DIFFRACTIVE SCATTERING

EXPERIMENTS

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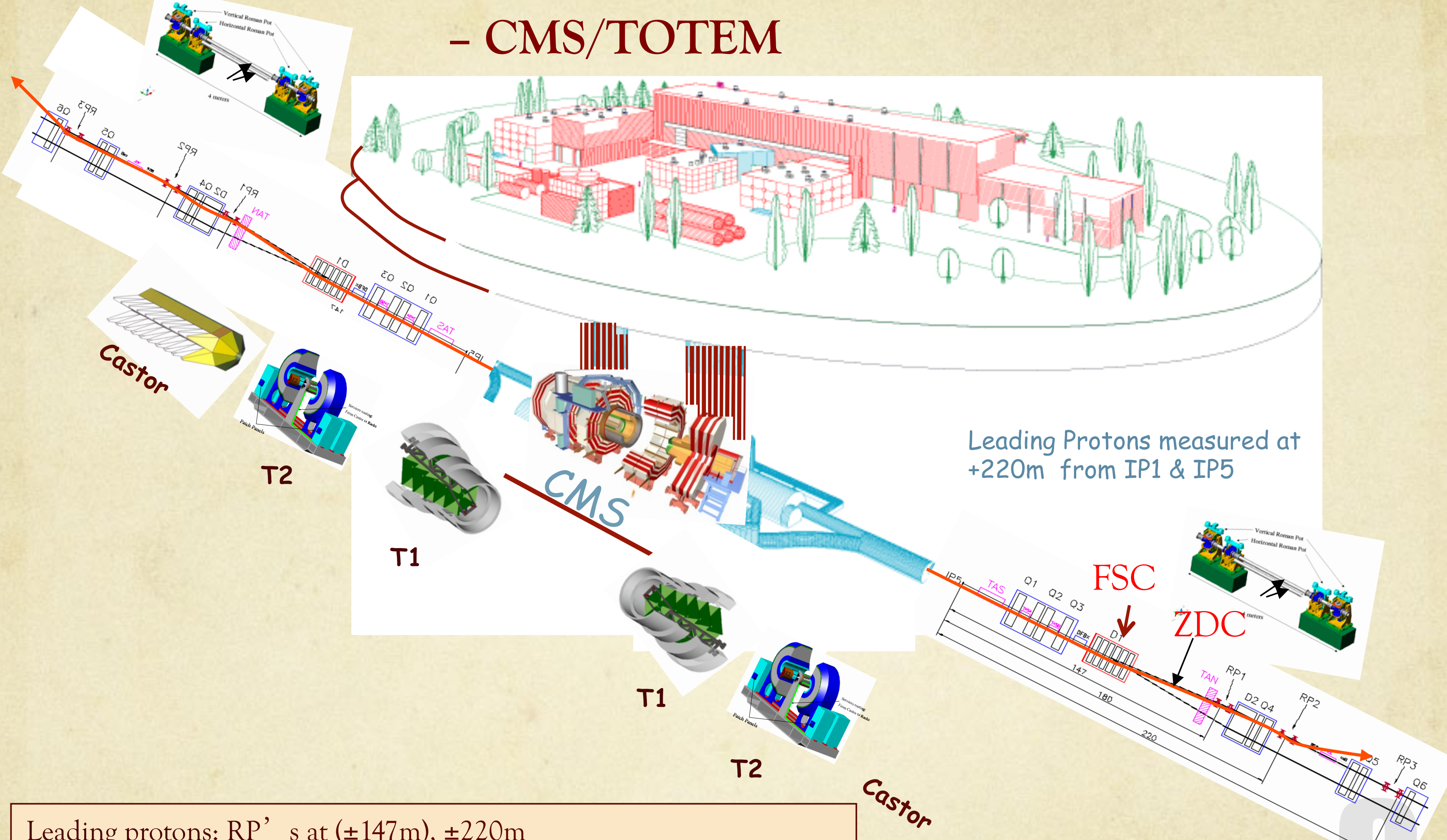
THE PLAN

- LECTURE 1:
  - WHAT DIFFRACTION?
  - SIGNATURES OF DIFFRACTIVE PROCESSES
- LECTURE 2:
  - EXPERIMENTS AT THE LHC
  - FUTURE PLANS

DETECTOR LAY-OUTS FOR DIFFRACTION – CMS/TOTEM

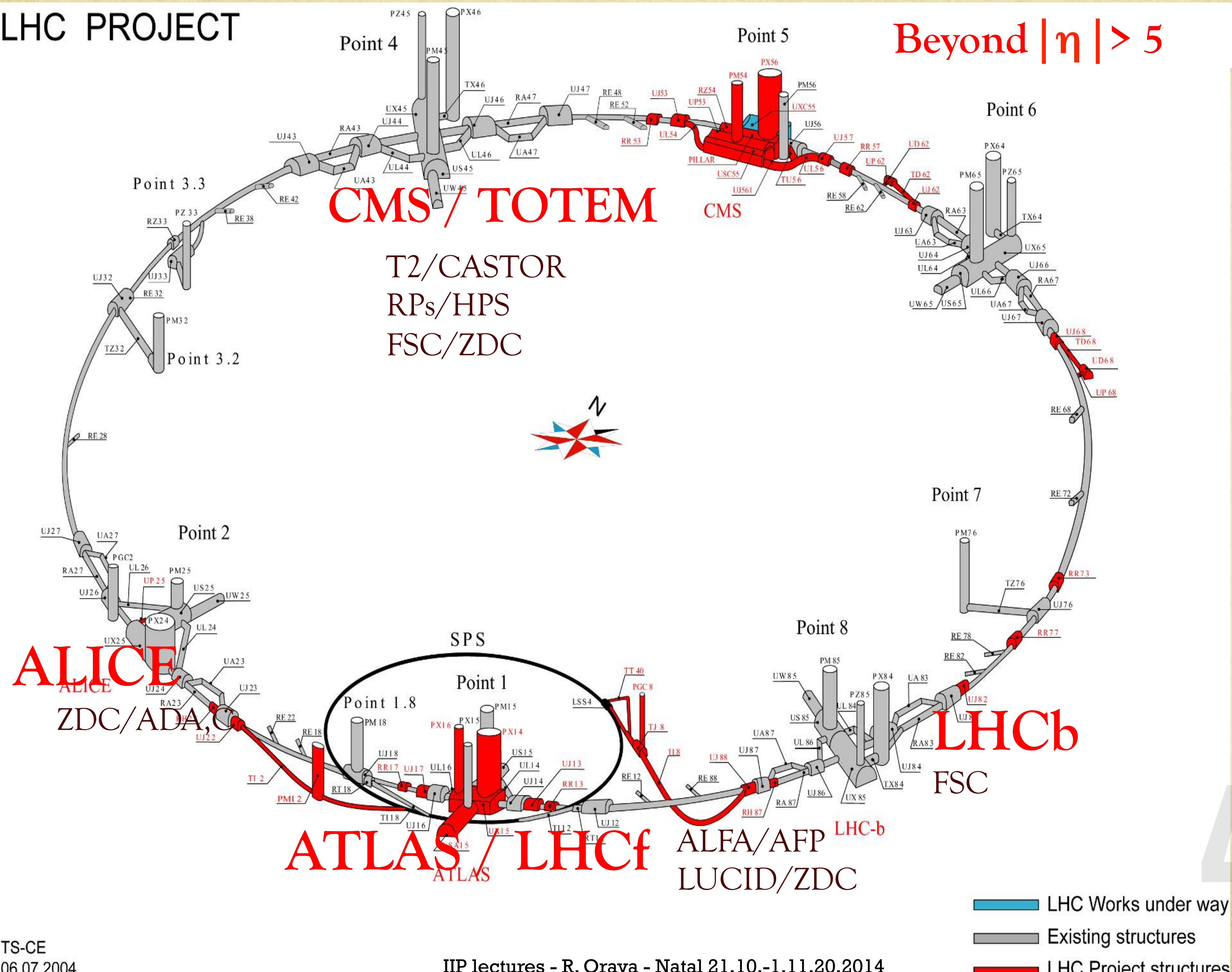
Leading Protons measured at -220m from IP1 & IP5



Leading Protons measured at +220m from IP1 & IP5

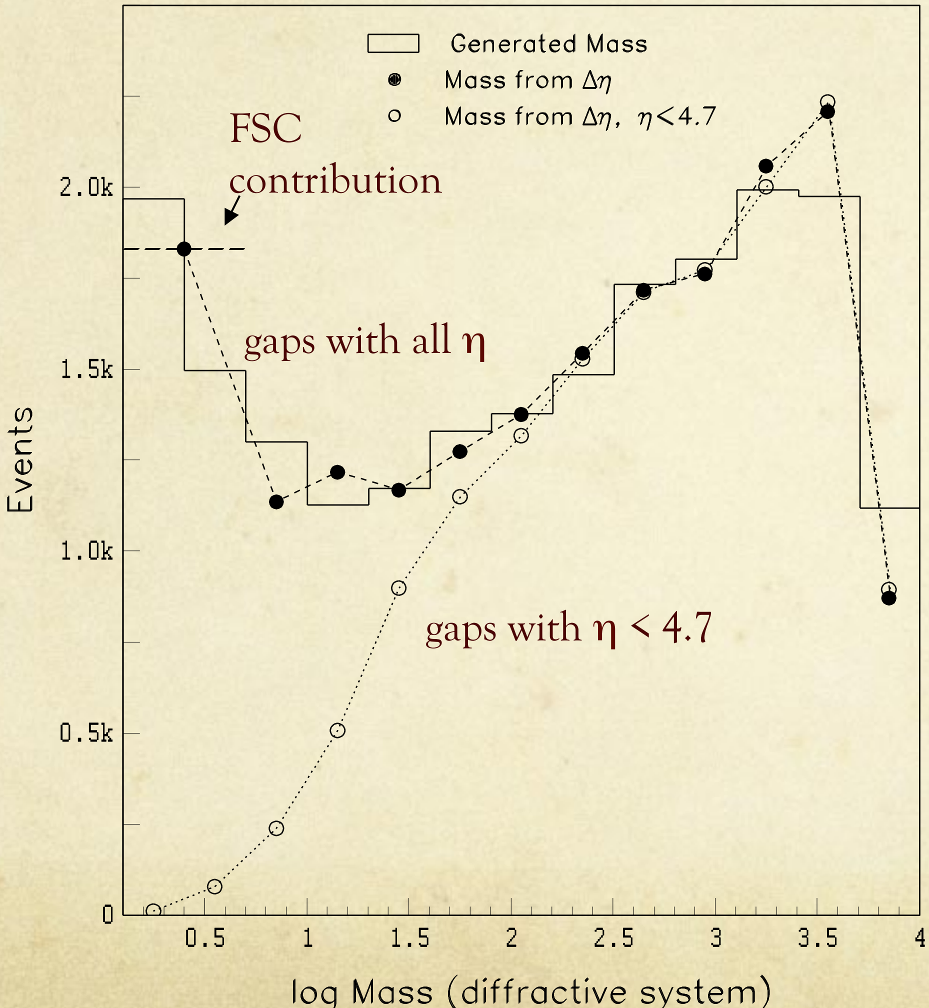
Leading protons: RP’s at (±147m), ±220m
Rap gaps & Fwd particle flows: T1 & T2 spectrometers
Fwd energy flows: Castor & ZDC
Fwd counters at: ±60m to ±100 (140)m - FSCs

Beyond $|\eta| > 5$



LHC PROJECT
Point 1
Point 1.8
Point 2
Point 3.2
Point 3.3
Point 4
Point 5
Point 6
Point 7
Point 8
SPS
CMS / TOTEM
T2/CASTOR
RPs/HPS
FSC/ZDC
CMS
ALICE
ZDC/ADA,C
ATLAS / LHCf
ATLAS
ALFA/AFP
LUCID/ZDC
LHCb
FSC
LHC-b
LHC Works under way
Existing structures
LHC Project structures
TS-CE
06.07.2004

FOR GOOD COVERAGE OF DIFFRACTIVE MASSES, NEED DETECTION AT SMALL ANGLES



FOR SEEING THE RAP GAPS, NEED GOOD COVERAGE in p_T

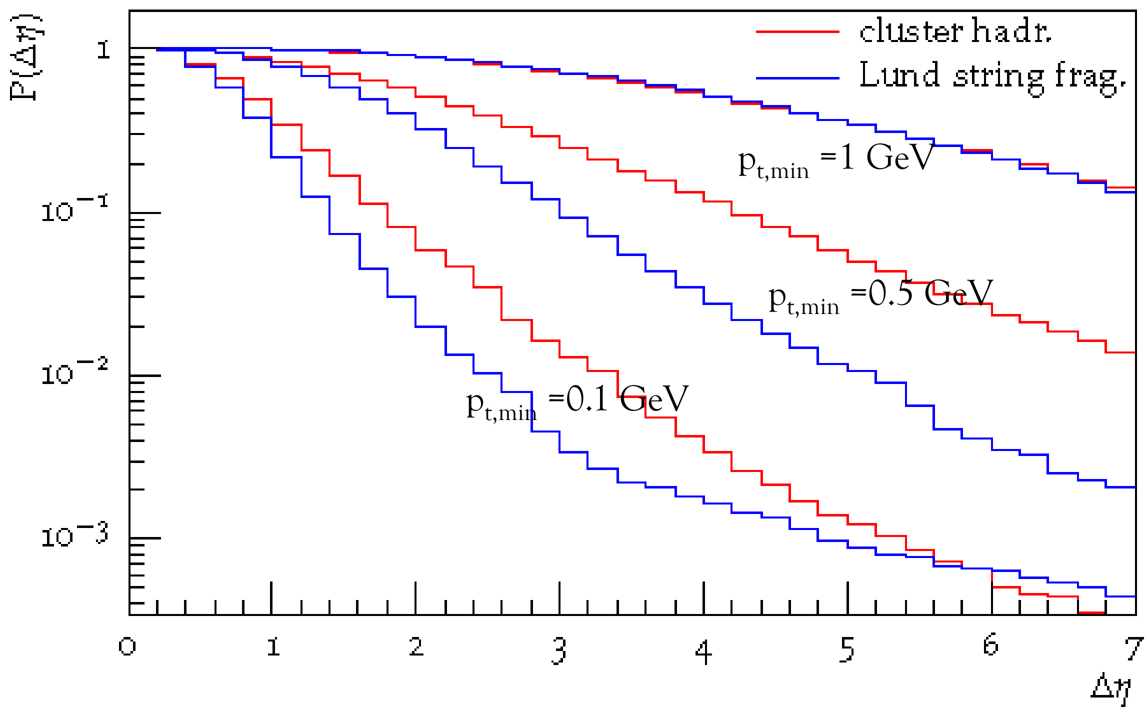
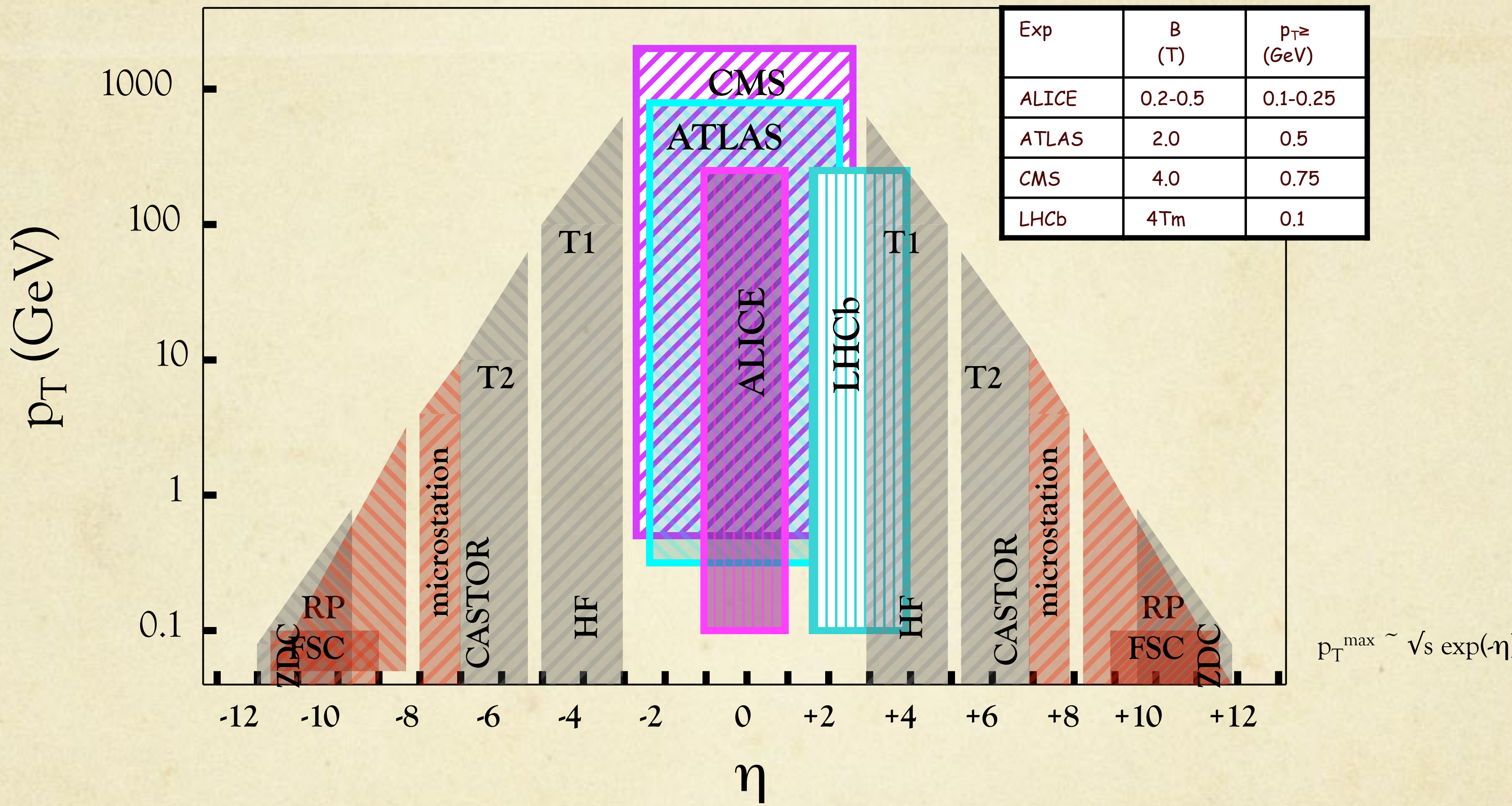


Fig. 4. Probability for finding a rapidity gap (definition 'all') larger than $\Delta\eta$ in an inclusive QCD event for different threshold $p_\perp$. From top to bottom the thresholds are $p_{\perp,\mathrm{cut}} = 1.0$, 0.5, 0.1 GeV. Note that the lines for cluster and string hadronisation lie on top of each other for $p_{\perp,\mathrm{cut}} = 1.0$ GeV. No trigger condition was required, $\sqrt{s} = 7$ TeV.

LHC EXPERIMENTS: p_T-η coverage

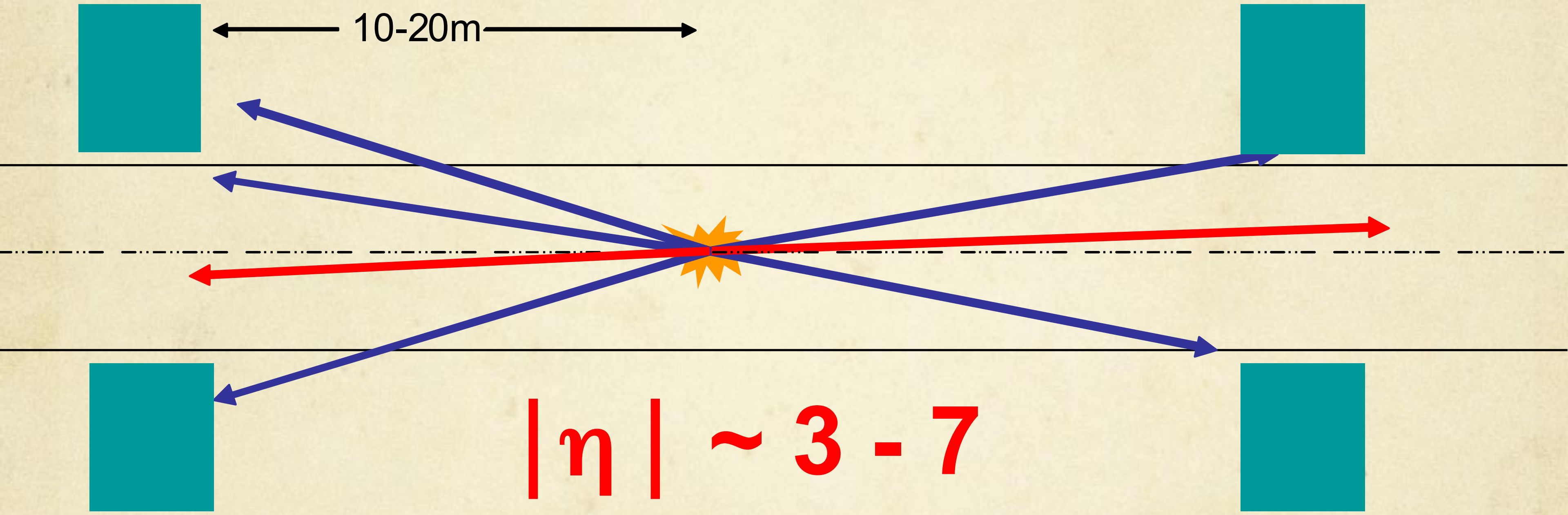
ATLAS & CMS fwd calorimetry up to |η| ≈ 5 + Lucid/Castor + ZDC



Exp	B (T)	$p_T \geq$ (GeV)
ALICE	0.2-0.5	0.1-0.25
ATLAS	2.0	0.5
CMS	4.0	0.75
LHCb	4Tm	0.1

The base line LHC experiments used to cover the central rapidity region. Forward Upgrades of CMS, ATLAS & ALICE amount to significant improvements!

Forward Particle Detection at the LHC (1): Surround the Beam Pipe {CALORIMETRY, TRACKING}

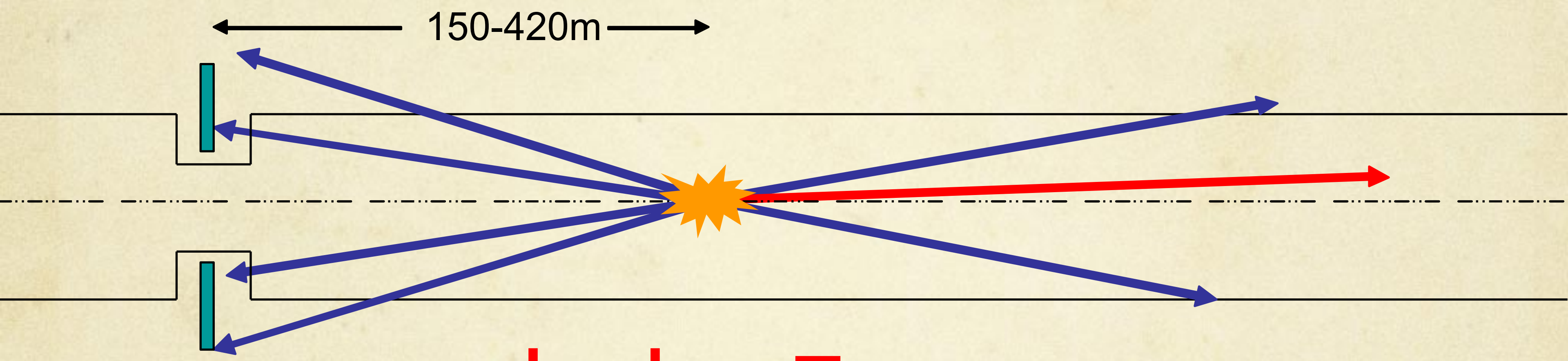


$|\eta| \sim 3 - 7$

Easy but miss the most forward ones!

ATLAS {HF, LUCID}, CMS {HF, CASTOR} and TOTEM {T1, T2}

Forward – Very Forward – Particle Detection at the LHC (2): Go into the Beam Pipe (or Move It!)

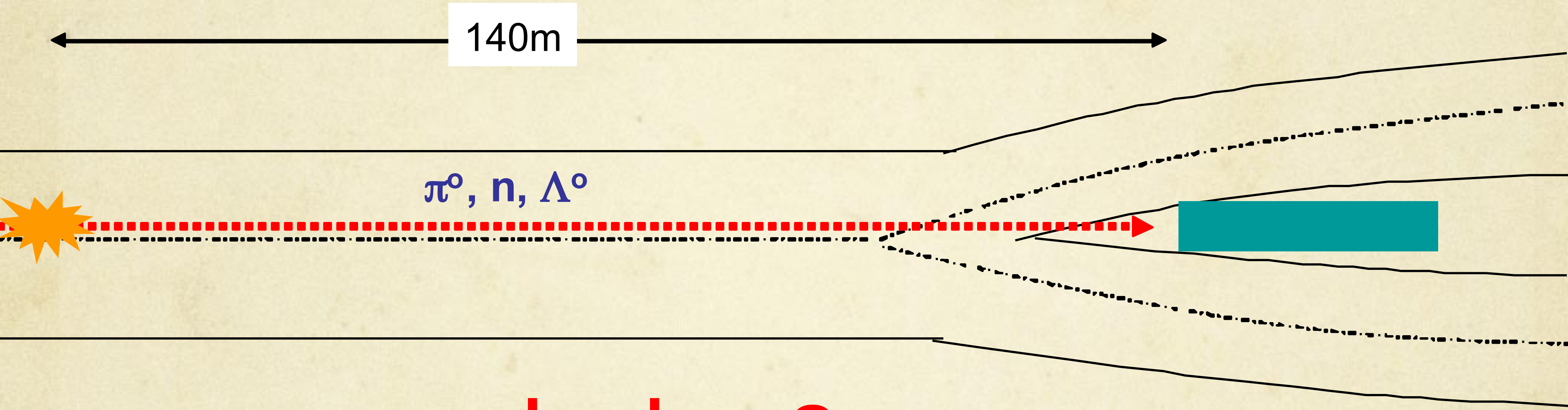


$|\eta| > 7$

Ideal solution - challenges the vacuum preservers (μStations!).

- ATLAS {RP's AFP? , CMS {RP's HPS? , TOTEM {RP's for leading protons

Forward – Very Forward – Particle Detection at the LHC (3): Use the beam split region (ZDC's)



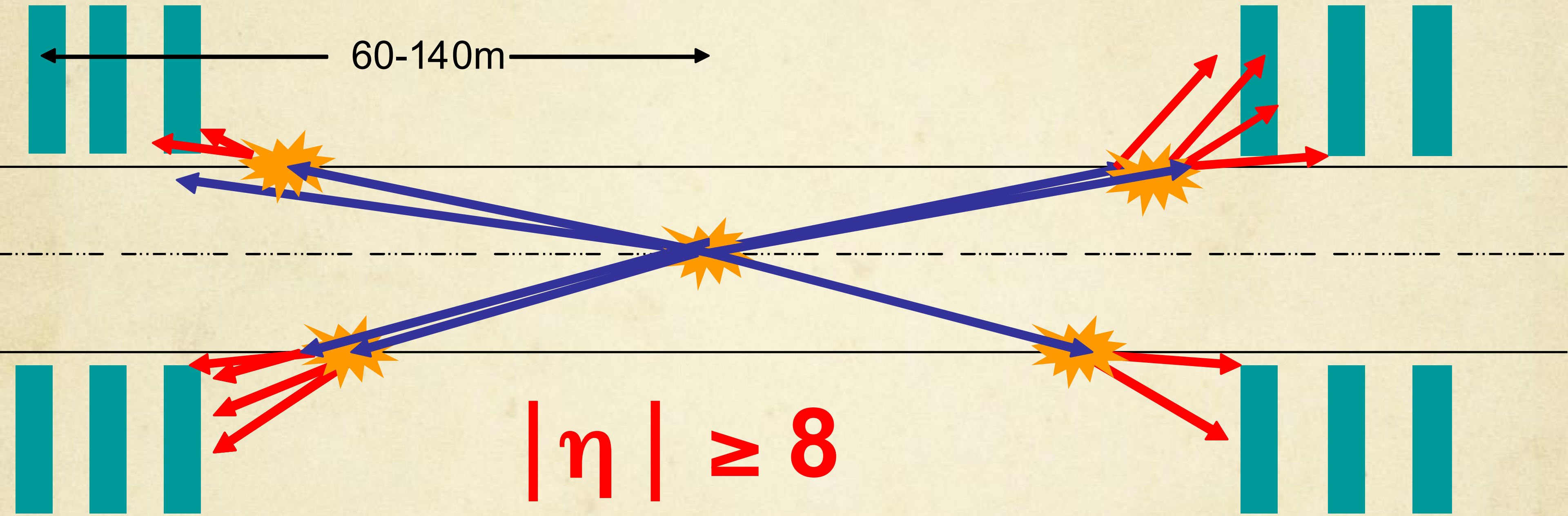
$|\eta| \geq 8$

Ideal for neutrons & gammas.

ALICE ZDCs , ATLAS ZDCs LHCf , CMS ZDCs

for leading neutrals

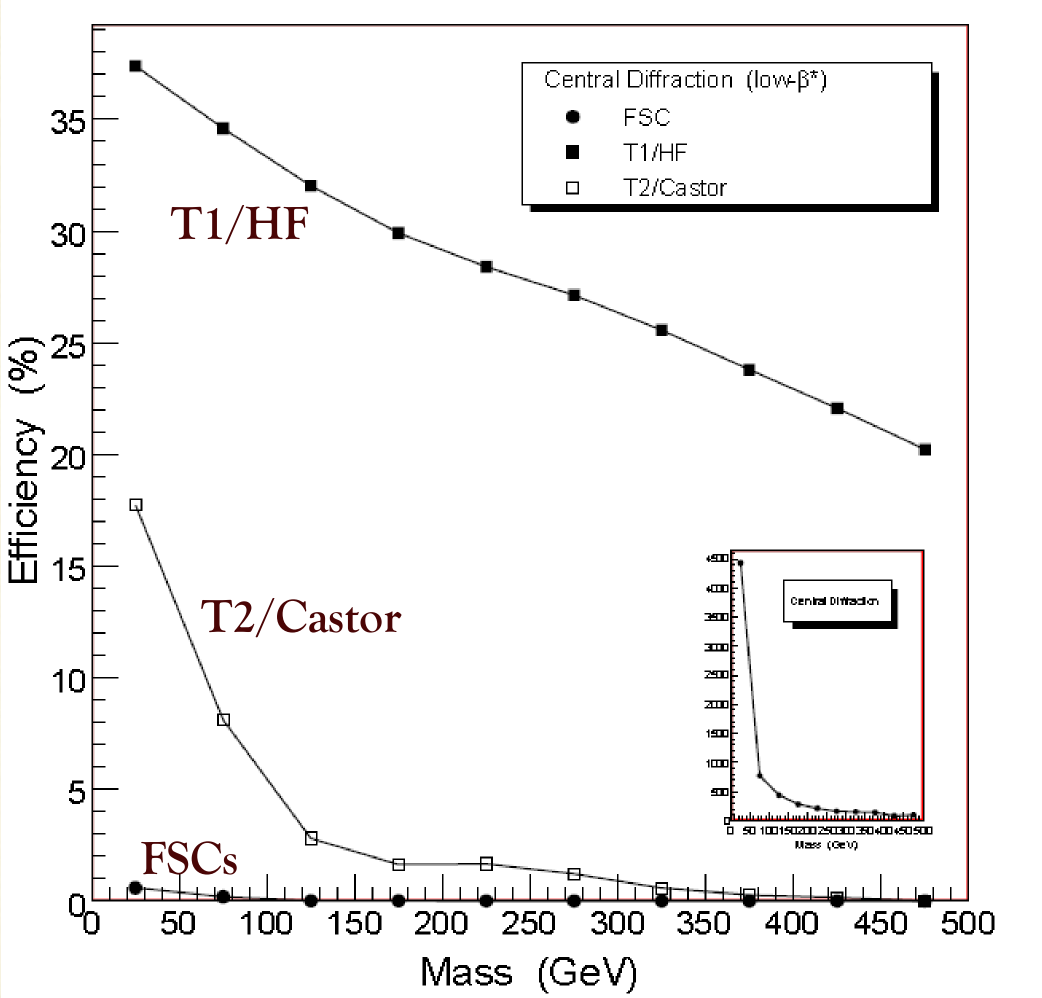
Forward – Very Forward – Particle Detection at the LHC (4): Detect the showers (FSCs)



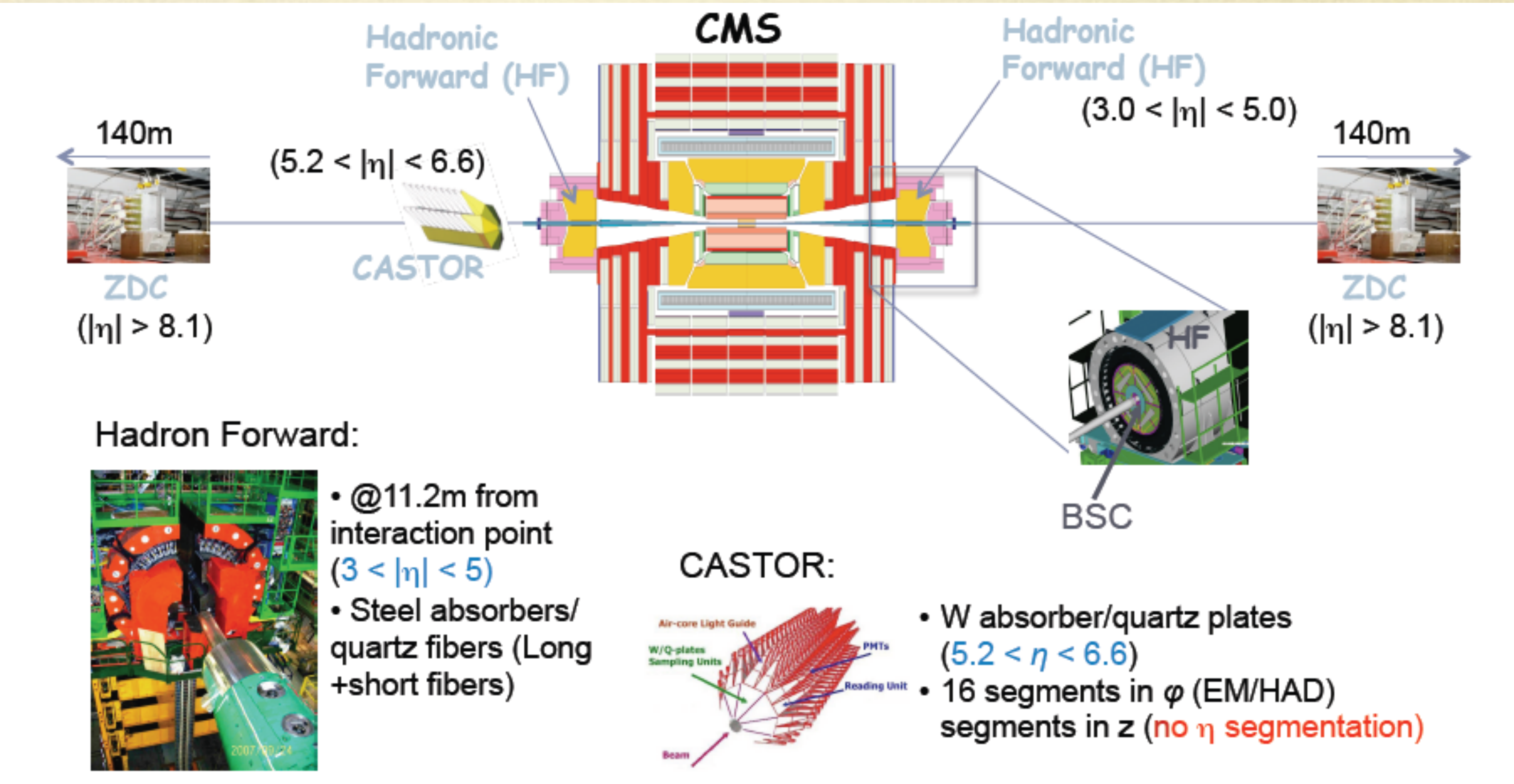
Easy and cheap!

