Direct photon yield and thermal dielectron flow in isobar collisions at STAR

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HIGH ENERGY PHYSICS BRANCH OF CPS

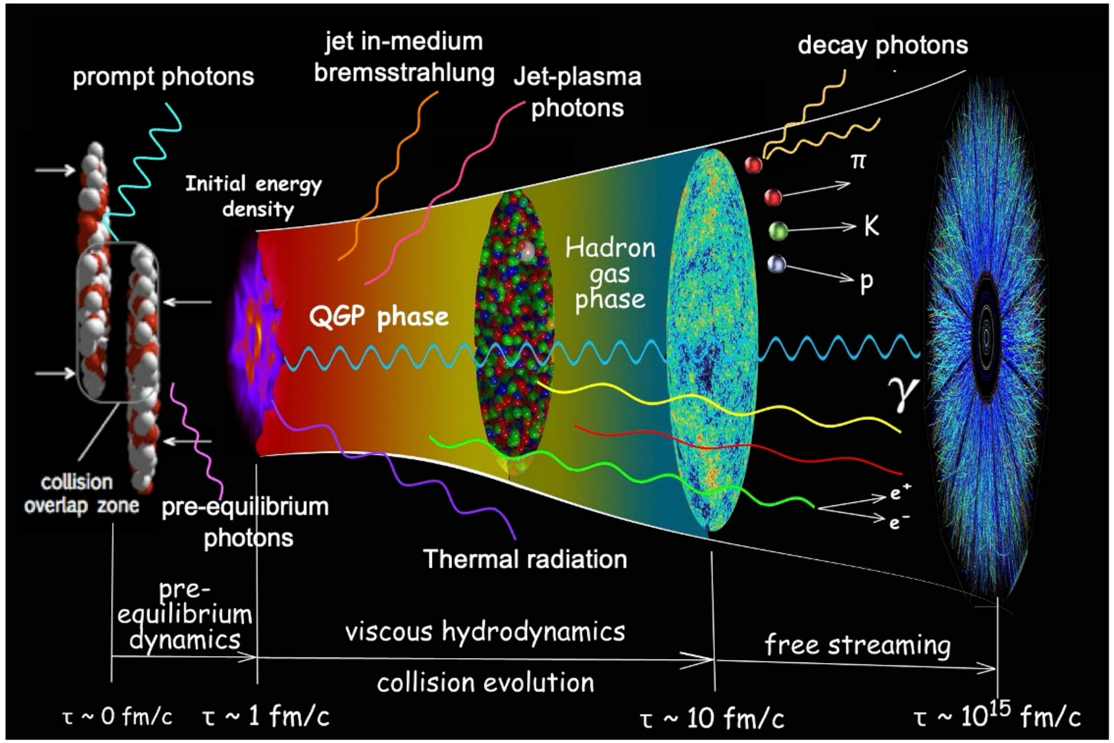
Introduction

- Create deconfined QCD matter at extreme temperature and/or baryon density
- Study the properties of the Quark-Gluon Plasma (QGP) in heavy-ion collisions

Why electromagnetic probes?

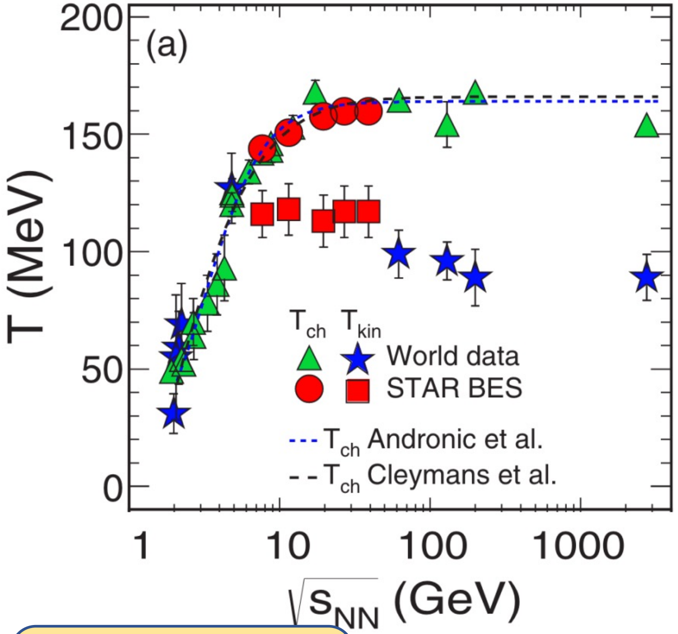
- No strong interaction with medium
- Emitted from initial stage to hadron gas phase
- Carry information on energy density, temperature and collective motion of QGP

Chun Shen et al, *Comput. Phys. Commun.*, 199:61–85, 2016

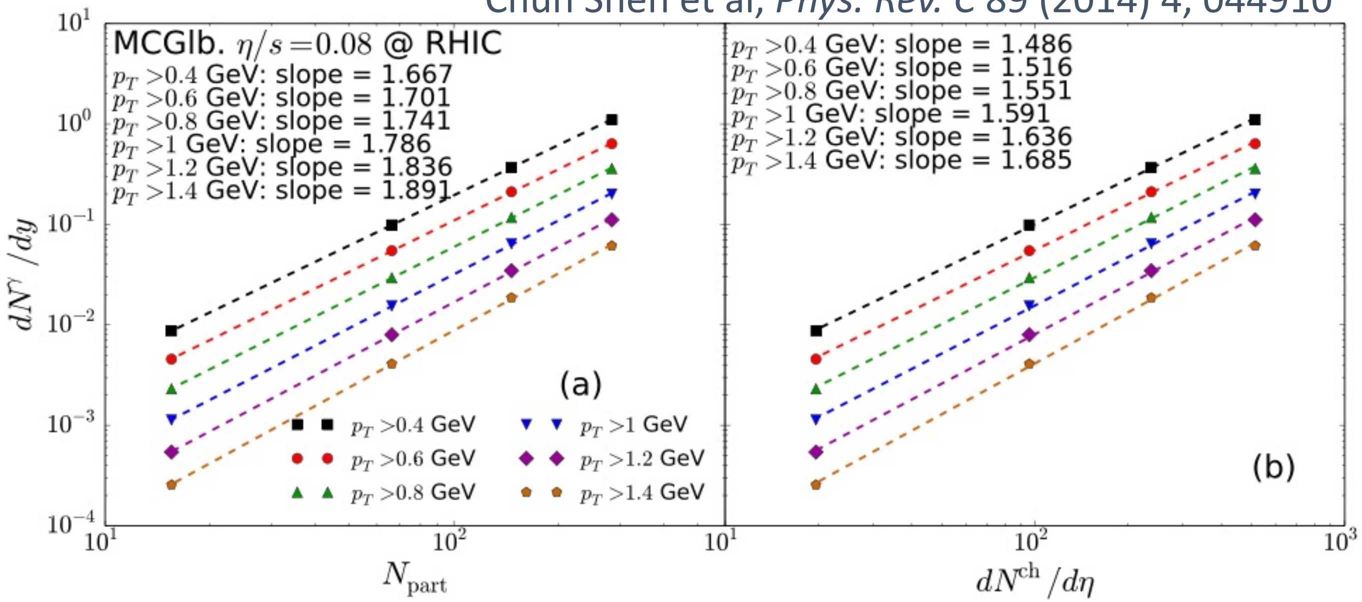


Thermal radiation from hot and dense medium

STAR, *Phys. Rev. C* 96, 044904 (2017)



