Elastic and Inelastic Diffraction at the LHC

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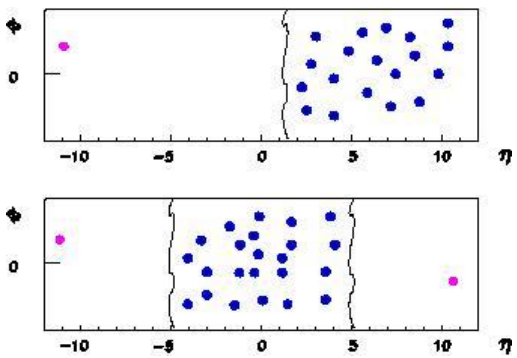
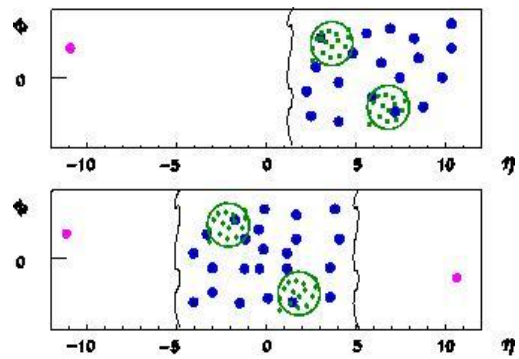
LHCp 2013 13 – 18 May 2013 Barcelona

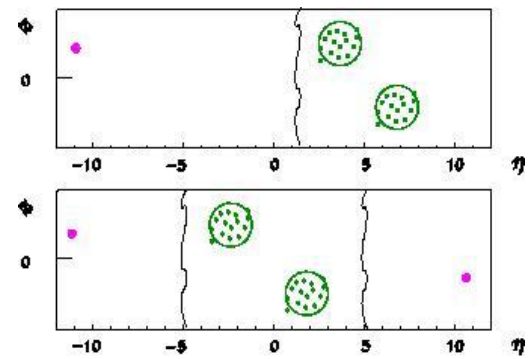
WHY DIFFRACTION?

- SPACE-TIME EVOLUTION OF HADRON-HADRON SCATTERING
- PARTON CONFIGURATIONS WITHIN HADRONS
- ASYMPTOPIA - QUARK-GLUON CONFINEMENT

TOTEM ⊗ CMS 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

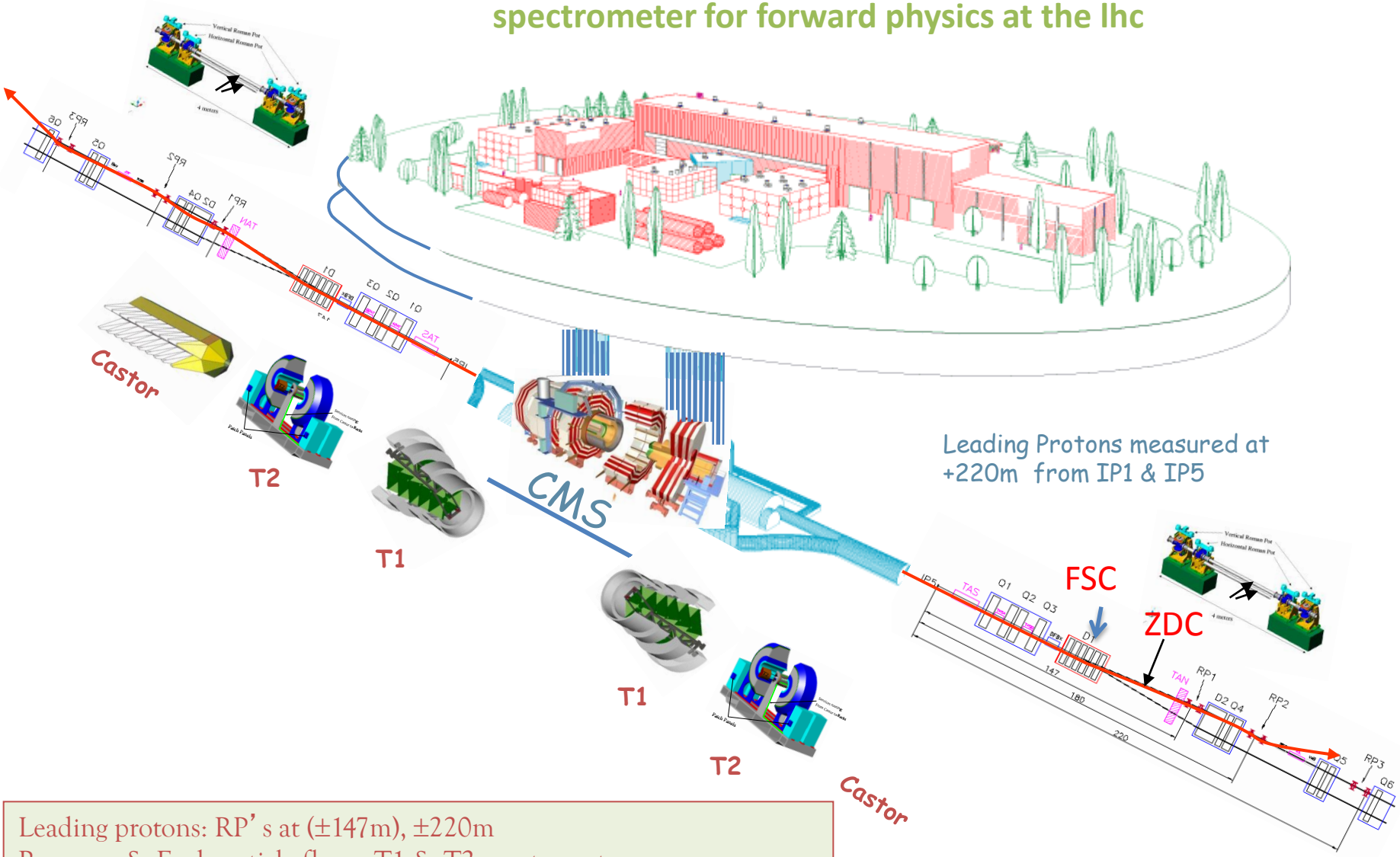
Cross section ⟷ Luminosity

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

S. Giani

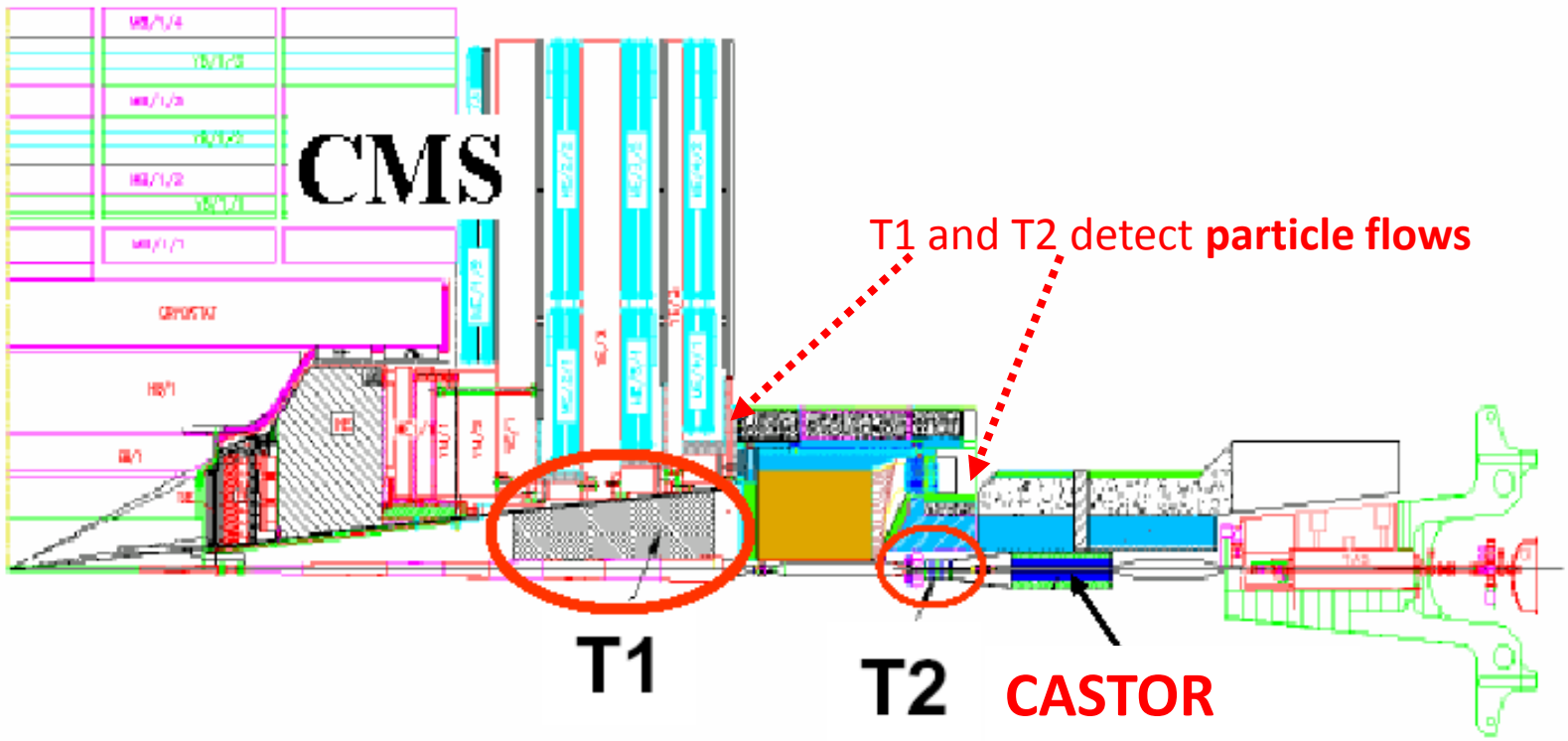
Leading Protons measured at
-220m from IP1 & IP5

cms-calorimetry + totem-tracking: unique fwd physics spectrometer for forward physics at the lhc



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

T1, T2 SPECTROMETERS, CASTOR



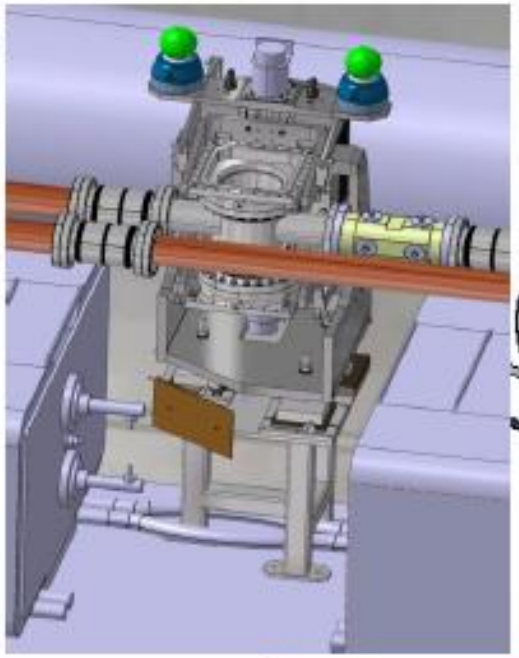
T1, T2 and CASTOR help in rejecting the backgrounds from SD and ND events.

Have good acceptance in p_T: T2 > 40MeV, T1 >100MeV

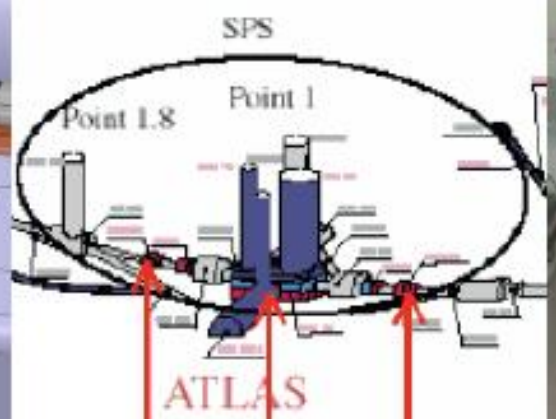
ATLAS

ALFA – Roman Pot stations

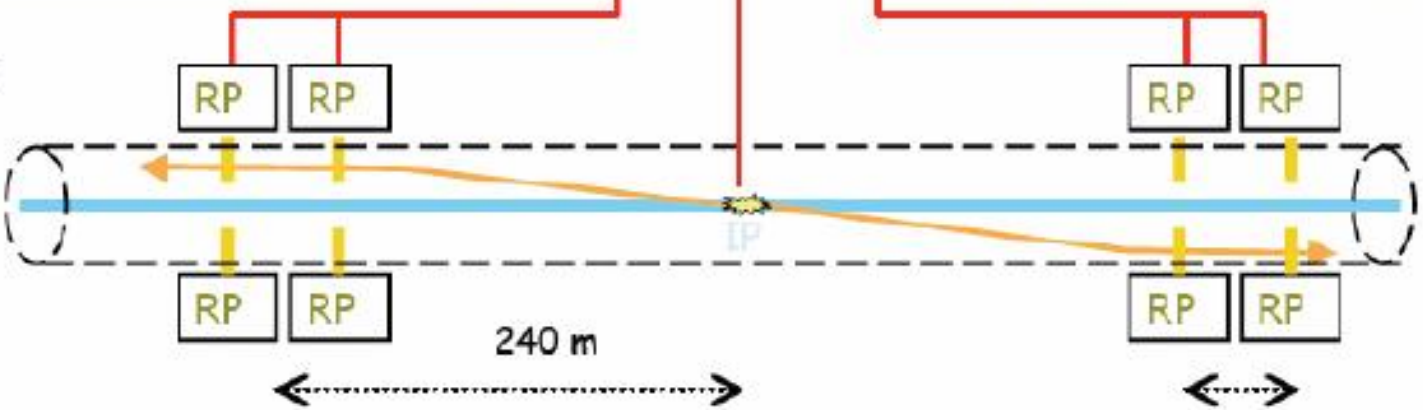
design...



