NSFC
National Natural Science
Foundation of China

Coherent photoproduction in heavy-ion collisions

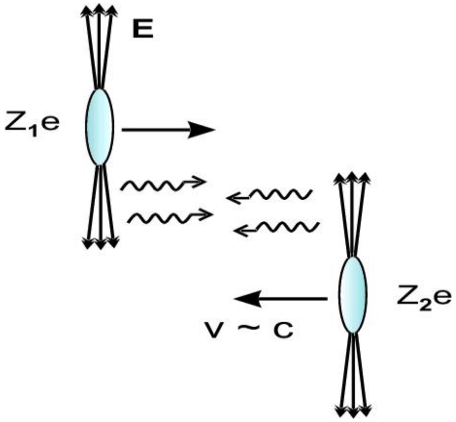
Wangmei Zha
University of Science and Technology of China

Collaborators: Daniel Brandenburg, Lijuan Ruan,
Zebo Tang, Zhangbu Xu

The 142nd HENPIC seminar, June 16, 2021

online

Coherent photons as “partons” in heavy-ion collisions



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

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

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

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

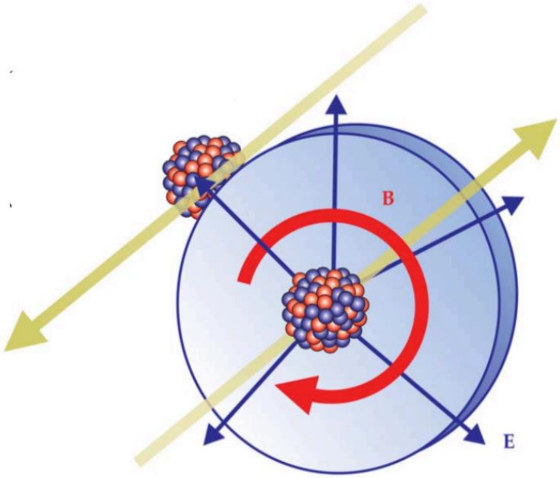
- View photons as “partons” being present with fast moving ions!

The extent of photons swarming about the ions:

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

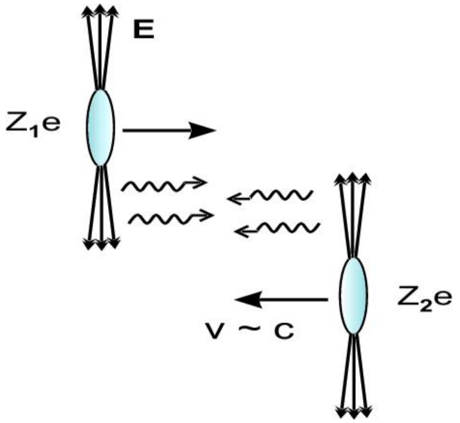
$R_{photons}$ >> R_{Nuc}

Take the photoproduction of ρ (Au+Au 200 GeV)in ultra-peripheral collisions (UPCs) as example: $<R_{producton}>$ ~ 40 fm



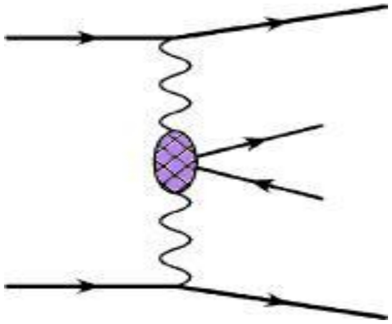
Physics Today **70**, 10, 40 (2017)

Photon interactions in A+A



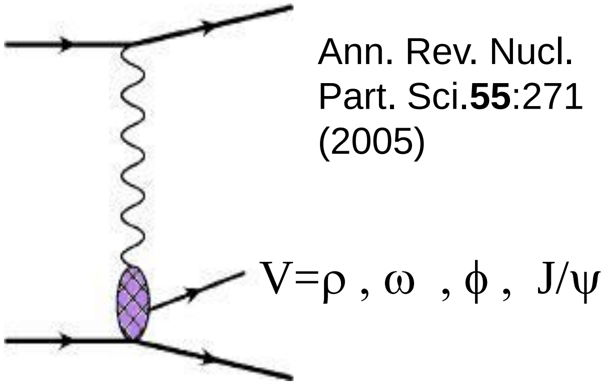
Electromagnetic interaction

=



Photon-photon interactions

+



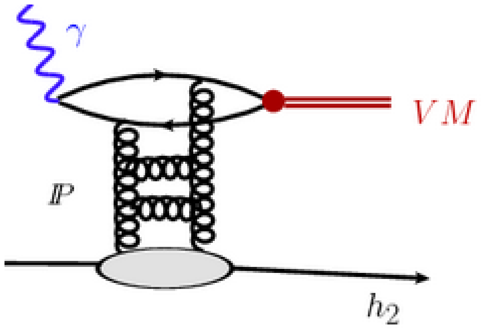
Ann. Rev. Nucl. Part. Sci.**55**:271 (2005)

Photon-nucleus interactions

- 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

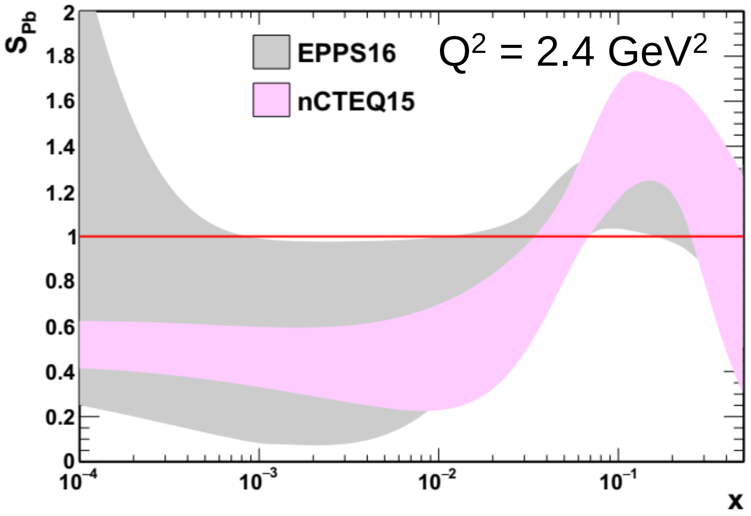
- Vector meson production:
  - ✓ chargeless ‘Pomeron exchange’
  - ✓ Light meson production is usually treated via vector meson dominance model: ρ, direct $\pi^+\pi^-$, ω….
  - ✓ Heavy quarkonia production could be treated with pQCD: J/ψ, ψ’, Υ(1S), Υ(2S), Υ(3S)…



- Sensitive to the gluon distribution:

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

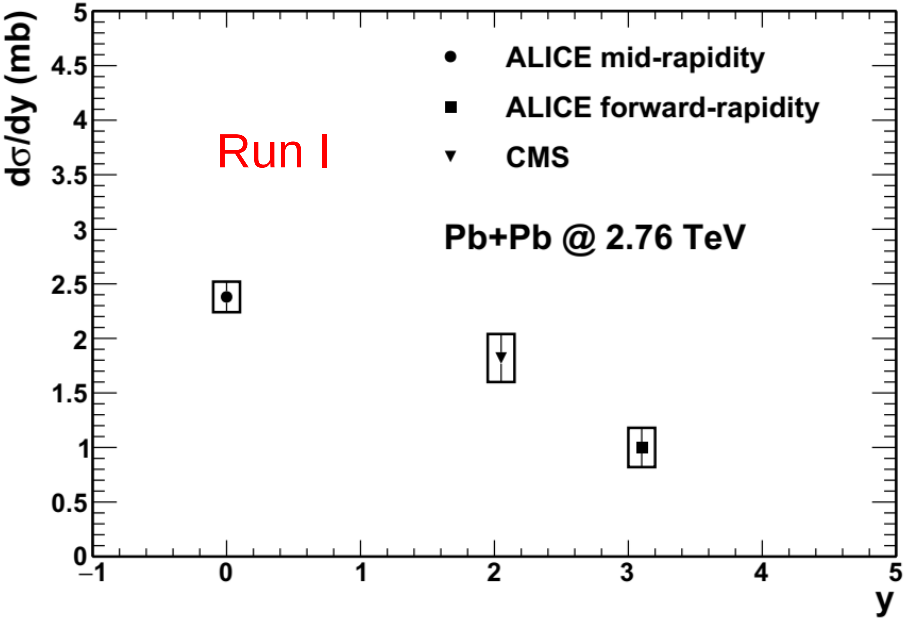
$$x = \frac{M_V e^{\pm y}}{\sqrt{s}} \quad Q^2 = M_V^2/4$$

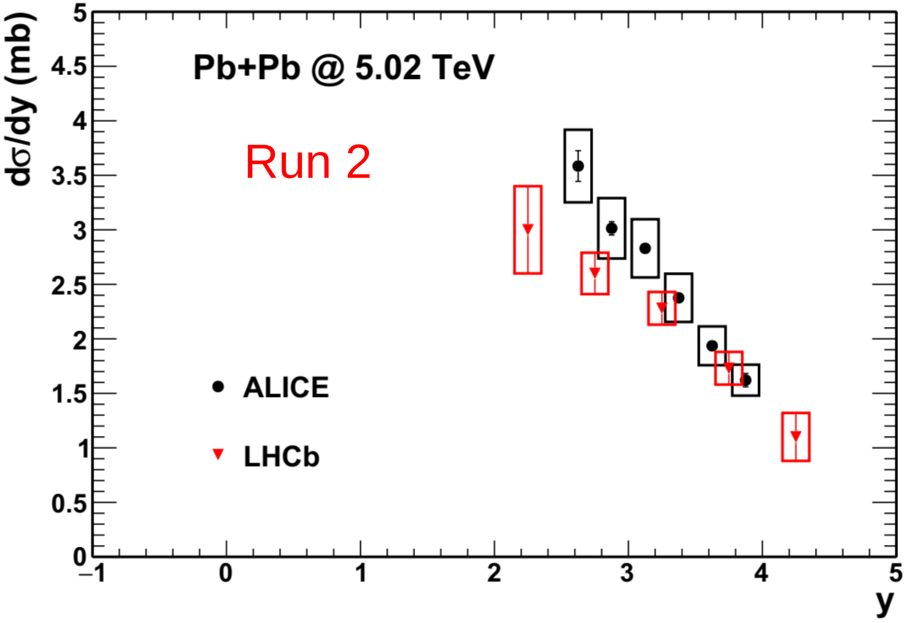


EPPS16: EPJC **77** (2017) 163

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

J/ψ photoproduction in Pb+Pb UPCs





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

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

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

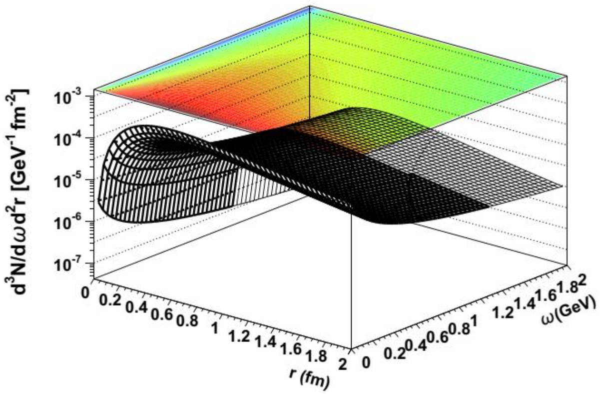
ALICE: PLB **798** (2019) 134926

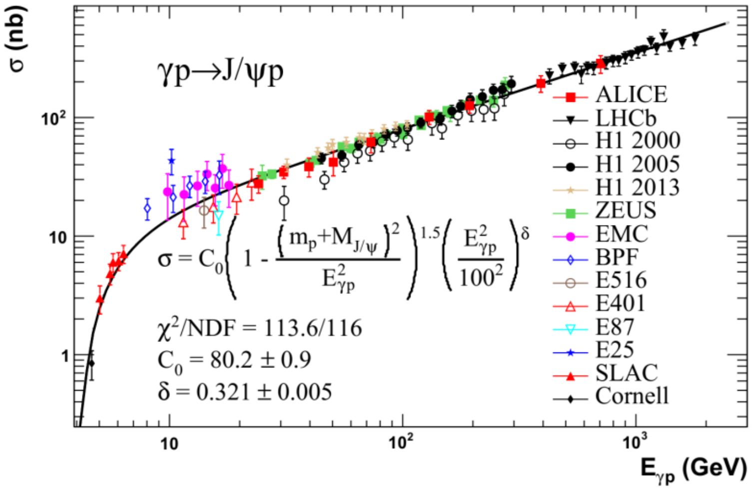
LHCb: LHCb-CONF-2018-003

Various precise measurements!
Powerful to constrain nPDF

The framework: impulse approximation

$$\frac{d\sigma_{AA\rightarrow AAJ/\psi}(y)}{dy} = N_{\gamma/A}(y)\sigma_{\gamma A\rightarrow J/\psi A}(y) + N_{\gamma/A}(-y)\sigma_{\gamma A\rightarrow J/\psi A}(-y)$$





Equivalent photon approximation

$$\sigma(\gamma A\rightarrow \mathrm{J}/\psi A) = \left.\frac{d\sigma(\gamma A\rightarrow \mathrm{J}/\psi A)}{dt}\right|_{t=0} \times$$

$$\int |F_P(\vec{k}_P)|^2 d^2\vec{k}_{P\perp} \qquad \vec{k}_P = (\vec{k}_{P\perp}, \frac{\omega_P}{\gamma_c})$$

$$\omega_P = \frac{1}{2}M_{\mathrm{J}/\psi}e^{\pm y} = \frac{M^2_{\mathrm{J}/\psi}}{4\omega_\gamma}$$

Z. Cao etal., Chin. Phys. C**43** (2019) 064103

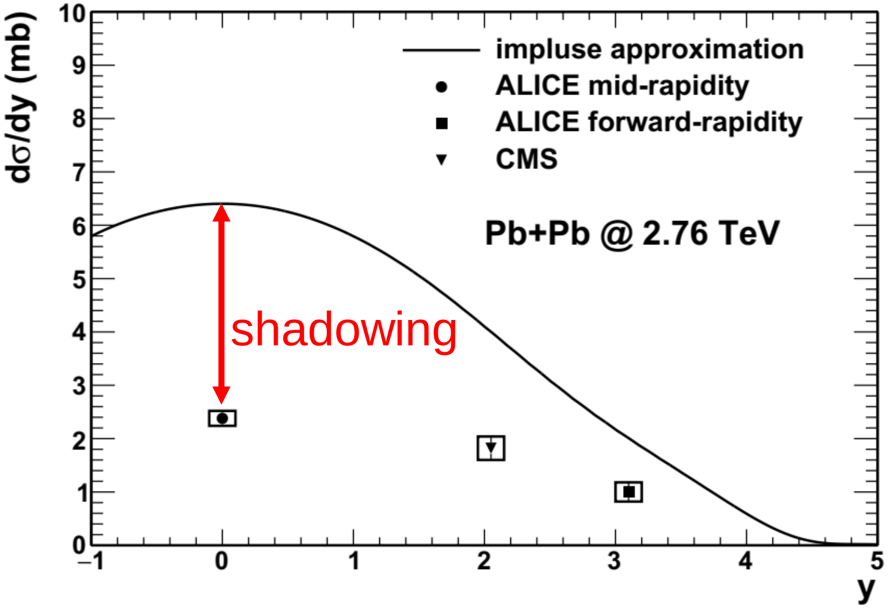
Impulse approximation

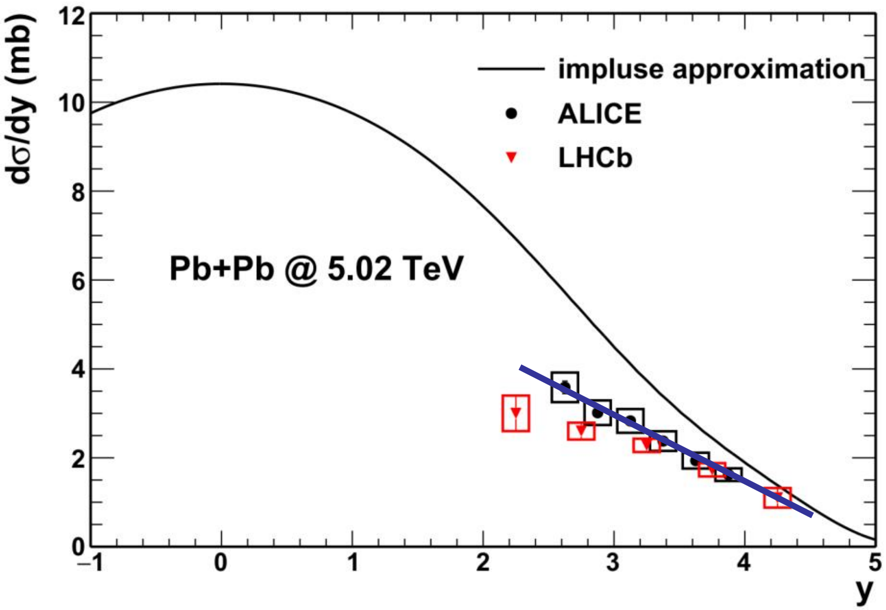
$$d\sigma_{\gamma A}/dt|_{t=0} = d\sigma_{\gamma p}/dt|_{t=0} \times A^2$$

$$d\sigma_{\gamma p}/dt = \sigma_0 \times e^{-bt}$$

$$d\sigma_{\gamma p}/dt|_{t=0} = \sigma_{\gamma p} \times b$$

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

The Bayesian reweighting of nuclear PDFs

The PDFs replica f_k can be constructed by the Hessian error set:

$$f_k \equiv f_{S_0} + \sum_i \left(\frac{f_{S_i^+} - f_{S_i^-}}{2} \right) R_{ik}$$

