Exclusive diffraction at the LHC

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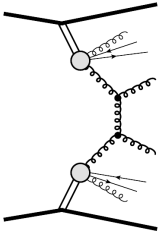
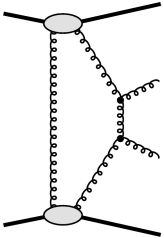
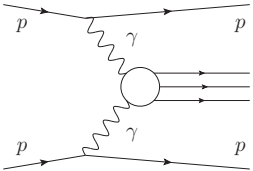
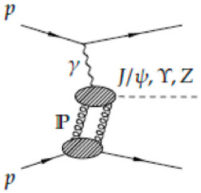
- Exclusive pion, J/Ψ, $\Psi(2S)$ production
- Exclusive dilepton production (with/without proton tagging)
- Exclusive $\gamma\gamma$ and WW productions
- Prospects: ALPs, anomalous coupling studies

What do we call Exclusive Diffraction / γ exchange events?



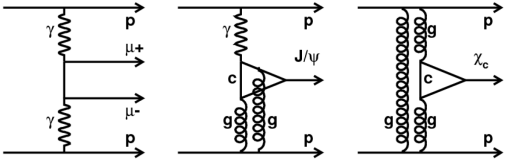






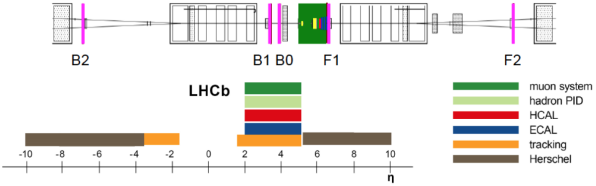
- Left diagram: Double Pomeron Exchange: some energy is "lost" in Pomeron remnants
- Next three diagrams: Exclusive production: the full energy is used to produce dijets, vector mesons, no energy loss
  - Dijet production via gluon exchange, QCD process (Khoze Martin Ryskin)
  - Photon exchange
- Possibility 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 larger than 2 TeV

Measurement of central exclusive production in LHCb



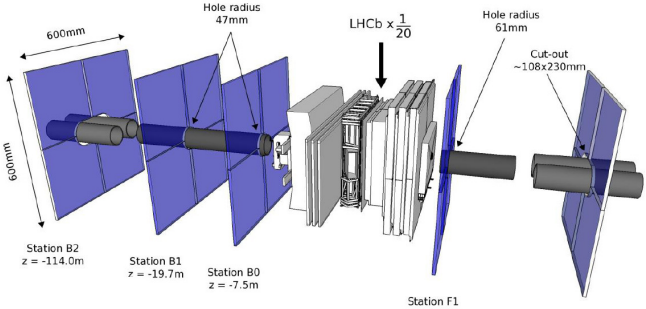
- Measurement of central exclusive production of J/Ψ and $\Psi(2S)$ vector mesons at 13 TeV: Sensitivity to gluon distribution in Pomeron
- Signal: Central system with rapidity gaps
- Background: Diffractive processes (pomeron remnants not detected, outside detector acceptance)
- Experimental issue: 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)

The HERSCHEL detector - LHCb



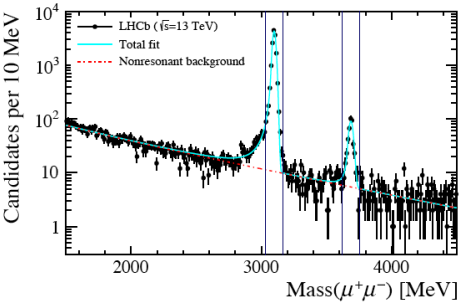
pseudorapidity coverage of HeRSCheL: $-10.0 < \eta < -3.5 \quad 5.0 < \eta < 10.0$

