Measurements of nuclear charge and mass radii at RHIC in UPC

超擦边碰撞测核半径

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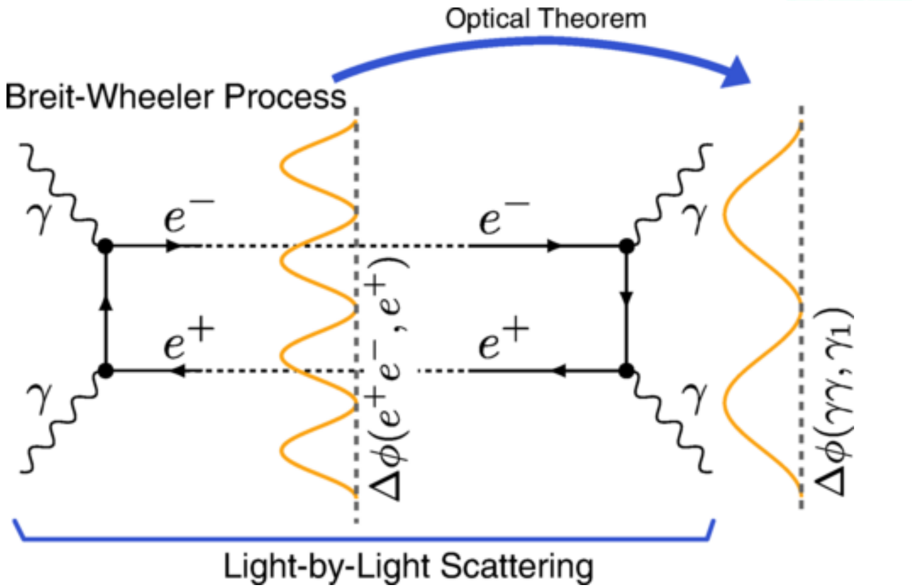
(Kent State Univerity)

arXiv:1806.02295 PRL
arXiv:1804.01813 PLB
arXiv:1705.01460 PRC
arXiv:1812.02820 PLB
arXiv:1910.12400 PRL
arXiv:2103.16623 EPJA
arXiv:2207.05595 PRC
arXiv:2204.01626 SA
arXiv:2208.14943 ROPP
STAR BUR 2021-2025

- Basic pure EM process in Heavy-ion collisions
- Constrain charge radius at RHIC
- Constrain mass radius at RHIC
- Summary

Measurement of e^+e^- Momentum and Angular Distributions from Linearly Polarized Photon Collisions
J. Adam *et al.* (STAR Collaboration)
Phys. Rev. Lett. **127**, 052302 – Published 27 July 2021



Center for Nuclear Research

KENT STATE UNIVERSITY

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UPC 04/13/2024

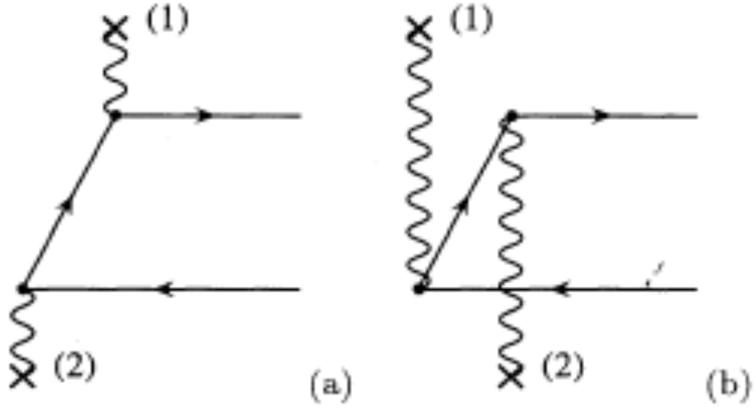
Two-photon QED in Particle Data Book

51.7 Two-photon processes

In the Weizsäcker-Williams picture, a high-energy electron beam is accompanied by a spectrum of virtual photons of energies ω and invariant-mass squared $q^2 = -Q^2$, for which the photon number density is

$$dn = \frac{\alpha}{\pi}\left[1 - \frac{\omega}{E} + \frac{\omega^2}{E^2} - \frac{m_e^2\,\omega^2}{Q^2 E^2}\right]\frac{d\omega}{\omega}\frac{dQ^2}{Q^2}, \tag{51.43}$$

where E is the energy of the electron beam. The cross section for $e^+e^- \to e^+e^- X$ is then [9]

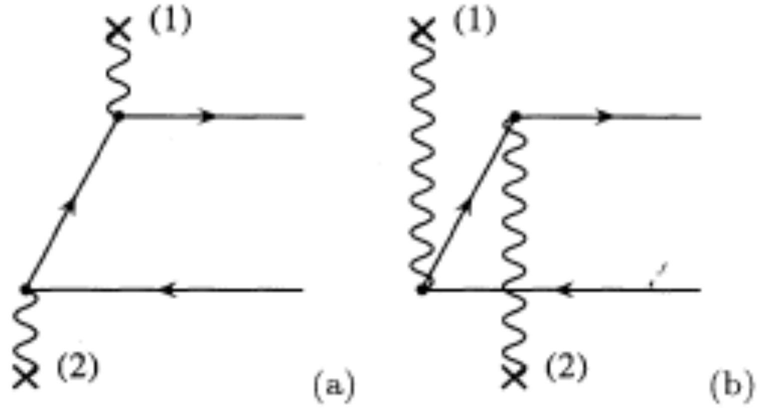


$$d\sigma_{e^+e^-\to e^+e^-X}(s) = dn_1 dn_2 d\sigma_{\gamma\gamma\to X}(W^2), \tag{51.44}$$

Natural extension to Heavy Ions

$$\rho_A(r) = \frac{\rho^0}{1+\exp[(r-R_{\mathrm{WS}})/d]}$$

$$dn_i = \frac{Z_i^2\alpha}{\pi^2}\frac{q_{i\perp}^2\left[F\left(q_{i\perp}^2+\frac{w_i^2}{\gamma^2}\right)\right]^2}{\left(q_{i\perp}^2+\frac{w_i^2}{\gamma^2}\right)^2}\frac{d^3q_i}{w_i} \qquad (1)$$

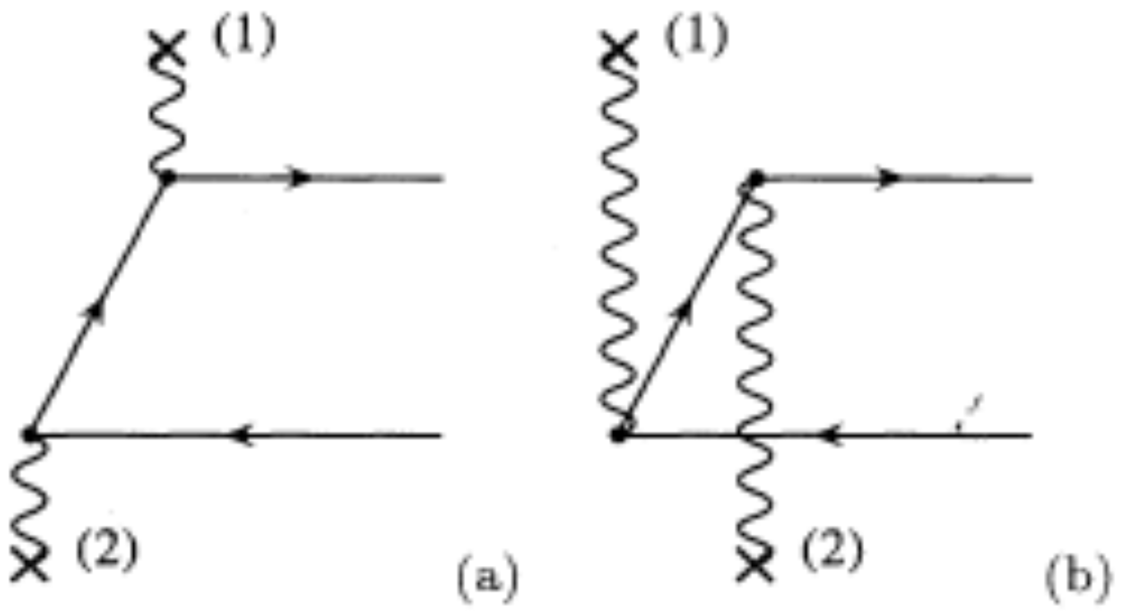


$$\sigma = 16\frac{Z^4e^4}{(4\pi)^2}\int\frac{dw_1}{w_1}\frac{dw_2}{w_2}\frac{d^2k_{1\perp}}{(2\pi)^2}\frac{d^2k_{2\perp}}{(2\pi)^2}\left|\frac{F(-k_1^2)}{k_1^2}\right|^2 \times\left|\frac{F(-k_2^2)}{k_2^2}\right|^2 k_{1\perp}^2k_{2\perp}^2\sigma(w_1,w_2) \qquad (6)$$

arXiv:1005.3531, unpublished

S. Klein, et al. Comput.Phys.Commun. 212 (2017) 258-268

Lowest-order QED calculation



$$\sigma = \int d^2b \frac{d^6P(\vec{b})}{d^3p_+d^3p_-} = \int d^2q \frac{d^6P(\vec{q})}{d^3p_+d^3p_-} \int d^2b e^{i\vec{q}\cdot\vec{b}}$$

$$\frac{d^6P(\vec{q})}{d^3p_+d^3p_-} = (Z\alpha)^4 \frac{4}{\beta^2} \frac{1}{(2\pi)^6 2\epsilon_+ 2\epsilon_-} \int d^2q_1$$
$$F(N_0)F(N_1)F(N_3)F(N_4)[N_0N_1N_3N_4]^{-1}$$
$$\times \mathrm{Tr}\{(\not{p}_- + m)[N_{2D}^{-1}\not{u}_1(\not{p}_- - \not{q}_1 + m)\not{u}_2 +$$
$$N_{2X}^{-1}\not{u}_2(\not{q}_1 - \not{p}_+ + m)\not{u}_1](\not{p}_+ - m)[N_{5D}^{-1}\not{u}_2$$
$$(\not{p}_- - \not{q}_1 - \not{q} + m)\not{u}_1 + N_{5X}^{-1}\not{u}_1(\not{q}_1 + \not{q} - \not{p}_+$$
$$+ m)\not{u}_2]\},$$

with

$$N_0 = -q_1^2, N_1 = -[q_1 - (p_+ + p_-)]^2,$$
$$N_3 = -(q_1 + q)^2, N_4 = -[q + (q_1 - p_+ - p_-)]^2,$$
$$N_{2D} = -(q_1 - p_-)^2 + m^2,$$
$$N_{2X} = -(q_1 - p_+)^2 + m^2,$$
$$N_{5D} = -(q_1 + q - p_-)^2 + m^2,$$
$$N_{5X} = -(q_1 + q - p_+)^2 + m^2,$$

Initial Transverse Momentum Broadening

$$\sigma = 16\frac{Z^4e^4}{(4\pi)^2}\int d^2b \int \frac{dw_1}{w_1}\frac{dw_2}{w_2}\frac{d^2k_{1\perp}}{(2\pi)^2}\frac{d^2k_{2\perp}}{(2\pi)^2}\frac{d^2q_\perp}{(2\pi)^2}$$
$$\times \frac{F(-k_1^2)}{k_1^2}\frac{F(-k_2^2)}{k_2^2}\frac{F^*(-k_1'^2)}{k_1'^2}\frac{F^*(-k_2'^2)}{k_2'^2}e^{-i\vec{b}\cdot\vec{q}_\perp}$$
$$\times [(\vec{k}_{1\perp}\cdot\vec{k}_{2\perp})(\vec{k}'_{1\perp}\cdot\vec{k}'_{2\perp})\sigma_s(w_1,w_2)$$
$$+ (\vec{k}_{1\perp}\times\vec{k}_{2\perp})(\vec{k}'_{1\perp}\times\vec{k}'_{2\perp})\sigma_{ps}(w_1,w_2)] \quad (2)$$

Zha, et al., arXiv: 1812.02820
M. Vidovic, et al., Phys.Rev. C47 (1993) 2308

$$\rho_A(r) = \frac{\rho^0}{1+\exp[(r-R_{\rm WS})/d]}$$

$$dn_i = \frac{Z_i^2\alpha}{\pi^2}\frac{q_{i\perp}^2\left[F\left(q_{i\perp}^2+\frac{w_i^2}{\gamma^2}\right)\right]^2}{\left(q_{i\perp}^2+\frac{w_i^2}{\gamma^2}\right)^2}\frac{d^3q_i}{w_i} \quad (1)$$

arXiv:1005.3531, unpublished

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$$\times \left|\frac{F(-k_2^2)}{k_2^2}\right|^2 k_{1\perp}^2 k_{2\perp}^2\sigma(w_1,w_2) \quad (6)$$

S. Klein, et al. Comput.Phys.Commun. 212 (2017) 258-268

Is photon pt really driven by uncertainty principle and independent of position-momentum correlation?

ω/γ≲kt<<ω
Higher-order/virtuality cancels to $1/\gamma^2$~$=10^{-4}$
NLO QED coupling constant α=1/137

Initial Transverse Momentum Broadening

$$\sigma = 16\frac{Z^4e^4}{(4\pi)^2}\int d^2b \int \frac{dw_1}{w_1}\frac{dw_2}{w_2}\frac{d^2k_{1\perp}}{(2\pi)^2}\frac{d^2k_{2\perp}}{(2\pi)^2}\frac{d^2q_\perp}{(2\pi)^2}$$
$$\times \frac{F(-k_1^2)}{k_1^2}\frac{F(-k_2^2)}{k_2^2}\frac{F^*(-k_1'^2)}{k_1'^2}\frac{F^*(-k_2'^2)}{k_2'^2}e^{-i\vec{b}\cdot\vec{q}_\perp} \quad (2)$$
$$\times \left[(\vec{k}_{1\perp}\cdot\vec{k}_{2\perp})(\vec{k}'_{1\perp}\cdot\vec{k}'_{2\perp})\sigma_s(w_1,w_2)\right.$$
$$\left.+(\vec{k}_{1\perp}\times\vec{k}_{2\perp})(\vec{k}'_{1\perp}\times\vec{k}'_{2\perp})\sigma_{ps}(w_1,w_2)\right]$$

Zha, et al., arXiv: 1812.02820
M. Vidovic, et al., Phys.Rev. C47 (1993) 2308

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arXiv:1005.3531, unpublished

$$\frac{d^2N_{\gamma\gamma}(k_1,k_2)}{dk_1dk_2} = \int\int d^2b_1d^2b_2^2P_{\rm NOHAD}(|\vec{b_1}-\vec{b_2}|)N(k_1,\vec{b}_1)N(k_2,\vec{b}_2) \quad (4)$$

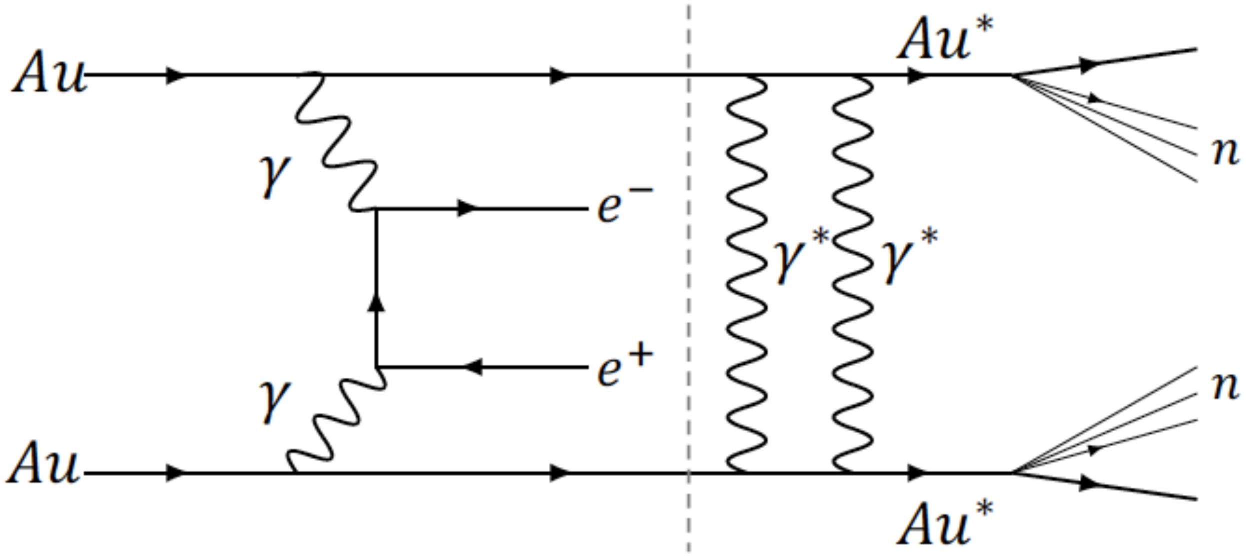
S. Klein, et al. Comput.Phys.Commun. 212 (2017) 258-268

