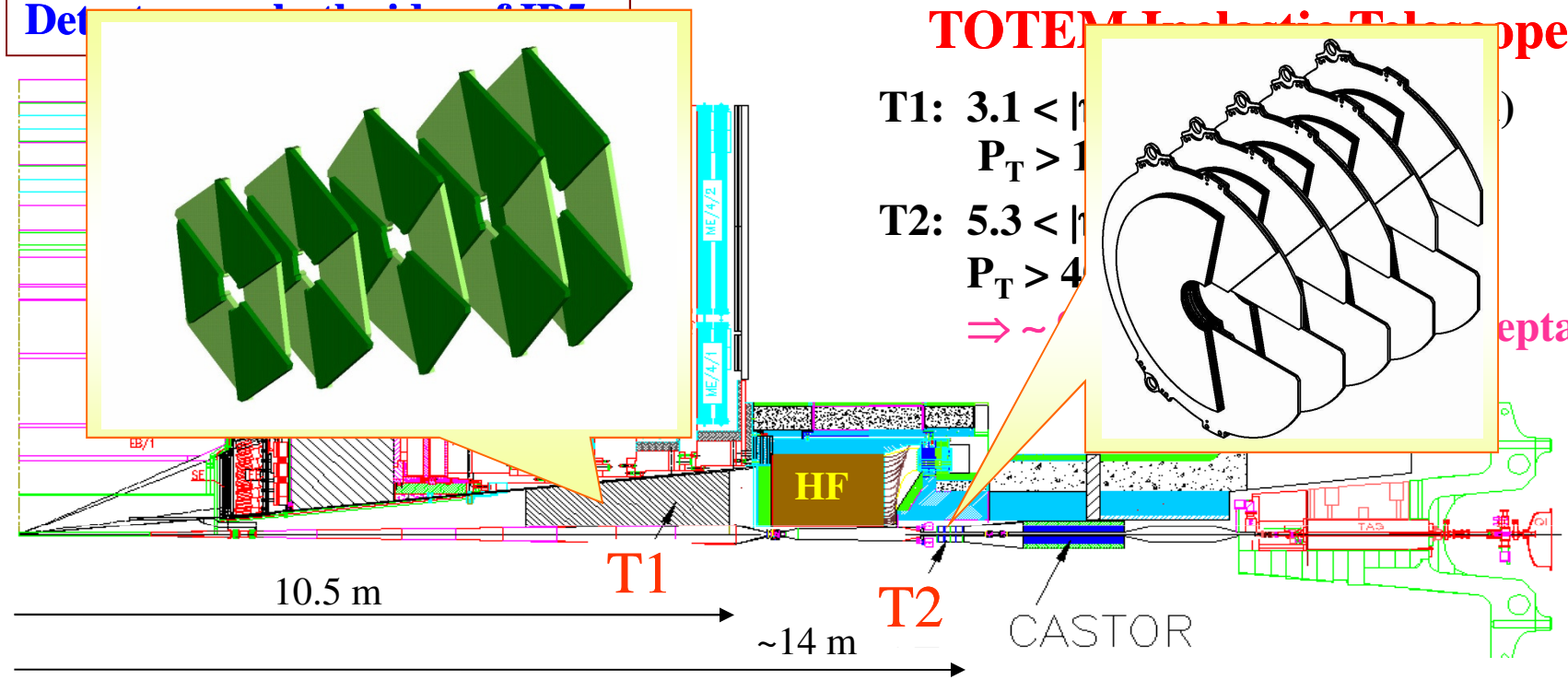
Det

TOTEM Inelastic Telescopes

T1: 3.1 < |η| < 6.5
P_T > 1 GeV

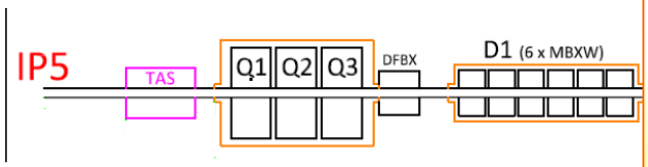
T2: 5.3 < |η| < 7
P_T > 4 GeV

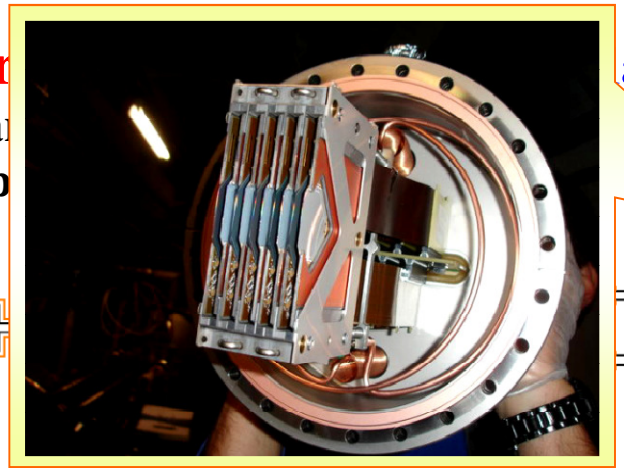
⇒ ~ 100% acceptance

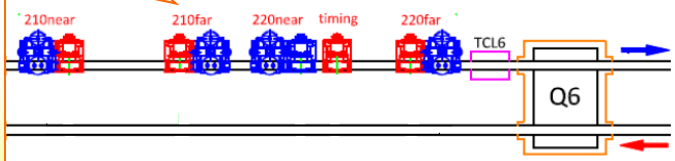


TOTEM Elastic Detector

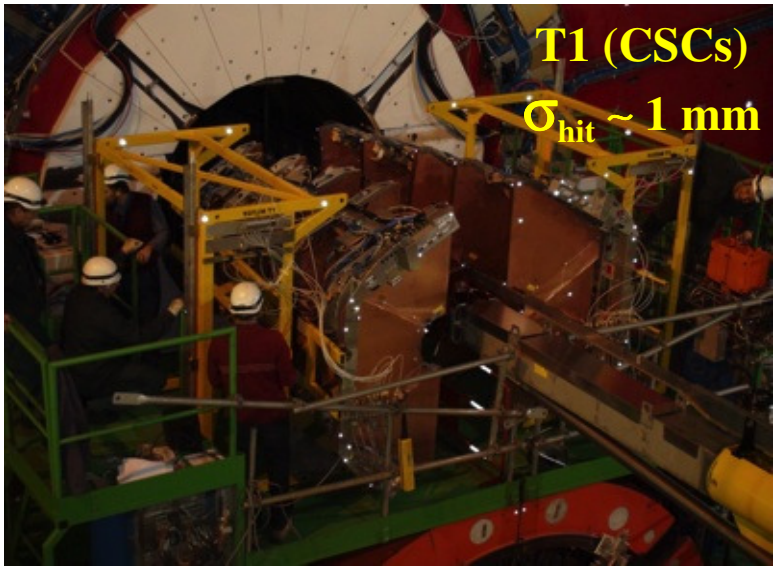
Si strip detectors with active area astic and diffractive p
beam-pipe insertions (RP) app border, hosted in movable
1 mm (θ down to 5-10 μrad)