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



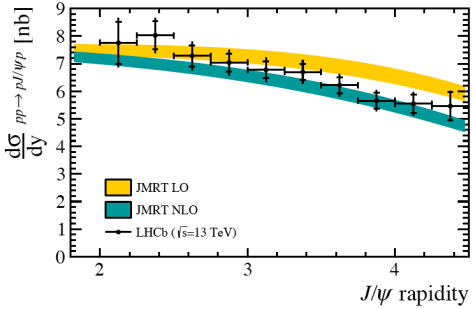
J/Ψ and $\Psi(2S)$ production at 13 TeV

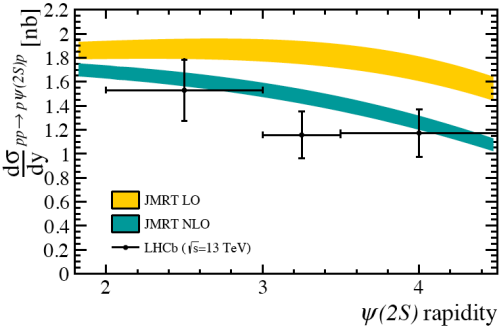
- Event selection requires 2 muons within $2 < \eta < 4.5$ and veto on additional forward track and energy
- for 204 pb^{-1} in 2015: 14753 J/Ψ and 440 $\Psi(2S)$
- Further cleanup by veto on HERSCHEL signal significance: purity of 0.755±0.015 for J/Ψ and 0.726 ± 0.061 for $\Psi(2S)$



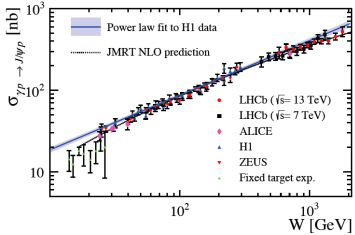
LHCb results on exclusive J/Ψ and $\Psi(2S)$

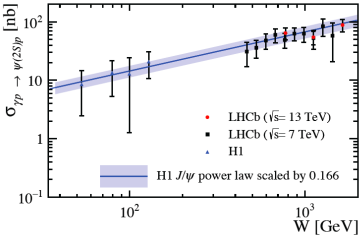
- Uncertainties highly correlated between bins
- Preferred model: JMRT NLO (JHEP 11 (2013) 085)
- $\sigma(J/\Psi \to \mu^+\mu^-)(2 < \eta < 4.5) = 435 \pm 18 \pm 11 \pm 17$ pb,
  $\sigma(\Psi(2S) \to \mu^+\mu^-)(2 < \eta < 4.5) = 11.1 \pm 1.1 \pm 0.3 \pm 0.4$ pb (JHEP 1810 (2018) 167)





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





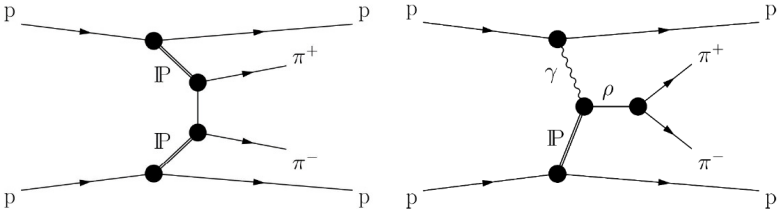
relation between ep (1 amplitude) and pp (2 amplitudes) scattering

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

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

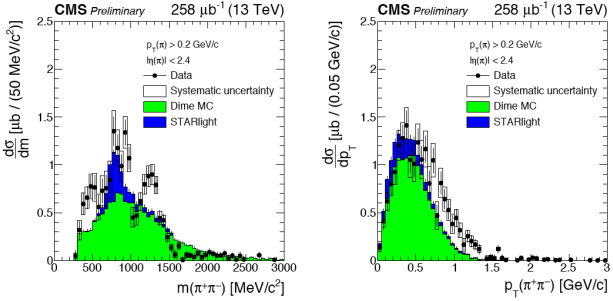
- Measure the cross section, get $\sigma(W-)$ from HERA $\rightarrow$ extract $\sigma(W+)$ (and vice versa at 13 TeV)
- A simple power law does not lead to a good description

