Recent Results from TOTEM @ CERN LHC

T. Csörgő, for the TOTEM Collaboration

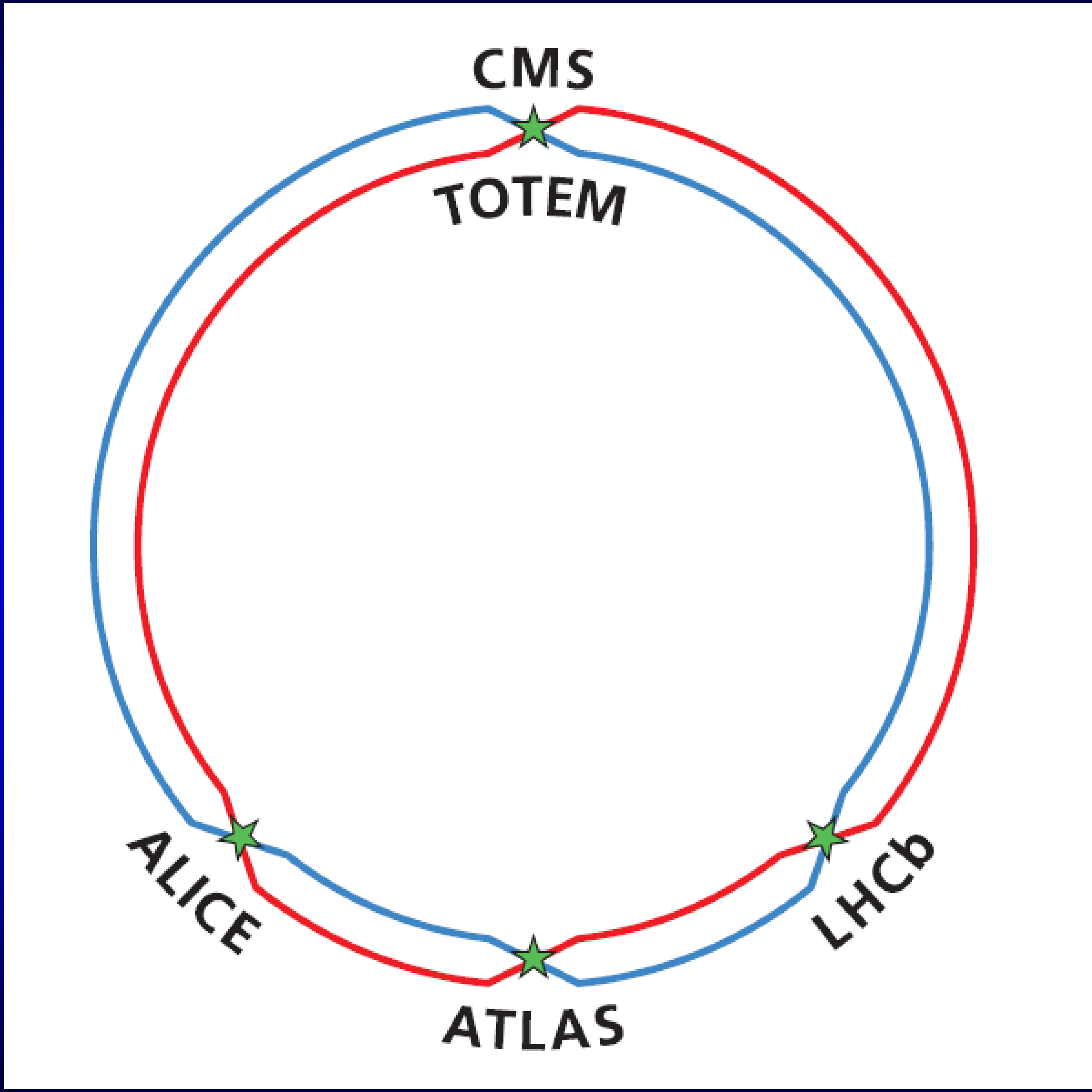
Wigner Research Center for Physics, Budapest, Hungary
EKE KRC, Gyöngyös, Hungary

Supported by EFOP 3.6.1-16-2016-00001 and NKFIH FK 123 842 grants

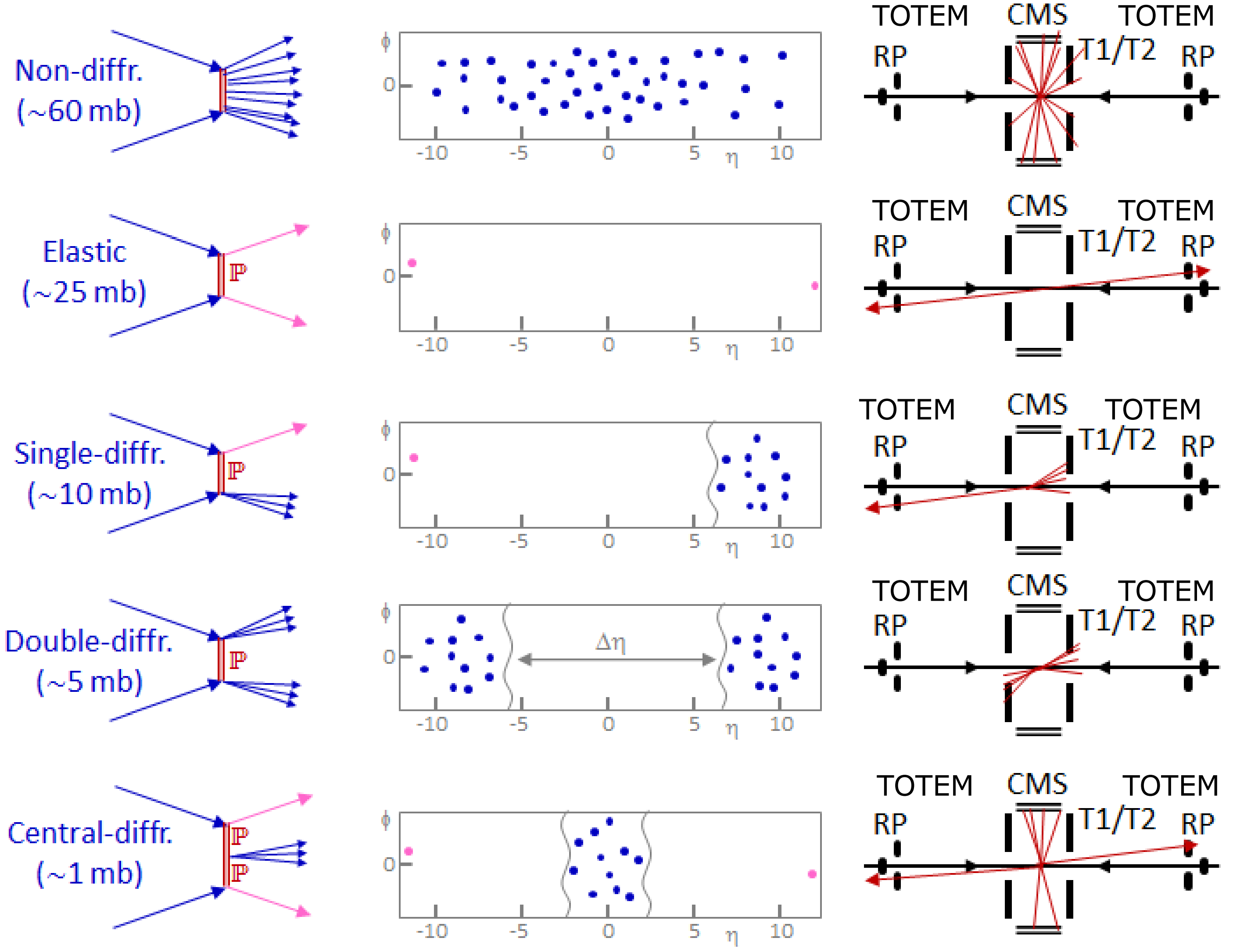
Outline

TOTEM physics
LHC Optics Determination
Elastic scattering results
2.76 TeV *
7 TeV
8 TeV
13 TeV *
Summary

LHC experiments reporting to RRB/LHCC

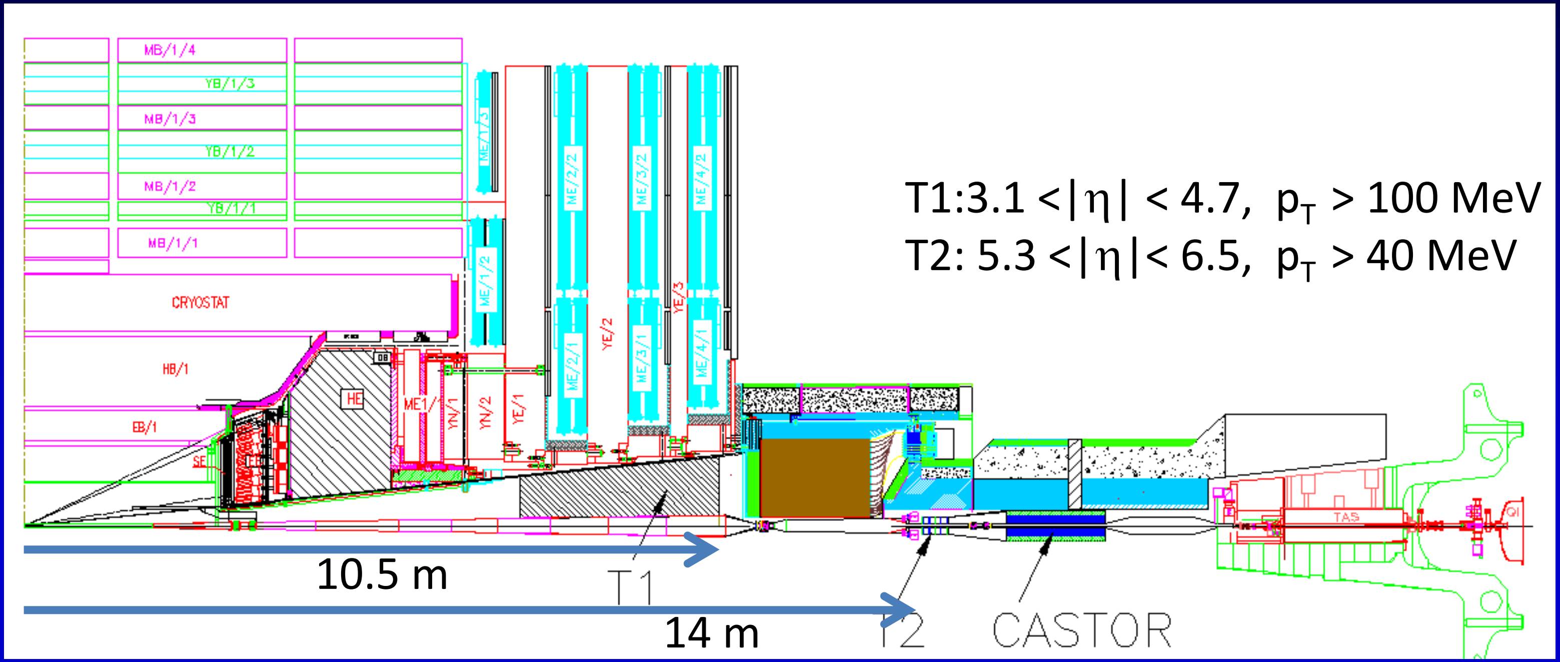


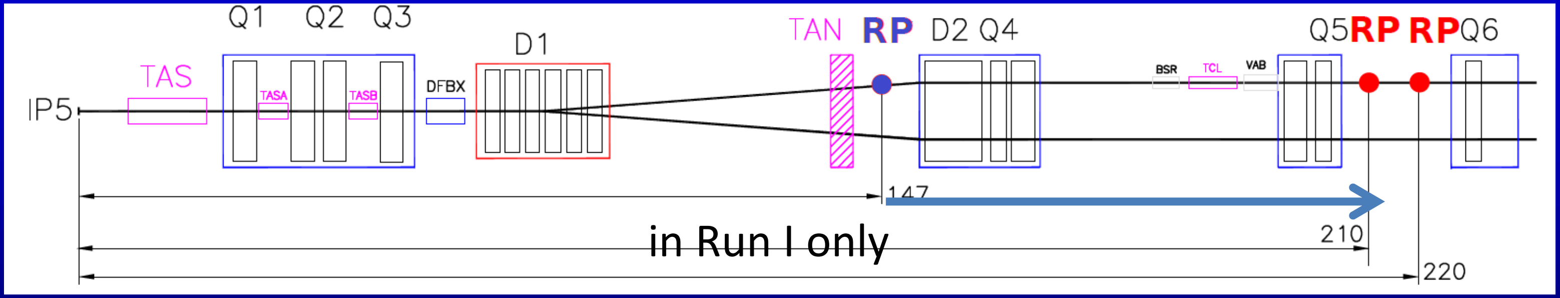
TOTEM physics at LHC



Elastic and diffractive scattering: colorless exchange

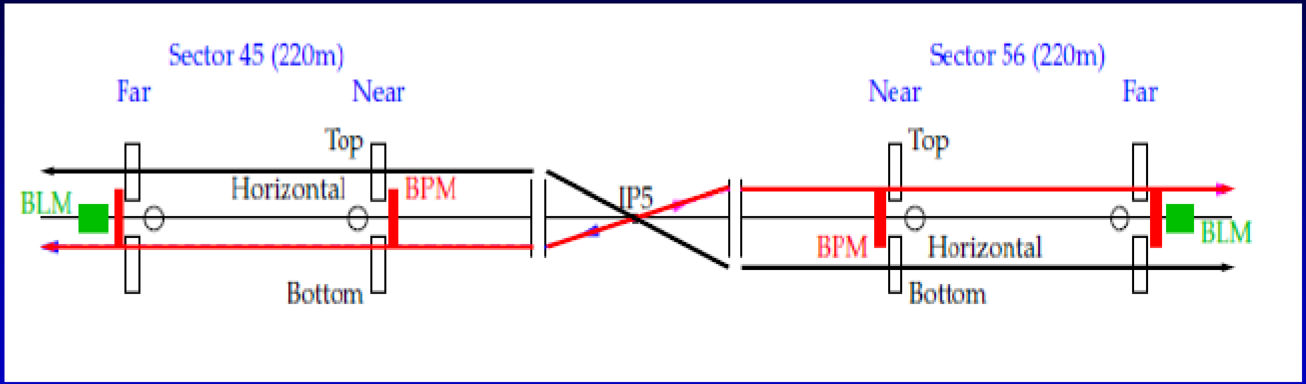
TOTEM – Experimental Setup





T1, T2: CSC and GEM Inelastic telescopes; RP: Roman Pots
[Details: JINST 3 (2008) S08007]

