Exclusive diffractive results from ATLAS, CMS, LHCb, TOTEM at the LHC

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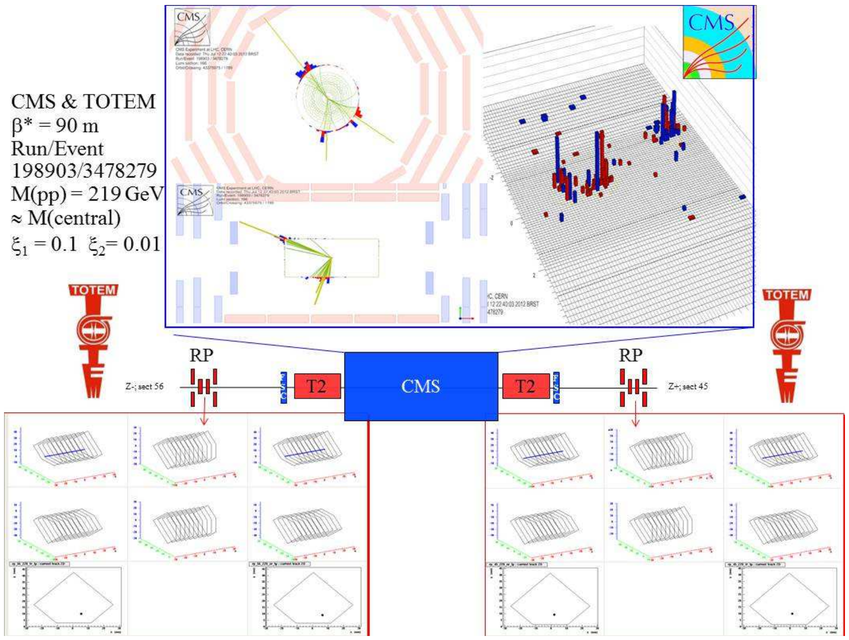
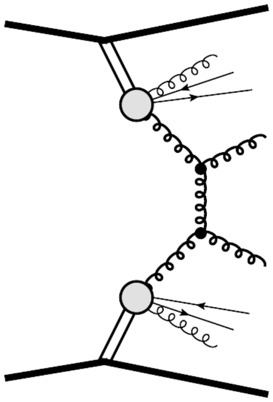
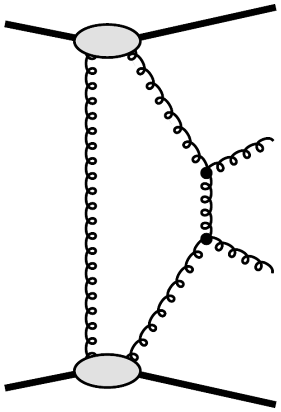
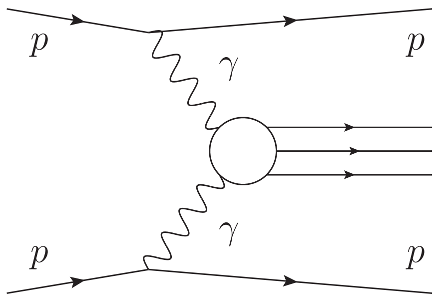


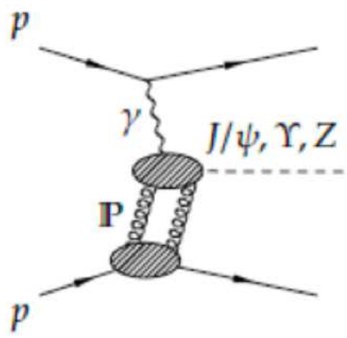
- LHCb results on vector meson production
- ATLAS results (dimuon, diphoton)
- CMS and CMS/TOTEM (dimuon, WW, pion) and prospects

What do we call Exclusive Diffraction / γ exchange events?



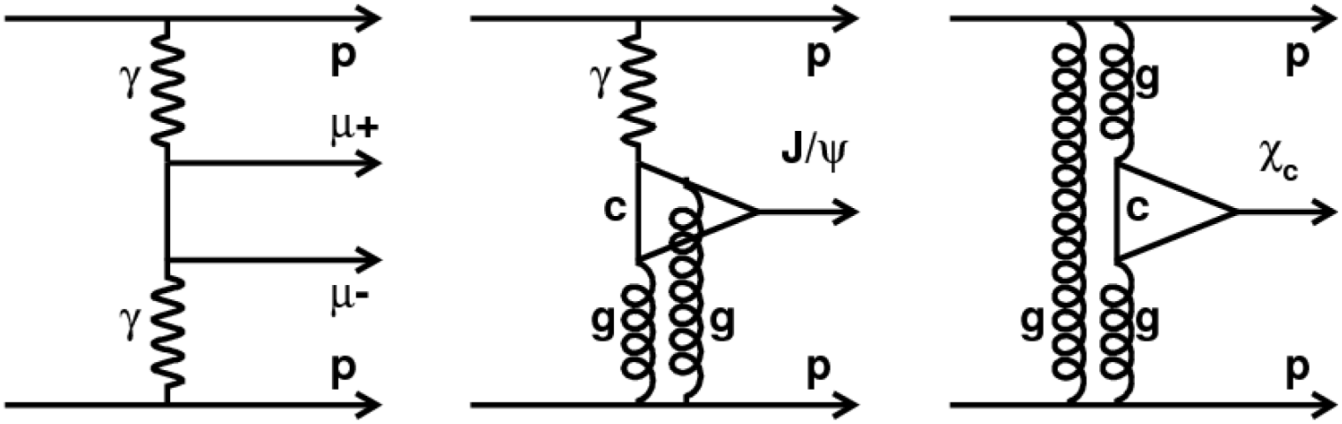






- Left diagram: Double Pomeron Exchange: some energy is "lost" in Pomeron remnanats
- Next three diagrams: Exclusive production: the full energy is used to produce dijets, vector mesons, no energy loss
  - Dijet production via gluon exchange, QCD process (KMR)
  - Photon exchange
  - Vector meson production
- Possibility to reconstruct the properties of the object produced exclusively (via photon and gluon exchanges) from the tagged proton: system completely constrained
- Central exclusive production is a potential channel for BSM physics: sensitivity to high masses up to 1.8 TeV

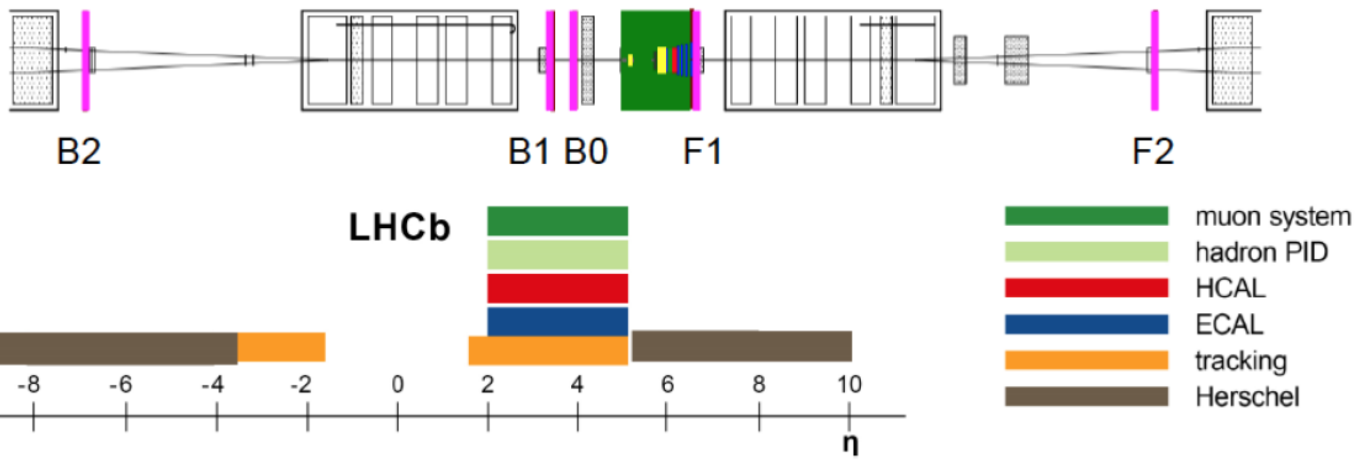
Measurement of central exclusive production in LHCb



QED photoproduction Double Pomeron Exchange

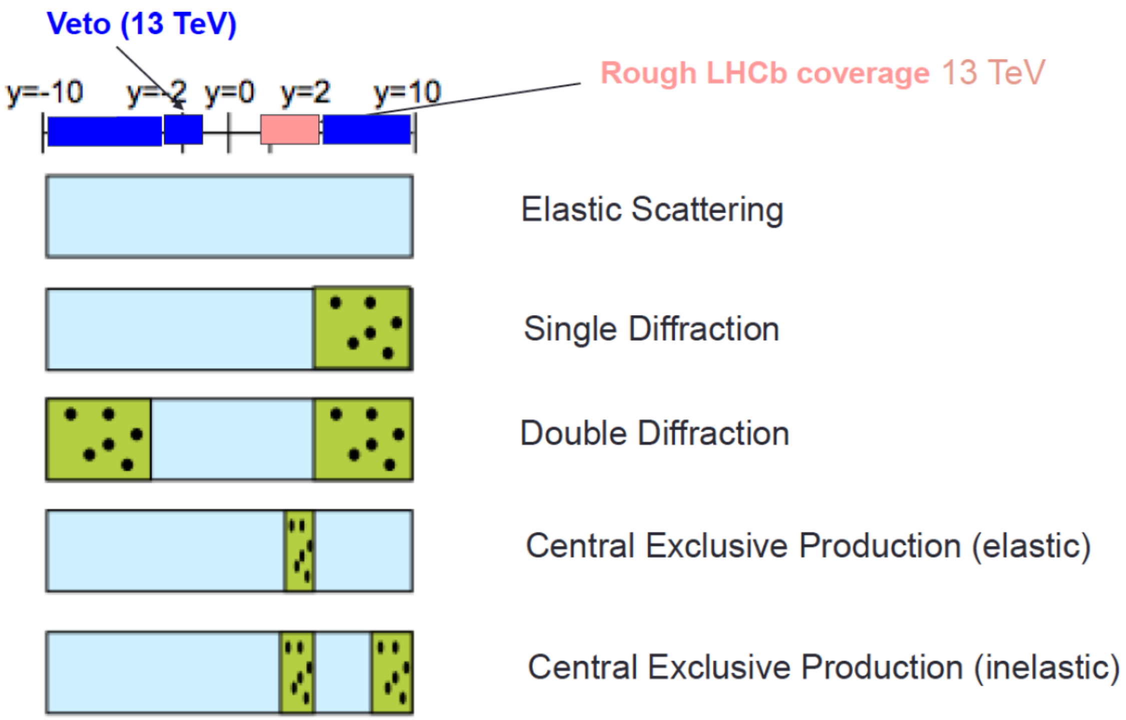
- Measurement of exclusive production of J/Ψ vector meson as an example: Sensitivity to gluon distribution in Pomeron
- Signal: Central system with rapidity gaps
- Background: Diffractive processes (pomeron remnants not detected, outside detector acceptance)
- Experimental issue: Detection of rapidity gaps
- New detectors in Run II: HERSCHEL, High Rapidity Shower Counters for LHCb that allow a better suppression of diffractive processes (detection of Pomeron remnants)

