Forward Physics

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Contents

- Introduction to forward physics
- Forward regions of present LHC detectors
- Physics topics

"Classical forward physics"

  - Total and elastic cross sections cross section
  - Diffractive scattering (general)

"New forward physics"

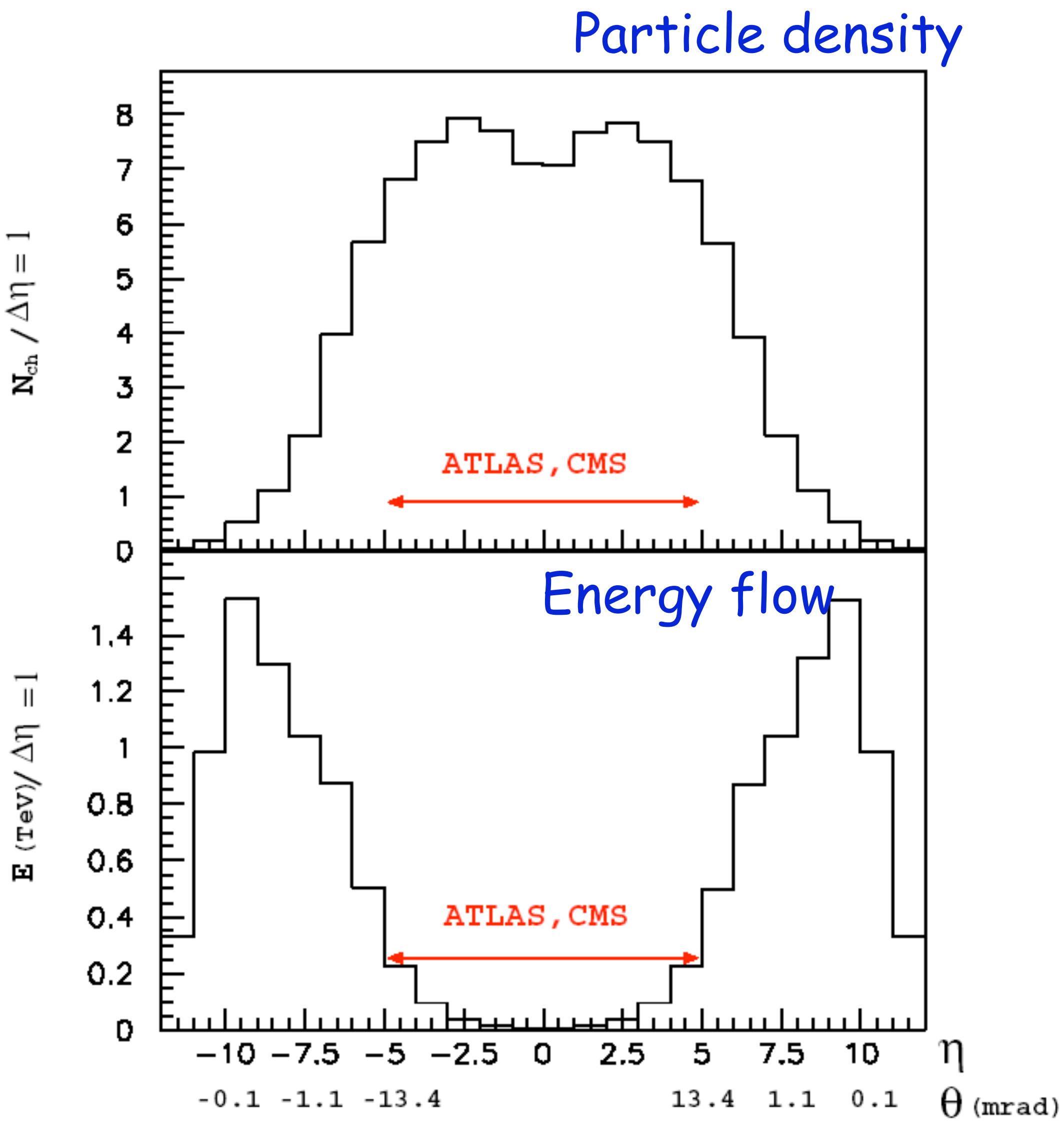
  - Hard diffractive scattering (HERA/Tevatron/LHC)
  - Exclusive production of the Higgs
    - Including detector upgrades needed (FP420)
  - Low-x QCD
  - Cosmic rays connections
  - (2-photon interactions)

LECTURE 1

LECTURE 2

Borrowed slides from M. Albrow, D Enterria…

Motivation



Experiments at previous colliders never had a "full acceptance" but essentially concentrated around central region

ATLAS,CMS: |η|<(3) 5

Forward region

- Diffractive phenomena
- Low-x
- Exotics (centauros, DCC's)
- Link with Cosmic Rays
- Surprises?Most of the energy of the event "down the beampipe"
- Forward tagging can act as filters for central production (e.g. Higgs)

Pseudo Rapidity: $\eta = -\ln \mathrm{tg}\Theta/2$

Θ: Polar angle of particle

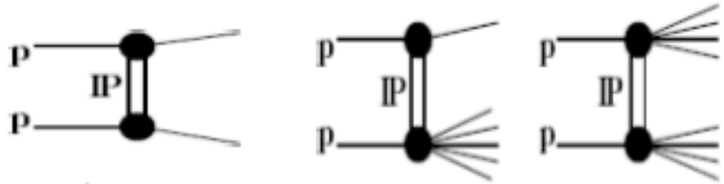
Diffractive/Forward Physics Topics

- Many interesting (mostly color-singlet exchange) scatt. processes at the LHC are characterized by forward particle production:

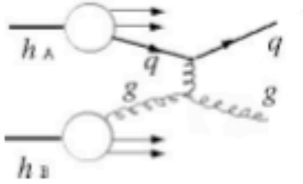
~25% of σ_{tot}

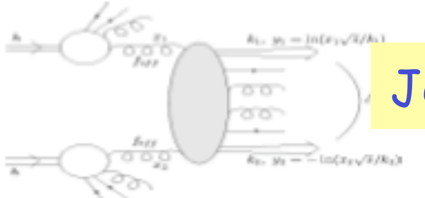
QCD:

elastic/diffractive interactions:



low-x:

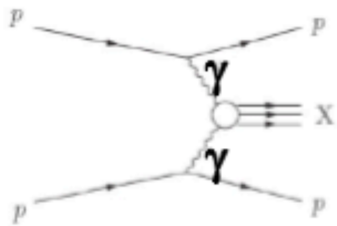


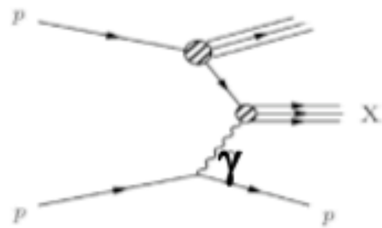


cosmic-rays MCs

Jets , W, J/ψ, Υ, t?...

EWK: two-photon, photon-proton colls.

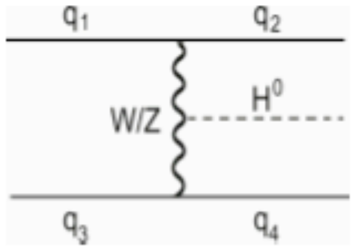


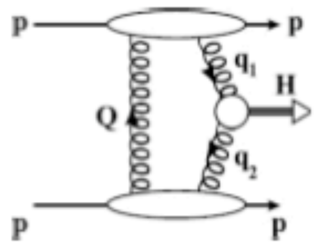


~10^{-13} of σ_{tot}

Higgs: VBF, central exclusive,

MSSM Higgs, ...





h,H,A

Example: Exclusive Higgs Production

Physical Review Focus

Focus Archive | Image Index | Focus Search

Previous Story / Next Story / Volume 23 archive

Phys. Rev. Lett. **102**, 242001
(issue of 19 June 2009)
Title and Authors

24 June 2009

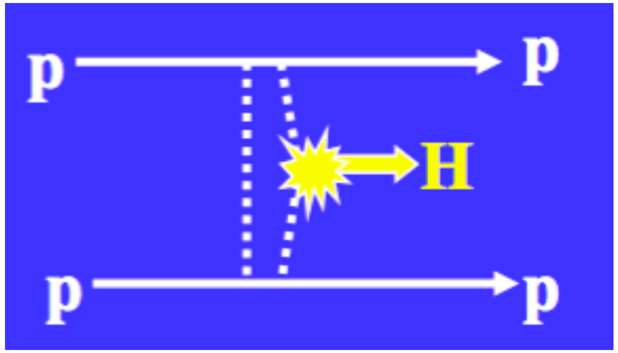
A Higgs Boson without the Mess

Particle physicists at CERN's Large Hadron Collider (LHC) hope to discover the Higgs boson amid the froth of particles born from proton-proton collisions. Results in the 19 June *Physical Review Letters* show that there may be a way to cut through some of that froth. An experiment at Fermilab's proton-antiproton collider in Illinois has identified a rare process that produces matter from the intense field of the strong nuclear force but leaves the proton and antiproton intact. There's a chance the same basic interaction could give LHC physicists a cleaner look at the Higgs.

CERN

Higgs machine. If CERN's Large Hadron Collider (LHC) can create Higgs bosons, a handful may appear in rare "exclusive" reactions that don't destroy the colliding protons--similar to a reaction now observed at Fermilab. CERN's ATLAS and CMS teams are considering adding equipment to their detectors (CMS shown here) to look for such events (click image to enlarge).

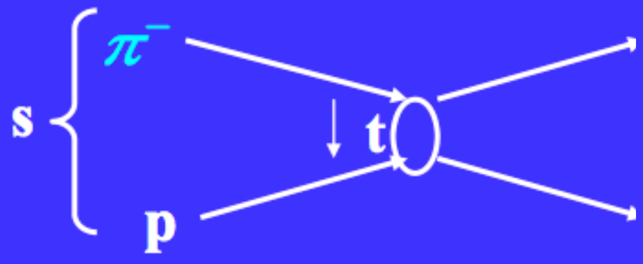
A proton is always surrounded by a swarm of ghostly virtual photons and gluons associated with the fields of the electromagnetic and strong nuclear forces. Researchers have predicted that when two protons (or a proton and an antiproton) fly past one another at close range, within about a proton's diameter, these virtual particle clouds may occasionally interact to create new, real (not virtual) particles. The original protons would merely lose some



Promising channel for Higgs property studies
⇒ Much more on that tomorrow…

Introduction: Forward Physics

In ancient times, pre-QCD (1960's),
Theory of strong interactions being developed: "Regge Theory"
Pre-quarks, pre-gluons, pre-deep inelastic scattering.



Tullio Regge

Based on scattering amplitudes "S"
(Square → cross sections) S(s,t)
S(s,t) required to be:

Analytic (no singularities)
Unitary (no probabilities > 1)
Crossing symmetric (s ⟷ t)

All good things!

t-channel exchange dominated by virtual:

$$\boxed{\rho^{\pm} \cong (\pi^{0}\pi^{\pm}) \cong (p\bar{n} + n\bar{p})}$$

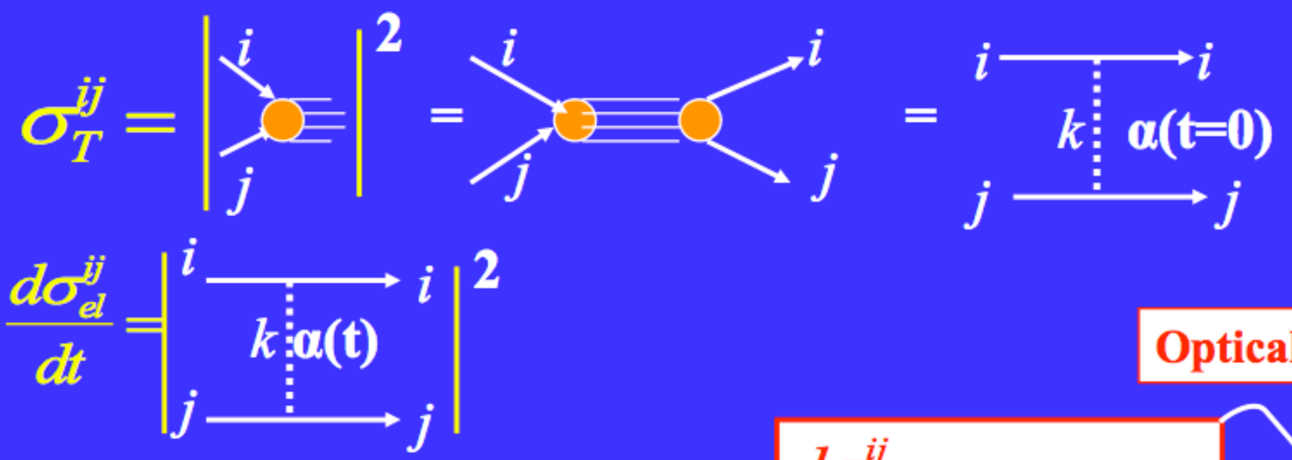
This still gives the best description of low-E reactions e.g. $\boxed{\pi^{-} + p \rightarrow \pi^{0} + n}$

But: Effective angular momentum / spin of exchange α(t) and complex

QCD became dominant, Regge theory almost left behind.

Introduction

Total cross section and elastic scattering closely related:



Optical theorem

Elastic scattering described by amplitude: $\frac{d\sigma_{el}^{ij}}{dt} = \pi |f(s,t)|^2$

Total cross section by Imaginary part of forward scattering amplitude. $\sigma_T^{ij}(s) = 4\pi . \mathrm{Im}\, f(s,0)$

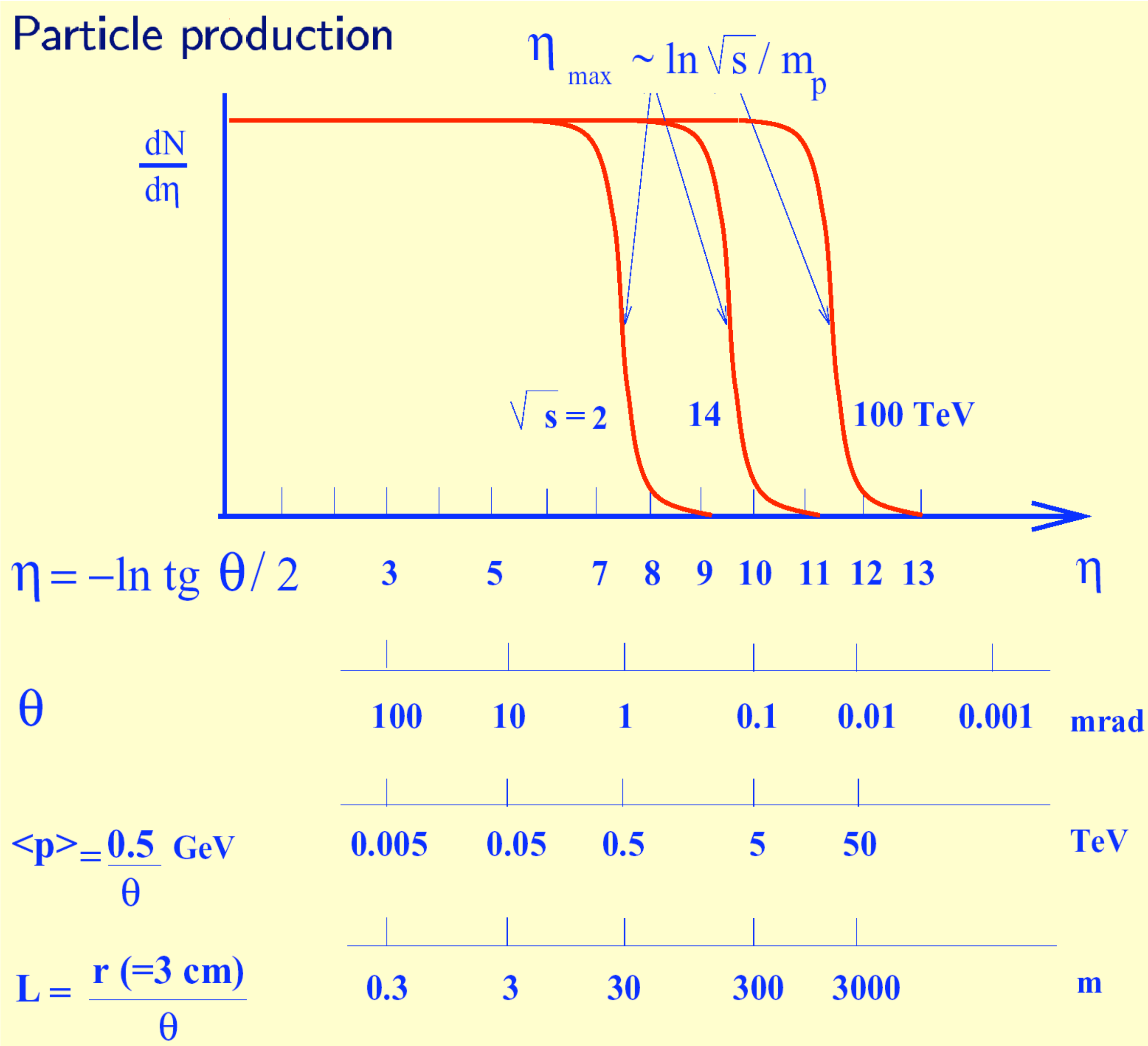
Regge theory:

$$\sigma_T^{ij}(s) = \sum_k \beta_{ik}(0)\beta_{kj}(0) s^{[\alpha_k(0)-1]}$$

$$\frac{d\sigma_{el}^{ij}}{dt} = \sum_k \frac{\beta_{ik}^2(t)\beta_{jk}^2(t)}{16\pi} s^{2[\alpha_k(t)-1]}$$