Chun Shen et al, *Phys. Rev. C* 89 (2014) 4, 044910



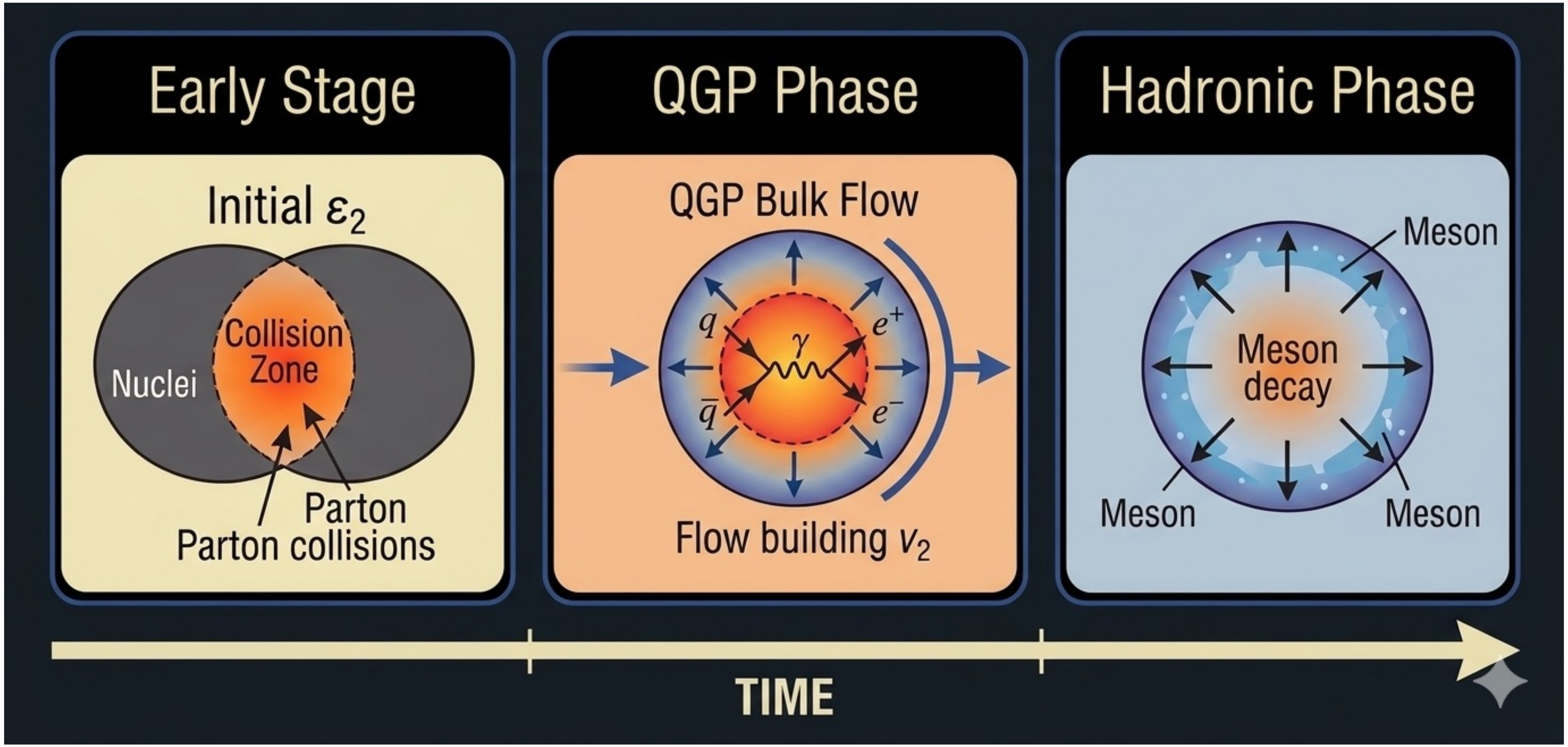
Hadrons (Yield, p_T) → **Statistical thermal model / Hydrodynamics-inspired model** → **Chemical freeze-out T_{ch} / Kinetic freeze-out T_{kin}**

Direct photon/Dilepton :

- **Thermometer**: extract temperature information from the slope of spectra
- **Chronometer**: integrated yield is sensitive to lifetime
- **Magnetometer**: extract magnetic field strength from elliptic flow?

Phys. Rev. C 109 (2024) 3, 034917

Dilepton elliptic flow

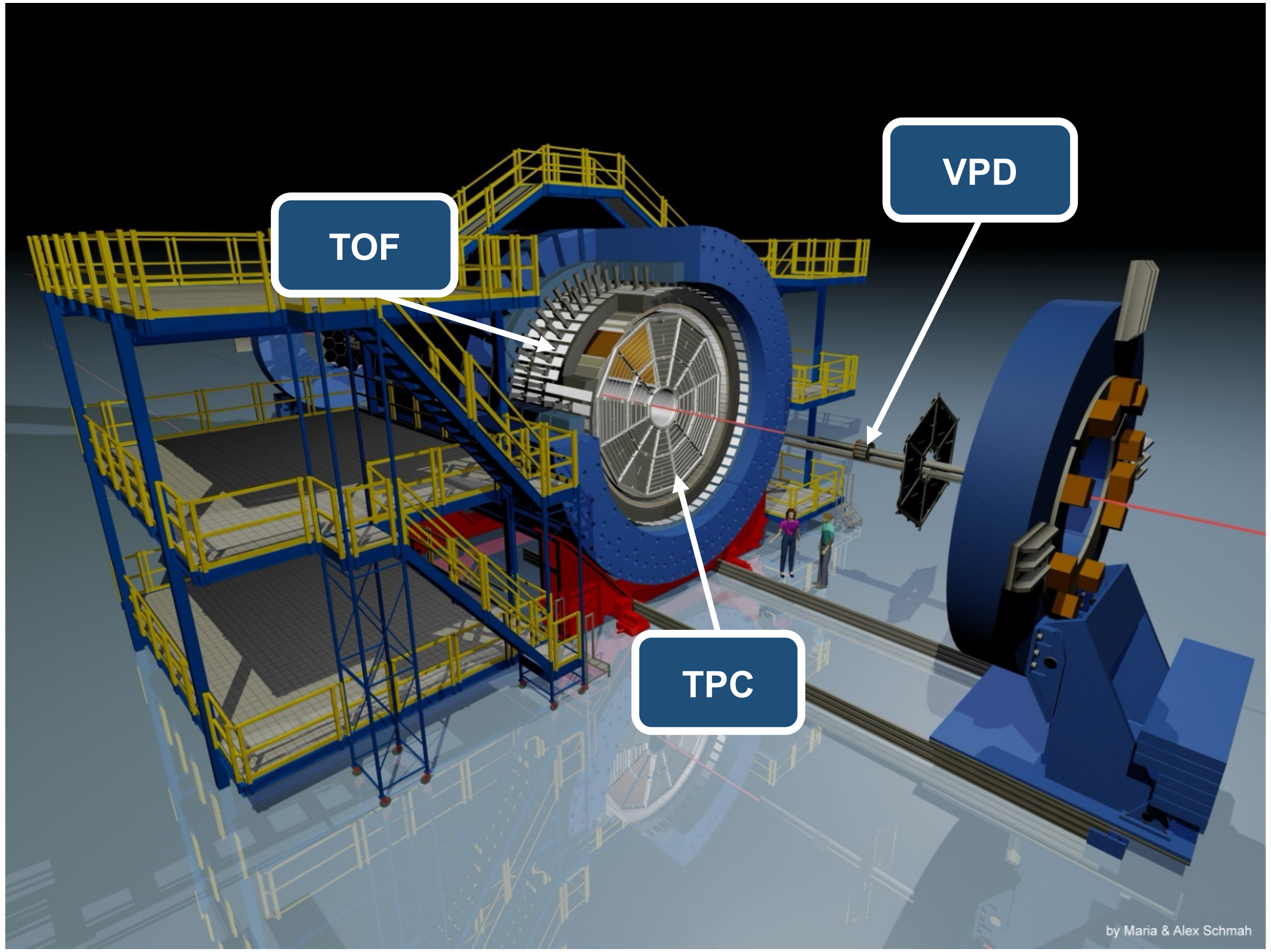


- Initial momentum anisotropy
- Hard scattering
- Primordial e^+e^- pairs

- Pressure gradients convert ε_2 to v_2
- Partonic e^+e^- acquire flow

- Hadron decays dominate low mass
- Final v_2 (p_T) established
- Medium modified spectral functions