- ALICE, CMS, LHCb ..

FORWARD SHOWER COUNTERS GIVE EFFICIENT VETO OF BACKGROUNDS



CMS FORWARD DETECTORS



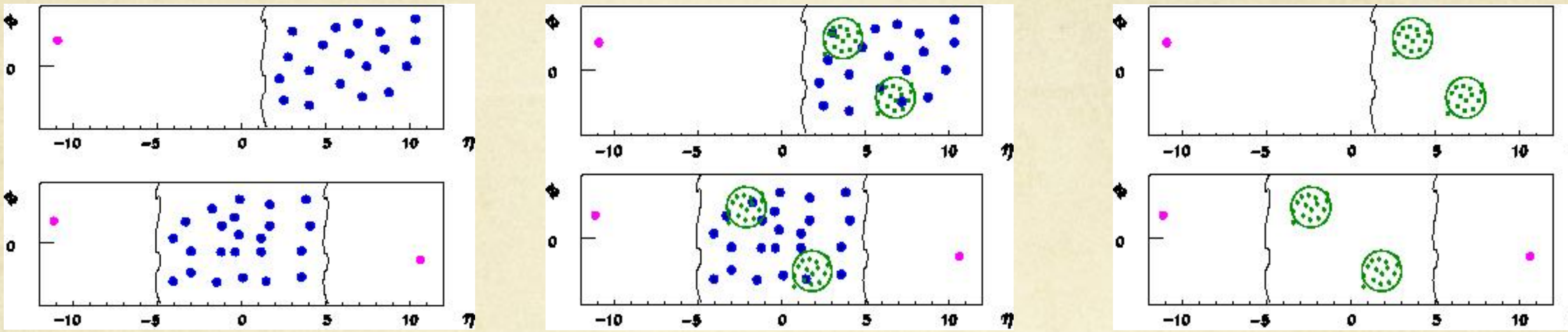
Tracking to $|\eta| < 2.4$
Hadronic calorimeter (HF) to $|\eta| < 5$
Forward calorimeters cover -6.6< < -5.2(CASTOR) and $|\eta| > 8.1$ (ZDC)

CMS DIFFRACTION - RESULTS

$$\sigma(\mathrm{pp} \to \mathrm{p}^{(*)}\mathrm{W}^{+}\mathrm{W}^{-}\mathrm{p}^{(*)} \to \mathrm{p}^{(*)}\mu^{\pm}\mathrm{e}^{\mp}\mathrm{p}^{(*)}) = 2.2^{+3.3}_{-2.0}\,\mathrm{fb},$$

- $\sigma^{SD}_{vis} = 4.27 \pm 0.04(stat.) + 0.65/-0.58(syst.)$ mb for $-5.5 < \log\xi < -2.5$
- $\sigma^{DD}_{vis} = 0.93 \pm 0.01(stat.) + 0.26/-0.22(syst.)$ mb for $\Delta\eta > 3$, $M_X > 10$ GeV, $M_Y > 10$ GeV

RUN SCENARIOS FOR DIFFRACTION

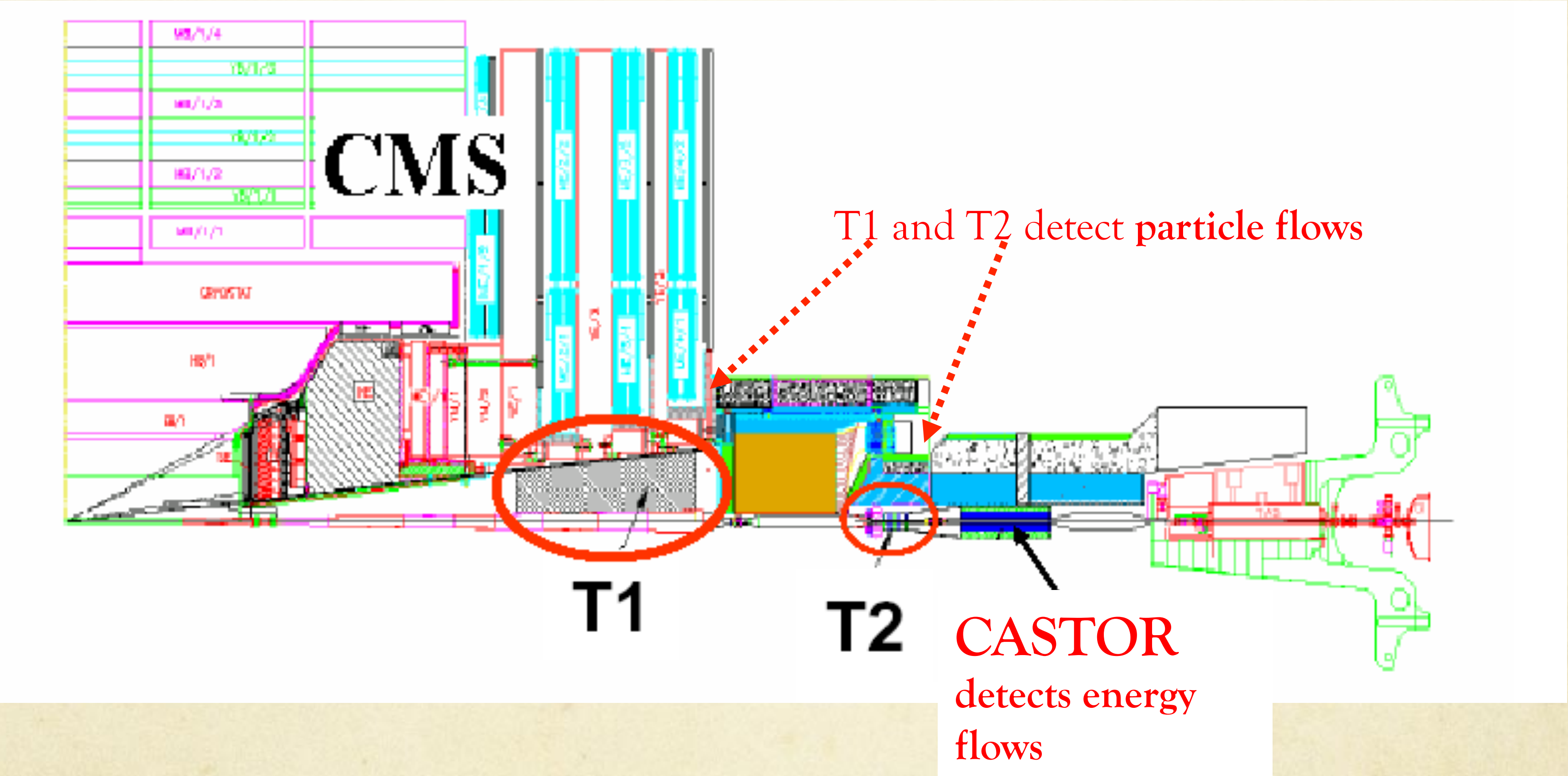


pp->pX pp->pXp	pp->pjjX pp->pjjXp	pp->pjj (bosons, heavy pp->pjjp quarks,Higgs...)
soft diffraction	(semi)-hard diffraction	hard diffraction

← Cross section — Luminosity →

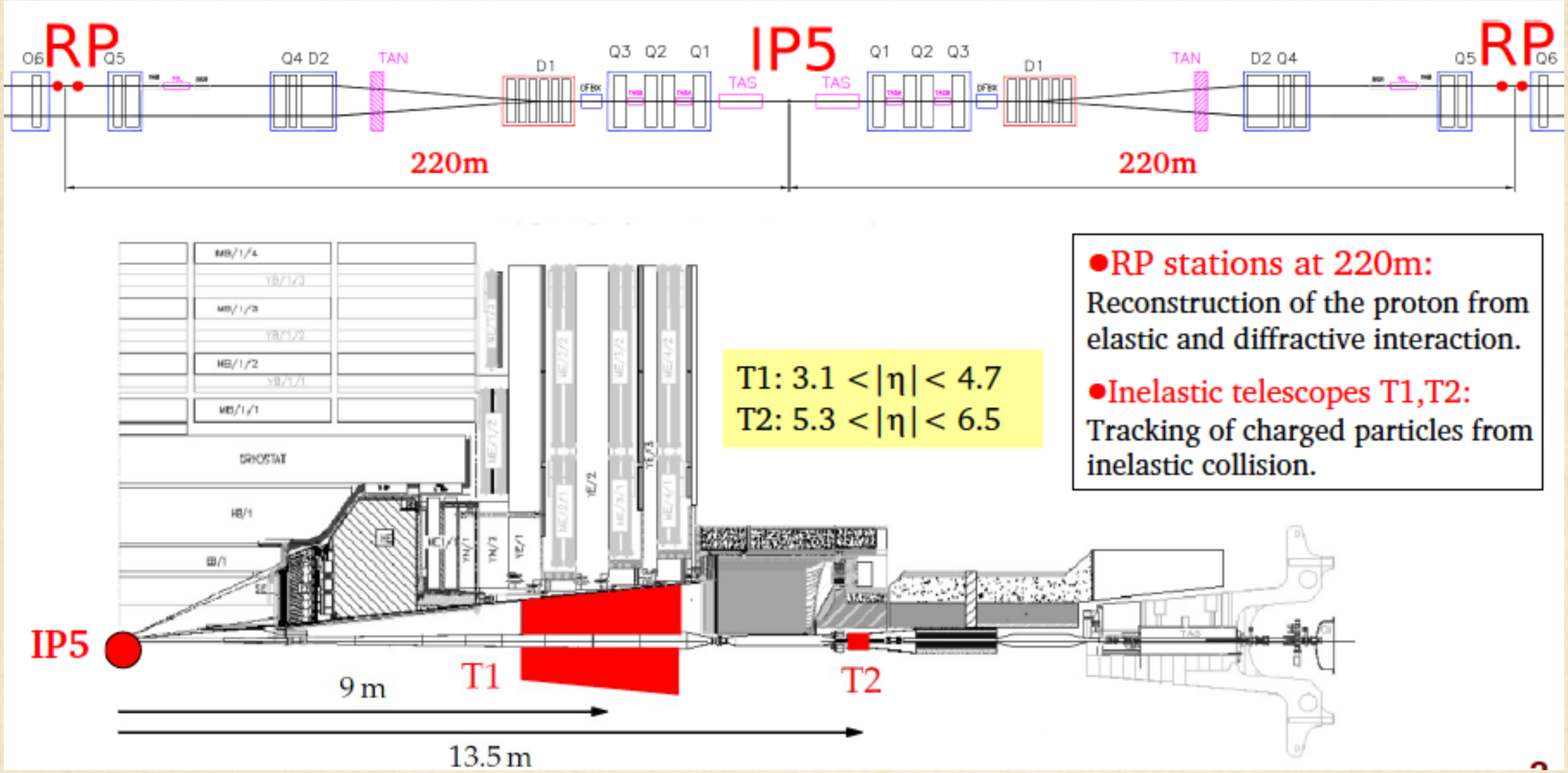
β (m)	1540	90	2	0.5	
L (cm^{-2} s^{-1})	10^{29}	10^{30}	10^{32}		10^{34}
	TOTEM LHC runs			Standard LHC runs	

T1, T2 SPECTROMETERS, CASTOR



T1, T2 and CASTOR help in rejecting the backgrounds from SD and ND events.
Have good acceptance in p_T: T2 > 40MeV, T1 >100MeV

TOTEM DETECTORS



T1 $3.1<\eta<4.7$

T2 $5.3<\eta<6.5$

LEADING PROTON MEASUREMENT

Consider the trajectory of a proton in the transverse plane:

$$y(s) = v_y(s) \bullet y^* + L_y^{eff}(s) \bullet \theta_y^*$$

$$x(s) = v_x(s) \bullet x^* + L_x^{eff}(s) \bullet \theta_x^* + \xi \bullet D(s),$$

x^* and y^* = position in the transverse plane
θ_x^*, θ_y^* = scattering angles
$\xi = 1-p'/p$ = the longitudinal momentum loss
$L_{x,y}^{eff}(s) = \sqrt{(\beta_{x,y}(s)\beta^*)} \sin\Delta\mu(s)$ the effective length with $\Delta\mu(s) = \int\beta^{-1}(s)ds$ the betatron phase advance
$v_{x,y}(s) = \sqrt{(\beta_{x,y}(s)/\beta^*)} \cos\Delta\mu(s)$ the magnification
$D(s)$ = the dispersion
$\beta_{x,y}(s)$ = the value of the b-function along the beam line
$\beta^* = \beta_x(s=0) = \beta_y(s=0)$ is the value of the β function at the interaction point

LEADING PROTON MEASUREMENT

The measured proton momentum:

$$p' = (1-\xi) \bullet p$$

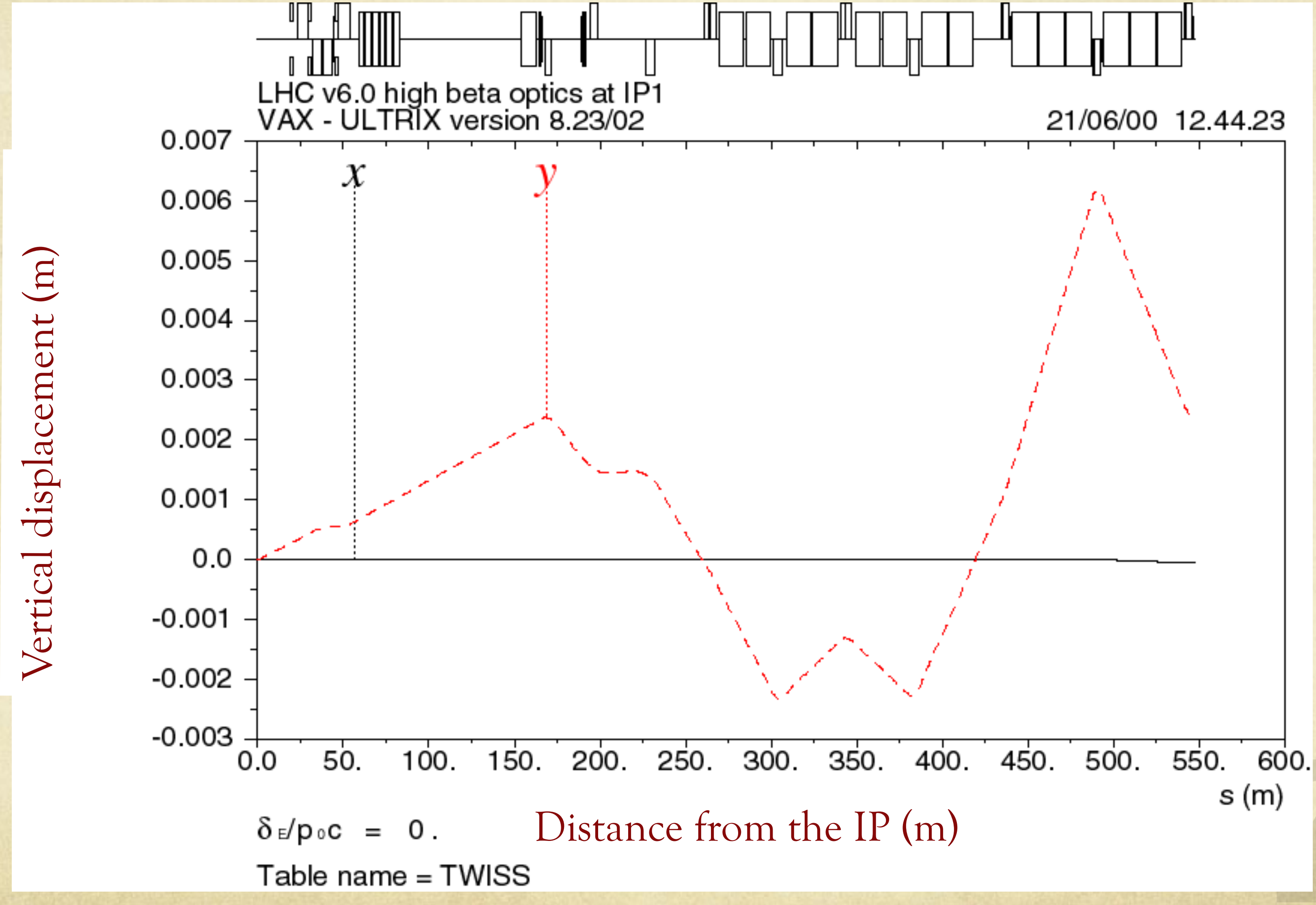
$$t = -(1-\xi)^2[\sin^2\theta_x^* + \sin^2\theta_y^*]$$

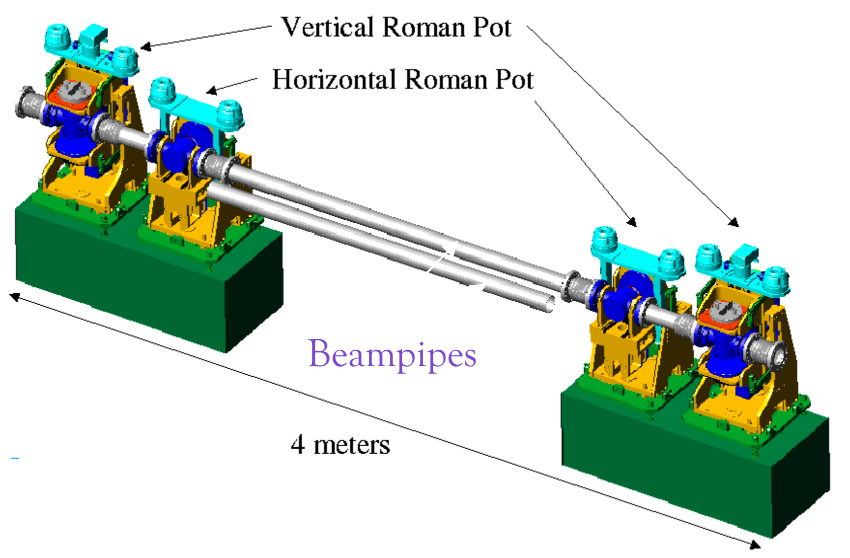
Uncertainties:

- dispersion, magnification, effective length of position i
- transverse position of the event at the IP
- position resolution of the detectors
- beam momentum spread: $\xi_o \approx 10^{-4}$
- angular divergence at the IP: $\sigma_{\theta x^*} = \sigma_{\theta x^*} = 32$ mrad.

Estimated accuracy: $\Delta\xi/\xi \approx 10^{-4}$, $\Delta t/t = 10\%$ for $-t = 0.01$ GeV^2

BEAM LINE AND RUN CONDITIONS



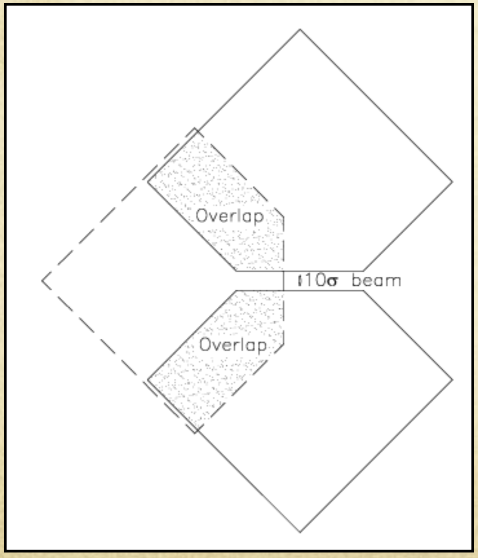


use roman pots to get close to the beam

fwd protons with a few μrad angles: detection at 10σ + d from the beam
(σ_{beam} ~ 80μm at RP)

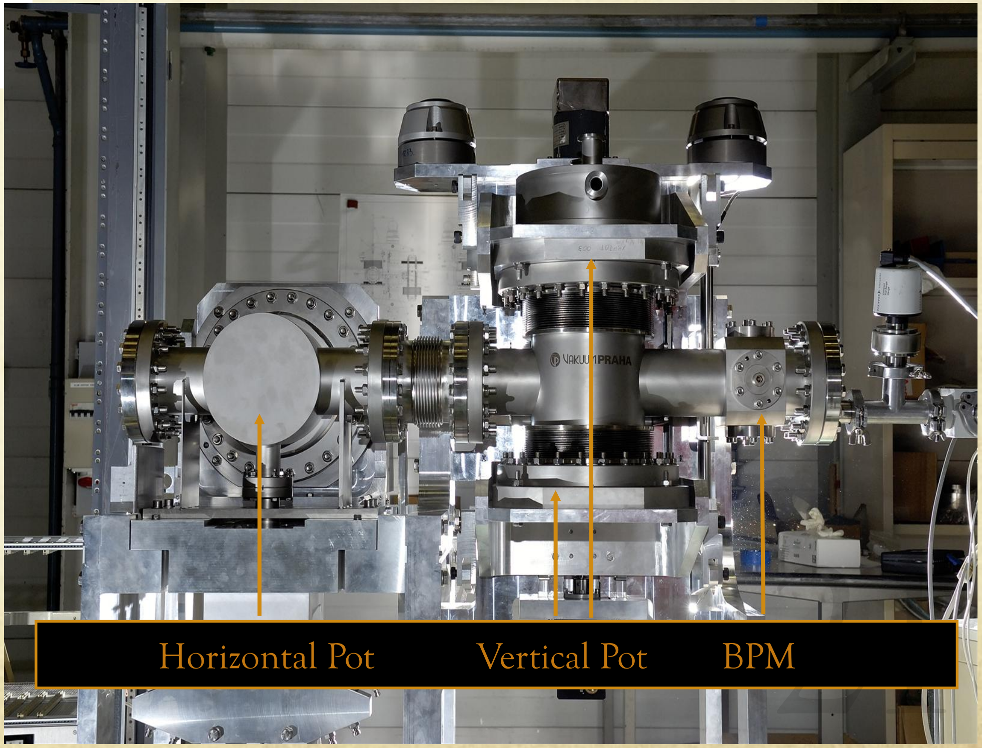
⇒ 'edgeless' detectors to minimize d

RP station:
- 2 units at 4m distance
- 2 vertical + 1 horizontal insertions ('pots')

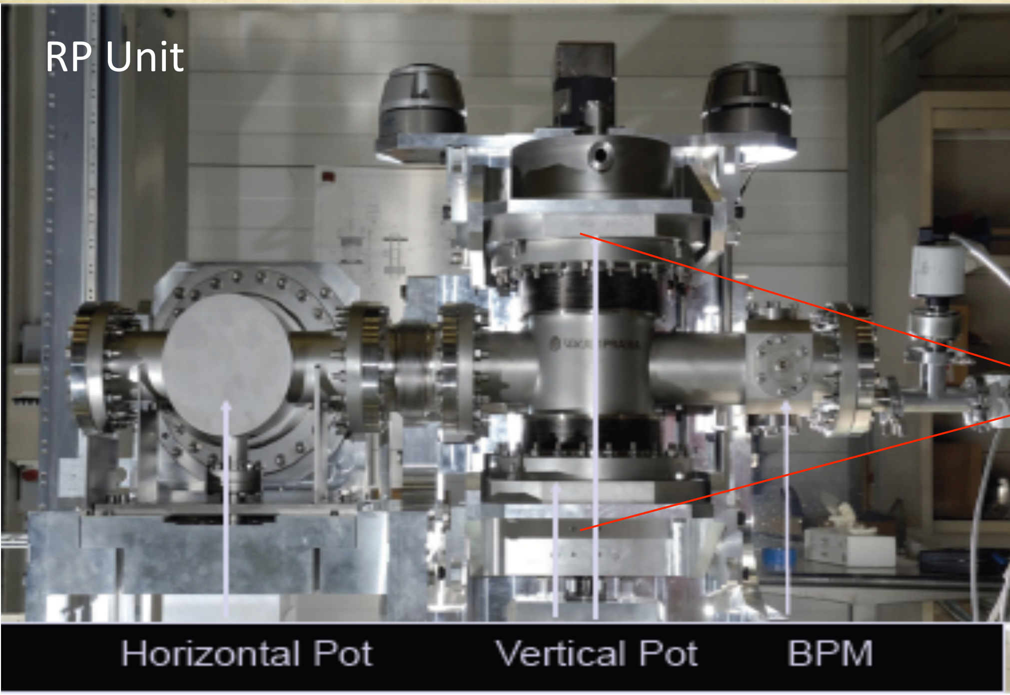


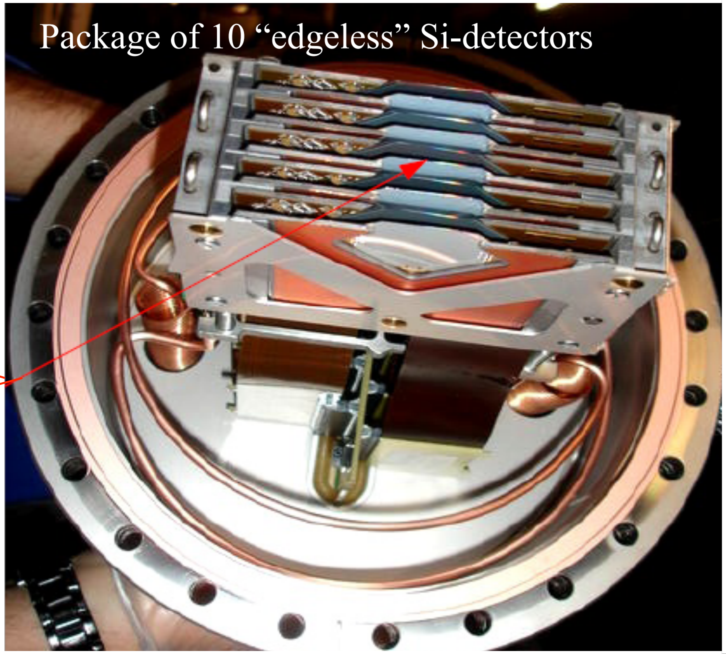
Horizontal Pot: extend acceptance; overlap for relative alignment using common track.

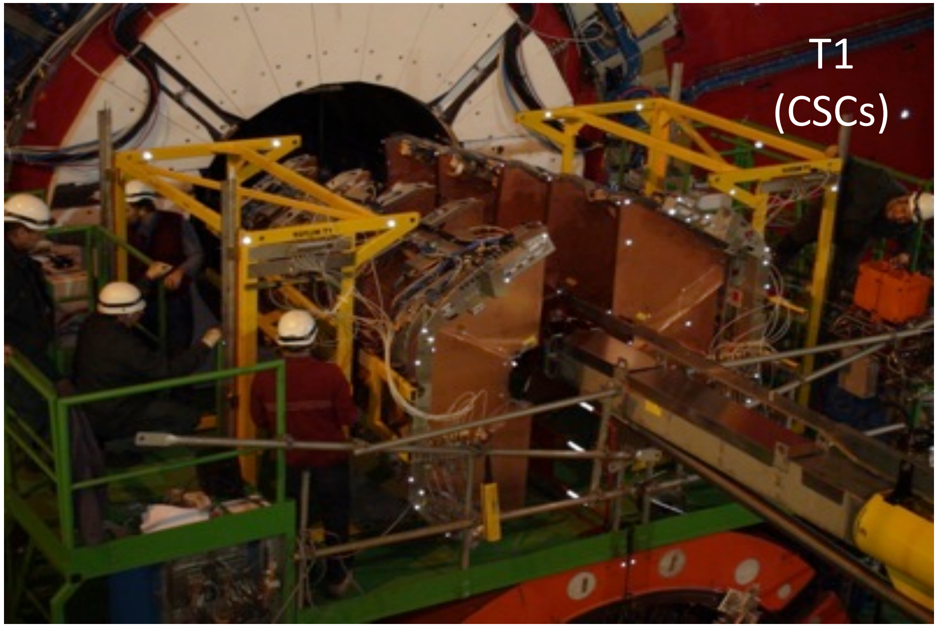
Absolute (w.r.t. beam) alignment from beam position monitor **(BPM)**

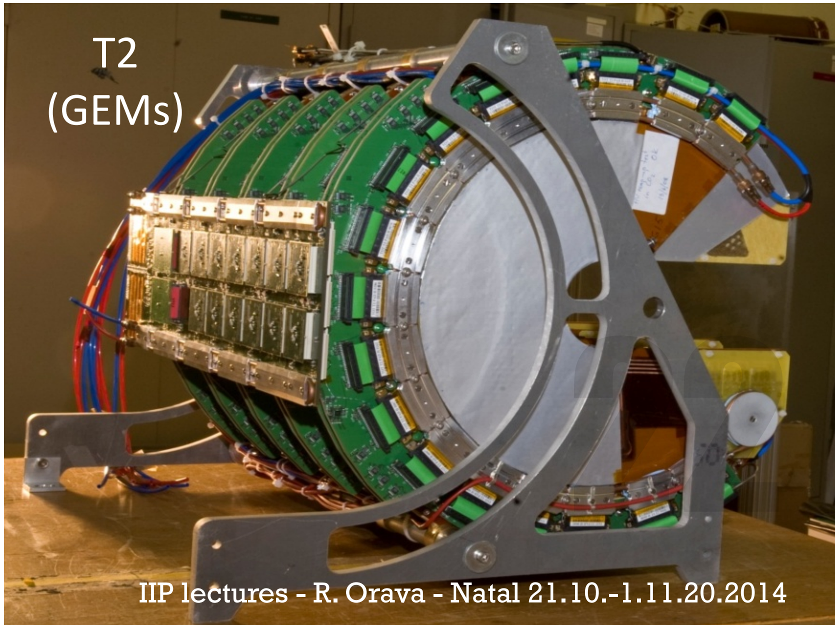


TOTEM DETECTORS

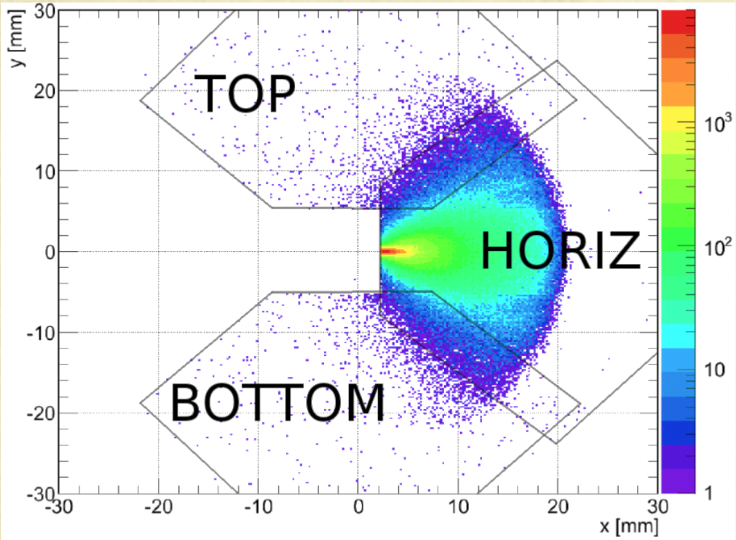








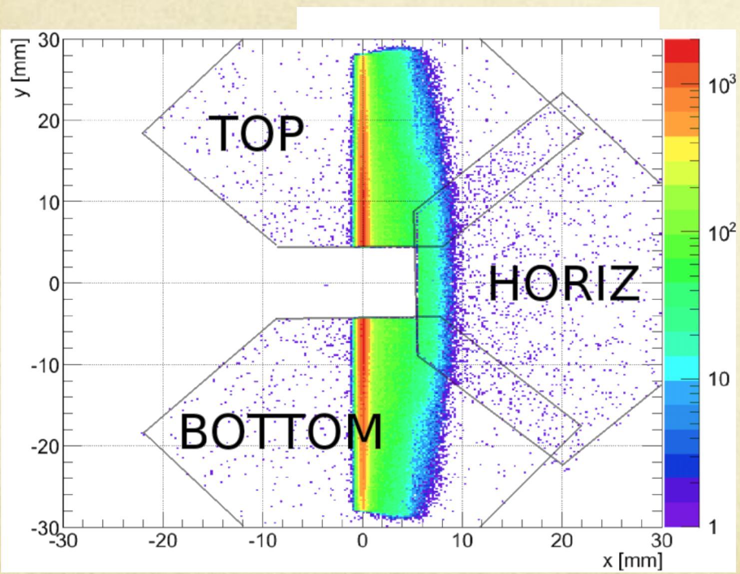
Leading forward protons at ±220 meters: Low & High β* (β*≈ 0.55m, 90m)



At low β* (nominal LHC beam optics) the protons are measured through their **horizontal** deviation from the beam axis.
The proton fractional longitudinal momentum loss, ξ, is proportional to the (horizontal) distance fom the beam axis:

$\xi = \Delta p/p \propto x$

- measurement sensitive to the transverse (x*,y*) position of the interaction vertex

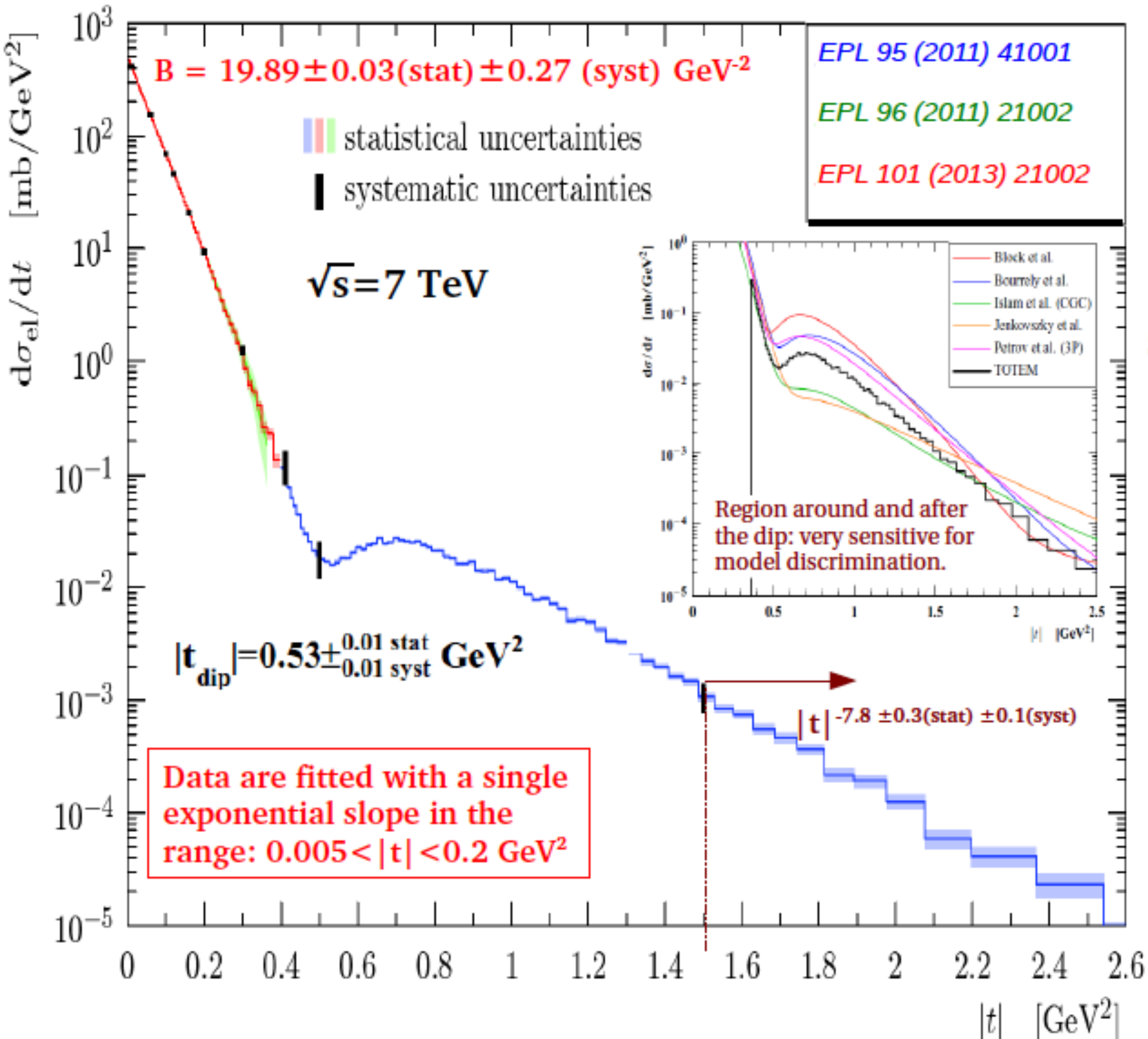


At high β* (β* ≈ 90m custom optics) the protons are measured through their scattering angle in **vertical** direction.

