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The UPC related physics in heavy-ion collisions

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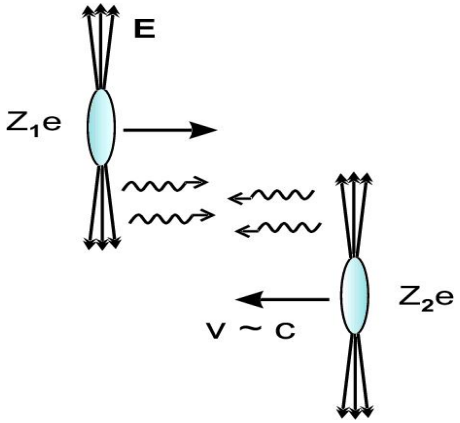
online

Coherent photons as “partons” in heavy-ion collisions



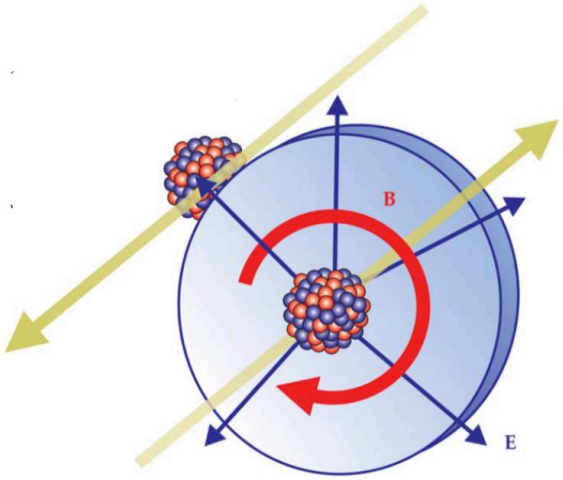
Coherent limitation: $Q^2 \leq 1/R^2$ => quasi-real !

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!



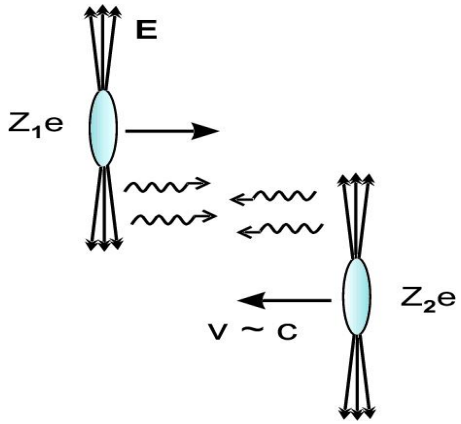
Physics Today **70**, 10, 40 (2017)

The extent of photons swarming about the ions:

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

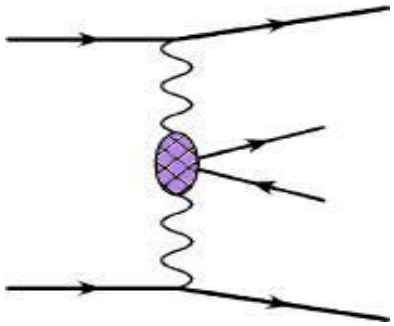
Take the photoproduction of ρ (Au+Au 200 GeV)in ultra-peripheral collisions (UPCs) as example: $<R_{producton}>$ ~ 40 fm

Photon interactions in A+A



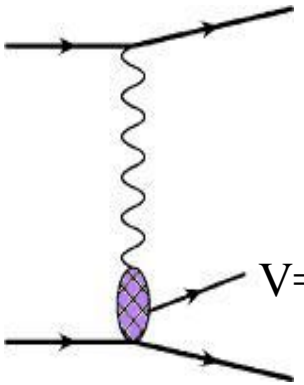
Electromagnetic interaction

=



Photon-photon interactions

+



Photon-nucleus interactions

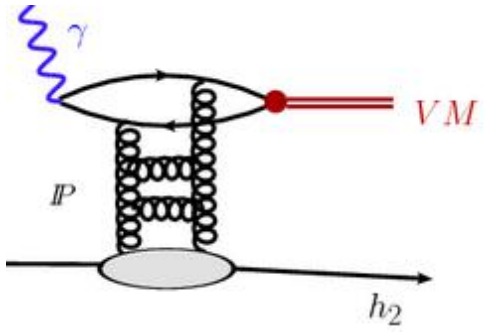
Ann. Rev. Nucl. Part. Sci.**55**:271 (2005)

$V=\rho\ ,\ \omega\ ,\ \phi\ ,\ J/\psi$

- 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

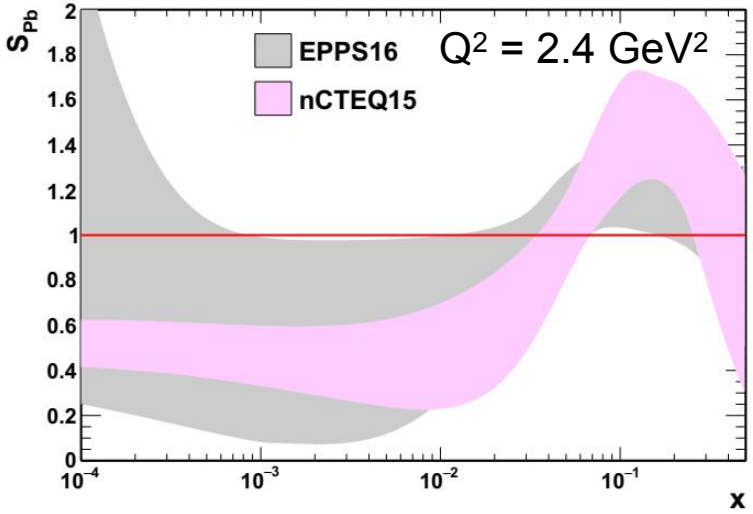
- Vector meson production:
  - ✓ chargeless 'Pomeron exchange'
  - ✓ Light meson production is usually treated via vector meson dominance model: ρ, direct $\pi^+\pi^-$, ω….
  - ✓ Heavy quarkonia production could be treated with pQCD: J/ψ, ψ', Υ(1S), Υ(2S), Υ(3S)…



- Sensitive to the gluon distribution:

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

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



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

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

J/ψ photoproduction in p+Pb UPCs

Equivalent photon Approximation:

$$\frac{d^3N_\gamma(k,r)}{dkd^2r} = \frac{Z^2\alpha x^2}{\pi^2 k r^2}K_1^2(x)$$

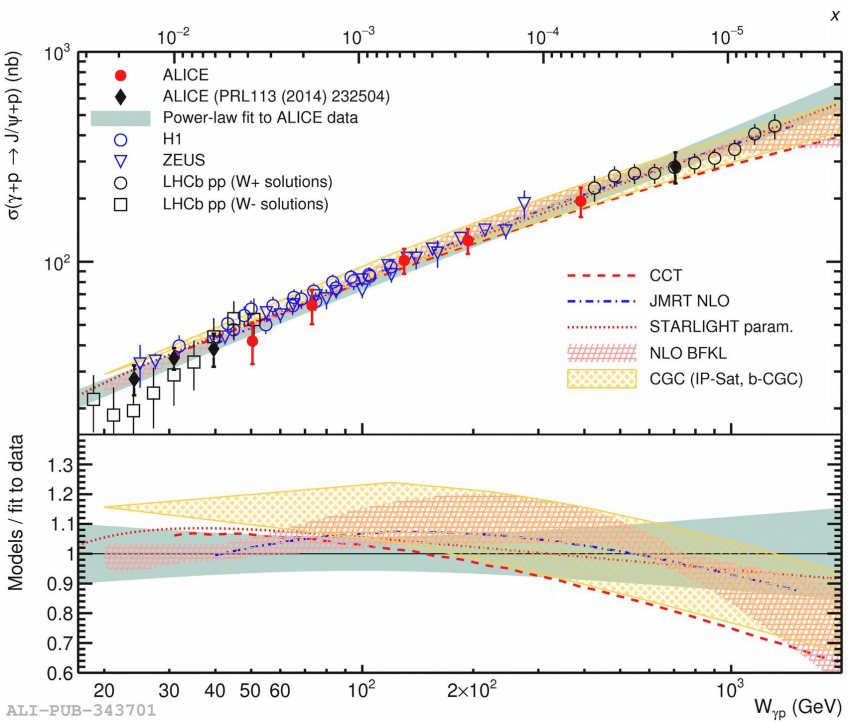
- Negligible contribution of photon flux from p side
  - ✓ No ambiguity for gamma-proton center-of-mass energy (in comparison with that in p+p collisions)
- Small background from gamma-gamma to lepton pair

