NLO EW Corrections and Spin Observables for $\gamma\gamma \to \tau^+\tau^-$ in Pb-Pb UPCs

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Outline

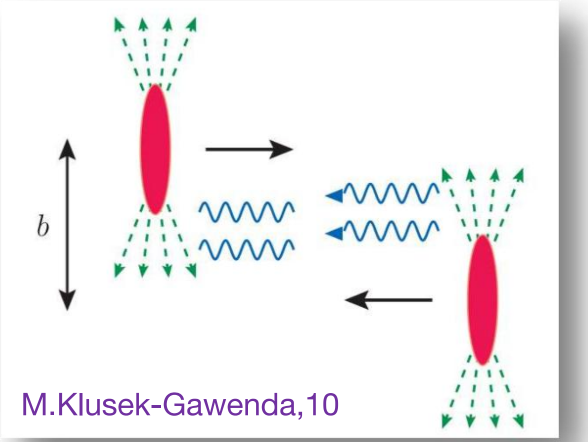
- Motivation and Background
- Theoretical Framework
- Results and Analysis
- Summary

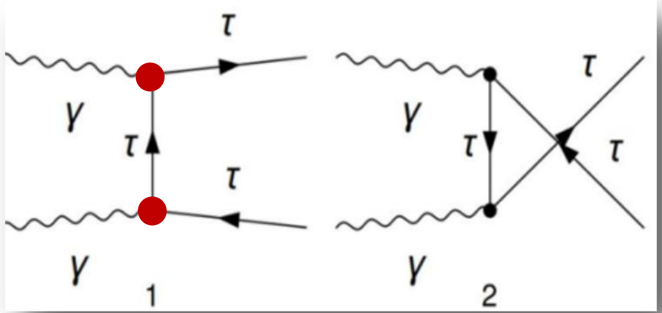
Motivation and Background

- ATLAS[ATLAS Collaboration 22] and CMS[CMS Collaboration 22] study τ-pair production in ultraperipheral collisions(UPCs) of two lead ions

Advantages for PbPb UPCs

- Provide a clean environment;
- Coherent photon emission gives Z^4 enhancement;
- Sensitive to $\gamma\tau\tau$ through its double appearance at LO





- τ-pair spin information
  - ✓ τ is the heaviest lepton in SM with a mass of ~1777 MeV[PDG2024]
  - ✓ Spin observables of tau are experimentslly accessible

Motivation and Background

- Concerning theoretical studies

$\gamma\gamma \to \tau^+\tau^-$ @ NLO QED [H.-S. Shao et al., 24]

$\gamma\gamma \to \tau^+\tau^-$ with leptonic τ decay @ NLO EW [Stefan Dittmaier et al. 25]

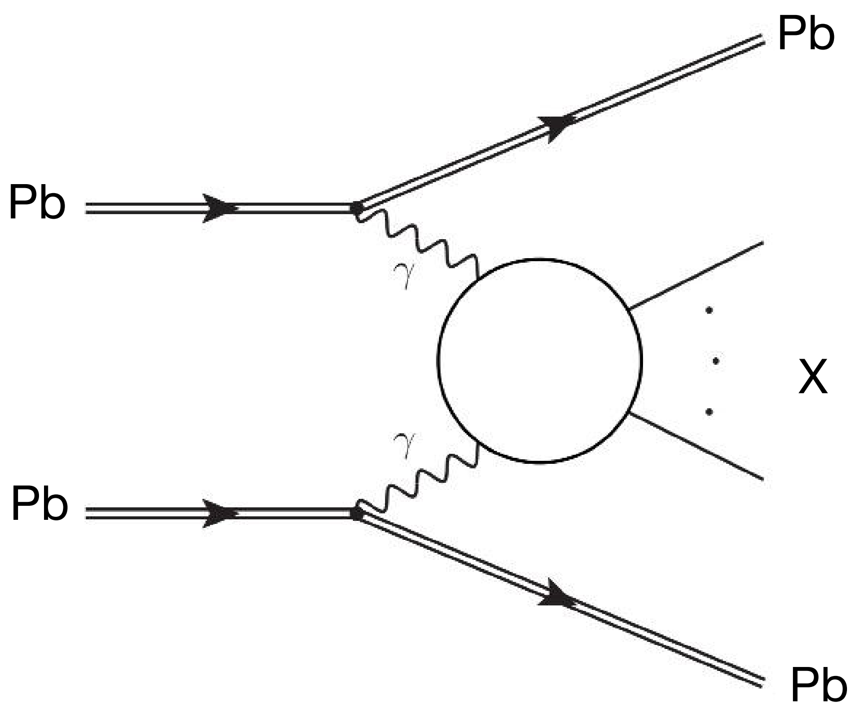
Automated NLO predictions [H.-S.Shao et al.25]

