New Results on Elastic, Diffractive and Exclusive Processes

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on behalf of
the LHC collaborations

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Outline

- Elastic pp scattering, total and inelastic pp cross-section
- Central Exclusive Production
- Photon-photon collisions

Concentrate on recent LHC results and trends with some personal preferences !

Apologies to all producing interesting theoretical work & experimental results not being covered !

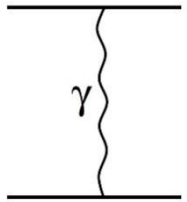
Elastic scattering, total and inelastic cross-section

Physics motivation:

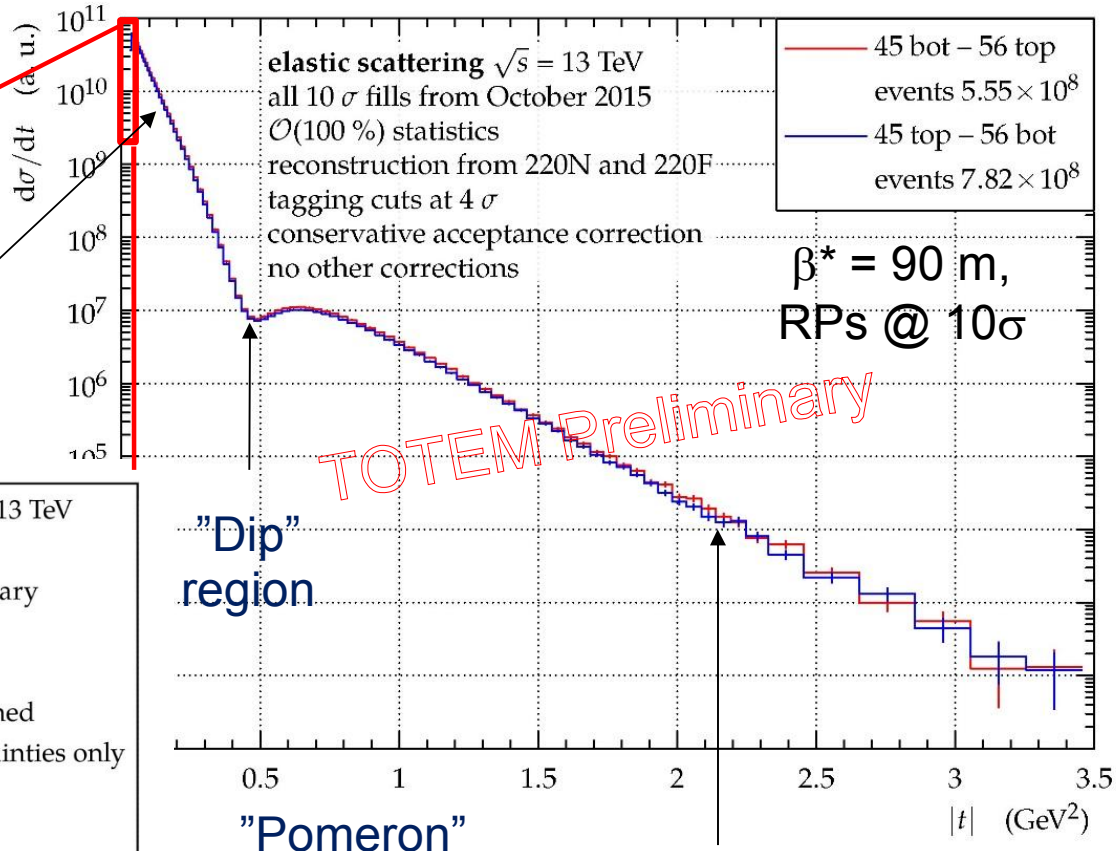
- Proton structure
- Non-perturbatuve QCD phenomena
- Soft diffraction
- Input to cosmic airshower modelling
- ….

Elastic pp scattering @ √s =13 TeV

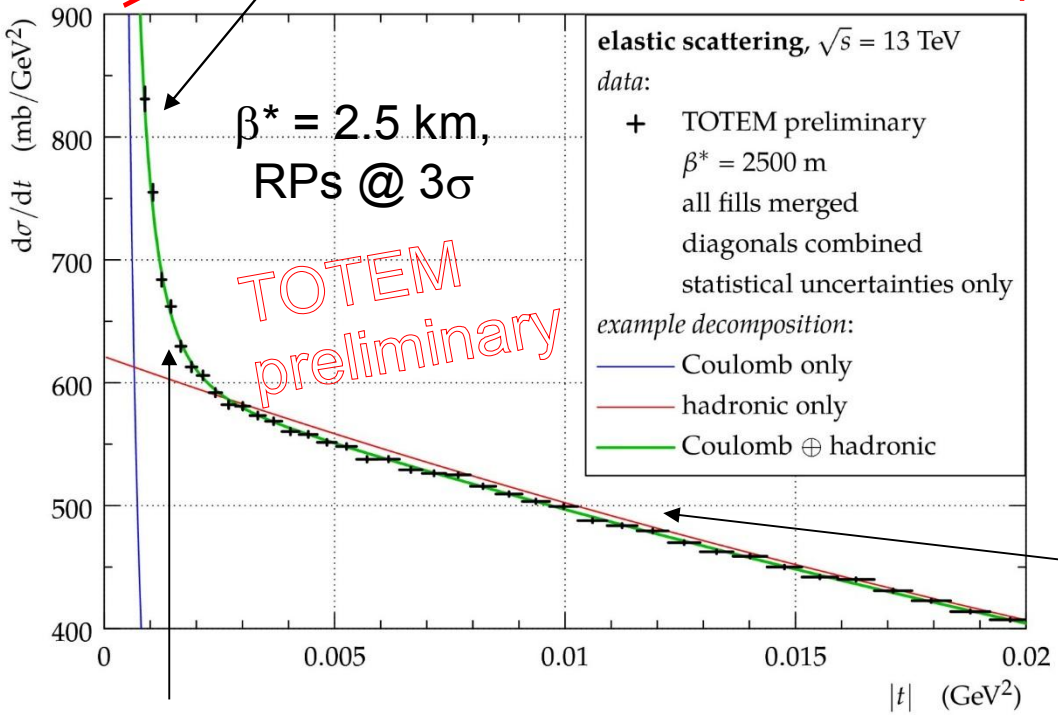
Photon exchange



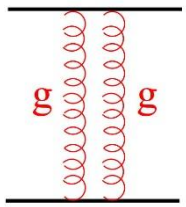
"Diffractive cone"



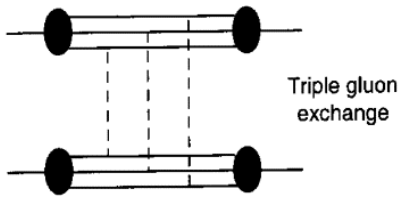
"Dip" region



"Pomeron" exchange



"Perturbative QCD" (pQCD) region

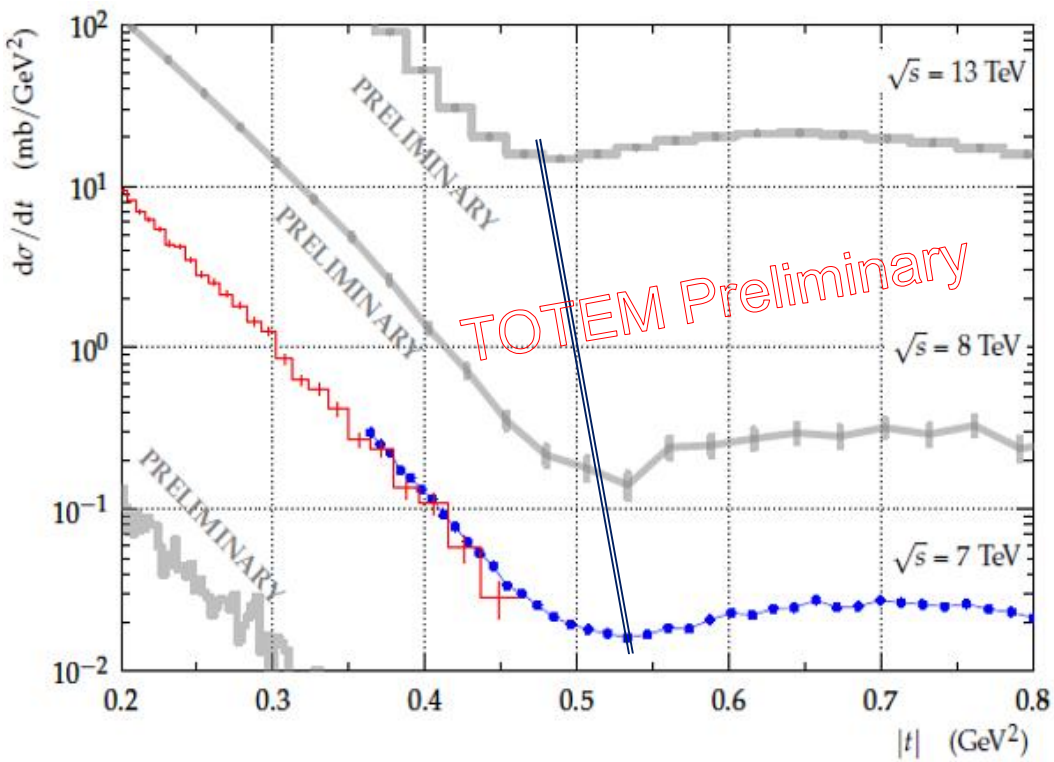


"Coulomb-nuclear interference" (CNI) region

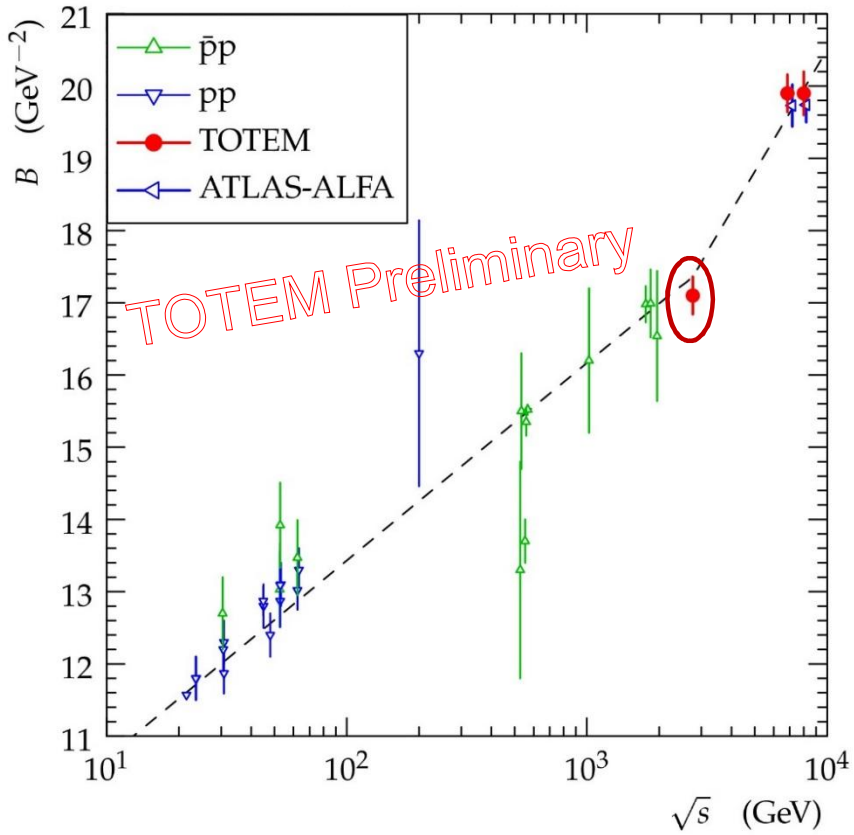
A. Donnachie and P. V. Landshoff, Z. Phys. C 2 (1979) 55.

Elastic pp scattering: trends

|t|-value of dip position decreases with increasing $\sqrt{s}$



diffractive slope parameter $B = \frac{d}{dt}\ln\left(\frac{d\sigma}{dt}\Big|_{t=0}\right)$ increase with $\sqrt{s}$



TOTEM measurement @ √s = 2.76 TeV:

$B = 17.10 \pm 0.26$ GeV^{-2} ($d\sigma_{el}/dt \propto e^{-B|t|}$)

$B \propto \ln\sqrt{s} \rightarrow \ln\sqrt{s^2}$ @ LHC: larger impact from contribution of multi-Pomeron exchanges

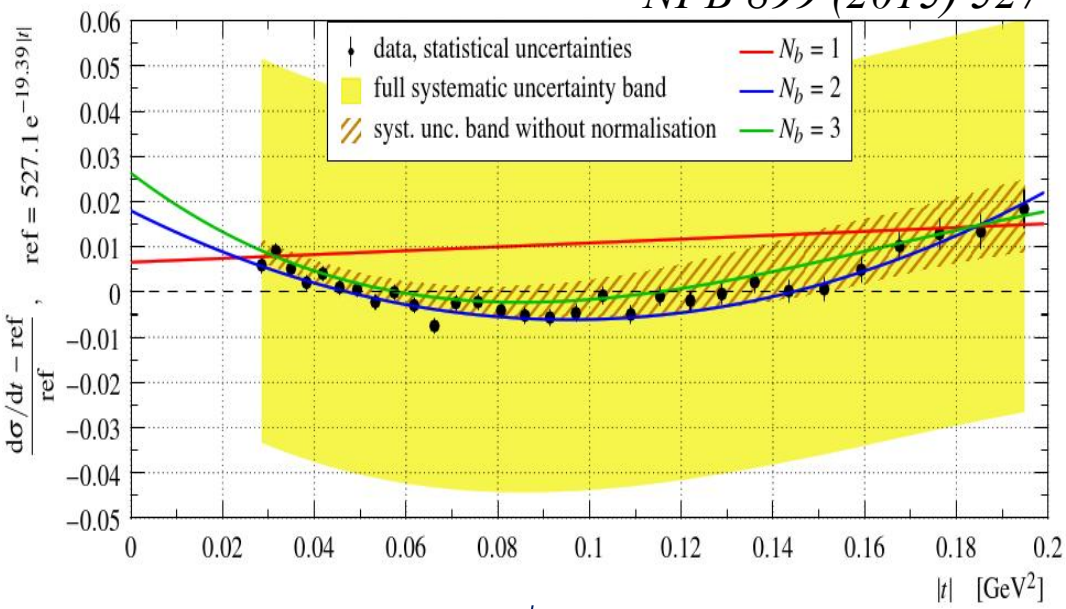
For details ⇒ see F. Nemes talk on Tuesday

A. Donnachie and P. V. Landshoff, arXiv1112.2485;
V. A. Schegelsky and M. G. Ryskin, PRD 85 (2012) 094024

Elastic pp scattering: non-exponentiality

- Diffractive cone looks almost ”perfectly exponential”
  magnify deviations ⇒ ($d\sigma_{el}/dt$ – ref. exp.)/ref. exp.

