Luminosity Measurement and Monitoring with TOTEM

M. Deile
(CERN)
for the TOTEM Collaboration

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1. Measurement methods
2. Strategies for different running scenarios

Measurement of the Luminosity (and σ_{tot})

1. Using the Optical Theorem

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

$$\mathcal{L}\,\sigma_{tot} = N_{el} + N_{inel}$$

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

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

Run for typically 1 day (for sufficient statistics) and:

	β^*=1540m	90m
• measure the inelastic rate N_{inel} (dominated by systematics from trigger losses and background);	0.8 %	0.8 %
• measure the elastic rate N_{el} and extrapolate the cross-section dN_{el}/dt to t = 0 (dominated by model-dependent systematics).	< 1 %	< 10 %
• ρ unknown, from COMPETE extrapolation: $\rho = 0.1361 \pm 0.0015 \,^{+0.0058}_{-0.0025}$		
relative error$[1 / (1 + \rho^2)]$:	0.16 %	

Requirement for this method: Optics with proton acceptance at low |t|

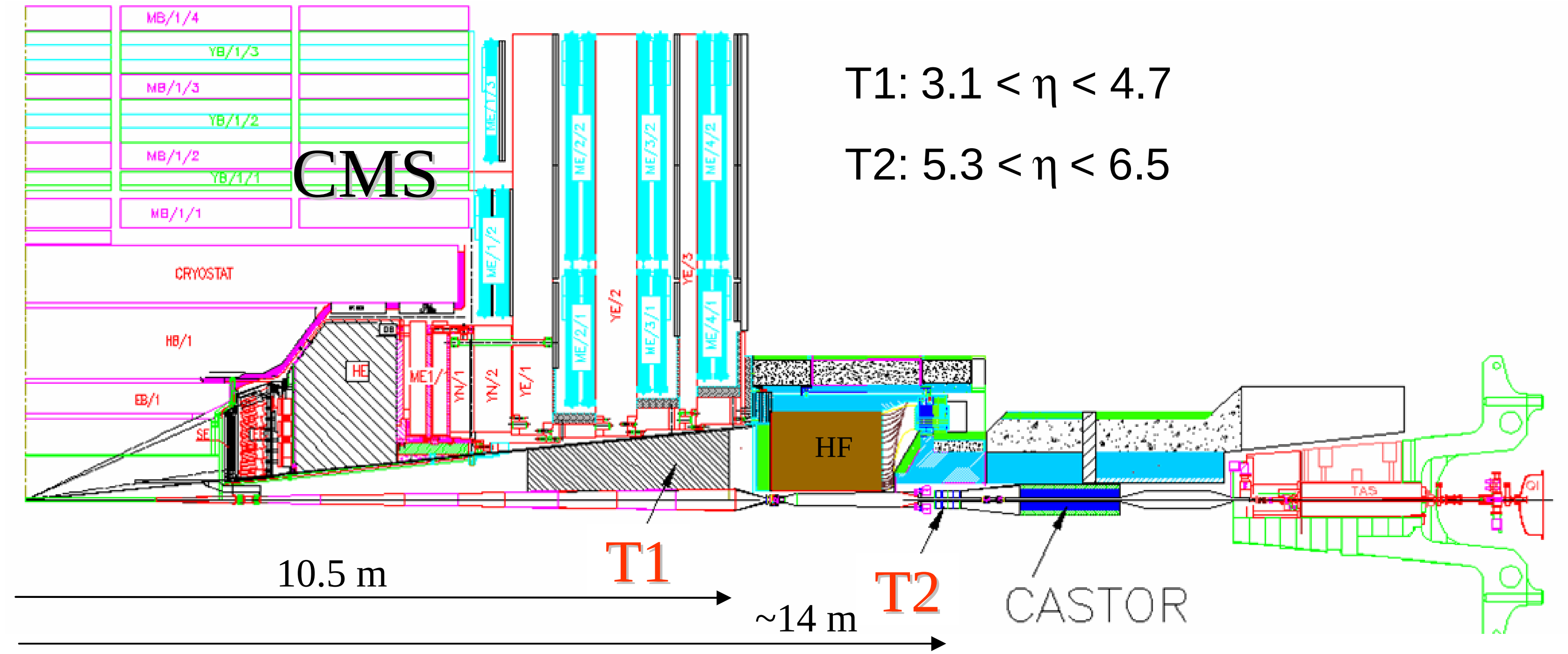
2. With known Cross-Section (at SppS energies or after reference measurement):

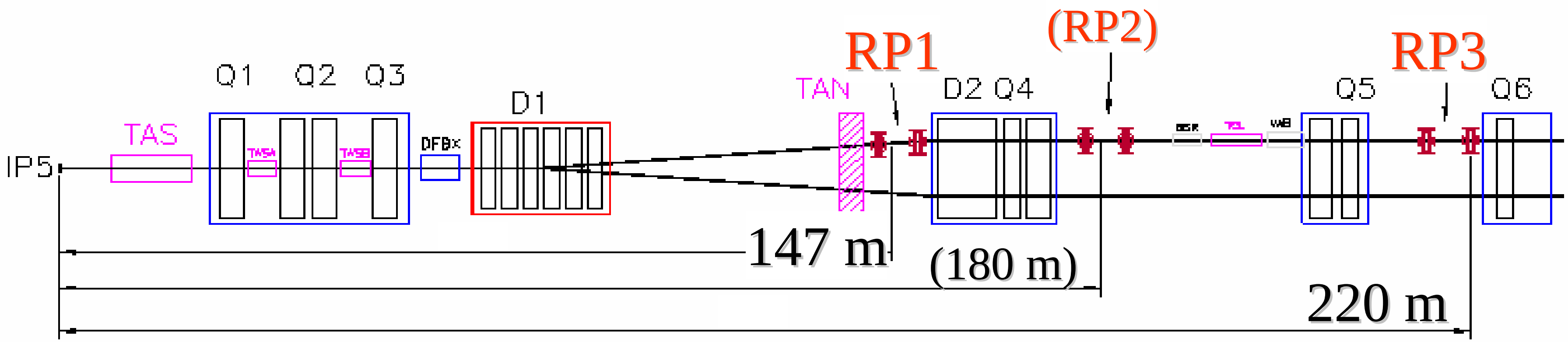
$$\mathcal{L} = \frac{N_{el}+N_{inel}}{\sigma_{tot}} \quad \text{or} \quad \mathcal{L} = \frac{N_{process}}{\sigma_{process}}$$