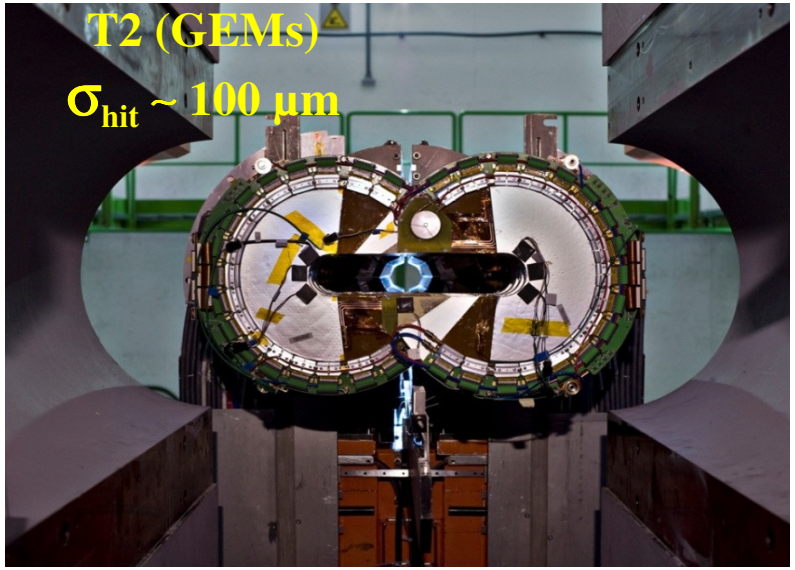




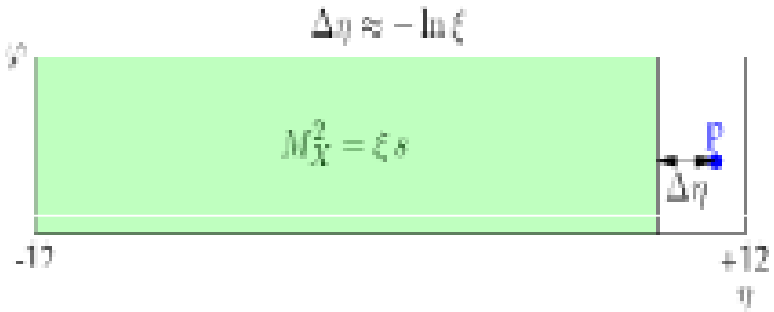


Measurement of Inelastic Rate

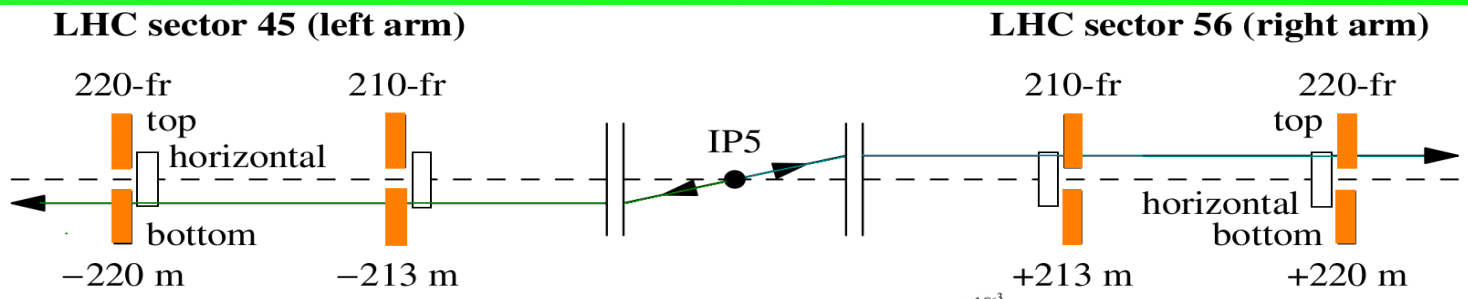




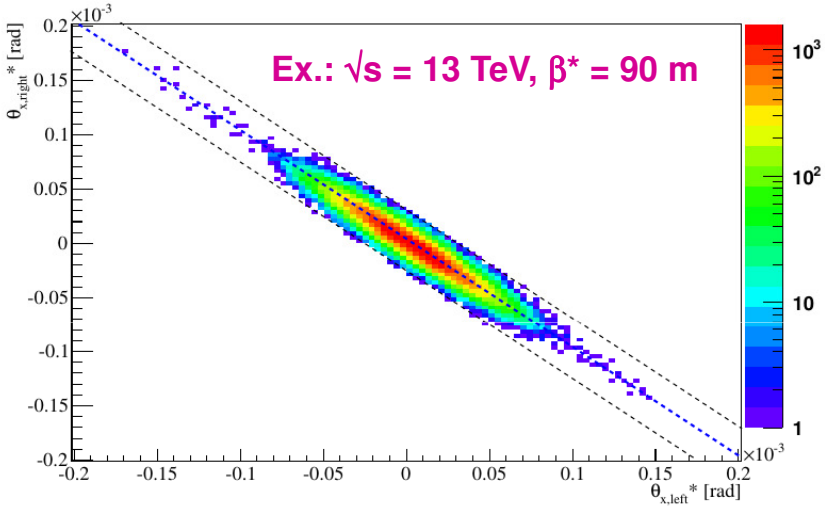
- **Trigger: from T2 (either arm); "Zero-Bias" (for calibration purposes)**
- **Experimental effects corrections (mostly data-driven):**
  beam-gas background, trigger and T2 reconstruction efficiency, pile-up , "T1-only" events
- **Physical effects corrections (MC-driven):**
  accounting for events with no particles in T1/T2 region (central diffraction, rapidity gap over T2, low-mass diffraction);
  → largest contribution from <u>low-mass diffraction</u>
  (Mx< 4.6 GeV for |η| > 6.5)
- **σ (N_{inel}) = 3.7% (@ 13 TeV)**

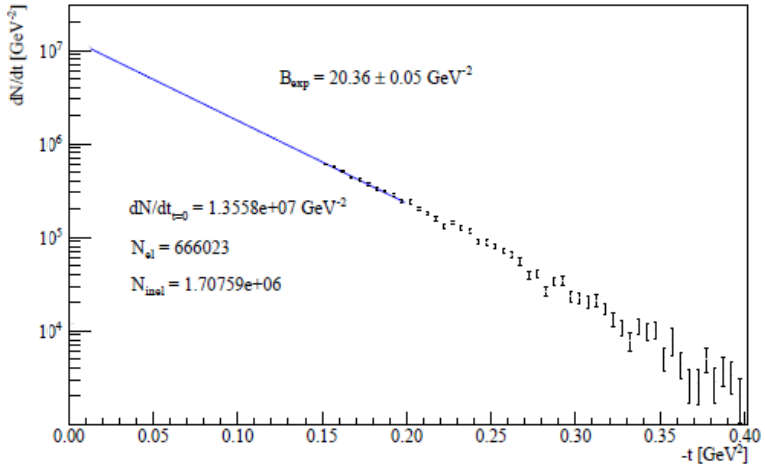


Measurement of Elastic Rate



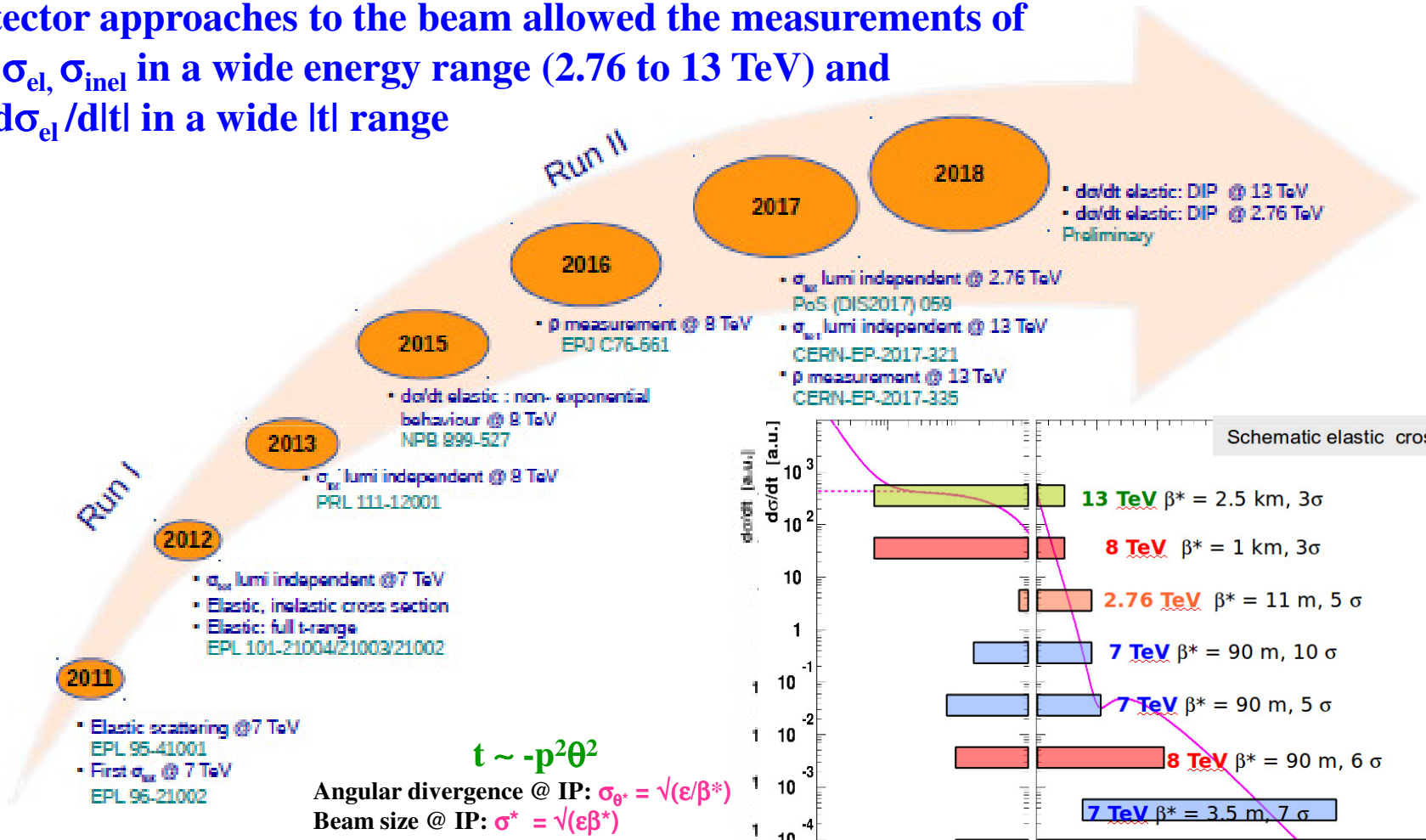
- **Trigger: from RP (double arm)**
- **Very good knowledge of proton transport from IP5 to RP (via excellent determination of optical functions) → precise proton kinematics reconstruction**
- **Two "anti-parallel" protons in final state (p tracks in opposite RP arms in diagonal topology) → very robust elastic pp event tagging**
- **Selection cuts: left-right correlation in several kinematic variables**
- **Differential rate corrections (mostly data-driven): acceptance, trigger/DAQ/reconstruction efficiencies, smearing in |t|**
- **Integrated rate: from differential rate extrapolated to low-|t| region (unobserved)**
- **$\sigma(N_{el}) = 2.3\%$; $\sigma(dN_{el}/dt)_{t=0} = 1.6\%$, (@ 13 TeV, $\beta^* = 90$ m)**





Overview on Cross-Section Measurements in TOTEM

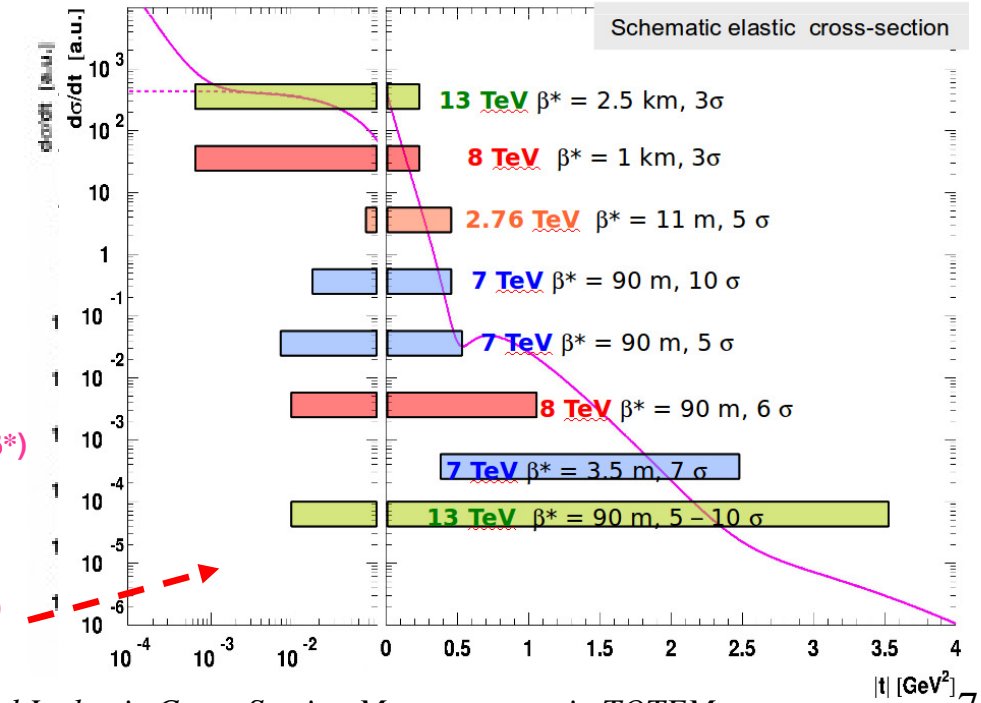
Data taking in various LHC configurations and different RP detector approaches to the beam allowed the measurements of σ_T, σ_{el}, σ_{inel} in a wide energy range (2.76 to 13 TeV) and of $d\sigma_{el}/d|t|$ in a wide $|t|$ range



$t \sim -p^2\theta^2$

Angular divergence @ IP: $\sigma_{\theta^*} = \sqrt{(\varepsilon/\beta^*)}$

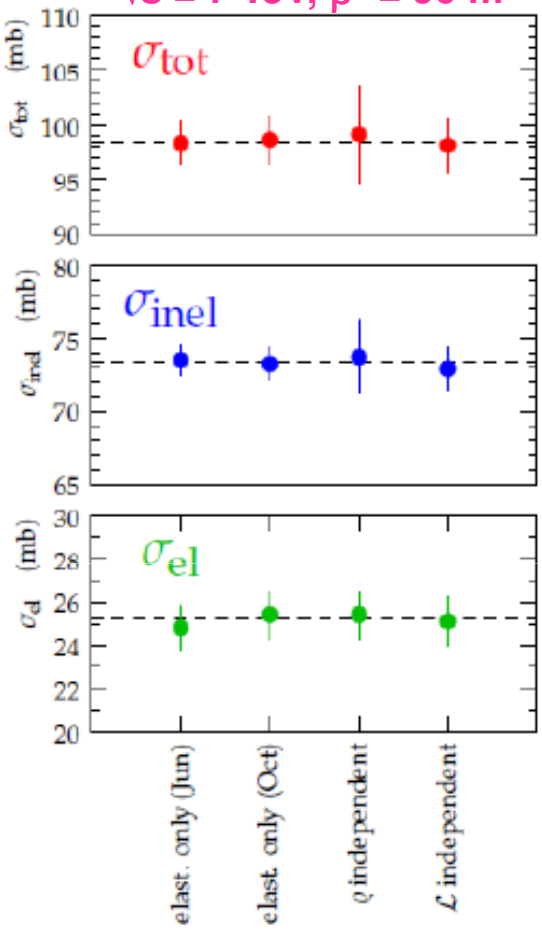
Beam size @ IP: $\sigma^* = \sqrt{(\varepsilon\beta^*)}$



