Photon-photon interactions in proton-proton collisions at the LHC

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IV Workshop on QCD and Diffraction at the LHC

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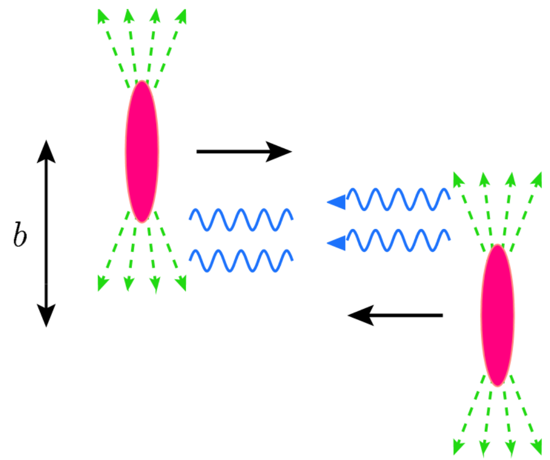
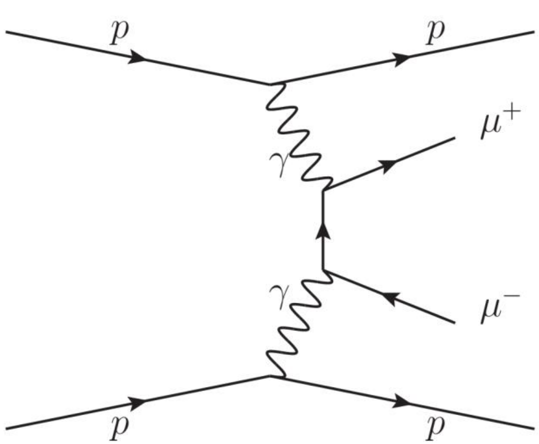
Outline

- Theory of elastic pp ($\gamma\gamma$) $\rightarrow$ pp X interactions
- γ - IP interactions in pp (LHCb results and STARLIGHT MC generator)
- Proton finite size effects (or "absorbtive corrections")
  - Interpretation of CMS data
  - $\gamma\gamma \rightarrow \ell^+\ell^-$ (and/or $\gamma\gamma \rightarrow W^+W^-$)
- Semi-elastic and double dissociative $\gamma\gamma$ interactions
  - Form-factors and Photon PDFs

Theory: elastic pp ($\gamma\gamma$) $\rightarrow$ pp X





Chen et al., Phys.Rev. D7 (1973) 3485-3502.
Budnev et al., Nucl.Phys. B63 (1973) 519-541.

The cross section for this process is calculated:

(1) Using the number of equivalent photons (EPA) by integration over the whole virtuality range:

$$dN = \frac{\alpha}{\pi}\frac{dQ^2}{Q^2}\frac{dx}{x}\left[(1-x)\left(1-\frac{Q^2_{min}}{Q^2}F_E(Q^2)\right)+\frac{x^2}{2}F_M(Q^2)\right]$$

$$Q^2_{min} \simeq m_p^2\frac{x^2}{1-x} \qquad Q^2_{max} = 2\ \mathrm{GeV}^2$$

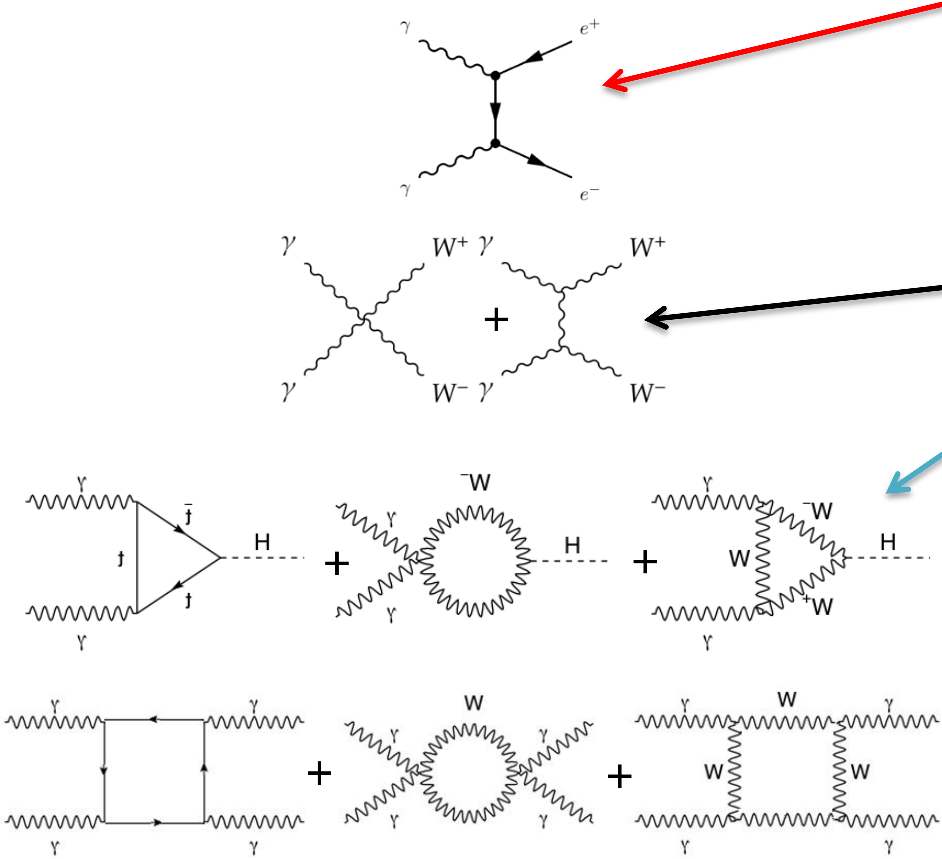
Integrand contains the proton EM form factors (calculations originally done by Chen, Terazawa, et al. for $\gamma\gamma \rightarrow \mu^+\mu^-$ process)

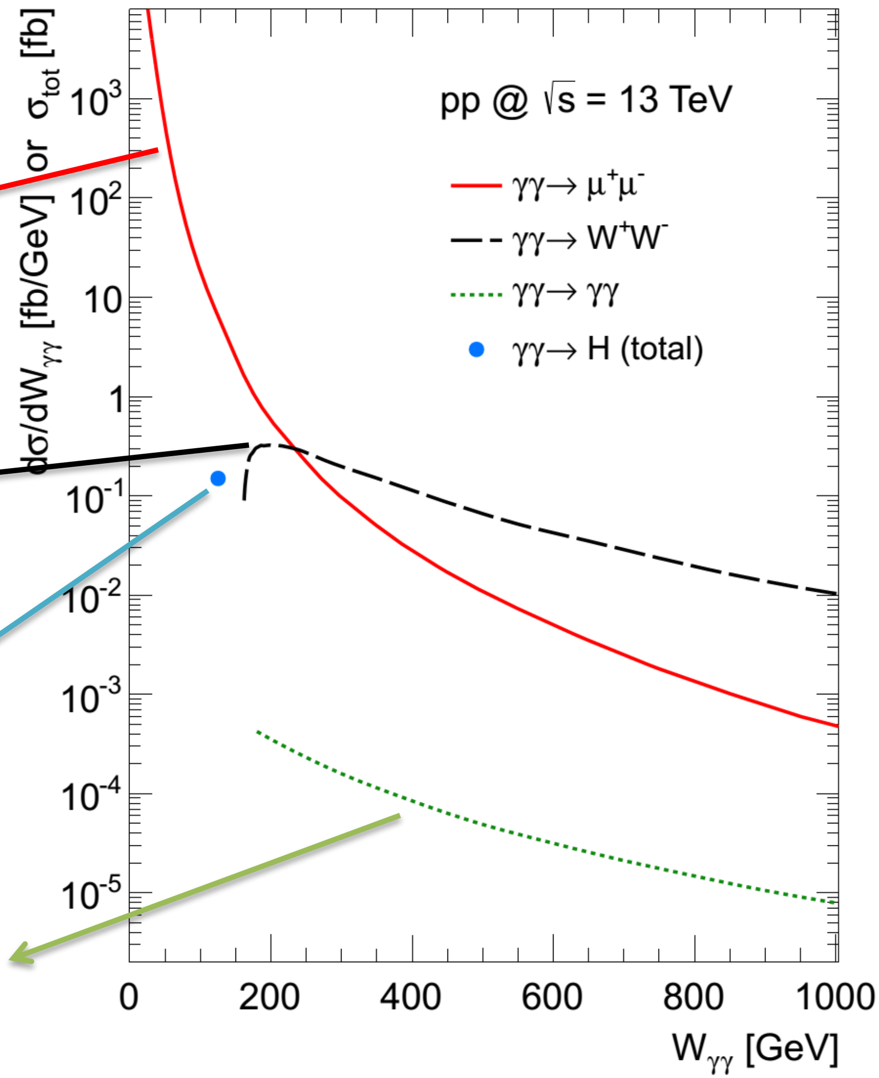
(2) EW $\gamma\gamma \rightarrow$ **X** cross section. **Note**: letting α_{EM} running wrt some scale (mass of the system???) is wrong. Here the photon virtualities are very small…