The Solenoidal Tracker At RHIC



Time Projection Chamber
- Tracking
- Momentum and energy loss
- Acceptance: $|\eta| < 1;\ 0 \le \varphi \le 2\pi$

Time Of Flight
- Time of flight
- Particle identification
- Acceptance: $|\eta| < 1;\ 0 \le \varphi \le 2\pi$

Collision energy $({}^{96}_{44}\mathrm{Ru}/{}^{96}_{40}\mathrm{Zr})$
- $\sqrt{s_{\mathrm{NN}}} = 200$ GeV (~3.7B events)

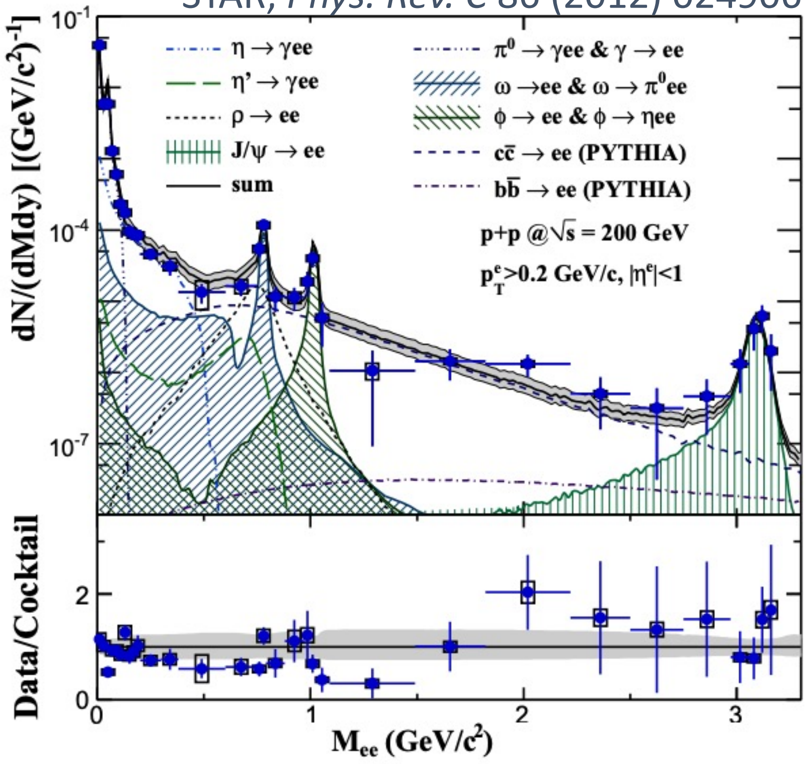
Signals and Hadronic

Hadronic cocktail was well examined in p+p collisions

Signals:
- **QGP radiation**
- **In-medium ρ**
- **Prompt photon**

Background sources (cocktail):
- **Two-body decay:** $\omega,\ \phi,\ J/\psi$
- **Dalitz decay:** $\pi^0,\ \eta,\ \eta'$
- **heavy-flavor decay:** $c\bar{c}$
- $\mathbf{Drell-Yan}$

STAR, *Phys. Rev. C* 86 (2012) 024906

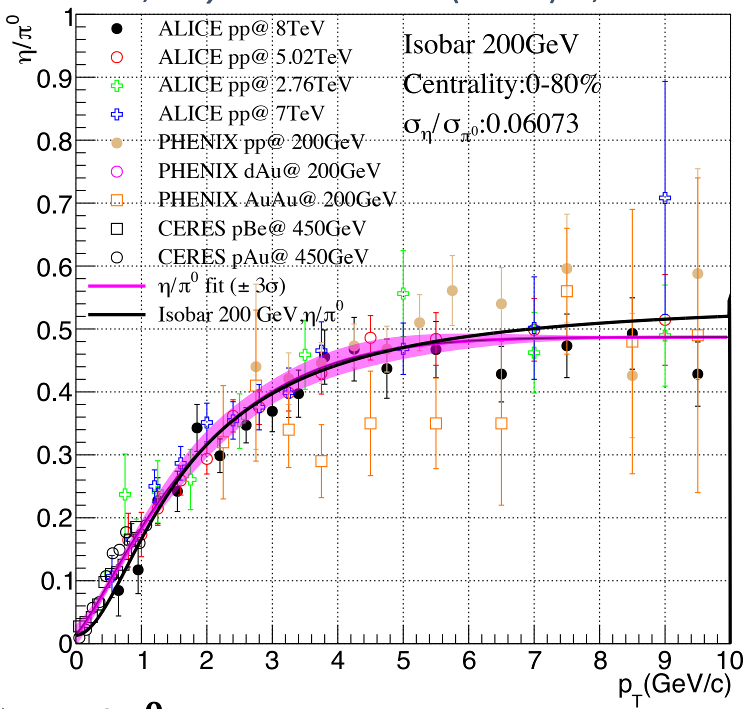


- Hadron p_T shape estimated using Tsallis Blast Wave (TBW) model
- Hadron yield in isobar collisions:
  - $\eta'/\pi^0 = 0.25 \pm 0.08$ (Fixed)
  - $\omega/\pi^0 = 0.90 \pm 0.06$ (Floated)
  - $\phi/K = 0.16 \pm 0.03$ (Floated)

STAR, *Phys. Lett. B* 612 (2005) 181-189
STAR, *Phys. Rev. C* 79 (2009) 064903
J Chen et al, *Phys.Rev.C* 104 (2021) 3, 034901

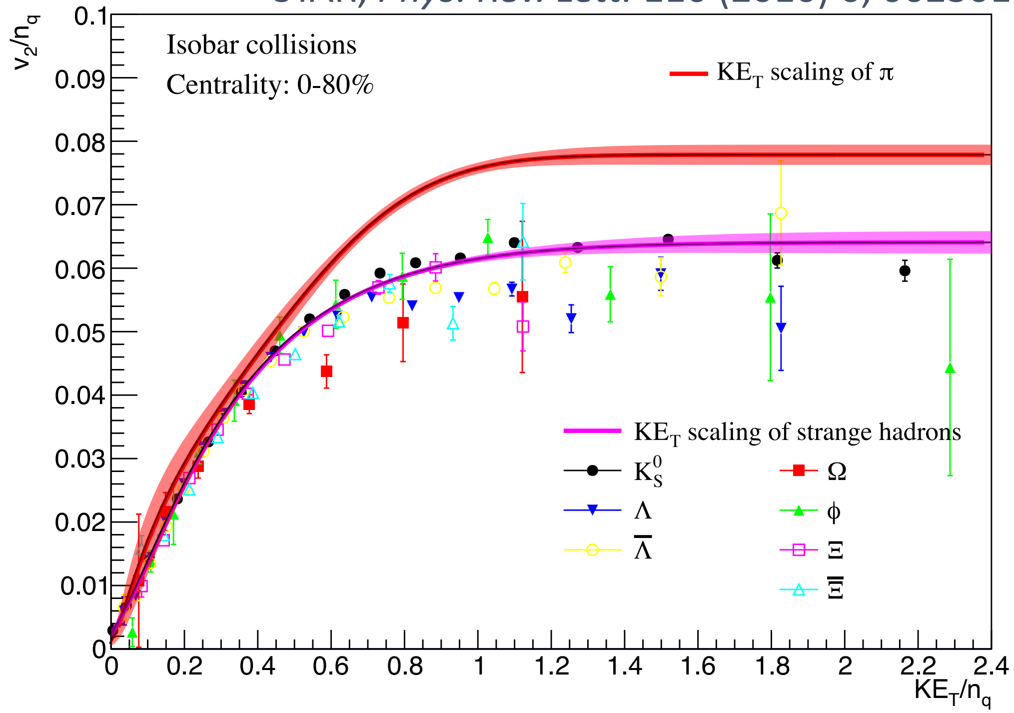
Hadronic cocktail and associated uncertainties