TOTEM Detector Configuration

T1: 3.1 < η < 4.7

T2: 5.3 < η < 6.5

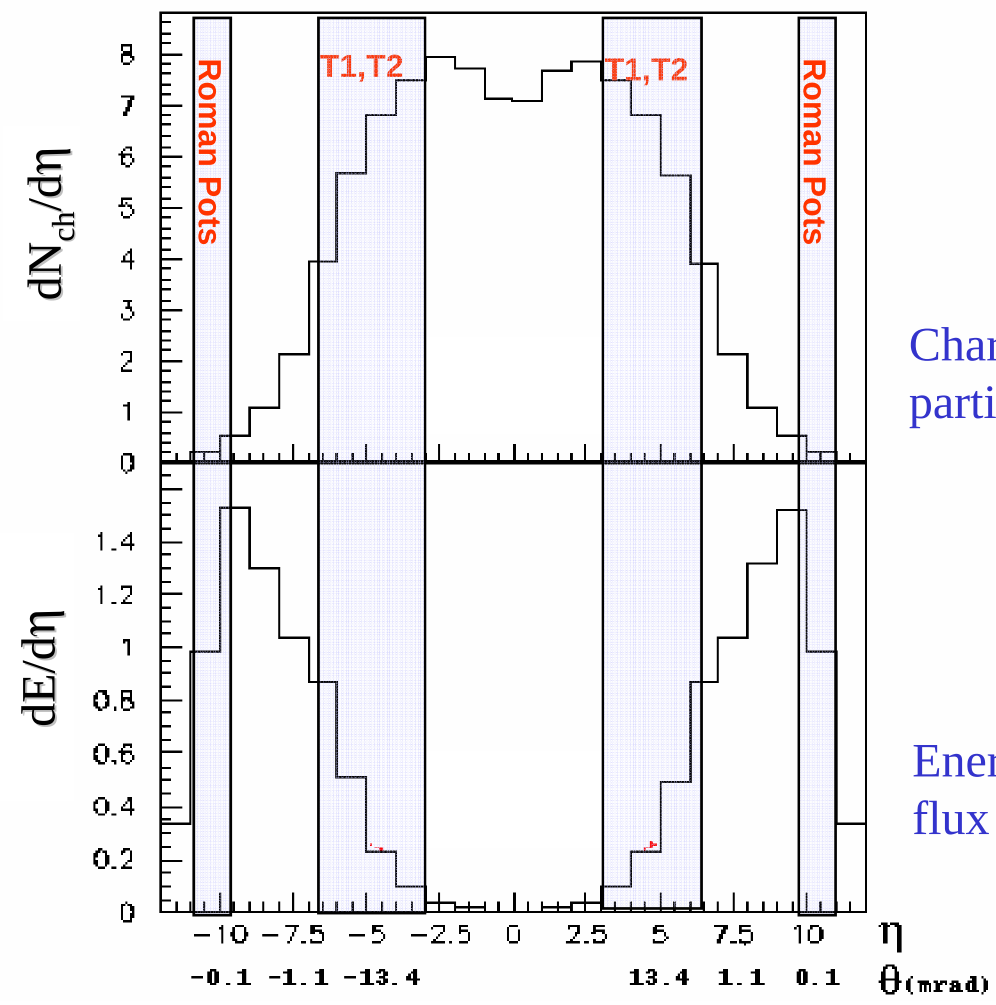




Symmetric experiment: all detectors on both sides!

TOTEM: Acceptance

Acceptance for general inelastic events:



Charged particles

Energy flux

Roman Pot acceptance for leading protons depends on optics.

Level-1 Trigger Schemes

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

Elastic Trigger:
$\sigma \approx 30$ mb

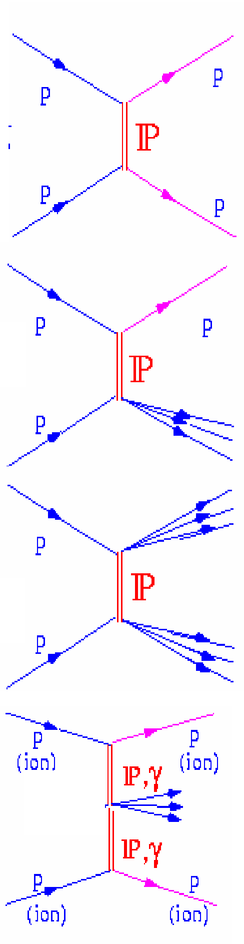
Single Diffractive Trigger:
$\sigma \approx 14$ mb
needs inelastic single-arm trigger
if optics with bad proton acceptance

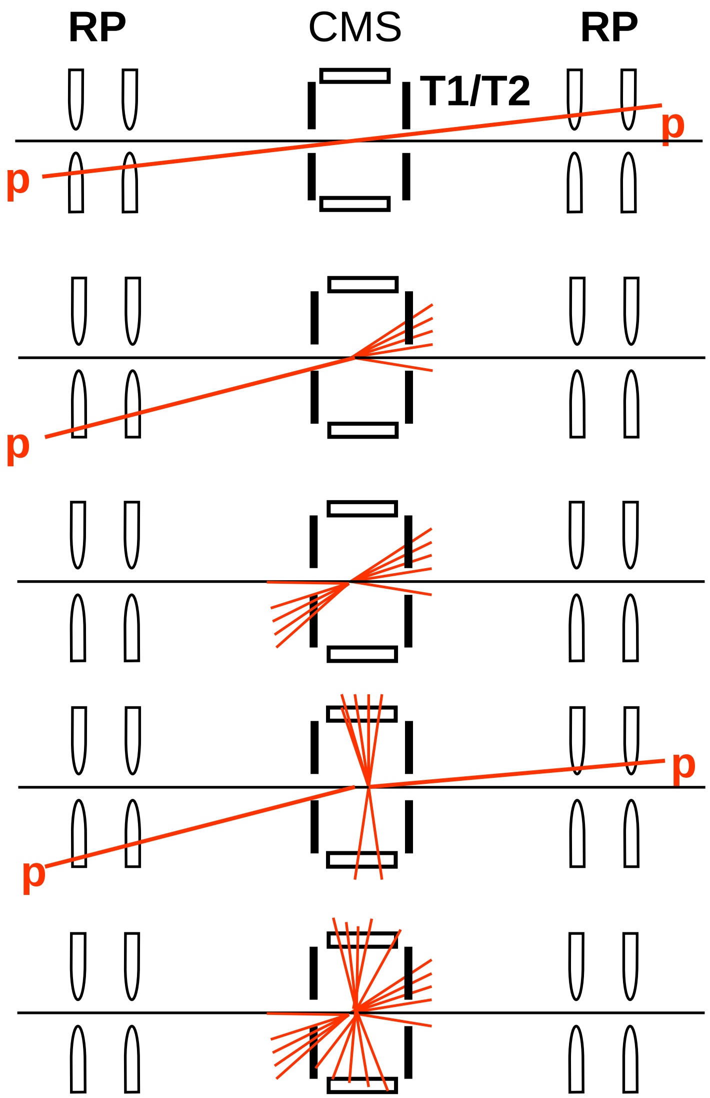
Double Diffractive Trigger:
$\sigma \approx 7$ mb