MC generators: HERWIG++, LPAIR, STARLIGHT, FPMC, …

Theory: elastic pp ($\gamma\gamma$) $\rightarrow$ pp X

- Some cross sections for $\sqrt{s}$ = 13 TeV
  - O(pb) for $W_{\gamma\gamma} > 10$ GeV ($\gamma\gamma \rightarrow \ell^+\ell^-$)
  - O(fb) for $W_{\gamma\gamma} > 200$ GeV ($\gamma\gamma \rightarrow W^+W^-$)

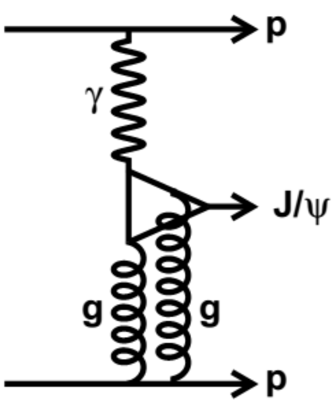




γ - IP interactions in pp

- LHCb measurement: **Exclusive J/ψ and ψ(2S) production in pp collisions at √s=7 TeV (Updated)** (J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002.)
- 930 pb^{-1} of data; $2.0 < \eta_{\mu} < 4.5$

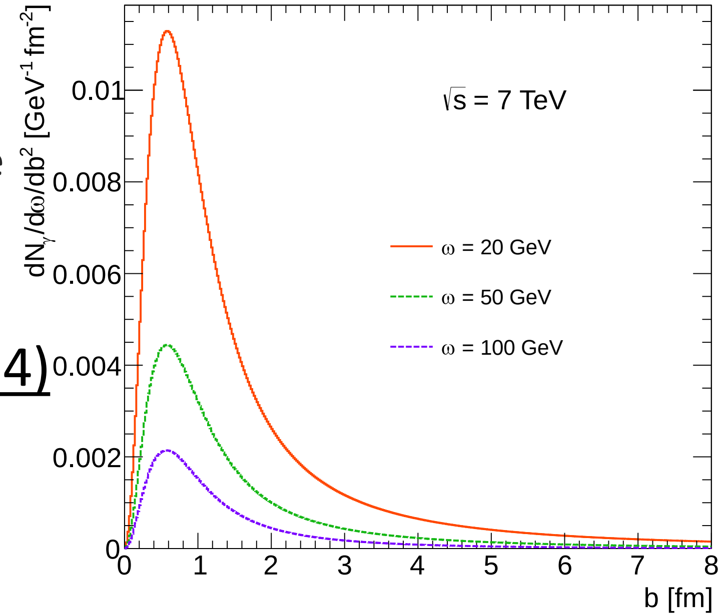
	J/ψ [pb]	$\psi(2S)$ [pb]
Gonçalves and Machado [29]	275	
JMRT [5]	282	8.3
Motyka and Watt [2]	334	
Schäfer and Szczurek [30]	317	
Starlight [31]	292	6.1
SUPERCHIC [19]	317	7.0
LHCb measured value	$291 \pm 7 \pm 19$	$6.5 \pm 0.9 \pm 0.4$



- STARLIGHT includes absorbtive correction treatment ($r \approx 0.85\text{-}0.9$ in this invariant mass range)
  - $r(y) = 0.85 - 0.1|y|/3$ assumed in the analysis
- Some approximations done in STARLIGHT: unable to use it for higher invariant masses (S. R. Klein and J. Nystrand, Phys. Rev. Lett. 92, 142003.)
  - No proton magnetic form-factor included

Proton finite size effects

- Many of the MC generators (HERWIG++, LPAIR, FPMC) for pp ($\gamma\gamma$) $\rightarrow$ pp X do not include the requirements that the:
  - Protons should remain intact (strong absorption correction)
  - Photons have to be emitted coherently from the proton (finite transverse size of the proton)



- **Formalism** (quite standard in HI collisions):
  MD and Laurent Schoeffel, Phys. Lett. B (2014)
  doi:10.1016/j.physletb.2014.12.019
  - Spectrum of the photons from the proton can be written in the impact parameter space (via Fourier transform):

$$n(b,\omega) = \frac{\alpha_{EM}}{\pi^2\omega}\left|\int dk_\perp k_\perp^2 \frac{G_E(Q^2)}{Q^2}\left[(1-x)\frac{4m_p^2+Q^2\mu_p^2}{4m_p^2+Q^2}+\frac{1}{2}x^2\frac{Q^2}{k_\perp^2}\mu_p^2\right]^{\frac{1}{2}} J_1(bk_\perp)\right|^2$$

virtuality of the photon $Q^2 = -k^2 = k_\perp^2 + \frac{\omega^2}{\gamma^2}$

energy fraction of the proton carried by the photon $x = 2\omega/\sqrt{s}$

Proton finite size effects

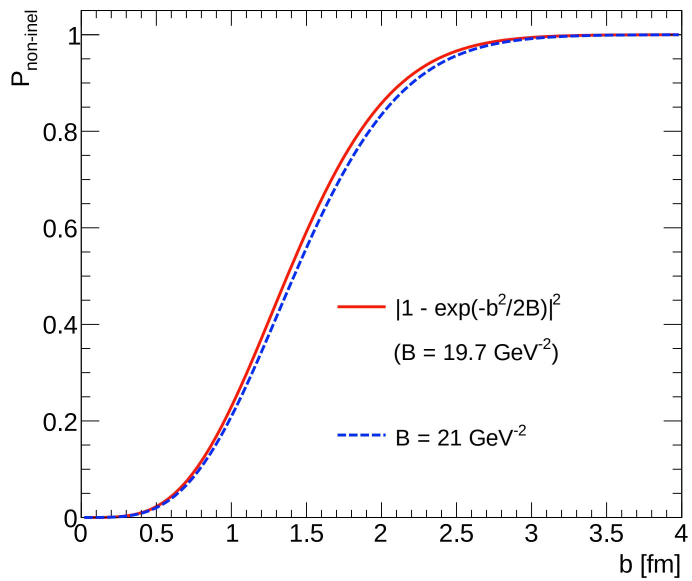
- No overlap -> photon spectra no longer factorize:

$$\sigma(p+p \to p+p+X) = \int\int f(\omega_1) f(\omega_2) \sigma_{\gamma\gamma\to X}(\omega_1,\omega_2) \frac{d\omega_1}{\omega_1}\frac{d\omega_2}{\omega_2}$$

$$f(\omega_1)f(\omega_2) \to \int\int n(\vec{b}_1,\omega_1) n(\vec{b}_2,\omega_2) P_{non-inel}(|\vec{b}_1 - \vec{b}_2|) d^2\vec{b}_1 d^2\vec{b}_2$$

- The pp (non-inelastic) interaction probability can be obtained from the pp elastic scattering amplitude **Γ(s,b)**
(L. Frankfurt, C. E. Hyde, M. Strikman and C. Weiss, Phys. Rev. D 75 (2007) 054009.)
-> with BDL: $\mathbf{P_{non\text{-}inel} = |1 - \exp(-b^2/2B)|^2}$

$$\left.\begin{matrix}\sigma_{\rm el}(s)\\ \sigma_{\rm tot}(s)\\ \sigma_{\rm inel}(s)\end{matrix}\right\} = \int d^2b \times \begin{cases} |\Gamma(s,\boldsymbol{b})|^2, \\ 2\,{\rm Re}\,\Gamma(s,\boldsymbol{b}), \\ \left[1 - |1-\Gamma(s,\boldsymbol{b})|^2\right] \end{cases}$$



