The Electromagnetic probes from coherent photon induced reactions in heavy-ion collisions

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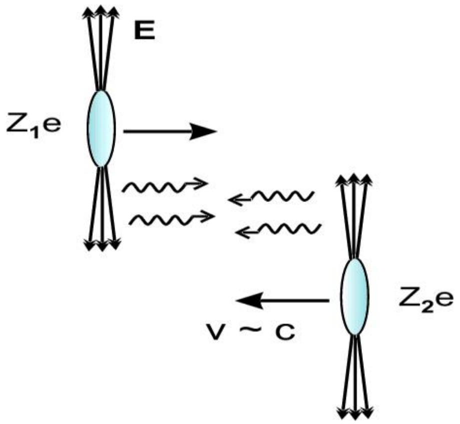
Coherent photons as “partons” in heavy-ion collisions



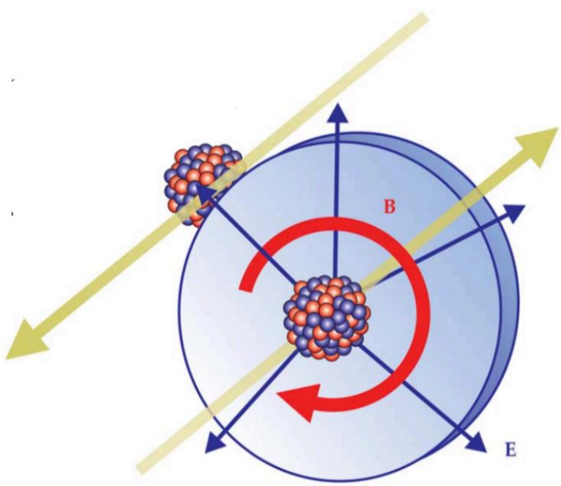
Coherent limitation: $Q^2 \ll 1/R^2$ => quasi-real !

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)

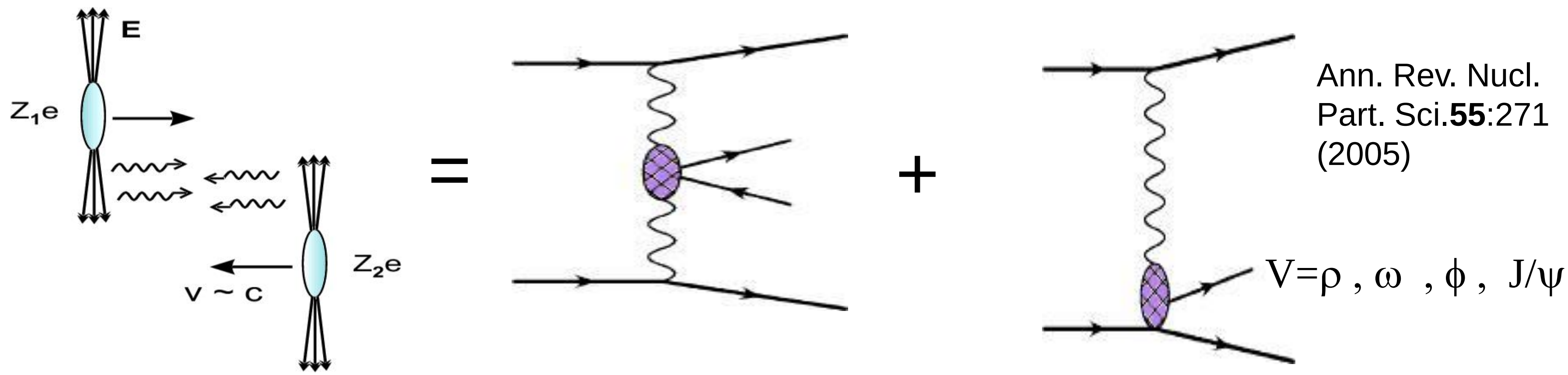
The extent of photons swarming about the ions:

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



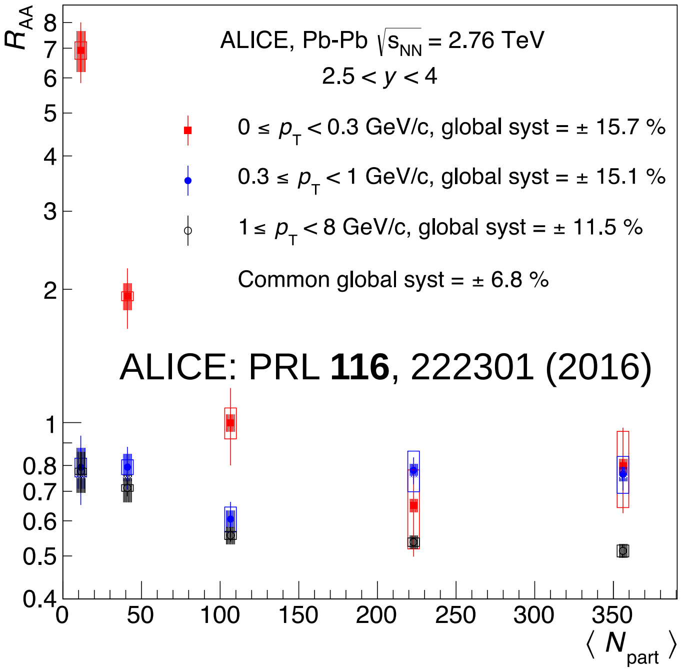
Electromagnetic interaction

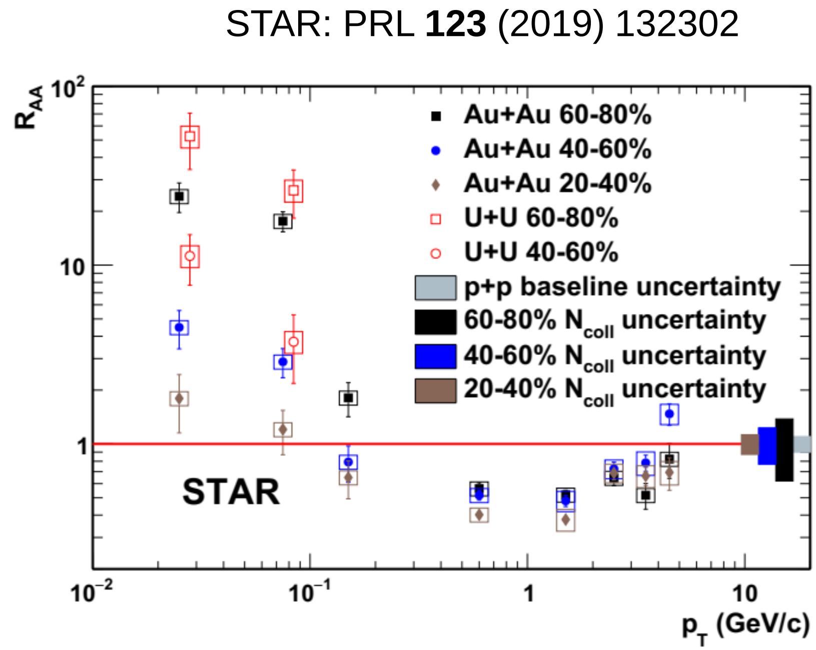
Photon-photon interactions

Photon-nucleus interactions

- 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”!

