TOTEM: Prospects for Total Cross-Section and Luminosity Measurements

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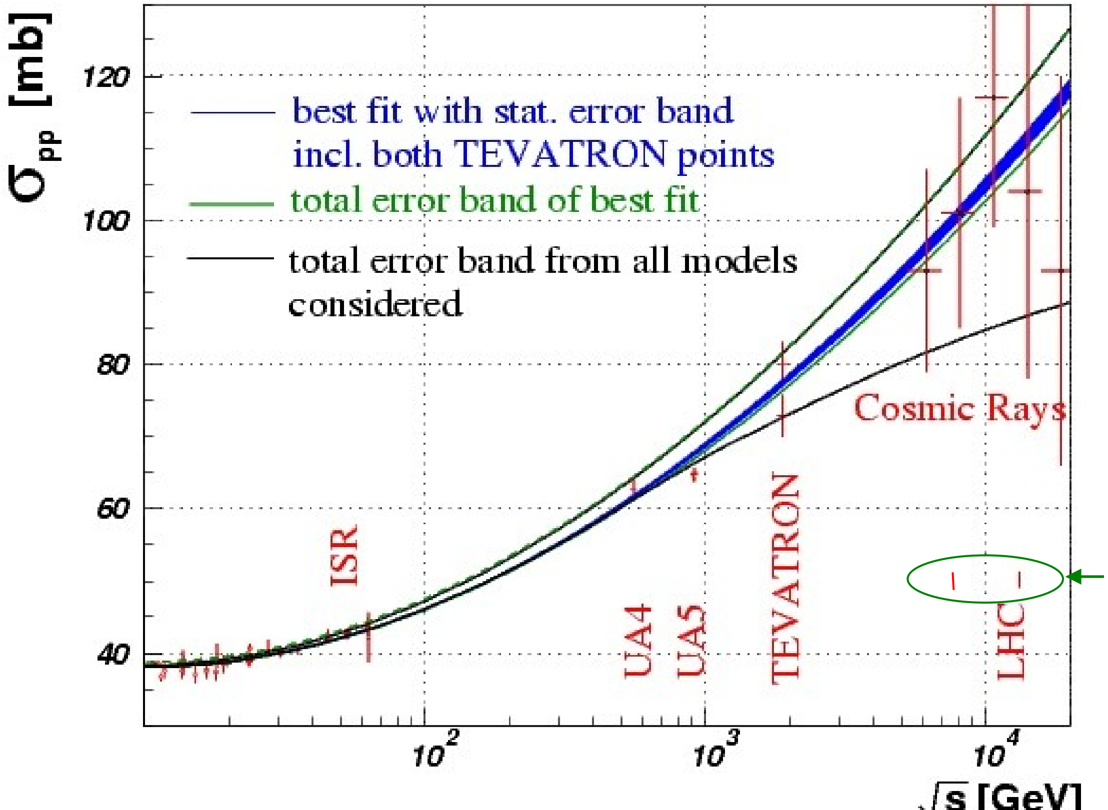
for the TOTEM Collaboration

13.01.2011



ultimate goal: ±1%
(2011: ±3%)

Luminosity-Independent Method based on the Optical Theorem

$$\left.\begin{aligned} \mathcal{L}\,\sigma_{tot}^2 &= \frac{16\pi}{1+\rho^2} \times \left.\frac{dN_{el}}{dt}\right|_{t=0} \\ \mathcal{L}\,\sigma_{tot} &= N_{el} + N_{inel} \end{aligned}\right\} \Rightarrow$$

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

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

- measure the **inelastic event rate N_{inel}** (with forward tracking chambers);
- measure the **elastic event rate N_{el}** (detect surviving protons with Roman Pots) and extrapolate the cross-section **dN_{el}/dt to $t = 0$**;
- take **ρ** = Re f(0) / Im f(0) [f(0) = forward elastic amplitude] from theory, e.g. COMPETE extrapolation: $\rho = 0.1361 \pm 0.0015 \begin{smallmatrix} +0.0058 \\ -0.0025 \end{smallmatrix}$

later: try to measure ρ at $\beta^* \sim 1$ km: elastic scattering in the Coulomb-nuclear interference region

Requirements for this method:

- Beam optics providing proton acceptance at low |t| in the Roman Pots
- Detector coverage at high |η|
- Trigger capability for all detector systems

