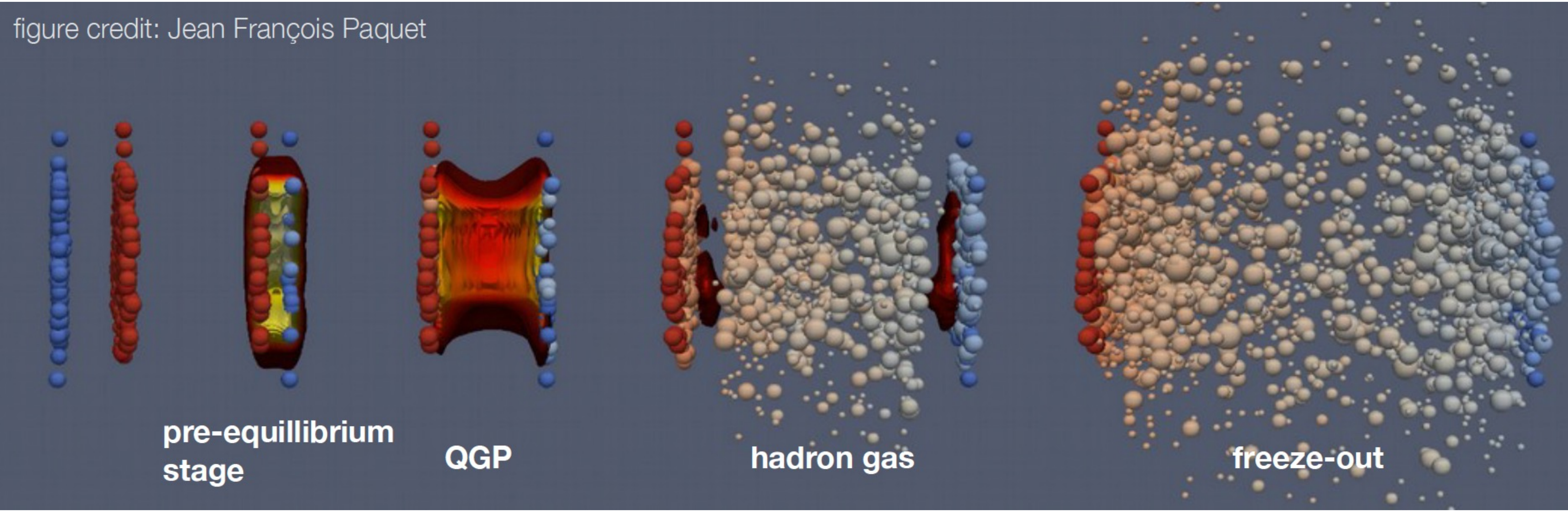
相对论重离子碰撞中的光子探针

杨 驰

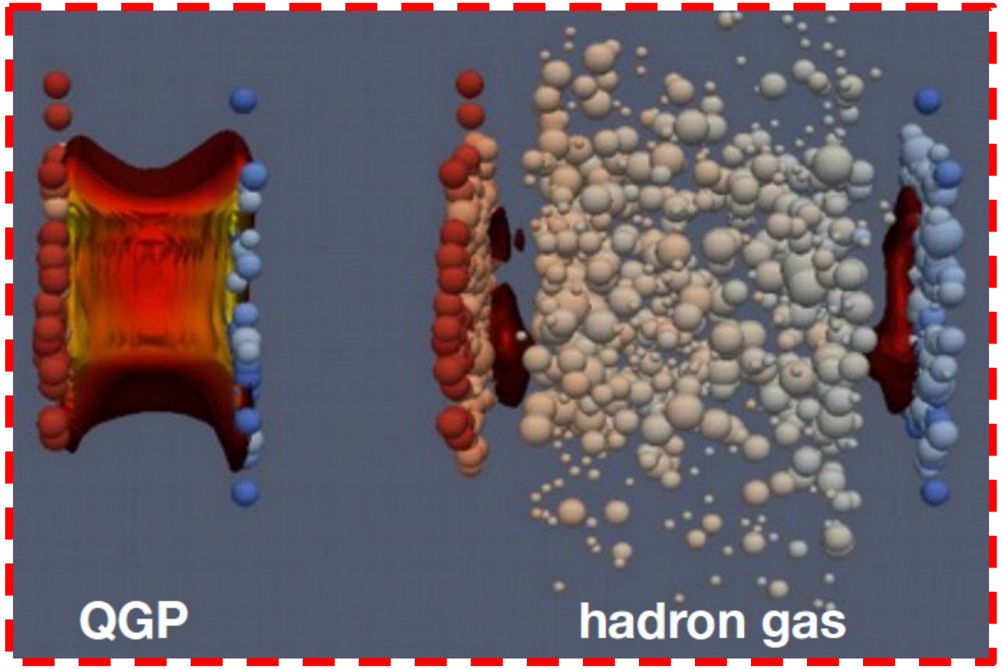
山东大学

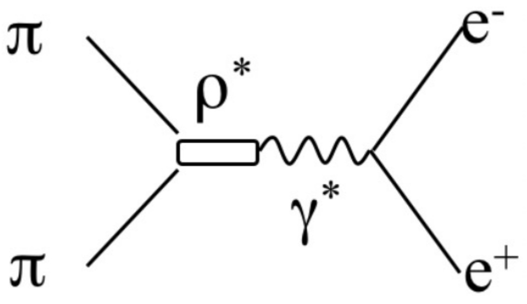
Evolution of relativistic heavy-ion collision system



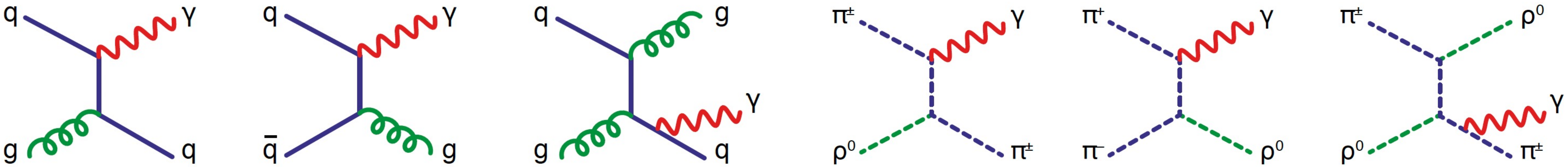
(Virtual) photons/dileptons productions HHICs

"Thermal sources"



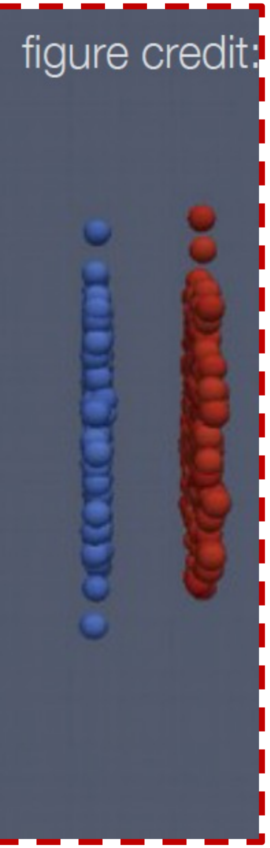


Direct photon:
photons not from hadron decay

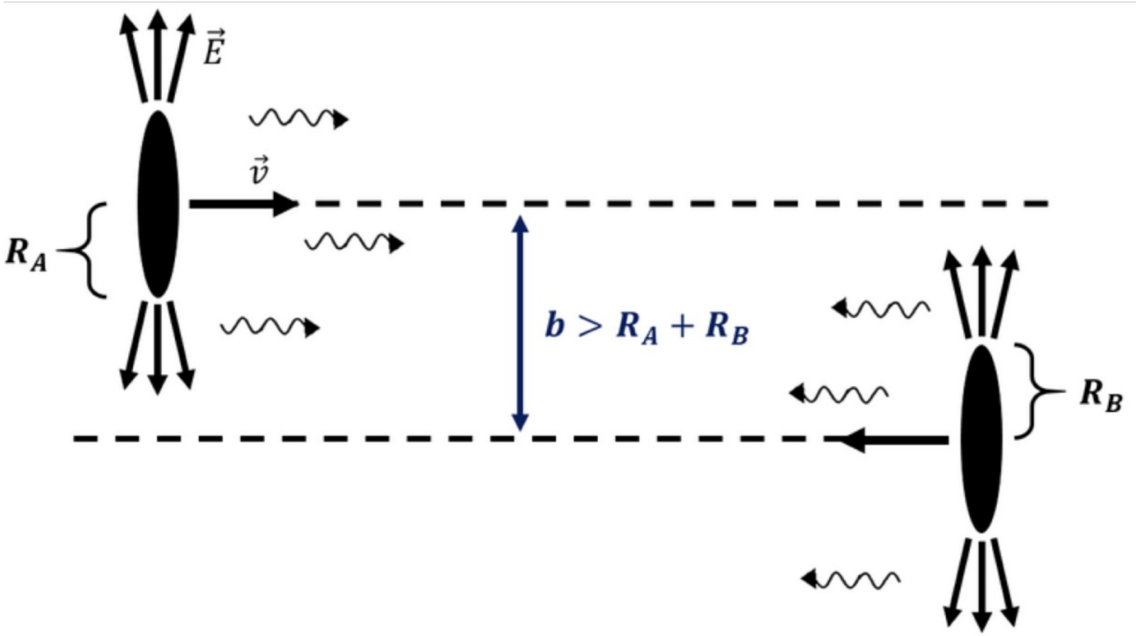


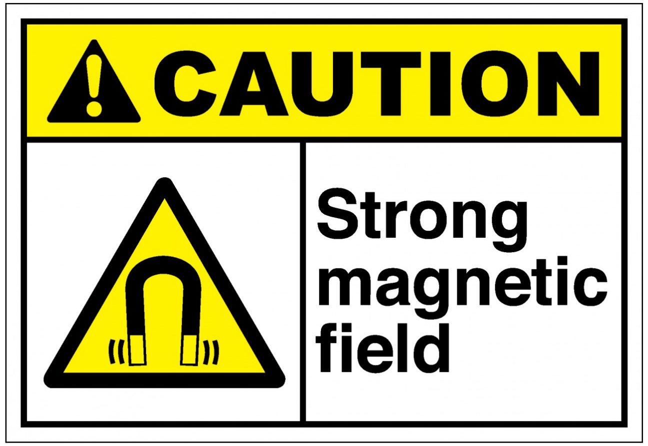
γ: could be either photon or virtual photon (important to direct virtual photon measurement)

Polarized (quasi-real) photons in UPCs



"Collisions w/o colliding"





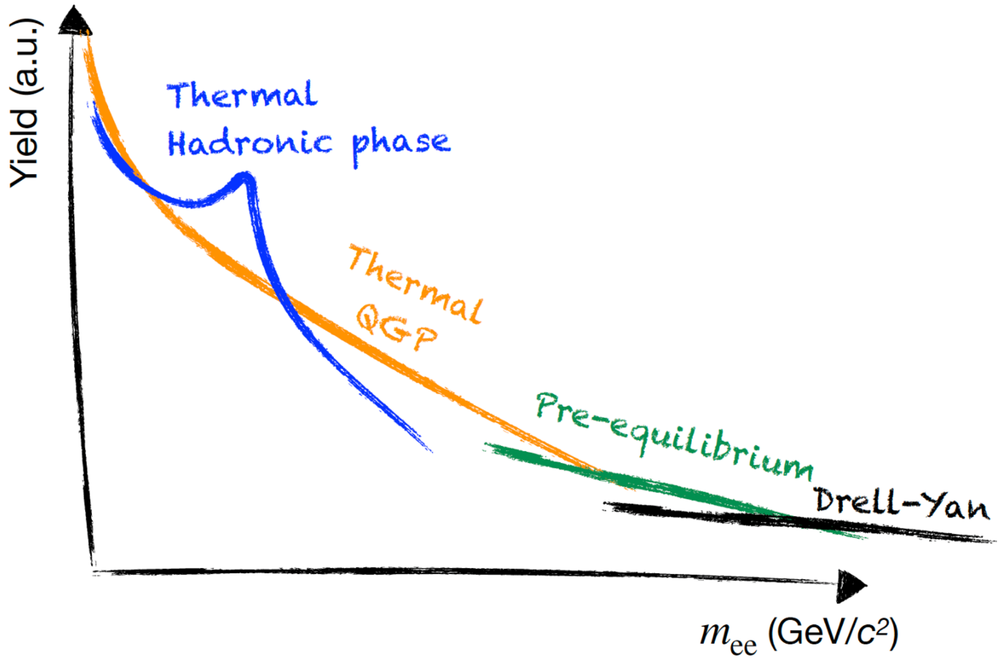
Global polarization study guide us to study our previous observables in spin and polarization dimensions

