Recent cross section, diffractive and forward multiplicity measurements with TOTEM

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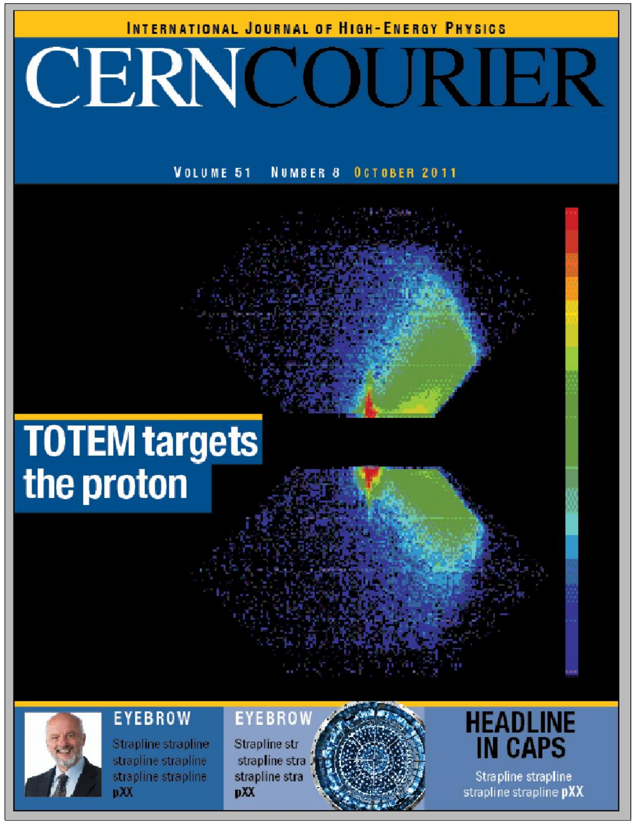
on behalf of
TOTEM collaboration

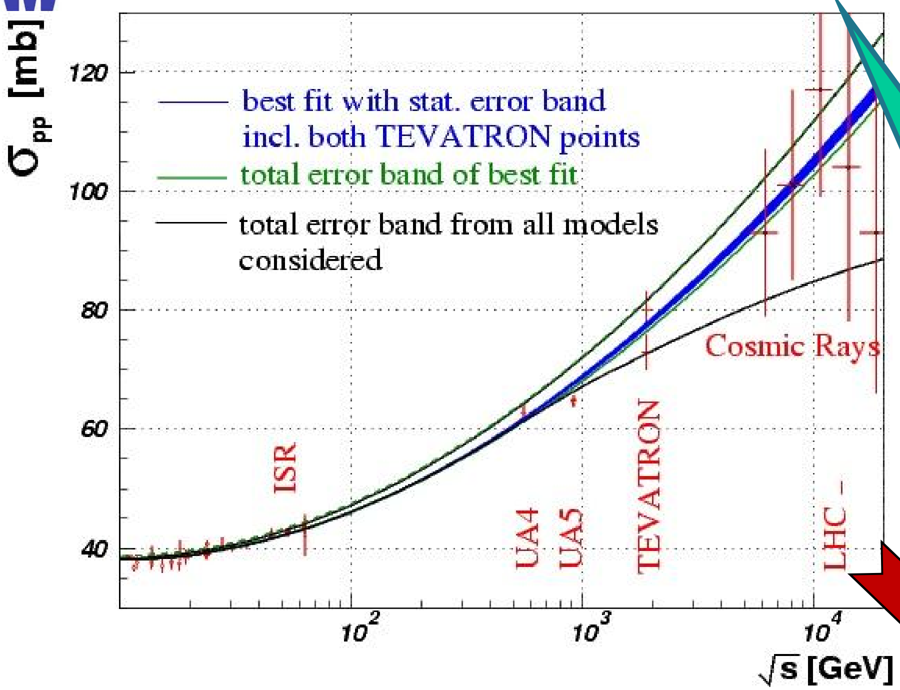
EPS-HEP 2013 conference



- Introduction
- Elastic, inelastic & total pp cross-section
- Forward multiplicity in pp (w/o CMS)
- Soft (& hard) diffraction in pp (w/o CMS)

TOTEM physics menu

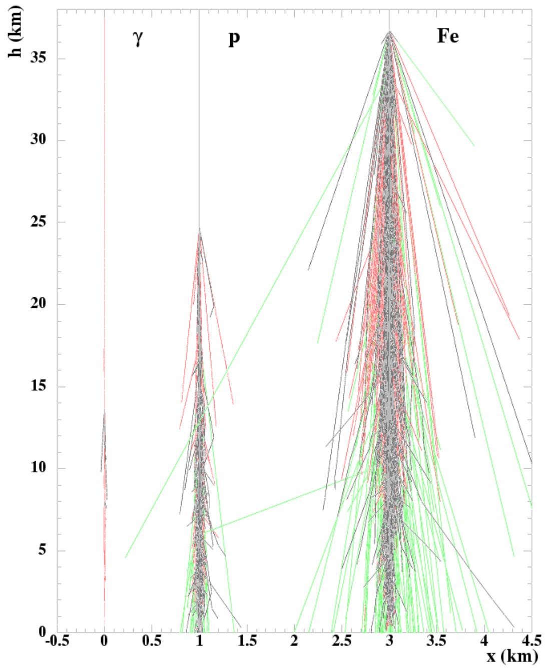
Total pp cross-section

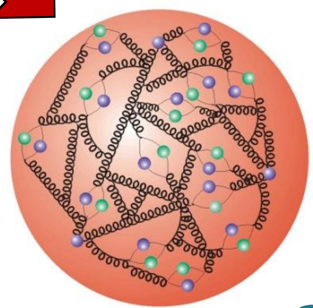


Ultimately ~1-2 % precision

Forward particle production

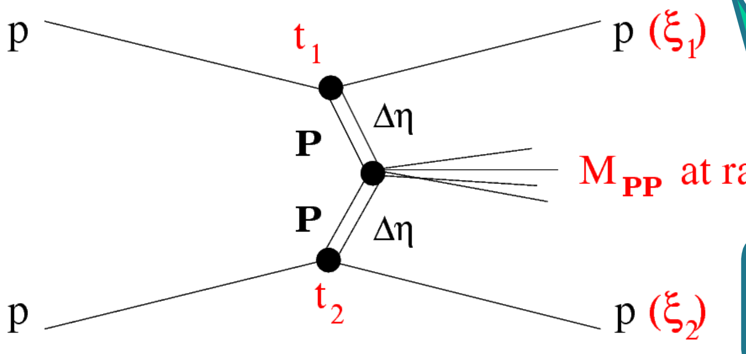
Cosmic ray connection





Proton

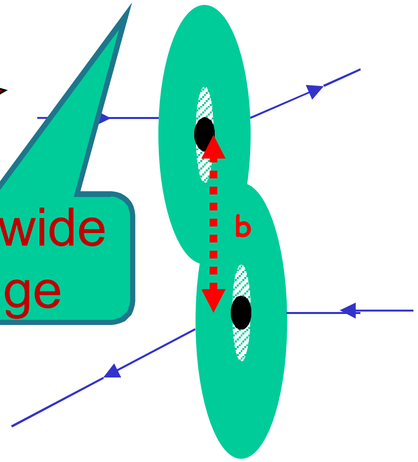
Diffraction: soft and hard



Understand QCD nature

Elastic pp scattering

Over a wide $|t|$ range



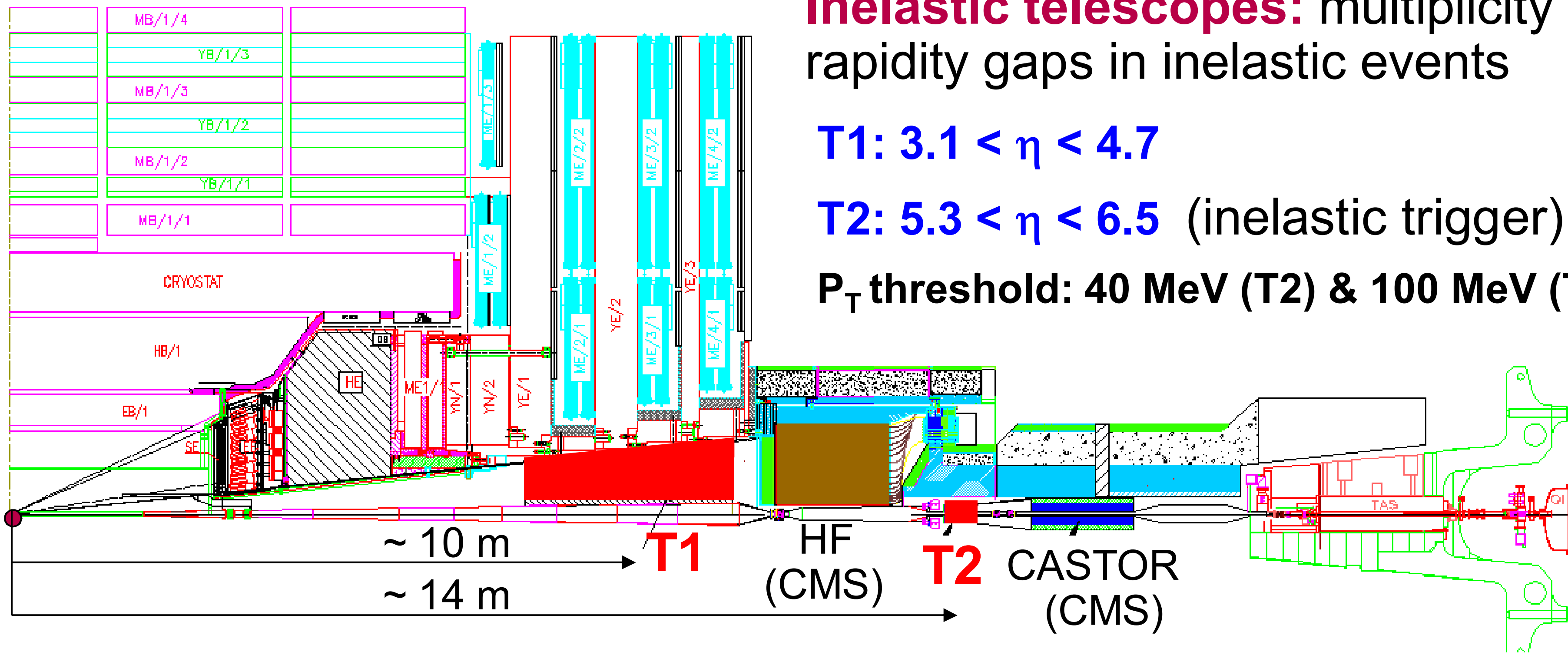
Experimental setup @ IP5

Inelastic telescopes: multiplicity & rapidity gaps in inelastic events

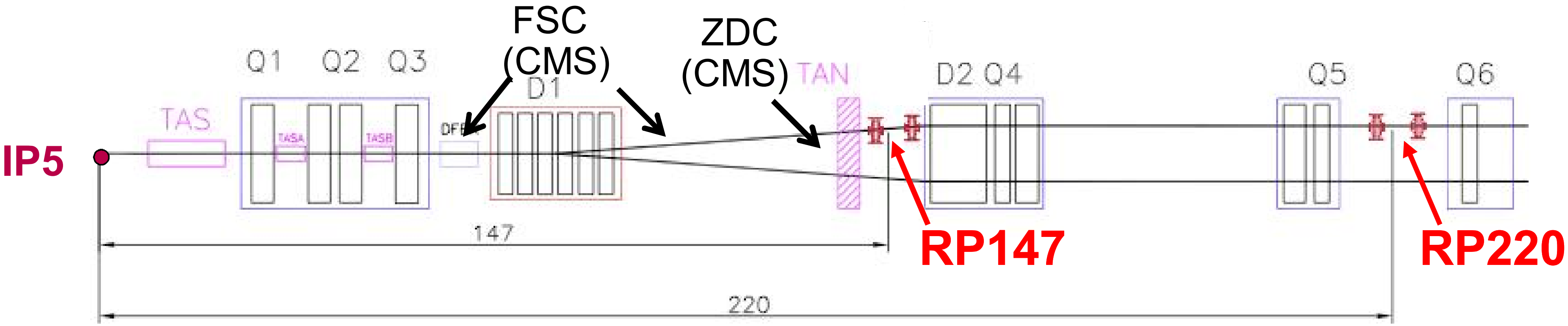
T1: $3.1 < \eta < 4.7$

T2: $5.3 < \eta < 6.5$ (inelastic trigger)

P_T threshold: 40 MeV (T2) & 100 MeV (T1)

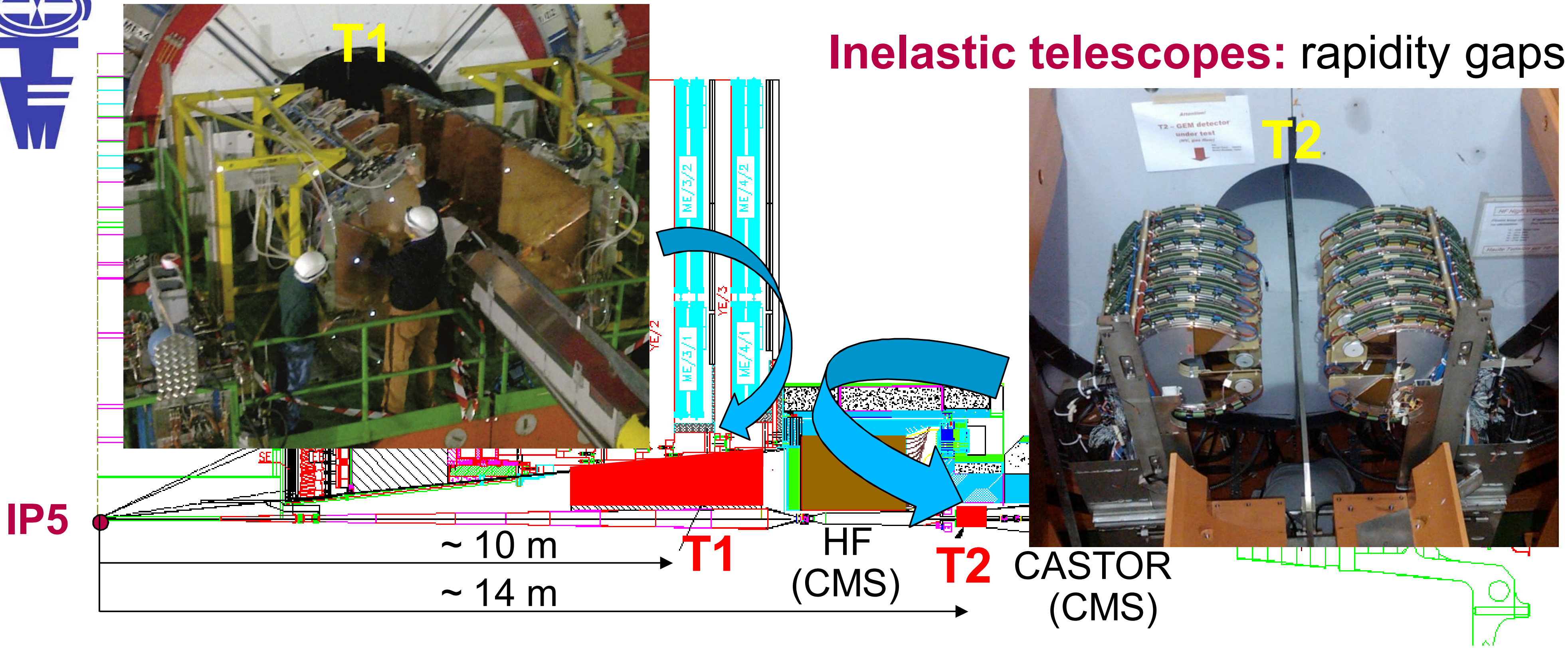


Roman Pots: elastic & diffractive protons (di-proton trigger)

