EDS'09: 13th International Conference on Elastic & Diffractive Scattering

# TOTEM Experiment: Elastic and Total Cross Sections

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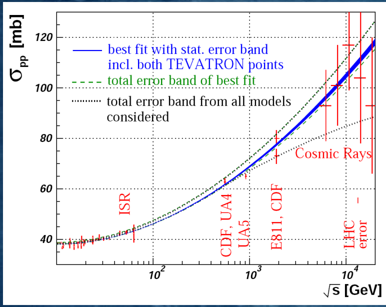
Institute of Physics of the AS CR
on behalf of the **TOTEM Collaboration**

CERN, June 30, 2009

# TOTEM Physics Programme

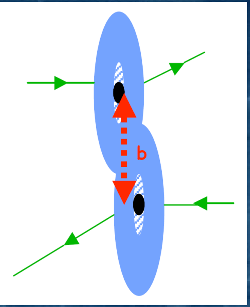
## Total cross section

ultimately ≈ 1% precision

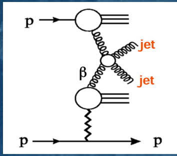


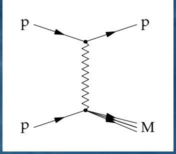

## Elastic scattering

wide $t$ range

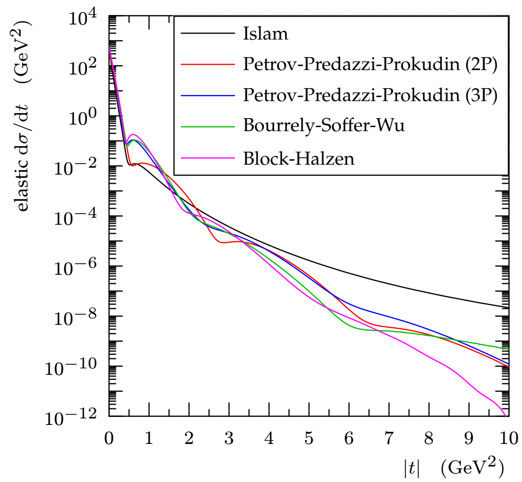


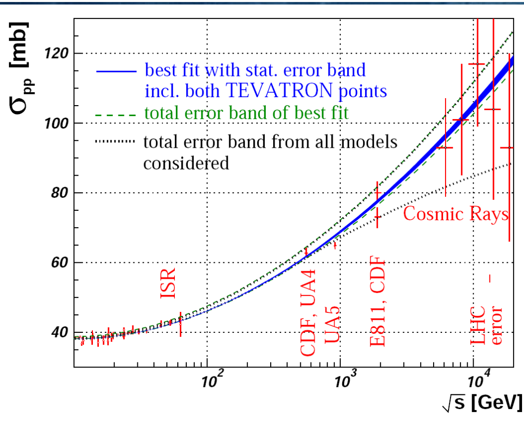

## Hard and Soft Diffraction




(covered by the talk of Simone)




# Why...

**Elastic scattering** (diffraction in general)

- theoretical understanding not complete
- number of approaches: Regge, geometrical, eikonal, QCD, ... ⇒ rather incompatible predictions
- intimately related to the structure of proton

**Total cross section**

- various models/approaches: $\sigma_{\text{tot}} \sim \ln s$, $\sigma_{\text{tot}} \sim \ln^2 s$, $\sigma_{\text{tot}} \sim s^{\alpha-1}$
- predictions for $\sqrt{s} = 14$ TeV: $90 \text{ mb} < \sigma_{\text{tot}} < 130 \text{ mb} \Rightarrow 40\%$ uncertainty
- available data not decisive (incompatible CDF/E810 measurements)
- implications to cosmic ray physics etc.

**TOTEM = precise and decisive measurement**

# Total Cross Section Measurement

- Luminosity Independent Method

$$\sigma_{\rm tot} \propto \Im A(t=0), \qquad {\rm d}\sigma/{\rm d}t \propto |A|^2, \qquad {\rm d}N = \mathcal{L}{\rm d}\sigma, \qquad N_{\rm tot} = N_{\rm el} + N_{\rm inel}$$

$$\Downarrow$$

$$\sigma_{\rm tot} = \frac{1}{1+\varrho^2}\frac{{\rm d}N/{\rm d}t|_0}{N_{\rm el}+N_{\rm inel}}, \qquad \mathcal{L} = (1+\varrho^2)\,\frac{(N_{\rm el}+N_{\rm inel})^2}{{\rm d}N/{\rm d}t|_0}$$

