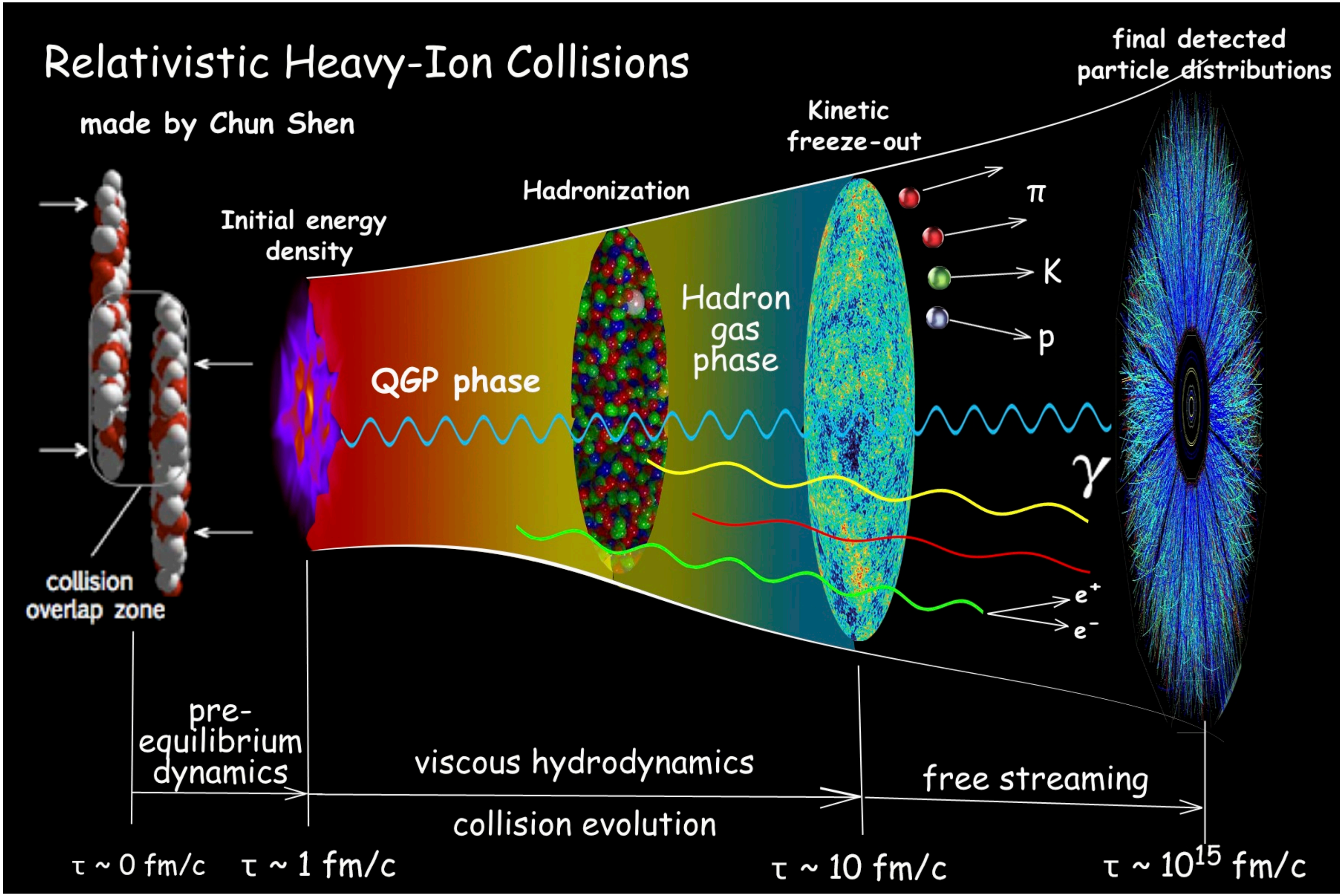
Initial Stages 2019 (IS2019)
24-28 June 2019, New York

Electromagnetic probes of the initial stages

Shuai Yang

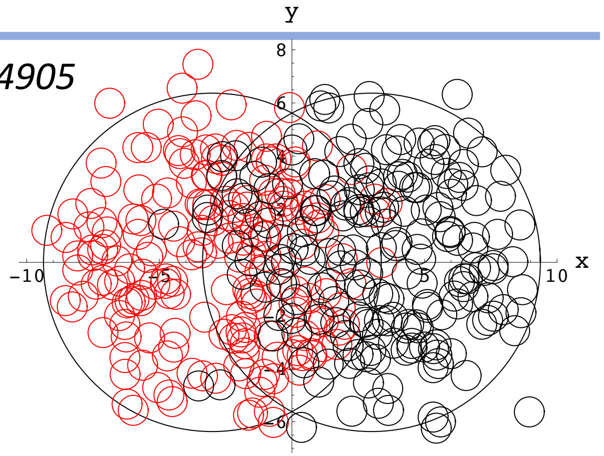
Brookhaven National Laboratory

Initial stage



Electroweak bosons

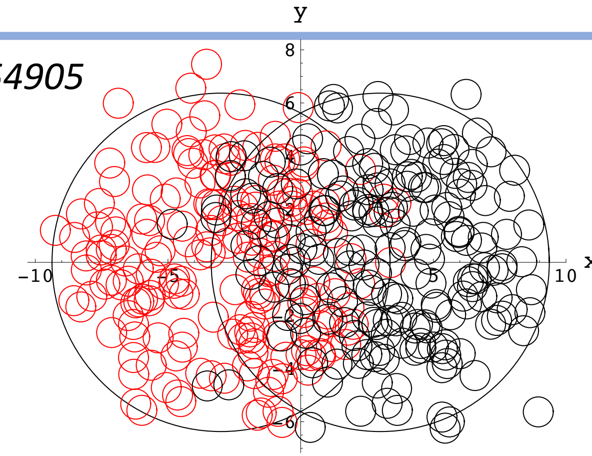
W. Broniowski et al., PRC 76 (2007) 054905



- Created in initial hard scattering
  - Test N_{coll} scaling ⇒ geometry (Glauber)

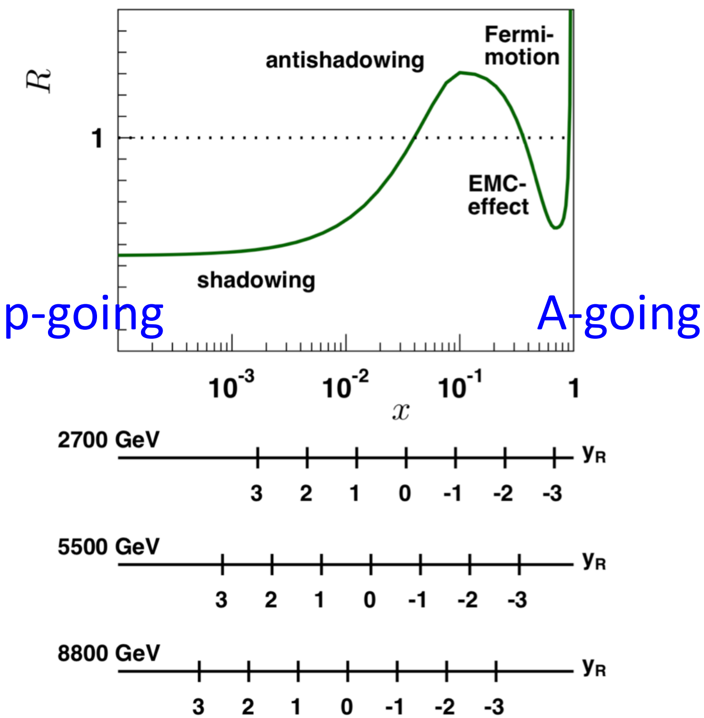
Electroweak bosons

W. Broniowski et al., PRC 76 (2007) 054905



- Created in initial hard scattering
  - Test N_{coll} scaling ⇒ geometry (Glauber)

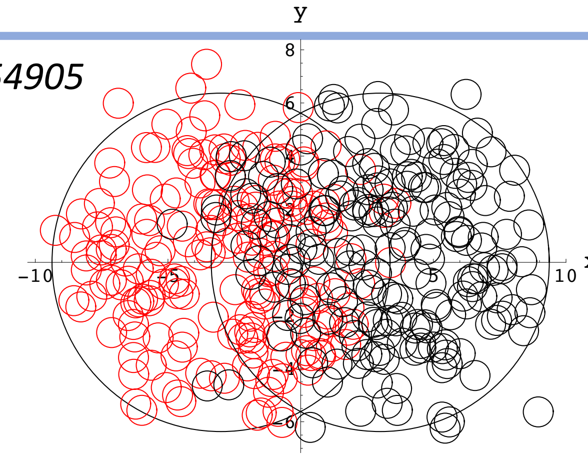
- Minimal interaction with QGP
  - Investigate initial stage effects
  - Sensitive to nuclear PDF (nPDF)



 H. Paukkunen et al., JHEP 03 (2011) 071

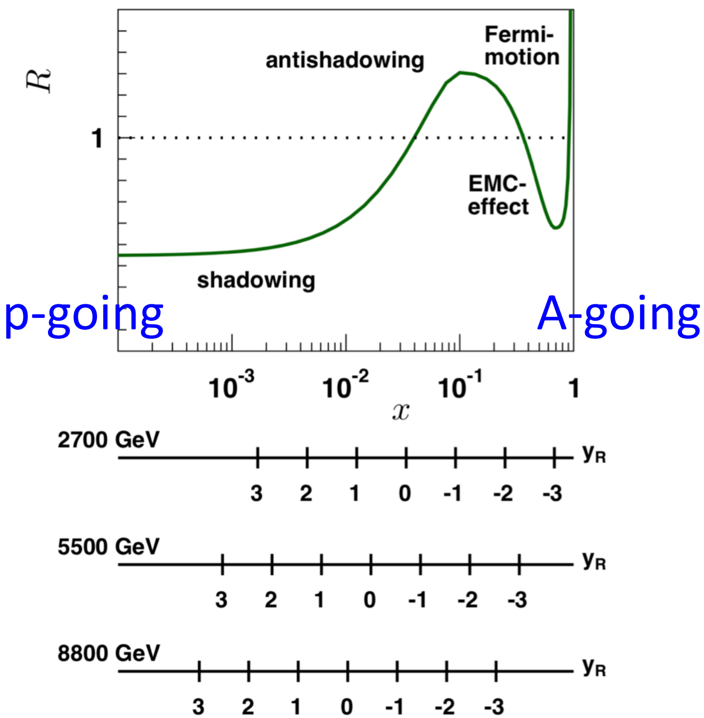
Electroweak bosons

W. Broniowski et al., PRC 76 (2007) 054905



- Created in initial hard scattering
  - Test N_{coll} scaling ⇒ geometry (Glauber)

- Minimal interaction with QGP
  - Investigate initial stage effects
  - Sensitive to nuclear PDF (nPDF)



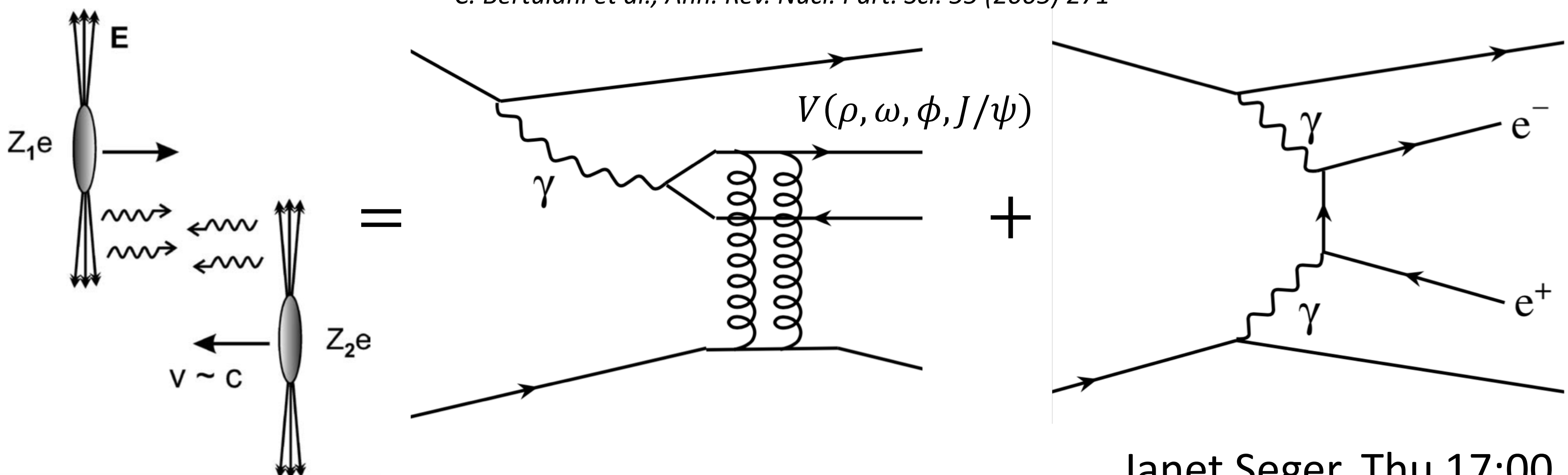
- Observables vs. rapidity (x_A)
  - Yields
  - $R_{AA} = \frac{1}{<T_{AA}>} \times \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$

nPDF

free PDF

Initial EM field induced probes

C. Bertulani et al., Ann. Rev. Nucl. Part. Sci. 55 (2005) 271

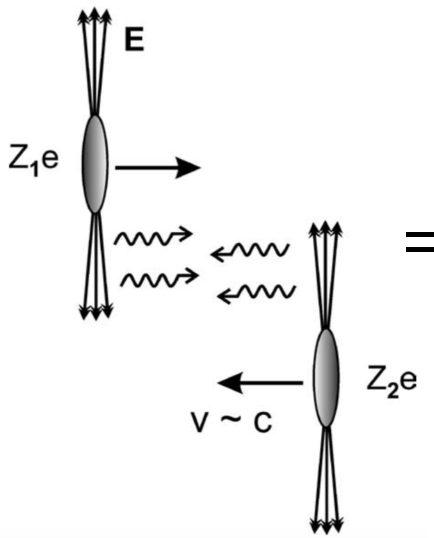


Janet Seger, Thu 17:00

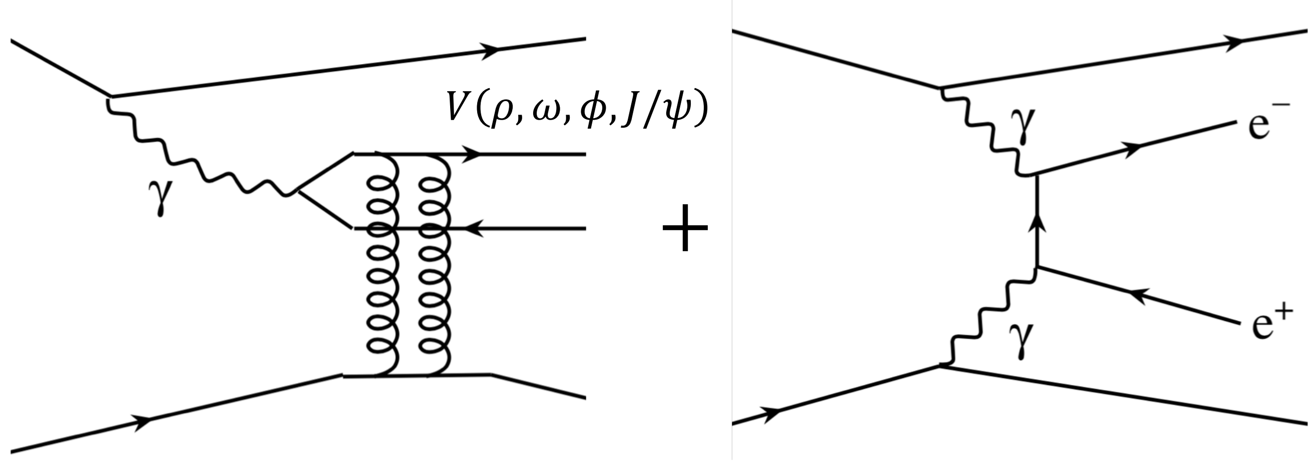
- Quasi-real photon (flux ∝ Z^2)
- Photonuclear interaction (vector mesons)
  - Meson production is sensitive to gluon nPDF
- Two-photon interactions (dilepton …)
  - Photon flux is sensitive to nucleus geometry

Initial EM field induced probes

C. Bertulani et al., Ann. Rev. Nucl. Part. Sci. 55 (2005) 271



=



Janet Seger, Thu 17:00

- Quasi-real photon (flux $\propto Z^2$)
- Photonuclear interaction (vector mesons)
  - Meson production is sensitive to gluon nPDF
- Two-photon interactions (dilepton …)
  - Photon flux is sensitive to nucleus geometry
- Only occur in UPC? What about in hadronic collisions?
  - Initial stage effects + final state effects?

