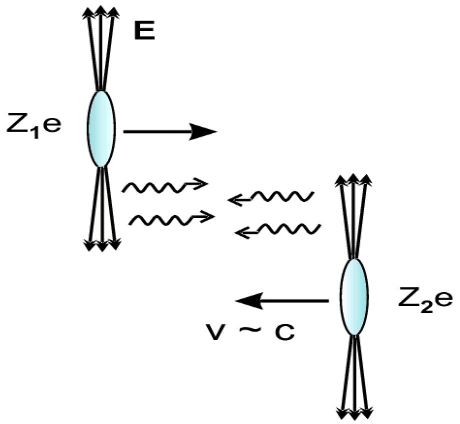
Exploring Coherent Photon Interactions from UPC to HHIC: Recent Advances and Future Directions

Seminar at University of Chinese Academy of Sciences, Beijing, 2023/03/24

National Natural Science Foundation of China

Wangmei Zha
University of Science and Technology of China

Coherent photons as "partons" in heavy-ion collisions



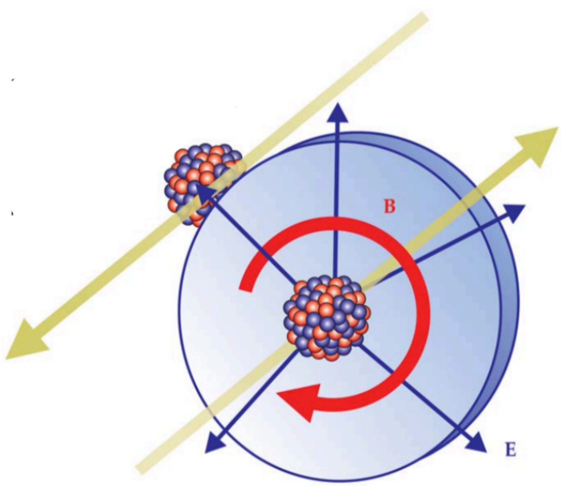
Coherent limitation: $Q^2 \ll 1/R^2$ => quasi-real !

Photon four momentum: $q^u = (\omega,\ \vec{q}_T, \omega/v)$

$$Q^2 = \frac{\omega^2}{\gamma^2} + q_T^2$$

$$\omega \leq \omega_{max} \sim \frac{\gamma}{R}$$

- View photons as "partons" being present with fast moving ions!



Physics Today **70**, 10, 40 (2017)

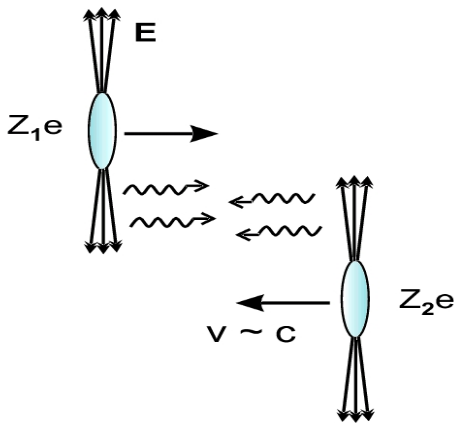
The extent of photons swarming about the ions:

The radius of nuclear matter R_{Nuc} ~ 6.3 fm (Au)

$R_{photons}$ >> R_{Nuc}

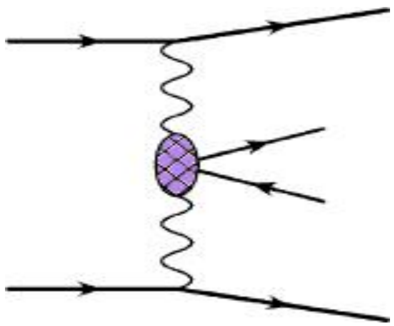
Take the photoproduction of dielectron (Au+Au 200 GeV)in ultra-peripheral collisions (UPCs) as example: $\langle R_{producton} \rangle$ ~ 60fm

Photon interactions in A+A



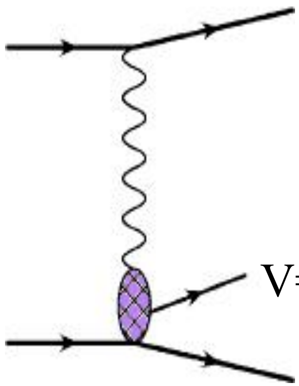
Electromagnetic interaction

=



Photon-photon interactions

+



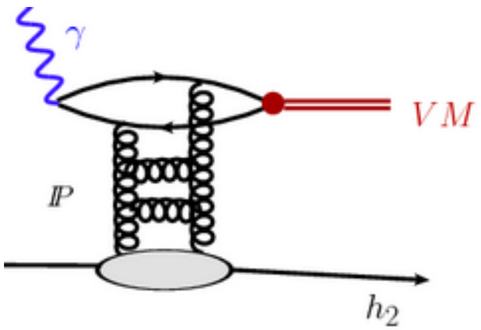
Photon-nucleus interactions

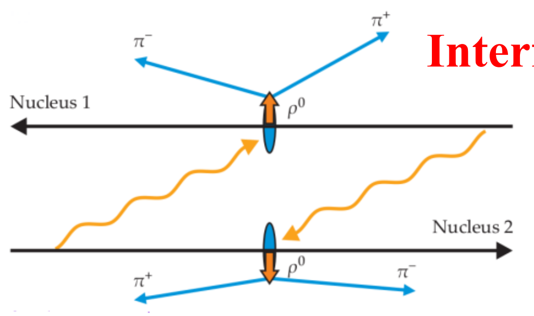
Ann. Rev. Nucl. Part. Sci.**55**:271 (2005)

- This large flux of quasi-real photons makes a hadron collider also a photon collider!
  - ✓ Photon-nucleus interactions: Vector meson
  - ✓ Photon-photon interactions: dileptons …
- Conventionally believed to be only exist in ultra-peripheral collisions (UPC) to keep "coherent"!

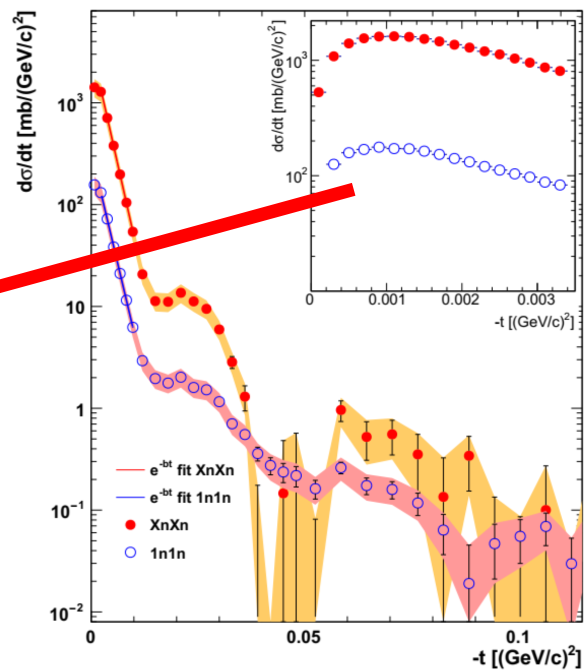
Vector meson photon-production

- Vector meson production:
  - ✓ chargeless ‘Pomeron exchange’
  - ✓ Light meson production is usually treated via vector meson dominance model:
    ρ, direct $\pi^+\pi^-$, ω….
  - ✓ Heavy quarkonia production could be treated with pQCD :
    J/ψ, ψ’, Υ(1S), Υ(2S), Υ(3S)…





Interference



STAR, PRC **96**, (2017) 054904

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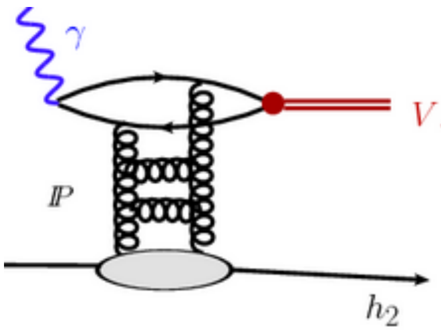
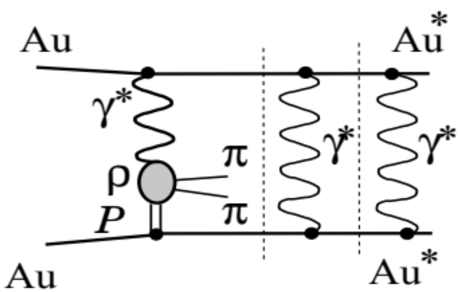
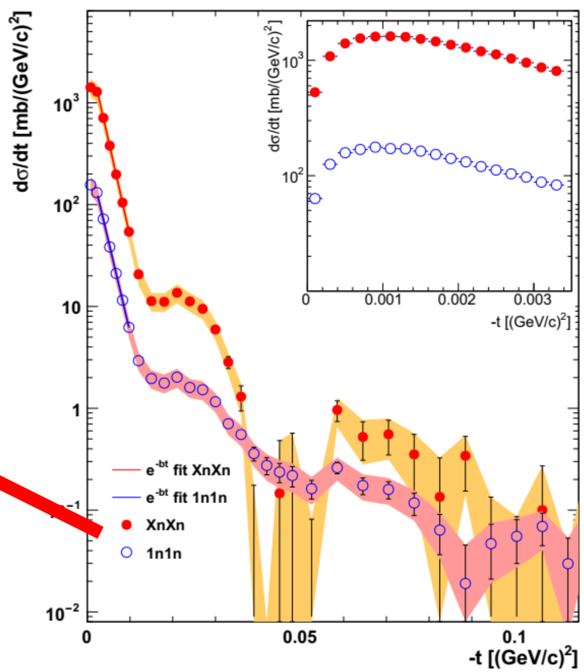




STAR, PRC **96**, (2017) 054904

When the nucleus break, coherent photoproduction can still occur!



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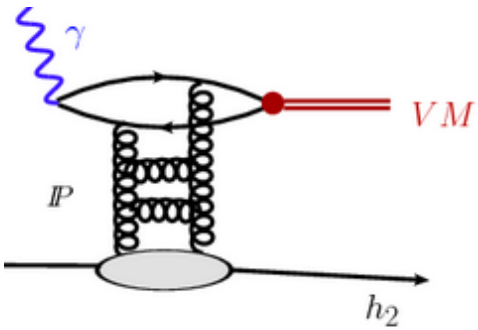
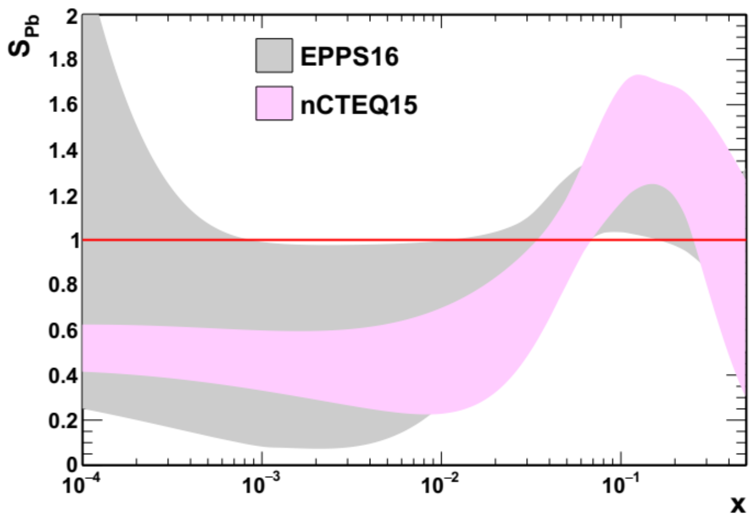


- Sensitive to the gluon distribution:

$$\left.\frac{d\sigma(\gamma A \to VA)}{dt}\right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 \left[xG_A(x, Q^2)\right]$$

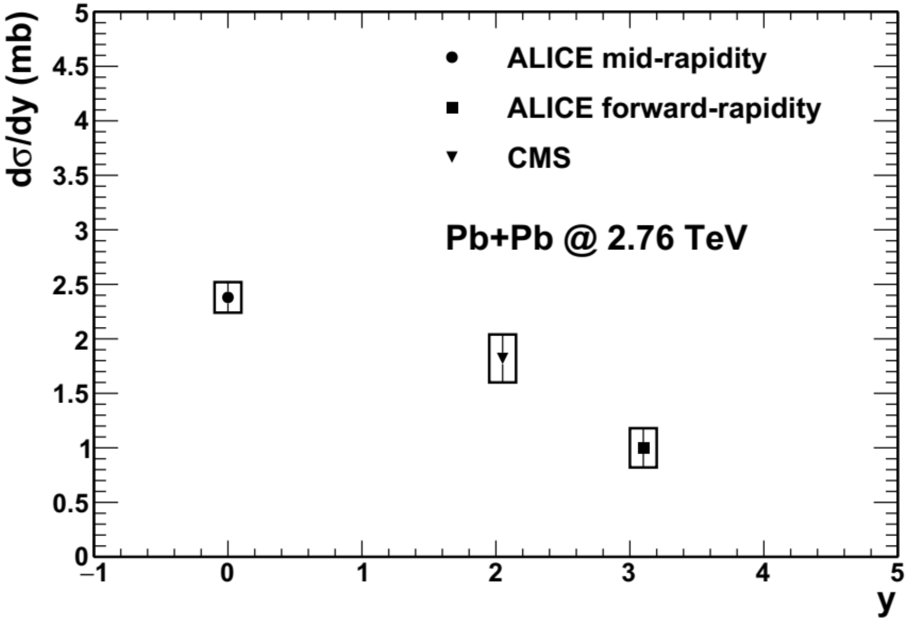
$$x = \frac{M_V e^{\pm y}}{\sqrt{s}} \quad Q^2 = M_V^2/4$$

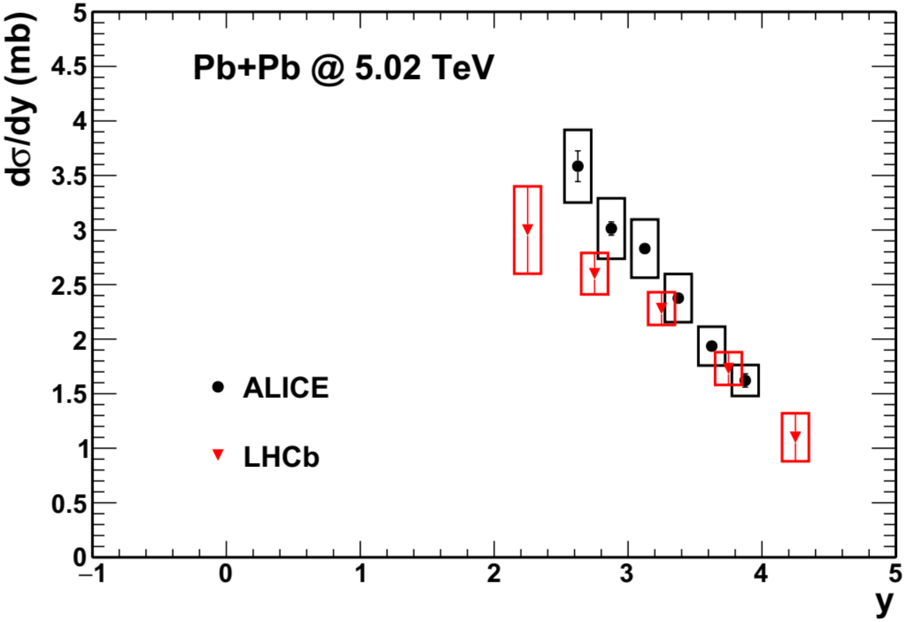


EPPS16: EPJC **77** (2017) 163

nCTEQ15:PRD **93** (2016) 085037

Nuclear shadowing from J/ψ measurements in UPCs





ALICE: EPJC **73** (2013) 2617

ALICE: PLB **718** (2013) 1273

CMS: PLB **772** (2017) 489

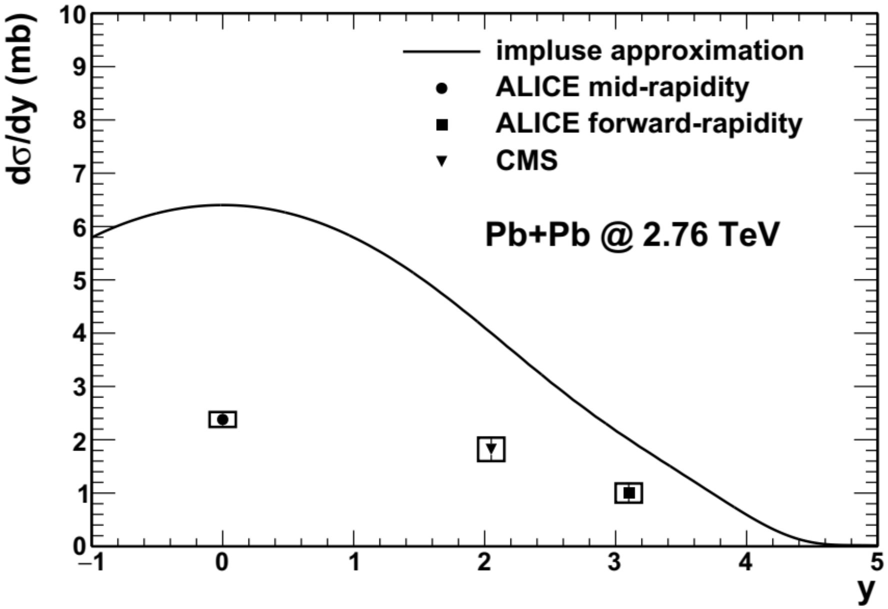
LHCb: LHCb-CONF-2018-003

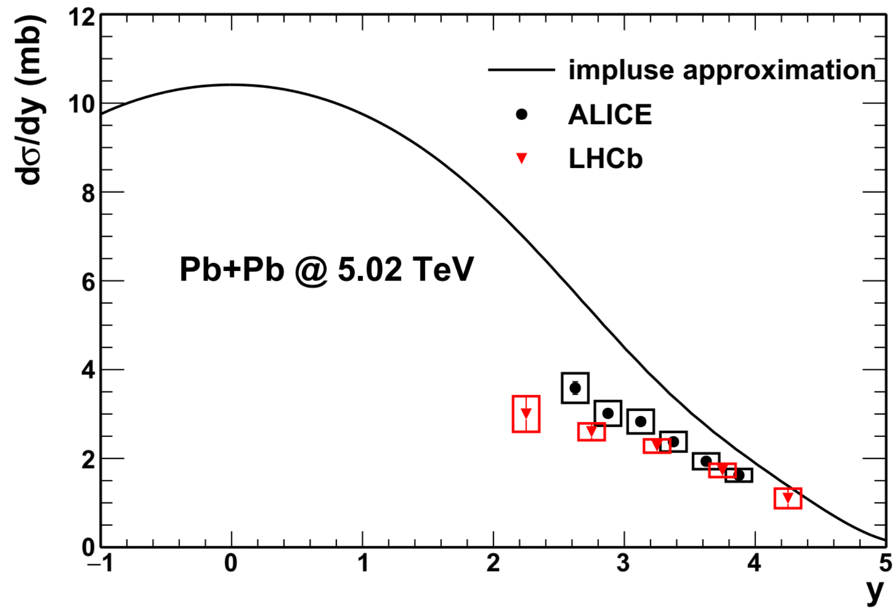
ALICE: PLB **798** (2019) 134926

Various precise measurements!