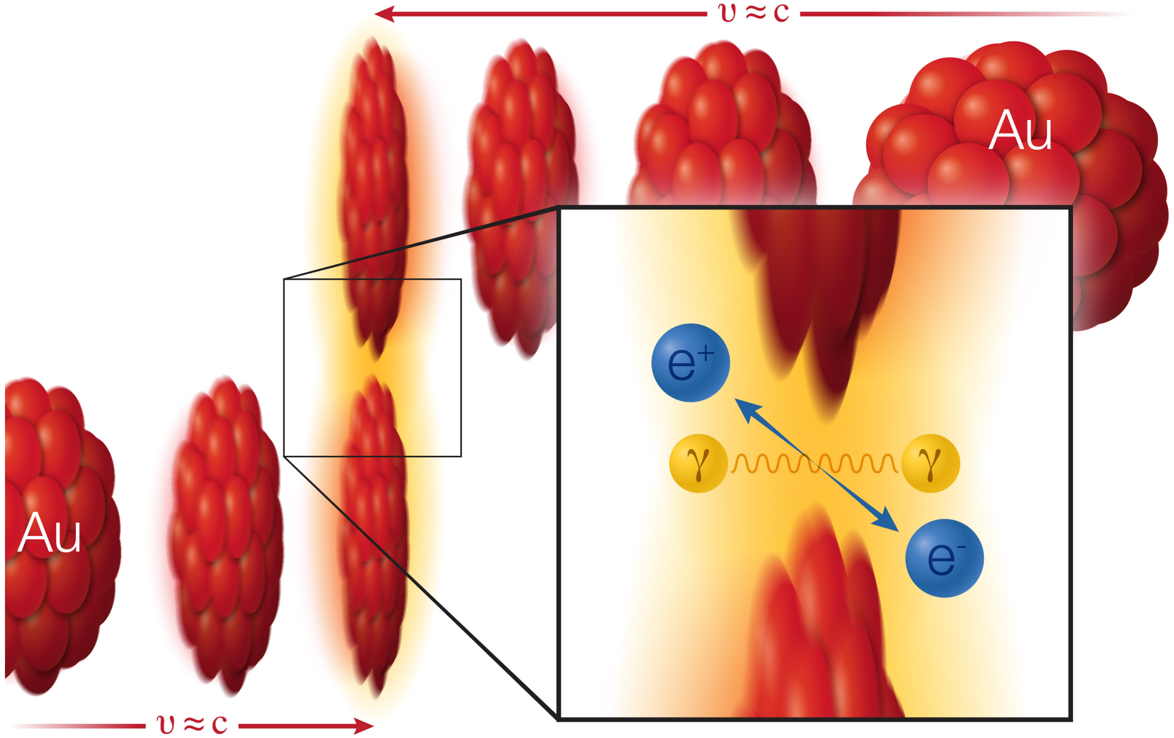
Is photon pt really driven by uncertainty principle and independent of position-momentum correlation?

we can afford many mistakes in the search. The main thing is to make them as fast as possible.
– John Archibald Wheeler
doi:10.1063/1.3120895

$\omega/\gamma \lesssim$ kt<<ω
Higher-order/virtuality cancels to $1/\gamma^2$~=10^{-4}
NLO QED coupling constant α=1/137

Ultra-Peripheral Collisions

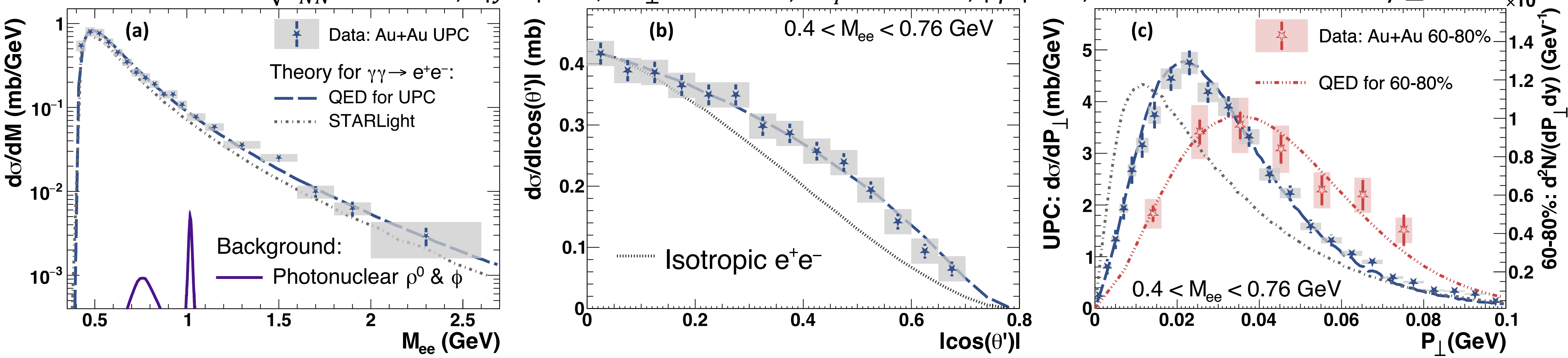




Two gold (Au) ions (red) move in opposite direction at 99.995% of the speed of light (v, for velocity, = approximately c, the speed of light). As the ions pass one another without colliding, two photons (γ) from the electromagnetic cloud surrounding the ions can interact with each other to create a matter-antimatter pair: an electron (e^-) and positron (e^+).

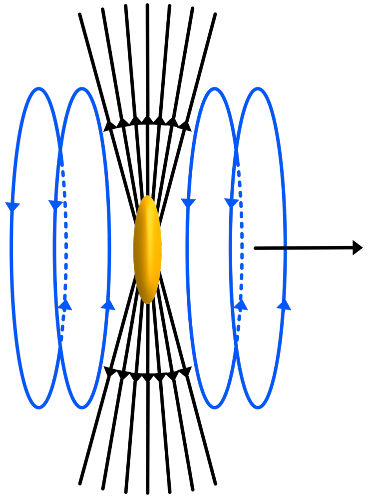
Well understood kinematics

STAR: Au+Au at $\sqrt{s_{NN}}$ = 200 GeV, $|y^{ee}| < 1$, $P_\perp < 0.1$ GeV, $P_T^e > 0.2$ GeV, $|\eta^e| < 1$, Overall scale uncertainty $\pm 13\%$



$\rho,\phi,\omega<\pm0.2\%$ $<\pm2\%$ $<\pm2\%$

photon p_T is simply due to finite electric field projection in the longitudinal direction,
It is classic EM field and not due to uncertainty principle of p_T~=1/R



E field has a z-component
B field is in x-y plane
➔
ExB has p_T component

50. STAR Collaboration, J., Adam *et al.* Probing Extreme Electromagnetic Fields with the Breit-Wheeler Process. (2019). https://arxiv.org/abs/1910.12400.

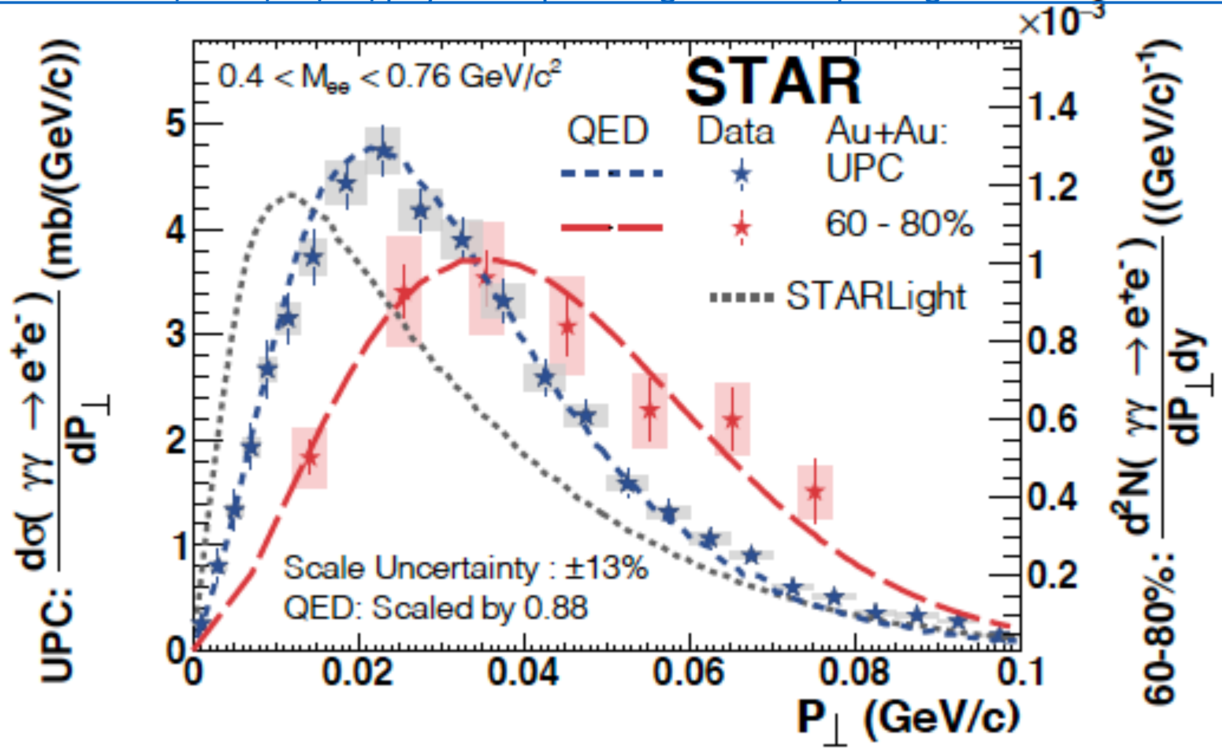
51. ATLAS Collaboration. Measurement of non-exclusive dimuon pairs produced via $\gamma\gamma$ scattering in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector. ATLAS-CONF-2019-051. (2019). https://inspirehep.net/literature/1762955.

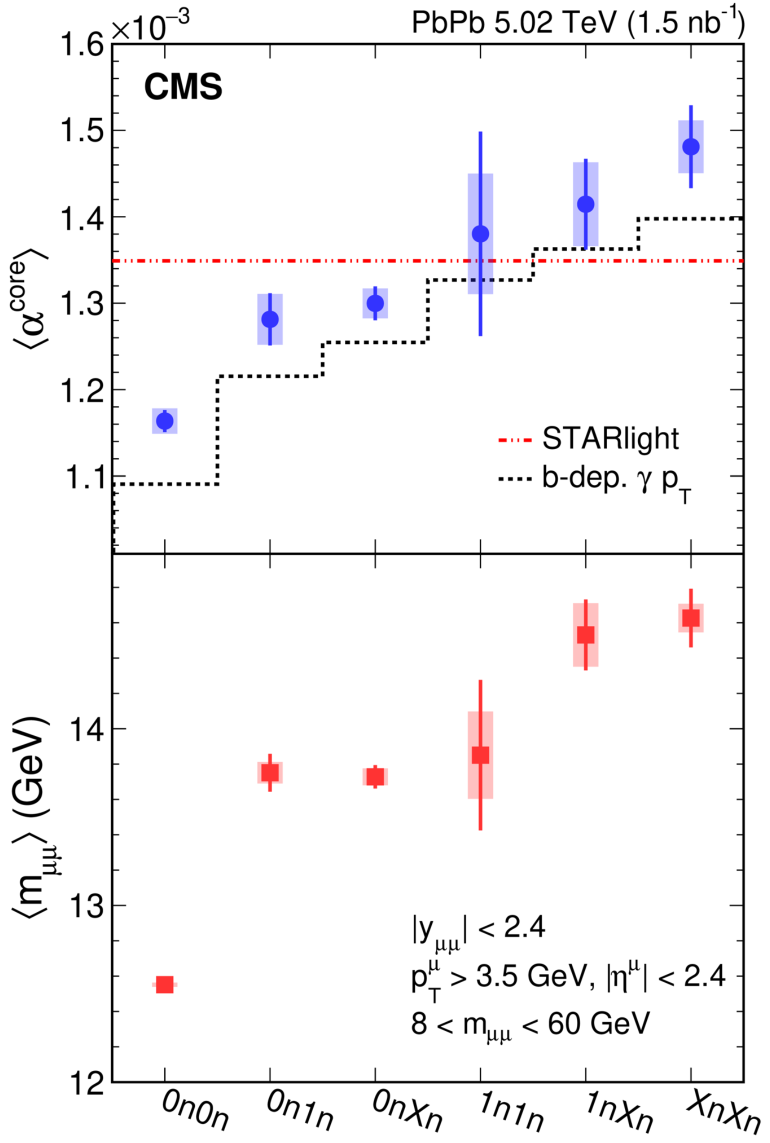
52. CMS Collaboration,. Observation of forward neutron multiplicity dependence of dimuon acoplanarity in ultra-peripheral PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV CMS-PAS-HIN-19-014. (2020). https://inspirehep.net/literature/1798862.

Photon TMD in UPC

CMS Abstract: "This observation demonstrates the transverse momentum and energy of photons emitted from relativistic ions have impact parameter dependence. These results constrain precision modeling of initial photon-induced interactions in ultra-peripheral collisions. They also provide a controllable baseline to search for possible final-state effects on lepton pairs resulting from the production of quark-gluon plasma in hadronic heavy ion collisions."

https://news.rice.edu/2021/09/20/physicists-probe-light-smashups-to-guide-future-research-2/





Criteria of a Breit-Wheeler process

2310 **M. VIDOVIĆ, MARTIN GR**

be interpreted as a transition current,

$$J_{\mu\nu}(k_1k_2;P\alpha)=\Gamma_{\mu\nu}(k_1k_2;\alpha)\,(2\pi)^4\delta^4(k_1+k_2-P)\quad, \tag{7}$$

so that the S-matrix element (4) may be written as

$$S(P\alpha,\mathbf{b})=\int\frac{d^4k_1}{(2\pi)^4}\int\frac{d^4k_2}{(2\pi)^4}\,A_1^\mu(k_1,\mathbf{b})\,A_2^\nu(k_2,0)\times J_{\mu\nu}(k_1k_2;P\alpha)\,. \tag{8}$$

The transition current is conserved, i.e.,

$$k_1^\mu J_{\mu\nu}=k_2^\nu J_{\mu\nu}=0\quad, \tag{9}$$

which follows quite generally from the gauge invariance of the S-matrix element.

For our following considerations the explicit expression for the transition current is irrelevant; it is only important that it acts like a conserved current (9) and contains a δ function (7) for the four-momentum conservation.

