Tale of coherent photon products: from **UPC** to **HHIC**

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Collaborators: Lijuan Ruan, Zebo Tang, Zhangbu Xu, Shuai Yang, Chi Yang, Spencer Klein, Rongrong Ma, Qian Yang, Zhen Liu, Zehua Cao

第十七届全国核物理大会暨第十三次会员代表大会

华中师范大学，武汉，2019年10月8－12 日

Coherent photons as “partons” in heavy-ion collisions

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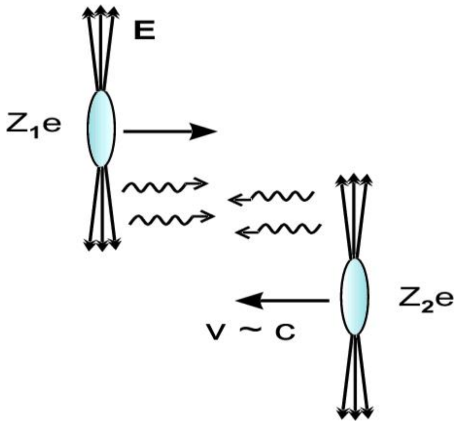

Coherent limitation: $Q^2 \leq 1/R^2$ => quasi-real !

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

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

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

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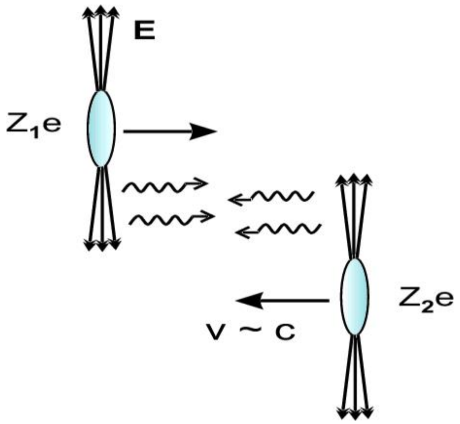

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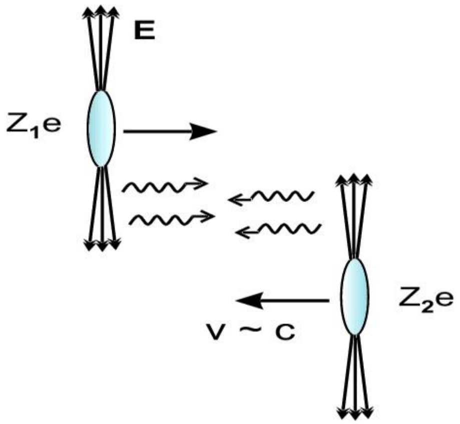

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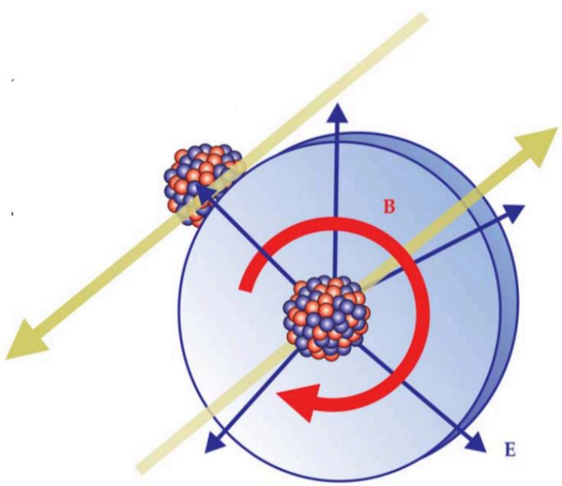

Physics Today **70**, 10, 40 (2017)

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 ρ (Au+Au 200 GeV)in ultra-peripheral collisions (UPCs) as example: $\langle R_{producton} \rangle$ ~ 40 fm

Photon interactions in A+A

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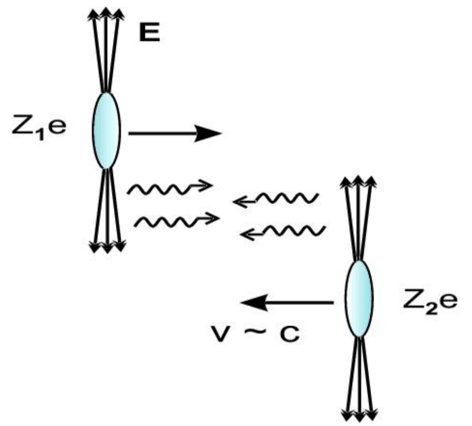
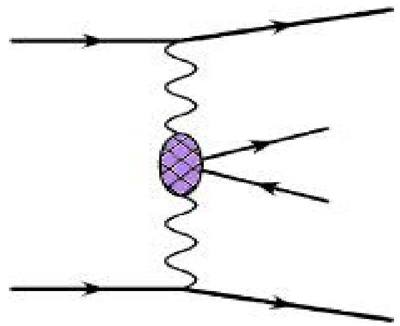


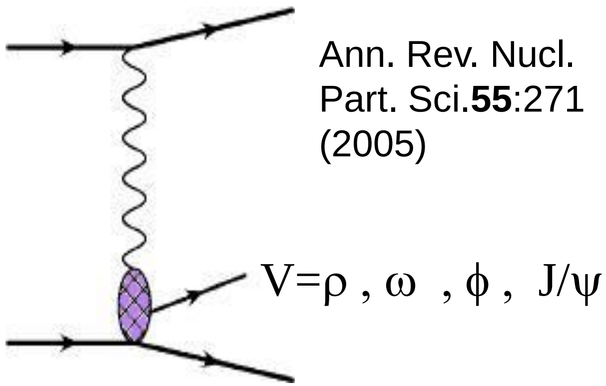
Electromagnetic interaction

=



Photon-photon interactions

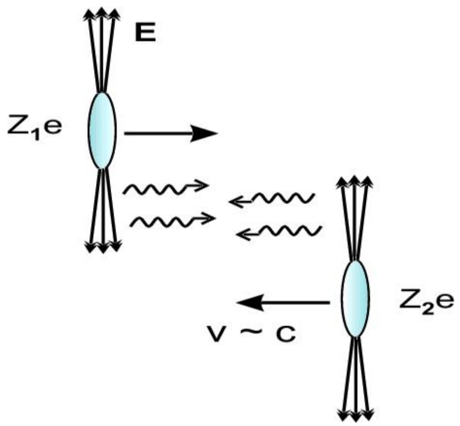
+



Photon-nucleus interactions

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

Photon interactions in A+A



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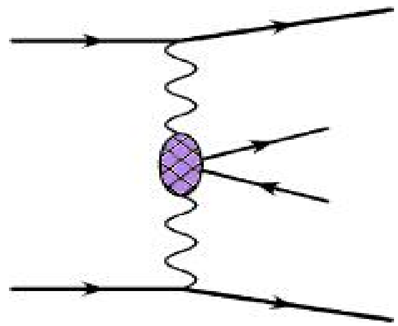

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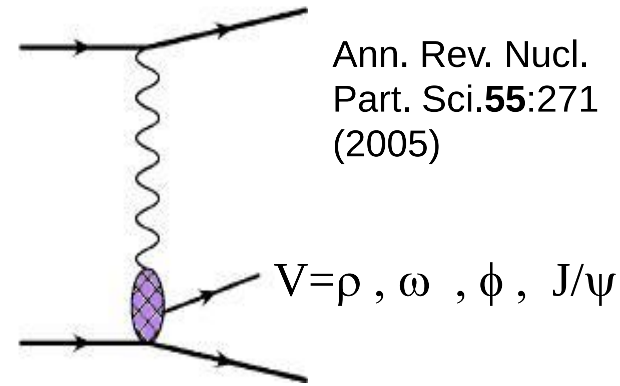

Photon-nucleus interactions

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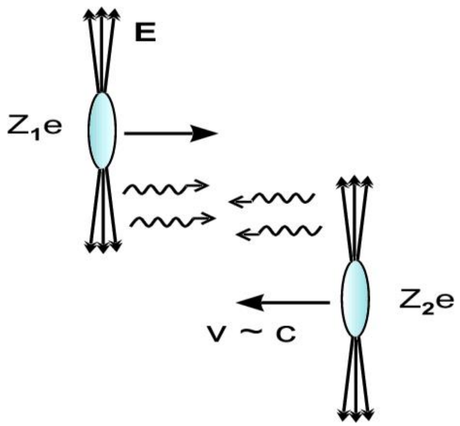
- This large flux of quasi-real photons makes a hadron collider also a photon collider!
  - ✓ Photon-nucleus interactions: Vector meson
  - ✓ Photon-photon interactions: dileptons …

Photon interactions in A+A



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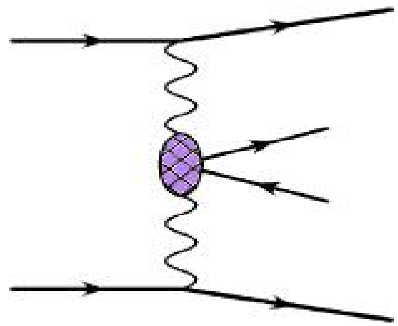

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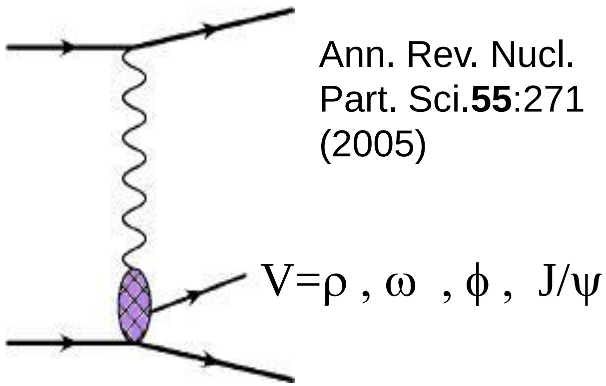

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Photon-photon interactions

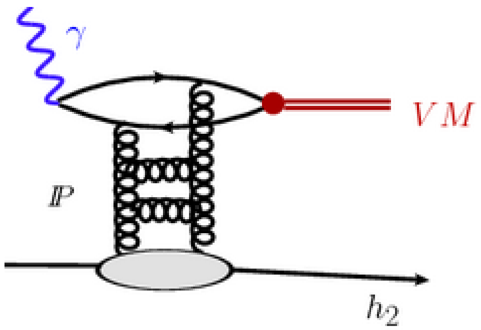
Photon-nucleus interactions

- 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 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)…



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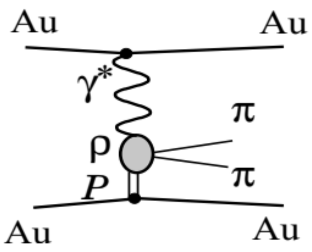

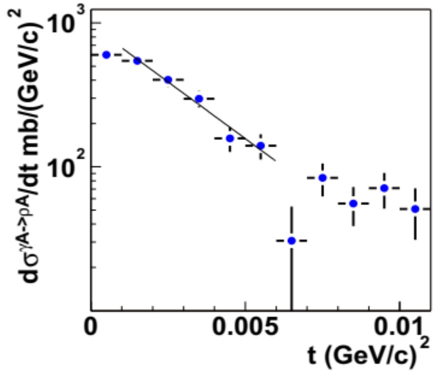

STAR, PRL **89** (2002) 272302

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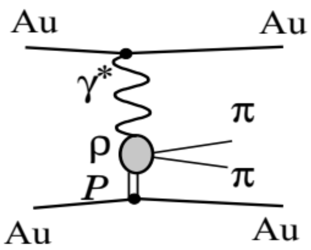

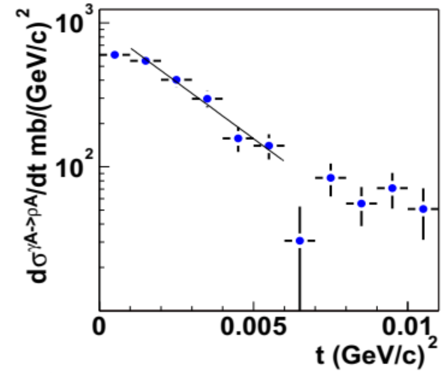

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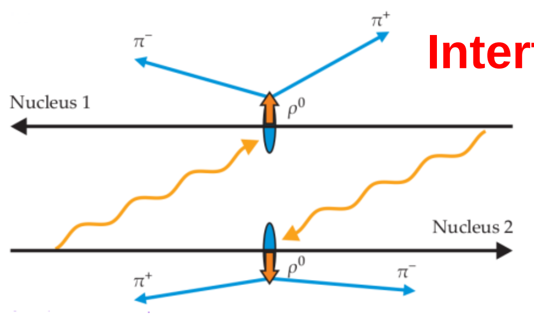
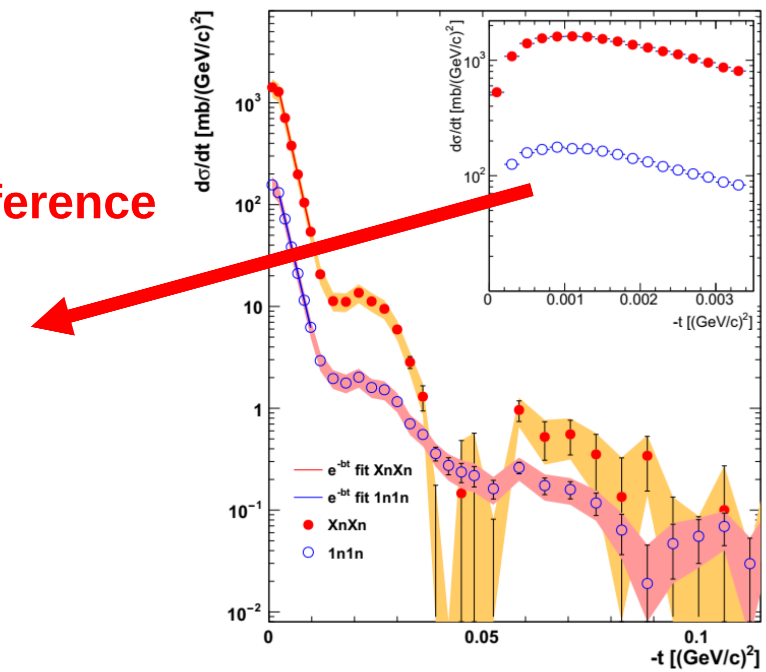