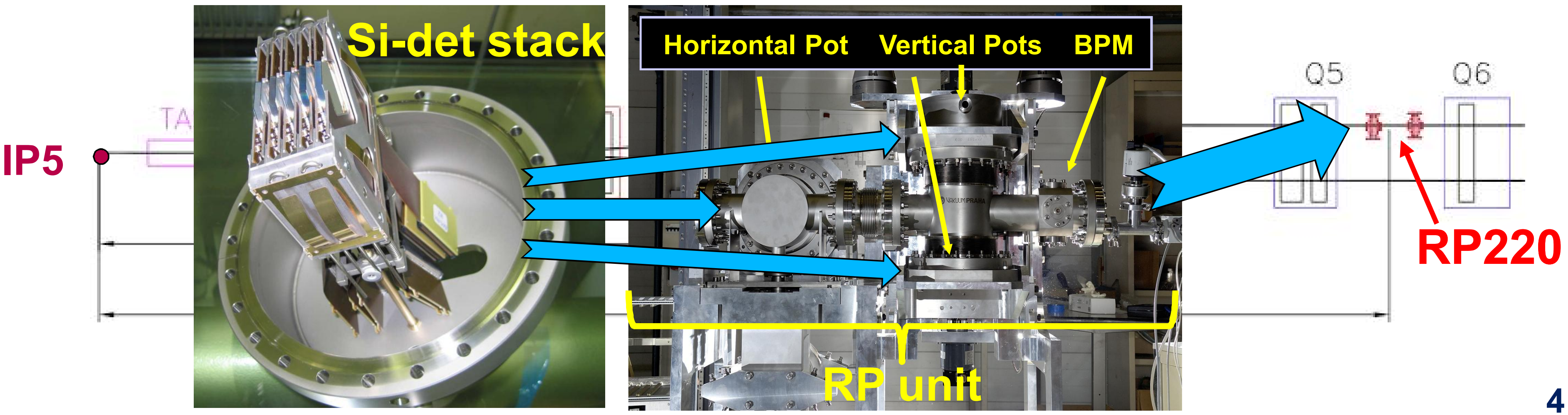


Experimental setup @ IP5

Inelastic telescopes: rapidity gaps

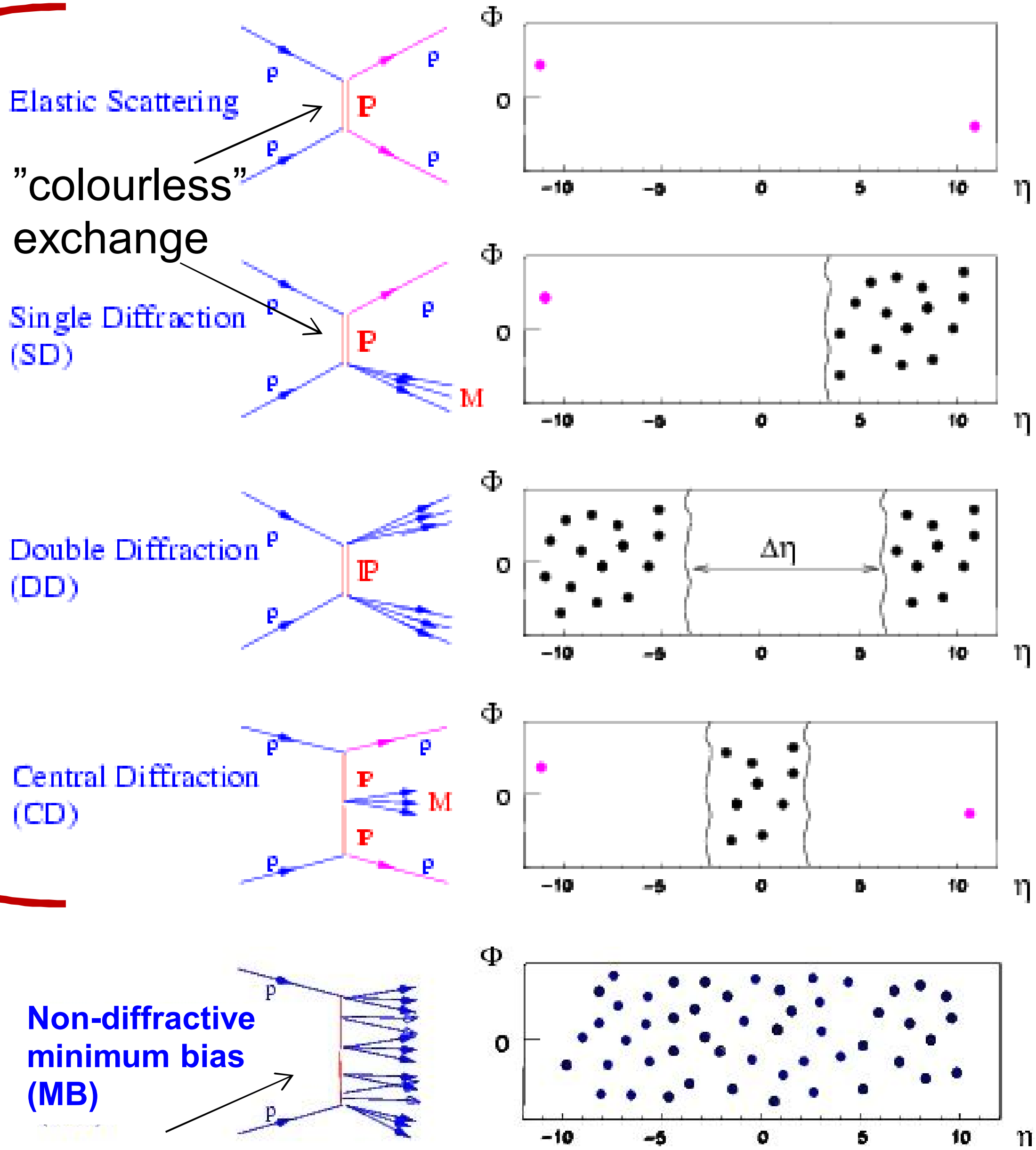


Roman Pots: diffractive protons (di-proton trigger)



Soft pp processes

Diffraction a large fraction of total pp cross-section !!



exchange of colour

σ @ LHC

~25 mb

~10 mb

~5 mb

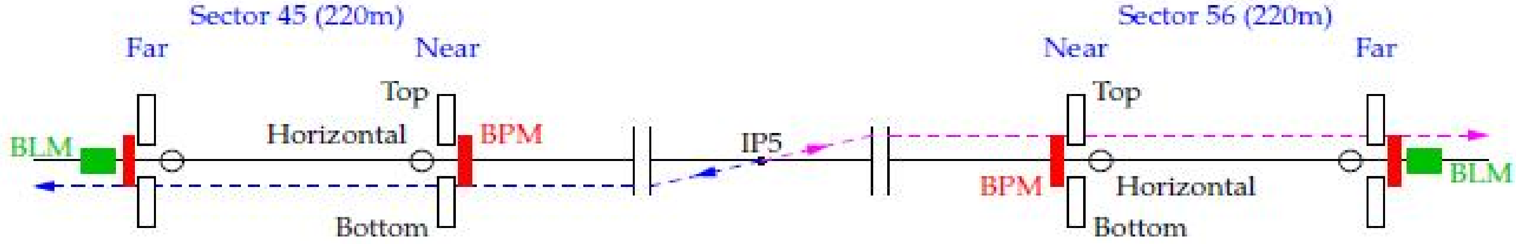
~1 mb

~60 mb

Measure σ (M,ξ,t)

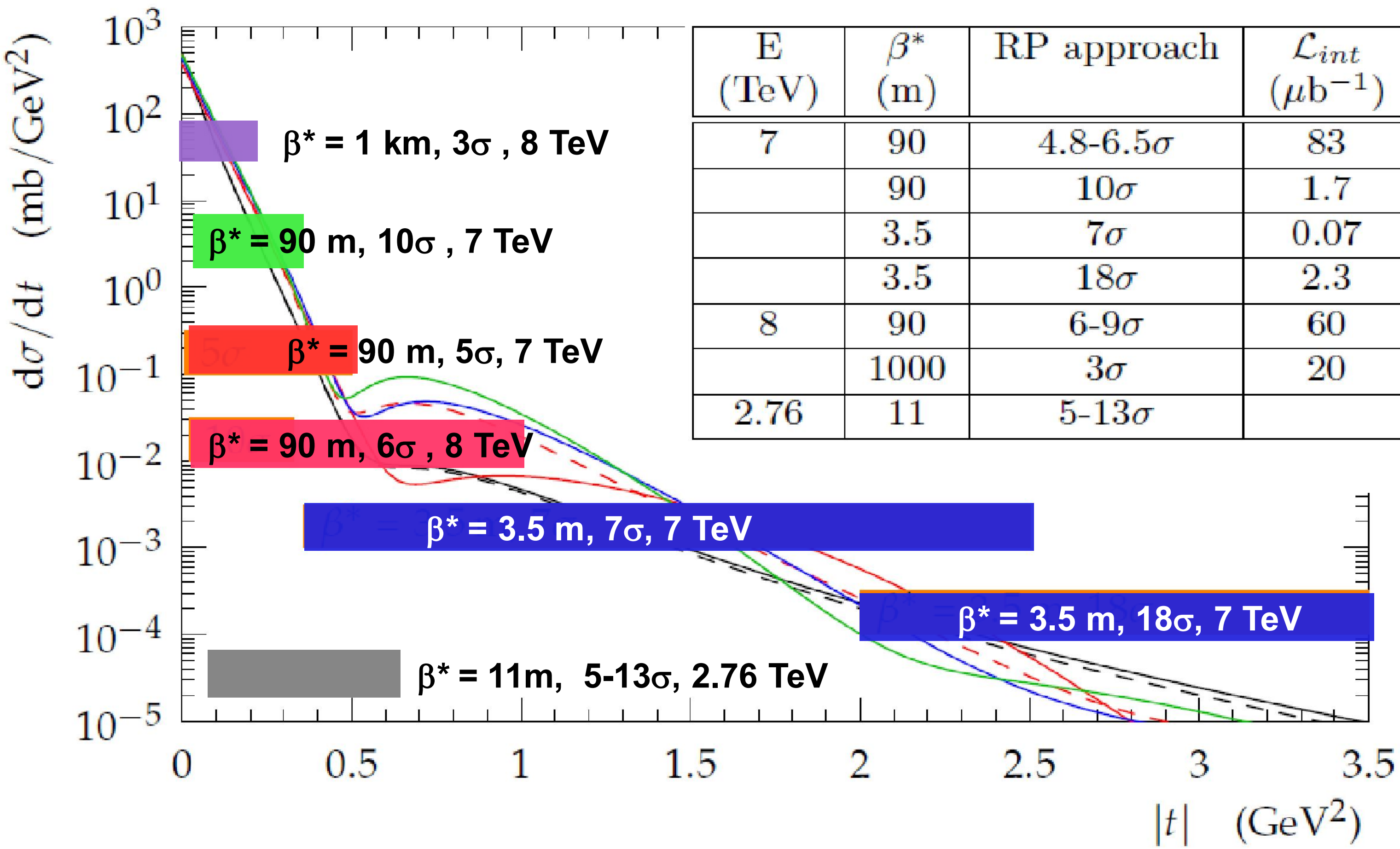
Elastic pp scattering: selection & data sets

Selected based on topology, low $|\xi|$, collinearity, & vertex



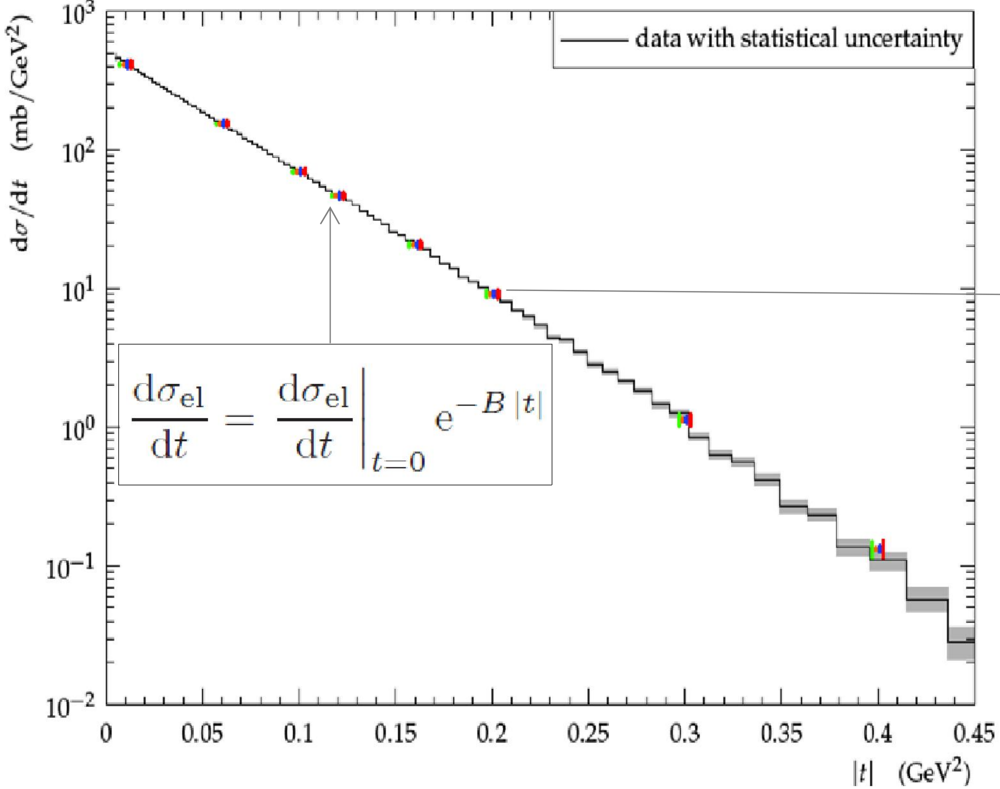
Key issues:
RP alignment
& optics

Data sets at different conditions to measure elastics over wide t-range including very low |t|

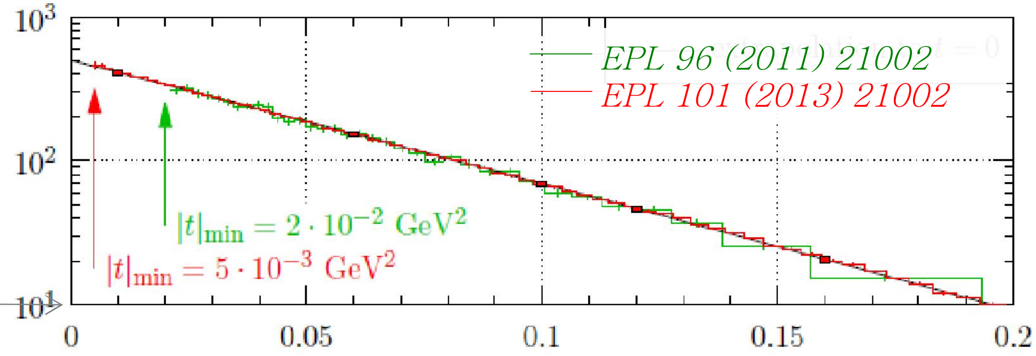


E (TeV)	β^* (m)	RP approach	$\mathcal{L}_{int}$ (μb^{-1})	t range (GeV^2)	Elastic events
7	90	$4.8\text{-}6.5\sigma$	83	$7{\cdot}10^{-3}$ - 0.5	1M
	90	10σ	1.7	0.02 - 0.4	14k
	3.5	7σ	0.07	0.36 - 3	66k
	3.5	18σ	2.3	2 - 3.5	10k
8	90	$6\text{-}9\sigma$	60	0.01 - 1	0.6M
	1000	3σ	20	$6{\cdot}10^{-4}$ - 0.2	0.4M
2.76	11	$5\text{-}13\sigma$		0.05-0.6	45k