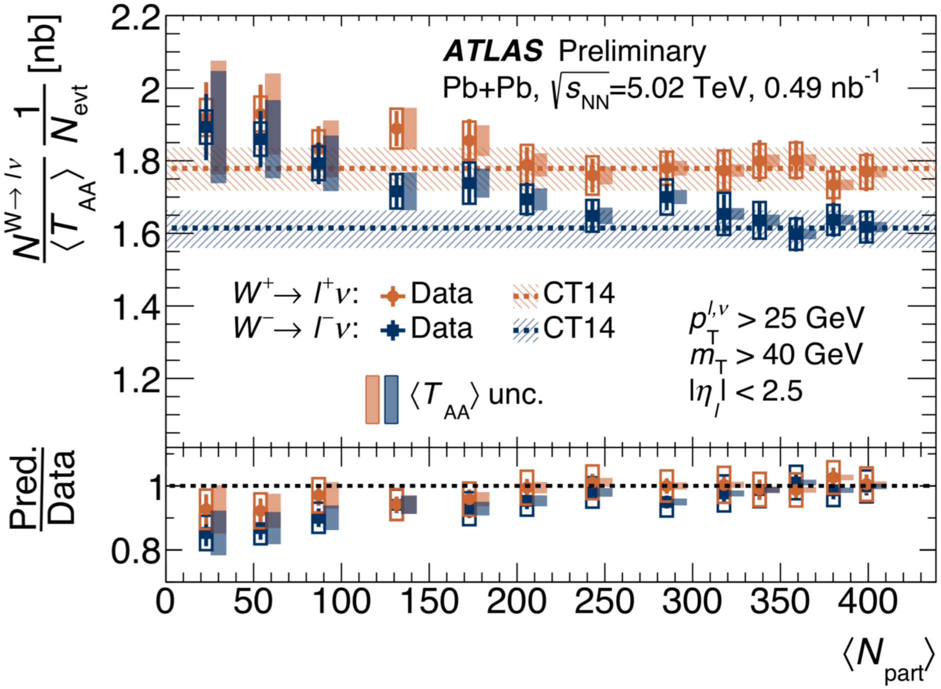
Electroweak bosons

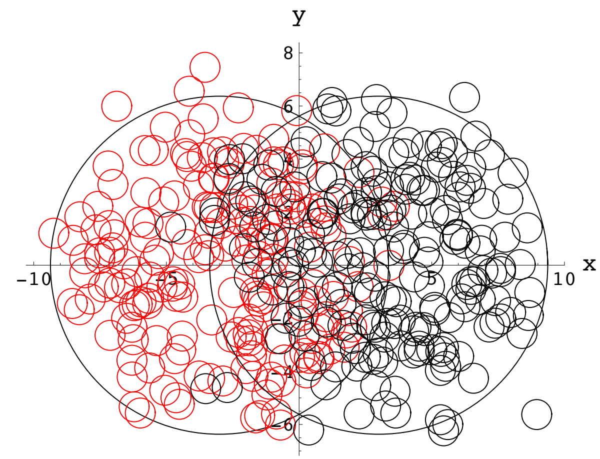
Initial EM field induced probes

Collision geometry in Pb+Pb

HION-2018-25

Mrita Dumancic, Tue 14:20





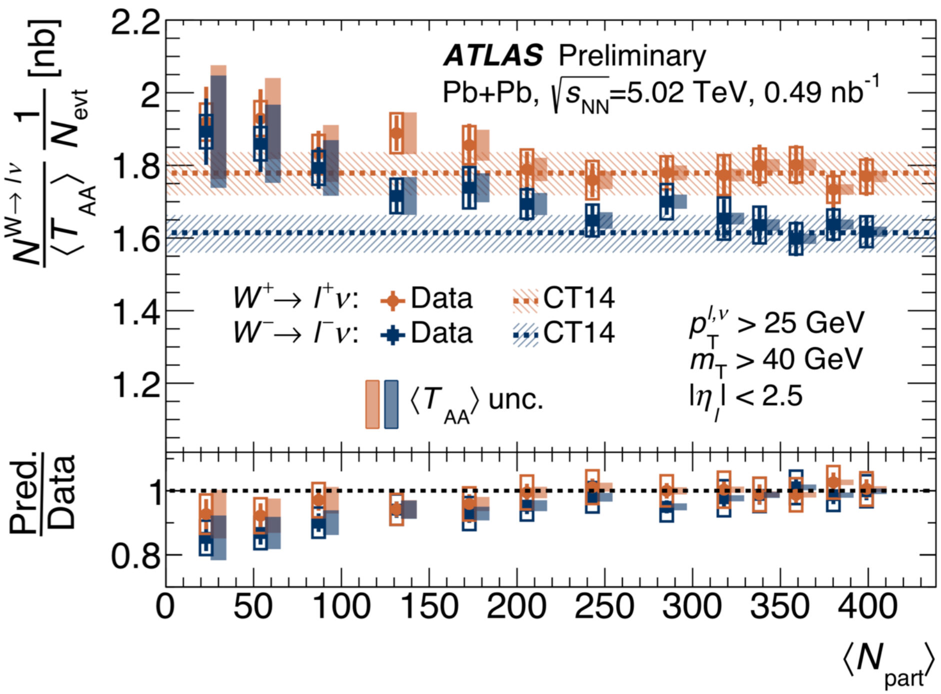
➢ W boson: nearly constant T_{AA} scaled yield for N_{part} > 200

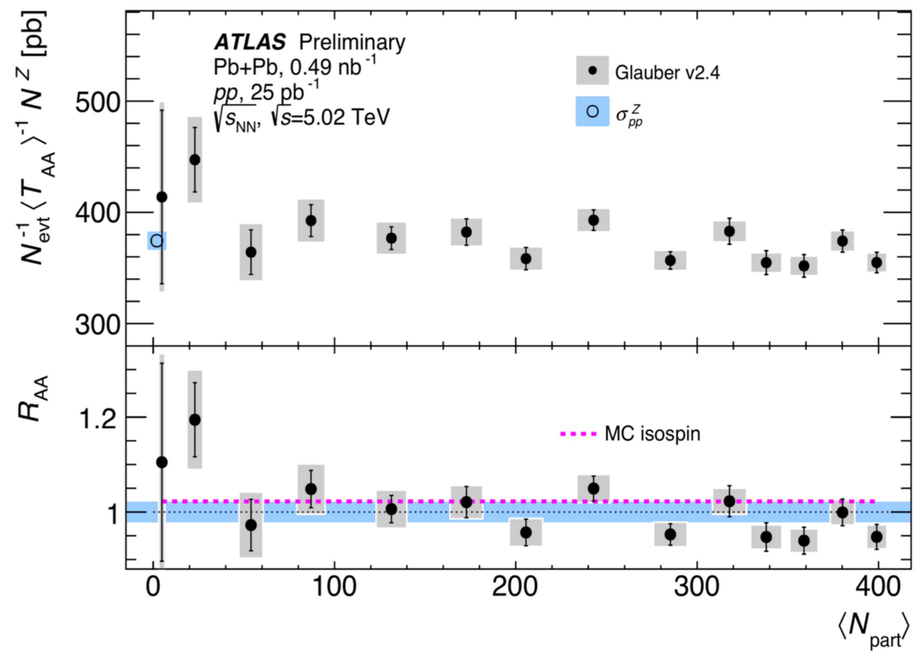
- ~1.7σ (0.9σ) tension for W^{-}(W^{+}) in 50-80% collisions

Collision geometry in Pb+Pb

HION-2018-25
ATLAS-CONF-2019-024

Mrita Dumancic, Tue 14:20



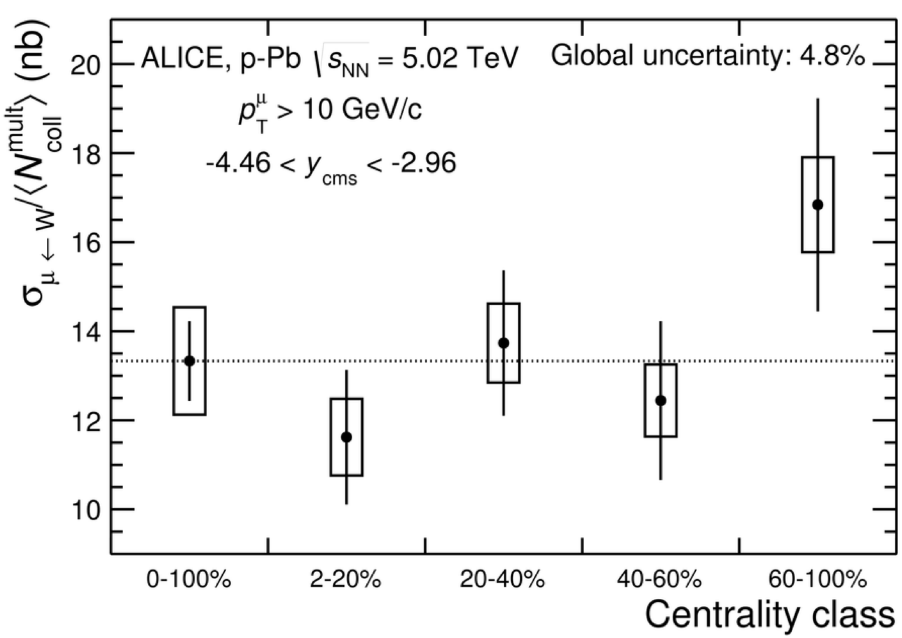


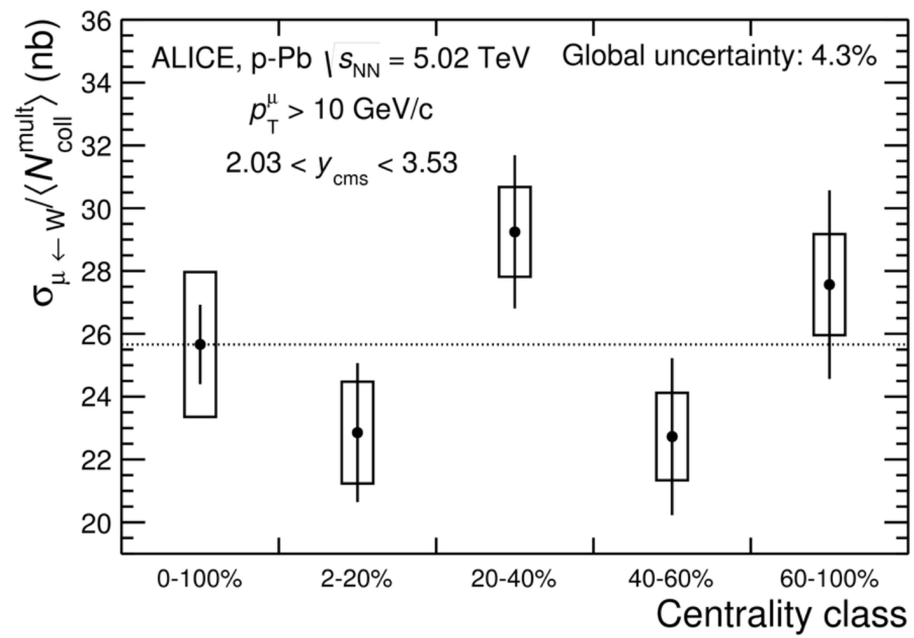
- W boson: nearly constant T_{AA} scaled yield for N_{part} > 200
  - ~1.7σ (0.9σ) tension for W^-(W^+) in 50-80% collisions
- Z boson consistent with geometry expectation within 1σ