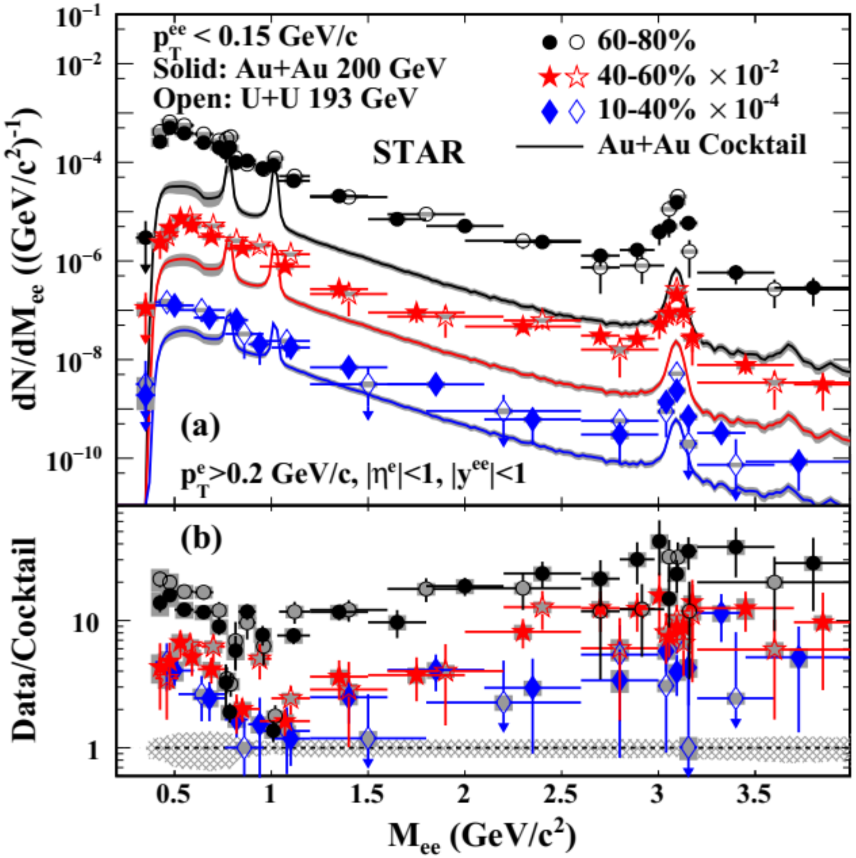
The beginning of the story

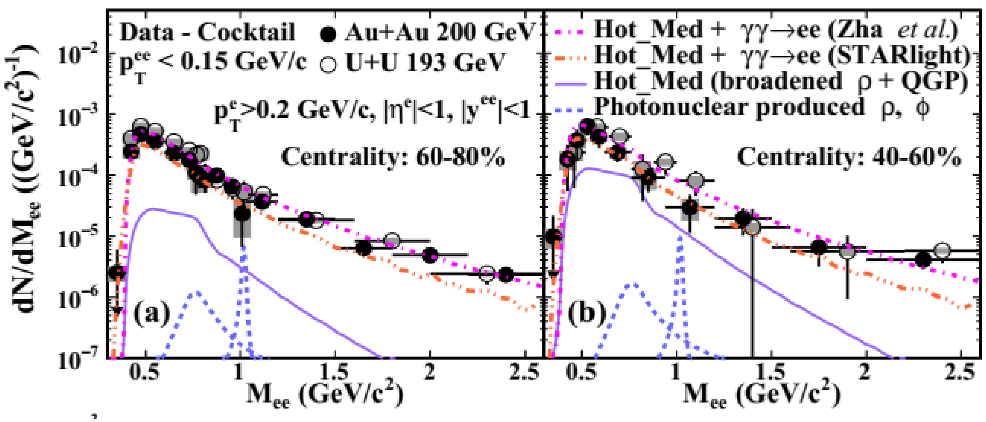




- Significant enhancement of J/ψ yield observed at very low p_T in peripheral heavy-ion collisions.
- Origin from coherent photon-nucleus interactions!
- New probe for QGP?

How about the ρ photoproduction?





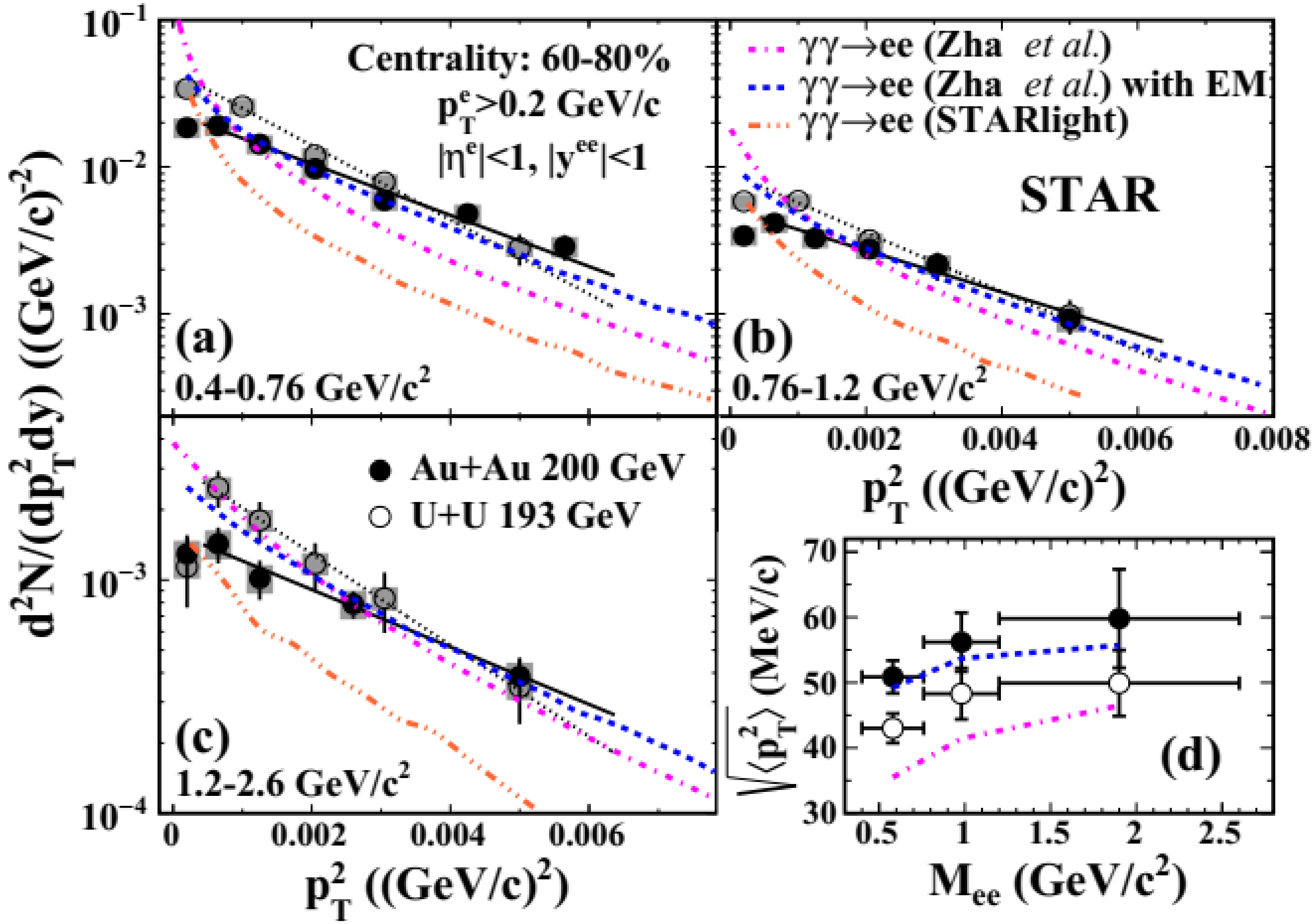
STAR, PRL **121** (2018) 132301

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

Negligible ρ photoproduction!

