Elastic and Total Cross Section with TOTEM

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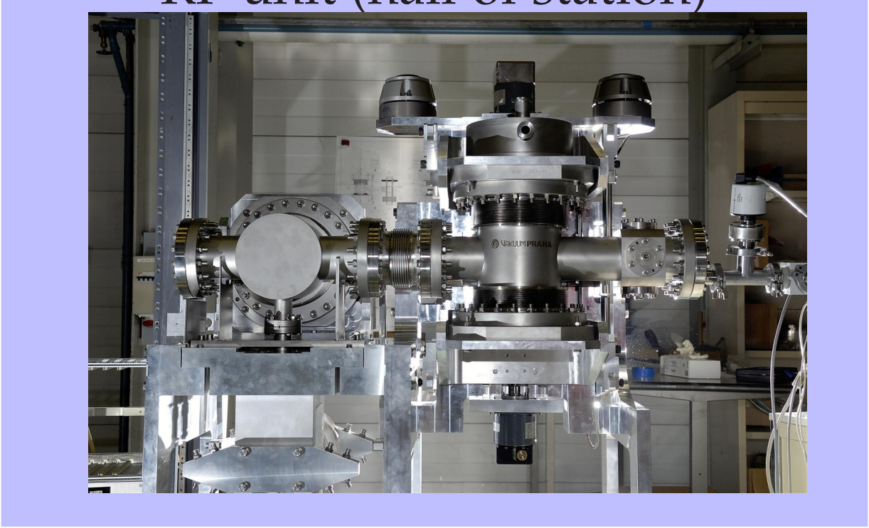
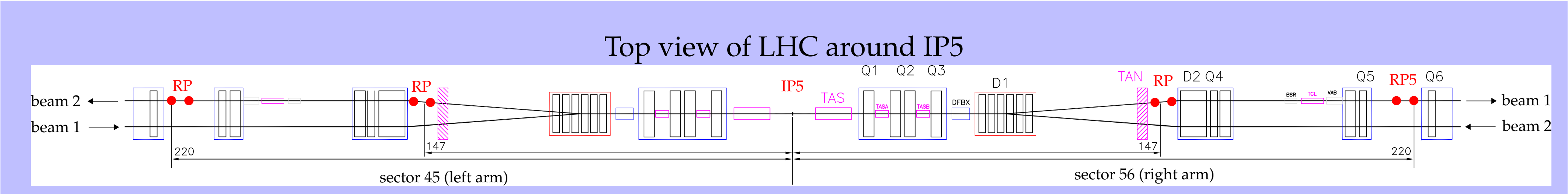
I. Elastic Scattering Measurement with Roman Pots

Roman Pot (RP)

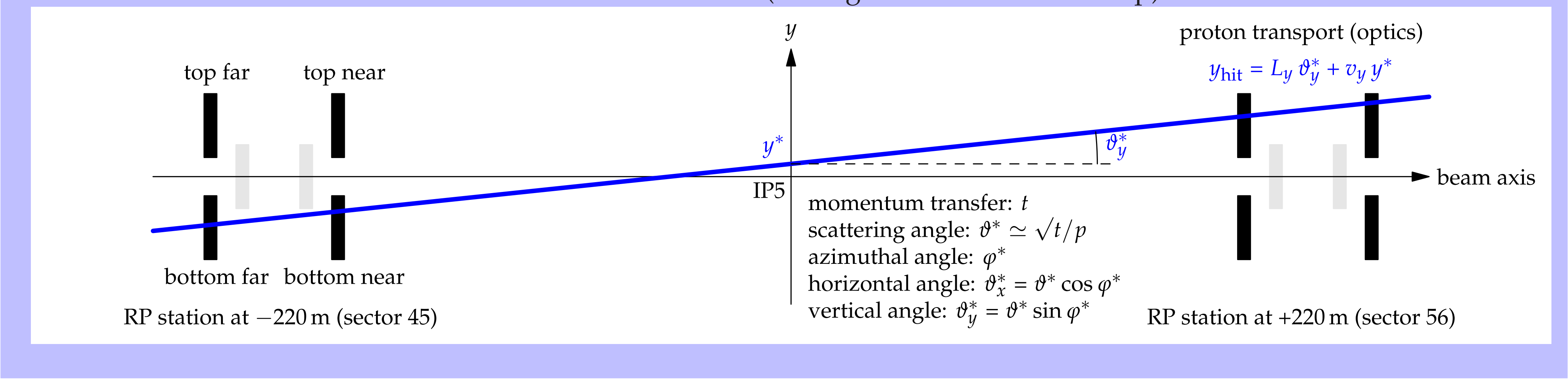
RP unit (half of station)



