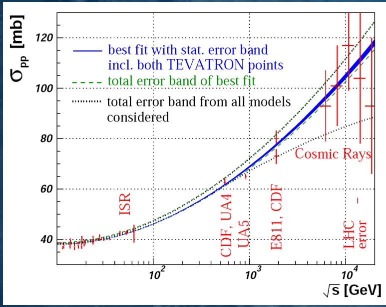
Soft Physics at the LHC with TOTEM

Jan Kašpar
CERN PH-TOT and
Institute of Physics of the AS CR
on behalf of the **TOTEM Collaboration**

La Thuile, March 3, 2009

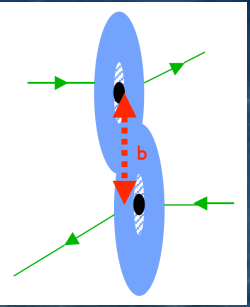
Total cross section

ultimately ≈ 1% precision

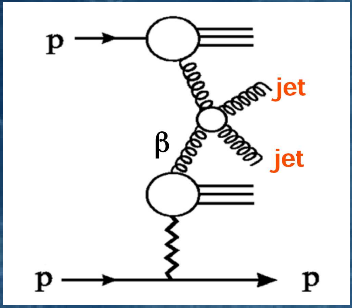


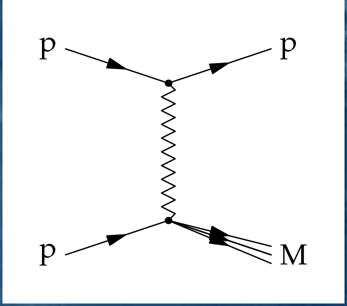
Elastic scattering

wide t range

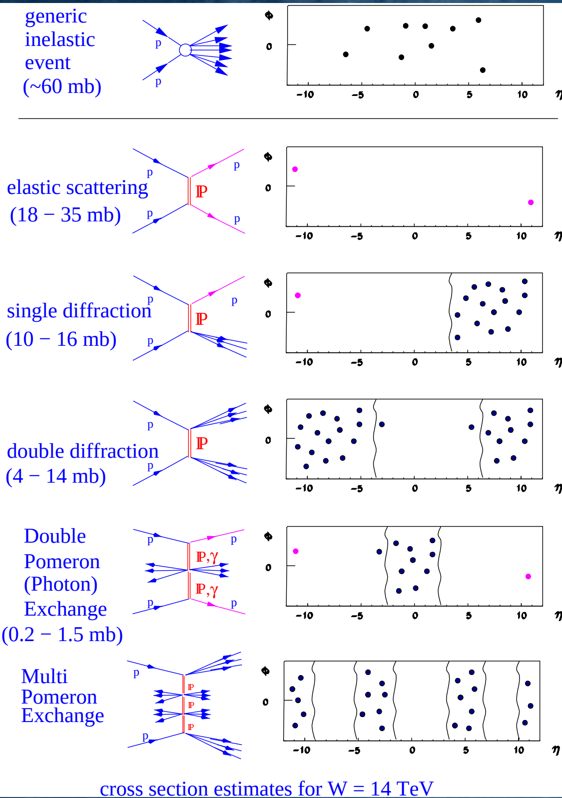


Hard and Soft Diffraction





Dominant Event Classes in pp Collisions



Non-diffractive events

- exchange of colour: Initial hadrons acquire colour and break up
- rapidity filled in hadronisation

$$\downarrow$$

exponential suppression of rapidity gaps

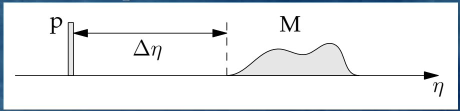
$$\downarrow$$

$$\text{prob}(\Delta\eta) \sim \exp^{-\lambda\,\Delta\eta}$$

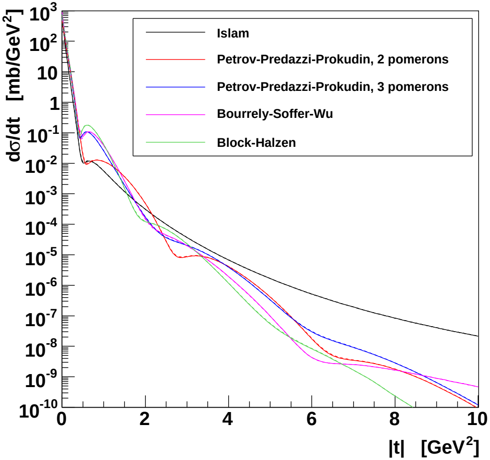
Diffractive events

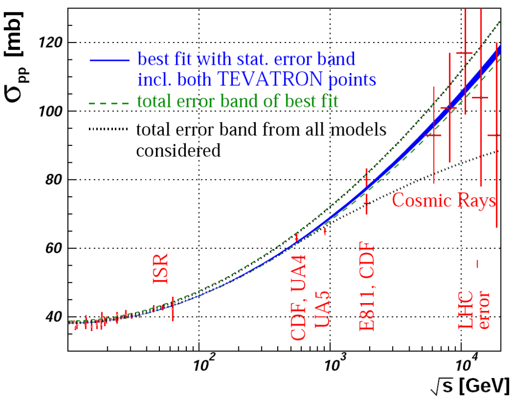
- exchange of colour singlets with vacuum quantum numbers (“Pomerons”)
- *rapidity gaps*