Performing the integrals over the δ functions, Eq. (8) becomes, with $Z_1=Z_2=Z$ and $F_1=F_2=F$,

$$S(P\alpha;\mathbf{b})=Z^2\frac{e^2}{2\gamma^2}\int\frac{d^2k_\perp}{(2\pi)^2}\,\frac{F(-k_1^2)}{-k_1^2}\,\frac{F(-k_2^2)}{-k_2^2}\times u_{1\mu}u_{2\nu}\Gamma^{\mu\nu}(k_1k_2;\alpha)\,e^{-i\mathbf{b}\cdot\mathbf{k}_\perp}\,, \tag{10}$$

Vidovic *et al.*, PRC 1993

The nuclei move on straight trajectories and thus $k_z/k^0=\pm1/v$, confer Eq. (11). We obtain

$$u_{1\mu}u_{2\nu}J^{\mu\nu}=\gamma^2\frac{k_{1i}}{k_{10}}\frac{k_{2j}}{k_{20}}J^{ij}+\frac{1}{v}\left(\frac{k_{2j}}{k_{20}}J^{3j}-\frac{k_{1i}}{k_{10}}J^{i3}\right)-\frac{1}{\gamma^2v^2}J^{33}\quad. \tag{25}$$

Precisely at this point we introduce the decisive approximations, which will lead to the equivalent photon result. The term ω/γ, which corresponds to k_0/γ or k_3/γ, is of the same order of magnitude as the term $|\mathbf{k}_\perp|$, which corresponds to k_i:

$$|\mathbf{k}_\perp|\approx\frac{1}{\gamma}|\mathbf{k}_\parallel|\approx\frac{\omega}{\gamma}\quad. \tag{26}$$

This can be verified by considering those values of $|\mathbf{k}_\perp|$, which contribute most in the integrand of the equivalent photon distribution (2). The same relation also holds, if one compares the transverse component of the Poynting vector to its longitudinal one.

For the scalar boson the dominant contribution in Eq. (25) originates from the first term; the second and third terms are suppressed by a factor of $1/\gamma^2$ with respect to the first one. The situation for the pseudoscalar boson (6), the charged boson pair, and the fermion pair is exactly the same.

ER, C. BEST, AND G. SOFF 47

$$u_{1\mu}u_{2\nu}\Gamma^{\mu\nu}(k_1k_2;\alpha)\approx\gamma^2\frac{k_{1i}}{\omega_1}\frac{k_{2j}}{\omega_2}\Gamma^{ij}(\omega_1\omega_2;\alpha). \tag{28}$$

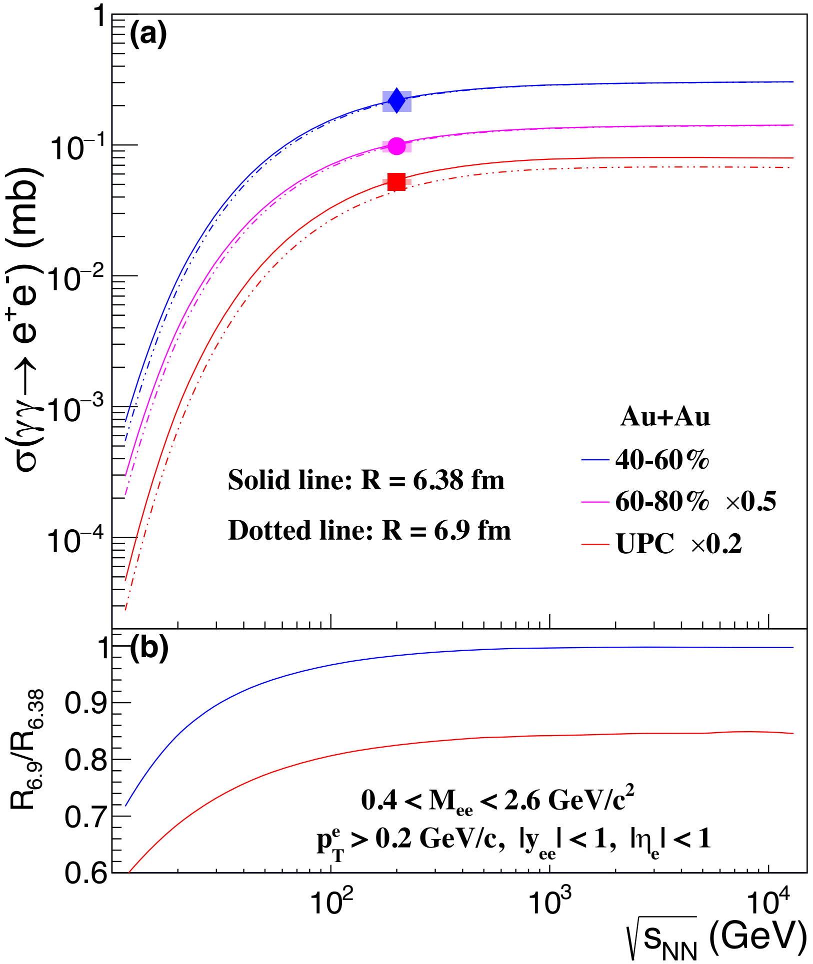
On the right-hand side now appears the vertex function for real photons as in (19). This identification is the heart of the equivalent photon approach.

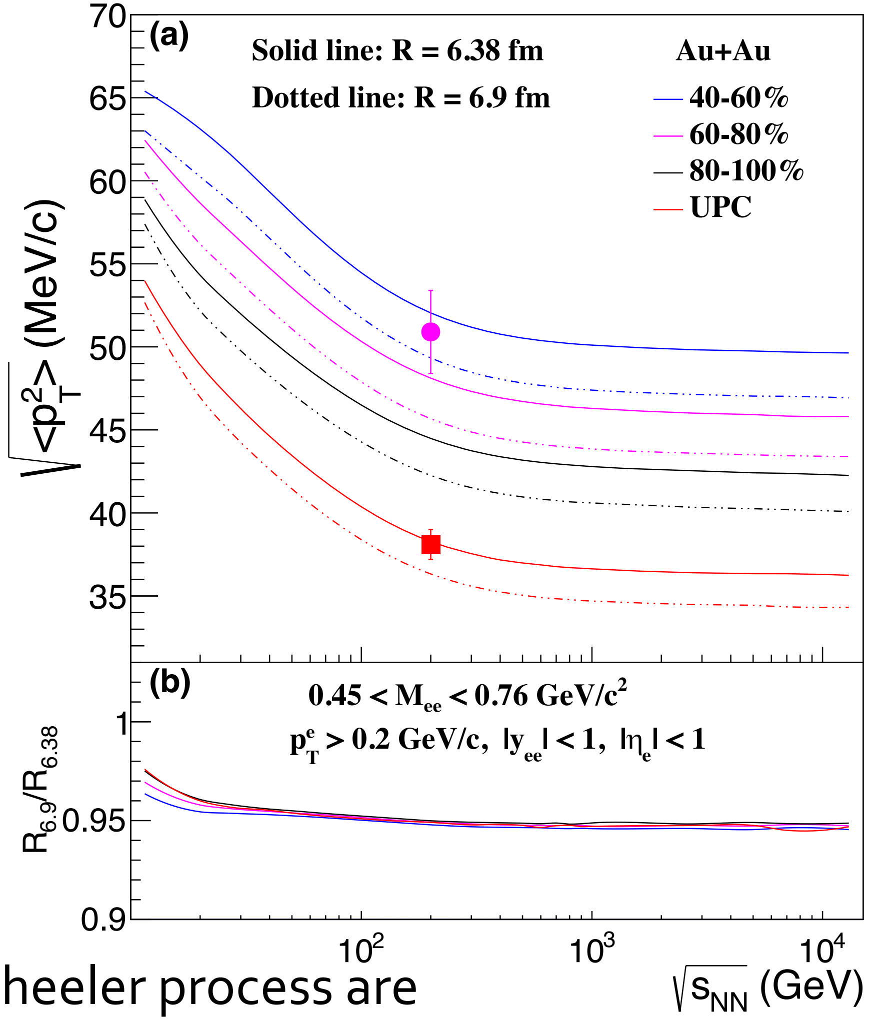
To qualify as a Breit-Wheeler process from Coulomb field:

$$\boxed{\omega/\gamma\lesssim k_\perp\lesssim 1/R\ll\omega}$$

X.F. Wang *et al.*, PRC 2023

Energy Dependence of Cross Section and $\sqrt{\langle p_T^2 \rangle}$





The kinematics of the Breit-Wheeler process are **sensitive** to the details of the **nuclear charge distribution**

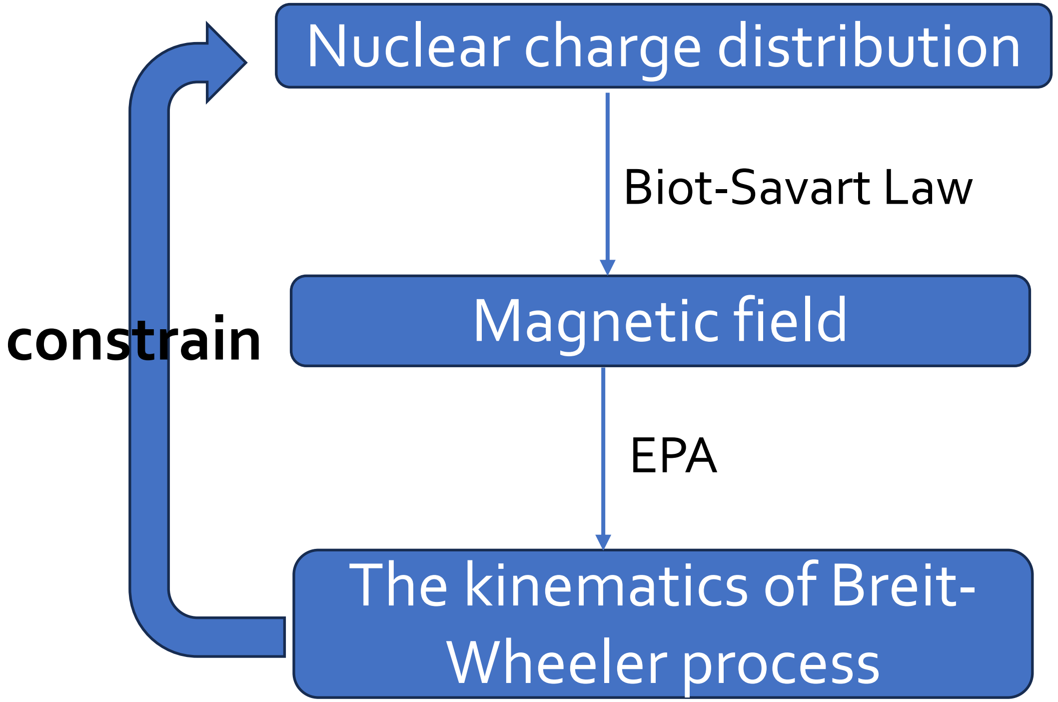
X. W, J.D. Brandenburg, L. Ruan, F. Shao, Z. Xu, C. Yang, and W. Zha. Phys. Rev. C 107, 044906 (2023)

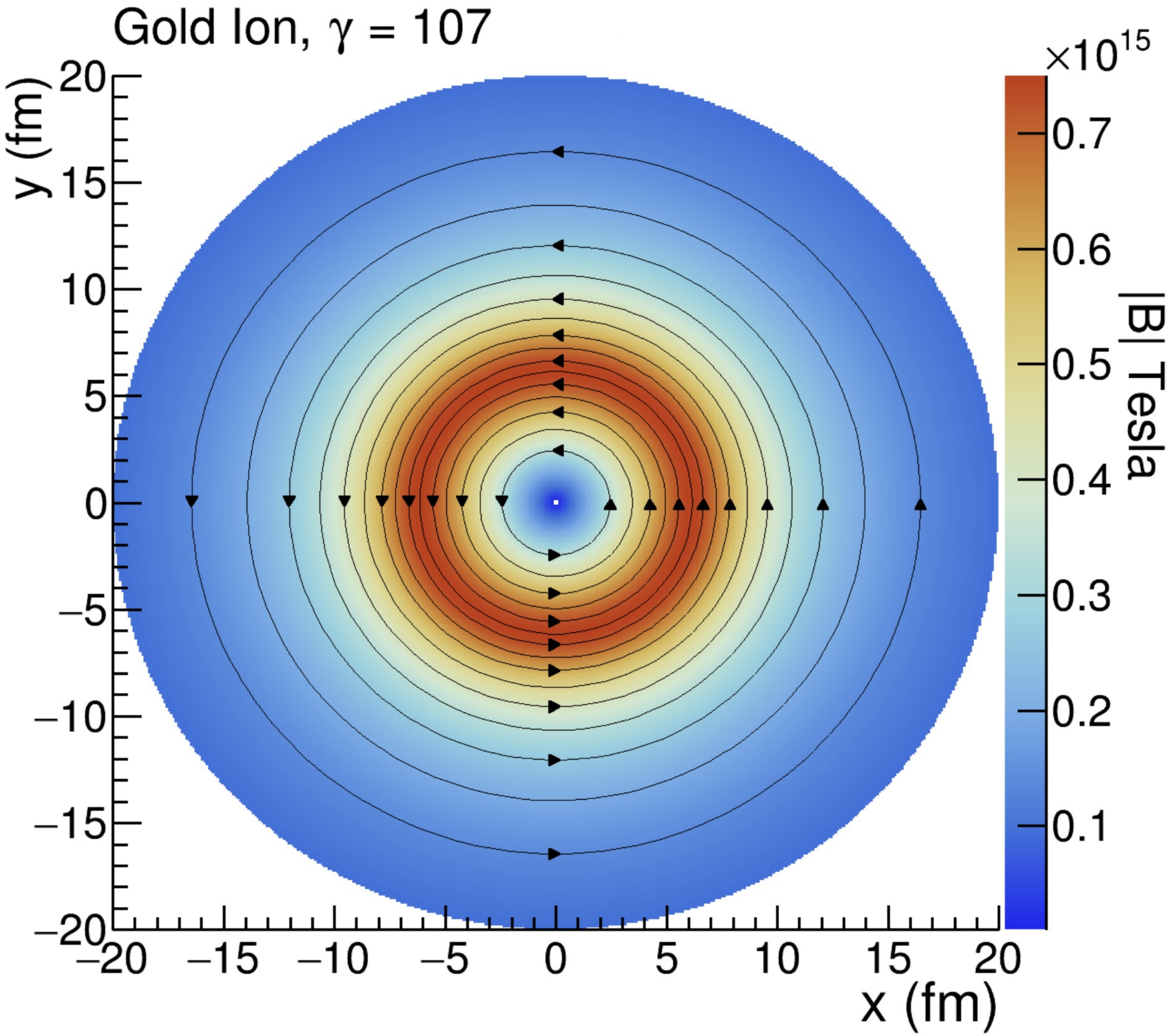
Application: Mapping the Magnetic Field

R. D. Woods and D. S. Saxon, Phys. Rev. 95, 577–578 (1954)

Woods-Saxon: $$\rho_A(r) = \frac{\rho^0}{1 + \exp[(r - R)/d]}$$

R: charge radius, d: skin depth





Constraint on charge distribution with precision

Using LO QED to calculate Breit-Wheeler process to match data with least-chi2

UPC consistent with nominal nuclear geometry

Peripheral collisions systematically larger

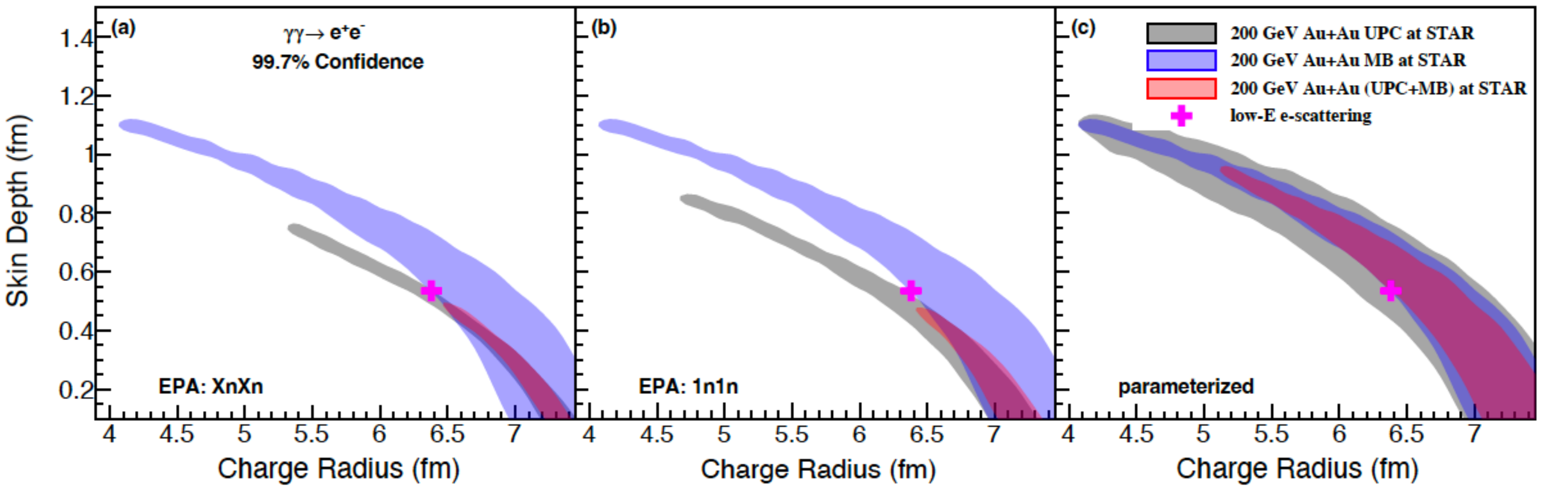


FIG. 5. (color online) The constraints on gold nuclear charge distribution obtained by the comparison ent of $\gamma\gamma \to e^+e^-$ and the lowest order QED calculation for different neutron C and parameterized probability, (a), (b), and (c) are for XnXn, 1n1n, and , respectively.

