TOTEM & CT-PPS physics

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on behalf of
TOTEM collaboration & CT-PPS

LHC forward workshop 22.3.2017

HELSINKI INSTITUTE OF PHYSICS

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Outline:
- ✓ Recent TOTEM physics results
- ✓ CT-PPS: data-taking & physics

TOTEM physics (special runs)

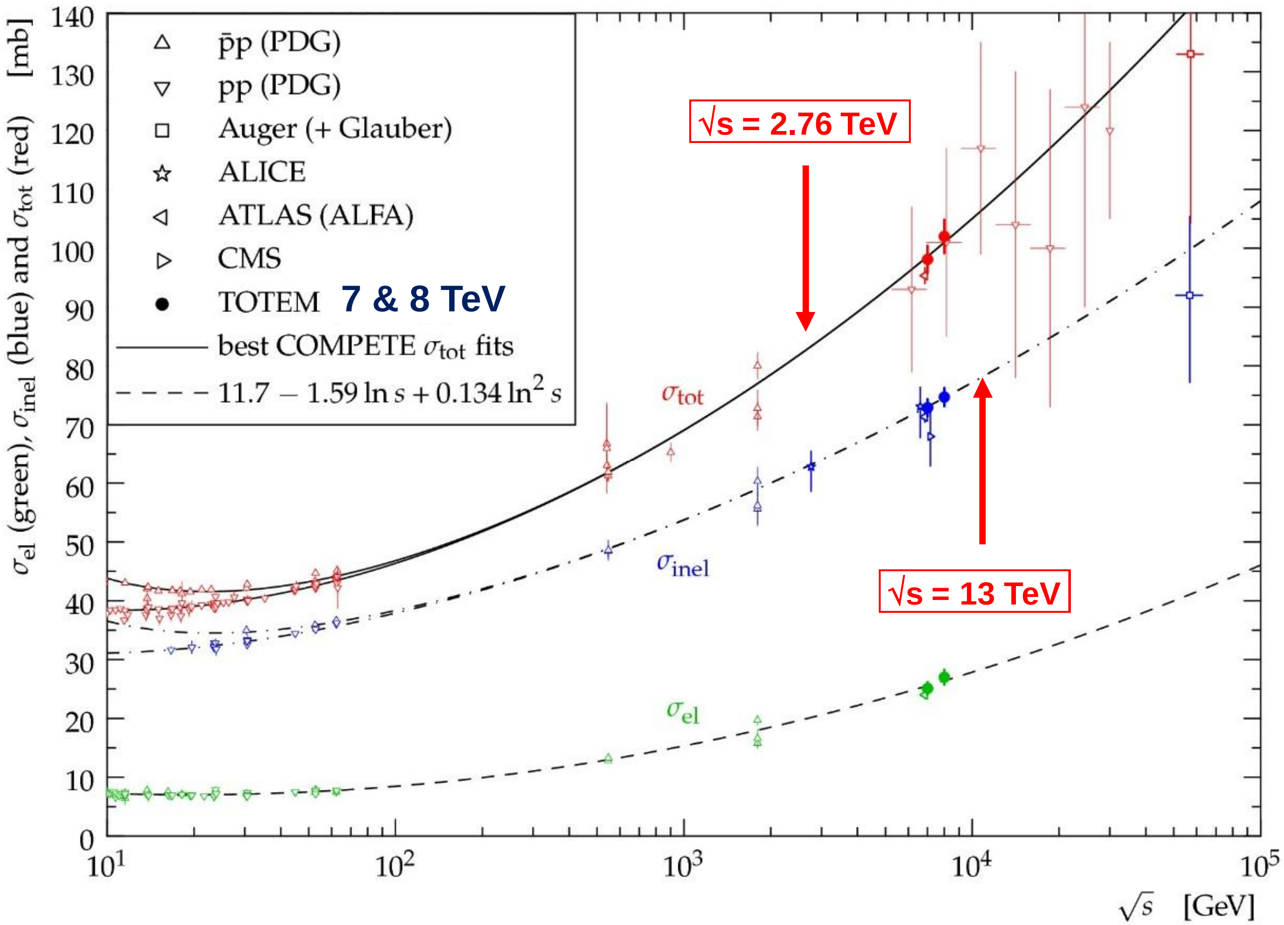
- Total, inelastic & elastic pp cross-section
- ρ (ratio of real & elastic hadronic amplitude at $|t| = 0$)

σ_{tot} measurements

Luminosity independent method:

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

- √s = 7 TeV (β* = 90 m) & 8 TeV (β* = 90 m & 1 km) results published
- √s = 2.76 TeV (β* = 11 m) results blessed & paper in preparation
- √s = 13 TeV analysis (β* = 90 m & 2.5 km) progressing well



σ_{tot} @ $\sqrt{s}$ = 2.76 TeV elastic

Jan 2013, RPs at 4.3σ, $\mu \sim 0.11$

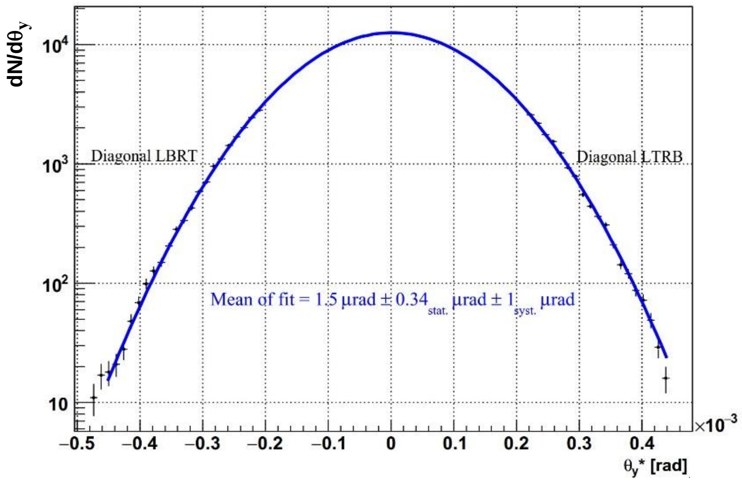
β^* = 11 m optics (not optimized for σ_{tot} measurement)

- Optics more sensitive to LHC perturbations & IP vertex size $\Rightarrow$ **optics determination using correlations of elastic candidates**
- Beam divergence large (~20 μrad) $\Rightarrow$ limits scattering angle resolution
- Extrapolation to t = 0 longer (observe ~3 % of σ_{el} $\leftrightarrow$ 80 – 90 % at β^* = 90m)

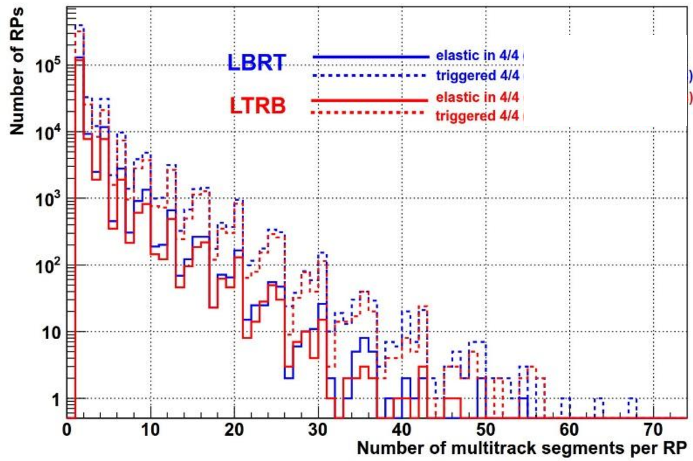
Other challenges overcome:

- Horizontal RPs not inserted $\Rightarrow$ **RP top – RP bottom relative alignment from ϕ symmetry of elastic scattering**
- Due to overlapping activity reduced single track efficiency $\Rightarrow$ **dedicated multitrack RP reconstruction to recover majority of elastic events**

ϕ symmetry of elastic (after alignment)



elastic vs # multitrack segments/RP



σ_{tot} @ $\sqrt{s}$ = 2.76 TeV

Inelastic rate analys:

method identical to 7 & 8 TeV

EPL 101 (2013) 21003;
PRL 111 (2013) 012001

- Count events with charged particles in T1 & T2 (~ 97 % of inelastic).
- Trigger: at least one track in T2.
- Corrections:
  1. Beam gas,
  2. T2 trigger efficiency
  3. Pileup
  4. T2 reconstruction
  5. T1 only events
  6. CD events (nothing in T1 or T2)
  7. Low mass diffraction

- Total uncertainty N_{inel}: ~ 2.1 %

largest contribution:
low mass diffraction (M_{diff} < 2.1 GeV)

Elastic rate analysis:

method similar to 7 & 8 TeV

EPL 101 (2013) 21002;
PRL 111 (2013) 012001

Analysis steps:

1. Geometrical & beam divergence acceptance corrections
2. Unfolding
3. DAQ efficiency
4. Optics reconstruction
5. Alignment
6. Multitrack
7. Single & double RP inefficiency
8. Trigger inefficiency
9. Extrapolaton to |t| = 0 ⇒ intercept
10. Integrate |t|-distribution ⇒ N_{el}

(4.–6.: modified)

- Total uncertainty N_{el}: ~ 2.5 %

- Total uncertainty intercept: ~ 3.5 %

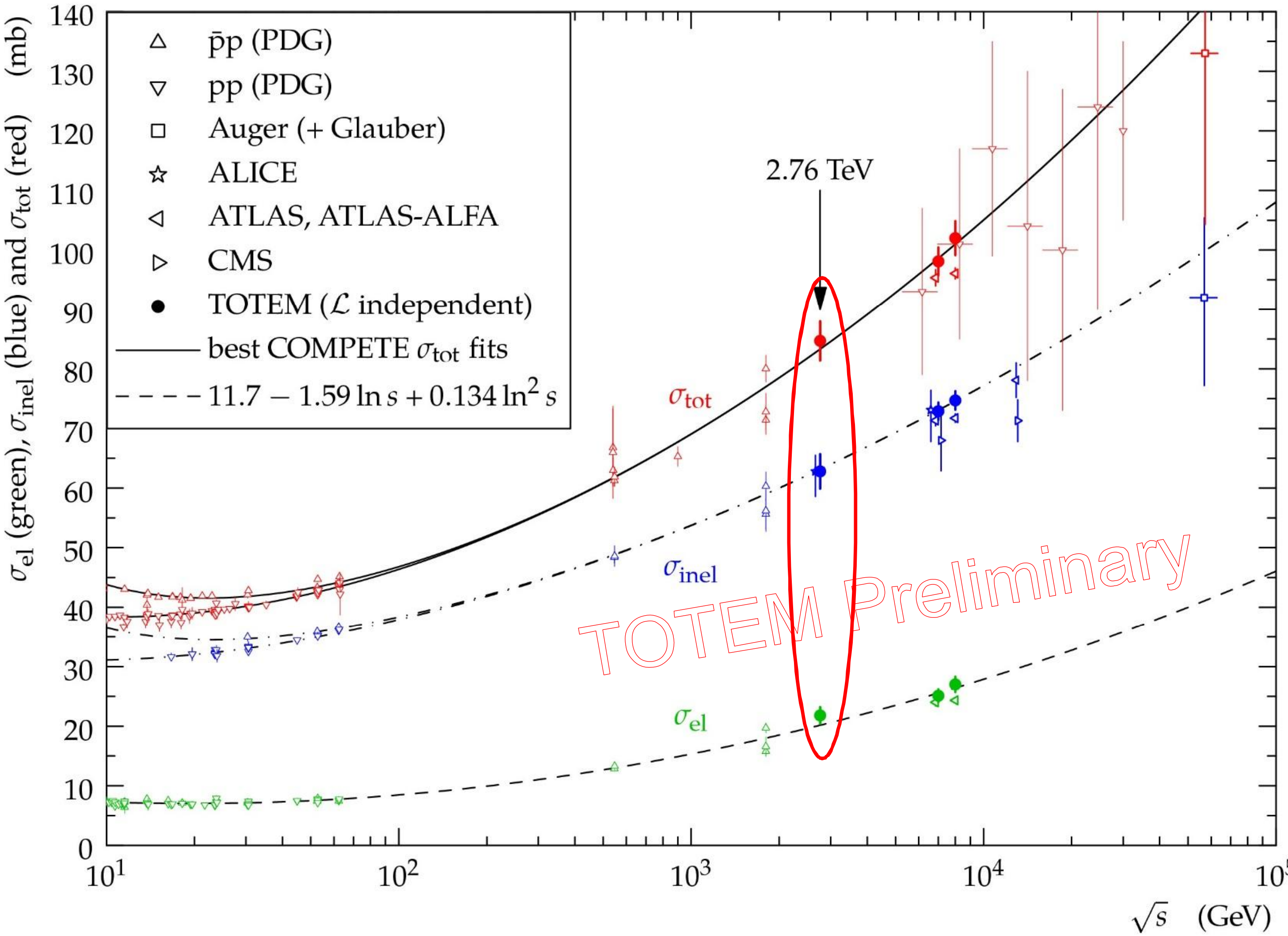
σ_{tot} @ $\sqrt{s}$ = 2.76 TeV

TOTEM @ 2.76 TeV
(ρ = 0.145):