$W_{\gamma p}$ ~ [20 – 700] GeV

$x \approx [10^{-2} – 10^{-5}]$

The results from Run I

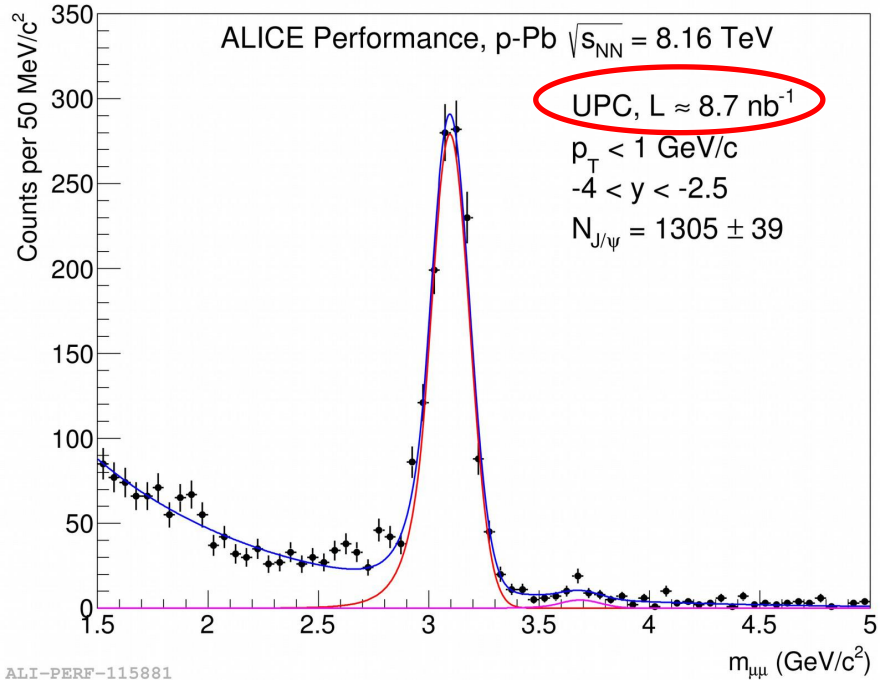
Eur. Phys. J. C **79** (2019) 402

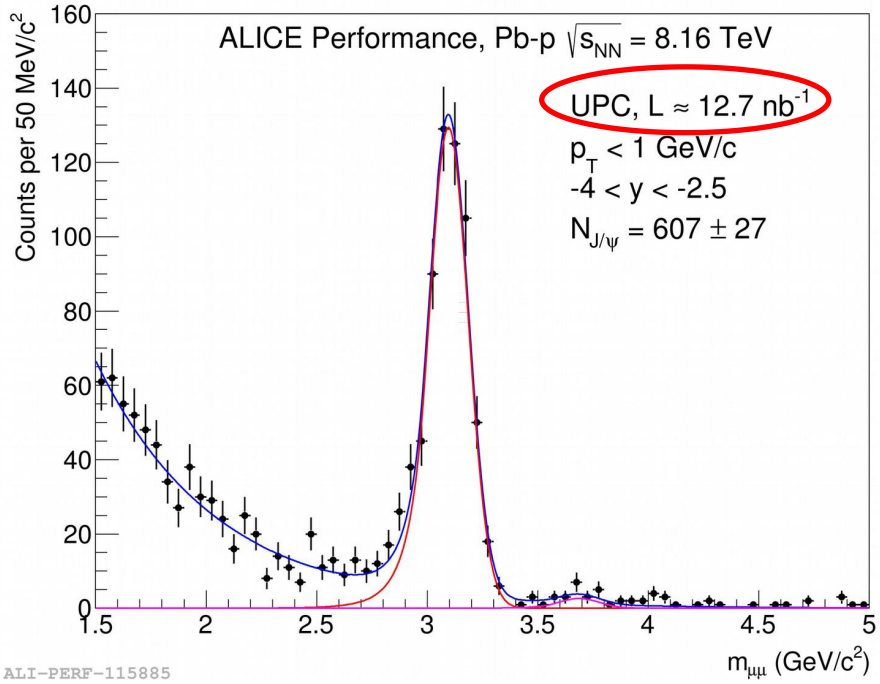


Exclusive J/ψ photoproduction off a proton with ALICE at $\sqrt{s_{NN}}$ = 5.02 TeV

J/ψ photoproduction in p+Pb UPCs

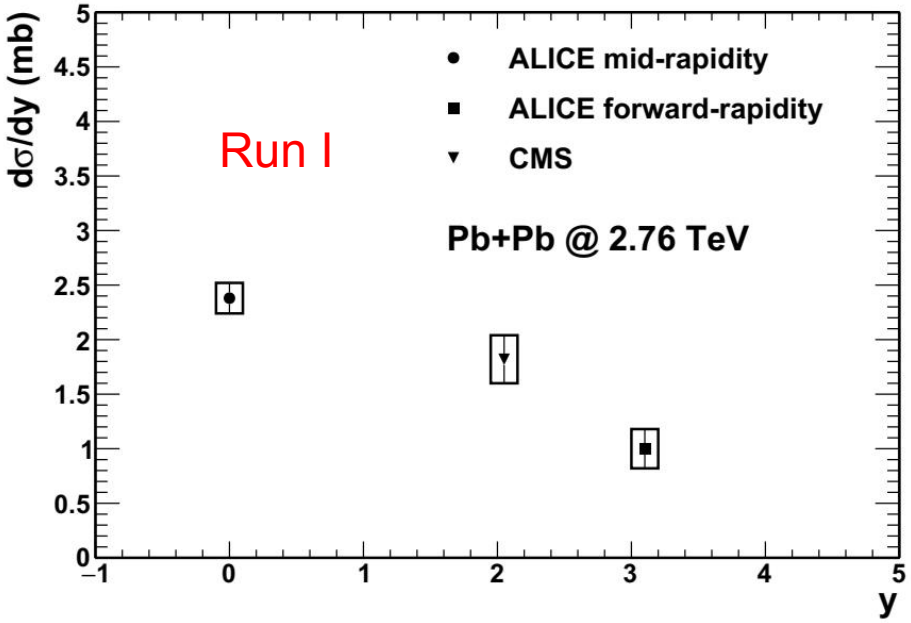
Run 2 results





- Collected statistics 2-5 times compared to Run 1 data (more efficient triggering)
- Reachable gamma-proton CMS above 1 TeV
- *x* reaches 10^{-5}

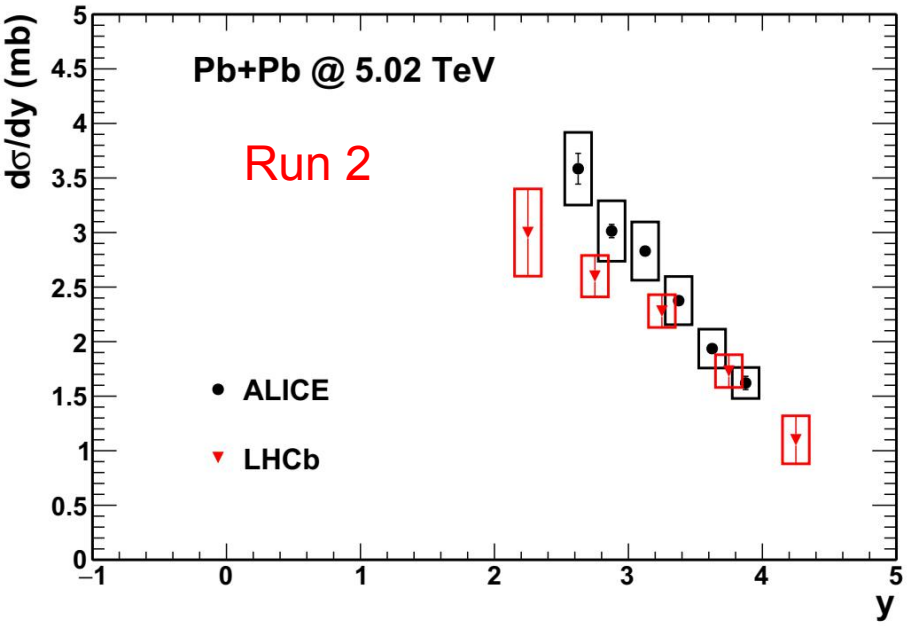
J/ψ photoproduction in Pb+Pb UPCs



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

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

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

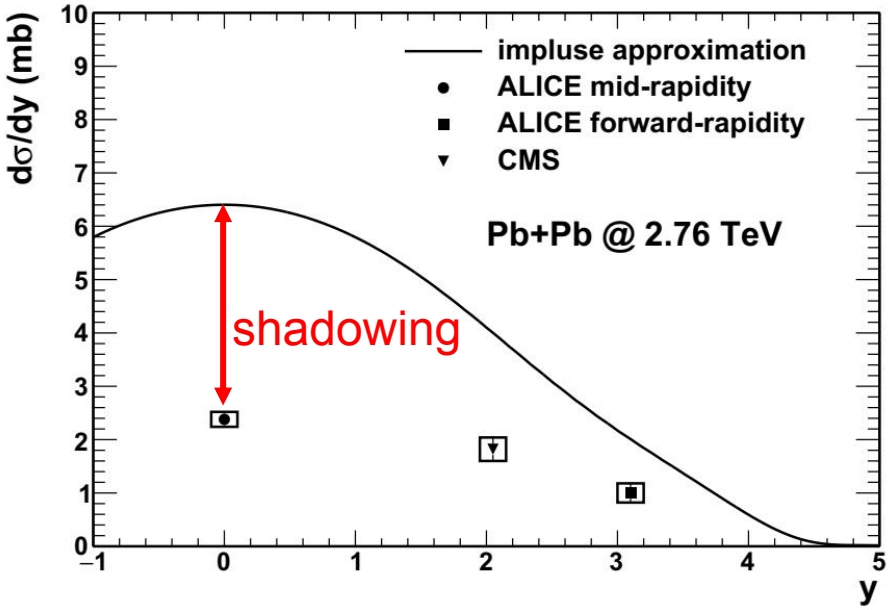


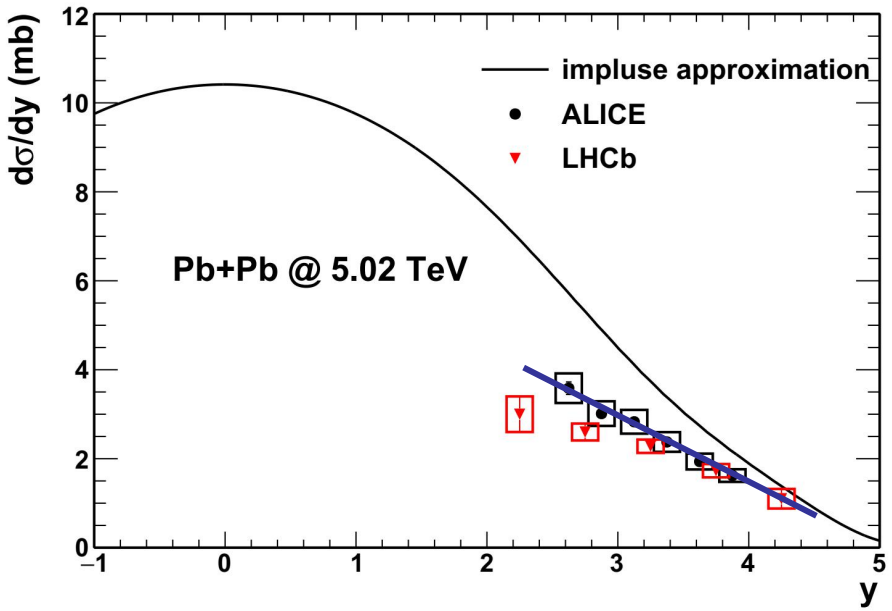
ALICE: PLB **798** (2019) 134926

LHCb: LHCb-CONF-2018-003

Various precise measurements!
Powerful to constrain nPDF

The 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:

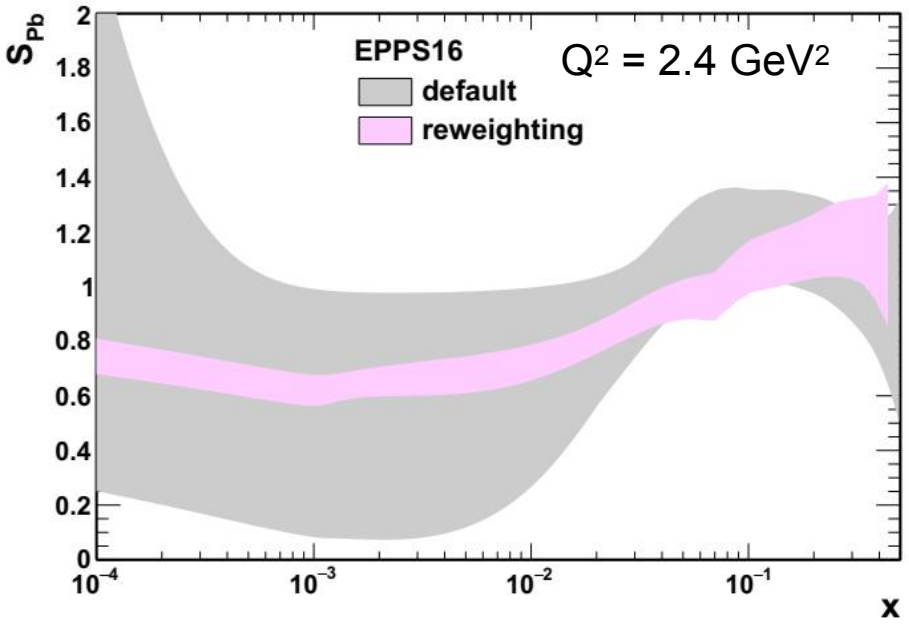
$$\langle \mathcal{O} \rangle = \frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} \mathcal{O}[f_k]$$

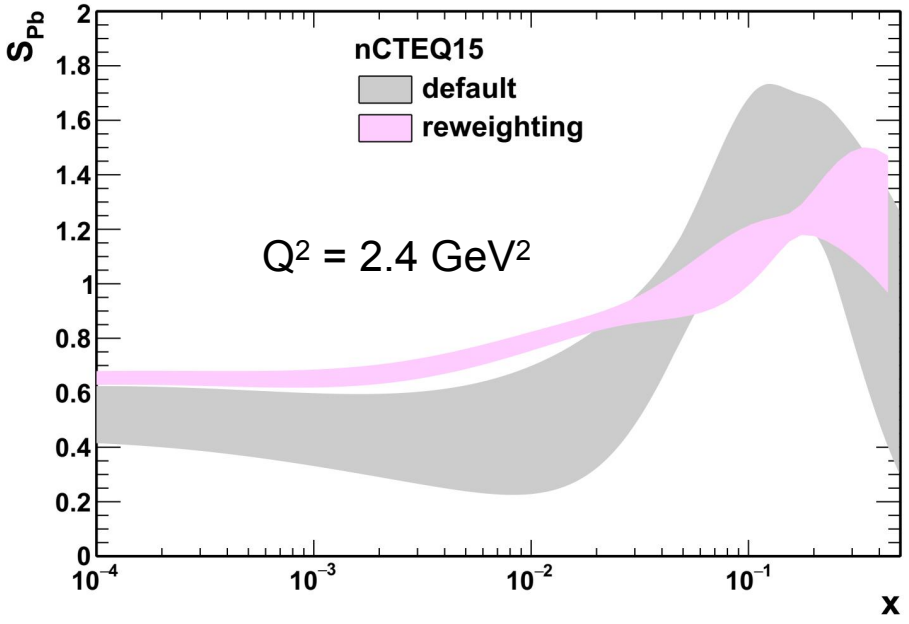
For a new measurement, $y = \{y_1, y_2, ..., y_n\}$, the reweighted PDF could be evaluated by:

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

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

Nuclear shadowing from J/ψ measurements in UPCs

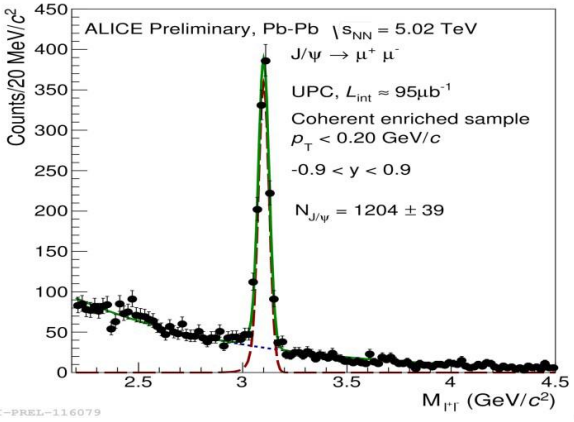




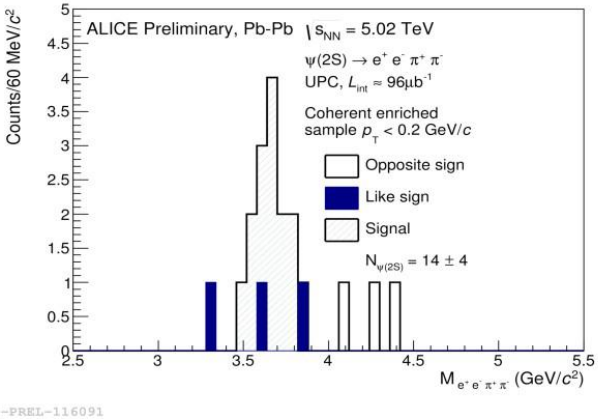
- The UPC measurements dramatically reduce the uncertainty band of EPPS16 and nCTEQ15 PDF sets.
- Significant shadowing effect has been observed in both PDF sets at small x.

Further measurements from Run 2 at mid-rapidity

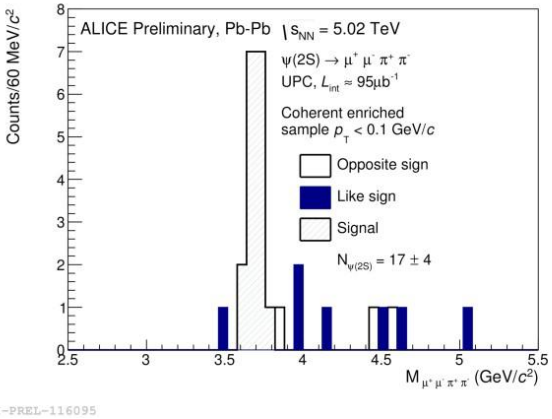
$J/\psi \rightarrow \mu^+ \mu^-$



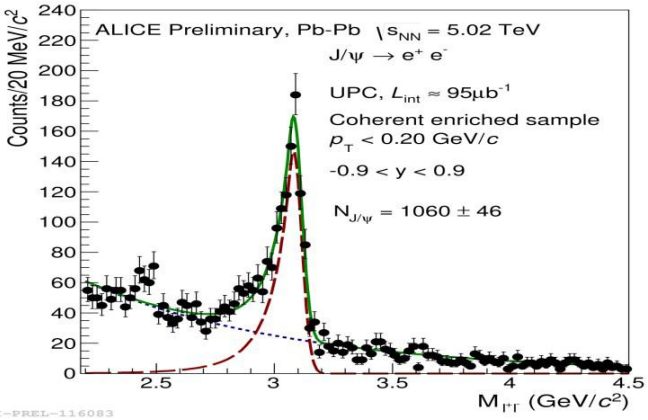
$\psi(2s) \rightarrow e^+ e^- \pi^+\pi^-$



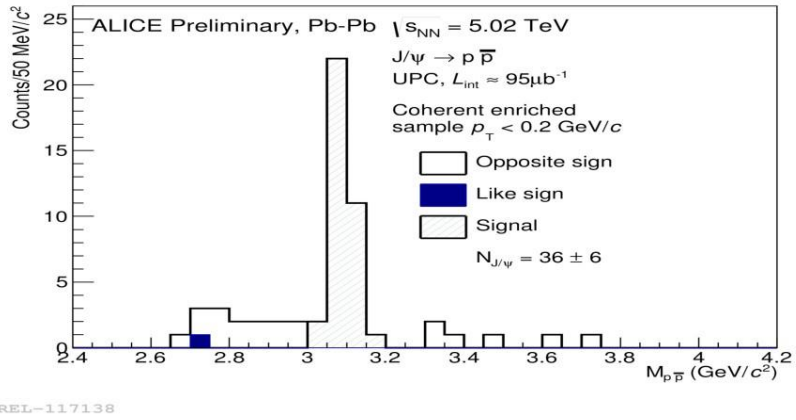
$\psi(2s) \rightarrow \mu^+ \mu^- \pi^+\pi^-$