梁作堂、王新年 PRL2005, PLB2005

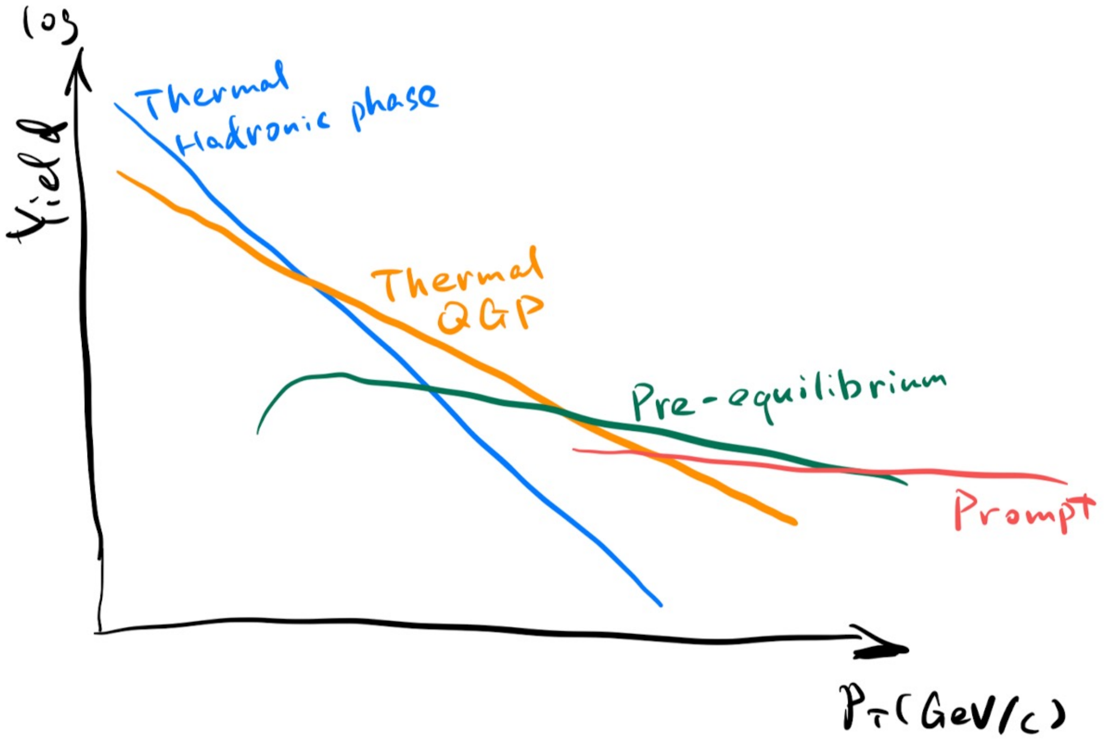
Chronometer and thermometer

Yield and Slope of EM probes： sensitive to system evolution and temperature

Schematic view of dielectron
invariant mass spectrum



Schematic view of direct photon
p_T spectrum

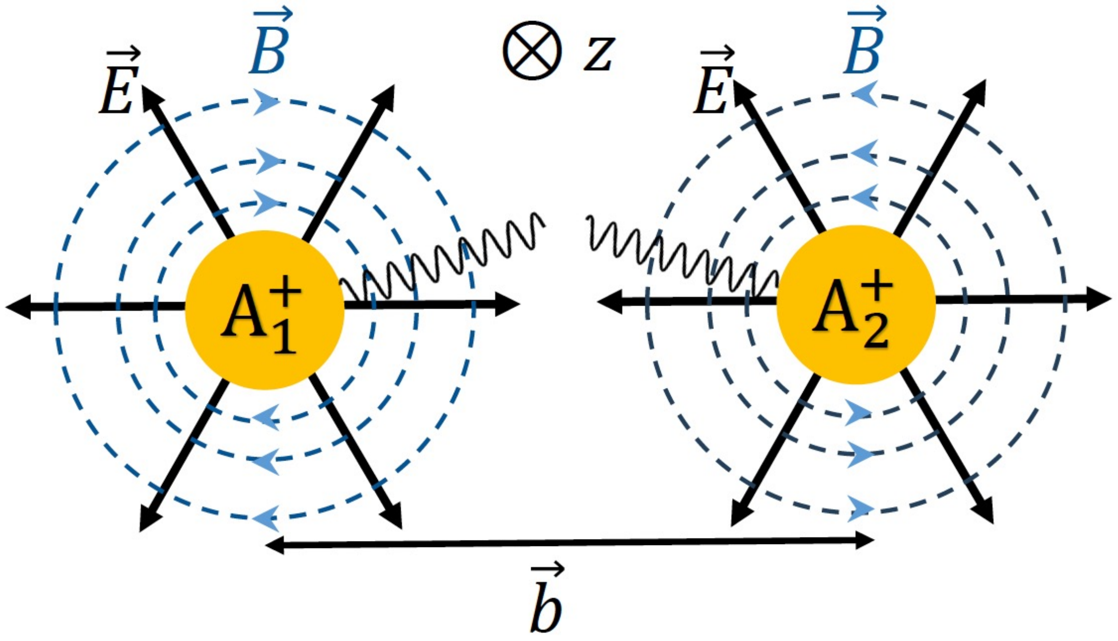


Late emission ⟵ Early emission

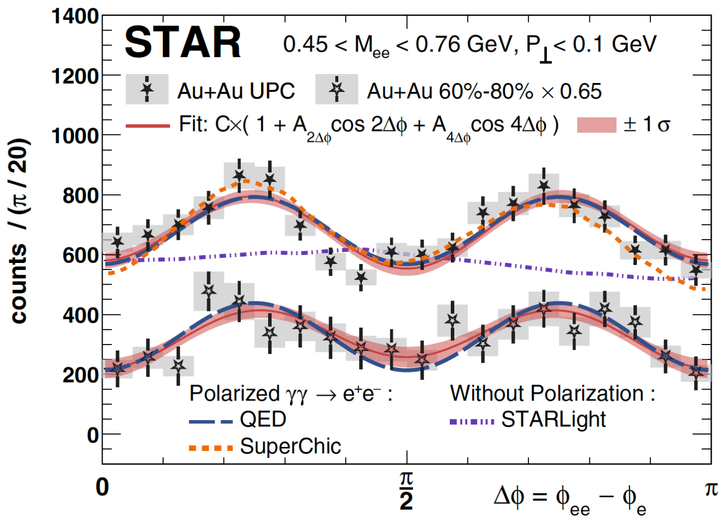
Late emission ⟵ Early emission

Temperature: one of the most important properties of the HOT and dense medium

Spin-induced OAM Effect



STAR, PRL 127, 052302 (2021)

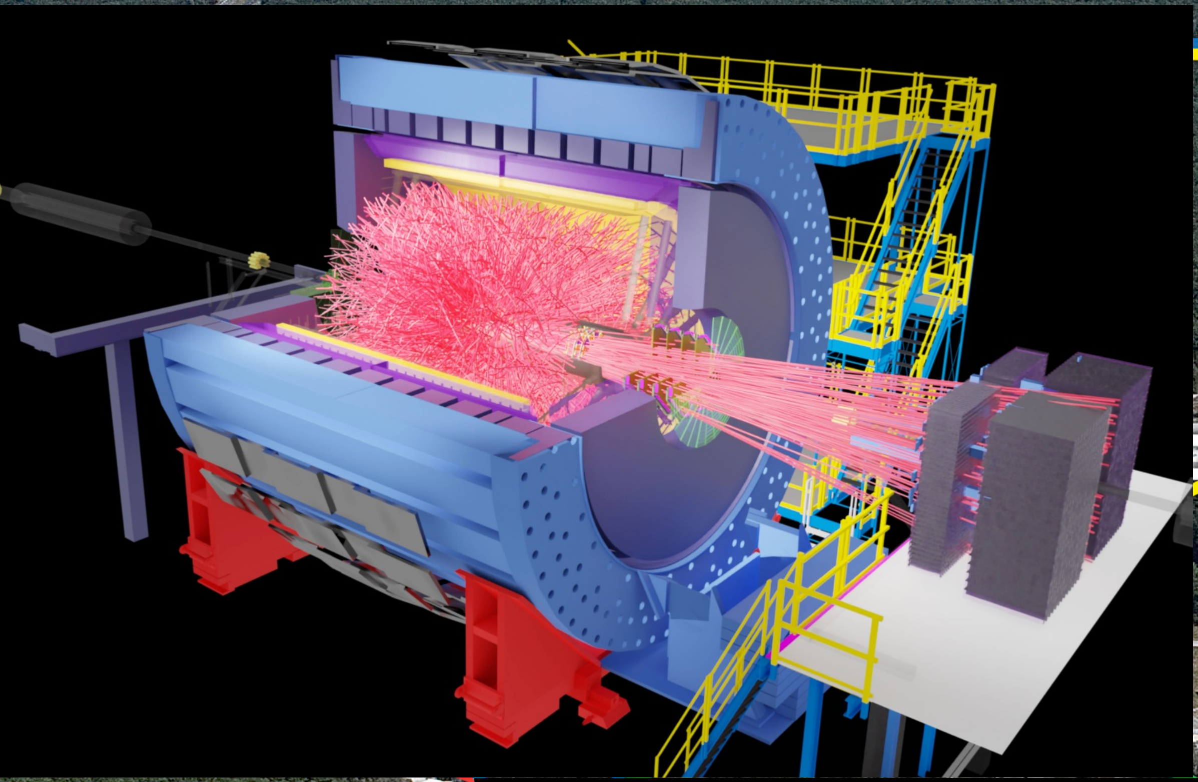


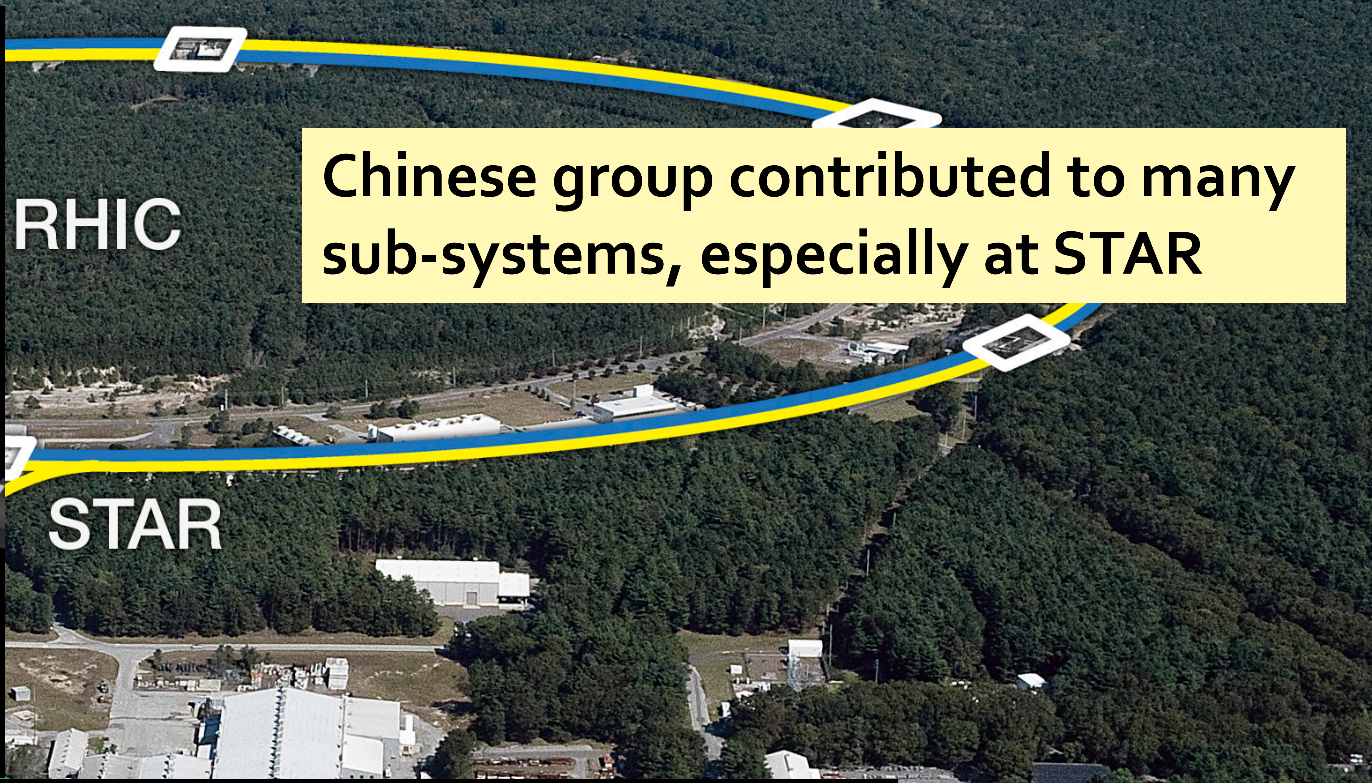
林硕、周雅瑾报告
佛山厅，周三 17:15-17:30

- **Quasi-real photons are linearly polarized, confirmed by observation of $\cos(4\Delta\phi)$ angular modulation in Breit-Wheeler process**

C. Li, J. Zhou, Y.-J. Zhou, PLB 795, 576 (2019)
C. Li, J. Zhou, Y.-J. Zhou, PRD 101, 034015 (2020)
E. J. Williams Phys. Rev. 45, 729 (1934)
K. F. Weizsacker, Z. Physik, 612 (1934)

	Ultraperipheral				Peripheral	
	Measured	QED	SC	SL	Measured	QED
$\lvert A_{4\Delta\phi}\rvert$ (%)	16.8 ± 2.5	16.5	19	0	27 ± 6	34.5
$\lvert A_{2\Delta\phi}\rvert$ (%)	2.0 ± 2.4	0	5	5	6 ± 6	0
$\sqrt{\langle P_\perp^2 \rangle}$ (MeV)	38.1 ± 0.9	37.6	35.4	35.9	50.9 ± 2.5	48.5





Chinese group contributed to many sub-systems, especially at STAR

STAR	TOF	MTD	HFT	iTPC	eTOF	EPD	FST	FTT	FCS
CCNU			✅		✅	✅			
FDU	✅		✅	✅		✅			✅
IMP			✅			✅	✅		
SDU				✅			✅	✅	✅
THU	✅	✅			✅				
USTC	✅	✅		✅	✅	✅		✅	