${\rm d}N/{\rm d}t|_0$ : extrapolation of elastic rate to $t=0$
$N_{\rm el}$ : total elastic rate
$N_{\rm inel}$ : total inelastic rate
$\varrho$ : ratio of real to imaginary part of elastic amplitude

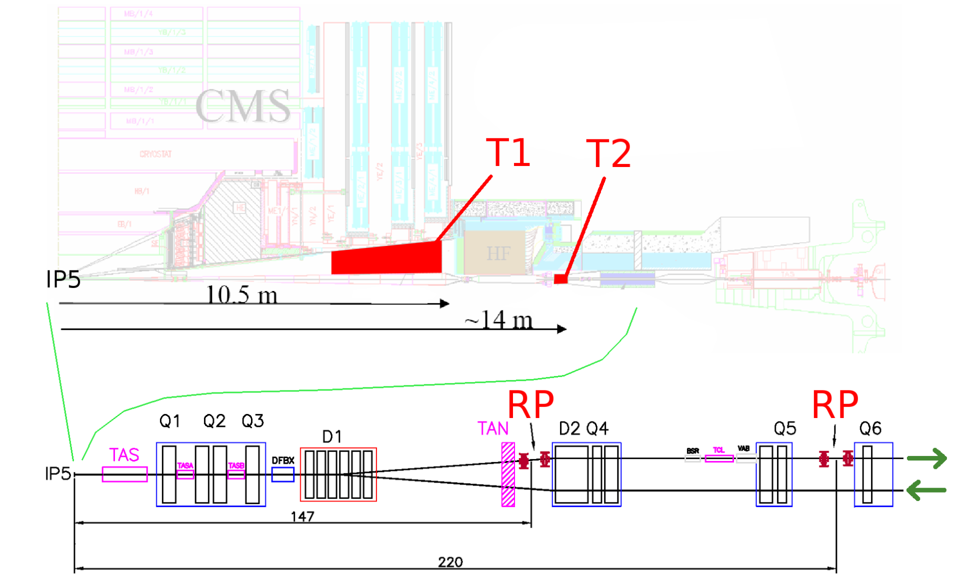
$$\Downarrow$$

requirements for detectors: *detection of forward protons* and *large pseudorapidity coverage*

# TOTEM Detectors

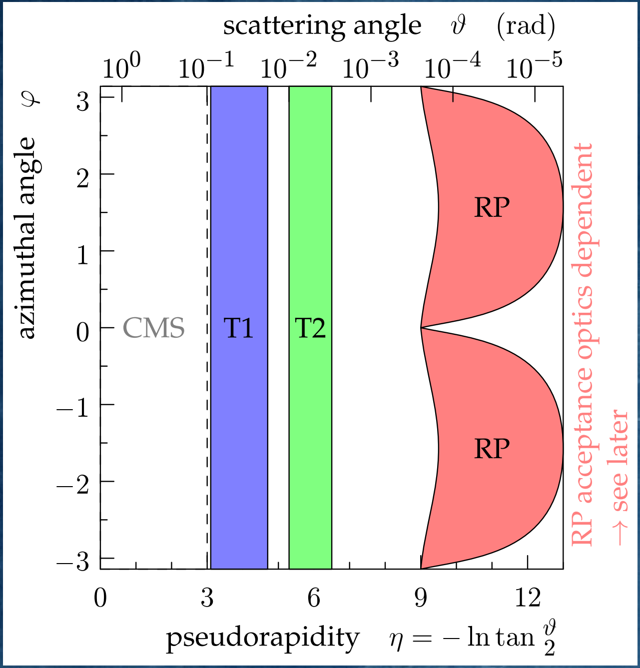
- **Roman Pots**
  – measurement of forward protons
- telescopes **T1** and **T2**: tracking of charged particles produced in inelastic events
  – measurement of inelastic rate

