12th International Conference on Elastic and Diffractive Scattering,
Forward Physics and QCD

Total Cross-Section Measurement and Diffractive Physics with TOTEM

Mario Deile

on behalf of the

TOTEM Collaboration

21.05.2007

TOTEM standalone programme:

- Total cross-section measurement
- Study of elastic scattering
- Soft diffraction

Here: focus on early running with the $\beta^* = 90$ m optics

Total p-p Cross-Section

Conflicting Tevatron measurements at 1.8 TeV:

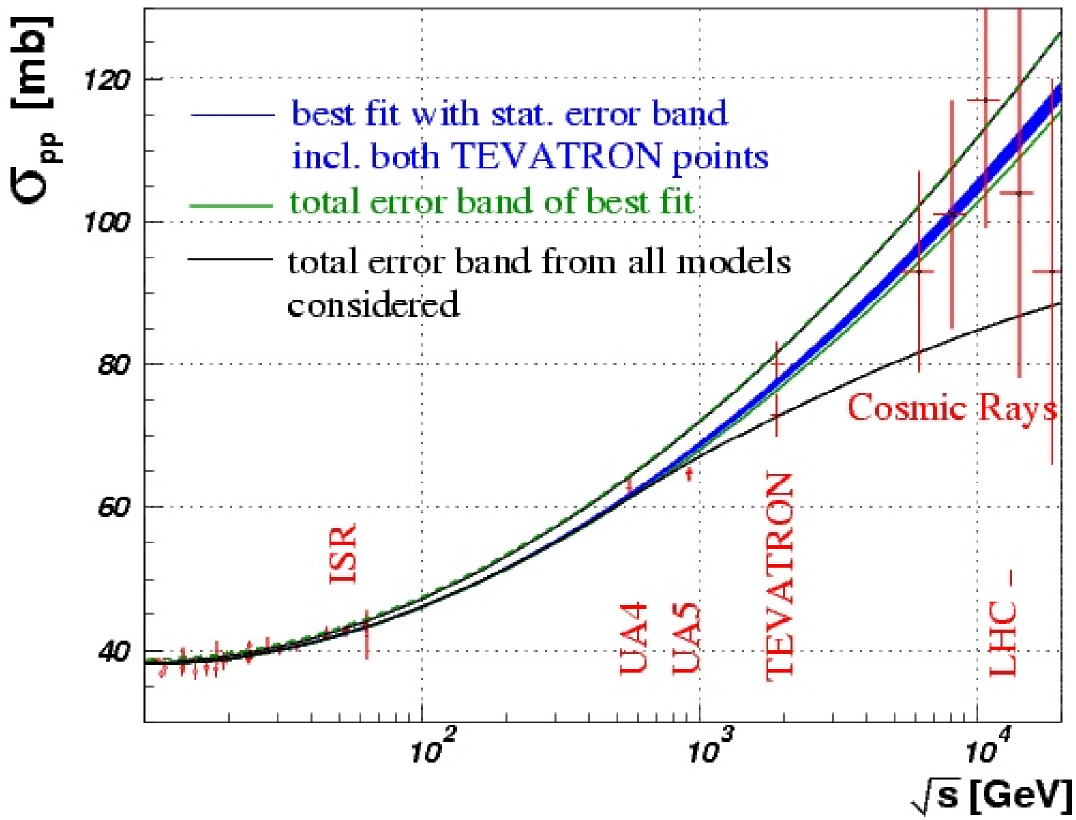
E710: $\sigma_{tot} = 72.8 \pm 3.1$ mb

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

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

Disagreement E811–CDF: 2.6 σ

COMPETE fits: [PRL 89 201801 (2002)]



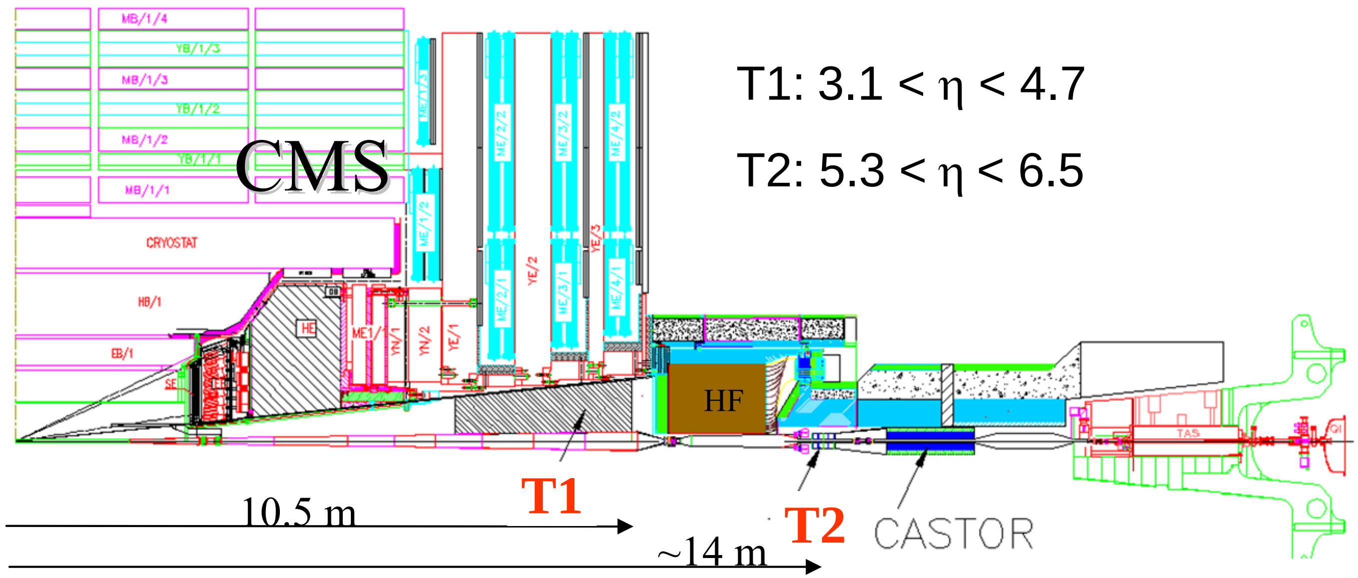
- Current predictions for LHC: 90 – 130 mb

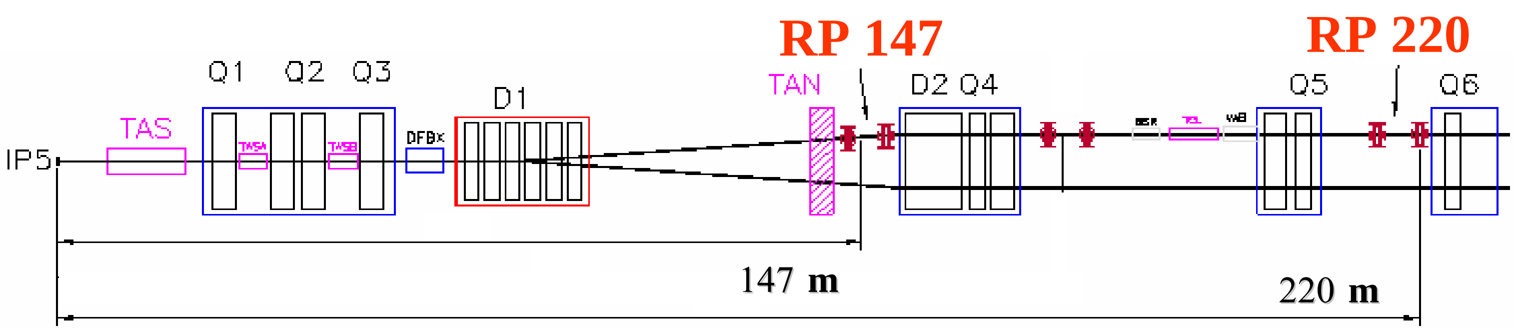
  Preferred COMPETE fit using both Tevatron points: $\sigma_{tot} = 111.5 \pm 1.2 \,{}^{+4.1}_{-2.1}$ mb
- Final aim of TOTEM: **~ 1%** accuracy
- First year: **~ 5%** accuracy