JHEP**08** (2012) 052

Any quantity $\mathcal{O}[f]$ depending on PDFs can be determined via:

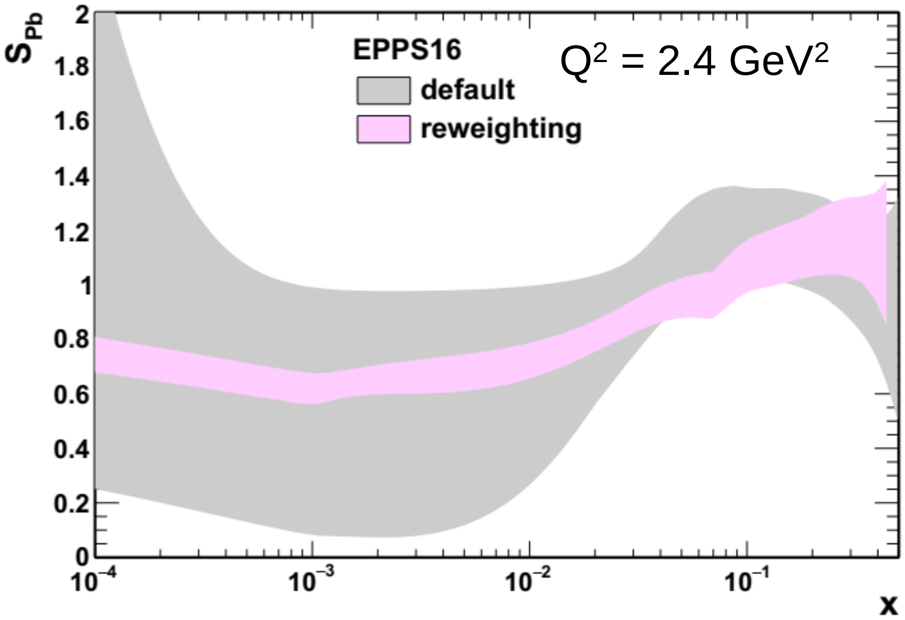
$$\langle \mathcal{O} \rangle = \frac{1}{N_{\text{rep}}} \sum_{k=1}^{N_{\text{rep}}} \mathcal{O}[f_k]$$

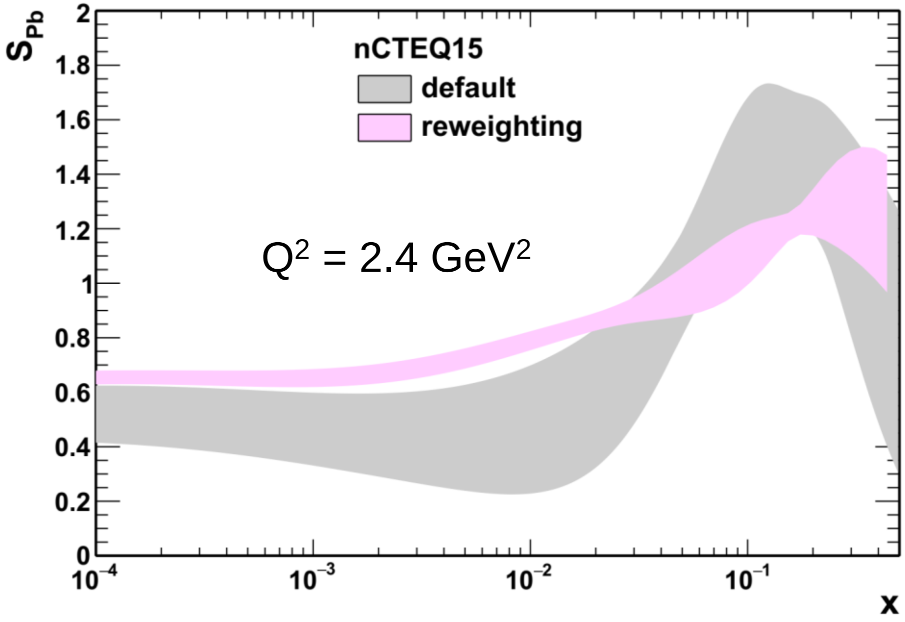
For a new measurement, $y = \{y_1, y_2, ..., y_n\}$, the reweighted PDF could be evaluated by:

$$\langle \mathcal{O} \rangle_{\text{new}} = \frac{1}{N_{\text{rep}}} \sum_{k=1}^{N_{\text{rep}}} w_k \mathcal{O}[f_k]$$

$$w_k = \frac{(\chi_k^2)^{\frac{1}{2}(n-1)} e^{-\chi_k^2/2}}{\frac{1}{N_{\text{rep}}} \sum_{k=1}^{N_{\text{rep}}} (\chi_k^2)^{\frac{1}{2}(n-1)} e^{-\chi_k^2/2}} \quad \chi_k^2(y, f_k) = \sum_{i,j=1}^{n} (y_i - y_i[f_k]) \text{cov}_{ij}^{-1} (y_j - y_j[f_k])$$

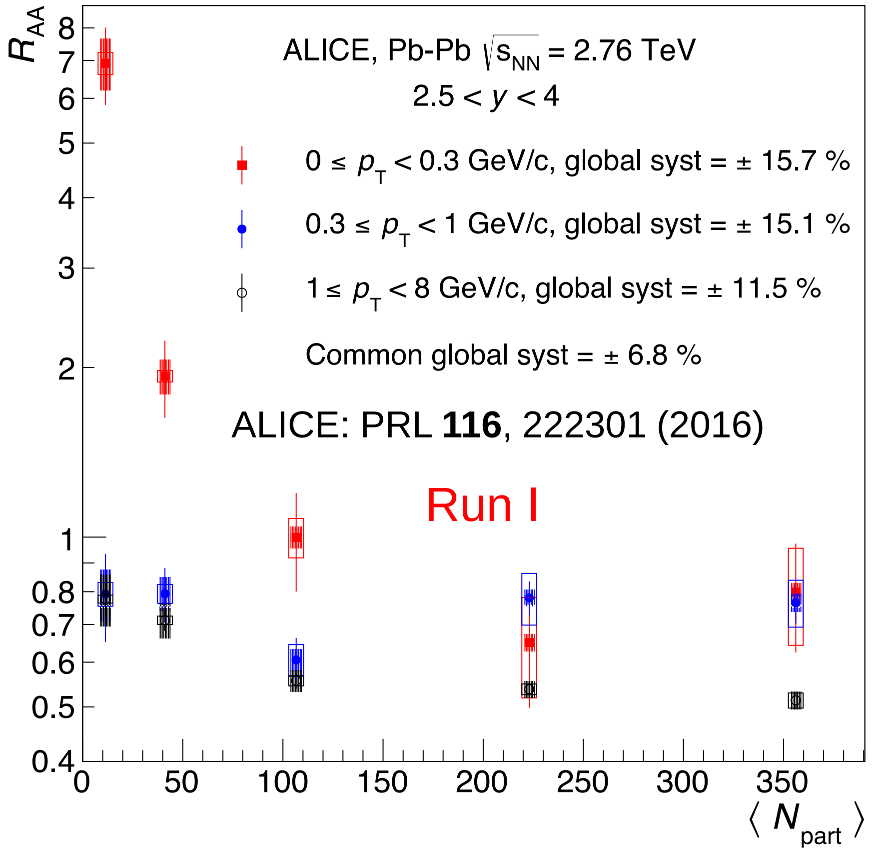
Nuclear shadowing from J/ψ measurements in UPCs





- 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.

Anomalous excess of J/ψ production observed at ALICE



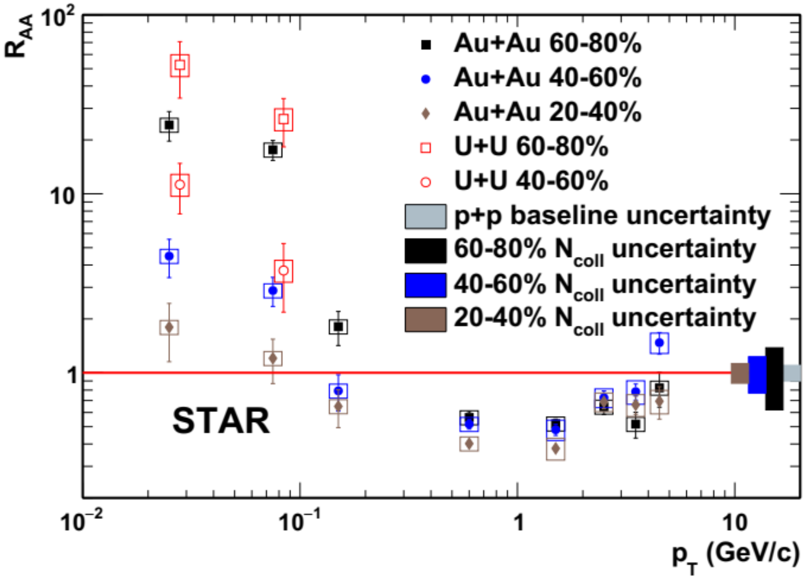
- Significant enhancement of J/ψ yield observed in p_T interval 0 – 0.3 GeV/c for peripheral collisions (50 – 90%).

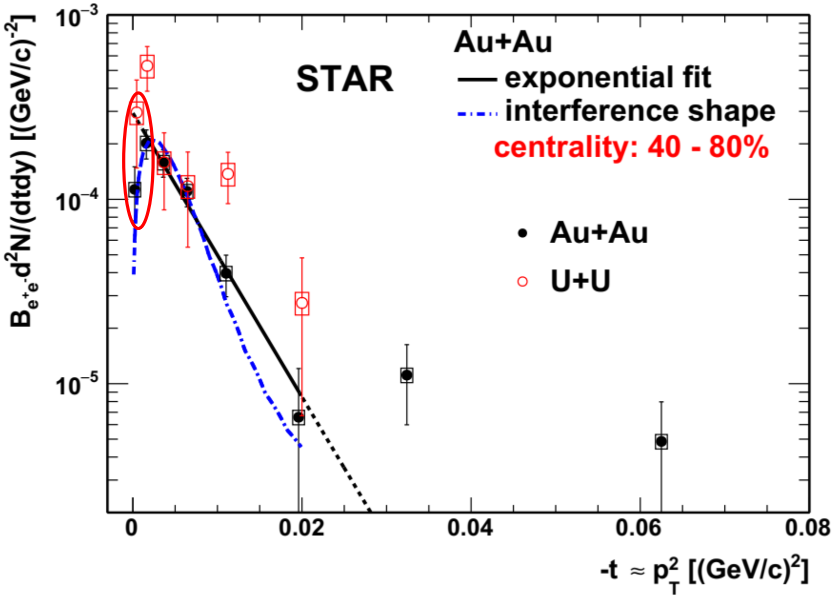
- Can not be described by hadronic production modified by the hot medium or cold nuclear matter effects!

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

The observations at STAR

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





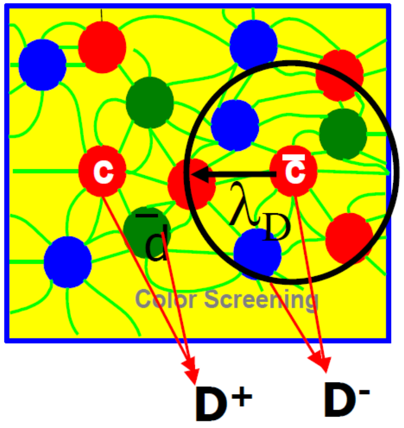
- Significant enhancement of J/ψ yield observed at p_T interval 0 – 0.2 GeV/c for peripheral collisions.
- No significant difference between Au+Au and U+U collisions.

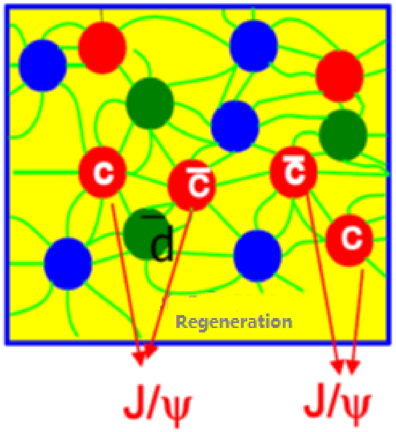
- Similar structure to that in UPC case!
- Indication of interference!
  - ✓ Interference shape from calculation PRC **97** (2018) 044910
- Similar slope parameter!
  - ✓ Slope from STARLIGHT prediction in UPC case – 196 (GeV/c)$^{-2}$
  - ✓ Slope w/o the first point: 177 ± 23(GeV/c)$^{-2}$ χ^2/NDF =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

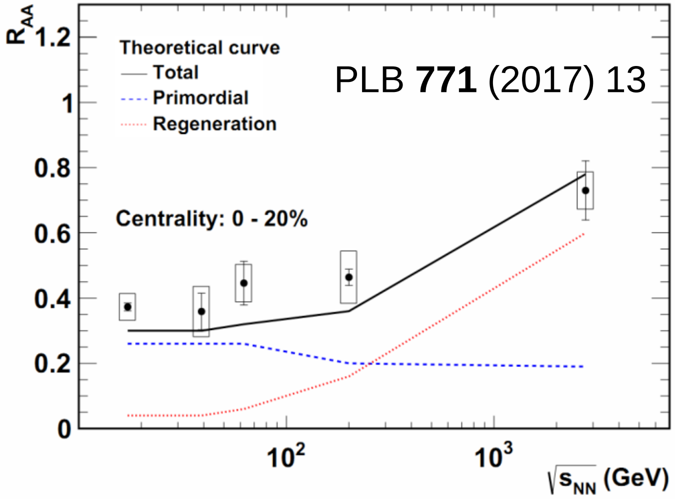
A novel probe for QGP?

- 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
  - ✓…

The baseline?