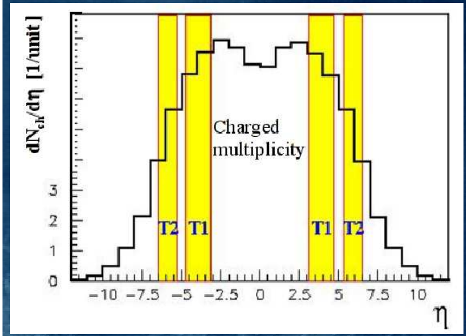
… and symmetrically on the left side

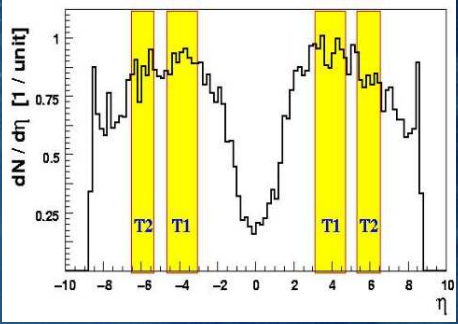



- for details on instrumentation see Gennaro's talk

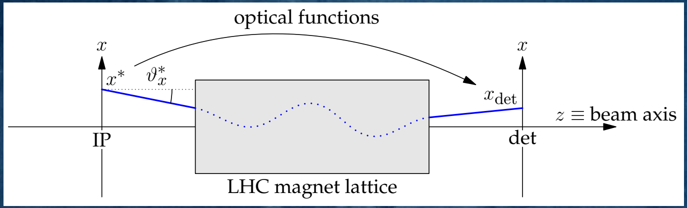
# Acceptance of TOTEM Detectors



# Optics




transport of *elastic* protons

$$x_{\rm det} = L_x \vartheta_x^* + v_x x^*$$

$$y_{\rm det} = L_y \vartheta_y^* + v_y y^*$$

$\vartheta_{x,y}^*$ are angles and $x^*, y^*$ are coordinates of a proton at IP

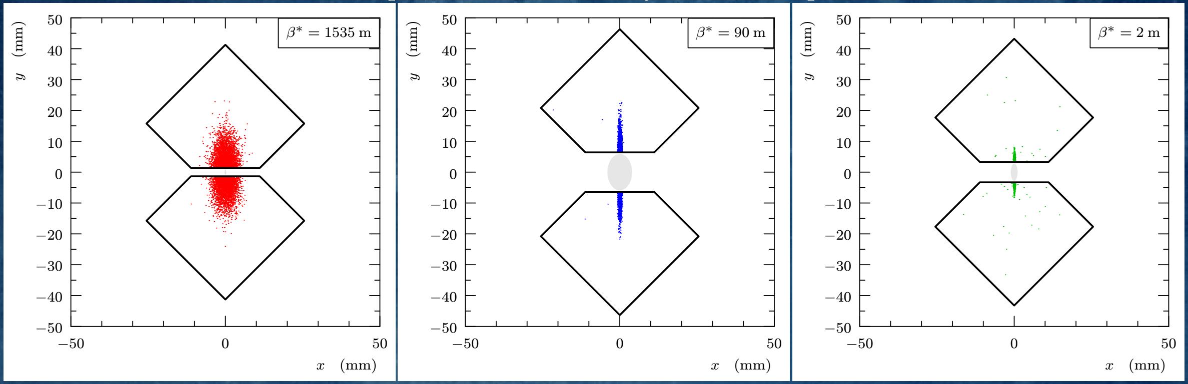
$L_{x,y}$ and $v_{x,y}$ are optical functions

↓

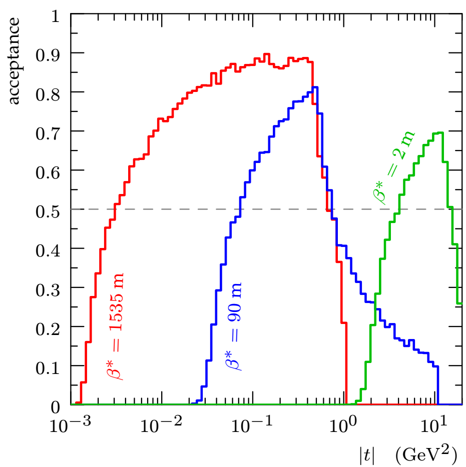
define which $t$ can be seen ($\equiv$ acceptance)

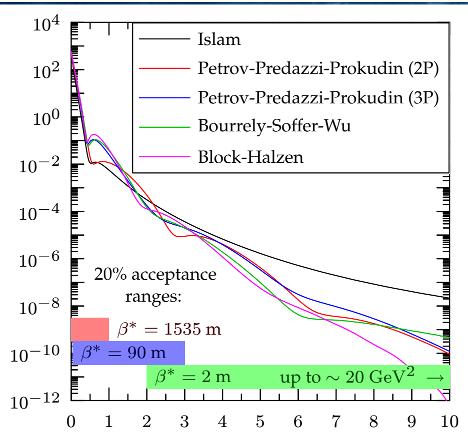
↓

example: elastic hits seen by 3 different optics




(the gray ellipse shows $10\sigma$ beam envelope)