- A reduction of the exclusive cross section is expected

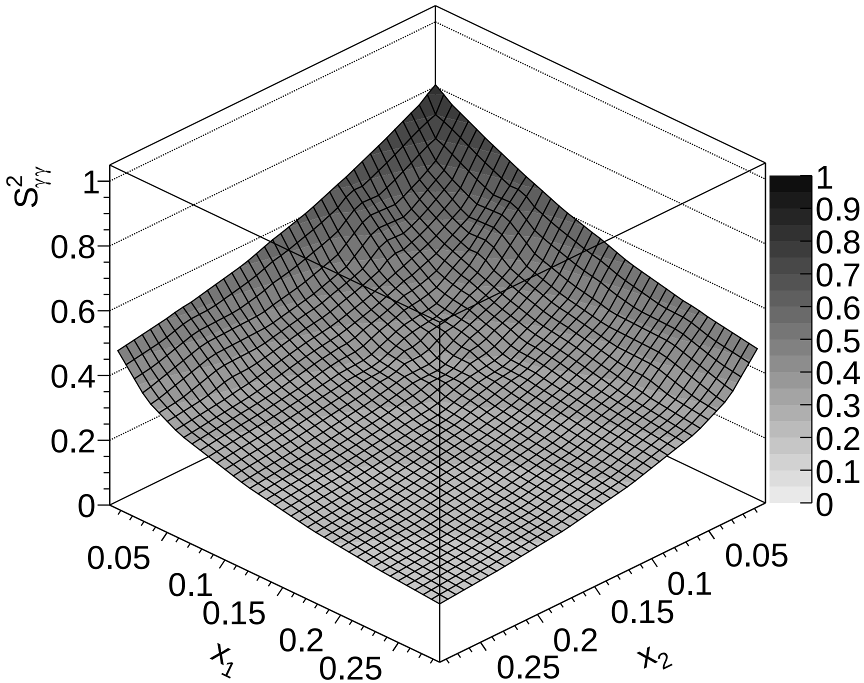
Proton finite size effects

- Using this formalism, a proton survival factor (or absorbtive correction) can be introduced:

$$S^2_{\gamma\gamma} = \frac{\int_{b_1>r_p}\int_{b_2>r_p} n(\vec{b}_1,\omega_1)n(\vec{b}_2,\omega_2)P_{non-inel}(|\vec{b}_1-\vec{b}_2|)d^2\vec{b}_1 d^2\vec{b}_2}{\int_{b_1>0}\int_{b_2>0} n(\vec{b}_1,\omega_1)n(\vec{b}_2,\omega_2)d^2\vec{b}_1 d^2\vec{b}_2}$$

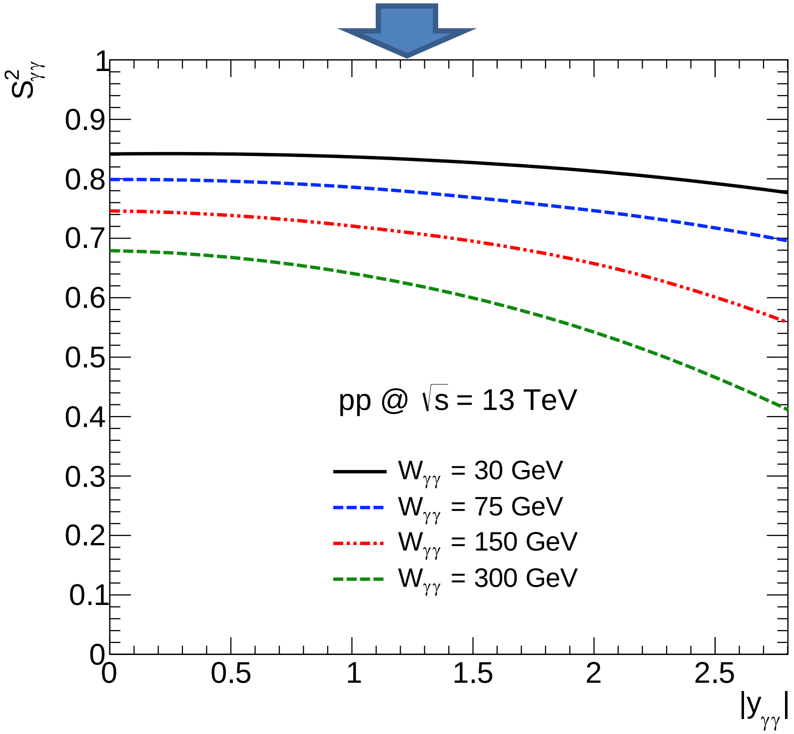
- The general dependence is wrt $x_{1,2}$ of colliding photons

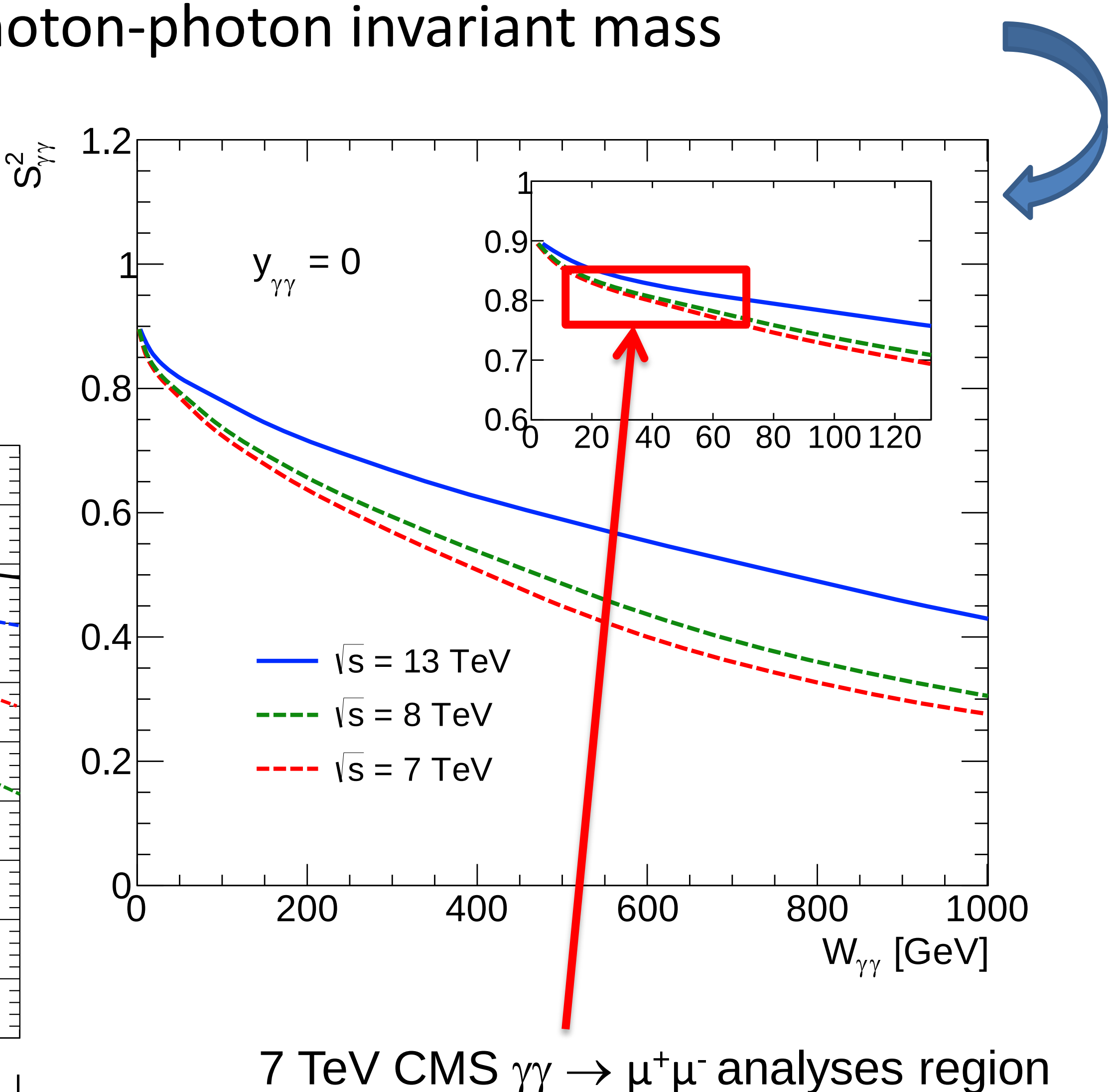
- Can be convoluted with MC events (reweighting)