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

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

$\sigma_{tot} \approx 110$ mb





Measurement of the Total Rate $N_{el} + N_{inel}$

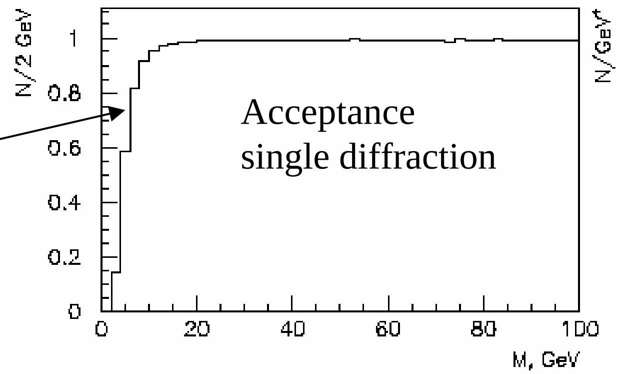
Trigger Losses

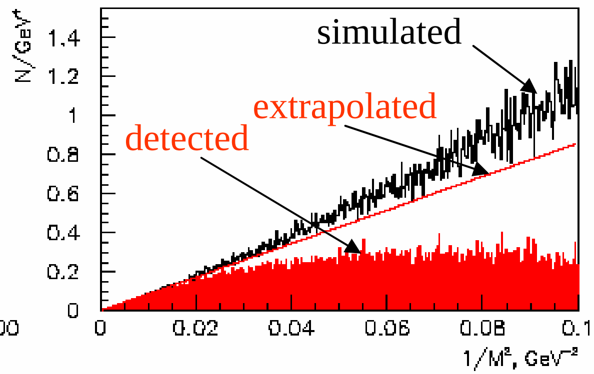
	σ [mb]	T1/T2 double arm trigger loss [mb]	T1/T2 single arm trigger loss [mb]	Systematic error after extrapolation [mb]	
Minimum bias	58	0.3	0.06	0.06	
Single diffractive	14	–	3	0.6	using p @ β* = 1540, 90 m
Double diffractive	7	2.8	0.3	0.1	
Double Pomeron	1	0.2		0.02	using p @ β* = 1540, 90 m
Elastic Scattering	30	–	–	0.2 (2)	@ β* = 1540 (90) m

Total: 0.8 mb ≈ 0.8 % @ β* = 1540 m
2 – 5 mb ≈ 2 – 5 % @ β* = 90 m

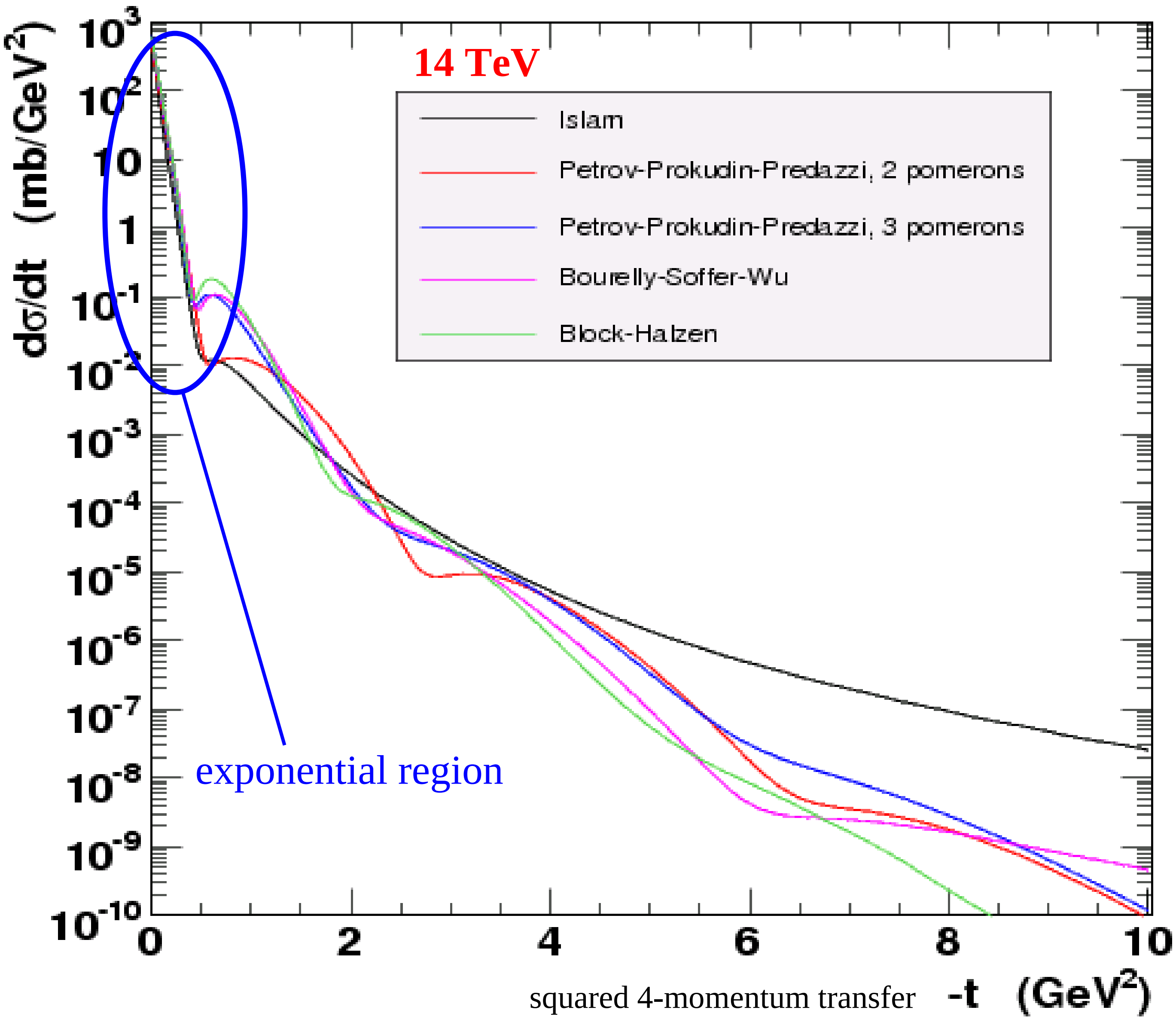
Extrapolation of diffractive cross-section to large $1/M^2$ using $d\sigma/dM^2 \sim 1/M^2$.