# Scenarios

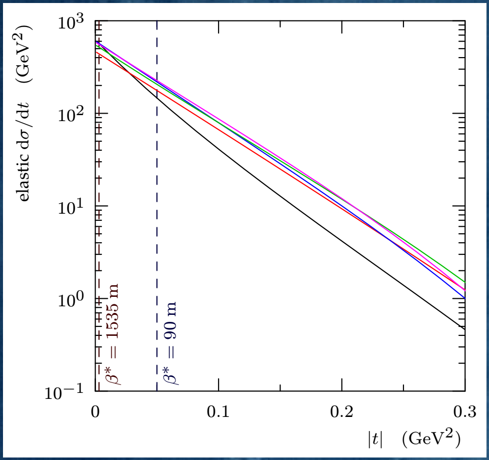
1) **high** $\beta^*$
- $\beta^* = 1535$ m
- $\mathcal{L} \approx 10^{28} \div 10^{29}$ cm$^{-2}$s$^{-1}$
- elastic resolution: $\sigma(\vartheta_x) \approx 0.23$ $\mu$rad, $\sigma(\vartheta_y) \approx 0.22$ $\mu$rad
- vertical sensors at 1.35 mm from beam center

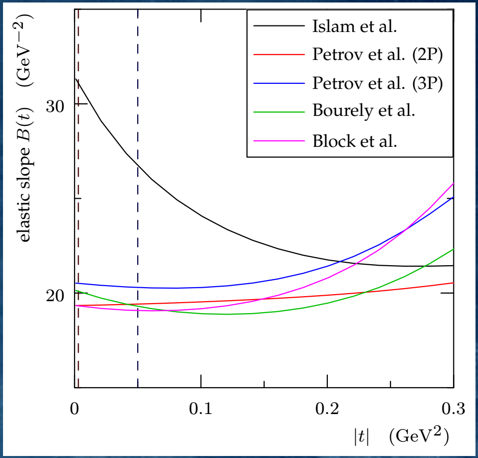
2) **medium** $\beta^*$
- $\beta^* = 90$ m
- $\mathcal{L} \approx 10^{30}$ cm$^{-2}$s$^{-1}$
- elastic resolution: $\sigma(\vartheta_x) \approx 5$ $\mu$rad (low effective length), $\sigma(\vartheta_y) \approx 1.7$ $\mu$rad
- vertical sensors at 6.4 mm from beam center

3) **low** $\beta^*$
- $\beta^* = 0.5 \div 2$ m (early running: $p = 5$ TeV, $\beta^* \sim 3$ m)
- $\mathcal{L} \approx 10^{33}$ cm$^{-2}$s$^{-1}$
- elastic resolution: $\sigma(\vartheta_x) \approx 16$ $\mu$rad, $\sigma(\vartheta_y) \approx 12$ $\mu$rad
- vertical sensors at 3.3 mm from beam center

- sensors at $10\sigma + 0.5$ mm from beam center
- resolution (usually) limited by beam divergence

# Extrapolation




- $\mathrm{d}\sigma/\mathrm{d}t|_0$ experimentally inaccessible
- extrapolation $\Rightarrow$ parameterization needed

$$T(t) = e^{M(t)} e^{iP(t)}, \quad \frac{\mathrm{d}\sigma}{\mathrm{d}t} = |T(t)|^2, \quad M, P \text{ polynomials}$$

- questions
  – optimal fit range
  – optimal degree of polynomials

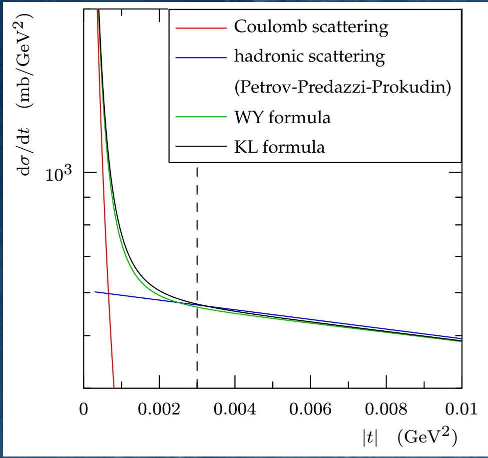
. . . as model independent as possible

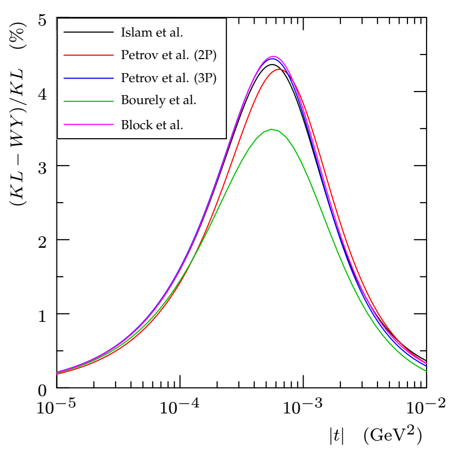
# Extrapolation and Coulomb scattering

- "elastic scattering = strong (hadronic) + electro-magnetic (Coulomb) interaction"
- 2 approaches
  - "*traditional*" (à la West-Yennie)