Proton finite size effects

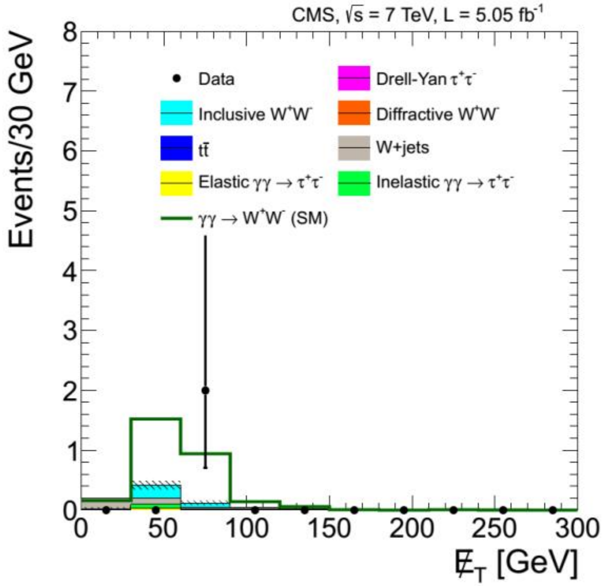
- Strong dependence on photon-photon invariant mass
- Small dependence on rapidity of the system (for smaller inv. masses)





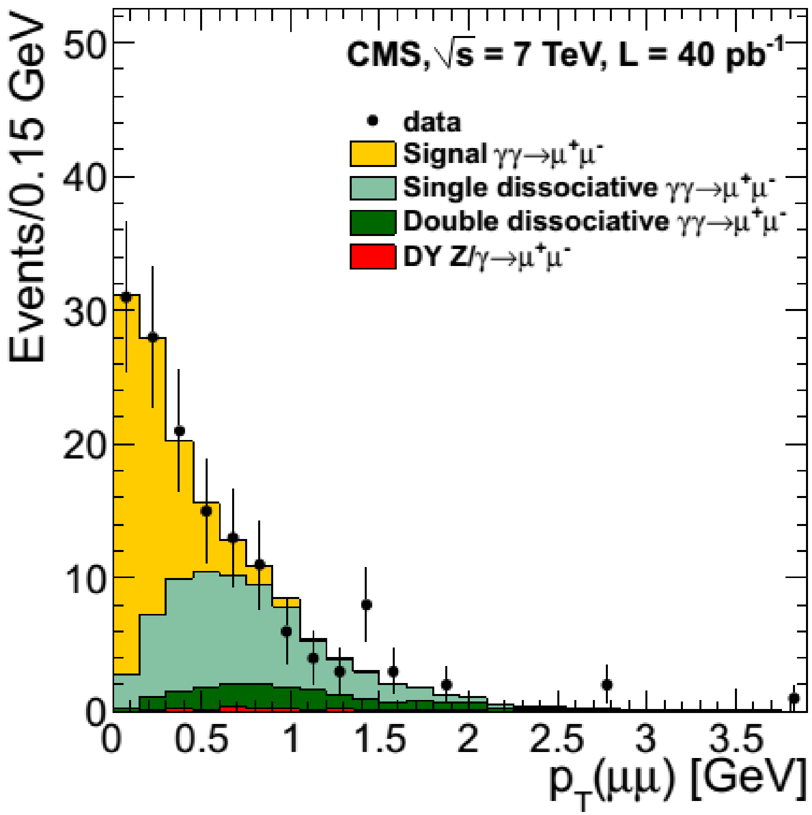
Interpretation of CMS data

- **Recent photon-induced reactions measurements in pp collisions at CMS:**
  - *1)* ***Exclusive $\gamma\gamma \rightarrow \mu\mu$ production in pp collisions at √s = 7 TeV;***
    JHEP 1201 (2012) 052. -> 2010 data, 40 pb^{-1}; pp $\rightarrow$ pp $\mu^+\mu^-$ cross section
  - *2)* ***Search for exclusive or semi-exclusive photon pair production and observation of exclusive and semi-exclusive electron pair production;***
    JHEP 1211 (2012) 080.
  - *3)* ***Study of exclusive $\gamma\gamma$ production of W(+)W(-) at √s = 7 TeV and constraints on anomalous quartic gauge couplings;***
    JHEP 1307 (2013) 116.
  - 2011 data, 5 fb^{-1}; Best limits on anomalous couplings (QGC) are obtained
  - Benchmark using $\gamma\gamma \rightarrow \mu\mu$ events



Interpretation of CMS data

- **Exclusive $\gamma\gamma \to \mu\mu$ production in pp collisions at $\sqrt{s}$ = 7 TeV**
- Kinematic region: $M_{\mu\mu}$ > 11.5 GeV, pT_{μ} > 4 GeV and $|\eta_{\mu}|$< 2.1
- Log-likelihood fit on exclusive and semi-exclusive yields (LPAIR) to get the exclusive cross section
- Cross section:
  $\boldsymbol{\sigma_{pp\,(\gamma\gamma) \to pp\,\mu\mu}}$ **= 3.38 ± 0.58 (stat.) ± 0.16 (syst.) ± 0.14 (lumi.) pb**
- Data-theory (LPAIR) signal ratio:
  0.83 ± 0.15



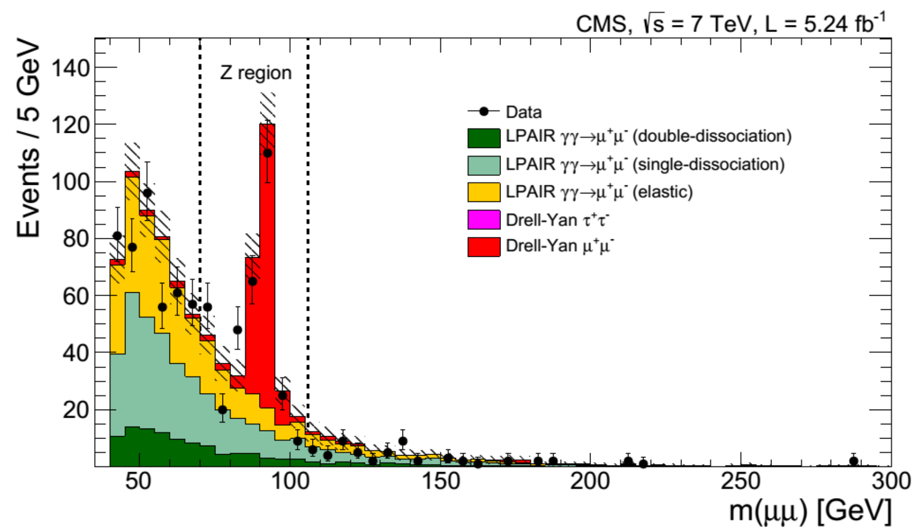
- **Our predictions for proton survival factor:**
  $\boldsymbol{S^2}$ **= 0.84** ($M_{\mu\mu}$ > 11.5 GeV, $|y_{\mu\mu}|$< 2.1)

Interpretation of CMS data

- **<u>Study of exclusive γγ production of W(+)W(-) at √s = 7 TeV and constraints on anomalous quartic gauge couplings</u>**
- $\gamma\gamma \to \mu\mu$ as a benchmark for exclusivity selection validation
- Kinematic region: $M_{\mu\mu} > 40$ GeV, $pT_{\mu} > 20$ GeV and $|\eta_{\mu}| < 2.4$
- Observation: Expected exclusive yield is **10% smaller** in data -> $\boldsymbol{S^2}$ **≈ 0.75** in this kinematic region

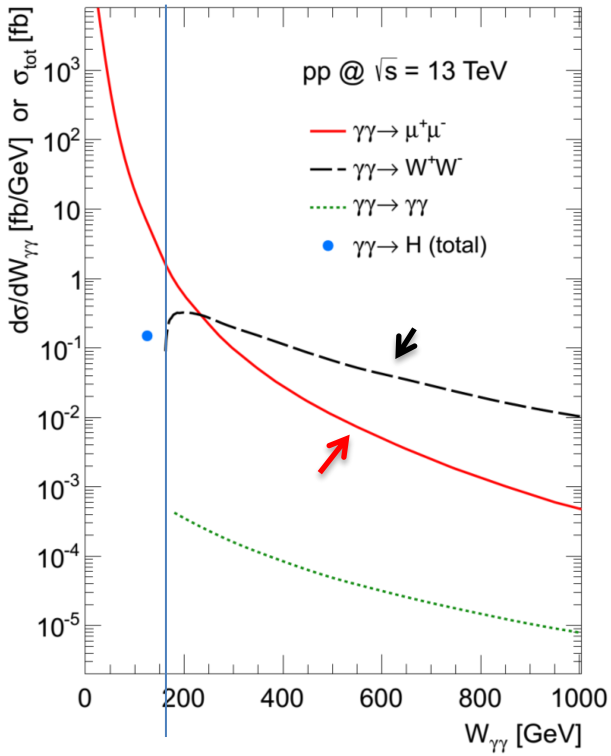
Region	Data	Simulation	Data/Simulation
Elastic	820	906 ± 9	0.91 ± 0.03

