Diffraction, total cross section and forward physics at the LHC

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Forward physics

- Elastic and total p-p cross section
- Soft and hard diffraction
- Rapidity gap survival probability
- Low-x QCD
  - Drell-Yan, jets, heavy flavours, W/Z production
- γ-p and γ-A processes

and also

- Anomalous gauge couplings
- Higgs physics

Forward physics needs forward detectors

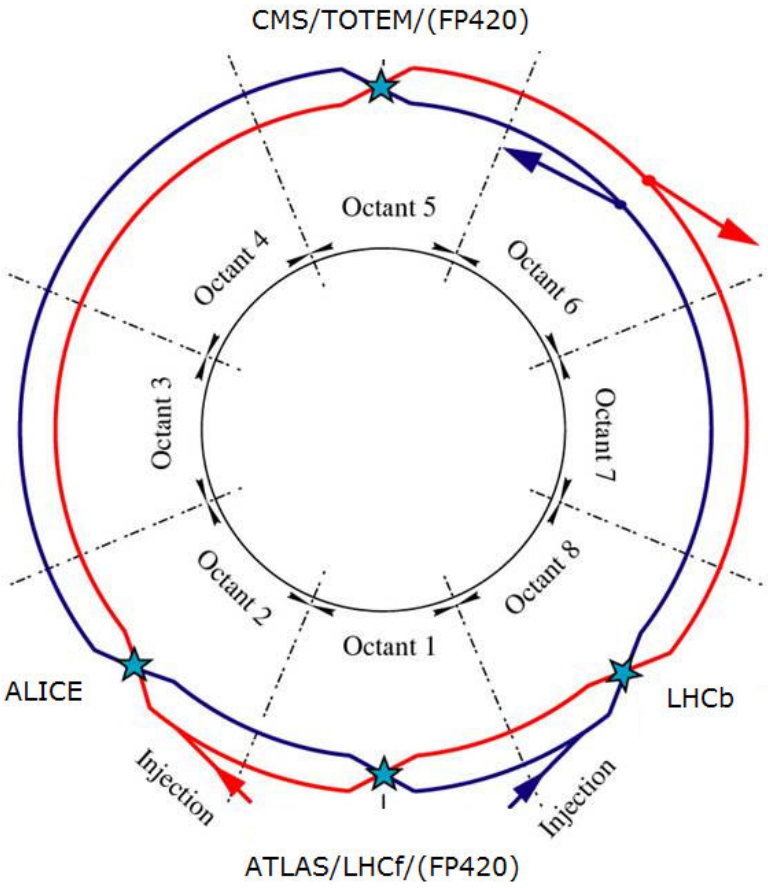
- Forward: $|\eta|> \sim 3$
- IP1: ATLAS/LHCf/(FP420)
- IP2: ALICE
- IP5: CMS/TOTEM/(FP420)
- IP8: LHCb

Proton detectors inside beampipe
TOTEM, ATLAS, (FP420)
Total cross section, elastic scattering, diffraction

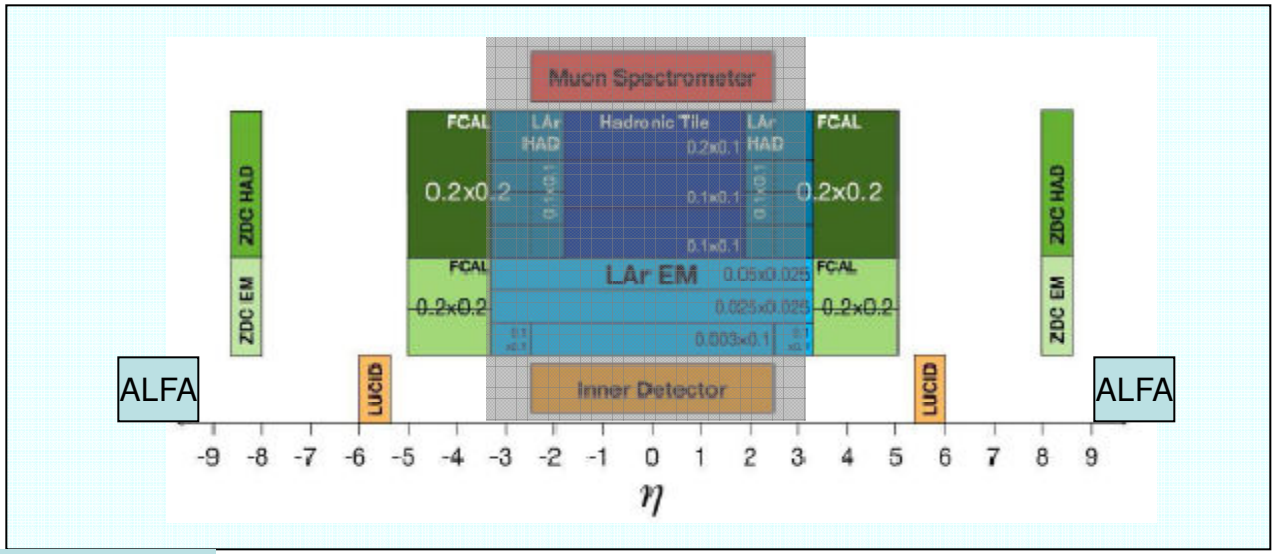
Tracking/multiplicity detectors
TOTEM, ALICE, LHCb
Total cross section, diffraction, low-x, CR

Calorimeters
CMS, ATLAS
Diffraction, low-x, CR, γ-p…

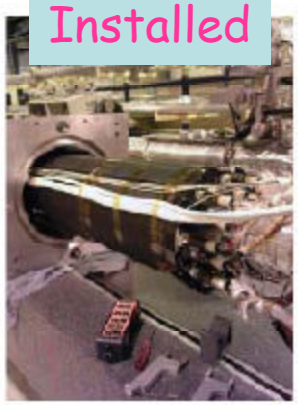
ZDCs
LHCf, CMS, ATLAS, ALICE
CR, diffraction, low-x



IP1: ATLAS

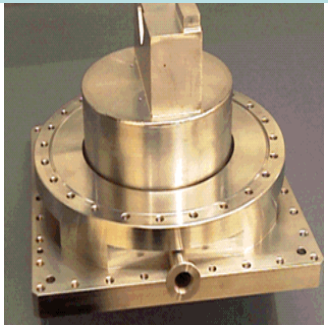


Installed



LUCID: Cerenkov for luminosity meas.

Mechanics partially installed

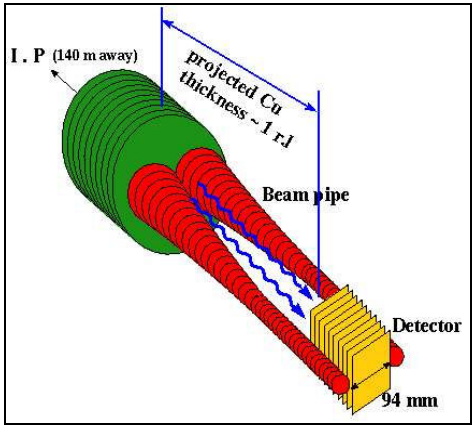


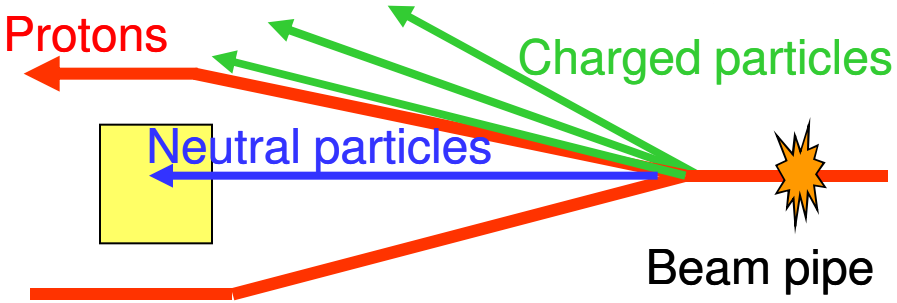
ALFA: Roman Pots with proton detectors (scintillating fibers)

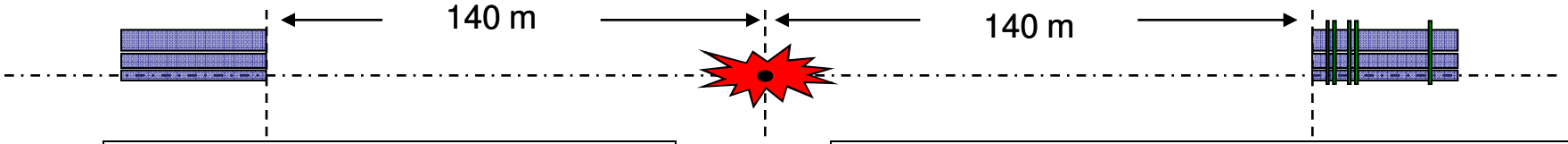
Installed

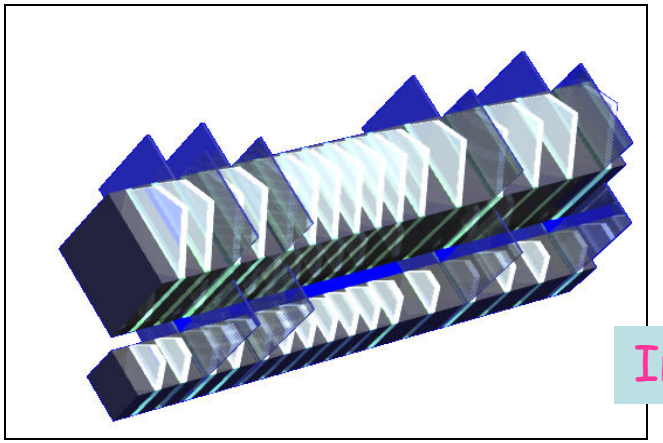
ZDC: EM and hadronic calorimeter

IP1: LHCf

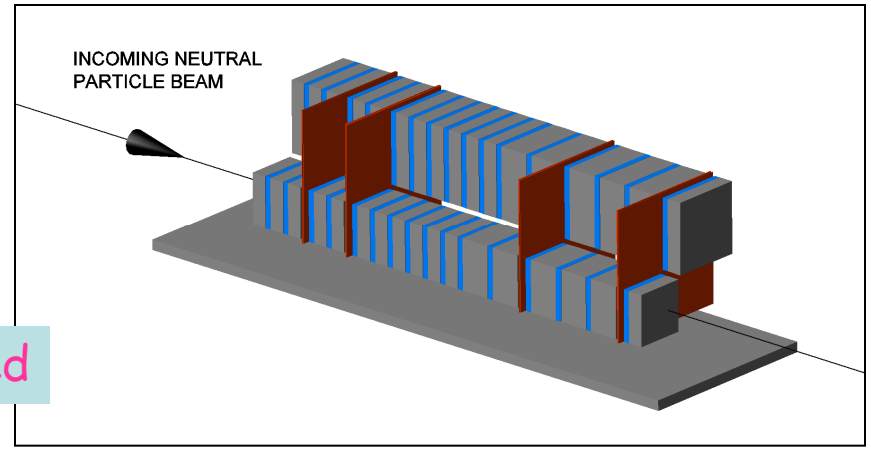








Installed



Detector I

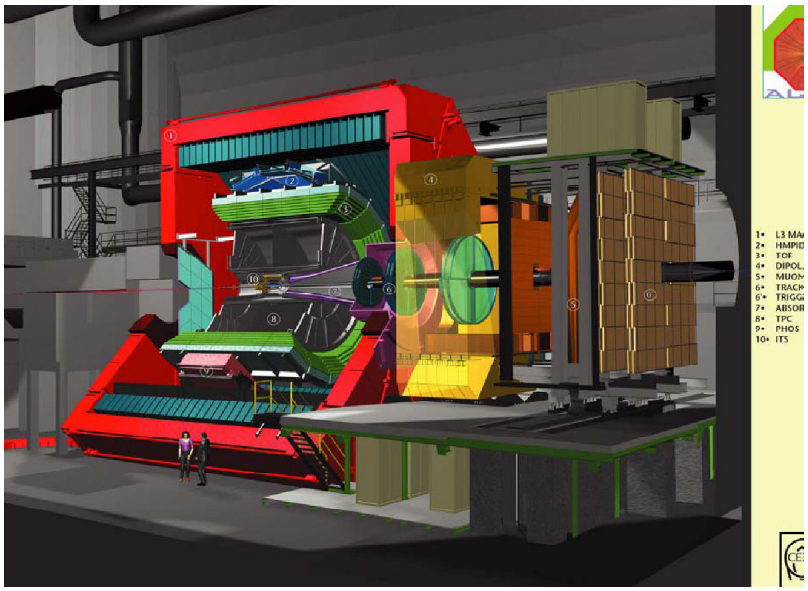
Tungsten Scintillator - Scintillating fibers