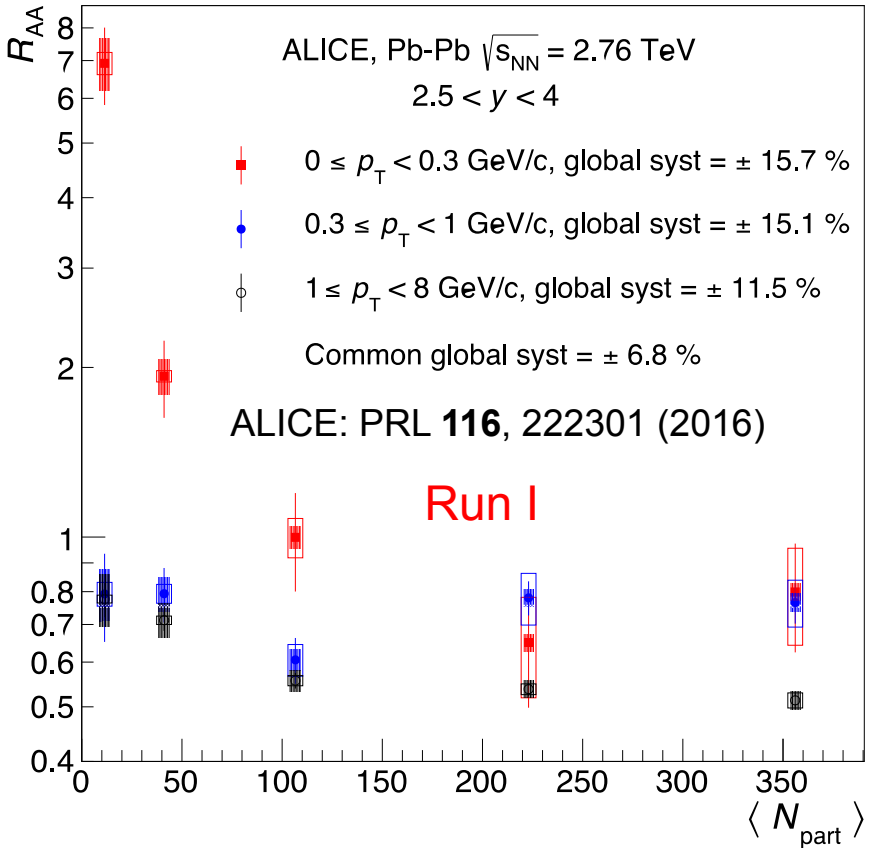
$J/\psi \rightarrow e^+ e^-$



$J/\psi \rightarrow p\ \bar{p}$



Anomalous excess of J/ψ production observed at ALICE

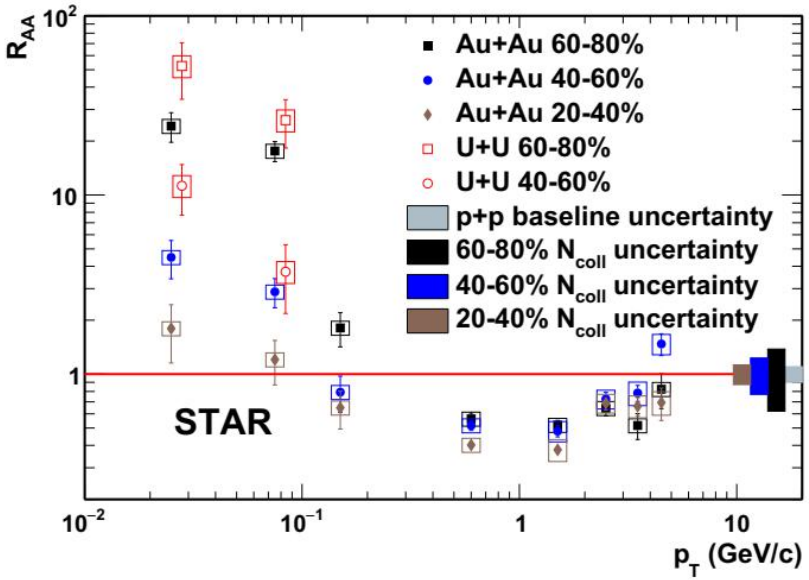


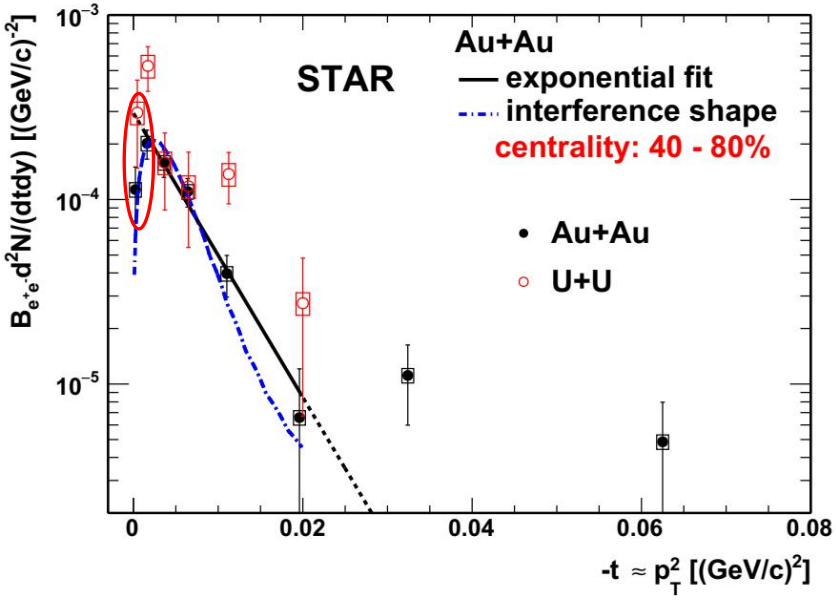
- Significant enhancement of J/ψ yield observed in p_T interval 0 – 0.3 GeV/c for peripheral collisions (50 – 90%).
- Can not be described by hadronic production modified by the hot medium or cold nuclear matter effects!

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

The observations at STAR

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

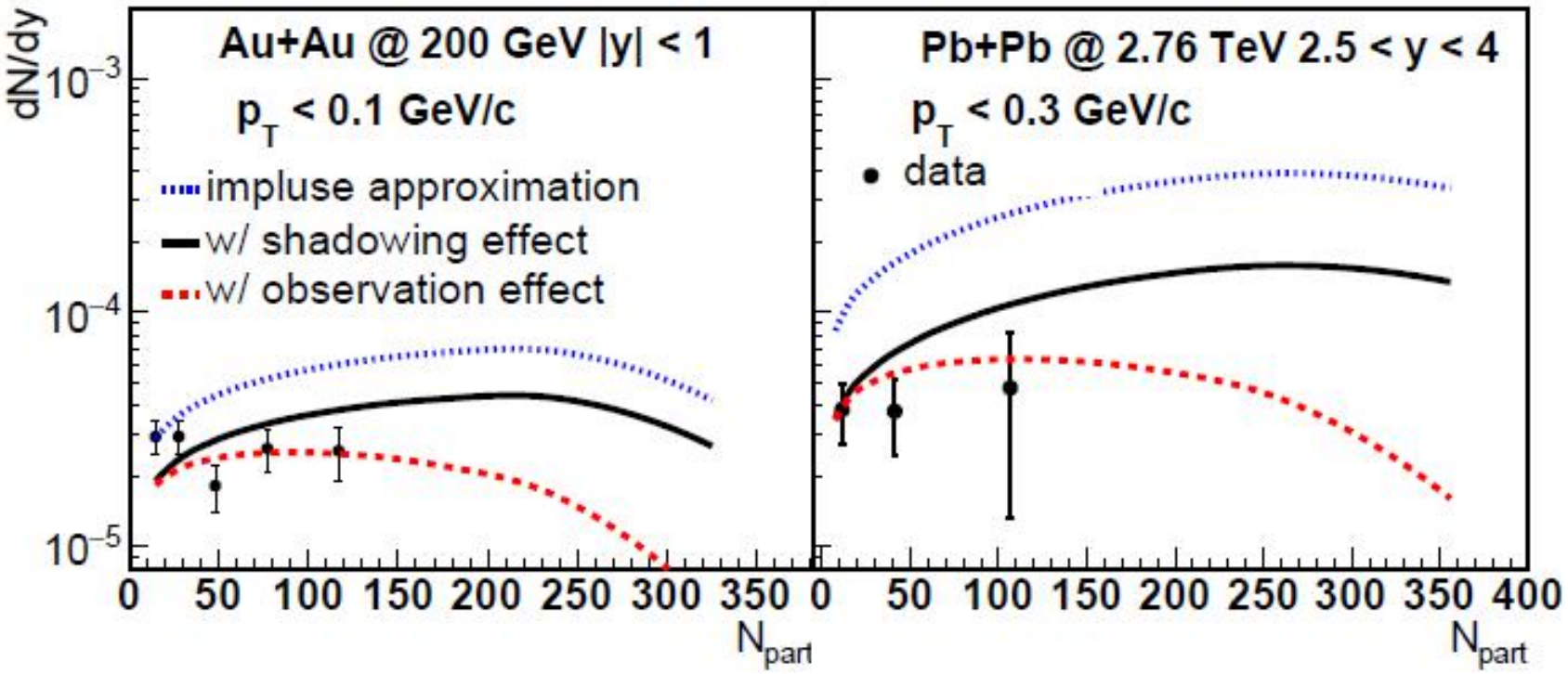




- Significant enhancement of J/ψ yield observed at p_T interval 0 – 0.2 GeV/c for peripheral collisions.
- No significant difference between Au+Au and U+U collisions.