σ_{tot} = 84.7 ± 3.3 mb

σ_{inel} = 62.8 ± 2.9 mb

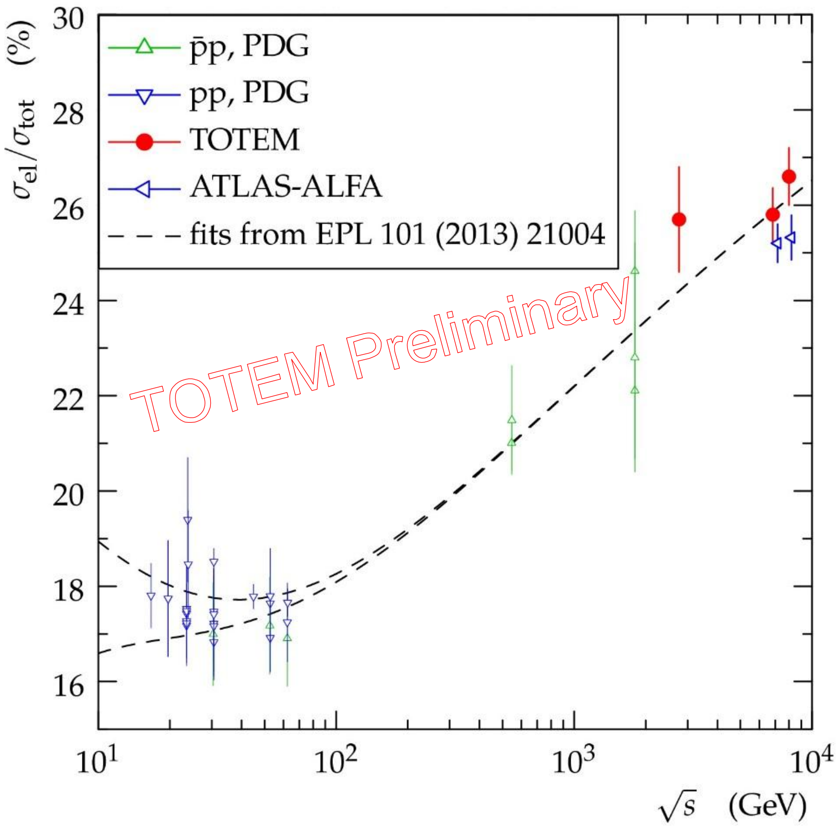
σ_{el} = 21.8 ± 1.4 mb



LHC comparison @ 2.76 TeV: $\sigma_{inel, ALICE} = 62.8\,^{+2.4}_{-4.0} \pm 1.2$ mb

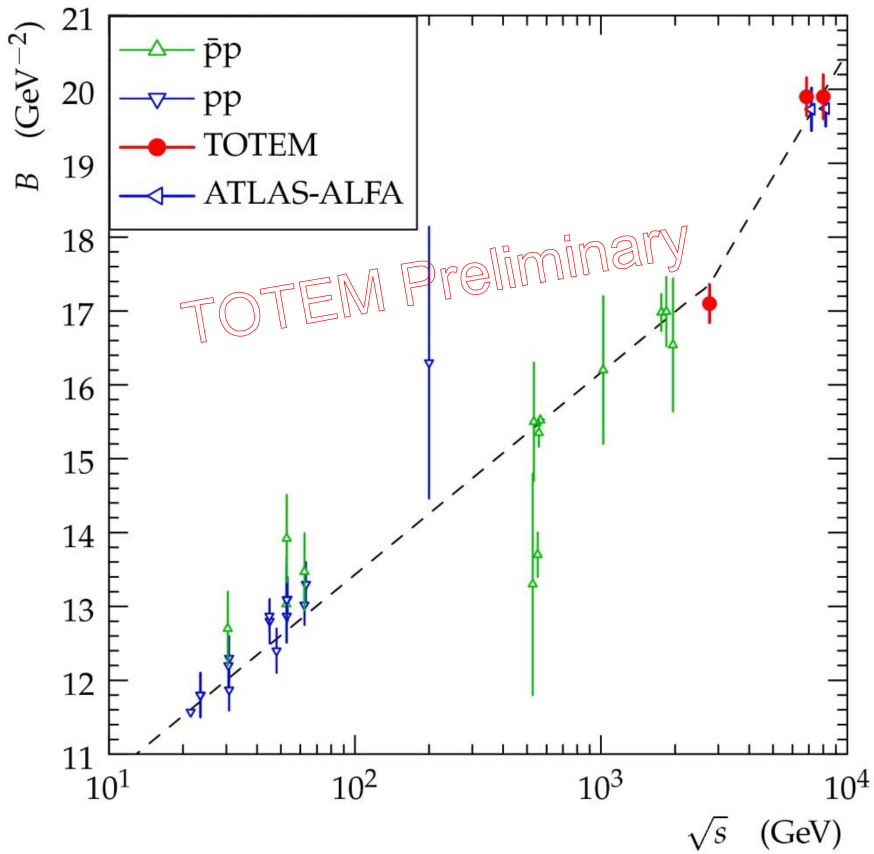
TOTEM @ √s = 2.76 TeV

$\sigma_{el} / \sigma_{tot}$ = (25.7 ± 1.1) %



B = 17.10 ± 0.26 GeV^{-2}

assume $d\sigma_{el}/dt \propto e^{-B|t|}$



Comparison with 1.8 TeV: B_{CDF} = 16.98 ± 0.25 GeV^{-2}

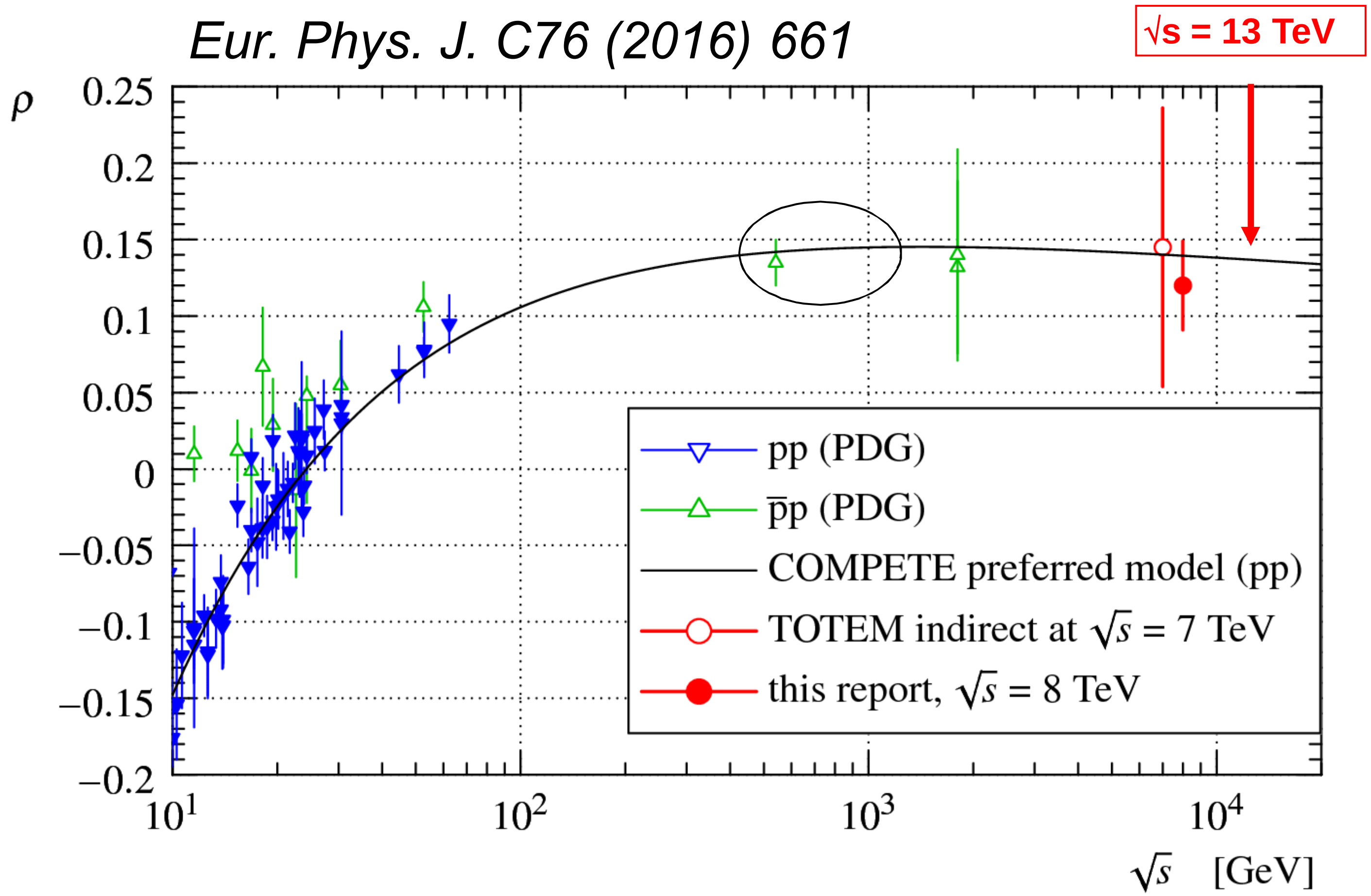
B_{E710} = 16.99 ± 0.47 GeV^{-2}

ρ measurements

By studying Coulomb-hadronic interference of elastic scattering at very low |t| able to measure: $\rho \equiv \Re\, F^{H} / \Im\, F^{H} |_{t=0}$

TOTEM @ 8 TeV: $\rho = 0.12 \pm 0.03$

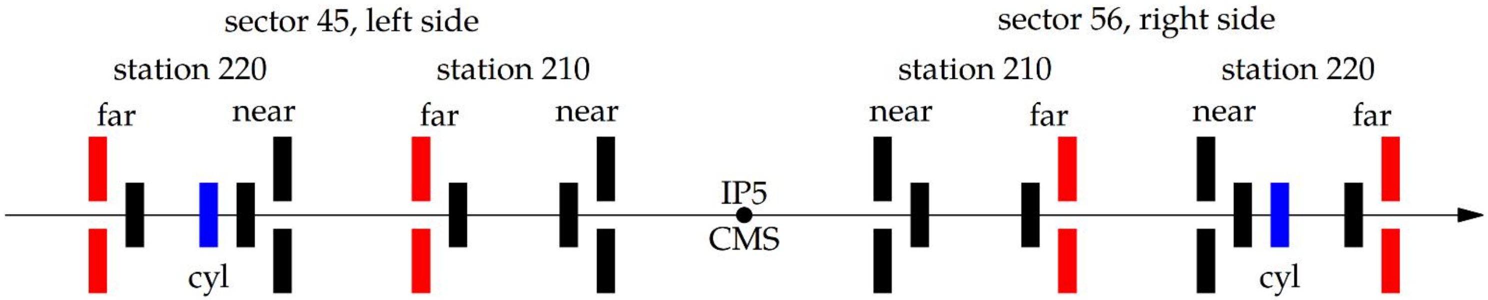
Eur. Phys. J. C76 (2016) 661



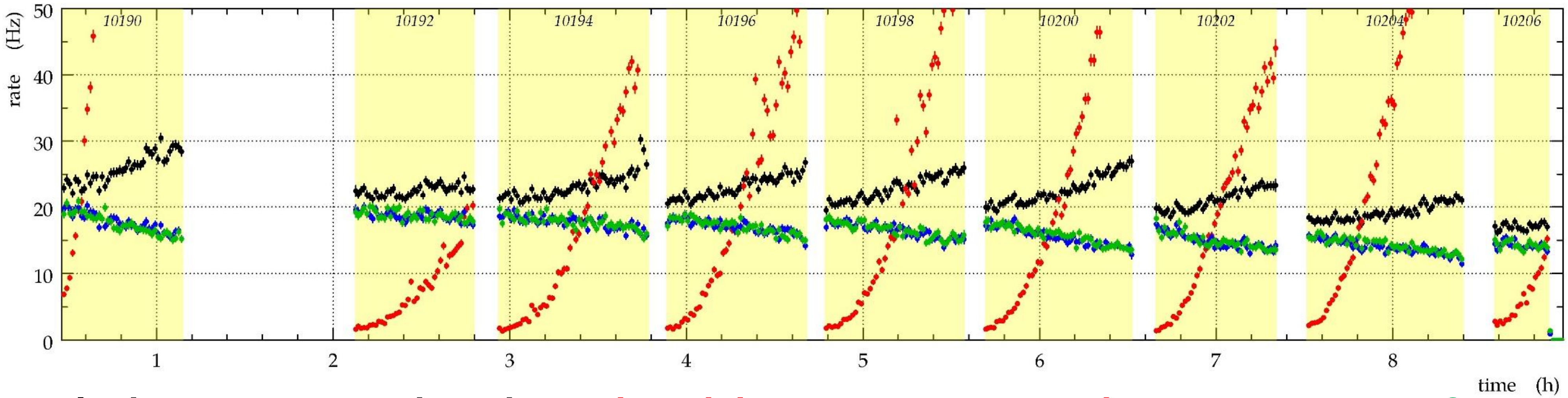
β^* = 2.5 km run @ 13 TeV

Vertical RPs @ 3σ ⇒ $|t|_{min} \approx 4 \cdot 10^{-4}$ $\mathcal{L}_{int} \approx 0.38$ nb^{-1} ⇒ 7.4 M elastic
(for analysis $8 \cdot 10^{-4}$ safe limit for now) (2 RP out of 4)