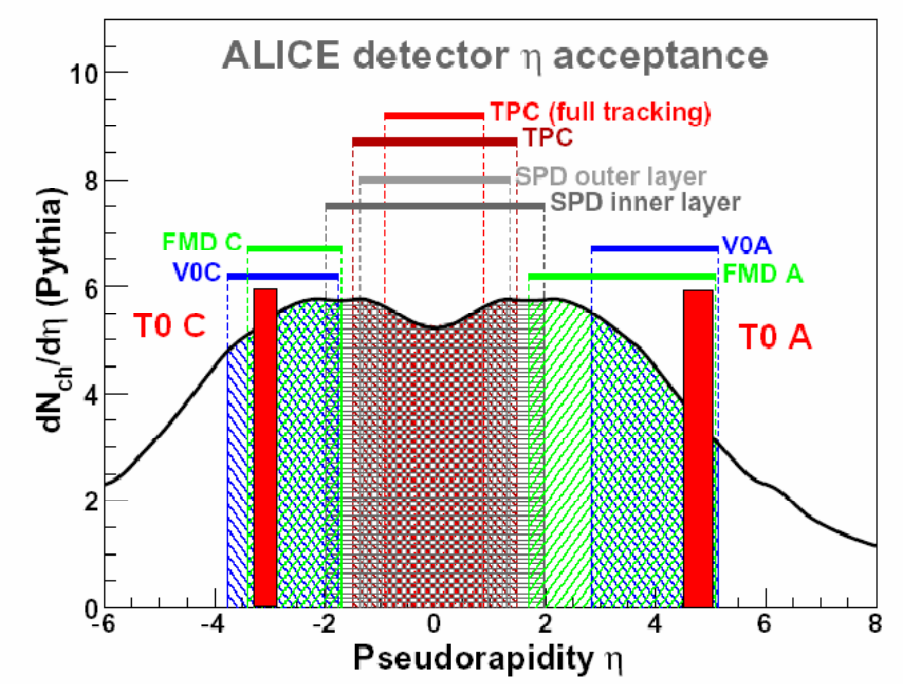
Detector II

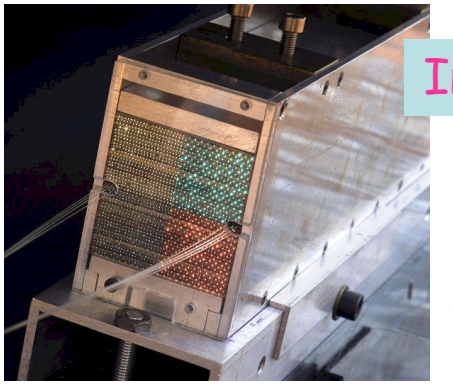
Tungsten Scintillator - Silicon μstrips

IP2: ALICE

Muon spectrometer
$-4 < \eta < -2.5$





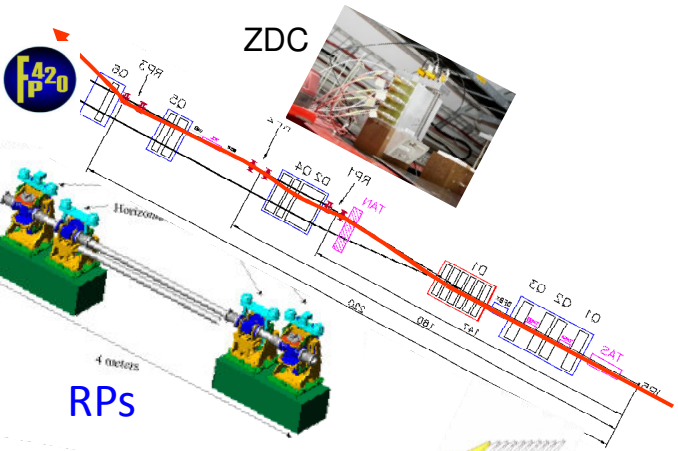


Installed

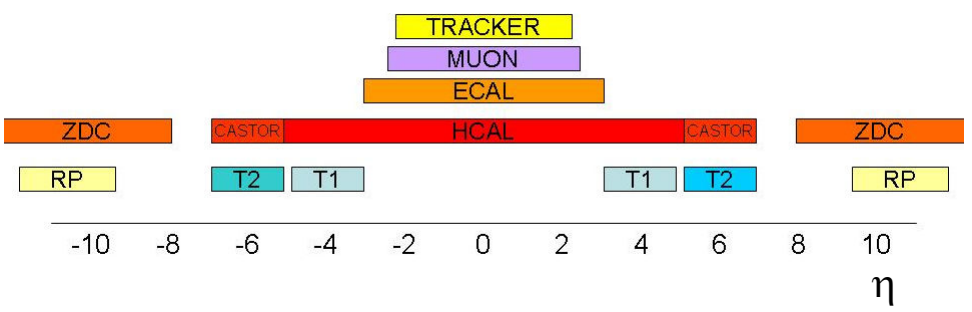
ZDC (at 116m from IP)

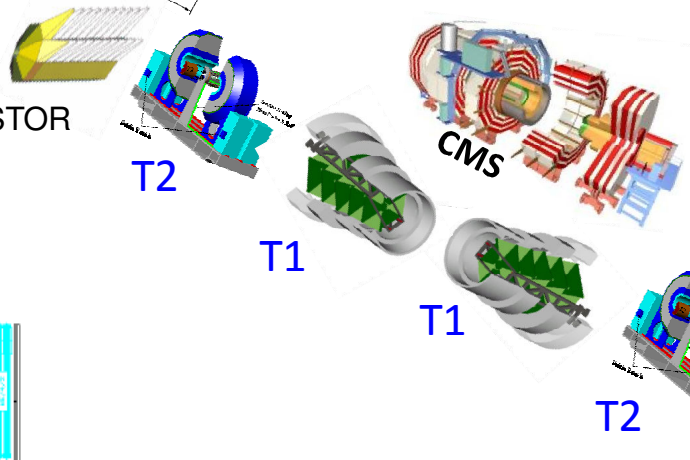
Additional forward detectors
$1 < \eta < 5$
$-4 < \eta < -1$

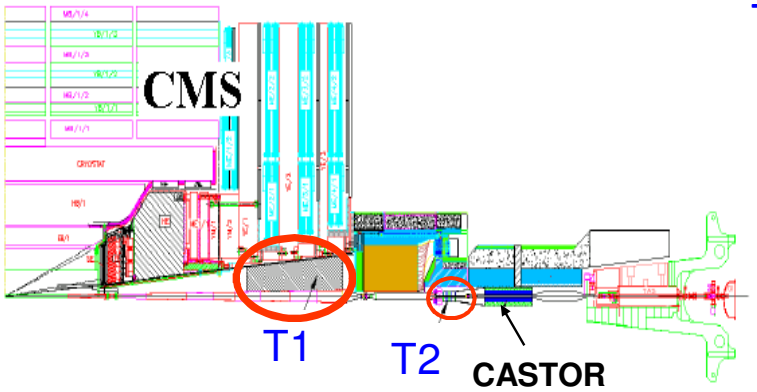
IP5: CMS/TOTEM/(FP420)

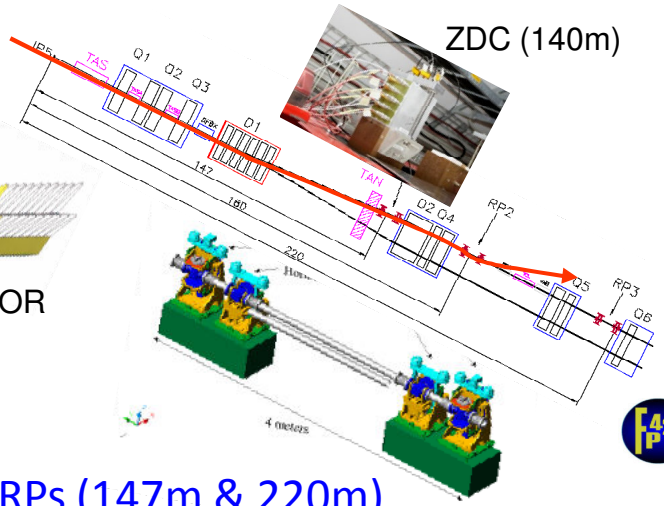


Unprecedented η coverage



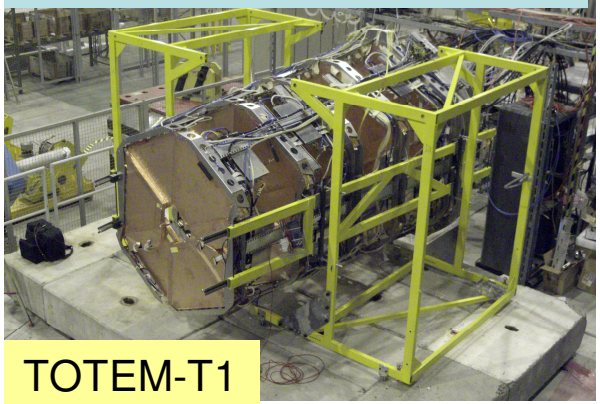






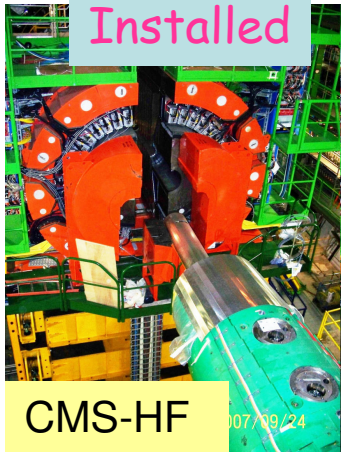
IP5: Forward detectors

Readying for installation



TOTEM-T1

Installed



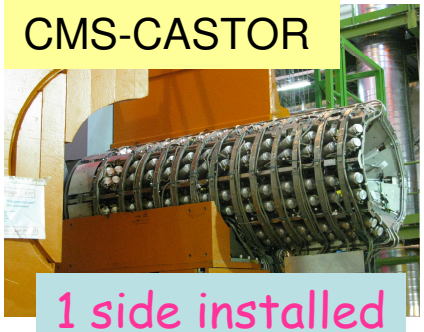
CMS-HF

T1 & HF:
tracking and calorimetry at
~3<|η|<~5

Installed

TOTEM-T2

CMS-CASTOR



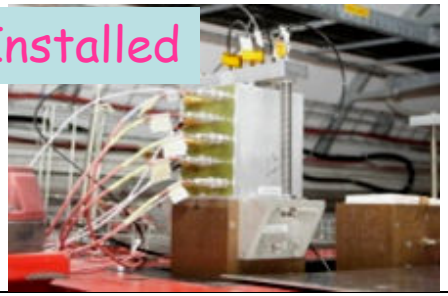
1 side installed

T2 & CASTOR:
tracking and calorimetry at
~5<|η|<~7

220m installed

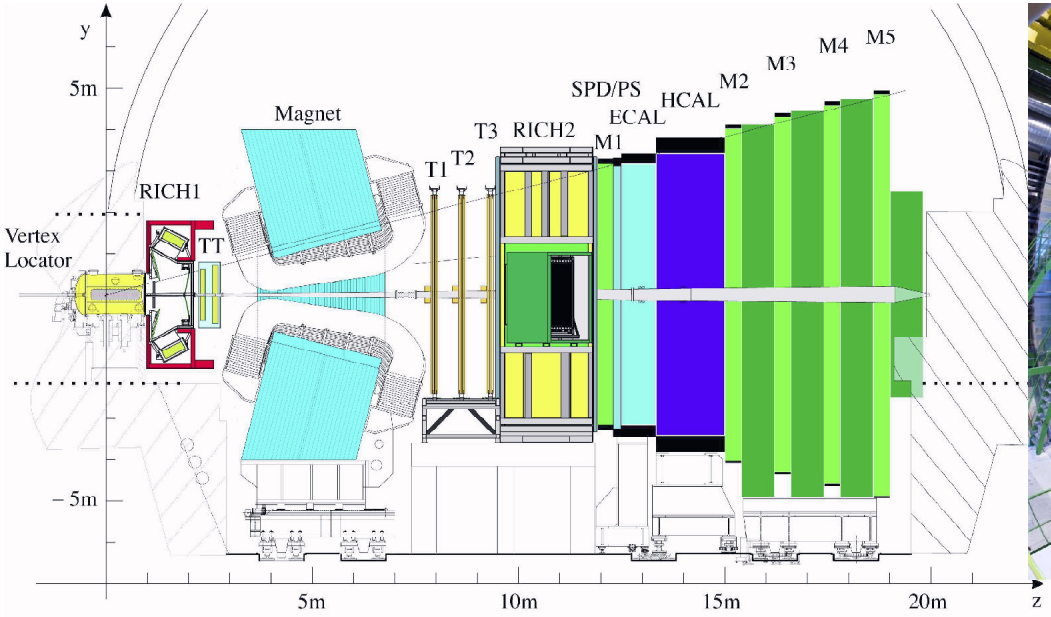
TOTEM Roman Pots with edgeless Si dets to measure the leading proton