Yuanjie Ren et al, *Phys. Rev. C* 104 (2021) 5, 054902



STAR, arXiv: 2602.12094

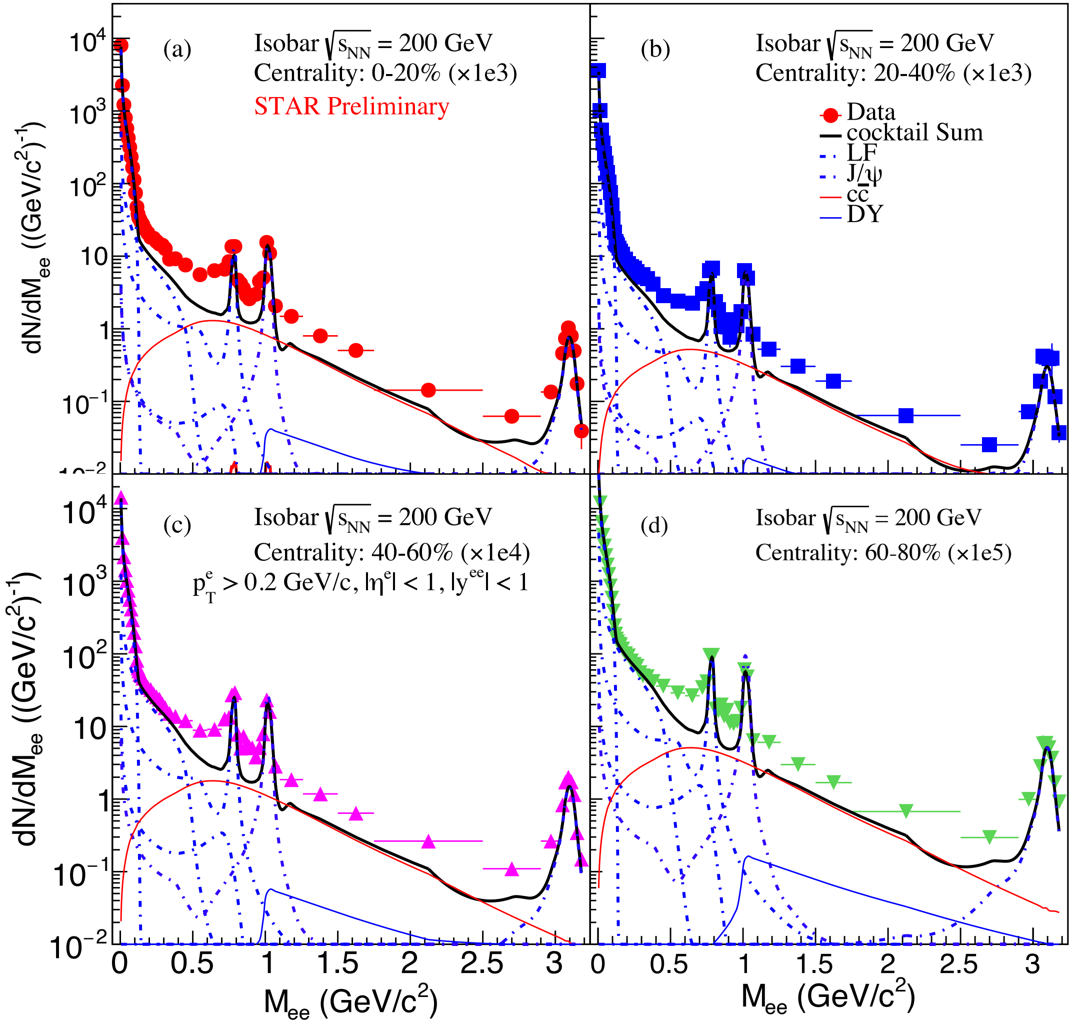
STAR, *Phys. Rev. Lett.* 116 (2016) 6, 062301



- η/π^0
  - Parametrized using Tsallis Blast Wave function
  - Fixed to **0.470±0.017** at p_T = 5 GeV/c

- **Cocktail v_2 input**
  - Deviation of π^0 v_2 is affected by non-flow
  - v_2 of other mesons and uncertainties estimated using KE_T scaling of strange hadrons

Dielectron continuum vs. cocktail in isobar collisions

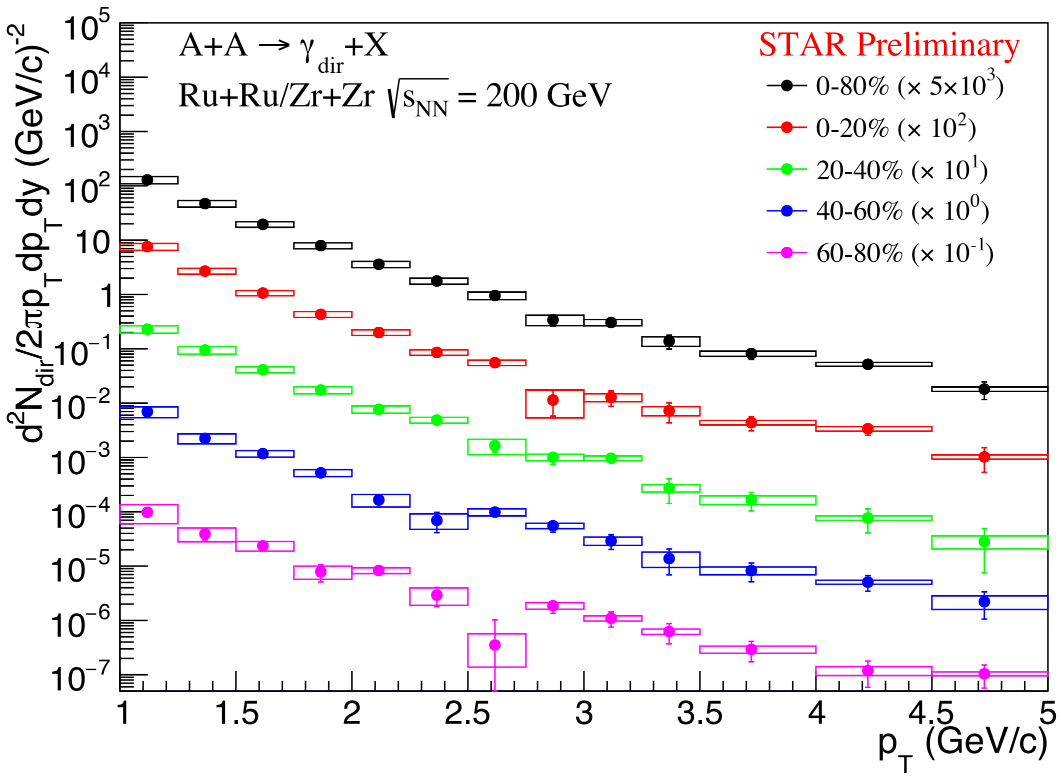


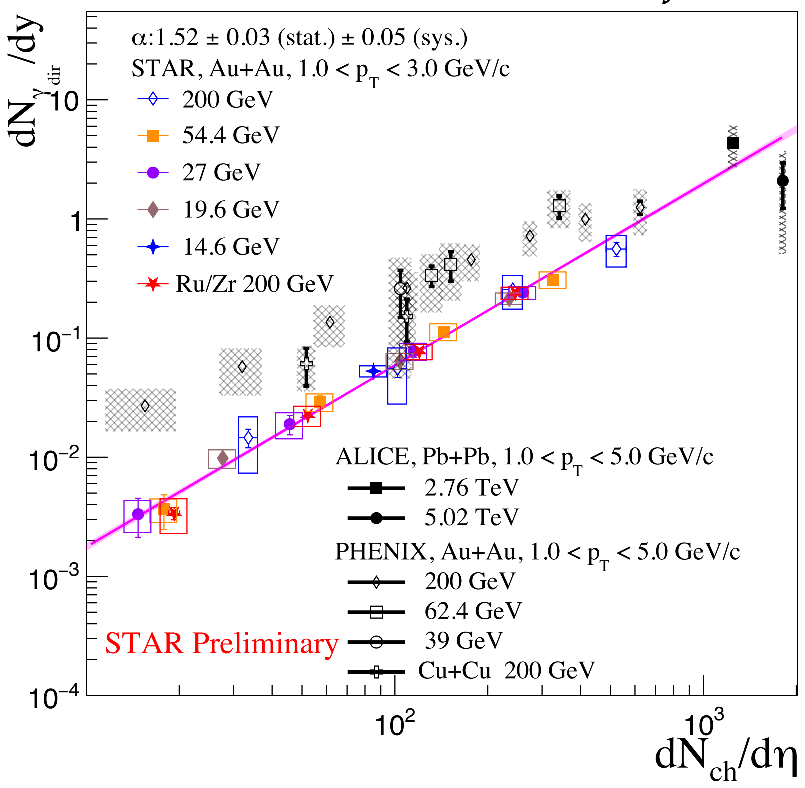
STAR, *Phys. Rev. C* 107 (2023) 6, L061901
STAR, *Nature Commun.* 16 (2025) 1, 9098