Collision geometry in p+Pb

ALICE, JHEP 02 (2017) 077

Nicolo Valle, Tue 14:00



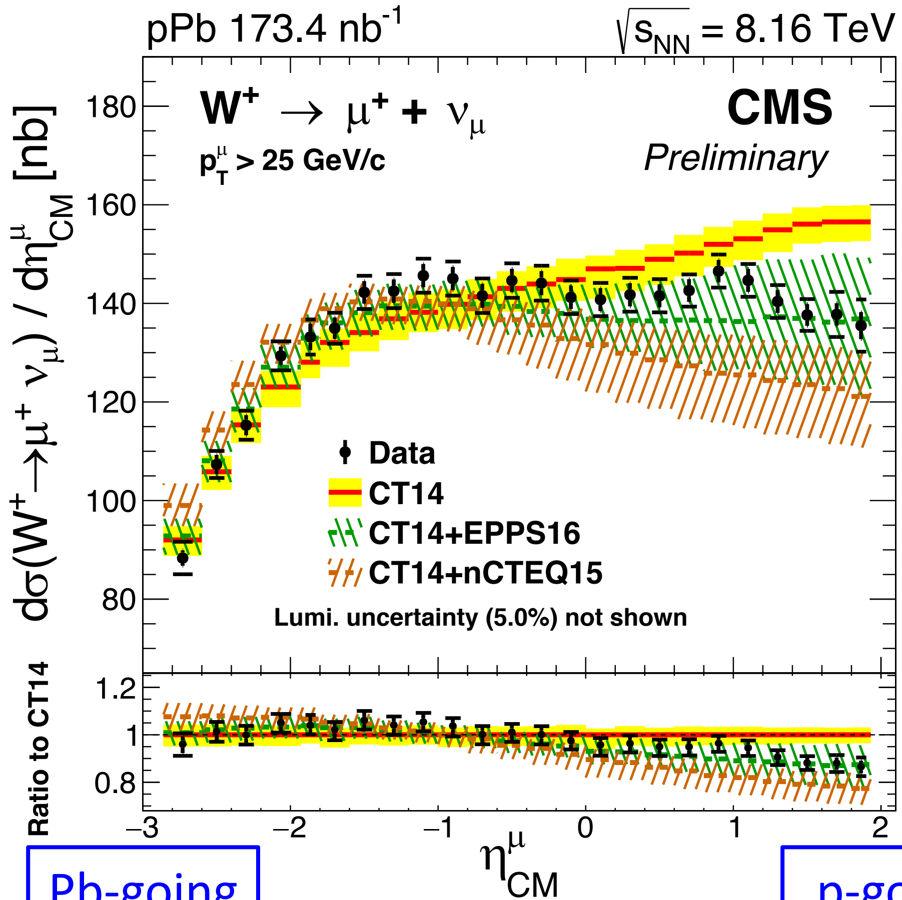


- Use W bosons to test N_{coll} calculation in pPb
- No significant centrality dependence of N_{coll} scaled W yields
  ⇒ Consistent with geometry expectation

nPDF: W bosons in p+Pb

CMS, arXiv:1905.01486

Emilien Chapon, Tue 14:40



Pb-going

p-going

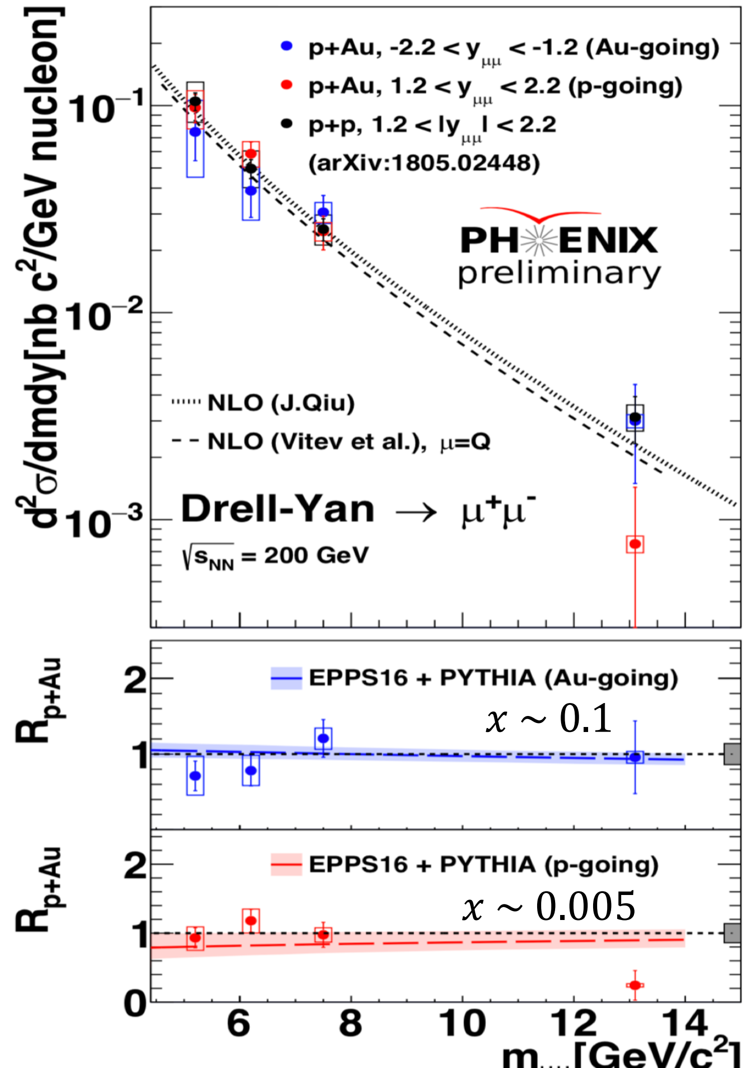
- nPDF is favored in p-going direction (small-x region)
  - Measured uncertainty smaller than that of nPDFs

nPDF: Drell-Yan in p+Au

PHENIX, PRD 99 (2019) 072003

Axel Drees, Tue 15:40

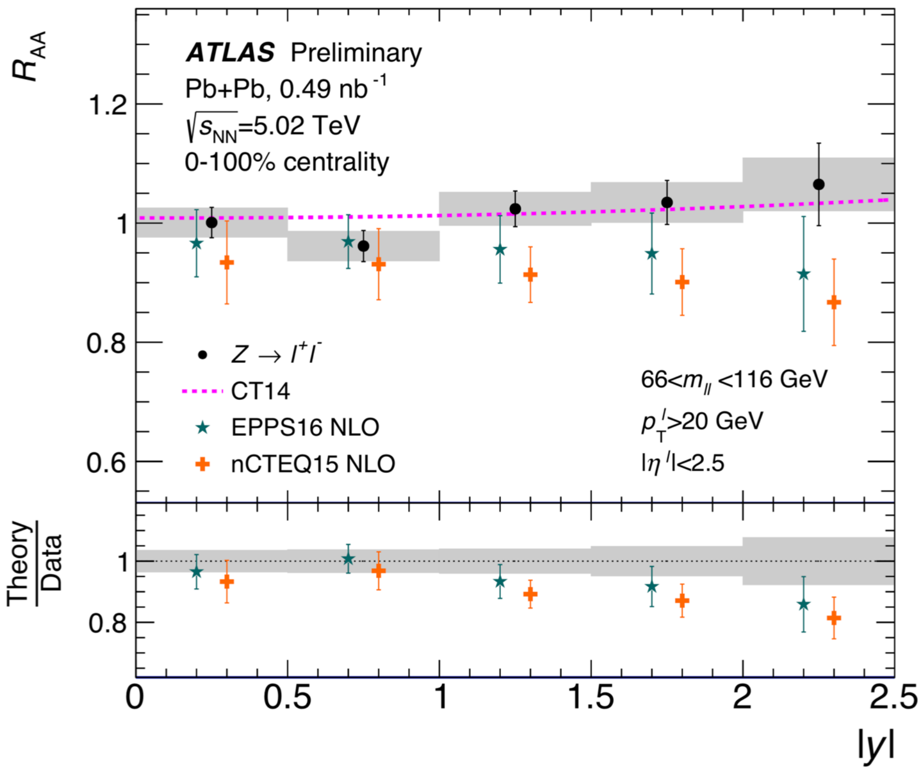
- ➢ Not affected by final state interaction
  - Clean probe of initial stage effects
- ➢ R_{pAu} are consistent with unity and EPPS16
  - nPDF effects are expected to be small



nPDF: Z boson in Pb+Pb

Mrita Dumancic, Tue 14:20

ATLAS-CONF-2019-024

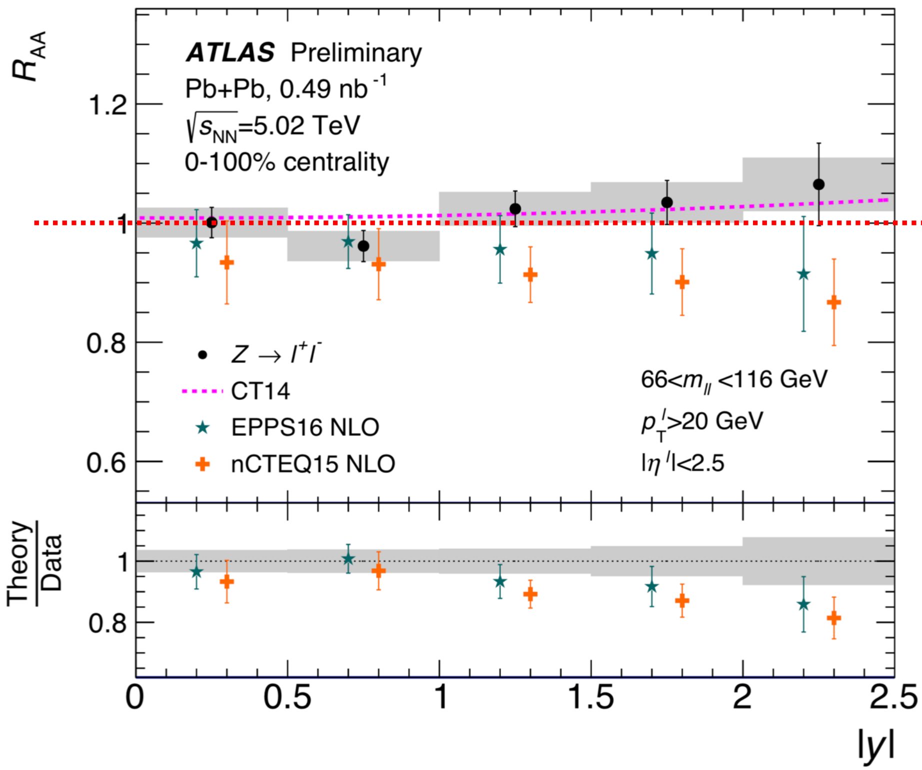


- nPDF depends on the rapidity
  - Mid-rapidity: best agreement with free proton PDF with isospin effect

nPDF: Z boson in Pb+Pb

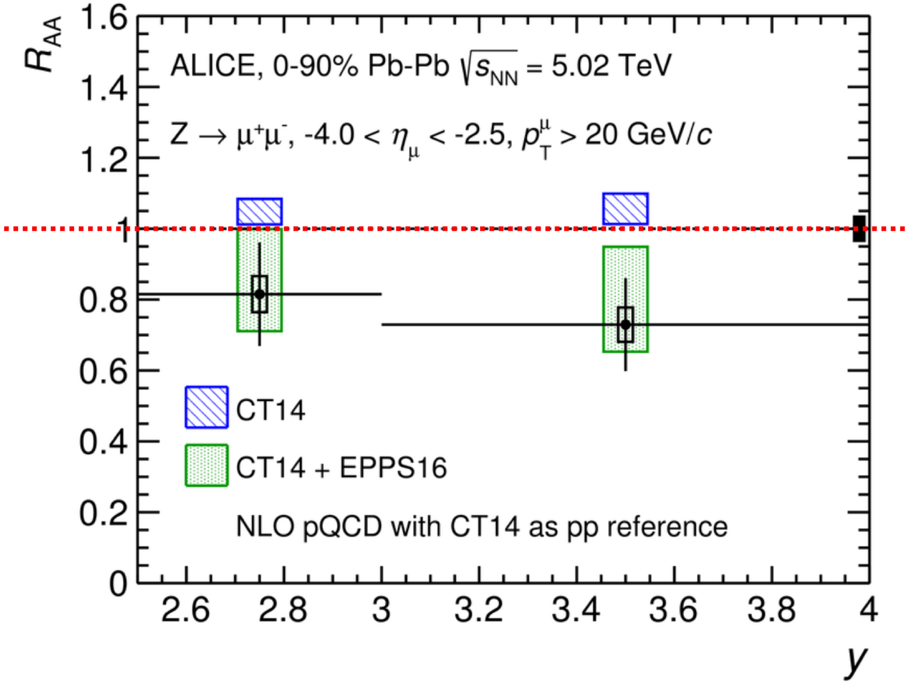
Mrita Dumancic, Tue 14:20

ATLAS-CONF-2019-024



Nicolo Valle, Tue 14:00

ALICE, PLB 780 (2018) 372



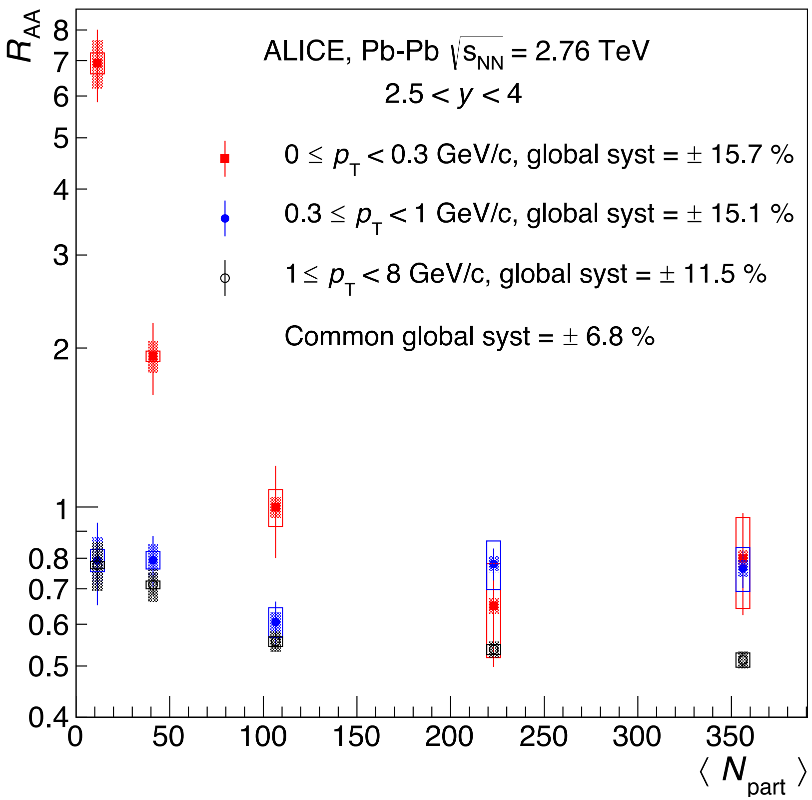
- nPDF depends on the rapidity
  - Mid-rapidity: best agreement with free proton PDF with isospin effect
  - Forward-rapidity: better agreement with calculations including nPDF