NPB 899 (2015) 527

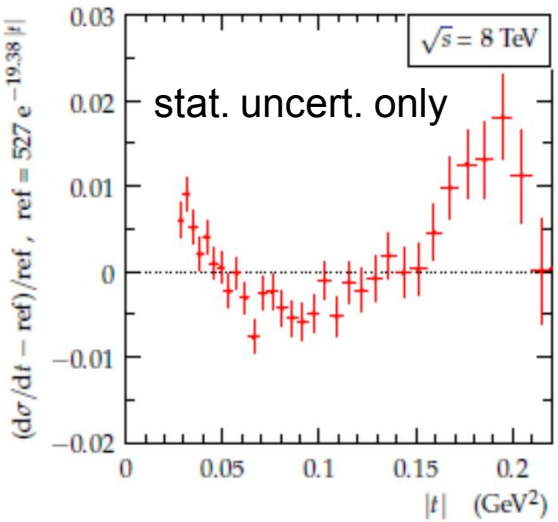


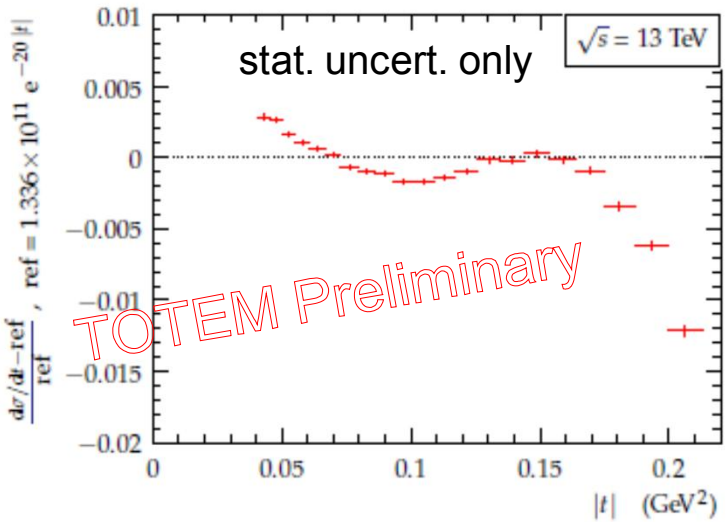
Pure (constant B) exponential slope excluded with > 7σ @ √s = 8 TeV
TOTEM collaboration, NPB 899 (2015) 527

Can only be due to hadronic amplitude having a non-purely exponential slope
TOTEM collaboration, EPJC 76 (2016) 661

Not only one single hadronic elastic pp scattering diagram
⇒ multiple exchange channels exists

Similar effect observed at √s = 13 TeV





A.D. Martin, V.A. Khoze, M.G. Ryskin, JPG 42 (2015) 025003; D.A. Fagundes et al., IJMPA 31´(2016) 1645022

Elastic pp scattering: ρ measurement

Study elastic pp scattering in CNI region at very low |t| able to measure:

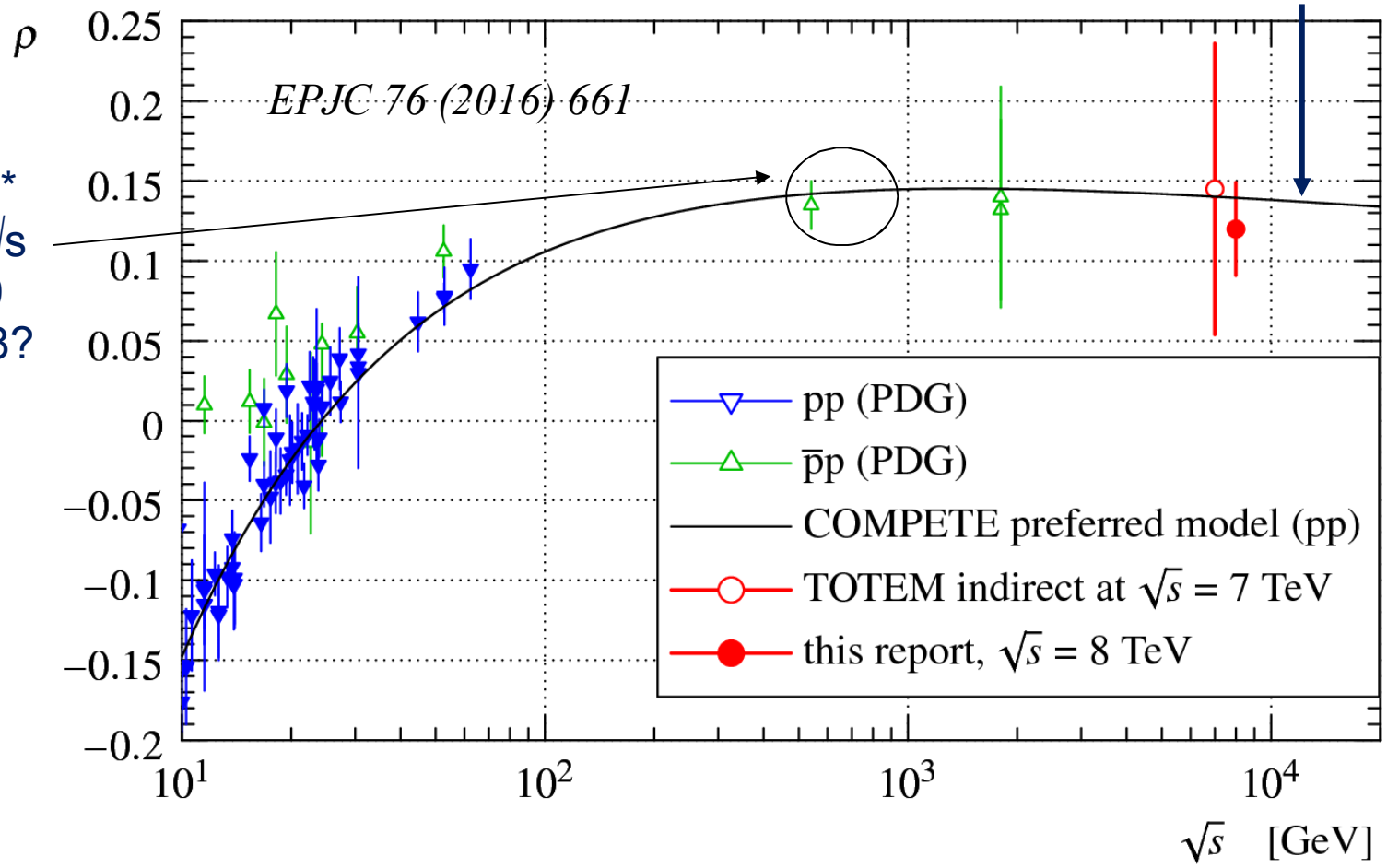
$$\rho \equiv \Re\, A^{\mathrm{had}} / \Im\, A^{\mathrm{had}}\big|_{t=0}$$

TOTEM measurement @ √s = 8 TeV: ρ = 0.12 ± 0.03

TOTEM collaboration, EPJC 76 (2016) 661

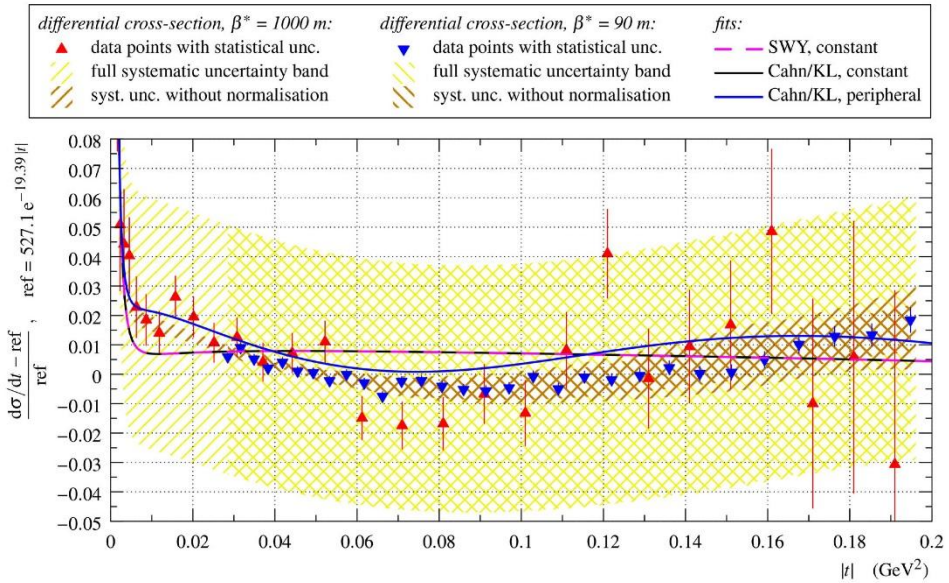
β* = 2.5 km @ √s = 13 TeV ⇒ σ(ρ) = 0.01

LHC high β* run @ low √s (0.65 – 0.9 TeV) in 2018?



Elastic pp CNI study: implications

EPJC 76 (2016) 661



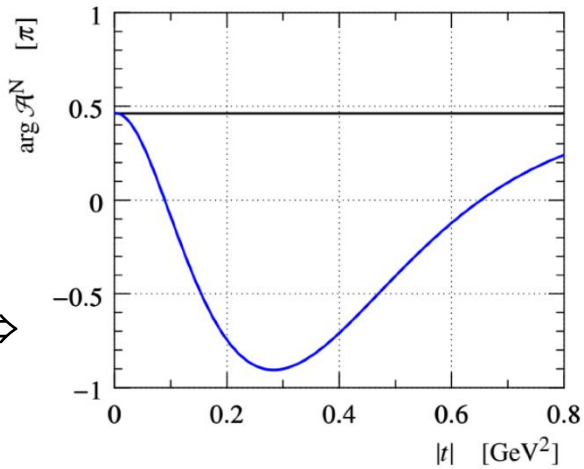
CNI with constant B and constant hadronic phase (labelled "SWY") excluded by TOTEM 8 TeV data ⇒ usage of most common CNI formula, simplified West-Yennie (SWY) not valid (since above conditions required)

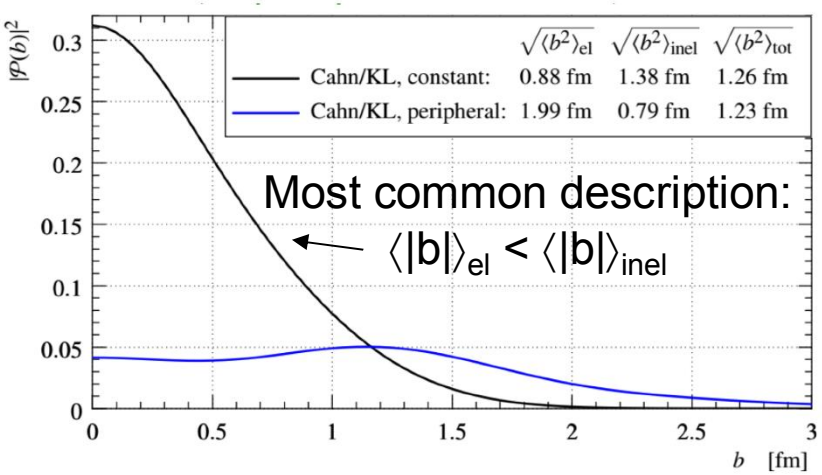
|t|-dependence of hadronic phase: controls behaviour in impact parameter space (b)

considered 2 options:
+ central: black
+ peripheral: blue

TOTEM 8 TeV data compatible with both ⇒ elastic pp scattering not necessarily central

EPJC 76 (2016) 661





σ_{tot}, σ_{inel}, σ_{el} vs $\sqrt{s}$

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

TOTEM @ $\sqrt{s}$ = 2.76 TeV (ρ = 0.145):

σ_{tot} = 84.7 ± 3.3 mb

σ_{inel} = 62.8 ± 2.9 mb

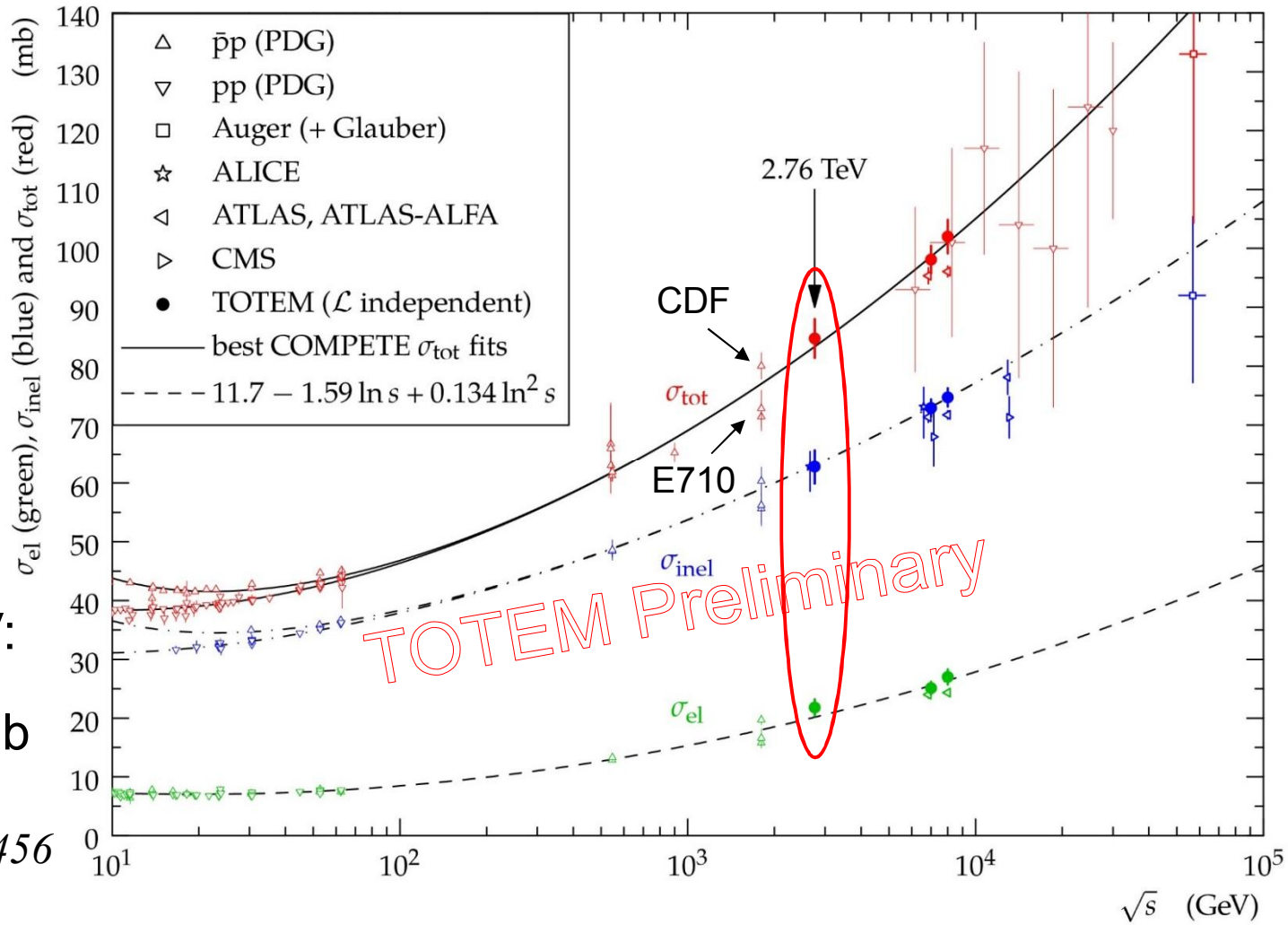
σ_{el} = 21.8 ± 1.4 mb

For details ⇒ see F. Nemes talk on Tuesday

ALICE @ $\sqrt{s}$ = 2.76 TeV:

$\sigma_{inel} = 62.8^{+2.4}_{-4.0} \pm 1.2$ mb

ALICE coll., EPJC 73 (2013) 2456



σ_{tot} @ LHC energies

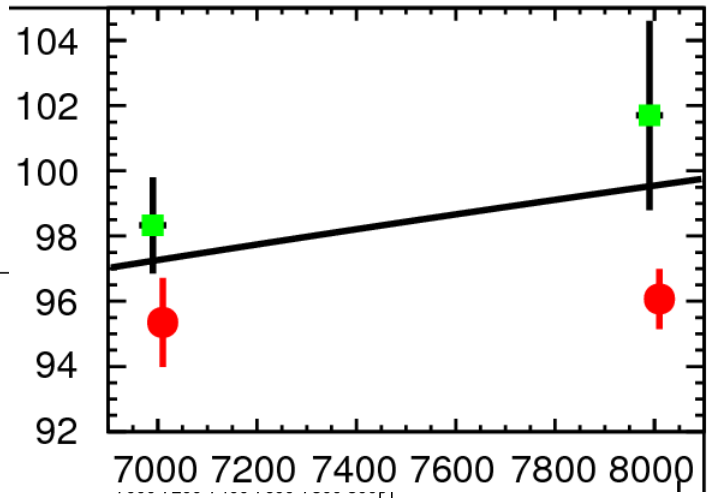
ATLAS @ $\sqrt{s}$ = 8 TeV: σ_{tot} = 96.07 ± 0.18 (stat.) ± 0.85 (exp.) ± 0.31 (ext.) mb

ATLAS collaboration, PLB 761 (2016) 158

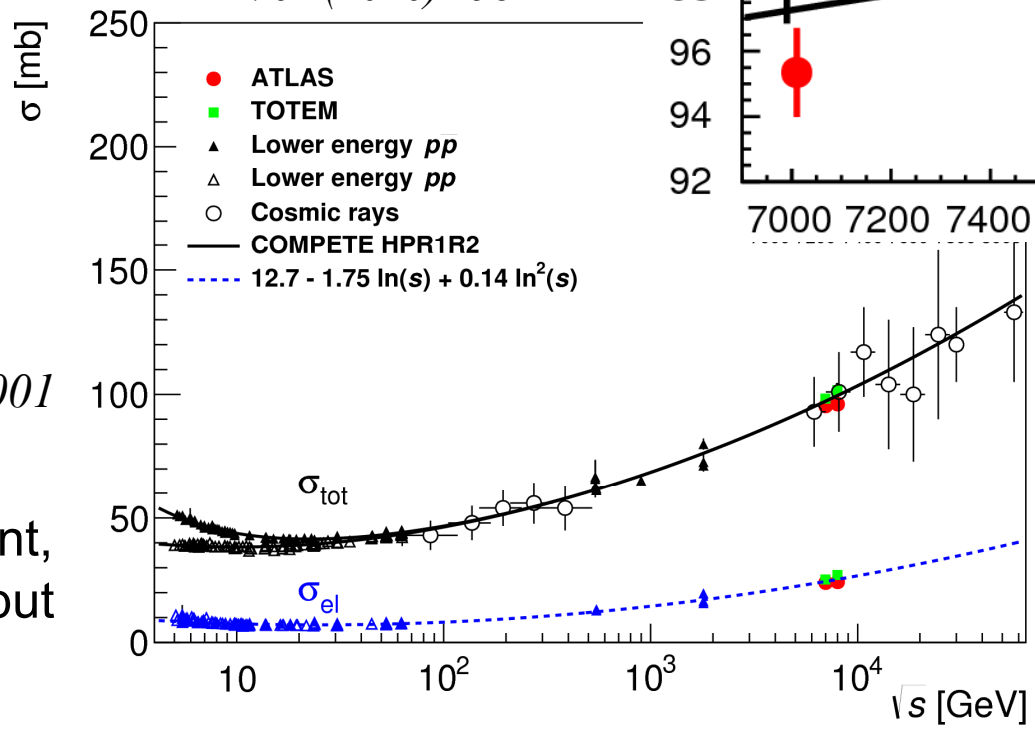
Luminosity dependent method:

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

|t| > 0.014; B constant, CNI taken into account, $\mathcal{L}$ and ρ external input



PLB 761 (2016) 158



TOTEM @ $\sqrt{s}$ = 8 TeV:

σ_{tot} = 101.7 ± 2.9 mb

TOTEM coll., PRL 111 (2013) 012001

Luminosity independent method, |t| > 0.01; B constant, CNI negliable, ρ external input

ATLAS & TOTEM B-slopes agree ⇒ difference normalisation

TOTEM @ $\sqrt{s}$ = 8 TeV:

σ_{tot} = 102.9 ± 2.3 mb

TOTEM coll., EPJC 76 (2016) 661

Normalisation from previous analysis, $|t| > 6 \cdot 10^{-4}$; B polynomial, CNI taken into account, ρ determined from data

Next: σ_{tot} @ $\sqrt{s}$ = 13 TeV

σ_{inel} @ LHC energies

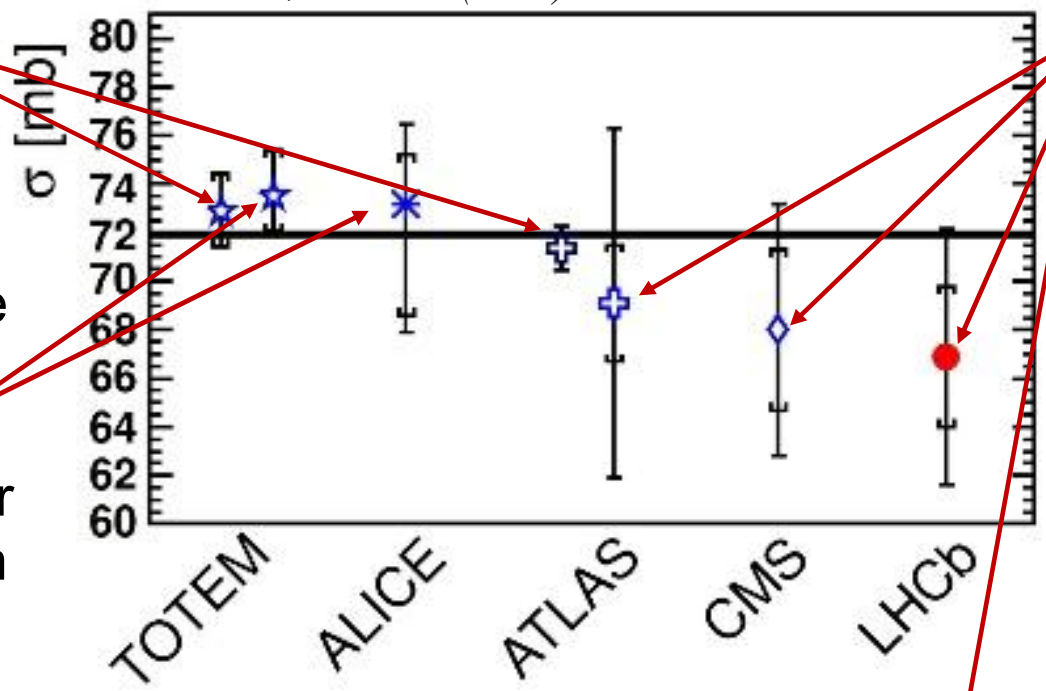
Low mass diffraction (M_{diff}) contribution? (i) resonances (ii) low mass continuum

@ $\sqrt{s}$ = 7 TeV: $\sigma_{inelastic,\ |\eta| > 6.5}$ < 6.3 mb @ 95 % CL *TOTEM coll., EPL 101 (2013) 21003*

From elastic pp scattering using optical theorem

σ_{inel} measurements @ $\sqrt{s}$ = 7 TeV:

LHCb coll., JHEP 02 (2015) 129



Visible inelastic rate + extrapolation using "average" of several MCs (not necessarily with good low M_{diff} model)

Visible inelastic rate + extrapolation using multi-Pomeron models for low mass diffraction

Shouldn't cosmic ray shower MCs with multi-Pomeron exchange be used for extrapolation ?

Shouldn't we try to measure low M_{diff} using very forward shower counters ?

σ_{inel} measurements @ $\sqrt{s}$ = 13 TeV:

ATLAS: σ_{inel} = 78.1 ± 2.9 mb

ATLAS coll., PRL 117 (2016) 182002

CMS: σ_{inel} = 71.3 ± 0.5 (exp.) ± 2.1 (lum.) ± 2.7 (ext.) mb

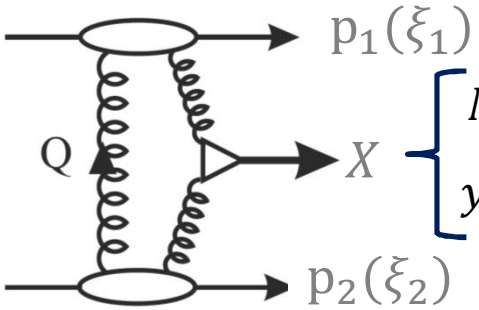
CMS-PAS-FSQ-15-005 (2016)

Central exclusive production

Physics motivations:

- study glueball candidates
- measure non-perturbative QCD effects: rapidity gap survival probability…
- study perturbative QCD: unintegrated gluon parton distributions…
- search for signs of new physics

Central Exclusive Production (CEP)



$$\begin{cases} M_X{}^2 = \xi_1 \xi_2 s \\ y_X = \frac{1}{2}\ln(\frac{\xi_1}{\xi_2}) \end{cases}$$

selection rules for system X:
$J^{PC} = 0^{++}, 2^{++}, \ldots$ (PP, gg)
$J^{PC} = 1^{--}$ (γP)

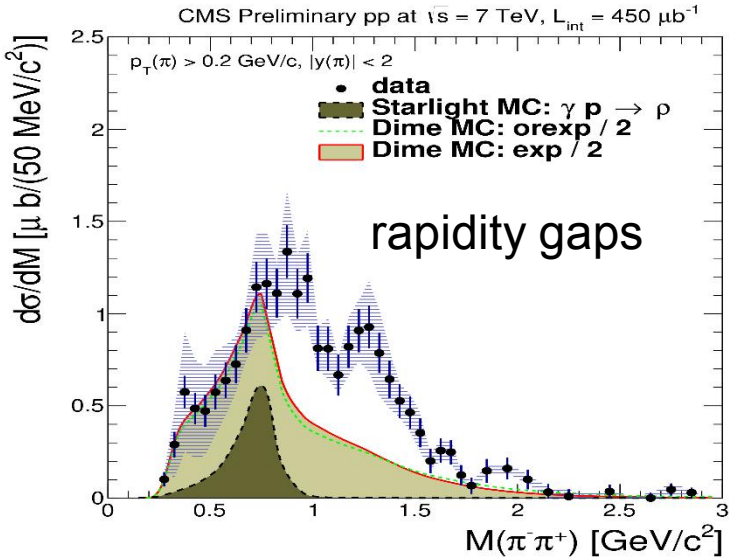
- CEP exclusivity verified by rapidity gaps or intact forward protons (p)
- Rapidity gap method: p dissociation contamination (giving only particles outside instrumented η regions) however no inefficiency due to p acceptance
- Intact proton method: require forward vs central system compatibility

M(pp) =? M(central), $p_{T,z}$(pp) =? $p_{T,z}$(central), vertex(pp) =? vertex(central)

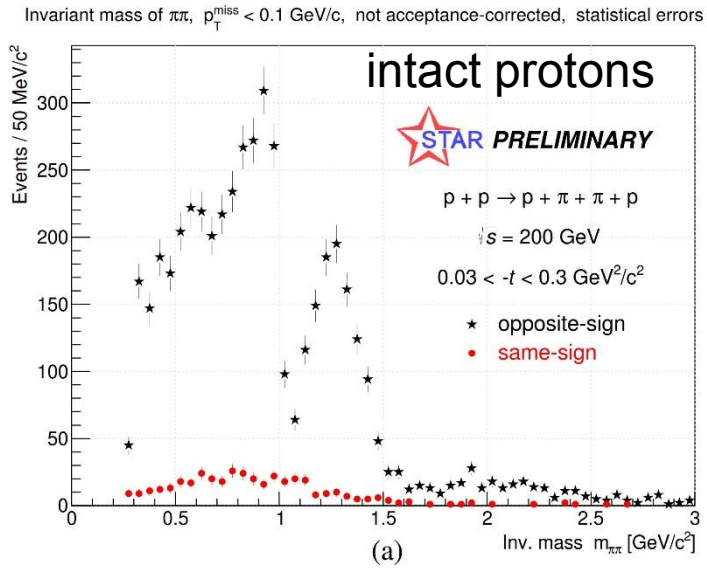
but limited p acceptance: high β^*: $|t| > 0.01$ GeV^2, low β^*: $M_X > 300$-400 GeV/c^2

Low mass exclusive $\pi^+\pi^-$ production

CMS-PAS-FSQ 12-004 (2015)



STAR coll., arXiv:1611.0723



Low mass resonance & glueball CEP

At x ~ 10^{-3} – 10^{-4} gluon overwhelms ⇒ CEP@LHC ideal for glueball production since @ LHC: CEP with M_X ~ 1 – 4 GeV produced very purely from gg

$0^{++}(2^{++})$ glueball candidates: f_0 (f_2) resonances in 1.3 -1.8 GeV(> 2 GeV) mass range

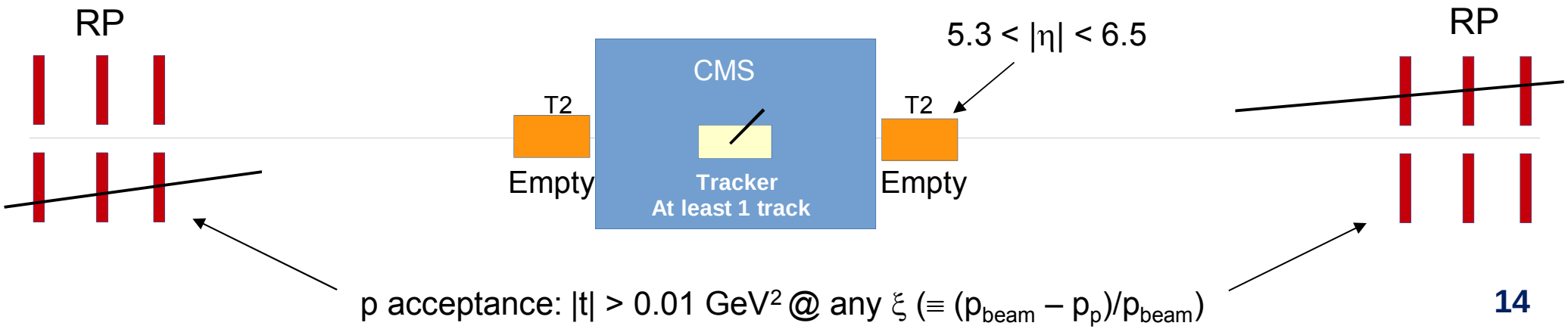
Determine σ_{CEP} of glueball candidates & characterize their decays: $\pi^+\pi^-$, K^+K^-, $\rho^0\rho^0$…