$$T^{C+H}_{\rm WY} = \pm \frac{\alpha s}{t} f_1(t) f_2(t) e^{\mp i\alpha(\ln(-Bt/2)+\gamma)} + \frac{\sigma_{\rm tot}}{4\pi} p\sqrt{s}(\varrho + i) e^{Bt/2}$$

  - *eikonal* (Kundrát-Lokajíček), formula too long → see the talk of Vojtěch
- traditional approach internally inconsistent → the eikonal one shall be preferred

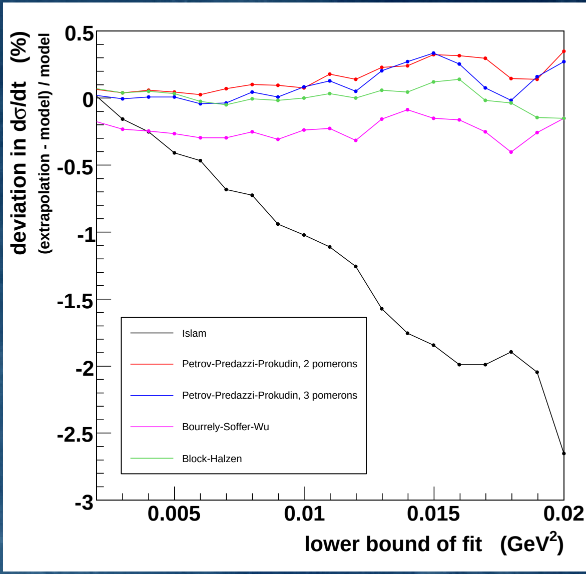


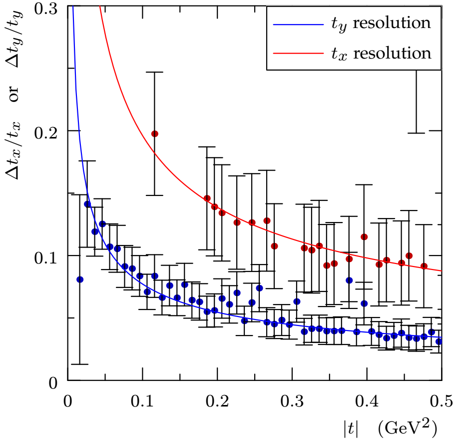



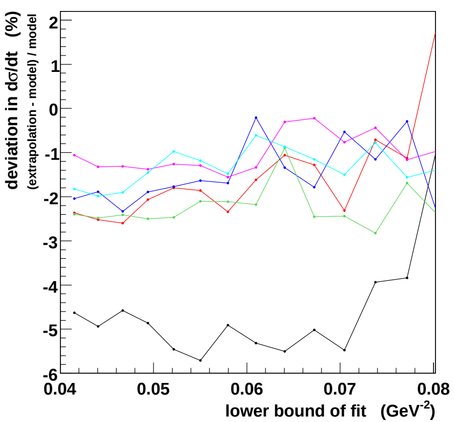
# Extrapolation at $\beta^* = 1535$ m

- parameterization
$$T(t) = e^{i\Phi} e^{a+(b_0+b_1 t+b_2 t^2)t}$$
(quadratic $B(t)$, constant phase)
- using Kundrát-Lokajíček formula
- upper bound $|t| = 4 \cdot 10^{-2}$ GeV$^2$
- based on preliminary simulation/reconstruction data

- most models within $\pm 0.2\%$






# Extrapolation at $\beta^* = 90$ m

- advantage: Coulomb effects negligible
- disadvantage: poor $t_x$ resolution ($t$ resolution as well)

- possible solutions:

**1)** use $t$-distribution anyway

**2)** "convert" $t_y$-distribution to $t$-distribution (azimuthal symmetry)

$$t = t_x + t_y, \qquad t_x = t\cos^2\varphi, \quad t_y = t\sin^2\varphi$$

$$\frac{d\sigma}{dt_y} = \frac{d\sigma}{dt_x} \quad \Rightarrow \quad \frac{d\sigma}{dt}(t) \propto \int_t^0 du\, \frac{d\sigma}{dt_y}(u)\, \frac{d\sigma}{dt_y}(t-u)$$