CMS results on exclusive pion production



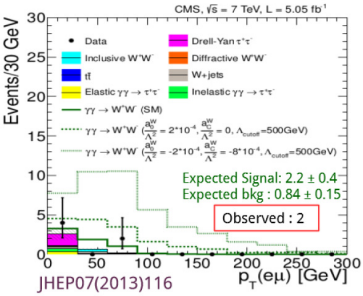
- Exclusive pion production in CMS
- Soft Pomeron exchange is dominant at low mass: Photon exchange contribution is much suppressed
- Measurement can be performed in special runs at low luminosity (at 13 and 5.02 TeV): no pile up, high cross section
- Experimental signature: only two opposite tracks from the same primary vertex; no additional signal in calorimeter; $p_T(\pi) > 0.2 GeV$; $|y(\pi)| < 2.4$
- 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)
- Disagreement with theory especially in missing resonances and in normalization as expected: MC does not contain proton dissociation events (ArXiv:1706.08310)
- $\sigma_{\pi^+\pi^-}(13\,TeV) = 19.0 \pm 0.6(stat) \pm 3.2(syst) \pm 0.01(lumi)\ \mu$b; $\sigma_{\pi^+\pi^-}(5.02\,TeV) = 19.6 \pm 0.4(stat) \pm 3.3(syst) \pm 0.01(lumi)\ \mu$b

ATLAS/CMS results on exclusive *WW* production



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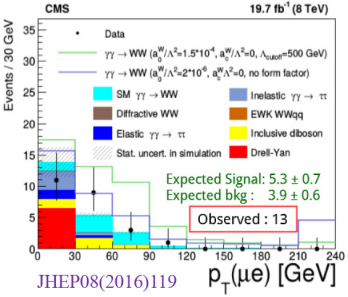
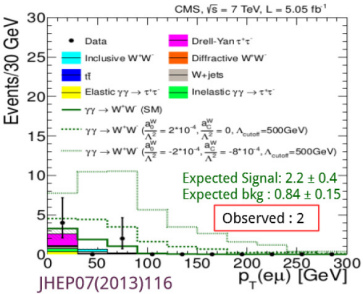


JHEP08(2016)119

- 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 $\gamma \rightarrow \tau\tau$

ATLAS/CMS results on exclusive *WW* production



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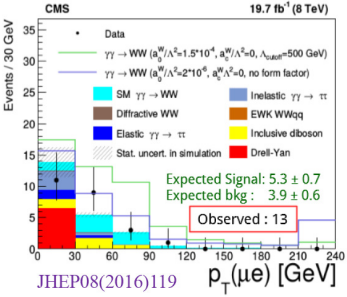

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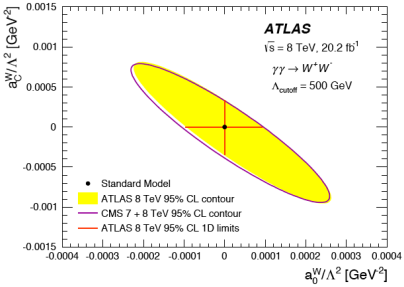
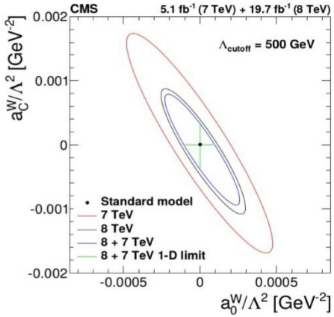
- CMS: $\sigma(pp \to pWWp \to p\mu ep) = 2.2^{+3.3}_{-2.0}$ fb at 7 TeV (SM 4.0 ± 0.7 fb) $\sigma(pp \to pWWp \to p\mu ep) = 10.8^{+5.1}_{-4.1}$ fb at 8 TeV (SM: 6.2 ± 0.5 fb) after correction for proton dissociation, ATLAS $\sigma = 6.9 \pm 2.2(stat) \pm 1.4(syst)$ fb (SM: 4.4 ± 0.3 fb)
- Observed 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)



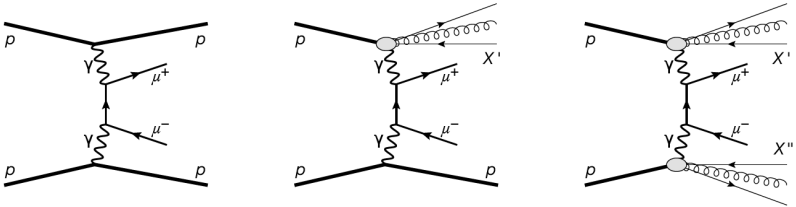


Dimension-6 AQGC parameter	7 TeV ($\times 10^{-4}$ GeV^{-2})	8 TeV ($\times 10^{-4}$ GeV^{-2})	7+8 TeV ($\times 10^{-4}$ GeV^{-2})
$a_0^W/\Lambda^2(\Lambda_{\text{cutoff}} = 500\,\text{GeV})$	$-1.5 < a_0^W/\Lambda^2 < 1.5$	$-1.1 < a_0^W/\Lambda^2 < 1.0$	$-0.9 < a_0^W/\Lambda^2 < 0.9$
$a_C^W/\Lambda^2(\Lambda_{\text{cutoff}}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