- 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

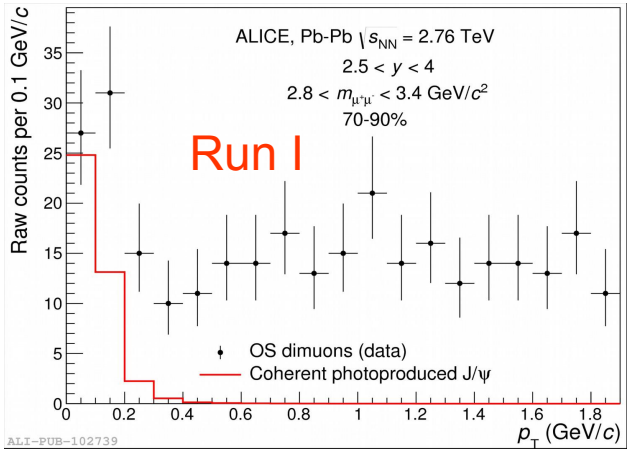
Comparison with model calculation

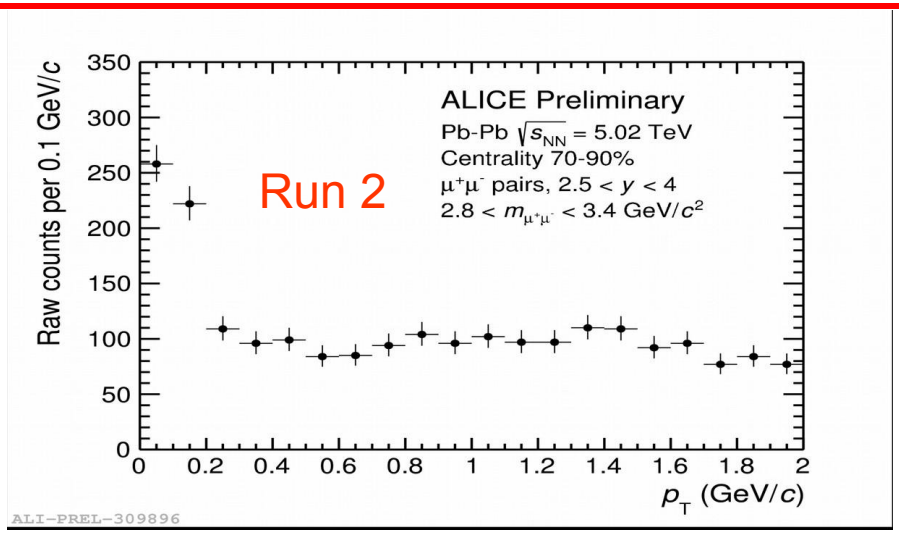


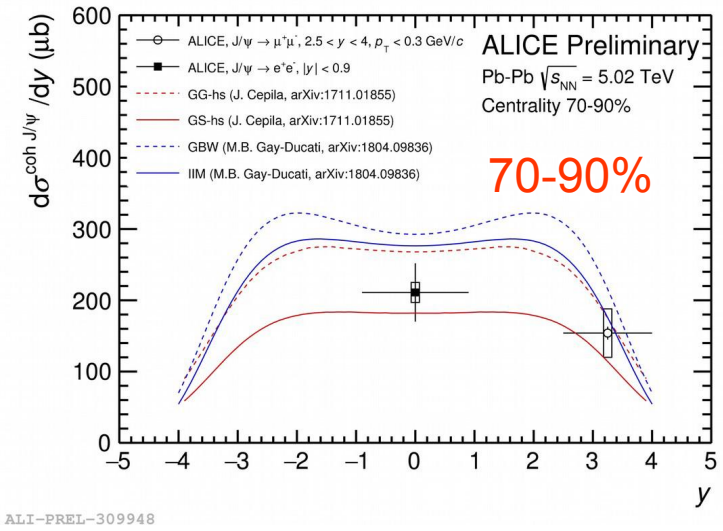
- Well described by the coherent photoproduction mechanism for peripheral collisions
- Hint of disruption from the medium
  - ✓ The observation effect
  - ✓ The QGP swallowing

PRC **99**, 061901 (2019)