$\Theta_y \propto p_T \approx \sqrt{|t_y|}$

- measurement sensitive to the horizontal x* position of the interaction vertex in diffractive events
- horizontal vertex position obtained by measuring elastic events (if beams assumed to be symmetric in the transverse plane)

Elastic scattering results: $5\cdot10^{-3}<|t|<2.5$ GeV^2@ 7 TeV



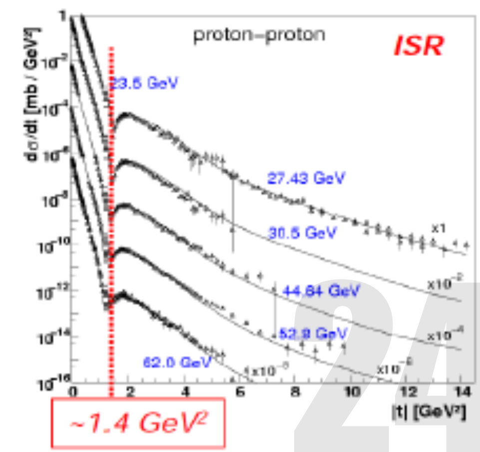
EPL 95 (2011) 41001 — $0.36 <|t|< 2.5$ GeV^2

EPL 96 (2011) 21002 — $0.02 <|t|< 0.33$ GeV^2

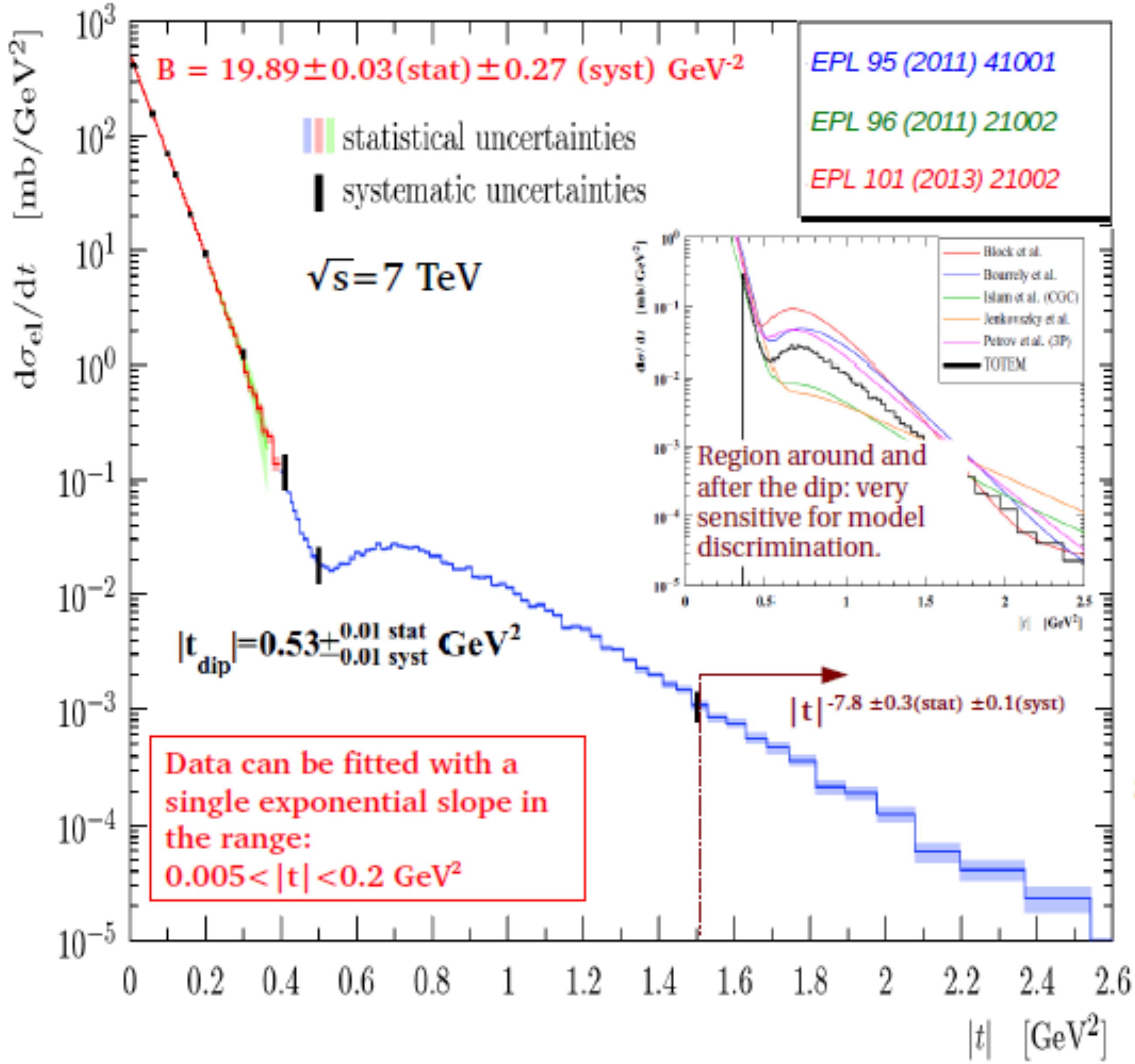
EPL 101 (2013) 21002 — $5\cdot10^{-3} <|t|< 0.4$ GeV^2

Shrinkage of the forward peak:

- minimum moves to lower |t| with increasing CM energy
- exponential slope grows with the CM energy



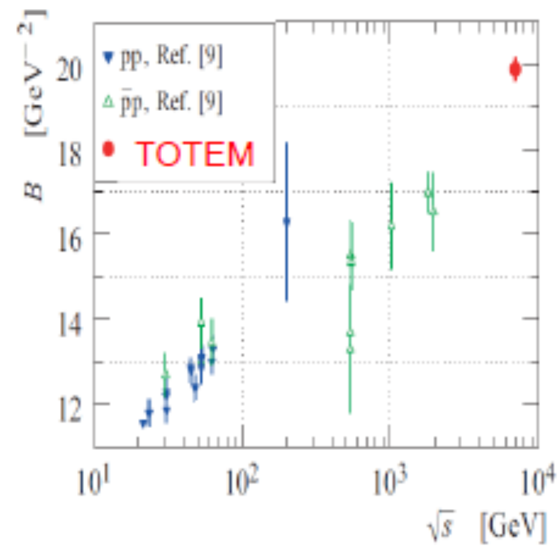
ELASTIC CROSS SECTION - TOTEM



$0.36 < |t| < 2.5\ GeV^2$

$0.02 < |t| < 0.33\ GeV^2$

$5 \cdot 10^{3} < |t| < 0.4\ GeV^2$

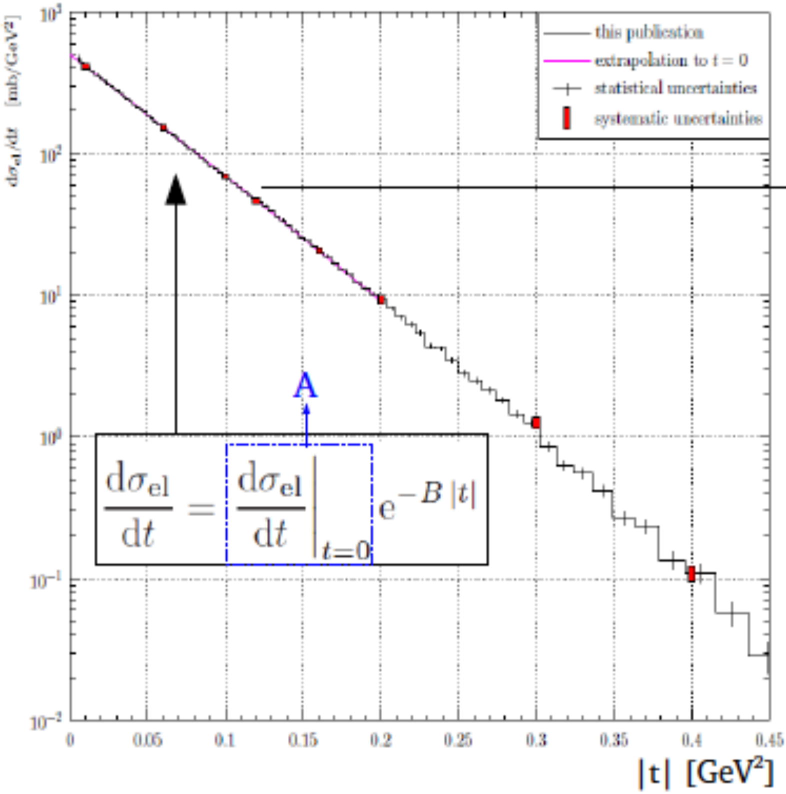


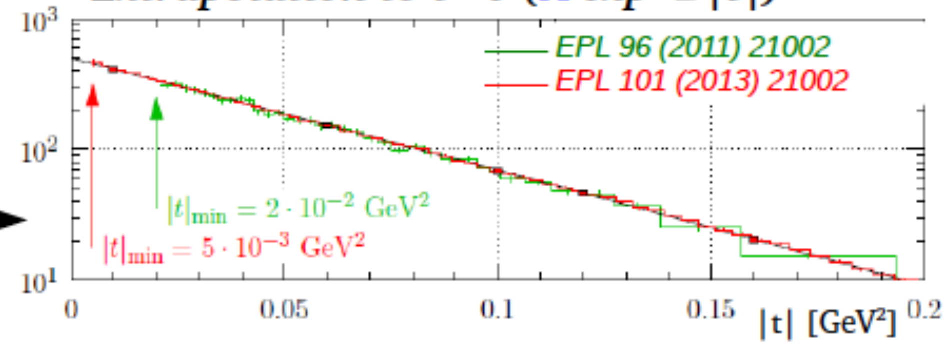
Shrinkage of the forward peak:

- minimum moves to lower |t| with increasing CM energy
- exponential slope grows with the CM energy

Elastic scattering results: $5\cdot10^{-3}<|t|<0.45\ GeV^2$ @ 7 TeV

- Elastic analysis performed in a wide range of |t|, with different beam conditions





Data are fitted with a single exponential slope in the range: $0.005<|t|<0.2\ GeV^2$

A (mb/GeV^2):

$506.4 \pm 23^{syst} \pm 0.9^{stat}$

$503 \pm 26.7^{syst} \pm 1.5^{stat}$

B (GeV^{-2}):

$19.89 \pm 0.27^{syst} \pm 0.03^{stat}$ ($5\ 10^{-3}<|t|<0.2\ GeV^2$)

$20.1 \pm 0.3^{syst} \pm 0.2^{stat}$ ($2\ 10^{-2}<|t|<0.33\ GeV^2$)

σ_{el}(Luminosity dependent):

$25.43 \pm 1.07^{syst} \pm 0.03^{stat}$ mb (91% measured)

$24.8 \pm 1.2^{syst} \pm 0.2^{stat}$ mb (67% measured)

Inelastic pp cross section measurement @ 7 TeV:

(EPL, 101 (2013) 21003)

- Luminosity dependent inelastic cross section obtained triggering <u>with T2</u>: $\sigma_{Inel,T2vis} = \frac{N_{T2}}{\mathcal{L}_{int}}$

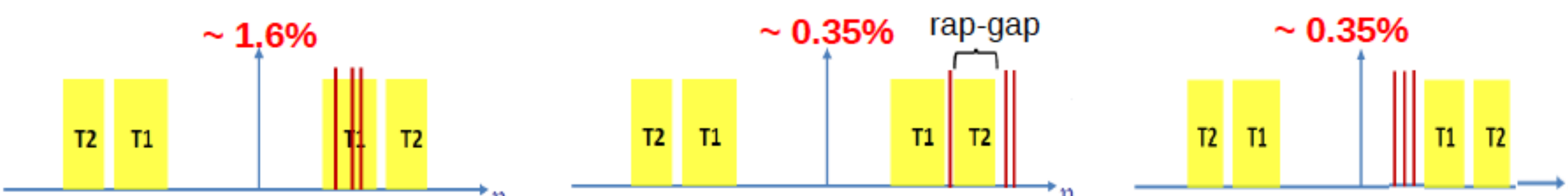
- Cross section for events with at least a stable particle in the T2 acceptance:

$$\sigma_{\text{Inel,T2 vis}}\ \text{(mb)}:\ 69.7 \pm 0.1\text{stat} \pm 0.7\text{syst} \pm 2.8\text{lumi}$$

- Cross section for events with at least a stable particle with $|\eta|<6.5$:

$$\sigma_{\text{Inel},|\eta|<6.5}\ \text{(mb)}:\ 70.5 \pm 0.1\text{stat} \pm 0.8\text{syst} \pm 2.8\text{lumi}$$

<u>Correction sizes:</u>



Track in T1 (& T2 empty) | Rapidity gap in T2 for 1-arm events | Central diffraction (T1,T2 empty)

- Correction for events having particles only at $|\eta|>6.5$: 4.2% ± 2.1% (syst):

$$\sigma_{\text{inel}}\ \text{(mb)}:\ 73.74 \pm 0.09\text{stat} \pm 1.74\text{syst} \pm 2.95\text{lumi}$$

QGSJET- II-03/II-04 predict a low mass (M<3.4 GeV/c^2) diffractive cross section compatible with the TOTEM measurements

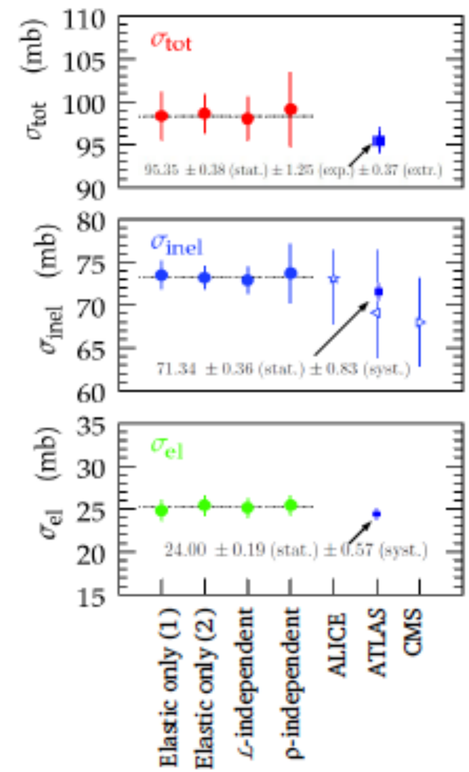
Total cross section @ 7 TeV

EPL 101 (2013) 21004

elastic observables only:

$$\sigma^2_{\mathrm{tot}} = \frac{16\pi}{1+\rho^2}\frac{1}{\mathcal{L}}\left.\frac{dN_{\mathrm{el}}}{dt}\right|_0$$

σ_{tot} = (98.6 ± 2.3) mb



Validity of the optical theorem tested at 3.5% level

σ_{tot}

ρ independent:

$$\sigma_{\mathrm{tot}} = \frac{1}{\mathcal{L}}(N_{\mathrm{el}} + N_{\mathrm{inel}})$$

σ_{tot} = (99.1 ± 4.4) mb

$$\rho \equiv \left.\frac{\Re A_{\mathrm{el}}}{\Im A_{\mathrm{el}}}\right|_{t=0}$$

luminosity independent:

$$\sigma_{\mathrm{tot}} = \frac{16\pi}{1+\rho^2}\frac{dN_{\mathrm{el}}/dt|_0}{N_{\mathrm{el}} + N_{\mathrm{inel}}}$$

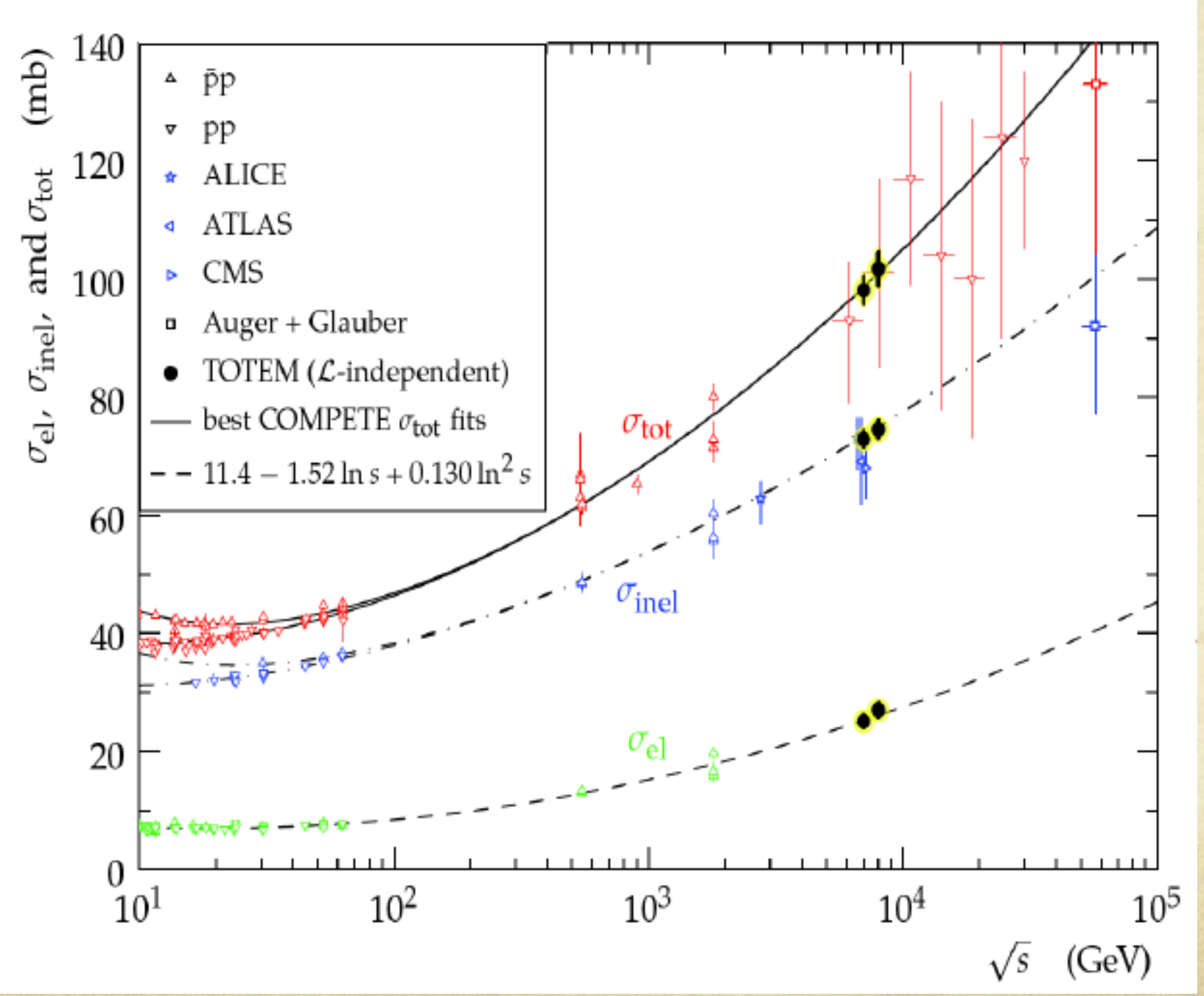
σ_{tot} = (98.1 ± 2.4) mb

Absolute calibration of the CMS luminosity

$\mathcal{L}_{\mathrm{int,\,CMS}}$ = 82.8 ± 3.3 μb^{-1} $\mathcal{L}_{\mathrm{int,\,TOTEM}}$ = 83.7 ± 3.2 μb^{-1}

$\mathcal{L}_{\mathrm{int,\,CMS}}$ = 1.65 ± 0.07 μb^{-1} $\mathcal{L}_{\mathrm{int,\,TOTEM}}$ = 1.65 ± 0.07 μb^{-1}

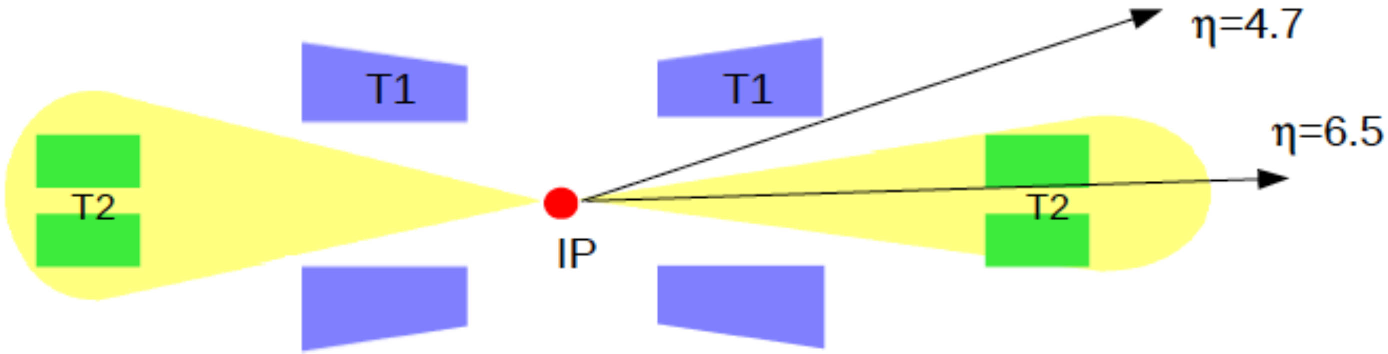
SUMMARY OF CROSS SECTION MEASUREMENTS AT THE LHC



Soft Double Diffractive cross section (7 TeV)

Phys. Rev. Lett. 111, 262001

Aim: Measurement of soft double diffractive cross section with particle η_{min} visible in TOTEM T2 ($4.7<|\eta_{min}|<6.5$). → $\sigma_{DD}(|\eta_{min}|)$ for $3.4 < M_{DIFF} < 8$ GeV



Event selection: Trigger with T2, at least one track in both T2 hemispheres , no tracks in T1.

Results from 7 TeV data:

$$\sigma_{DD(4.7<|\eta_{min}|<6.5)} = 120 \pm 25 \mu b$$

	$-4.7>\eta_{min}>-5.9$	$-5.9>\eta_{min}>-6.5$
$4.7<\eta_{min}<5.9$	66±19 μb	27±4 μb
$5.9<\eta_{min}<6.5$	28±5 μb	12±4 μb

MC predictions:

Pythia

$$\sigma_{DD(4.7<|\eta_{min}|<6.5)} = 159 \mu b$$

	$-4.7>\eta_{min}>-5.9$	$-5.9>\eta_{min}>-6.5$
$4.7<\eta_{min}<5.9$	70 μb	37 μb
$5.9<\eta_{min}<6.5$	35 μb	17 μb

Phojet

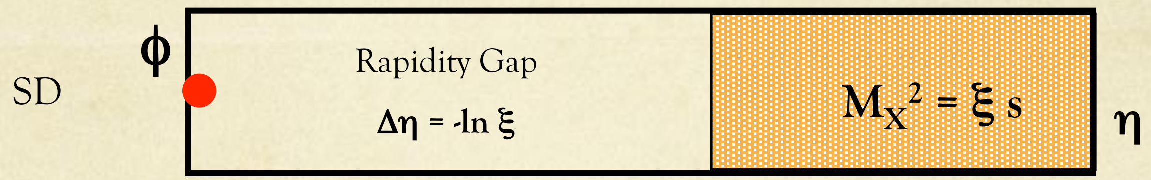
$$\sigma_{DD(4.7<|\eta_{min}|<6.5)} = 101 \mu b$$

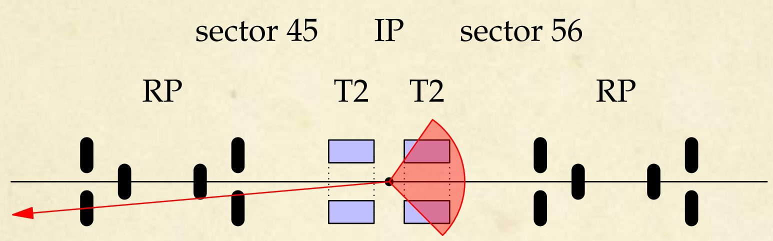
	$-4.7>\eta_{min}>-5.9$	$-5.9>\eta_{min}>-6.5$
$4.7<\eta_{min}<5.9$	44 μb	23 μb
$5.9<\eta_{min}<6.5$	23 μb	12 μb

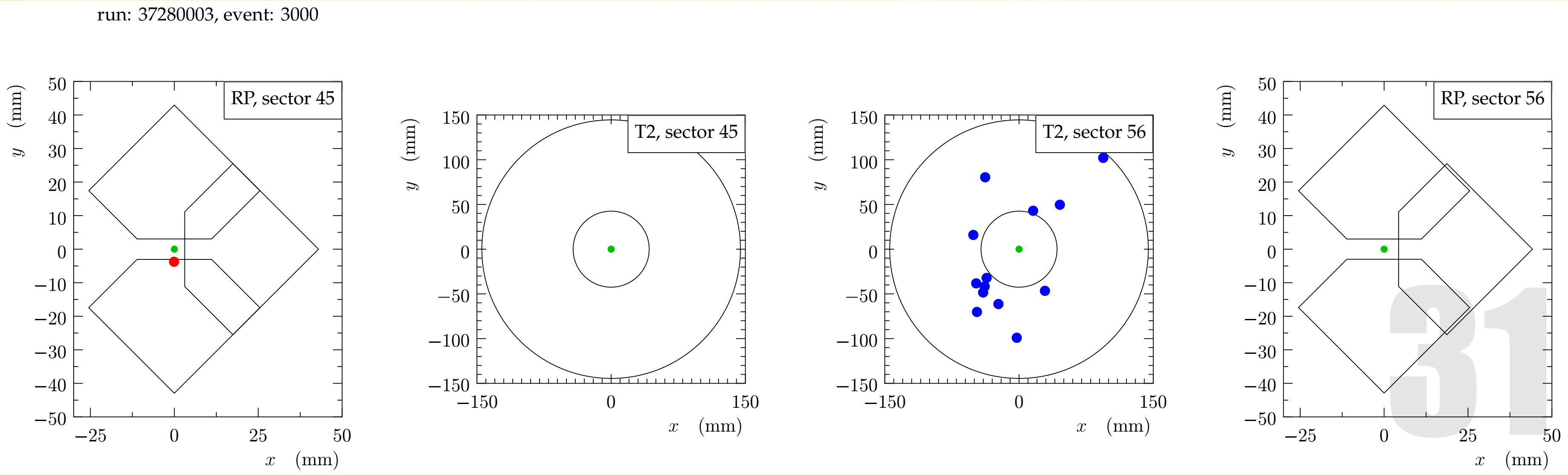
- σ_{DD} uncertainty dominated by migrations from generator η_{min} to track reconstructed η_{min}

Single diffraction low ξ

Correlation between leading proton and forward detector T2

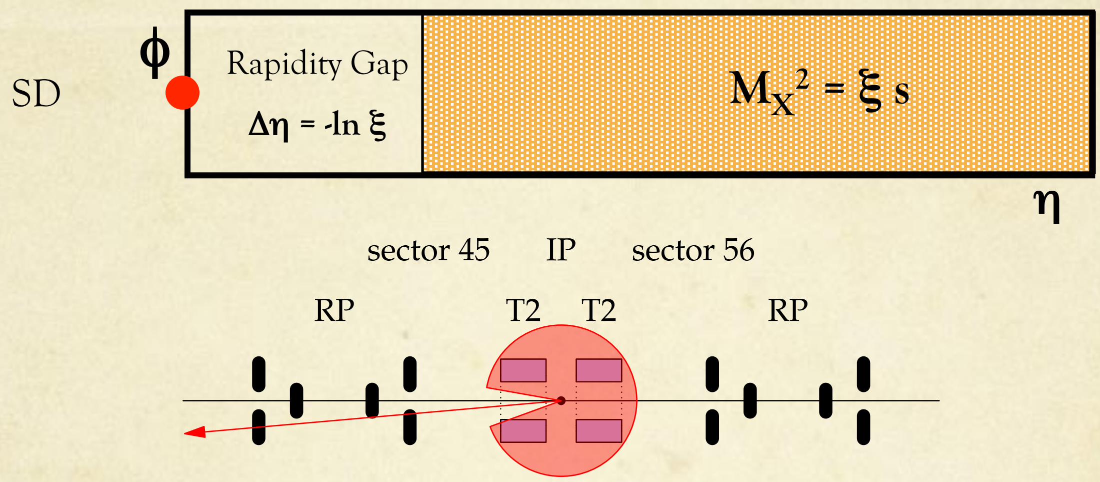


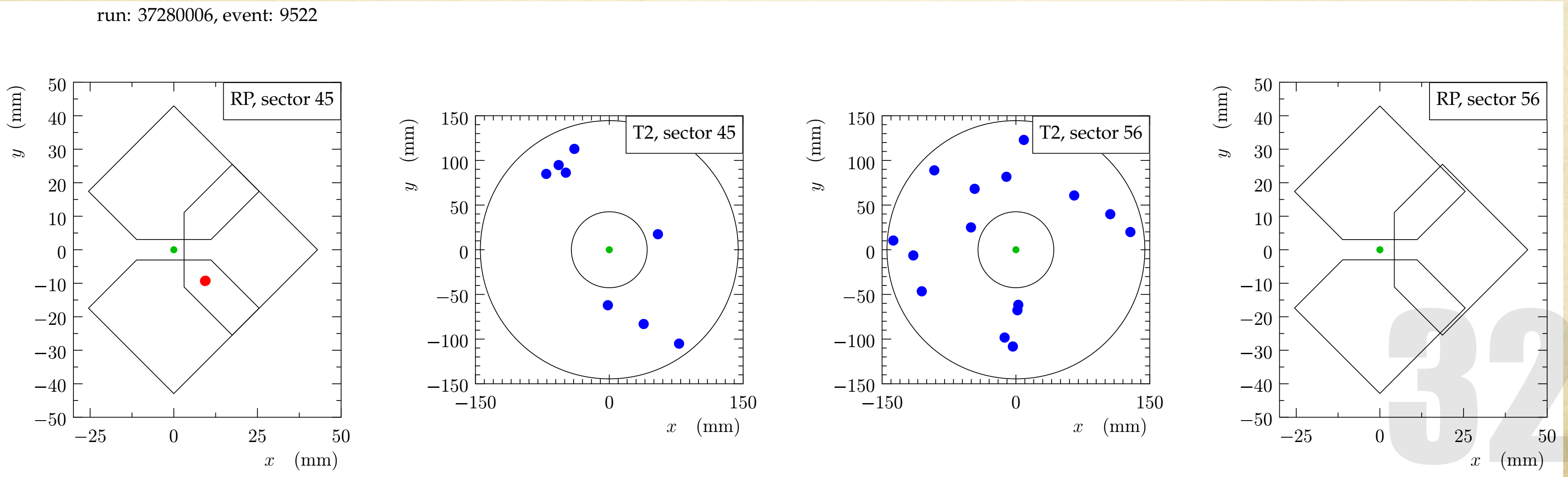




Single diffraction large ξ

correlation between leading proton and forward detector T2



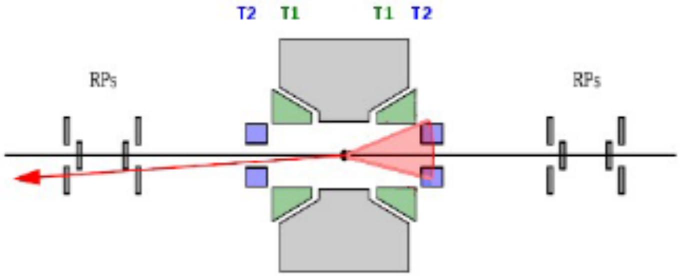


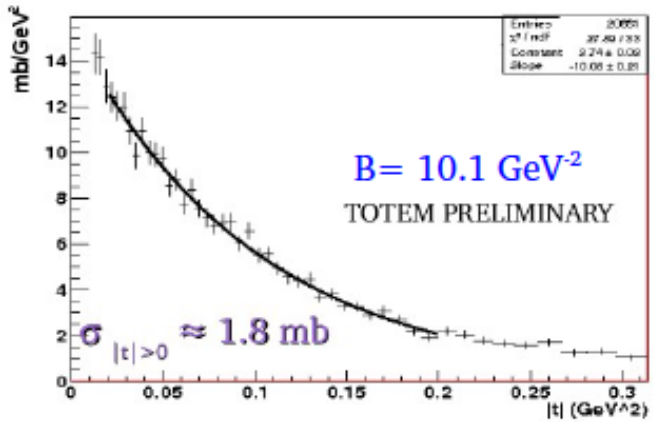
Soft Single Diffractive cross section (7 TeV)

