Review of TOTEM results

Jan Kašpar
on behalf of the TOTEM collaboration

Low x, Nicosia, Cyprus
30 Aug 2019

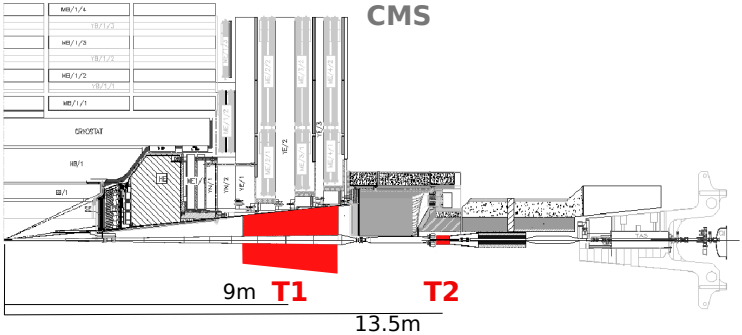
Outline

- selection of topics for this talk (all connected by optical theorem)
  - differential elastic cross-section
  - total cross-section
  - parameter $\rho \equiv \frac{\Re \mathcal{A}^{\mathrm{N}}}{\Im \mathcal{A}^{\mathrm{N}}}\Big|_{t=0}$

- complete list of TOTEM results:

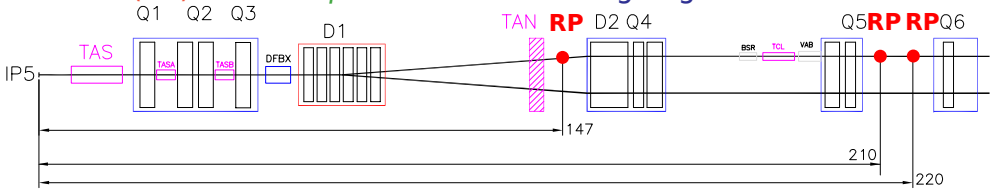
  http://totem.web.cern.ch/Totem/publ_new.html

- TOTEM: LHC experiment at IP5 (together with CMS)
- Inelastic telescopes T1 and T2: charged particles from *inelastic* collisions



- T1: $3.1 < |\eta| < 4.7$, $p_T > 100 MeV$
- T2: $5.3 < |\eta| < 6.5$, $p_T > 40 MeV$

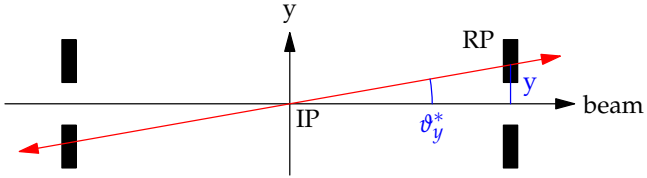
- Roman Pots (RP): *forward protons* close to outgoing beam