Loss at low diffractive masses M





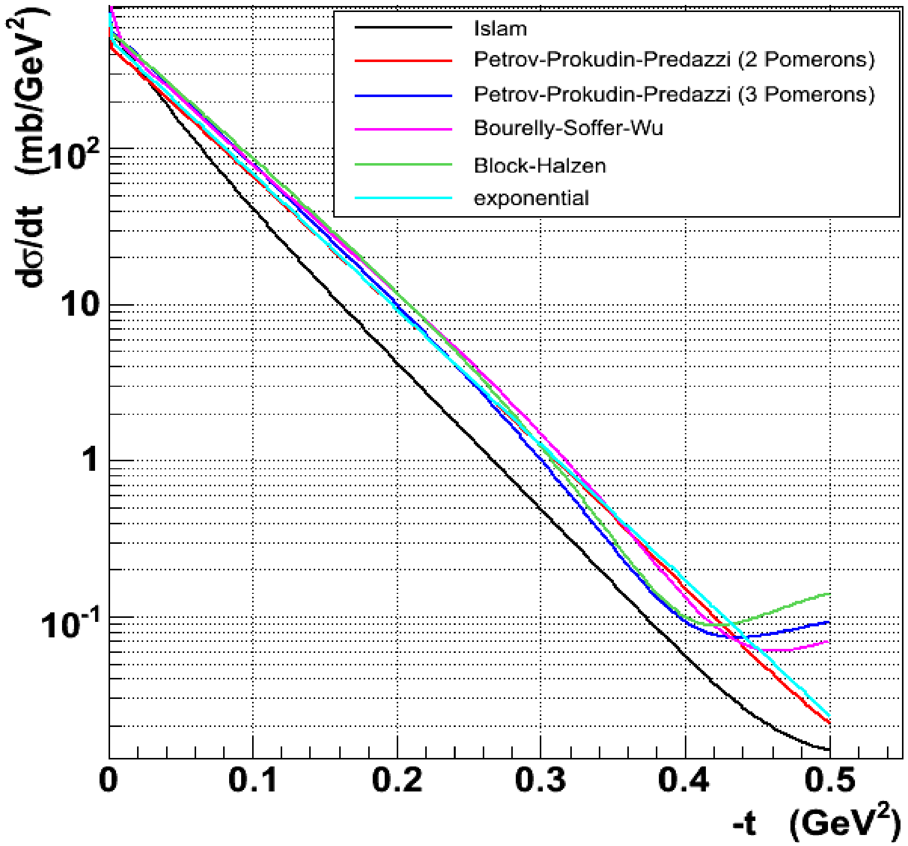
Elastic Scattering



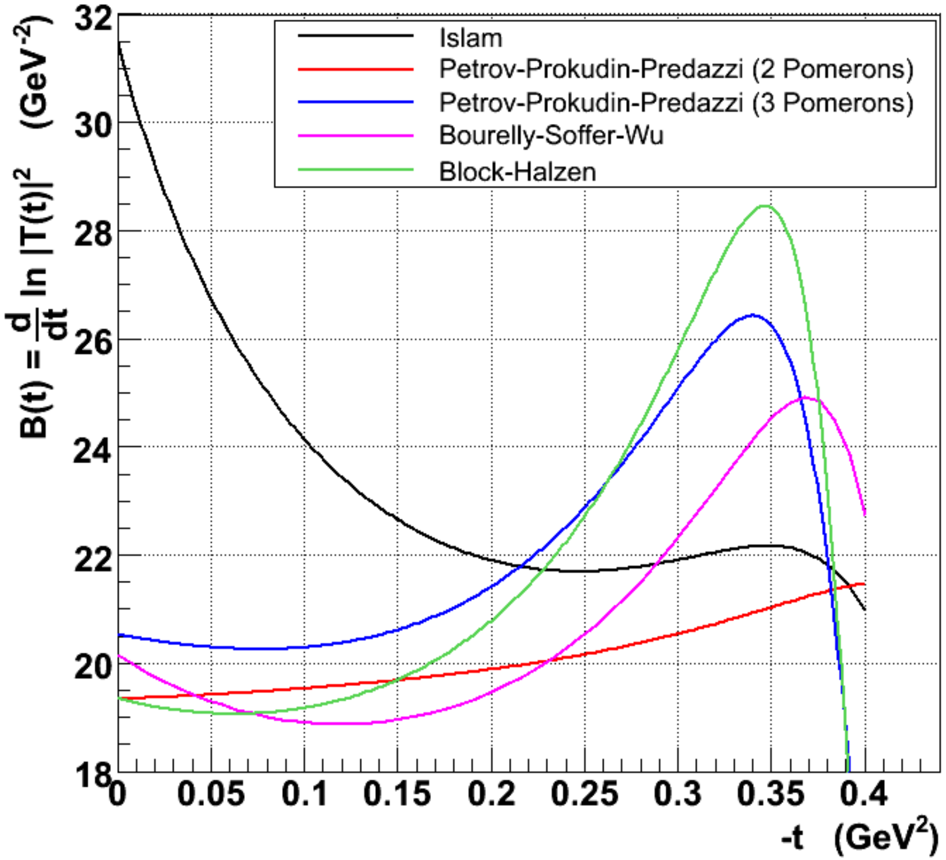
Elastic Scattering at low |t|

14 TeV:

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



Exponential Slope B(t)



$\beta^* = 1540$ m: $|t|_{min} = 0.001$ GeV^2

$\beta^* = 90$ m: $|t|_{min} = 0.03$ GeV^2

$\beta^* = 11$ m: $|t|_{min} = 0.4$ GeV^2

The Run at $\sqrt{s}$ = 900 GeV

[If CMS already closed and hence T1 + T2 in place]

Advantage: Cross-Sections known from S$\bar{p}$pS:

UA4: σ_{tot} = 67.5 ± 1.3 mb (1.9 %)

UA5: σ_{tot} = 65.3 ± 1.7 mb (2.6 %), σ_{inel} = 50.3 ± 1.1 mb (2.2 %)

➔ Measure inelastic and elastic rates and calculate

$$\mathcal{L} = \frac{N_{inel}}{\sigma_{inel}} \quad \text{or} \quad \mathcal{L} = \frac{N_{el} + N_{inel}}{\sigma_{tot}}$$

with 3 – 7 % precision.

What about measuring $\mathcal{L}$ and σ_{tot} with the Optical Theorem at 900 GeV ?

$|t|_{min} \propto \sqrt{s}$: β^* = 11 m, 14 TeV: $|t|_{min}$ = 0.4 GeV^2 $\rightarrow$ 900 GeV: $|t|_{min}$ = 0.03 GeV^2

But:

* β^* = 11 m optics not designed for precise proton measurement.
* Roman Pot detectors only installed when beams stable

Extrapolation of σ_{tot} to $\sqrt{s}$ = 14 TeV for β^* = 11 m

β^* = 11 m: Bad low-|t| acceptance for elastic scattering

⇒ Method based on Optical Theorem not applicable

Approximate luminosity determination using extrapolated σ_{tot} :

Conflicting Tevatron measurements at 1.8 TeV:

E710: σ_{tot} = 72.8 ± 3.1 mb

E811: σ_{tot} = 71.42 ± 2.41 mb

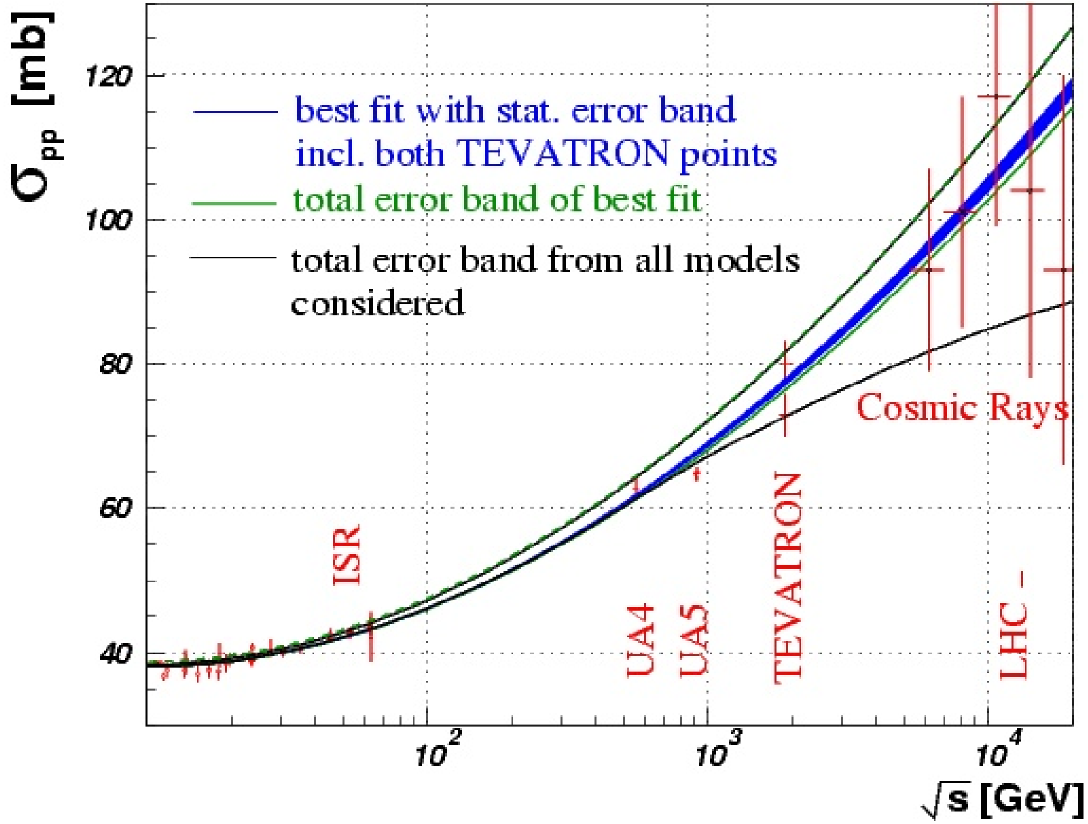
CDF: σ_{tot} = 80.03 ± 2.24 mb

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) $^{+10}_{-20}$ %.