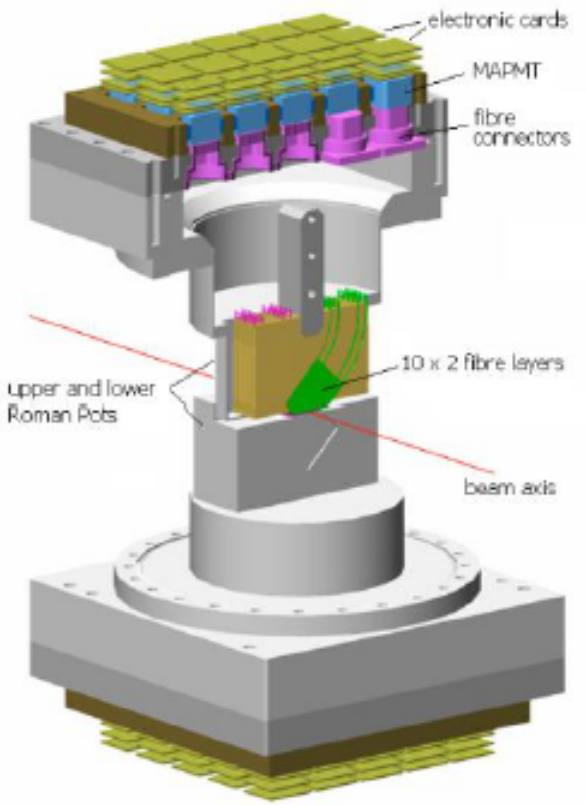
and reality



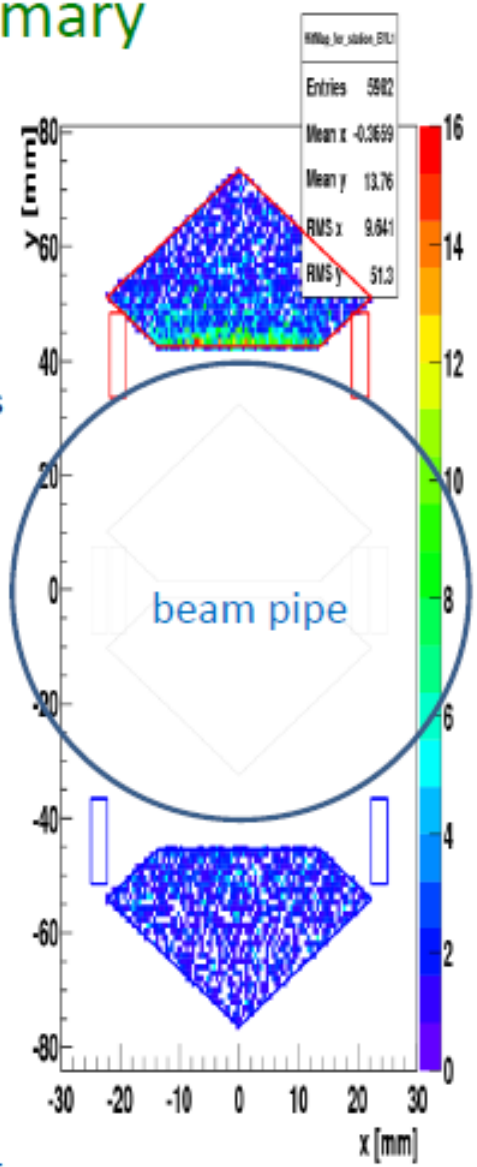
locations:



ATLAS detector properties – summary

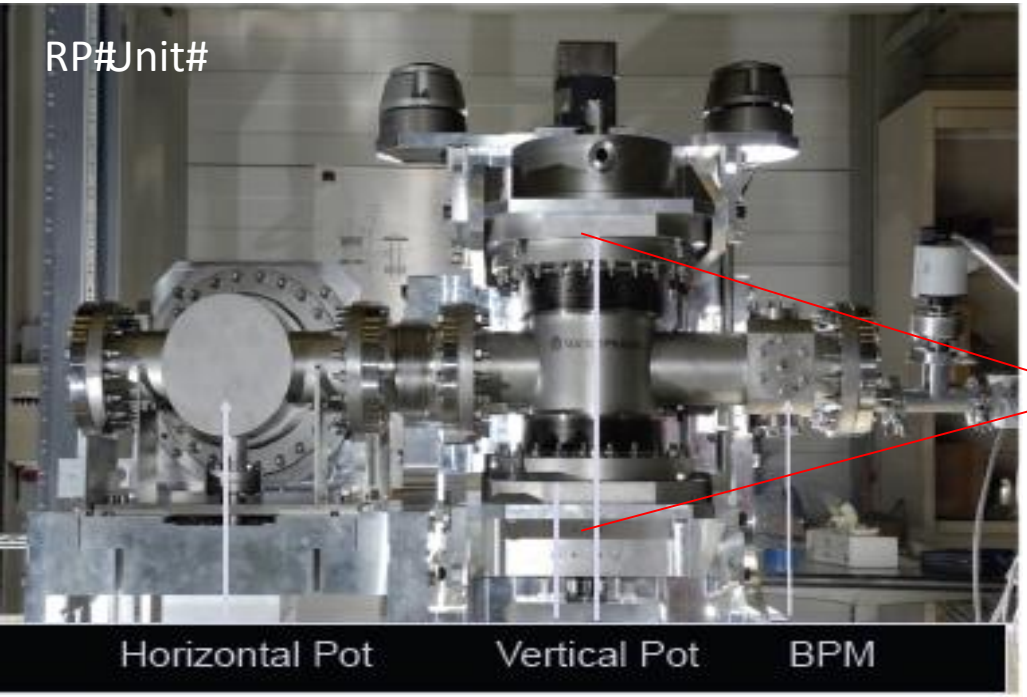


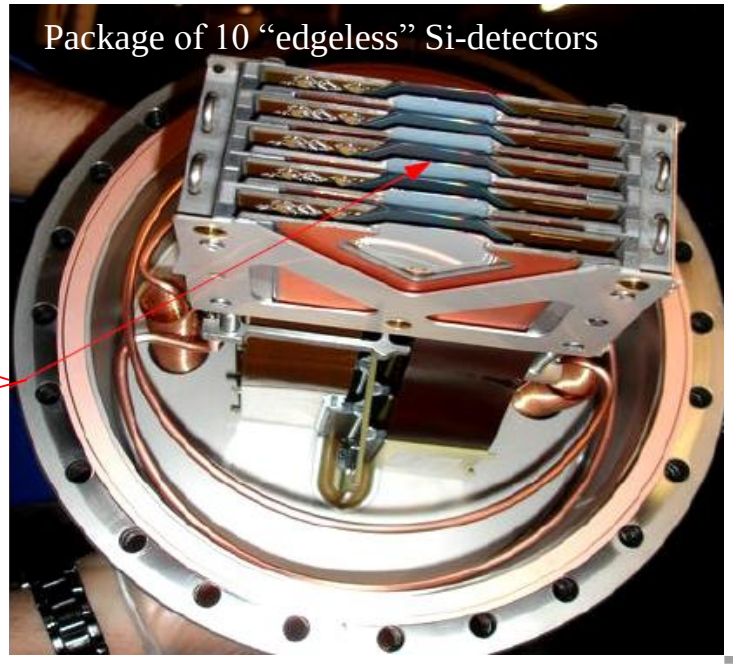
first tunnel output
detectors in parking positions

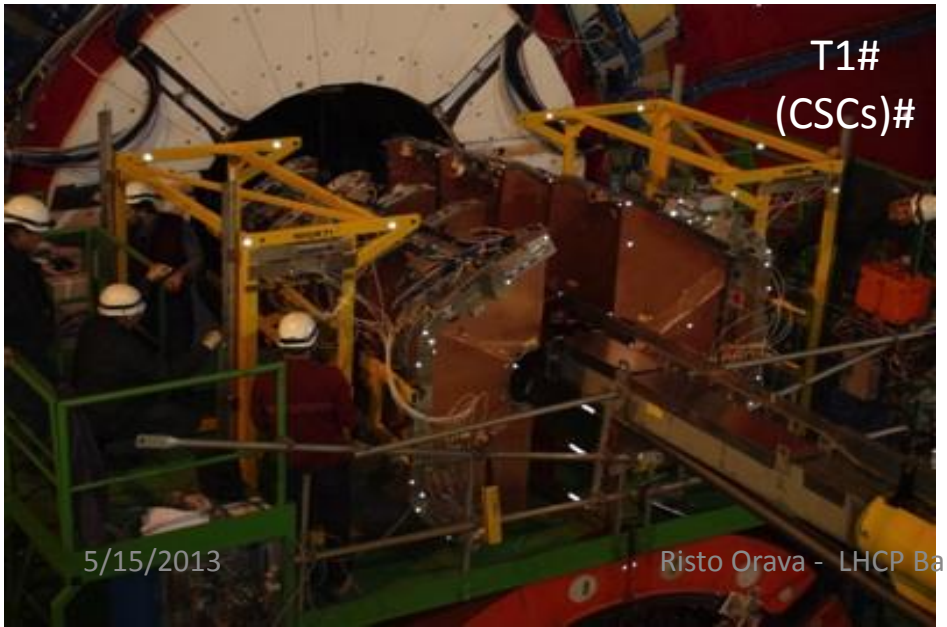


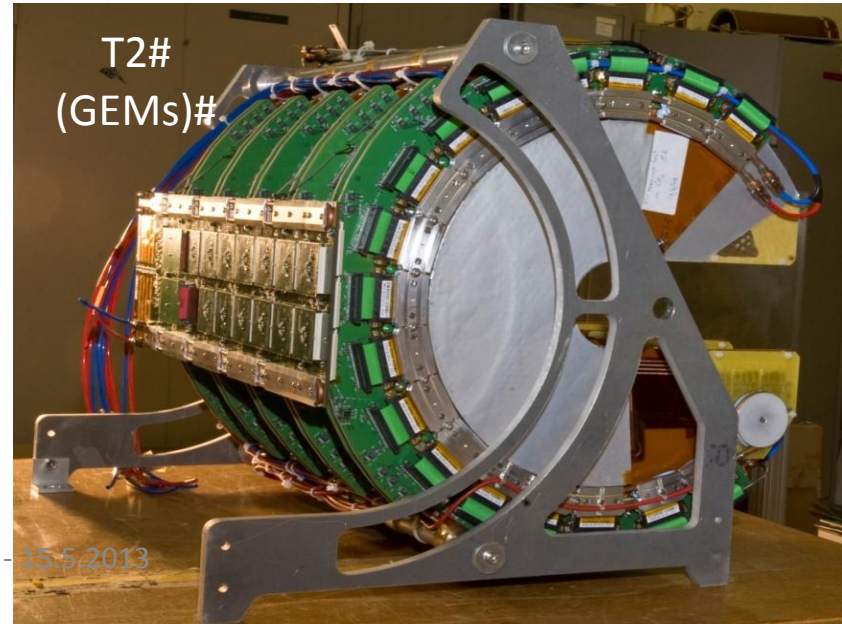
- single cladded 0.5 mm x 0.5 mm (square) fibers
- 10 layers in U, 10 in V; staggering
- ~ 30 μm position resolution
- efficiency ~ 90% per plane → ~ 100% efficiency of the detector