  - station at 147m in Run I → station 210m in Run II

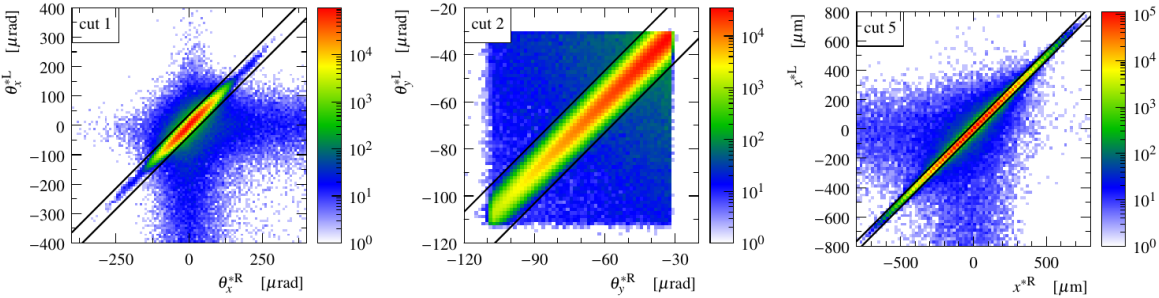
Elastic scattering

- LHC as magnetic spectrometer



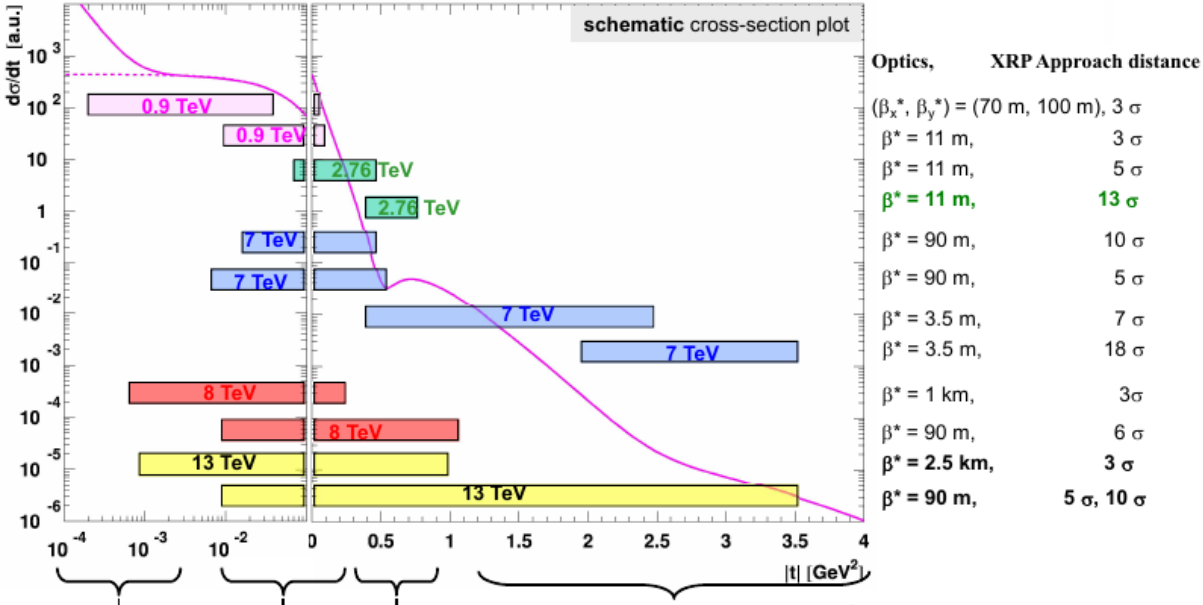
$$\theta_y^* = \frac{y}{L_y}, \quad t = -p^2\sqrt{\theta_x^{*2} + \theta_y^{*2}}$$

- 2 outgoing protons: anti-parallel, from the same vertex
  - strong tagging → low background



- analysis almost fully data-driven → confidence

Elastic scattering : *Data summary*



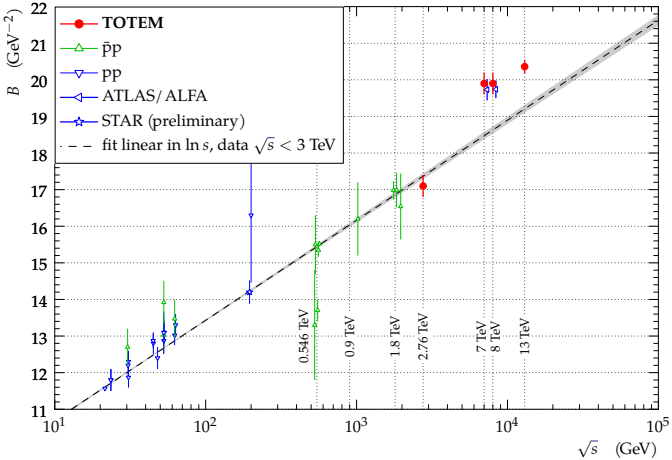
(transition to) perturbative QCD

"dip-bump": amplitude interference, Odderon effects

"forward code": non-perturbative Pomeron(s)

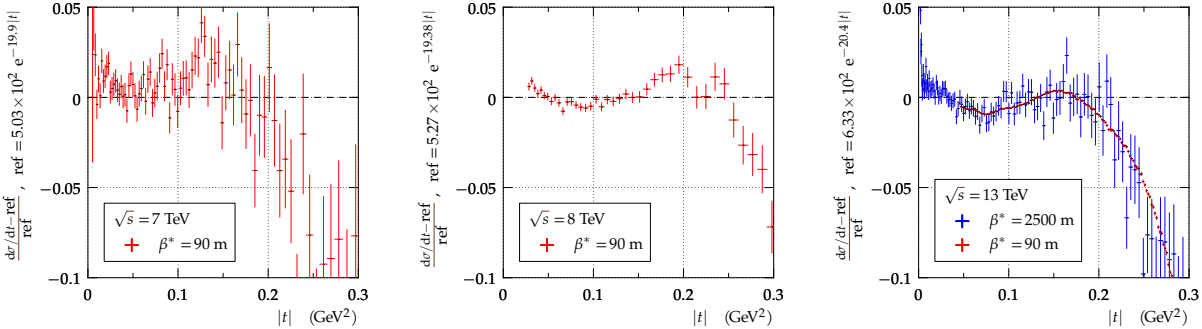
Coulomb-nuclear interference (CNI): phase determination (ρ)

- at "low $|t|$": $d\sigma/dt \propto e^{-B|t|}$



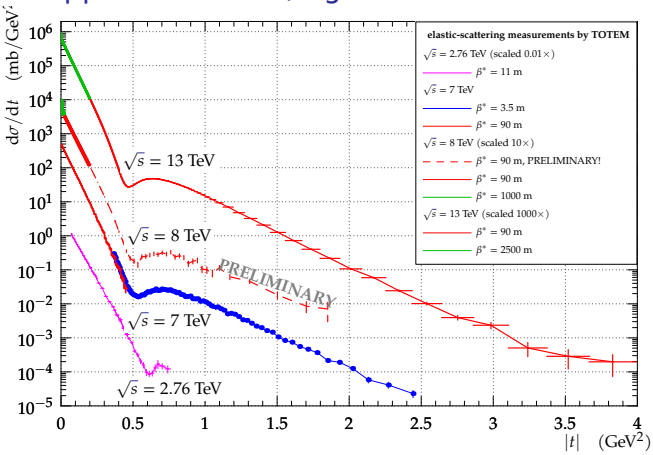
- up to $\sqrt{s} \approx 3$ TeV: linear in $\ln s$; agrees with simplistic Regge model:
$$d\sigma/dt \propto s^{2(\alpha(t)-1)}\,, \quad \alpha(t) = \alpha_0 + \alpha' t \quad \Rightarrow \quad B = B_0 + 2\alpha' \ln s$$
- above $\sqrt{s} \approx 3$ TeV: change of regime? interpretation ?
- or more general energy dependence: e.g. $B = a + b \ln^2 s$ due to multi-Pomeron exchanges [Ryskin and Schegelsky, PRD 85 (2012)]

