Spin asymmetry and dipole moments in tau-pair production with ultraperipheral heavy ion collisions

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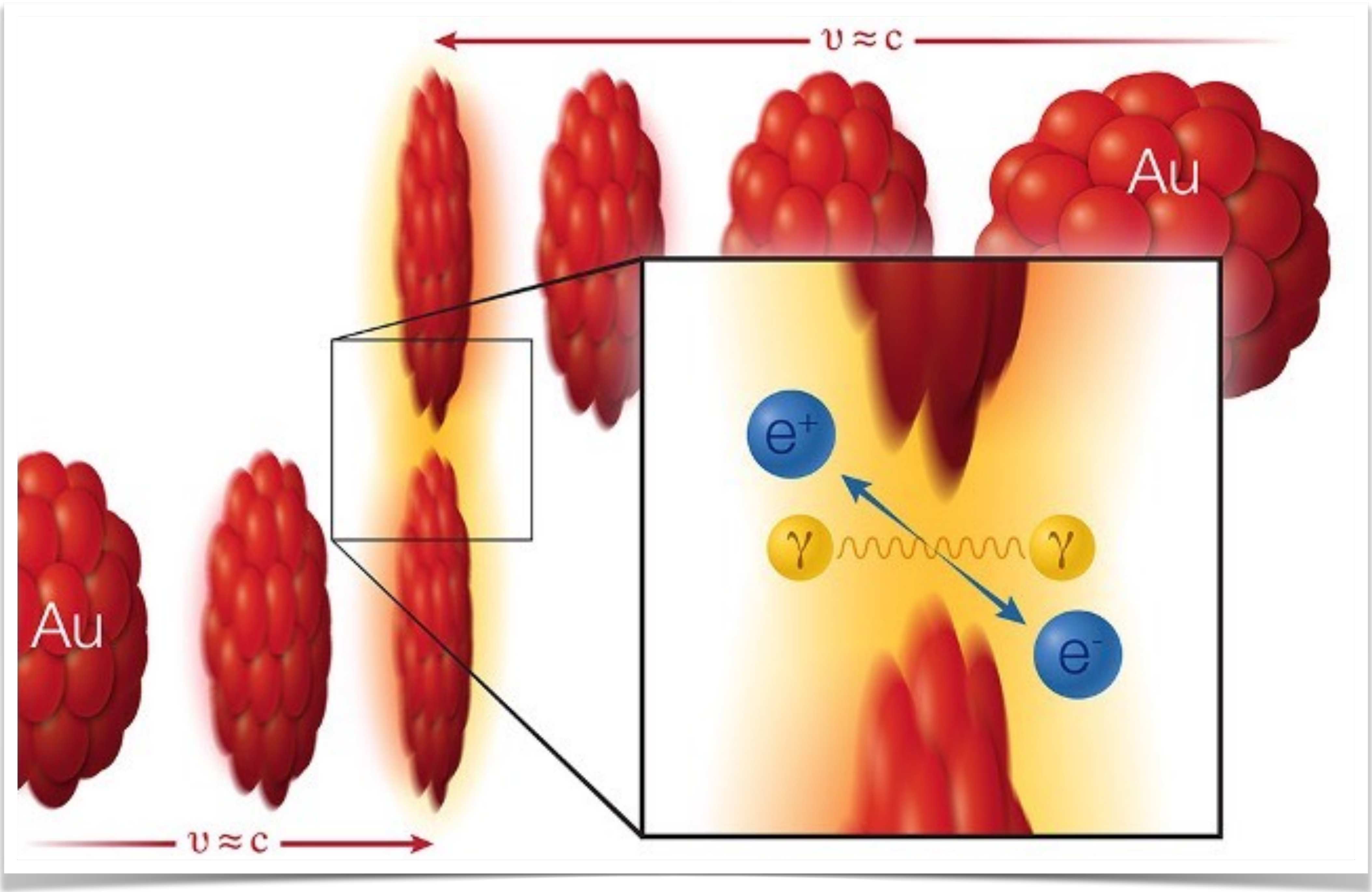
第27届LHC Mini-Workshop   中山大学物理与天文学院   Jan 22, 2024



see also 成瞳光's talk

高能重离子超边缘碰撞中极化光致反应

- **相对论重离子碰撞产生极强电磁场**：两个带电重离子在相对论性条件下碰撞，可以产生高达 10^{15} T 的电磁场。
- **等效光子近似**：从量子场论的角度出发，这种超强电磁场可以被视为一种准实光子束流。
- **准实光子与核电荷的耦合**：当光子波长远长于原子核半径，准实光子与原子核中的电荷源会整体地耦合在一起。
- **相干光子的数密度**：相应的准实光子的数密度与重离子的核电数 Z 的平方成正比，并被称为相干光子。
- **相干光子束流的亮度**：对于重离子来说，Z 通常是一个相当大的数，因此其伴随的相干光子束流具有极高的亮度。

Weizsäcker-Williams method of virtual photon

The photon distribution from a relativistically moving charge particle can be computed from its boosted electromagnetic fields

Fermi 1924, Weizsäcker 1934, Williams 1934

11.18 The electric and magnetic fields of a particle of charge q moving in a straight line with speed $v = \beta c$, given by (11.152), become more and more concentrated as $\beta \to 1$, as is indicated in Fig. 11.9. Choose axes so that the charge moves along the z axis in the positive direction, passing the origin at $t = 0$. Let the spatial coordinates of the observation point be (x, y, z) and define the transverse vector $\mathbf{r}_\perp$, with components x and y. Consider the fields and the source in the limit of $\beta = 1$.

(a) Show that the fields can be written as

$$\mathbf{E} = 2q \frac{\mathbf{r}_\perp}{r_\perp^2} \delta(ct - z); \qquad \mathbf{B} = 2q \frac{\hat{\mathbf{v}} \times \mathbf{r}_\perp}{r_\perp^2} \delta(ct - z)$$

where $\hat{\mathbf{v}}$ is a unit vector in the direction of the particle's velocity.

(b) Show by substitution into the Maxwell equations that these fields are consistent with a 4-vector source density,

$$J^\alpha = qcv^\alpha \delta^{(2)}(\mathbf{r}_\perp)\delta(ct - z)$$

where the 4-vector $v^\alpha = (1, \hat{\mathbf{v}})$.

(c) Show that the fields of part a are derivable from either of the following 4-vector potentials,

$$A^0 = A^z = -2q\delta(ct - z)\ln(\lambda r_\perp); \qquad \mathbf{A}_\perp = 0$$

or

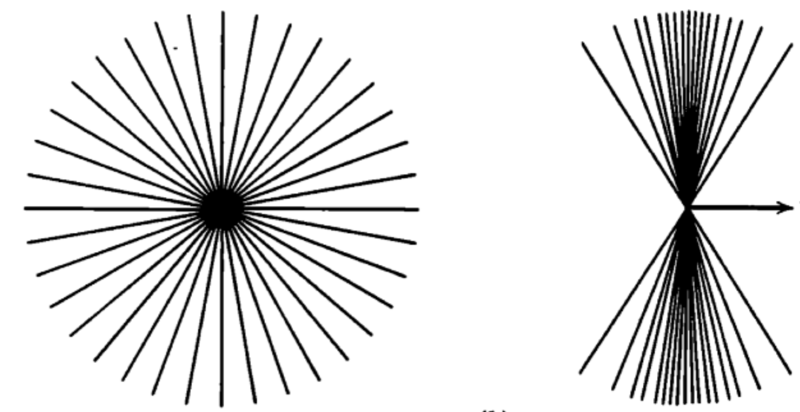
$$A^0 = 0 = A^z; \qquad \mathbf{A}_\perp = -2q\Theta(ct - z)\, \nabla_\perp \ln(\lambda r_\perp)$$

where λ is an irrelevant parameter setting the scale of the logarithm.

Show that the two potentials differ by a gauge transformation and find the gauge function, χ.

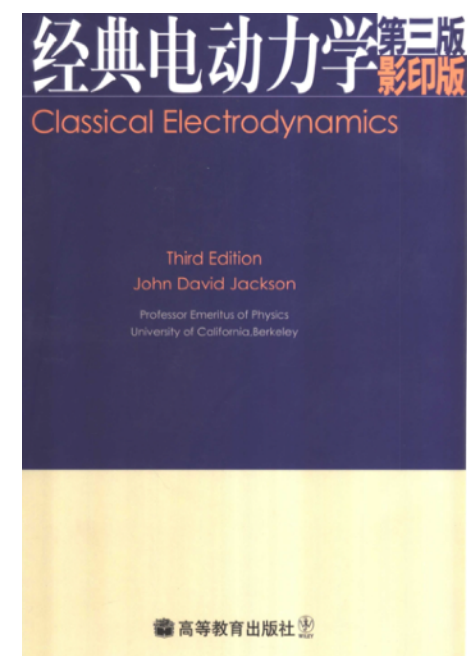
Reference: R. Jackiw, D. Kabat, and M. Ortiz, *Phys. Lett. B* **277**, 148 (1992).

(a)



(b)

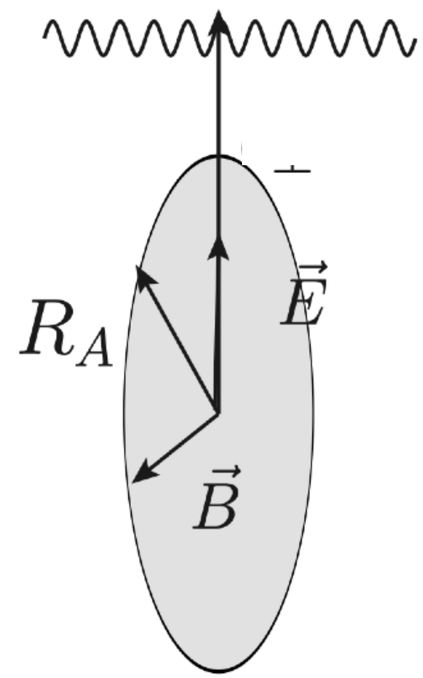
Figure 11.9 Fields of a uniformly moving charged particle. (*a*) Fields at the observation point *P* in Fig. 11.8 as a function of time. (*b*) Lines of electric force for a particle at rest and in motion ($\gamma = 3$). The field lines emanate from the *present* position of the charge.