TOTEM DETECTORS

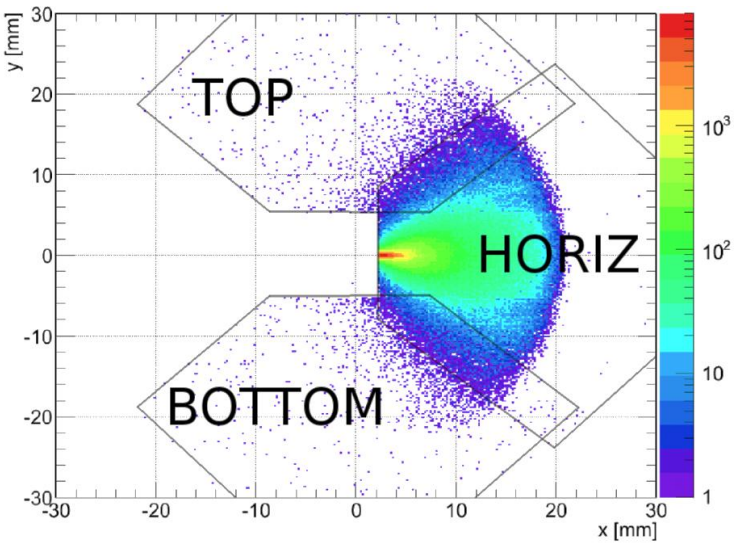








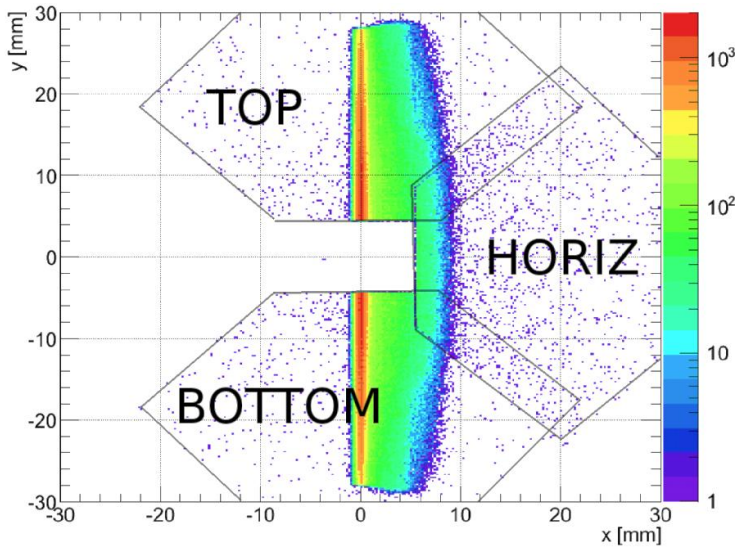
Leading forward protons at ±220 meters: Low & High β* (β*≈ 0.55m, 90m)



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

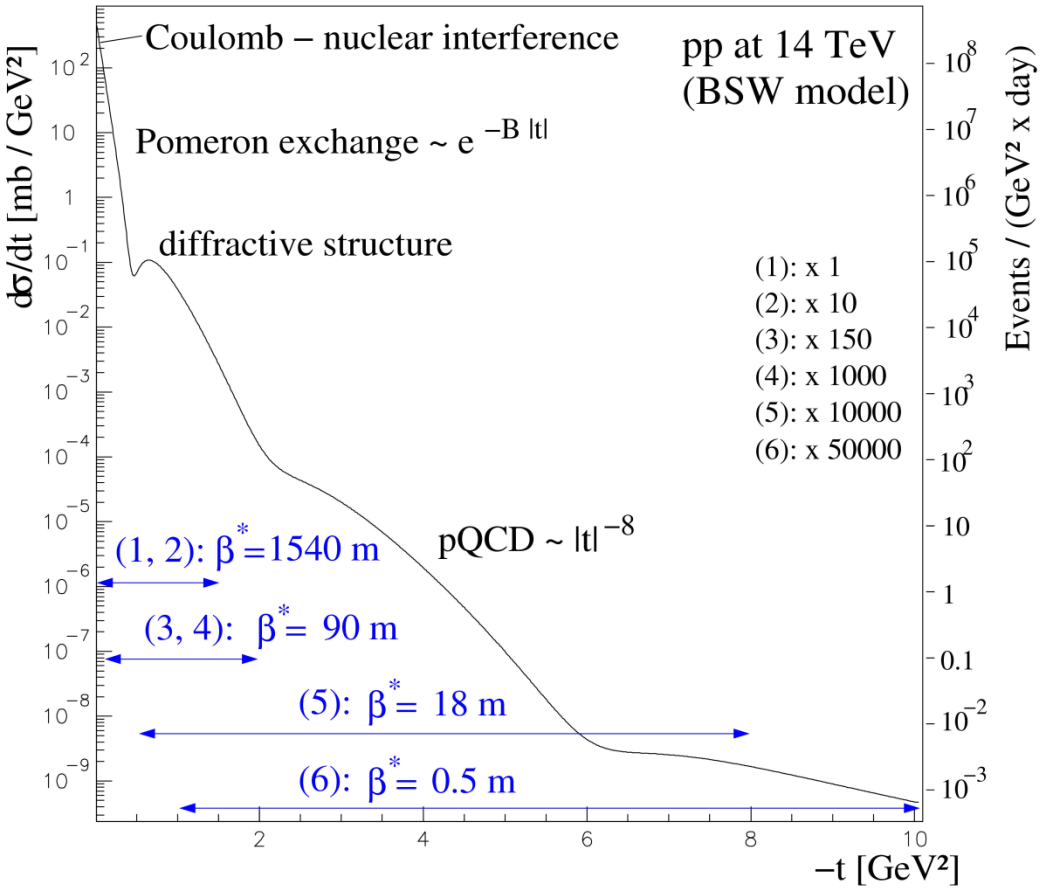


At high β* (β* ≈ 90m custom optics) the protons are measured through their scattering angle in **vertical** direction.

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

- 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 CROSS SECTION



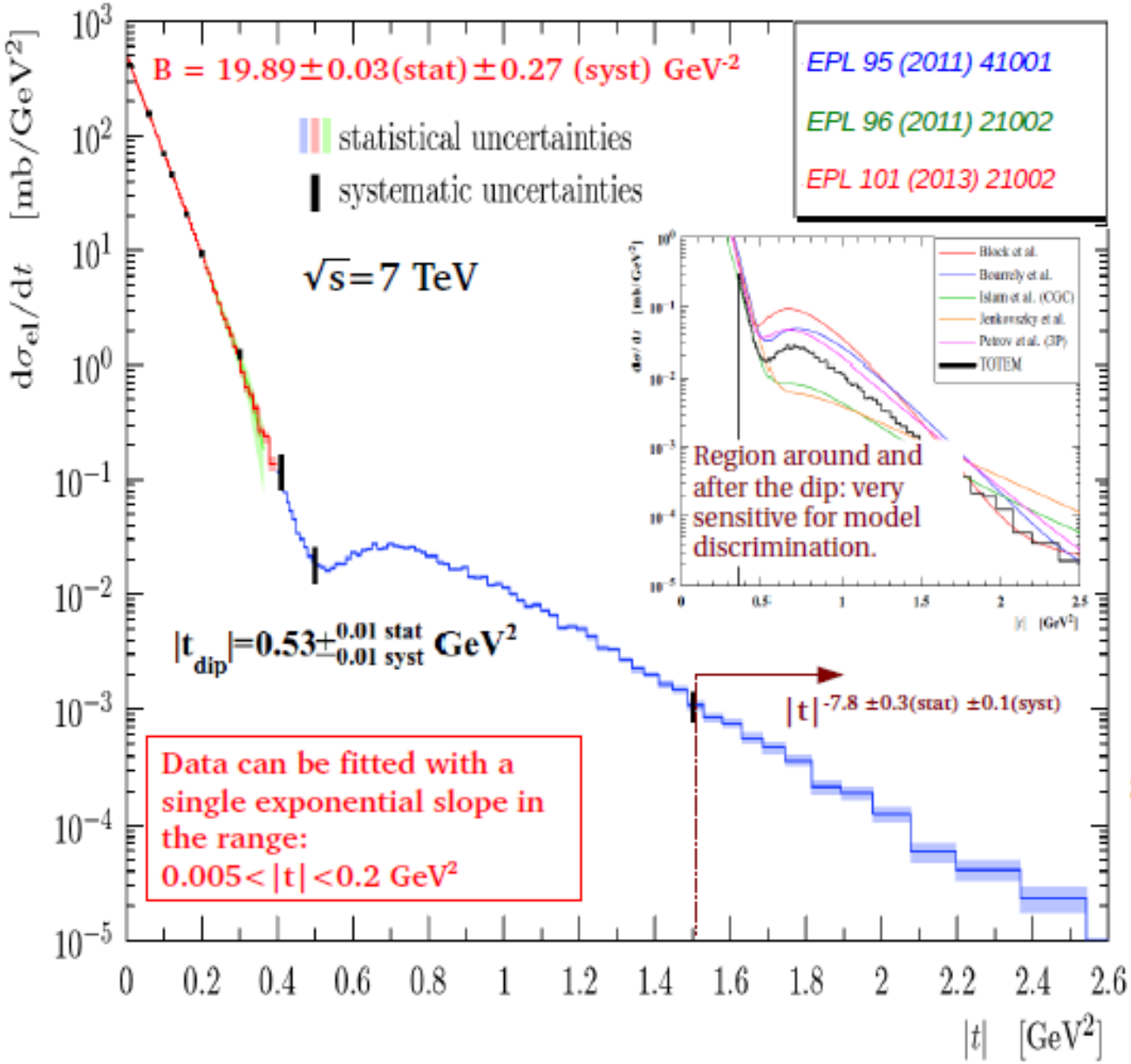
$d\sigma_{el}/dt$ yields:

- pp *interaction radius* (slope of the $d\sigma_{el}/dt$ distribution)
- with the measurement of the total inelastic rate - the *total pp cross section*,
- A test of the *Coulomb-nuclear Interference* (expected to have an effect over *large* interval in –t).
- A measurement of the *ratio of the real and imaginary parts* of the forward pp scattering amplitude, ρ = ReA(s,t)/ImA(s,t)

⇒ Through dispersion relations, a precise measurement of ρ will constrain σ_{tot} at substantially higher energies

⇒ "Shadow scattering"

ELASTIC CROSS SECTION - TOTEM



EPL 95 (2011) 41001

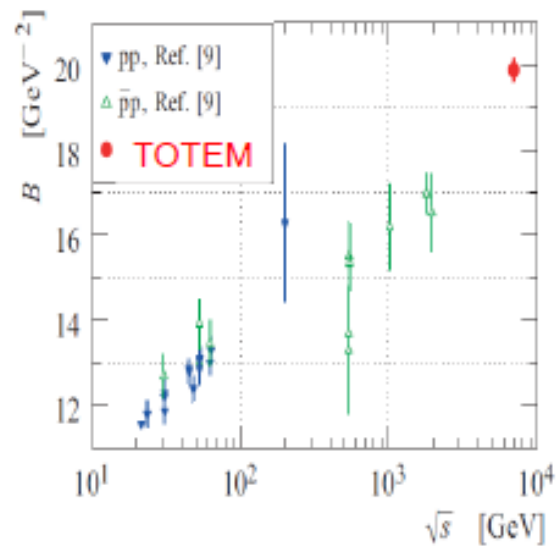
EPL 96 (2011) 21002

EPL 101 (2013) 21002

$0.36 < |t| < 2.5$ GeV²

$0.02 < |t| < 0.33$ GeV²

$5 \cdot 10^{3} < |t| < 0.4$ GeV²



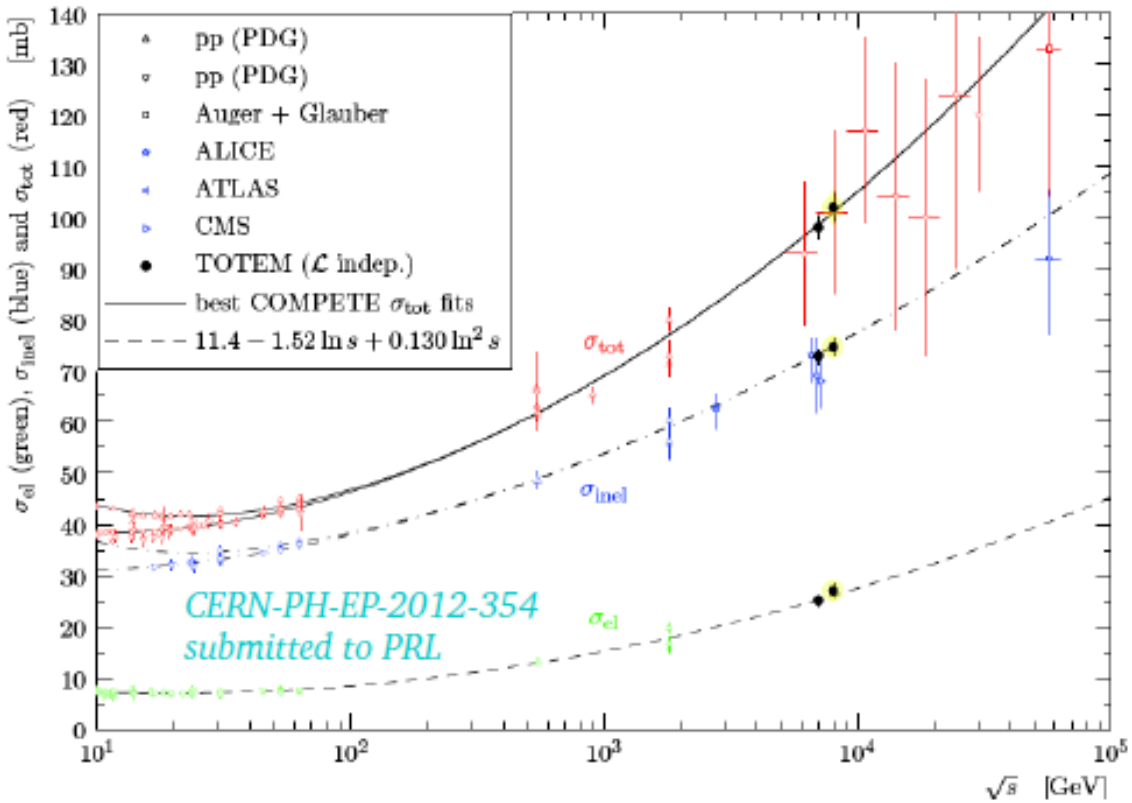
Shrinkage of the forward peak:

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

CROSS SECTION MEASUREMENTS - TOTEM

- Dedicated fill with t_{min} = 0.01 GeV^2, 90% of the nuclear elastic scattering events detected
- With the same analysis performed at 7 TeV, the luminosity independent cross sections are found:

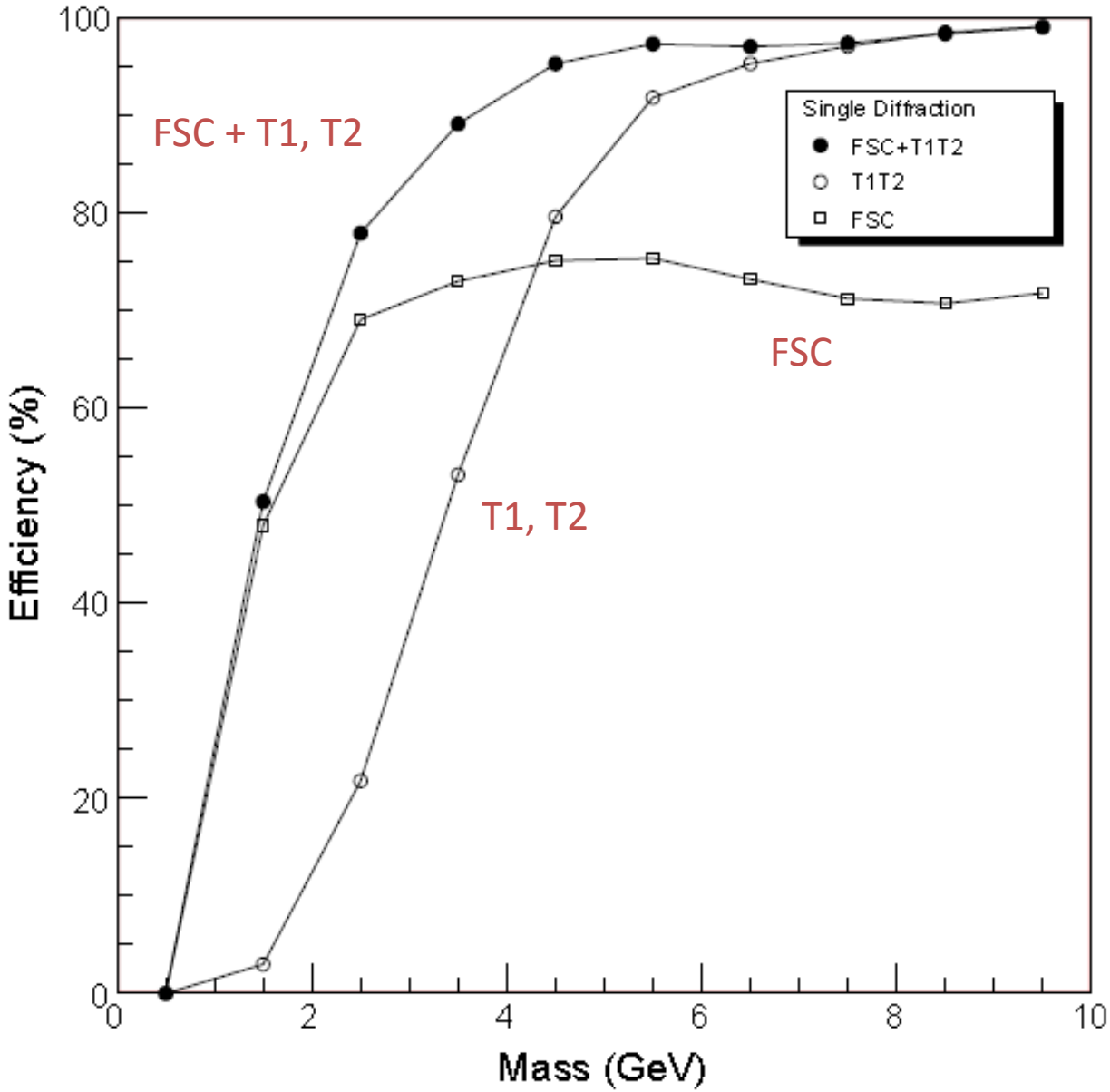
σ_{TOT} = 101.7 ± 2.9 mb σ_{EL} = 27.1 ±1.4 mb σ_{INEL} =74.7 ±1.7 mb



Comparison of 7 and 8 TeV measurements:

- consistent in terms of detectors performance.
- comparable systematics uncertainties.
- both in good agreement with the extrapolation of the lower energy measurements.

EFFICIENCY OF DETECTING SD EVENTS

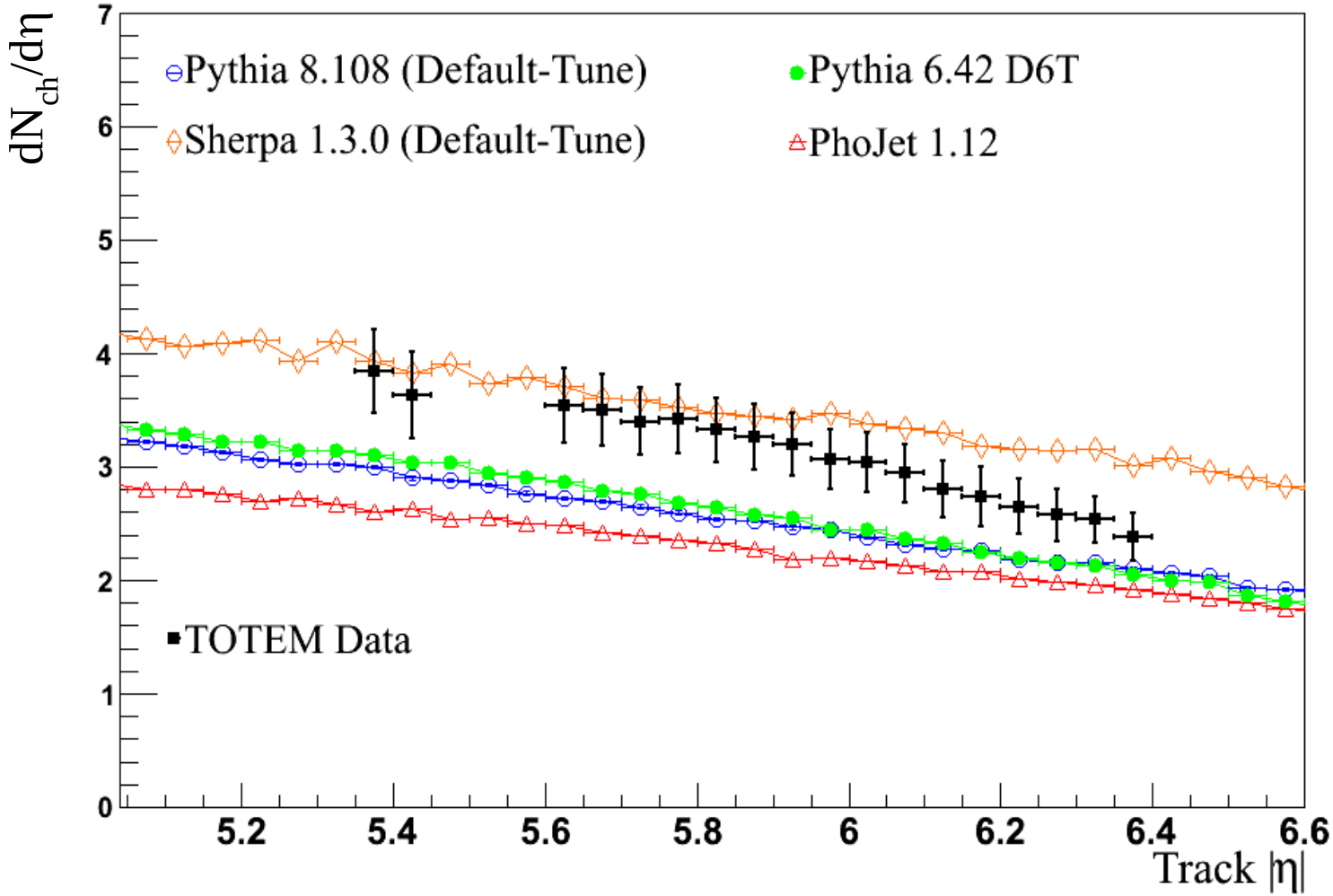


WITH FSC, DETECT SD EVENTS DOWN TO $M_{diff} \geq 1.1$ GeV

THE FWD DETECTORS AS DIFFRACTIVE MASS SELECTORS – CLASSIFICATION

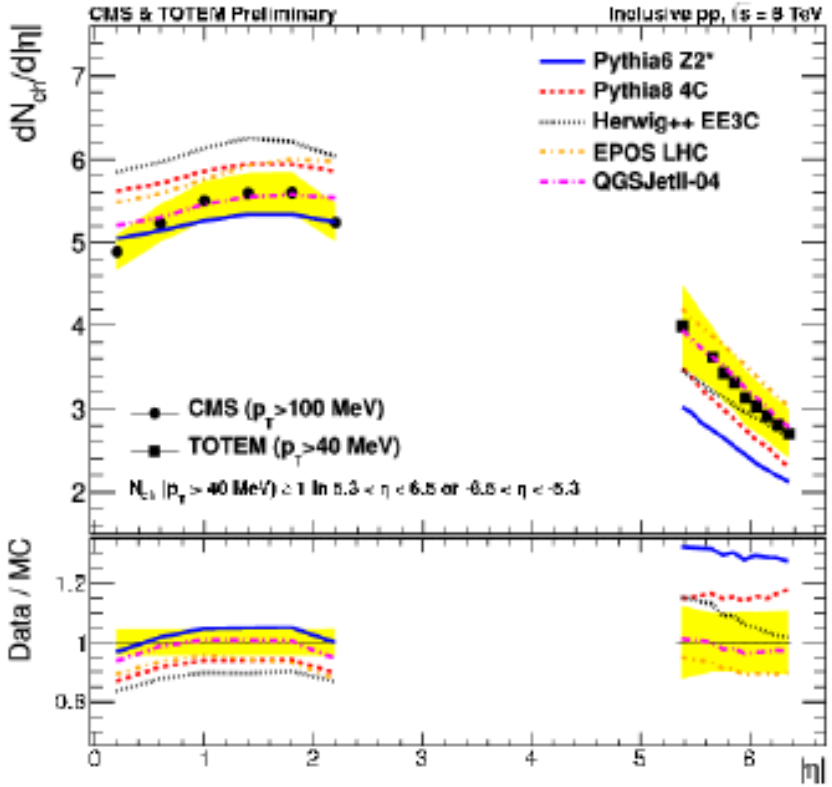
J.W.Lämsä & RO

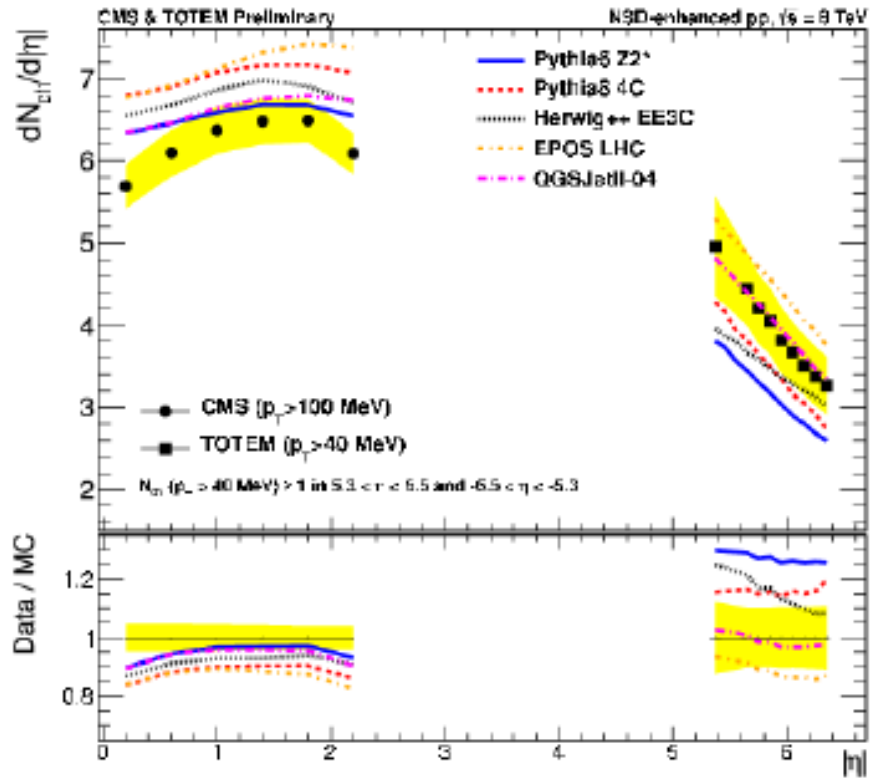
$dN_{ch}/d\eta$ measured in T2, sqrt s = 7 TeV