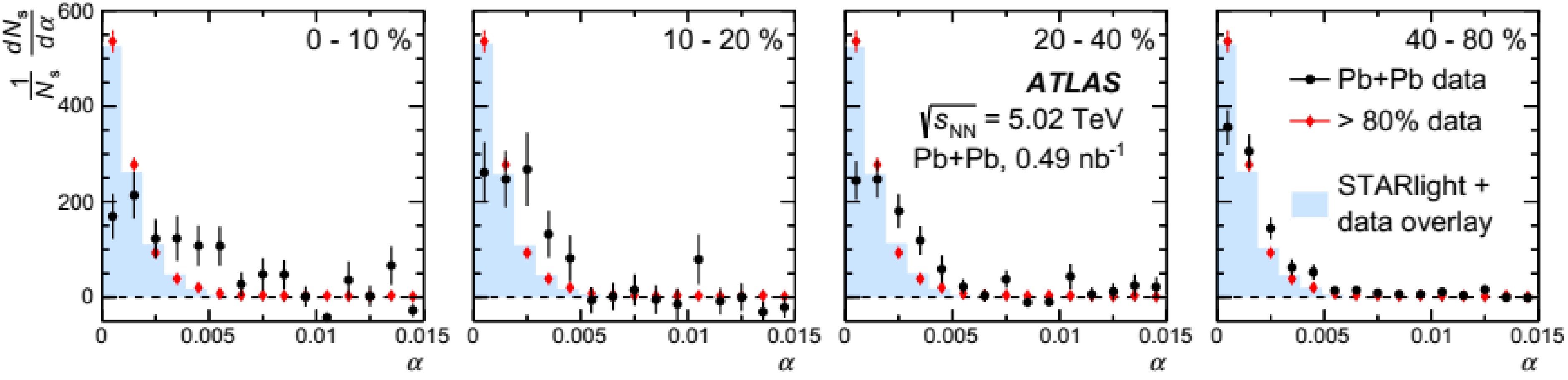
- Significant excess in 60-80% central Au + Au and U + U collisions for the whole invariant mass range!
- The excess can be described by the coherent photon-photon process!

A sensitive probe: 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?

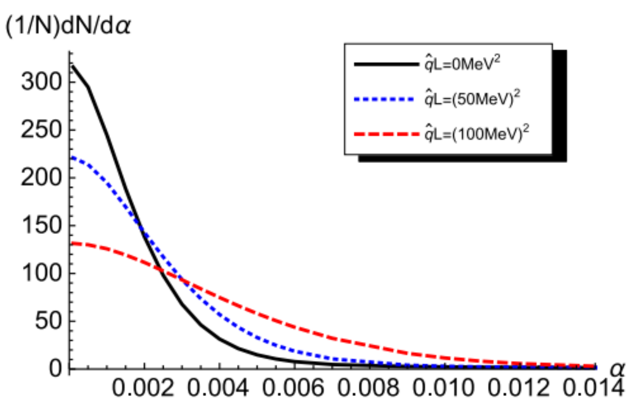
A sensitive probe: pair p_T broadening



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

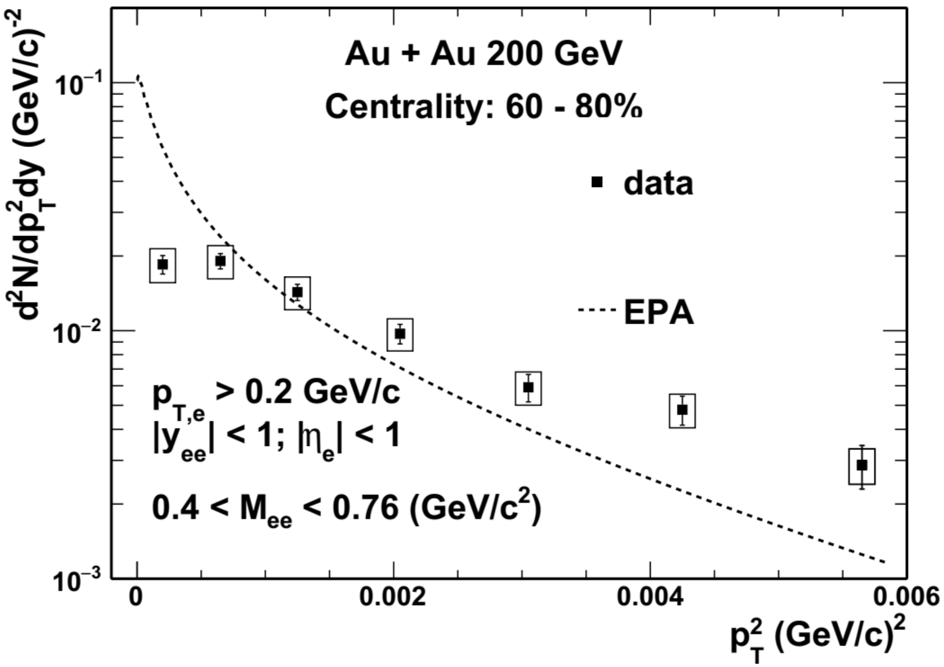
The baseline study from theoretical side