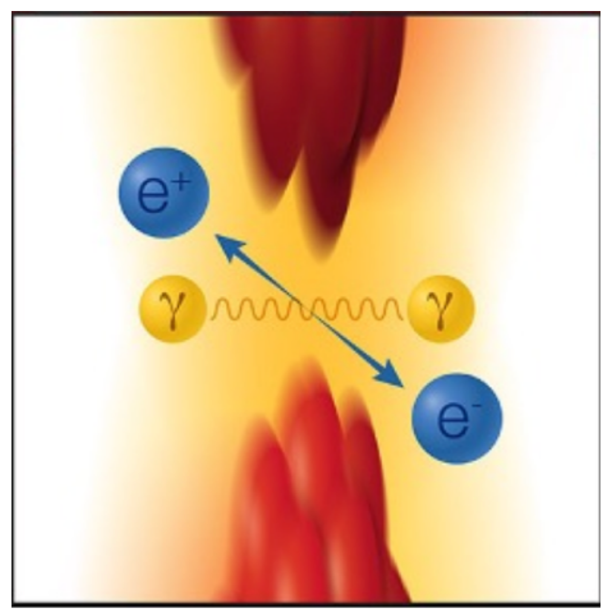


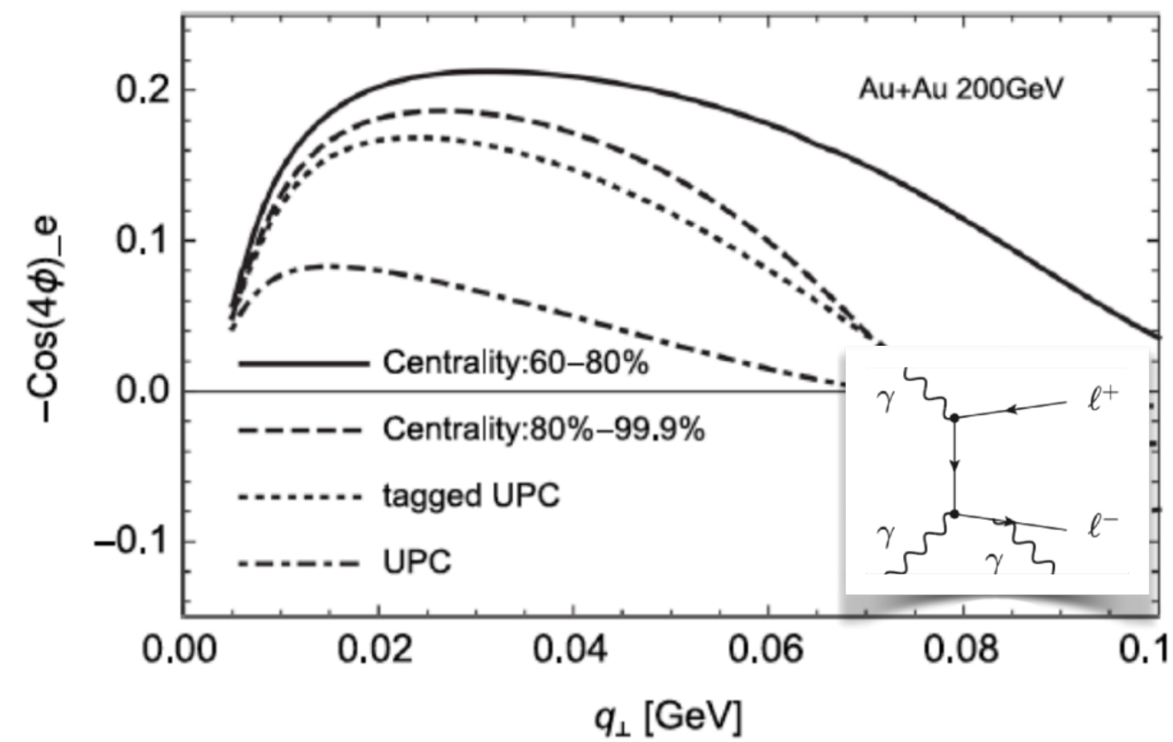
"Classical Electrodynamics" Jackson

Linearly Polarized Photon

- Typical transverse momentum of the photon is 1/R, e.g. 30MeV for Pb
- Photons from the highly Lorentz contracted EM filed are linearly polarized in the transverse plane







In the high energy limit

$$F_+^\mu \propto k_+ A^\mu - k_\perp^\mu A_+ \propto -k_\perp A_+$$

Polarization vector $\vec{\epsilon} \propto \vec{k}_\perp$

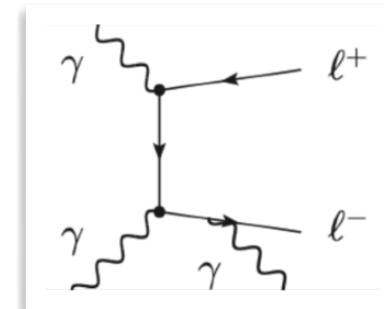
$q_\perp \equiv p_{1\perp} + p_{2\perp}$

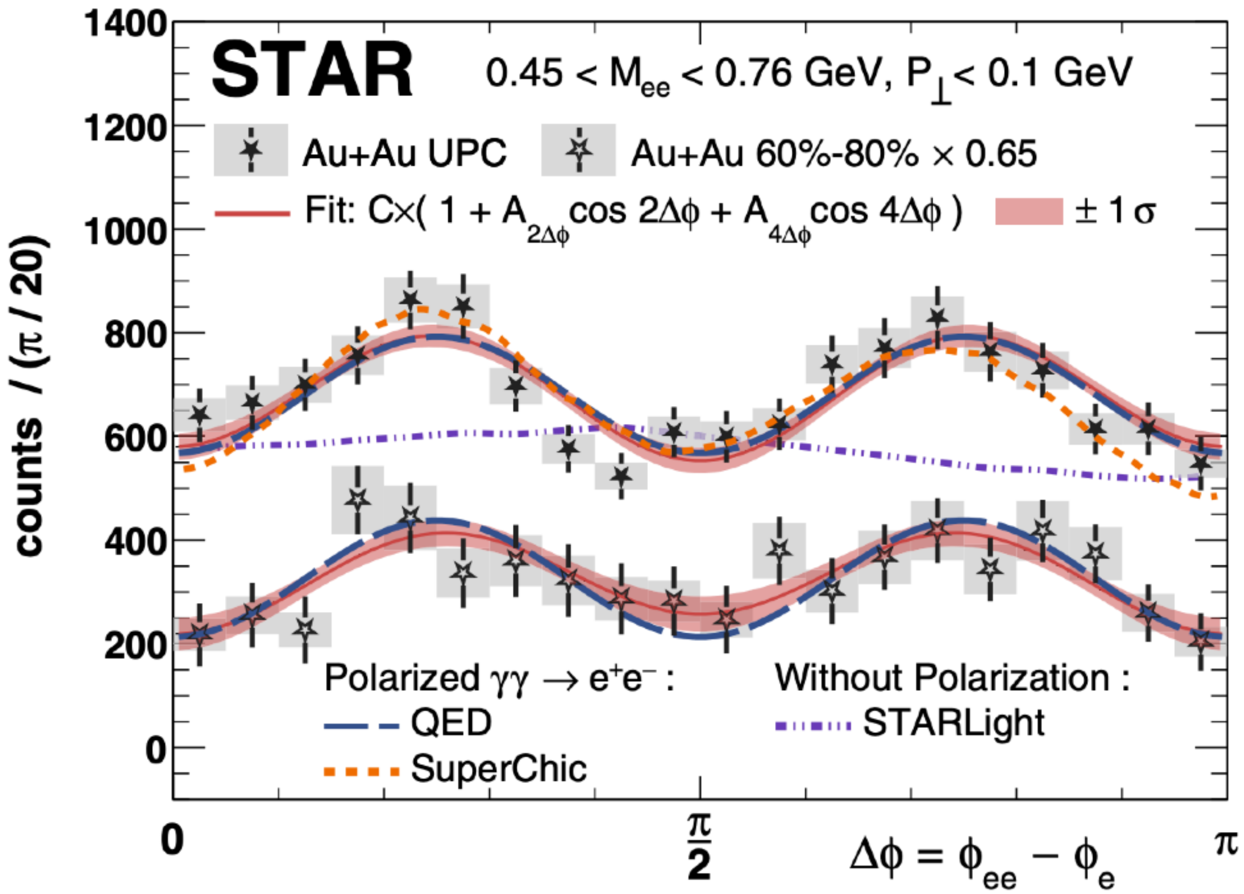
Li, Zhou, Zhou '19

$P_\perp \equiv (p_{1\perp} - p_{2\perp})/2$

Spin interference effect predicts cos4φ modulation

Azimuthal angle distribution for dilepton photoproduction





				Data	QED
$A_{4\Delta\phi}$	Au+Au	UPC	ee	16.8 ± 2.5	16.5
	Au+Au	PC	ee	27 ± 6	34.5
	Ru/Zr	PC	ee	47 ± 14	40
	Au+Au	PC	μμ	35 ± 8± 7	22
$A_{2\Delta\phi}$	Au+Au	UPC	ee	2.0 ± 2.4	0
	Au+Au	PC	ee	6 ± 6	0
	Ru/Zr	PC	ee	6 ± 13	0
	Au+Au	**PC**	**μμ**	**20 ± 8± 3**	**13**

Phys. Rev. Lett. 127(2021)052302

cos2φ modulation $\propto m_l^2/p_T^2$

Azimuthal asymmetries of muon pair production in UPCs

DYS, Zhang, Zhou, Zhou '23

- We consider

$$\gamma(x_1 P + k_{1\perp}) + \gamma(x_2 \bar{P} + k_{2\perp}) \to l^+(p_1) + l^-(p_2)$$

- The joint impact parameter and transverse momentum dependent cross section

$$\frac{d\sigma_0}{d^2q_\perp d^2P_\perp dy_1 dy_2 d^2b_\perp} = A_0 + A_2 \cos 2\phi + A_4 \cos 4\phi$$

$$q_\perp \equiv p_{1\perp} + p_{2\perp}$$

$$P_\perp \equiv (p_{1\perp} - p_{2\perp})/2$$

- The resumed cross section reads

$$\frac{d\sigma(q_\perp)}{d\mathcal{P}.\mathcal{S}.} = \int \frac{d^2r_\perp}{(2\pi)^2}\left[1 - \frac{2\alpha_e c_2}{\pi}\cos 2\phi_r + \frac{\alpha_e c_4}{\pi}\cos 4\phi_r\right] e^{ir_\perp \cdot q_\perp} e^{-\mathrm{Sud}(r_\perp)} \int d^2q'_\perp e^{ir_\perp \cdot q'_\perp} \frac{d\sigma_0(q'_\perp)}{d\mathcal{P}.\mathcal{S}.}$$