In Hadronic Heavy-Ion Collisions

Fundamental QGP properties

Temperature

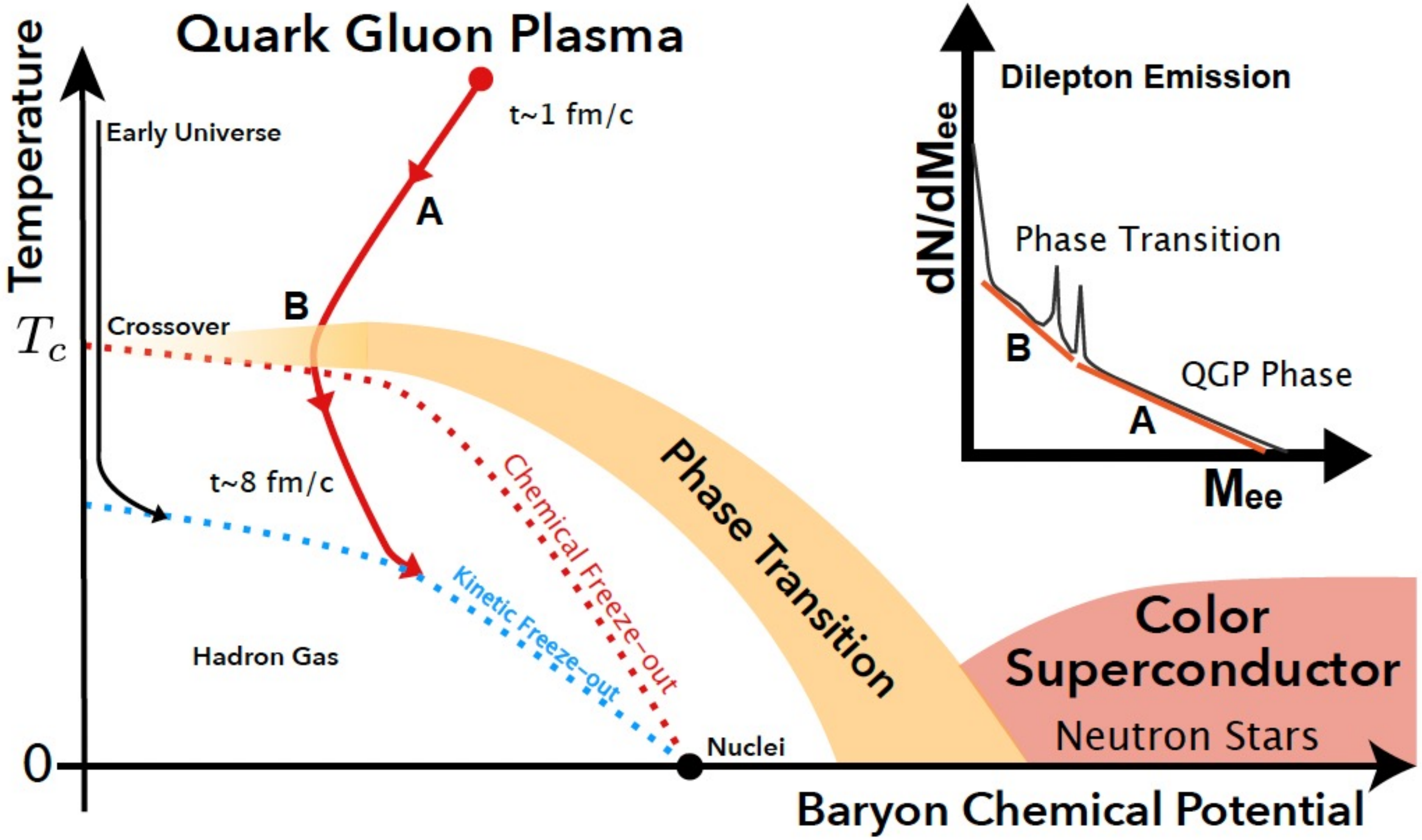
Life time

Evolution

Collectivity

Access the QCD phase diagram with temperature

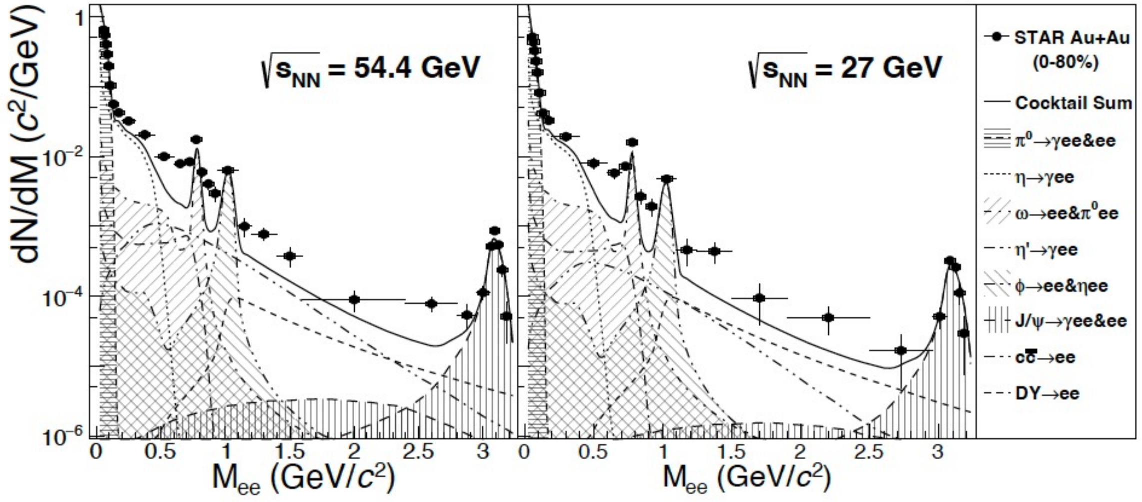
STAR, Nature Communications 16 (2025) 9098

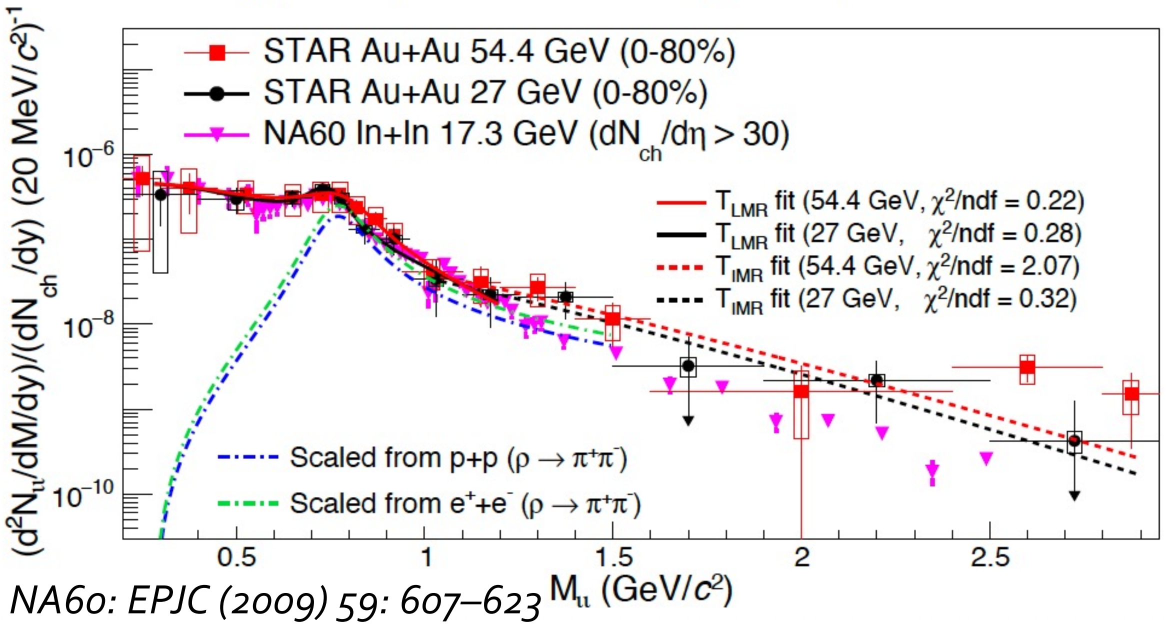


- **A (IMR):** above T_{pc}, emitted from partonic phase
- **B (LMR):** close or above T_{pc}?

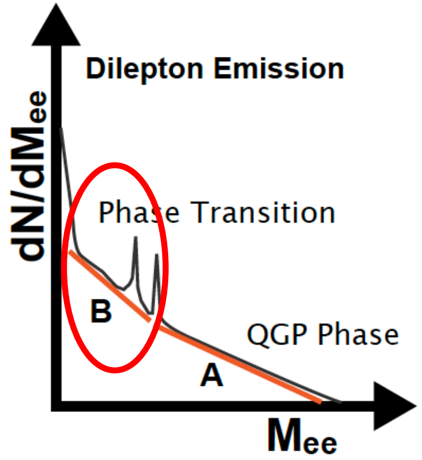
Thermal dileptons in LMR

STAR, Nature Communications 16 (2025) 9098





NA60: EPJC (2009) 59: 607–623
HotQCD: PLB 795 (2019) 15-21



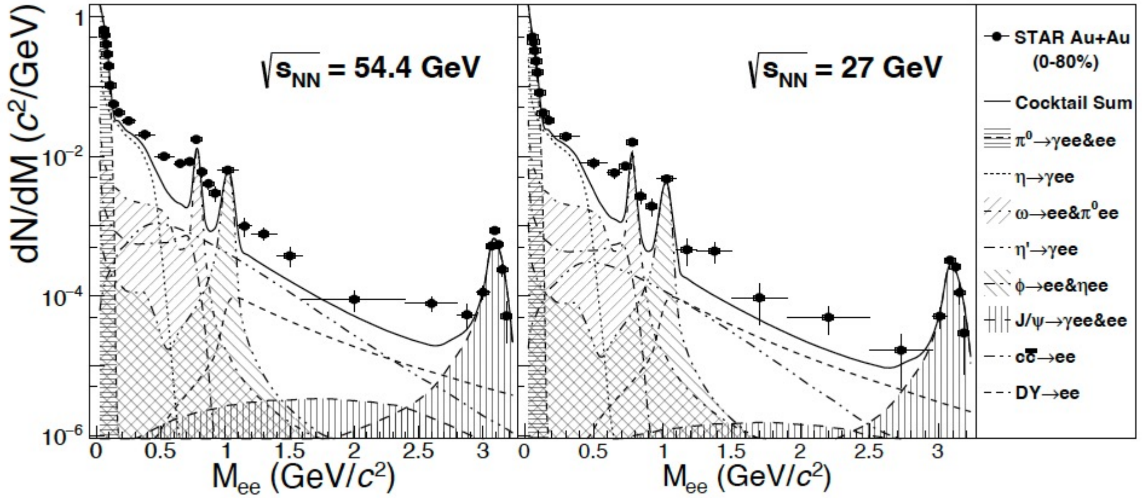
fitting function: $(a*BW+b*M^{3/2})*e^{-M/T}$

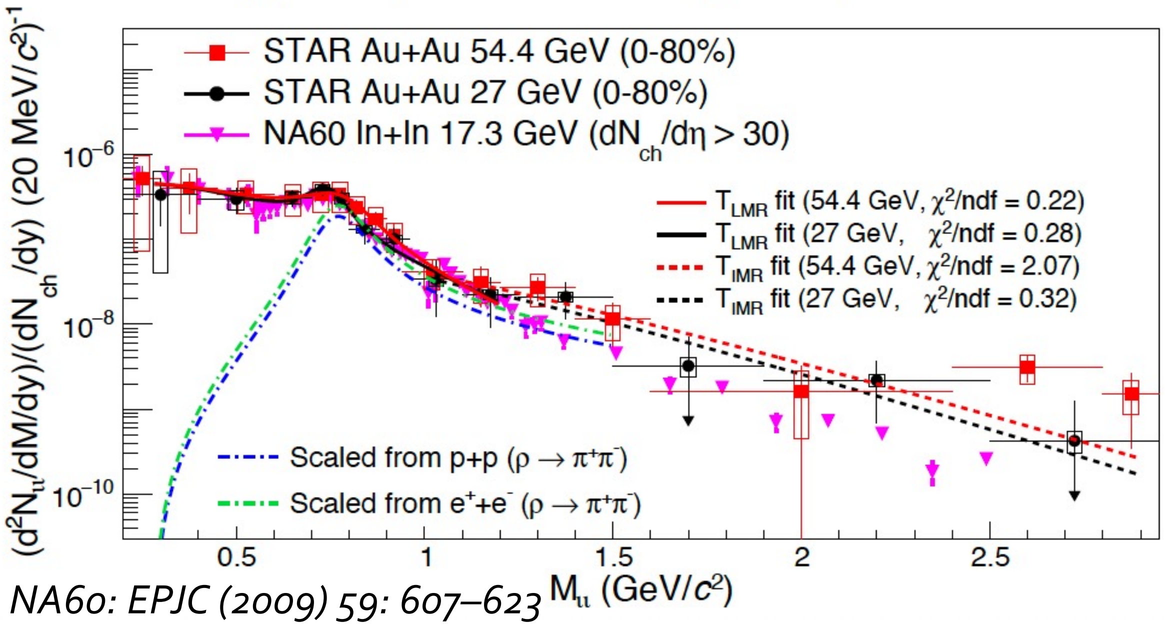
- Excess dielectron spectra of 27 and 54.4 GeV Au+Au collisions and NA60 In+In collisions are similar
- T is similar despite significant differences in collision energy and system size
- T_{LMR} around the pseudo critical temperature T_{pc} (156 MeV)

27 GeV: 165 ± 20 (stat.) ± 21 (syst.) MeV
54.4 GeV: 178 ± 15 (stat.) ± 13 (syst.) MeV

Thermal dileptons in IMR

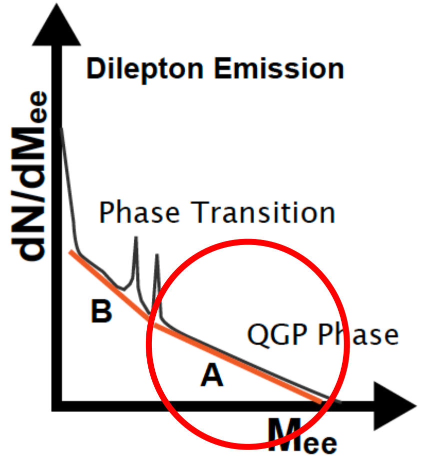
STAR, Nature Communications 16 (2025) 9098





NA60: EPJC (2009) 59: 607–623

HotQCD: PLB 795 (2019) 15-21



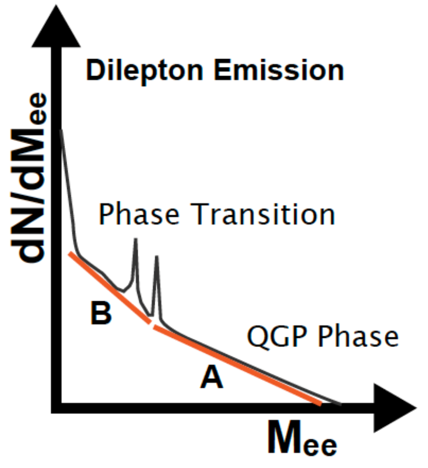
fitting function: $M^{3/2} * e^{-M/T}$

- Thermal dielectrons is the major source in IMR
- T in 27 and 54.4 GeV are consistent with each other
- $T > T_{pc}$: emission dominantly from QGP
- QGP is hotter at RHIC than that in NA60 (205+/-12 MeV)