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

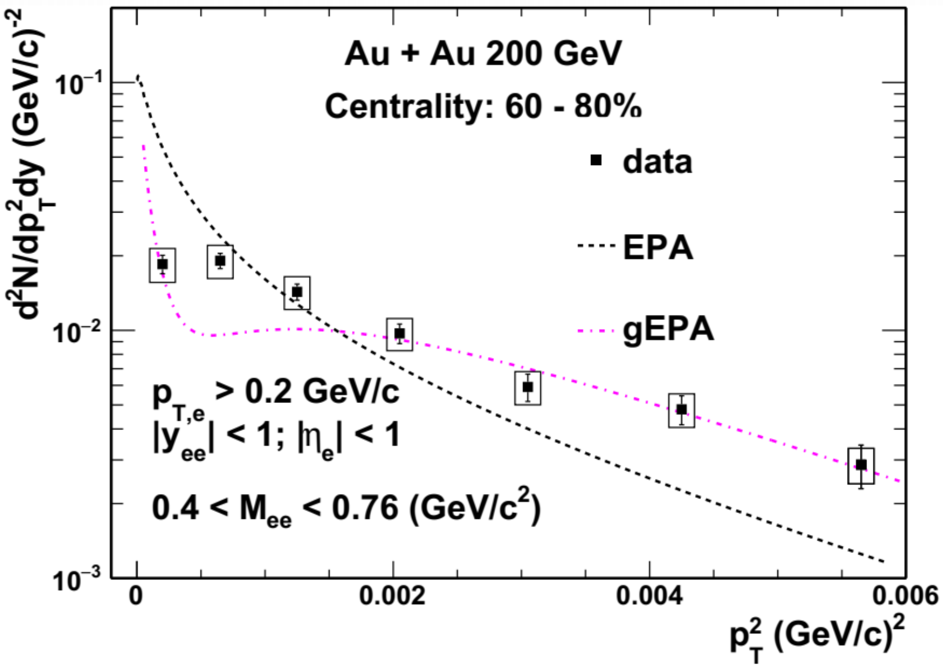
gEPA approach

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

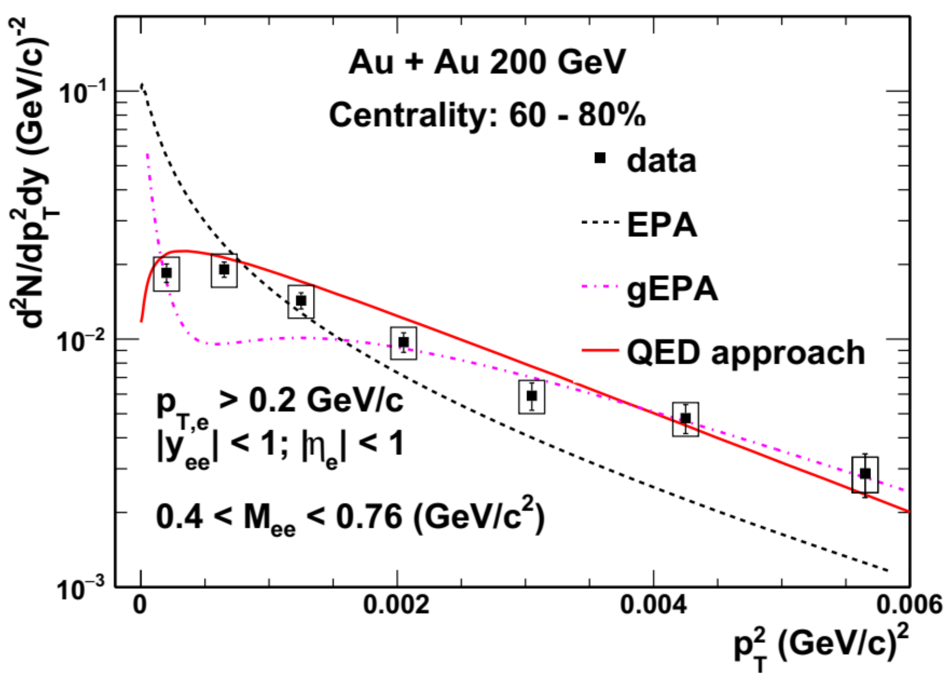


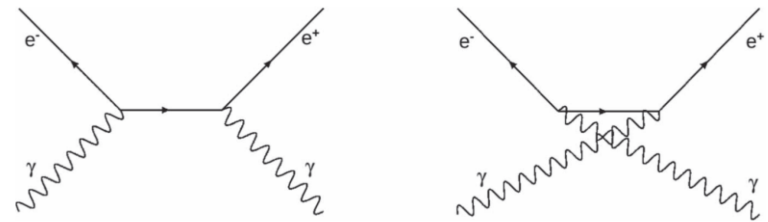
- Fail to reproduce data at very low p_T !
- Strange dip structure!

The baseline study from theoretical side

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

QED approach



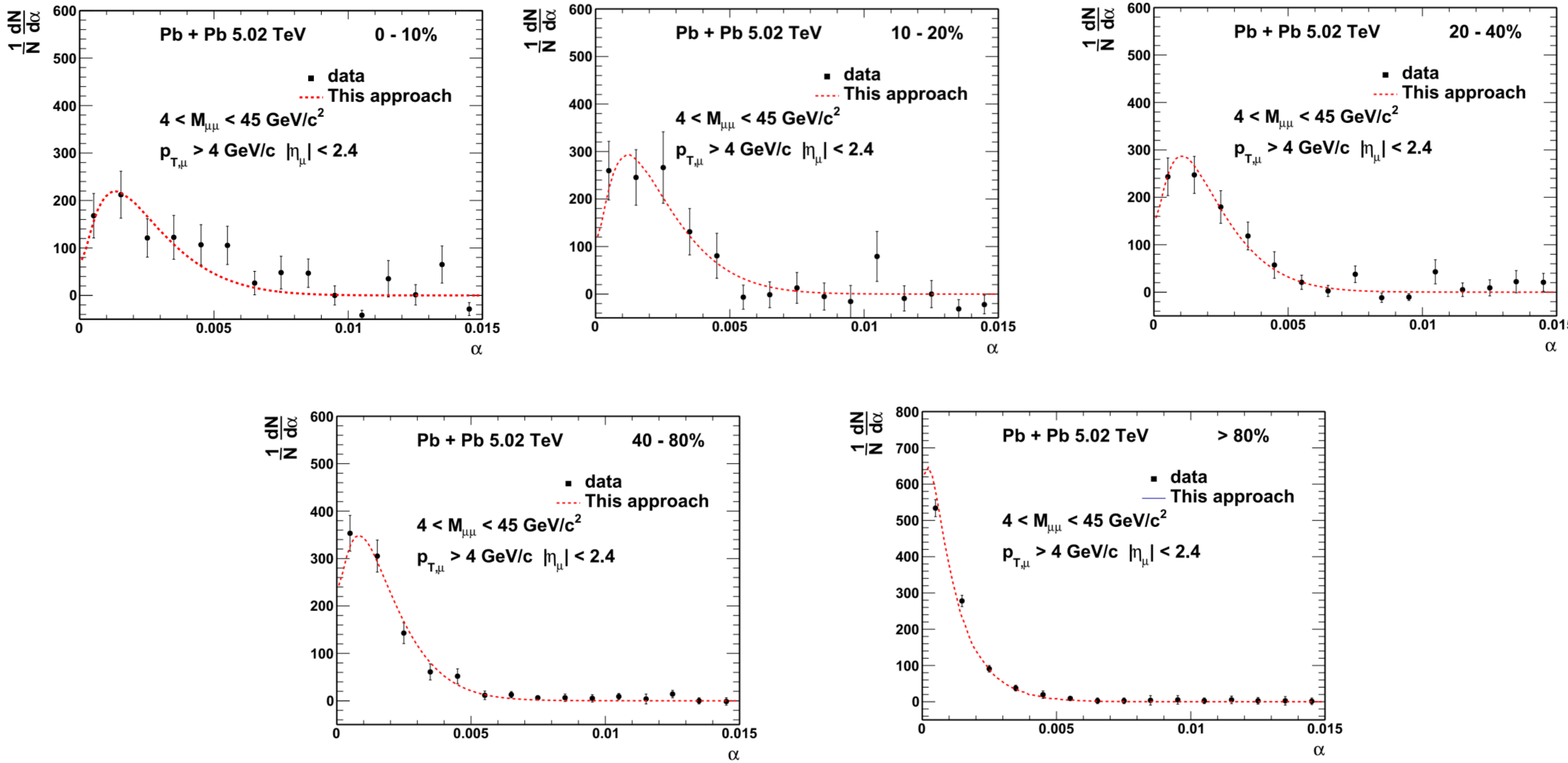


PRA **51** (1995) 1874

- Reasonably describe the p_T spectrum.