RP210 far (rotated) & RP220 far used in run (indicated by red boxes)



Reasonable background ⇒ regular beam cleaning procedure



Black: reconstructed tracks, red: activity not reconstructed, green: 4 RP out of 4

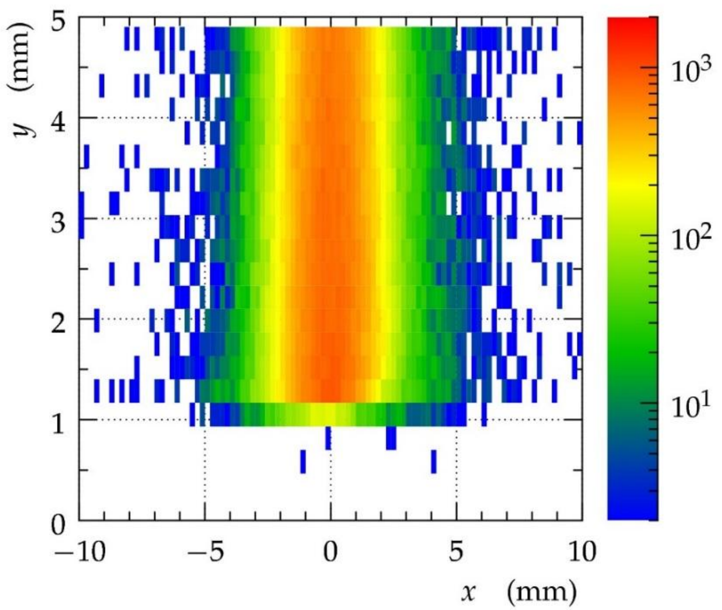
β^* = 2.5 km analysis @ 13 TeV

Two complementary analyses:

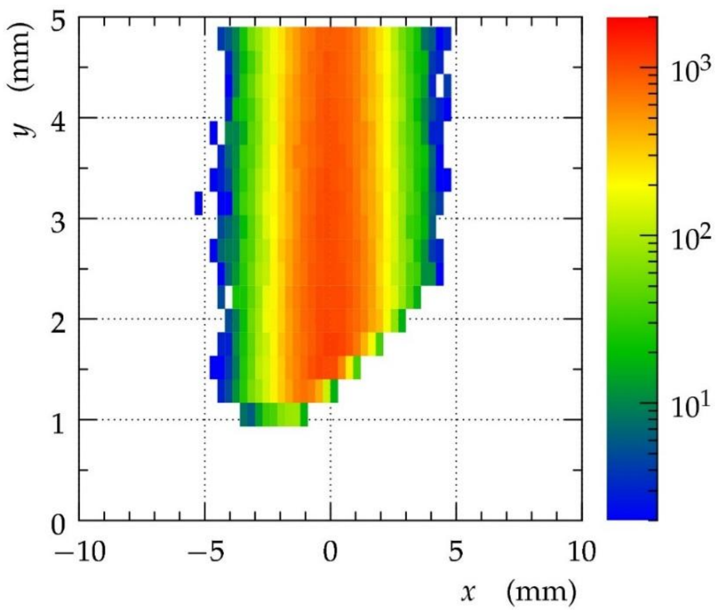
- 4 RPs out of 4 (very similar to β^* = 1 km @ 8 TeV): low-|t| acceptance insufficient ⇒ control analysis
- **2 RPs out of 4: using RPs at 220m ⇒ acceptance optimization ⇒ reference analysis**

– worse single-arm θ^*_x resolution but still good double-arm resolution
– less elastic-tagging cuts ⇒ slightly increased background (~ 0.1 %)

No selection

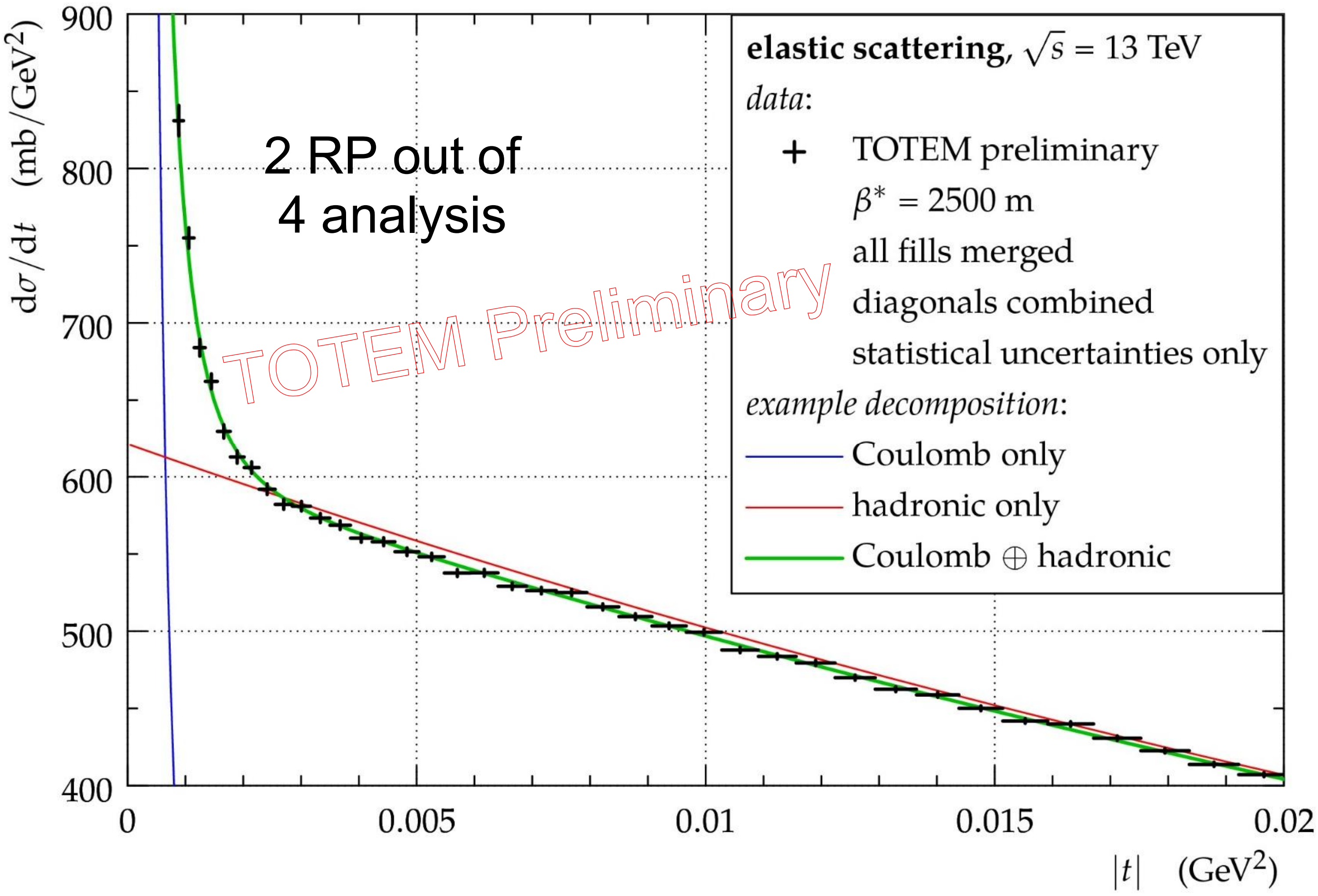


Elastic selection including correlation with 210m far station (tilted)



β^* = 2.5 km analysis @ 13 TeV

2 RP out of 4 analysis verified nicely by 4 RP out of 4 analysis for larger |t|'s (> $2 \cdot 10^{-3}$ GeV^2)



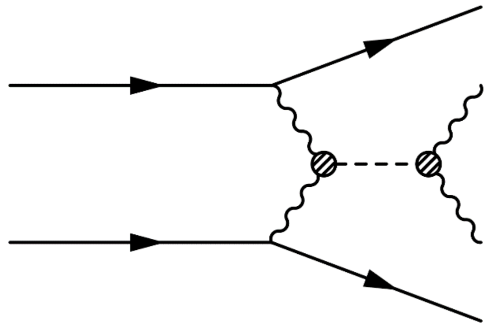
CT-PPS

- CMS-TOTEM Precision Proton Spectrometer (PPS)
- Data taking
- Physics potential

CT-PPS has initiated high luminosity diffractive physics program at LHC

CT-PPS

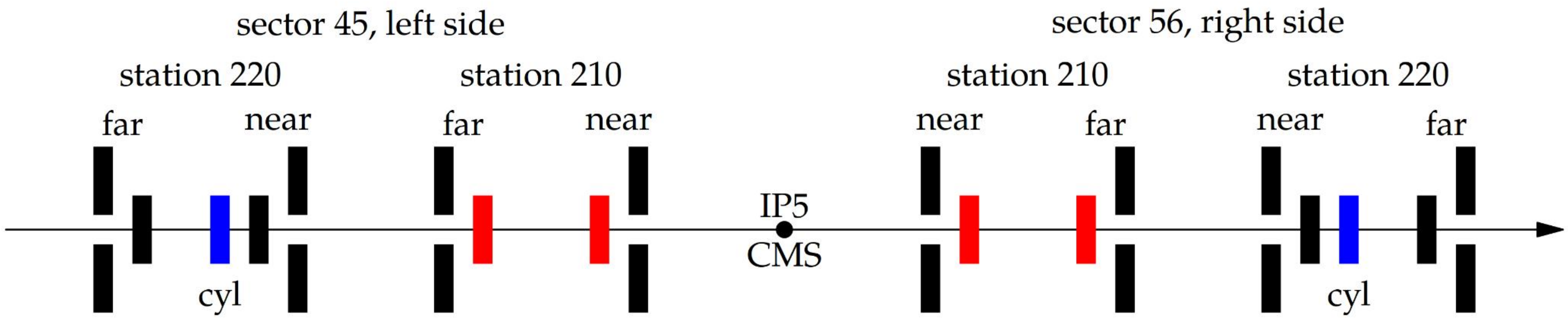
Motivation: study high mass exclusive central production at standard high luminosity runs



$$M_{\gamma\gamma} = M_{pp}$$

Accelerated CT-PPS for 2016: using existing/advanced developed technology

- Beam pockets: horizontal RPs (with RF shields or new cylindrical design)
- Tracking detectors: TOTEM Si strips (red)
- Timing detectors: TOTEM diamonds