Top view of LHC around IP5



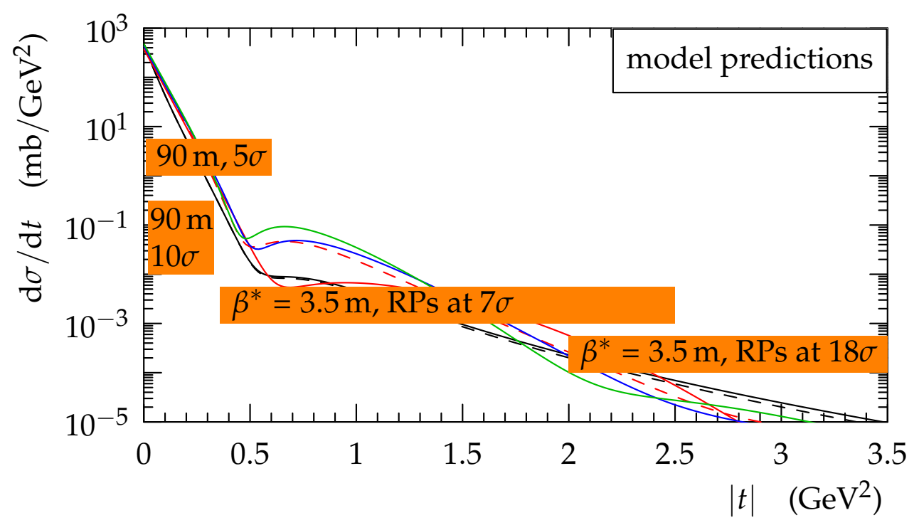
Side view of an elastic event (in diagonal 45 bottom – 56 top)



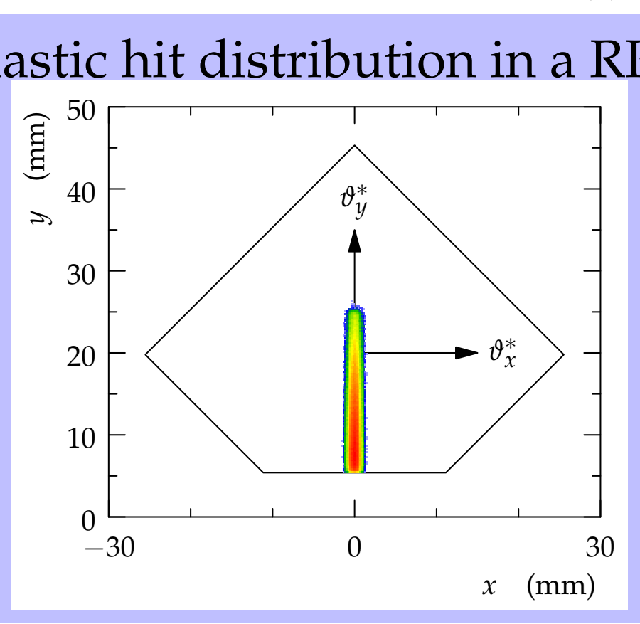
$y_\mathrm{hit} = L_y\,\vartheta_y^* + v_y\,y^*$

momentum transfer: t
scattering angle: $\vartheta^* \simeq \sqrt{t/p}$
azimuthal angle: φ^*
horizontal angle: $\vartheta_x^* = \vartheta^* \cos\varphi^*$
vertical angle: $\vartheta_y^* = \vartheta^* \sin\varphi^*$

Stitching measurements (like a puzzle)



