Diffraction, elastic scattering at LHC

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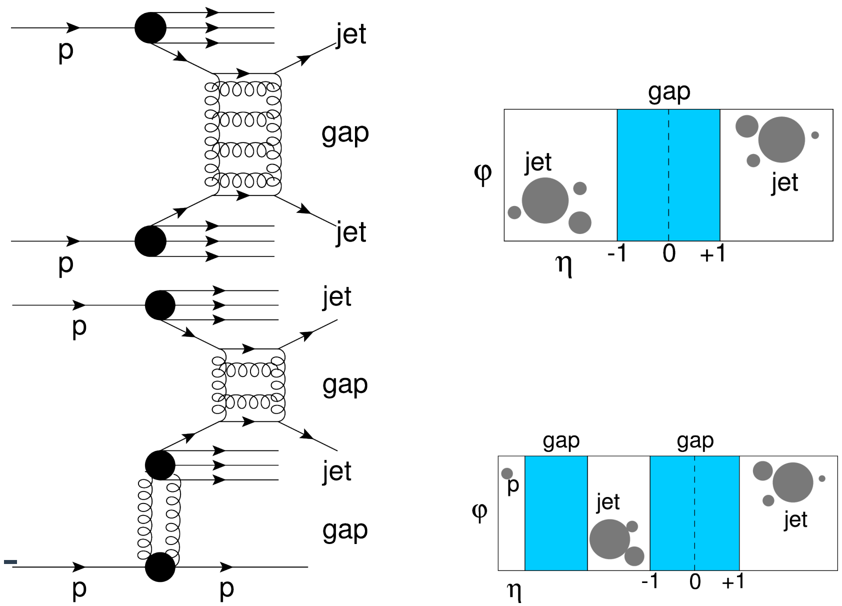
on behalf of ATLAS, CMS and LHCb Collaborations

May 22-26 2023

Diffraction at the LHC

- **Jet-gap-jet events**
- **Photon-induced processes:**
  - *WW / ZZ* (quartic anomalous couplings)
  - $\gamma\gamma \rightarrow \gamma\gamma$
    - Axion-like particles (ALPs)
    - Quartic photon anomalous couplings
  - $Z/\gamma+X$
  - Central exclusive production (CEP) of $t\bar{t}$
  - Coherent charmonium production in ultra-peripheral PbPb collisions (PbPb UPC)
- **Pion pair production**
- **Total cross section measurements**
  - ϱ-parameter
  - Nuclear slope

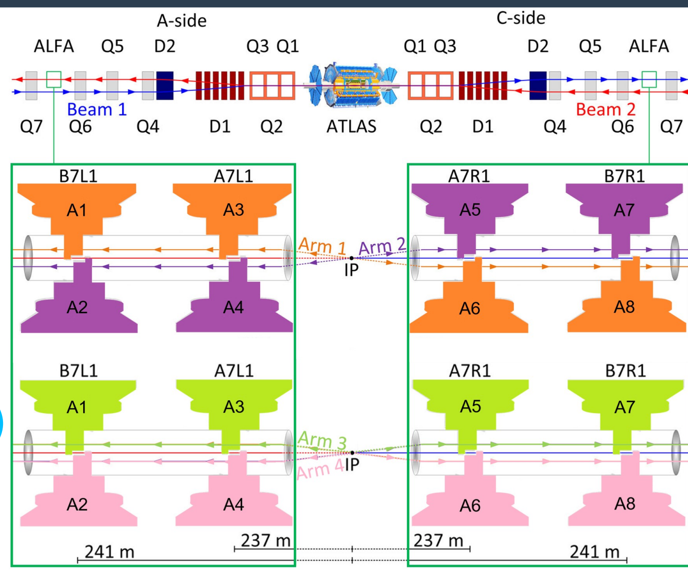
(CMS, SMP-19-006)



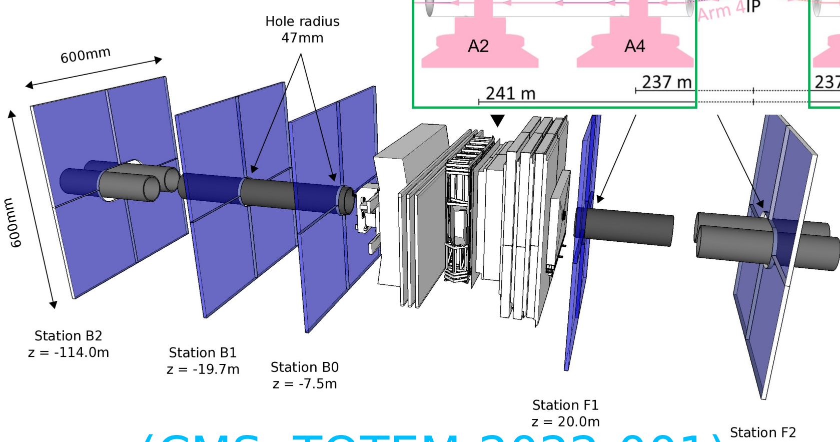
Generally *pp*, $\sqrt{s}$ = 13 TeV (indicated, where different)

Experiments in scope

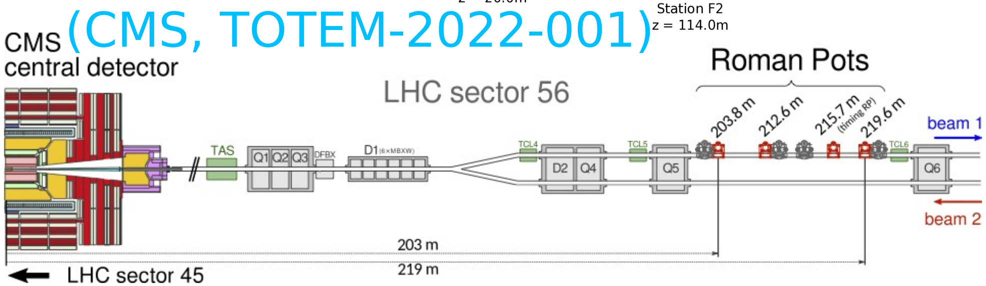
(ATLAS, STDM-2017-07)



(cds/cern.ch/record/2300319)



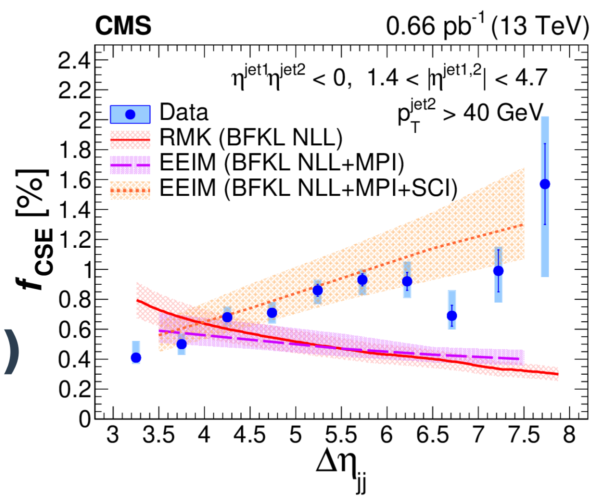
(CMS, TOTEM-2022-001)

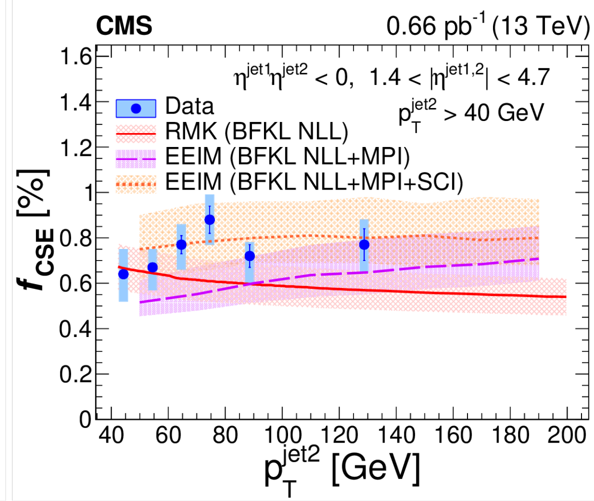


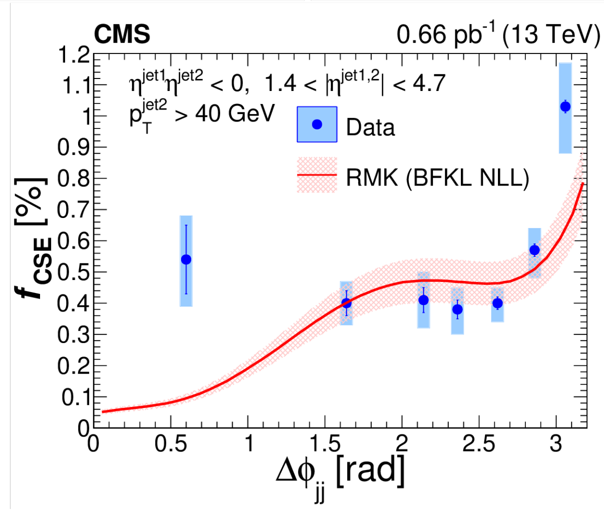
- **ATLAS**
  - ATLAS Forward Detectors (AFP)
  - ALFA
- **CMS**
  - Roman pots (RPs)
    - TOTEM
    - Precision Proton Spectrometer (PPS)
- **LHCb**

Jet-gap-jet events in diffraction I.

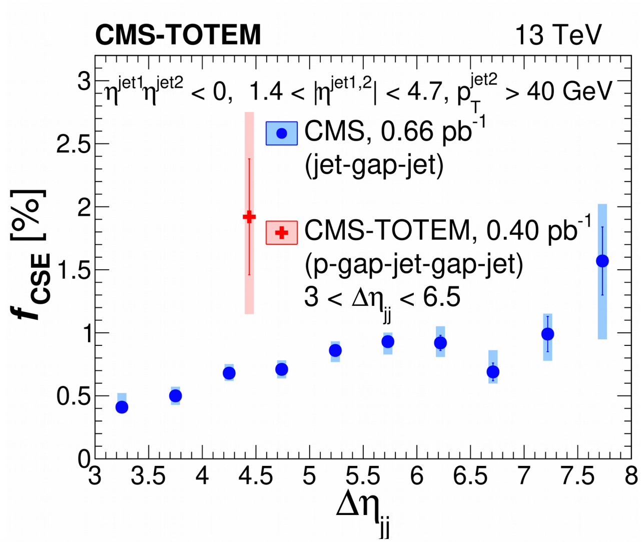
- **Searching for rapidity gap between the two jets:**
  - $p_T^{jet} > 40$ GeV, $\eta^{jet1}\eta^{jet2} < 0$, $1.4 < |\eta^{jet}| < 4.7$
- **Exchange of a Balitsky–Fadin–Kuraev–Lipatov (BFKL) Pomeron between jets:**
  - Hard color-singlet exchange
  - Two-gluon exchange in order to neutralize color flow
- **Comparison with BFKL NLL (with LO impact factors) as implemented in PYTHIA**
  - Fraction of jet-gap-jet events:
    $f_{CSE} = (N^{\#track<3} - N^{\#track<3}{}_{ULE}) / N^{tot}{}_{dijet}$
- **Soft color interaction based models**

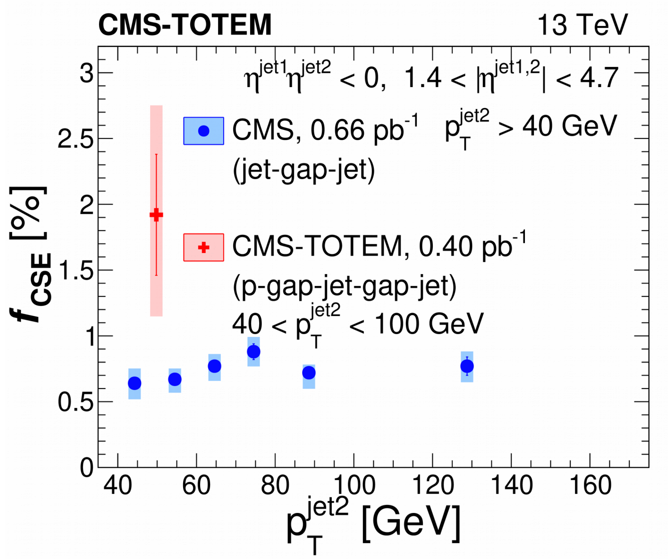






Jet-gap-jet events in diffraction II.



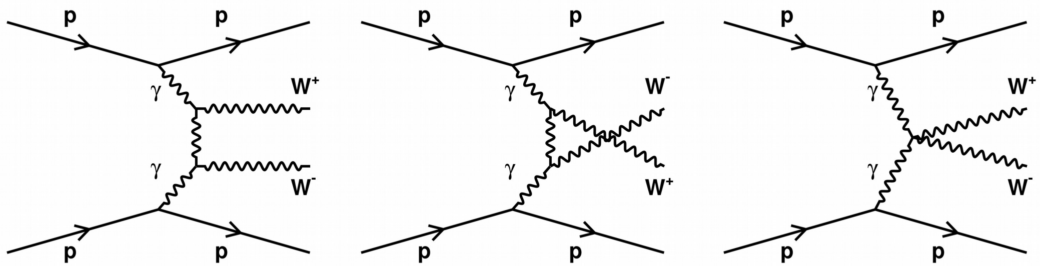


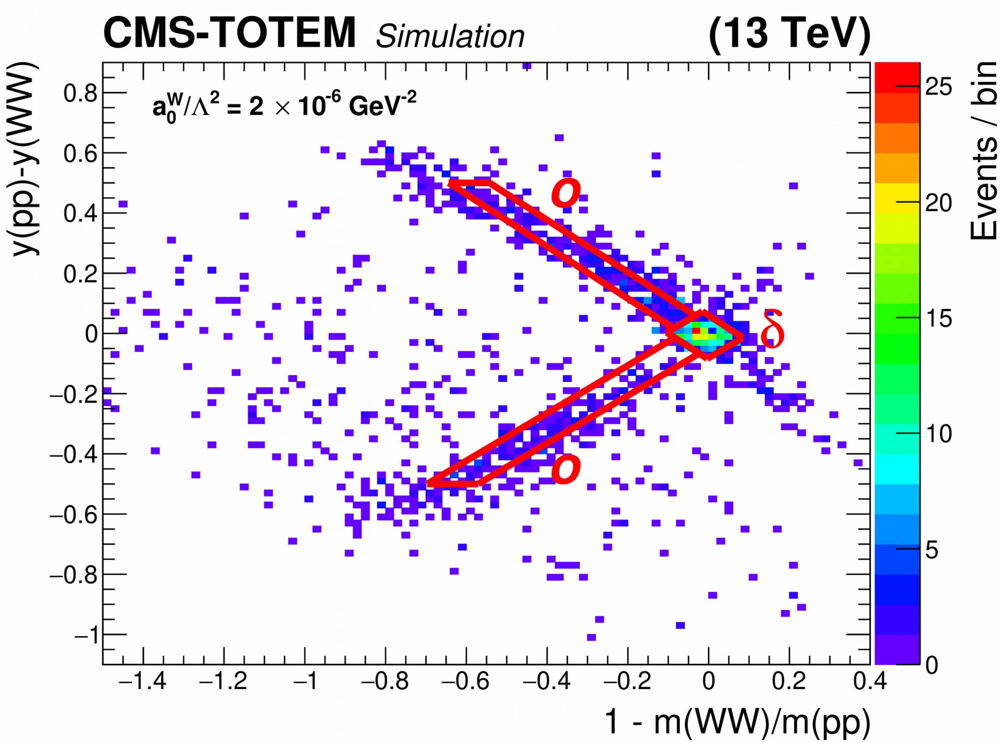
- **Powerful test of BFKL resummation**
- **Subsample requesting in addition at least one intact proton on either side of CMS: proton-gap-jet-gap-jet**

- **First observation (CMS): 11 events**
  - Minimum one proton tagged with ~0.7 pb^{-1}
- **Very clean events**
  - Since mutiple-parton interactions are suppressed
  - Might be the “ideal” way to probe BFKL
- ***f_{CSE}* extracted: ~3x larger than that of in the inclusive case**

Exclusive production of *W/Z* pairs I.

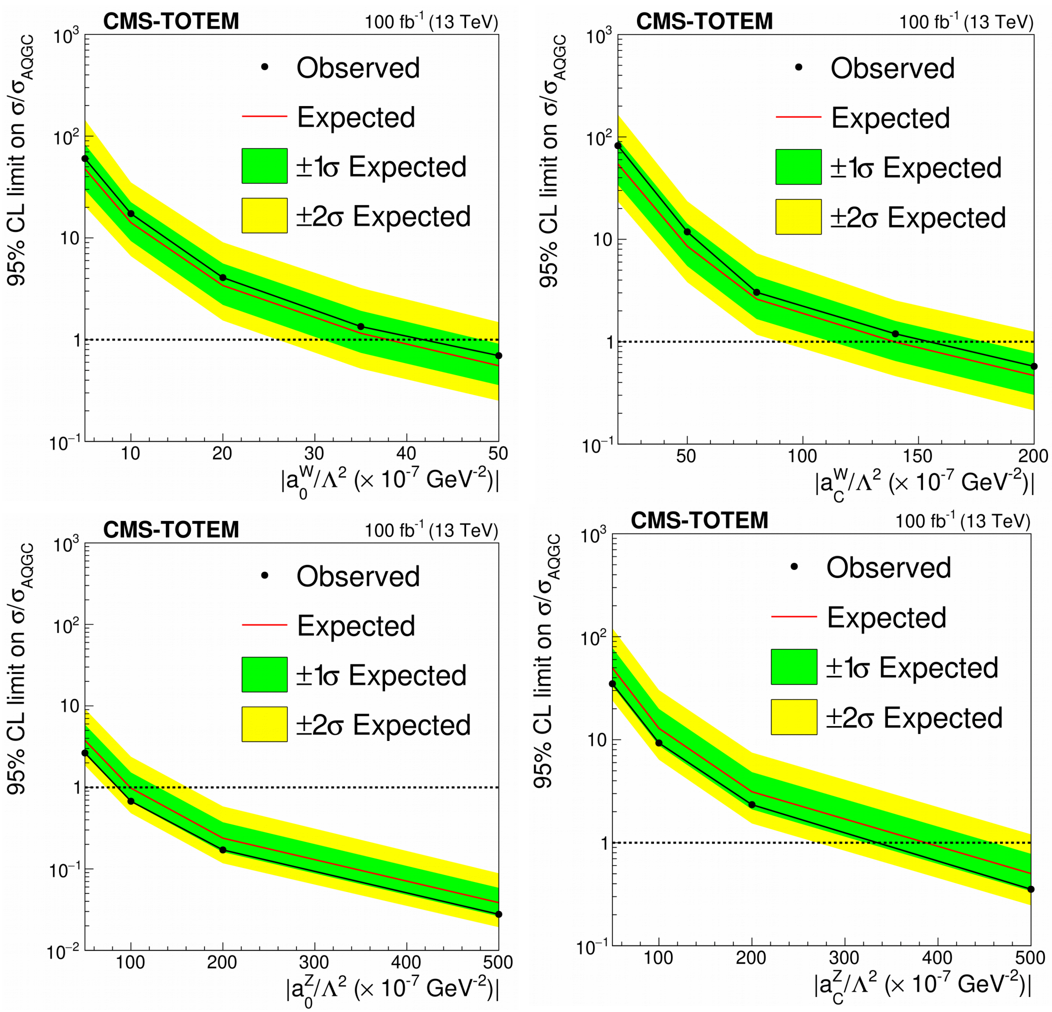
- **Search with fully hadronic decays**
  - 2 jets back-to-back ($|1 - \phi_{jj}/\pi| < 0.01$ $R = 0.8$, jet $p_T > 200$ GeV, 1126 GeV $< m_{jj}$
- **Signal region defined by the correlation between the *WW / ZZ* system (invariant mass & rapidity) and tagged proton information**
  - If *WW / ZZ* produced with large boost (many BSM scenarios): merged (single-area) jet
  - Highest branching fraction for fully hadronic decays, but without proton tagging: inaccessible mode (large QCD background, pileup)





arXiv: 2211.16320 (CMS, SMP-21-014)

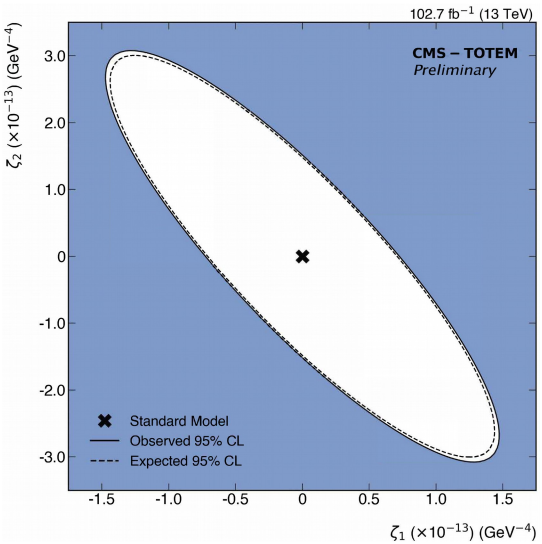
Exclusive production of *W/Z* pairs II.