CT-PPS detectors fully integrated into CMS DAQ

CT-PPS data taking

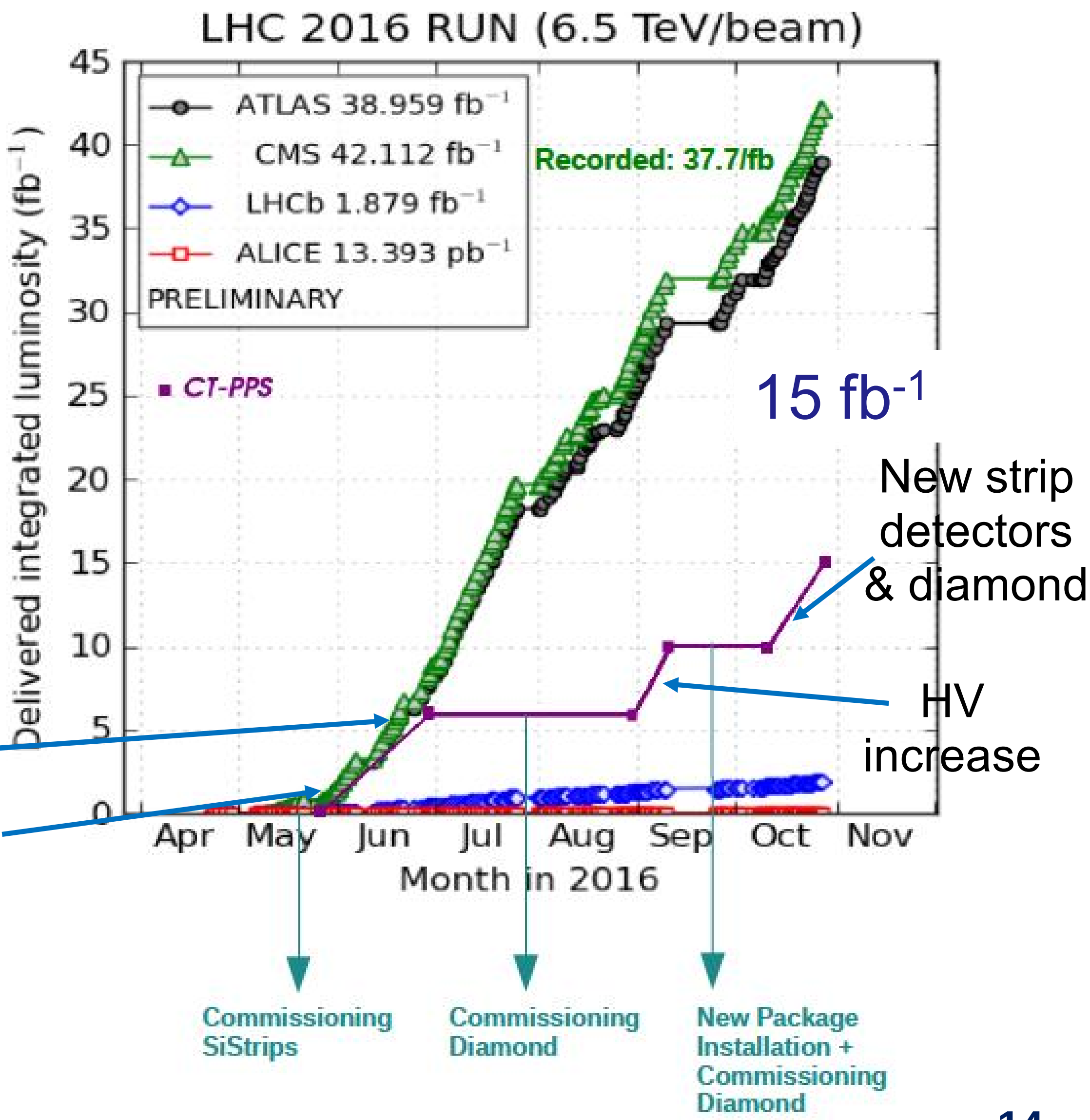
RPs at15σ & readout as part of CMS standard high luminosity running

2016 luminosity with CT-PPS:

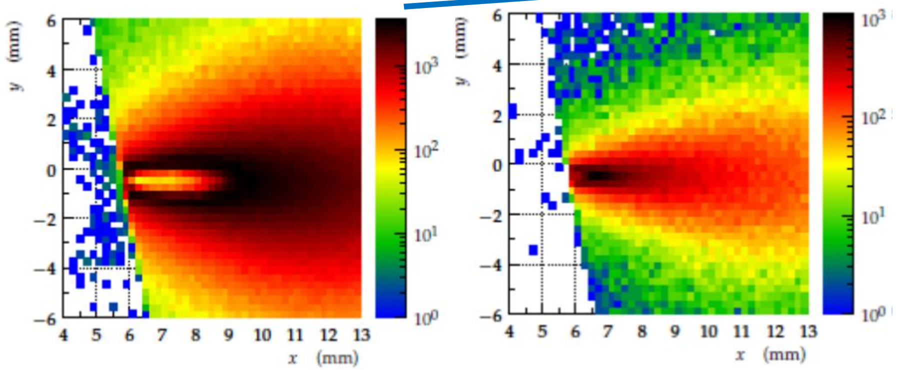
- Strip detectors ~15 fb^{-1}
- Diamond detectors ~2.5 fb^{-1}

(as tracking devices)

~ 2/3 of data strip detector fully efficient, ~ 1/3 efficiency loss in most occupied region due to radiation damage in silicon



e.g. in 56 210-far:

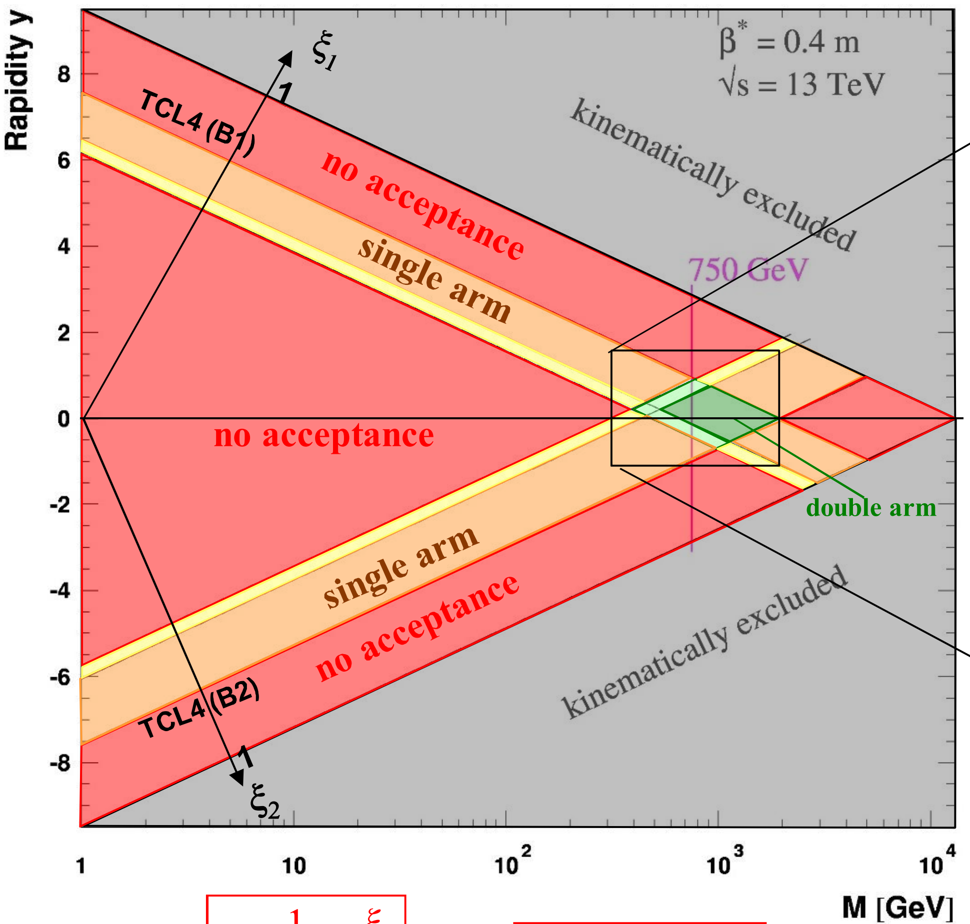


CT-PPS mass acceptance

(e.g. 2016 before TS2)

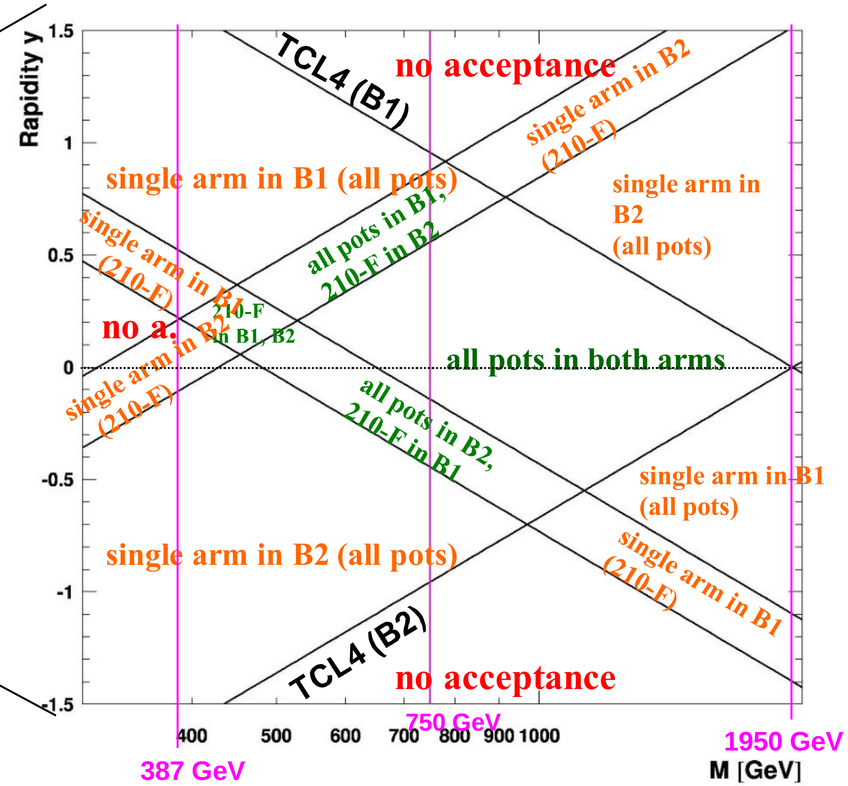
$\beta^* = 0.4$ m, $\alpha_X = 370\ \mu$rad, mild orbit bump, RPs @ 15σ

Using asymmetric dispersion as measured in data



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

$$M^2 = \xi_1 \xi_2 s$$



Mass acceptance in 2016 after TS2 slightly better ($\alpha_X = 280\ \mu$rad)

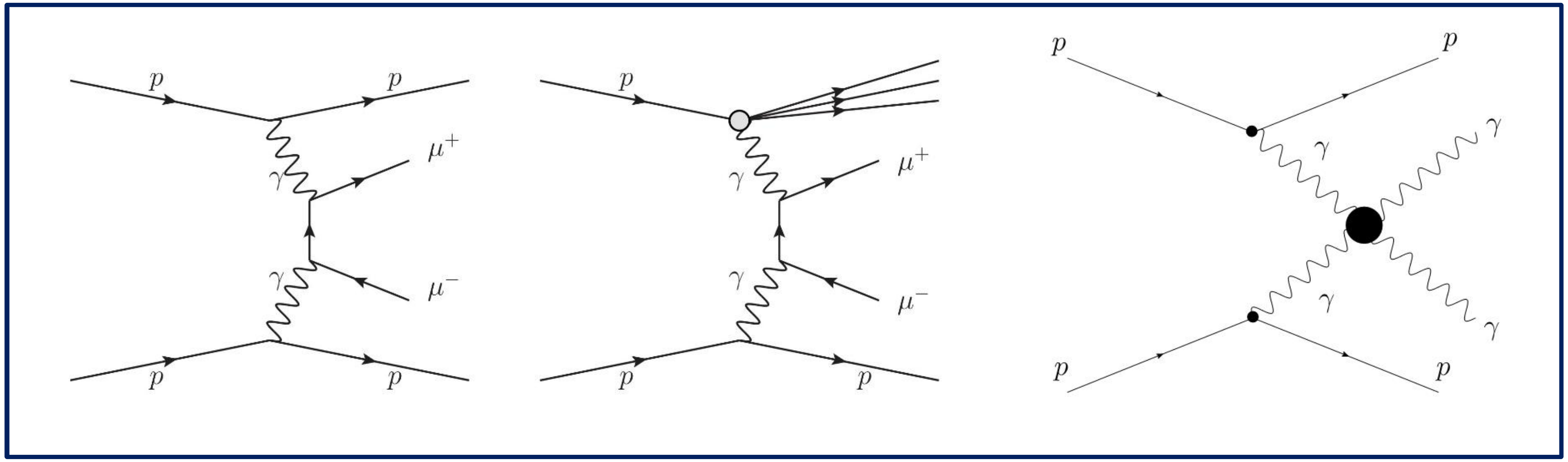
CT-PPS physics potential

Exclusive Production:

- photon-photon fusion
- gluon-gluon fusion in colour-singlet state ($J^{PC} = 0^{++}, 2^{++}$ ..)

Strategy: require correlation central system & forward protons

Early analyses (not requiring timing):



Diphoton production sensitive to anomalous quartic couplings ($\gamma\gamma\gamma\gamma$).