$d\sigma/dt \sim C \cdot e^{Bt}$

Low Mass

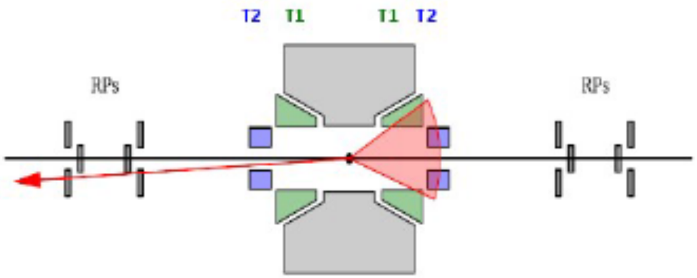
M=3.4 - 8 GeV

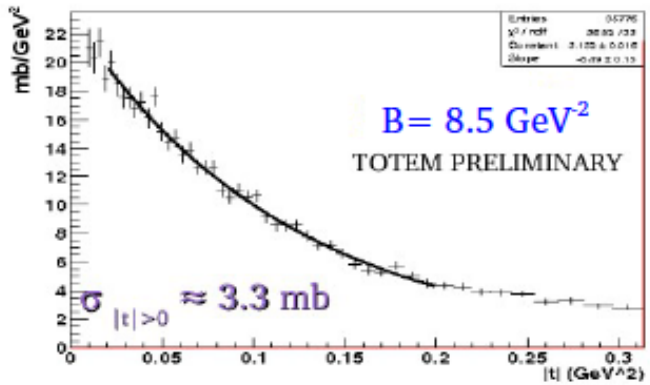




Medium Mass

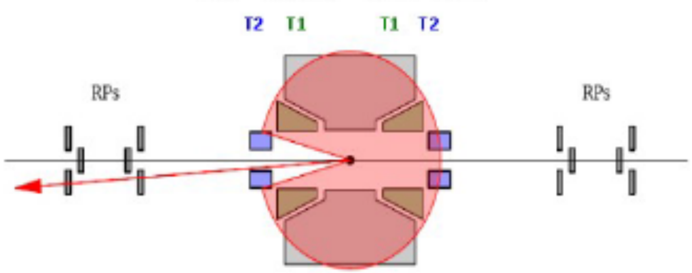
M=8 - 350 GeV

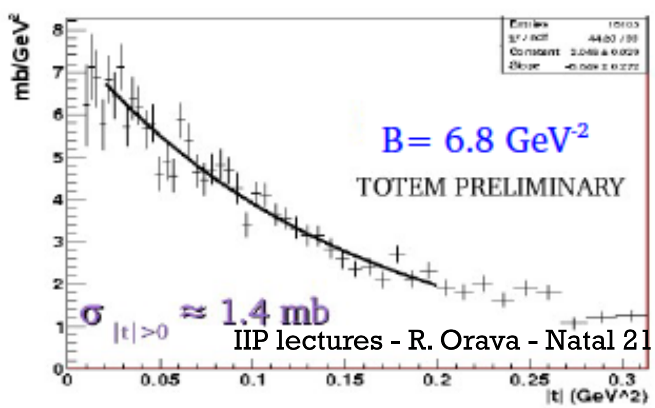




High Mass

M=0.35 - 1.1 TeV





Corrections include:
- Trigger efficiency
- Reconstruction efficiency
- Proton acceptance
- Background subtraction
- Extrapolation to t=0

Missing corrections:
- Class migrations
- Effects due to resolutions and beam divergence

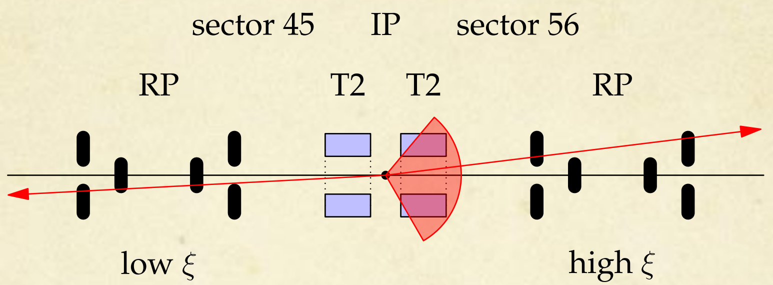
- Estimated uncertainties: B~15% σ~20%

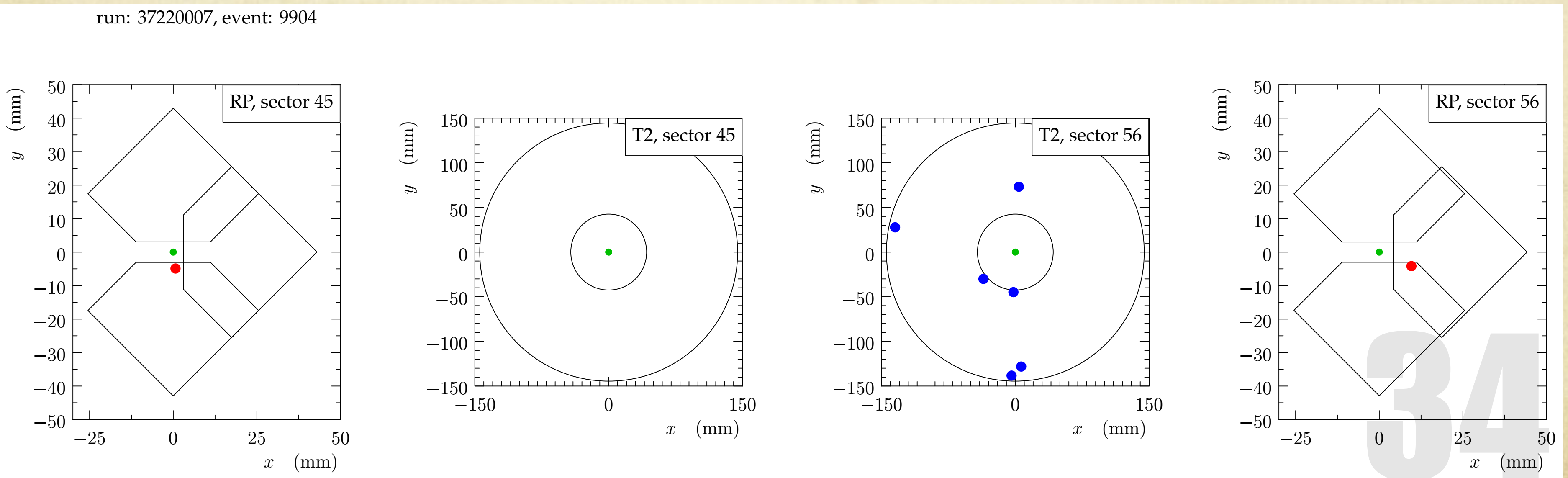
Preliminary:
σ_{SD} = 6.5 ± 1.3 mb
($3.4 < M_{SD} < 1100$ GeV)

Very high masses measurement ongoing

Central Exclusive Diffraction (CED)

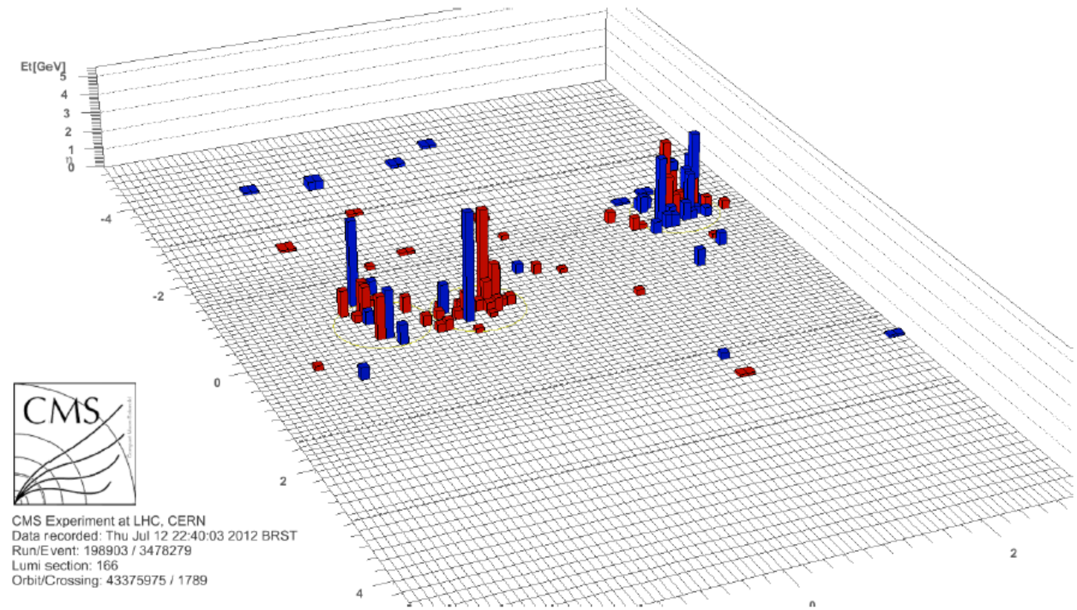
correlation between leading protons and forward detector T2





DI-JET CANDIDATE EVENT

- E_T of 3 jets: 65 GeV, 45 GeV, 27 GeV
- M(pp, TOTEM) = 244 GeV
- M(CMS) = 219 GeV
- Proton $\Delta p/p$ = 0.01 (+z)
- Proton $\Delta p/p$ = 0.1 (-z)
- Σ(pT, CMS) = 3.4 GeV



- CMS thresholds for event display
  - ECAL and HCAL E_T > 200 MeV
  - Track p_T > 1 GeV

Soft Central Diffraction Exchange

TOTEM alone, 20.10.2011 data

β^* = 90m optics runs, sqrt s = 7 TeV:

- y < 11σ removed : protection against pile-up
  beam halo × beam halo
  beam halo × elastic proton
- DPE protons of -t > 0.02GeV^2 detected by RP
- nearly complete ξ -acceptance

σ_{DPE} estimation:

$$\frac{d^2\sigma_{DPE}}{dt_1 dt_2} = C(\Delta\varphi_{1,2}) e^{-Bt_1} e^{-Bt_2} - \text{backgr.}$$

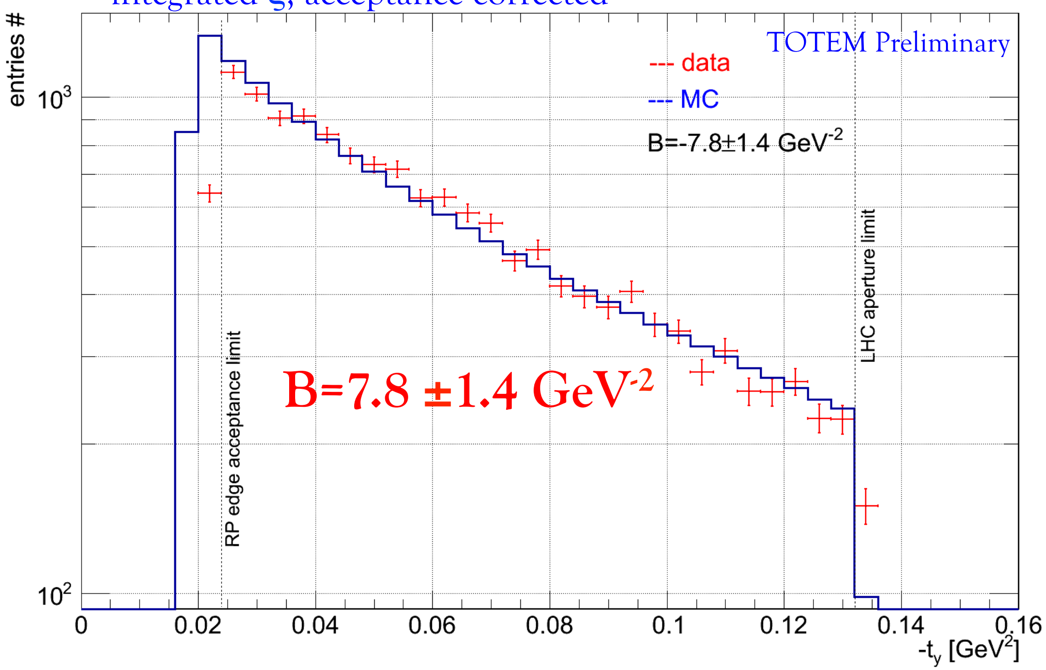
$$\sigma_{DPE} = \int_0^\infty dt_1 \int_0^\infty dt_2 \frac{d^2\sigma_{DPE}}{dt_1 dt_2} \approx 1\text{mb}$$

Work in progress:

$$\sigma_{DPE} = \int \frac{d^4\sigma_{DPE}}{dt_1 dt_2 d\xi_1 d\xi_2} dt_1 dt_2 d\xi_1 d\xi_2$$

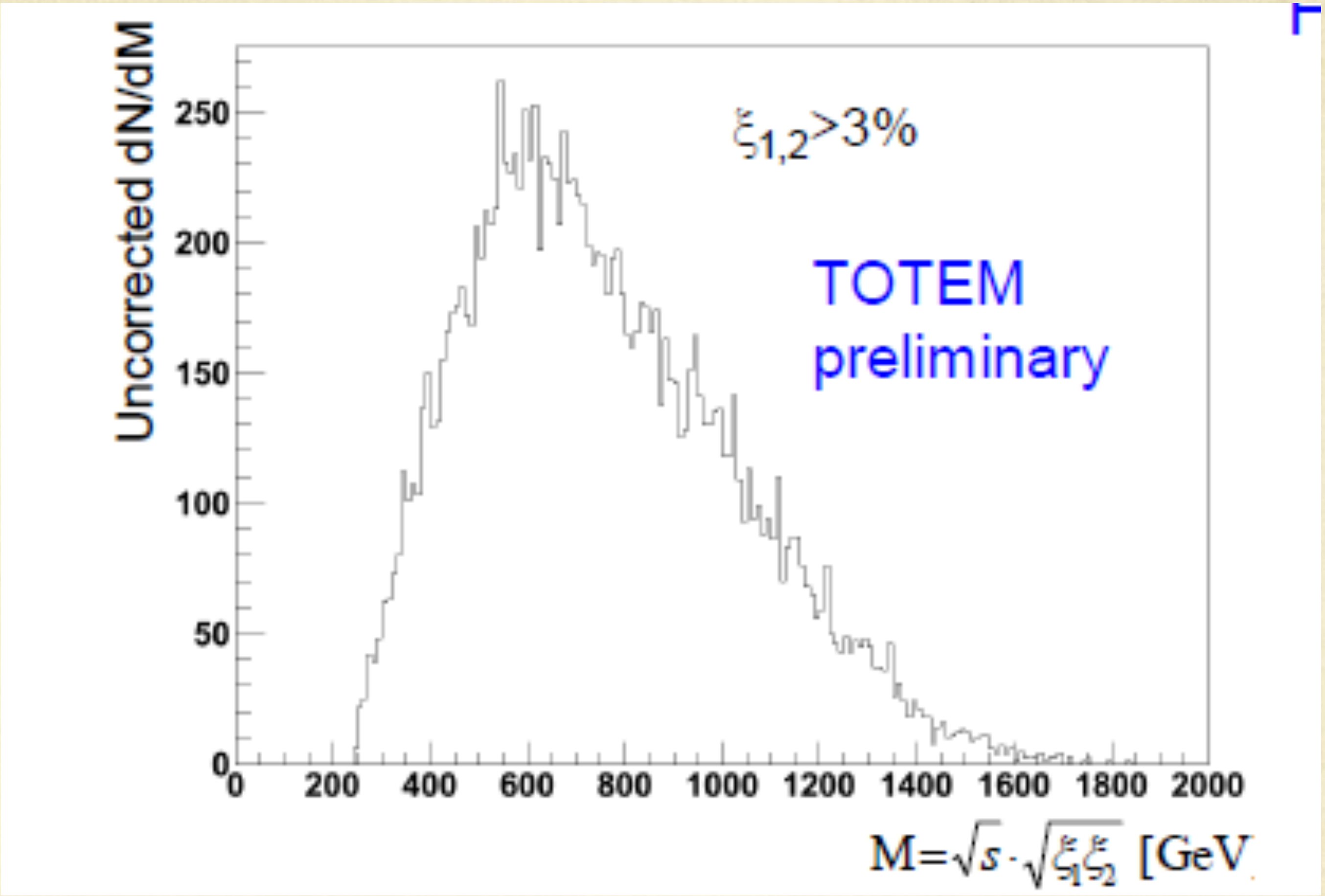
Single arm DPE event rate in RP

integrated ξ, acceptance corrected

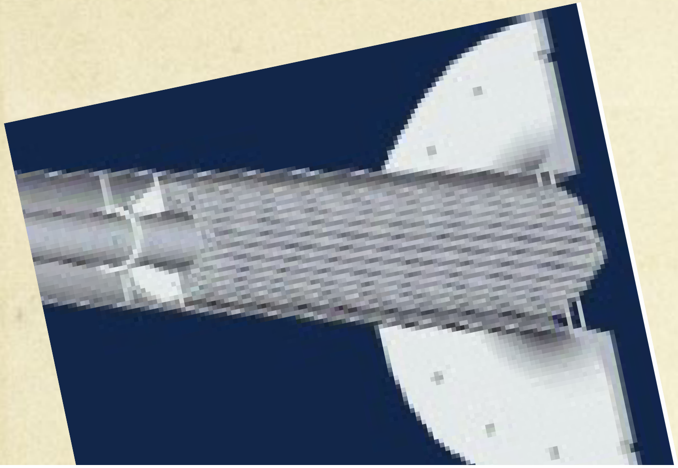


Soft Central Diffraction – dN/dM

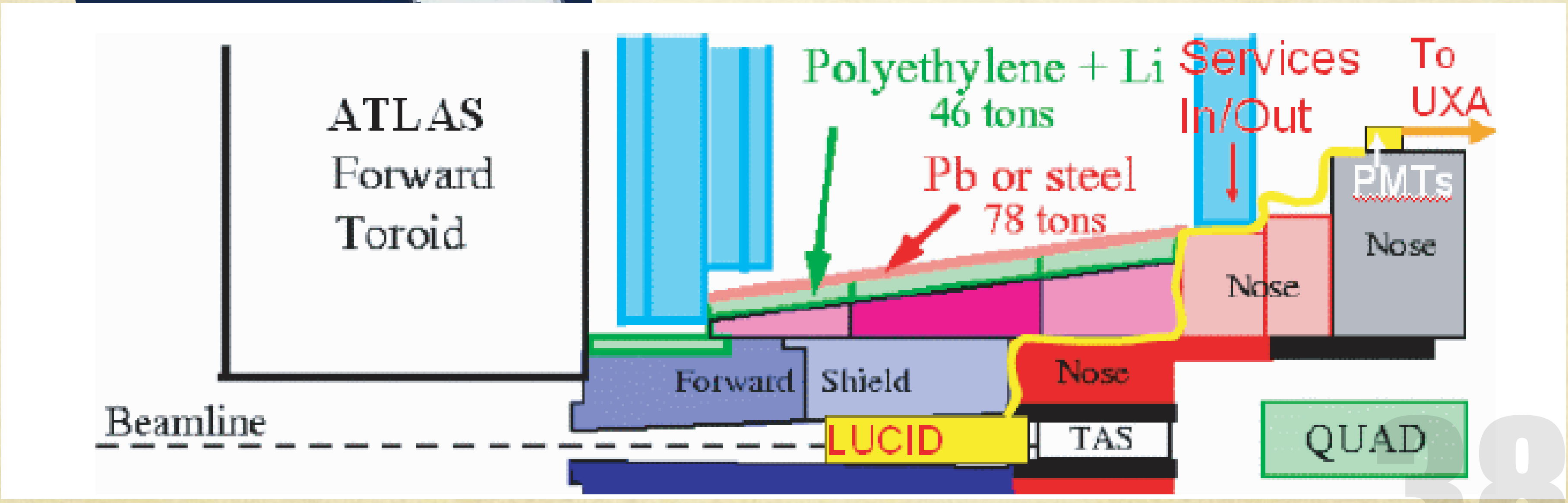
TOTEM alone, 20.10.2011 data



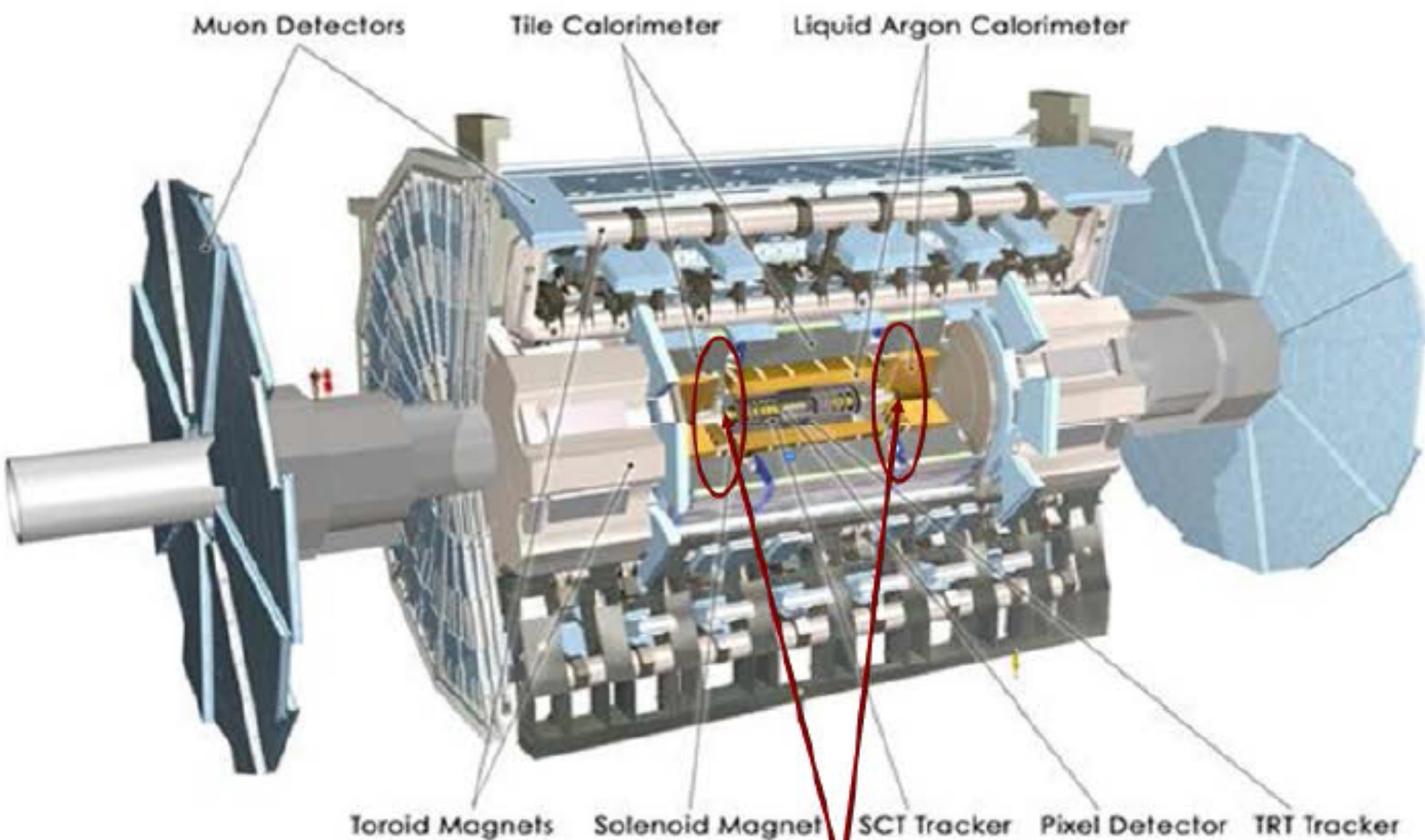
ATLAS: LUminosity measurement using a Cherenkov Imaging Detector LUCID



- dedicated luminosity monitors
- 5 x 40 counters
- 5.4 < |η| < 6.1
- 17 m from IP1
- counts tracks from min bias & diffractive events



The ATLAS Detector

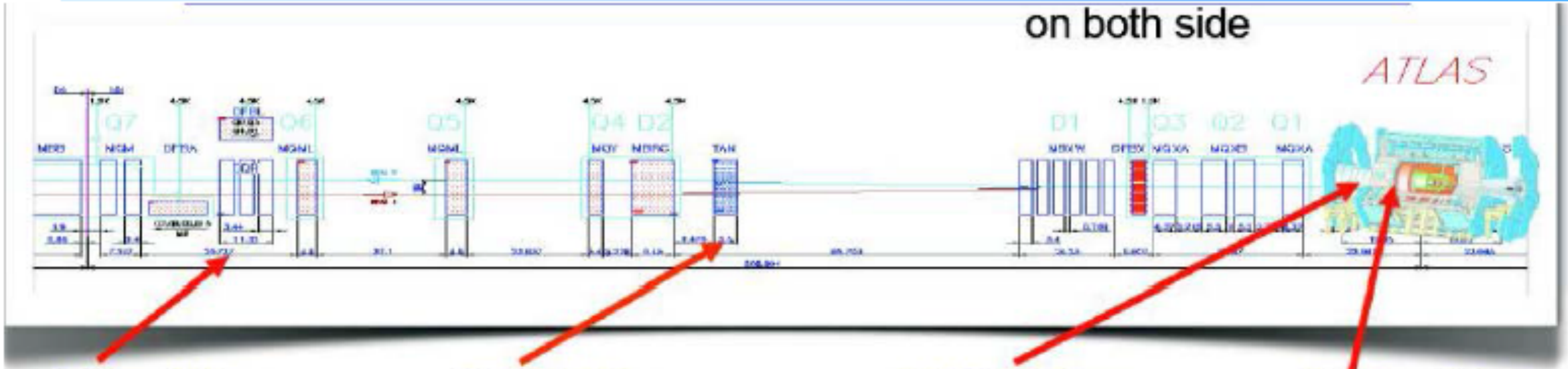


Trackers: $|\eta|<2.5$

Calorimeters: $|\eta|<4.9$

Minimum **B**ias
Trigger **S**cintillator
$2.1< |\eta|<3.8$

ATLAS Forward detectors

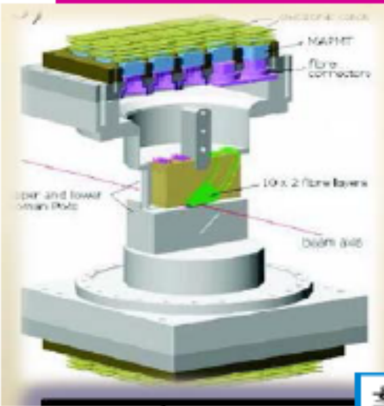


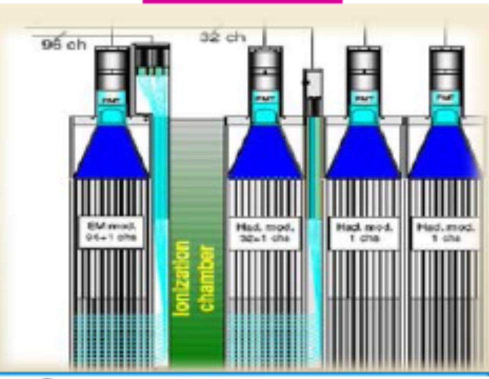
ALFA at 240 m — $10.6 < |\eta| < 13.5$

ZDC at 140 m — $|\eta| > 8.3$

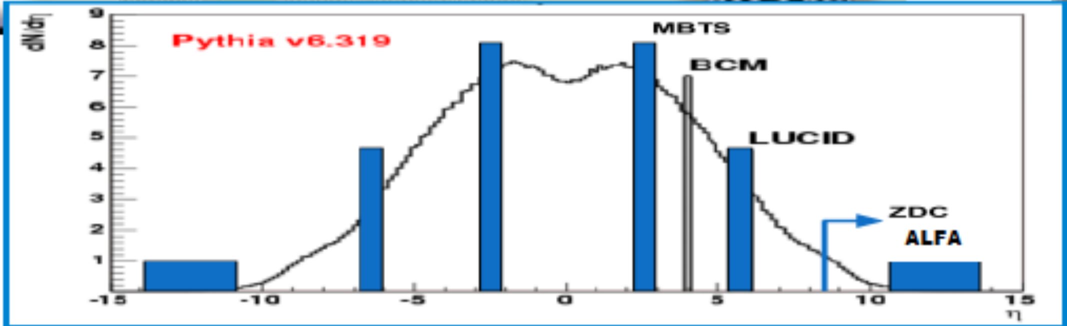
LUCID at 17 m — $5.6 < |\eta| < 5.9$

MBTS at 3.6 m — $2.1 < |\eta| < 3.8$





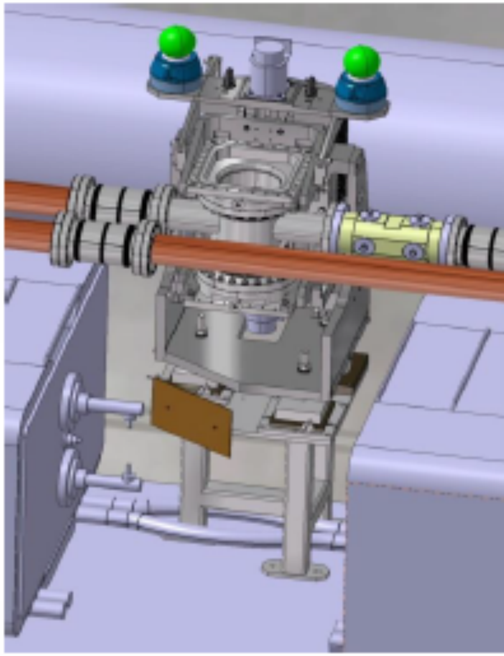
In operation since 2011



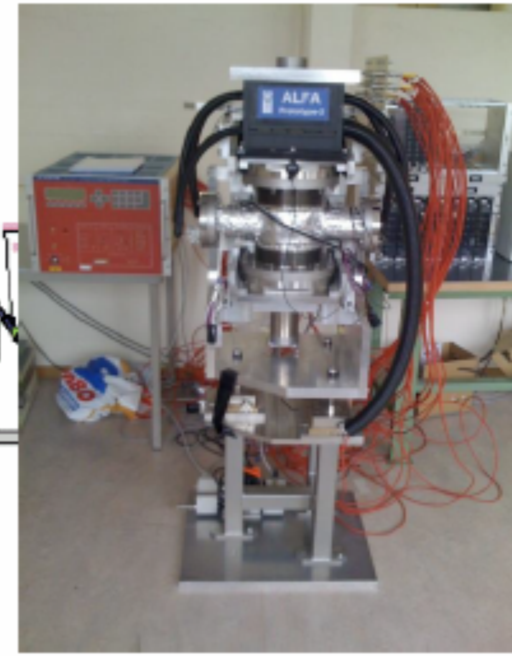
ATLAS

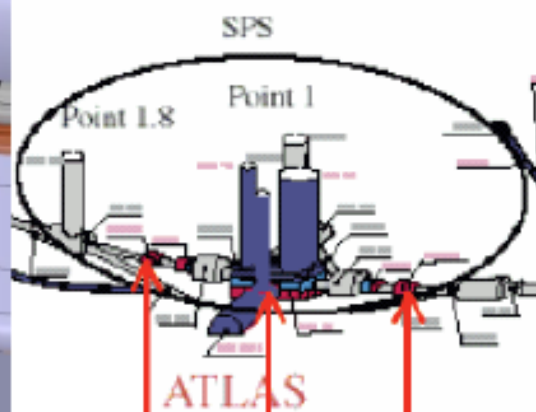
ALFA – Roman Pot stations

design...

