Photon-induced & diffractive physics results at CMS

Excited QCD'22, Sicily

24th Oct. 2022

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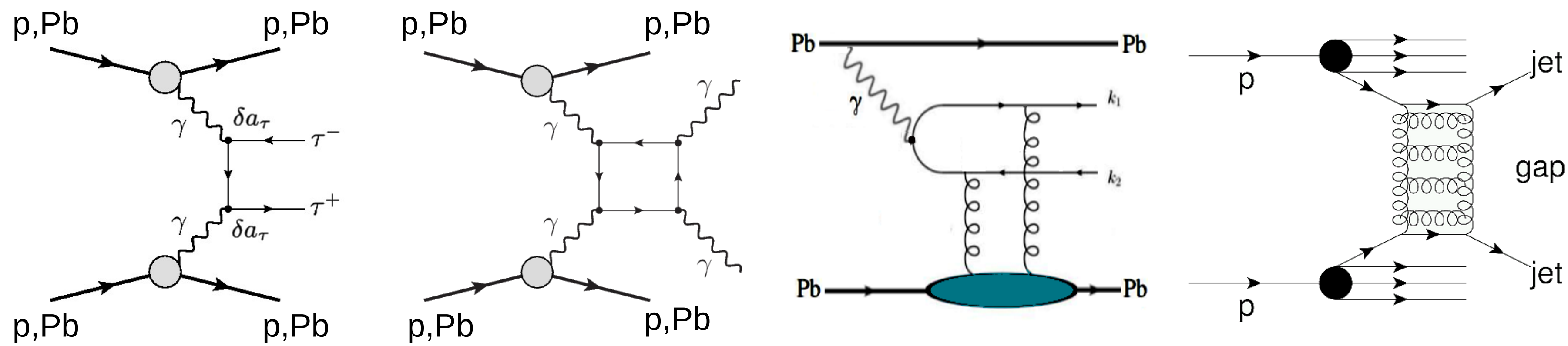
(for the CMS Collaboration)

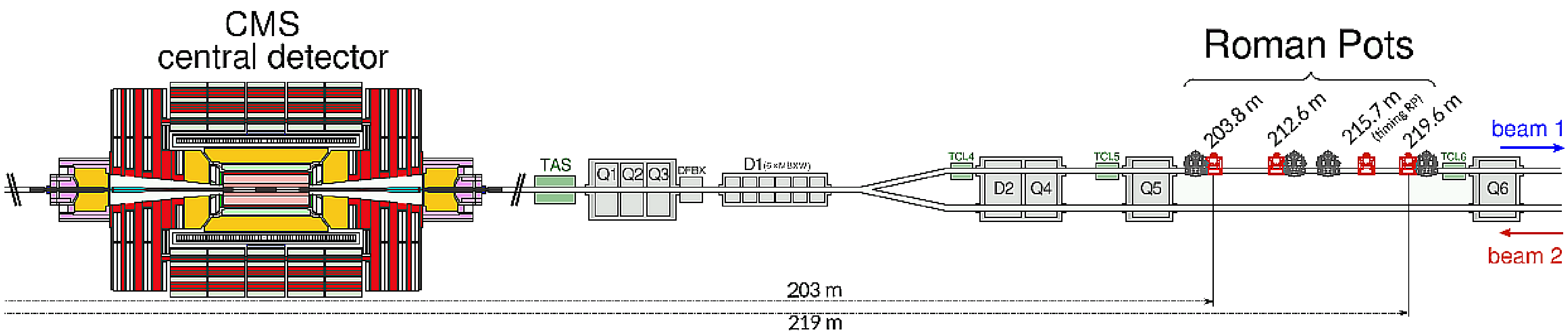
CERN

Color-singlet scatterings at CMS

- Many interesting scatterings at the LHC are mediated by color-singlet (photon and/or 2-gluon |P) exchanges with proton/ion surviving:



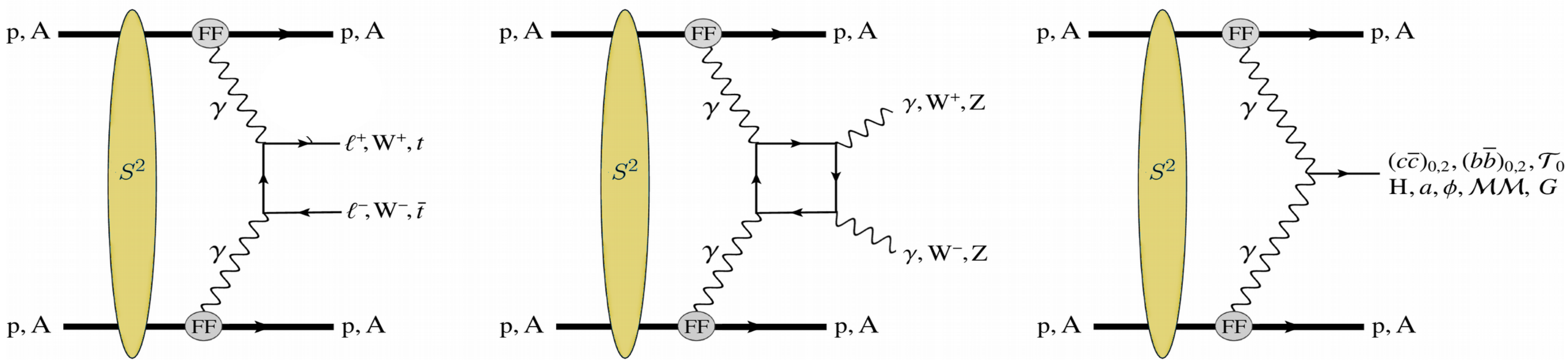
- Signatures: 1) excl. central system, 2) rapidity gaps, 3) near-beam fwd. protons

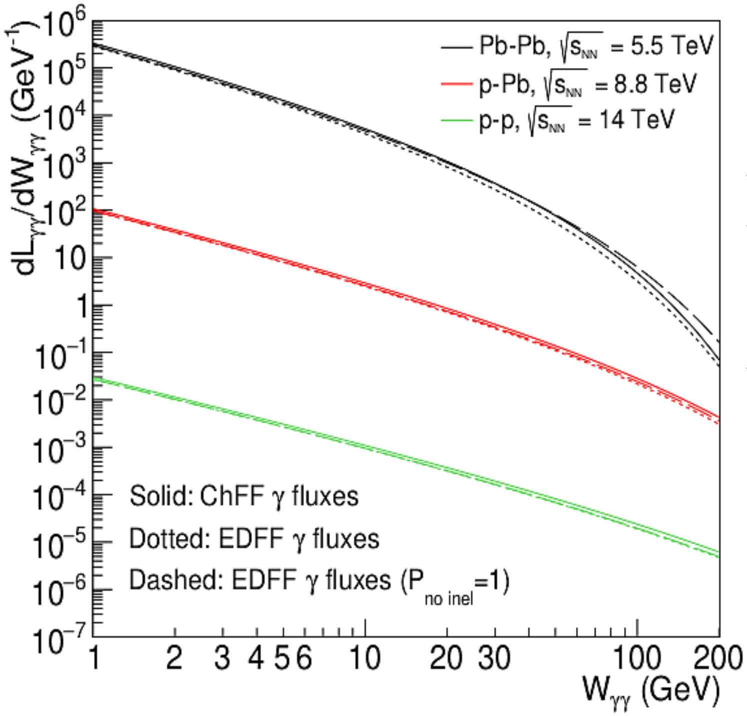


- PPS: CMS+TOTEM tracking (2016–) & timing (2018–) detectors inside beam pipe at ±210m
  Measure protons that loose ξ~2–20% of initial momenta. Double-RP acceptance at m_X>300 GeV
- Kinematics matching (m_X,y_X) in central CMS and RPs for backgd reduction in signal searches

Rich & unique (B)SM γγ physics at the LHC

- Many interesting photon fusion processes in ultraperipheral colls (UPCs):





... at the highest energies (~TeV) & lumis (∝ Z^4~$5\cdot10^6$ for Pb) ever reached:

System	$\sqrt{s_{NN}}$	$\mathcal{L}_{int}$	γ_L	R_A	E_γ^{max}	$\sqrt{s_{\gamma\gamma}^{max}}$
Pb-Pb	5.52 TeV	5 nb^{-1}	2960	7.1 fm	80 GeV	160 GeV
p-Pb	8.8 TeV	1 pb^{-1}	7450, 2960	0.7, 7.1 fm	2.45 TeV, 130 GeV	2.6 TeV
p-p	14 TeV	150 fb^{-1}	7450	0.7 fm	2.45 TeV	4.5 TeV

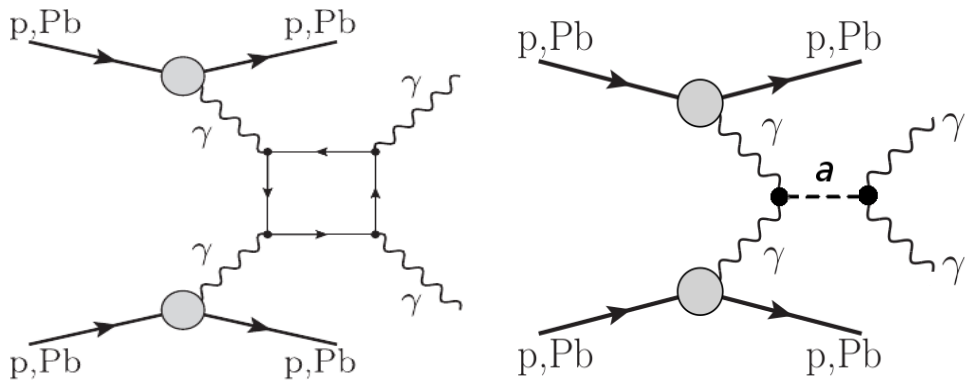
- MCs available to compute EPA x-sections at LO (soon NLO) QED plus NLO QCD accuracies.
- Uncertainties: 7–15% from p,Pb charge form factor (photon flux, survival probability $|S|^2$ factor)

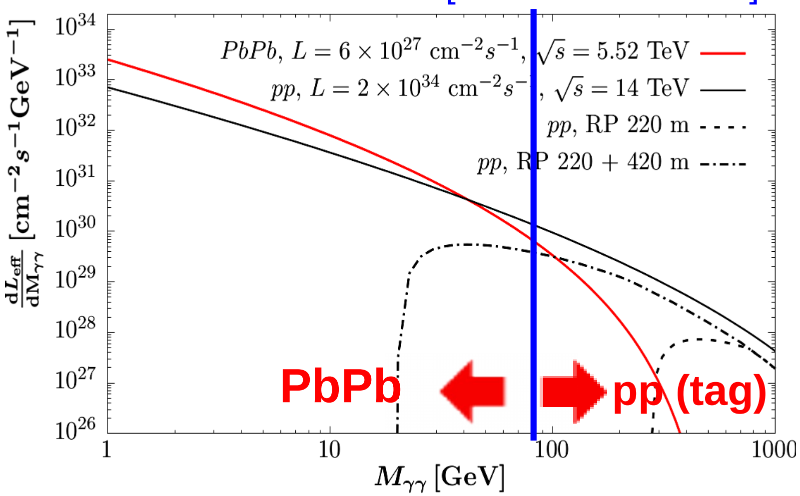
[gammaUPC: H.-S. Shao & DdE,arXiv:2207.03012]

Exclusive diphotons in Pb-Pb & p-p

- LbL scattering & ALP searches via exclusive γγ production in UPCs:

[arXiv:1812.07688]





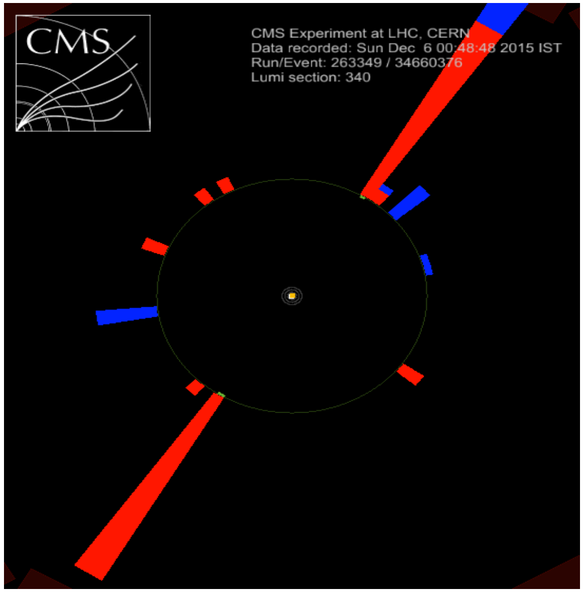
- Evt selection in Pb-Pb at 5.02 TeV (0.4 nb^{-1}):

  Exclusivity: No track with p_T>0.1 GeV, |η|<2.4

  No neutral activity over |η|<5.2

  Photon: E_T>2 GeV, |η|<2.4

  Diphoton: $m_{\gamma\gamma}$ > 5 GeV, p_T<1 GeV, $A_{\Delta\varphi}$<0.01



- Evt selection in p-p at 13 TeV (9–103. fb^{-1}, pileup):

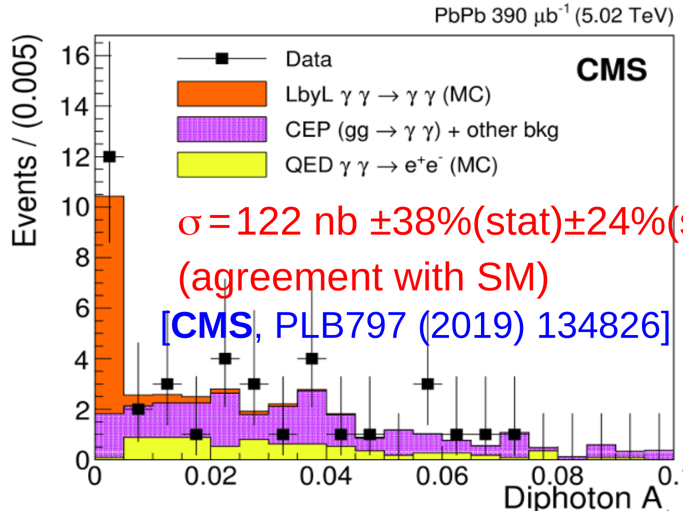
  Diphoton: $m_{\gamma\gamma}$ > 350 GeV, $A_{\Delta\varphi}$<0.005

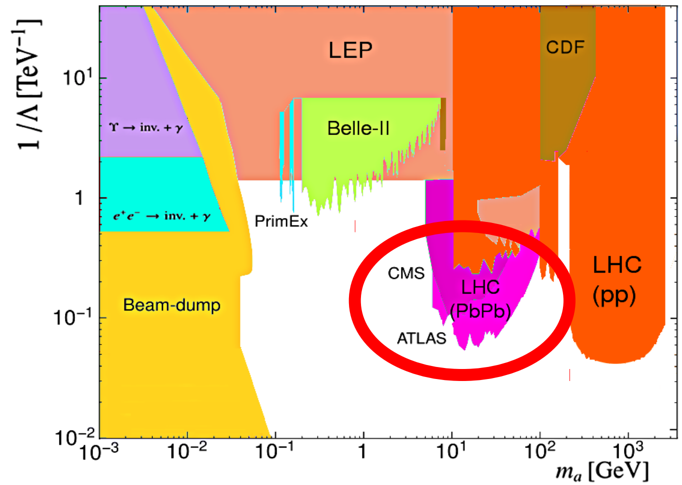
  Match X→γγ mass & rapidity in central CMS/RPs:

$$M_X = \sqrt{s\xi_1\xi_2}\ ,\ \ y_X = \frac{1}{2}\ln\frac{\xi_1}{\xi_2}$$

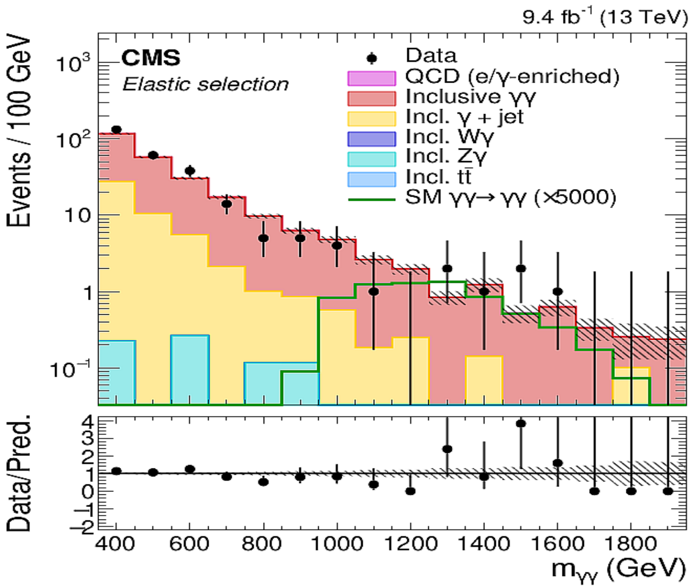
LbL scattering, ALPs, anomalous γ couplings

- PbPb: Evidence for LbL scattering & best ALP limits over $m_{\gamma\gamma}$ = 5–100 GeV





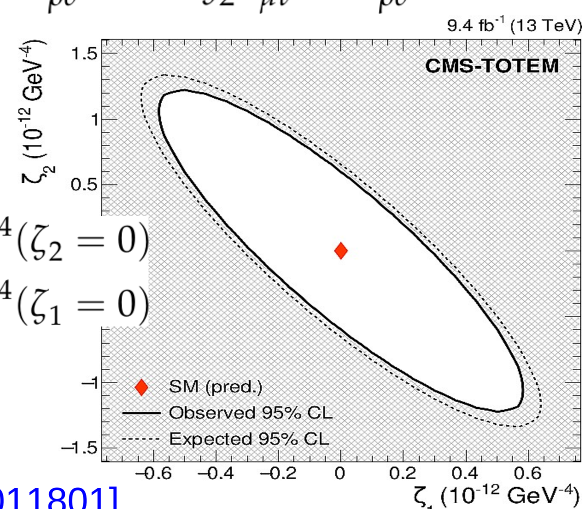
- pp: Searches for high-mass LbL & limits on anomal. neutral quartic couplings:



$$L_8^{\gamma\gamma\gamma\gamma} = \zeta_1 F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2 F_{\mu\nu}F^{\mu\rho}F_{\rho\sigma}F^{\sigma\nu}$$

$$|\zeta_1| < 2.9 \times 10^{-13}\,\mathrm{GeV}^{-4} (\zeta_2 = 0)$$

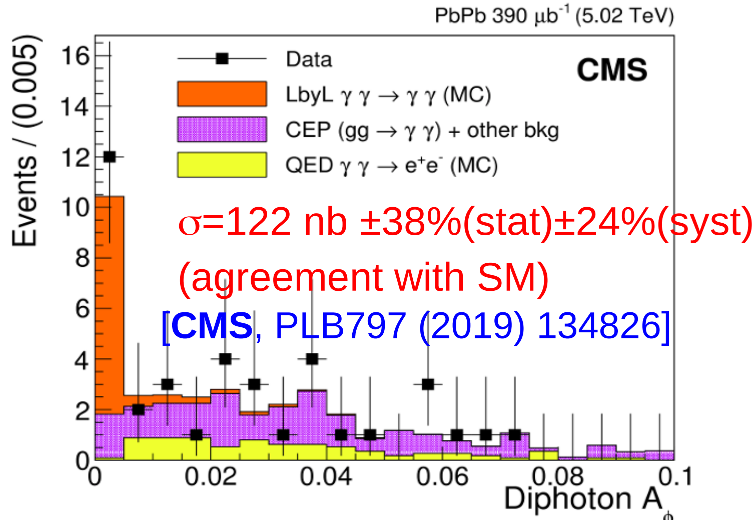
$$|\zeta_2| < 6.0 \times 10^{-13}\,\mathrm{GeV}^{-4} (\zeta_1 = 0)$$



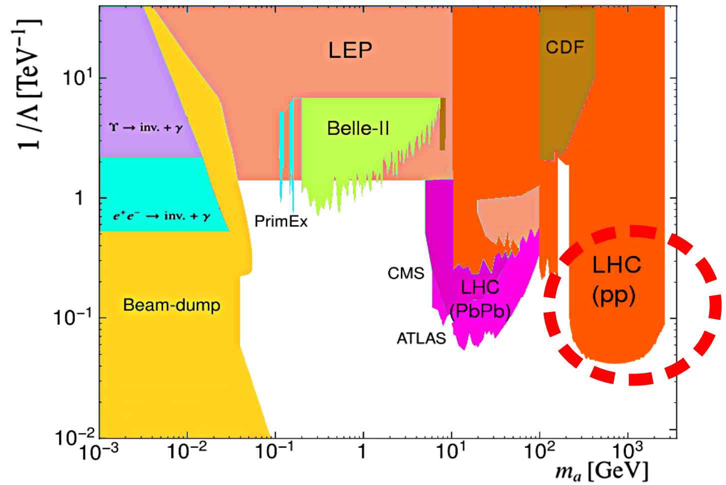
[CMS, PRL129 (2022) 011801]

LbL scattering, ALPs, anomalous γ couplings

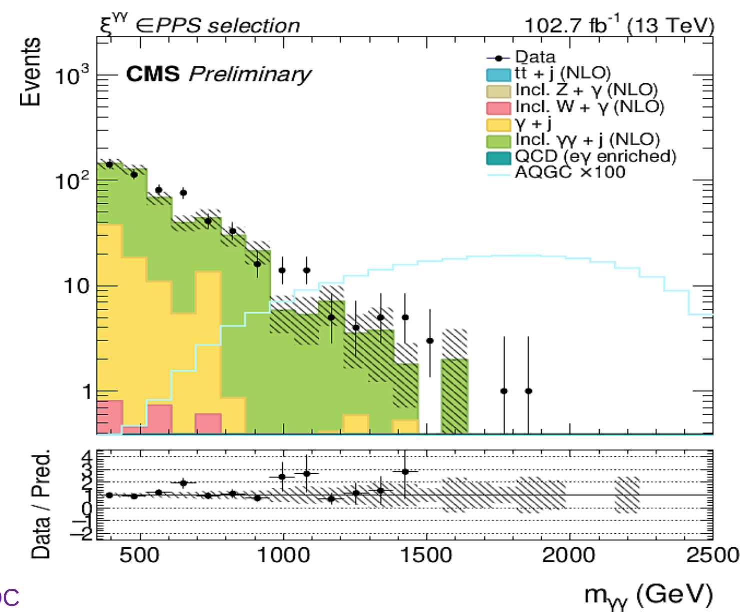
- PbPb: Evidence for LbL scattering & best ALP limits over $m_{\gamma\gamma}$ = 5–100 GeV

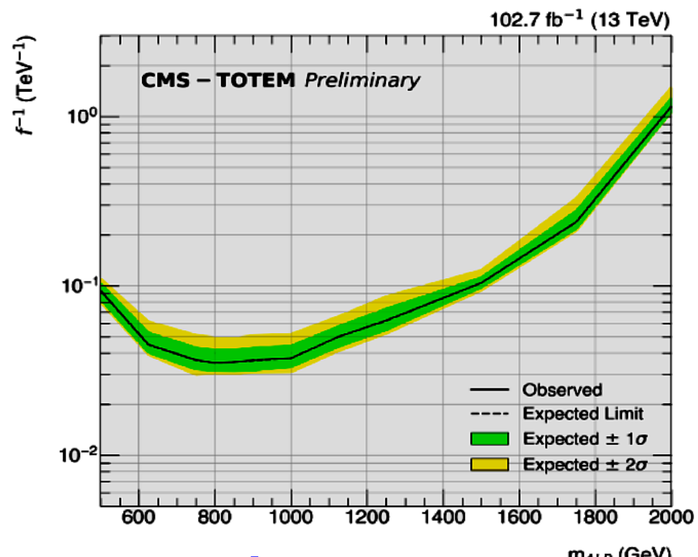


σ=122 nb ±38%(stat)±24%(syst)
(agreement with SM)
[CMS, PLB797 (2019) 134826]



- pp (full Run-2): Searches for high-mass LbL & limits on high-mass ALPs

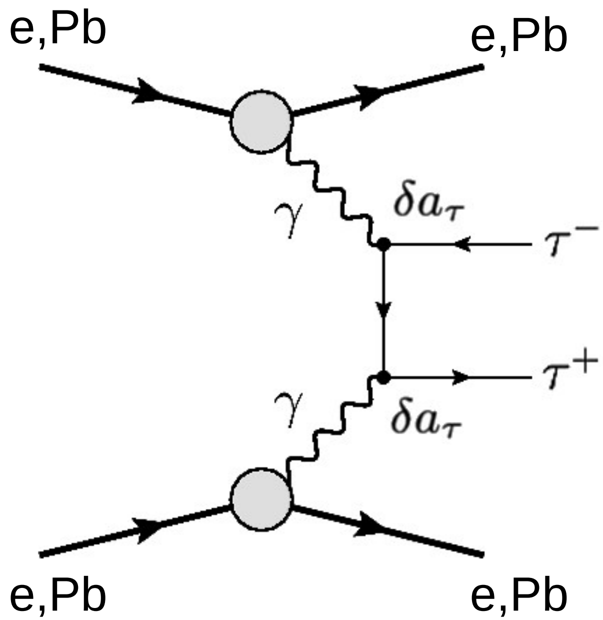


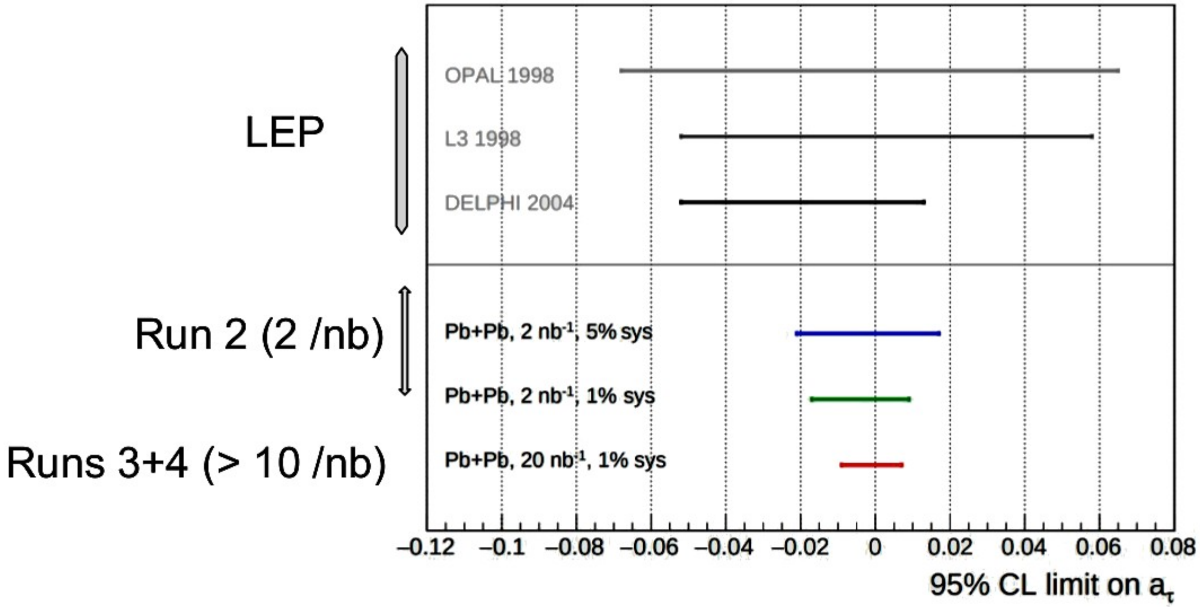


[CMS, PAS-EXO-21-007]

Tau magnetic moment via $\gamma\gamma \rightarrow \tau^+\tau^-$

- Useful process to determine the anomalous magnetic dipole moment of the tau lepton: $a_\tau = (g_\tau - 2)/2$. Done at LEP, accessible at LHC via UPCs:





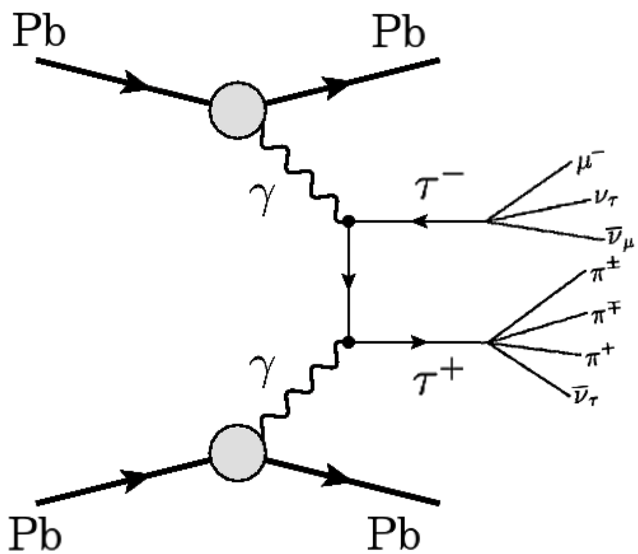
- Data-theory comparison of absolute and/or diff. x-sections = sensitive to $(g_\tau - 2)$
- Cross section in UPCs with ions enhanced by Z^4 factor relative to e^+e^-.

LHC can improve the precision on a_τ relative to best LEP (DELPHI) results

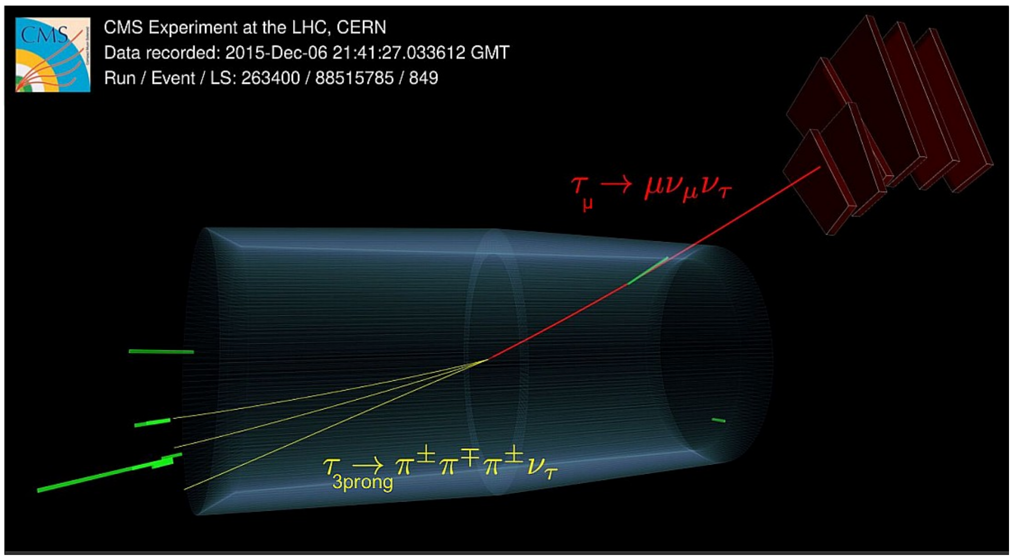
[F.del Aguila et al. (1991), Atag&Billur (2010), Beresford&Liu (2019), Dyndal et al. (2020)]

$\gamma\gamma \to \tau^+\tau^-$ measurement in PbPb

- Measurement in PbPb (5.02 TeV, 0.4 nb^{-1}) UPCs in 1ℓ+3-prong decays



CMS-PHO-EVENTS-2022-003-2



[**CMS**, arXiv:2206.05192]

- Relatively small BR $\approx$ 3% but clean final state with controlled backgrounds ("ABCD method" regions: 1 for signal, 3 for inverted cuts): $\gamma\gamma \to \mu\mu, c\bar{c}, b\bar{b}$,...

- Event Selection:

Trigger: 1 μ, 1+ tracks, zero activity in HF fwd calo

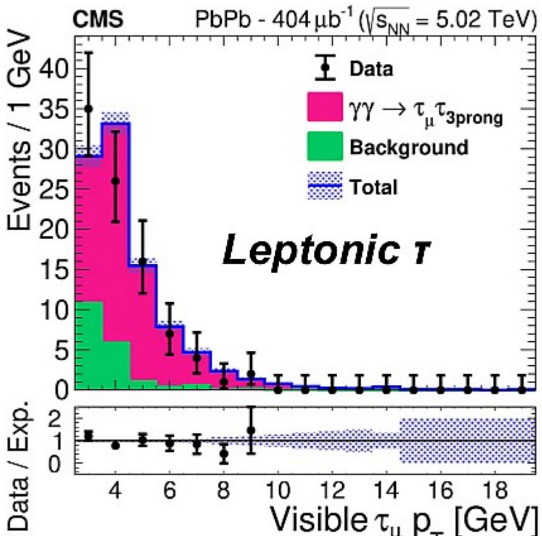
Offline:

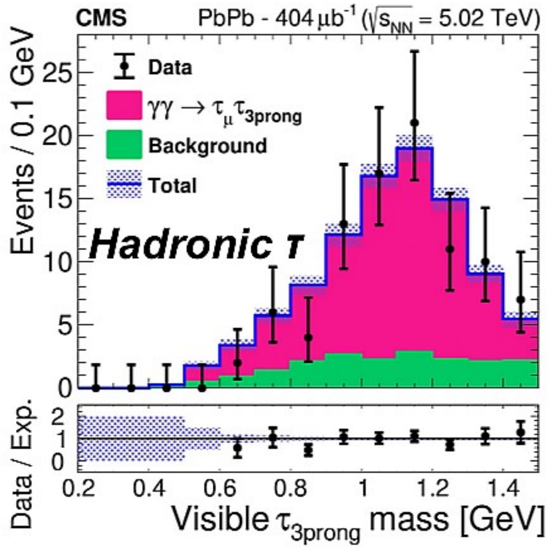
Muon	$p_T > 3.5$ GeV for $\lvert\eta\rvert < 1.2$ $p_T > 2.5$ GeV for $1.2 < \lvert\eta\rvert < 2.4$
Pion	$p_T > 0.5$ GeV for the leading $p_T > 0.3$ GeV for the (sub-)subleading $\lvert\eta\rvert < 2.5$
τ_{3prong}	$p_T^{vis} > 2$ GeV and $0.2 < m_\tau^{vis} < 1.5$ GeV

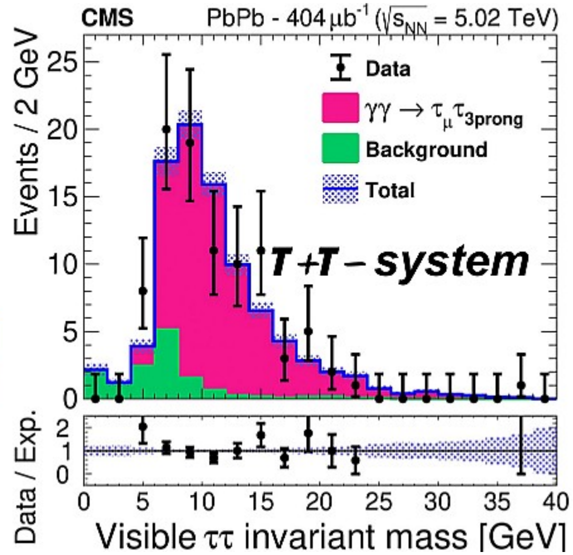
$\gamma\gamma \rightarrow \tau^+\tau^-$: Signal extraction

[**CMS**, arXiv:2206.05192]

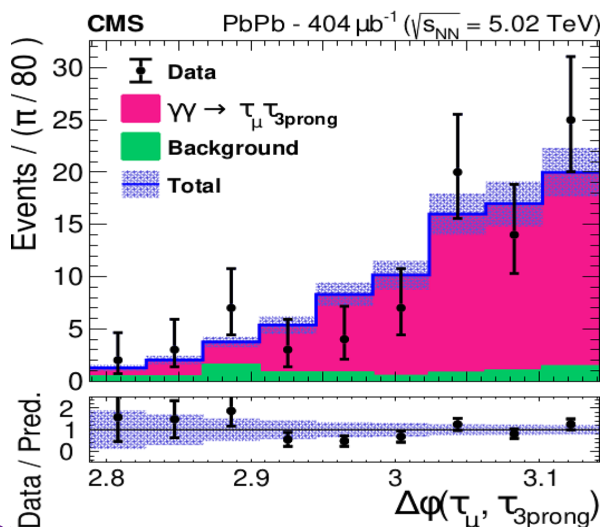
- Good agreement between reconstructed data & MC kinematic distributions:



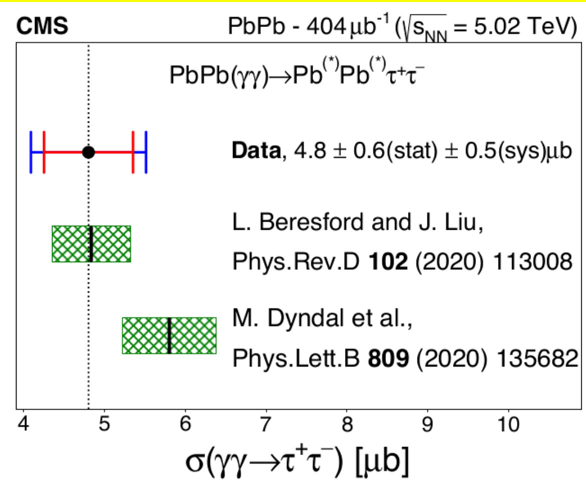




- Yield extraction (77 ± 12, 5σ) likelihood fit to $\Delta\varphi(\tau_{lep},\tau_{had})$ discriminating variable



$$\sigma(\gamma\gamma \rightarrow \tau^+\tau^-) = 4.8 \pm 0.6\,(\text{stat}) \pm 0.5\,(\text{syst})\,\mu\text{b},$$



$\gamma\gamma \to \tau^+\tau^-$: Signal extraction & a_τ limits

[**CMS**, arXiv:2206.05192]

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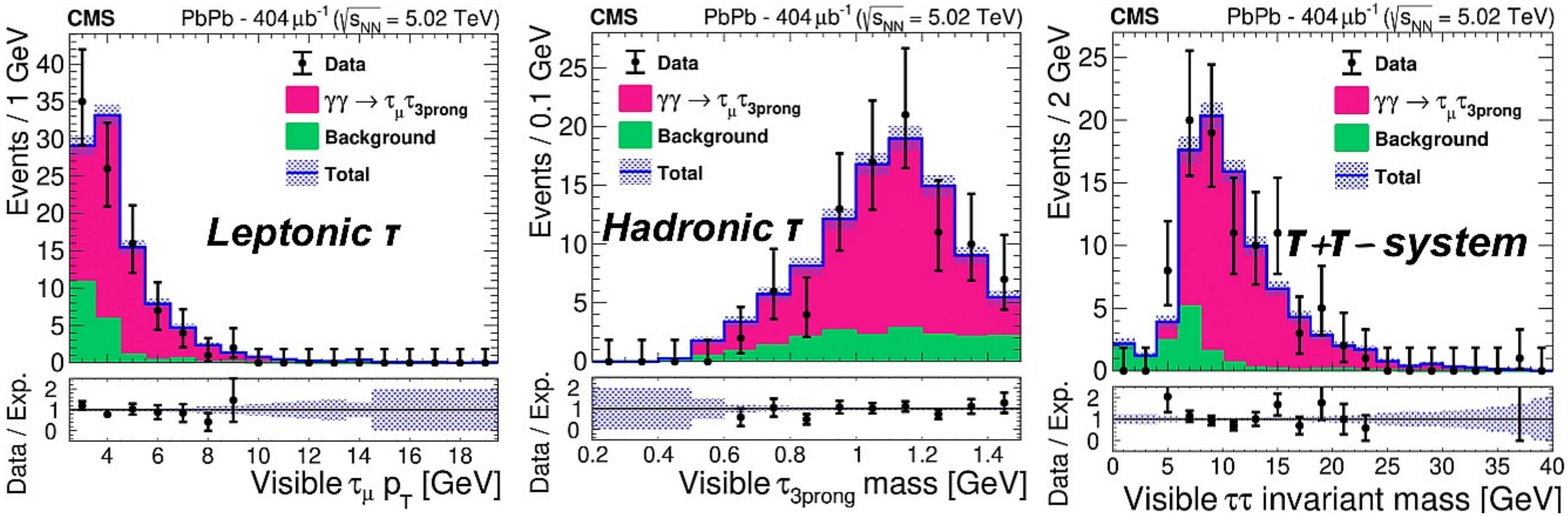
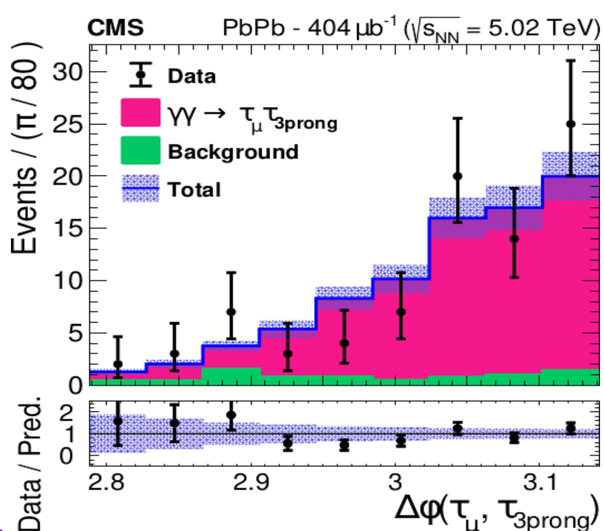


- Comparison of experimental & theoretical x-sections: $(g\text{–}2)_\tau$ constraint



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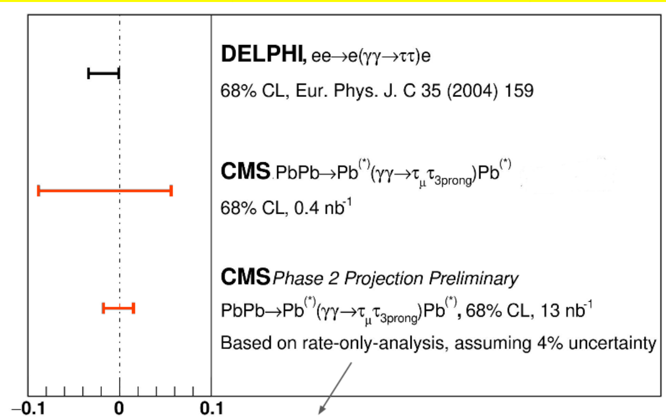
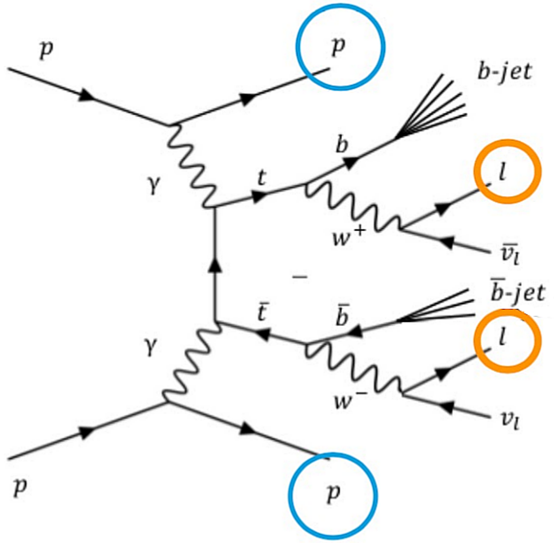


More final states → further improvements

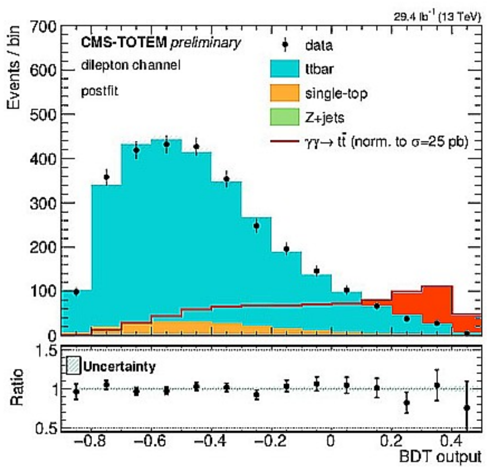
γγ → ttbar measurement in p-p

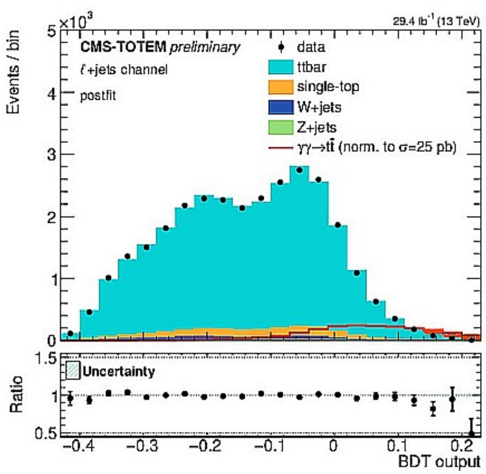
- Exclusive ttbar: sensitivity to anomalous top quark e.m. couplings
  Never observed so far: tiny $\sigma \approx 0.2$ fb at NLO. [CMS, PAS-TOP-21-007]

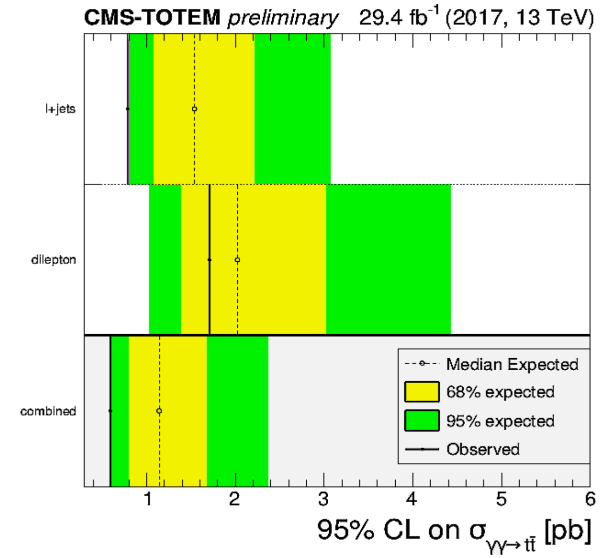


- Measurement in p-p (13 TeV, 29 fb^{-1}):
  - ttbar in central CMS: ℓℓ & ℓ+jets decays
  - Protons recontructed in RPs
- Search above dominant inclusive ttbar backgd
  Multivariate analysis: protons & ttbar kinem.vars.
- Cross-section limits (dominated by stats.):
  Upper limit σ = 0.59 pb 95% CL (1.14 pb expect)

- Boosted Decision Trees outputs for 2 decays:

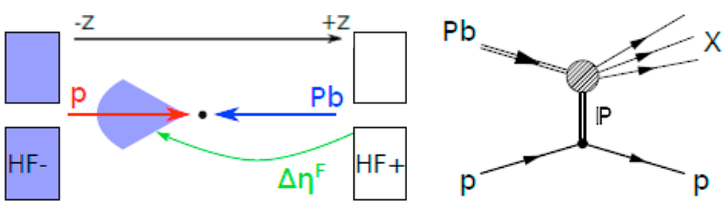


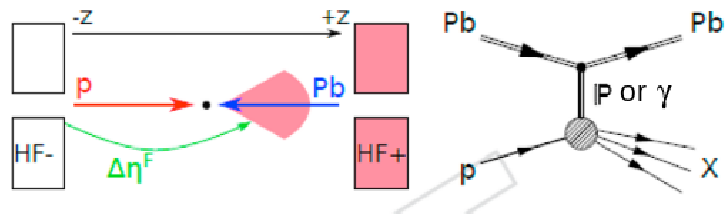




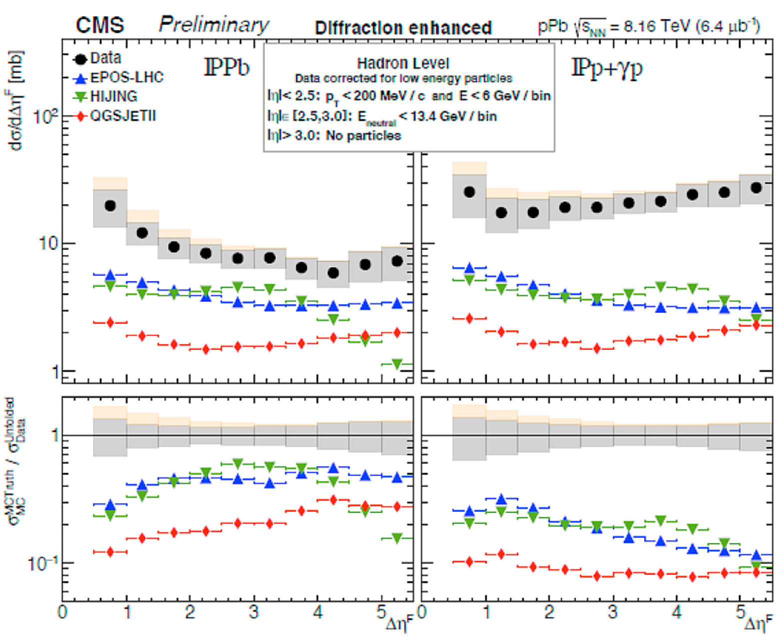
Rapidity-gap events in p-Pb

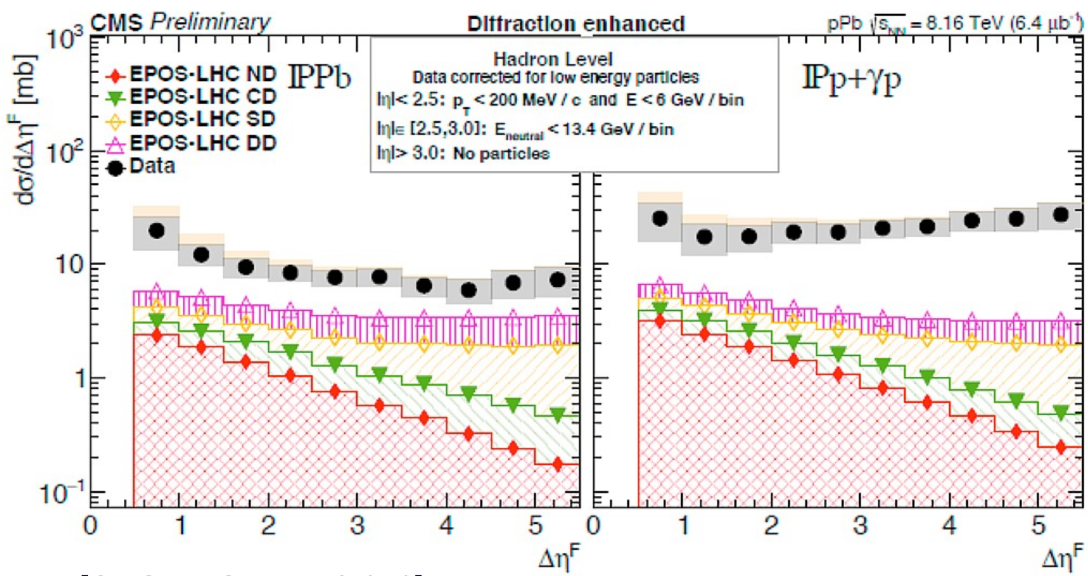
- p-Pb collisions allow the study of both |P and γ interactions with nuclei:





- Rapidity gaps (Pb & p directions) distributions in data & MC for p-Pb(8.16 TeV):



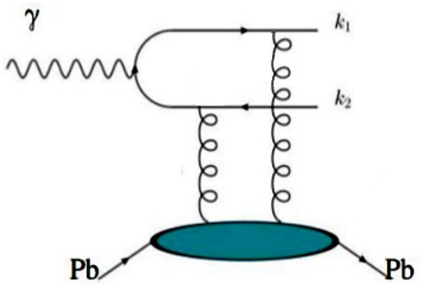


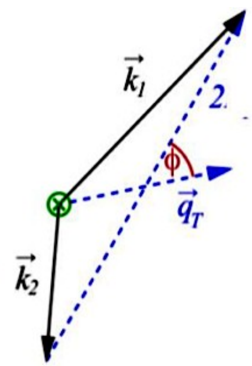
[**CMS**, PAS-HIN-18-019]

- Hadronic MCs (EPOS, QGSJETII, HIJING) clearly underpredict size of rap.gaps
  More prominent MC deficit for photon-induced collisions.
  Diffraction improvements needed for description of air showers of UHE cosmic-rays

Exclusive dijet photoproduction in PbPb

- Azimuthal decorrelation of exclusive dijets in γ-lead interactions sensitive to polarization of gluons within nuclei (depend on orientation of the $q\bar{q}$ dipole wrt. impact parameter vector):





Vector sum of 2 jets:

$$\vec{Q}_T = \vec{k}_1 + \vec{k}_2$$

Vector difference of 2 jets:

$$\vec{P}_T = \frac{1}{2}(\vec{k}_1 - \vec{k}_2)$$

Measure angle φ between Q_T and P_T vectors.

$$\cos(\phi) = \vec{Q}_T \cdot \vec{P}_T / (|| \vec{Q}_T || \cdot || \vec{P}_T ||)$$

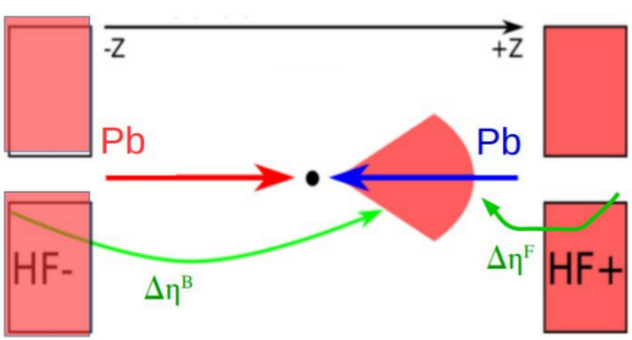
$$v_2 = \langle \cos(2\phi) \rangle$$

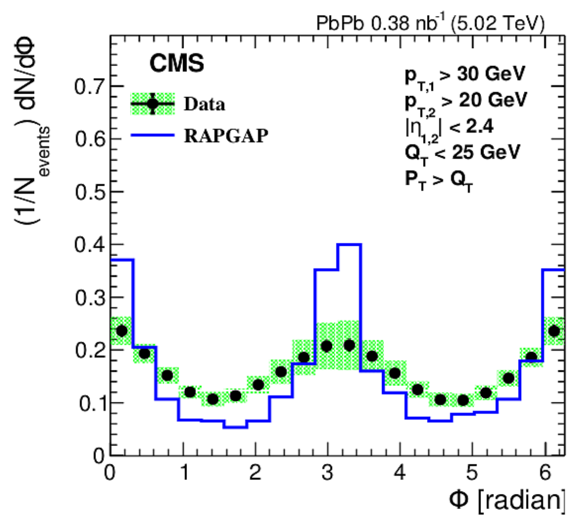
Gluon polarization effects probed by analyzing 2nd Fourier moment v_2

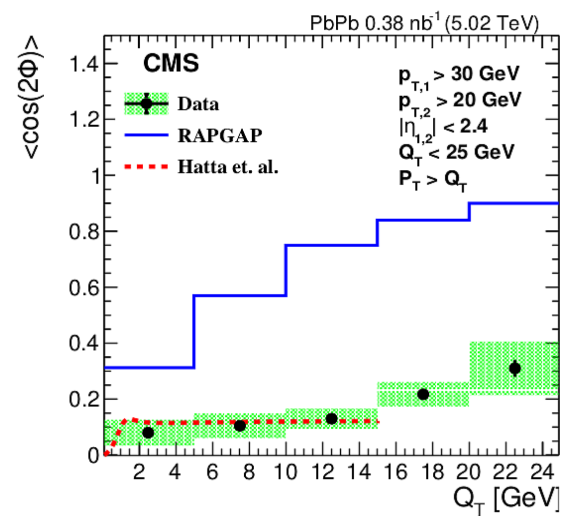
Hatta, et al, PRL 116, 202301 (2016)

- TMD-based calc. reproduces data (HERA-photoprod.-tuned RAPGAP does not)

- anti-kT R = 0.4 particle-flow jets.
- Two jets with |η| < 2.4, p_T^{lead} > 30 GeV and $p_T^{sublead}$ > 30 GeV > 20 GeV.
- Hadronic activity is vetoed in backward and forward regions (2.8 < |η| < 5.2)



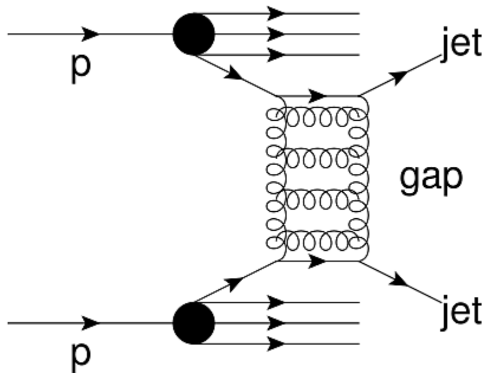


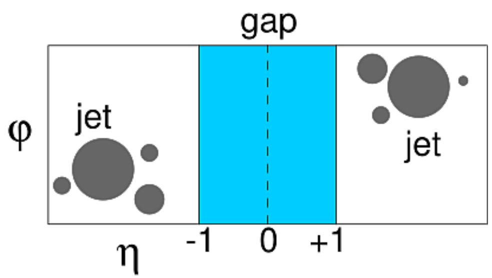


[**CMS**, arXiv:2205.00045]

Jet-gap-jet events in p-p

- Mueller-Tang jets events characterized by production of 2 jets with a large rapidity gap: Hard color-singlet exchange (t-channel 2-gluon ladder in BFKL).



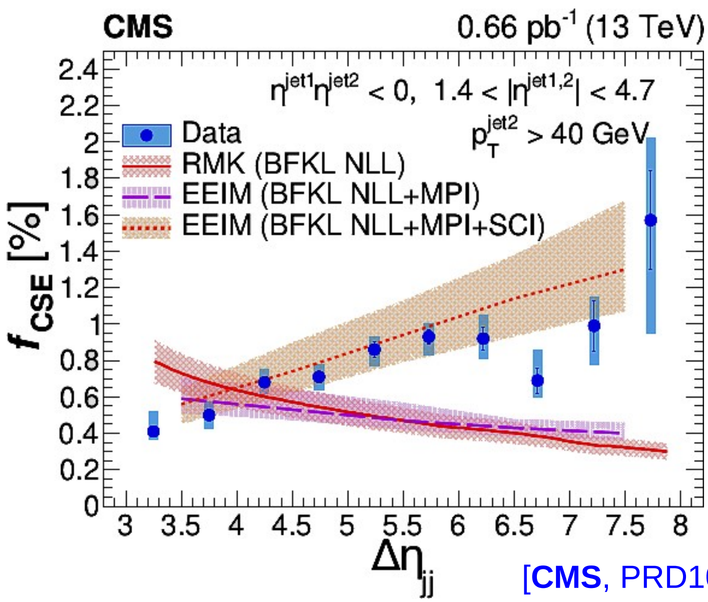


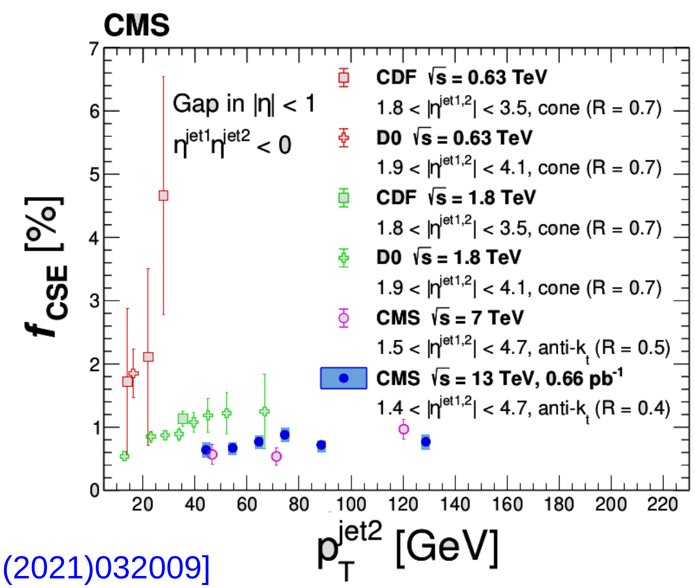
Jets: anti-k_T (R=0.4), p_T > 40 GeV, $|\eta_{jet}|$ = 1.4–4.7, $|\eta_1\eta_2| < 0$

Gap: No ch.part. with p_T > 0.2 GeV and $|\eta| < 1$ between the jets (Low pileup high-β* run)

- Fraction color-singlet evts.=0.5–1%: Rises w/ jj gap, flat w/ p_T, saturates at LHC

Constraints for BFKL LO NLL models

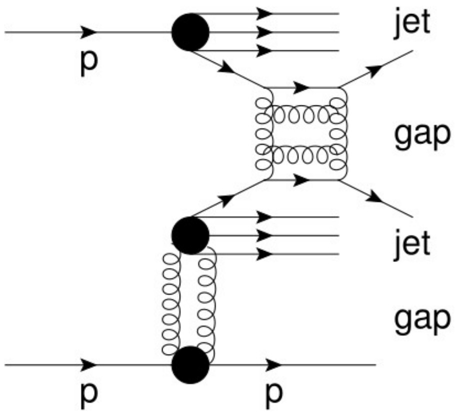


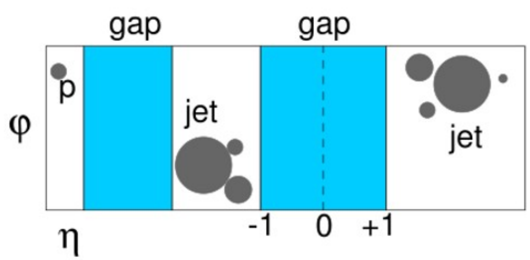


[CMS, PRD104 (2021)032009]

Jet-gap-jet events with intact proton in p-p

- Mueller-Tang jets in events where one of the proton survives:





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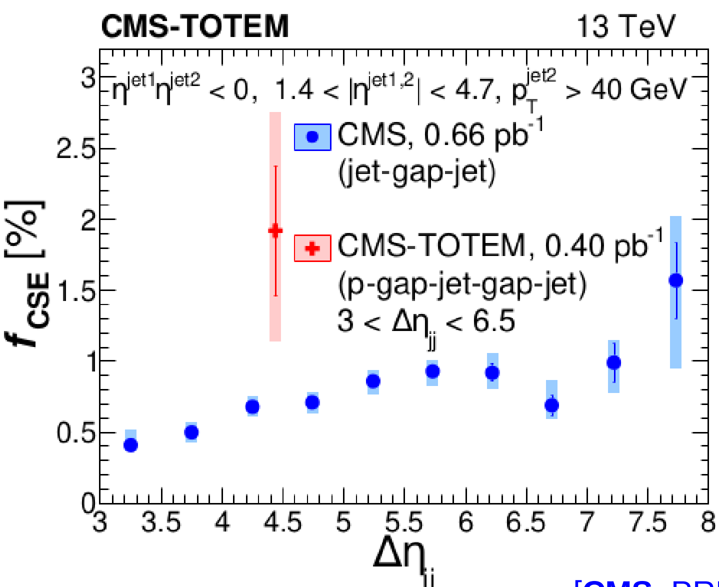
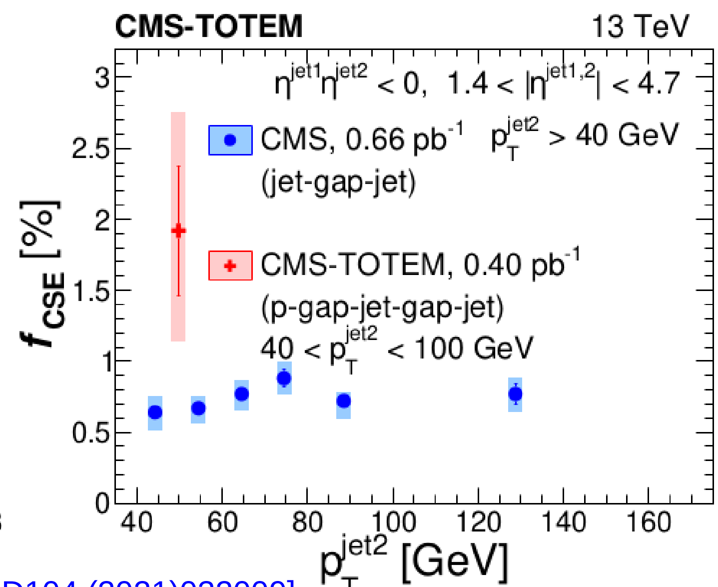
Gap: No ch.part. with p_T > 0.2 GeV and $|\eta|$ < 1 between the jets (Low pileup high-β^* run)

Forward proton: Tagged in RPs

- Fraction of Mueller-Tang jets in diffractive events = ~2%





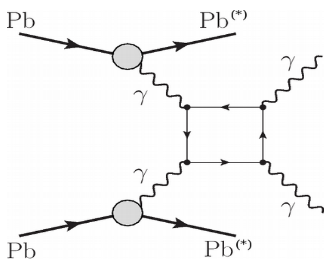
Diffractive requirement suppresses soft scatterings among 2 protons (larger $|S|^2$)

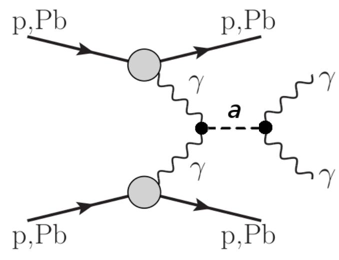
[CMS, PRD104 (2021)032009]

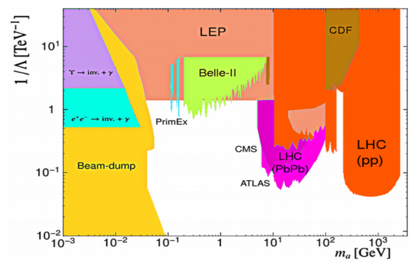
Summary

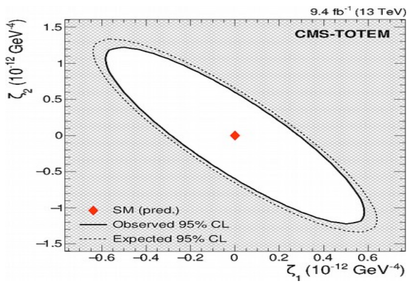
■ Multiple studies of color-singlet (γ,|P) exch. processes in p-p,p-A,A-A colls. obtained via exclusivity/rap.gaps and/or fwd. proton reconstruction:

▶ Evidence for LbL scatt., competitive limits: ALPs, anomal. quartic γ couplings

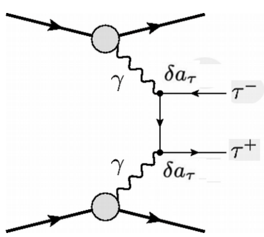


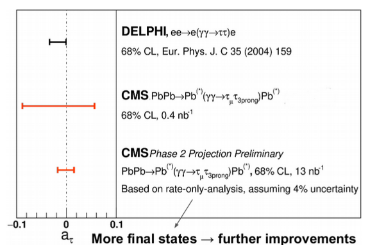


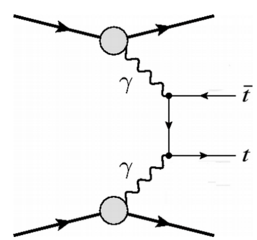


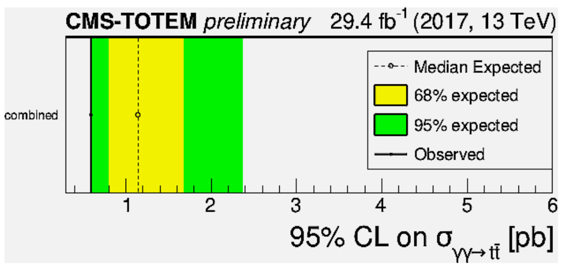


▶ Observation of $\gamma\gamma \to \tau\tau$, future $(g-2)_\tau$ constraints. Search for $\gamma\gamma \to$ ttbar

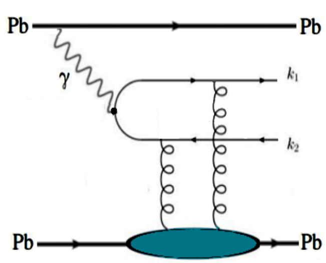


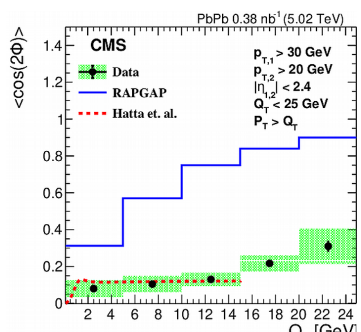


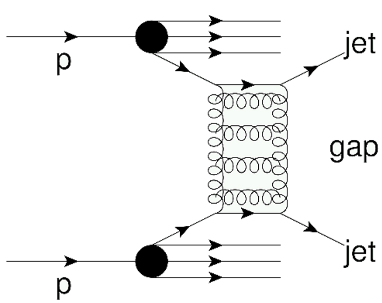


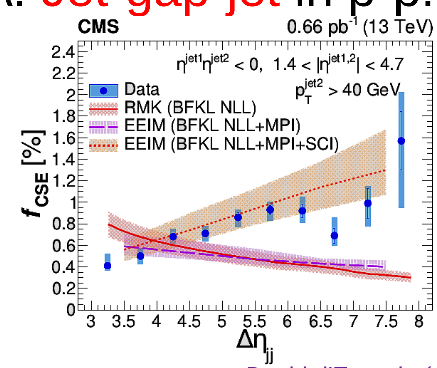


▶ Rap. gaps in p-A. Exclusive dijet photoproduction in A-A. Jet-gap-jet in p-p:









Back-up slides

γγ theoretical cross sections

- **Cross section:**

$$\sigma(\mathrm{A\ B} \xrightarrow{\gamma\gamma} \mathrm{A}\ X\ \mathrm{B}) = \int \frac{dE_{\gamma_1}}{E_{\gamma_1}} \frac{dE_{\gamma_2}}{E_{\gamma_2}} \frac{\mathrm{d}^2 N^{(\mathrm{AB})}_{\gamma_1/\mathrm{Z}_1,\gamma_2/\mathrm{Z}_2}}{\mathrm{d}E_{\gamma_1}\mathrm{d}E_{\gamma_2}} \sigma_{\gamma\gamma\to X}(W_{\gamma\gamma})$$

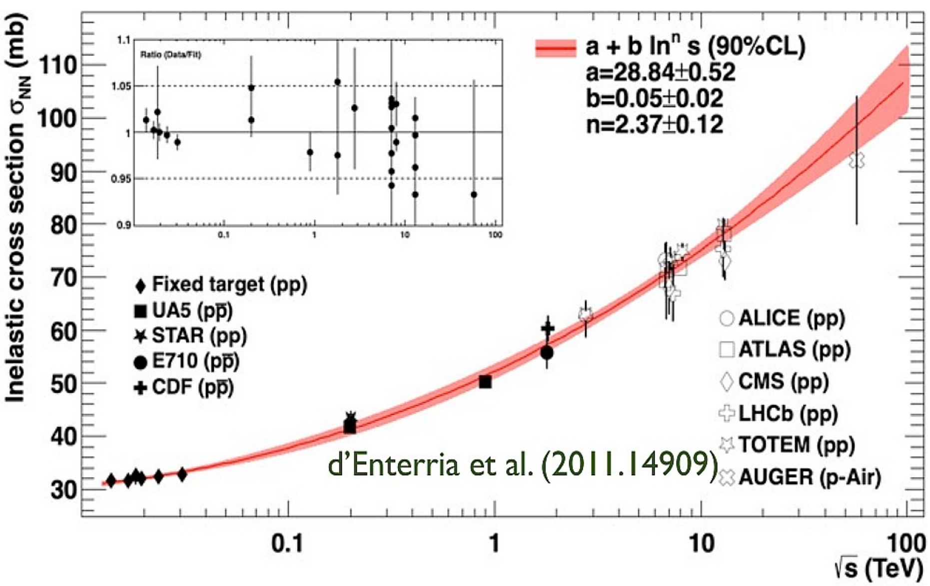
- **Effective two-photon luminosity:**

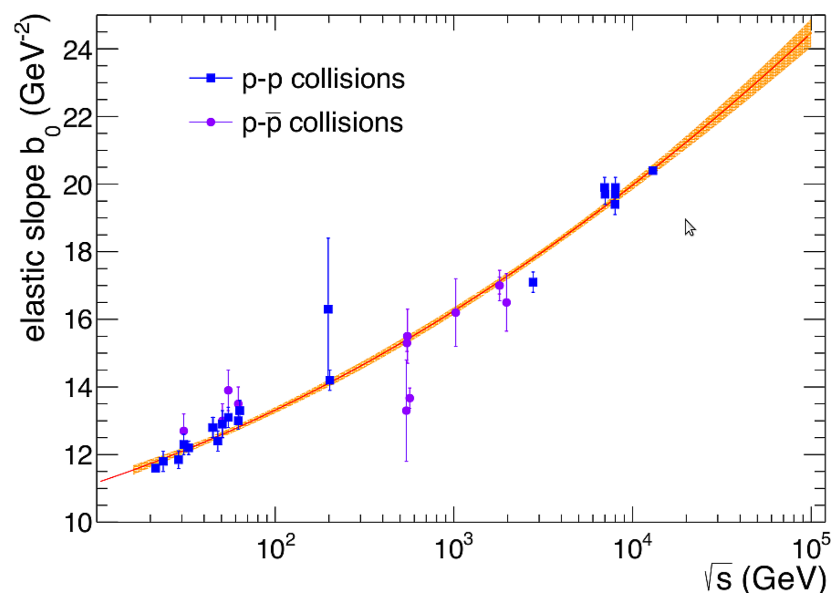
$$\frac{\mathrm{d}^2 N^{(\mathrm{AB})}_{\gamma_1/\mathrm{Z}_1,\gamma_2/\mathrm{Z}_2}}{\mathrm{d}E_{\gamma_1}\mathrm{d}E_{\gamma_2}} = \int \mathrm{d}^2\boldsymbol{b}_1 \mathrm{d}^2\boldsymbol{b}_2\, P_{\mathrm{no\,inel}}(|\boldsymbol{b}_1 - \boldsymbol{b}_2|)\; N_{\gamma_1/\mathrm{Z}_1}(E_{\gamma_1}, \boldsymbol{b}_1) N_{\gamma_2/\mathrm{Z}_2}(E_{\gamma_2}, \boldsymbol{b}_2) \times\theta(b_1 - \epsilon R_{\mathrm{A}})\theta(b_2 - \epsilon R_{\mathrm{B}})$$

- **No hadronic/inelastic interaction probability density:**

$$P_{\mathrm{no\,inel}}(b) = \begin{cases} e^{-\sigma_{\mathrm{inel}}^{\mathrm{NN}} \cdot T_{\mathrm{AB}}(b)}, & \text{nucleus-nucleus} \\ e^{-\sigma_{\mathrm{inel}}^{\mathrm{NN}} \cdot T_{\mathrm{A}}(b)}, & \text{proton-nucleus} \\ |1 - \Gamma(s_{\mathrm{NN}}, b)|^2, \quad \text{with}\ \ \Gamma(s_{\mathrm{NN}}, b) \propto e^{-b^2/(2b_0)} & \text{p-p} \end{cases}$$

$T_{AB}(b)$ from (parametrized)
Glauber MC





p,A form factors & γ fluxes: ChFF, EDFF

Electric dipole form factor (EDFF)

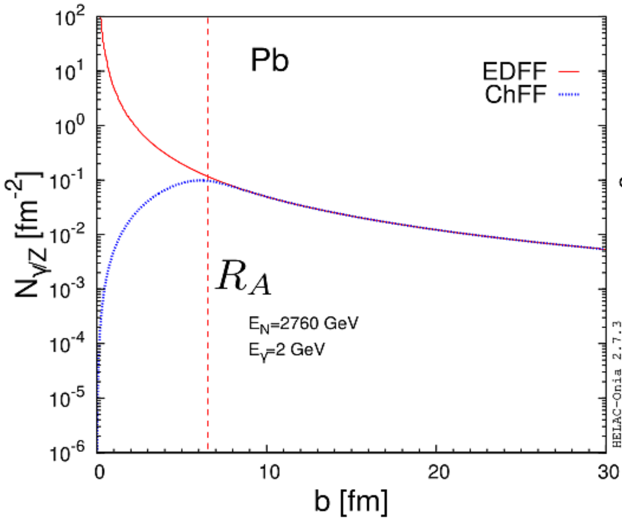
- Same as STARlight

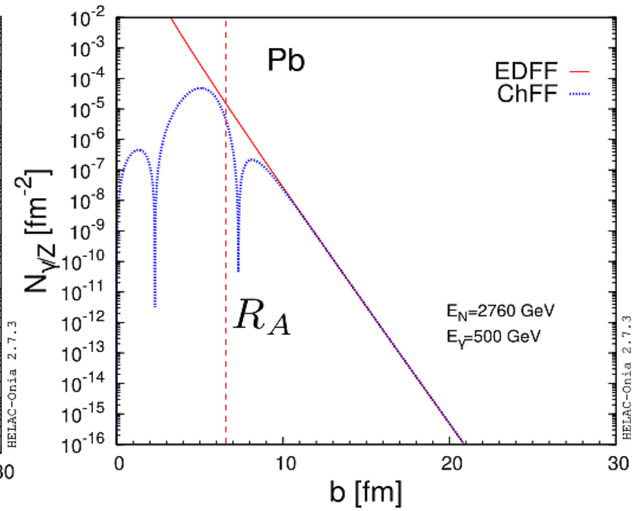
$$N^{\rm EDFF}_{\gamma/{\rm Z}}(E_\gamma,b) = \frac{Z^2\alpha}{\pi^2}\frac{\xi^2}{b^2}\left[K_1^2(\xi)+\frac{1}{\gamma_{\rm L}^2}K_0^2(\xi)\right] \qquad \xi = \frac{E_\gamma b}{\gamma_{\rm L}}$$

Charge form factor (ChFF)

$$N^{\rm ChFF}_{\gamma/{\rm Z}}(E_\gamma,b) = \frac{Z^2\alpha}{\pi^2}\left|\int_0^{+\infty}\frac{dk_\perp k_\perp^2}{k_\perp^2+E_\gamma^2/\gamma_{\rm L}^2}F_{\rm ch,A}\left(\sqrt{k_\perp^2+E_\gamma^2/\gamma_{\rm L}^2}\right)J_1(bk_\perp)\right|^2$$

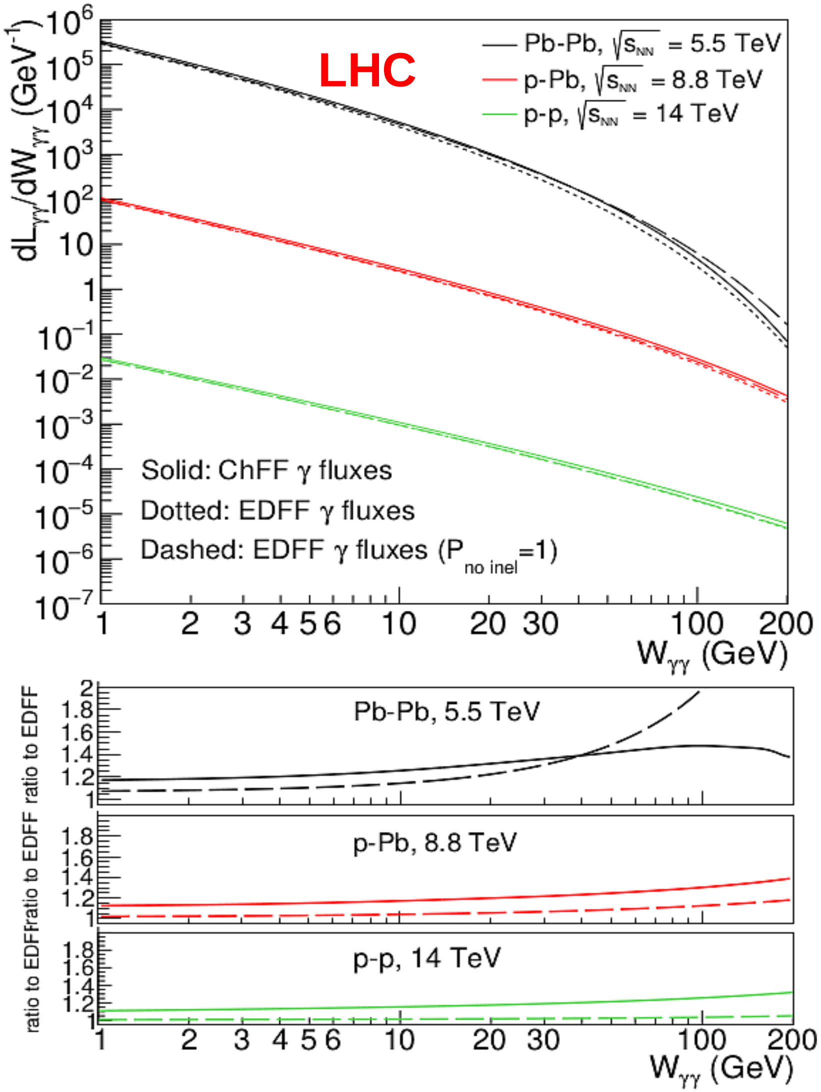
$$F_{\rm ch,A}(q) = \int {\rm d}^3\boldsymbol{r}e^{i\boldsymbol{q}\cdot\boldsymbol{r}}\rho_{\rm A}(\boldsymbol{r}) = \frac{4\pi}{q}\int_0^{+\infty}{\rm d}r\,\rho_{\rm A}(r)r\sin(qr)$$

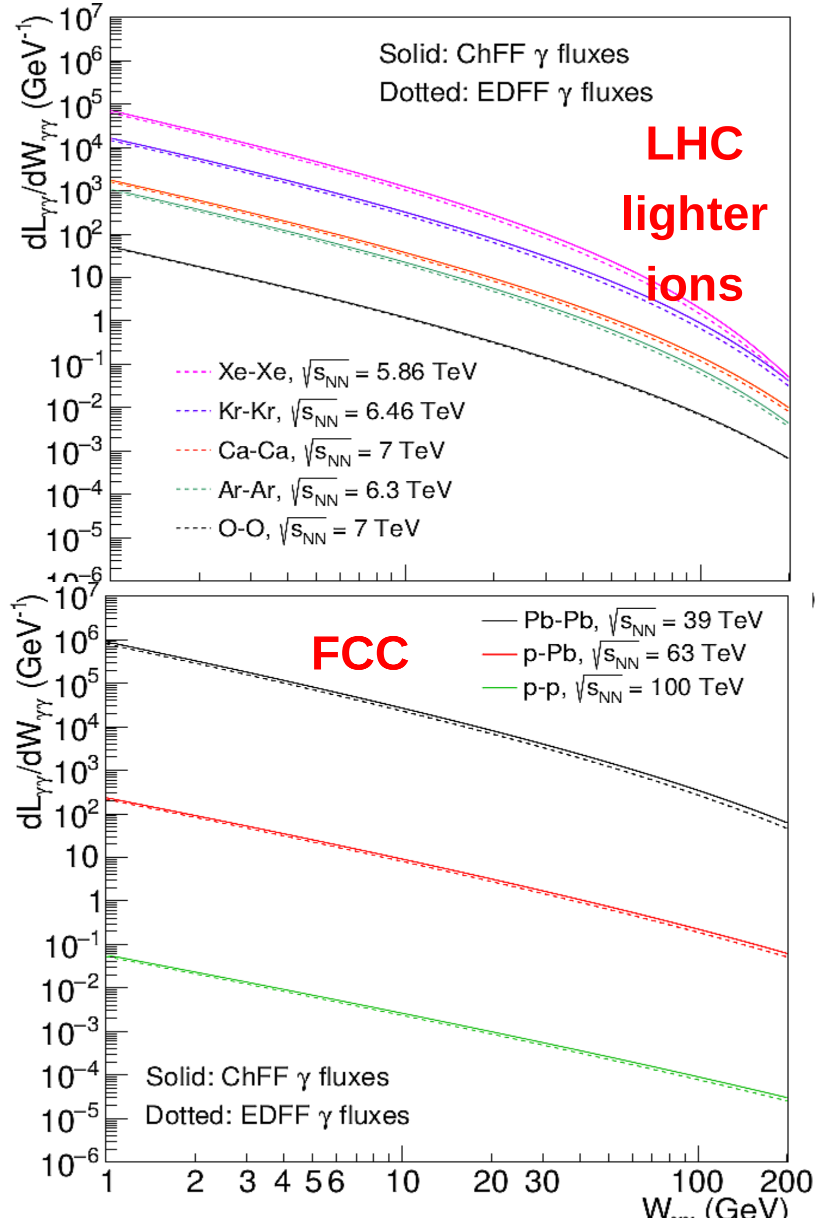




- Main difference comes from the $b < R_A$ regime
- EDFF photon number density is divergent at $b = 0$
  - Need a (arbitrary) cutoff when convoluting with ME

γγ effective luminosities





- ChFF/EDDF γ-fluxes differences (pp–PbPb):
  Low masses: ~7–15%. High masses: 20–50%