NLO EW corrections to tau pair production via photon fusion in Pb-Pb UPC

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Outline

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

Motivation and Background

- Anomalous magnetic moments of leptons are an important type of precision observables used to test the SM

- a_e: Shows one of the best agreement observed between theory[T.Kinoshita 14] and experiment[M.Rivasl 24]. a_e provides one of the ways to determine the fine structure constant

- a_μ: The discrepancy between theory[T.Aoyama et al. 20] and experiment[Muon g-2 Collatoration 24] reached 5.1σ in 2023. Recent results have relaxed this tension to less than 2σ [B.C.Toth et al.22, P.Masjuan et al. 24]

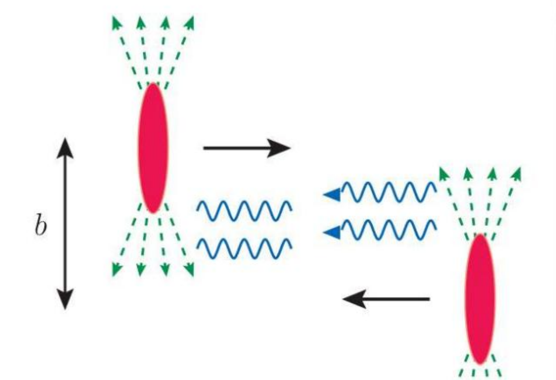
- a_τ: $-0.0042 < a_\tau < 0.0062$, 95% CL, Proton-Proton collisions at LHC[CMS Collaboration 24]. The SM prediction: $a_\tau^{SM} = (117717.1 \pm 3.9) \times 10^{-8}$[A.Keshavarzi et al. 20]

Motivation and Background

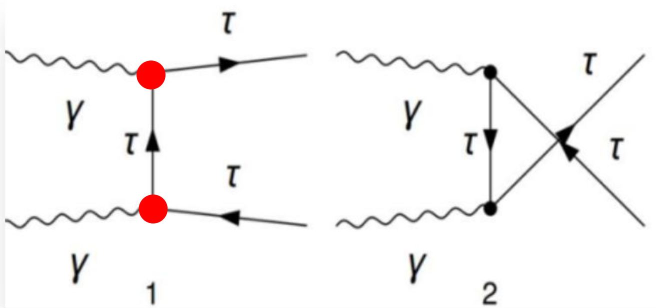
- ATLAS[ATLAS Collaboration 23] and CMS[CMS Collaboration 22] currently study τ-pair production in ultraperipheral collisions(UPCs) of two lead ions

Advantages for studying a_τ in PbPb UPCs

- Provide a clean enviroment
- More sensitive to $\gamma\tau\tau$ vertex
- lead to a total Z^4 enhancement for the production cross section for two photon fusion processes.



[M.Klusek-Gawenda,10]



Motivation and Background

➢ Concerning theoretical studies

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

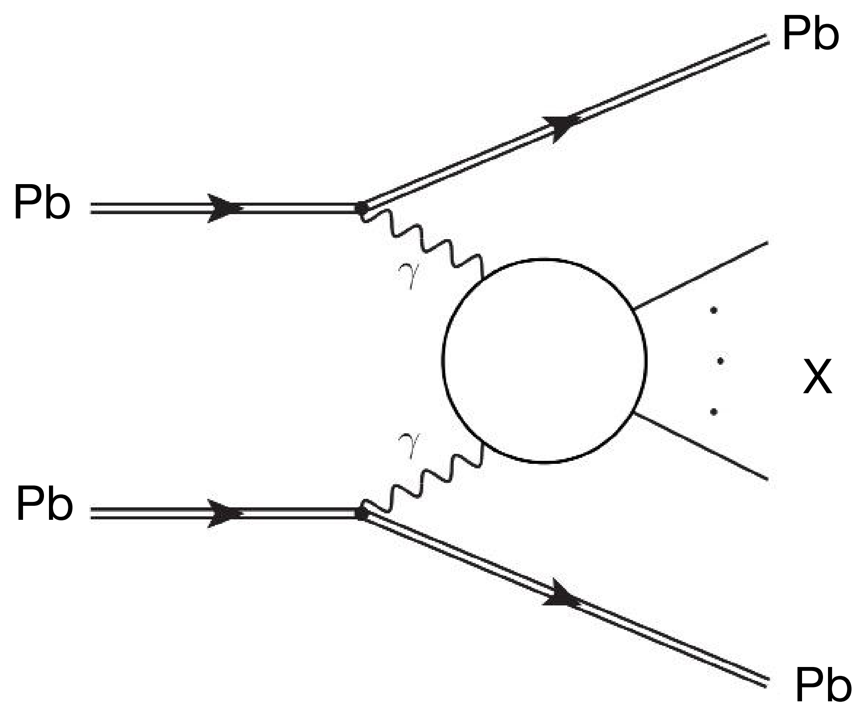
A simulation of the effect of the a_τ on the $PbPb \to PbPb\tau^+\tau^-$ in UPCs including τ lepton decays. [M.Dyndal et al. 20]