Powerful to constrain nPDF

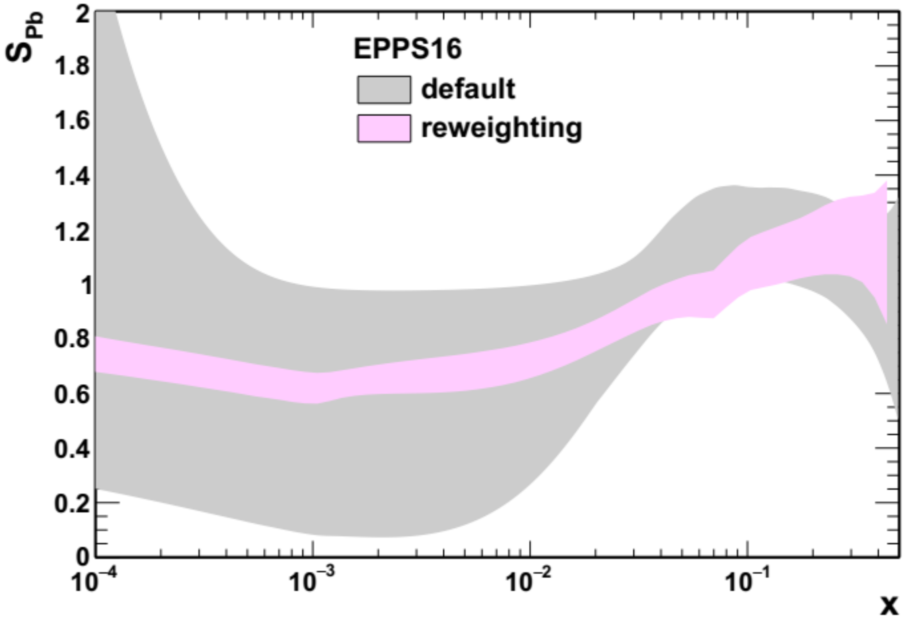
The results: impulse approximation

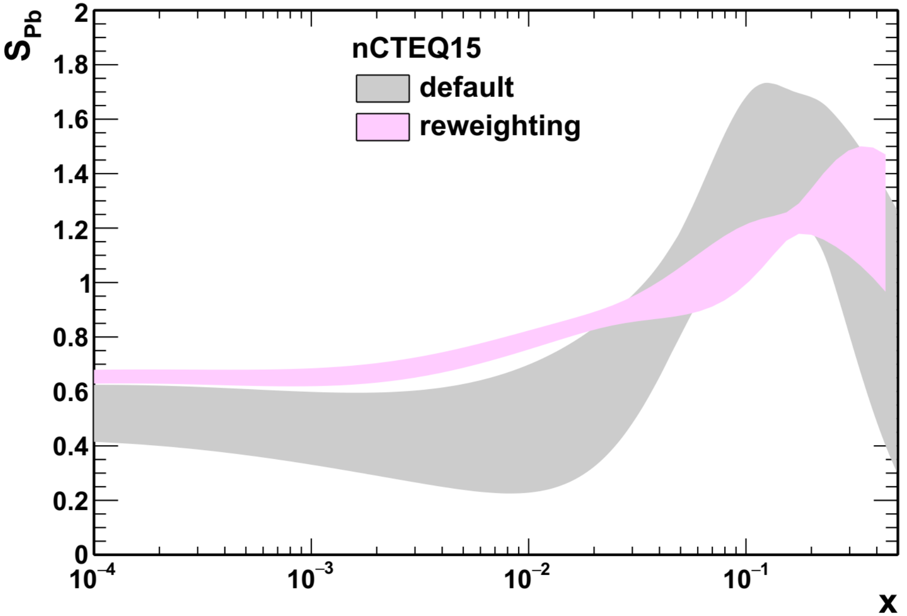




- The impulse approximation significantly overestimates the data => Significant shadowing effect
- The difference becomes smaller towards forward rapidity => Less shadowing effect towards high x

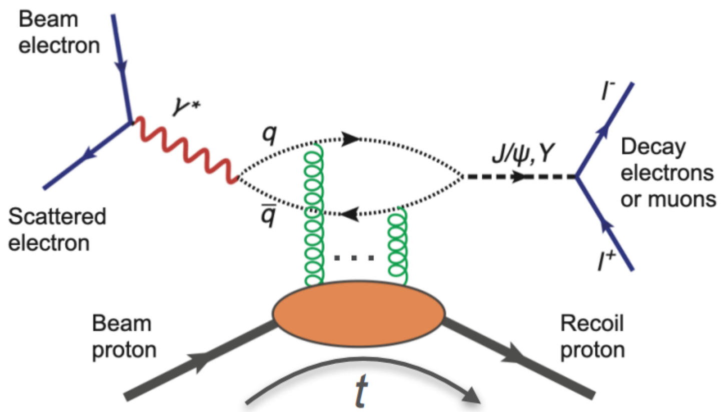
Nuclear shadowing from J/ψ measurements in UPCs





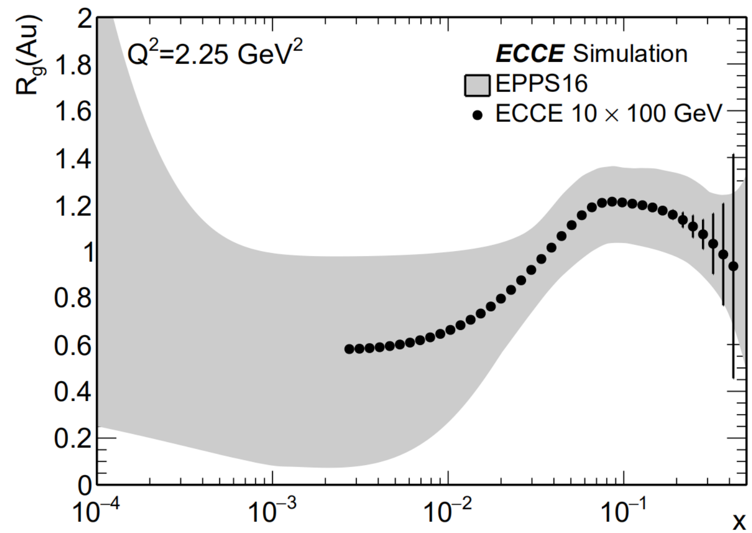
- The UPC measurements dramatically reduce the uncertainty band of EPPS16 and nCTEQ15 PDF sets.
- Significant shadowing effect has been observed in both PDF sets at small x.

The projection for future EIC facility

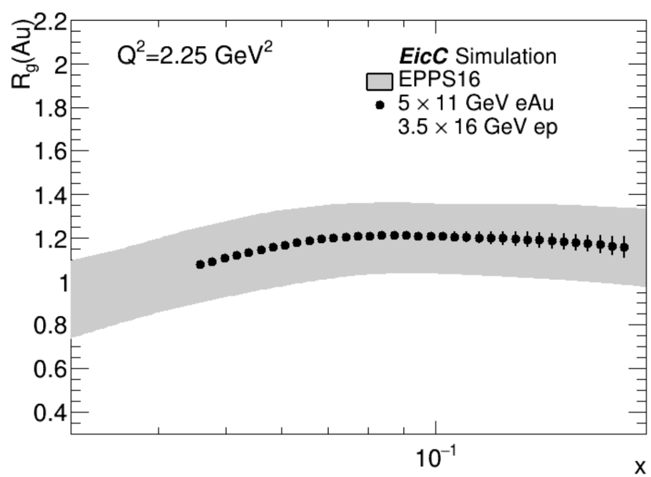


X. Li et al. NIMA **1048** (2023) 167956

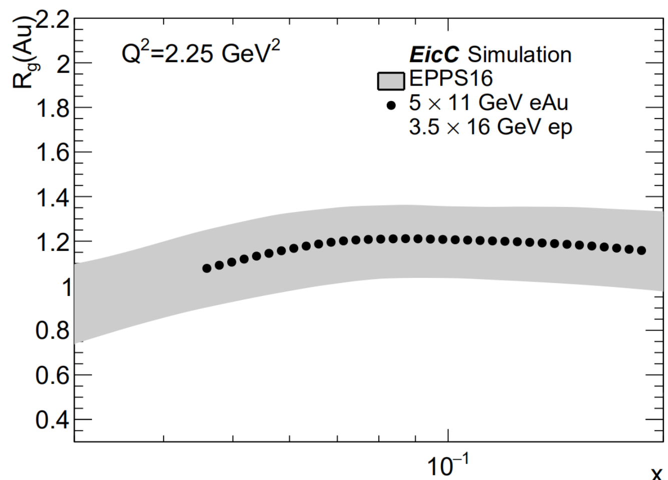
L_{int}=100 fb^{-1} ep; 10/197 fb^{-1} eAu



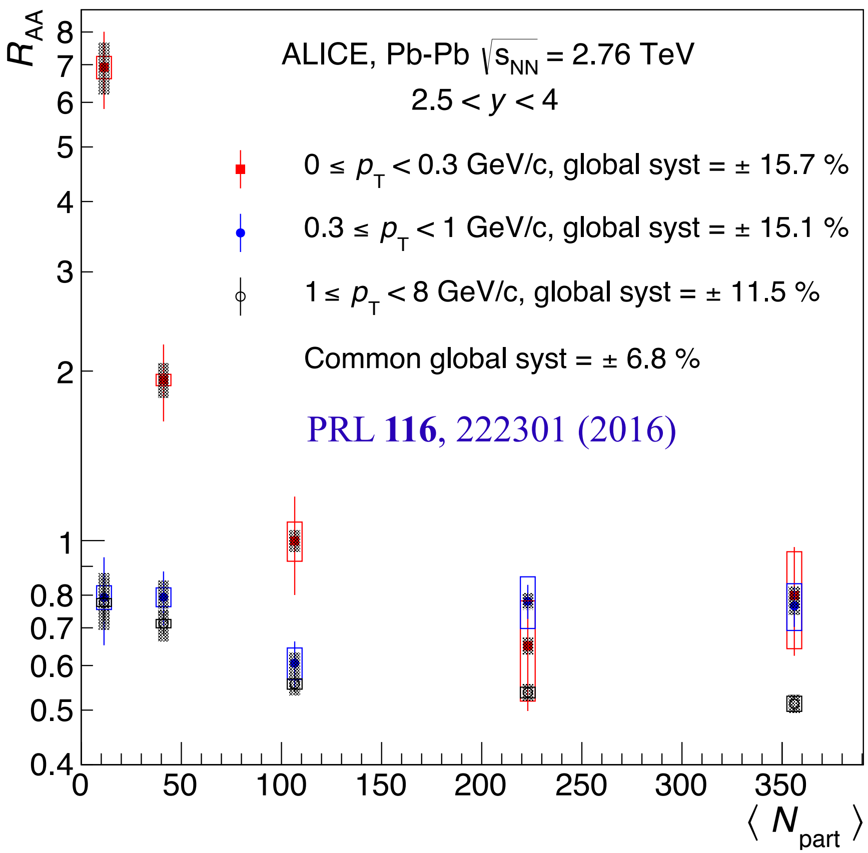
L_{int}=50 fb^{-1} ep; 50/197 fb^{-1} eAu



L_{int}=20 fb^{-1} eAu



The beginning of the story in HHIC

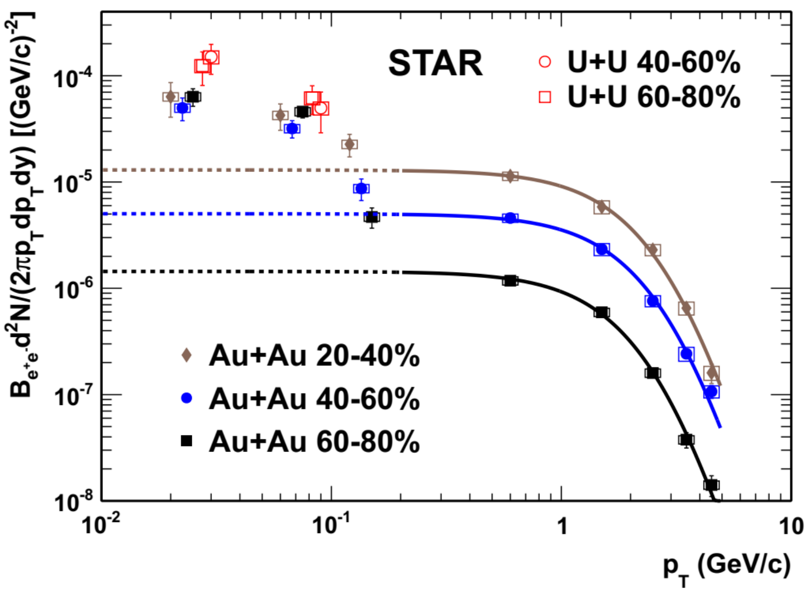


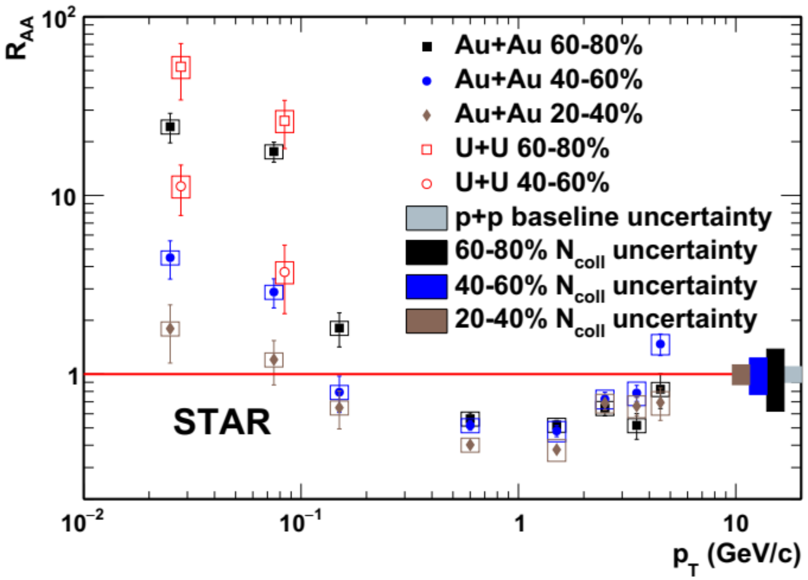
- Significant enhancement of J/ψ yield observed in p_T interval 0 – 0.3 GeV/c for peripheral collisions (50 – 90%).
- Can not be described by hadronic production modified by the hot medium or cold nuclear matter effects!

- Origin from **coherent photon-nucleus interactions**?

What does STAR say for the excess?

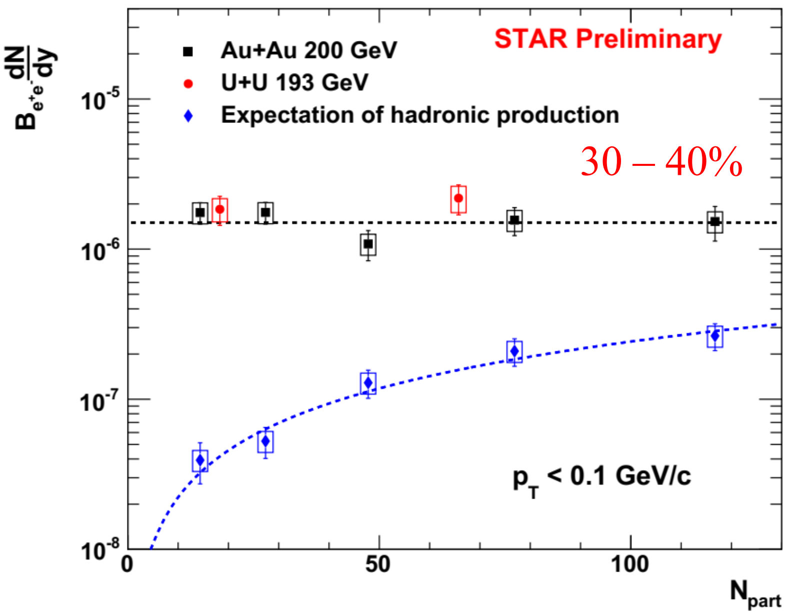
STAR: PRL **123** (2019) 132302

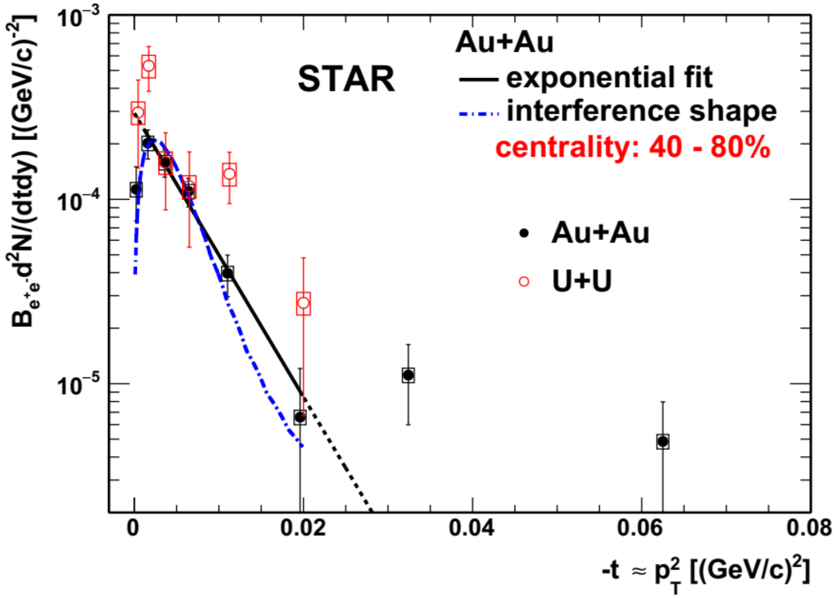




- Significant enhancement of J/ψ yield observed at p_T interval 0 – 0.2 GeV/c for peripheral collisions (40 – 80 %)!
- No significant difference between Au+Au and U+U collisions.