TOTEM Detector Configuration

T1: 3.1 < η < 4.7

T2: 5.3 < η < 6.5





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

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

$$\Rightarrow$$

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

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

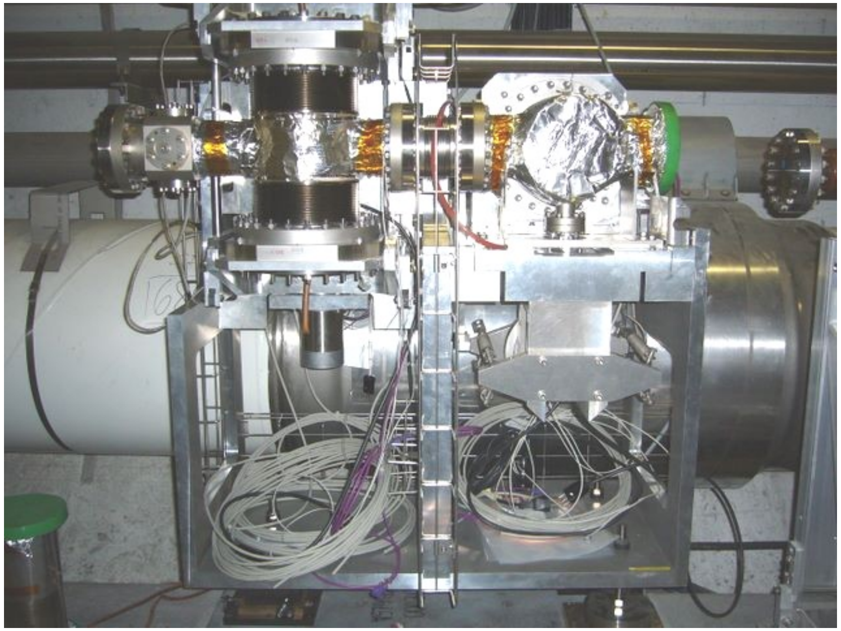
N_{el}, dN_{el}/dt : elastic rate

N_{inel} : inelastic rate

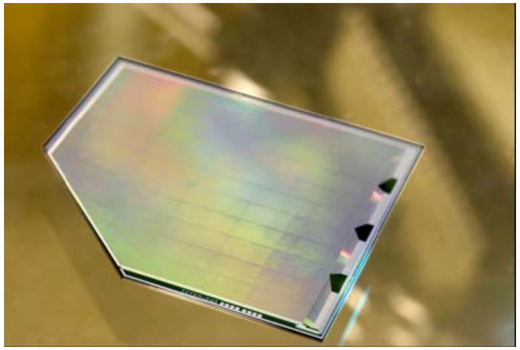
$\rho = \Re\, f(0) / \Im\, f(0)$:
external input (small effect)

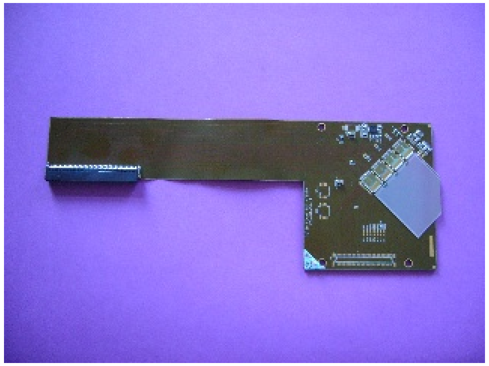
TOTEM Detectors: Roman Pots

Last week: first 220m RP station installed in the LHC; opposite station will follow next week.



“Edgeless” silicon strip detectors in production; tests in progress.

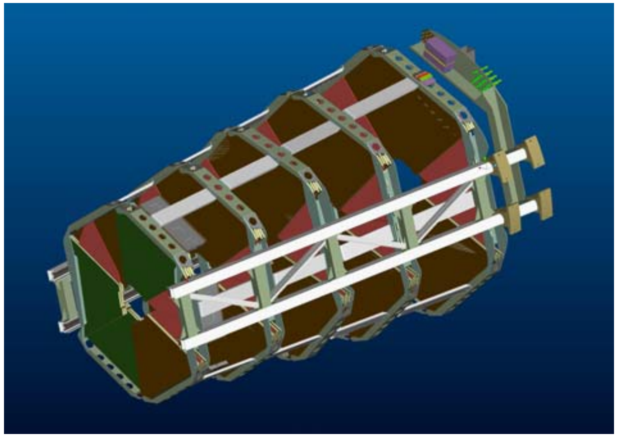




Hybrid board with detector and VFAT front-end chips.

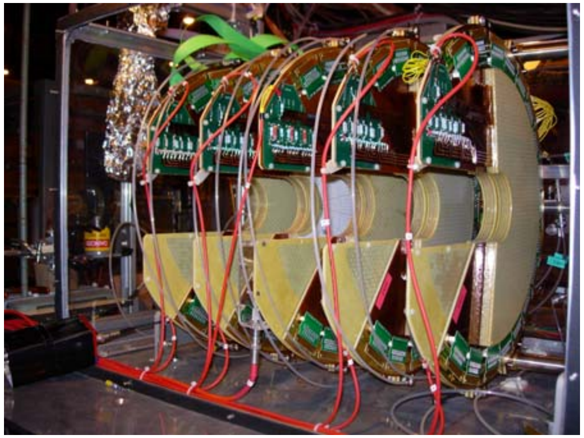
TOTEM Detectors: T1 and T2

T1 Telescope



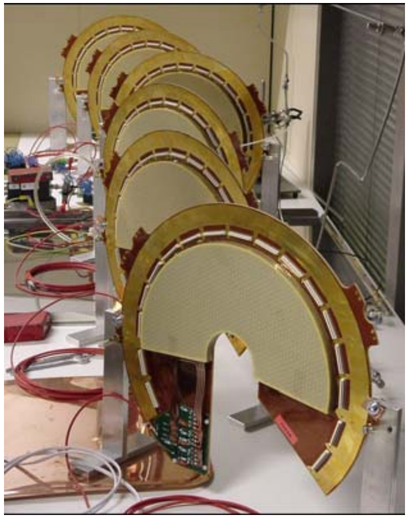
Mechanical frames and
CSC detectors in production;
tests in progress.
Installation depends on CMS.

T2 Telescope



testbeam setup

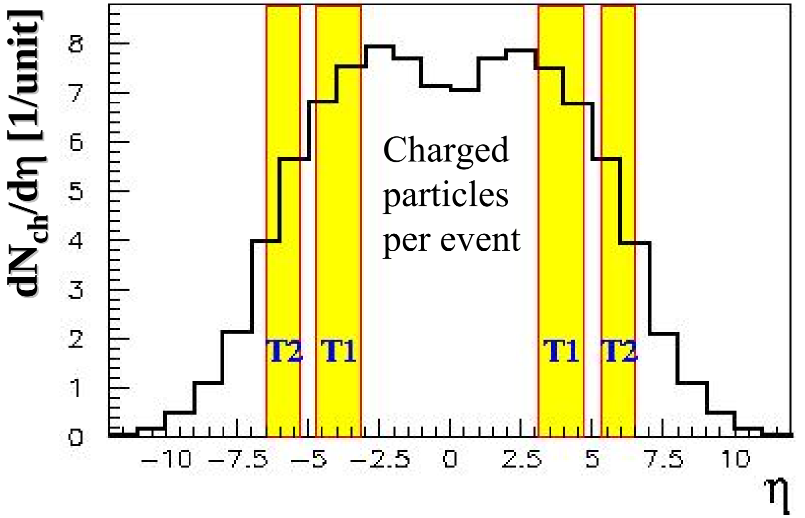
75 % of GEM chambers produced and tested up to a gain of 8 x 10^4.



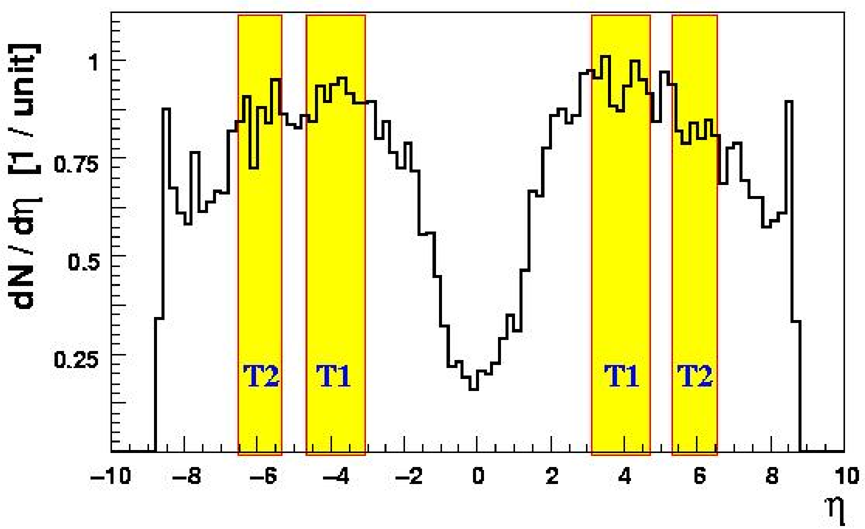
TOTEM: Acceptance

Inelastic Acceptance in η:

non-diffractive minimum bias events:

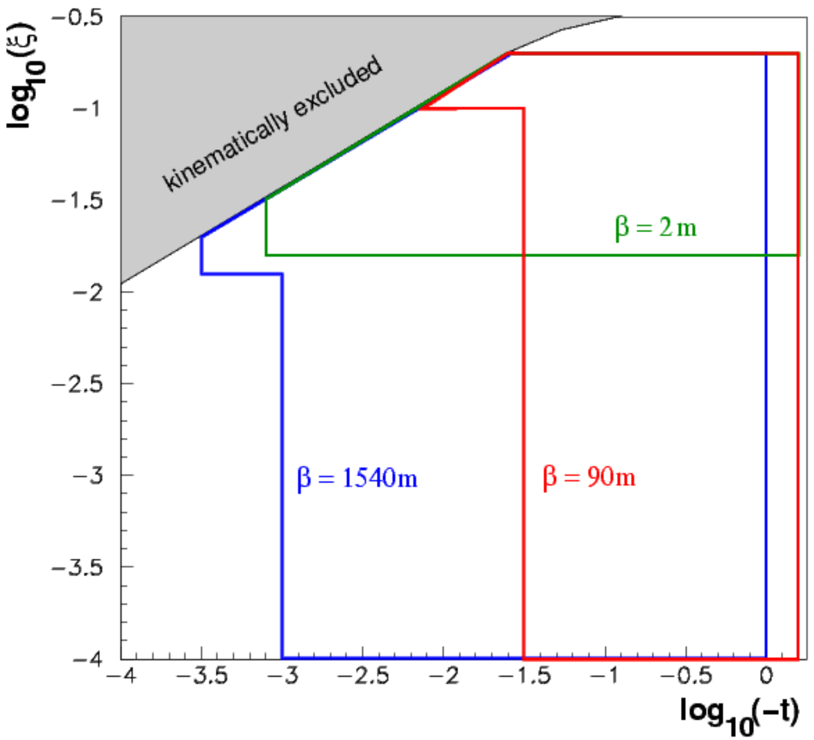


single-diffractive events:



Proton Acceptance in (t, ξ): (ξ = Δp/p)

(contour lines at A = 10 %)



All TOTEM detectors have trigger capability.