Proton kinematic reconstruction cross-checked using $pp \rightarrow p + \mu\mu + X/p$ events (where only one p is detected in CT-PPS RPs)

With timing detectors:

- Exclusive WW
- Exclusive dijets
- Inclusive missing mass/missing energy
- …

Summary

TOTEM physics:

- Preliminary results: σ_{tot}, σ_{inel} & σ_{el} at $\sqrt{s}$ = 2.76 TeV
- σ_{tot}, σ_{inel} & σ_{el} at $\sqrt{s}$ = 13 TeV (β^* = 90 m) progressing well
- β^* = 2.5 km at $\sqrt{s}$ = 13 TeV potential for precise ρ measurement

CT-PPS:

- RPs operated at 15σ & highest luminosity
- 15 fb^{-1} of data with CT-PPS (in ~ 2/3 strips 100 % efficient)
- Commissioned diamond detectors & collected first data
- First analysis on-going

CT-PPS has first proven the feasibility of operating near-beam proton spectrometer at high luminosity on regular basis

CMS & TOTEM has paved the way for other such spectrometers

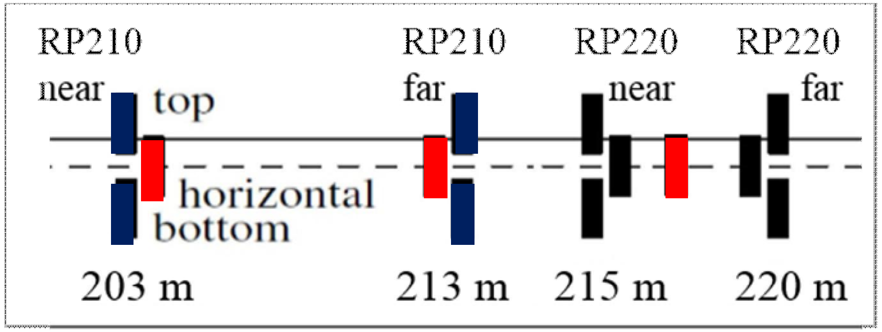
Backup

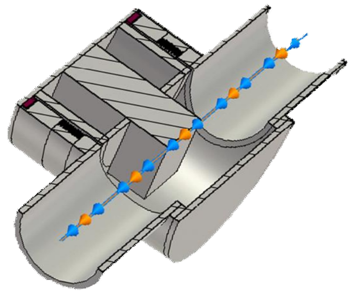
Roman Pot system 2015 →

Movable beam pipe section allowing insertion of detector to O(mm) distance from the beam

High luminosity standard running:

- 2-3 horizontal RPs (+ 4 vertical for RP alignment runs)

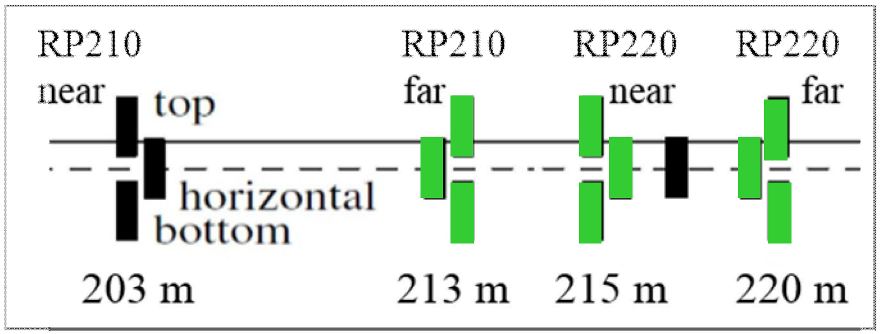


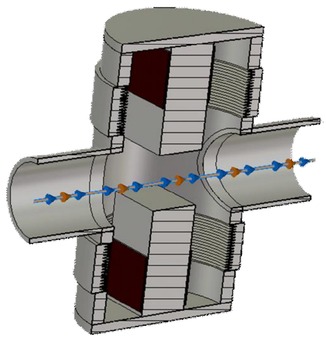


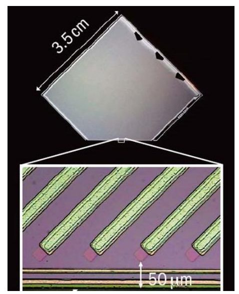
Special high β* runs (90 m, 1 km, 2.5 km):

- 4-6 vertical RPs & 2-3 horizontal RPs

2010-13 data: only RP220

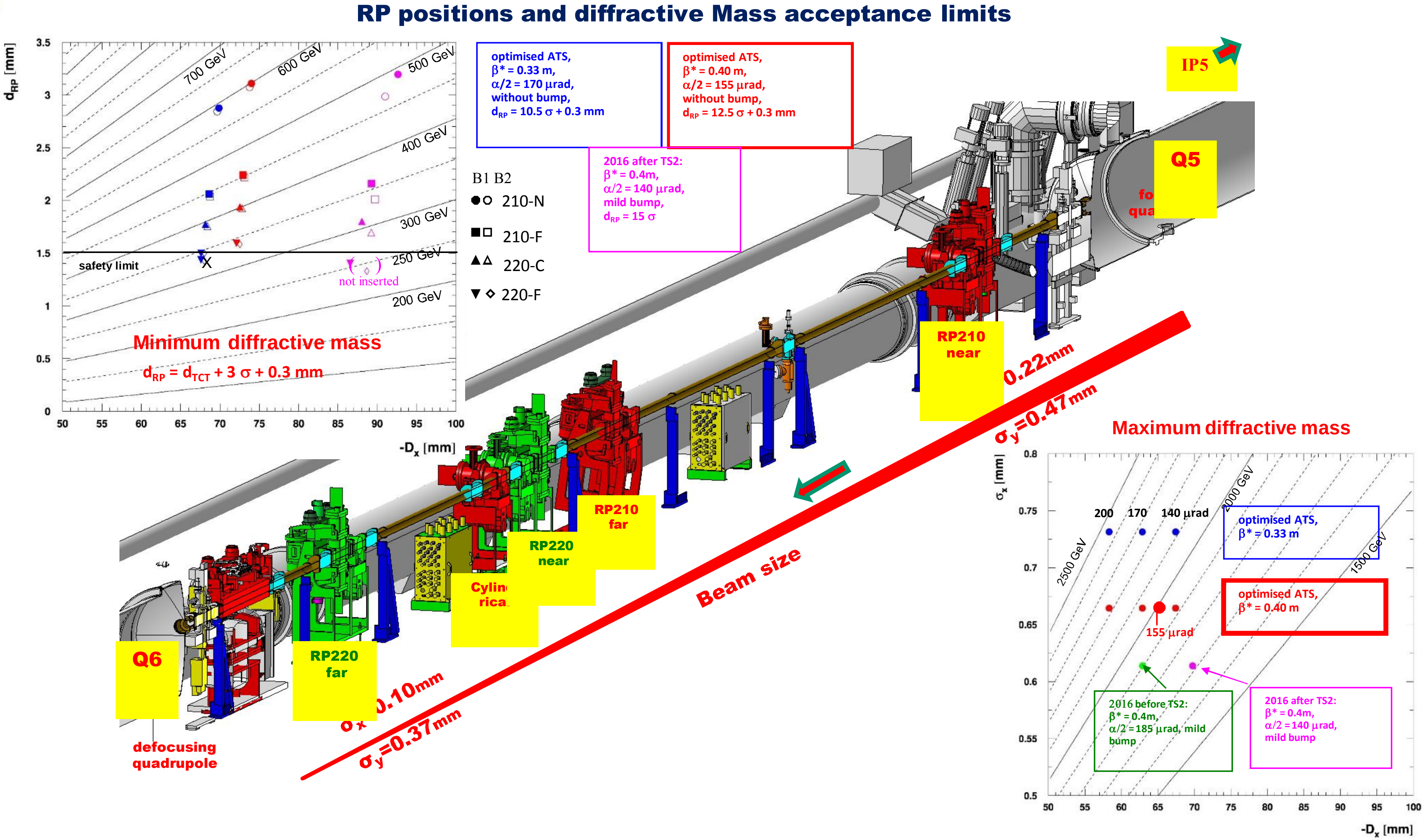






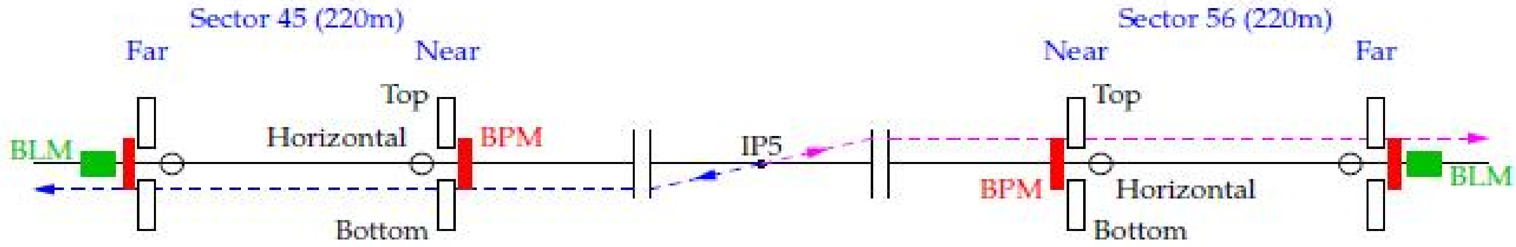
For more details see Joachim Baechlers talk Thursday

RP system & acceptance in 2017



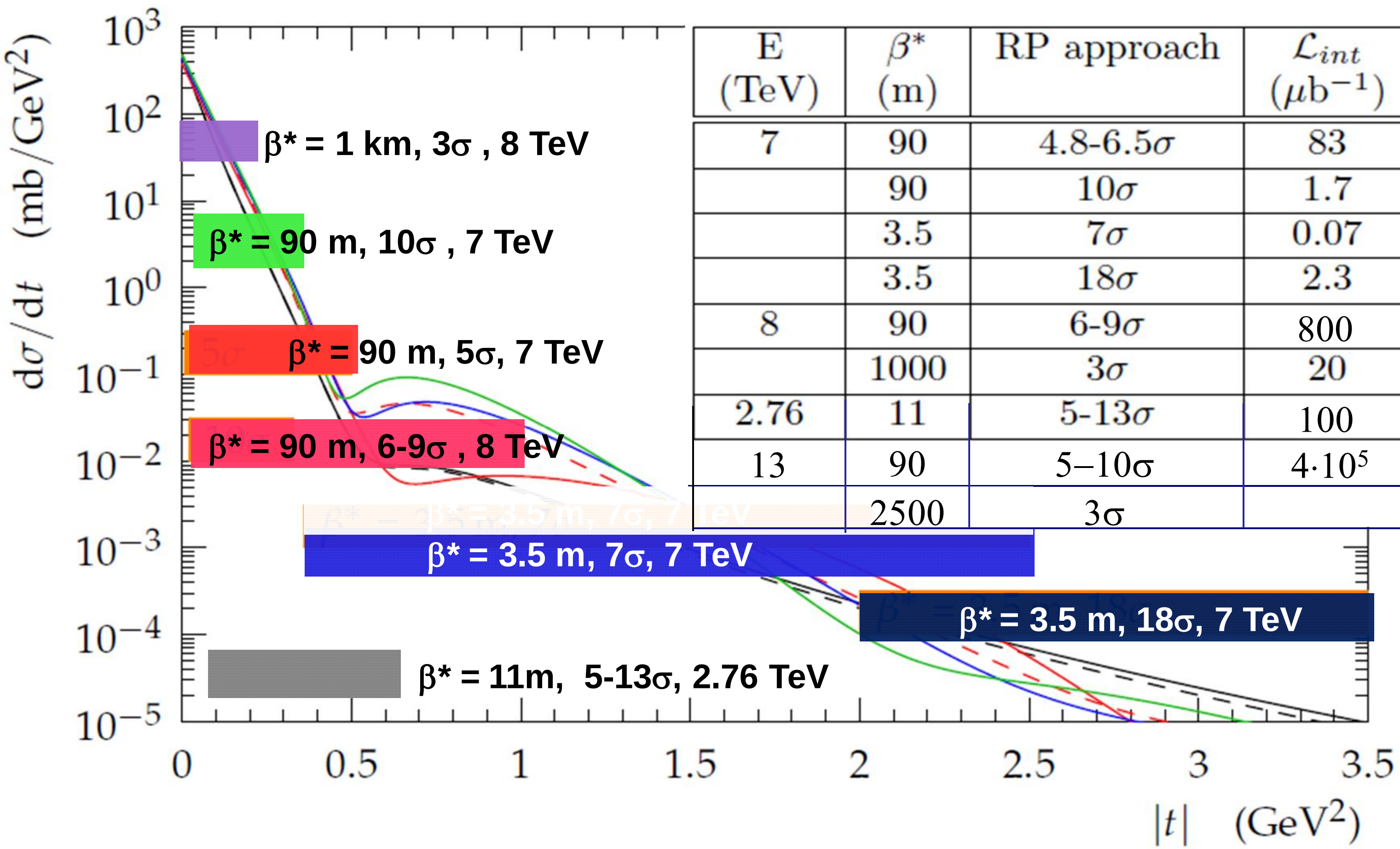
Elastic pp scattering: selection & data sets