– low $|t_y|$ information missing ⇒ extrapolation needed

**3)** "convert" $t$-parameterization to $t_y$-parameterization

$$\frac{d\sigma}{dt_y}(t_y) = \frac{2}{\pi}\int_0^{\pi/2} \frac{d\varphi}{\sin^2\varphi}\, \frac{d\sigma}{dt}\left(\frac{t_y}{\sin^2\varphi}\right)$$

$$\frac{d\sigma}{dt_y}(t_y) \approx \frac{1}{\sqrt{\pi}}\, \frac{e^{a + bt_y + ct_y^2 + dt_y^3}}{\sqrt{|b\, t_y|}} \qquad (c, d \text{ small})$$

- left: results of approach 3)
  - upper bound $|t| = 0.25$ GeV$^2$
  - based on preliminary simulation/reconstruction data
  - the offset $-2\%$ due to beam divergence

# Total Cross Section – Combined Uncertainty

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

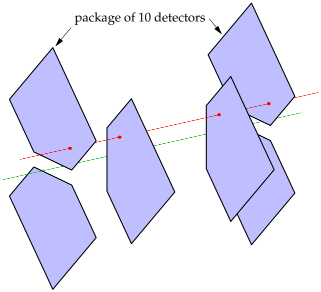
| | | $\beta^* = 90$ (m) | 1535 (m) |
|---|---|---|---|
| $\mathrm{d}N/\mathrm{d}t|_0$ | Extrapolation of elastic rate to $t = 0$ | 4% | 0.2% |
| $N_{\mathrm{el}}$ | Total elastic rate (correlated with extrapolation) | 2% | 0.1% |
| $N_{\mathrm{inel}}$ | Total inelastic rate (error dominated by Single Diffractive trigger losses) | 1% | 0.8% |
| $\varrho \equiv \Re A(t)/\Im A(t)|_{t=0}$ | **External input**, e.g. from COMPETE. Error contribution from $(1+\varrho^2)$ | 1.2% | |
| | Total for $\sigma_{\mathrm{tot}}$ | 5% | $1 \div 2\%$ |
| | Total for $\mathcal{L}$ | 7% | 2% |

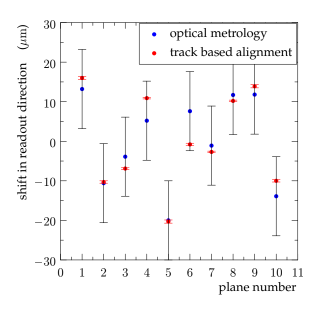
# Sensitivity to Misalignment

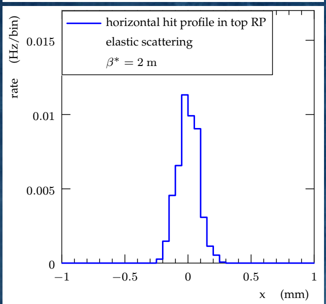
- a simple (but instructive) example
- proton transport: $y_{\mathrm{det}} = L_y \vartheta_y^* + v_y y^*$
- a Roman Pot in 220 m station displaced by 100 $\mu$m $\Rightarrow$ angular error $\Delta\vartheta$ :

| $\beta^*$ (m) | $L_y$ (m) | $\Delta\vartheta$ ($\mu$rad) | beam divergence ($\mu$rad) |
|---|---|---|---|
| 1535 | 272 | 0.36 | 0.3 |
| 90 | 264 | 0.38 | 2.4 |
| 2 | 18 | 5.5 | 15.8 |

$\Rightarrow$ 1535 m optics needs perfect alignment




# Alignment Procedures

**1) internal alignment** (one Roman Pot level)

- track-based (Millepede-like) alignment
- whatever straight tracks: beam test, commissioning, etc.

