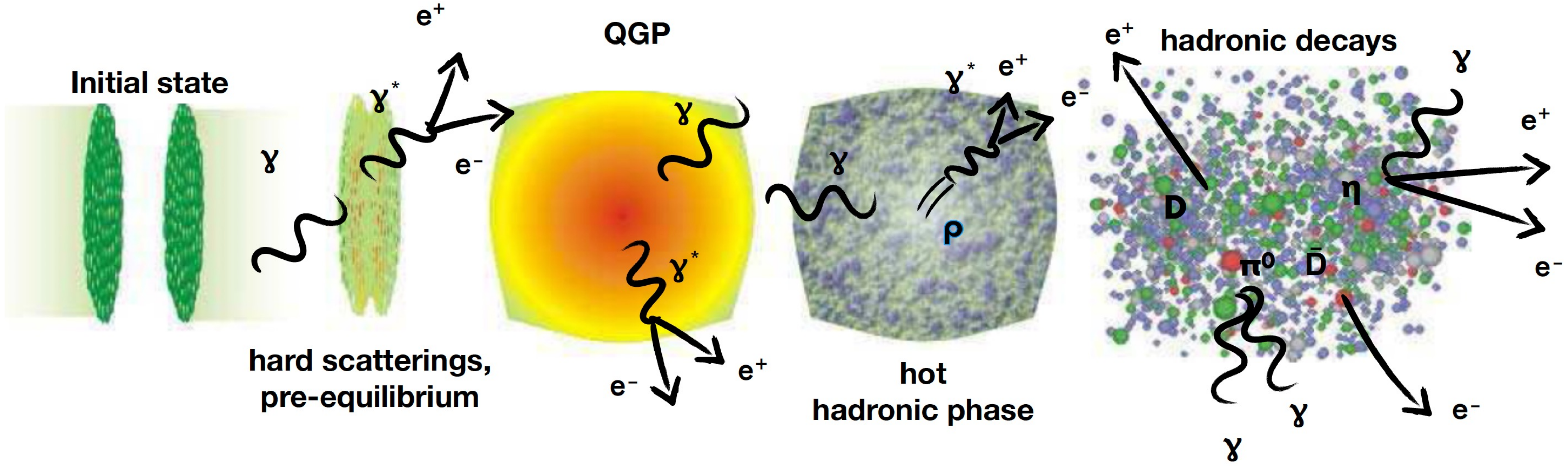
Dileptons and Direct Photons in Beam Energy Scan: Current and Future

Chi Yang 杨 驰

Shandong University 山东大学

The QCD Phase Diagram: From Theory to Experimental Signatures, Dalian, China Oct. 8-11 2025

Why EM probes?

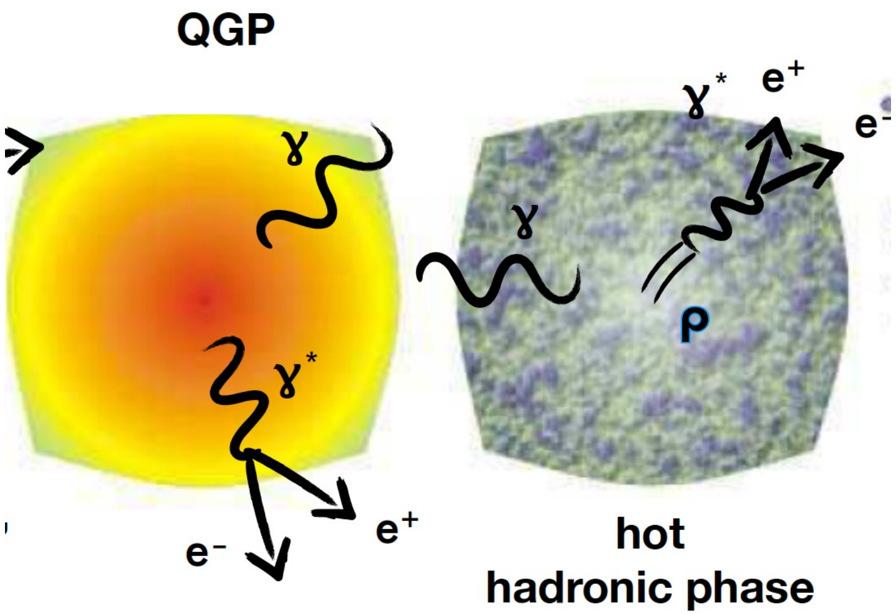


EM probes such as dileptons and direct photons:

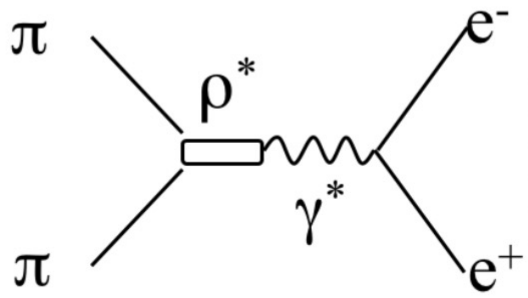
- Emitted from early to final stages
- Carry original information of emission sources
- Probe earlier and hotter phases of medium
- Direct information about the medium

Dilepton and photon productions in hot medium

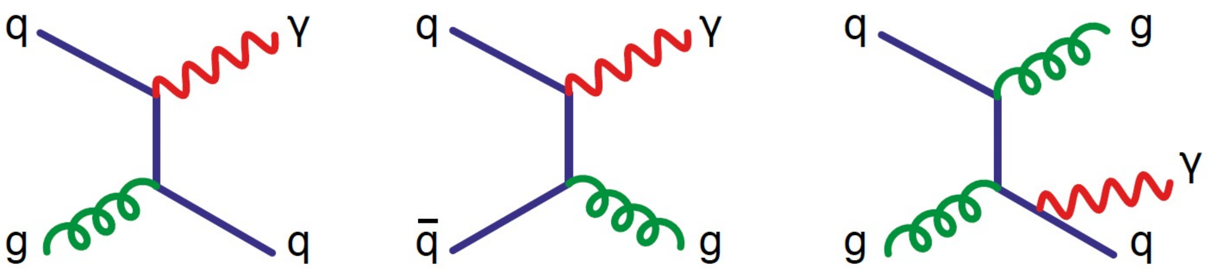
Only "thermal sources" will be discussed in this talk

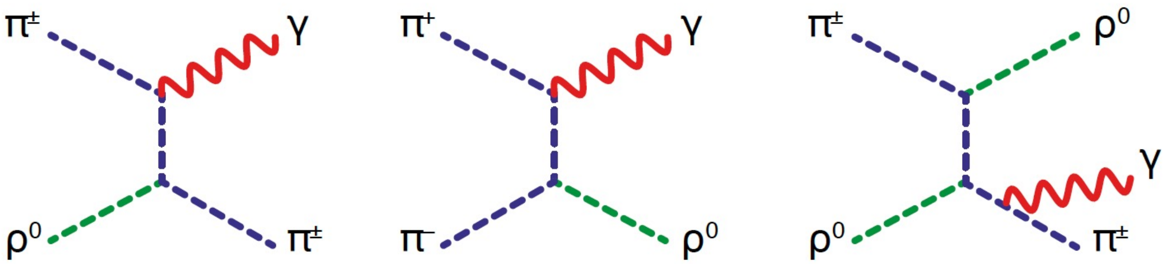


Direct photon:
photons not from hadron decay



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





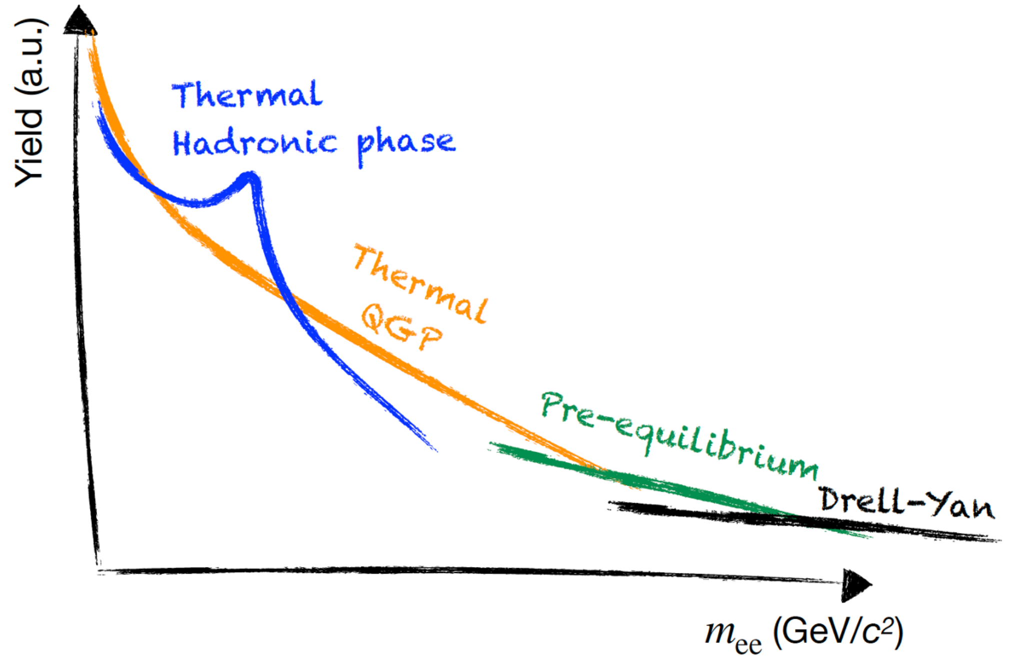
……

Chronometer and Thermometer

Yield and Slope of dileptons and direct photons:

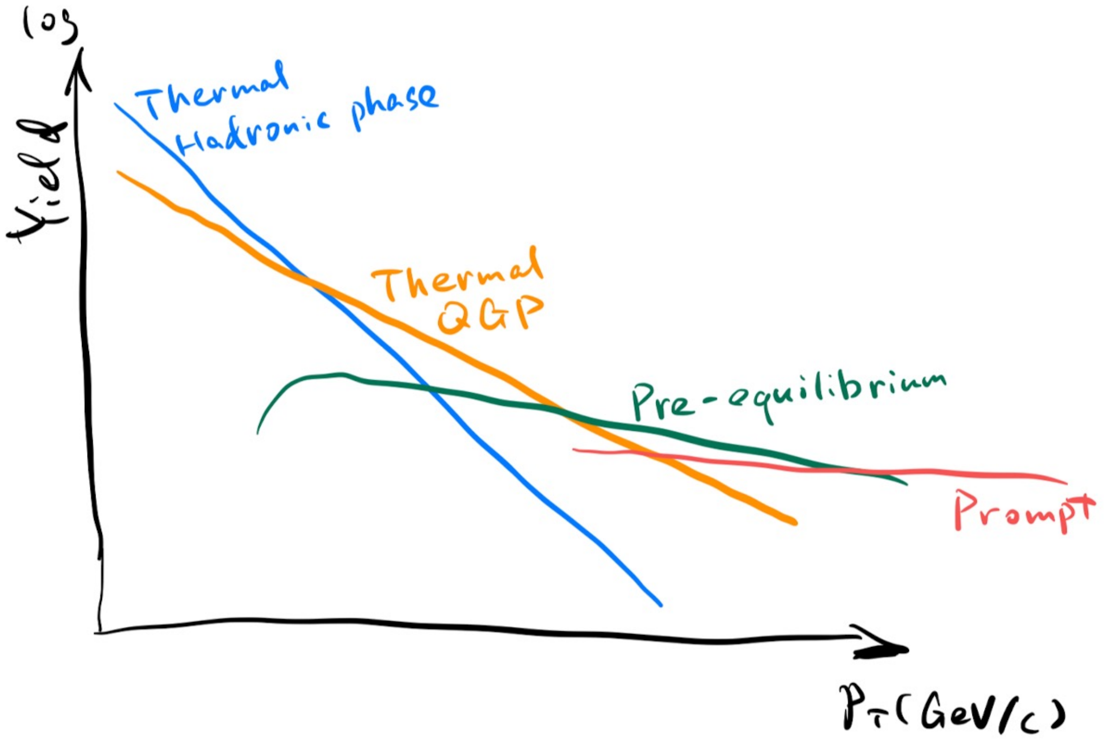
sensitive to system evolution and temperature

Schematic view of dielectron invariant mass spectrum



Late emission ⟵ Early emission

Schematic view of direct photon p_T spectrum



Late emission ⟵ Early emission

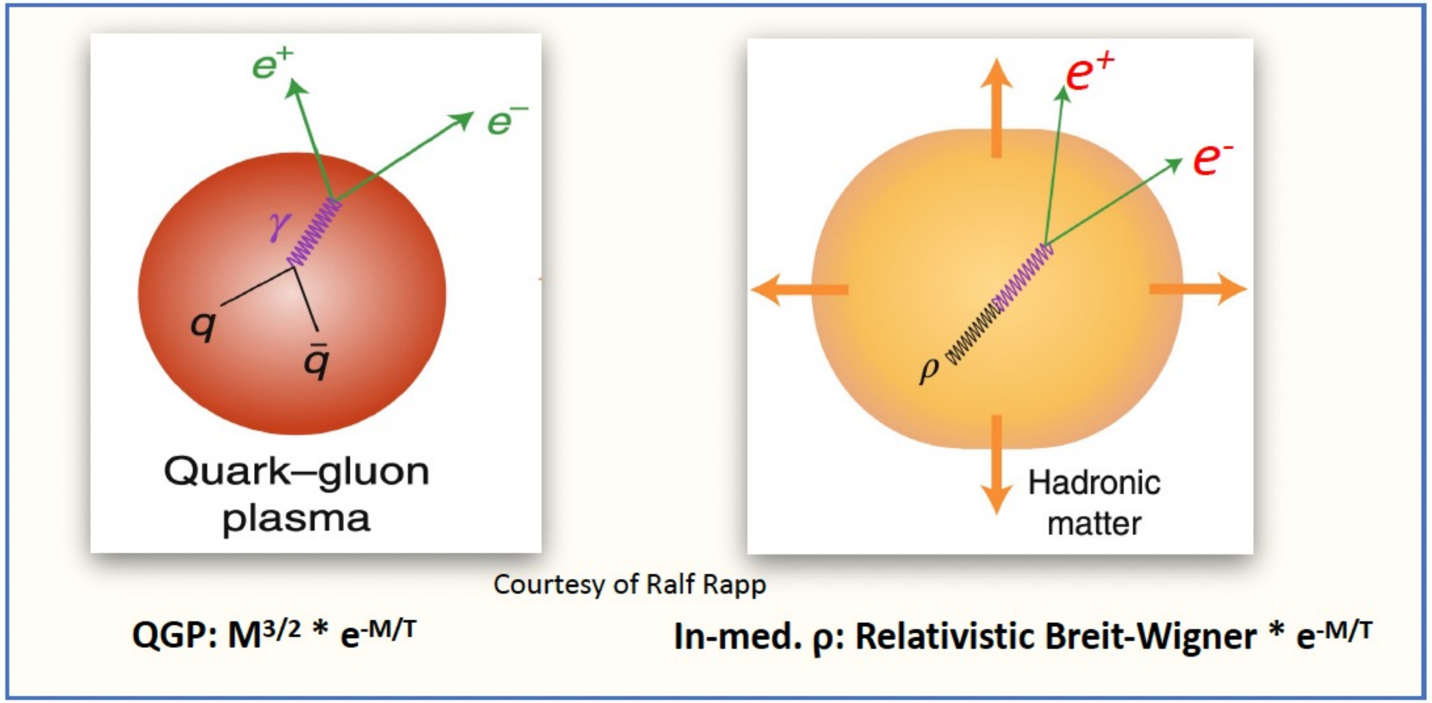
Temperature: one of the most important properties of the **HOT** and dense medium

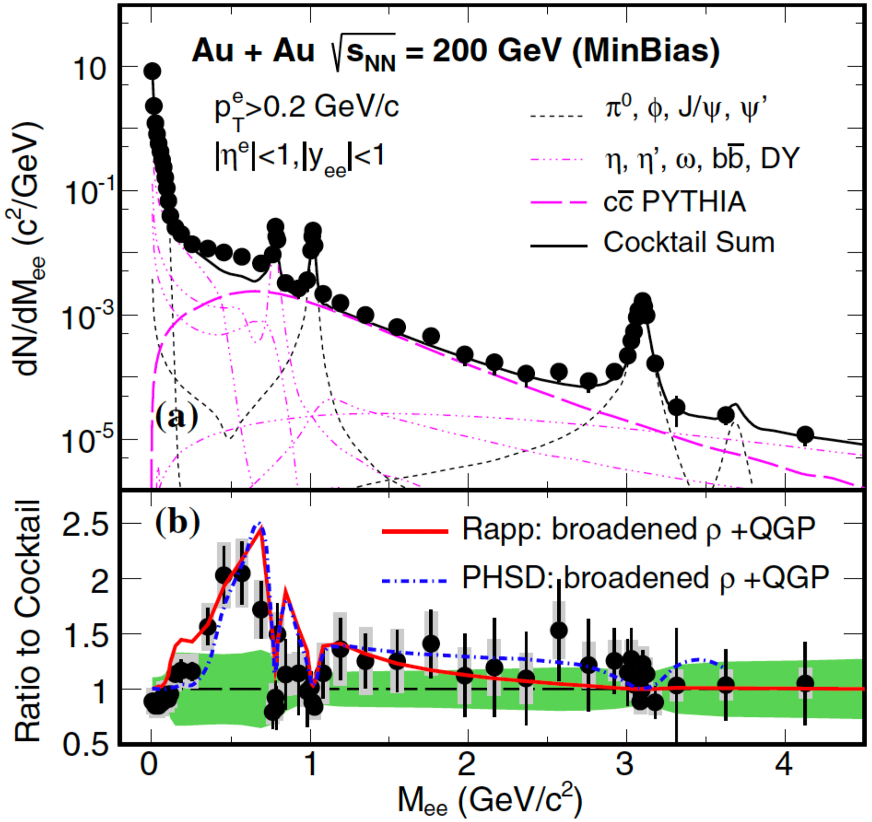
Dileptons in Beam Energy Scan

Why dileptons?