RP stations for elastic scattering



Near(214 m) and Far(220 m) TOTEM RP units on both sides of IP5

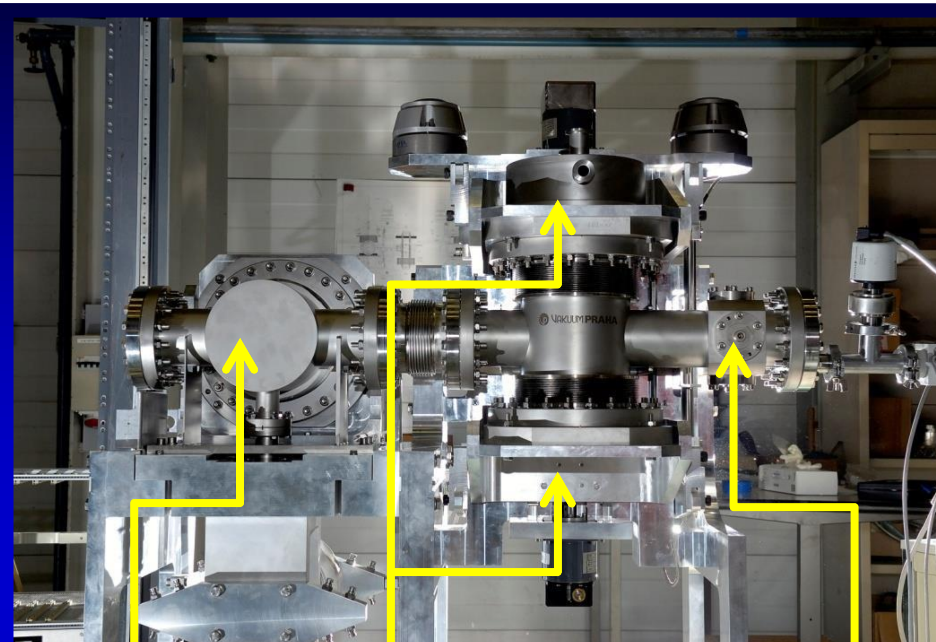
Three RP-s in each unit:
(top, horizontal, bottom)
Each RP:
Stack of 10 silicon strips (pitch 66 μm)
„edgeless" (active in few x 10 μm)
Trigger capable electronics

Elastic scattering: two anti-parallel protons
→ two topologies, analyzed independently:
→ 45 bottom-56 top, 45 top-56 bottom

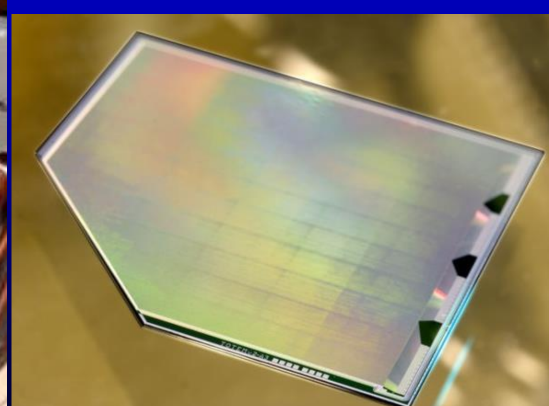
RP stations in Run 2

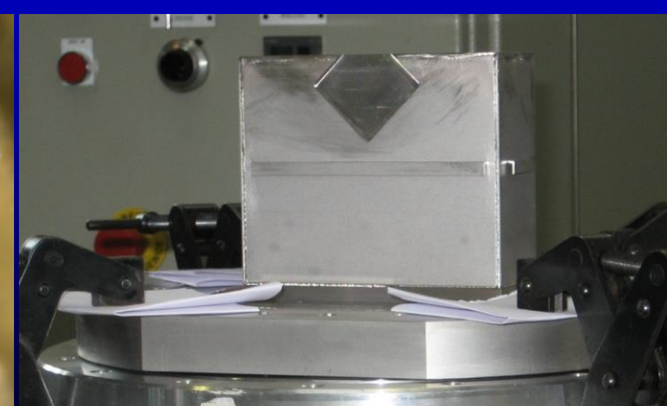
RP stations:

- 2 units (Near, Far) at about 5 m (RP220) and 10 m (RP210) distance
- 1 unit: 3 moveable RPs to approach the beam and detect very small proton scattering angles (few µrad)
- BPM: precise position relative to beam
- Overlapping detectors: relative alignment (10 µm inside unit among 3 RPs)

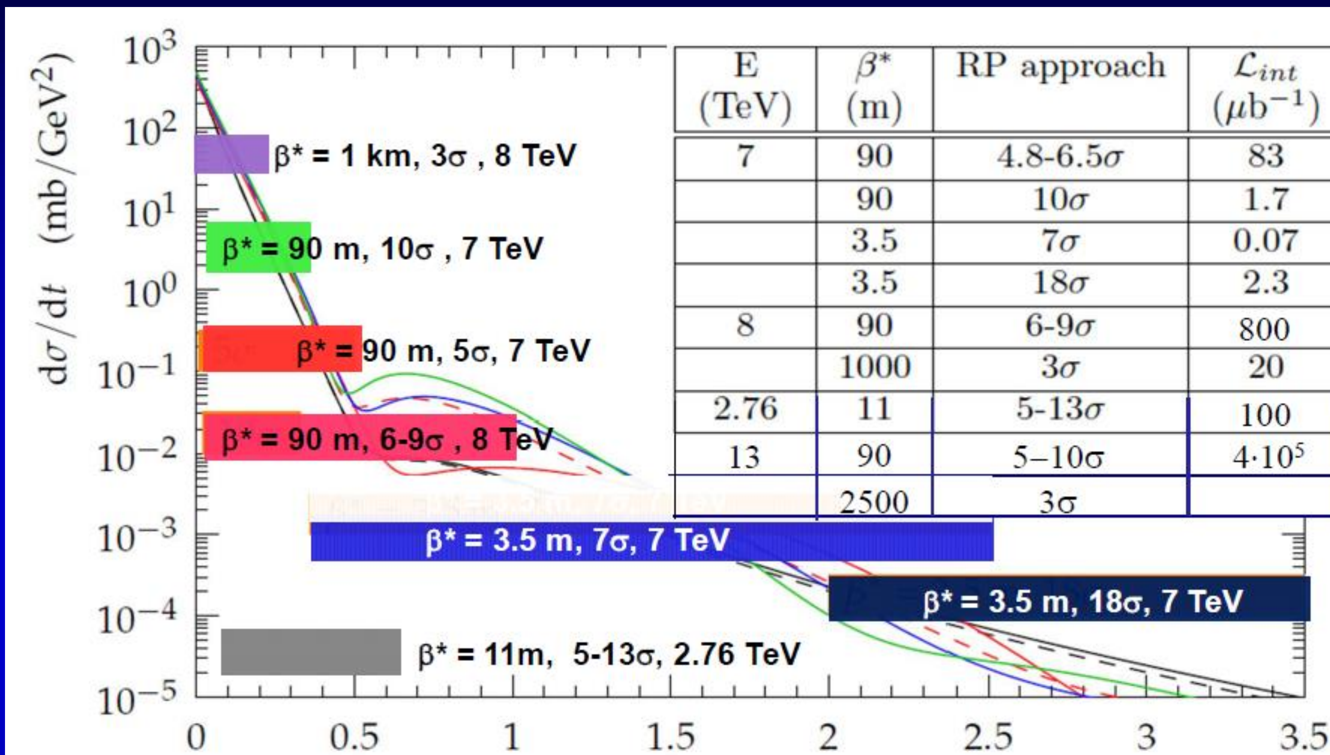


Horizontal RP, Vertical RPs, Horizontal RP, BPM
RP unit = 2 vertical + 1 horizontal pot + BPM





TOTEM data taking



E (TeV)	β^* (m)	RP approach	$\mathcal{L}_{int}$ (μb^{-1})	t range (GeV^2)	Elastic events	
7	90	4.8-6.5σ	83	$7\cdot10^{-3}$ - 0.5	1M	√
	90	10σ	1.7	0.02 - 0.4	14k	√
	3.5	7σ	0.07	0.36 - 3	66k	√
	3.5	18σ	2.3	2 - 3.5	10k	
8	90	6-9σ	800	0.01 - 1	7M	√
	1000	3σ	20	$6\cdot10^{-4}$ - 0.2	0.4M	√
2.76	11	5-13σ	100	0.05-0.6	45k	O
13	90	5–10σ	$4\cdot10^5$	0.01 – 3.5	~ 1400M	O
	2500	3σ		$6\cdot10^{-4}$ – 0.2	~ 5M	O

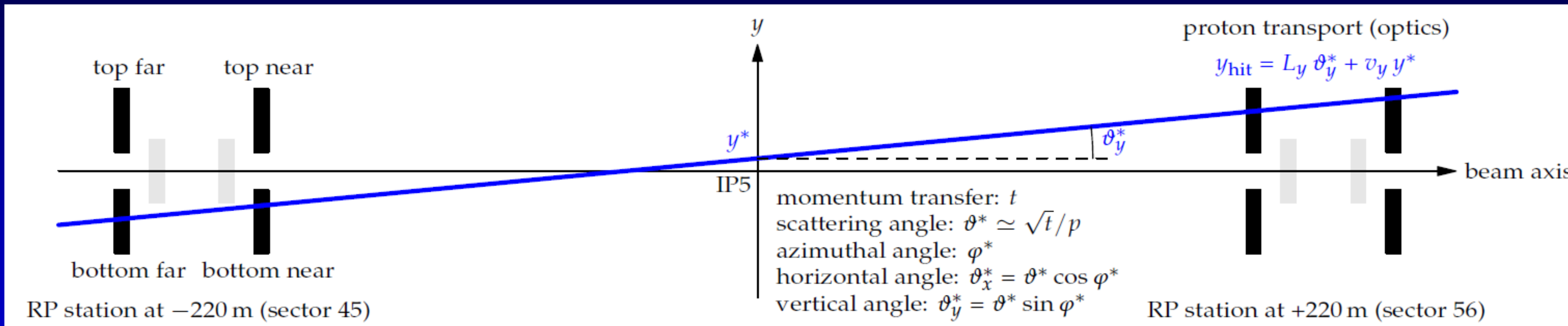
√ Data published
O Analysis finished
O Analysis on-going

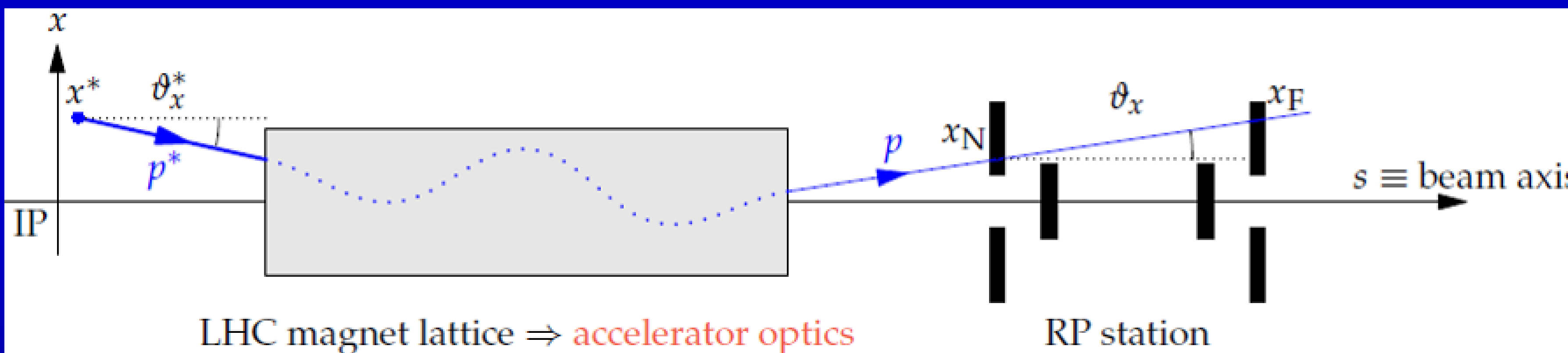
Elastic event selection: topology,anti-collinearity, vertex,low |ξ|

Data sets at different conditions to measure in a wide |t| range

Key issues: RP alignment and LHC optics recalibration

LHC Optics for Elastic pp Scattering





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

Precise σ_{tot} and $d\sigma/dt$ determination by TOTEM needs excellent controll of LHC optics from data

LHC Optics Determination, $\beta^* = 90$ m

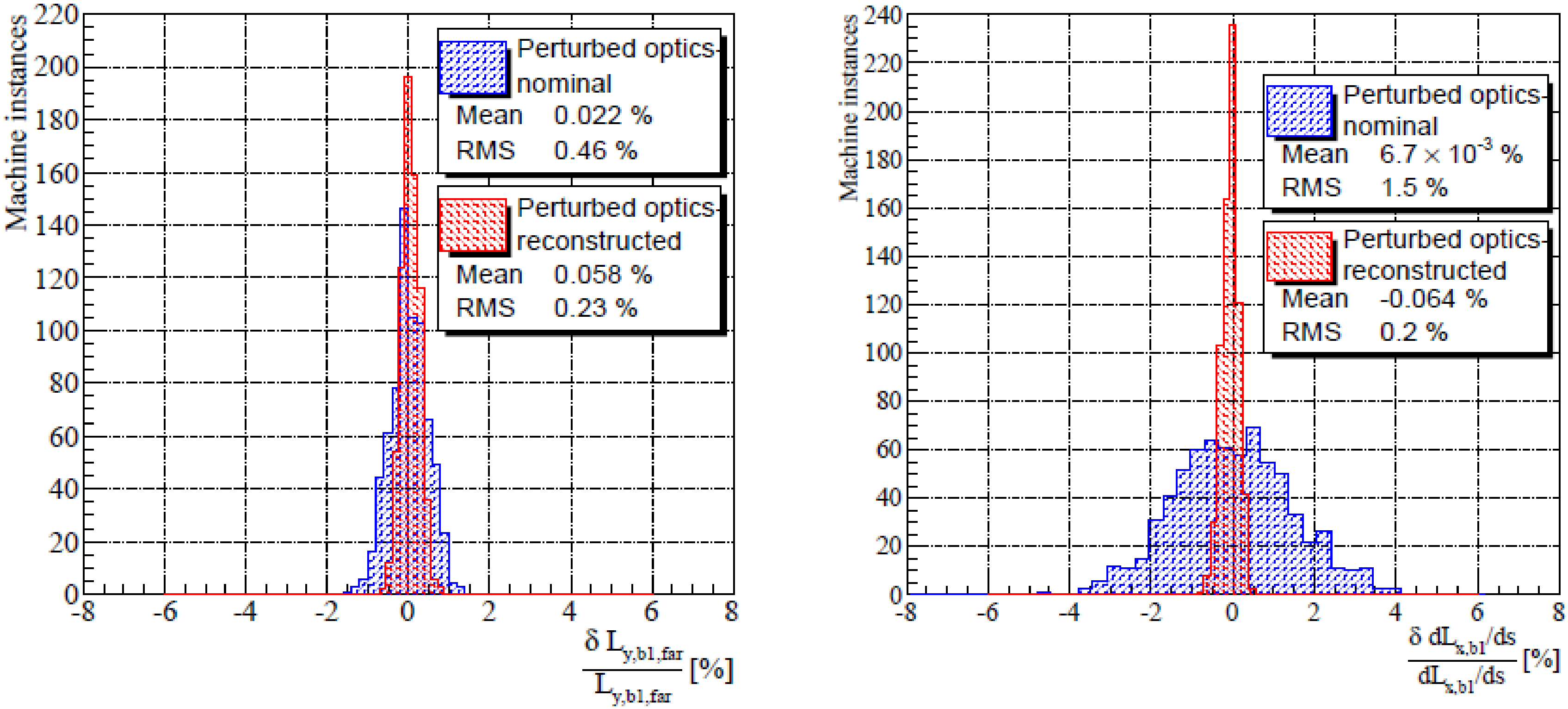


Figure 12. (color online) The MC error distribution of $\beta^* = 90$ m optical functions L_y and dL_x/ds for Beam 1 at $E = 4$ TeV, before and after optics estimation.