- Dielectron signal is consistent with cocktail in $\boldsymbol{\pi^0}$ mass region
- Observed excess yield in different mass regions
  - **0.10-0.30 GeV/c²:** direct virtual photon extraction
  - **0.40-1.10 GeV/c²:** dominated by in-medium ρ
  - **1.10-2.80 GeV/c²:** dominated by thermal radiation from QGP
- Internal conversion method:
  Two-component fit to extract direct virtual photon yield

$$\frac{dN_{ee}}{dM_{ee}} = r * f_{dir} + (1-r) * f_{cocktail}$$

Direct virtual photon p_T spectra and integrated yields $\frac{dN_{\gamma_{dir}}}{dy} = A(dN_{ch}/d\eta)^{\alpha}$





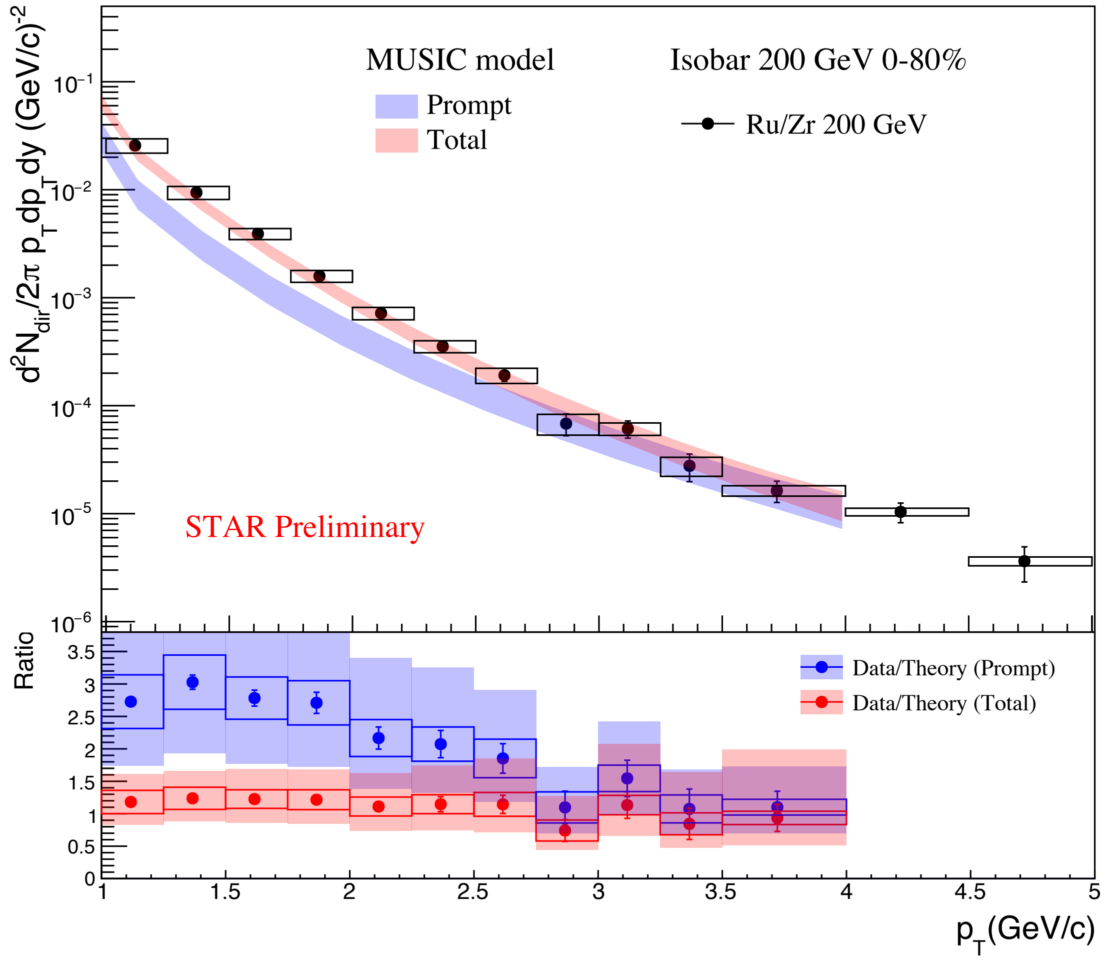
- Direct virtual photon p_T spectra in isobar collisions
- $dN_{\gamma_{dir}}/dy$ exhibits a strong $dN_{ch}/d\eta$ dependence
- The yields in different collision energies and systems measured by STAR follow a common scaling, with

$$\alpha = 1.52 \pm 0.03 \pm 0.05$$

STAR, *Phys. Lett. B* 770 (2017) 451-45
PHENIX, *Phys. Rev. C* 109 (2024) 044912
A. Marrin (ALICE), *PoS HardProbes2023* (2024) 061
X. Bao (STAR), *EPJ Web Conf.* 364 (2026) 07002

Comparison with MUSIC model

Patrick Aurebche et al, *Phys. Rev.* D73:094007,2006
PHENIX, *Phys. Rev. C* 107 (2023) 2,024914
PHENIX, *Phys. Rev. C* 87 (2013) 054907



- Enhancement observed compared with prompt photon yield estimated by MUSIC model
- Indication of **thermal photon** contribution
- Measured direct photon yield can be **well described by theoretical calculation**
- Fit data in p_T range **[1, 4]** GeV/c

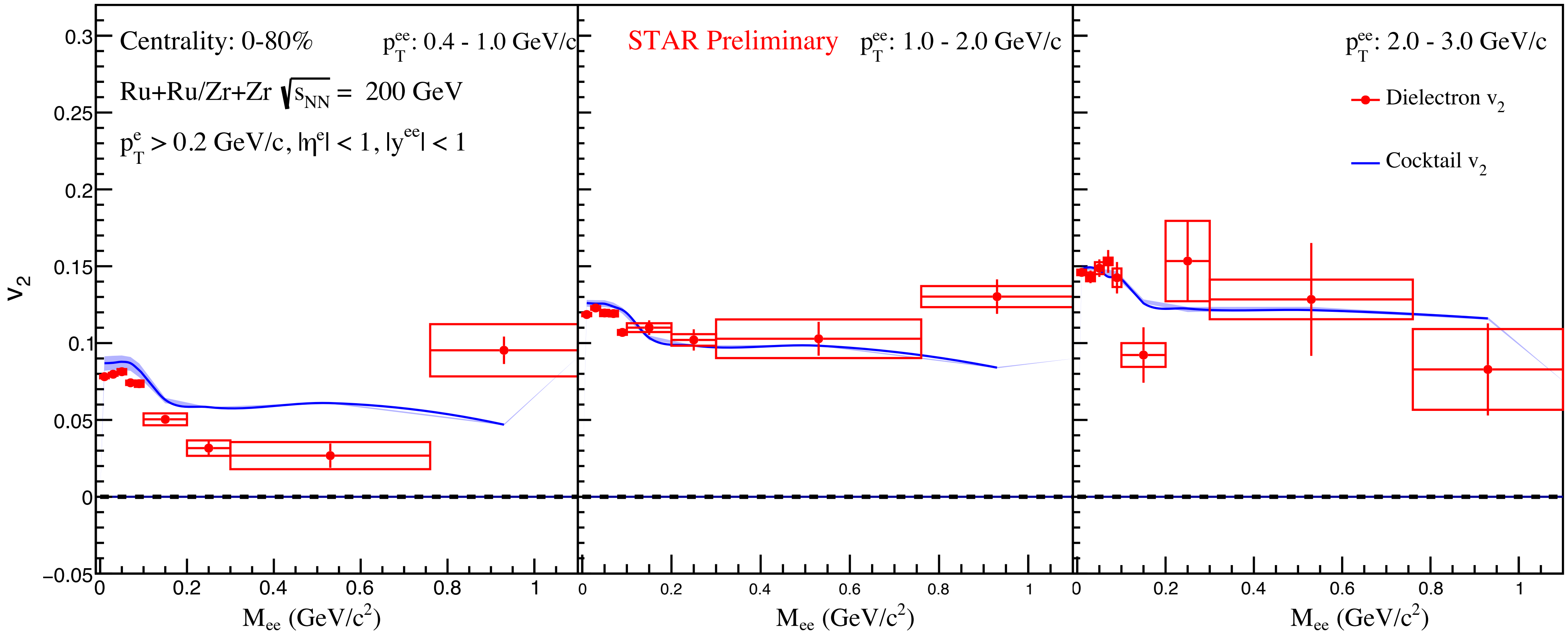
$$\boxed{Ae^{-p_T/T_{eff}}} + \boxed{N_{coll}^{STAR} * A_{pp}(1 + p_T^2/b)^{-n}}$$