Elastic hit distribution in a RP



II. Elastic Scattering Data Analysis

Alignment

1) collimation alignment

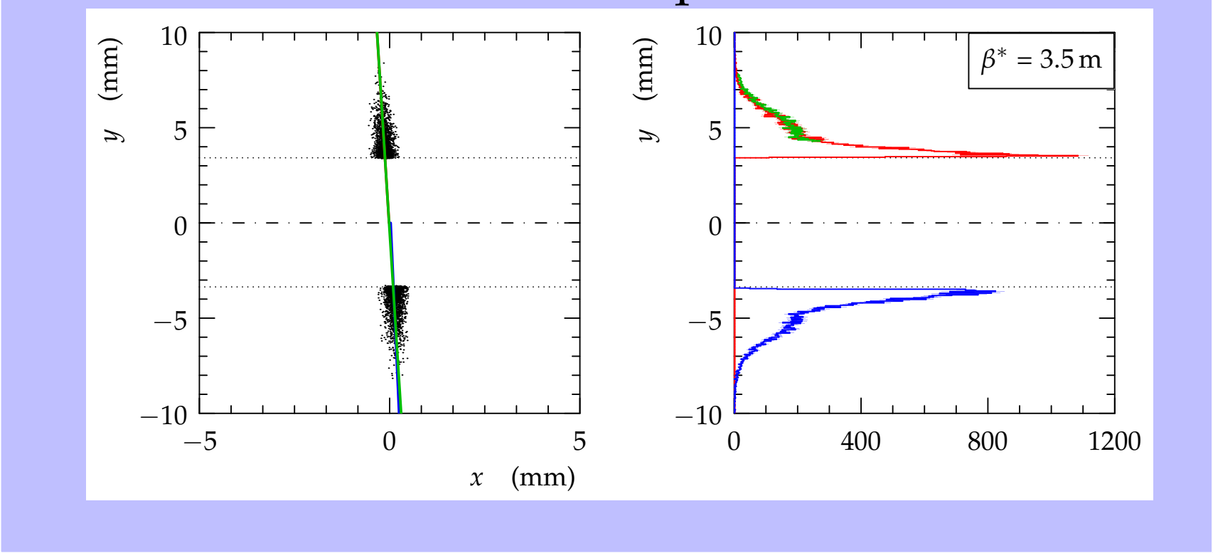
- alignment of RPs wrt. LHC collimators (+ beam)
- collimators scrape the beam at a given distance
  - scraping symmetric around the beam center
- then RPs are approached until a “touch” is signalized by BLMs downstream

2) track-based alignment

- analysis of fit residuals of tracks passing through the overlap of several RPs ⇒ relative alignment between RPs of a station

3) alignment with elastic events (bottom plot)

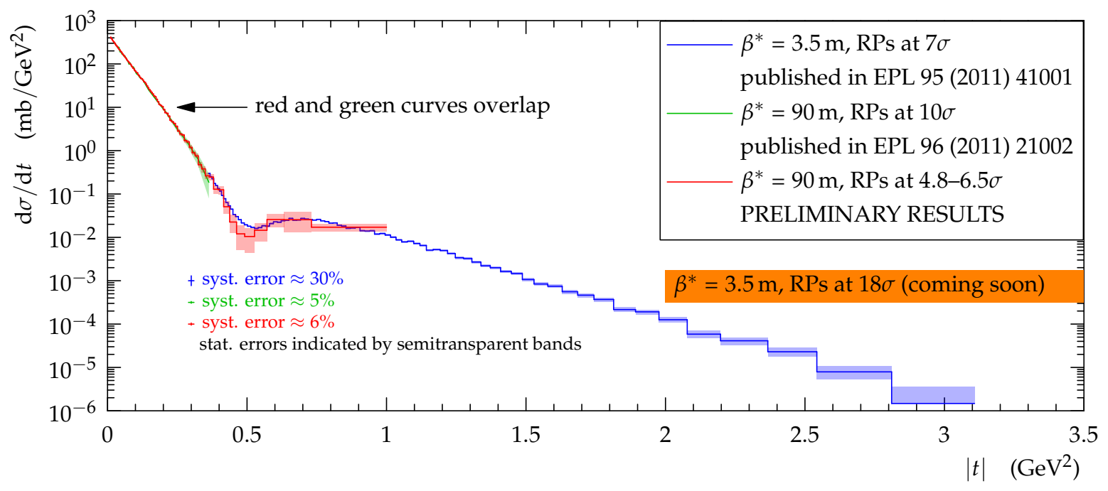
- fine alignment wrt. beam
- vertical alignment (right): bottom pot distribution (blue) flipped (green) and shifted up and down until a match with the top pot distribution (red) is found ⇒ vertical beam position (dashed line)
- horizontal alignment (left): the crossing of elastic-scattering axis and the dashed line indicates the horizontal beam position