Extrapolation of σ_{tot} to $\sqrt{s}$ = 14 TeV for β^* = 11 m

Use predicted σ_{tot} despite its big uncertainty and measure the rate:

- Problem: elastic rate very uncertain because of poor proton acceptance
  → measure only N_{inel} (diffractive triggers w/o protons → ~ 5 % error)

  and use $\sigma_{inel}/\sigma_{tot} \approx$ 0.70 ÷ 0.76 (4 % error) from extrapolation of data at lower energies:

$$\mathcal{L} = \frac{N_{inel}}{\sigma_{tot} \cdot \left(\frac{\sigma_{inel}}{\sigma_{tot}} \right)}$$

  Rather high uncertainty: ~ 15 ÷ 20 %

- Same problem with other low-β^* optics (2 m, 1 m, 0.55 m, …)

- **Solution:** perform first an absolute measurement of σ_{tot} at 14 TeV with an appropriate optics,

  e.g. $\boldsymbol{\beta^*}$ **= 90 m**

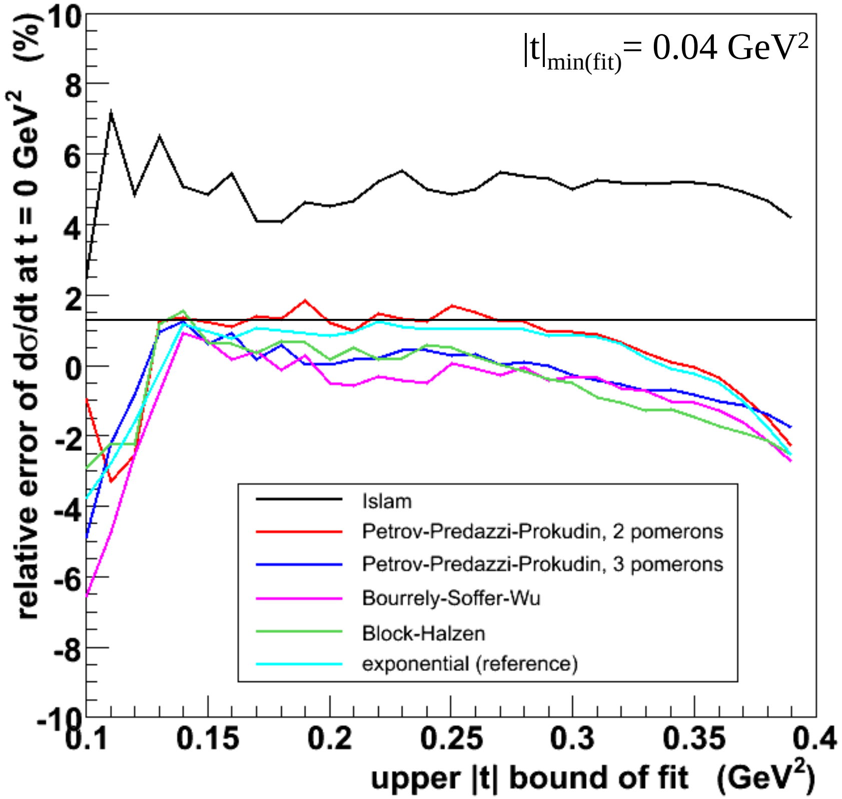
Proposal: Optics with $\beta^* = 90$ m

Measure $\mathcal{L}$ and σ_{tot} with Optical Theorem:

* |t|-acceptance down to 0.03 GeV^2 , covering well the exponential region of $d\sigma/dt$;
* beam rather thick (σ_y = 0.6 mm): $\delta t/t \propto \delta y/\sigma_b \Rightarrow$ RP position systematics less critical

Typical luminosity L ~ $10^{29} - 10^{30}$ cm^{-2} s^{-1}

Systematic error of extrapolation of the elastic cross-section to t = 0:



Fitting function: $\frac{d\sigma}{dt} = A e^{B(t)\,t}$

with $B(t)$ = polynomial$_2$(t)

Uncertainty < 10 % (most cases < 2 %)

(not as good as with $\beta^* = 1540$ m, but optics easier to commission $\rightarrow$ ideal for an early run)

With known $\mathcal{L}$ determine absolute cross-sections of various processes.

$\rightarrow$ absolute calibration of luminosity monitors

Proposal to the LHCC in preparation: early runs with 90m optics.

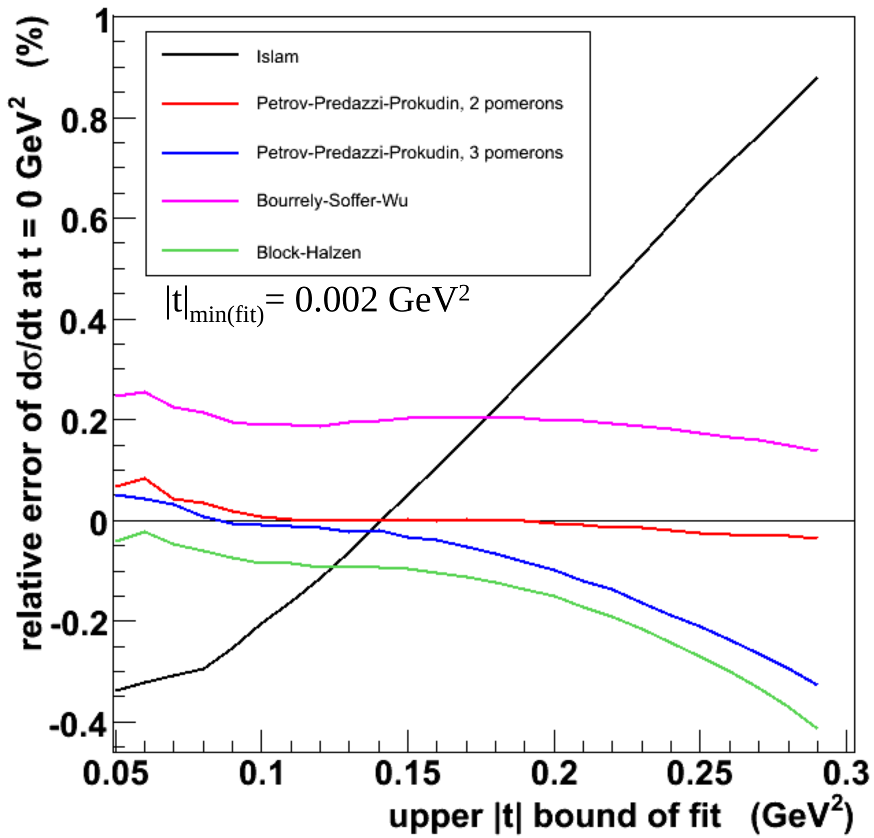
TOTEM's Baseline Optics: $\beta^* = 1540$ m

Ultimate goal: measurement of $\mathcal{L}$ and σ_{tot} with Optical Theorem at the 1 % level.

|t|-acceptance down to 0.001 GeV^2 $\rightarrow$ good lever arm for choosing a suitable fitting function for the extrapolation to t = 0.