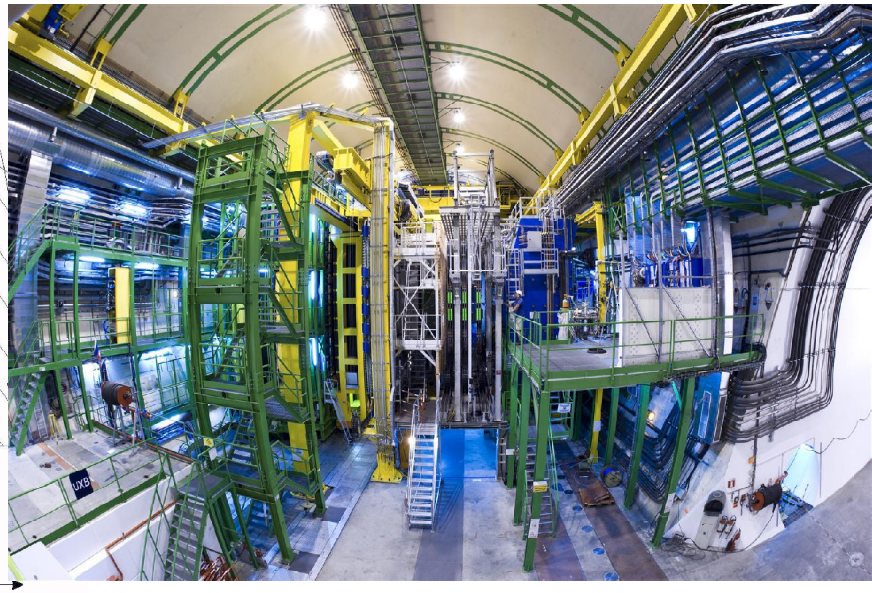
Installed



CMS-ZDC for calorimetry of neutral particles

IP8: LHCb





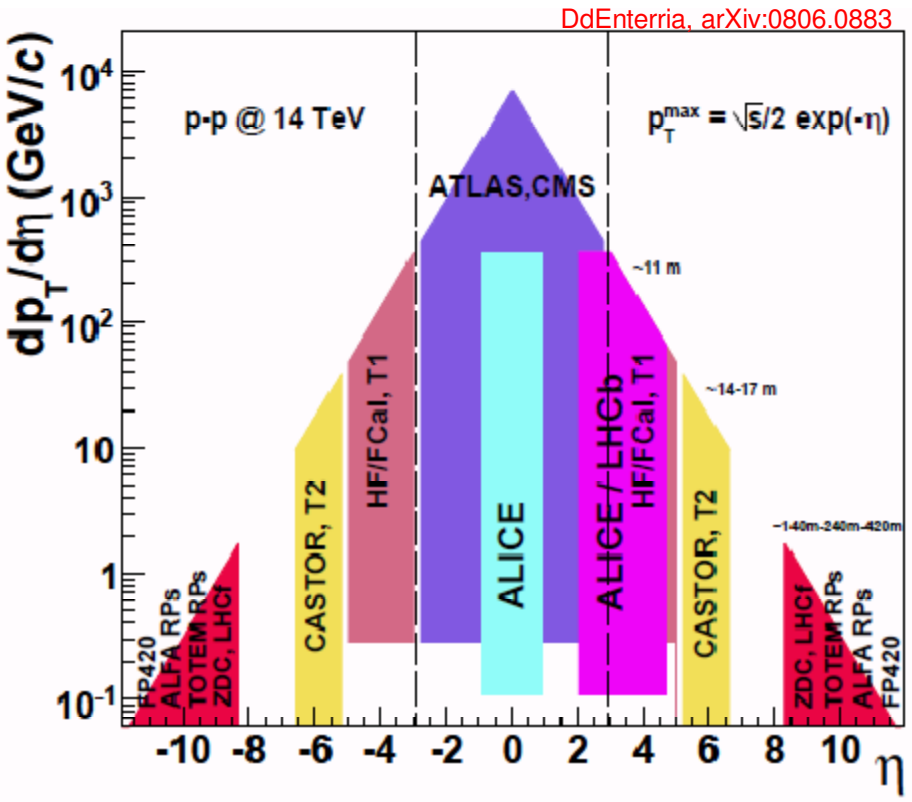
~2<η<~5

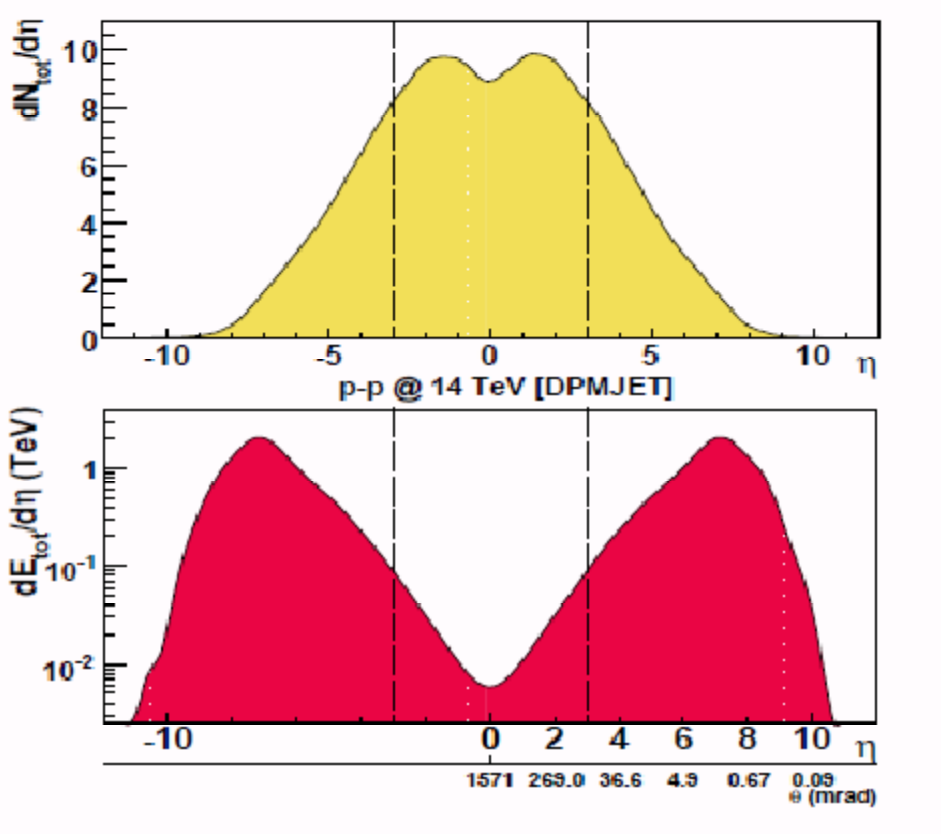
TT,T1,T2,T3
MUON
ECAL
HCAL
RICH1,2

Forward spectrometer optimized for B-physics

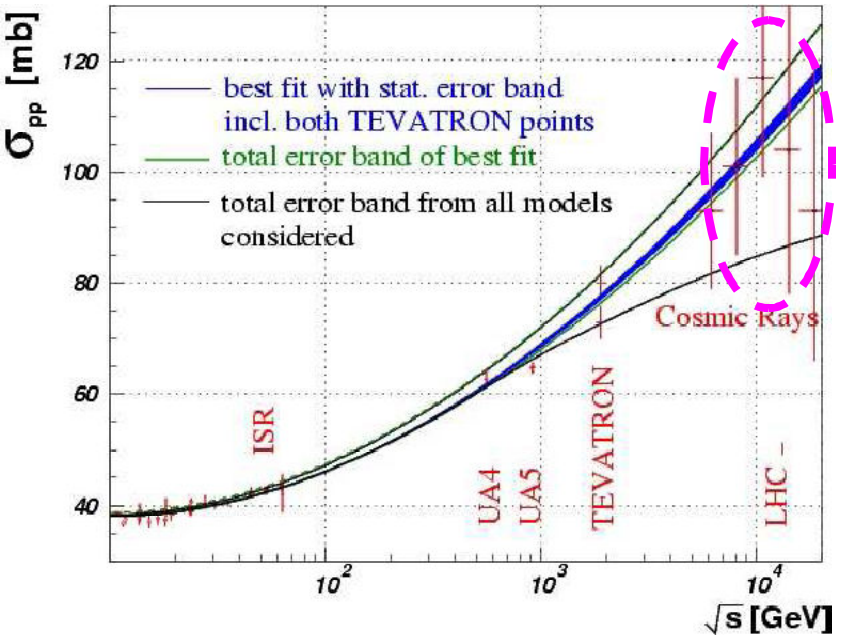
-10 -8 -6 -4 -2 0 2 4 6 8 10 η

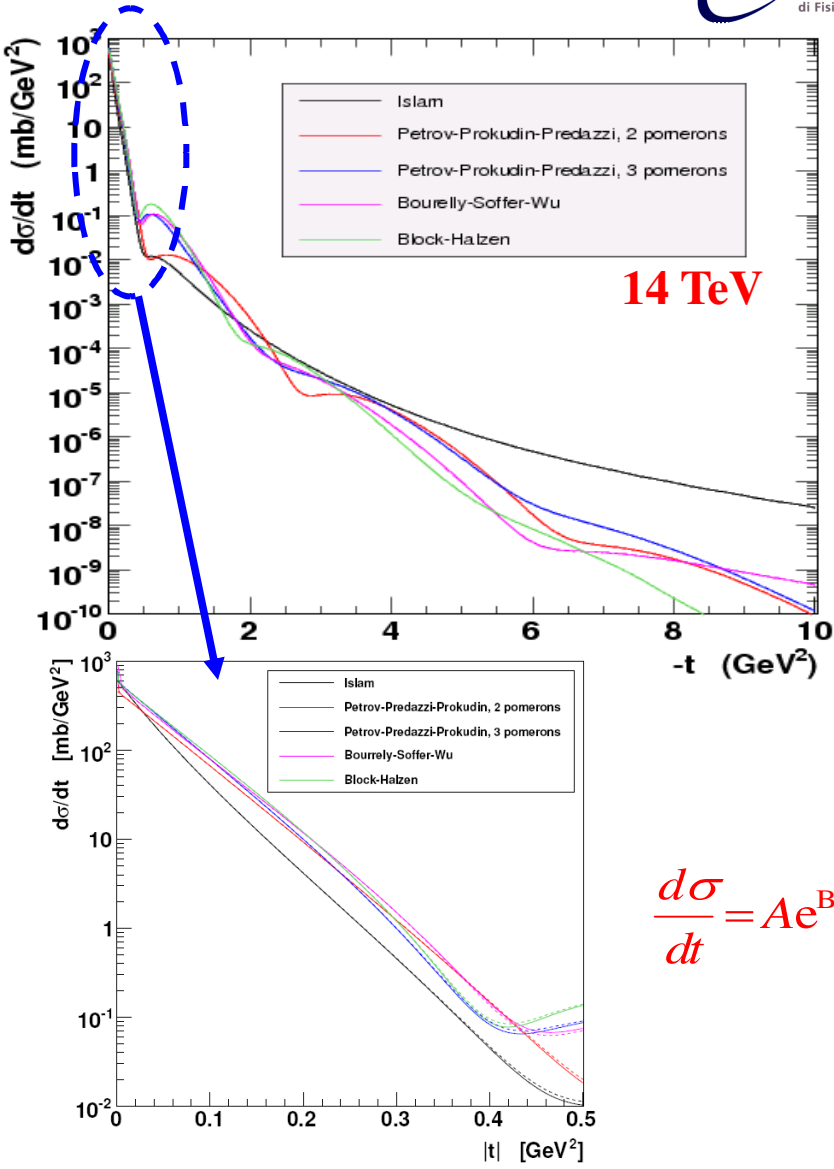
η coverage: all experiments





Total cross section and elastic scattering





Tevatron measurements (1.8 TeV):