Electroweak bosons

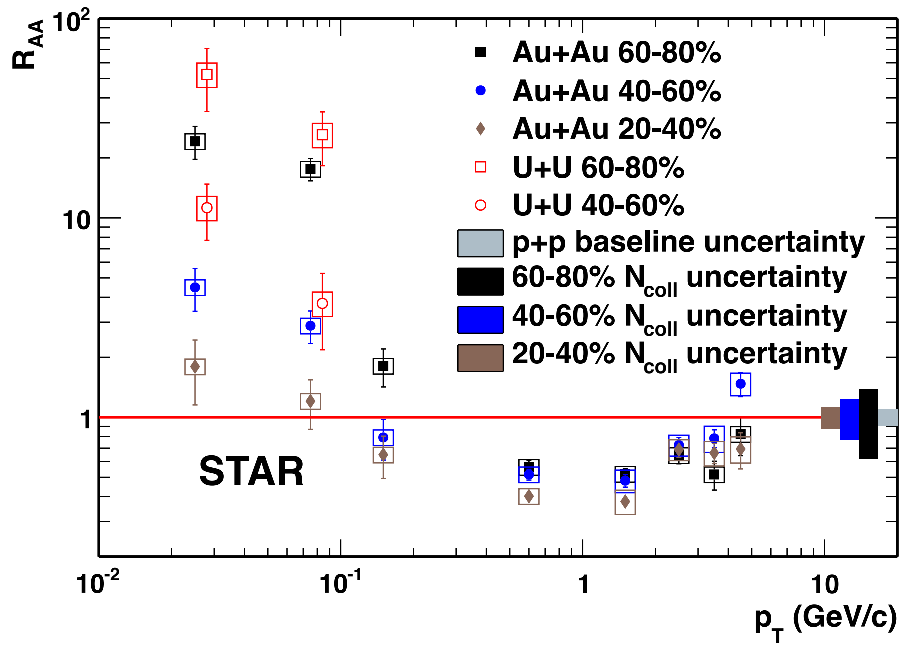
Initial EM field induced probes

Anomalous J/ψ enhancement at LHC and RHIC

ALICE, PRL 116 (2016) 222301



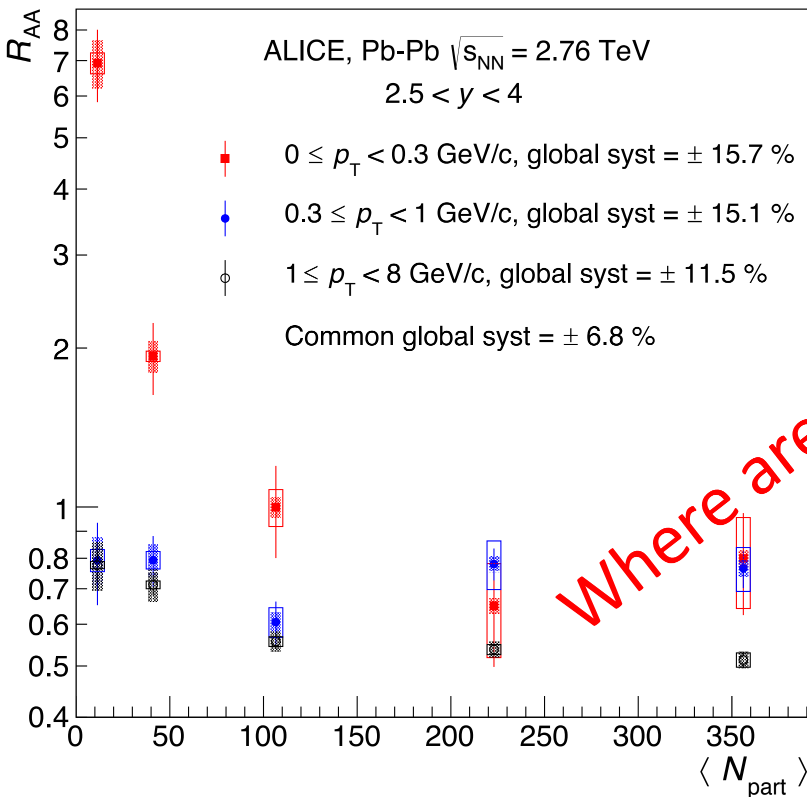
STAR, arxiv: 1904.11658



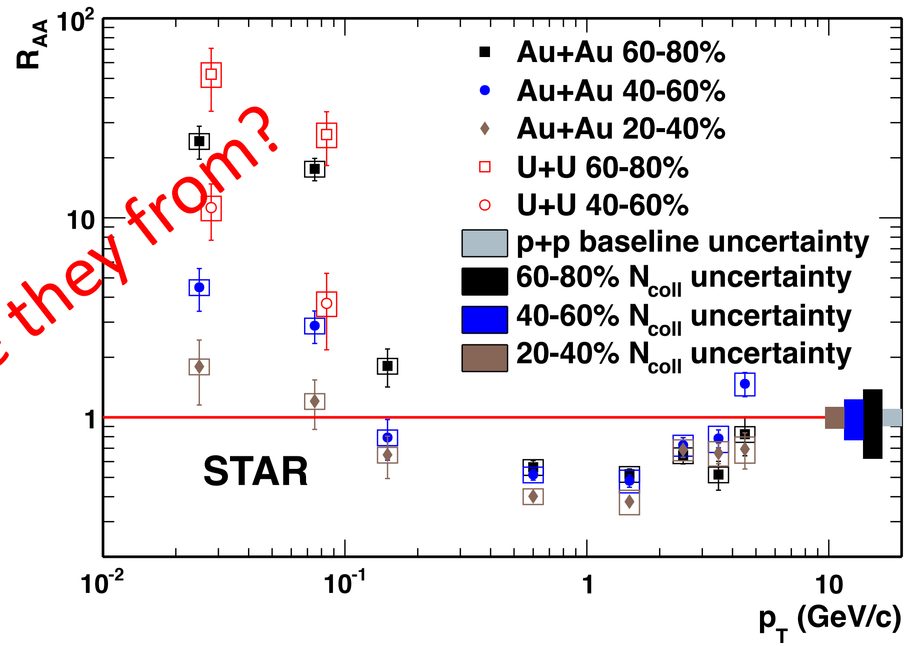
- Significant enhancement at low p_T in peripheral A+A collisions
  - Cannot be explained by cold + hot nuclear effects

Anomalous J/ψ enhancement at LHC and RHIC

ALICE, PRL 116 (2016) 222301



STAR, arxiv: 1904.11658

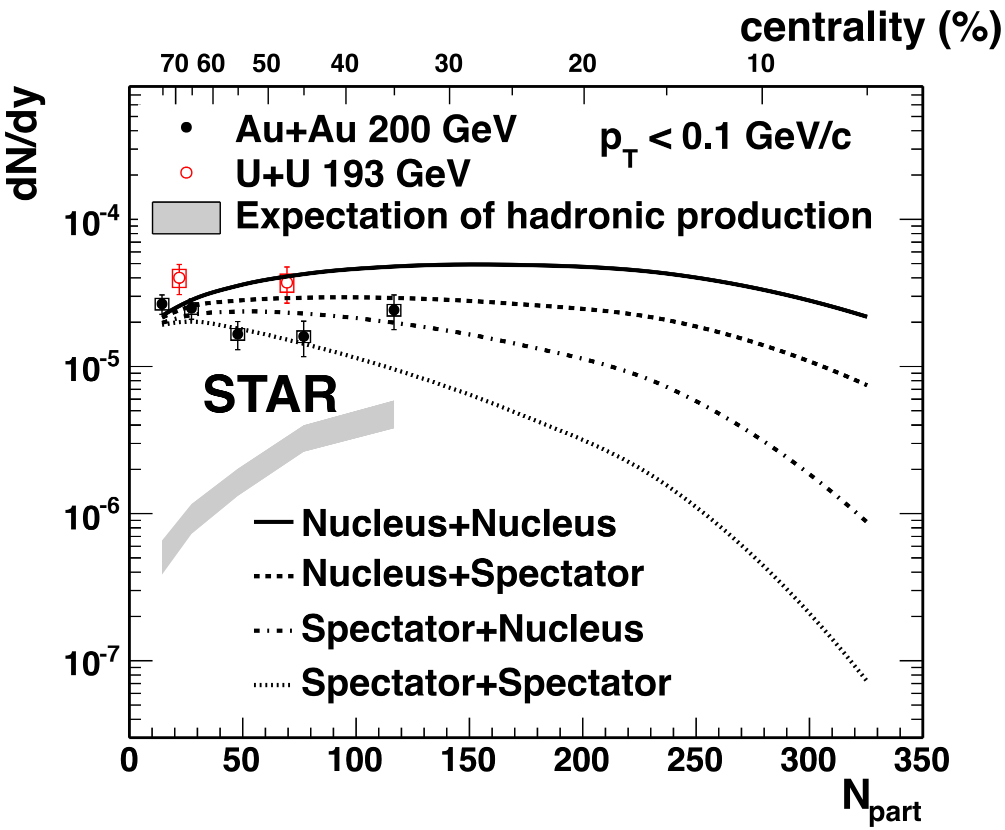


Where are they from?

- ➢ Significant enhancement at low p_T in peripheral A+A collisions
  - Cannot be explained by cold + hot nuclear effects

Low-p_T J/ψ enhancement

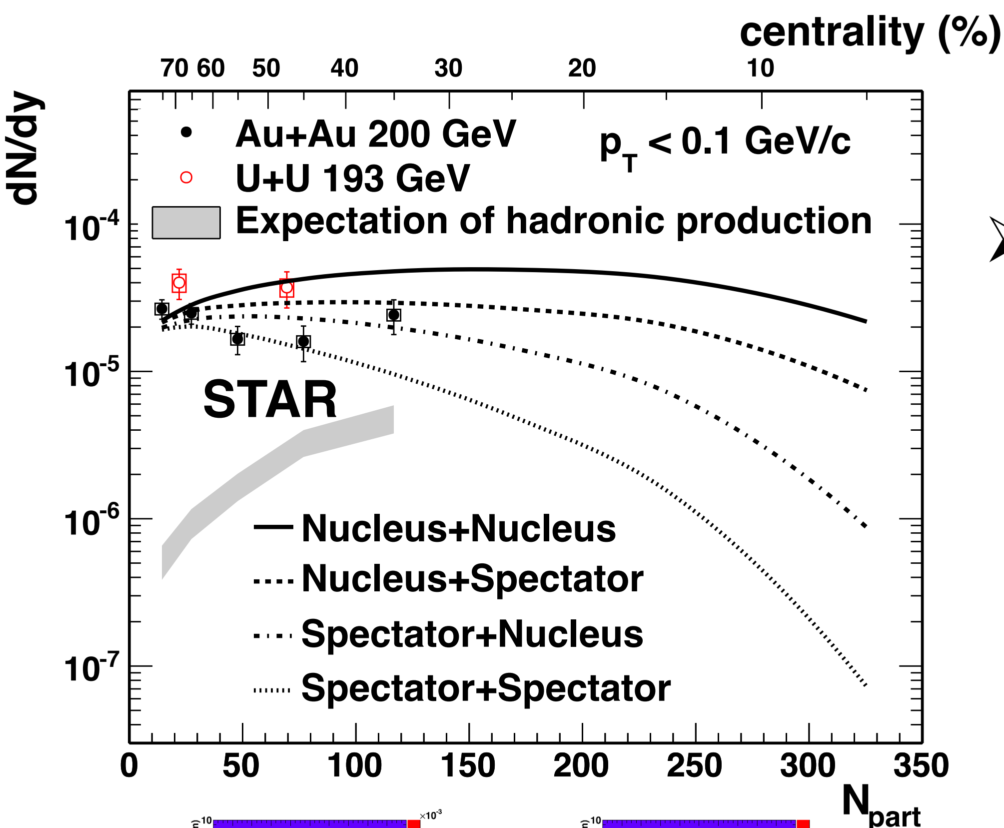
STAR, arxiv: 1904.11658
W. Zha et al. PRC 97 (2018) 044910

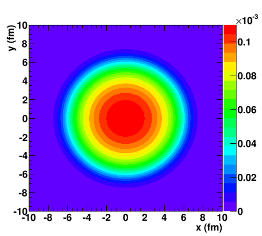


- No significant centrality dependence of the excess yield
  - Contradict to hadronic production

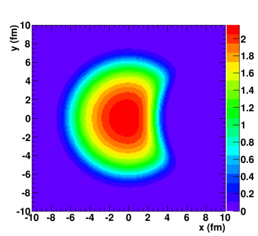
Low-p_T J/ψ enhancement

STAR, arxiv: 1904.11658
W. Zha et al. PRC 97 (2018) 044910





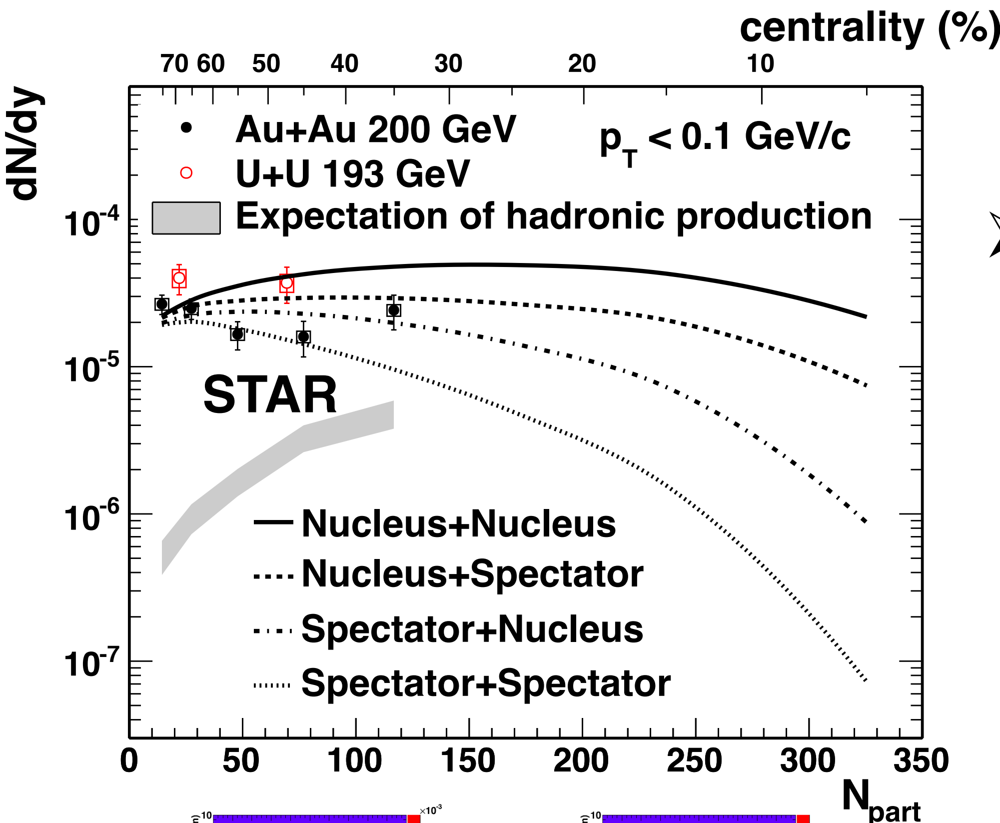
OR

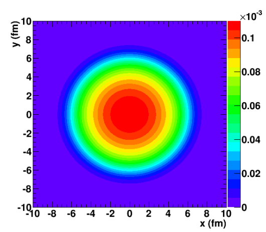


- No significant centrality dependence of the excess yield
  - Contradict to hadronic production
- Compared to photoproduction model
  - Glauber+VMD $\oplus$ γp without hot medium effects
  - Qualitatively describe data
  - N+N scenario overestimates data in semi-central collisions $\Rightarrow$ partial disruption of the coherent production?