The excess yield and dN/dt distribution





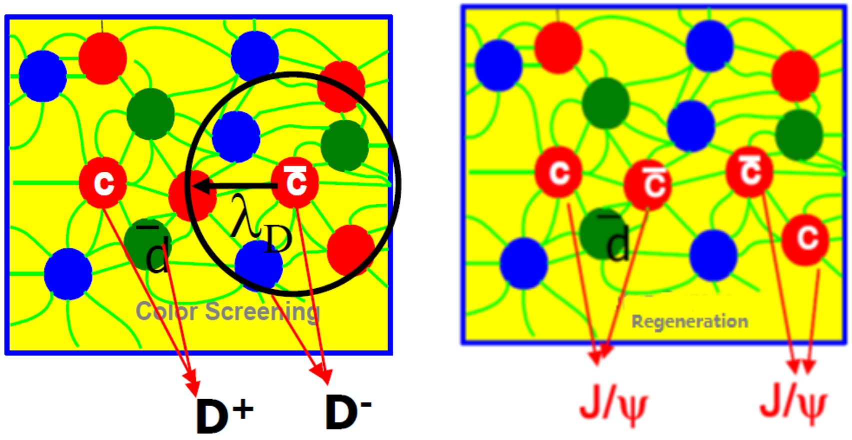
- Low p_T J/ψ from hadronic production is expected to increase dramatically with N_{part}.
- No significant centrality dependence of the excess yield!

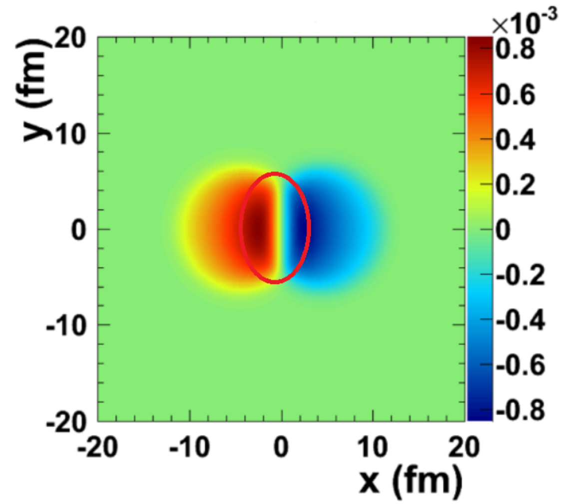
- Similar structure to that in UPC case!
- Indication of interference!
  - ✓ Interference shape from calculation PRC **97** (2018) 044910
- Similar slope parameter!
  - ✓ Slope from STARLIGHT prediction in UPC case – 196 (GeV/c)$^{-2}$
  - ✓ Slope w/o the first point: 177 ± 23(GeV/c)$^{-2}$ $\chi^2/NDF = 1.7/2$

A novel probe for QGP?

- Hot medium effects:
  - ✓ Color Screening
    -"Smoking gun" signature for QGP PLB **178** (1986) 416
  - ✓ Regeneration
    -Recombination of charm quarks
- Cold Nuclear Matter effects:
  - ✓PDF modification in nucleus
  - ✓Initial state energy loss
  - ✓…

A cleaner probe of color screening?



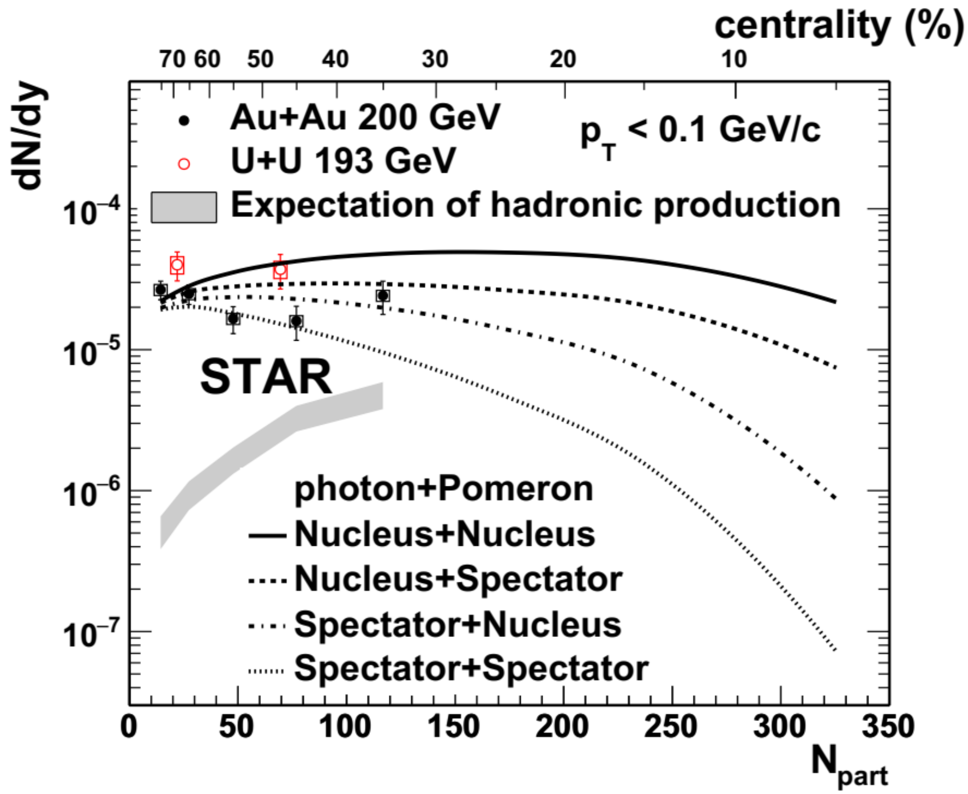


b=10fm

PRC 99 (2019) 6, 061901

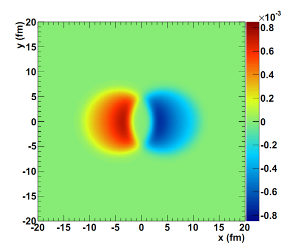
The key question: baseline?

Comparison with baseline from model calculation

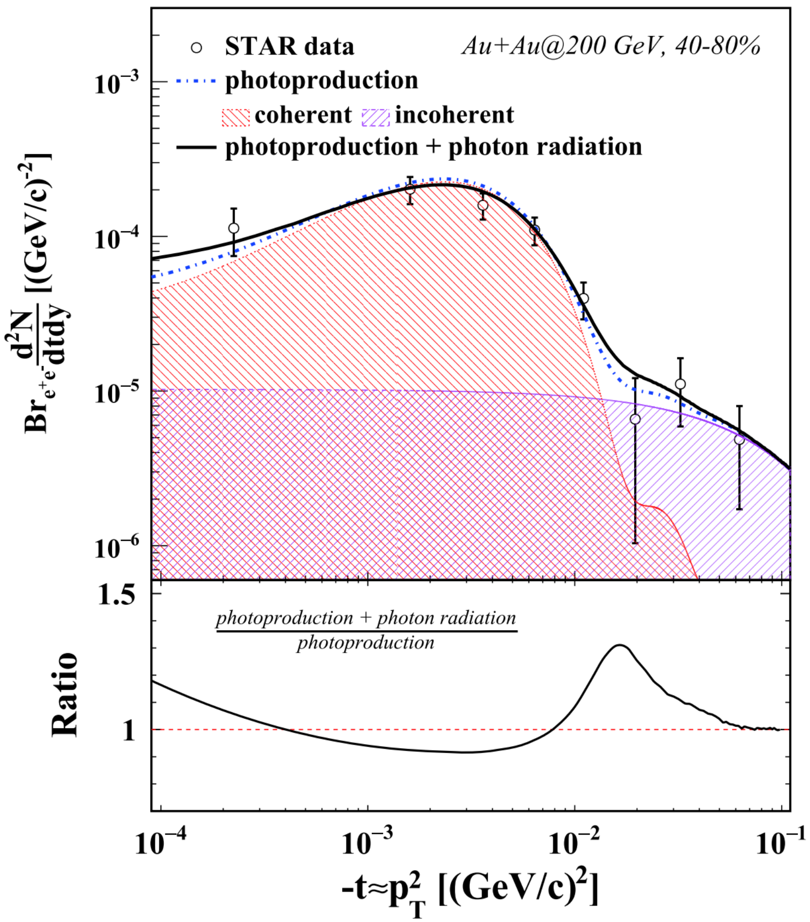


PRC **97** (2018) 044910
PRC **99**, (2019) 061901(R)

- ✓ Well described by the coherent photoproduction mechanism for peripheral collisions
- ✓ Hint of disruption from the medium
  - -The observation effect
  - -The QGP swallowing

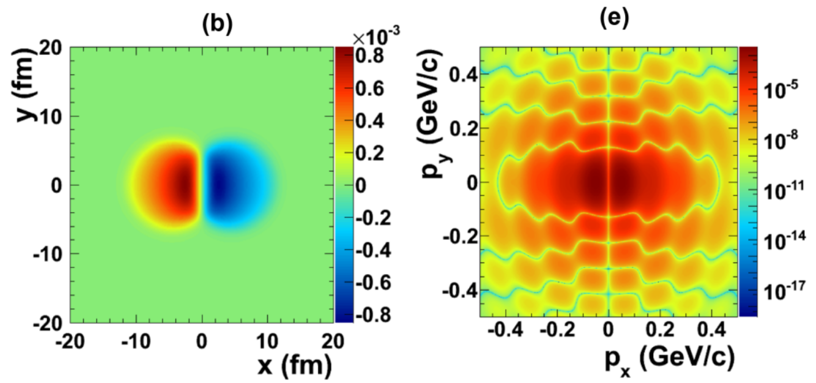


Comparison with baseline from model calculation



Chinese Phys. C (2022) **46** 074103

The destructive interference



The internal photon radiation

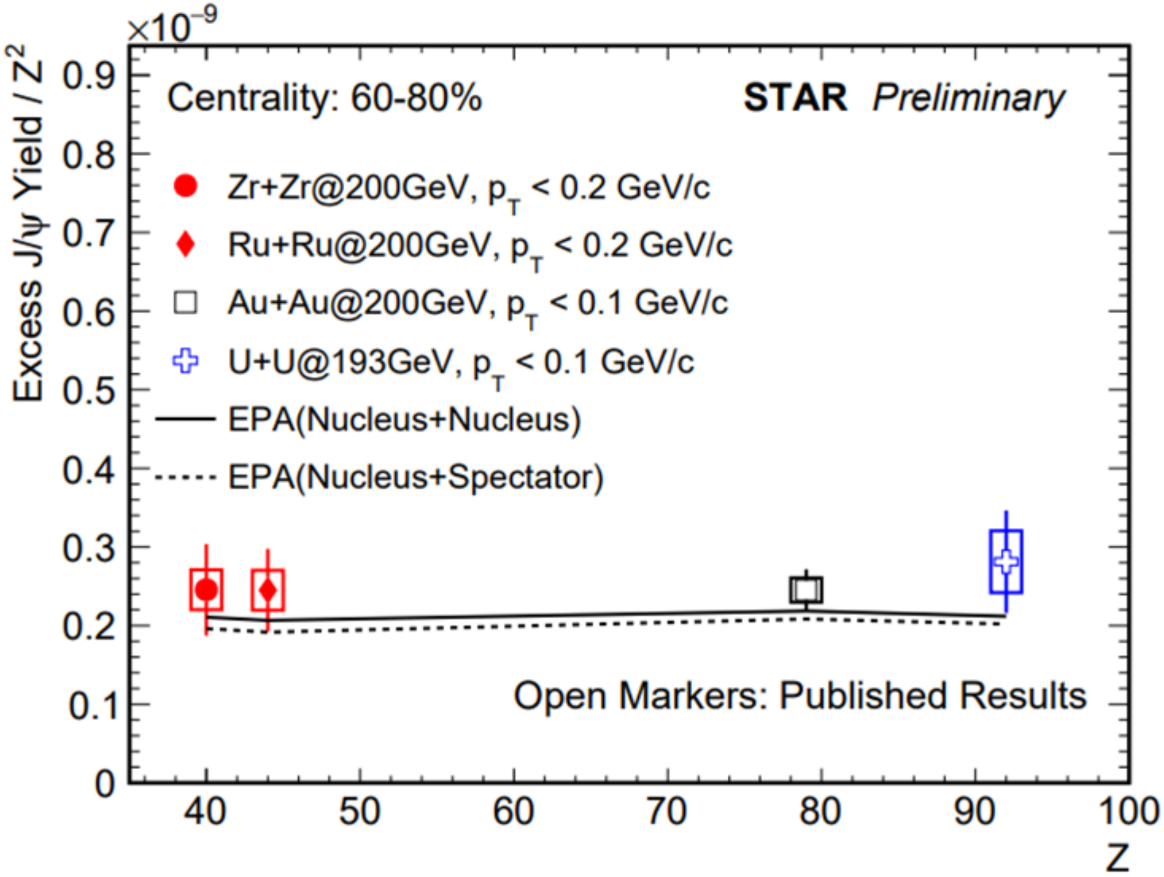
$$J/\psi(p_0) \rightarrow e^-(p_1) + e^+(p_2) + \gamma(k)$$

Consistent with current picture

Medium effect?

✓ Hidden in the error, if exist

The collision species dependence

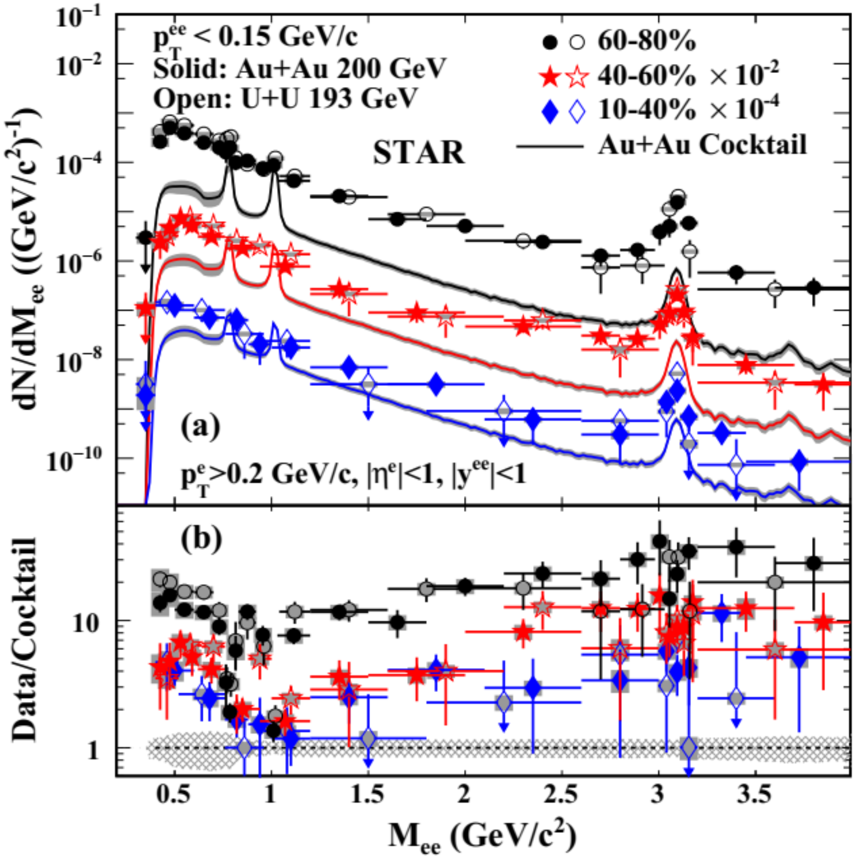


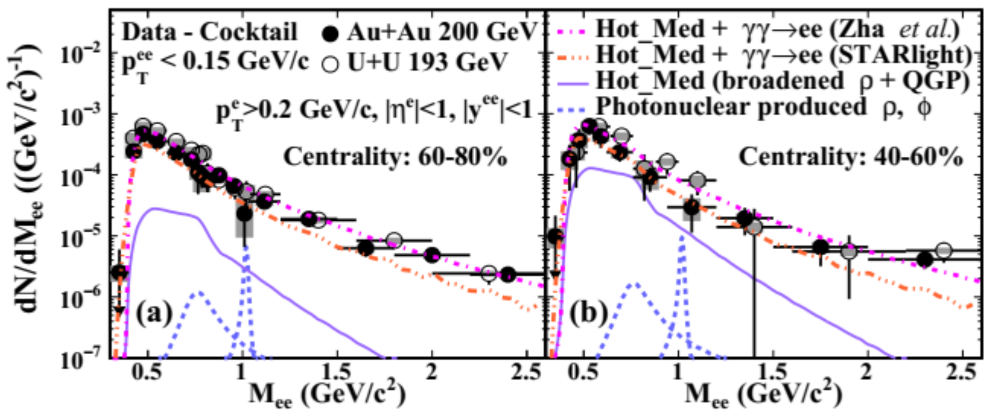
Well described by Z^2 scaling

Independent of collision species

Balance of form factor and impact parameter

How about the ρ photoproduction?