$$\text{prob}(\Delta\eta) \sim \text{const.}$$



- (often) *forward protons*





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

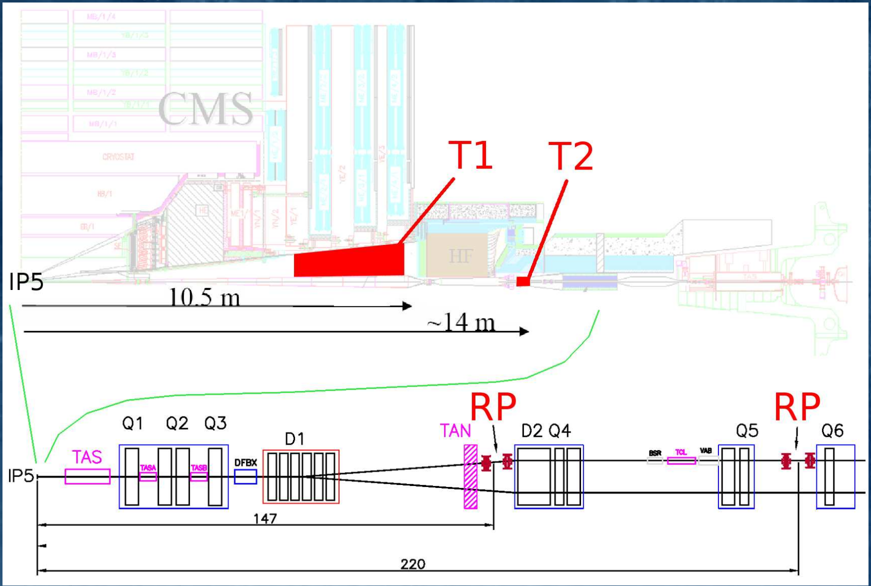
Total cross section

- 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.

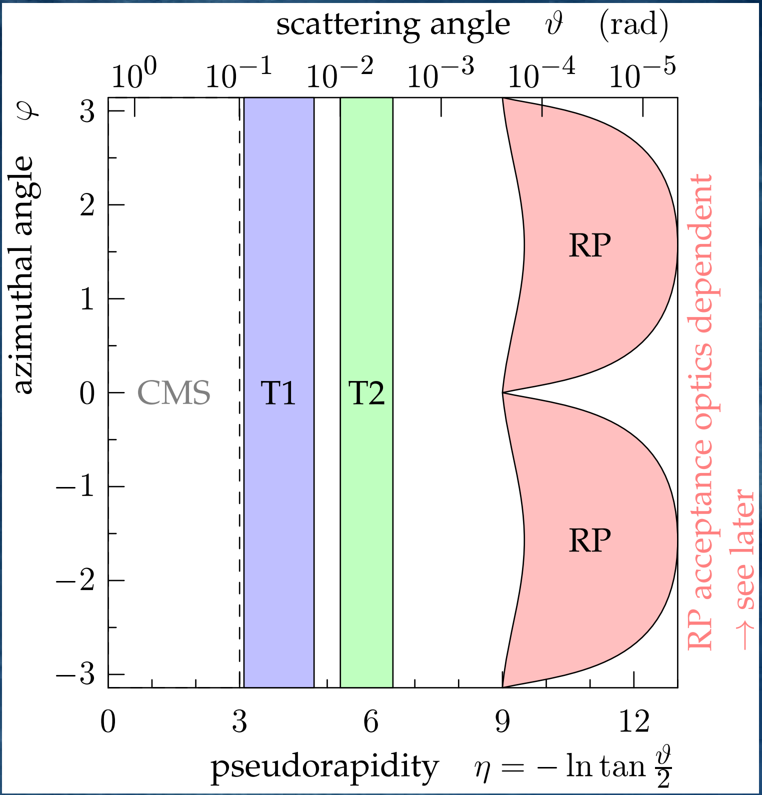
TOTEM = precise and decisive measurement

TOTEM Detectors

- physics requirements: *forward proton detectors* and *large pseudorapidity coverage*
- **Roman Pots**
  – measurement of forward protons
- telescopes **T1** and **T2**: tracking of charged particles produced in inelastic events
  – vertex reconstruction
  – measurement of inelastic rate
- all detectors symmetrically on both sides of IP5
- all detectors L1 *trigger capable*