- **Our predictions for proton survival factor:**
  $\boldsymbol{S^2}$ **= 0.76**
  ($M_{\mu\mu} > 40$ GeV, $|y_{\mu\mu}| < 2.4$)



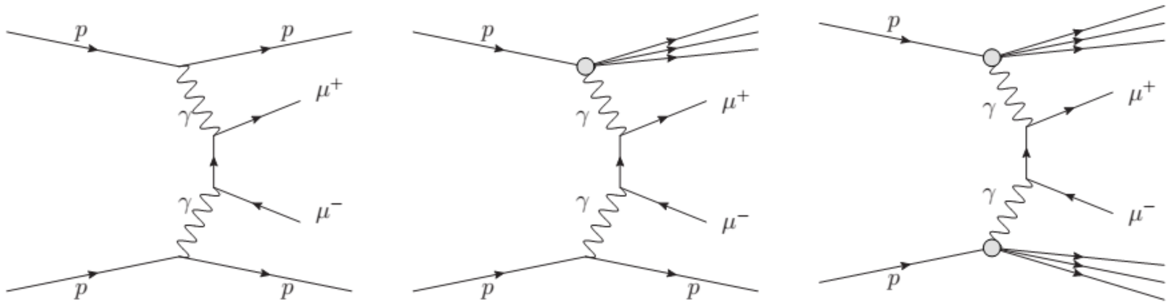
Interpretation of CMS data

- **Study of exclusive $\gamma\gamma$ production of W(+)W(-) at $\sqrt{s}$ = 7 TeV and constraints on anomalous quartic gauge couplings**
- $\gamma\gamma \to \mu\mu$ events used to determine an effective, observed "luminosity" of two-photon interactions at high energies relevant for W-pair production -> simply taking the ratio (Data - MC_{DY})/$MC_{elastic}$ for $M_{\mu\mu}$ > 160 GeV
- Not a clean way to proceed… Some reasons:
  - Elementary cross section shape $d\sigma/dW_{\gamma\gamma}$ is very different for $\gamma\gamma \to \mu\mu$ and $\gamma\gamma \to$ WW -> Proton survival factor is different, even if the same kinematic domain is studied
  - Different lepton kinematic distributions for elastic and dissociative reactions
  - Different contributions from NLO effects (e.g. QED FSR)



Photon-induced reactions

- A family of interactions, including photon-proton inelastic reactions

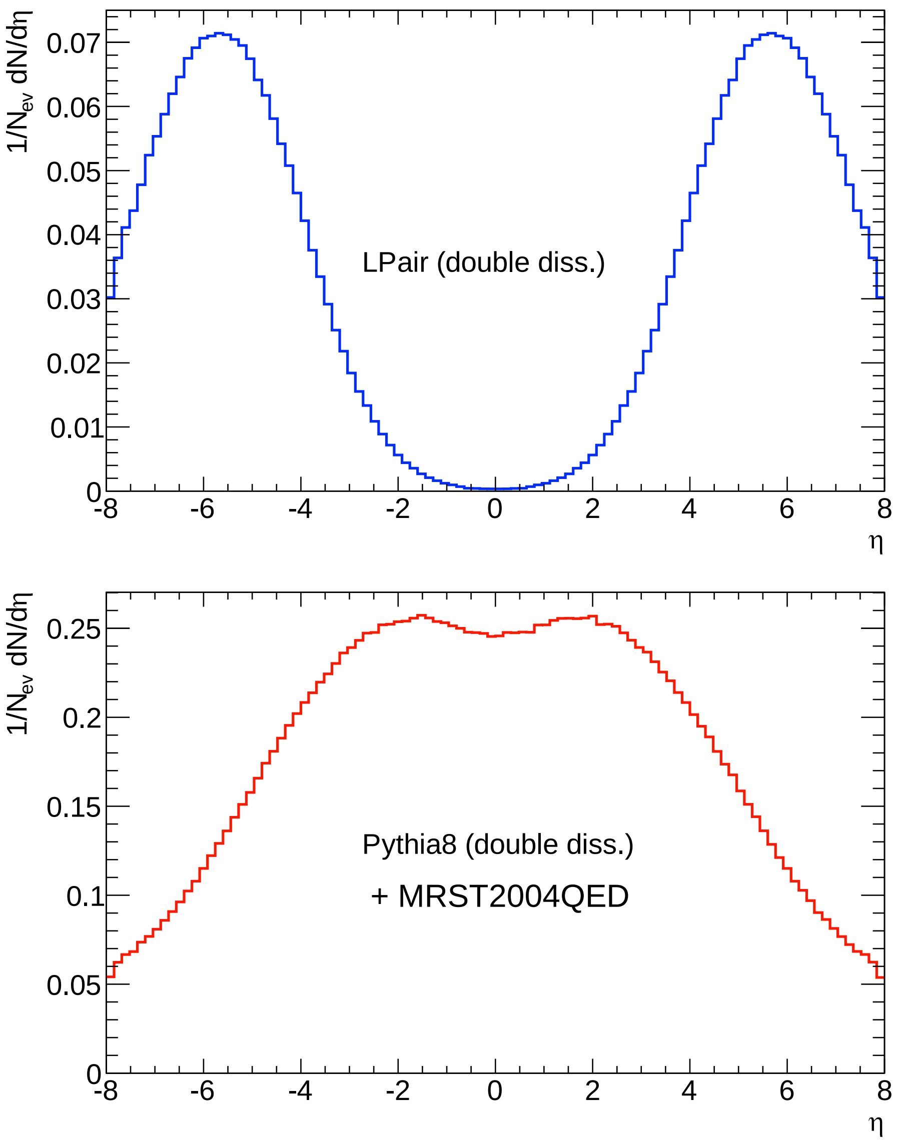


(Very simplified scheme…)

- Two (alternative) ways of description
  - **Photon-proton inelastic Form Factor** (e.g. Suri-Yenni FF in LPAIR + JETSET)
    - proton dissociation -> forward resonance(s) production
    - adequate for small Q^2
    - does not guarantee correct dependence at large Q^2
  - **Photon-PDF approach** (like NNPDF2.3QED incorporated with PYTHIA8)
    - should be relevant for higher Q^2
    - PYTHIA recombination scheme used for forward resonance production

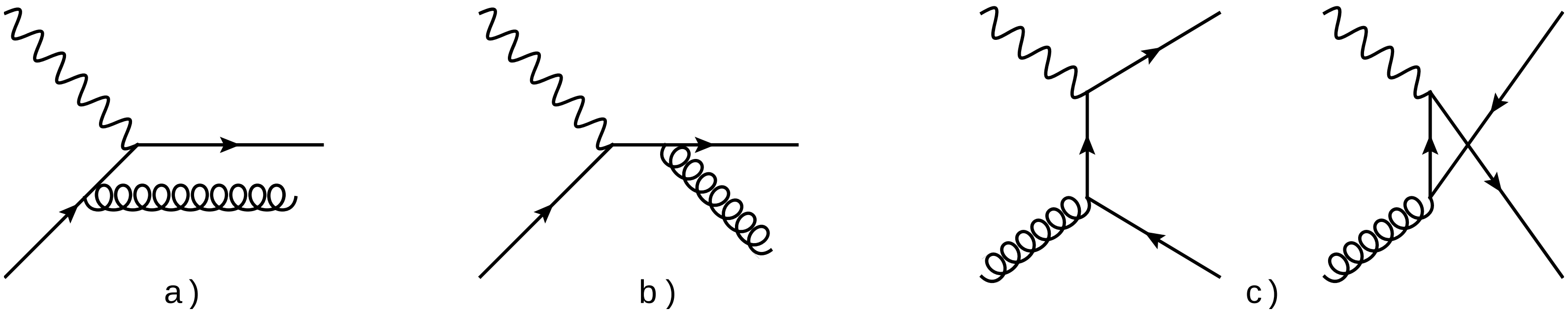
Photon-induced reactions

- Pseudorapidity distribution of particles produced in the proton(s) fragmentation
- LPAIR + Inelastic FF –>
  - Δ^+ (Δ^{++}) resonances produced for the low-mass system ->low multiplicity fwd states
  - For higher masses, multiple resonance production
- PYTHIA8 + Photon-PDF –>
  - Includes also γ-$q/\bar{q}$ interactions +O(α_S) corrections
  - Production of particles also in the central direction