Photon flux tools and libraries [S. R. Klein et al, 16, H.-S. Shao et al, 22, L. A. Harland-Lang et al, 07]

Spin and entanglement studies [T.Han et al.25,B.Yang et al.26,etc]

Our aim was to provide the NLO EW prediction for the production of a τ-pair via photon fusion in the UPC of lead ions, taking into account polarization and spin correlation effects of τ-pair, then to study quantum entaglement in τ-pair system.

Theoretical Framework



Equivalent Photon Approximation(EPA)

$$\sigma(\mathrm{PbPb} \to \mathrm{PbPb}\ \tau^+ \tau^-)$$
$$= \int \mathrm{d}x_1 \mathrm{d}x_2 \underbrace{n(x_1)}_{\text{Photon flux}} n(x_2)\ \underbrace{\sigma(\gamma\gamma \to \tau^+ \tau^-)}_{\text{Hard process}}$$

EDFF approach: $n(x_i) =$

$$\frac{2Z^2\alpha}{x_i\pi}\{\bar{x}_i K_0(\bar{x}_i) K_1(\bar{x}_i) - \frac{\bar{x}_i^{\,2}}{2}[K_1^2(\bar{x}_i) - K_0^2(\bar{x}_i)]\}$$

Coherence condition limitation $\quad Q^2 \le \frac{1}{R^2} \qquad \sqrt{s_{\gamma\gamma}} \le \frac{\gamma_L}{R}$

Theoretical Framework

Hard Process $\gamma(p_1, \lambda_1) + \gamma(p_2, \lambda_2) \to \tau^-(k_1, s_1) + \tau^+(k_2, s_2)$

Production density matrix

$$R_{\alpha_1\alpha_2\beta_1\beta_2} = \sum_{\lambda_1\lambda_1} \langle \tau^-(k_1, \alpha_2), \tau^+(k_2, \beta_2)|\mathcal{T}|\gamma(p_1, \lambda_1), \gamma(p_2, \lambda_2)\rangle^* \times \langle \tau^-(k_1, \alpha_1), \tau^+(k_2, \beta_1)|\mathcal{T}|\gamma(p_1, \lambda_1), \gamma(p_2, \lambda_2)\rangle$$

Decomposed in $\tau\tau$ spin space

$$R = \tilde{A}\, 1\otimes 1 + \tilde{B}_i^+\, \sigma^i\otimes 1 + \tilde{B}_i^-\, 1\otimes\sigma^i + \tilde{C}_{ij}\, \sigma^i\otimes\sigma_j$$

unpolarized production rate

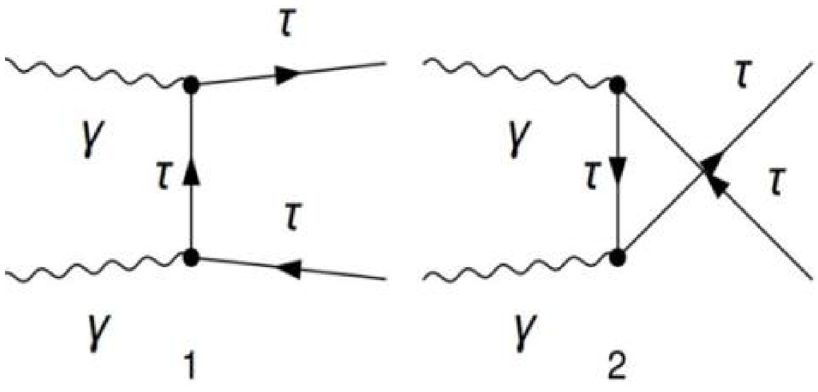
single-spin polarization vanishes at LO QED

spin-correlation tensor

$\tilde{C}_{ij}$ can be further decomposed in the orthonormal basis.