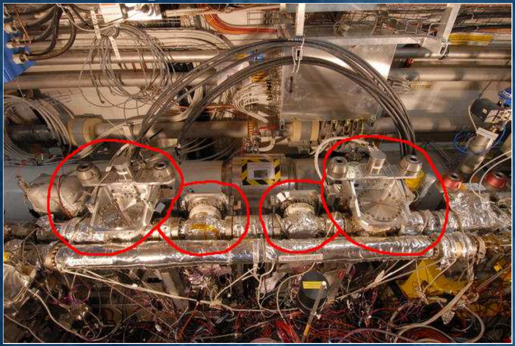
Acceptance of TOTEM Detectors

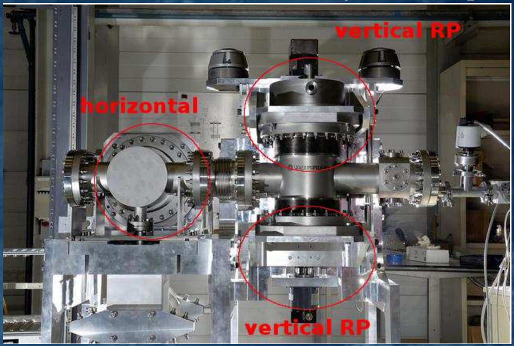


Roman Pots

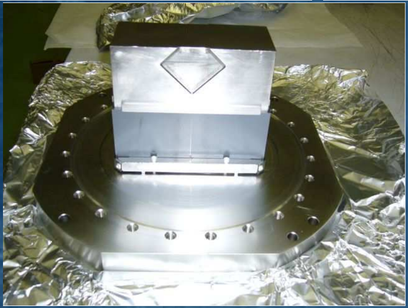
- stations at $-200, -147, +147$ and $+220$ m (measured from IP5)
- each station 2 units
- each unit 2 vertical and one horizontal RP
- each RP 10 strip silicon detectors

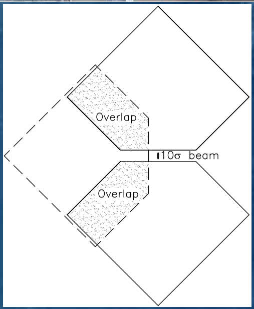
- *movable* insertions
  – instable beam → safe position
  – measurement: as close to beam as possible ($10\sigma + 0.5$ mm)
  → measurement of very forward protons





thin window 150 μm

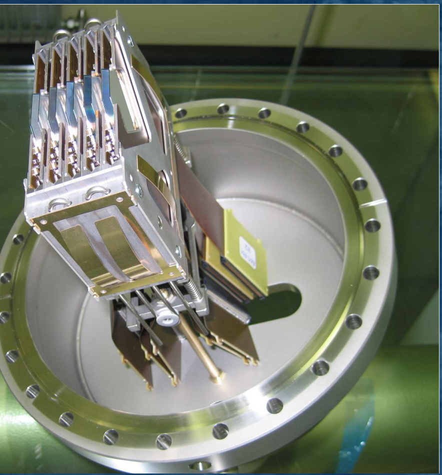


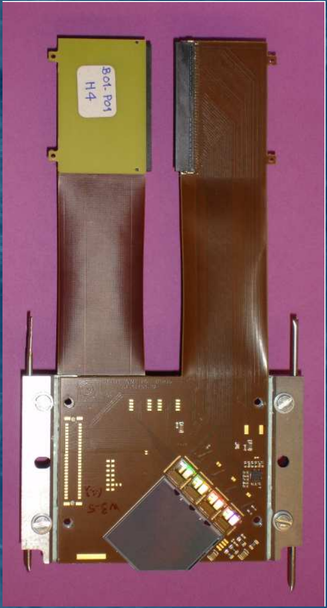


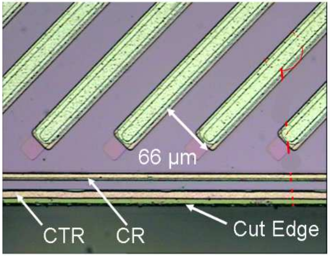
overlap ↓ alignment

Silicon Detectors

- each RP: 5×2 (back-to-back mounted) strip silicon detectors
- strip pitch 66 μm
- detection of low angles $\Rightarrow$ "edge less": only ≈ 50 μm dead area
- L1 trigger capability



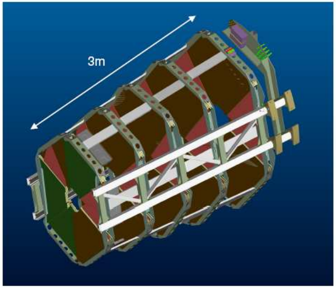




- installation ongoing, 220 m stations fully equipped by June
- for safety reasons (high background) 147 m stations only partially equipped (by June)

Telescope T1

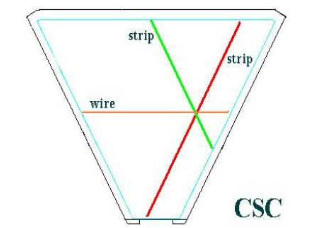
(in the center of the CMS end cup)