Typical luminosity L ~ 10^{28} cm^{-2} s^{-1}

Model-dependent systematic error of extrapolation of the elastic cross-section to t = 0:



$\Rightarrow$ Uncertainty < 1 % (most cases < 0.2 %)

$\oplus$ experimental systematics: 0.5 – 1 %

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):

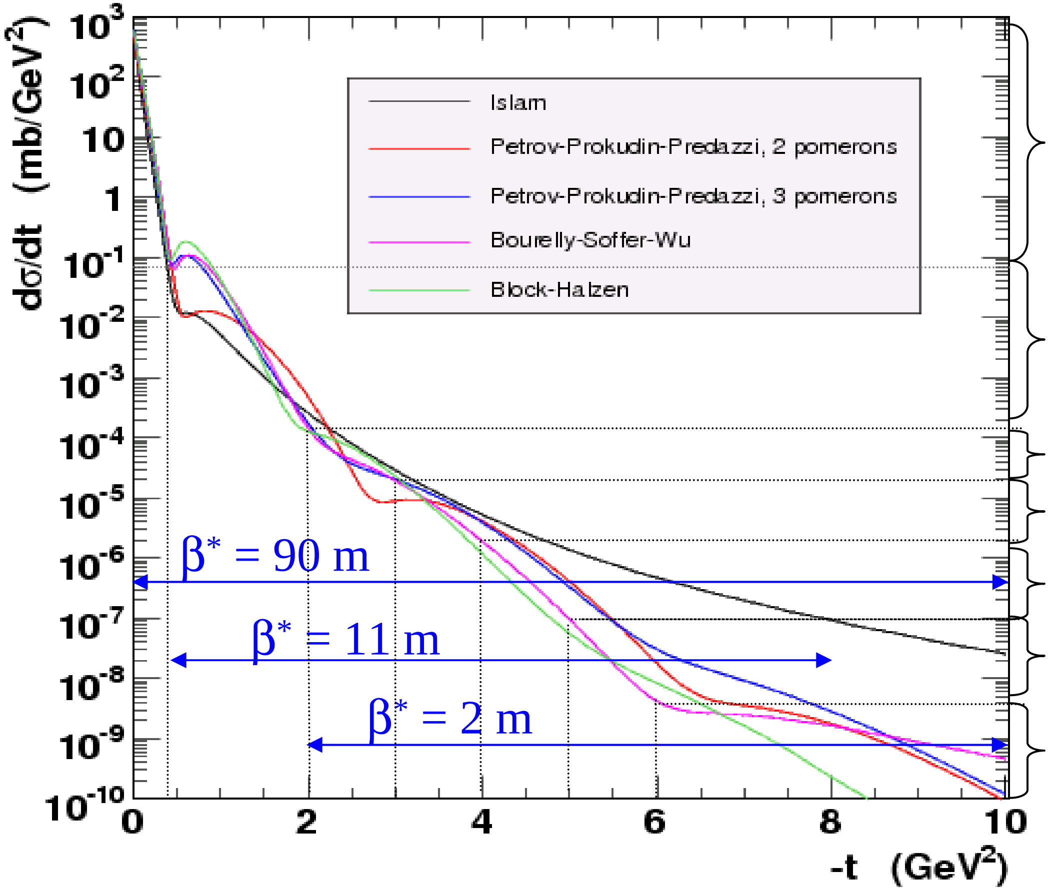
$$\mathcal{L} = -\frac{1}{\sigma_{tot} A_{T2lxT2r} \Delta t} \ln P(n=0)$$

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).

Relative Luminosity Measurement with Large-|t| Elastic Scattering

Accepted Events (BSW model) at 220m in 10^5 s



β^*=90m $\mathcal{L}=3\times10^{30}$	β^*=2m $\mathcal{L}=10^{32}$
2×10^9	0
1.5×10^6	1×10^6
4000	1.2×10^5
500	4×10^4
30	3000
1	160
0.3	50

$\beta^* = 90$ m $\rightarrow$ $\beta^* = 11$ m: 2.4×10^6 ev @ $\mathcal{L} = 3 \times 10^{30}$ $\rightarrow$ 8×10^7 ev @ $\mathcal{L} = 10^{32}$

$\beta^* = 90$ m $\rightarrow$ $\beta^* = 2$ m: 4500 ev @ $\mathcal{L} = 3 \times 10^{30}$ $\rightarrow$ 1.6×10^5 ev @ $\mathcal{L} = 10^{32}$

} in acceptance overlap per 10^5 s

$d\sigma/dt \propto |t|^{-8}$: steep region: beam shifts cause rate errors at the t-acceptance thresholds

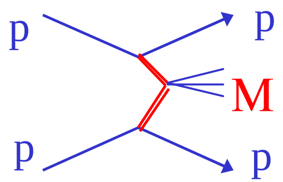
Luminosity Monitoring

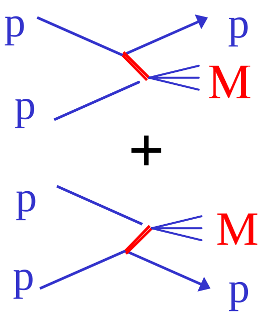
Monitor luminosity variations during machine operation using simple and fast trigger combinations (use scaler, without writing all on tape)

All TOTEM detectors have trigger capability.

Example: 2-arm Roman-Pot coincidence rate at $\beta^* = 2$ m :
(independent of CMS/T1/T2 detector configuration)

Contributions from Double Pomeron exchange and Single Diffraction pileup





Coincidence rate $R = \mathcal{L}\,\sigma_{DPE} + \mathcal{L}^2\,\sigma_{SD}^2\,\Delta t_{bunch}$ + background

$\beta^* = 2$ m: within acceptance: $\sigma_{DPE} \sim 35\ \mu b$, $\sigma_{SD} \sim 1.6$ mb

$\mathcal{L} = 10^{33}\ cm^{-2}\ s^{-1}$: R = 35 kHz (DPE) + 65 kHz (SD) = 100 kHz

Calibration of σ_{DPE} and σ_{SD} at $\beta^* = 90$ m: linear and quadratic terms can be separated.

- integrate over 1 s : 10^5 events
- monitor each of the 2808 bunches (integrated over 1 min): 2140 ev./bunch

Background still needs to be separated.

More work required.