Elastic pp scattering: cross-section @ 7 TeV



Extrapolation to t = 0: $d\sigma/dt = A\, e^{-Bt}$



A (mb/GeV^2) = $506 \pm 23^{syst} \pm 0.9^{stat}$

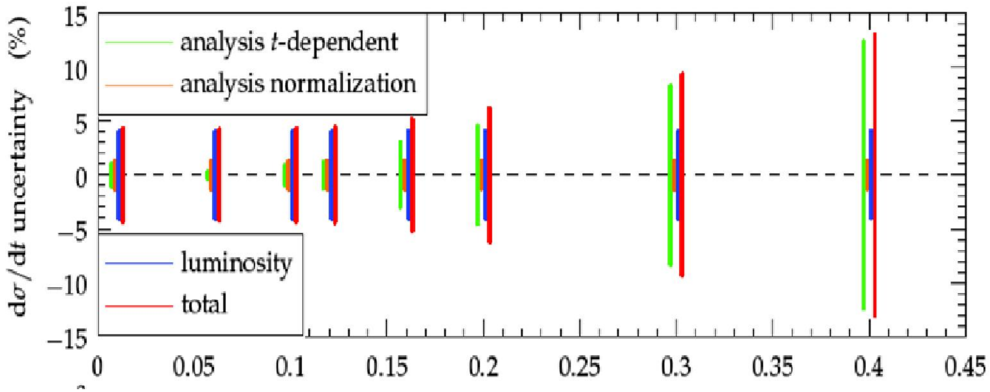
$503 \pm 27^{syst} \pm 1.5^{stat}$

B (GeV^{-2}) = $19.89 \pm 0.27^{syst} \pm 0.03^{stat}$

(fit range: $5{\cdot}10^{-3} < |t| < 0.2$ GeV^2)

$20.1 \pm 0.3^{syst} \pm 0.2^{stat}$

(fit range: $2{\cdot}10^{-2} < |t| < 0.33$ GeV^2)

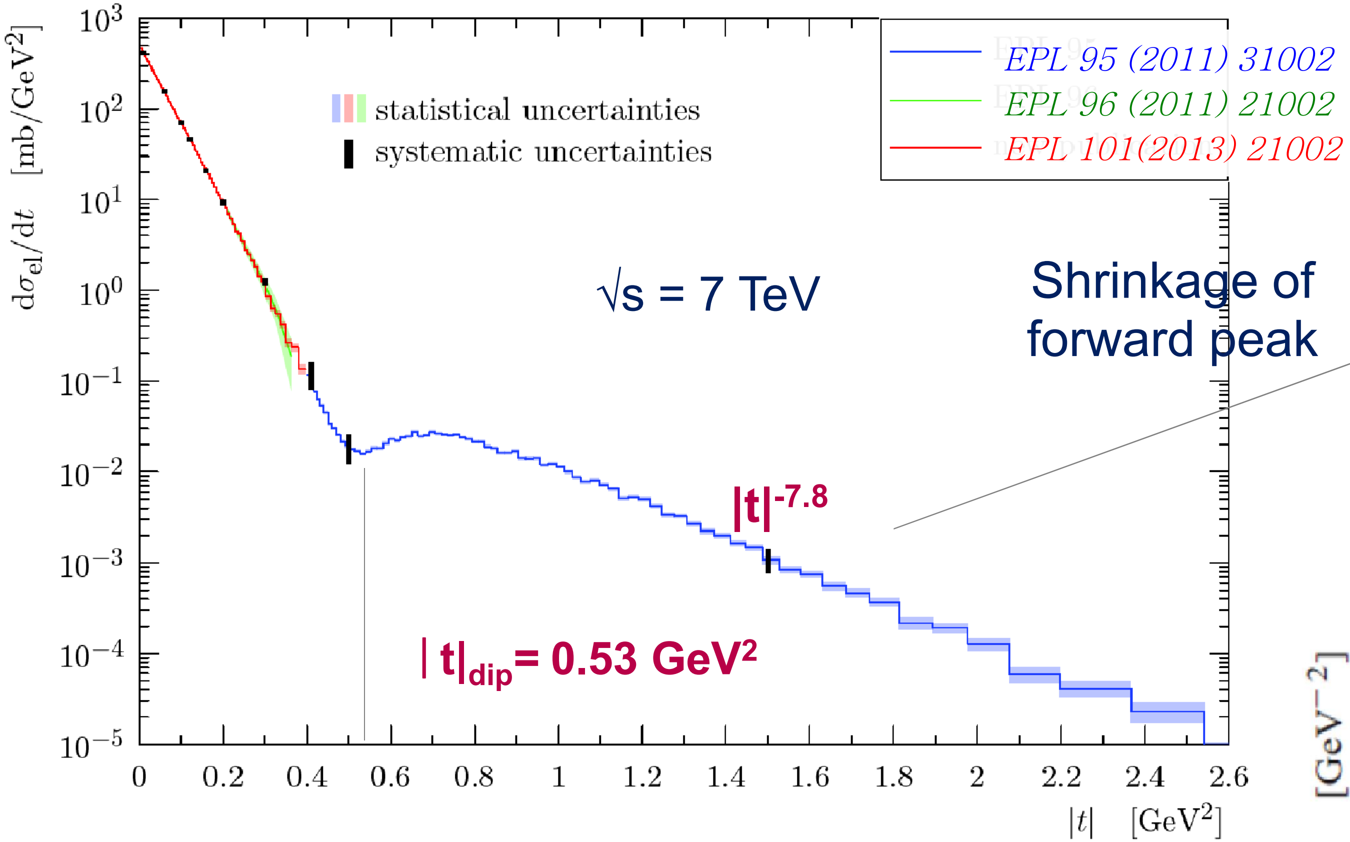


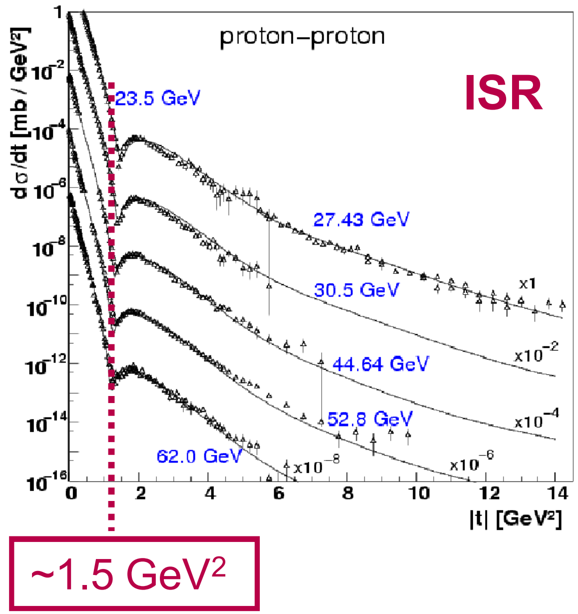
Elastic cross section $\sigma_{elastic}$

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

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

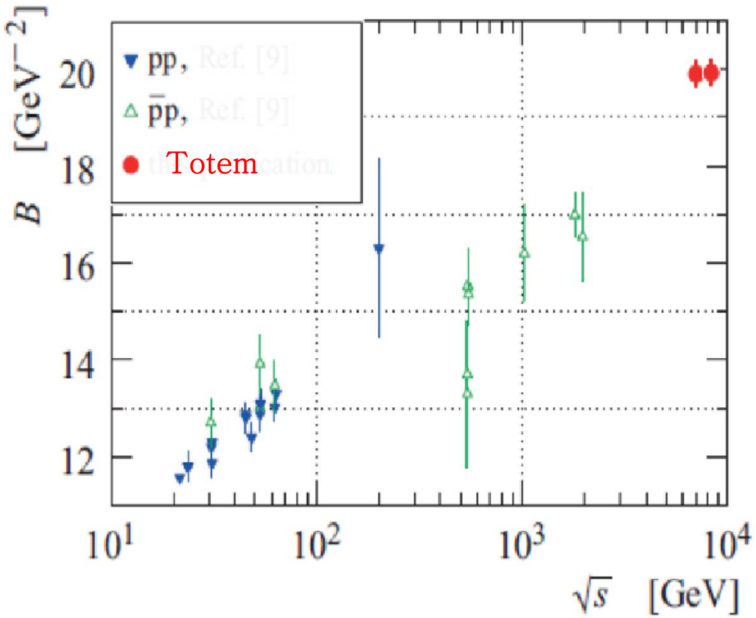
Elastic pp scattering: implications





$$d\sigma/dt \sim e^{-B|t|}$$

Increase of B slope with collision energy



$$B_{7TeV} = (19.89 \pm 0.27)\ \mathrm{GeV}^{-2}$$
$$B_{8TeV} = (19.90 \pm 0.30)\ \mathrm{GeV}^{-2}$$

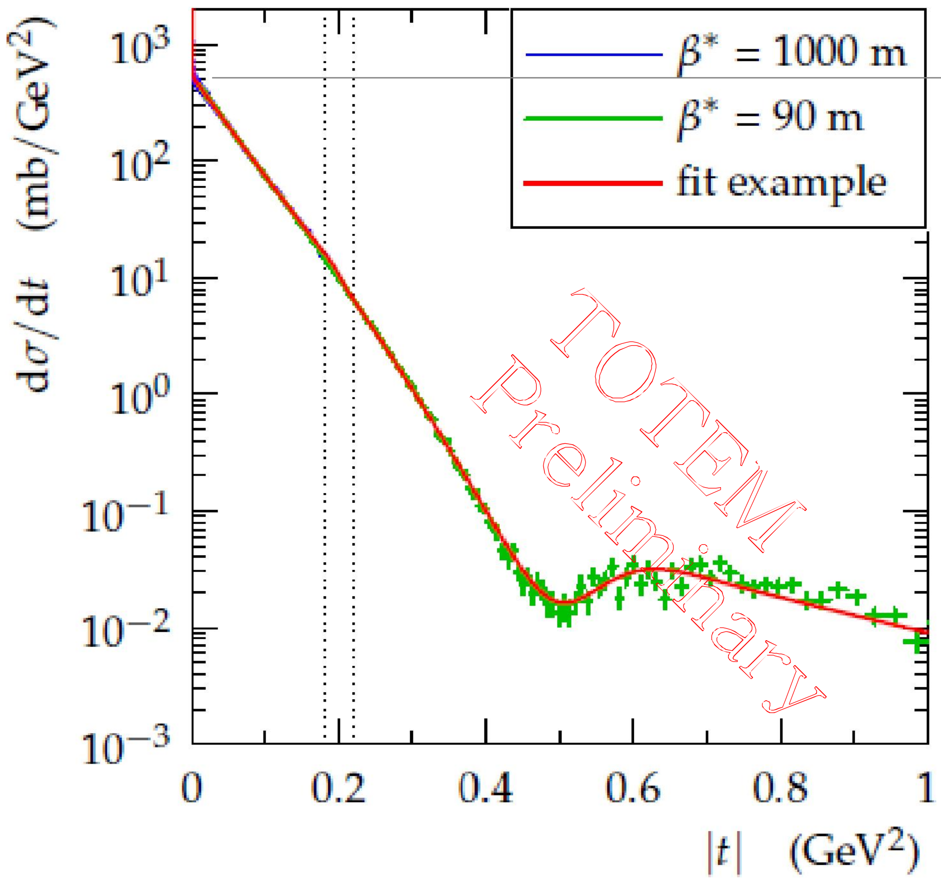
Elastic pp scattering: σ & very low-|t| @ 8 TeV

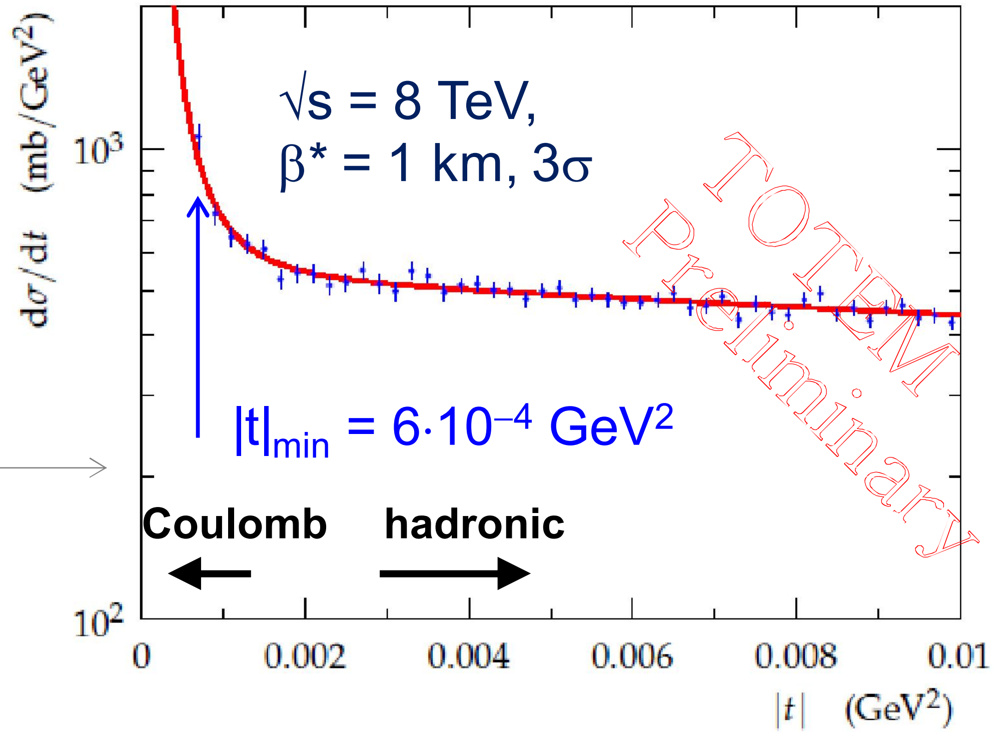
$\beta^* = 90$ m:

$\sigma_{elastic}$ = 27.1 ± 1.4 mb

Luminosity-independent

PRL 111 (2013) 012001





$\beta^* = 1$ km:

Access to Coulomb-hadronic interference term ⇒ ρ ($= \Re F^h / \Im F^h|_0$) & σ_{total} measurements