Interference



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

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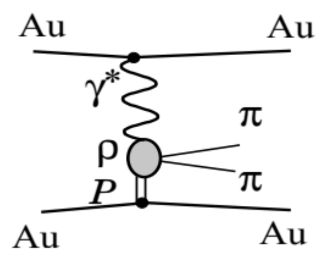

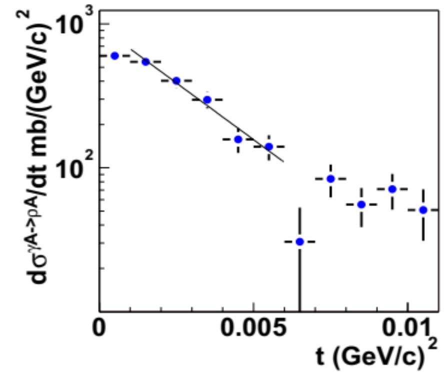

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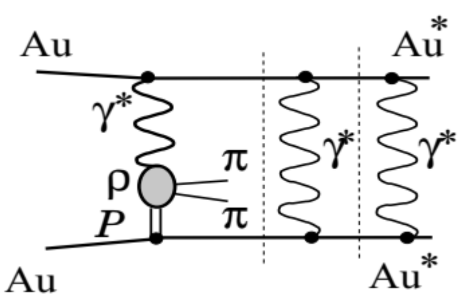
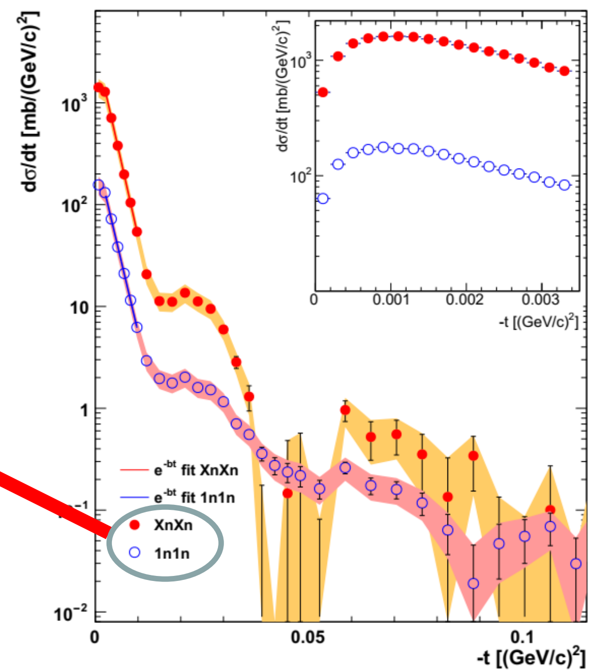


STAR, PRC **96**, (2017) 054904

When the nucleus break, coherent photoproduction can still occur!



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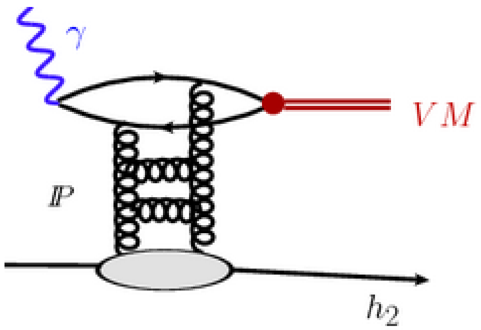
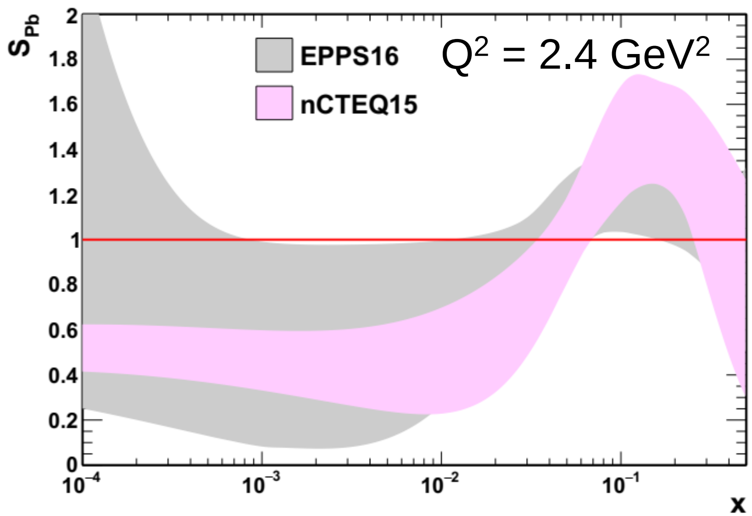


- Sensitive to the gluon distribution:

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

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



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

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

Nuclear shadowing from J/ψ measurements in UPCs

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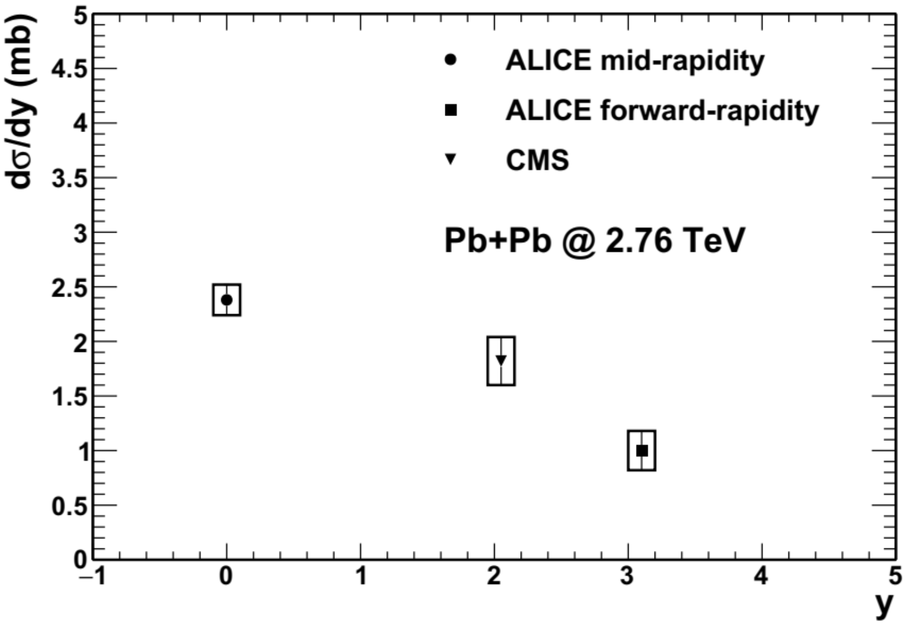
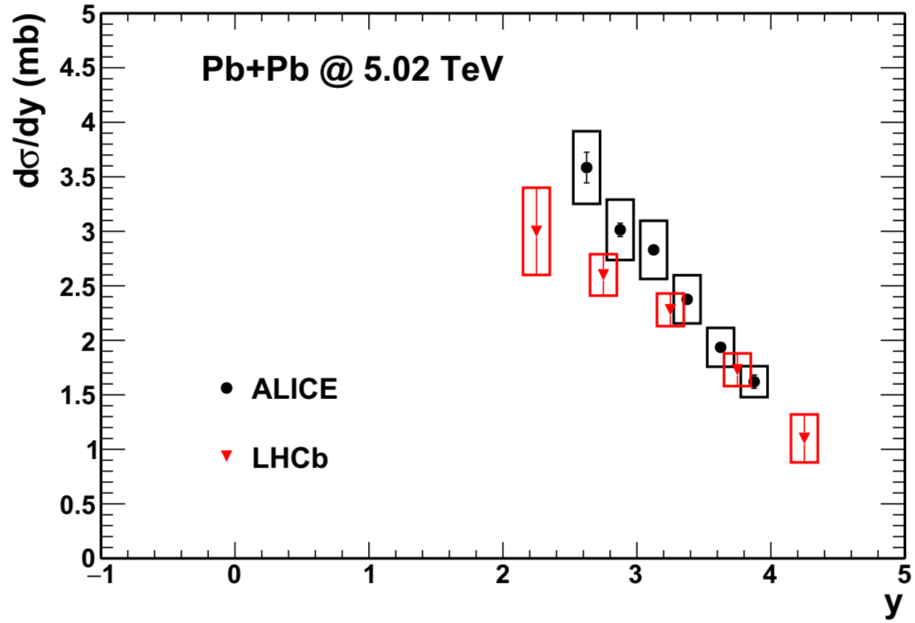




ALICE: EPJC **73** (2013) 2617

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

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

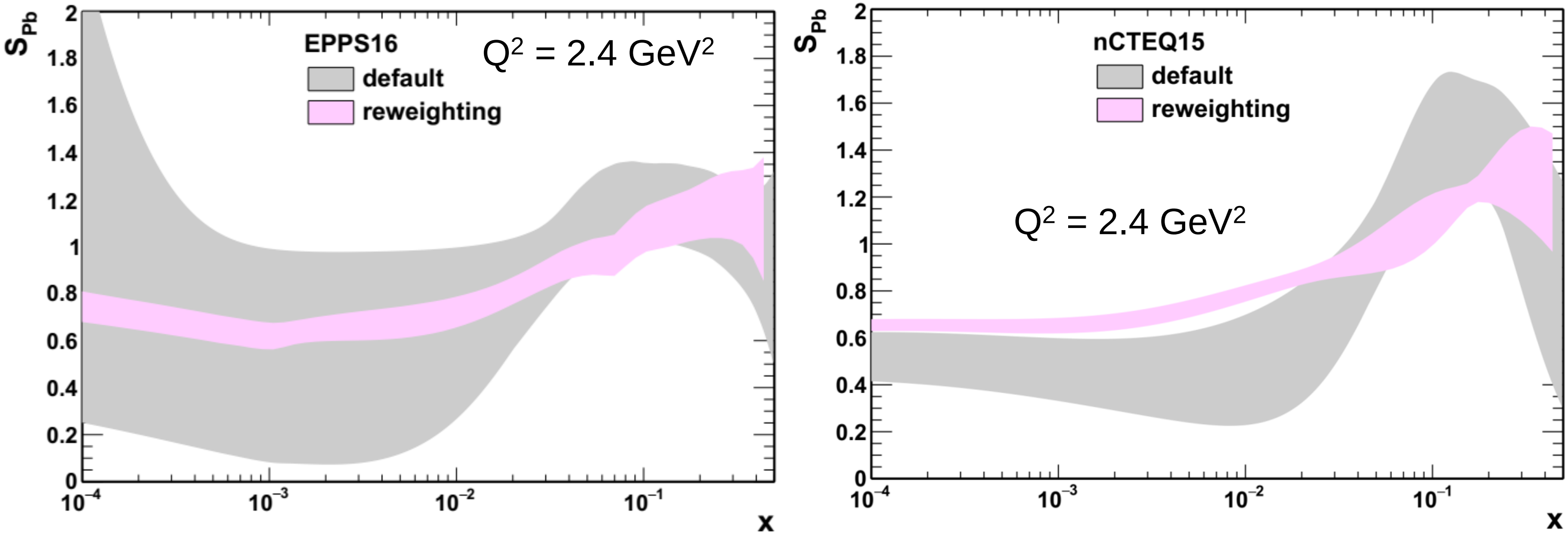
LHCb: LHCb-CONF-2018-003

ALICE: arXiv: 1904.06272

Various precise measurements!

Powerful to constrain nPDF

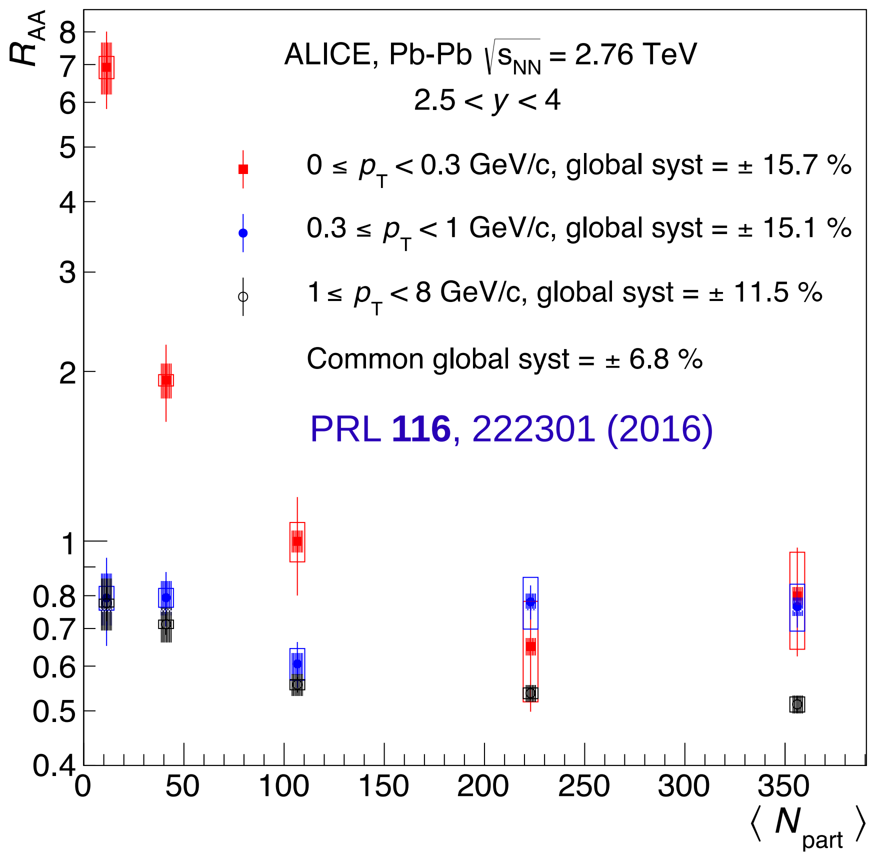
Nuclear shadowing from J/ψ measurements in UPCs



- 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.