Dileptons:

- Temperature w/o distortion by blue-shift effects
- Connection between chiral symmetry restoration and in-medium ρ modification
- Only direct observable to directly access in-medium spectral function

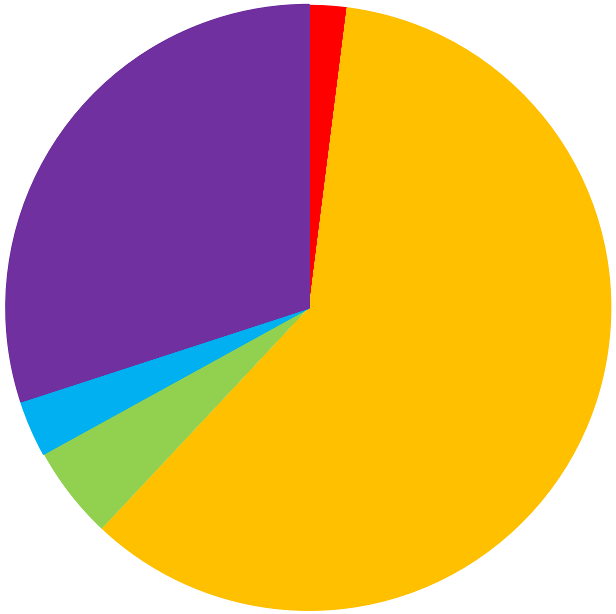




STAR: PRL 92, 092301 (2004), Rapp: PLB 753, 586 (2016)

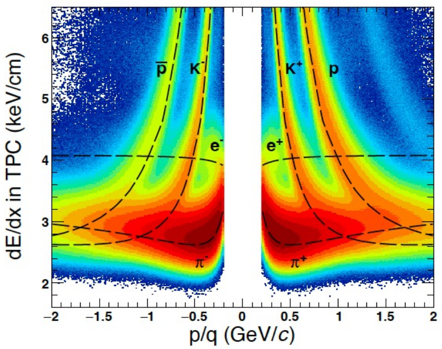
Methodology of dilepton analysis

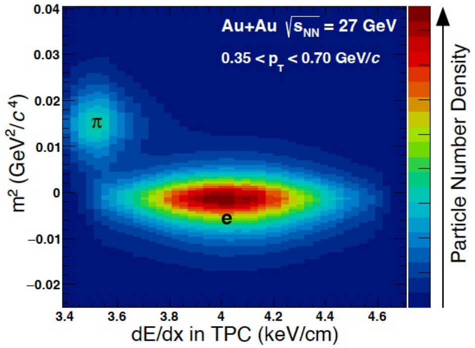
Inclusive e^+e^-



- Measure the inclusive dielectron
- Compare to/subtract our known sources
- These known sources： from simulation based on the experimental inputs and named as "hadronic decay cocktail"

■ ***Interested part (rho signal, thermal radiation contribution, …)***
■ From three body decays
■ From semi-leptonic decays
■ From Drell-Yan process
■ From two body decays

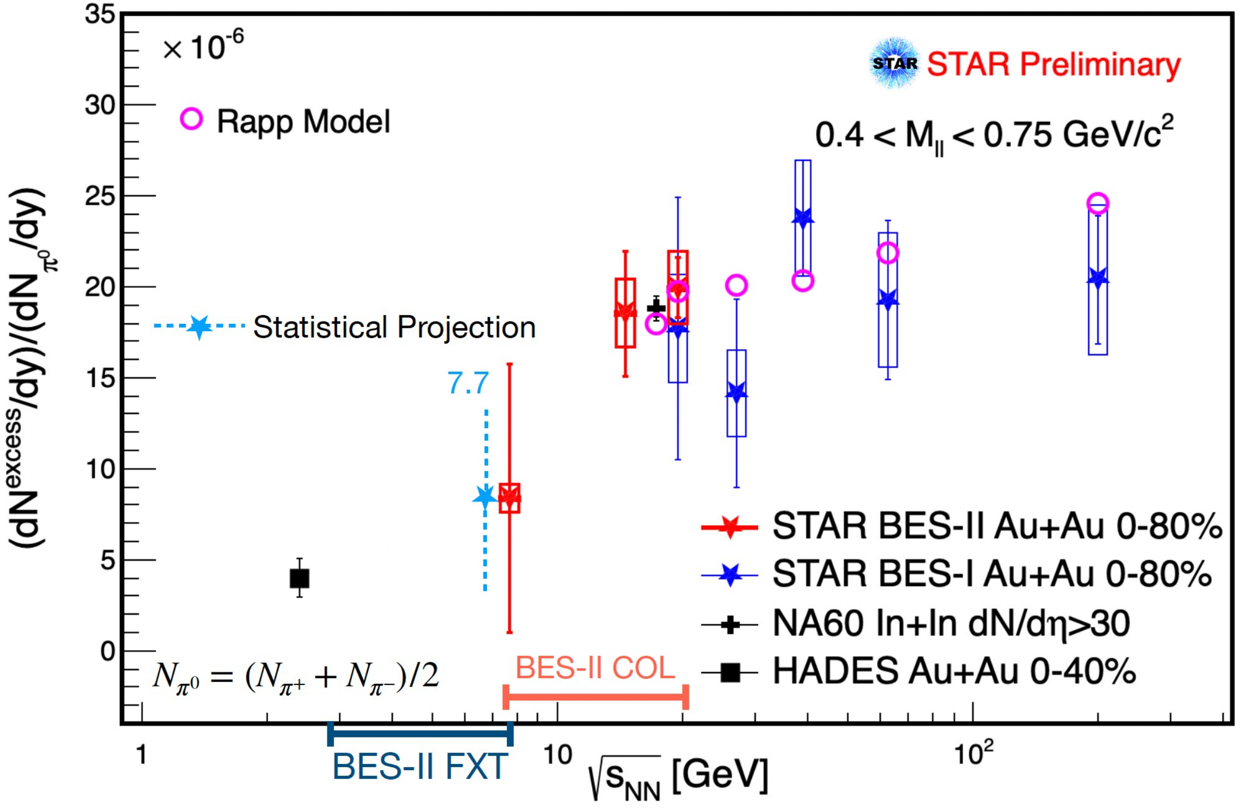




Technique challenges：
- Particle identification
- Low S/B ratio
- Pollution from hadron
- Need large statistics

Why study dilepton in low energy region?

LMR excesses measured in BES



Total baryon density increases

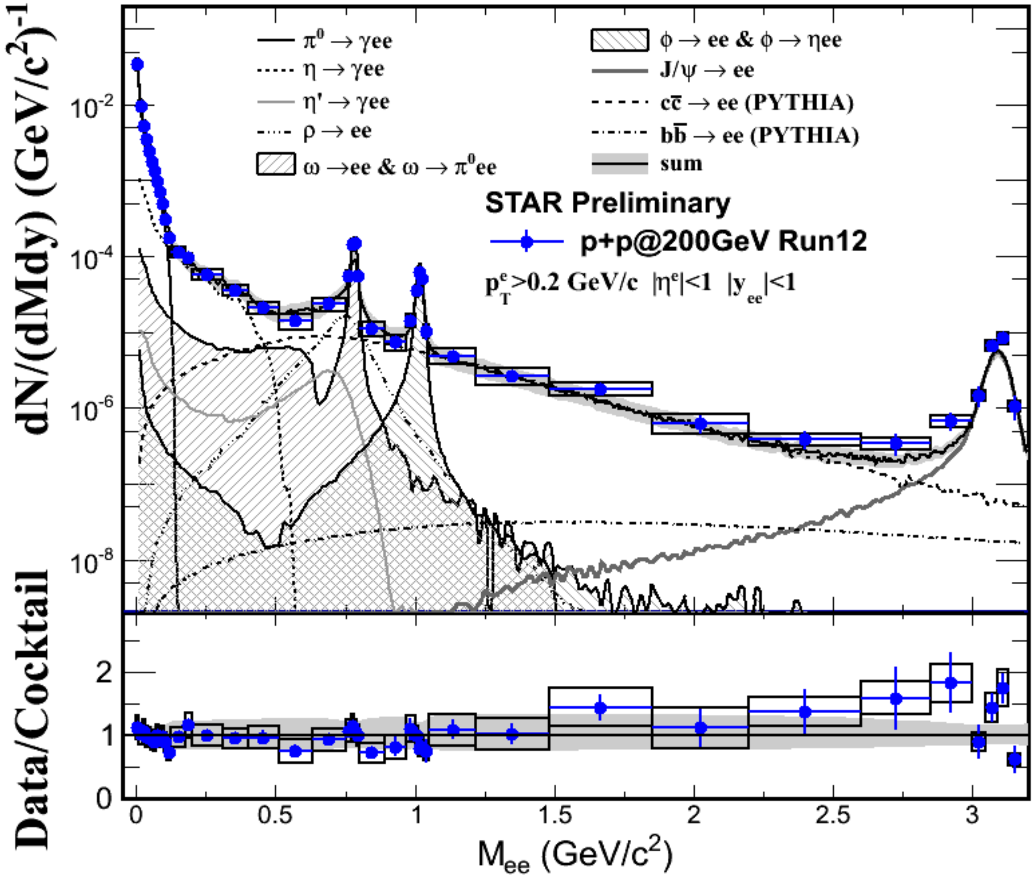
Constant total baryon density

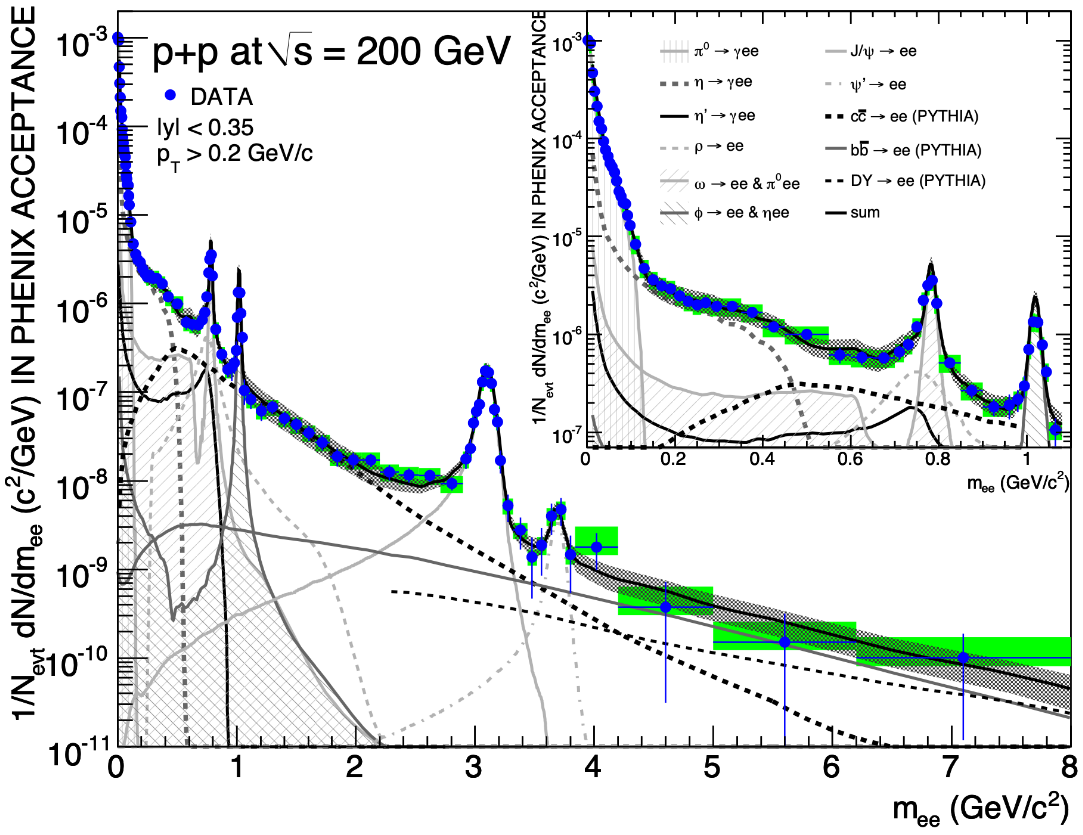
Low-mass e^+e^- emission is affected by:

T, total baryon density, lifetime

- Emission rate is dominant in the T_c region
- More clear pictures of the excess versus lifetime and total baryon density

Dielectrons in p+p at RHIC

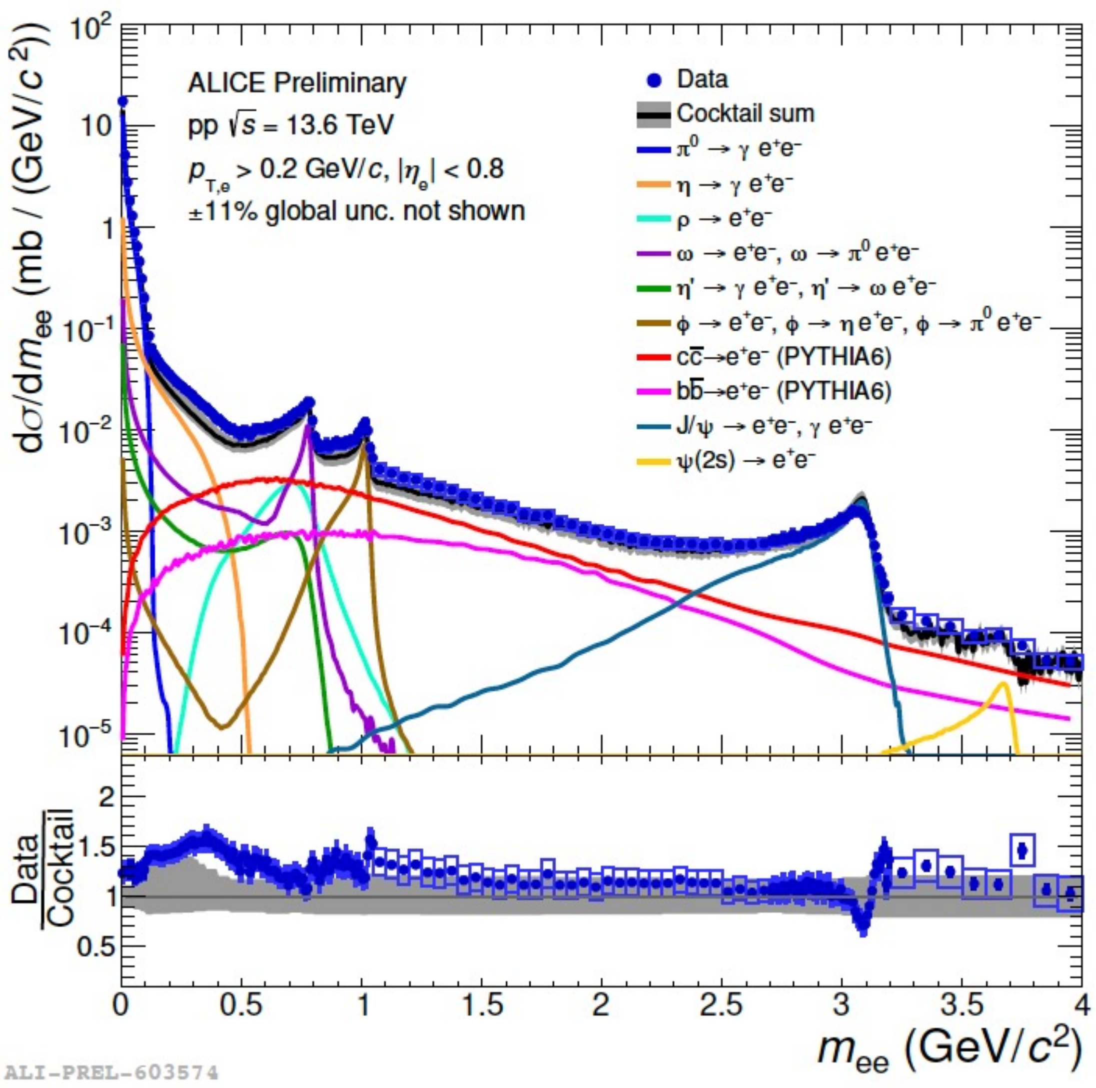




PHENIX, PLB 670, 313-320 (2009)