Elastic pp: Coulomb-hadronic interference

$d\sigma/dt \propto |F^{C+h}|^2$ = Coulomb + "interference" + hadronic

from theory

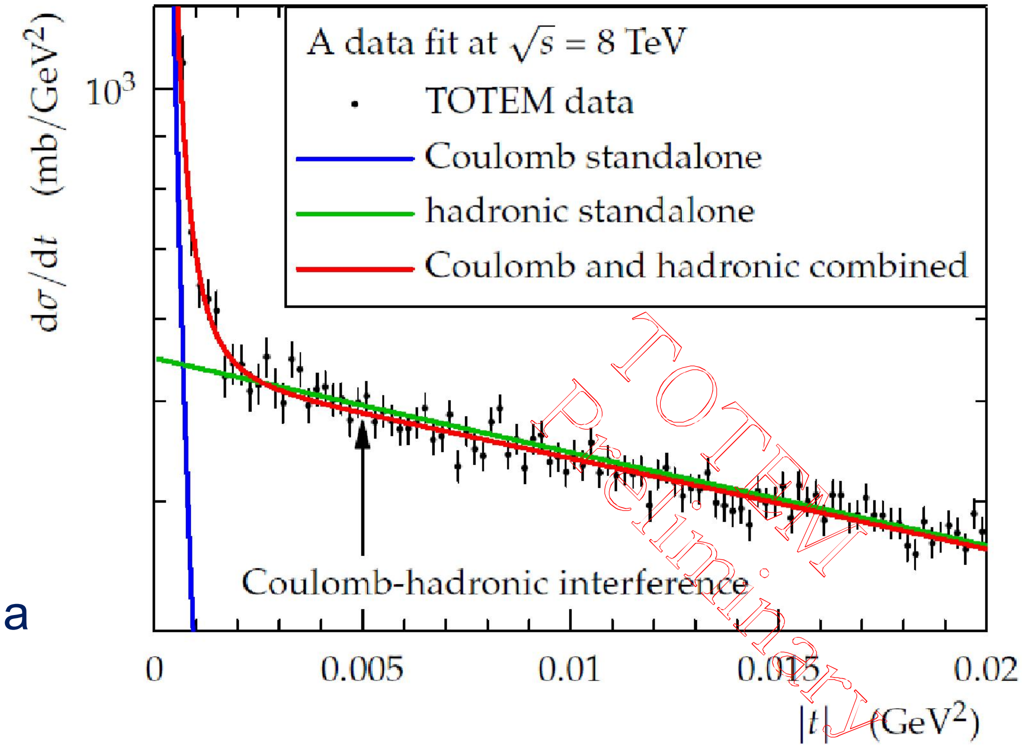
Modulus constrained by measurement $e^{-B(t)}$

B(t) described by **n > 1** parameters

Key elements considered:

- number of parameters to describe B(t)
- description of interference term: from simplified West-Yennie [1] formula to general Kundrát-Lokajícek [2] formula
- ψ phase of hadronic amplitude (t dependence not constrained by measurements): central or peripheral

$\rho = 1 / \tan(\psi|_0)$



Example: χ^2 fit with **K**undrát-**L**okajícek formula

$B(t) \sim b_0 + b_1 t + b_2 t^2$

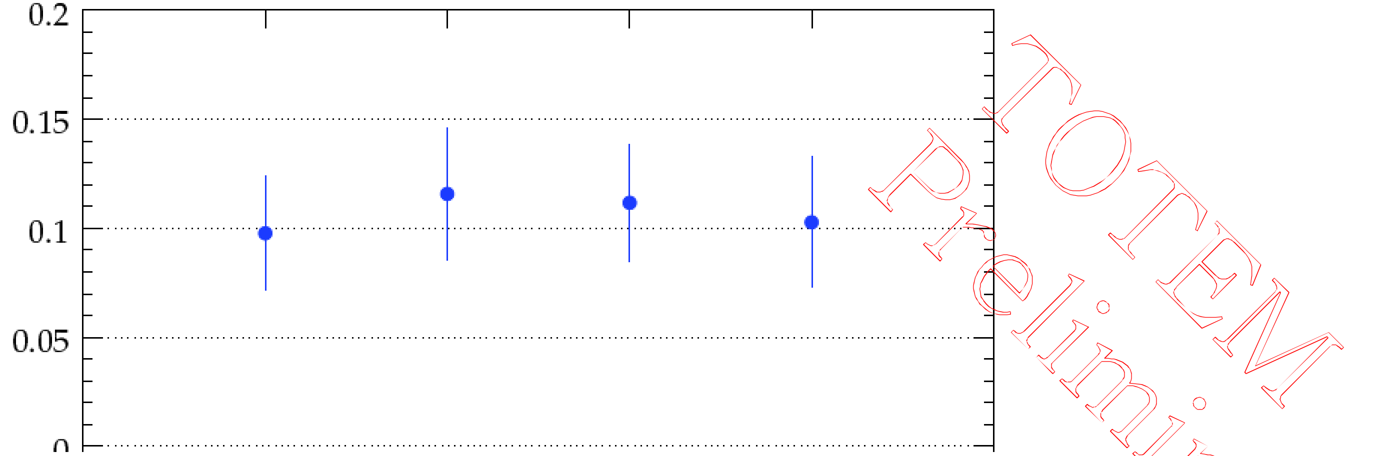
Central hadronic phase

All errors included

[1] *G. B. West and D. R. Jennie, Phys. Rev. 172 (1968)1413.*
[2] *V. Kundrát and M. Lokajıcek, Z. Phys. C 63 (1994) 619.*

Elastic pp scattering: ρ measurement

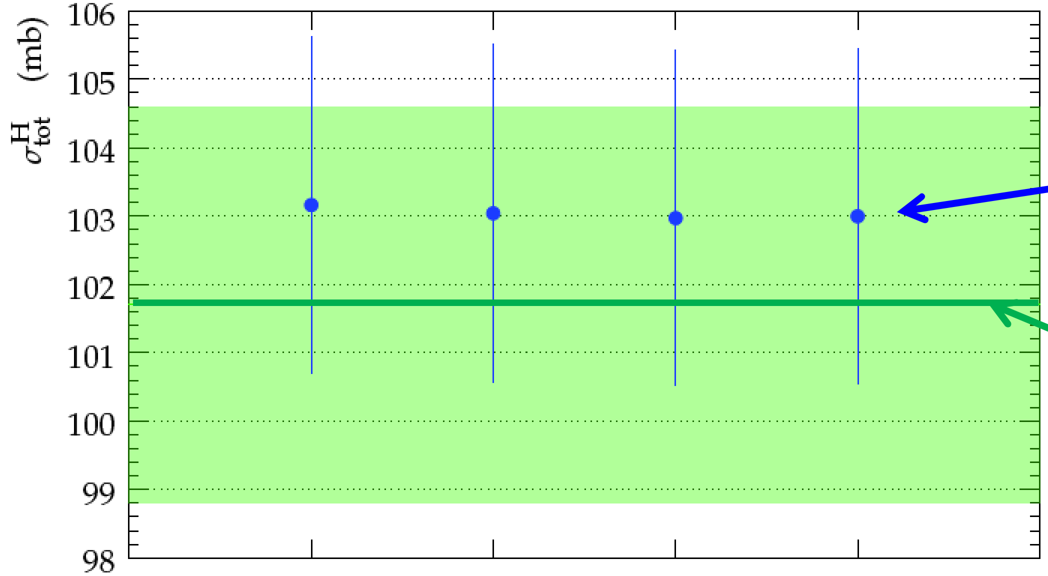
$$\varrho \equiv \left.\frac{\Re F^{\mathrm{H}}}{\Im F^{\mathrm{H}}}\right|_0$$



Method: χ^2 fit
KL formula

B(t) parameters:	2	3	2	3
Phase:	central	central	periph.	periph.

$$\rho = 0.107 \pm 0.027^{(\mathrm{stat})} \pm 0.010^{(\mathrm{syst})} {}^{+0.009}_{-0.009} \,(\mathrm{model})$$



$$\sigma^2_{tot} = \frac{16\pi}{(1+\rho^2)} \frac{1}{\mathcal{L}} \left(\frac{dN_{el}}{dt}\right)^{had}_{t=0}$$

σ_{total}= 101.7 ± 2.9 mb
luminosity independent
PRL111(2013)012001

Inelastic pp cross-section

- Count events with charged particles in T1 & T2 (~ 95 % of inelastic).
- Trigger: at least one track in T2.

- Corrections:
– beam-gas background (non-colliding bunches)
– trigger efficiency, pile-up, T1 only events (zero-bias)
– central diffraction unseen (PHOJET & MBR)
– **Low mass diffraction** @ M_{diff} < 3.4-3.6 GeV (tuned QGSJETII-03 to observed 1hemi fraction)

8 TeV

Source	Correction	Uncertainty
Beam gas	0.45 %	0.45 %
Trigger Efficiency	1.2 %	0.6 %
Pile up	2.8 %	0.6 %
T2 reconstruction	0.35 %	0.2 %
	0.8 %	0.4 %
"T1 only"	1.2 %	0.4 %
Internal Gap covering T2	0.4 %	0.2 %
Central diffraction	-	0.35 %
Low mass diffraction (seen)	0.4 %	0.2 %
Low mass diffraction	4.8 %	2.4 %

σ_{inel} (mb)	@ 7 TeV	@ 8 TeV
Direct	**73.7 ± 3.4** *EPL 101 (2013) 21003*	
Indirect	**73.15 ± 1.26** *EPL 101 (2013) 21002*	
$\mathcal{L}$ *independent*	**72.9 ±1.5** *EPL 101 (2013) 21004*	**74.7 ± 1.7** *PRL 111 (2013) 012001*

Total pp cross-section: methods & results

$$\sigma_{tot}^2 = \frac{16\pi}{(1+\rho^2)} \frac{1}{\mathcal{L}} \left(\frac{dN_{el}}{dt} \right)_{t=0}$$

based on elastic scattering ⇒ low mass diffraction independent

σ_{total} = 98.3 mb ± 2.0 mb
EPL 96 (2011) 21002

σ_{total} = 98.6 mb ± 2.3 mb
EPL 101 (2013) 21002

$$\sigma_{tot} = \sigma_{el} + \sigma_{inel}$$

optical theorem & ρ independent

σ_{total} = 99.1 mb ± 4.3 mb
EPL 101 (2013) 21004

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

$\mathcal{L}$ independent

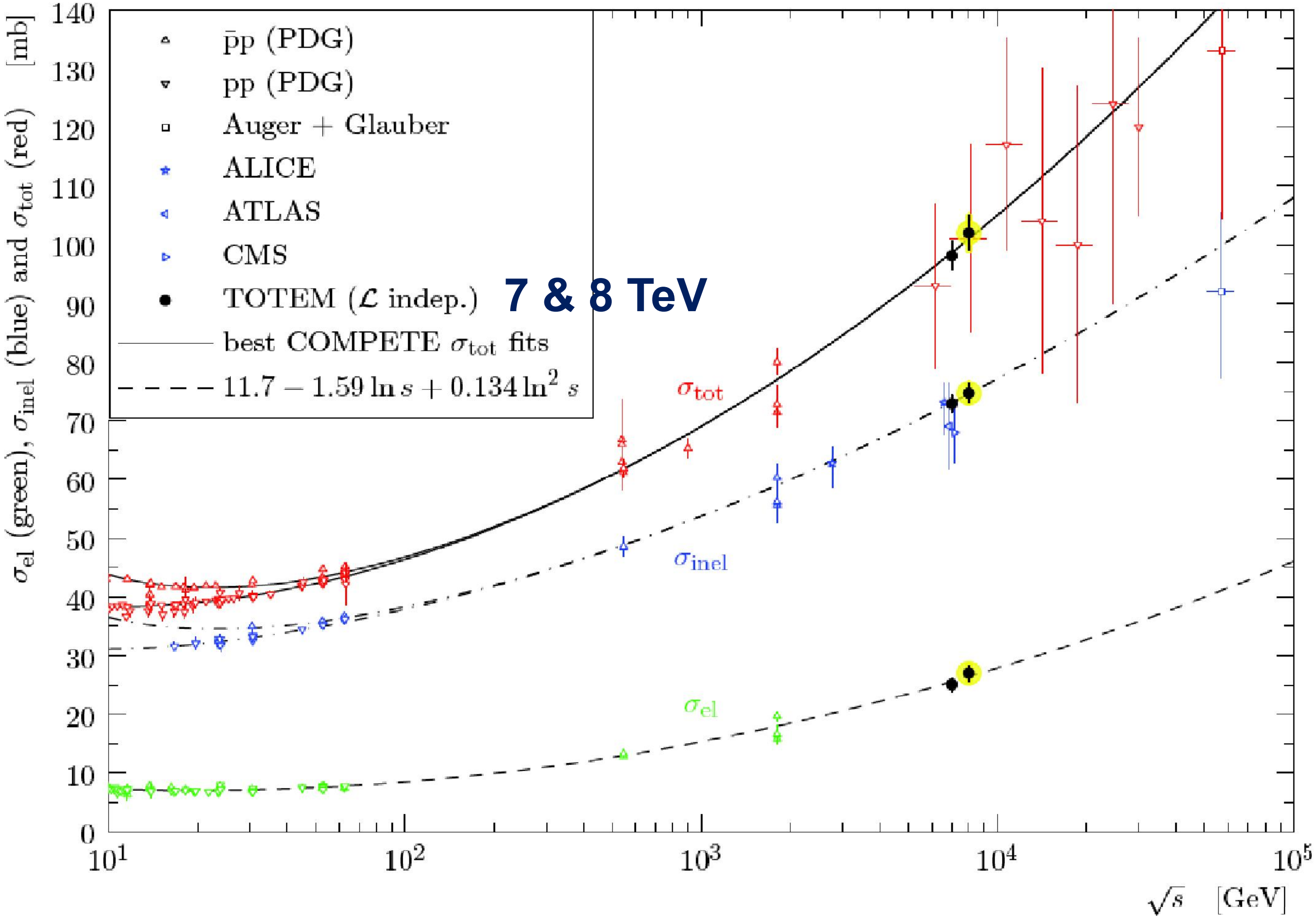
σ_{total} = 98.1 mb ± 2.4 mb
EPL 101 (2013) 21004

$\underbrace{\qquad}_{\text{7 TeV}}$ 7 TeV

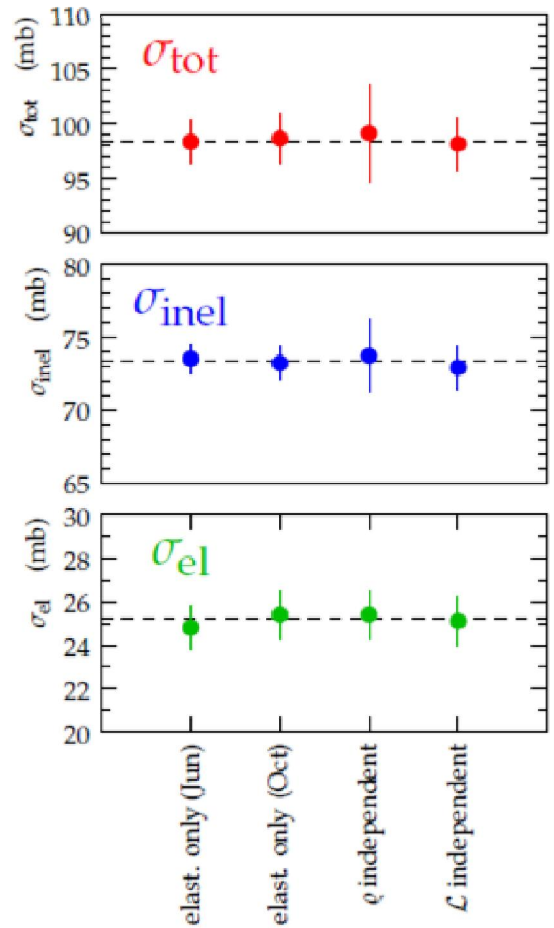
σ_{total} = 101.7 mb ± 2.9 mb
PRL 111(2013) 012001