- Sudakov factor in the large mass approximation

$$\mathrm{Sud}(r_\perp) = \frac{\alpha_e}{\pi} \ln\frac{M^2}{m^2} \ln\frac{P_\perp^2}{\mu_r^2}$$

Hatta, Xiao, Yuan & Zhou '21 PRL & PRD

Azimuthal asymmetries of muon pair production in UPCs

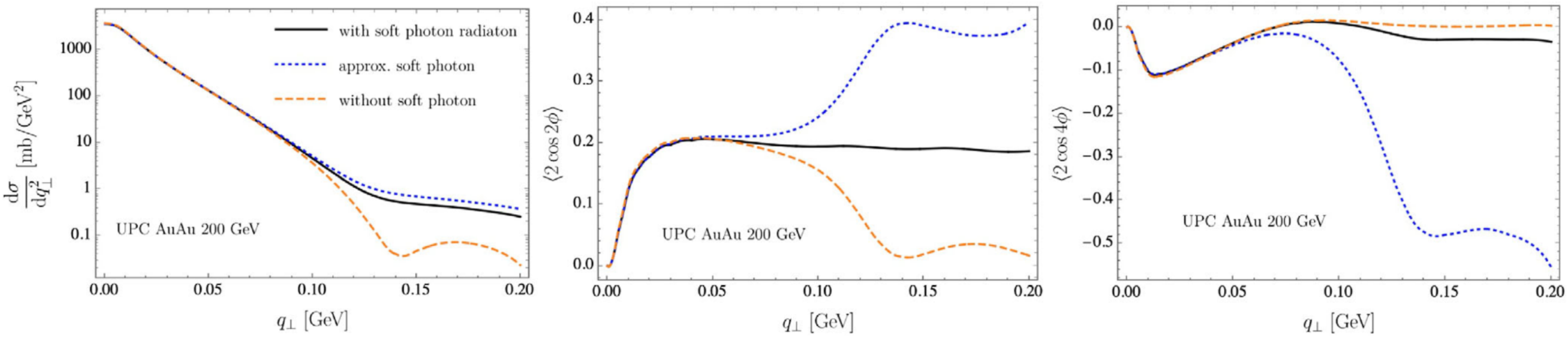
DYS, Zhang, Zhou, Zhou '23

- However, at RHIC energy, where the muon mass is roughly the same order of p_T *or* M, the soft factor receives the sizable finite lepton mass correction

$$q_\perp \ll m \sim M$$

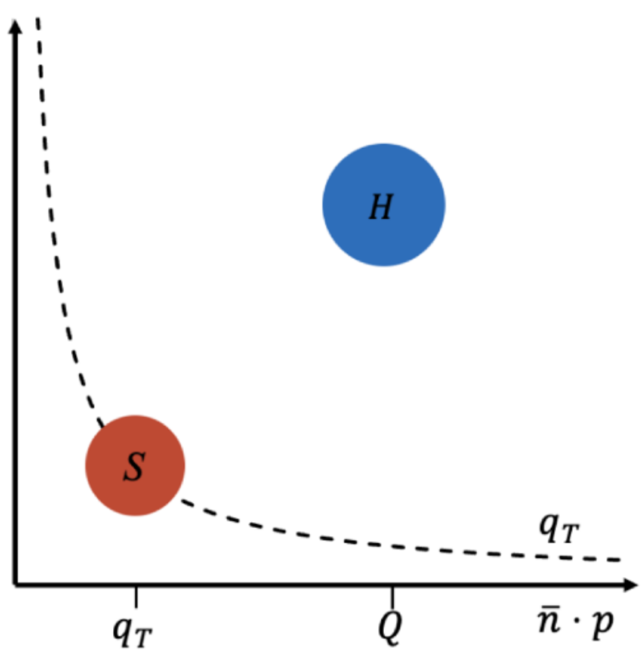
- We consider the full finite lepton-mass correction. Its correction to the unpolarized cross section is tiny.