STAR, PRL **121** (2018) 132301

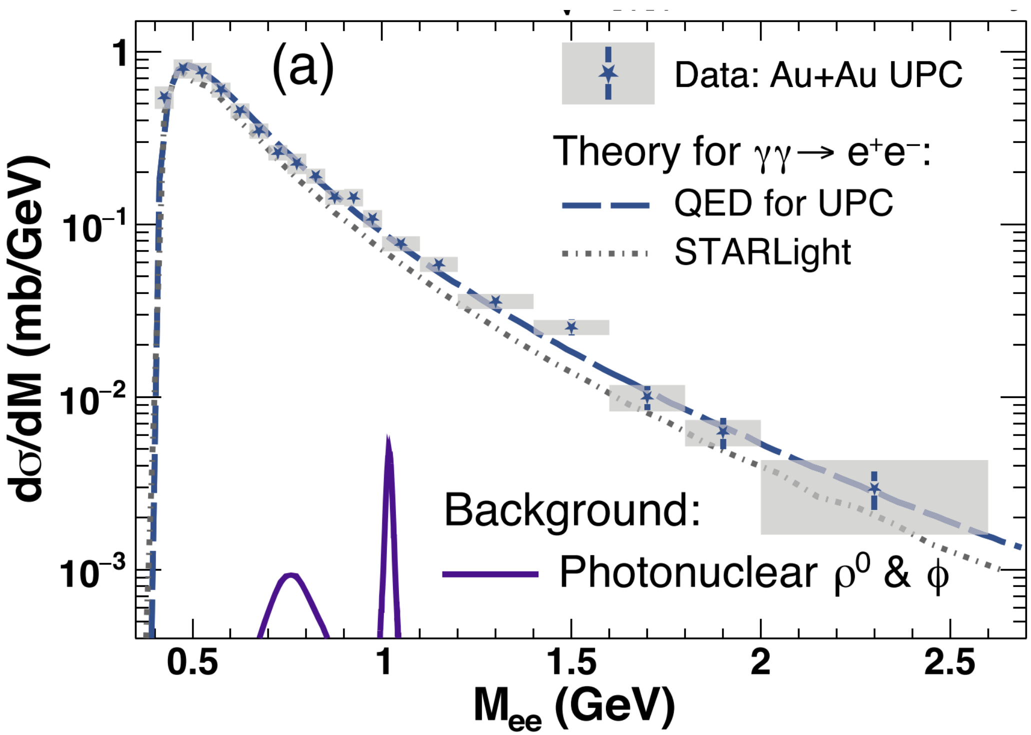
PLB **781** (2018) 182

Negligible ρ photoproduction!

- Significant excess in 60-80% central Au + Au and U + U collisions for the whole invariant mass range!
- The excess can be described by the coherent photon-photon process!

The observation of Breit-Wheeler process

STAR, PRL 127 (2021) 052302



MCD

Data : 0.261 ± 0.004 (stat.) ± 0.013 (sys.) ± 0.034 (scale) mb

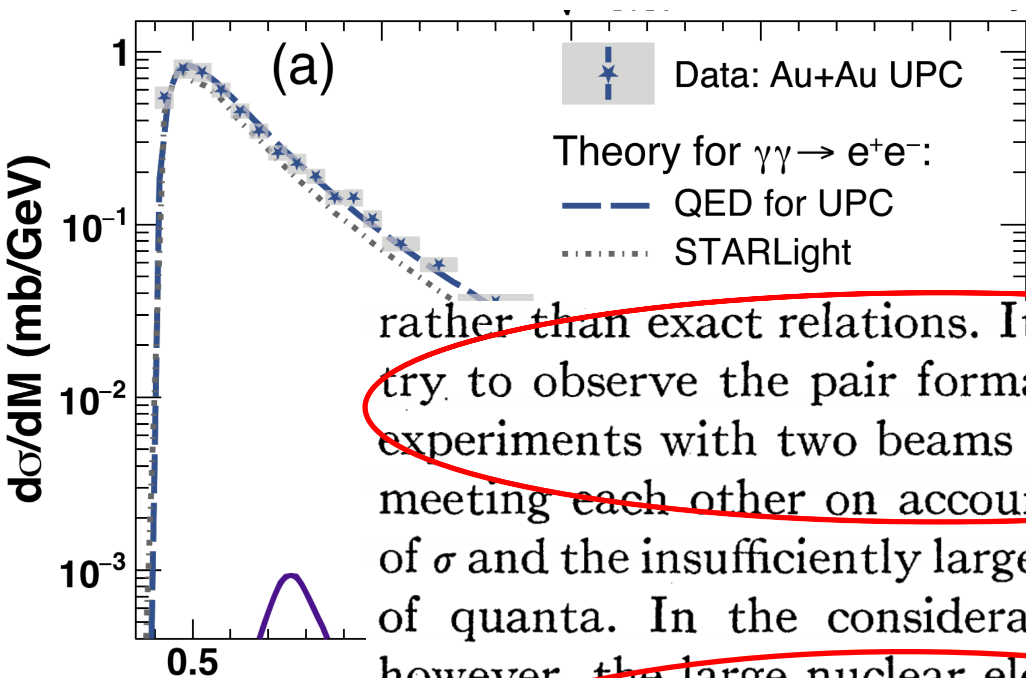
STARLight	gEPA	QED
0.22 mb	0.26 mb	0.26 mb

Consistent with theoretical calculations with $\pm 1\sigma$ level!

1934 Breit & Wheeler : "Collision of two Light Quanta"
Physical Review 46 (1934): 1087

The observation of Breit-Wheeler process

STAR, PRL 127 (2021) 052302



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QED

ıb 0.26 mb

theoretical

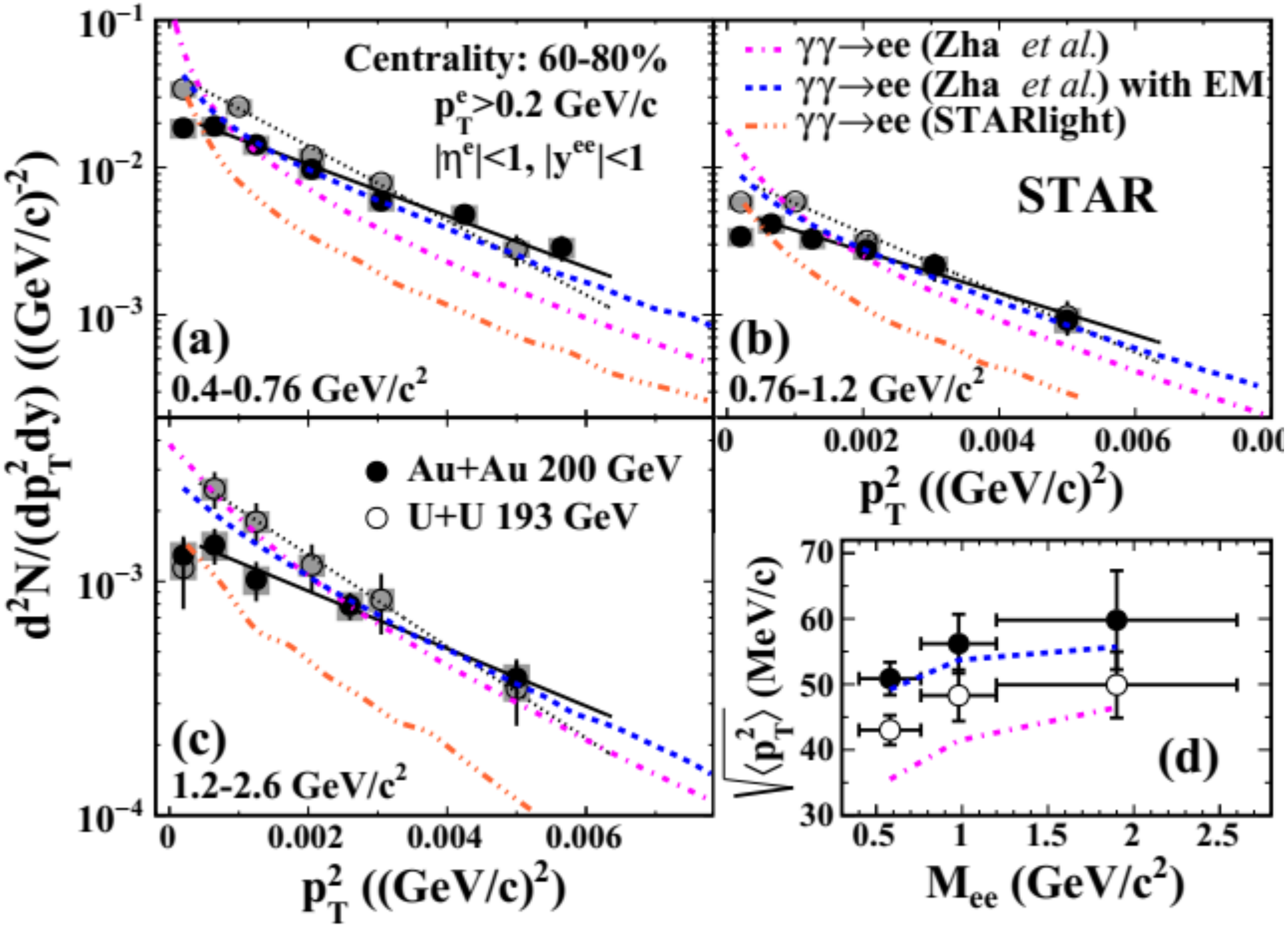
ı $\pm 1\sigma$ level!

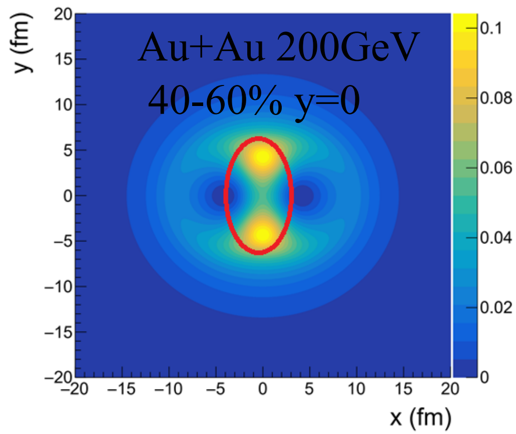
1934 Breit & Wh

Physical Review 46

rather than exact relations. It is also hopeless to try to observe the pair formation in laboratory experiments with two beams of x-rays or γ-rays meeting each other on account of the smallness of σ and the insufficiently large available densities of quanta. In the considerations of Williams, however, the large nuclear electric fields lead to large densities of quanta in moving frames of reference. This, together with the large number of nucleii available in unit volume of ordinary materials, increases the effect to observable amounts. Analyzing the field of the nucleus into

A sensitive probe: pair p_T broadening



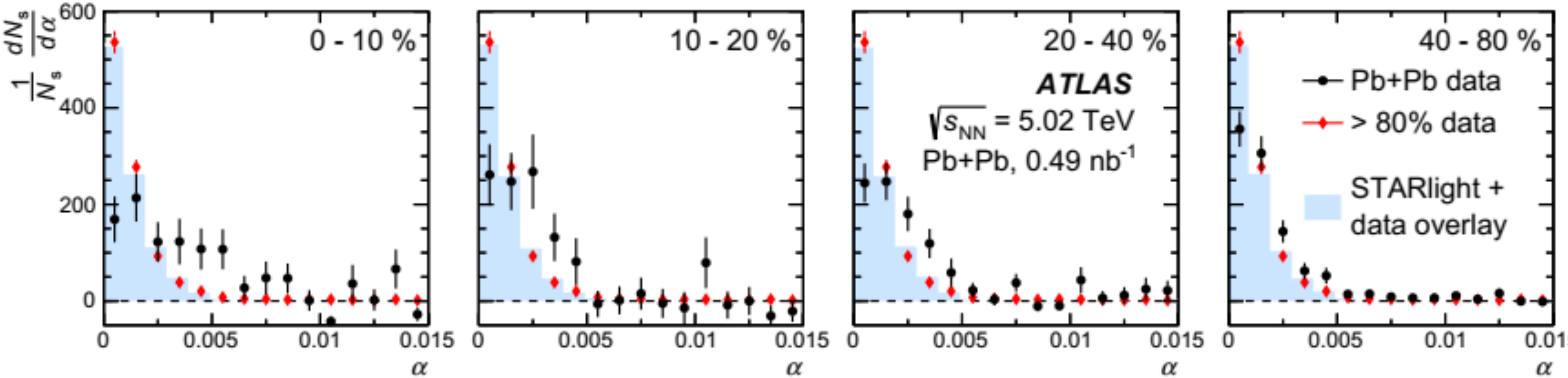


Novel probe for QGP?

12% in nuclear overlap region

- The equivalent photon approximation could not describe the pair p_T distribution
- Possible medium effects --- magnetic field trapped in the QGP?

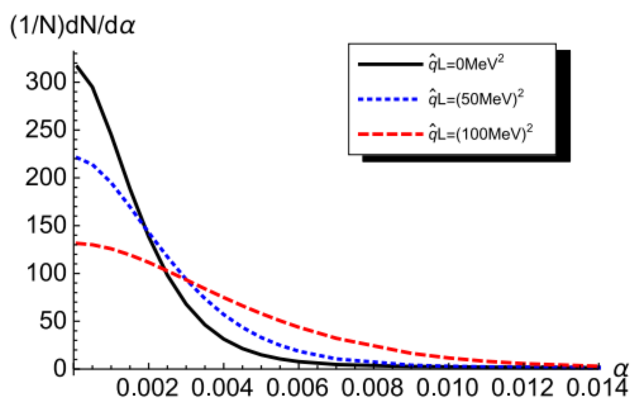
A sensitive probe: pair p_T broadening



ATLAS, PRL **121** (2018) 212 301

$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi}$$

- The broadening increases towards central collisions
- Possible medium effects --- QED multiple scattering?



S.R. Klein etal., PRL**122** (2019) 132301

The baseline study from theoretical side

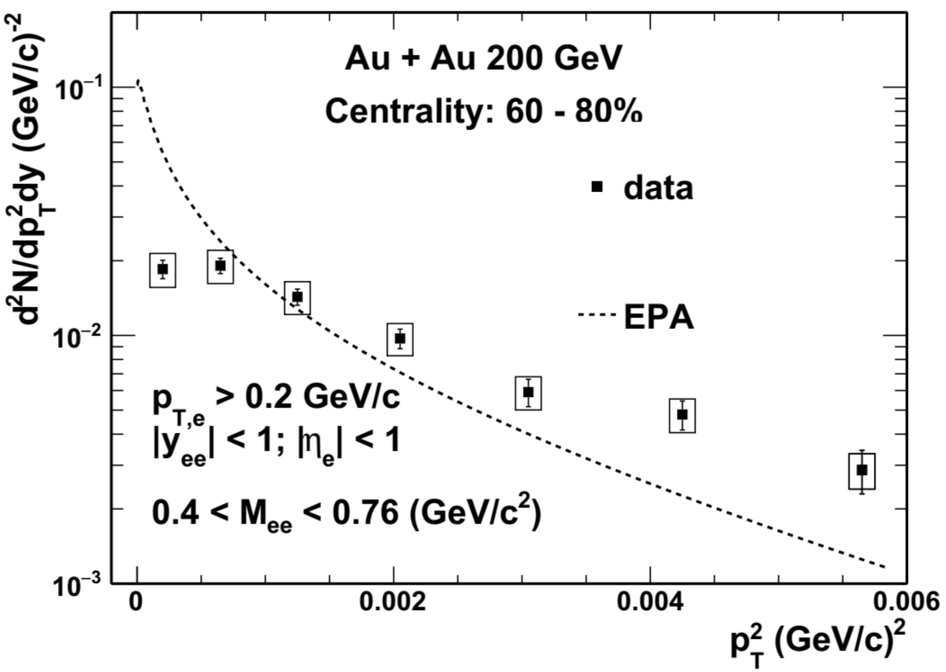
EPA approach

The photon k_T spectrum for fixed k:

The final-state p_T is the vector sum of the two photon.

$$\frac{dN}{dk_\perp} = \frac{2Z^2\alpha F^2(k_\perp^2 + k^2/\gamma^2)k_\perp^3}{\pi[k_\perp^2 + k^2/\gamma^2]^2}$$

No impact parameter dependence!



Fail to reproduce the pair p_T !