HERSCHEL



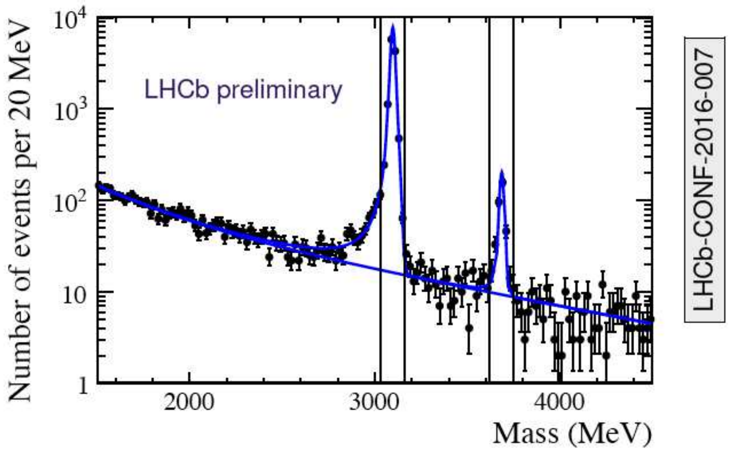
pseudorapidity coverage of HeRSCheL: $-10.0 < \eta < -3.5 \quad 5.0 < \eta < 10.0$

pseudorapidity coverage of LHCb (Run 2) : $-10.0 < \eta < -1.5 \quad 2.0 < \eta < 10.0$

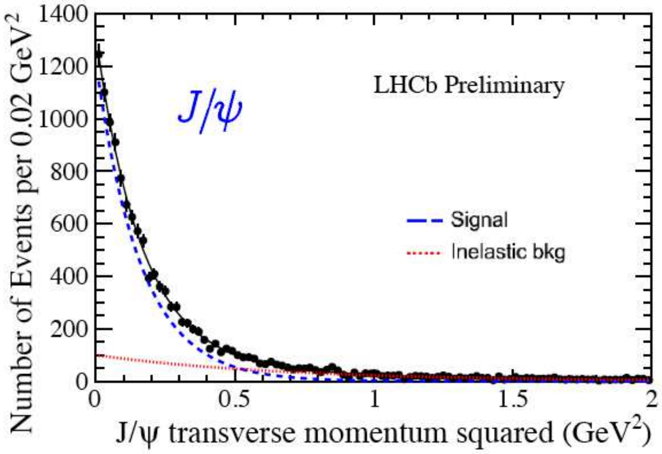


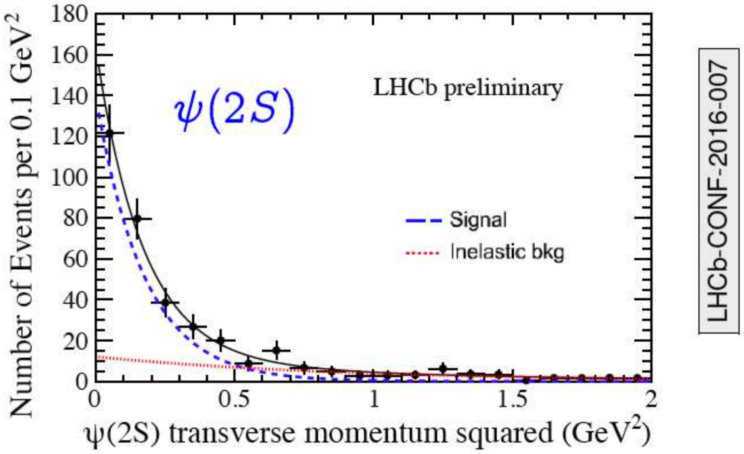
Event selection and results at 13 TeV

- Veto on forward tracks
- Further cleanup by veto on HERSCHEL signal significance



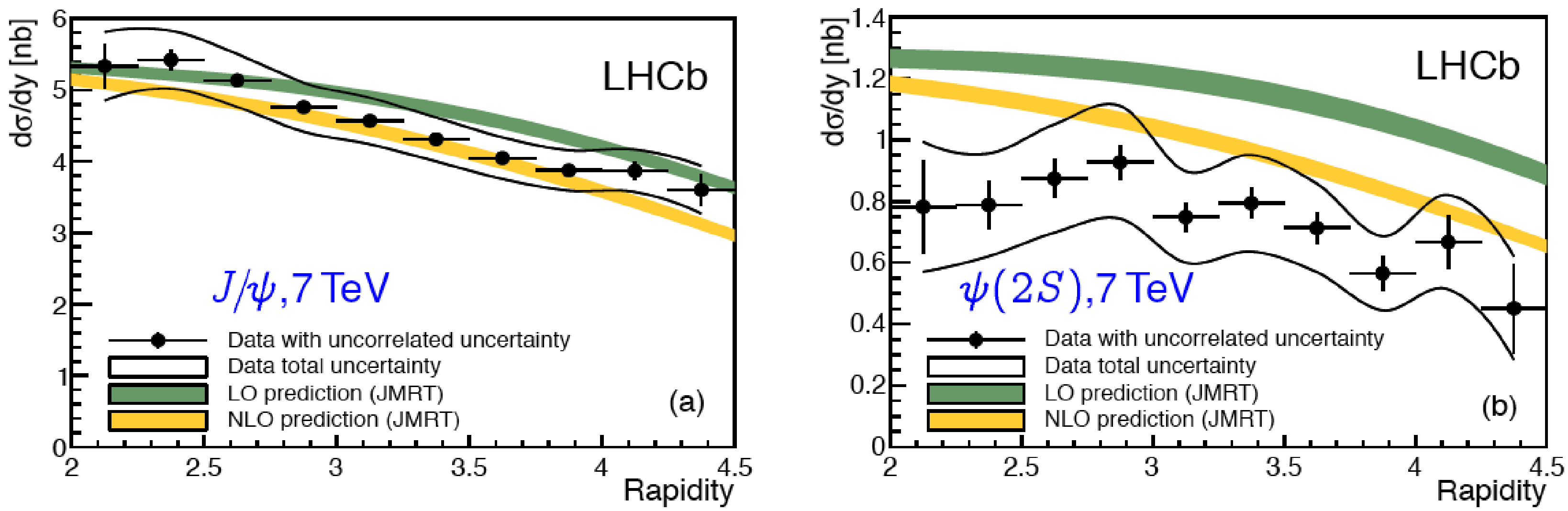
- L=204 pb^{-1} (1 fb^{-1} at 7 TeV)
- low-p_T CEP signature
- inelastic: ∼20%, (40% at 7 TeV)
- feeddown: J/ψ 6% (10% at 7 TeV)





LHCb results on exclusive J/Ψ and $\Psi(2S)$

- Uncertainties highly correlated between bins
- Preferred model: JMRT NLO (JHEP 11 (2013) 085)



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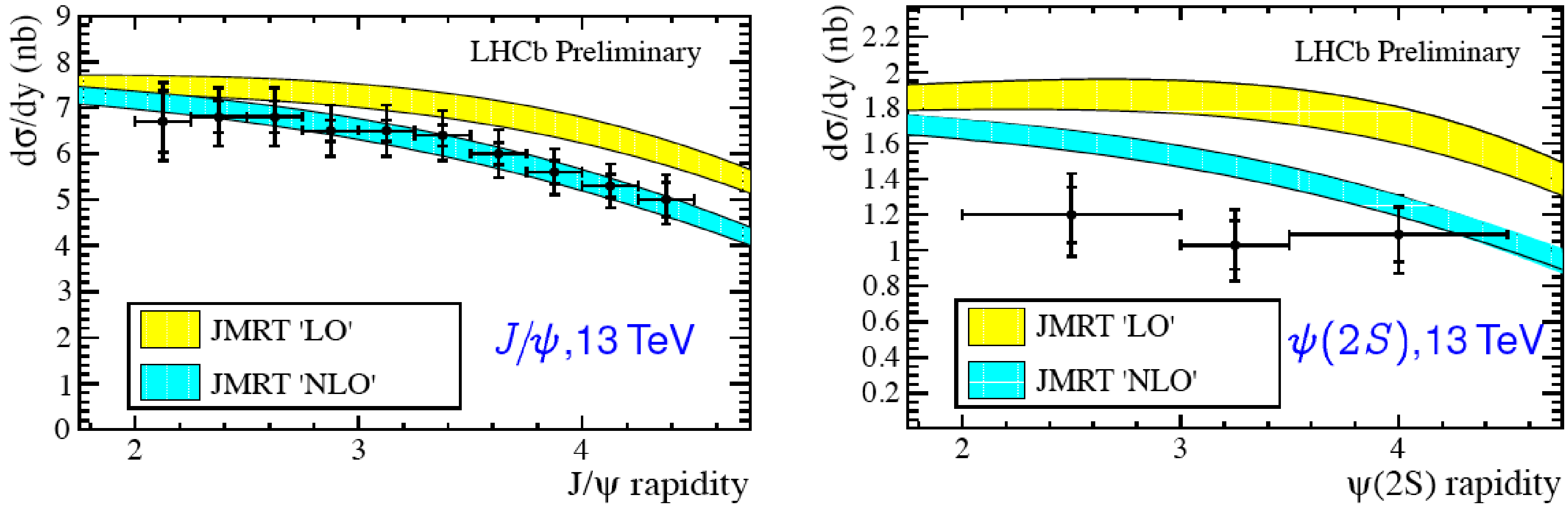


LHCb-CONF-2016-007

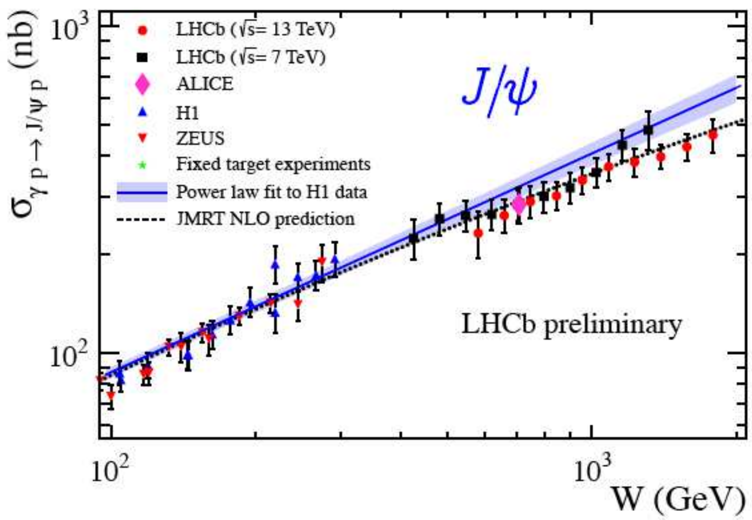
LHCb results on exclusive J/Ψ and $\Psi(2S)$ cross sections

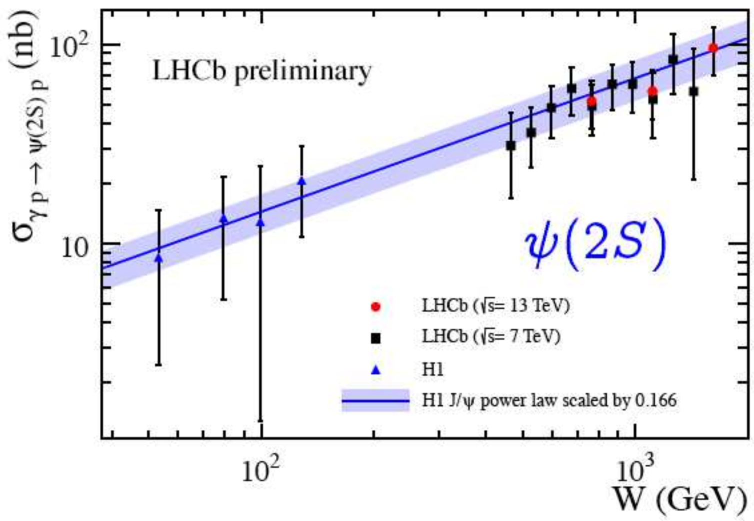
relation between ep (1 amplitude) and pp (2 amplitudes) scattering

$$\frac{d\sigma}{dy_{pp\to pVp}} = r(y)\left[k_+\frac{dn}{dk_+}\sigma_{\gamma p\to Vp}(W_+) + k_-\frac{dn}{dk_-}\sigma_{\gamma p\to Vp}(W_-)\right]$$