- The contribution from the muon mass effect to the asymmetries is quite sizable



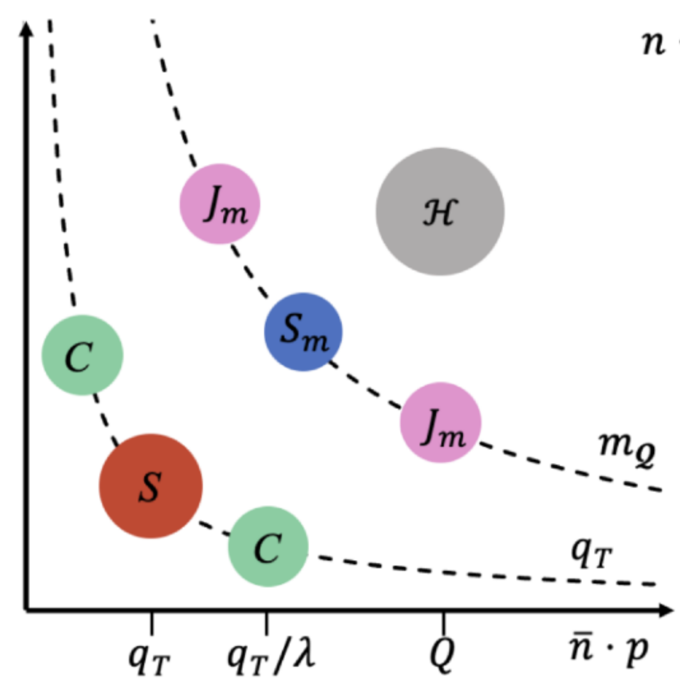
More EFTs

$q_\perp \ll m \sim M$



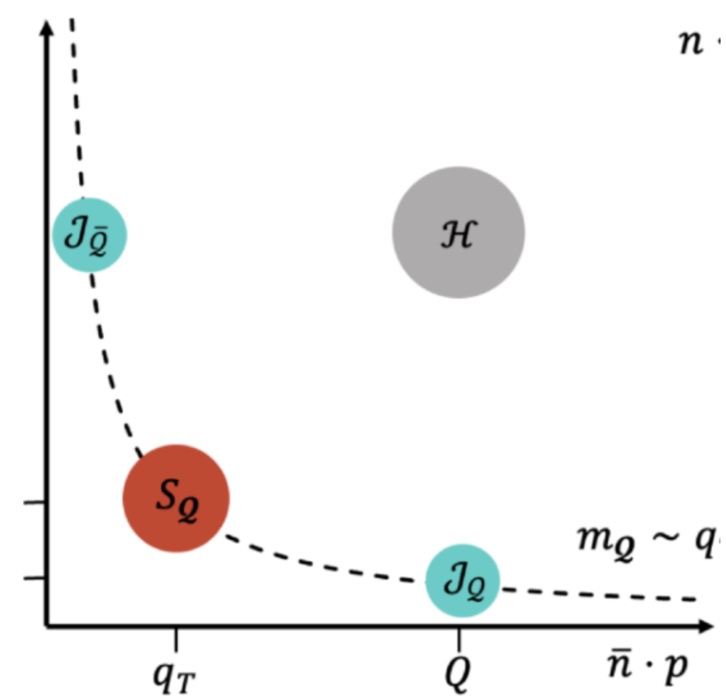
HQET

$q_\perp \ll m \ll M$



b-HQET

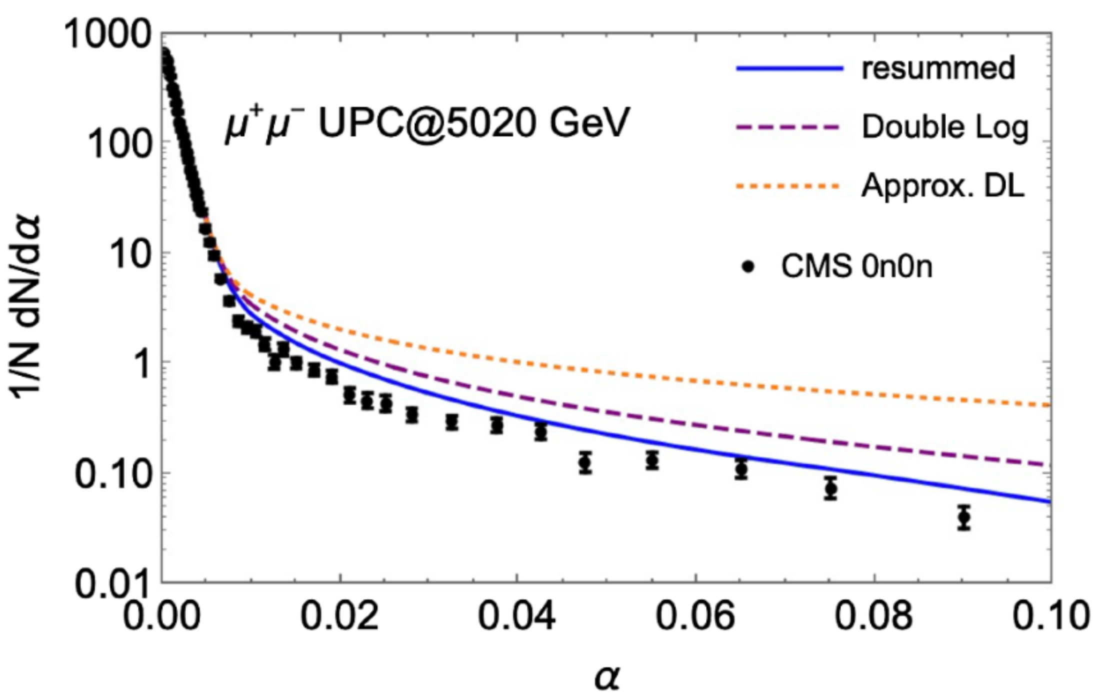
$q_\perp \sim m \ll M$

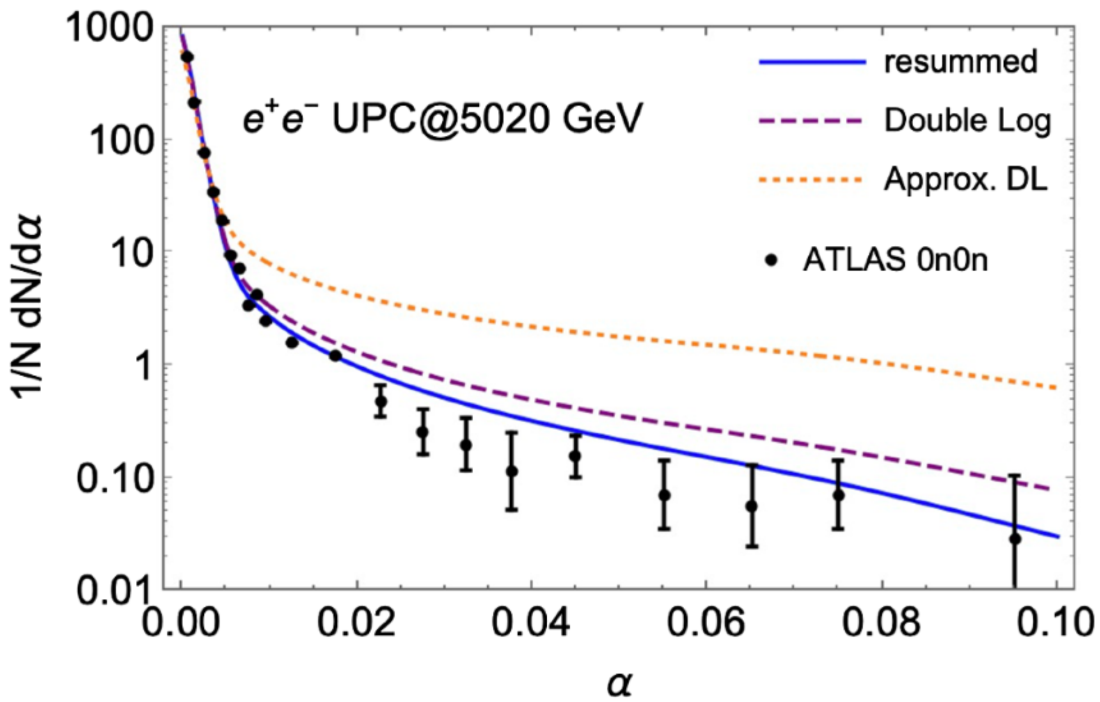


SCET-M

Lepton pair production in UPCs
Toward a precision test of the resummation formalism

DYS, Zhang, Zhou, Zhou '23





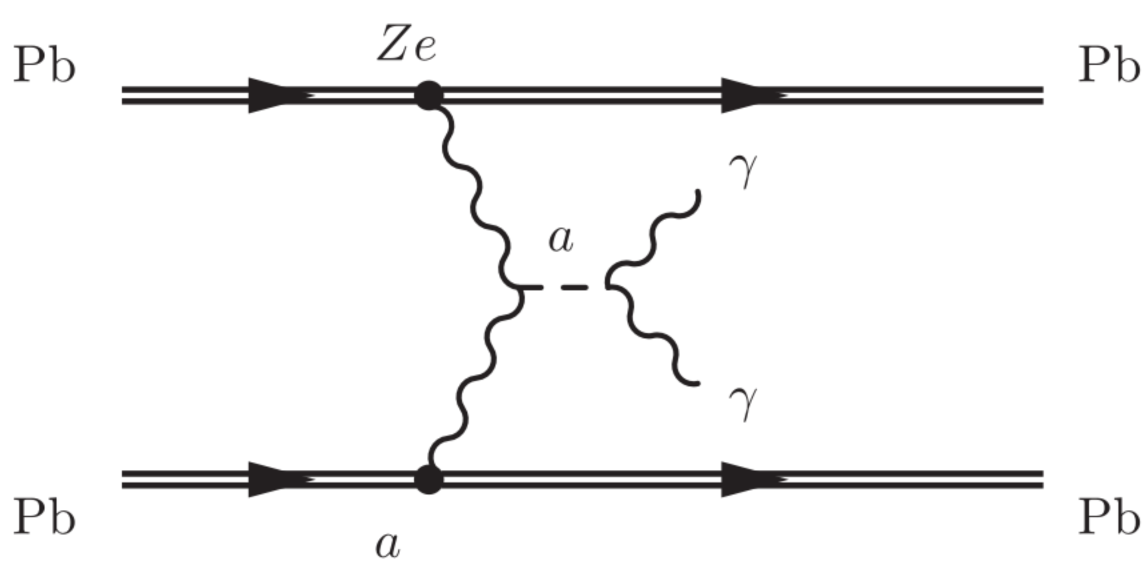
- We improve the accuracy of the previous calculations beyond the double leading logarithm approximation.
- Notably, the single logs arising from the collinear region are greatly enhanced by the small mass of the leptons.
- Our findings demonstrate the accessibility of these subleading resummation effects through the analysis of angular correlations in lepton pairs produced in UPCs.

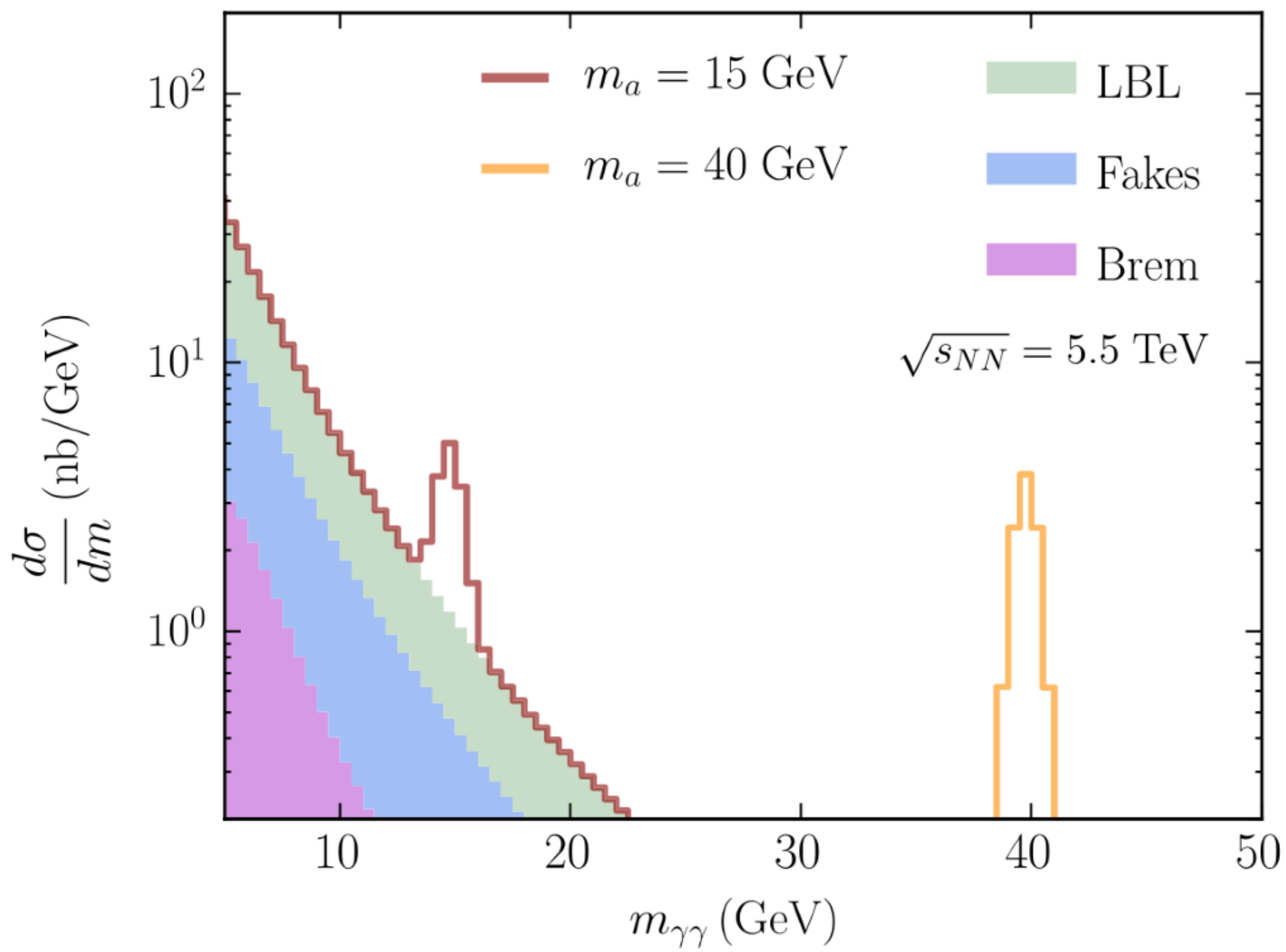
Precision physics at Heavy ion collisions