Thermal photon **Prompt photon (MUSIC model)**

- Extracted $\mathbf{T_{eff} = 271 \pm 6 \pm 41\ MeV}$ with MUSIC model as p+p reference

MUSIC model, Xiangyu-Wu et al, arXiv: 2511.08773

Inclusive dielectron v_2 vs. cocktail v_2



- Inclusive dielectron v_2 obtained by 3-D efficiency-corrected dielectron spectra
- Dielectron v_2 is consistent with cocktail v_2 within uncertainty in π^0 mass region

STAR, *Phys. Rev. C* 90 (2014) 64904
STAR, arXiv: 2602.12094

Thermal dielectron v_2

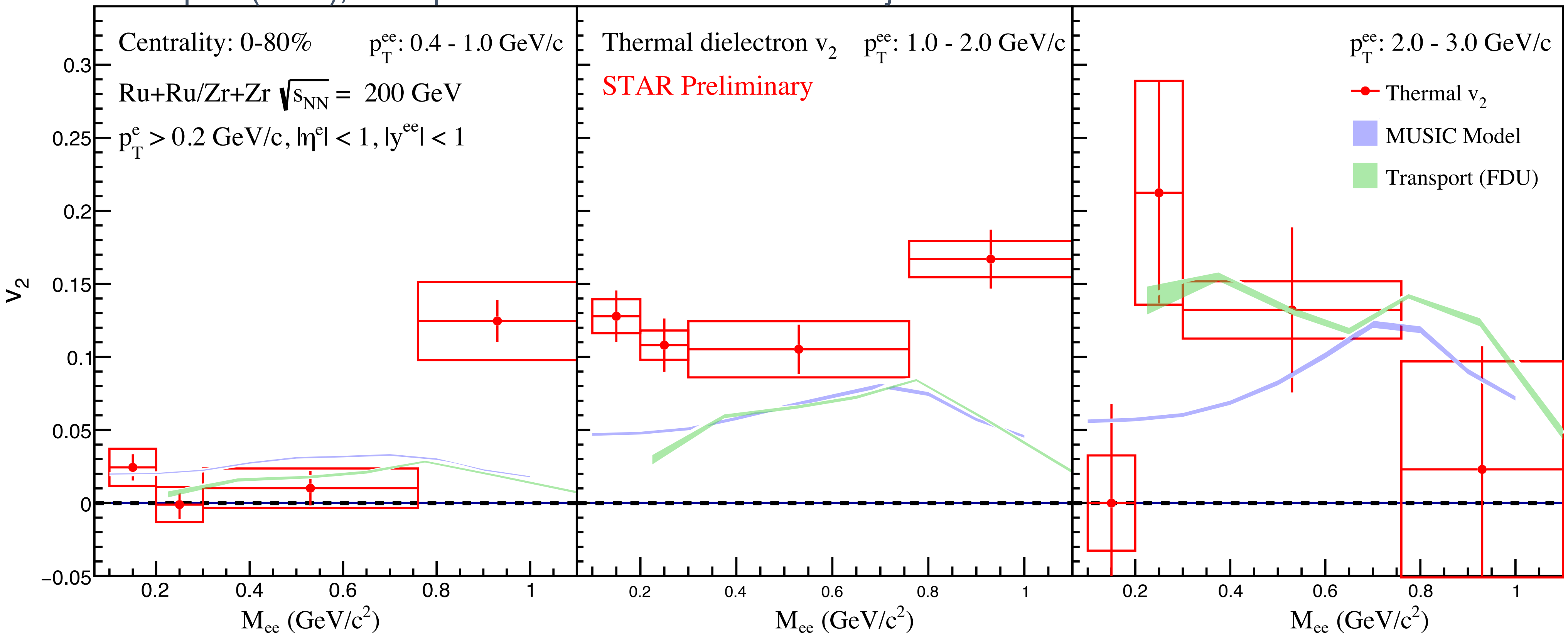
$$v_2^{thermal} = v_2^{dielectron} * \frac{R}{R-1} - v_2^{ckt} * \frac{1}{R-1}$$

$$R = \frac{N_{incl}^{dielectron}}{N_{CKT}}$$ (within STAR acceptance)

(w/o freeze-out ρ in MUSIC model)

MUSIC model, Xiangyu-Wu et al, arXiv: 2511.08773

Transport (FDU), from private communication with Kaijia Sun



- **First measurement of thermal dielectron v_2 at RHIC**
- MUSIC and Transport (FDU) model underestimate the data in $1 < p_T < 2$GeV/c