The baseline study from theoretical side

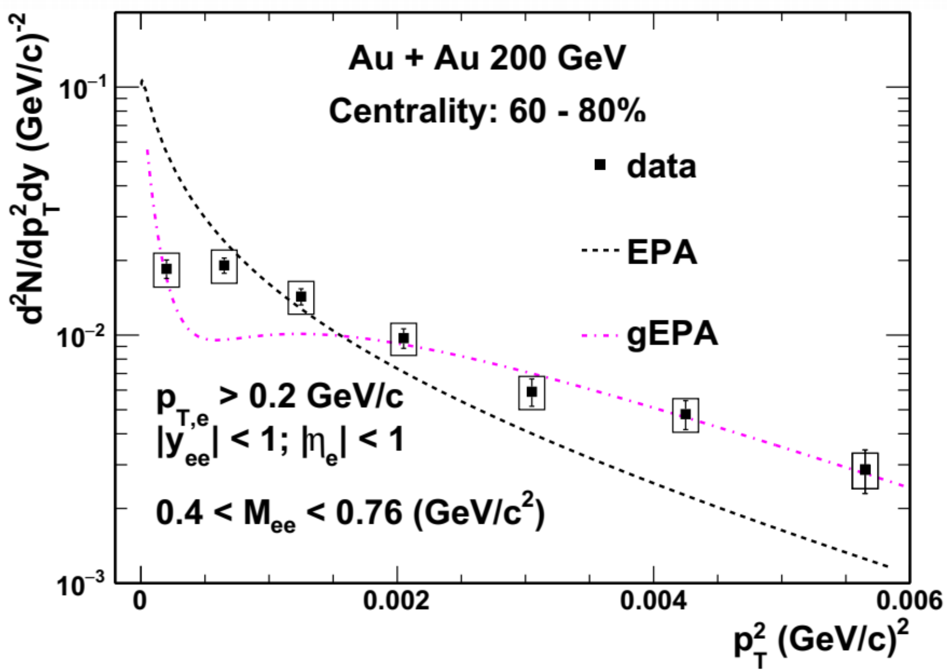
gEPA approach

Impact parameter dependence!

$$\sigma = 16\frac{Z^4e^4}{(4\pi)^2}\int d^2b \int \frac{d\omega_1}{\omega_1}\int \frac{d\omega_2}{\omega_2}\int \frac{d^2k_{1\perp}}{(2\pi)^2}\int \frac{d^2k_{2\perp}}{(2\pi)^2}\int \frac{d^2q_{\perp}}{(2\pi)^2} e^{-i\mathbf{b}\cdot\mathbf{q}_\perp}$$

$$\times \mathcal{F}_1(\mathbf{k}_{1\perp},\omega_1)\,\mathcal{F}_2(\mathbf{k}_{2\perp},\omega_2)\,\mathcal{F}_1^*(\mathbf{k}_{1\perp}-\mathbf{q}_\perp,\omega_1)\,\mathcal{F}_2^*(\mathbf{k}_{2\perp}+\mathbf{q}_\perp,\omega_2)$$
$$\times\{(\mathbf{k}_{1\perp}\cdot\mathbf{k}_{2\perp})\,((\mathbf{k}_{1\perp}-\mathbf{q}_\perp)\cdot(\mathbf{k}_{2\perp}+\mathbf{q}_\perp))\,\sigma_s(\omega_1,\omega_2)$$
$$+(\mathbf{k}_{1\perp}\times\mathbf{k}_{2\perp})\cdot((\mathbf{k}_{1\perp}-\mathbf{q}_\perp)\times(\mathbf{k}_{2\perp}+\mathbf{q}_\perp))\,\sigma_{ps}(\omega_1,\omega_2)\} \quad .$$

PRC **47** (1993) 2308



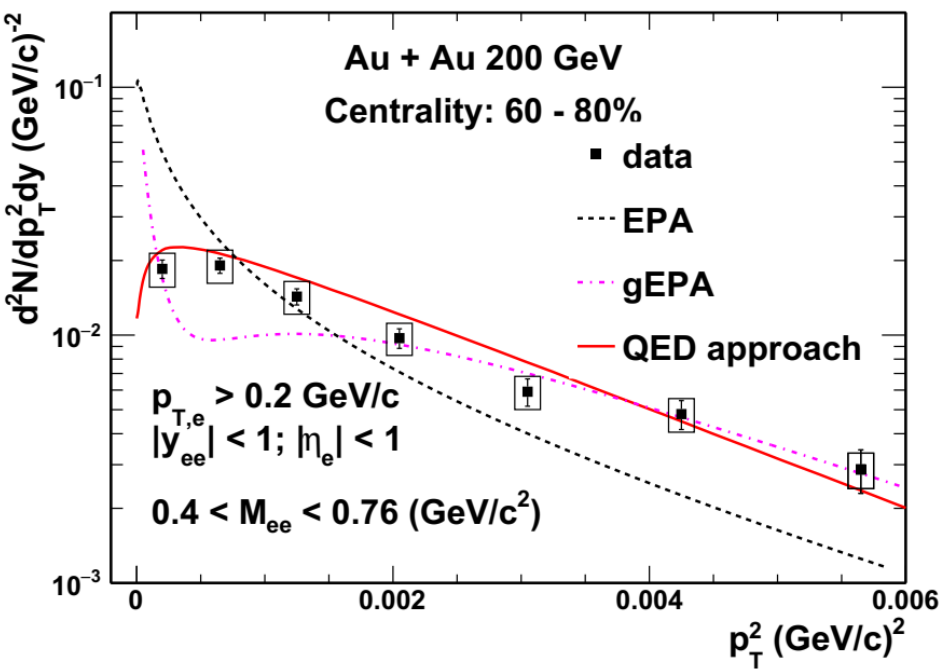
Phys. Rev. D 104 (2021) 056011

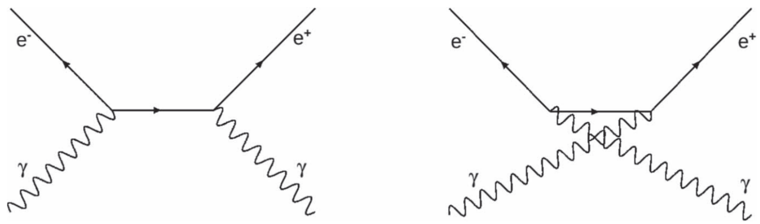
- Fail to reproduce data at very low p_T !
- Strange dip structure!

The baseline study from theoretical side

$$\sum_s |M|^2 = (Z\alpha)^4 \frac{4}{\beta^2} \int d^2\Delta q_1 d^2 q_1 \; [N_0 N_1 N_3 N_4]^{-1} \exp(i\Delta\vec{q}_1 \cdot \vec{b})$$
$$\times \mathrm{Tr}\Big\{ (\not{p}_- + m) \Big[N_{2D}^{-1} \not{u}^{(1)} (\not{p}_- - \not{q}_1 + m) \not{u}^{(2)} + N_{2X}^{-1} \not{u}^{(2)} (\not{q}_1 - \not{p}_+ + m) \not{u}^{(1)} \Big]$$
$$\times (\not{p}_+ - m) \Big[N_{5D}^{-1} \not{u}^{(2)} (\not{p}_- - \not{q}'_1 + m) \not{u}^{(1)} + N_{5X}^{-1} \not{u}^{(1)} (\not{q}'_1 - \not{p}_+ + m) \not{u}^{(2)} \Big] \Big\}$$

QED approach



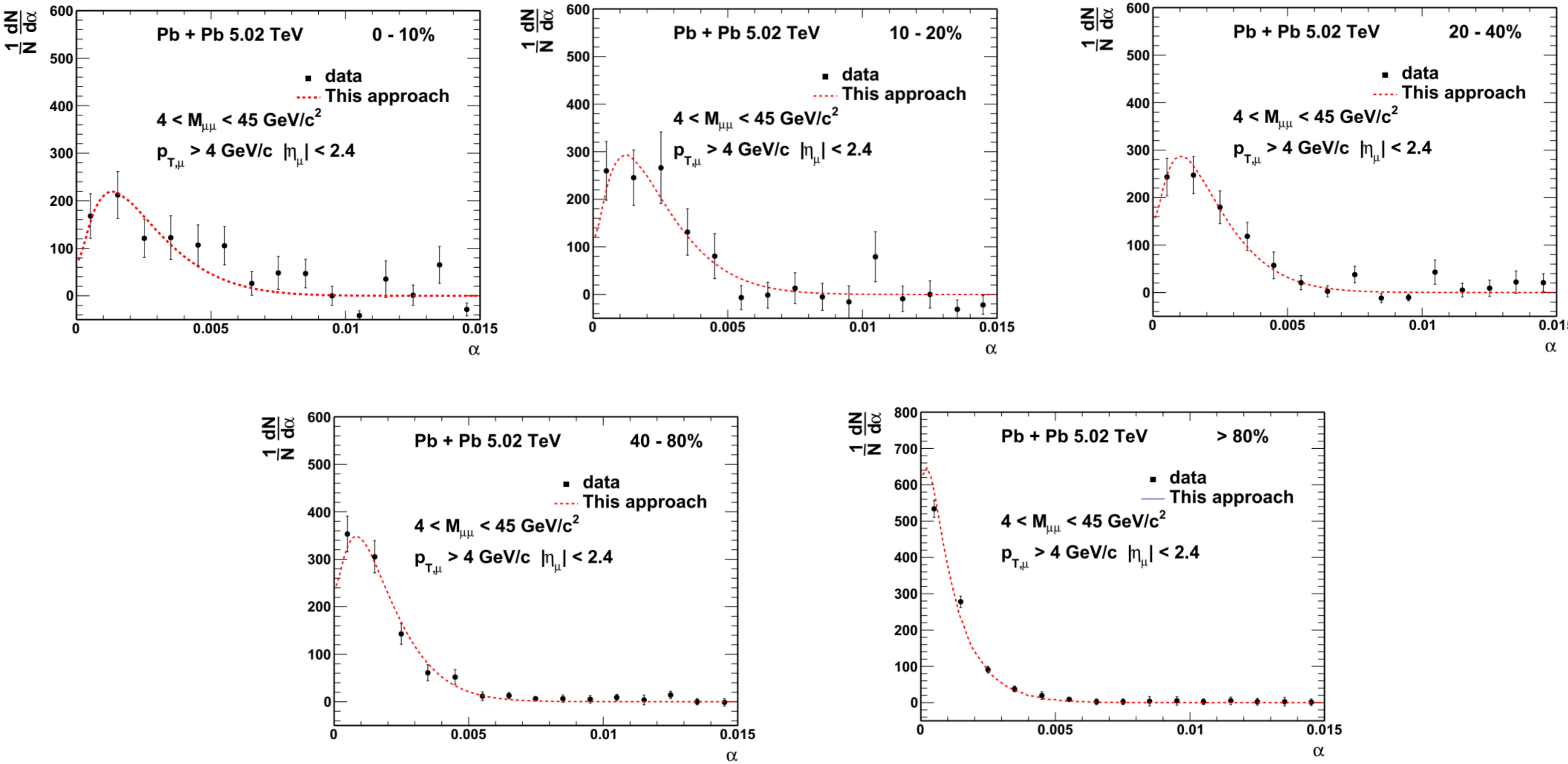


PRA **51** (1995) 1874

- Reasonably describe the p_T spectrum.

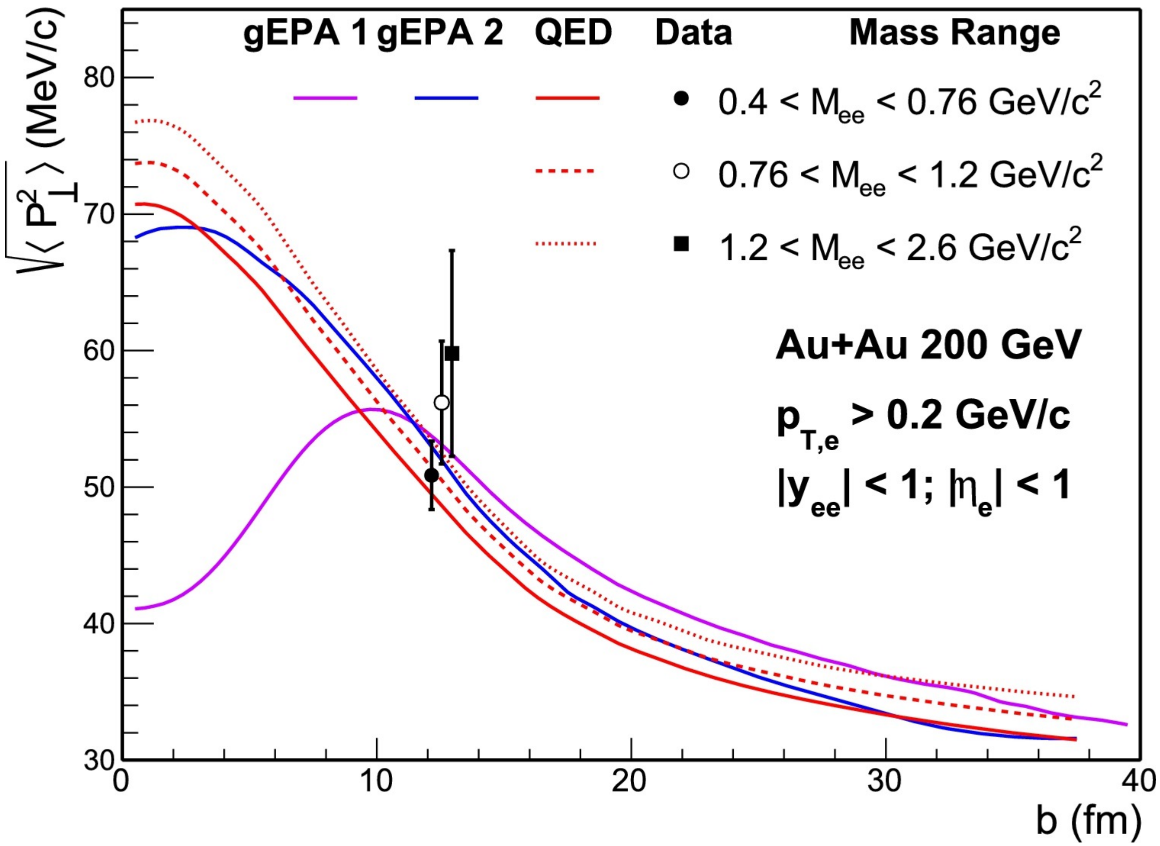
W. Zha etal, PLB 800 (2020) 135089

The baseline study from theoretical side



Successfully reproduce the centrality dependence of acoplanarity!

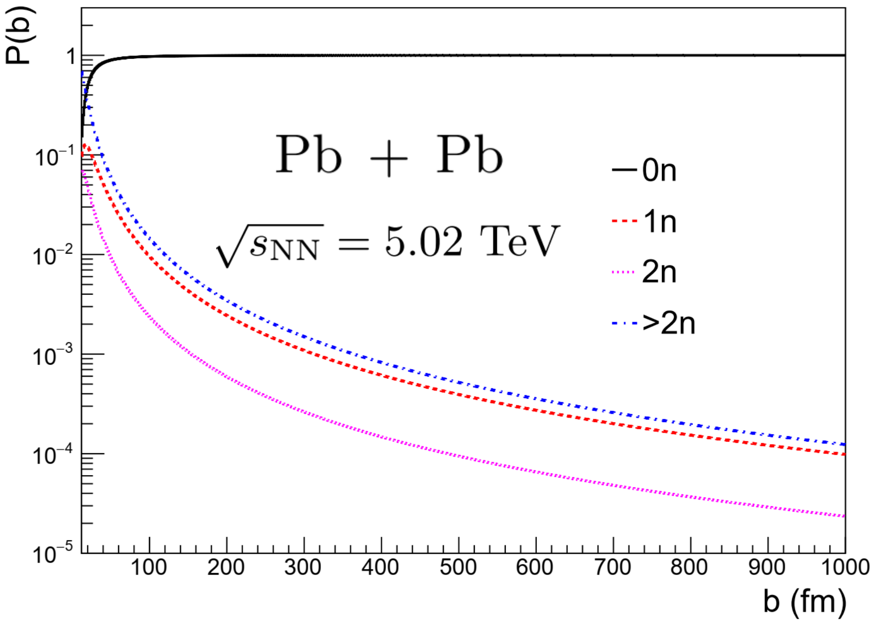
The impact parameter dependence of baseline

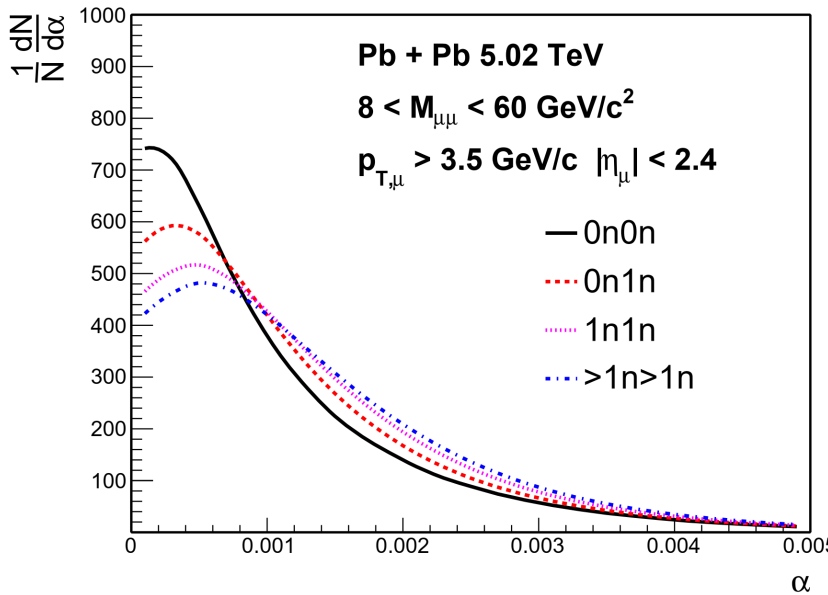


Strong dependence on impact parameter and pair mass!

"Centrality" engineering in UPCs

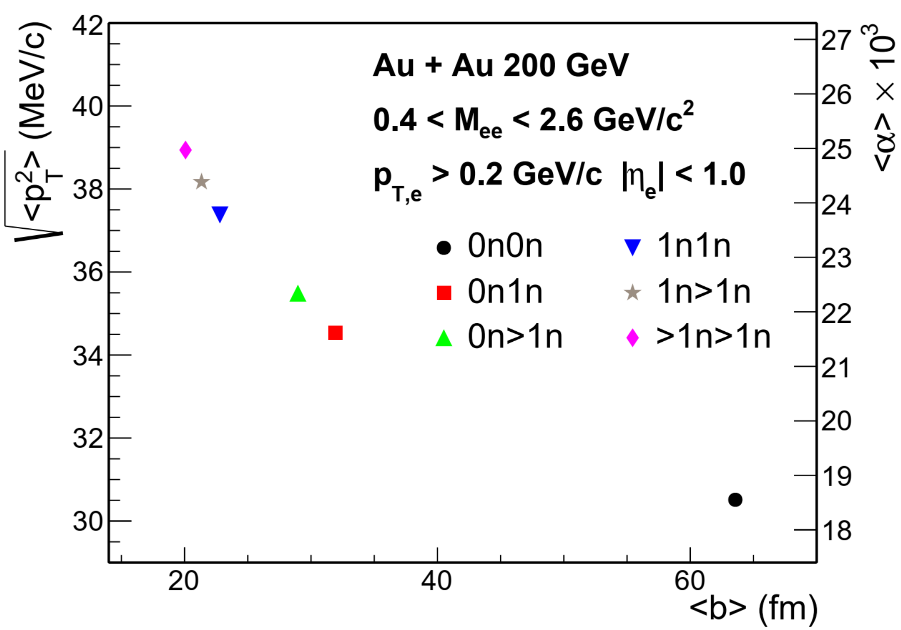
Neutron tagging!