Combining data sets

- 4 data sets in various stages of analysis

β^* (m)	RP approach	$\|t\|$ range (GeV^2)	$\mathcal{L}$ (μb^{-1})	elastic events
3.5	7σ	0.36 – 3	6100	66k
3.5	18σ	2 – 3.5		≈ 10k
90	10σ	0.02 – 0.4	1.65	14k
90	4.8–6.5σ	0.007 – 1	82.8	1029k



Kinematics reconstruction

- guide: robustness against beam imperfections
- vertical angle: from hit positions

$$\vartheta_y^* = \frac{1}{2}\left(\frac{y^\mathrm{N}}{L_y^\mathrm{N}} + \frac{y^\mathrm{F}}{L_y^\mathrm{F}}\right)$$

- horizontal angle: from local angle

$$\vartheta_x^* = \frac{1}{\frac{\mathrm{d}L_x}{\mathrm{d}s}}\,\frac{x^\mathrm{F} - x^\mathrm{N}}{d} - \text{[vertex contamination]}$$

- reconstruction per arm, then averaged

$$\vartheta_{x,y}^* = \frac{\vartheta_{x,y}^{*,\mathrm{R}} + \vartheta_{x,y}^{*,\mathrm{L}}}{2}$$

Optics fine-tuning

- how well do we know optical functions?
  - stringent magnet quality requirements ⇒ limited optics variations
  - $\beta^* = 3.5\,\mathrm{m}$: $\delta L_y < 2\%$, $\delta \mathrm{d}L_x/\mathrm{d}s < 1\%$
- can we improve it?
  - 36 optics-related quantities observables by RPs ($L_y^\mathrm{R}/L_y^\mathrm{L}$, $s(L_x = 0)$, etc.)
  - adjust magnet parameters to match these constraints
  - after matching for $\beta^* = 3.5\,\mathrm{m}$: $\delta L_y < 0.1\%$, $\delta \mathrm{d}L_x/\mathrm{d}s < 0.1\%$

Normalization to $\mathrm{d}\sigma/\mathrm{d}t$

- luminosity
  - taken from CMS
  - corrections based on TOTEM measurements
- DAQ efficiency
  - ratio of recorded and triggered events
- trigger efficiency
  - can be studied with BX (zero-bias) data stream
- detection efficiency
  - intrinsic detector inefficiency (1 – 2% per RP)
  - proton loss in interactions with RP (≈ 1.5% per RP)
  - studied by comparing samples with 4 and 3 single-RP tracks
- pile up
  - RPs can reconstruct only one track per event
  - physics pile up or coincidence with beam halo
  - beam halo important for RP distances $\lesssim 5\sigma$
  - studied with BX data stream

Event selection

- elastic event consists of two protons
  - originating from the same vertex,
  - having no momentum loss (ξ) and
  - having the same scattering angles left and right