Please see Zehua Cao's talk for detail
Aug. 19th Parallel I.5 15:00

Anomalous excess of J/ψ production observed at ALICE



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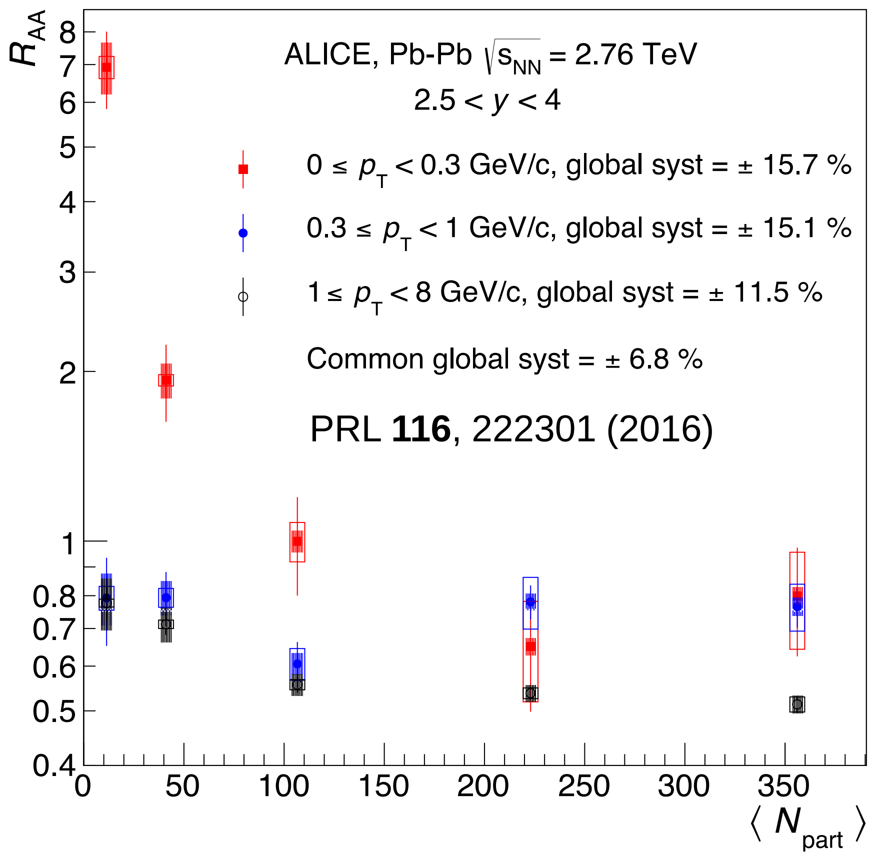

- Significant enhancement of J/ψ yield observed in p_T interval 0 – 0.3 GeV/c for peripheral collisions (50 – 90%).
- Can not be described by hadronic production modified by the hot medium or cold nuclear matter effects!

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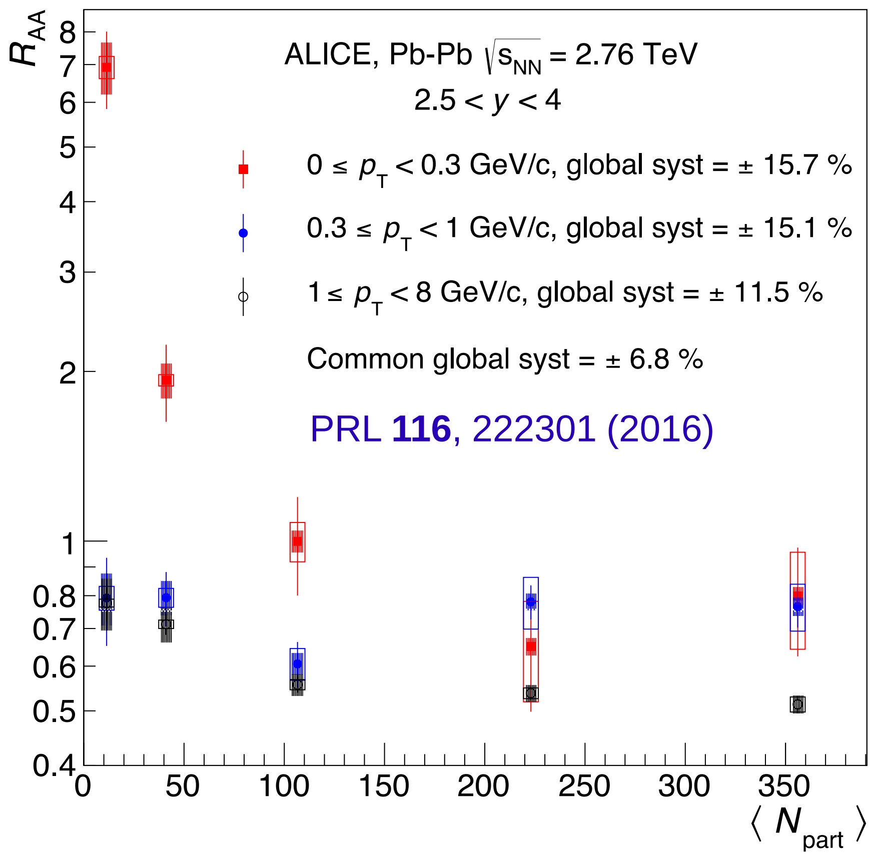

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- Can not be described by hadronic production modified by the hot medium or cold nuclear matter effects!

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

What does STAR say for the excess?

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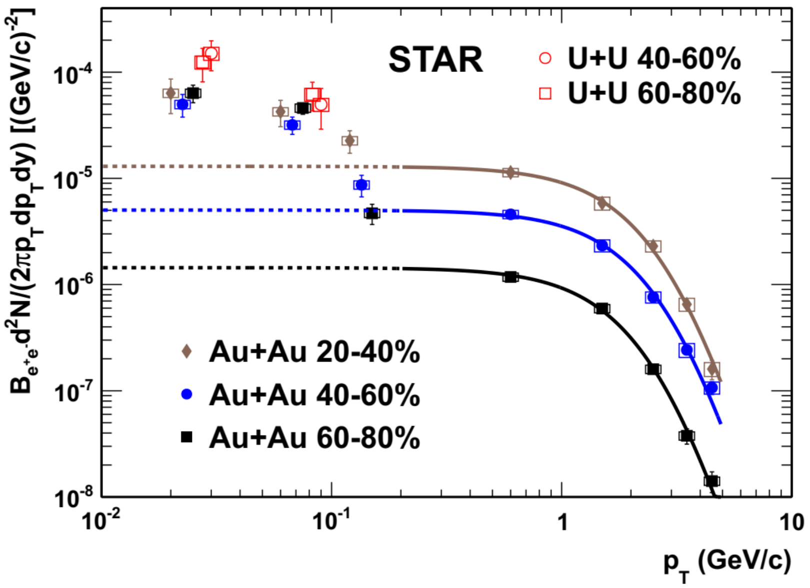
PRL **123** (2019) 132302



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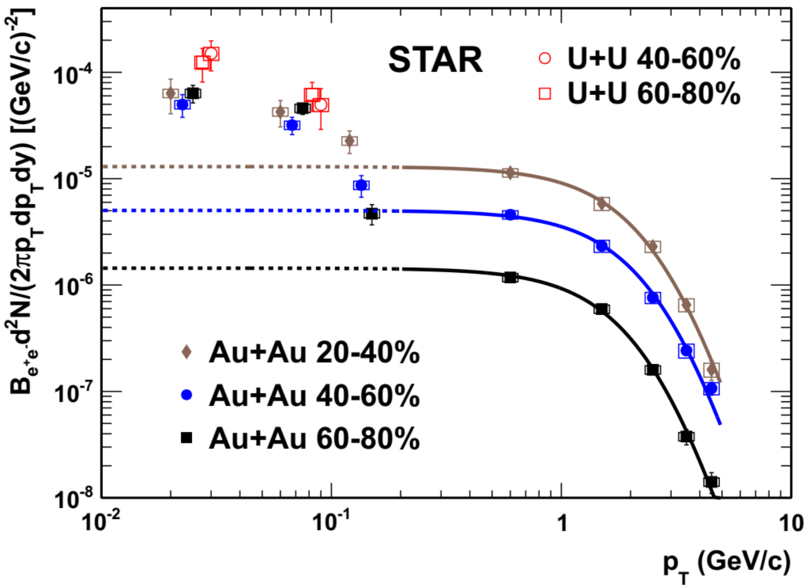

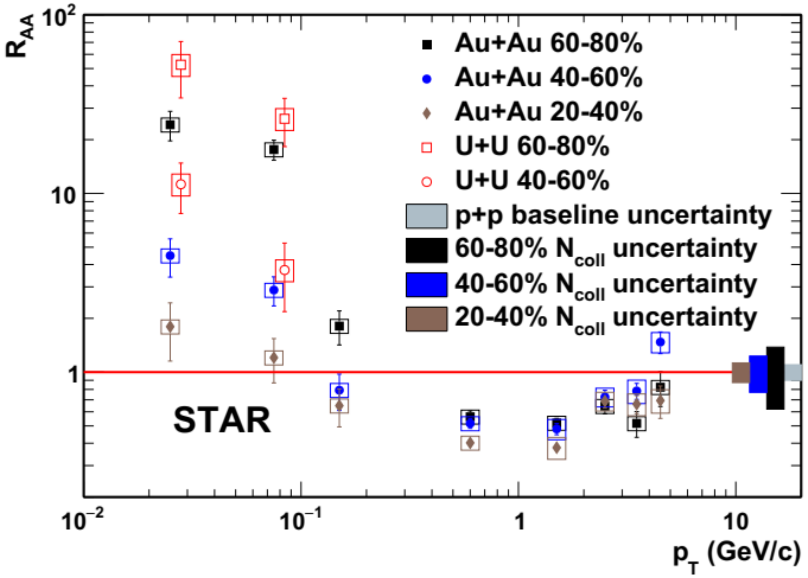

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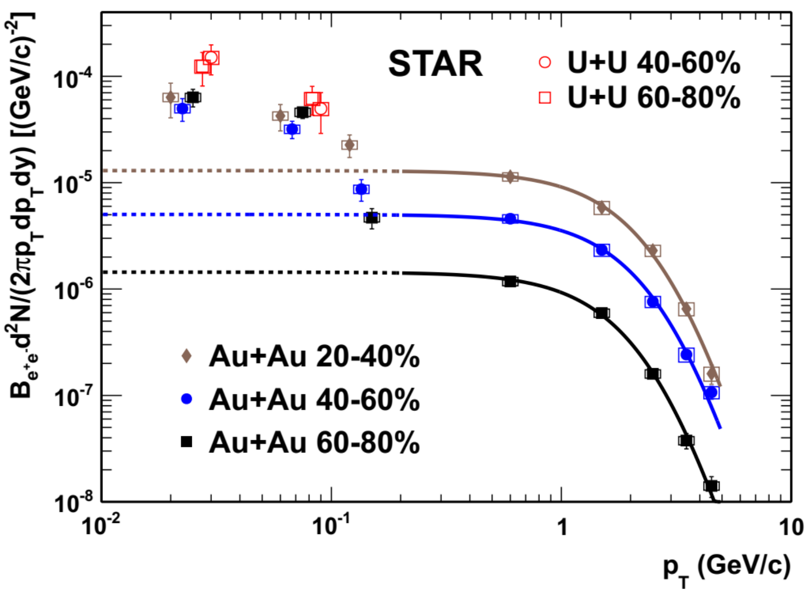

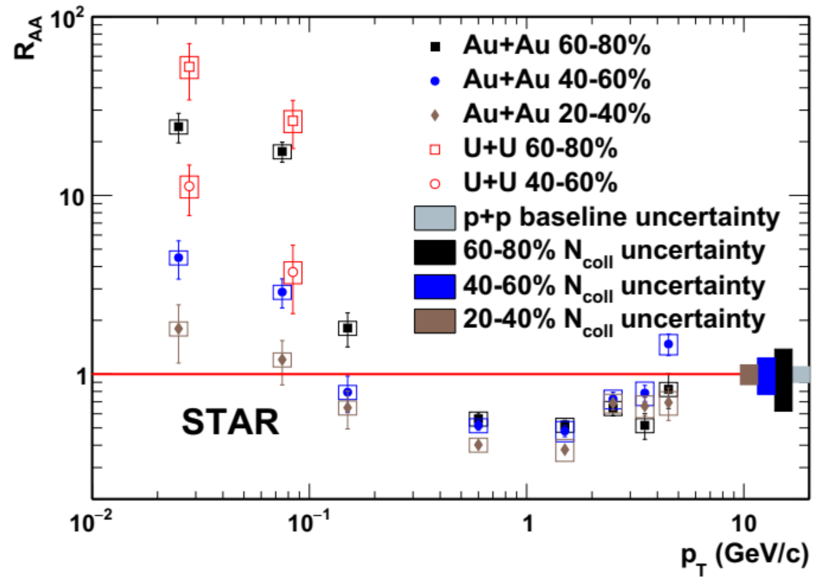

- Significant enhancement of J/ψ yield observed at p_T interval 0 – 0.2 GeV/c for peripheral collisions (40 – 80 %)!
- No significant difference between Au+Au and U+U collisions.