$r(y)$: gap survival, $k_\pm$: photon energy, $dn/dk_\pm$: photon flux $W_\pm$: γp mass

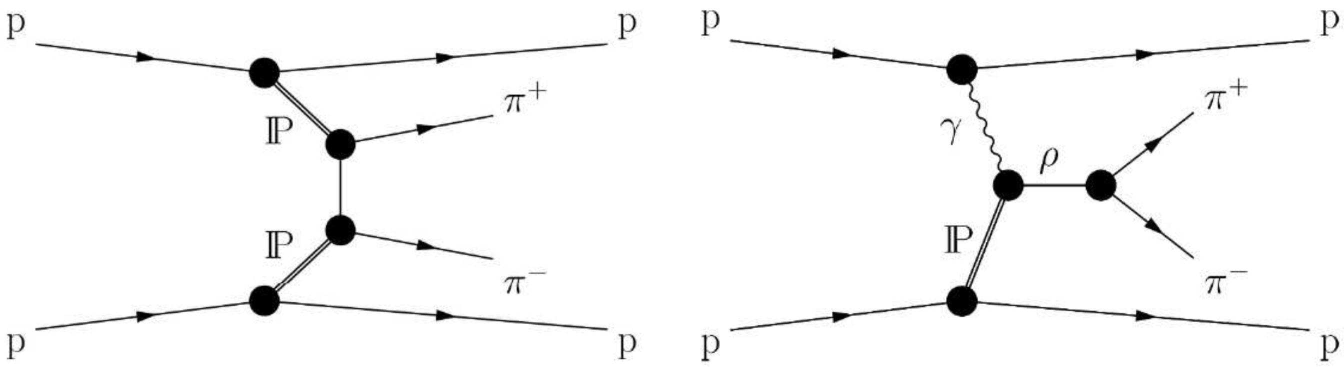
- Measure the cross section, get $\sigma(W-)$ from HERA $\to$ extract $\sigma(W+)$ (and vice versa at 7 TeV)
- Kinematic range extended at 13 TeV
- A simple power law does not lead to a good description





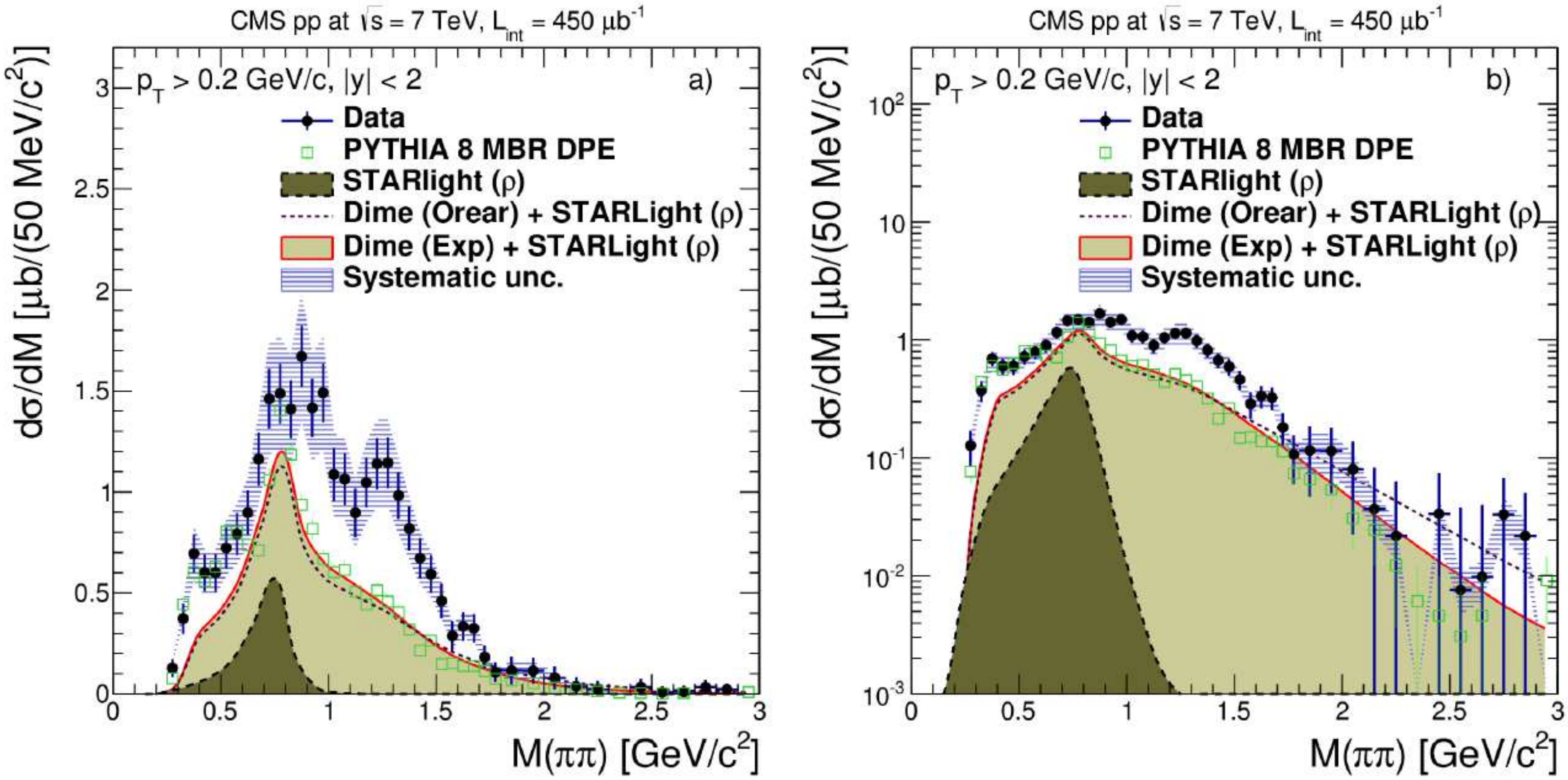
LHCb-CONF-2016-007

CMS results on exclusive pion production



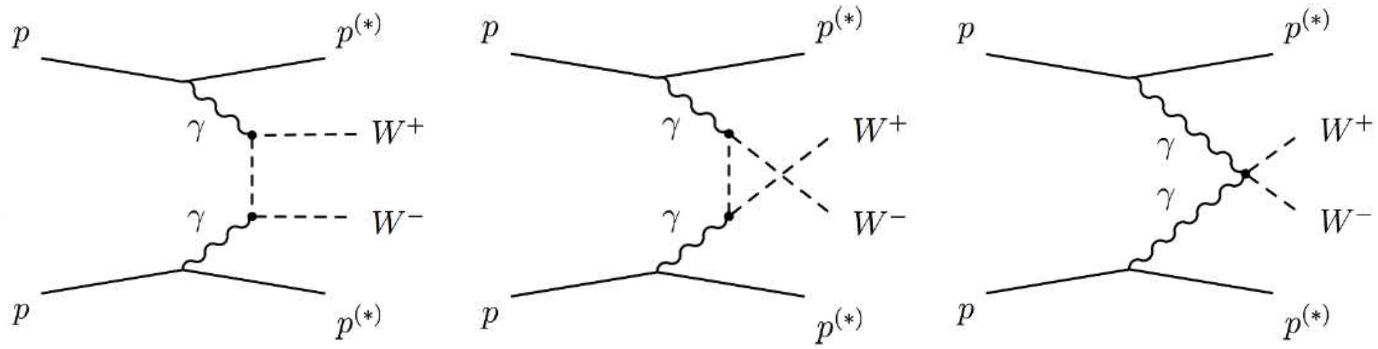
- Exclusive pion production in CMS
- Soft Pomeron exchange is dominant at low mass: Photon exchange contribution is much suppressed
- Measurement can be performed in special runs at low luminosity: no pile up, high cross section
- Experimental signature: only two opposite tracks from the same primary vertex; no additional signal in calorimeter; $p_T(\pi) > 0.2 GeV$; $|y(\pi)| < 2$
- Background computed directly using data and same sign events (pure background sample)

CMS results on exclusive pion production



- Data compared to the predictions from DIME MC (DPE) and STARLIGHT MC (ρ contribution)
- Disagreement with theory especially in normalization as expected: MC does not contain proton dissociation events (ArXiv:1706.08310)
- $\sigma_{\pi^+\pi^-} = 26.5 \pm 0.3(stat) \pm 5.0(syst) \pm 1.1(lumi)$ μb

ATLAS/CMS results on exclusive WW production



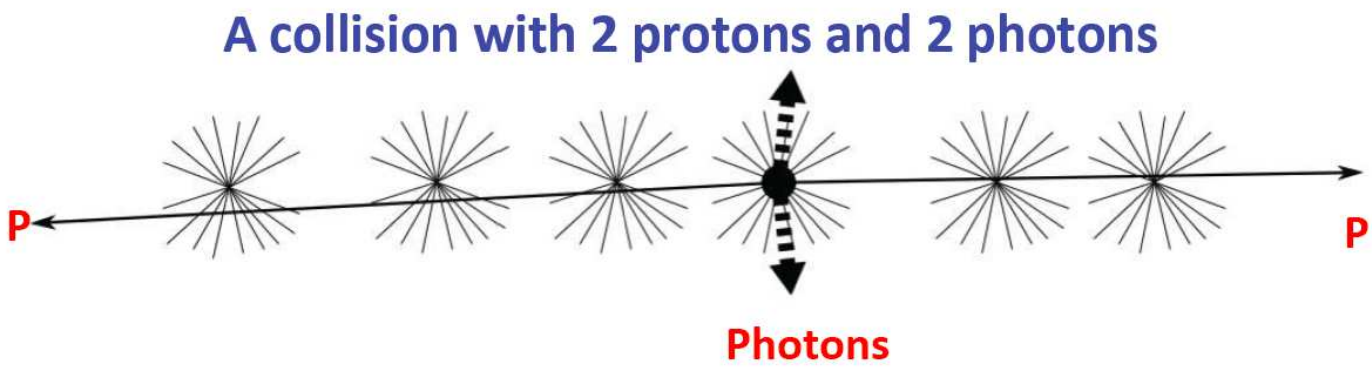
- Look for WW exclusive production
- Motivation: sensitive to $\gamma\gamma WW$ quartic anomalous couplings that could be a sign of new physics
- Quartic gauge anomalous $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings parametrised by a_0^W, a_0^Z, a_C^W, a_C^Z