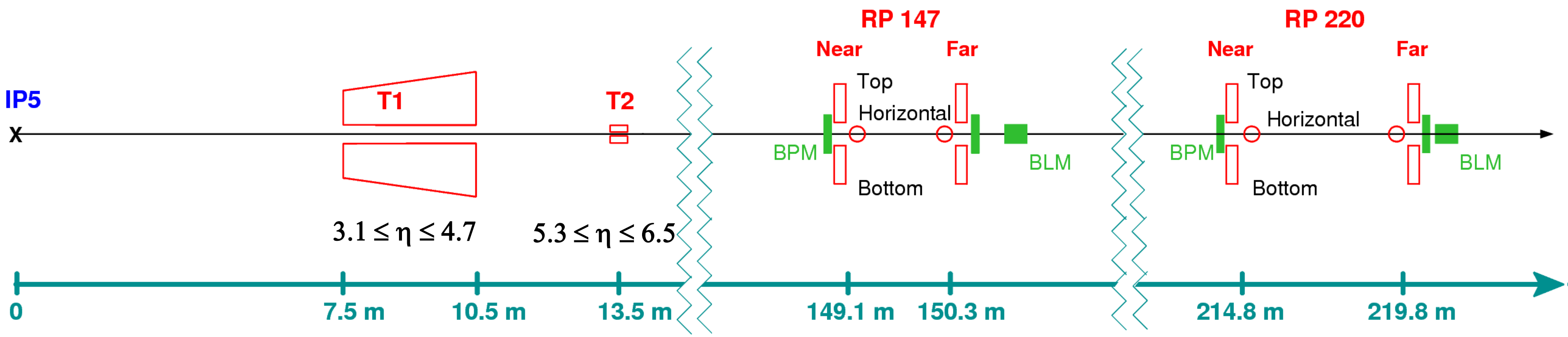
The TOTEM Detector Setup

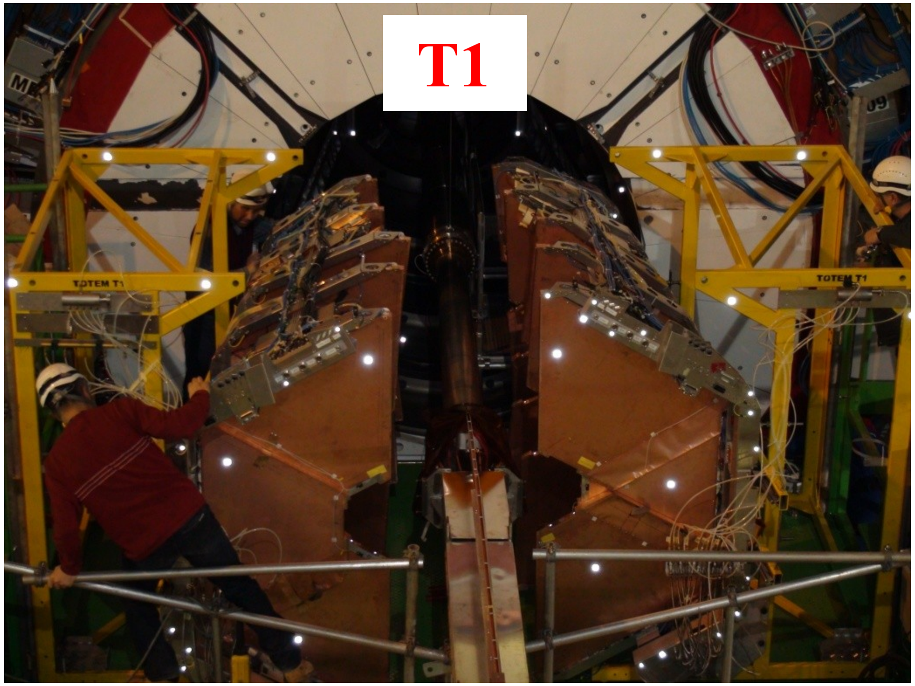
installation in progress

operational in 2010

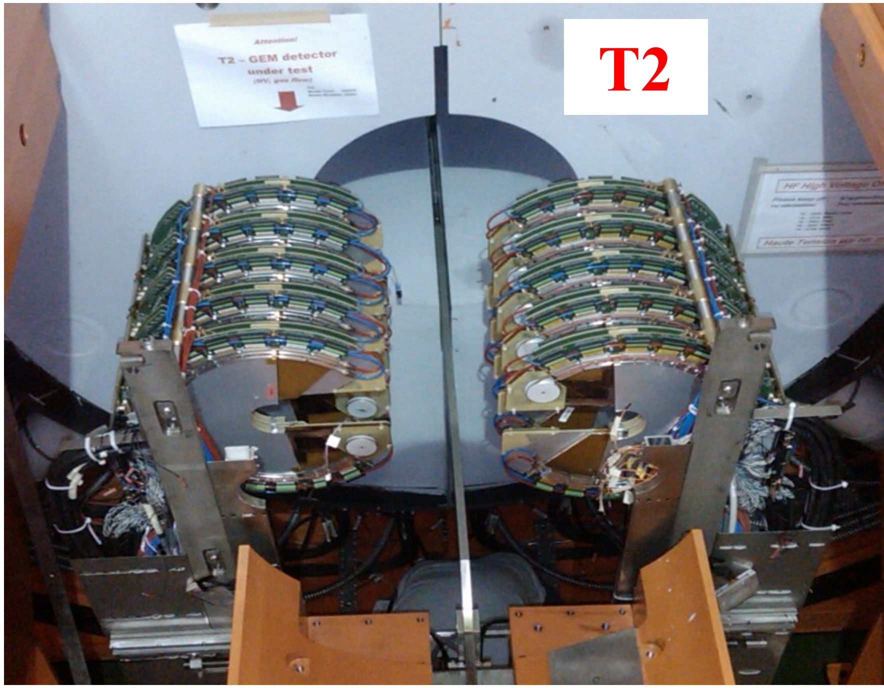
now installed

operational in 2010





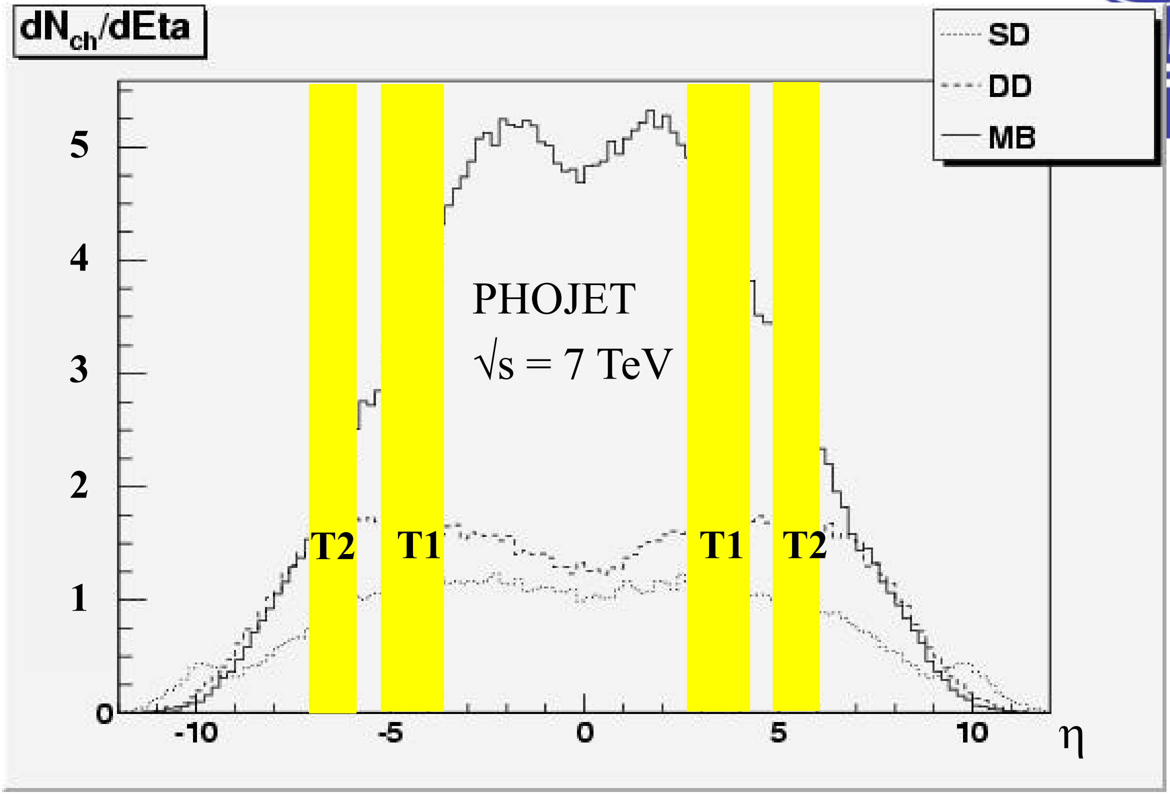
T1 "–" arm during installation



Acceptance for Inelastic Events

Uncertainties in inelastic cross sections large:

- non-diffractive min. bias (MB): 40 – 60 mb
- single diffraction (SD): 10 – 15 mb
- double diffraction (DD): 4 – 11 mb



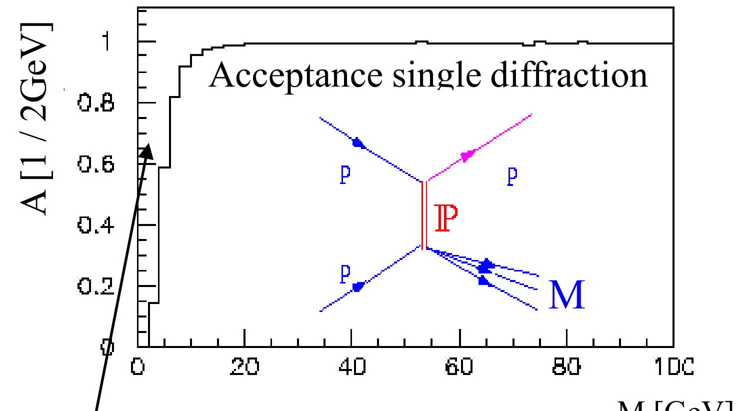
Accepted event fractions:

Min. number of tracks	MB T1+T2	MB 1/2 T1 + T2	MB T2 only	DD T1+T2	DD 1/2 T1 + T2	DD T2 only	SD T1+T2	SD 1/2 T1 + T2	SD T2 only
≥1(L + R)	100,0%	100,0%	98,2%	94,1%	92,9%	89,8%	77,6%	75,4%	71,3%
≥2(L + R)	100,0%	99,5%	95,1%	88,9%	83,4%	73,8%	68,6%	61,9%	51,3%
≥3(L + R)	99,9%	98,1%	89,0%	83,9%	75,3%	57,5%	61,4%	49,9%	32,3%
≥4(L + R)	99,1%	95,9%	82,2%	78,2%	66,3%	45,5%	55,0%	40,0%	19,0%
≥5(L + R)	98,3%	93,2%	71,7%	73,3%	59,5%	33,3%	48,4%	31,4%	11,5%

Measurement of the Inelastic Rate N_{inel}

Trigger Losses at √s = 7 TeV, requiring 3 tracks pointing to the IP

	σ	T1/T2 trigger and selection loss
Minimum bias	50 mb	0.05 mb
Single diffractive	12.5 mb	4.83 mb
Double diffractive	7.5 mb	1.21 mb
Total	**70 mb**	**6.1 mb**

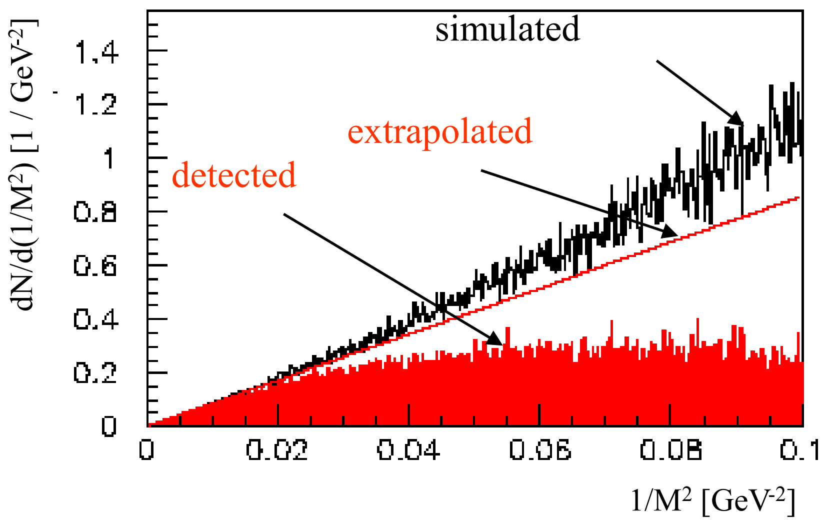


Loss at low diffractive masses M

Correction for trigger losses:

- Extrapolation of the mass spectrum:

fit $dN/dM^2 \sim 1/M^n$ with $n \sim 2$
uncertainty depends on the purity of the diffractive event sample used for the extrapolation
(e.g. errors from minimum bias events misidentified as diffractive events)

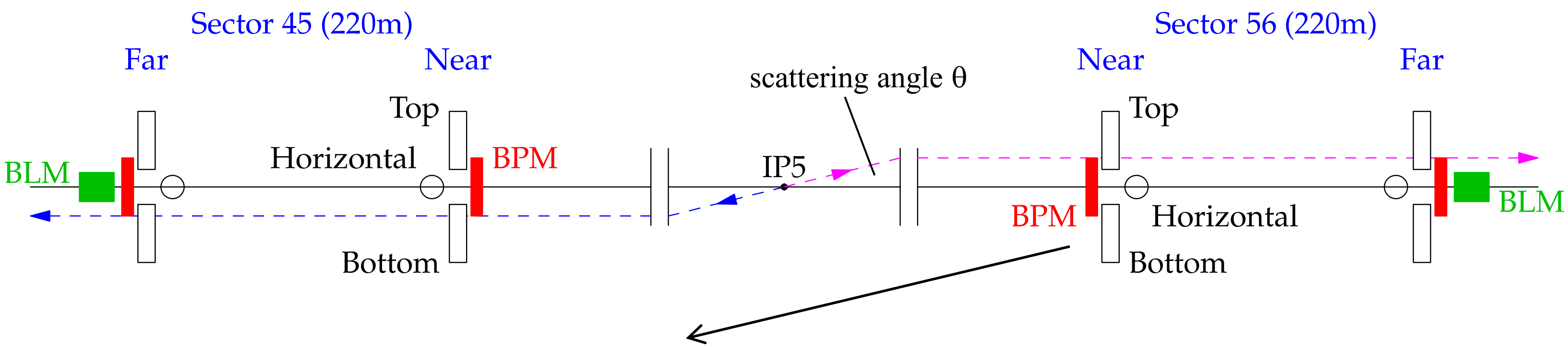


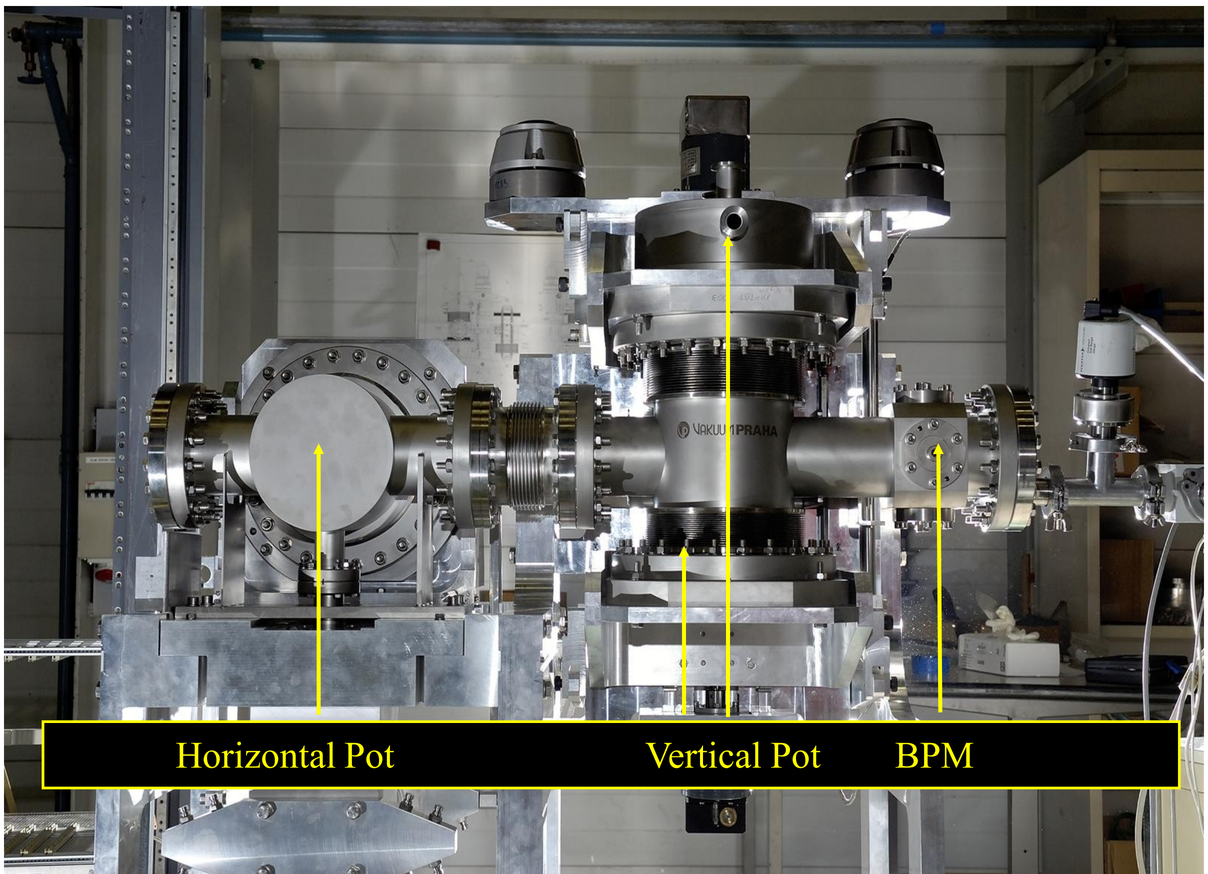
- Independent handle on low-mass diffraction:

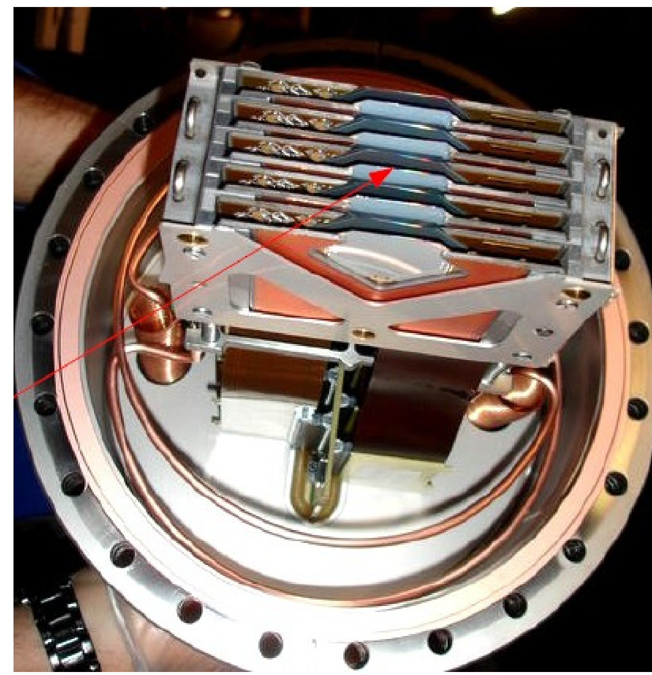
At β* = 90 m the protons for all diffractive masses are visible (for $|t| > \sim 10^{-2}$ GeV²).

→ total uncertainty on N_{inel} : 1.0 mb (1.4 %).

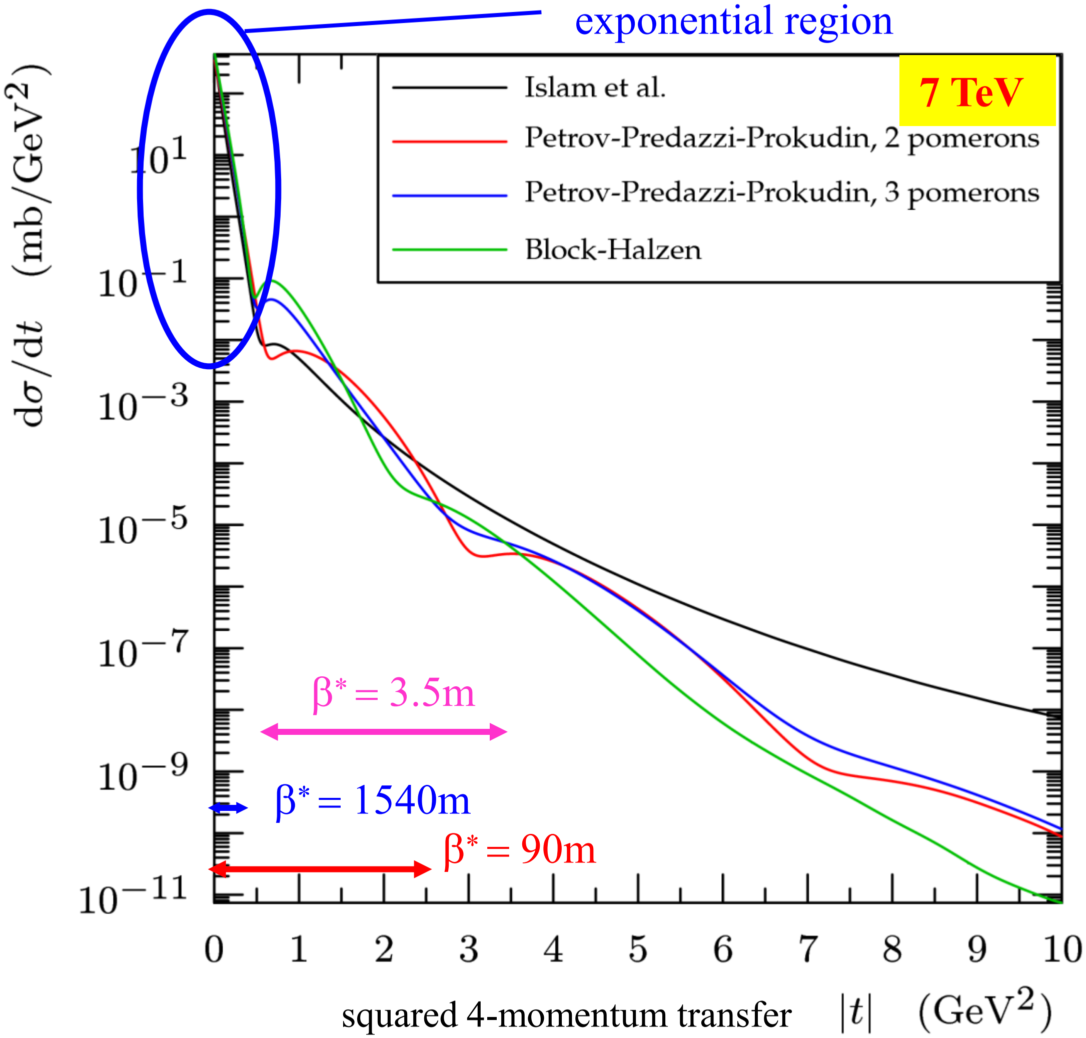
Roman Pot System: Leading Proton Detection







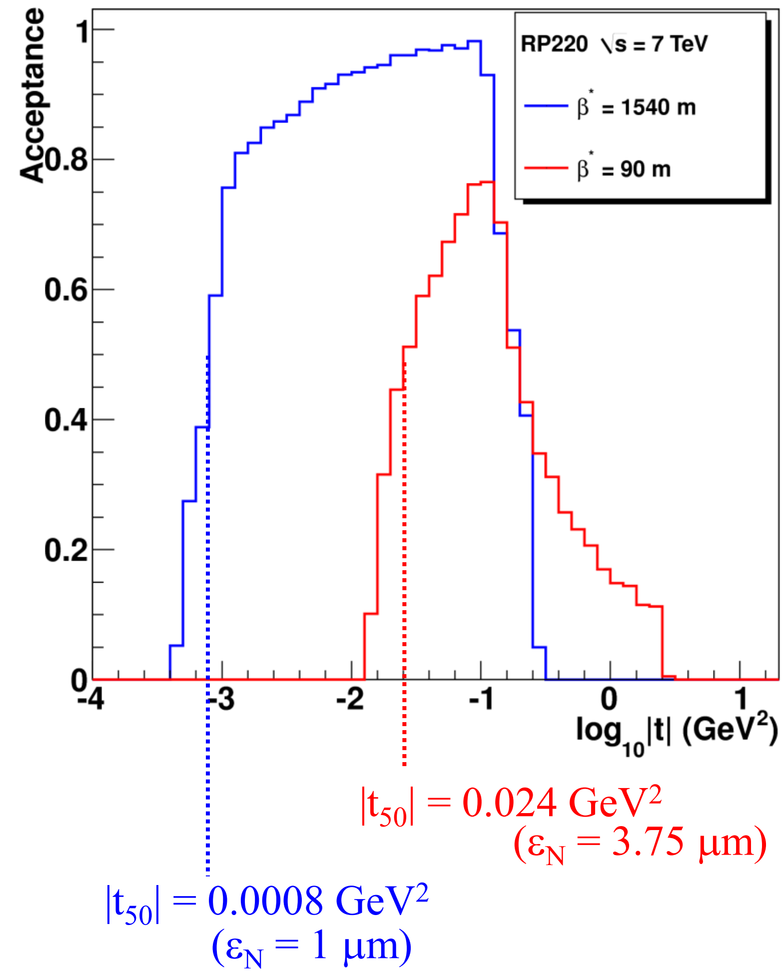
Elastic Scattering



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

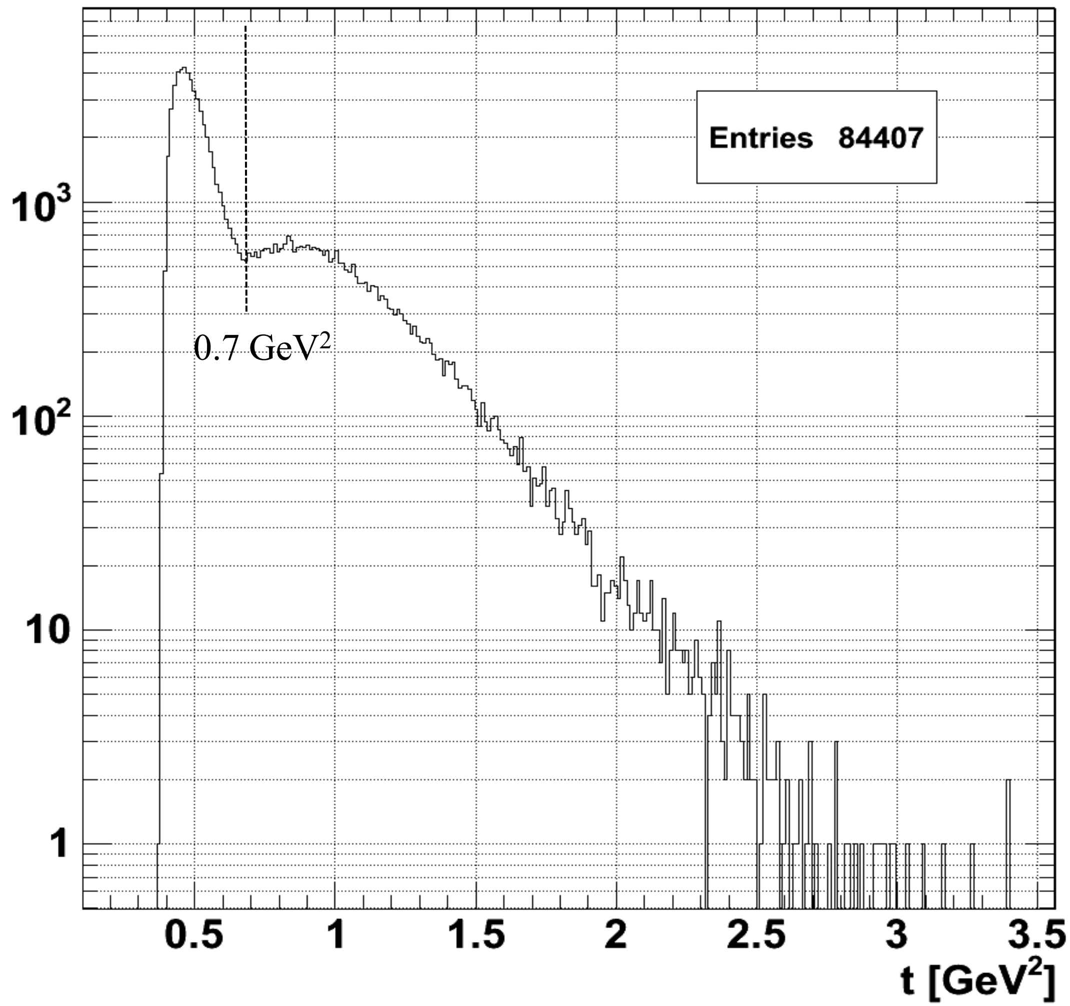
Elastic Scattering Acceptance at $\sqrt{s}$ = 7 TeV