Optics and Beam Parameters

Parameters	β^* = 2 m (standard step in LHC start-up)	β^* = 90 m (early TOTEM optics)	β^* = 1540 m (final TOTEM optics)
Crossing angle	0.0	0.0	0.0
N of bunches	156	156	43
N of part./bunch	$(4 – 9) \times 10^{10}$	$(4 – 9) \times 10^{10}$	3×10^{10}
Emittance ε_n [μm · rad]	3.75	3.75	1
10 σ_y beam width at RP220 [mm]	~ 3	6.25	0.8
Luminosity [$cm^{-2} s^{-1}$]	$(2 – 11) \times 10^{31}$	$(5 – 25) \times 10^{29}$	1.6×10^{28}

β^* = 90 m ideal for early running:

- fits well into the LHC start-up running scenario;
- uses standard injection (β^* = 11m) → easier to commission than 1540 m optics
- wide beam → ideal for training the RP operation (less sensitive to alignment)

β^* = 90 m optics proposal submitted to the LHCC and well received.

The $\beta^* = 90$ m Optics

Concept: Optics optimised for both elastic and diffractive scattering.

Proton coordinates w.r.t. beam in the RP at 220 m:

(x^*, y^*): vertex position
(θ_x^*, θ_y^*): emission angle
$\xi = \Delta p/p$

$$\boxed{y = L_y \theta_y^* + \cancel{v_y y^*}}$$

$L_y = 265$m (large) $v_y = 0$

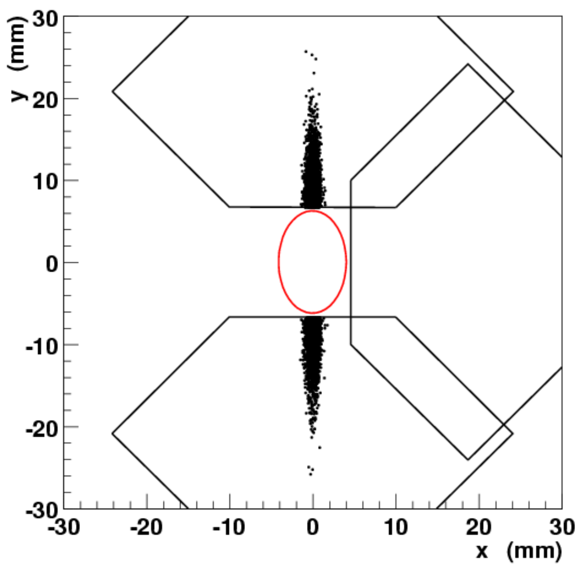
vertical parallel-to-point focussing
→ optimum sensitivity to θ_y^*
and hence to t (azimuth. symmetry)

$$\boxed{x = \cancel{L_x \theta_x^*} + v_x x^* + D\xi}$$

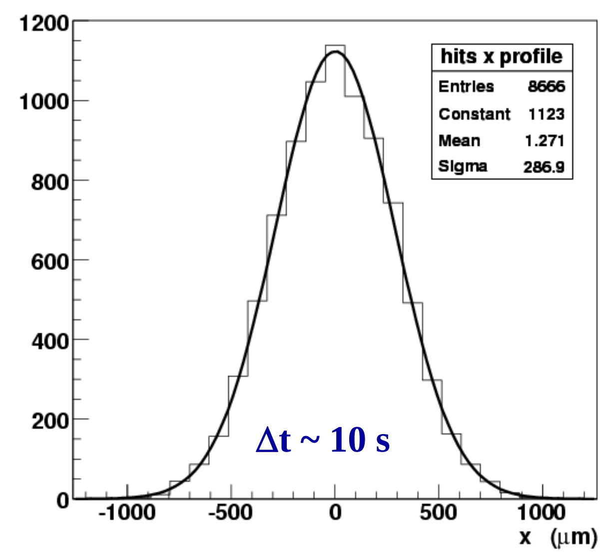
$L_x = 0$ $v_x = -2$ $D = 23$mm

elimination of θ_x^* dependence
→ enhanced sensitivity to ξ in diffractive events,
→ horizontal vertex measurement in elastic events.

RP (220m) hit distribution (elastic)



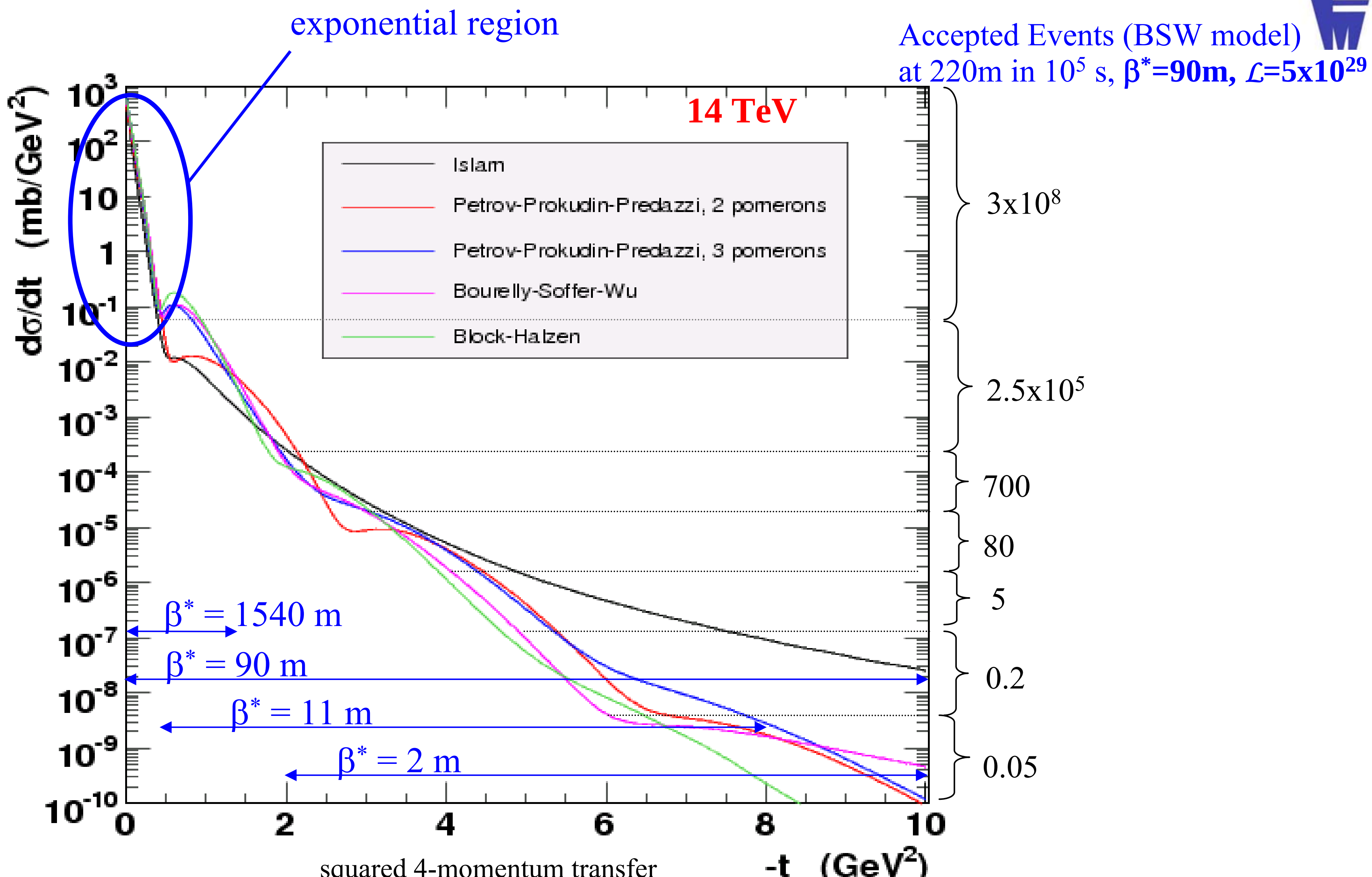
x-projection



→ horiz. vertex distribution (shape, width)
→ assuming round beams: luminosity from beam parameters