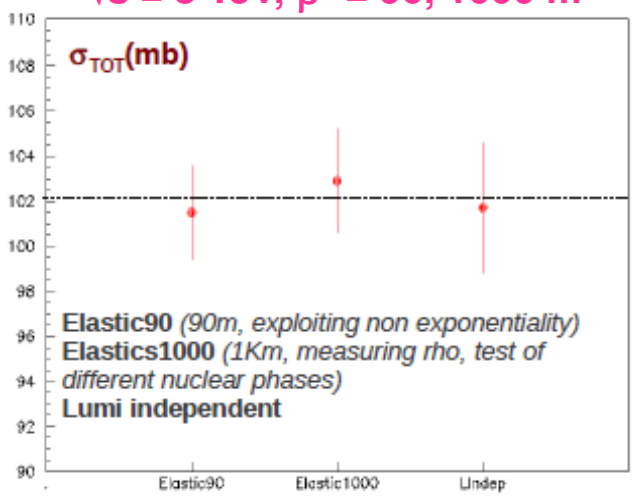
Allowed $|t|$ range depends on beam optics (special high β^*– low $\mathcal{L}$ runs required for low $|t|$) and on proton detector approach to the beam

Comparing Results from σ_T Measurement Methods

$\sqrt{s}$ = 7 TeV, β^* = 90 m



$\sqrt{s}$ = 8 TeV, β^* = 90, 1000 m



$\sqrt{s}$ = 13 TeV, β^* = 90, 2500 m

- $\mathcal{L}$-independent method
- Measurement of ρ

$\sqrt{s}$ = 2.76 TeV, β^* = 11 m

$\mathcal{L}$-independent method

Overview on $\mathcal{L}$-independent method results

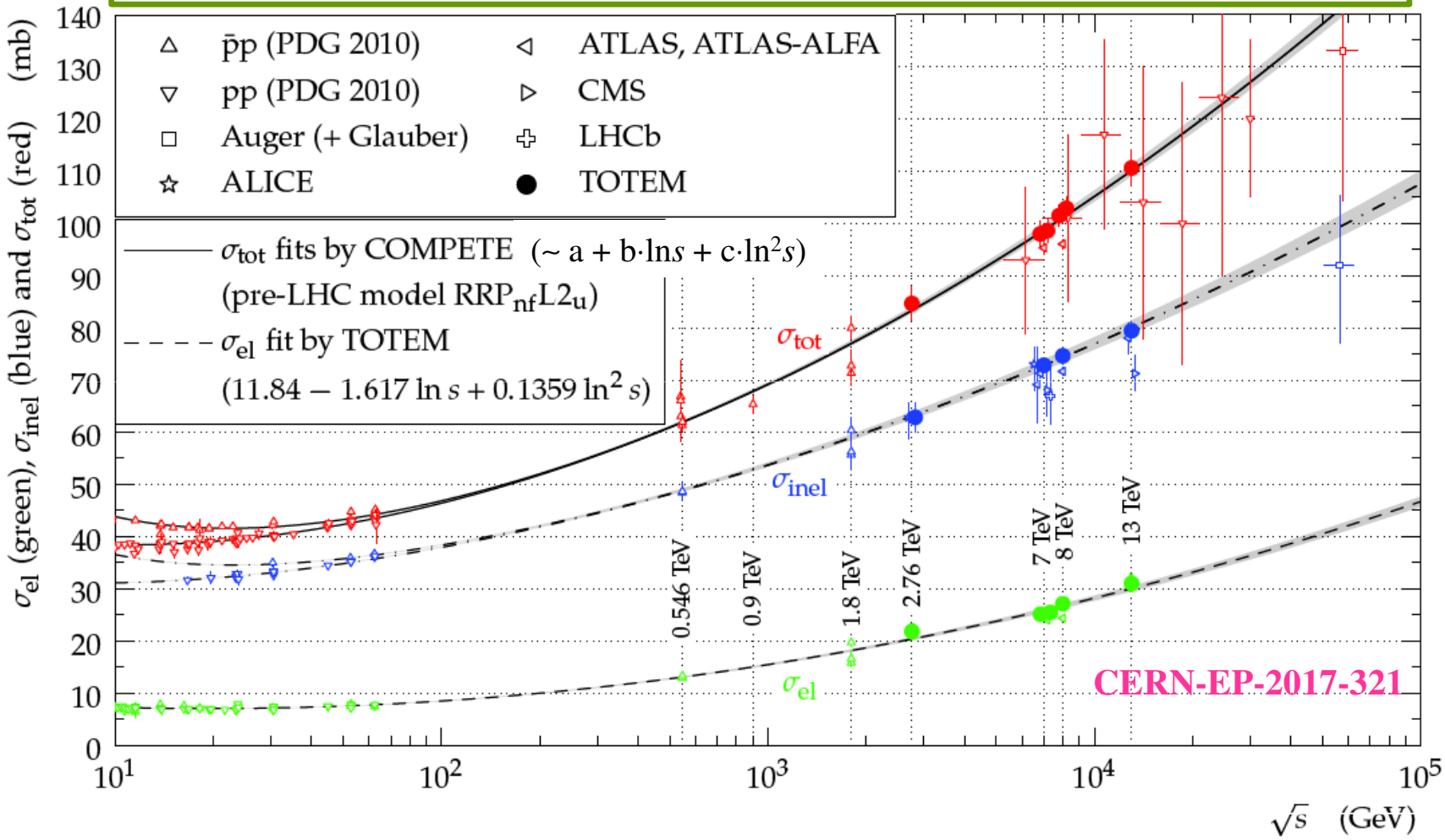
$\sqrt{s}$	σ_T (mb)	σ_{inel} (mb)	σ_{el} (mb)	Reference
2.76	84.7 ± 3.3	62.8 ± 2.9	21.8 ± 1.4	PoS (DIS2017) 059
7	98.0 ± 2.5	72.9 ± 1.5	25.1 ± 1.1	EPL 101 (2013), 21004
8	101.7 ± 2.9	74.1 ± 1.7	27.1 ± 1.4	PRL 111 (2013) 012001
13	110.6 ± 3.4	79.5 ± 1.8	31.0 ± 1.7	CERN-EP-2017-321

- **Measurement of N_{el} / N_{inel} → additional determination of σ_{el} and σ_{inel}**
- **Very good agreement among different measurement methods and beam cond. (@ $\sqrt{s}$ = 7, 8 TeV)**
  → very good understanding of systematic uncertainties and correction procedures
  → proof of reliability of the $\mathcal{L}$-independent method
- **Typical global uncertainty: σ_T ~ 2-4 %, σ_{inel} ~ 2-4 %, σ_{el} ~ 4-5 %**

Summary of σ_T Measurement Results

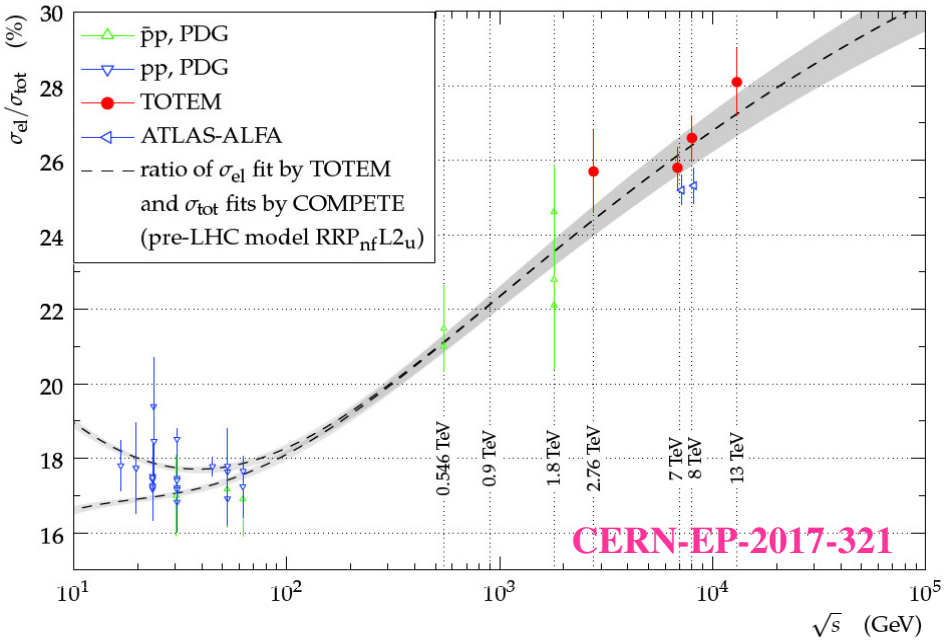
Latest results (@ $\sqrt{s}$ = 13 TeV, $\mathcal{L}$-independent method assuming ρ = 0.10):

σ_T = 110.6 ± 3.4 mb, σ_{inel} = 79.5 ± 1.8 mb, σ_{el} = 31.0 ± 1.7 mb



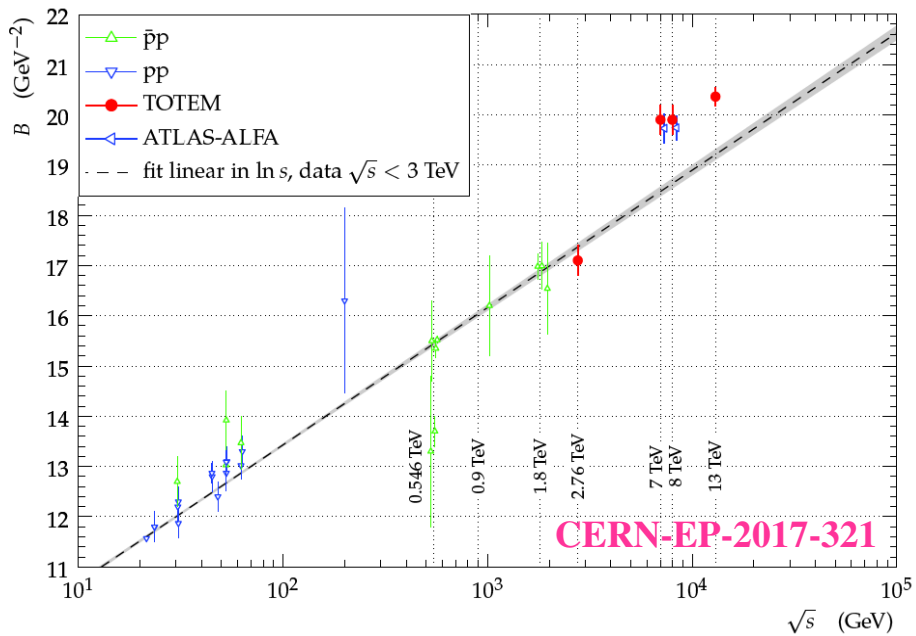
- **σ_T growth with energy compatible with COMPETE predictions (asymptotically with ln^{2}s)**
- **Fair agreement with other LHC experiments results**