**2) station alignment** – 2 aspects

- relative RP alignment within a station
  – track-based using *overlap*
- alignment wrt. beam
  – physics processes: hit and angular distributions

**3) global alignment** (left–right)

- elastic tracks
- track-based alignment with *elastic* tracks

**4) external information**

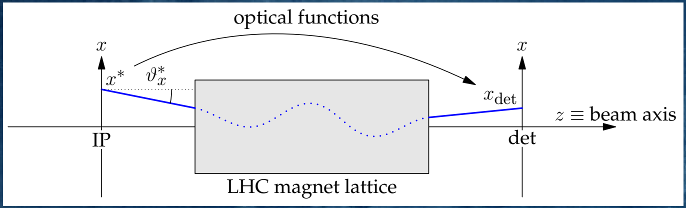
– Beam Position Monitors – can watch fast beam variations

– motor control – very useful after calibration

**Thank you for your attention**

(kašpar = joker :-)

# Optics




proton transport equation

$$x_{det} = L_x \vartheta_x^* + v_x x^* + D\xi$$

$$y_{det} = L_y \vartheta_y^* + v_y y^*$$

$\vartheta_{x,y}^*$ and $x^*, y^*$ are angles and coordinates of a proton at IP, $\xi \equiv \Delta p/p$ is proton momentum loss

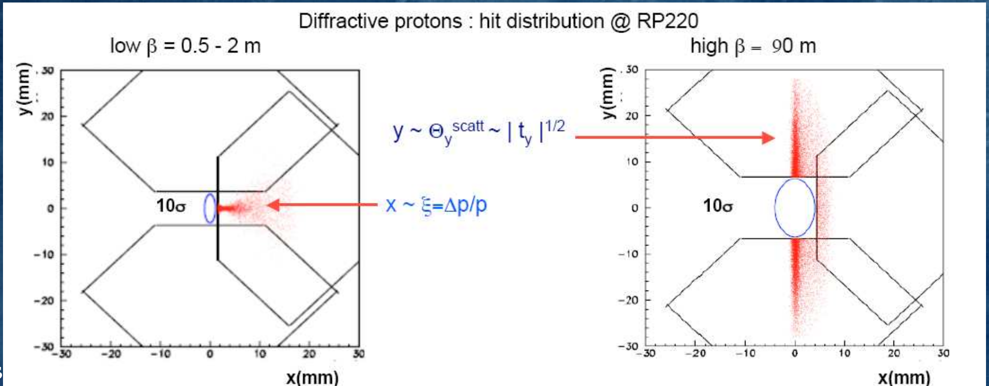
$L_{x,y}$, $v_{x,y}$ and D are optical functions

↓

define which $t$ and $\xi$ can be seen ($\equiv$ acceptance)

↓

example: with the same sample of diffractive protons

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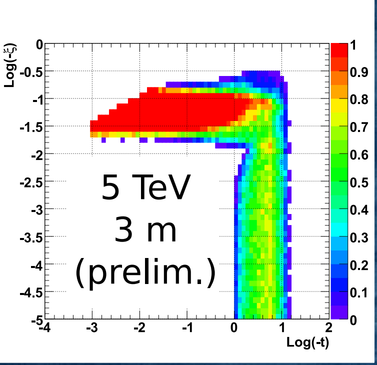
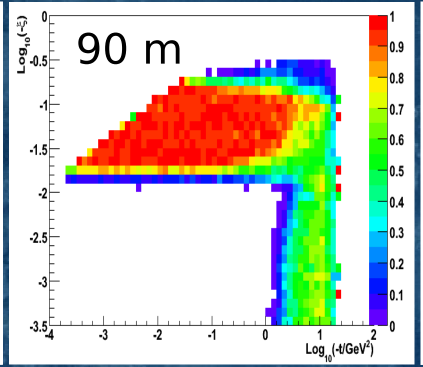
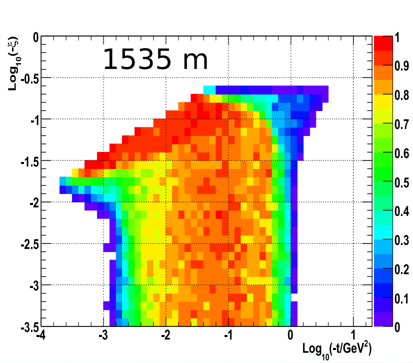
# Scenarios




## low $\beta^*$

$\beta^* = 0.5 \div 2$ m, $\mathcal{L} \approx 10^{33}$ cm$^{-2}$s$^{-1}$
early running: $p = 5$ TeV, $\beta^* \sim 3$ m

elastic acceptance
$2 \lesssim |t/\mathrm{GeV}^2| \lesssim 10$

resolution
$\sigma(\vartheta) \approx 15\ \mu$rad
$\sigma(\xi) \approx 1 \div 6 \cdot 10^{-3}$