- Consistent with vacuum **ρ** distribution (**ρ** spectra is not modified)
- No “hot” contribution
- Cocktail simulation can be trusted

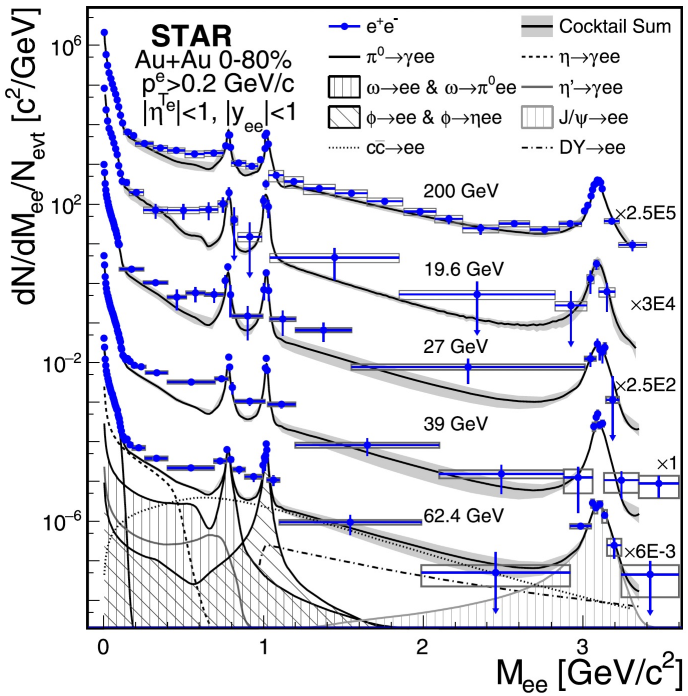
Dielectrons in p+p at ALICE

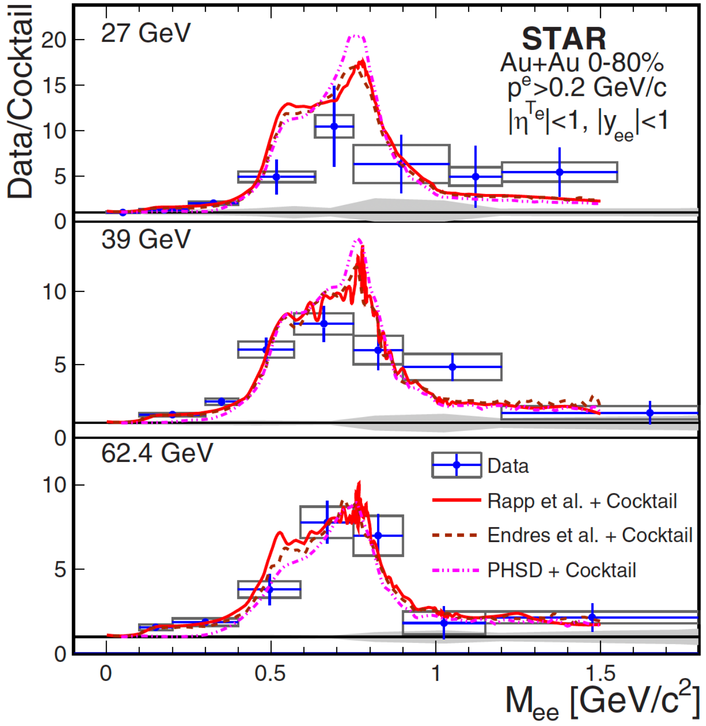


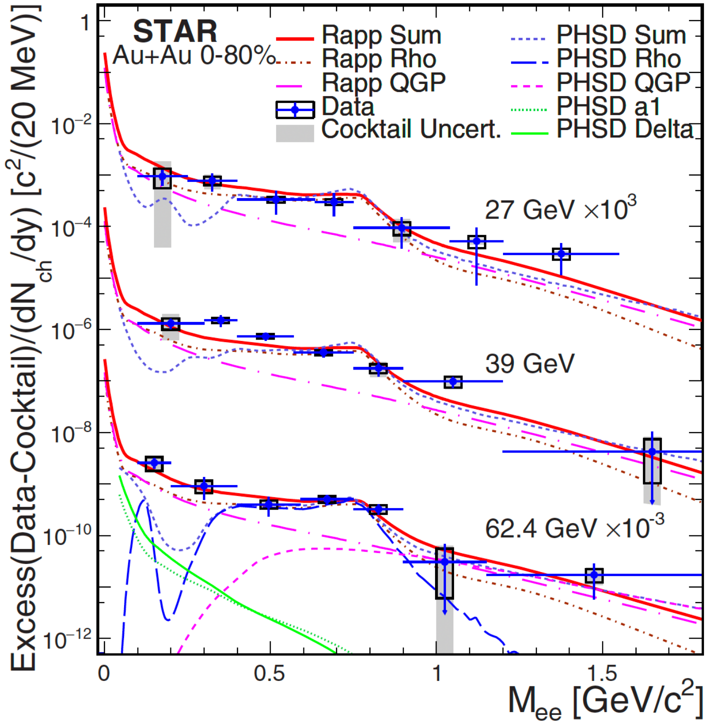
- Can not make conclusion on the existence of excesses

Dielectrons in Beam Energy Scan Phase I

STAR, PRC 107, L061901 (2023); PLB 750,64-71(2015); PRL 113,022301 (2014)







Low mass excesses are consistent with ρ broadening scenario from RHIC top energy down to 19.6GeV

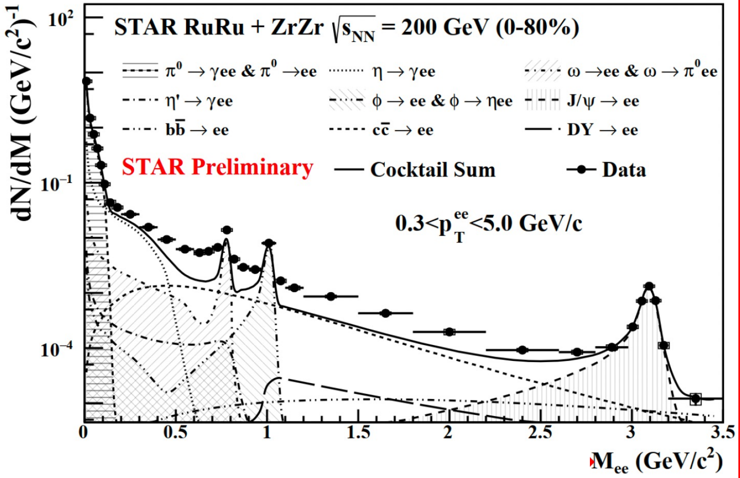
To extract temperature

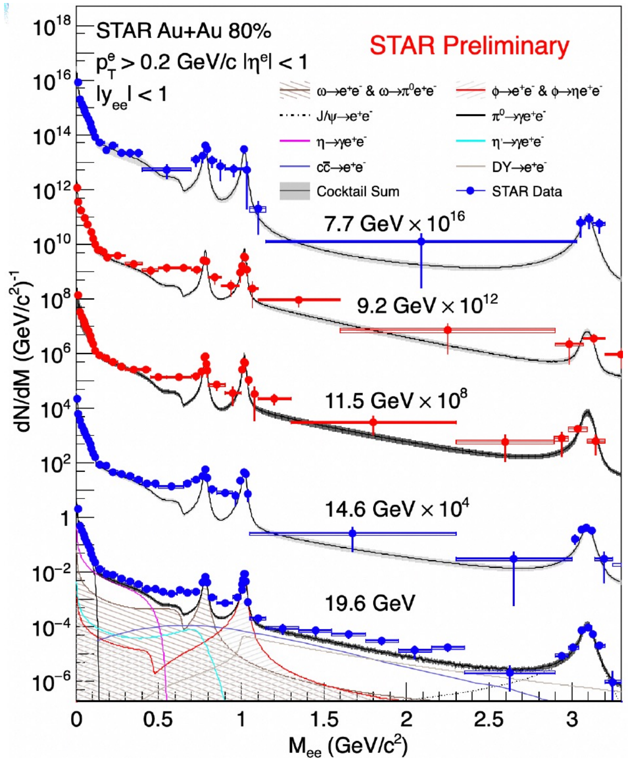
200 GeV: high yield of heavy flavor quark semi-leptonic decay

19.6–62.4 GeV: lack of statistics

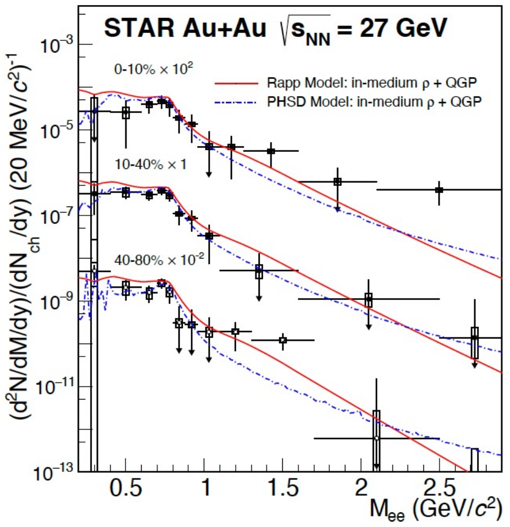
Dielectrons in Beam Energy Scan Phase II and Isobar

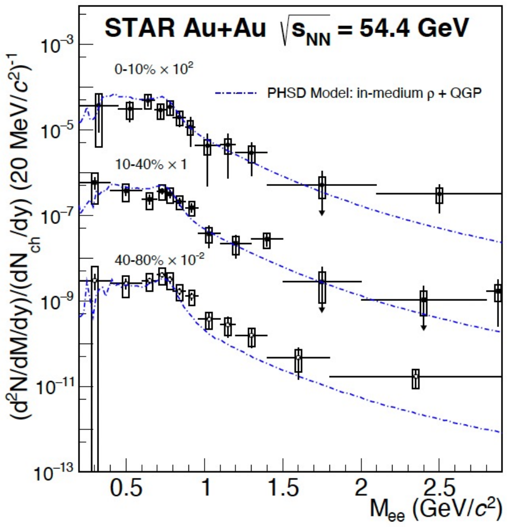
Isobar: Ru+Ru, Zr+Zr





BES-II: Au+Au

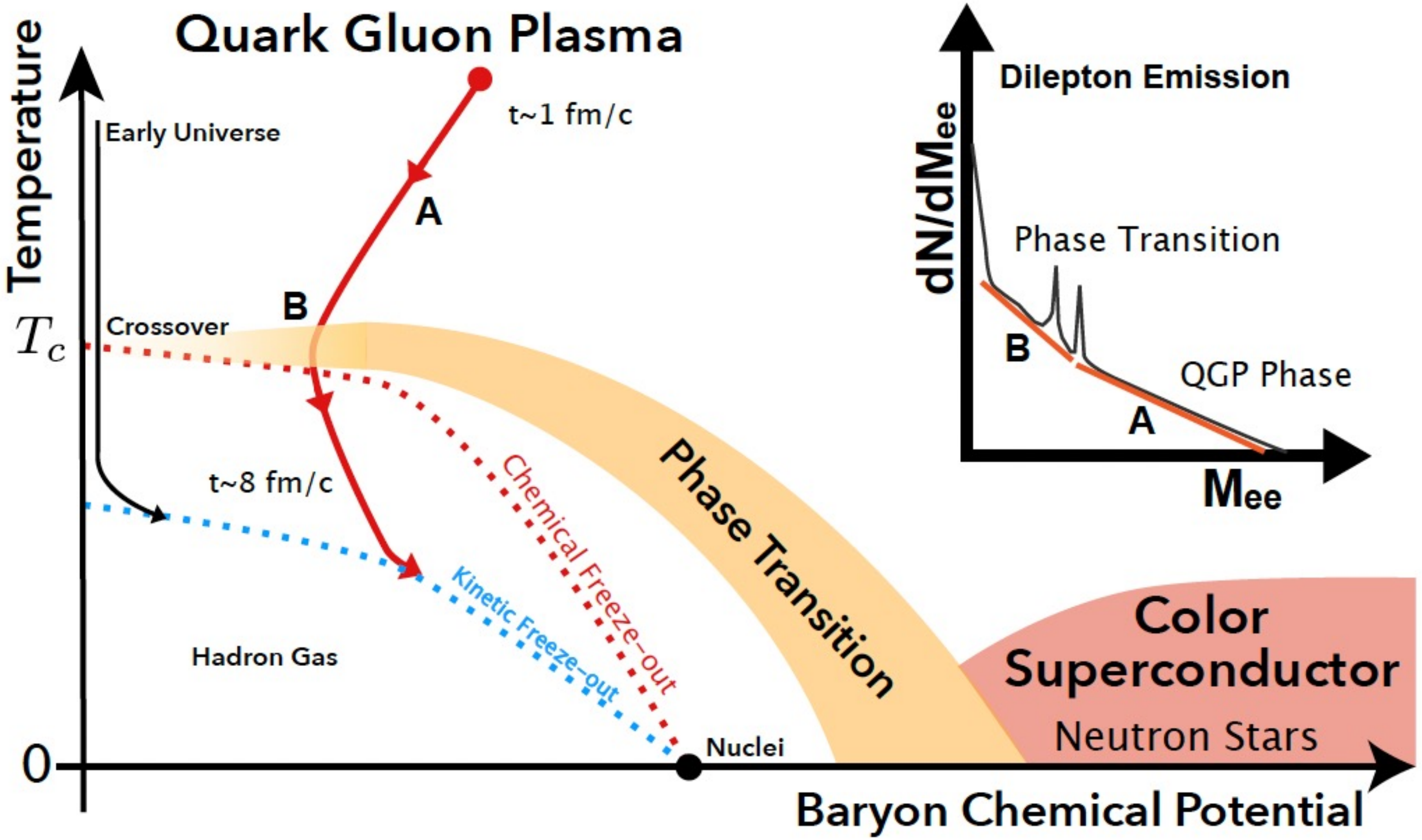




STAR, arXiv: 2403.01998

Enough precision to help theory research, can be used to extract temperature

Access the QCD phase diagram with temperature measurements via dileptons

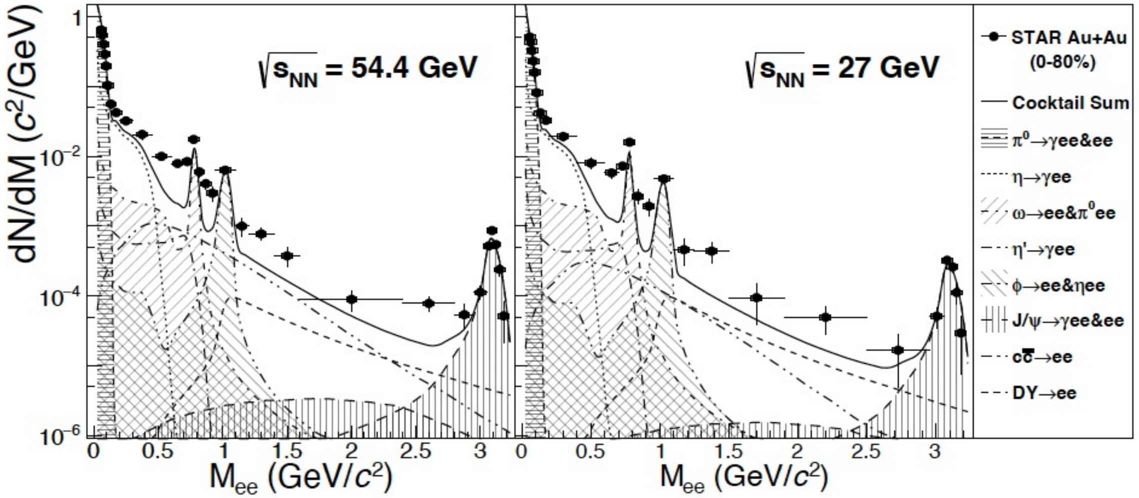


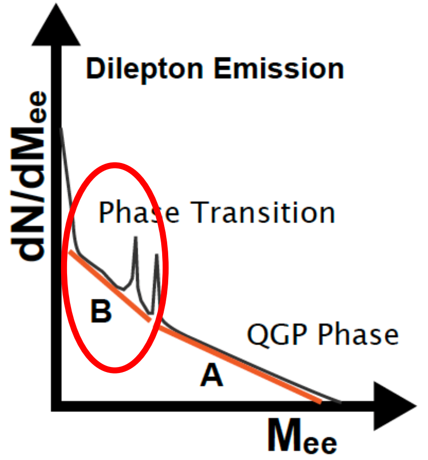
- **A (IMR):** above T_{pc}, emitted from partonic phase
- **B (LMR):** close or above T_{pc}?