8 TeV

pp cross-section: summary



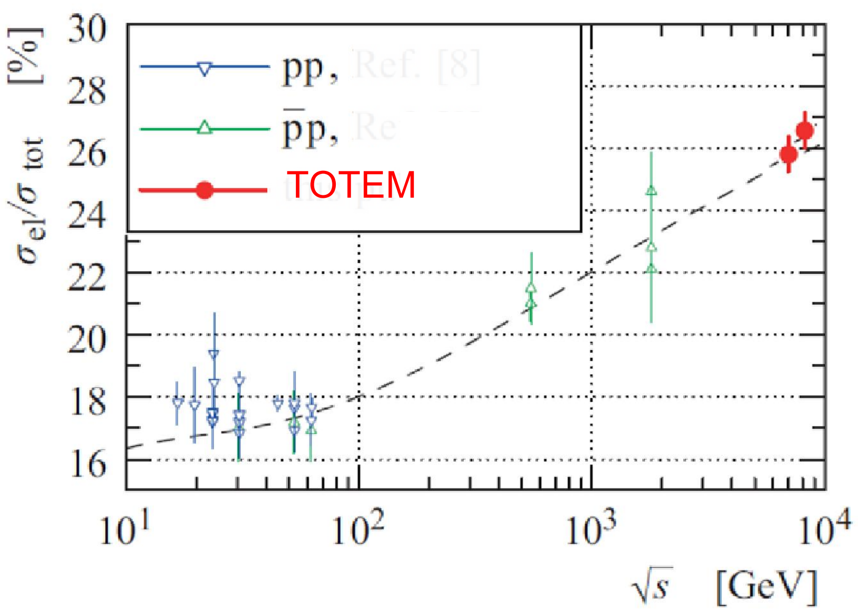
7 TeV



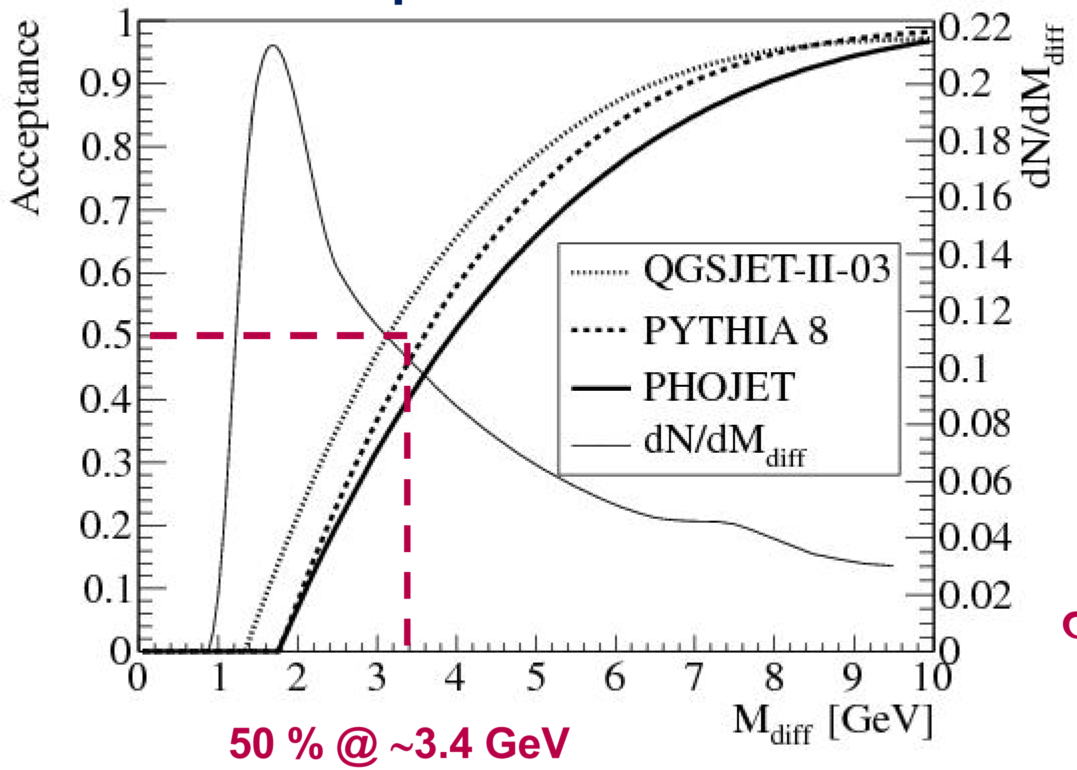
pp cross-section: implications

Luminosity & ρ independent ratios:

	7 TeV	8 TeV
$\sigma_{elastic} / \sigma_{total}$ =	0.257 ± 0.005	0.266 ± 0.006
$\sigma_{elastic} / \sigma_{inelastic}$ =	0.354 ± 0.009	0.362 ± 0.011



SD acceptance for T1+T2



50 % @ ~3.4 GeV

Low mass diffraction (7 TeV):

$\sigma_{inelastic, |\eta| > 6.5} =$

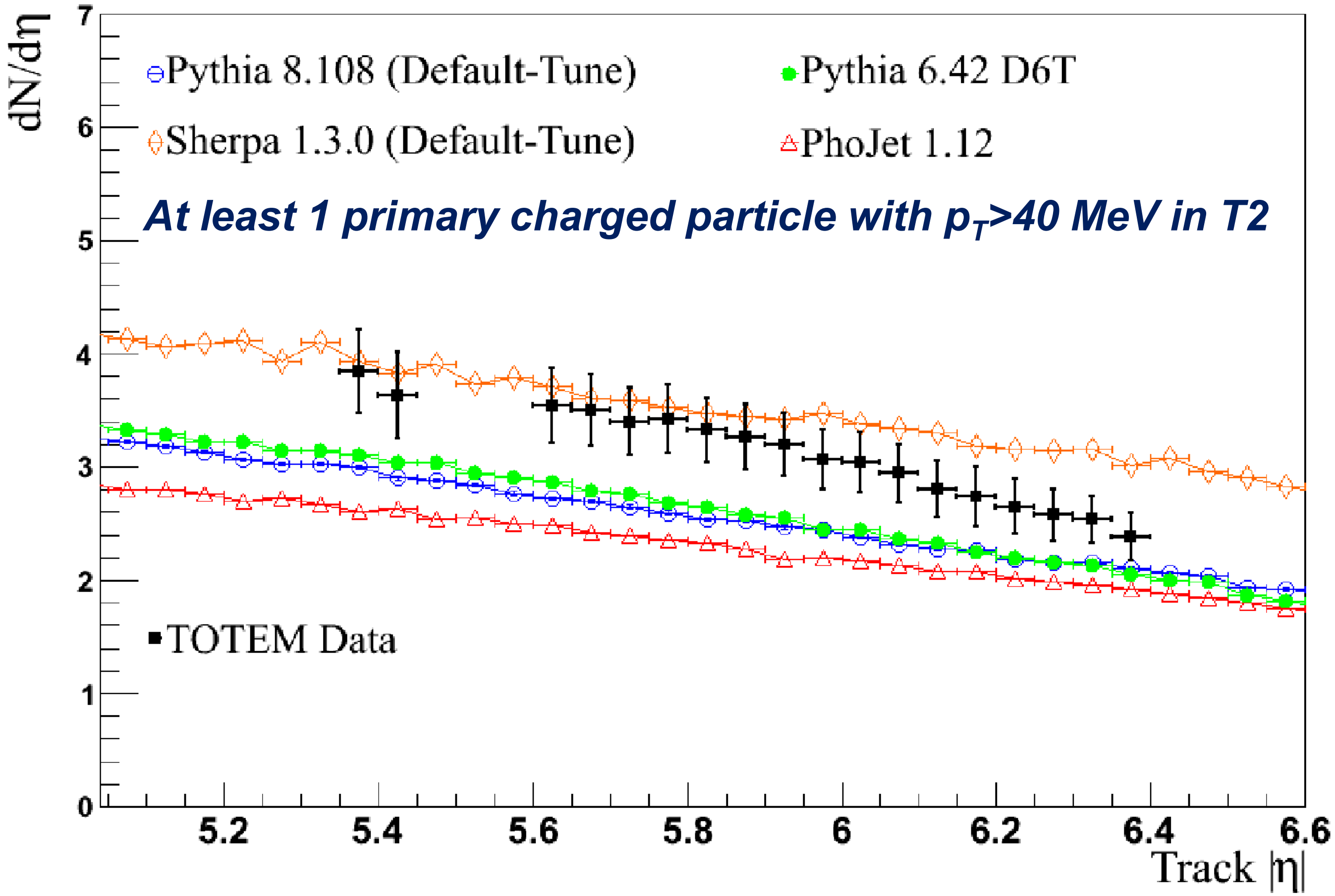
$\sigma_{total} - \sigma_{elastic} - \sigma_{inelastic, |\eta| < 6.5}$

$= 2.62 \pm 2.17$ mb

$\sigma_{inelastic, |\eta| > 6.5} \leq 6.3$ mb @ 95 % CL

Very forward $dN_{ch}/d\eta$ @ 7 TeV

Measured with T2 on T2 triggered events (*EPL 98 (2012) 31002*)
Visible inelastic cross-section ~ 93 %, diffractive events with M_{diff} > 3.4 GeV

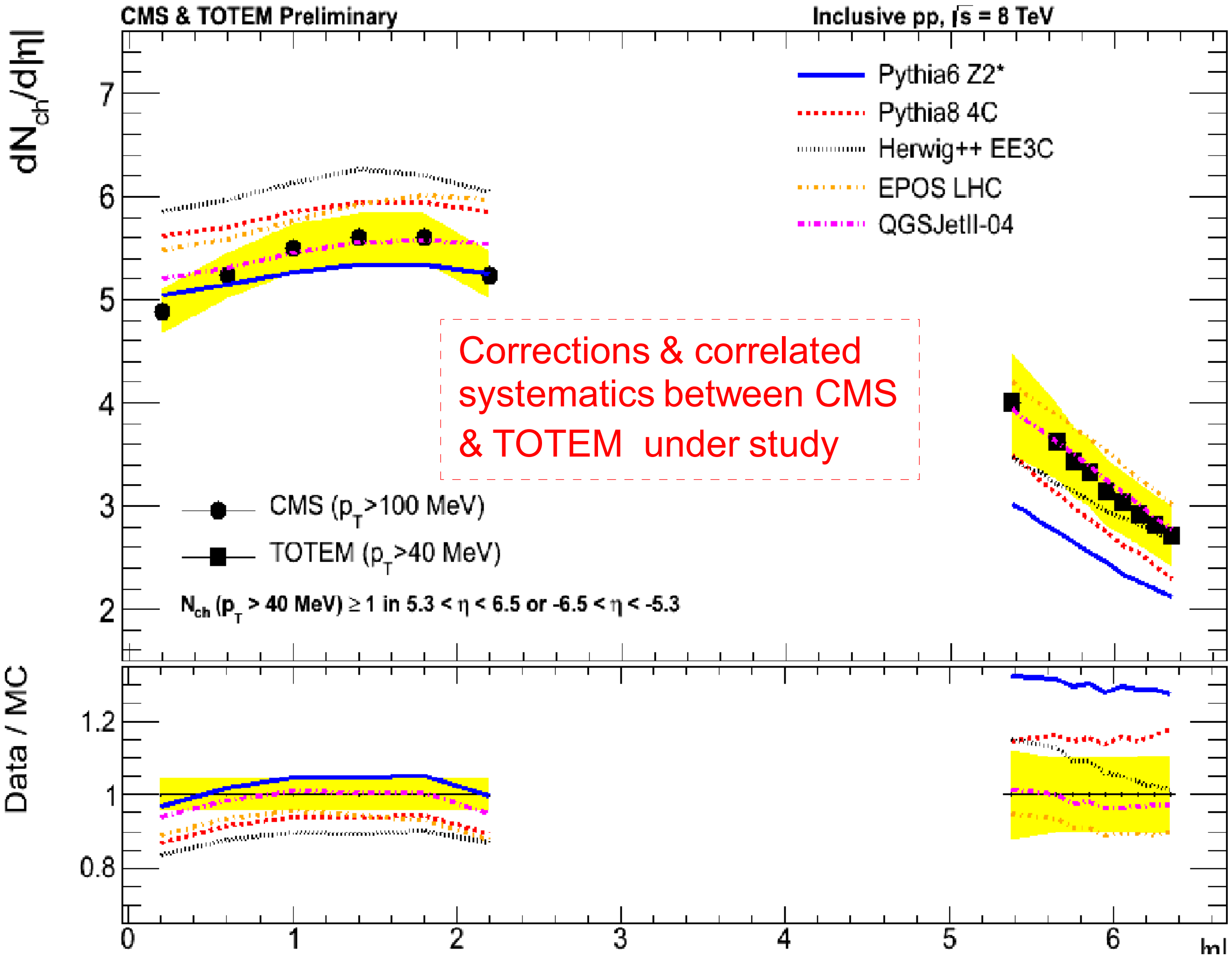


Main contributions to systematic error ~10%:
- Subtraction of large secondary contribution
- Track efficiency & misalignment uncertainties (θ < 10 mrad!)

Very forward $dN_{ch}/d\eta$ @ 8 TeV (with CMS!)

TOTEM analysis similar to 7 TeV one ***(EPL 98 (2012) 31002)***:

- Improved simulation of T2 response, secondary particles production, event selection strategy & alignment procedures.
- Uses of vertex information from CMS to reduce pile-up correction
- Better MC tuning to LHC measurements (important for estimation of secondaries)

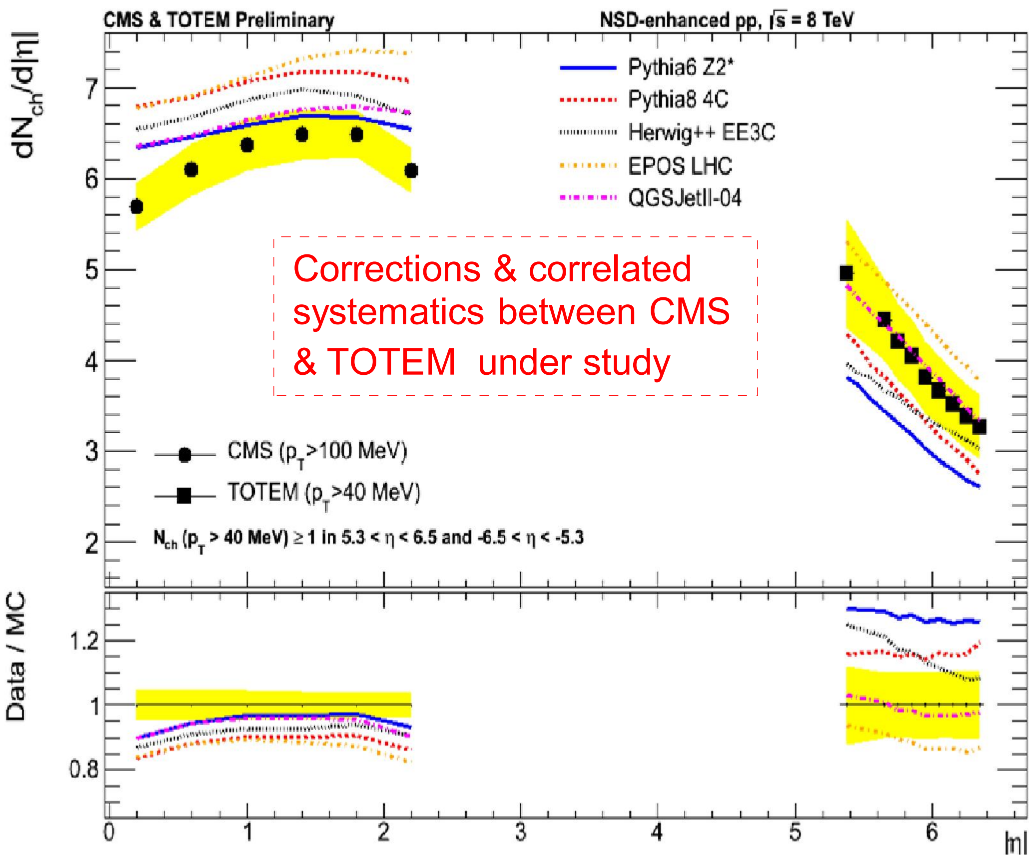


- CMS & TOTEM analysis <u>on same</u> events trigger by T2 (~ 93 % of inelastic)
- Same CMS-TOTEM event selection (at least a "pointing" track in T2)
- For inelastic events with at least 1 primary charged particle with p_T > 40 MeV/c in 5.3 < |η| < 6.5.