Highlights from σ_T Measurements

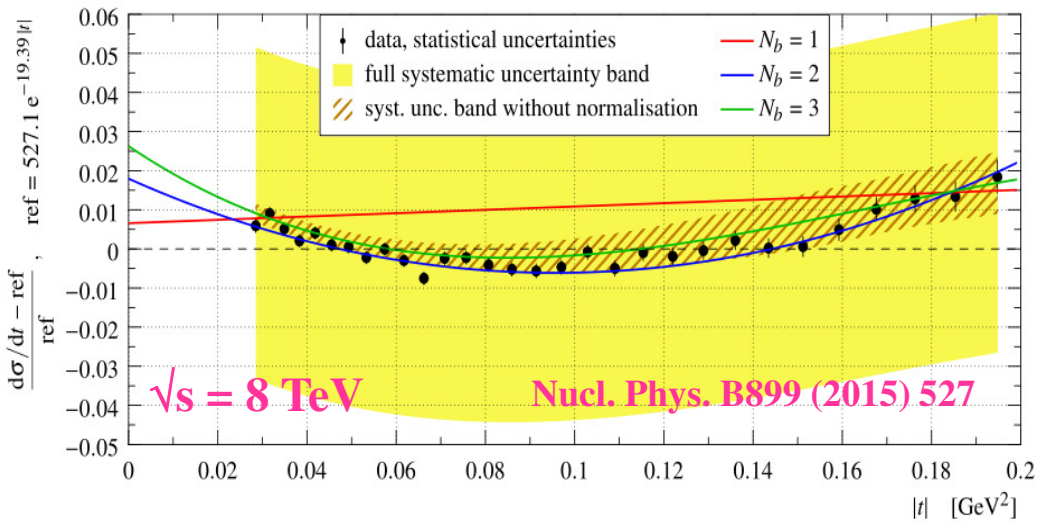


- σ_{el} / σ_T ratio increase with energy confirmed @ LHC
- Increase with √s

- For √s > 3 TeV: deviation of nuclear slope B from the low energy linear (with ln s) extrapolation
- Diffraction cone shrinkage speeds up with energy

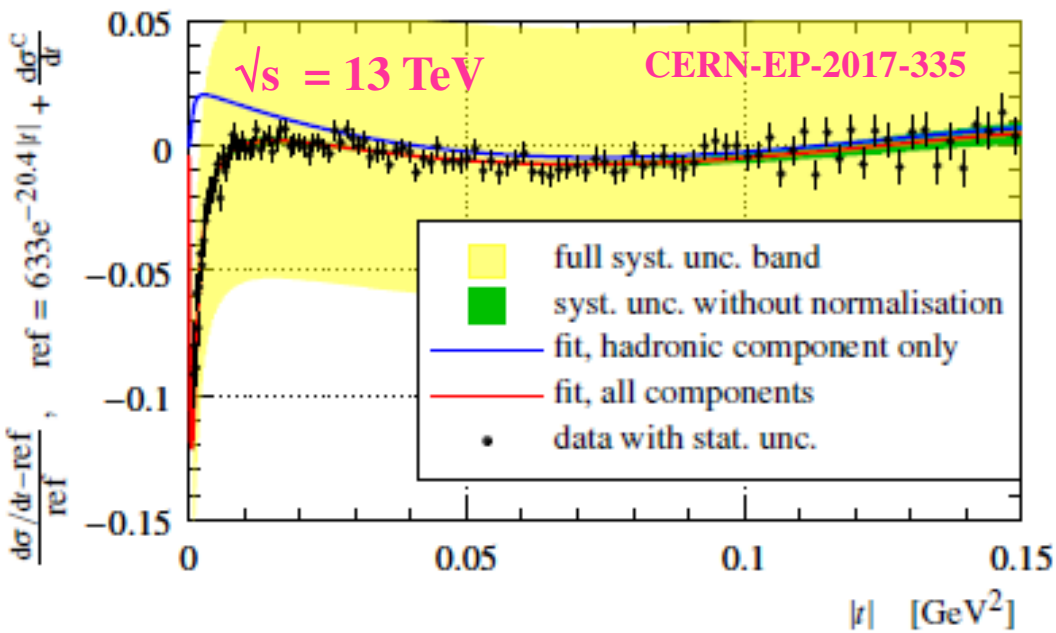


$d\sigma_{el}/d|t|$ at Low-|t|: Non-Exponential Behavior

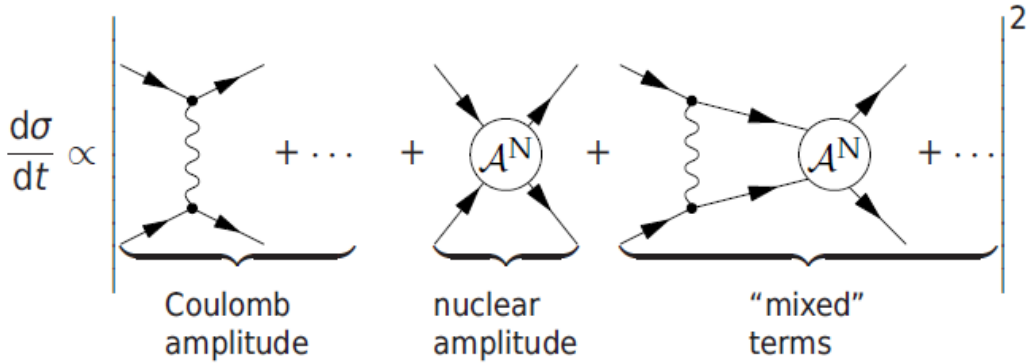


- **Confirmed @ LHC (already observed at ISR and SPS)**
- **First clear evidence with 8 TeV high statistics data sample: "purely" exponential slope excluded with a significance > 7σ**
  → $d\sigma_{el}/d|t| = Ae^{-B(t)|t|}$
- **Quadratic (Nb = 2) and cubic (Nb = 3) polynomials well describe data** $a\exp\left(\sum_{n=1}^{N_b} b_n t^n\right)$

- **Using the optimized parameterization for extrapolation to t = 0: new results for σ_T are found in agreement with previous measurement**
- **Non-exponential measurement in nuclear component at low-|t| → empirical guidance for hadronic modulus of A^N determination in the Coulomb-nuclear interference region (ρ measurement ….)**



$d\sigma_{el}/d|t|$ at Very Low-|t|: ρ Measurement



QED + experimental form factors

Modulus constrained by measurement of $e^{-B(t)|t|}$ at higher-|t|

Proper modeling of CNI

Coulomb-Nuclear interference (CNI) region:

$$d\sigma/dt \sim |A^C + A^N(1\text{-}i\alpha G(t))|^2$$

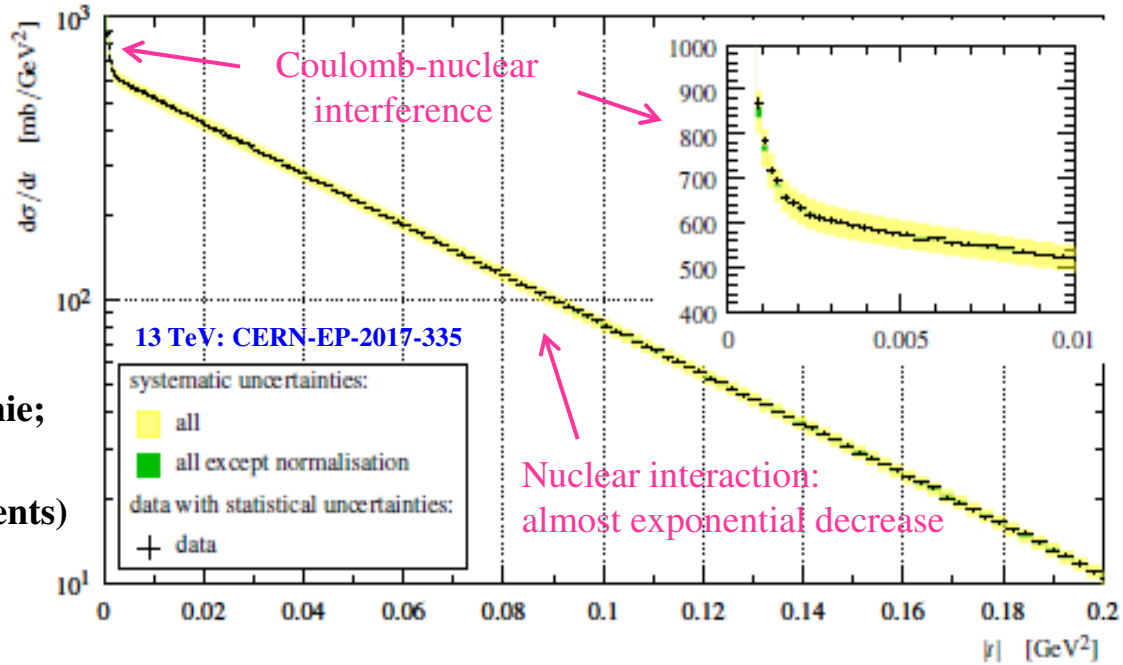
- **sensitive to the phase of the nuclear amplitude A^N**
- **|t|-dependent modulus (constrained by hadronic region measurement) and phase of A^N can be derived to give:**