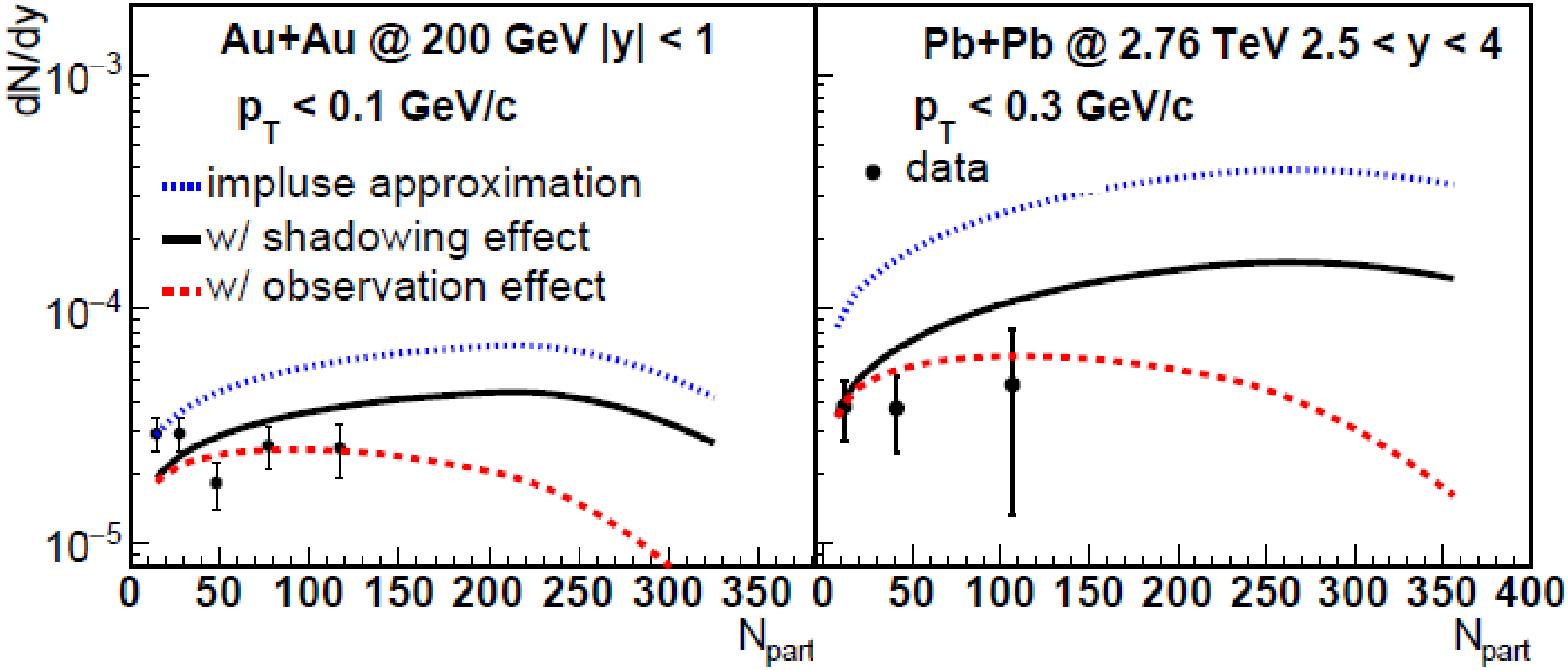




PLB **771** (2017) 13

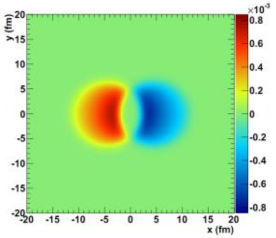
A cleaner probe of color screening?

Comparison with model calculation



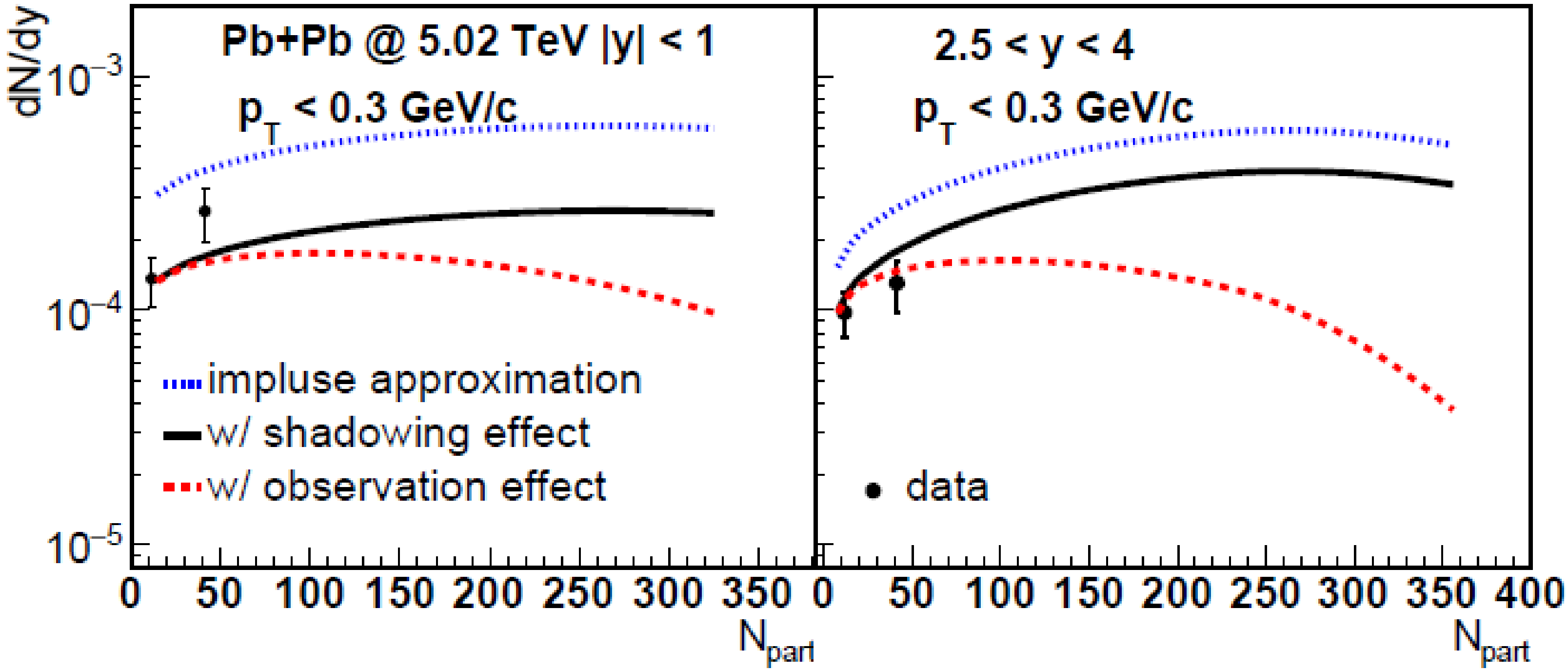
- Well described by the coherent photoproduction mechanism for peripheral collisions
- Hint of disruption from the medium
  - ✓ The observation effect
  - ✓ The QGP swallowing

W. Zha etal., PRC **99**, 061901 (2019)



Comparison with model calculation

ALICE: ALI-PREL-309953



- Well described by the coherent photoproduction mechanism for peripheral collisions
- Hint of disruption from the medium
  - ✓ More statistics at mid-rapidity
  - ✓ More precise measurements toward central collisions

The transverse linearly polarized photons

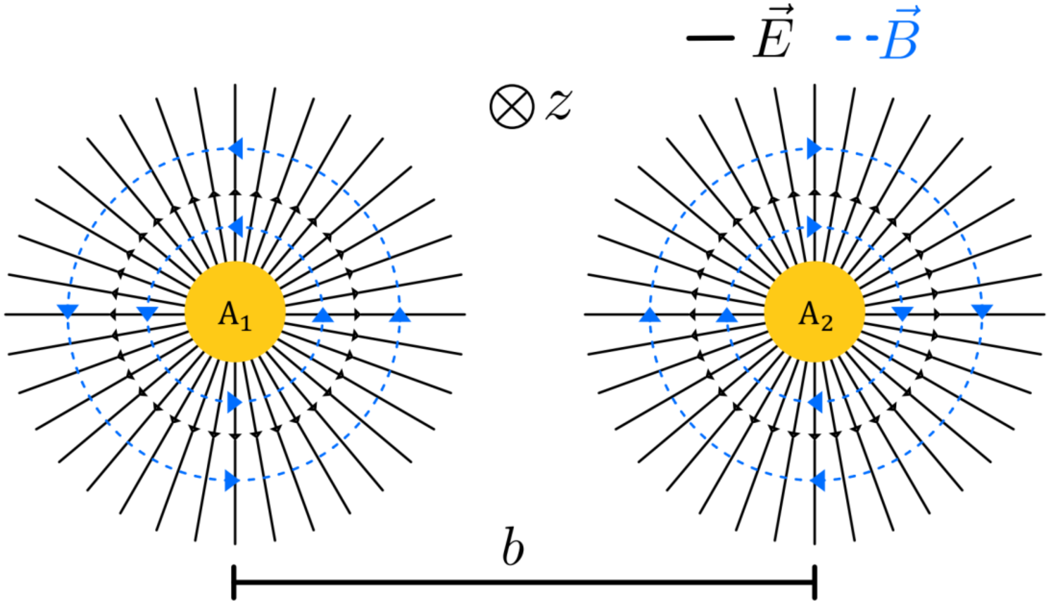
Extreme Lorentz contraction of EM fields $\vec{E} \perp \vec{B} \perp z$

- ✓ Linearly polarized in transverse plane

Polarization vector: follows the electrical vector of photons

Well defined in the position and momentum eigenstates

Aligned radially with the “emitting” source



The transverse linearly polarized photons

Extreme Lorentz contraction of EM fields $\vec{E} \perp \vec{B} \perp z$

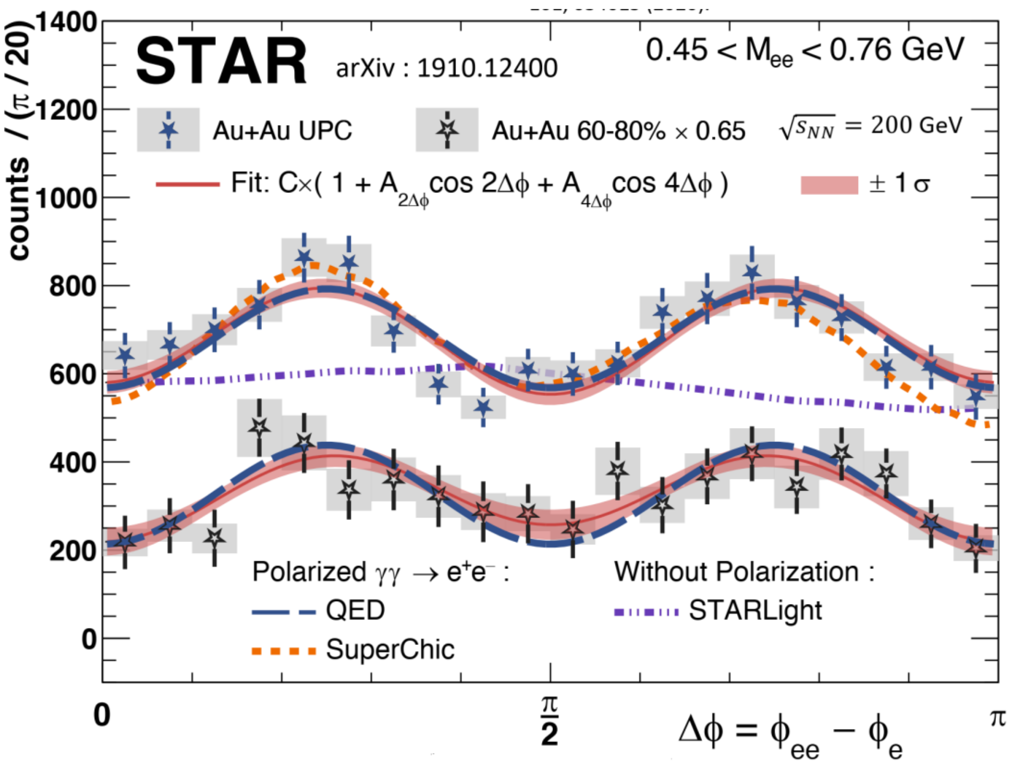
- ✓ Linearly polarized in transverse plane

Polarized $\gamma + \gamma \rightarrow e^{+} + e^{-}$

leads to $\cos 4\Delta\phi$ modulation

C. Li, J. Zhou, Y.-j. Zhou, PLB 795, 576 (2019)

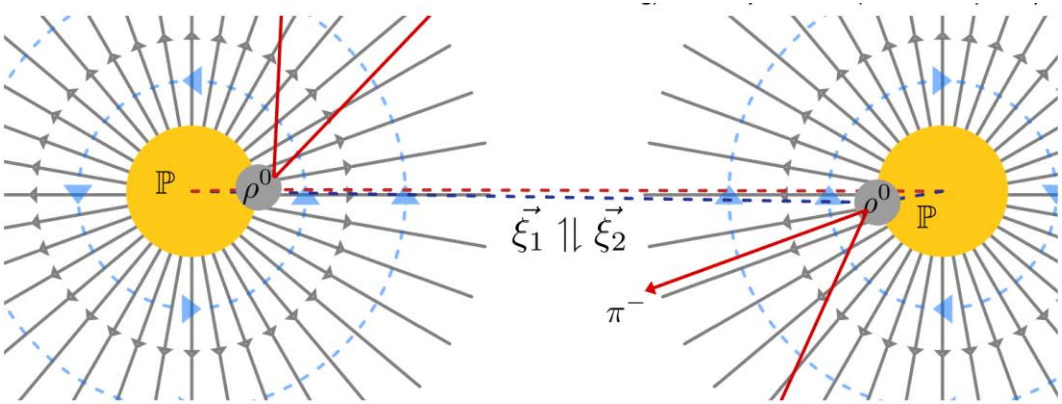
Confirmed by STAR Collaboration!



STAR Collaboration, arXiv1910.12400
Li, C., Zhou, J. & Zhou, Y. Phys. Rev. D101, 034015 (2020)

Polarized photon + gluon collisions

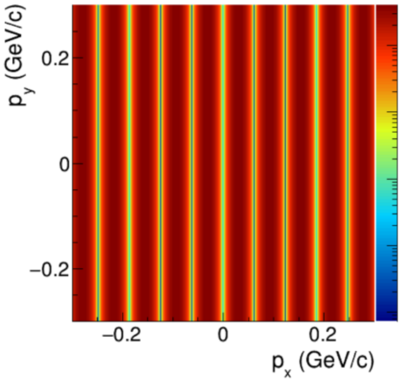
Polarization vector : aligned along the impact parameter



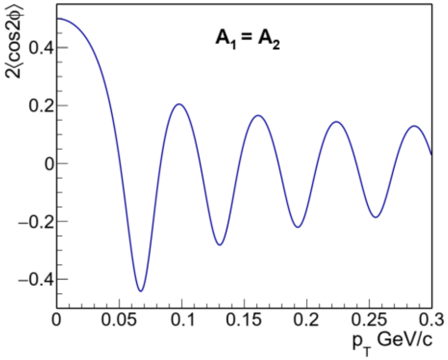
Helicity conservation: the produced vector meson inherits the polarization state of photon