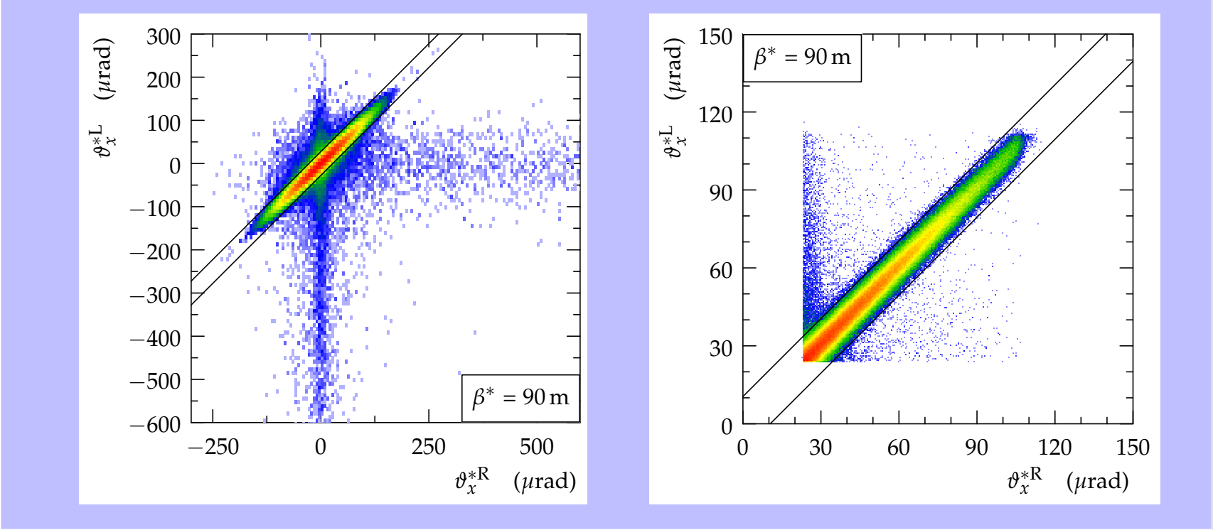
⇓

- vertex left-right cut (only form $\beta^* = 90\,\mathrm{m}$): $\sigma(\Delta x^*) \approx 9\,\mu\mathrm{m}$
- low-ξ cuts: exploit correlations between track position and angle
- left-right collinearity cuts (bottom plots)
  - for $\beta^* = 3.5\,\mathrm{m}$:

$$\sigma(\Delta\vartheta_x^*) \approx 18\,\mu\mathrm{rad} \qquad \sigma(\Delta\vartheta_y^*) \approx 3.5\,\mu\mathrm{rad}$$

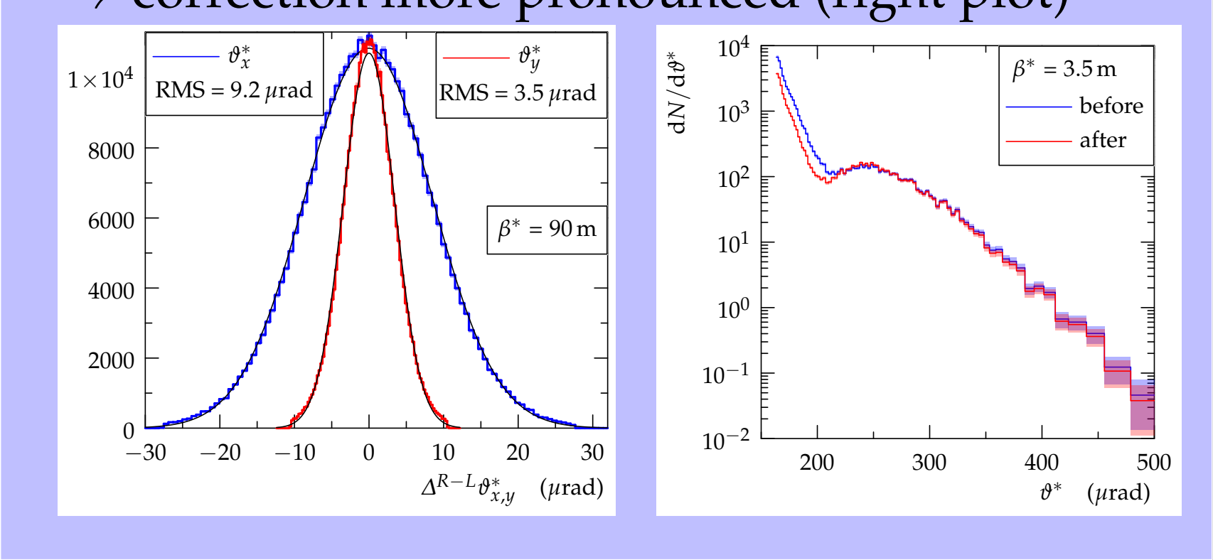
  - for $\beta^* = 90\,\mathrm{m}$:

$$\sigma(\Delta\vartheta_x^*) \approx 9.2\,\mu\mathrm{rad} \qquad \sigma(\Delta\vartheta_y^*) \approx 3.5\,\mu\mathrm{rad}$$