$$\rho = \mathrm{Re}(A^N(0))/\mathrm{Im}(A^N(0)) = \cot[\mathrm{Arg}\, A^N(0)]$$

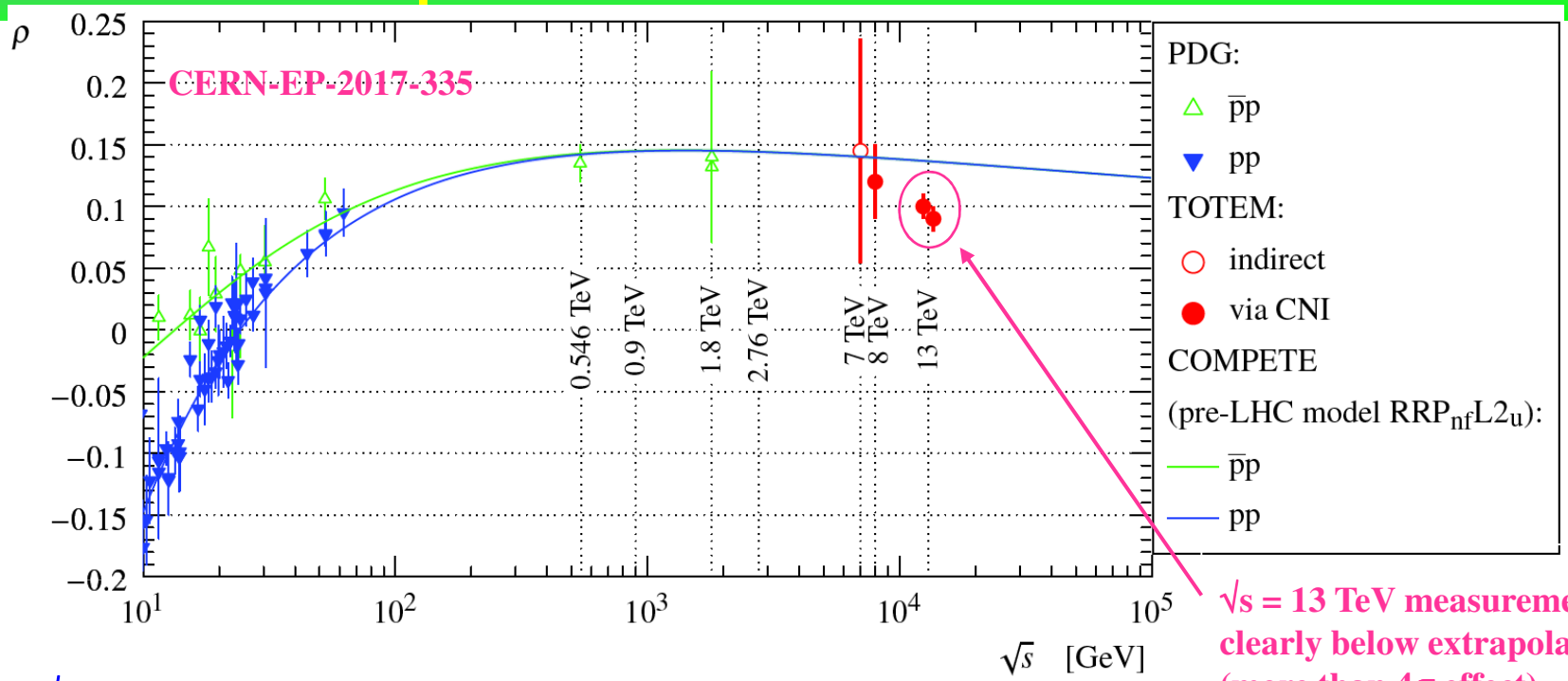
CNI region reached @ √s = 13 TeV (down to |t| ~ $8\cdot10^{-4}$ GeV²): special high statistics run with β* = 2500 m and RP approaching the beam centre @ ~ 3σ

More details on our modeling:

- **"interference formula": most general (Kundrát-Lokajíček) considered, also compared to others by Cahn and West-Yennie;**
- **phase of A^N: assume slow variation with |t| (same assumption as in pre-LHC measurements) → fair comparison; more exploration in forthcoming studies ….**



ρ Measurement: Results



√s = 13 TeV measurement clearly below extrapolation (more than 4σ effect)

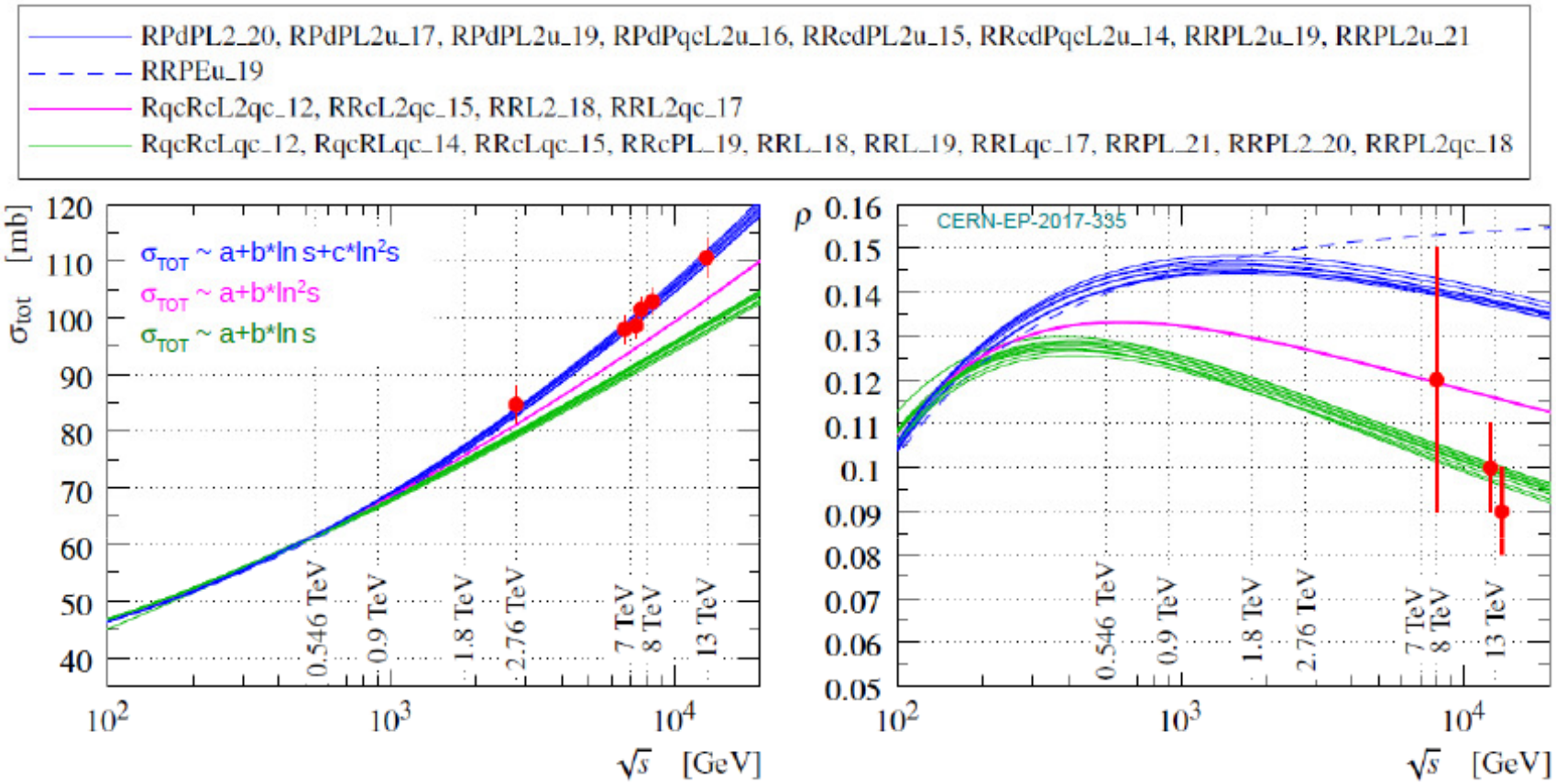
- **@ √s = 8 TeV (β* = 1000 m) – Eur. Phys. J. C76 (2016) 661**
  first LHC ρ measurement from CNI; uncertainty too high due to low statistics: ρ = 0.12 ± 0.03

- **@ √s = 13 TeV (β* = 2500 m) – CERN-EP-2017-335**
  ρ measurement with unprecedented precision thanks to a very high statistics sample:

	$\lvert t\rvert_{max}$ = 0.07 GeV^2		$\lvert t\rvert_{max}$ = 0.15 GeV^2	
N_b	χ^2/ndf	ρ	χ^2/ndf	ρ
1	0.7	0.09 ± 0.01	2.6	–
2	0.6	0.10 ± 0.01	1.0	0.09 ± 0.01
3	0.6	0.09 ± 0.01	0.9	0.10 ± 0.01

Red: important fit configurations
- Nb = 3, $\lvert t\rvert_{max}$ = 0.15 GeV^2: "our best" determination
- Nb = 1, $\lvert t\rvert_{max}$ = 0.07 GeV^2: "most fair" comparison to past measurements (same |t|-range of UA4/2)

σ_T and ρ @ $\sqrt{s}$ = 13 TeV: Comparison to Models I



COMPETE Collaboration: very comprehensive study of pre-LHC data [PRL 89 (2002) 201801]

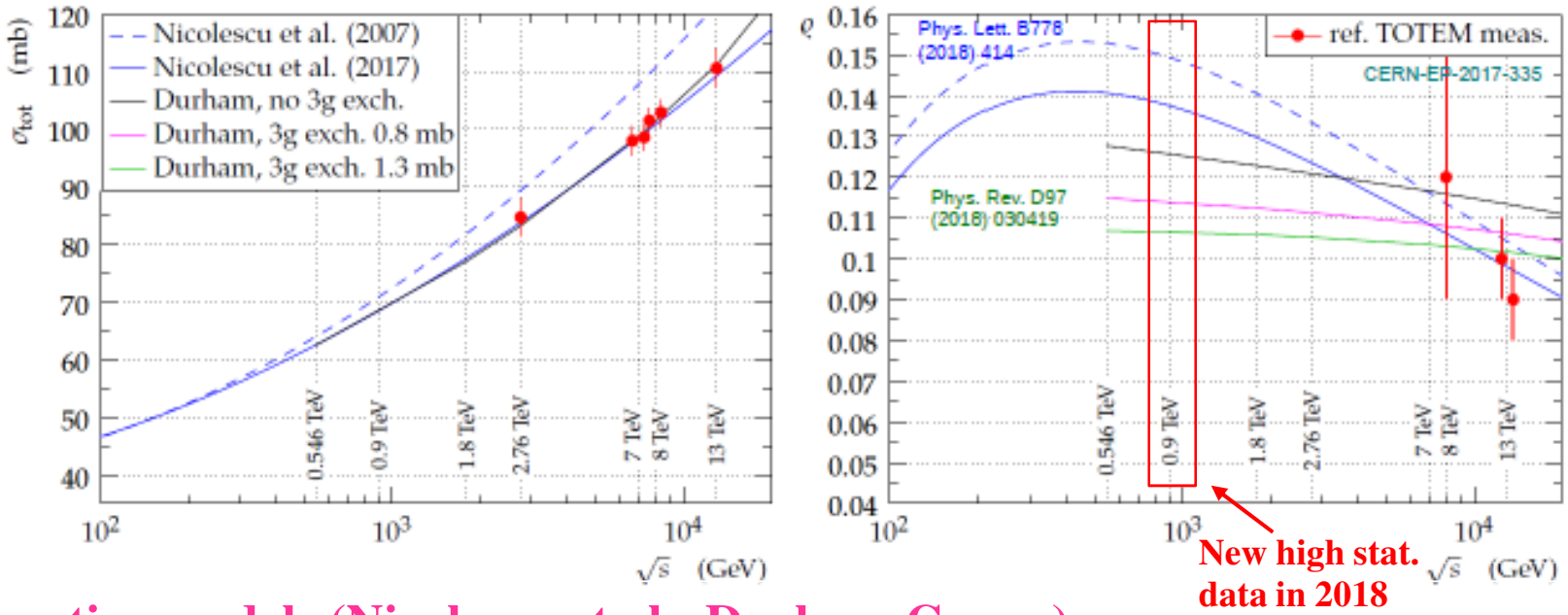
- **256 models, based on various assumptions with crossing-even *only* asymptotic component**
- **23 models found to reasonably describe data and give predictions which cluster in 3 bands**

None of the COMPETE models is able to simultaneously describe the σ_T and ρ LHC measurements @ $\sqrt{s}$ = 13 TeV

Compatibility of TOTEM results with COMPETE models (p-value):

	σ_{tot} (4 to 6 TOTEM measurements)	ρ at 13 TeV (0.09 ± 0.01)
blue	0.990 to 0.995	$3 \cdot 10^{-6}$
magenta	$4 \cdot 10^{-3}$ to $7 \cdot 10^{-5}$	$9 \cdot 10^{-3}$
green	$3 \cdot 10^{-9}$ to $2 \cdot 10^{-15}$	0.4

σ_T and ρ @ $\sqrt{s}$ = 13 TeV: Comparison to Models II



Alternative models (Nicolescu et al.; Durham Group):

- including a t-channel exchange of a crossing-odd (opposite sign for p-p and p-pbar) component
- agreement with TOTEM data

⇒ Crossing-odd component needed to describe TOTEM data: hint for the "Odderon"?