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

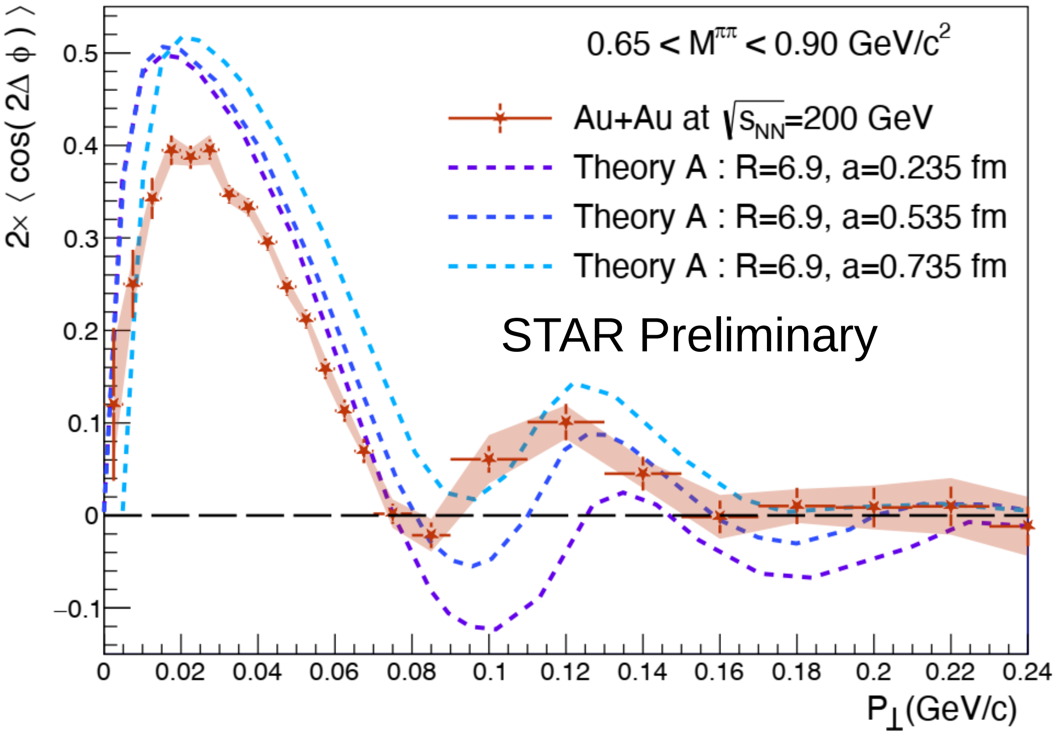
The interference in momentum space



$\cos 2\Delta\phi$ modulation



Polarized photon + gluon collisions



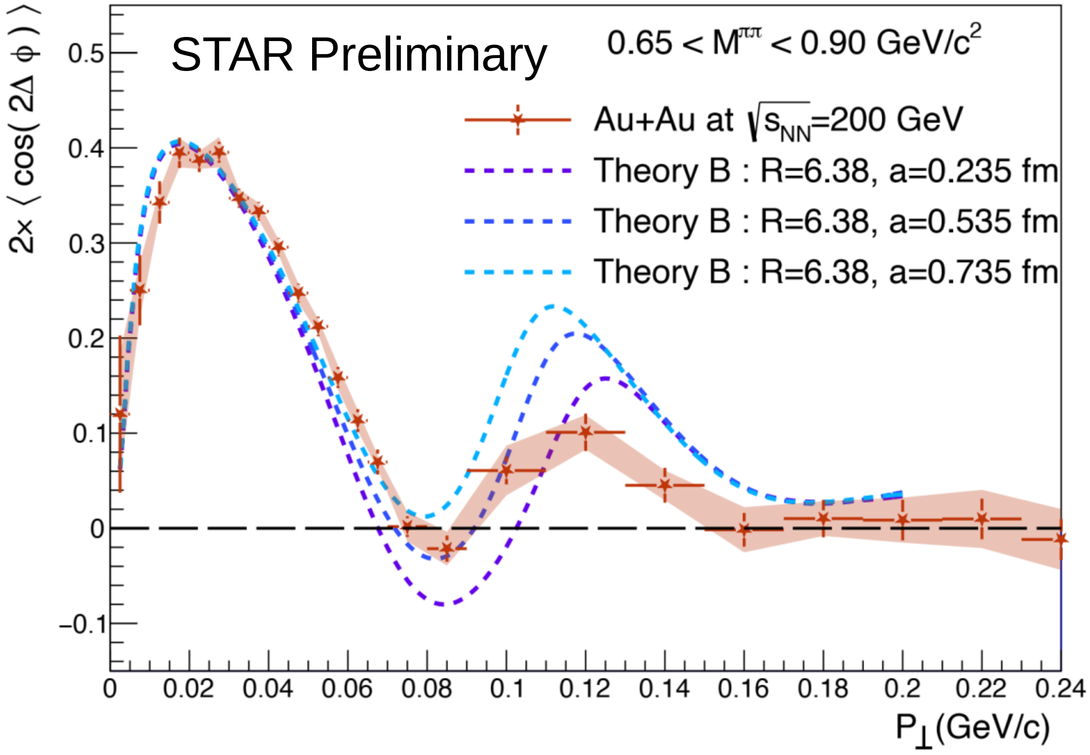
Qualitative description of data
- Large first peak
- Approximate location of second peak

Second peak shows strong dependence on details of nuclear geometry

Xing, H. et.al. JHEP. 2020, 64 (2020)

A two-source interference pattern resulting from quantum spin-momentum correlations

Polarized photon + gluon collisions



Qualitative description of data

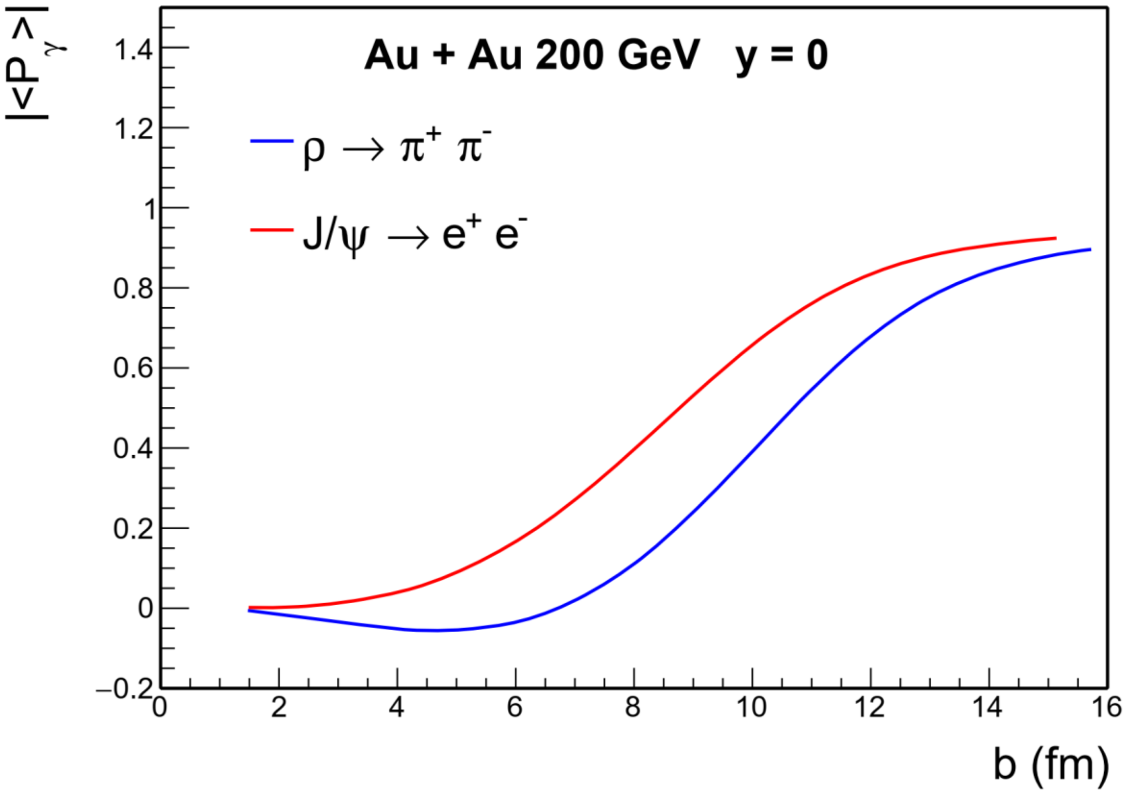
- Large first peak
- Approximate location of second peak

Second peak shows strong dependence on details of nuclear geometry

Zha, W., J.D. Brandenburg, Ruan, L. & Tang, Z. *PRD* **103**, 033007 (2021)

A two-source interference pattern resulting from quantum spin-momentum correlations

Align the reaction plane with linearly polarized photons



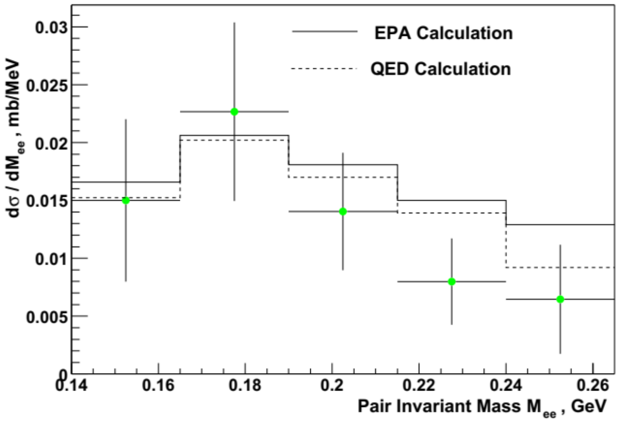
$$P_\gamma = < \frac{E_x^2 - E_y^2}{E_x^2 + E_y^2} >$$

- ✓ Determined by collision geometry
- ✓ Strongly aligned to reaction plane
- ✓ No event-event fluctuation

Could directly link the final flow to initial geometry!

Photon-photon interactions in UPC

- Test QED --- $\gamma\gamma \rightarrow$ Dileptons
  - ✓ $Z\alpha \sim 0.6$, so perturbation theory might fail
  - ✓ Data is in excellent agreement with lowest order QED



STAR, PRC **70** (2004) 031902

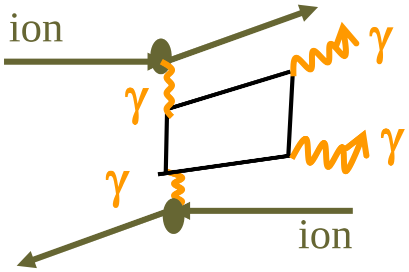
- To study the meson spectroscopy

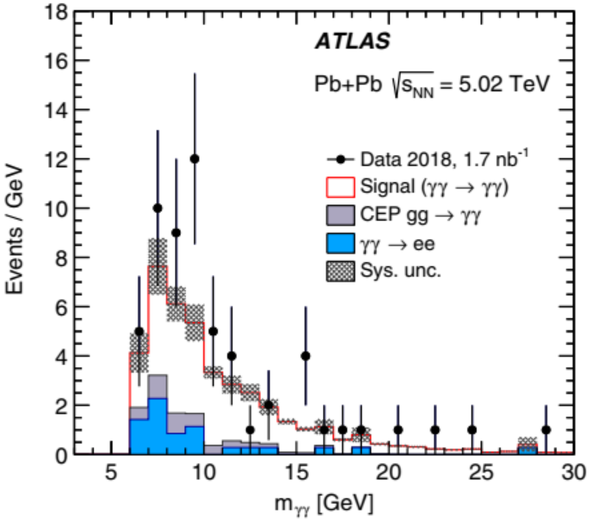
meson	mass [MeV]	σ^{RHIC} [mb]	σ^{LHC} [mb]
π_0	134	4.9	28
η	547	1.0	16
η'	958	0.75	21
$f_2(1270)$	1275	0.54	22
$a_2(1320)$	1318	0.19	8.2
η_c	2981	3.3×10^{-3}	0.61
χ_{0c}	3415	0.63×10^{-3}	0.16
χ_{2c}	3556	0.59×10^{-3}	0.15

No measurements in UPCs yet!

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

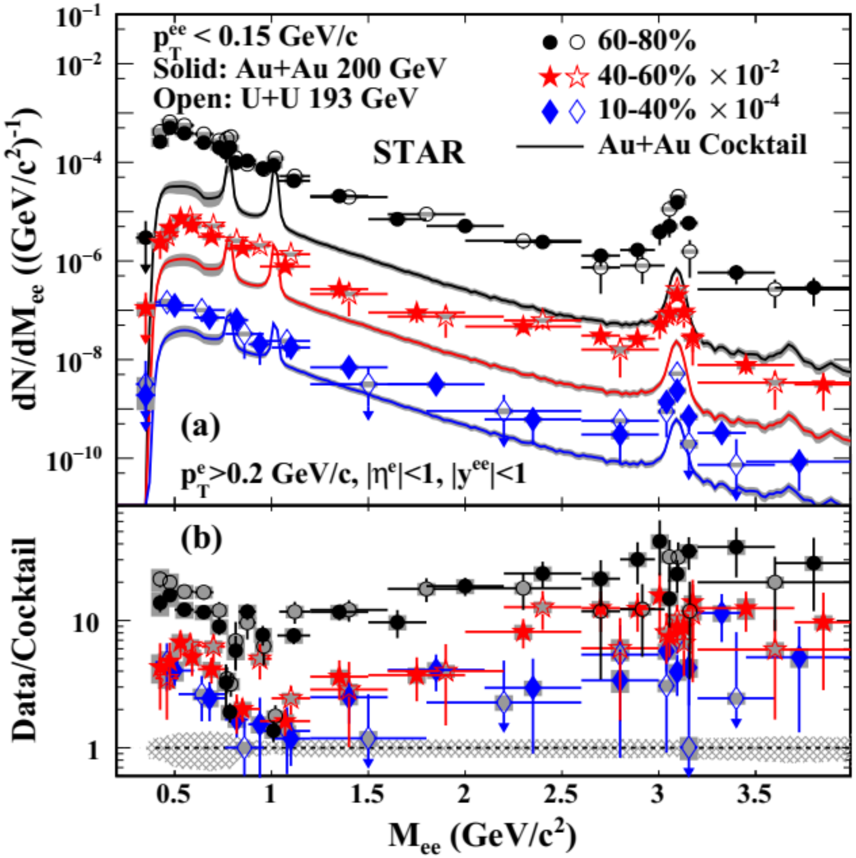
- From “virtual” to “real”
  - ✓ Light-by-light scattering seen by ATLAS