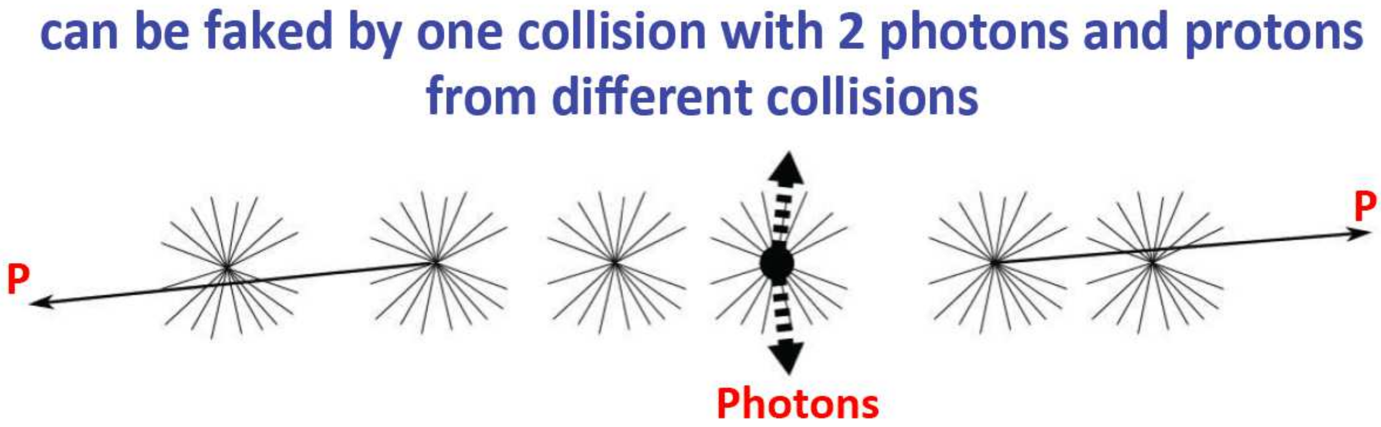
$$\mathcal{L}_6^0 \sim \frac{-e^2}{8}\frac{a_0^W}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^-_\alpha - \frac{e^2}{16\cos^2(\theta_W)}\frac{a_0^Z}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}Z^\alpha Z_\alpha$$

$$\mathcal{L}_6^C \sim \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W^-_\beta + W^{-\alpha}W^+_\beta) - \frac{e^2}{16\cos^2(\theta_W)}\frac{a_C^Z}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}Z^\alpha Z_\beta$$

- Anomalous parameters equal to 0 for SM

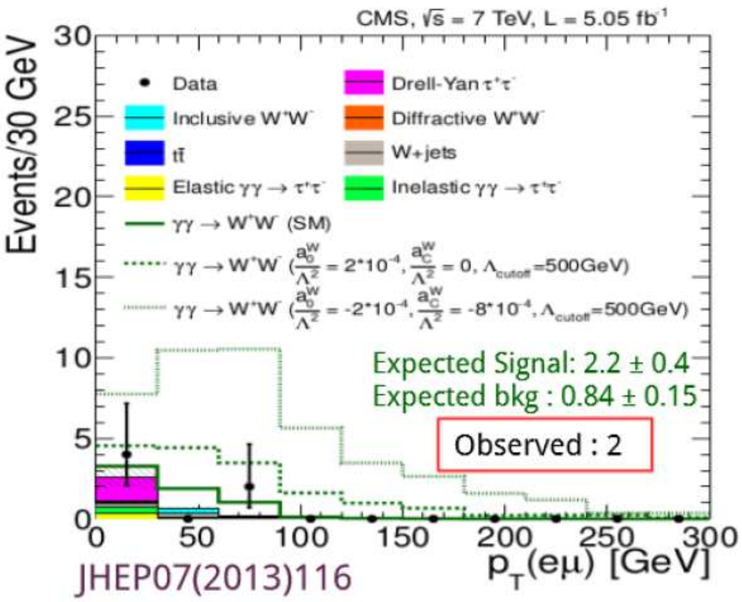
One aside: what is pile up at LHC?





- Due to high number of protons in one packet, there can be more than one pp interaction when two packets collide
- Typically up to 50 pile up events in Run II (about 25-30 now)
- Analyses at high luminosity because of lower production cross section (exclusive WW, $\gamma\gamma$...): need to fight pile up!

ATLAS/CMS results on exclusive WW production



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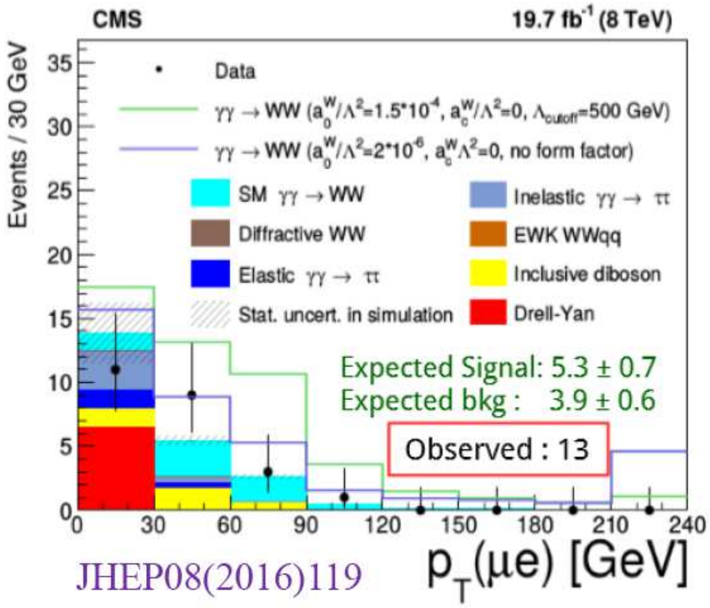
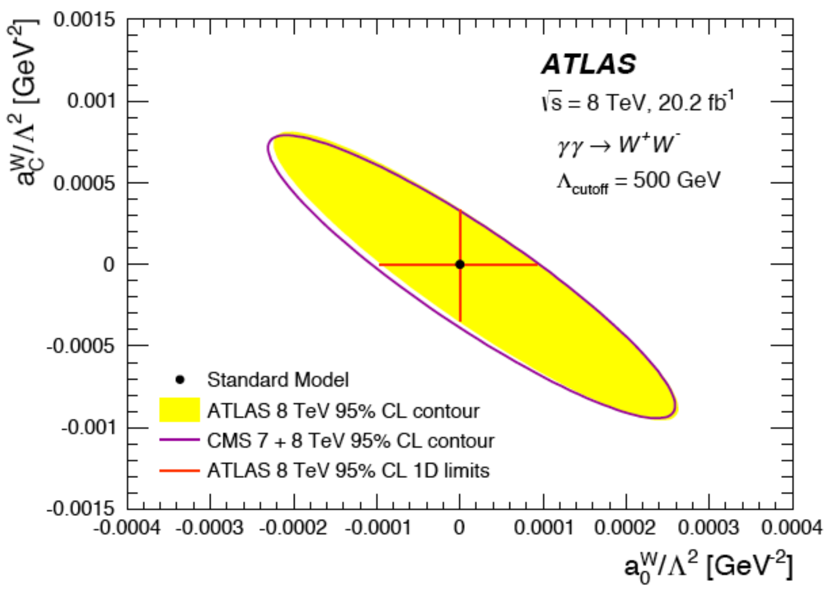


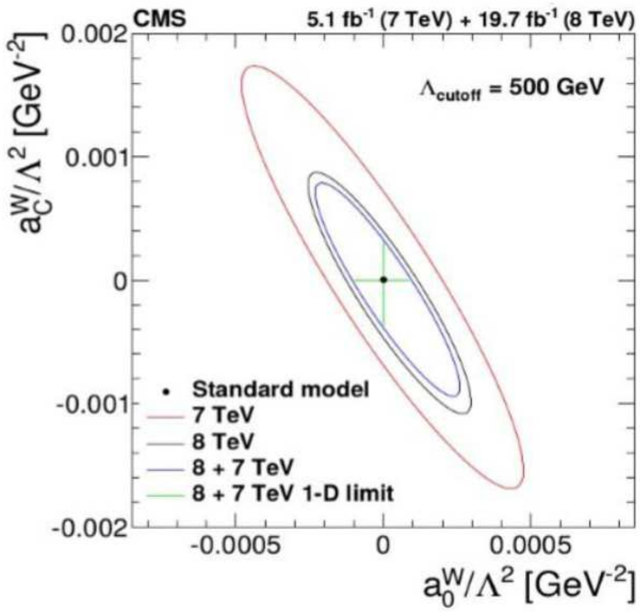
JHEP08(2016)119

- Exclusive WW are rare (SM cross section of the order of 96.7 fb^{-1}) $\rightarrow$ full luminosity needed and reject pile up background
- CMS: 2011 at 7 TeV: 5.05 fb^{-1}; 2012 at 8 TeV: 19.7 fb^{-1}; ATLAS: 20.2 fb^{-1}
- Exclusive selection: opposite sign $e\mu$ from common primary vertex, no extra track from vertex, $M_{e\mu} > 20$ GeV to avoid low mass resonances, $p_T^{e\mu} >$ 30 GeV to remove Drell Yan and $\gamma \rightarrow \tau\tau$
- CMS: $\sigma(pp \rightarrow pWWp \rightarrow p\mu ep) = 2.2^{+3.3}_{-2.0}$ fb at 7 TeV (SM 4.0 $\pm$ 0.7 fb) $\sigma(pp \rightarrow pWWp \rightarrow p\mu ep) = 10.8^{+5.1}_{-4.1}$ fb at 8 TeV (SM: 6.2 $\pm$ 0.5 fb) after correction for proton dissociation, ATLAS $\sigma = 6.9 \pm 2.2(stat) \pm 1.4(syst)$ fb (SM: 4.4 $\pm$ 0.3 fb)
- Observed significance for 7 and 8 TeV combination: 3.4 σ (CMS), 3.0 σ (ATLAS)

ATLAS/CMS results on exclusive WW production

- Most stringent limits on $\gamma\gamma WW$ quartic anomalous coupling
- JHEP08 (2016) 119 (CMS), Phys. Rev. D94 (2016) 032011 (ATLAS)