Precise control of LHC imperfections with perturbed LHC optics and recalibration from data at IP5: factors of 2 - 10
arXiv:1406.0546

LHC Optics Determination, $\beta^* = 3.5$ m

Machine imperfections alter the optics:

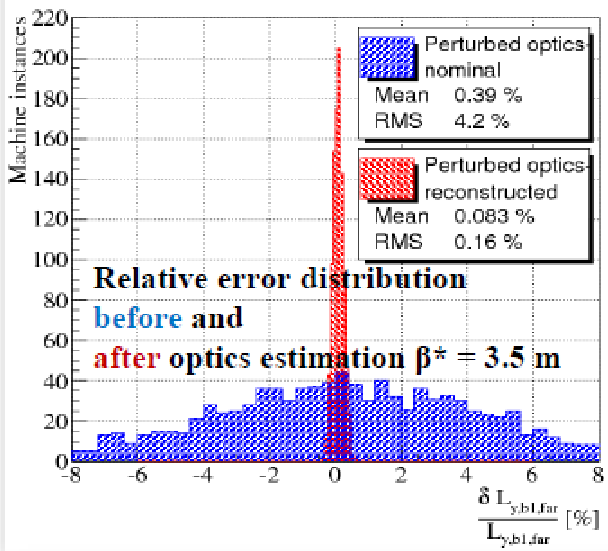
- **Strength conversion error, $\sigma(B)/B \approx 10^{-3}$**
- **Beam momentum offset, $\sigma(p)/p \approx 10^{-3}$**
- Magnet rotations, $\sigma(\phi) \approx 1$ mrad
- Magnetic field harmonics, $\sigma(B)/B \approx 10^{-4}$
- Power converter errors, $\sigma(I)/I \approx 10^{-4}$
- Magnet positions Δx, $\Delta y \approx 100$ µm

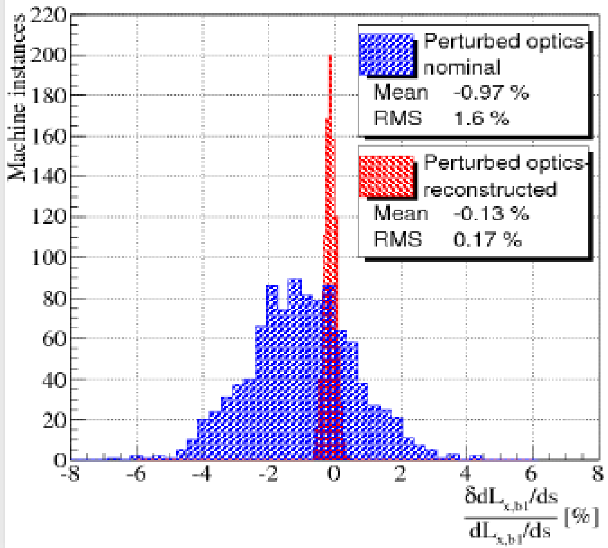
$$t(v_x, L_x, L_y, \ldots, p) = -p^2 \cdot \left(\Theta_x^{*2} + \Theta_y^{*2}\right)$$

→ Precise model of the LHC optics is indispensable!

Novel method from TOTEM:

- Use **measured** proton data from RPs
- Based on kinematics of elastic candidates
- Published in New Journal of Physics
- http://iopscience.iop.org/1367-2630/16/10/103041/

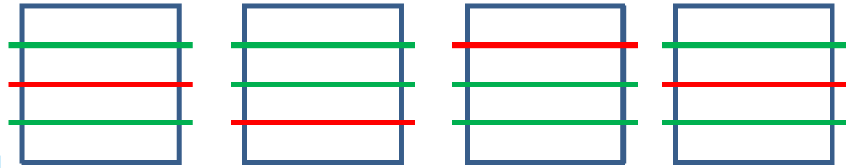




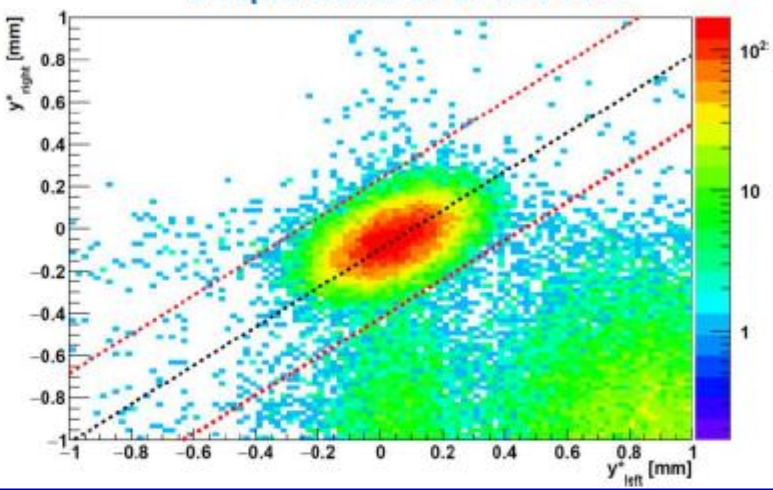
TOTEM results at √s = 2.76 TeV

TOTEM results at $\sqrt{s}$ = 2.76 TeV

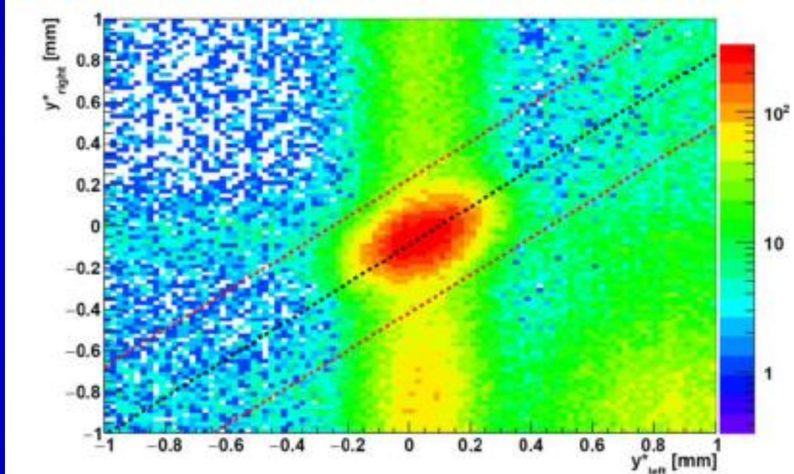
- RP can resolve uniquely single tracks
- If cannot be resolved: array of multitrack candidates per RP
- Elastic cuts defined with unique tracks
- **Every** combination of the 4 RPs of a diagonal
- **One** combination is selected with elastic cuts (+physics oriented topology studies)



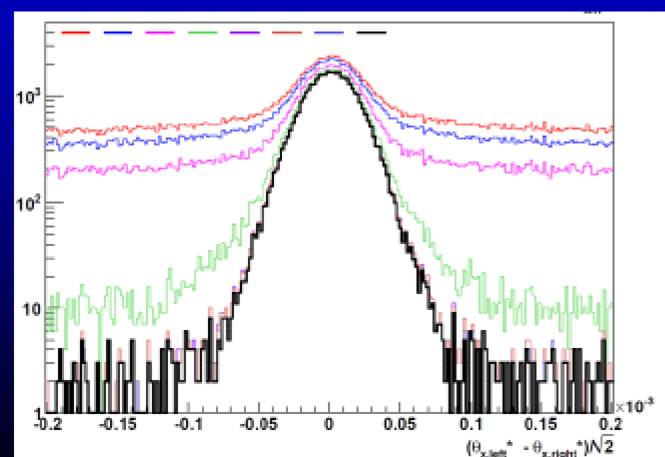
Unique tracks to define cuts



... to select elastic candidates from multitracks



Step by step progressive selection of cuts to find elastic events

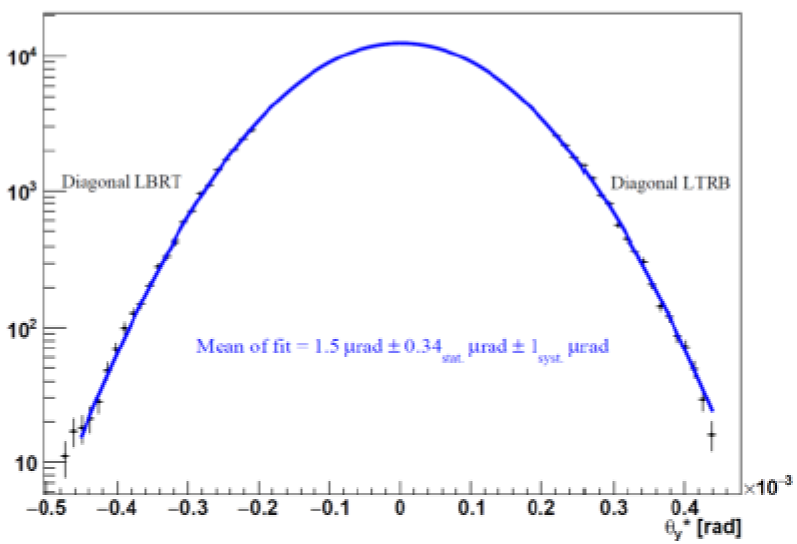


Alignment, LHC Optics at $\sqrt{s}$ = 2.76 TeV

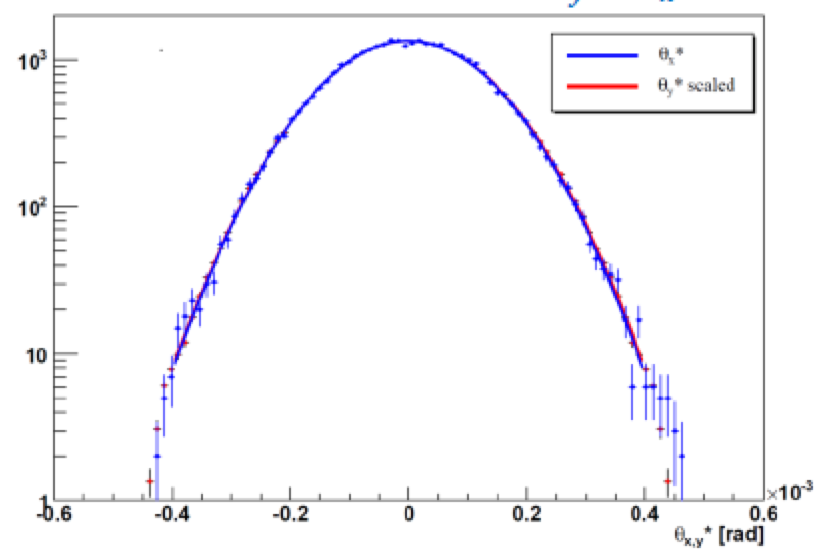
Horizontal RPs were not inserted:

- No track based **top - bottom** RP alignment
- Horizontal and relative near-far alignment is done
- New methods to find absolute y-alignment of the 2 diagonals
- 2 diagonals: 2 constraints from elastic scattering symmetries

[1st] constraint: alignment of θ_y^* barycenter to 0

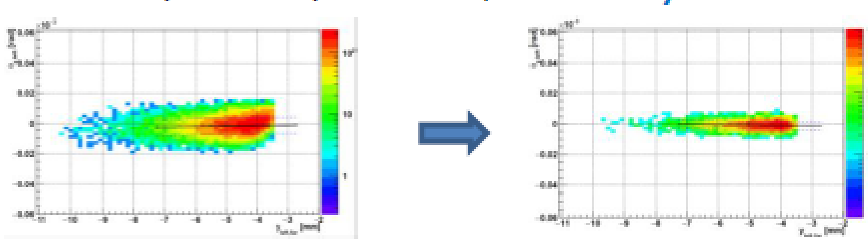


[2nd] constraint: alignment of θ_y^* to θ_x^*

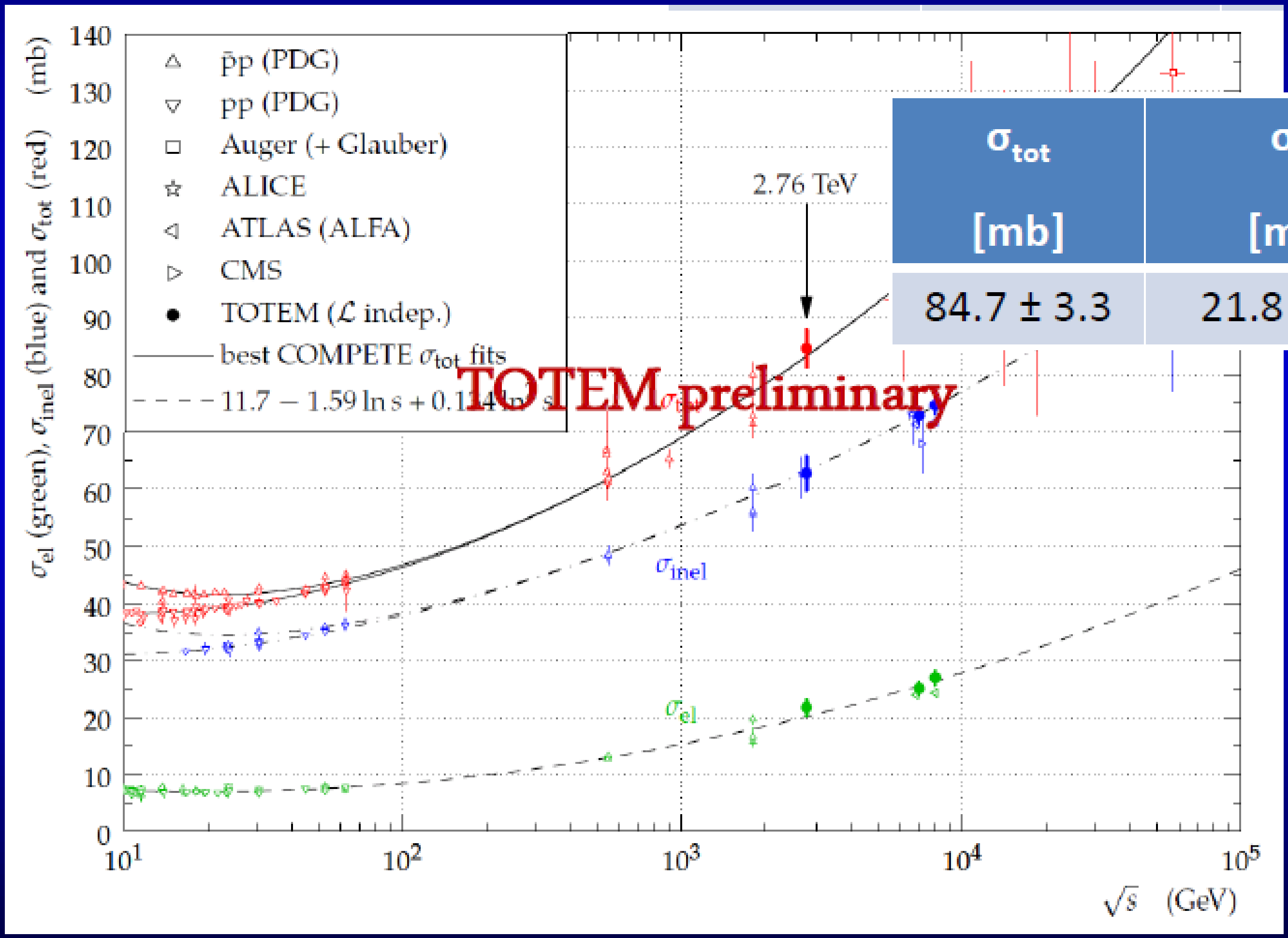


- Optics calibration done in the usual way (alignment independent procedure)
- Careful measurement of optics estimators:

After y* vertex cut

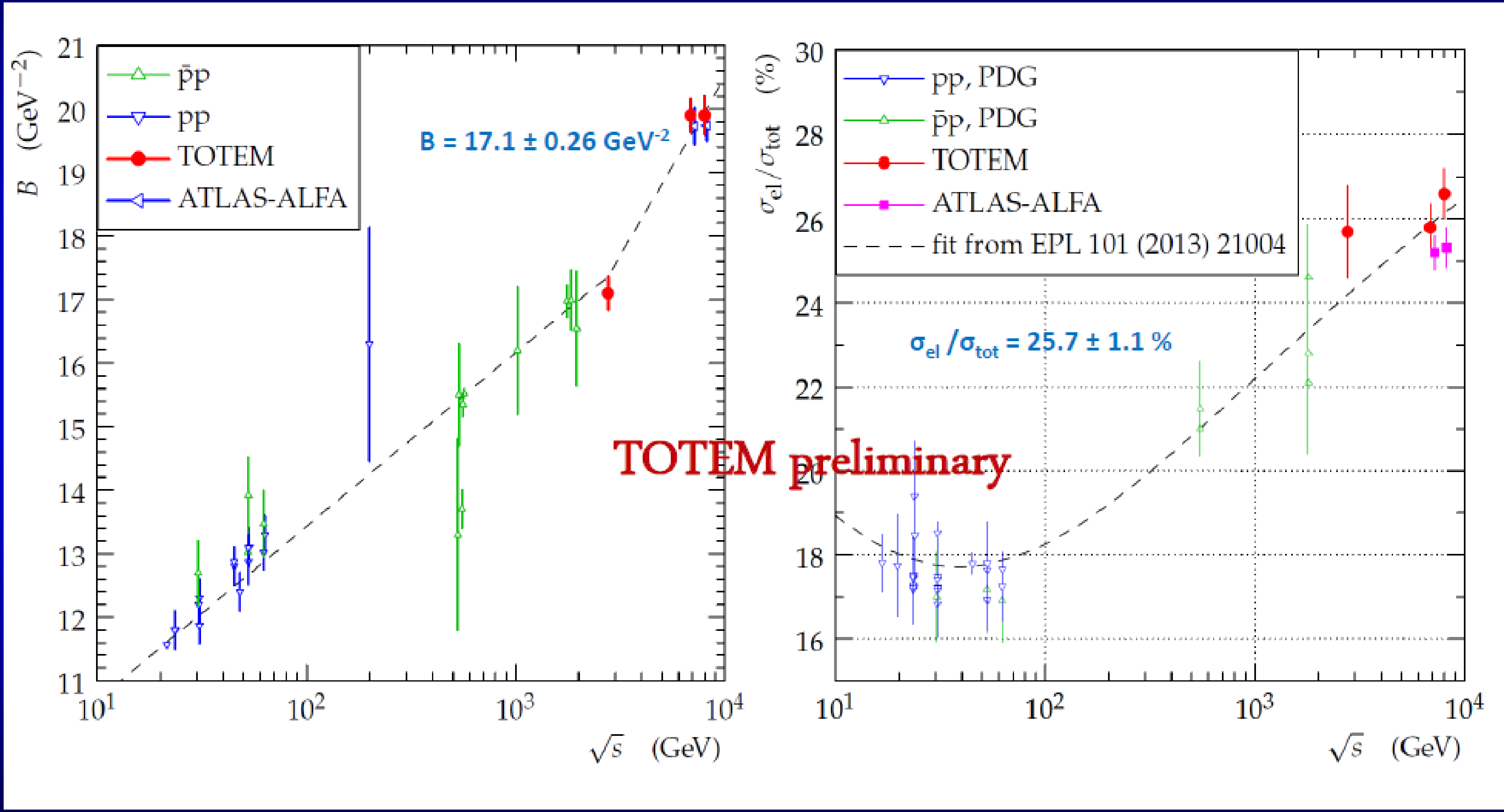


√s = 2.76 TeV preliminary results: cross-sections



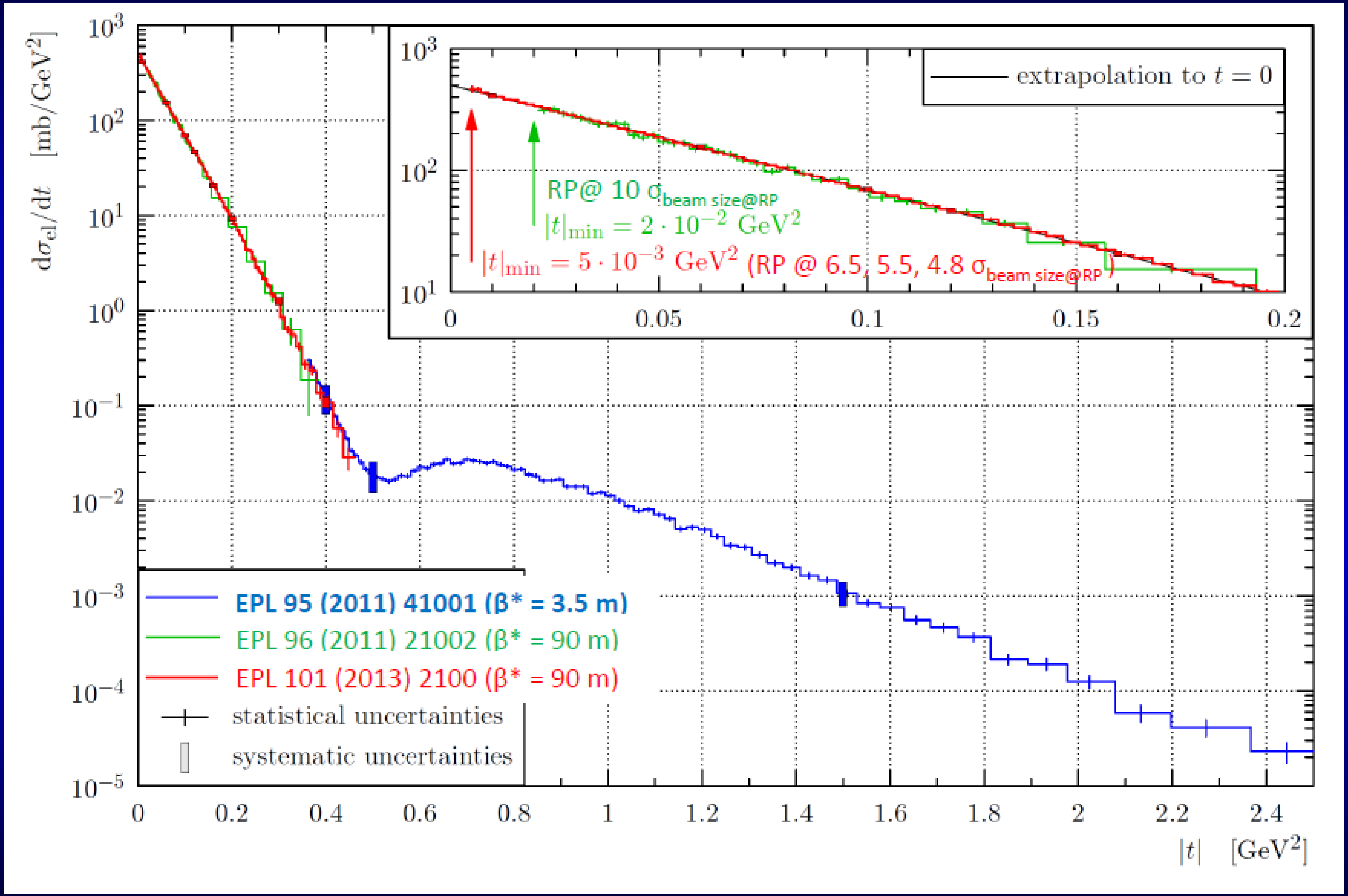
σ_{tot} [mb]	σ_{el} [mb]	σ_{inel} [mb]
84.7 ± 3.3	21.8 ± 1.4	62.8 ± 2.9

$\sqrt{s}$ = 2.76 TeV preliminary results: slope parameter B and σ_{el}/σ_{tot} ratio



TOTEM results at $\sqrt{s}$ = 7 TeV

TOTEM dσ/dt results at √s = 7 TeV



Inelastic cross-section at $\sqrt{s}$ = 7 TeV

Trigger: at least one track in T2

- 95 % of inelastic events

1. **Raw rate**: event counting with T2

   Experimental corrections: trigger and reconstruction inefficiencies, beam-gas event suppression, pile-up

2. **Visible rate**: visible with T2 in perfect conditions

   Estimation of events with no tracks in T2: T1-only events, events with gap over T2, low-mass diffraction

3. **Physics rate**: true rate of inelastic events
   - Only one major Monte-Carlo-based correction: low-mass diffraction (which can be constrained from data, 6.31 mb upper limit for $M_x < 3.4$ GeV)

4. **Cross-section**: uses CMS luminosity measurement

Measurement of proton-proton inelastic scattering cross-section at $\sqrt{s}$ = 7 TeV

EPL **101** (2013) 21003

$$\sigma_{inel} = 73.7 \pm 3.4 \text{ mb}$$

TOTEM σ_{tot} at $\sqrt{s}$ = 7 TeV

1. Low luminosity (CMS) + Elastic dσ/dt + Optical th. (EPL 96(2011) 21002)
   - depends on CMS luminosity for low-L bunches, elastic efficiencies and on ρ

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

σ_{tot} = 98.3 ± 2.8 mb

2. High luminosity (CMS) + Elastic + Optical theorem (EPL 101 (2013) 21002)

σ_{tot} = 98.6 ± 2.2 mb

3. High luminosity (CMS) + Elastic + Inelastic (EPL, 101 (2013) 21004)
   - minimizes dependence on elastic efficiencies and no dependence on ρ

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

σ_{tot} = 99.1 ± 4.3 mb

4. Elastic ratios + Inelastic ratios (T1, T2) + Optical theorem (EPL, 101 (2013) 21004)
   - Eliminates dependence on luminosity

$$\sigma_{\text{tot}} = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \frac{\left.\frac{dN_{\text{el}}}{dt}\right|_{t=0}}{N_{\text{el}} + N_{\text{inel}}}$$

σ_{tot} = 98.0 ± 2.5 mb

Four different methods yield self-consistent results

TOTEM results at $\sqrt{s}$ = 8 TeV

Earlier results on elastic scattering

Earlier hints on
non-exponential dσ/d|t|:

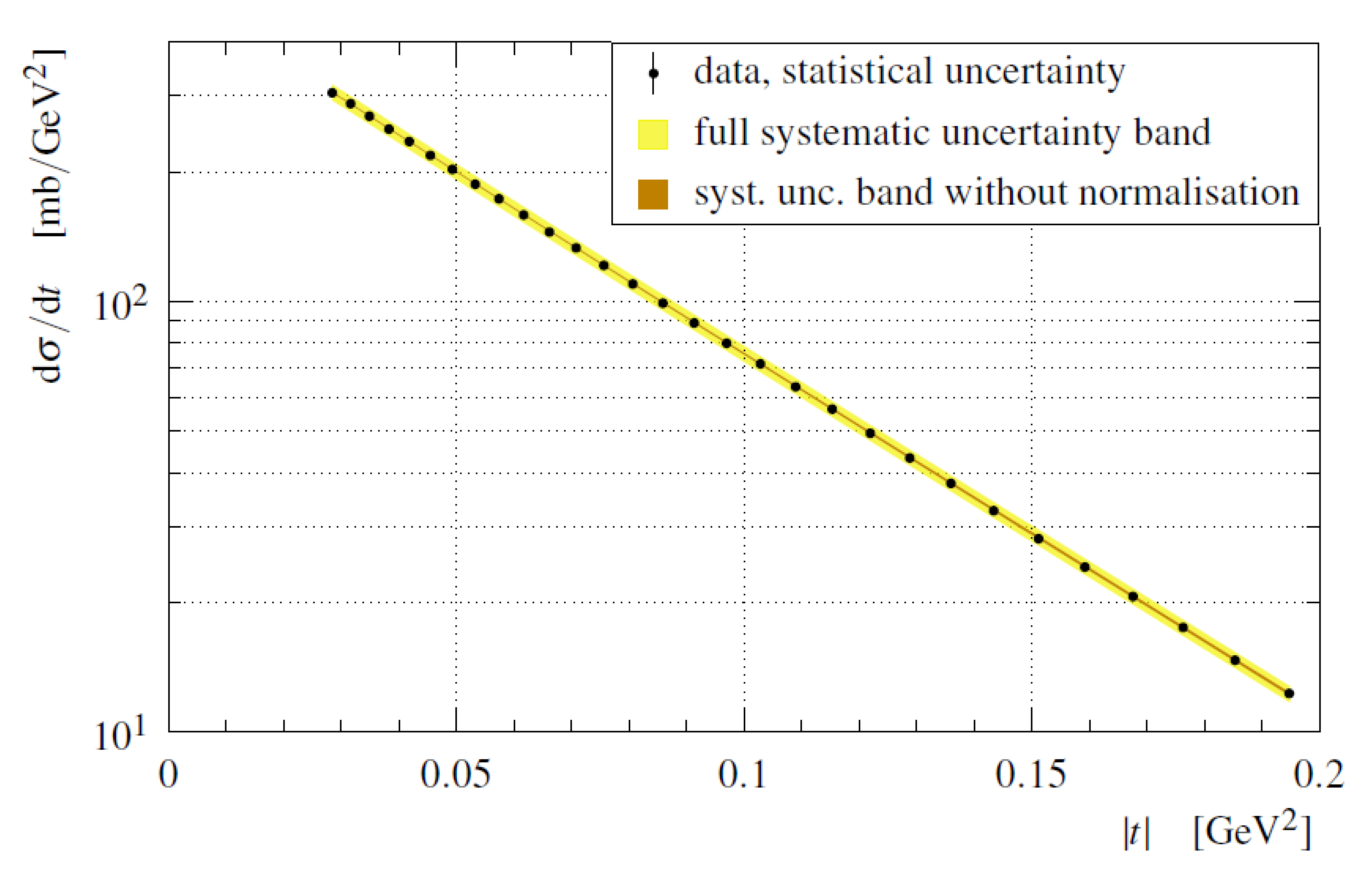
at ISR: 21.5 to 52.8 GeV,
change of slope
and better fits with
$\exp(-B\,|t| - C\,t^2)$

at SppS:
Change of slope only, at
$|t| \sim 0.14$ GeV^2

At Tevatron,
non-exponential not seen

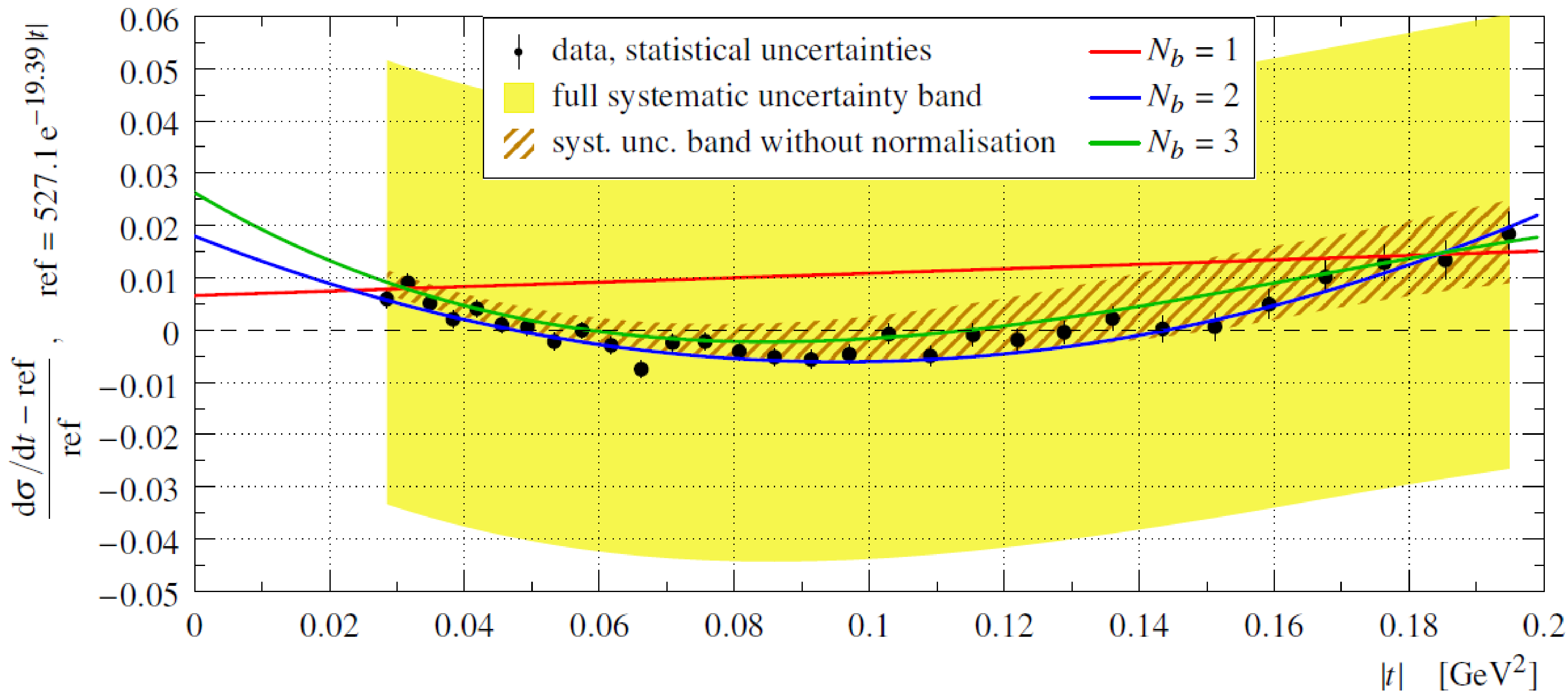
first LHC data @7 TeV ~ exponential,
satisfactory fits with $\exp(-B\,|t|)$,
but $\sqrt{s}$ =8 TeV TOTEM data at low |t|: non-exponential @ 7 σ