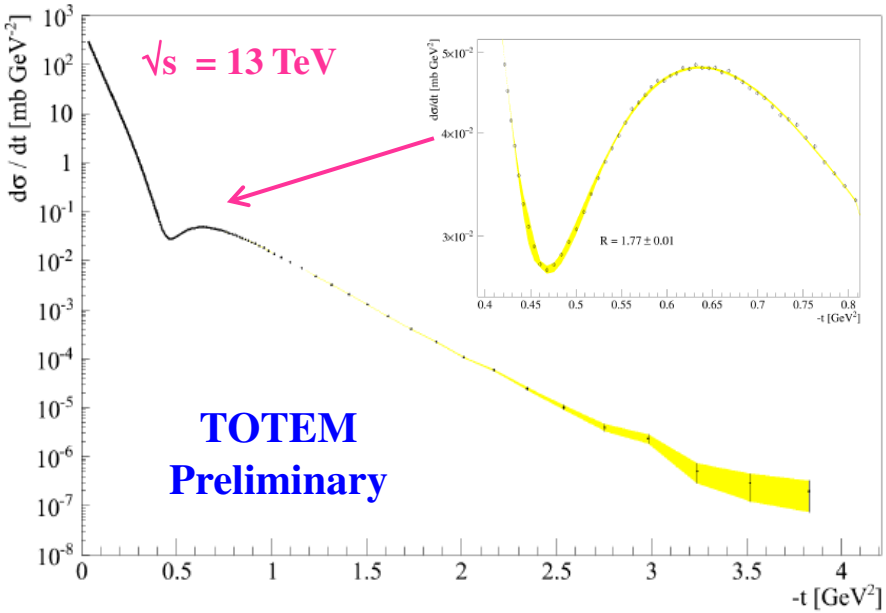
⇒ … or first indication of "slowing down" of σ_T growth at higher energies, as predicted by dispersion relations when only crossing-even amplitude component considered ?

$$\rho \approx \frac{\pi}{2\sigma_{tot}} \frac{d\sigma_{tot}}{d \ln s}$$

Odderon:

- Originally introduced within axiomatic theory to account for differences between p-p and p-pbar data
- Studied in the framework of Regge theory as counterpart of crossing-even Pomeron
- Predicted in QCD as a colorless 3-gluons bound state with quantum numbers $J^{PC} = 1^{--}$
- Predicted in lattice-QCD (named "oddball" or "vector glueball") with M = 3-4 GeV

Latest Results on $d\sigma_{el}/d|t|$ Measurements at High-|t|

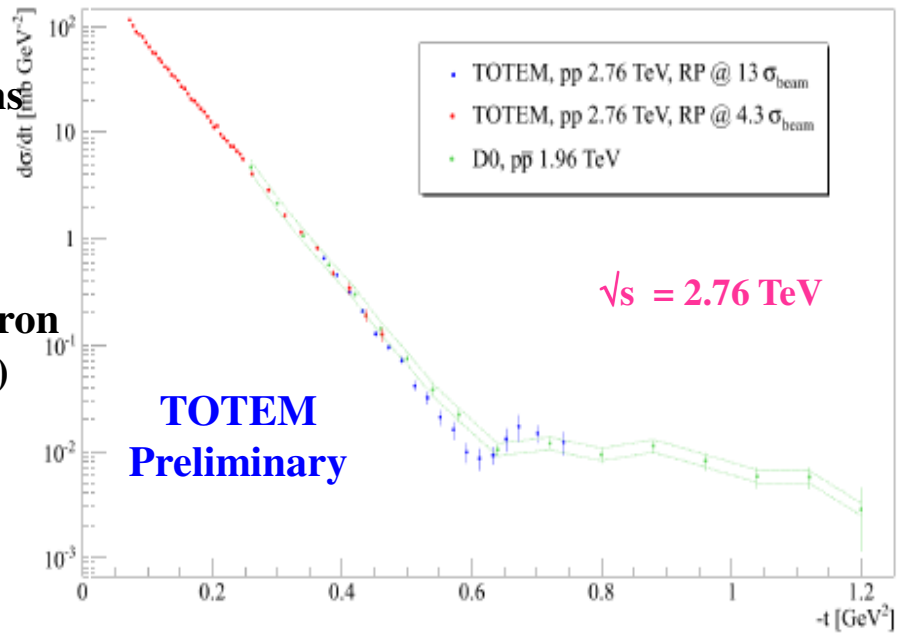


Other indications of Odderon exchange in $d\sigma_{el}/d|t|$

- Energy dependent difference in "deep" structure between p-p (pronounced also at LHC) and p-pbar (shallower)
- High-|t| region power-low behavior without "oscillations"
- Low-|t| deviation from pure exponential and not constant hadronic phase
- Deviation of elastic slope from a linear logs dependence

TOTEM Results

- Pronounced "deep/bump" structure in pp collisions confirmed at TeV scale (first seen @ √s = 7 TeV), with the deep position approaching |t| = 0 with increasing energies
- Comparison of results @ √s = 2.76 TeV with Tevatron data (@ √s = 1.96 TeV, shallower deep as expected)
  → first comparison of p-p and p-pbar results (at the TeV scale !) since ISR times ….
- Observed power-low behavior at high-|t| without "oscillations"



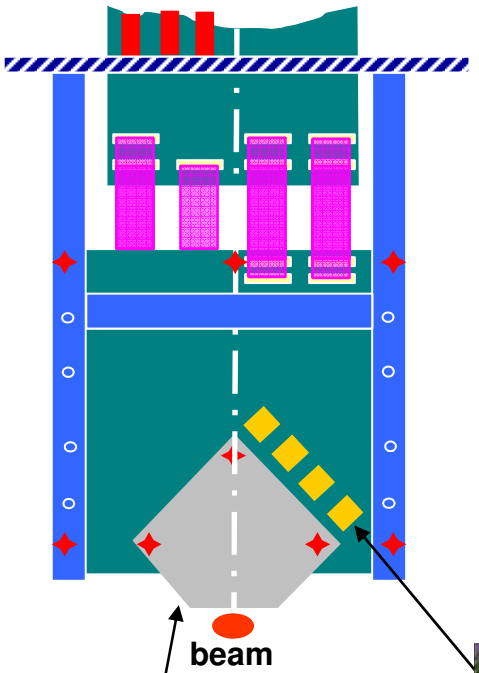
Summary & Outlook

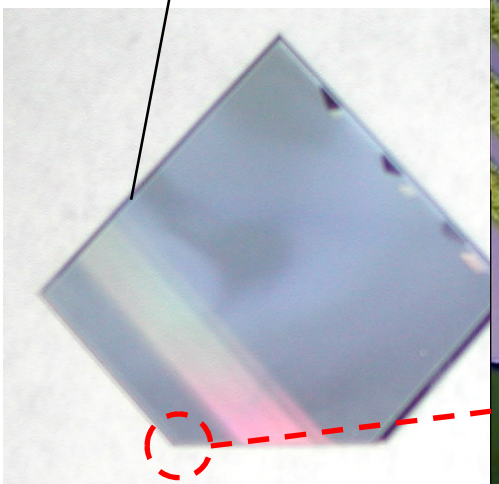
- Extensive programme of σ_T, σ_{el} and σ_{inel} measurements in Run I and II
- @ $\sqrt{s}$ = 13 TeV
  - ρ measurement significantly below expectations from pre-LHC fits
  - none of the COMPETE "no-Odderon" models is able to simultaneously describe the σ_T and ρ measurements
  - alternative "Odderon" models are able to describe TOTEM data
    - → inclusion of crossing-odd component (3-gluons bound state with $J^{PC} = 1^{--}$) essential
    - → if crossing-odd component not important, current measurements give first indication (via dispersion relations) of slower rise of σ_T at higher energies
- TOTEM observations of pronounced "dip/bump" structures in p-p $d\sigma_{el}/d|t|$ at the TeV scale represent another independent indication for Odderon
  - → confirmed by comparisons to Tevatron (D0) results on p-pbar @ $\sqrt{s}$ = 1.96 TeV (shallower dip structure, as expected)
- Other TOTEM observations consistent with "Odderon" models:

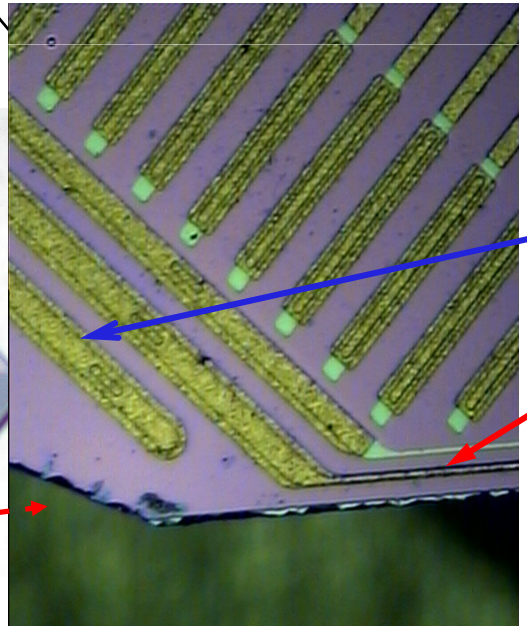
  deviation from pure exponentially in the elastic slope (B) and not constant hadronic phase at low-|t|; deviation of B from a linear log(s) dependence; power-low behavior at high-|t| in $d\sigma_{el}/d|t|$ without "oscillations"; growth rate of σ_T as a function of $\sqrt{s}$
- Next: analysis of new data @ $\sqrt{s}$ = 900 GeV and ...
  looking forward for new data taking @ $\sqrt{s}$ = 14 TeV from LHC Run III

Backup Slides

Roman Pots (II)