Photon flux simulation libraries [E.V.Zhemchugov et al. 23, H.-S. Shao et al. 22]

$\gamma\gamma \to \tau^+\tau^-$ @ NLO EW, off-shell τ [Stefan Ditmaier et al. 25]

Our aim was to provide the NLO EW prediction for the production of a τ-pair in the UPC of lead ions and discuss the effect on the measurement of a_τ in this reaction.

Theoretical Framework



Equivalent Photon Approximation(EPA)

$$\sigma(\mathrm{PbPb} \rightarrow \mathrm{PbPb}\ \tau^+\tau^-)$$
$$= \int \mathrm{d}x_1 \mathrm{d}x_2\, \underline{n(x_1)}\, n(x_2)\ \underline{\sigma(\gamma\gamma \rightarrow \tau^+\tau^-)}$$

Photon flux Hard process

EDFF approach $n(x_i) =$

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

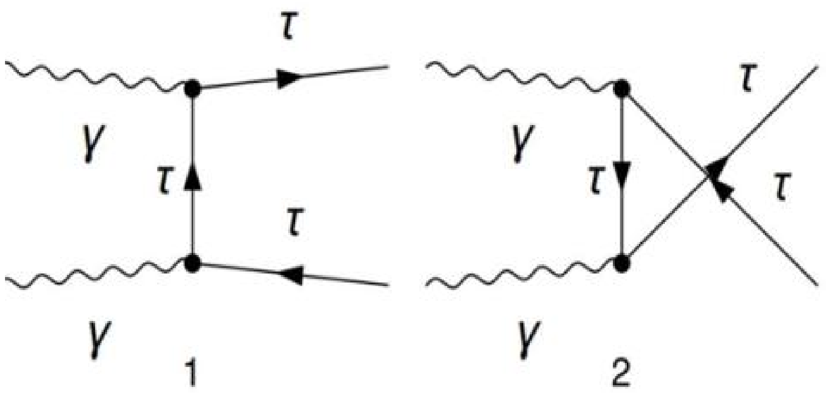
Coherence condition limitation $Q^2 \leq \frac{1}{R^2}$ $\sqrt{s_{\gamma\gamma}} \leq \frac{\gamma_L}{R}$