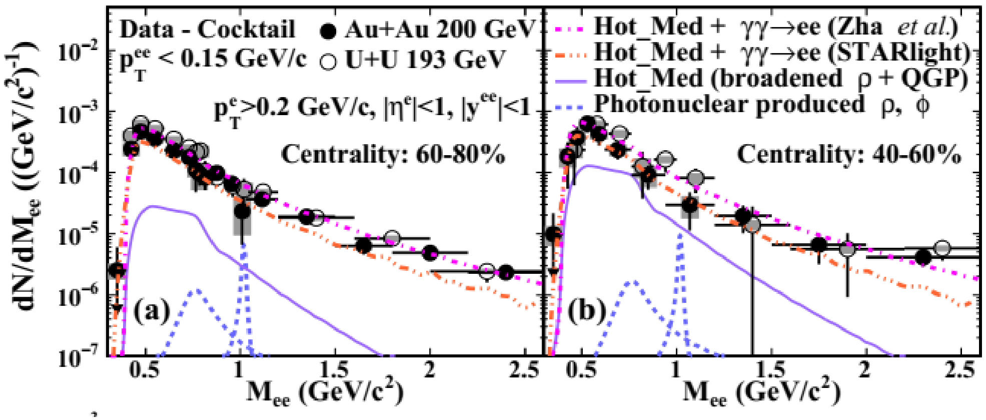




Nature Phys. 13 (2017) 852
PRL **123** (2019) 052001

The measurements in non-UPC collisions



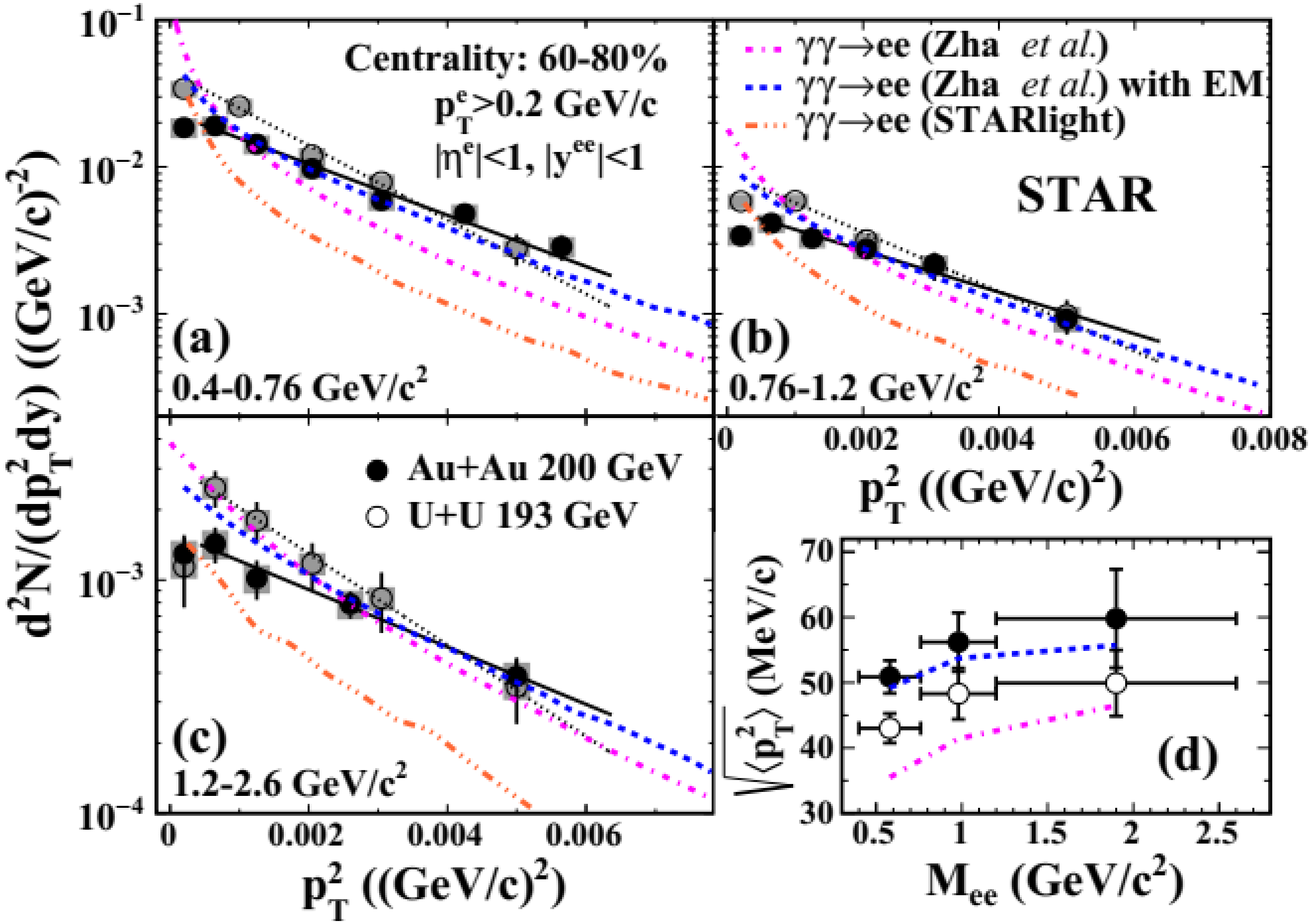


STAR, PRL **121** (2018) 132301

W. Zha etal., PLB **781** (2018) 182

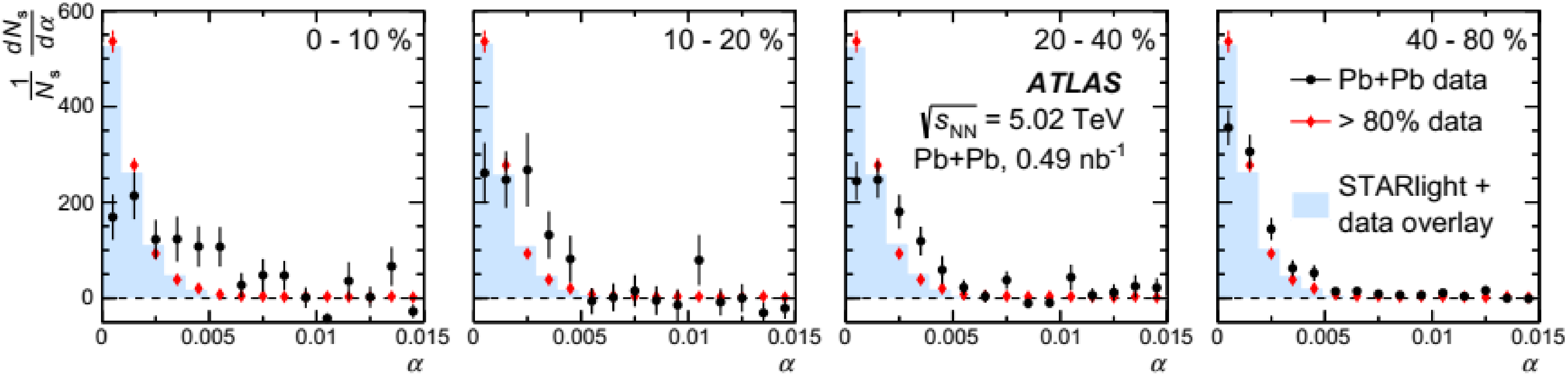
- Significant excess in 60-80% central Au + Au and U + U collisions for the whole invariant mass range!
- The excess can be described by the coherent photon-photon process!

The puzzle: pair p_T broadening

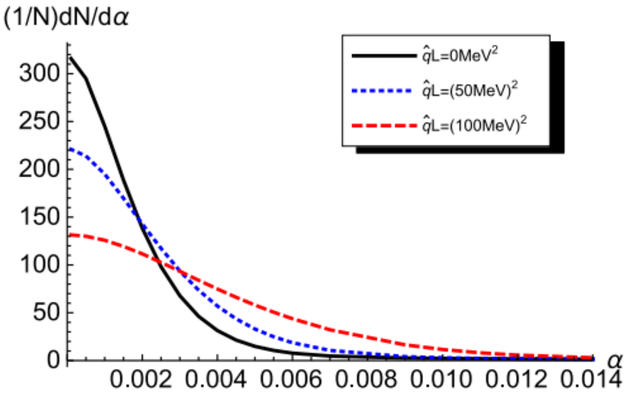


- The equivalent photon approximation could not describe the pair p_T distribution
- Possible medium effects --- magnetic field trapped in the QGP?

The puzzle: pair p_T broadening



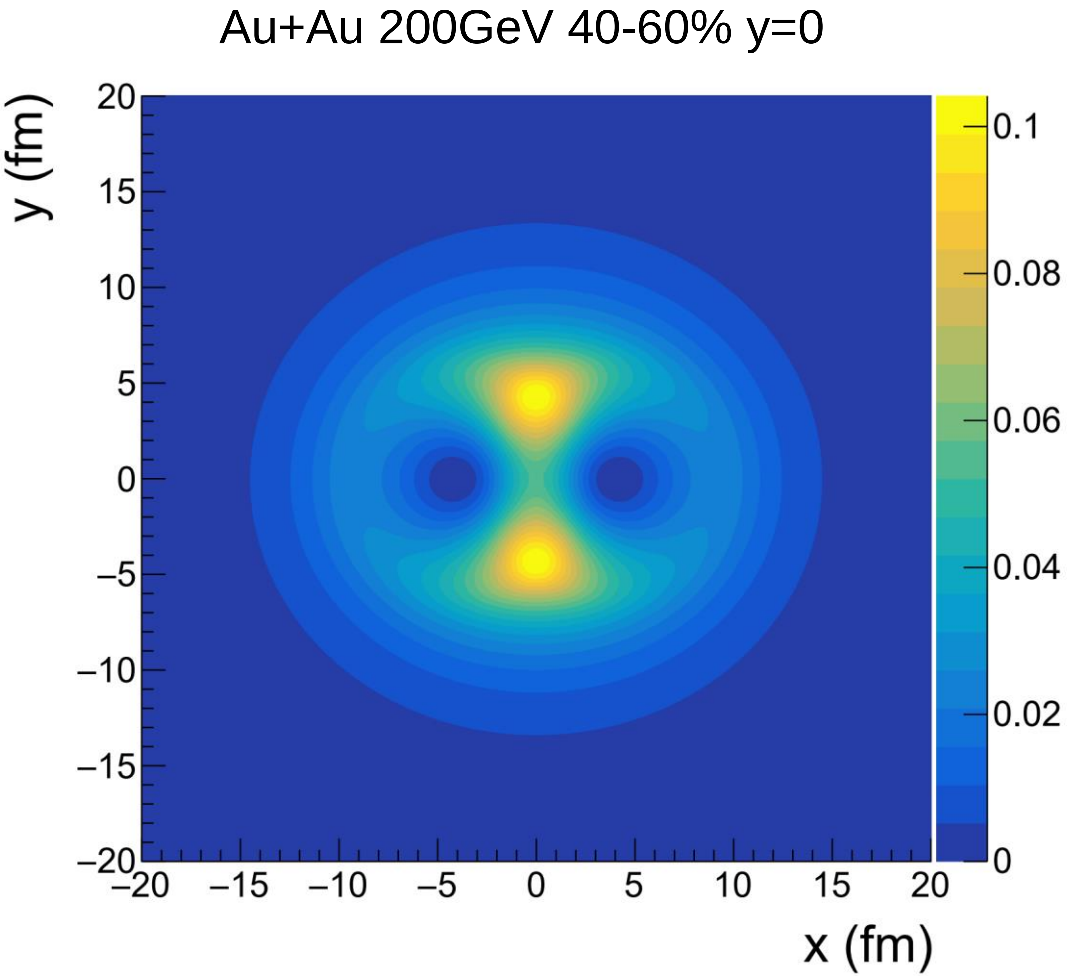
ATLAS, PRL **121** (2018) 212 301



PRL**122** (2019) 132301

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

The spatial distribution of dileptons



The portion in overlap region ~ 12%

Overlap region:

$b_1 < R_{Nuc}$ && $b_2 < R_{Nuc}$

R_{Nuc} = 6.38 fm

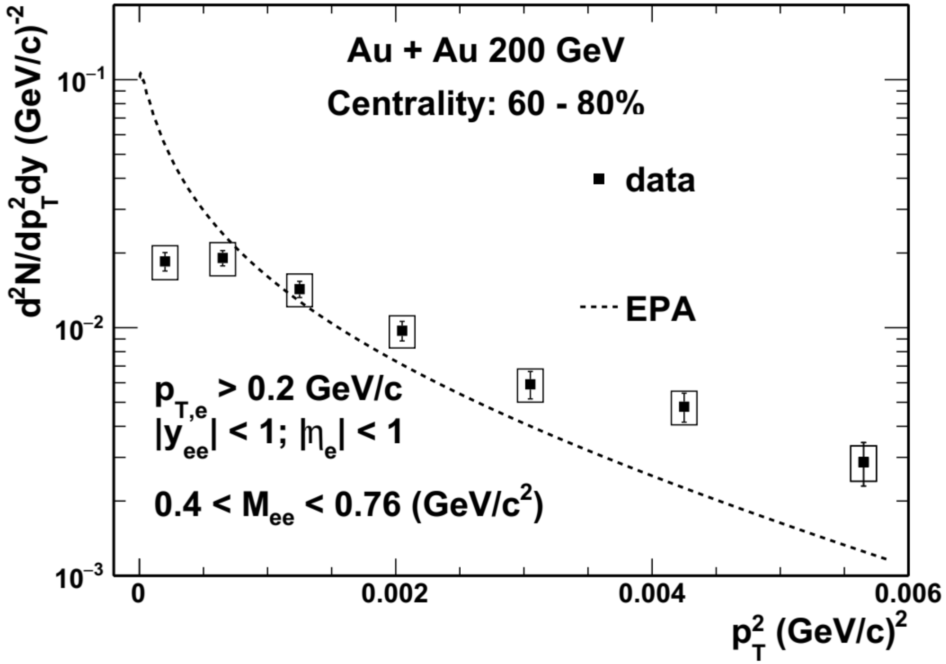
The impact parameter dependence

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 impact parameter dependence

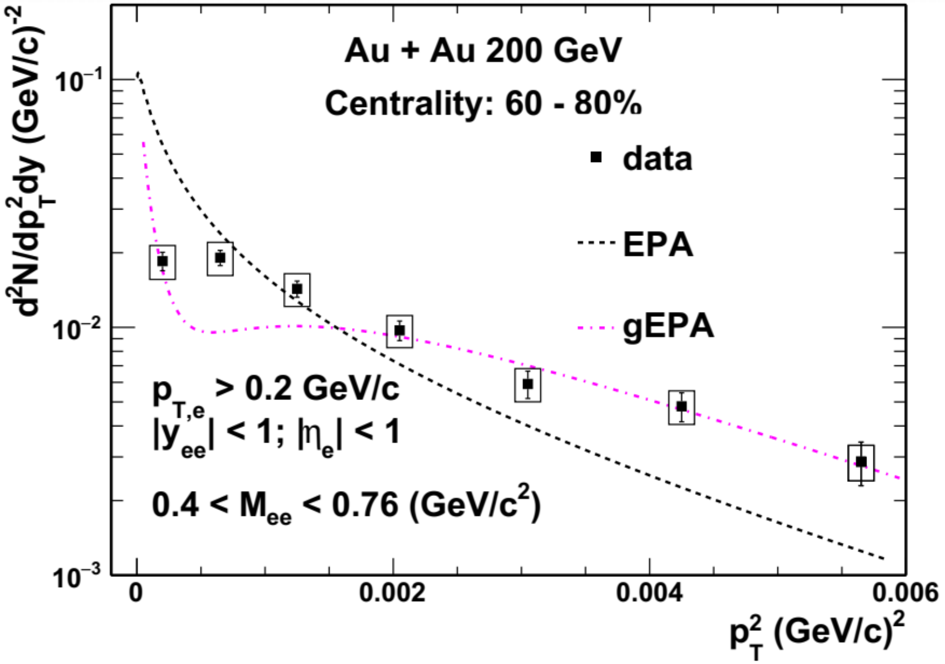
gEPA approach

Impact parameter dependence!

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

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

PRC **47** (1993) 2308



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

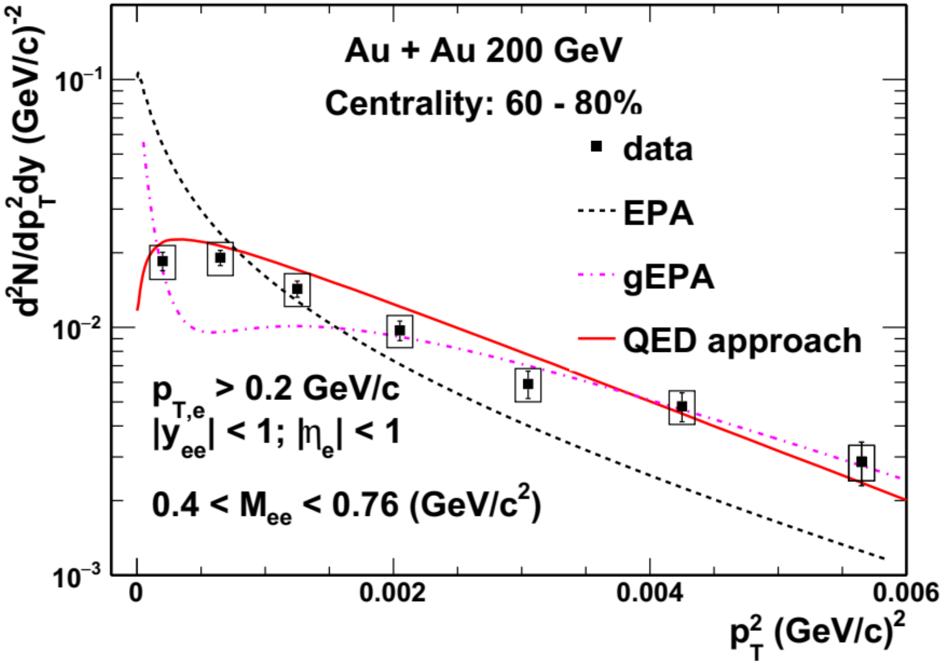
The impact parameter dependence

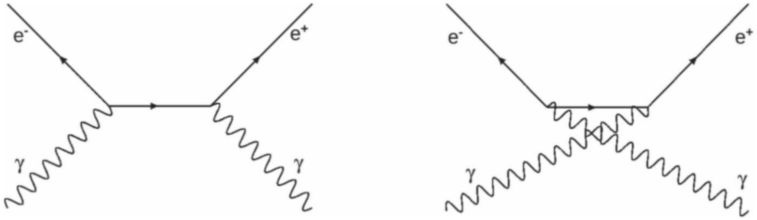
$$\sum_s |M|^2 = (Z\alpha)^4 \frac{4}{\beta^2}\int d^2\Delta q_1 d^2 q_1 \,[N_0N_1N_3N_4]^{-1}\exp(i\Delta\vec{q}_1\cdot\vec{b})$$

$$\times \mathrm{Tr}\Big\{(\not p_- + m)\Big[N_{2D}^{-1}\not\epsilon^{(1)}(\not p_- - \not q_1 + m)\not\epsilon^{(2)} + N_{2X}^{-1}\not\epsilon^{(2)}(\not q_1 - \not p_+ + m)\not\epsilon^{(1)}\Big]$$

$$\times(\not p_+ - m)\Big[N_{5D}^{-1}\not\epsilon^{(2)}(\not p_- - \not q_1' + m)\not\epsilon^{(1)} + N_{5X}^{-1}\not\epsilon^{(1)}(\not q_1' - \not p_+ + m)\not\epsilon^{(2)}\Big]\Big\}$$