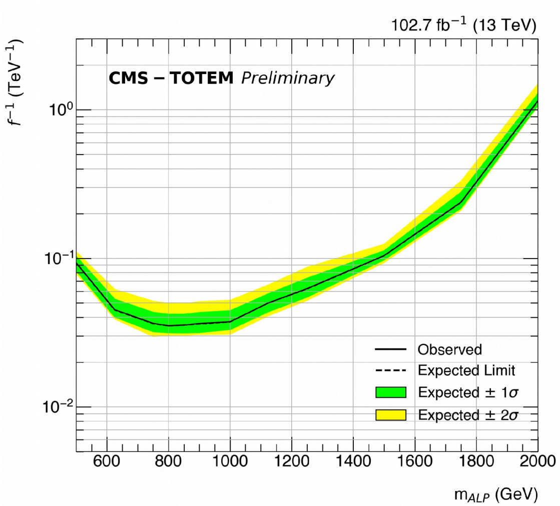


- **Limits on SM cross section for $0.04 < \xi < 0.2$, *m(VV)* > 1 TeV:**
  - (Fractional momentum loss: $\xi = \Delta p / p$ = horizontal displacement / horizontal dispersion)
  - $\sigma_{WW} < 67$ fb
  - $\sigma_{ZZ} < 43$ fb
- **New limits on quartic anomalous couplings:**
  - $a_0^W / \Lambda^2 < 4.3 \cdot 10^{-6}$ GeV^{-2}
  - $a_C^W / \Lambda^2 < 1.6 \cdot 10^{-5}$ GeV^{-2}
  - $a_0^Z / \Lambda^2 < 0.9 \cdot 10^{-5}$ GeV^{-2}
  - $a_C^Z / \Lambda^2 < 4.0 \cdot 10^{-5}$ GeV^{-2}
- **This means better constrains wrt analyses without proton tagging for the *W* case**
- **First obtained values in *Z* case from the exclusive channel**

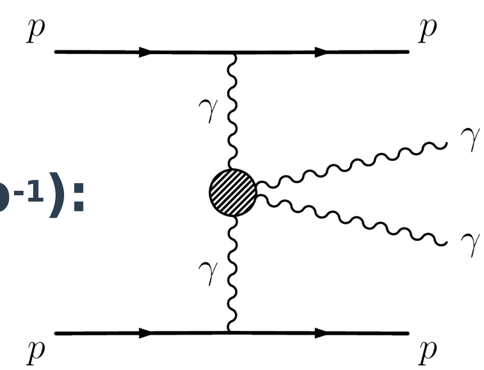
Phys. Rev. Lett. 129 (2022) 011801 (CMS, EXO-18-014) & (CMS-PAS-EXO-21-007)

Exclusive $\gamma\gamma$ production at high mass with tagged protons - preliminary updates





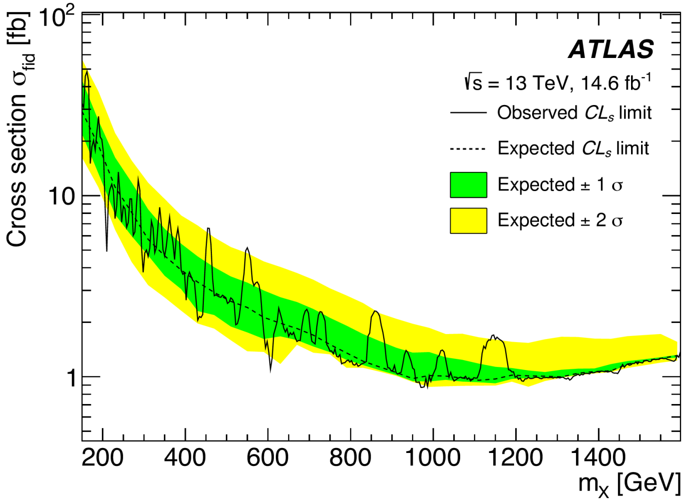
- **Search for exclusive diphoton production:**
  - Back-to-back ($|1 - \phi_{\gamma\gamma}/\pi| < 0.005$ or 0.0025), high diphoton mass ($m_{\gamma\gamma} > 350$ GeV), matching in rapidity and mass between diphoton and proton information
- **First limit on standard model light-by-light production cross section: 4.4 fb**
- **Previous limits on quartic photon anomalous couplings (~10 fb^{-1}):**
  - $|\zeta_1| < 2.9 \cdot 10^{-13}$ GeV^{-4} ($\zeta_2 = 0$)
  - $|\zeta_2| < 6.0 \cdot 10^{-13}$ GeV^{-4} ($\zeta_1 = 0$)

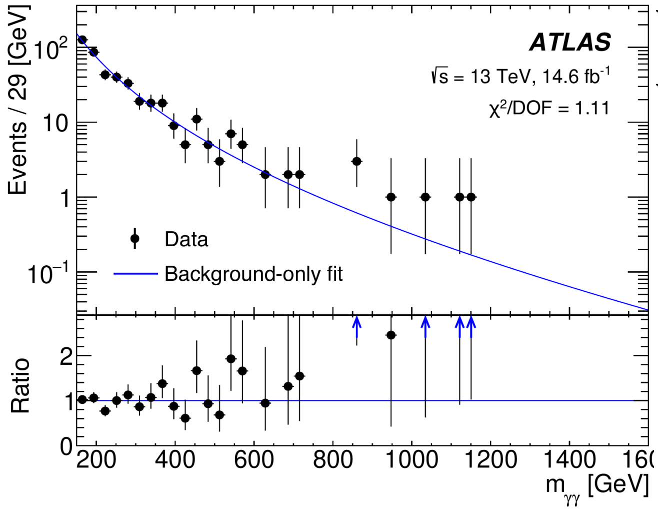


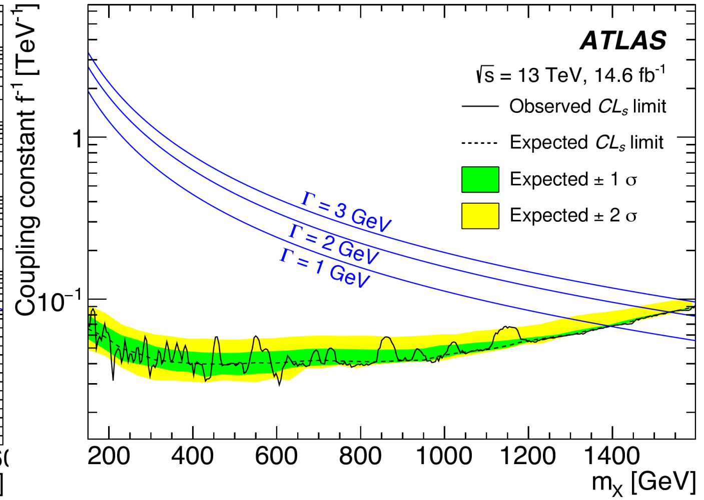
- **Using full Run 2 data (102.7 fb^{-1}):**
  - $|\zeta_1| < 7.3 \cdot 10^{-14}$ GeV^{-4} ($\zeta_2 = 0$)
  - $|\zeta_2| < 1.5 \cdot 10^{-14}$ GeV^{-4} ($\zeta_1 = 0$)
- **Limits on axion-like particles (ALPs) at high mass**

Axion-like particles with AFP

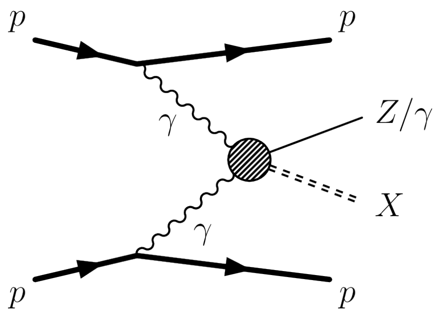
- **Search for exclusive diphoton production:**
  - Proton tagging
  - 150 GeV < $m_{\gamma\gamma}$ < 1600 GeV
- **Upper limit on ALP coupling constant: 0.04-0.09 TeV^{-1}**
- **Most significant excess (m_X = 454 GeV):**
  - Local significance of 2.51σ
  - Global *p*-value for the null hypothesis > 0.5

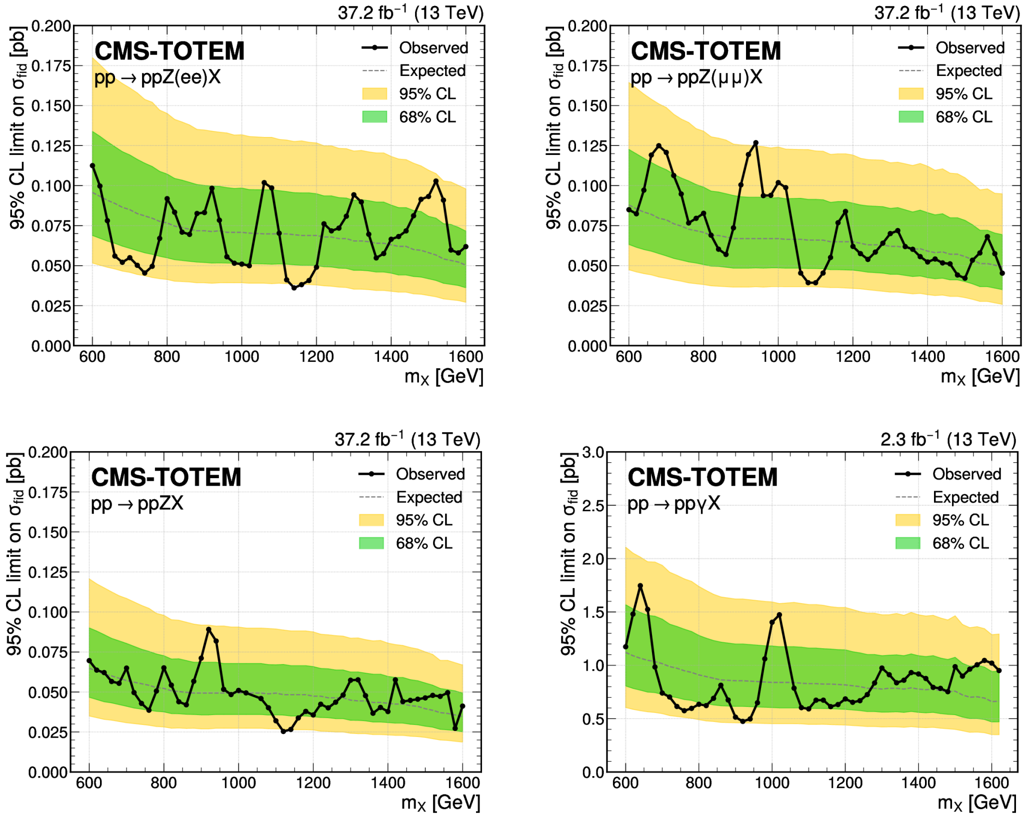






Z/γ + X production

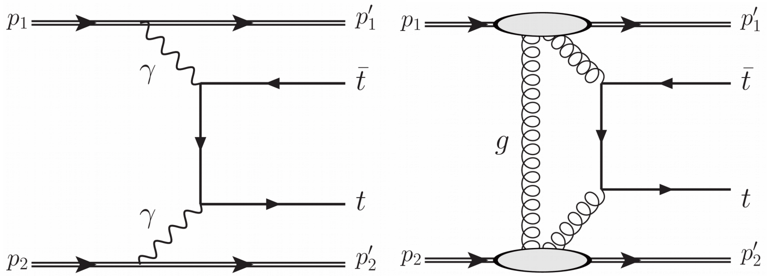


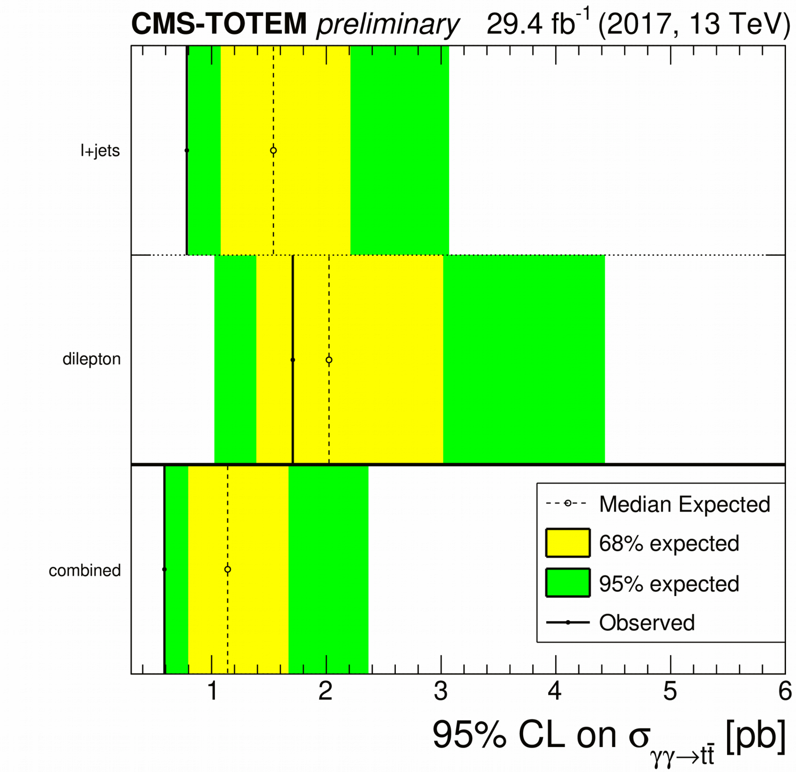


- **Due to proton tagging the total mass can be reconstructed, which allows obtaining mass of *Z*+*X***
  - 0.6 TeV < m_X < 1.6 TeV
  - Using missing mass distribution the search becomes model-independent (*X* does not have to be reconstructed)
- **Upper limits on the cross section obtained:**
  - In the *Z* case 0.025-0.089 pb
  - In the γ case 0.47-1.75 pb

CEP of $t\bar{t}$ with tagged protons

- ***$t\bar{t}$* searched either in:**
  - Dilepton channel
  - Lepton+jets (R = 0.4) decay mode (only b-jets, identified with DeepCSV algorithm)
  - Combined results
- **Multivariate Analysis (MVA):**
  - Boosted Decision Tree (BDT) algorithm used to enhance signal content
- **Upper bound on production cross-section: 0.59 pb**

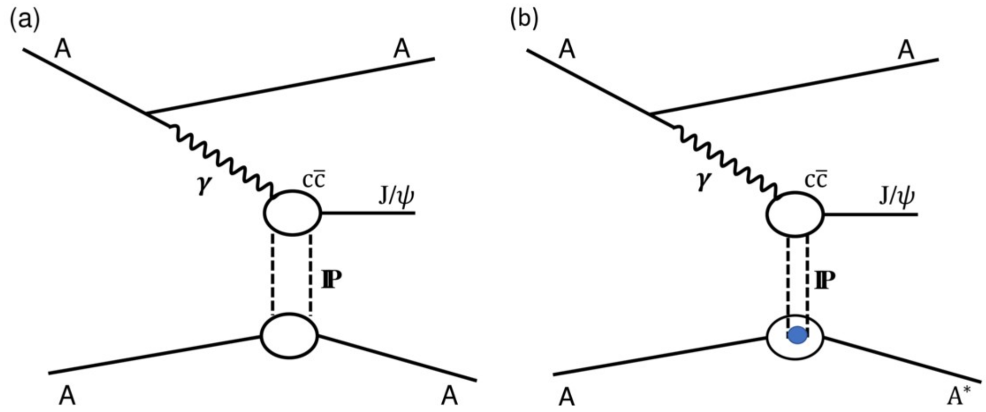


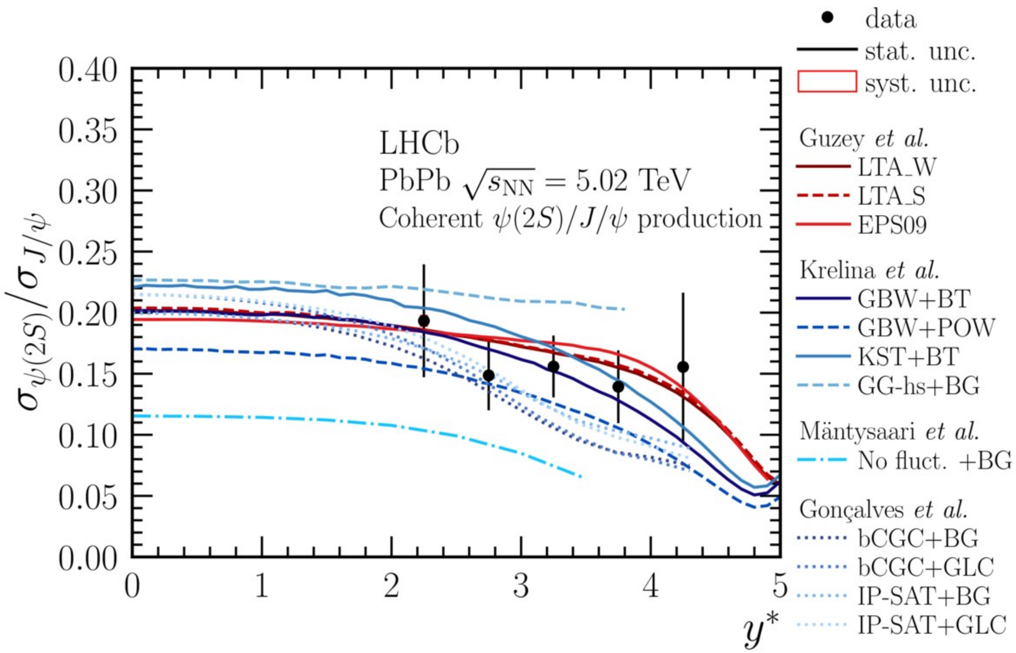


Coherent charmonium production in UPC

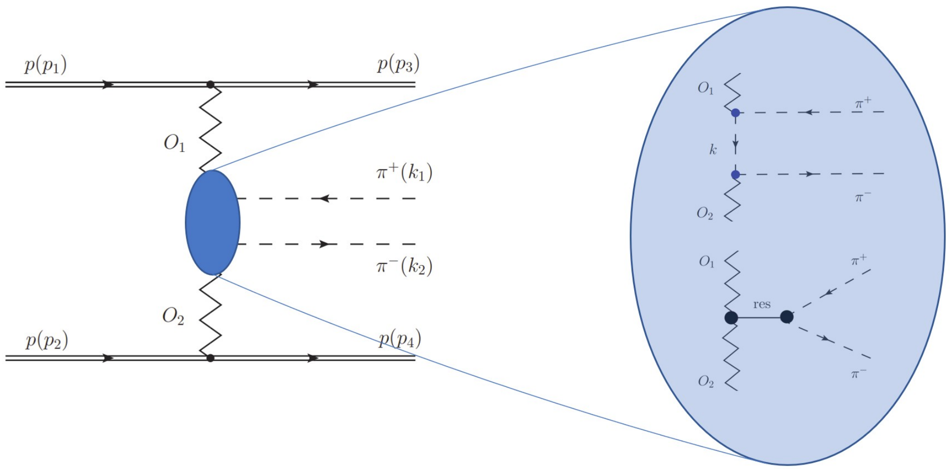
(*PbPb*, $\sqrt{s_{NN}}$ = 5.02 TeV)

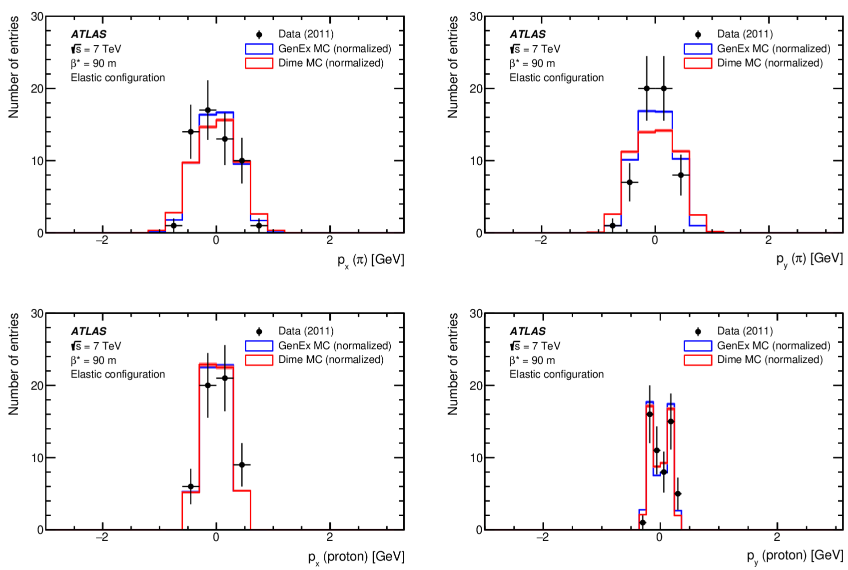
- **Searching for coherent (a) production:**
  - In 2.0 < y^* < 4.5
- **Cross-sections of coherent production in *PbPb*, also compared to theoretical predictions:**
  - $\sigma_{J/\psi}^{coh}$ = 5.965 ± 0.059 ± 0.232 ± 0.262 mb (most precise)
  - σ_{ψ}^{coh} = 0.923 ± 0.086 ± 0.028 ± 0.040 mb (first)
  - Uncertainties: stat, syst, lumi