Theoretical Framework

Hard Proecss

$$\gamma(p_1) + \gamma(p_2) \to \tau^+(k_1) + \tau^-(k_2)$$

- Leading-order results



t-channel u-channel

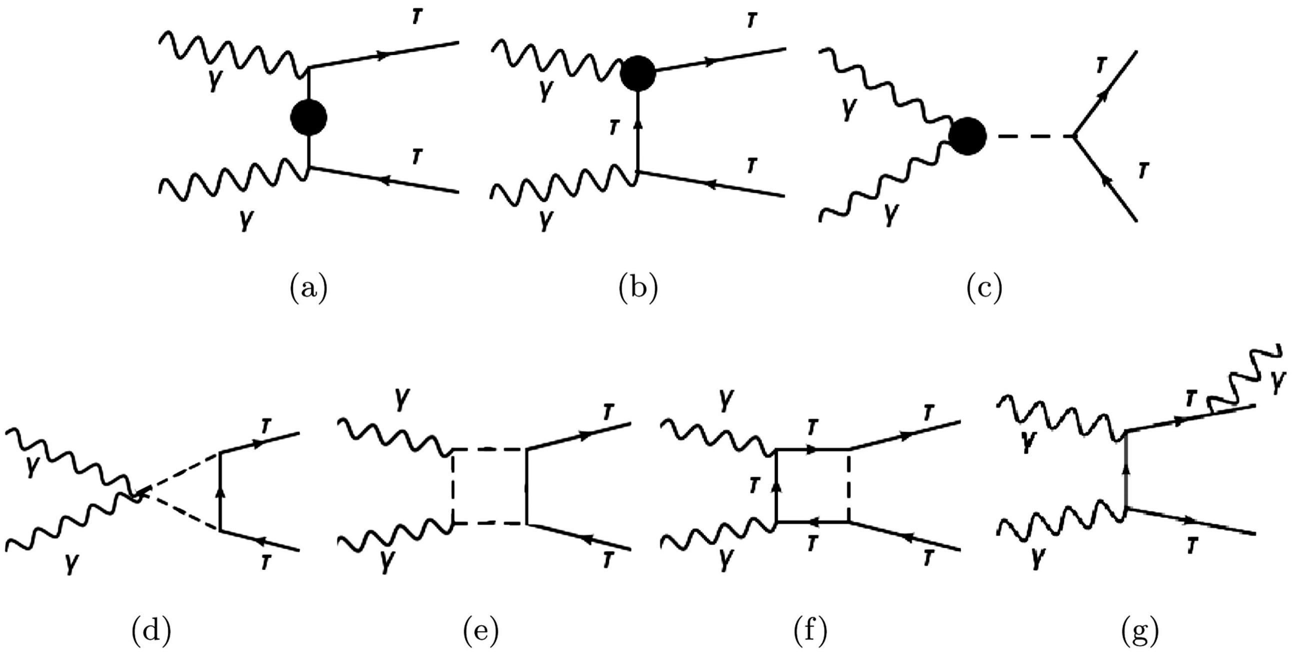
$$\begin{aligned} M =& (-ie^2)\epsilon_{1\mu}\epsilon_{2\nu}\bar{u}(k_1) \\ & \times [i\Gamma^\mu(p_1)\frac{i(\not p_t + m)}{p_t^2 - m^2 + i\epsilon} i\Gamma^\nu(p_2) \\ & + i\Gamma^\nu(p_2)\frac{i(\not p_u + m)}{p_u^2 - m^2 + i\epsilon} i\Gamma^\mu(p_1)]v(k_2). \end{aligned}$$

$$\Gamma^\mu(q) = \gamma^\mu F_1(q^2) + i\frac{\sigma^{\mu\nu}q_\nu}{2m}F_2(q^2)$$

Theoretical Framework

➢ NLO EW radiative corrections:

Typical Feynman graphs



Virtual correction:

(The one-loop corrections is calculated in 'tHooft-Feynman gauge)

Self-energy corrections: (a)
Vertex corrections: (b) (c)
Box corrections: (d)(e)(f)

Real correction:(g)

Set up of the calculation

We use dimensional regularization to regularize both the UV and IR divergences

The UV renomalization is carried out in On-Shell scheme for the parameters and fields of the EW part

IR singularities: Phase space slicing method[B.W.Harris,02]