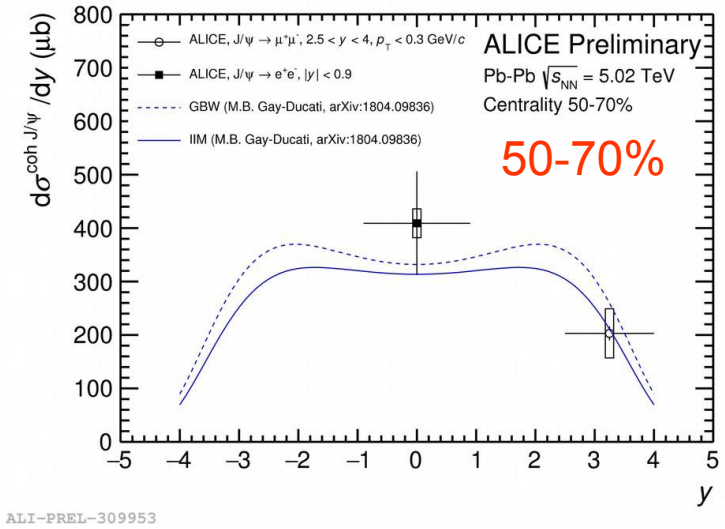
The observations at Run 2





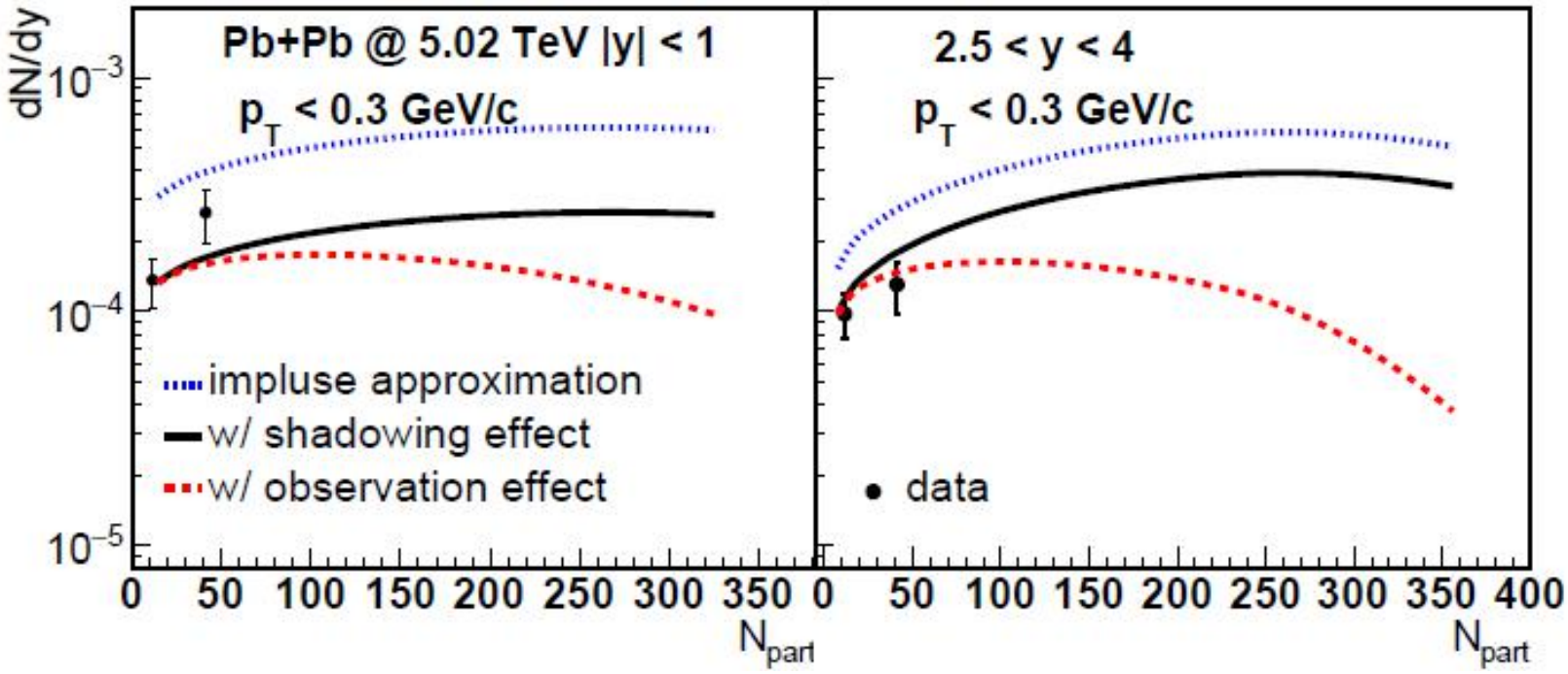


More statistics



New measurements at mid-rapidity

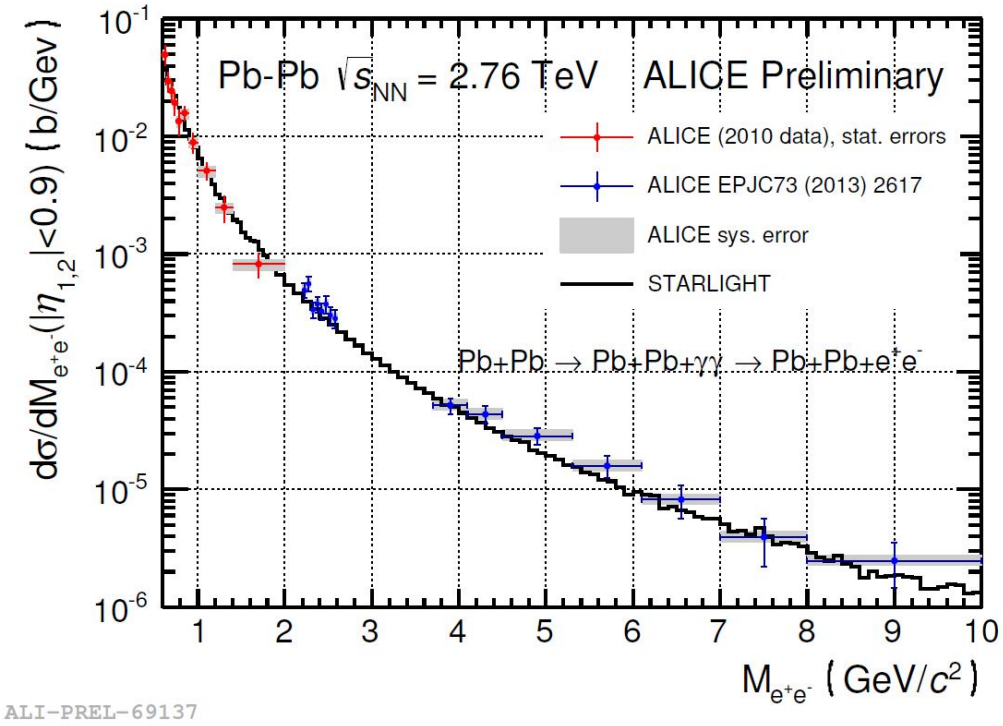
Comparison with model calculation



- 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

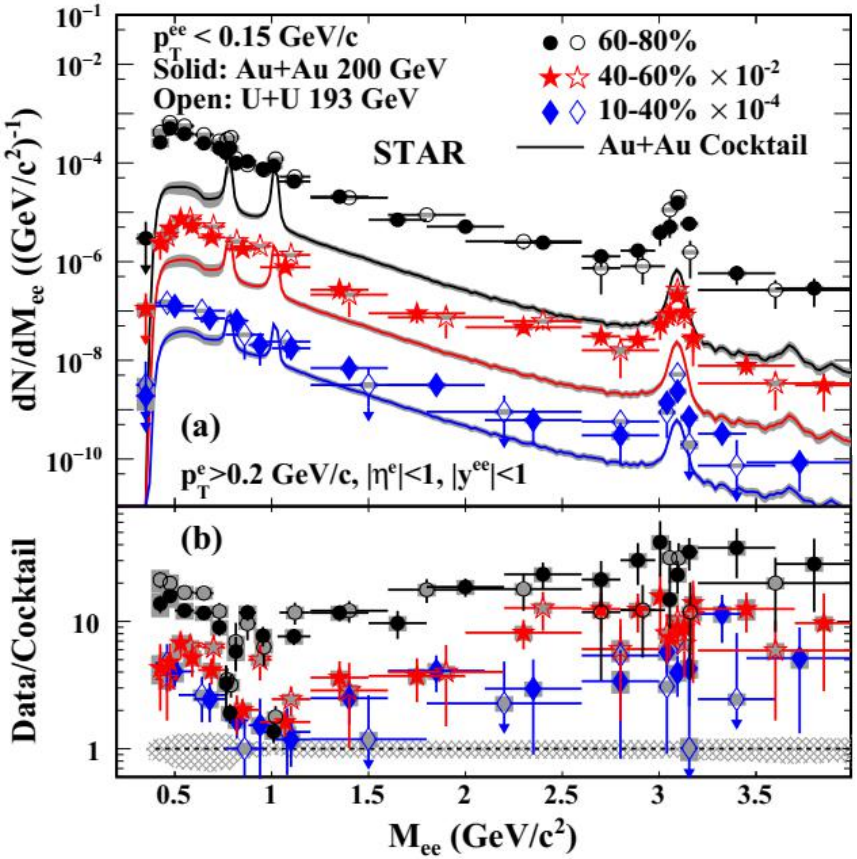
Photon-photon interactions in UPC

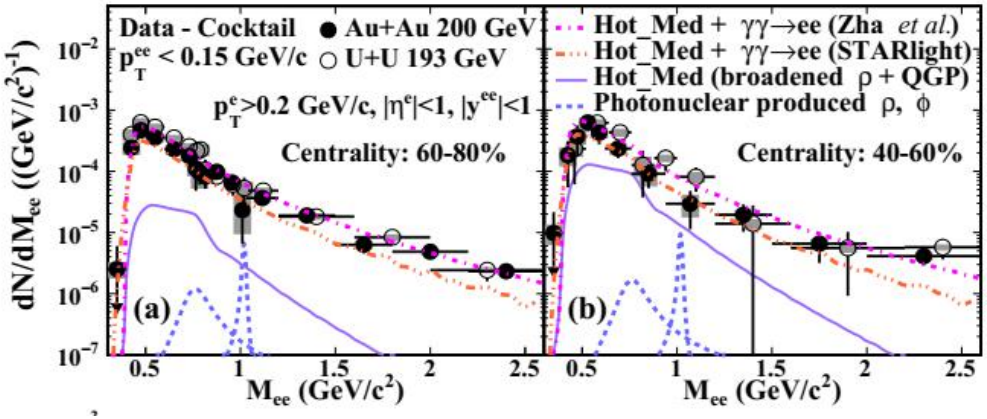
- Test QED --- $\gamma\gamma \rightarrow$ Dileptons
  - ✓$Z\alpha \sim 0.6$, so perturbation theory might fail



Data is in excellent agreement with lowest order QED!

The measurements in non-UPC collisions



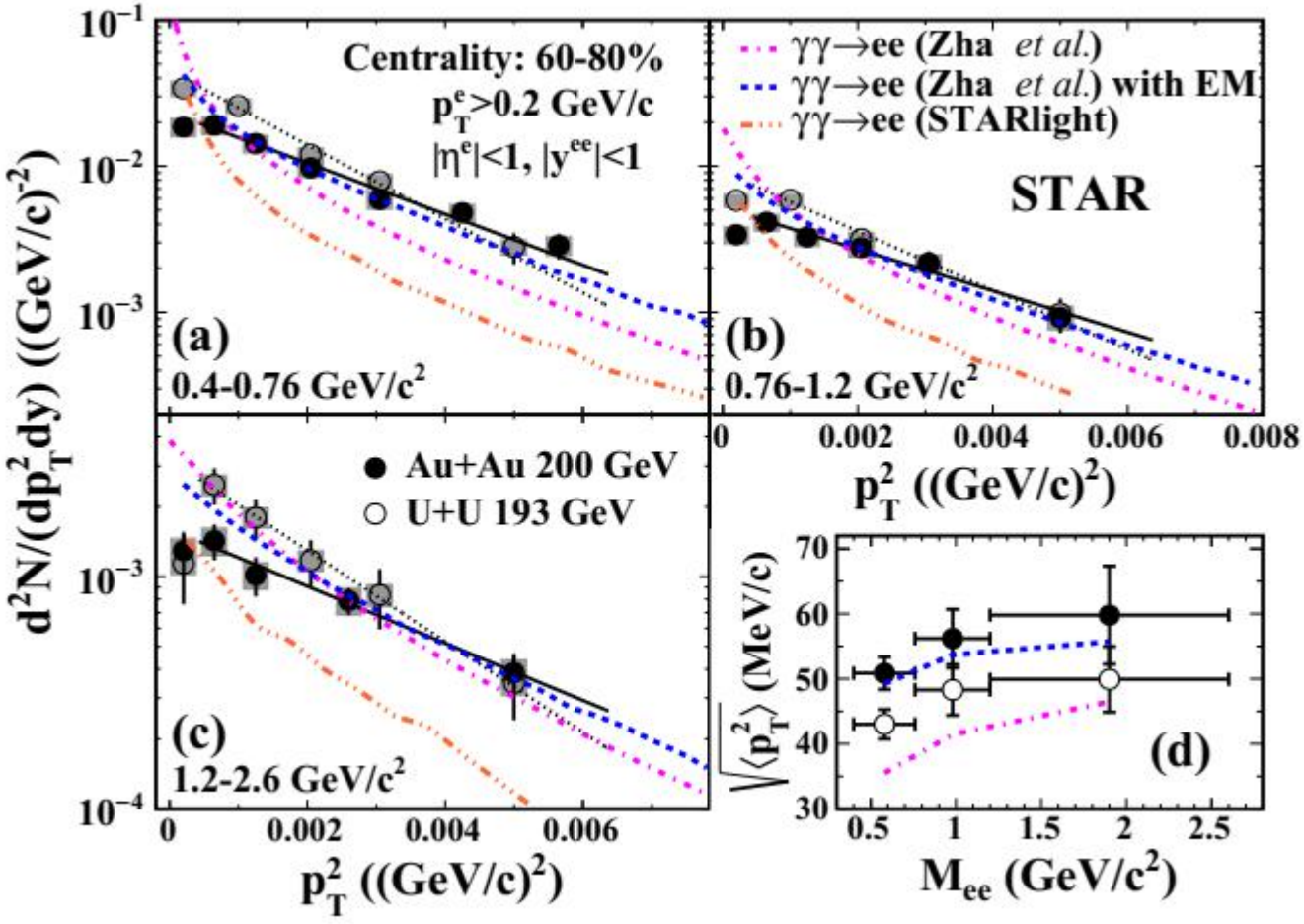


STAR, PRL **121** (2018) 132301

PLB **781** (2018) 182

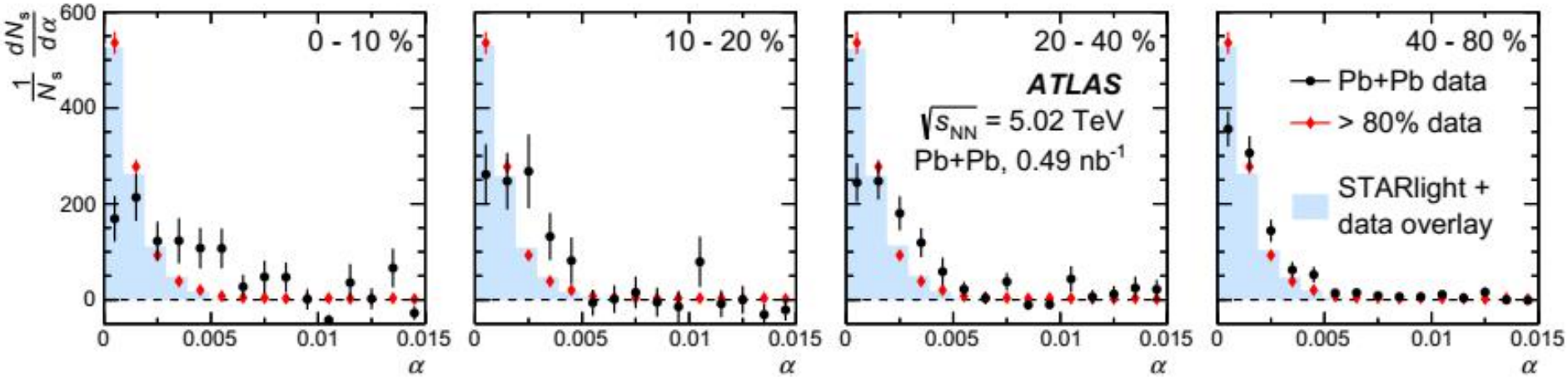
- Significant excess in 60-80% central Au + Au and U + U collisions for the whole invariant mass range!
- The excess can be described by the coherent photon-photon process!