Exclusive pion pair production ($\sqrt{s}$ = 7 TeV)



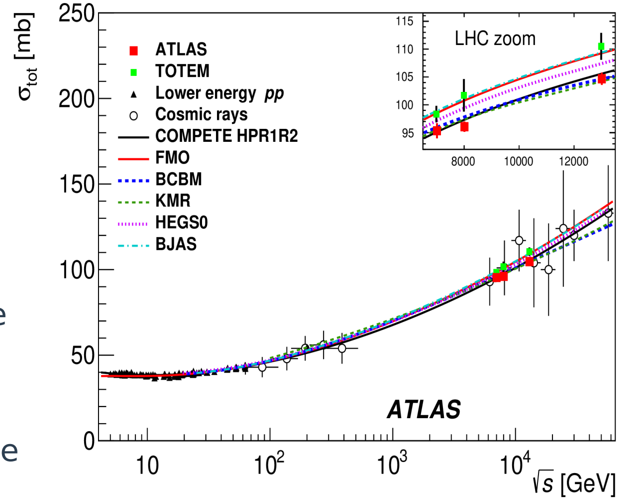


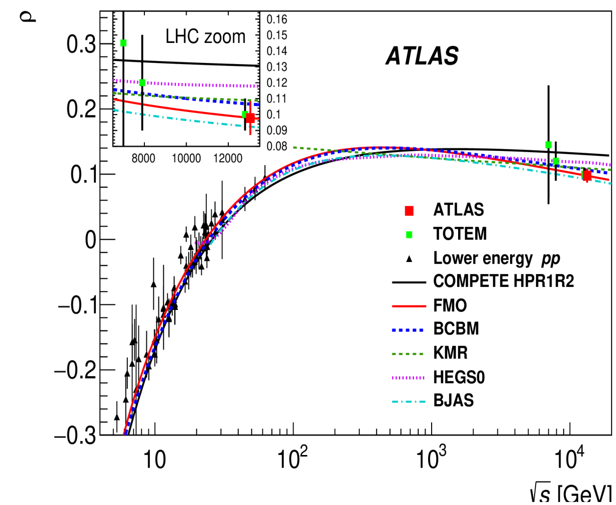
- **Search for pions in correlation with protons detected by ALFA**
  - First use of proton tagging to measure exclusive hadronic final state
- **Cross section determined in two kinematic regions (defined by $p^{protons}$ & p_T^{pions}, y^{pions} and $m_{\pi\pi}$):**
  - 4.8 ± 1.0 (stat) $^{+0.3}_{-0.2}$ (syst) μb
  - 9 ± 6 (stat) $\pm$ 2 (syst) μb
- **Tuning / excluding existing physical models not possible (limited statistical precision)**
  - Used ones (GenEx, Dime) provide preliminary theoretical estimates

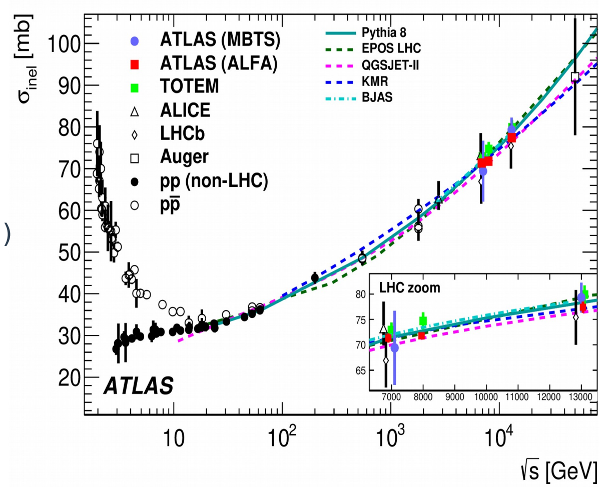
arXiv: 2207.12246 (ATLAS, STDM-2018-08)

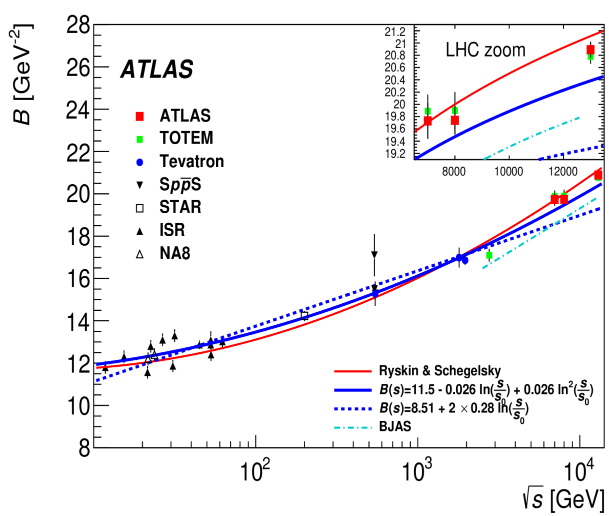
Total cross section measurements with ALFA

- **Measuring elastic cross section in:**
  - Special run: $\beta^* = 2.5$ km
  - Differentially in t Mandelstam: $2.5 \cdot 10^{-4}$ GeV^2 < $-t$ < 0.46 GeV^2
- **Optical theorem:**
  - Hadronic component of σ_{tot} connected to the imaginary part of the scattering amplitude in the forward direction: $\sigma_{tot} = 4\pi\, \mathrm{Im}[f_{el}(t)]_{t\to 0}$
  - ϱ-parameter: $\varrho = \{\mathrm{Re}[f_{el}(t)]_{t\to 0} \,/\, \mathrm{Im}[f_{el}(t)]\}_{t\to 0}$
  - Nuclear slope: purely strong-interaction amplitude $f_N = (\varrho + i)\sigma_{tot}/\hbar c \, \exp[(-B|t| - C|t|^2 - D|t|^3)/2]$
- **(Data-driven) fit on σ_{elast} distribution (with different parameterizations of *t*-dependence) leads to obtain:**
  - $\sigma_{tot}(pp \to X) = 104.7 \pm 1.1$ mb
    - 5.8 mb lower than TOTEM: 2.2 σ tension: unresolved (methodology lumi-dep @ ALFA vs lumi-indep @ TOTEM)
  - $\varrho = 0.098 \pm 0.011$
    - Mostly sensitive to the shape of the elastic spectrum: agrees between TOTEM & ALFA
  - Nuclear slope parameters:
    - $B = 21.14 \pm 0.13$ GeV^{-2}
    - $C = -6.7 \pm 2.2$ GeV^{-4}
    - $D = 17.4 \pm 7.8$ GeV^{-6}









Conclusion

- **Jet-gap-jet events seem to be a powerful test of BFKL resummation even if one proton has been tagged**
- **Using LHC as a $\gamma\gamma$ collider very clean events can be obtained, if we measure intact protons and produced particles in CMS/ATLAS**
- **Proton tagging draws us to higher selection efficiency even in hadronic production processes**
- **Search for exclusive $\gamma\gamma$, ZZ, WW, $t\bar{t}$ leads to best sensitivities to quartic anomalous couplings as well as to the productions of ALPs at high mass**
- **Even the ratio (determined for the first time) of the cross-sections between coherent J/ψ and $\psi(2S)$ production found to be compatible with theoretical models**
- **The commonly accepted models are in agreement with only one of the σ_{tot} or ϱ measurements, while a simultaneous fit was found to give a good description of both quantities**
- **It is still a question if the low value of ϱ can be attributed to the Odderon or other effects in strong interactions**

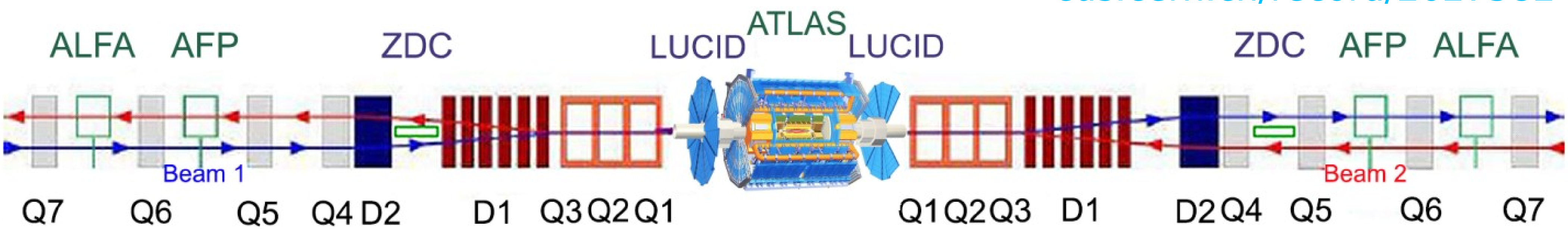
Thank You for Your attention!

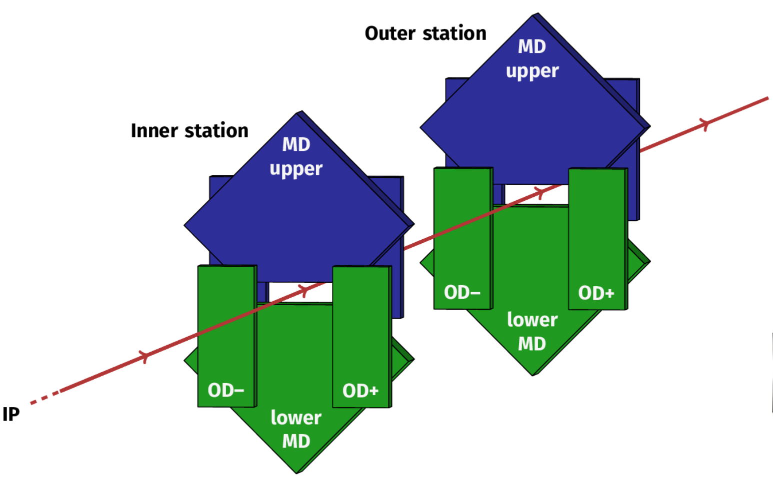
Questions are welcomed :)

Backups

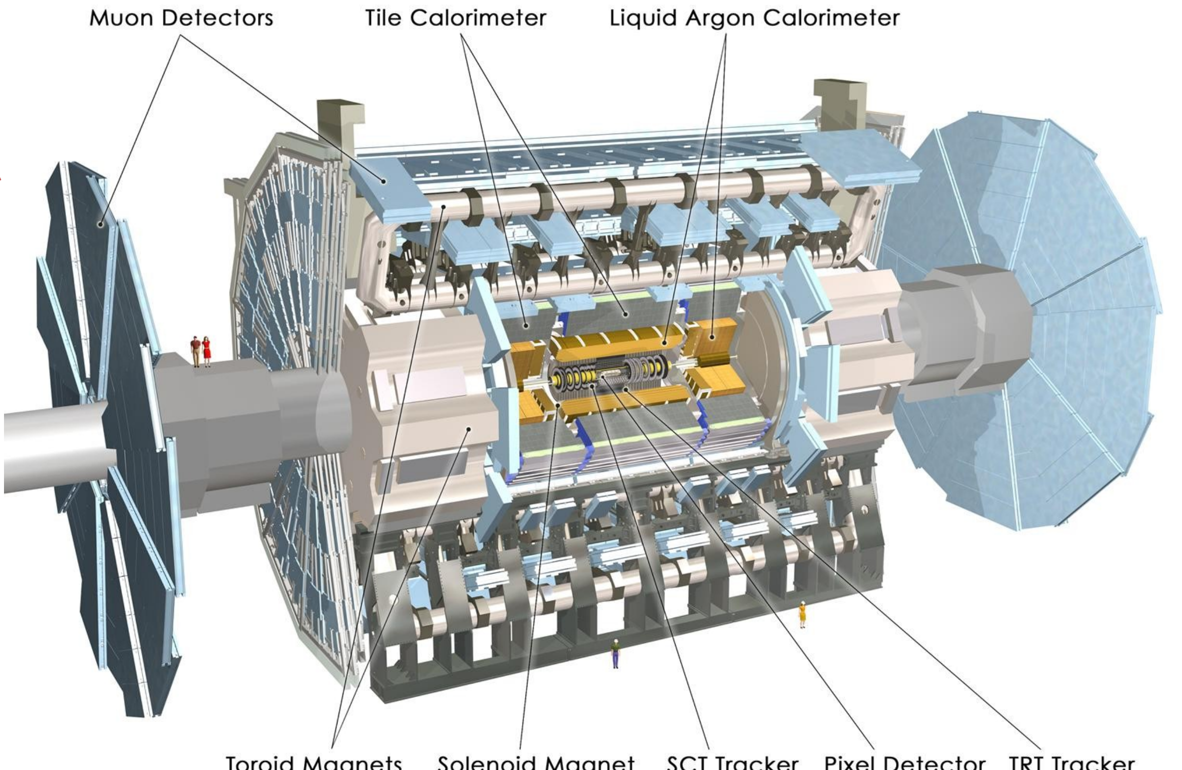
Experiments in scope: ATLAS

cds.cern.ch/record/2627582



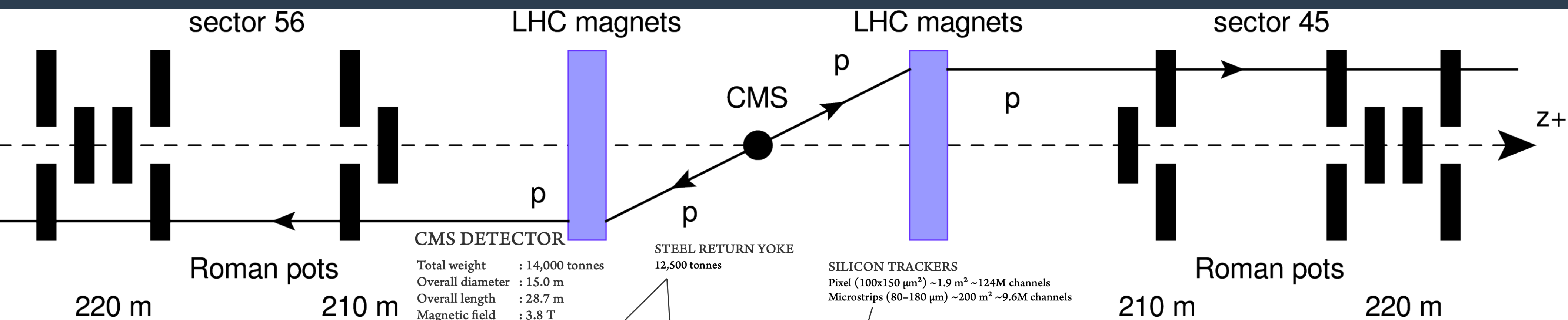


(ATLAS, STDM-2018-08)

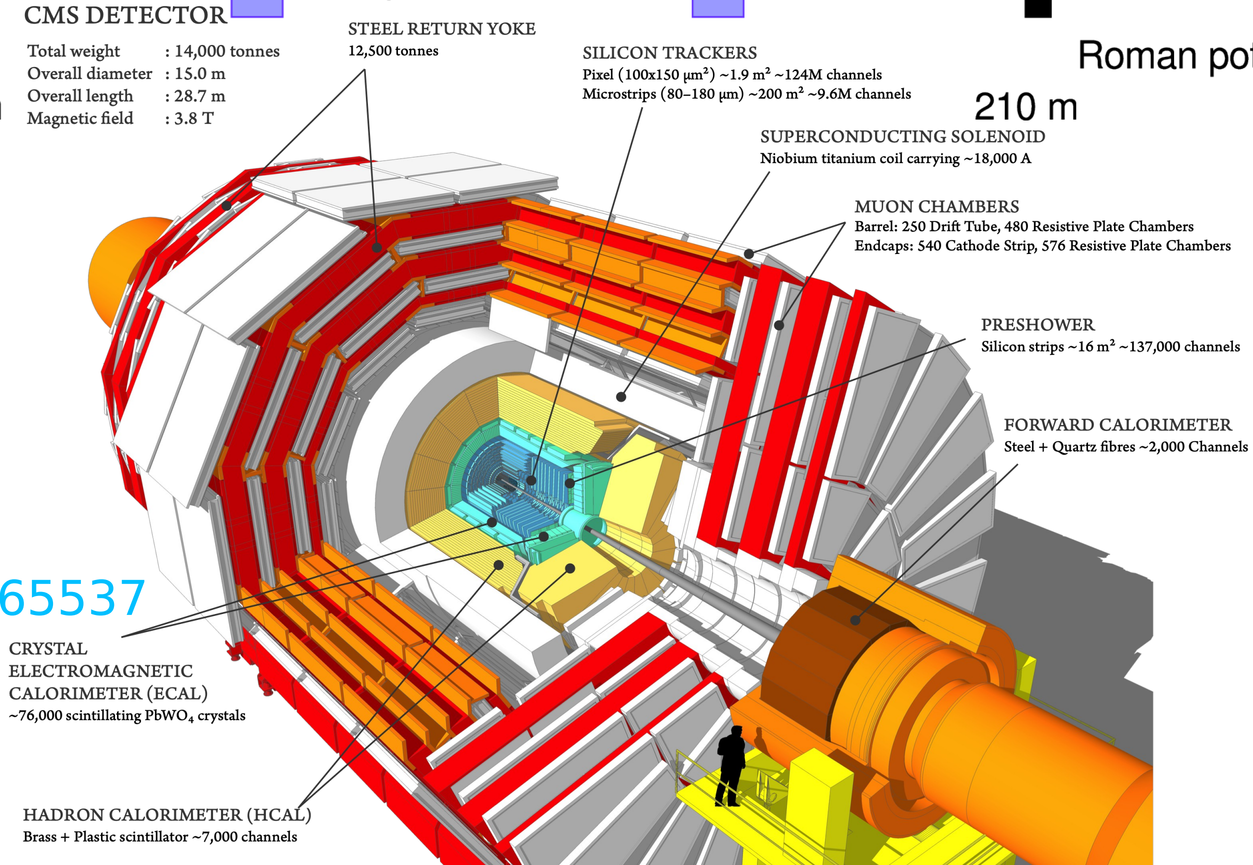


cds.cern.ch/record/1095924

Experiments in scope: CMS

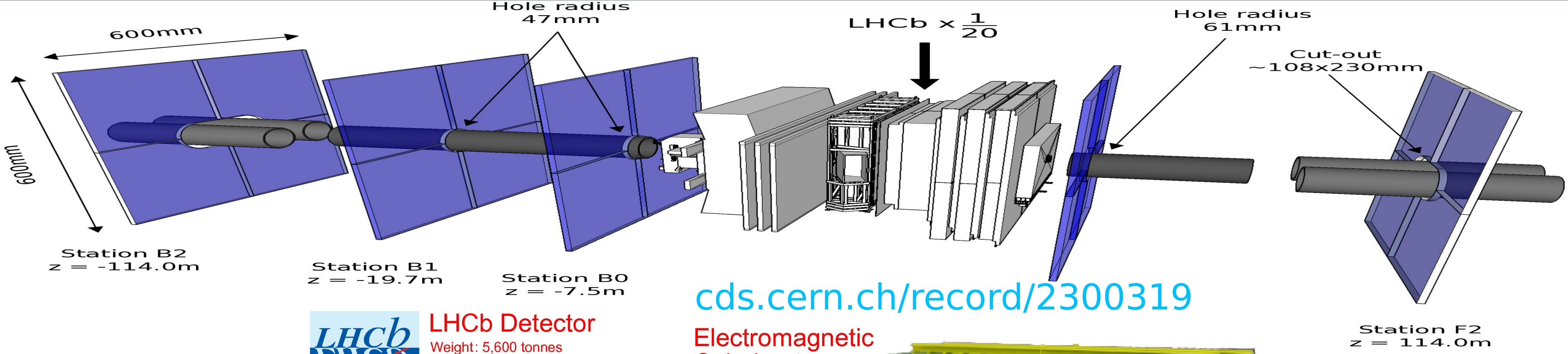


(CMS, SMP-19-006)



cds.cern.ch/record/2665537

Experiments in scope: LHCb



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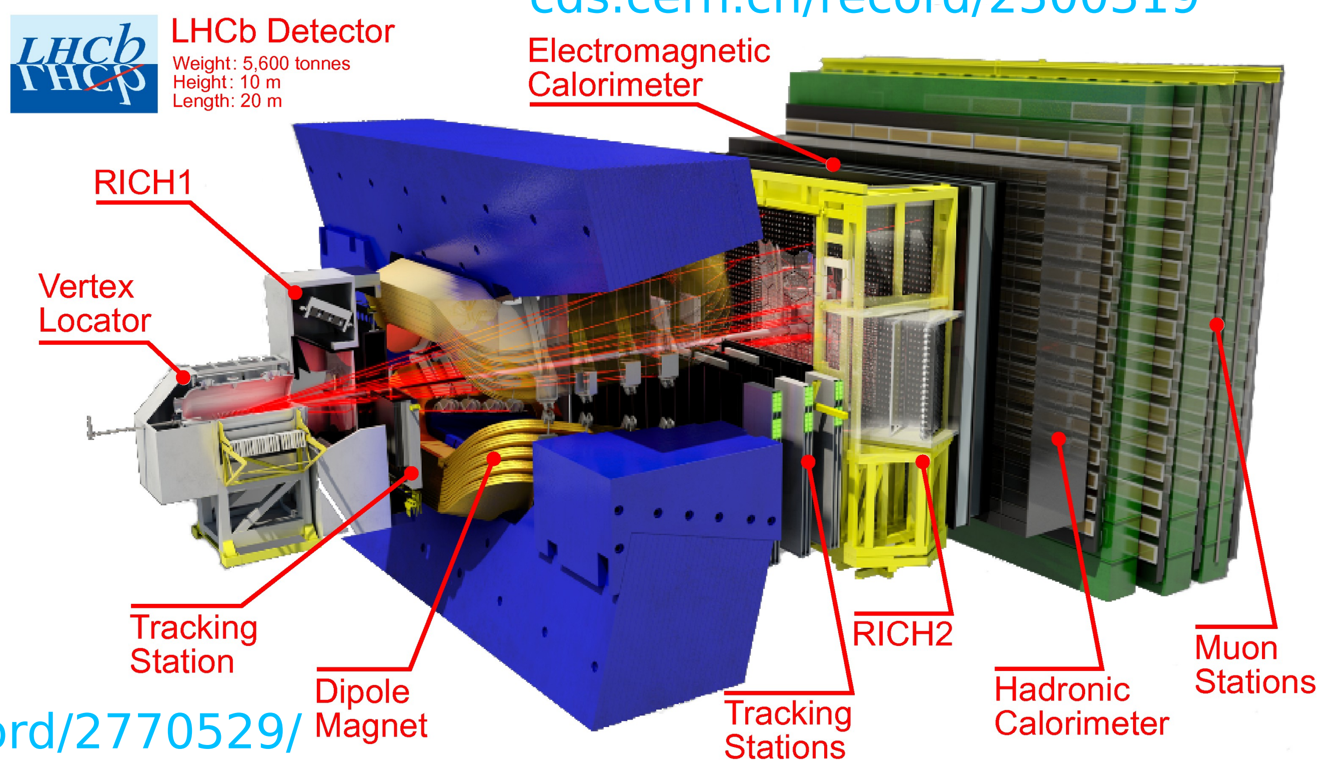


cds.cern.ch/record/2770529/

Jet-gap-jet events in diffraction I.