Input-parameter scheme: G_μ-scheme

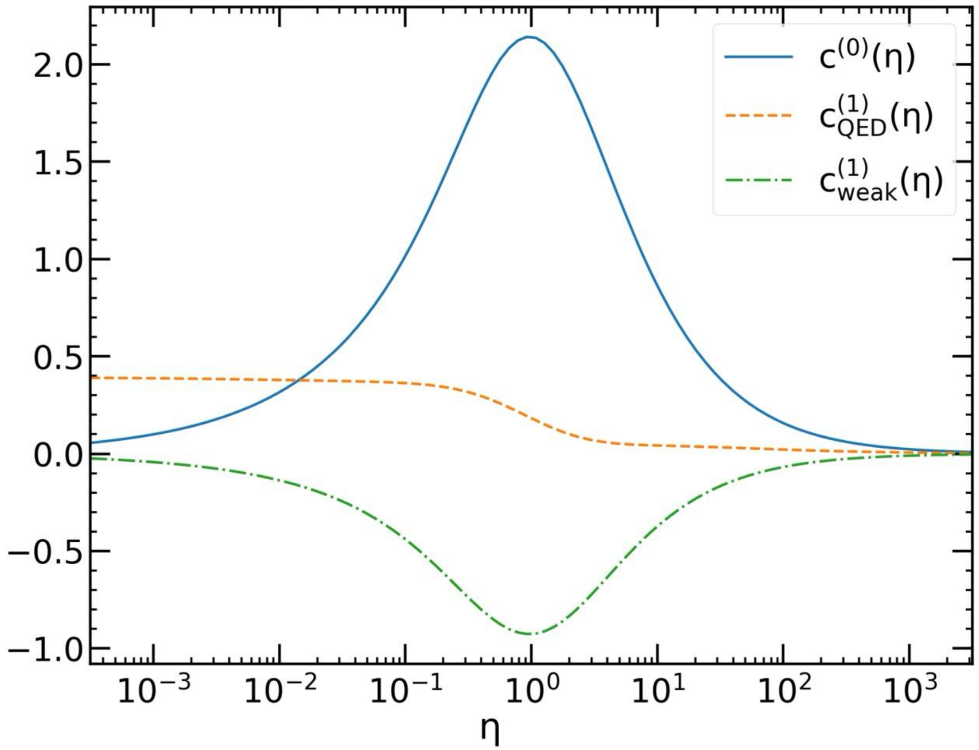
$$m = 1.777\,\text{GeV} \quad m_W = 80.369\,\text{GeV}$$
$$m_Z = 91.188\,\text{GeV} \quad m_H = 125.20\,\text{GeV}$$
$$m_t = 172.4\,\text{GeV} \quad m_b = 4.183\,\text{GeV}$$
$$m_c = 1.273\,\text{GeV} \quad G_\mu = 1.166379 \times 10^{-5}\,\text{GeV}^{-2}$$

$$\alpha_{G_\mu} = \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right)$$

Numerical Results

$$\sigma(\gamma\gamma \to \tau^+\tau^-) = \frac{\alpha^2}{m^2}\left\{c^{(0)}(\eta) + 4\pi\alpha\left[c^{(1)}_{\rm QED}(\eta) + c^{(1)}_{\rm weak}(\eta)\right]\right\}$$

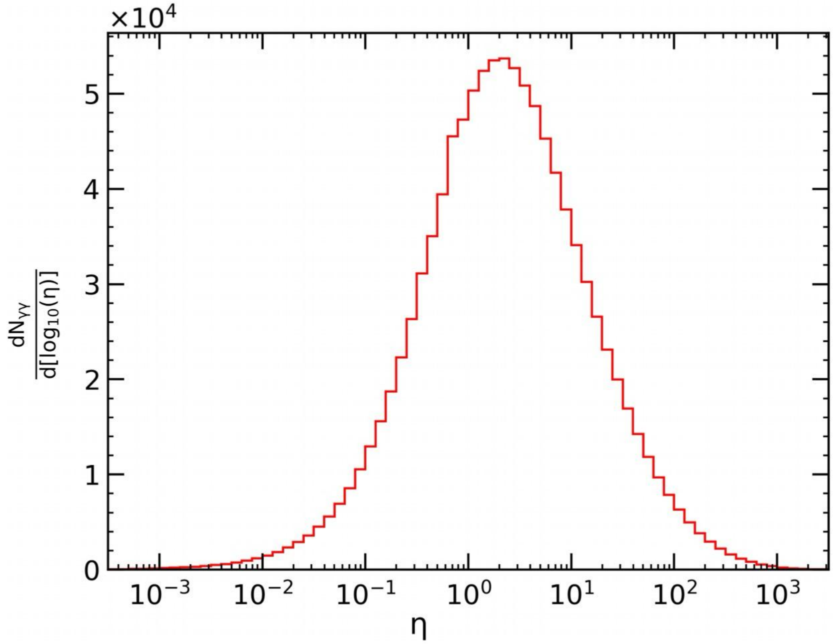
with $\eta = s_{\gamma\gamma}/(4m^2)$ - 1



- Near η = 0.92($\sqrt{s_{\gamma\gamma}}$ = 4.9 GeV), c^0, $c^{(1)}_{weak}$ approach its absolute maximum
- $c^{(1)}_{\rm QED}$ has large downgrade around $\eta = 1$
- Total EW correction reaches its maximum with contributions about -3.7% correction at η=4.7