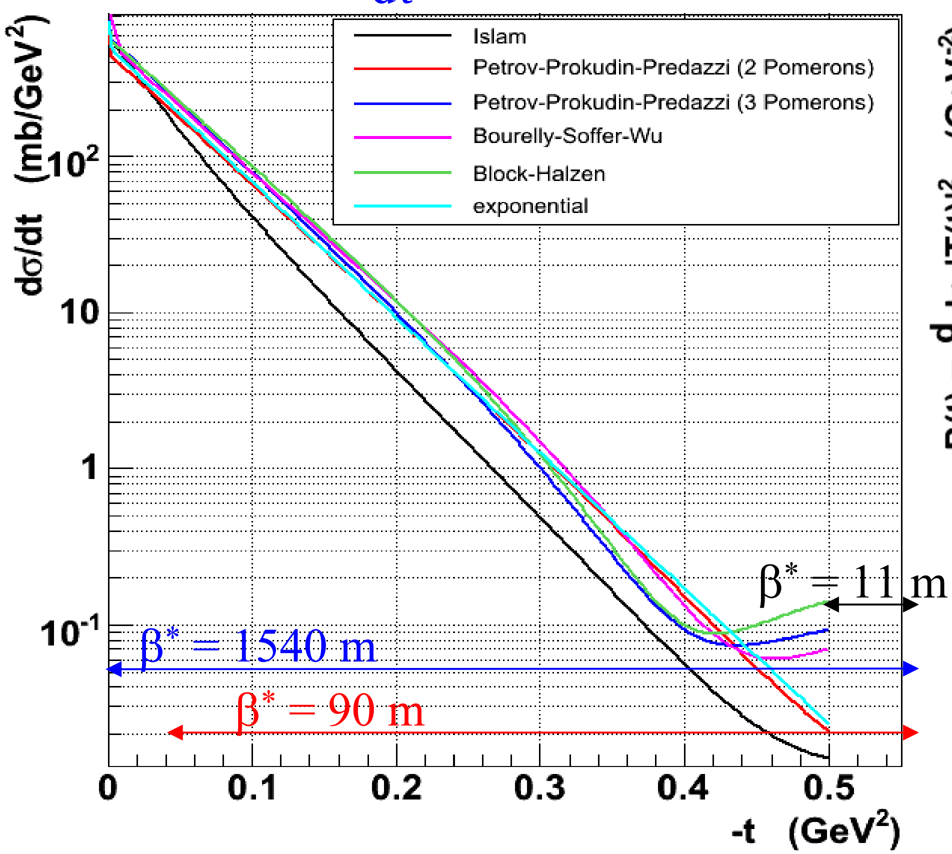
→ directly: beam position measurement to ~ 1μm every minute

Elastic Scattering

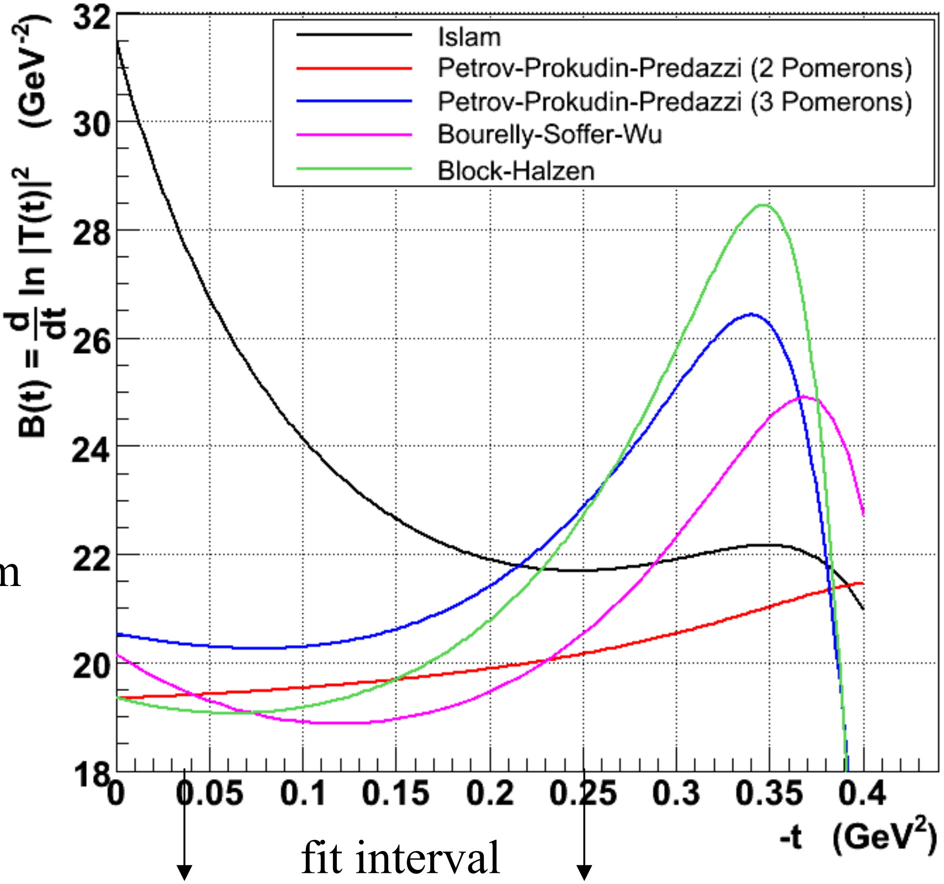


Elastic Scattering at low |t|

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



Exponential Slope B(t)



$\beta^* = 1540$ m: $|t|_{min} = 0.002$ GeV^2

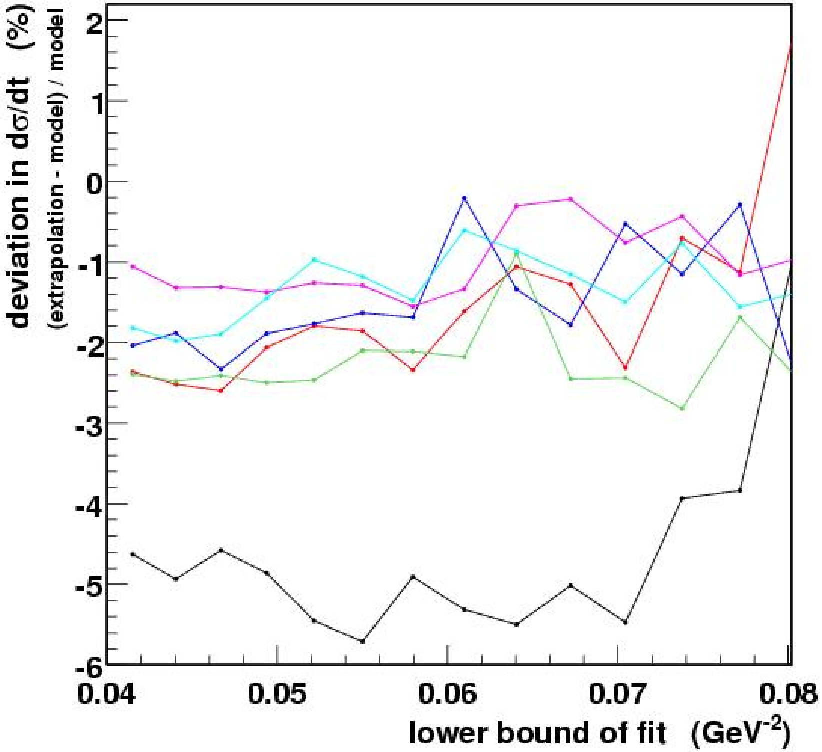
$\beta^* = 90$ m: $|t|_{min} = 0.04$ GeV^2

best parameterisation:

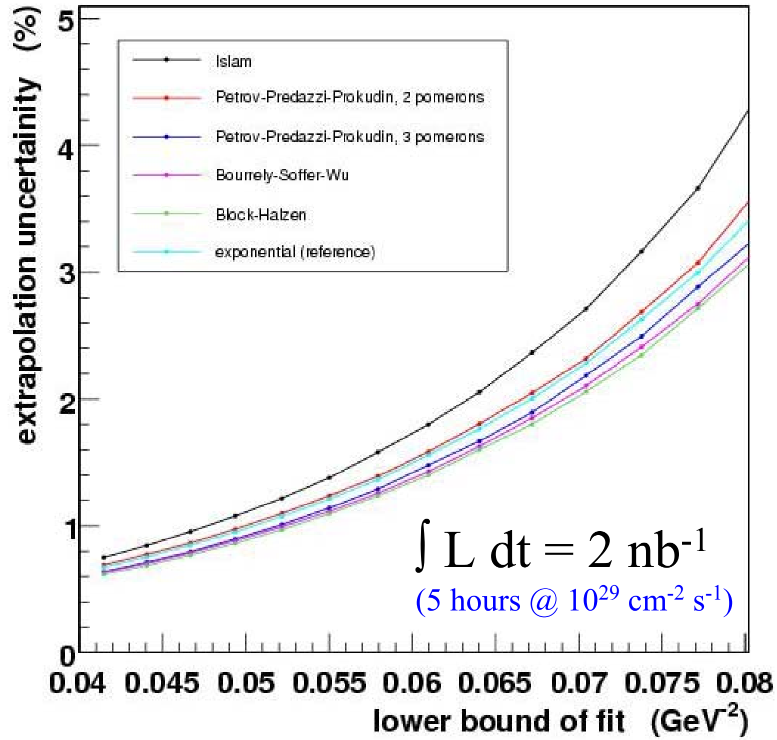
$B(t) = B_0 + B_1\, t + B_2\, t^2$

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

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



Statistical extrapolation uncertainty



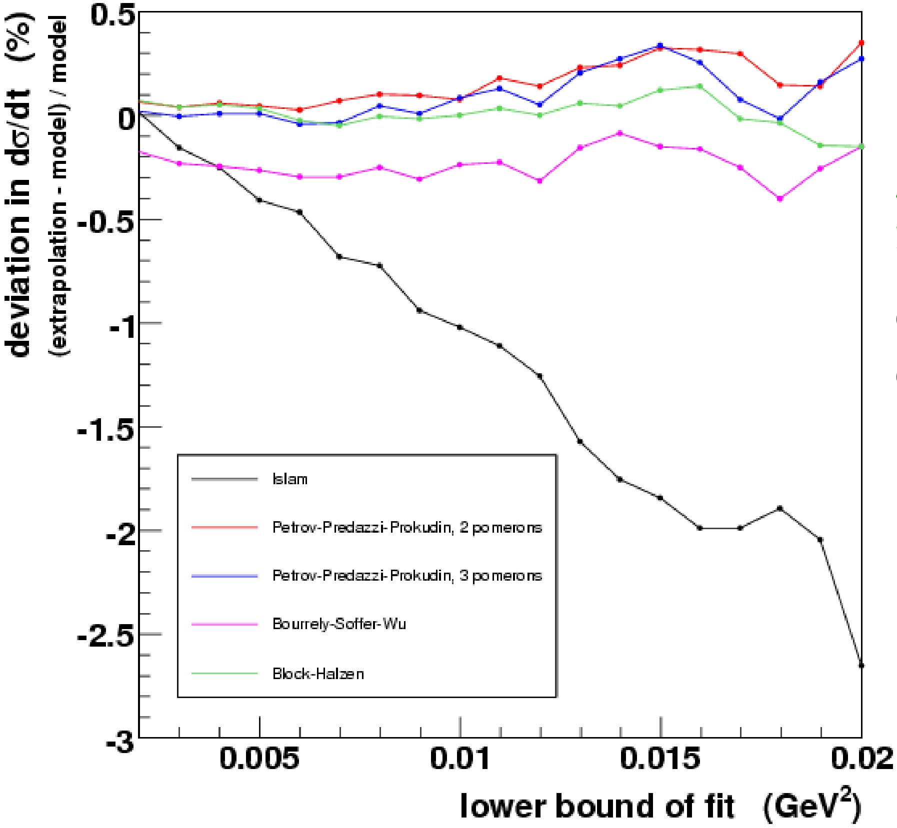
Common bias due to beam divergence : – 2 % (angular spread flattens dN/dt distribution)

Spread between most of the models: ±1%

Systematic error due to uncertainty of optical functions: ± 3%

Different parameterisations for extrapolation tested (e.g. const. B, linear continuation of B(t)): negligible impact

Extrapolation with the Final Optics ($\beta^* = 1540$ m)



|t|-acceptance down to 0.0012 GeV^2 $\rightarrow$

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 $\beta(t)$ is a function of $f_C(t)$ and $f_H(t)$.

For most models: extrapolation within ± 0.2 %.

Islam model needs different treatment; to be distinguished in the visible t-range.

Level-1 Trigger Schemes

Whenever possible, use 2-arm coincidence to suppress background.

Elastic Trigger:
$\sigma \approx 30$ mb

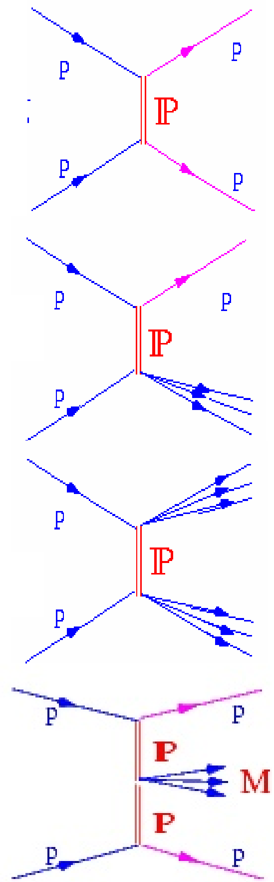
Single Diffractive Trigger:
$\sigma \approx 14$ mb

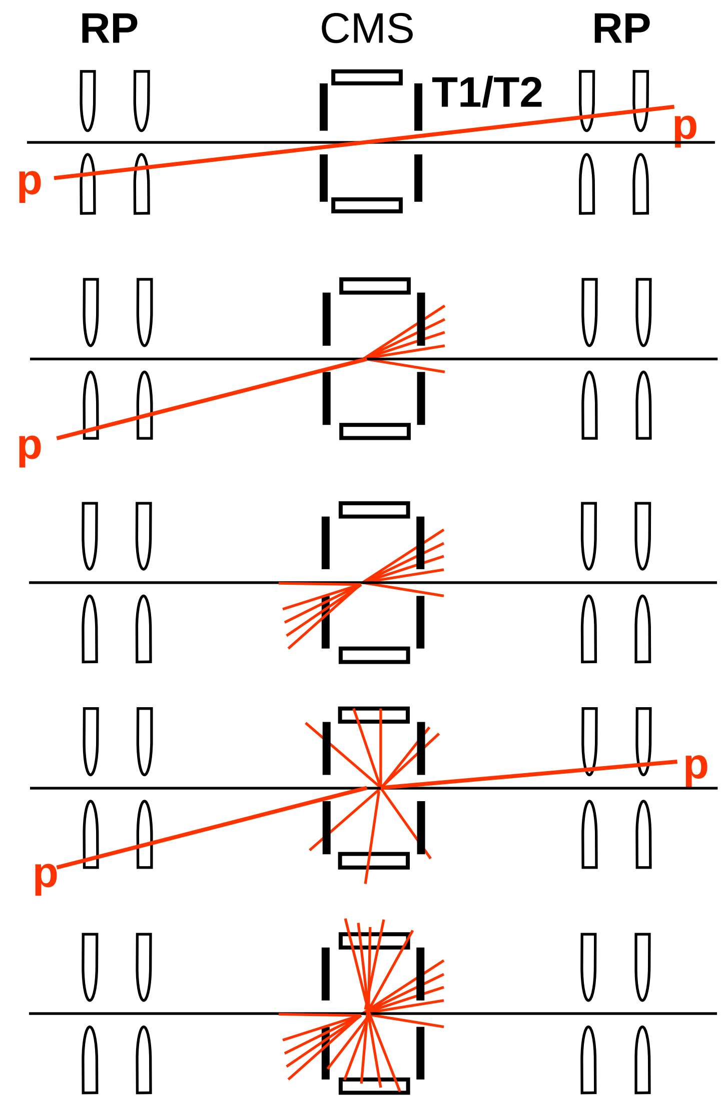
Double Diffractive Trigger:
$\sigma \approx 7$ mb

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

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

$\sigma_{tot} \approx 110$ mb

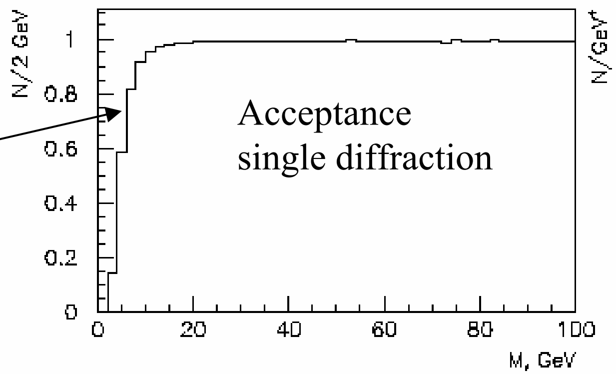


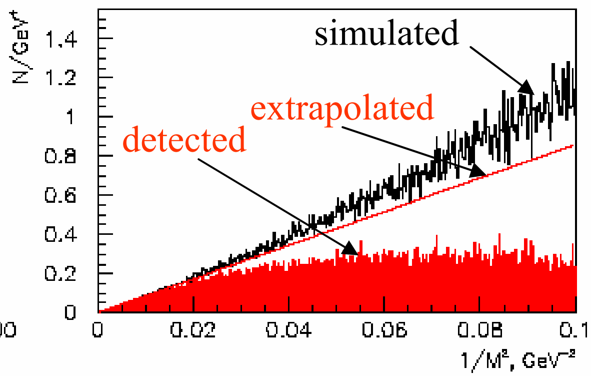


Measurement of the Inelastic Rate N_{inel}

- Inelastic double arm trigger: robust against background, inefficient at small M
- Inelastic single arm trigger: suffers from beam-gas + halo background, best efficiency
- Inelastic triggers and proton (SD, DPE): cleanest trigger, proton inefficiency to be extrapolated
- Trigger on non-colliding bunches to determine beam-gas + halo rates.
- Vertex reconstruction with T1, T2 to suppress background
- Extrapolation of diffractive cross-section to large $1/M^2$ assuming $d\sigma/dM^2 \sim 1/M^2$