STAR, arXiv: 2403.01998

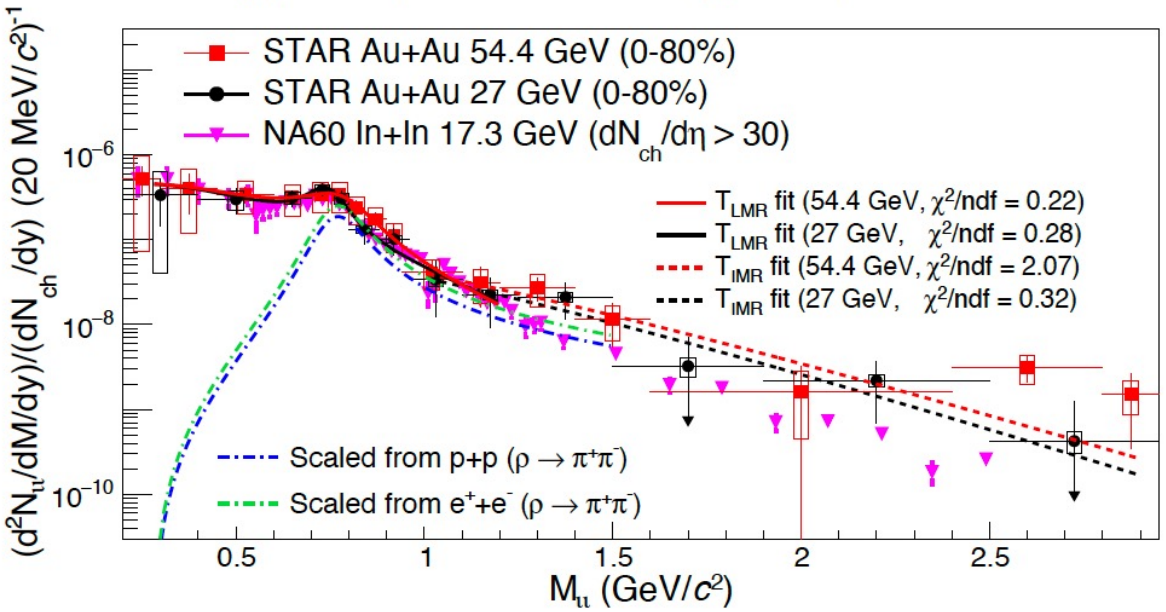
Thermal dileptons in low mass

STAR, arXiv: 2403.01998





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



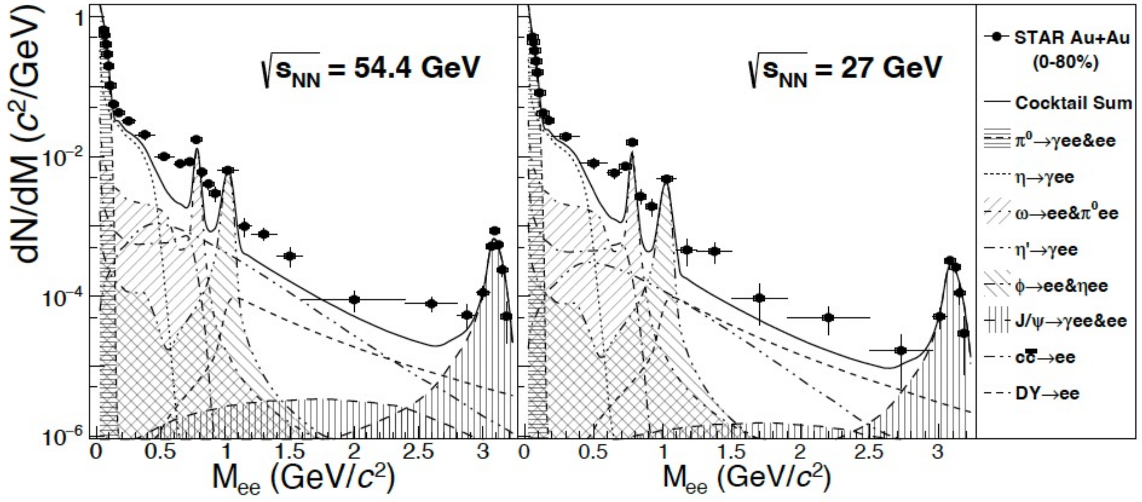
- Excess dielectron spectra of 27 and 54.4 GeV Au+Au collisions and NA60 In+In collisions are similar
- T is similar despite significant differences in collision energy and system size
- T_{LMR} around the pseudo critical temperature T_{pc} (156 MeV)

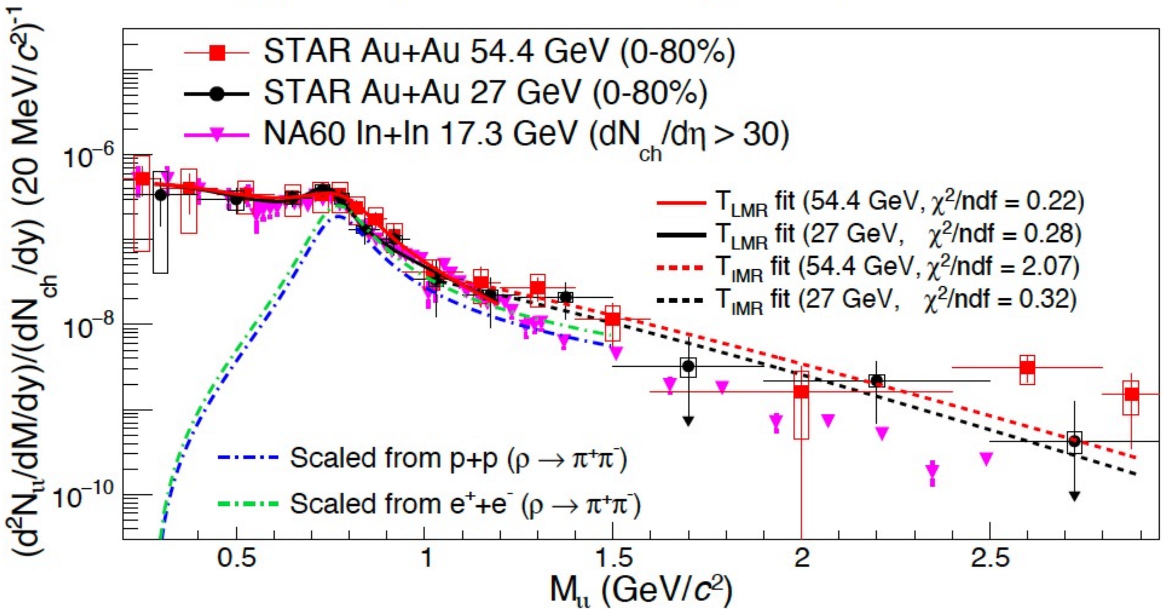
27 GeV: 165 ± 20 (stat.) ± 21 (syst.) MeV
54.4 GeV: 178 ± 15 (stat.) ± 13 (syst.) MeV

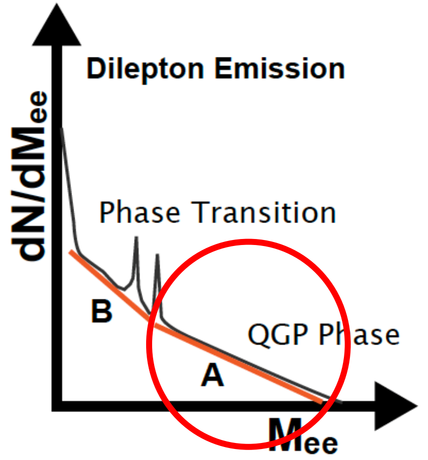
NA60: EPJC (2009) 59: 607–623
HotQCD: PLB 795 (2019) 15-21

Thermal dileptons in intermediate mass

STAR, arXiv: 2403.01998







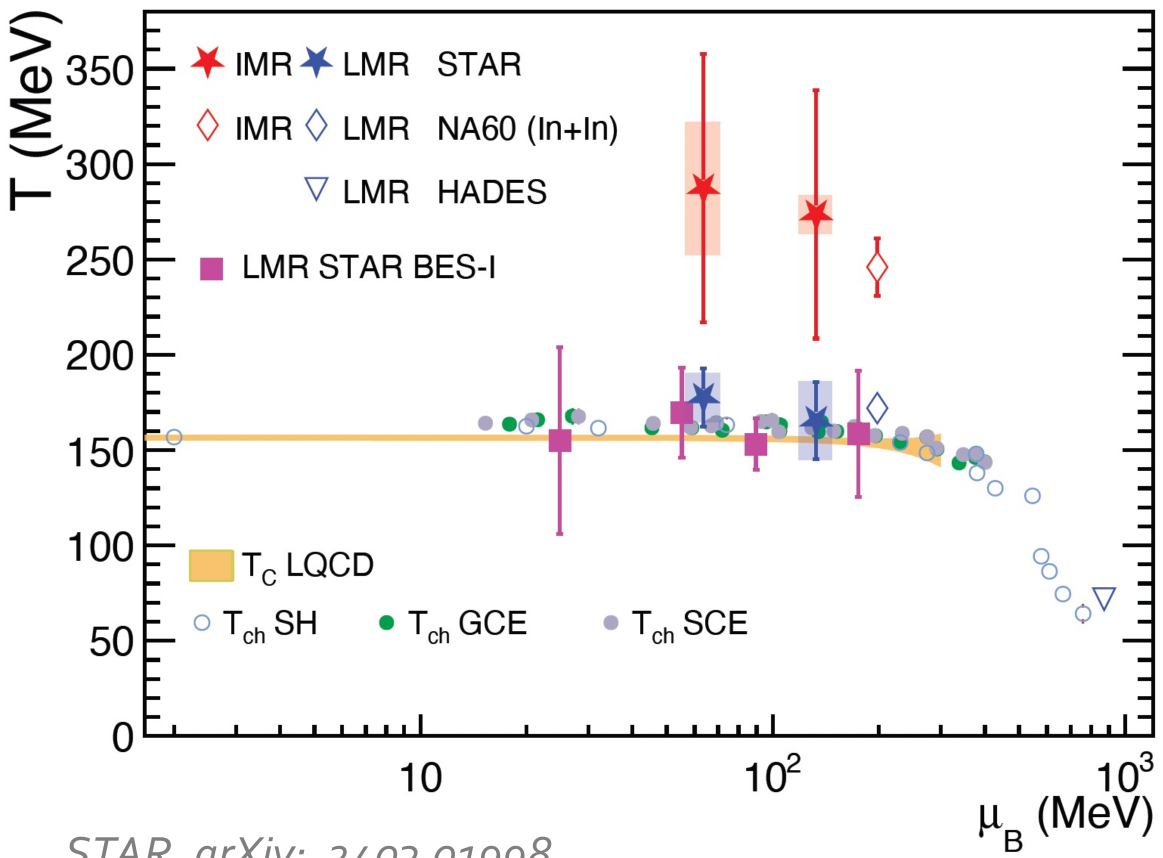
fitting function: $M^{3/2} * e^{-M/T}$

- 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 $\pm$ 65 (stat.) $\pm$ 10 (syst.) MeV
54.4 GeV: 287 $\pm$ 70 (stat.) $\pm$ 34 (syst.) MeV

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

Temperature v.s. μ_B



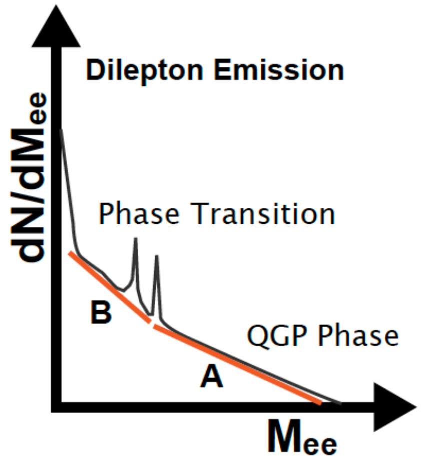
STAR, arXiv: 2403.01998

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}:

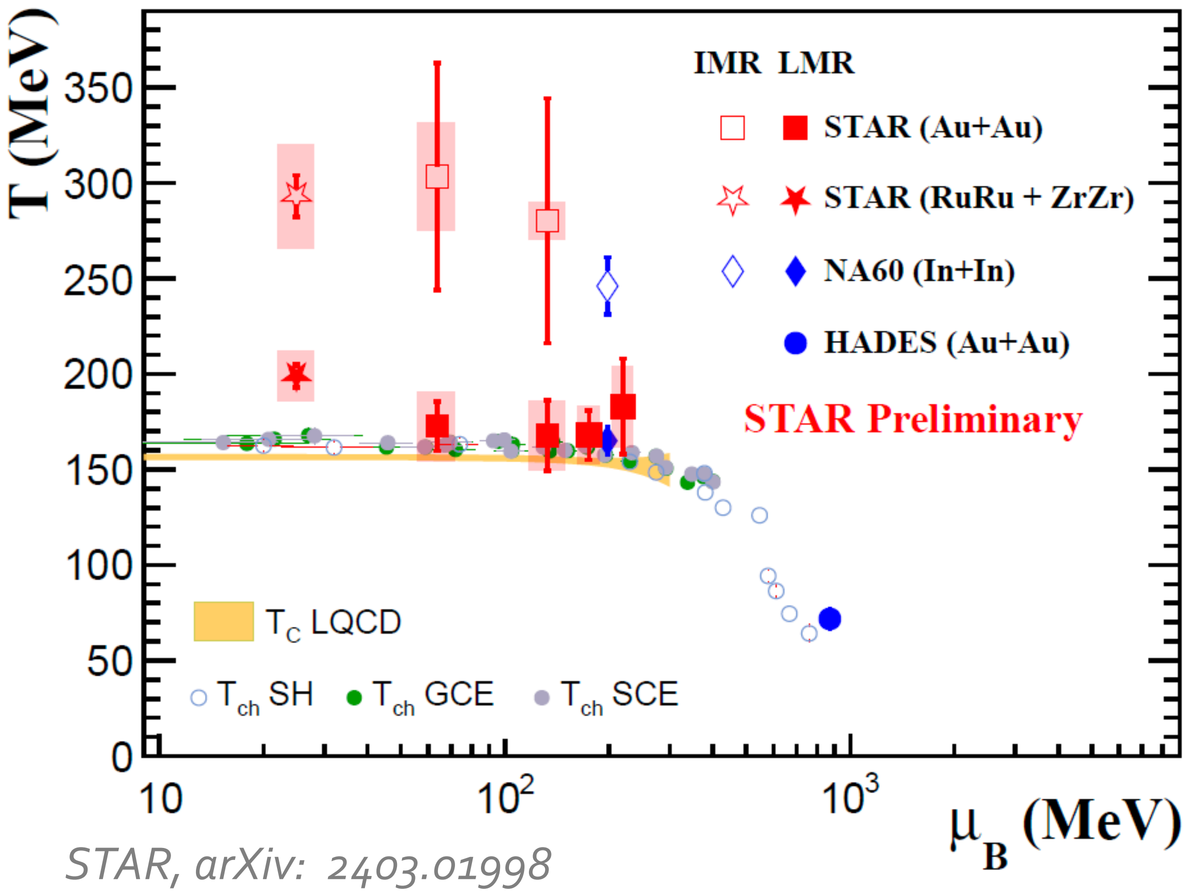
- Close to T_{ch} and T_{pc}
- Dielectrons dominantly emitted around phase transition