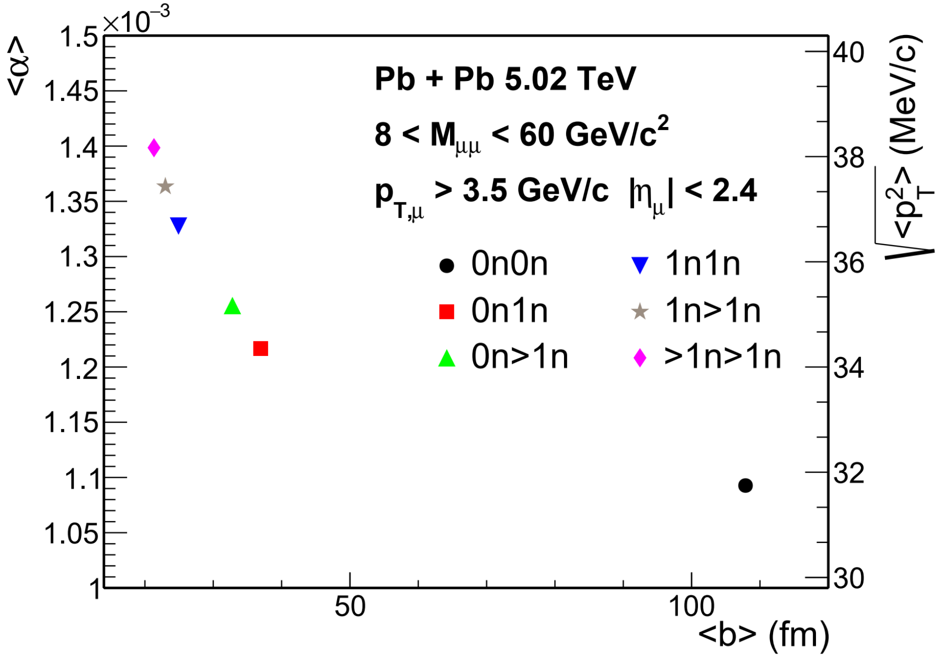




- The neutron multiplicity from multi-coulomb dissociation (MCD)
- Significant difference for pair p_T broadening in different centralities of UPCs!

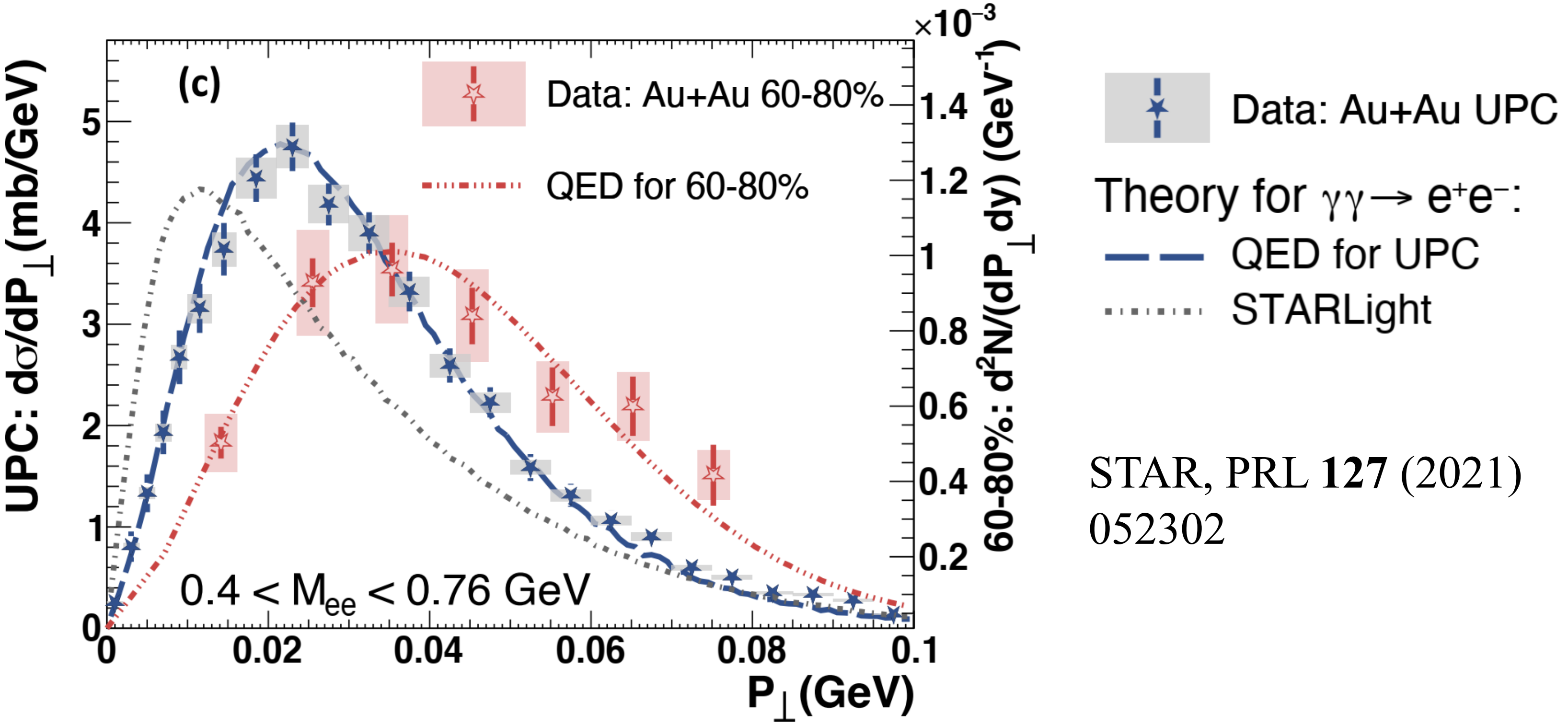
Initial broadening for different centralities in UPCs





- The average impact parameters vary significantly!
- Strong dependence on the centralities!

The efforts from experimental side

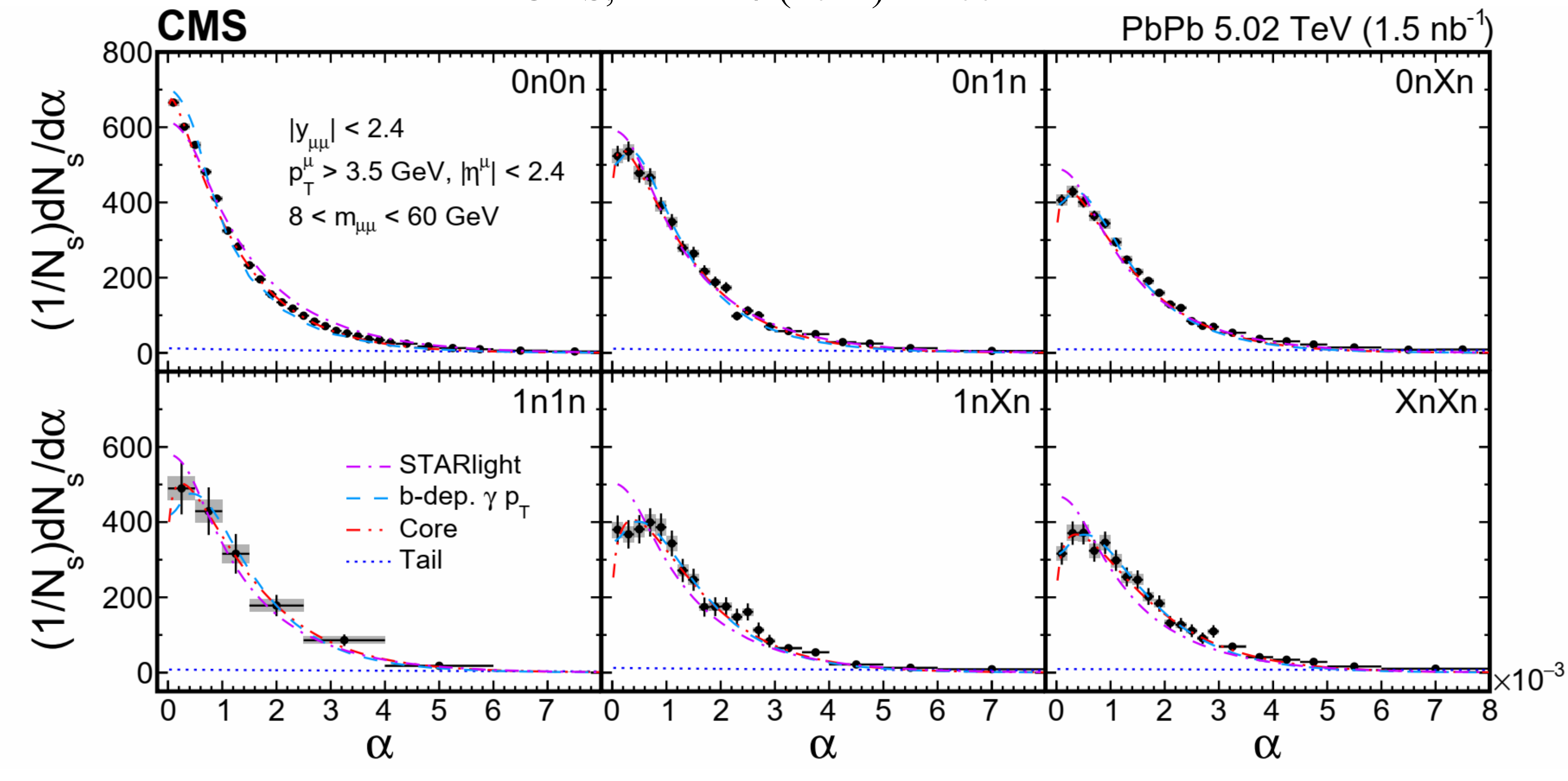


STAR, PRL **127** (2021) 052302

- The EPA approach even failed in UPCs !
- Significant difference between peripheral collisions and UPCs!

The efforts from experimental side

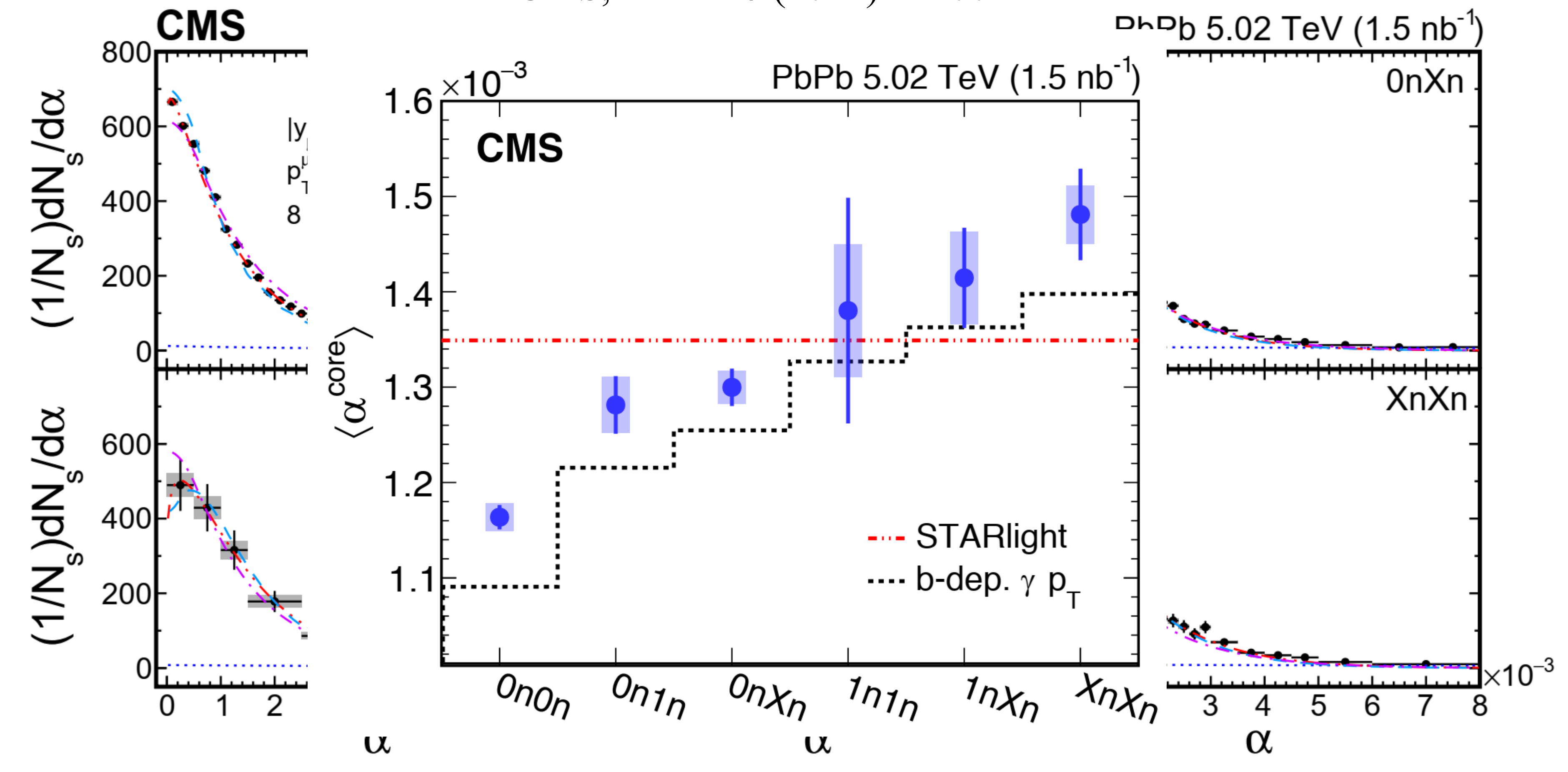
CMS, PRL **127** (2021) 122001



Significant difference in different centralities of UPCs!

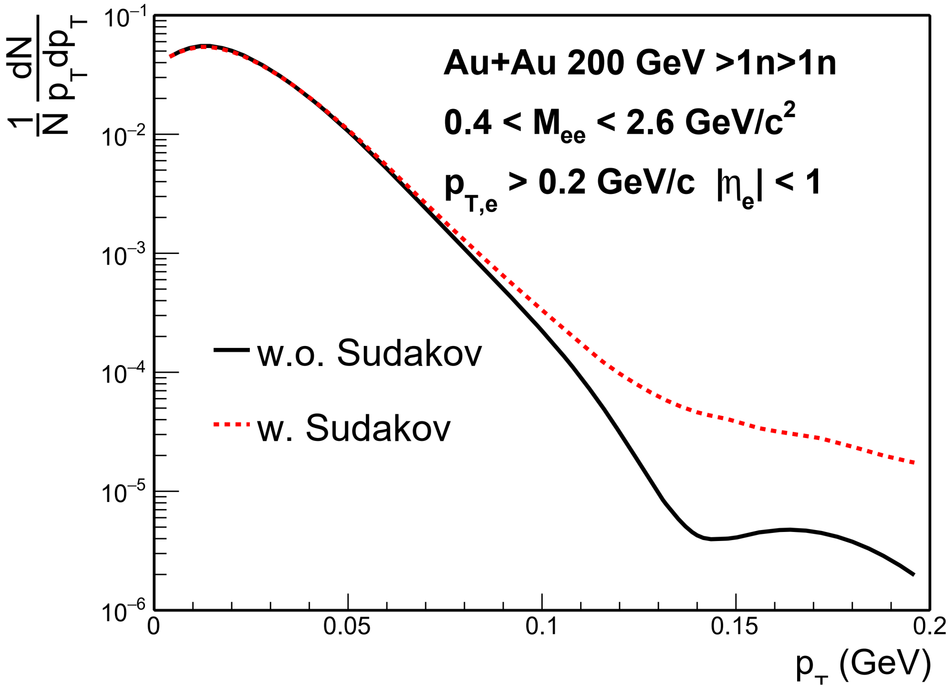
The efforts from experimental side

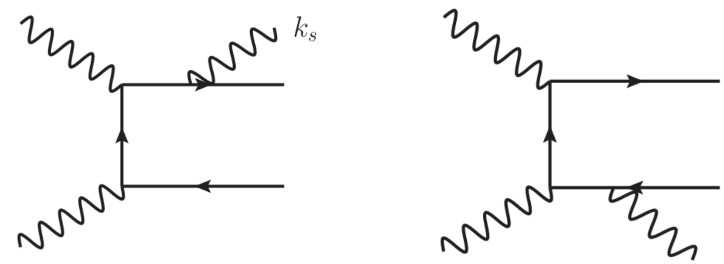
CMS, PRL **127** (2021) 122001



Sizable gap between measurement and QED calculation!

The higher-order tail: Sudakov effect





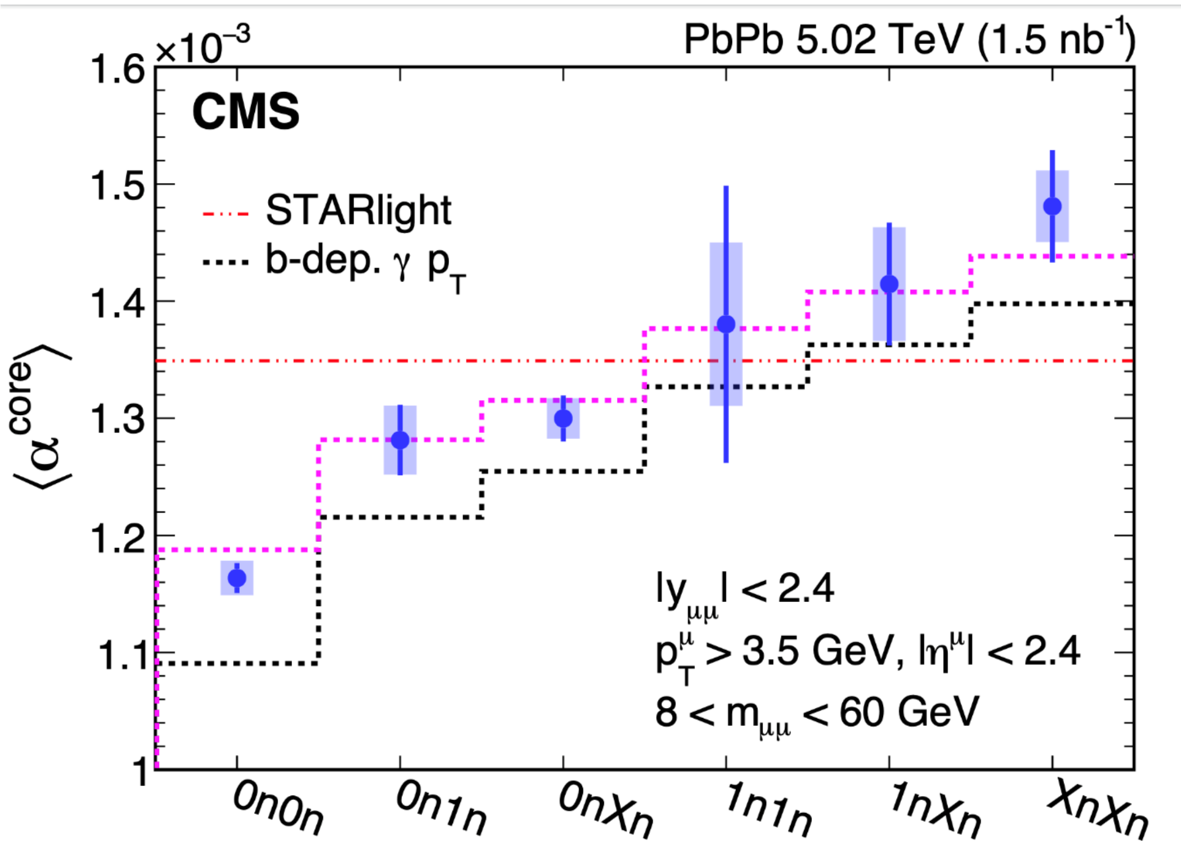
$$\int \frac{d^2 r_\perp}{(2\pi)^2} e^{i r_\perp \cdot q_\perp} e^{-S(Q,r_\perp)} \int d^2 q'_\perp e^{i r_\perp \cdot q'_\perp} d\sigma_0(q'_\perp, \ldots)$$

$$S(Q, r_\perp) = \begin{cases} \frac{\alpha_e}{2\pi} \ln^2 \frac{Q^2}{\mu_r^2}, & \mu_r > m_\mu \\ \frac{\alpha_e}{2\pi} \ln \frac{Q^2}{m_\mu^2} \left[\ln \frac{Q^2}{\mu_r^2} + \ln \frac{m_\mu^2}{\mu_r^2} \right], & \mu_r < m_\mu \end{cases}$$

S.R. Klein etal., PRL**122** (2019) 132301

- Negligible effect of soft photon radiation for low p_T at RHIC!
- Produce a long tail at relative high p_T!