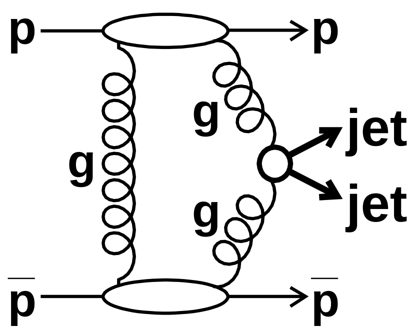


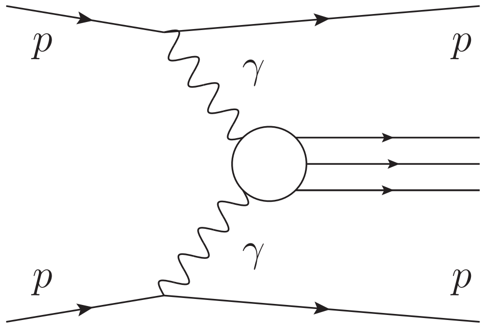


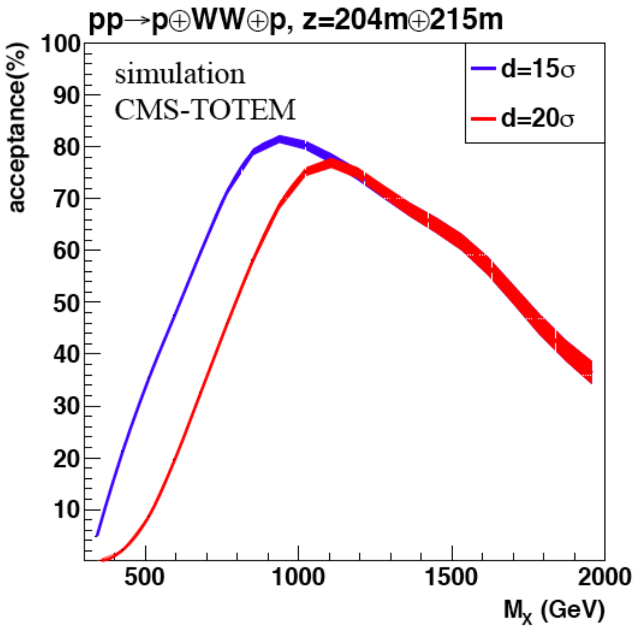
Dimension-6 AQGC parameter	7 TeV ($\times 10^{-4}$ GeV^{-2})	8 TeV ($\times 10^{-4}$ GeV^{-2})	7+8 TeV ($\times 10^{-4}$ GeV^{-2})
$a_0^W/\Lambda^2(\Lambda_{cutoff} = 500\,\mathrm{GeV})$	$-1.5 < a_0^W/\Lambda^2 < 1.5$	$-1.1 < a_0^W/\Lambda^2 < 1.0$	$-0.9 < a_0^W/\Lambda^2 < 0.9$
$a_C^W/\Lambda^2(\Lambda_{cutoff} = 500\,\mathrm{GeV})$	$-5 < a_C^W/\Lambda^2 < 5$	$-4.2 < a_C^W/\Lambda^2 < 3.4$	$-3.6 < a_C^W/\Lambda^2 < 3.0$

Coupling	Λ_{cutoff}	Observed allowed range [GeV $^{-2}$]	Expected allowed range [GeV $^{-2}$]
a_0^W/Λ^2	500 GeV	$[-0.96\times10^{-4},\ 0.93\times10^{-4}]$	$[-0.90\times10^{-4},\ 0.87\times10^{-4}]$
a_C^W/Λ^2	500 GeV	$[-3.5\times10^{-4},\ 3.3\times10^{-4}]$	$[-3.3\times10^{-4},\ 3.1\times10^{-4}]$
a_0^W/Λ^2	∞	$[-1.7\times10^{-6},\ 1.7\times10^{-6}]$	$[-1.5\times10^{-6},\ 1.6\times10^{-6}]$
a_C^W/Λ^2	∞	$[-6.4\times10^{-6},\ 6.3\times10^{-6}]$	$[-5.9\times10^{-6},\ 5.8\times10^{-6}]$

What is AFP/CT-PPS?

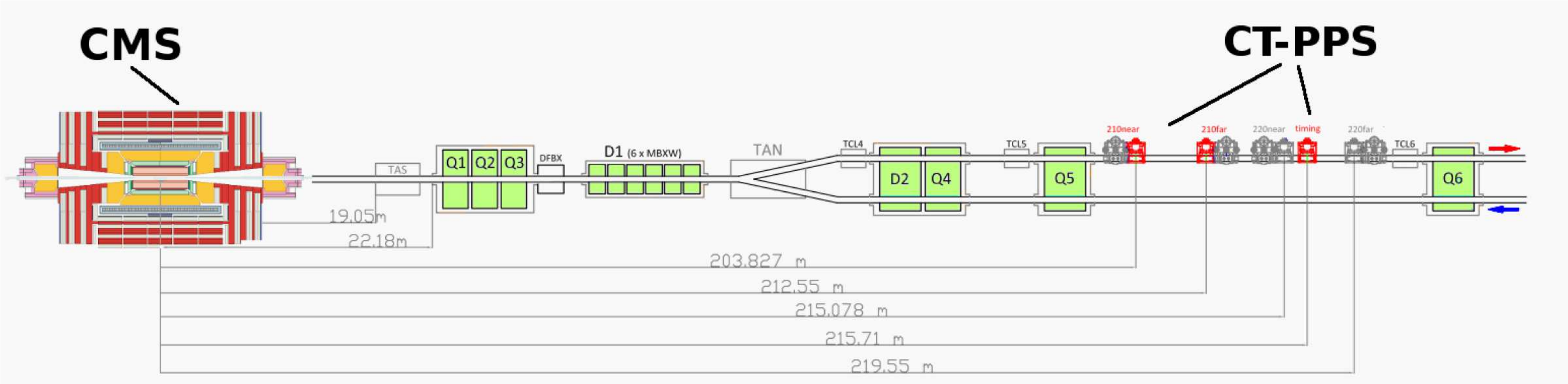


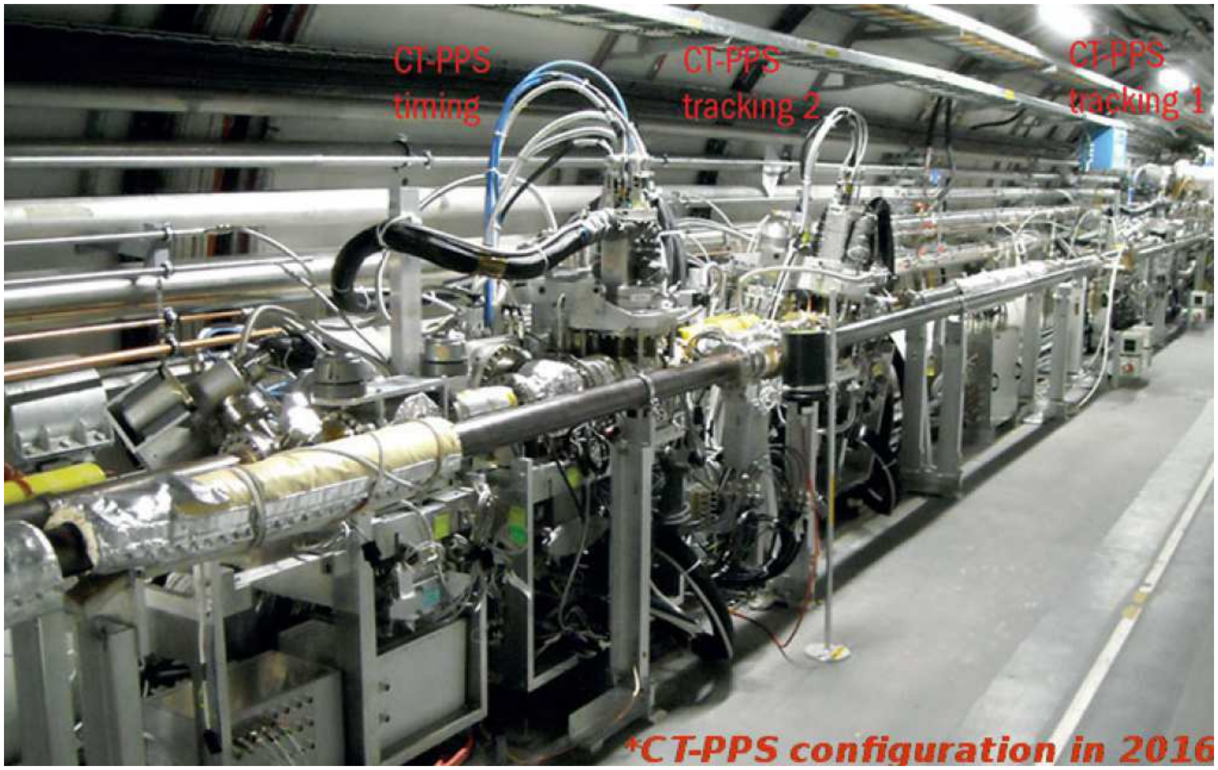




- Tag and measure protons at ± 210 m: AFP (ATLAS Forward Proton), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)
- All photon-induced cross sections involving anomalous couplings computed using the Forward Physics Monte Carlo (FPMC)
- Sensitivity to high mass central system, X, as determined using AFP/CT-PPS: Very powerful for exclusive states: kinematical constraints coming from AFP and CT-PPS proton measurements

What is CT-PPS?