Coupling	Λ_{cutoff}	Observed allowed range [GeV^{-2}]	Expected allowed range [GeV^{-2}]
a_0^W/Λ^2	500 GeV	$[-0.96 \times 10^{-4},\ 0.93 \times 10^{-4}]$	$[-0.90 \times 10^{-4},\ 0.87 \times 10^{-4}]$
a_C^W/Λ^2	500 GeV	$[-3.5 \times 10^{-4},\ 3.3 \times 10^{-4}]$	$[-3.3 \times 10^{-4},\ 3.1 \times 10^{-4}]$
a_0^W/Λ^2	∞	$[-1.7 \times 10^{-6},\ 1.7 \times 10^{-6}]$	$[-1.5 \times 10^{-6},\ 1.6 \times 10^{-6}]$
a_C^W/Λ^2	∞	$[-6.4 \times 10^{-6},\ 6.3 \times 10^{-6}]$	$[-5.9 \times 10^{-6},\ 5.8 \times 10^{-6}]$

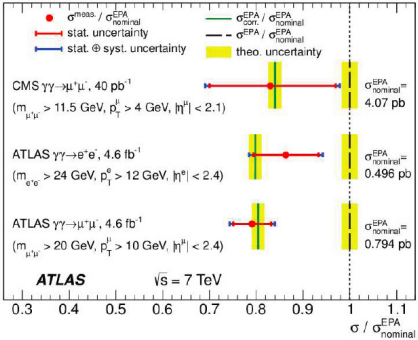
Exclusive $\mu\mu$ production in ATLAS and in CMS-TOTEM

- 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
- CMS TOTEM-Precision Proton Spectrometer: Tag one of the two protons

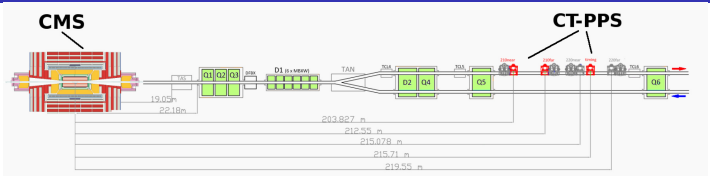


ATLAS results on exclusive dimuon production

- Cross section binned in dimuon mass and in dimuon mass divided by center-of-mass energy (ATLAS, ArXiv 1708.04503)
- Dominant uncertainty from template fit to acoplanarity shape
- Results compatible with SM expectation (taking into account ∼20 % of proton dissociation)

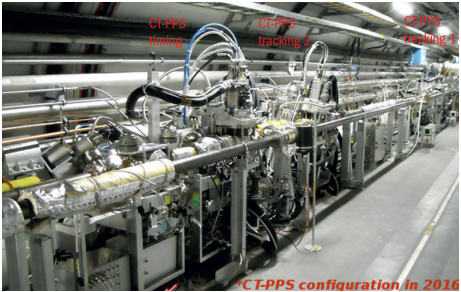


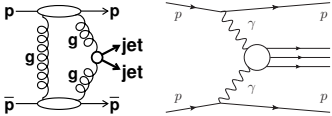
Proton detectors in CMS-TOTEM/ATLAS-AFP: Running at high luminosity

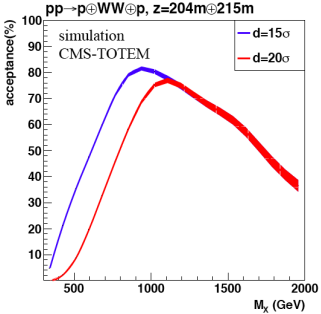


- Tag and measure protons at ± 210 m CMS-TOTEM Precision Proton Spectrometer (PPS), ATLAS Forward Proton (AFP)
- Detectors: measure proton position (3D pixel or strip Silicon detectors) and time-of-flight (Ultrafast Si, diamond detectors)
- About 110 fb^{-1} of data have been accumulated
- Many analyses in progress
- Observation of semi-exclusive dileptons already published by CMS/TOTEM (PPS: JHEP 1807 (2018) 153)