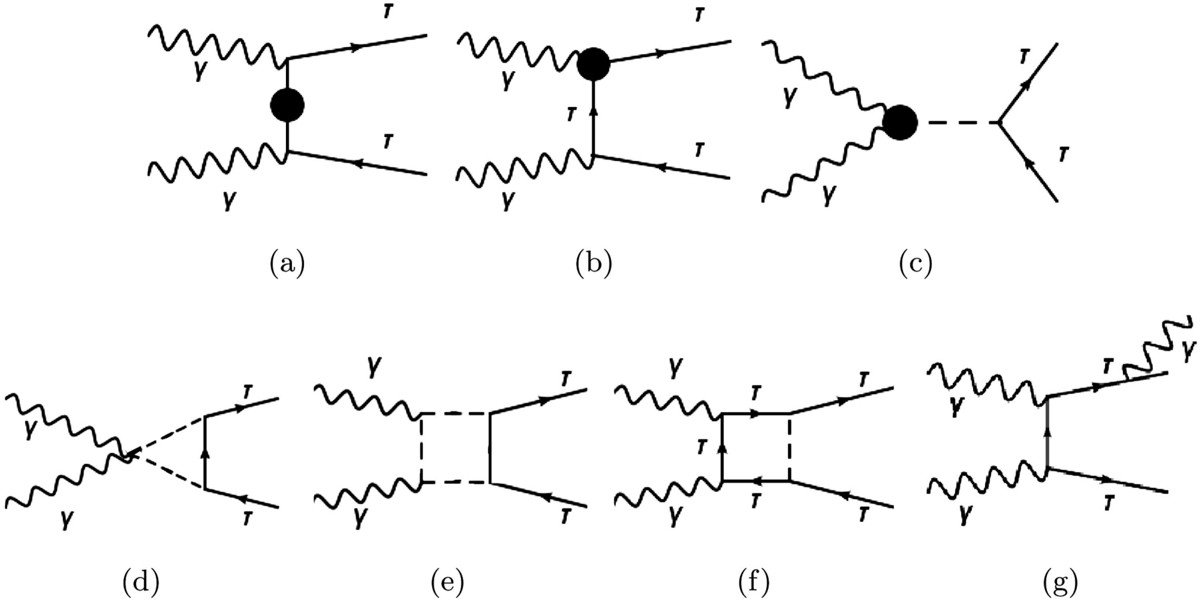
Theoretical Framework

➢ Leading-order



t-channel u-channel

➢ NLO EW radiative corrections



Technical setup
- dimensional regularization for UV and IR divergences
- on-shell renormalization scheme
- phase-space slicing for real radiation[B.W.Harris,02]
- α(0) input scheme for quasi-real photons

- Virtual corrections:
  Self-energy corrections: (a);
  Vertex corrections: (b) (c);
  Box corrections: (d)(e)(f)
- Real correction:(g)

Numerical Results

Total cross section results

	$\sigma^{\rm LO}$[mb]	$\delta\sigma^{\rm NLO}$[mb]	$\sigma^{\rm NLO}$[mb]	δ[%]
5.02	0.940	8.55×10^{-3}	0.949	0.91
5.36	1.003	9.44×10^{-3}	1.012	0.94
5.52	1.030	9.93×10^{-3}	1.040	0.96

Comparison ($\sqrt{S_{NN}}$=5.02TeV) [JHEP 08 (2025) 051]	
σ[mb]	δ[%]
LO: 1.063	-
NLO: 1.073	0.94

- Total cross section at NLO is of the order of magnitude of about 1 mb
- The $\delta\sigma^{\rm NLO}$ has about 1% positive correction
- The size of NLO corrections show mild energy dependence