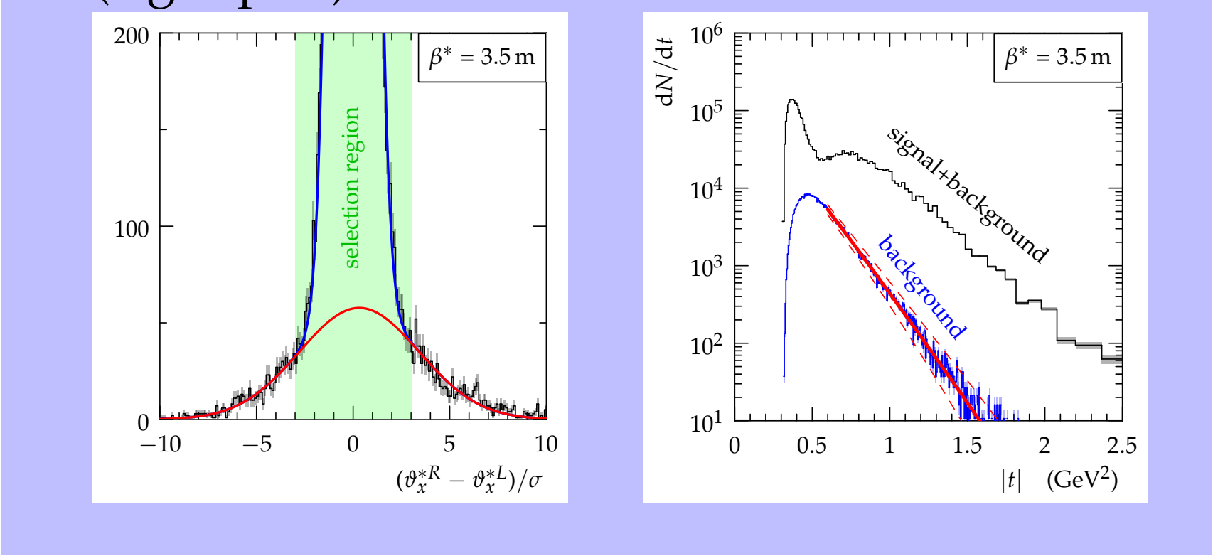
Unfolding of resolution effects

- accounts for smearing in ϑ_x^* and ϑ_y^*
  - beam divergence and detector resolution
- resolution extracted from data: right-left differences (left plot)
- several unsmearing methods used
- method of correction factors – iterative procedure
  1) fit $\frac{\mathrm{d}N}{\mathrm{d}t}$ data (reasonable smoothing)
  2) with fit result run MC with and without smearing
  3) extract per-bin correction factor
  4) correct original $\frac{\mathrm{d}N}{\mathrm{d}t}$ and return to 1)
- resolution significantly worse for $\beta^* = 3.5\,\mathrm{m}$ ⇒ correction more pronounced (right plot)