Roman pot detectors from CMS-TOTEM (PPS) installed in the tunnel



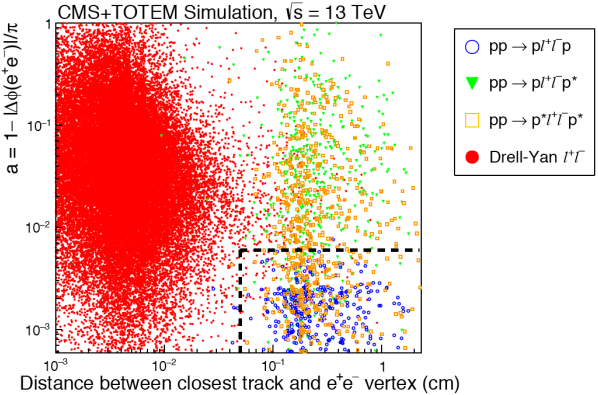




- Good acceptance at high mass
- Roman pots inserted routinely in every store without issues

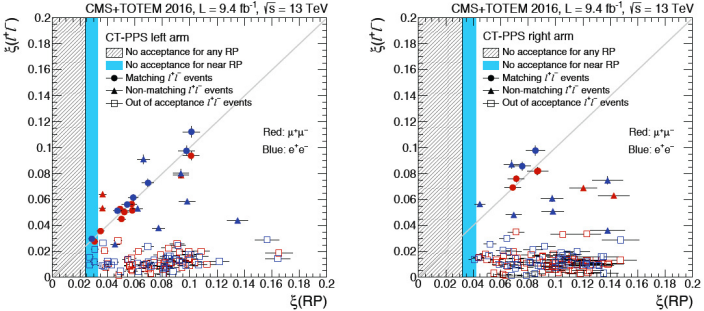
PPS: Event selection: dimuons and dielectrons

- Request pair of opposite sign muons or electrons with $p_T > 50$ GeV and $M_{ll} > 110$ GeV above the Z boson peak
- To suppress background: Veto additional tracks around dimuon/dielectron vertex (within 0.5 mm) and require back-to-back muons/electrons $|1 - \Delta\Phi/\pi| < 0.006$ for electrons (0.009 for muons)

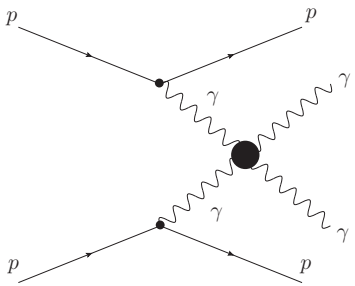


Observed signal

- First measurement of semi-exclusive dilepton process with proton tag
- PPS works as expected (validates alignment, optics determination...)
- 17 (res. 23) events are found with protons in the PPS acceptance and 12 (resp. 8) $< 2\sigma$ matching in the $\mu\mu$ (res. ee) channel
- Significance $> 5\sigma$ for observing 20 events for a background of 3.85 ($1.49 \pm 0.07(stat) \pm 0.53(syst)$ for $\mu\mu$ and $2.36 \pm 0.09(stat) \pm 0.47(syst)$ for ee)



Search for extra dimensions in the universe using γ induced processes

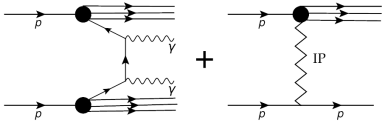


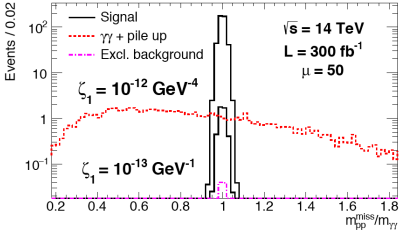
- Additional channels: WW, ZZ, γZ, dilepton production ($\gamma\gamma$ described in more detail as an example)