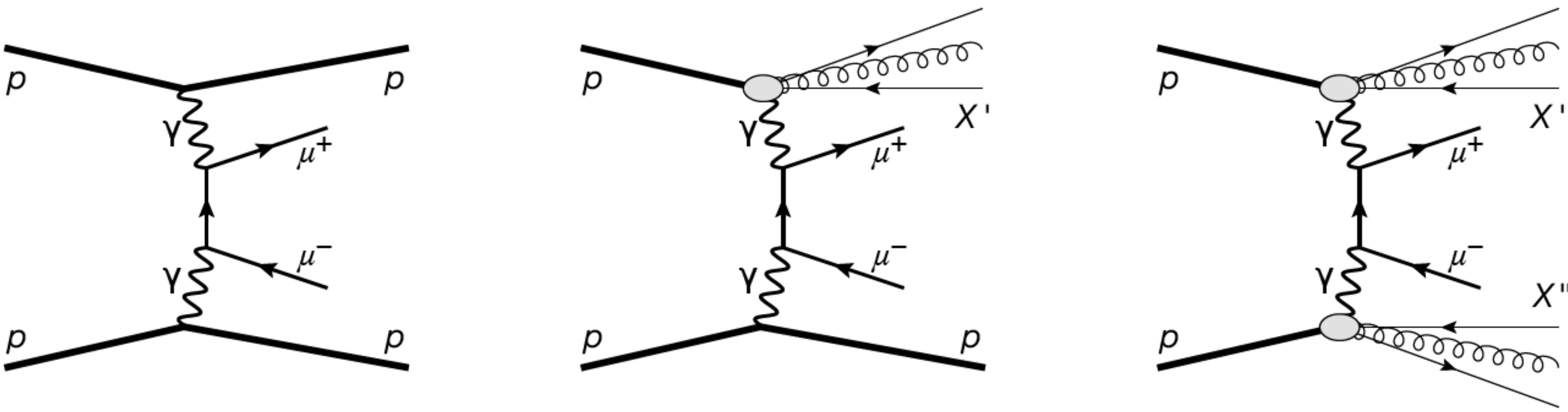




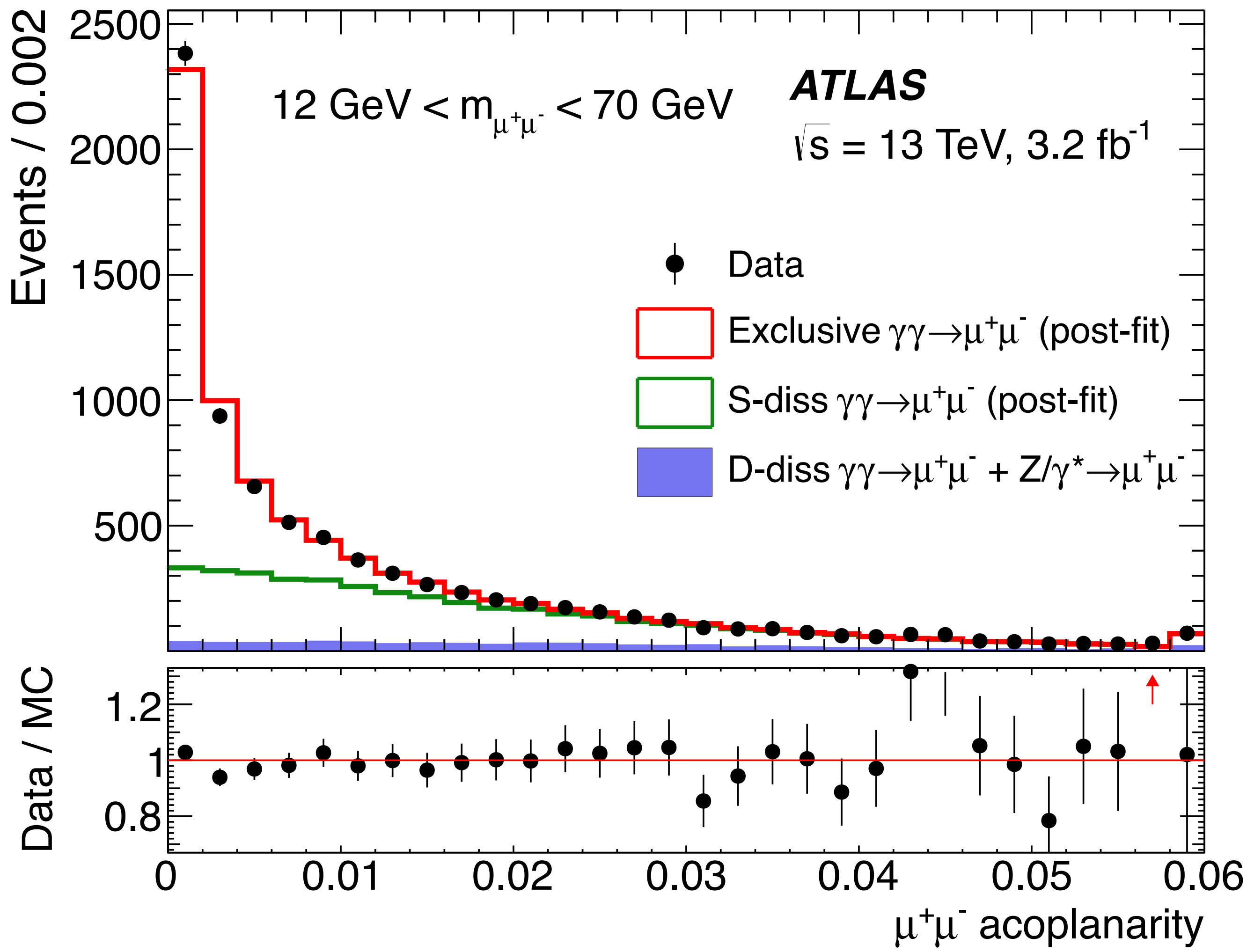
- Joint CMS and TOTEM project: https://cds.cern.ch/record/1753795
- LHC magnets bend scattered protons out of the beam envelope
- Detect scattered protons a few mm from the beam on both sides of CMS: 2016, first data taking ($\sim 15\ \mathrm{fb}^{-1}$)

Exclusive $\mu\mu$ production in ATLAS and in CT-PPS

- Turn the LHC into a $\gamma\gamma$ collider: flux of quasi-real photons under the Equivalent Photon Approximation, dilepton production dominated by photon exchange processes
- ATLAS: rapidity gap selection: Exclusivity selection in presence of pile up vertices ($\mu \sim 13$): Require 0 additional track within 1 mm of $\mu^+\mu^-$ vertex, the challenge being to control the dissociative background, somewhat irreducible
- ATLAS: Fight Drell-Yan and other backgrounds by comparing data and MC background around the Z mass
- CT-PPS: Tag one of the two protons



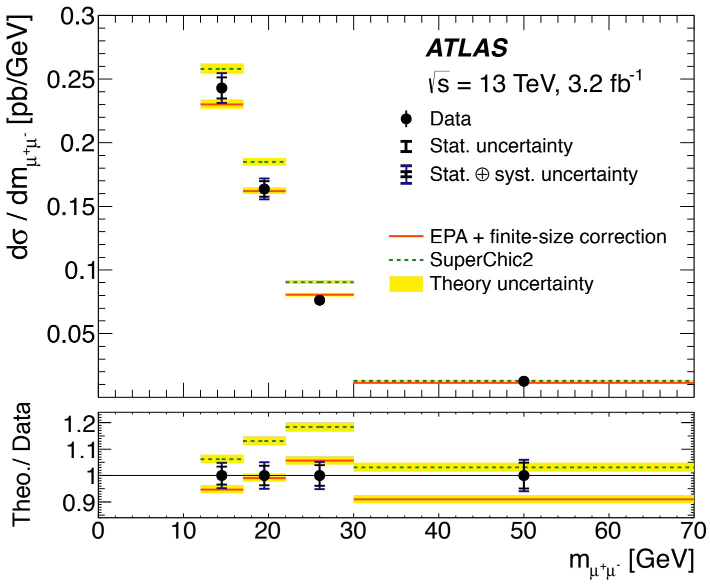
ATLAS: Fit the acoplanarity

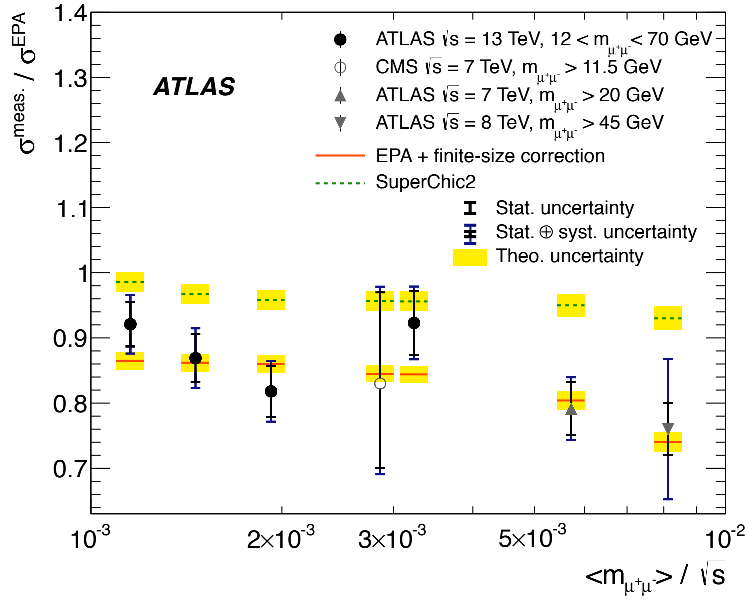


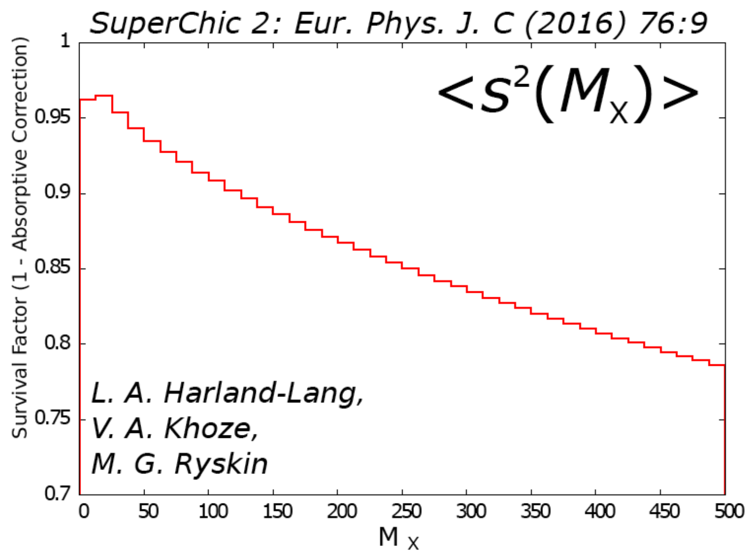
- Fiducial cross section for $p_T^\mu > 6$ GeV ($12 < m_{\mu\mu}$ <30 GeV); $p_T^\mu > 10$ GeV ($30 < m_{\mu\mu}$ <70 GeV) and corrected for detector inefficiency
- Cross section extracted using binned maximum likelihood fit of N_{excl}, N_{s-diss}: $\sigma^{excl.fid}_{\gamma\gamma\to\mu\mu} = 3.12 \pm 0.07(stat) \pm 0.10(syst)$ pb

ATLAS results on exclusive dimuon production

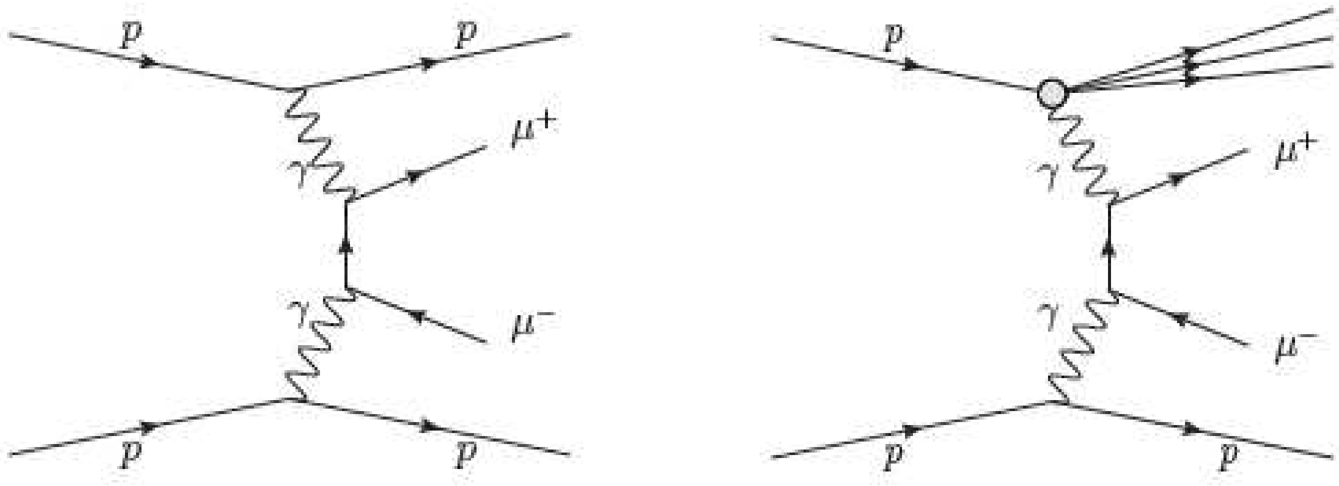
- Cross section binned in dimuon mass and in dimuon mass divided by center-of-mass energy (ATLAS, ArXiv 1708.04503)
- Look for absorptive effects: Insufficient suppression in Superchic 2 (Khoze, Harland-Lang, Ryskin)