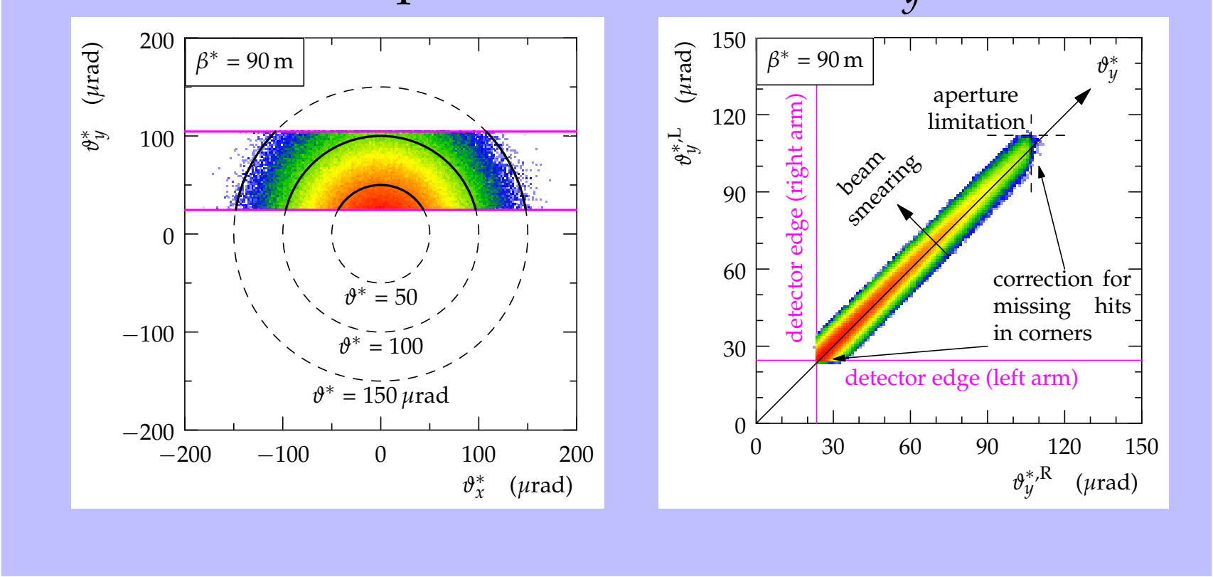
Background subtraction

- background = non-elastic events passing the cuts
- background integral
  - relax one of the cuts, keep others and plot the cut quantity (left plot)
  - fit signal (blue) and background (red)
  - integrate background collected in the selection region
- background typically < 1%
- background distribution
  - most of background protons left–right independent
  - extract one-arm t_x and t_y background distribution
  - calculate its contribution to elastic t distribution (right plot)



Acceptance correction

- acceptance limits:
  - detector size and position
  - LHC aperture limitations
- “φ correction” (left plot)
  - histogram of accepted events
  - events of fixed ϑ^* form circles (examples)
  - only part of the circle accepted (solid arcs)
  - need correction for the missed pieces (dashed arcs)
- “divergence correction” (right plot)
  - accounts for smearing around acceptance edges
  - beam smearing independent in right and left arms
  - reduced acceptance in corners of ϑ_y^*



III. Implications on the Total Cross Section

Method 1

- based on optical theorem

$$\sigma_\mathrm{tot}^2 = \frac{16\pi\,(\hbar c)^2}{1+\varrho^2}\,\left.\frac{\mathrm{d}\sigma_\mathrm{el}}{\mathrm{d}t}\right|_0$$

- $\mathrm{d}\sigma_\mathrm{el}/\mathrm{d}t|_0$ extrapolated from elastic differential cross section
- CMS luminosity used (4% uncertainty)
- result for small-bunch ($\approx 1\cdot 10^{10}$) data: EPL 96 (2011) 21002

$$\sigma_\mathrm{tot} = (98.3 \pm 2^\mathrm{lumi} \pm 0.5^\mathrm{syst} {}^{+0.8}_{-0.15}{}^{\varrho})\,\mathrm{mb}$$

- *preliminary* result for big-bunch ($\approx 6\cdot 10^{10}$) data

$$\sigma_\mathrm{tot} = (98.2 \pm 2^\mathrm{lumi} \pm 1^\mathrm{syst} {}^{+0.8}_{-0.15}{}^{\varrho})\,\mathrm{mb}$$

Method 2

- sum of elastic and inelastic cross sections

$$\sigma_\mathrm{tot} = \sigma_\mathrm{el} + \sigma_\mathrm{inel}$$

- σ_el by integrating elastic differential cross section, σ_inel from T1 and T2 telescopes (see the poster of Jan Welti)
- CMS luminosity used (4% uncertainty)
- ϱ not used as input
- *preliminary* result for big-bunch data

$$\sigma_\mathrm{tot} = (98.7 \pm 3.9^\mathrm{lumi} \pm 2.0^\mathrm{syst})\,\mathrm{mb}$$

Method 3

- based on optical theorem

$$\sigma_\mathrm{tot} = \frac{16\pi\,(\hbar c)^2}{1+\varrho^2}\,\frac{\left.\frac{\mathrm{d}N_\mathrm{el}}{\mathrm{d}t}\right|_0}{N_\mathrm{el} + N_\mathrm{inel}}$$

- N_el and $\mathrm{d}N_\mathrm{el}/\mathrm{d}t|_0$ from elastic differential rate, N_inel from T1 and T2 telescopes (see the poster of Jan Welti)
- luminosity independent
- *preliminary* result for big-bunch data

$$\sigma_\mathrm{tot} = (97.8 \pm 2.4^\mathrm{syst} {}^{+1.6}_{-0.3}{}^{\varrho})\,\mathrm{mb}$$