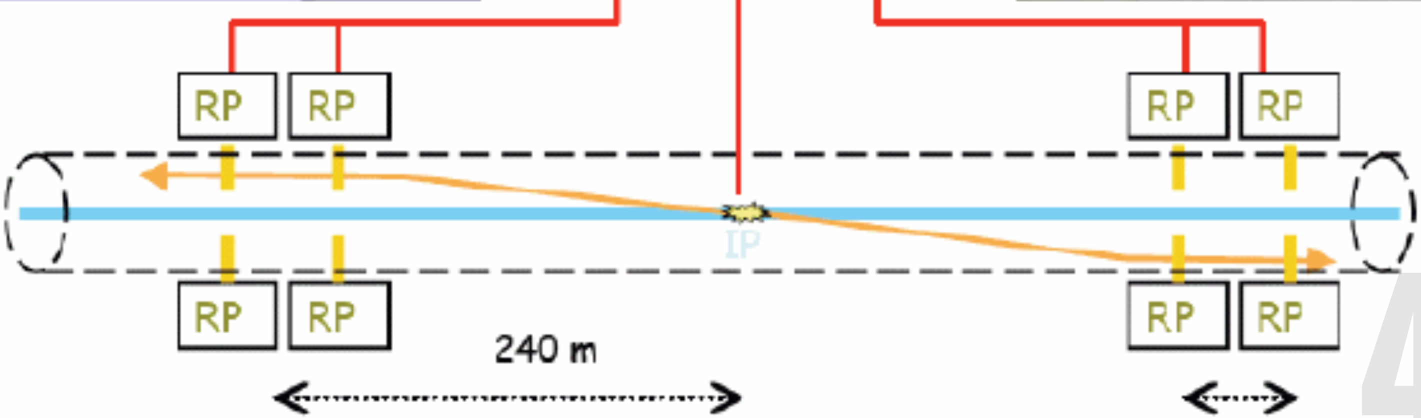


and reality

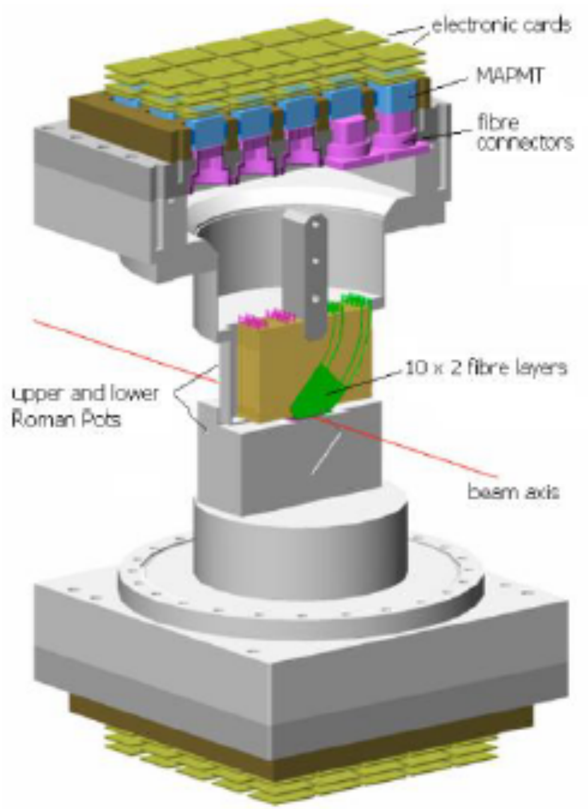




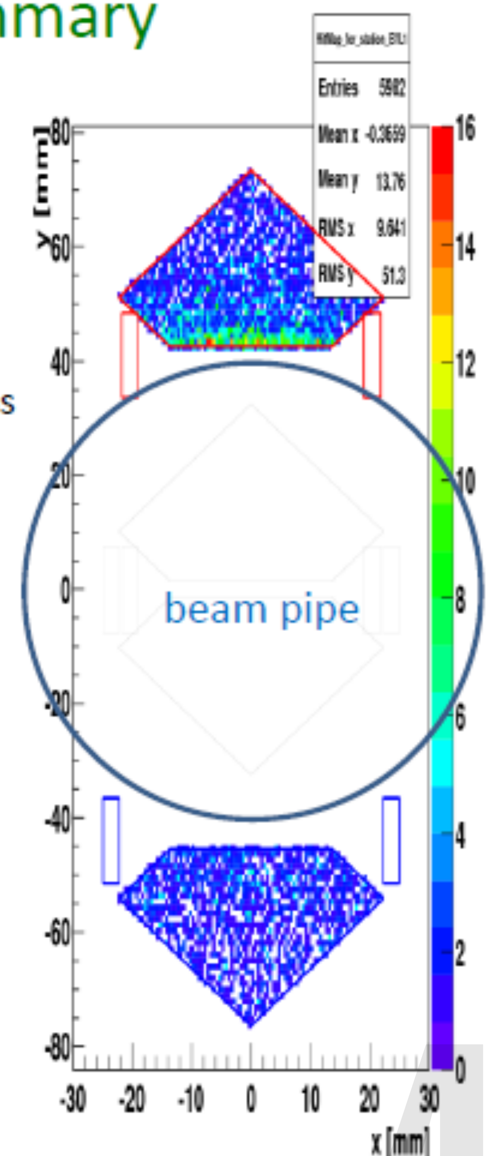
locations:



ATLAS detector properties – summary

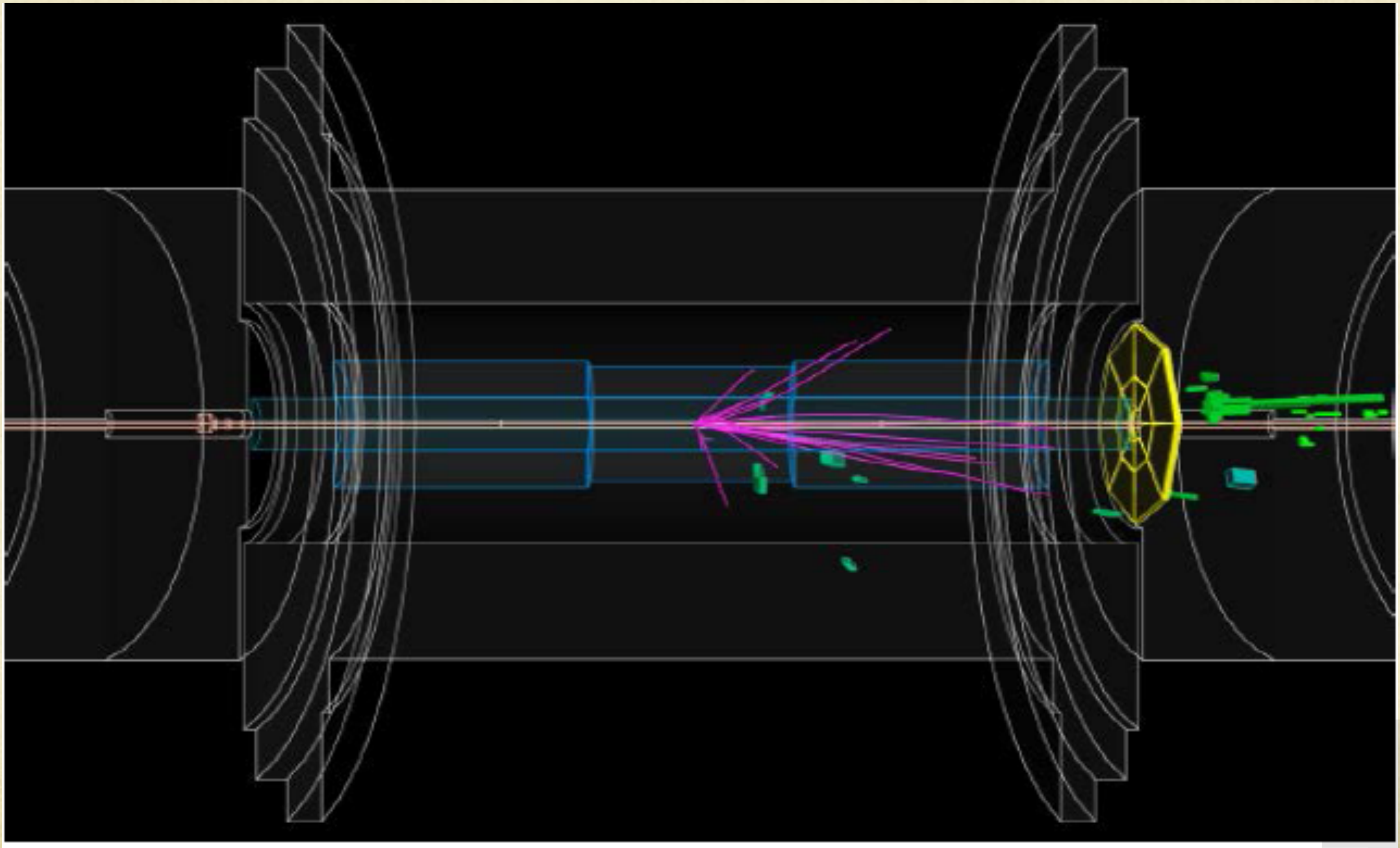


first tunnel output
detectors in parking positions

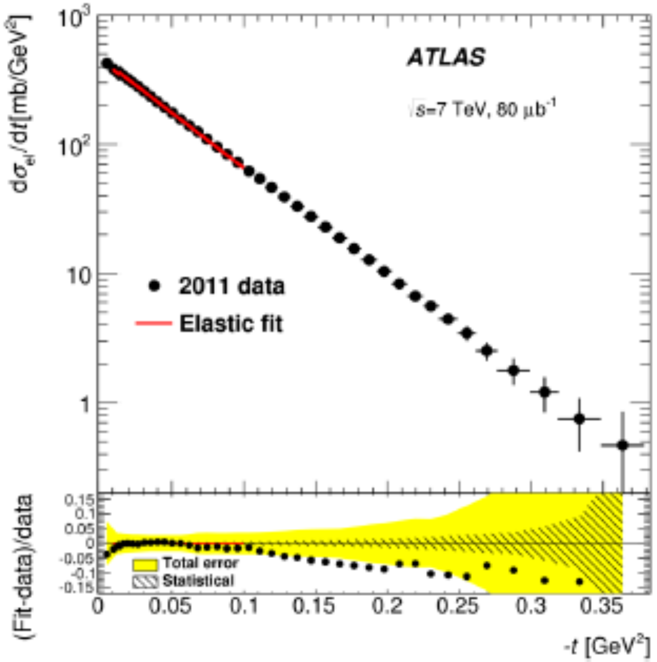


- single cladded 0.5 mm x 0.5 mm (square) fibers
- 10 layers in U, 10 in V; staggering
- ~ 30 μm position resolution
- efficiency ~ 90% per plane → ~ 100% efficiency of the detector

SINGLE DIFFRACTIVE EVENT IN ATLAS



Fitting elastic cr.section → $\sigma_{tot}, \sigma_{el}, \sigma_{inel}$, B-slope



Theoretical formula used to fit the data:

$$\frac{d\sigma}{dt} = \frac{4\pi\alpha^2(\hbar c)^2}{|t|^2}\cdot G^4(t)$$ Coulomb interactions

$$- \sigma_{tot}\cdot\frac{\alpha G^2(t)}{|t|}\left[\sin(\alpha\phi(t)) + \rho\cos(\alpha\phi(t))\right]\cdot\exp\frac{-B|t|}{2}$$ Coulomb-Nuclear interference

$$+ \sigma_{tot}^2\frac{1+\rho^2}{16\pi(\hbar c)^2}\cdot\exp(-B|t|)$$ Nuclear interactions

$$G(t) = \left(\frac{\Lambda}{\Lambda+|t|}\right)^2$$ Proton dipole form factor

$$\phi(t) = -\ln\frac{B|t|}{2} - \phi_C$$ Coulomb phase

$\rho = 0.14$ ← From COMPETE Global analysis

$\Lambda = 0.71\ \mathrm{GeV}^2$

$\Phi_c = 0.577$

(Conventional values. Other models in syst. uncert.)

- **Fit result:** σ_{tot} = **95.35** ± 0.38 (stat.) ± 1.25 (syst.) ± 0.37 (extr.) mb

  B = **19.73** ± 0.14 (stat.) ± 0.26 (syst.) GeV^{-2} {40%-correlation between σ_{tot} and B}

Fit quality good: χ^2/N_{dof} = 7.4/16, Fit range: -t ϵ <0.01, 0.1> GeV² - good Accept. & small deviations from exponential

Extrapolation uncertainty from changing the upper end **0.1** to **0.15** and **0.059**

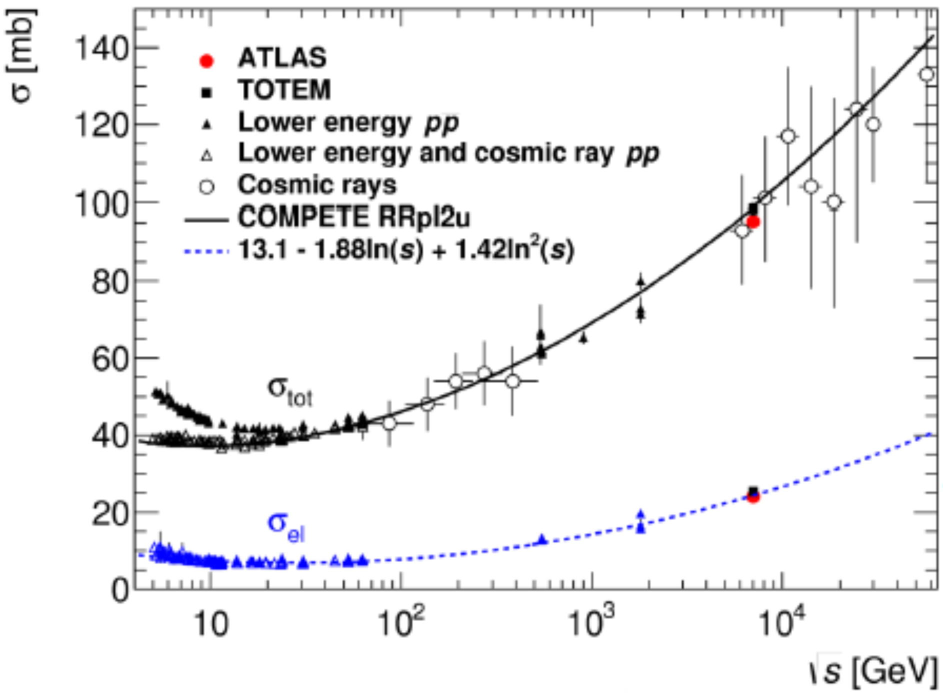
- Extraction of σ_{el}: assume Nuclear term only and B(t)=const:

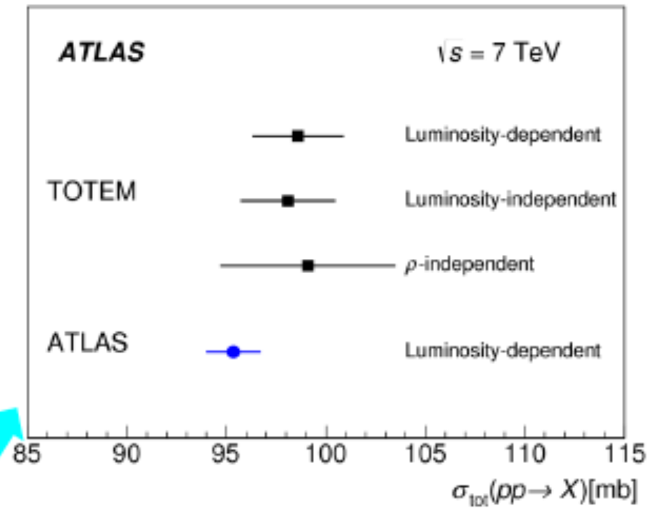
Integrating over full t-range σ_{el} = **24.00** ± 0.19 (stat.) ± 0.57 (syst.) mb

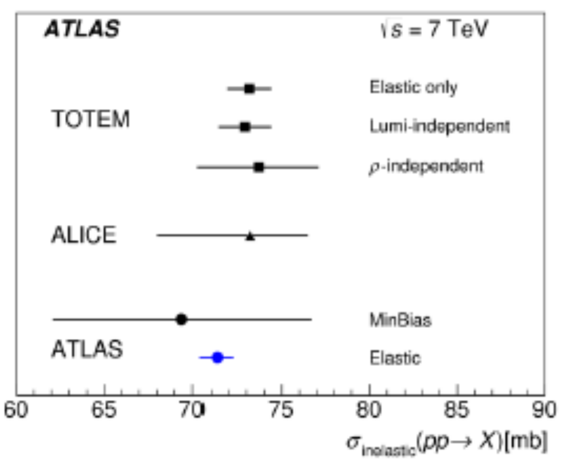
[Observed in -t ϵ <0.0025, 0.38> GeV²: σ_{el} = 21.66 ± 0.02 (stat.) ± 0.58 (syst.) mb (90% of the total σ_{el})]

- $\sigma_{inel} = \sigma_{tot} - \sigma_{el}$ ⟶ σ_{inel} = **71.34** ± 0.36 (stat.) ± 0.83 (syst.) mb

Comparison with previous measurements







σ_{inel}:
ALFA significantly improves precision of the previous ATLAS σ_{inel} measurement

The same run in 2011, Lumi-dependent method:

ATLAS: σ_{tot} = 95.4 ± 1.4 mb (Lumi unc=2.3%)
TOTEM: σ_{tot} = 98.6 ± 2.2 mb (Lumi unc=4%)
→ Difference = 1.3 σ
ATLAS value ~2σ below COMPETE fit, but closer to predictions by Block & Halzen, KMR, Soffer.

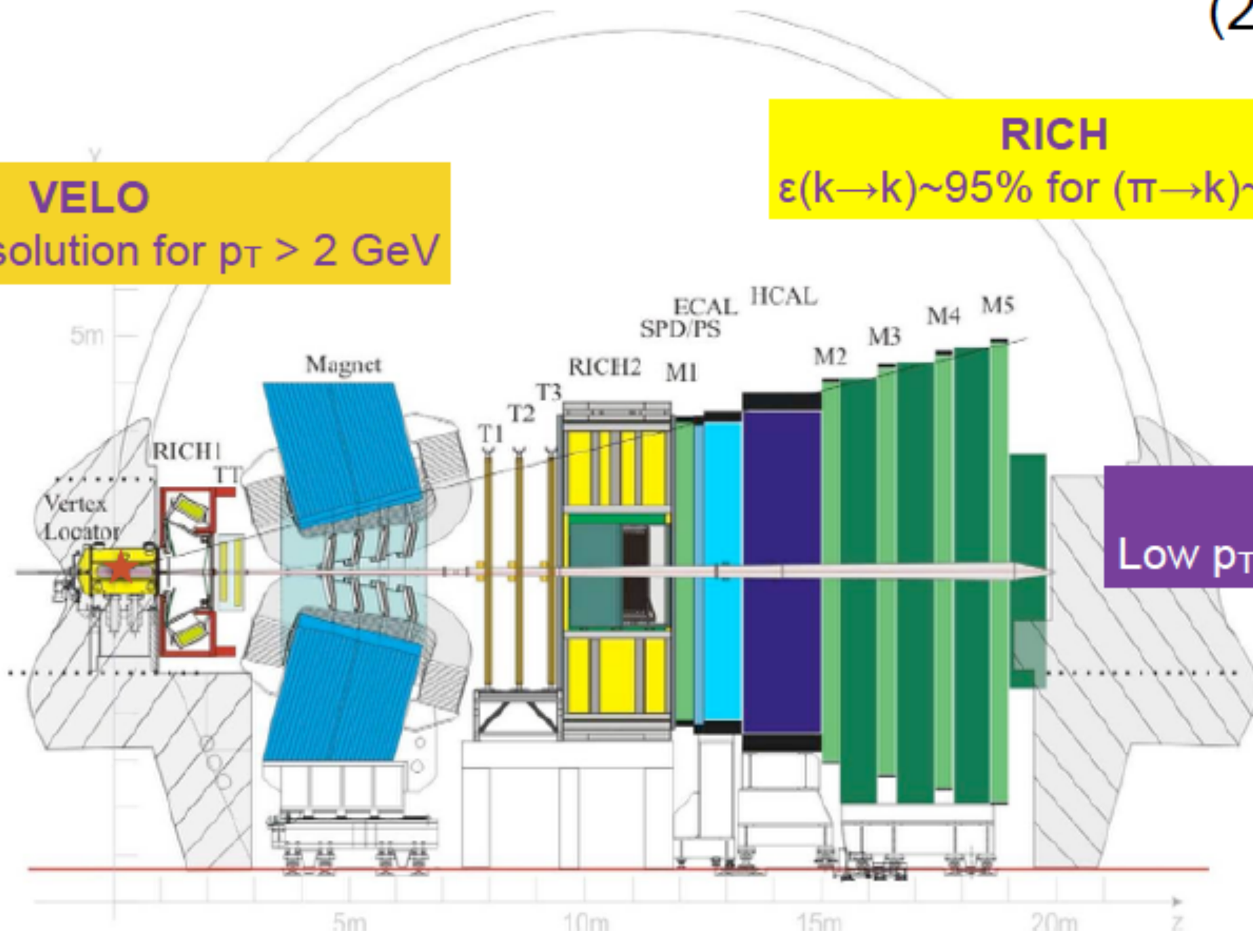
ATLAS: σ_{el} = 24.0 ± 0.6 mb (Lumi unc=2.3%)
Totem: σ_{el} = 25.4 ± 1.1 mb (Lumi unc=4%)
→ Difference = 1.1 σ

LHCb Experiment

LHCb is a single arm spectrometer fully instrumented in the forward region ($2.0<\eta<5.0$)

VELO
~20µm IP resolution for p_T > 2 GeV

RICH
$\varepsilon(k\rightarrow k)$~95% for $(\pi\rightarrow k)$~5%



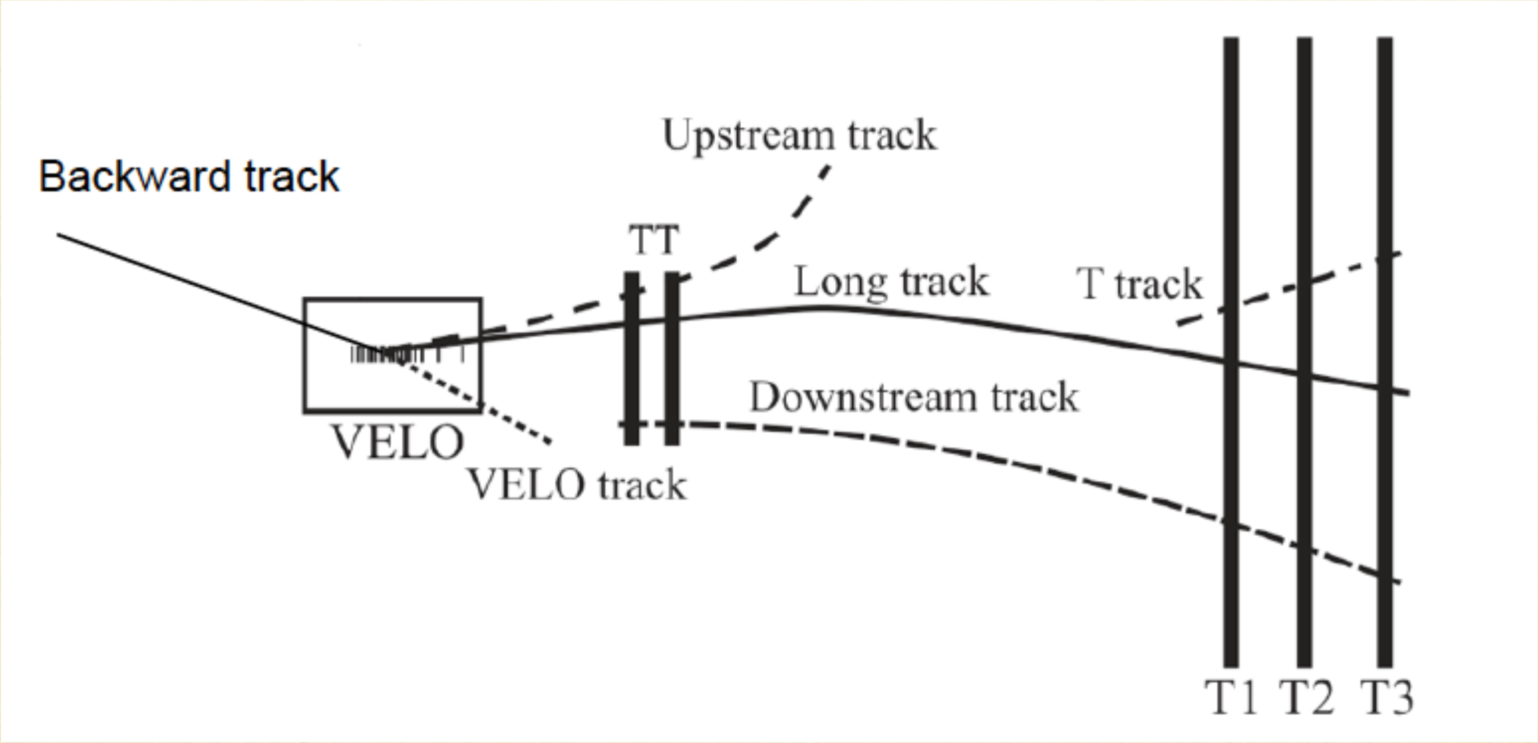
Trigger
Low p_T Minimum Bias

TRACK
0.4%-0.6% momentum resolution

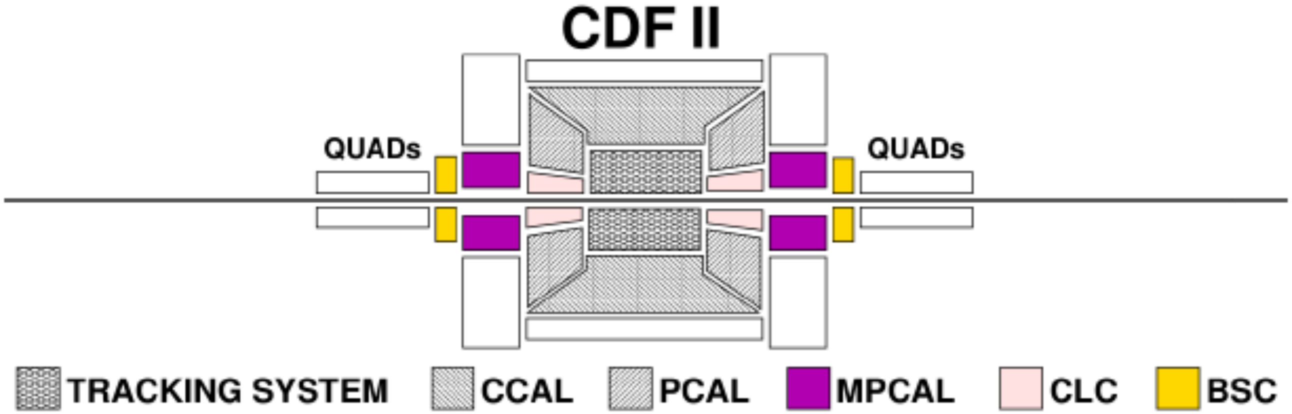
MUON
Muon Identification ε~97% misID~2%

46

LHCb FORWARD TRACKING



Collider Detector at Fermilab

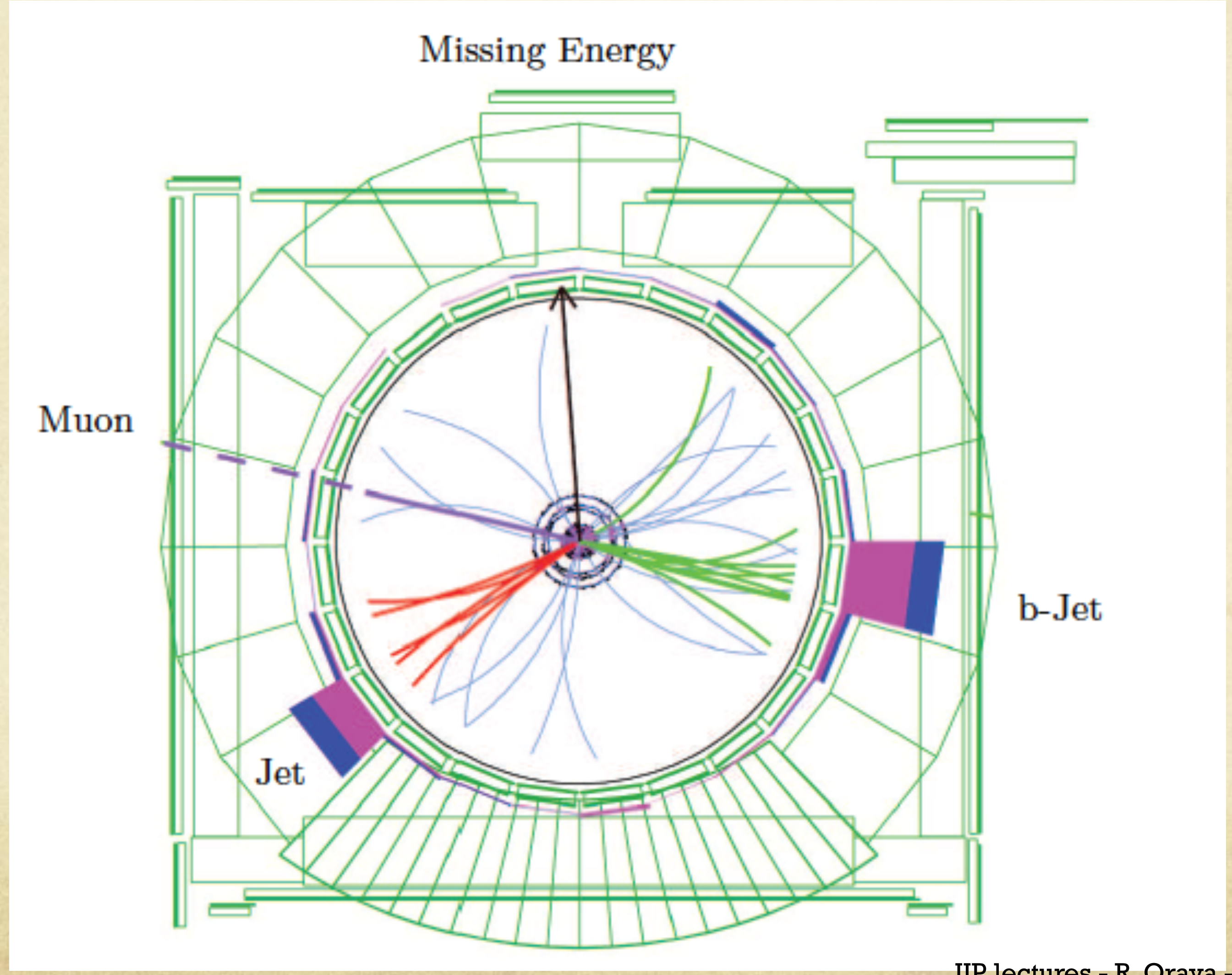


- We do not detect outgoing protons
- Forward detectors in veto

- BSC – Beam Shower Counters
- CLC – Cherenkov Luminosity Counters
- PCAL – Plug Calorimeter

We require all detectors, $|\eta| < 5.9$, to be empty except for two tracks

CDF



Central Hadronic State Analysis
Candidates selection

Trigger requirements:

- 2 central ($|\eta|<1.3$) towers with $E_t > 0.5$ GeV
- PCAL ($2.11<|\eta|<3.64$) in veto
- CLC ($3.75<|\eta|<4.75$) in veto
- BSC1 ($5.4<|\eta|<5.9$) in veto

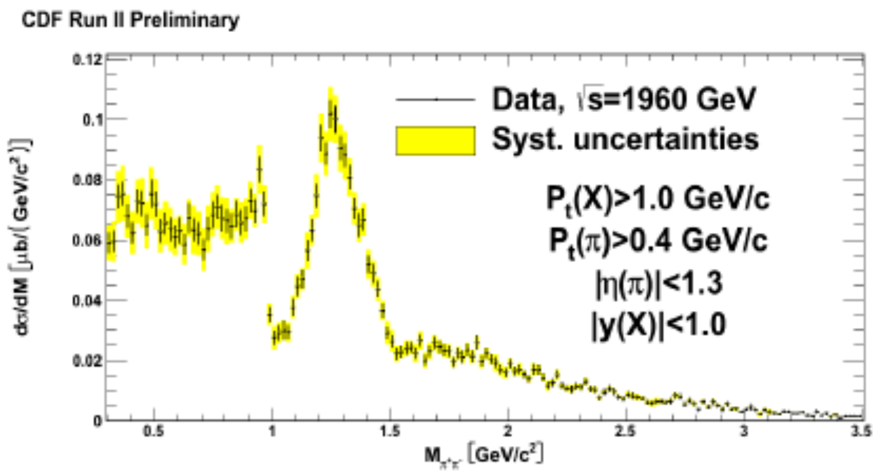
Gap cuts:

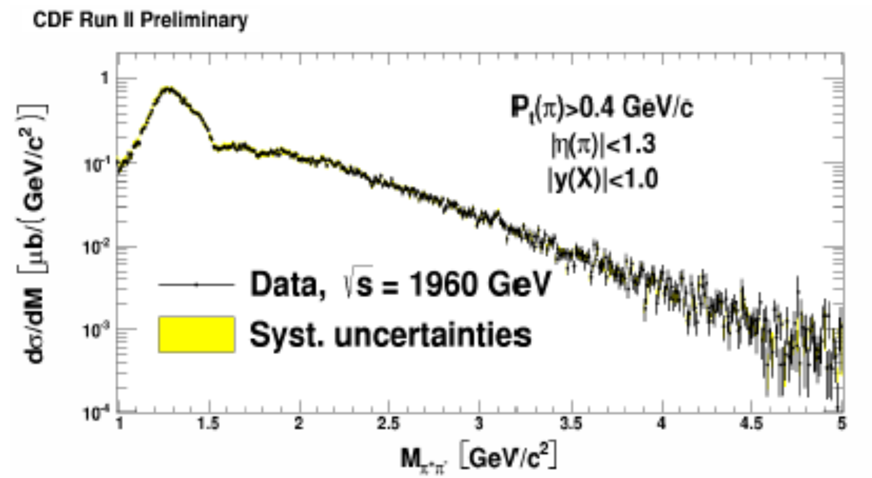
To determine noise levels in subdetectors we divide zero-bias sample from same periods into two sub-samples:

No Interaction:	**Interaction:**
• No tracks and • No CLC hits and • No muon stubs	At least one • Track or • CLC hit or • Muon stub

Central Hadronic State Analysis

$M(\pi^+\pi^-)$ for 1960 GeV

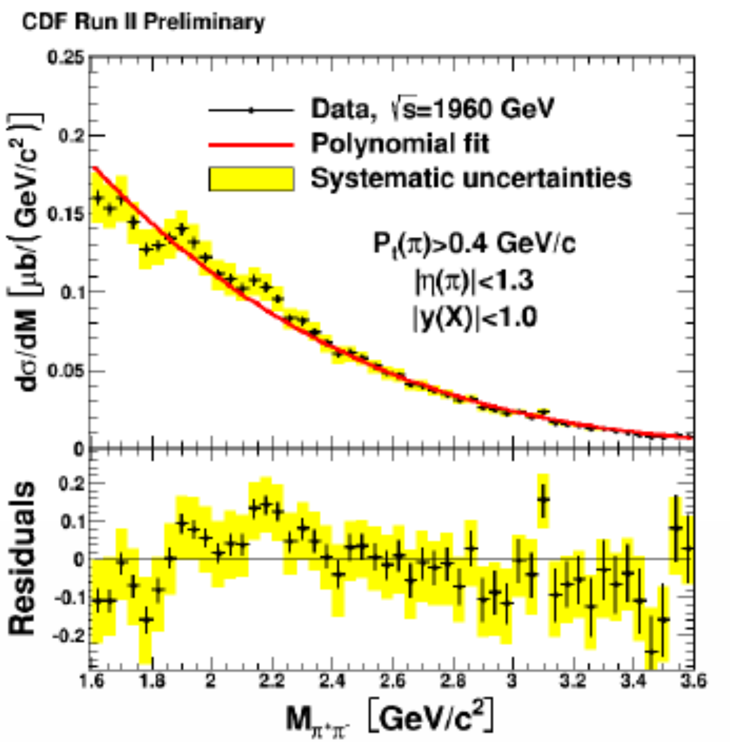


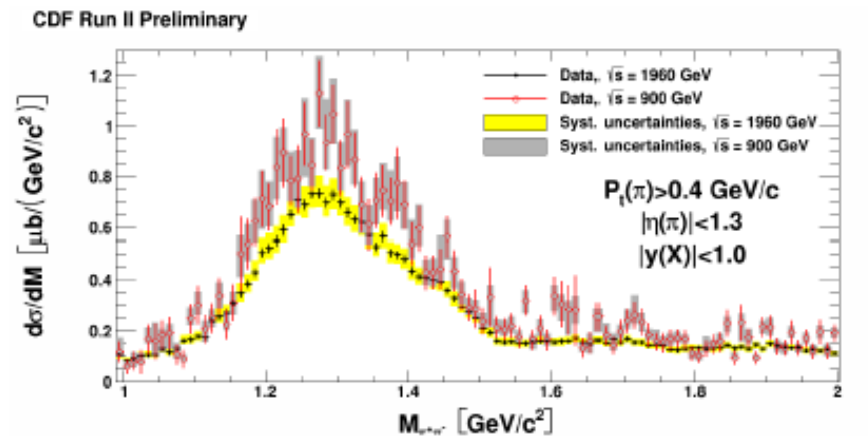


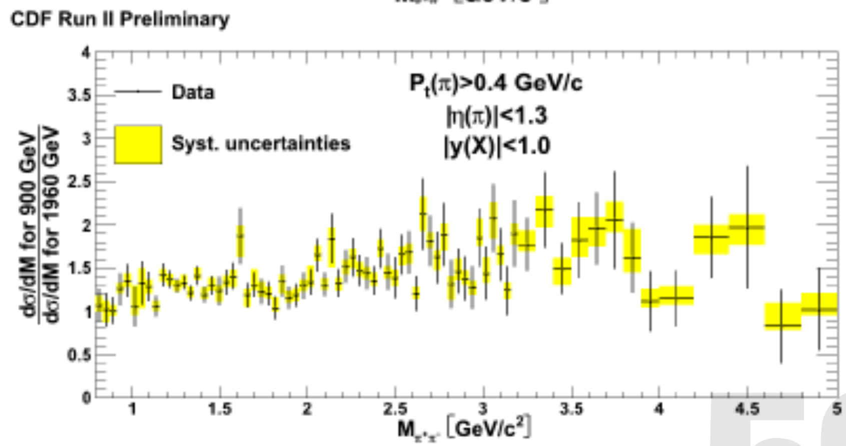
→ Broad continuum below 1 GeV/c^2
→ Cusp at 1 GeV/c^2
→ Resonant enhancement around 1.0 – 1.5 GeV/c^2 dominated by $f_2(1270)$