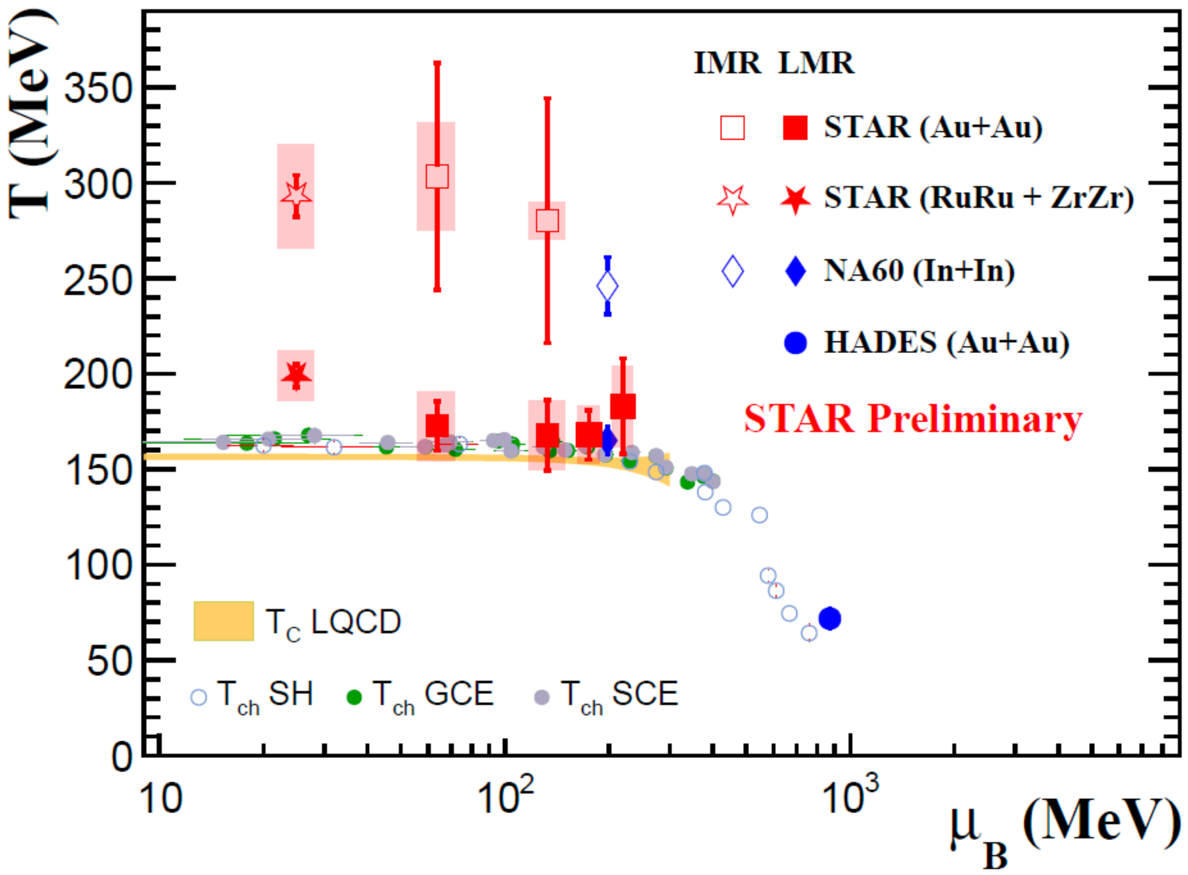
27 GeV: 274 ± 65 (stat.) $\pm$ 10 (syst.) MeV

54.4 GeV: 287 ± 70 (stat.) $\pm$ 34 (syst.) MeV

Temperature v.s. μ_B



54.4 GeV + 27 GeV + 19.6 GeV + 14.6 GeV +isobar



STAR, Nature Communications 16 (2025) 9098
NA60: EPJC (2009) 59 607–623
HADES: Nature Physics 15, 1040-1045 (2019)
Tch SH: P. Braun-Munzinger et al. Nature 561, 321-330 (2018)
Tch GCE/SCE: STAR PRC 96, 044904 (2017) c

T_{LMR} at 200 GeV > T_{pc} and T_{ch}:

- QGP radiation?
- non-equilibrium contribution?

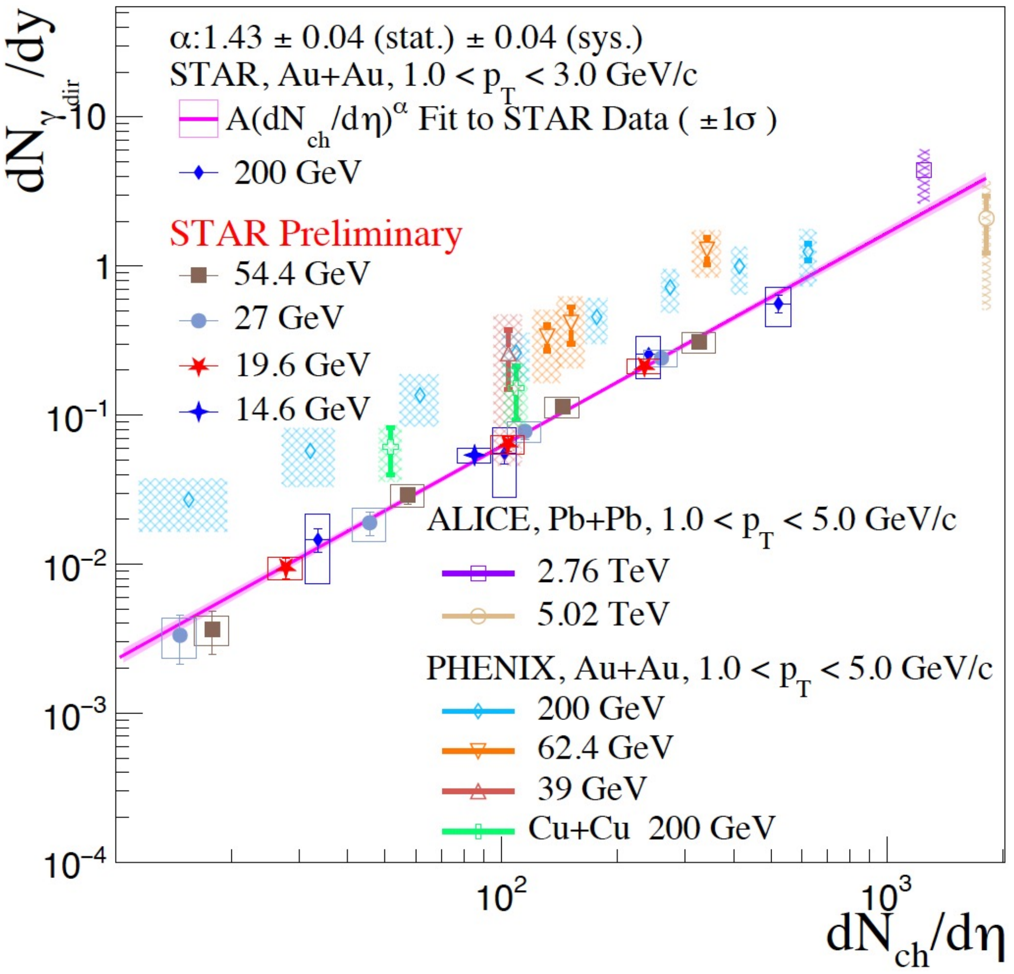
T_{LMR}:

- Close to T_{ch} and T_{pc}
- Dielectrons dominantly emitted around phase transition

T_{IMR}:

- Higher than T_{LMR}, T_{ch} and T_{pc}
- Dielectrons dominantly emitted from QGP phase

Direct photon productions at RHIC



- ***dN_{ch} /dη* scaling** over centralities and energies （200GeV to 14.6 GeV）
- Indicating **similar emission source and properties**
- Can be linked to the search of CEP?

包贤文报告
佛山厅，周四 17:15-17:30

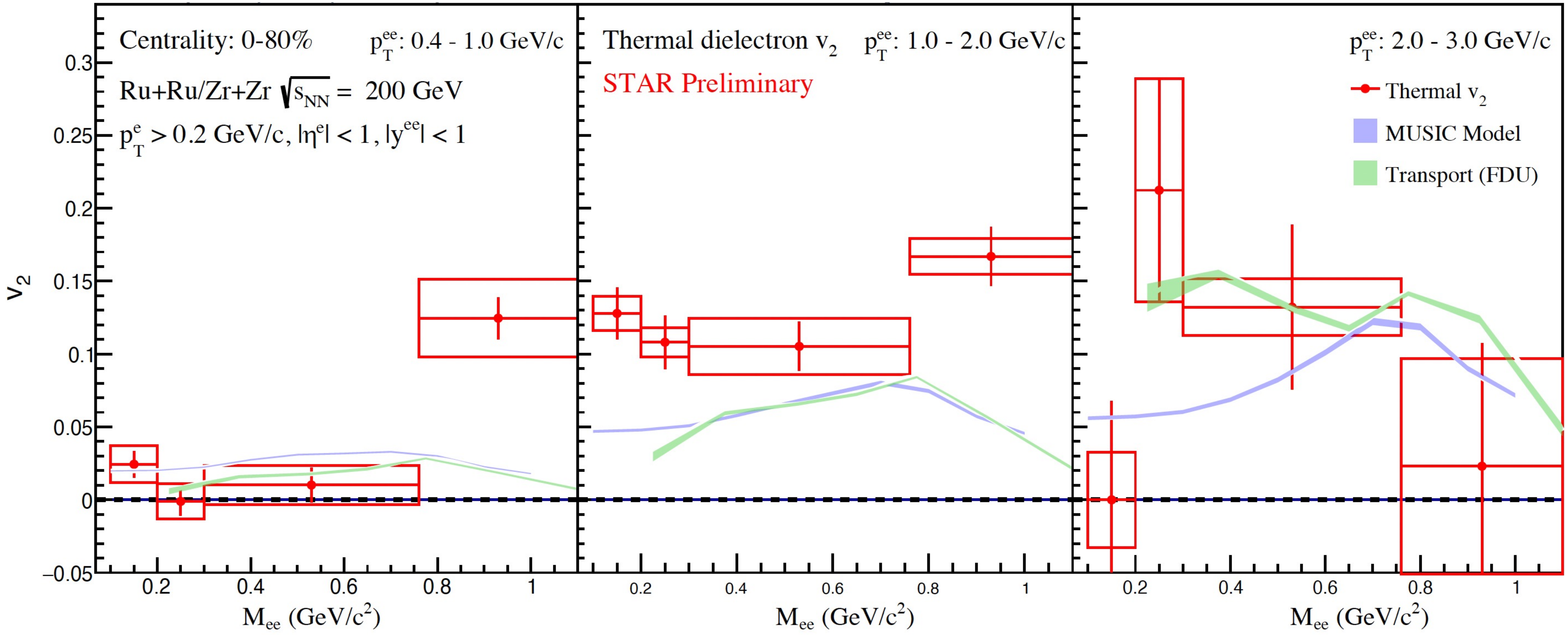
"A puzzle in a puzzle"

- Tension observed between STAR and PHENIX from QM14
- Need to solve/confirm this tension firstly
- Can we measure direct photon v_2 at STAR?

Dielectron and thermal dielectron v_2

包贤文报告
佛山厅，周四 17:15-17:30

- MUSIC model, Xiangyu-Wu et al, arXiv: 2511.08773
- Transport (FDU), from private communication with Kaijia Sun



None-zero thermal dielectron v_2

Theoretical calculations should simultaneously describe direct photons and dileptons