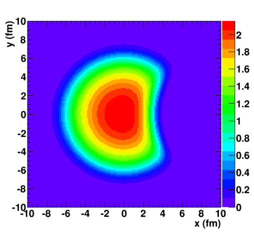
Low-p_T J/ψ enhancement

STAR, arxiv: 1904.11658
W. Zha et al. PRC 97 (2018) 044910





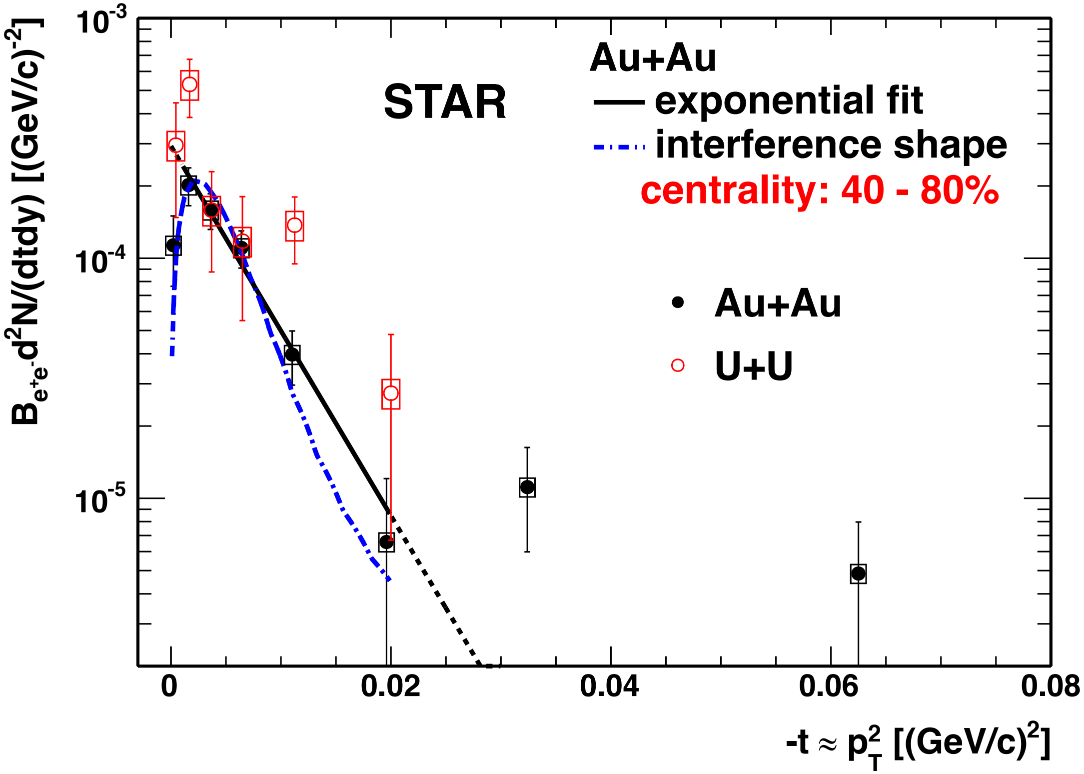
OR



- No significant centrality dependence of the excess yield
  - Contradict to hadronic production
- Compared to photoproduction model
  - Glauber+VMD $\oplus$ γp without hot medium effects
  - Qualitatively describe data
  - N+N scenario overestimates data in semi-central collisions $\Rightarrow$ partial disruption of the coherent production?
- Need precise data in central collisions + advanced mode with hot medium effects

t distribution of J/ψ

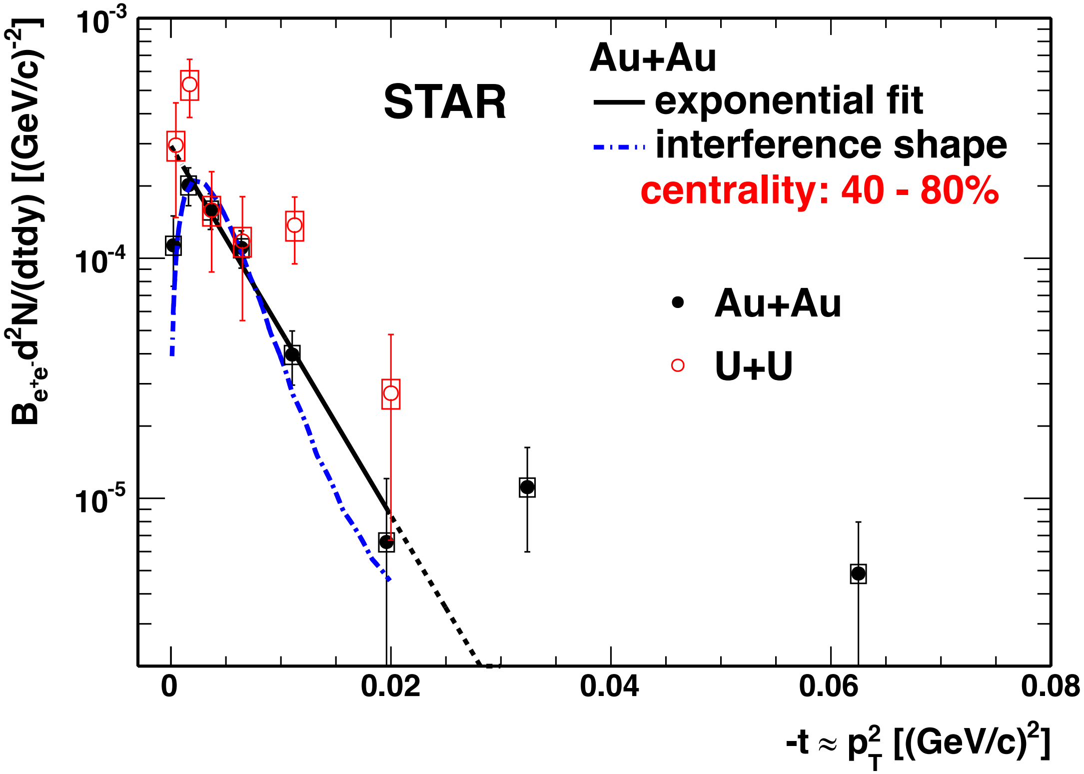
STAR, arxiv: 1904.11658



- Similar slope parameter (interaction size)
  - Slope = 177 $\pm$ 23 (GeV/c)$^{-2}$ in 40-80% collisions
  - Slope = 196 (GeV/c)$^{-2}$ in UPC case

t distribution of J/ψ

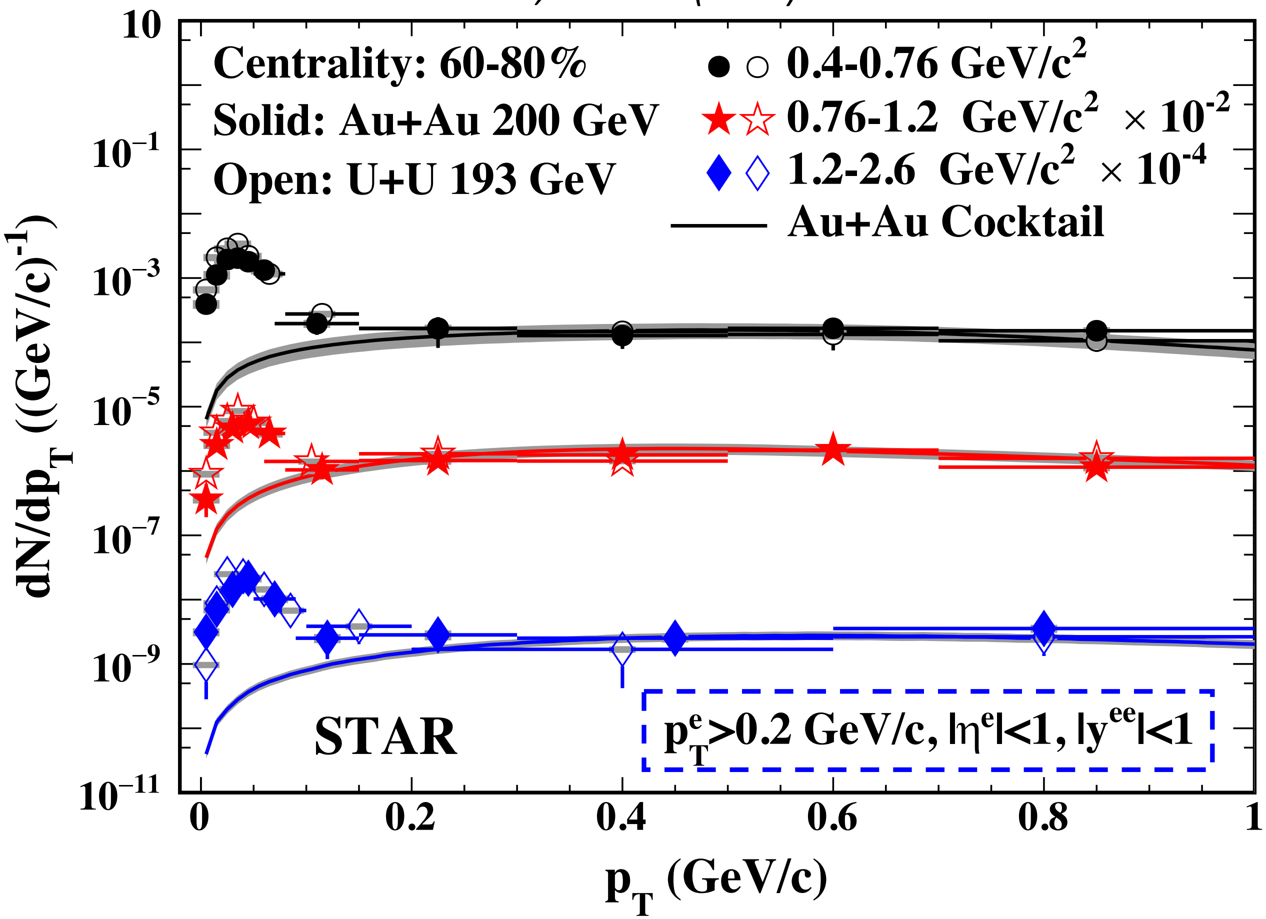
STAR, arxiv: 1904.11658



- Similar slope parameter (interaction size)
  - Slope = 177 $\pm$ 23 (GeV/c)$^{-2}$ in 40-80% collisions
  - Slope = 196 (GeV/c)$^{-2}$ in UPC case
- Indication of interference *[S. Klein, PRL 84 (2000) 2330]*

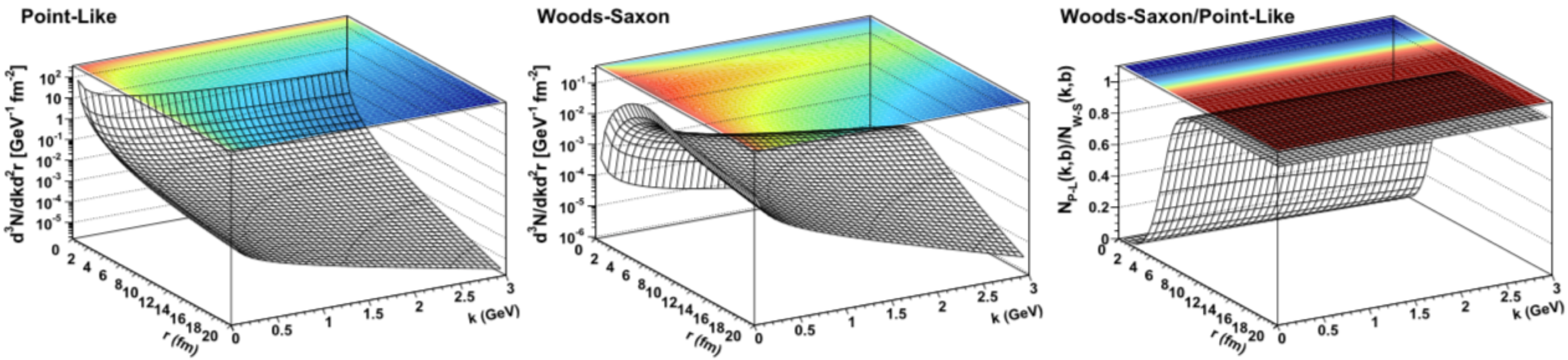
Low-p_T e^+e^- enhancement at RHIC

STAR, PRL 121 (2018) 132301



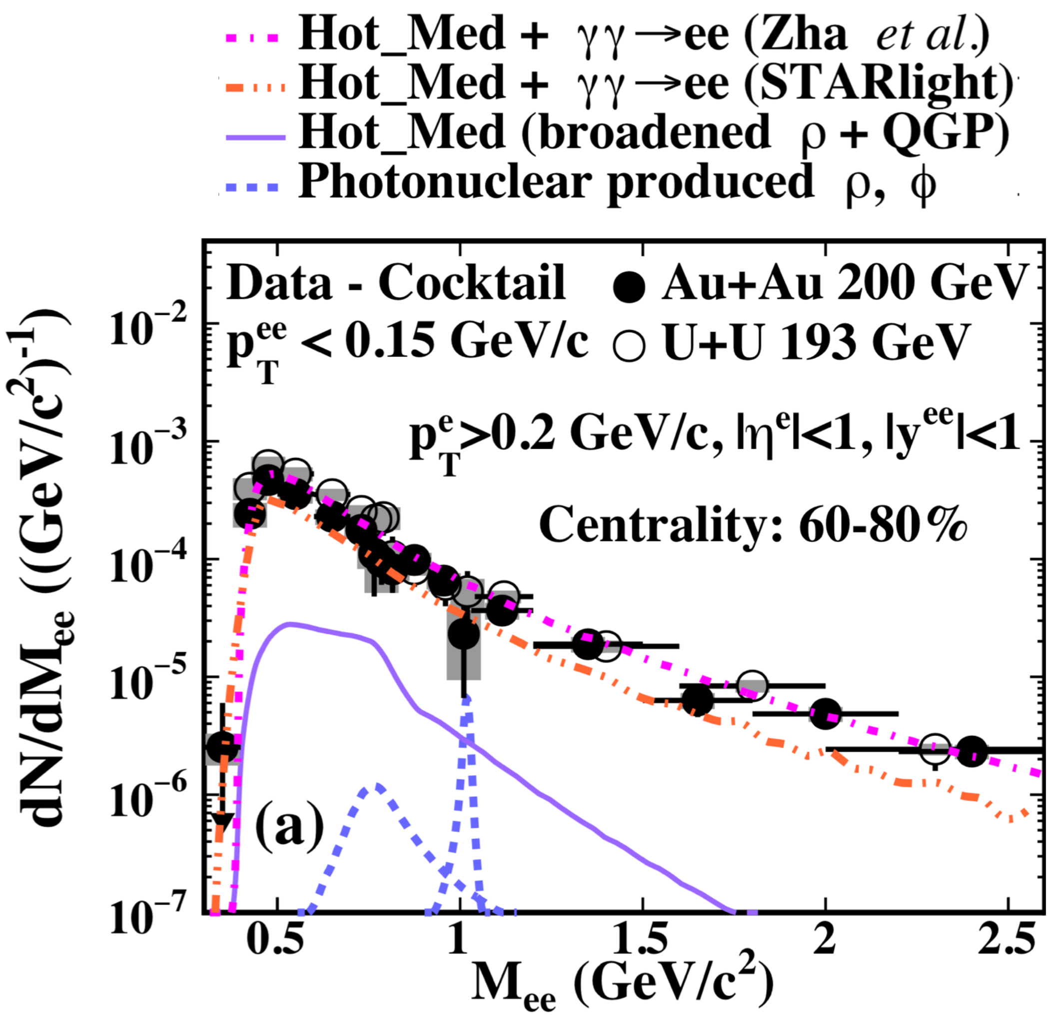
- Significant excess observed in $0.4 < M_{ee} < 2.6$ GeV/c^2
- Concentrated below $p_T \approx 0.15$ GeV/c