EPL, 98 (2012) 31002

COMBINED CMS-TOTEM CHARGED PARTICLE DENSITIES





Inelastic Diffraction

Probability of finding a rap gap (in inclusive QCD events) depends on the p_T cut-off

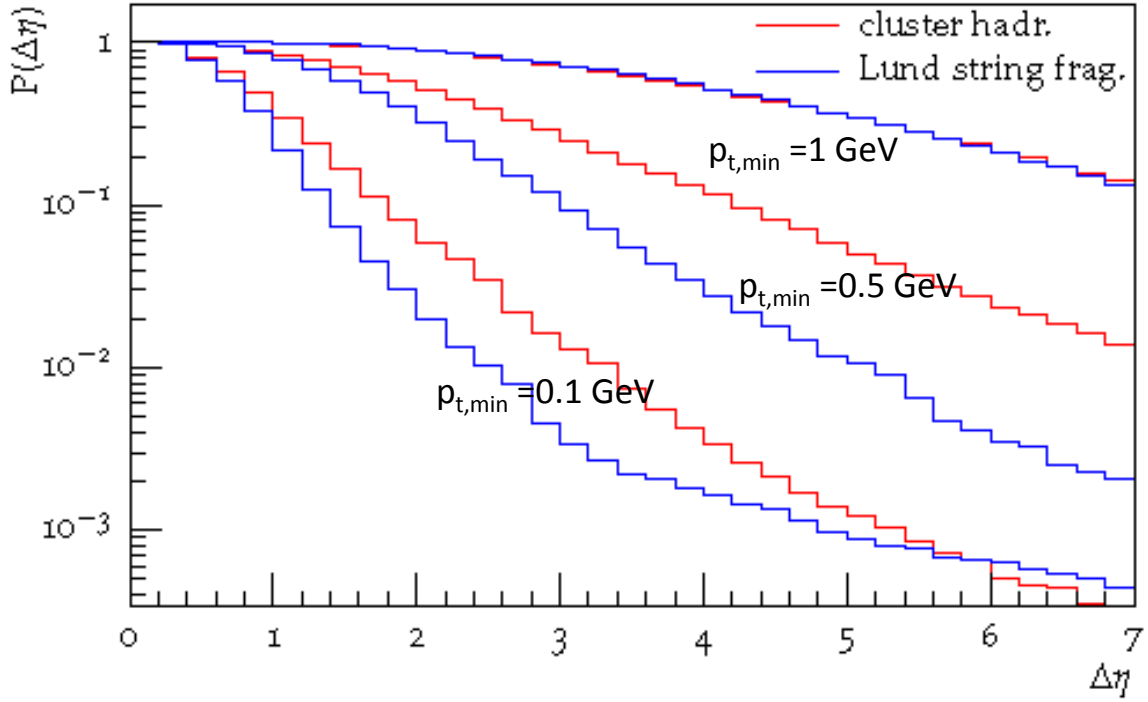
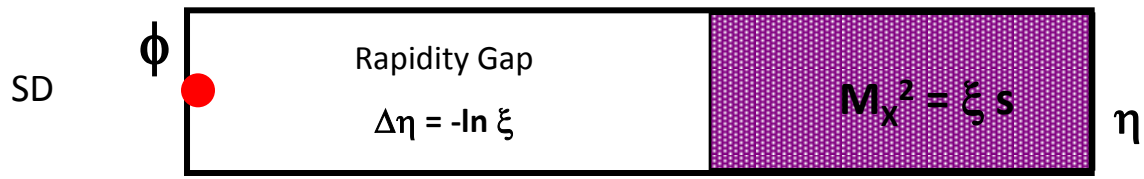


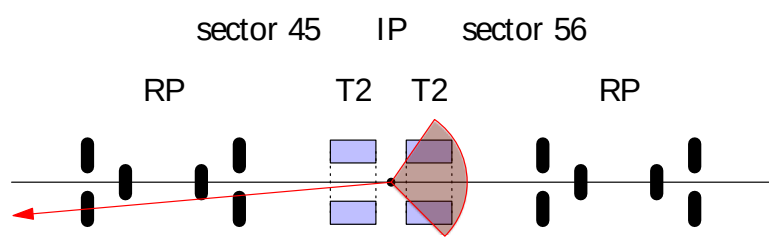
Fig. 4. Probability for finding a rapidity gap (definition 'all') larger than $\Delta\eta$ in an inclusive QCD event for different threshold $p_\perp$. From top to bottom the thresholds are $p_{\perp,cut} = 1.0$, 0.5, 0.1 GeV. Note that the lines for cluster and string hadronisation lie on top of each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

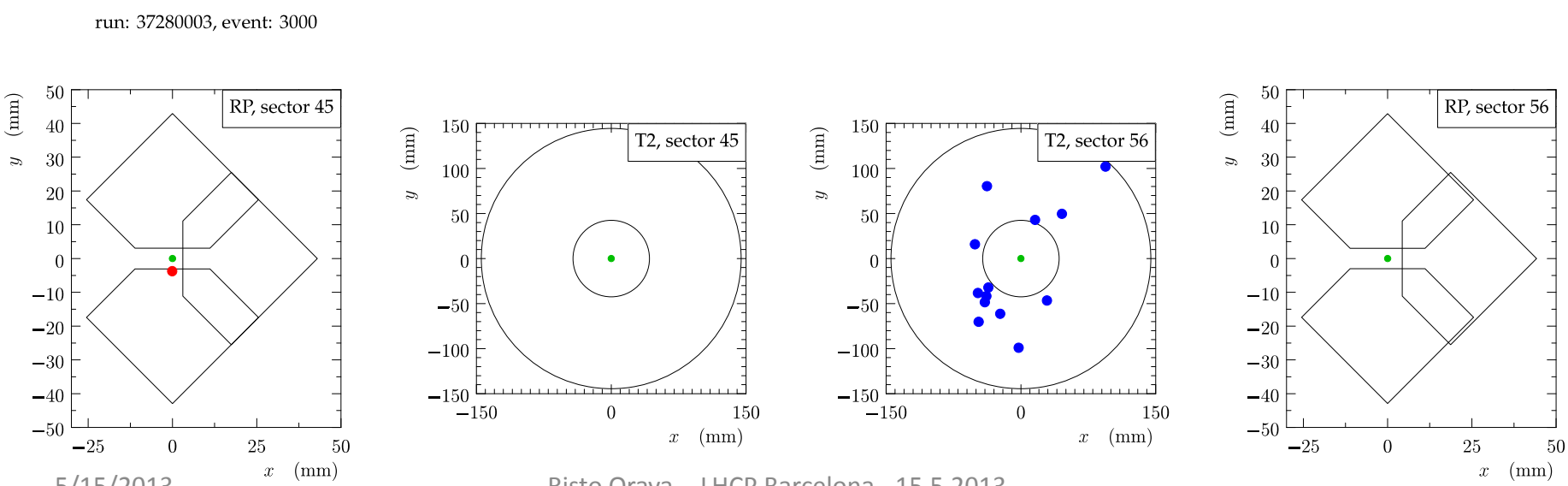
KKMRZ:
V.A. Khoze, (Durham U., IPPP & St. Petersburg, INP) , F. Krauss, A.D. Martin, (Durham U., IPPP) , M.G. Ryskin, (Durham U., IPPP & St. Petersburg, INP) , K.C. Zapp, (Durham U., IPPP) . IPPP-10-38, DCPT-10-76, MCNET-10-10, 2010. 19pp.

Single diffraction low x

Correlation between leading proton and forward detector T2

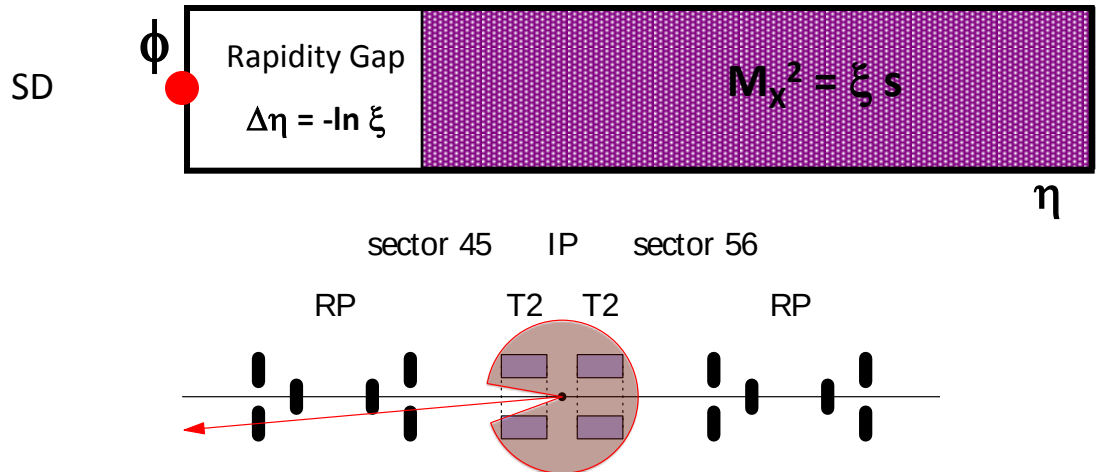


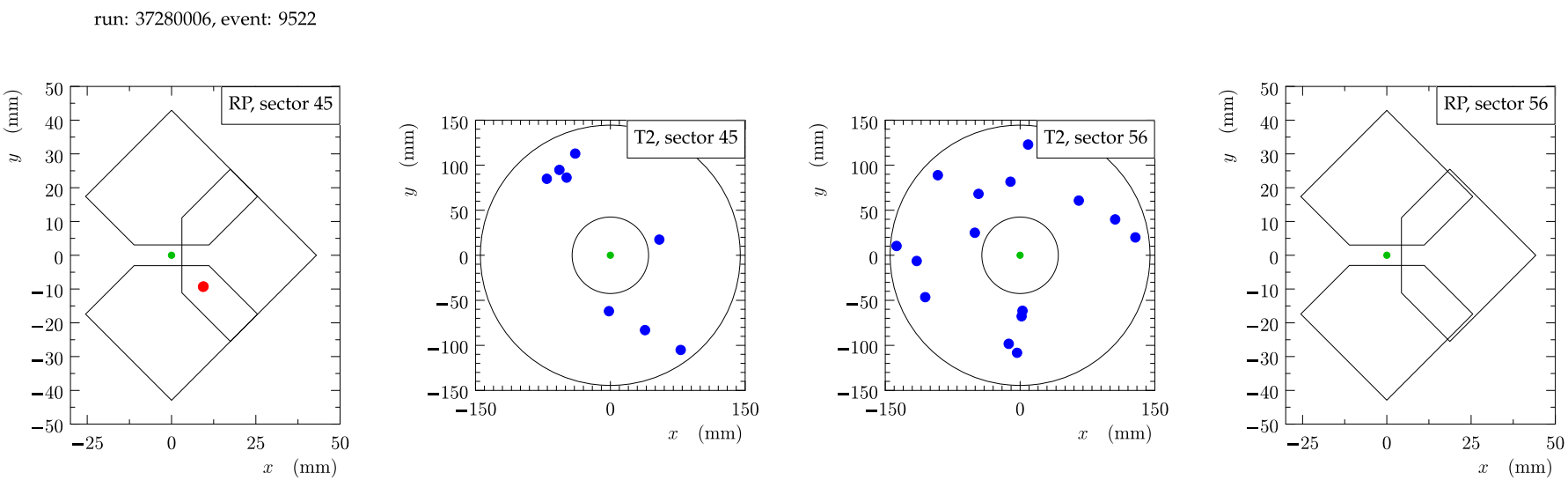




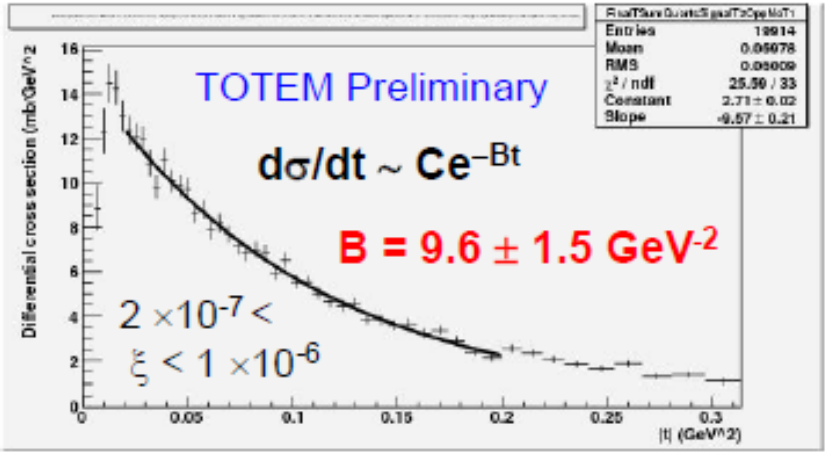
Single diffraction large x

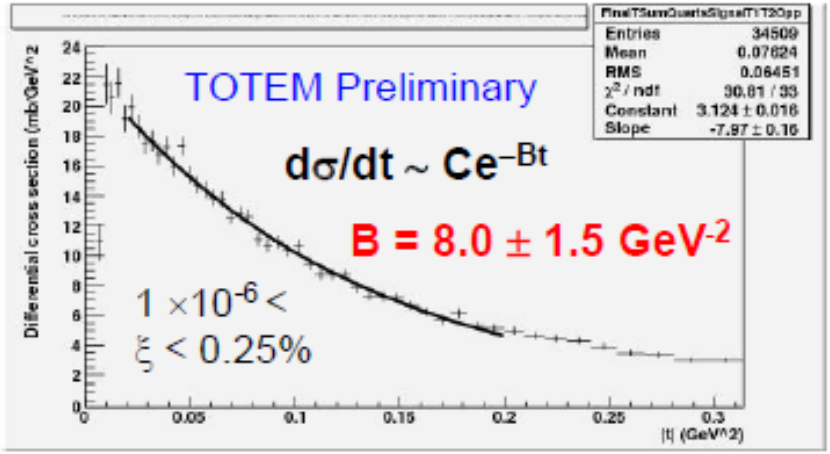
correlation between leading proton and forward detector T2