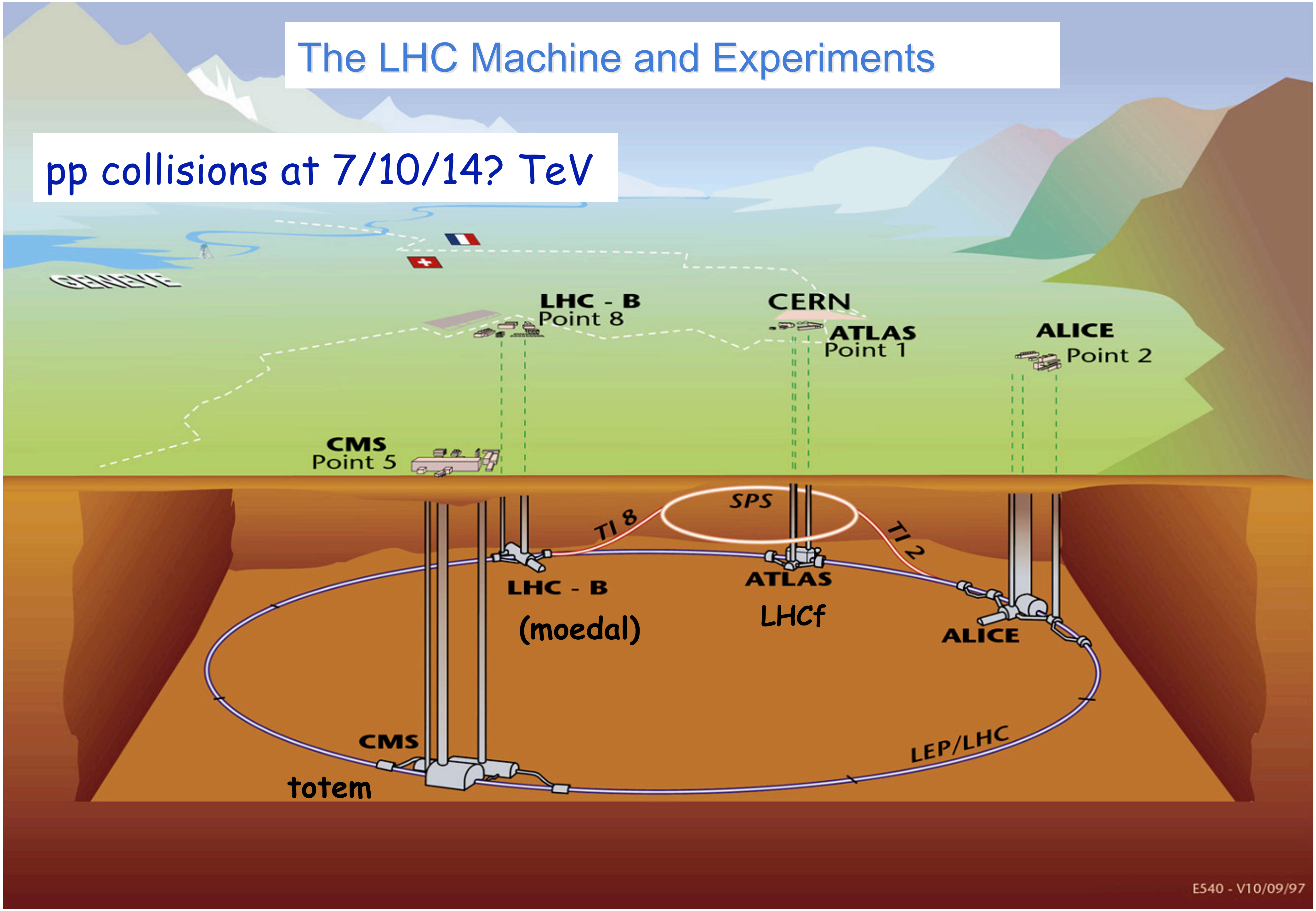
Couplings at vertices and propagator (~ Feynman diagrams)

Forward Particle Production Versus √s



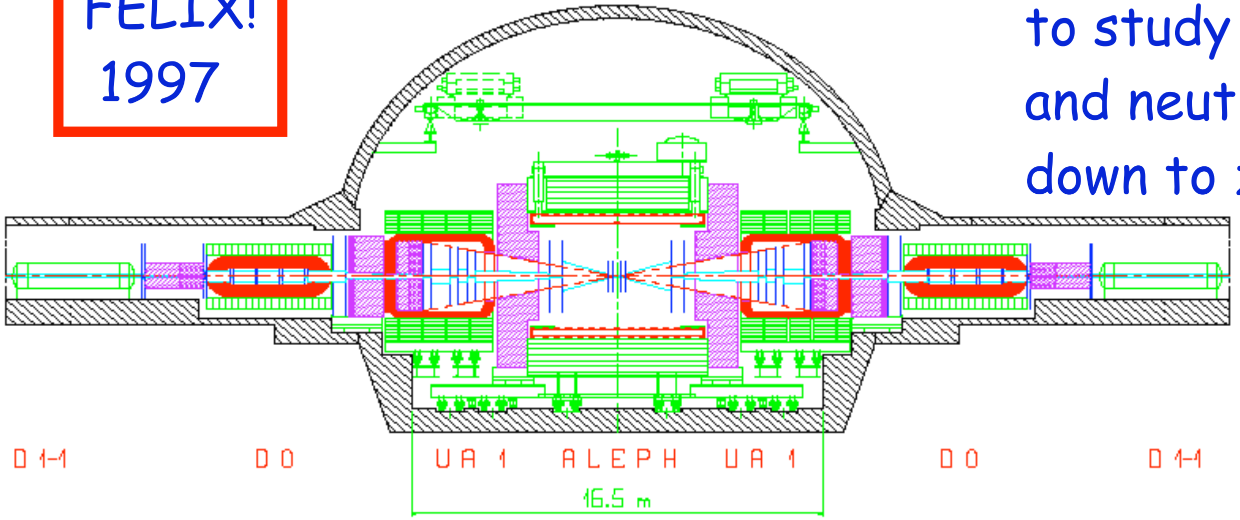
The LHC Machine and Experiments

pp collisions at 7/10/14? TeV

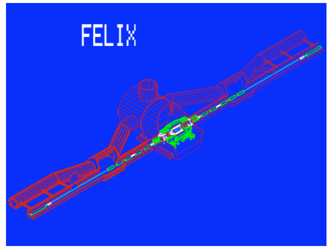


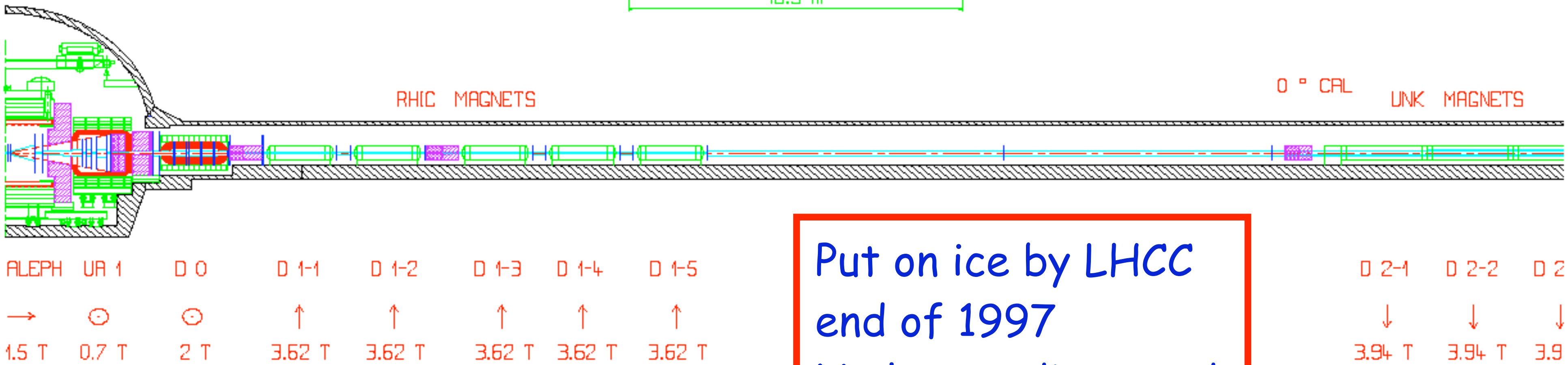
Proposal for a full acceptance detector for LHC (1997)

FELIX!
1997



Would allow
to study charged
and neutral particles
down to zero angles





Put on ice by LHCC
end of 1997
No longer discussed.

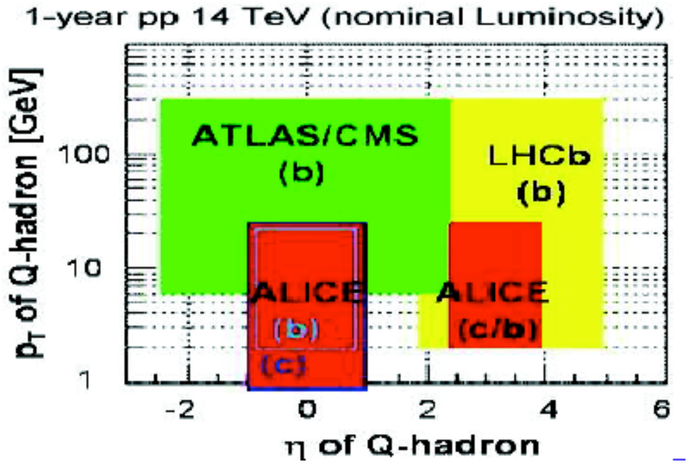
Forward Detectors at the LHC

1. **CMS** (fwd. EOI submitted Jan.'04, CMS+TOTEM LOI LHCC-2006-039):
   - → CASTOR, ZDCs, TAS (under consideration) + TOTEM
   - • Soft&hard diffraction (w/ TOTEM or rapgaps), low-x QCD, cosmic-rays, γ–p, γ–A, γ–γ

2. **ATLAS** (fwd. LOI submitted Mar.'04):
   - → ALPHA RPs (LOI R&D), LUCID, ZDC (approved 2007), TAS (under consideration)
   - • Total p-p cross-section, photo-production (UPC Pb-Pb)
   - • RP220: detectors for diffraction at 220 m

3. **ALICE**:
   - → ZDCs, fwd. muon spectrometer
   - • Diffraction, low-x QCD

4. **LHCb**:
   - → Forward muon
   - • Low-x PDFs



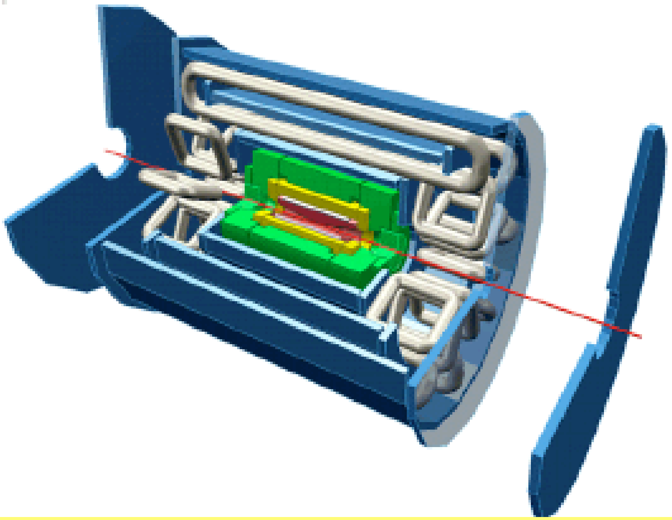
5. **TOTEM** (approved LHCC July'04):
   - → Roman pots (220 m), trackers (T1, T2)
   - • Elastic scattering, total p-p cross section, soft diffraction

6. **LHCf** (approved LHCC 2006):
   - → EM Calo (ATLAS-TAN, 140 m)
   - • Cosmic-rays (forward γ,π^0)

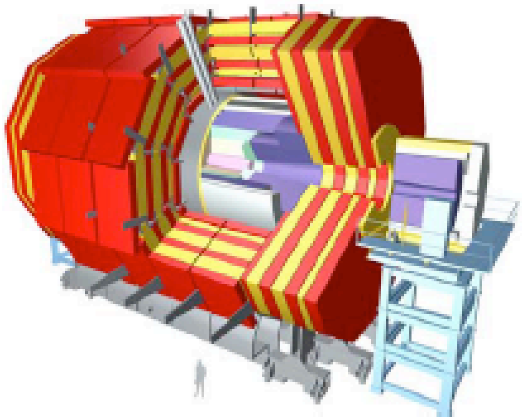
7. **FP420** (R&D collab. LHCC-2005-025):
   - → Feasibility studies for near-beam dets. at 420m
   - • QCD, exclusive Higgs, new physics

General Purpose Detectors at the LHC

ATLAS A Toroidal LHC ApparatuS



CMS Compact Muon Solenoid



ATLAS and CMS are central detectors!

typically: tracking $|\eta| < 2.5$

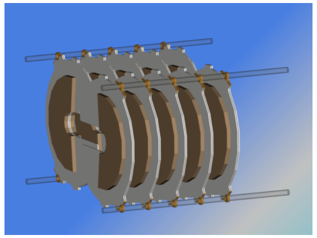
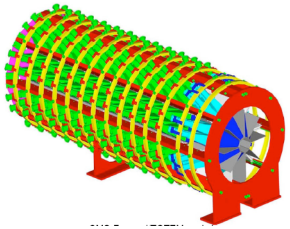
calorimetry $|\eta| < 5$

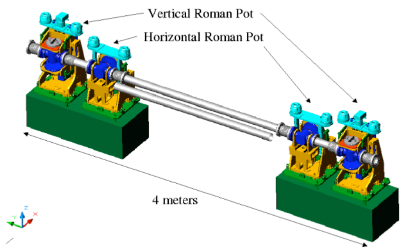
Coverage of forward physics typically needs more

Several extensions being implemented or being discussed

(New:) Forward detectors in ATLAS/CMS

TOTEM -T2 CASTOR ZDC/FwdCal TOTEM-RP FP420

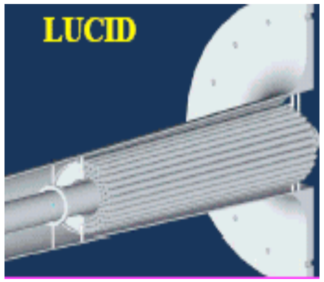



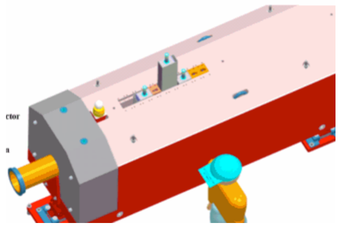
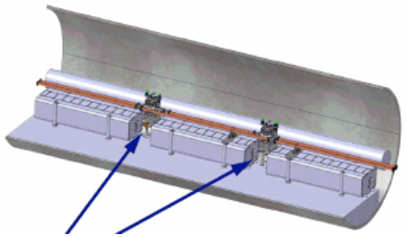
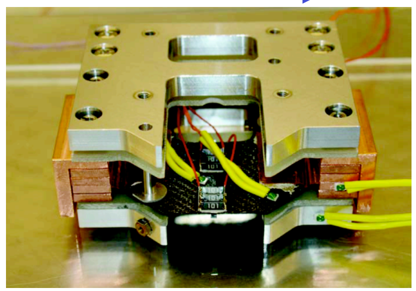