T_{IMR}:

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

Temperature v.s. μ_B

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

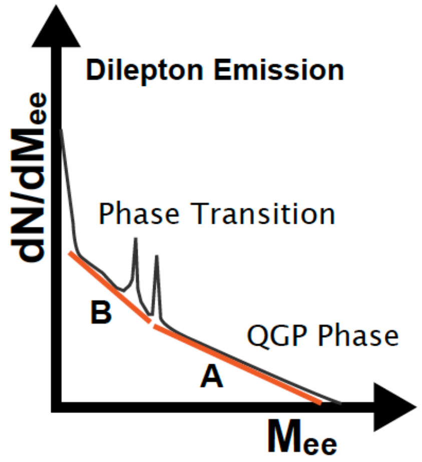


STAR, arXiv: 2403.01998

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 photons in Beam Energy Scan

Challenges: Direct Photon Puzzle

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

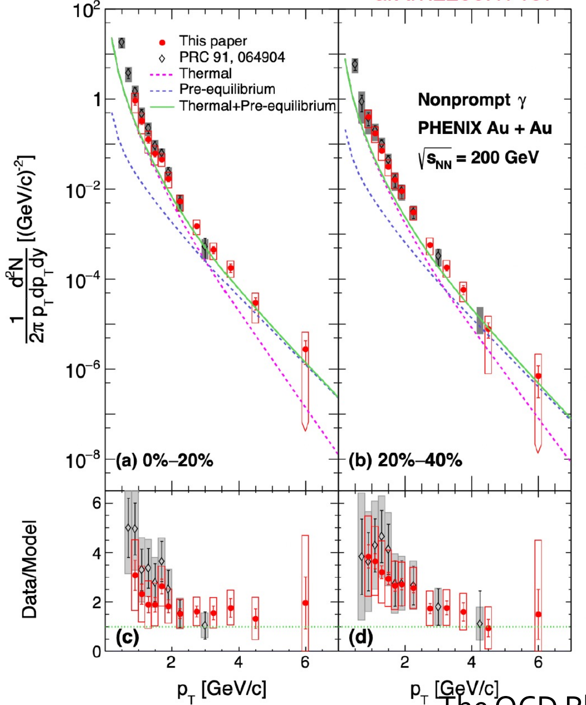
Theoretical calculation can not explain the spectra and v_n simultaneously

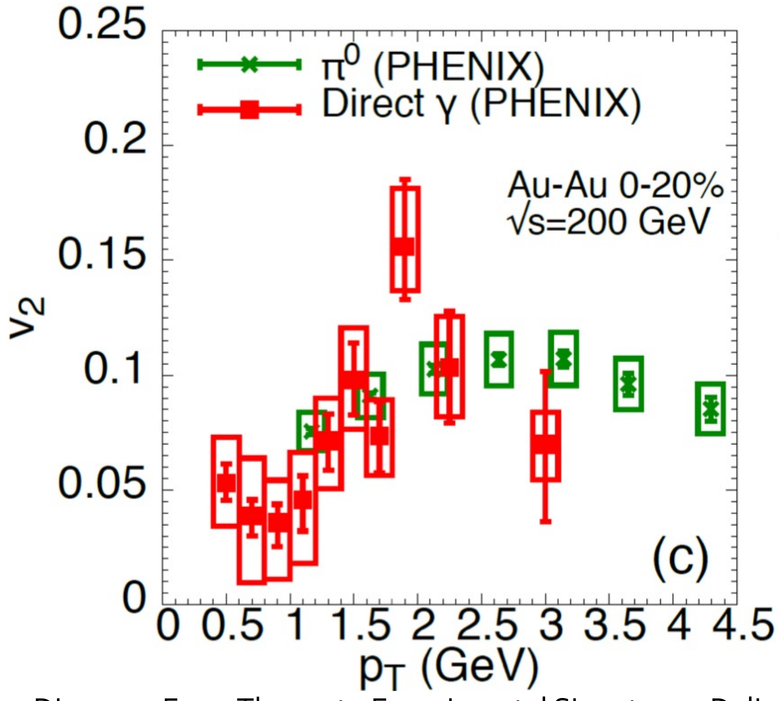
Helmholtz Alliance
Extremes of Density and Temperature: Cosmic Matter in the Laboratory
ExtreMe Matter Institute EMMI
EMMI Rapid Reaction Task Force
Direct-Photon Flow Puzzle
February 24-28, 2014, GSI, Darmstadt, Germany

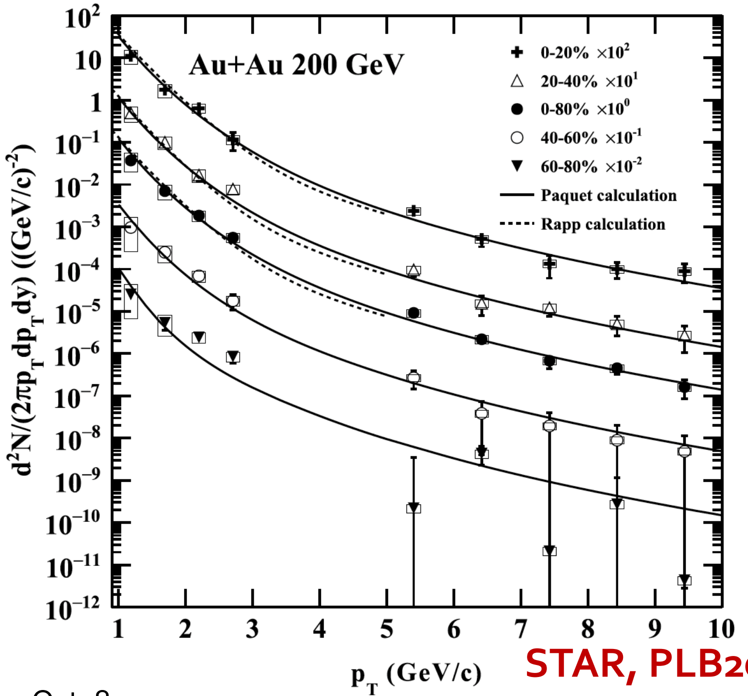
Became even more complicated

ExtreMe Matter Institute EMMI
EMMI Rapid Reaction Task Force
Direct-Photon Puzzle
Heidelberg University, Germany July 24 – 27, 2023

arXiv:2203.17187



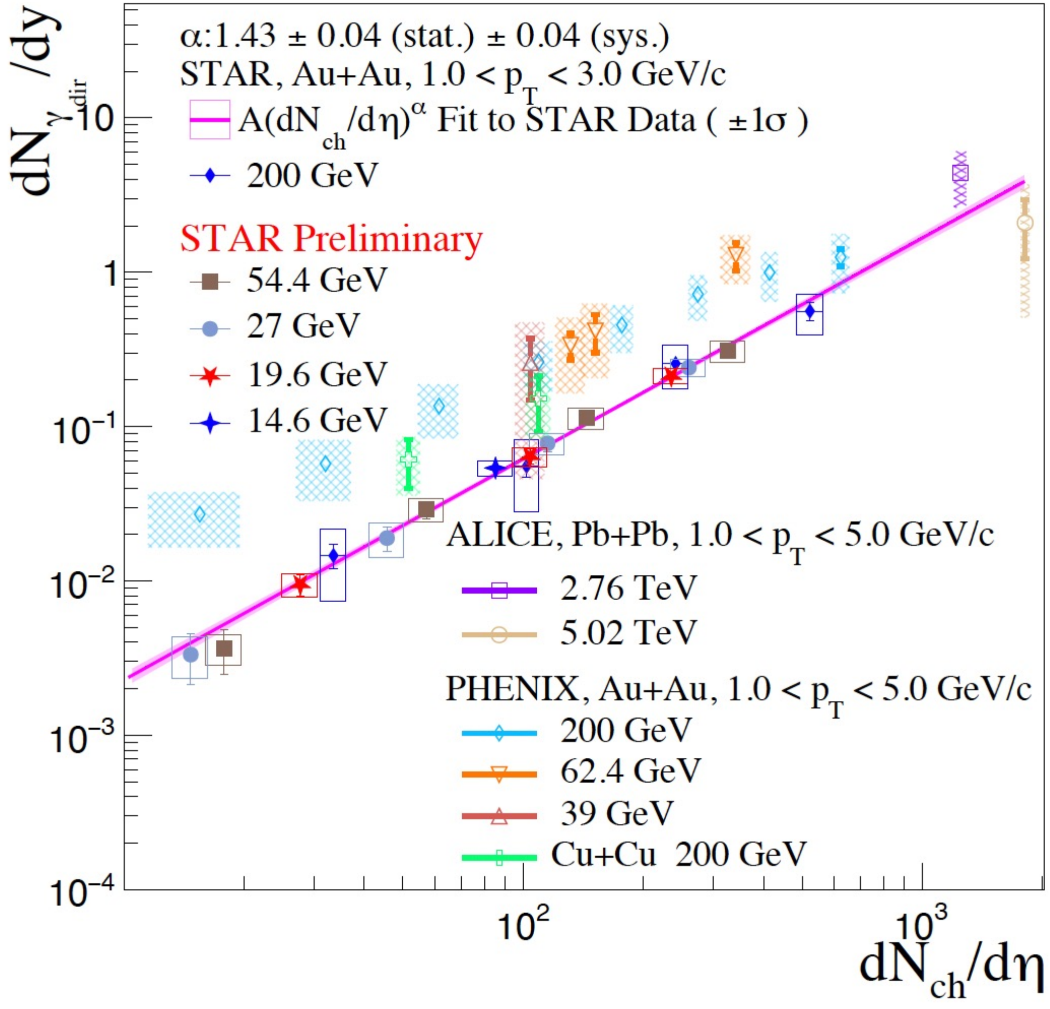




STAR, PLB2017

Direct photon yields at RHIC and LHC

Prompt + Thermal Photons



- dN_{ch} **/dη scaling over centralities and energies**

(200GeV to 14.6 GeV)

- Indicating **similar emission source and properties**

Scaling power **STAR: ~ 1.4 PHENIX: ~ 1.1**

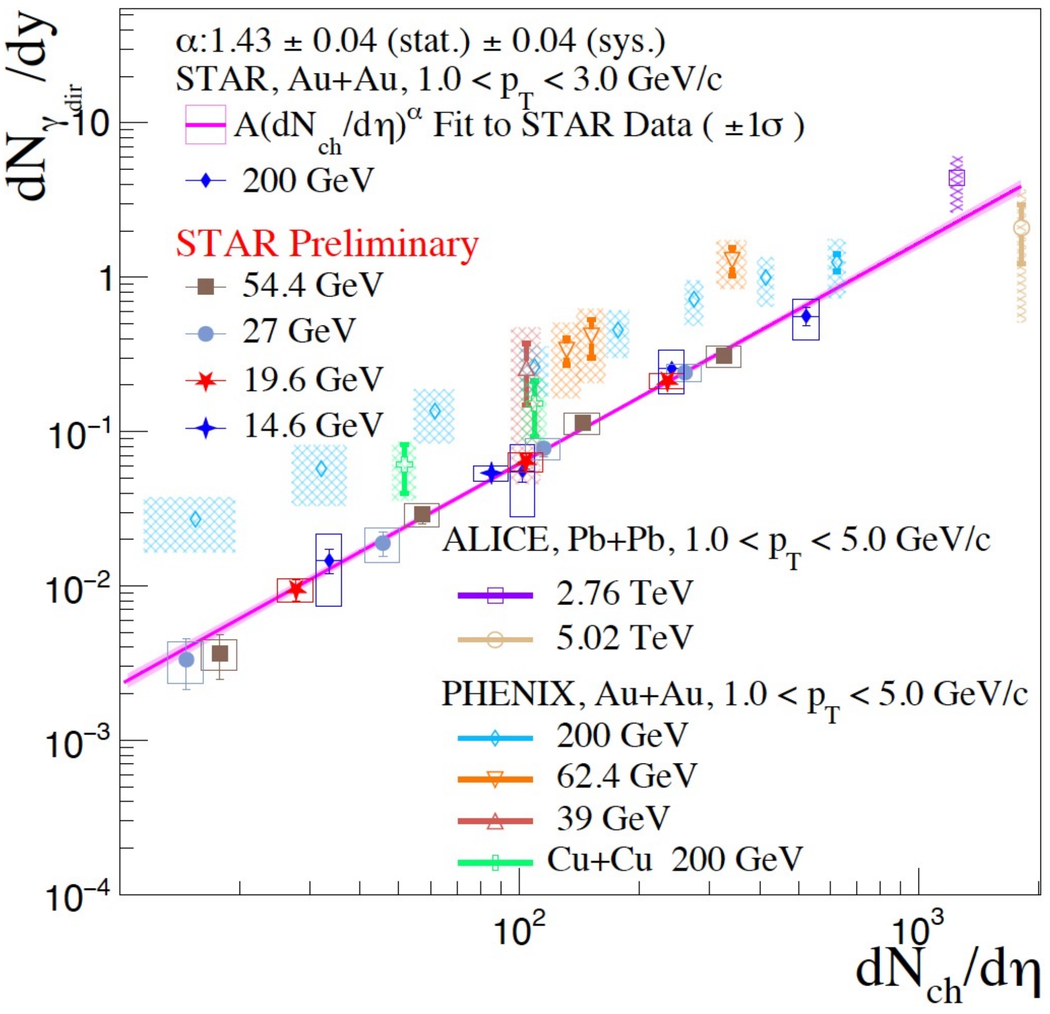
(QGP: ~ 1.8 Hadronic medium: ~ 1.2)

C. Shen et al., PRC 89 (2014) 0444910

STAR, PLB 770 (2017) 451-45
PHENIX, PRC 109 (2024) 044912
ALICE, arXiv: 2308.16704; arXiv: 2411.14366