Thermal dielectron v_2

- Vacuum-like ρ: 0.76-1.10 GeV/c^2
- In-medium ρ: 0.30-0.76 GeV/c^2

MUSIC model, Xiangyu-Wu et al, arXiv: 2511.08773
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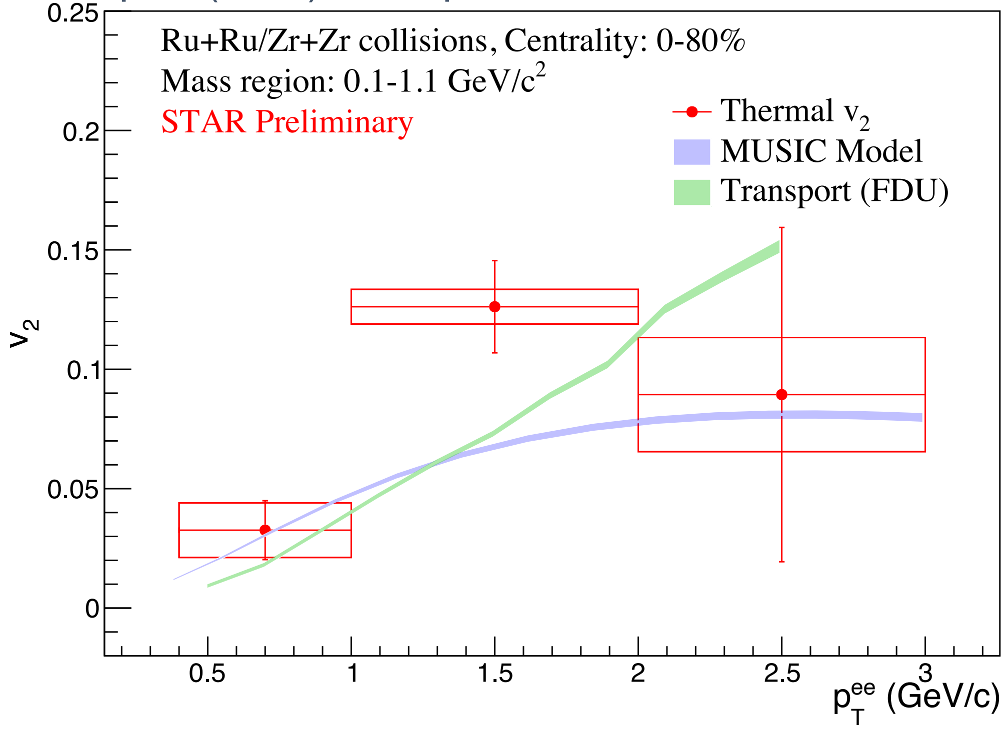
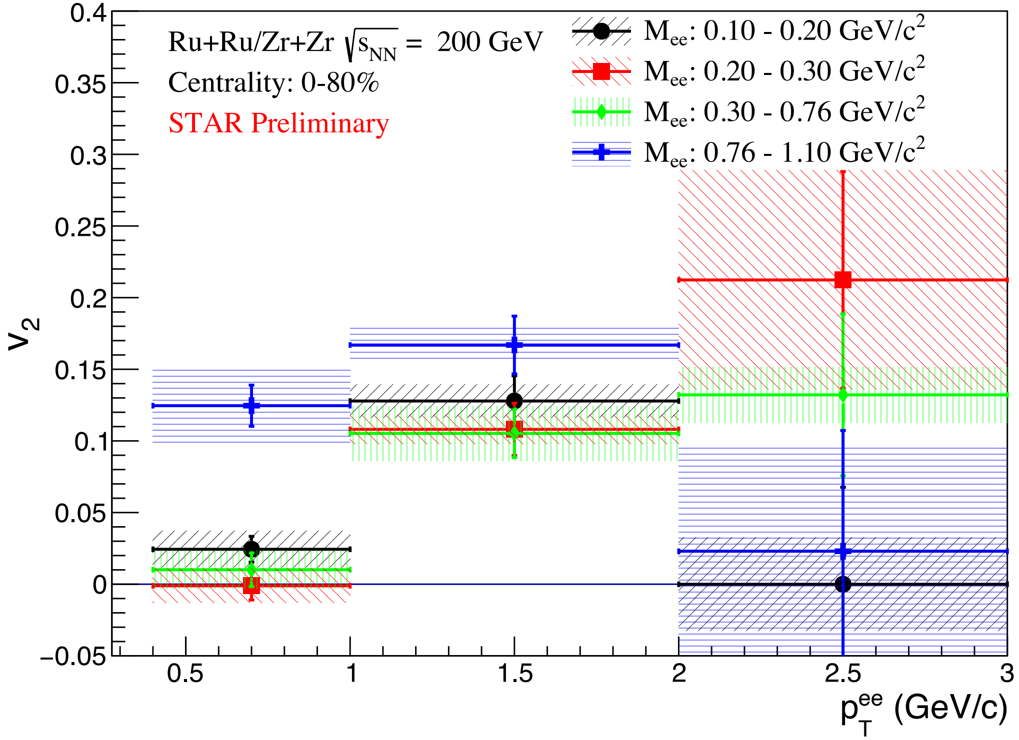


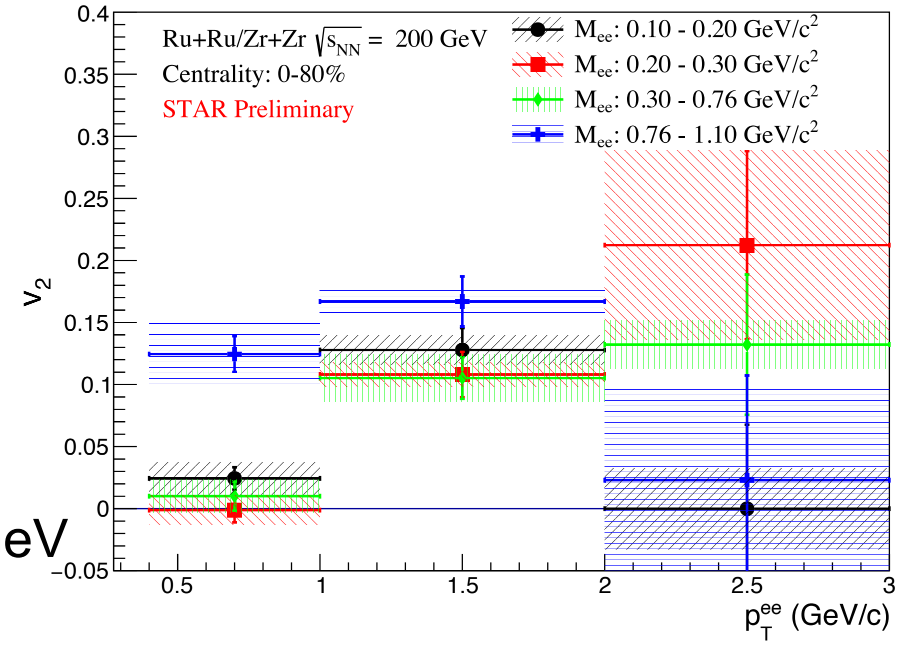


➢ Significant thermal dielectron v_2 observed in $0.1 < M_{ee} < 1.1 \mathrm{GeV}/c^2$, $1 < p_T < 2$ GeV/c

$$\mathbf{0.13 \pm 0.02\ (stat.) \pm 0.01 (sys.)\ (\sim 6\sigma)}$$

Summary

- First measurement of thermal dielectron v_2 in isobar collisions
  - **About 6σ: $0.13 \pm 0.02\ (\mathrm{stat.}) \pm 0.01 (\mathrm{sys.})$**
    in $0.1 < M_{ee} < 1.1 \mathrm{GeV}/c^2$, $1 < p_T < 2$ GeV/c
- The measured direct photon yields from STAR are proportional to $(dN_{ch}/d\eta)^{\alpha}$
  - **Scaling power α = $1.52 \pm 0.03\ (\mathrm{stat.}) \pm 0.05\ (\mathrm{sys.})$**



Outlook:

- High statistics Au+Au/O+O collisions at 200 GeV
- Fixed-target data at lower collision energies
  - High pseudo-rapidity and total baryon density regions

Summary

Thanks for your attention!

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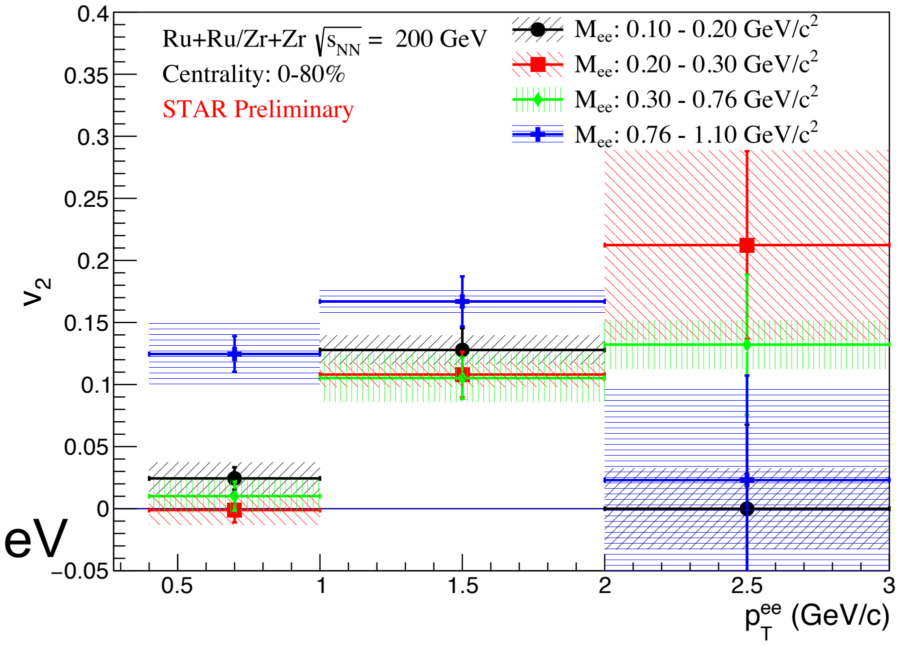