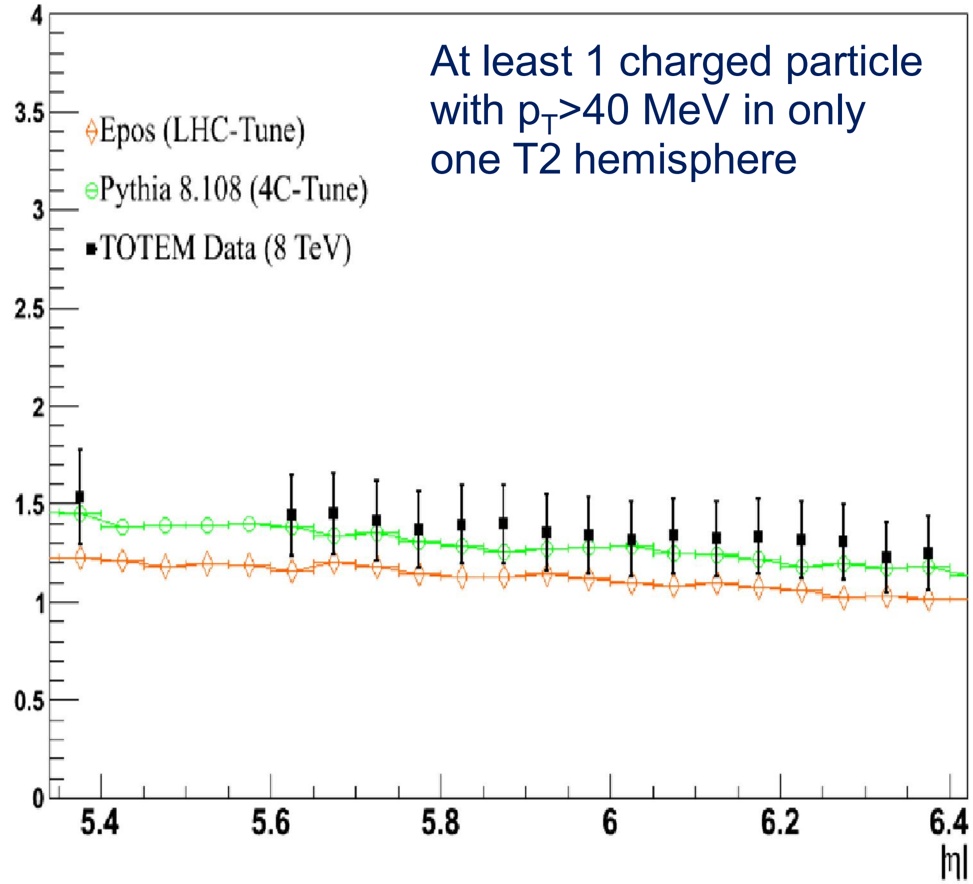
Very forward $dN_{ch}/d\eta$ @ 8 TeV (with CMS!)

"Non-Single diffractive enhanced": primary tracks in both T2 hemispheres
"Single diffractive enhanced": primary tracks in only one T2 hemispheres

NSD-enhanced



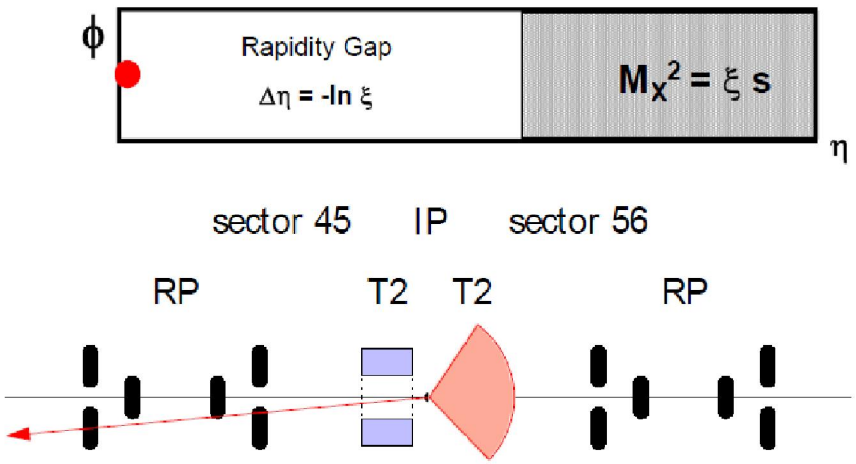
SD-enhanced



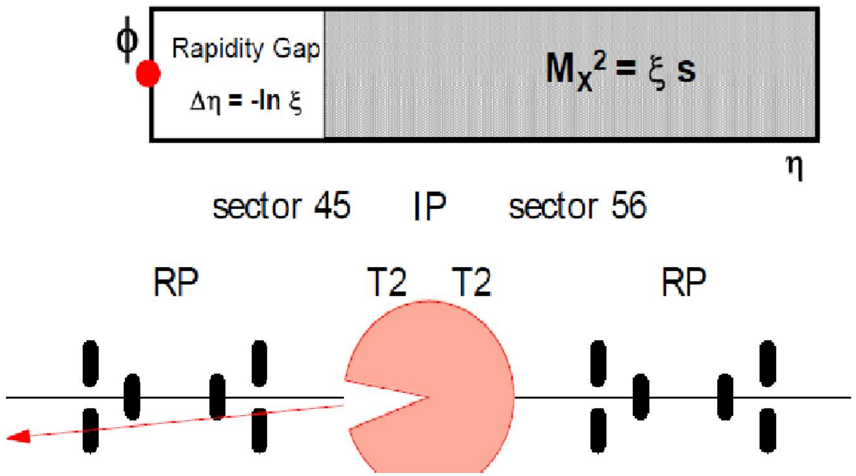
Updated analysis with a common $p_T = 0$ thresholds ongoing in both CMS & TOTEM !

Soft single diffraction @ 7 TeV

Low & medium mass SD:
Tracks in T2 hemisphere opposite to proton $(2 \cdot 10^{-7} < \xi < 0.025)$



Very high mass SD:
Tracks also in same T2 hemisphere as proton (ξ > 2.5%)



- **SD events triggered with T2, only 1 proton required in RP**
- M_{diff} from rapidity gap based on charged particles in T1 & T2: $M_{diff} = \sqrt{s \cdot e^{-\Delta\eta}}$ allows better ξ resolution ($\delta(\xi)/\xi \sim 1$) for low & medium M_{diff}
- SD events classified into 4 classes, based on rapidity gap:

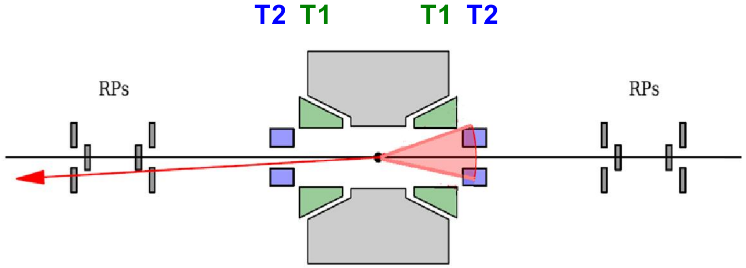
SD class	Inelastic telescopes configuration	Mass	ξ
Low Mass	p + T2 opposite only (no T1)	3.4 - 8 GeV	$2 \cdot 10^{-7} < \xi < 10^{-6}$
Medium Mass	p + T2 opposite + T1 opposite	8 - 350 GeV	$10^{-6} < \xi < 0.25\%$
High Mass	p + T2 opposite + T1 same	0.35 - 1.1 TeV	$0.25\% < \xi < 2.5\%$
Very High Mass	p + both T2 arms	> 1.1 TeV	> 2.5%

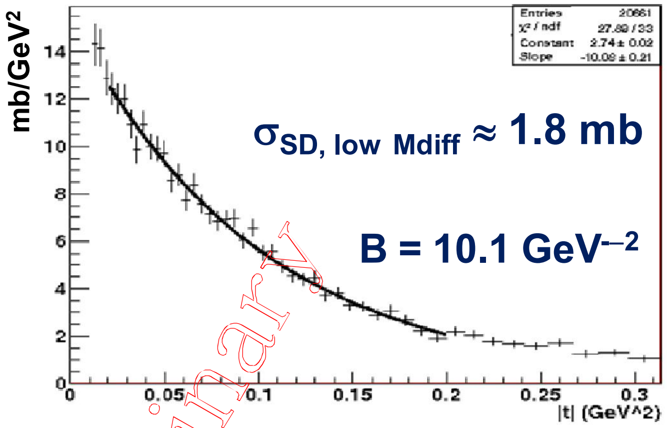
Soft single diffraction @ 7 TeV

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

Low mass

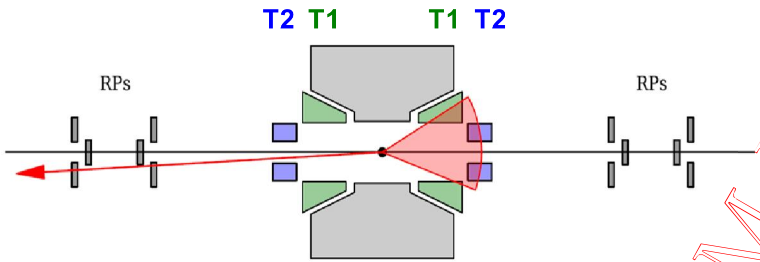
M_{diff} = 3.4 - 8 GeV

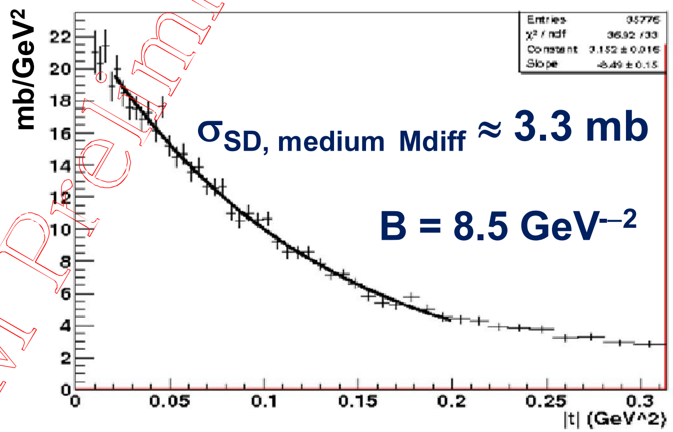




Medium mass

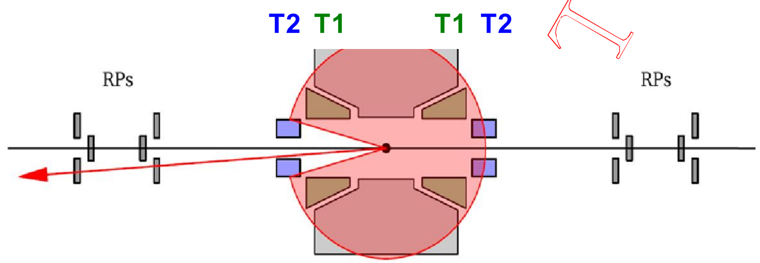
M_{diff} = 8 - 350 GeV

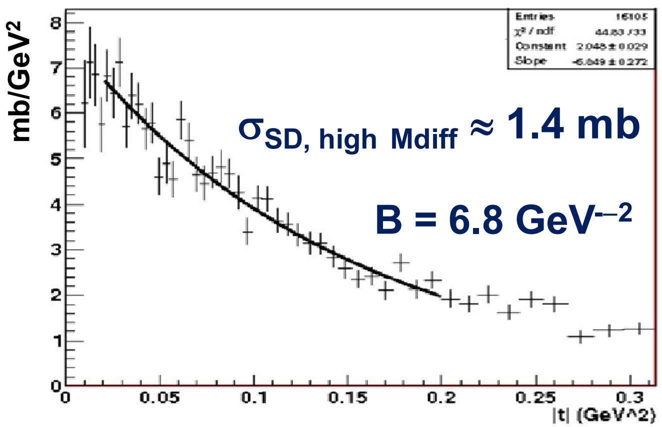




High mass

M_{diff} = 0.35 - 1.1 TeV





Corrections included:
- Trigger efficiency
- Proton acceptance & reconstruction efficiency
- Background subtraction
- Extrapolation to t = 0

Missing corrections:
- Class migration
- ξ resolution & beam divergence effects

Estimated uncertainties:

B ~ 15% ; σ ~ 20%

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

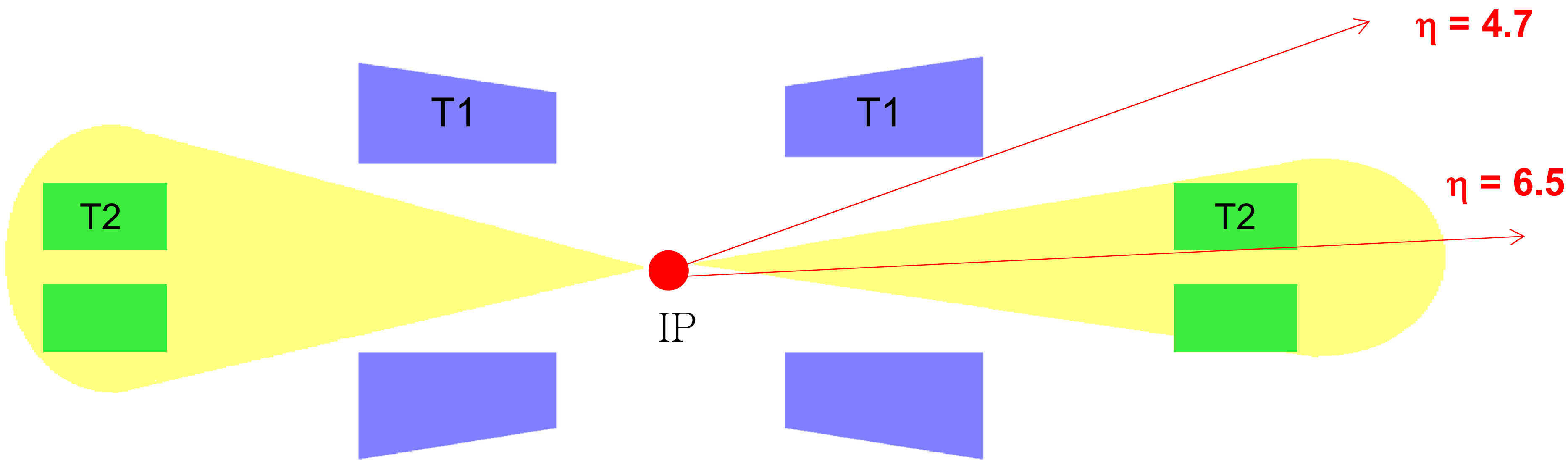
Analysis of very high mass events ongoing

8 TeV SD analysis started

Soft double diffraction @ 7 TeV

Measurement of soft DD cross section with only particles visible in T2 ($4.7 < |\xi|_{min} < 6.5$)

$\sigma_{DD}(|\xi|_{min})$ for $3.4 < M_{diff} < 8$ GeV



Event selection: Trigger with T2,
at least one track in both T2 hemispheres , no tracks in T1 "(0T1+2T2) topology".