Photon-induced reactions

- $O(\alpha_S)$ corrections to the $\gamma q \to q$ process should have to be also considered



Initial state radiaiton — Final state radiaiton — Quark pair production

≈ **40% contribution** to the double-dissociative cross section (PYTHIA8)

- Enhancement of the cross section (diss part)
- Increased underlying event activity in the central detector
- Total cross section comparison: ($M_{\mu\mu} > 20$ GeV, $p_T^{\mu} > 10$ GeV, $|\eta_{\mu}| < 2.5$)

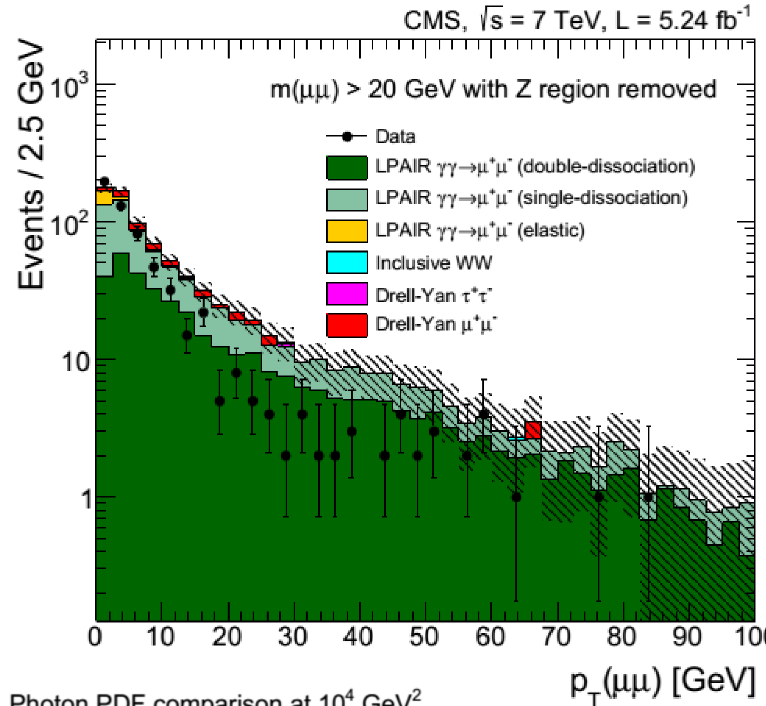
Generator	LPAIR (s-diss)	LPAIR (d-diss)	PYTHIA 8 (d-diss)
Cross-section	0.87 pb	1.02 pb	7.72 pb

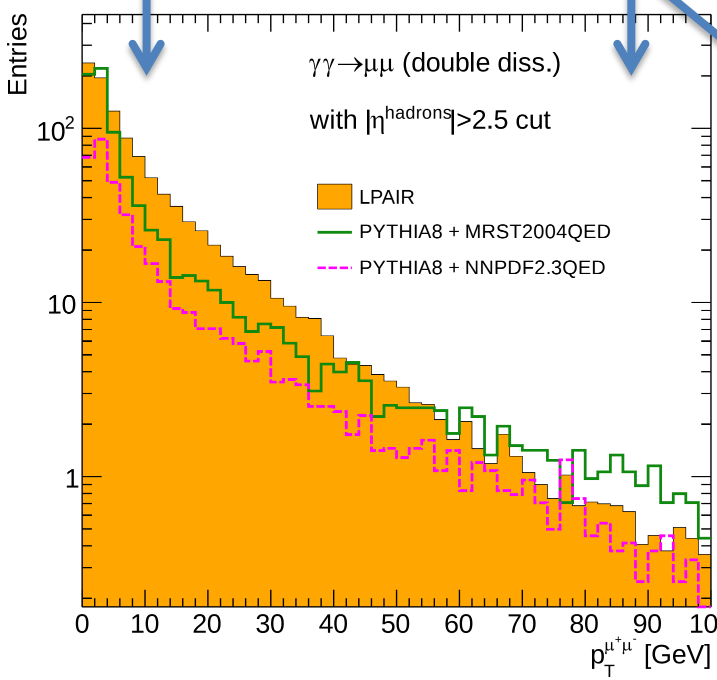
+ MRST2004QED

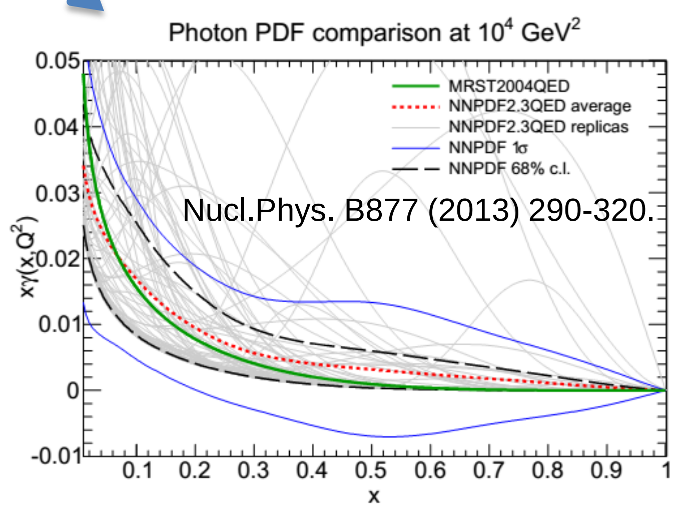
Photon-induced reactions

- **CMS data interpretation** (dissociative selection) -> LPAIR overshoots the data at higher $p_T(\mu\mu)$ values ->
- Testing different approaches (and different Photon-PDFs!)

LPAIR vs PYTHIA8; MRST2004QED vs NNPDF2.3QED







Conclusions

- There is a strong physics case of pp ($\gamma\gamma$) $\rightarrow$ $p^{(*)}$ $p^{(*)}$ X interactions
- (Usually) simpler final states + small theory (QED) uncertainties
  - A crucial role of proton finite size effects: some advances in photon-photon interactions have been made
    - In itself (EWK) and to reach searches domains
    - With a difficult and subtle problem of what is the radius of proton (or HI)
    - Direct application: Luminosity determination using exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$ reactions
  - However, smaller cross-sections for higher invariant masses -> HI collisions? The trade off between pp and PbPb: the maximum energy of photons: **γ/R** favors pp for high mass objects, while the $\mathbf{Z^4}$ factor in PbPb cross section reaches 4.5e7...
- Photon-induced reactions as a source of background for many EWK analyses (low, high-mass DY, ϕ*/pT(Z) measurement, …)
  - A clear need for precise photon-PDF (currently, O(50%) uncertainty in NNPDF2.3QED…)