In Ultra-Peripheral Collisions

Fundamental QED process and nuclear tomography

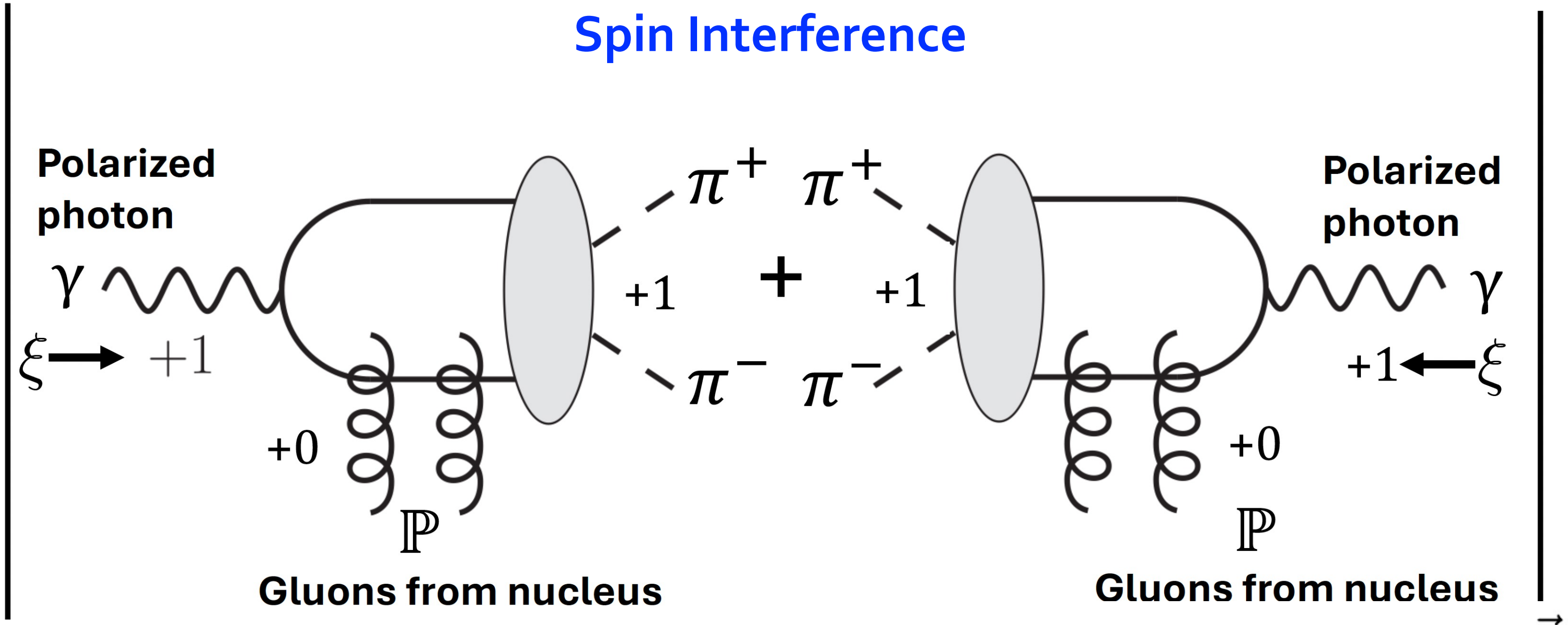
Charge distribution

Mass distribution

Spin interference effect

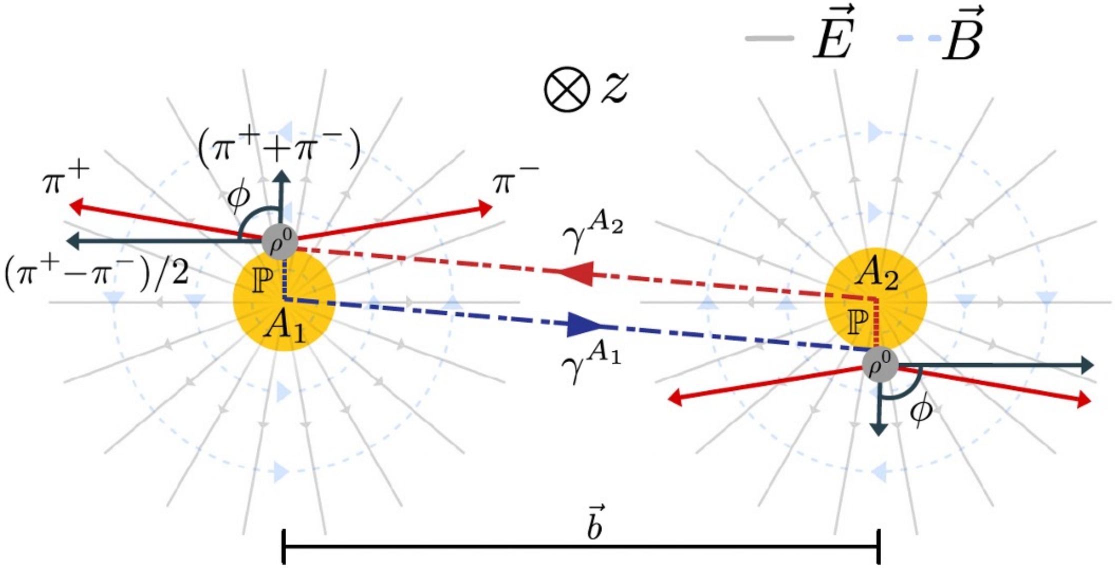
Excited states

Linearly polarized photons in UPCs

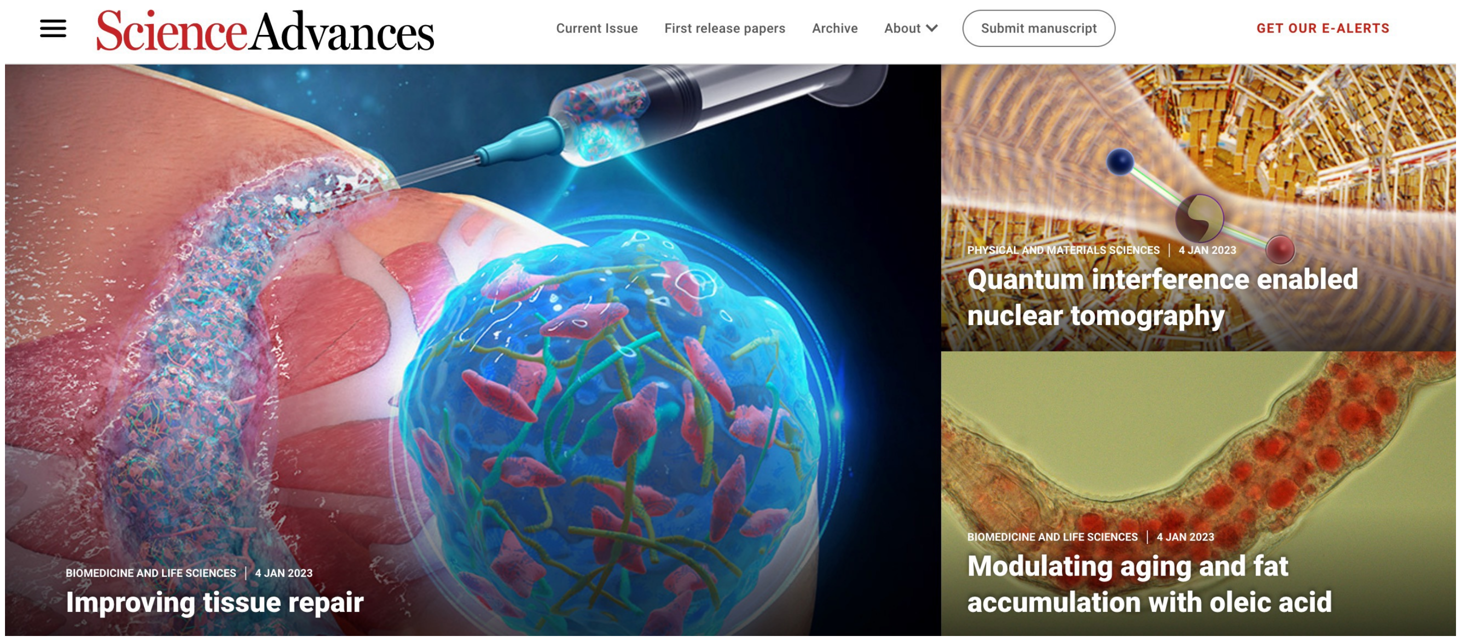


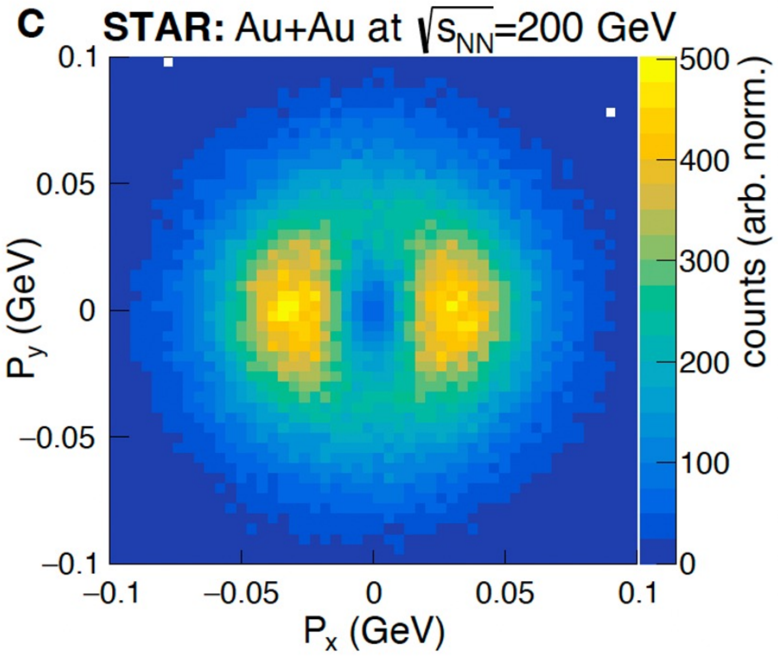
Quantum interference effects are sensitive to:

- Nuclear geometry (gluon distribution)
- Impact parameter (spatial distribution)
- Final-state azimuthal modulation similar to the Breit-Wheeler process



Quantum Interference Enabled Nuclear Tomography





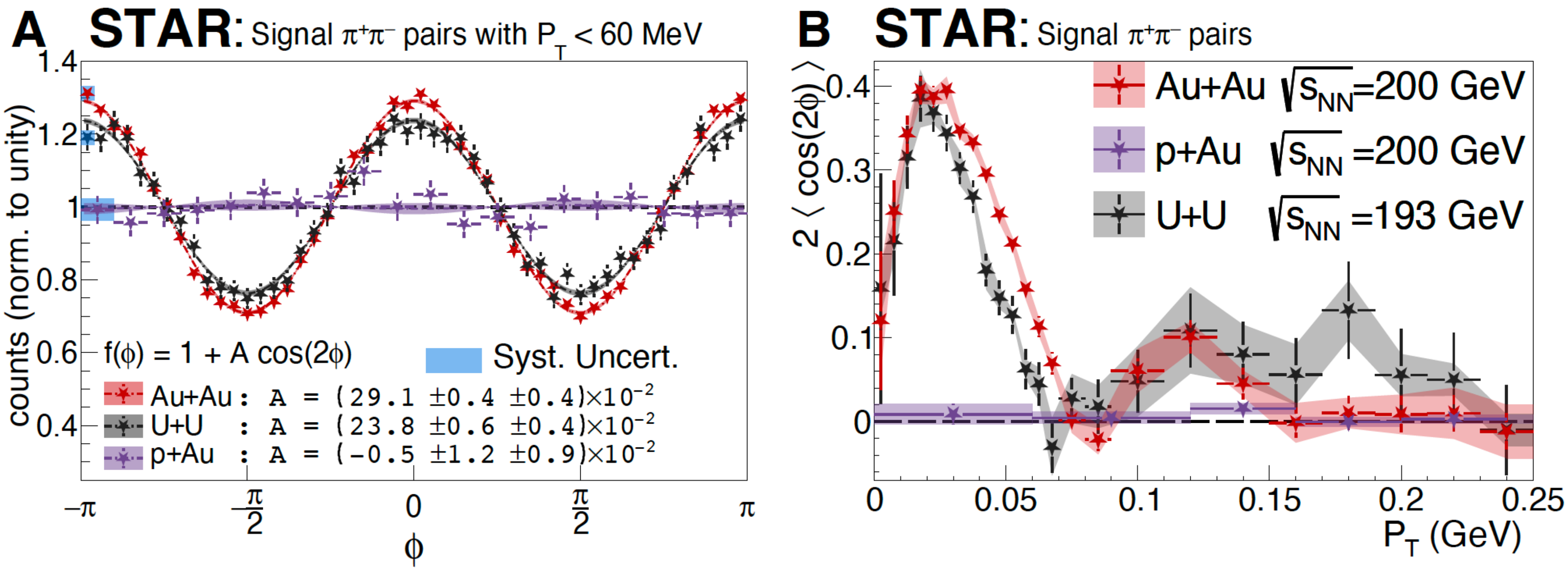
$$P_x = p_T \times \cos\phi$$
$$P_y = p_T \times \sin\phi$$

- Momentum space -> polarization space
- Max interference parallel to polarization, min perpendicular
- Interference & Diffraction pattern

$$\gamma A \to \rho^0 \to \pi^+\pi^-$$

STAR, Science Advances 9, eabq3903 (2023)

Spin-induced OAM Effect



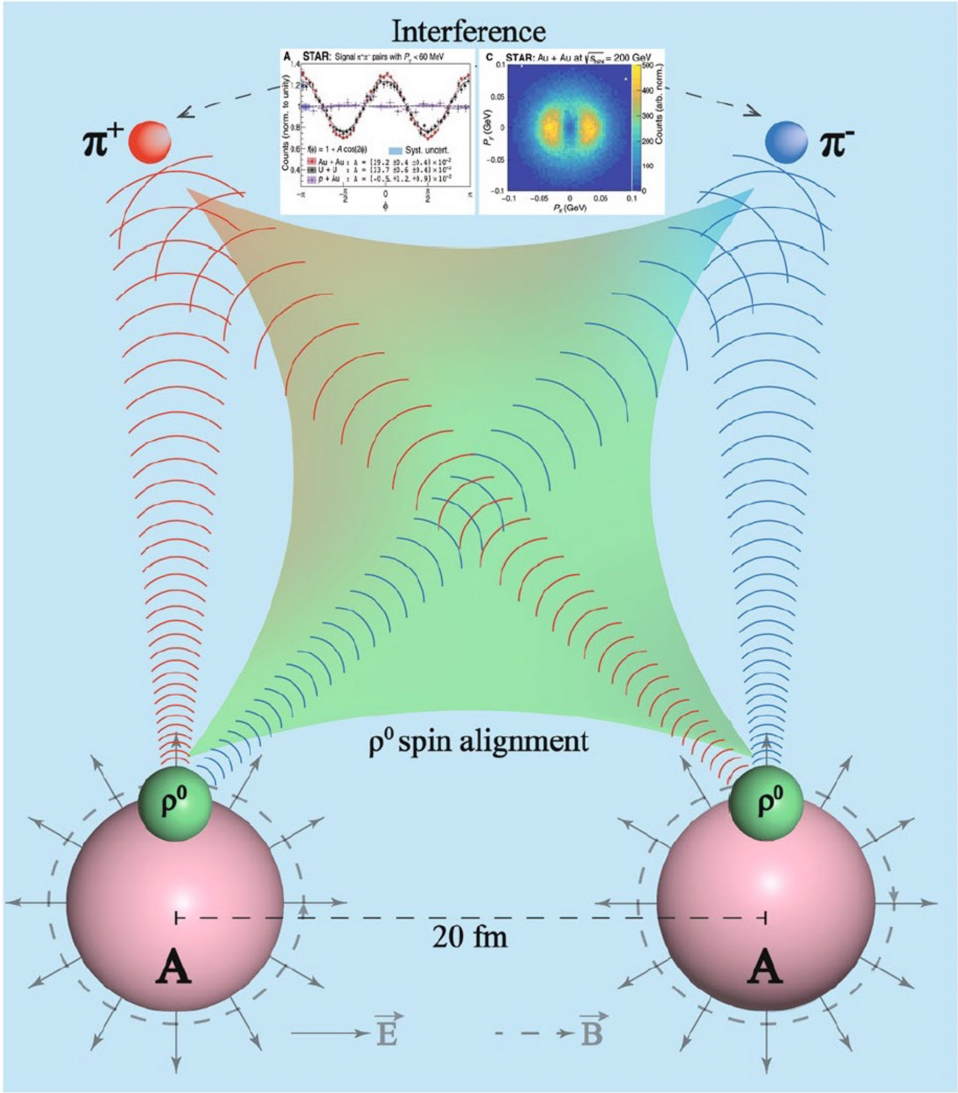
- **Observation of $\cos 2\Delta\phi$ modulation**
- Different amplitudes for AA and UU