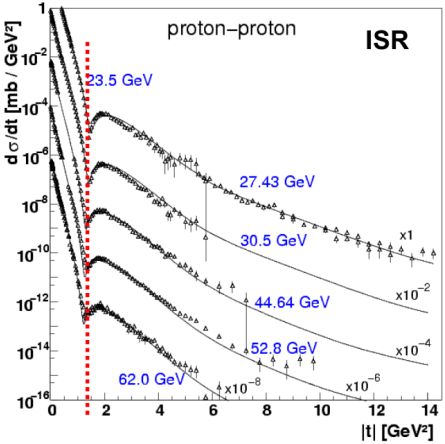
- deviations from the leading exponential behaviour: $\dfrac{d\sigma/dt - \text{ref. exp.}}{\text{ref. exp.}}$



  - $|t| \lesssim 0.2$ GeV^2: similar pattern at all energies
    - non-exponentiality evaluated at 8 TeV: 7.2 σ
  - $|t| \gtrsim 0.2$ GeV^2: rapid change of behaviour (faster decrease towards dip)
- interpretation
  - several theoretical reasons for non-exponentiality: [Khoze et al., J.Phys. G42 (2015) no.2, 025003]
  - why it is so close to an exponential ?
- could the non-exponentiality be due to CNI? see leater...

- left pp from TOTEM, right from ISR

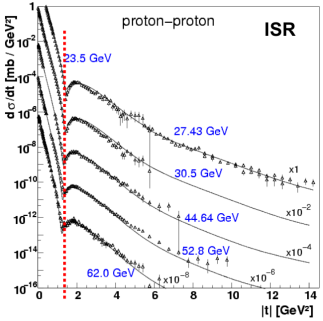


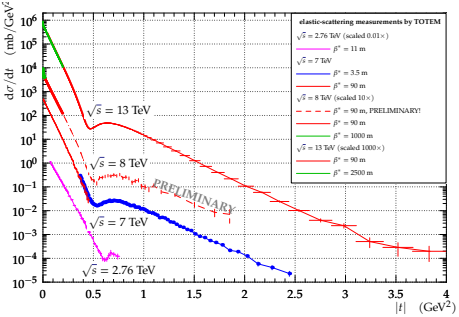


  - increasing $\sqrt{s} \Rightarrow$ dip at lower $|t|$

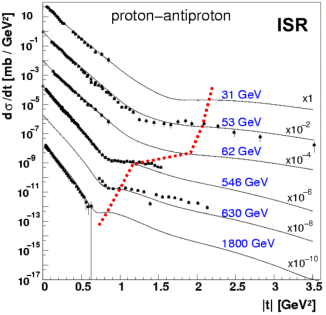
- interpretation
  - related to forward-cone shrinkage?
  - dynamical details?

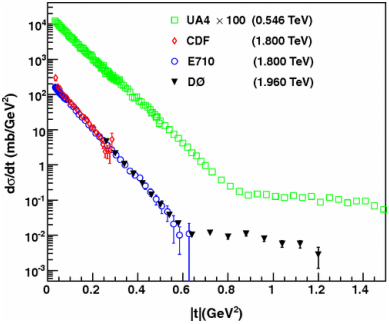
- pp: always pronounced *dip* (ISR, LHC)





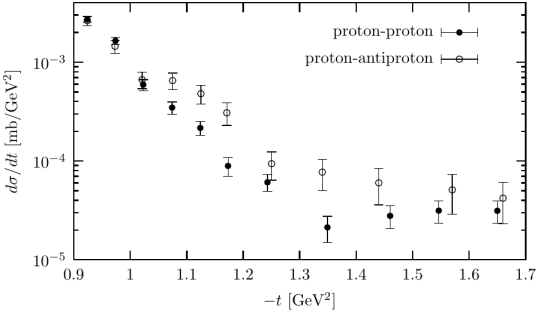
- $p\bar{p}$: always *shoulder* only (ISR, Sp$\bar{p}$S, Tevatron)





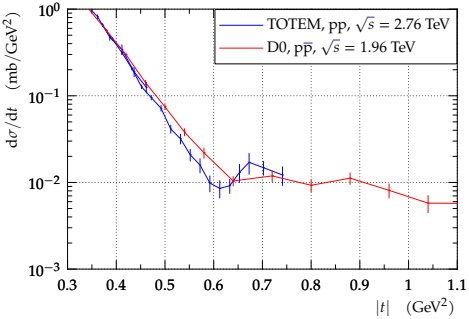
⇒ *recurrent difference between pp and $p\bar{p}$*