Summary

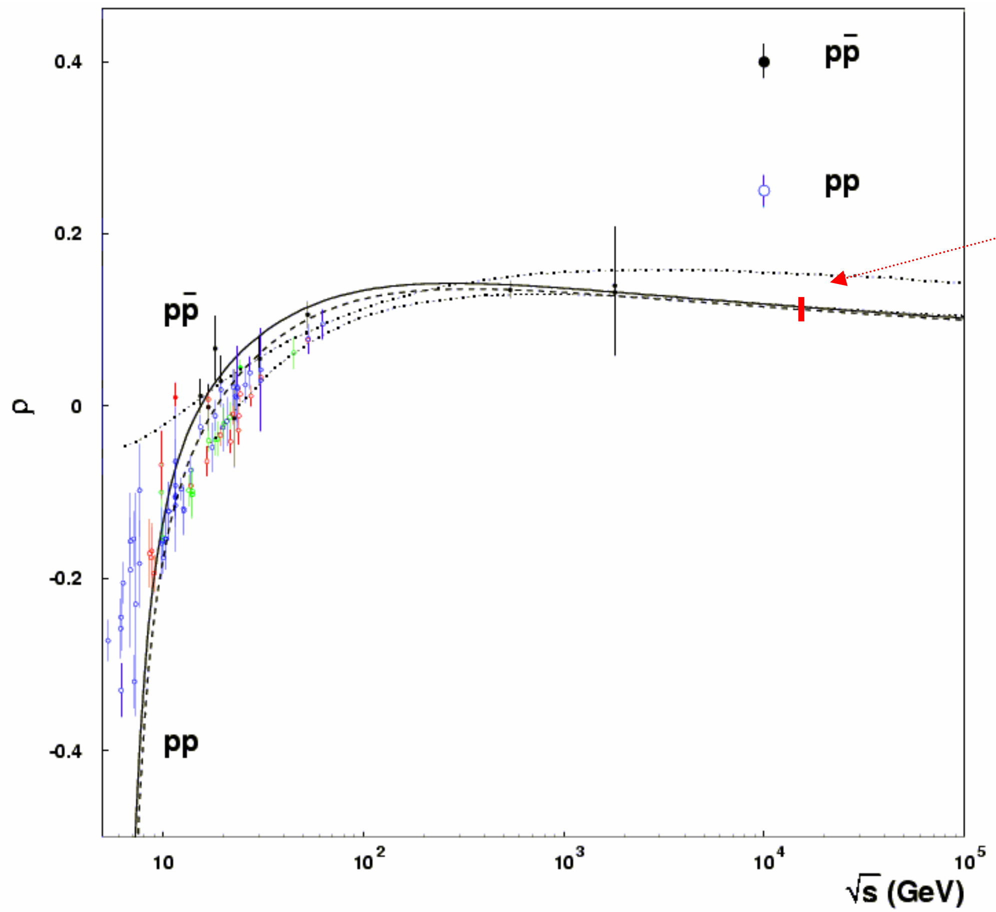
1. At 900 GeV:
   Use known cross-sections from S$\bar{p}$pS and calculate luminosity from measured rate.
   Better than 10 %.

2. At 14 TeV:
   β^* = 90 m: absolute luminosity measurement with Optical Theorem to ~ 5 %
   β^* = 1540 m: absolute luminosity measurement with Optical Theorem to ~ 1 %
   β^* = 11 m, 2 m, 0.5 m: relative luminosity measurements after absolute calibrations of cross-sections with β^* = 90 or 1540 m

3. Continuous luminosity monitoring using simple trigger combinations in a scaler

TOTEM

Elastic Scattering: $\rho = \Re f(0) / \Im f(0)$



Prediction for LHC:

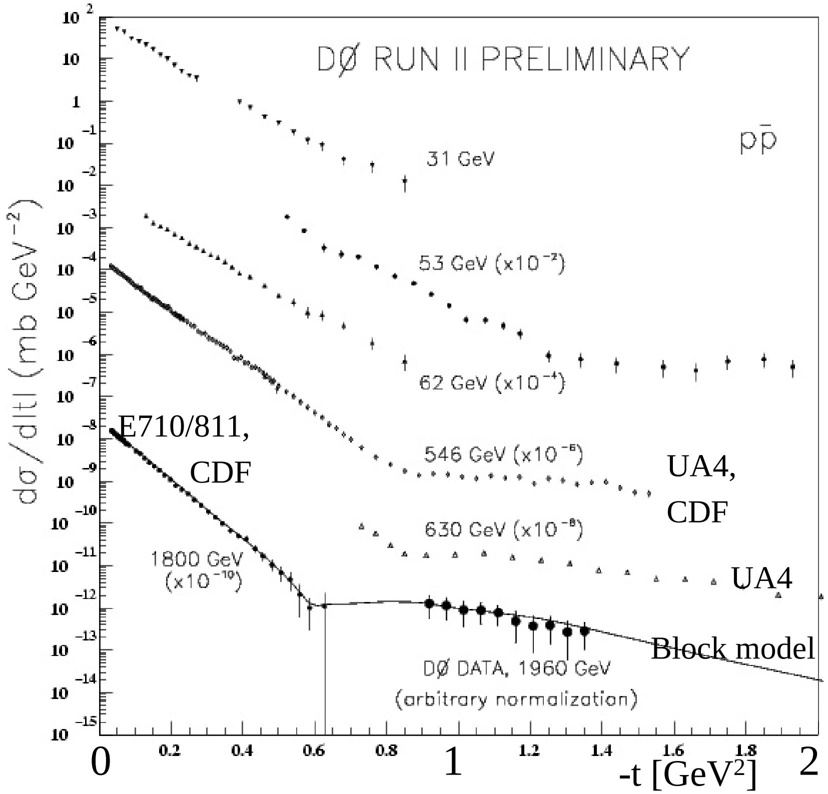
$$\rho = 0.1361 \pm 0.0015 \,{}^{+0.0058}_{-0.0025}$$

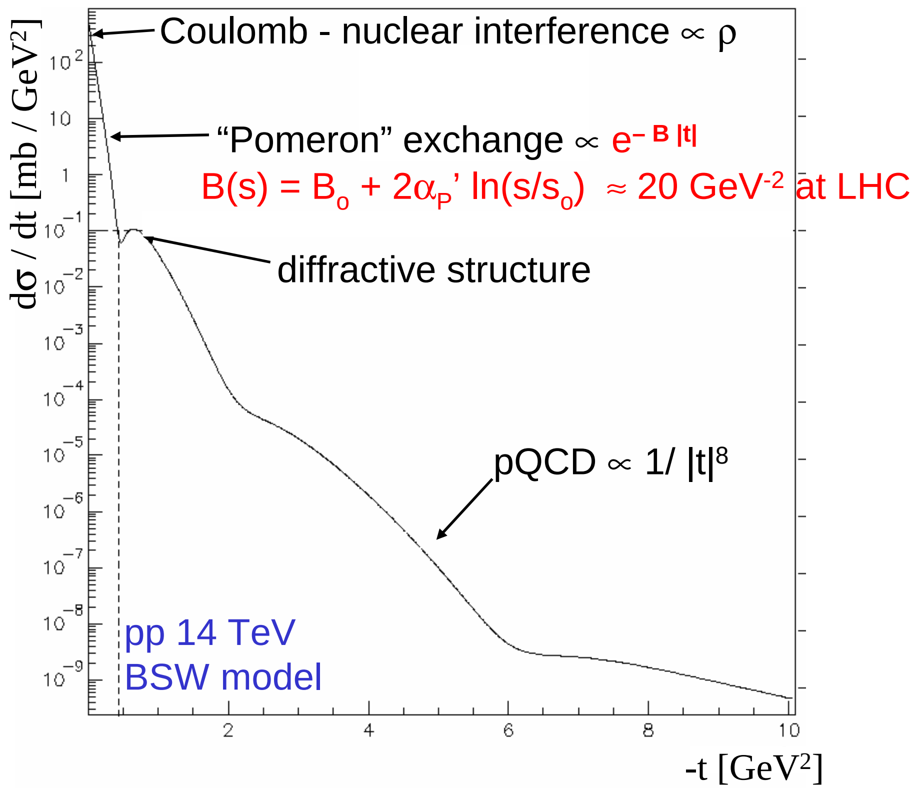
asymptotic behaviour:
$\propto 1 / \ln s$ for $s \to \infty$