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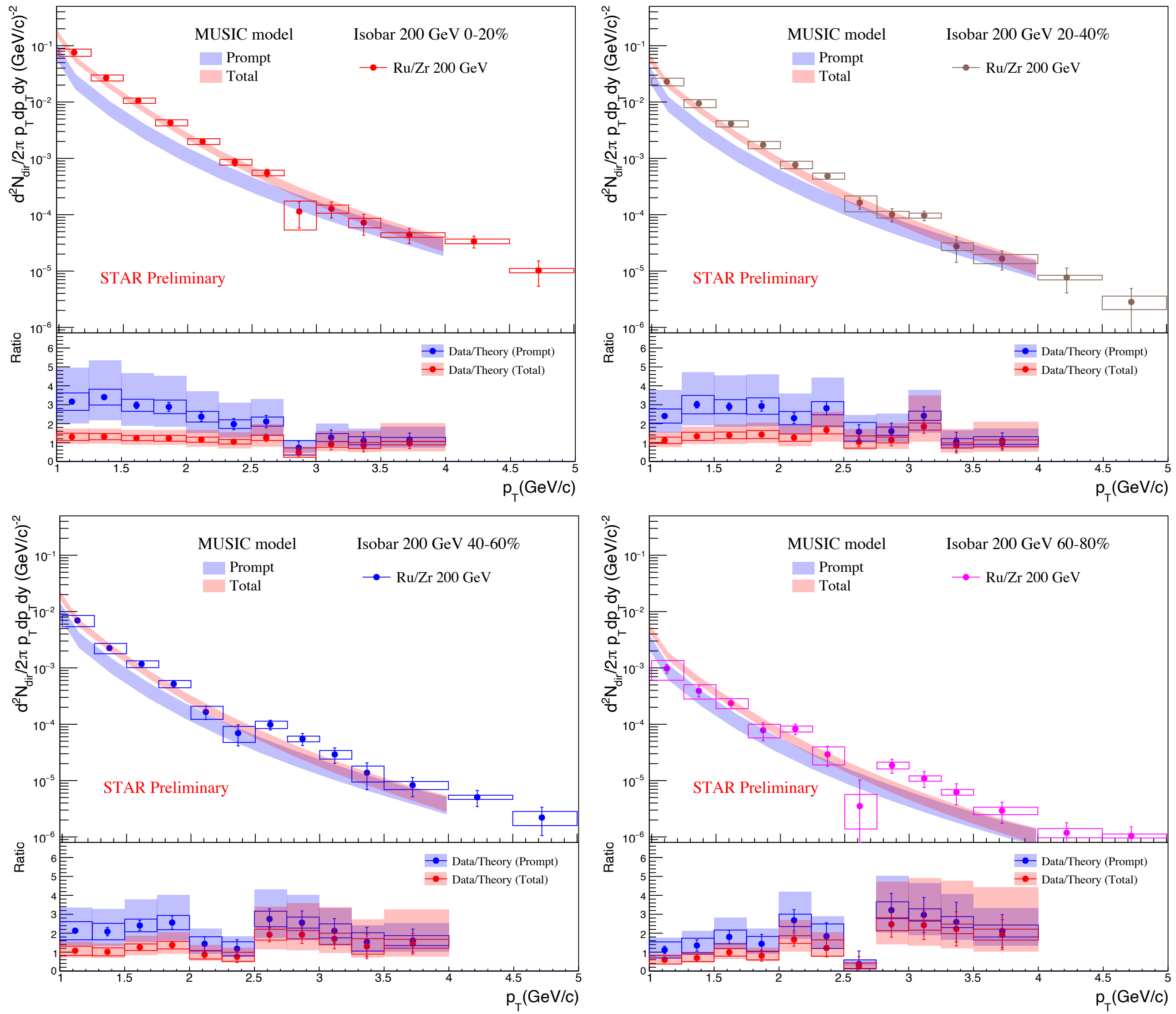
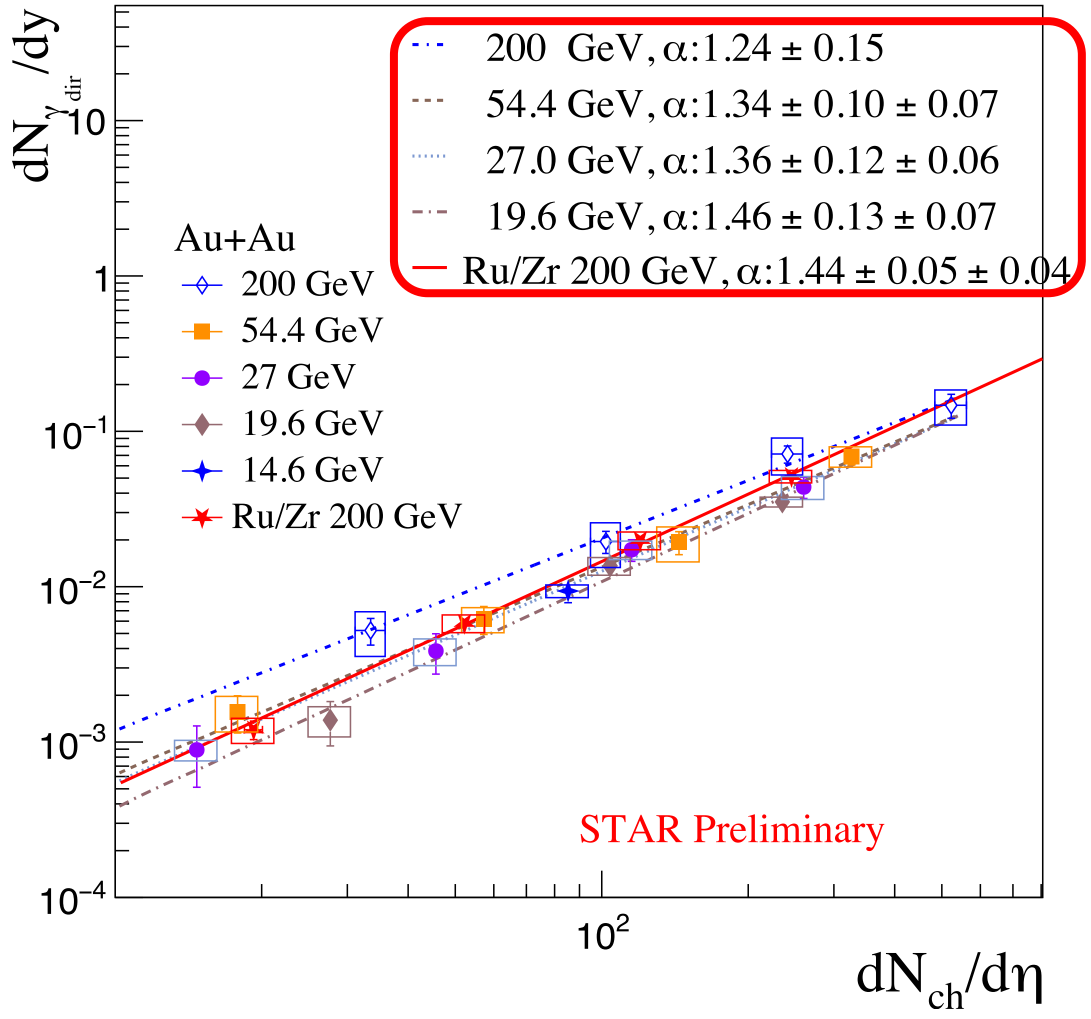
Backup

Experiment vs. Theory



- MUSIC model well describes experiment measurement in different system sizes
- **Prompt photon contribution estimated by the MUSIC model**

Direct virtual photon yield (1.5 < p_T < 3 GeV/c)



- Obvious $dN_{ch}/d\eta$ dependence in energies from 200 to 19.6 GeV

- ✓ **Hint that increasing proportion of prompt photon at lower collision energies at high p_T**
- ✓ **Thermal photons emitted by QGP rarely extend to higher p_T at lower collision energies**