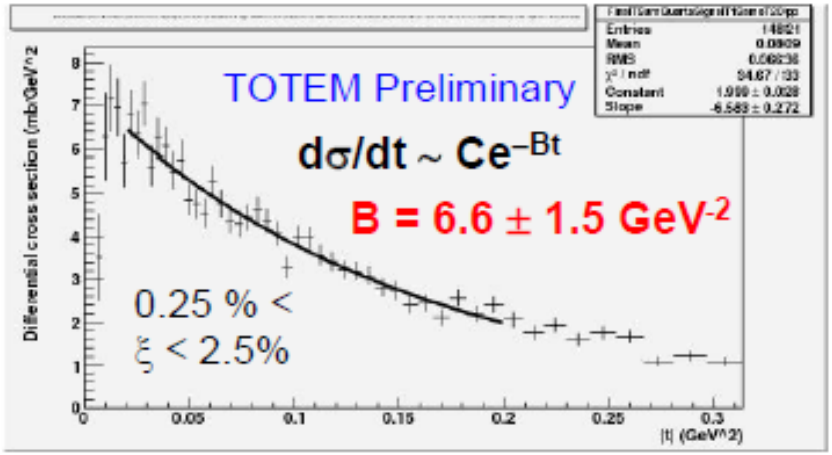




Single diffraction: dσ/dt vs. ξ





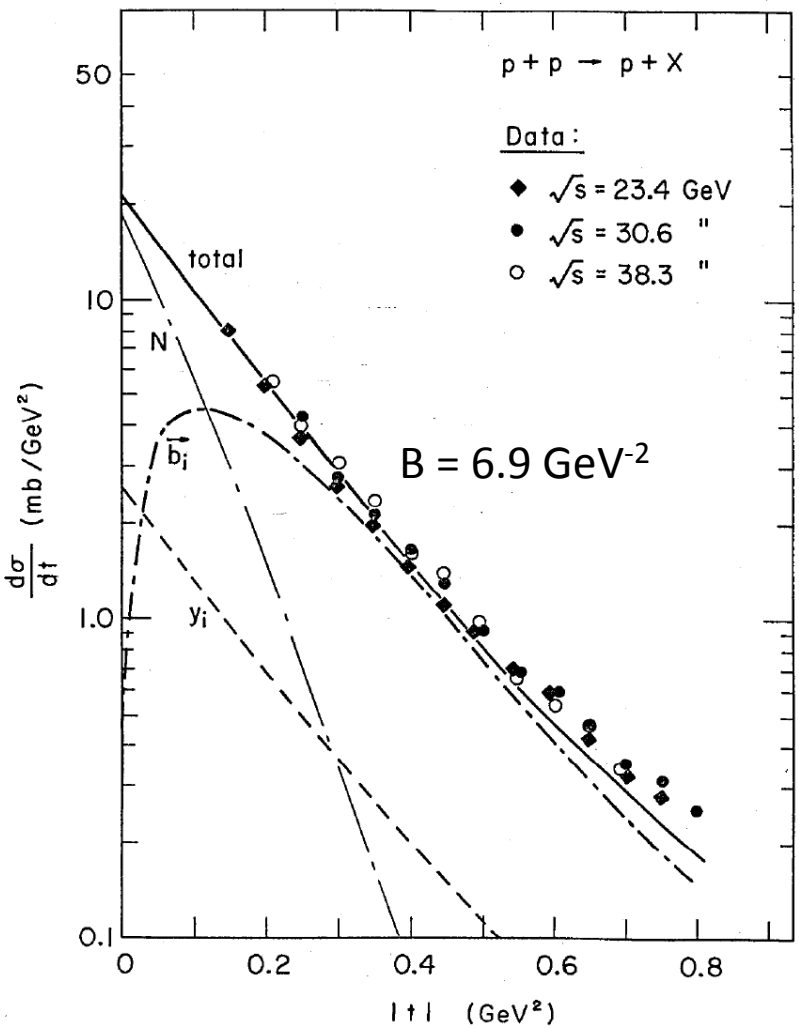


t-distributions still to be corrected for beam divergence & effect of ξ on proton ϕ-acceptance correction

$$\frac{d\sigma_{SD}^{class\ i}}{dt} = e^{-B_i t} - \text{backgr.}$$

$$\sigma_{SD}(\xi > 2\times10^{-7}) = \sum_i \int_0^\infty dt\, \frac{d\sigma_{SD}^{class\ i}}{dt}$$

Diffractive cross section at the ISR ($0.95 < x_F < 1.0$)



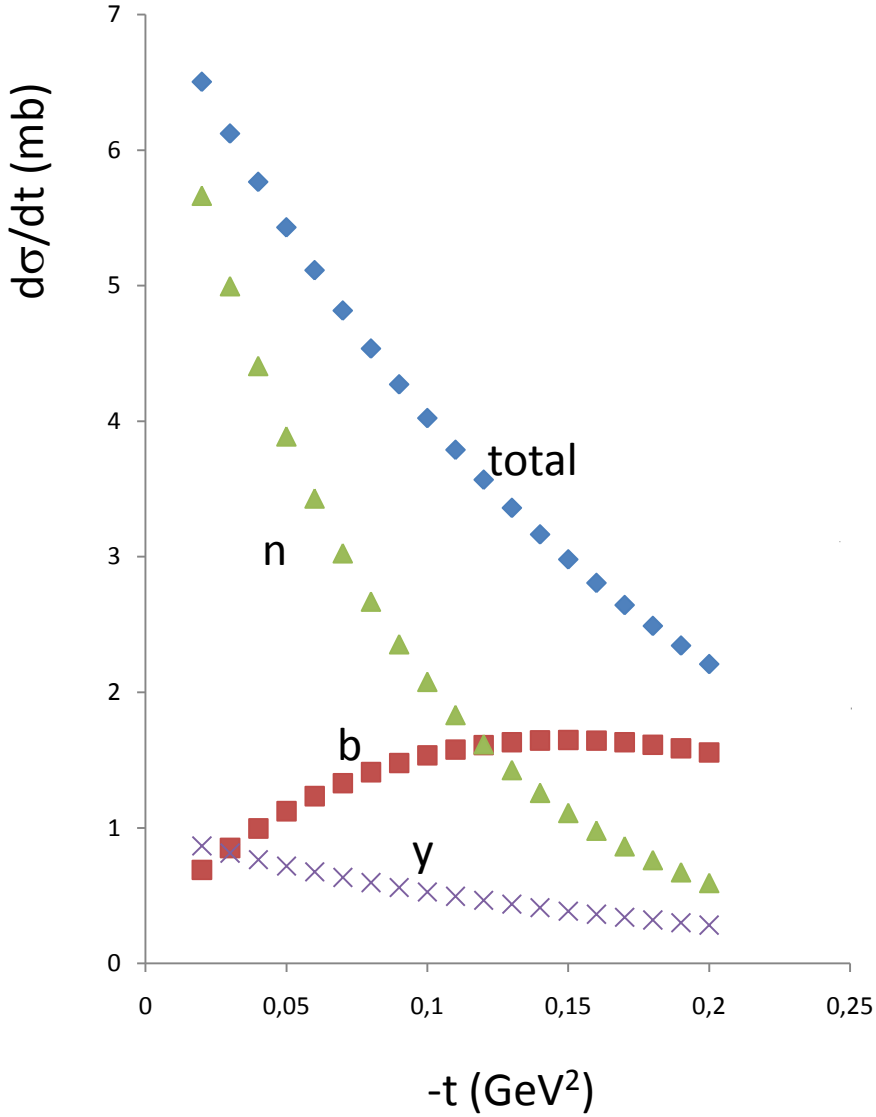
Diffraction due to peripheral interactions; fluctuations in :

- impact parameter 45%
- number of 45%
- rapidities 10%

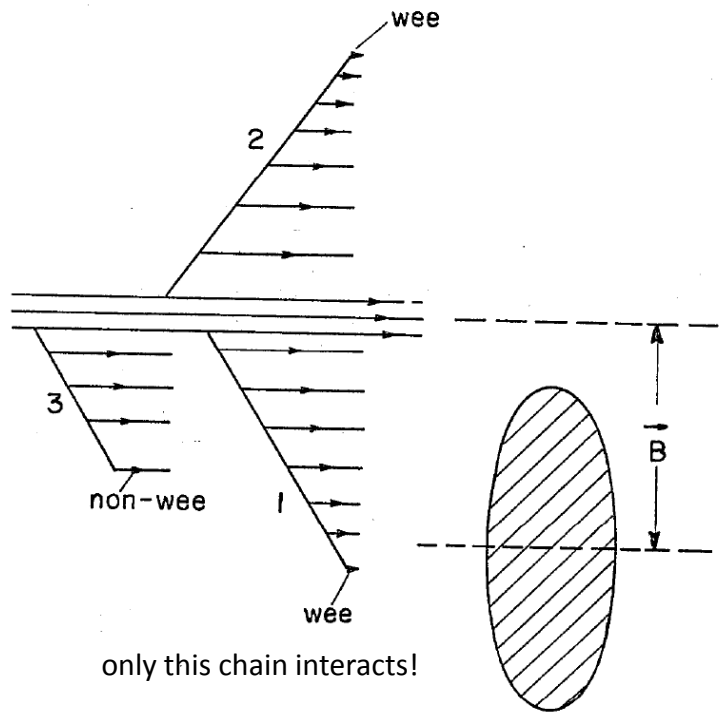
of the wee partons.

Miettinen & Pumplin, PRD 1978

Diffractive cross section at the ISR ($0.95 < x_F < 1.0$)



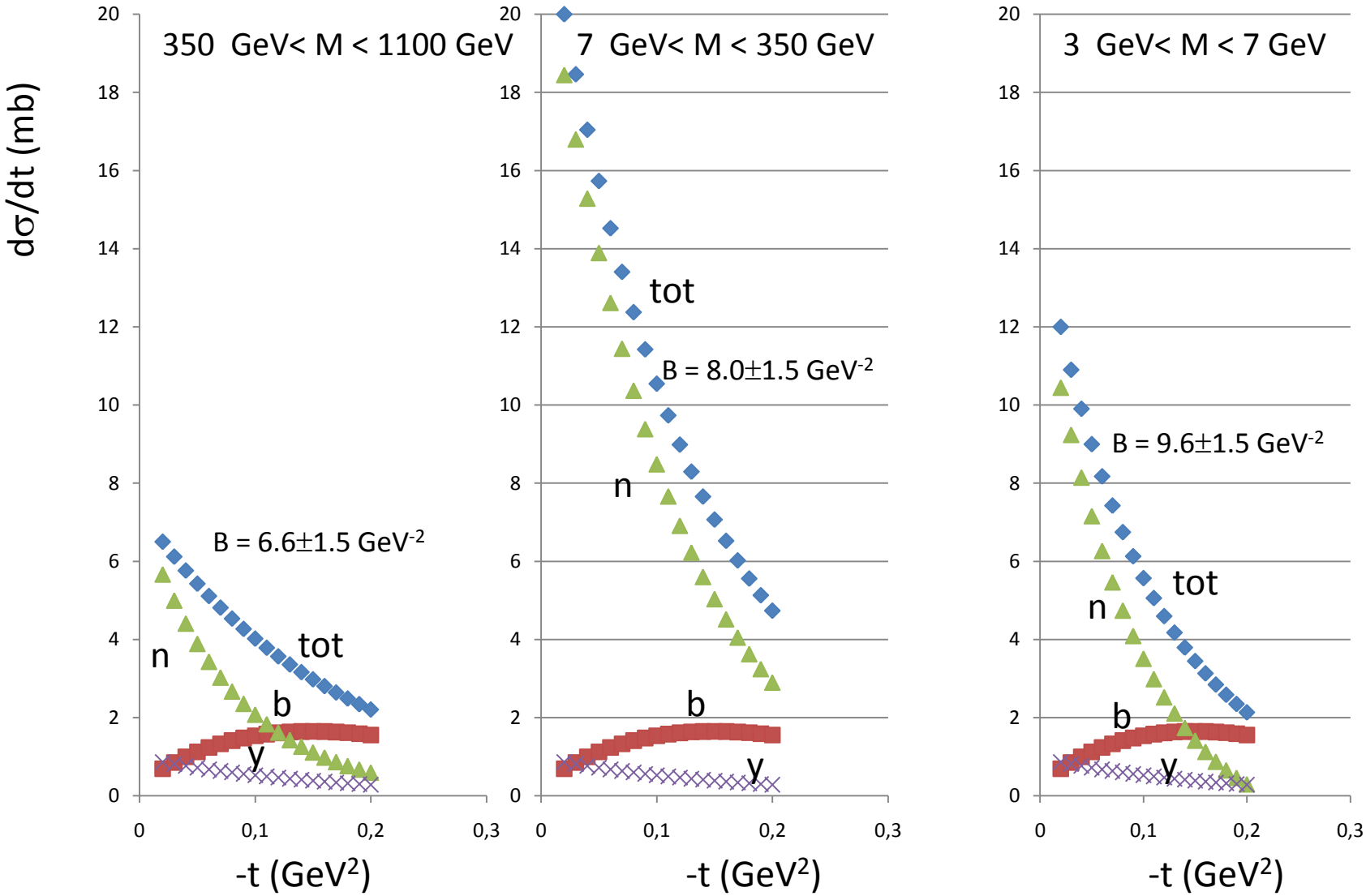
At small -t
fluctuations in the no. of
wee parton states dominate?