Edgeless Si detector:
50 µm of dead area

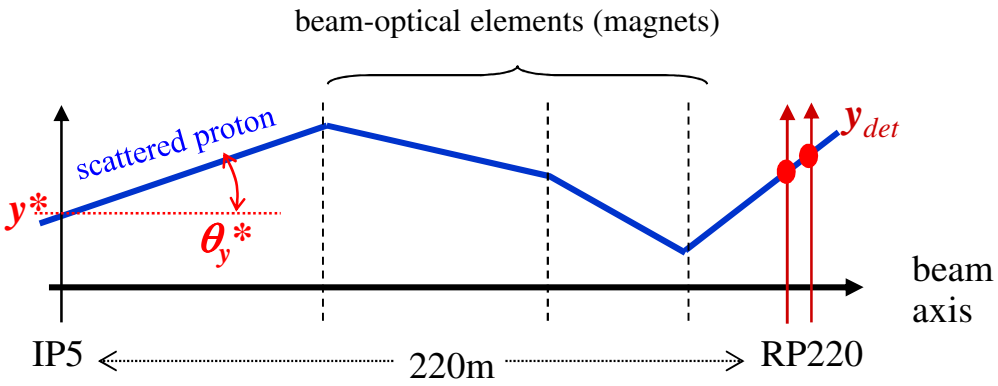
Each Pot:

- **10 planes** of Si detectors
- 512 strips at 45° orthogonal
- Pitch: 66 µm
- Total ~ 5.1K channels
- Digital readout (VFAT): trigger/tracking
- Hit Resolution: σ ~ 10 µm

Integration of traditional
Voltage Terminating Structure
with the
Current Terminating Structure

Detectors expected to work
up to $\mathcal{L}_{int}$ ~ 1 fb^{-1}
(no loss of performance during Run I)

Proton Transport from IP5 to RP Location



$$\underbrace{\begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \\ \Delta p/p \end{pmatrix}_{RP}}_{\text{Measured in RP}} = \underbrace{\begin{pmatrix} v_x & L_x & 0 & 0 & D_x \\ v'_x & L'_x & 0 & 0 & D'_x \\ 0 & 0 & v_y & L_y & 0 \\ 0 & 0 & v'_y & L'_y & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}}_{\text{Proton transport matrix}} \underbrace{\begin{pmatrix} x^* \\ \Theta^*_x \\ y^* \\ \Theta^*_y \\ \Delta p/p \end{pmatrix}_{IP5}}_{\text{Reconstructed}}$$

Optical functions:

L (effective length), **v** (magnification), **D** (machine dispersion)

- Describe the explicit path of particles through the magnetic elements as a function of the particle parameters at IP
- Define t and ξ-range (acceptance)
- Depend on LHC machine optics configuration

With: $\xi = \Delta p/p$; $t = t_x + t_y$; $t_i \sim -(p\theta_i^*)^2$

(x, y): vertex position at RP location (s)

(x^*, y^*): vertex position at IP

(θ_x^*, θ_y^*): emission angle at IP

→ **Elastic proton kinematics reconstruction (θ_x^*, θ_y^*)**

(for $\beta^* = 90$ m @ RP220m: $L_y = 263$ m, $v_y \approx 0$, $L_x \approx 0$, $v_x = -1.9$):

$$\begin{cases} \Theta^*_x \approx \left(\Theta_x - \dfrac{dv_x}{ds} x^* \right) / \dfrac{dL_x}{ds} , \\ \Theta^*_y \approx y / L_y \end{cases} \qquad \frac{\Delta p}{p} = 0$$

(θ_x measured with ~ 5m lever arm spectrometer)

Excellent optics determination (~ 0.25% using constraints from proton tracks in RPs, TOTEM: *New J. Phys. 16 (2014) 103041*) and <u>detector alignment</u>

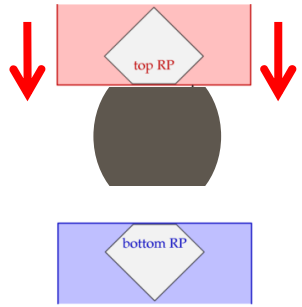
→ precise proton reconstruction

TOTEM Roman Pot Alignment Procedures

Critical procedures (fill-based): movable devices, beam optics variations

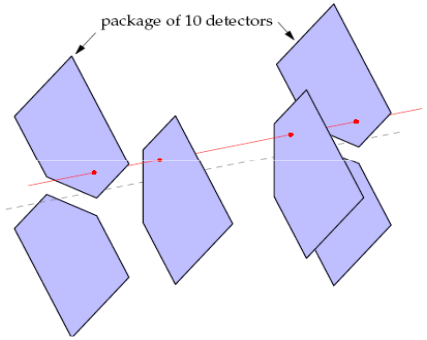
- **Pot position wrt LHC beam center:**

  alignment wrt collimators by approaching the beam "cut edge" (~ 20 μm)



- **Internal alignment of components within detector assembly:**

  metrology, local tracks (few μm)

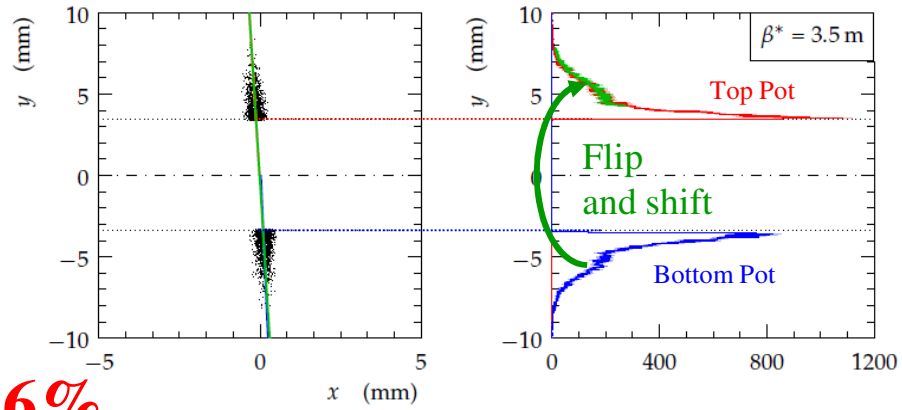


- **Relative alignment of the pots in a station:**

  tracks in overlapping regions (Millepede algorithm, few μm)

- **Global alignment:**

  track based exploiting symmetries (co-linearity) of hit profiles for elastically scattered protons, also allows "left-right" constraints (< 10 μm in x, ~ 20 μm in y)



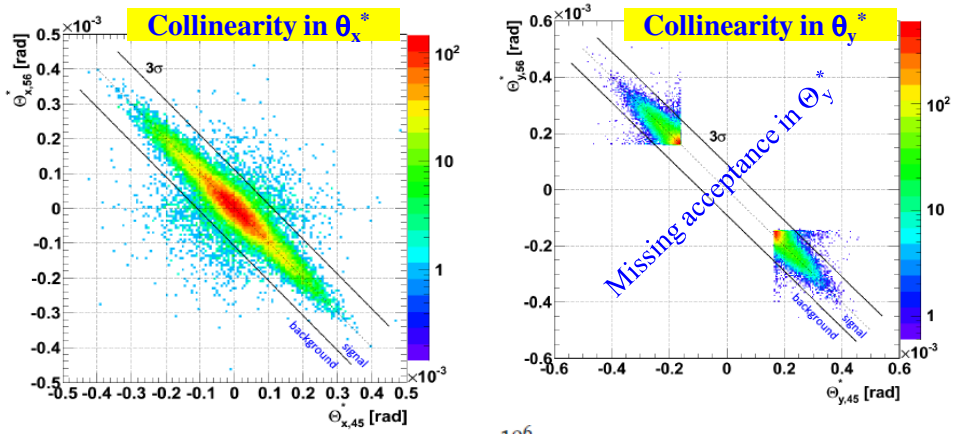
Final precision achieved:

~ 10(50) μm in x(y) → δt/t ~ 0.3-0.6%

TOTEM Elastic pp Scattering: Analysis (I)

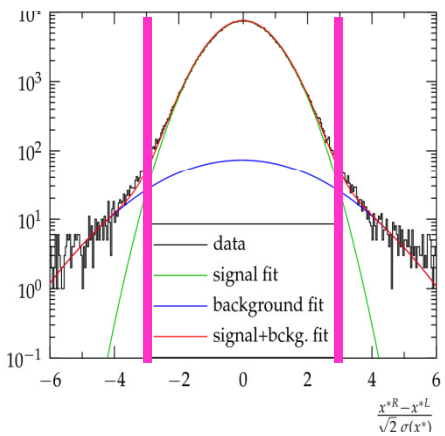
Proton selection cuts

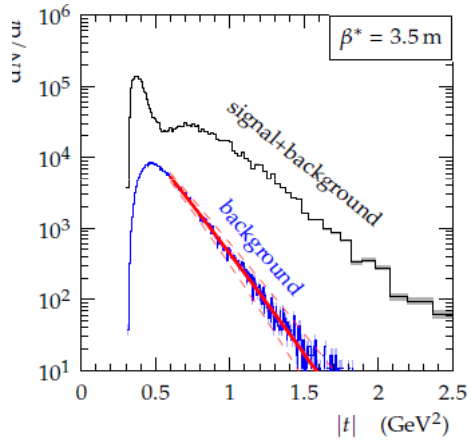
- collinearity cuts (left-right):
  $\Theta^*_{x,45} \leftrightarrow \Theta^*_{x,56}$
  $\Theta^*_{y,45} \leftrightarrow \Theta^*_{y,56}$
  (width in agreement with beam divergence)
- low ξ cuts: $|x^*| < 0.6$ mm and 2σ cut in $\Delta\theta_y^*$
- vertex cuts (beam halo): $|x^*_{45} - x^*_{56}| < 27\ \mu m$
- optics related cuts



Background subtraction

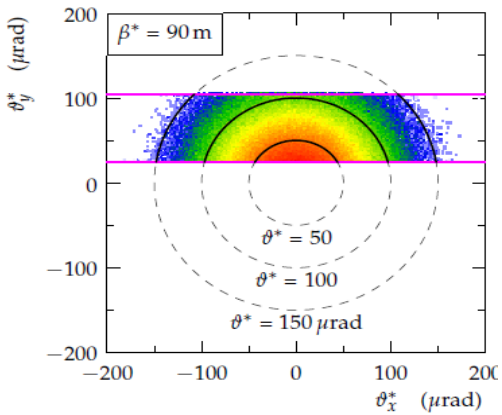
- interpolating the background tails (> 3 σ) into the signal region (< 3 σ)