TABLE I. RMS of radius ($\sqrt{\langle r^2 \rangle}$) at minimum χ^2 (χ^2_{min}) and uncertainties within $\chi^2_{min}+1$ with different σ_{NN} and with different neutron selection conditions in ZDC and parameterized probability. A default $\sigma_{NN}=41.6$ mb has been used in all other calculations. These are to be compared to the default value of nuclear charge radius RMS of $\sqrt{\langle r^2 \rangle}=5.33$ fm at $R=6.38$ fm and $d=0.535$ fm.

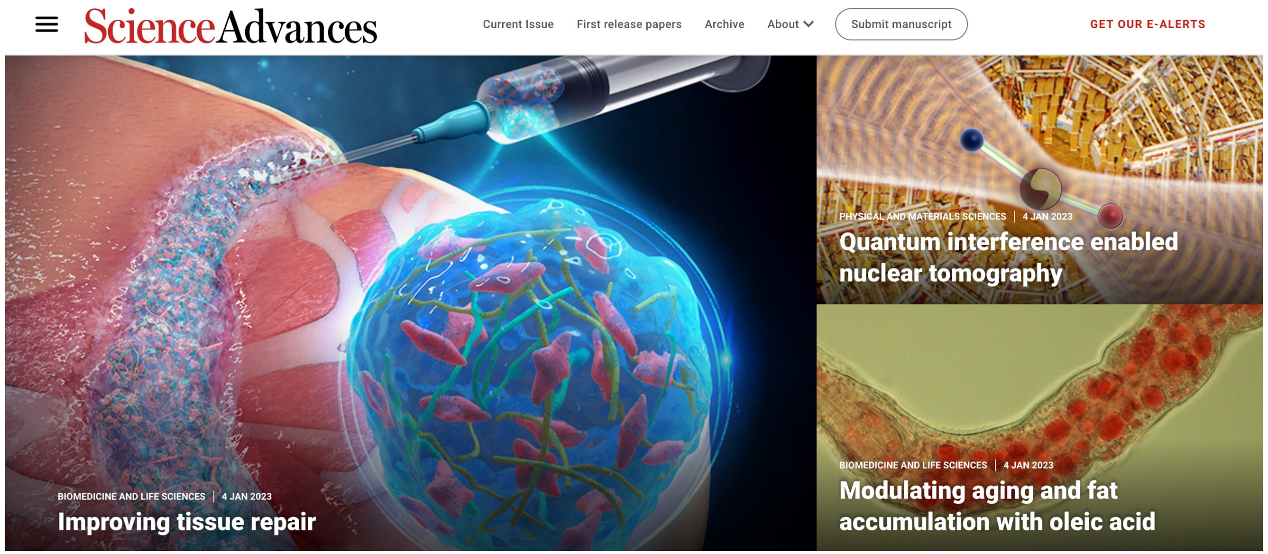
condition	σ_{NN} (mb)	UPC	MB	UPC+MB
1n1n	35.0	5.55 + 0.03 - 0.30	5.66 + 0.09 - 0.12	5.55 + 0.03 - 0.03
	40.0	5.32 + 0.26 - 0.21	5.67 + 0.08 - 0.10	5.58 + 0.01 - 0.04
	41.6	5.39 + 0.14 - 0.21	5.67 + 0.08 - 0.12	5.53 + 0.10 - 0.02
	45.0	5.47 + 0.02 - 0.21	5.66 + 0.09 - 0.11	5.54 + 0.08 - 0.03
XnXn	35.0	5.70 + 0.01 - 0.29	5.66 + 0.09 - 0.12	5.64 + 0.07 - 0.07
	40.0	5.70 + 0.01 - 0.30	5.67 + 0.08 - 0.10	5.70 + 0.01 - 0.12
	41.6	5.67 + 0.03 - 0.17	5.67 + 0.08 - 0.12	5.67 + 0.03 - 0.09
	45.0	5.54 + 0.17 - 0.16	5.66 + 0.09 - 0.11	5.64 + 0.06 - 0.11
Parameterized	35.0	5.51 + 0.15 - 0.18	5.66 + 0.09 - 0.12	5.61 + 0.13 - 0.11
	40.0	5.43 + 0.22 - 0.08	5.67 + 0.08 - 0.10	5.67 + 0.04 - 0.16
	41.6	5.41 + 0.25 - 0.09	5.67 + 0.08 - 0.12	5.62 + 0.12 - 0.11
	45.0	5.40 + 0.23 - 0.17	5.66 + 0.09 - 0.11	5.62 + 0.09 - 0.11

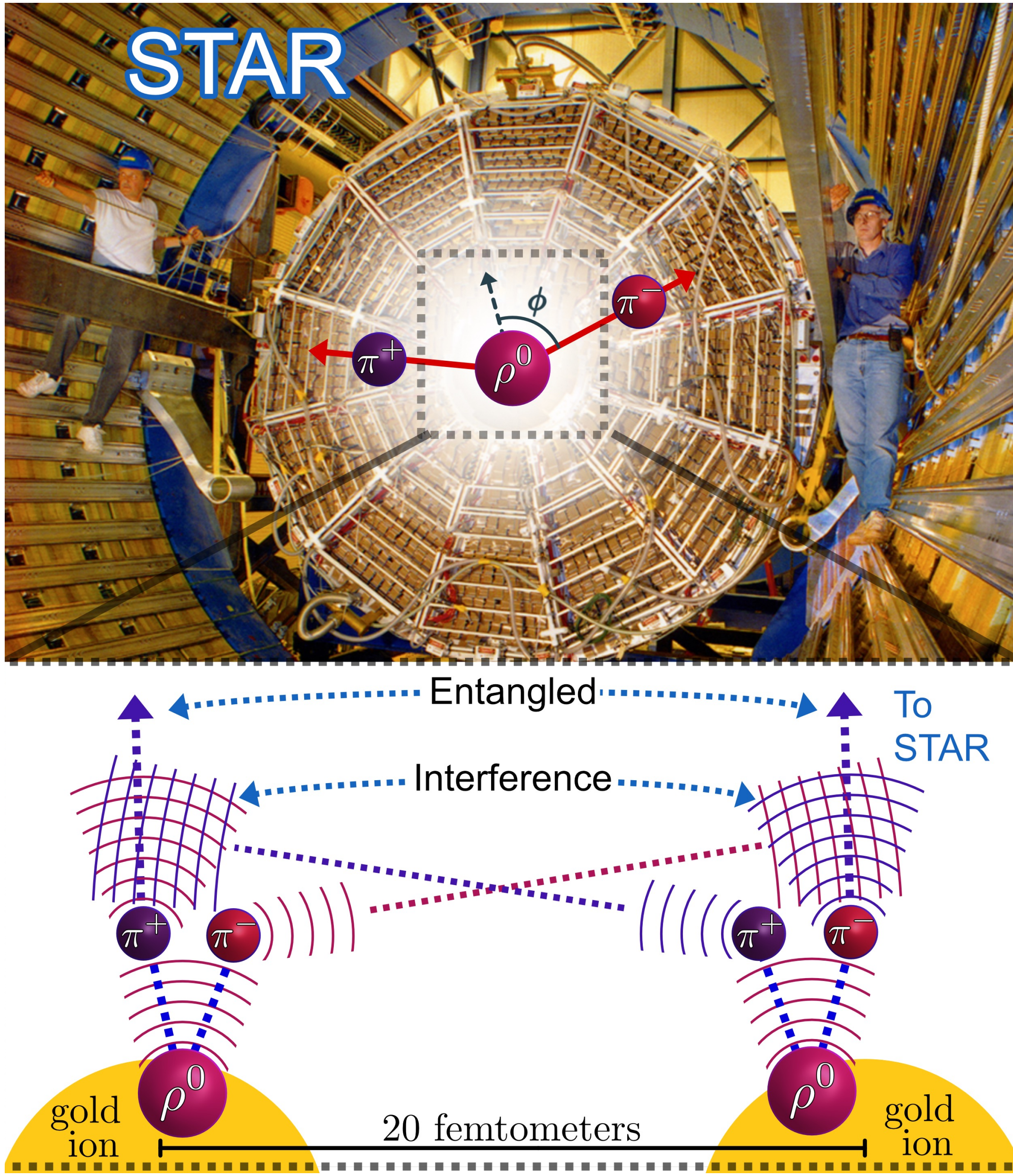
X.F. Wang, arXiv:2207.05595

Spin Interference Enabled Nuclear Tomography

STAR, arXiv:2204.01625

- Teaser:
  Polarized photon-gluon fusion reveals quantum wave interference of non-identical particles and shape of high-energy nuclei



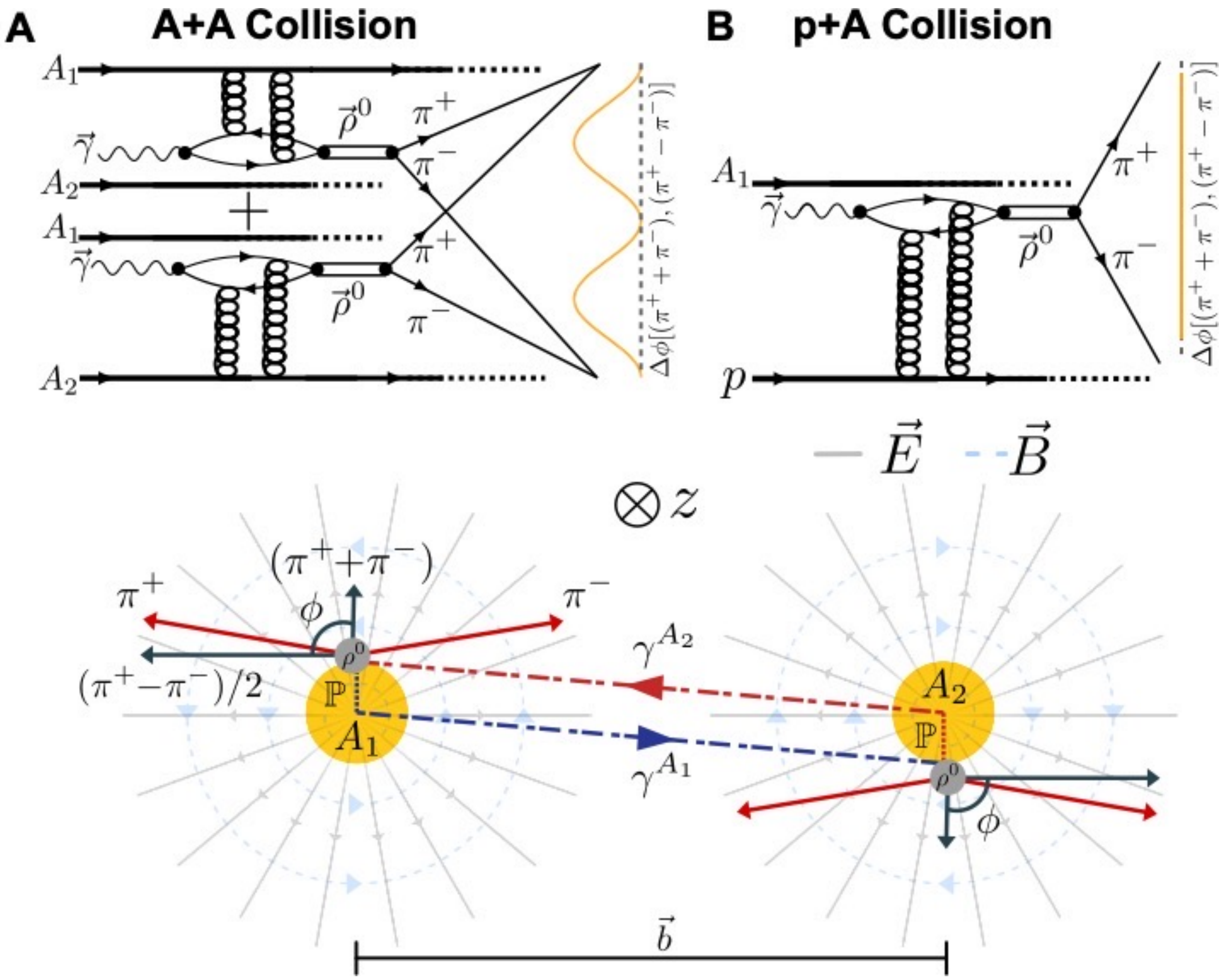


Three Ingredients

- Linearly Polarized photoproduction of vector meson
- At a distance with two wavefunctions (180º rotation symmetry)
- Entanglement between $\pi^{\pm}$ from ρ decay and interference between identical pion wavefunction

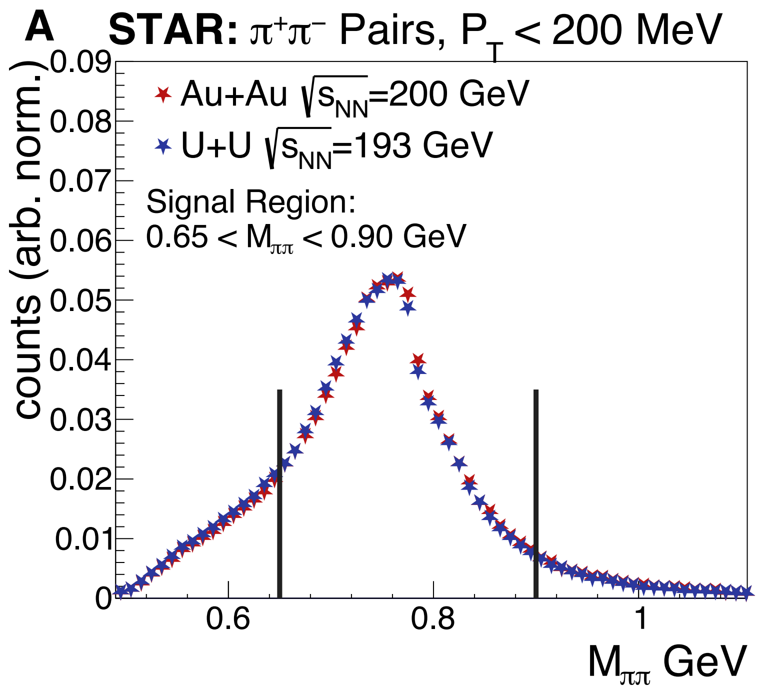
IF I have said that this is what reality is without any experimental evidence, most people would have thought that I am crazy.