E710: $\sigma_{tot} = 72.8 \pm 3.1$ mb

E811: $\sigma_{tot} = 71.4 \pm 2.4$ mb

CDF: $\sigma_{tot} = 80.0 \pm 2.2$ mb

2.6 σ discrepancy

$$\frac{d\sigma}{dt} = Ae^{B(t)t}$$

COMPETE fit

$$\sigma_{tot} = 111.5 \pm 1.2\ ^{+4.1}_{-2.1}\ \text{mb}$$

Total cross section and elastic scattering

1. σ_{tot} using the Optical theorem (needed elastic and inelastic rate)

TOTEM

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

$$\rho = \left.\frac{\mathrm{Re}(f_{el}(t))}{\mathrm{Im}(f_{el}(t))}\right|_{t\to 0}$$

Precision:
1-2% β^*=1540m
5% β^*=90m (early runs)

2. Measurement of elastic scattering in the Coulomb-Nuclear Interference region

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

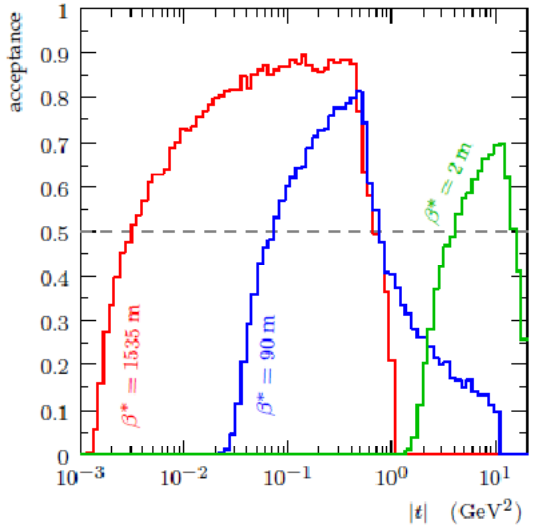
Precision:
3% β^*=2600m
(after 2010)

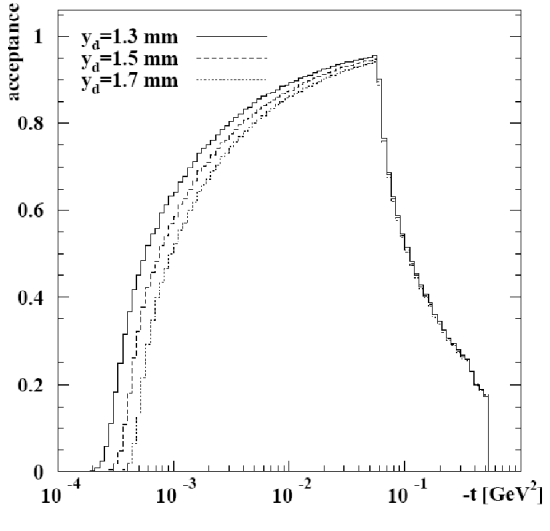
Special LHC optics with good acceptance at low $|t| \sim p^2\theta^2$
Very high cross sections O(mb) → high statistics in short running time
Mainly systematical errors

Elastic scattering
Acceptance and resolution of leading proton detectors

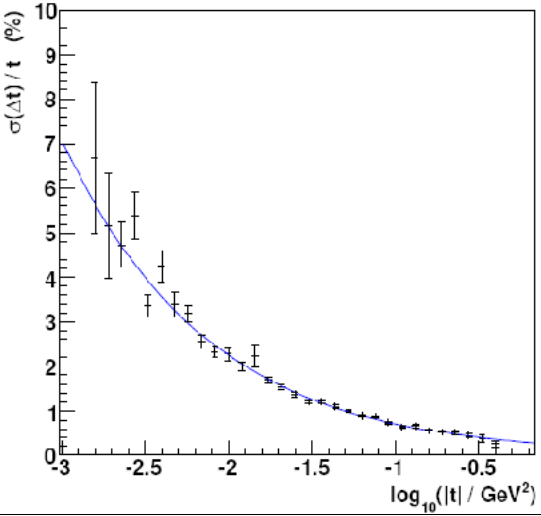
$|t| = p^2\,\theta^2$

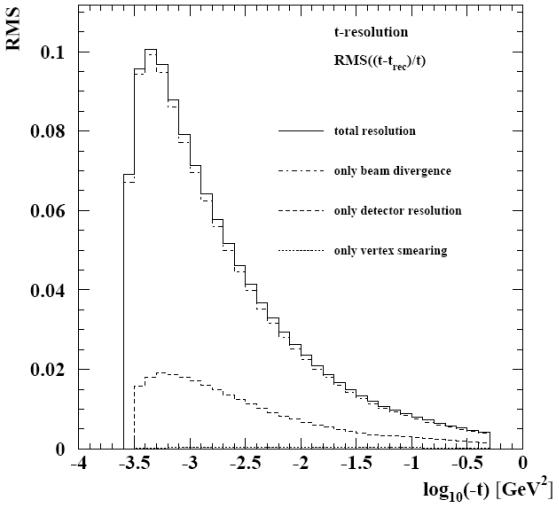
t acceptance





t resolution





TOTEM

$\beta^* = 1540$ m: $|t|_{min} = 0.001$ GeV^2
low-t elastic + high prec. σ_{tot}

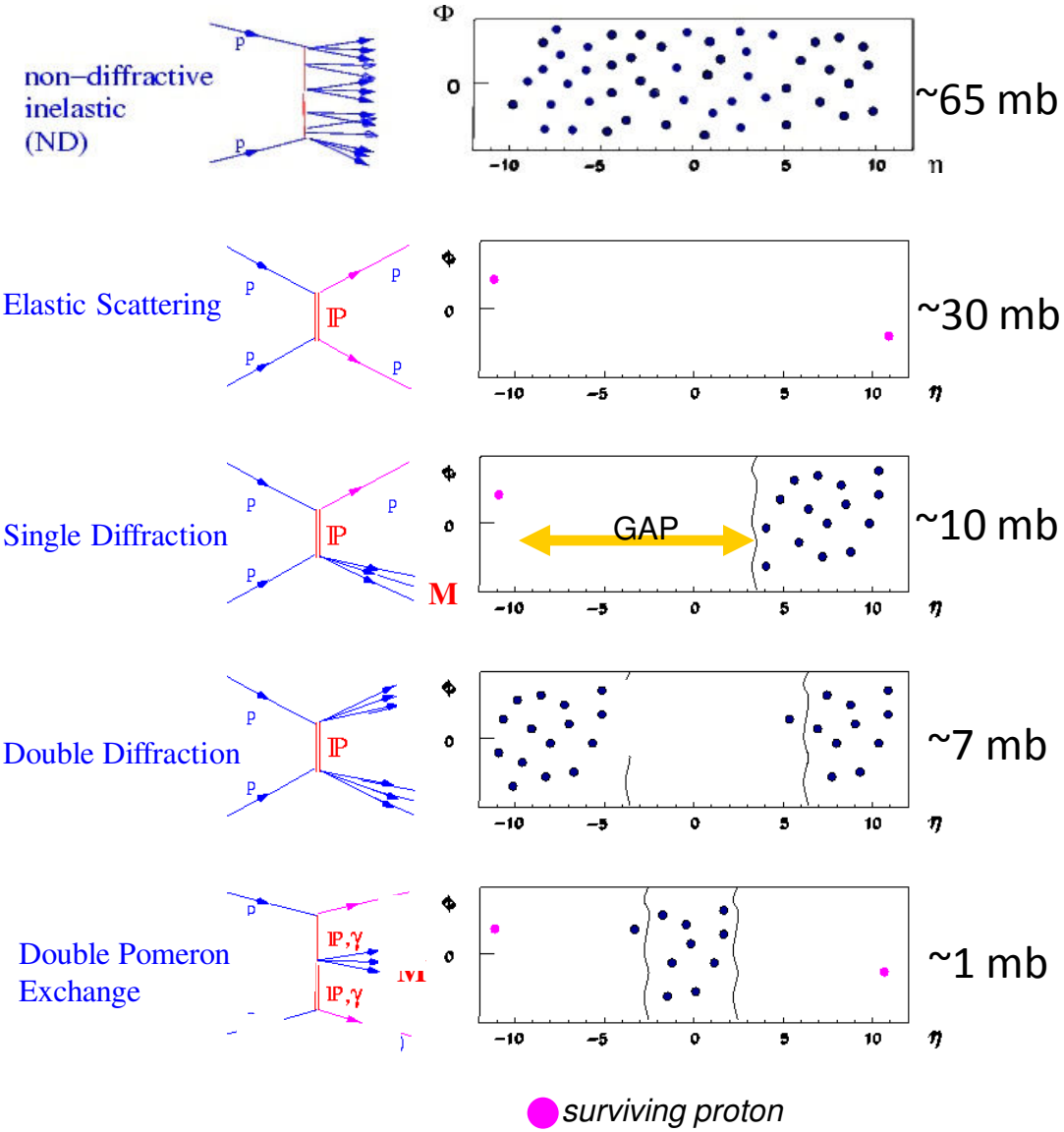
$\beta^* = 90$ m: $|t|_{min} = 0.03$ GeV^2
mid-t elastic + σ_{tot}

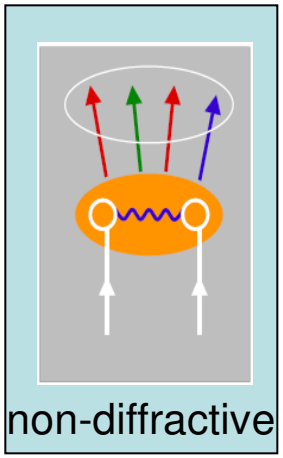
$\beta^* = 2$ m: $|t|_{min} = 0.4$ GeV^2
High-t elastic scattering

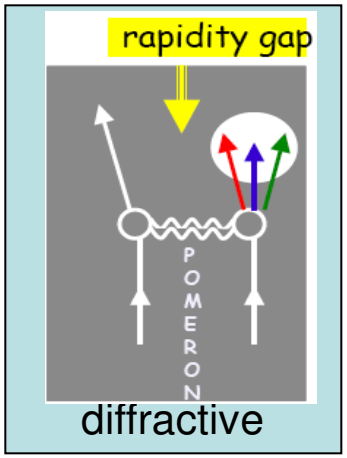
ATLAS

$\beta^* = 2600$ m: $|t|_{min} = 0.0006$ GeV^2

Diffraction







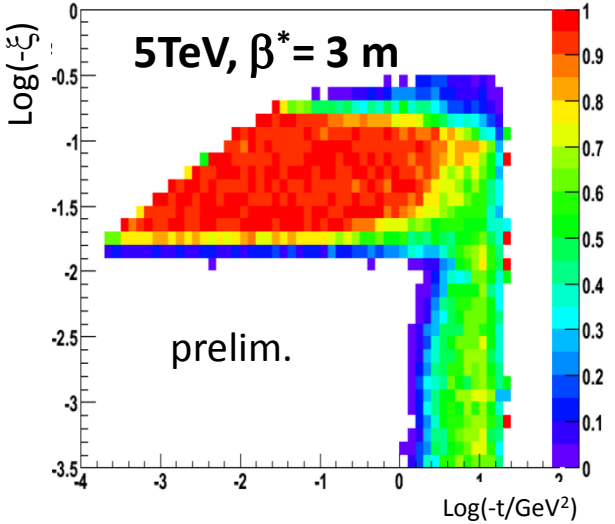
- Colourless exchange of vacuum quantum numbers
- Rapidity Gaps
- ~30% of total pp x-section

$$\frac{d\sigma}{d\Delta\eta} \sim const$$

Diffraction: proton measurement

Diffractive protons in TOTEM

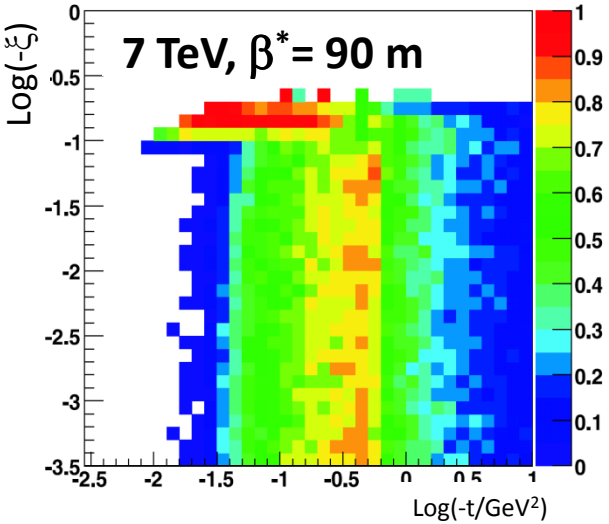
$\xi = \Delta p/p$ $(M_{SD}^2 = \xi s)$



$\sigma(\xi) = 1 - 6 \cdot 10^{-3}$

$-\xi > 2$ % seen

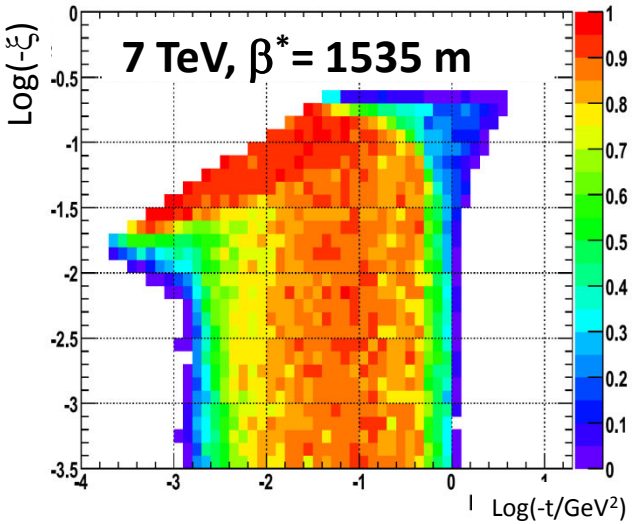
(hard) diffraction, high |t| elastic scattering