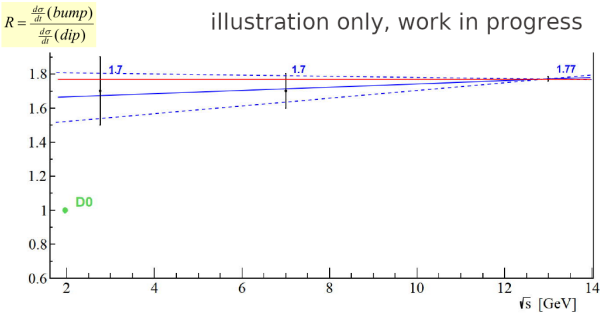
- ISR, 53 GeV – the only comparison from same machine and same energy



  - low energy – interpretation complicated by secondary reggeons

- Tevatron (D0, $\sqrt{s}$ = 1.96 TeV) – LHC (TOTEM, $\sqrt{s}$ = 2.76 TeV, ...)



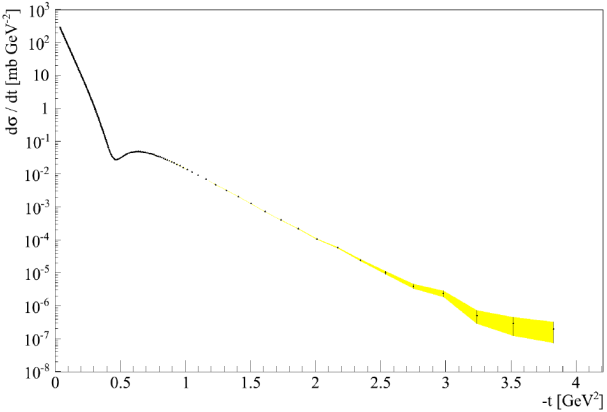


- experiment
  - difference between pp and $p\bar{p}$ scattering
    - (indirectly) even at same energy
    - at high energies $\rightarrow$ cannot be attributed to C-odd reggeons
  - high $\sqrt{s}$, low $|t|$: gluon-dominated, non-perturbative regime

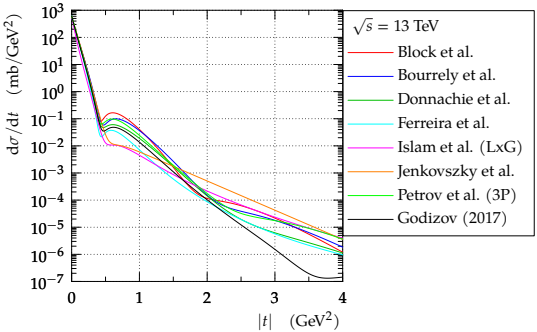
matches

- theory
  - Regge: Odderon as C-odd partner of Pomeron
  - (perturbative) QCD: Odderon $\sim C = -1$ state of mutually interacting gluons
  - lattice calculations: vector glueballs firmly in predicted spectrum
  - AdS/CFT: Odderon on same footing as Pomeron

- $\sqrt{s}$ = 13 TeV: very high statistics ⇒ precise measurement to high $|t|$



model predictions:



oscillations in almost each model

- *no structures observed up to $|t| \sim 3$ GeV*
  - rules out many models, e.g. "optical" models (recurrent diffractive structures)
  - interpretation – transition to perturbative QCD? Already in many models, e.g. 3-gluon in Donnachie-Landshoff, hard Pomeron in Godizov, ...

Total cross-section

- 3 ways to combine TOTEM observables:

elastic observables only:

$$\sigma_{\mathrm{tot}}^2 = \frac{16\pi}{1+\varrho^2}\,\frac{1}{\mathcal{L}}\,\left.\frac{\mathrm{d}N_{\mathrm{el}}}{\mathrm{d}t}\right|_0$$

$$\sigma_{\mathrm{tot}}$$

ϱ-independent:

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

luminosity-independent:

$$\sigma_{\mathrm{tot}} = \frac{16\pi}{1+\varrho^2}\,\frac{\mathrm{d}N_{\mathrm{el}}/\mathrm{d}t|_0}{N_{\mathrm{el}} + N_{\mathrm{inel}}}$$