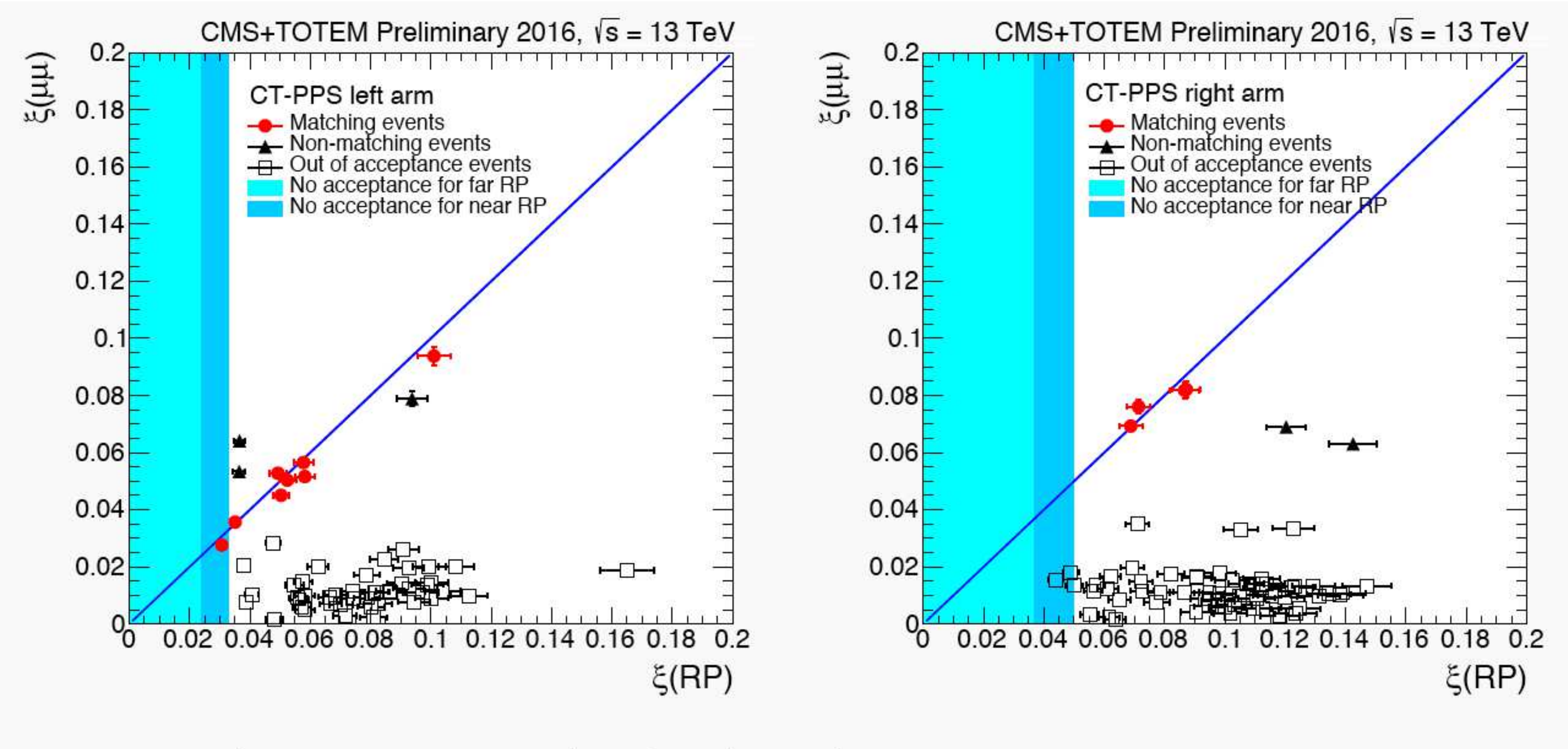
Observation of semi-exclusive dimuon production in CT-PPS



- Observation of semi-exclusive dimuon production in CT-PPS
- First time a near-beam detector operates at a hadron collider at high luminosity (single tag events), Request only one proton tagged (< 1 event expected for double tagged events due to acceptance)
- Main Background is Drell-Yan di-muon production with proton from pile-up event: Data-driven estimate based on sample of Drell-Yan Z events, count number of Z events with $\xi(\mu\mu)$ and $\xi(p)$ within 2σ and use MC to extrapolate from Z peak to signal region

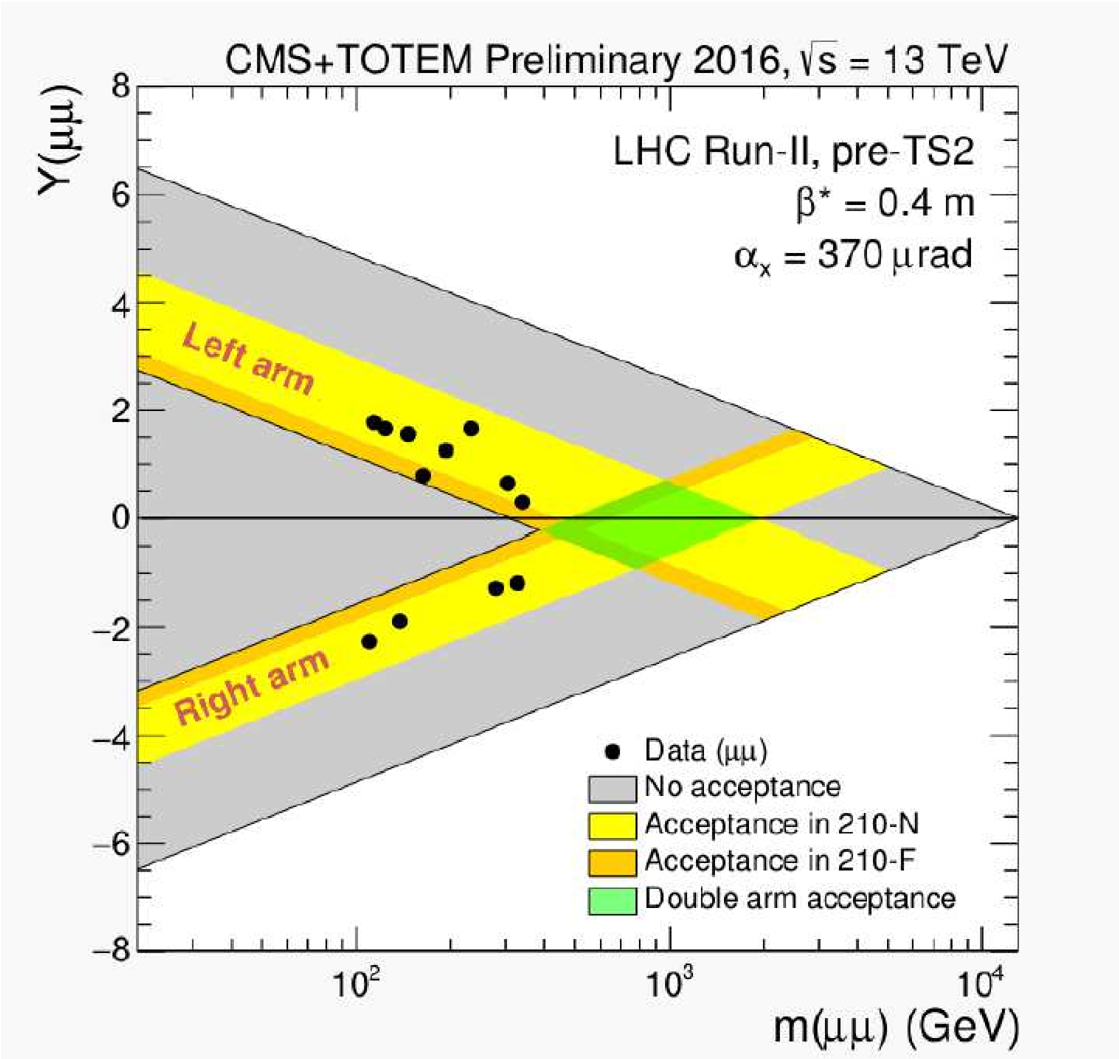
Observed signal (CT-PPS)

- First measurement of semi-exclusive di-muon process with proton tag
- CT-PPS works as expected (validates alignment, optics determination...)
- 17 events are found with protons in the CT-PPS acceptance and 12 $< 2\sigma$ matching
- Significance for observing 12 events for a background of $1.47 \pm 0.06(stat) \pm 0.52(syst)$: 4.3 σ

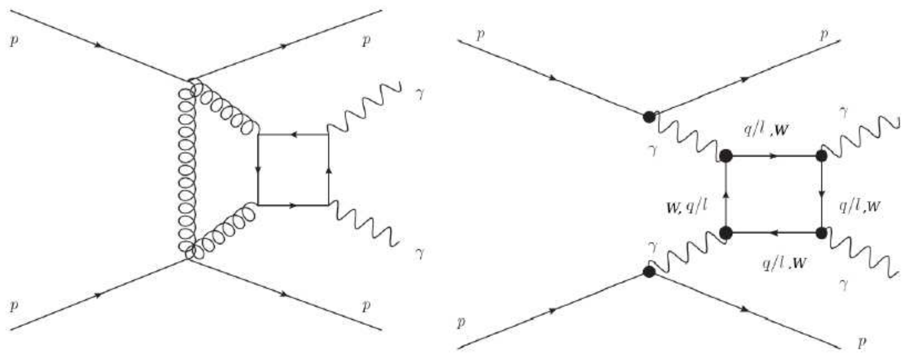


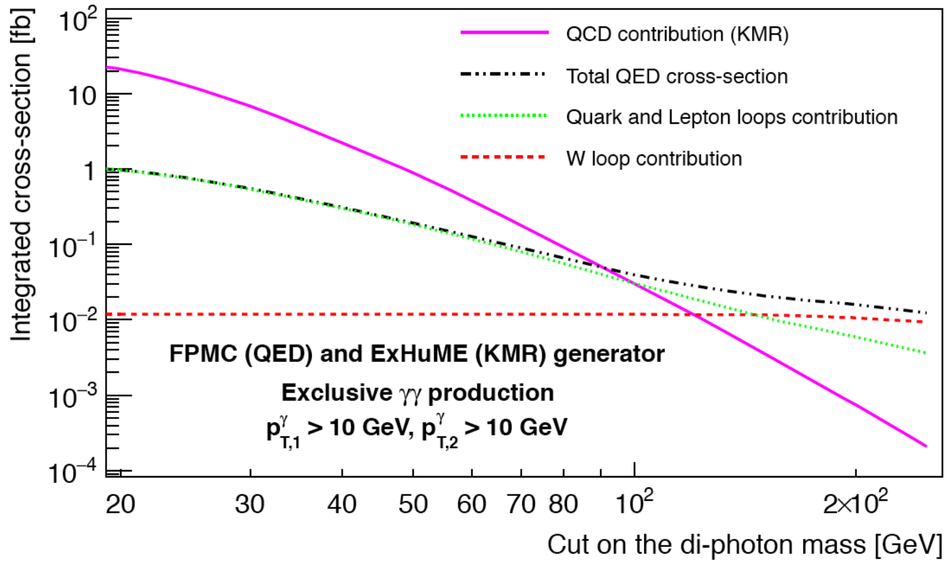
Summary of 12 candidates properties

- Dimuon invariant mass vs rapidity distributions in the range expected for single arm acceptance
- No event at higher mass that would be in the acceptance for double tagging
- Highest mass event: 341 GeV
- CMS-PAS-PPS-17-001