$\sigma(\xi) = 6 - 15 \cdot 10^{-3}$

all ξ seen

diffraction, mid |t| elastic scattering, total cross-section



$\sigma(\xi) = 2 - 10 \cdot 10^{-3}$

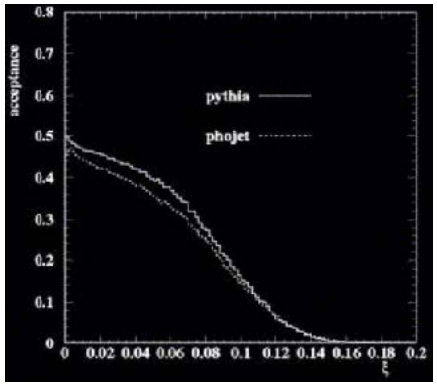
all ξ seen

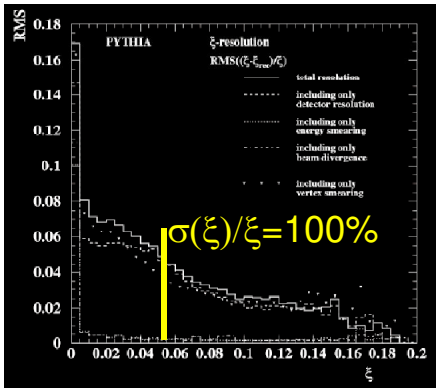
total cross-section, low |t| elastic scattering

SD in ATLAS high β^* runs

$-\xi < 1$ % seen

$\sigma(\xi)/\xi > 100\%$ for $\xi < 0.05$





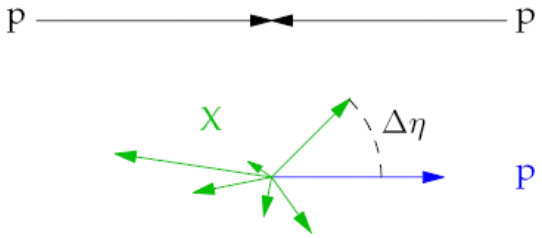
Soft diffraction: example of early measurements

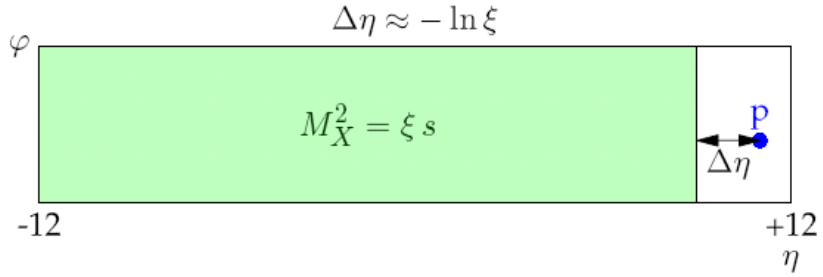
$\xi = \Delta p/p$, $M^2 = \xi s$

TOTEM

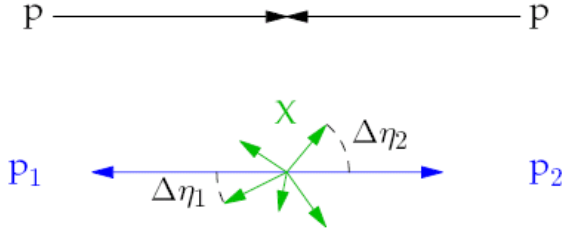
$$\left(\frac{d\sigma}{d\Delta\eta}\right)_{t=0} \approx \text{constant} \Rightarrow \frac{d\sigma}{dM^2} \sim \frac{1}{M^2} \Rightarrow \frac{d\sigma}{d\xi} \sim \frac{1}{\xi}$$

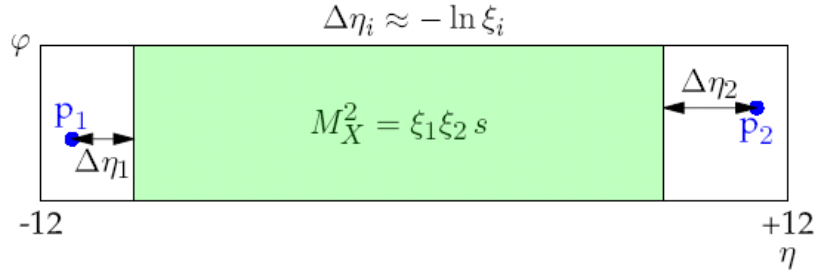
- Single Diffraction (SD):
  $d\sigma^{SD}/dM$ at high masses,
  $1.4 < M < 4.2$ TeV, $\sigma(M)/M = 2 - 4$ %



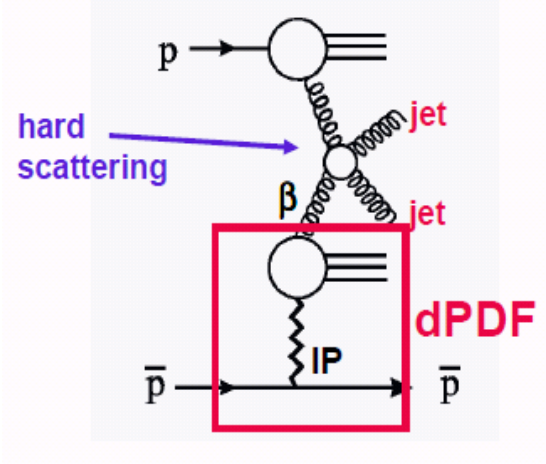


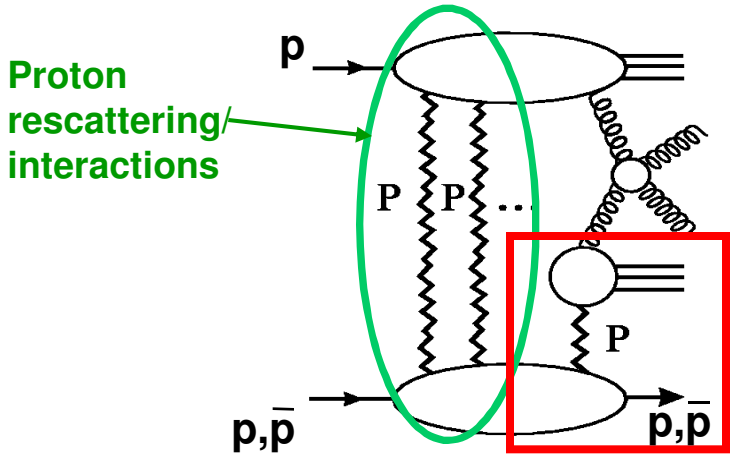
- Double Pomeron Exchange (DPE):
  $d\sigma^{DPE}/dM$ at high masses,
  $0.2 < M < 1.8$ TeV, $\sigma(M)/M < 2 - 4$ %

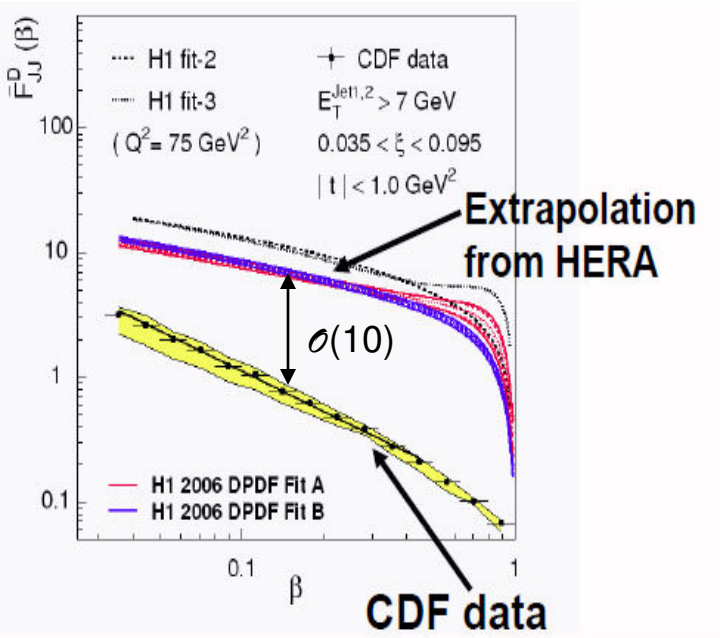




Hard diffraction



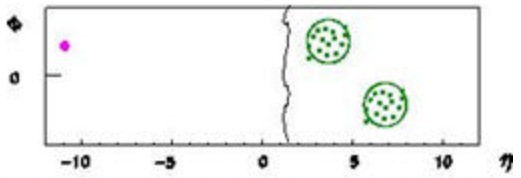


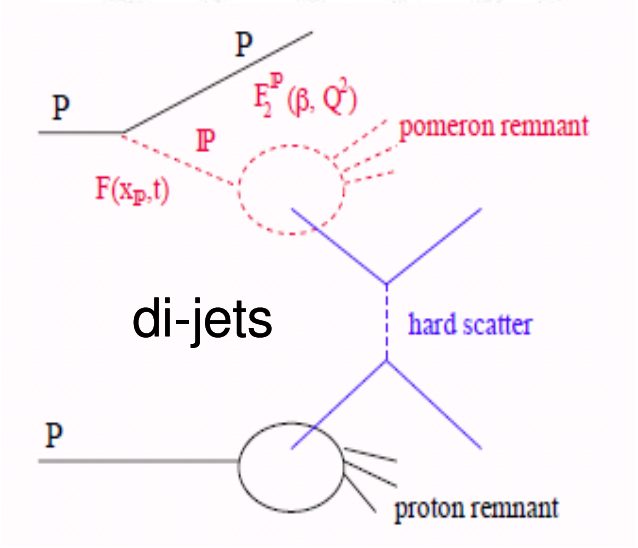


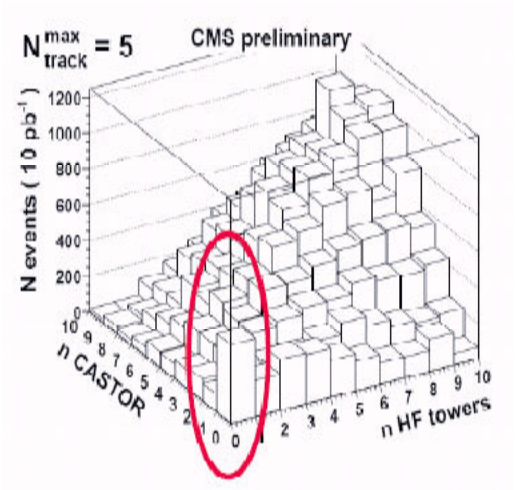
Factorization: σ (hDiff) = σ(hard) x dPDF
Seen at HERA. Broken at Tevatron due to rescattering between spectator partons.