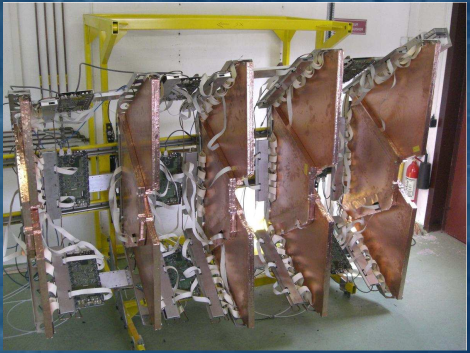
- 1 station per side of IP5
- each station: 5 planes
- each plane: 6 trapezoidal CSC detectors

- L1 trigger capability

- Cathode Strip Chamber detector
  - 3 coordinates: 2 cathode strips, 1 anode wire
  - Resolution ≈ 1 mm



- installation foreseen for May/June (eventually September)



Telescope T2

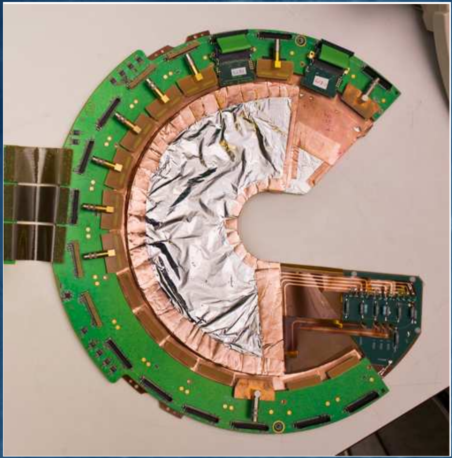
(after CMS HF calorimeter)

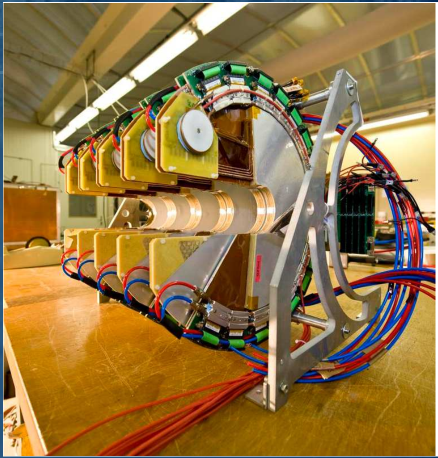
- one station on each side of IP5
- each station: two halves (left/right)
- each half: 5× 2 (back-to-back mounted) GEM detectors

- L1 trigger capability

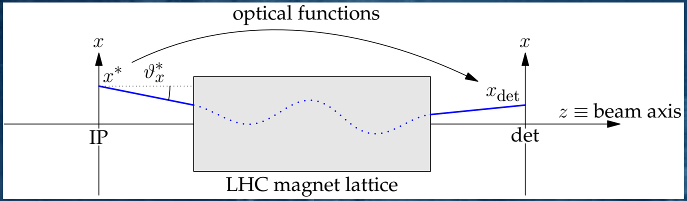
- triple Gas Electron Multiplier detectors
  - double readout: strips (radial) and pads (coarse radial and azimuthal)
  - resolution: radial 0.15 mm, azimuthal 0.8°

- installation ongoing, fully finished by May





Optics



proton transport equation

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

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

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

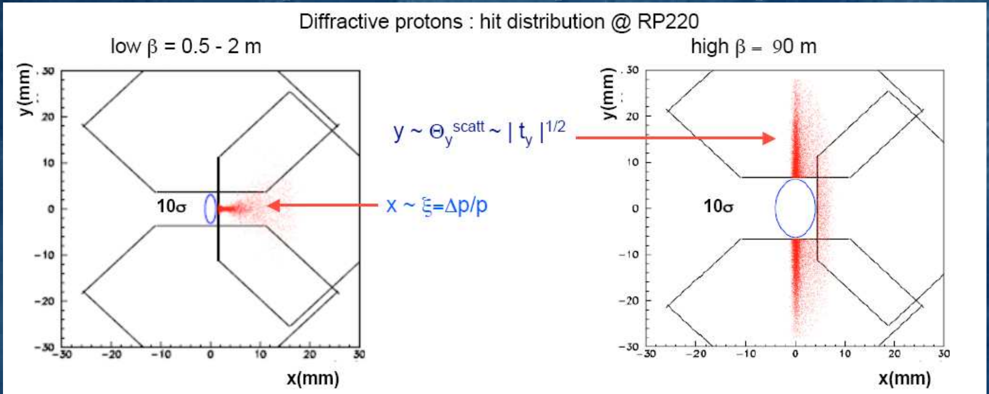
$L_{x,y}$, $v_{x,y}$ and D are optical functions

↓

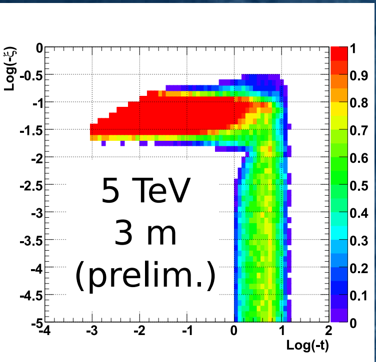
define which t and ξ can be seen ($\equiv$ acceptance)