The puzzle: pair p_T broadening



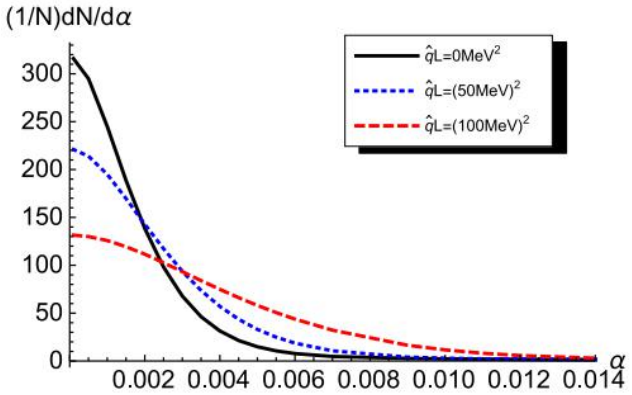
- The equivalent photon approximation could not describe the pair p_T distribution
- Possible medium effects --- magnetic field trapped in the QGP?

The puzzle: pair p_T broadening



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

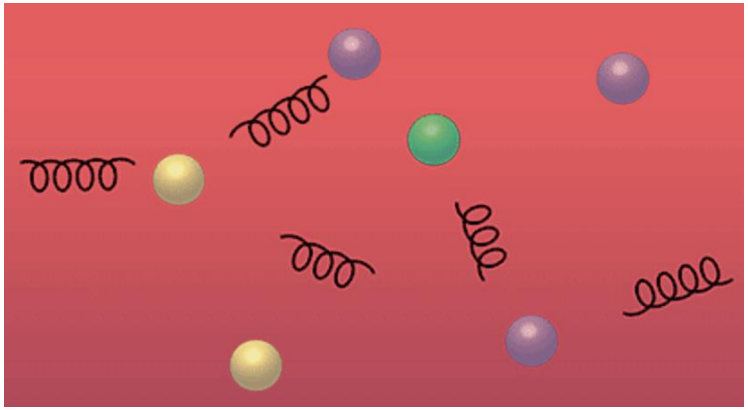
- The broadening increases towards central collisions
- Possible medium effects --- QED multiple scattering?

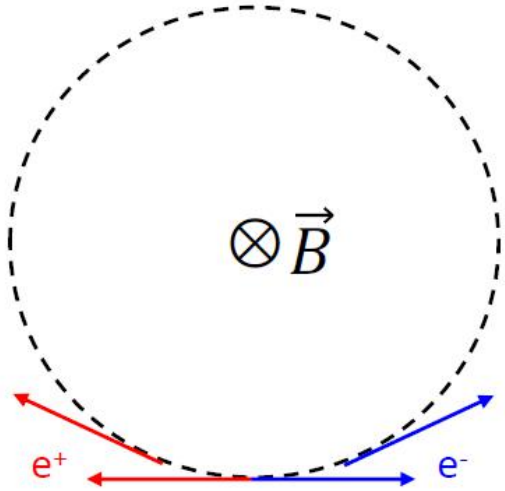


S.R. Klein etal, PRL**122** (2019) 132301

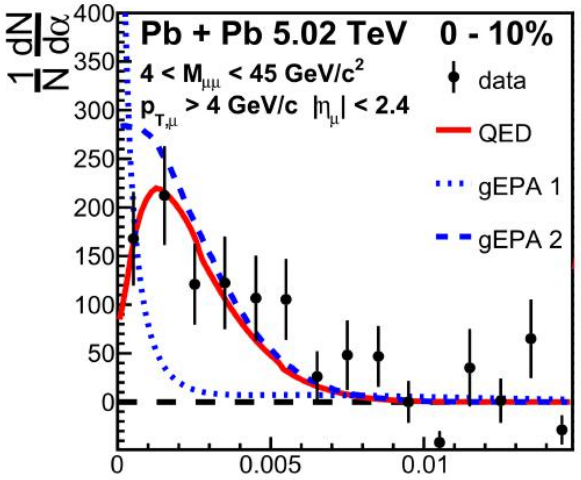
The physics origin of the puzzle

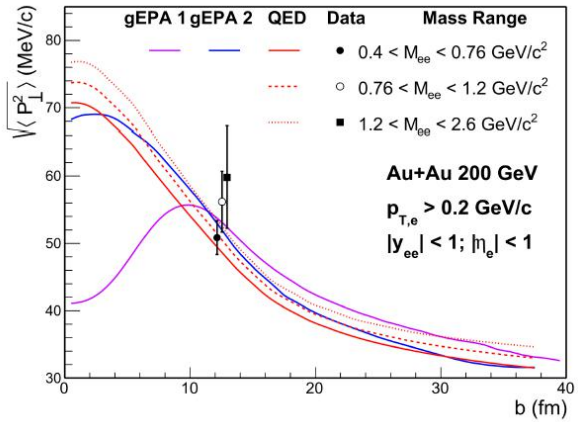
Final-state broadening





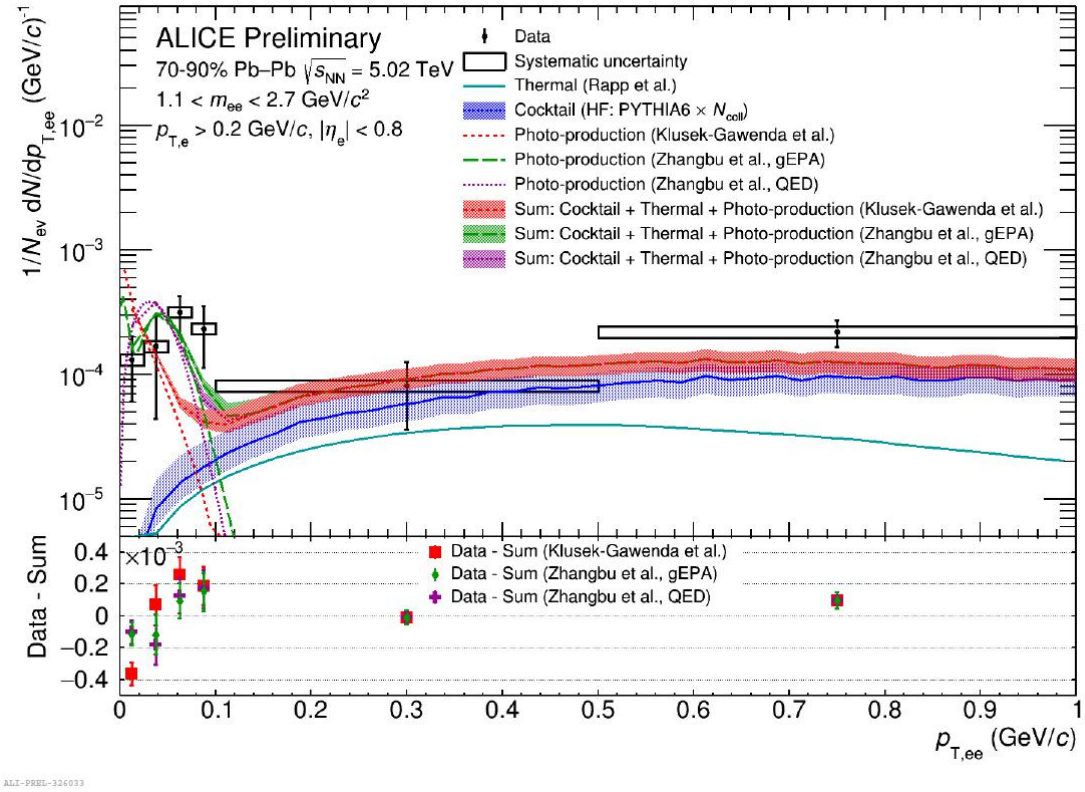
Initial-state broadening





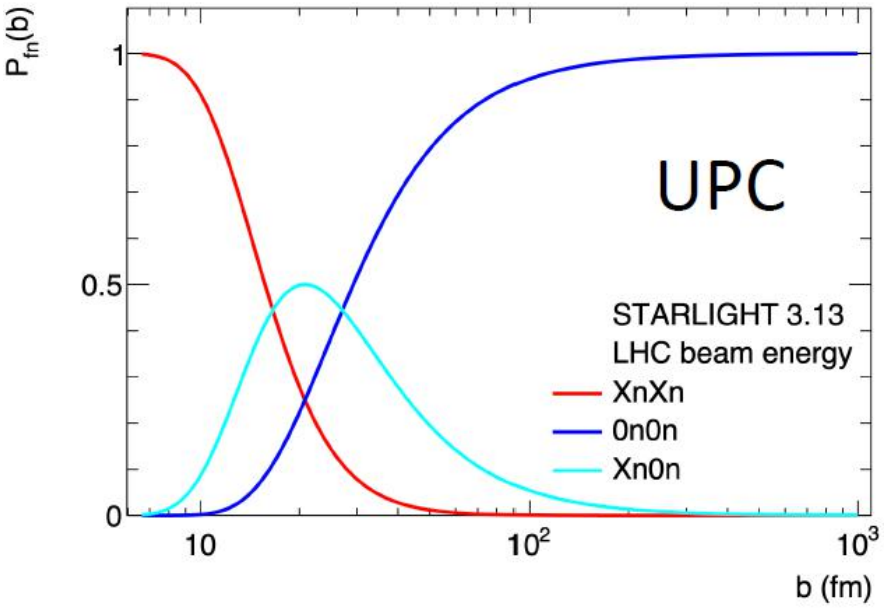
PLB**800**, 135080 (2020)