Models of photon-photon interactions



- Models **based on EPA method**: **No *b* dependence of p_T spectrum**
  - Model by Zha *et al.* *[W. Zha et al., PLB 781 (2018) 182]*
    - ✓ Woods-Saxon charge distribution
    - ✓ Consider dilepton production insides nucleus
  - STARlight *[S. Klein, PRC 97 (2018) 054903]*
    - ✓ Ignore dilepton production insides nucleus
- Model based on external classical field approach: **Consider *b* dependence of p_T spectrum** *[M. Vidovic et al., PRC 47 (1993) 2308]*
  - Model by Zha *et al.* *[W. Zha et al., arxiv: 1812.02820]*

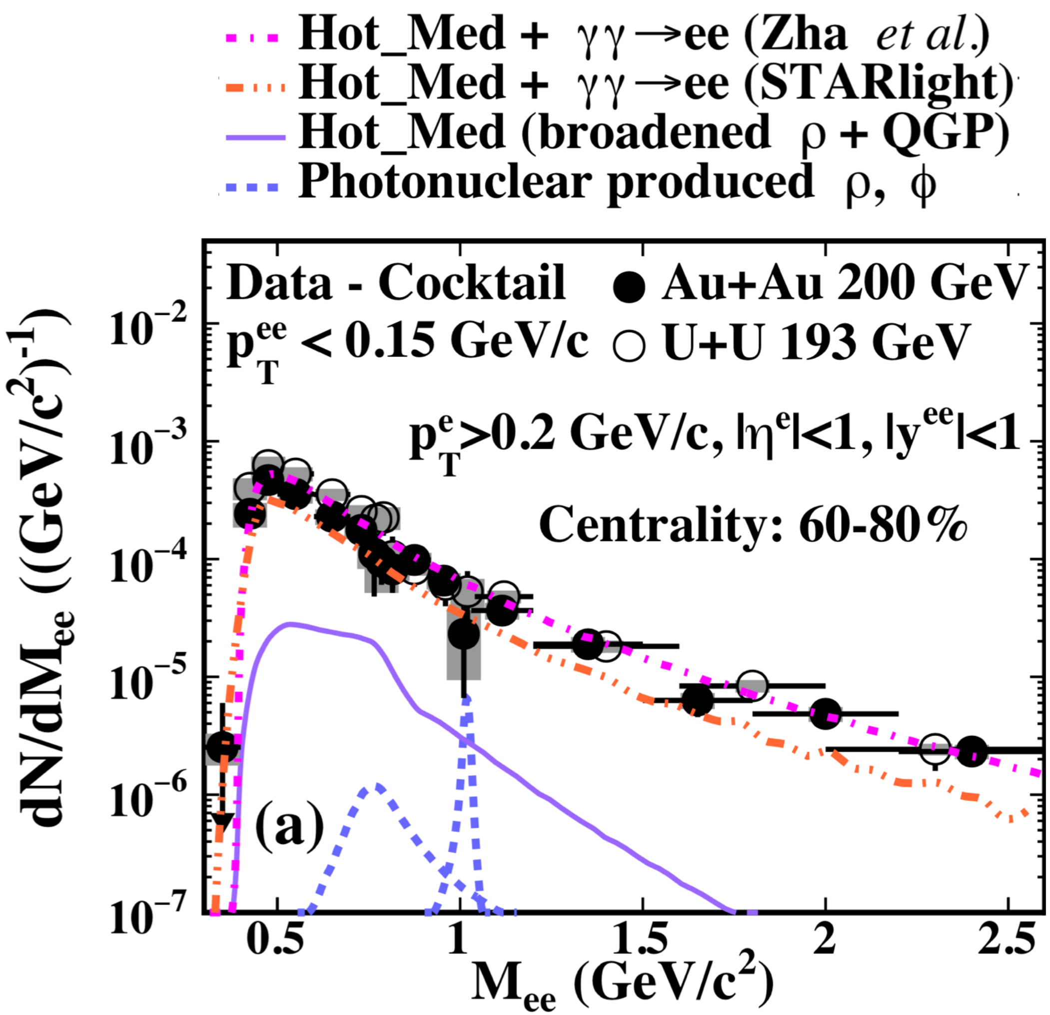
Origin of the low-p_T e^+e^- enhancement



STAR, PRL 121 (2018) 132301
W. Zha et al., PRC 97 (2018) 044910 , PLB 781 (2018) 182
S. Klein, PRC 97 (2018) 054903
R. Rapp, PRC 63 (2001) 054907

- Qualitatively described by two photon-photon interaction models
  - Broadened ρ model cannot count observed excess
  - Negligible photoproduction contributions

Origin of the low-p_T e^+e^- enhancement

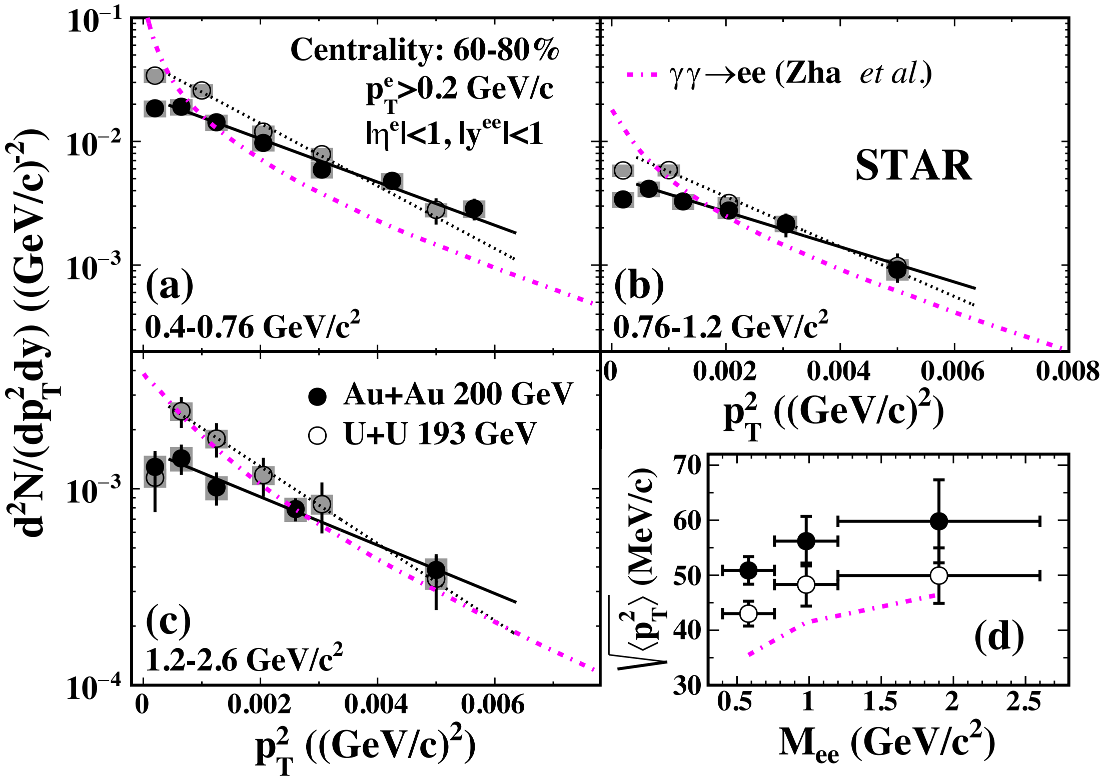


STAR, PRL 121 (2018) 132301
W. Zha et al., PRC 97 (2018) 044910 , PLB 781 (2018) 182
S. Klein, PRC 97 (2018) 054903
R. Rapp, PRC 63 (2001) 054907

- Qualitatively described by two photon-photon interaction models
  - Broadened ρ model cannot count observed excess
  - Negligible photoproduction contributions
- Incorporating dilepton production inside nucleus describes data better
  - χ^2/ndf: 19/15 vs. 32/15

p_T^2 distributions in 60-80% collisions

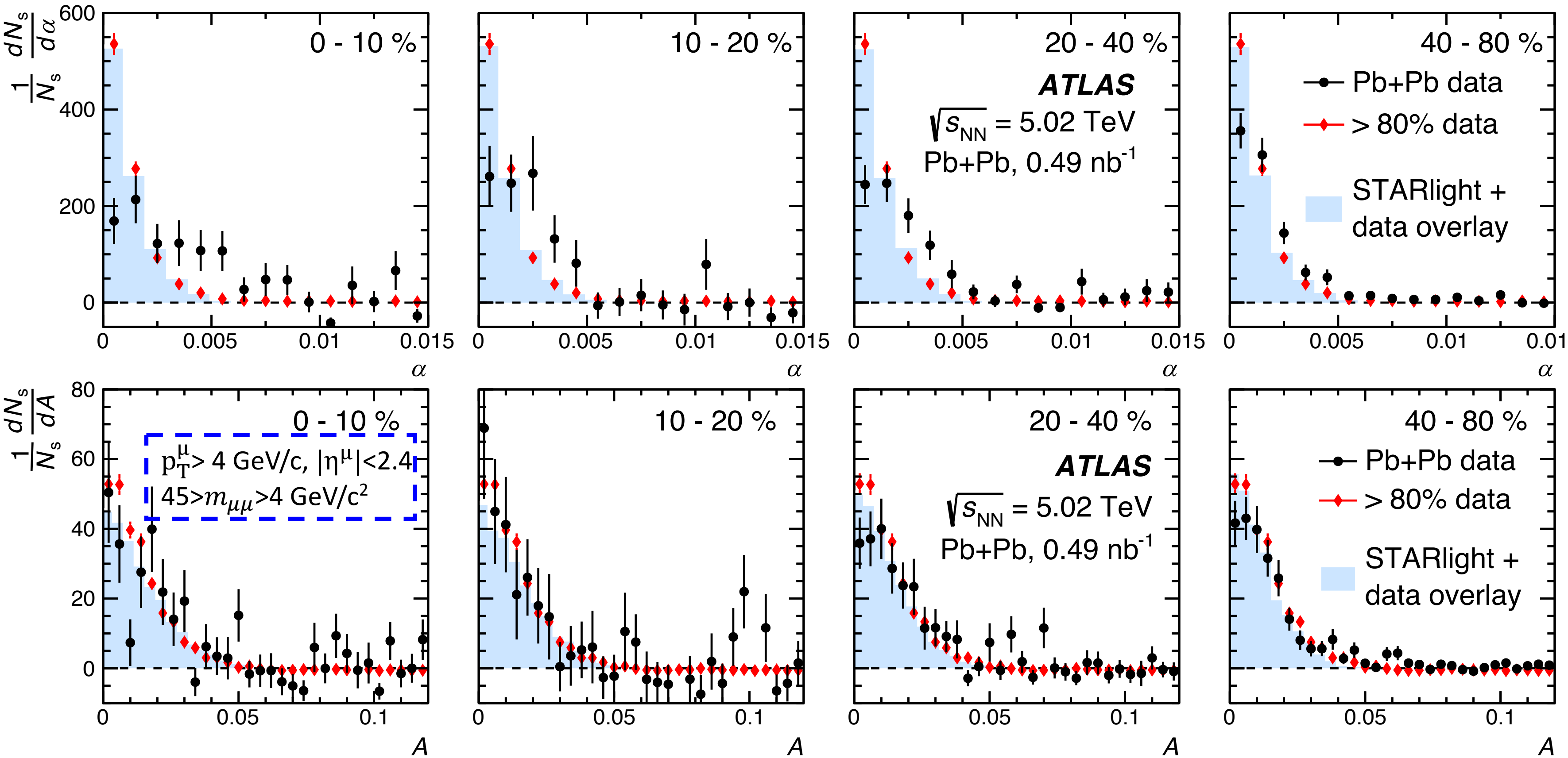
STAR, PRL 121 (2018) 132301
W. Zha et al., PLB 781 (2018) 182



- Models fail to describe p_T^2 distributions
- $\sqrt{< p_T^2 >}$
  - Mass and collision species dependence
  - Data are systematically higher than models