- ND background estimated scaling MC prediction using a control sample from data dominated by ND (2T1+2T2 events)

- SD background estimated completely from data using a SD-dominated control sample (0T1+1T2) with protons in RP

Soft double diffraction @ 7 TeV

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

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

- σ_{DD} uncertainty dominated by:

  "Internal migration": real DD events that have a $|\eta|_{min}$ smaller than T1 but with no tracks in T1 η-range

Pythia 8 (σ_{DD} = 8.1 mb)

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

	$-4.7>\eta_{min}>-5.9$	$-5.9>\eta_{min}>-6.5$
$4.7<\eta_{min}<5.9$	70 μb	**36 μb**
$5.9<\eta_{min}<6.5$	**36 μb**	17 μb

Improvement expected with 8 TeV data sample that includes also CMS detector information.

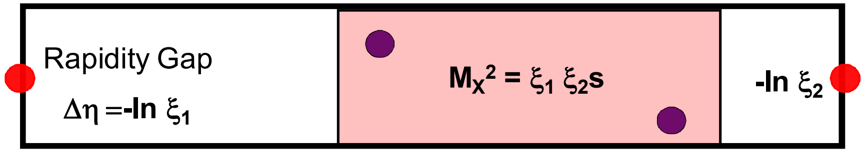
Phojet (σ_{DD} = 3.9 mb)

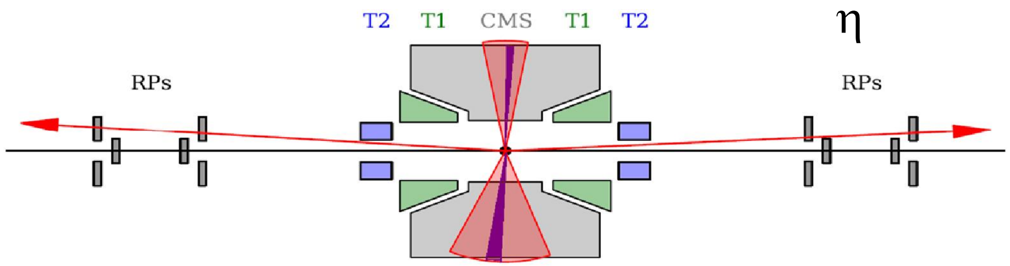
$$\sigma_{DD(4.7<|\eta_{min}|<6.5)} = 101 \mu b$$

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

Central diffraction: TOTEM + CMS

CD (aka DPE):





Large η-coverage:

- CMS: $-5.5<\eta<5.5$
- T1: $3.1 < |\eta| < 4.7$
- T2: $5.3 < |\eta| < 6.5$
- FSC: $6 < |\eta| < 8$

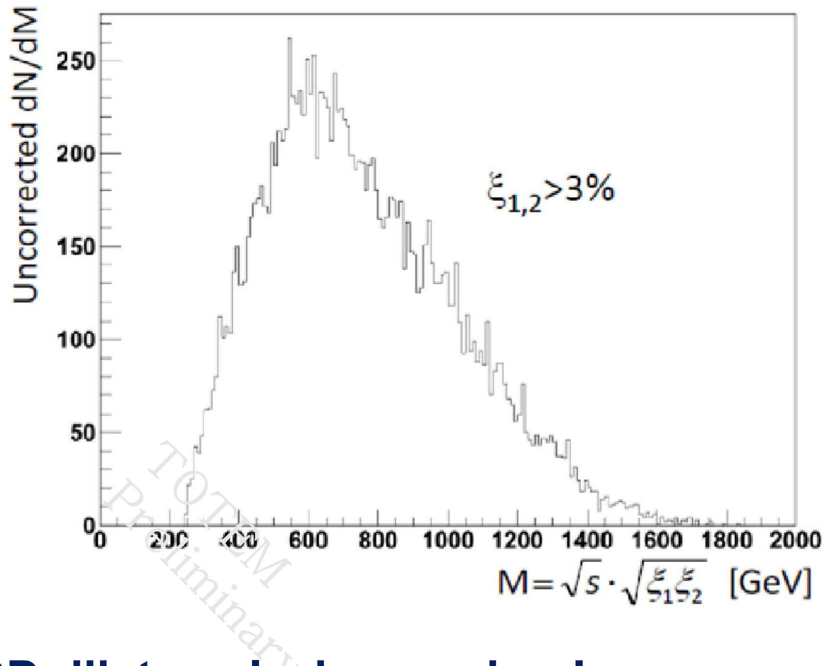
Double-arm proton detection

Prediction of mass to be seen in CMS from reconstructed protons: $M^2 = s\,\xi_1\xi_2$

Initial vs. final state comparison: M_{TOTEM} (pp) =? M_{CMS}

Prediction of central particle flow topology from proton ξ's (rapidity gaps): $\Delta\eta_{1,2} = -\ln\xi_{1,2}$

Masses up to 1.8 TeV with pp survival!

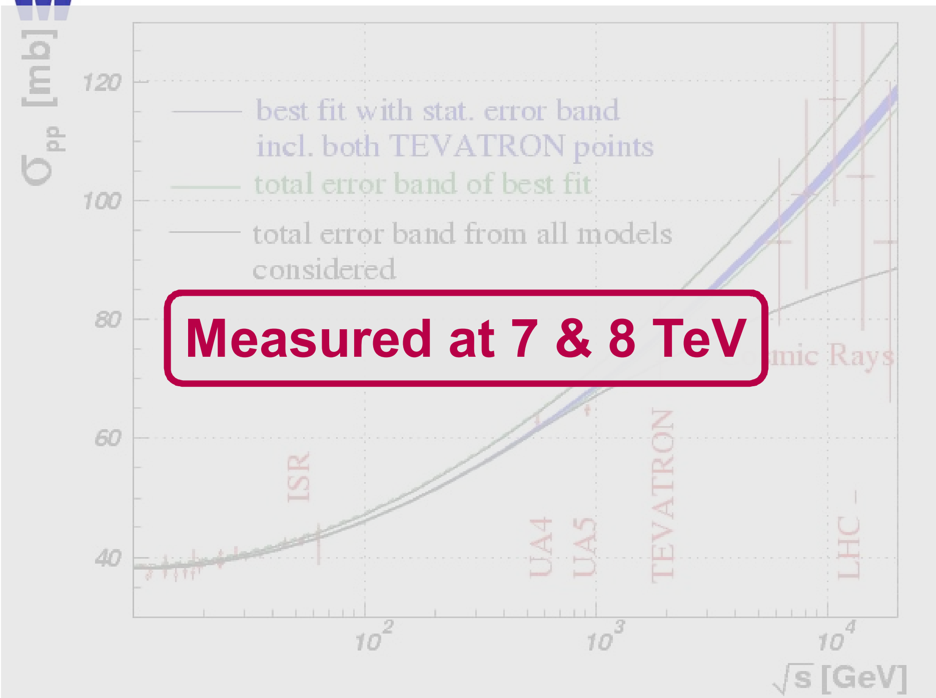


Analysis on going.
Good statistics for soft central diffraction;
limited for hard central diffraction

Good statistics for hard single diffraction, SD dijet analysis ongoing !

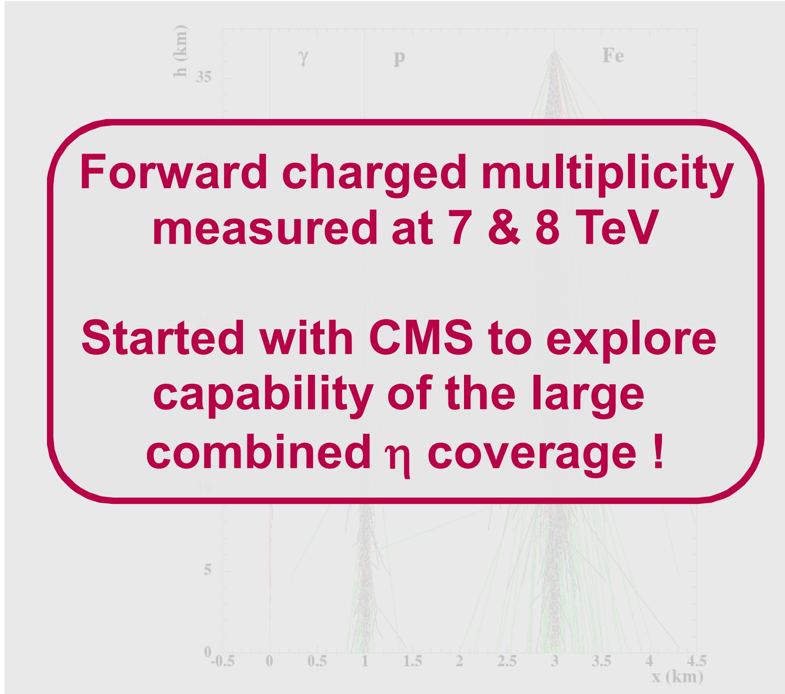
Summary

Total pp cross-section



Measured at 7 & 8 TeV

Forward particle production



Forward charged multiplicity measured at 7 & 8 TeV

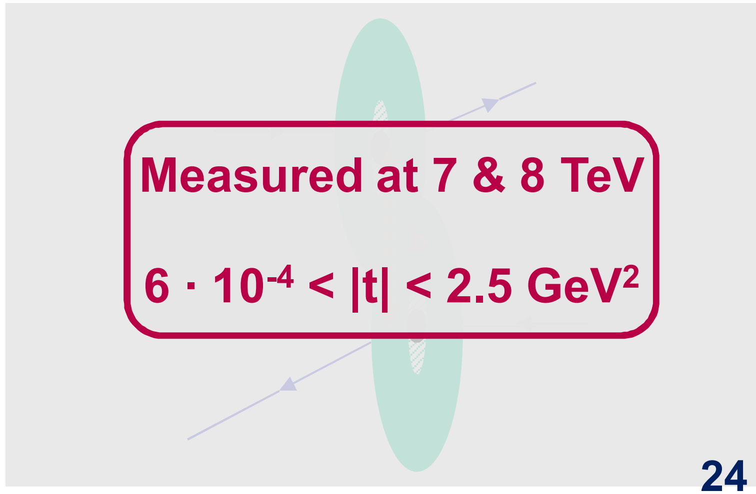
Started with CMS to explore capability of the large combined η coverage !

Diffraction: soft and hard

Preliminary results on DD, SD & CD

Many analysis in progress!