Rapidity gap filled $\Rightarrow$ reduced σ_{Diff}

Rapidity gap survival probability:
$\langle|S|^2\rangle$ ~ 10% Tevatron
$\langle|S|^2\rangle$ ~ 1 - 5% predicted at LHC







Hard single diffraction

High E_T jets, heavy quarks, heavy bosons production

detection depends on optics

Rapidity Gap (and surviving proton) on one side

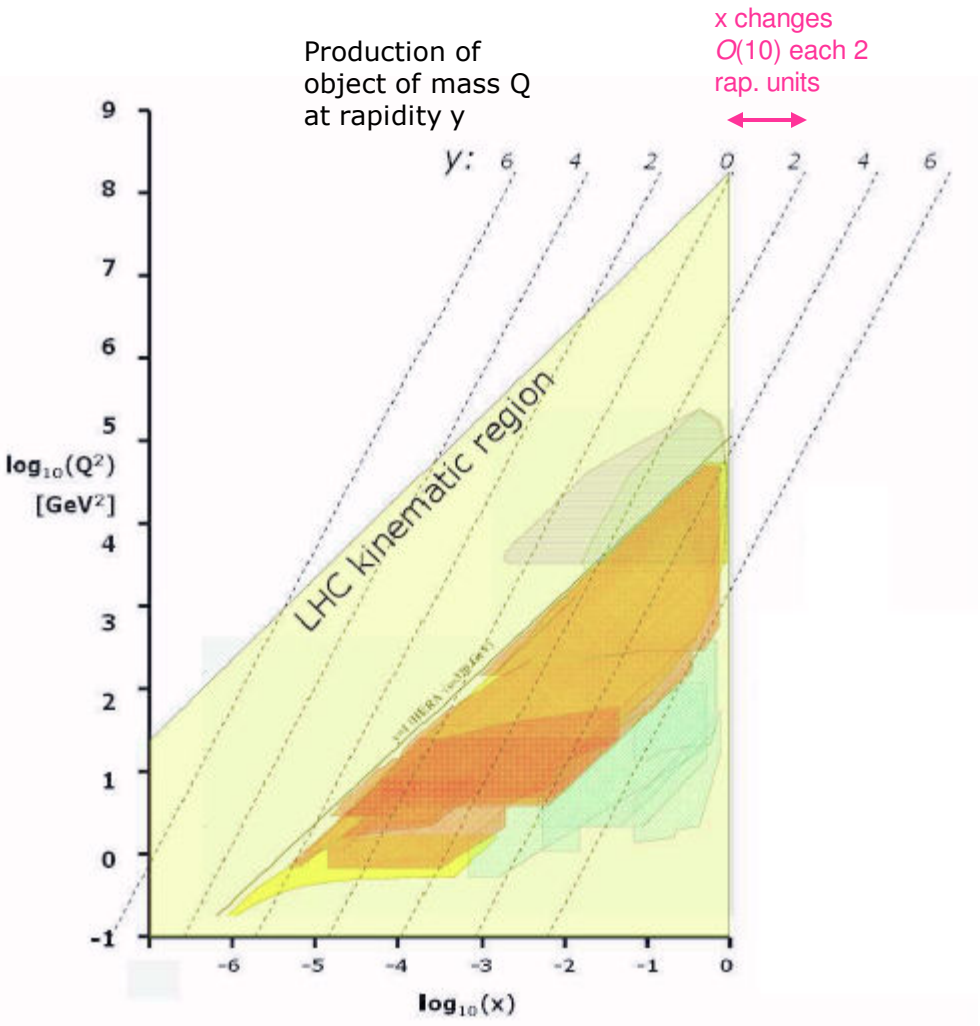
CMS/TOTEM: gap in HF/CASTOR + (p in RP)
ATLAS: gap in FCAL, LUCID, ZDC
ALICE: gap in ZDC

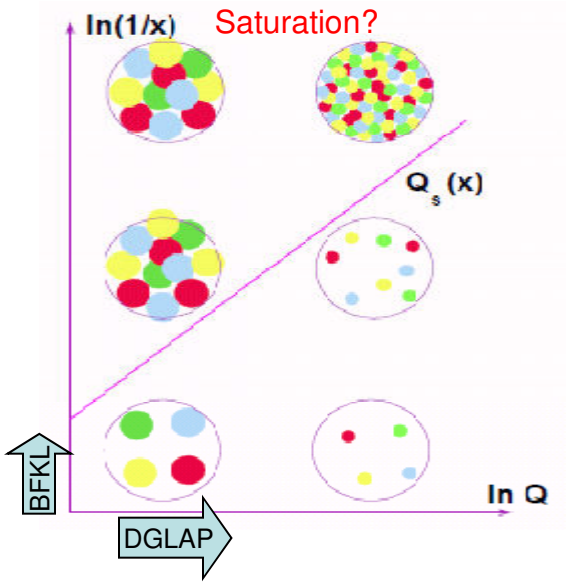
Expected ~ 300 SD di-jets with $E_T > 55$ Gev in ~10 pb^{-1}

Example: CMS di-jets: (nCASTOR,nHF)=(0,0) bin

Low-x physics

$x=p_{part}/p_{prot}$





Proton as a dynamic object

PDFs are $f(x,Q^2)$

DGLAP: strong ordering in k_T

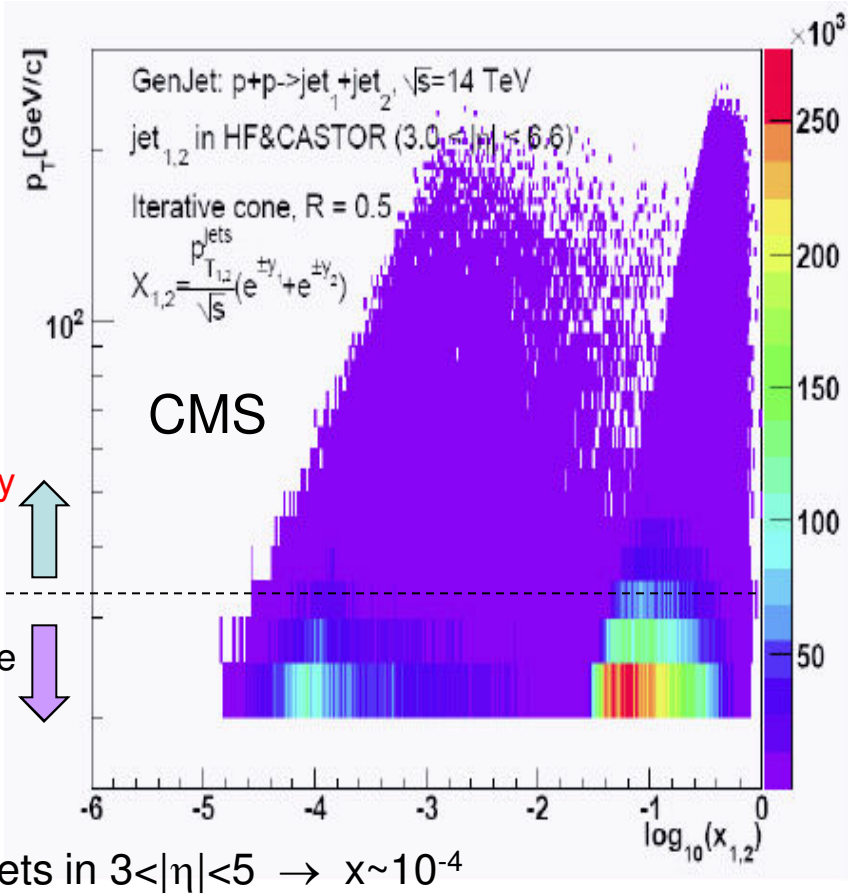
BFKL: strong ordering in x

$$x = \frac{Q}{\sqrt{s}} e^{-\eta} \rightarrow$$ At LHC $x_{min} \sim 10^{-6}$

Forward jets

Study low-x partons from forward jets

CMS,ATLAS,LHCb



Good sensitivity to PDFs diff.

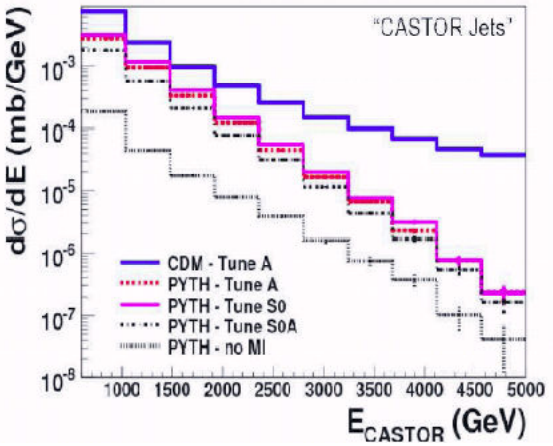
High fake jet rate (S.Cerci,DdEnterria: arXiv:0812.2665)

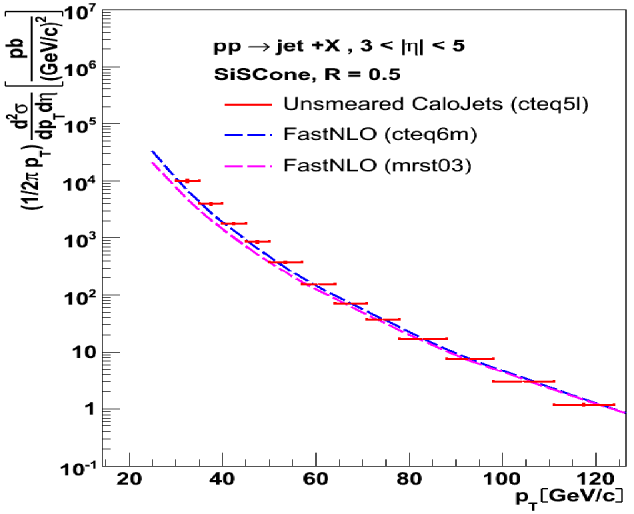
Jets in $3<|\eta|<5 \rightarrow x\sim10^{-4}$

Jets in $5<|\eta|<7 \rightarrow x\sim10^{-5}$

Major error source: systematics (JES, luminosity,…)

Study of the underlying event

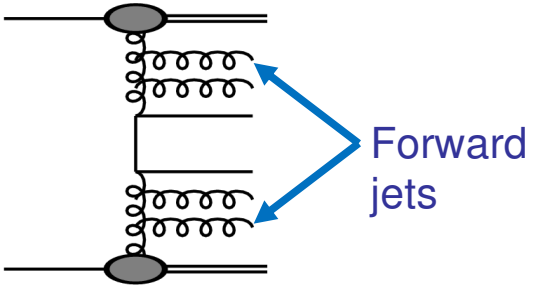




Possibility of distinguishing among different PDFs (main error source JES)

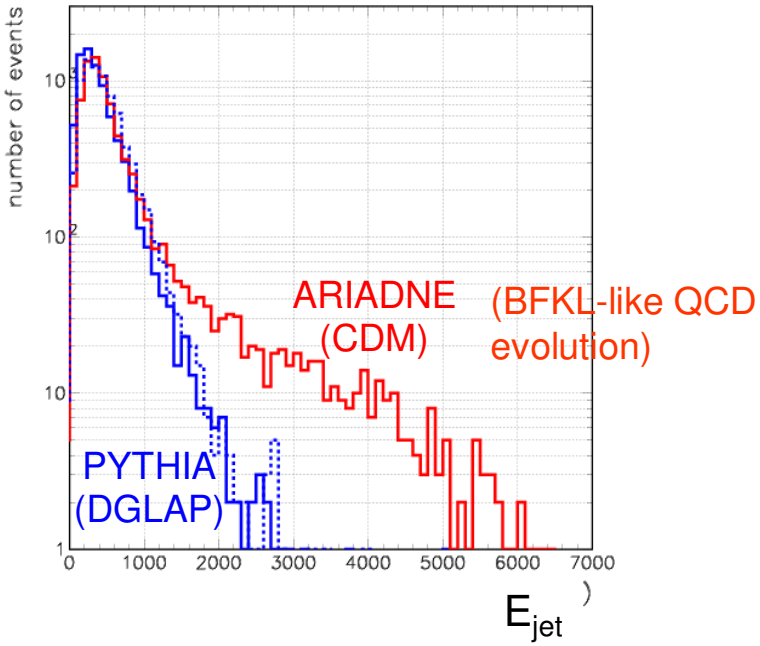
Low-x QCD evolution

Mueller-Navelet di-jets: large rapidity gap between jets (~5k evts with $\Delta\eta$~6 with1pb^{-1})