Spin Correlation Observables

- Spin basis in $\tau\tau$ zero-momentum frame

$\{\hat{r}, \hat{k}, \hat{n}\}$ right-hand orthonormal basis:

$$\hat{r} = \frac{1}{r}(\hat{p} - y\hat{k}) \qquad \hat{n} = \frac{1}{r}(\hat{p} \times \hat{k}) \qquad y = \hat{k} \cdot \hat{p} \qquad r = \sqrt{1 - y^2}$$

$\hat{k}$: τ^-flight direction

$\hat{p}$: photon direction

Spin-correlation tensor

$$\tilde{C}_{ij} = c_{rr}\hat{r}_i\hat{r}_j + c_{kk}\hat{k}_i\hat{k}_j + c_{nn}\hat{n}_i\hat{n}_j + c_{rk}(\hat{r}_i\hat{k}_j + \hat{k}_i\hat{r}_j) + \ldots$$

For this analysis, focus on P-even and CP even components: $C_{rr}, C_{kk}, C_{nn}, C_{pp}$

Observables

$$C_{ab} = 4\langle(\hat{a} \cdot \vec{s}_1)(\hat{b} \cdot \vec{s}_2)\rangle$$

$$C_{ab} = \frac{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) - \sigma(\uparrow\downarrow) - \sigma(\downarrow\uparrow)}{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) + \sigma(\uparrow\downarrow) + \sigma(\downarrow\uparrow)}$$

$C_{ab} > 0$: parallel spin preference
$C_{ab} < 0$: anti-parallel spin preference

Spin Correlation Results

Spin correlation observable

$$C_{ab} = 4\langle(\hat{a}\cdot\vec{s}_1)(\hat{b}\cdot\vec{s}_2)\rangle = \frac{\int \phi a_i \tilde{C}_{ij} b_j dP_{lips}}{\int do}$$

$\sqrt{s_{NN}}$ [TeV]	Order	C_{pp}	C_{nn}	C_{rr}	C_{kk}
5.02	LO	−0.0213	−0.3281	0.0199	−0.2998
	NLO	−0.0214	−0.3230	0.0195	−0.2956
5.36	LO	−0.0192	−0.3273	0.0214	−0.2968
	NLO	−0.0193	−0.3223	0.0210	−0.2926
5.52	LO	−0.0183	−0.3270	0.0221	−0.2955
	NLO	−0.0184	−0.3220	0.0216	−0.2913

- Dominant inclusive correlations
  $C_{nn} =- 0.32$
  $C_{kk} =- 0.30$
  →anti-correlated $\tau^+\tau^-$ spins
- Suppressed components
  $C_{rr} = 0.02$, $C_{pp} =- 0.02$
- NLO EW corrections
  →small numerical shfts only
  →stable SM baseline

Quantum Entanglement in the $\tau^+\tau^-$ System

- Entanglement criterion

- Concurrence

$$\mathcal{C}(\rho) = \max\{0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4\}$$

λ_is: eigenvalues of the matrix $\sqrt{\sqrt{R}\tilde{R}\sqrt{R}}$

$1 \geq \mathcal{C}(\rho) > 0$: entangled,

$\mathcal{C}(\rho) = 1$: maximal entanglement

- In the nonrelativistic limit:

$$\mathcal{C}(\rho) = -\frac{1}{2}(1 + C_{11} + C_{22} + C_{33}) = -\frac{1}{2}(1 + 3D)$$