Direct photon yields at RHIC and LHC

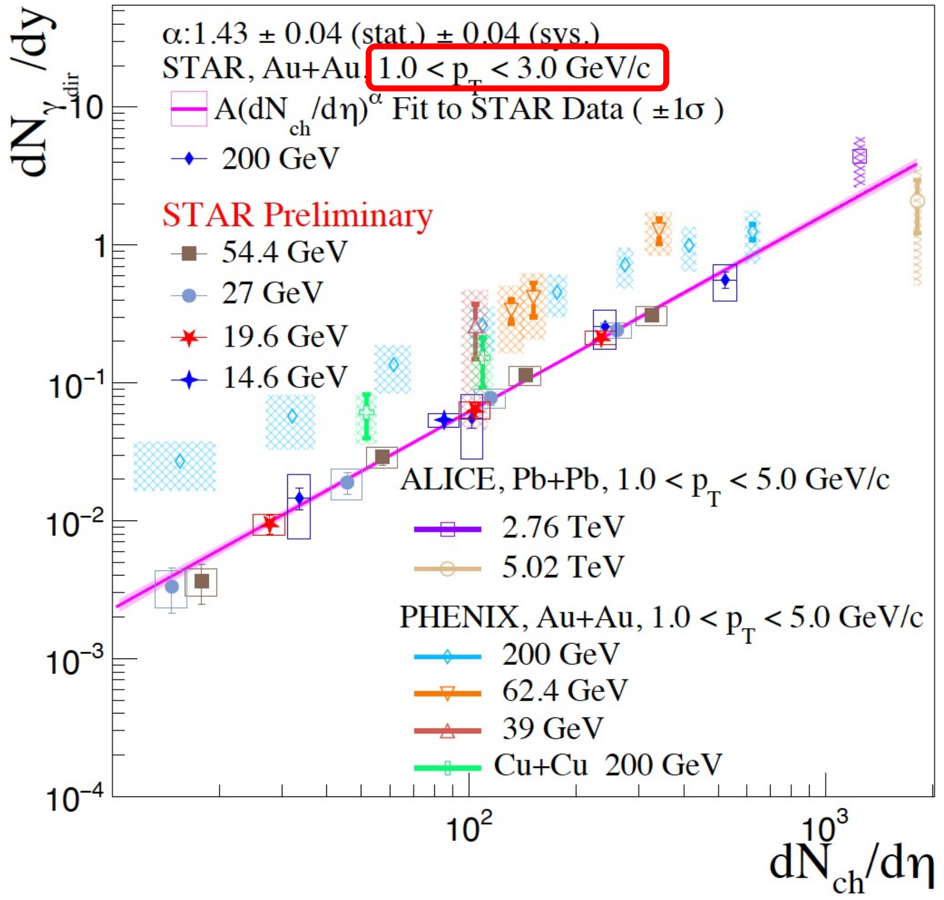
Prompt + Thermal Photons

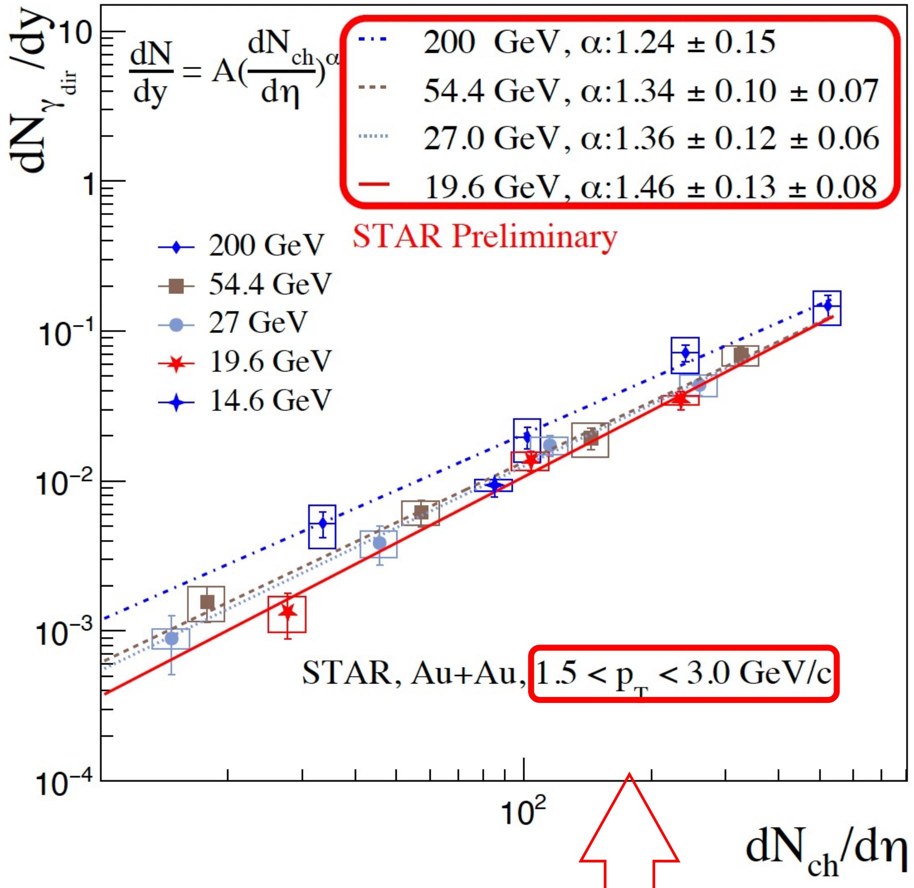


- Universal scaling with multiplicity?
- Onset of thermalization?
- **Can be linked to the search of CEP?**

STAR, PLB 770 (2017) 451-45
PHENIX, PRC 109 (2024) 044912
ALICE, arXiv: 2308.16704; arXiv: 2411.14366

Direct photon yields in different p_T region





- Hint of increasing α with decreasing collision energies from 200 to 19.6 GeV
- Hint of prompt photon fraction at higher p_T is larger in low energy than that in high energy

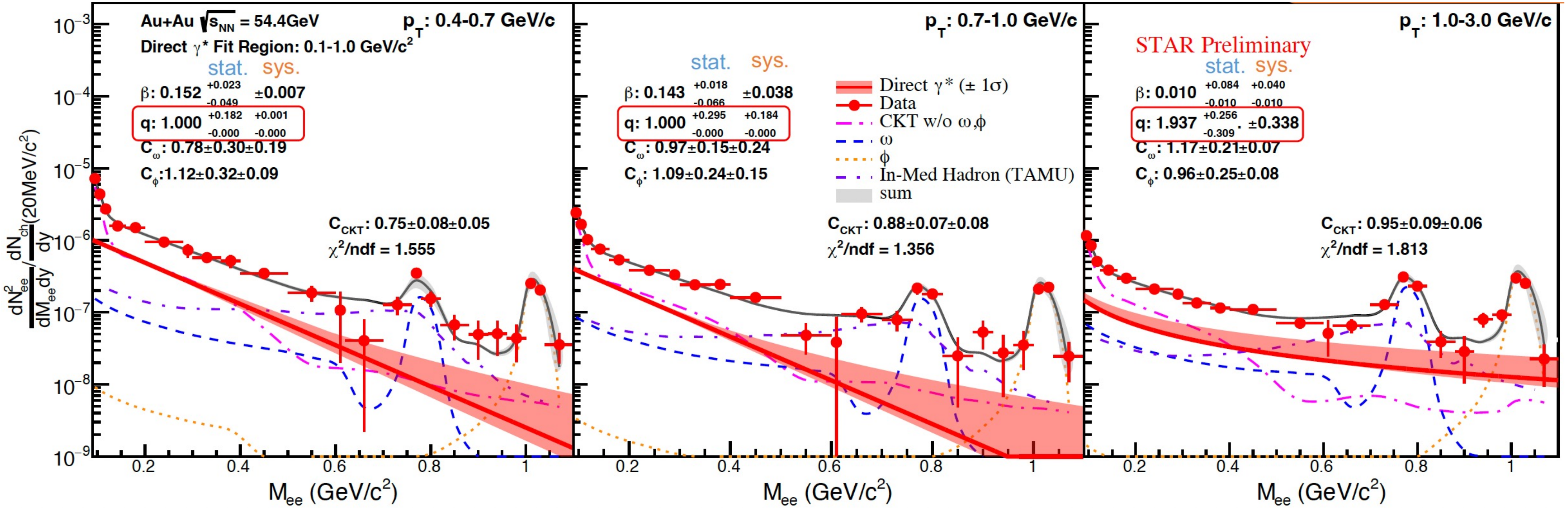
Direct virtual photon mass shape

$$\frac{dN_{ee}}{dM_{ee}} = \gamma^{direct} + C_{ckt} * f_{ckt(w/o\ \omega,\phi)} + H_{In-medium} + C_{\omega} * f_{\omega} + C_{\varphi} * f_{\varphi}$$

Build a function to describe the mass shape

$$\frac{dN}{dM} = C * [1 + (q-1)\frac{M_{ee}}{\beta}]^{-\frac{1}{q-1}}$$

- **Power-law** (1/M) ⟵ dominated by internal conversion from earlier stage (**q~2**)
- **Exponential** (e^{-M}) ⟵ dominated by thermal radiation from later stage (**q~1**)



- As p_T increases, shape changes from exponential to power-law, indicating the direct virtual photon produced in later to earlier stages respectively
- Need to go to lower pT (< 1 GeV/c) to access "critical" region?

About Direct Photon Puzzle

Yield

- Seems more clear with new measured STAR and ALICE results (arXiv: 2411.14366)

v_n

- Still need more measurements especially for π^0 and v_2 from other experiment (STAR Run 23 and 25, MPD, CBM)

Theoretical calculations should simultaneously describe direct photons and dileptons.

Detail double check is still ongoing…

Future Opportunities

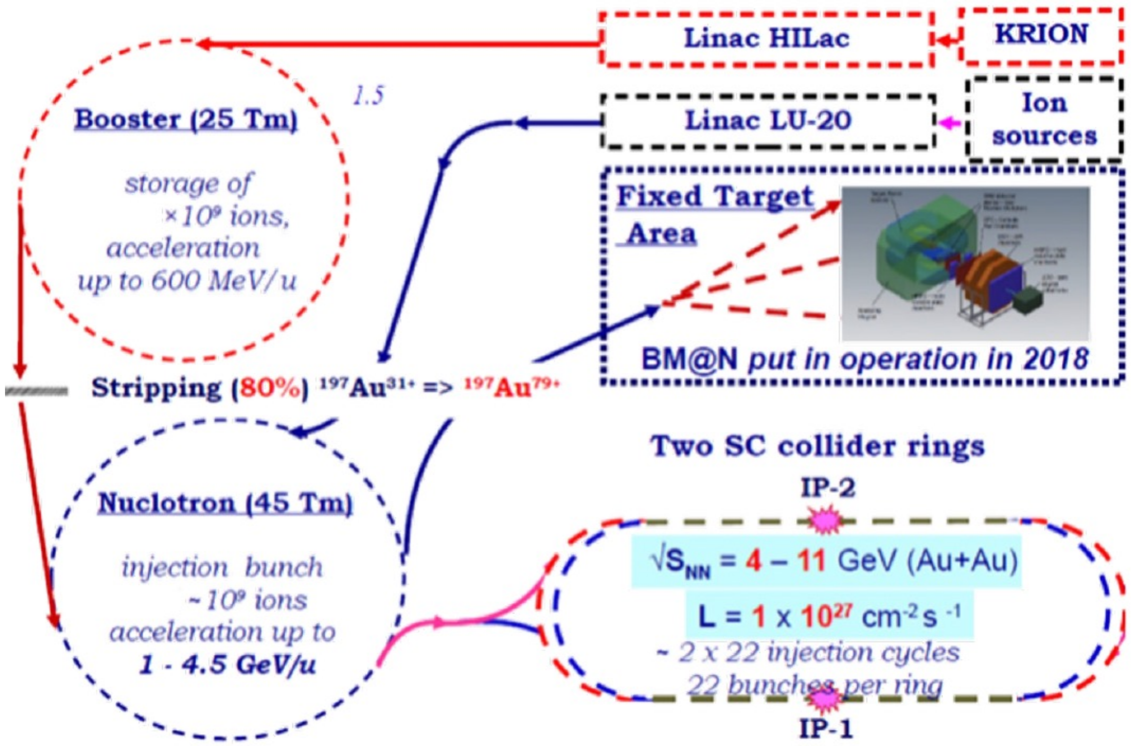
In RHIC and LHC

ALICE Run 3 and RHIC Run 23-25: in low baryon chemical potential region with large statistics and good precision

In FAIR and NICA

Extend to lower beam energy with good statistics

Nuclotron based Ion Collider fAcility (NICA)

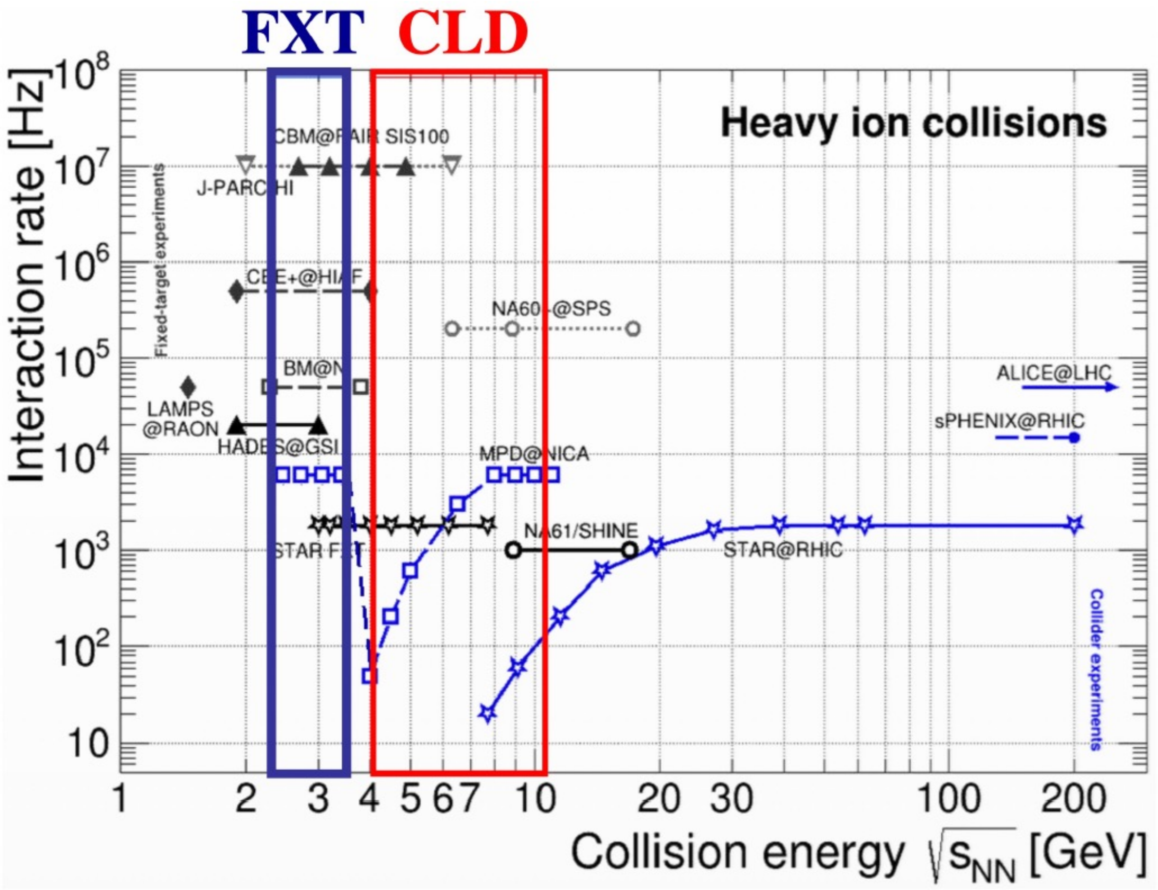


The mega-science project -- NICA, is approaching its full commissioning:

- 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):

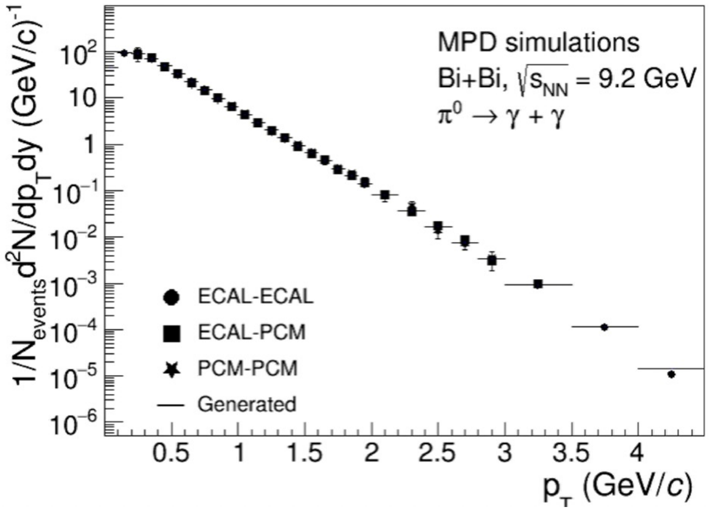
- MPD-CLD (collider mode): Xe/Bi + Xe/Bi at 7 GeV
- MPD-FXT (fixed target mode): Xe/Bi + W at 3 GeV
- 4 - 11GeV at collider mode

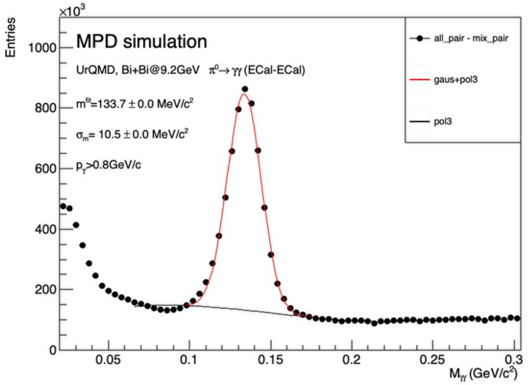
Beam energy overlap: HADES, STAR BES, HIAF, NA61/SHINE and CBM