- **Data sample:**
  - 2015, *pp*, $\sqrt{s}$ = 13 TeV, β^* = 90 m, PU ~ 0.05-0.1
  - Integrated luminosity: 0.4 pb^{-1}
  - Unprescaled dijet trigger:
    - At least 2 leading jets: both with p_T > 32 GeV, $|\eta|$ < 5
      - 85% efficient for p_T = 40 GeV
      - Fully efficient at p_T > 55 GeV
      - Efficiency obtained from zero bias (ZB) using random trigger in nonempty bunch crossings
      - Efficiency effects mostly cancel in f_{CSE} → no correction applied

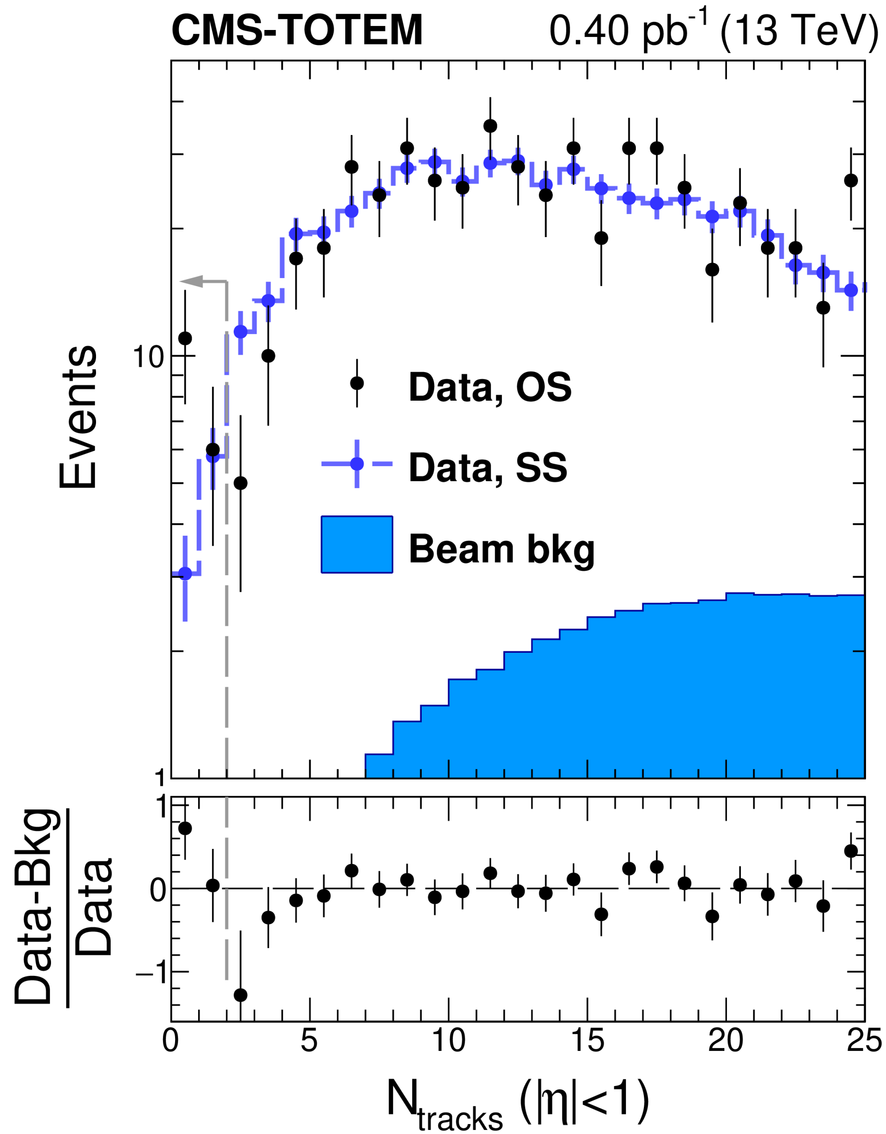
Jet-gap-jet events in diffraction II.

- **Event selection: 341 events in sector 45, 336 events in sector 56**
  - Dijet event selection:
    - $p_T > 40$ GeV, $1.4 < |\eta| < 4.7$, $\eta^{jet1}\eta^{jet2} < 0$
    - Anti-k_T algorithm, $R = 0.4$
  - Intcat proton selection:
    - At least 1 proton in either sector 45 or 56 RP stations
    - Proton track crosses at least 2 overlapping RP units (ensuring reconstruction quality)
    - RP acceptance: $\xi < 0.2$, $-4 < t < -0.025$ GeV^2
    - Fiducial selection (while beam position at x(RP) = y(RP) = 0):
      - Vertical RPs: $8 < |y(\mathrm{RP})| < 30$ mm, $0 < |x(\mathrm{RP})| < 20$ mm
      - Horizontal RPs: $|y(\mathrm{RP})| < 25$ mm, $7 < |x(\mathrm{RP})| < 25$ mm
    - Particle flow (PF) calculations:
      - $\xi(\mathrm{PF}) - \xi(\mathrm{RP}) < 0$ (reconstruction inefficiencies & acceptance limitations)

Phys. Rev. D 104, 032009 (2021) (CMS, SMP-19-006)

Jet-gap-jet events in diffraction III.

- **Background treatment: data-based**
  - Independent sample (same side "SS" jets) of the nominal one (opposite side "OS" jets)
    - Negative binomial distribution (NBD) fit
  - Particle multiplicity distribution parametrization
    - Using NBD method estimate the standard diffractive dijet contribution that feature a central gap
  - Avoiding model-dependent treatment of underlying event (ULE) activity, hadronization effects, etc. that have impact on the description of particle activity between jets in the MC events
  - Separately for jet-gap-jet and proton-gap-jet-gap-jet events



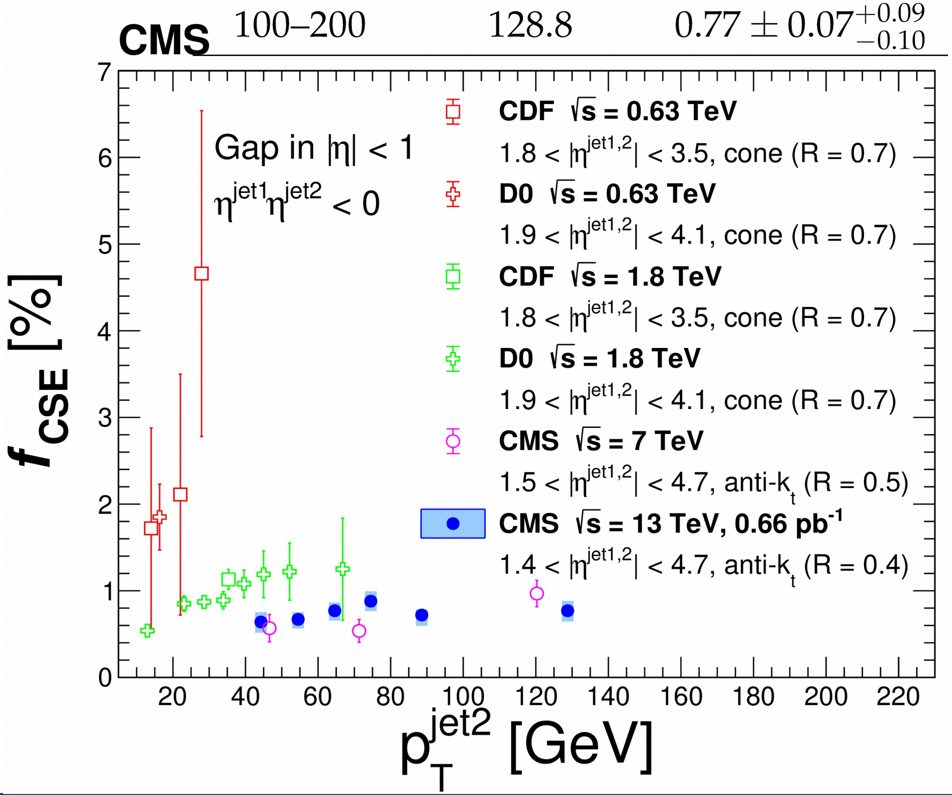
Jet-gap-jet events in diffraction IV.

- **Systematic uncertainties:**

Source	Jet-gap-jet (%) $\Delta\eta_{jj}$	Jet-gap-jet (%) p_T^{jet2}	Jet-gap-jet (%) $\Delta\phi_{jj}$	Proton-gap-jet-gap-jet (%)
Jet energy scale	1.0–5.0	1.5–6.0	0.5–3.0	0.7
Track quality	6.0–8.0	5.4–8.0	1.5–8.0	8
Charged particle p_T threshold	2.0–5.8	1.6–4.0	1.1–5.8	11
Background subtraction method	4.7–15	2–15	12	28
NBD fit parameters	0.8–2.6	0.6–1.7	0.1–0.6	7.0
Functional form of the fit	2–7.3	1.4–8.0	0.6–7.8	11.5
NBD fit interval	—	—	—	12
Calorimeter energy scale	—	—	—	5.0
Horizontal dispersion	—	—	—	6.0
Fiducial selection requirements	—	—	—	2.6
Total	7–23	9–15	12–18.5	35

Jet-gap-jet events in diffraction V.

p_T^{jet2} [GeV]	$\langle p_T^{jet2} \rangle$ [GeV]	f_{CSE} [%]
40–50	44.3	$0.64 \pm 0.01^{+0.11}_{-0.12}$
50–60	54.5	$0.67 \pm 0.02^{+0.08}_{-0.10}$
60–70	64.6	$0.77 \pm 0.04^{+0.08}_{-0.10}$
70–80	74.5	$0.88 \pm 0.06^{+0.09}_{-0.09}$
80–100	88.6	$0.72 \pm 0.05^{+0.04}_{-0.11}$
100–200	128.8	$0.77 \pm 0.07^{+0.09}_{-0.10}$



$\Delta\phi_{jj}$	$\langle \Delta\phi_{jj} \rangle$	f_{CSE} [%]
0.00–1.00	0.60	$0.54 \pm 0.11^{+0.09}_{-0.10}$
1.00–2.00	1.64	$0.40 \pm 0.04^{+0.06}_{-0.06}$
2.00–2.25	2.14	$0.41 \pm 0.04^{+0.08}_{-0.08}$
2.25–2.50	2.36	$0.38 \pm 0.03^{+0.06}_{-0.07}$
2.50–2.75	2.62	$0.40 \pm 0.02^{+0.05}_{-0.06}$
2.75–3.00	2.86	$0.57 \pm 0.02^{+0.07}_{-0.09}$
3.00–π	3.06	$1.03 \pm 0.02^{+0.14}_{-0.15}$

$\Delta\eta_{jj}$	$\langle \Delta\eta_{jj} \rangle$	f_{CSE} [%]
3.0–3.5	3.24	$0.41 \pm 0.02^{+0.11}_{-0.04}$
3.5–4.0	3.75	$0.50 \pm 0.02^{+0.07}_{-0.07}$
4.0–4.5	4.25	$0.68 \pm 0.02^{+0.07}_{-0.06}$
4.5–5.0	4.74	$0.71 \pm 0.03^{+0.06}_{-0.06}$
5.0–5.5	5.24	$0.86 \pm 0.04^{+0.06}_{-0.08}$
5.5–6.0	5.73	$0.93 \pm 0.04^{+0.06}_{-0.09}$
6.0–6.5	6.22	$0.92 \pm 0.06^{+0.11}_{-0.09}$
6.5–7.0	6.71	$0.69 \pm 0.07^{+0.15}_{-0.05}$
7.0–7.5	7.22	$0.99 \pm 0.14^{+0.07}_{-0.15}$
7.5–8.0	7.73	$1.57 \pm 0.27^{+0.35}_{-0.56}$

Exclusive production of *W/Z* pairs I.

- **Data sample:**
  - 2016-2018, *pp*, $\sqrt{s}$ = 13 TeV
  - Integrated luminosity: 100 fb^{-1}
- **Signal simulation: LO with FPMC**
- **Background simulations:**
  - Dominant nonexclusive (from QCD multijet): LO, PYTHIA 8.205 (with CP5 tune)
  - *W/Z*+jet: NLO, MadGraph5_aMC@NLO
  - Top pair production: NLO, POWHEG
  - SM contribution in *ZZ/WW* considered to be negligible
- **Parton showers: PYTHIA**
- **Detector response:**
  - Central CMS: Geant4
  - Forward protons: “direct simulation”

Exclusive production of *W/Z* pairs II.

- **Event selection:**
  - Jet selection:
    - $|\eta| < 2.5$, $p_T > 200$ GeV (choosing the 2 highest), $R = 0.8$
    - Acoplanarity $|1 - \phi_{jj}/\pi| < 0.01$, p_T-ratio < 1.3, 1126 GeV < m_{jj}
    - 60 < pruned mass < 107 GeV (compatible with *W/Z*)
    - Subjettiness ratio $\tau_2/\tau_1 < 0.75$
  - *W/Z* selection:
    - summed pruned jet masses $m(j_1) + m(j_2) = 166.6$ GeV differentiating between *W/Z*
  - Proton selection:
    - $\xi > 0.05$
  - Proton-jet matching:
    - $|1 - m(\mathrm{VV})/m(\mathrm{pp})| < 1.0$
    - $|y(\mathrm{pp}) - y(\mathrm{VV})| < 0.5$

Exclusive production of W/Z pairs III/a.

Number of events	region	N_{evt} (2016)	N_{evt} (2017)	N_{evt} (2018)
Anti-acoplanarity sideband	δ	0.4 ± 0.4	1.6 ± 1.0	11.6 ± 2.6
Anti-pruned mass sideband	δ	0.5 ± 0.2	1.5 ± 0.3	11.3 ± 0.8
Event mixing	δ	$0.5\ (< 2.2)$	$1.8\ (< 4.2)$	14.3 ± 8.9
Expected signal ($a_0^{\mathrm{W}} / \Lambda^2 = 5 \times 10^{-6}\,\mathrm{GeV}^{-2}$)	δ	1.7	2.2	16.1
Expected signal (SM)	δ	0.006	< 0.05	0.03
Anti-acoplanarity sideband	o	1.4 ± 0.9	10.0 ± 3.2	41.4 ± 5.7
Anti-pruned mass sideband	o	2.5 ± 0.8	7.1 ± 1.3	43.0 ± 3.0
Event mixing	o	2.4 ± 1.9	8.4 ± 6.3	49 ± 13
Expected signal ($a_0^{\mathrm{W}} / \Lambda^2 = 5 \times 10^{-6}\,\mathrm{GeV}^{-2}$)	o	1.5	1.7	16.8
Expected signal (SM)	o	0.005	< 0.05	< 0.07

Exclusive production of *W/Z* pairs III/b.

Number of events	region	N_{evt} (2016)	N_{evt} (2017)	N_{evt} (2018)
Anti-acoplanarity sideband	δ	1.5 ± 1.1	1.6 ± 0.8	14.2 ± 3.0
Anti-pruned mass sideband	δ	0.4 ± 0.2	0.9 ± 0.2	9.9 ± 0.9
Event mixing	δ	$0.5\ (< 2.1)$	$1.5\ (< 3.6)$	11.6 ± 9.4
Expected signal ($a_0^Z / \Lambda^2 = 1 \times 10^{-5}\,\mathrm{GeV}^{-2}$)	δ	1.3	1.4	9.0
Anti-acoplanarity sideband	o	1.5 ± 1.1	3.7 ± 1.5	37.4 ± 5.6
Anti-pruned mass sideband	o	2.1 ± 0.8	5.4 ± 1.3	41.7 ± 3.1
Event mixing	o	2.0 ± 1.8	6.3 ± 5.1	42 ± 16
Expected signal ($a_0^Z / \Lambda^2 = 1 \times 10^{-5}\,\mathrm{GeV}^{-2}$)	o	1.0	1.6	12.8

Exclusive production of *W/Z* pairs IV.

- **Systematic uncertainties:**
  - Tight matching between protons and jets: 30%
  - Jet energy scale: few-10%
  - Total efficiency uncertainty per arm: 10% (2016), 2-3% (2017-2018)
  - Integrated luminosity: 1.2% (2016), 2.3% (2017), 2.5% (2018)
  - Overall uncertainty for PPS data: 1.8%
  - Data vs MC (pruned mass and τ_{21}): below 1%
  - Background:
    - Normalization (nominal acoplanarity sideband method): 15-20% (2018), >100% (2016)
    - Dependence on the sideband region: few% (2018), 80% (2016)

Exclusive production of *W/Z* pairs V.

Coupling	Observed (expected) 95% CL upper limit No clipping	Observed (expected) 95% CL upper limit Clipping at 1.4 TeV
$\lvert f_{M,0}/\Lambda^4 \rvert$	66.0 (60.0) TeV^{-4}	79.8 (78.2) TeV^{-4}
$\lvert f_{M,1}/\Lambda^4 \rvert$	245.5 (214.8) TeV^{-4}	306.8 (306.8) TeV^{-4}
$\lvert f_{M,2}/\Lambda^4 \rvert$	9.8 (9.0) TeV^{-4}	11.9 (11.8) TeV^{-4}
$\lvert f_{M,3}/\Lambda^4 \rvert$	73.0 (64.6) TeV^{-4}	91.3 (92.3) TeV^{-4}
$\lvert f_{M,4}/\Lambda^4 \rvert$	36.0 (32.9) TeV^{-4}	43.5 (42.9) TeV^{-4}
$\lvert f_{M,5}/\Lambda^4 \rvert$	67.0 (58.9) TeV^{-4}	83.7 (84.1) TeV^{-4}
$\lvert f_{M,7}/\Lambda^4 \rvert$	490.9 (429.6) TeV^{-4}	613.7 (613.7) TeV^{-4}

- **Further results:**
  - conversion of limits to dim-8 operators (if all, but one $f_{M,i}$ are zero)

Exclusive $\gamma\gamma$ production at high mass with tagged protons: preliminary updates I.