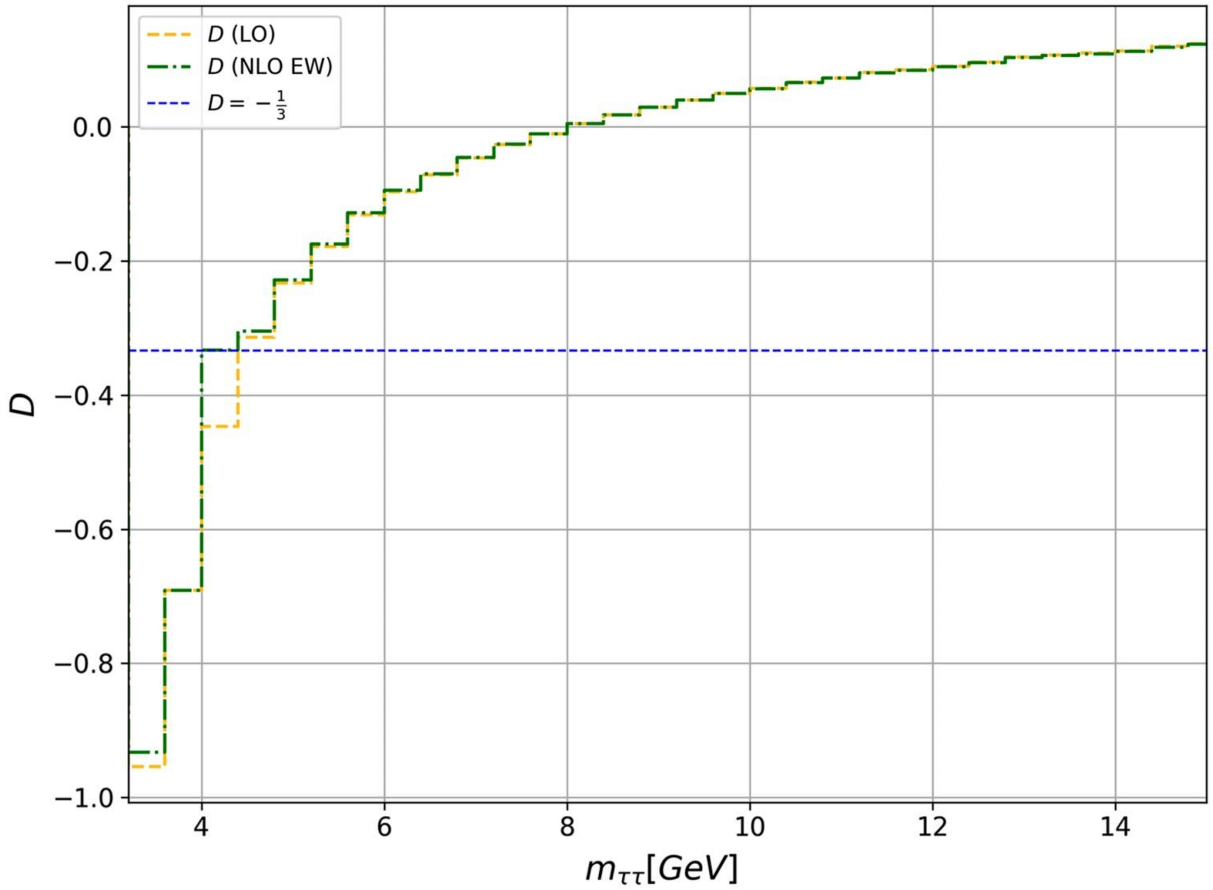
- Rotation-invariant: $\mathrm{D} = \frac{\mathrm{C}_{11}+\mathrm{C}_{22}+\mathrm{C}_{33}}{3} = \frac{\mathrm{Tr[C]}}{3}$

$-1 \leq \mathrm{D} < -\frac{1}{3}$: Entangled

$D = -1$: Maximal Entanglement

Quantum Entanglement in the $\tau^+\tau^-$ System

➢ Differential entanglement observable $D(m_{\tau\tau}) = \dfrac{C_{11}+C_{22}+C_{33}}{3}$ at 5.02 TeV



- Inclusive phase-space average:
  $D > -1/3$
  →no net entanglement after integration
- Near threshold: $D < -1/3$
  →genuine quantum entanglement
- Physical:
  near threshold, $\beta \to 0$
  →spin-singlet dominates
  →two spin are anti-parallel
- NLO EW effect: small shift only

Summary

- A NLO EW calculation to $\gamma\gamma \rightarrow \tau^+\tau^-$ process in PbPb UPC collisions, including τ-pair spin information, was done at different nucleon-nucleon CM energy

  - ✓ $\delta\sigma_{NLO}$ is about 1%
  - ✓ σ_{NLO} is about 1mb

- $\tau^+\tau^-$ Spin correlation

  - ✓ C_{nn} and C_{kk} are the dominant inclusive correlations
  - ✓ $\tau^+\tau^-$ is genuinely quantum-entagled near threshold
  - ✓ NLO EW corrections are numerically small

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Thanks!