I P 5

14 m 16 m 140 m 147m - 220 m 420 m

I P 1



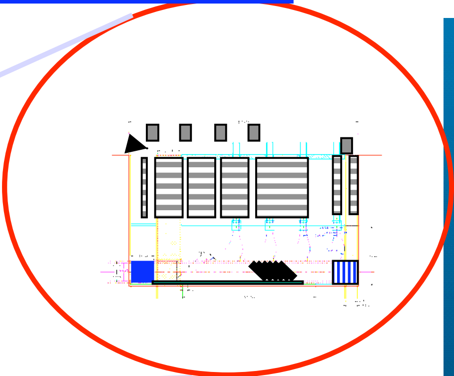




LUCID ZDC ALFA/RP220 FP420

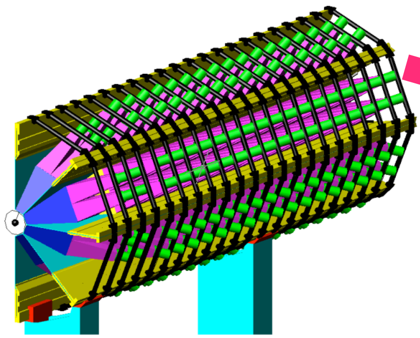
Forward Detectors: CMS/TOTEM

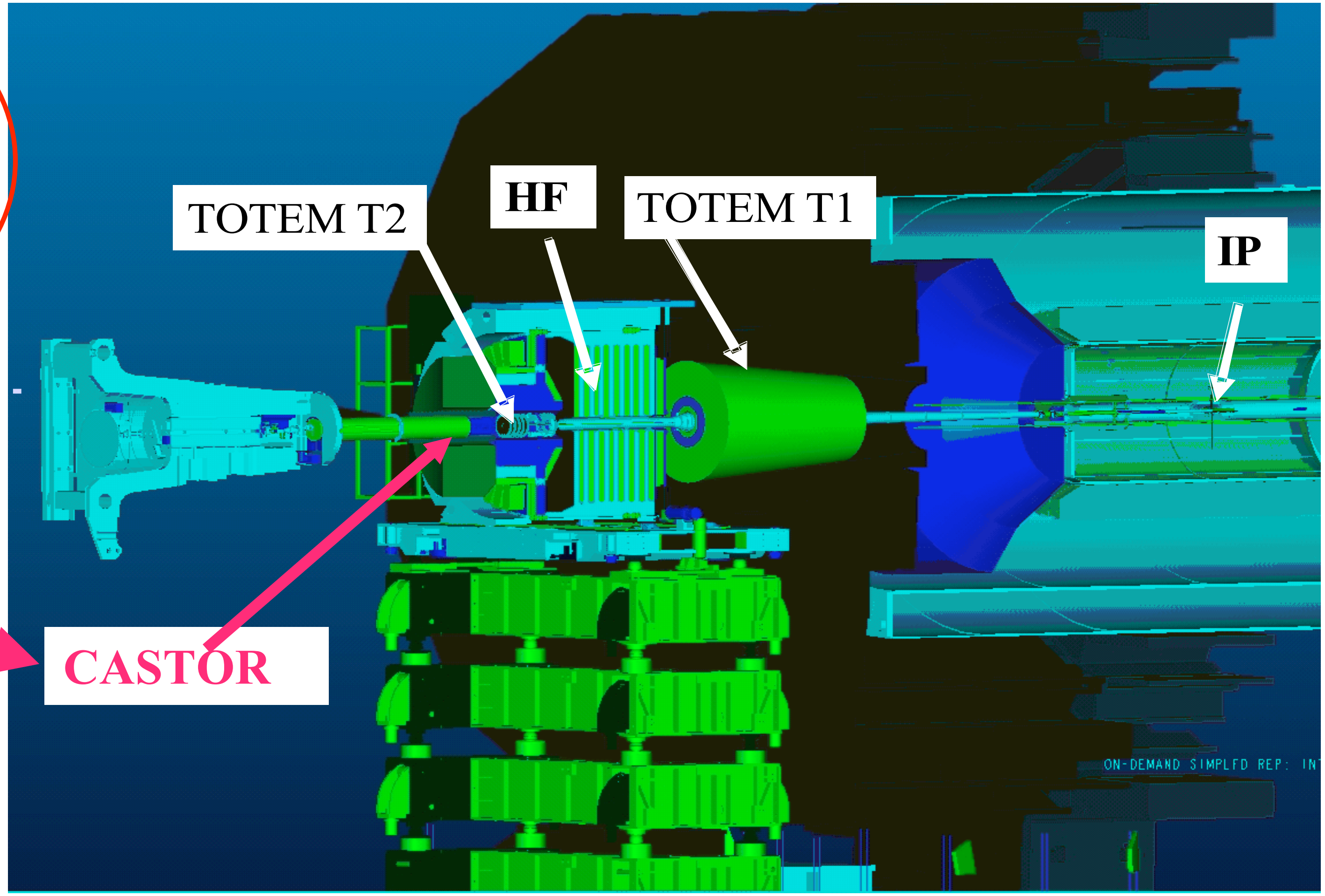
T1 3.1< η <4.7
T2 5.3<η <6.7
Castor 5.25<η <6.5

Extend the reach in η from |η|<5
to |η| <6.7
+ neutral energy at zero degrees

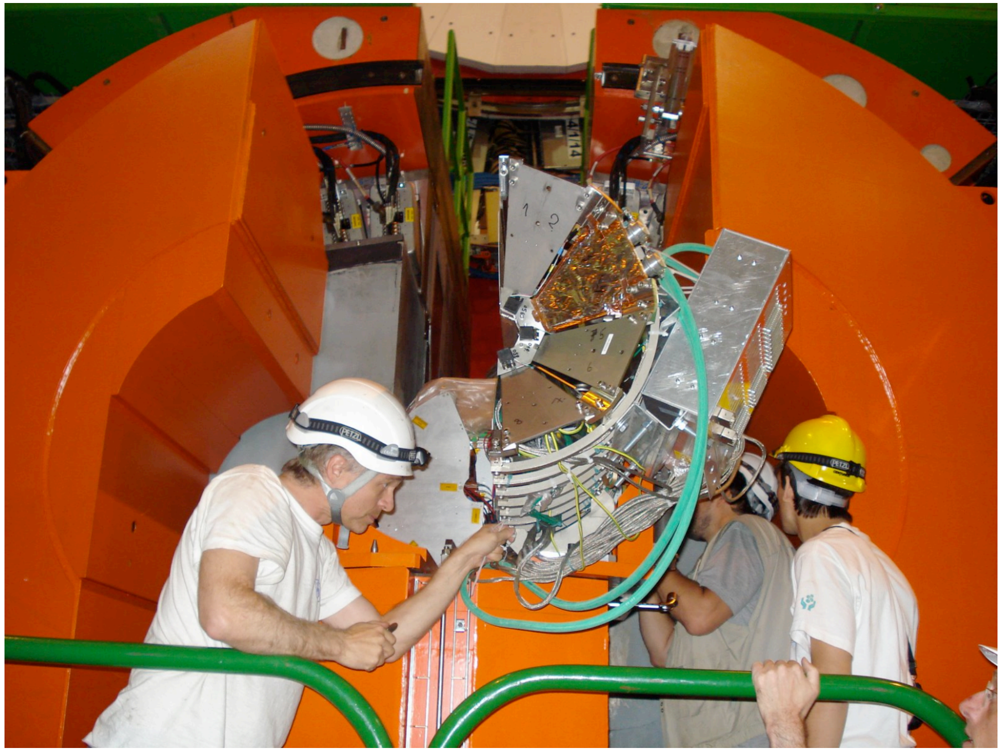


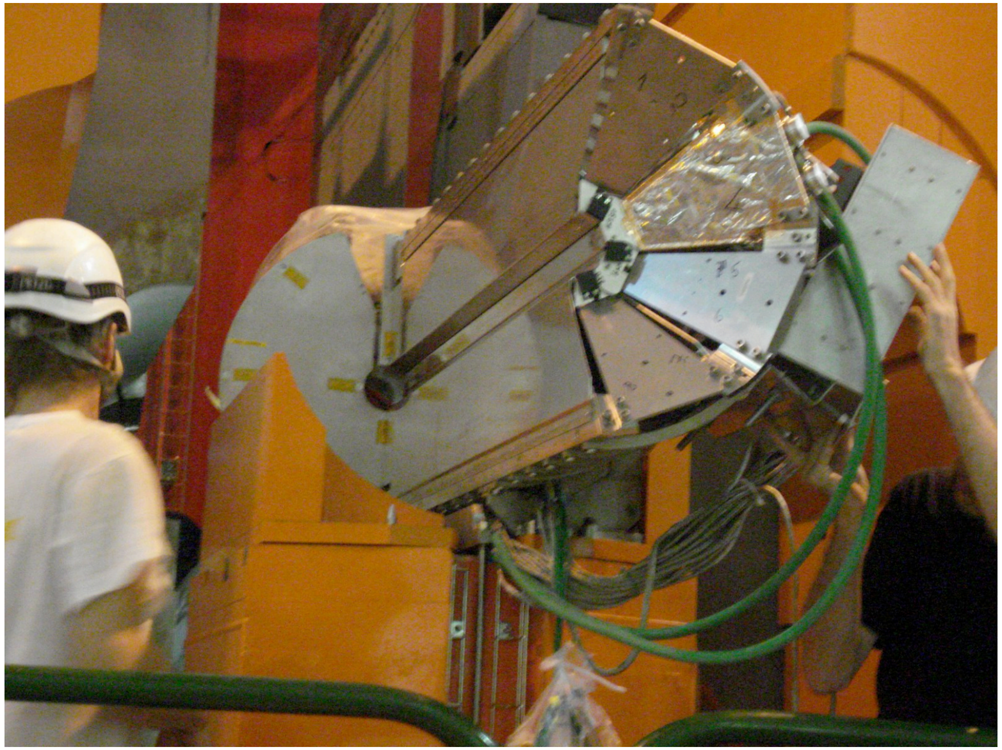
ZDC @ 140 m





Last minute CASTOR installation in CMS..

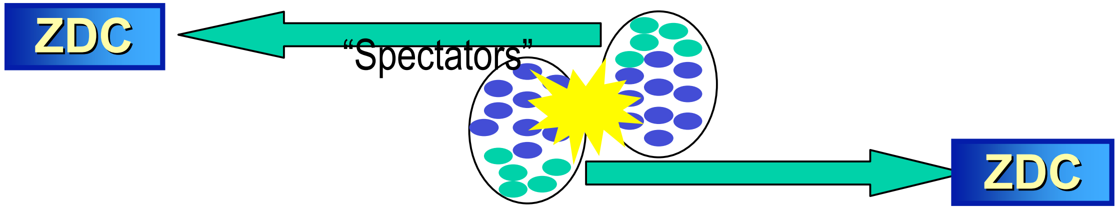




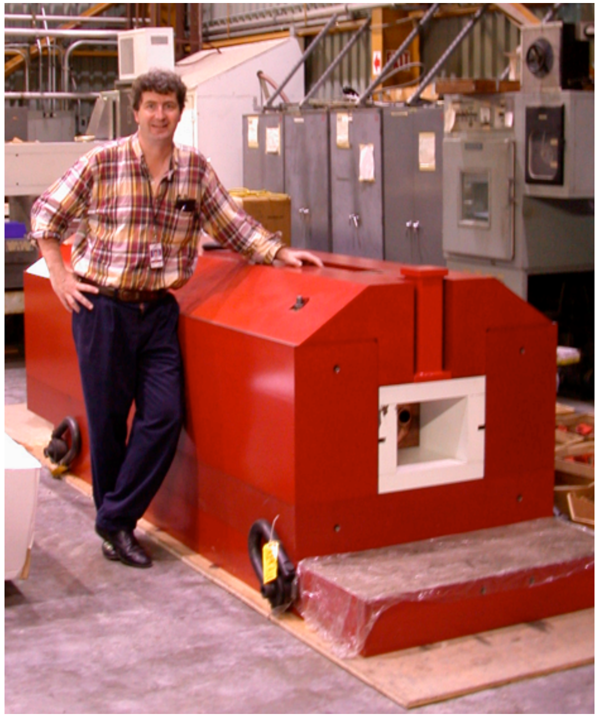
Castor calorimeter acceptance $5.25<\eta<6.5$


CASTOR

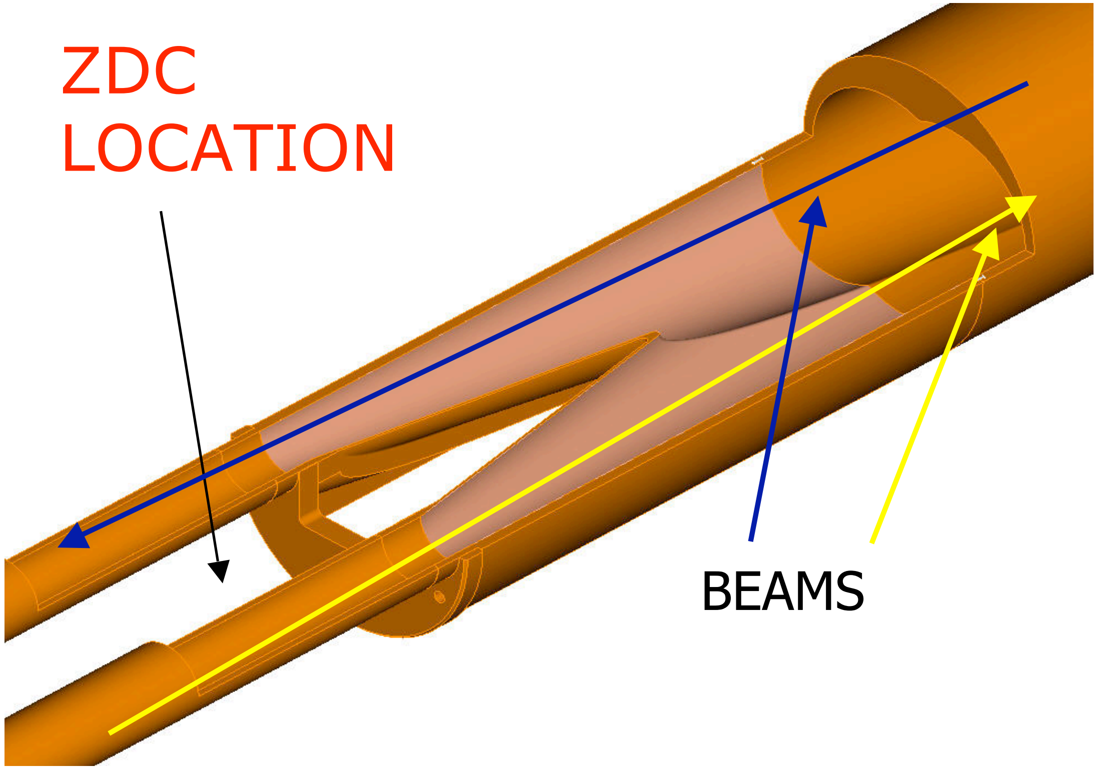
ZDC: zero degree calorimeter (CMS)



Beam pipe splits 140m from IR



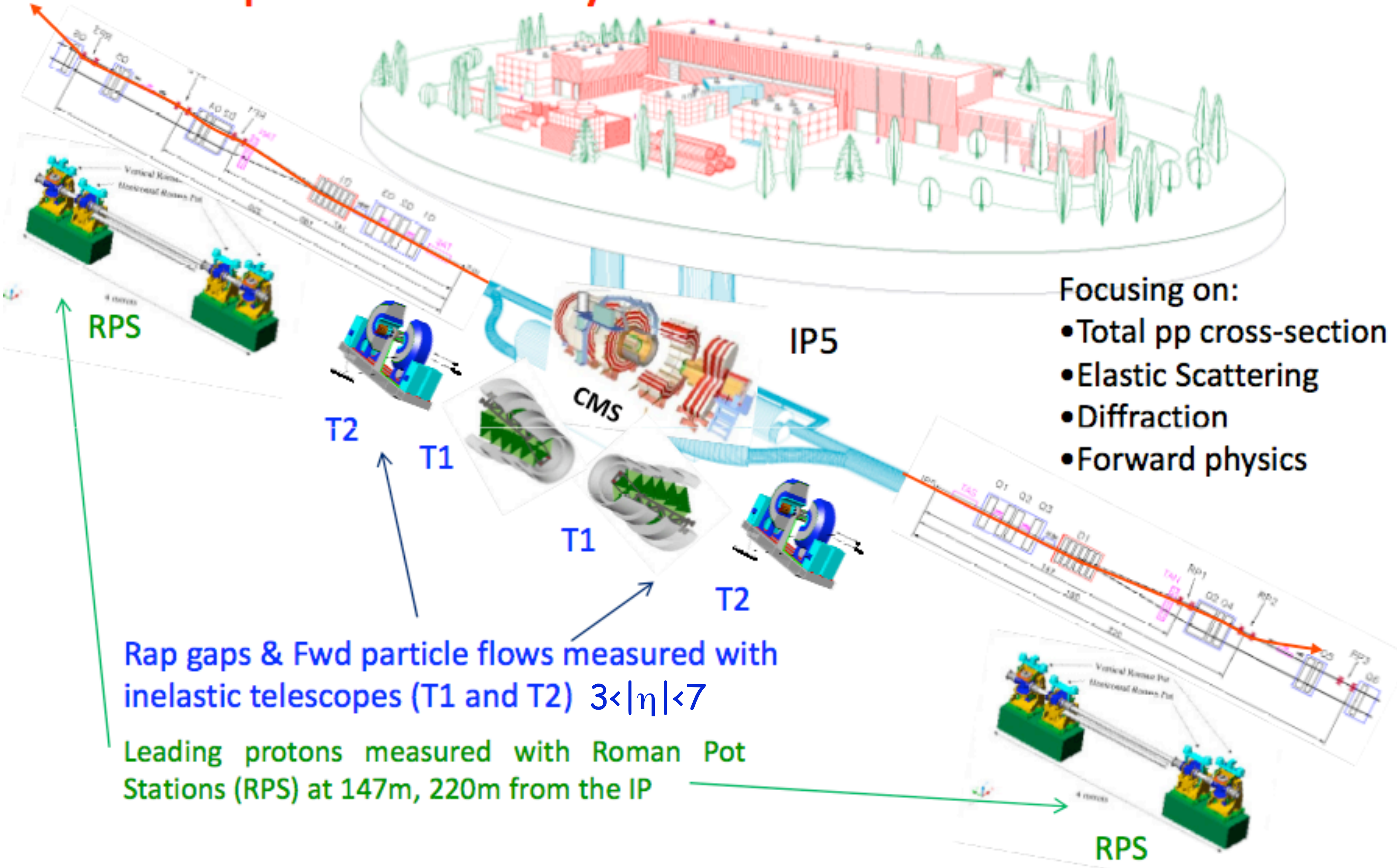
ZDC
LOCATION



Tungsten/ quartz fiber calorimeter
EM and HAD section

Installed on both sides of CMS
Also in ATLAS

Experimental layout of the TOTEM Detector

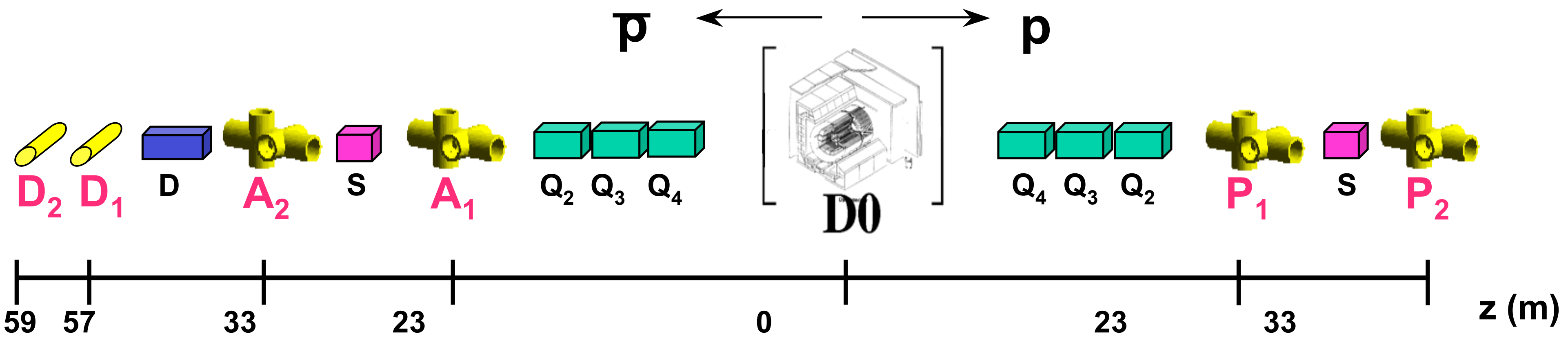


Focusing on:
- Total pp cross-section
- Elastic Scattering
- Diffraction
- Forward physics

Rap gaps & Fwd particle flows measured with inelastic telescopes (T1 and T2) $3<|\eta|<7$

Leading protons measured with Roman Pot Stations (RPS) at 147m, 220m from the IP

Roman Pot Extensions of Experiments



Tevatron

D0: Roman Pots added for Run II

CDF: Roman Pots (till 2007)

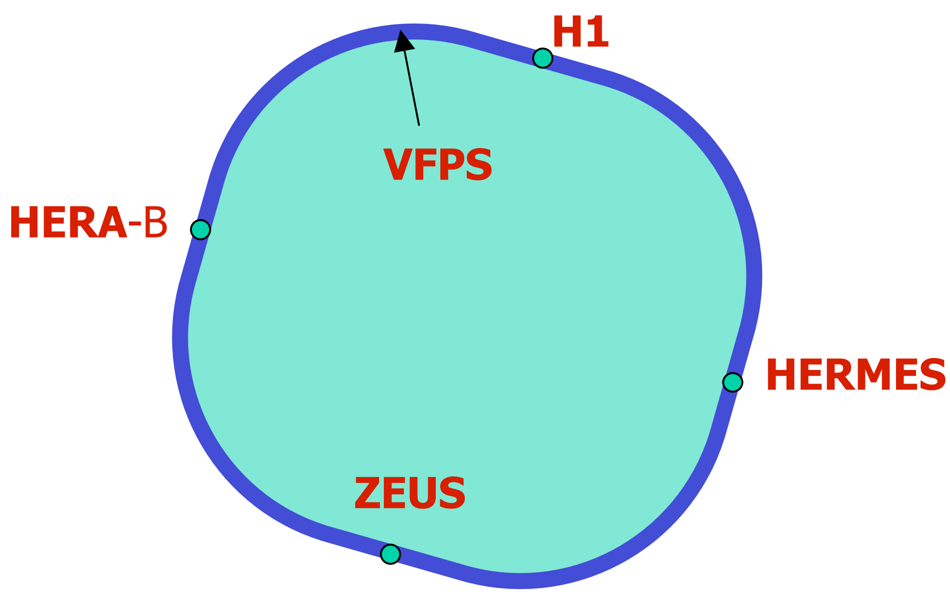
HERA

H1: FPS/VFPS

ZEUS: LPS

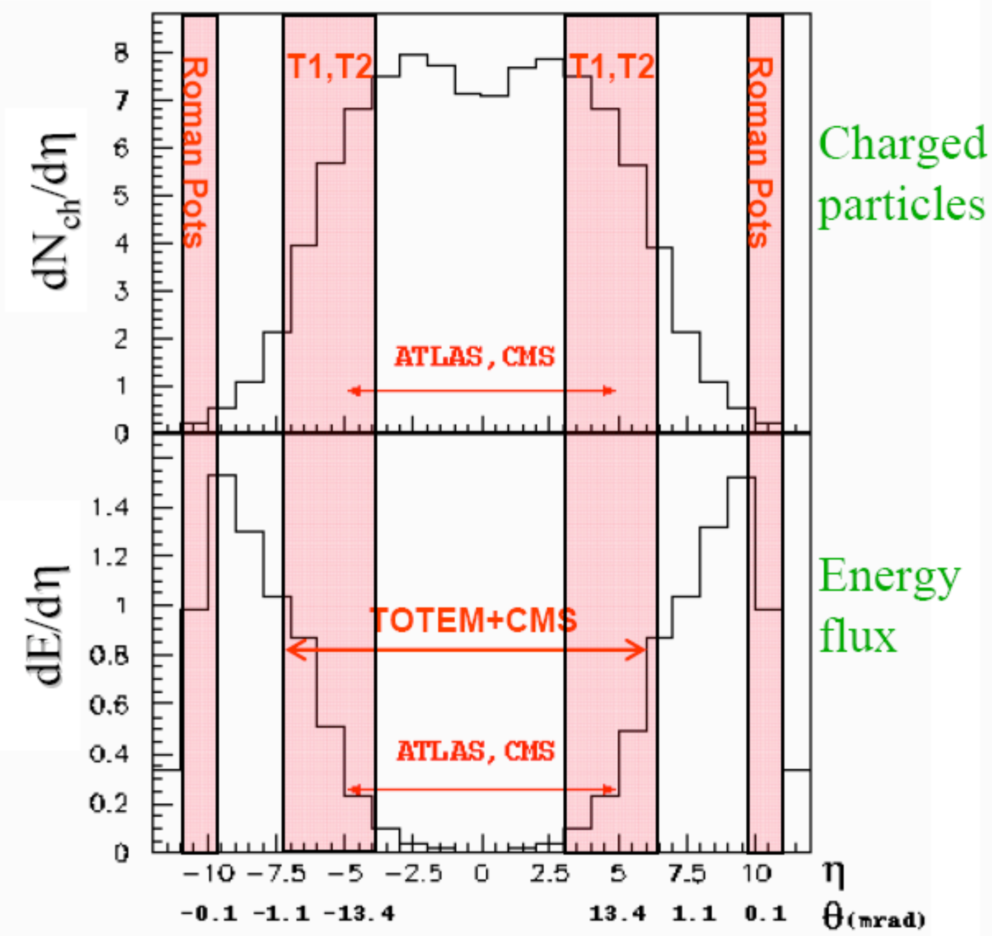
RHIC

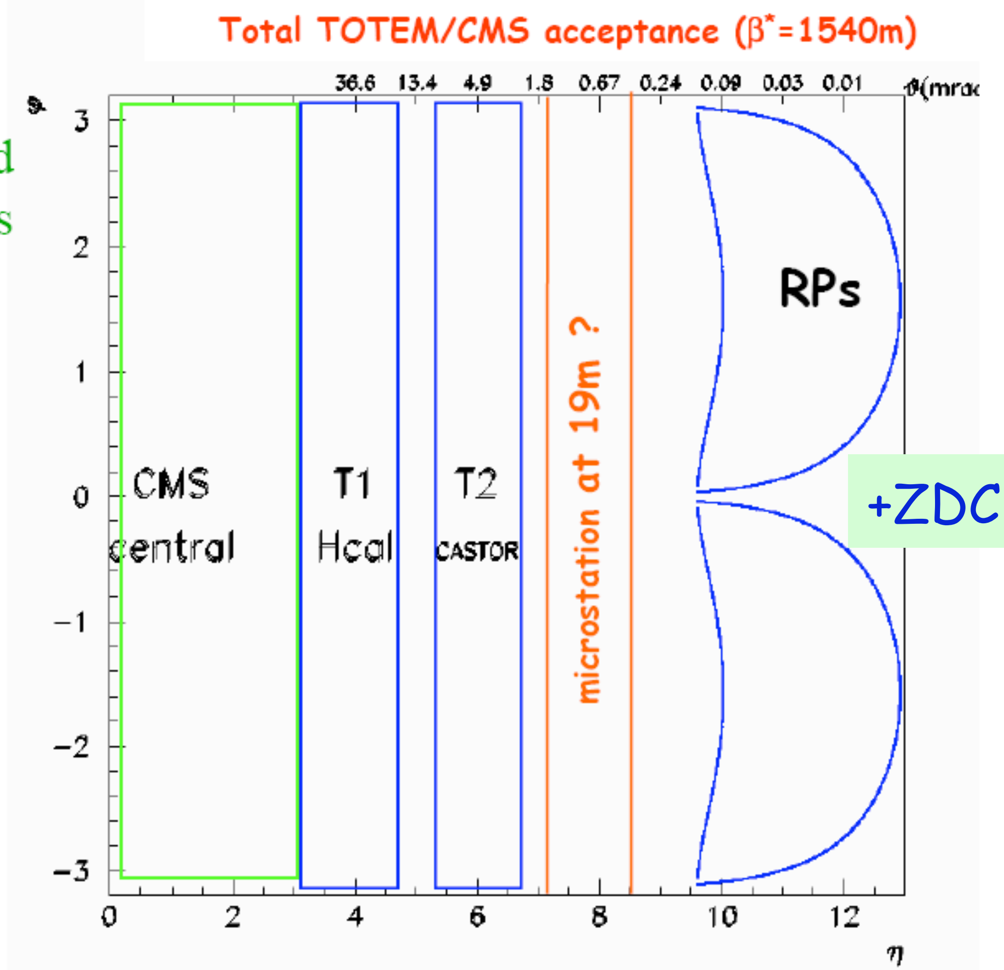
pp2pp $\rightarrow$STAR



CMS/TOTEM: a "complete" LHC detector

CMS/TOTEM will be the largest acceptance detector ever built at a hadron collider





+ZDC

ADR & K. Eggert
2003

Other possible detector regions (19m, 25m, 60-140m…)

UA8 = UA2 + Roman Pot Spectrometer

Combining central detector with Roman Pots has been done before (1988)

P. Schlein et al.

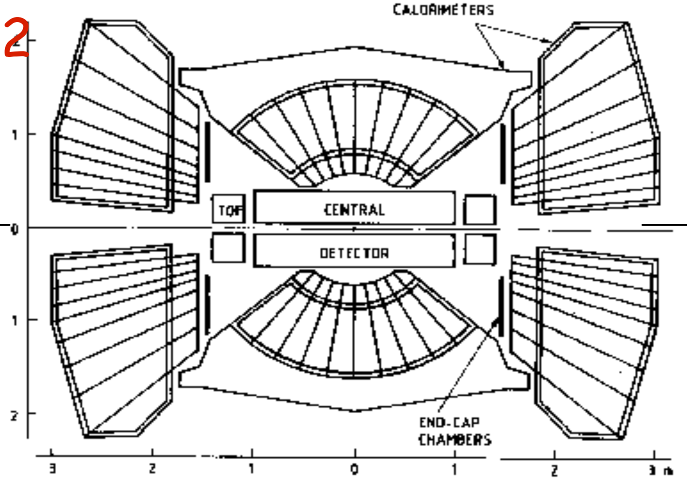
TOF counters had pseudorapidity 2.3-4.1

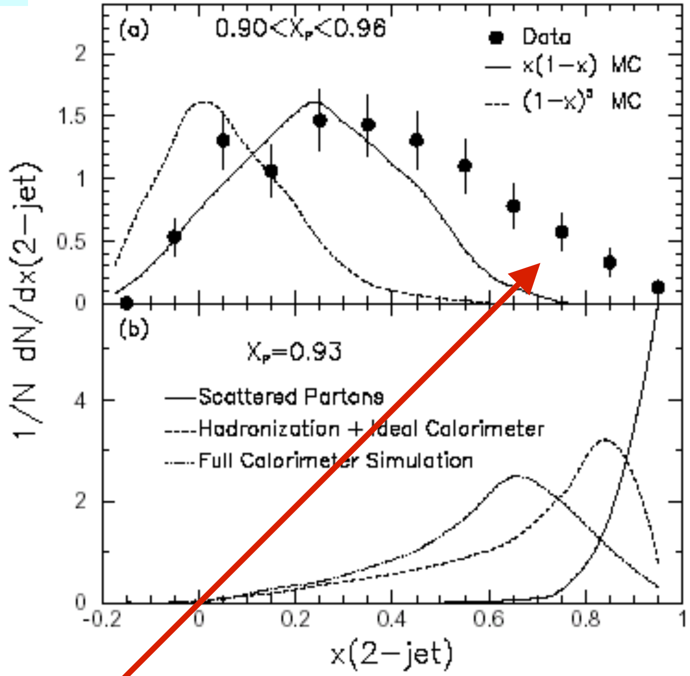
UA2

R.p.

R.p.

UA4

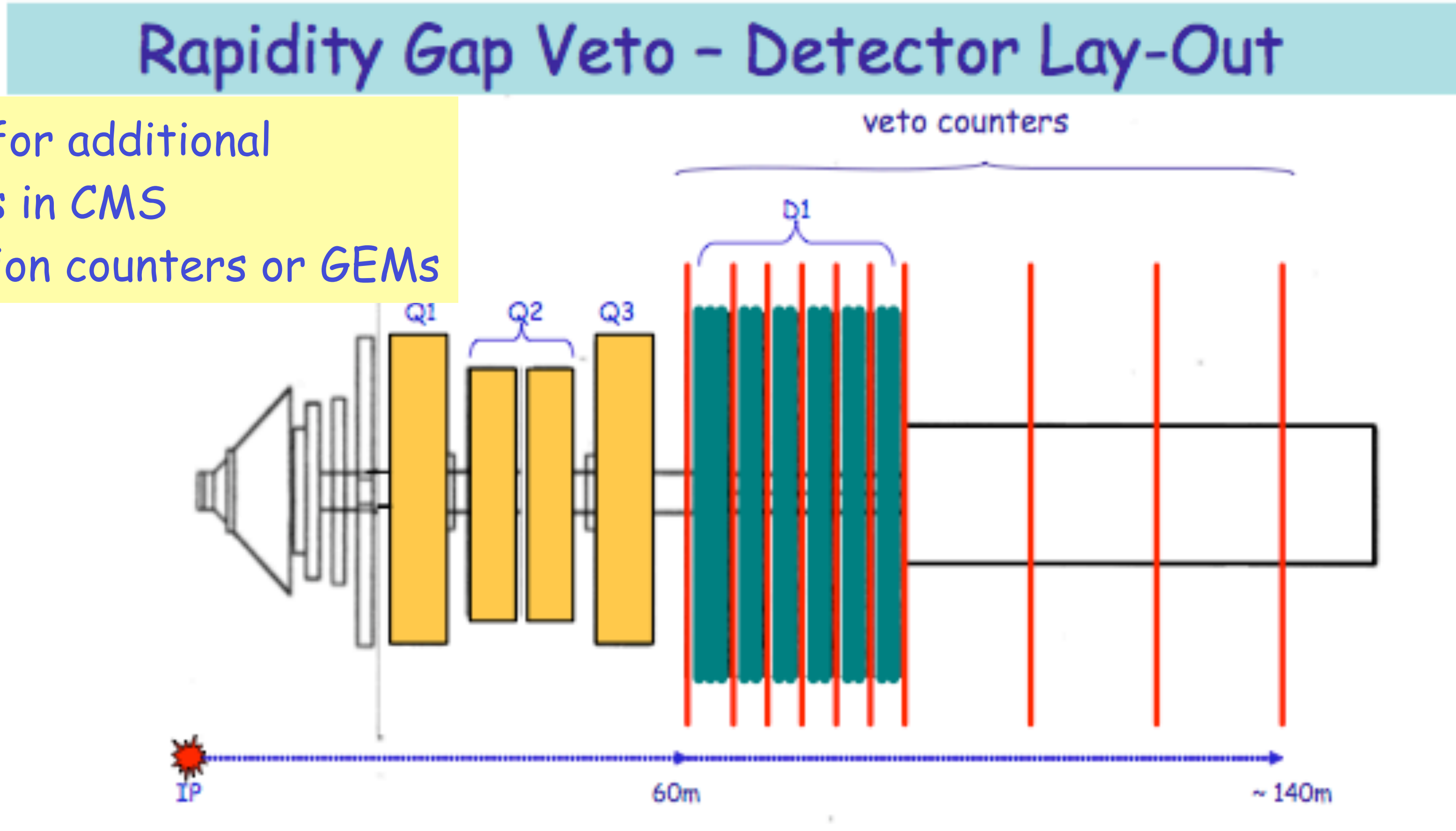




P. Schlein
1932-2008

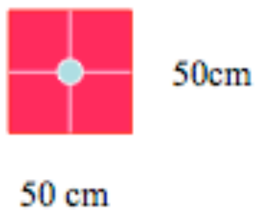
Still puzzling result: “superhard” component in the diffractive exchange (large t)
More on this later…

Extend the forward acceptance in CMS



Proposal for additional detectors in CMS
Scintillation counters or GEMs

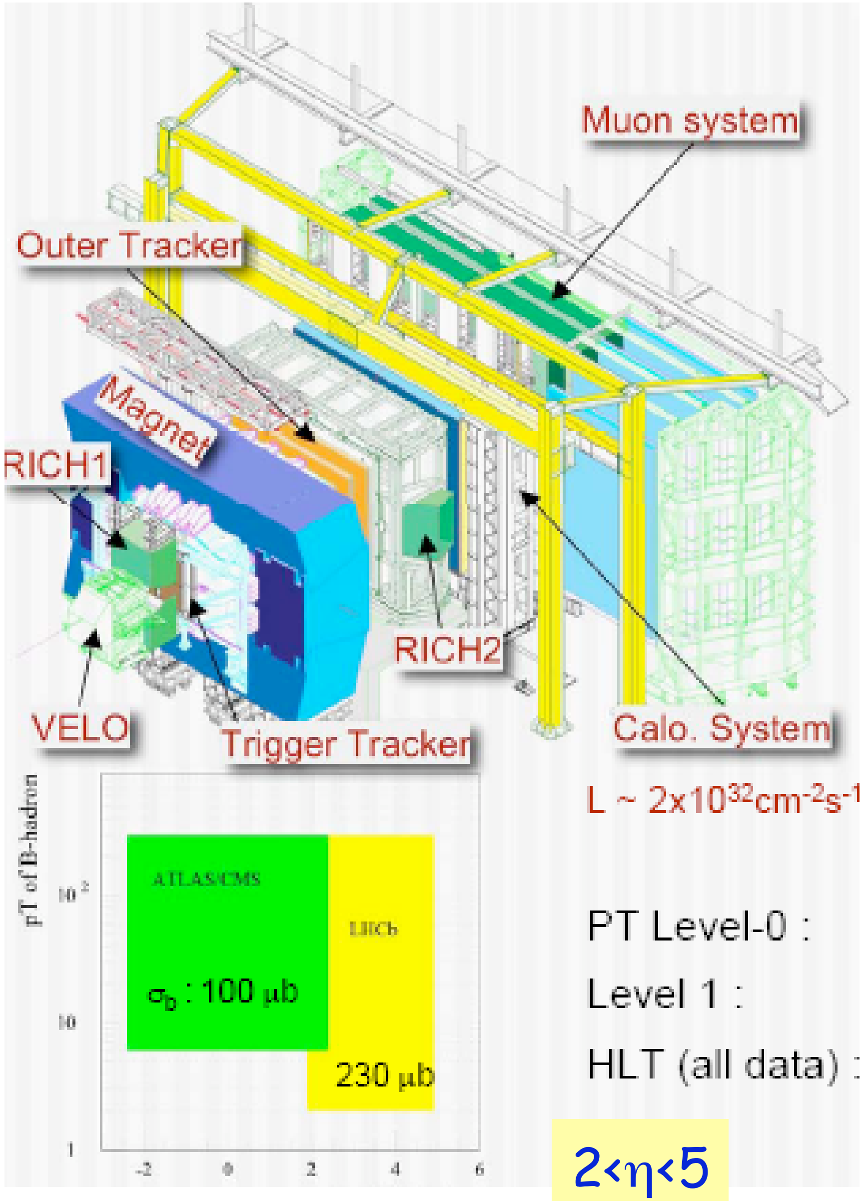
Useful if it can be included in 2010/11 run



Eg Tag low mass diffractive dissociation

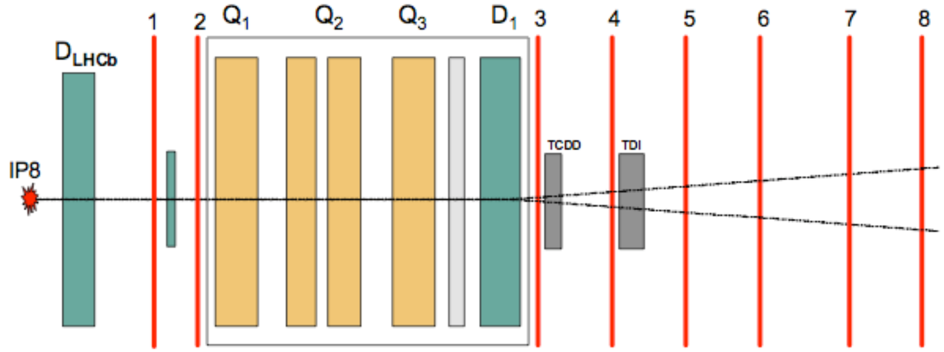
LHCb Forward Shower Counters?

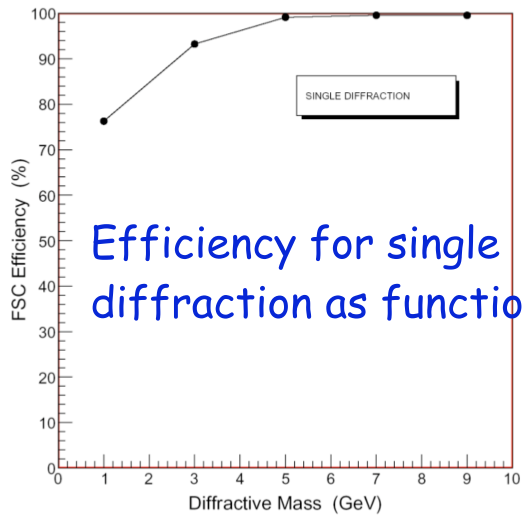
Orava, Lamsa



$2<\eta<5$

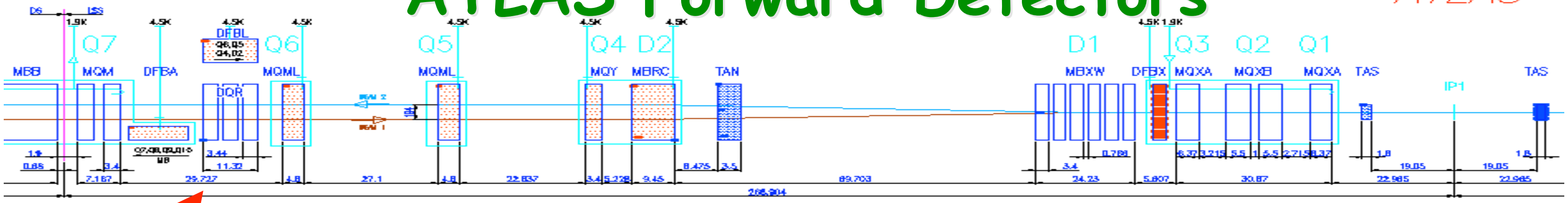
Forward shower counters now also suggested for LHCb





Efficiency for single diffraction as function of mass

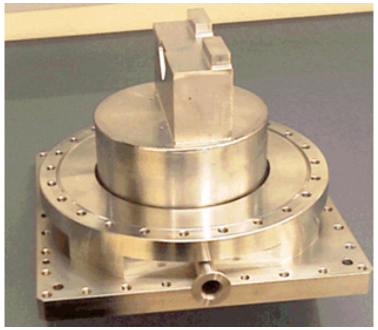
ATLAS Forward Detectors

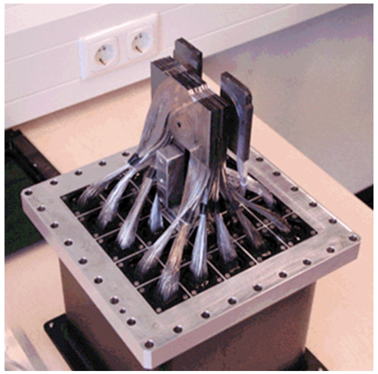


ALFA at 240 m

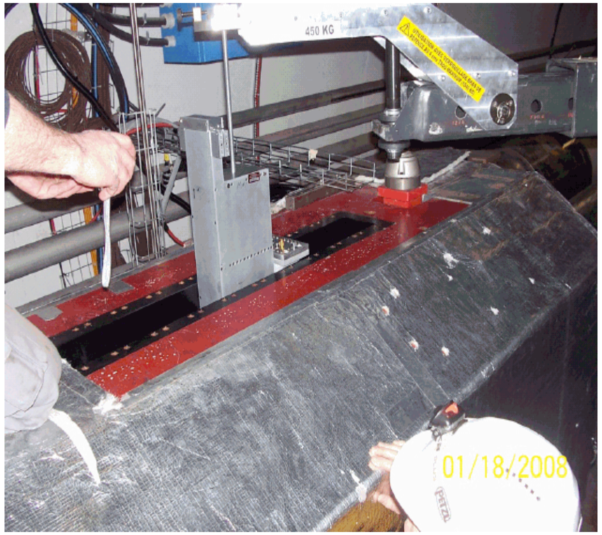
ZDC at 140 m

LUCID at 17 m

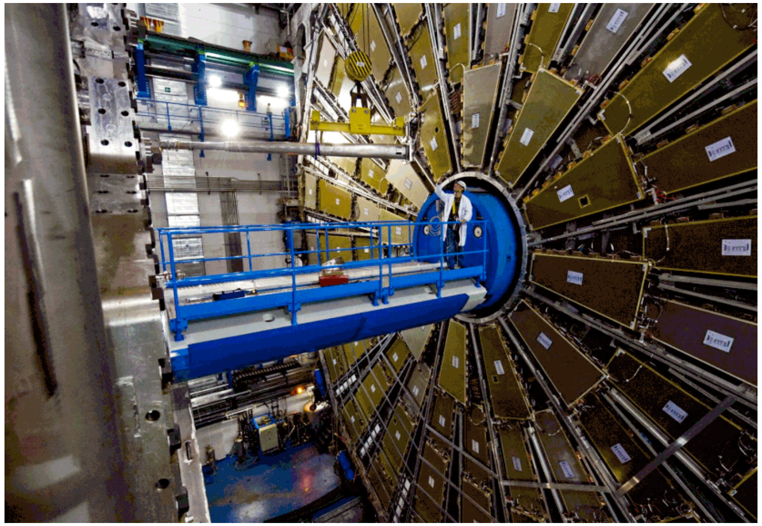


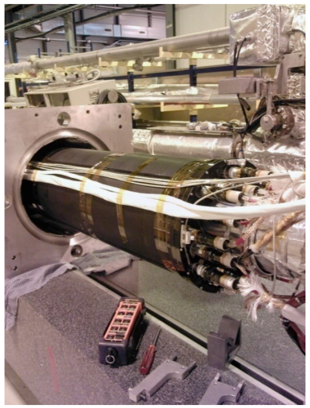


Absolute Luminosity for ATLAS (2010)



Zero Degree Calorimeter (2008)





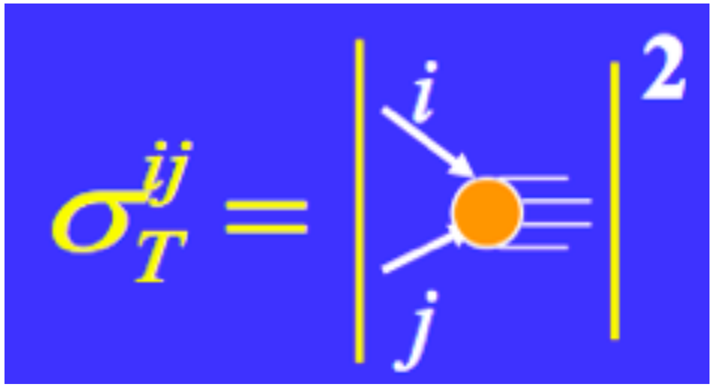
Luminosity Cerenkov Integrating Detector (2008)

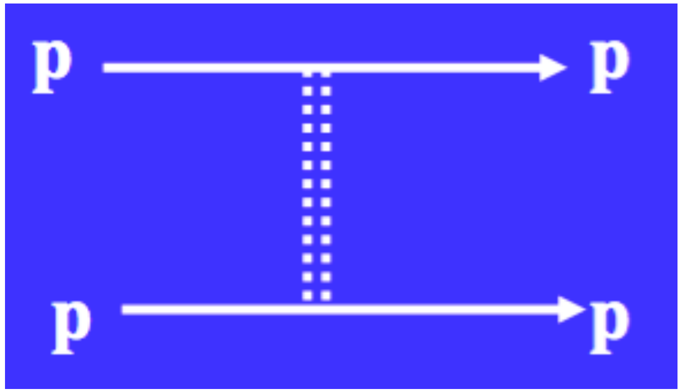
Forward Physics Program

- Soft & Hard diffraction
  - Total cross section and elastic scattering
  - Gap survival dynamics, multi-gap events, proton light cone ($pp \rightarrow 3jets+p$)
  - Diffractive structure: Production of jets, W, J/ψ, b, t, hard photons
  - Double Pomeron exchange events as a gluon factory
  - Diffractive Higgs production, (diffractive Radion production)
  - SUSY & other (low mass) exotics & exclusive processes
- Low-x Dynamics
  - Parton saturation, BFKL/CCFM dynamics, proton structure, multi-parton scattering…
- New Forward Physics phenomena
  - New phenomena such as DCCs, incoherent pion emission, Centauro's
- Strong interest from cosmic rays community
  - Forward energy and particle flows/minimum bias event structure
- Two-photon interactions and peripheral collisions
- Forward physics in pA and AA collisions
- Use QED processes to determine the luminosity to 1% ($pp \rightarrow ppee$, $pp \rightarrow pp\mu\mu$)

Many studies can be done best with L ~$10^{33} cm^{-2} s^{-1}$(or lower)

Elastic and Total Cross Section

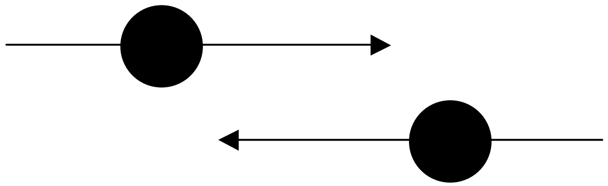


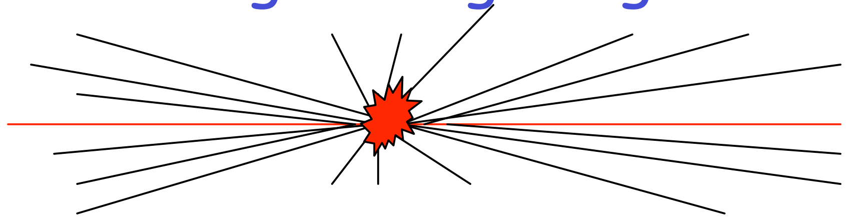


Proton-Proton Collisions

Most interactions due to collisions at large distance between incoming protons where protons interact as " a whole "
→ small momentum transfer ($\Delta p \approx \hbar / \Delta x$)

⇒ particles in final state have large longitudinal momentum but small transverse momentum (scattering at large angle is small)





$< p_T > \approx 500$ MeV of charged particles in final state

Most energy escapes down the beam pipe.

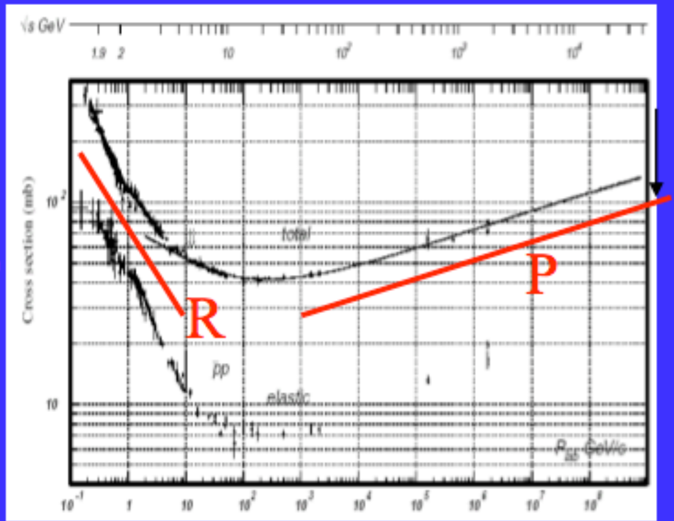
These are often called minimum-bias events (" soft " events)..

More correct: minimum bias events are dominated by soft events

Total Cross Section

Total and elastic cross sections: **fall then rise (universal)**

$\sigma(p\bar{p})$



ln s

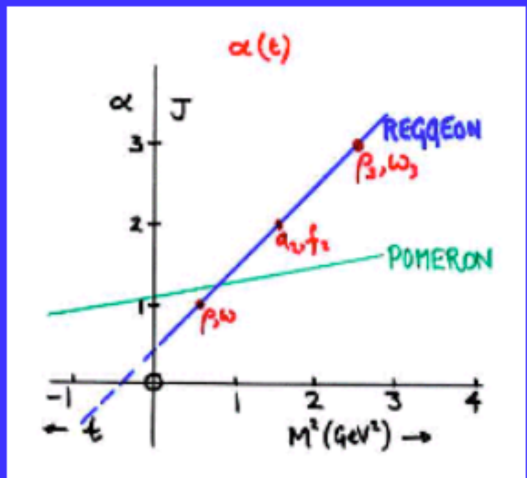
Two terms: $s^{\alpha_i(t=0)-1}$

$\alpha_R(t=0) \approx 0.55 \Rightarrow s^{-0.45}$

$\alpha_P(t=0) \approx 1.08 \Rightarrow s^{+0.08}$

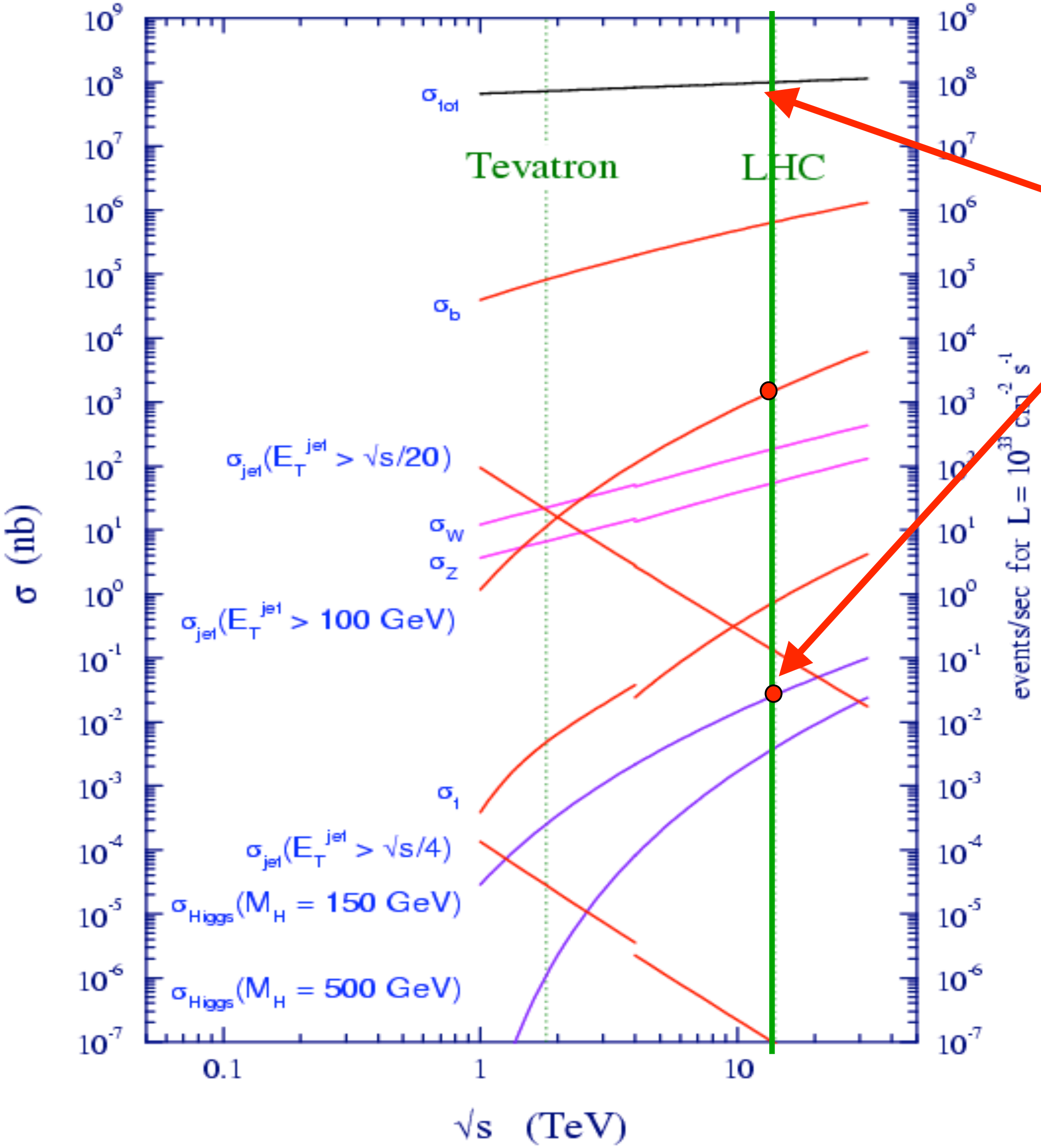
Total Elastic: $\sim s^{2\alpha(t=0)-2}$

$\alpha(t) \equiv$ effective spin of exchange



R (Reggeon) = sum of all allowed $q\bar{q}$ meson exchanges ρ, ω, ρ' etc
P (Pomeron) = (?) sum of all allowed non-meson (gg etc?) exchanges. Glueballs

Comparison of Cross Sections…



Huge minimum bias event cross section compared to, say, the Higgs cross section (9 orders of magnitude…)

Shape of these minimum bias events not accurately known. (multiple interactions, underlying event structure)

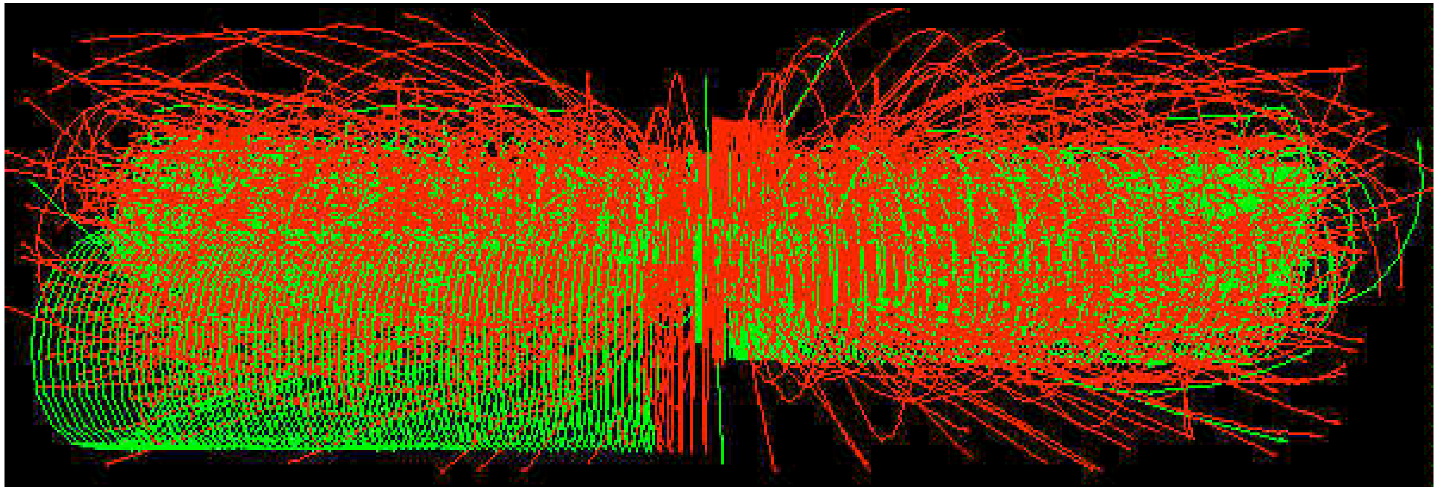
Pile up: ~ 20 minimum bias Events per bunch crossing at high luminosity

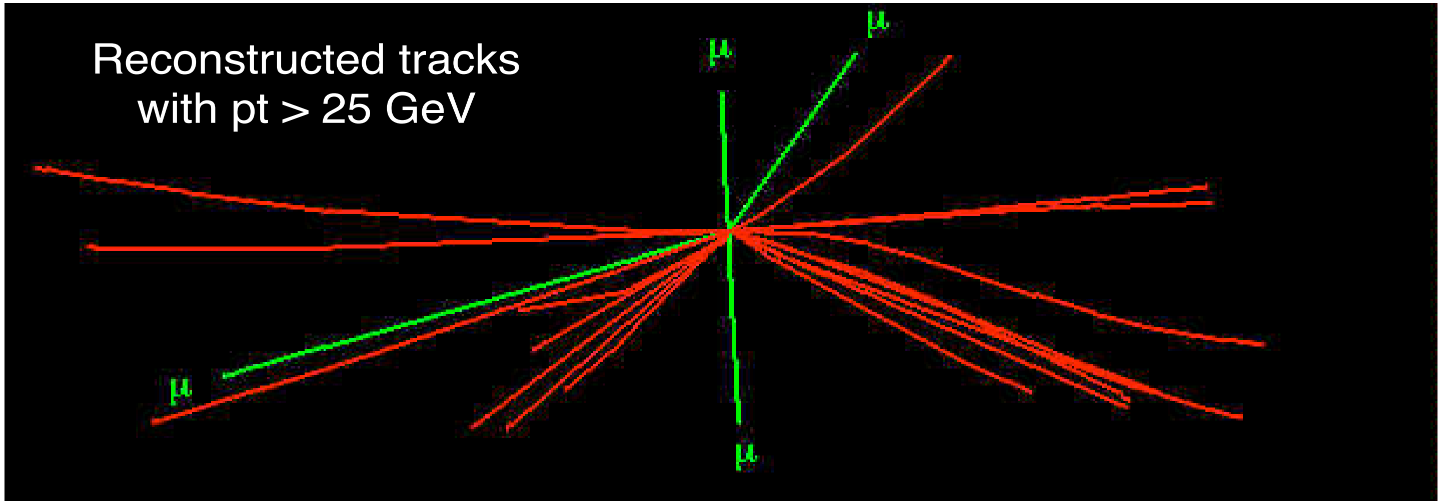
pp collisions at 14 TeV at 10^{34} cm^{-2}s^{-1}

- 20 min bias events overlap
- H→ZZ

Z →mm

H→ 4 muons: the cleanest ("golden") signature

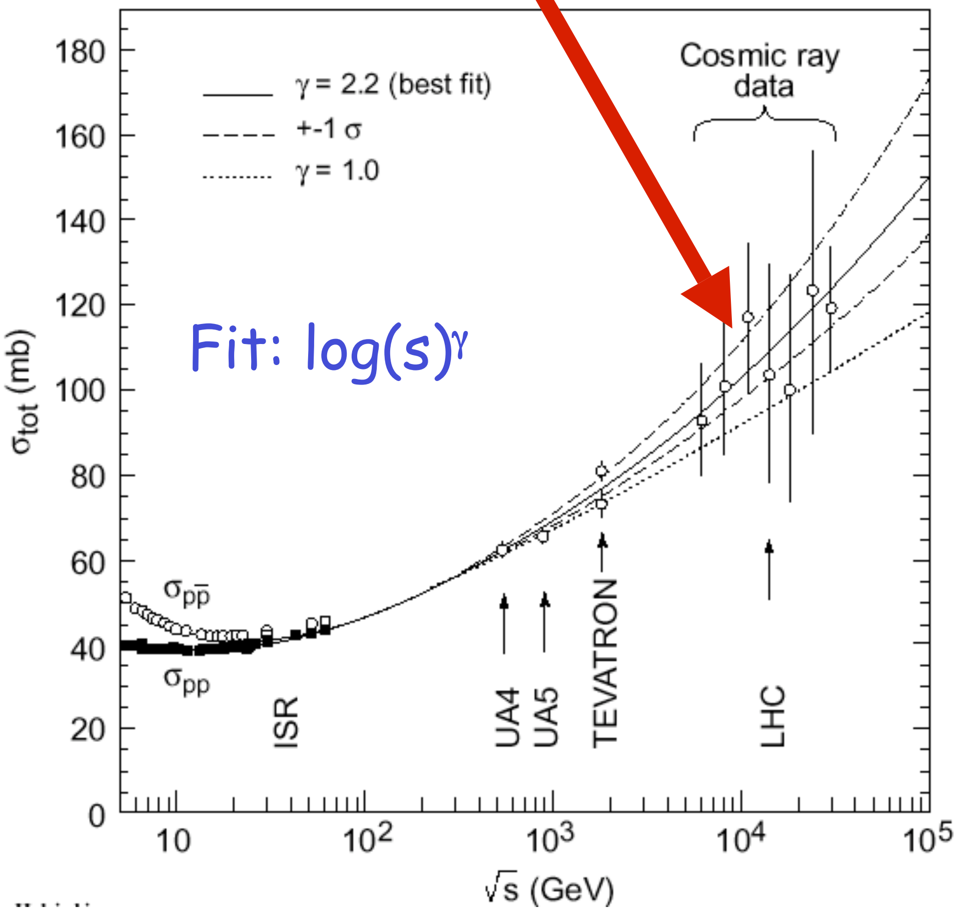


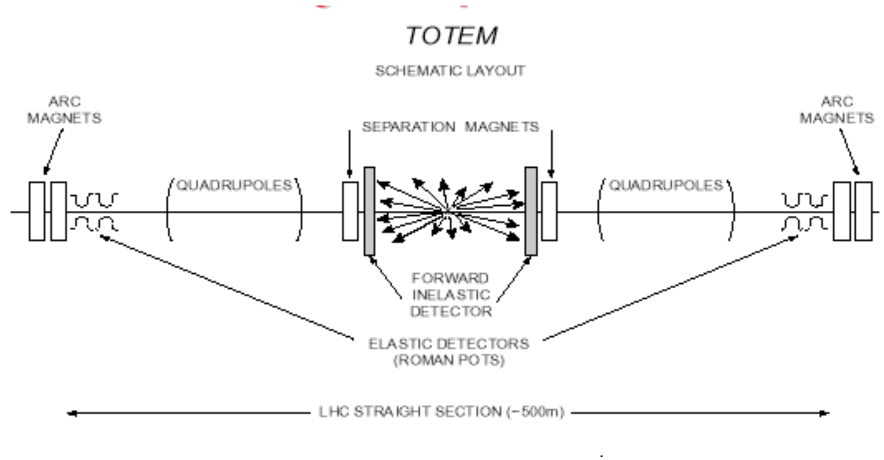


And this (not the H though…) repeats every 25 ns…

TOTEM: Total cross sections

Aim: ~1-2 mb precision





$\gamma = 2 \rightarrow \sigma_{tot}$ @LHC = 110 mb
$\gamma = 1 \rightarrow \sigma_{tot}$ @LHC = 95 mb

The measurement of σ_{tot}
Historical: CERN tradition (PS-ISR-SPS)
Current model predictions 95-130 mb at the LHC
Some extreme models give higher values (like 200 mb!!)

How to measure σ_{tot} ?
(naively..) Well, just count the events…

TOTEM: Total and Elastic Cross Sections

Here is a catch! σ_{tot} = # events/ luminosity

How to measure luminosity? Precision? (5-10% estimated)

Get σ_{tot} from Luminosity independent method

(i) $$L\sigma_{tot}^2 = \frac{16}{1+\rho^2} \times \left.\frac{dN}{dt}\right|_{t=0}$$ "OPTICAL THEOREM"

(ii) $$L\sigma_{tot} = N_{elastic} + N_{inelastic}$$

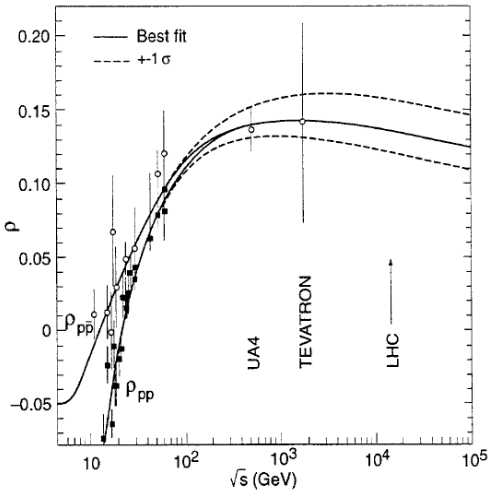
$$\boxed{\sigma_{tot} = \frac{16\pi}{1+\rho^2} \times \frac{(dN/dt)|_{t=0}}{N_{el} + N_{inel}}}$$

Use elastic scattering ($t \rightarrow 0$) and total inelastic rate

Here ρ = ratio of the real to imaginary part of the forward scattering amplitude

Measurement difficult at LHC

But impact on precision small

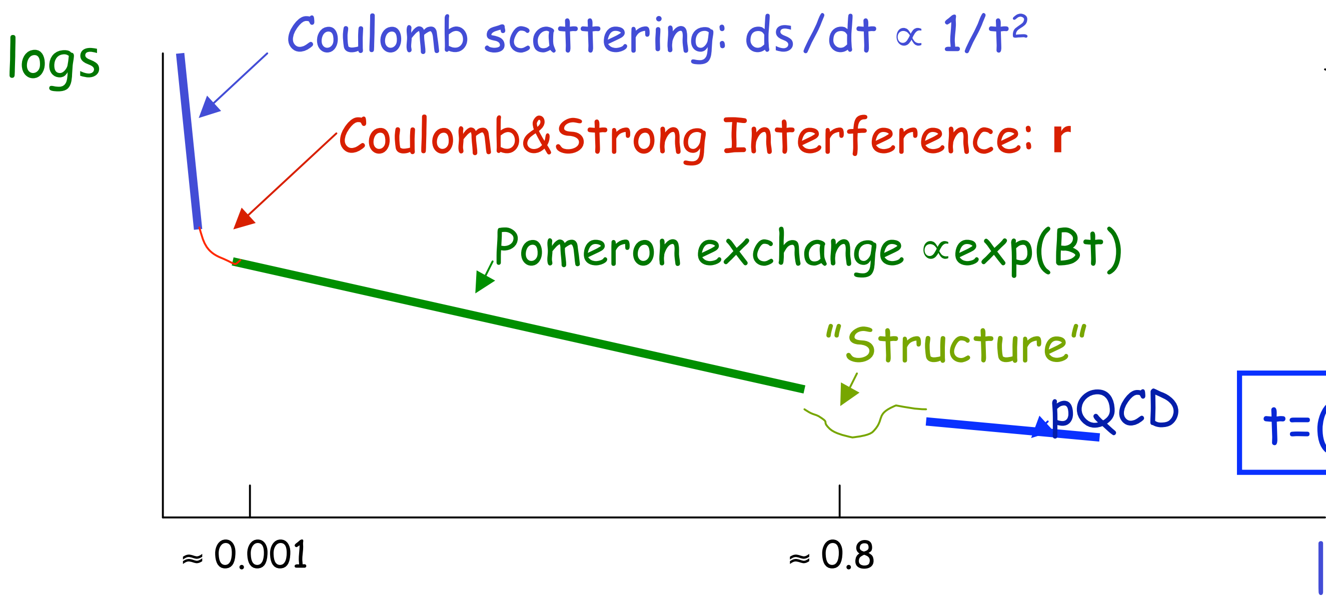


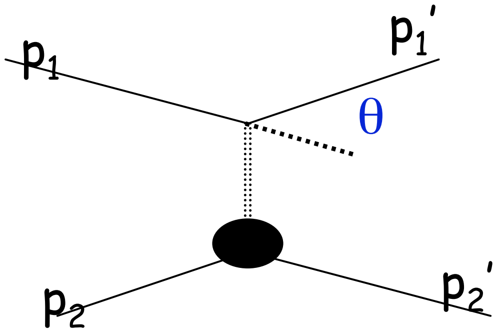
Aim of TOTEM try to measure σ_{tot} with ~1-2% accuracy

(~5% at startup with preliminary optics)

σ_{tot} can then be used for an absolute calibration of the luminosity

TOTEM: Elastic Scattering $pp \rightarrow pp$





$$\boxed{t=(p_1-p_1')^2=(p_2-p_2')^2 \sim -\theta^2 p^2}$$

Region	Characteristic –t (GeV/c)^2	Run type[1]
Coulomb region	$\leq 10^{-4}$	~~super~~ b*
Coulomb –Strong Interference	$\approx 10^{-3}$	high b* ?
Pomeron – Diffraction	$\geq 10^{-3}$	high/low b*
Structure – Peaks & Bumps	≈ 0.8	low/high b*
Large –t – Perturbative QCD	$\geq$ few GeV^2	low b*

[1]The official LHC optics is based on low b*=0.5m and high b* =1100m.

Experimental Aspects of Elastic Scattering

pp→pp: Scattered proton detected in Roman Pot telescope

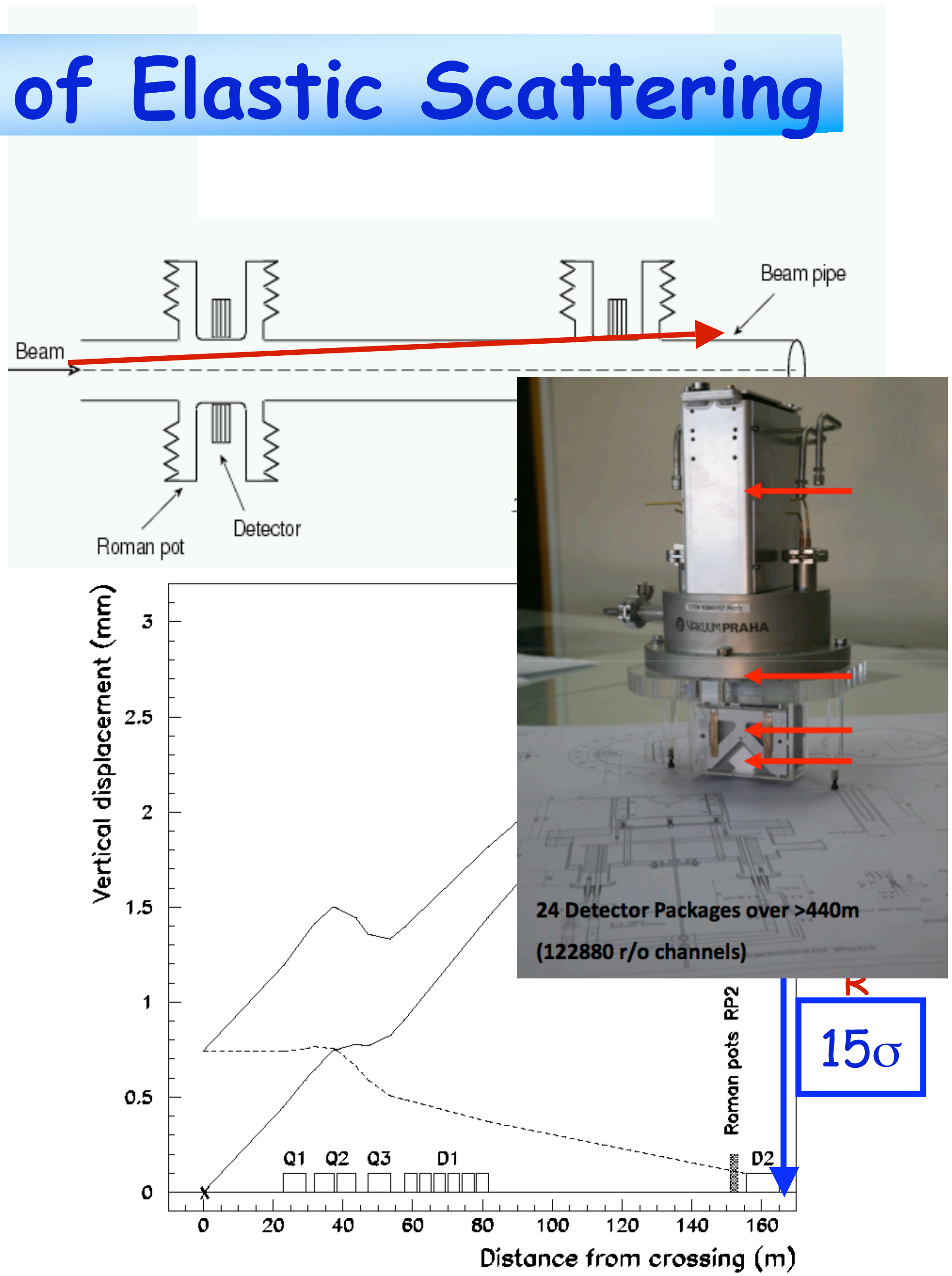
Measure x,y position in the roman pot detectors

Position the Pots at locations of "parallel to point" focussing

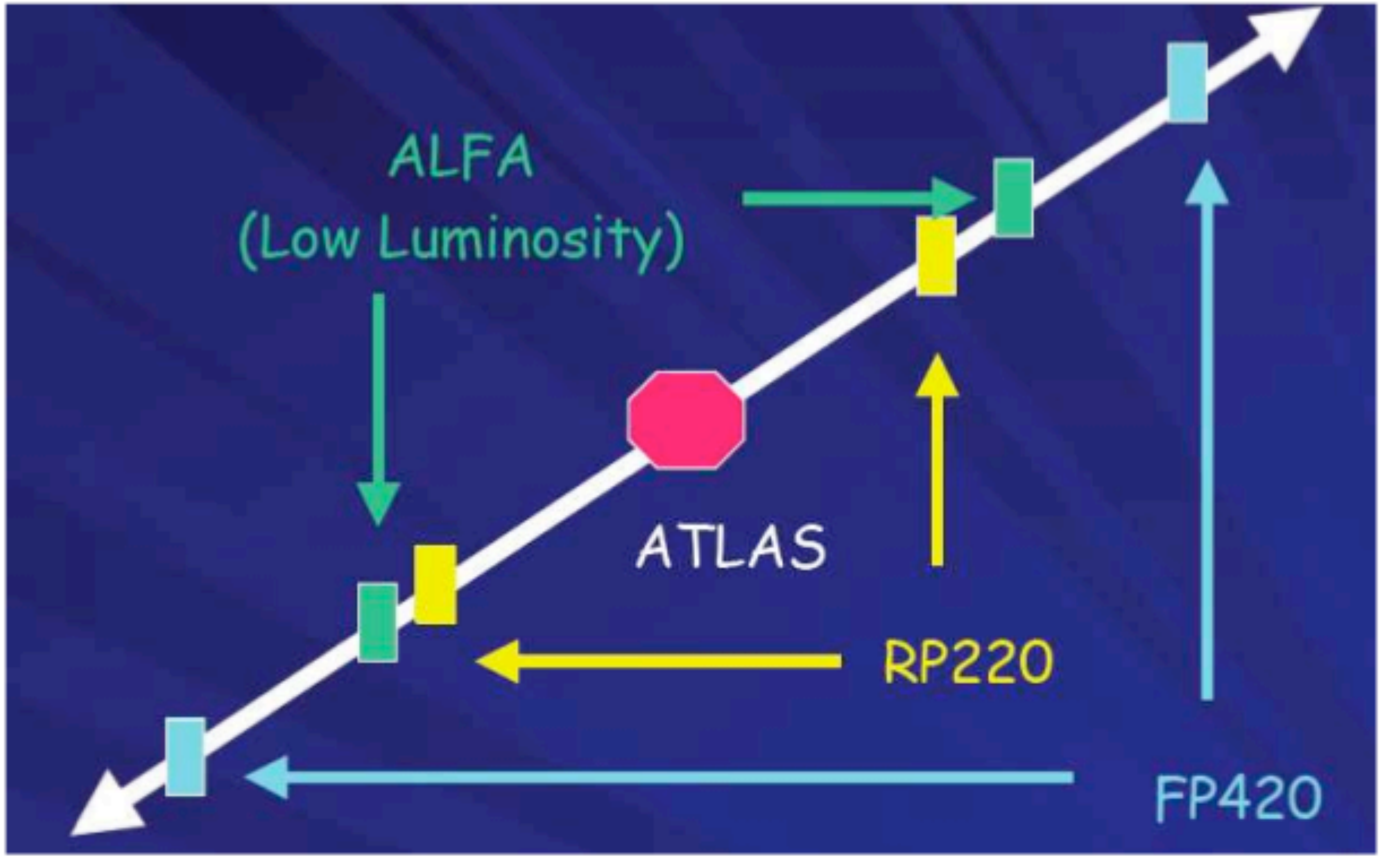
Use special optics with a large value of the accelerator β function (weak focusing, here β^* = 1100 m and beam angular spread ~ 0.67μrad)

Roman Pot can be lowered to "15 sigma" from beam (ie 15 times the beam size)

Resolution: $\Delta t \approx 0.7 \times 10^{-2} \sqrt{|\, t\, |}.$



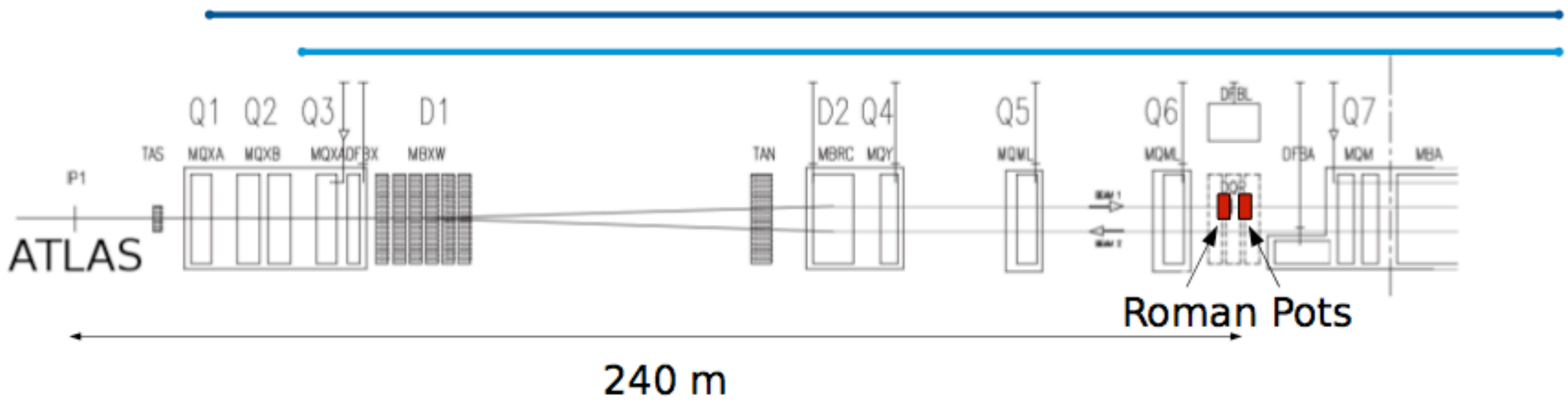
ATLAS: Total Cross Section Measurement



⇒Near beam detectors

- ALFA is an approved project
- RP220 & FP420 merged into one proposal for ATLAS

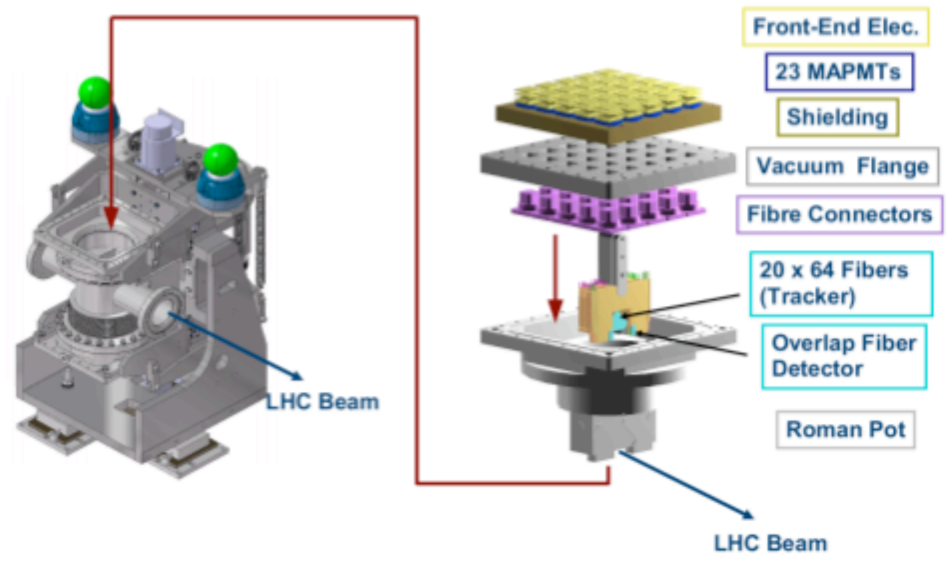
The ALFA Detector



- **ALFA** ≡ **A**bsolute **L**uminosity **F**or **A**TLAS

- Two roman pot stations in the forward direction on each side of the interaction point of ATLAS. Each station contains an upper and a lower detector.

- Each detector is made of a 20x64 scintillating fibers tracker readout by a 64 channels MAPMT. The compact front end electronics is mounted on top of the MAPMT.



$\boxed{\text{Nominal result for } \int_{100h} \mathscr{L} = 3.6\ 10^{32}\ \text{cm}^{-2}}$ 2.8%

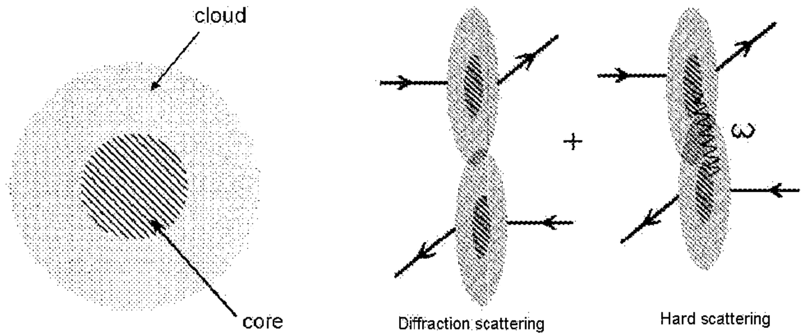
Interest in Total and Elastic Cross Sections

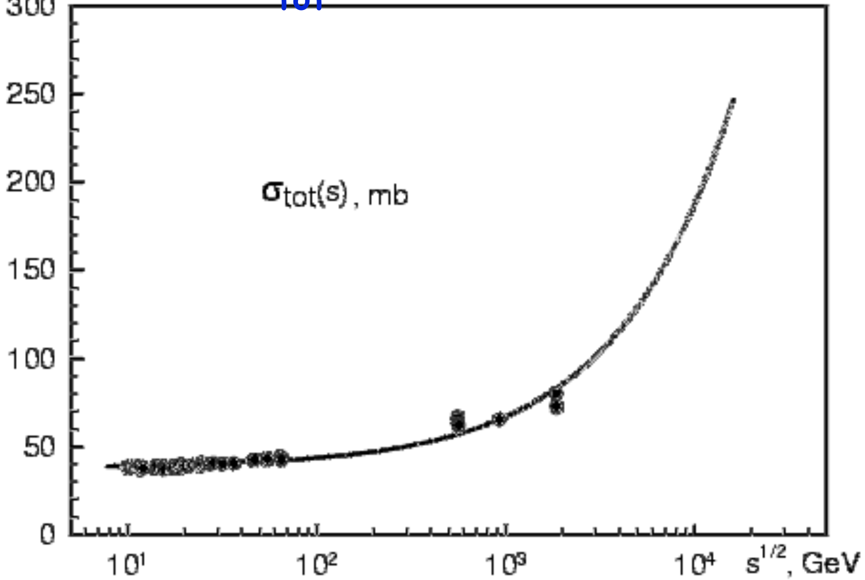
Example (slightly exotic?)

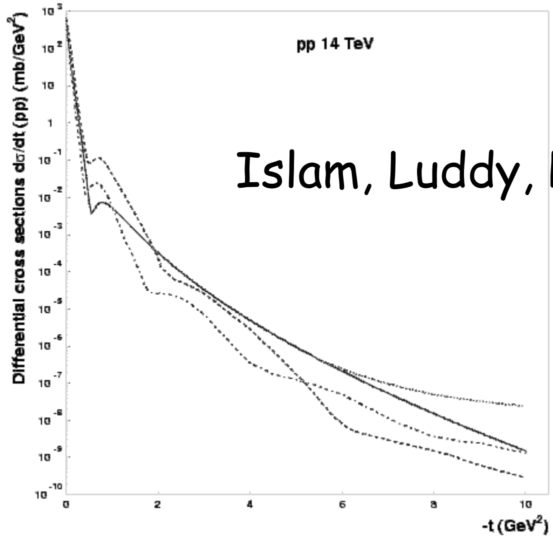
(Tuyrin & Troshin)

Abnormal strong rise due to "antishadowing"

Leads to σ_{tot} of 200 mb!!







Islam, Luddy, Prokudin

Disaster! ~ 40 events overlap at LHC

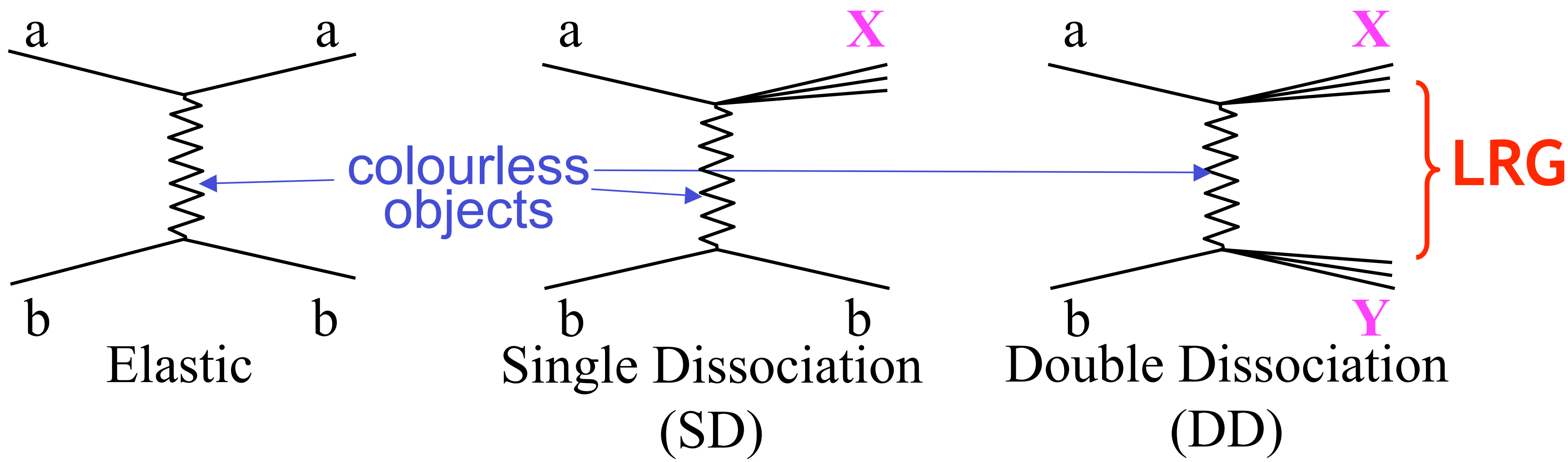
Model predicts $\sigma_{elastic} > 0.5\sigma_{total}$ suspicious!

Comparison of the elastic t distribution for different models

Diffraction

Diffraction in Hadronic Scattering

Diffraction is a large component of hadron interactions (~30% of σ_{tot}):



o) Beam particles emerge intact or dissociated into low-mass states.
Energy ≈ beam energy

o) Final-state particles separated by large polar angle
(or pseudorapidity, ln tan(θ/2)): Large Rapidity Gap (LRG)

o) Interaction mediated by t-channel exchange of object with vacuum
quantum numbers (no colour): the Pomeron…

A Pomeron ?!?

Pomeron goes back to the '60s: Regge trajectory, i.e. a moving pole in complex angular momentum plane. Would like to understand diffraction in terms of quarks, gluons and QCD (need a hard process)

A worthwhile task:

•Diffraction is a significant part of σ_{tot}

•Novel tool to study the transition between hard (perturbative

(confinement) regions of QCD: hard diffractive scattering

In the last 5-10 years, we learned a lot about diffraction by scattering pointlike probes (electrons) on Pomeron – the same technique used for studying the structure of the proton

→ now clear that diffraction has a well deserved place in QCD

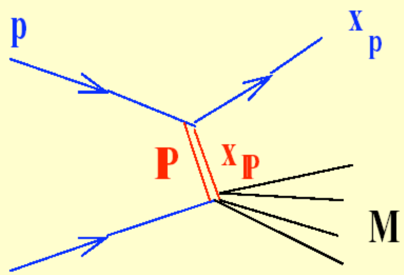
NB in following will often refer to Pomeron as if it were real particle: it isn't (some die-hards believe it could be a glueball)

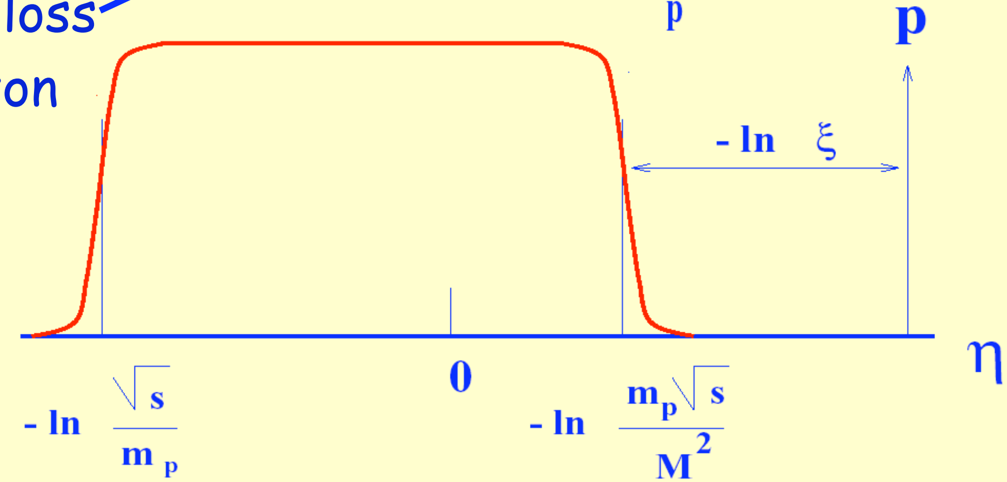
Diffractive Scattering

Diffraction:

$$x_{I\!P} = 1 - x_p = \xi = \frac{M^2}{s}$$

Momentum loss by the proton





$$\frac{d^2\sigma_{sd}}{d\xi dt} = \frac{A}{\xi} b e^{-bt}$$

$b \sim 10$ GeV^{-2}
$t \sim \theta^2 p^2$

One proton "dissociates" in system with mass M "single diffractive dissociation" (SD)

Data from 70-80's: Coherence condition

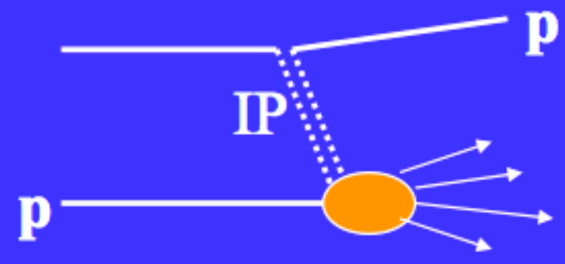
- $\boxed{\xi = \frac{\Delta P_L}{P_L} = \frac{M_X^2}{S} \le \frac{m_\pi}{m_p}}$
- $d\sigma/dM \sim 1/M^2$

Diffractive Excitation

Diffractive excitation range ("rule of thumb") $M_{max} \sim 0.22\sqrt{s}$

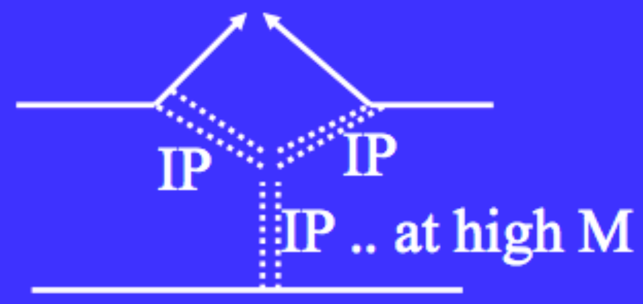
(GeV)

	$\sqrt{s}$	M_{max}	
PS	7.4 ---	1.6	resonances
ISR	63 ---	14	
Tevatron	1960 ---	430	Jets/W/Z
LHC1	10,000 ---	2200	top ??



p-IP total cross section
optical theorem :
p-IP elastic scattering

$$\boxed{\begin{aligned} &\ln M_X^2 \leq \ln s - 3 \\ &M_X^2 \leq e^{(\ln s - 3)} = \frac{e^{\ln s}}{e^3} = \frac{s}{20} \\ &\frac{M_X^2}{s} = 1 - x_F = \xi \leq 0.05 \end{aligned}}$$



Rapidity Gaps and Diffraction

✓ **rapidity gaps are regions of rapidity devoid of particles**

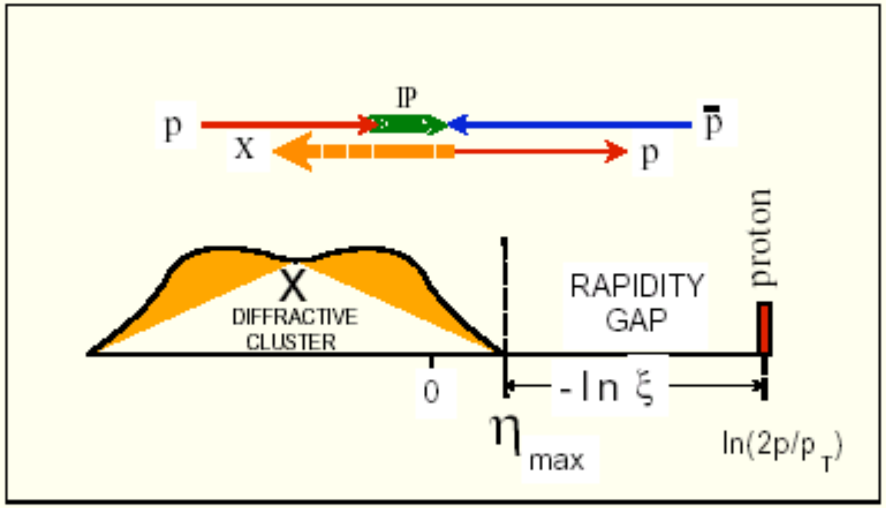
- ❑ Non-diffractive interactions: rapidity gaps are formed by multiplicity fluctuations
- ❑ Diffractive interactions: rapidity gaps, like diamonds, 'live for ever'

$$\Delta y \approx -\ln \xi = \ln s - \ln M^2$$

From Poisson statistics:

$$P(\Delta\eta) = e^{-\rho \Delta y} \quad \left(\rho = \frac{dn}{dy}\right)$$

(r=particle density in rapidity space)



Gaps are exponentially suppressed

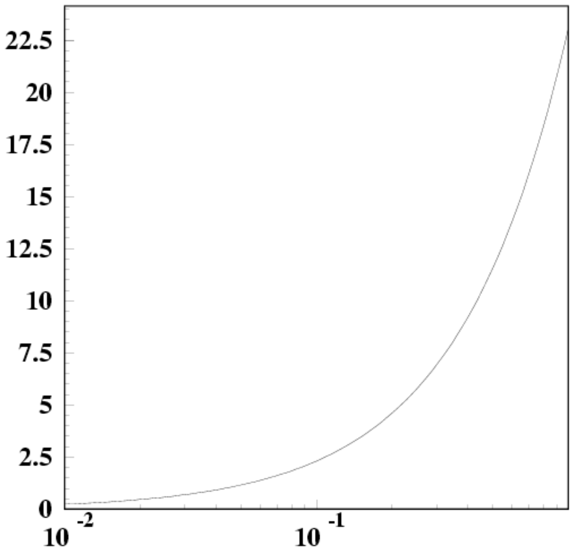
$$\boxed{\frac{d\sigma}{dM^2} \sim \frac{1}{M^2} \quad \rightarrow \quad \frac{d\sigma}{d\Delta y} \sim \text{constant}}$$

✓ large rapidity gaps are signatures for diffraction

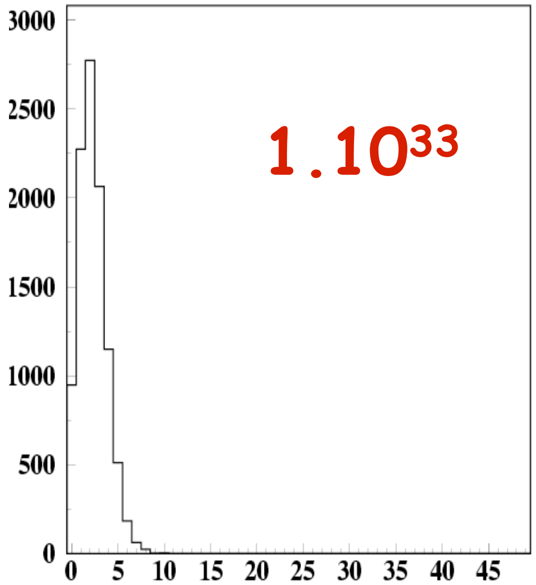
Rapidity Gaps at LHC

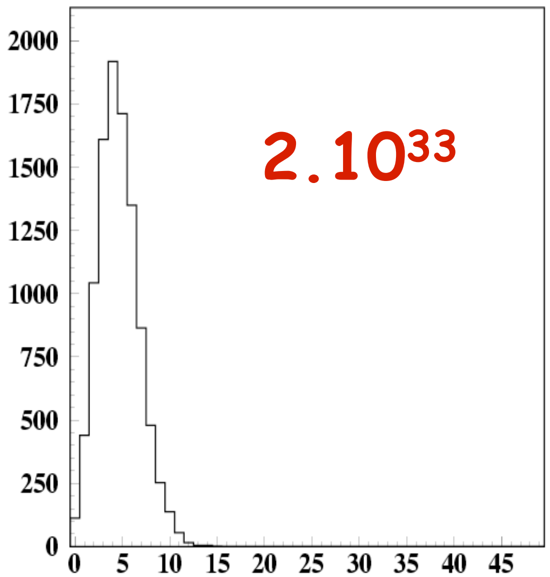
Number of overlap events versus LHC luminosity

distribution of number of interactions



10^{32} 10^{33} 10^{34}

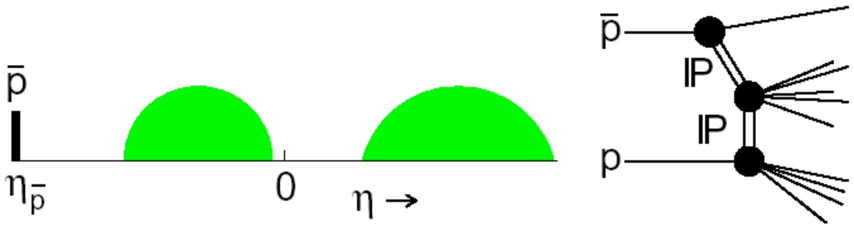


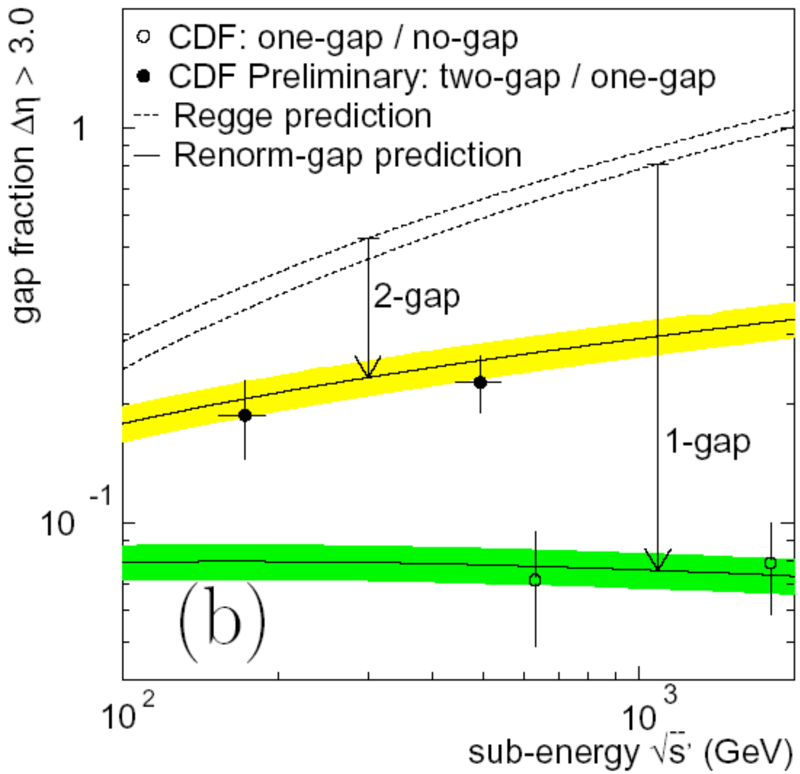


1 int. 22% **4%**

Doable at startup luminosity without Roman Pots!

Gaps in events: still not fully understood

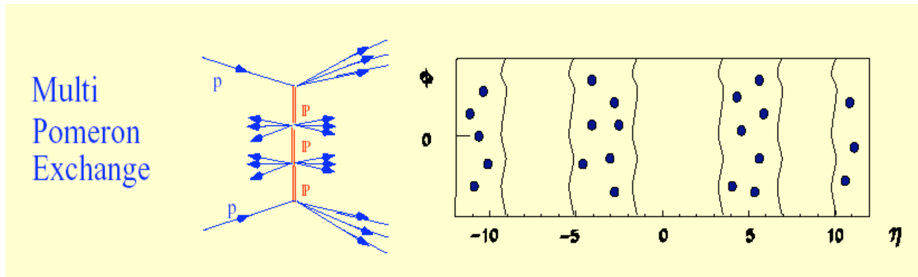




CDF data

Two gap suppression is smaller than 1 gap suppression

What happens for more gaps?



CMS/TOTEM acceptance: |η|<7

End of Lecture one