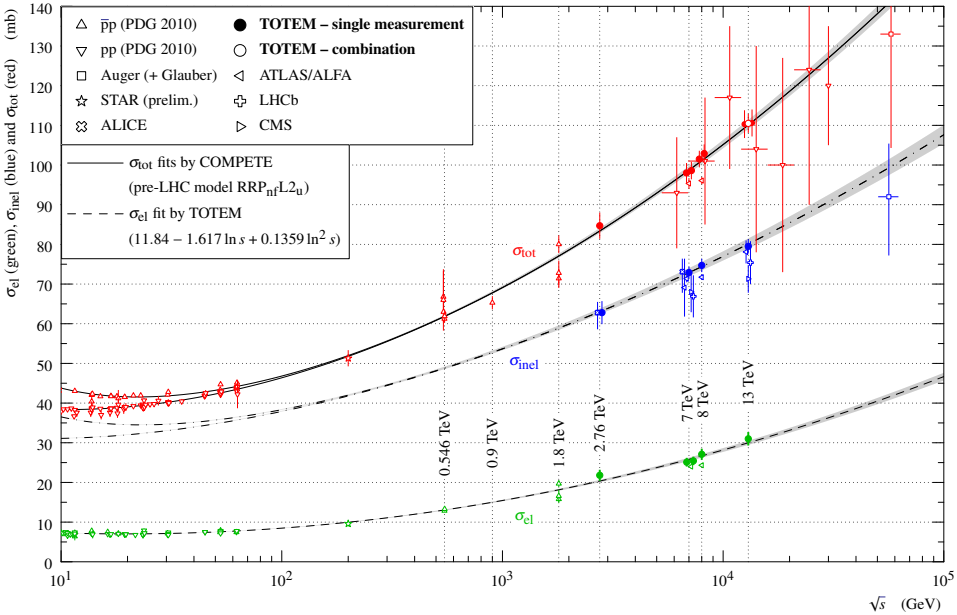
- at 7 TeV: all applied, consistent results found
- N_{el}: CNI may be explicitly subtracted
- $\mathrm{d}N_{\mathrm{el}}/\mathrm{d}t$: sensitive to “non-exponentiality”
- luminosity: from CMS or from CNI (“Coulomb normalisation”)

- 2 (complementary) datasets available
  - β^* = 90 m: inelastic data available, CNI region not covered
  - β^* = 2500 m: inelastic data not available, region CNI covered
- comparison

data	method	ρ	$\sigma_{\rm tot}$ [mb]
$\beta^* = 90\,\mathrm{m}$	Ref. [6]	-	110.6 ± 3.4
$\beta^* = 2500\,\mathrm{m}$	approach 1	0.09 ± 0.01	111.8 ± 3.1
	approach 2	0.09 ± 0.01	111.3 ± 3.2
	approach 3	$0.08(5) \pm 0.01$	110.3 ± 3.5
	approach 3 (single fit)	0.10 ± 0.01	109.3 ± 3.5
$\beta^* = 90$ and $2500\,\mathrm{m}$	Ref. [6] $\oplus$ approach 3		110.5 ± 2.4

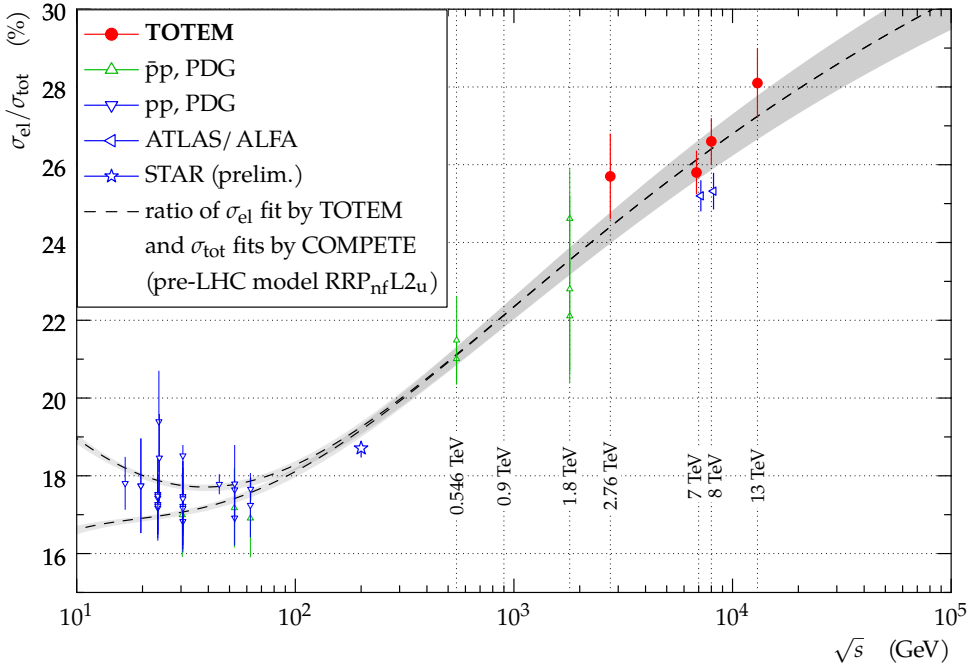
  - approach 1: normalisation from 90 m dataset
  - approach 2: normalisation from 2500 m dataset within uncertainty of 90 m
  - approach 3: normalisation from 2500 m – (partial) Coulomb normalisation
    - at lowest $|t|$: $\mathrm{d}N/\mathrm{d}t \approx \mathcal{L}\,\mathrm{d}\sigma^{\mathrm{QED}}/\mathrm{d}t$

- selected TOTEM measurements (representing the full range)



- energy dependence: in general compatible with $\ln^2(s)$ at high energies
  - BTW: what about s^α dependence
- no sign of slow down