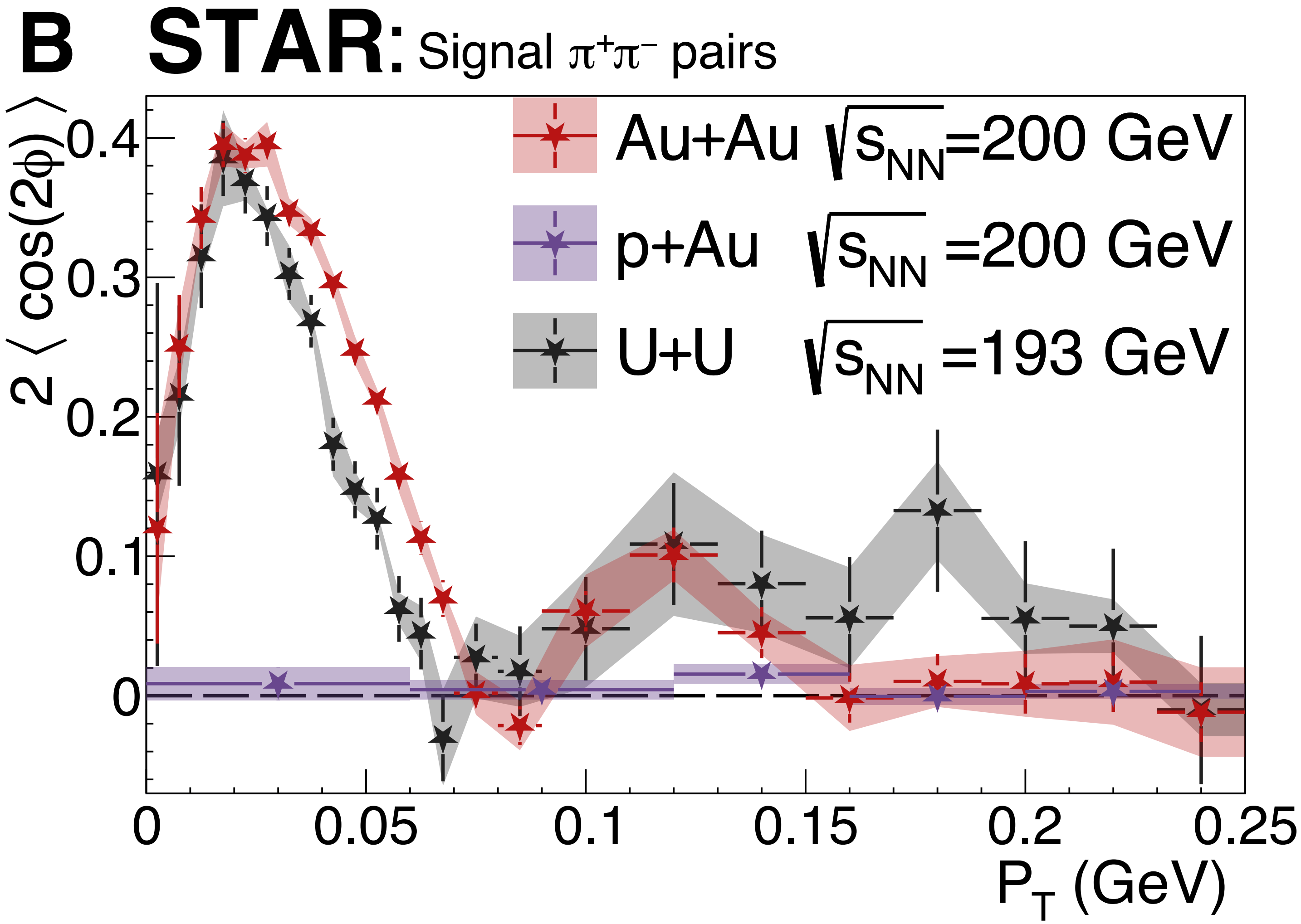
"Truth is Stranger than Fiction,
but it is because Fiction is obligated
to stick to possibilities; Truth isn't."
– Mark Twain



查王妹，周剑等原创性的理论模型

$\Delta\phi$ in Au+Au and U+U Collisions





Quantify the difference in strength for Au+Au vs. U+U via a fit:

$$f(\Delta\phi) = 1 + a\ \cos 2\Delta\phi$$

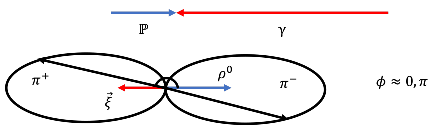
Au+Au : $a = 0.292 \pm 0.004$ (stat) ± 0.004 (syst.)
U+U : $a = 0.237 \pm 0.006$ (stat) ± 0.004 (syst.)
Difference of 4.3σ (stat. & syst.):

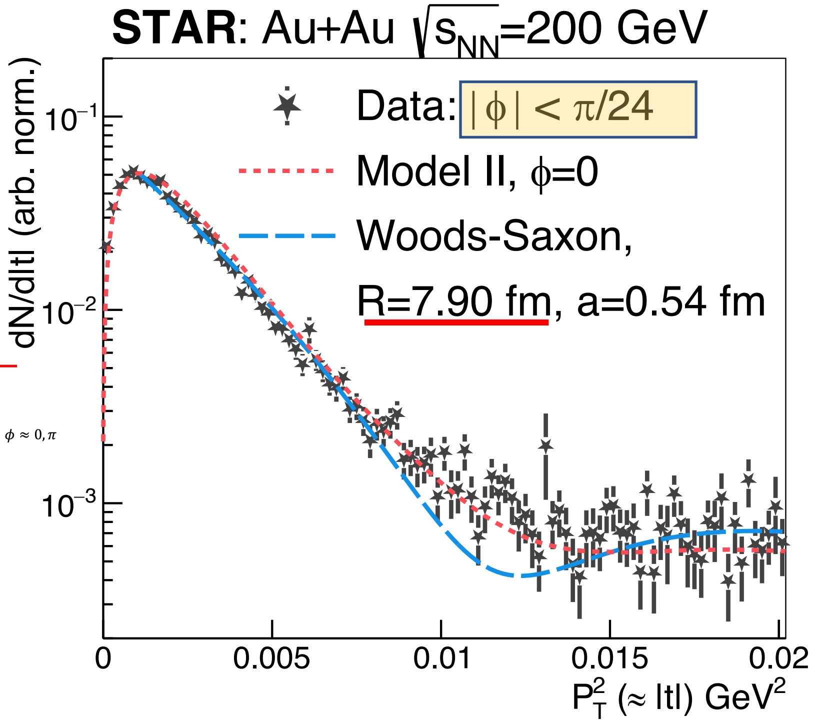
arXiv:2204.01625

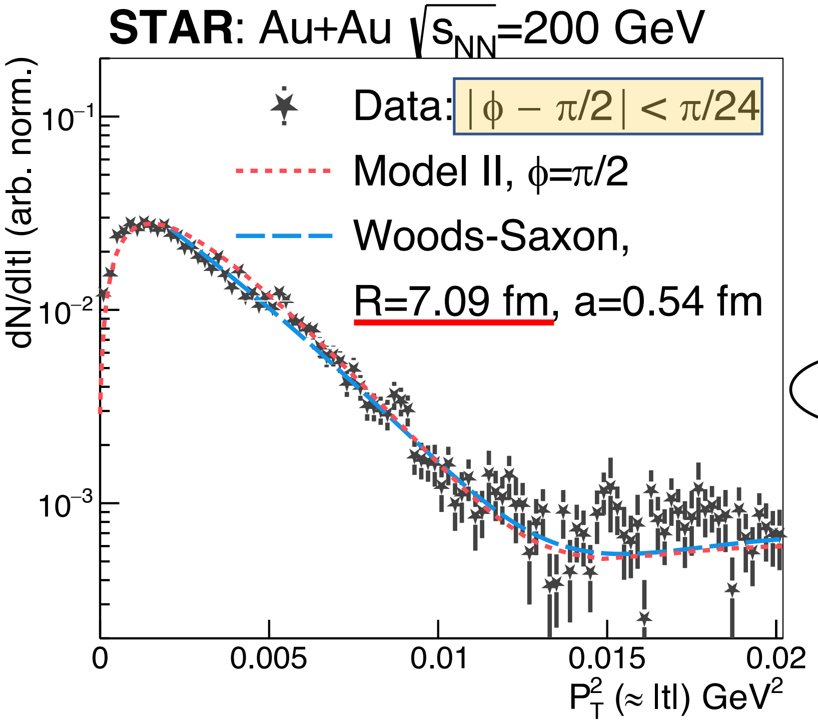
- Interference effect is sensitive to the nuclear geometry (gluon distribution) – difference between Au and U

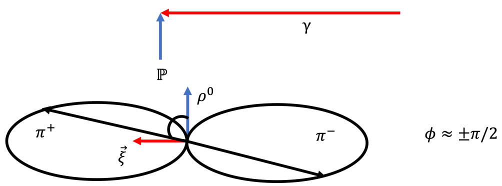
Different radius from different angle?

Now instead of p_x and p_y lets look at $|t|$ with a 2D approach









- Drastically different radius depending on ϕ, still way too big
- Notice how much better the Woods-Saxon dip is resolved for $\phi = \pi/2$ -> experimentally able to **remove photon momentum, which blurs diffraction pattern**
- **Can we extract the 'true' nuclear radius from |t| vs. ϕ inforn**

arXiv:2204.01625

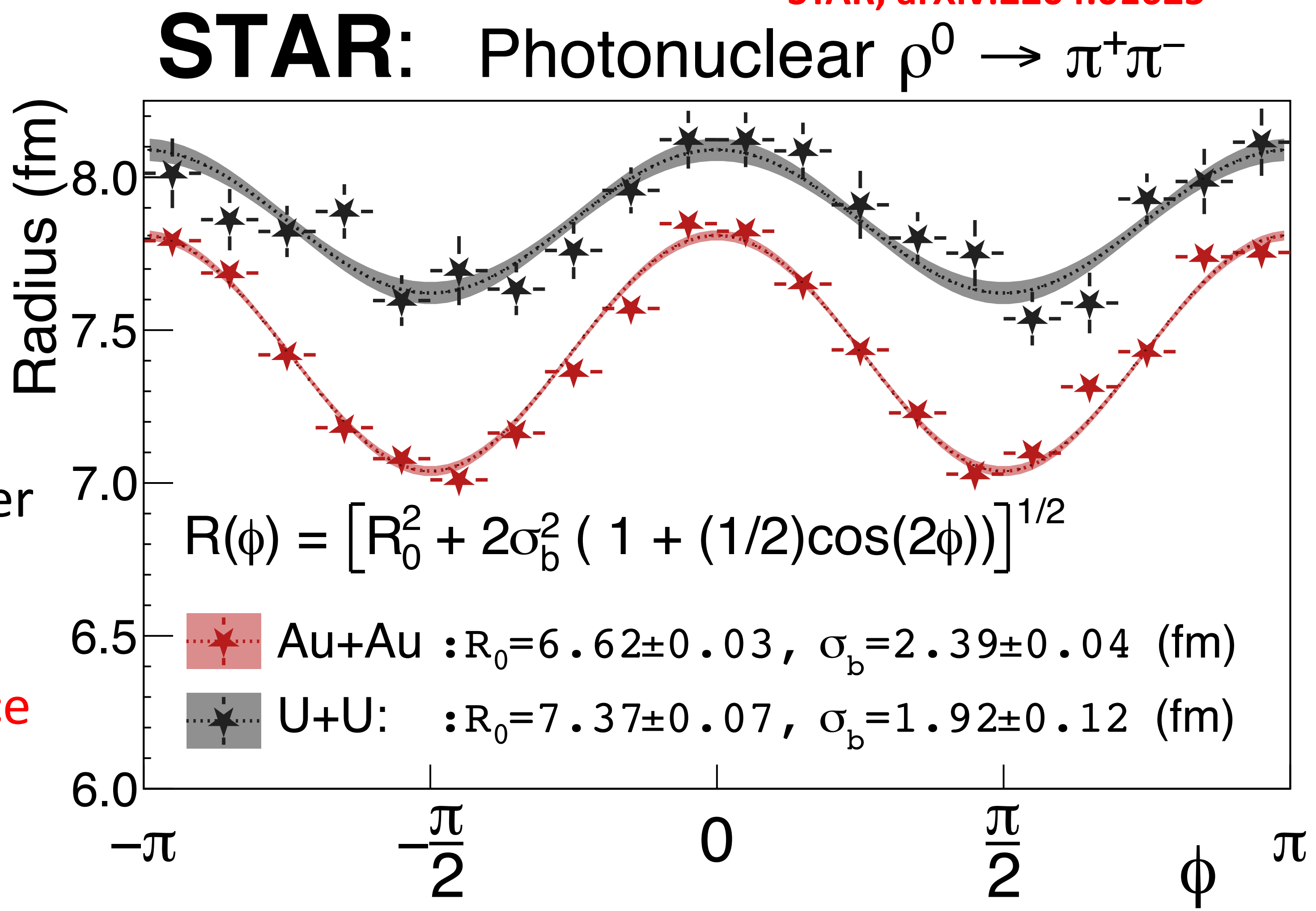
Precision radius measurement with interference

Azimuthal variation due to:

- Photon linear polarization,
- Spin transfer to VM
- Photon finite k_T
- VM spin 1 decay to spin 0 pions
- Interference along impact parameter

These image blurring effects can be improved with the angular dependence

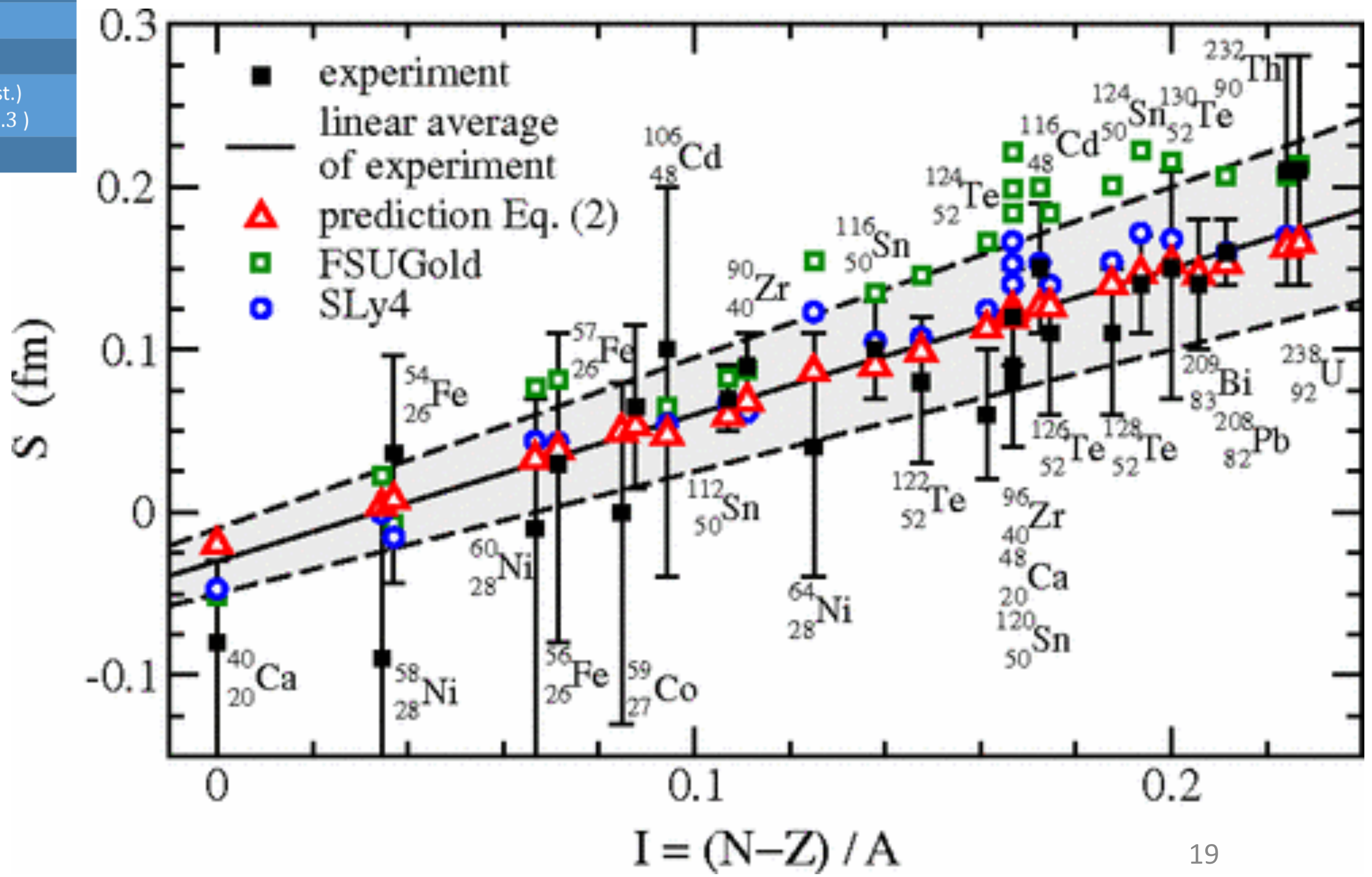
STAR, arXiv:2204.01625



Extracted neutron skins and comparison to world data

	Au+Au (fm)	U+U (fm)
Charge Radius	6.38 (long: 6.58, short: 6.05)	6.81 (long: 8.01, short: 6.23)
Inclusive |t| slope (STAR 2017) [1]	7.95 ± 0.03	--
Inclusive |t| slope (WSFF fit)*	7.47 ± 0.03	7.98 ± 0.03
Tomographic technique*	6.53 ± 0.03 (stat.) ± 0.05 (syst.)	7.29 ± 0.06 (stat.) ± 0.05 (syst.)
DESY [2]	6.45 ± 0.27	6.90 ± 0.14
Cornell [3]	6.74 ± 0.06	--
Neutron Skin (Tomographic Technique)*	0.17 ± 0.03(stat.) ± 0.08(syst.) $\sim 2\sigma$	0.44 ± 0.05 (stat.) ± 0.08 (syst.) $\sim 4.7\sigma$ (Note: for Pb $\approx$ 0.3)