RP220: detectors at 10 σ from beam centre



Preliminary t-distribution

~ 84K elastic scattering candidate events TOTEM special run (~ 9 nb^{-1})



$\sqrt{s}$ = 7 TeV

β^* = 3.5 m

RPs @ 7 σ (V) and 16 σ (H)

"Raw" distribution:

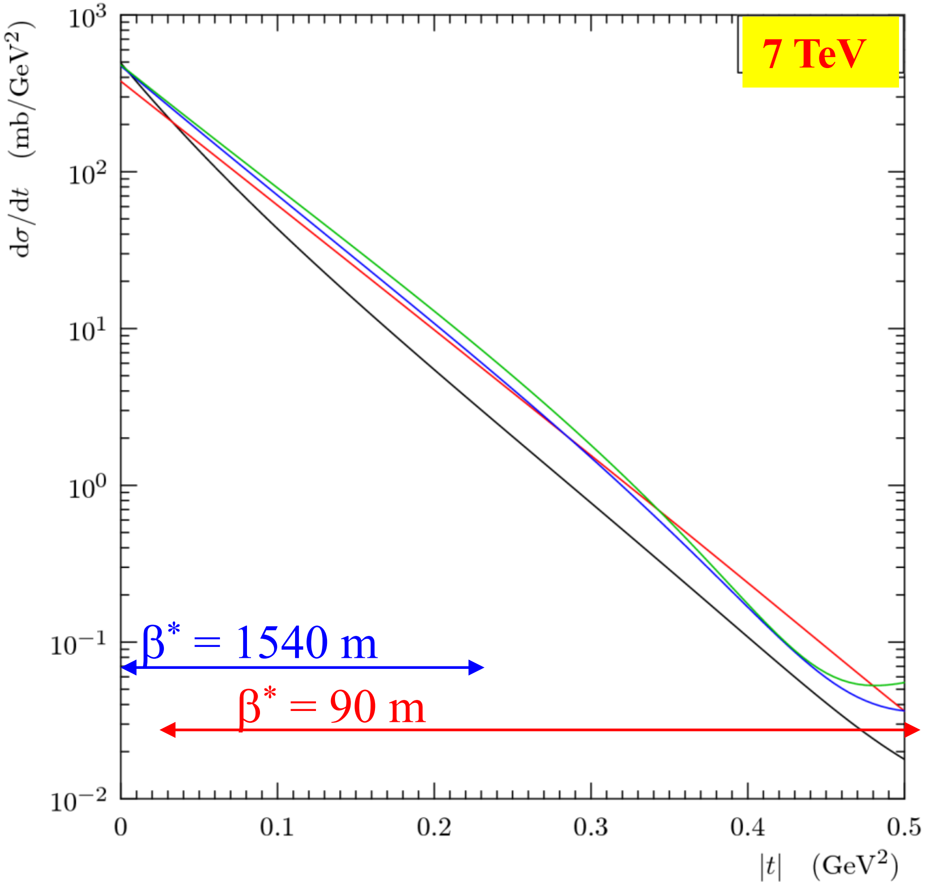
- No smearing corrections
- No acceptance corrections
- No background subtraction

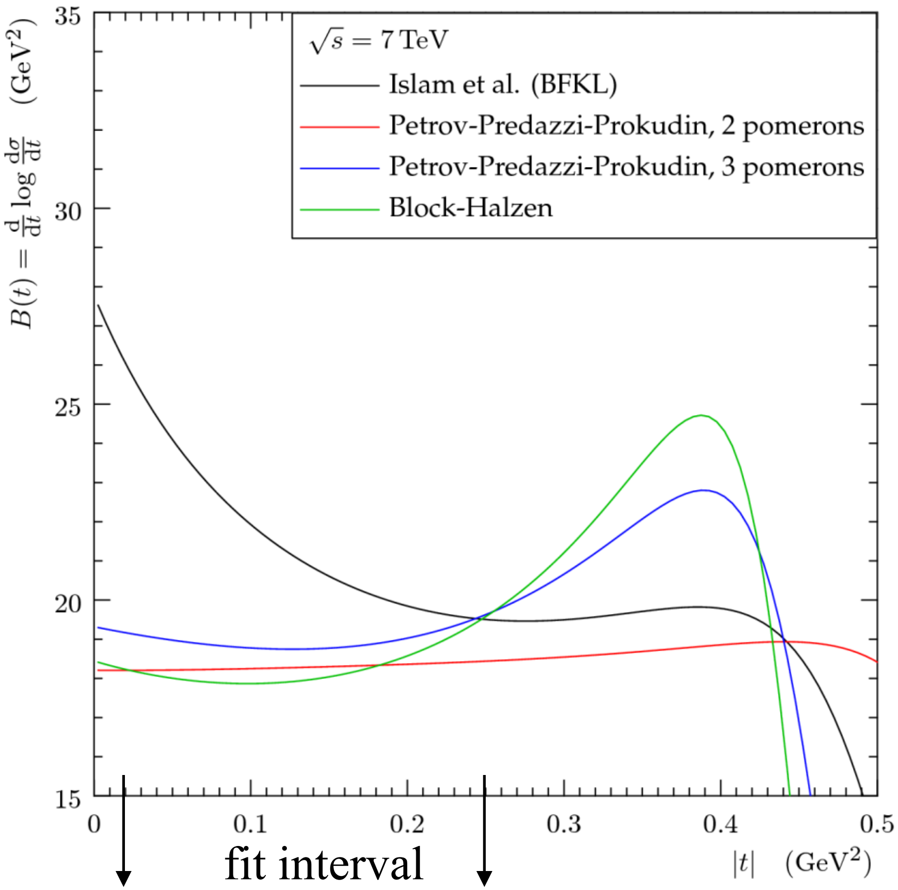
Syst. error sources under study: alignment, beam position and divergence, background, optical functions, efficiency, …

Elastic Scattering at low |t|

Cross-section $\frac{d\sigma}{dt} = e^{B(t)t}$

Exponential Slope B(t)





with detectors at 10 σ:

β* = 1540 m: $|t_{50}|$ = 0.0008 GeV^2

β* = 90 m: $|t_{50}|$ = 0.024 GeV^2

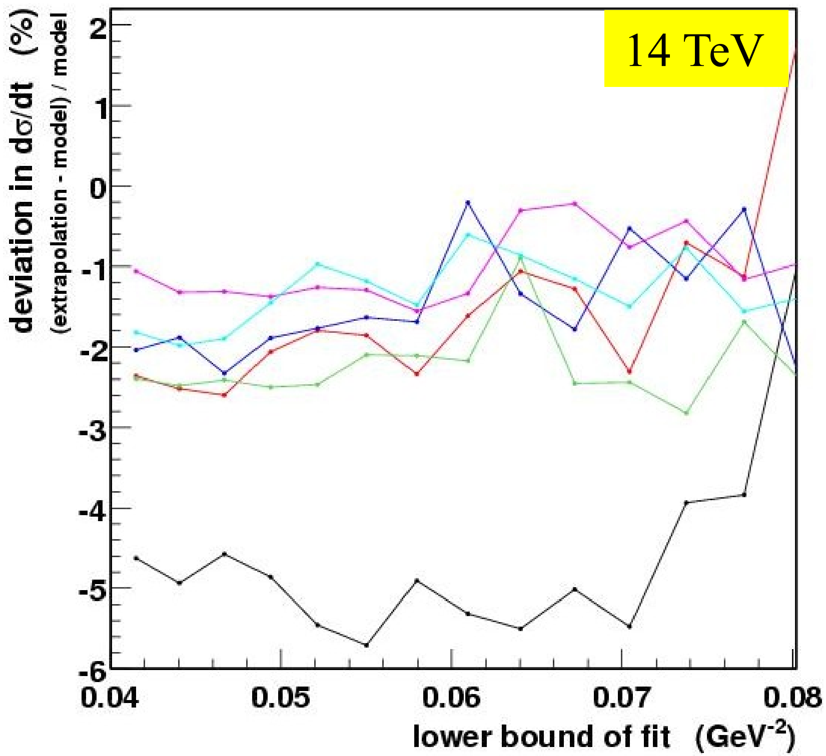
best parameterisation:

$B(t) = B_0 + B_1\ t + B_2\ t^2$

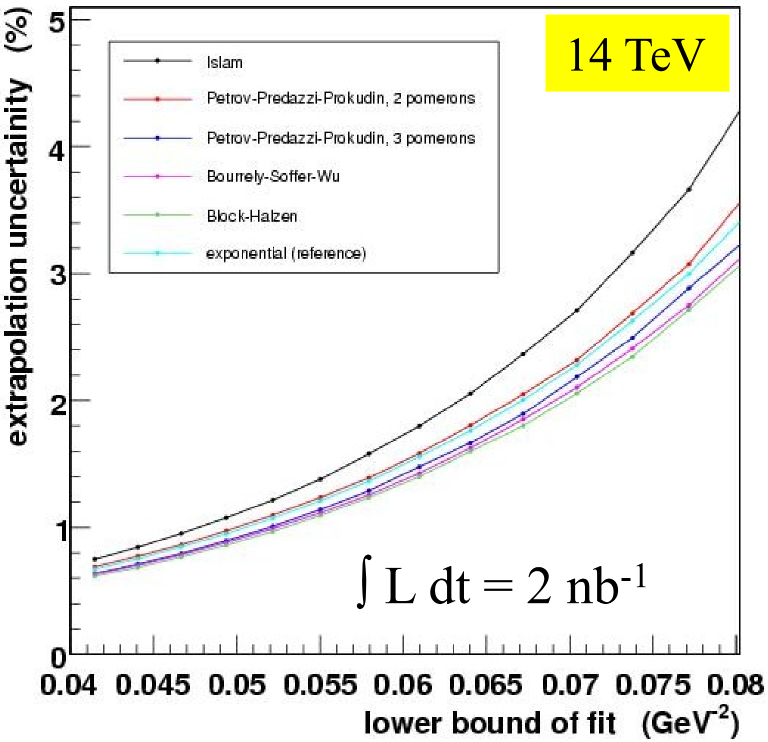
Extrapolation to the Optical Point (t = 0) at $\beta^* = 90$ m

