Physics at LHC

The First Year at LHC: Diffractive Physics

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17.07.2004

Diffraction at LHC Experiments

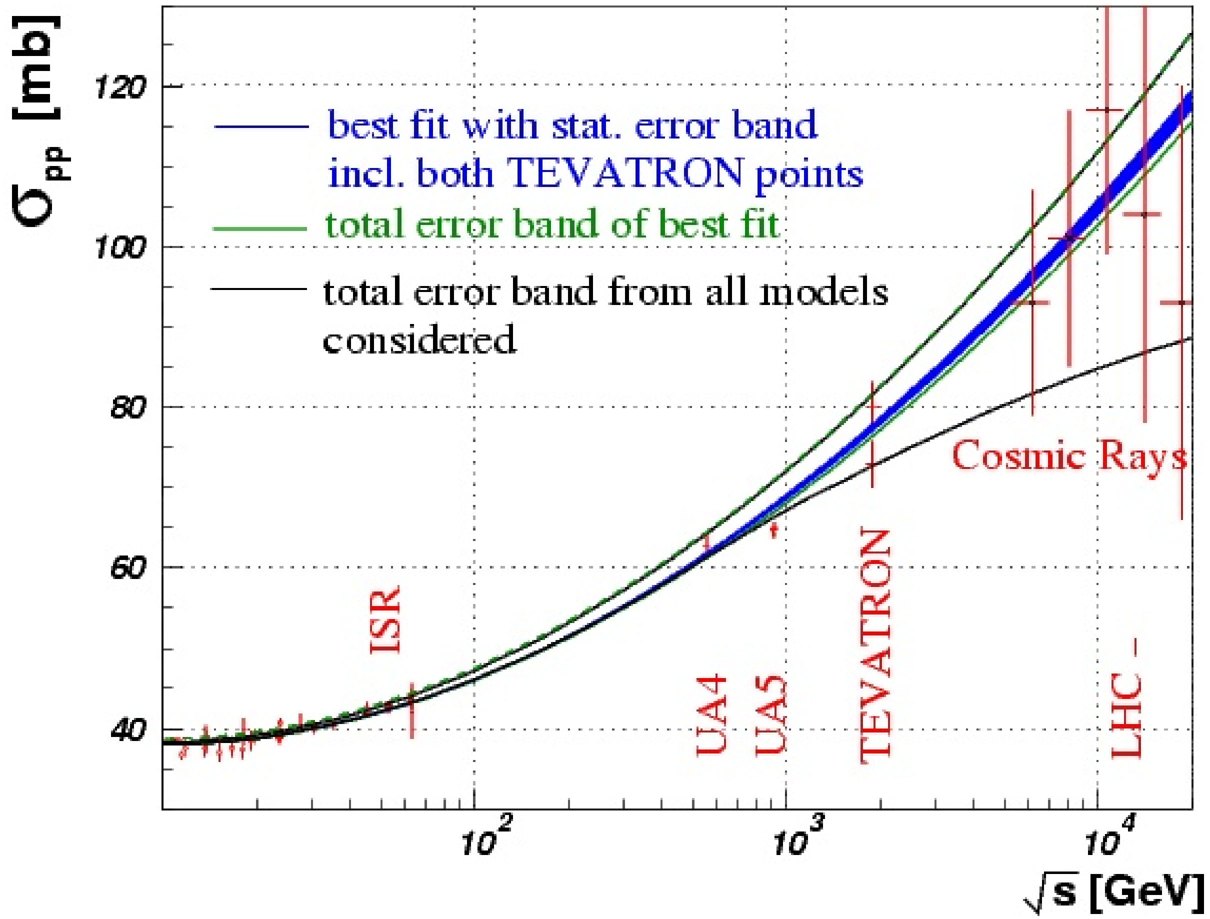
- TOTEM: approved for:
  - Elastic p-p scattering cross-section dσ/dt in the range $10^{-3}\ \mathrm{GeV}^2 < -t < 8\ \mathrm{GeV}^2$
  - Total p-p cross section at 14 TeV with 1% uncertainty using the Optical Theorem (luminosity independent method)
  - Absolute luminosity measurement
  - Study of diffractive events (together with CMS)
- ATLAS: Letter of Intent:
  - Luminosity measurement using elastic scattering in Coulomb region
  - Interest in diffraction
- ALICE:

  Interest in diffraction

Running Scenarios

Scenario **Physics:**	1 **low |t| elastic, σ_{tot}, min. bias, soft diffraction**	2 **large |t| elastic**	3 **diffraction**	4 **hard diffraction** (under study)
β^* [m]	**1540**	**18**	**1540**	**200 - 400**
N of bunches	**43**	**2808**	**156**	**936**
N of part. per bunch	**0.3×10^{11}**	**1.15×10^{11}**	**$(0.6 - 1.15) \times 10^{11}$**	**1.15×10^{11}**
Half crossing angle [µrad]	**0**	**160**	**0**	**100 - 200**
Transv. norm. emitt. [µm rad]	**1**	**3.75**	**1 - 3.75**	**3.75**
RMS beam size at IP [µm]	**454**	**95**	**454 - 880**	**317 - 448**
RMS beam diverg. [µrad]	**0.29**	**5.28**	**0.29 - 0.57**	**1.6 - 1.1**
Peak luminosity [$cm^{-2} s^{-1}$]	**1.6×10^{28}**	**3.6×10^{32}**	**2.4×10^{29}**	**$\sim 10^{31}$**

Total p-p Cross-Section



Current models predictions: 90-130 mb

Aim of TOTEM: **~1%** accuracy

COMPETE Collaboration fits all available hadronic data and predicts:

LHC:

$$\boxed{\sigma_{tot} = 111.5 \pm 1.2 \begin{array}{l} +4.1 \\ -2.1 \end{array} \text{ mb}}$$

[PRL 89 201801 (2002)]

Measurement of σ_{tot}

TOTEM: Luminosity-independent measurement using the Optical Theorem:

$$\left.\begin{array}{l} \mathcal{L}\sigma_{tot}^2 = \dfrac{16\pi}{1+\rho^2}\times\left.\dfrac{dN_{el}}{dt}\right|_{t=0} \\[2ex] \mathcal{L}\,\sigma_{tot} = N_{el}+N_{inel} \end{array}\right\} \Rightarrow \boxed{\sigma_{tot} = \frac{16\pi}{1+\rho^2}\times\frac{\left.(dN_{el}/dt)\right|_{t=0}}{N_{el}+N_{inel}}}$$

- Measure the total rate $N_{el} + N_{inel}$ with a precision of better than 1% (running for 1 day at $\mathcal{L} = 1.6 \times 10^{28}$ cm^{-2} s^{-1}).
- Extrapolate the elastic cross-section to $t = 0$ (0.5 % ≅ 1 day).

Or conversely: extract luminosity:

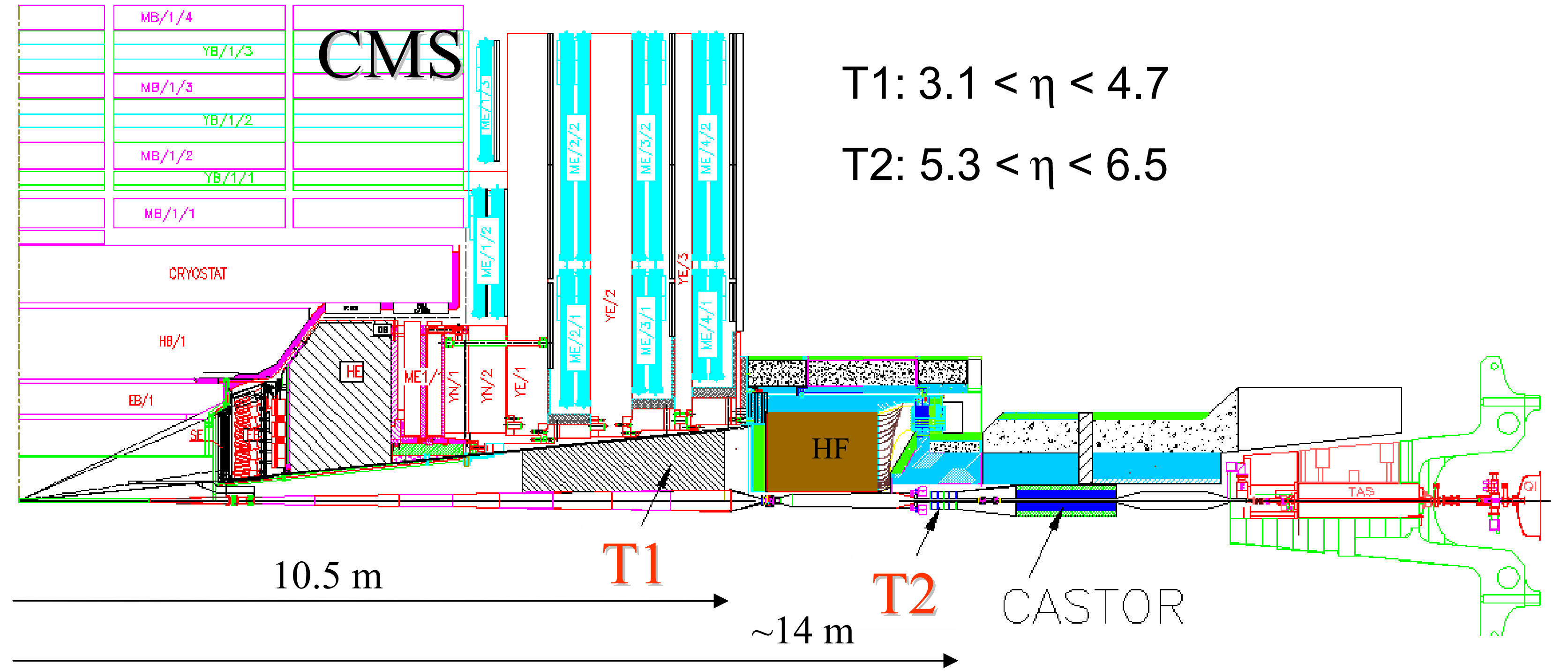
$$\mathcal{L} = \frac{1+\rho^2}{16\pi}\,\frac{(N_{el}+N_{inel})^2}{\left.(dN_{el}/dt)\right|_{t=0}}$$

ATLAS approach: try to reach Coulomb region.