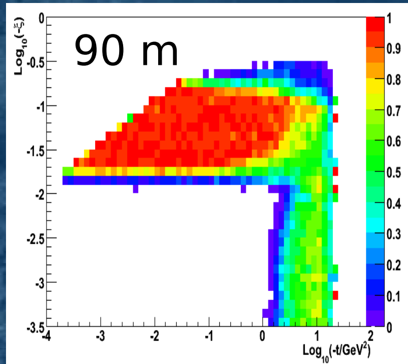
↓

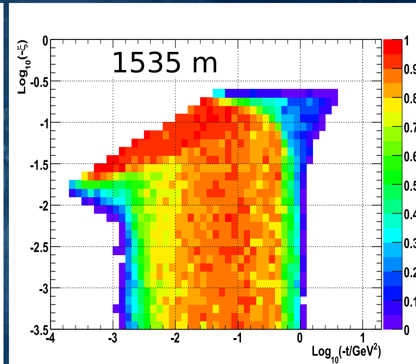
example: with the same sample of diffractive protons



Scenarios







low β^*

$\beta^* = 0.5 \div 2$ 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 ξ 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 ξ seen

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

Total Cross Section

- Luminosity Independent Method
  – based on Optical theorem: $\sigma_{\rm tot} \propto \Im A(t=0)$

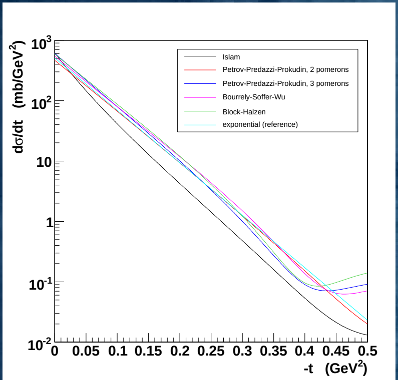
$$\sigma_{\rm tot} = \frac{1}{1+\varrho^2}\frac{{\rm d}N/{\rm d}t|_0}{N_{\rm el}+N_{\rm inel}}, \qquad \mathcal{L} = (1+\varrho^2)\frac{(N_{\rm el}+N_{\rm inel})^2}{{\rm d}N/{\rm d}t|_0}$$

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

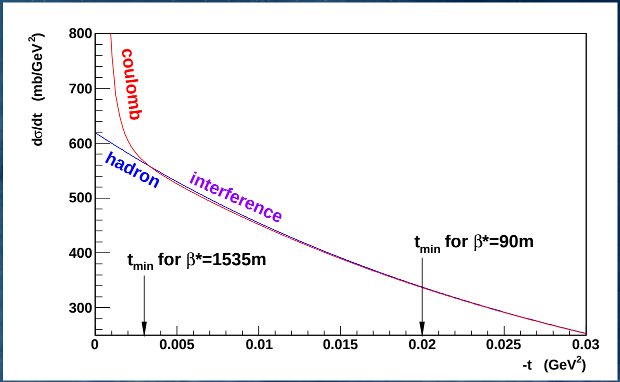
Table 1: Uncertainty estimates

Total Cross Section – details

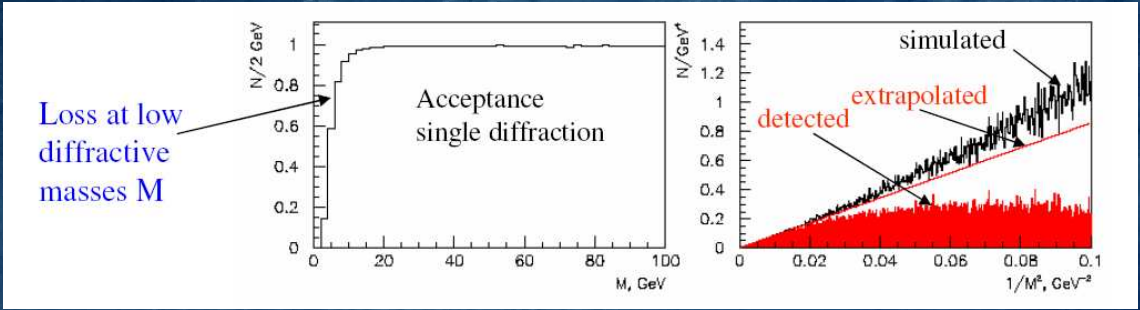
- exponential extrapolation



- coulomb interference ⇒ CKL formula



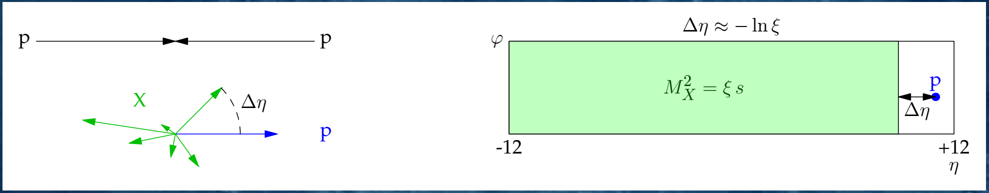
- inelastic rate – dominant trigger loss