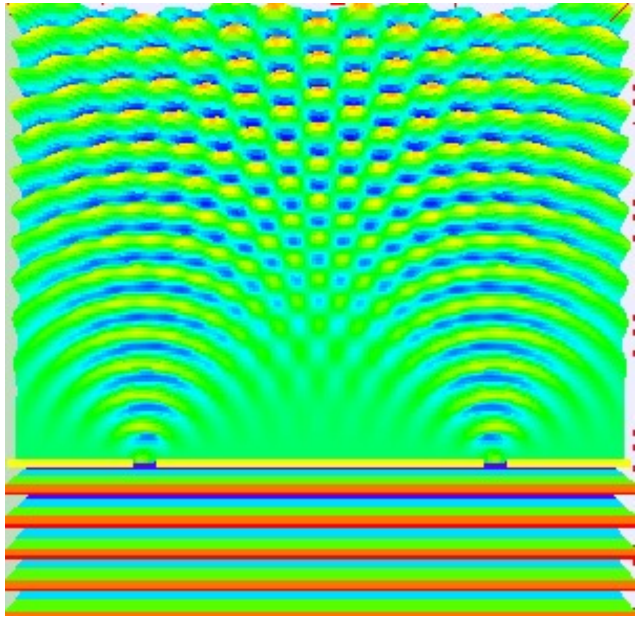
- **The interference pattern depends on the nuclear radius**
- Not observed in p+Au

STAR, Science Advances 9, eabq3903 (2023)

Entanglement Enabled Spin Interference (EESI)

Double Slit Experiment at Fermi Scale





- “Slit” distance >> ρ^0 lifetime，joint π^++π^- interference
- Measured π^+ and π^- from same ρ^0, but no interference in p+Au
- Quantum entanglement

Y.- G. Ma, NST 34:16 (2023)
W. - M. Zha, et al., PRD 103, 033007 (2021)

Study Nuclear Structure via ρ^0 Photoproduction

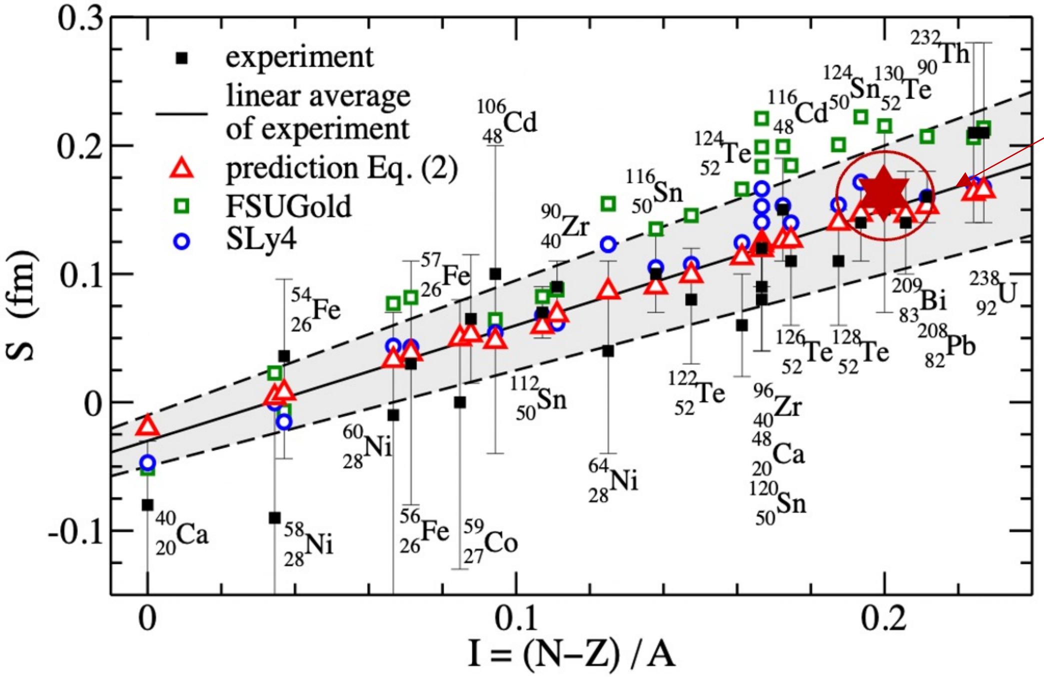
	^{197}Au	^{238}U
STAR *R* (fm)	6.53 ± 0.03 ± 0.05	7.29 ± 0.06 ± 0.05
STAR ⟨cos 2ϕ⟩ (%)	29.2 ± 0.4 (statistical) ± 0.4 (systematic)	23.7 ± 0.6 (statistical) ± 0.4 (systematic)

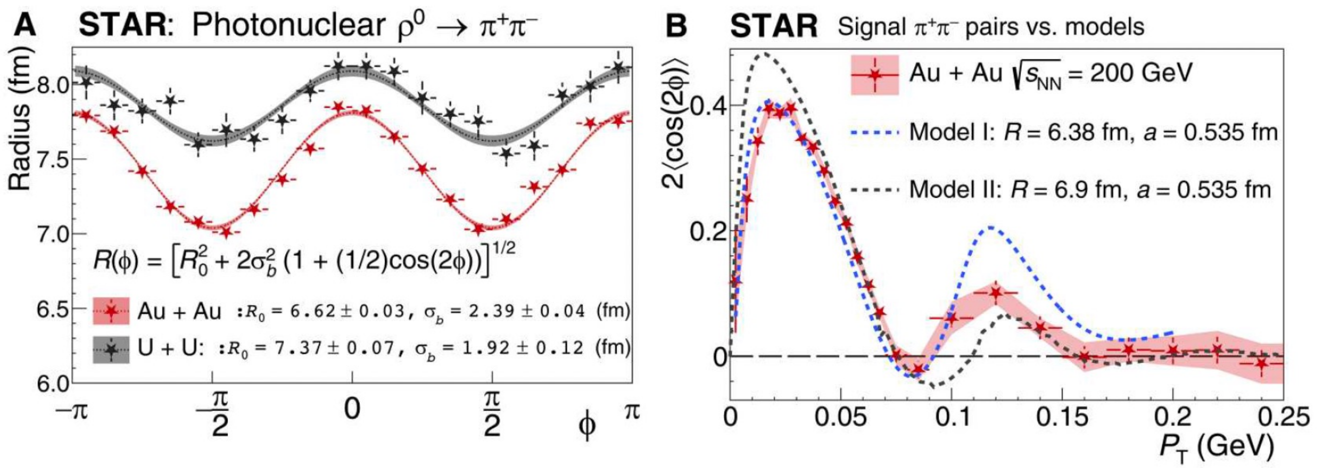
$\gamma A \to \rho^0 \to \pi^+\pi^-$

Extracted neutron skin:

$S_{238U} = 0.44 \pm 0.05 \pm 0.08$ fm

$S_{197Au} = 0.17 \pm 0.03 \pm 0.08$ fm





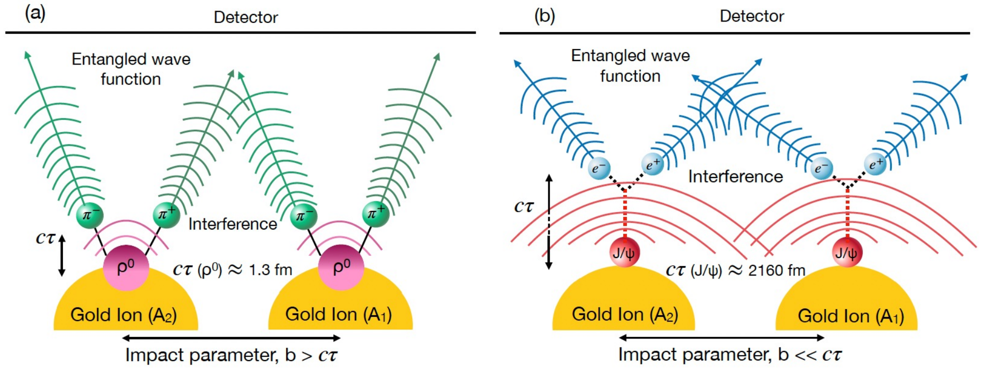
Larger radius ("neutron skin") of U :
Indication of the nuclear deformation?

Extracting the "true" mass radius considering EESI effect

M. Centelles, et al., PRL 102, 122502 (2009)
Q. Shou, et al., Phys. Lett. B 2015
H. De Vries, et al., At. Data Nucl. Data Tables 1987

STAR, Science Adv. 9, eabq3903 (2023)

Spin Interference of J/ψ Photoproduction in UPCs

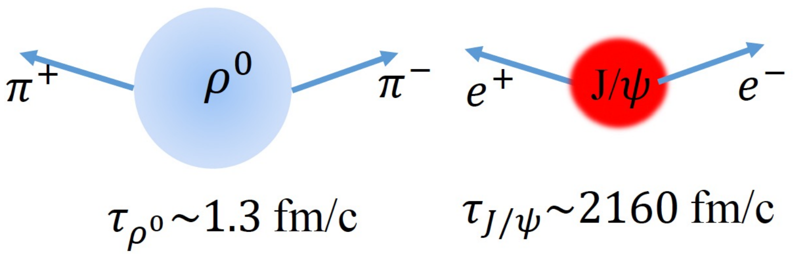


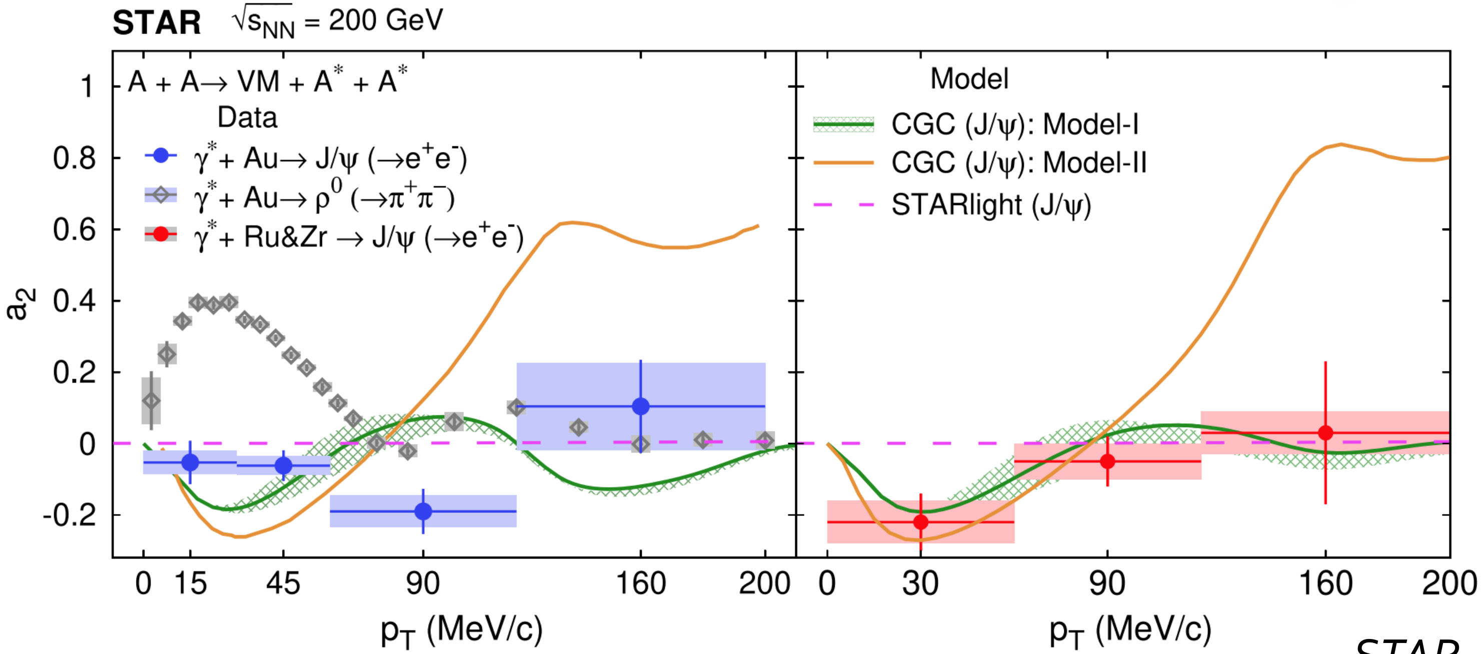
$\gamma A \to J/\psi \to e^+e^-$

Compared to ρ^0:

- Much longer life time (>>b)
- Larger mass

  Decay to Fermion





STAR, PRL 136, 242302 (2026)

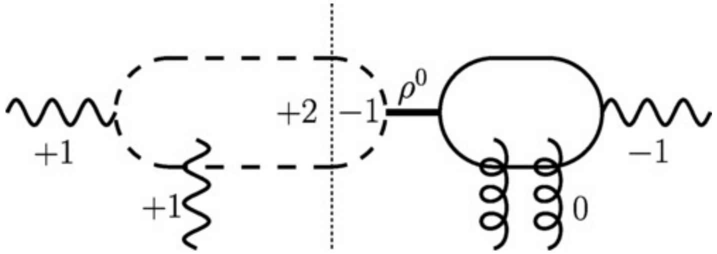
Observed spin interference and its p_T dependence