UPC and beyond SM

Axion-like particle search

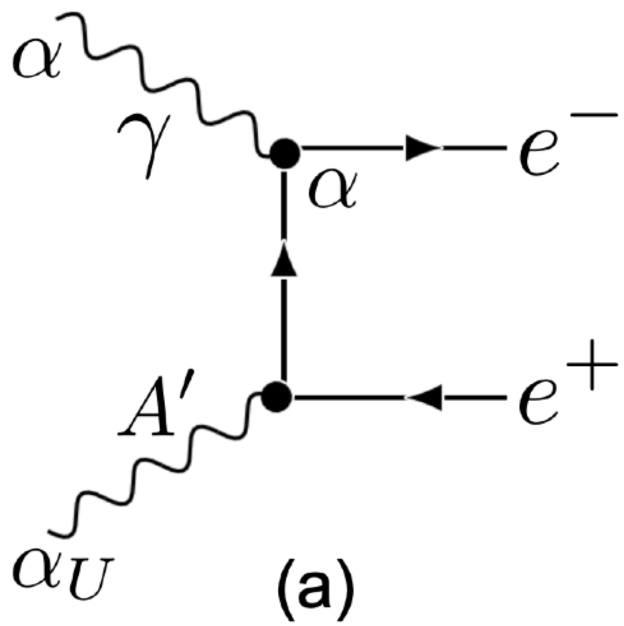
Knapen, Lin, Lou, and Melia '17 PRL

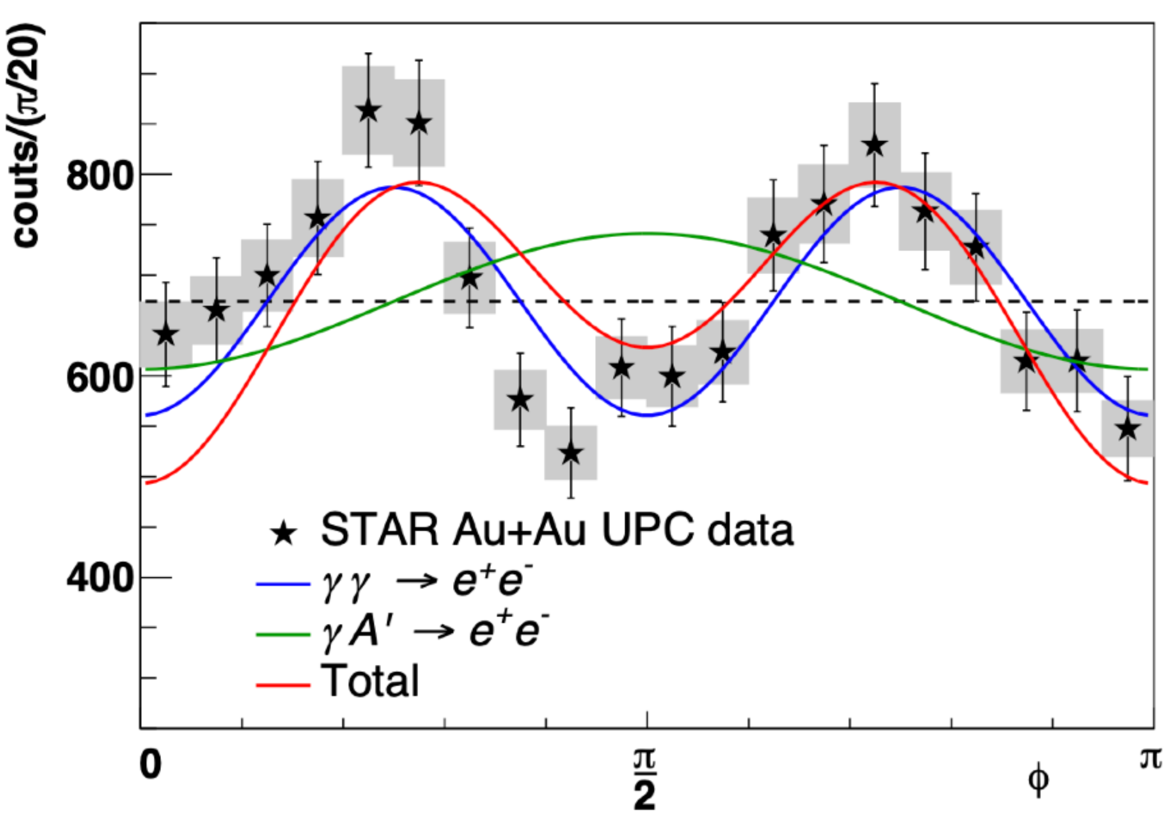


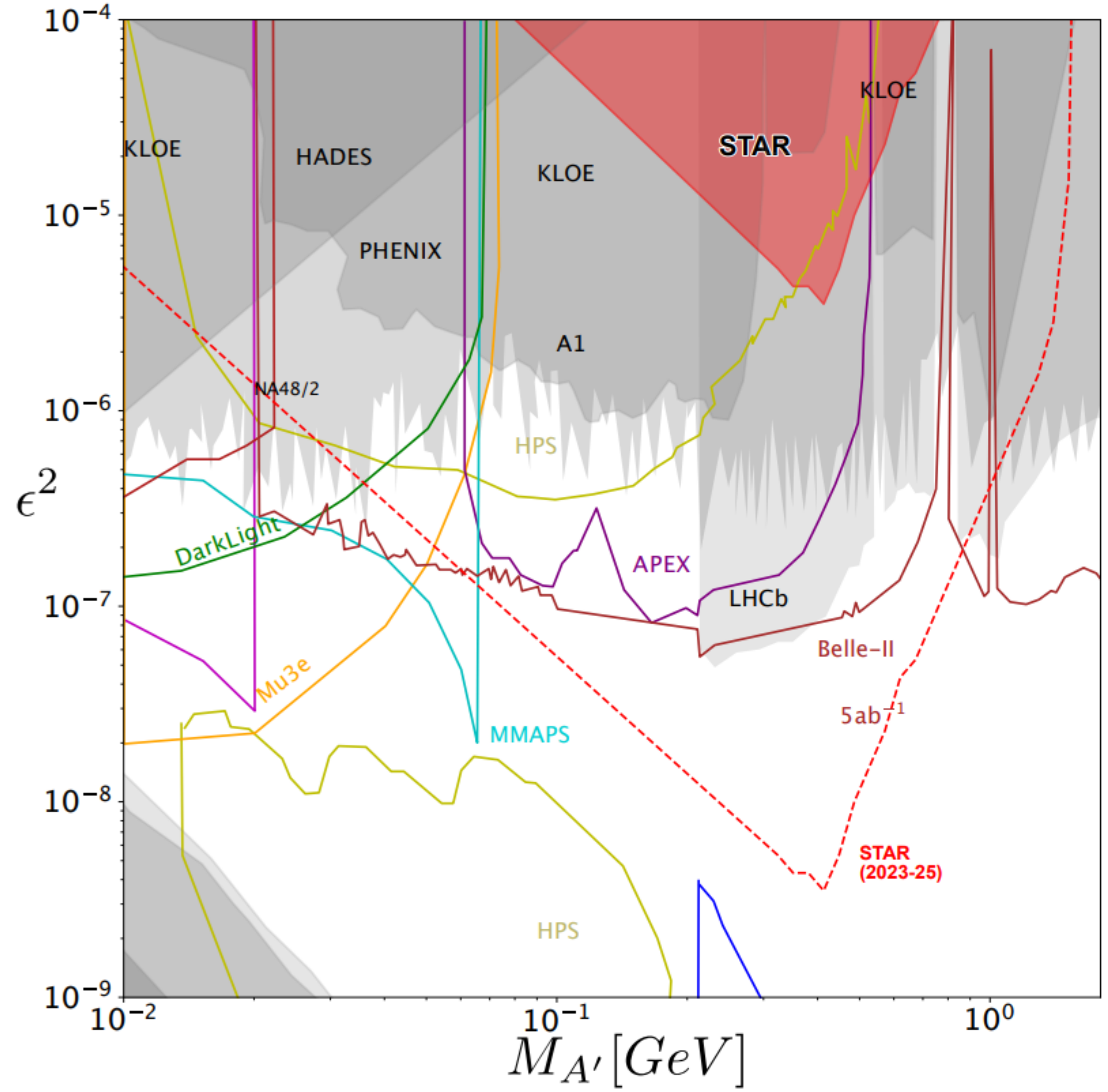


Dark photon search

Xu, Lewis, Wang, Brandenburg, Ruan ’22

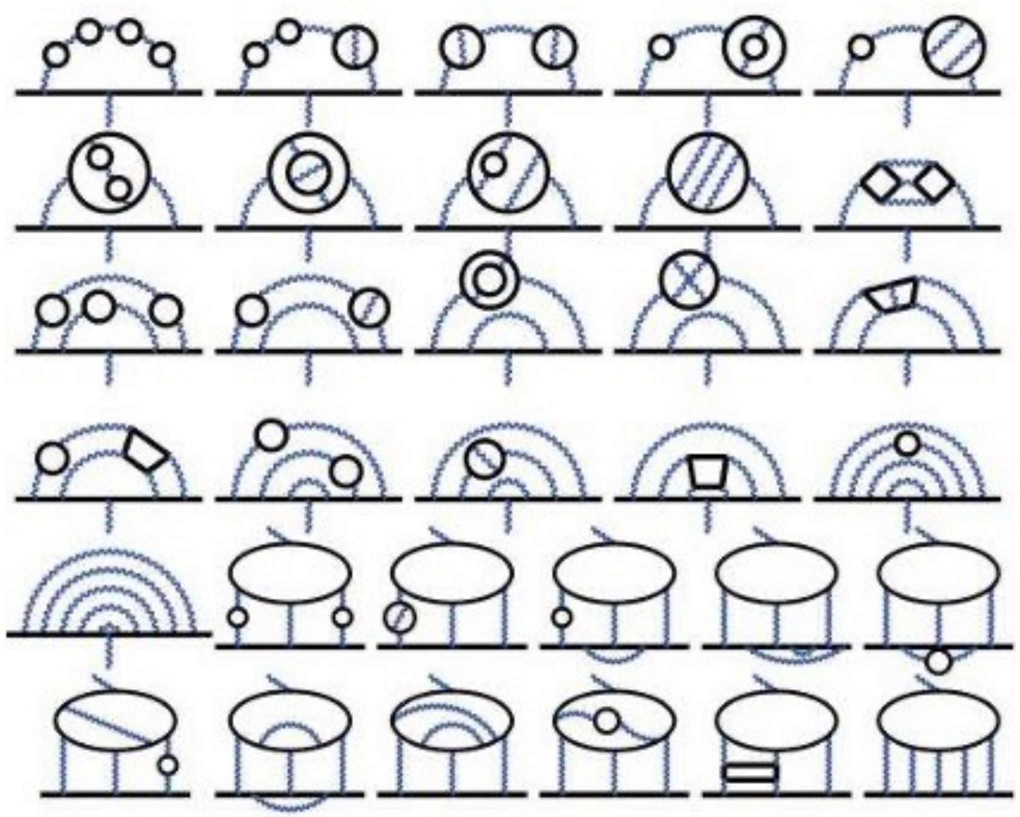




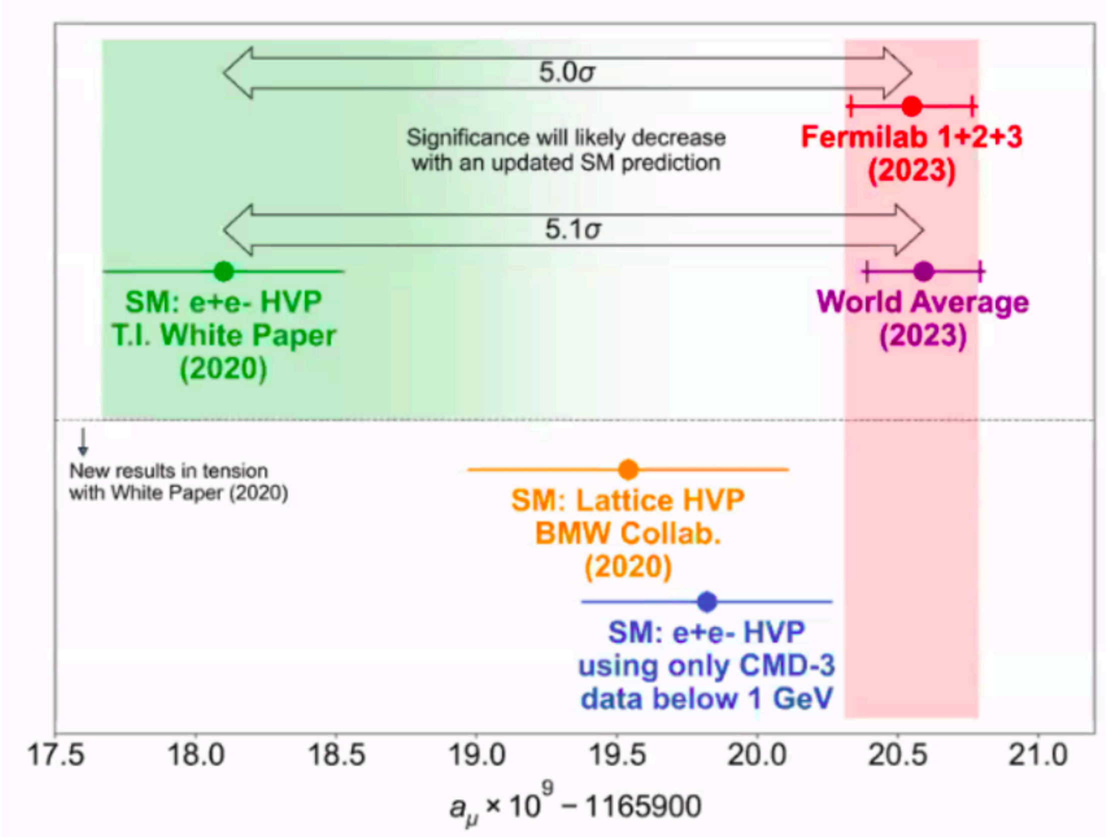


Anomalous magnetic dipole moments

电子反常磁矩



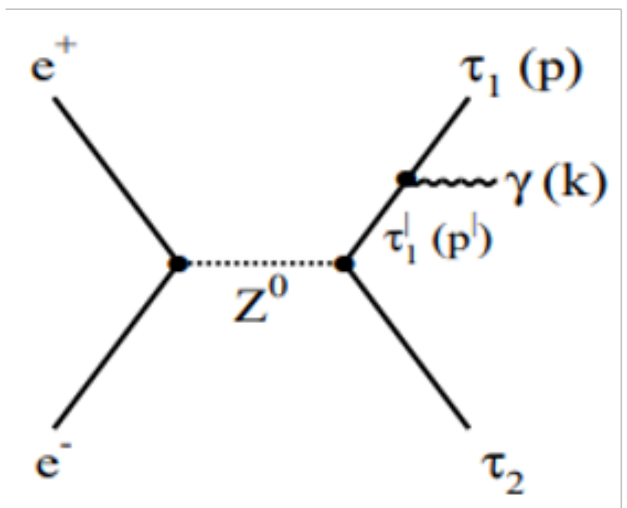
缪子反常磁矩

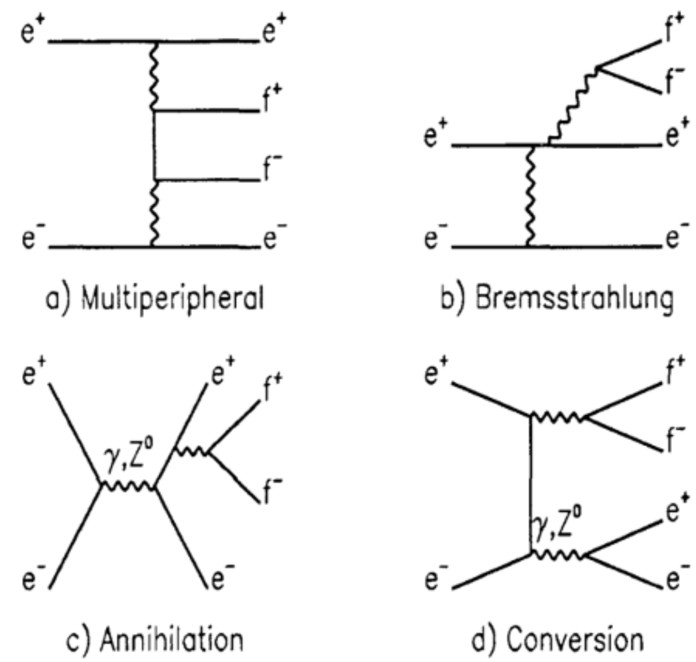


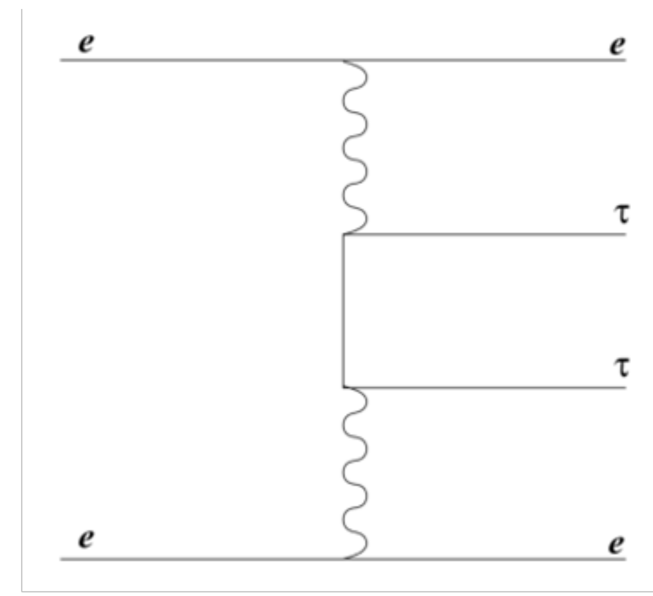
A significant challenge arises due to the short lifetime of the τ lepton.

Tau magnetic moments at e$^+$e$^-$

$$\Gamma^{\mu}_{\text{eff.}}(q^2) = -ie\left[iF_2(q^2) + F_3(q^2)\gamma^5\right]\frac{\sigma^{\mu\nu}q_\nu}{2m_\tau}. \qquad F_2(0) = a_\tau \qquad F_3(0) = 2m_\tau d_\tau/e$$