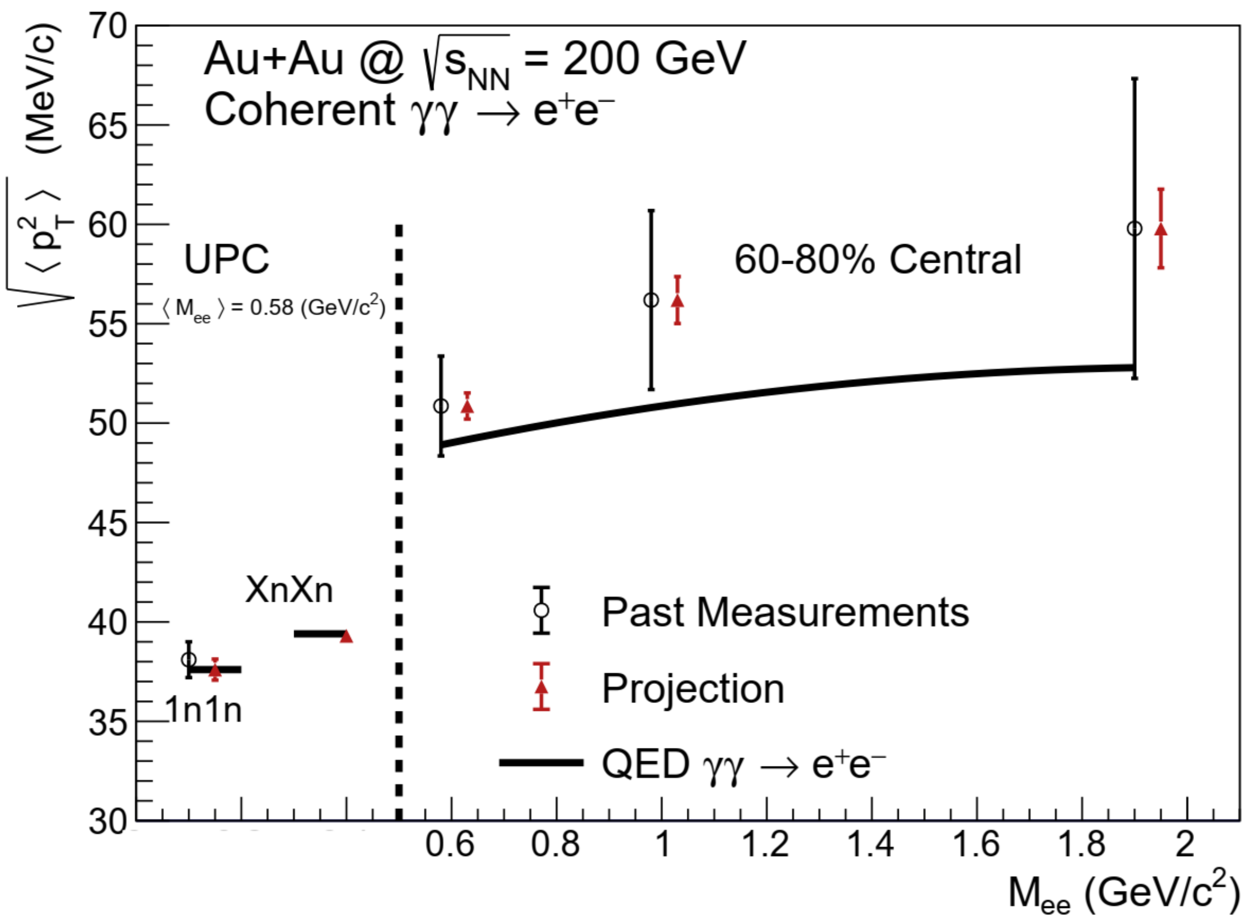
The QED method with Sudakov effect



- The Sudakov effect is sizable at LHC!
- Describe the data very well for different centralities in UPCs!

Can we see the medium effect?

The projection for RHIC run 2023-2025



The Schwinger Mechanism and higher order effect

The production rate of Schwinger Mechanism at a given constant electric field E:

C. Itzykson, J.B. Zuber
Quantum Electrodynamics of Strong Fields

$E_c = 1.3\times10^{16}\, V/cm$

$$\frac{d^4 n_{e^+e^-}}{d^3x dt} \sim \frac{c}{4\pi^3 \lambda_c^4} \exp(-\pi \frac{E_c}{E})$$

At RHIC b = 15 fm:

$E_{Max} = 5.3\times10^{16}\, V/cm$

The non-perturbative nature of the production mechanism.

-Related to the "$Z\alpha > 1$" problem.

$\Delta t \approx \hbar/2mc^2 \approx 5\times10^3$ fm/c

$\Delta t_{HIC} \approx \frac{R_A}{\gamma}$ 0.06 fm/c at RHIC

$\Delta t_{Laser} >> \Delta t >> \Delta t_{HIC}$

⇓ Non-perturbative

⇓ Perturbative

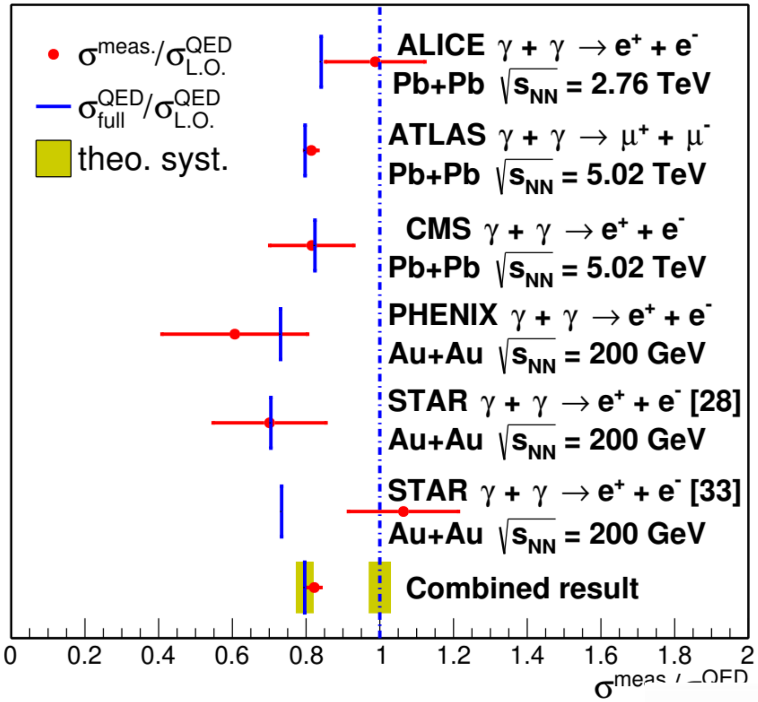
At RHIC and LHC $Z\alpha \sim 0.6$

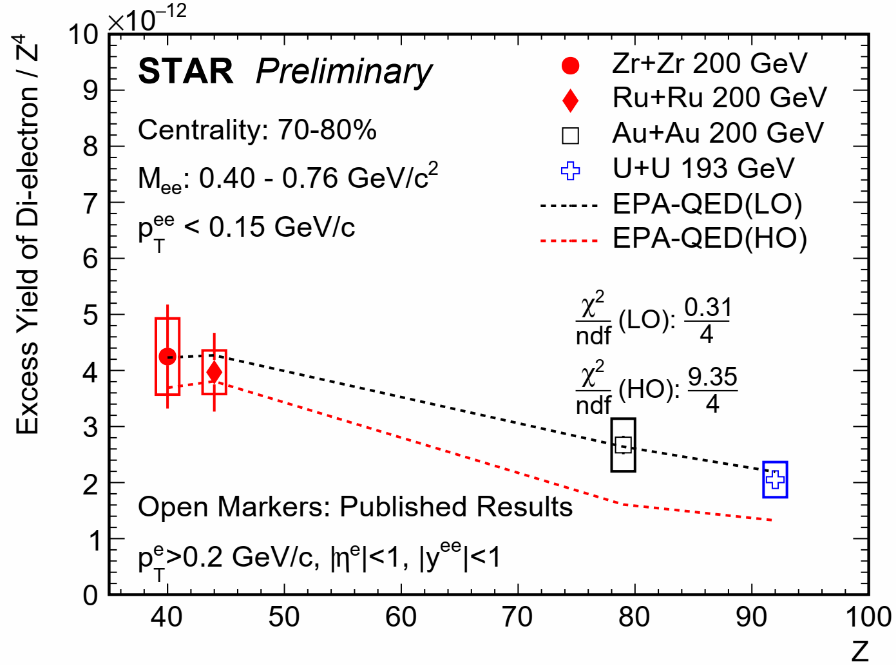
Still Perturbative, but with sizable higher-order effect!

Link the crossover from perturbative to non-perturbative region!

The higher-order effect puzzle

JHEP 08 (2021) 083

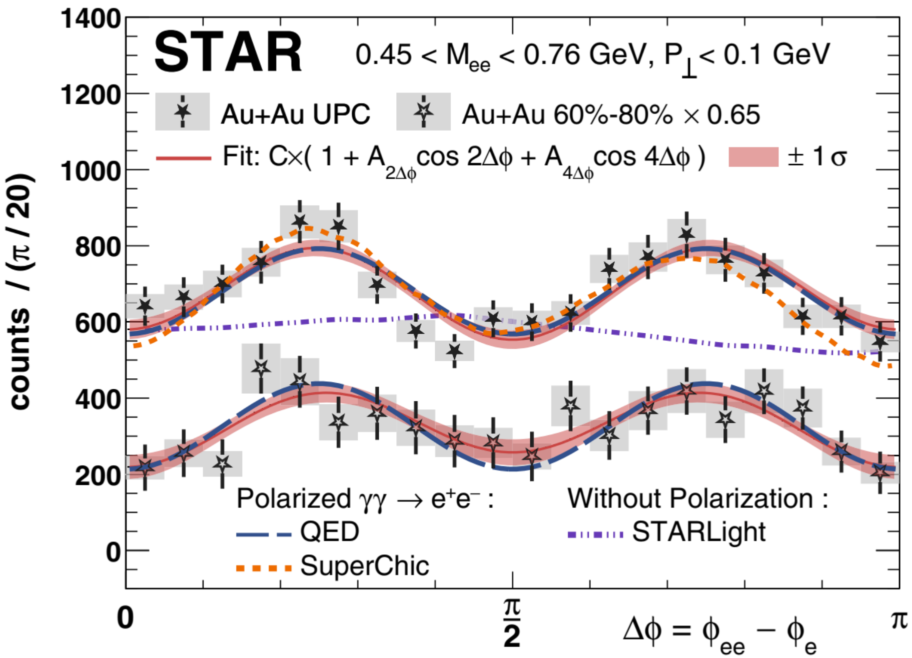




Consistent with Higher Order results

Favor the Leading Order predictions

The observation of the linear polarization



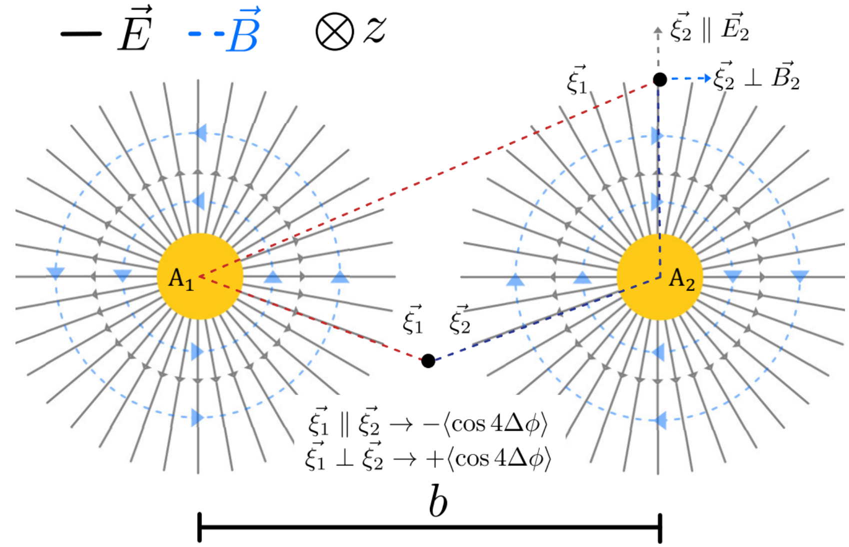
Ultra-Peripheral

Quantity	Measured	QED	χ^2/ndf
$-A_{4\Delta\phi}(\%)$	16.8 $\pm$ 2.5	16.5	18.8 / 16

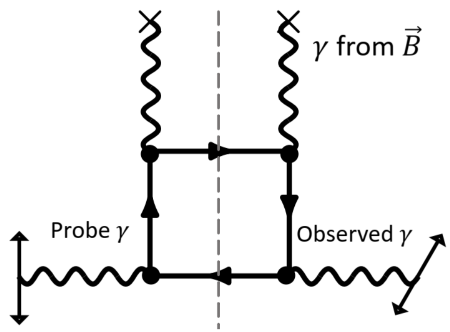
Peripheral (60−80%)

Quantity	Measured	QED	χ^2/ndf
$-A_{4\Delta\phi}(\%)$	27 $\pm$ 6	34.5	10.2 / 17

The photons are linearly polarized!

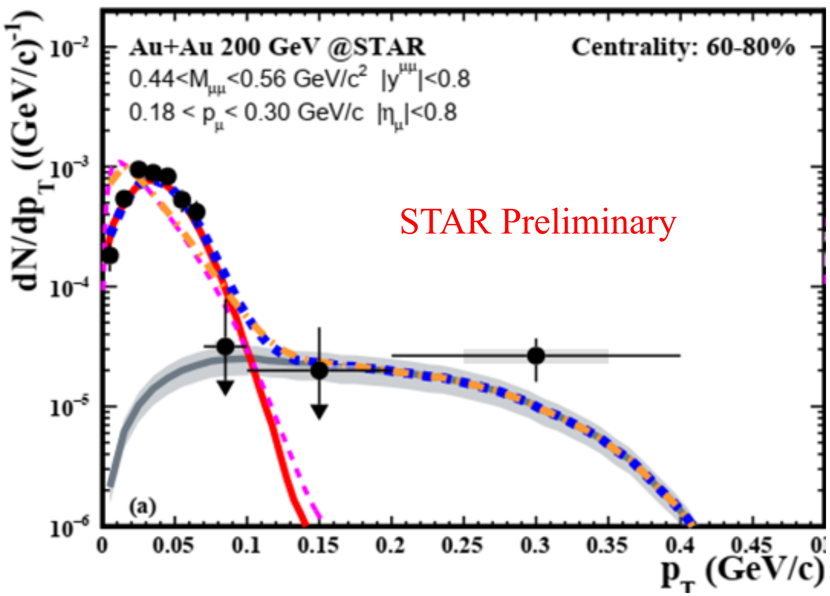


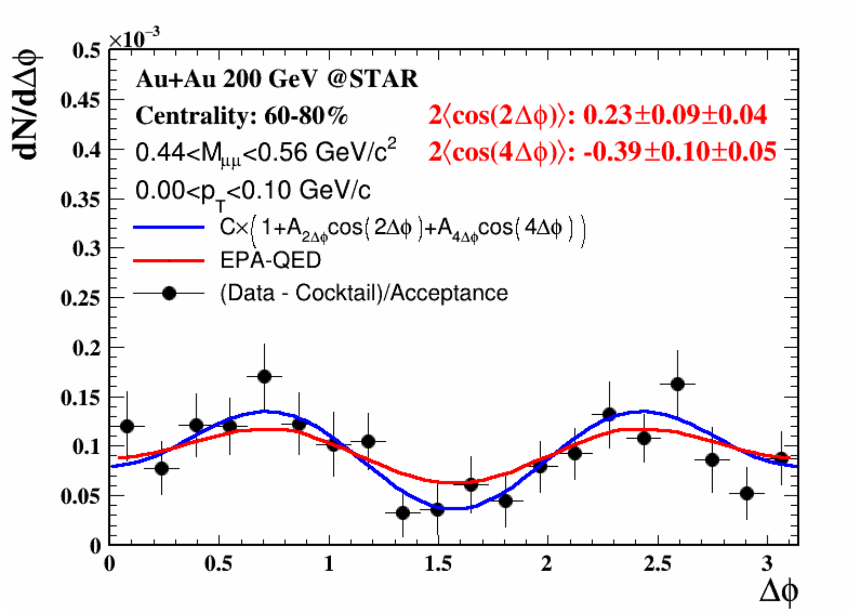
C. Li, J. Zhou, Y.-j. Zhou, Phys. Lett. B 795, 576 (2019)



Link to Vacuum Birefringence!