The excess yield and dN/dt distribution

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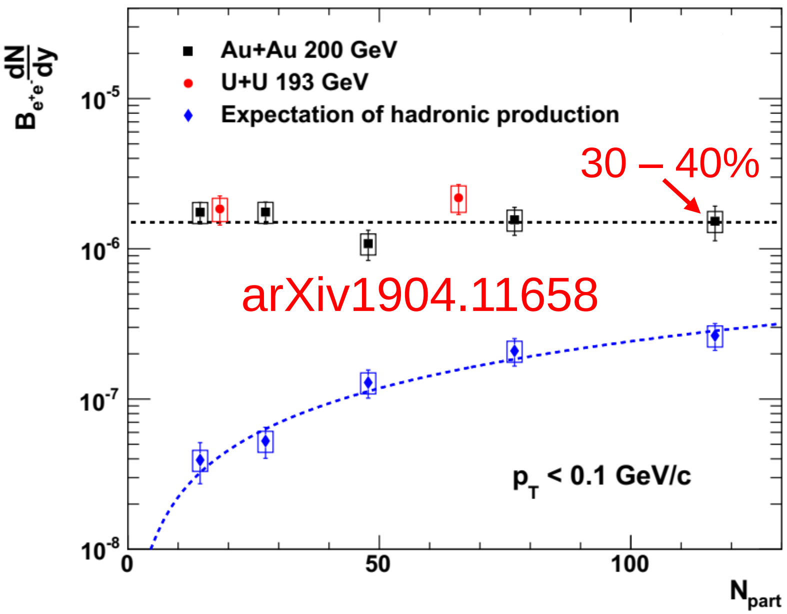

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- No significant centrality dependence of the excess yield!

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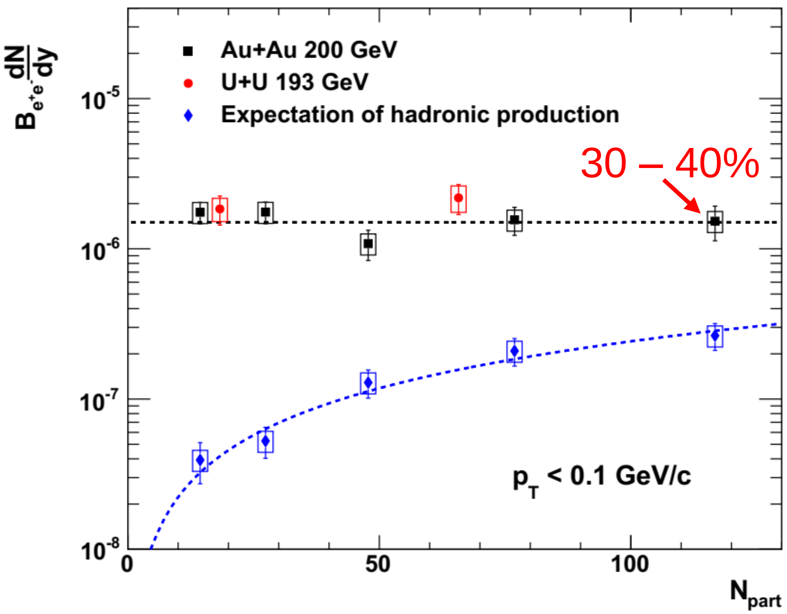

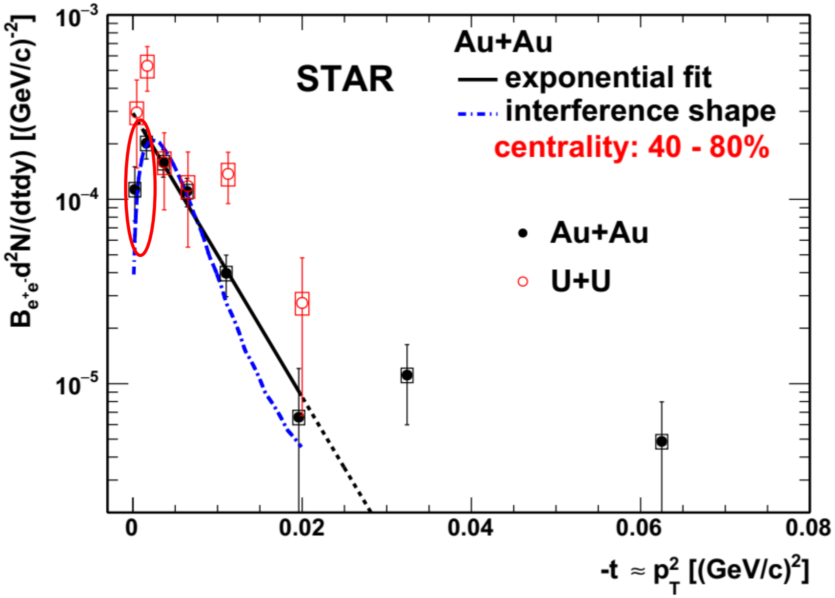

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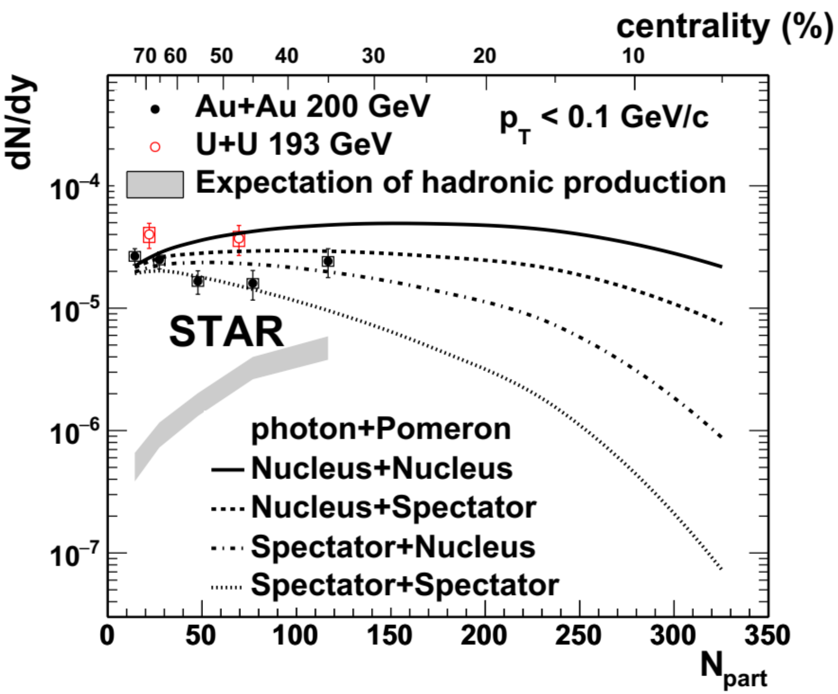
- Similar structure to that in UPC case!
- Indication of interference!
  - ✓ Interference shape from calculation PRC **97** (2018) 044910
- Similar slope parameter!
  - ✓ Slope from STARLIGHT prediction in UPC case – 196 $(GeV/c)^{-2}$
  - ✓ Slope w/o the first point: 177 ± 23$(GeV/c)^{-2}$ χ^2/NDF =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

Comparison with theoretical calculations



W. Zha etal., PRC **97** (2018) 044910
W. Zha etal., PRC **99**, (2019) 061901(R)

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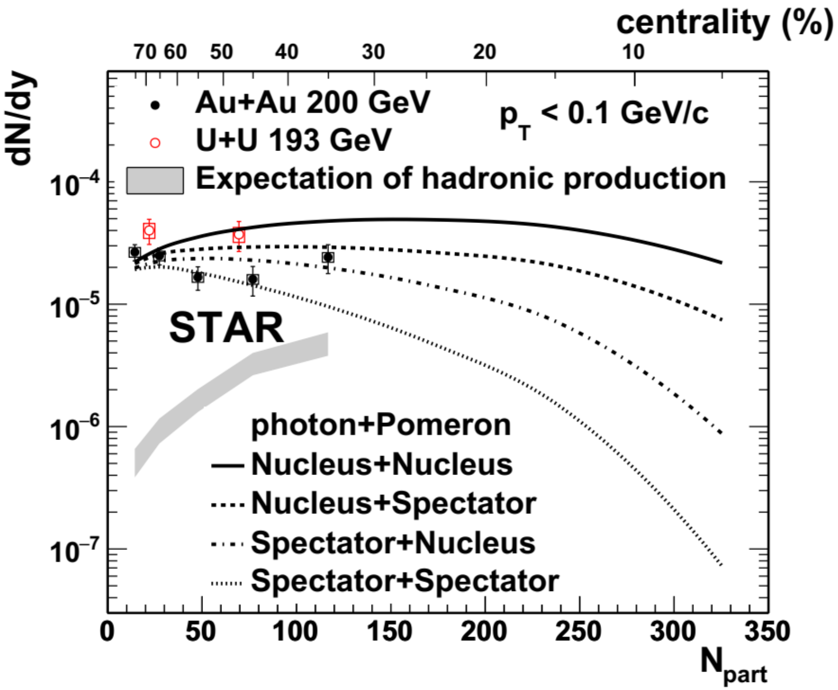

W. Zha etal., PRC **97** (2018) 044910
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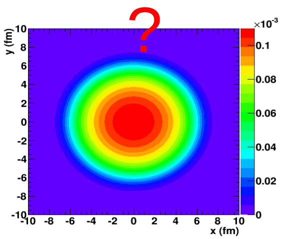
How coherence keep? --- Time scale matters

Collision (production) time > GeV

Fragment of spectator and nucleus excitation ~ MeV

Photon emitter:

Pomeron emitter



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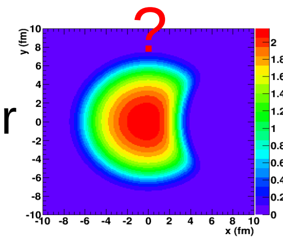

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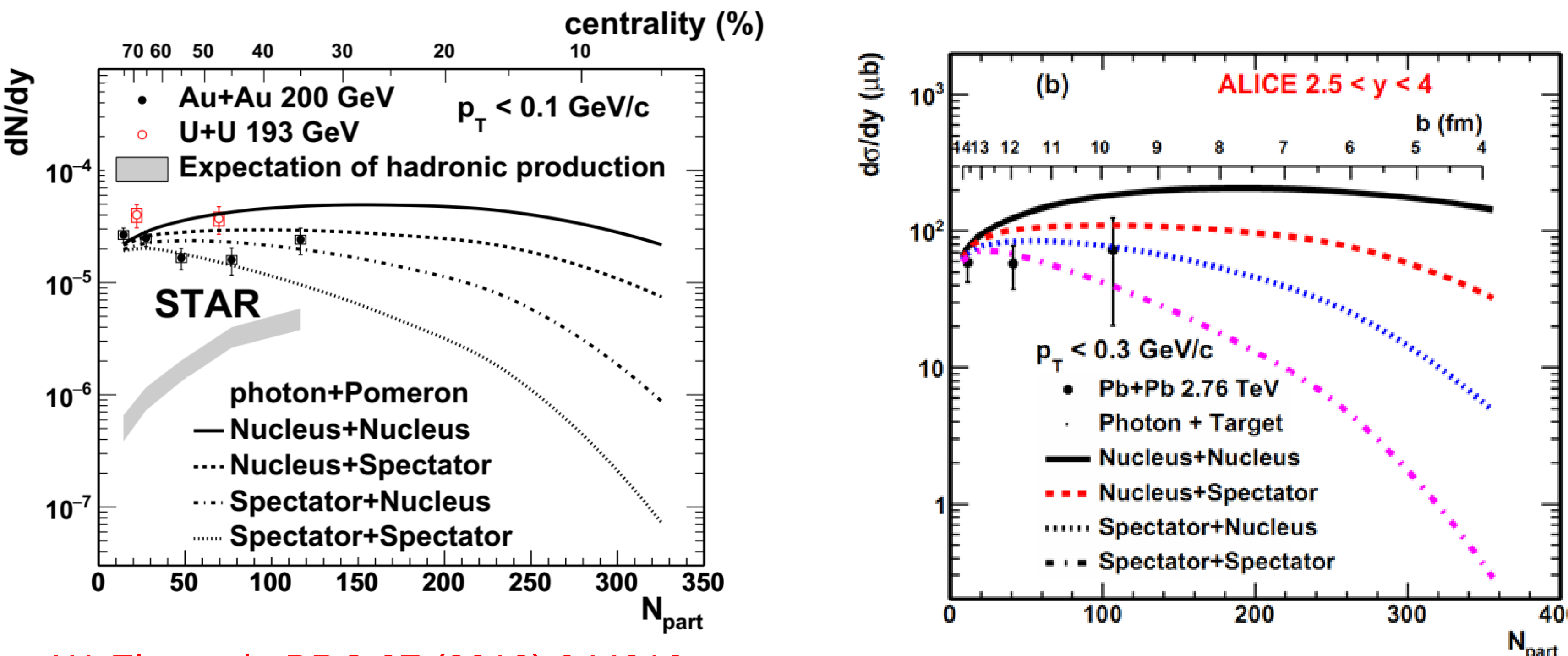

W. Zha etal., PRC **97** (2018) 044910
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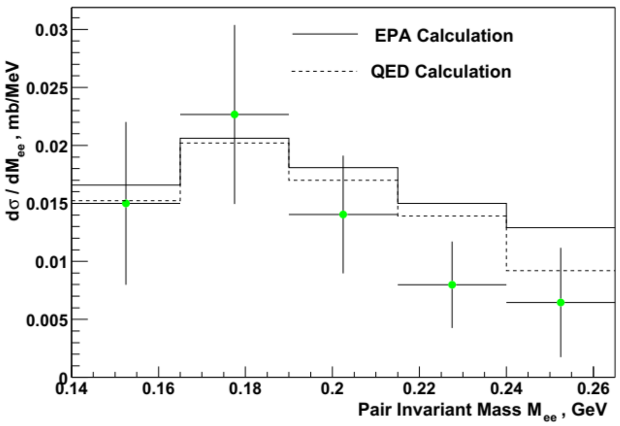
- All scenarios describe the data very well in peripheral collisions!
- Nuclues+Nucleus: overestimate the data in semi-central collisions.
- Spectator+Spectator: under predict the data in semi-central collisions.
- To distinguish the different scenarios, measurements at central collisions are needed!