Study at 14 TeV, $\varepsilon_N = 3.75$ µm rad

(extrapol. - model) / model in $d\sigma/dt\,|_{t=0}$



Statistical extrapolation uncertainty



upper bound: 0.25 GeV^2

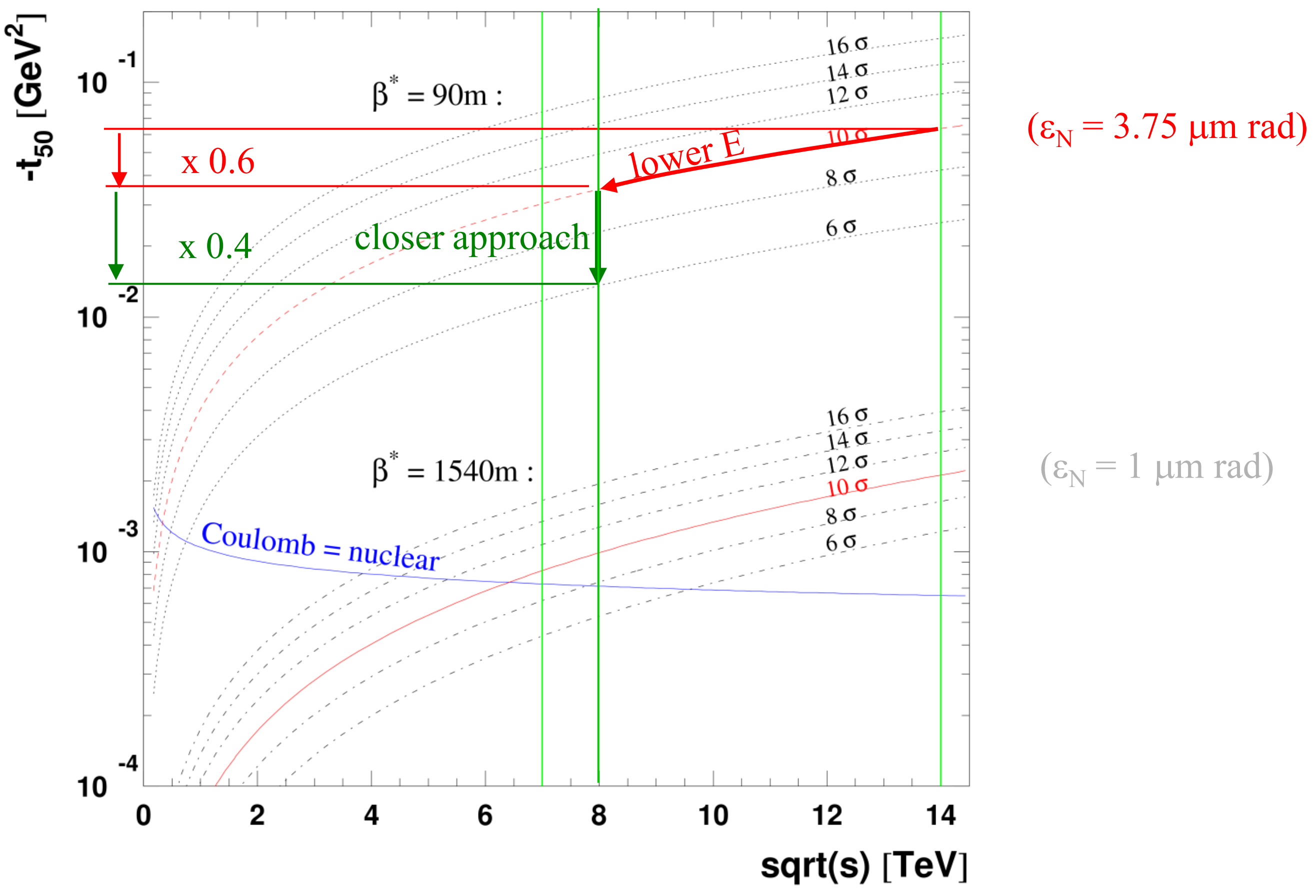
- Common bias due to beam divergence (angular spread flattens dN/dt distribution):
  –2% @14 TeV → –3% @7 TeV, **can be corrected.**
- Spread between most of the models: ±1%
  (Islam model needs different treatment, can be distinguished at larger |t|)
- Systematic error due to uncertainty of optical functions: ± 1.5 % , assuming $\delta L/L = 1\%$
- Different parameterisations for extrapolation (e.g. const. B, linear continuation of B(t)): negligible impact

Acceptance versus Energy and Detector Approach

Advantage of 7 or 8 TeV w.r.t. 14 TeV: $|t_{50}|$ reduced → **shorter extrapolation**

→reduced model dependence

→reduced statistical uncertainty



Desired Scenario for Runs at $\beta^* = 90$ m

(subject to discussions with MPP and collimation experts
and to commissioning progress / surprises)

4 special runs (assuming E = 4 TeV):

ε_n [μm rad]	RP distance (window)	bunching	L [$cm^{-2} s^{-1}$]	μ (inelastic pileup)	$\lvert t_{50} \rvert$ [GeV^2]	statistics per 8 h	statistical uncertainty of extrapol.
3	8 σ	1b, 7×10^{10} p/b	6.9×10^{27}	0.05	0.019	0.2 nb^{-1}	~ 1.5 %
3	6 σ	1b, 7×10^{10} p/b	6.9×10^{27}	0.05	0.011	0.2 nb^{-1}	~ 1 %
1	8 σ	1b, 6×10^{10} p/b	1.5×10^{28}	0.1	0.0070	0.4 nb^{-1}	< 1 %
1	6 σ	1b, 6×10^{10} p/b	1.5×10^{28}	0.1	0.0043	0.4 nb^{-1}	< 1 %

Dominated by systematics → small RP distance much more important than luminosity !

Crucial: good knowledge of the optical functions

Aim: contribution from optical functions not larger than angle resolution limit from beam divergence

$\delta L_y / L_y < 1.1$ % or $\delta\beta_y / \beta_y < 1.1$ %

$\delta L_x / L_x < 0.2$ % or $\delta\beta_x / \beta_x < 0.2$ % (but our error estimates are based on 1%: sufficient)

Combined Uncertainty in σ_{tot}

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

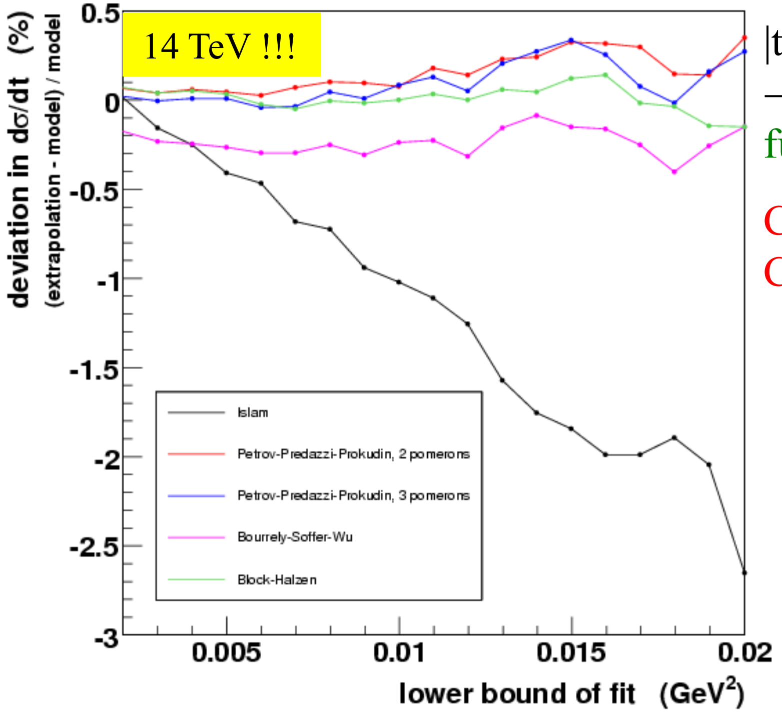
At $\beta^* = 90$ m, $\sqrt{s} = 7$ TeV :

- Extrapolation of elastic cross-section to t = 0: ± 2 %
- Total elastic rate (strongly correlated with extrapolation): ± 1 %
- Total inelastic rate: ± 1.4 %
- Error contribution from $(1+\rho^2)$ using full COMPETE error band $\delta\rho/\rho = 33$ % (very pessimistic): ± 1.2 %

⇒ Total uncertainty in σ_{tot} including correlations in the error propagation: ± 3 %

Slightly worse in $\mathcal{L}$ (~ total rate squared!) : ± 4 %

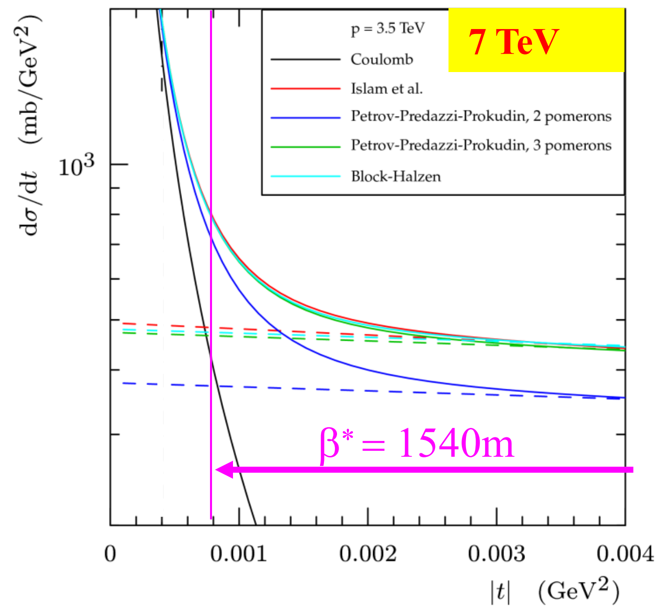
Outlook: Extrapolation with the Ultimate Optics (β* = 1540 m)



$|t_{50}| = 0.0008\ \mathrm{GeV}^2$ for RP window at 10 σ

→ good lever arm for choosing a suitable fitting function for the extrapolation to t = 0.