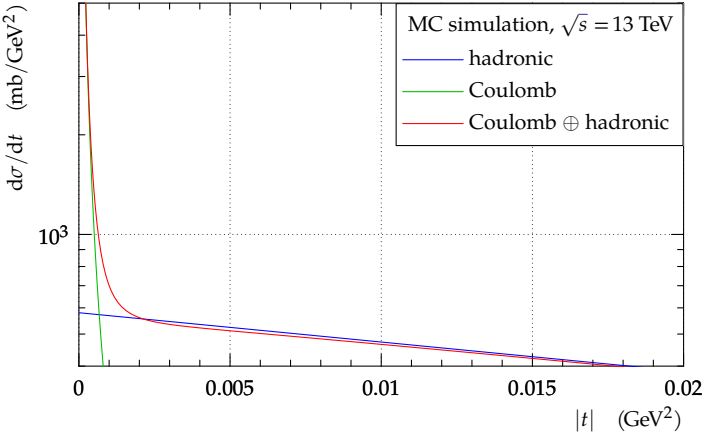
Ratio of elastic to total cross-section



- relevance? interpretation? more figures of interest?

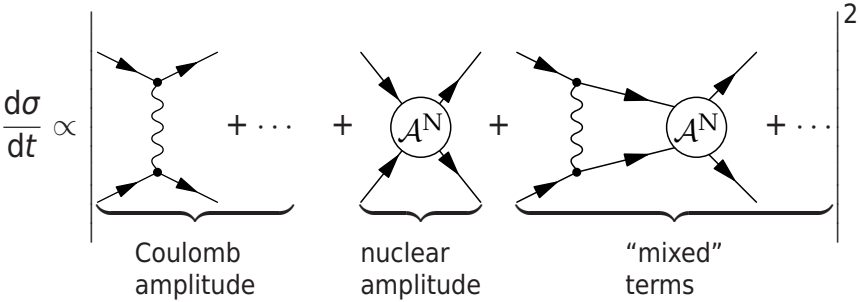
ρ parameter

- $\rho = \left.\dfrac{\Re\mathcal{A}^{\mathrm{N}}}{\Im\mathcal{A}^{\mathrm{N}}}\right|_{t=0}$
- theory prediction
  - Pomeron: $\mathcal{A}(t=0) \sim$ imaginary
  - Odderon: $\mathcal{A}(t=0) \sim$ real $\Rightarrow$ ρ *sensitive to Odderon* contributions
- dispersion relations: ρ related to σ_{tot} energy growth rate
- tool: Coulomb-nuclear interference $\rightarrow$ phase exposed in $\mathrm{d}\sigma/\mathrm{d}t$



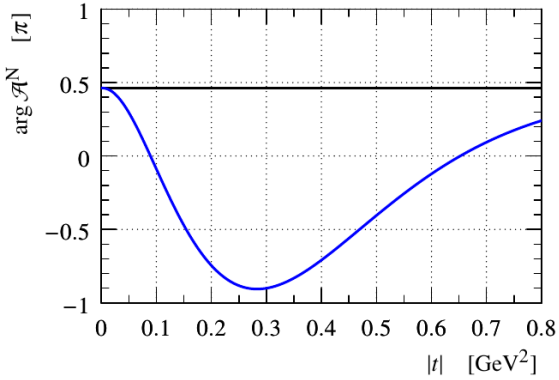
- determine nuclear phase wrt. known QED amplitude

- observed cross-section

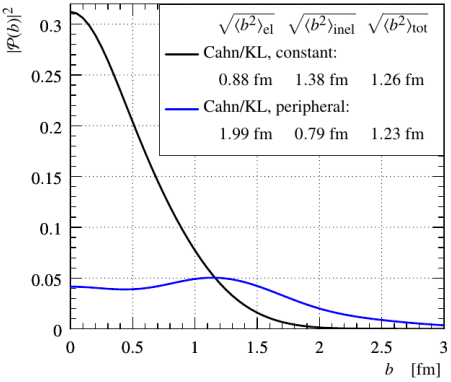


- our modelling
  - "*interference formula*" = summation for practical applications
    - considered: West-Yennie, Cahn and Kundrát-Lokajíček
  - *Coulomb amplitude*: QED + experimental form factors
  - *modulus of* $\mathcal{A}^{\mathrm{N}}$: empirical guidance $\Rightarrow$ at low $|t|$: $a \exp\left(\sum_{n=1}^{N_b} b_n t^n\right)$
  - *phase of* $\mathcal{A}^{\mathrm{N}}$
    - little/no experimental guidance $\Rightarrow$ theory suggestions welcome!
    - different assumptions $\Rightarrow$ different behaviour in b space
    - fair comparison with pre-LHC data $\Rightarrow$ assume slow variation with $|t|$