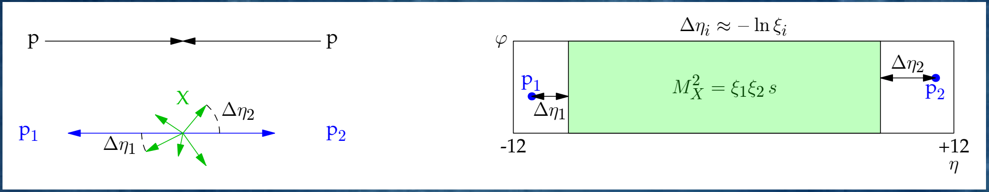
Early Measurements with RP

- the low β^* optics: $p = 5$ TeV, $\beta^* = 3$ m
  - acceptance: $0.02 < \xi < 0.18$
  - resolution: $\sigma(\xi) \lesssim 6 \cdot 10^{-3}$

1) SD, using horizontal RPs
   - $\mathrm{d}\sigma^{\mathrm{SD}}/\mathrm{d}M$ at high masses 1.4 TeV $< M < 4.2$ TeV, $\sigma(M)/M \approx 2 \div 4\%$



2) DPE, using horizontal RPs
   - $\mathrm{d}\sigma^{\mathrm{DPE}}/\mathrm{d}M$ at high masses 0.2 TeV $< M < 1.8$ TeV, $\sigma(M)/M \approx 2.1 \div 3.5\%$

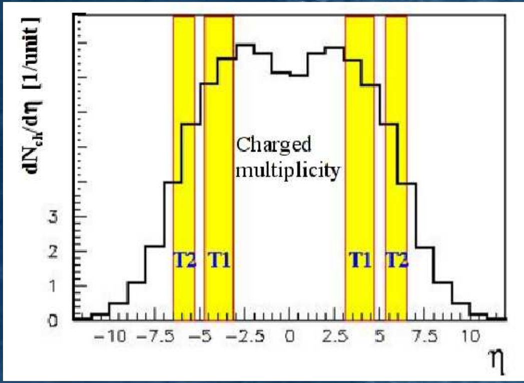


3) ES, using vertical RPs
   - $\mathrm{d}\sigma^{\mathrm{ES}}/\mathrm{d}t$, $2 \lesssim |t| \lesssim 10$ GeV^2, $\sigma(t) \approx 0.2/\sqrt{|t|}$

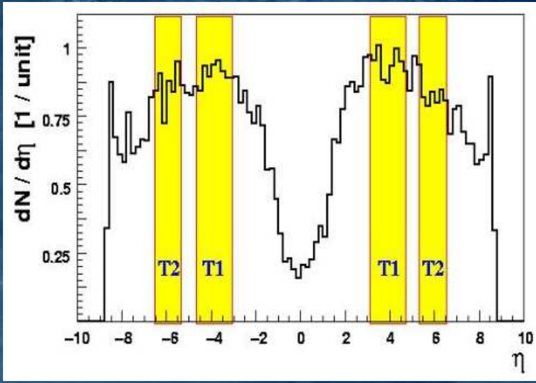
Early Measurements with T1 and T2

- charged multiplicity studies
  – important implications for cosmic ray physcis
- measurement of rapidity gaps

non-diffractive



single diffractive



Conclusions

- status
  - detectors partially installed, *fully installed* by ...
  - *TOTEM ready* for LHC restart
- beam conditions
  - TOTEM will run under *all beam conditions*
  - TOTEM will *need high β^* optics* $\rightarrow$ will require $\beta^* = 90$ m optics for early running

Early measurements

- low β^*
  - study of SD and DPE at high masses
  - elastic scattering at high $|t|$
  - measurement of forward charged multiplicity
- $\beta^* = 90$ m
  - 5% measurement of σ_{tot}
  - inclusive studies of the main diffractive processes
  - elastic scattering already in a wide range of t
  - measurement of forward charged multiplicity

Later

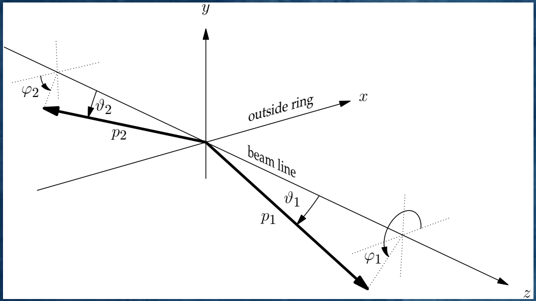
- precision σ_{tot} measurement ($1 \div 2\%$), will need the $\beta^* = 1535$ m optics at dedicated short TOTEM runs
- an extensive physics programme together with CMS