Photon-photon interactions in UPC

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

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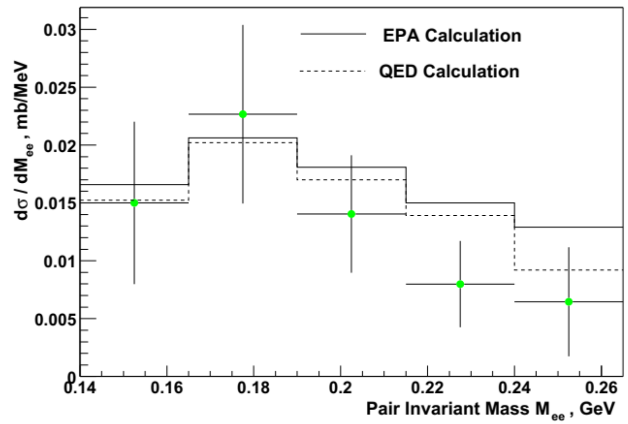
- To study the meson spectroscopy

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)



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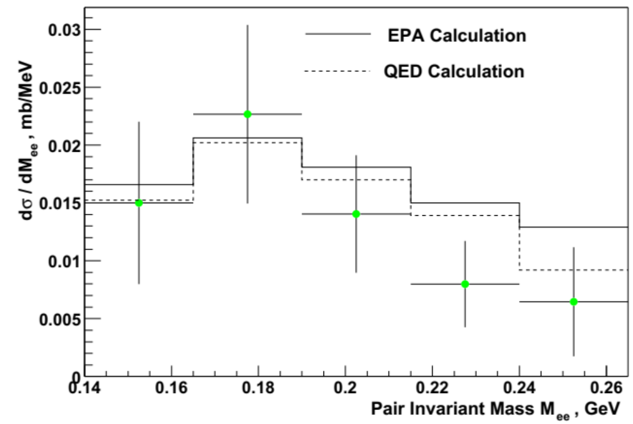

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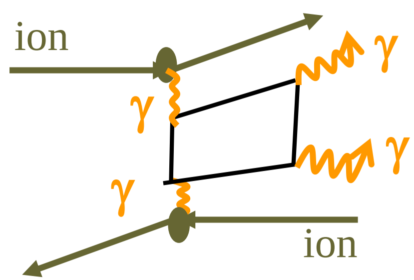
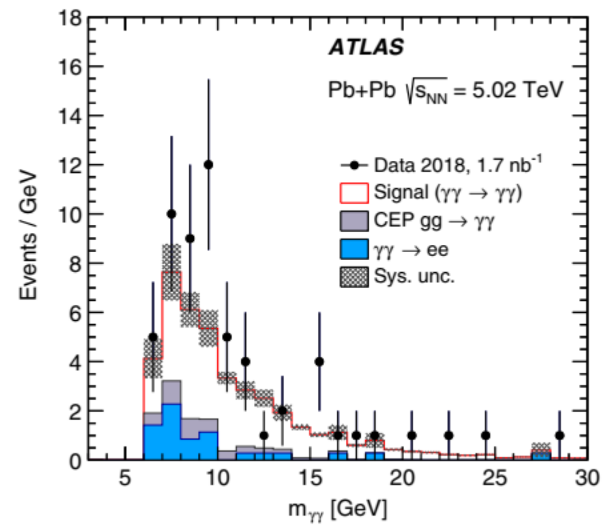
η'	958	0.75	21
$f_2(1270)$	1275	0.54	22
$a_2(1320)$	1318	0.19	8.2
η_c	2981	3.3×10^{-3}	0.61
χ_{0c}	3415	0.63×10^{-3}	0.16
χ_{2c}	3556	0.59×10^{-3}	0.15

No measurements in UPCs yet!

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

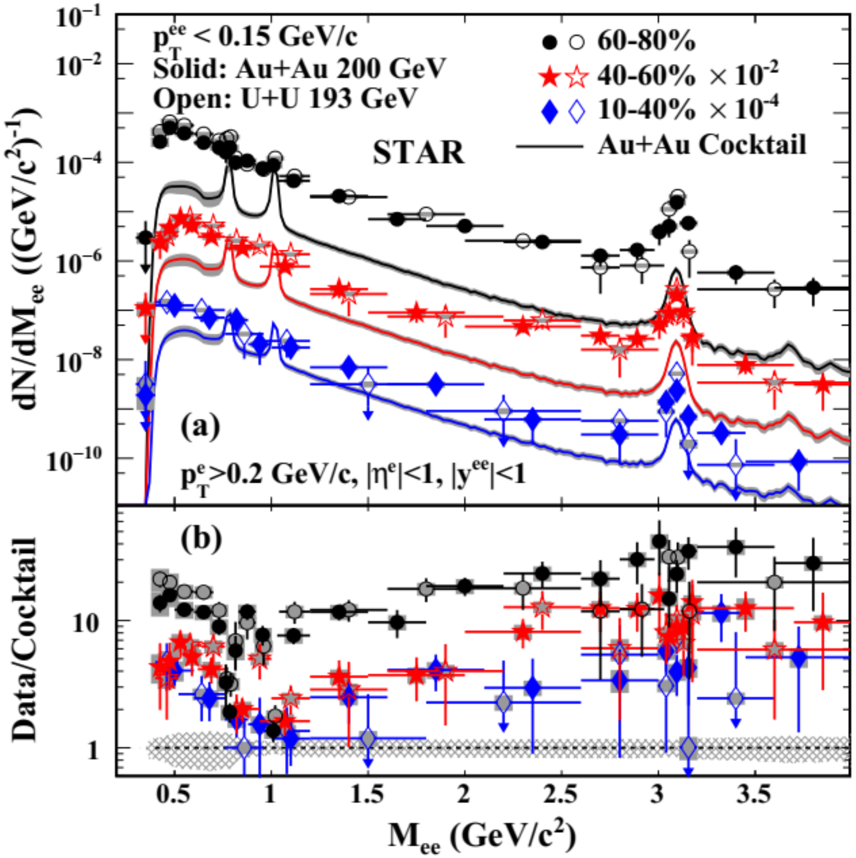
- From “virtual” to “real”
  - ✓ Light-by-light scattering seen by ATLAS





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

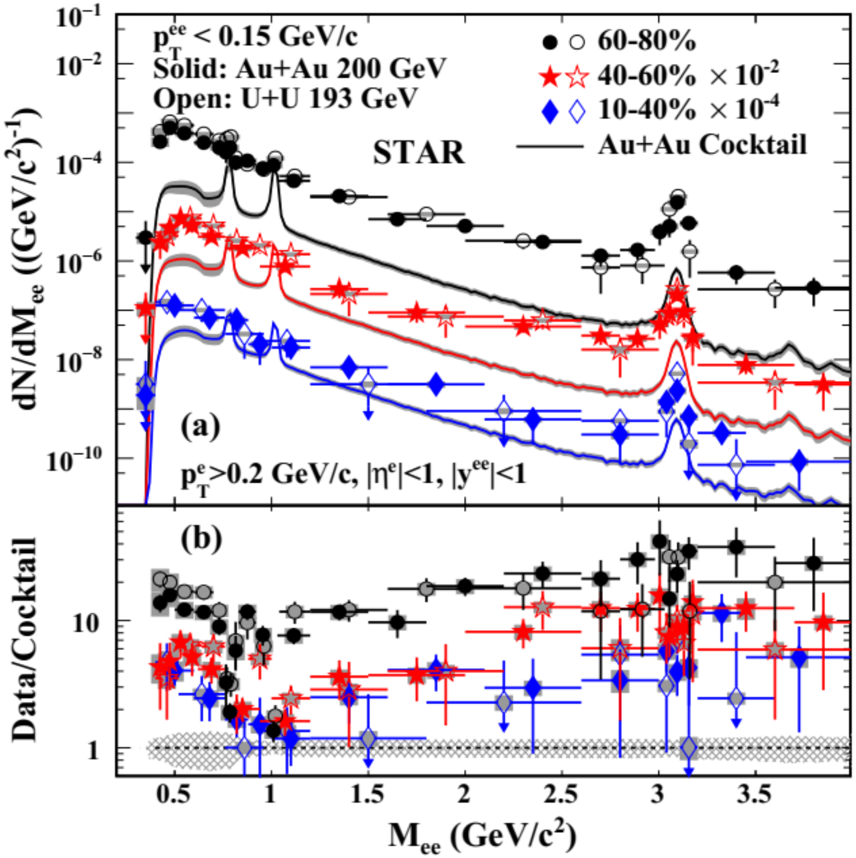
How about the contribution in HHIC?

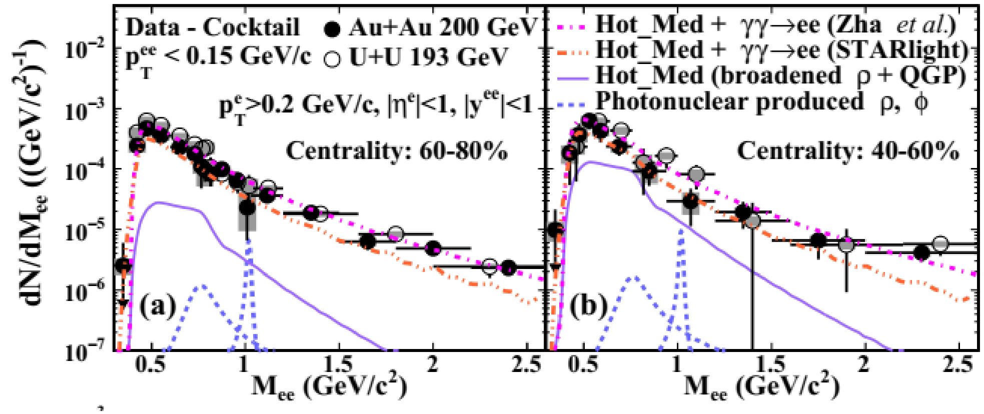


STAR, PRL **121** (2018) 132301

- Significant excess in 60-80% central Au + Au and U + U collisions for the whole invariant mass range!

How about the contribution in HHIC?





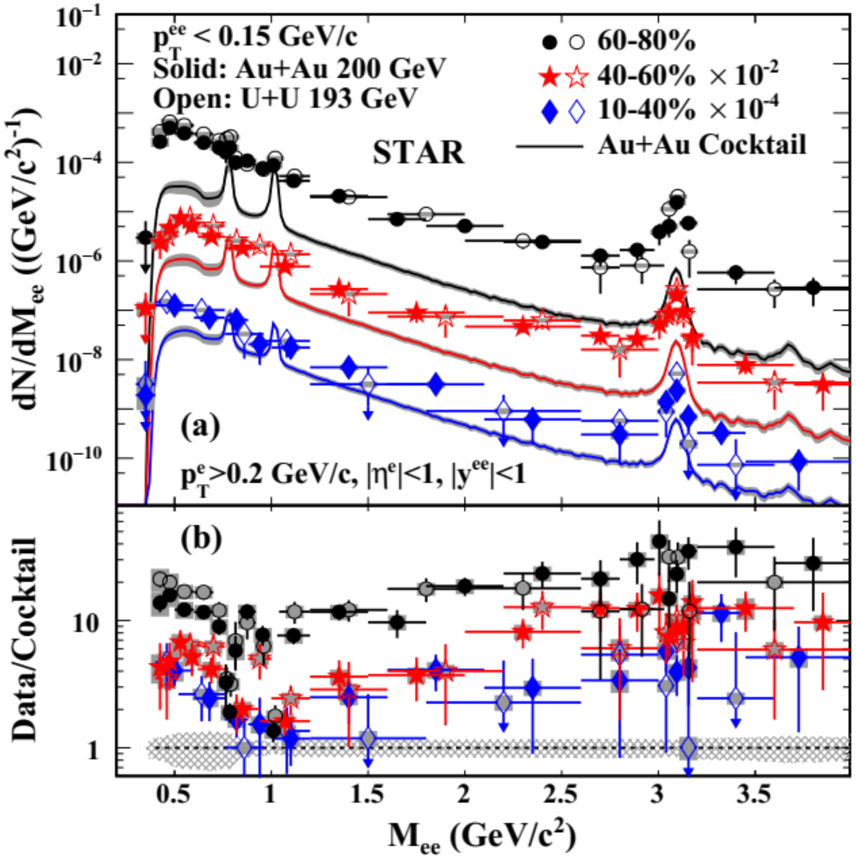
STAR, PRL **121** (2018) 132301

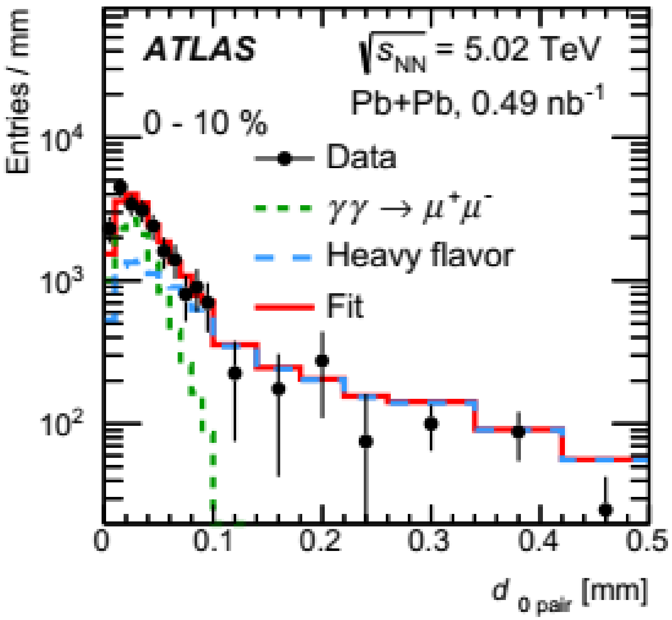
W. Zha etal., PLB **781** (2018) 182

W. Zha etal., PLB **789** (2019) 238

- 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!