The excess observed from Run 2 data

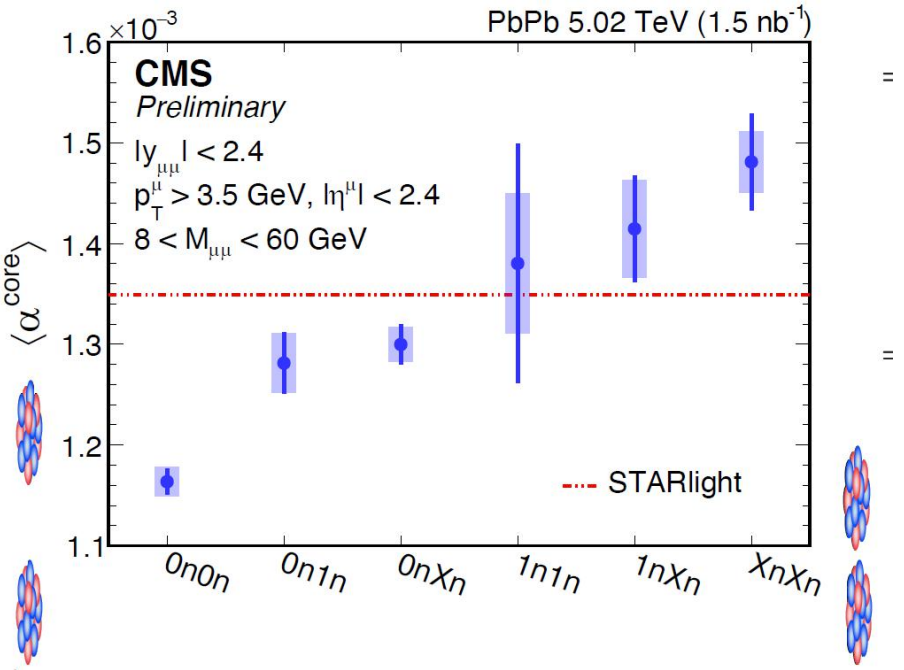


- Significant excess has been observed in peripheral collisions
- Can be described the lowest-order QED calculation (initial broadening)

Check the broadening baseline in UPCs



Shuai Yang, Hard Probe 2020

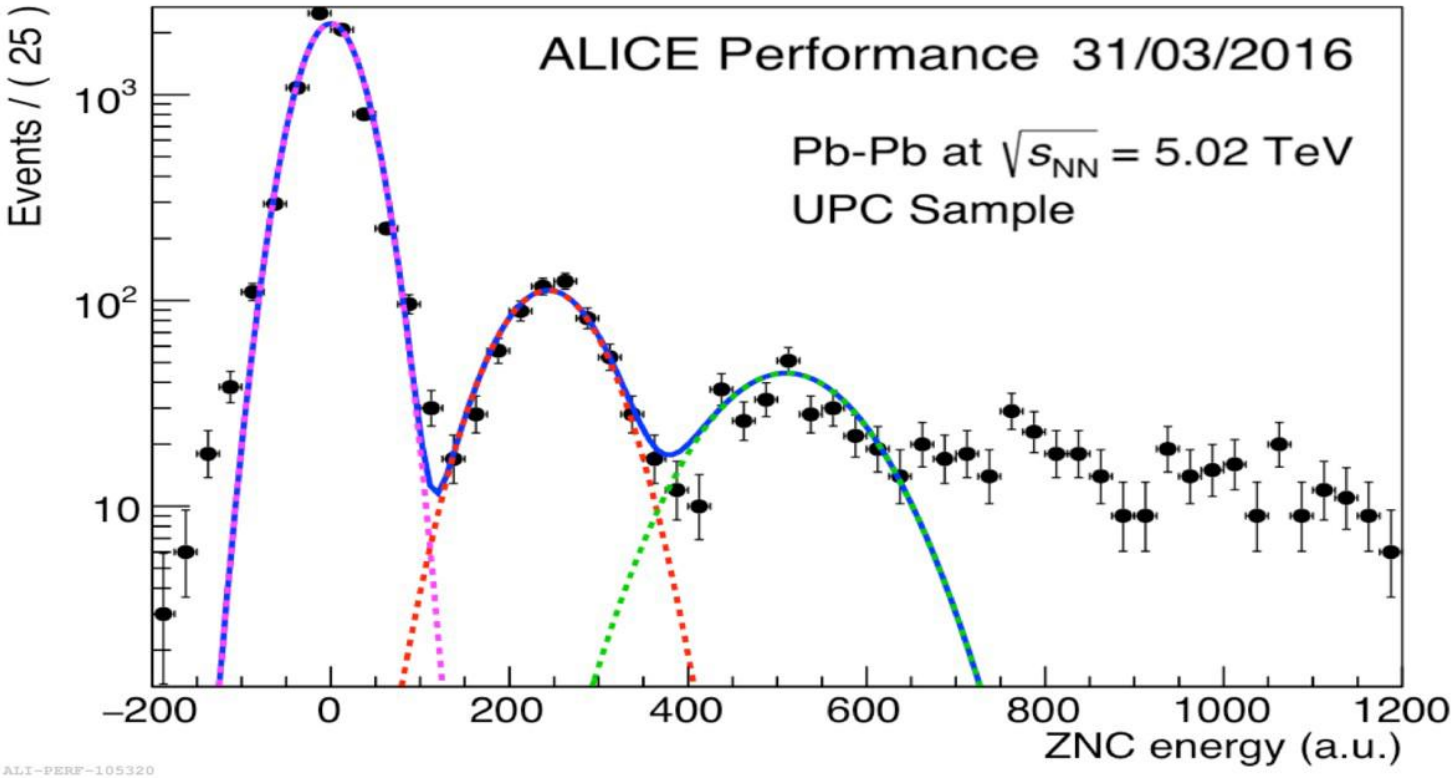


CMS-PAS-HIN-19-014

Control the "centralities" in UPCs

Significant "centrality" dependence for the broadening in UPCs

The “centrality” trigger capability in UPC at ALICE

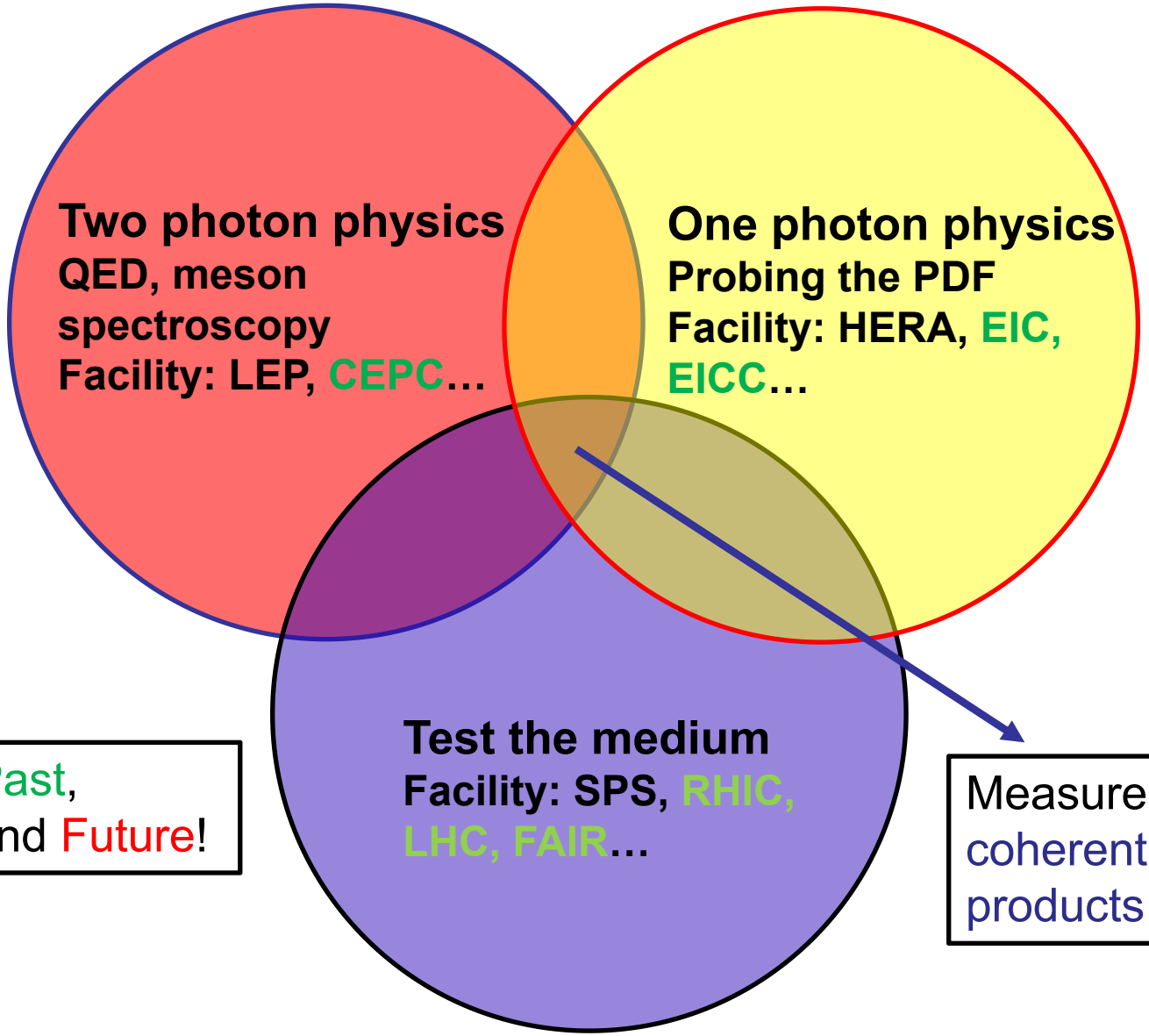


Excellent “centrality” trigger capability in UPCs

Summary

- The J/ψ photoproduction in p+Pb UPCs
  - ✓Constrain the gluon PDF in proton at small x
- The J/ψ photoproduction in Pb+Pb UPCs
  - ✓Significant shadowing effect
- Excess of J/ψ production at very low p_T in Pb+Pb peripheral collisions
  - ✓Existence of coherent photoproduction in non UPCs
  - ✓Novel probe for QGP?
- Dielectron photoproduction in UPC
  - ✓Agree well with lowest order QED
- Excess of dielectron at very low p_T in Pb+Pb peripheral collisions
  - ✓Coherent photon-photon interaction in non UPCs
  - ✓Can be described by initial broadening

Outlook



Link the Past, Present and Future!

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