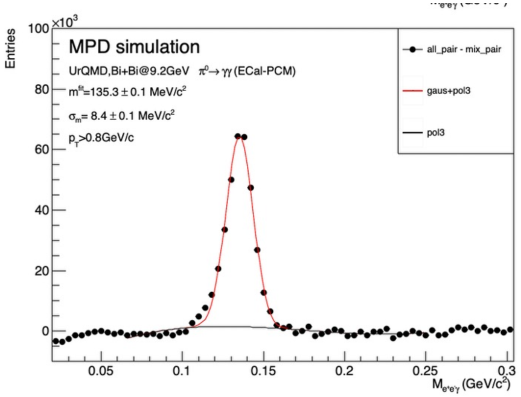
Advantages of MPD in EM probes study

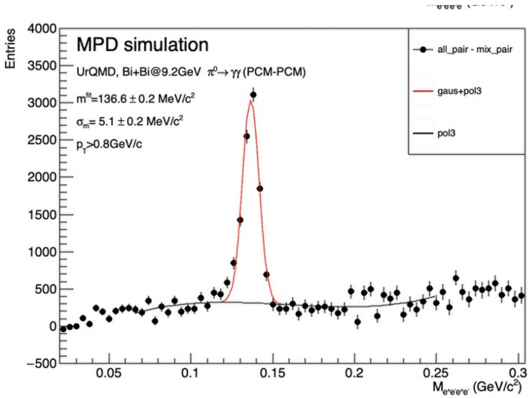
- **Neutral particles reconstruction capability via ECal (π^0 , η ...)**
- TPC+TOF+EMC eID and $\boldsymbol{\gamma}$ID
- Expect large data sample in the finite μ_B region
- **Can measure various observables via different methods (yield, v_2, internal, external...)**
- Connecting RHIC and HADES/CBM

MPD, EPJA 58,140 (2022)







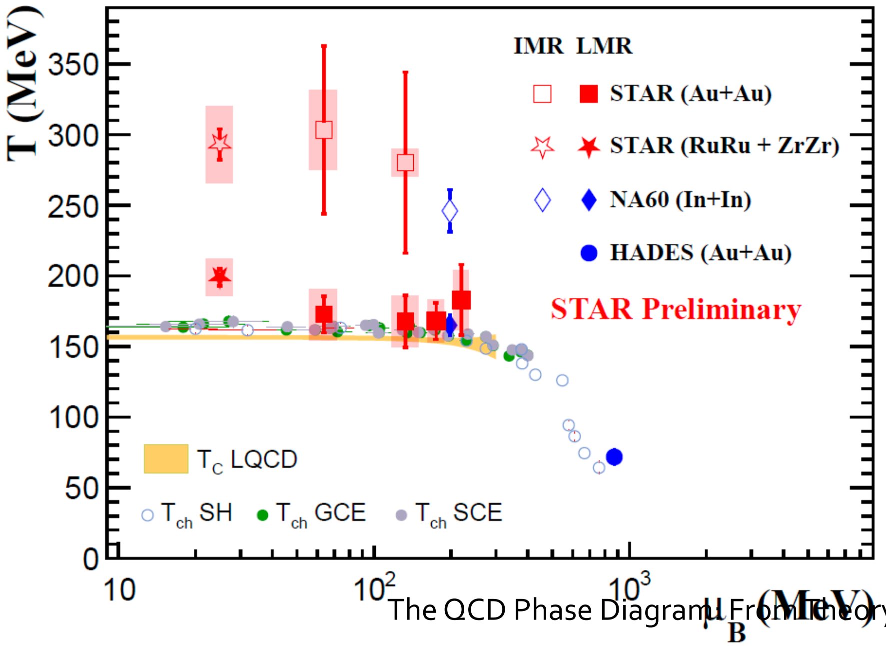


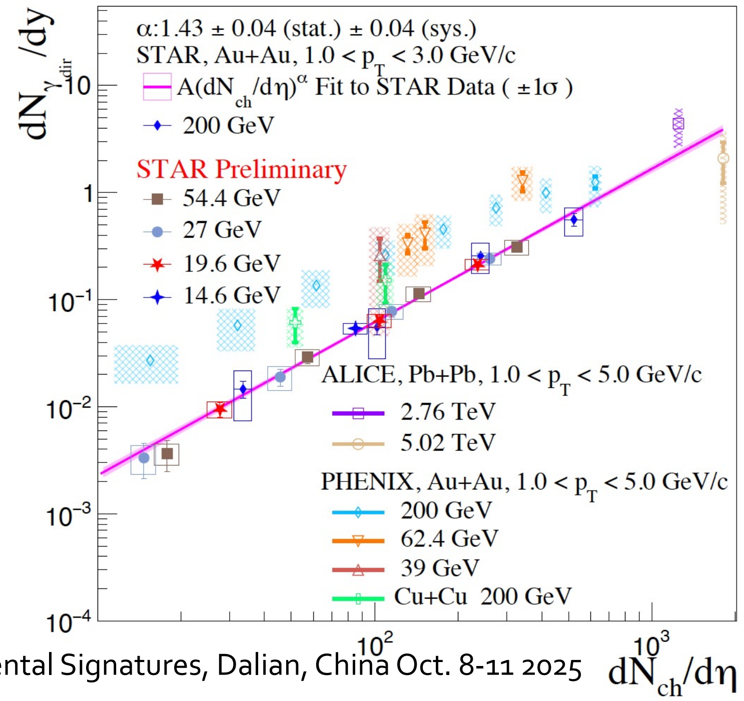
Summary

Over the last decade, there are plenty of physics measurements on dileptons and direct photons

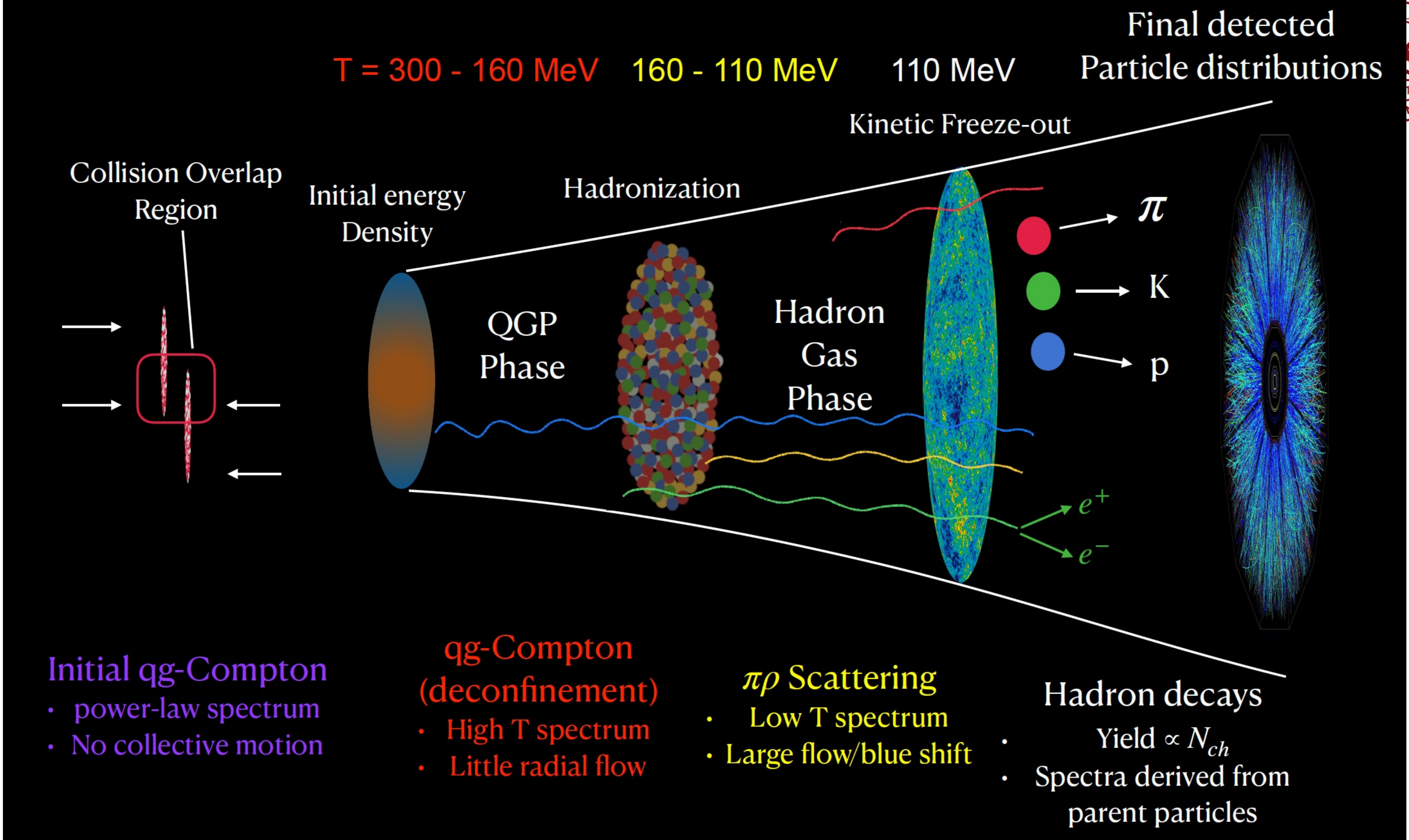
- **Temperature** of QGP in different stages measured via dielectron
- **VM in-medium modification** with improved precision

- **Scaling behavior** of direct photons yield observed
- **Production mechanism** of the direct photon have been studied
- NICA-MPD and FAIR-CBM will enable the detail studies of dileptons and direct photons in the "critical" energy region





Backup



T = 300 - 160 MeV
160 - 110 MeV
110 MeV
Final detected Particle distributions
Kinetic Freeze-out
Collision Overlap Region
Initial energy Density
Hadronization
QGP Phase
Hadron Gas Phase
π
K
p
e^+
e^-
Initial qg-Compton
• power-law spectrum
• No collective motion
qg-Compton (deconfinement)
• High T spectrum
• Little radial flow
$\pi\rho$ Scattering
• Low T spectrum
• Large flow/blue shift
Hadron decays
• Yield $\propto N_{ch}$
• Spectra derived from parent particles

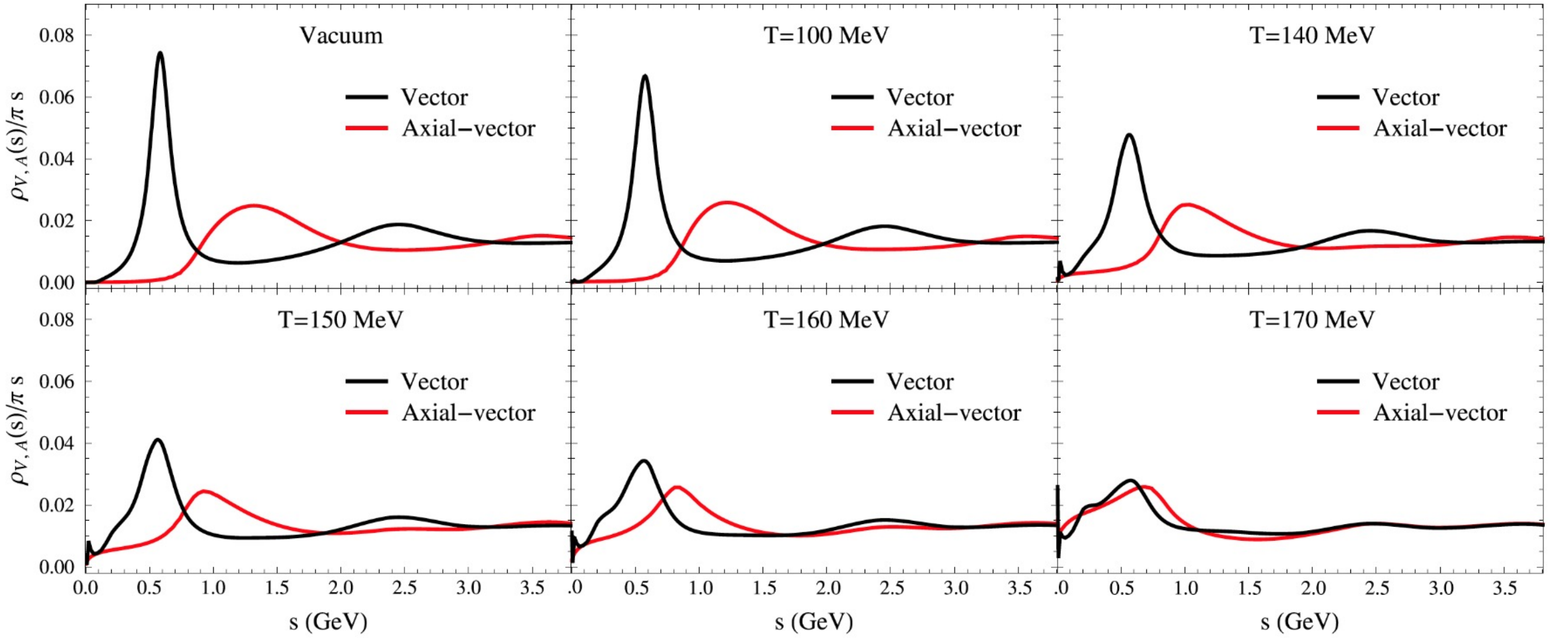
Why ρ?

π in final states: suffer absorption effect

a1(1260) resonance : low rates; broad structure, 0.4 GeV in vacuum

ρ: short lifetime,1.3 fm/c in vacuum

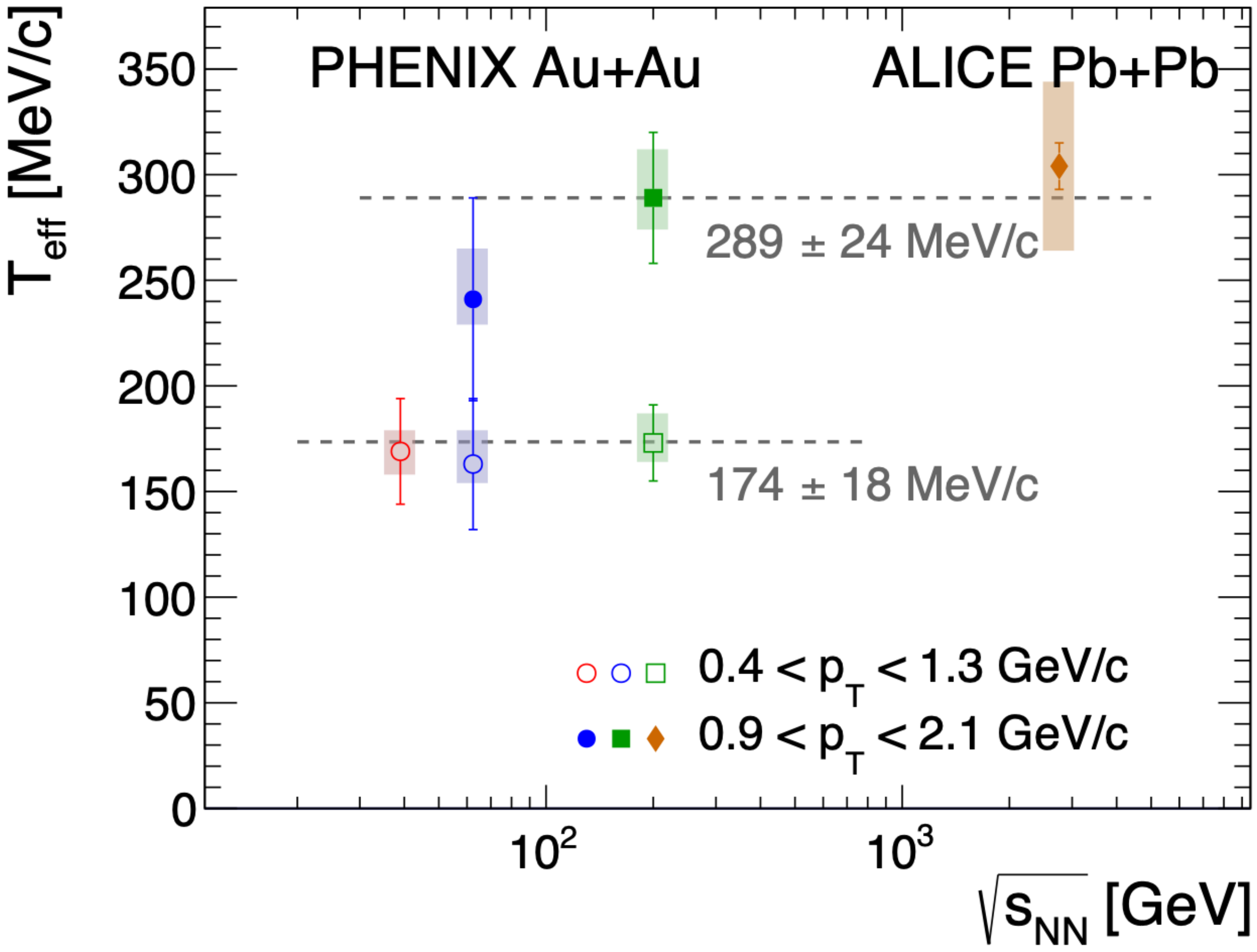
prevalent coupling to **ππ** annihilation



P.M. Hohler, R. Rapp PLB 731, 103–109 (2014)