Numerical Results

$\sqrt{s_{NN}}$ [TeV]	σ_{LO} [mb]	$\delta\sigma_{QED}$ [mb]	$\delta\sigma_{weak}$ [mb]	σ_{NLO} [mb]	$\frac{\sigma_{NLO}}{\sigma_{LO}}$
5.02	1.02	1.00×10^{-2}	-4.18×10^{-2}	0.99	0.97
5.36	1.08	1.06×10^{-2}	-4.44×10^{-2}	1.05	0.97
5.52	1.11	1.09×10^{-2}	-4.57×10^{-2}	1.08	0.97
6.00	1.20	1.17×10^{-2}	-4.92×10^{-2}	1.16	0.97



Two-photon flux

- Total cross section at NLO is of the order of magnitude of about 1 mb
- The $\delta\sigma_{weak}$ has about -4% to Leading order results
- The $\delta\sigma_{QED}$ has about 1% positive correction
- The size of NLO corrections do not change across different energy

- Two-photon flux reaches its maximum at the bin of [2.0,2.5], where weak correction has its negative maximum value

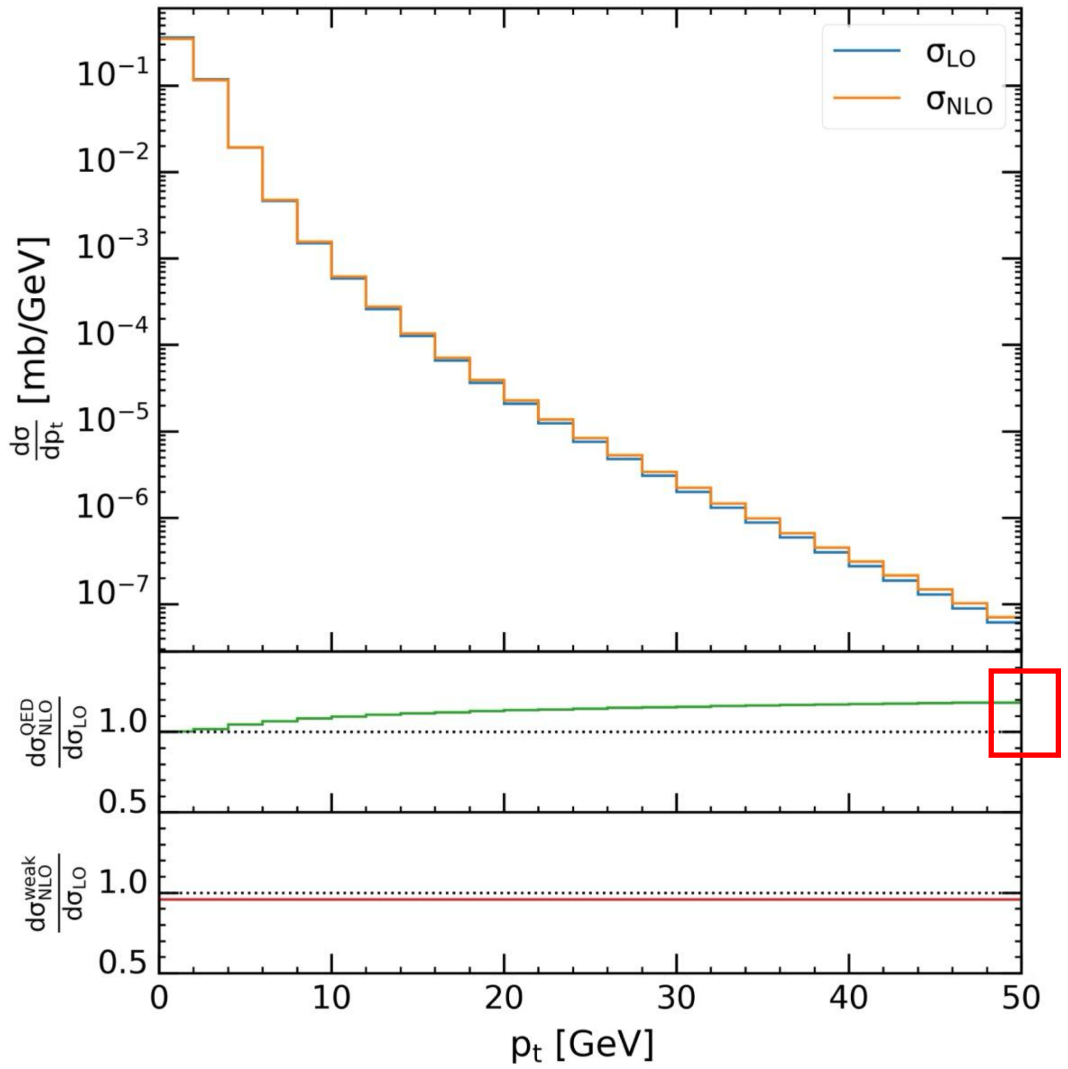
Numerical Results

Results from different input-parameter scheme

$\gamma\gamma \to \tau^+\tau^-$ in the UPC of lead ions	G_μ-scheme ($\sqrt{S_{NN}}$=5.02TeV) [This work]		G_μ-scheme ($\sqrt{S_{NN}}$=5.02TeV) [arXiv:2504.11391 [hep-ph]]		$\alpha(0)$-scheme ($\sqrt{S_{NN}}$=5.52TeV) [arXiv:2504.10104 [hep-ph]]	
	σ[mb]	δ[%]	σ[mb]	δ[%]	σ[mb]	δ[%]
σ^{LO}	1.02	-	1.14	-	1.16	-
$\delta\sigma^{\text{NLO}}_{\text{QED}}$	0.010	0.98	0.012	1.05	-	-
$\delta\sigma^{\text{NLO}}_{\text{weak}}$	-0.042	-4.12	-0.067	-5.90	-	-
σ^{NLO}	0.99	-3.14	1.08	-4.82	1.17	0.86

- The minor discrepancies arise from differences in the parametrization of the photon flux and the values of input parameters