Selected based on topology, low |ξ|, anti-collinearity & vertex



Key issues:
RP alignment
& optics

Data sets at different conditions to measure over as wide |t|-range as possible

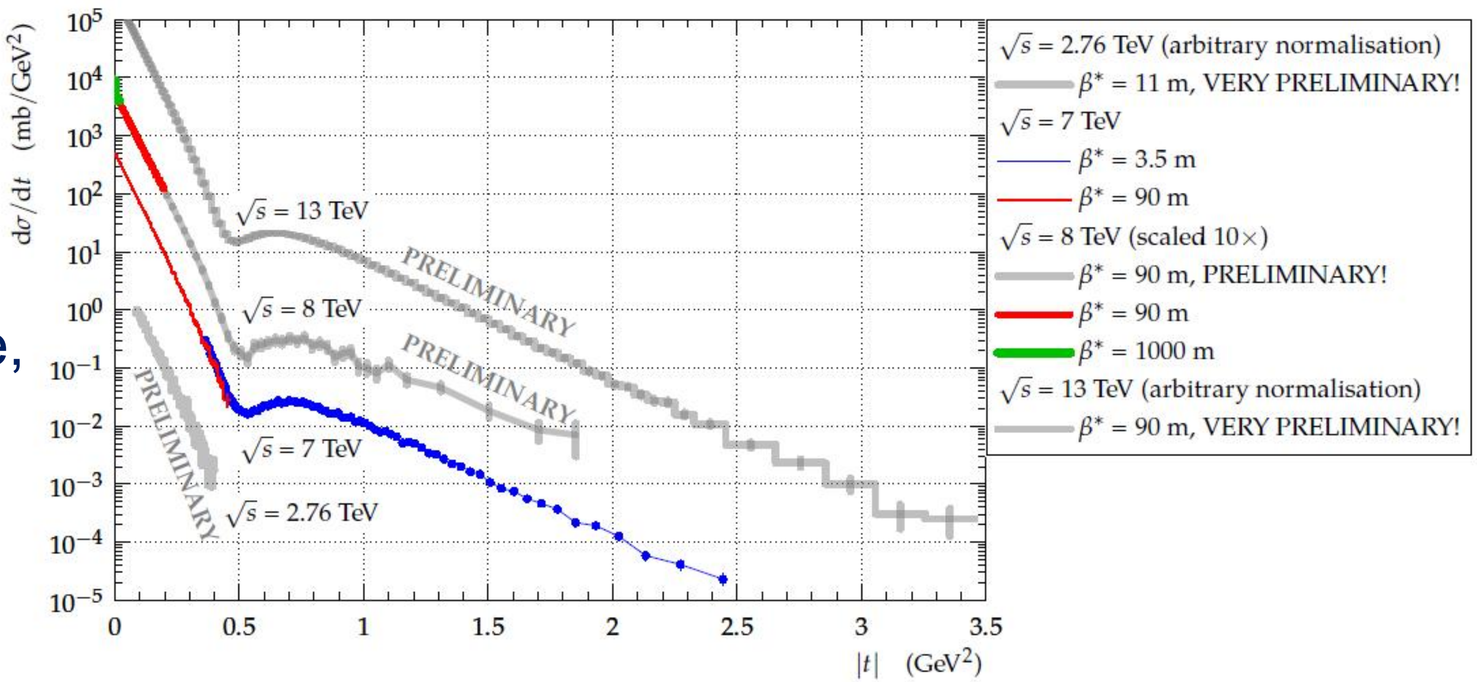


E (TeV)	β^* (m)	RP approach	$\mathcal{L}_{int}$ (μb^{-1})	t range (GeV^2)	Elastic events	
7	90	4.8-6.5σ	83	$7 \cdot 10^{-3}$ - 0.5	1M	√
	90	10σ	1.7	0.02 - 0.4	14k	√
	3.5	7σ	0.07	0.36 - 3	66k	√
	3.5	18σ	2.3	2 - 3.5	10k	
8	90	6-9σ	800	0.01 - 1	7M	√
	1000	3σ	20	$6 \cdot 10^{-4}$ - 0.2	0.4M	√
2.76	11	5-13σ	100	0.05-0.6	45k	O
13	90	5–10σ	$4 \cdot 10^5$	0.01 – 3.5	~ 1400M	O
	2500	3σ		$6 \cdot 10^{-4}$ – 0.2	~ 5M	O

√ Data published
O Analysis finished
O Analysis on-going

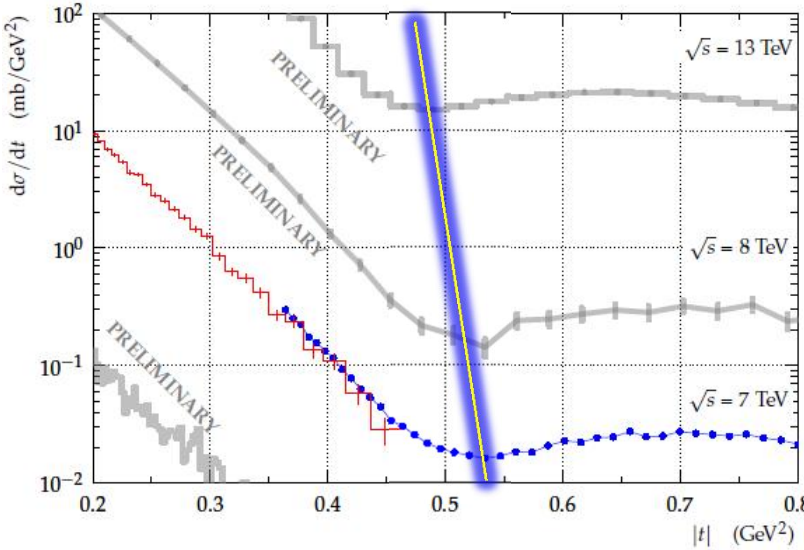
Elastic pp scattering: data summary & trends

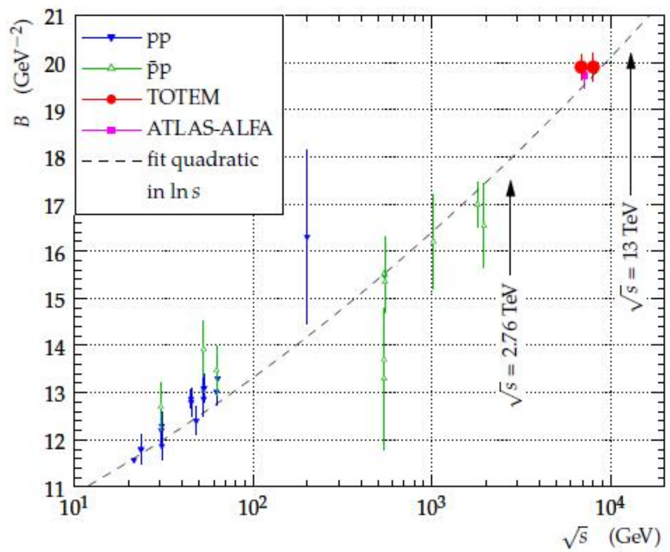
different |t|-ranges probes different physics regimes: Coulomb interference, diffractive cone, dip-bump, transition to pQCD etc…



Trends:

- dip position in |t| decreases with increasing $\sqrt{s}$
- Forward slope $B = \frac{d}{dt}\ln(\frac{d\sigma}{dt}\Big|_{t=0})$ increase with $\sqrt{s}$

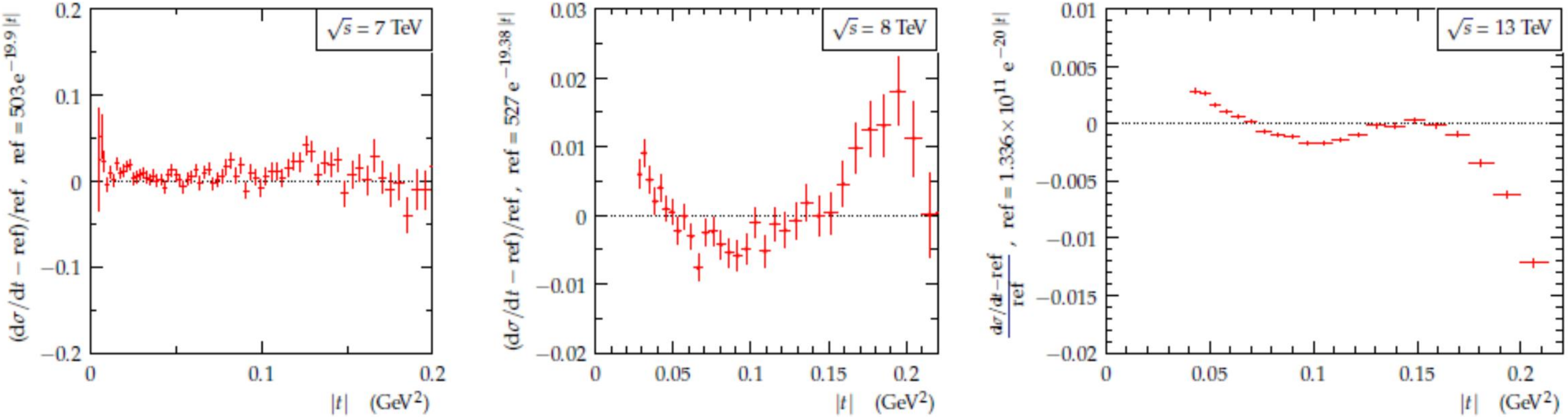




Elastic pp scattering: non-exponentiality at low |t|

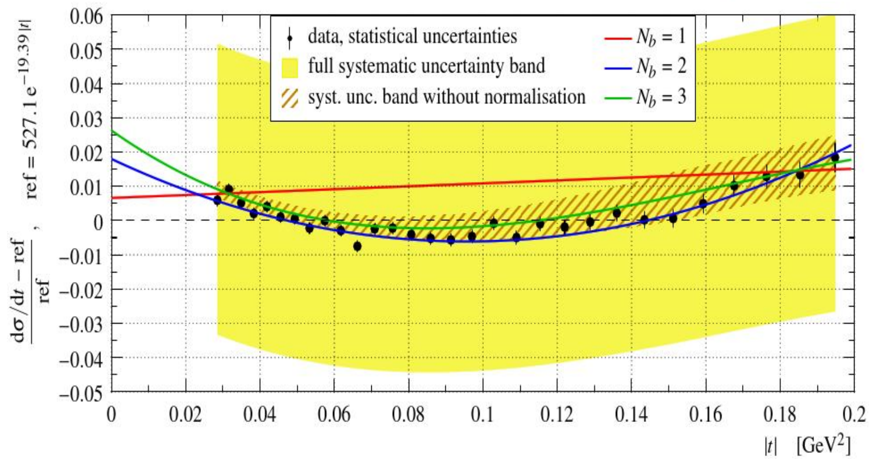
- Diffraction cone ”looks almost exponential”
  Magnify deviation ⇒ show (dσ/dt – ref. exp.)/ref. exp.