- test of assumptions on nuclear modulus and phase
- choice of phase

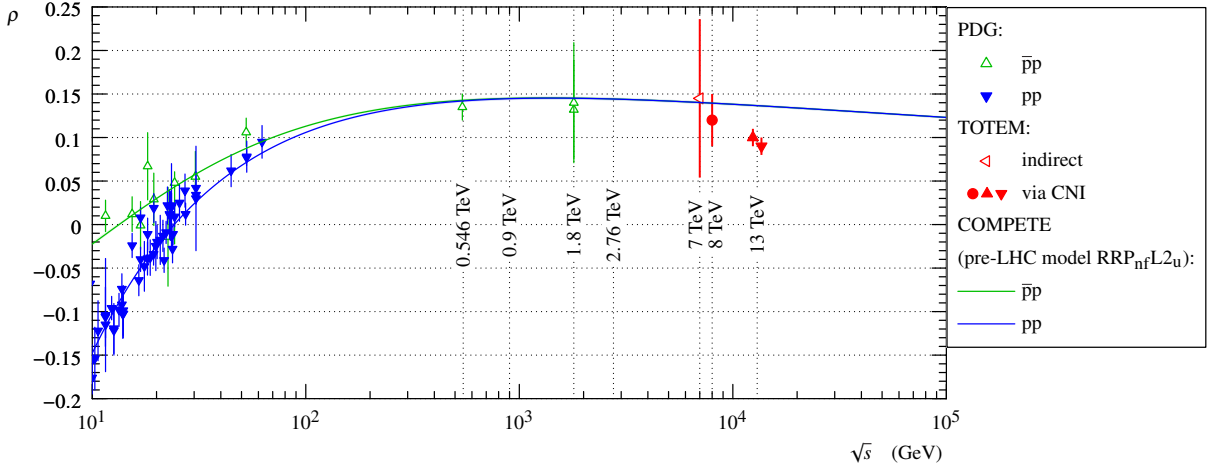


→



- data fit quality
  - B = const, constant phase: excluded
  - B = const, peripheral phase: not excluded, but disfavoured
  - $B \neq$ const, both phases compatible with data

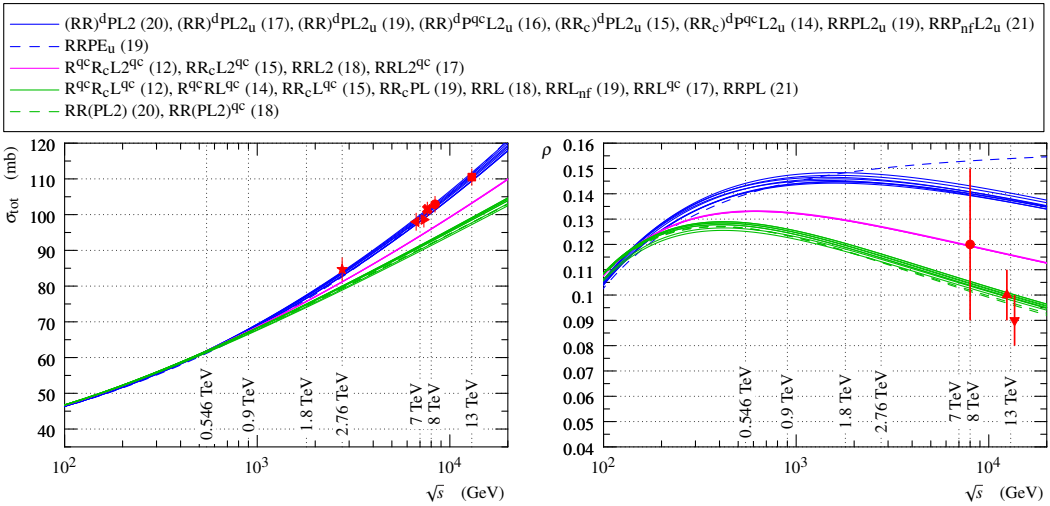
ρ : Comparison to previous measurements



- 8 TeV – uncertainty dominated by statistics
- 13 TeV – two points plotted
  - represent the range of numerical results
  - represent the range of concepts
  - the lower point – most similar conditions to the UA4/2 measurement

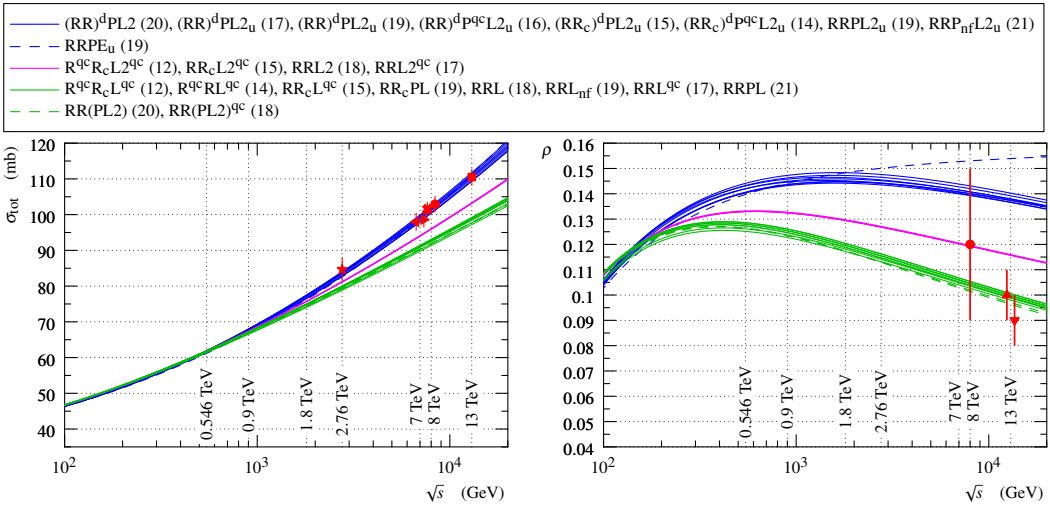
$\Rightarrow$ *13 TeV measurement significantly lower than extrapolations (more than 4 σ effect)*