CMS+TOTEM advantages:

- ✓ Good reconstruction of charged-particle-only events using dedicated low p_T tracking
- ✓ Good particle ID & mass resolution (σ(M) ~ 30 MeV) using CMS tracker
- ✓ RP protons from TOTEM to assure exclusivity ($p_{T,RP} \sim p_{T,tracker}$, $vtx_{RP} \sim vtx_{tracker}$)

CMS+TOTEM 2015: $\mathcal{L}$ = 0.4 pb^{-1} of high β^* with dedicated low mass CEP trigger

Low mass CEP trigger: double arm RP & T2 Veto & at least 1 track in CMS tracker

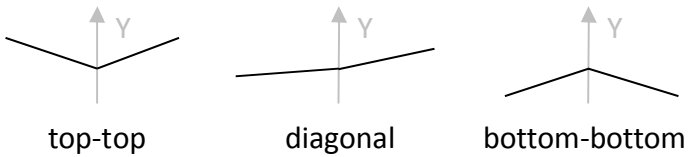


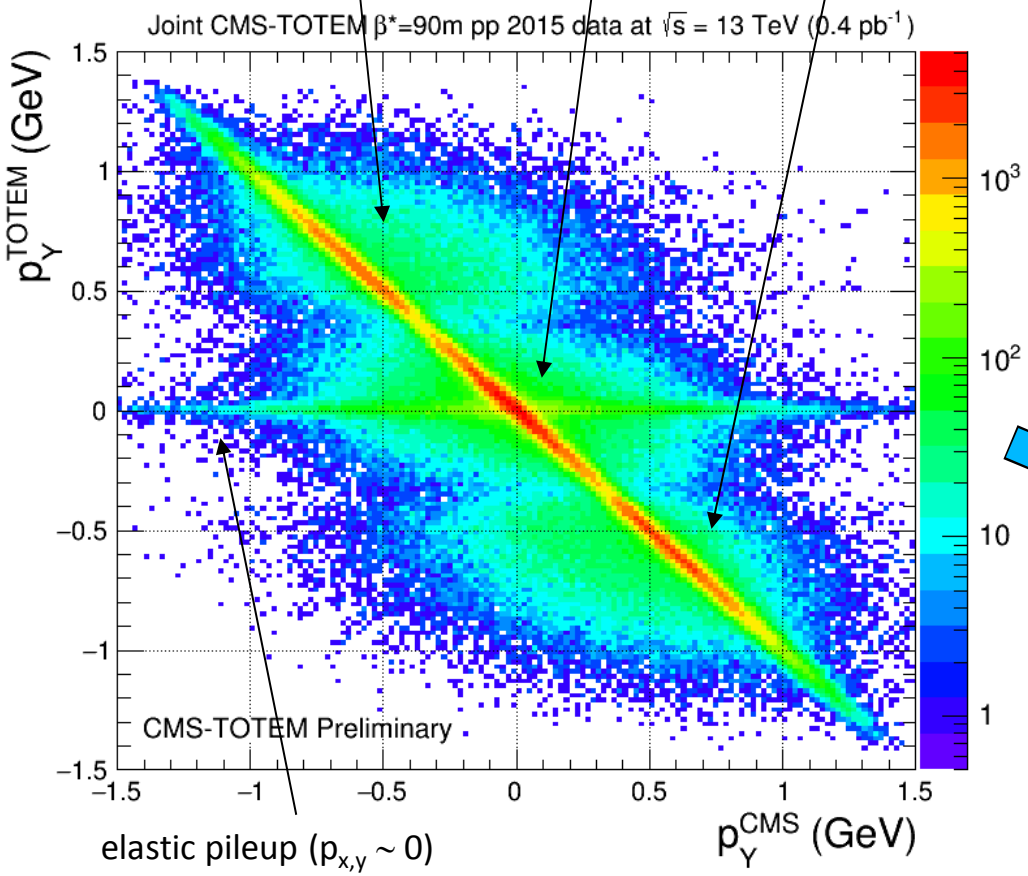
Low mass resonance CEP

$pp \rightarrow p + \pi^+\pi^- + p$ candidates

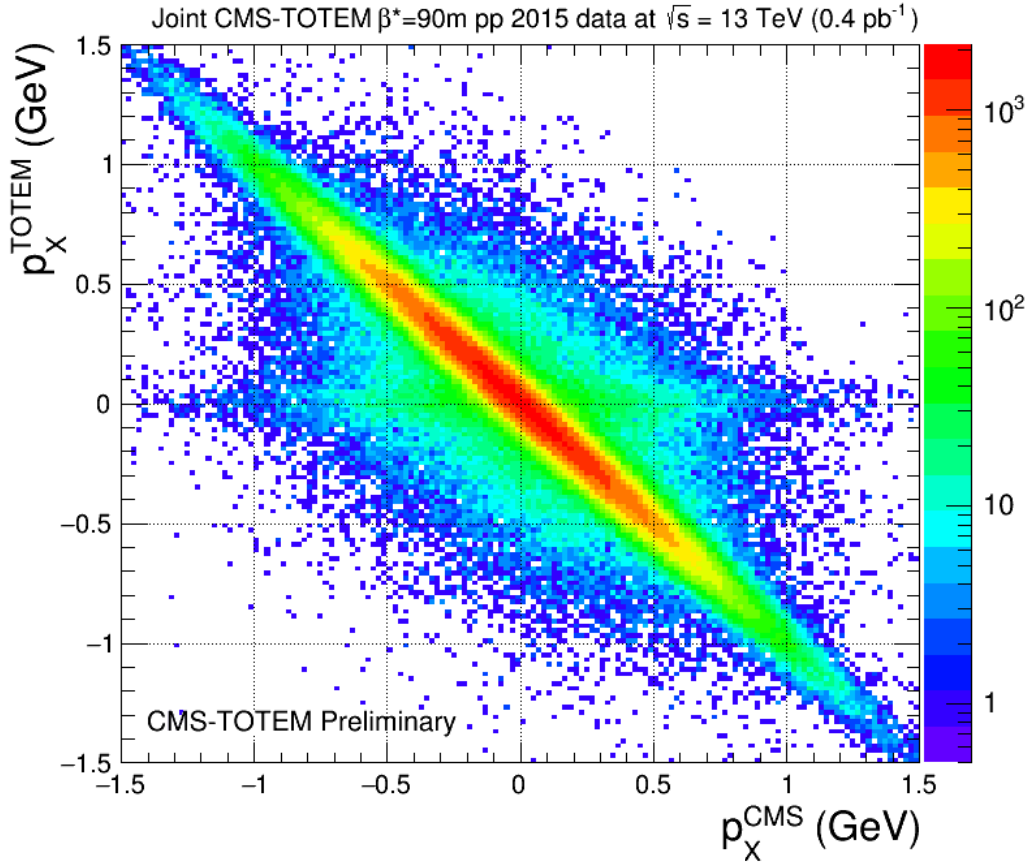
Transverse momentum sum of protons ($p_{x,y}^{TOTEM}$) vs transverse momentum sum of charged particles in tracker ($p_{x,y}^{CMS}$)

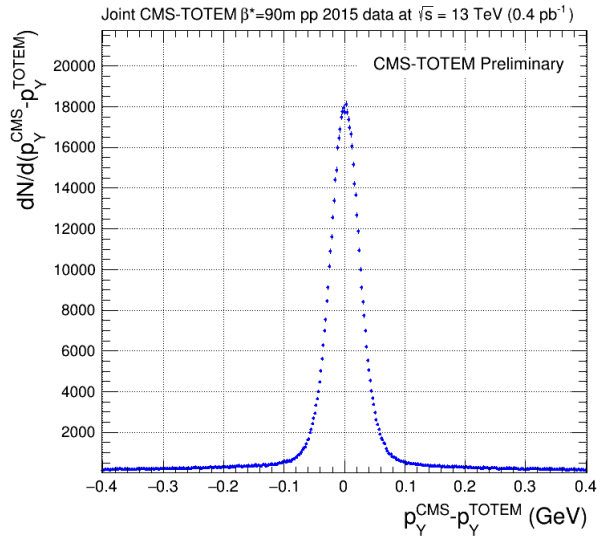
Different proton configu-rations





elastic pileup ($p_{x,y} \sim 0$)





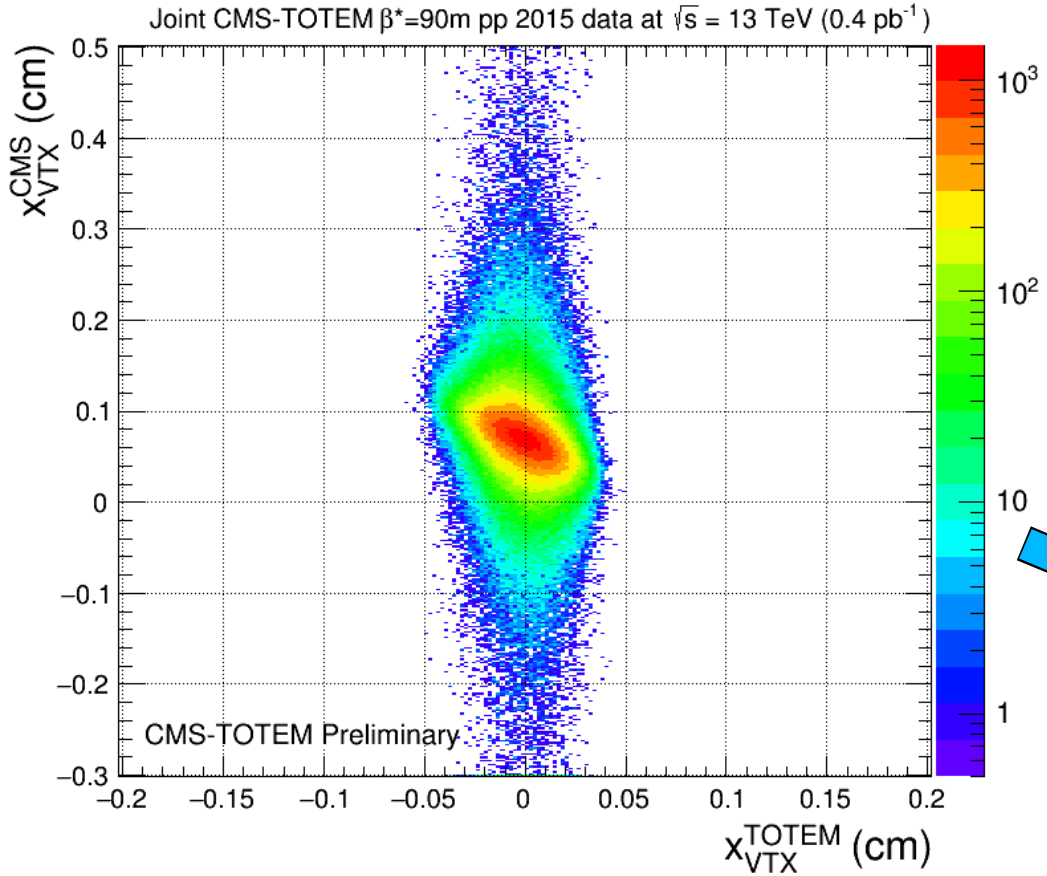
Very pure exclusive sample selected !!

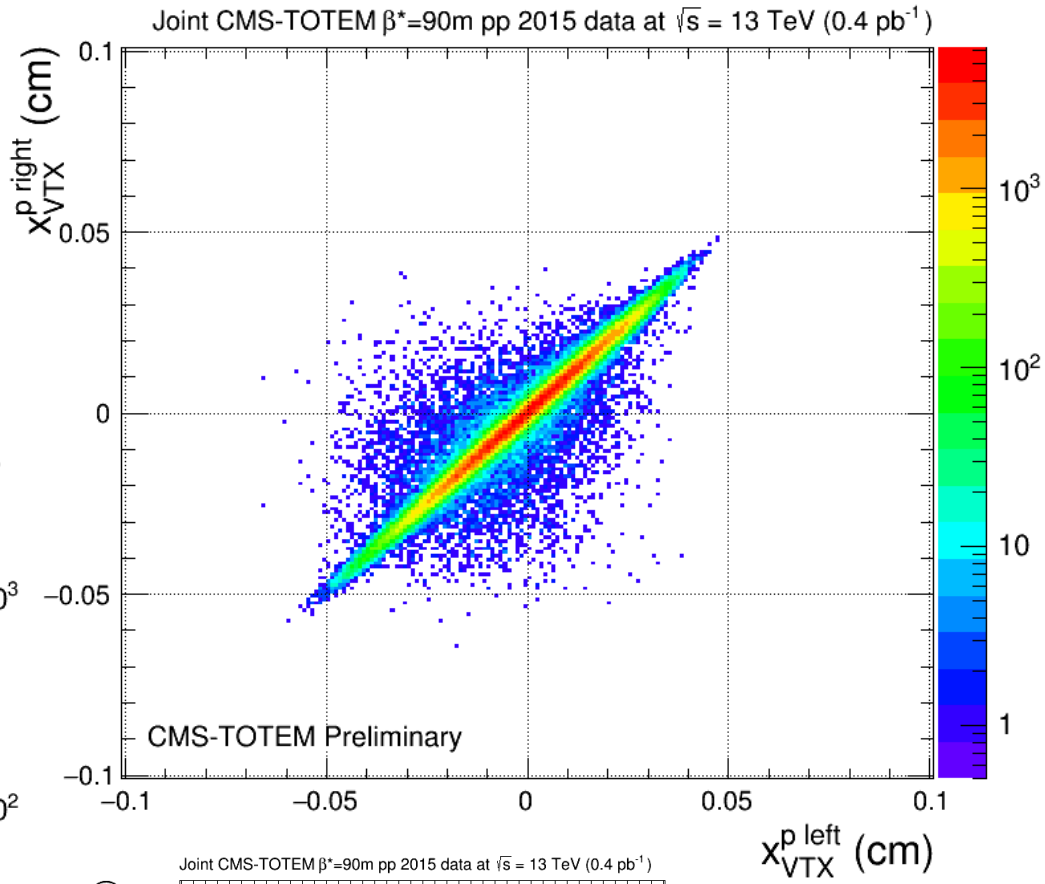
Low mass resonance CEP

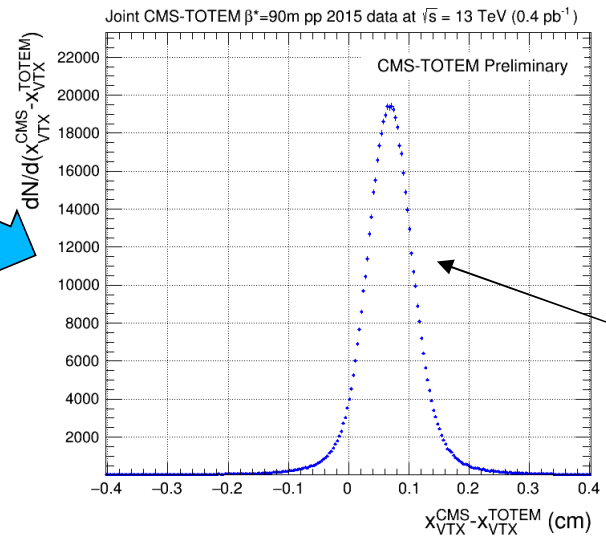
$pp \rightarrow p + \pi^+\pi^- + p$ candidates

Horizontal vertex position from tracks (x_{VTX}^{CMS}), proton left ($x_{VTX}^{p\ left}$), right ($x_{VTX}^{p\ right}$) and both protons (x_{VTX}^{TOTEM}).

no sensitivity to proton y_{VTX} due to LHC optics







Results coming ! Stay tuned !