Fit
$$\frac{dN}{dt} = \mathcal{L}\pi\left|f_C+f_N\right|^2 \approx \mathcal{L}\pi\left|-\frac{2\alpha}{|t|}+\frac{\sigma_{\mathrm{tot}}}{4\pi}(i+\rho)\mathrm{e}^{-\mathrm{b}|\mathrm{t}|/2}\right|^2$$

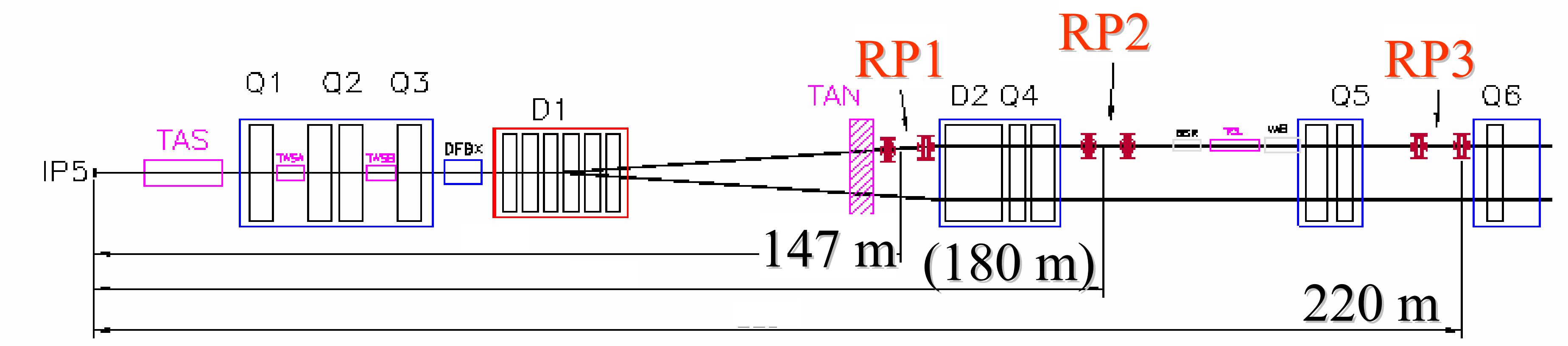
Required reach in t: $|t|_{\min} \leq -t\ (|f_C|=|f_N|) \approx 6\times10^{-4}$ GeV^2

TOTEM+CMS Detector Configuration



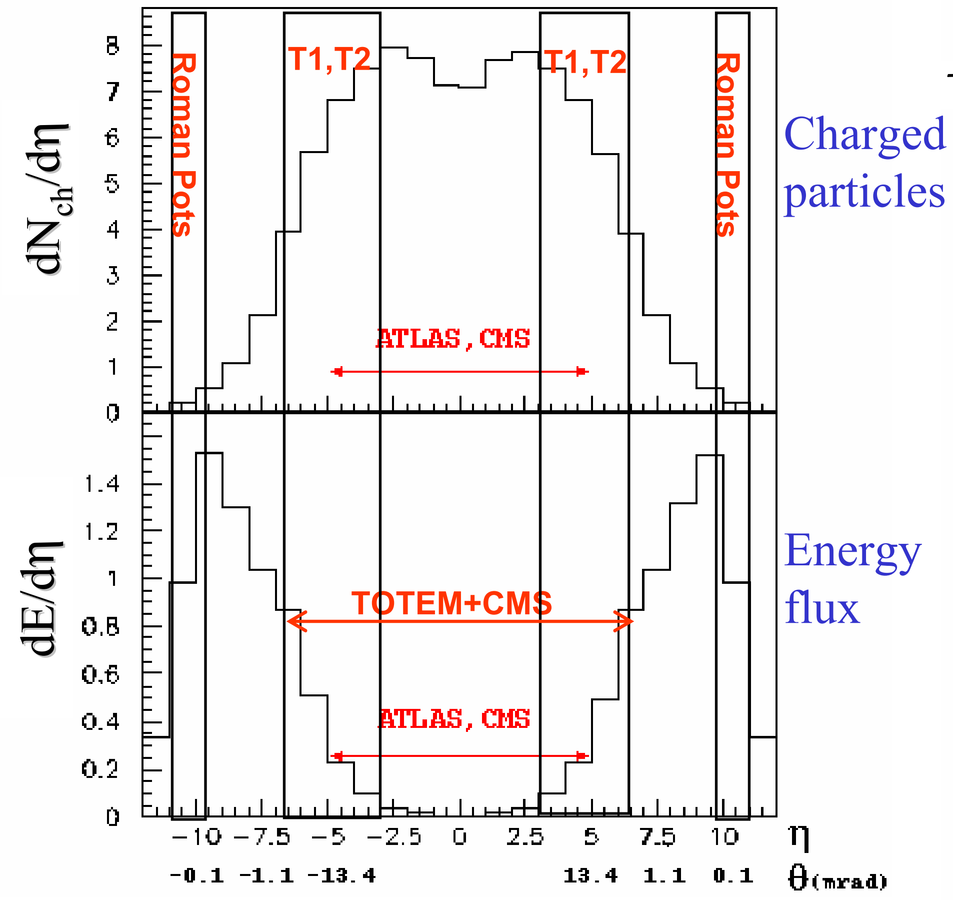
T1: 3.1 < η < 4.7

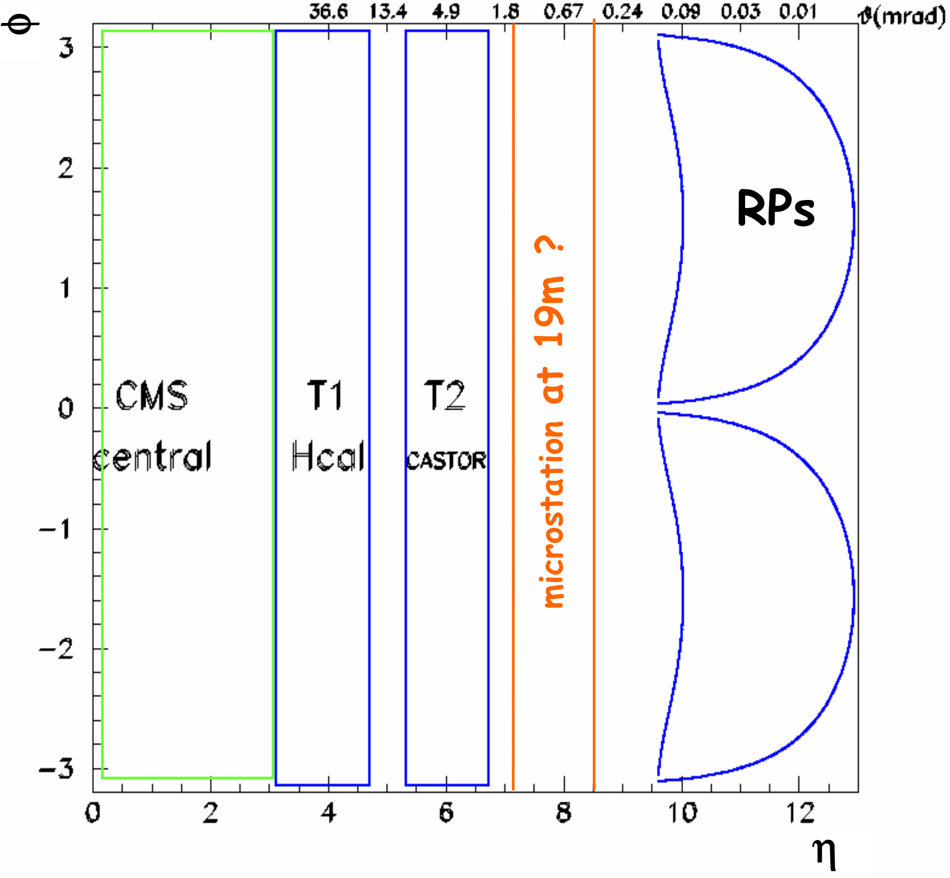
T2: 5.3 < η < 6.5



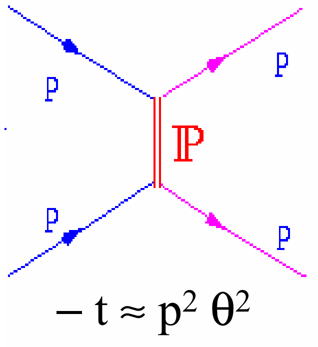
CMS + TOTEM: Acceptance

Rapidity distributions per inelastic event:

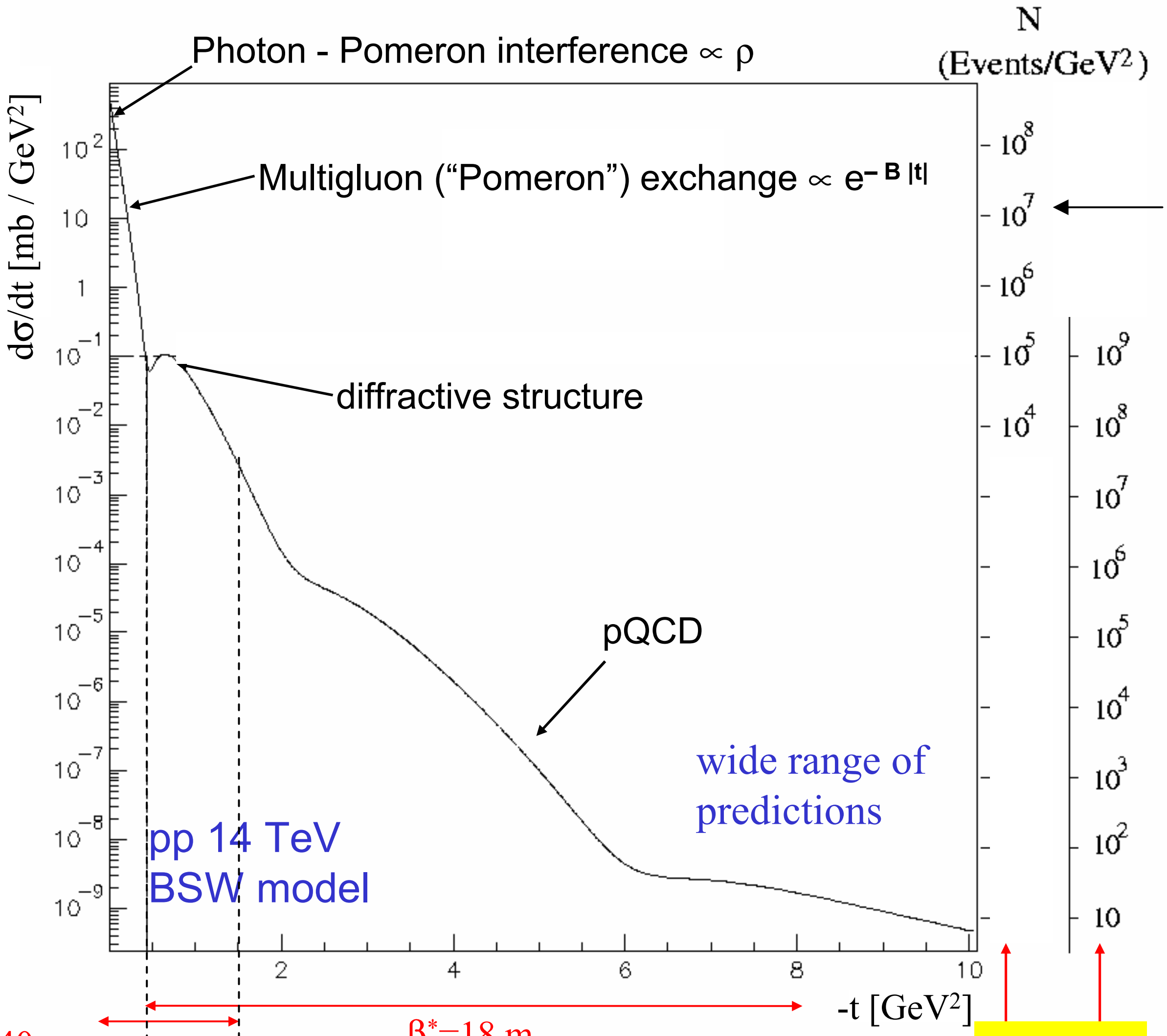




Elastic Scattering Cross-Section



$-t \approx p^2 \theta^2$



Photon - Pomeron interference ∝ ρ

Multigluon ("Pomeron") exchange $\propto e^{-B|t|}$

diffractive structure

pQCD

wide range of predictions

pp 14 TeV
BSW model

10^4 per bin of 10^{-3} GeV²

$\beta^* = 1540$ m
$\mathcal{L} = 1.6 \times 10^{28}$ cm^{-2} s^{-1}

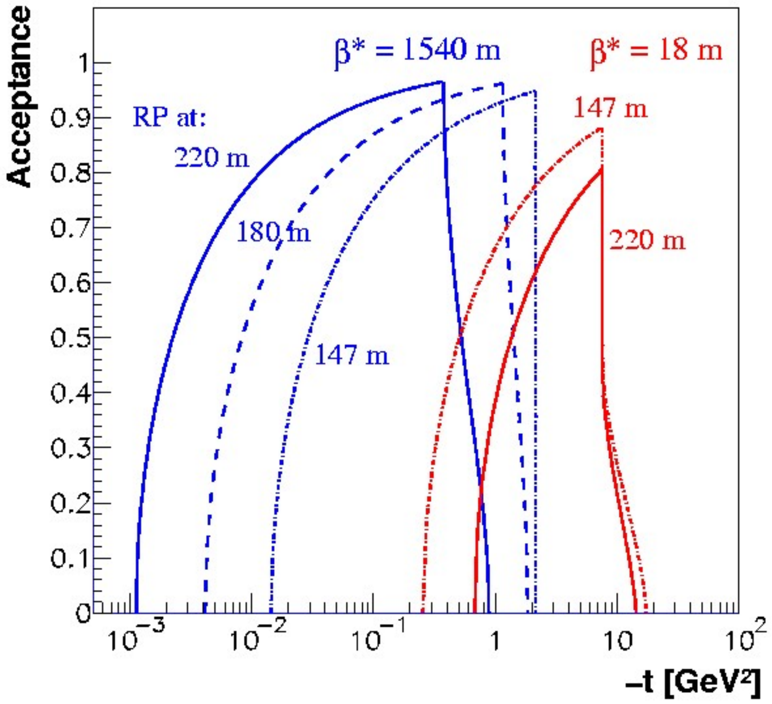
(1)

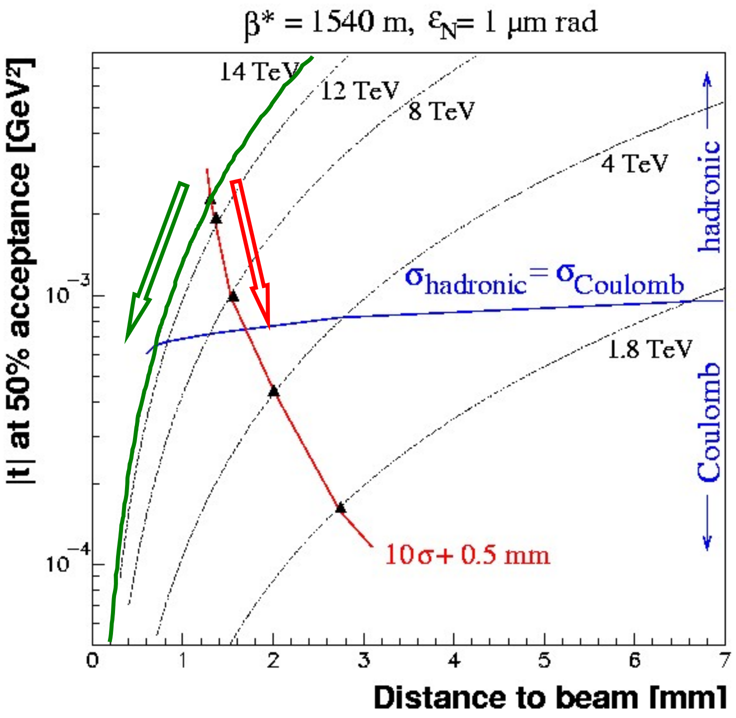
$\beta^* = 18$ m
$\mathcal{L} = 3.6 \times 10^{32}$ cm^{-2} s^{-1}

(2)

~1 day
(1) **(2)**

Elastic Scattering: t-Acceptance





Try to reach the Coulomb region and measure interference:

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

Conclusions, Outlook (1)

With runs of typically 1 day (repeated several times)
at $\beta^* = 1540$ m and 18 m:

- Total cross-section and luminosity measurement to ~1%
- Elastic scattering: 5×10^7 elastic events

  $d\sigma/dt$ in 10^{-3} GeV^2 $< -t <$ 8 GeV^2
- Try to measure Coulomb/nuclear interference at lower $\sqrt{s}$

Conclusions, Outlook (1)

With runs of typically 1 day (repeated several times) at $\beta^* = 1540$ m and 18 m:

- Total cross-section and luminosity measurement to ~1%
- Elastic scattering: $5\text{x}10^7$ elastic events
  $d\sigma/dt$ in 10^{-3} GeV$^2 < -t < 8$ GeV^2
- Try to measure Coulomb/nuclear interference at lower $\sqrt{s}$

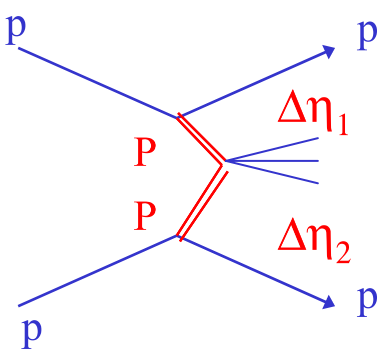
But: We can do more even without taking additional data.

At that point already collected:

- ~ 10^8 minimum bias events
- ~ 5 x 10^7 elastic events
- ~ 3.5 x 10^7 diffractive events

Diffraction

Example:

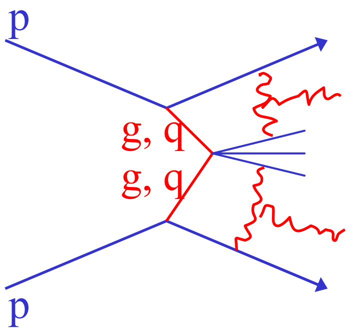


Exchange of colour singlets ("Pomerons")

→ **rapidity gaps** Δη

Most cases: leading proton(s) with momentum loss $\Delta p / p \equiv \xi$

Unlike minimum bias events:



Exchange of colour triplets or octets:

Gaps filled by colour exchange in hadronisation

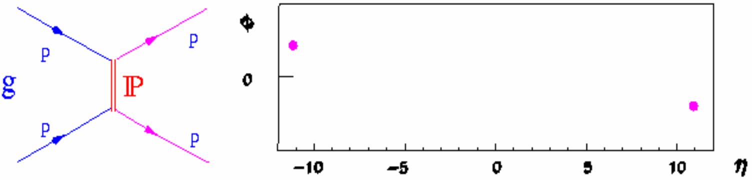
→ **Exponential suppression of rapidity gaps:**

$P(\Delta\eta) = e^{-\rho\,\Delta\eta}$, $\rho = dn/d\eta$

Diffractive Events at β*= 1540 m

$\mathcal{L}$ = 1.6 x 10^{28} cm^{-2} s^{-1} | 2.4 x 10^{29} cm^{-2} s^{-1}

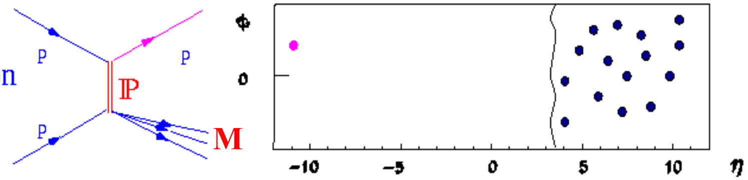
elastic scattering



σ ≈ 30 mb
480 Hz

7.2 kHz
(but limited by DAQ)

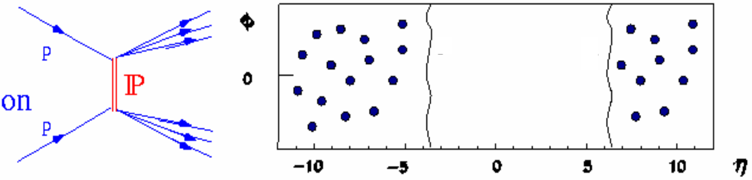
single diffraction



σ ≈ 14 mb
240 Hz

3.6 kHz

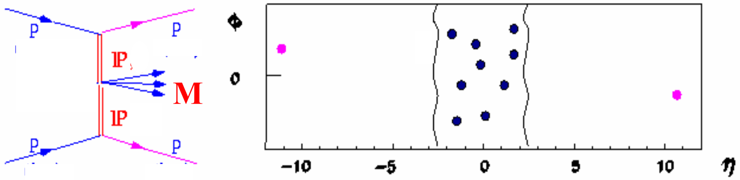
double diffraction



σ ≈ 7 mb
120 Hz

1.8 kHz

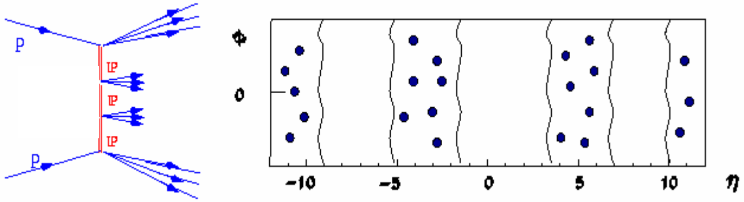
Double
Pomeron
Exchange



σ ≈ 0.5 mb
8 Hz

120 Hz

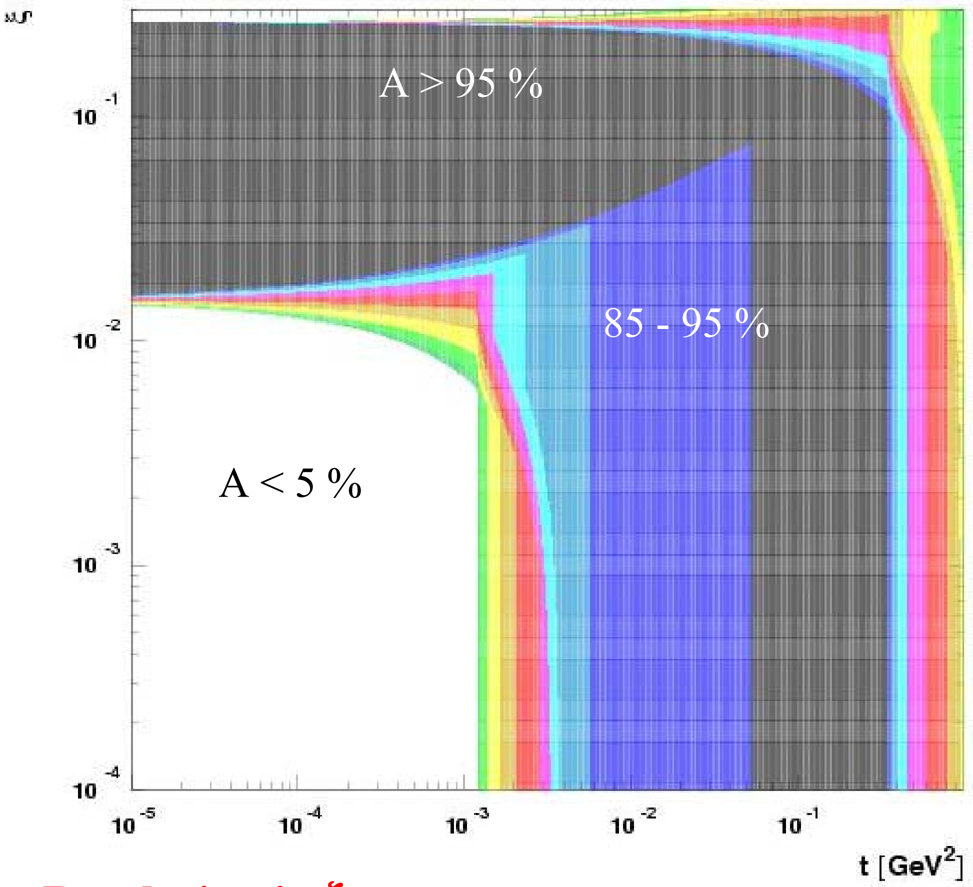
Multi
Pomeron
Exchange



Ask Bj.

Diffraction at high β*: Acceptance

Leading protons in diffraction characterised by $t = -p^2 \theta^2$ and $\xi = \Delta p / p$



β* = 1540 m,
RP at 220 m:

~ 90 % of all diffractive protons are seen in the Roman Pots

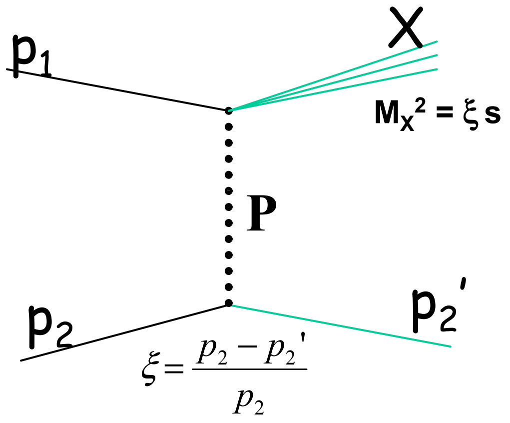
(assuming $\frac{d\sigma}{d\xi dt} \propto \frac{1}{\xi} e^{-7|t|}$ **).**

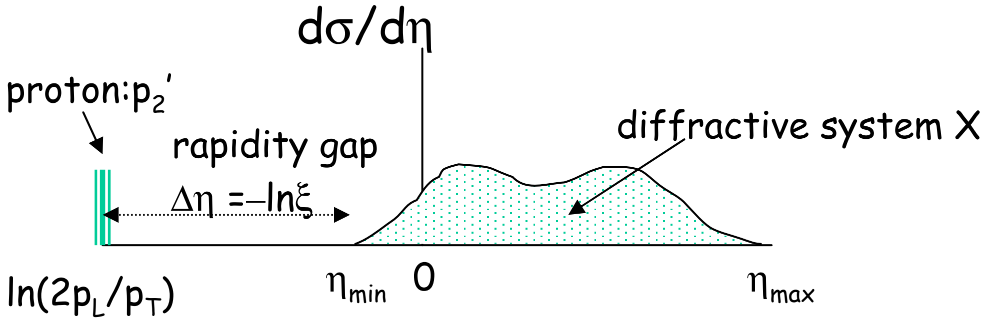
Resolution in ξ:

β* = 1540 m:	$\sigma(\xi) = 5 \times 10^{-3}$	($\mathcal{L} \leq 2.4 \times 10^{29}$ cm^{-2} s^{-1})
β* = 200 ÷ 400 m:	$\sigma(\xi) \sim 1 \times 10^{-3}$	($\mathcal{L} \leq 10^{31}$ cm^{-2} s^{-1})

Example Processes

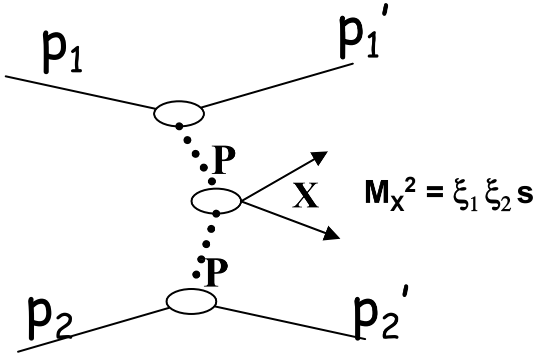
Single Diffraction:

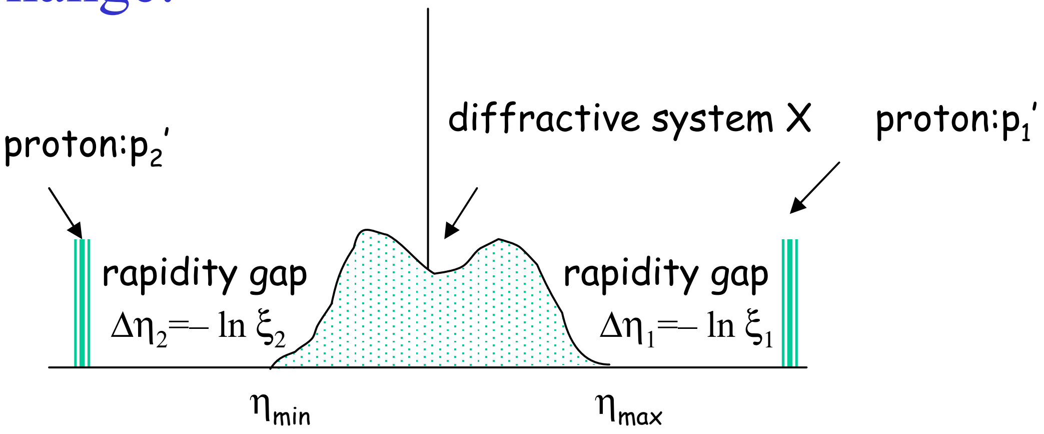




Measure leading proton (→ ξ) and rapidity gap (⇒ test gap survival).

Double Pomeron Exchange:

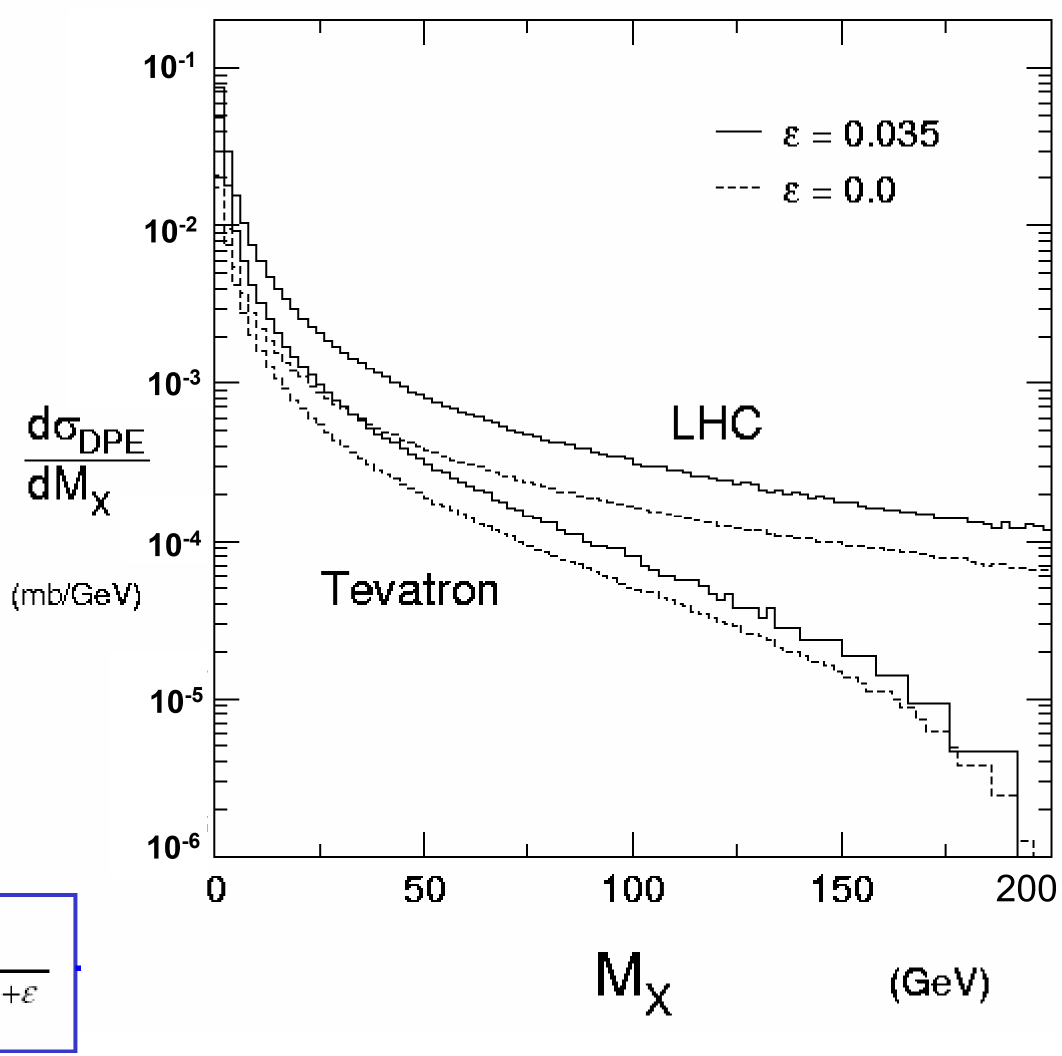




Measure leading protons (→ ξ_1, ξ_2) and compare with M_X, $\Delta\eta_1$, $\Delta\eta_2$

Double Pomeron Exchange: Cross-Section

$\sigma_{DPE} = 0.5 - 1$ mb $\Rightarrow$ (1–2) x 10^7 events per day at $\beta^* = 1540$ m, $\mathcal{L} = 2 \times 10^{29}$ cm^{-2} s^{-1}



Events / GeV

2×10^6	**10^8**
2×10^5	**10^7**
2×10^4	**10^6**
2000	**10^5**
200	**10^4**
20	**10^3**

~ 1 day

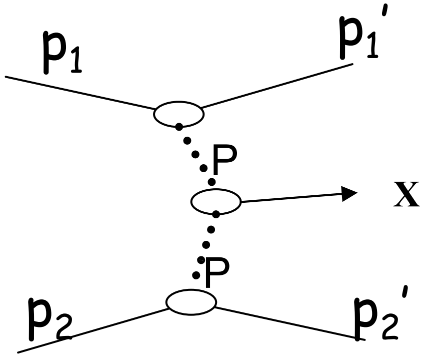
(3) , (4)

$\mathcal{L} = 2 \times 10^{29}, 10^{31}$ cm^{-2}s^{-1}

$$\frac{d\sigma}{dM^2} \propto \frac{1}{(M^2)^{1+\varepsilon}}$$

[ε from Pomeron trajectory α(t) = 1 + ε + α' t]

Exclusive Production by DPE



Advantages:

- exchange of colour singlets with vacuum quantum numbers

  $\Rightarrow$ Selection rules: $J^P = 0^+, (2^+, 4^+); C = +1$

  $\Rightarrow$ reduced background $gg \rightarrow qq$ (0 if $m_q = 0$ and $t_p = 0$)

  constraints on quantum numbers of resonances.

- Good ϕ resolution in TOTEM: determine parity:

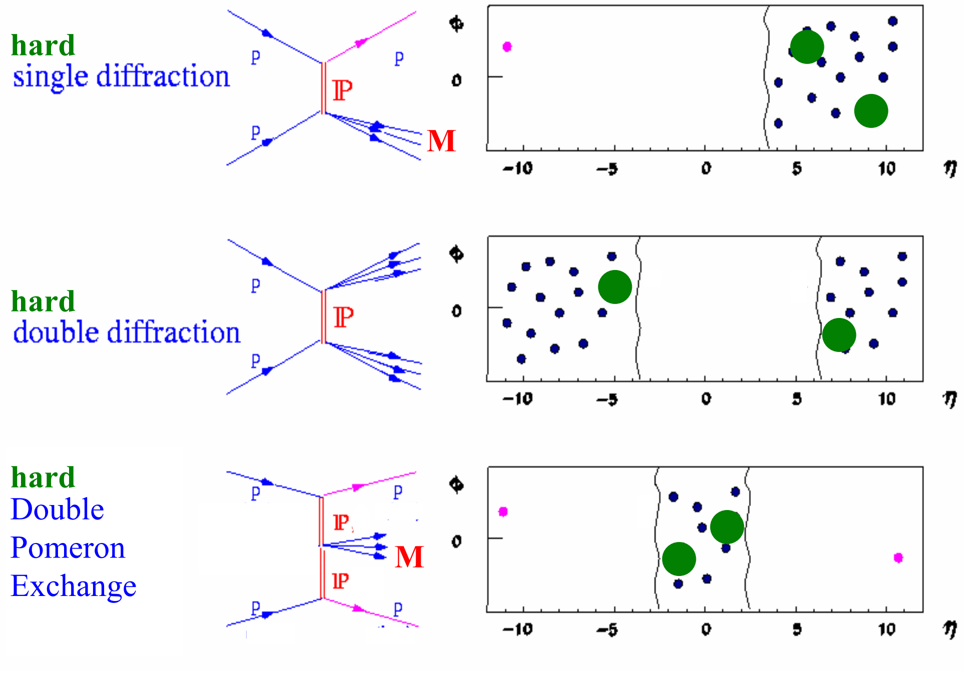
  $P = (-1)^{J(+1)} \Leftrightarrow d\sigma/d\phi \sim 1 +(-) \cos 2\phi$

Particle	σ_{excl}	Decay channel	BR	Rate at $2\text{x}10^{29}$ cm^{-2} s^{-1}	Rate at 10^{31} cm^{-2} s^{-1}
χ_{c0} (3.4 GeV)	3 μb [KMRS]	$\gamma J/\psi \rightarrow \gamma \mu^+\mu^-$ $\pi^+\pi^- K^+K^-$	$6 \text{ x } 10^{-4}$ 0.018	1.3 / h 39 / h	65 / h 1900 / h
χ_{b0} (9.9 GeV)	4 nb [KMRS]	$\gamma Y \rightarrow \gamma \mu^+\mu^-$	$\leq 10^{-3}$	≤ 0.07 / d	≤ 3 / d
H (SM) (120 GeV)	1 ÷ 10 fb assume 3 fb	$b\bar{b}$	0.68	0.02 / y	1 / y (hopeless)

Higgs needs $\mathcal{L} \sim 10^{33}$ cm^{-2} s^{-1}, i.e. a running scenario for $\beta^* = 0.5$ m.

Hard Diffractive Events

Diffractive events with high p_T particles produced



Rate at

$E_T > 10$ GeV:	$\mathcal{L} = 2 \times 10^{29}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$,	$10^{31}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
$\sigma_{incl} \sim 1\ \mu b$	720 / h	10 / s
$\sigma_{exl} \sim 7$ nb	5 / h	4 / min

Conclusions, Outlook (2)

With the same data as used for the measurement of σ_{tot}, $\mathcal{L}$ and elastic cross-section:

Study soft diffraction:

- 2.4×10^7 single diffractive events
- $(1–2) \times 10^6$ double Pomeron events

With $\mathcal{L} = 2.4 \times 10^{29}\ cm^{-2}\ s^{-1}$ (scenario 3) and identical optics:

Study semi-hard diffraction ($p_T > 10$ GeV).

With $\beta^* = 200 – 400$ m optics (under study): hard diffraction at $\mathcal{L} \sim 10^{31} cm^{-2}\ s^{-1}$:

Some central exclusive production channels within reach.

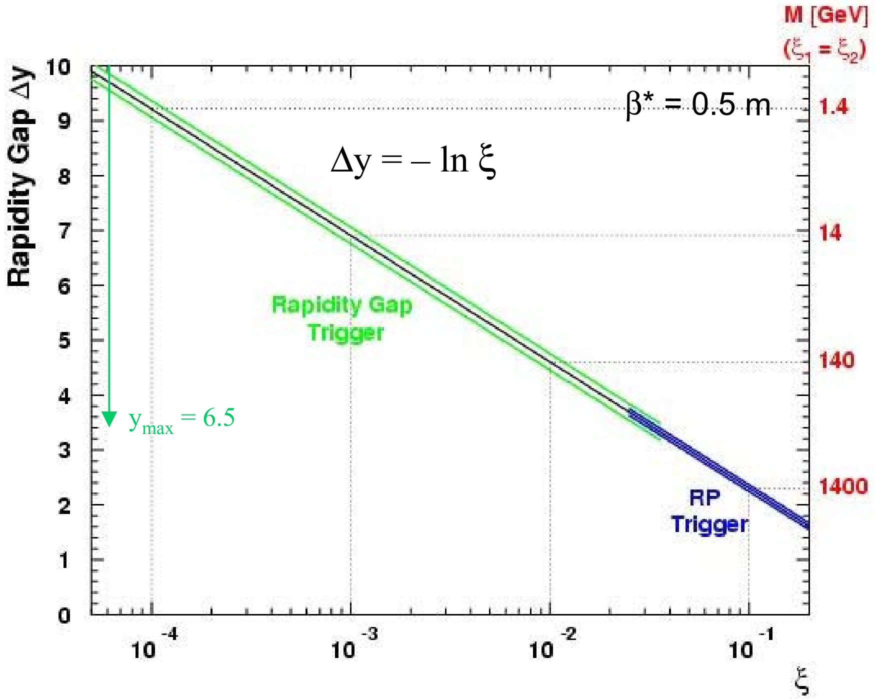
Farther future: develop diffractive running scenario for $\beta^* = 0.5$ m

→ rare events (e.g. Higgs).

Later: Hard Diffraction at high Luminosity ($\beta^* = 0.5$m)

(e.g. exclusive Higgs production via DPE)

Problem 1: Acceptance of 220m Roman Pot station at $\beta^* = 0.5$m:



Trigger via Roman Pots $\xi > 2.5 \times 10^{-2}$

Trigger via rapidity gap $\xi < 2.5 \times 10^{-2}$

Problem 2: Resolution $\sigma(\xi) \sim 10^{-3} \Leftrightarrow \sigma(M) \sim 14$ GeV (symmetric case $\xi_1 = \xi_2$)

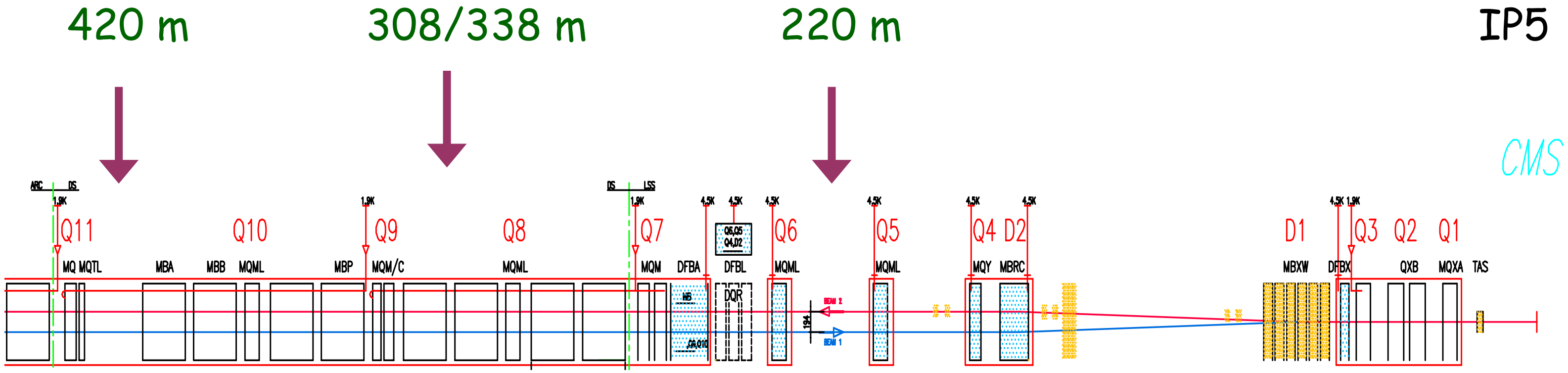
Would like leading proton acceptance down to $\xi \approx \frac{M}{\sqrt{s}} \approx 0.8 \times 10^{-2}$

and resolution $\sigma(M) \sim 3$GeV $\Leftrightarrow \sigma(\xi) \sim 2 \times 10^{-4}$.(LHC machine limit)

Diffraction at $\beta^* = 0.5$m: Ideas

Need bigger dispersion.

1. Roman Pots / Microstations further away from IP (308 – 420 m)



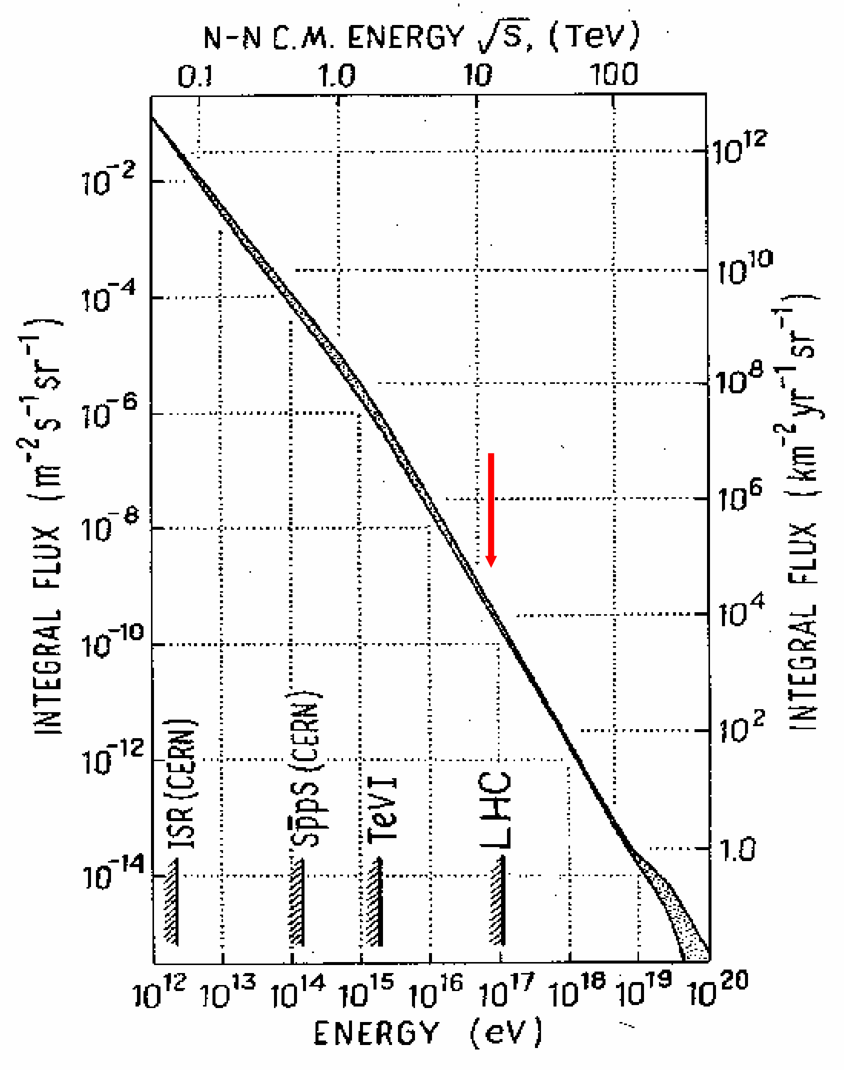
Problems:

- Cryogenic region of LHC! Detector installation difficult.
- Long signal propagation time ⇒ no level 1 trigger with RP.

⇒ Currently not discussed.

2. Local modifications of the beam optics
   Detectors closer to the beam (microstations?)

Integral Flux of High Energy Cosmic Rays



Measurements of the very forward energy flux (including diffraction) and of the total cross section are essential for the understanding of cosmic ray events.

At LHC *pp* energy:

10^4 cosmic events km^{-2} year^{-1}

> 10^7 events at the LHC in one day

Beam Optics for Leading Proton Measurement

Want to detect leading protons with scattering angles down to a few mrad.

Proton trajectory:

$$y(s) = L_y \theta_y^* + v_y(s) y^* \qquad L(s) = \sqrt{\beta^* \beta(s)} \sin \mu(s)$$

$$x(s) = L_x \theta_x^* + v_x(s) x^* + D_x(s)\xi \qquad v(s) = \sqrt{\frac{\beta(s)}{\beta^*}} \cos \mu(s)$$

- Maximise $L_x(s_{RP})$, $L_y(s_{RP})$ at Roman Pot
- Minimise $v_x(s_{RP})$, $v_y(s_{RP})$ at Roman Pot

⇒ High-β^* optics: for TOTEM $\beta^* = 1540$ m (ATLAS: 2625 m)

- $v_x(220\text{m}) \approx v_y(220\text{m}) \approx 0$, i.e. parallel-to-point focussing in both projections
- good azimuthal resolution
- but: crossing angle = 0, low angular spread (0.3µrad), wide beam (0.4mm) at IP

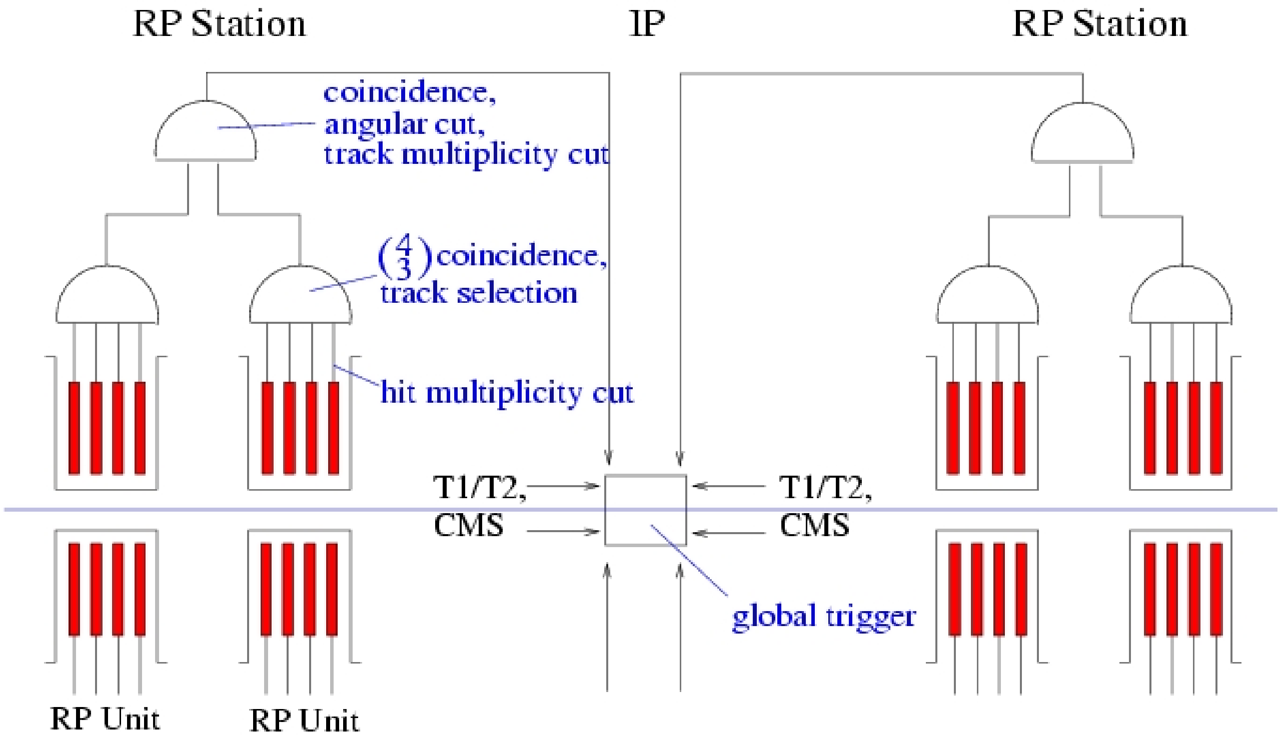
⇒ Danger of parasitical bunch crossings up/downstream from IP

⇒ Reduce number of bunches (43 and 156 instead of 2808)

$\mathcal{L}_{\text{TOTEM}} = 1.6 \times 10^{28}\ \text{cm}^{-2}\ \text{s}^{-1}$ and $2.4 \times 10^{29}\ \text{cm}^{-2}\ \text{s}^{-1}$

Trigger Logic and Background Suppression

Each Roman Pot houses:
- 6 tracking planes (analogue APV 25 readout)
- 4 trigger planes (digital VFAT readout)



Dominant background: beam halo: reduction only by 2-arm coincidence.

T1/T2: beam-gas suppression by vertex reconstruction: $\sigma(r) = 3$ mm, $\sigma(z) = 45$ mm

Level-1 Trigger Schemes

Elastic Trigger:

$\sigma \approx 30$ mb

Rate: 480 Hz @ $\mathcal{L} = 1.6 \times 10^{28}$ cm^{-2} s^{-1}

Single Diffractive Trigger:

$\sigma \approx 20$ mb

Rate: 320 Hz

Double Diffractive Trigger:

$\sigma \approx 7$ mb

Rate: 110 Hz

Central Diffractive Trigger:

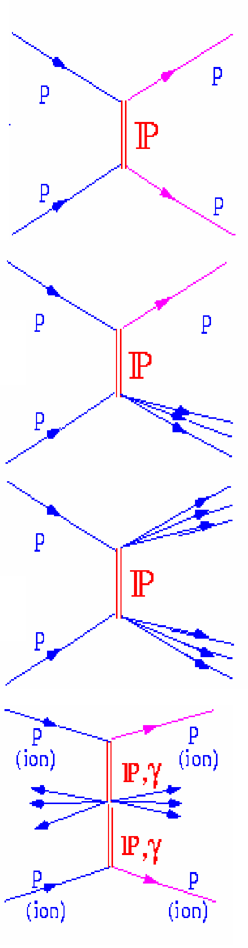
$\sigma \approx 0.5$ mb

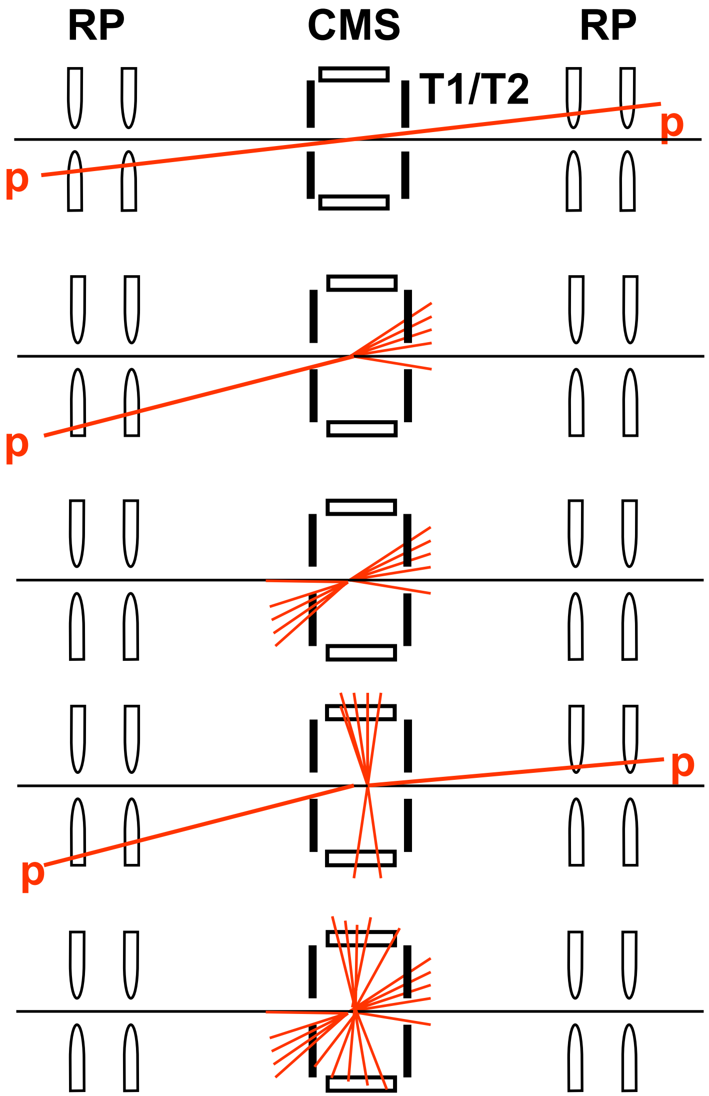
Rate: 8 Hz

Minimum Bias Trigger:

$\sigma \approx 60$ mb

Rate: 1 kHz





Backgrounds under study.

Standalone and with CMS

- Standalone running:

  only for elastic scattering and total cross-section.

- Common running:
  - DAQ and Trigger will be CMS-compatible (hardware and software)
  - TOTEM can act as a CMS subdetector.
  - TOTEM can trigger CMS at level 1:

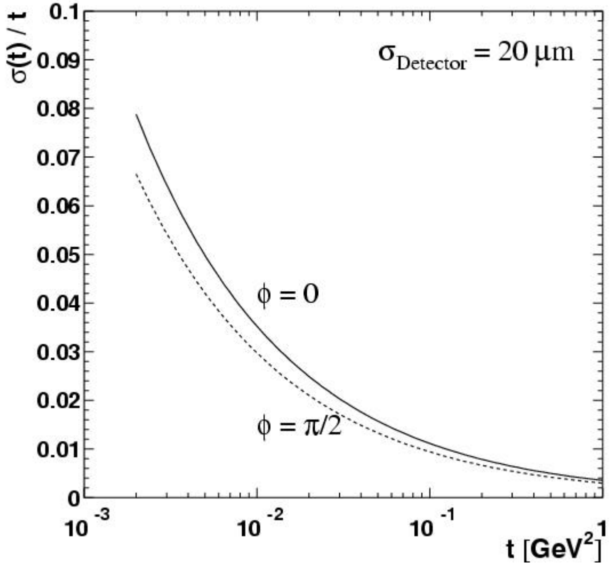
    Trigger from the Roman Pots must arrive at CMS within the CMS trigger latency:

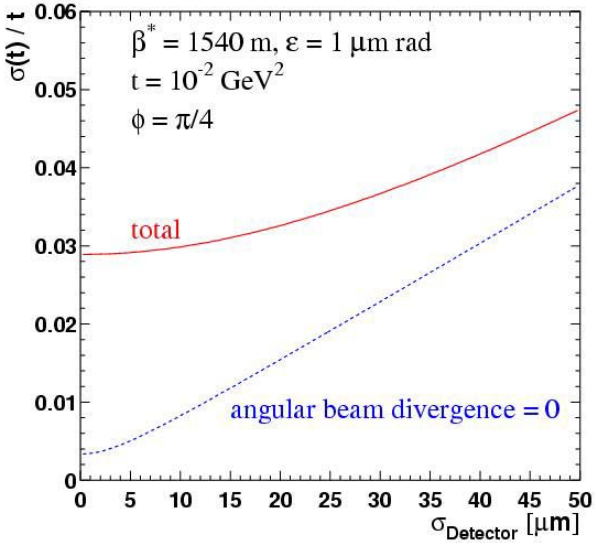
    Very tight for the Pot at 220 m, but still feasible.

    Pots farther than 220 m from IP (none foreseen) cannot trigger!

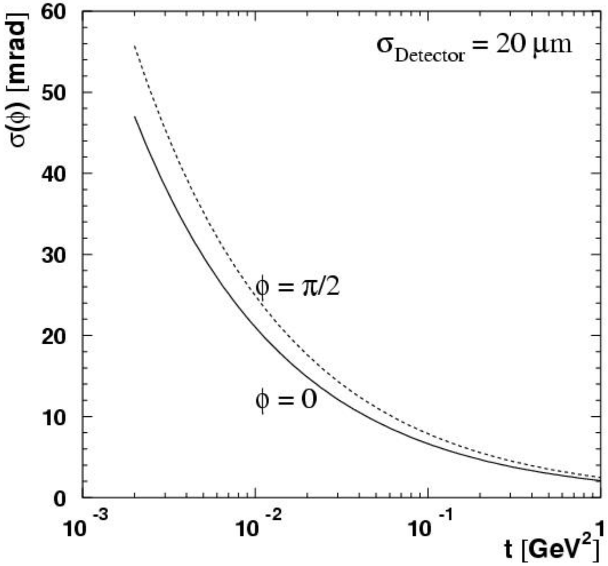
Elastic Scattering: Resolution

t-resolution (2-arm measurement)





ϕ-resolution (1-arm measurement)



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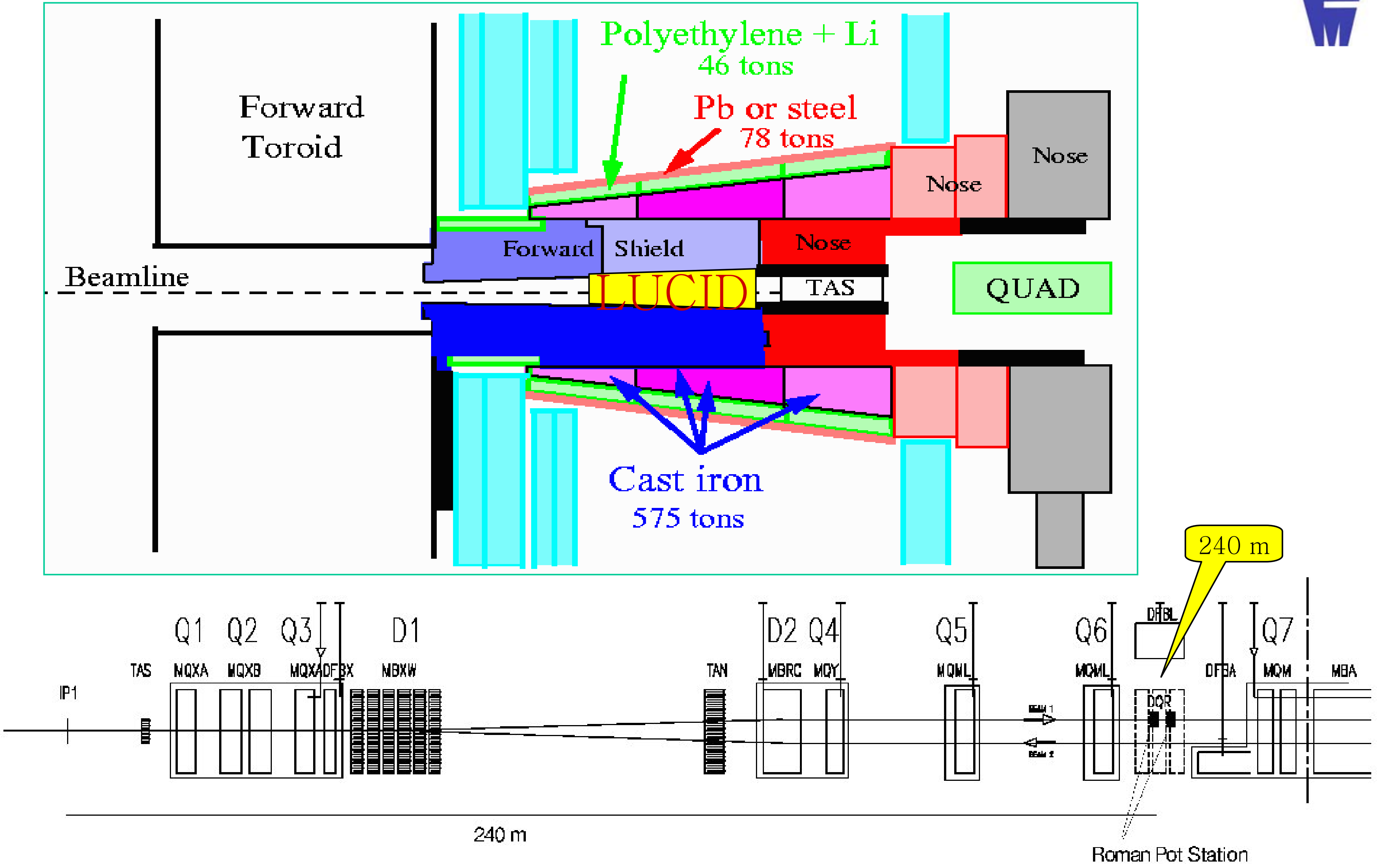
Test collinearity of particles in the 2 arms
⇒ Background reduction.

ATLAS Forward Detectors



Forward Coverage of LHC Experiments

- TOTEM+CMS:
  - Trackers, calorimeters: $\eta < 6.5$
  - Roman Pots for leading protons
- ATLAS:
  - Calorimeters: $\eta < 5$
  - LUCID: $5.4 < \eta < 6.1$
  - Roman Pots for leading protons
- ALICE:
  - Muon spectrometer: $\eta < 4$
  - ZDC for leading neutrons
- LHCb:
  - Forward spectrometer: $\eta < 4.9$