Physics at LHC

Diffractive Physics:

What answers do we expect from the LHC?

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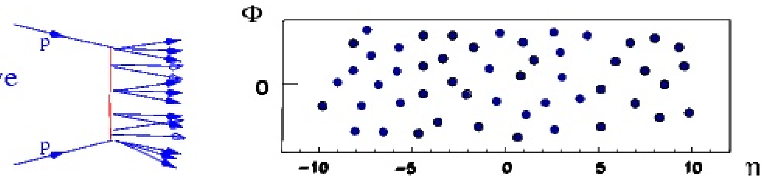
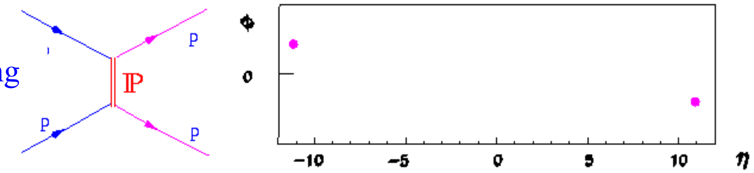
Dominant Event Classes in p-p Collisions

non–diffractive inelastic (ND)



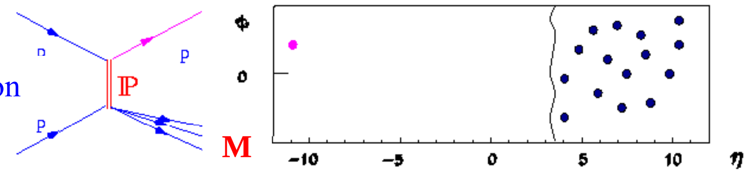
~65 mb ~ 58 %

Elastic Scattering



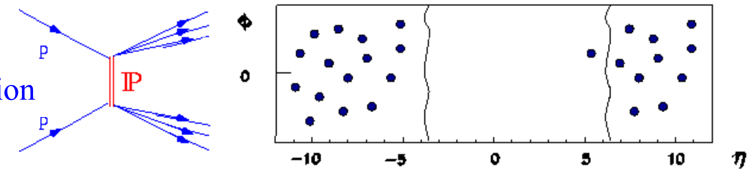
~30 mb

Single Diffraction



~10 mb

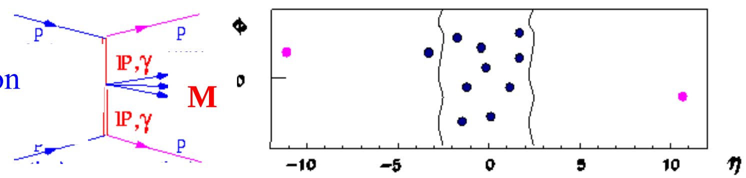
Double Diffraction



~7 mb

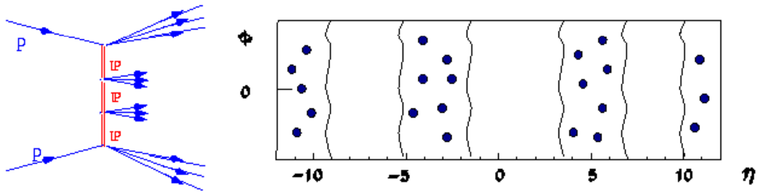
~ 42 %

Double Pomeron Exchange



~1 mb

Multi Pomeron Exchange

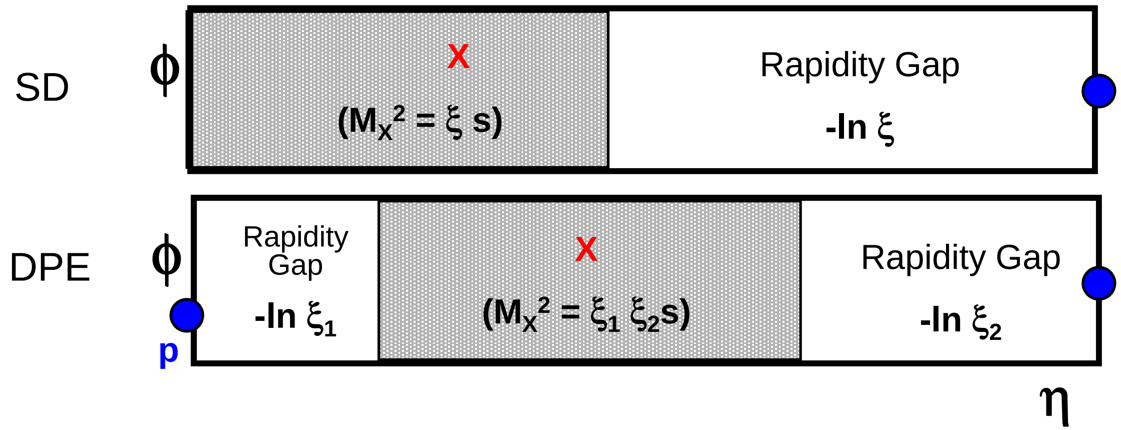


<< 1 mb

Processes with large cross-sections!

Signatures of Diffractive Events

- By rapidity gap:



Reconstruct proton momentum loss ξ=Δp/p from diffractive system X (inelastic component):

$$\xi_{1,2} = \frac{\Delta p}{p} = \frac{1}{\sqrt{s}} \sum_{i \in X} E_T^i \, e^{\pm \eta_i}$$

or from rapidity gap:

$$\xi_{1,2} = e^{-\Delta \eta_{1,2}}$$

→ needs good rapidity coverage

- By leading protons:

needs detectors in beam-pipe insertions far from IP close to the beam (e.g. Roman Pots, moving beam pipes etc.);
Already done at ISR, SppS, HERA, RHIC, Tevatron.

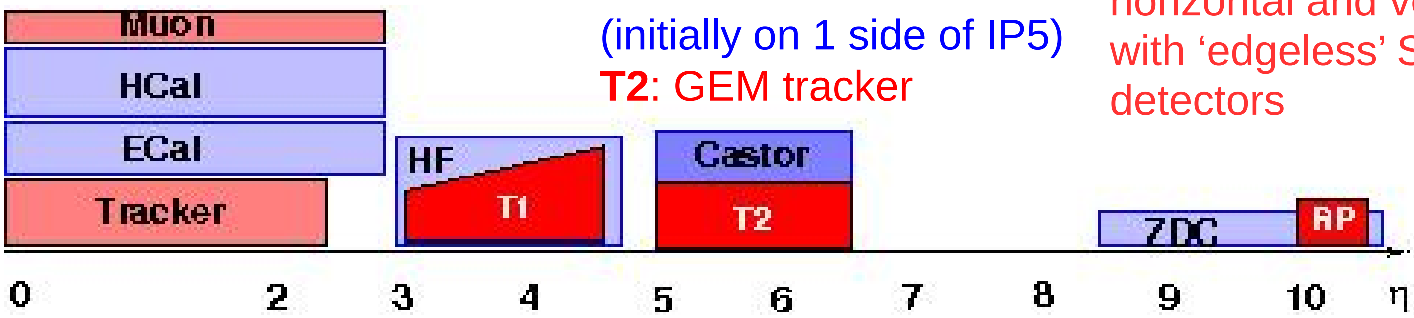
Particularly strong focus on leading proton measurement at LHC.
Roman Pots on both sides of the IPs.

LHC Experiments: Pseudorapidity Acceptance

HF: calorimeter
T1: CSC tracker

CASTOR: calorimeter
(initially on 1 side of IP5)
T2: GEM tracker

TOTEM Roman Pots:
horizontal and vertical
with ‘edgeless’ Si
detectors



FP420,
IR 3

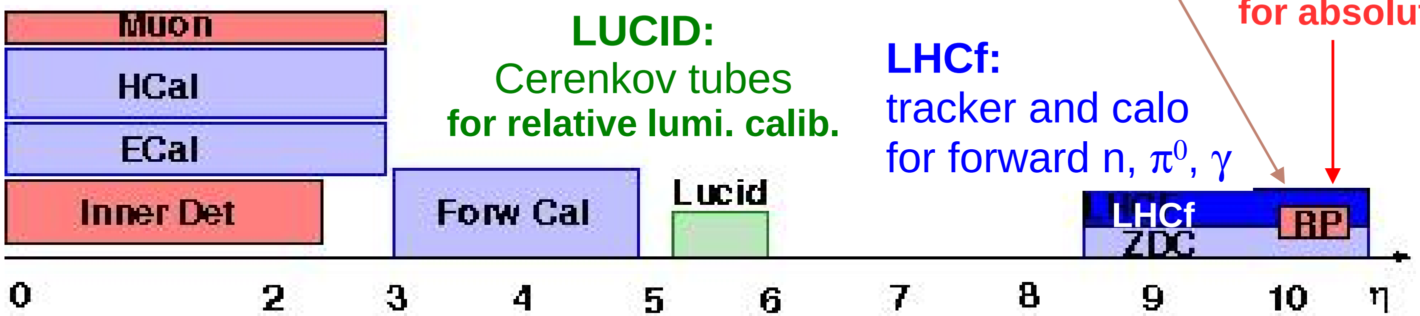
0m 6m 14m 16m 140m 147-220m 420m,
~7 km

RP220 project for diffraction:
vert. RP and movable beampipe

ALFA (RP240):
vertical Roman Pot
with scintillating fibres
for absolute lumi. meas.

LUCID:
Cerenkov tubes
for relative lumi. calib.

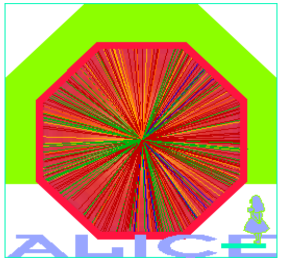
LHCf:
tracker and calo
for forward n, π^0, γ

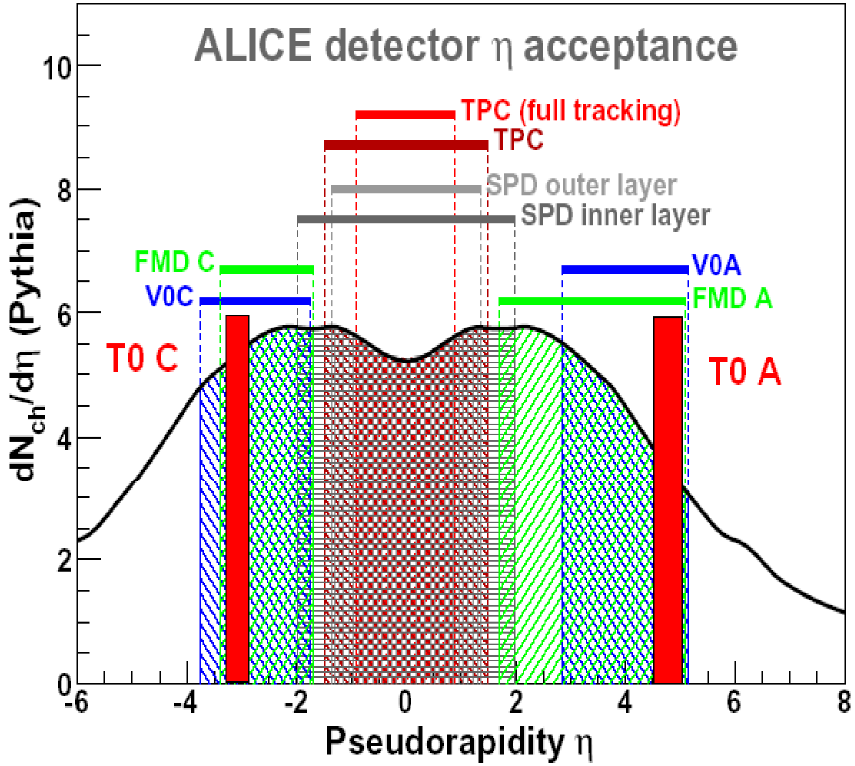


FP420

0m 17m 140m 220m 240m 420m

ALICE: diffractive gap trigger



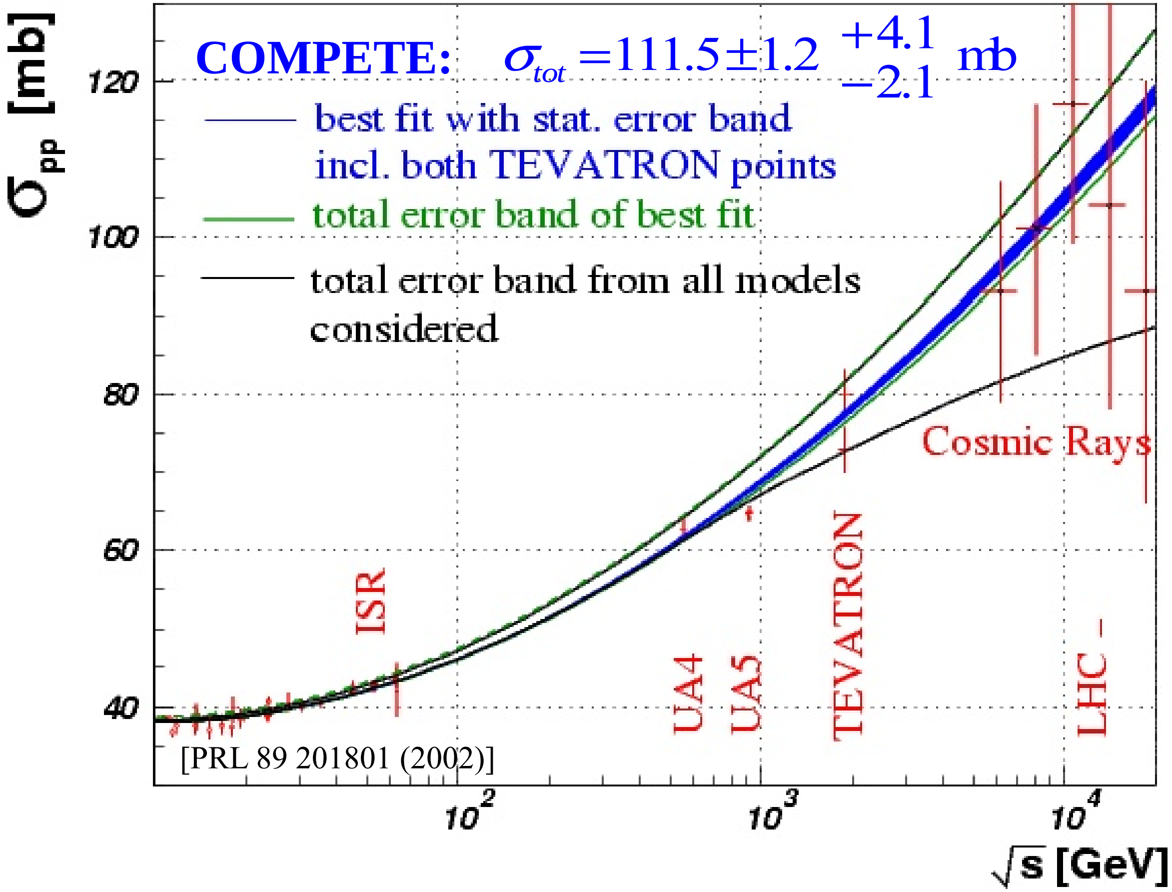


No Roman Pots, but Zero Degree Calorimeter for neutral particles.

Identify diffractive events by their rapidity gap and leading neutrals from N^* excitations.

See presentation on ALICE diffractive physics programme by R. Schicker.

Total p-p Cross-Section



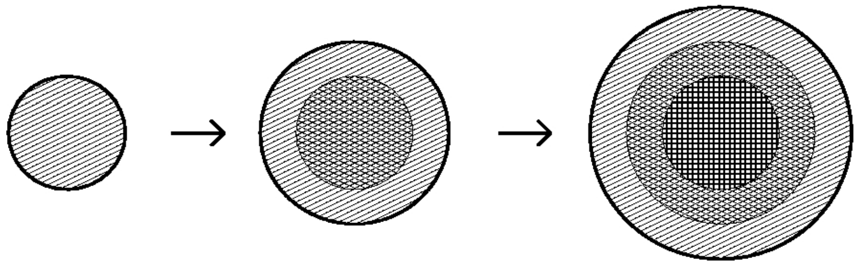
~ ln² s or ~ $s^{0.08}$ or ~ ln s ?

Disagreement E811–CDF: 2.6 σ

Typical range of model predictions: 90 – 130 mb.

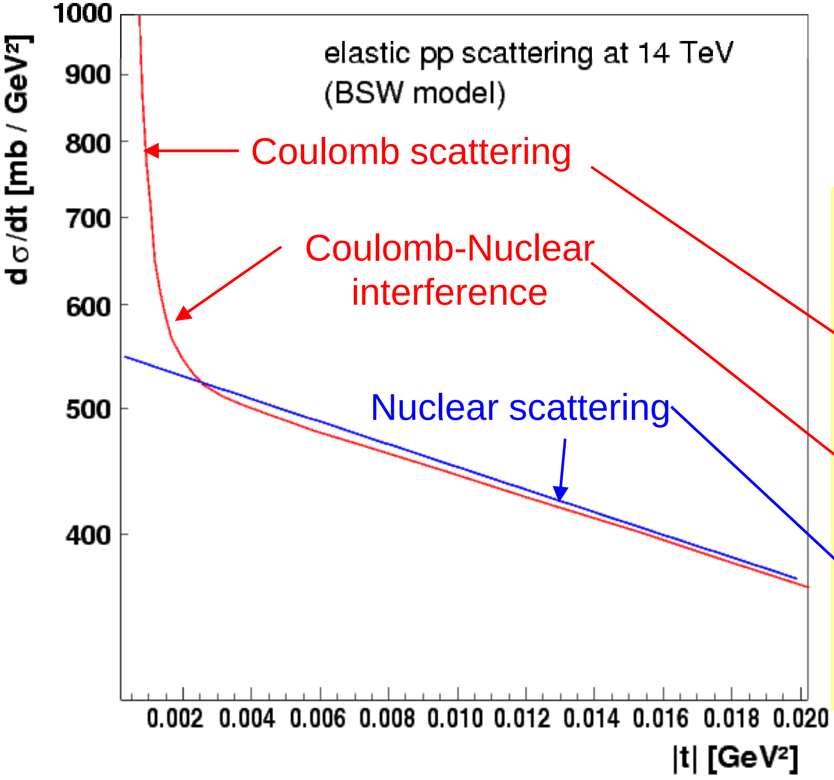
Aim of TOTEM / ATLAS at the LHC:

~ 1 – 2 % accuracy



"radius increases"

Total Cross-Section and Elastic Scattering at low |t|

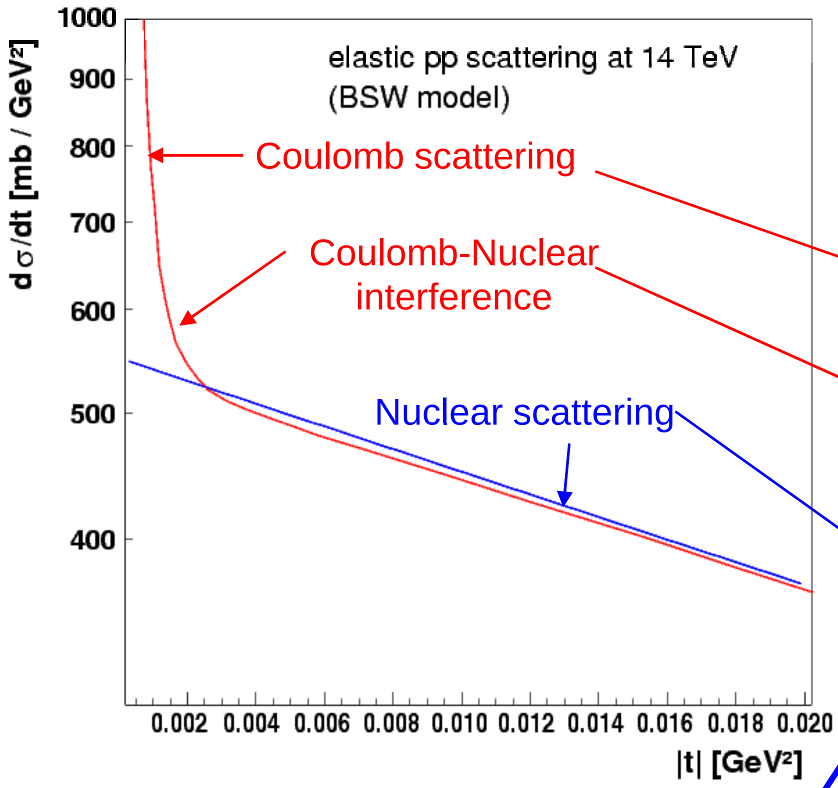


Optical Theorem: $\sigma_{tot} = \frac{4\pi}{s} \Im\left(T_{elastic,nuclear}(t=0)\right)$

$$\frac{d\sigma}{dt} = \frac{4\pi\alpha^2 (\hbar c)^2 G^4(t)}{|t|^2} + \frac{\alpha(\rho - \alpha\phi)\sigma_{tot} G^2(t)}{|t|} e^{-B|t|/2} + \frac{\sigma_{tot}^2 (1+\rho^2)}{16\pi(\hbar c)^2} e^{-B|t|}$$

α = fine structure constant
ϕ = relative Coulomb-nuclear phase
G(t) = nucleon el.-mag. form factor = $(1 + |t| / 0.71)^{-2}$
ρ = Re / Im $T_{elastic,nuclear}(t = 0)$

Total Cross-Section and Elastic Scattering at low |t|



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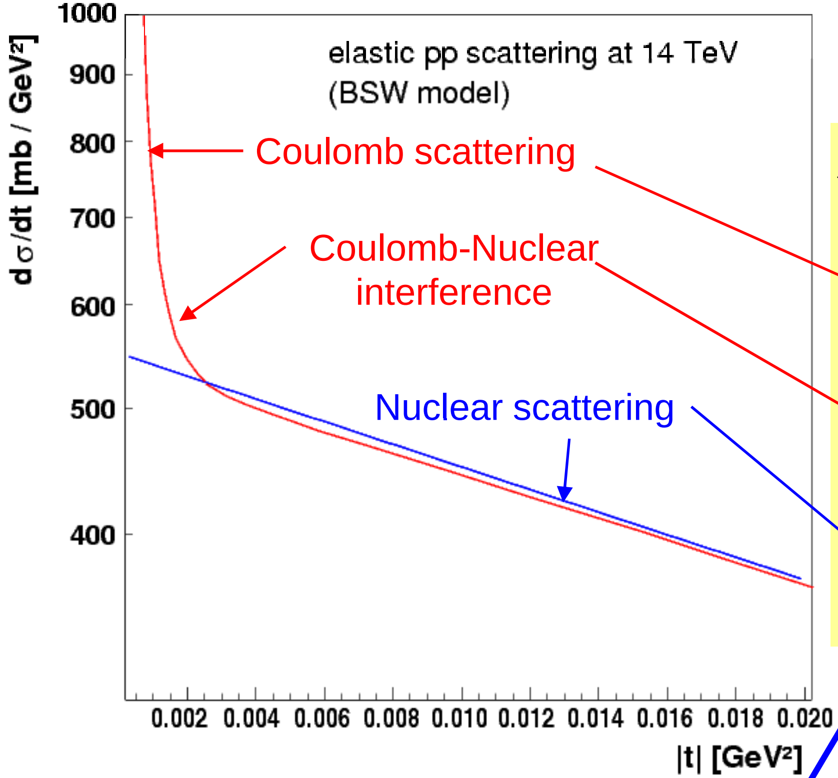
TOTEM Approach:

Measure the exponential slope B in the t-range 0.002 - 0.2 GeV², extrapolate dσ/dt to t=0, measure total inelastic and elastic rates **(all TOTEM detectors provide L1 triggers)**:

$$\left.\begin{aligned} L\sigma_{tot}^2 &= \frac{16\pi}{1+\rho^2} \times \left.\frac{dN_{elastic,nuclear}}{dt}\right|_{t=0} \\ L\sigma_{tot} &= N_{elastic,nuclear} + N_{inelastic} \end{aligned}\right\} \Longrightarrow \boxed{\sigma_{tot} = \frac{16\pi}{1+\rho^2} \times \frac{\left.(dN_{elastic,nuclear}/dt)\right|_{t=0}}{N_{elastic,nuclear} + N_{inelastic}}}$$

Total Cross-Section and Elastic Scattering at low |t|



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ATLAS Approach:

Measure dσ/dt down into Coulomb region and use el.-mag. cross-section for normalisation

α = fine structure constant

ϕ = relative Coulomb-nuclear phase

G(t) = nucleon el.-mag. form factor = $(1 + |t| / 0.71)^{-2}$

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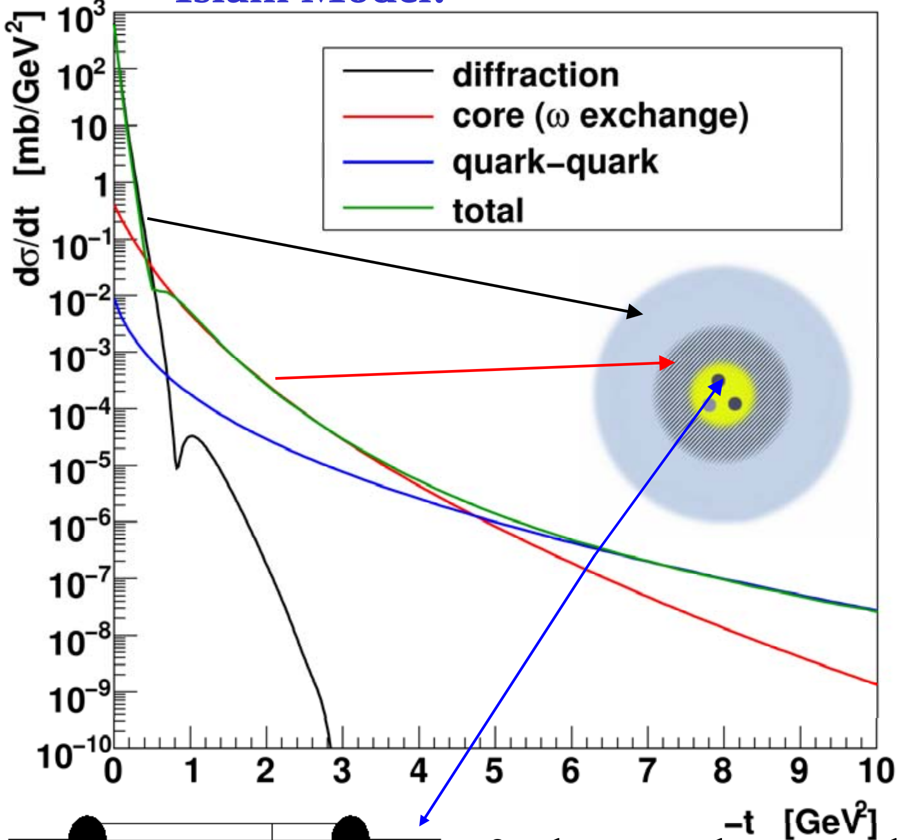
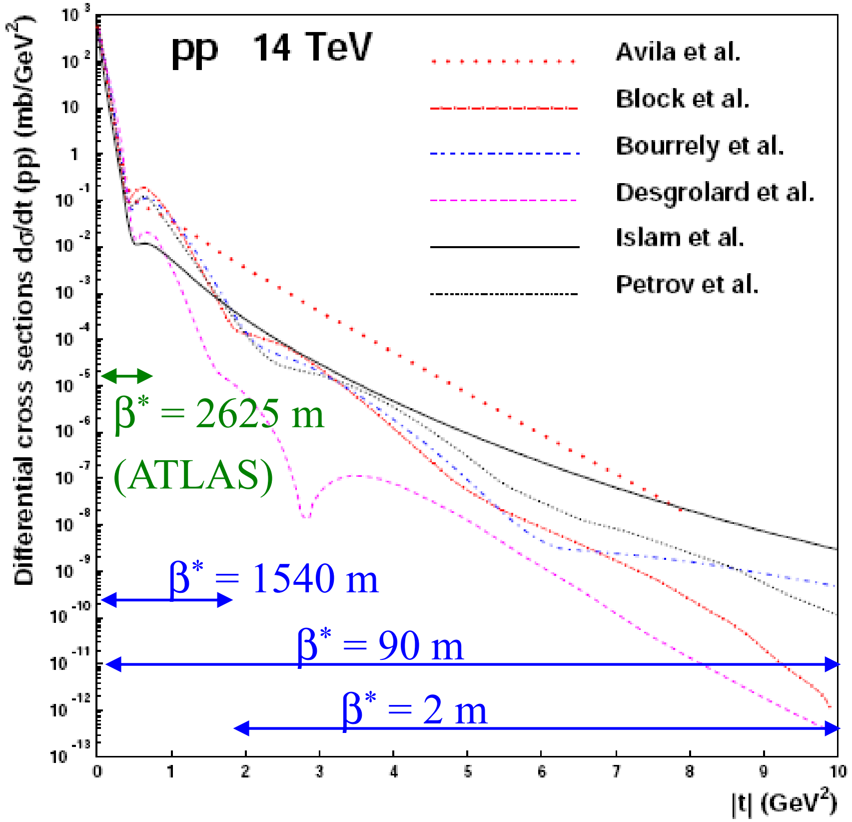
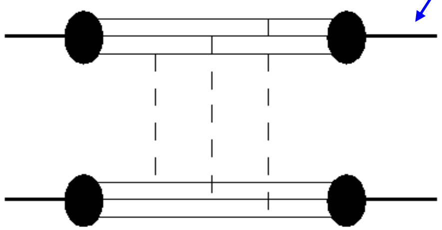
Elastic pp Scattering at 14 TeV: Model Predictions

Islam Model:







3-gluon exchange at large |t|:

$$\frac{d\sigma}{dt} \sim t^{-8}$$

Big uncertainties at large |t|: Models differ by ~ 3 orders of magnitude!

TOTEM will measure the complete range with good statistics

Detection of Diffractively Scattered Protons

Transport equations:

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

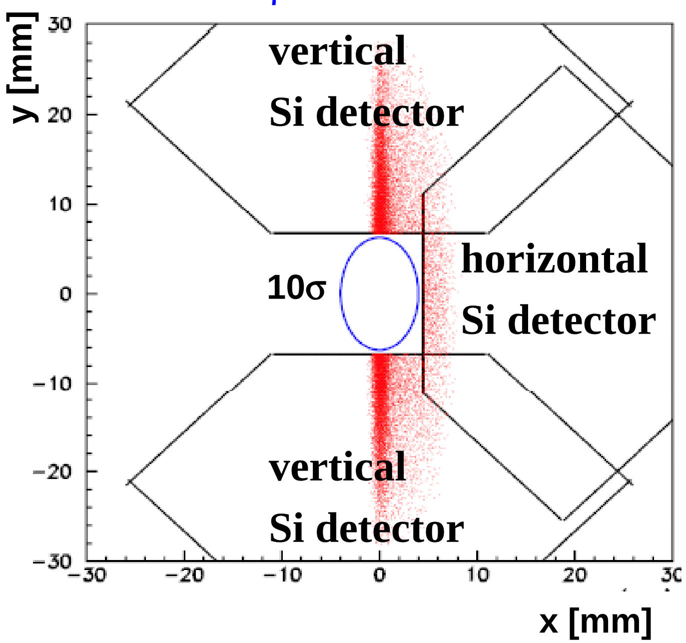
$$x_{\rm det} = L_x \theta_x^* + v_x x^* + D\xi$$

(x^*, y^*): vertex position

(θ_x^*, θ_y^*): emission angle

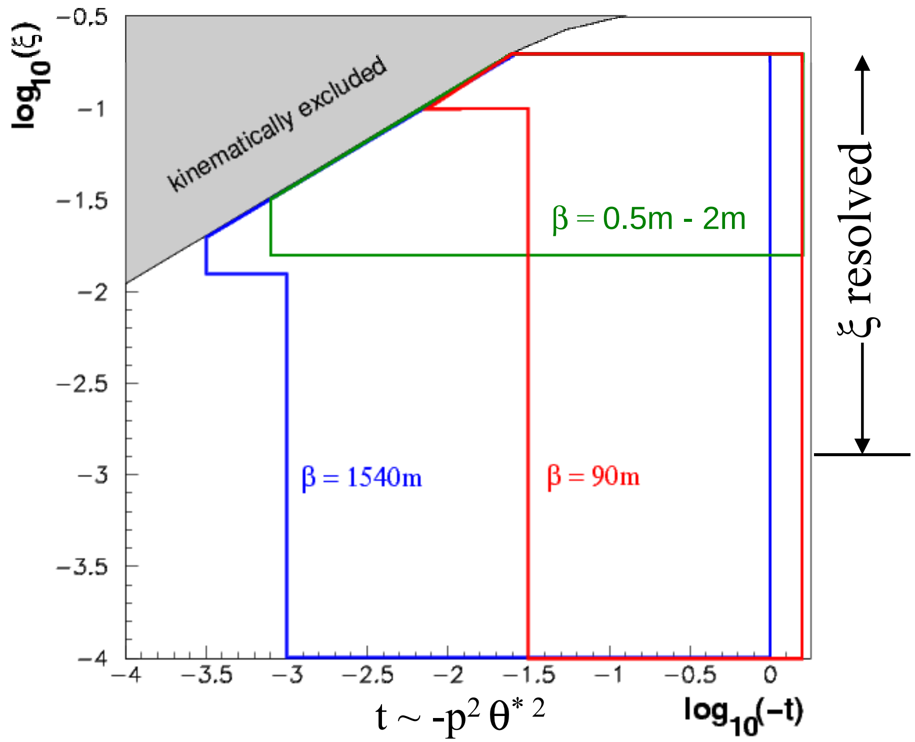
$\xi = \Delta p/p$

Example: Hit distribution @ TOTEM RP220 with $\beta^* = 90$m



TOTEM: Proton Acceptance in (t, ξ):

(contour lines at A = 10 %) RP220

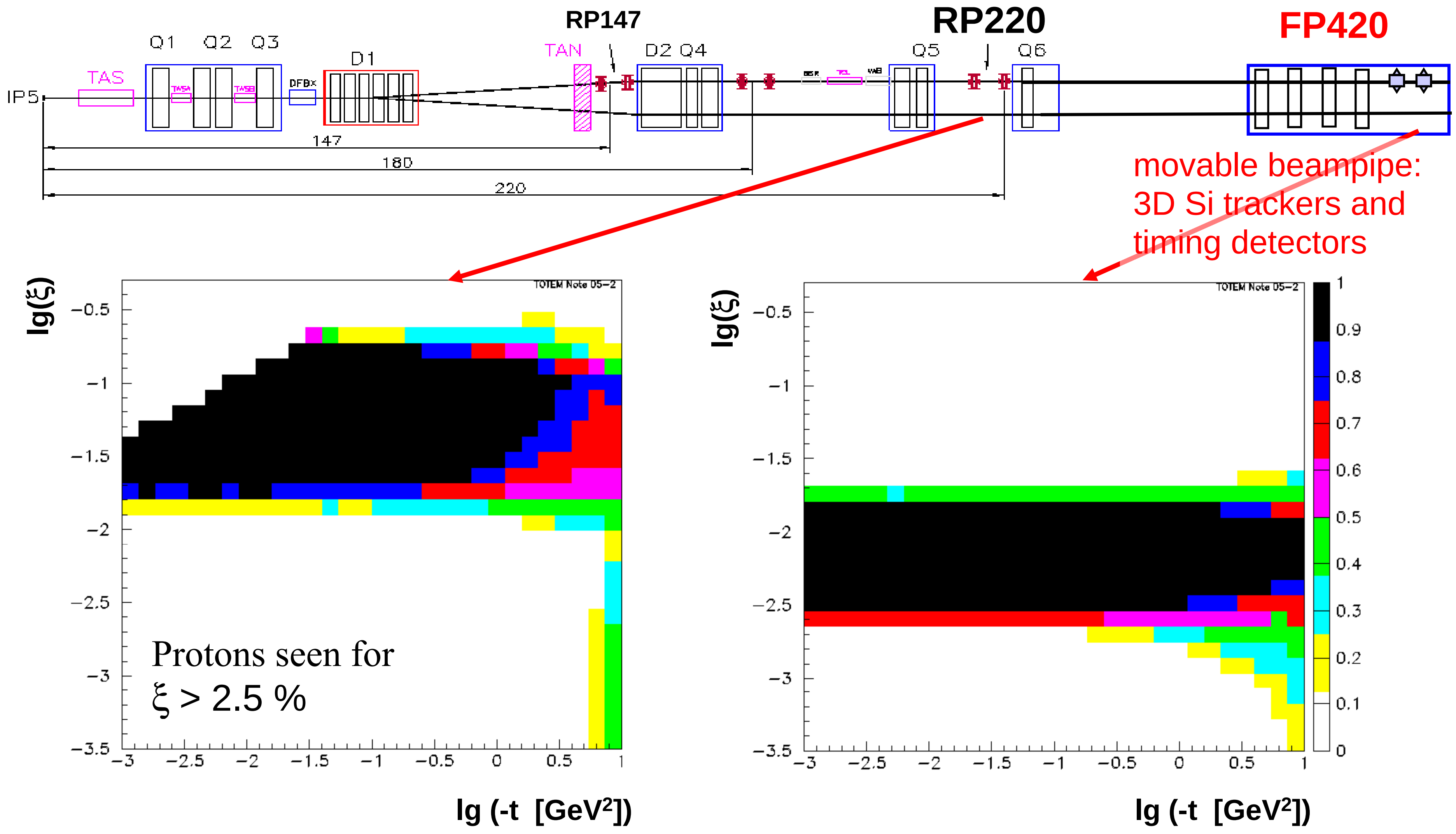


Optics properties at RP220:

$\beta^* = 1540$ m	$L = 10^{28} – 2 \times 10^{29}$	95% of all p seen; all ξ
$\beta^* = 90$ m	$L = 10^{29} – 3 \times 10^{30}$	65% of all p seen; all ξ
$\beta^* = 0.5 – 2$ m	$L = 10^{30} – 10^{34}$	p with ξ > 0.02 seen; all t

Diffraction at β* = 0.5 – 2 m with high Luminosity

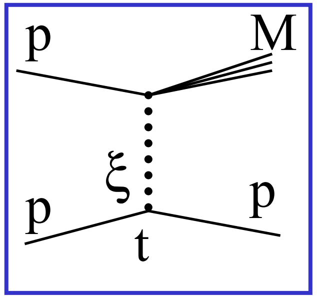
FP420 Project (IP1 and IP5)



Alternative idea: put detectors in momentum cleaning region IR3 (→ talk by K. Eggert)

Measurement of Diffractive Cross-Sections

Aim: measurement of all kinematic variables and their correlations.



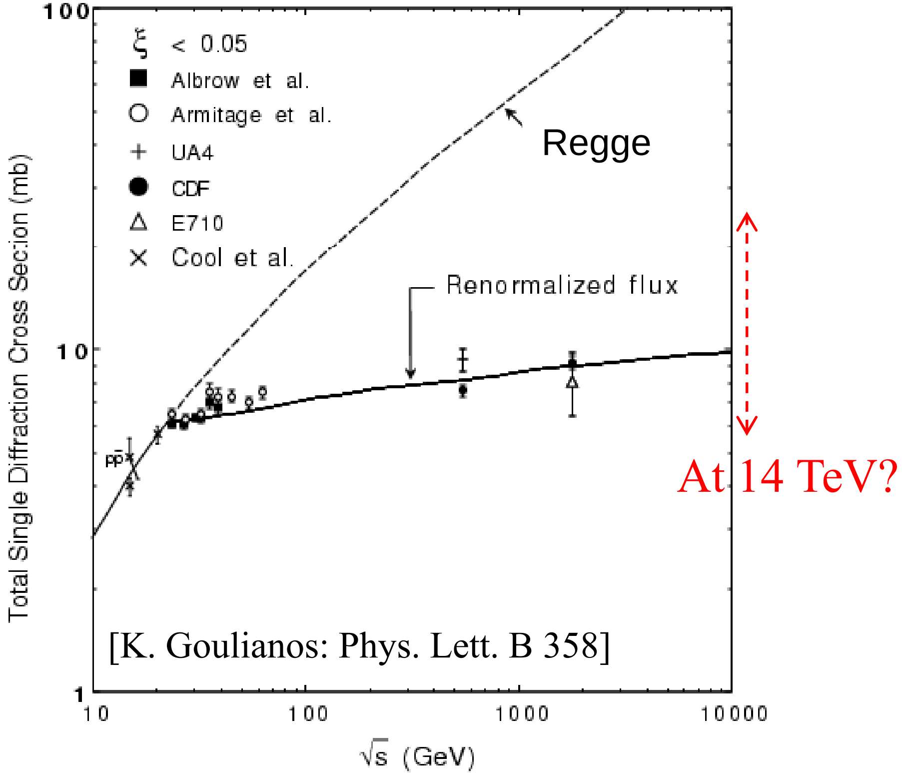
Single Diffraction:
(Regge theory)

$$\frac{d^2\sigma_{SD}}{dt\,d\xi} = f_{IP/p}(t,\xi)\cdot\sigma_{IP-\bar{p}}(s\xi) \sim \frac{1}{\xi^{1+\varepsilon}}e^{-b|t|}$$

Pomeron flux in proton $\sim e^{b\,t} / \xi^{1+2\varepsilon}$ Pomeron-proton cross-section $\sim (s\xi)^{\varepsilon}$

Slope parameter at LHC: b ~ 5 – 7 GeV^{-2} ? ⇔ distance of diffractive interaction R ~ 0.5 fm

ξ and t dependence experimentally confirmed up to Tevatron, but total SD cross-section lower.



Difficulty in Single Diffraction:

Mass from proton measurement:

$$M = \sqrt{\xi s}$$

$\sigma(\xi) \sim 2 \times 10^{-3}$
(principally limited to 10^{-4} by beam energy spread!)

→ Mass resolved for M > 450 GeV

→ need to calculate M directly from diffractive system

Rapidity Gap vs. Proton Momentum

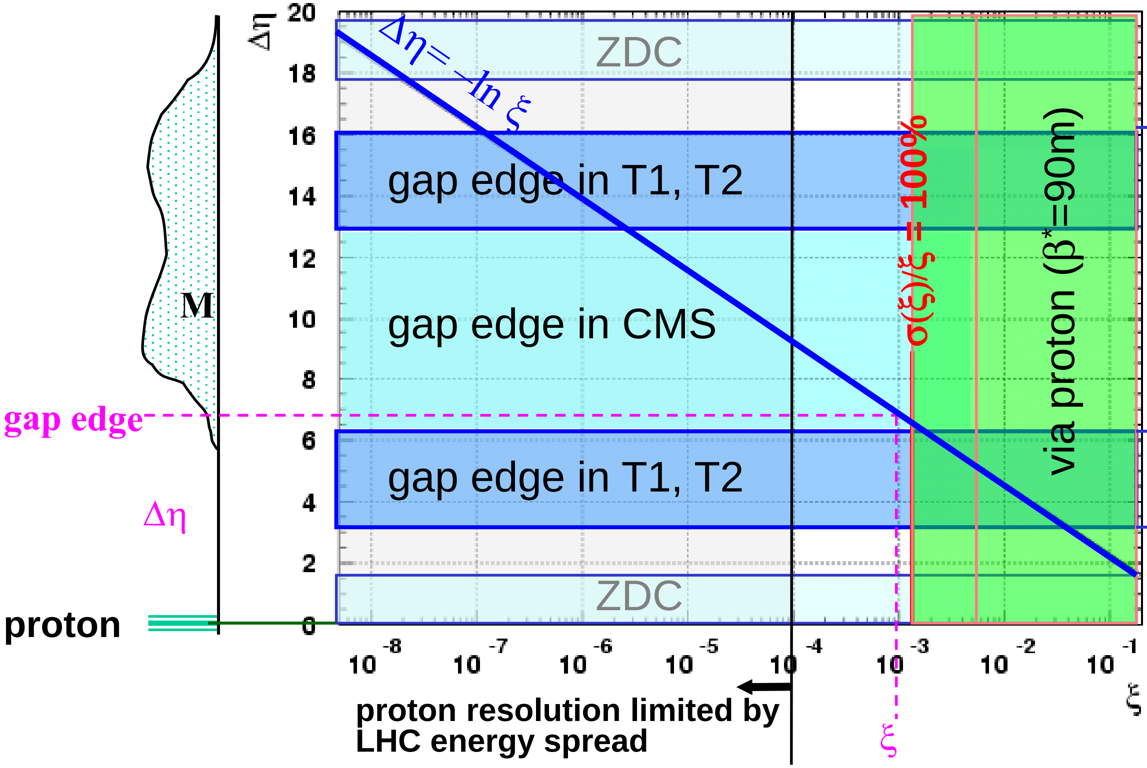
Example: Single Diffraction measured with $\beta^* = 90$ m (protons with all ξ detected).

Proton momentum resolution: $\beta^* = 90$ m: $\sigma_p(\xi) = 1.6 \times 10^{-3}$

Rapidity gap measurement resolution: $\sigma(\Delta\eta) = 0.8 – 1$

Compare the proton momentum loss ξ with the rapidity gap $\Delta\eta$:

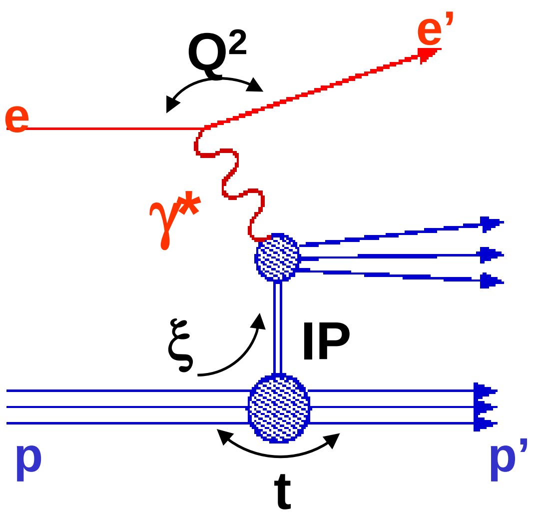
verify $\Delta\eta = –\ln \xi$

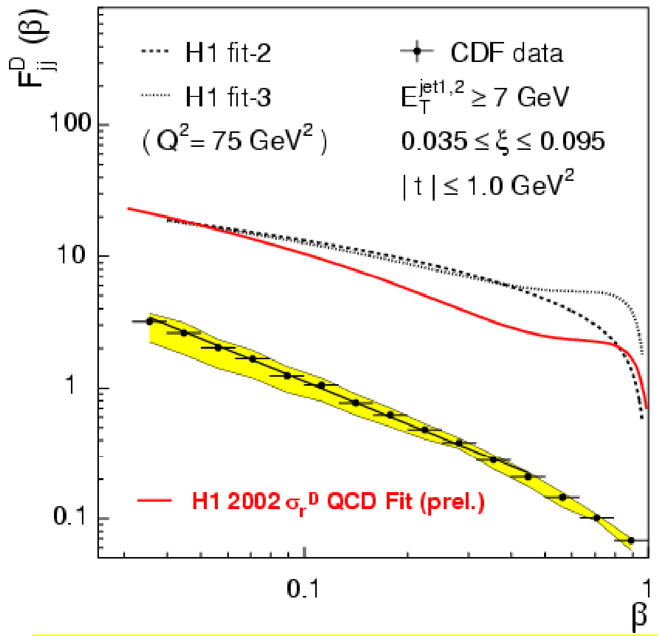


ξ–range	M (SD) [GeV]	
< 1 x 10^{-7}	< 5	proton seen, ξ not resolved, gap not meas., detectors empty
1 x 10^{-7} – 1.6 x 10^{-3}	**5 – 450**	**proton seen, ξ not resolved, gap measured**
1.6 x 10^{-3} – 0.045	**450 – 3000**	**ξ measured, gap measured**
> 0.045	> 3000	ξ measured, gap not seen, detectors full

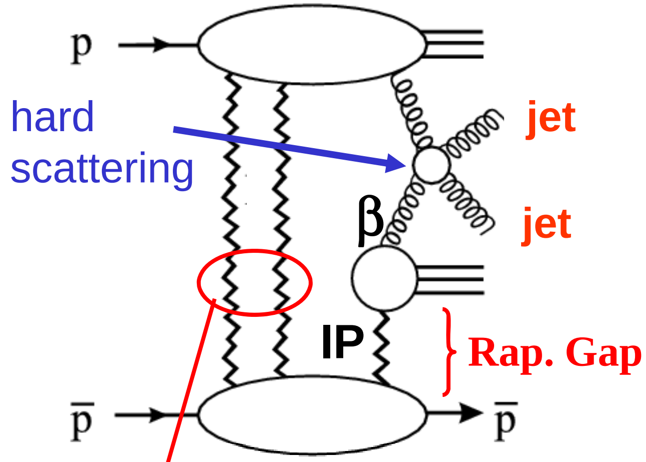
Rapidity Gap Survival in Hard Diffraction

Diffractive DIS at HERA





Tevatron



$$\sigma \sim \underbrace{F^D(\beta, Q^2, \xi, t)}_{\text{diffractive structure function}} \otimes \hat{\sigma}_{jj} \otimes |S|^2$$

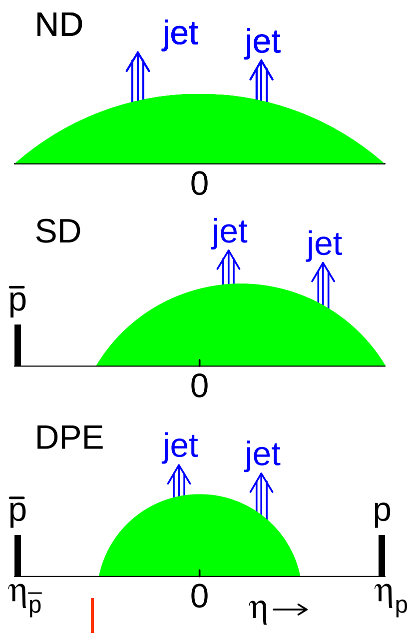
gap survival probability

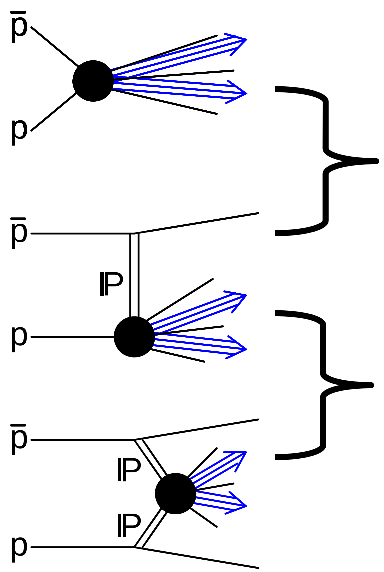
hard scattering cross-section

- shape of function F^D similar
- normalisation different (factor 10)

} difference related to (soft) rescattering effects between spectator partons

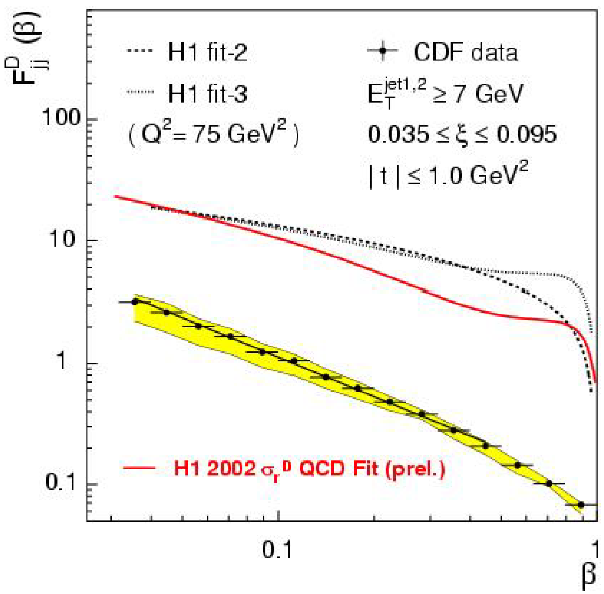
Rapidity Gap Survival Probability: 2 gaps vs 1 gap





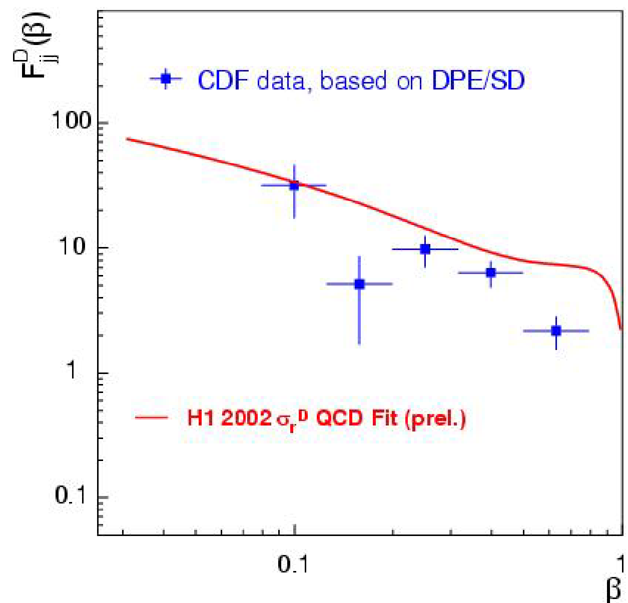
R(SD/ND) $\propto F^D_{\bar{p}} |S|^2$

R(DPE/SD) $\propto \dfrac{F^D_p \cancel{F^D_{\bar{p}}} \cancel{|S|^2}}{\cancel{F^D_{\bar{p}}} \cancel{|S|^2}}$

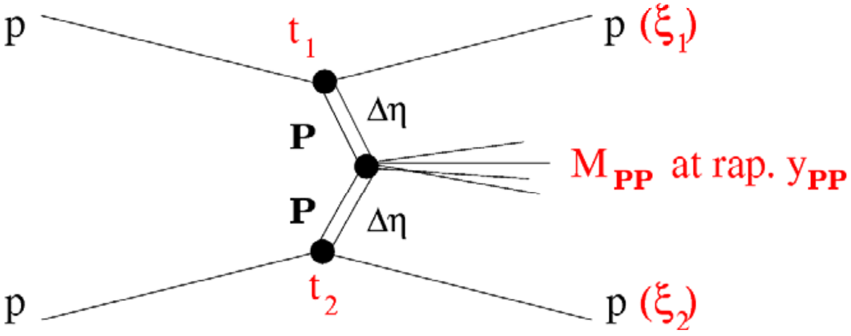


Suppression similar for 2 gaps and 1 gap

$$\Rightarrow |S|^2 \sim \frac{R(SD/ND)}{R(DPE/SD)}$$



Central Diffraction (DPE)

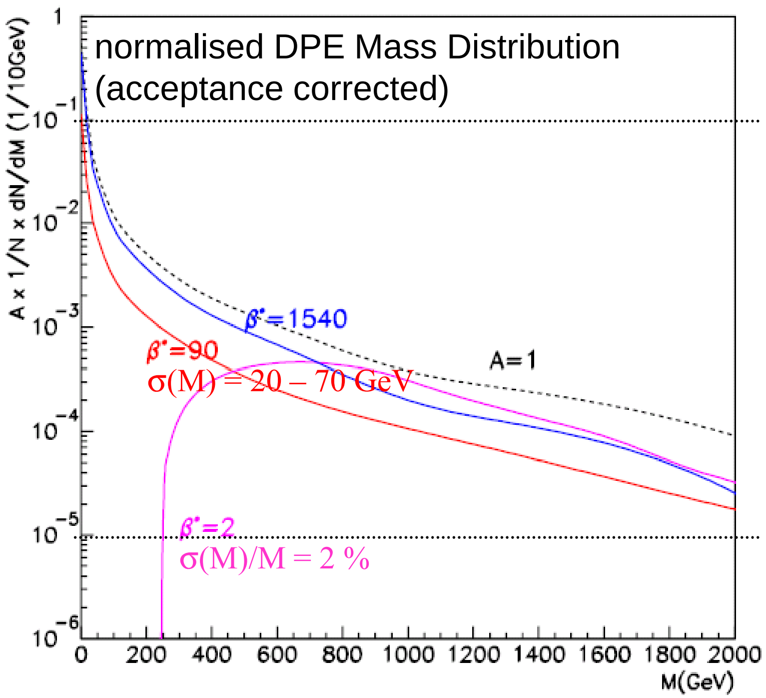


5-dimensional differential cross-section:

$$\frac{d^5\sigma}{dt_1\, dt_2\, d\xi_1\, d\xi_2\, d\phi} \propto \frac{1}{\xi_1^{1+\varepsilon}} \frac{1}{\xi_2^{1+\varepsilon}} e^{-b|t_1|-b|t_2|}$$

Any correlations?

Mass spectrum: change variables $(\xi_1,\xi_2) \rightarrow (M_{PP}, y_{PP})$: $M_{PP}^2 = \xi_1\, \xi_2\, s$; $y_{PP} = \frac{1}{2}\ln\frac{\xi_1}{\xi_2}$



14 μb / GeV

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

β*=90m: σ(M) = 20 – 70 GeV

1.4 nb / GeV ⇔ **50 events / (h •10GeV) @ 10^{30} cm^{-2} s^{-1}**

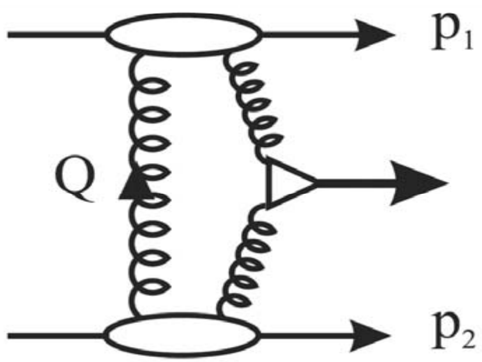
→ sufficient statistics to measure the inclusive mass spectrum

Central Production

High gluon fraction in Pomeron (measured by HERA, Tevatron)

$\Rightarrow$ Use the LHC as a gluon-gluon collider and look for resonances in $d\sigma/dM$

Special Case: Exclusive production



X = $\underbrace{\gamma\gamma, jj, \chi_{c0}}_{\text{seen at the Tevatron}}$, χ_{b0}, H, SUSY H, glueballs?

- clean signature and redundancy: measure both protons and central system
- exchange of colour singlets with vacuum quantum numbers

  $\Rightarrow$ Selection rules for system X: $J^{PC} = 0^{++}, (2^{++}, 4^{++})$

Study the kinematic properties of exclusive production (e.g. t-spectrum and p_T distrib. of X), compare with inclusive production (M = X + ?)

Exclusive Production: Examples

Predictions for the LHC:

System M	σ_{excl}	Decay channel	BR	Events at L_{int} = 0.3 pb^{-1}	Events at L_{int} = 0.3 fb^{-1}
χ_{c0} (3.4 GeV)	3 μb [KMRS]	$\gamma J/\psi \to \gamma \mu^+\mu^-$ $\pi^+\pi^- K^+K^-$	6×10^{-4} 0.018	140 4500	140000 4.5×10^6
χ_{b0} (9.9 GeV)	4 nb [KMRS]	$\gamma \Upsilon \to \gamma \mu^+\mu^-$	$\leq 1.5\mathrm{x}10^{-3}$	≤ 0.5	≤ 500
jj ($\eta_1 - \eta_2 > 1$, E > 50 GeV)	0.2 nb			60	60000
$\gamma\gamma$ (E > 5 GeV)	600 fb			0.18	180

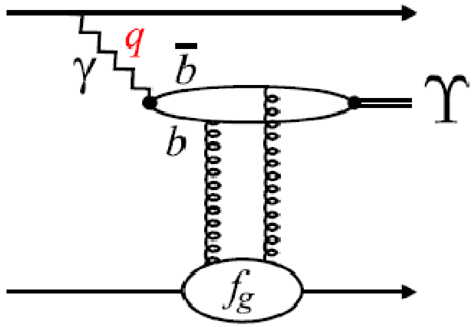
$\beta^* = 90$ m
$L = 10^{29} - 3 \times 10^{30}$

$\beta^* = 0.5 - 2$ m
$L = 10^{30} - 10^{34}$

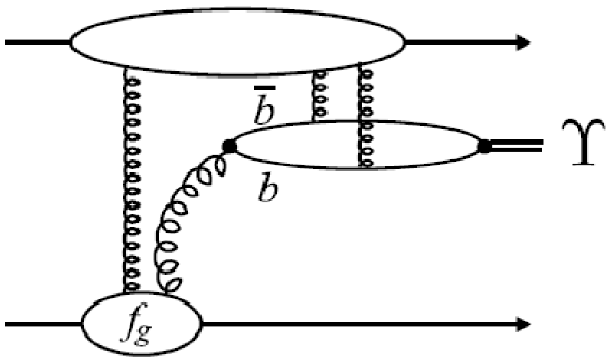
Other Central Production Processes

Odderon = hypothetical analogon to Pomeron with C = -1
QCD: Pomeron = 2 gluons, Odderon = 3 gluons

Pomeron – Photon fusion



Pomeron – Odderon fusion



→ systems with C = P = – 1 : e.g. J/Ψ, Y

See Photon/Odderon studies by Alice.

Detection of Central Production

Ideal scenario:

reconstruct kinematics from protons AND resonance decay products (→ redundancy!)

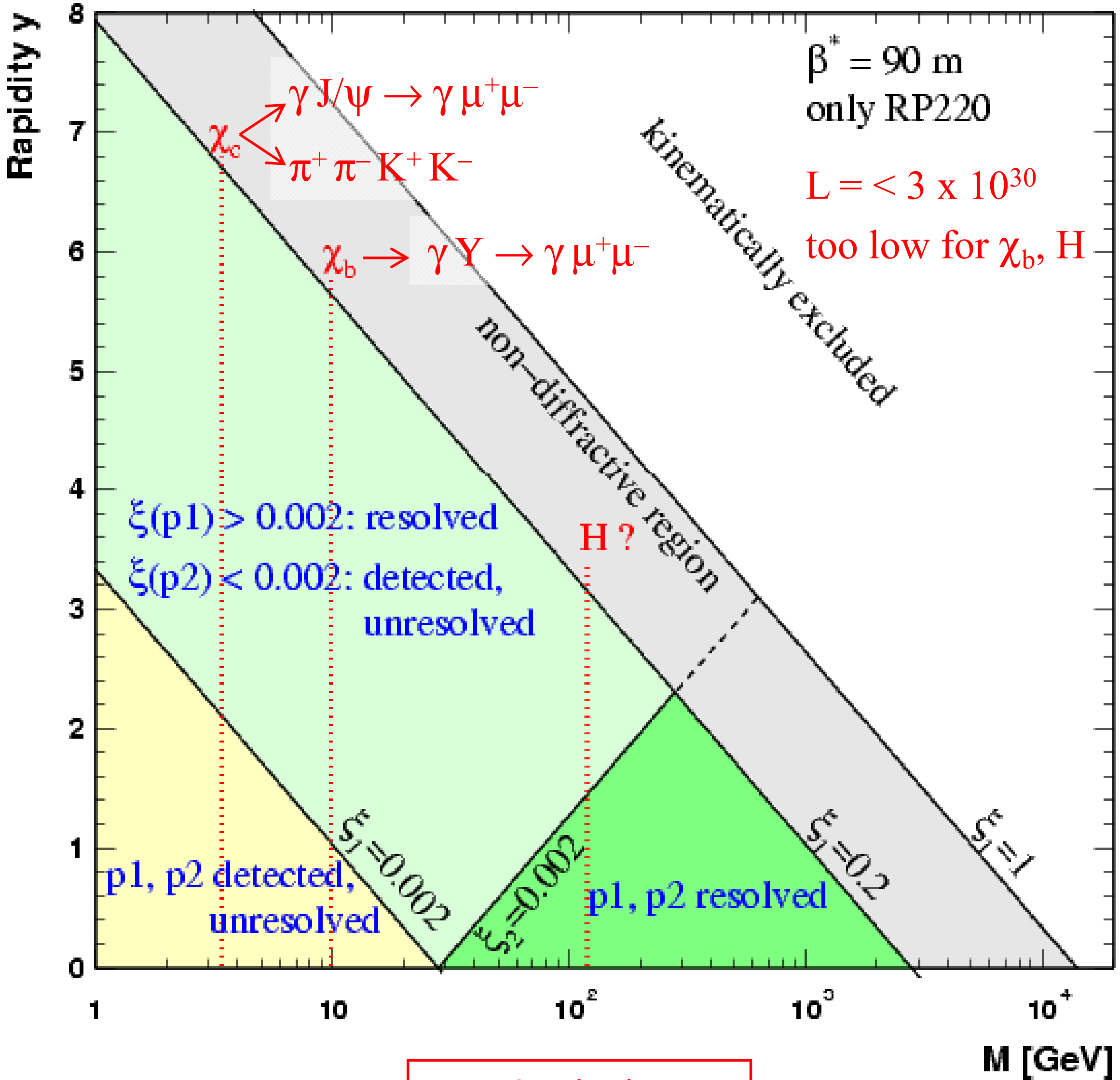
But:

Only possible for small production rapidities y

i.e. symmetric events

$\xi_1 \approx \xi_2$

$$\boxed{y_{PP} = \frac{1}{2}\ln\frac{\xi_1}{\xi_2}}$$



$$\boxed{M_{PP}^2 = \xi_1\,\xi_2\,s}$$

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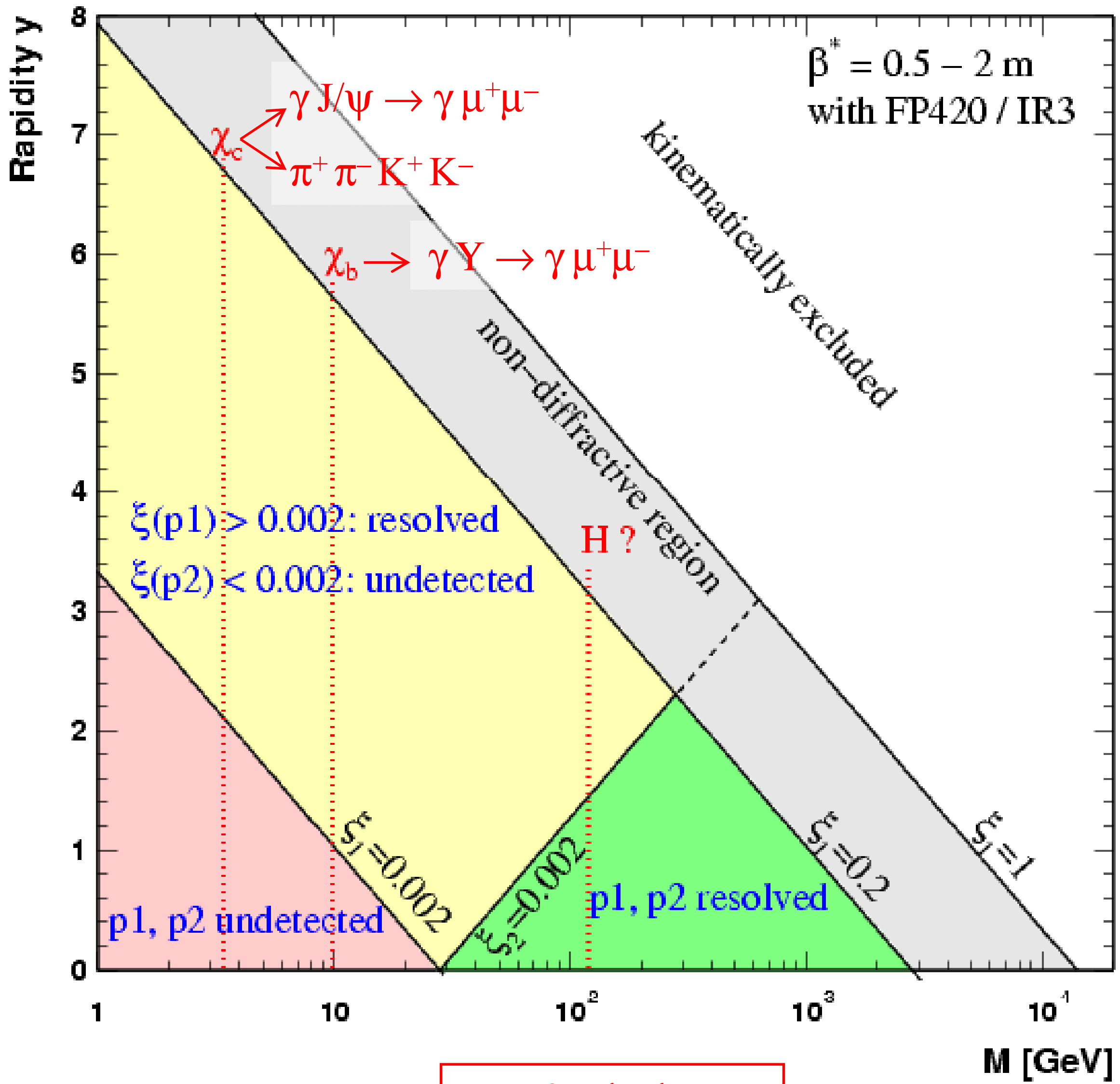
$$\boxed{y_{PP} = \frac{1}{2}\ln\frac{\xi_1}{\xi_2}}$$

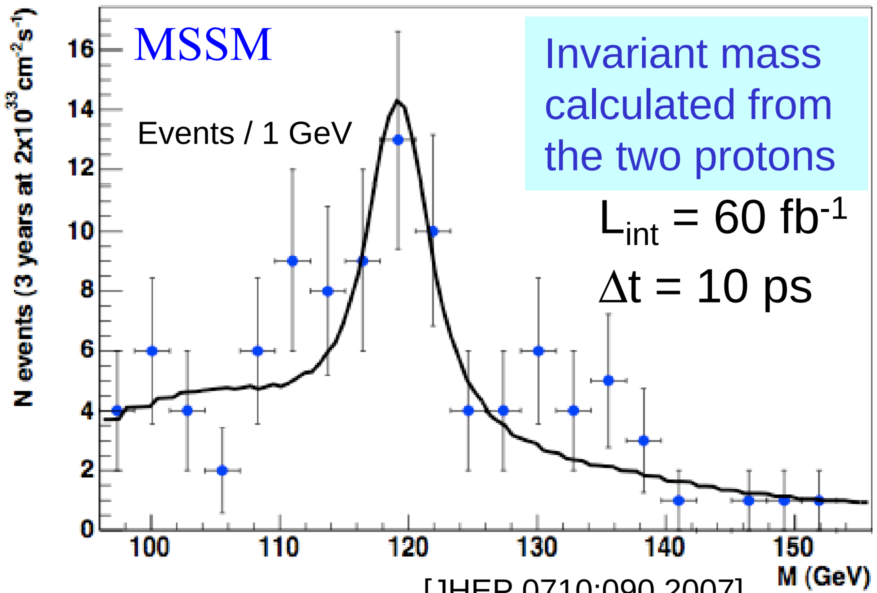


$$\boxed{M_{PP}^2 = \xi_1\, \xi_2\, s}$$

Diffractive Higgs Production

Various Higgs studies:

- SM with m_H = 120 GeV:
  σ x BR (H $\rightarrow$ bb) = 2 fb , S/B ~ 1
- MSSM M_h^{max} scenario
  (m_A = 120 GeV, tan β = 40)
  σ x BR (h $\rightarrow$ bb) = 20 fb
- NMSSM scenario (m_h = 93 GeV, m_a = 10 GeV)
  σ x BR (h $\rightarrow$ aa $\rightarrow$ 4 τ) = 4.8 fb but S/B $\geq$ 10 !



[JHEP 0710:090,2007]

Difficulty of diffraction at high luminosity: Pile-up of several events per bunch crossing;
L = 1 x 10^{34}: 35 events / bunch crossing
Combinations faking DPE signature:
e.g. (single diffraction) + (non-diffractive inelastic) + (single diffraction)

→ Leading protons and central diffractive system have to be matched:
timing measurements in leading proton detectors (10 – 20 ps in FP420) → z(vertex)

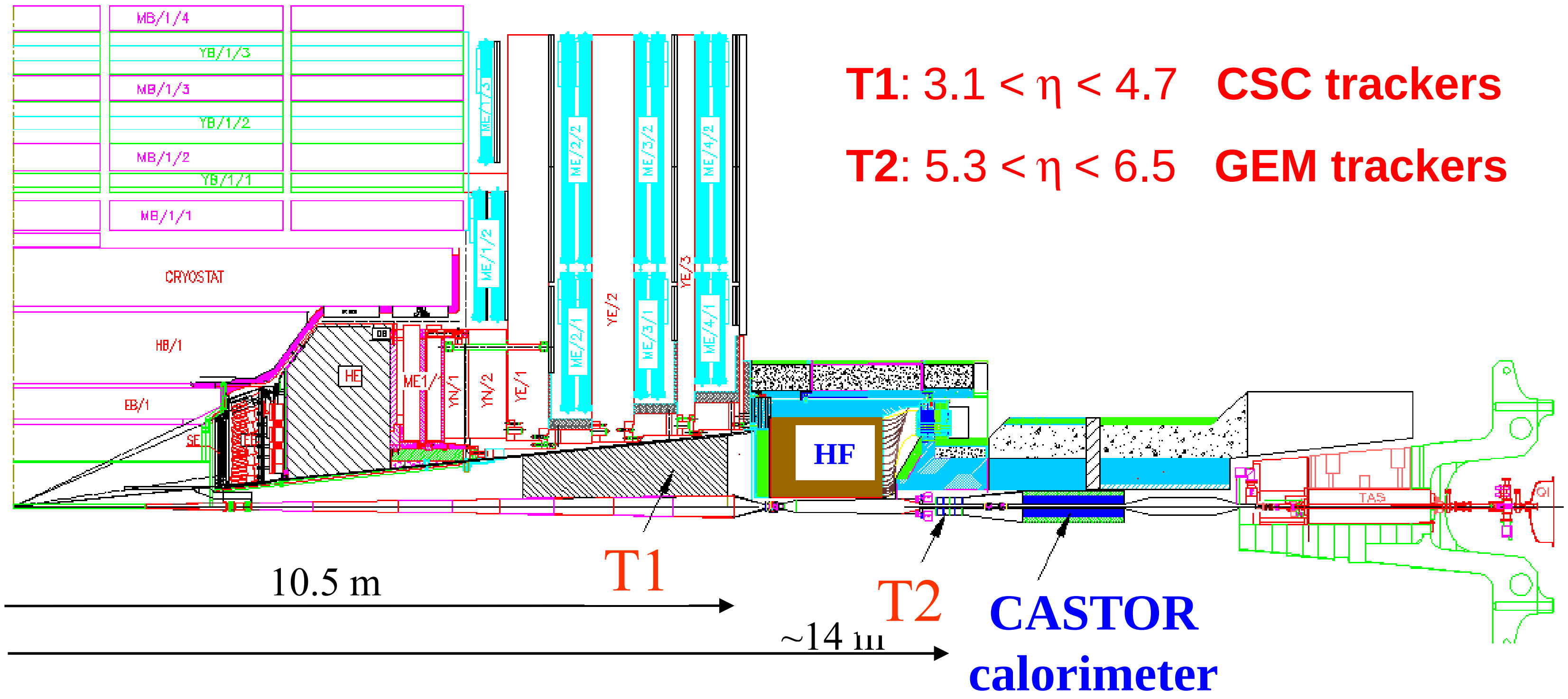
Summary: Questions on diffraction addressed by the LHC

- Total p-p cross-section measurement on the ~1% level
- Differential elastic cross-section measured over 4 orders of magnitude in t with very different scattering mechanisms
- Event topologies and differential cross-sections of diffractive processes (Tools: leading proton detectors, different specially designed beam optics, good rapidity coverage)
- Rapidity gap studies based on proton tagging
- Study of central production with search for resonances: inclusive vs exclusive processes

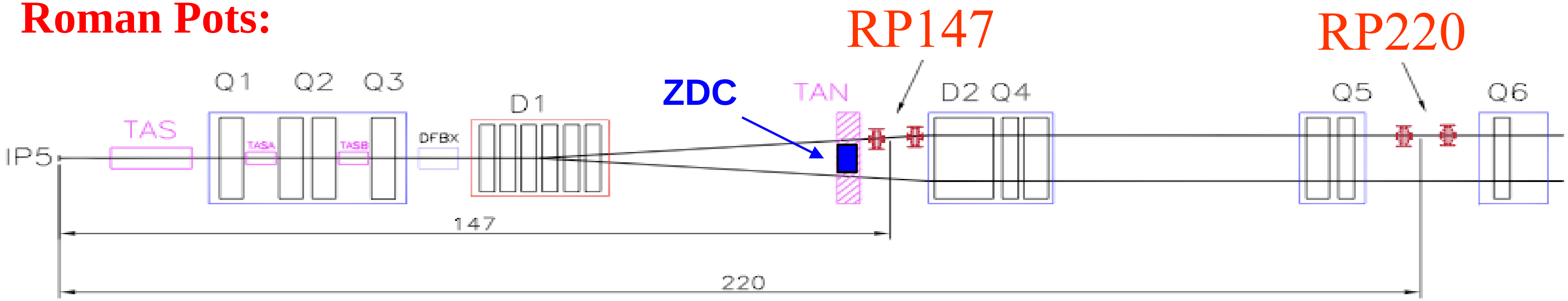
CMS+TOTEM Forward Detectors

T1: 3.1 < η < 4.7 **CSC trackers**

T2: 5.3 < η < 6.5 **GEM trackers**



Roman Pots:

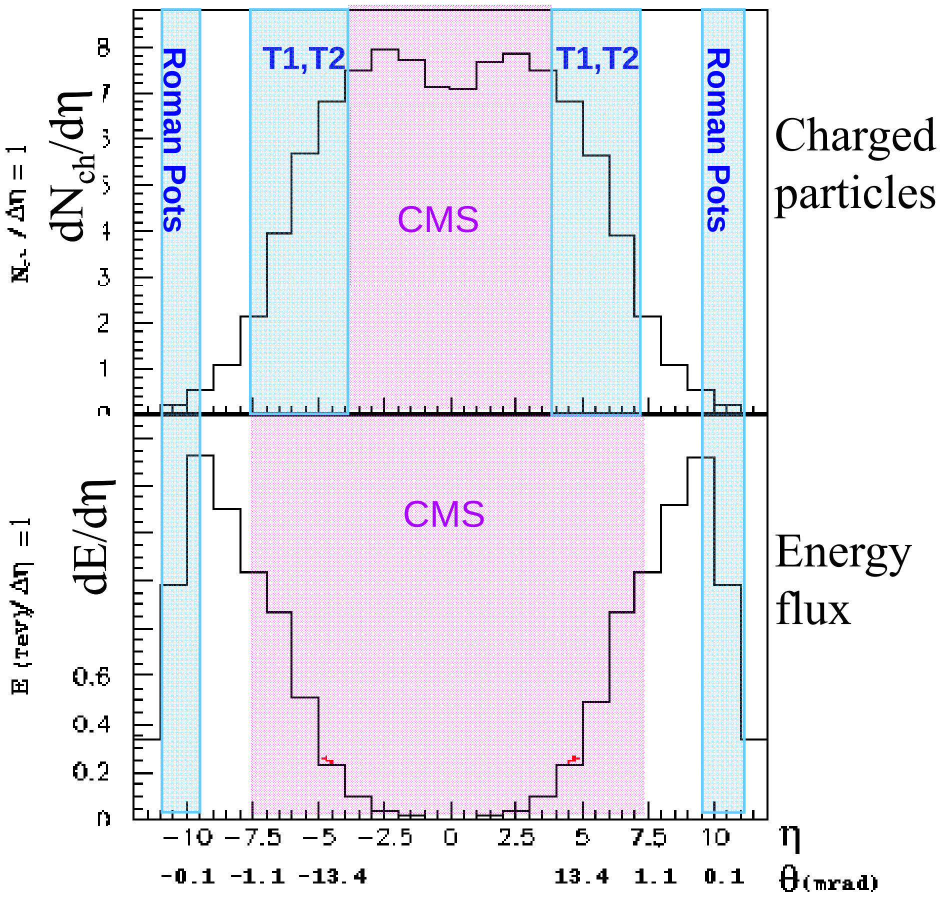


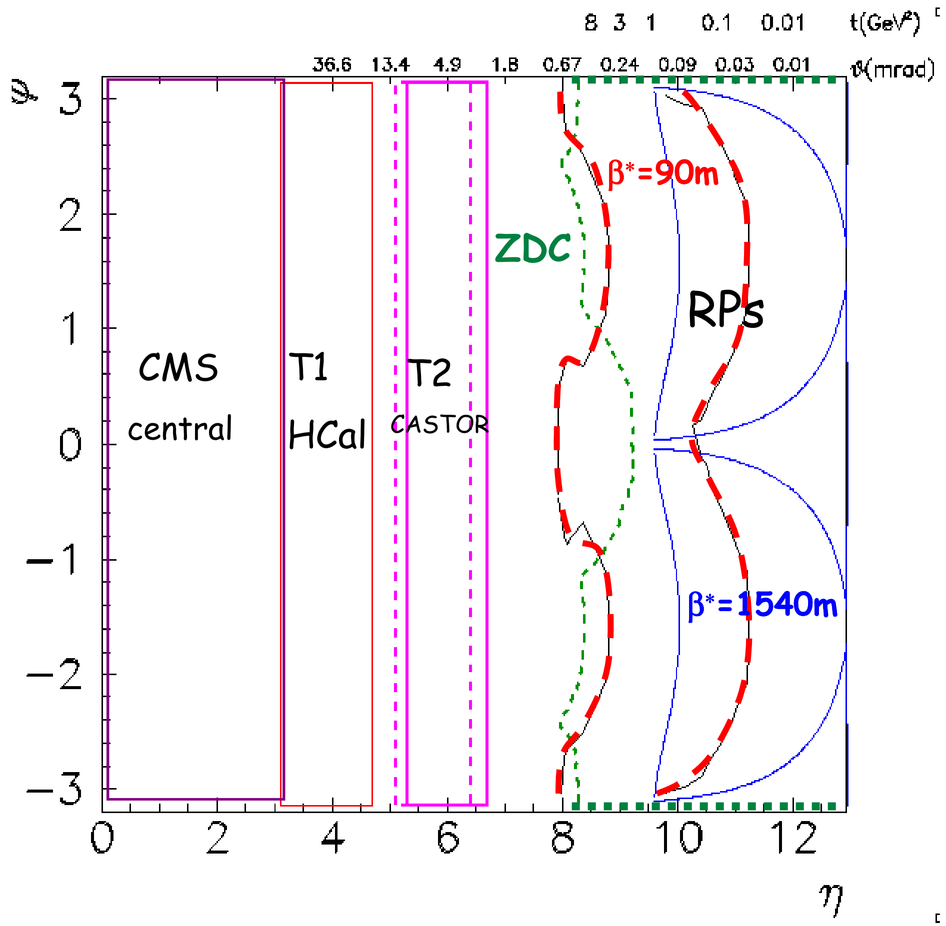
Symmetric experiment: RPs on both sides! → Unique tool for diffraction

CMS + TOTEM: Acceptance

largest acceptance detector ever built at a hadron collider

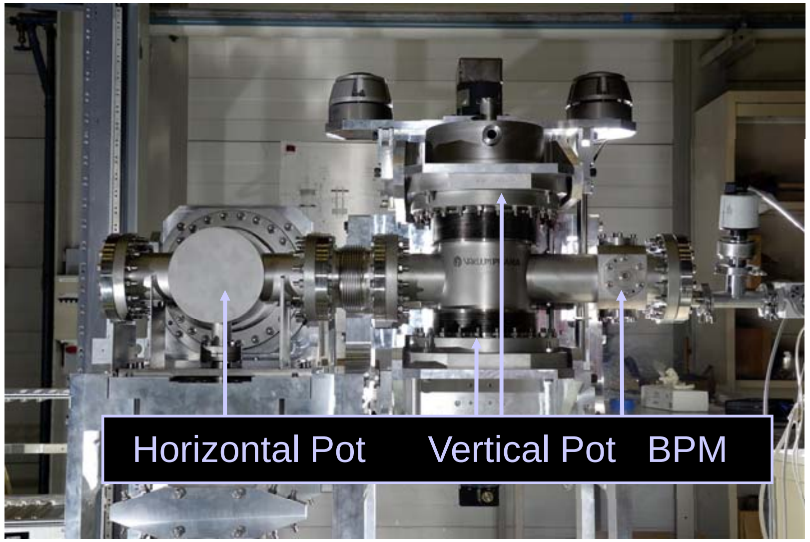
90% (65%) of all diffractive protons are detected for β* = 1540 (90) m

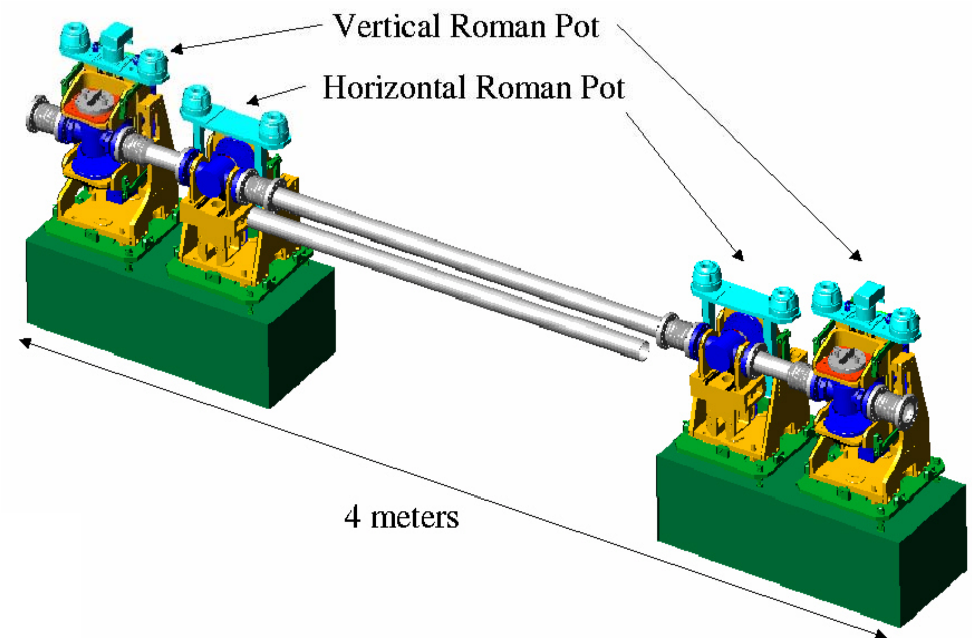




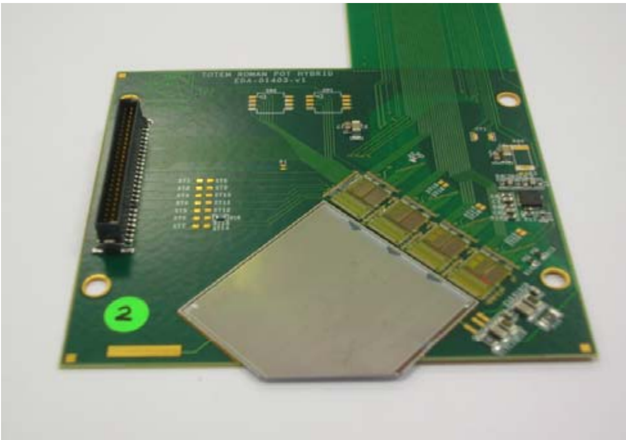
η = - ln tg θ/2

Leading Proton Detection: TOTEM Roman Pots





“edgeless” Si strip detectors
(10 planes per pot)



Leading proton detection at distances down 10 $\sigma_{\text{beam}} + d$

Need “edgeless” detectors (efficient up to physical edge) to minimise width d of dead space.

TOTEM: specially designed silicon strip detectors (CTS), efficient within 50 μm from the edge

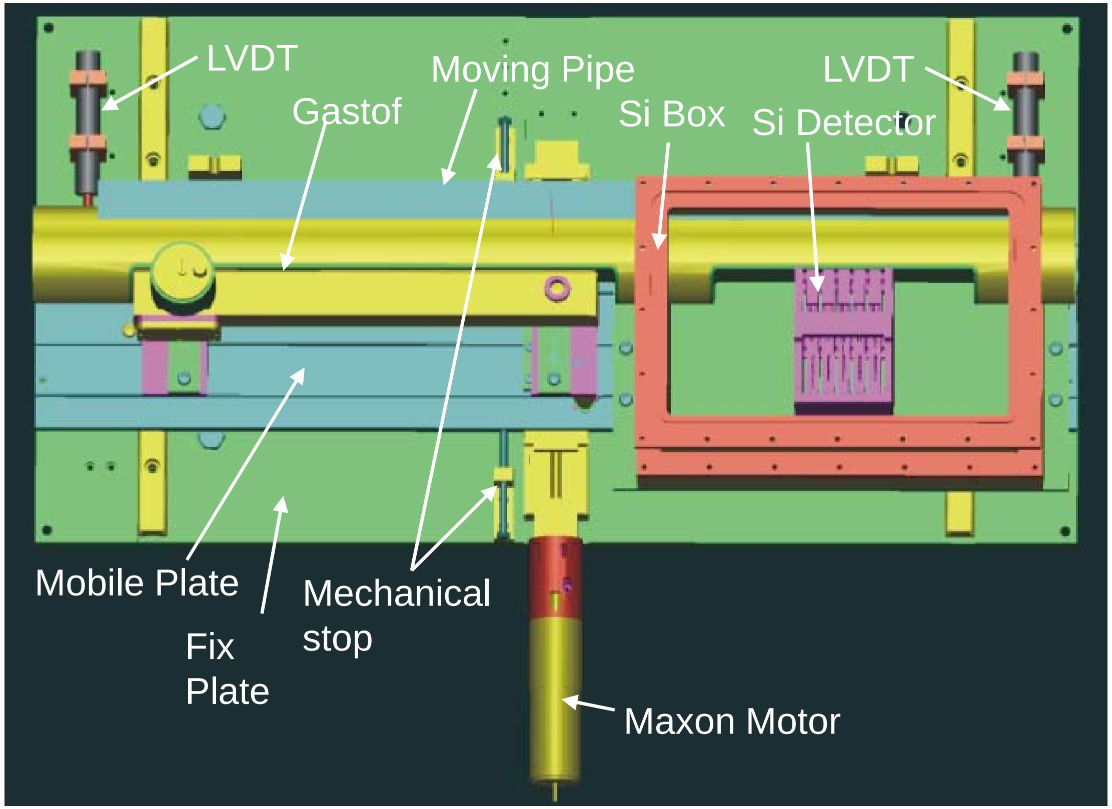
Leading Proton Detection: FP420 (IP1 and IP5) and ATLAS RP220

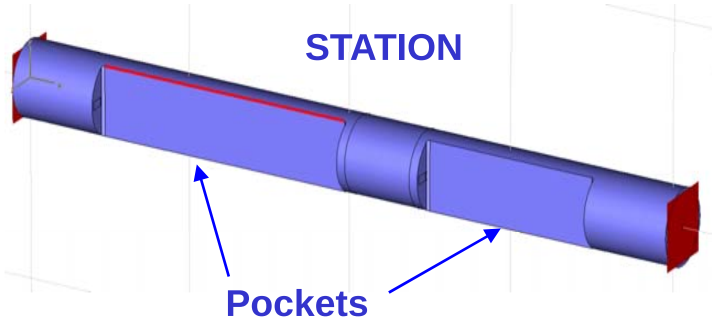
Proton spectrometers proposed: at 220m and ~420 m from IP1 and at ~420m from IP5

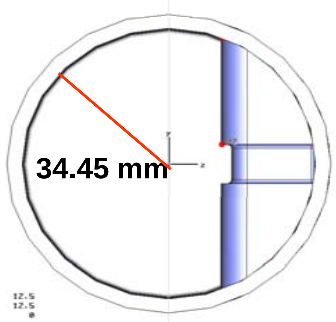
Two (or three) stations for each spectrometer

Two pockets for each station: tracking and timing detectors

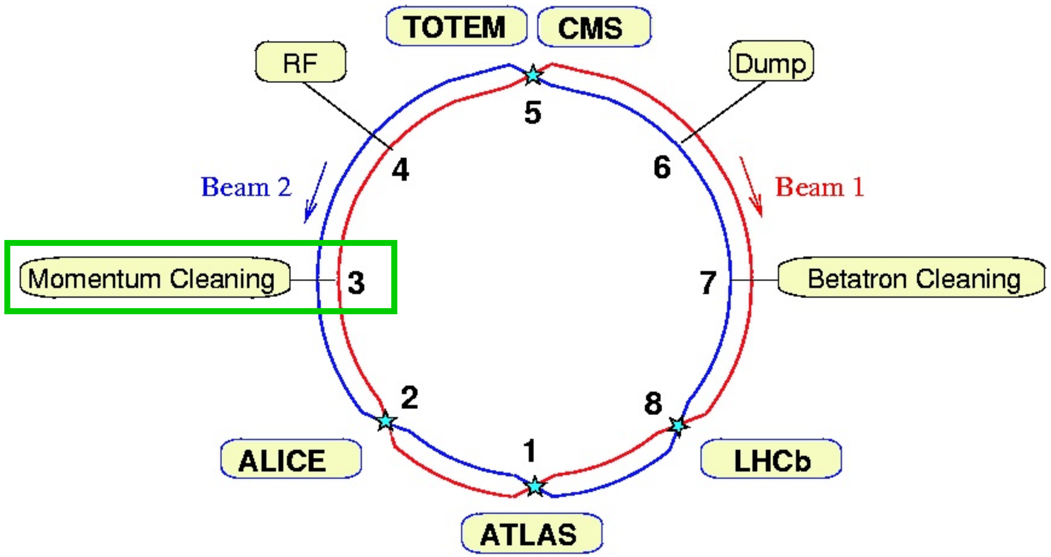
Mechanical design based on **movable "Hamburg Pipe":**





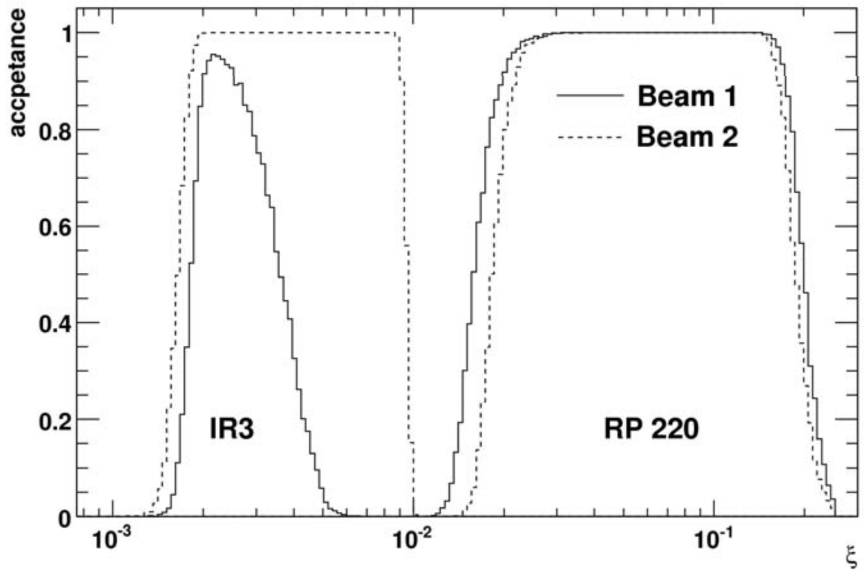


New Idea: Proton Measurement in IP3

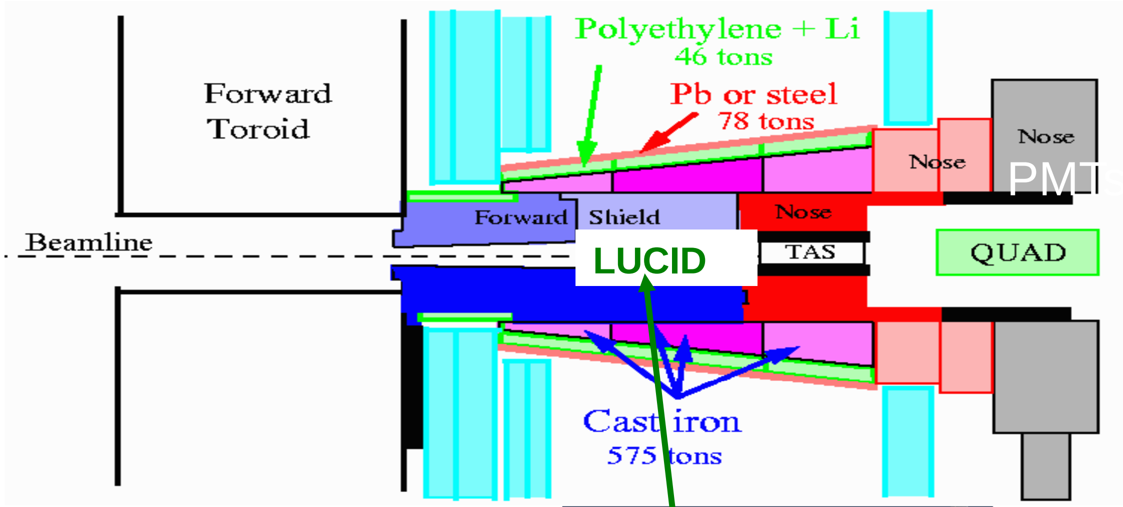


Detects protons from all interaction points.

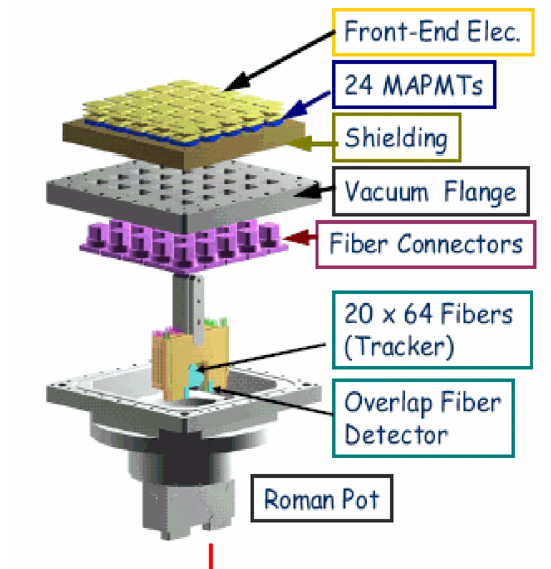
Acceptance in Momentum Loss ξ



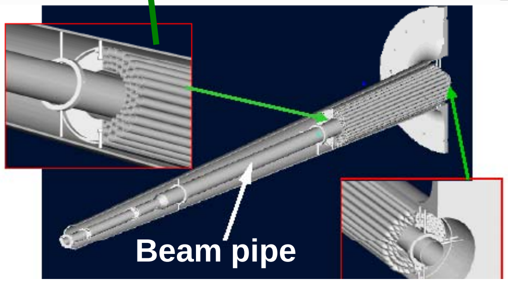
ATLAS + LHCf Forward Detectors

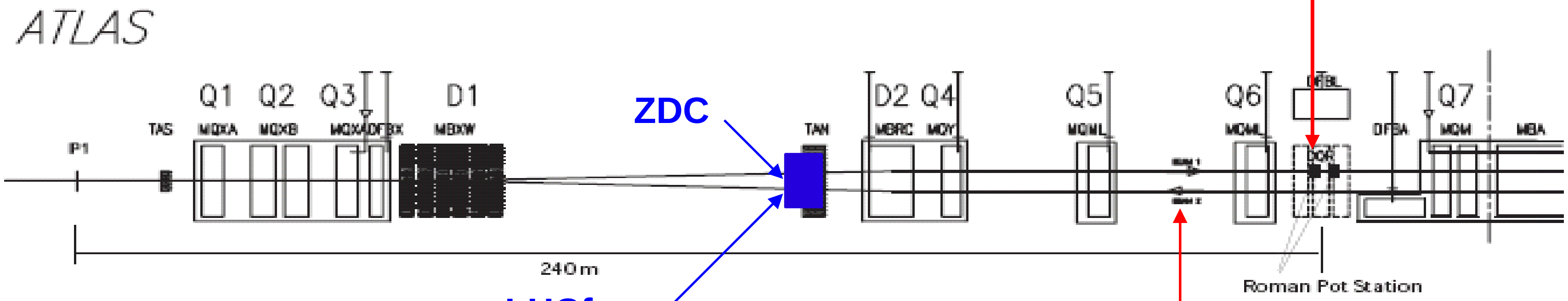


ALFA (RP240):
vertical Roman Pot with
scintillating fibres
for absolute lumi. meas.



LUCID:
Cerenkov tubes
at |z| ~17 m (5.4< |η| <6.1)
for relative lumi. calib.



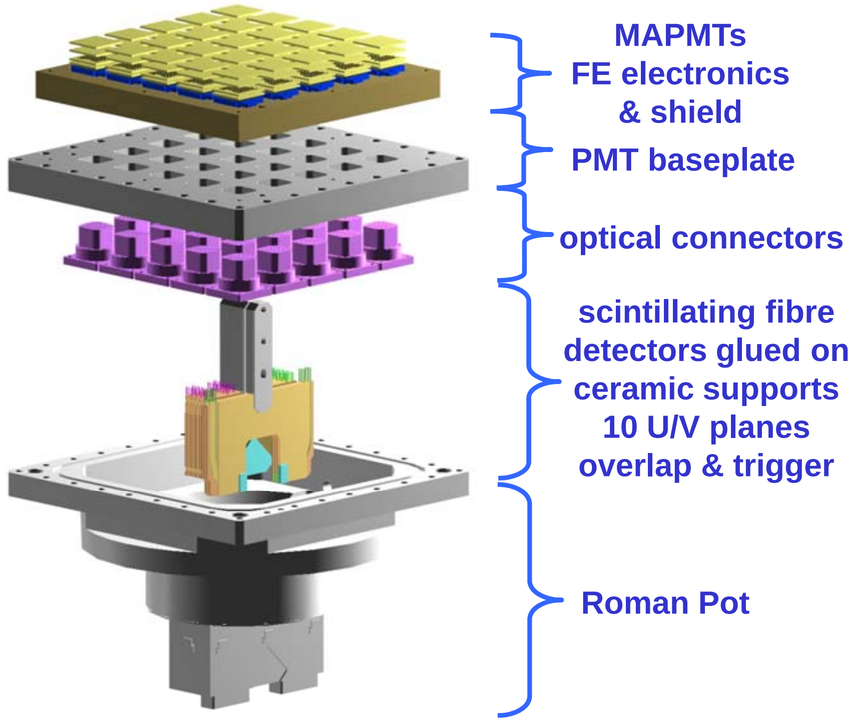


LHCf:
tracker and calo
for forward n, π^0, γ

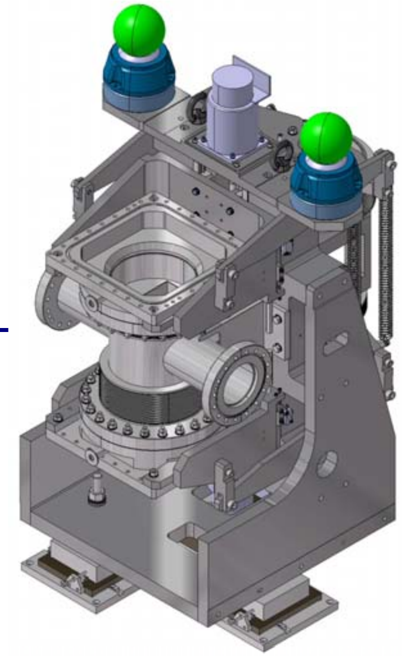
RP220 project for diffraction:
vert. RP and movable beampipe

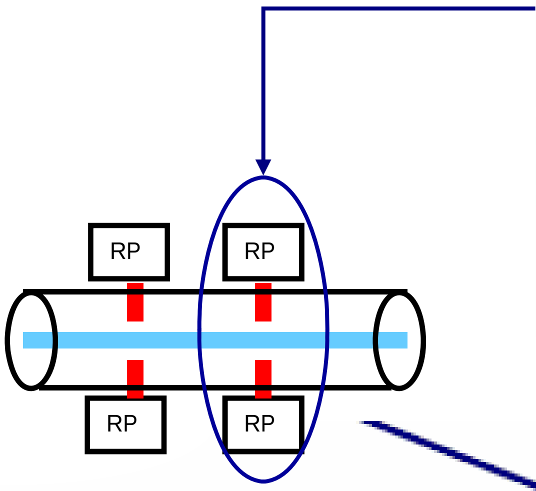
The Experiments: ALFA (IP1)

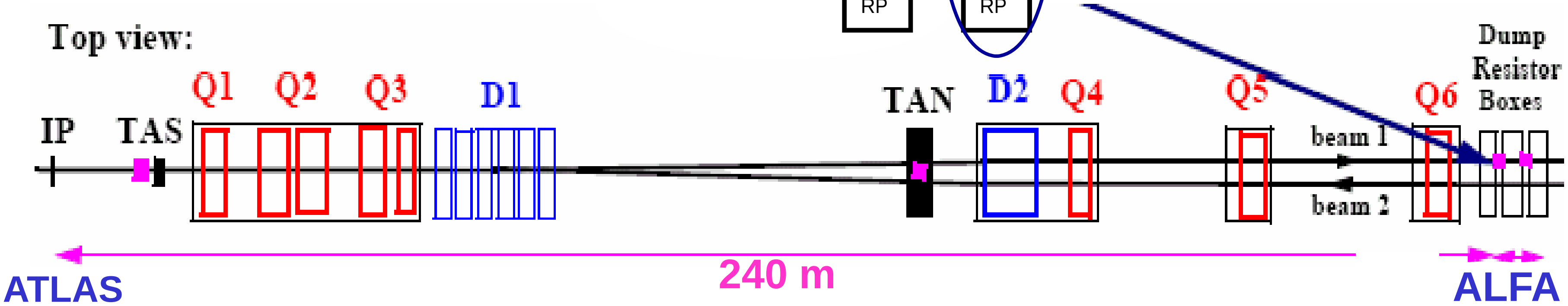
The ATLAS Experiment
ALFA - absolute luminosity for ATLAS



Roman Pot Unit

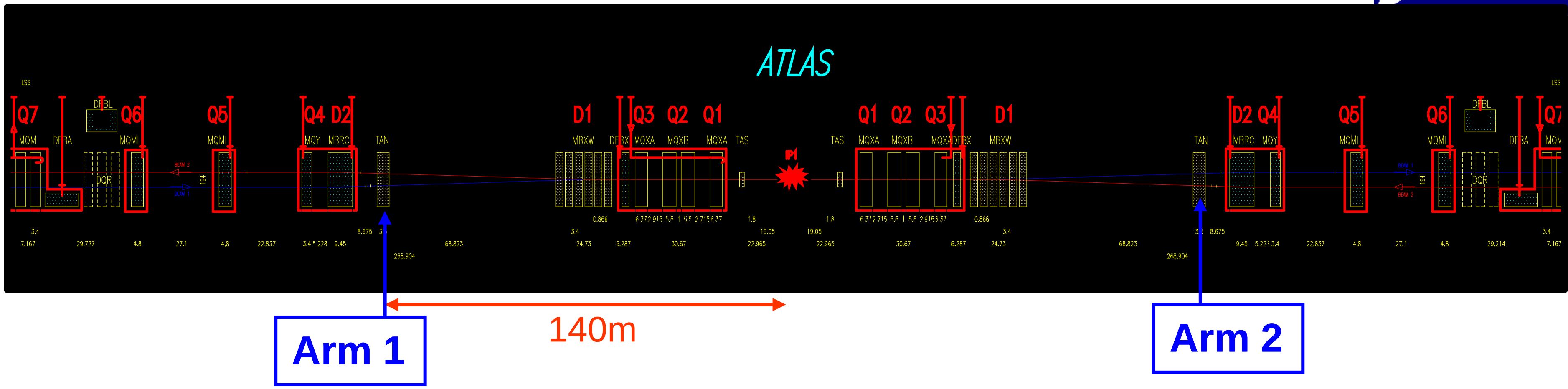


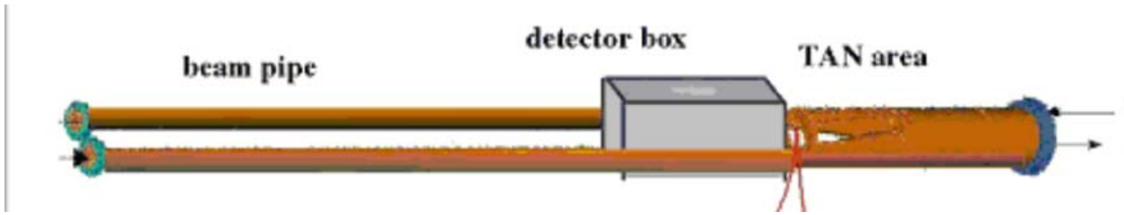


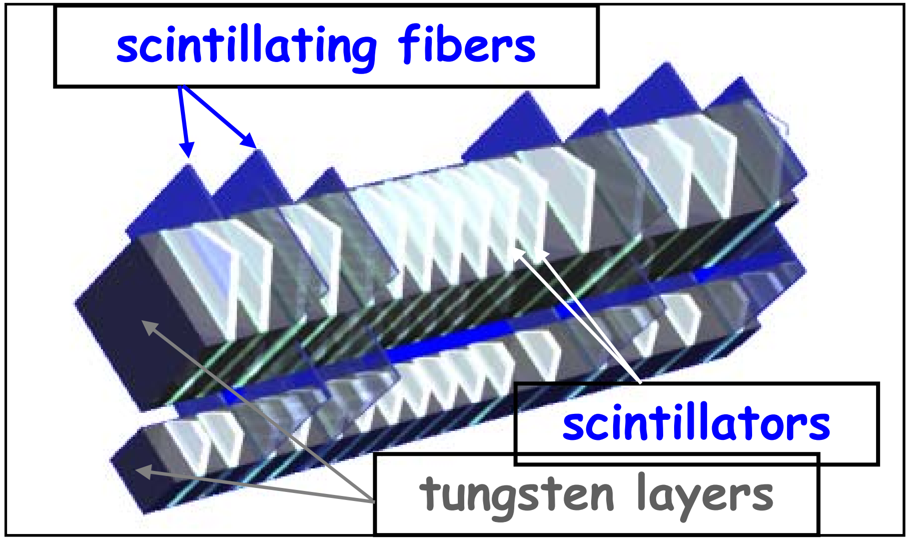


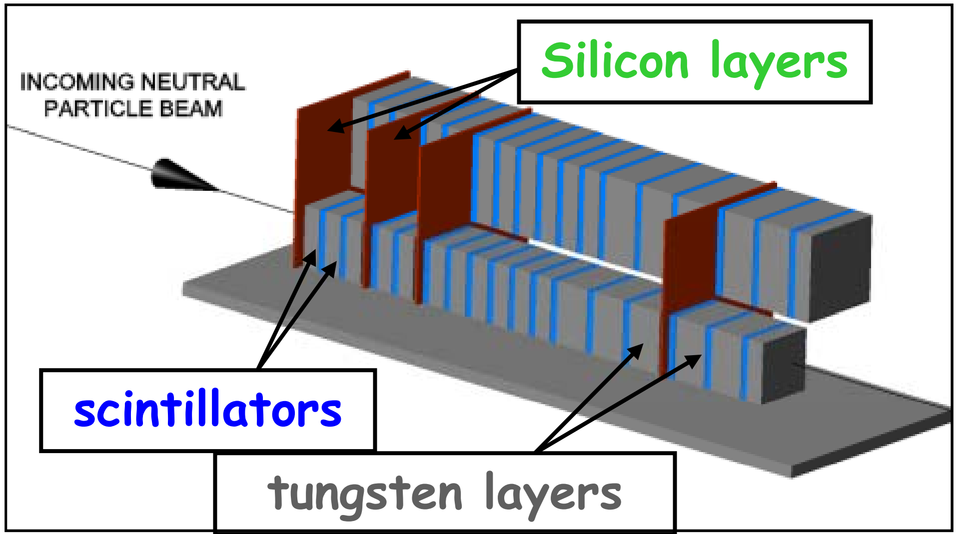
Same configuration on the other side of IP1

The Experiments: LHCf (IP1)



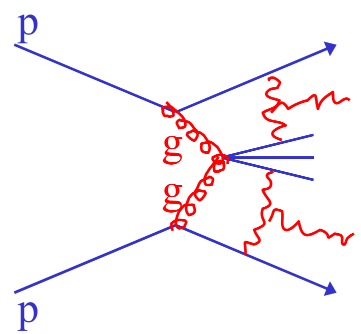






Characteristics of Diffractive Events

Non-diffractive events:

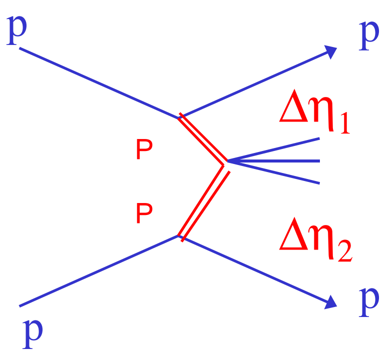


Exchange of colour:
Initial hadrons acquire colour and break up.
Rapidity gaps filled in hadronisation

$\rightarrow$ **Exponential suppression of rapidity gaps:**

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

Diffractive events:

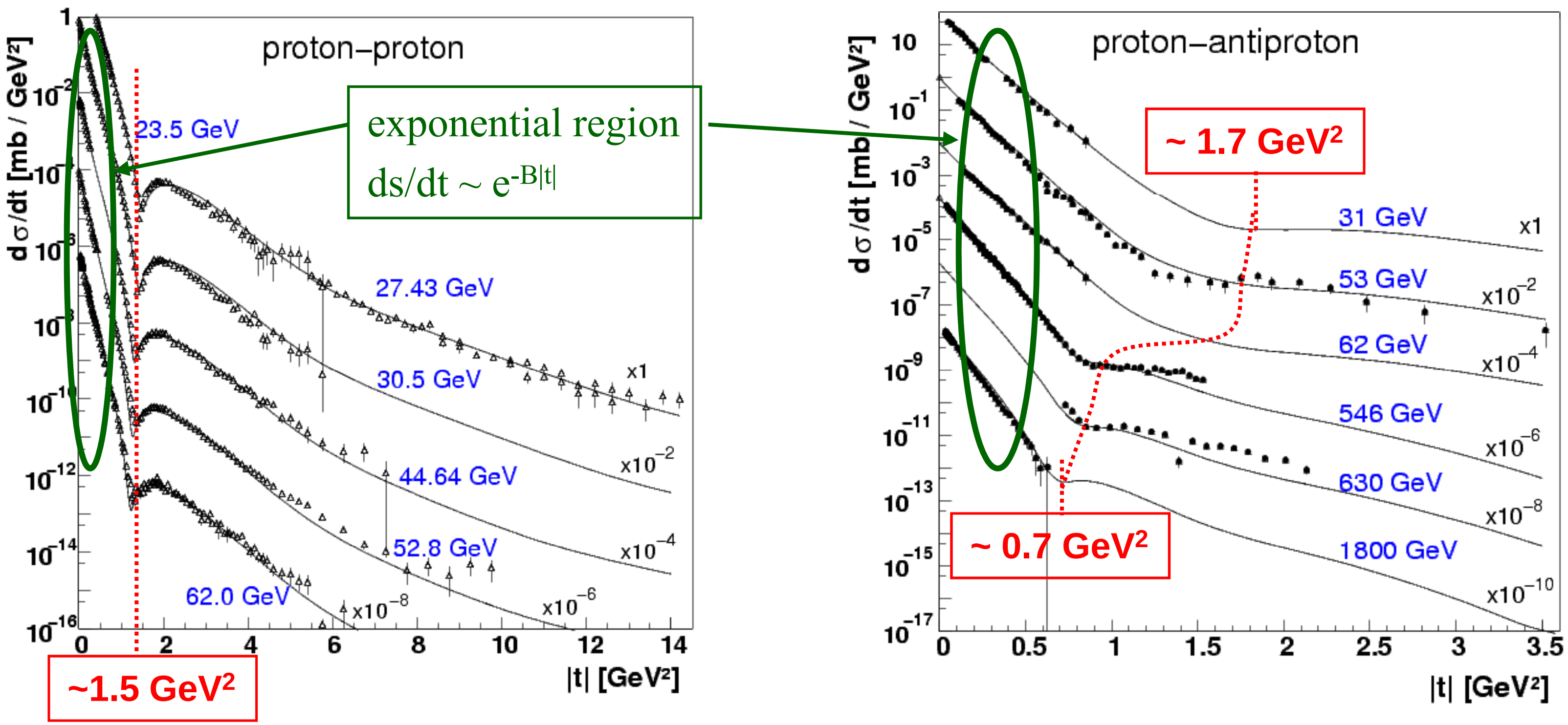


Exchange of colour singlets with vacuum quantum numbers ("Pomerons")

$\rightarrow$ **rapidity gaps** $\Delta\eta$ **with** $\mathbf{P(\Delta\eta) = const.}$

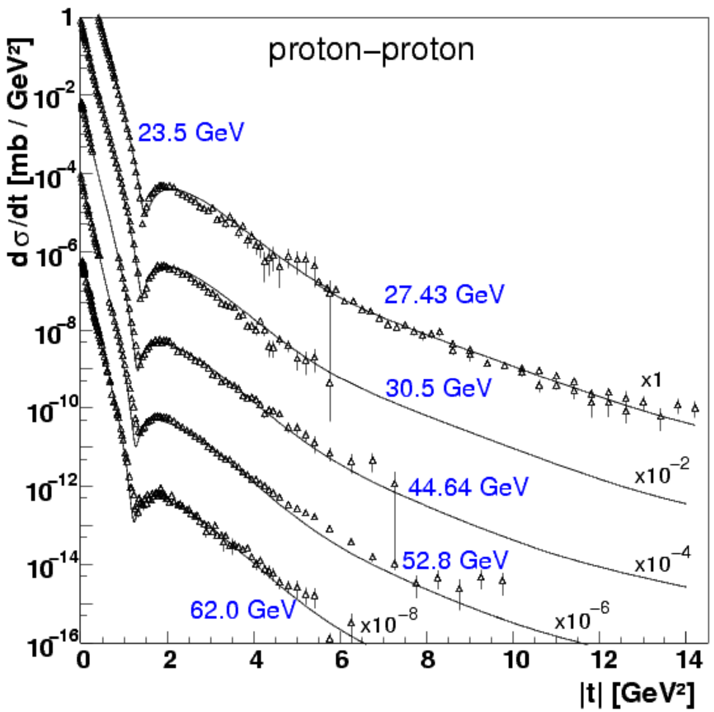
Many cases: leading proton(s) with momentum loss $\Delta p / p \equiv \xi$
(typically $\xi < 0.1$)

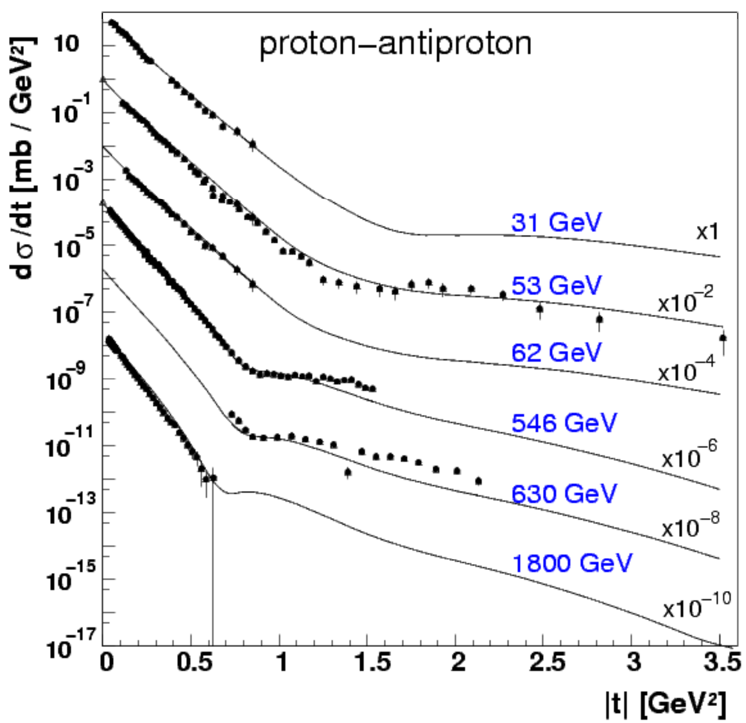
Elastic Scattering - from ISR to Tevatron



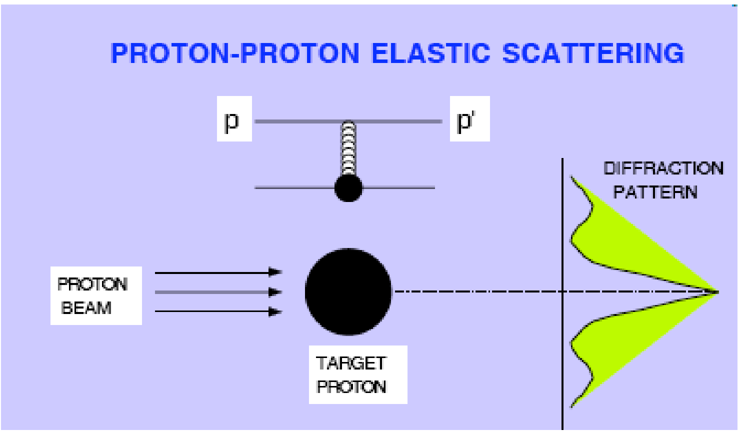
- exponential slope B at low |t| increases: $B \sim R^2$

Elastic Scattering - from ISR to Tevatron





Diffractive minimum: analogous to Fraunhofer diffraction: $|t| \sim p^2 \theta^2$



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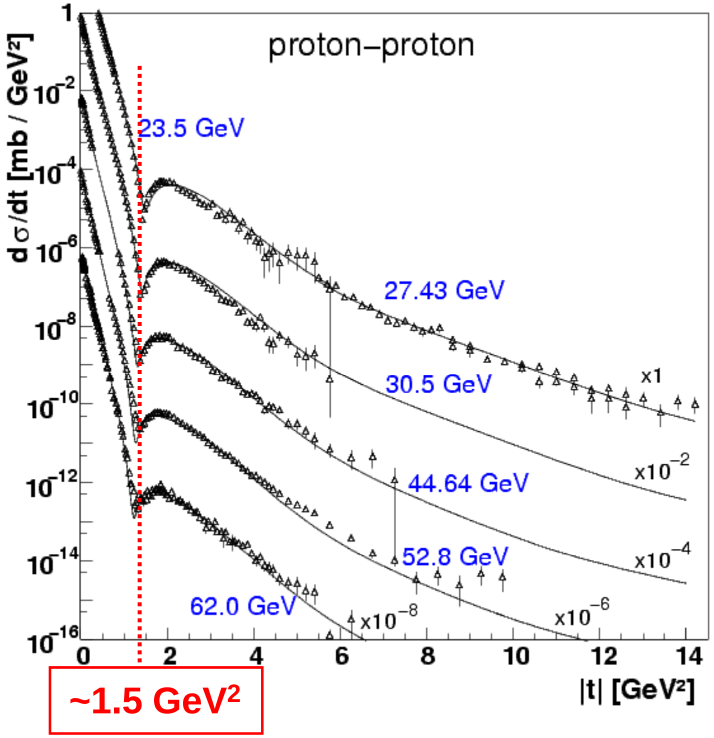
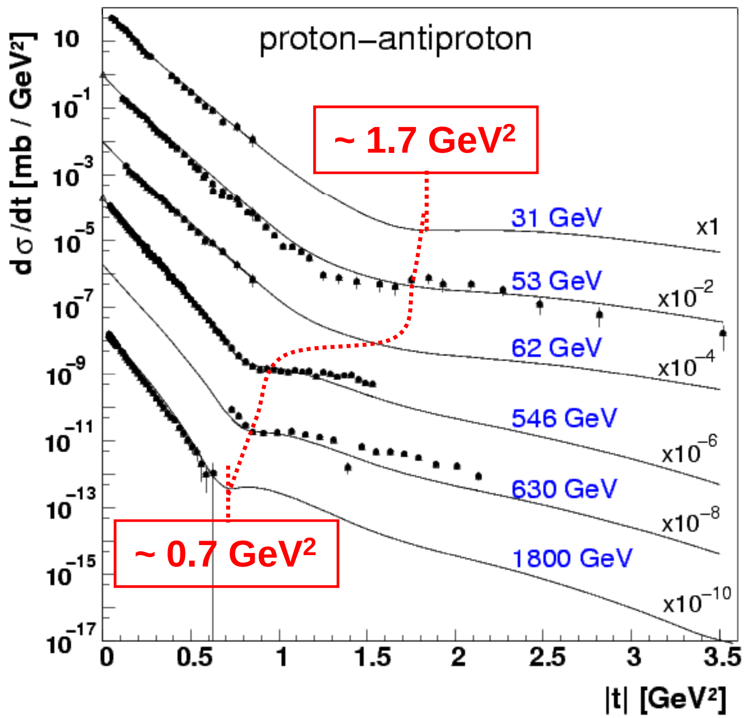
Elastic Scattering - from ISR to Tevatron





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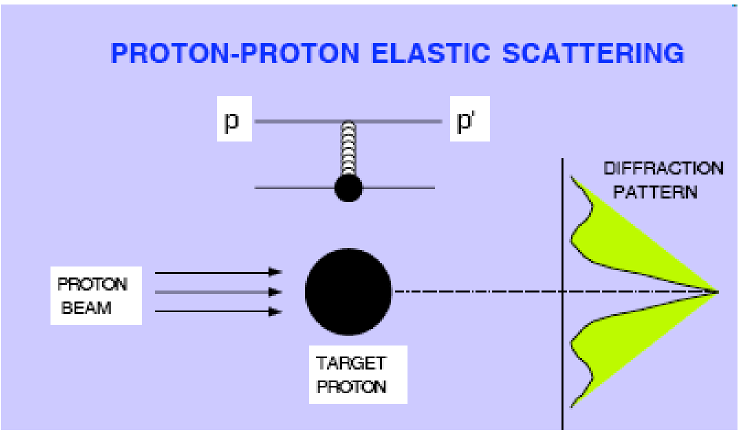
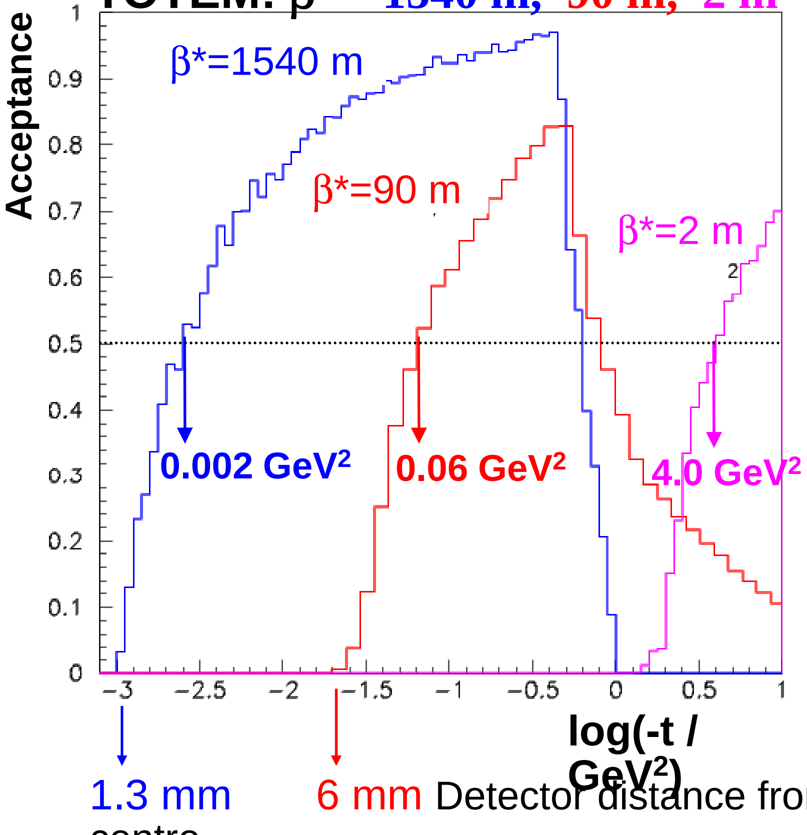


- exponential slope B at low |t| increases
- minimum moves to lower |t| with increasing s
  → interaction region grows (as also seen from σ_{tot})
- depth of minimum changes
  → shape of proton profile changes
- depth of minimum differs between pp, $\bar{p}$p
  → different mix of processes

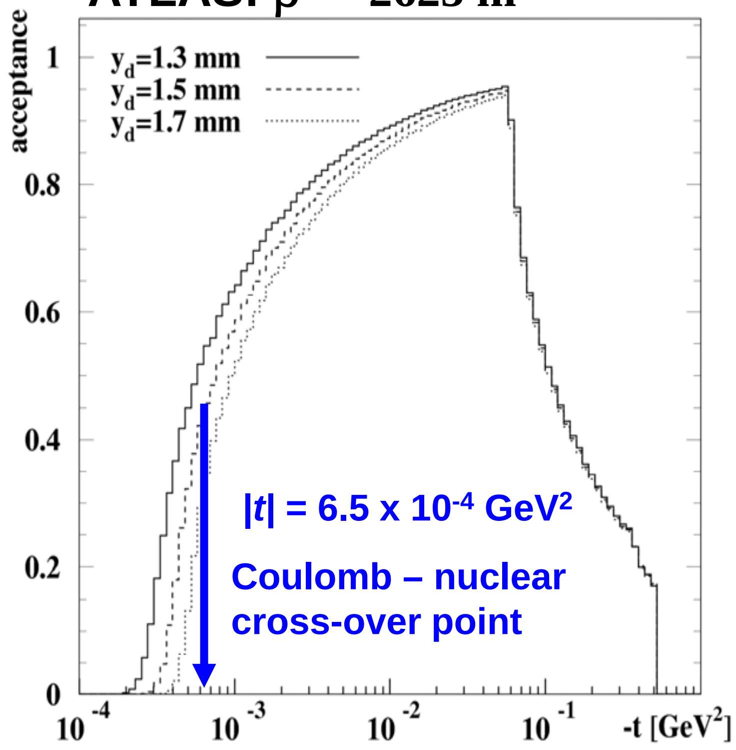
Elastic Scattering Acceptance

Acceptance for elastically scattered protons depends on machine optics (β^*)

TOTEM: β^* = 1540 m, 90 m, 2 m



ATLAS: β^* = 2625 m



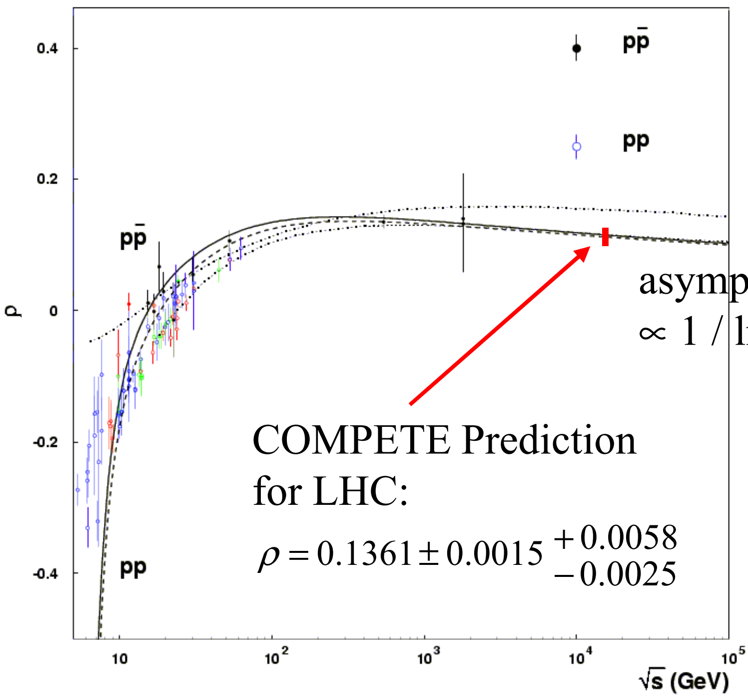
TOTEM: better extrapolation lever arm with β^* = 1540 m than with β^* = 90 m.

Expected uncertainty in σ_{tot}: ~ 1% ~ 5%

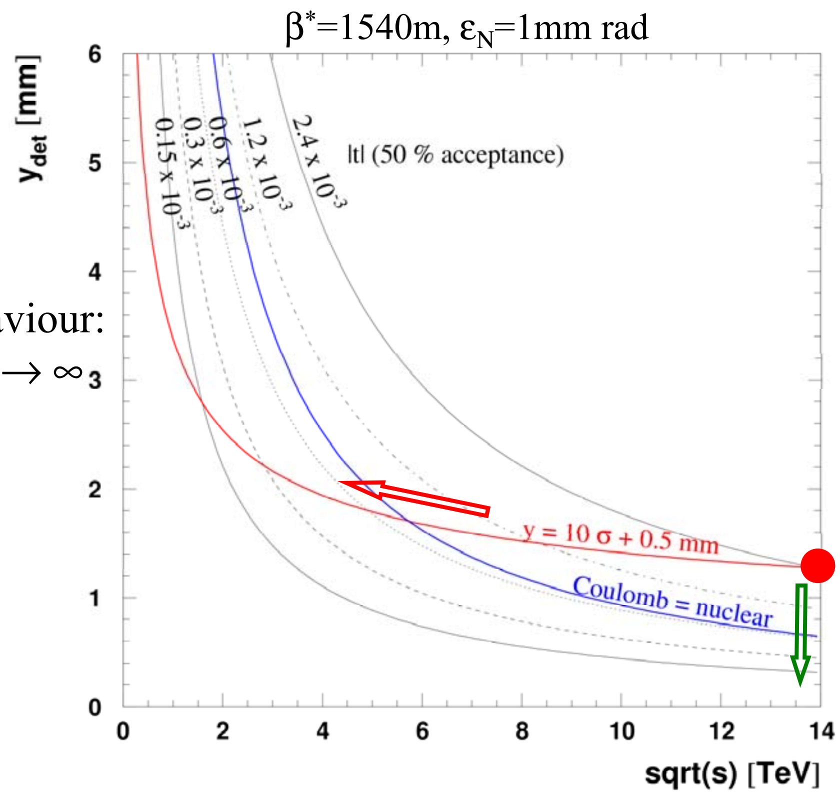
ATLAS: Expected uncertainty in σ_{tot}: ~ 2% if Coulomb region can be reached.

Measurements down to lowest |t| need reduced beam emittance and very close detector approach to the beam → difficult

Measurement of $\rho = \Re f(0) / \Im f(0)$



asymptotic behaviour:
$\propto 1 / \ln s$ for $s \to \infty$



ρ is interesting for σ_{tot}:

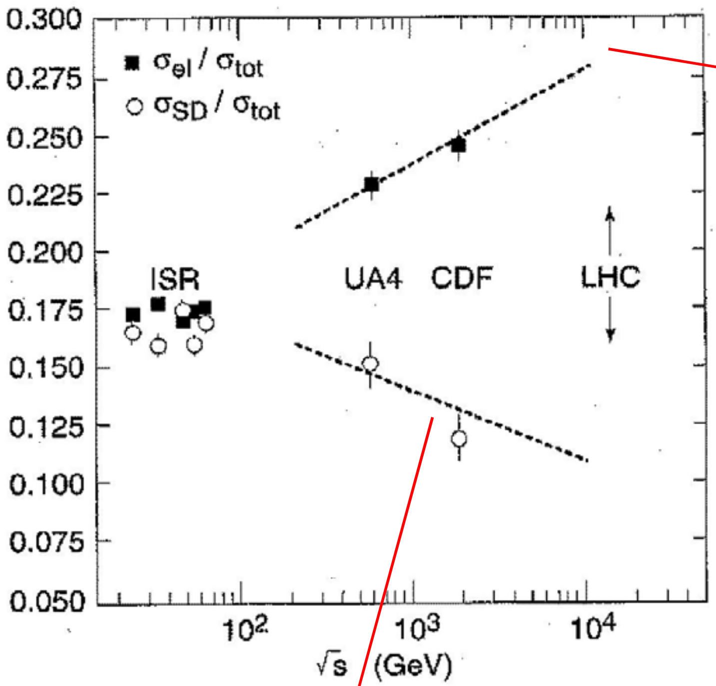
prediction of σ_{tot} at higher s via dispersion relation:

$$\rho(s) = \frac{\pi}{2\sigma_{tot}(s)} \frac{d\sigma_{tot}}{d \ln s}$$

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: $|t|_{min} = p^2 \theta^2$

Elastic and Diffractive Fractions of σ_{tot}



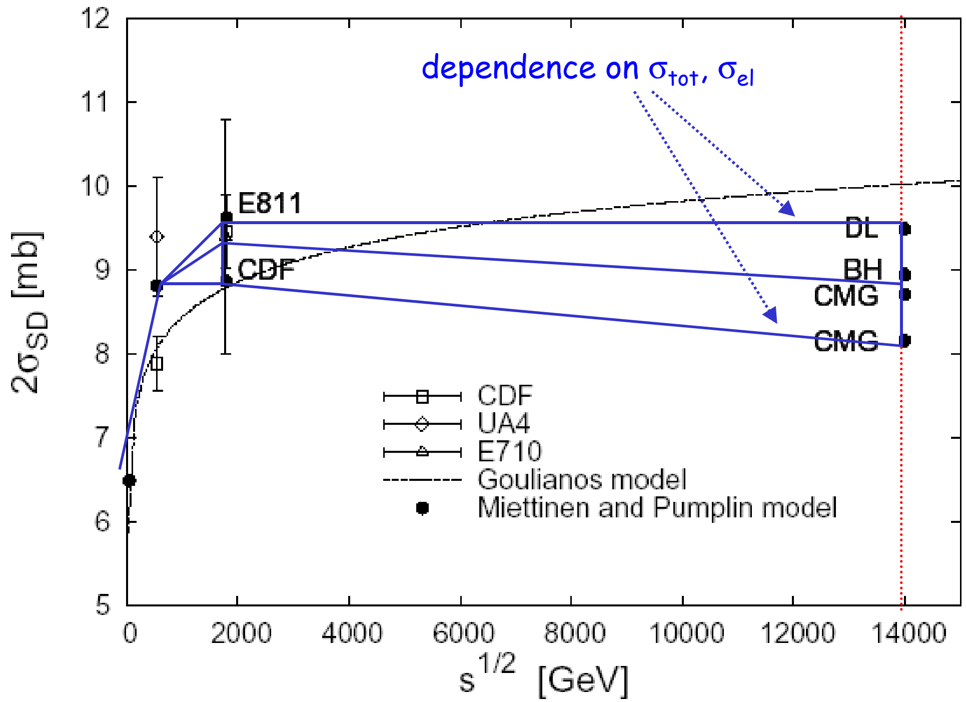
$\sigma_{el} / \sigma_{tot} \sim 30\%$ at the LHC ?

$\sigma_{el}/\sigma_{tot} = 50\%$: black disk limit

The proton not only grows but becomes blacker. Saturation?

SD / total ratio observed to decrease.

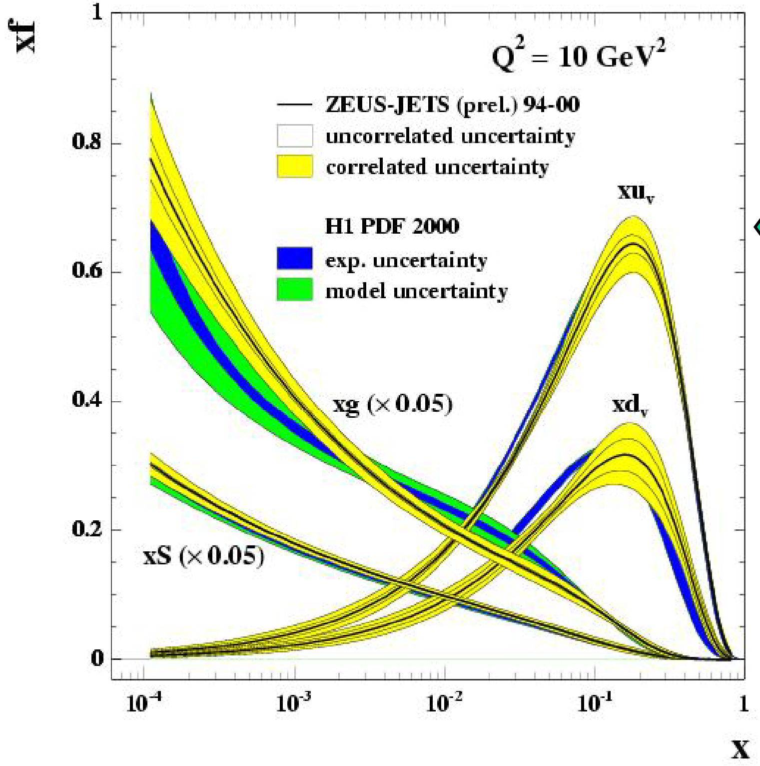
At 14 TeV? Various models:

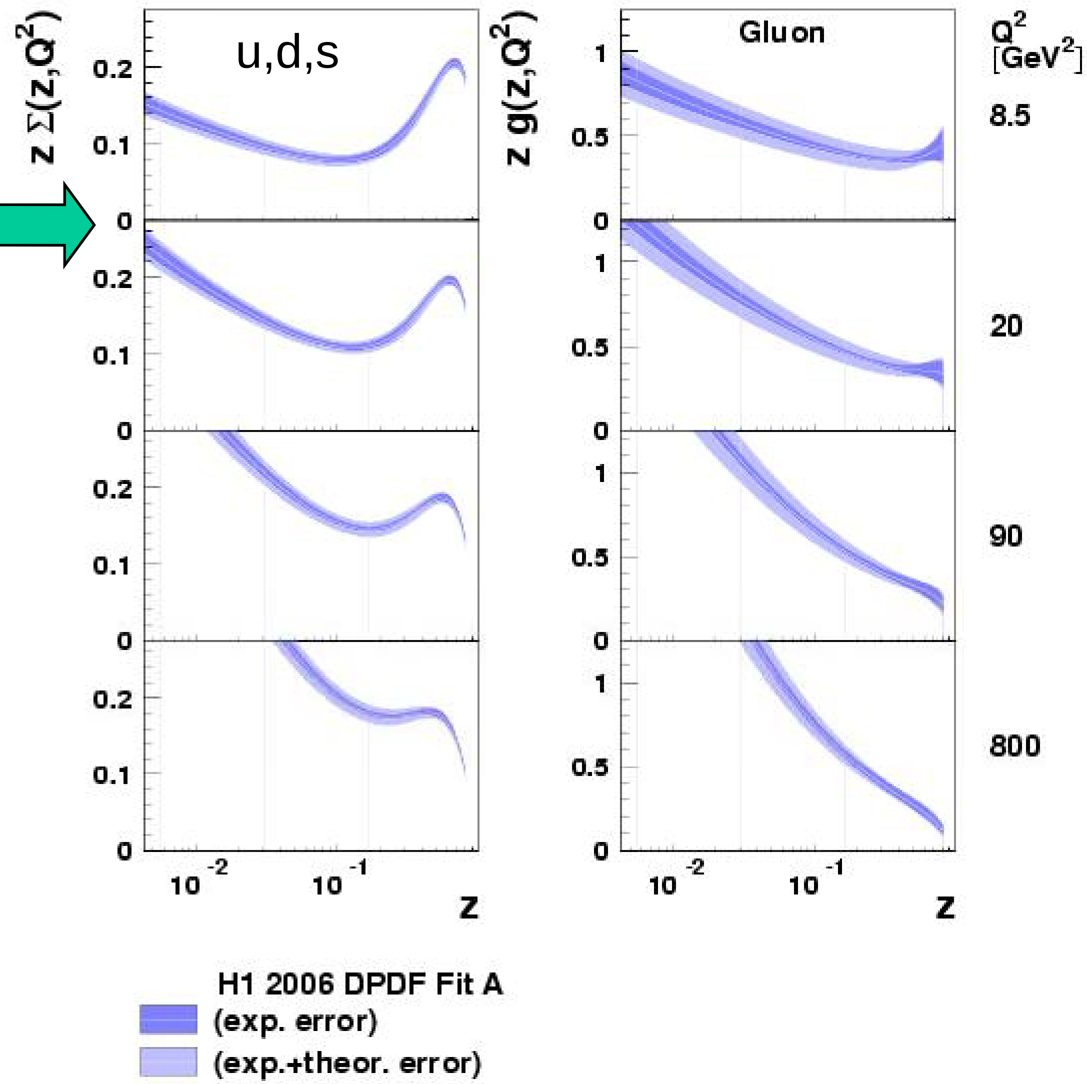


Interpretation of diffractive PDF's

proton PDF's

diffractive PDF's





diffractive vs proton PDF's:

- larger gluon content
- harder gluon structure

Measurement of Resonances

Ideal scenario:

reconstruct kinematics from protons AND resonance decay products (→ redundancy!)

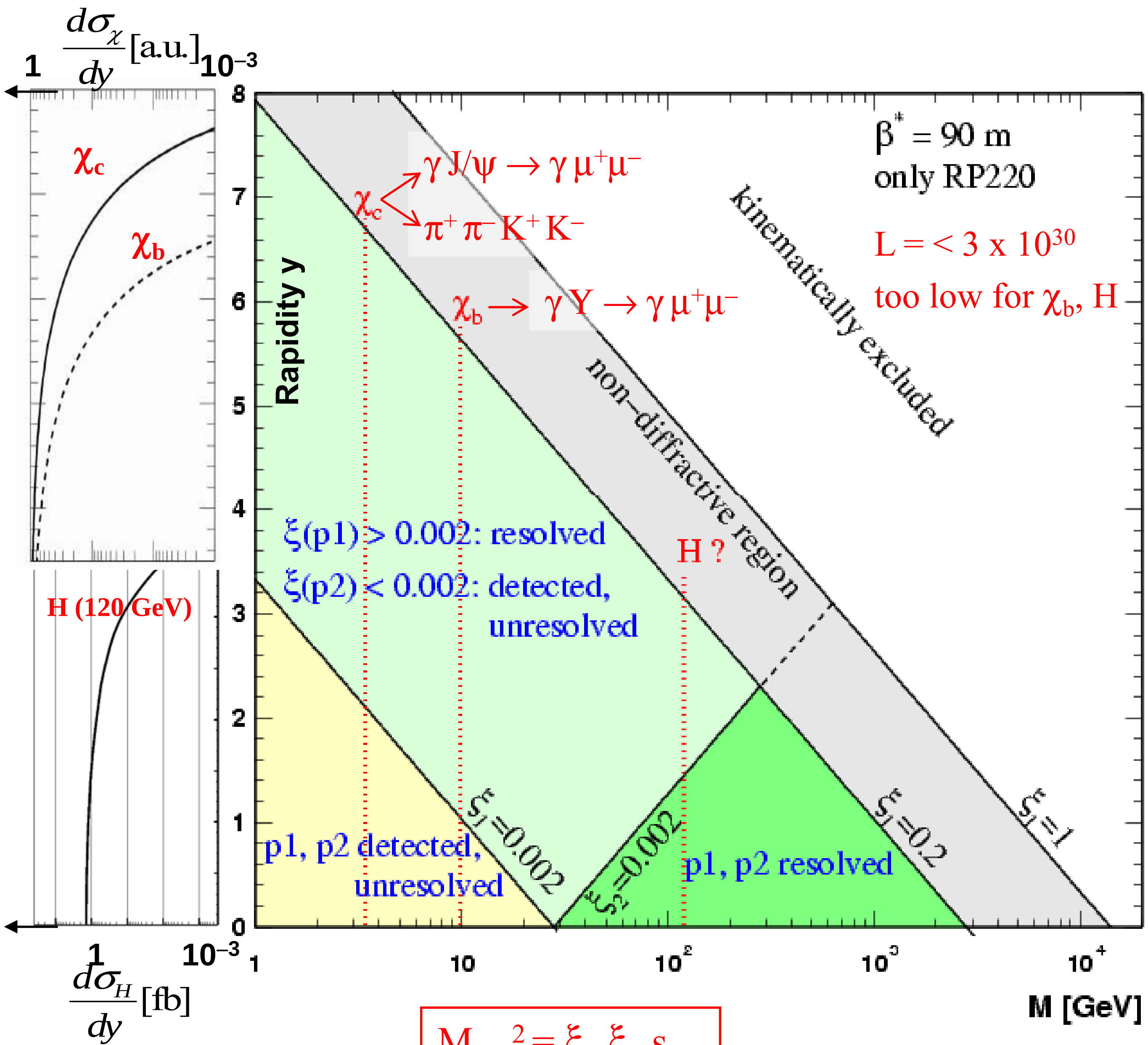
But:

Only possible for small production rapidities y

i.e. symmetric events

$\xi_1 \approx \xi_2$

$$\boxed{y_{PP} = \frac{1}{2}\ln\frac{\xi_1}{\xi_2}}$$



$$\boxed{M_{PP}^2 = \xi_1\, \xi_2\, s}$$

Measurement of Resonances

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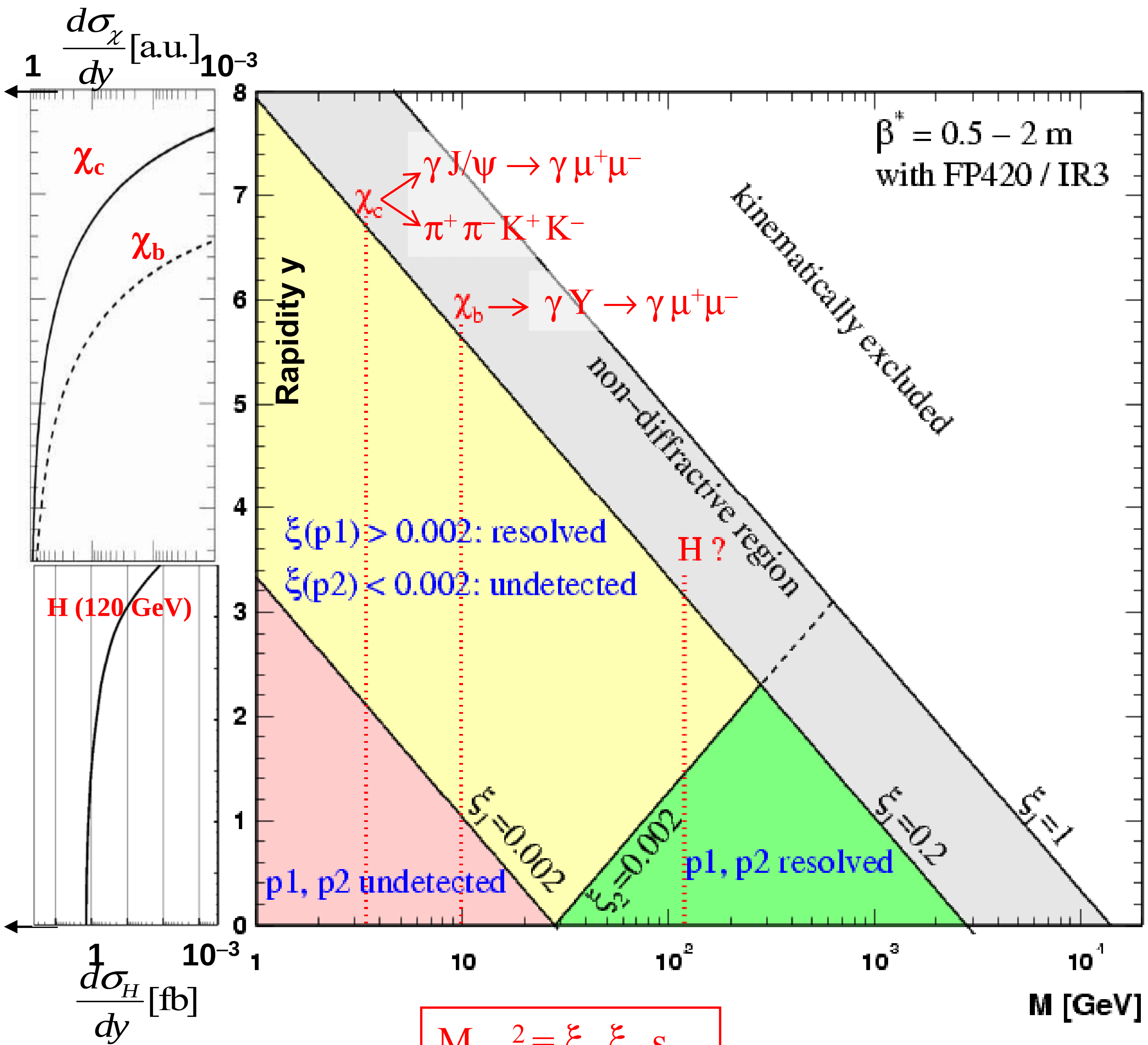


$$\boxed{M_{PP}^2 = \xi_1 \xi_2 s}$$

Higgs (SM, MSSM)

SM with m_H = 120 GeV:

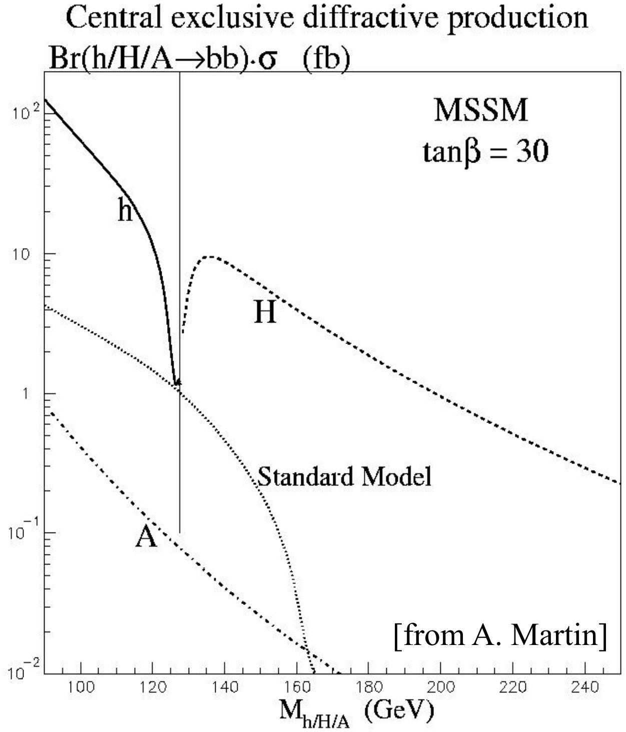
σ x BR (H→ bb) = 2 fb

30 fb^{-1}, δm = 3 GeV: S/B = 11/10

σ x BR (H→ WW*) = 0.4 fb

30 fb^{-1}: S/B = 8/3

MSSM:



MSSM Examples:

m_A = 130 GeV

	tan β = 30	tan β = 50
m_A σ x BR (A→ bb)	130 GeV 0.07 fb	130 GeV 0.2 fb
m_h σ x BR (h→ bb)	122.7 GeV 5.6 fb	124.4 GeV 13 fb
m_H σ x BR (H→ bb)	134.2 GeV 8.7 fb	133.5 GeV 23 fb

m_A = 100 GeV

	tan β = 30	tan β = 50
m_A σ x BR (A→ bb)	100 GeV 0.4 fb	100 GeV 1.1 fb
m_h σ x BR (h→ bb)	98 GeV 70 fb	99 GeV 200 fb
m_H σ x BR (H→ bb)	133 GeV 8 fb	131 GeV 15 fb