Thank you for your attention

Backup slides

Kinematics

- using small ϑ and high energy approximation

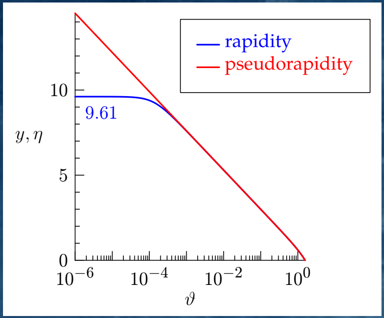


$$\mathbf{p}_1 = p_{\mathrm{nom}}(1+\xi_1)\begin{pmatrix}\vartheta_1\cos\varphi_1\\ \vartheta_1\sin\varphi_1\\ 1\end{pmatrix}$$

$$\mathbf{p}_2 = -p_{\mathrm{nom}}(1+\xi_2)\begin{pmatrix}\vartheta_2\cos\varphi_2\\ \vartheta_2\sin\varphi_2\\ 1\end{pmatrix}$$

- momentum transfer (capital P denotes four-momentum)

$$t_1 = (P_1' - P_1)^2 \approx -p_{\mathrm{nom}}^2(1+\xi_1)^2\vartheta_1^2$$



- rapidity

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

- pseudorapidity

$$\eta = -\ln\tan\frac{\vartheta}{2}$$

$\longleftarrow$ for proton of $p = 7$ TeV

Optics details

- ε = emittance (3.75 normal, 1 reduced for low β^* optics)
- $\gamma = E/m_0$ relativistic factor of proton
- proton trajectory

$$x(s) = \sqrt{\varepsilon\beta(s)}\cos\phi(s) + D(s)\xi$$

- high β^* $\Rightarrow$ thick beam $\Rightarrow$ need for parallel-to-point focusing $\equiv$ negligible v-terms
- optical functions

$$v(s) = \sqrt{\frac{\beta(s)}{\beta^*}}\cos\phi(s)$$

$$L(s) = \sqrt{\beta(s)\beta^*}\sin\phi(s)$$

$$\phi(s) = \int_0^s \frac{\mathrm{d}s'}{\beta(s')}$$

$$\sigma(\text{vertex}) = \sqrt{\frac{\varepsilon\beta^*}{\gamma}}$$

$$\sigma(\text{beam divergence}) = \sqrt{\frac{\varepsilon}{\beta^*\gamma}}$$

- details: see Ref. [1]

Scenarios

- $p = 5$ TeV, $\beta^* \sim 3$ m, $\mathcal{L} = low$ for early runs, $\approx 10^{33}$ later
- σ(vertex) $\approx 32\ \mu$m, σ(beam divergence) $\approx 16\ \mu$rad
- only t_y practically resolvable
- elastic acceptance: $2 \lesssim |t/\text{GeV}^2| \lesssim 10$
- reco. precision: $\sigma(\vartheta) \approx 15\ \mu$rad, $\sigma(\xi) \approx 0.006 \div 0.01$

$\Rightarrow$ diffraction, high $|t|$ elastic scattering

- $p = 7$ TeV, $\beta^* = 90$ m, $\mathcal{L} \approx 10^{30}$
- σ(vertex) $\approx 212\ \mu$m, σ(beam divergence) $\approx 2.3\ \mu$rad
- vertical parallel-to-point focusing, all ξ seen
- $L_x \approx 0 \Rightarrow$ only t_y practically resolvable
- elastic acceptance: $10^{-2} < |t_y/\text{GeV}^2| \lesssim 10$
- reco. precision: $\sigma(\vartheta) \approx 1.7\ \mu$rad, $\sigma(\xi) \approx 0.006$

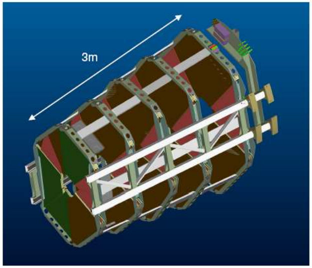
$\Rightarrow$ diffraction, mid $|t|$ el. scat., total cross section

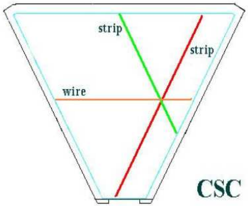
- $p = 7$ TeV, $\beta^* = 1535$ m, $\mathcal{L} \approx 10^{28} \div 10^{29}$
- σ(vertex) $\approx 450\ \mu$m, σ(beam divergence) $\approx 0.3\ \mu$rad
- parallel-to-point focusing, all ξ seen
- elastic acceptance: $3 \cdot 10^{-3} < |t/\text{GeV}^2| < 0.5$
- reco. precision: $\sigma(\vartheta) \approx 0.3\ \mu$rad, $\sigma(\xi) \approx 0.005$