Differential cross-section @ 8 TeV



$t = -p^2\,\theta_*^2$; „optimized binning"; almost exponential but if one looks in detail, NOT

Differential cross-section @ 8 TeV



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

$$\chi^2 = \Delta^T V^{-1} \Delta\,,$$

$$\Delta_i = \left.\frac{d\sigma}{dt}\right|_{\text{bin } i} - \frac{1}{\Delta t_i}\int_{\text{bin } i} f(t)\, dt\,,$$

$$V = V_{stat} + V_{syst}$$

N_b = 1 fits excluded. Relative to best exponential, a significant (7σ) deviation found

TOTEM pp cross-sections @ 8 TeV

Read more:

- EPL 101 (2013) 21004
- Phys. Rev. Lett. 111, 012001 (2013)
- Evidence for non-exponentiality

σ_{tot} [mb]	σ_{el} [mb]	σ_{inel} [mb]
101.7 ± 2.9	27.1 ± 1.4	74.7 ± 1.7

The observed differential cross-section w.r.t. reference exponential:

- Fits with different assumptions on hadronic component

$$|A^N| = a \cdot \exp(b_1 t) \Rightarrow |A^N| = a \cdot \exp(b_1 t + b_2 t^2 + b_3 t^3)$$

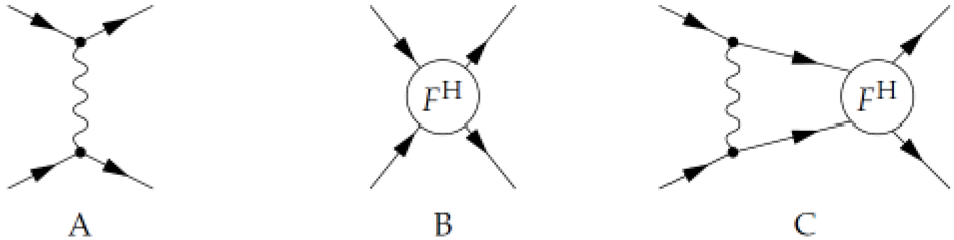
- Pure exponential **excluded** with more than 7σ significance !

N_b	σ_{tot} [mb]
2	101.5 ± 2.1
3	101.9 ± 2.1

Coulomb-Nuclear Interference @ 8 TeV

Basic properties of the data:

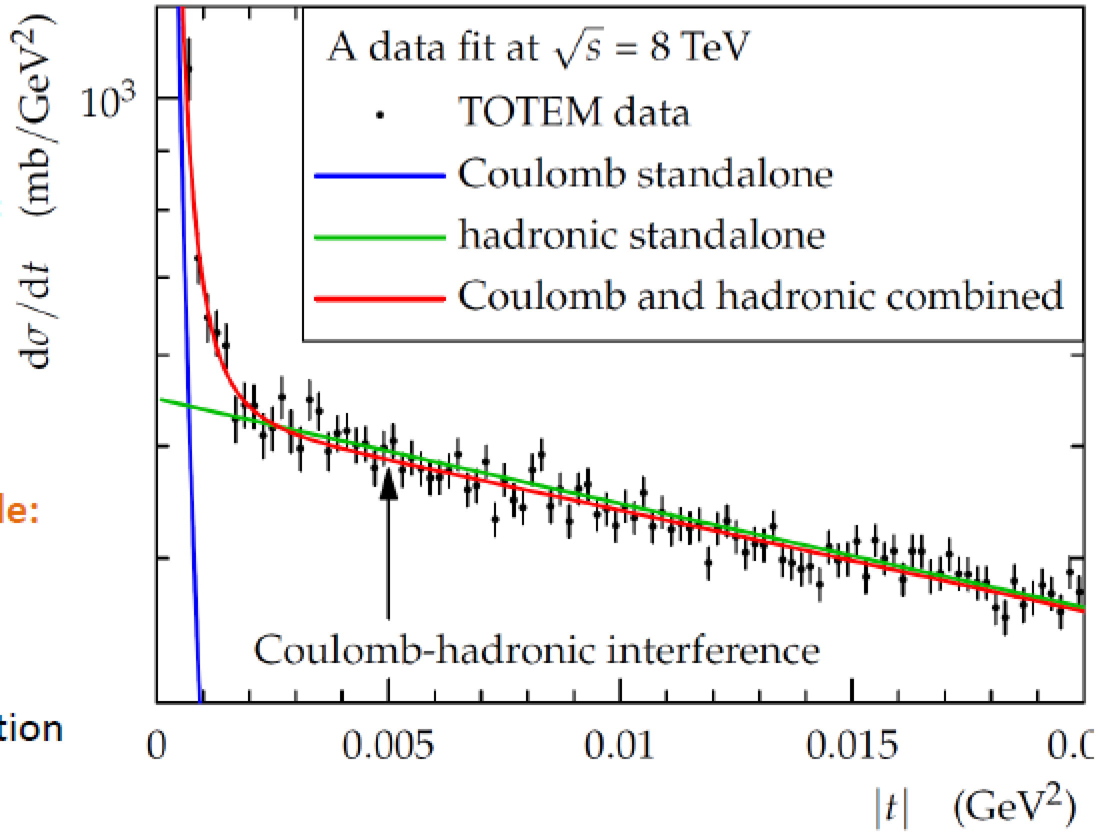
- RP detectors at about $3 \times \sigma_{beam}$
- $|t|_{min} = 6 \times 10^{-4}$ GeV^2



Analysis aims:

- Measure $d\sigma_{el}/dt$ at the smallest possible $|t|$
- A_{C+H}= Coulomb + Hadronic + Interference terms
- Interference: the phase of hadronic amplitude appears in

$$\frac{d\sigma}{dt} \propto \left|A_{C+H}\right|^2$$



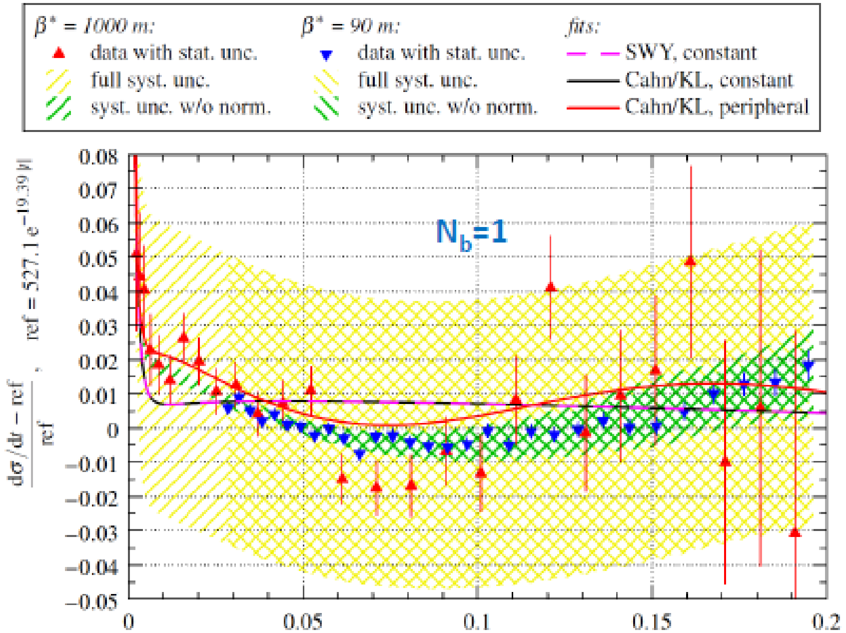
- **Determination of ρ became possible:**

$$\rho = \left.\frac{\mathrm{Re}\, A^H}{\mathrm{Im}\, A^H}\right|_{t=0}$$

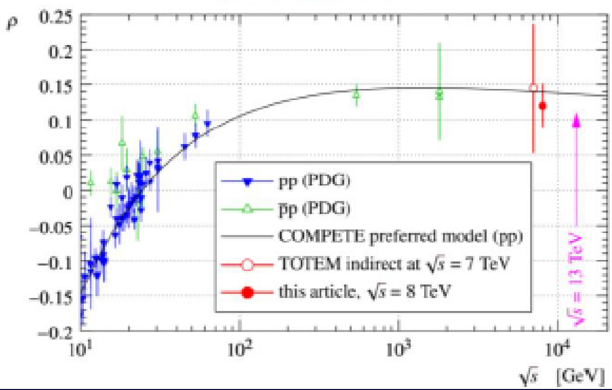
- Further improve the total cross-section σ_{tot} measurement

First measurement of ρ @ 8 TeV

Publication Eur. Phys. J. C (2016) 76: 661



$\rho = 0.12 \pm 0.03$

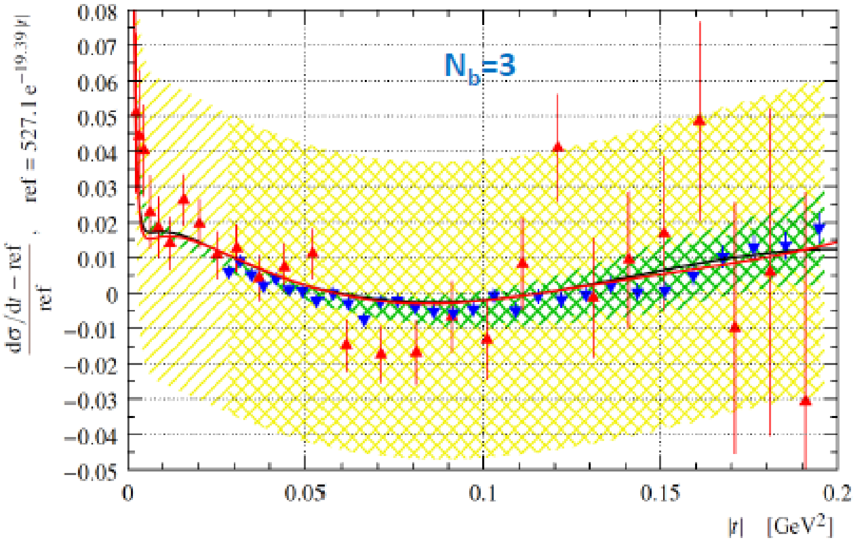


Purely exponential hadronic amplitude:

- Constant phase: excluded
- Peripheral phase: disfavored

Non-exponential hadronic amplitude:

- Both peripheral and constant phase compatible with data

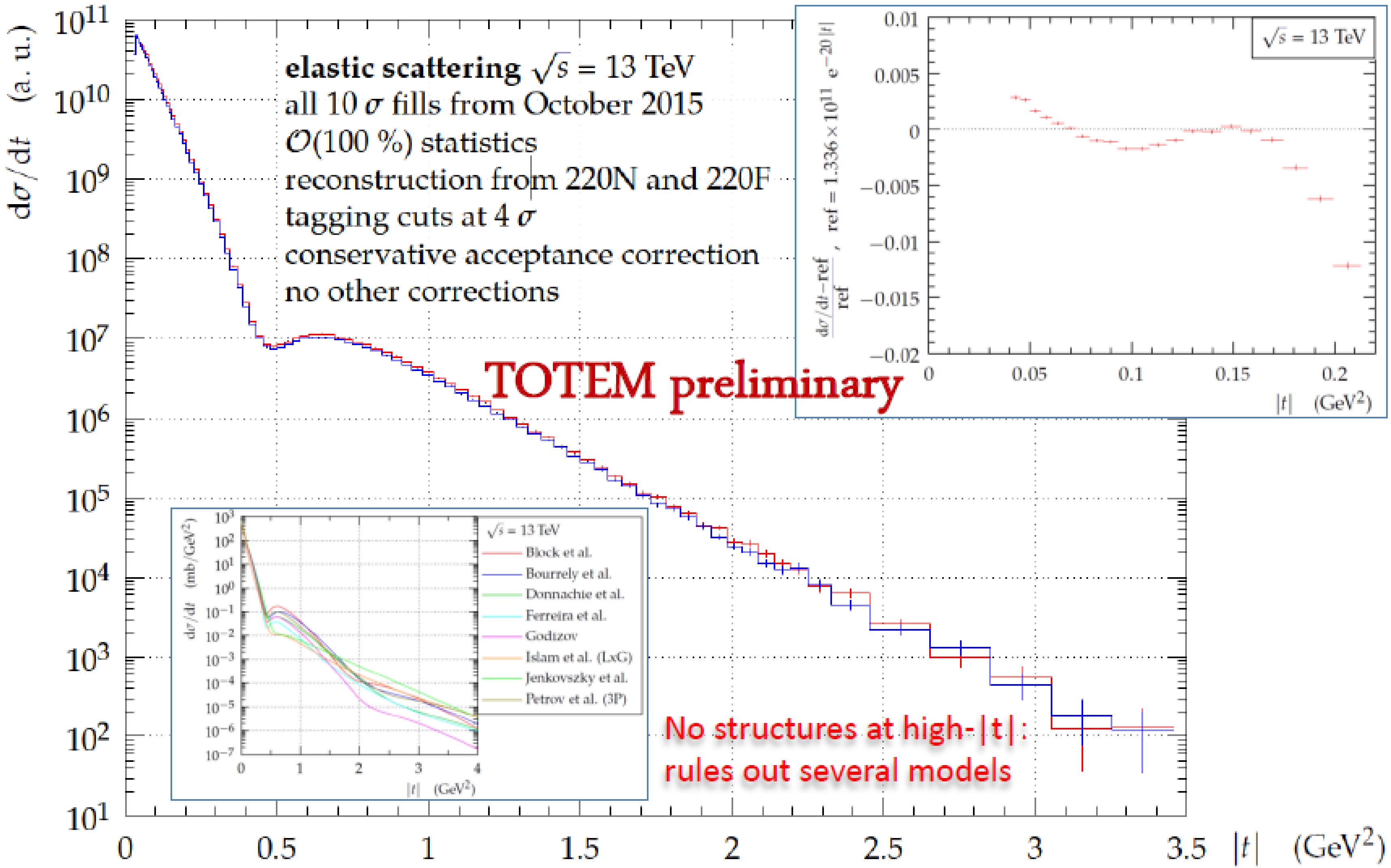


Hadronic phase	σ_{tot} [mb]
Central	102.9 ± 2.3
Peripheral	103.0 ± 2.3

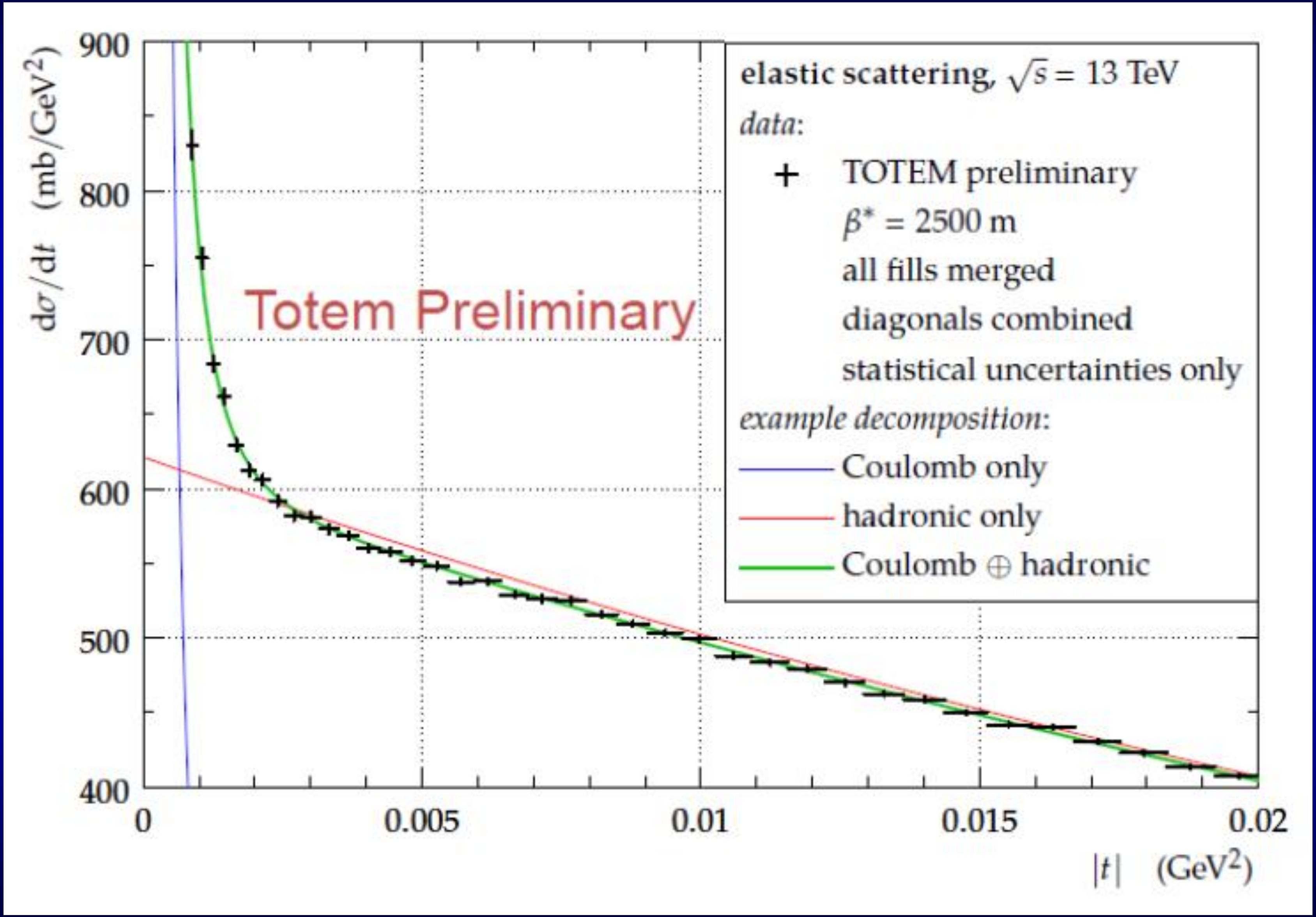
TOTEM preliminary at $\sqrt{s}$ = 13 TeV

TOTEM preliminary at √s = 13 TeV

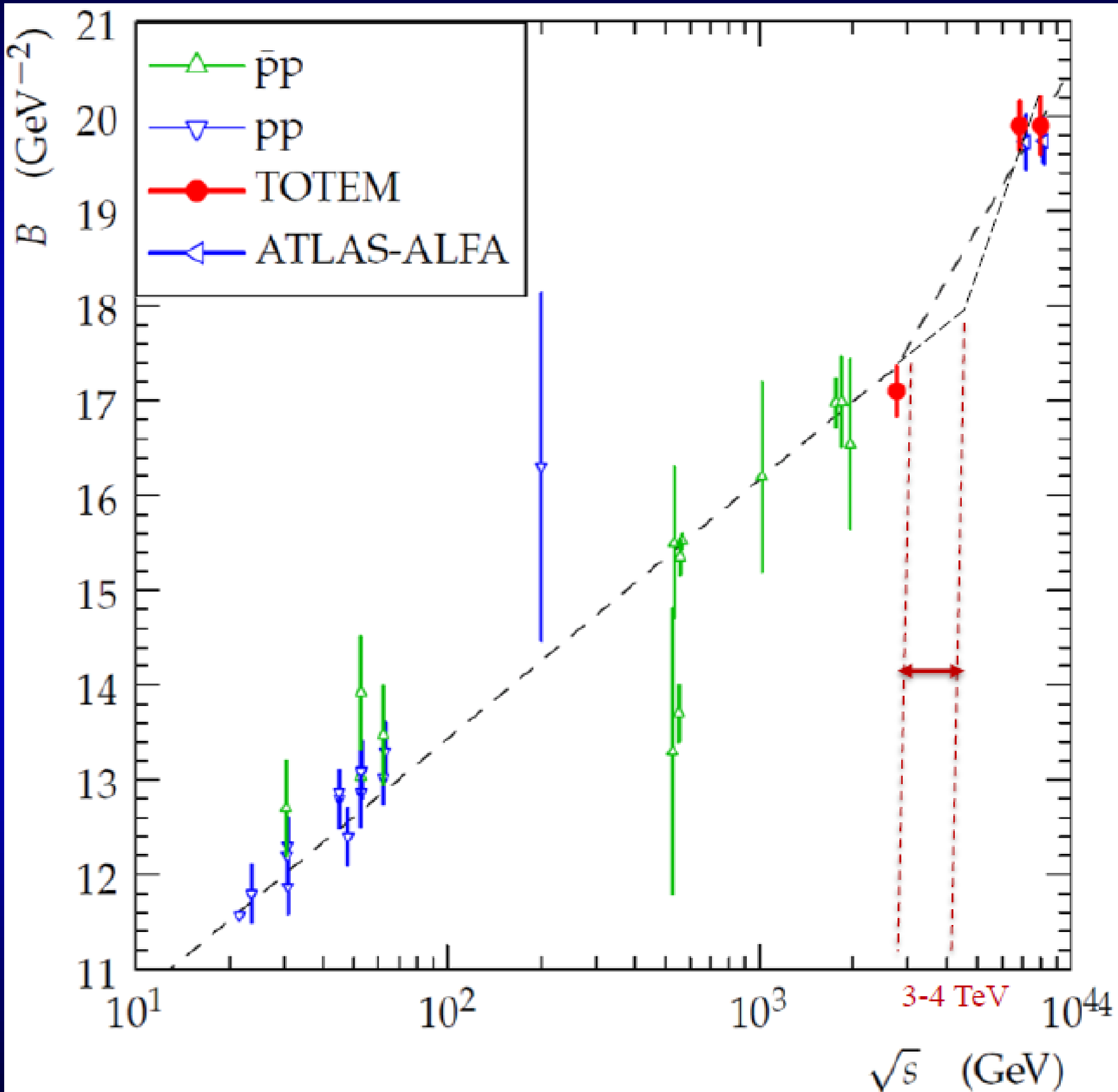
- Large amount of data (trigger rate 50× w.r.t. Run I)



TOTEM preliminary at √s = 13 TeV



TOTEM preliminary at $\sqrt{s}$ = 13 TeV



Growth of B:
Universal properties
of Pomeron

Acceleration of B:
Opening of an
additional physics
channel
from
TOTEM preliminary
2.76 and 13 TeV

threshold ≤ 3-4 TeV
followed by
very sharp growth

Change of low-|t|
trend at LHC

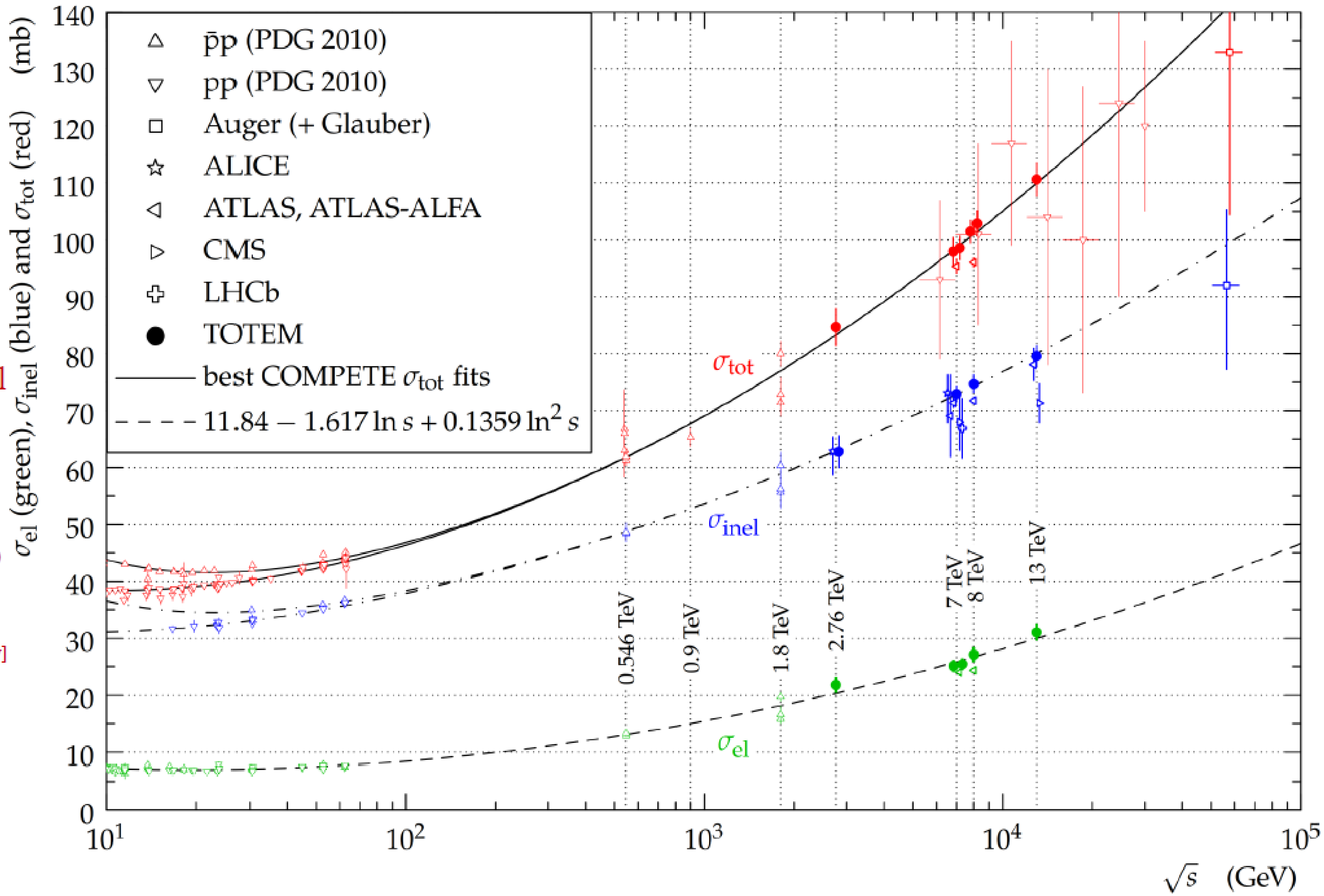
TOTEM preliminary at $\sqrt{s}$ = 13 TeV

1st measurement of elastic, inelastic, total cross-section at $\sqrt{s}$ = 13 TeV

σ_{tot} = 110.6 mb

$\Delta\sigma_{tot} \sim \pm 3$ mb [preliminary]

[ρ = 0.10]



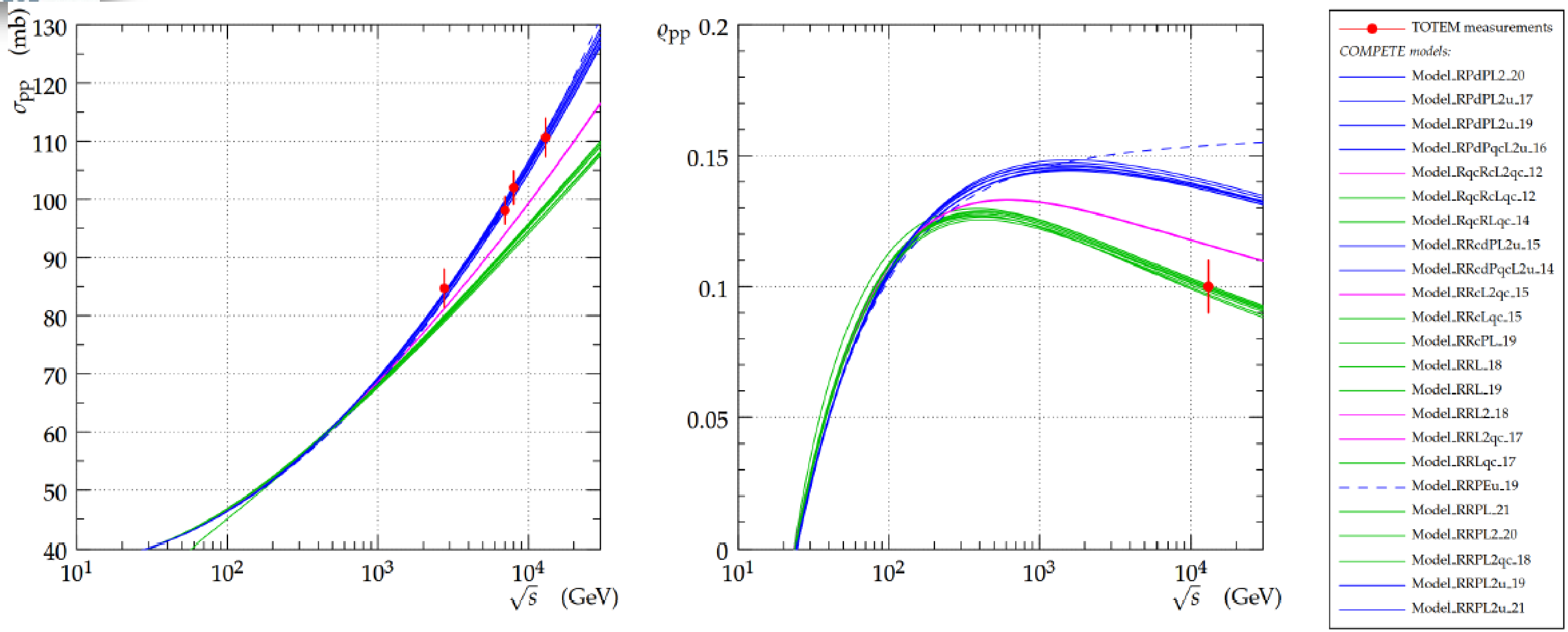
First measurement of cross-sections at 13 TeV at LHC

TOTEM preliminary at √s = 13 TeV

TOTEM

1[st] measurement of ρ at √s = 13 TeV **ρ = 0.10 ± 0.01** [preliminary]