All the knowledge regarding the a_τ and d_τ relies heavily on the theoretical assumptions made in the analysis, such as the frequent exclusion of other possible NP effects.

Tau lepton pair production in UPCs

PHYSICAL REVIEW LETTERS

Observation of the $\gamma\gamma \to \tau\tau$ Process in $\mathrm{Pb}+\mathrm{Pb}$ Collisions and Constraints on the τ-Lepton Anomalous Magnetic Moment with the ATLAS Detector

G. Aad *et al.* (ATLAS Collaboration)

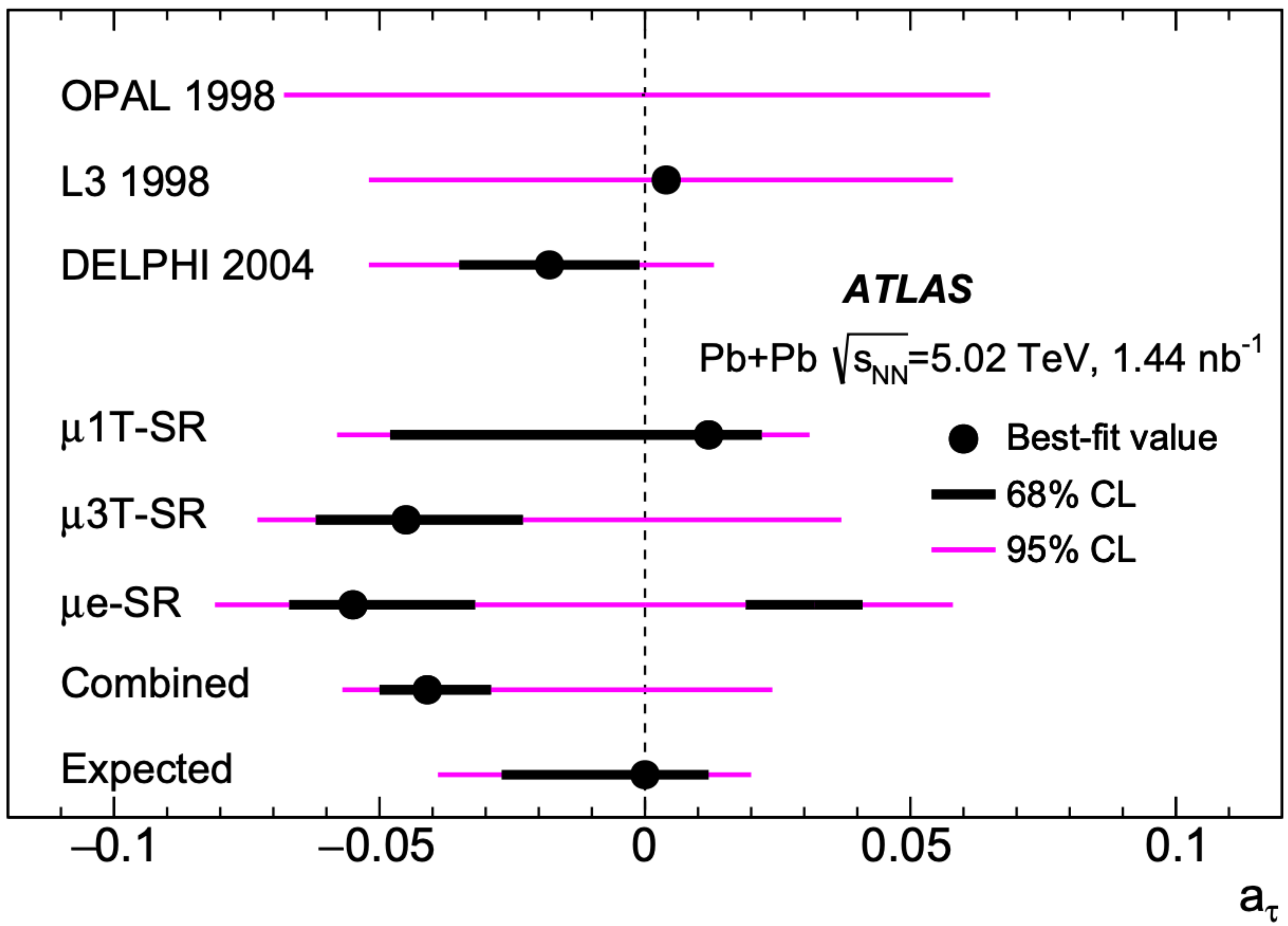
Phys. Rev. Lett. **131**, 151802 – Published 12 October 2023

Observation of τ Lepton Pair Production in Ultraperipheral Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02\ \mathrm{TeV}$

A. Tumasyan *et al.* (CMS Collaboration)

Phys. Rev. Lett. **131**, 151803 – Published 12 October 2023

Magnetic moments in UPCs



see also 成瞳光's talk

With this measurement, ATLAS can now measure the tau lepton's magnetic moment with precision competitive with lepton colliders.