How about the contribution in HHIC?

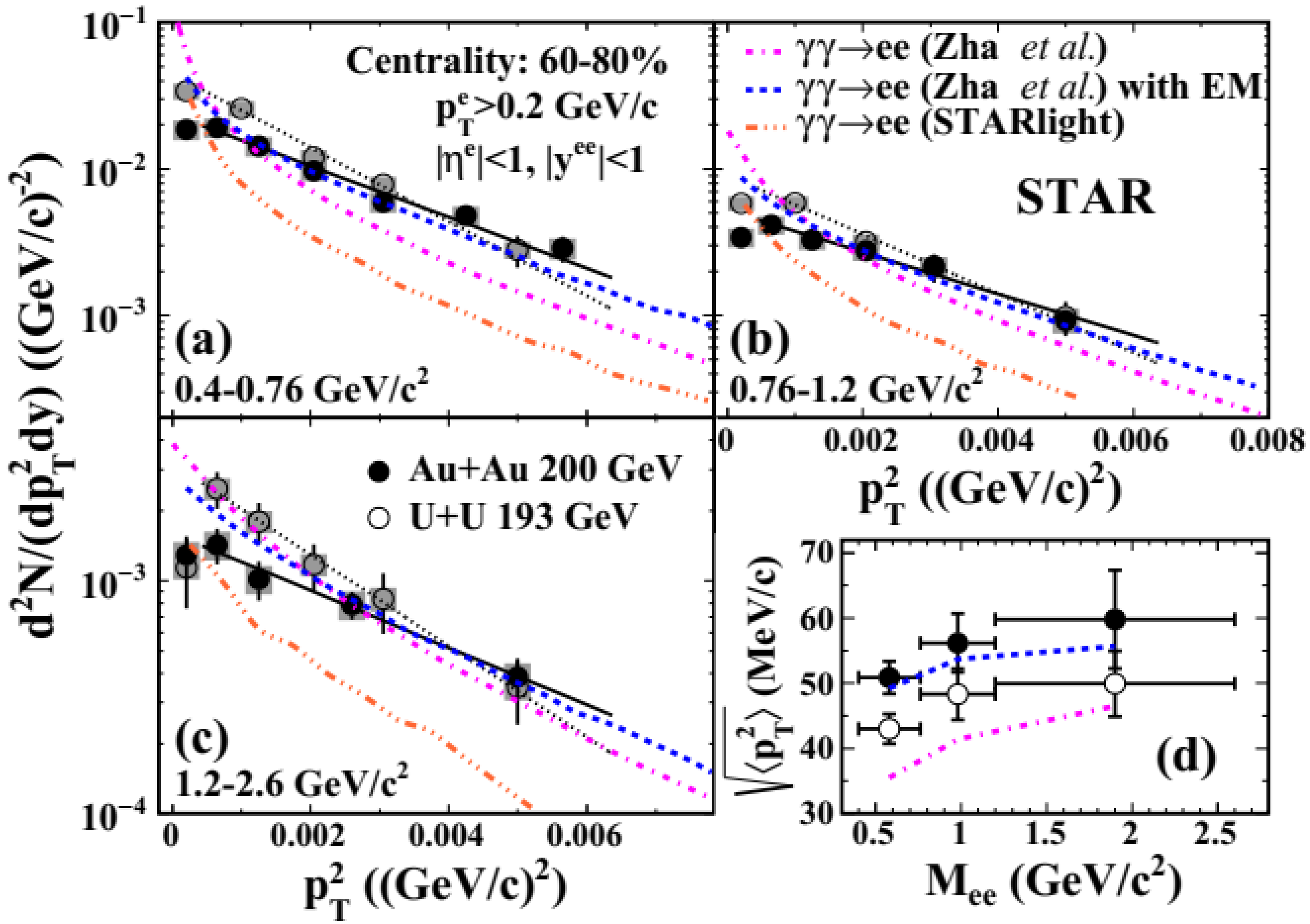




ATLAS, PRL **121** (2018) 212 301

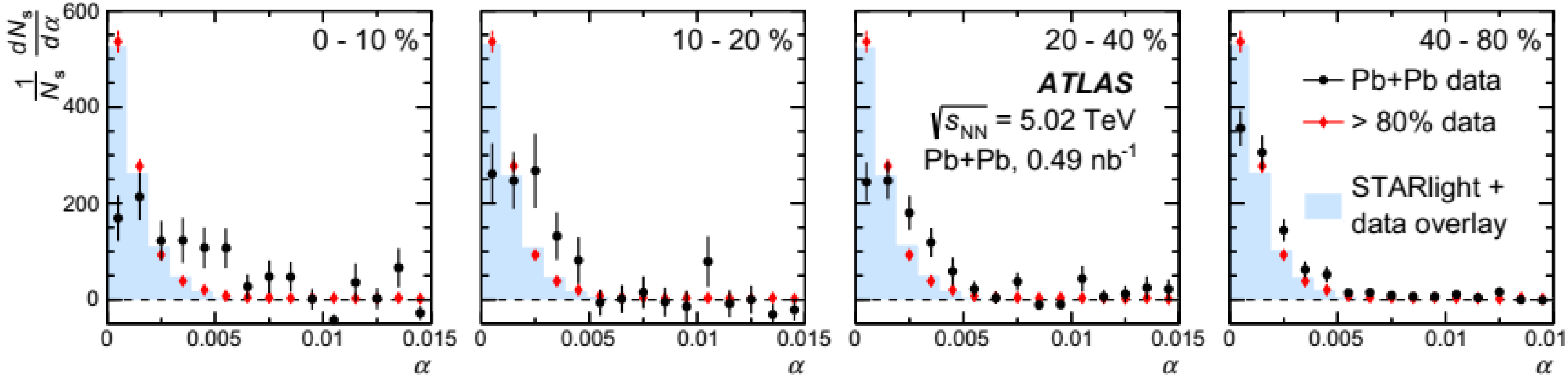
- Significant excess in 60-80% central Au + Au and U + U collisions for the whole invariant mass range!
- The excess can be described by the coherent photon-photon process!

The puzzle: pair p_T broadening



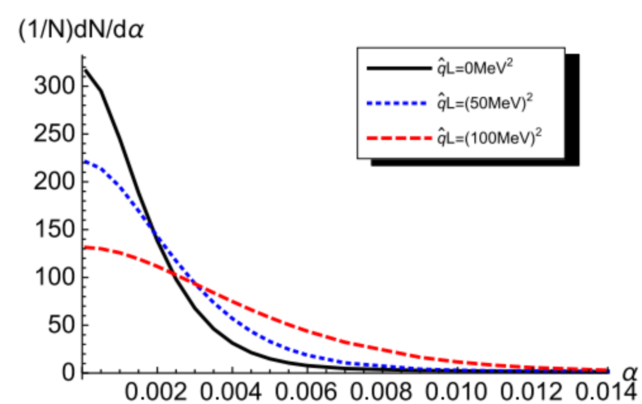
- The equivalent photon approximation could not describe the pair p_T distribution
- Possible medium effects --- magnetic field trapped in the QGP?

The puzzle: pair p_T broadening



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

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



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

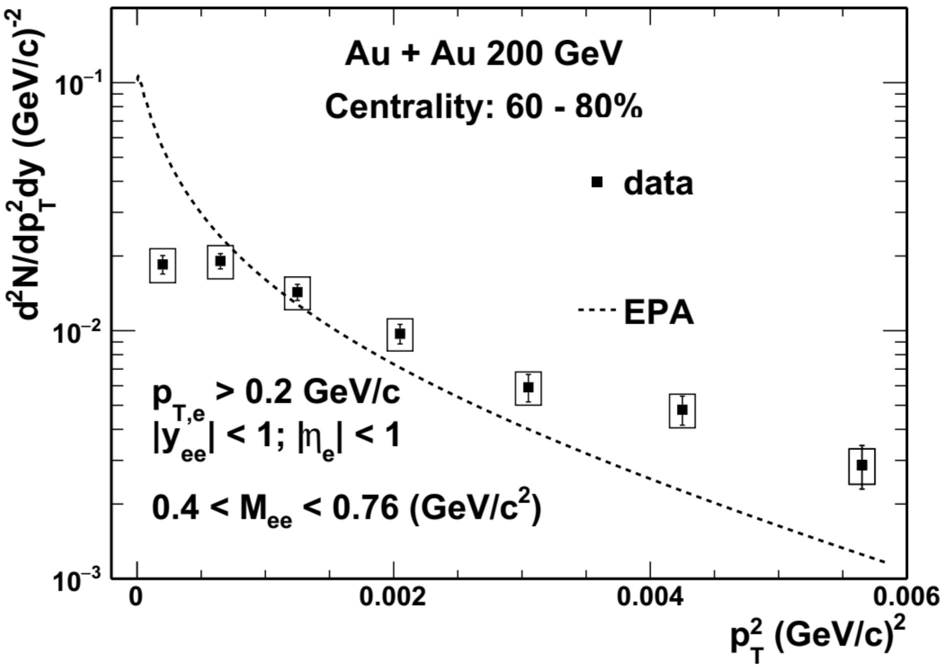
The initial impact parameter dependence

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 !

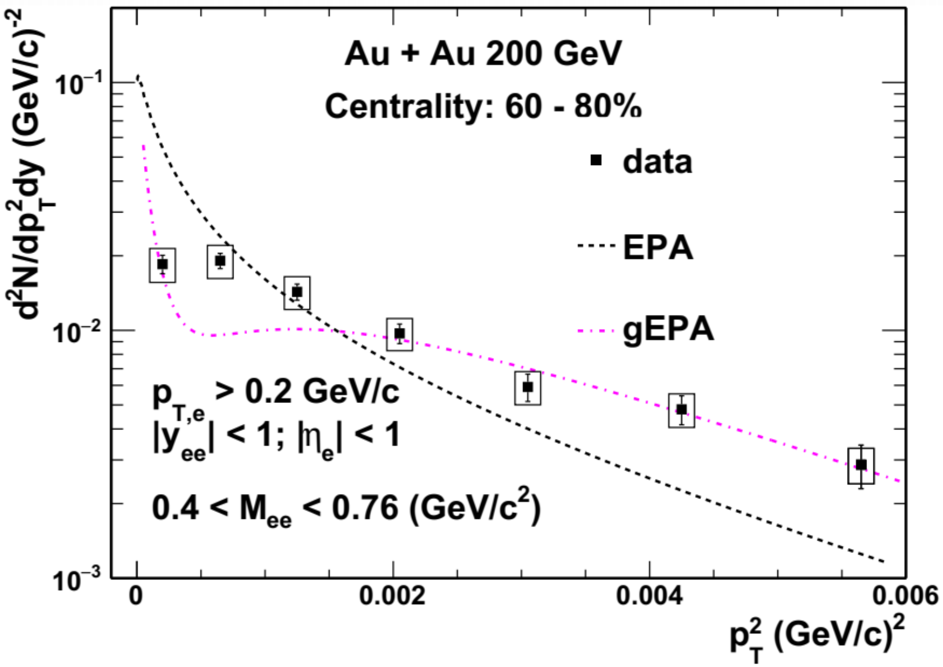
The initial impact parameter dependence

gEPA approach

Impact parameter dependence!

$$\sigma = 16\frac{Z^4e^4}{(4\pi)^2}\int d^2b\int\frac{d\omega_1}{\omega_1}\int\frac{d\omega_2}{\omega_2}\int\frac{d^2k_{1\perp}}{(2\pi)^2}\int\frac{d^2k_{2\perp}}{(2\pi)^2}\int\frac{d^2q_\perp}{(2\pi)^2}e^{-i\mathbf{b}\cdot\mathbf{q}_\perp}$$
$$\times\mathcal{F}_1(\mathbf{k}_{1\perp},\omega_1)\,\mathcal{F}_2(\mathbf{k}_{2\perp},\omega_2)\,\mathcal{F}_1^*(\mathbf{k}_{1\perp}-\mathbf{q}_\perp,\omega_1)\,\mathcal{F}_2^*(\mathbf{k}_{2\perp}+\mathbf{q}_\perp,\omega_2)$$
$$\times\{(\mathbf{k}_{1\perp}\cdot\mathbf{k}_{2\perp})\,((\mathbf{k}_{1\perp}-\mathbf{q}_\perp)\cdot(\mathbf{k}_{2\perp}+\mathbf{q}_\perp))\,\sigma_s(\omega_1,\omega_2)$$
$$+(\mathbf{k}_{1\perp}\times\mathbf{k}_{2\perp})\cdot((\mathbf{k}_{1\perp}-\mathbf{q}_\perp)\times(\mathbf{k}_{2\perp}+\mathbf{q}_\perp))\,\sigma_{ps}(\omega_1,\omega_2)\}\quad .$$