QED approach



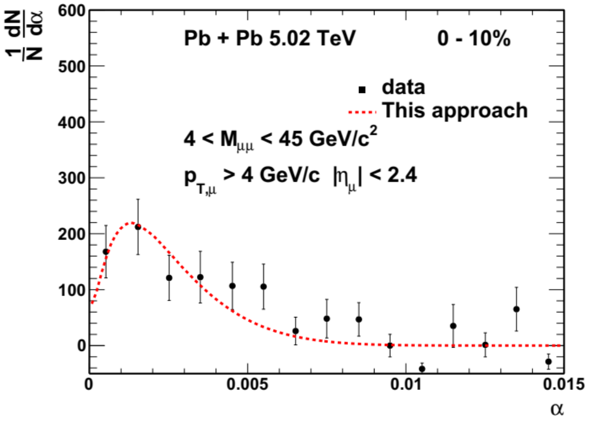


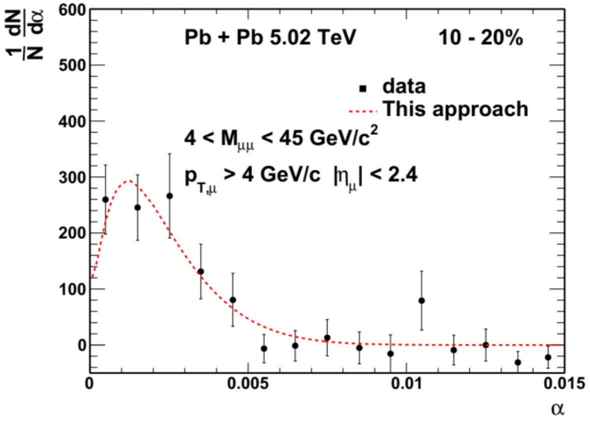
PRA **51** (1995) 1874

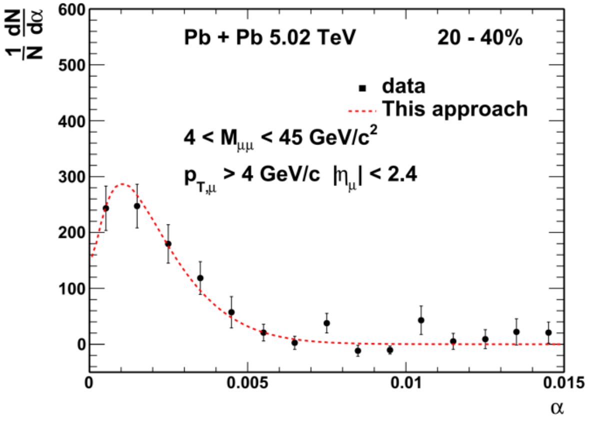
- Reasonably describe the p_T spectrum.

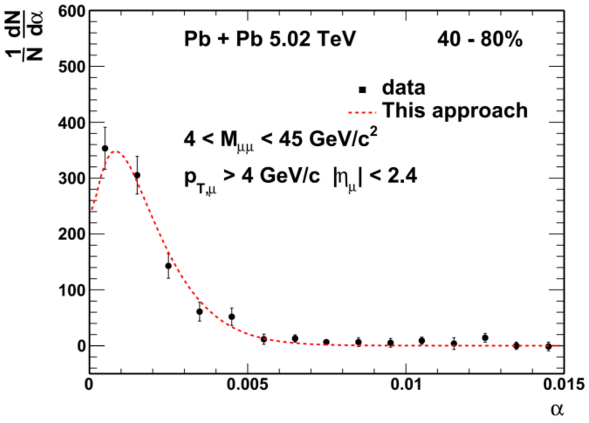
W. Zha etal., PLB 800 (2020) 135089

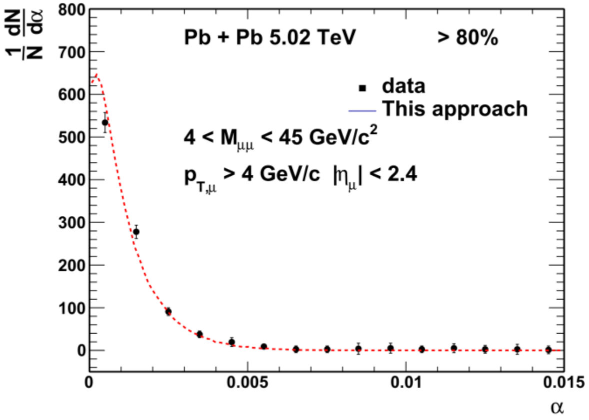
The impact parameter dependence





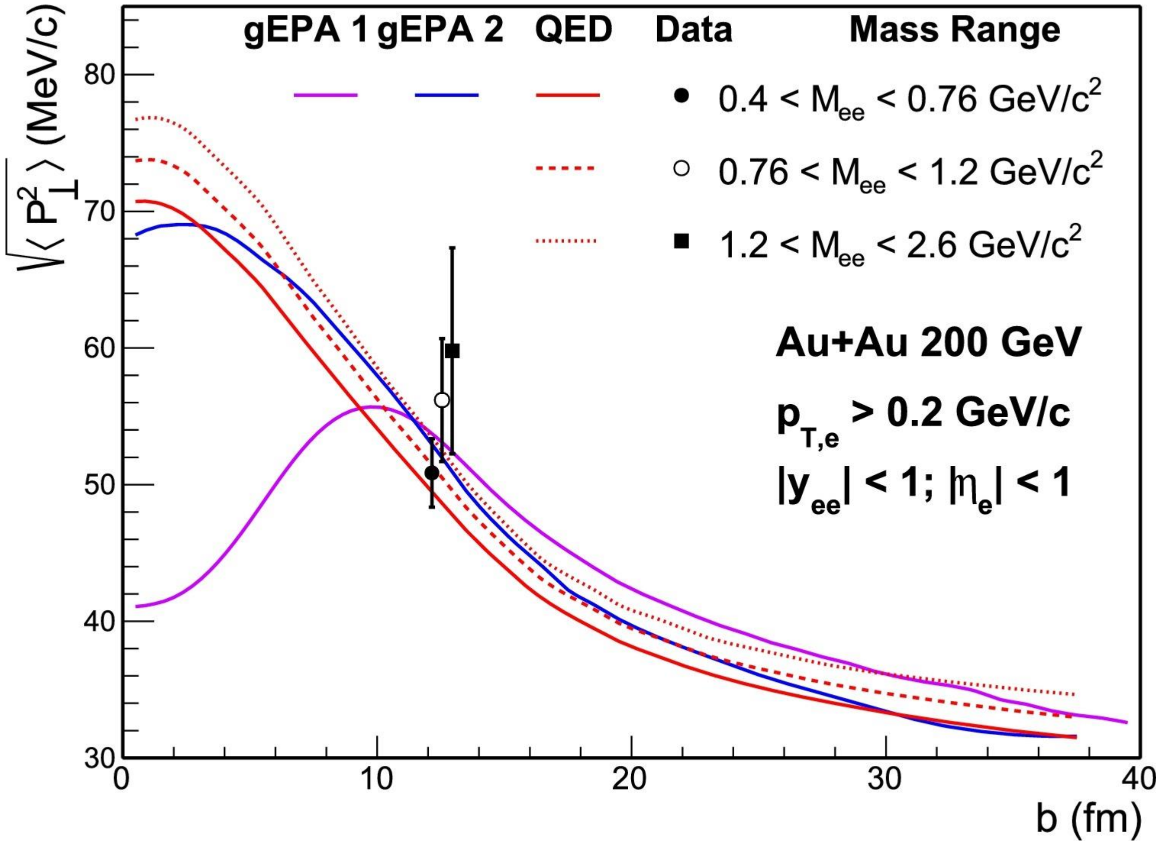






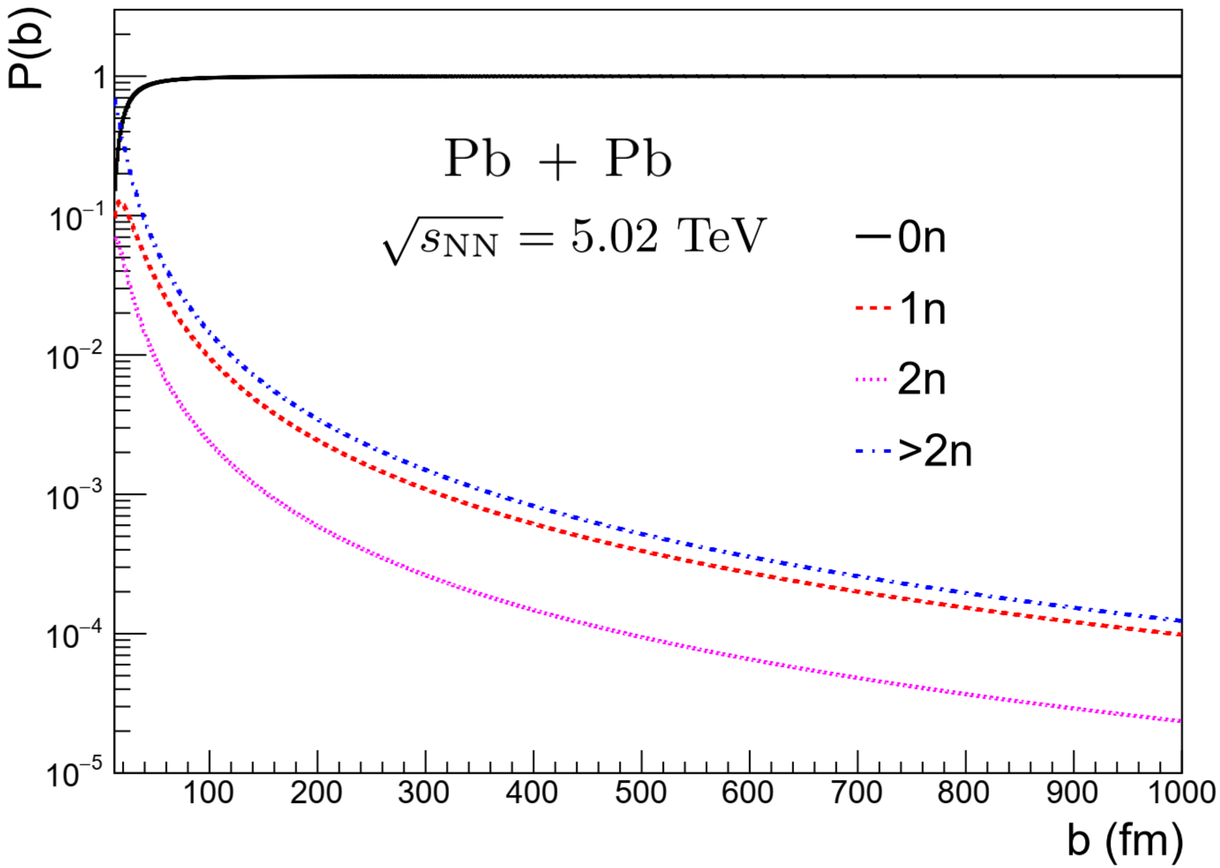
Successfully reproduce the centrality dependence of acoplanarity

The impact parameter dependence



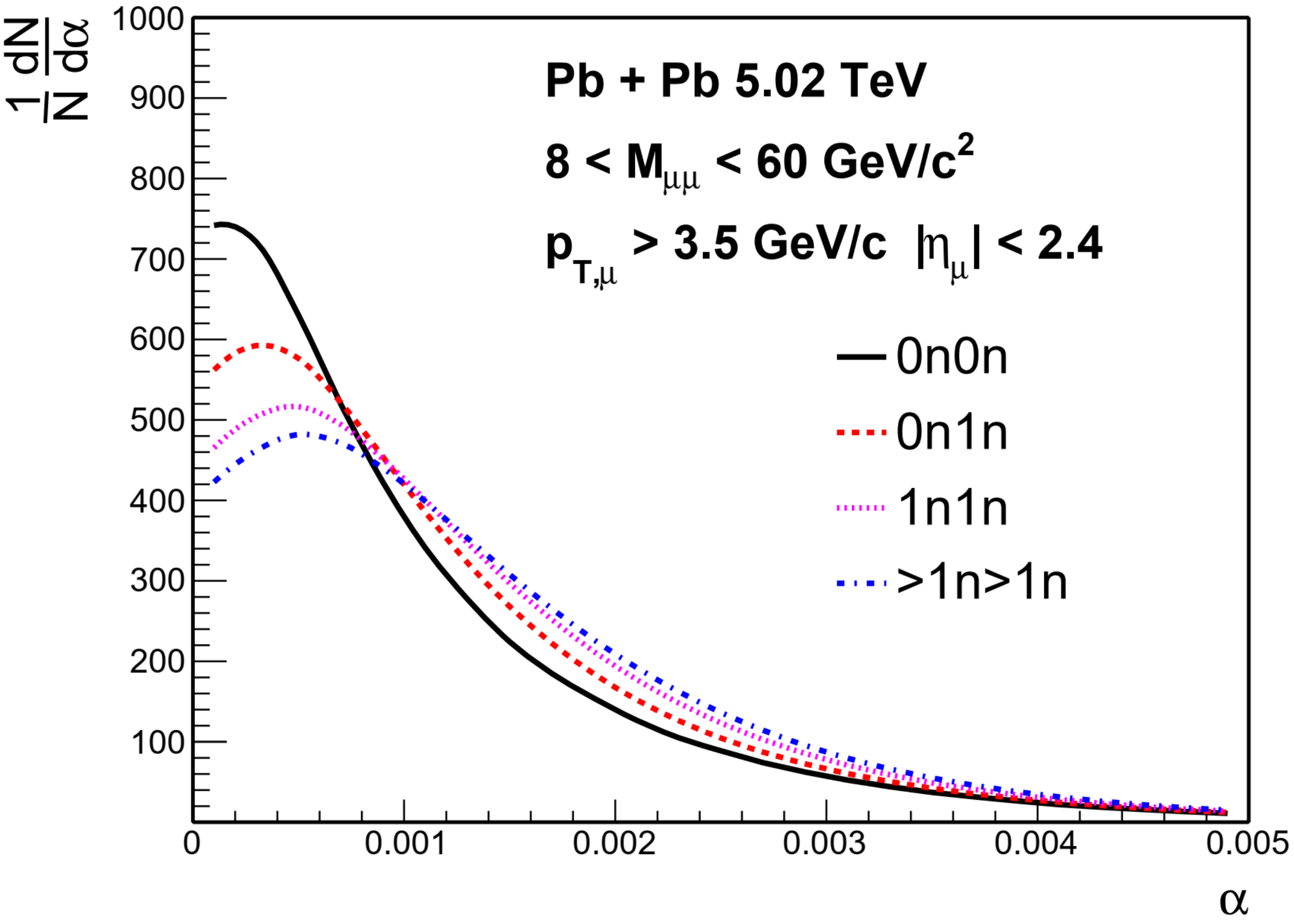
Strong dependence on impact parameter and pair mass.