Complication:
Coulomb-nuclear interference must be included:



$$\frac{d\sigma}{dt} = \frac{\pi}{sp^2}\left| f_C(t) + f_N(t)\left[1 + i\left(\cancel{\alpha(t)} + \beta(t)\right)\right]\right|^2$$

[Cahn, Kundrát, Lokajíček]

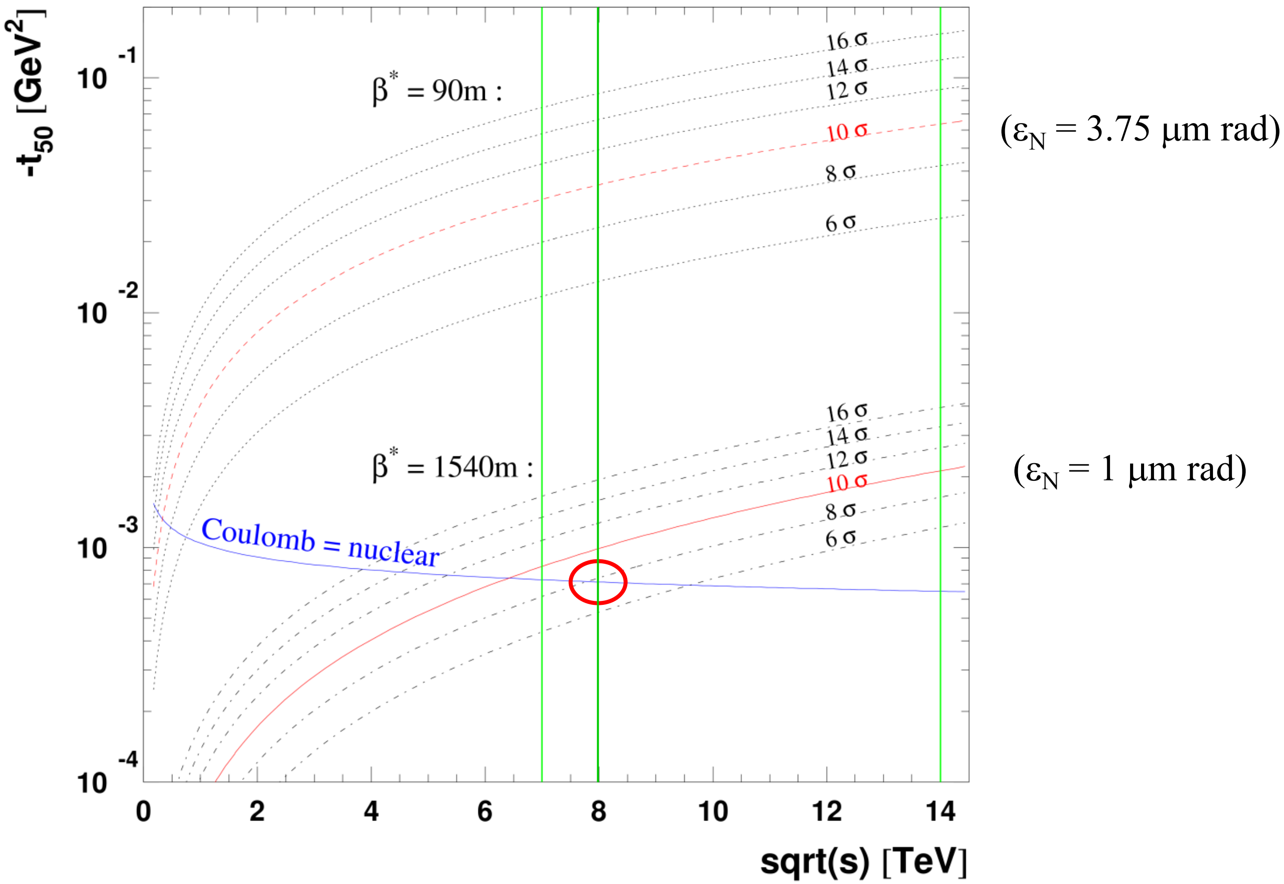
where $f_N(t) = A\, e^{i\Phi}\, e^{\left(b_0 + b_1 t + b_2 t^2\right) t}$ and β(t) is a function of $f_C(t)$ and $f_H(t)$.

For most models: extrapolation within ± 0.2 %.
Islam model needs different treatment; can be distinguished in the visible t-range.

Difficulties: - very-high-β* optics at 7 or 8 TeV still to be developed (β*=1540m exists only for 14 TeV).
- additional magnet powering cables needed.

Outlook: Measurement of ρ in the Coulomb-nuclear Interference Region?

Aim: get also the last ingredient to σ_{tot} from measurement rather than theory.



→might be possible at 8 TeV with RPs at 8 σ

→incentive to develop very-high-β* optics before reaching 14 TeV !

E.g. try to use the same optics principle as for 90m and unsqueeze further.

Summary

TOTEM is ready for a first σ_{tot} and luminosity measurement in 2011 with $\beta^* = 90$m using the Optical Theorem.

Expected precision: ~3% in σ_{tot} , ~4% in L

Wish: start soon with the development of the $\beta^* = 90$m optics to have enough time for learning.

Desired running conditions: low beam intensity, small RP distance to the beam

Longer term:

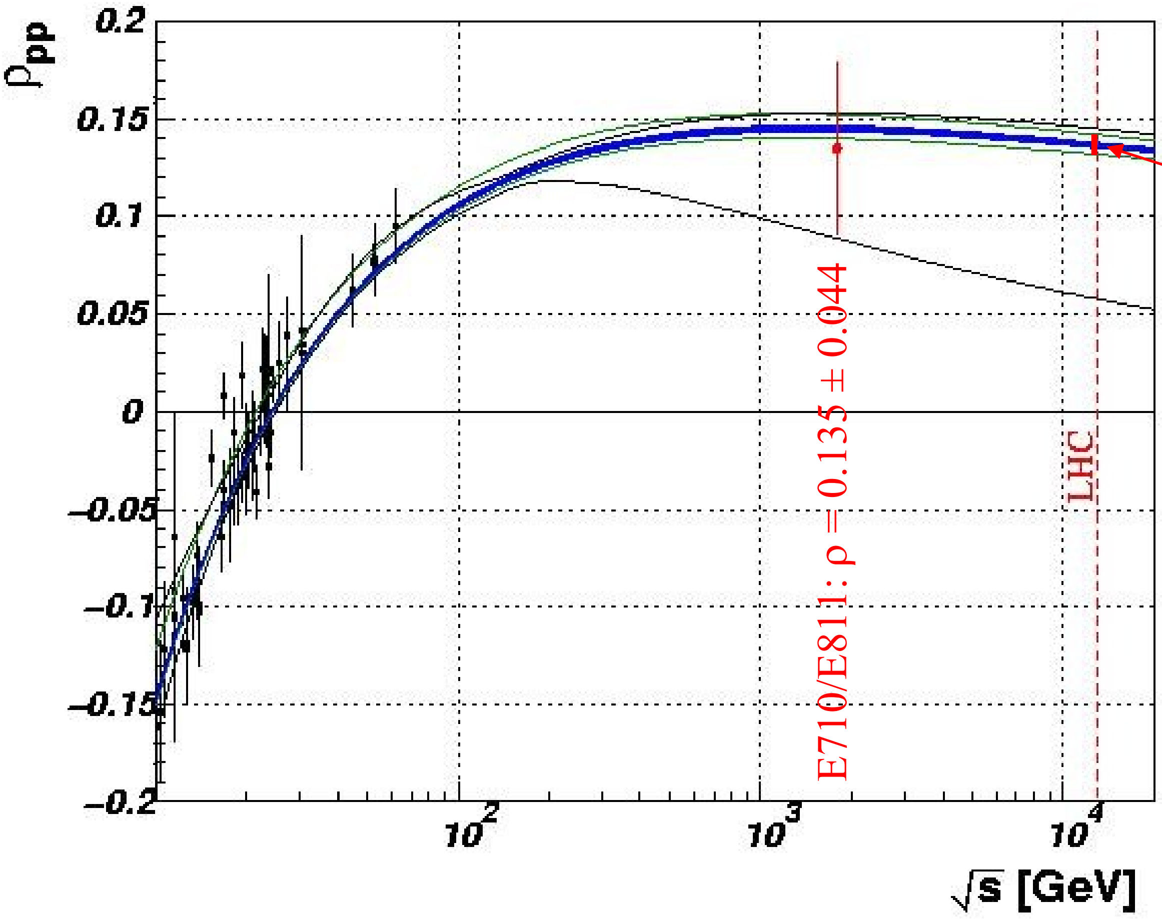
Measurement at the 1% level with very-high-β^* optics (~1 km);

might give access to the ρ parameter if the energy is still low ($\sqrt{s}$ ~ 8 TeV);

needs optics development work.

Backup

Elastic Scattering: ρ = ℜ f(0) / ℑ f(0)



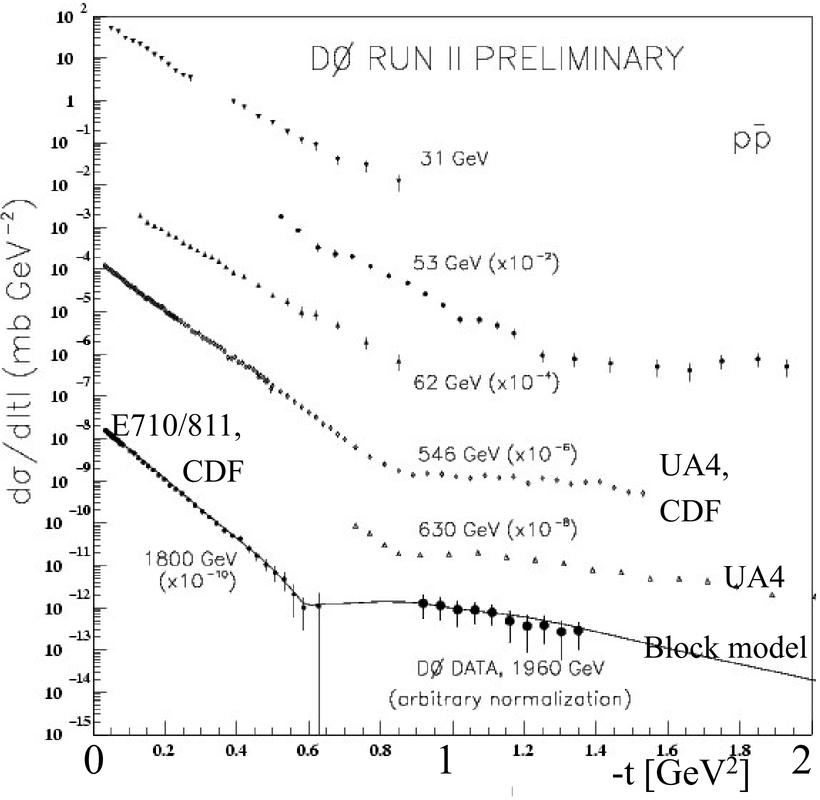
COMPETE [PRL 89 201801 (2002)]