Different modulation for ρ^0 and J/ψ

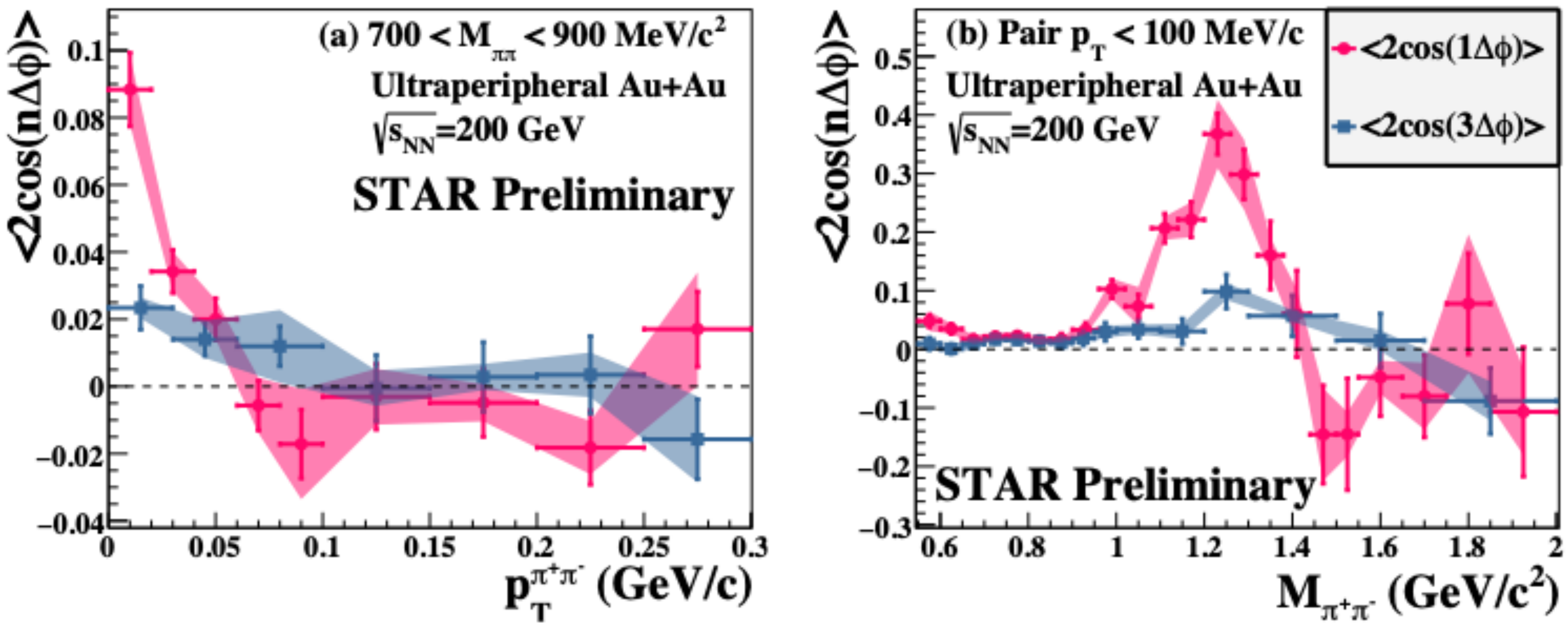
化雪丽报告 CMS实验
佛山厅，周五 11:00-11:15

李曾志报告 STAR实验
佛山厅，周四 17:15-17:30

EESI in $\pi^+\pi^-$ Final State



$\gamma A \to \rho^0 \to \pi^+\pi^-$
$\gamma\gamma \to \pi^+\pi^-$

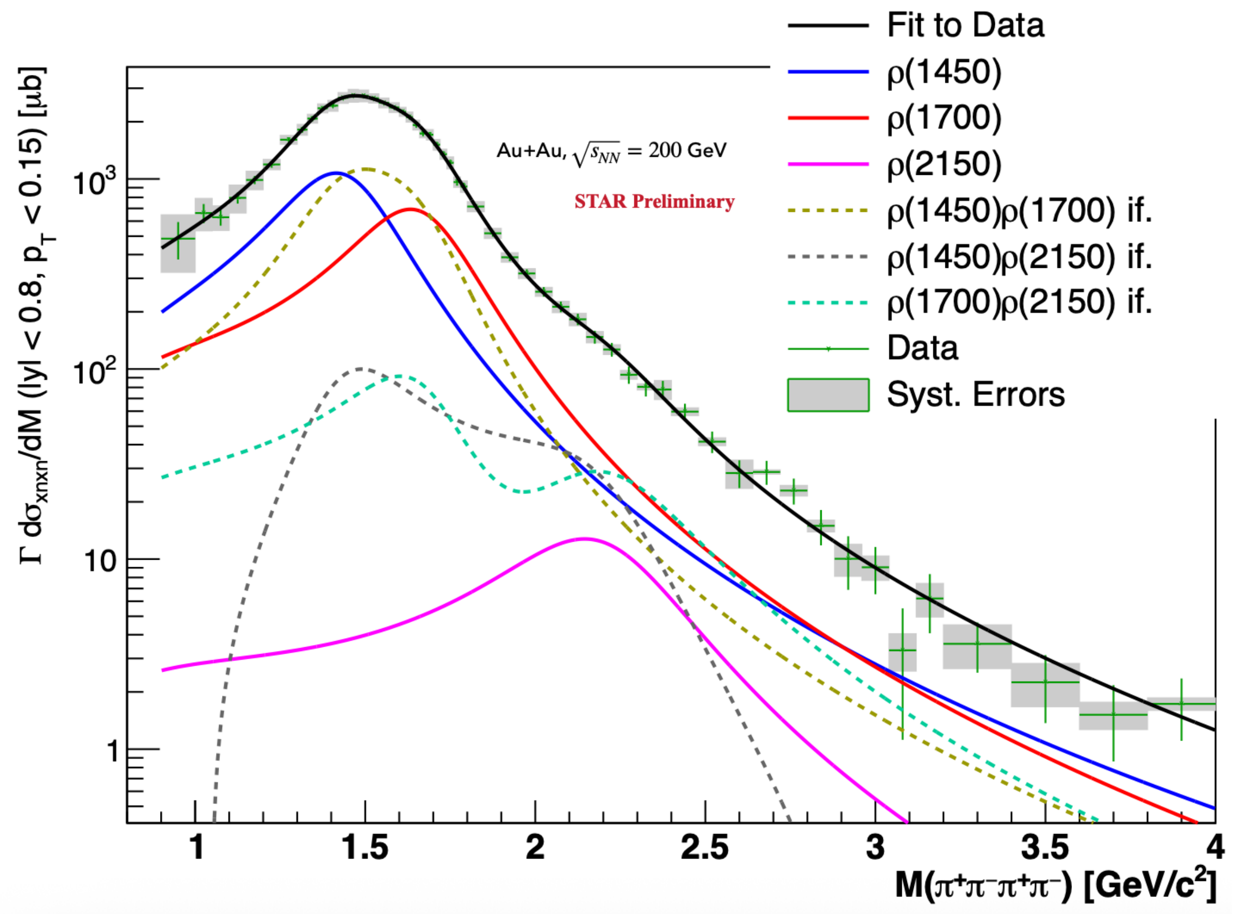


Non-zero $A_{1\Delta\phi}$ and $A_{3\Delta\phi}$ around the ρ^0 mass

- Evidence for spin interference between photonuclear and hadronic light-by-light production of $\pi^+\pi^-$
- Indication of the contribution from $f_2(1270)$， possible way to study exotics

EESI in Excited States

$\gamma A \to \rho' \to \pi^+\pi^-\pi^+\pi^-$



Lots of excited states above ground state rho have been observed

EESI in Excited States

$\rho(1450)$ $\quad I^G(J^{PC}) = 1^+(1^{--})$

$\rho(1450)$ DECAY MODES

	Mode	Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$\pi\pi$	seen		720
Γ_2	$\pi^+\pi^-$	seen		719
Γ_3	4 π	seen		669
Γ_4	$\omega\pi$			512
Γ_5	$a_1(1260)\pi$			177
Γ_6	$h_1(1170)\pi$			239
Γ_7	$\pi(1300)\pi$			89
Γ_8	$\rho\rho$			−1
Γ_9	$\rho(\pi\pi)_{S-\text{wave}}$			
Γ_{10}	e^+e^-	seen		732
Γ_{11}	$\eta\rho$	seen		311
Γ_{12}	$a_2(1320)\pi$	not seen		55
Γ_{13}	$K\overline{K}$	seen		541
Γ_{14}	K^+K^-	seen		541
Γ_{15}	$K\overline{K}^*(892)$ + c.c.	possibly seen		229
Γ_{16}	$\pi^0\gamma$	seen		726
Γ_{17}	$\eta\gamma$	seen		630
Γ_{18}	$f_0(500)\gamma$	not seen		
Γ_{19}	$f_0(980)\gamma$	not seen		398
Γ_{20}	$f_0(1370)\gamma$	not seen		92
Γ_{21}	$f_2(1270)\gamma$	not seen		177

From PDG

Mode	Decay chain	J^{PC}
1	$\rho(1450) \to a_1(1260)\pi$	$1^{--} \to 1^{++} + 0^-$
	$\quad \to a_1(1260) \to \rho\pi$	$1^{++} \to 1^{--} + 0^-$
	$\quad\quad \to \rho \to \pi^+\pi^-$	$1^{--} \to 0^- + 0^-$
2	$\rho(1450) \to h_1(1170)\pi$	$1^{--} \to 1^{+-} + 0^-$
	$\quad \to h_1(1170) \to \rho\pi$	$1^{+-} \to 1^{--} + 0^-$
	$\quad\quad \to \rho \to \pi^+\pi^-$	$1^{--} \to 0^- + 0^-$
3	$\rho(1450) \to \rho(\pi\pi)_{S\text{-wave}}$	$1^{--} \to 1^{--} + 0^{++}$
	$\quad \to \rho \to \pi^+\pi^-$	$1^{--} \to 0^- + 0^-$
4	$\rho(1450) \to \pi(1300)\pi$	$1^{--} \to 0^- + 0^-$
	$\quad \to \pi(1300) \to \rho\pi$	$0^{-+} \to 1^{--} + 0^-$
	$\quad\quad \to \rho \to \pi^+\pi^-$	$1^{--} \to 0^- + 0^-$
5	$\rho(1450) \to \rho\rho$	$1^{--} \to 1^{--} + 1^{--}$

✓ Polarization of quasi-real photon -> spin of vector meson

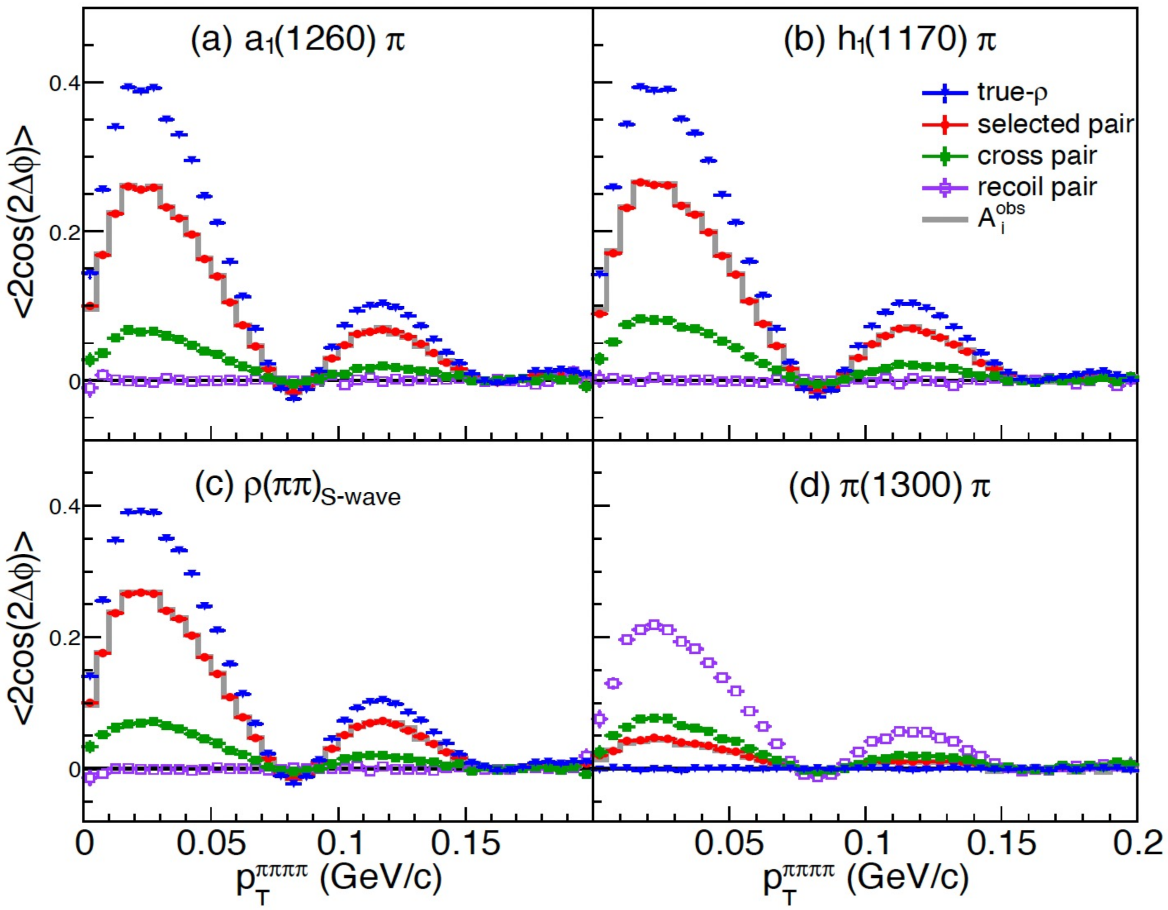
(s-channel helicity conservation at small momentum transfer)

✓ 1->1+0 spin "keeps" *D. Zhang, Z. Xu, CY, arXiv: 2606.05691*

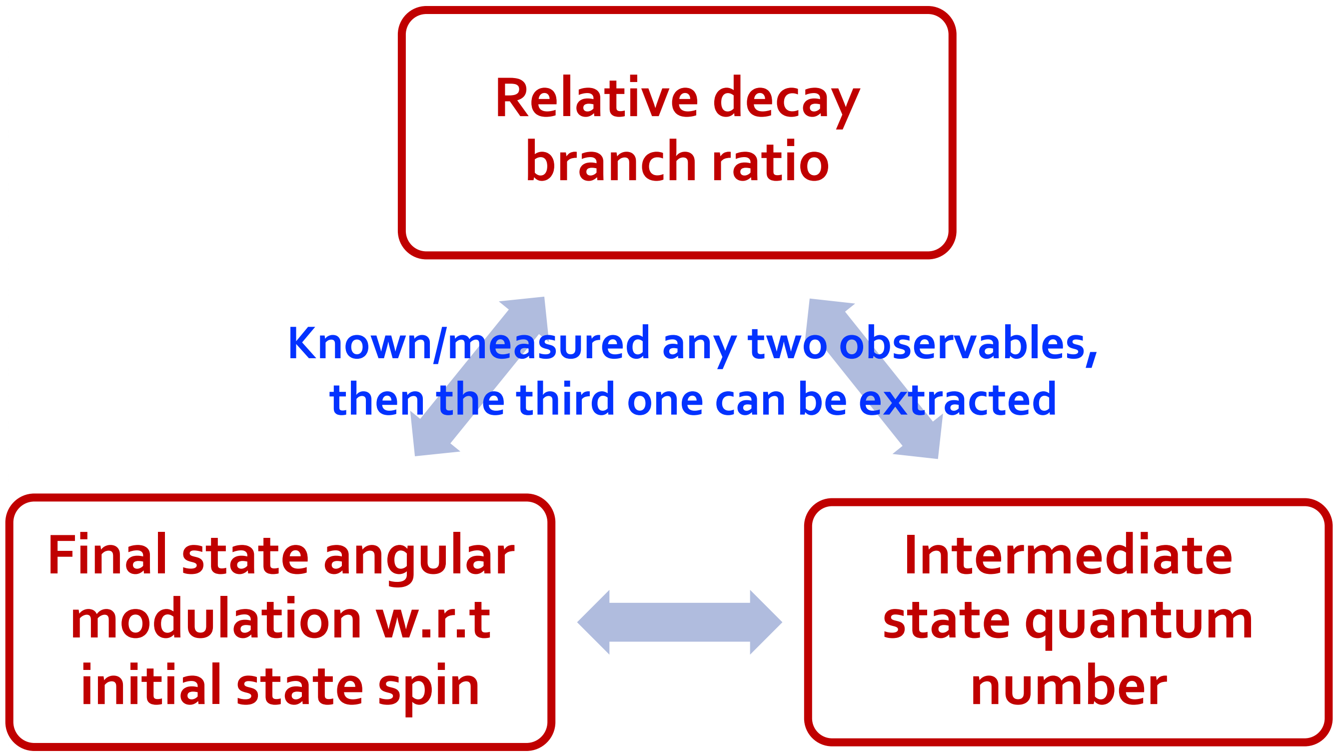
✓ 1->0+0 spin "transfers to" orbital angular momentum