Elastic pp scattering



Measured at 7 & 8 TeV

$6 \cdot 10^{-4} < |t| < 2.5$ GeV^2

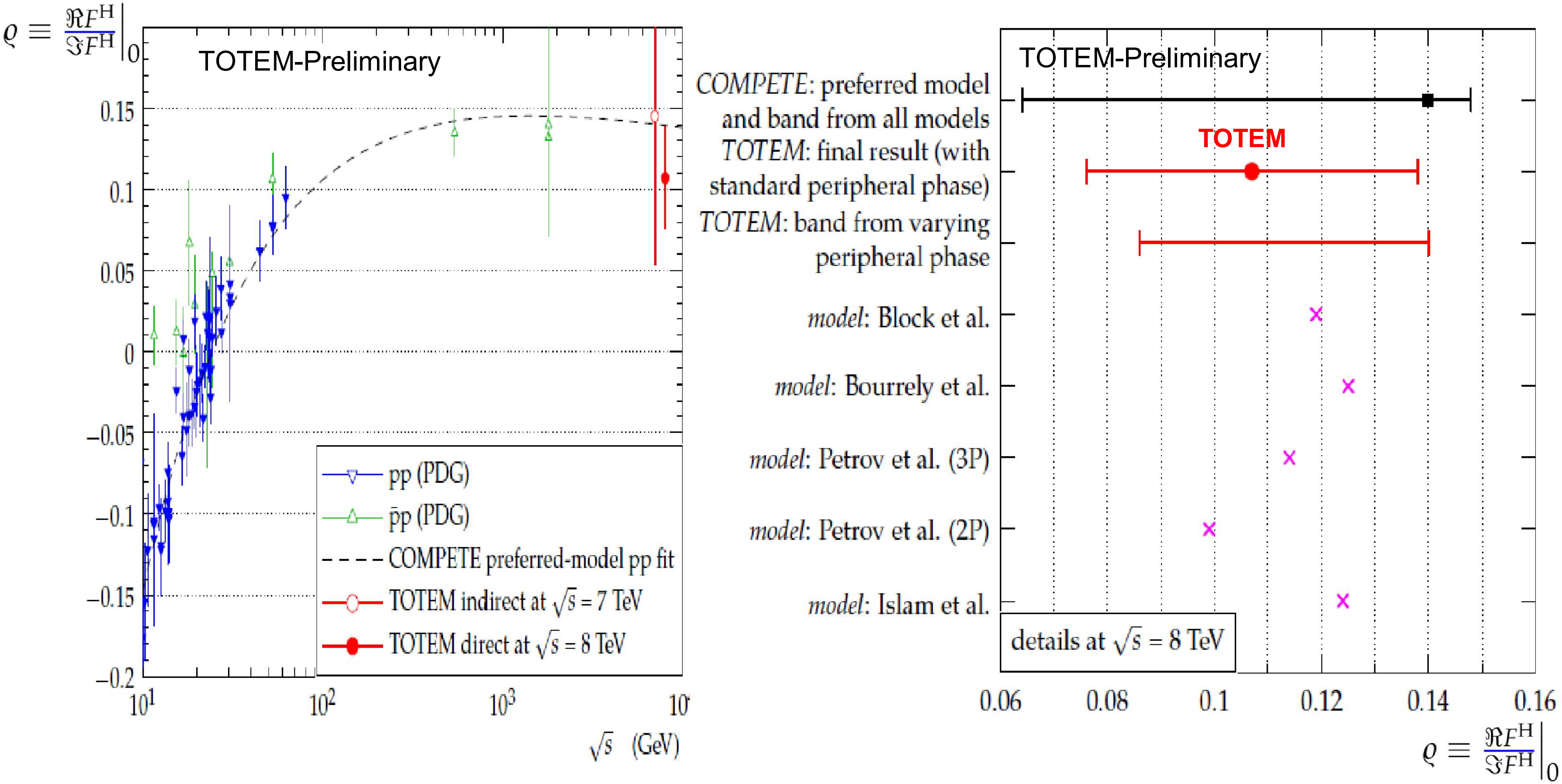
The End

Elastic pp scattering: ρ measurement

Comparison of ρ with models and measurements at lower energy

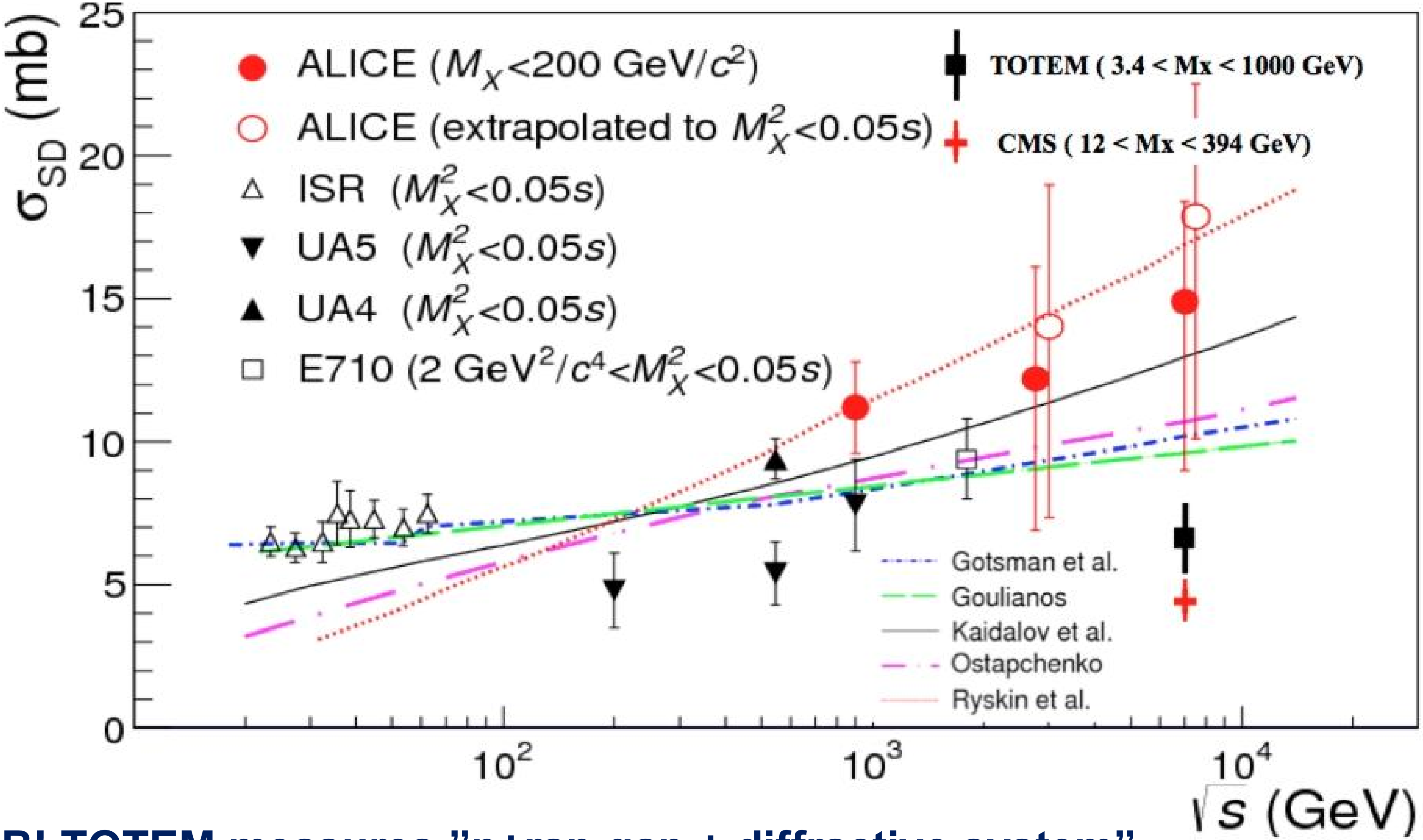
$$\rho = 0.107 \pm 0.027^{(\mathrm{stat})} \pm 0.010^{(\mathrm{syst})} \begin{matrix} +0.009 \\ -0.009 \end{matrix} \text{ (model)}$$

TOTEM Preliminary



SD cross-section comparison

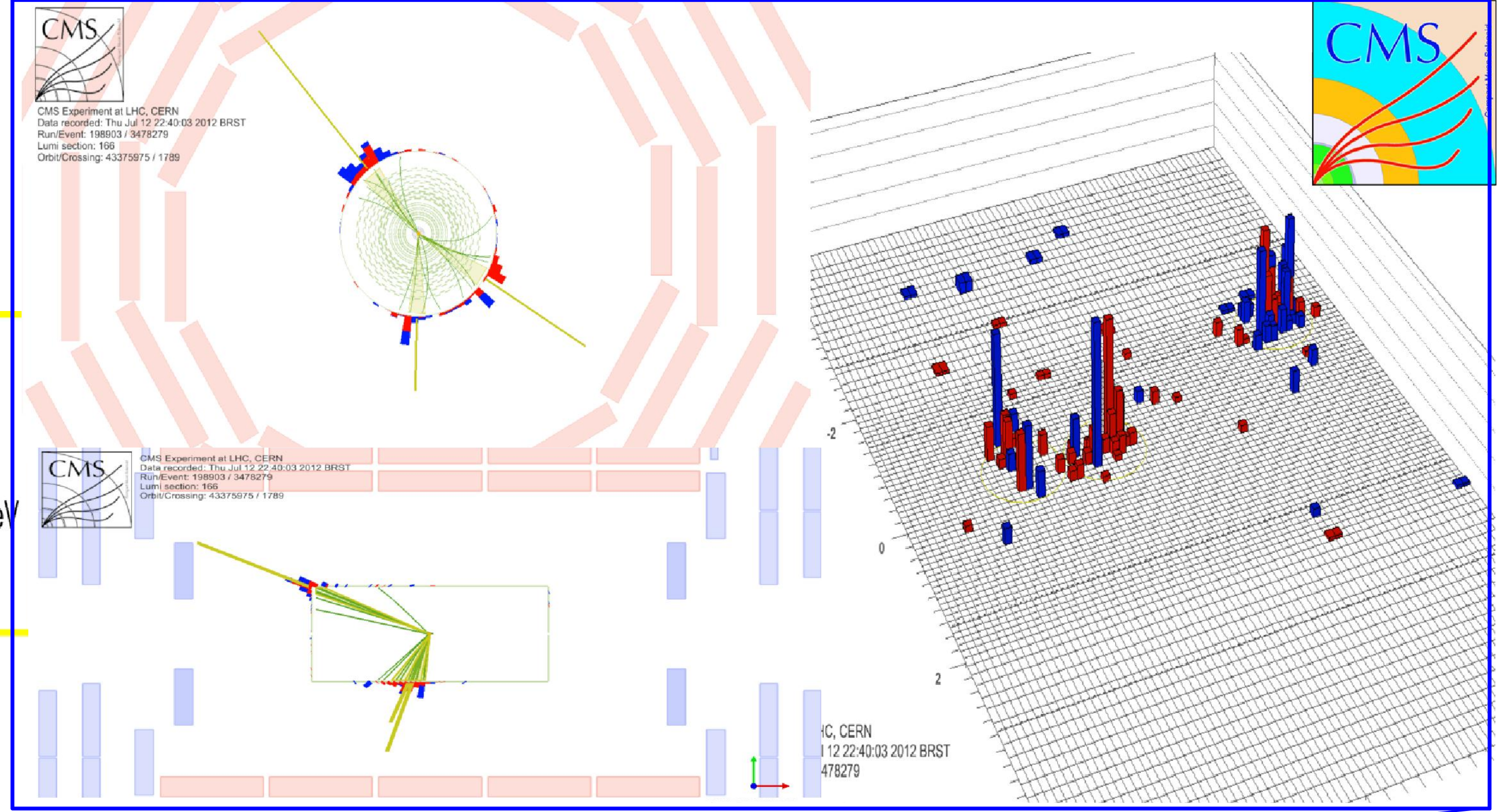
Courtesy N. Cartiglia



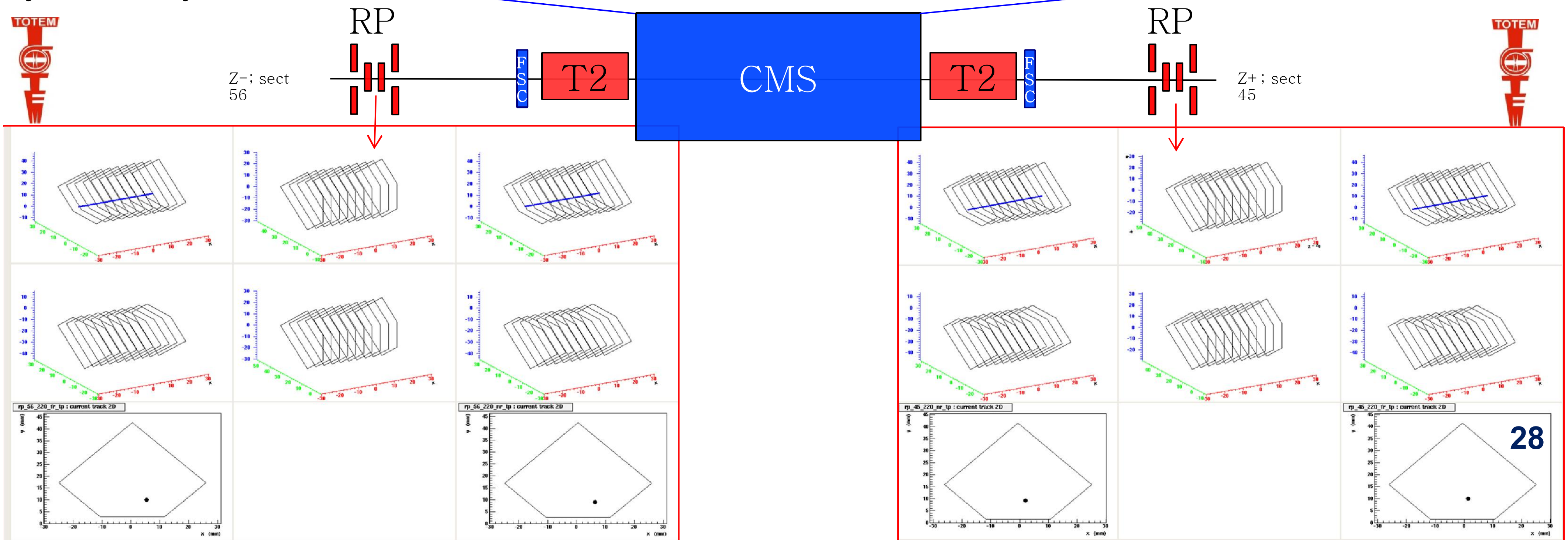
NB! TOTEM measures ”p+rap gap + diffractive system”, ALICE & CMS ”rap gap + diffractive system”

CMS + TOTEM 90m β^*
Run/Event 198903/3478279
Jets E_T = 65,45,27 GeV

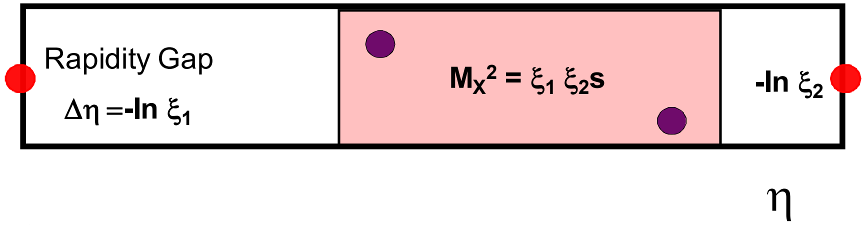
MM(pp) = 244 GeV; M(CMS) = 219 GeV
Σp_T(CMS) = 3.4 GeV
FSC empty both sides



M(pp)= 244 GeV
ξ_-= −0.1 ξ= −0.01



Central diffraction: TOTEM + CMS



Cuts:
- Vertex ≤ 1
- RP near edge area removed (background suppression)
- RP top-top/bot-bot topology
- ξ> 1.5%, better resolution
- FSC empty (background suppression)

Categories of events :

- CMS and TOTEM consistent (within resolution)

  M_{CMS}(Particle Flow) = M_{TOTEM}(pp)
  p_{CMS}(Particle Flow) = p_{TOTEM}(pp) → Many candidates in the soft sample
  Few candidates in the dijet sample; none exclusive!

- Missing “tracks” in CMS
  M_{CMS}(Particle Flow + missing momentum) ≤ M_{TOTEM}(pp)

➢ Additional tracks indeed observed in forward detectors where allowed by x-predicted gaps → Large fraction of soft events
Several candidates in the dijet sample

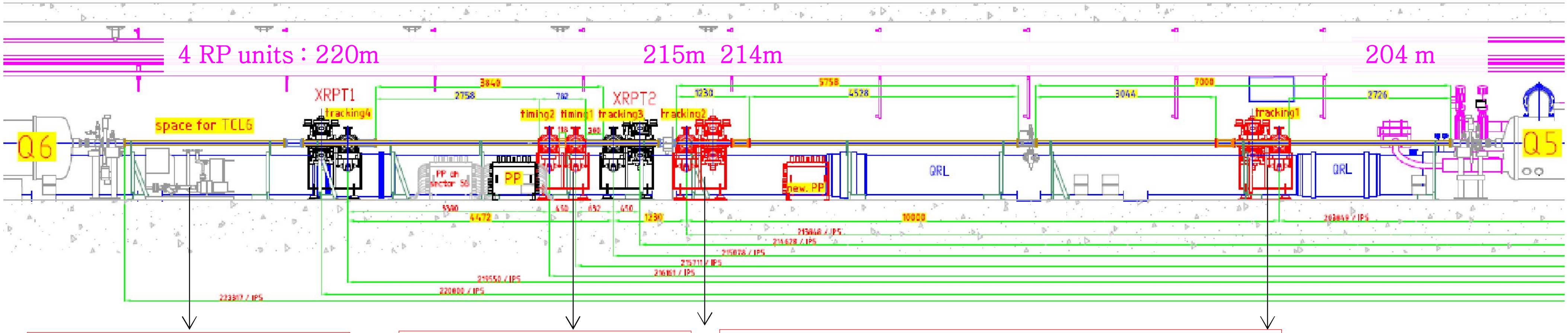
➢ Secondary particles violating rapidity gaps → No candidates in the dijet sample;
Background issue in the soft sample

➢ <u>escaping-mass candidates</u>

Additional tracks NOT observed in forward detectors where allowed by x-predicted gaps → few candidates with $\Delta M \geq 400$ GeV

Additional tracks NOT observed in forward detectors forbidden by x-predicted gaps → no candidates

RP system: LHCC endorsed program



Installation of a collimator to protect Q6

Allow insertion of (horizontal) pots closer to the beam in high intensity scenario
→**improved ξ acceptance**

Infrastructure to install 2 new horizontal pots

Cylindrical pots to host any **timing detectors**

RP147 (fully equipped) relocated at 203-213m
1 unit rotated by 8 degrees

Long lever arm (~15m) improves angular resolution (until beam divergence limit)

Si-strip detectors rotated to improve multitrack event reconstruction (beam halo pileup, background)

&

On going studies to implement high beta optics with 1000 bunches
Pileup ≈ 0.09 ; L ~ 10^{31} $cm^2 s^{-1}$ ⟶ 1 pb^{-1}/day

- forward proton detector system will consist of 4 units/arm, each with 2 vert. and 1 horiz., pot equipped with 10 planes Si-strip detectors, with full trigger capability

- Extreme flexibility in using 4 units according to running scenario; possibility to dedicate pots to new **Si-pixel detectors** as well as to timing detectors with low material budget