The dimuon channel



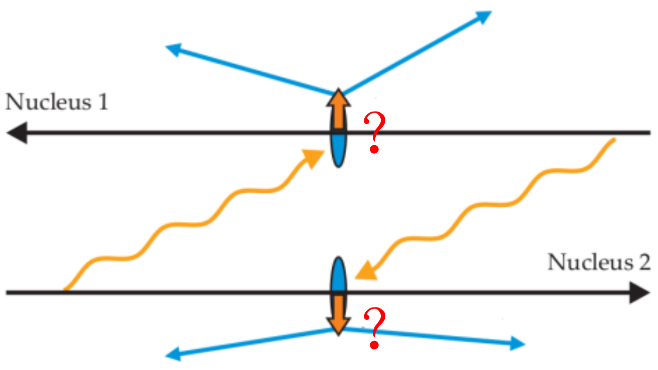


- ✓ Observation of dimuon excess from photoproduction
- ✓ Consistent with impact parameter dependence picture

- ✓ Evidence of the 4th-order azimuthal angular modulation
- ✓ First indication of the 2nd-order azimuthal angular modulation

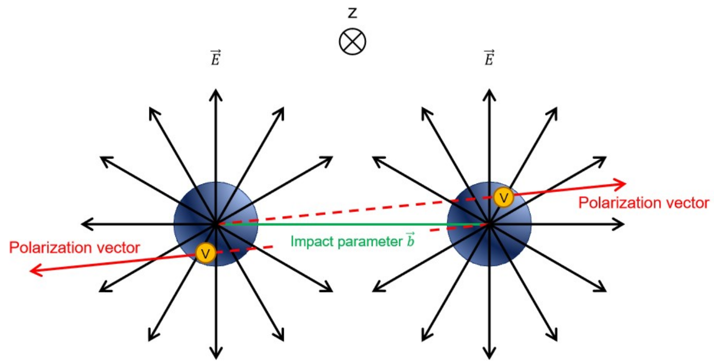
$$< \cos 2\Delta\phi > \propto m^2/p_\perp^2$$

Linear polarization and interference



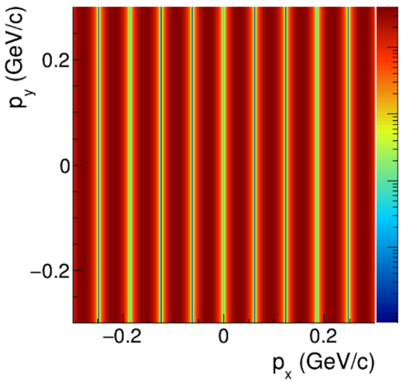
PRD 103 (2021), 033007

Linearly polarized photons

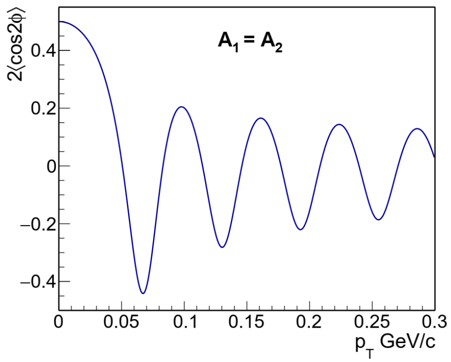


Decay along the impact parameter

$$\frac{d^2N}{d\cos\theta d\phi} = \frac{3}{8\pi}\sin^2\theta[1+\cos 2(\phi-\Phi)]$$

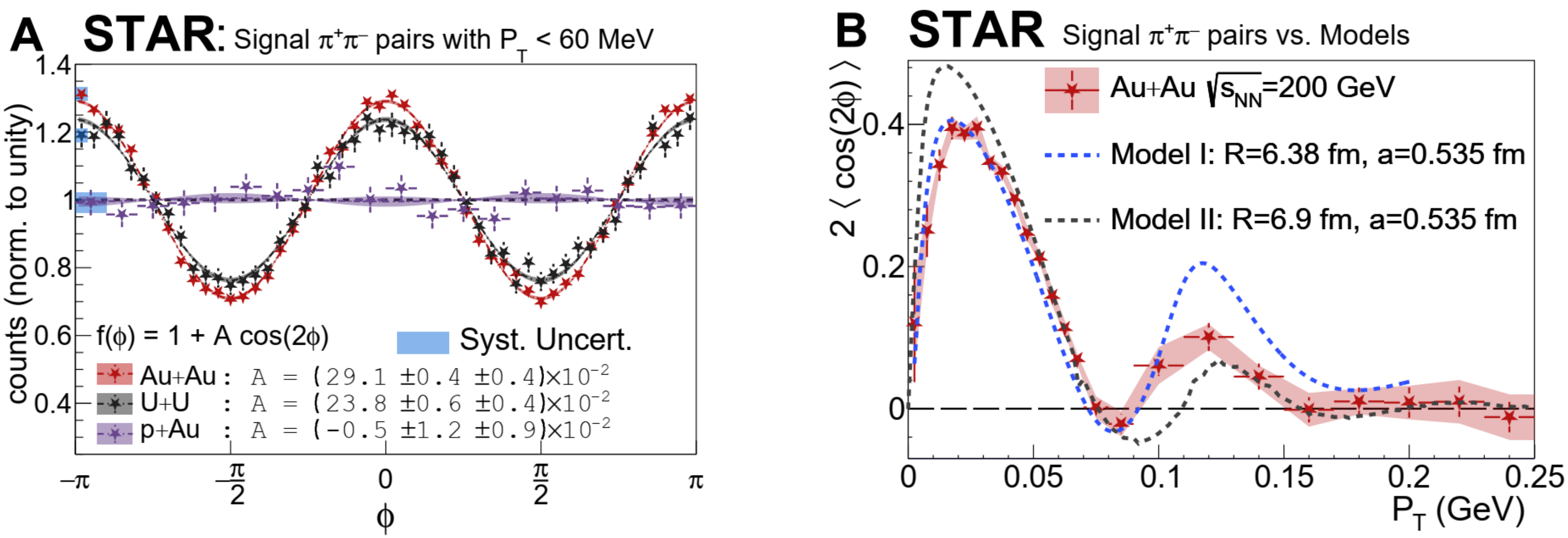


The second order modulation



The double slits interference in polarization space

STAR， Sci. Adv. **9** (2023) eabq3903



[1] J. High Ener. Phys. **2020**, 64 (2020).
[2] Phys. Rev. D **103**,033007 (2021)

Significant difference between Au and U

Prediction for U? Second peak?

Sensitive to the nuclear geometry / gluon distribution

The double slits interference in polarization space

Example of EPR paradox

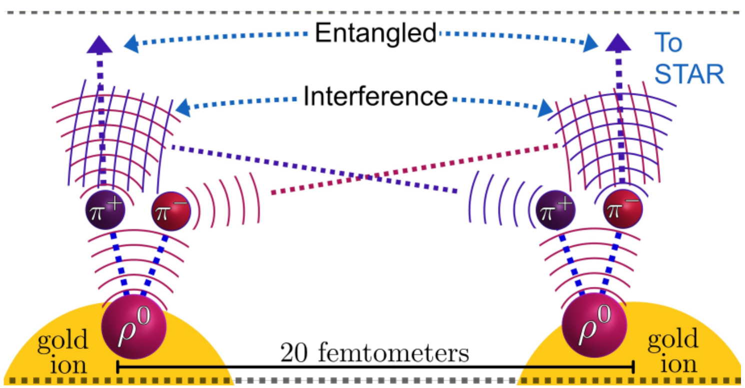
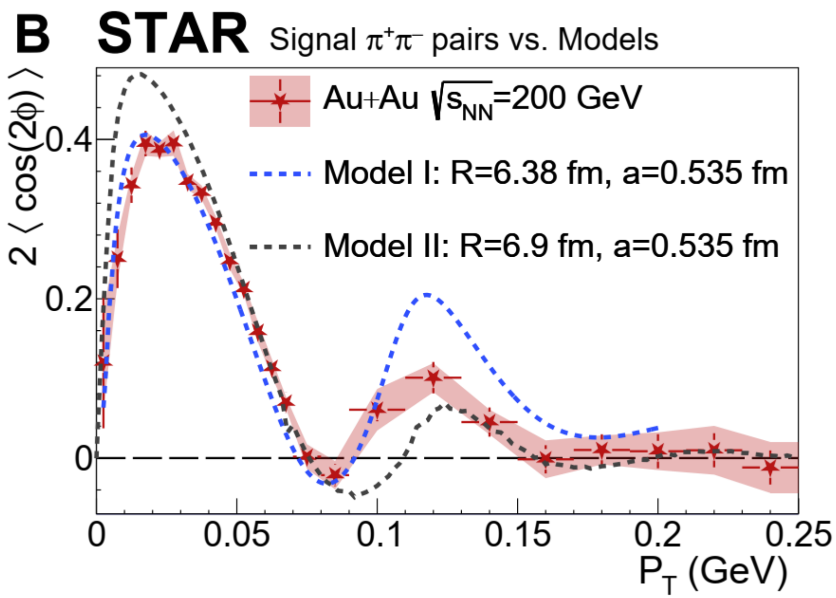


Figure from Zhangbu



[1] J. High Ener. Phys. **2020**, 64 (2020).
[2] Phys. Rev. D **103**,033007 (2021)

The life time ρ : ~1fm/c

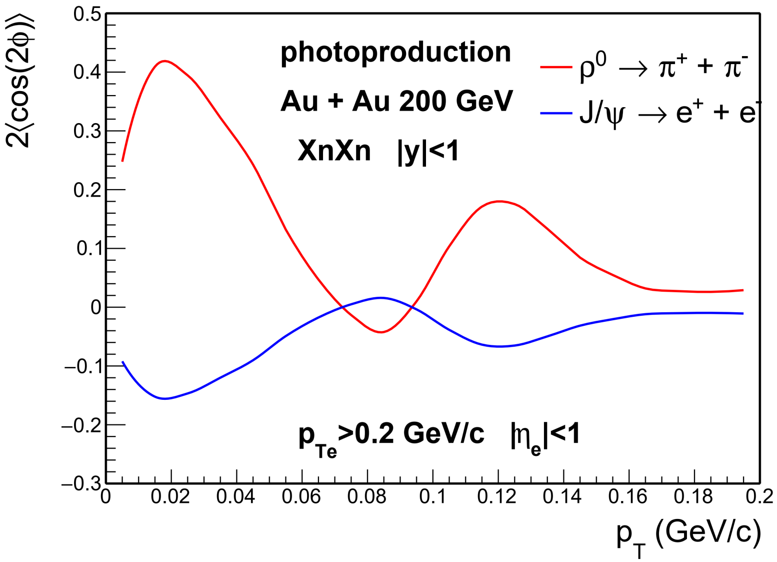
b ~20fm

Prediction for U? Second peak?

Sensitive to the nuclear geometry / gluon distribution

The case for J/ψ

Prediction



$$\frac{d^2N}{d\cos\theta d\phi} = \frac{3}{16\pi}(1+\cos^2\theta)\left[1 - \frac{\sin^2\theta}{1+\cos^2\theta}\cos 2(\phi - \Phi)\right]$$

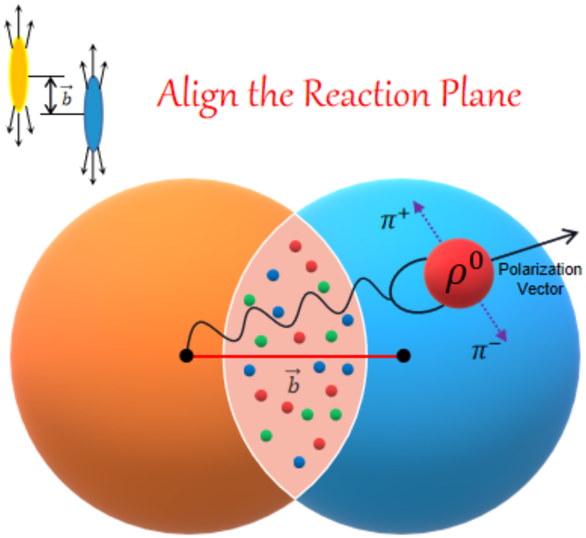
- ✓ Opposite sign
- ✓ Also sizable

Experimental result

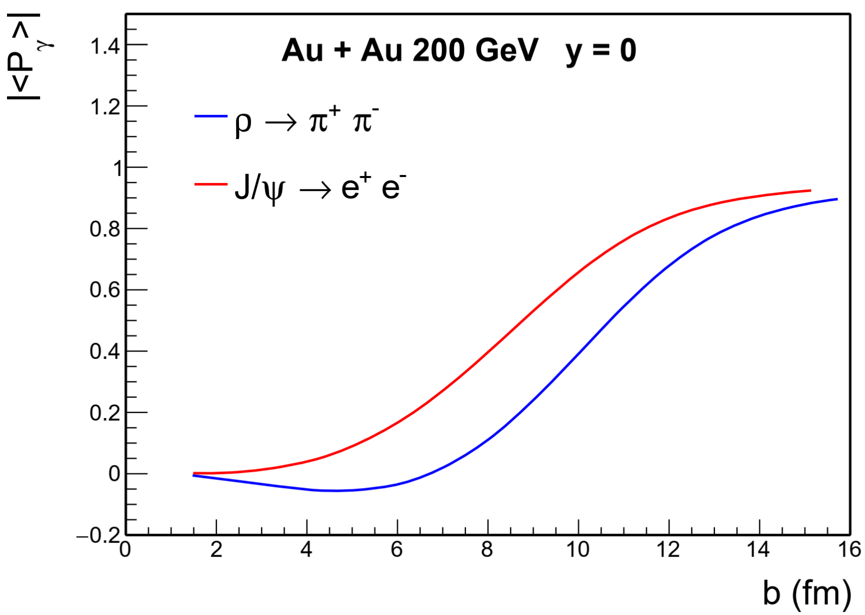
Still in progress

Align the reaction plane

X. Wu et al., PRR **4** (2022) L042048



$$P_\gamma = < \frac{E_x^2 - E_y^2}{E_x^2 + E_y^2} >$$



- ✓ Determined by collision geometry
- ✓ Natural resistance to non-flow correlation
- ✓ No event-event fluctuation
  -Good-Walker paradigm

Could directly link the final flow to initial geometry!

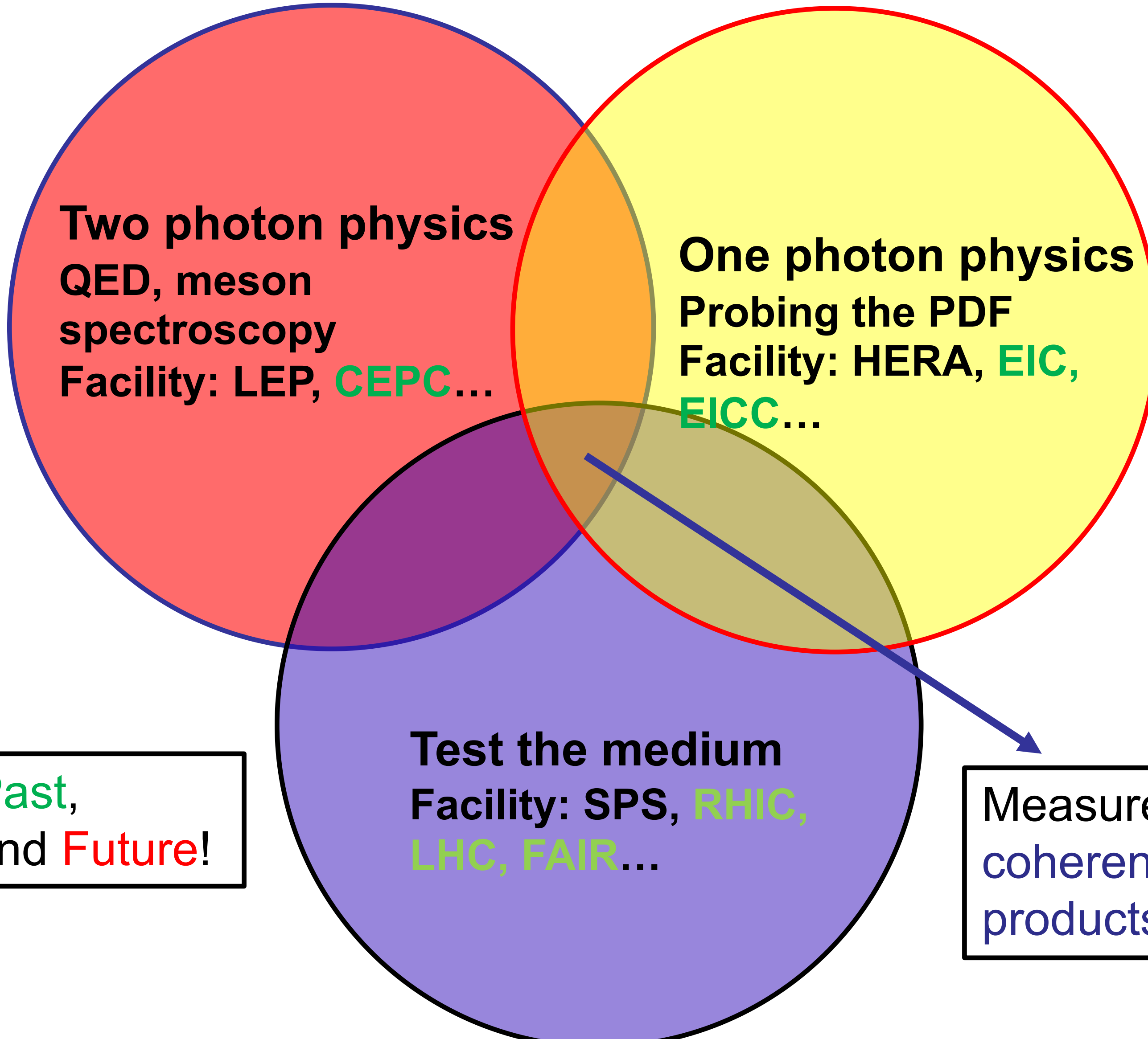
Summary

- Significant excess of dilepton and quarkonium production in hadronic heavy-ion collisions
  - --- Existence of coherent photoproduction in non-UPCs
  - --- The impact parameter dependence
  - --- Higher order effect

- The linear polarization of the process in heavy-ion collisions
  - --- Angular modulation
  - --- Reaction plane determination

- Novel probe for QGP?
  - --- Precise knowledge on the baseline
  - --- Precise measurement in the future

Outlook



Link the Past, Present and Future!

Measurements of coherent photon products in **HHIC**!