Central Hadronic State Analysis

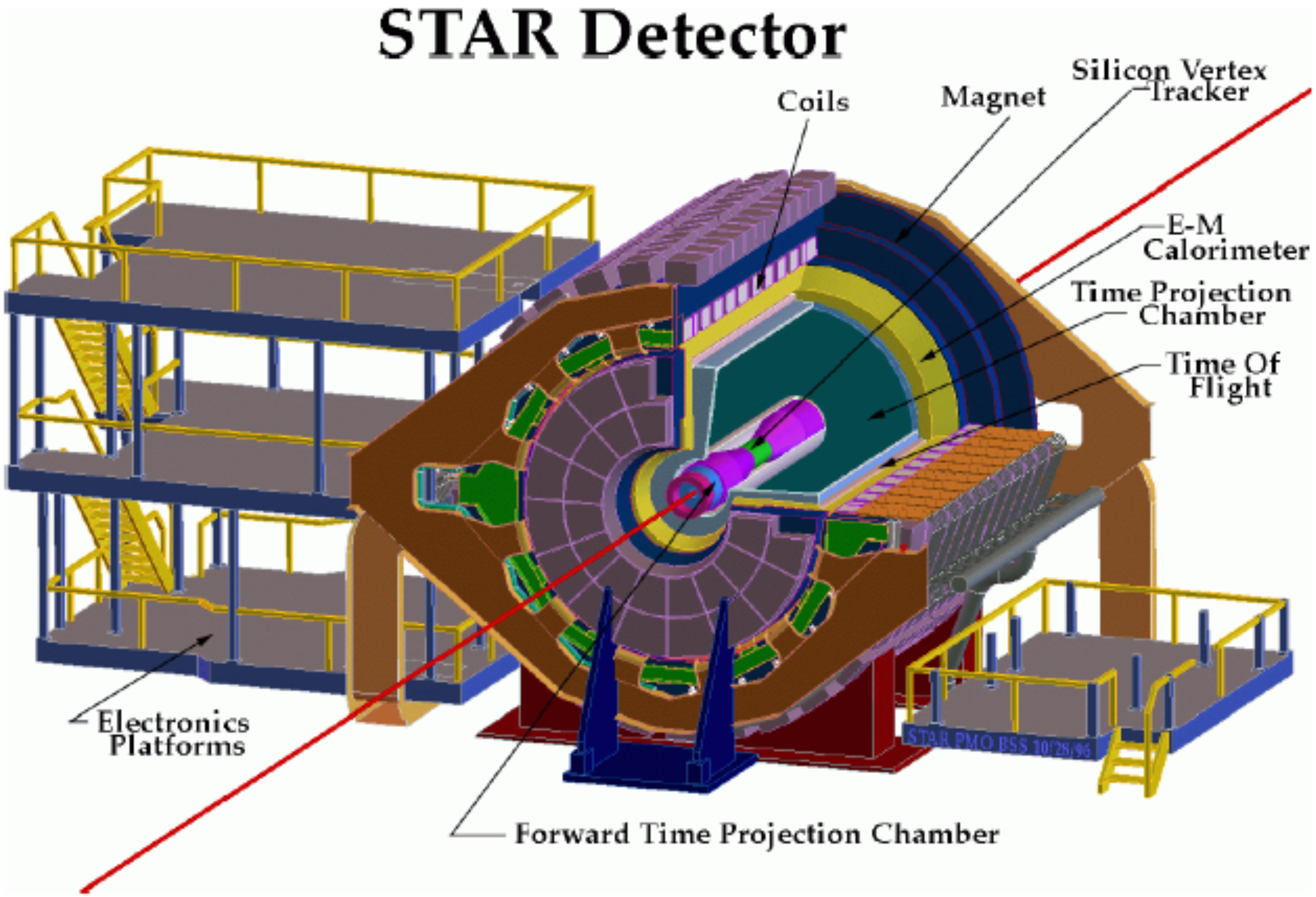
$M(\pi^+\pi^-)$ for 1960 GeV and 900 GeV

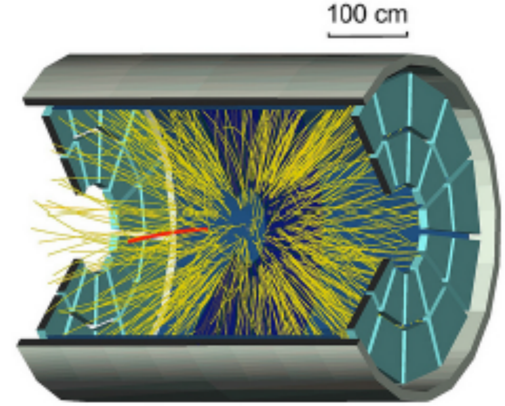


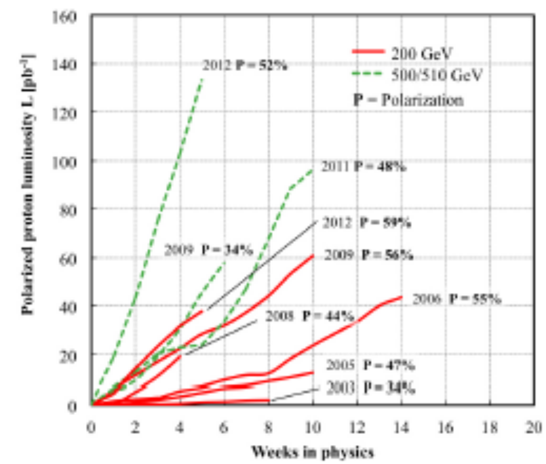




Indications of structure up to 2.4 GeV/c²





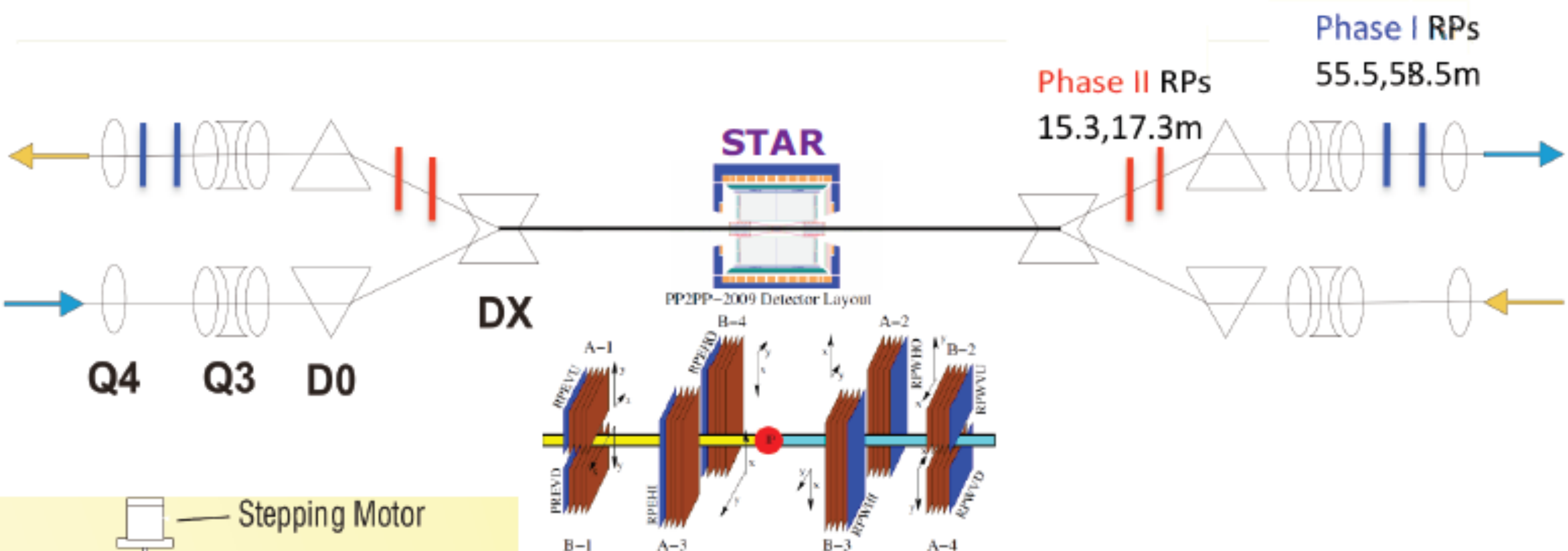


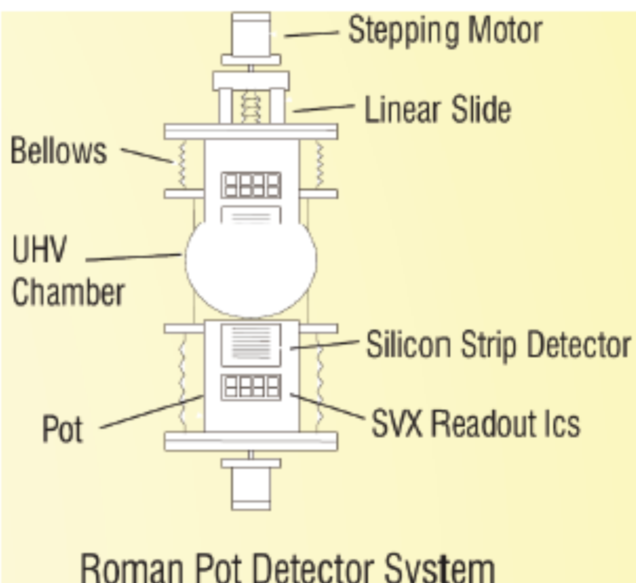
STAR - large acceptance detector running since 2000

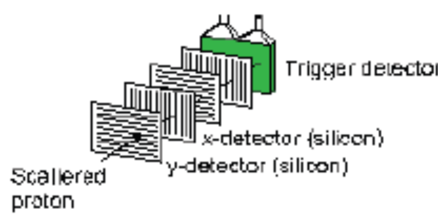
- high resolution tracking device: TPC in $-1 < \eta < 1$, $-\pi < \phi < \pi$
- forward rapidity gap veto: FTPC: $2.5 < |\eta| < 4.2$, BBC: $3.8 < |\eta| < 5.2$
- excellent particle identification capability: TPC dE/dx, ToF
- this analysis is based on data collected in 2009 during 5 day period of running with special optics $\beta^* = 20$ m.

Forward Proton Taggers

Need detectors (Roman Pots) to measure forward protons:
small t (four momentum transfer) and ξ (fraction of proton momentum loss).







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Total cross section in visible kinematic range

Definition of visible kinematic range:

- momentum transfered to protons: $0.005 < -t_1, -t_2 < 0.03$ GeV^2
- pseudorapidity of pions measured in TPC: $|\eta_\pi| < 1.0$
- pseudorapidity of $\pi\pi$ system: $|\eta_{\pi\pi}| < 2.0$

Data are normalized using elastic pp scattering events measured in the same experiment and $\sigma_{\text{tot}} = 51.6$ mb (from fit to world data). As the RP trigger and detector are common for elastic stattering and central production, many systematic uncertainties cancel out in cross section calculation.

Preliminary cross section for Central Exclusive Production of $\pi^+\pi^-$ pairs in pp collisions at $\sqrt{s} = 200$ GeV in visible kinematic range:

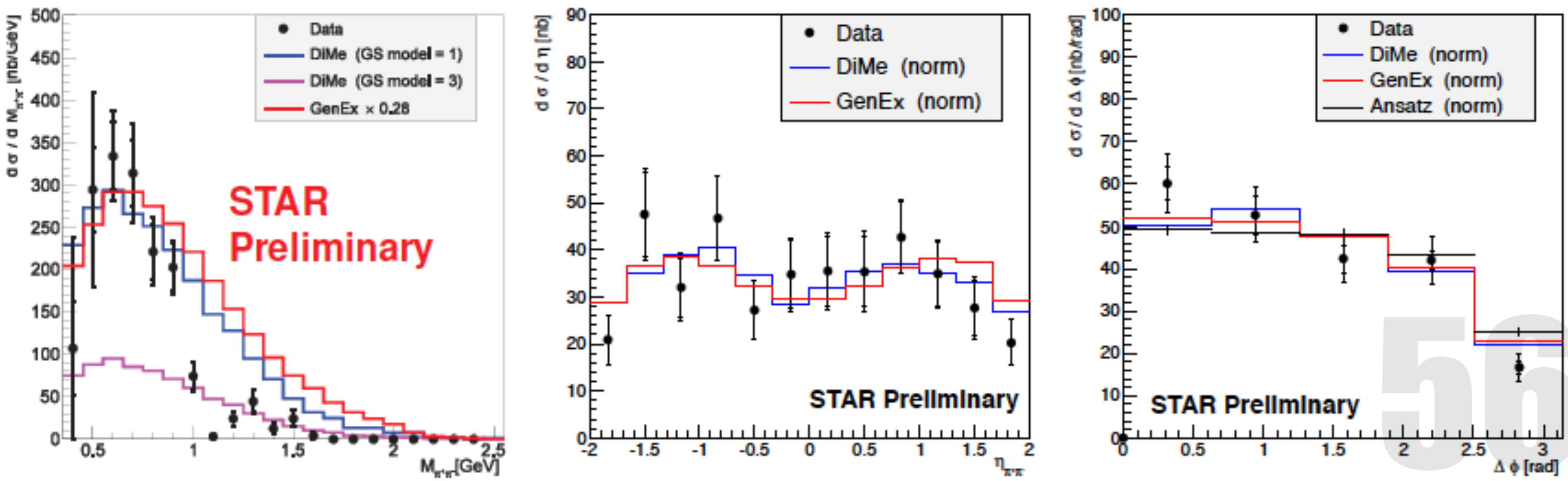
$$\sigma_{\text{CEP}}(200) = 133 \pm 8\,(\text{stat}) \pm 12\,(\text{syst})\text{ nb}$$

Main sources of systematic uncertainty:

- sensitivity to variation of TPC track selection cuts - 6%
- uncertainty of absolute normalization using elastic sample - 5%
- uncertainty of ToF trigger efficiency - 5% (estimated from ToF independent trigger)

Differential cross sections measurements

- Dime model (Eur. Phys. J. C (2014) 74:2848, http://dimemc.hepforge.org) for non-resonant background with model 1 gap survival is consistent with the measured cross section.
- GenEx model (based on Phys. Rev. D81 (2010) 036003) is also consistent with measured cross section assuming survival factor ≈ 0.28.
- Cross sections in function of $\eta_{\pi\pi}$ and $\Delta\phi$ (difference in azimuthal angle of the scattered protons) in the mass range $0.5 < M_{\pi\pi} < 1$ GeV are also well described by both models (predictions of the models are normalized to measured cross section in this mass range).



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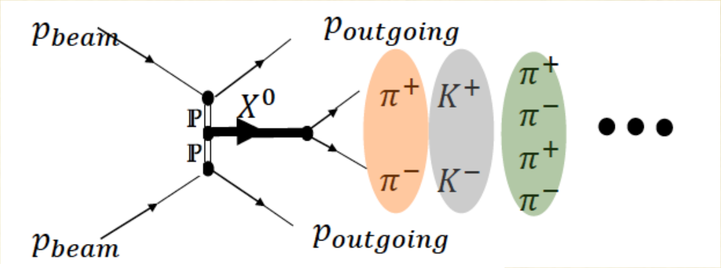
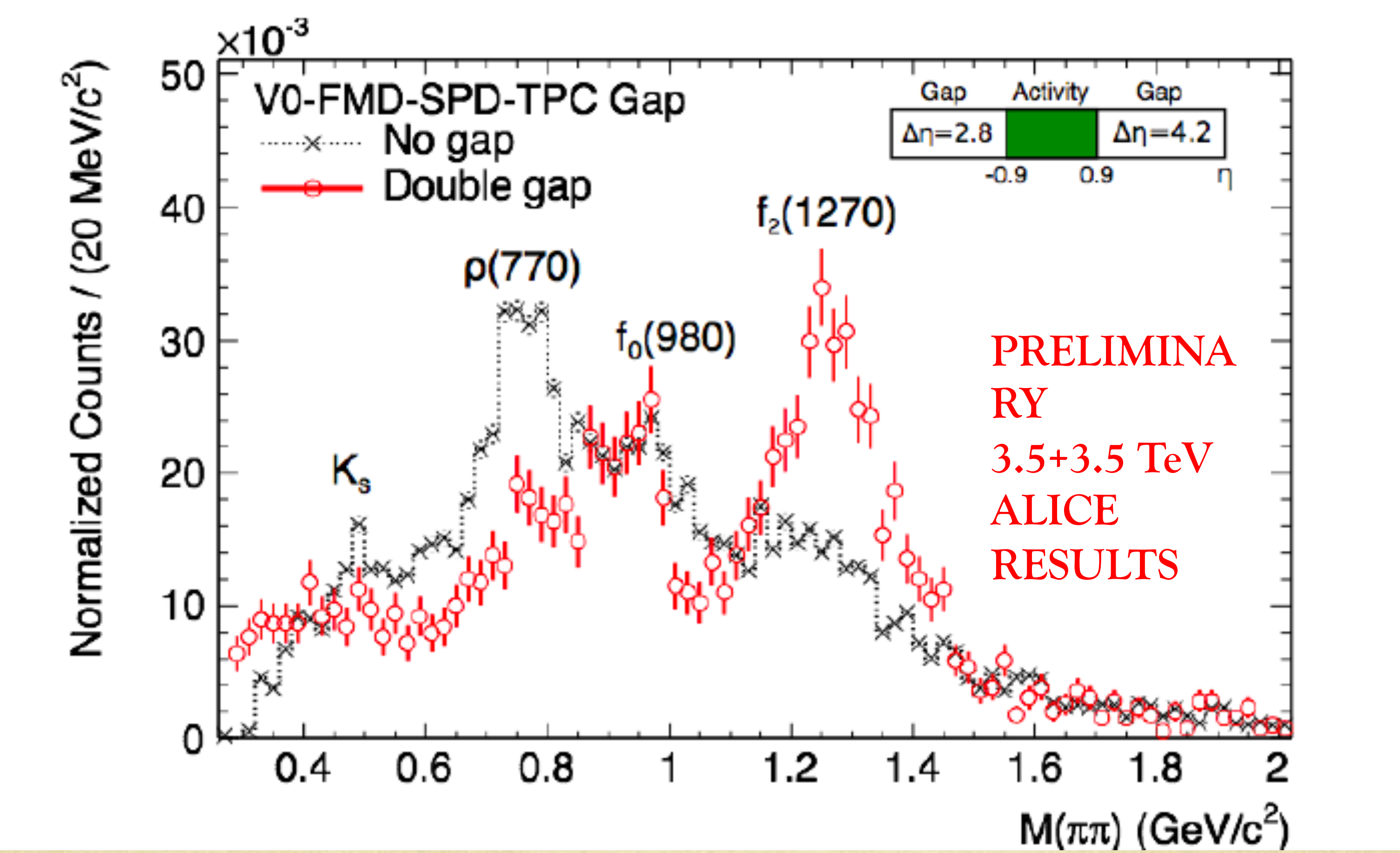
ALICE-LHC

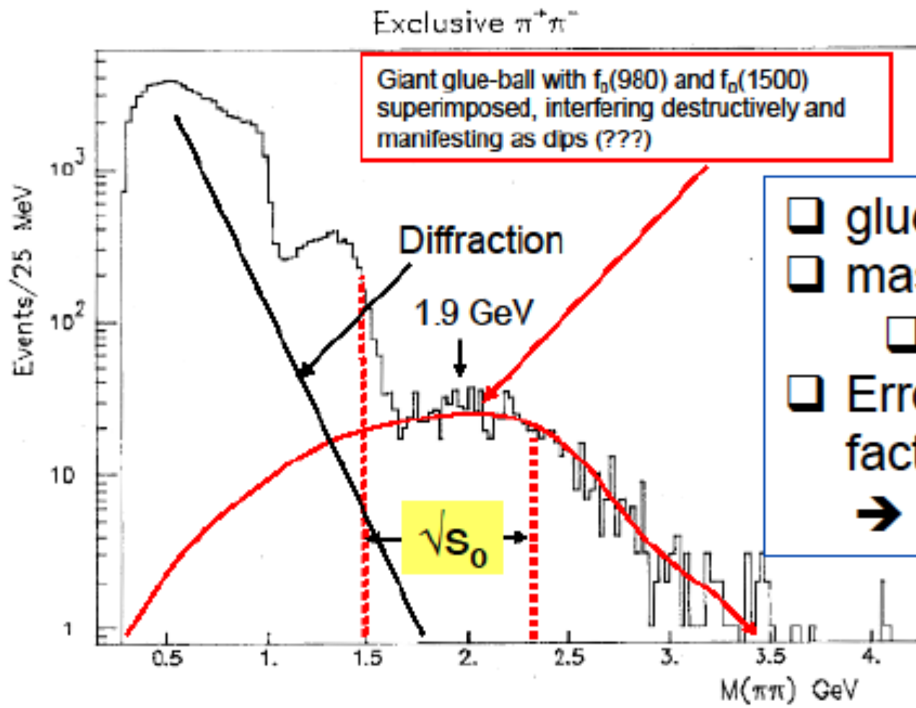
CENTRAL ππ MASS: EXCLUSIVE vs. INCLUSIVE





DINO's GLUEBALL?

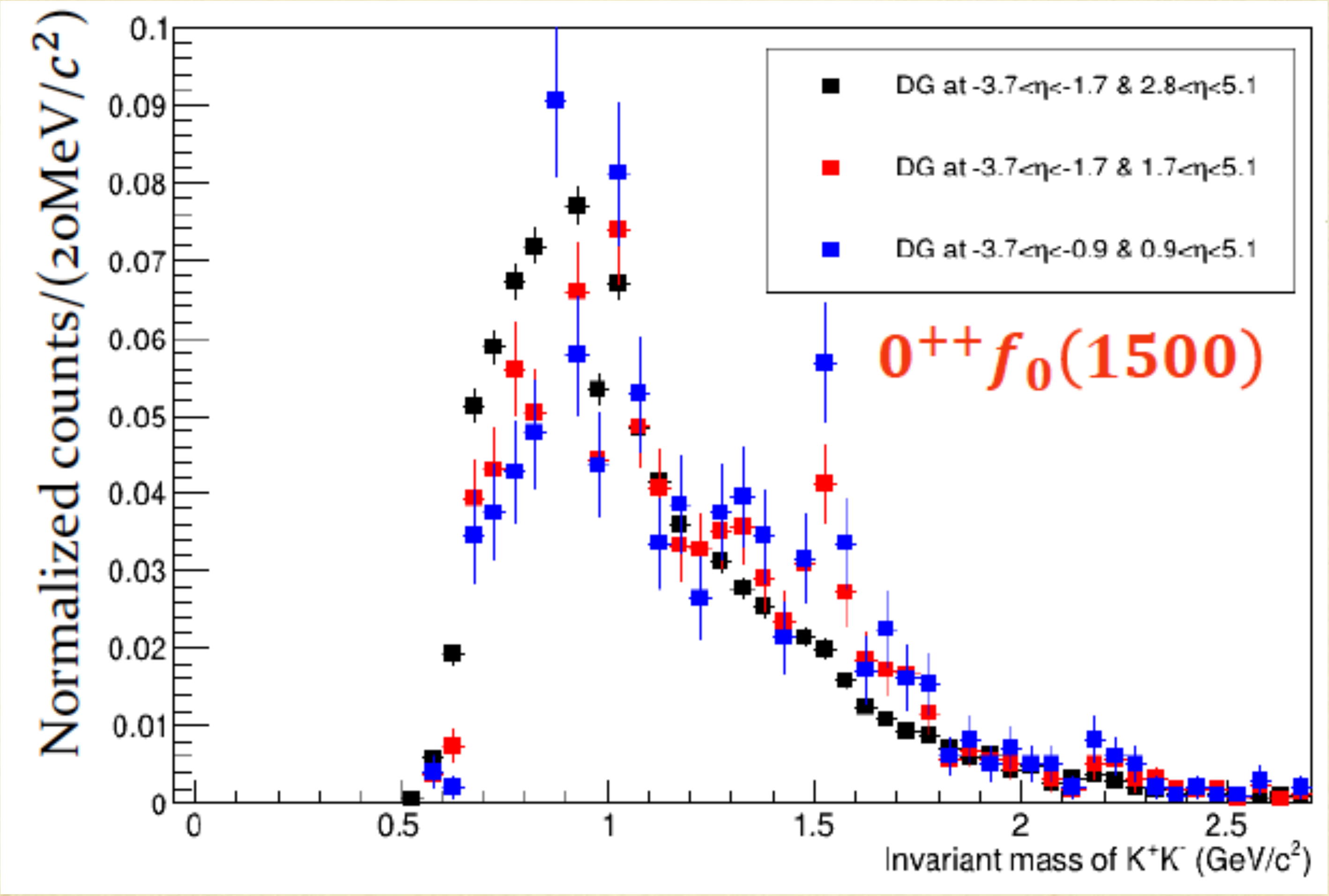
Saturation glueball?



- glue-ball-like object ➔ "superball"
- mass →1.9 GeV ➔ m_s^2= 3.7 GeV
  - agrees with RENORM s_o=3.7
- Error in s_0 can be reduced by factor ~4 from a fit to these data!
  ➔ reduces error in σ_t.

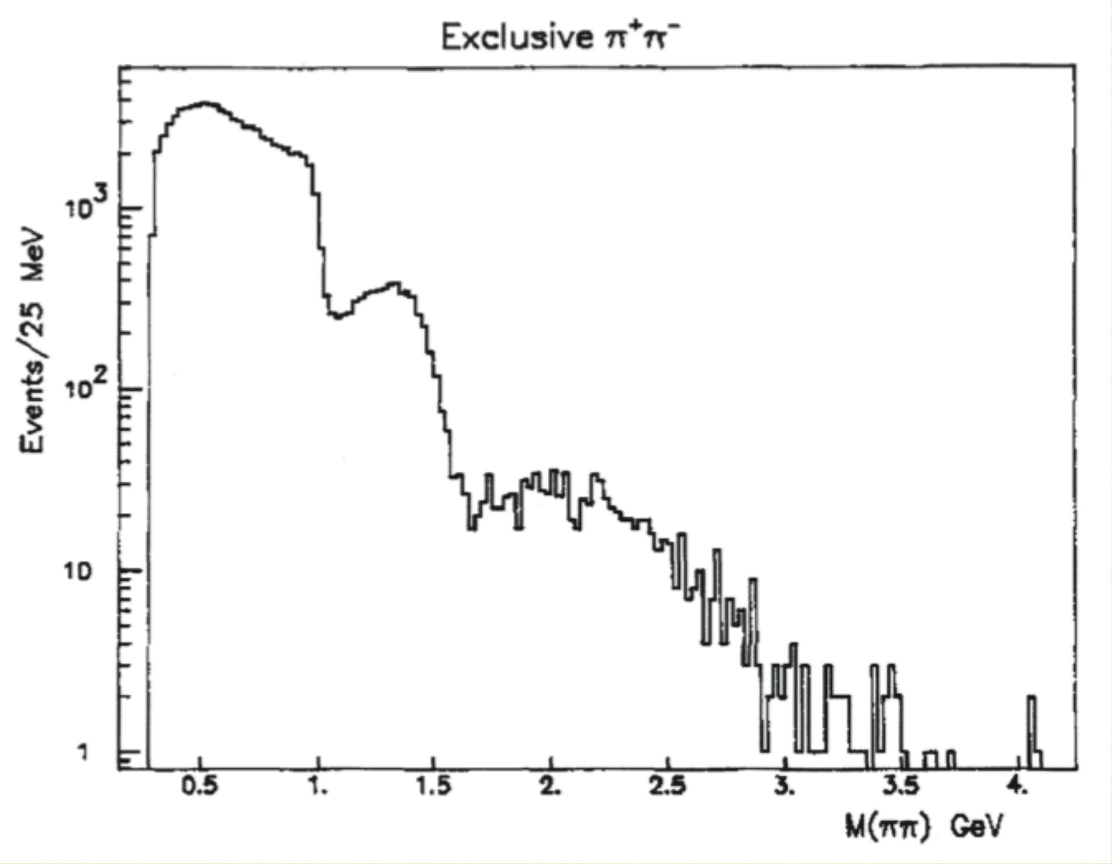
Figure 8: $M_{\pi^+\pi^-}$ spectrum in *DPE* at the ISR (Axial Field Spectrometer, R807 [97, 98]). Figure from Ref. [98]. **See M.G.Albrow, T.D. Goughlin, J.R. Forshaw, hep-ph>arXiv:1006.1289**

CENTRAL K^+K^- MASS vs. RAP GAP SELECTION - PRELIMINARY!



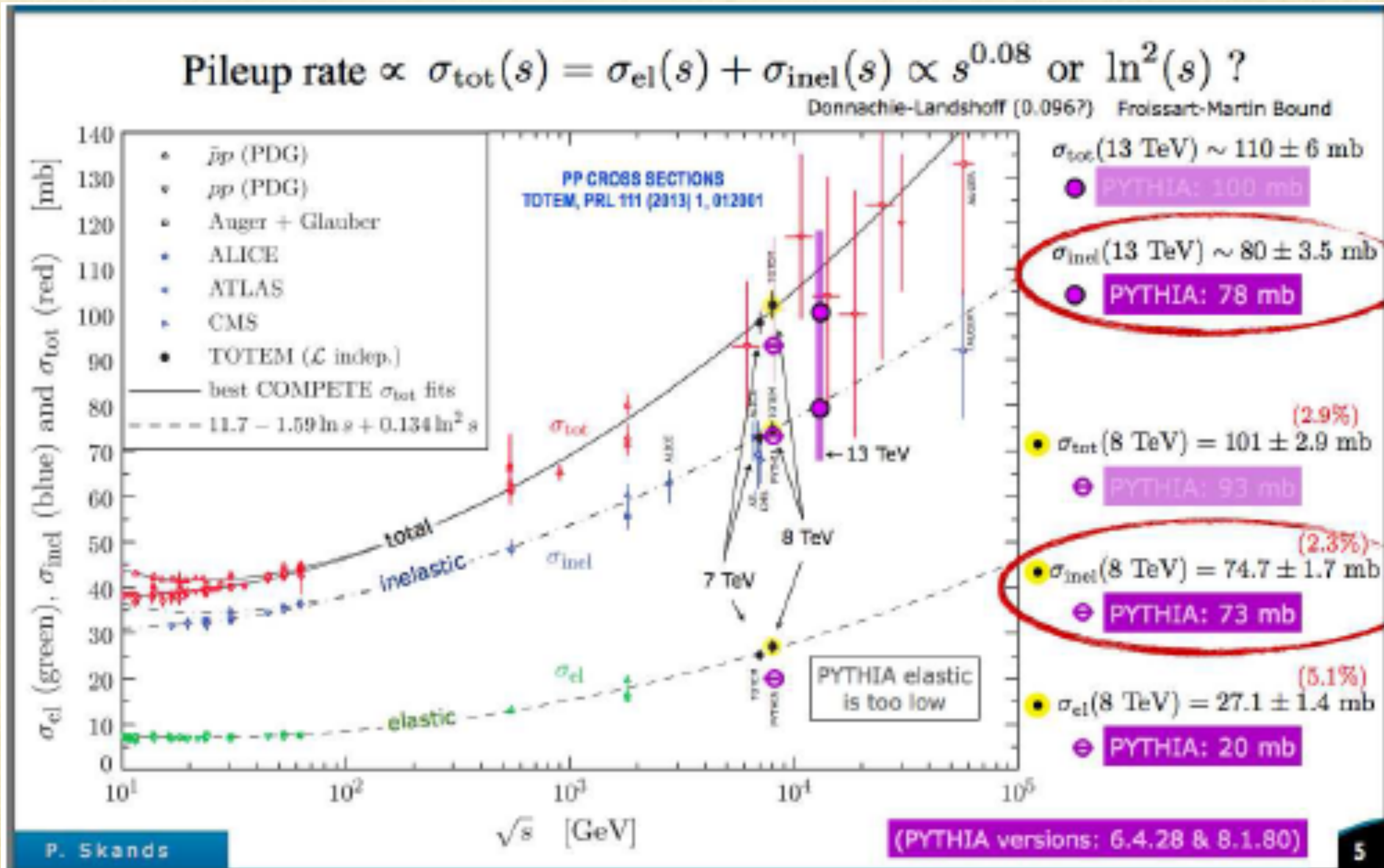
SFM at THE ISR...