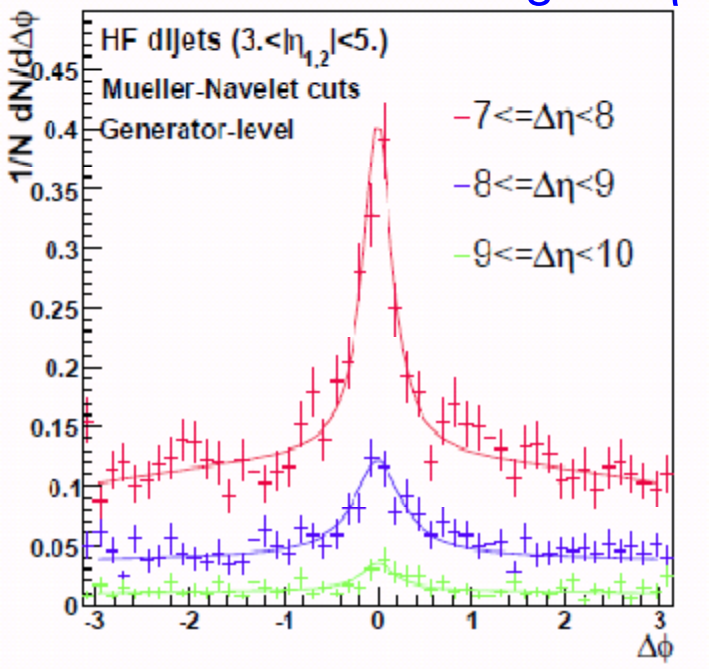


ATLAS, CMS

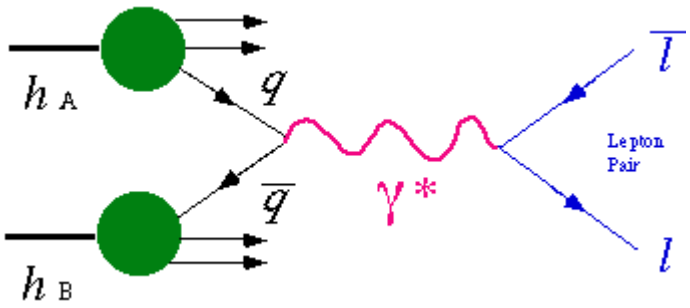
BFKL: large yield of high E jets in the forward direction



BFKL: more azimuthal decorrelation for larger $\Delta\eta$



Drell-Yan

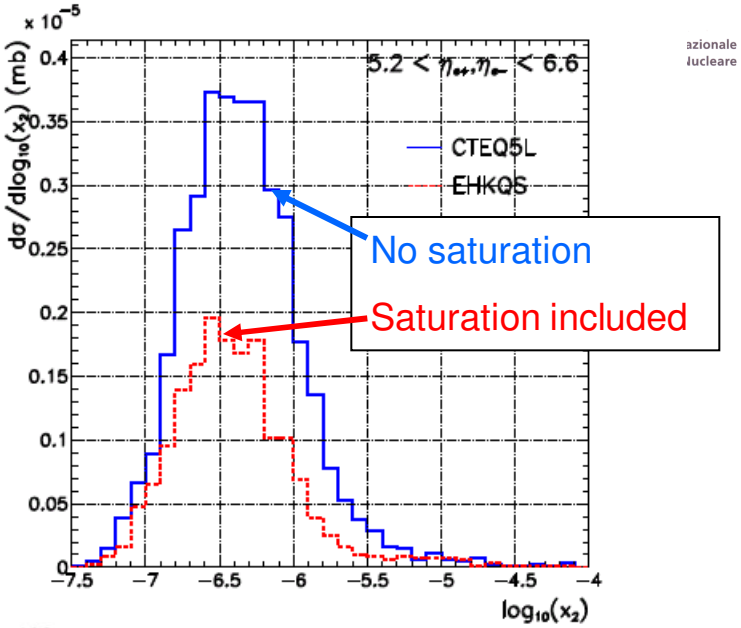


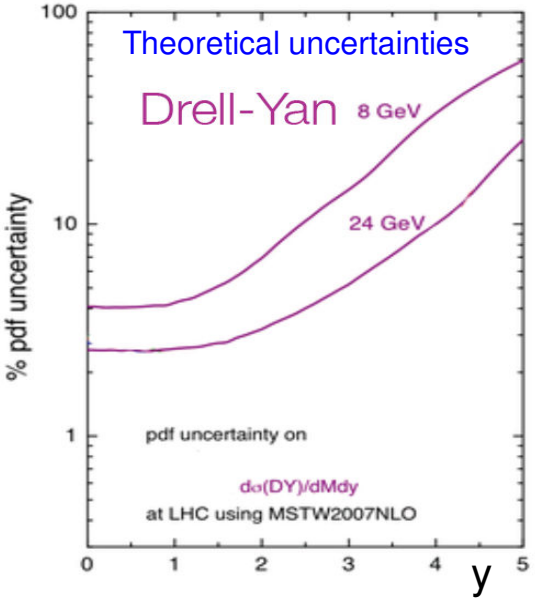
Saturation energy scale @LHC ~ 3 GeV

CMS+TOTEM: M(ee) > 4 GeV/c²
LHCb: M(μμ) > 5 GeV/c²
ATLAS: M(ee) ~ 8-60 GeV/c²

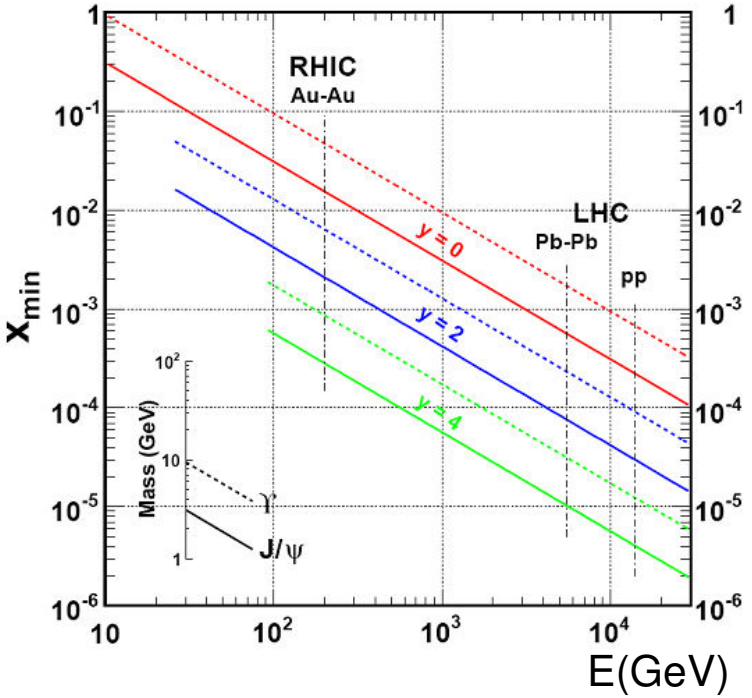
Improve uncertainties on PDFs
Sensitive to saturation effects

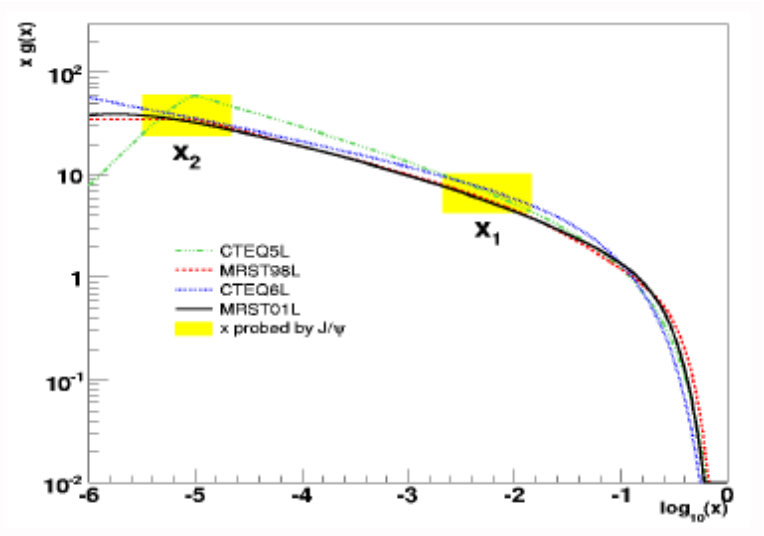
Probing $x>10^{-6}$





J/Ψ in ALICE



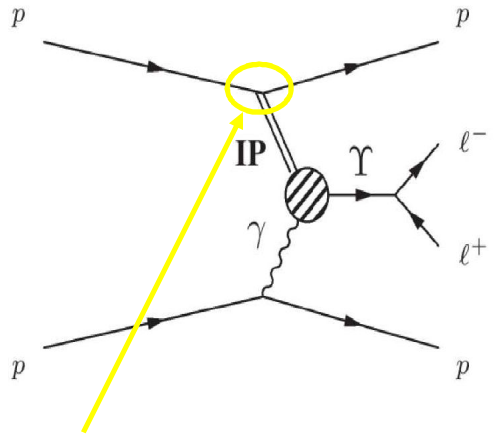


Forward J/Ψ production probes $x>10^{-6}$

Diffractive J/Ψ photo-production

- Clean event signature
- Study of γ-Pomeron, Pomeron-Odderon phenomenology
- ~2000 evts in e^+e^- channel in $1pb^{-1}$

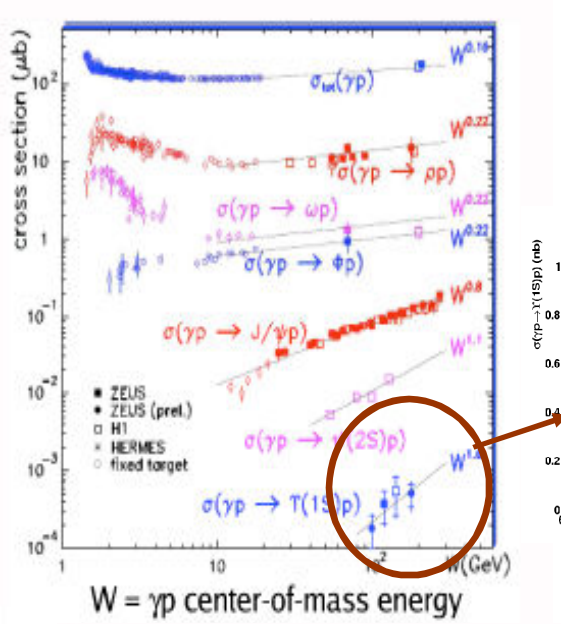
Vector meson photo-production

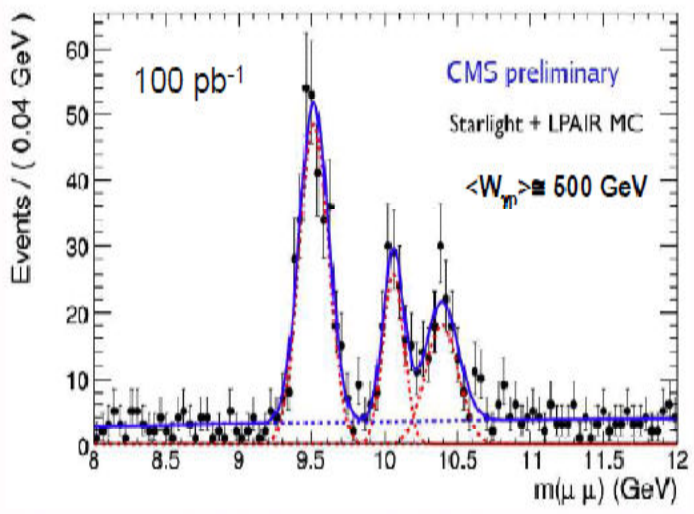


- Proton t (4-mom.-transfer) highly correlated with $p_T^2(\mu\mu)$
- $\sigma \propto$ GPD

- γp c.m.energy extended by factor ~3 wrt HERA (slope sensitive to rise in gluon density)