$\Rightarrow$ total cross section, low $|t|$ elastic scattering

Telescope T1

- 5 planes, each formed by 6 trapezoidal CSC detectors
  - 3° rotation and overlap between adjacent planes
  - Resolution ≈ 0.8 mm
- CSC detector
  - 3 coordinates: 2 cathode strips, 1 anode wire
  - Anode wires: diameter 30 μm, 3 mm pitch
  - Cathode strips: 4.5 mm width, 5 mm pitch
  - Trigger with anode wires
  - Gas Mixture $Ar/CO_2/CF_4$
  - Gas gap: 10 mm
  - Max size: ≈ 1 mx0.68 m

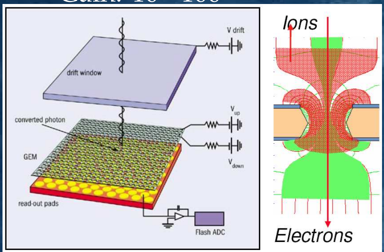


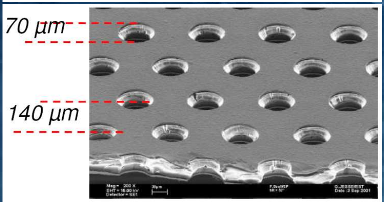


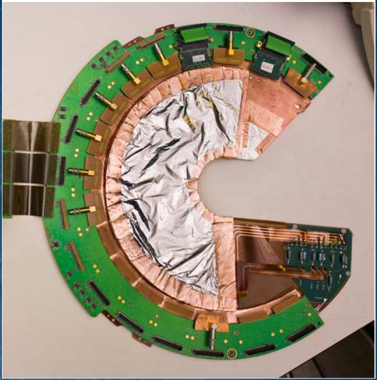
Telescope T2

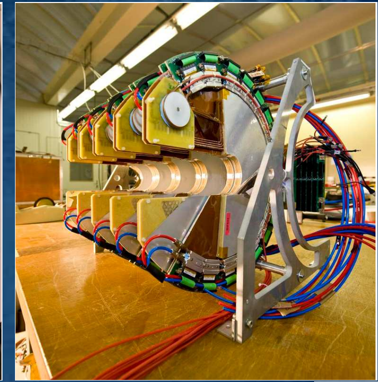
- T2: 10 planes formed by 20 GEM semi-circular modules
  – back-to-back assembly and overlap between modules
  – double read-out: strips for radial position, pads for both rad and azimuthal
  – Trigger from Pads, 1560/chamber,

- triple GEM detectors
  – gas detector, radiation hard, high rate, good spatial, and timing resolution
  – Electrodes: 50 μm kapton + 2×5 μm Cu
  – Density: $50 - 100$ holes/mm^2
  – Electric field (channel) ≈ 100 KV/cm $\Rightarrow$ electron cascade
  – Gain: 10 - 100









Trigger Schemes

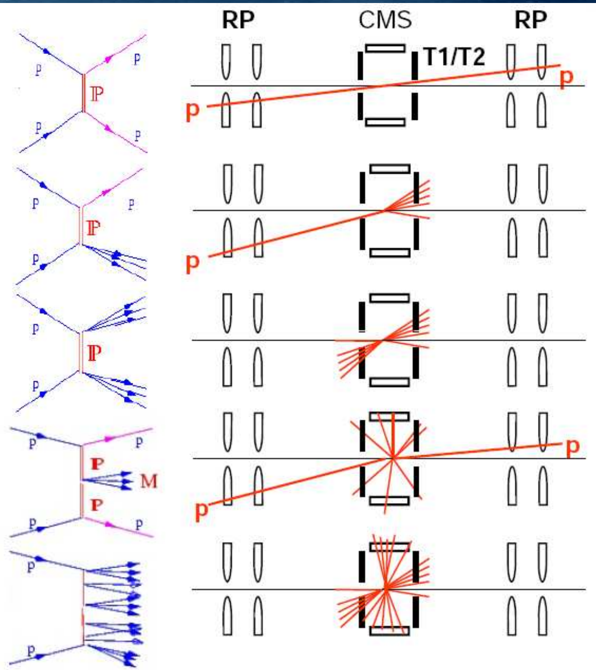
Elastic Trigger:

Single Diffractive Trigger:

Double Diffractive Trigger:

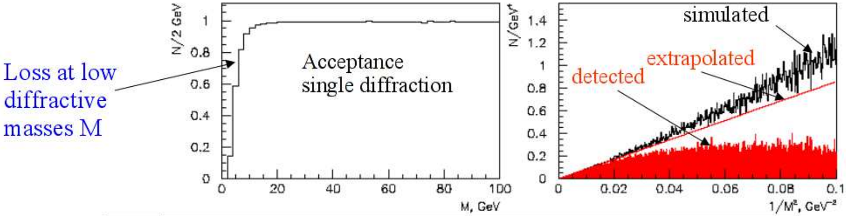
Central Diffractive Trigger
(Double Pomeron Exchange DPE)

Non-diffractive Inelastic Trigger:



Measurement of the inelastic rate

- 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 $d\sigma/dM^2 \sim 1/M^2$:
  - $d\sigma_{SD}/dM$ can be measured with high β optics, not with low β (only for very high 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**

Pseudorapidity Distributions for SD