Offset due to different CMS & TOTEM reference frames

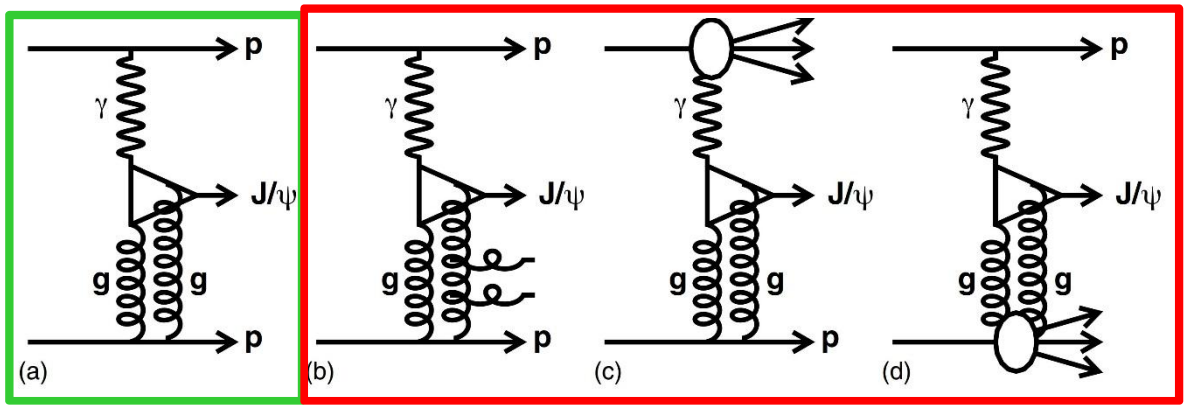
Charmonium CEP

LHCb@ √s = 13 TeV:

$pp \rightarrow p + J/\Psi\ (\rightarrow \mu^+\mu^-) + pp$

$pp \rightarrow p + \Psi(2s)\ (\rightarrow \mu^+\mu^-) + p$

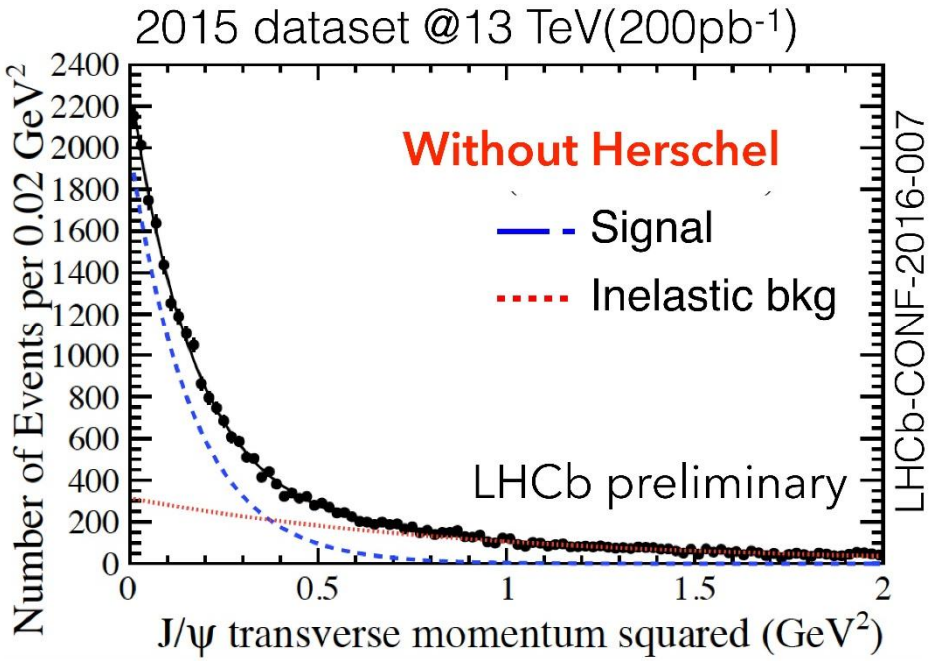
Repeat of 7 TeV analysis with an increased veto η-coverage (Herschel: ~ 5 < |η| < ~10)

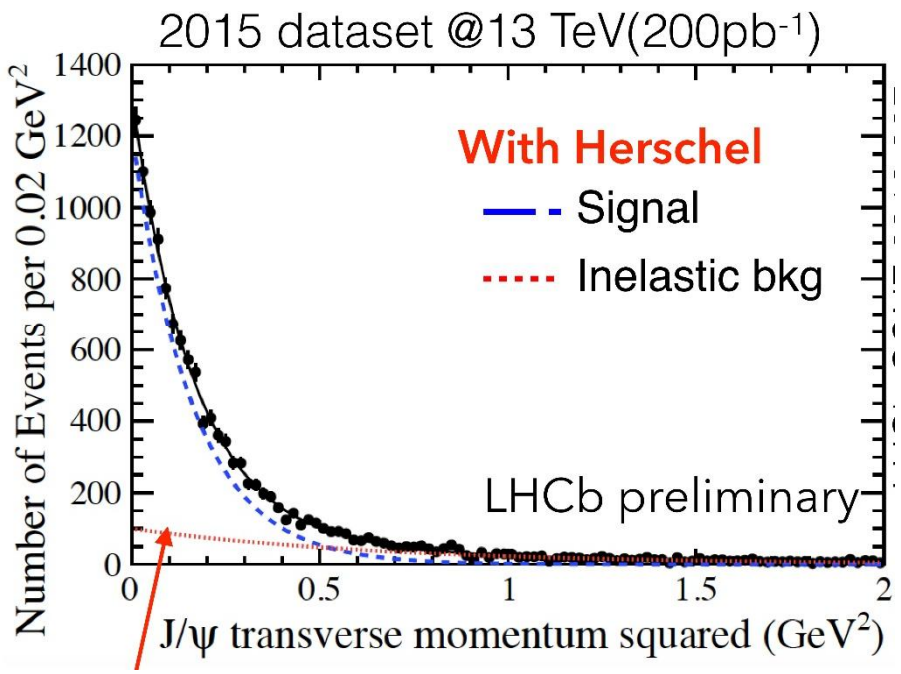


signal backgrounds

For details ⇒ see B. Rachwals talk on Tuesday

LHCb-CONF-2016-007 (2016)



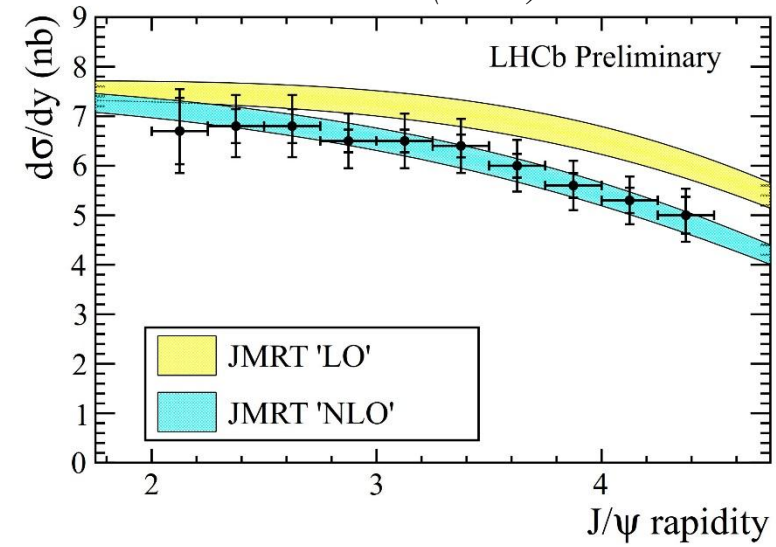


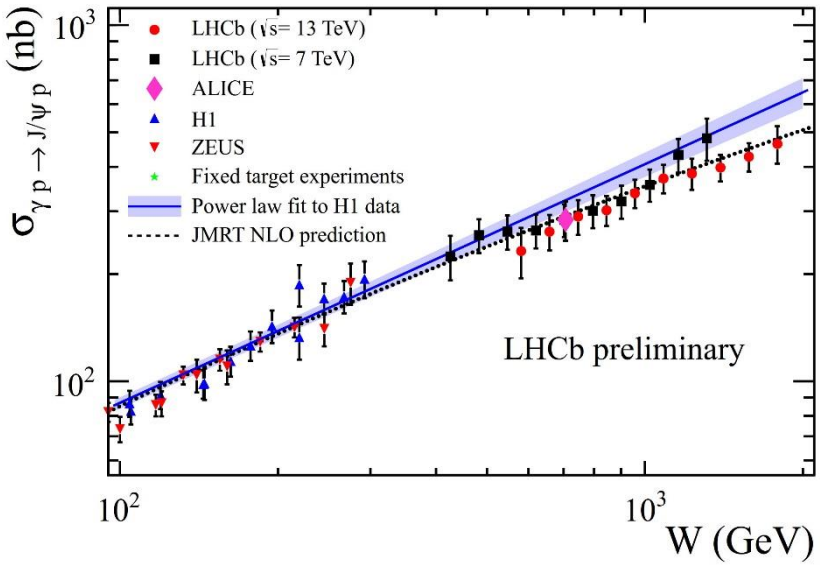
Charmonium CEP

LHCb@13 TeV: $\sigma_{J/\Psi\to\mu^+\mu^-}$ (2.0 < $\eta_{\mu^+},\eta_{\mu^-}$ < 4.5) = 407 ± 8 (stat) ± 24 (syst) ± 16 (lumi) pb

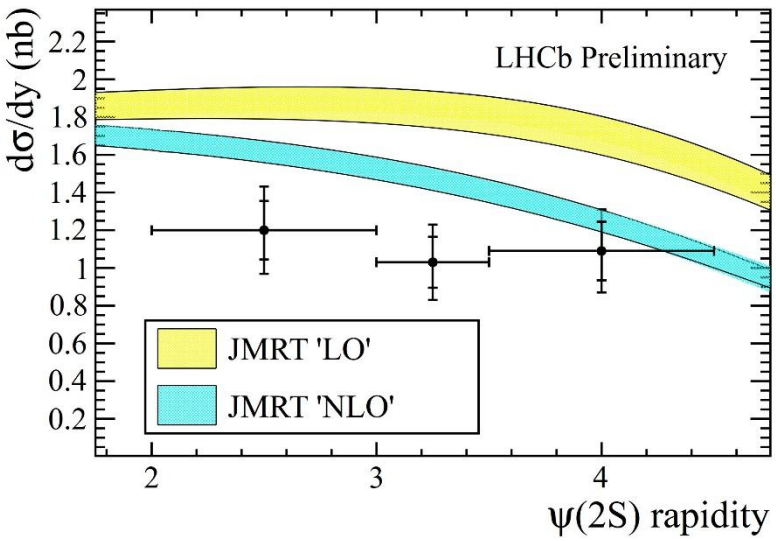
$\sigma_{\Psi(2s)\to\mu^+\mu^-}$ (2.0 < $\eta_{\mu^+},\eta_{\mu^-}$ < 4.5) = 9.4 ± 0.9 (stat) ± 0.6 (syst) ± 0.4 (lumi) pb

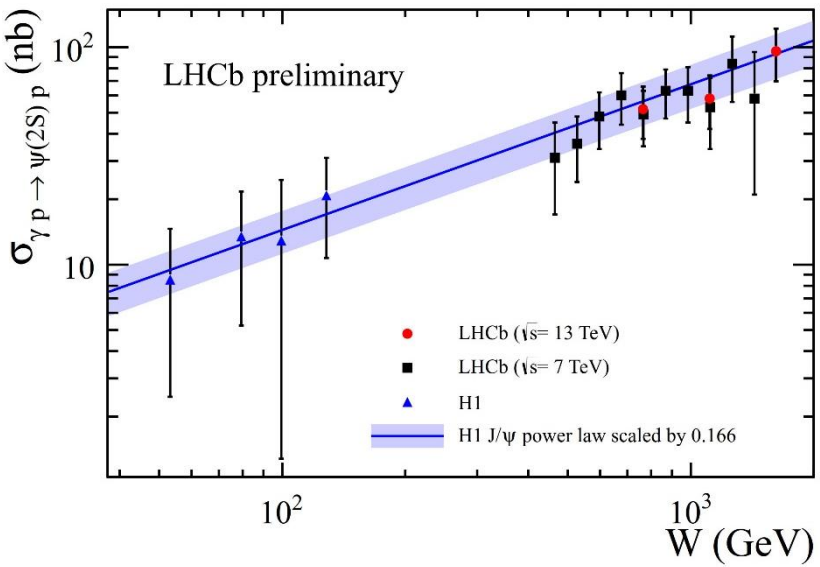
LHCb-CONF-2016-007 (2016)





Observed deviation from pure power law for J/Ψ CEP reproduced well by NLO calculation





Photon- photon collisions

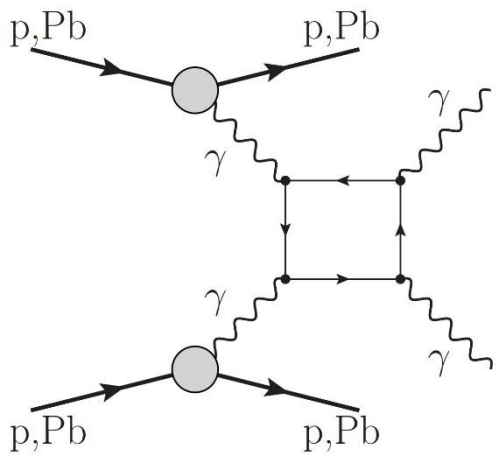
Physics motivations:

- luminosity
- anomalous gauge couplings
- searches for new physics

Photon-photon collisions

cross section for **AA (γγ)** → **AA X** process:

(i) Number of equivalent photons (EPA) by integration of relevant EM form factors:



$$n(b,\omega) = \frac{Z^2\alpha_{em}}{\pi^2\omega}\left|\int \mathrm{d}q_\perp q_\perp^2 \frac{F(Q^2)}{Q^2} J_1(bq_\perp)\right|^2$$

$$Q^2 < 1/R^2 \qquad \omega_{\max} \approx \gamma/R$$

(ii) EW **γγ** → **X** (elementary) cross section

$$\sigma^{\mathrm{EPA}}_{A_1A_2(\gamma\gamma)\to A_1A_2X} = \iint \mathrm{d}\omega_1\ \mathrm{d}\omega_2\ n_1(\omega_1)\ n_2(\omega_2)\ \sigma_{\gamma\gamma\to X}(W_{\gamma\gamma})$$

pp collisions

+ harder spectrum (ω_{max} ~ TeV)
- large pile-up
- harder to trigger on low pT objects
+ large datasets, O(40 fb^{-1})

Timely with first LHC high-lumi forward proton detector (CT-PPS & AFP) data

PbPb collisions

- softer spectrum (ω_{max} ~ 100 GeV)
+ AA (γγ) cross-sections ∝ Z^4
+ gluonic cross-sections ∝ ~A^2 (lower CEP background wrt pp)
+ lower pile-up (<1%)
- smaller data set