“Centrality” definition in UPCs



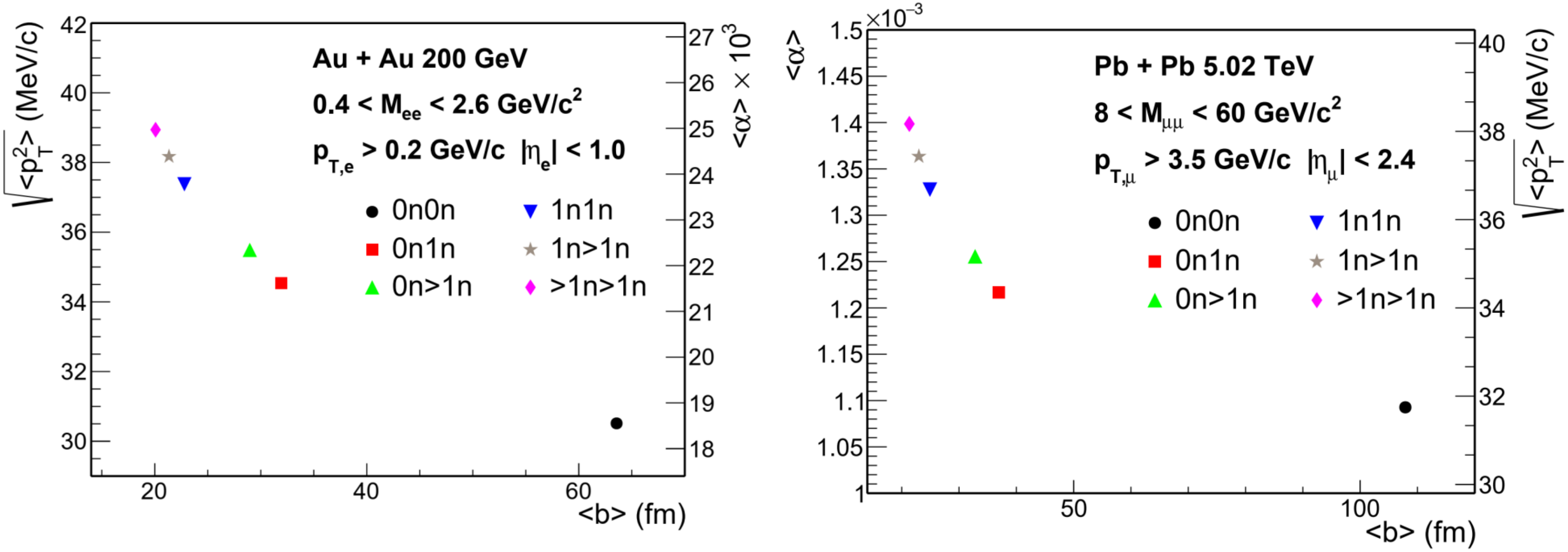
Neutron tagging!

Acoplanarity for different centralities in UPCs



Significant differences!

Initial broadening for different centralities in UPCs

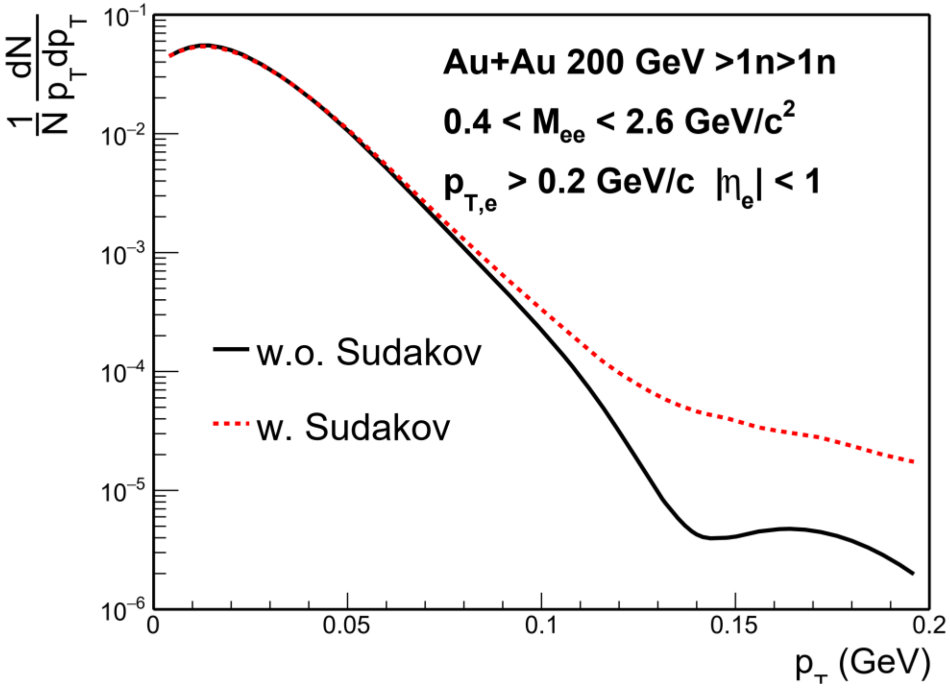


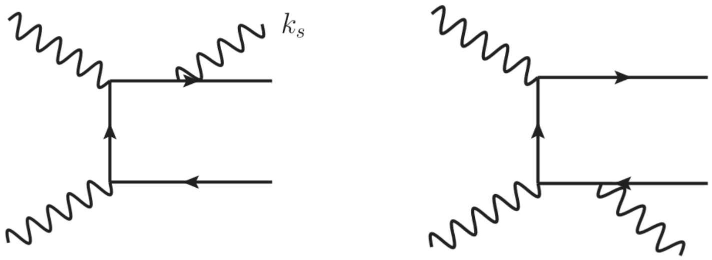
J. D. Brandenburg etal., arXiv2006.07365

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

The Sudakov effect

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



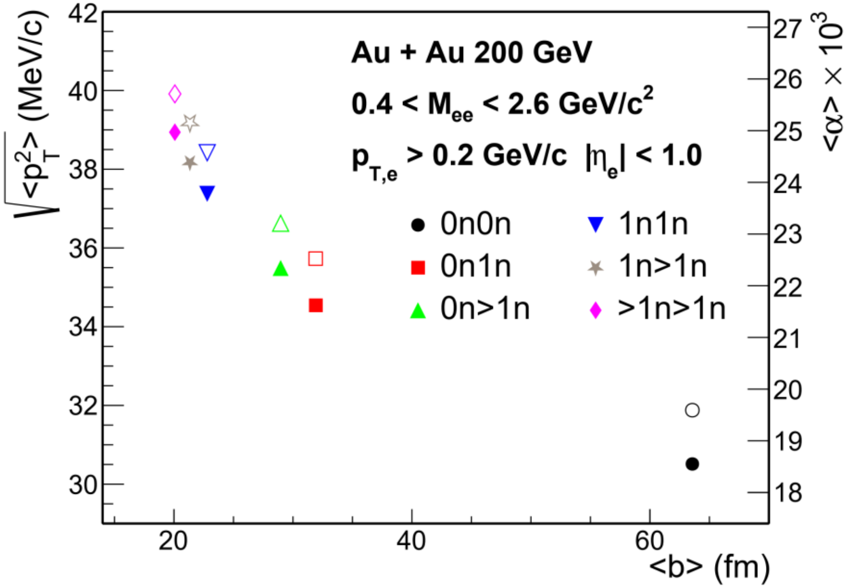


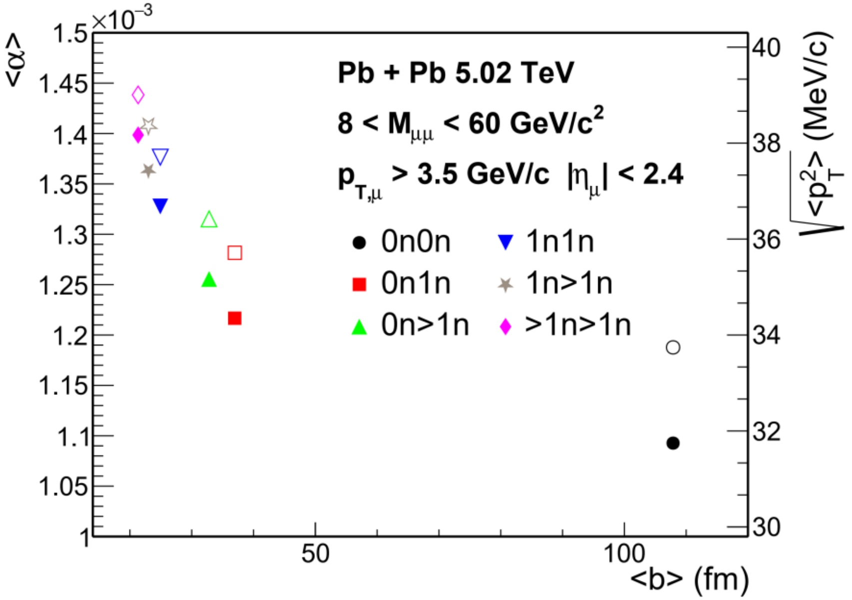
$$\int \frac{d^2 r_\perp}{(2\pi)^2} e^{i r_\perp \cdot q_\perp} e^{-S(Q,r_\perp)} \int d^2 q'_\perp e^{i r_\perp \cdot q'_\perp} d\sigma_0(q'_\perp, \ \ldots)$$

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

- ✓ Produce a tail at large p_T
- ✓ Small effect at small p_T

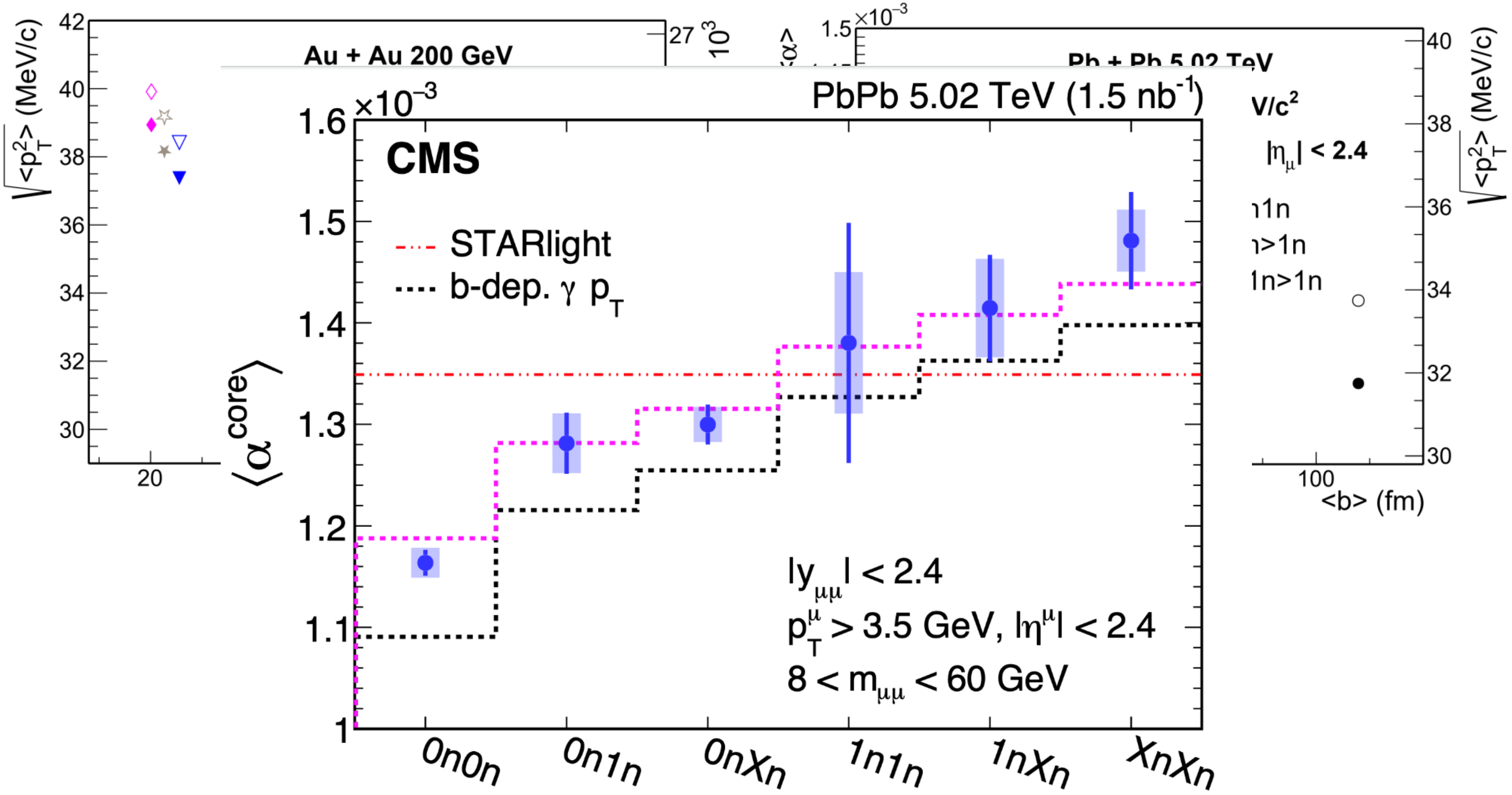
The Sudakov effect





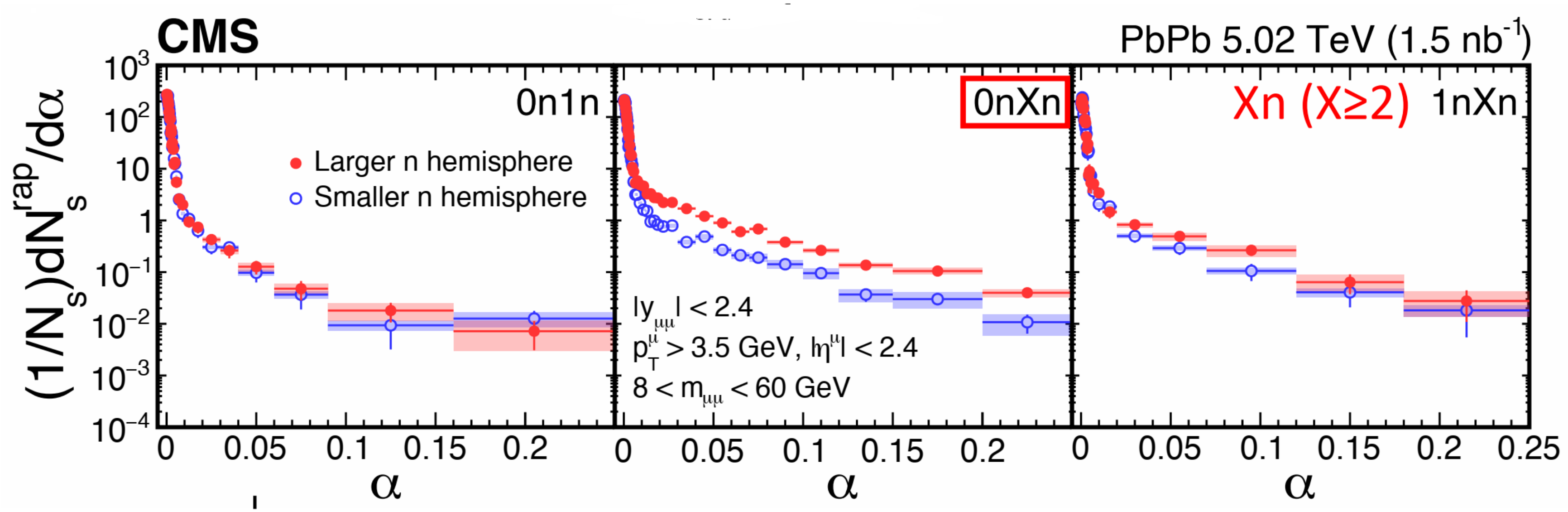
- ✓ The effect is sizable
- ✓ More significant at large impact parameter.

The Sudakov effect



CMS[PAS-HIN-19-014]

Evidence of semi-coherent production?