Backup

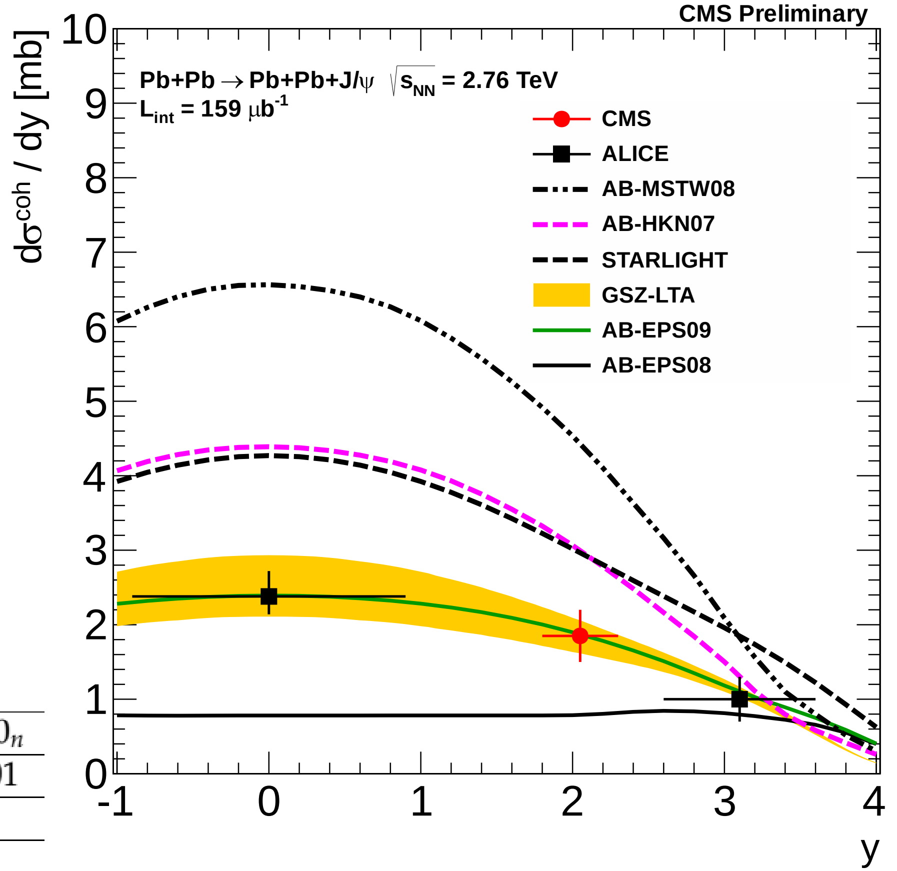
Projections for √s = 13 TeV

Process	σ_{tot}	$\sigma_{tot} \otimes S^2_{\gamma\gamma}$	$< S^2_{\gamma\gamma} >$
$\gamma\gamma \to H$ ($M_H = 125$ GeV)	0.15 fb	0.11 fb	0.74
$\gamma\gamma \to \mu^+\mu^-$ ($W_{\gamma\gamma} > 40$ GeV)	12 pb	10 pb	0.8
$\gamma\gamma \to \mu^+\mu^-$ ($W_{\gamma\gamma} > 160$ GeV)	36 fb	25 fb	0.7
$\gamma\gamma \to W^+W^-$	82 fb	53 fb	0.65
$\gamma\gamma \to \gamma\gamma$ ($W_{\gamma\gamma} > 200$ GeV)	0.06 fb	0.04 fb	0.64

Table 1: Comparison of total cross sections at $\sqrt{s} = 13$ TeV for different procsesses $pp(\gamma\gamma) \to ppX$ with and without proton survival factor applied.

The case of HI collisions

+ Cross section for **photon-nucleus** collisions is proportional to **Z^2**
- The coupling **$\sqrt{\alpha_{EM}}$ -> $Z\sqrt{\alpha_{EM}}$** (higher-order terms become important)
  - Exclusive J/Psi in Pb-Pb:
    - **Eur. Phys. J. C 73 (2013) 2617**
      (ALICE "barrel" J/Psi + $\gamma\gamma \rightarrow$ ee)
    - **Phys. Lett. B 718 (2013) 1273**
      (ALICE "forward" J/Psi)
    - **CMS-PAS-HIN-12-009**
      (CMS coherent J/Psi + neutrons)
  - Data favors models that incorporate nuclear shadowing
  - Accompanied neutron(s) emission -> even more precise tests



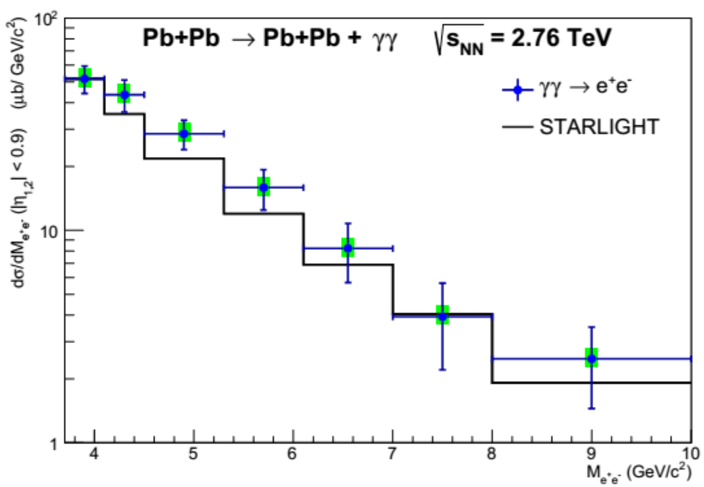
J/ψ with p_T <0.15 GeV/c	X_nX_n/X_n0_n	$1_n0_n/X_n0_n$	$1_n1_n/X_n0_n$
Data	0.36±0.04	0.26±0.03	0.03±0.01
STARLIGHT	0.37	N/A	0.02
GSZ	0.32	0.30	0.02

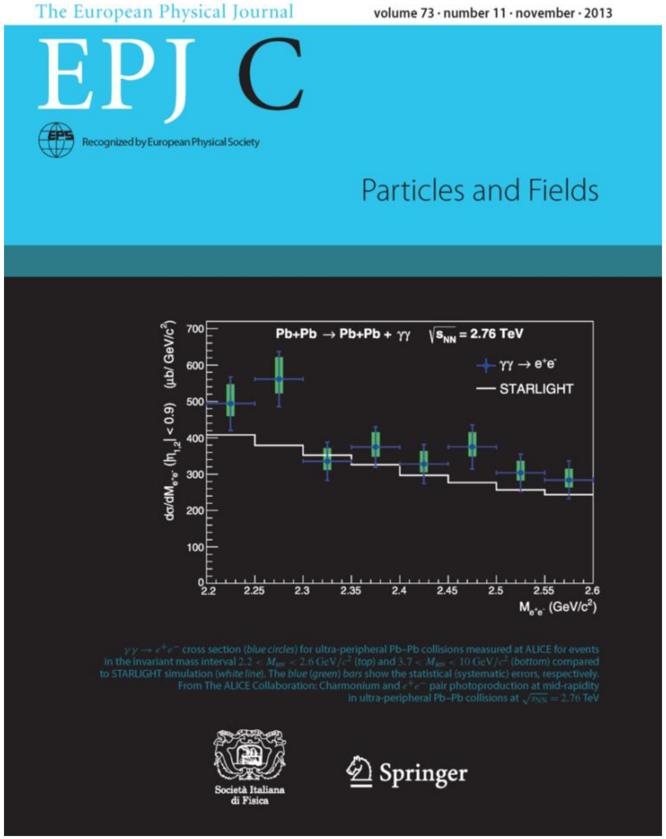
The case of HI collisions

+ Cross section for **photon-photon** collisions is proportional to $\mathbf{Z^4}$
- Maximum photon energy approximately given by $\boldsymbol{\gamma / b_{min}}$
  -> Maximum $\mathbf{W_{\gamma\gamma} \approx 160}$ **GeV** for Pb-Pb at $\mathbf{\sqrt{s_{NN}} = 5.5}$ **TeV**
  -> Maximum $\mathbf{W_{\gamma\gamma} \approx 2}$ **TeV** for p-p at $\mathbf{\sqrt{s} = 14}$ **TeV**

- $\gamma\gamma \rightarrow$ ee from ALICE
- Data ≈ 20% above the STARLIGHT predictions

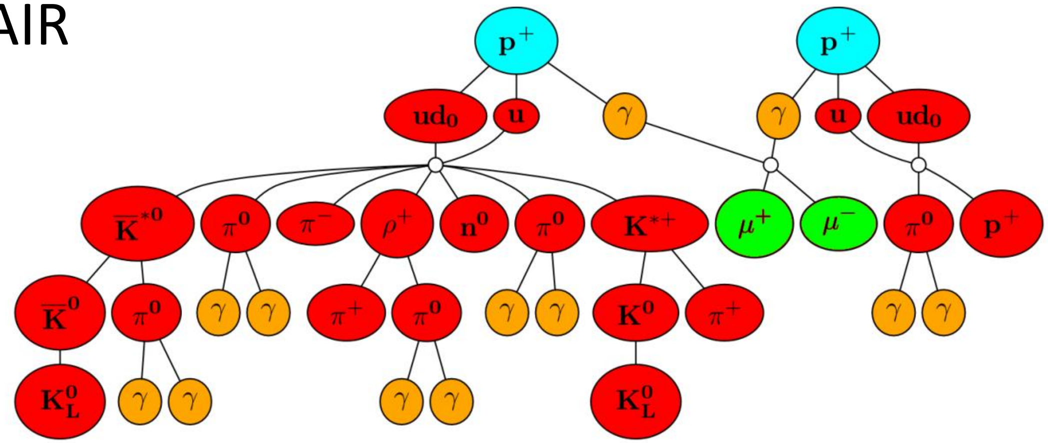
-> higher order terms in α_{EM} are important here