- β^* = 90 m measurements at different energies (stat. uncert. only)



Non-exponentiality observed at 8 & 13 TeV

- 8 TeV: 7σ significance
- 13 TeV: preliminary high significance
- observed cross-section non-exponential



dσ/dt = hadronic + Coulomb + interference

Nucl. Phys. B 899 (2015) 527

Coulomb-hadronic interference – analysis strategy

Central question:

Observed non-exponentiality due to hadronic Coulomb or both

- fits with 2 different assumptions on hadronic amplitude
  - purely-exponential – non-exponentiality due to Coulomb (& interference)

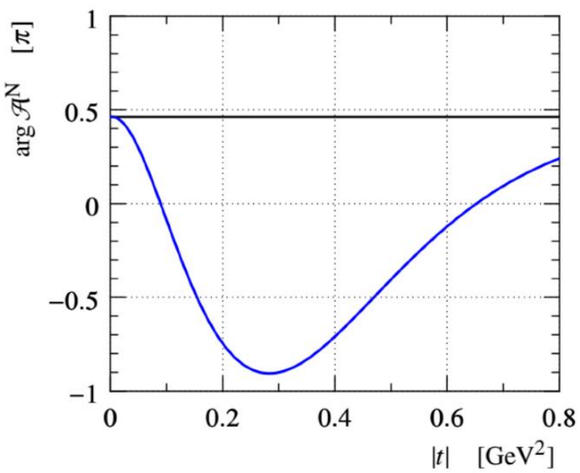
$$\Rightarrow |F^{H}| = a \exp(b_1 t)$$

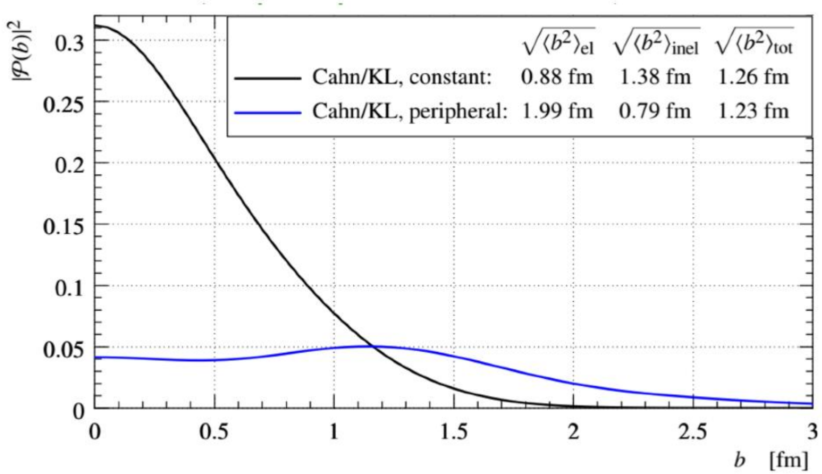
  - flexible enough to describe non-exponentiality even without Coulomb

$$\Rightarrow |F^{H}| = a \exp(b_1 t + b_2 t^2 + b_3 t^3)$$

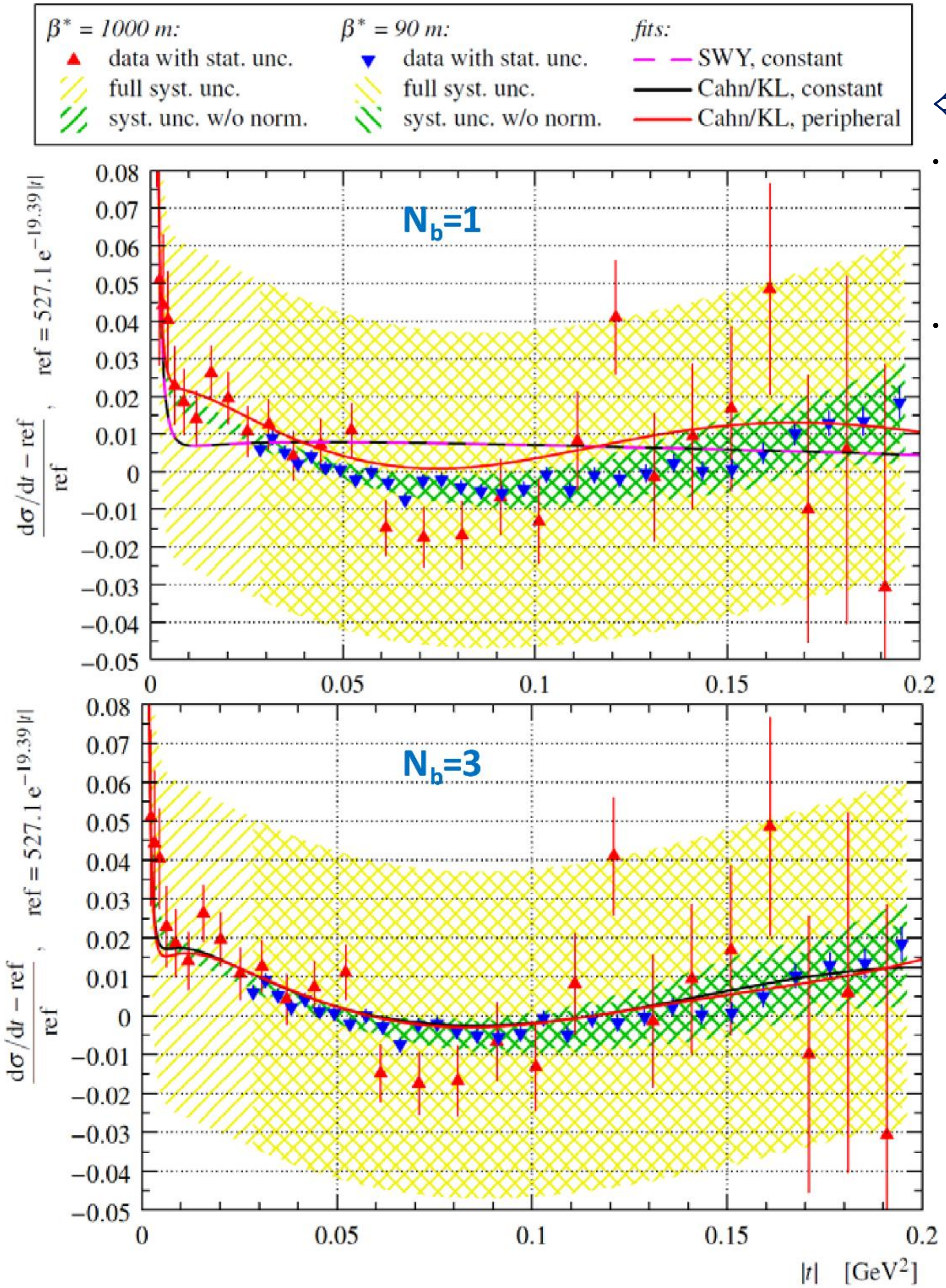
- role of |t|-dependence of hadronic phase?
  - large impact at low |t|
  - controls behaviour in impact parameter space (b)

  - consider 2 options:
    + central: black
    + peripheral: blue





Coulomb-hadronic interference – fits



⇐ **Purely-exponential hadronic amplitude**

- Central phase excluded (with SWY, Cahn & KL) ⇒ application of SWY formula excluded too
- Peripheral phase not explicitly excluded by data but disfavoured
  - ρ value outside a consistent pattern of other fits & theoretical predictions
  - several theoretical reasons for non-expontential hadronic amplitude

⇐ **Non-exponential hadronic amplitude**

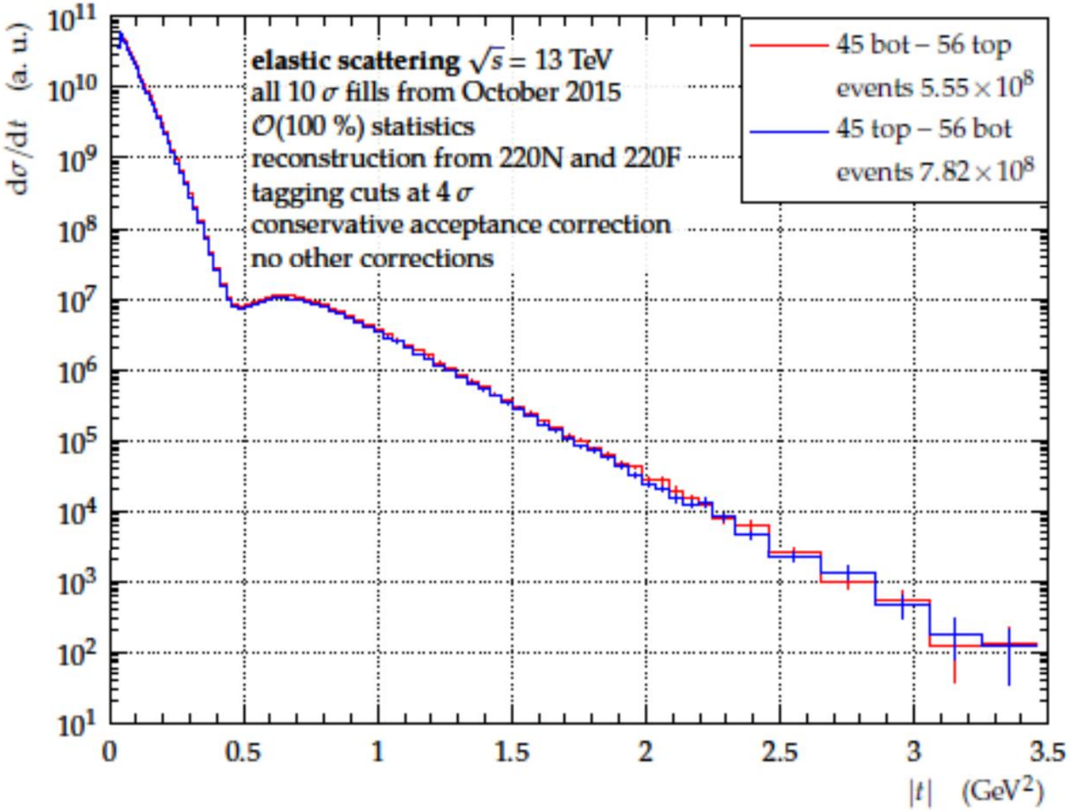
- Both central & peripheral phase compatible with data ⇒ centrality not a necessary description for elastic scattering

Not one single hadronic scattering amplitude ⇒ multiple exchange channels for elastic scattering

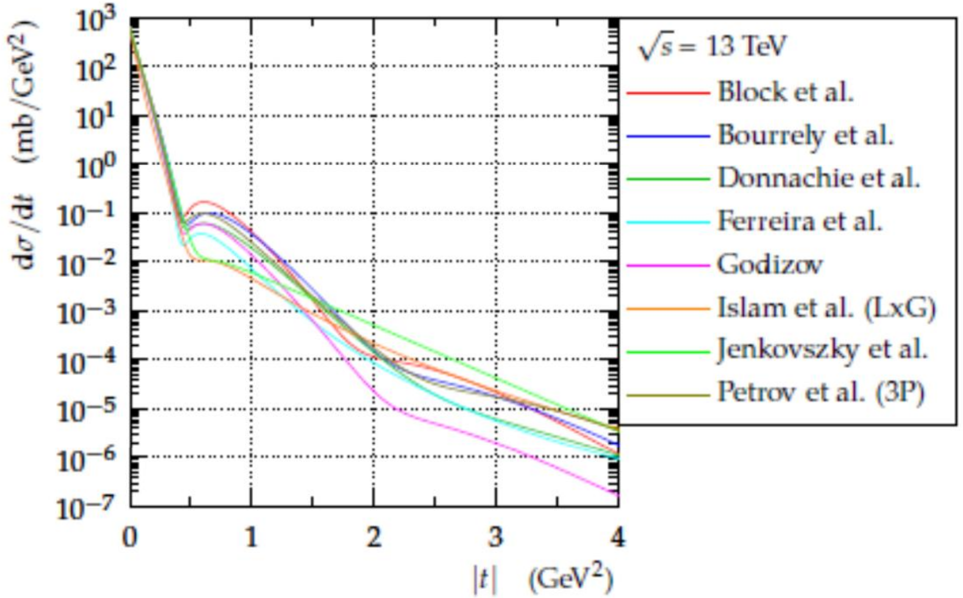
CERN-PH-EP-2015-235, accepted by EPJC

Elastic pp scattering: structures at high |t| ?

Very preliminary 13 TeV data give already very strong indications



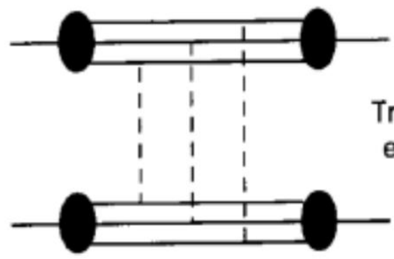
model predictions:



oscillations in almost each model

No structures at high-|t| !