only this chain interacts!

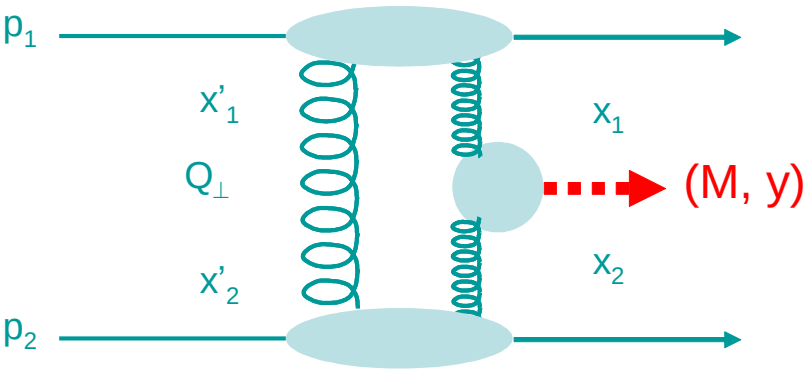
Miettinen & Pumplin, PRD 1978

Diffractive cross section at the LHC - speculation



At small diffractive masses (small ξ values), fluctuations in number of wee states grows in relative importance vs. b- or y- fluctuations?

Central diffraction



TIME?

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

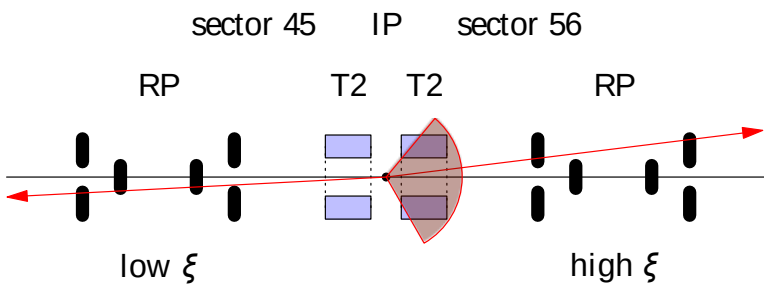
(2) $\beta^* = 90m$
$d\sigma^{CD}/dM_X dt$ (soft & semihard CD)

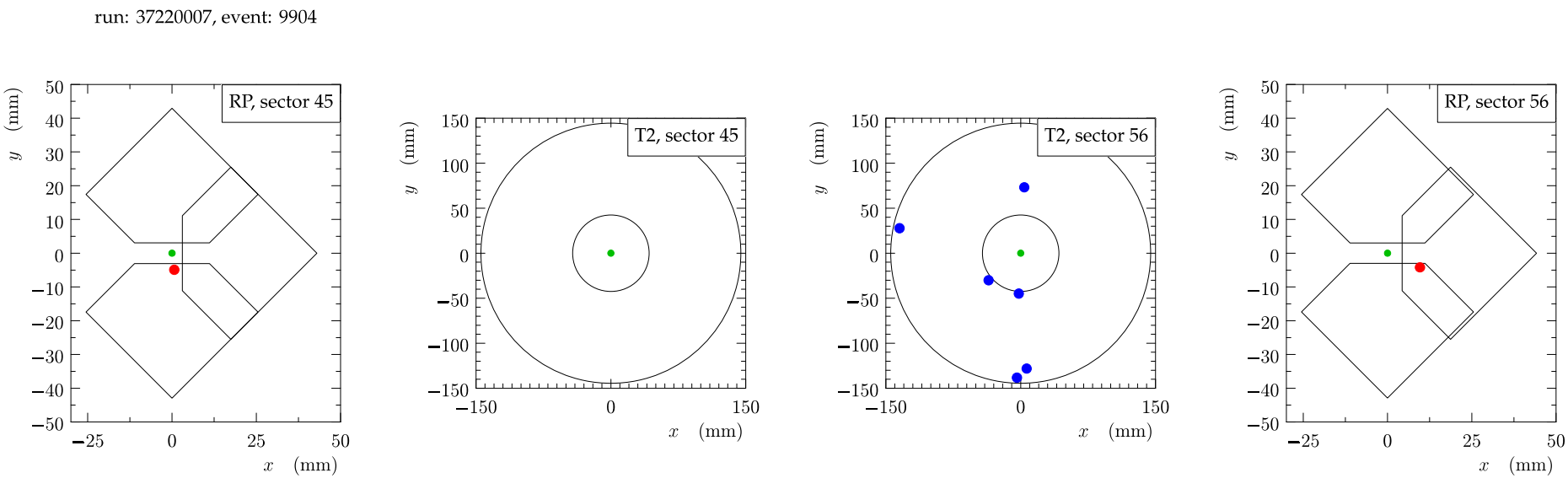
(3) $\beta^* = 0.55m$
$d\sigma^{CD}/dM_X dt$ (hard CD, discoveries)

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

Central Exclusive Diffraction (CED)

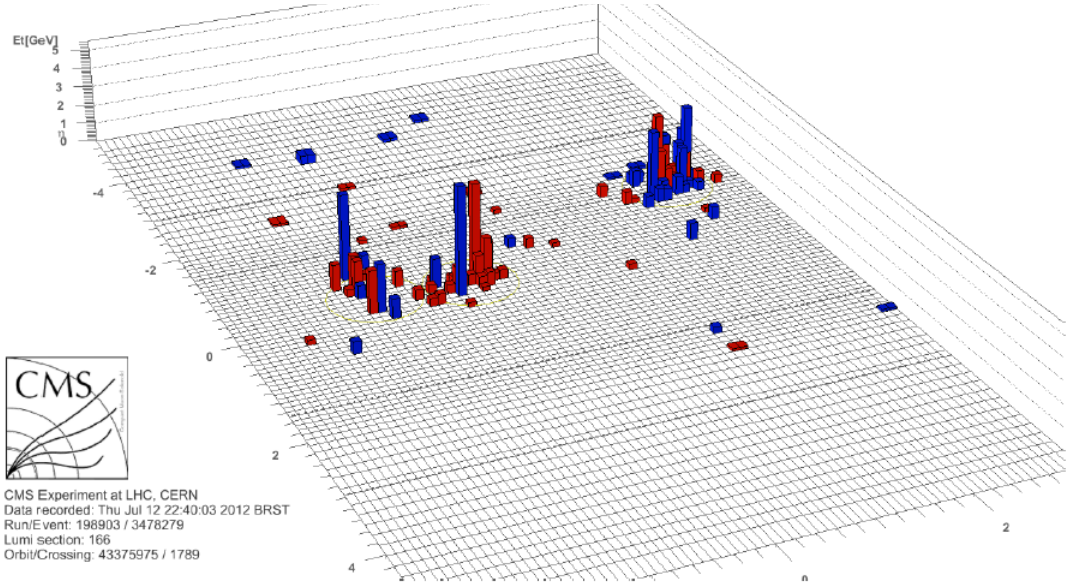
correlation between leading protons and forward detector T2





DI-JET CANDIDATE EVENT

- E_T of 3 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

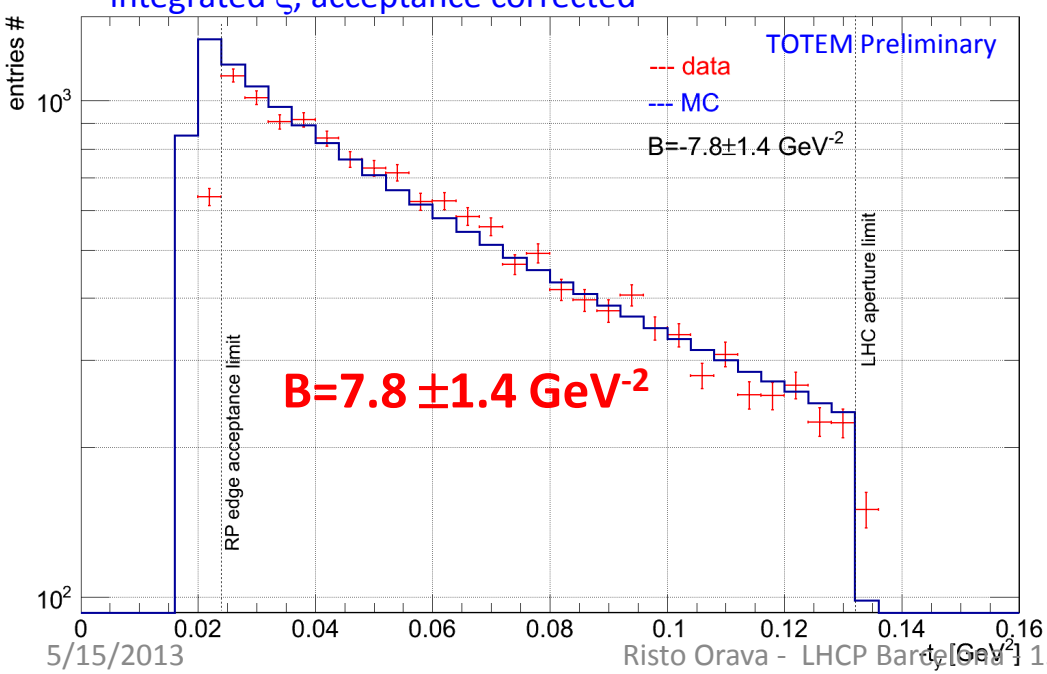
TOTEM alone, 20.10.2011 data

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

Single arm DPE event rate in RP

integrated ξ, acceptance corrected



σ_{DPE} estimation:

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

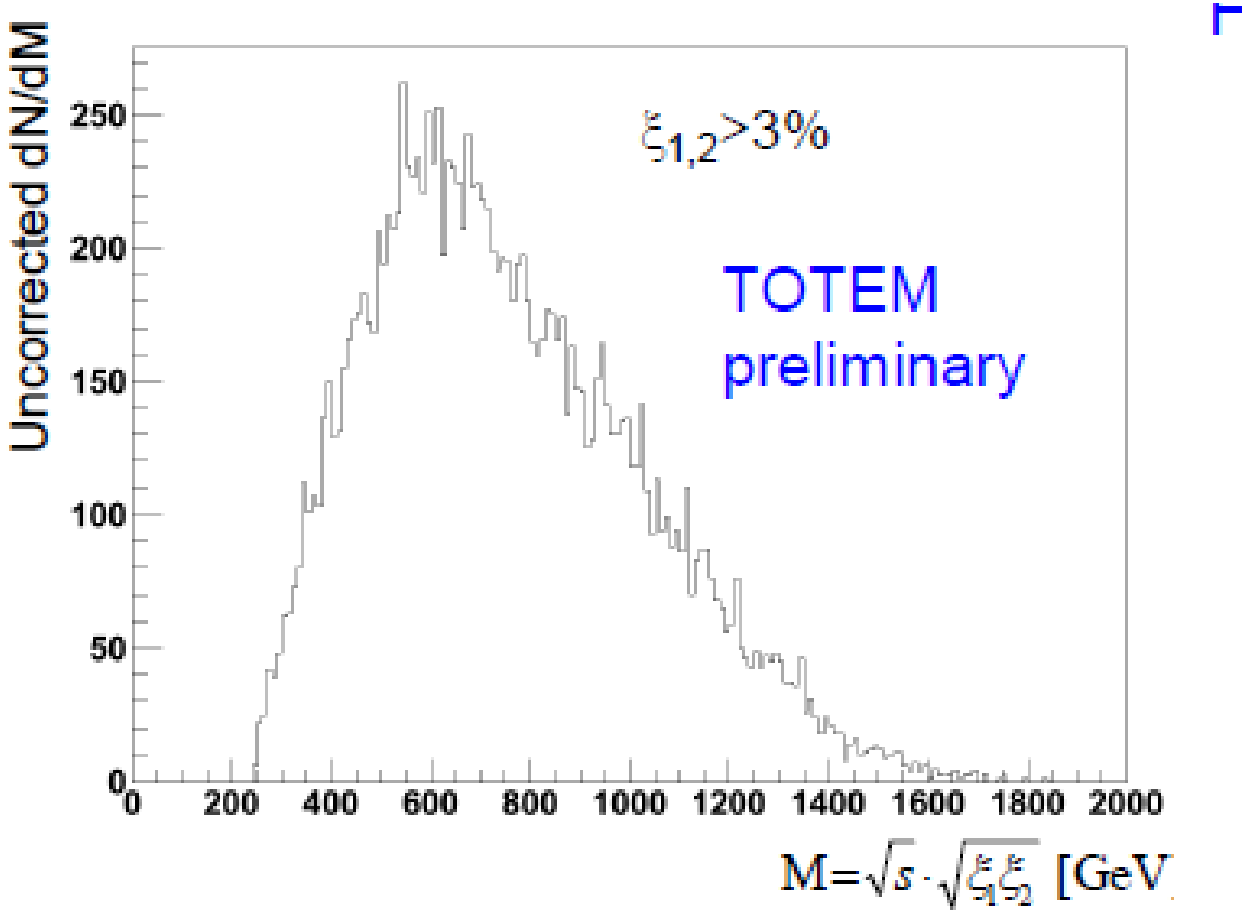
$$\sigma_{DPE} = \int_0^\infty dt_1 \int_0^\infty dt_2 \frac{d^2\sigma_{DPE}}{dt_1 dt_2} \approx 1\text{mb}$$

Work in progress:

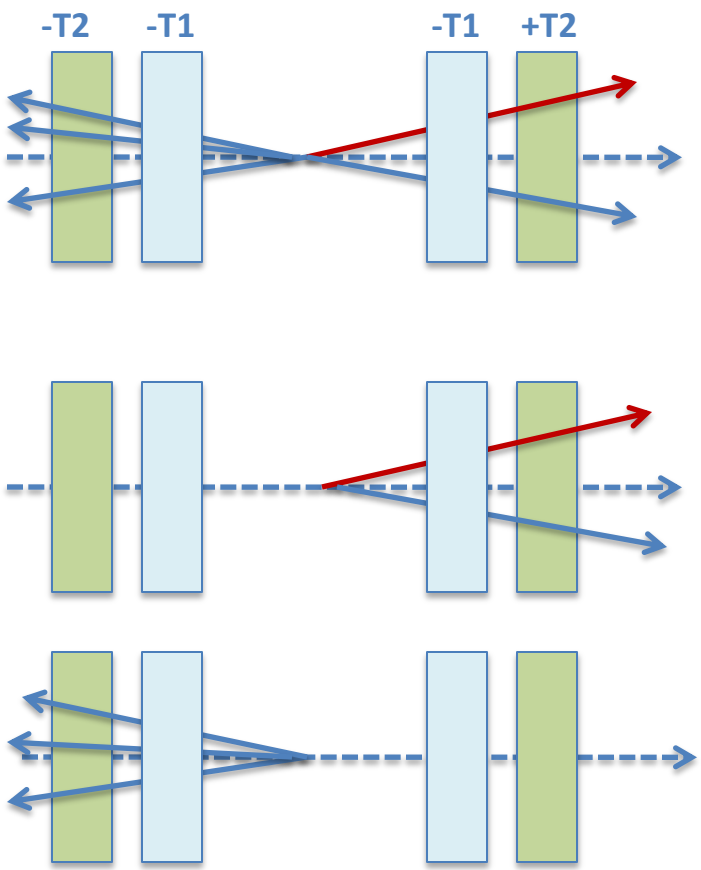
$$\sigma_{DPE} = \int \frac{d^4\sigma_{DPE}}{dt_1 dt_2 d\xi_1 d\xi_2} dt_1 dt_2 d\xi_1 d\xi_2$$

Soft Central Diffraction – dN/dM

TOTEM alone, 20.10.2011 data



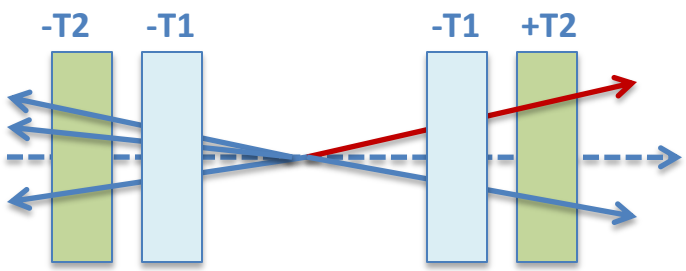
Event Classification by the T2s



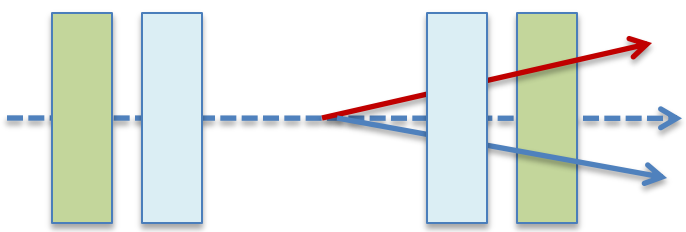
Tracks in both T2s: dd & nd

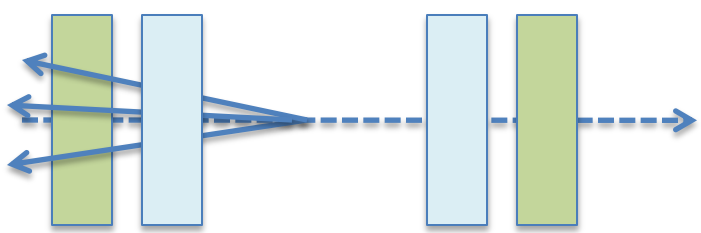
Tracks in ±T2: mostly sd
(M* > 3.5 GeV)

Event Classification by the T1s&T2s



Tracks in both ±T2s
No Tracks in ±T1s : Clean dd!
- A study being completed

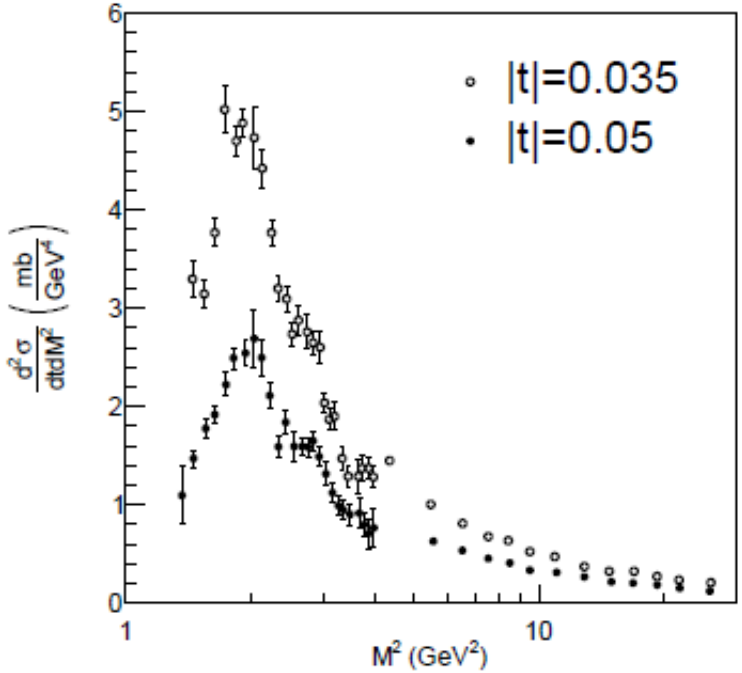




Tracks in either +T2 or –T2
No Tracks in T1s:
Mostly sd (M* > 3.5 GeV),
- But not so clean

Small Mass Diffractive States

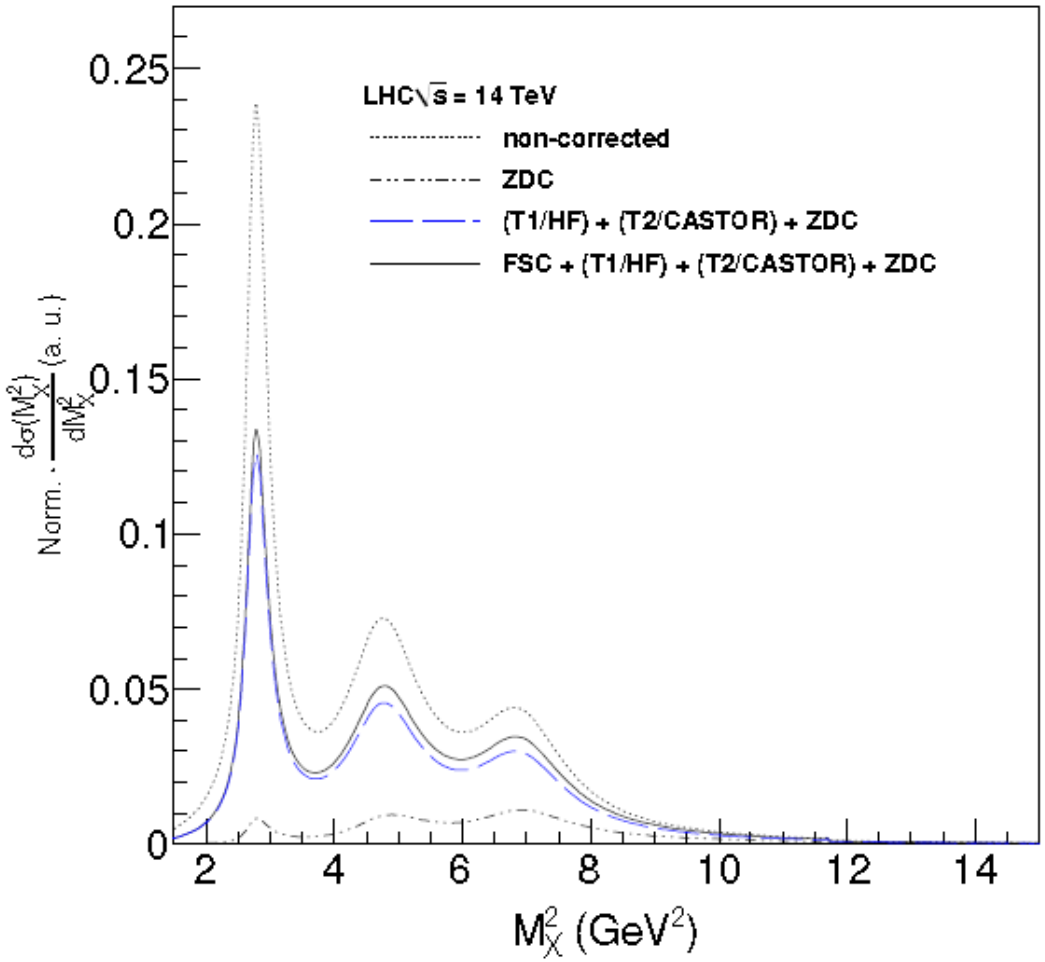
SMALL MASS REGION DOMINATED BY N* RESONANCES



N*(1680MeV)

Fig. 1 Compilation of low-mass SD data form Fermilab experiments $p + d \to X + d$, $P_{lab} = 275\,\mathrm{GeV/c}$, see [2]. The first peak has the mean value of $M_{X,1} = 1400\,\mathrm{MeV}$ and the second bump has $M_{X,1} = 1688\,\mathrm{MeV}$, wich correspond to the masses of N^* resonances, see Sec. 4.2

Single Diffraction at M_X < 10 GeV



For σ_{tot}^{pp}
via Optical Theorem
need to measure
the inelastic
rate.

$\sigma_{SD}(M_X < 3\ \text{GeV}) = ?$

FSCs will solve the
problem.

L.Jenkovzsky, O. Kuprash, J.W. Lämsä, V.Magas, RO

WHAT NEXT...

- Analysis of Castor and ZDC data: N*, neutral leading states
- Soft SD, CDE, Double Diffraction, (Soft) Evt Classification
- CMS + TOTEM data :
  - Homework: beam halo pile-up, optics, resolutions, acceptance, reconstruction …
  - Soft and Hard CDE (differential) cross-sections
  - Further studies of particular events (common visualisation soon)
- Upgrade of TOTEM Roman Pot detectors to profit from low-β^* optics after LHC shut-down
- More data welcome:
  - Data taking : 1000 bunches + x-angles @ β^*=90m

Roman Pot detector system

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