- **Data sample (full Run 2 data):**
  - Integrated luminosity: 9.8 fb^{-1} (2016), 37.2 fb^{-1} (2017), 55.7 fb^{-1} (2018)
- **LbL signal simulation: FPMC**
  - ALP masses: 500-2000 GeV
- **Background simulations:**
  - Dominant $\gamma\gamma$+jets & sub leading ($t\bar{t}+j$ and $V+\gamma$): NLO, MadGraph5_aMC@NLO (with NNPDF3.0 PDFs at NNLO)
  - QCD background estimation (electron and photon enriched QCD sample): PYTHIA 8 (with CP5 ULE tune)
- **Detector response of CMS: Geant4**

Exclusive γγ production at high mass with tagged protons: preliminary updates II.

- **Event selection:**

Region	**Selection**
Preselection	Double photon HLT $p_T^\gamma > 75$ (100) GeV for 2016 (2017-2018) $H/E < 0.10$ MVA WP90 photon ID with electron veto $\lvert\eta^\gamma\rvert < 2.5$ (transition veto) $m_{\gamma\gamma} > 350$ GeV
Exclusive selection	$a < 0.0025$
$\xi \in$ PPS	$0.02 < \xi^{\pm}_{\gamma\gamma} < 0.20$
Asymmetric ξ acceptance	$0.035 < \xi_{PPS} < 0.15$ (0.18) for sector-45 (sector-56)

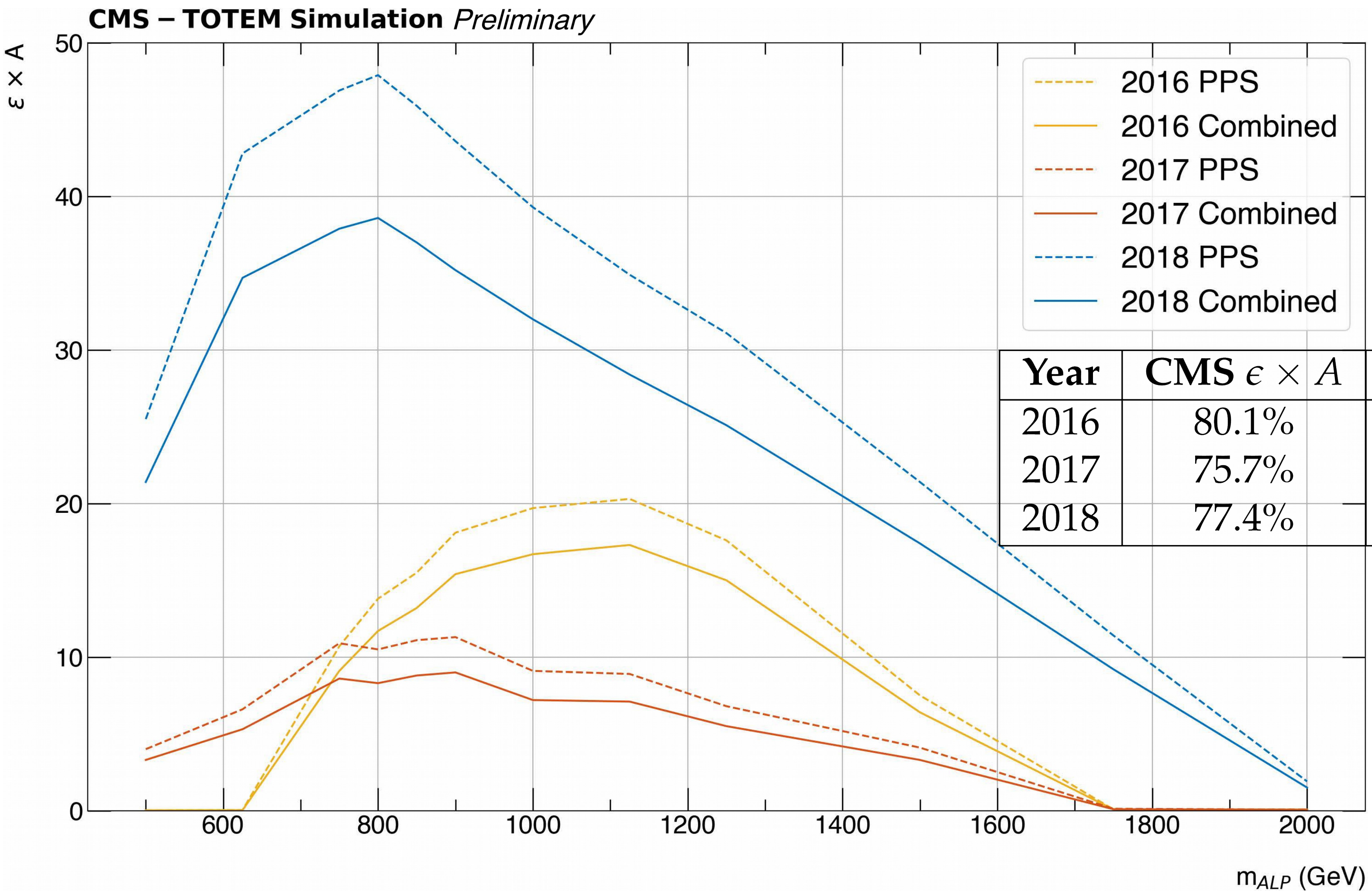
Exclusive γγ production at high mass with tagged protons: preliminary updates III.

- **Background estimation (PU as main source):**
  - Adding protons to the diphoton pair (from same run, LHC crossing-angle)
  - Validation from orthogonal set (reversed acoplanarity criterium) or using simulated events
  - Total number of background events: 1.103 ± 0.003 (stat)
- **Systematic uncertainties:**

Source	**2016**	**2017**	**2018**
CMS Luminosity	1.2%	2.3%	2.5%
Background estimation	23.3%	25.2%	20.9%
Photon ID scale factors	3.1%	7.0%	2.9%
Rapidity Gap Survival Probability	10%	10%	10%
Particle Showers in PPS	–	–	1.7%

Exclusive γγ production at high mass with tagged protons: preliminary updates IV.

- **Further results: ALP signal efficiency · acceptance**



Year	CMS $\epsilon \times A$	PPS $\epsilon \times A$	$\epsilon \times A$
2016	80.1%	6.5%	5.2%
2017	75.7%	3.3%	2.5%
2018	77.4%	18.4%	14.2%

Axion-like particles with AFP I.

- **Data sample:**
  - 2017, *pp*, √s = 13 TeV
  - Integrated luminosity: 14.6 fb^{-1}
  - <#interaction/bunch> = 36
  - Diphoton trigger:
  - 2 EM calorimeter clusters with E_T > 35 (or 25) GeV
  - AFP: at least 3 operational Si planes
- **Simulated signal: SuperChic 4.02 MC**
  - ALP mass range: 150-1600 GeV
  - ALP diphoton coupling: 0.05 TeV^{-1}
  - $|\eta| < 2.4$, $|y_{\gamma\gamma}| < 2.4$, $p_T > 20$ GeV
- **Hadronization of dissociated-proton systems: PYTHIA 8.307**
- **Detector response: Geant4-based**

Axion-like particles with AFP II.

- **Event selection:**
  - Calorimeter isolation (cluster $R = 0.4$) transverse momentum < $0.022E_T$ +2.45 GeV
  - At least 2 photon: $p_T > 40$ GeV, $|\eta| < 2.37$, excluding barrel-to-endcap region $1.37 < |\eta| < 1.52$
  - Acoplanarity < 0.01
  - At least 1 (A-side / C-side) tagged proton, for which $0.035 < \xi < 0.08$
  - $m_{\gamma\gamma} < 500$ GeV

Axion-like particles with AFP III.

- **Background estimation:**
  - Dominant from PU: “combinatorical”
    - Fully data-driven method
    - Fit on the mixed-data sample
    - Validation on a new mixed-data sample, orthogonal to the previous one (reversed acoplanarity condition)
  - “Single-vertex”: MC samples → negligible
    - Photon-induced: SuperChic4.13
    - Diffractive processes: PYTHIA 8.306

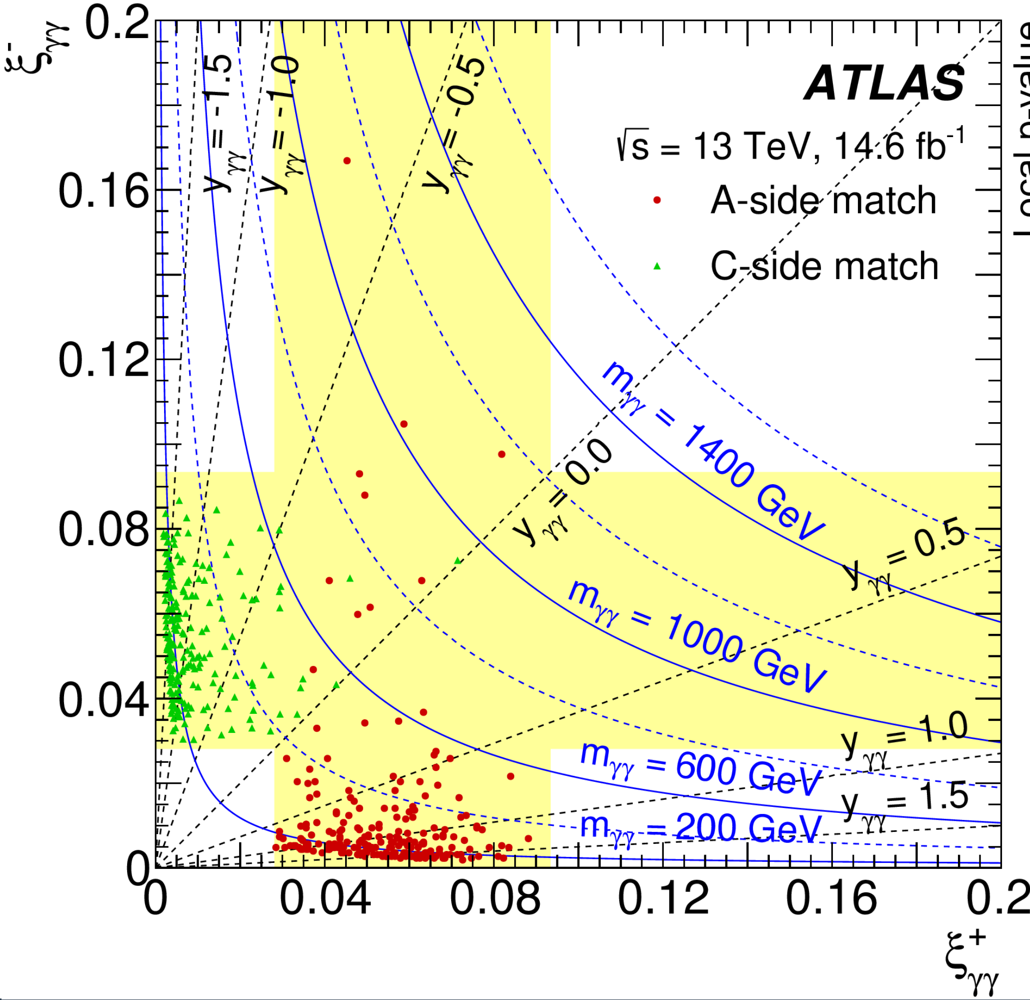
Axion-like particles with AFP IV.

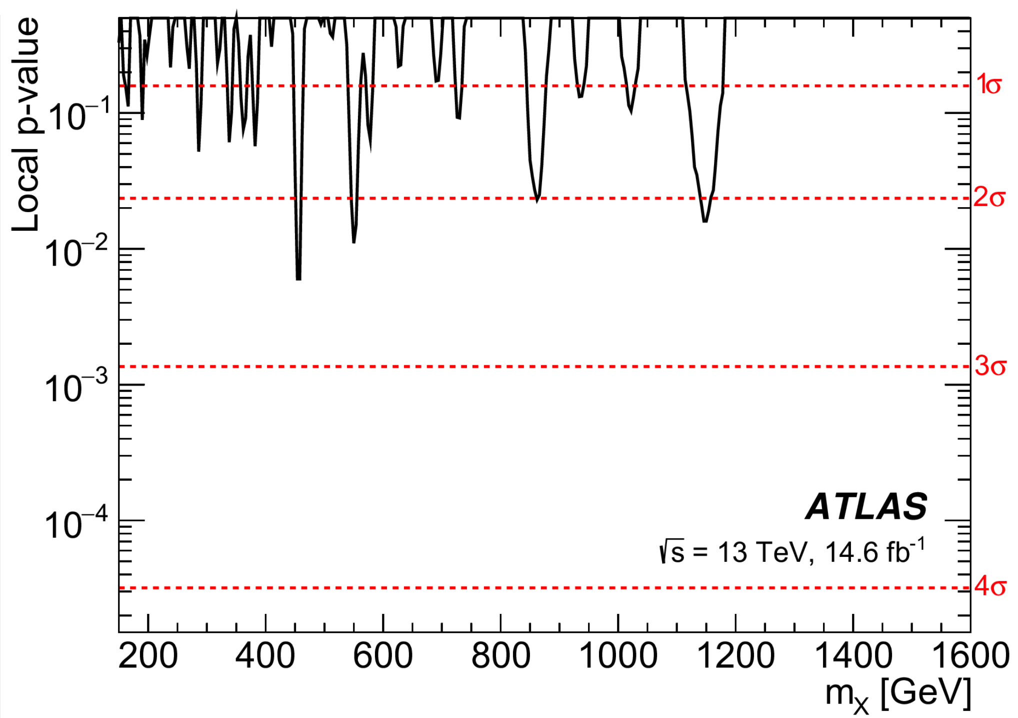
- **Systematic uncertainties:**

Source	Uncertainty
Signal yield uncertainty	
Pile-up reweighting	$^{+2.7}_{-2.6}\%$
Luminosity	$\pm 2.4\%$
Photon identification efficiency	$^{+1.6}_{-1.5}\%$
Photon isolation efficiency	$\pm 1.9\%$
Beam optics between ATLAS central and AFP detectors	$^{+0.8}_{-3.4}\%$
AFP global alignment	$^{+10.0}_{-8.6}\%$
Proton reconstruction efficiency	$^{+3.0}_{-2.2}\%$
Showering in the AFP	$^{+0.0}_{-6.6}\%$
Background modelling (mass-dependent)	$\pm(0.02$–$0.7)$ events
Signal modelling	
Photon energy resolution	$^{+14.1}_{-4.8}\%$
Photon energy scale	$\pm(0.5$–$1.0)\%$
Signal cross-section uncertainty	
Soft survival factor (exclusive process)	$\pm 2\%$
Soft survival factor (single-dissociative process)	$\pm 10\%$
Soft survival factor (double-dissociative process)	$\pm 50\%$

Axion-like particles with AFP V.

- **Further results:**





$\xi_{\gamma\gamma}^{\pm} = (m_{\gamma\gamma}/\sqrt{s})\exp(\pm y_{\gamma\gamma})$
+/-: A/C side

Z/γ + X production I.

- **Data sample:**
  - 2017, *pp*, $\sqrt{s}$ = 13 TeV
  - Integrated luminosity: 37.2 fb^{-1}
  - Trigger either for:
    - Isolated proton
    - Electron/muon pair from Z
    - Prescaled trigger for photon case
- **Signal simulation:**
  - m_{VX} distribution with exponential spectrum ($m_{VX} = m_X + \varepsilon + 100$ GeV)
    - m_X produced in a range
    - ε randomly distributed variable following exponential probability distribution function with decay constant of 0.04 GeV^{-1}
  - Detector acceptance as average of corresponding configurations at LHC
- **Background simulation: for validation (background modelled from data)**
  - Each process in coincidence with additional minimum-bias events: PYTHIA8 (PU events)
  - Drell-Yan (Z+j): NLO, MadGraph5_aMC@NLO v2.2.2 (with FxFx merging)
  - Isolated γ+j: LO, MadGraph5_aMC@NLO (with MLM merging)
  - Top production (single top tW & $t\bar{t}$): POWHEG
  - Diboson production (*WW, ZZ, WZ*): PYTHIA8 version 8.226
  - SD & DD Z production: PYTHIA8 & POMWIG
- **Parton shower generator: PYTHIA8**
- **Detector response: Geant4**

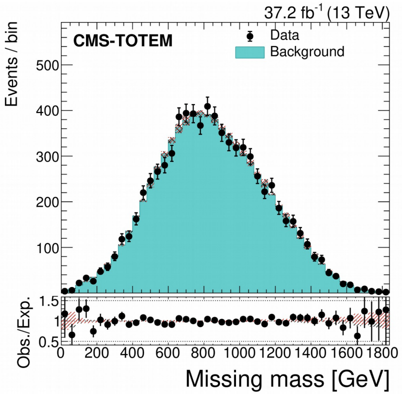
Z/γ + X production II.

- **Event selection:**

Selection/analysis	$\mathrm{Z} \to \mathrm{e}^{+}\mathrm{e}^{-}/\mathrm{Z} \to \mu^{+}\mu^{-}$	γ
	$\geq$2 same-flavour leptons (e or μ)	
	opposite electric charge	
Leptons/photons	$p_{\mathrm{T}}(\ell_1) > 30\,\mathrm{GeV}$, $\lvert\eta(\ell_1)\rvert < 2.4$	1γ within $\lvert\eta(\gamma)\rvert < 1.44$
	$p_{\mathrm{T}}(\ell_2) > 20\,\mathrm{GeV}$, $\lvert\eta(\ell_2)\rvert < 2.4$	
	$\lvert m(\ell_1, \ell_2) - m_{\mathrm{Z}}\rvert < 10\,\mathrm{GeV}$	
Boson p_{T}	$p_{\mathrm{T}}(\mathrm{Z}) > 40\,\mathrm{GeV}$	$p_{\mathrm{T}}(\gamma) > 95\,\mathrm{GeV}$
Protons	$0.02 < \xi_{+}^{\mathrm{gen}} < 0.16$ and $0.03 < \xi_{-}^{\mathrm{gen}} < 0.18$	

Z/γ + X production III.

- **Background estimation:**
  - Sources:
    - Inclusive SM (Z+j / γ+j) & 2 protons from PU: "combinatorical"
    - Single diffractive (SD) & 1 proton from PU
    - Double diffractive (DD): assumed to be negligible
    - Exclusive SM ($\gamma\gamma \rightarrow ll$): assumed to be negligible
    - Signal-induced background (1/2 protons escaped)
  - Event mixing (single & double) on control sample orthogonal to the signal one (p_Z < 10 GeV):
    - Replacing 1/2 proton from random event, repeatedly 100 times
    - Correctly reproduces combinatorical background
    - Good approximation of SD case
  - Twofold validation:
    - MC
    - Control sample ($e\mu$)

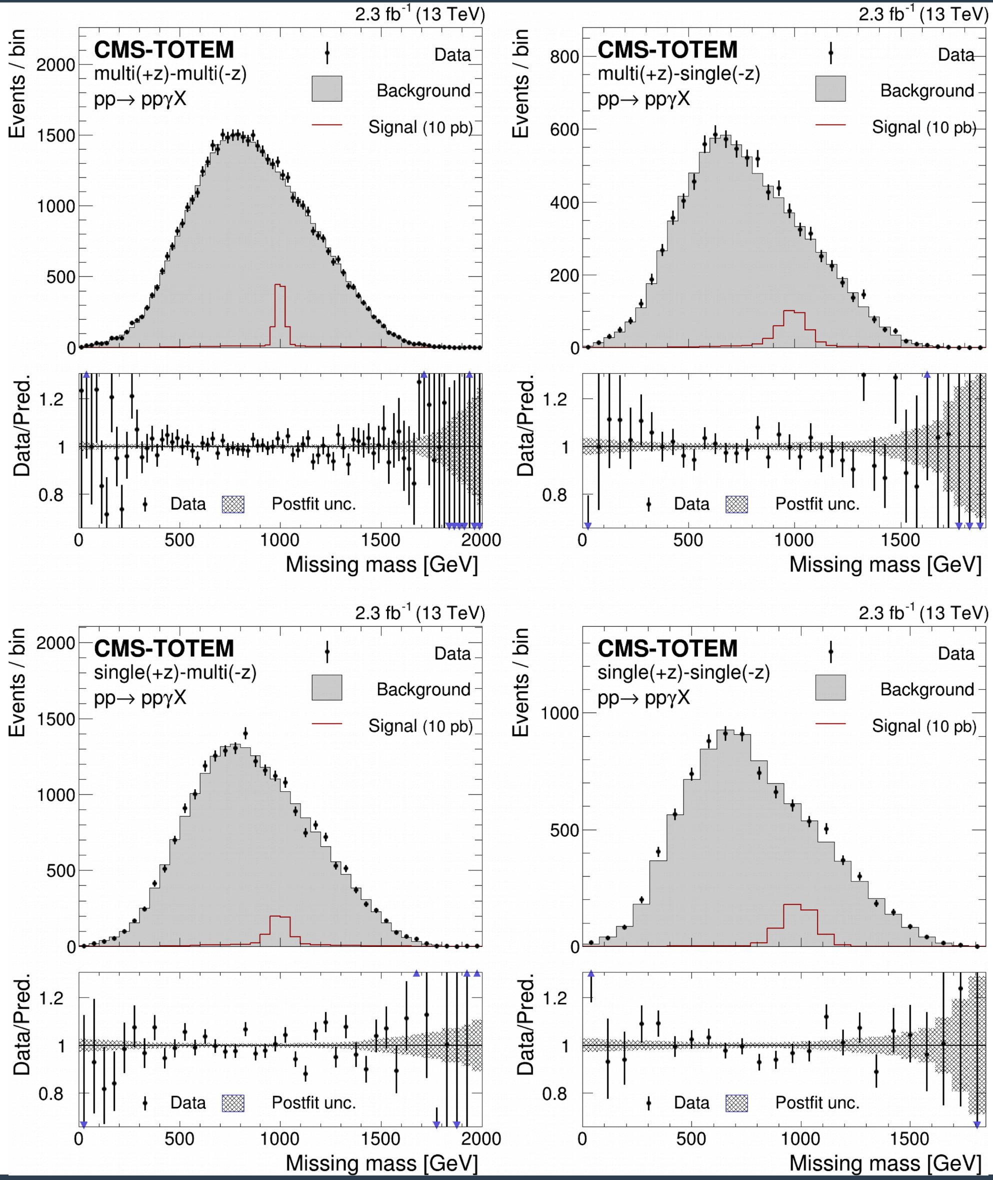


Z/γ + *X* production IV.