Loss at low diffractive masses M





	σ [mb]	trigger loss [mb]	systematic error after extrapolations [mb]
Non-diffractive inelastic	58	0.06	0.06
Single diffractive	14	3	0.6
Double diffractive	7	0.3	0.1
Double Pomeron	1	0.2	0.02
Total	80	3.6	**0.8**

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:

- Extrapolation of elastic cross-section to t = 0: ± 4 %
- Total elastic rate (strongly correlated with extrapolation): ± 2 %
- Total inelastic rate: ± 1 %
  (error dominated by Single Diffractive trigger losses)
- Error contribution from $(1+\rho^2)$
  using full COMPETE error band $\delta\rho/\rho = 33$ % ± 1.2 %

==> Total uncertainty in σ_{tot} including correlations in the error propagation: ± 5 %
Slightly worse in $\mathcal{L}$ (~ total rate squared!) : ± 7 %

Later improvement to ~ 1 % with $\beta^* = 1540$ m requires:

- improved knowledge of optical functions
- alignment precision < 50 μm

Soft Diffraction

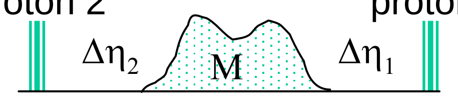
$\beta^* = 90$ m: 65 %
$\beta^* = 1540$ m: 95 %
of all diffractive proton are detected, independent of their ξ

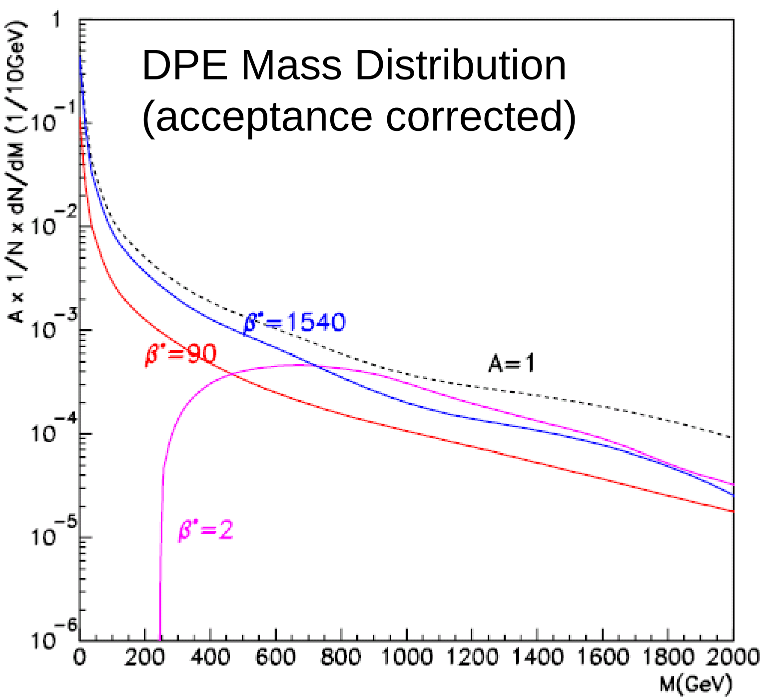
Reconstruction of ξ via protons or rapidity gap ($\Delta\eta = -\ln \xi$):

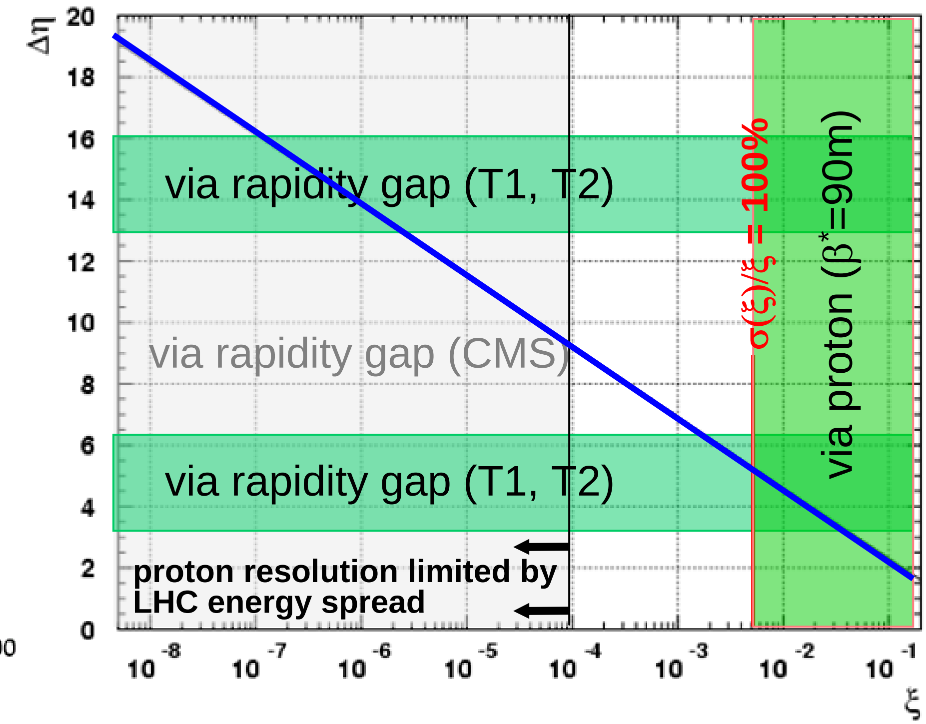
$\beta^* = 90$ m: $\sigma_p(\xi) = 6 \times 10^{-3}$ (without CMS vertex knowledge)

$\beta^* = 1540$ m: $\sigma_p(\xi) \leq 9 \times 10^{-3}$

$\sigma(\Delta\eta) = 0.8 - 1 \rightarrow \sigma_{\Delta\eta}(\xi) = (0.8 - 1)\ \xi$







==> various diffractive studies (Single Diffraction and Double Pomeron Exchange)

To be extended later together with CMS.

Summary

TOTEM will be ready for running at the start of LHC.

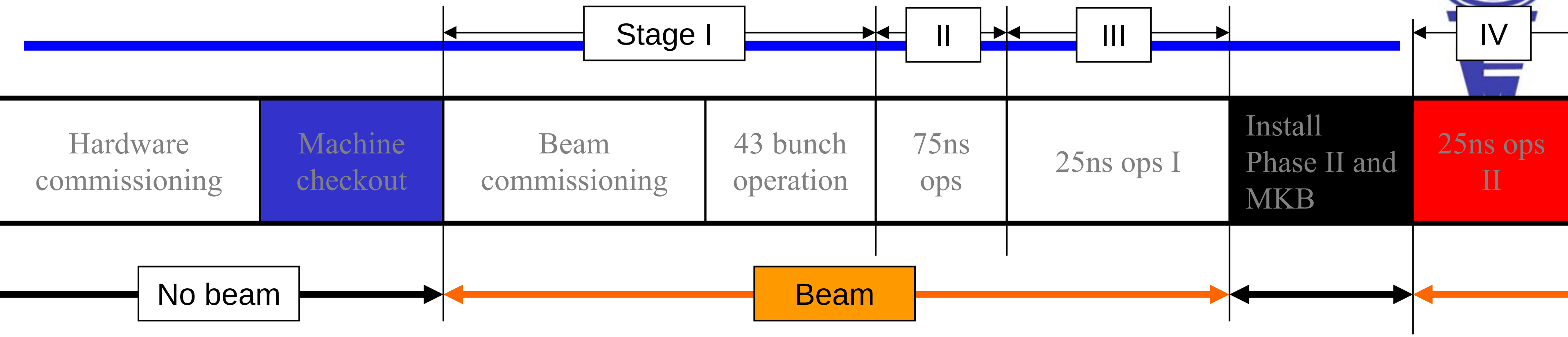
For early runs: optics with β^* = 90 m requested at the LHCC

- Optics commissioning fits well into LHC startup planning
- Typical running time: several periods of a few days
- Total cross section within ± 5%
- Luminosity within ± 7%
- Soft diffraction with ξ–independent proton acceptance (~ 65%)

After gaining experience at β^* = 90 m, more precise measurements with the baseline optics (β^* = 1540 m): needs very good control of systematics.