Dimuon pairs from two-photon interactions at LHC

ATLAS, PRL 121 (2018) 212301

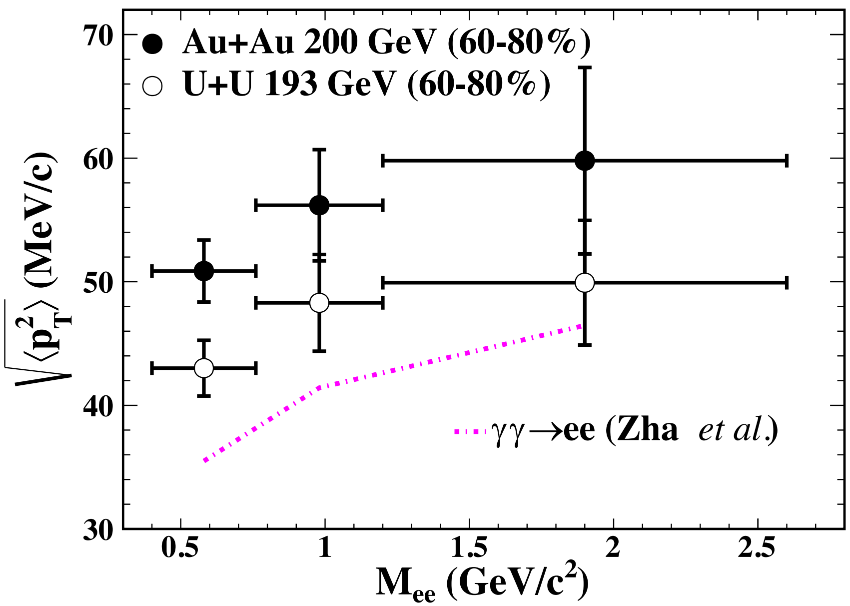


- ➢ Acoplanarity has strong centrality dependence

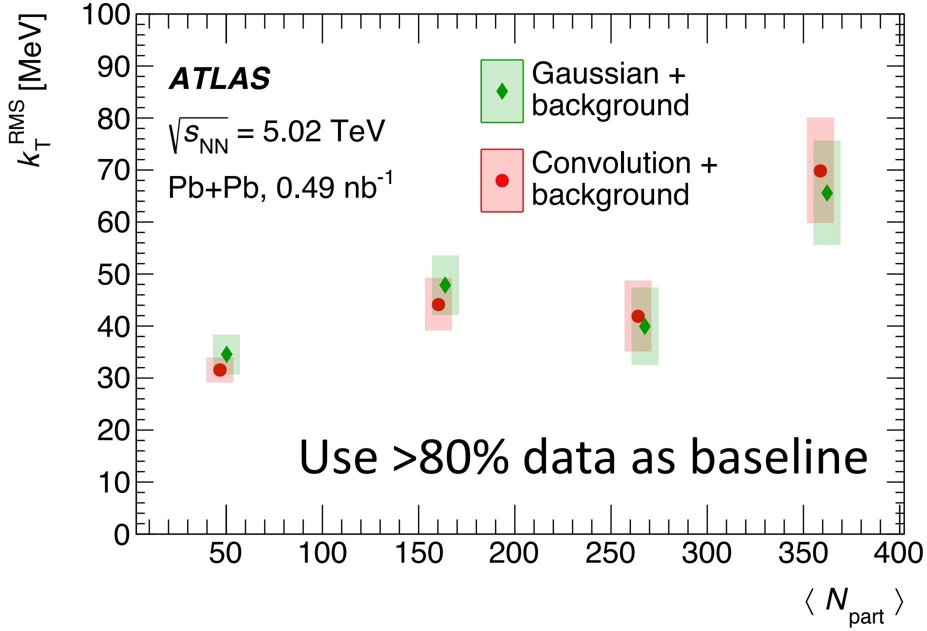
$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi}, \quad A \equiv \left|\frac{p_T^+ - p_T^-}{p_T^+ + p_T^-}\right|$$

p_T broadening for l^+l^- at RHIC and LHC

STAR PRL 121 (2018) 212301



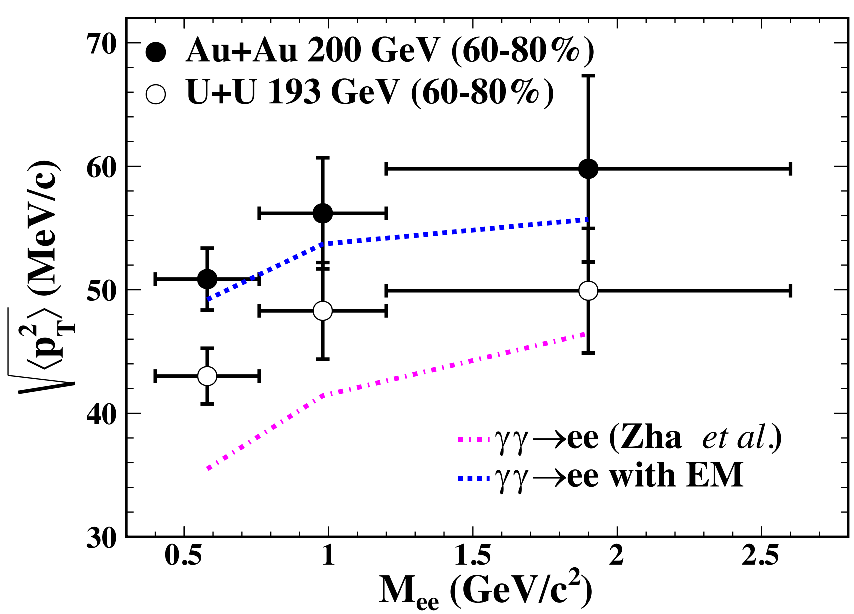
ATLAS, PRL 121 (2018) 212301



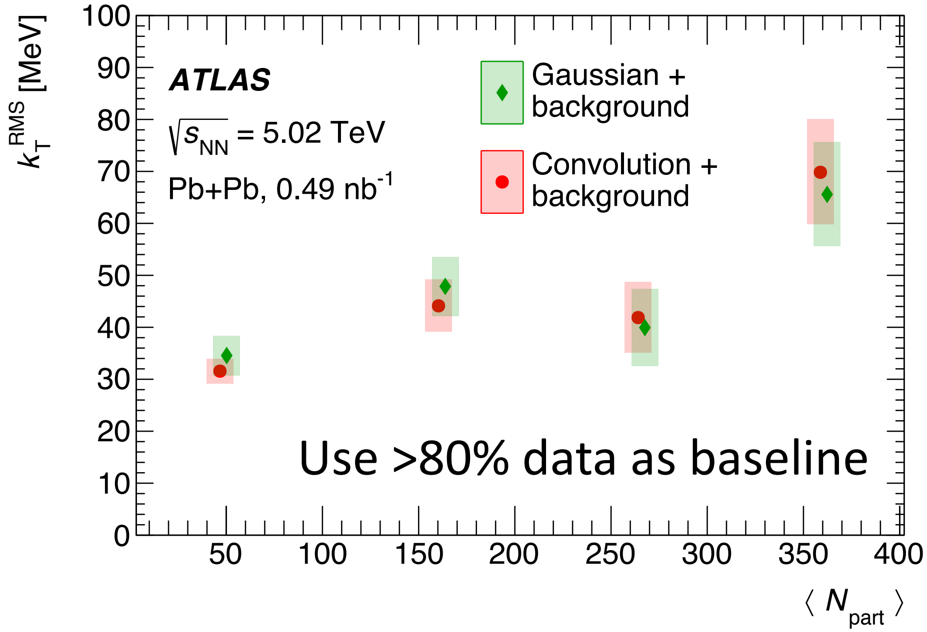
Use >80% data as baseline

p_T broadening from final stage?

STAR PRL 121 (2018) 212301



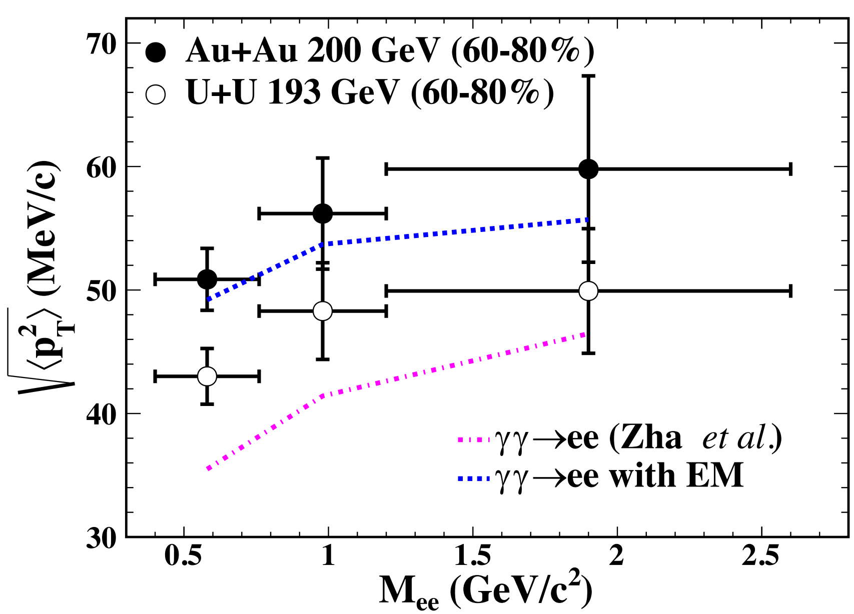
ATLAS, PRL 121 (2018) 212301



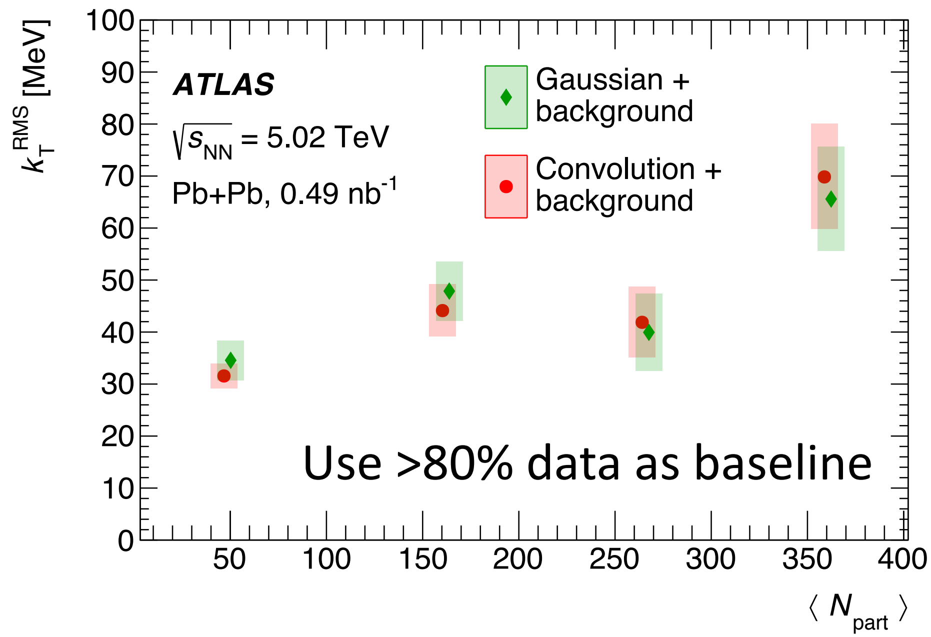
- Magnetic field trapped in QGP?
  - $e\bar{B}L \approx$ 30 MeV/c
- Multiple scattering with hot medium?
  - Supported by EPA model with NLO correction incorporating Coulomb scattering *[S. Klein et al. PRL 122 (2019) 132301]*

p_T broadening from final stage?

STAR PRL 121 (2018) 212301

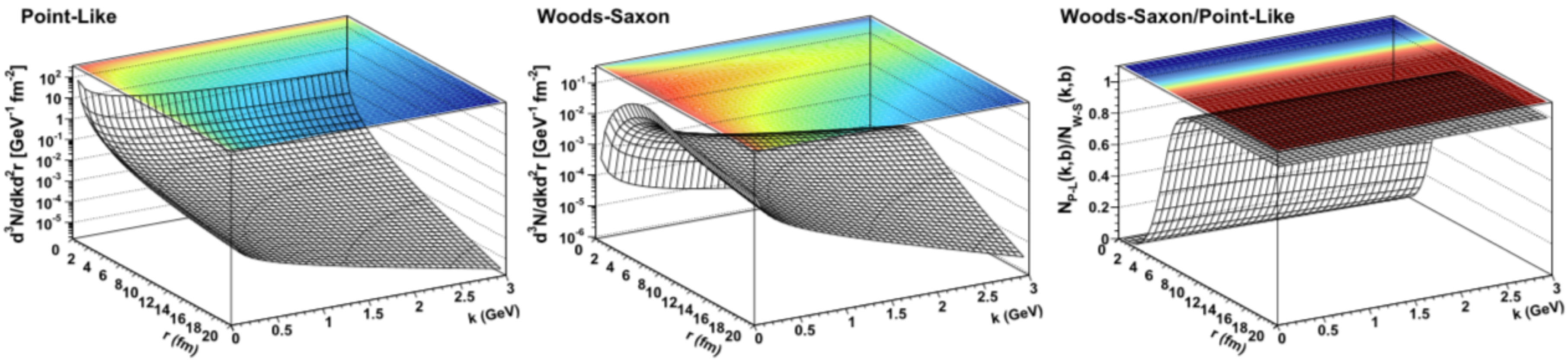


ATLAS, PRL 121 (2018) 212301



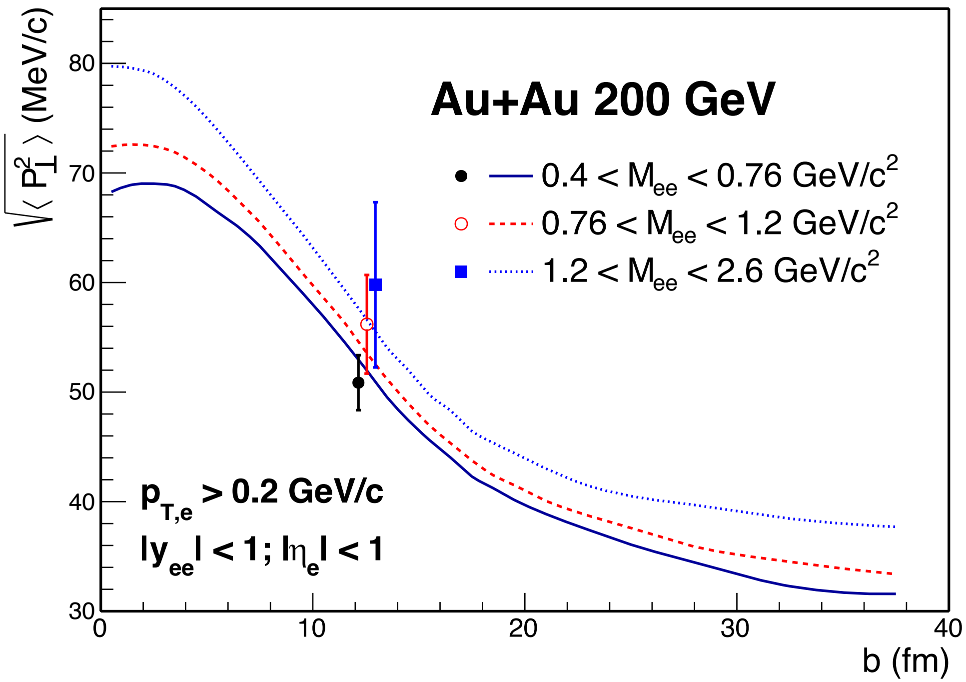
- Magnetic field trapped in QGP?
  - $e\bar{B}L \approx 30$ MeV/c
- Multiple scattering with hot medium?
  - Supported by EPA model with NLO correction incorporating Coulomb scattering *[S. Klein et al. PRL 122 (2019) 132301]*
- Assume NO *b* dependence for the base lines

Models of photon-photon interactions



- Models based on EPA method: **No *b* dependence of p_T spectrum**
  - Model by Zha *et al.* *[W. Zha et al., PLB 781 (2018) 182]*
    - ✓ Woods-Saxon charge distribution
    - ✓ Consider dilepton production insides nucleus
  - STARlight *[S. Klein, PRC 97 (2018) 054903]*
    - ✓ Ignore dilepton production insides nucleus
- Model based on external classical field approach: **Consider *b* dependence of p_T spectrum** *[M. Vidovic et al., PRC 47 (1993) 2308]*
  - Model by Zha *et al.* *[W. Zha et al., arxiv: 1812.02820]*