*diffraction, high $|t|$ elastic scattering*

## $\beta^* = 90$ m

$\mathcal{L} \approx 10^{30}$ cm$^{-2}$s$^{-1}$

elastic acceptance
$10^{-2} < |t_y/\mathrm{GeV}^2| \lesssim 10$

resolution
$\sigma(\vartheta) \approx 1.7\ \mu$rad
$\sigma(\xi) \approx 6 \div 15 \cdot 10^{-3}$

all $\xi$ seen, universal optics

*diffraction, mid $|t|$ elastic scattering, total cross section*

## $\beta^* = 1535$ m

$\mathcal{L} \approx 10^{28} \div 10^{29}$ cm$^{-2}$s$^{-1}$

elastic acceptance
$3 \cdot 10^{-3} < |t/\mathrm{GeV}^2| < 0.5$

resolution
$\sigma(\vartheta) \approx 0.3\ \mu$rad
$\sigma(\xi) \approx 2 \div 10 \cdot 10^{-3}$

all $\xi$ seen

*total cross section, low $|t|$ elastic scattering*

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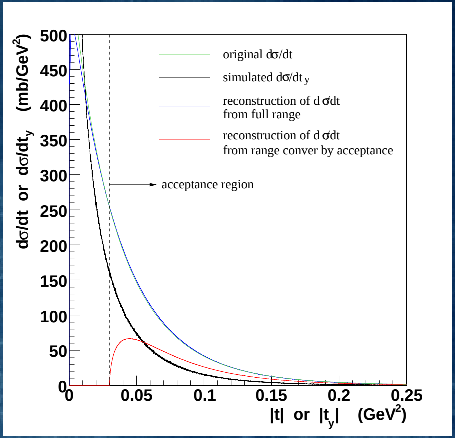
# Complication at $\beta^*$ = 90 m: only $t_y$ is measured

- $L_x \approx 0$ m $\Rightarrow$ only $t_y$ can practically be reconstructed $\Rightarrow$ $\mathrm{d}\sigma/\mathrm{d}t_y$ measured instead of $\mathrm{d}\sigma/\mathrm{d}t$




- transformation between p.d.fs. of random variables $t, \varphi$ and $t_y, \varphi$

$$t_y(t,\varphi) = t \sin^2\varphi \Rightarrow$$

$$\Rightarrow \quad \frac{\mathrm{d}\sigma}{\mathrm{d}t_y}(t_y) = \frac{2}{\pi} \int\limits_0^{\pi/2} \frac{\mathrm{d}\varphi}{\sin^2\varphi}\ \frac{\mathrm{d}\sigma}{\mathrm{d}t}\left(\frac{t_y}{\sin^2\varphi}\right) \qquad (1)$$

- inverse transformation (consequence of azimuthal symmetry)

$$t = t_x + t_y, \qquad t_x = t\cos^2\varphi, \quad t_y = t\sin^2\varphi$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t_y} = \frac{\mathrm{d}\sigma}{\mathrm{d}t_x} \quad \Rightarrow \quad \frac{\mathrm{d}\sigma}{\mathrm{d}t}(t) \propto \int\limits_t^0 \mathrm{d}u\ \frac{\mathrm{d}\sigma}{\mathrm{d}t_y}(u)\ \frac{\mathrm{d}\sigma}{\mathrm{d}t_y}(t-u)$$

– can be well adapted for discrete case of histograms

– cannot be used because *information from low $|t_y|$ region is missing*

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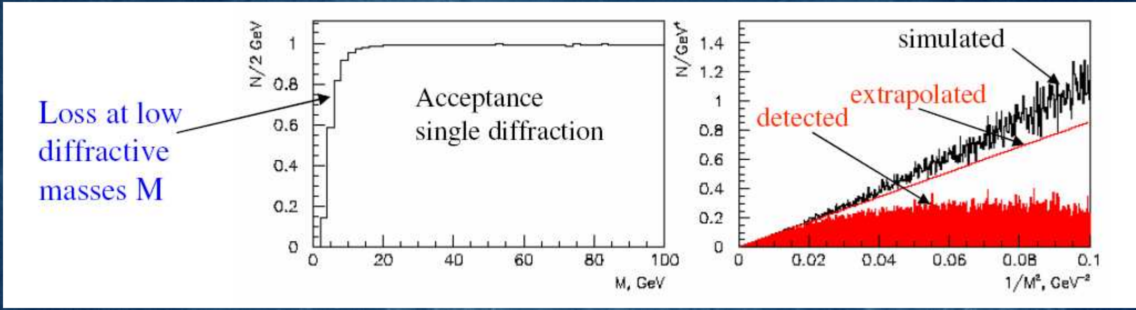
# SD extrapolation to low masses

- assuming $\mathrm{d}\sigma/\mathrm{d}M^2 \propto 1/M^2$

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This background is a photo of ice from inside of the Mer de Glace glacier.