Exclusive (UPC) dimuons

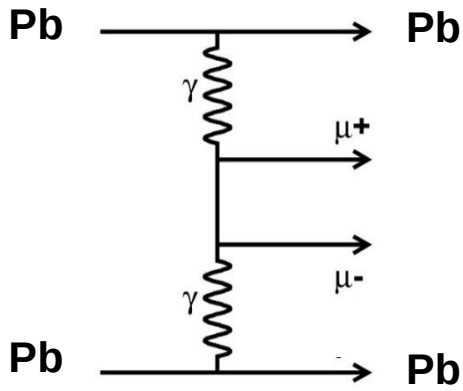
ATLAS @ $\sqrt{s_{NN}}$ = 5.02 TeV:

σ = 32.2 ± 0.3 (stat) ± 4.0 (syst) μb

STARLIGHT1.1: 31.6 μb

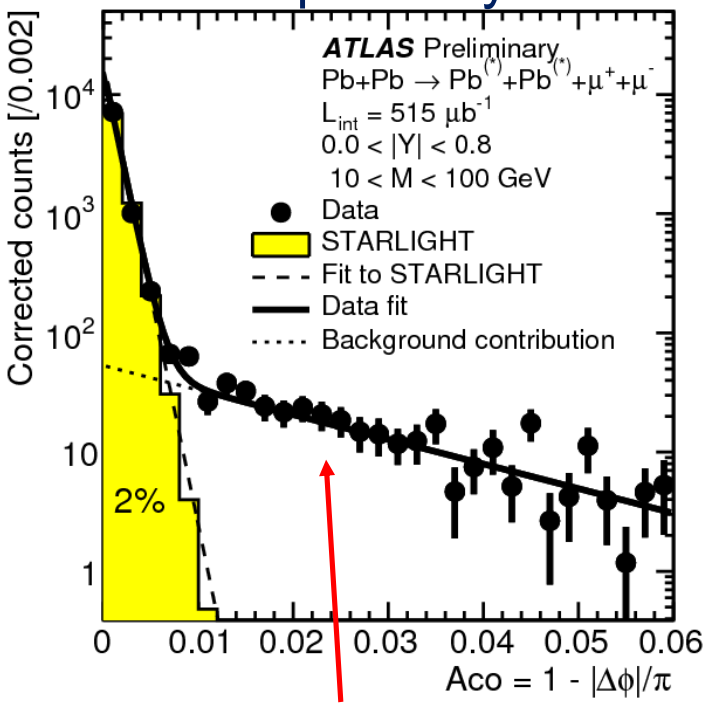
($p_{T,\mu}$ > 4 GeV, $|\eta_\mu|$ < 2.4 and $M_{\mu+\mu-}$ > 10 GeV)

ATLAS-CONF-2016-025 (2016)



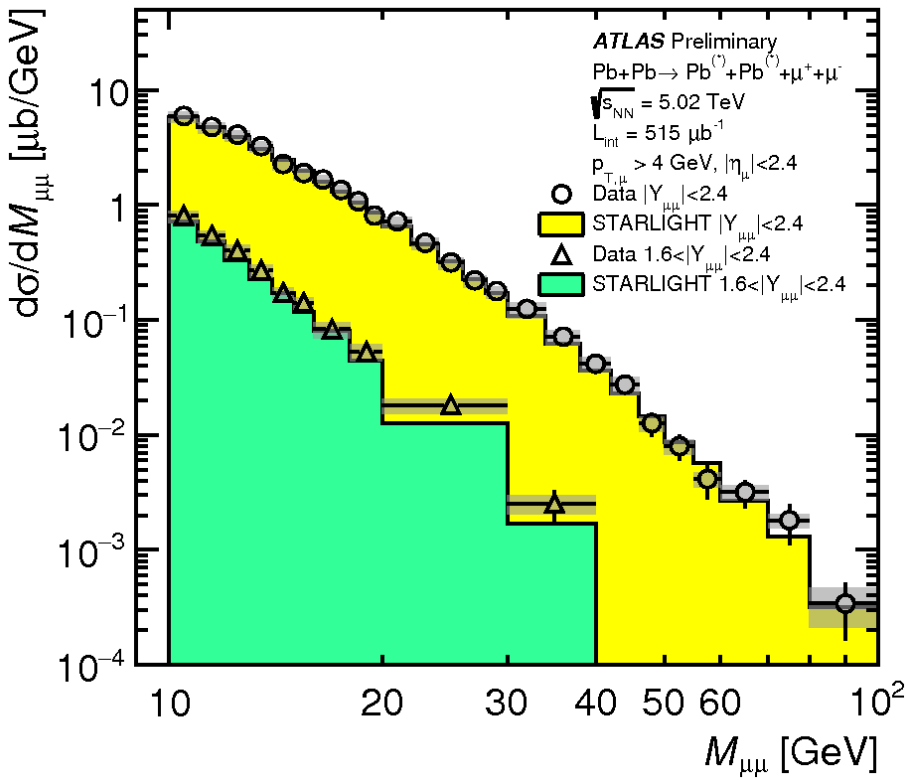
$M_{\mu+\mu-}$ & $y_{\mu+\mu-}$ agree with STARLIGHT prediction

Acoplanarity



Amount of exclusive $\mu^+\mu^-$ in tail?
(High order QED corrections)

ATLAS-CONF-2016-025 (2016)



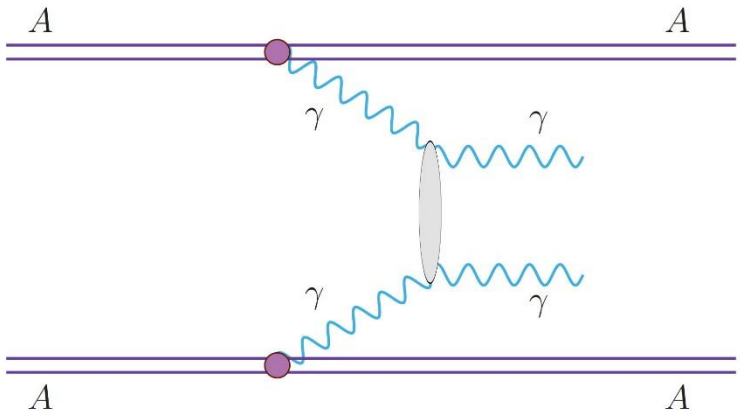
For details ⇒ see M. Guziks talk on Tuesday

Exclusive (UPC) diphotons

ATLAS @ $\sqrt{s_{NN}}$ = 5.02 TeV:

Light-by-light ($\gamma\gamma \rightarrow \gamma\gamma$) scattering:

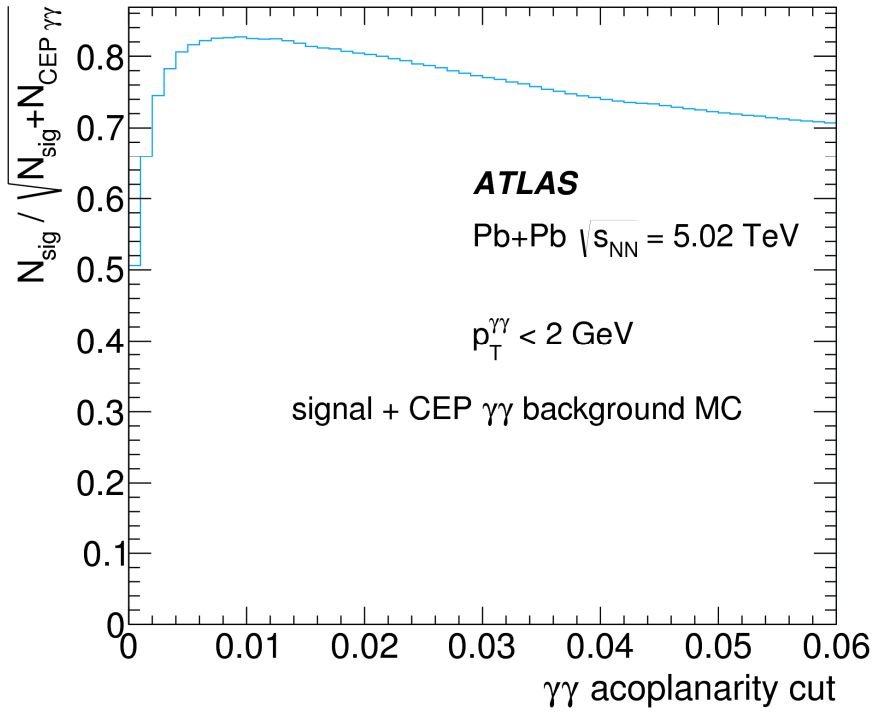
- Indirectly in measurements of electron & muon anomalous magnetic moment
- At lower energies measured in both Delbrück scattering and photon splitting
- Not observed previously in HEP



Proposed as possible channel to study

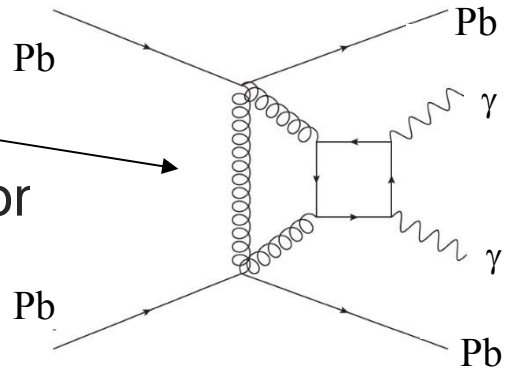
- Anomalous gauge couplings
- Contributions from BSM particles (axions etc.)

Signal significance:



Main backgrounds:

- CEP gg → γγ
- Misidentified electron from $\gamma\gamma \rightarrow e^+e^-$



Light-by-light scattering

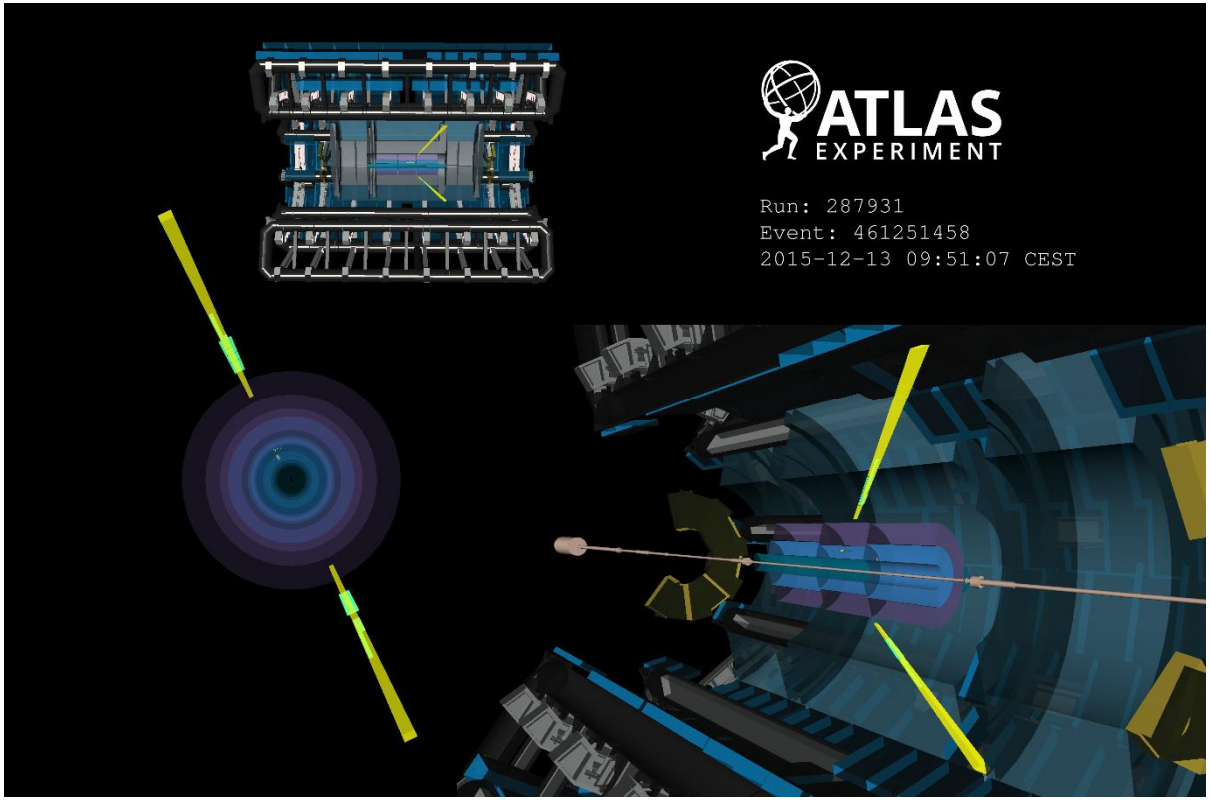
ATLAS @ $\sqrt{s_{NN}}$ = 5.02 TeV:

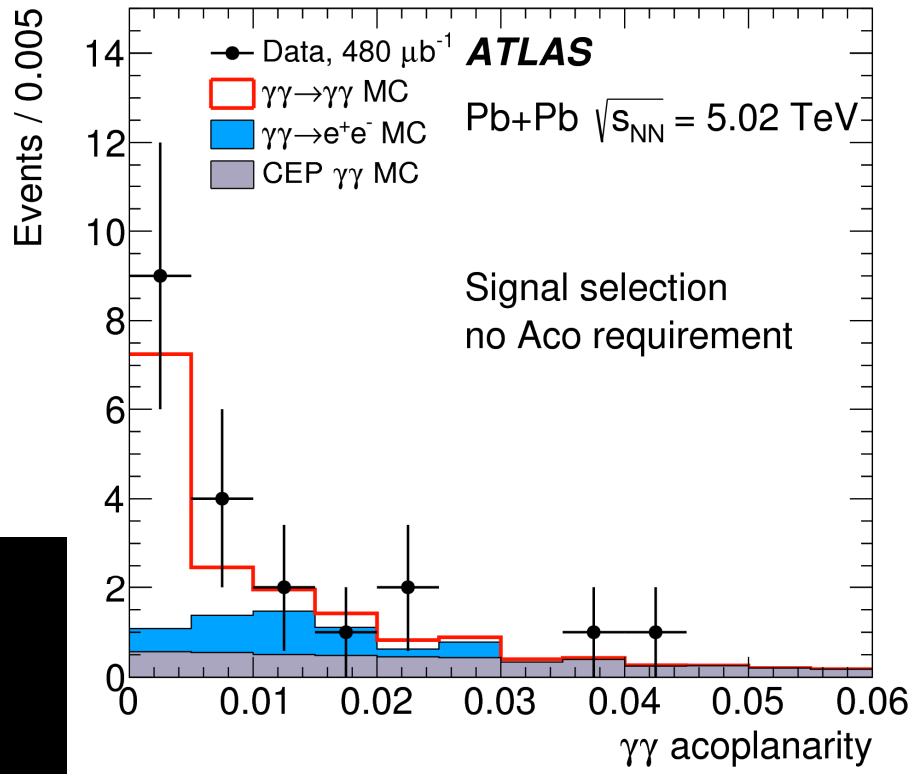
13 events (bkgd 2.6) $\Rightarrow$ 4.4σ evidence