T_{slope} from Thermal Photons

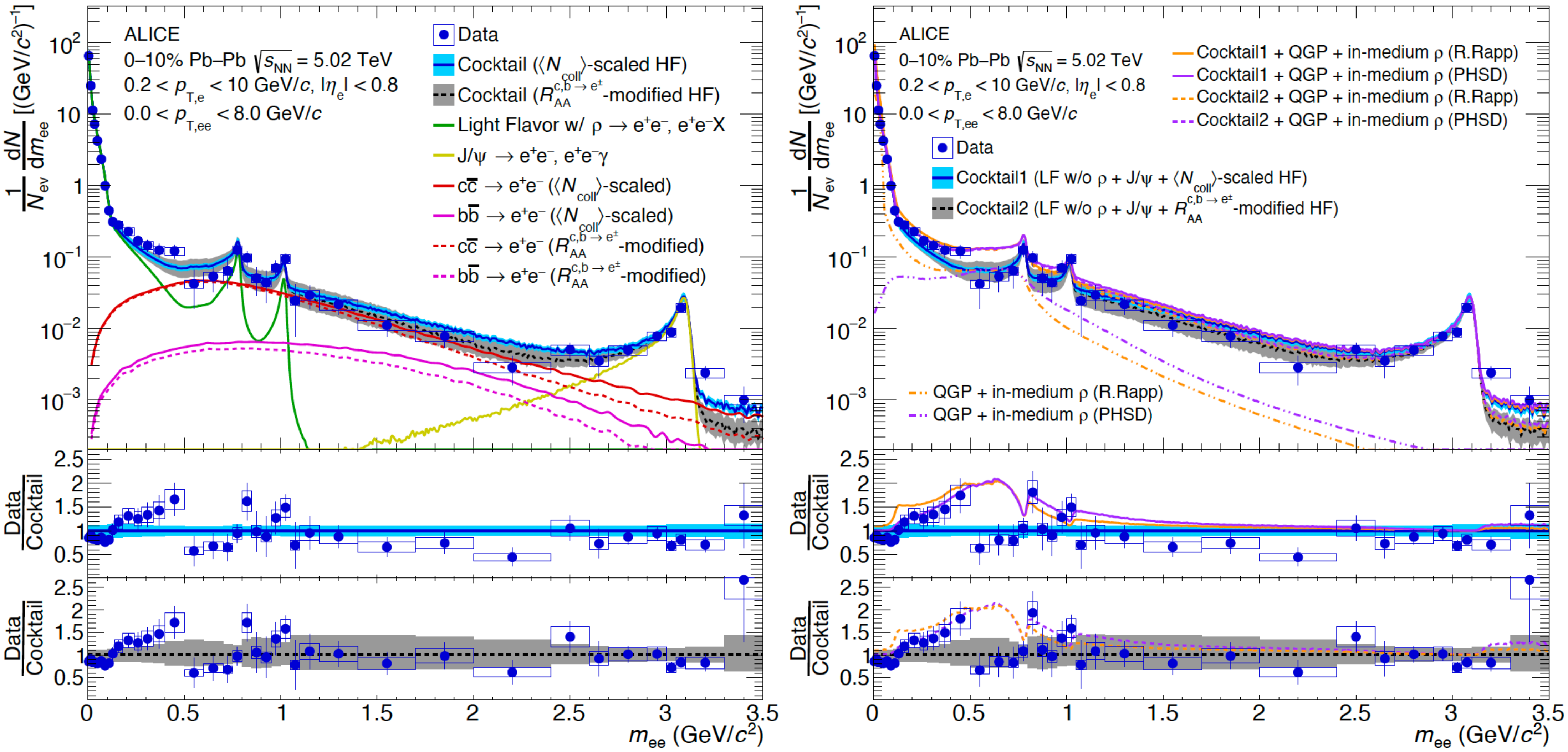
PHENIX, PRC 107, 024914 (2023)



- Clear p_T dependence
- The later, the cooler

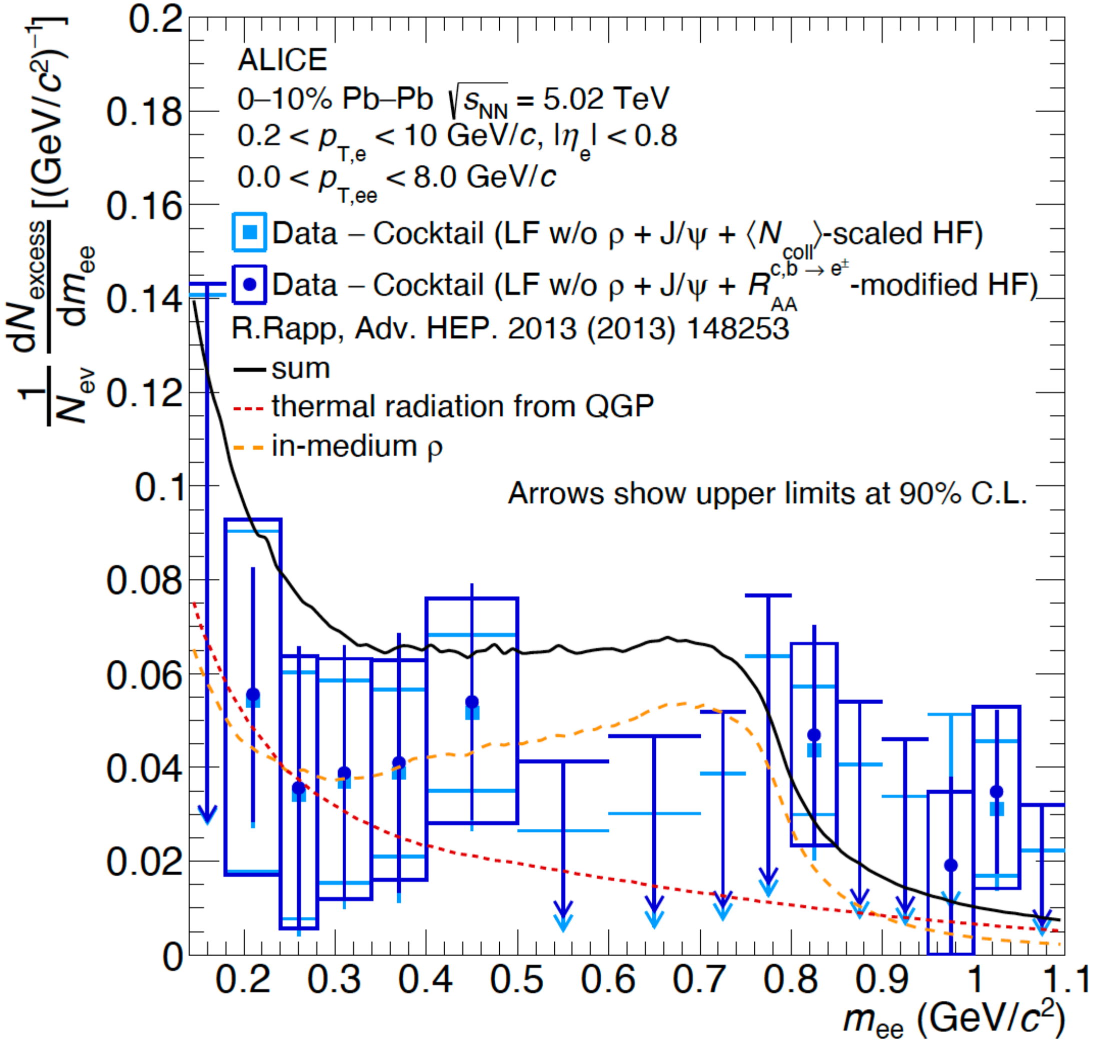
Some theory prediction indicated the blue-shift effect can be used to extract the initial T.

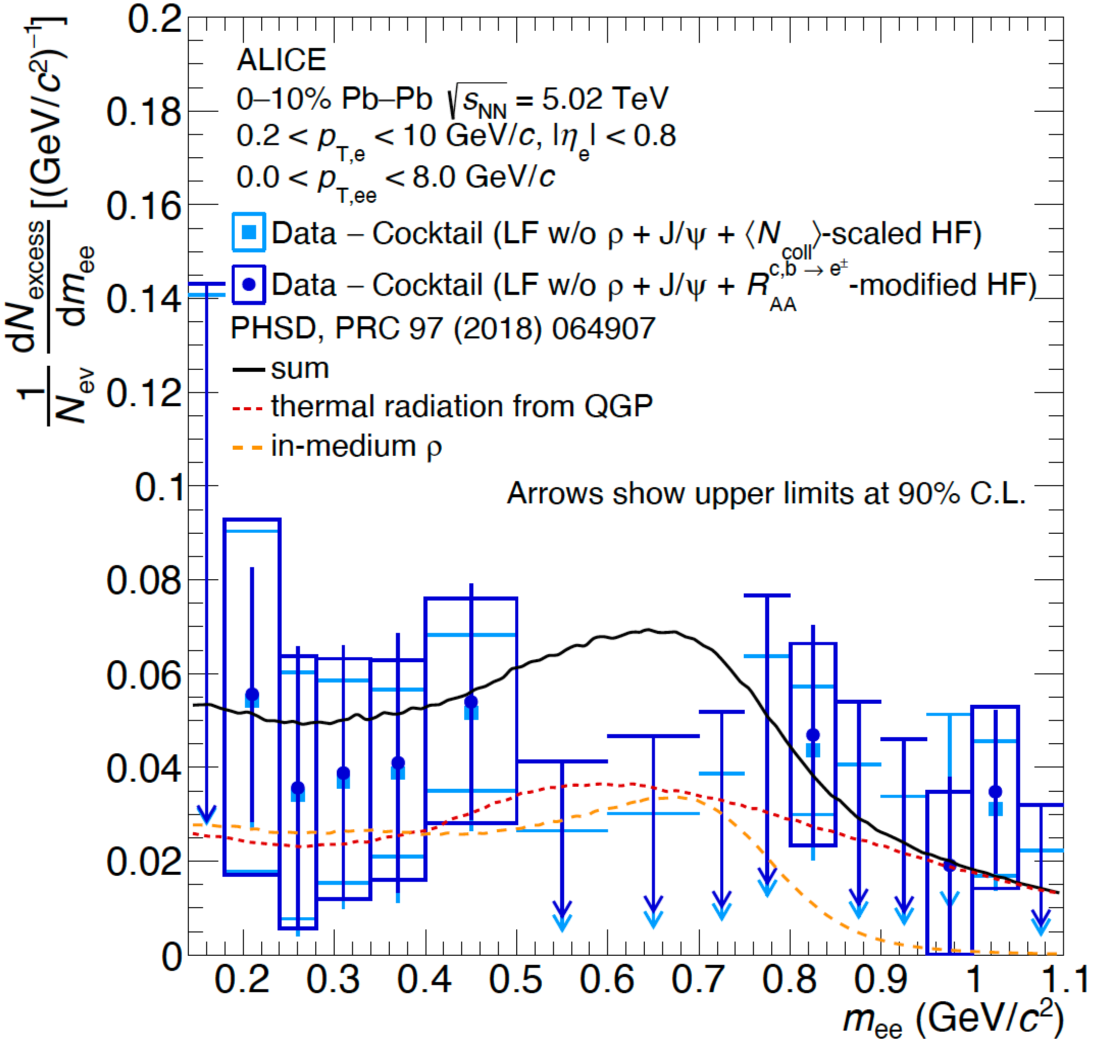
Dileptons at ALICE



- HF semi-leptonic decay impact the low mass cocktail precision *ALICE, arXiv:2308.16704*

Dileptons at ALICE



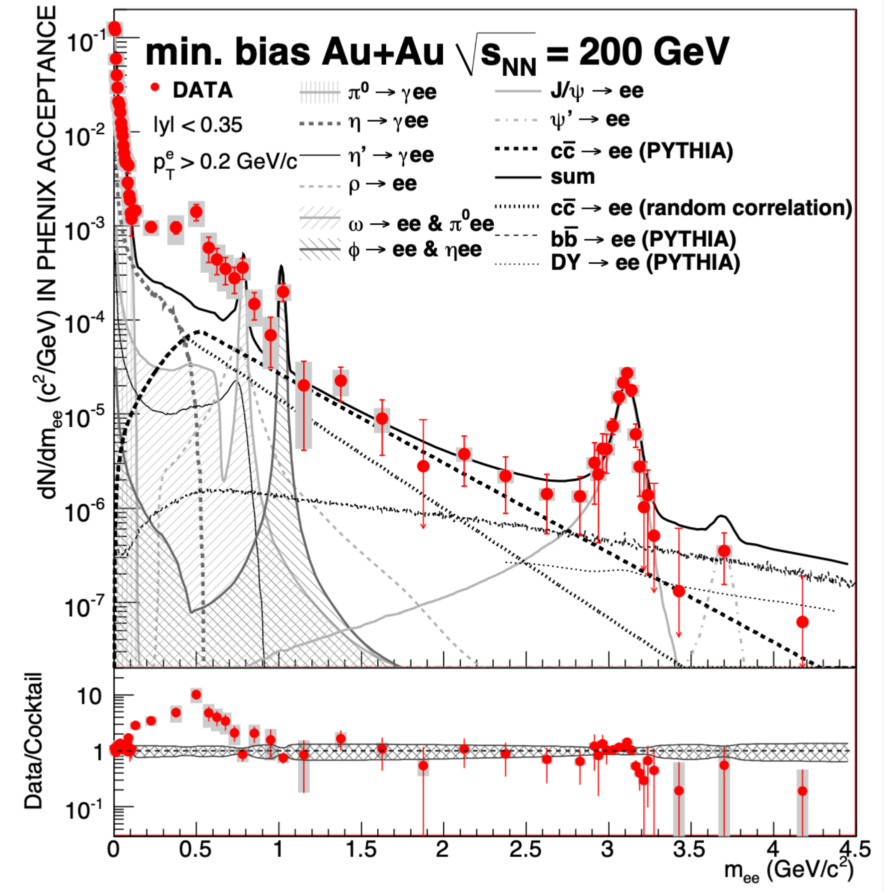


Can not make conclusion on the existence of excesses

ALICE, arXiv:2308.16704

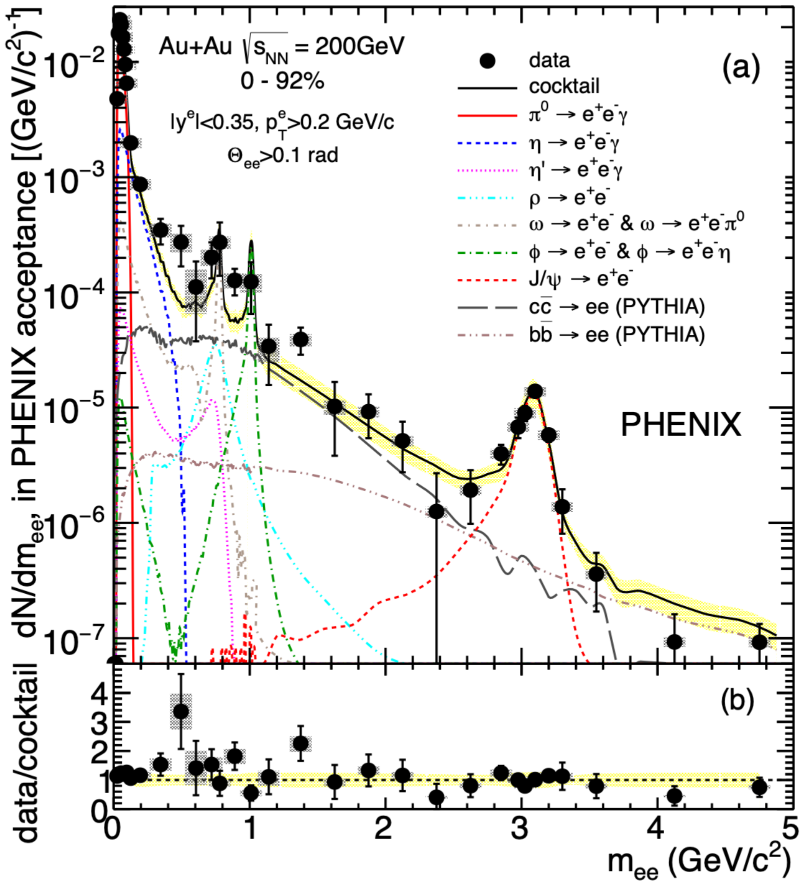
Dileptons at PHENIX

PHENIX, PRC 81, 034911 (2010)



Used to have huge LMR excess

PHENIX, PRC 93, 014904 (2016)



Now consistent with STAR