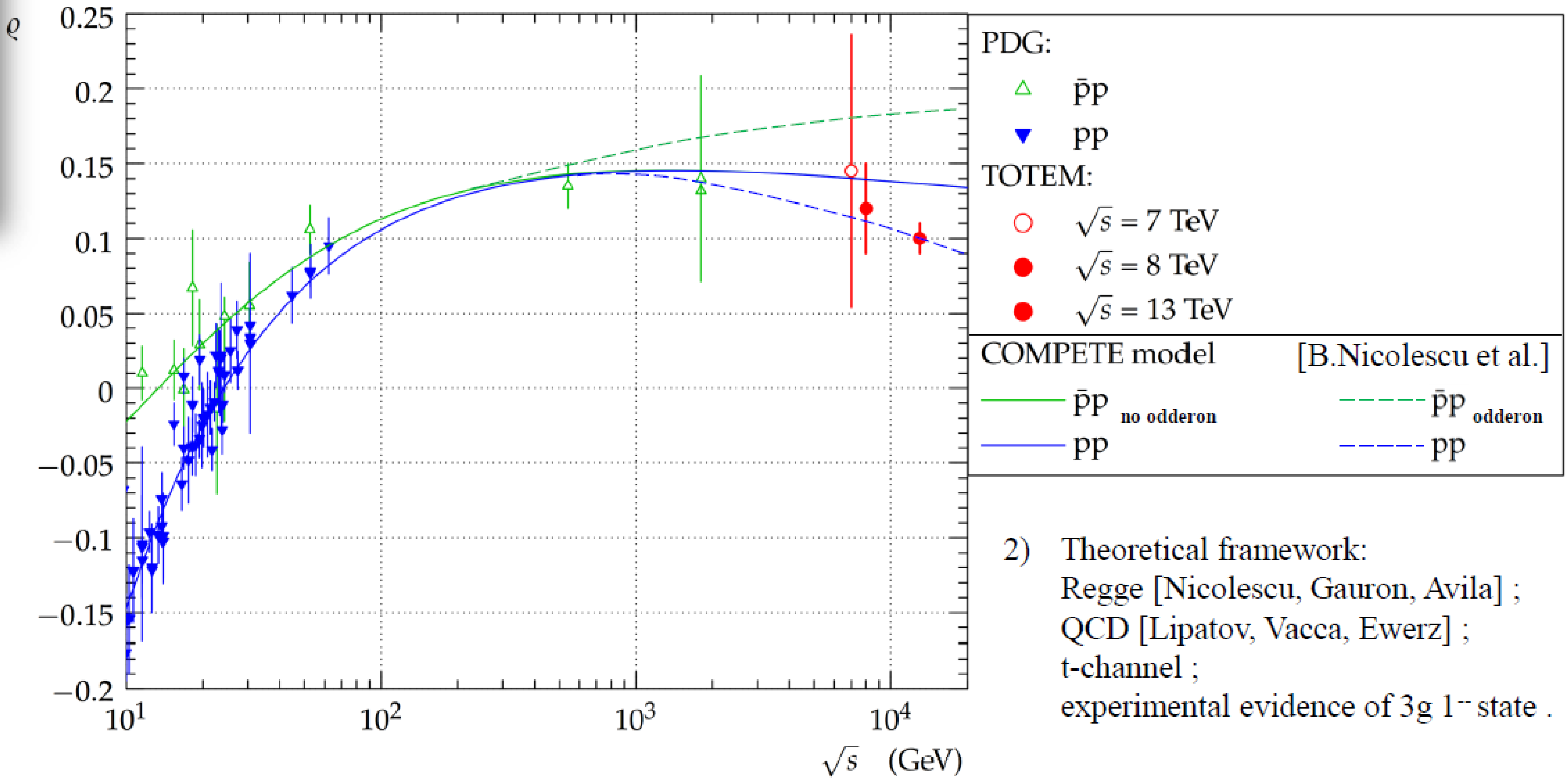
1) Theoretical framework :
current models [COMPETE] cannot describe measured total cross-section and ρ simultaneously at √s 13 TeV ;
dispersion relation requires derivative of total cross-section to decrease in next decade(s) of √s ;
extrapolations to high-E LHC and/or FCC .



First measurement of ρ at 13 TeV at LHC → Odderon
Indication of the weak version of Pomeranchuk's theorem!

TOTEM preliminary at $\sqrt{s}$ = 13 TeV

1st measurement of ρ at $\sqrt{s}$ = 13 TeV **ρ = 0.10 ± 0.01** [preliminary]



2) Theoretical framework:
Regge [Nicolescu, Gauron, Avila] ;
QCD [Lipatov, Vacca, Ewerz] ;
t-channel ;
experimental evidence of 3g 1^{--} state .

First measurement of ρ at 13 TeV at LHC → evidence for Odderon
Indication of the weak version of Pomeranchuk's theorem!

Summary

TOTEM has measured very precisely
pp cross sections
from 2.76 to 13 TeV

High precision of these measurements
impossible without the recalibration of LHC
optics from TOTEM RP data.

The results change our understanding
of elastic scattering:

New physics trends seen
at LHC energies:

threshold ≤ 3-4 TeV
followed by
very sharp growth of B
Value of ρ = 0.10 : evidence for Odderon.

The TOTEM Collaboration

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G. Antchev[l], P. Aspell[q], I. Atanassov[l], V. Avati[q], J. Baechler[q], V. Berardi[j,i], M. Berretti[q,o], E. Bossini[o], U. Bottigli[o], M. Bozzo[l], P. Broulím[a], A. Buzzo[l], F. S. Cafagna[i], C. E. Campanella[k,i], M. G. Catanesi[i], M. Csanád[g,2], T. Csörgő[g,h], M. Deile[q], F. De Leonardis[k,i], A. D'Orazio[k,i], M. Doubek[c], K. Eggert[r], V. Eremin[5], F. Ferro[l], A. Fiergolski[i,4], F. Garcia[e], V. Georgiev[a], S. Giani[q], L. Grzanka[p,3], C. Guaragnella[k,i], J. Hammerbauer[a], J. Heino[e], A. Karev[q], J. Kašpar[b,q], J. Kopal[b], V. Kundrát[b], S. Lami[n], G. Latino[o], R. Lauhakangas[e], R. Linhart[a], E. Lippmaa[d], J. Lippmaa[d], M. V. Lokajíček[b], L. Losurdo[o], M. Lo Vetere[m,l], F. Lucas Rodríguez[q], M. Macrí[l], A. Mercadante[i], N. Minafra[q,j], S. Minutoli[l], T. Naaranoja[e,f], F. Nemes[g,2], H. Niewiadomski[r], E. Oliveri[q], F. Oljemark[e,f], R. Orava[e,f], M. Oriunno[6], K. Österberg[e,f], P. Palazzi[q], L. Paločko[a], V. Passaro[k,i], Z. Peroutka[a], V. Petruzzelli[k,i], T. Politi[k,i], J. Procházka[b], F. Prudenzano[k,i], M. Quinto[i,j], E. Radermacher[q], E. Radicioni[i], F. Ravotti[q], E. Robutti[l], L. Ropelewski[q], G. Ruggiero[q], H. Saarikko[e,f], A. Scribano[n], J. Smajek[q], W. Snoeys[q], T. Sodzawiczny[q], J. Sziklai[g], C. Taylor[r], N. Turini[o], V. Vacek[c], J. Welti[e,f], P. Wyszkowski[p], K. Zielinski[p]

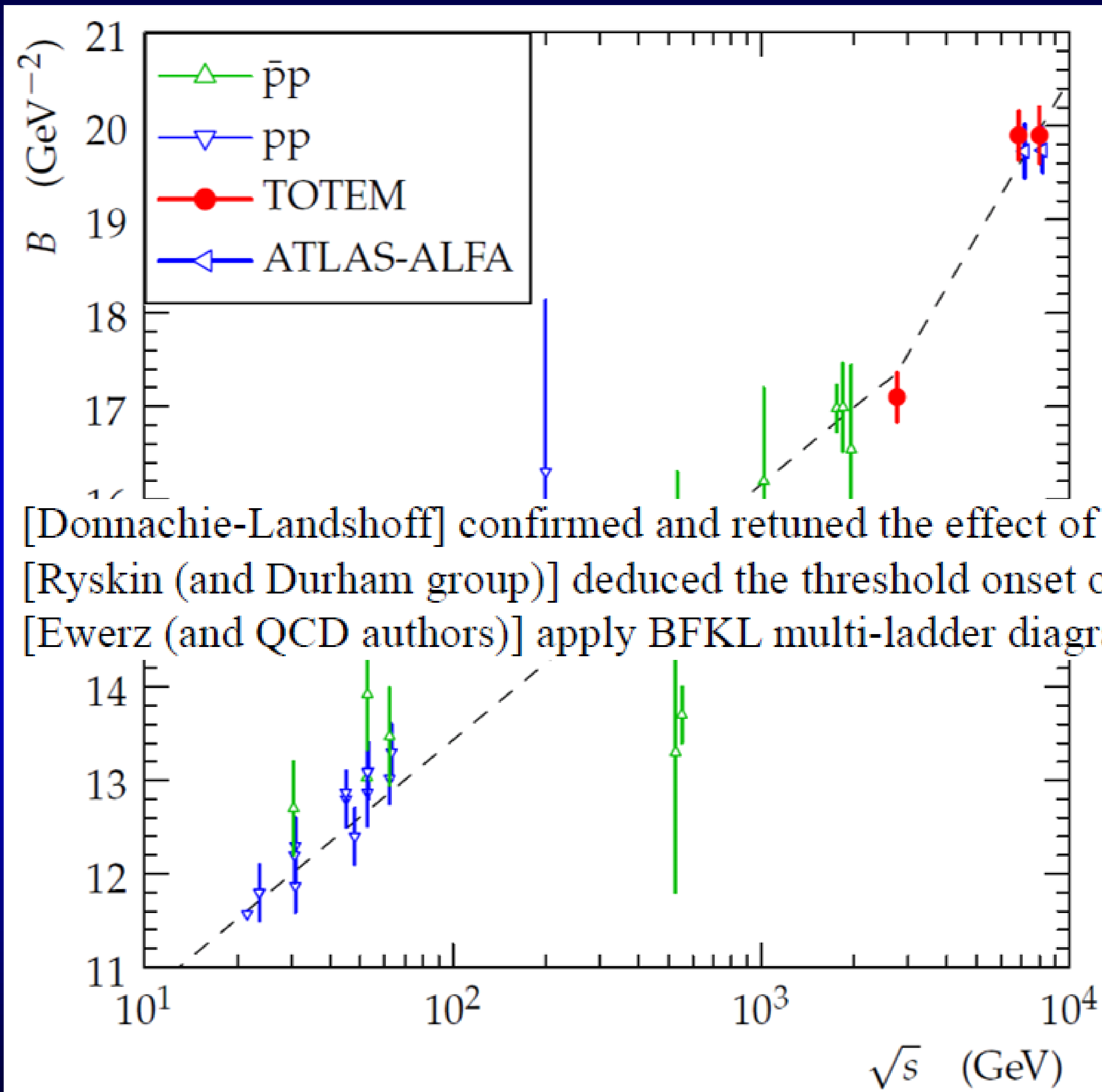
[a]University of West Bohemia, Pilsen, Czech Republic.
[b]Institute of Physics of the Academy of Sciences of the Czech Republic, Praha, Czech Republic.
[c]Czech Technical University, Praha, Czech Republic.
[d]National Institute of Chemical Physics and Biophysics NICPB, Tallinn, Estonia.
[e]Helsinki Institute of Physics, Helsinki, Finland.
[f]Department of Physics, University of Helsinki, Helsinki, Finland.
[g]Wigner Research Centre for Physics, RMKI, Budapest, Hungary.
[h]KRF University College, Gyöngyös, Hungary.
[i]INFN Sezione di Bari, Bari, Italy.
[j]Dipartimento Interateneo di Fisica di Bari, Bari, Italy.
[k]Dipartimento di Ingegneria Elettrica e dell'Informazione - Politecnico di Bari, Bari, Italy.
[l]INFN Sezione di Genova, Genova, Italy.
[m]Università degli Studi di Genova, Italy.
[n]INFN Sezione di Pisa, Pisa, Italy.
[o]Università degli Studi di Siena and Gruppo Collegato INFN di Siena, Siena, Italy.
[p]AGH University of Science and Technology, Krakow, Poland.
[q]CERN, Geneva, Switzerland.
[r]Case Western Reserve University, Dept. of Physics, Cleveland, OH, USA.

8 countries
18 institutions
85 people

Thank you!

Backup slides – Questions?

TOTEM preliminary at $\sqrt{s}$ = 13 TeV



[Donnachie-Landshoff] confirmed and retuned the effect of the hard-Pomeron;
[Ryskin (and Durham group)] deduced the threshold onset of the multi-Pomeron exchange;
[Ewerz (and QCD authors)] apply BFKL multi-ladder diagrams in non-perturbative domain.

Growth of B:
Universal properties of Pomeron

Acceleration of B:
Opening of an additional physics channel

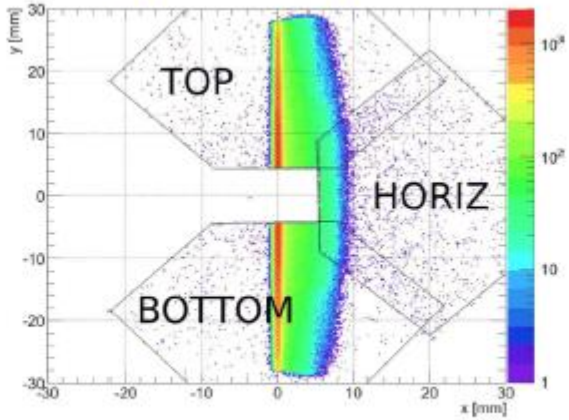
threshold ≤ 3-4 TeV
followed by
very sharp growth

Change of low-|t| trend at LHC

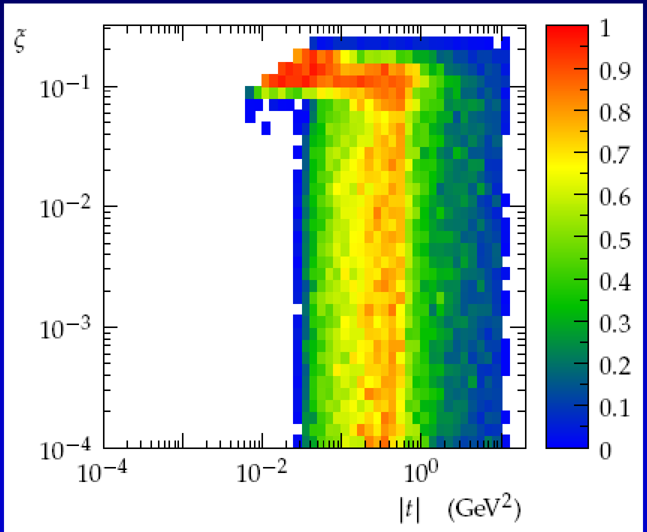
LHC optics and proton acceptance

$t = -p^2 \theta_*^2$: four-momentum transfer squared; $\xi = \Delta p/p$: fractional momentum loss

$\beta^* = 90$ m (special development for RP runs)



$L_x = 0$, $L_y = 260$ m, $v_y = 0$, $D_x = 4$ cm
diffractive protons: mainly in vertical RP
elastic protons: in narrow band at $x \cong 0$,
sensitivity for small vertical scattering angles



$\beta^* = 90$ m MC simulation shown
Parallel to point focussing, $v_y \sim 0$
Large effective lenght L_y
Elastic scattering events: in vertical RPs

$\beta^* = 90$ m
Diffraction: all ξ if $|t| \geq 10^{-2}$ GeV^2,
soft & semi-hard diffr.
Elastic: low to mid $|t|$
Total cross-section

RP unit	L_x	v_x	L_y	v_y
near	2.45 m	−2.17	239 m	0.040
far	−0.37 m	−1.87	264 m	0.021

Differential cross-section @ 8 TeV

Table 4: Details of the fits in Figure 11 using parametrisation Eq. (15). The matrices give the correlation factors between the fit parameters.