σ = 70 ± 20 (stat) ± 17 (syst) nb

($p_{T,\gamma}$ > 3 GeV, $|\eta_\gamma|$ < 2.4, $M_{\mu^+\mu^-}$ > 6 GeV, $p_T(\gamma\gamma)$ < 2 GeV, Aco < 0.01)

ATLAS coll., ArXiv:1702.01625(2017)





SM predictions:

- 45 ± 9 nb

D. d'Enterria et al., PRL 111 (2013) 080405

- 49 ± 10 nb

A. Szczurek et al., PRC 93 (2016) 044907

For details $\Rightarrow$ see M. Guziks talk on Tuesday

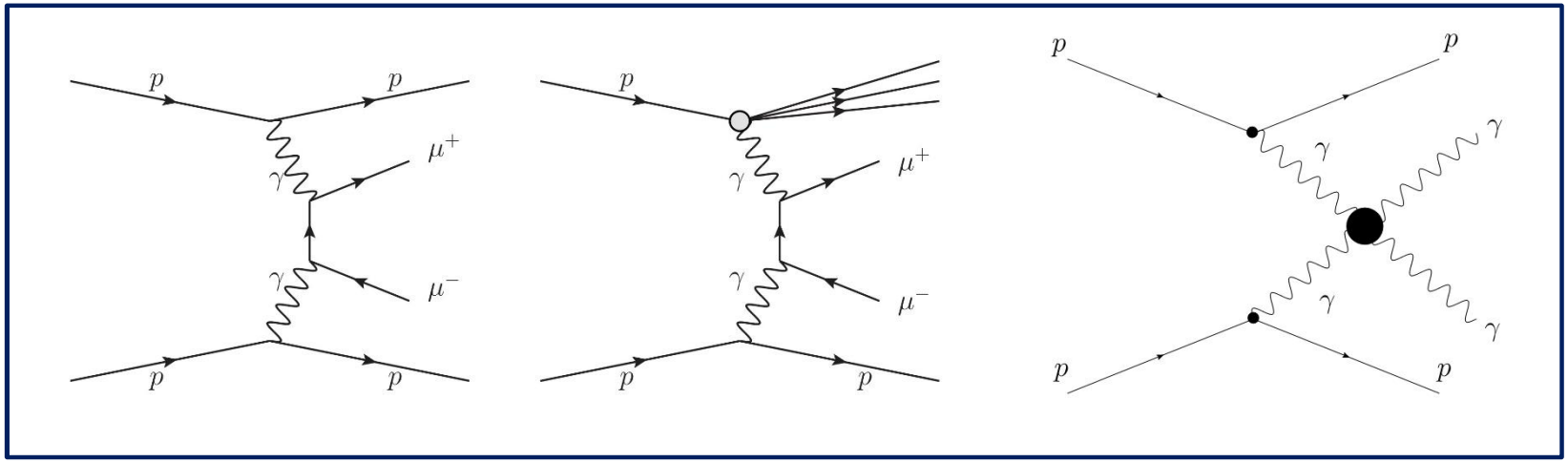
High-lumi proton detector physics

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):



Proton kinematic reconstruction:

- cross-checked using pp → p + μμ + X/p events (with only one p detected in Roman Pots)

With timing detectors:

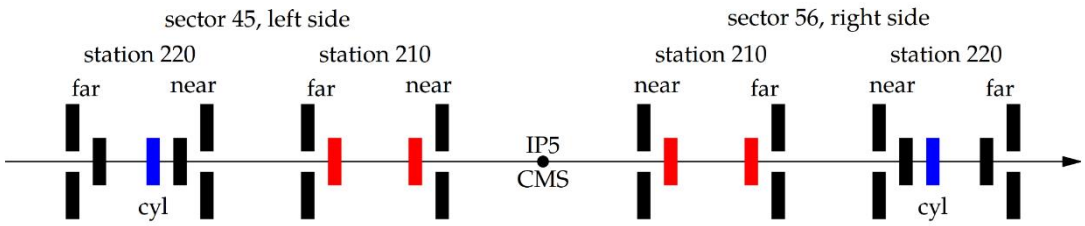
- Exclusive WW
- Exclusive dijets
- Inclusive missing mass/missing energy..

CT-PPS (CMS-TOTEM) & AFP (ATLAS) ⇒

for details see L. Forthomme's and G. Gachs talks on Tuesday

CT-PPS 2016

- Beam pockets: horizontal RPs (with RF shields or new cylindrical design)
- Tracking detectors: TOTEM Si strips (red) (2017: added Si Pixels)
- Timing detectors: TOTEM diamonds (2017: added UFSD)



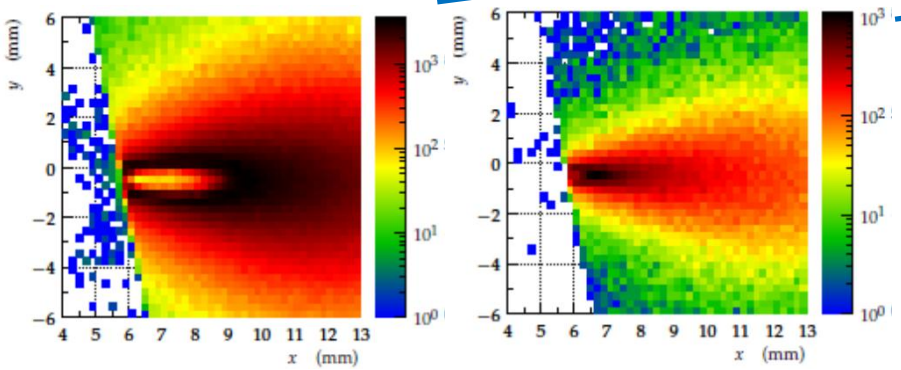
RPs at 15σ regularly in all high-lumi fills

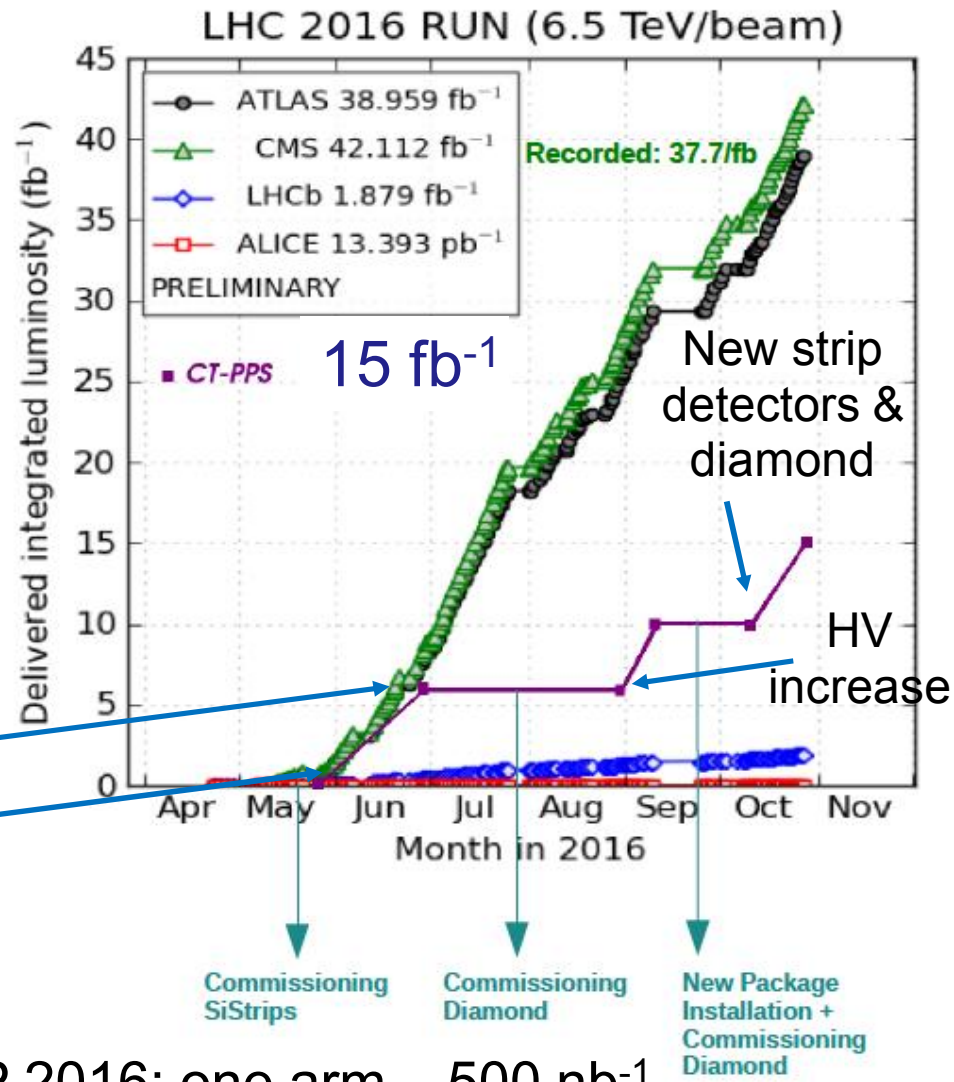
2016 luminosity with CT-PPS:

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

Si strips suffered radiation damage

e.g. in 56 210-far:





AFP 2016: one arm ~ 500 nb^{-1}

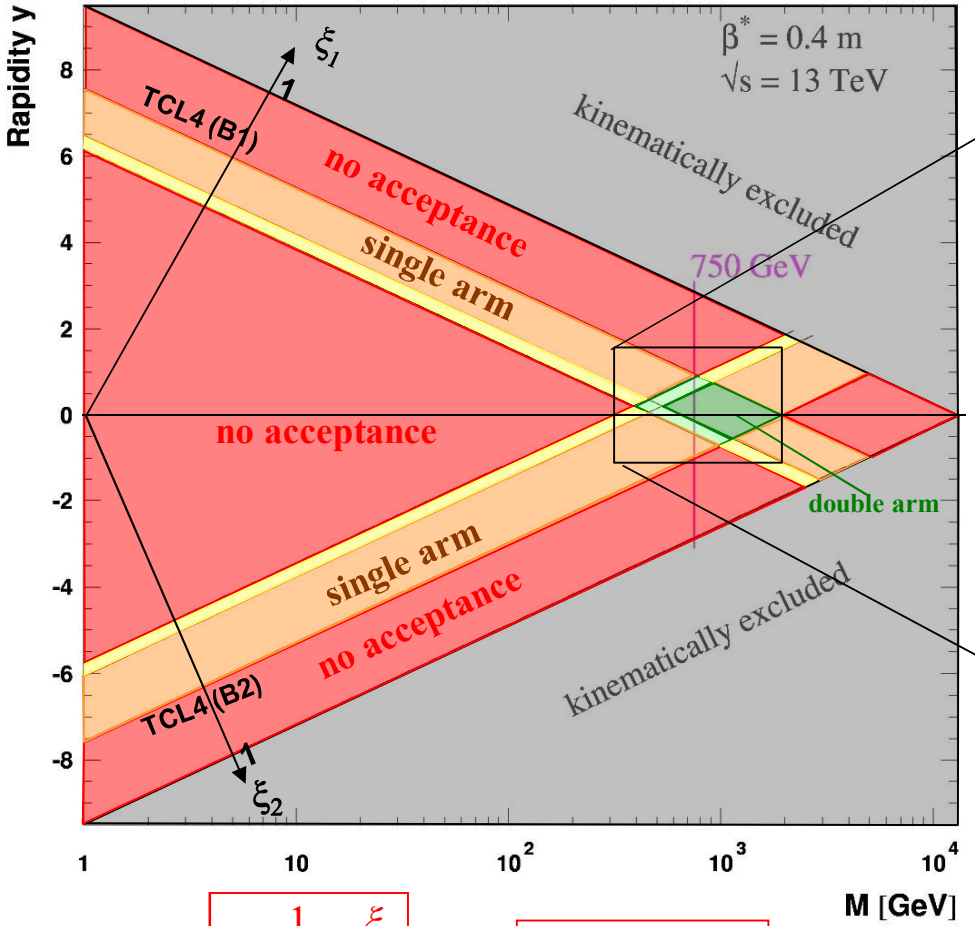
AFP 2017: both arms

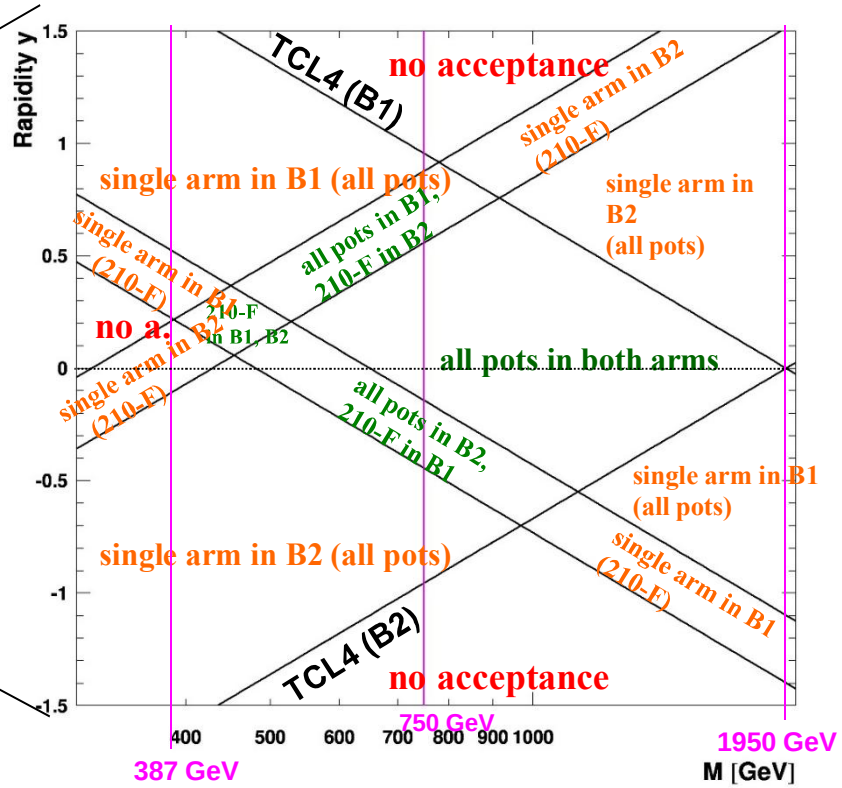
CT-PPS mass acceptance

(e.g. 2016 before TS2)

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

Using asymmetric dispersion as measured in data





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

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

Results coming ! Stay tuned !