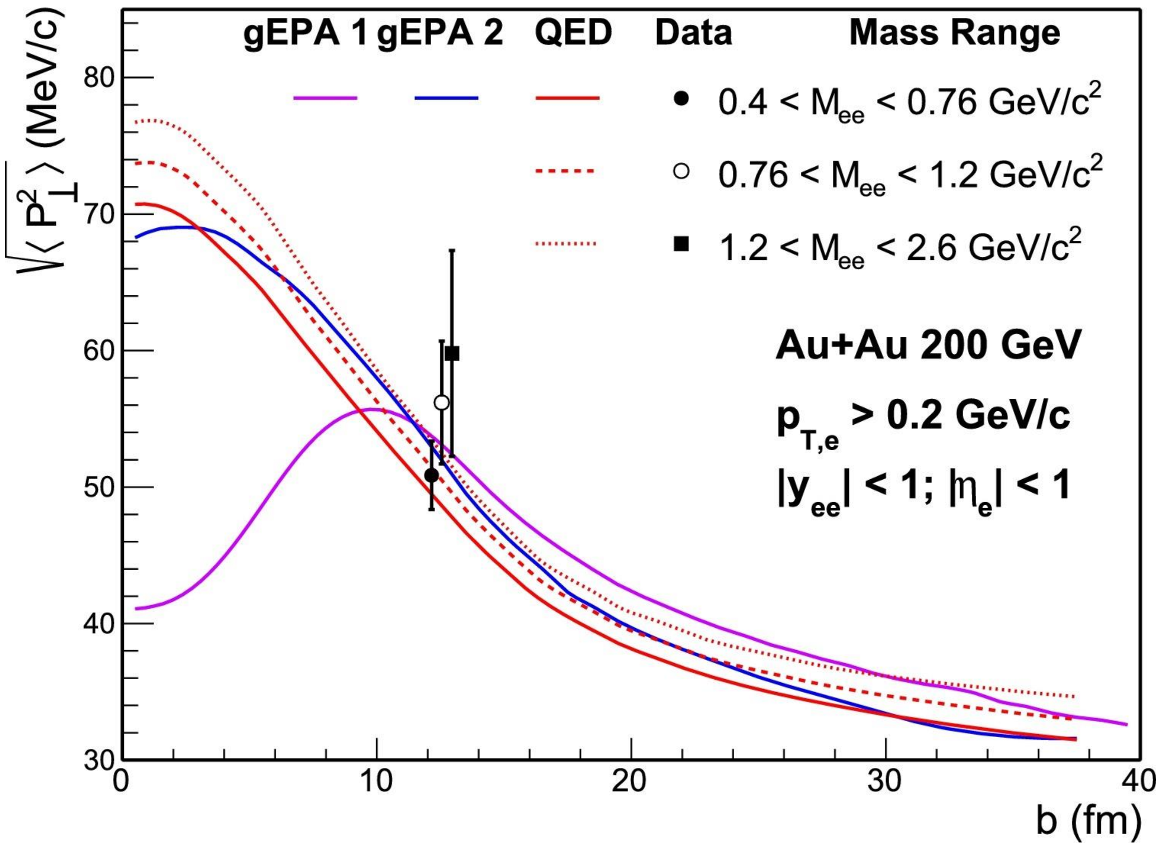
W. Zha etal, PLB 800 (2020) 135089

The baseline study from theoretical side



Successfully reproduce the centrality dependence of acoplanarity!

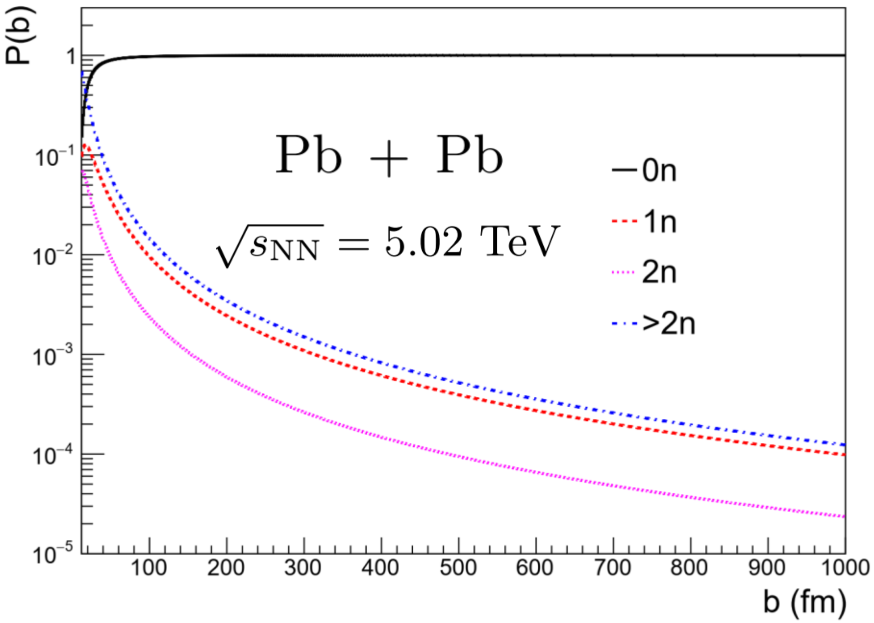
The impact parameter dependence of baseline

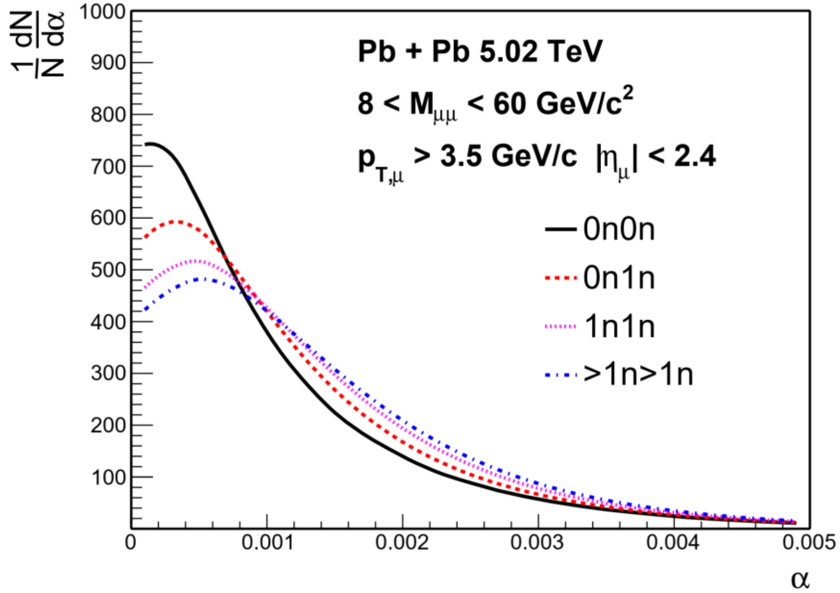


Strong dependence on impact parameter and pair mass!

“Centrality” engineering in UPCs

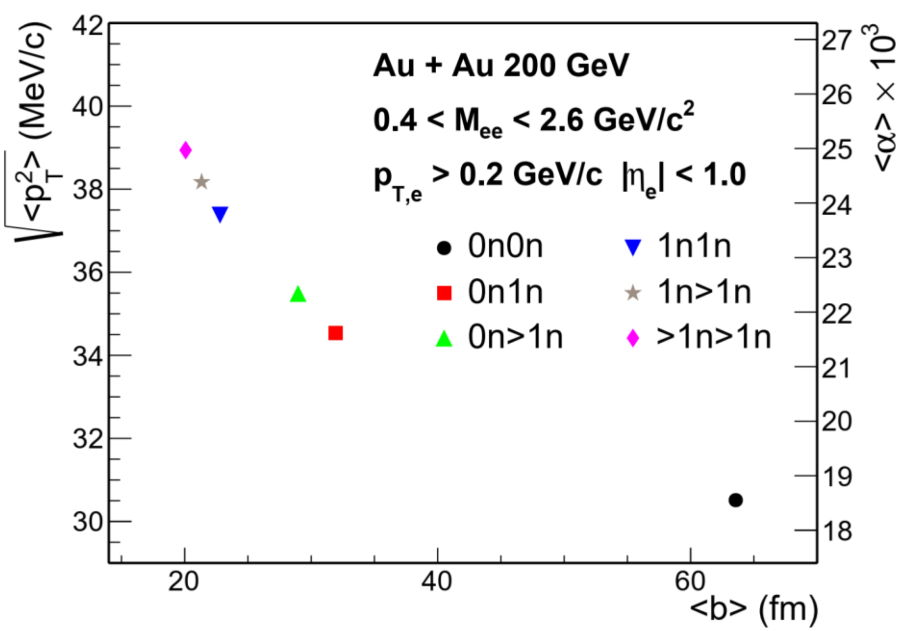
Neutron tagging!