Probing Quantum Numbers and Decay Branching Ratios

arXiv: 2606.05691   Toy MC simulation



$$A_{\rm obs} = B\,A_{\pi(1300)\pi} + (1-B)\,A_{\rm Other}$$



$$B = \frac{\langle 2\cos(2\Delta\phi)\rangle_{\rm exp} - \langle 2\cos(2\Delta\phi)\rangle_{\rm Other}}{\langle 2\cos(2\Delta\phi)\rangle_{\pi(1300)\pi} - \langle 2\cos(2\Delta\phi)\rangle_{\rm Other}}$$

D. Zhang, Z. Xu, CY, arXiv: 2606.05691

Summary

Photon as probes

Hot QCD in HHIC

Temperature, VM in-medium modification, collectivity, potential magnetic effect

Cold QCD and QED in UPC

Fundamental QED process, EESI, nuclear/nucleon structure, hadron spectroscopy

Lots of current and future opportunities at RHIC, LHC and NICA

Backup

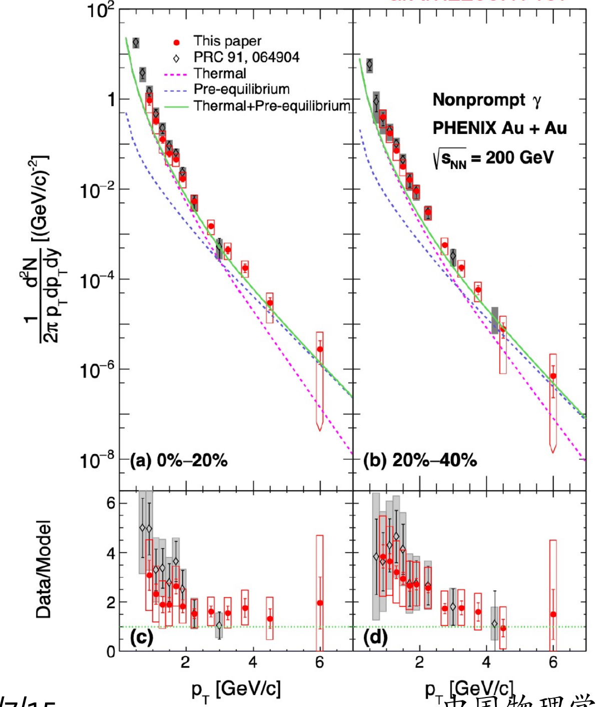
Facing challenges: Direct Photon Puzzle as an example

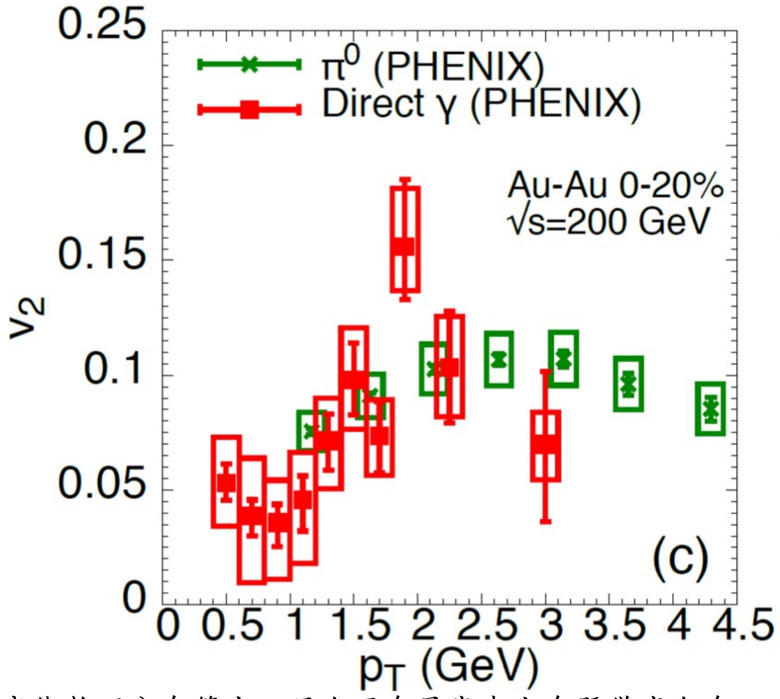
Large yield: produced in early stage, high T
Large v_n: produced in late stage, low T

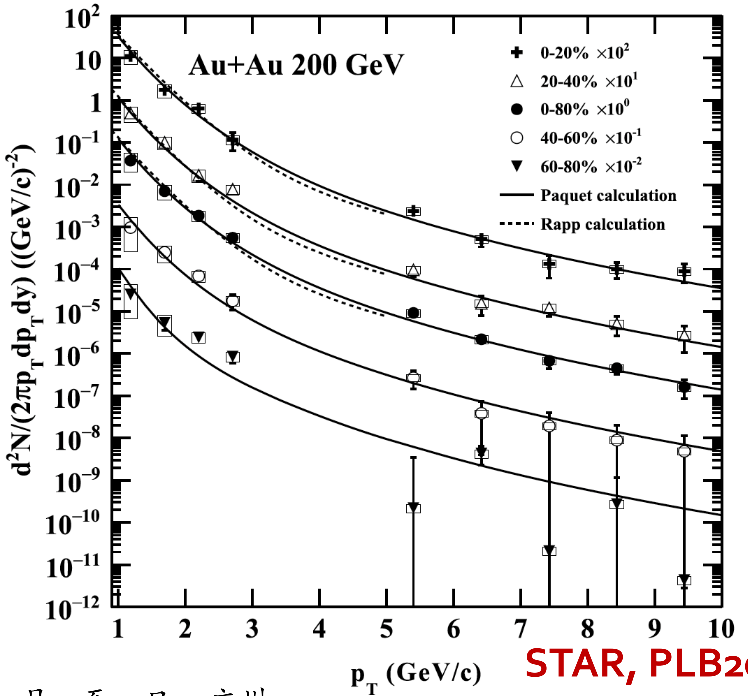
Theoretical calculation can not explain the spectra and v_n simultaneously

Became even more complicated

arXiv:2203.17187

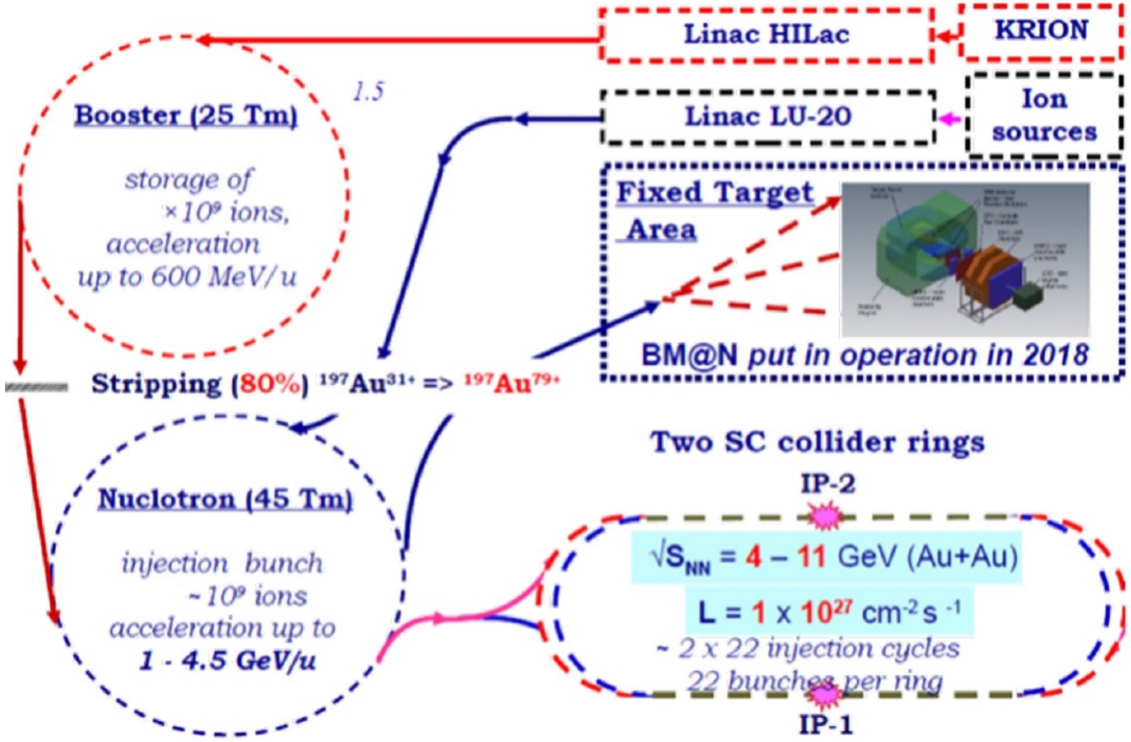






STAR, PLB2017

Nuclotron based Ion Collider fAcility (NICA)

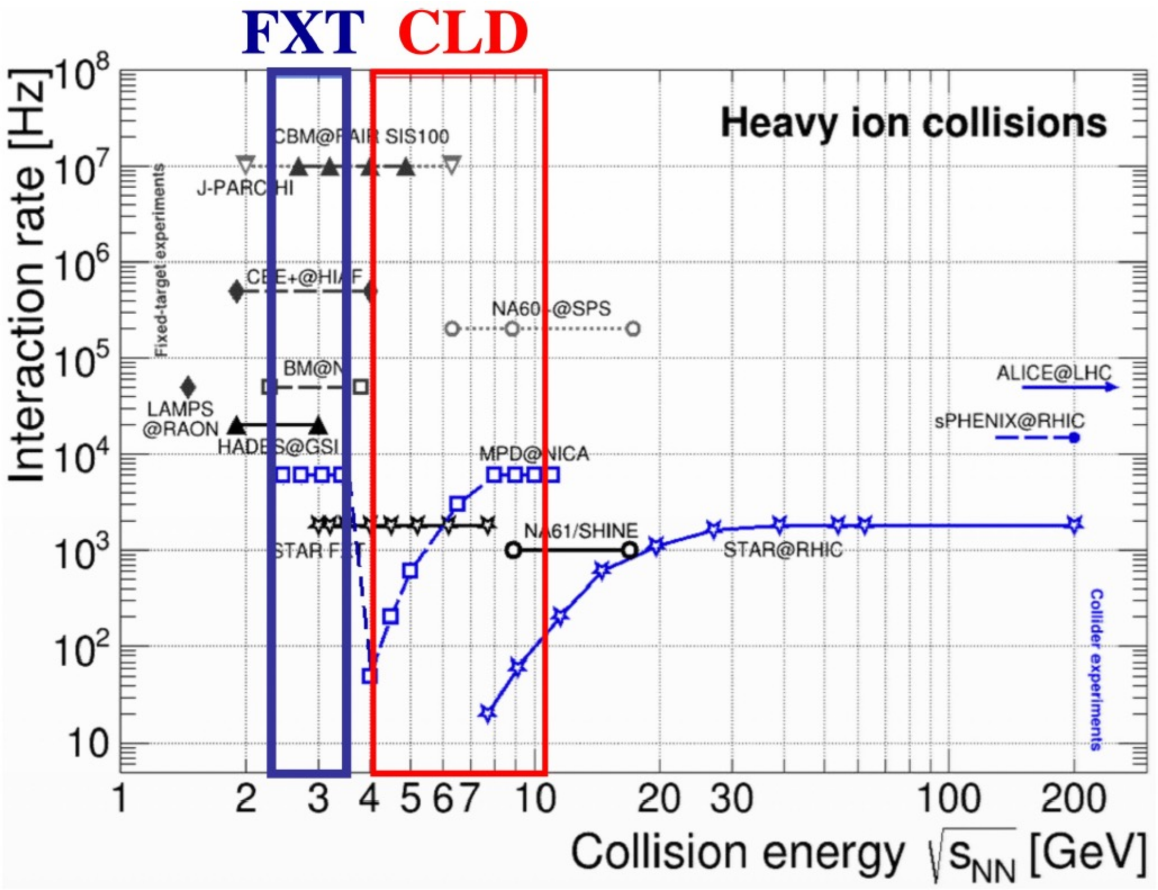


The mega-science project -- NICA, is approaching its full commissioning:

- Already running in the fixed-target mode – **Baryonic Matter @ Nuclotron (BM@N)**
- Start of operation in fixed-target and collider mode from end of 2025 – **Multipurpose Detector (MPD)**
- Operating on polarized deuterons later - **Spin Physics Detector (SPD)**

Multi-Purpose Detector (MPD)

Main subsystems at Stage-I: TPC+TOF+ECal+FHCal+FFD



Expected beams at the first year(s) of operation (Stage-I):

- MPD-CLD (collider mode): Xe/Bi + Xe/Bi at 7 GeV
- MPD-FXT (fixed target mode): Xe/Bi + W at 3 GeV
- 4 - 11GeV at collider mode

Beam energy overlap: HADES, STAR BES, HIAF, NA61/SHINE and CBM