No ϕ, rapid onset



SUMMARY OF NEW RESULTS

SUMMARY



Pileup rate ∝ $\sigma_{tot}(s) = \sigma_{el}(s) + \sigma_{inel}(s) \propto s^{0.08}$ or $\ln^2(s)$?
Donnachie-Landshoff (0.096?)
Froissart-Martin Bound
PP CROSS SECTIONS
TOTEM, PRL 111 (2013) 1, 012001
$\bar{p}p$ (PDG)
pp (PDG)
Auger + Glauber
ALICE
ATLAS
CMS
TOTEM ($\mathcal{L}$ indep.)
best COMPETE σ_{tot} fits
$11.7 - 1.59 \ln s + 0.134 \ln^2 s$
total
inelastic
elastic
σ_{tot}
σ_{inel}
σ_{el}
13 TeV
8 TeV
7 TeV
PYTHIA elastic is too low
σ_{el} (green), σ_{inel} (blue) and σ_{tot} (red) [mb]
$\sqrt{s}$ [GeV]
σ_{tot}(13 TeV) ~ 110 ± 6 mb
PYTHIA: 100 mb
σ_{inel}(13 TeV) ~ 80 ± 3.5 mb
PYTHIA: 78 mb
(2.9%)
σ_{tot}(8 TeV) = 101 ± 2.9 mb
PYTHIA: 93 mb
(2.3%)
σ_{inel}(8 TeV) = 74.7 ± 1.7 mb
PYTHIA: 73 mb
(5.1%)
σ_{el}(8 TeV) = 27.1 ± 1.4 mb
PYTHIA: 20 mb
(PYTHIA versions: 6.4.28 & 8.1.80)
P. Skands
5

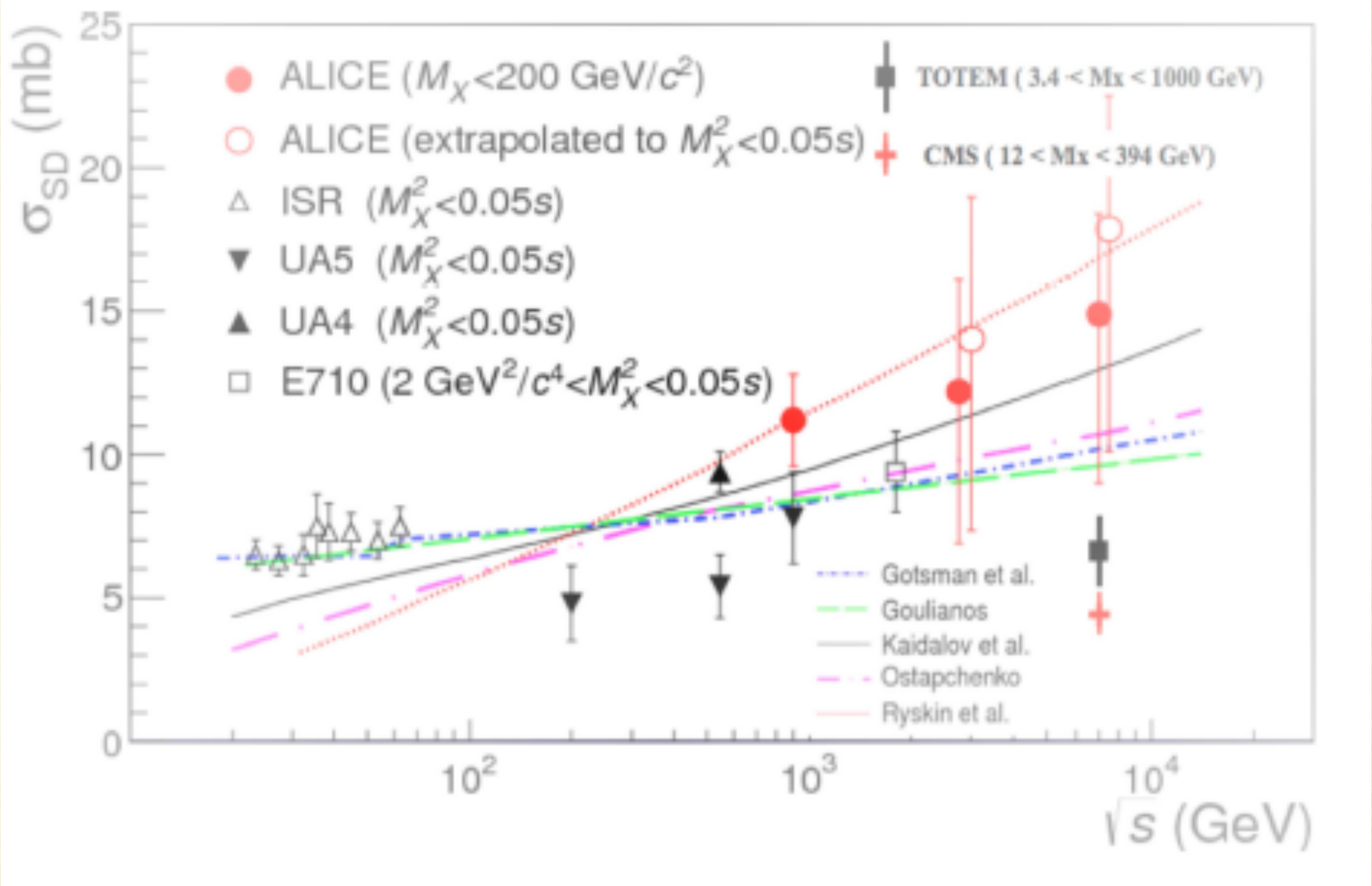
SINGLE DIFFRACTION - SUMMARY

Experiment	Energy	Mass	$\sigma_{sd}(pp)$
	[TeV]	[GeV]	[mb]
TOTEM	7	3.4 - 1100	6.5 ± 1.3
(preliminary)			
CMS	7	12 - 394	4.27 ± 0.04 (sta) $^{+0.65}_{-0.58}$ (sys)
ALICE	2.76	0 - 200	$12.2^{+3.9}_{-5.3}$
ALICE	7	0 - 200	$14.9^{+3.4}_{-5.9}$

LOW MASS SINGLE DIFFRACTION - TOTEM

M_X range	< 3.4 GeV	3.4-1100 GeV	3.4 - 7 GeV	7 - 350 GeV	350 -1100 GeV
TOTEM *[mb]	2.62 ±2.17	6.5 ± 1.3	≈ 1.8	≈ 3.3	≈ 1.4
QGSJET-II-04 [mb]	3.9	7.2	1.9	3.9	1.5
KMR(2014) [mb]		7.7	2.3	4.0	1.4

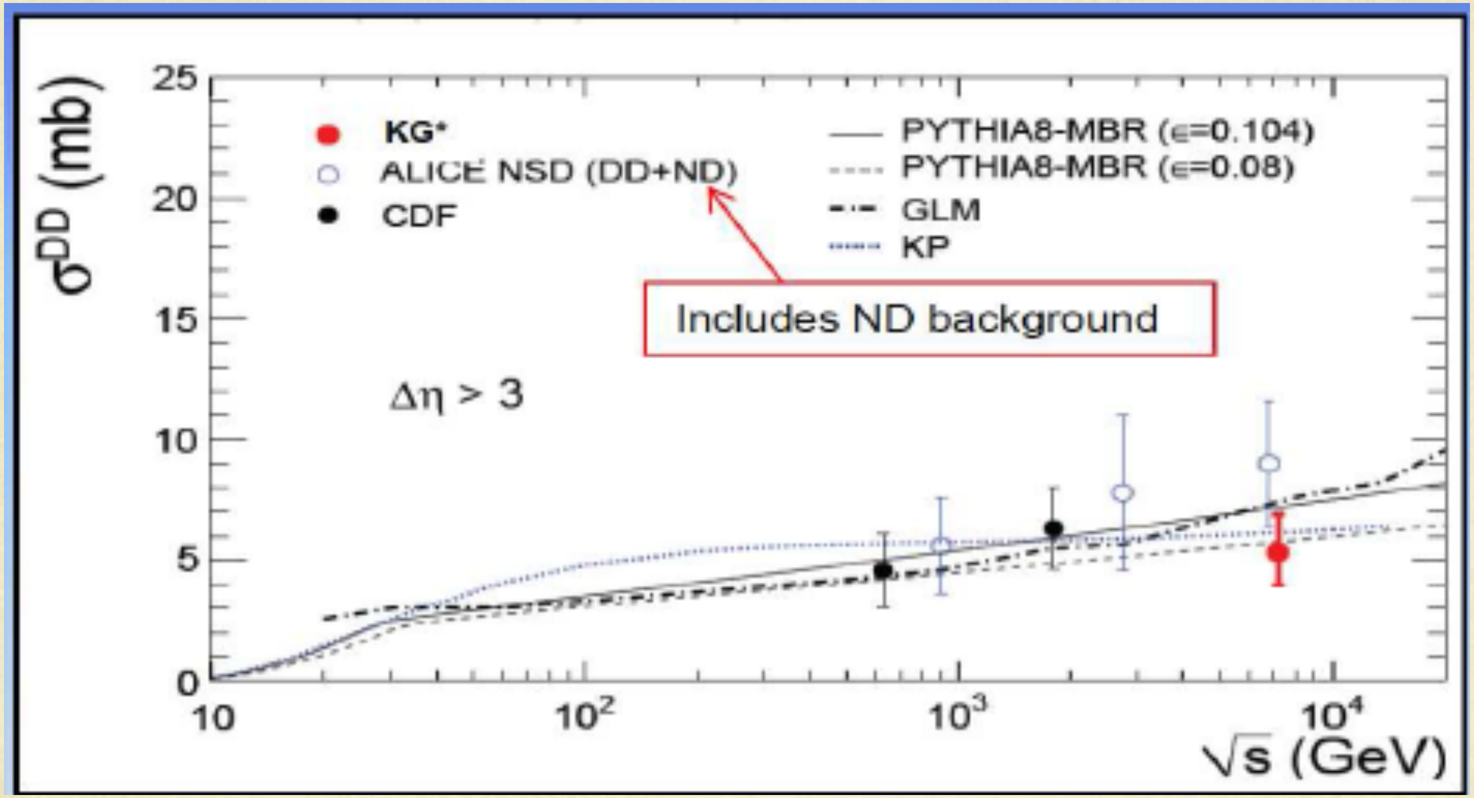
SINGLE DIFFRACTION - SUMMARY



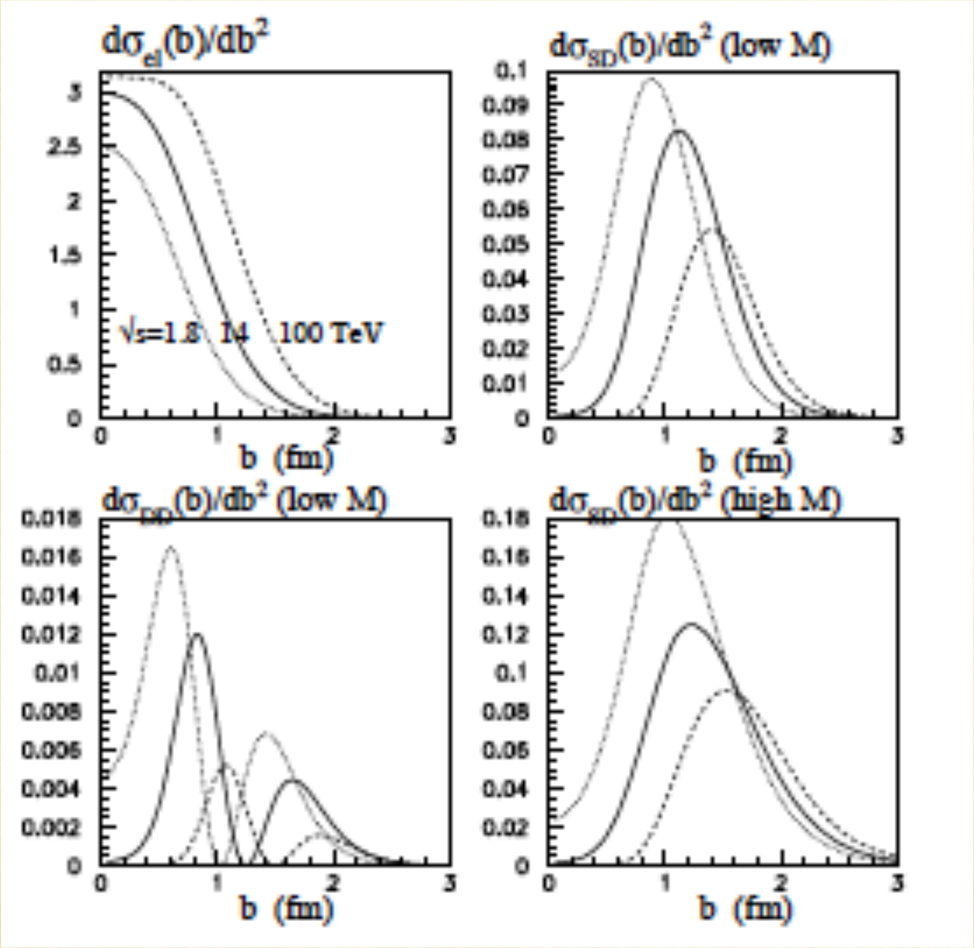
DOUBLE DIFFRACTION - SUMMARY

Experiment	Mass [GeV]	$\sigma_{dd}(pp)$ [mb]
TOTEM (preliminary)	$3.4 < M_{diff} < 8$	0.116 ± 0.025
PYTHIA 8		0.159
PHOJET		0.101
CMS	$M_X, M_Y > 10 : \Delta\eta > 3$	$0.93 \pm 0.01 \,^{+0.26}_{-0.22}$
ALICE	0 - 200	9.0 ± 2.6

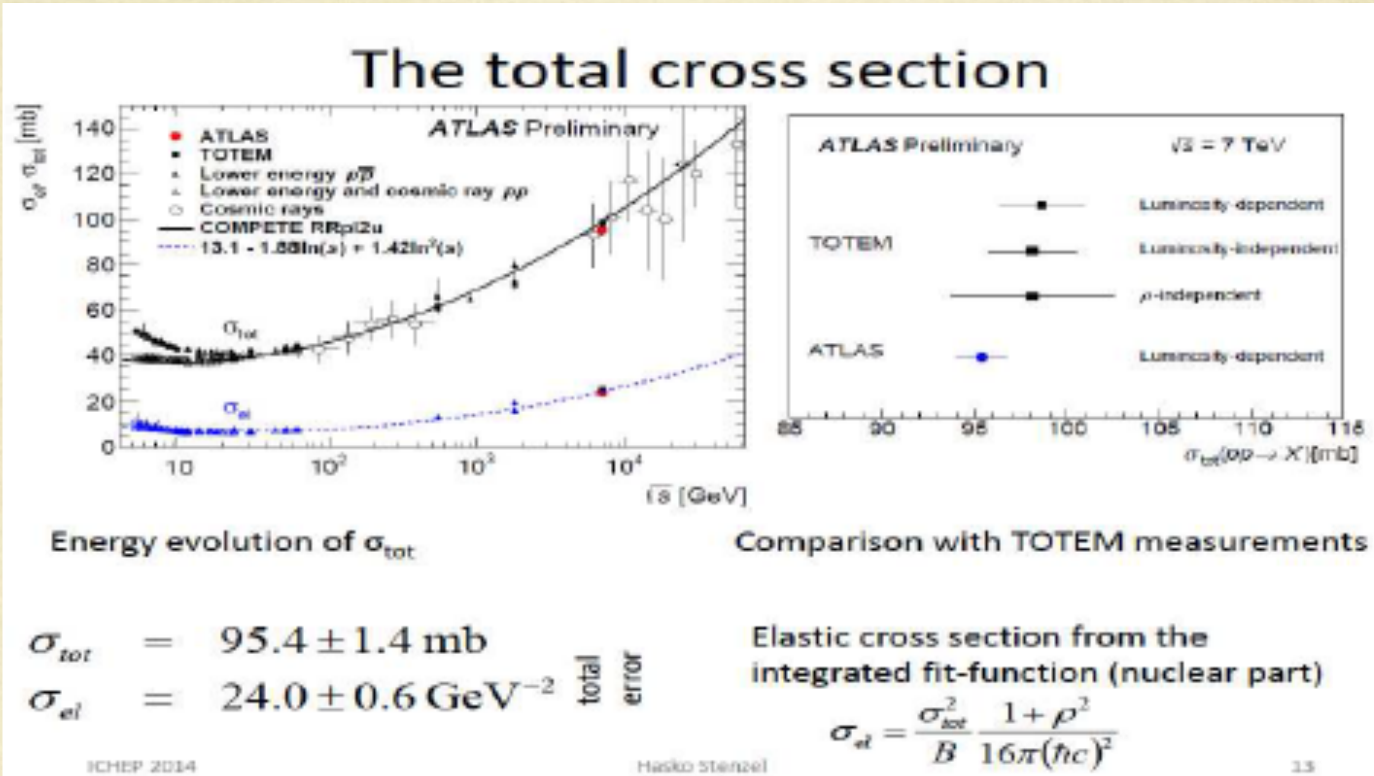
DOUBLE DIFFRACTION - SUMMARY



TEL AVIV GROUP

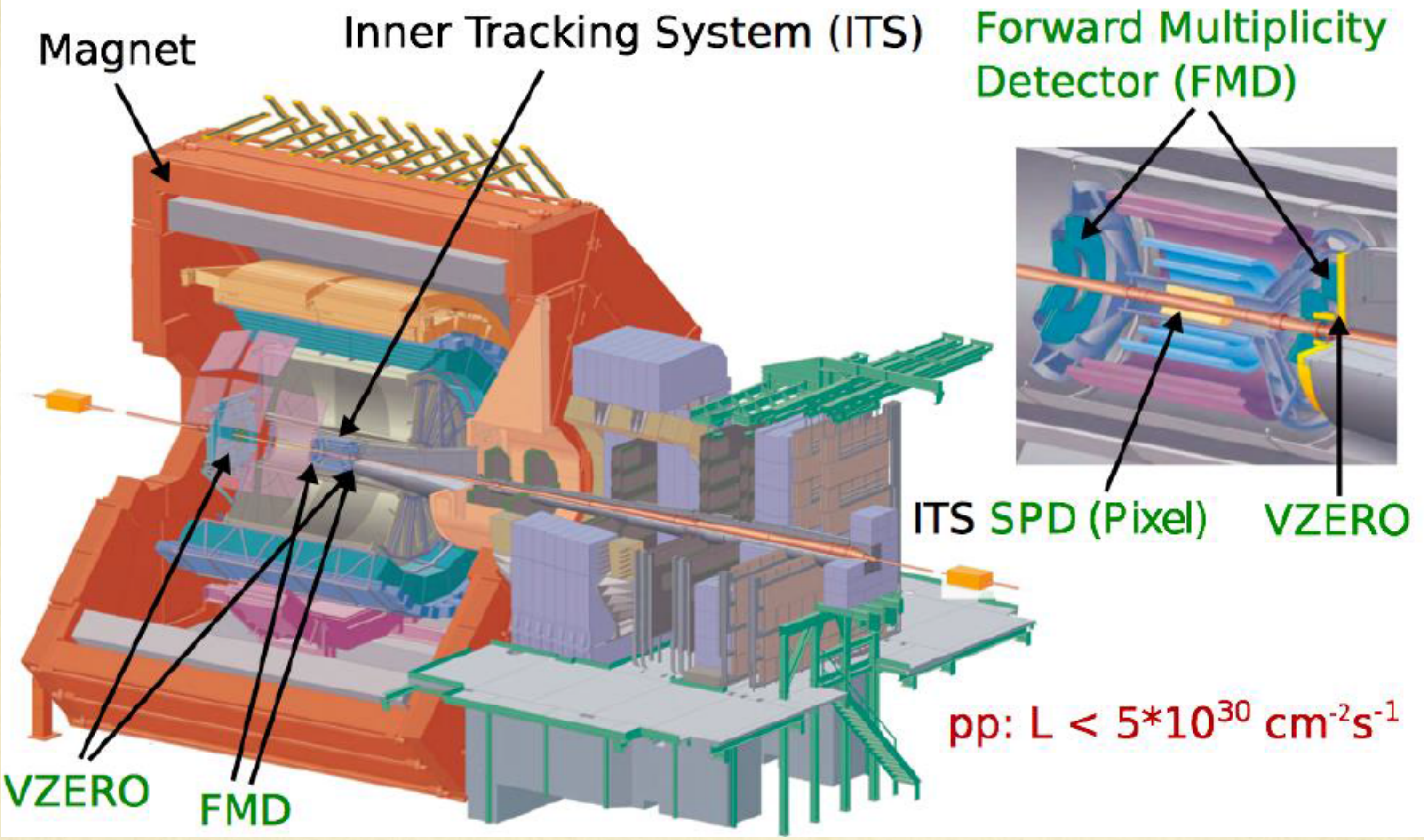


TOTAL CROSS SECTION - ATLAS



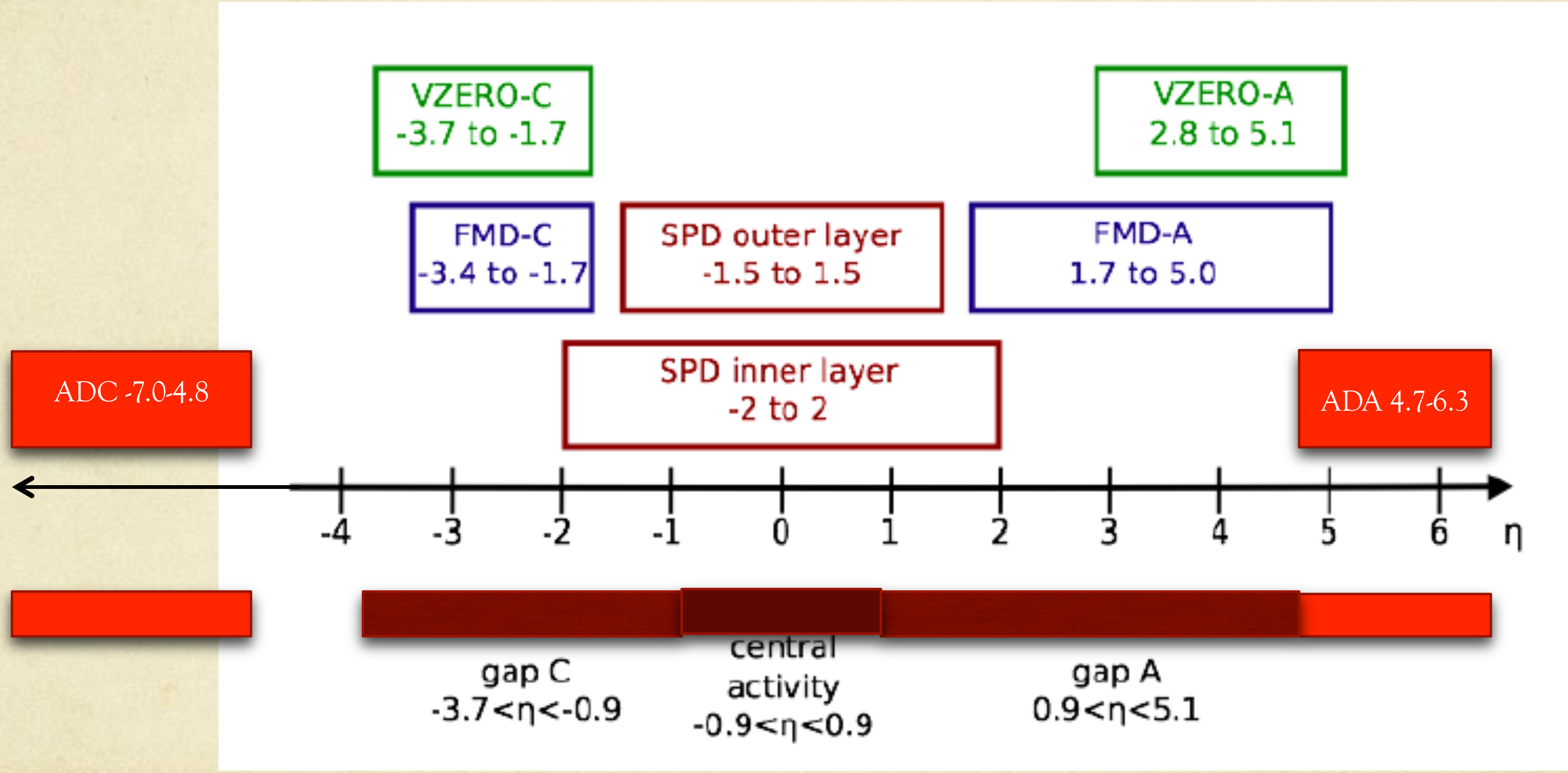
FUTURE PLANS

ALICE FORWARD DETECTORS

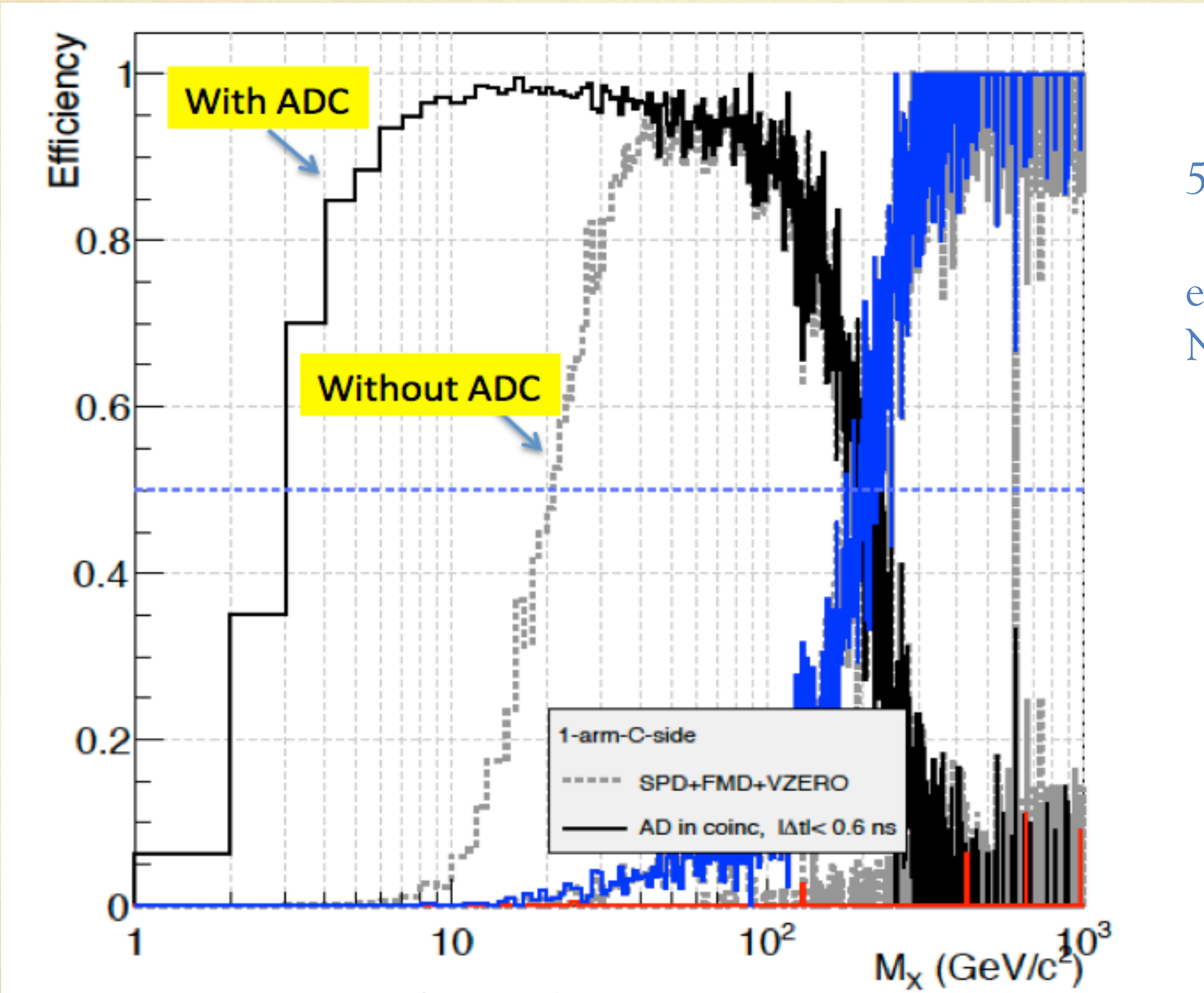


ADA/ADC UPGRADE FOR IMPROVED FORWARD COVERAGE:
8 + 8 PMD QUADRANTS AT BOTH SIDES OF THE EXPERIMENT.

ALICE FORWARD DETECTORS – ADA/ADC COMPLETE THE COVERAGE



ADC FORWARD TRIGGER EFFICIENCY

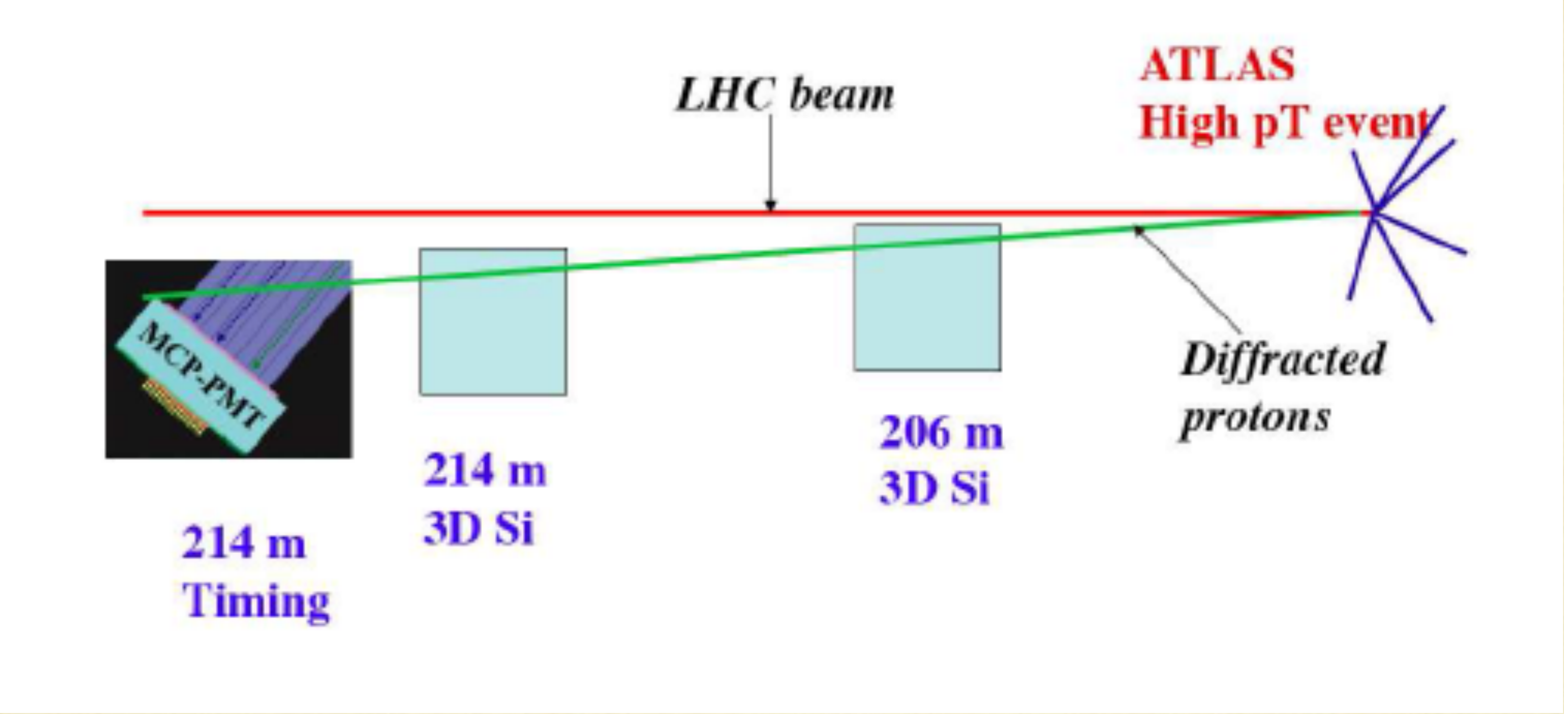


forward mass

50% acceptance at 3 GeV

efficiency down to lowest N* masses

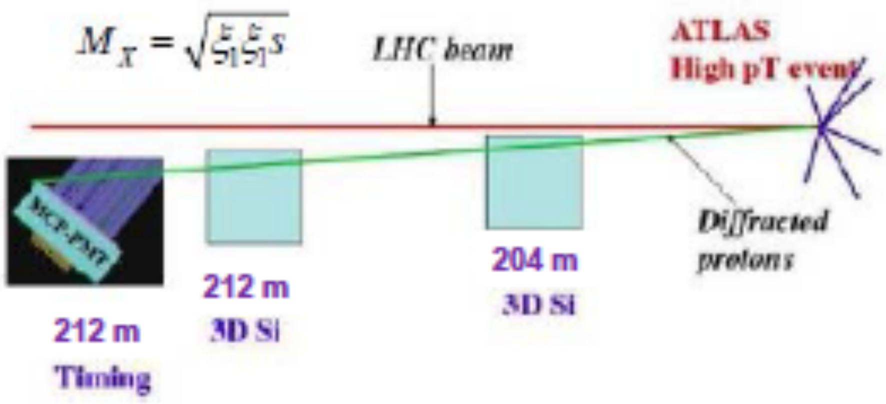
ATLAS FUTURE PLANS

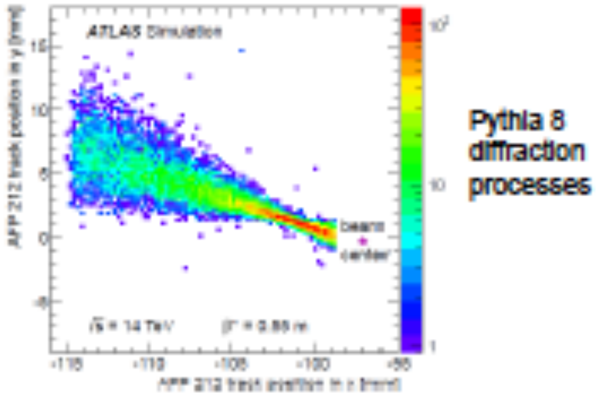


Christophe Royon in Diffraction 2014

ATLAS AFP

Proton leaves the interaction intact, travels through LHC optics and is detected at ~210 m





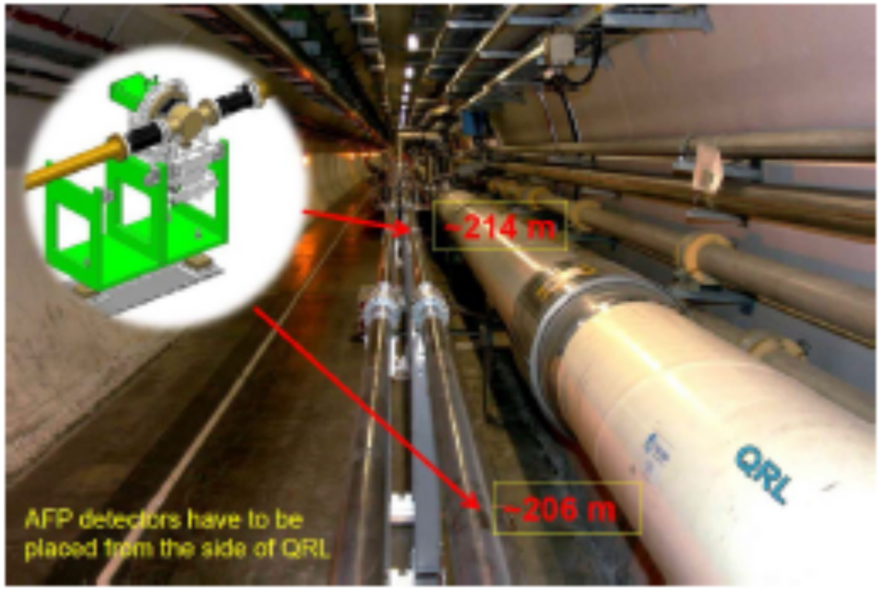
AFP: 2 stations on each side of Inter.Point with tracking detectors at 204 and 212m and timing detectors at 212m

What is AFP?