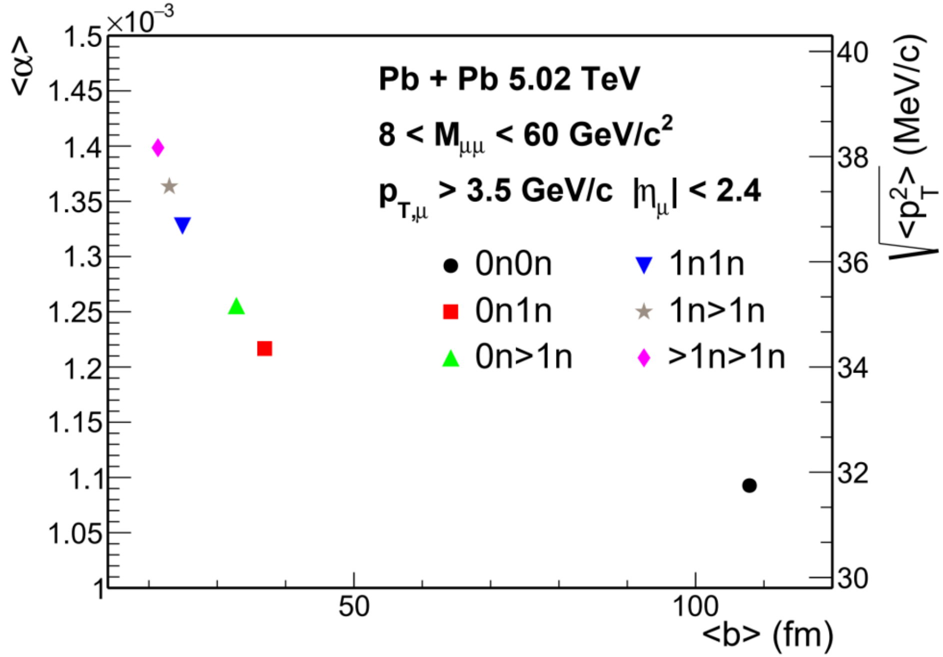




- The neutron multiplicity from multi-coulomb dissociation (MCD)
- Significant difference for pair p_T broadening in different centralities of UPCs!

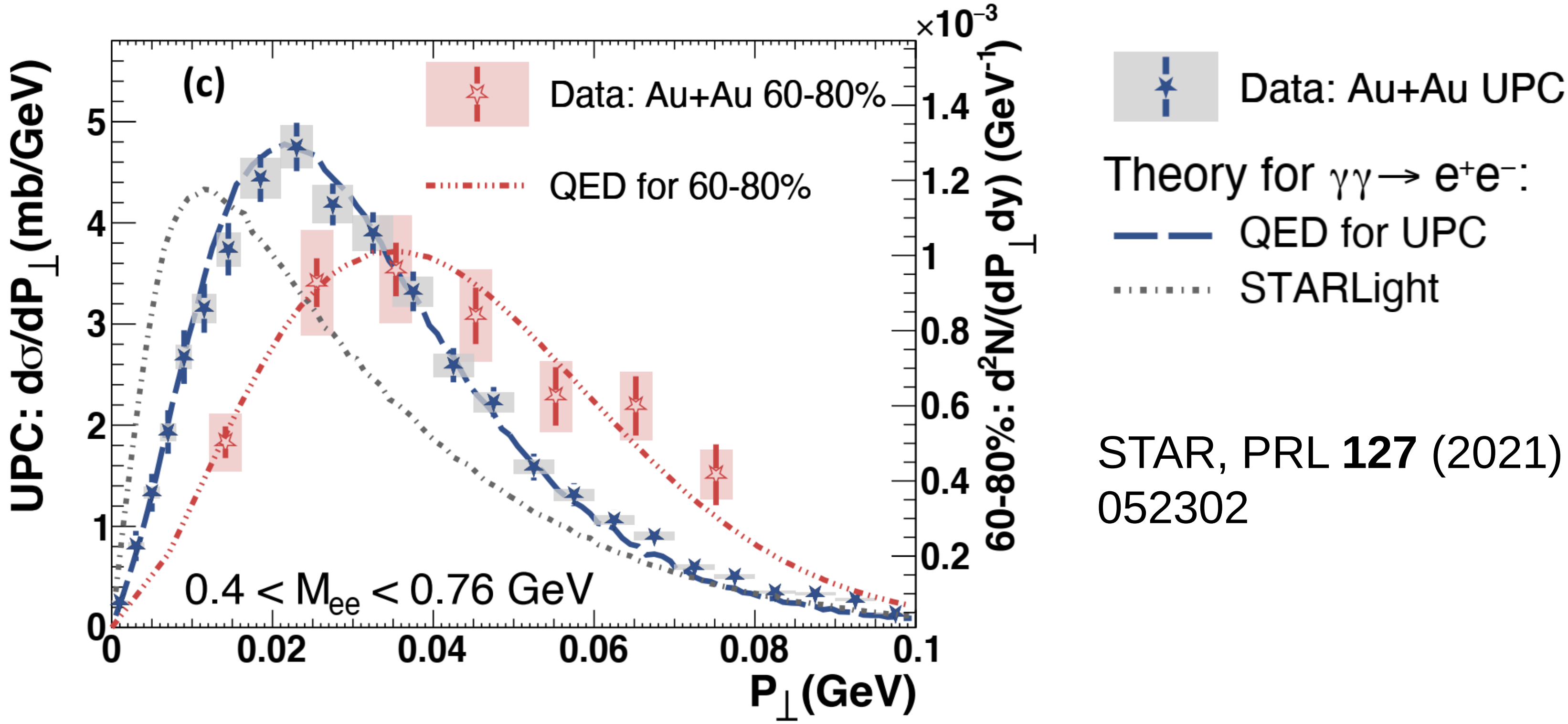
Initial broadening for different centralities in UPCs