Conclusions

- Elastic scattering: contains rich physics (not theoretically and experimentally well understood)
- Central Exclusive Production: high potential in glueball studies, (non-)perturbative QCD, new physics searches
- Photon-photon physics: new physics searches
- CT-PPS (& AFP) pave way for high mass & low cross-section CEP & photon-photon physics
- Exclusive UPC production: rich physics opening up

Examples of topics covered in parallel sessions but not here:

- AQGC from $\gamma\gamma \rightarrow$ WW (CMS)
- Exclusive Υ in pPb(CMS)
- Low x: J/Ψ and ρ photoproduction in UPC (ALICE), inclusive E spectrum in pp (CMS), underlying event with DY (CMS)

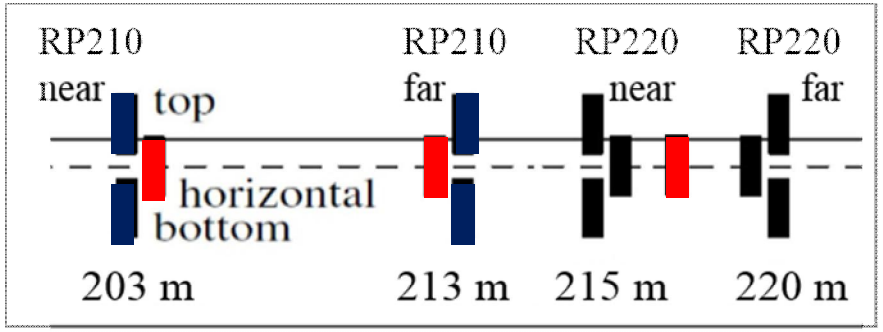
Backup

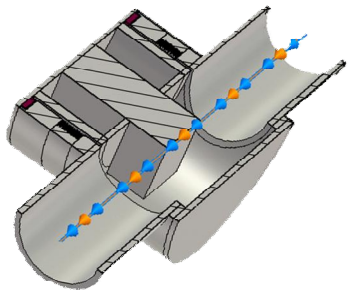
Roman Pot system 2015 →

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)

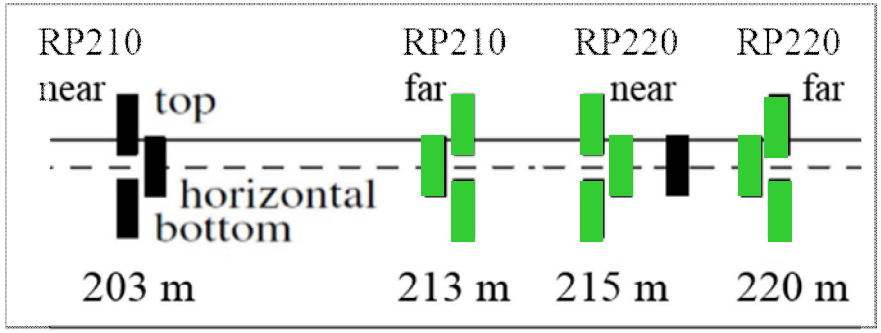


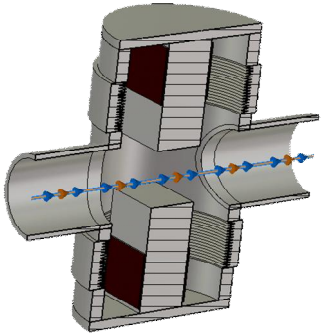


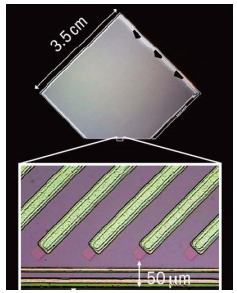
Special high β* runs (90 m, 1 km, 2.5 km):

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

2010-13 data: only RP220

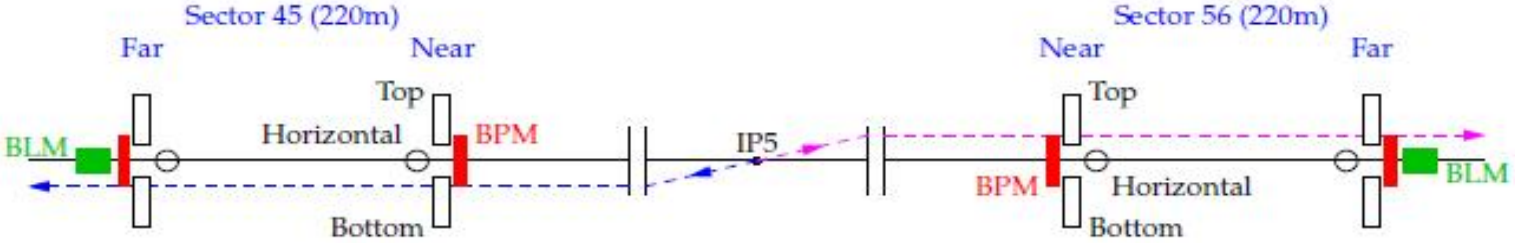






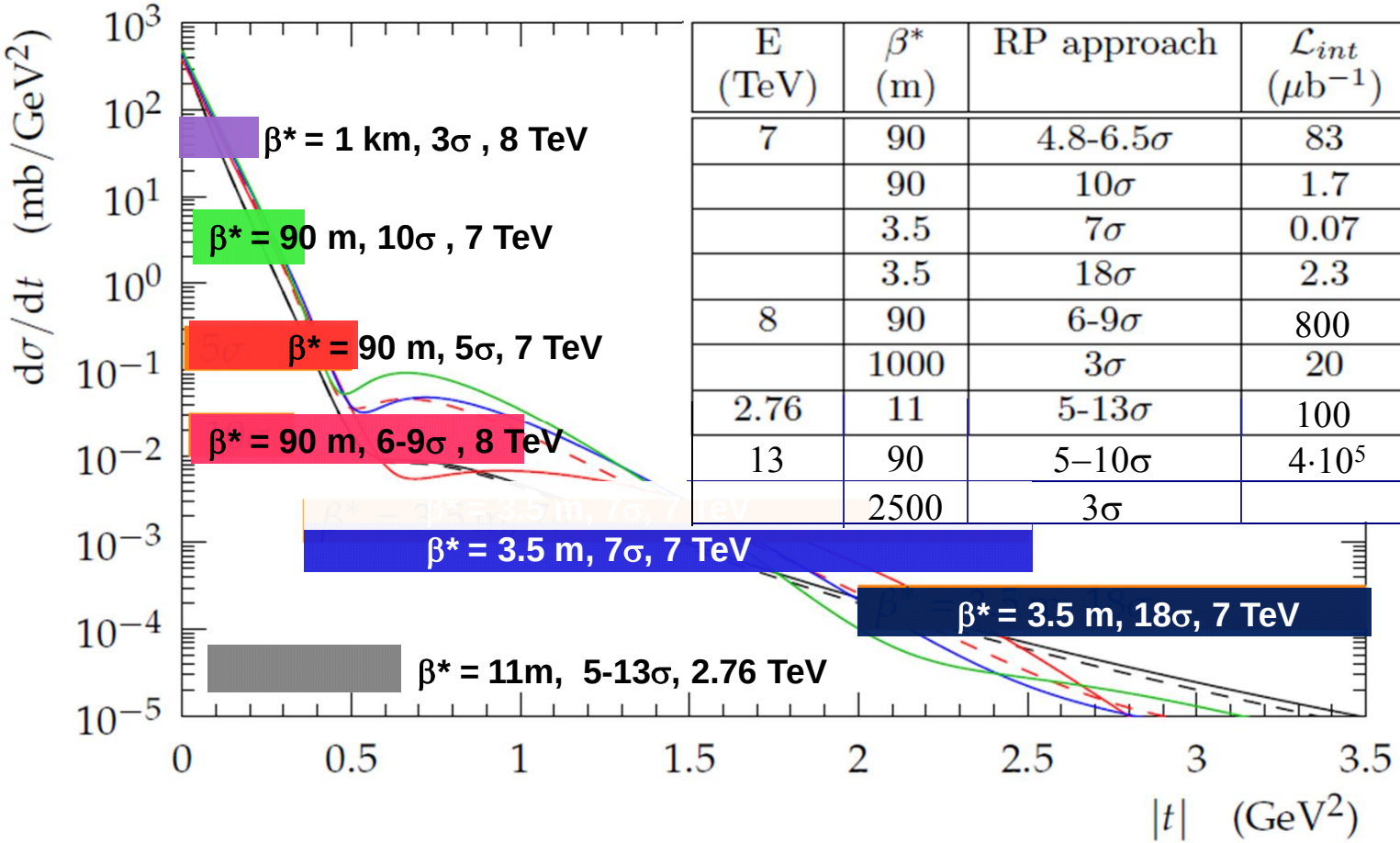
Elastic pp scattering: selection & data sets

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	$7\cdot10^{-3}$ - 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	$6\cdot10^{-4}$ - 0.2	0.4M	√
2.76	11	5-13σ	100	0.05-0.6	45k	O
13	90	5–10σ	$4\cdot10^5$	0.01 – 3.5	~ 1400M	O
	2500	3σ		$6\cdot10^{-4}$ – 0.2	~ 5M	O

√ Data published
O Analysis finished
O Analysis on-going

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

testing validity of optical theorem at ~3.5 % level

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

optical theorem & ρ independent

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

$\mathcal{L}$ 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

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

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

Coulomb-hadronic interference – analysis strategy

Central question:

Observed non-exponentiality due to hadronic Coulomb or both

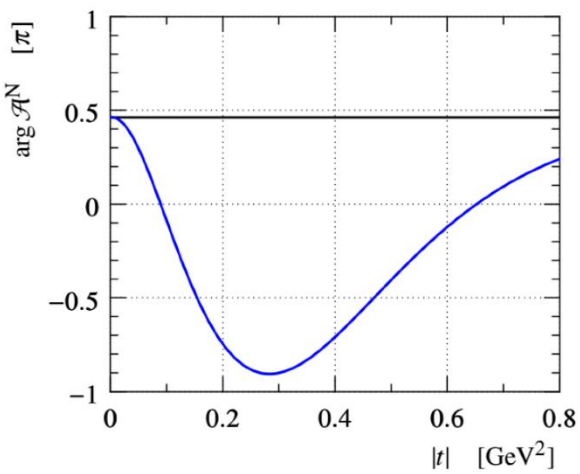
- fits with 2 different assumptions on hadronic amplitude
  - purely-exponential – non-exponentiality due to Coulomb (& interference)

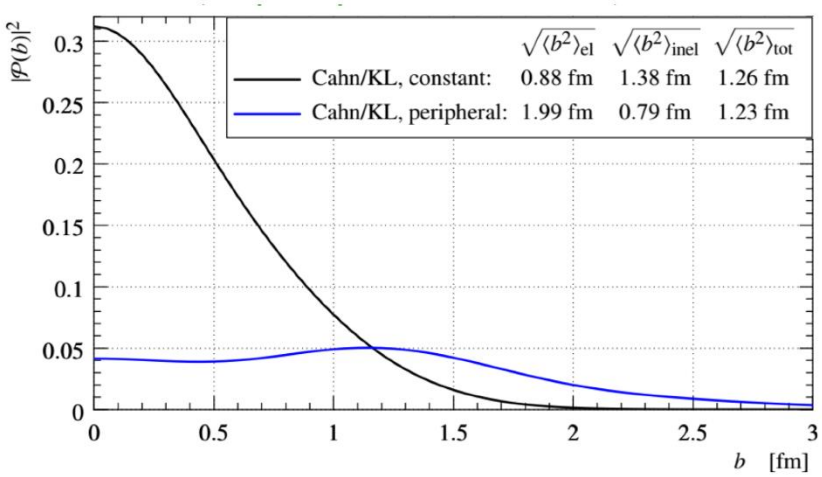
$$\Rightarrow |F^{\mathrm{H}}| = \mathrm{a}\ \exp\,(\mathrm{b}_1 \mathrm{t})$$

  - flexible enough to describe non-exponentiality even without Coulomb

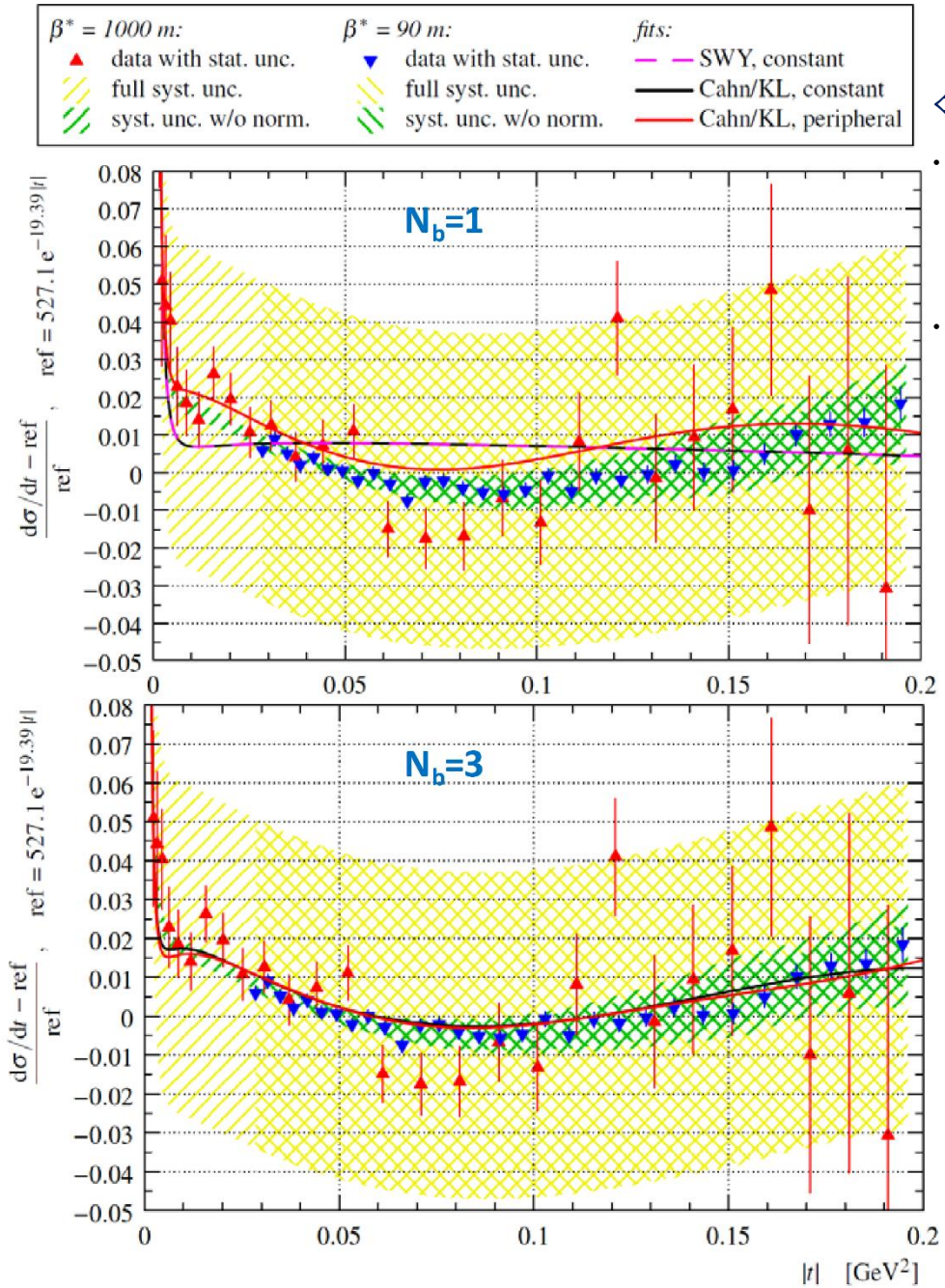
$$\Rightarrow |F^{\mathrm{H}}| = \mathrm{a}\ \exp\,(\mathrm{b}_1 \mathrm{t} + \mathrm{b}_2 \mathrm{t}^2 + \mathrm{b}_3 \mathrm{t}^3)$$

- 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

TOTEM collaboration, EPJC 76 (2016) 661