Comparison to COMPETE



- comprehensive study of pre-LHC data by COMPETE
  - 256 models considered to describe σ_{tot} and ρ data in pp, pπ, pK, ...
    - various assumptions on energy dependence, reaction dependence
    - asymptotic component: *only crossing-even*
  - 23 models (shown above) found to give reasonable description
    - predictions cluster in 3 bands
- red: selection of TOTEM measurements

Dispersion relations

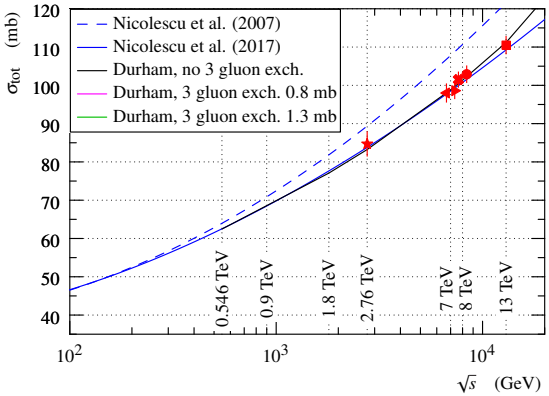


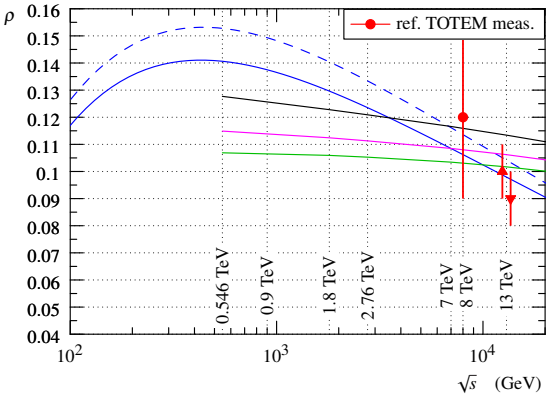
- simple version of derivative dispersion relation for *crossing-even* amplitude

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

  - faster $\sigma_{\rm tot}$ rise $\Rightarrow$ higher value of ρ
  - TOTEM data show the opposite $\Rightarrow$ *model-independent argument for crossing-odd component*

Models compatible with TOTEM data





- Nicolescu et al. (updated version of original model)
  - crossing-odd effect: strong energy dependence, increase with energy
  - TOTEM's ρ measurement at $\sqrt{s}$ = 13 TeV correctly predicted long before LHC
  - considered as first experimental evidence for "Odderon"
- Durham group (model enhanced with crossing-odd contribution)
  - crossing-odd effect: mild energy dependence, decrease with energy

$\Rightarrow$ *crossing-odd component needed to describe data*

Summary and outlook

- measurements
  - elastic scattering and total cross-section: 2.76, 7, 8 and 13 TeV
  - ρ parameter: 8 and 13 TeV

- observation/confirmation of trends
  - forward-cone shrinkage, but change of regime?
  - non-exponentiality at low $|t|$
  - dip moves to lower $|t|$ with increasing s
  - cross-sections: sustained growth

- evidence for Odderon
  - at $t \neq 0$: dip in pp, shoulder in $p\bar{p}$
  - at $t = 0$: low value of ρ, high value of σ_{tot}

- outlook
  - $\sqrt{s} = 900$ GeV elastic, σ_{tot} and ρ analysis in progress
  - plans for Run III: elastic, σ_{tot} and ρ measurement at 14 TeV

Thank you for your attention!

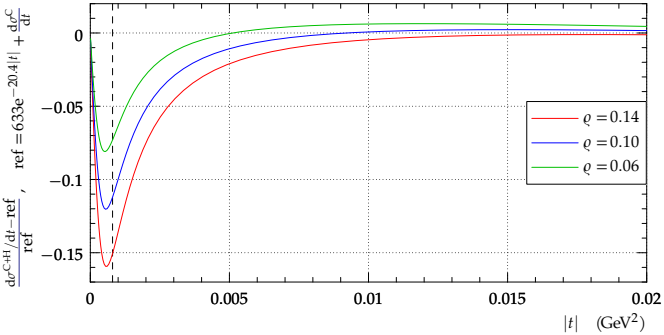
This work has been supported by

- grant MNiSW DIR/WK/2018/13 by the Polish Ministry of Science and Higher Education
- MŠMT ČR (Czech Republic)

Backup

Effect of ρ on differential cross-section

- simulation (with realistic nuclear component):



- TOTEM data, $\sqrt{s}$ = 13 TeV, β^* = 2500 m: