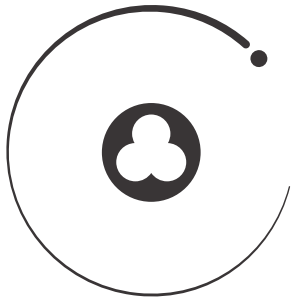

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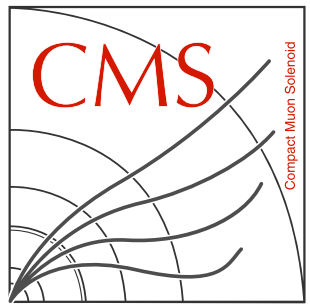


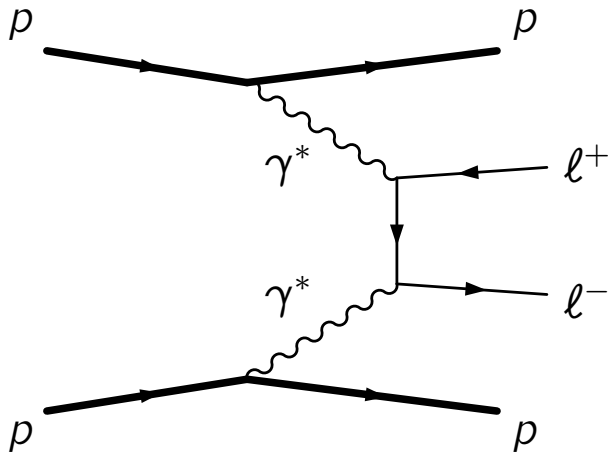
Two-photon production of lepton pairs processes at LHC

L. Forthomme (HIP)

LHC EW precision sub-group meeting

Oct 7, 2020

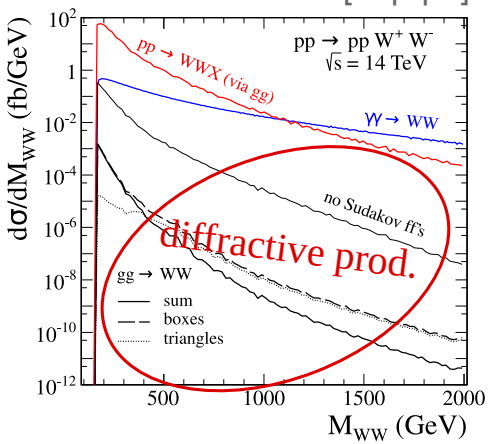
General motivations for a $\gamma\gamma \to l^+l^-$ study



Relatively **large cross-section**, t-channel **central exclusive process** (CEP)

- colour-singlet ($J^{PC} = 0^{++}$) exchange yielding large rapidity gaps between the central and scattered/remnant beam particles system
- low-Q^2 elastic emission of photons ensures "interesting" kinematic properties of the central system: good p_T balance of leptons, tend to be produced back-to-back in transverse plane, ...
- possible **background source** for other l^+l^- searches (e.g. exclusive/diffractive production of **low-mass resonances**, higher-mass Z' **searches**, W^+W^- cross section measurement, ...)

arXiv:1203.1832 [hep-ph]

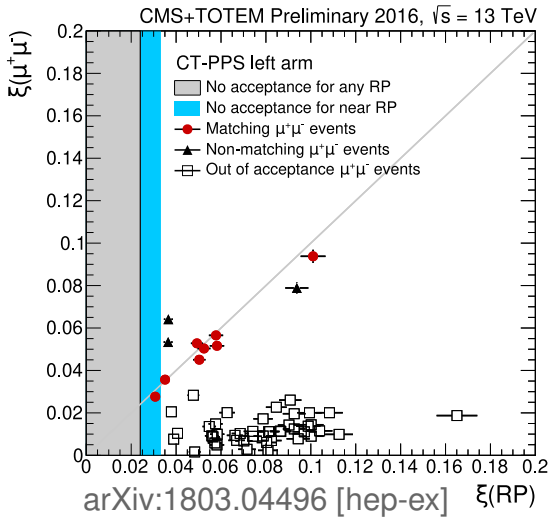


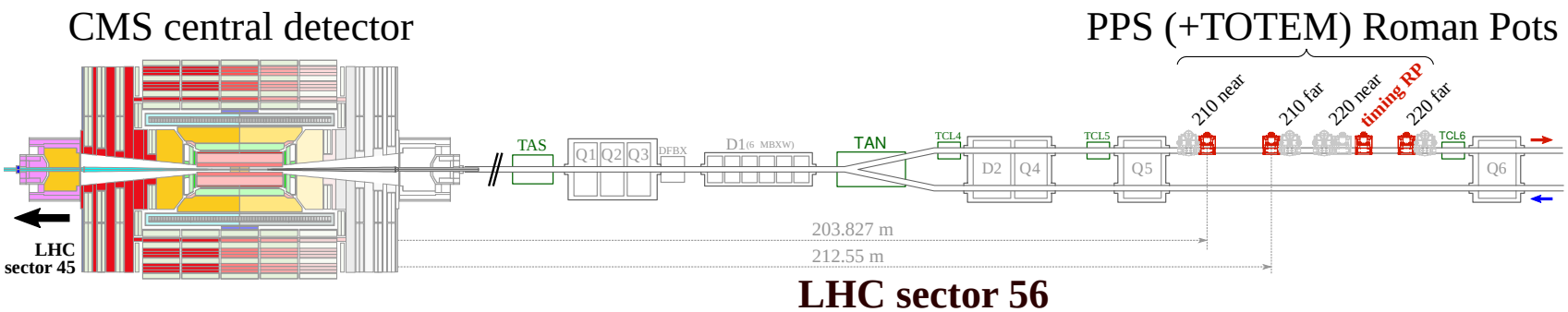
General motivations for a $\gamma\gamma \to l^+l^-$ study (cont.)

Proposed as **"standard candle"** for, e.g.

- luminosity measurement [Nucl.Instrum.Meth.A 494 (2002) 51, . . .]
  - elastic emission well described theoretically, clear experimental signature, simple counting experiment to evaluate luminosity in hadron-hadron collisions

- direct CEPs experimental tagging
  - e.g. for CMS Precision Proton Spectrometer tagging leading scattered protons in high-luminosity *pp* interactions, LHC optics validation through the matching of the $\gamma\gamma \to l^+l^-$ system and its corresponding scattered protons system





Well studied in the past at SLAC, HERA, and multiple fixed targets/laser beams experiments, but also more recently at LHC energies

The story so far: LHC results

Numerous $\gamma\gamma$ precision searches already released with LHC energies.

Using "central detectors" only (*pp*, *PbPb*):

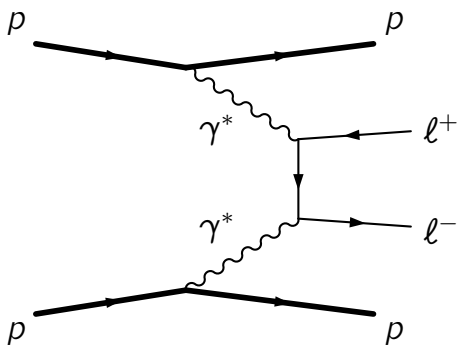
- CMS: [JHEP 01 (2012) 052, JHEP 11 (2012) 080] ($\gamma\gamma \to l^+l^-$), [JHEP 07 (2013) 116, JHEP 08 (2016) 119] ($\gamma\gamma \to W^+W^-$), [Phys.Lett.B 797 (2019) 134826] ($\gamma\gamma \to \gamma\gamma$)
- ATLAS: [Phys.Lett.B 749 (2015) 242, Phys.Lett.B 777 (2018) 303] ($\gamma\gamma \to l^+l^-$), [Phys.Rev.D 94 (2016) 3, 032011, ATLAS-CONF-2020-038] ($\gamma\gamma \to W^+W^-$), [Nature Phys. 13 (2017) 9, 852] ($\gamma\gamma \to \gamma\gamma$)
- LHCb: [LHCb-CONF-2011-022]

or adding forward proton tagging (PPS/AFP): [JHEP 07 (2018) 153, arXiv:2009.14537] ($\gamma\gamma \to l^+l^-$), [CMS-PAS-EXO-18-014/TOTEM-NOTE-2020-003] ($\gamma\gamma \to \gamma\gamma$)

Lots of *"first"* with $\gamma\gamma$ processes at LHC:

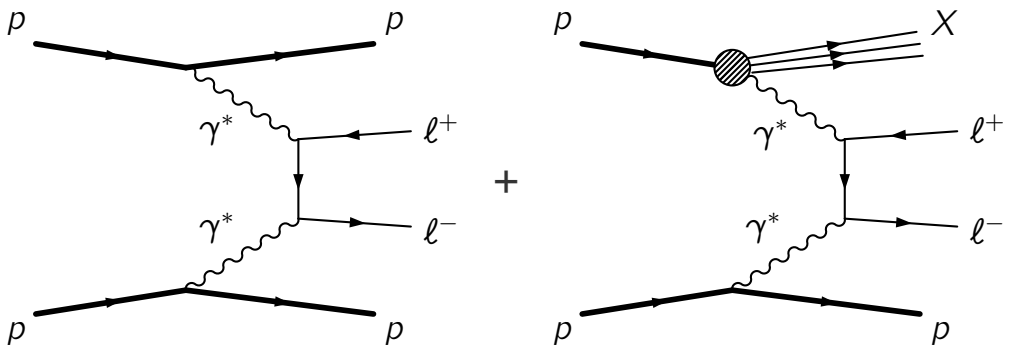
- first **evidence**, and **observation** of $\gamma\gamma \to W^+W^-$ at 7 and 8 TeV
- first **competitive limits** on anomalous quartic $\gamma\gamma W^+W^-$ coupling since LEP EWK programme
- first **observation** of $\gamma\gamma \to l^+l^-$ **with leading protons** at 13 TeV
- . . . and more to come in a near future

$\gamma\gamma \to l^+l^-$: how many processes?



Elastic photon emission, pure QED process. Theoretical uncertainties dominated by definition of proton electromagnetic form factors ($p + X \to p + \gamma^{(*)} + X'$)

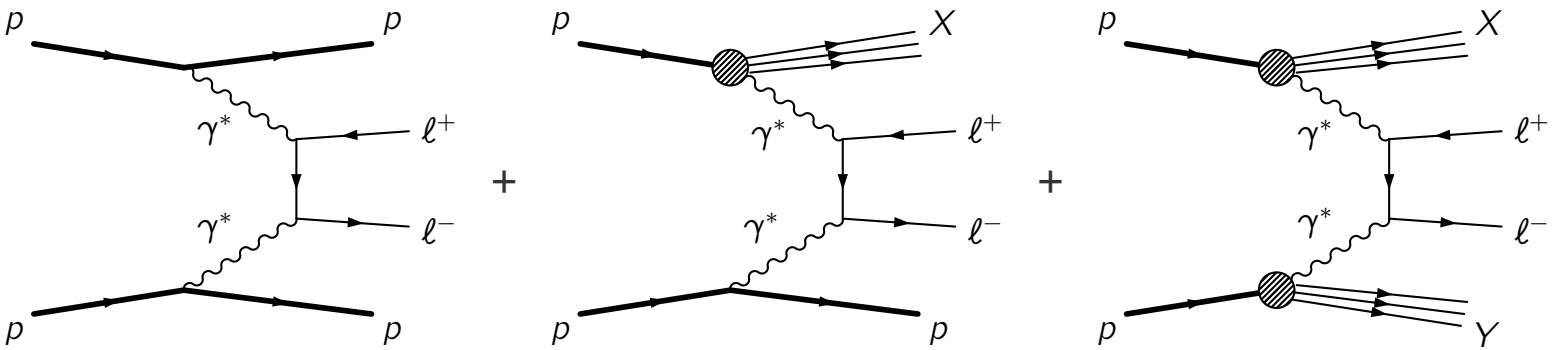
$\gamma\gamma \to l^+l^-$: how many processes?



Elastic photon emission, pure QED process. Theoretical uncertainties dominated by definition of proton electromagnetic form factors ($p + X \to p + \gamma^{(*)} + X'$)

Single proton breakup after photon emission, either fully DIS emission (probing partonic content of proton) or rescattering effects inducing nuclear break-up of nucleon

$\gamma\gamma \to l^+l^-$: how many processes?



Elastic photon emission, pure QED process. Theoretical uncertainties dominated by definition of proton electromagnetic form factors ($p + X \to p + \gamma^{(*)} + X'$)

Single proton breakup after photon emission, either fully DIS emission (probing partonic content of proton) or rescattering effects inducing nuclear break-up of nucleon

Fully inelastic photon emission, inducing broader photon virtuality spectra, and much closer experimentally to inclusive production processes, although central kinematics tends to retain properties of a photon-induced process

Various computation techniques for two-photon processes (in general), and $\gamma\gamma \to l^+l^-$ (in particular):

- **exact calculation** of the QED matrix element (using high-order techniques for numerical estimation), used in e.g. LPAIR simulation (Vermaseren, Baranov *et al.*, 1982)
  - developed in the scope of HERA physics programme (*ep*, asymmetric photon emission)
  - later ported to $p\bar{p}/pp$ collisions (CDF)

- **factorisation** of central **matrix element** from photon emission: equivalent photon approximation (EPA), or other techniques ("partonic" photon PDF, k_T-factorisation, ...)
  - EPA: assuming *quasi-real, Q^2-integrated photon fluxes* (Weizsäcker-Williams method, *J.D. Jackson-like* electrodynamics)

    $$\sigma_{pp} = \int_{w_0}^{\sqrt{s}} \mathrm{d}w_{\gamma\gamma} \left(\frac{\mathrm{d}L_{\gamma\gamma}}{\mathrm{d}w_{\gamma\gamma}} \cdot \sigma_{\gamma\gamma} \right), \text{ with } \frac{\mathrm{d}L_{\gamma\gamma}}{\mathrm{d}w_{\gamma\gamma}} = \int_{w^2_{\gamma\gamma}/s}^{1} \mathrm{d}x \, \frac{2w_{\gamma\gamma}}{xs} \, f_\gamma(x) f(w^2_{\gamma\gamma}/xs), \; x = E_\gamma/E_p$$

    valid for low-Q^2 (photon virtualities), e.g. elastic $\gamma\gamma \to l^+l^-$ production, does not include dynamics for proton dissociation
  - other techniques: photon fluxes as any collinear $\gamma(x_{\mathrm{Bj}}, Q^2)$ PDF, or as k_T-dependent:

    $$F^\gamma_{\mathrm{el}}(x = E_\gamma/E_p, \mathbf{k}^2_\perp) = \frac{\alpha}{\pi} \left[(1-x) \left(\frac{\mathbf{k}^2_\perp}{\mathbf{k}^2_\perp + x^2 m_p^2} \right)^2 F_E(Q^2) + \frac{x^2}{4} \left(\frac{\mathbf{k}^2_\perp}{\mathbf{k}^2_\perp + x^2 m_p^2} \right) F_M(Q^2) \right]$$

    $$F^\gamma_{\mathrm{inel}}(x, \mathbf{k}^2_\perp) =$$

    $$\frac{\alpha}{\pi} \left[(1-x) \left(\frac{\mathbf{k}^2_\perp}{\mathbf{k}^2_\perp + x(M_X^2 - m_p^2) + x^2 m_p^2} \right)^2 \frac{F_2(x_{\mathrm{Bj}}, Q^2)}{Q^2 + M_X^2 - m_p^2} + \frac{x^2}{4} \frac{1}{x^2_{\mathrm{Bj}}} \left(\frac{\mathbf{k}^2_\perp}{\mathbf{k}^2_\perp + x(M_X^2 - m_p^2) + x^2 m_p^2} \right) \frac{2x_{\mathrm{Bj}} F_1(x_{\mathrm{Bj}}, Q^2)}{Q^2 + M_X^2 - m_p^2} \right]$$

Photon fluxes & proton modelling

Elastic photon emission

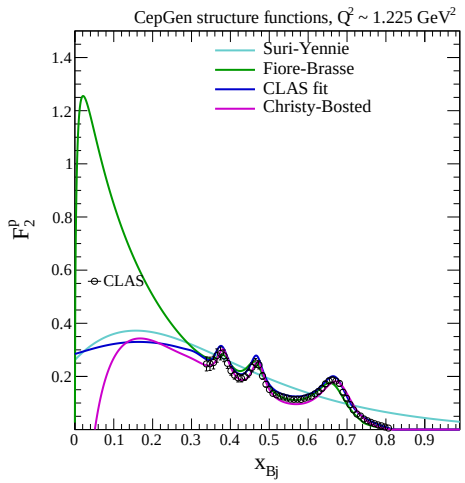
- theoretical uncertainty dominated by *proton electromagnetic form factors* modelling
- usually dipole model for F_E and F_M is a good extrapolation of low-Q^2 measurements
- later parameterisations for broader Q^2 ranges can be used too

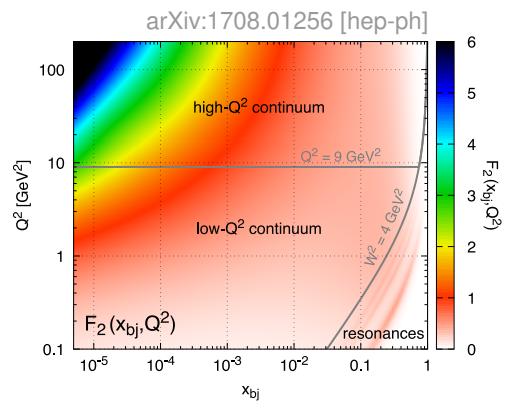
[Nucl. Phys. A **596**, 367, Phys. Rev. C **65**, 051001(R), Phys. Rev. C **76**, 035205, ...]

Inelastic photon fluxes derived from *proton structure functions*, defined over a broad range of Q^2/x_{Bj}:

- **resonances**-dominated regime for low-Q^2, high-x_{Bj}
  - e.g. Fiore-Brasse, Christy-Bosted fits of CLAS/JLab-C measurements
- **continuum** fit of measurements of photoproduction processes ($\mathbb{P}$, $\mathbb{R}$ exchanges) cross sections $\sigma(\gamma^* p)$
  - e.g. Suri-Yennie (default in LPAIR), ALLM, GRV
- DIS, **partonic**-like SFs in high-Q^2 range (typically > 10 GeV^2)
  - from PDFs,
    $F_2(x_{\text{Bj}}, Q^2) = \sum_{i=1}^{nq} e_i^2 \left[q_i(x_{\text{Bj}}, Q^2) + \bar{q}_i(x_{\text{Bj}}, Q^2) \right]$
- cocktail of all three regimes, with interfacing conditions (see e.g. LUXqed sets)

Depending on process kinematics (e.g. $w_{\gamma\gamma}$ range of interest), each structure functions set may be used to derive an envelope of systematics

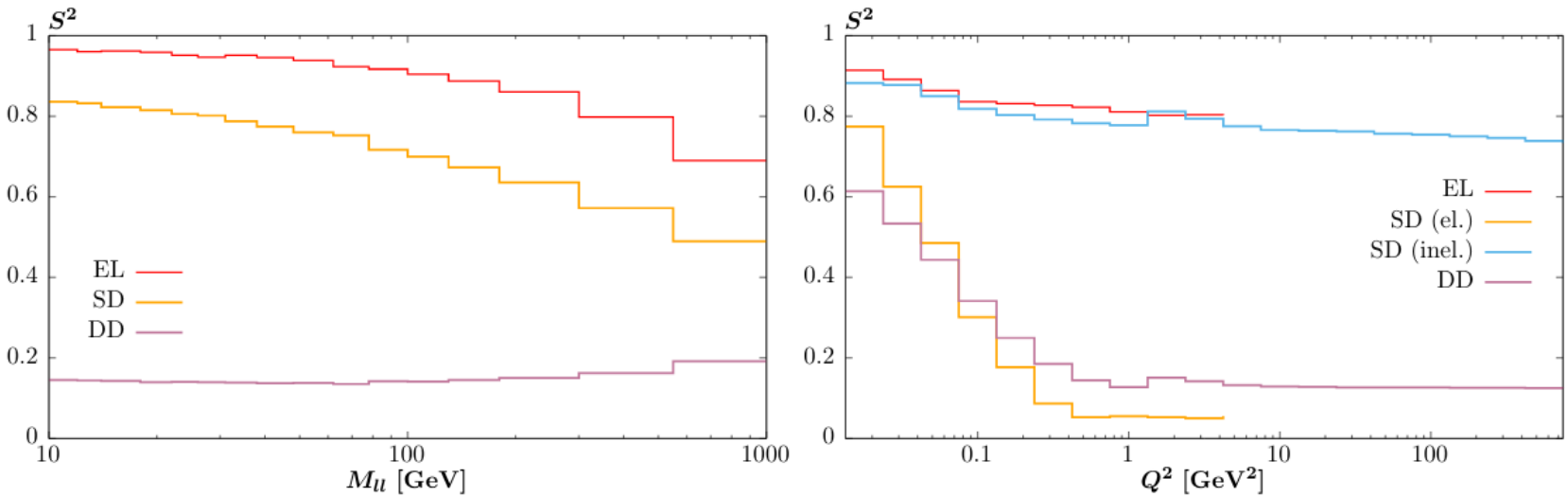




Proton survival probability

In exclusive mode, observed cross section expected to be spoiled by kinematics-dependent rapidity gap survival probability

- fraction of events in which colliding beam particles kinematics is not affected by extra soft interactions
- reduction of visible cross section **if rapidity gap veto is assumed**, production of additional final state particles
- in PPS $\gamma\gamma \to l^+l^-$ observation with forward proton tagging, with track veto of 500 µm surrounding dilepton vertex [arXiv:1803.04496]:
  - 89%, 76%, and 13% survival probability expected for elastic, SD and DD subprocesses!
- depending on overall kinematics ranges, usually process-dependent soft survival effects



arXiv:2007.12704 [hep-ph]

Toolboxes for photon-induced processes simulation

CepGen [arXiv:1808.06059]

- limited number of processes handled
  - includes LPAIR $\gamma\gamma \to l^+l^-$ as "mother process", but also k_T-factorisation with on- and off-shell $\gamma\gamma \to l^+l^-$, $\gamma\gamma \to W^+W^-$, more to come: $\tilde{l}^+\tilde{l}^-$, H^+H^-, …
  - very modular, simple interfacing can be used to generate a large variety of processes (C++ and Fortran definitions)
- current snapshot, 4 proton electromagnetic form factors and 12+ structure functions modellings implemented
  - from HERA-like Suri-Yennie to "LUX-like" cocktail
  - interfacing to LHAPDF for partonic SFs
- kinematics-dependant taming functions to simulate effect of a survival factor on full phase space
- still a few "childhood illnesses" to be cured, but mostly stable

SuperChic [arXiv:2007:12704]

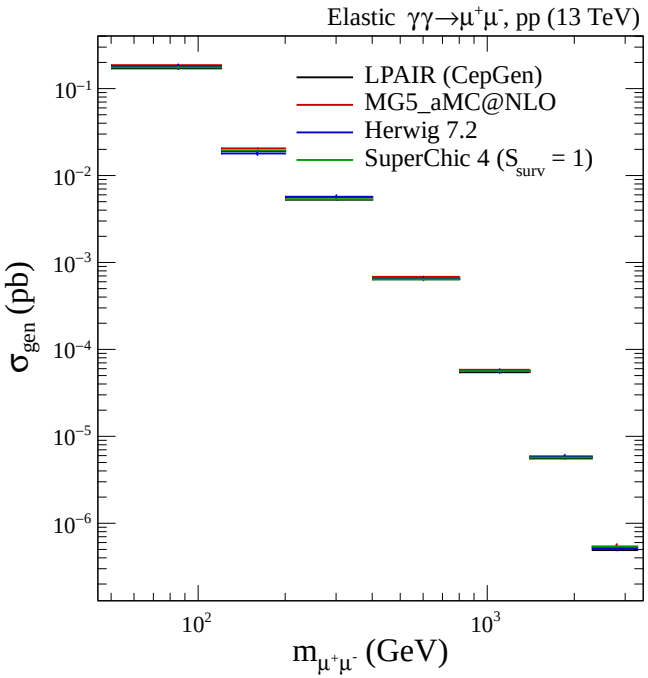
- collinear photon PDF, with partonic treatment (DGLAP evolution) of coherent-incoherent photon emission schemes
- many processes already implemented, both on-shell and off-shell treatments of matrix element

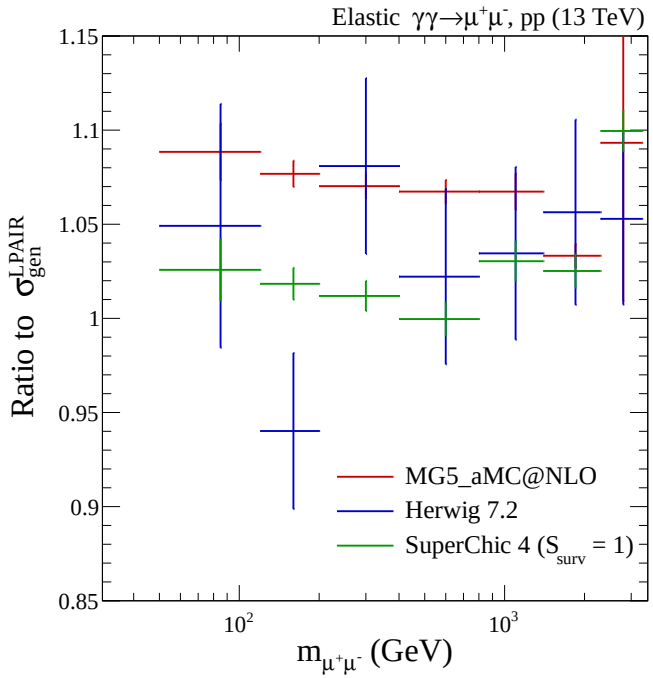
Other **EPA** (MadGraph_aMC, Pythia, Herwig, CalcHEP, …) and **non-EPA** (Graniitti, …) simulation tools

- large variety of processes handled internally, or relying on external matrix elements definitions (usually only on-shell matrix elements are considered)
- usually no survival factor treatment, "Born-level" cross-sections

Comparison of approaches

Baseline comparison: generator-level cross section for elastic $\gamma\gamma \to \mu^+\mu^-$ with "realistic" LHC conditions ($p_{\mathrm{T}}^{\mu} > 15$ GeV, $|\eta_\mu| < 2.5$), binned in m_{ll}





Compatibility (10% difference at most) between all elastic $\gamma\gamma \to l^+l^-$ predictions, gives a good hint of **EPA validity** for this kinematics mode

Dissociative predictions (only handled by SuperChic and LPAIR/CepGen) differ by a few percents too, neglecting soft survival factor contributions (SuperChic 4 only)

- for processes probing a high-Q^2/perturbative regime (e.g. $\gamma\gamma \to t\bar{t}$), combined el.+SD+DD in the same ballpark as CepGen (k_{T}) and SuperChic

Summary

LHC experiments are now probing two-photon processes (and more subclasses of central exclusive processes) on a more regular basis

- first confined to “specialised forward study groups”, now extending to more SM/BSM studies probing higher and higher mass ranges where they become noticeable
- not only an extra background source, also interesting observations to be made
  - see for instance, still competitive sensitivity to AQGCs for $\gamma\gamma \rightarrow W^+W^-$ studies in CMS and ATLAS)
- differential distributions are a good input to theorists, either in the modelling of structure functions, or characterisation of rapidity gap survival factor