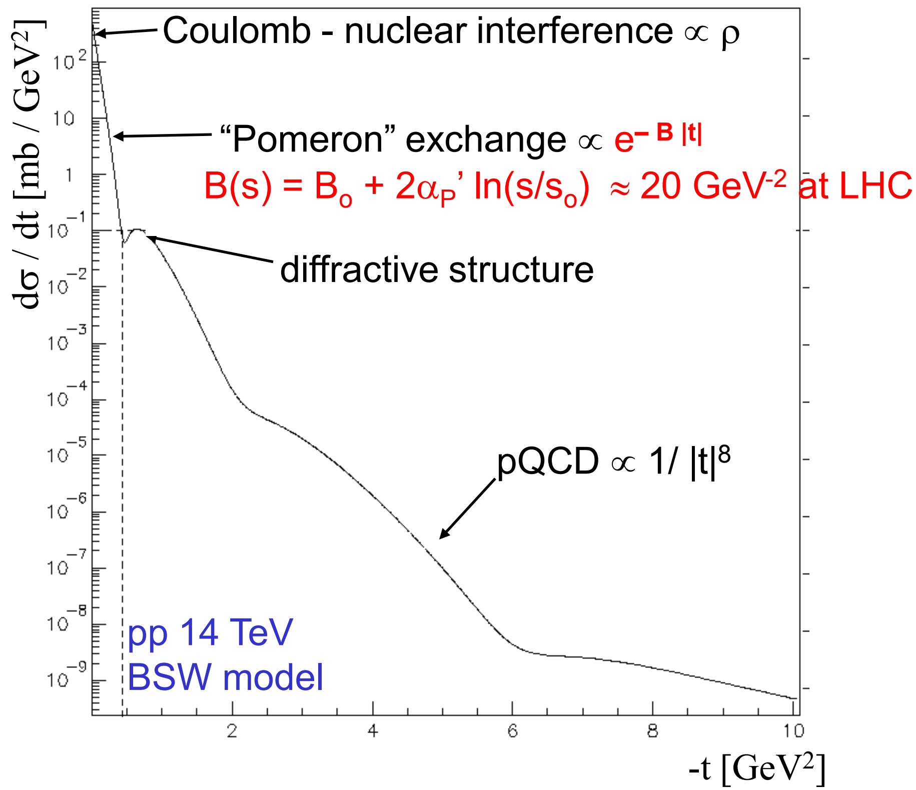
Preferred fit predicts:

$$\rho = 0.1361 \pm 0.0015 \begin{array}{l} +0.0058 \\ -0.0025 \end{array}$$

asymptotic behaviour:
$\propto 1 / \ln s$ for $s \to \infty$

Elastic Scattering from ISR to LHC





546 GeV: CDF: $0.025 < |t| < 0.08$ GeV^2 : $B = 15.28 \pm 0.58$ GeV^{-2} (agreement with UA4(/2))

1.8 TeV: CDF: $0.04 < |t| < 0.29$ GeV^2 : $B = 16.98 \pm 0.25$ GeV^{-2}

E710: $0.034 < |t| < 0.65$ GeV^2 : $B = 16.3 \pm 0.3$ GeV^{-2}

$0.001 < |t| < 0.14$ GeV^2 : $B = 16.99 \pm 0.25$ GeV^{-2} , $\rho = 0.140 \pm 0.069$

E811: $0.002 < |t| < 0.035$ GeV^2 : using $\langle B \rangle$ from CDF, E710: $\rho = 0.132 \pm 0.056$

1.96 TeV: D0: $0.9 < |t| < 1.35$ GeV^2

Relative Luminosity Measurement

For running conditions where measurement via Optical Theorem impossible:
relative measurement after a prior absolute calibration at $\beta^* = 90$ m or 1540 m.

Examples:

- partial inelastic rates, e.g. (T2 left) x (T2 right): robust against beam-gas background
- for running conditions with pileup:
  count zero-events, e.g. failing (T2 left) x (T2 right):

$$\mathcal{L} = -\frac{1}{\sigma_{tot} A_{T2lxT2r} \Delta t} \ln P(n=0)$$

e.g. P(n=0) = 15 % @ $\mathcal{L}=10^{33}$ cm^{-2}s^{-1} , 2808 bunches

Also usable for continuous luminosity monitoring (to be studied further).

Measurements of σ_{tot}

Conflicting Tevatron measurements at 1.8 TeV:

E710: $\sigma_{tot} = 72.8 \pm 3.1$ mb

E811: $\sigma_{tot} = 71.42 \pm 2.41$ mb

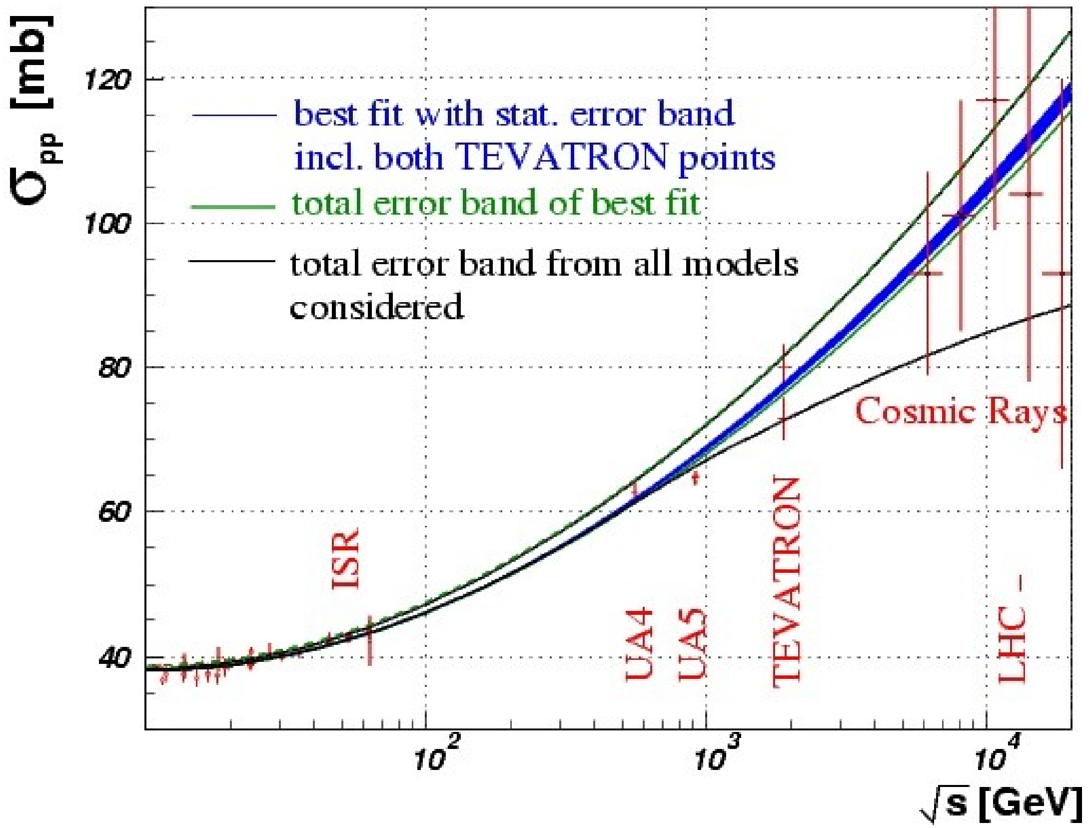
CDF: $\sigma_{tot} = 80.03 \pm 2.24$ mb

Disagreement E811–CDF: 2.6 σ

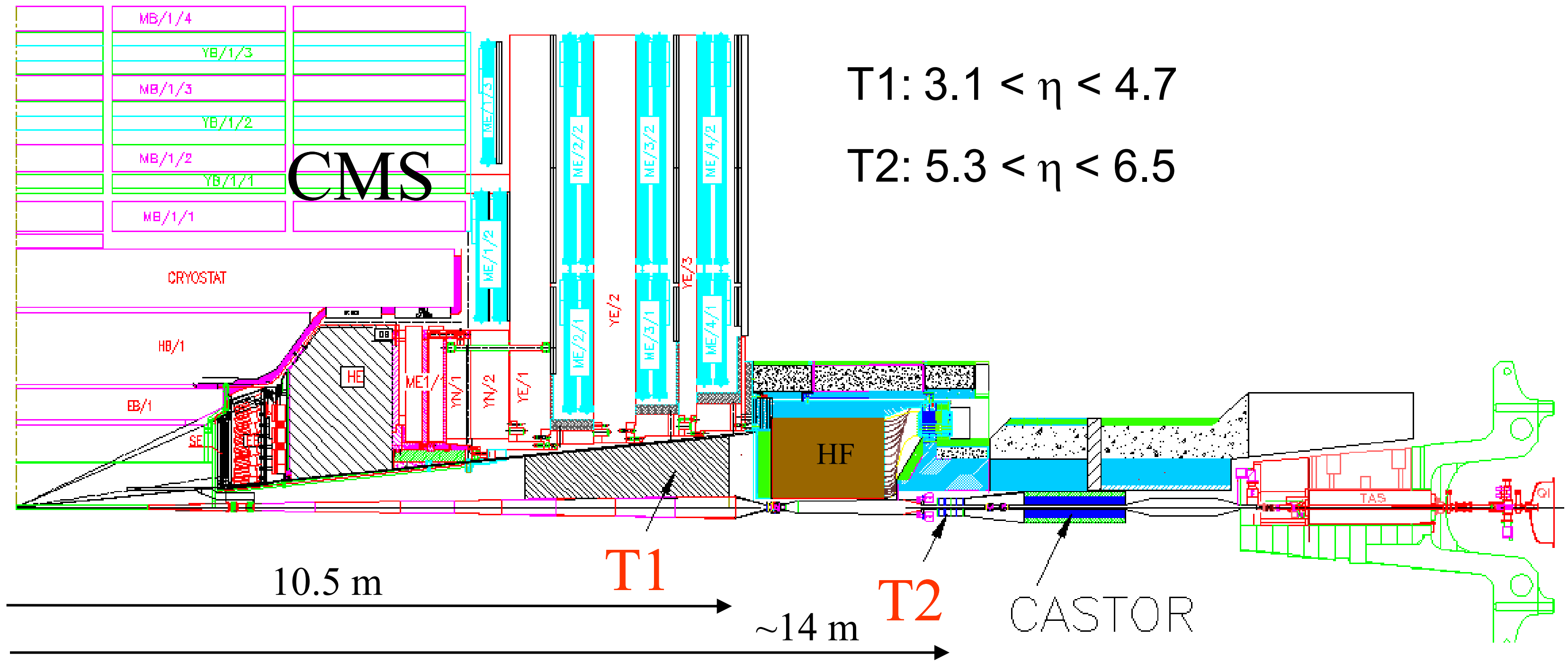
Best combined fit by COMPETE:

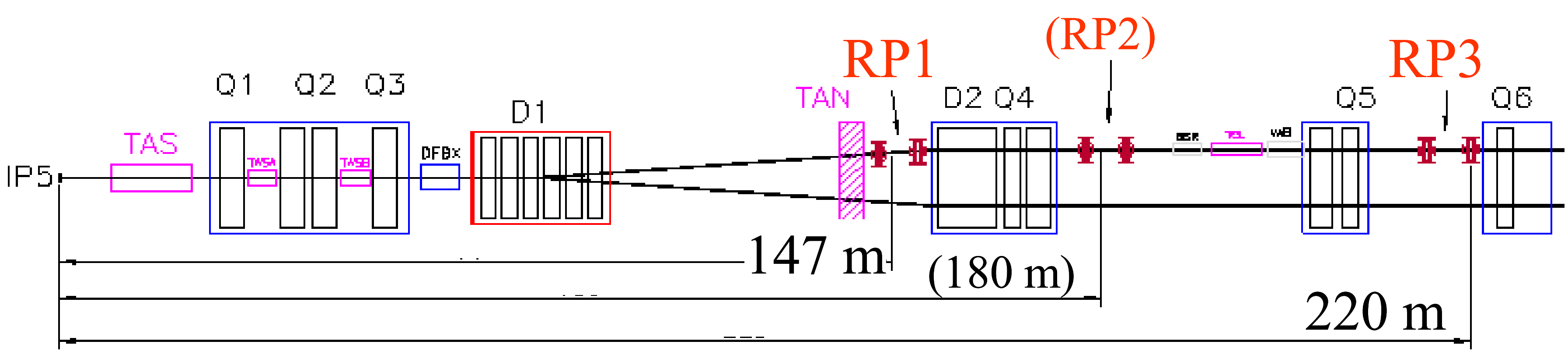
$$\sigma_{tot} = 111.5 \pm 1.2 \;{}^{+4.1}_{-2.1}\ \text{mb}$$

But models vary within (at least) ${}^{+10}_{-20}$ %.