M. Centelles, X. Roca-Maza, X. Viñas, and M. Warda
Phys. Rev. Lett. **102**, (2009) 122502



GIULIANO GIACALONE, July 22, 2022

$$\Delta r_{np} = 0.283 \pm 0.071 \text{ fm}$$

$$L = (106 \pm 37) \text{ MeV}$$

[PREX-II experiment,
PRL **126** (2021) 17, 172502]

Stiffer EoS than expected.

[Reed et al., PRL **126** (2021) 17, 172503]
[Fattoyev et al., PRL **120** (2018) 17, 172702]

From GW170817

of $\Lambda_{1.4} \lesssim 580$ [44], we eagerly await the next generation of terrestrial experiments and astronomical observations to verify whether the tension remains. If so, the softening of the EOS at intermediate densities, together with the subsequent stiffening at high densities required to support massive neutron stars, may be indicative of a phase transition in the stellar core [42].

Can we get an independent estimate at RHIC?

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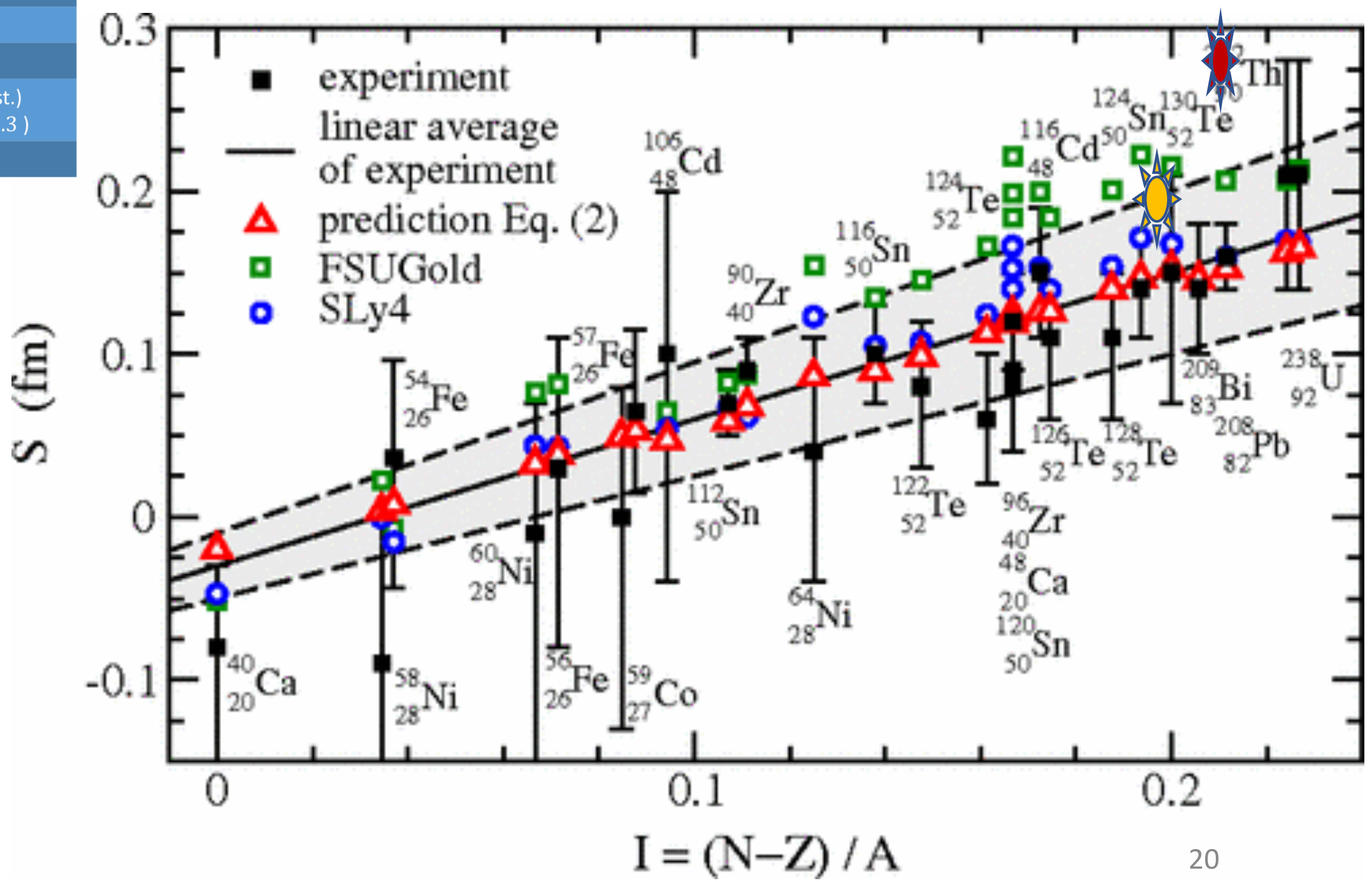


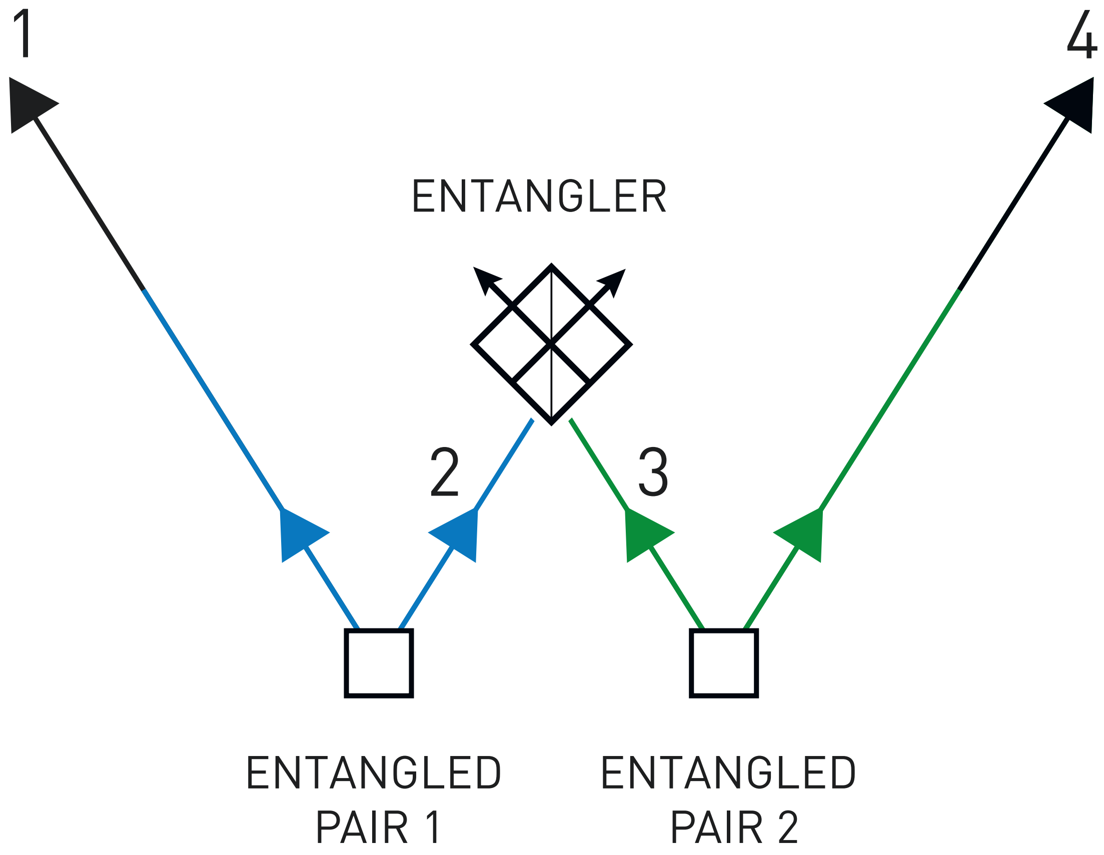
Can we get an independent estimate at RHIC?

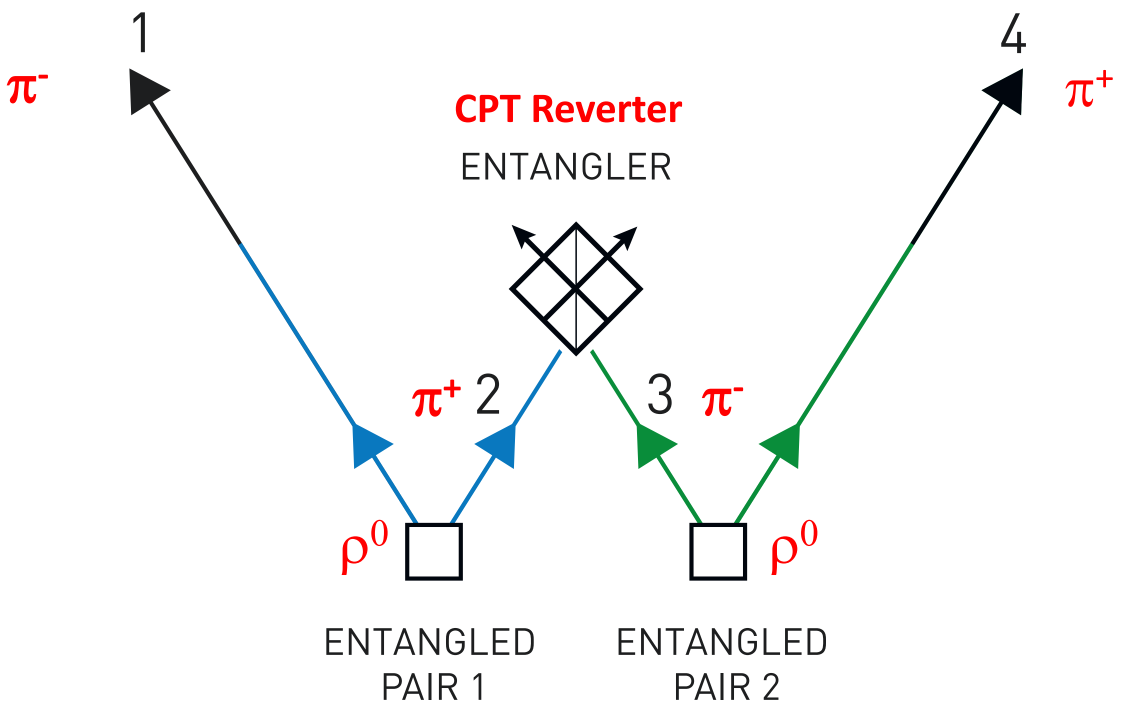
Entangled particles that never met

Two pairs of entangled particles are emitted from different sources. One particle from each pair is brought together in a special way that entangles them. The two other particles (1 and 4 in the diagram) are then also entangled. In this way, two particles that have never been in contact can become entangled.

Since π^+ and π^- are particle and antiparticle of each other, their wavefunctions could "annihilate"?

Nobel Prize in Physics 2022





Entangled particles that never met

Two pai ... ces. One particle
from ea ... s them. The two
other pa ... In this way, two
particle

$$|\pi^-\rangle = |\pi_1^-\rangle e^{i\phi_1} + |\pi_2^-\rangle e^{i\phi_2}$$

$$|\pi^+\rangle = |\pi_1^+\rangle e^{i\phi_1} + |\pi_2^+\rangle e^{i\phi_2}$$

$$|\pi^-\rangle|\pi^+\rangle = \left(|\pi_1^-\rangle e^{i\phi_1} + |\pi_2^-\rangle e^{i\phi_2}\right)\left(|\pi_1^+\rangle e^{i\phi_1} + |\pi_2^+\rangle e^{i\phi_2}\right)$$

$$= \left(|\pi_1^-\rangle|\pi_1^+\rangle e^{i2\phi_1} + |\pi_2^-\rangle|\pi_2^+\rangle e^{i2\phi_2} + |\pi_1^-\rangle|\pi_2^+\rangle e^{i(\phi_1+\phi_2)} + |\pi_2^-\rangle|\pi_1^+\rangle e^{i(\phi_1+\phi_2)}\right)$$

$$\left(\langle\pi^-|\langle\pi^+|\right)\left(|\pi^-\rangle|\pi^+\rangle\right)$$

$$= \left(\langle\pi_1^-|\langle\pi_1^+| e^{-i2\phi_1} + \langle\pi_2^-|\langle\pi_2^+| e^{-i2\phi_2} + \langle\pi_1^-|\langle\pi_2^+| e^{-i(\phi_1+\phi_2)} + \langle\pi_2^-|\langle\pi_1^+| e^{-i(\phi_1+\phi_2)}\right)$$

$$\left(|\pi_1^-\rangle|\pi_1^+\rangle e^{i2\phi_1} + |\pi_2^-\rangle|\pi_2^+\rangle e^{i2\phi_2} + |\pi_1^-\rangle|\pi_2^+\rangle e^{i(\phi_1+\phi_2)} + |\pi_2^-\rangle|\pi_1^+\rangle e^{i(\phi_1+\phi_2)}\right)$$

$$= \langle\pi_1^-|\pi_1^-\rangle\langle\pi_1^+|\pi_1^+\rangle + \langle\pi_2^-|\pi_2^-\rangle\langle\pi_2^+|\pi_2^+\rangle$$

$$+ \langle\pi_1^-|\pi_1^-\rangle\langle\pi_2^+|\pi_2^+\rangle + \langle\pi_1^-|\pi_2^-\rangle\langle\pi_2^+|\pi_1^+\rangle$$