- **Systematic uncertainties:**
  - Incorporated as nuisance parameters in profile likelihood fit
  - Assumed to be uncorrelated between signal and background shapes or categories
  - Sources:
    - PU proton spectra (mostly affects background): 4%
    - SD: 2%
    - CT-PPS efficiency: 2-5% (depending on event category)
    - Time dependence (signal): 1%
    - p_z spectrum: < 1%
    - Selection efficiency: 3%
    - Integrated luminosity: 2.3%
    - Limited event count: < 1%

Z/γ + *X* production V.

- **Further results:**



CEP of $t\bar{t}$ with tagged protons I.

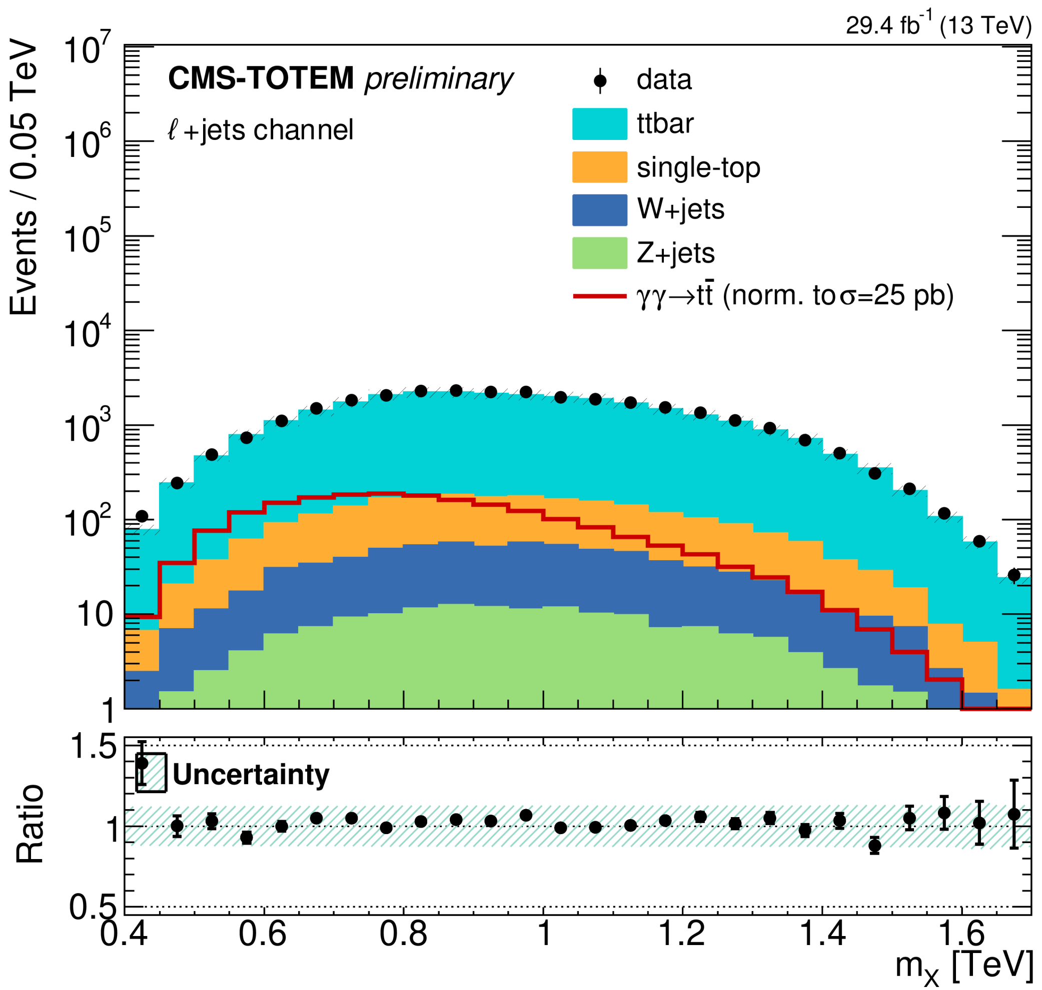
- **Data sample:**
  - 2017, *pp*, $\sqrt{s}$ = 13 TeV
  - Integrated luminosity: 29.4 fb^{-1}
- **Signal simulation:**
  - FPMC (and equivalent for photons: EPA)
    - $0.02 < \xi < 0.2$
  - Top decays (vetoing fully hadronic decays): MadSpin
- **Background simulation:**
  - Dominant inclusive $t\bar{t}$ & 2 PU protons: NLO, POWHEG v2.0
    - Cross section scaled to best theoretical prediction (NNLO): 832 pb
  - Single top (*tW*): NNLO
  - *V+j*, *VV,* Drell-Yan (DY)
- **Parton showering and hadronization: PYTHIA8 (with CP5 ULE tune, NNPDF3.1 NNLO PDFs)**
- **Detector response: Geant4**

CEP of $t\bar{t}$ with tagged protons II.

- **Event selection:**
  - Multi-RP proton track in both arms
  - lepton+jets:
    - Exactly 1 lepton satisfying: 30 GeV < p_T^{lepton}, $|\eta| < 2.1$ (electrons) or 2.4 (muons)
    - 25 GeV < p_T^{jet}, $|\eta| < 2.4$, $R = 0.4$
      - At least 2 jets b-tagged
      - At least 2 jets failing b-tagging
  - Dilepton:
    - At least 2 charged leptons:
      - At least 1: 30 GeV < p_T, $|\eta| < 2.1$
      - Highest-p_T candidates: opposite charge
      - Dilepton system: 20 GeV < M_{ll}
      - Same-flavour dilepton system outside of Z peak range: M_{ll} < 76 GeV or 106 GeV < M_{ll}
    - At least 2 b-tagged jets satisfying: 30 GeV < p_T^{jet}, $|\eta| < 2.4$, $R = 0.4$
- **B-tagging with Deep CSV**

CEP of $t\bar{t}$ with tagged protons III.

- **Background estimation:**
  - MC samples
  - Source:
    - PU proton
    - Misidentification of signal
  - Event mixing
  - MVA: TMVA toolkit

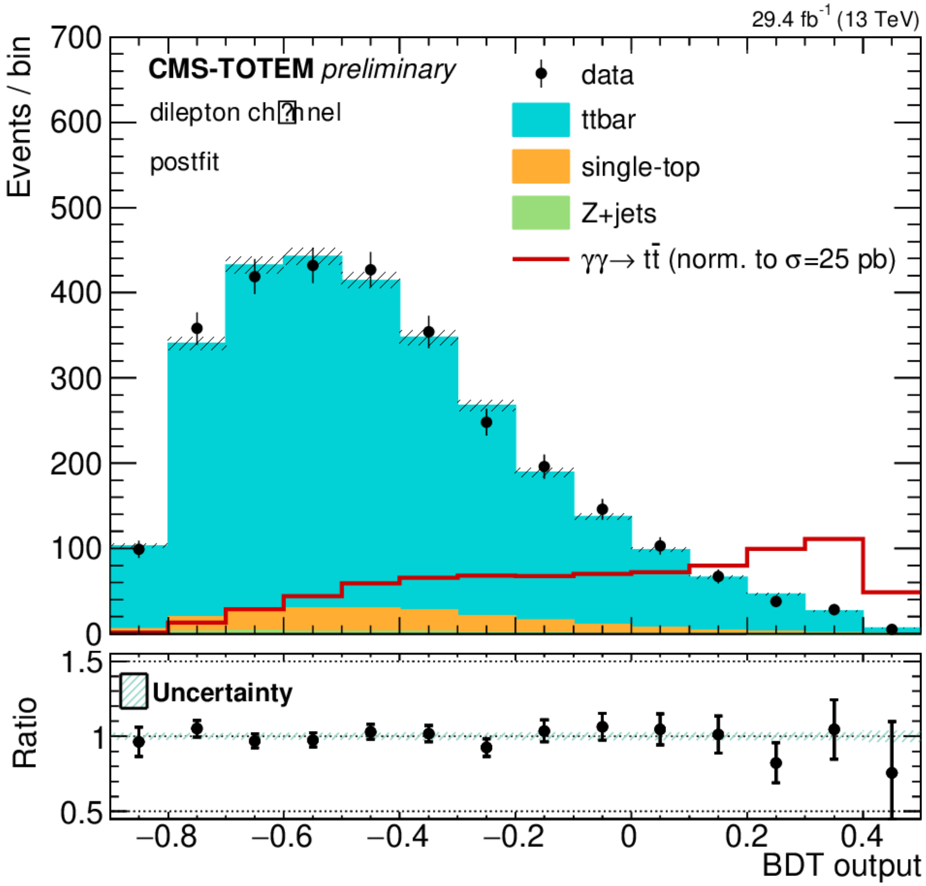


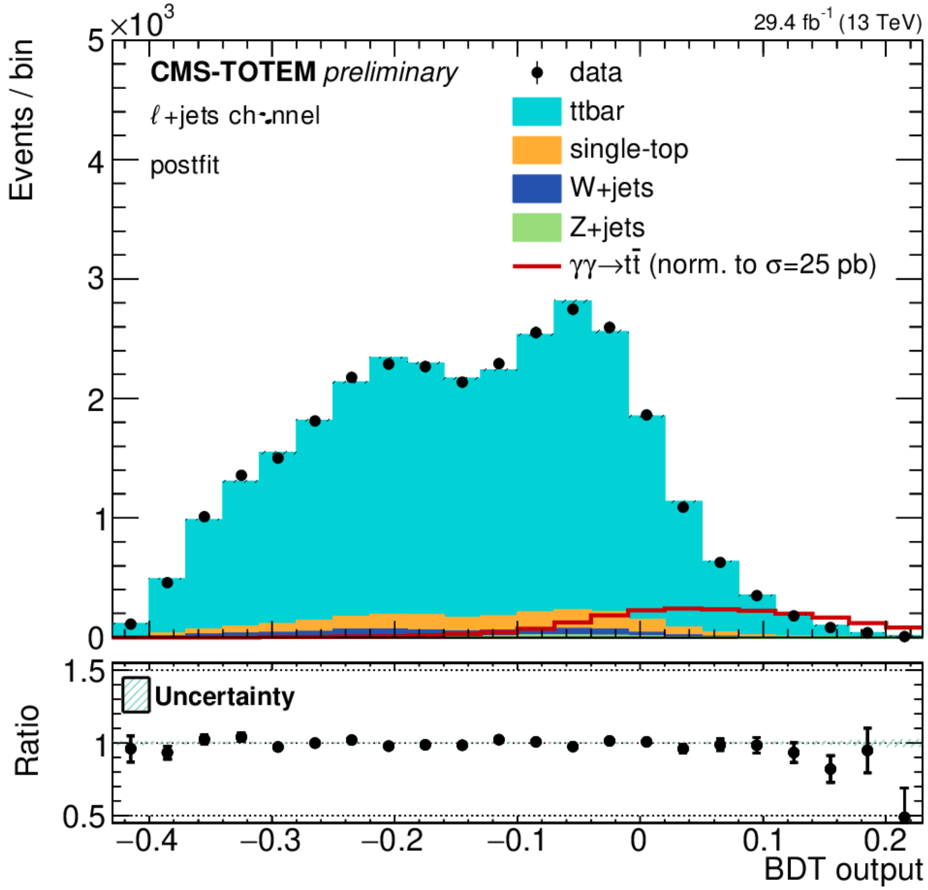
CEP of $t\bar{t}$ with tagged protons IV.

- **Systematic uncertainties:**
  - If BDT shape affected:
    - 353QH smoothing algorithm
    - Modified shapes compared to the nominal using Kolmogorov-Smirnov test
  - Experimental:
    - Integrated luminosity: 2.3%
    - Efficiency corrections for the lepton trigger: 1-8%
  - Theoretical:
    - Single top background normalization: 5%
    - Electroweak background normalization: 30%

CEP of $t\bar{t}$ with tagged protons V.

- **Further results:**





Coherent charmonium production in UPC I.

- **Data sample:**
  - 2018, *PbPb*, $\sqrt{s_{NN}} = 5.02$ TeV
  - Integrated luminosity: $228 \pm 10\ \mu b^{-1}$
- **Simulated events (for corrections for detector resolution, acceptance and efficiency):**
  - UPCs: STARlight (with specific LHCb configuration)
  - Decays of unstable particles: EvtGen (with QED final-state radiation handled by PHOTOS)
- **Detector response: Geant4**

Coherent charmonium production in UPC II.

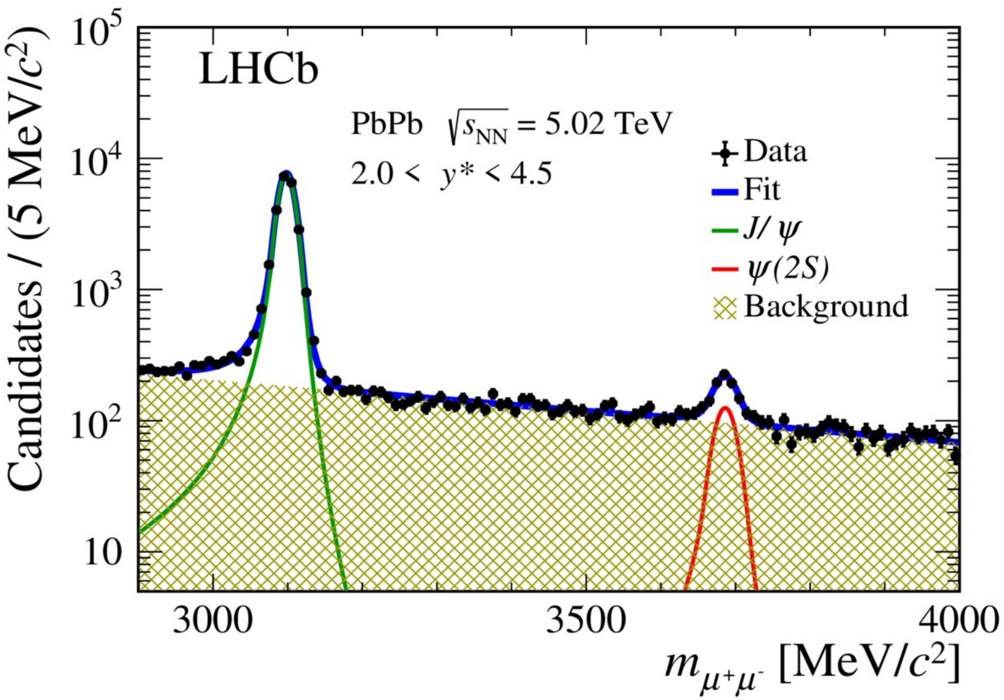
- **Event selection:**
  - Decay channels:
    - $J/\psi \to \mu^+\mu^-$
    - $\psi(2S) \to \mu^+\mu^-$
  - $2.0 < y^{\textit{in nucleus-nucleus center-of-mass frame}} < 4.5$
  - Triggers:
    - Hardware-level: at least 1 muon of $p_T > 900$ MeV
    - Software-level (minimum bias): at least 1 track reconstructed by the vertex detector
  - Offline:
    - 2 muons with $p_T > 700$ MeV in $2.0 < \eta < 4.5$
    - Dimuon candidate with $p_T < 1$ GeV, $\Delta\phi > 0.9\pi$
    - Dimuon mass in either ± 65 MeV (J/ψ) or ± 77.35 MeV ($\psi(2S)$)
  - Vetoes for too high activity in HeRSCheL & SPD

Coherent charmonium production in UPC III.

- **Background estimation: fits**

Interval [MeV/c]	$N^{\text{tot}}_{J/\psi}$	$N^{\text{coh}}_{J/\psi}$
$0 < p^*_{\text{T}} < 200$	$21\,153 \pm 175$	$20\,180 \pm 175$
$0 < p^*_{\text{T}} < 20$	$2\,216 \pm 58$	$2\,204 \pm 58$
$20 < p^*_{\text{T}} < 40$	$5\,647 \pm 92$	$5\,619 \pm 92$
$40 < p^*_{\text{T}} < 60$	$5\,931 \pm 83$	$5\,885 \pm 83$
$60 < p^*_{\text{T}} < 80$	$3\,928 \pm 65$	$3\,863 \pm 65$
$80 < p^*_{\text{T}} < 100$	$1\,848 \pm 44$	$1\,759 \pm 44$
$100 < p^*_{\text{T}} < 120$	497 ± 23	381 ± 24
$120 < p^*_{\text{T}} < 140$	225 ± 16	88 ± 17
$140 < p^*_{\text{T}} < 160$	289 ± 17	137 ± 18
$160 < p^*_{\text{T}} < 180$	328 ± 18	167 ± 20
$180 < p^*_{\text{T}} < 200$	244 ± 16	77 ± 17

Interval [MeV/c]	$N^{\text{tot}}_{\psi(2S)}$	$N^{\text{coh}}_{\psi(2S)}$
$0 < p^*_{\text{T}} < 200$	475 ± 41	468 ± 41
$0 < p^*_{\text{T}} < 30$	77 ± 35	77 ± 35
$30 < p^*_{\text{T}} < 70$	275 ± 39	274 ± 39
$70 < p^*_{\text{T}} < 90$	91 ± 14	91 ± 14
$90 < p^*_{\text{T}} < 110$	27 ± 8	27 ± 8
$110 < p^*_{\text{T}} < 150$	0 ± 5	0 ± 5
$150 < p^*_{\text{T}} < 200$	5 ± 4	2 ± 4



Interval	$N^{\text{tot}}_{J/\psi}$	$N^{\text{coh}}_{J/\psi}$	$N^{\text{tot}}_{\psi(2S)}$	$N^{\text{coh}}_{\psi(2S)}$
$2.0 < y^* < 4.5$	$23\,355 \pm 183$	$20\,193 \pm 199$	513 ± 43	471 ± 44
$2.0 < y^* < 2.5$	$2\,457 \pm 60$	$2\,070 \pm 66$	75 ± 15	65 ± 15
$2.5 < y^* < 3.0$	$6\,845 \pm 100$	$5\,926 \pm 108$	147 ± 26	137 ± 26
$3.0 < y^* < 3.5$	$7\,875 \pm 106$	$6\,883 \pm 115$	168 ± 26	161 ± 26
$3.5 < y^* < 4.0$	$5\,019 \pm 82$	$4\,362 \pm 90$	102 ± 18	85 ± 18
$4.0 < y^* < 4.5$	$1\,166 \pm 38$	956 ± 44	24 ± 8	21 ± 8

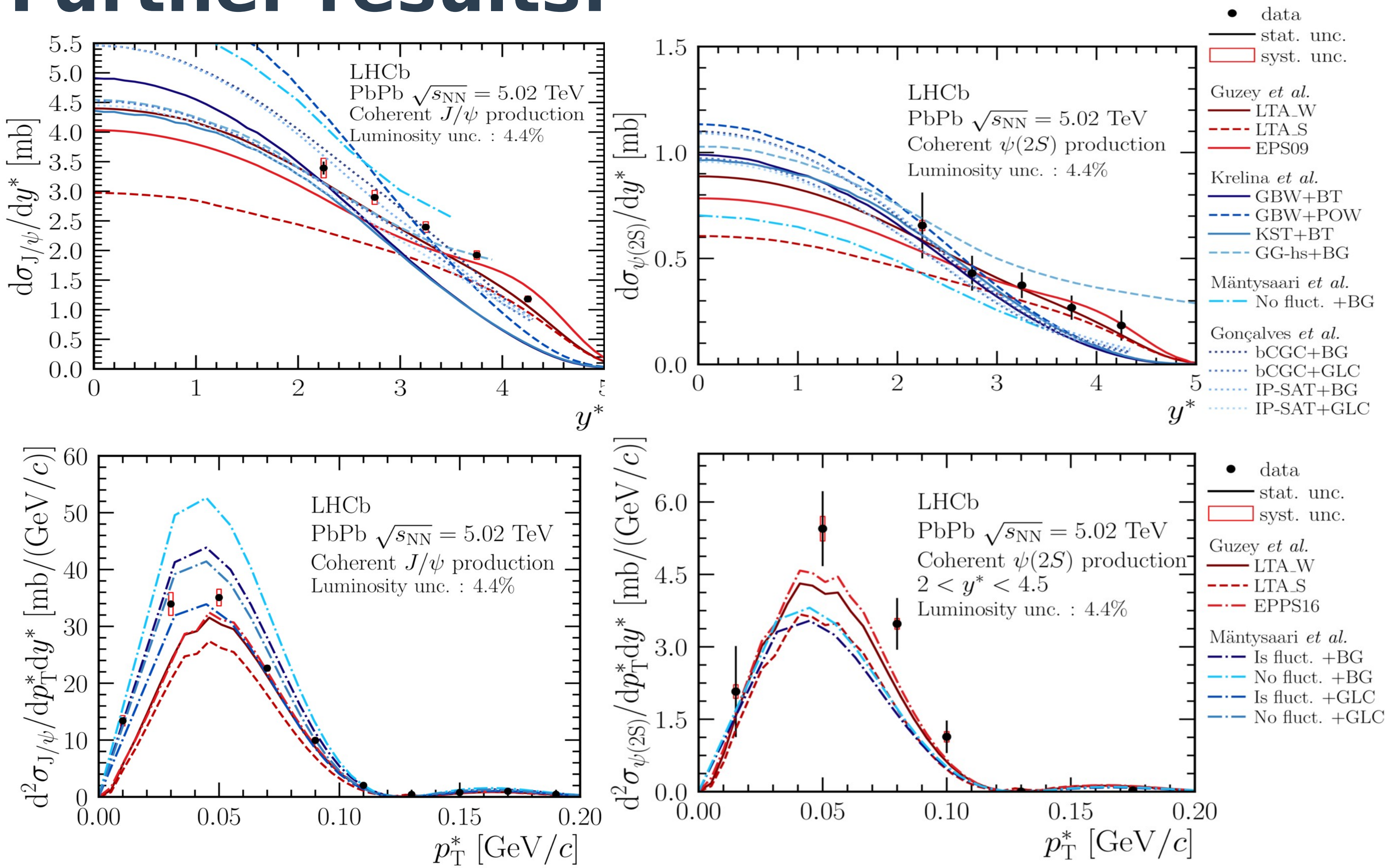
Coherent charmonium production in UPC IV.