N_b	$\mathrm{d}\sigma/\mathrm{d}t\|_{t=0}$ [mb/GeV^2]	b_1 [GeV^{-2}]	b_2 [GeV^{-4}]	b_3 [GeV^{-6}]	χ^2/ndf	p-value	significance
1	531 ± 22	-19.35 ± 0.06	-	-	$117.5/28 = 4.20$	$6.2 \cdot 10^{-13}$	$7.20\,\sigma$
	$\begin{pmatrix} +1.00 & -0.11 \\ -0.11 & +1.00 \end{pmatrix}$						
2	537 ± 22	-19.89 ± 0.08	2.61 ± 0.30	-	$29.3/27 = 1.09$	0.35	$0.94\,\sigma$
	$\begin{pmatrix} +1.00 & +0.19 & -0.34 \\ +0.19 & +1.00 & -0.76 \\ -0.34 & -0.76 & +1.00 \end{pmatrix}$						
3	541 ± 22	-20.14 ± 0.15	5.95 ± 1.75	-12.0 ± 6.2	$25.5/26 = 0.98$	0.49	$0.69\,\sigma$
	$\begin{pmatrix} +1.00 & +0.08 & -0.04 & -0.02 \\ +0.08 & +1.00 & -0.90 & +0.85 \\ -0.04 & -0.90 & +1.00 & -0.99 \\ -0.02 & +0.85 & -0.99 & +1.00 \end{pmatrix}$						

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

$$\chi^2 = \Delta^{\mathrm{T}} \mathrm{V}^{-1} \Delta\,,$$

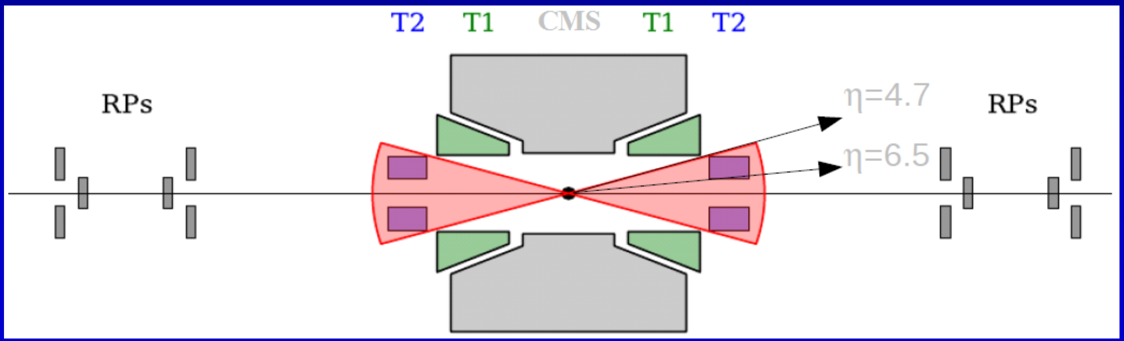
$$\mathrm{V} = \mathrm{V}_{\mathrm{stat}} + \mathrm{V}_{\mathrm{syst}}$$

$$\Delta_i = \left.\frac{\mathrm{d}\sigma}{\mathrm{d}t}\right|_{\mathrm{bin}\ i} - \frac{1}{\Delta t_i}\int_{\mathrm{bin}\ i} f(t)\,\mathrm{d}t\,,$$

$N_b = 1$ fits excluded. Relative to best exponential, a significant (7σ) deviation found

TOTEM for double diffraction

Aim: Measurement of soft double diffractive cross section with particle η_{min} visible to TOTEM T2 ($4.7 < |\eta_{min}| < 6.5$). → $\sigma_{DD}(|\eta_{min}|)$ for $3.4 < M_{DIFF} < 8$ GeV



Event selection: Trigger with T2, at least one track in both T2 hemispheres , no tracks in T1 "(0T1+2T2) topology".

- ND background estimated scaling the MC prediction using a control sample from data dominated by ND (2T1+2T2 events)
- SD background estimated completely from data using a SD-dominated control sample (0T1+1T2) with protons in the RP

TOTEM results on double diffraction

Phys. Rev. Lett. 111, 262001

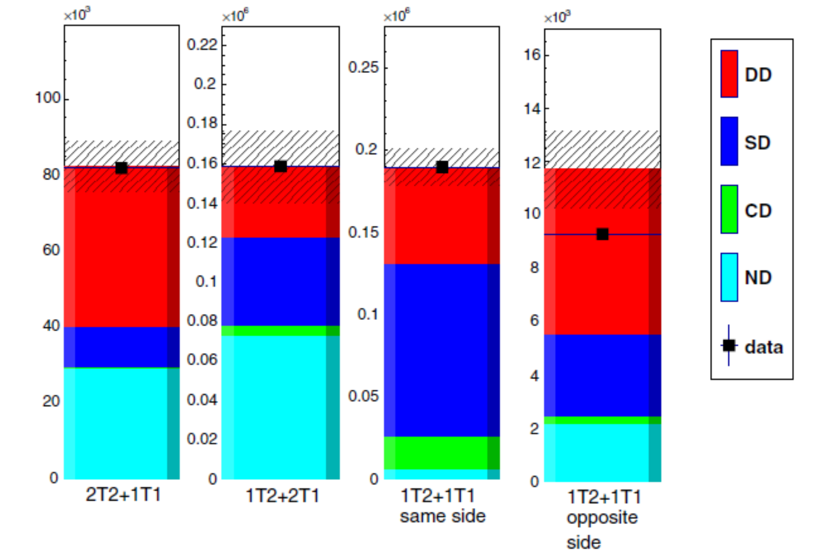


FIG. 1 (color online). Validation of background estimates for the full selection I_{track}. Each plot shows the corrected number of events in data (black squares) and the combined estimate with background uncertainties. The combined estimate is the sum of all components, from bottom to top: the ND estimate (cyan), CD estimate (green), SD estimate (blue), and DD estimate (red).

$$\sigma_{\mathrm{DD}} = \frac{E(N_{\mathrm{data}}^{2T2+0T1} - N_{\mathrm{bckg}}^{2T2+0T1})}{\mathcal{L}},$$

E: experimental correction includes
acceptance,
tracking,
reconstruction efficiencies (T2)
and for only neutrals in T2

E = 0.9 ± 0.1

L = 40.1 ± 1.6 μb^{-1}

TOTEM result:
σ_{DD} = 116 ± 25 μb
4.7 < $|\eta|_{min}$ < 6.5
for both diffractive systems

TOTEM for double diffraction

TABLE III. Double diffractive cross-section measurements (μb) in the forward region. Both visible and η_{min} corrected cross sections are given. The latter is compared to PYTHIA and PHOJET predictions. PYTHIA estimate for total σ_{DD} = 8.1 mb and PHOJET estimate σ_{DD} = 3.9 mb.

	I_{track}	$D11_{track}$	$D22_{track}$	$D12_{track}$	$D21_{track}$
Visible	131 ± 22	58 ± 14	20 ± 8	31 ± 5	34 ± 5
	I	$D11$	$D22$	$D12$	$D21$
η_{min}	116 ± 25	65 ± 20	12 ± 5	26 ± 5	27 ± 5
PYTHIA η_{min}	159	70	17	36	36
PHOJET η_{min}	101	44	12	23	23

TABLE IV. Summary of statistical and systematic uncertainties (μb).

	I	$D11$	$D22$	$D12$	$D21$
Statistical	1.5	1.1	0.7	0.9	0.9
Background estimate	9.0	6.0	3.5	2.7	2.2
Trigger efficiency	2.1	1.2	1.0	0.9	0.9
Pileup correction	2.4	2.1	0.4	1.1	1.0
$T1$ multiplicity	7.0	3.9	0.7	1.6	1.7
Luminosity	4.7	2.6	0.5	1.1	1.1
Experimental correction	14.7	14.1	2.6	2.0	2.0
η_{min}	15.4	11.0	1.5	2.9	2.9
Total uncertainty	24.8	19.6	4.8	5.1	4.9

Event cathegories:
I: $|\eta|_{min}$ corrected

D11:
$4.7 < |\eta^{\pm}|_{min} < 5.9$

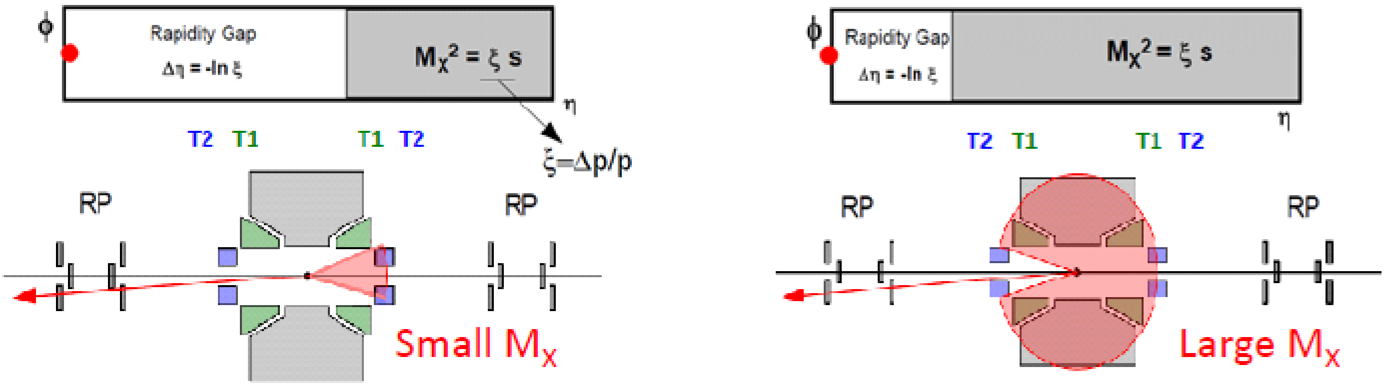
D22:
$5.9 < |\eta^{\pm}|_{min} < 6.5$

SD & DD results combined seems to indicate factorisation breaking:
$\sigma_{DD}(4.7 \leq |\eta_{min}| \leq 6.5) >>$
$\sigma_{SD}(-4.7 \geq \eta_{min} \geq -6.5) \times$
$\sigma_{SD}(4.7 \leq \eta_{min} \leq 6.5) / \sigma_{elastic}$

Note: $|\eta|_{min}$ correction: the dominant source of the uncertaintly

TOTEM for single diffraction

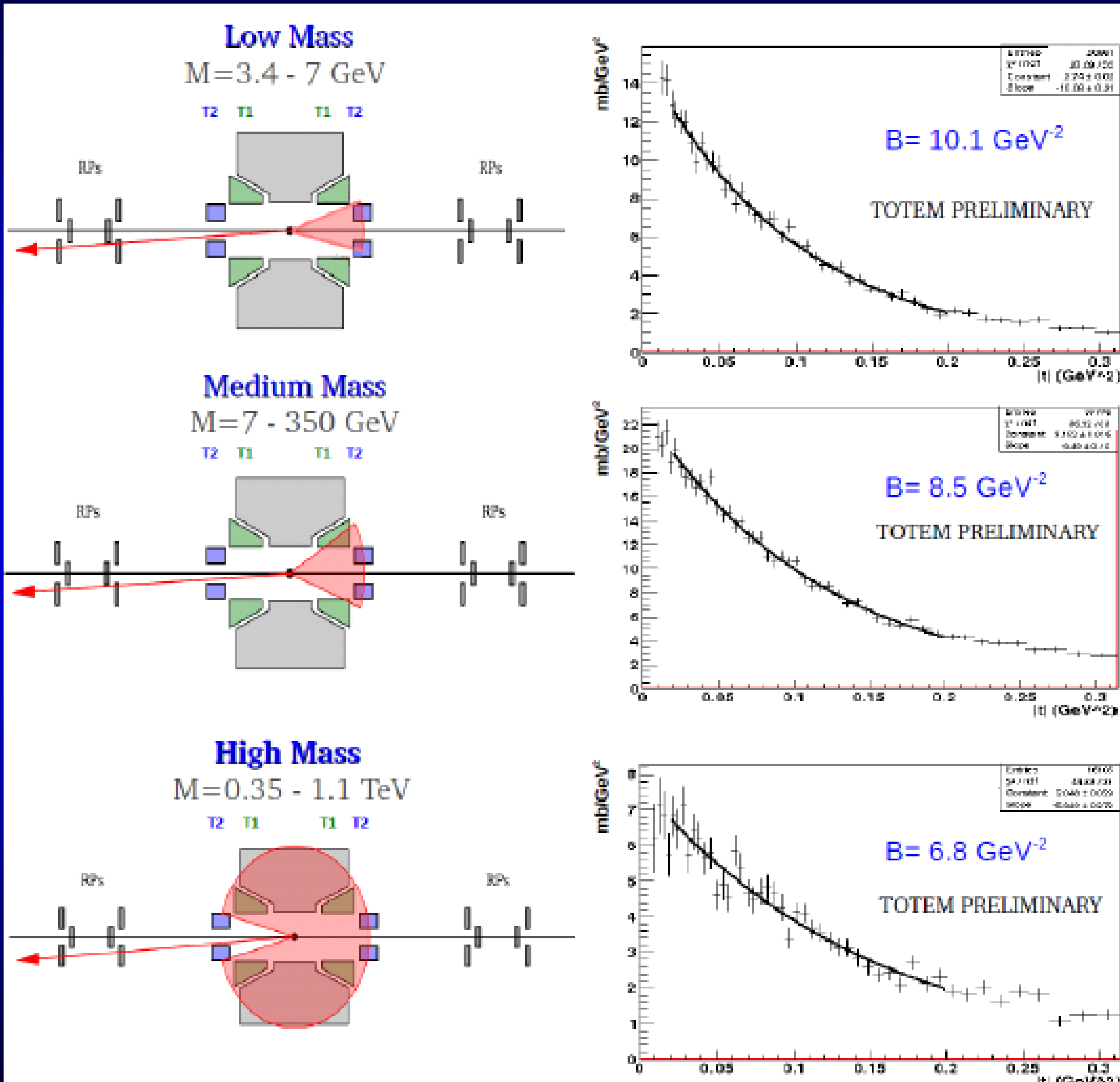
Rapidity gap ($\Delta\eta = -\ln\xi$) determines diffractive mass ($M_X^2 = \xi s$)



Event classification based on tracks in T1 & T2, proton in RP

SD class	Configuration	M_X [GeV]	$\xi = \Delta p/p$
Low mass	1 RP + opp. T2	3.4 – **8**	**2x** $10^{-7} - 10^{-6}$
Medium mass	1 RP + opp. T2 + opp. T1	**8** – 350	10^{-6} – 0.0025
High mass	1 RP + opp. T2 + same T1	350 – 1100	0.0025 – 0.025
Very high mass	1 RP + both T2	1100 – ...	0.025 – ...

TOTEM on single diffraction, 7 TeV



Corrections included:
- Trigger efficiency
- Proton acceptance & reconstruction efficiency
- Background subtraction
- Extrapolation to t = 0

Missing corrections:
- Class migration
- ξ resolution & beam divergence effects

Estimated uncertainties:
B ~ 15% ; σ ~ 20%

TOTEM preliminary:
$\sigma_{SD} = 6.5 \pm 1.3$ mb
3.4 GeV < M_{diff} < 1.1 TeV