ρ is interesting for σ_{tot}:

prediction of σ_{tot} at higher s via dispersion relation: $\rho(s) = \frac{\pi}{2\sigma_{tot}(s)} \frac{d\sigma_{tot}}{d \ln s}$

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}

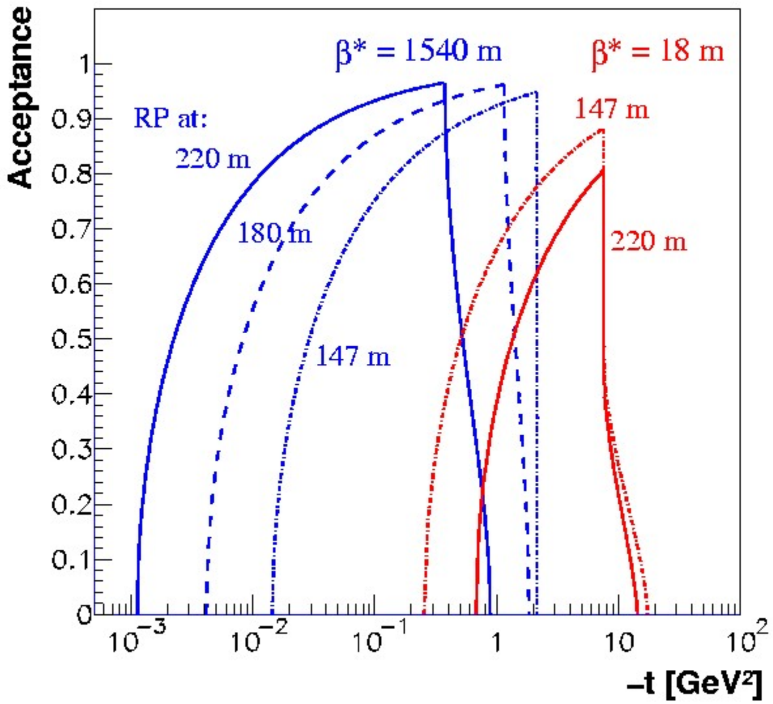
E710: $0.034 < |t| < 0.65$ GeV^2 : $B = 16.3 \pm 0.3$ GeV^{-2}

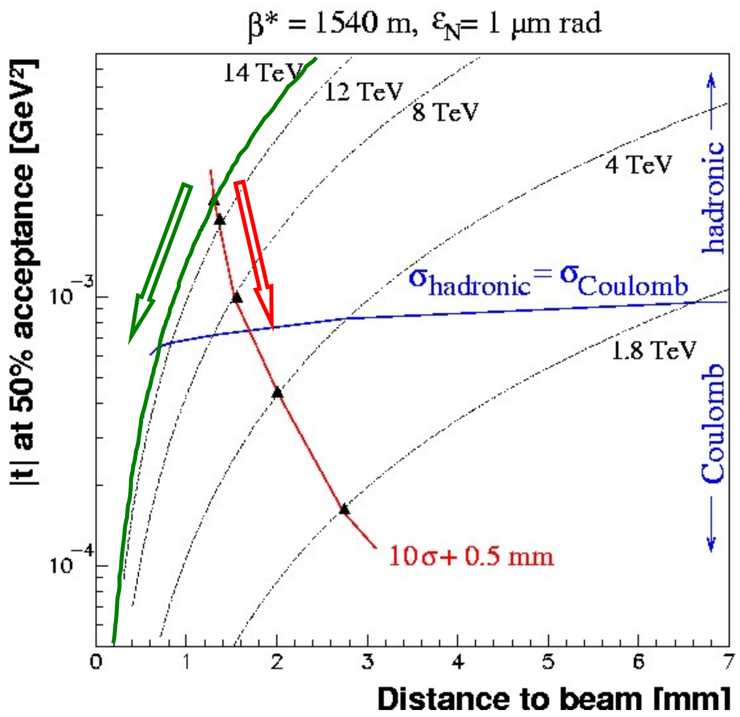
$0.001 < |t| < 0.14$ GeV^2 : $B = 16.99 \pm 0.25$ GeV^{-2} , $\rho = 0.140 \pm 0.069$

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

Elastic Scattering at TOTEM: t-Acceptance



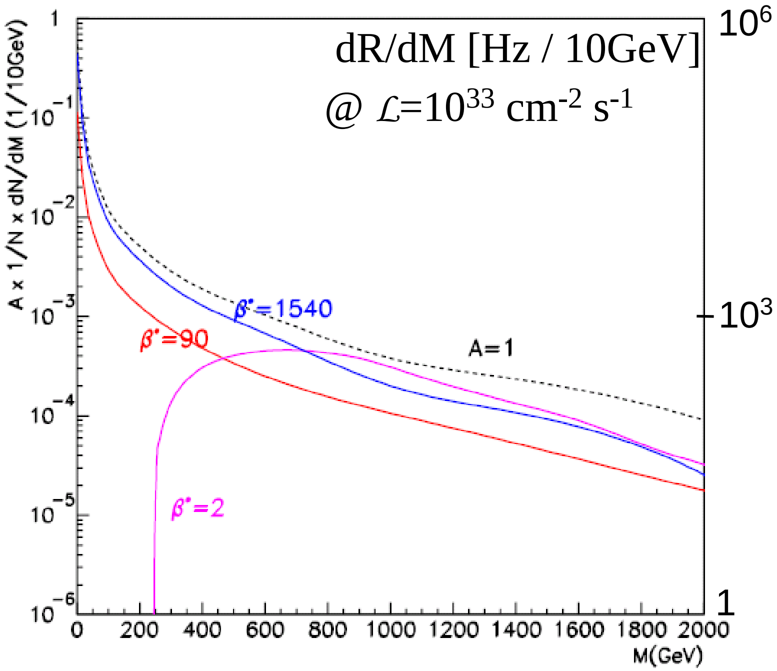


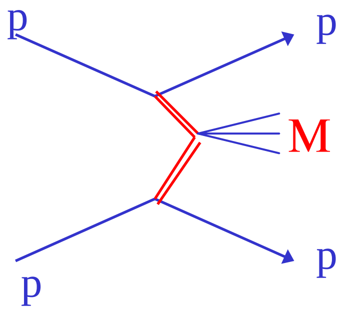
Try to reach the interference region:

- move the detectors closer to the beam than 10 σ + 0.5 mm
- run at lower energy $\sqrt{s} = 2p < 14$ TeV: $|t|_{min} = p^2\,\theta^2$

Luminosity Monitoring

Example: Double Pomeron Exchange (DPE) at $\beta^* = 2$ m:





Integrated cross-section within acceptance: ~ 35 μb

$\mathcal{L}=10^{33}$ cm^{-2} s^{-1}: rate ≈ 35 kHz

Cross-section $d\sigma/dM \propto 1/M$: not very steep

$\Rightarrow$ less edge effects from beam shifts than in the elastic $d\sigma/dt$