Differential distributions



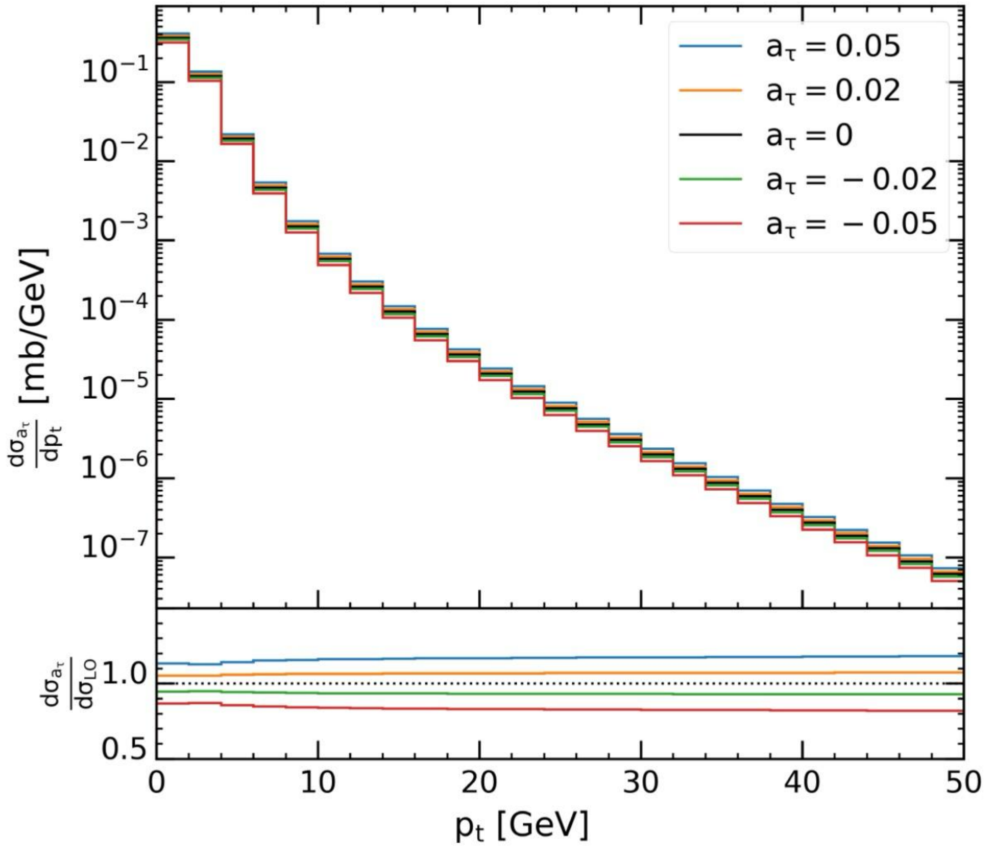
Transverse momentum of τ^-

$\sqrt{S_{NN}}$ = 5.02 TeV

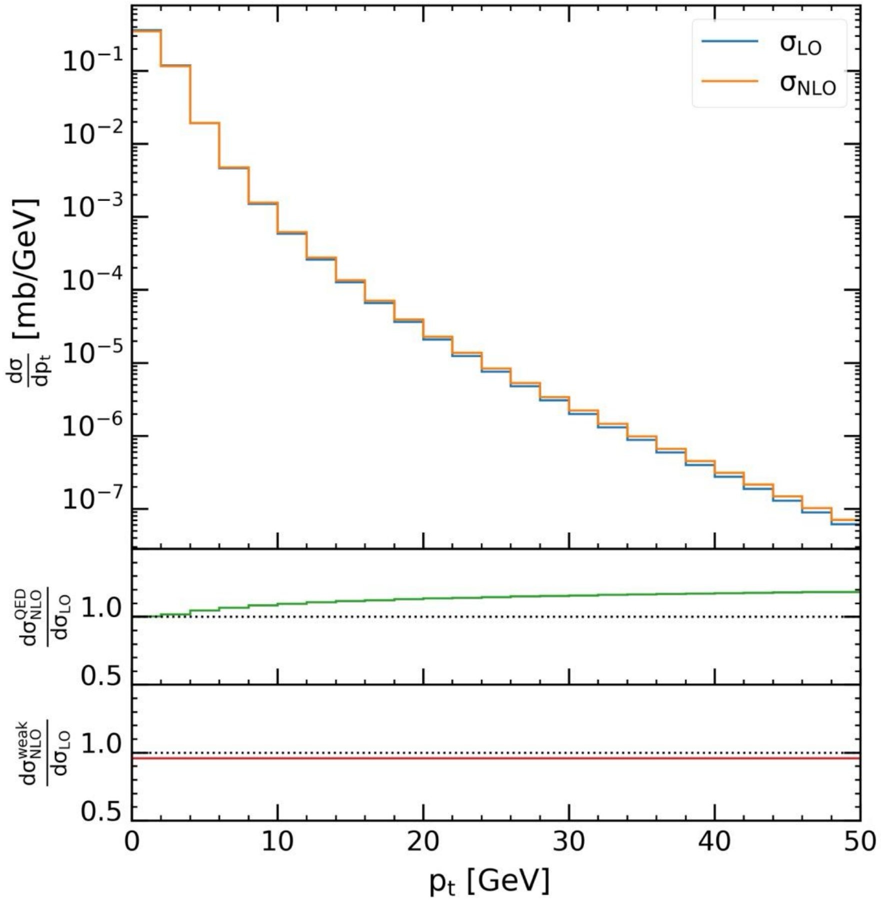
- The impact of NLO corrections is more visible in the differental distribution
- QED K factor reaches a factor of 4% in the high-pt tail of differential distributions
- The ratio of weak correction is almost flat
- NLO EW corrections increasee with p_{τ^-}

Differential distributions

$$\sigma_{a_\tau} = \sigma_{LO} + \delta\sigma_{a_\tau}, \quad \Gamma^\mu = \gamma^\mu + i\frac{\sigma^{\mu\nu}q_\nu}{2m}a_\tau$$



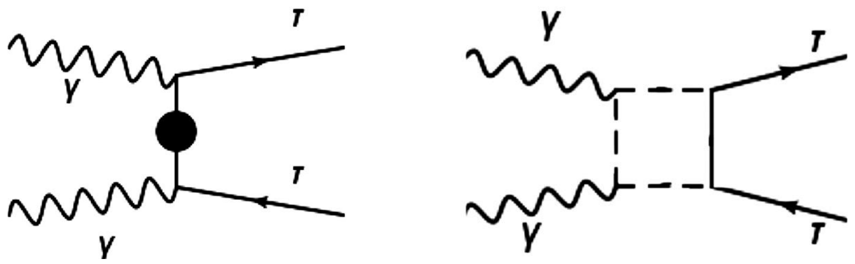
$$\sigma = \sigma_{LO} + \delta\sigma_{QED} + \delta\sigma_{weak}$$