TOTEM Detector Configuration

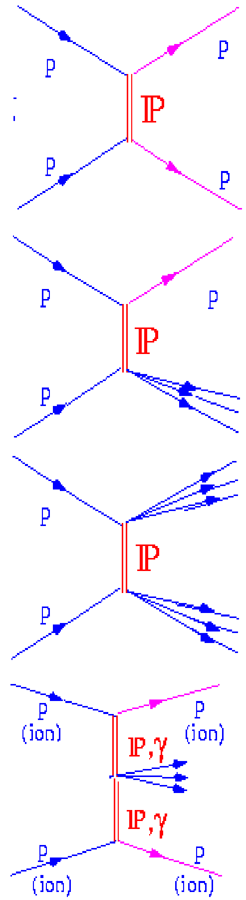


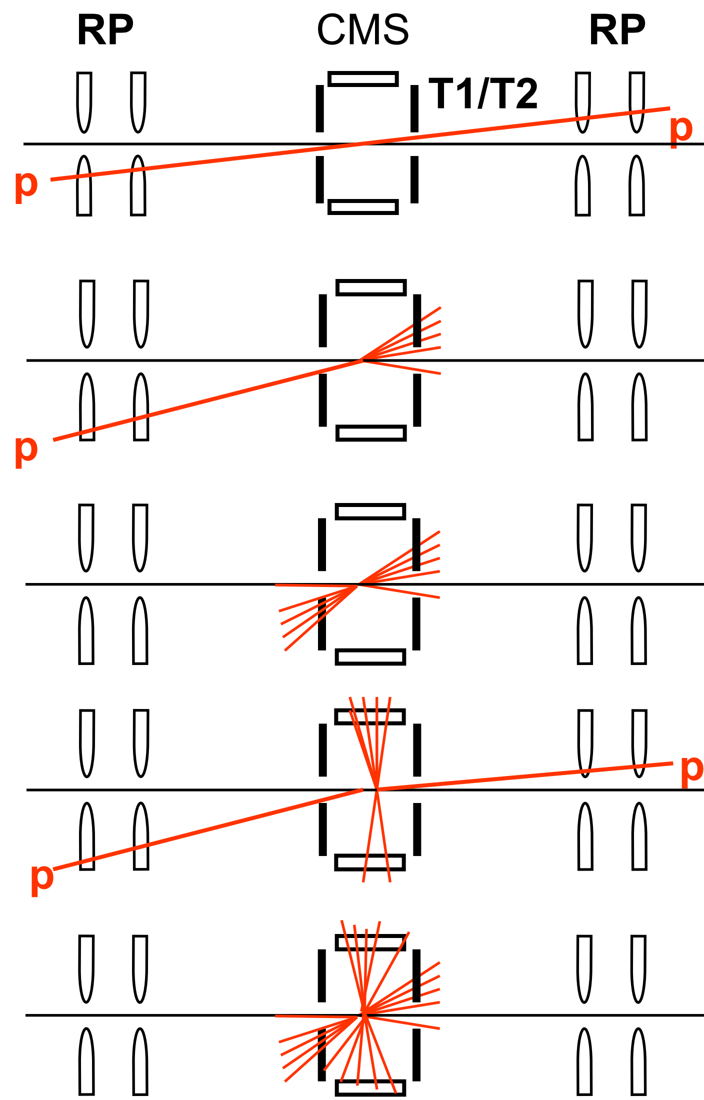


Symmetric experiment: all detectors on both sides!

Level-1 Trigger Schemes

Always try to use 2-arm coincidence to suppress background.





Elastic Trigger:
$\sigma \approx 30$ mb

Single Diffractive Trigger:
$\sigma \approx 14$ mb

Double Diffractive Trigger:
$\sigma \approx 7$ mb

Central Diffractive Trigger
(Double Pomeron Exchange DPE)
$\sigma \approx 1$ mb

Non-diffractive Inelastic Trigger:
$\sigma \approx 58$ mb

$\sigma_{tot} \approx 110$ mb

Acceptance Losses and Selection Losses

	MB			DD			SD		
	T1+T2	**1/2 T1 + T2**	**T2 only**	**T1+T2**	**1/2 T1 + T2**	**T2 only**	**T1+T2**	**1/2 T1 + T2**	**T2 only**
1(L+R)	100.0%	100.0%	98.2%	94.1%	92.9%	89.8%	77.6%	75.4%	71.3%
2(L+R)	100.0%	99.5%	95.1%	88.9%	83.4%	73.8%	68.6%	61.9%	51.3%
3(L+R)	99.9%	98.1%	89.0%	83.9%	75.3%	57.5%	61.4%	49.9%	32.3%
4(L+R)	99.1%	95.9%	82.2%	78.2%	66.3%	45.5%	55.0%	40.0%	19.0%
5(L+R)	98.3%	93.2%	71.7%	73.3%	59.5%	33.3%	48.4%	31.4%	11.5%

Acc. lost events:	T2 only	T2+ ½ T1	T2+ full T1
SD	4.8 mb	4.0 mb	3.5 mb
DD	1.2 mb	0.81 mb	0.61 mb

Ineff. lost events:	T2 only	T2+ ½ T1	T2+ full T1
SD	1.33 mb	0.74 mb	0.39 mb
DD	0.82 mb	0.44 mb	0.22 mb
MB	2.45 mb	0.25 mb	0 (?) mb
Sum	4.6 mb	1.4 mb	0.61 mb

Detection of Leading Protons

Transport equations:

$$y_{det} = L_y \theta_y^* + v_y y^* + D_y \xi$$

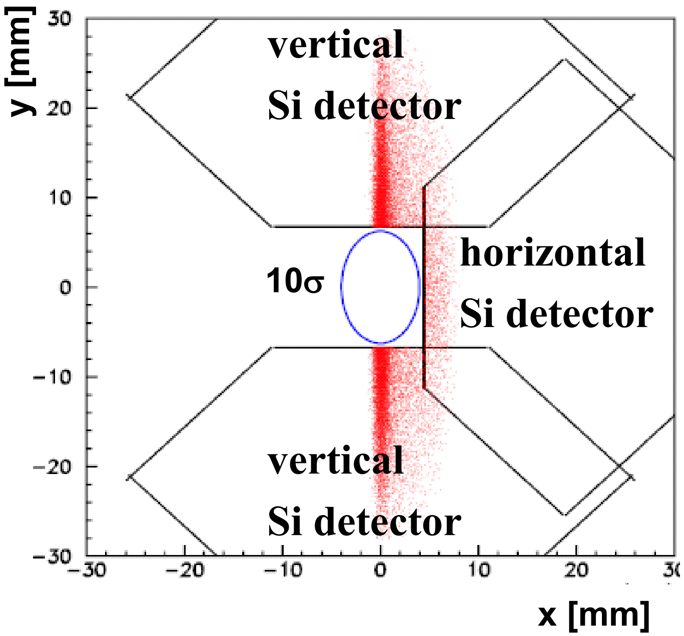
$$x_{det} = L_x \theta_x^* + v_x x^* + D_x \xi$$

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

(θ_x^*, θ_y^*): emission angle

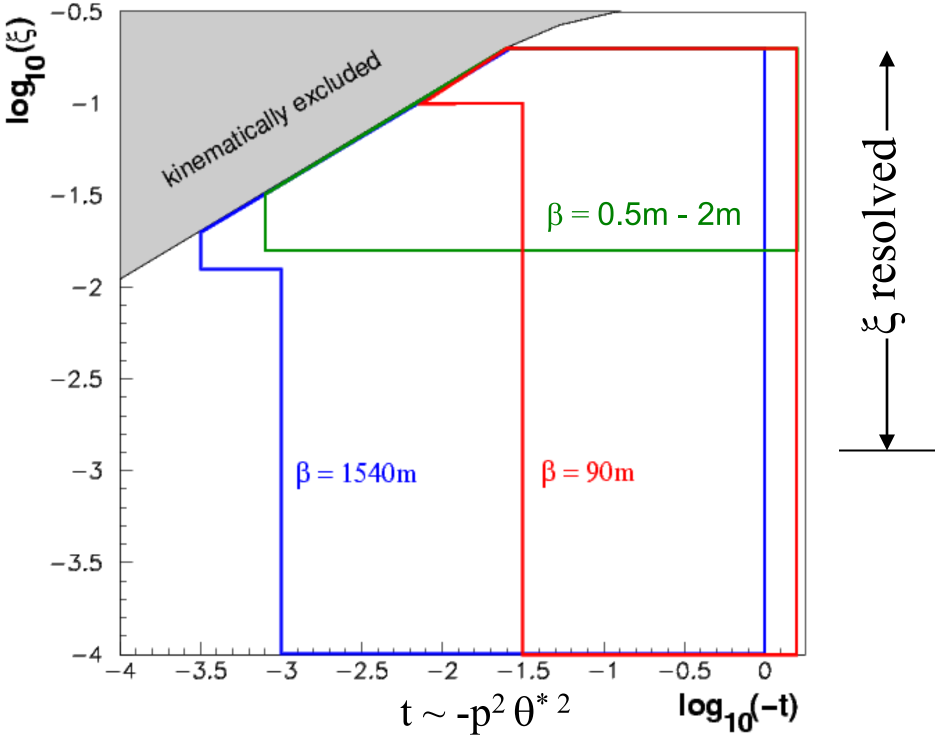
$\xi = \Delta p/p$

Example: Hit distribution @ TOTEM RP220 with $\beta^* = 90$m



TOTEM: Proton Acceptance in (t, ξ):

(contour lines at A = 10 %) RP220



Optics properties at RP220:

$\beta^* = 1540$ m	$L = 10^{28} – 2 \times 10^{29}$	95% of all p seen; all ξ
$\beta^* = 90$ m	$L = 10^{29} – 3 \times 10^{30}$	65% of all p seen; all ξ
$\beta^* = 0.5 – 2$ m	$L = 10^{30} – 10^{34}$	p with ξ > 0.02 seen; all t