PRC **47** (1993) 2308

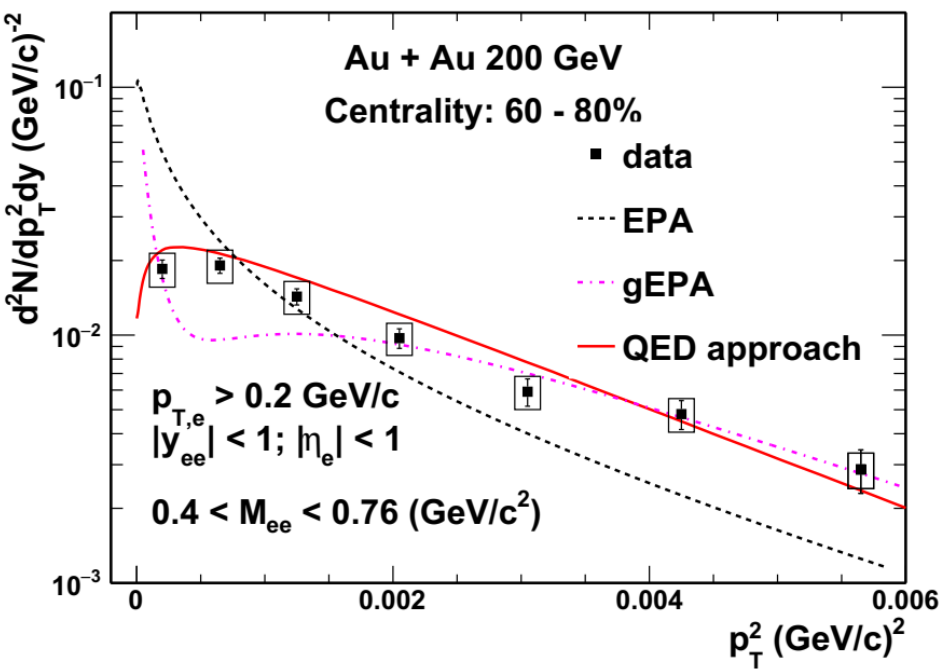


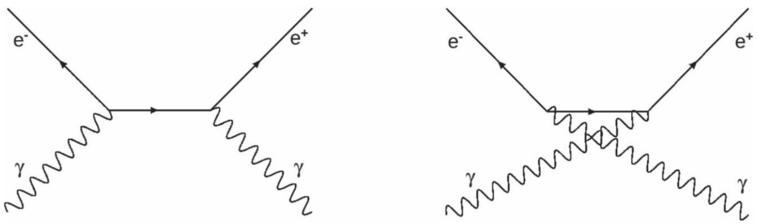
- Fail to reproduce data at very low p_T !
- Strange dip structure!

The initial impact parameter dependence

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

QED approach



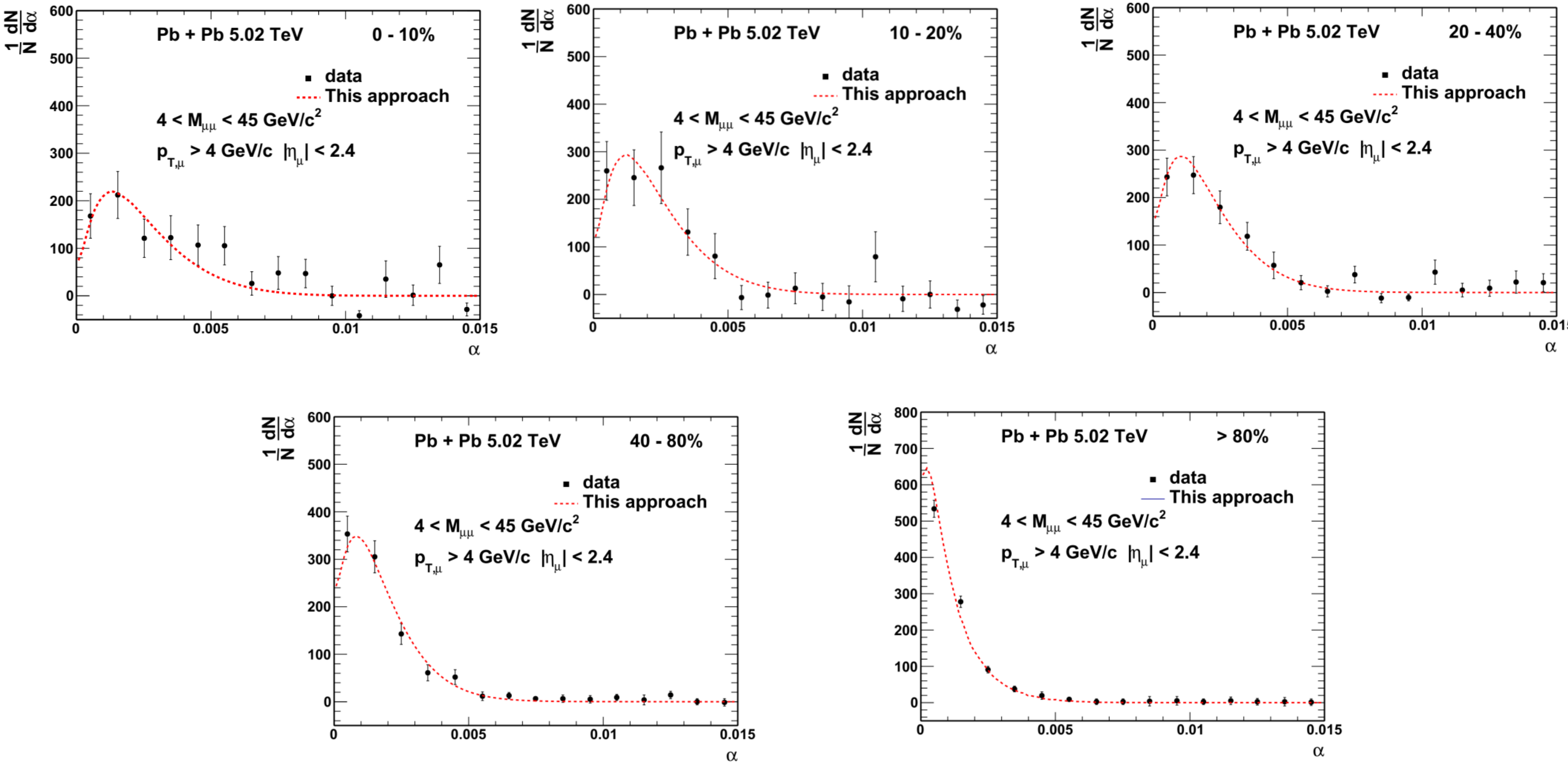


PRA **51** (1995) 1874

- Reasonably describe the p_T spectrum.

W. Zha etal., arXiv: 1812.02820

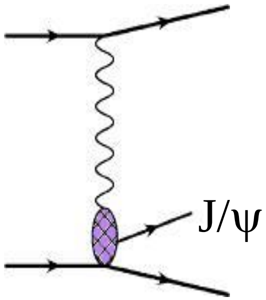
The initial impact parameter dependence

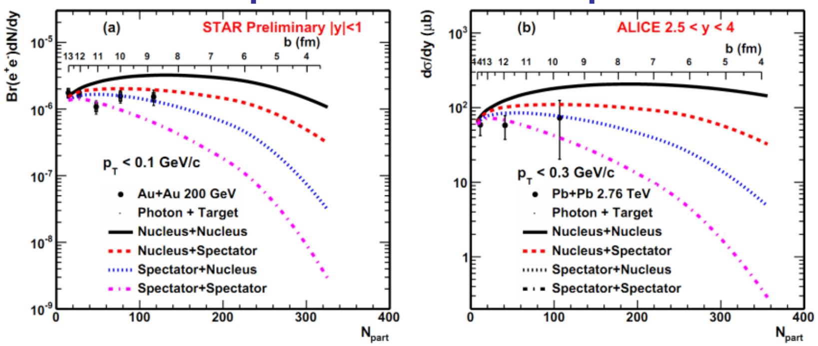


Successfully reproduce the centrality dependence of acoplanarity

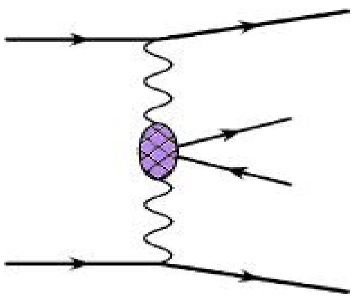
Summary

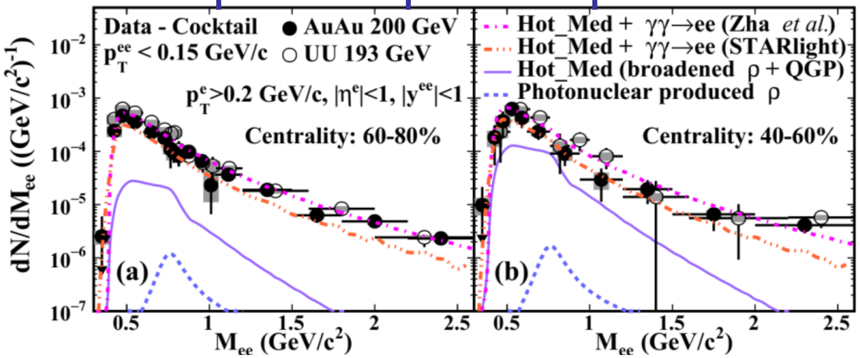
- **Excess of J/ψ at very low p_T!**
  - ✓Consistent with coherent photonuclear production in HHIC!





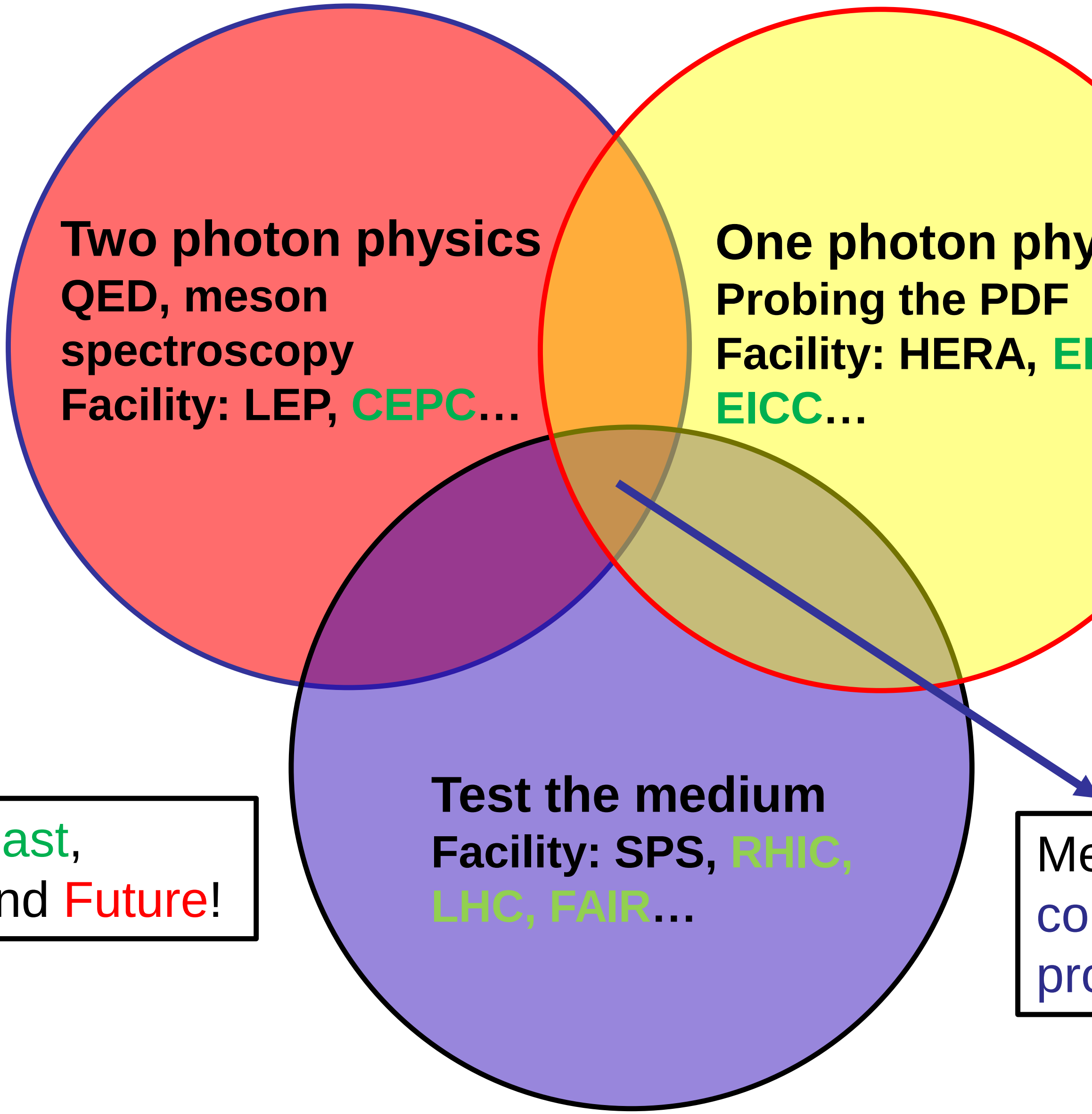
- **Excess of dielectron at very low p_T!**
  - ✓Consistent with coherent photon-photon production in HHIC!





- More **coherent photon products** are promising in HHIC!

Outlook



Link the Past, Present and Future!