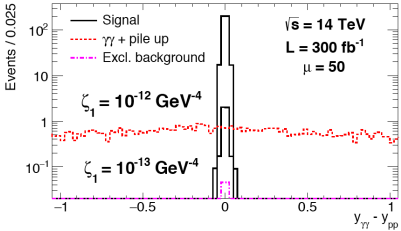
- Search for production of two photons and two intact protons in the final state: $pp \to p\gamma\gamma p$
- Possible larger number of events than expected in SM due to extra-dimensions, composite Higgs models, dark matter particles
- Anomalous couplings can appear via loops of new particles coupling to photons or via resonances decaying into two photons

Removing pile up at the LHC

- **Negligible background** after matching invariant mass and rapidity of diphoton system to prediction from protons (S. Fichet, G. von Gersdorff, B. Lenzi, C. Royon, M. Saimpert. JHEP 1502 (2015) 165)
- Use fast timing detectors in the case of *WW* production and *W*s decaying leptonically

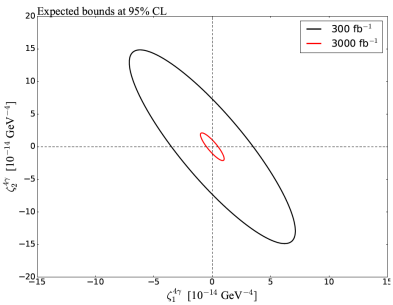


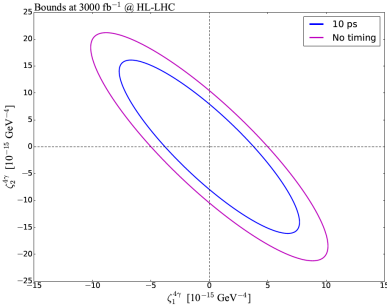




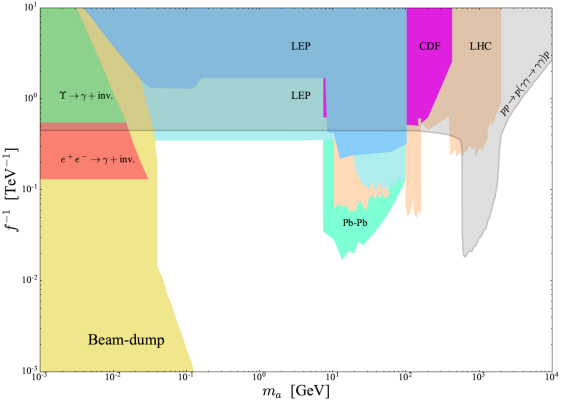
Sensitivity to anomalous couplings at medium and high lumi LHC

- With 300 fb^{-1} (Run III), gain of sensitivity by more than 2 orders of magnitude with respect to "usual" LHC sensitivity (similar for γZ, ZZ and WW)
- Run 4 (HL-LHC):Assuming similar proton acceptance as in Run 3, sensitivity further increased by about one order of magnitude with $\sim$ 3000 fb^{-1} (CERN-LPCC-2018-03)
- For exclusive diphoton production, timing detectors are not crucial

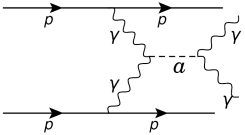




Application of exclusive $\gamma\gamma$: Looking for Axion Like Particles (ALPs)



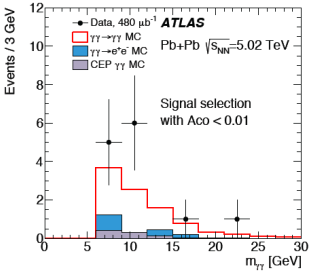
- ALPs decaying into two γs

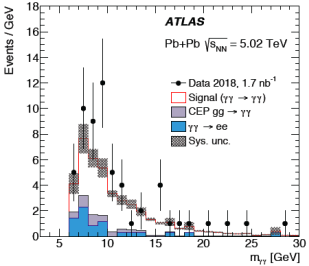


- Same analysis: two photons and two intact protons: sensitivity improved by 2 (resp. 3) orders of magnitude with 300 (resp. 3000) fb^{-1} (C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1806 (2018) 131)
- Searching for high mass ALPs coupling to γ without PPS: Difficult to perform, usually combines couplings to gluons, quarks, leptons, γ

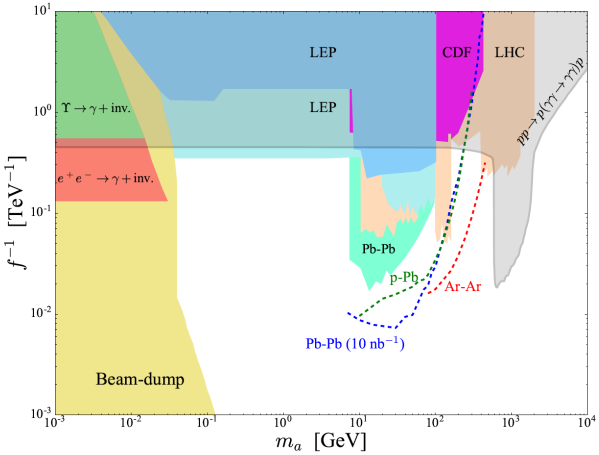
Exclusive diphoton production in ATLAS in *PbPb* collisions

- Look for exclusive diphoton production in heavy ion *PbPb* collisions
- Cross section enhanced by a factor Z^4
- In 480 μb^{-1} of data in 2015 at $\sqrt{s} = 5.02$ TeV, 13 events observed for 2.6 ± 0.7 background events
- More data in 2018: 1.7 nb^{-1}: 59 events (background of 12±3)
- For photon $E_T > 3$ GeV, $|\eta| < 2.37$, $M_{\gamma\gamma}$ >6 GeV, $p_T^{\gamma\gamma} < 2$ GeV: $\sigma = 78 \pm 13(stat) \pm 8(syst)$ nb in agreement with SM (49 ± 5 nb)
- Nature Physics 13 (2017) 852; Phys. Rev. Lett. 123 (2019) 052001





Search for axion like particles: complementarity with heavy ion runs



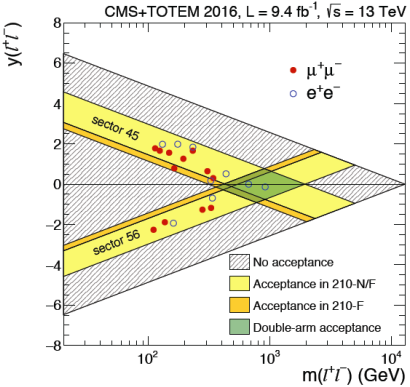
- Production of ALPs via photon exchanges in heavy ion runs: Complementarity to *pp* running
- Sensitivity to low mass ALPs: low luminosity but cross section increased by Z^4, C. Baldenegro, S. Hassani, C.R., L. Schoeffel, ArXiv:1903.04151
- Similar gain of three orders of magnitude on sensitivity for $\gamma\gamma\gamma Z$ couplings in *pp* collisions: C. Baldenegro, S. Fichet, G. von Gersdorff, C. R., JHEP 1706 (2017) 142

Conclusion

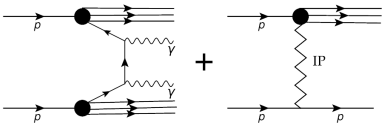
- Many complementary results concerning exclusive diffraction at the LHC from the different experiments: either using "rapidity gap" technique or proton tags
- LHCb: J/Ψ and $\Psi(2S)$ production: preferred model JMRT NLO
- CMS exclusive pion production: disagreement with theoretical expectations probably 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...
- More details about anomalous couplings, ALPs... in Justin's talk

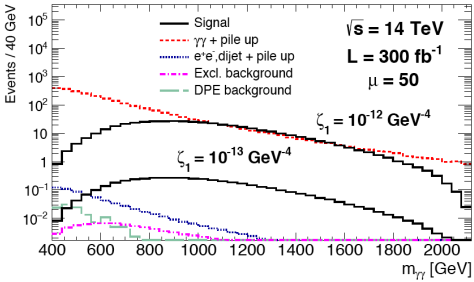
Summary of 20 candidates properties

- Dimuon invariant mass vs rapidity distributions in the range expected for single arm acceptance
- No event at higher mass that are double tagged: The two dielectron events in the acceptance region are compatible with pile up contamination (2.36 events expected)
- Highest mass event: 917 GeV



SM background





- SM exclusive diphoton production negligible at high diphoton mass
- γ selection: High p_T photon (>150 GeV), back-to-back, high mass di-photon (above 500 GeV)
- Proton selection: in the acceptance of the forward proton detectors (mass above 400 GeV)
- **Only background remaining after cuts: pile up**