- **Systematic uncertainties:**

Source	Relative uncertainty [%]	
	$\sigma_{J/\psi}^{\text{coh}}$	$\sigma_{\psi}(2S)^{\text{coh}}$
Tracking efficiency	0.5–2.0	0.5–2.0
PID efficiency	0.9–1.6	0.9–1.6
Trigger efficiency	2.7–3.7	2.1–2.5
HeRSChel efficiency	1.4	1.4
Background estimation	1.2	1.2
Signal shape	0.04	0.04
Momentum resolution	0.9–34	1.3–27
Branching fraction	0.6	2.1
Luminosity	4.4	4.4

Coherent charmonium production in UPC V.

- **Further results:**



Exclusive pion pair production I.

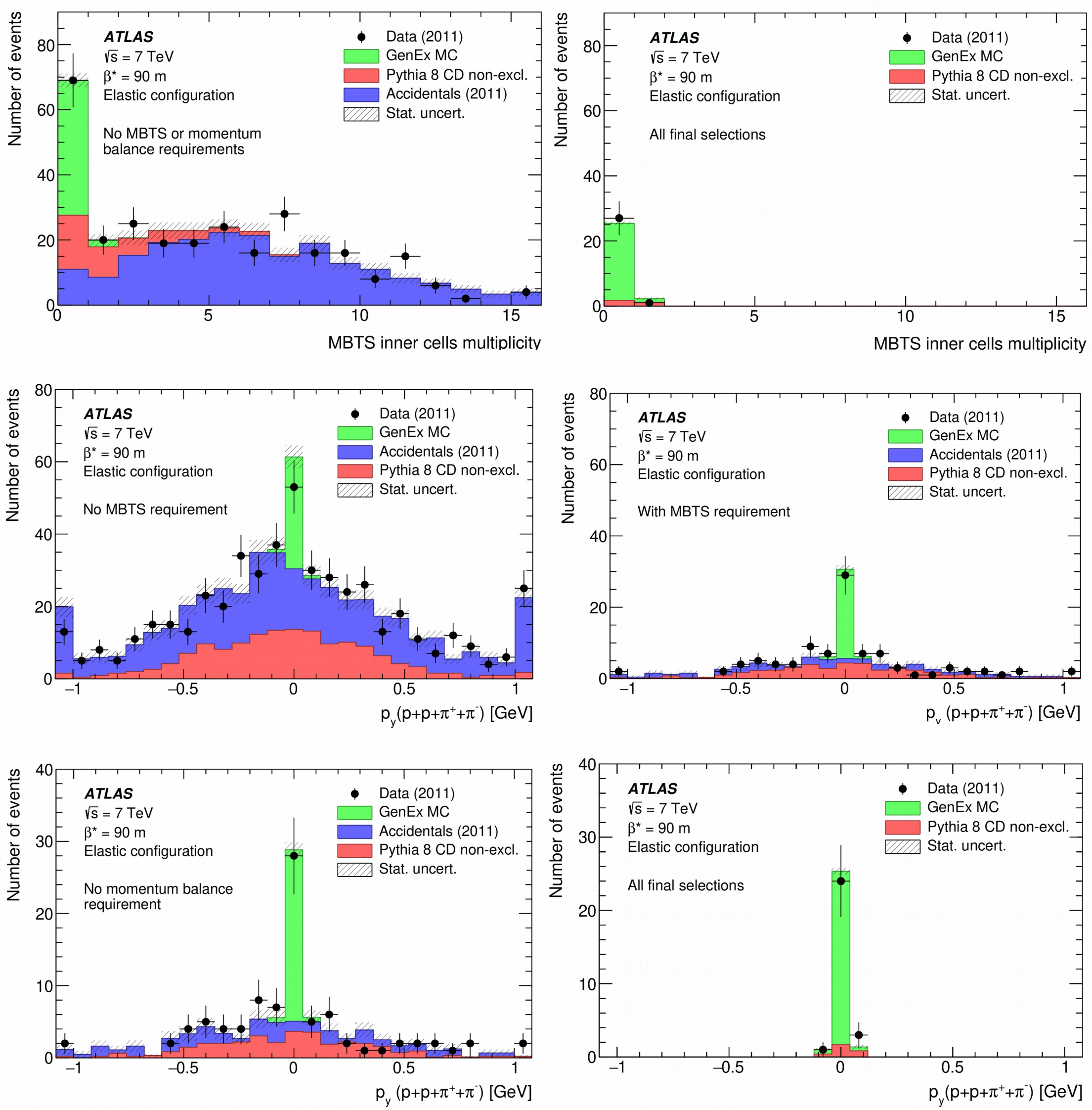
- **Data sample:**
  - October 2011, *pp*, $\sqrt{s}$ = 7 TeV
  - Special run: β^* = 90 m, low PU (μ = 0.035), 7 $\cdot 10^{10}$ protons / bunch
  - Integrated luminosity: 78.7 $\pm$ 0.1 (stat) $\pm$ 1.9 (syst) μb^{-1}
- **MC generators:**
  - GenEx (baseline calculations of detection & reconstruction efficiency):
    - Exclusive continuum of $\pi^+\pi^-$ & K^+K^-
    - Exponential parametrization for the meson form factor (only free parameter)
    - Non-resonant production without absorption correction
    - No rapidity gap survival probability
    - Pions generated: $|\eta|$ < 2.7, off-shell-pion form-factor parameter = 1 GeV
  - Dime (for comparison & model uncertainties):
    - Other channels also included: exclusive $\rho\rho$ or $\phi\phi$
    - 4 different models for absorption with 3 different parametrization of the meson form factor (exponential, Orear-like, power-like)
- **CEP background: PYTHIA8 version 8.183 (with ATLAS A2 set of tuned parameters and MSTW20008LO PDF set, excluding exclusive pion-pair process)**
- **Detector response: Geant4**

Exclusive pion pair production II.

- **Event selection:**

Selection
Bunch selection
Lumi blocks selection
Trigger configuration
Pions:
number of tracks
primary vertex
ID track quality
MBTS veto
Protons:
ALFA track quality
ALFA *uv*-condition
ALFA clean track
ALFA geometry condition
Full system momentum balance in p_x and p_y
Fiducial region

Exclusive pion pair production III.



Background estimation:

- Combinatorical: suppressed by event selection
- MBTS veto: great background suppression
- Other central diffraction processes also suppressed

Exclusive pion pair production IV.

- **Systematic uncertainties:**

Source of uncertainty	Uncertainty [%] elastic	Uncertainty [%] anti-elastic
Trigger efficiency ϵ_{trig}	± 0.1	± 0.3
Background determination	± 3.5	± 3.5
Signal and background corrections:		
Beam energy	± 0.1	± 0.1
ID material	$+4.8$	$+4.1$
Veto on MBTS signal	± 1.3	± 2.0
ALFA single-track selection	± 0.9	± 0.9
ALFA reconstruction efficiency	± 0.9	± 0.8
ALFA geometry selection	± 0.5	± 0.5
Optics	± 1.1	± 1.0
Overall systematic uncertainty	$+6.4$ -4.2	$+6.0$ -4.4
Statistical uncertainty	± 21.2	± 61.6
Theoretical modelling	± 2.8	± 8.0
Luminosity	± 1.2	± 1.2

Exclusive pion pair production V.

- **Further results:**

Exclusive $\pi^+\pi^-$ cross-section [μb]	
Elastic configuration	
Measurement	4.8 ± 1.0 (stat) $^{+0.3}_{-0.2}$ (syst) ± 0.1 (lumi) ± 0.1 (model)
GenEx $\times$ 0.22 (absorptive correction)	1.5
Dime	1.6
Anti-elastic configuration	
measurement	9 ± 6 (stat) $^{+1}_{-1}$ (syst) ± 1 (lumi) ± 1 (model)
GenEx $\times$ 0.22 (absorptive correction)	2
Dime	3

Total cross section measurements with ALFA I.

- **Data sample:**
  - September 2016, *pp*, $\sqrt{s}$ = 13 TeV
  - Special run: β^* = 2.5 km, 6 $\cdot 10^{10}$ protons / bunch
  - Integrated luminosity: 339.9 $\pm$ 0.1 (stat) $\pm$ 7.3 (syst) μb^{-1}
- **Simulation model:**
  - MC for acceptance and unfolding corrections
  - Background DPE: PYTHIA 8.303
  - Detector response: Geant4

Total cross section measurements with ALFA II.

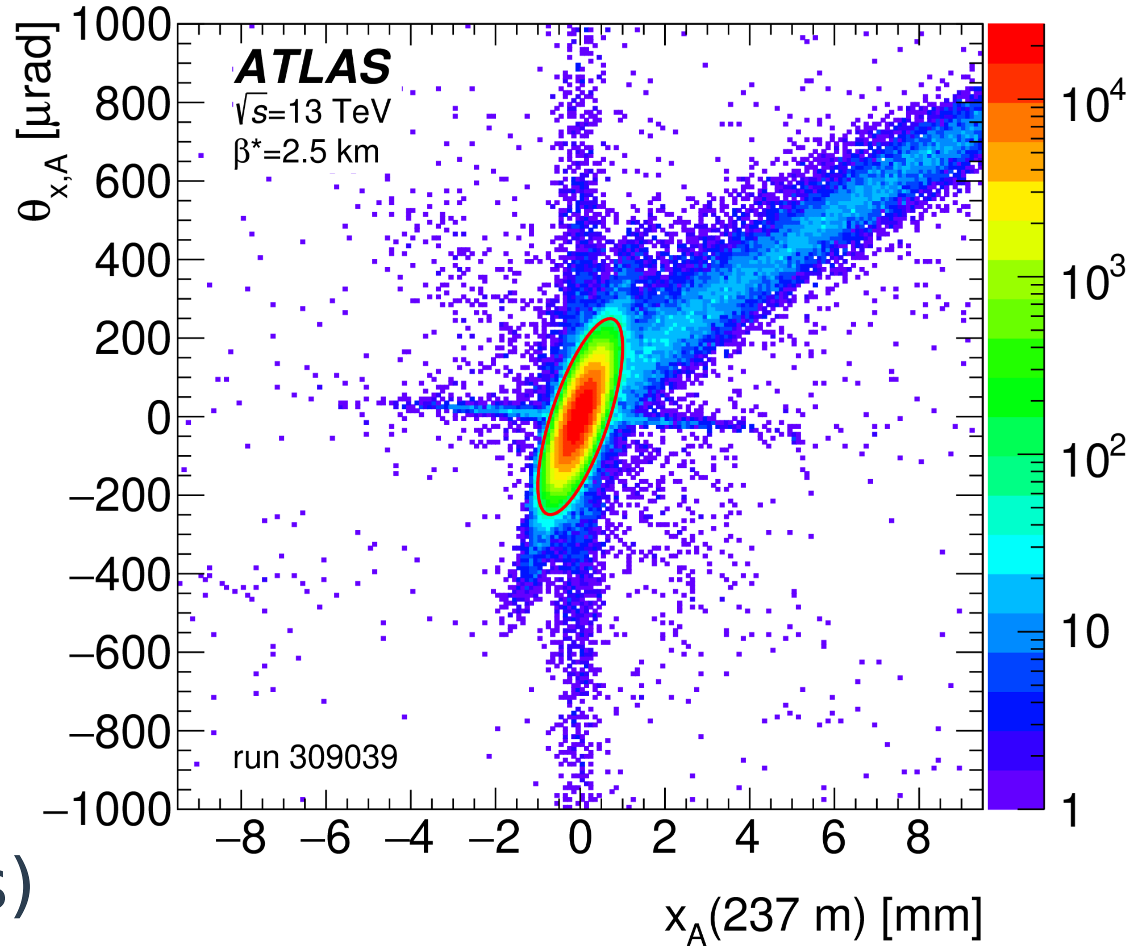
- **Event selection:**

Selection criterion	Numbers of events			
Preselection	2 558 637			
	Arm 1	Fraction	Arm 2	Fraction
Reconstructed tracks	1 289 282		1 269 355	
Cut on x A vs C (3.5σ)	1 254 738	97.32%	1 235 792	97.36%
Cut on y A vs C (2 mm)	1 249 888	96.95%	1 231 251	96.99%
Cut on x vs θ_x (3.5σ)	1 248 597	96.84%	1 230 084	96.91%
Beam-screen cut	1 243 941	96.48%	1 225 375	96.53%
Edge cut	1 231 848	95.55%	1 210 759	95.38%
Cut on y vs θ_y (40 µrad)	1 214 717	94.22%	1 195 251	94.16%
Total selected	2 409 968			

Fill	Run	Luminosity [μb^{-1}]	Selected elastic event candidates	Reconstruction efficiency Arm 1 [%]	Arm 2 [%]
5313	308979	21.38	423 862	84.82 ± 0.56	83.11 ± 0.87
5313	308982	6.81	136 499	85.84 ± 0.54	84.44 ± 0.55
5314	309010	41.27	846 581	87.11 ± 0.51	85.00 ± 0.64
5317	309039	120.08	2 409 968	85.45 ± 0.49	83.23 ± 0.52
5317	309074	44.31	887 373	85.55 ± 0.39	83.48 ± 0.48
5321	309165	55.87	1 149 499	87.08 ± 0.40	85.41 ± 0.44
5321	309166	50.17	1 043 576	88.28 ± 0.38	86.43 ± 0.45
Total		339.89	6 897 358		

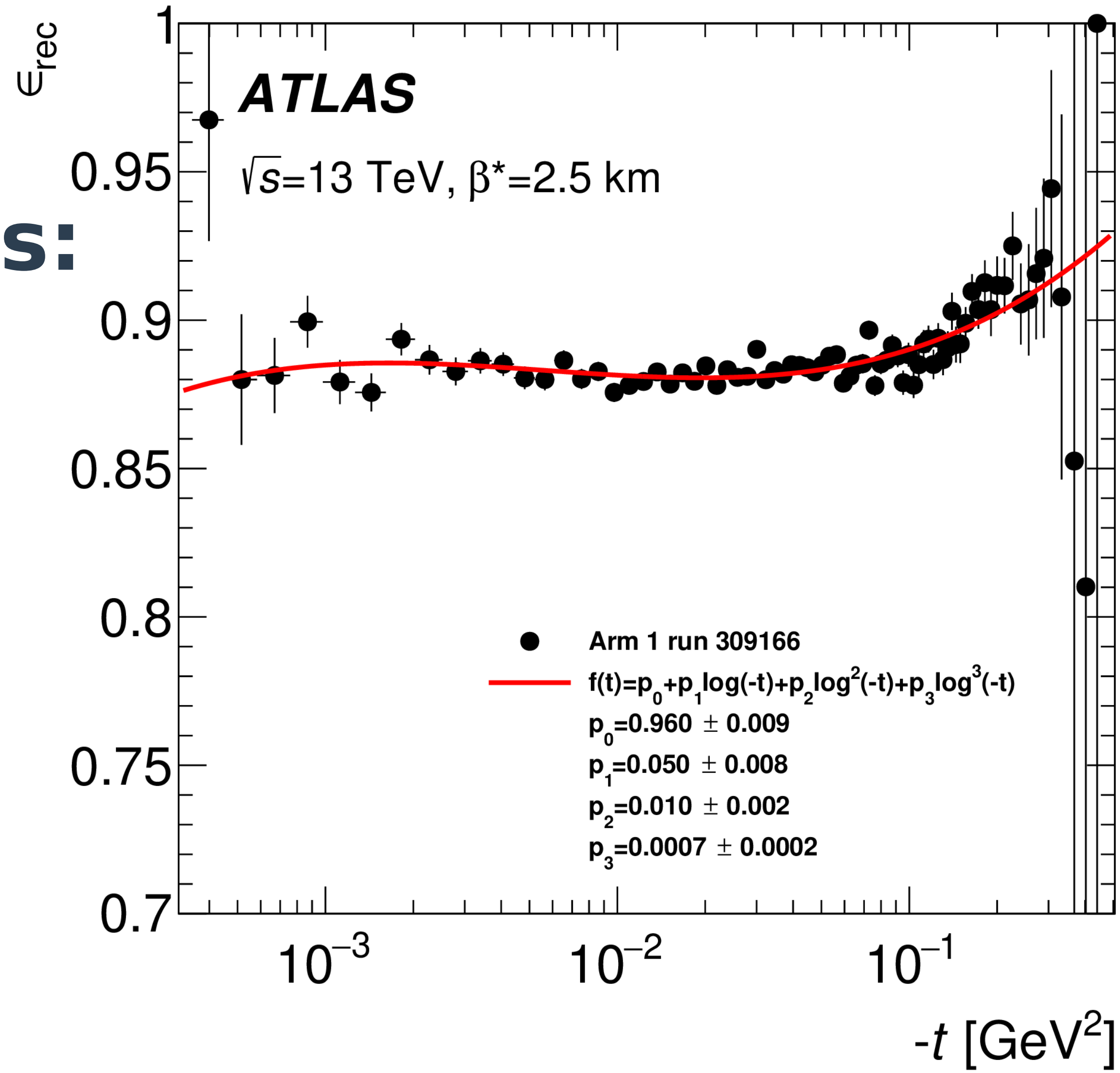
Total cross section measurements with ALFA III.