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

Recover the impact parameter dependence: gEPA

$$A_1^\mu(k_1, b) = -2\pi Z_1 e\, e^{ik_1^\tau b_\tau}\, \delta(k_1^\nu u_{1\nu}) \frac{F(-k_1^\rho k_{1\rho})}{k_1^\sigma k_{1\sigma}} u_1^\mu$$

$$A_2^\mu(k_2, 0) = -2\pi Z_2 e\, \delta(k_2^\rho u_{2\rho}) \frac{F(-k_2^\rho k_{2\rho})}{k_2^\sigma k_{2\sigma}} u_2^\mu$$

$$S(P\alpha, \mathbf{b}) = \int \frac{d^4k_1}{(2\pi)^4} \int \frac{d^4k_2}{(2\pi)^4} \left[A_1^\mu(k_1, \mathbf{b})\, \Gamma_{\mu\nu}(k_1k_2; P\alpha)\, A_2^\nu(k_2, 0)\right] (2\pi)^4 \delta^4(k_1 + k_2 - P)$$

$$\sigma = \int d^2b \int |S(P\alpha; \mathbf{b})|^2 \frac{d^4P}{(2\pi)^4} d\alpha$$

Impact parameter dependence!

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

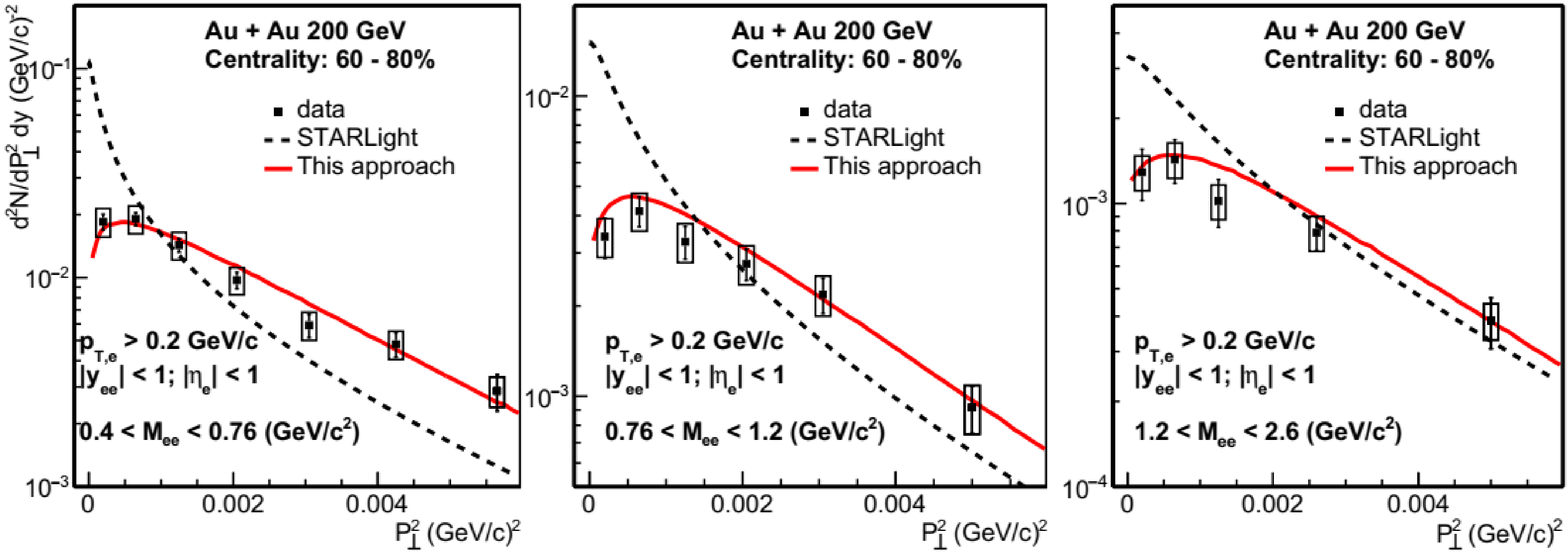
$$\times \mathcal{F}_1(\mathbf{k}_{1\perp}, \omega_1)\, \mathcal{F}_2(\mathbf{k}_{2\perp}, \omega_2)\, \mathcal{F}_1^*(\mathbf{k}_{1\perp} - \mathbf{q}_\perp, \omega_1)\, \mathcal{F}_2^*(\mathbf{k}_{2\perp} + \mathbf{q}_\perp, \omega_2)$$
$$\times \{(\mathbf{k}_{1\perp} \cdot \mathbf{k}_{2\perp})\, ((\mathbf{k}_{1\perp}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

Phys. Rev. C**47** (1993) 2308-2319

The dilepton cross section from two real photons

The results

The approach describes the data reasonably well!



However, in the code implementation, an additional phase shift has been added:

$$\sigma = 16\frac{Z^4e^4}{(4\pi)^2}\int d^2b \int\frac{d\omega_1}{\omega_1}\int\frac{d\omega_2}{\omega_2}\int\frac{d^2k_{1\perp}}{(2\pi)^2}\int\frac{d^2k_{2\perp}}{(2\pi)^2}\int\frac{d^2q_\perp}{(2\pi)^2}e^{-i\mathbf{b}\cdot\mathbf{q}_\perp} \times e^{-i(\alpha_1+\alpha_2)}$$

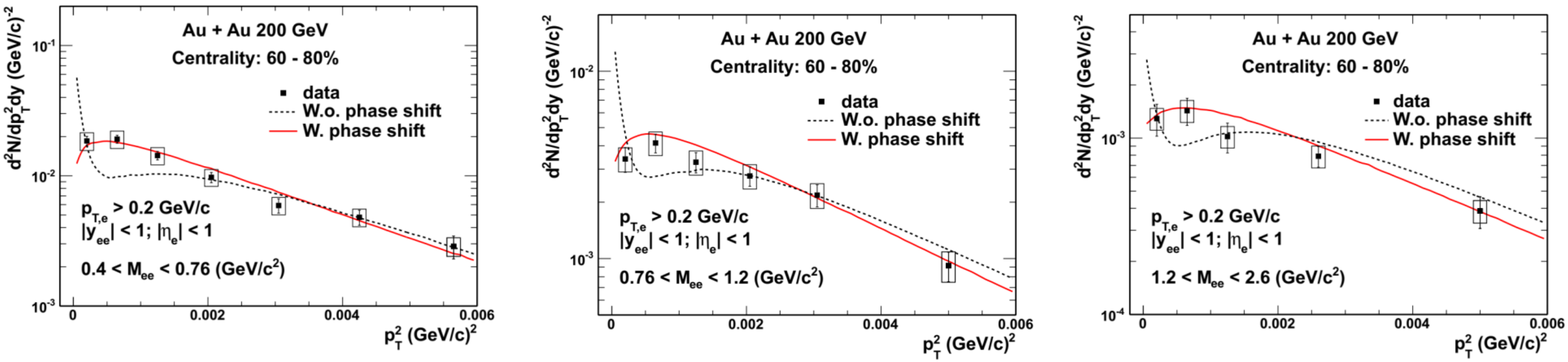
phase shift

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

$$\alpha_1 = k_1.Angle(k_1 - q)$$
$$\alpha_2 = k_2.Angle(k_2 + q)$$

F(k) $e^{i\phi}$
ϕ is the direction of k_T

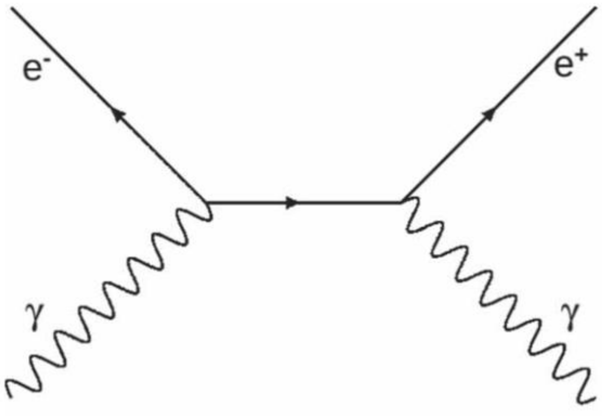
The phase shift matters

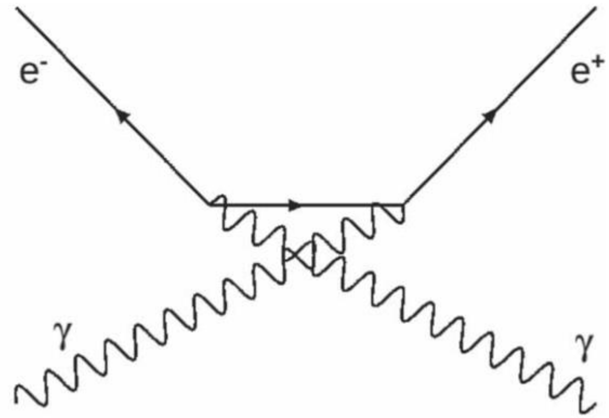


Without the phase shift, the approach can not describe the data!
However, we can not find the physical meaning for the additional phase shift.

One check:
Replace the cross section of dilepton production in the gEPA equation with the lowest order feynman diagram

The lowest order Feynman diagram

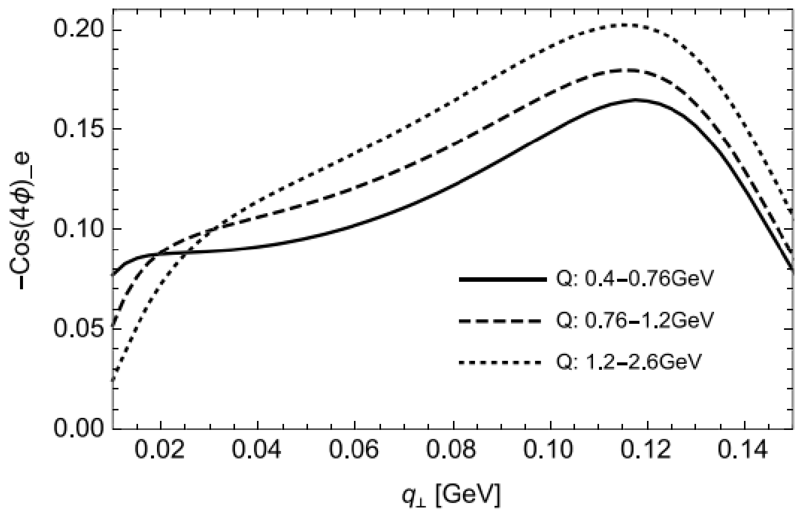




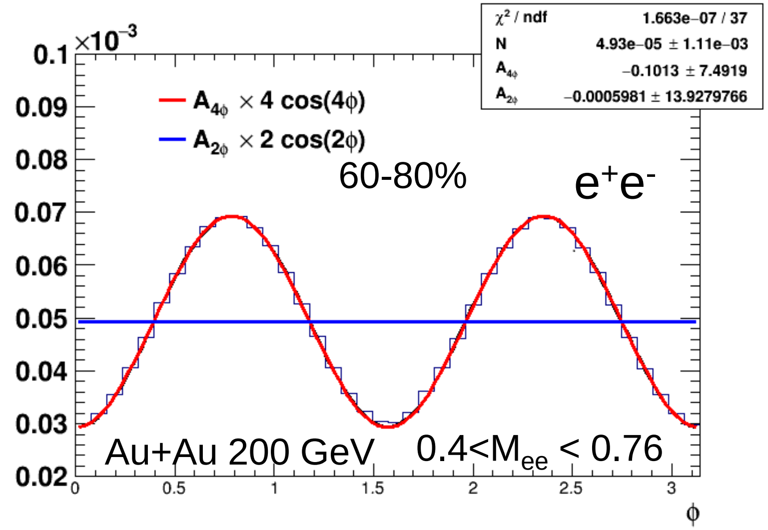
$$\sum_s |M|^2 = (Z\alpha)^4 \frac{4}{\beta^2}\int d^2\Delta q_1 d^2 q_1 \; [N_0 N_1 N_3 N_4]^{-1} \exp(i\Delta\vec{q}_1\cdot\vec{b})$$
$$\times \mathrm{Tr}\Big\{(\not{p}_- + m)\left[N_{2D}^{-1}\,\not{\epsilon}^{(1)}(\not{p}_- - \not{q}_1 + m)\,\not{\epsilon}^{(2)} + N_{2X}^{-1}\,\not{\epsilon}^{(2)}(\not{q}_1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

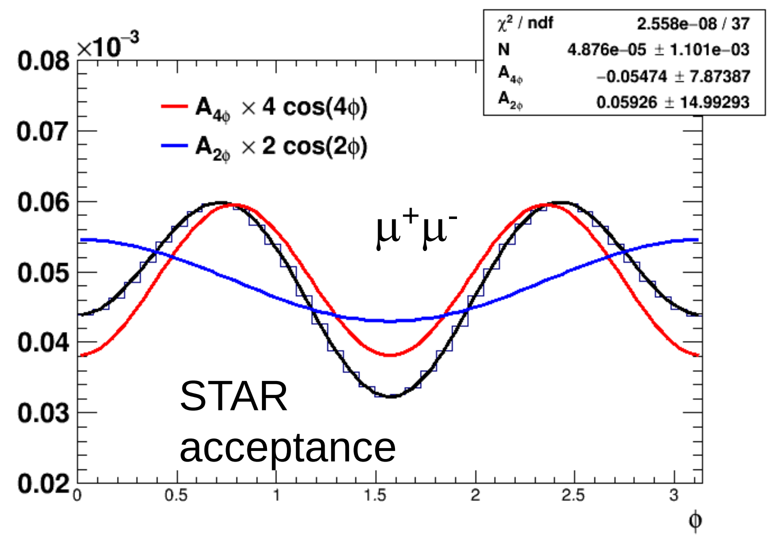
Phys. Rev. A**51** (1995) 1874-1882

Linear polarization for photons



Phys. Lett. B **795** (2019) 576





- ✓ The linear polarization of photons leads to the cos4ϕ and cos2ϕ terms.