The End

Overall commissioning strategy for protons (est^{d}. 2005)



I. Pilot physics run
- First collisions
- 43 bunches, no crossing angle, no squeeze, moderate intensities
- Push performance
- Performance limit 10^{32} cm^{-2} s^{-1} (event pileup)

II. 75ns operation
- Establish multi-bunch operation, moderate intensities
- Relaxed machine parameters (squeeze and crossing angle)
- Push squeeze and crossing angle
- Performance limit 10^{33} cm^{-2} s^{-1} (event pileup)

III. 25ns operation I
- Nominal crossing angle
- Push squeeze
- Increase intensity to 50% nominal
- Performance limit 2 10^{33} cm^{-2} s^{-1}

IV. 25ns operation II
- Push towards nominal performance

Minimise
– *Complexity*
– *Beampower*
– *Losses* (β^*)
– *Pileup*

Optimise
$-N$
$-k_b$
$-\beta^*$

Parameter Evolution and Rates

$$L = \frac{N^2 k_b f \gamma}{4\pi\varepsilon_n \beta^*} F$$

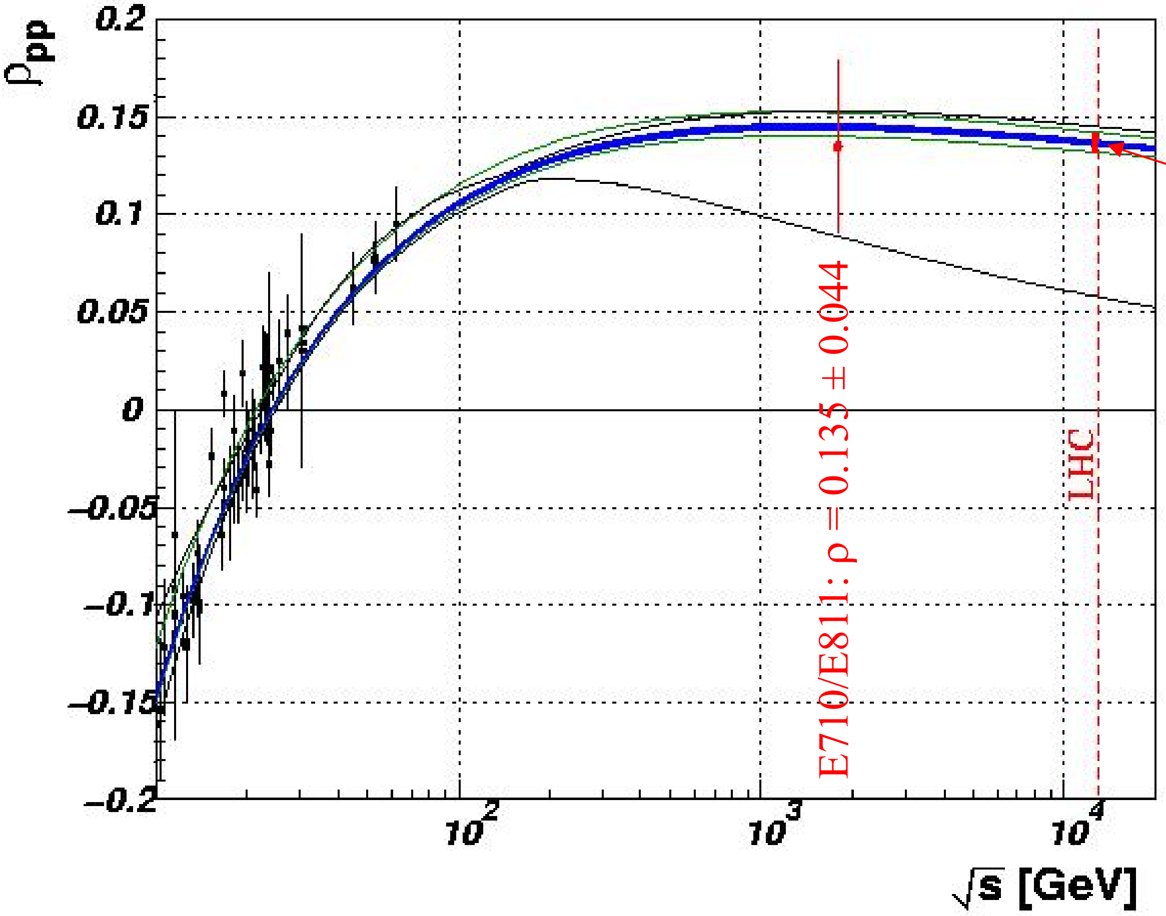
$$Eventrate / Cross = \frac{L \sigma_{TOT}}{k_b f}$$

All values for nominal emittance, 7TeV and 10m β* in points 2 and 8

Parameters			Beam levels		Rates in 1 and 5		Rates in 2 (and 8)	
k_b	N	β* 1,5 (m)	I_{beam} proton	E_{beam} (MJ)	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing
43	$4\ 10^{10}$	11	$1.7\ 10^{12}$	2	$1.1\ 10^{30}$	<< 1	$1.2\ 10^{30}$	0.15
43	$4\ 10^{10}$	2	$1.7\ 10^{12}$	2	$6.1\ 10^{30}$	0.76	$1.2\ 10^{30}$	0.15
156	$4\ 10^{10}$	2	$6.2\ 10^{12}$	7	$2.2\ 10^{31}$	0.76	$4.4\ 10^{30}$	0.15
156	$9\ 10^{10}$	2	$1.4\ 10^{13}$	16	$1.1\ 10^{32}$	3.9	$2.2\ 10^{31}$	0.77
936	$4\ 10^{10}$	11	$3.7\ 10^{13}$	42	$2.4\ 10^{31}$	<< 1	$2.6\ 10^{31}$	0.15
936	$4\ 10^{10}$	2	$3.7\ 10^{13}$	42	$1.3\ 10^{32}$	0.73	$2.6\ 10^{31}$	0.15
936	$6\ 10^{10}$	2	$5.6\ 10^{13}$	63	$2.9\ 10^{32}$	1.6	$6.0\ 10^{31}$	0.34
936	$9\ 10^{10}$	1	$8.4\ 10^{13}$	94	$1.2\ 10^{33}$	7	$1.3\ 10^{32}$	0.76
2808	$4\ 10^{10}$	11	$1.1\ 10^{14}$	126	$7.2\ 10^{31}$	<< 1	$7.9\ 10^{31}$	0.15
2808	$4\ 10^{10}$	2	$1.1\ 10^{14}$	126	$3.8\ 10^{32}$	0.72	$7.9\ 10^{31}$	0.15
2808	$5\ 10^{10}$	1	$1.4\ 10^{14}$	157	$1.1\ 10^{33}$	2.1	$1.2\ 10^{32}$	0.24
2808	$5\ 10^{10}$	0.55	$1.4\ 10^{14}$	157	$1.9\ 10^{33}$	3.6	$1.2\ 10^{32}$	0.24

R. Bailey

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



COMPETE [PRL 89 201801 (2002)]

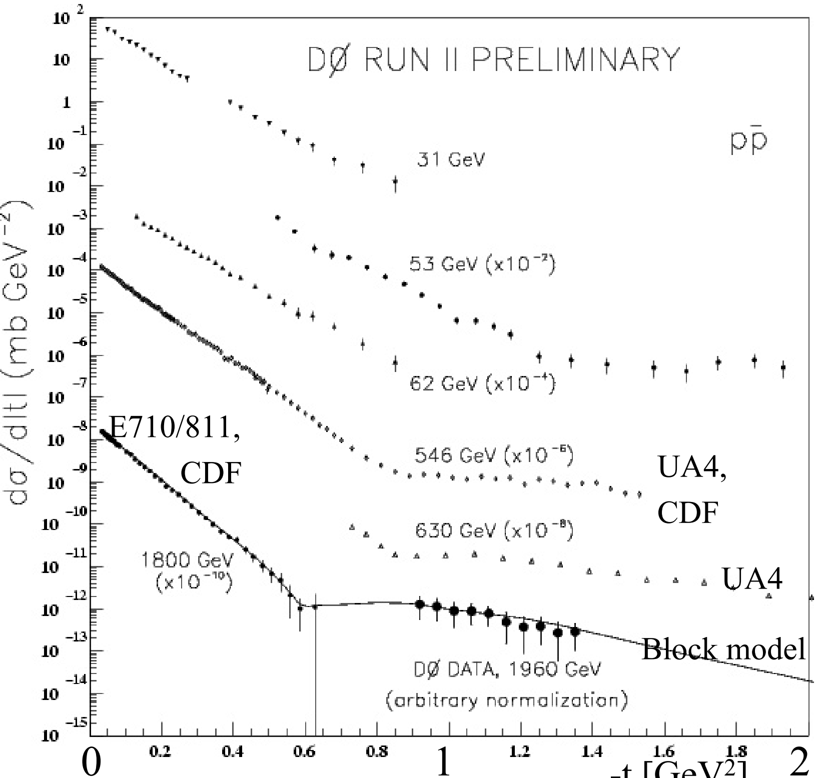
Preferred fit predicts:

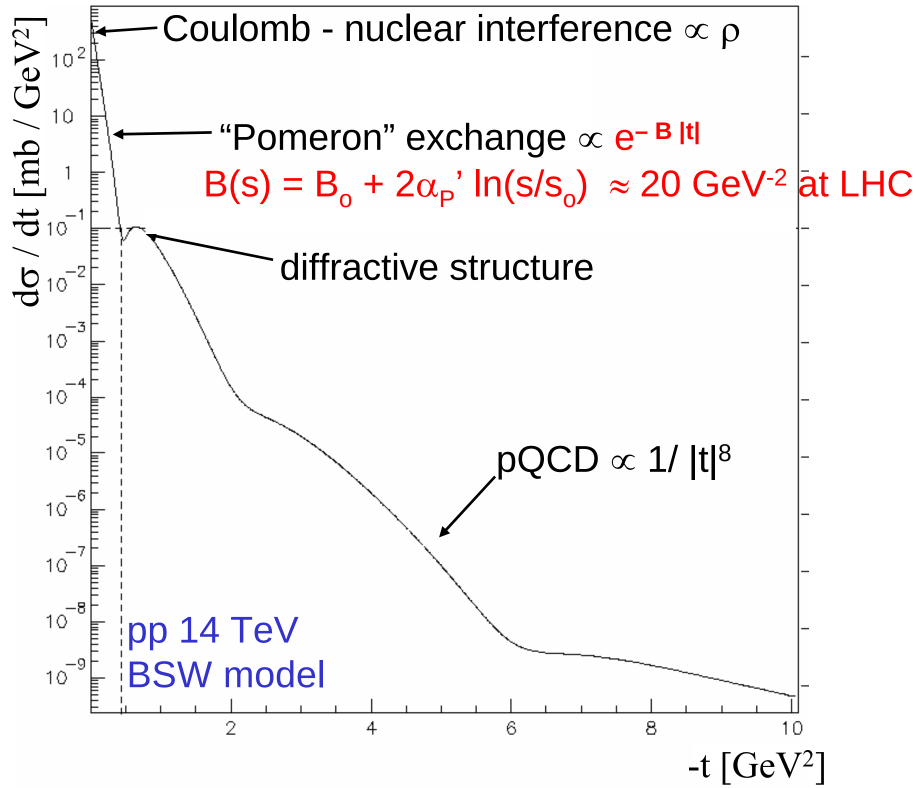
$$\rho = 0.1361 \pm 0.0015 \begin{smallmatrix} +0.0058 \\ -0.0025 \end{smallmatrix}$$

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}

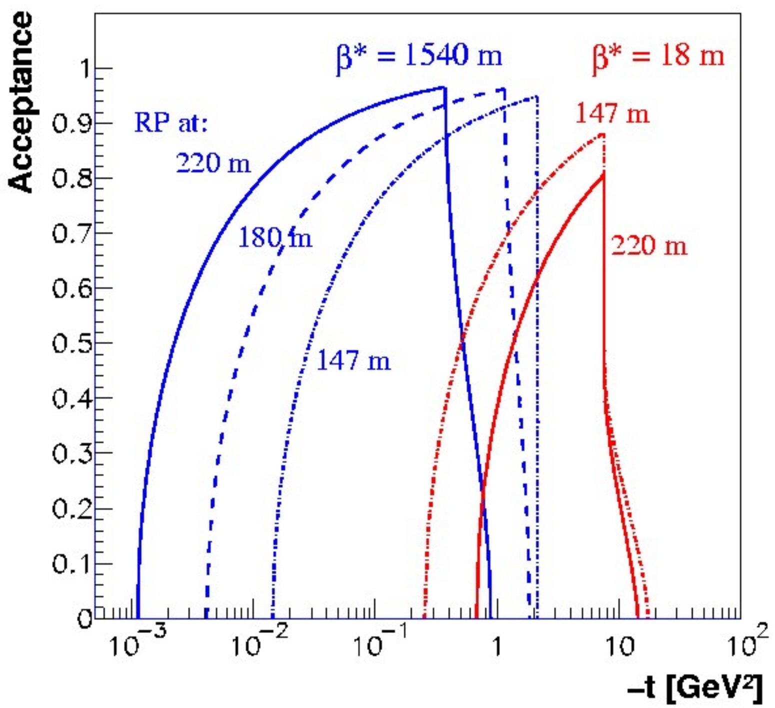
E710: $0.034 < |t| < 0.65$ GeV^2 : $B = 16.3 \pm 0.3$ GeV^{-2}

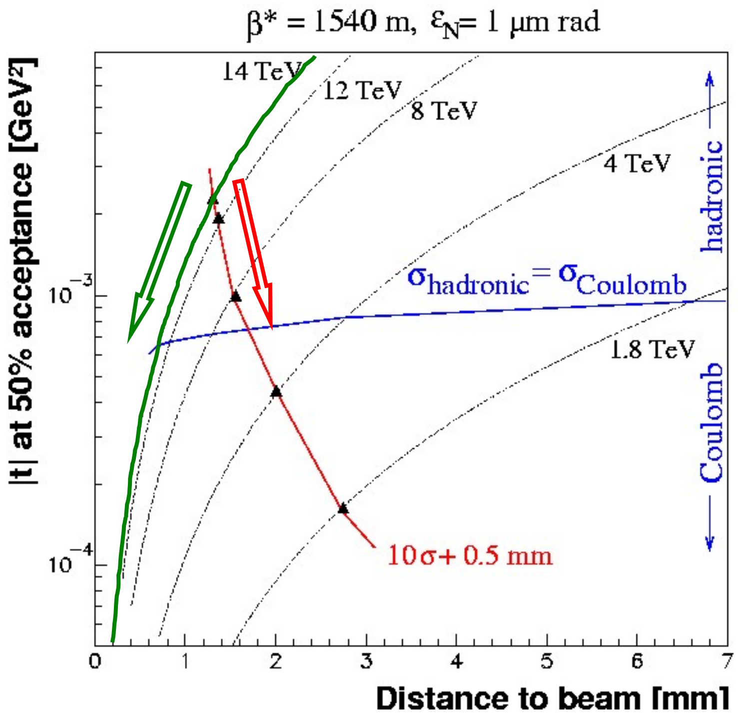
$0.001 < |t| < 0.14$ GeV^2 : $B = 16.99 \pm 0.25$ GeV^{-2}, $\rho = 0.140 \pm 0.069$

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

Elastic Scattering at TOTEM: t-Acceptance



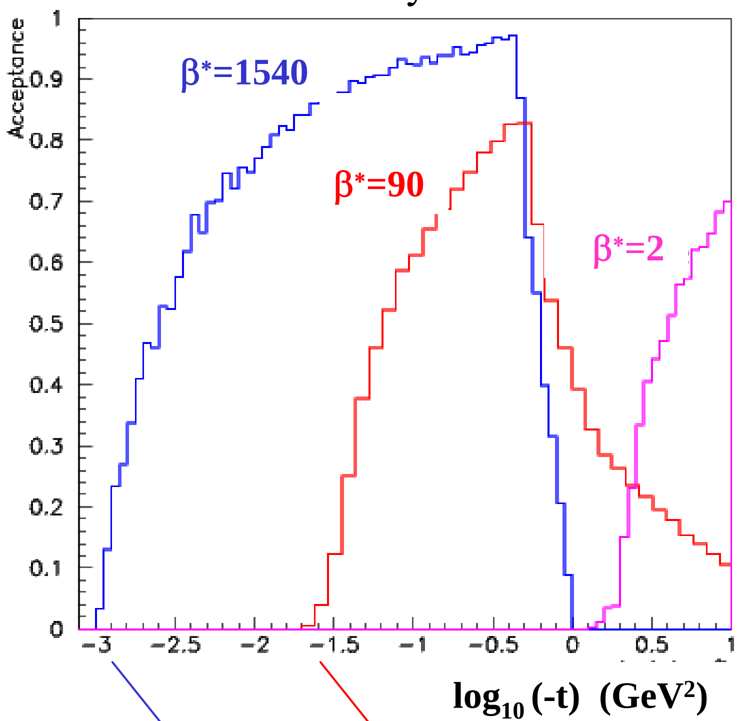


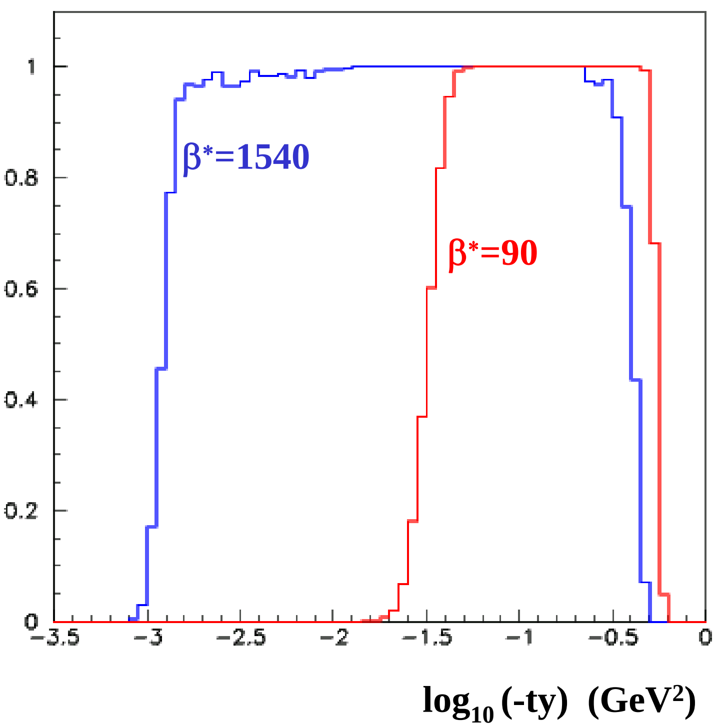
Try to reach the interference region:

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

t-Acceptance at RP220 for Elastic Scattering

$t = t_x + t_y$ $\qquad$ $t \sim -(p\,\theta)^2$ $\qquad$ t_y





$10\sigma_{beam}$ = 0.8 mm $\quad$ 6.25 mm

+ 0.5 mm detector displacement

$\sigma(t_y) / t_y \sim 0.02\ \mathrm{GeV} / t_y^{1/2}$