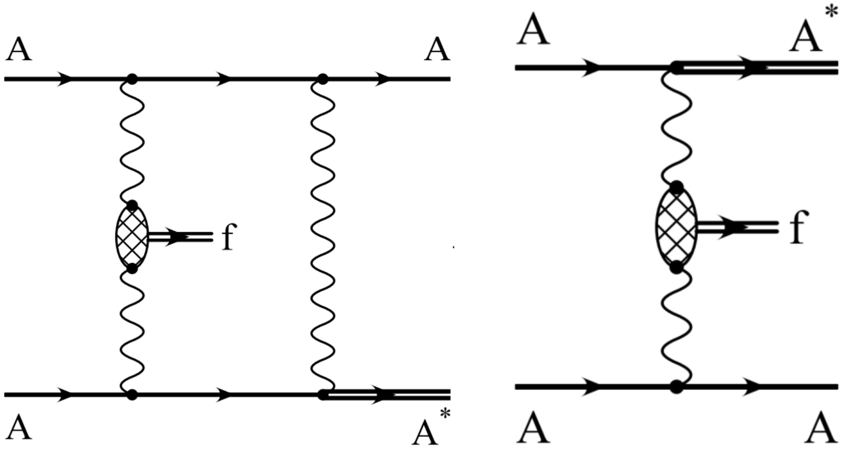


In 0nXn, the tail contribution

- ✓ Larger n hemisphere > Smaller n hemisphere

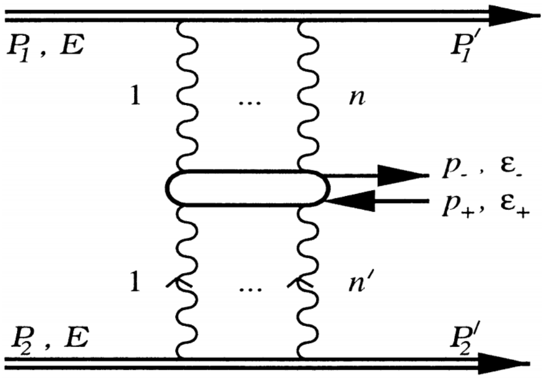
Quantitative calculation is in progress

Incoherent



Coherent

Higher order effect



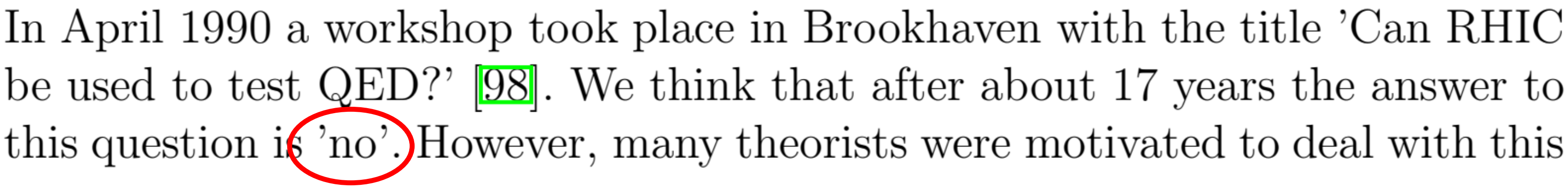
Phys. Lett B454 (1999) 155

Zα ~0.6 for Au and Pb

The effect should be sizeable!

H. A. Bethe and L. C. Maximon, Phys. Rev. **93**, 768 (1954); Handel Davies, H. A. Bethe, and L. C. Maximon, Phys. Rev. **93**, 788 (1954).

However:



In April 1990 a workshop took place in Brookhaven with the title 'Can RHIC be used to test QED?' [98]. We think that after about 17 years the answer to this question is 'no'. However, many theorists were motivated to deal with this

Phys. Rep. **453**, 1 (2007)

M. Fatyga, M. Rhoades-Brown, and M. Tannenbaum, Can RHIC be used to test QED: Workshop summary, Workshop "Can RHIC be used to test QED?", Upton, N.Y., Apr 20-21, 1990, BNL 52247 Formal Report.

Higher order effect

The photon propagator in the perturbative limit:

$$F^{0}_{A,B}(\mathbf{k}) = \frac{4\pi i Z_{A,B}\alpha}{k^2+\omega^2/\gamma^2}$$

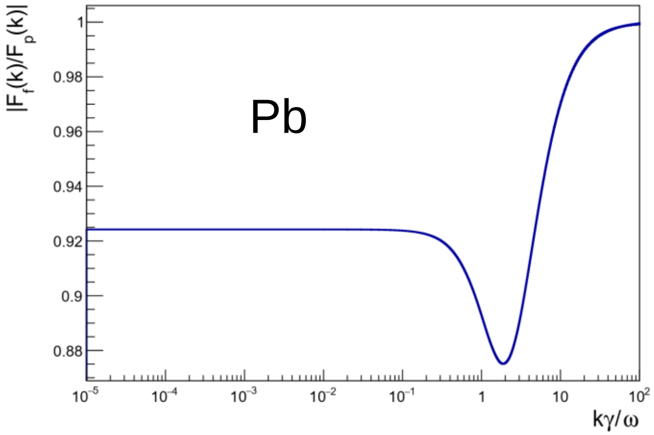
Regularized by hand

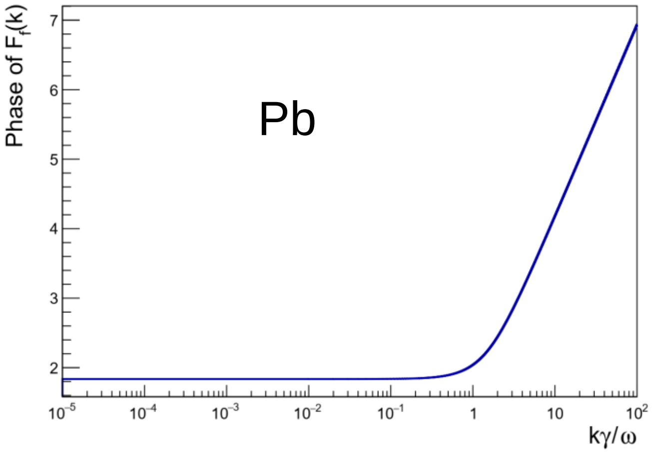
$$F(\mathbf{k}) = \frac{4\pi\alpha Z}{(k^2+\omega^2/\gamma^2)^{1-i\alpha Z}}$$

Properly regularized

$$F(\mathbf{k}) = 2\pi\int d\rho\,\rho J_0(k\rho)\{\exp[2iZ\alpha K_0(\rho\omega/\gamma)]-1\},$$

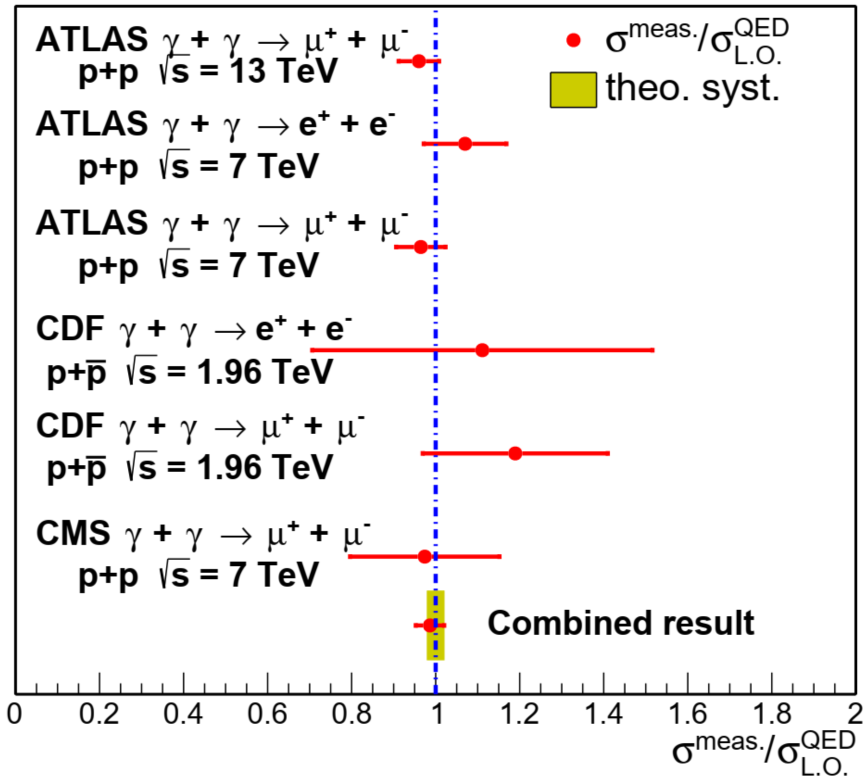
PRL **100,** 062302 (2008)





all orders in *Zα !*

Higher order effect



CDF collaboration, *Phys. Rev. Lett.* **102** (2009) 242001.

[CDF collaboration,, *Phys. Rev. Lett.* **98** (2007) 112001.

ATLAS collaboration, *Phys. Lett. B* **749** (2015) 242.

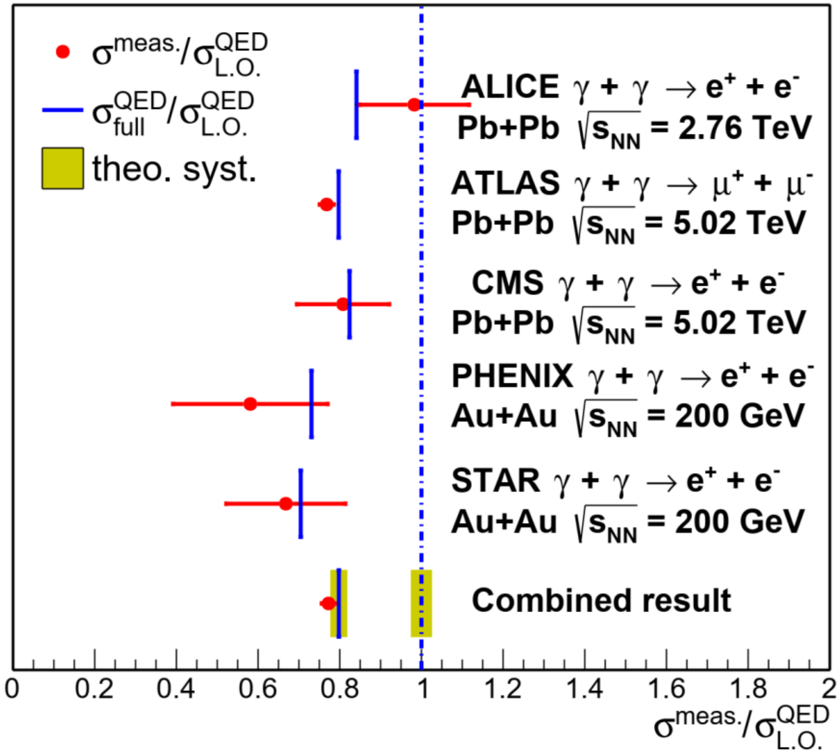
ATLAS collaboration, *Phys. Lett. B 777 (2018) 303*

CMS collaboration, *JHEP* **11** (2012) 080

W. Zha and Z. Tang, arXiv2103.04605

Consistent with Leading order results！

Higher order effect



STAR collaboration, *Phys. Rev. C* **70** (2004) 031902.

PHENIX collaboration, *Phys. Lett. B* **679** (2009) 321.

ALICE collaboration, *Eur. Phys. J. C* **73** (2013) 2617.

CMS collaboration, *Phys. Lett. B* **797** (2019) 134826.

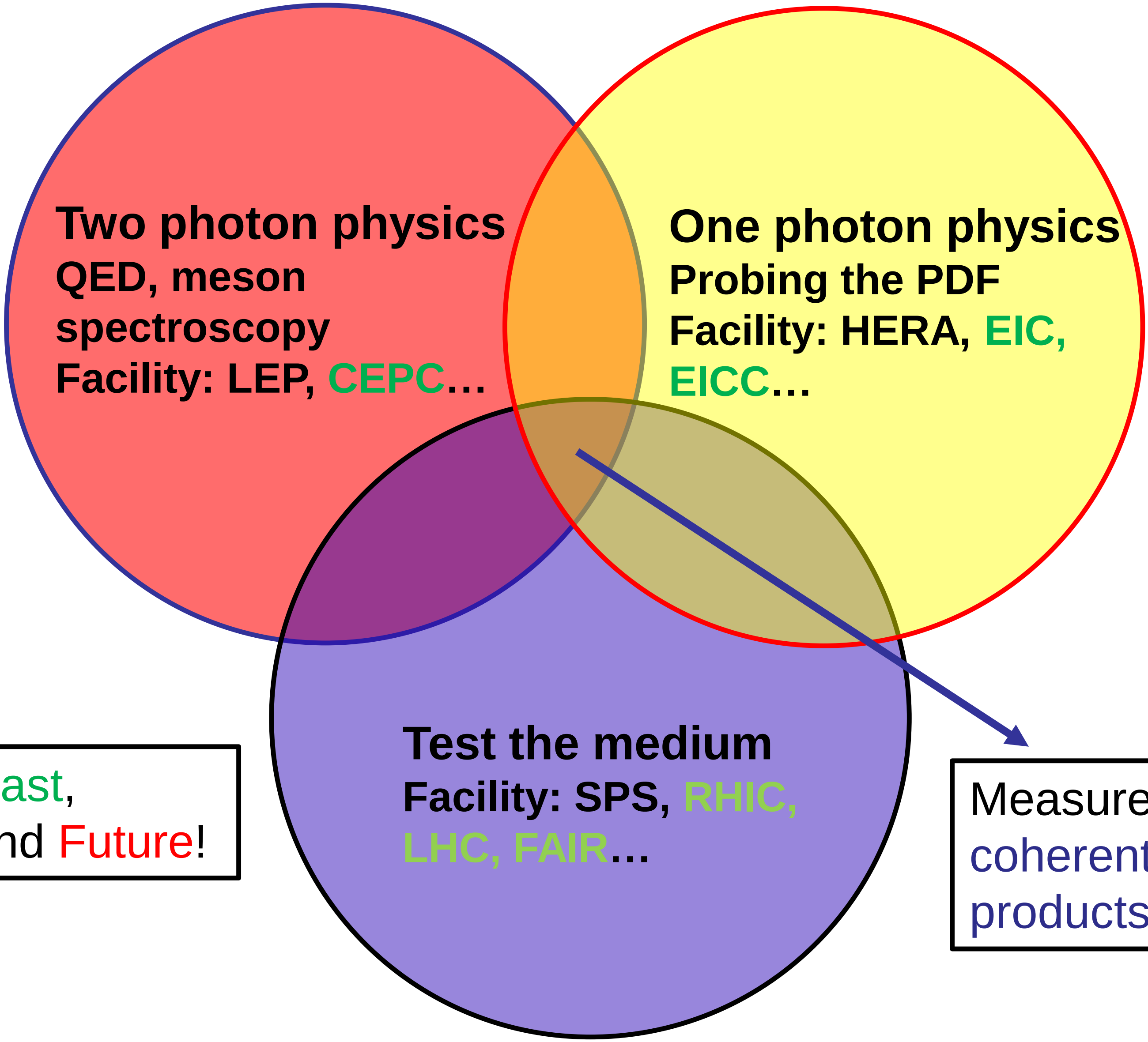
ATLAS collaboration, *arXiv* (2020) [2011.12211]

- ✓ 7σ deviation from Leading order results !
- ✓ Consistent with Full order results!

Summary

- The vector meson photoproduction in UPCs
  - ✓Significant shadowing effect
  - ✓The interference effect in spin-momentum correlation
- Excess of J/ψ production at very low p_T in peripheral A+A collisions
  - ✓Existence of coherent photoproduction in non UPCs
  - ✓Novel probe for QGP?
- Dielectron photoproduction in UPCs
  - ✓The baseline study
  - ✓ Higher order effects matter!
- Dielectron photoproduction in HHICs
  - ✓Probe the EM property of QGP?

Outlook



Two photon physics
QED, meson spectroscopy
Facility: LEP, CEPC…

One photon physics
Probing the PDF
Facility: HERA, EIC, EICC…

Test the medium
Facility: SPS, RHIC, LHC, FAIR…

Link the Past, Present and Future!

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