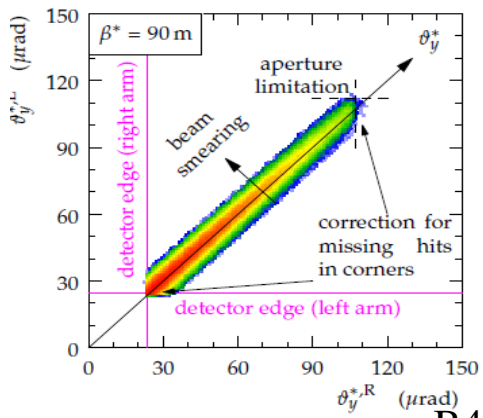




Acceptance correction

- assuming azimuthal symmetry
- correcting for smearing around limitation edges

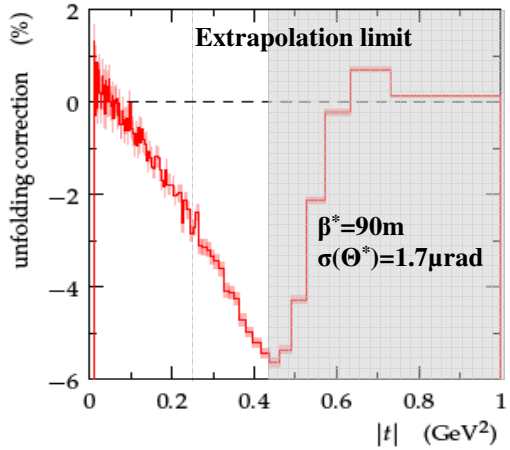


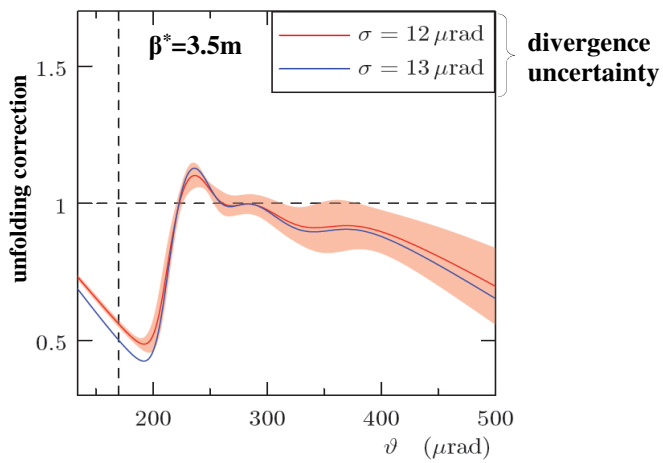


TOTEM Elastic pp Scattering: Analysis (II)

Unfolding of resolution effects:

MC based iterative procedure





Normalization (reconstruction efficiencies):

Trigger Efficiency **(from zero-bias data stream)**	**> 99.8% (68% CL)**
DAQ Efficiency	**98.142 ± 0.001 %**
Reconstruction Efficiency	
– intrinsic detector inefficiency:	**1.5 – 3 % / pot**
– elastic proton lost due to interaction:	**1.5% / pot**
– event lost due to overlap with beam halo (depends on RP position wrt beam and diagonals):	**4 – 8% (β*=90m); 30% (β*=3.5m)**

Luminosity from CMS: systematic error of 4%

Systematic uncertainties: dominated by $\mathcal{L}$ and by analysis t-dependent effects

(misalignments, optics imperfections, energy offset, acceptance correction and un-smearing correction)

Elastic Scattering in the Coulomb-Nuclear Interference Region

Experimental data → **Physics parameters (ρ, …)**

Theoretical/phenomenological models

Comparison

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

(QED)

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

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

Simplified West-Yennie formula:

- constant slope $B(t) = b_0$
- constant hadronic phase $\arg(F^H) = p_0$ ("costant phase")
- $\Psi(t)$ acts as real interference phase:

$$\Psi(t) = \ln\frac{B(t)}{2} + \gamma_{\text{Euler}}$$

General Kundrát-Lokajíček formula:

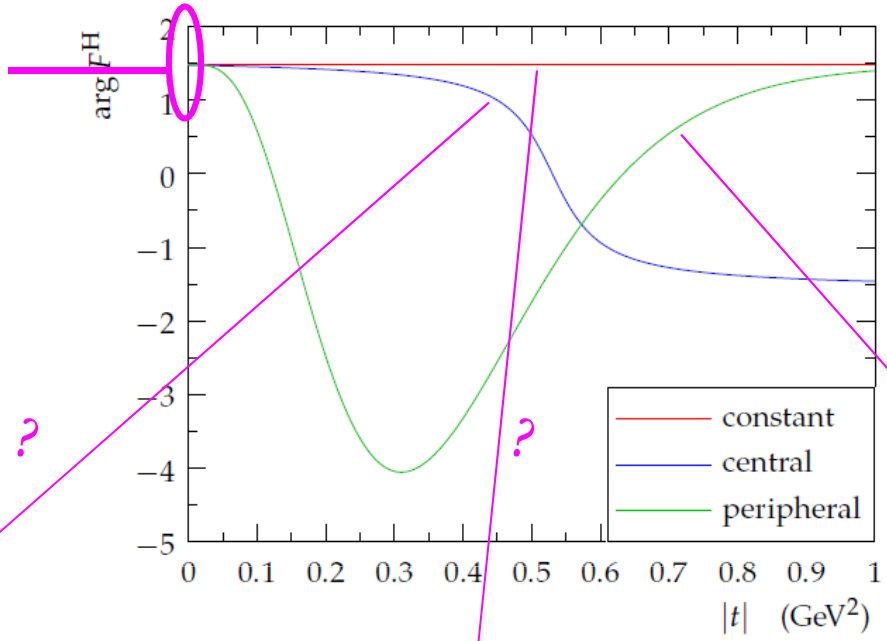
- any slope $B(t)$
- any hadronic phase:
  if $\arg F^H(t) \rightarrow$ "peripheral phase"
  if $\arg F^H \sim$ cost $\rightarrow$ "central phase"
- complex $\Psi(t)$:

$$\Psi(t) = \mp \int_{t_{min}}^{0} dt' \ln\frac{t'}{t}\frac{d}{dt'}\mathcal{F}^{2}(t') \pm \int_{t_{min}}^{0} dt' \left(\frac{F^H(t')}{F^H(t)} - 1\right)\frac{I(t,t')}{2\pi}$$

$$I(t,t') = \int_{0}^{2\pi} d\varphi\, \frac{\mathcal{F}^{2}(t'')}{t''}, \qquad t'' = t + t' + 2\sqrt{tt'}\cos\varphi$$

Elastic Scattering in the Coulomb-Nuclear Interference Region

data sensitivity region



"central phase":

$$\arg F^H(t) = \frac{\pi}{2} - \operatorname{atan}\frac{\cot p_0}{1-\frac{t}{t_d}}$$

"constant phase":

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

"peripheral phase":

$$\arg F^H(t) = p_0 + p_A \exp\left[\kappa\left(\ln\frac{t}{t_m} - \frac{t}{t_m} + 1\right)\right]$$

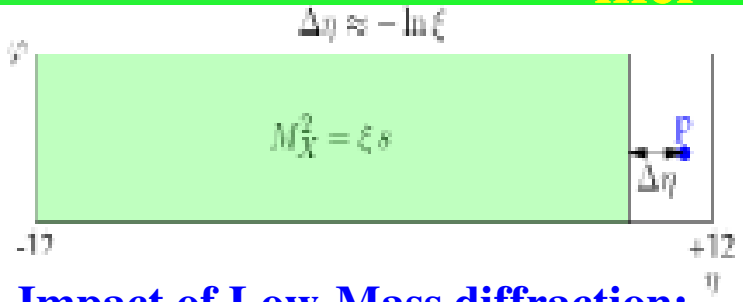
Only 1 free parameter: $p_0 = \psi(0)$ ➔

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

Most recent details on:

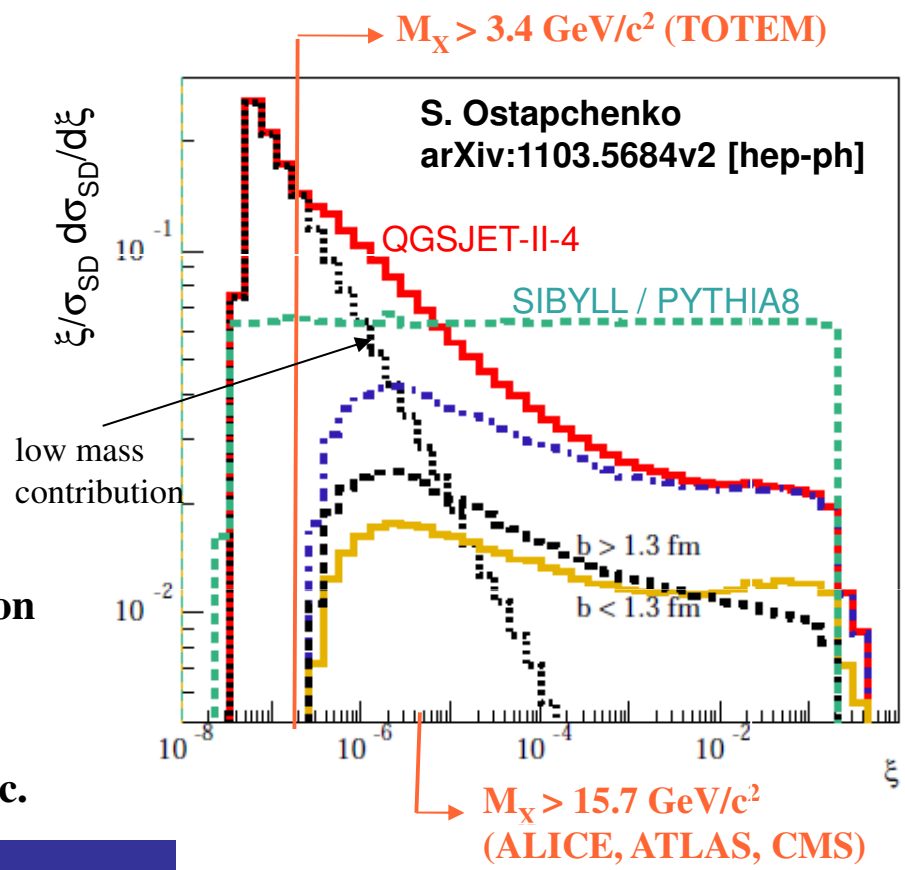
- Prochazka and V. Kundrat, "Eikonal model analysis of elastic hadron collisions at high energies", arXiv:1606.09479 (2016).
- Jiri Prochazka (jiri.prochazka@cern.ch) PhD thesis: "Elastic proton-proton collisions at high energies", Prague 2018 - Charles University

Direct σ_{inel} Measurement @ 7 TeV



Impact of Low-Mass diffraction:

- Extrapolation to low M_X region: main source of systematic uncertainty on σ_{inel}
- Minimal M_X depends on maximal $|\eta|$ coverage: lower M_X reachable → minimal model dependence on corrections for low mass diffraction
- TOTEM (T1+T2: $3.1 < |\eta| < 6.5$) gives an unique forward charged particle coverage @ LHC → direct measurement of σ_{inel} with lower sys. unc.



Experiment	σ_{inel} (mb)
ALICE	$73.2\ ^{+2.0}_{-4.6}$ (model) ± 2.6 (exp)
ATLAS	69.1 ± 6.9 (model) ± 2.4 (exp)
CMS	68.0 ± 4.0 (model) ± 3.1 (exp)
LHCb	66.9 ± 4.4 (model) ± 2.9 (exp)
TOTEM	73.7 ± 1.5 (model) ± 2.9 (exp)