1) Array of radiation-hard near-beam **Silicon detectors** with resolution ~10 μm, 1μrad

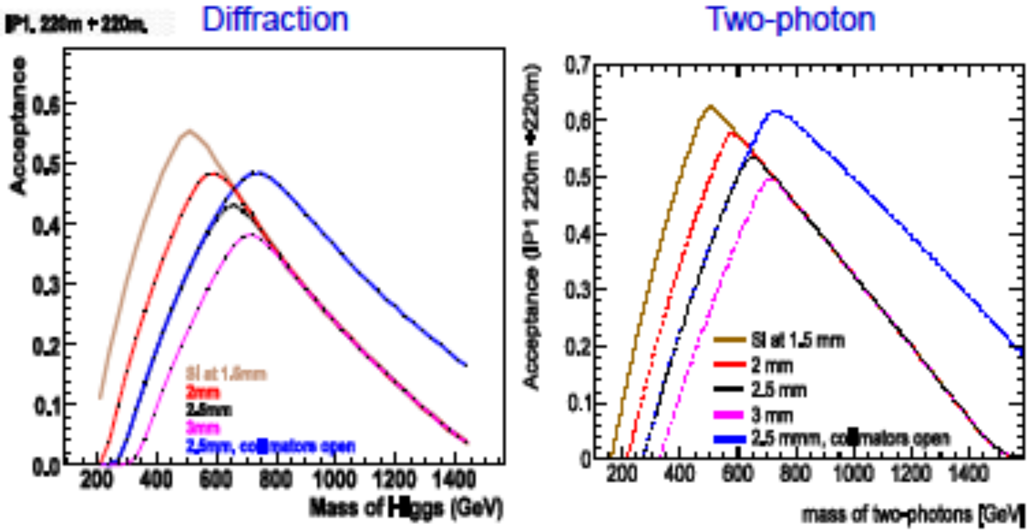
2) **Timing detectors** with up to ~10 ps resolution for overlap background rejection (SD+JJ+SD)

3) **Roman Pots**



AFP PHYSICS GOALS

210+210 at IP 1



Acceptance >40% for wide range of resonance mass

- Mass and rapidity of centrally produced system

$$M = \sqrt{\xi_1 \xi_2} \cdot \sqrt{s}$$

$$y = \frac{1}{2} \ln(\xi_1 / \xi_2)$$

- where $\xi_{1,2}$ are the fractional momentum loss of the protons
- Mass resolution of 3-5 GeV *per event*

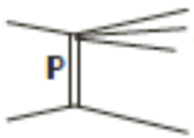
Allows ATLAS to use LHC as a tunable √s gluon-gluon or γγ collider while simultaneously pursuing standard physics program

AFP PHYSICS GOALS

In a fraction of Forward Physics: one or both protons stay intact: measure them with AFP and provide ξ & t *(these make up around 20% of total pp x-section)*

Single-tag: Single Diffraction

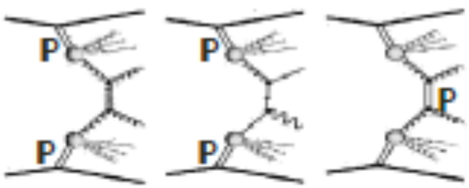
- Jets, W, Z: Soft survival prob. S^2
- Particle spectra, Gap spectra: SD vs. DD



P:= 'Pomeron', a **color-less** object with *Q*-numbers of the vacuum

Double-tag: Double-Pomeron Exchange

- Dijet: constrain gluon content of IP
- γ+Jet: constrain quark content of IP
- Jet-gap-jet: test BFKL IP



Double-Photon Exchange

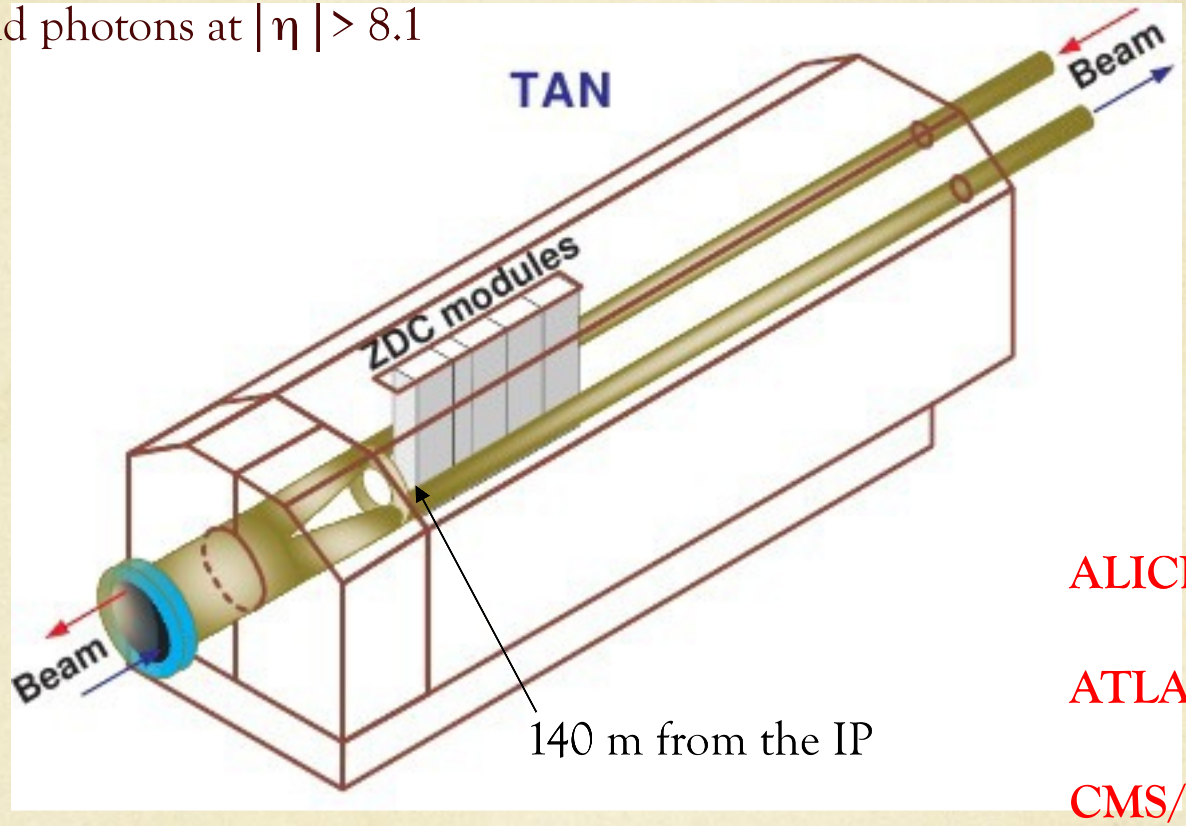
- γγ→ WW/ZZ/γγ: Anomalous quartic couplings → sens. ~x100 wrt only central det.
- γγ→ μμ: calibration/alignment of AFP

Central Exclusive Production

- Dijets, Trijets: constrain predictions to CEP of Higgs (S^2, Sudakov suppr., unintegr. f_g)

Zero Degree Calorimeter - ZDC

Quartz fiber Tungsten sampling calorimeter
for neutrons and photons at $|\eta| > 8.1$



ALICE

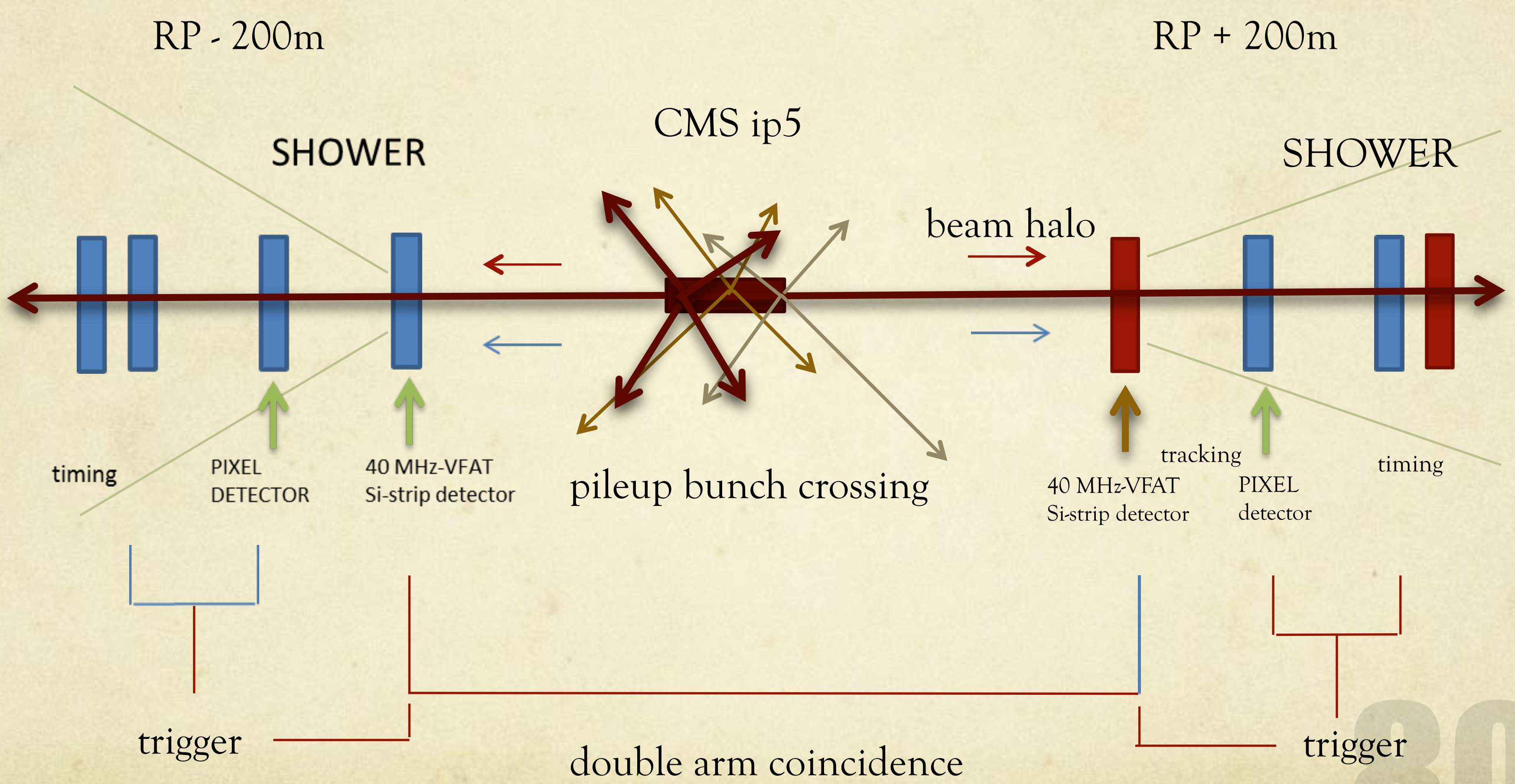
ATLAS/LHCf

CMS/TOTEM

Reconstruction of π^0, η, η', Δ, Σ, Λ

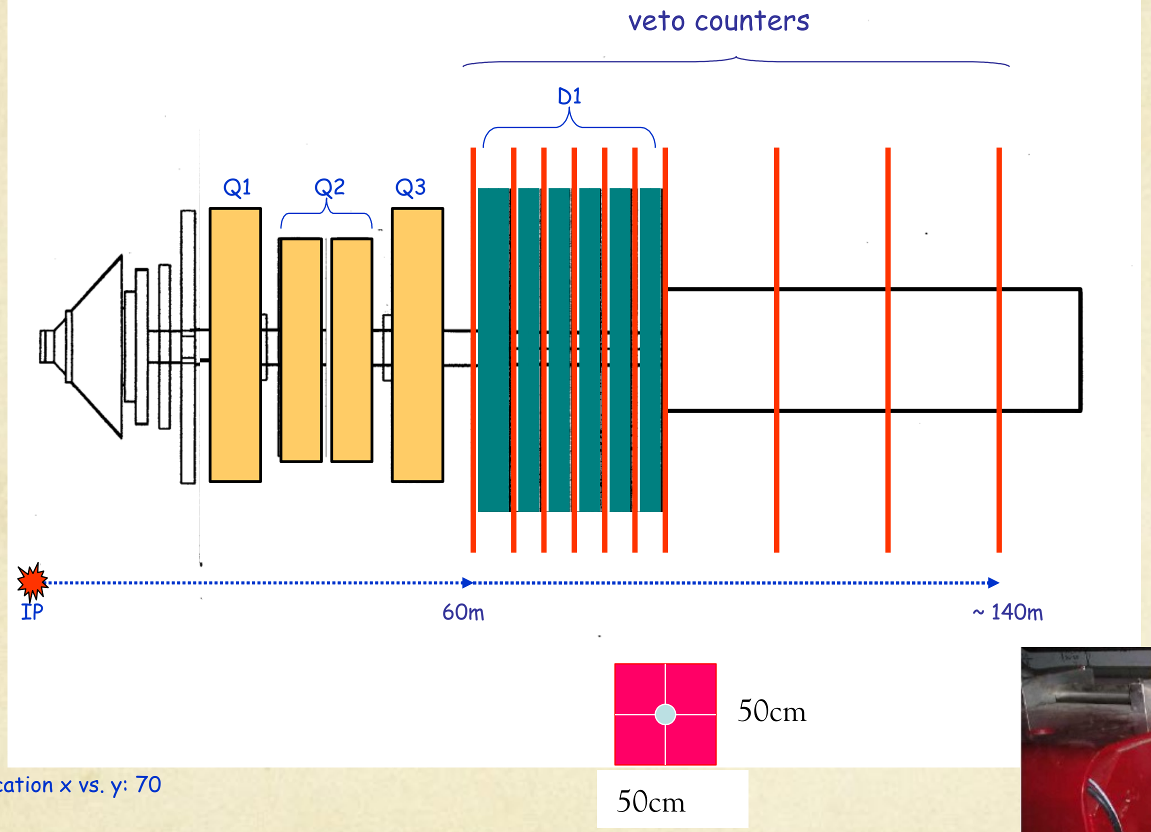
Roman Pot detector system

study of combination: Si strip- Si pixel- timing (schematic)

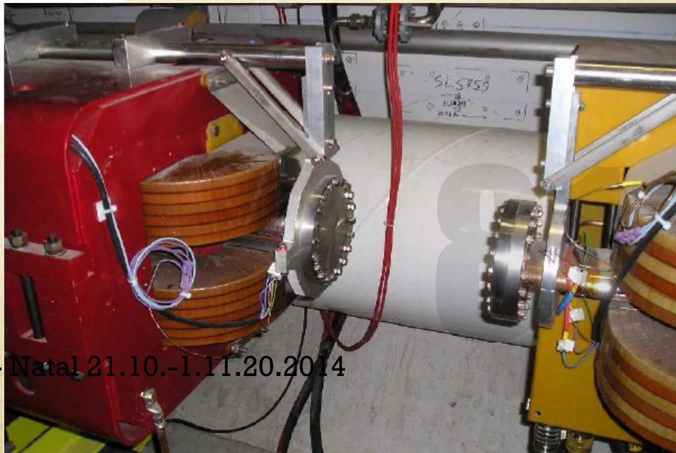


EXTEND FORWARD ACCEPTANCES BY SHOWER COUNTERS

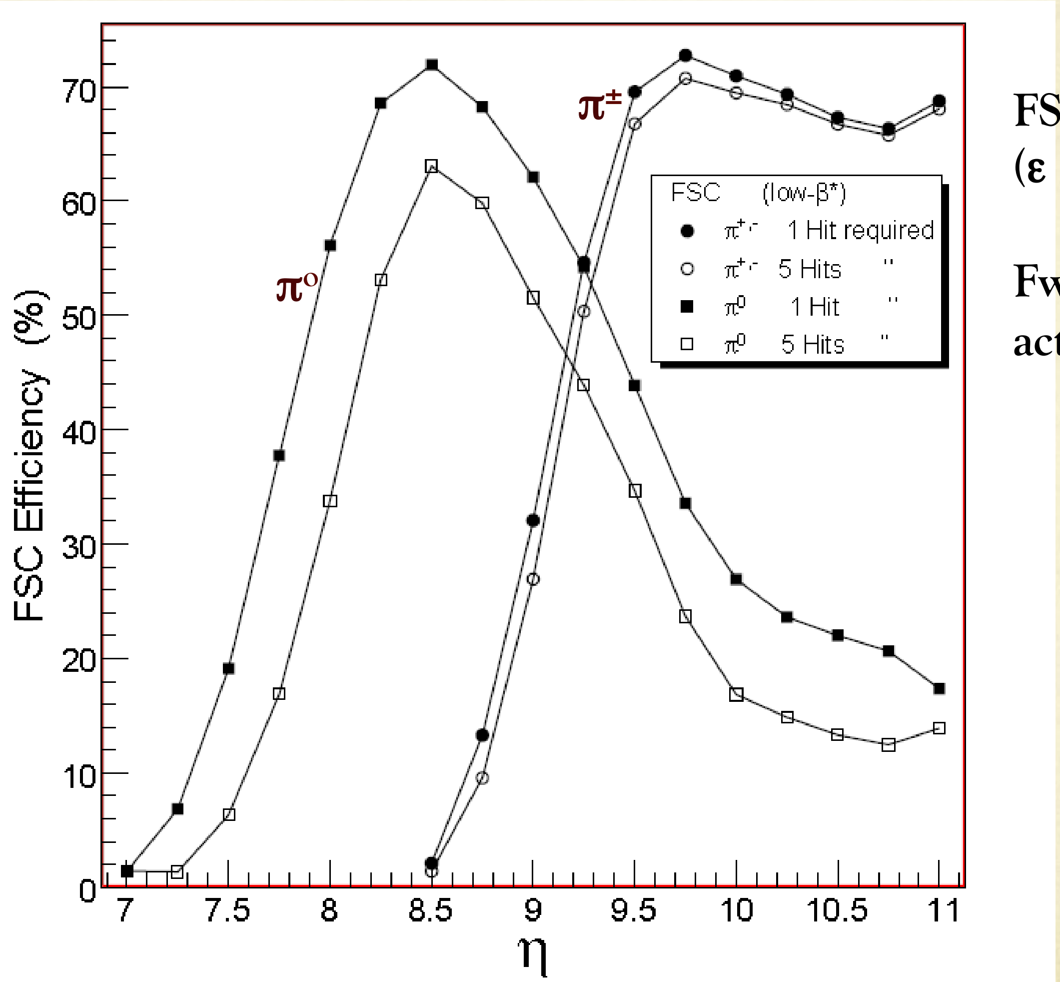
Rapidity Gap Veto – Detector Lay-Out



magnification x vs. y: 70



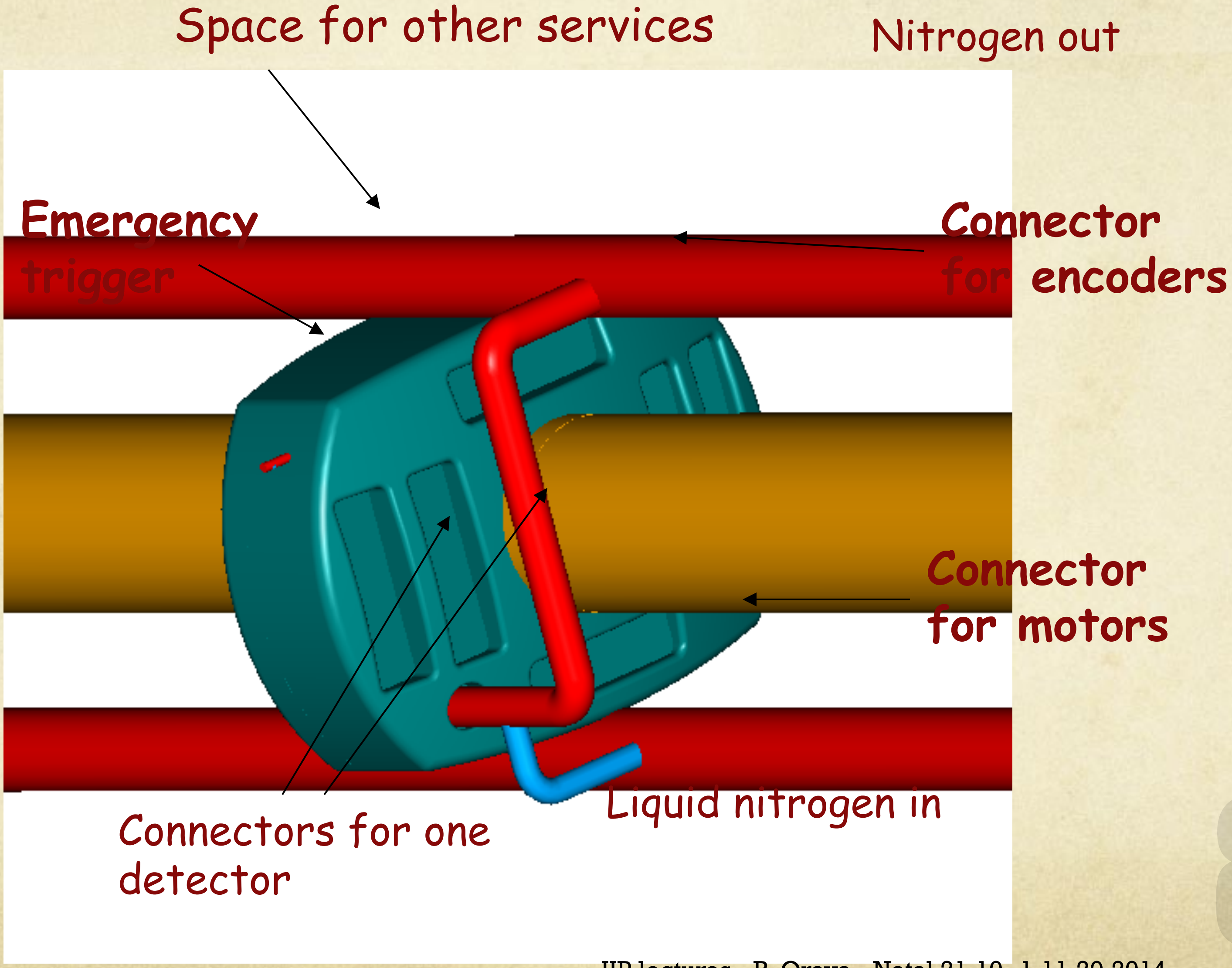
FORWARD DETECTION EFFICIENCIES ARE IMPROVED



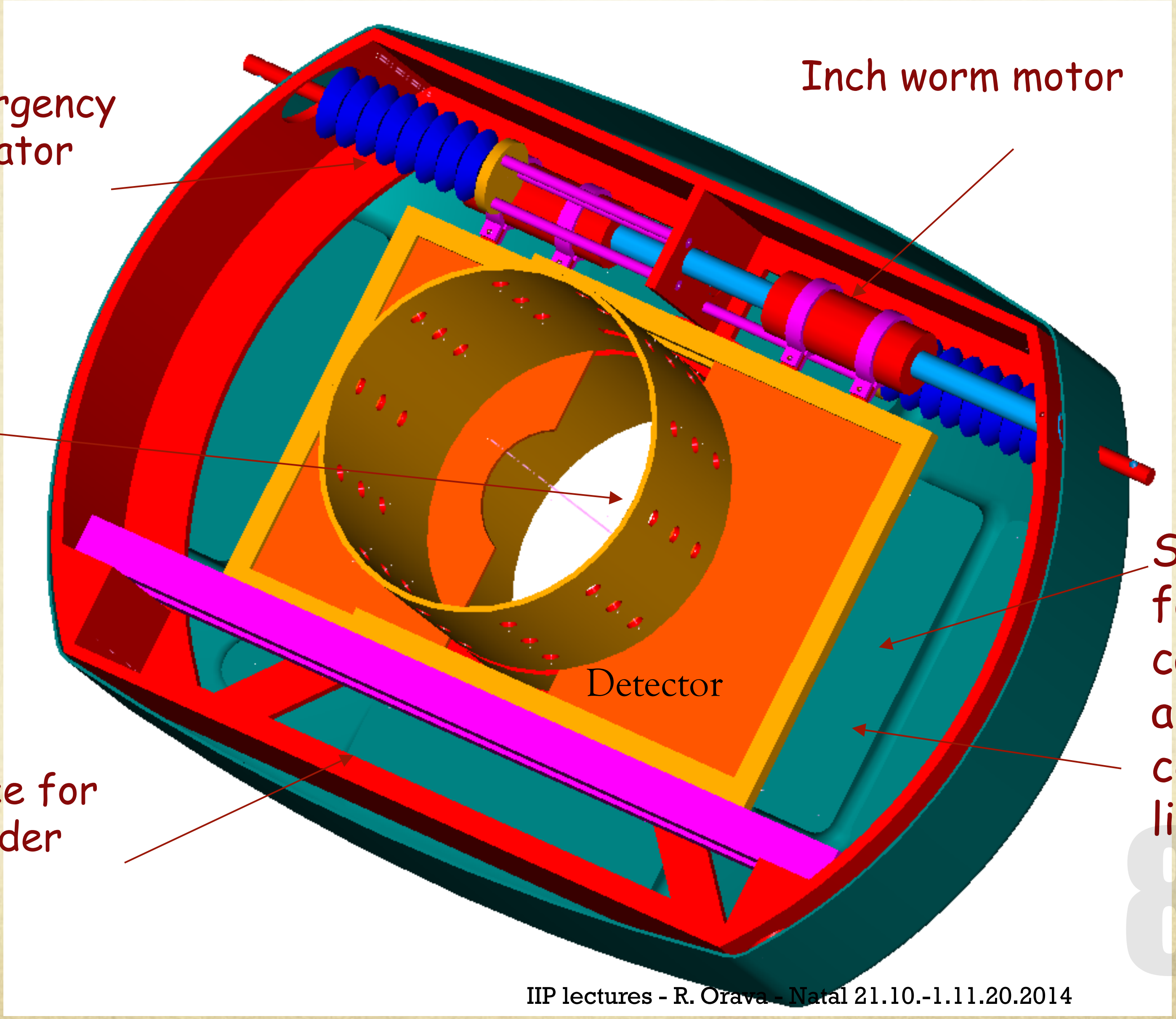
FSCs see forward particles (ε =50%) with rapidities |η|> 8

Fwd particles detected via inter-actions in the beam pipe

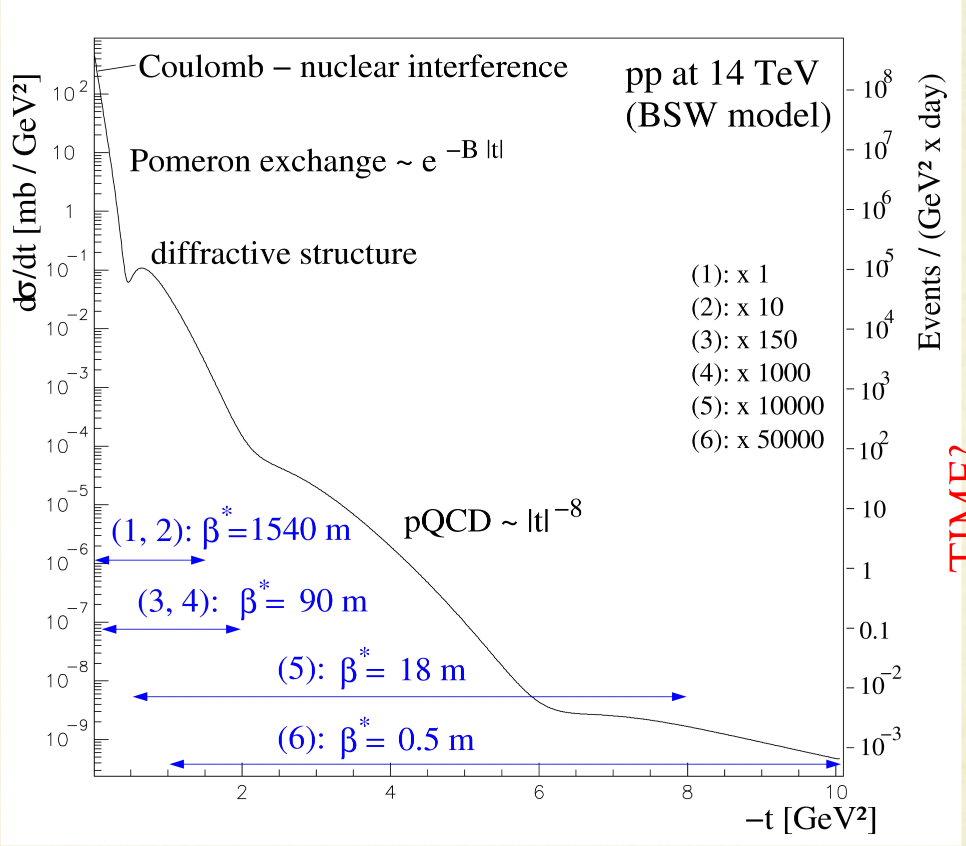
MICROSTATIONS



µStation


Emergency actuator
Inch worm motor
Inner tube for rf fitting
Detector
Space for cables and cooling link
Space for encoder

Physics priorities vs. the initial phases of the LHC – Elastic scattering & σ_{tot}



TIME?

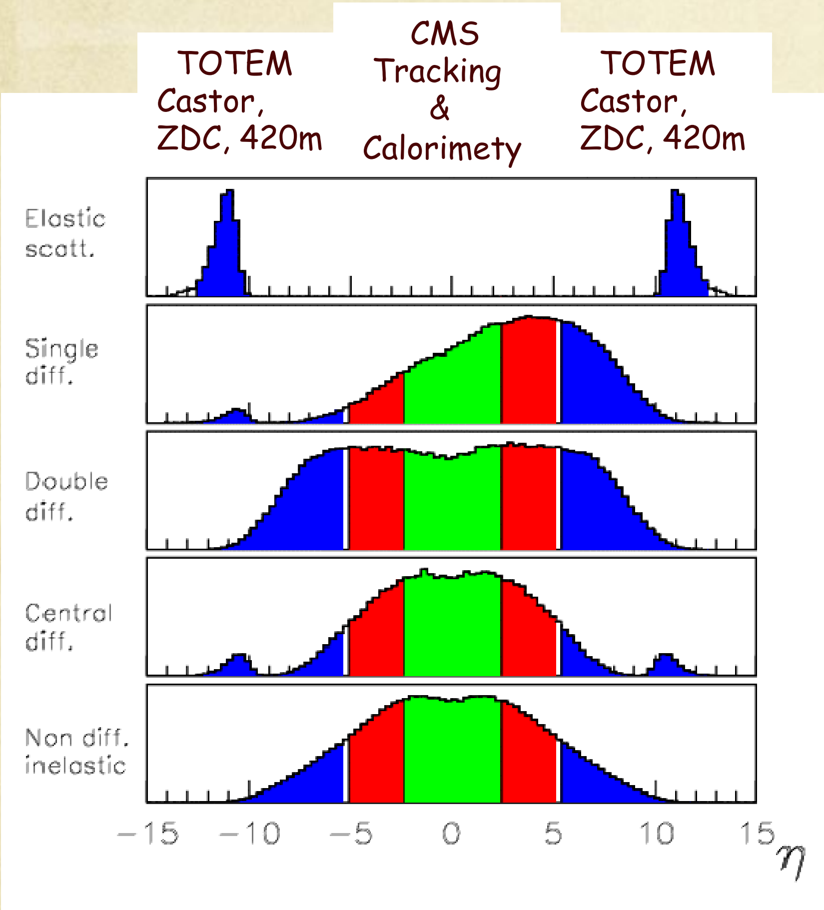
(1) β^* = 2m-18m??
$d\sigma_{el}/dt$ (large –t)

(2) β^* = 90m
$d\sigma_{el}/dt$ (moderate –t)
σ_{tot} & L(quick & dirty?)

(3) β^* = 0.55m
$d\sigma_{el}/dt$ (large –t)

(4) β^* = 1540m
$d\sigma_{el}/dt$ (small –t)
σ_{tot} & L (TOTEM TDR)

Physics priorities vs. the initial phases of the LHC – Single diffraction & low-x



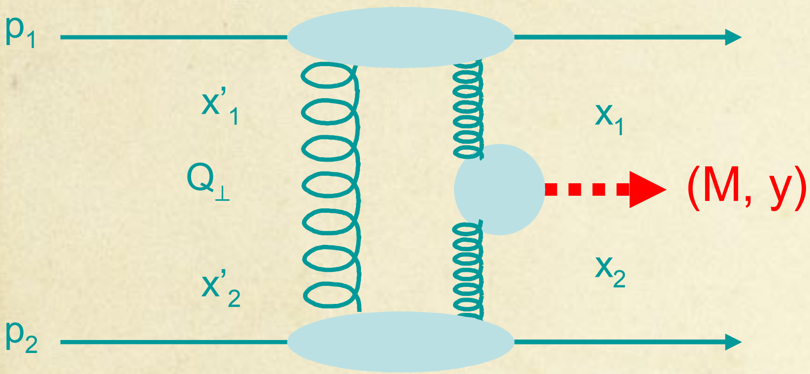
(1) β* = 2m -18m??
$d\sigma^{SD}/d\xi dt$ (limited acc.)

(2) β* = 90m
$d\sigma^{SD}/d\xi dt$ (50% acc.)
semi-hard diffraction
low-x phenomena

(3) β* = 0.55m
$d\sigma^{SD}/d\xi dt$ (limited acc.)
low-x phenomena

(4) β* = 1540m
$d\sigma^{SD}/d\xi dt$ (85% acc.)

Physics priorities vs. the initial phases of the LHC – Central diffraction



TIME?

(1) β^* = 2m, 6m, 18m??
$d\sigma^{CD}/dM_X dt$ (hard CD?)

(2) β^* = 90m
$d\sigma^{CD}/dM_X dt$ (soft & semihard CD)

(3) β^* = 0.55m
$d\sigma^{CD}/dM_X dt$ (hard CD, discoveries)

(4) β^* = 1540m
$d\sigma^{CD}/dt$ (soft CD, ξ-t coverage!)