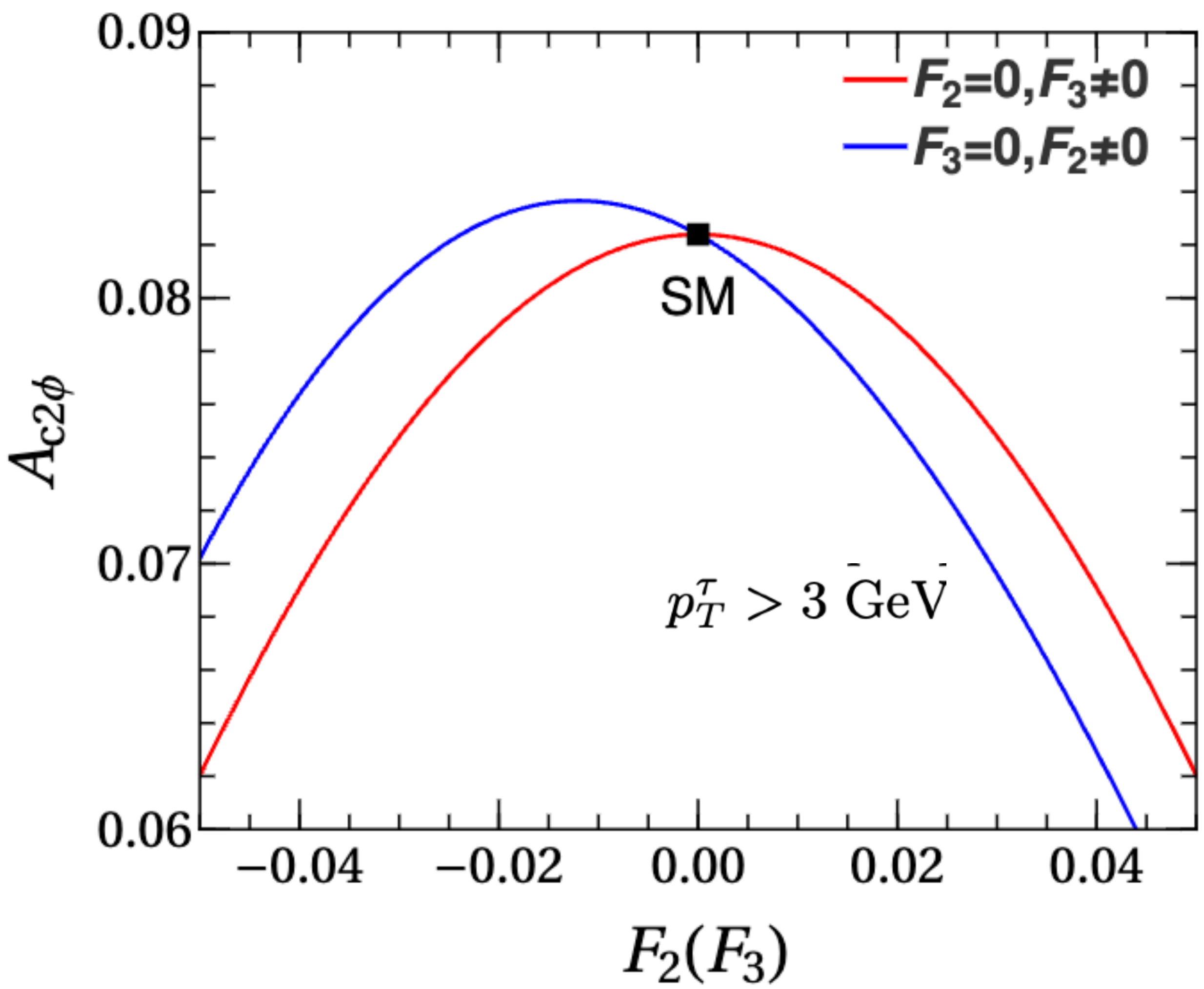
https://atlas.cern/updates/briefing/observation-taupair-heavy-ions

Spin asymmetry and dipole moments in tau-pair production with UPCs

DYS, Yan, Yuan, Zhang '23

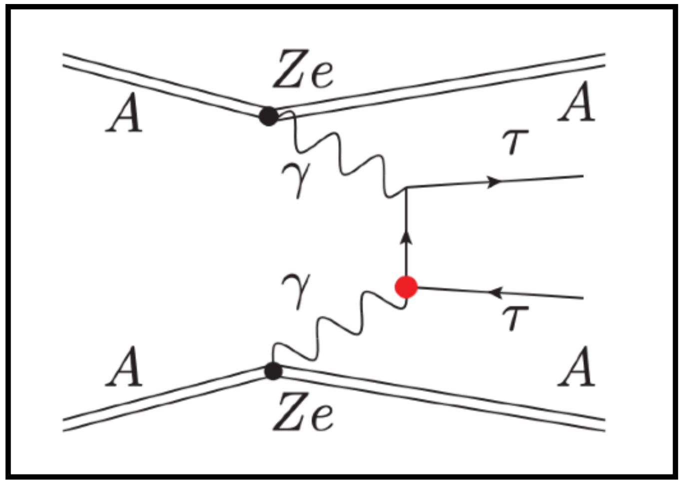
The joint impact parameter $b_\perp$ and $q_\perp$ dependent cross section from the QED and dipole interactions

$$d\sigma \sim \left[A_0 + B_0^{(1)} F_2 + B_0^{(2)} F_2^2 + C_0^{(2)} F_3^2 + \left(A_2 + B_2^{(2)} F_2^2 + C_2^{(2)} F_3^2\right) \cos 2\phi + A_4 \cos 4\phi\right]$$



benchmark parameters from the DELPHI

$a_\tau = -0.018$ $\quad$ $|d_\tau| = 3.7 \times 10^{-16}\, e \cdot \mathrm{cm}$



$$\Gamma^\mu_{\text{eff.}}(q^2) = -ie\left[iF_2(q^2) + F_3(q^2)\gamma^5\right]\frac{\sigma^{\mu\nu} q_\nu}{2m_\tau}$$

$$F_2(0) = a_\tau$$

$$F_3(0) = 2m_\tau d_\tau / e$$

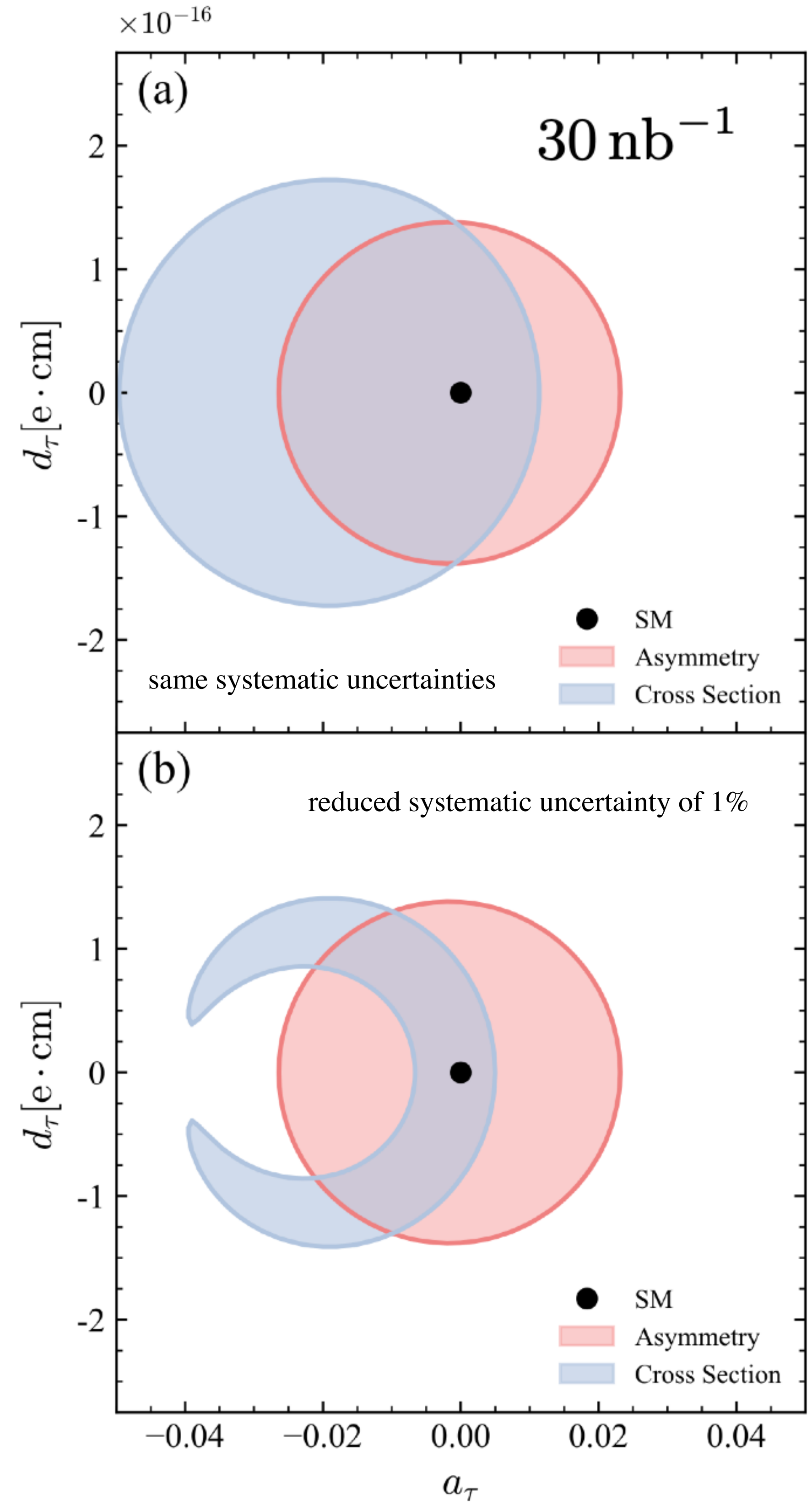
Spin asymmetry and dipole moments in tau-pair production with UPCs

DYS, Yan, Yuan, Zhang ’23

- To determine the coefficients of the cos2ϕ modulation, it is convenient to define

$$A_{c2\phi} = \frac{\sigma(\cos 2\phi > 0) - \sigma(\cos 2\phi < 0)}{\sigma(\cos 2\phi > 0) + \sigma(\cos 2\phi < 0)}$$