※ Different line shapes between $d\sigma_{a_\tau}/d\sigma_{LO}$ and $d\sigma/d\sigma_{LO}$

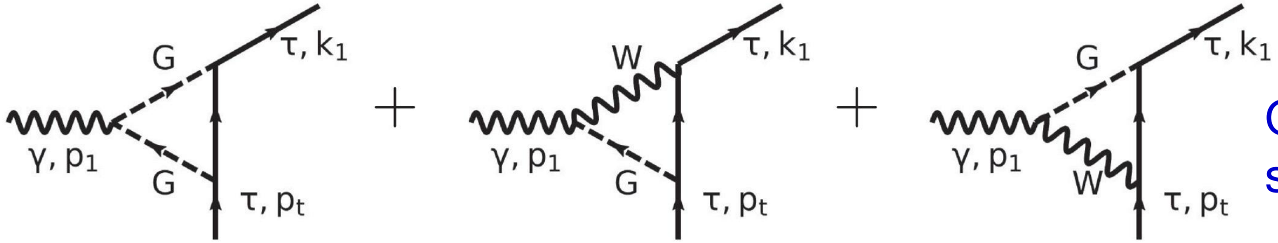
Numerical Results

- Exist further contributions in addition to corrections to $\gamma\tau\tau$ vertex
- Extra form factors other than $F_{1,2}$ in one-loop corrections to $\gamma\tau\tau$ vertex

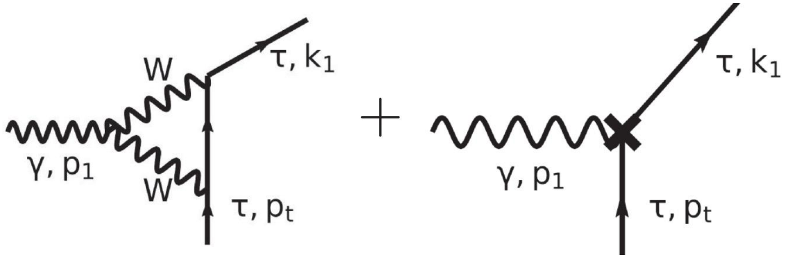


$$\Gamma^{\mu}(q^2) = F_1(q^2)\gamma^{\mu} + iF_2(q^2)\frac{\sigma^{\mu\nu}q^{\nu}}{2m}$$

$\Gamma^{\mu}_{\text{weak}} =$



One of the τ leptons is not the on-shell spinor but an inner propagator



$$= \frac{\alpha}{4\pi s_W^2}\Big(\gamma^{\mu}\widetilde{F}_1 + \gamma^{\mu}\gamma^5\widetilde{F}_2 + \gamma^{\mu}\not{p}_1\widetilde{F}_3 + \gamma^{\mu}\not{p}_1\gamma^5\widetilde{F}_4 + k_{1\mu}\not{p}_1\widetilde{F}_5 + k_{1\mu}\not{p}_1\gamma^5\widetilde{F}_6 + i\frac{\sigma^{\mu\nu}k_{1\nu}}{2m}\widetilde{F}_7 + i\frac{\sigma^{\mu\nu}k_{1\nu}\gamma^5}{2m}\widetilde{F}_8\Big).$$

Summary

- A NLO EW calculation to $\gamma\gamma \rightarrow \tau^+\tau^-$ process in PbPb UPC collisions was done at different nucleon-nucleon CM energy
  - ✓ Within the theoretical framework considered, $\delta\sigma_{QED}$ is about 1%, while the $\delta\sigma_{weak}$ is about -4%
  - ✓ Predictions for the some differential distributions

- Discussion the effect on the measurement of a_τ in the $\gamma\gamma \rightarrow \tau^+\tau^-$ reaction
  - ✓ Two facts are considered:

    extra contributions from box-type,self eneryg-type etc.;

    extra form factors other than $F_{1,2}$ in the $\gamma\tau\tau$ vertex

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Thanks !