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

The efforts from experimental side

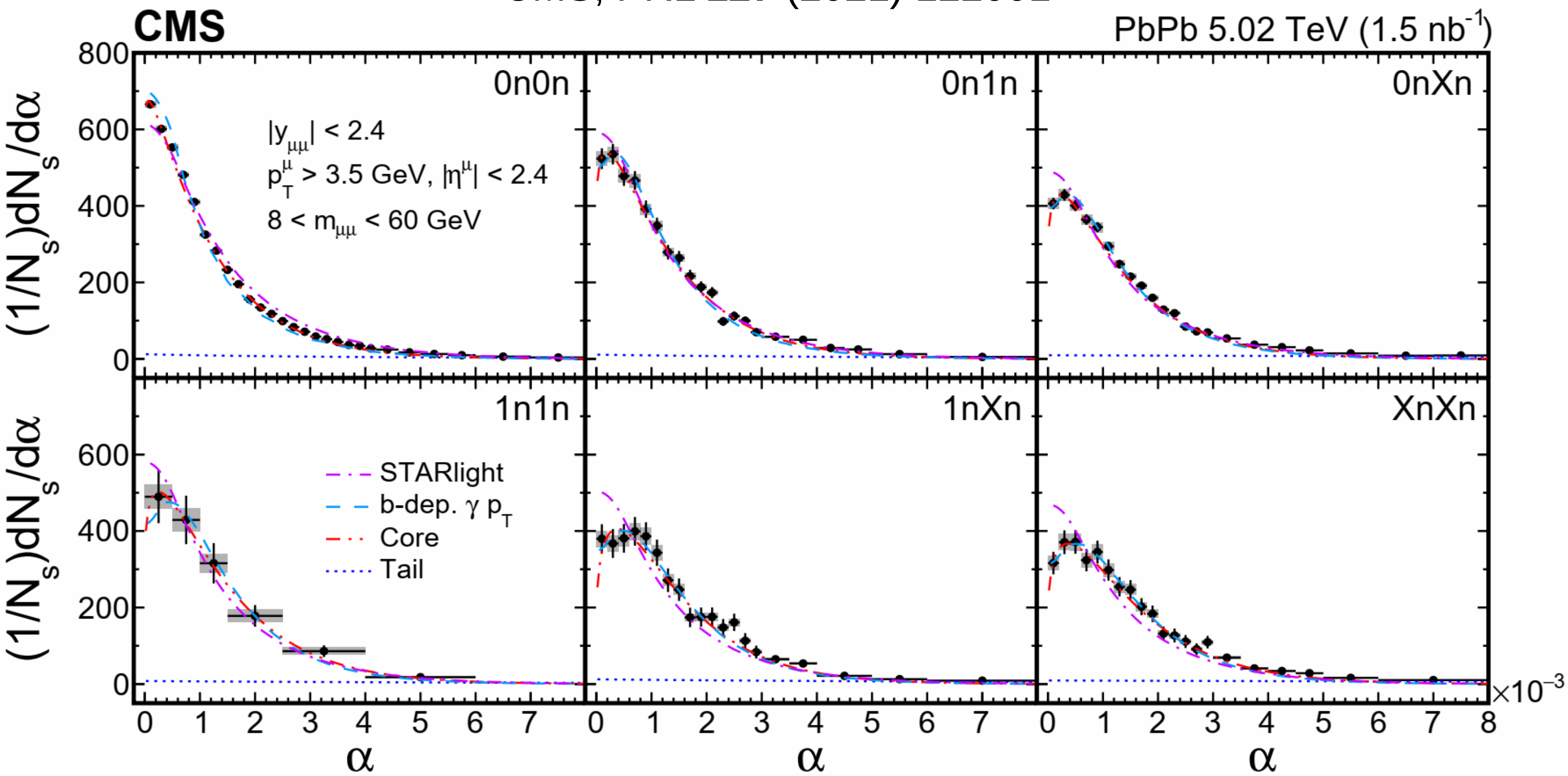


STAR, PRL **127** (2021) 052302

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

The efforts from experimental side

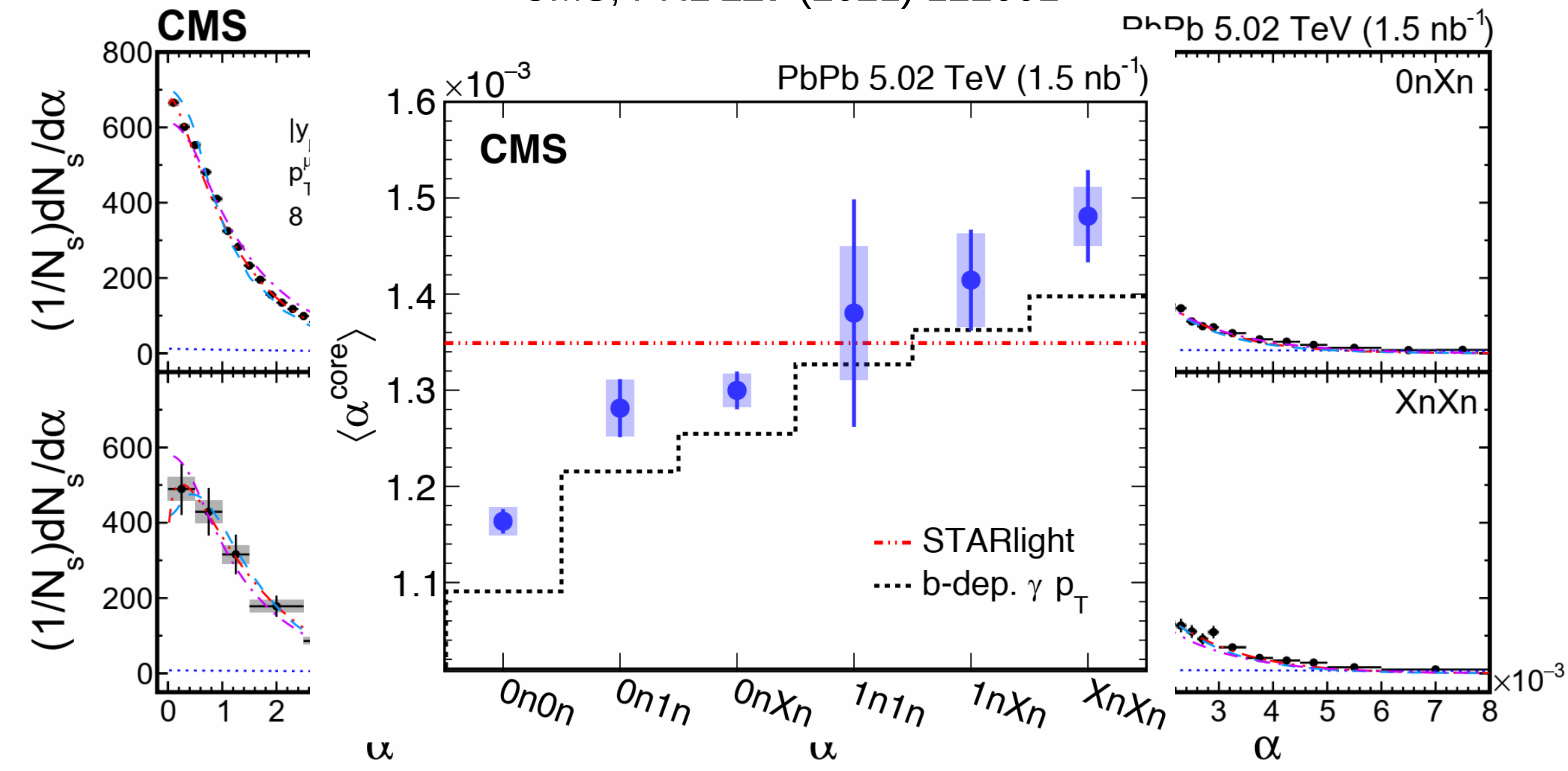
CMS, PRL **127** (2021) 122001



Significant difference in different centralities of UPCs!

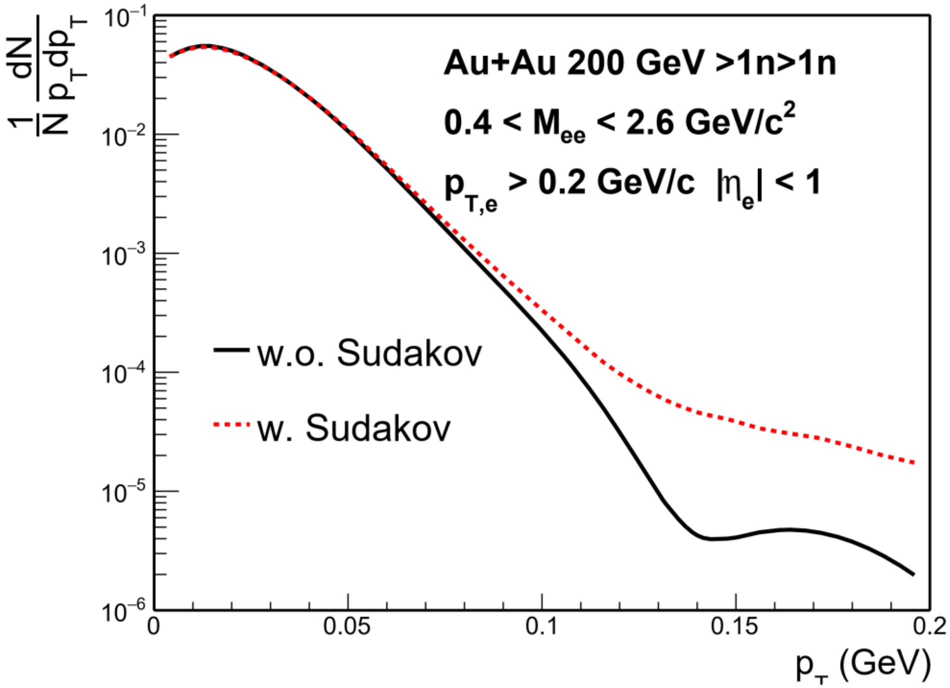
The efforts from experimental side

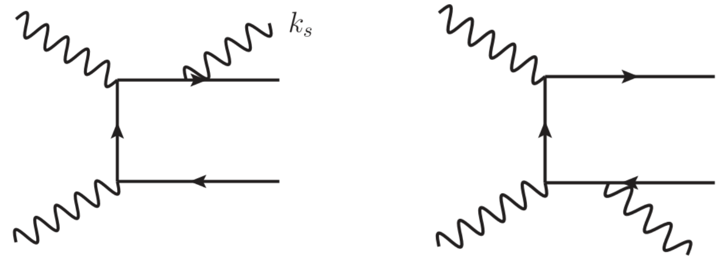
CMS, PRL **127** (2021) 122001



Sizable gap between measurement and QED calculation!