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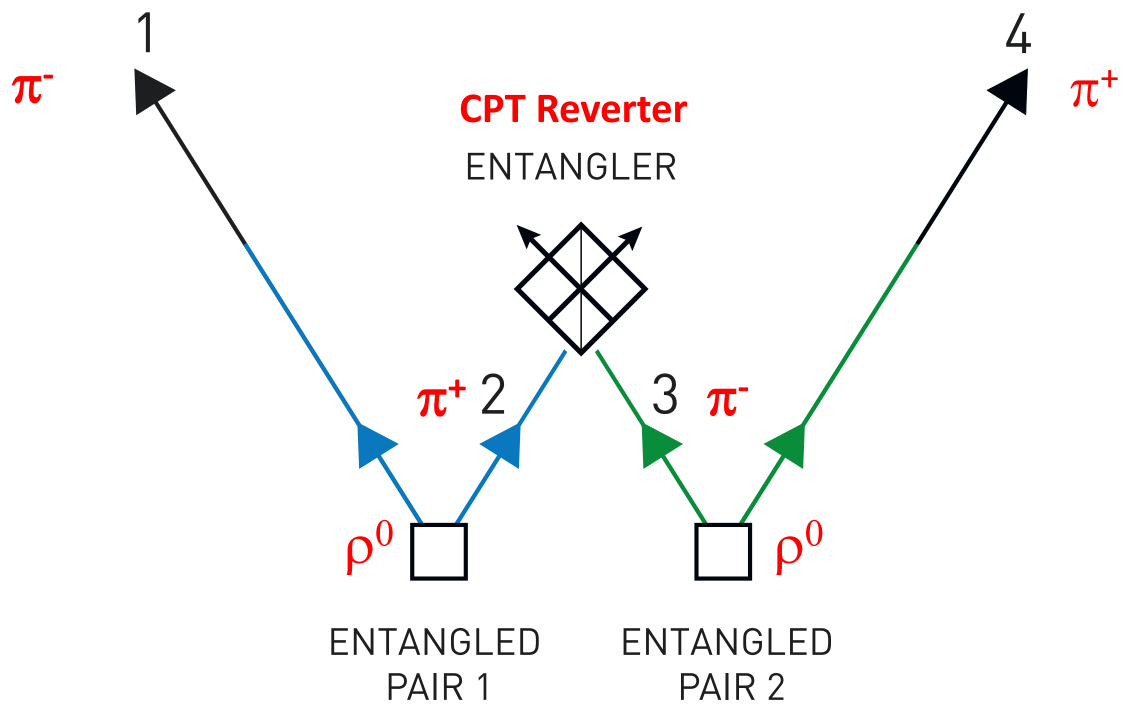

Entangled particles that never met

Two p … es. One particle
from … s them. The two
other … n this way, two
partic

1

$$\langle\pi^+|\langle\pi^-|\pi^-\rangle|\pi^+\rangle =$$

$$|f_{a+}|^2\langle\pi_a^+|\pi_a^+\rangle|f_{a-}|^2\langle\pi_a^-|\pi_a^-\rangle +$$
$$|f_{a+}|^2\langle\pi_a^+|\pi_a^+\rangle f_{a-}^* f_{b-}\langle\pi_a^-|\pi_b^-\rangle e^{-i\psi_a^-}e^{i\psi_b^-} +$$
$$f_{a+}^* f_{b+}\langle\pi_a^+|\pi_b^+\rangle e^{-i\psi_a^+}e^{i\psi_b^+}|f_{a-}|^2\langle\pi_a^-|\pi_a^-\rangle +$$
$$f_{a+}^* f_{b+}\langle\pi_a^+|\pi_b^+\rangle e^{-i\psi_a^+}e^{i\psi_b^+} f_{a-}^* f_{b-}\langle\pi_a^-|\pi_b^-\rangle e^{-i\psi_a^-}e^{i\psi_b^-}$$
$$+$$
$$|f_{a+}|^2\langle\pi_a^+|\pi_a^+\rangle f_{b-}^* f_{a-}\langle\pi_b^-|\pi_a^-\rangle e^{-i\psi_b^-}e^{i\psi_a^-} +$$
$$\underline{|f_{a+}|^2\langle\pi_a^+|\pi_a^+\rangle|f_{b-}|^2\langle\pi_b^-|\pi_b^-\rangle} +$$
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$$+$$
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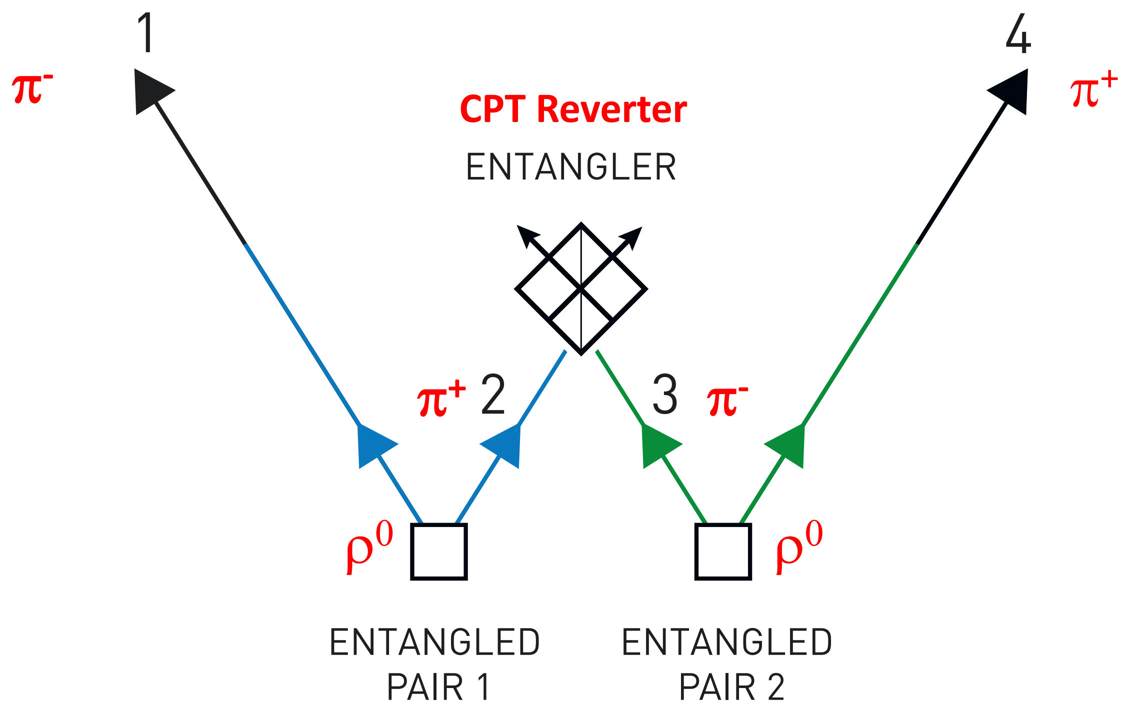

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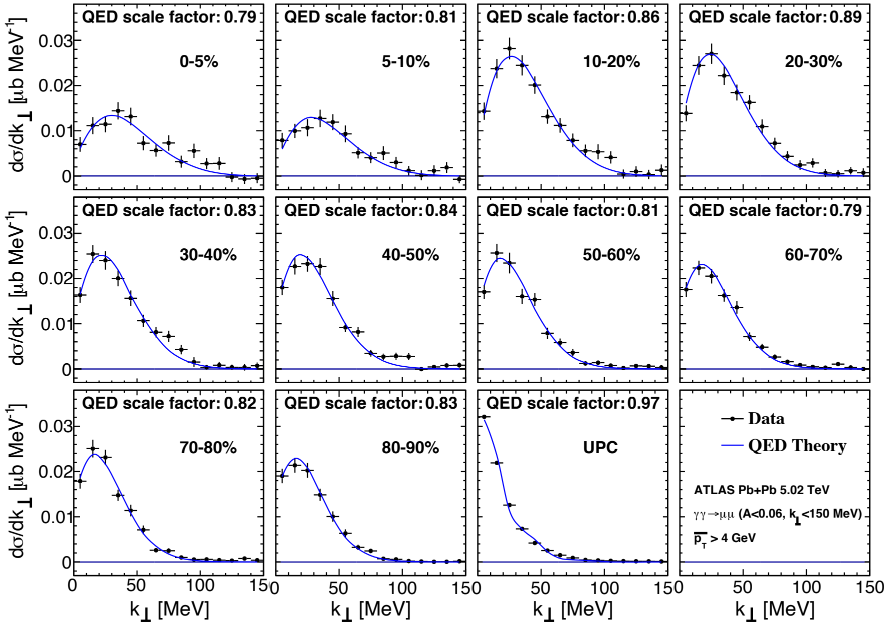
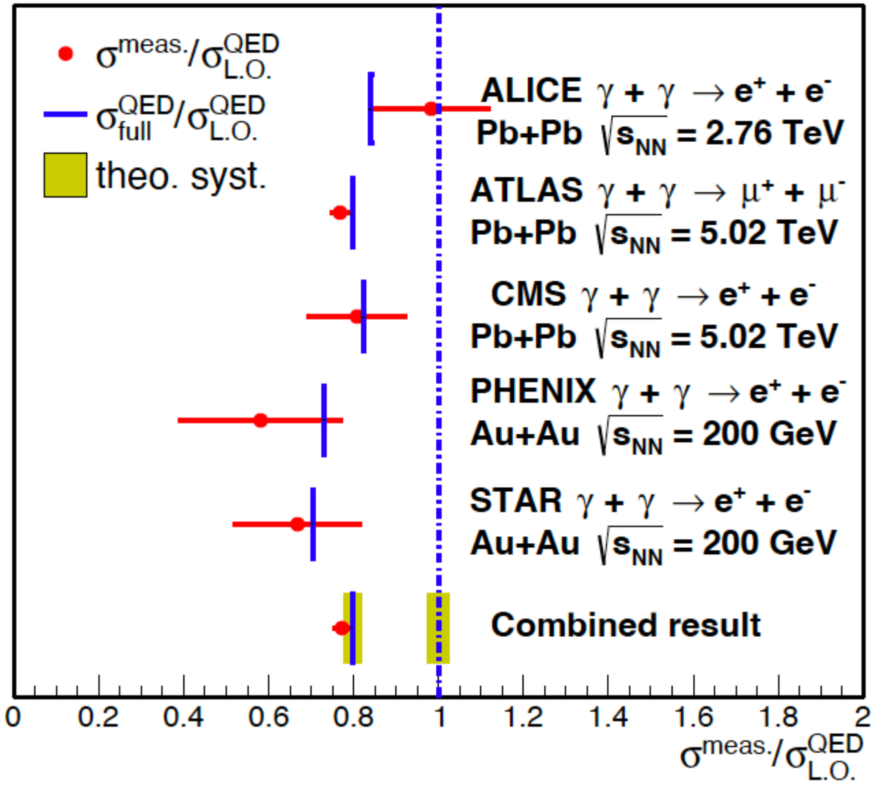
Radius Measurements from RHIC to LHC?





Is the charge radius consistent with low energy measurement?

Is there significant Coulomb correction at LHC energy (20%)?

Will all these affect measurement of g-2 of tau?

RMS of charge radius of Pb (LHC) best fit: 4.91fm
Standard charge radius from low energy: 5.51fm

Tang and Zha, arXiv:2103.04605;

FIG. 3. (Color online) Comparison of the ratios of the measured cross sections from world-wide experiments [26–30] and the predicted higher order QED results to the lowest order QED calculations for lepton pair production in $A + A$ collisions. The error bar represents the total uncertainty for each measurement, which includes the statistical and systematic errors. The yellow bands denote the uncertainties for QED calculations.

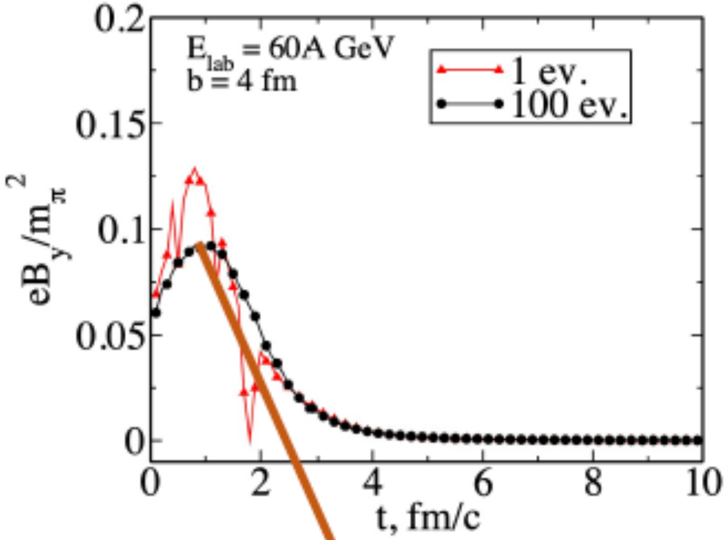
Summary and Perspectives

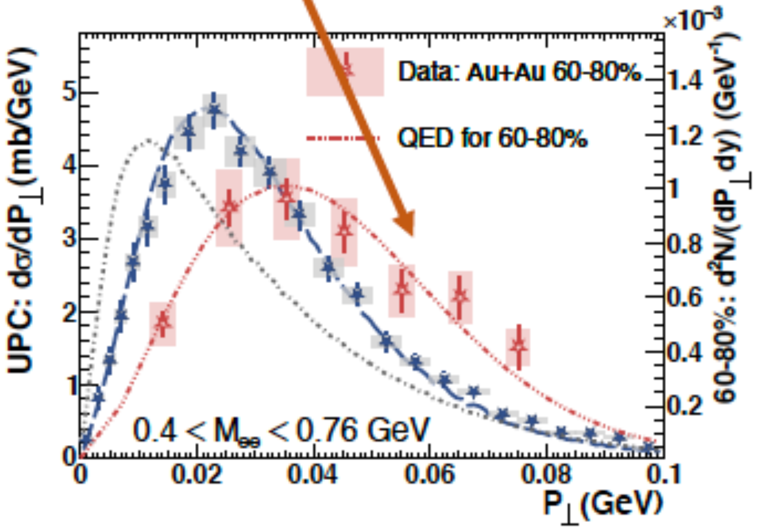
- Precise QED calculations and matching experimental data with high statistics from initial photon collisions
- Vector Meson Production with Quantum Entanglement provides very precise mass radius measurement

- Both measurements provide a good constraint on quark and gluon distributions at high energy

- Possible systematical deviation in peripheral at RHIC and central collisions at LHC due to final-state B-field effect
- Model: QED+final-state B-field to match data
- RHIC data with more central collisions and high statistics (2023-2025)
- Derive Pb charge radius from LHC data

Event-by-event Fluctuations + Interactions





- Significantly stronger field possible at small radial distances (based on current data)
- Fluctuating nucleon positions effect field inside nucleus
- OR Long-lived magnetic field
  → Lorentz-force bending of pairs
- High precision data from STAR 2023-25
- What to look for:
  - Field at small distance→ large $P_\perp$ and α
  - Look for modification of $d\sigma/dP_\perp$ shape

Hint of modification in 60 − 80% central collisions:
Additional 14 ± 4 (stat.)±4 (syst.) MeV/c broadening

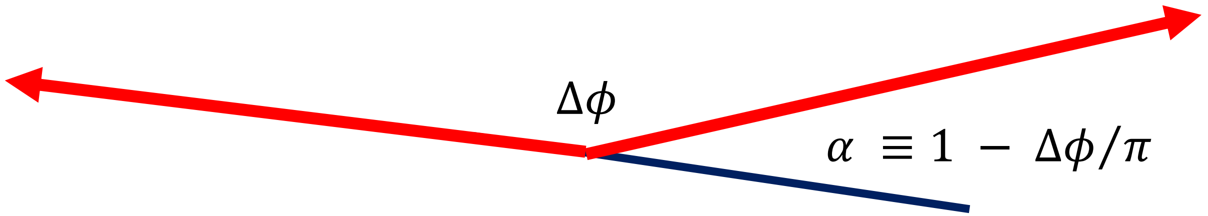
Most Precision test in Central Pb+Pb at LHC