Additional photon exchange processes: diphoton production

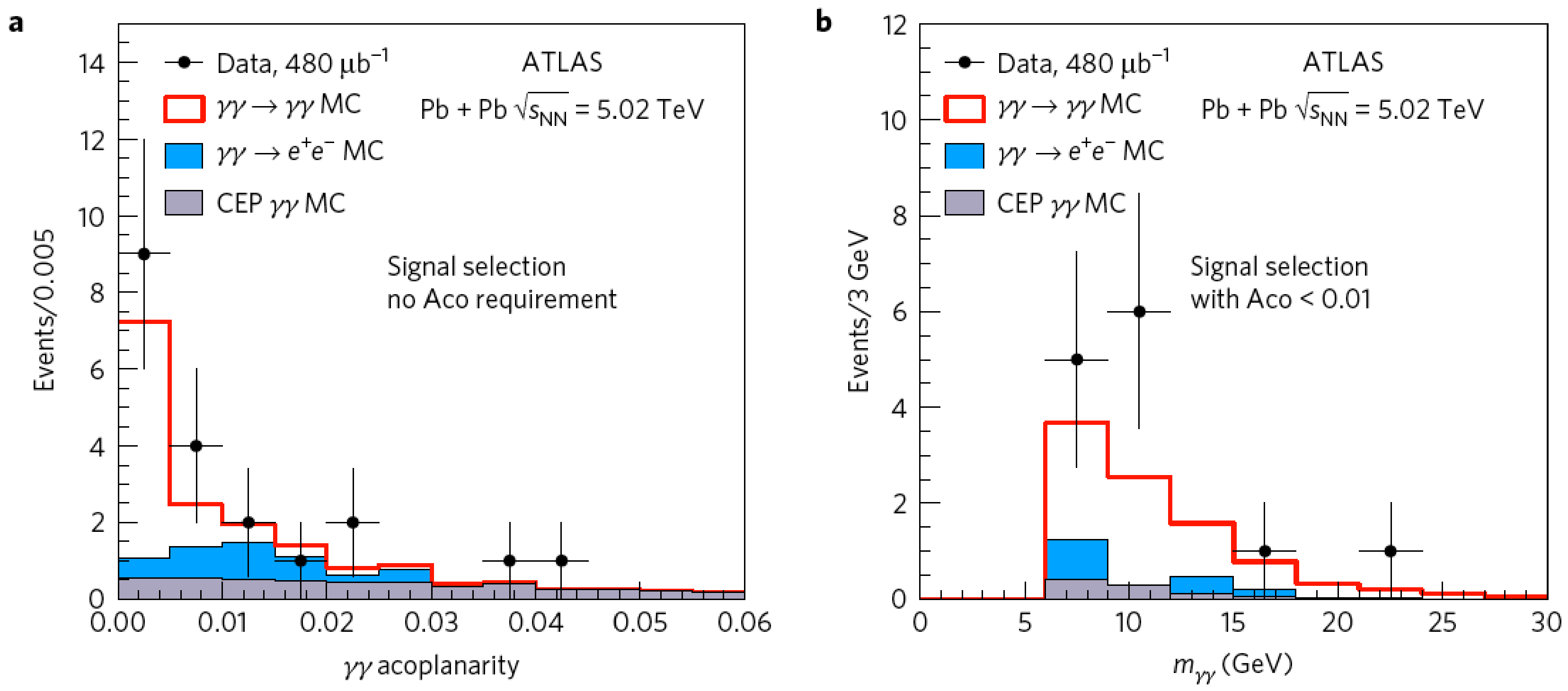




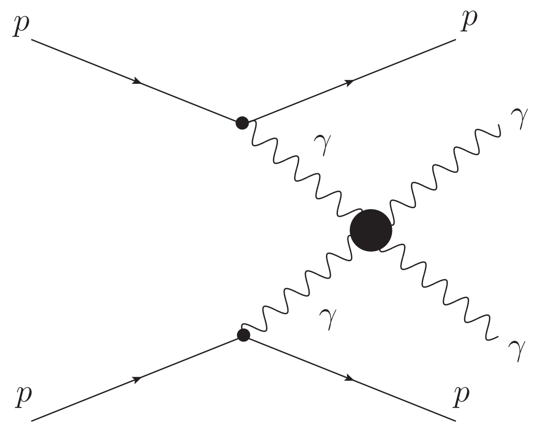
- SM QCD production dominates at low $m_{\gamma\gamma}$, QED at high $m_{\gamma\gamma}$
- Important to consider W loops at high $m_{\gamma\gamma}$
- At high masses (~ 750 GeV), the photon induced processes are dominant
- **Conclusion: Two photons and two tagged protons means photon-induced process**

Exclusive diphoton production in ATLAS

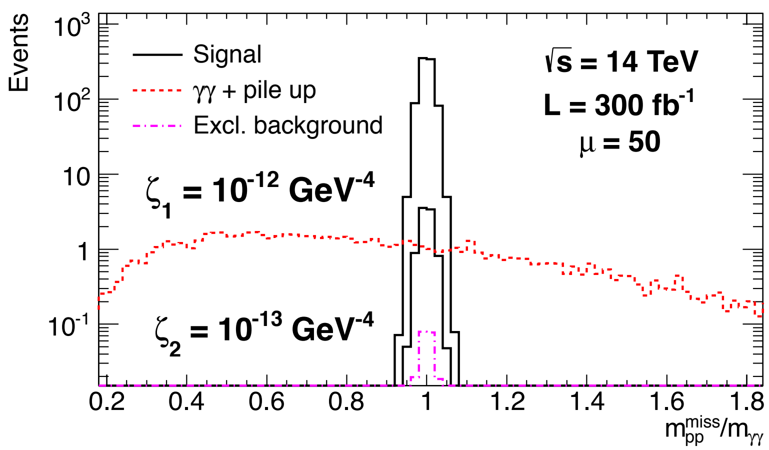
- Look for exclusive diphoton production in heavy ion $PbPb$ collisions
- Cross section enhanced by a factor Z^4
- In 480 μb^{-1} of data at $\sqrt{s} = 5.02$ TeV, 13 events observed for 2.6 $\pm$ 0.7 background events
- For photon $E_T > 3$ GeV, $|\eta| < 2.4$, $M_{\gamma\gamma}$ >6 GeV, $p_T^{\gamma\gamma} < 2$ GeV: $\sigma = 70 \pm 24(stat) \pm 17(syst)$ nb in agreement with SM
- Nature Physics 13 (2017) 852

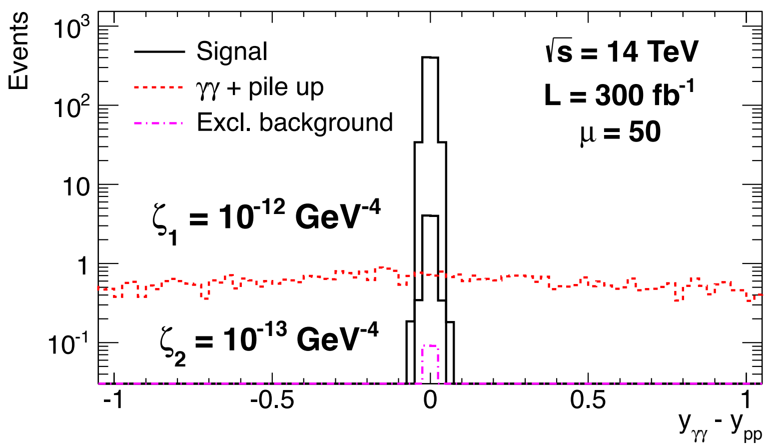


Search for quartic $\gamma\gamma$ anomalous couplings in AFP/CT-PPS



- Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings
- Couplings predicted by extra-dim, composite Higgs models
- No background after cuts for 300 fb^{-1}
- Phenomenology studies in collaboration between E. Chapon, O. Kepka, C. Royon, M. Saimpert, G. von Gersdorff, S. Fichet: Phys. Rev. D81 (2010) 074003; Phys.Rev. D89 (2014) 114004, JHEP 1502 (2015) 165; Phys. Rev. Lett. 116 (2016) no 23, 231801 and Phys. Rev. D93 (2016) no 7, 075031



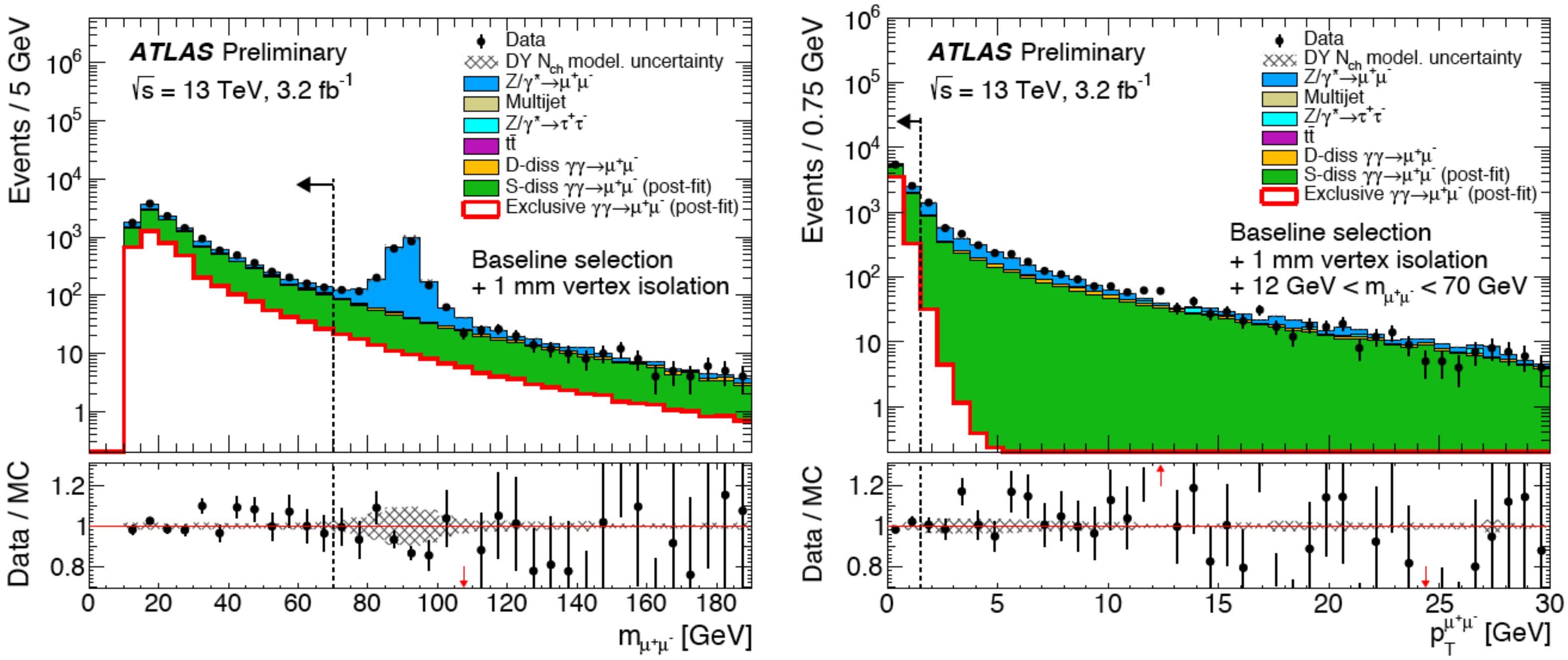


Conclusion

- Many complementary results concerning exclusive diffraction at the LHC from the different experiments: either using the "rapidity gap" technique or the proton tags
- LHCb: J/Ψ and $\Psi(2S)$ production: preferred model JMRT NLO
- CMS exclusive pion production: disagreement with theoretical expectations probably due to the fact that proton dissociation is not included in models
- Best limits on $\gamma\gamma WW$ anomalous couplings in CMS
- Exclusive di-muon production: Complementary measurements between CMS-TOTEM and ATLAS (first observation of high-mass exclusive dimuon production)
- $\gamma\gamma\gamma\gamma$ couplings: Observation by ATLAS in heavy ion mode and prospects for AFP and CT-PPS, highest possible sensitivities to $\gamma\gamma\gamma\gamma$, $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma Z$ anomalous couplings due to new resonances, extra-dim. or composite Higgs...

Example of ATLAS selection:

1 mm Vertex exclusivity, $p_T^{\mu^+\mu^-} < 1.5$ GeV requirement



Data with typical pileup $\mu \sim 13$. Data-driven $78 \pm 1\%$ veto efficiency.

p_T cut - further single dissociative suppression.