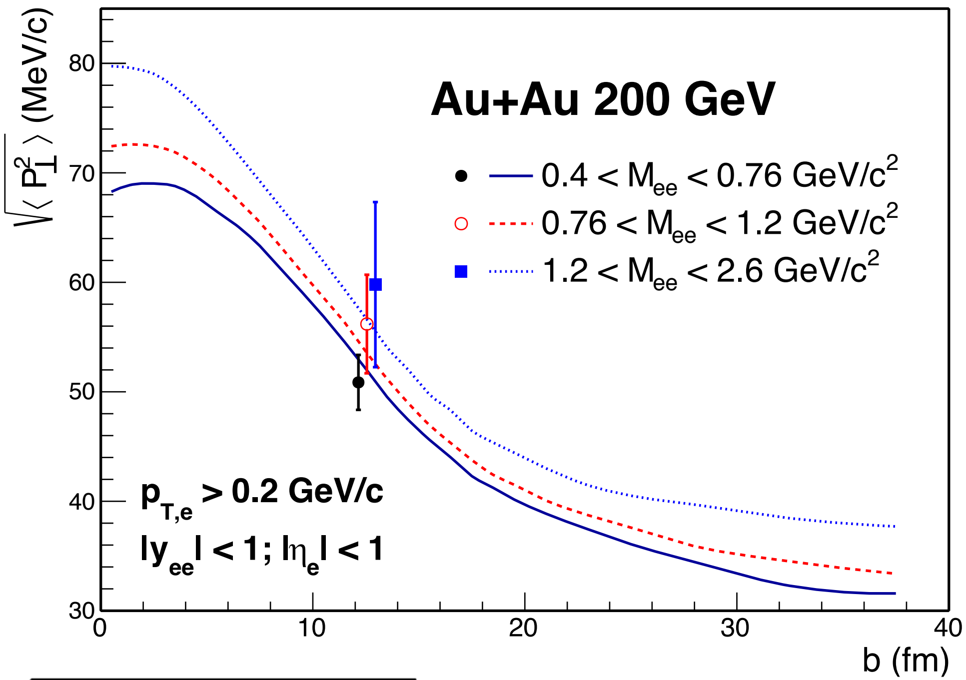
p_T broadening from initial stage?



W. Zha et al., arxiv: 1812.02820

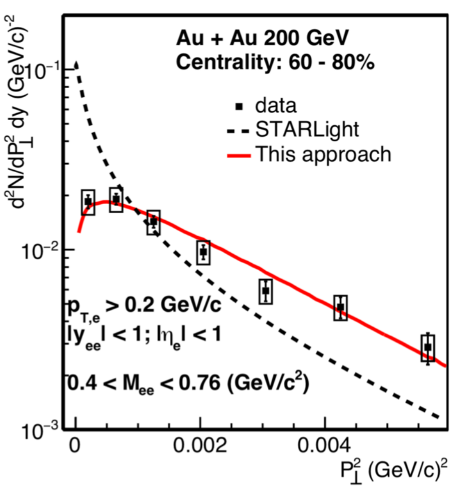
- Strong impact parameter dependence

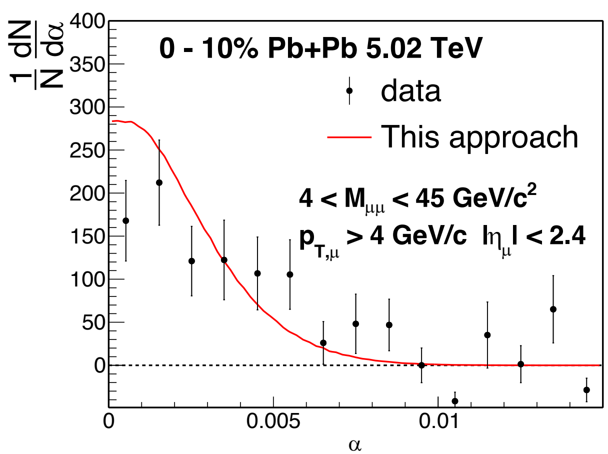
p_T broadening from initial stage?



W. Zha et al., arxiv: 1812.02820

- Strong impact parameter dependence

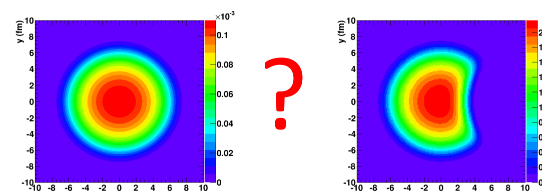




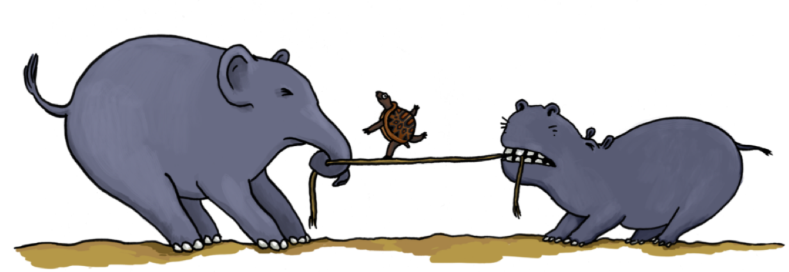
- Simultaneously describe STAR and ATLAS data without hot medium effects

Summary

- Electroweak bosons
  - N_{coll} scaling ⇒ consistent with geometry expectation
  - Data favor models with nPDFs at forward rapidity ⇒ high precision data could be used to constrain nPDFs
- Observed photon-nuclear and photon-photon interactions in non-UPC collisions.



  - Mechanism of initial photon-nuclear interaction
  - Origin of p_T broadening for two-photon produced l^+l^-
  - Need more help from theorists



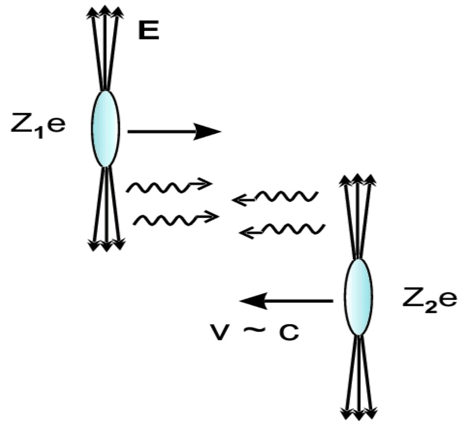
Backup

H. Kim, HP 18’

	EPPS16	EPS09	nCTEQ15	DSSZ12	HKN07	KA15
FT e-DIS	✓	✓	✓	✓	✓	✓
FT ν-DIS	✓	✗	✗#	✓	✗	✗
FT Drell-Yan	✓	✓	✓	✓	✓	✓
RHIC π^0	✓	✓	✓	✗	✗	✗
LHC W/Z	✓	✗	✗*	✗	✗	✗
LHC dijet	✓	✗	✗	✗	✗	✗
QCD order	NLO	LO & NLO	NLO	NLO	LO & NLO	NNLO
Kinematic cuts	$Q > 1.3$GeV	$Q > 1.3$GeV	$Q > 2$GeV $W > 3.5$GeV	$Q > 1$GeV	$Q > 1$GeV	$Q > 1$GeV
No data points	1811	929	740	1579	1241	1479
No free param.	20	15	16	25	12	16
χ^2/dof	1.00	0.79	0.81	0.99	1.21	1.15
Error analysis	Hessian	Hessian	Hessian	Hessian	Hessian	Hessian
Tolerance $\Delta\chi^2$	52	50	35	30	13.7	1?
Proton baseline	CT14NLO	CTEQ6.1	CTEQ6.1-like	MSTW2008	MRST1998	JR09
Heavy-quark eff.	✓	✗	✓	✓	✗	✗
Flavour sep.	✓	✗	✓ (val.)	✗	✗	✗
Reference	[1612.05741]	[0902.4154]	[1509.00792]	[1112.6324]	[0709.3038]	[1601.00939]

In a separate dedicated analysis [PRL106, 122301, (2011), 1012.0286; PRD80, 094004, (2009), 0907.2357]
* See a reweighting study [EPJC77, 488 (2017), 1610.02925]

Coherent photons as “partons” in heavy-ion collisions

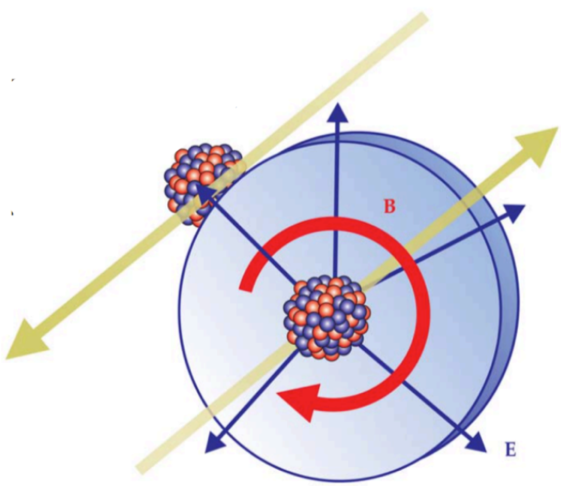


Coherent limitation: $Q^2 \leq 1/R^2$ => quasi-real !

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

$$Q^2 = \frac{\omega^2}{\gamma^2} + q_T^2$$
$$\omega \leq \omega_{max} \sim \frac{\gamma}{R}$$
$$q_T \leq 1/R$$

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



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

The extent of photons swarming about the ions:

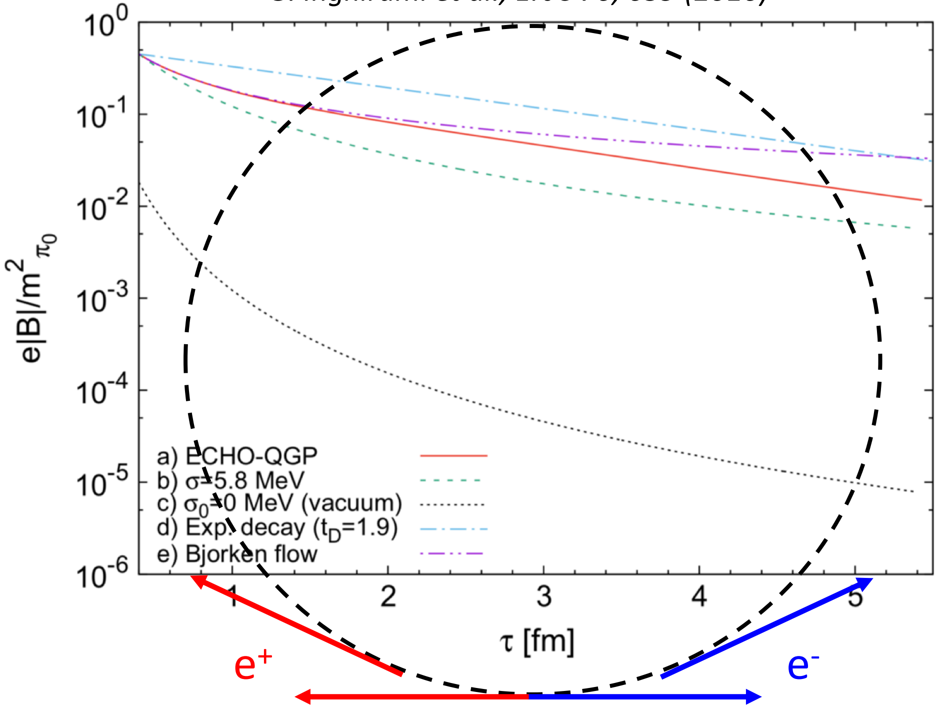
The radius of nuclear matter $R_{Nuc} \sim 6.3$ fm (Au)

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

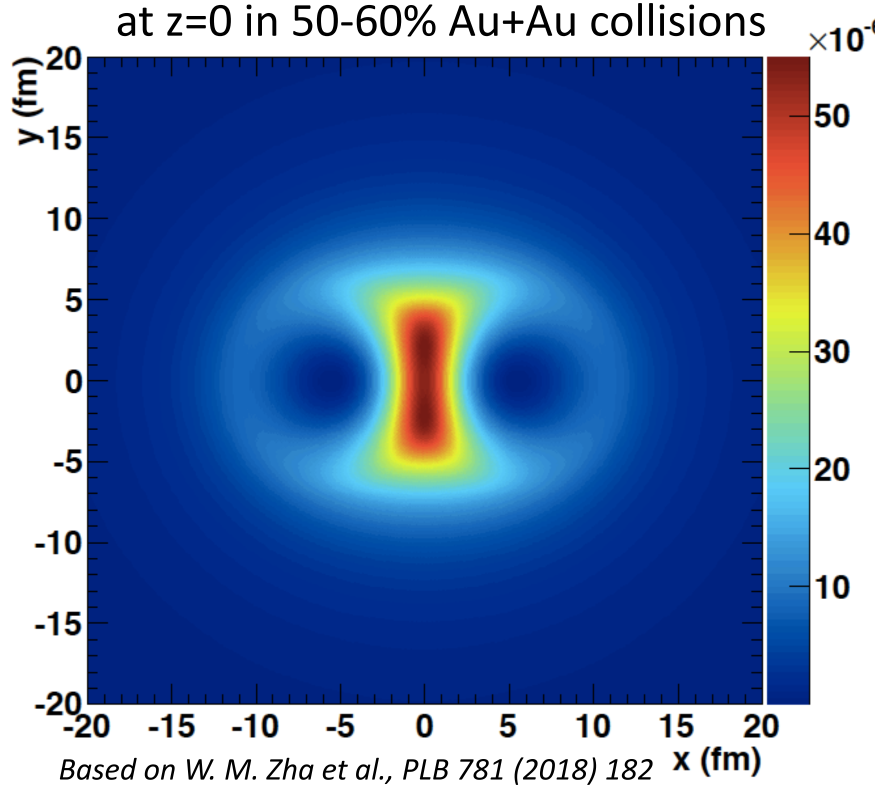
Take the photoproduction of ρ (Au+Au 200 GeV) in UPC as example: $<R_{producton}> \sim 40$ fm

Sensitivity to residual magnetic field?

G. Inghirami et al., EPJC 76, 659 (2016)



Example of e$^+$e$^-$ spatial distributions at z=0 in 50-60% Au+Au collisions



Based on W. M. Zha et al., PLB 781 (2018) 182

- To account for the effect of the time-dependent magnetic field on average, the model assumes that all the e$^+$e$^-$ pairs traverse 1 fm through a magnetic field of 10^{14} T perpendicular to the beam line
  - The net effect of this approach is close to $\int eB(t)cdt = e\bar{B}L$
  - $e\bar{B}L \approx$ 30 MeV/c, the extreme pair p_T increase: $2e\bar{B}L \approx$ 60 MeV/c