The higher-order tail: Sudakov effect





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

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

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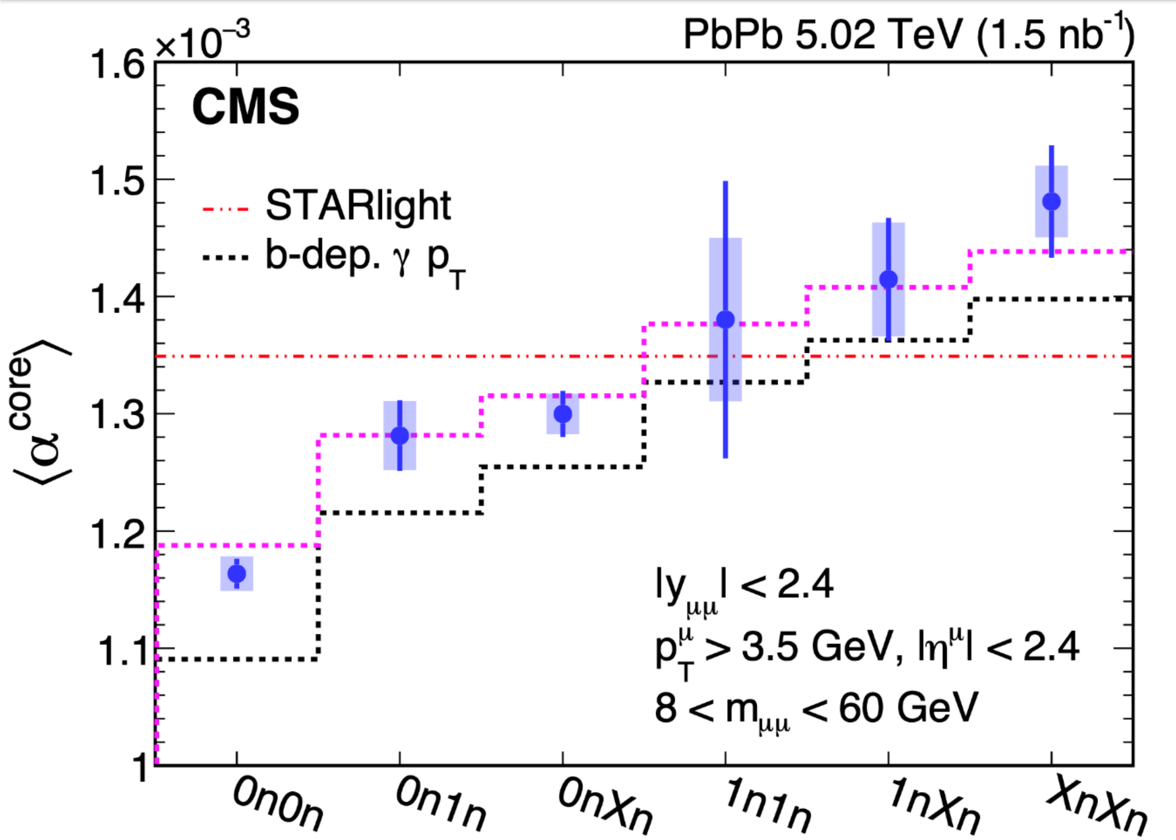
- Negligible effect of soft photon radiation for low p_T at RHIC!
- Produce a long tail at relative high p_T!

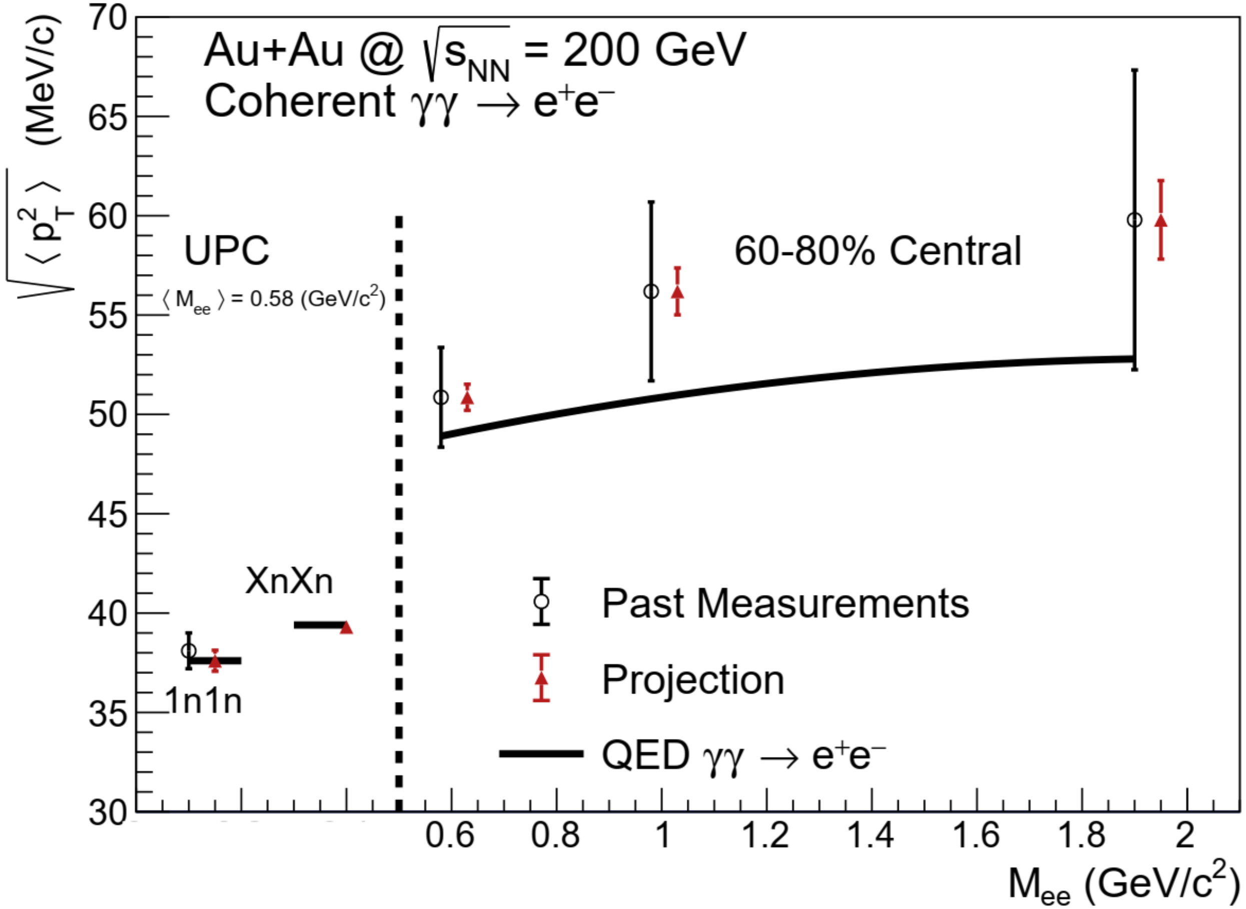
The QED method with Sudakov effect



- 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



Summary

- Significant excess of dilepton production in hadronic heavy-ion collisions

  --- Existence of coherent photoproduction in non UPCs

- The transverse momentum broadening of dilepton from photoprouction

  --- The impact parameter dependence

- Novel probe for QGP?

  --- Precise knowledge on the baseline

  --- Precise measurement in the future