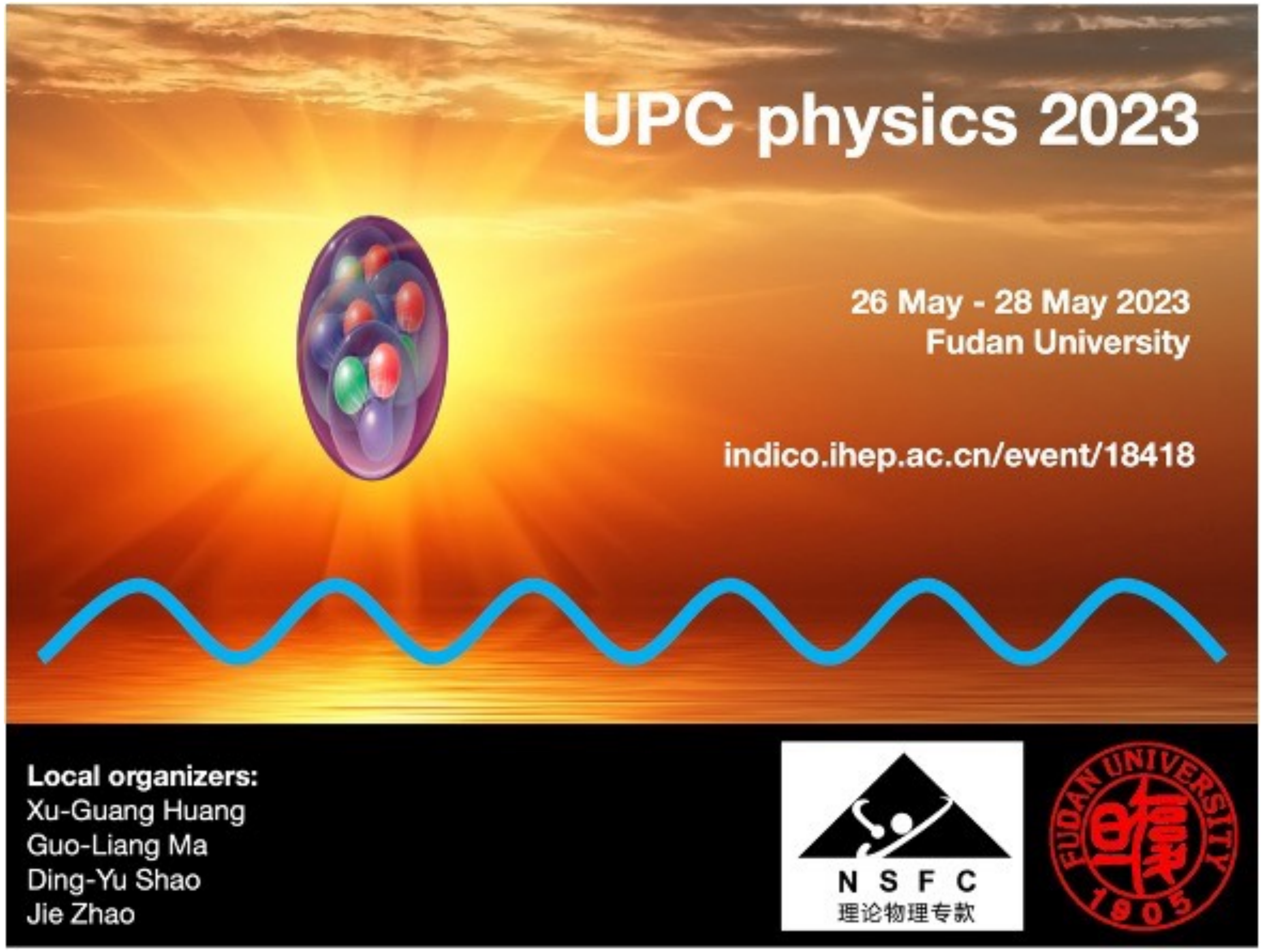
- Assume that the cut efficiencies for future Pb+Pb collision would be same as the current values of the ATLAS and CMS experiments, and the statistical uncertainty $\delta A_{c2\phi}$ can be obtained by properly rescaling.
- Incorporating the azimuthal asymmetry into the analysis can significantly reduce the parameter space of a_τ and d_τ
- With the inclusion of more decay modes of τ leptons and further optimization, we expect that future experimental analyses could significantly improve the limit for d_τ



Summary

- **UPC is a golden probe of the strong electromagnetic field**
- **All the results support linear polarization**
- **Spin interference generates many interesting phenomena**
- **It provides a great laboratory to study:**
  - **Gluon saturation**
  - **QGP in EM field**
  - **all-order precision resummation**
  - **BSM (tau MDM & EDM, axion-like particle, dark photon)**

Thank you



注册	08:30 - 09:00
开幕致辞	09:00 - 09:10
强场光光散射和类轴子产生 沈百飞	09:10 - 09:50
Searching for the new physics at the EIC 岩斌	09:50 - 10:20
茶歇+合影	10:20 - 10:50
The Curious Story of the Photon 肖博文	10:50 - 11:20
Impact parameter dependence of photon-induced processes in heavy-ion collisions 杨帅	11:20 - 11:50
Results on Breit-Wheeler Process in Heavy-Ion Collisions and its Application to Nuclear Charge Radius Measurements 晓凤	
午餐	12:10 - 14:00
Studying Coulomb correction at EIC and EicC 周剑	14:00 - 14:30
Nuclear excitation by electron capture in electron-ion collisions 吴远彬	14:30 - 15:00
Photoproduction of e+e− in peripheral isobar collisions 林硕	
茶歇	
UPC Quarkonium Production at LHCb 李衡讷	
gamma-UPC 邵华圣（线上）	
Initial electromagnetic field dependence of photon-induced production in is	

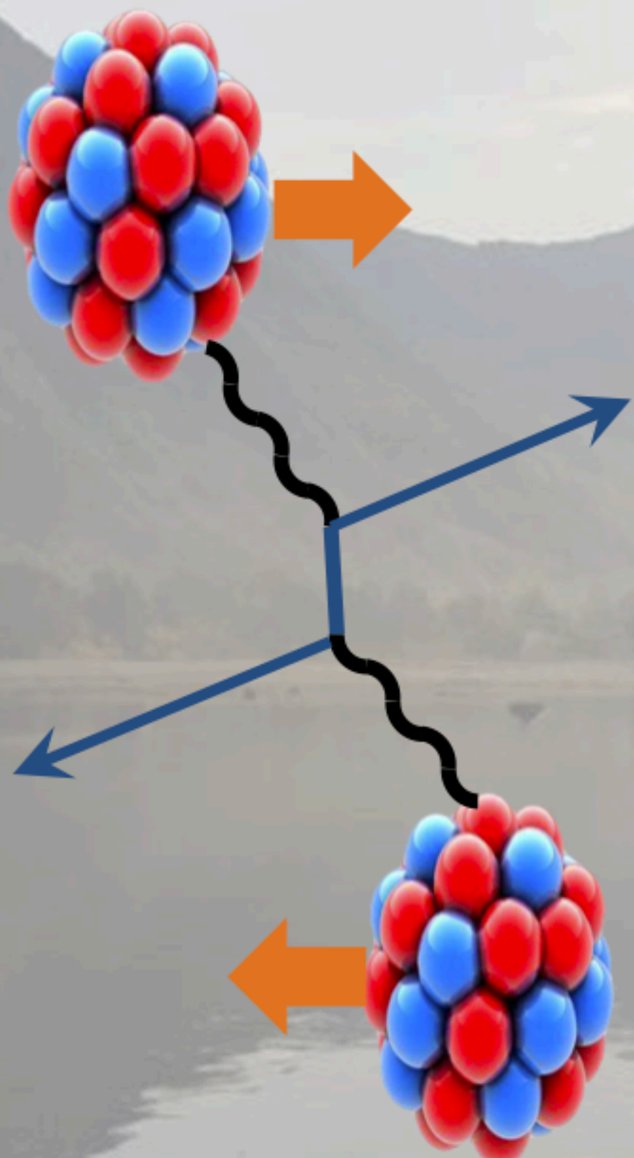
粒子物理

核物理

强场物理

Multi-scale Imaging of Nuclear and Proton Geometries 赵文彬（线上）	09:00 - 09:30
Probing ultra-dense gluonic matter via UPCs at CMS 叶早晨（线上）	09:30 - 10:00
Very low-pT J/ψ production in Au+Au collision at 200 GeV and U+U collisions at 193 GeV at STAR 李子阳	10:00 - 10:20
茶歇	10:20 - 10:50
Lepton pair photoproduction in peripheral, ultra- peripheral and isobar heavy-ion collisions 浦实	10:50 - 11:20
Probing the small-x gluon tomography in polarized photo-nuclear reactions 周雅瑾	11:20 - 11:50
Photon-induced lepton pairs production in Au+Au collisions at √sNN = 200 GeV at STAR 王恺扬	11:50 - 12:10
午餐	12:10 - 14:00
EicC review 林德旭	14:00 - 14:30
Azimuthal asymmetries in photon induced ultraperipheral heavy ion collisions 张成	14:30 - 15:00
Reaction plane alignment with linearly polarized photon in heavy-ion collisions 吴鑫	15:00 - 15:20
茶歇	15:20 - 15:50
Two-point functions from chiral kinetic theory in magnetized plasma 杨立新	15:50 - 16:20
Exclusive J/psi photoproduction simulation and physics at EIC 李欣柏	16:20 - 16:40
Probing positivity with UPC 舒驰	16:40 - 17:00

The 2nd Workshop on Ultra-Peripheral Collision Physics: Strong Electromagnetic fields, UPC and EIC/EicC



April 12 – 15, 2024
Particle and Nuclear Physics
School of Physical Sciences, USTC
https://indico.pnp.ustc.edu.cn/e/upc2024

Local organizers:

Qi-peng Hu, Shi Pu (co-chair), Ze-bo Tang, Qun Wang, Wang-mei Zha (co-chair), Yi-fei Zhang

Selected events must contain exactly one muon, which targets a muonic decay of one of the τ leptons while reducing backgrounds from $\gamma\gamma \to \mu\mu$ and $\gamma\gamma \to q\bar{q}$. Three signal regions (SRs) then categorize events by the decay signature of the other τ lepton. The μe-SR category additionally requires one electron and no additional tracks separated from the muon (electron) by $\Delta R_{\mu(e),\mathrm{trk}} > 0.1$, which targets fully leptonic decays of both τ leptons. The different-flavor (μe) requirement suppresses same-flavor backgrounds dominated by $\gamma\gamma \to \mu\mu/ee$. The μ1T-SR (μ3T-SR) category requires exactly one track (three tracks) separated from the muon by $\Delta R_{\mu,\mathrm{trk}} > 0.1$, which targets τ-lepton decays to one or three charged hadrons. The one-track requirement also captures leptonic τ-lepton decays that fail electron or muon reconstruction. The electric charges of the muon, electron, and tracks must sum to zero.