- Rules out many modules
- Rules out "optical" models?
- Physics interpretation: transition between diffraction & pQCD a la Donnachie-Landshoff



Triple gluon exchange

3g $J^{PC} = 1^{--}$ search

- Originally predicted as Odderon in Regge theory framework [Lukaszuk, Nicolescu], confirmed in QCD [Vacca, Braun, Dosch et al.]: Colorless 3-gluon bound state with strong internal coupling

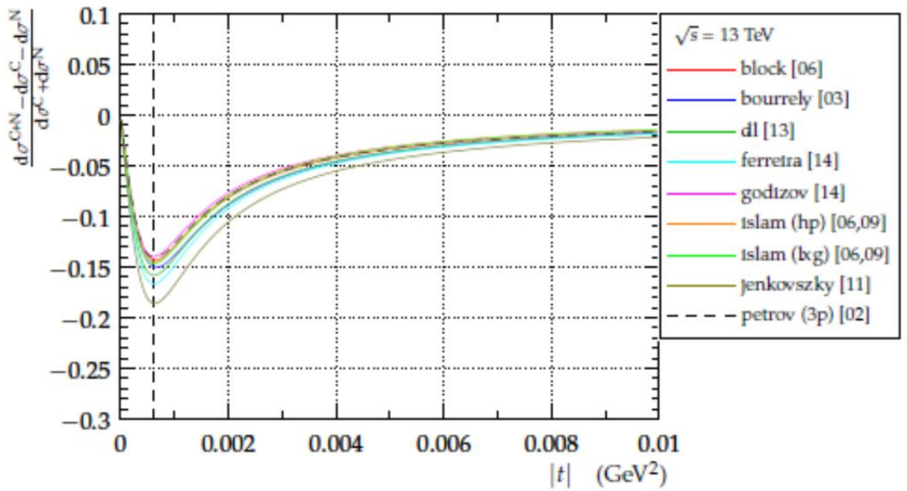
Theory: 3g $J^{PC}=1^{--}$ existence would imply for pp elastic scattering :

- persistence of dip at LHC energies, faster increase of σ_{tot} with $\sqrt{s}$
- non-constant hadronic phase & low-t deviation from pure exponential
- faster decrease of ρ with $\sqrt{s}$: @14 TeV $\rho \approx 0.14$ (without 3g $J^{PC} = 1^{--}$) vs $\rho \approx 0.10$ (with 3g $J^{PC} = 1^{--}$); TOTEM @8 TeV: $\rho = 0.12 \pm 0.03$
  $\Rightarrow$ need ρ with $\pm$ 0.01 precision @13 TeV
- pQCD (without oscillatory effects) at large |t|

$\Rightarrow$ TOTEM measurements consistent with existence of 3g $J^{PC} = 1^{--}$

Coulomb-hadronic interference 13 TeV:

- equality point (Coulomb = nuclear) has optimal sensitivity to ρ
  $\Rightarrow \beta^* = 2.5$ km with RP at 3σ
- $\pm$ 0.01 precision on ρ requires $\leq$ 1% error on data points $\Rightarrow$ successful data taking last week

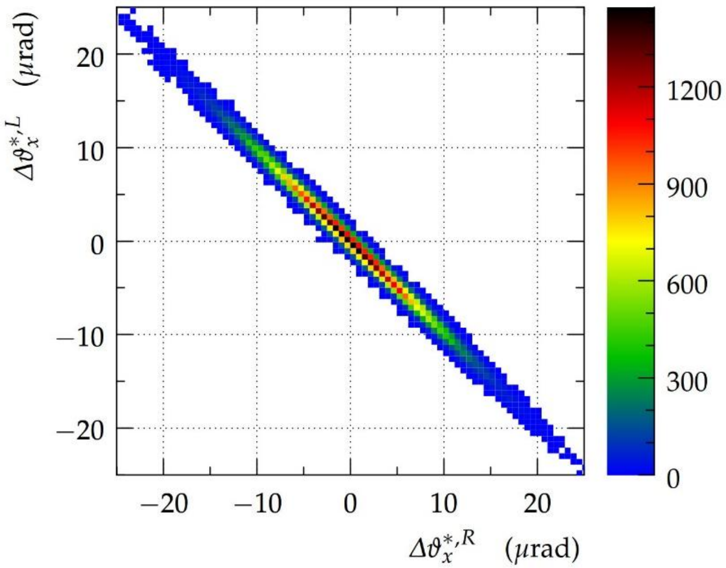


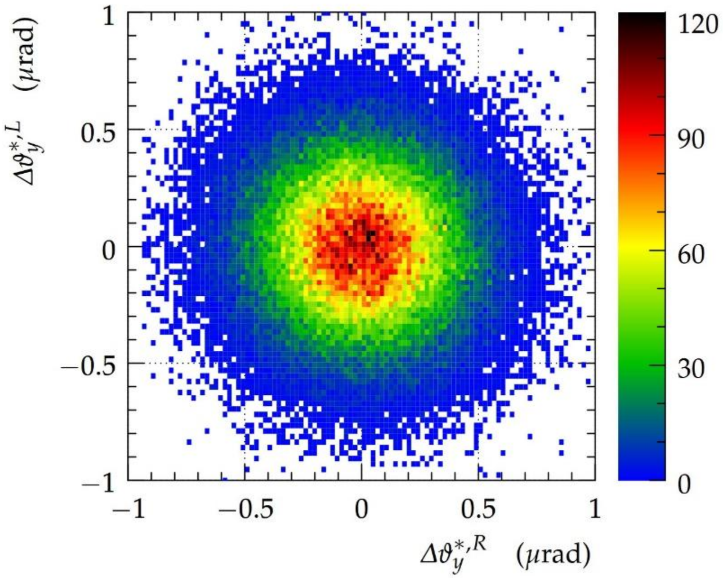
Resolution for β* = 2.5 km

- 4-RP analysis: reconstruction with 2 RPs per arm ⇒ x^* and θ_x^* disentangled
  - $\sigma(x^*)$ and $\sigma(\Delta^{R-L}\theta_x^*)$ deconvolved into

$$\sigma(x^*) \approx 600\ \mu m\ , \quad \sigma^{bd}(\theta_x^*) \approx 0.35\ \mu rad\ , \quad \sigma^{1RP}(x) \approx 11.8\ \mu m\ , \quad \sigma^{bd}(\theta_y^*) \approx 0.26\ \mu rad$$

- reconstruction with 1 RP per arm ⇒ only θ_x^* reconstructed
  - θ_x^* biased by x^*: optics symmetry ⇒ anti-correlated
  - simulation with 4-RP input (pitch, vertex, beam divergence)





$$\sigma(\Delta^{R-L}\theta_x^*) \approx 12.9\ \mu rad\ , \quad \sigma\left(\frac{\theta_x^{L*} + \theta_x^{R*}}{2}\right) \approx 0.3\ \mu rad\ , \quad \sigma(\Delta^{R-L}\theta_y^*) = 0.38\ \mu rad$$

– first value for acceptance correction, second for t-distribution smearing

- 2-RP analysis

$$\sigma(\Delta^{R-L}\theta_x^*) \approx 12.5\ \mu rad\ , \quad \sigma(\Delta^{R-L}\theta_y^*) = 0.37\ \mu rad$$

Total pp cross-section: methods & results

Excellent agreement between 7 TeV σ measurements:

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

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

testing validity of optical theorem at ~3.5 % level

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

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

7 TeV

σ_{total} = **101.7 mb ± 2.9 mb** **8 TeV**
PRL 111(2013) 012001

↕ compatible

σ_{total} = **102.9 mb ± 2.3 mb** (central hadronic phase)
σ_{total} = **103.0 mb ± 2.3 mb** (peripheral hadronic phase)
CERN-PH-EP-2015-235, accepted by EPJC

8 TeV

Combining 8 TeV β* = 90 m & 1 km data: Improved extrapolation of hadronic amplitude to t = 0 (Coulomb interference measured) & simultaneous ρ determination

CT-PPS Data Taking Summary

STRIPS (PACK2) : 45 NR-FR / 56 FR
DIAMONDS : 45/ 56
OPTICS_140
L=2.5/fb

STRIPS (PACK2) : 45 NR-FR / 56 FR
OPTICS_140
L=2.8/fb

STRIPS (PACK1) : 45 NR-FR / 56 NR-FR
OPTICS_185
L=3.8/fb

STRIPS (PACK1) : 45 NR-FR / 56 NR-FR
OPTICS_185
L=5.6/fb

STRIPS (PACK1) : 45 NR-FR / 56 NR-FR
With margin
OPTICS_185
L=0.6/fb

Fill	Runs	Recorded Lumi /pb	RP IN (15σ+0.5mm) [Local time]	Comments
5451	284029 284035 284036 284037 284038 284039 284040 284041 284042 284043	332.25	09:10:00 AM	diamonds IN / HV strips 300 V
5450	284006 284014	106.42	02:00:00 AM	diamonds IN / HV strips 300 V
5448	283946 (LS115) 283964	355.03	07:40:00 AM	diamonds IN / HV strips 300 V
5446	283934	280.27	06:40:00 PM	diamonds IN / HV strips 300 V
5443	283884 (LS406) 283885	386.05	12:06:00 AM	diamonds IN global / HV strips=300V
5442	283876 283877	411.45	03:50:00 AM	diamonds IN global
5441	283865	220.28	06:25:00 PM	diamonds IN global
5439	283820 283830 283834 283835	383.4	09:00:00 PM	diamonds IN global
		2475.15		
5437	283675 283676 283680 283681 283682	126.83	01:30:00 AM	Run 283685/ test diamond with beam separation
5433	283548 (LS 244) 283549 283550 283551 283553 283560	156.97	11:36:00 PM	HLT: PixelScan ?
5427	283478 283481	209.65	04:30:00 AM	
5424	283453	110.6	07:30:00 PM	
5423	283408 283413 283414 283415 283416	487.88	10:10:00 PM	HV=250 V
5421	283353 283358 283359	413.41	08:16:00 PM	
5418	283306 283307 283308	348.81	09:57:00 PM	
5406	283050 283052 283059 283067	213.71	05:16:00 AM	HV=150V at 1pm run 283059 LS 447 ; HV=200 at 1.13pm run283067 LS 31
5405	283041 283042 283043	149.47	09:48:00 PM	
5401	282917(LS 146) 282918 282919 282920 282921 282922 282923 282924	188.09	01:37:00 AM	
5393	good runs 282733 282734 282735	384.45	01:06:00 PM	NEW packages; 56nrfr not in data; HV=100 V ; ~75/pb in commissioning
		2789.86		
5288	280384, 280385	374.33	08:57:30 AM	HV=250V
5287	280330, 280349, 280363, 280364	506.53	8:35:20 AM (from 4:05 to 4:48 in garage)	HV=250V
5279	280187,280188,280189,280190,280191,280192 ,280194	286.48	08:32:43 PM	HV=250V
5277	279993,279994,279995,280001,280002,280006 ,280007,280013,280014,280015,280016,28001 7,280018	522.31	12:36:00 AM	HV=250V
5276	279975	242.72	03:24:11 PM	HV=250V
5275	279966	92.44	09:37:46 AM	HV=250V
5274	279931	471.25	11:51:28 AM	HV=250V
5267	279844 (279845 279846 279848 279849)	146.2	09:38:43 AM	HV=250V Rps out at ~2:45PM
5266	279841	382.27	05:36:49 PM	HV=250 V
5265	279823	82.15	12:14:18 PM	HV=250V
5264	279794	224.66	01:58:38 AM	HV=250V 56-fr-hr = off
5261	279760 279766 279767	513.64	10:35:43 PM	HV=250V for all ; Run279767 LS=337 56-fr LV trip (then pot off)
		3843.95		
5052	275911 275912 275913 275918 275920 275921 275922 275923 275931	327.04	04:10:24 AM	Run 275920=raw mode ; 275921 crashed tried HV=300V , pots out
5048	275886 275887 275890	237.37	10:59:54 AM	275890 LS>821 => 45FR 200V
5045	275828 275829 275831 275832 275833 275834 275835 275836 275837 275838 275841 275846 275847	649.62	05:54:16 PM	
5043	275757 275758 275759 275761 275763 275764 275766 275767 275768 275769 275772 275773 275774 275776 275777 275778 275781 275782 275783	472.01	06:54:25 AM	
5038	275656 275657 275658 275659	73.94	05:37:12 AM	SW integration
5030	275375 275376	505.42	04:08:41 AM	
5029	275370 275371	133.99	06:37:16 PM	
5028	275344 275345	100.72	10:31:26 AM	
5027	275319 275326 275337 275338	181.99	09:06:04 PM	
5026	275309 275310 275311	387.75	04:00:24 PM	
5024	275282 275283 275284 275285 275286 275289 275290 275291 275292 275293	158.79	02:21:58 AM	
5021	275124 275125	191.39	08:13:33 PM	
5020	275059 275062 275063 275064 275066 275067 275068 275073 275074	365.32	07:19:49 PM	
5017	274998 274999 275000 275001	464.58	06:33:06 AM	
5013	274966 274967 274968 274969 274970 274971	400.21	12:47:36 AM	
5005	274954 274955 274956 274957 274958 274959	42.83	12:02:02 PM	
4990	274440 274441 274442 274443	219.43	09:54:45 PM	
4988	274420 274421 274422	338.64	10:44:31 PM	
4985	274387 274388	293.83	09:53:38 PM	
4964	274241(LS1156) 274243 274244	55.64	10:12:01 PM	
		5600.52		
4976	274282 274283 274284 274285 274286	48.78	05:36:00 AM	
4964	274240 274241	134.23	04:58:00 PM	
4961	274198 274199 274200	130.56	10:37:00 PM	
4960	274172	5.9	03:03:00 AM	
4953	274094	9.36	04:37:17 AM	
4947	273725 273728 273730	256.59	06:42:00 AM	
		585.42		

TOTAL : 15.3/fb