- **Background estimation:**
  - Data-driven: templates of halo-halo & halo+SD
  - Non-elastic, from central diffraction: double-pomeron exchange (DPE)
  - SD with PU proton(s)
  - Event mixing



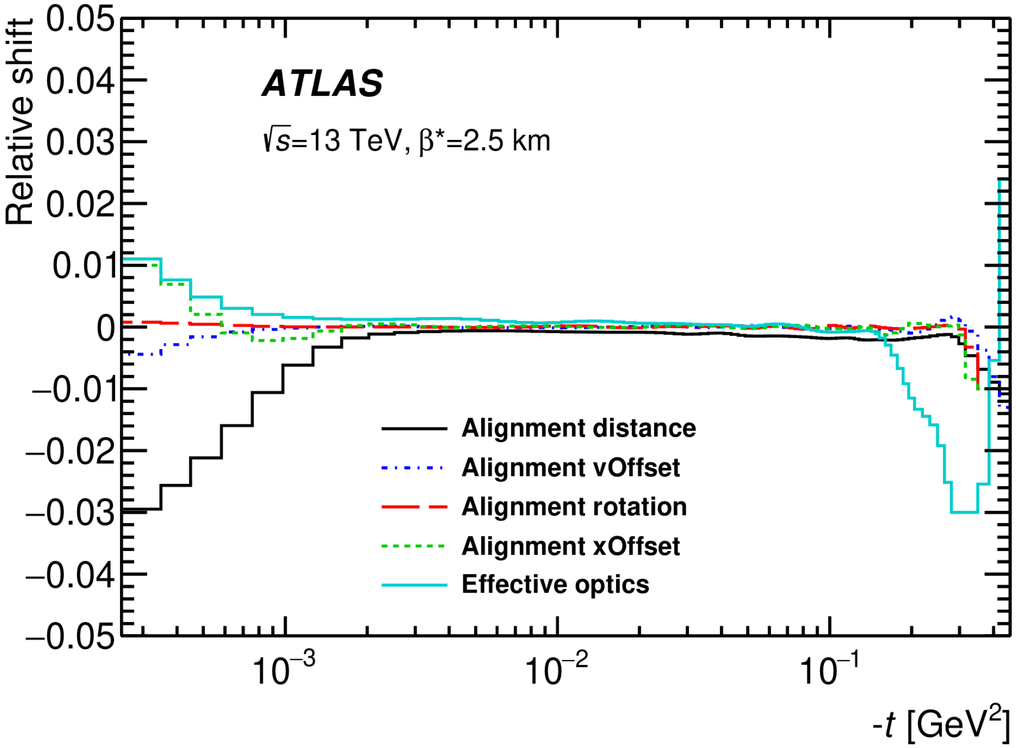
Total cross section measurements with ALFA IV.

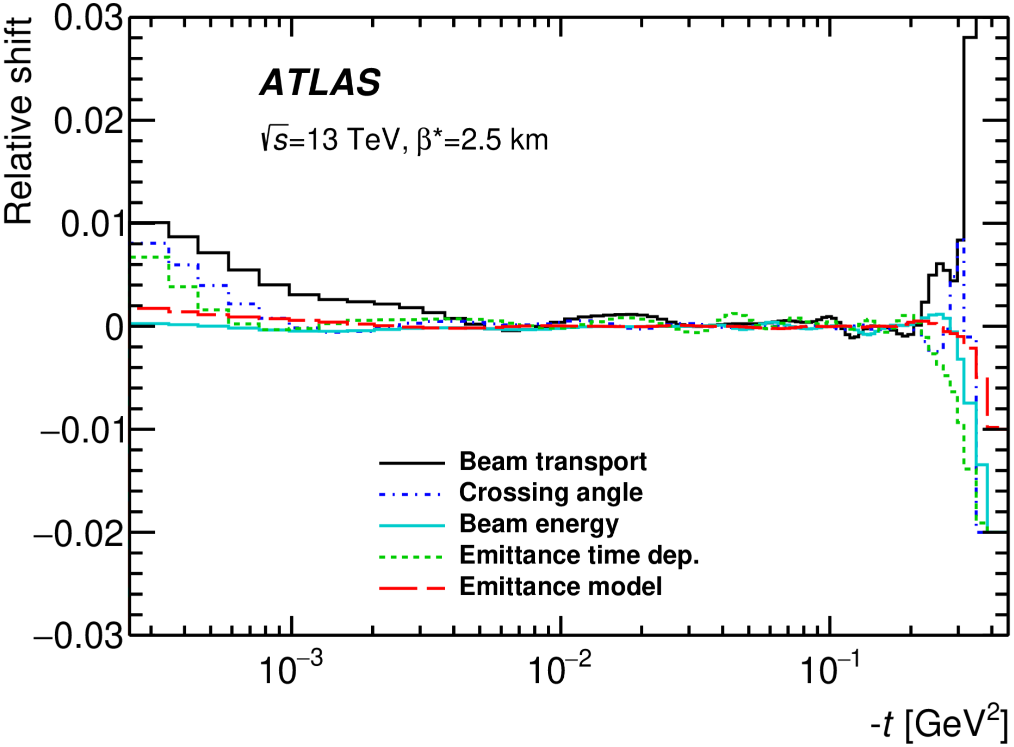
- **Systematic uncertainties:**



Total cross section measurements with ALFA V/a.

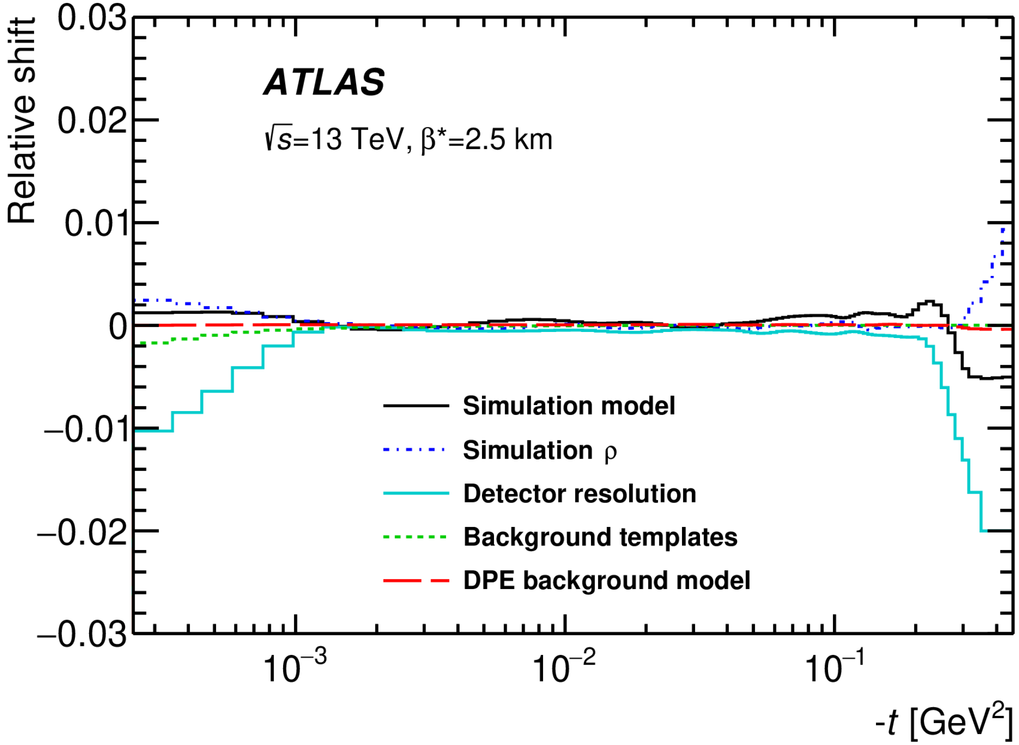
- **Further results: relative systematic shifts resulting from uncertainties**

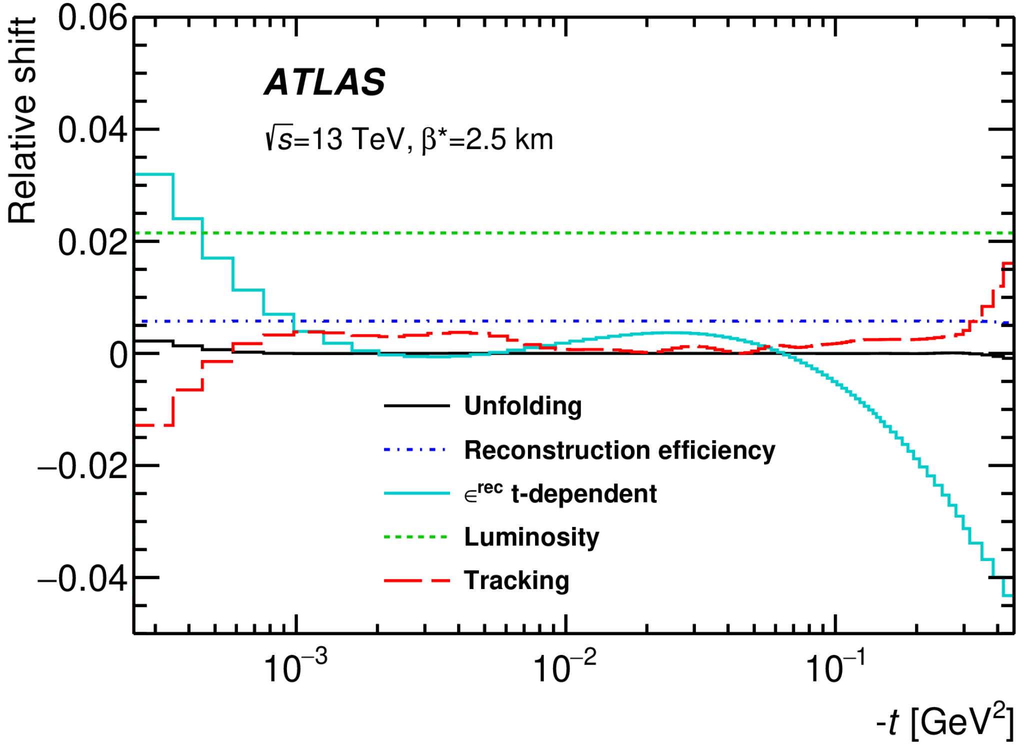




Total cross section measurements with ALFA V/b.

- **Further results: relative systematic shifts resulting from uncertainties**

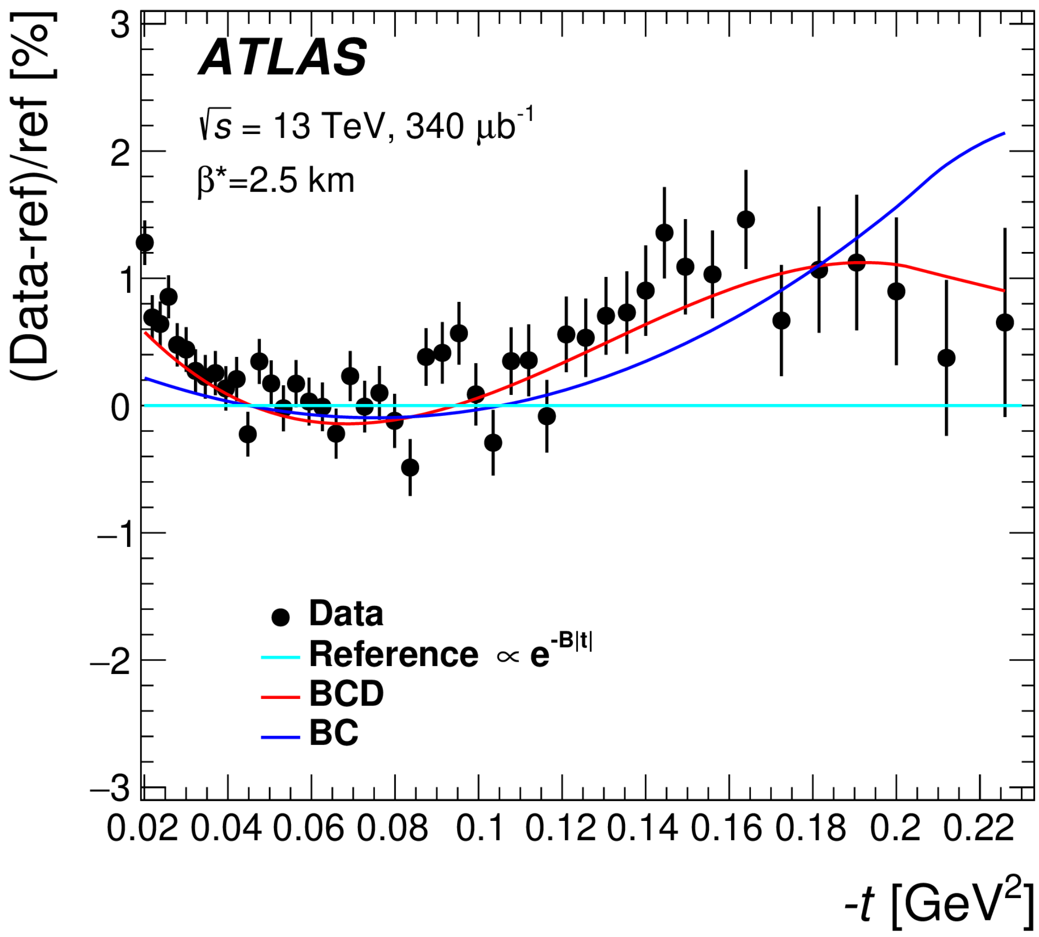


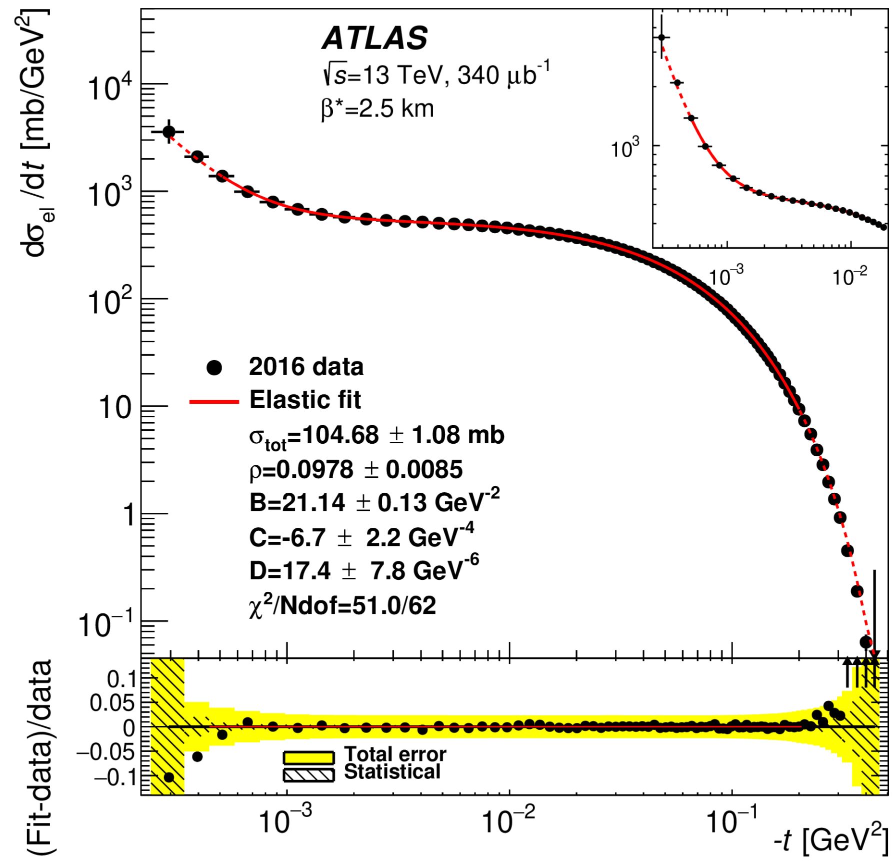


arXiv: 2207.12246 (ATLAS, STDM-2018-08)

Total cross section measurements with ALFA V/c.

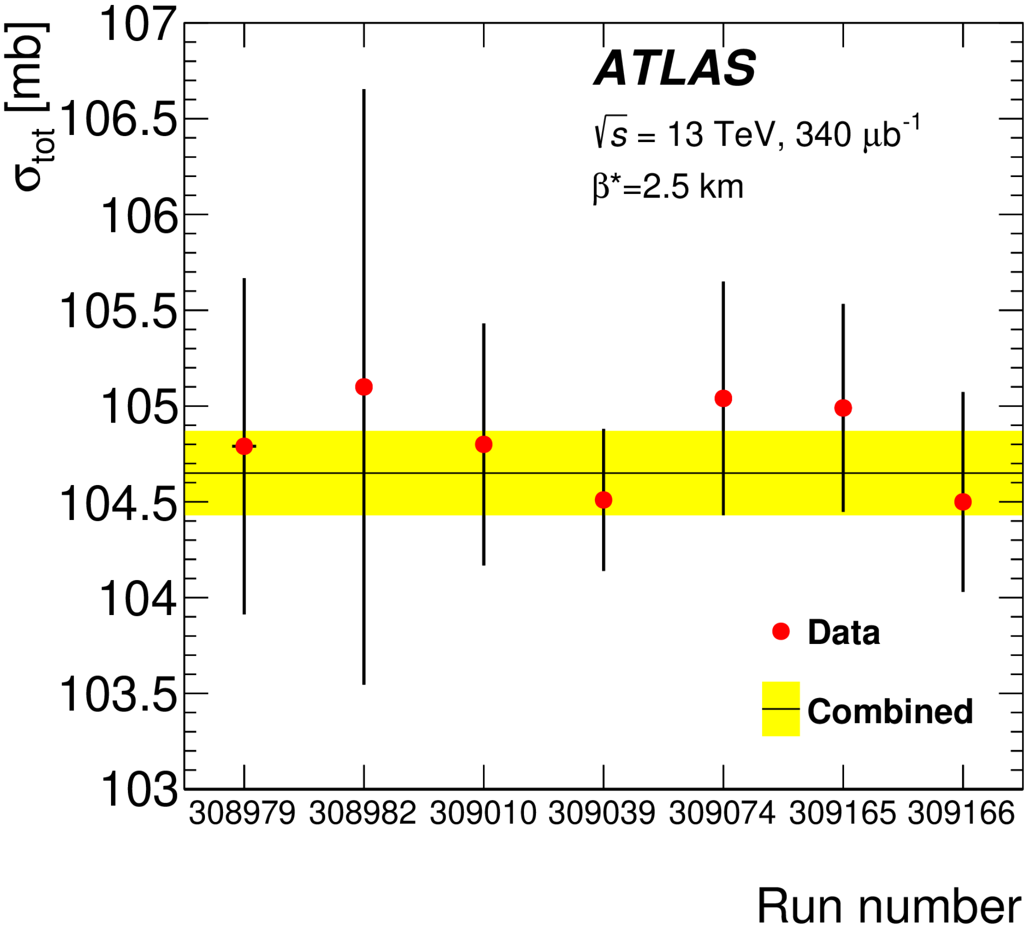
- **Further results: Nuclear slope fits**

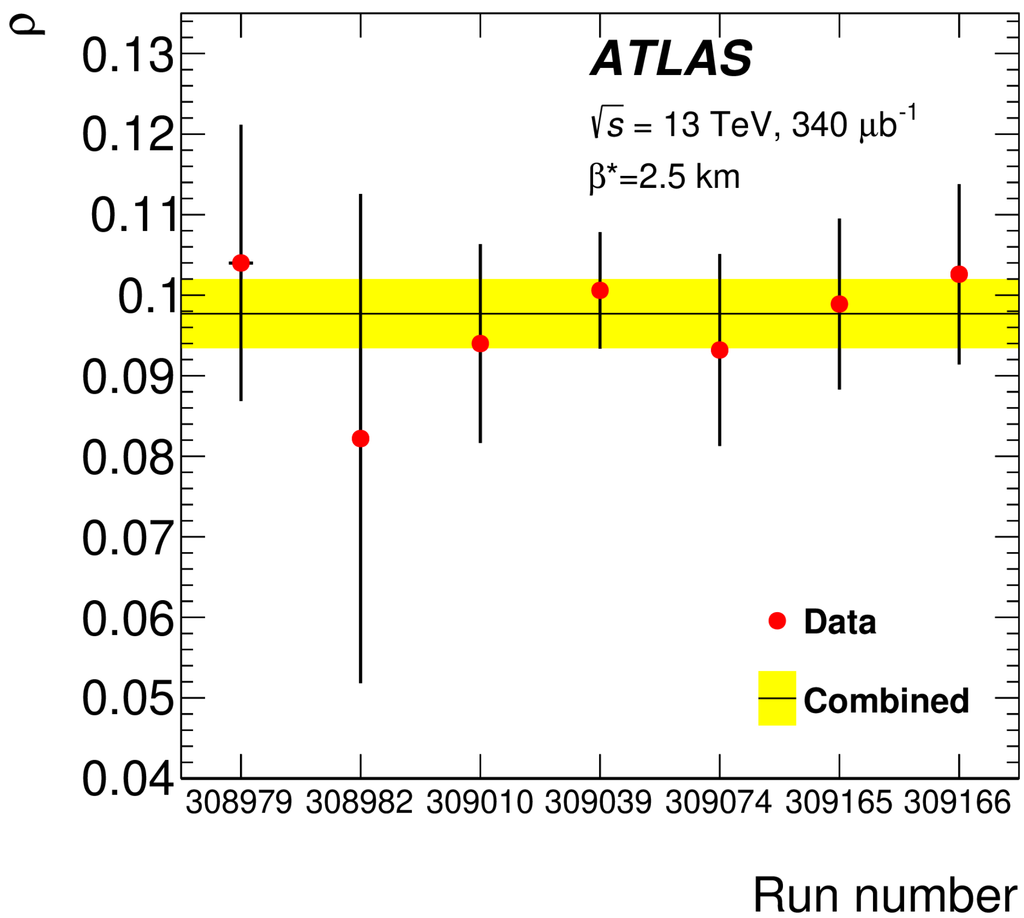




Total cross section measurements with ALFA V/d.

- **Further results: time evolution**





Total cross section measurements with ALFA V/e.

- **Further results:**