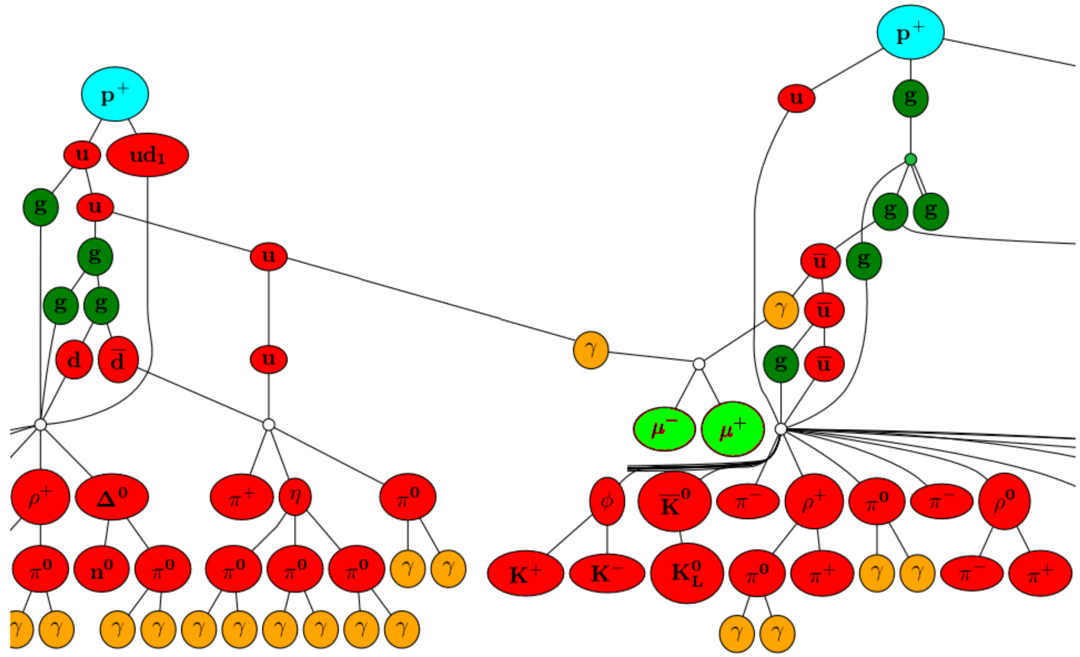


PYTHIA8 vs LPAIR (d-diss)

- Double-diss PYTHIA8 vs LPAIR
- LPAIR: only **γ-p** inelastic processes ->
- Production of forward particles



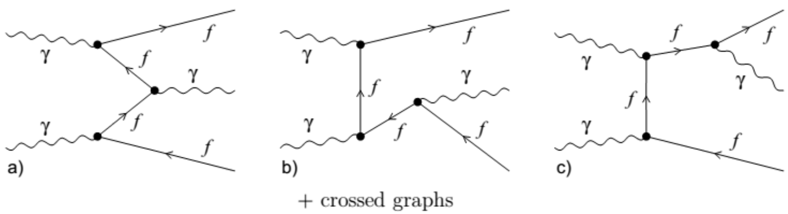
- PYTHIA8: x-s dominant by the γ-$q/\bar{q}$ interactions + O(α_S) corrections ->
- Particles also visible in the central part of the detector



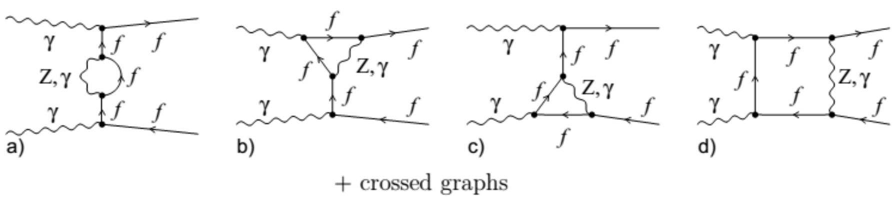
$\gamma\gamma \rightarrow l^+l^-$ NLO corrections

- A. Denner and S. Dittmaier, **Eur. Phys. J. C9 (1999) 425-435.**
- The O(α) corrections (QED + weak) to γγ → ff in the standard model are calculated for light fermions
- Results are provided as a function of √s for photon-photon system

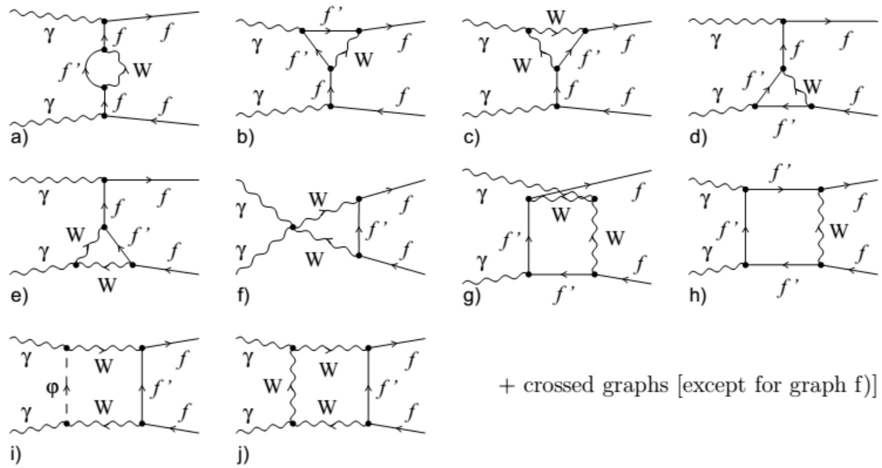
Diagrams for photon bremsstrahlung:



Diagrams with virtual Z-boson or photon exchange:

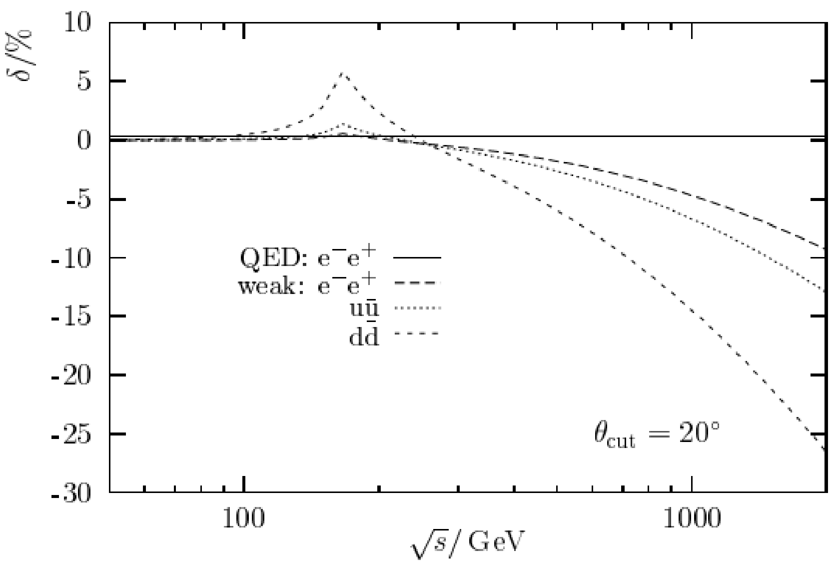


Diagrams with virtual W-boson exchange:



$\gamma\gamma \rightarrow l^+l^-$ NLO corrections

- " The cancellation of all potentially large QED corrections such as $\alpha\ln(m^2/s)/\pi$ implies that the resulting QED correction is of the order of $O(\alpha/\pi)$, i.e., **of the order of several per mille** "
- " The weak corrections stay **below 0.05%** for energies below 100 GeV "



$\sqrt{s}$/ GeV	θ_{cut}	$\sigma^{e^-e^+}_{\text{Born}}$ / pb	$\delta^{e^-e^+}_{\text{QED}}$ /%	$\delta^{e^-e^+}_{\text{weak}}$ /%
10	5°	13722	1.30	0.00
	10°	10130	0.74	0.00
	20°	6595.2	0.33	0.00
	40°	3270.9	−0.02	0.00
100	5°	137.22	1.30	0.02
	10°	101.30	0.74	0.02
	20°	65.952	0.33	0.03
	40°	32.709	−0.02	0.05
500	5°	5.4889	1.30	−0.97
	10°	4.0520	0.74	−1.29
	20°	2.6381	0.33	−1.78
	40°	1.3084	−0.02	−2.47