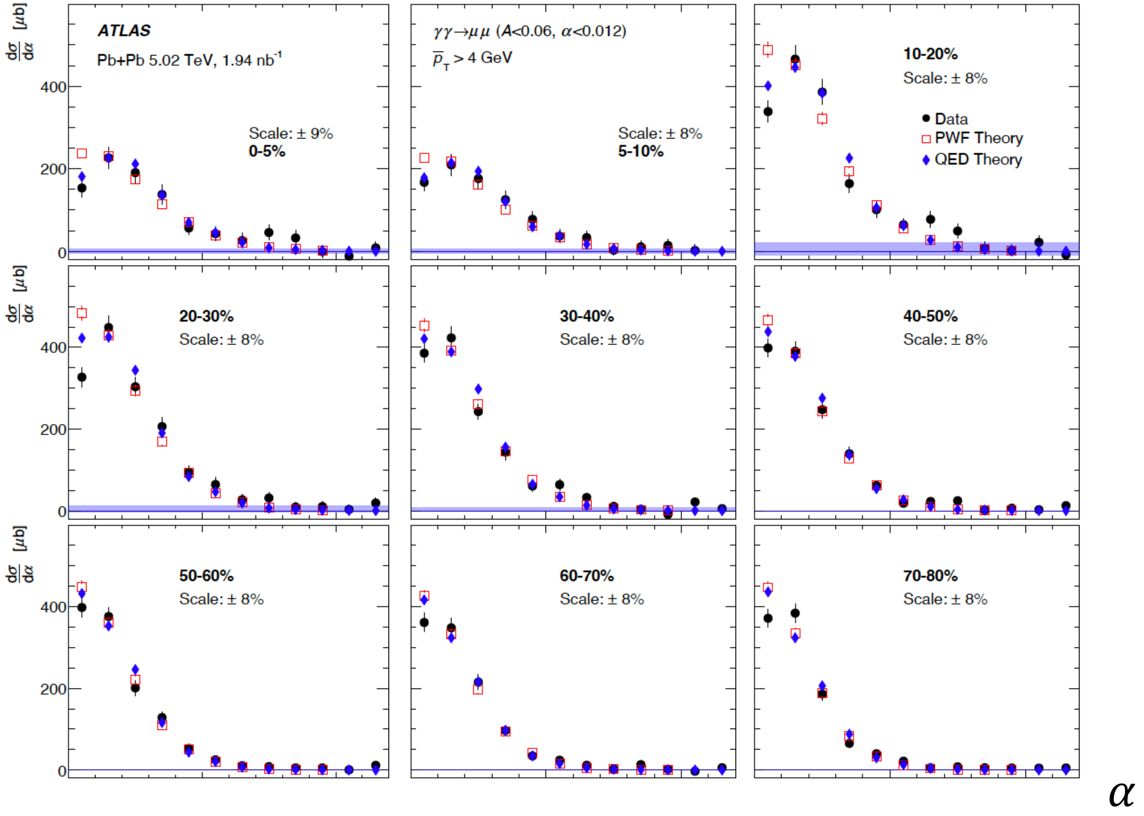
- Under what condition do these photons interact as real photons?
  - Photon Wigner Function (PWF) formalism & LO-QED formalism agree very well
  - How to understand the minor differences between them?

    - Possible difference between data and QED due to final-state B-field?

$$\omega/\gamma \lesssim k_\perp \lesssim 1/R \ll \omega,$$

$$\frac{\sqrt{2}}{\gamma} \lesssim \frac{\pi}{2}\alpha \lesssim \frac{\sqrt{2}}{\omega R} \ll 1$$





ATLAS, arXiv:2206.12594; PRL 2018

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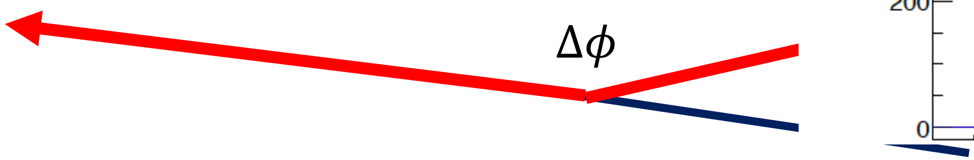

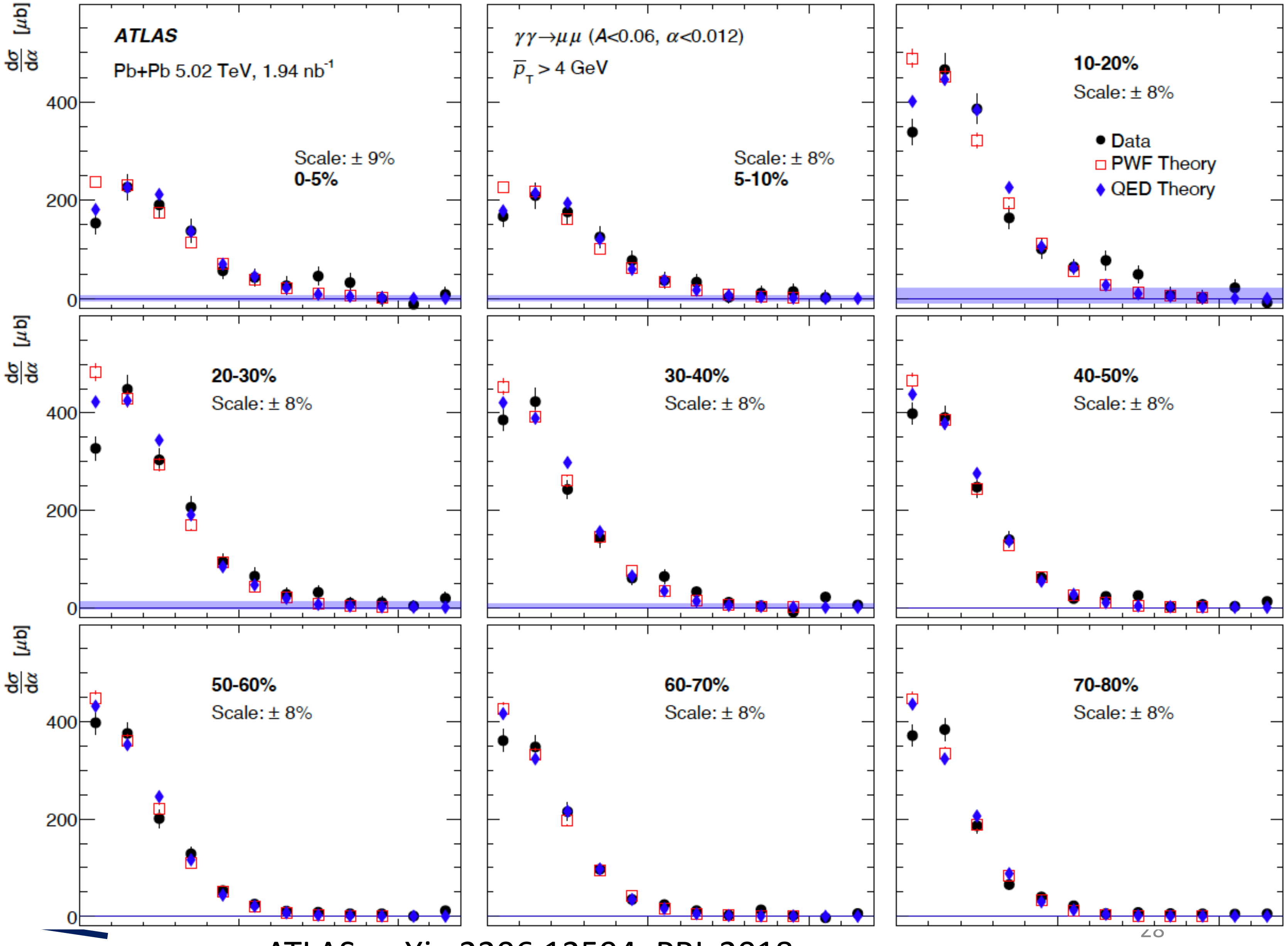

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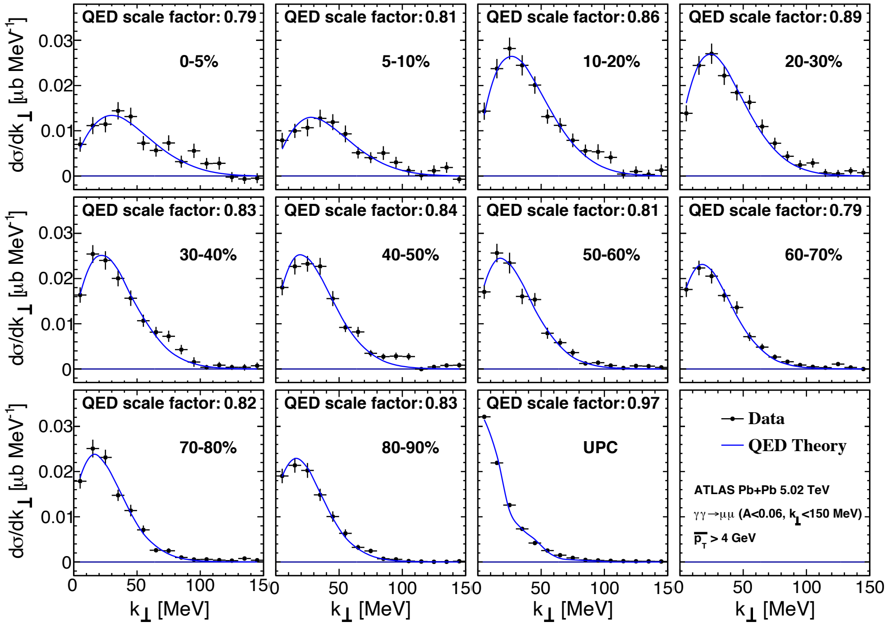

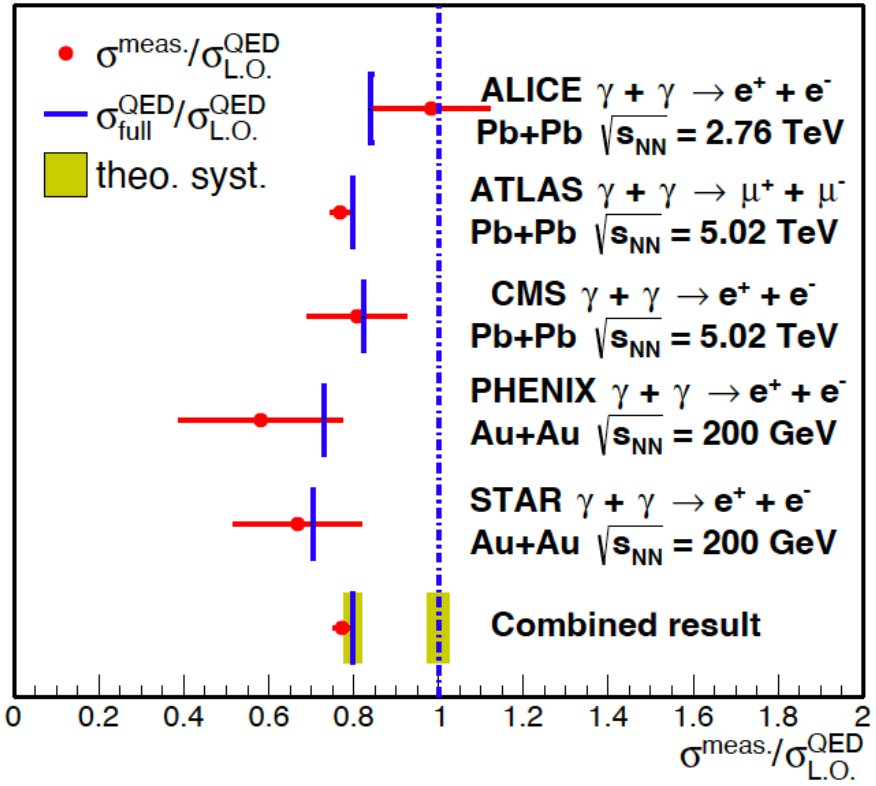

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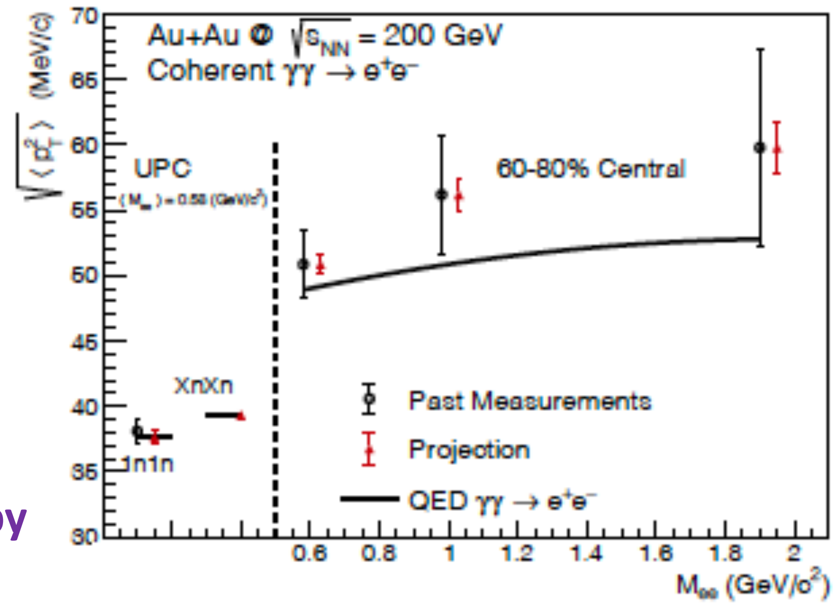
Are there final-state QED effects?

Precision data with
QED theory comparisons:
Both on-going at LHC and RHIC

How about azimuthal anisotropy
relative to reaction plane?



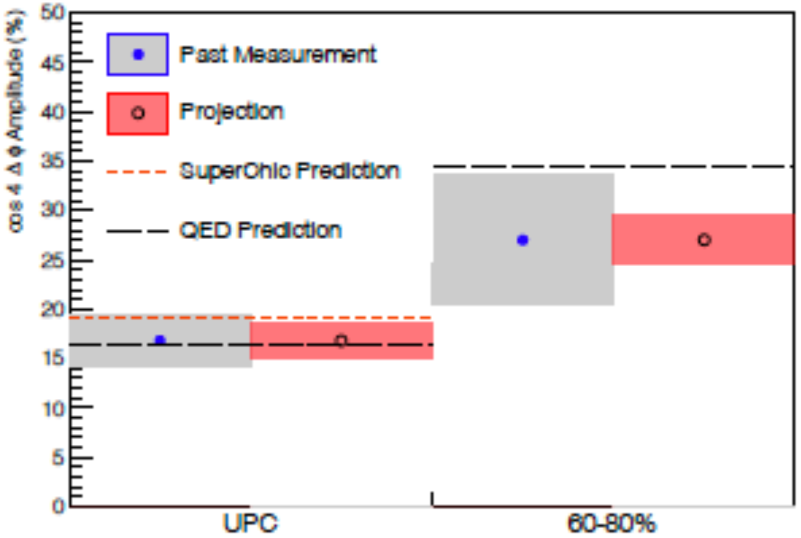


Figure 57: (Color online) Projections for measurements of the $\gamma\gamma \to e^+e^-$ process in peripheral and ultra-peripheral collisions. Left: The $\sqrt{\langle p_T^2 \rangle}$ of di-electron pairs within the fiducial acceptance as a function of pair mass, M_{ee}, for $60-80\%$ central and ultra-peripheral Au+Au collisions at $\sqrt{s_{NN}}$ $= 200$ GeV. Right: The projection of the $\cos 4\Delta\phi$ measurement for both peripheral $(60-80\%)$ and ultra-peripheral collisions.

STAR Beam Use Request (2023-2025):

https://drupal.star.bnl.gov/STAR/system/files/BUR2020_final.pdf

p_T broadening and azimuthal correlations of e^+e^- pairs sensitive to electro-magnetic (EM) field;
Impact parameter dependence of transverse momentum distribution of EM production is the key component to describe data.

Is there a sensitivity to final magnetic field in QGP?

Precise measurement of p_T broadening and angular correlation will tell at >3σ for each observable.