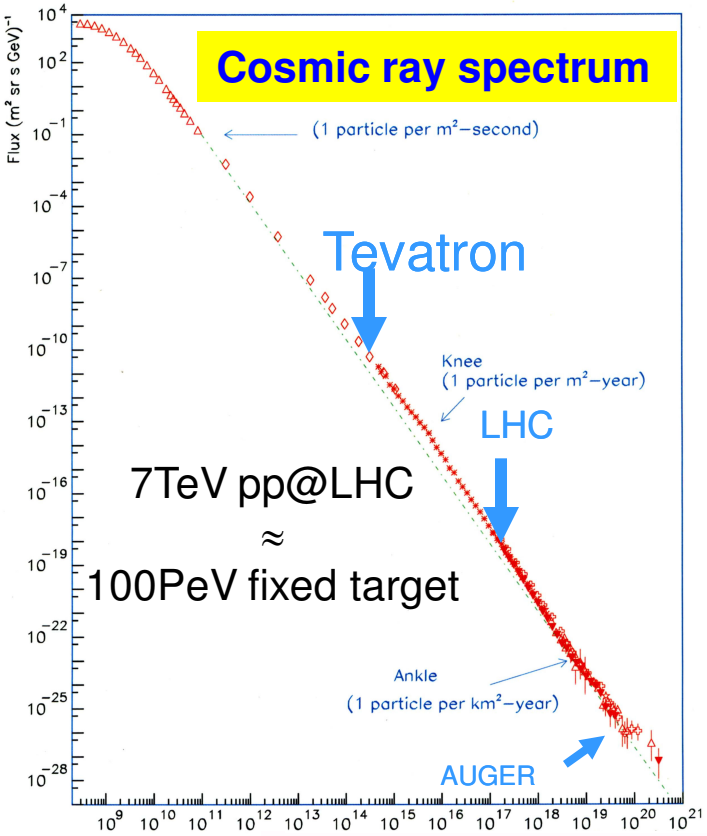
CMS, ALICE, LHCb



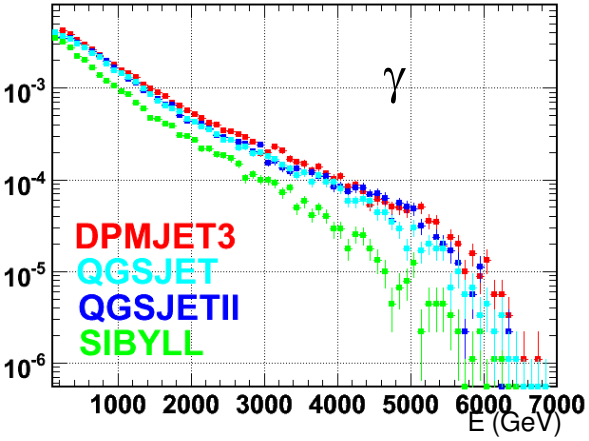


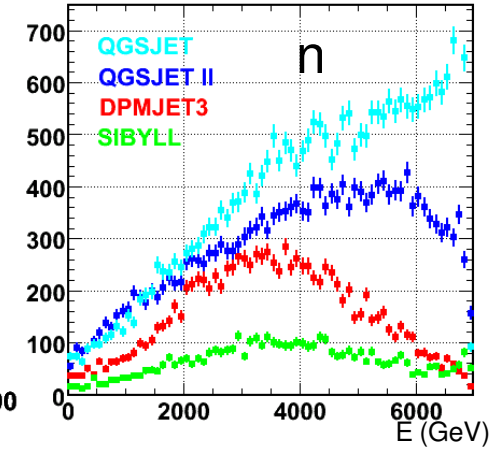
Cosmic Rays

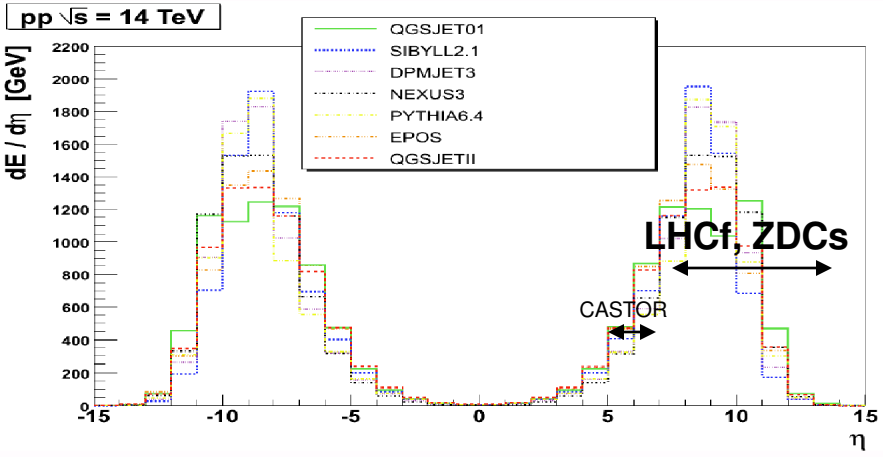
Hadronic Monte Carlo tuning

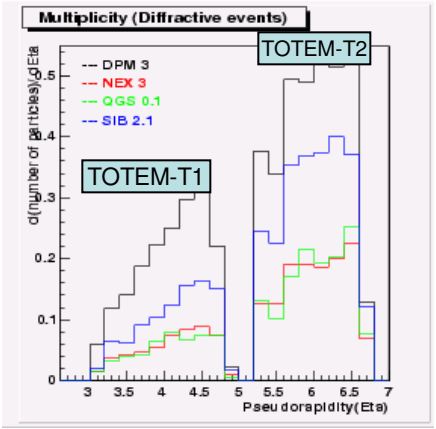


Neutral part. energy meas. with LHCf

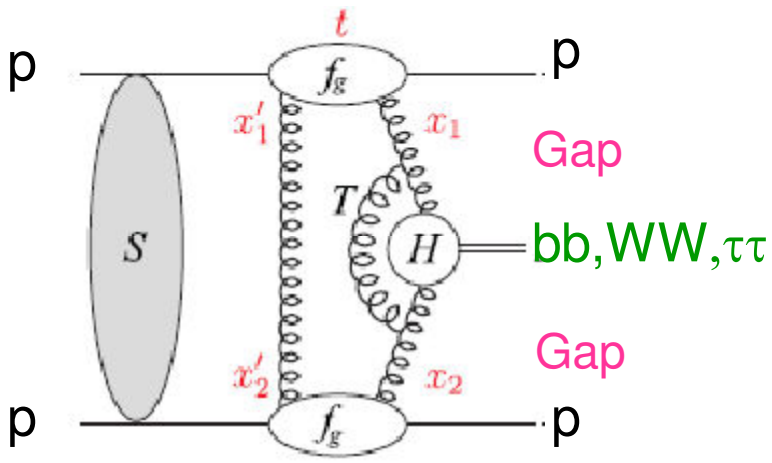








Central Exclusive Diffraction: Higgs



$M^2 = s\xi_1\xi_2$ measured with Roman Pots

J_z=0, CP even selection rules suppress QCD background

Interesting mainly for M_H=120-250 GeV/c^2

Very low cross sections (*O*(fb)) with uncertainties of a factor (at least?) 3

Probably higher cross sections (factor 10-100?) in certain MSSM scenarios

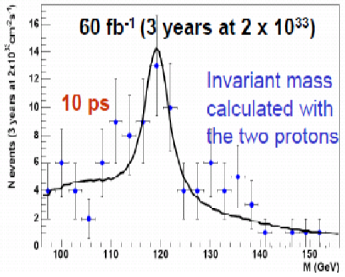
High luminosity needed:

high pile-up background

"low" mass Higgs out of acceptance of existing proton detectors

New proton detectors needed:

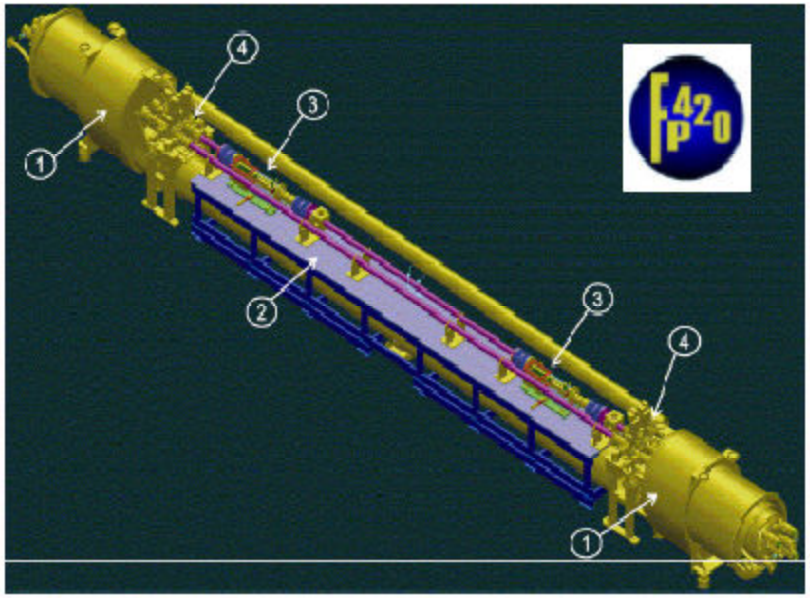
ATLAS AFP and FP420 projects



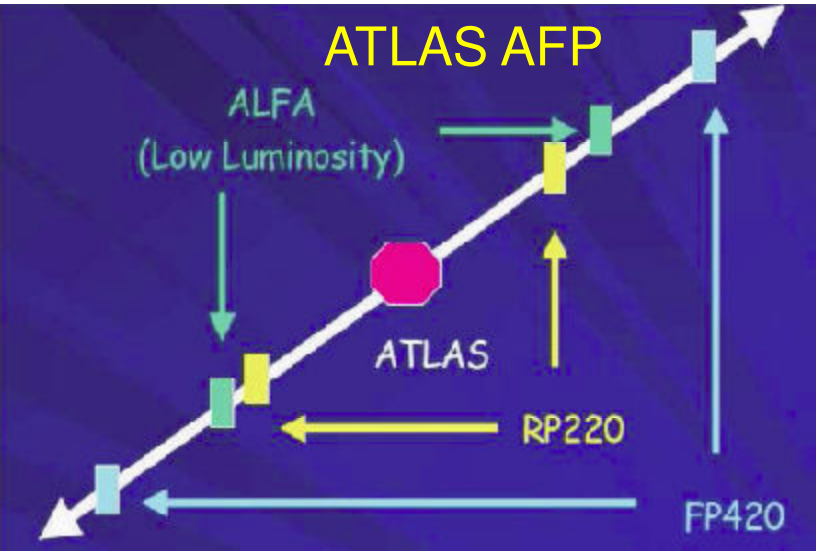
MSSM h→bb, tanβ=40

M_A = 120GeV/c^2

Projects for new proton detectors



- Installation of Si detectors in cold LHC regions at 420m from IP
- Cryostat redesign needed
- Use of movable beampipes
- Novel 3-D silicon det. technology (resolution and radiation hardness)
- Very fast timing (10ps) for pile-up
- Acceptance in $2 \cdot 10^{-3} < \xi < 2 \cdot 10^{-2}$ at (nominal) $\beta^* = 0.5$m



- Installation of Si detectors at 220 and 420m from IP1
- Very fast timing (Cerenkov detectors)

Summary

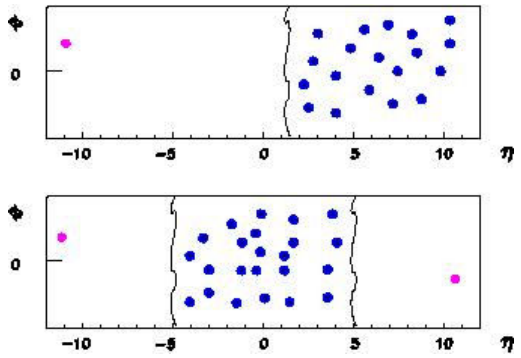
- The 6 LHC experiments provide a very good coverage of the forward region with trackers, calorimeters and proton detectors
- Using different running scenarios a huge physics program can be carried on
  - Total cross section and elastic scattering
  - Diffractive processes (soft and hard)
  - Parton structure and low-x evolution of the proton dynamics
  - Validation of QCD Monte Carlo for the high energy cosmic ray physics
- Projects for new forward detectors mainly focused on the Higgs sector are ongoing

Acknowledgements

Many thanks to the people that helped me in this review providing useful ideas and material. Especially:
M.Arneodo, K.Osterberg, M.Bruschi, A.Zoccoli, R.McNulty, R.Schicker, A.Tricomi

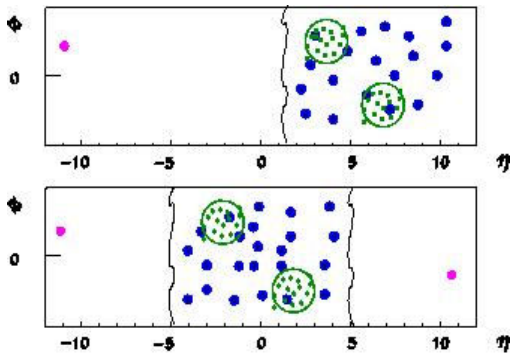
Back up

Running scenarios



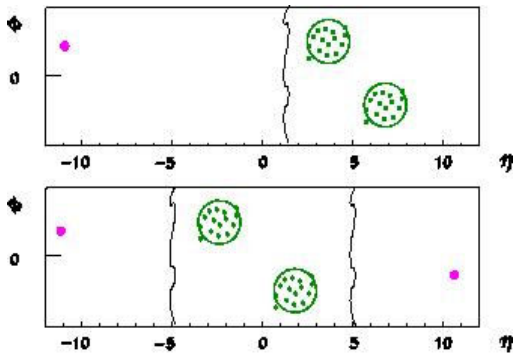
pp->pX
pp->pXp

soft diffraction



pp->pjjX
pp->pjjXp

(semi)-hard diffraction



pp->pjj (bosons, heavy
pp->pjjp quarks,Higgs...)

hard diffraction

Cross section ← → Luminosity

β (m)	1540	90	2	0.5
L (cm^{-2} s^{-1})	10^{29}	10^{30}	10^{32}	10^{34}
	Special (eg. TOTEM) runs			Standard LHC runs