Thermal Radiation: An Experimental Review

Axel Drees, December 15th, QCD meets HI, Heidelberg 2014

- **Introduction**
- **Thermal Photon Measurements**
  - High low p_T direct photon yield
  - Centrality dependence ~ $N_{part}^{3/2}$
  - Large direct photon angular anisotropy
- **Comparison to Theoretical Models**
  - Thermal Photon Puzzle
- **Outlook and Summary**

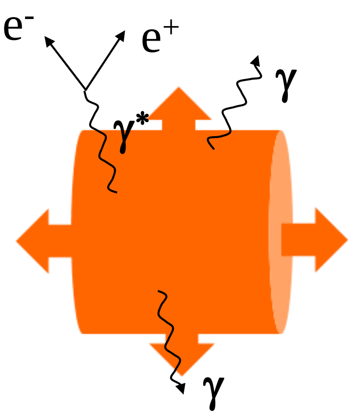
Thermal Radiation from Hot & Dense Matter

- **Black Body Radiation**
  - **Real or virtual photons**
  - **Spectrum and yield sensitive to temperature**

    Avg. inv. slope $\propto$ T, Yield $\propto$ T^3
  - **Space-time evolution of matter**

    collective motion → Doppler shift

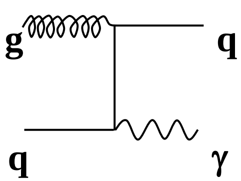
    → anisotropy



High yield → high T → early emission
Large anisotropy → Doppler shift → late emission

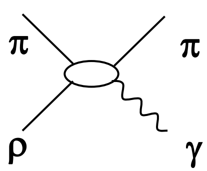
- **Microscopic view of thermal radiation**

QGP:



photons

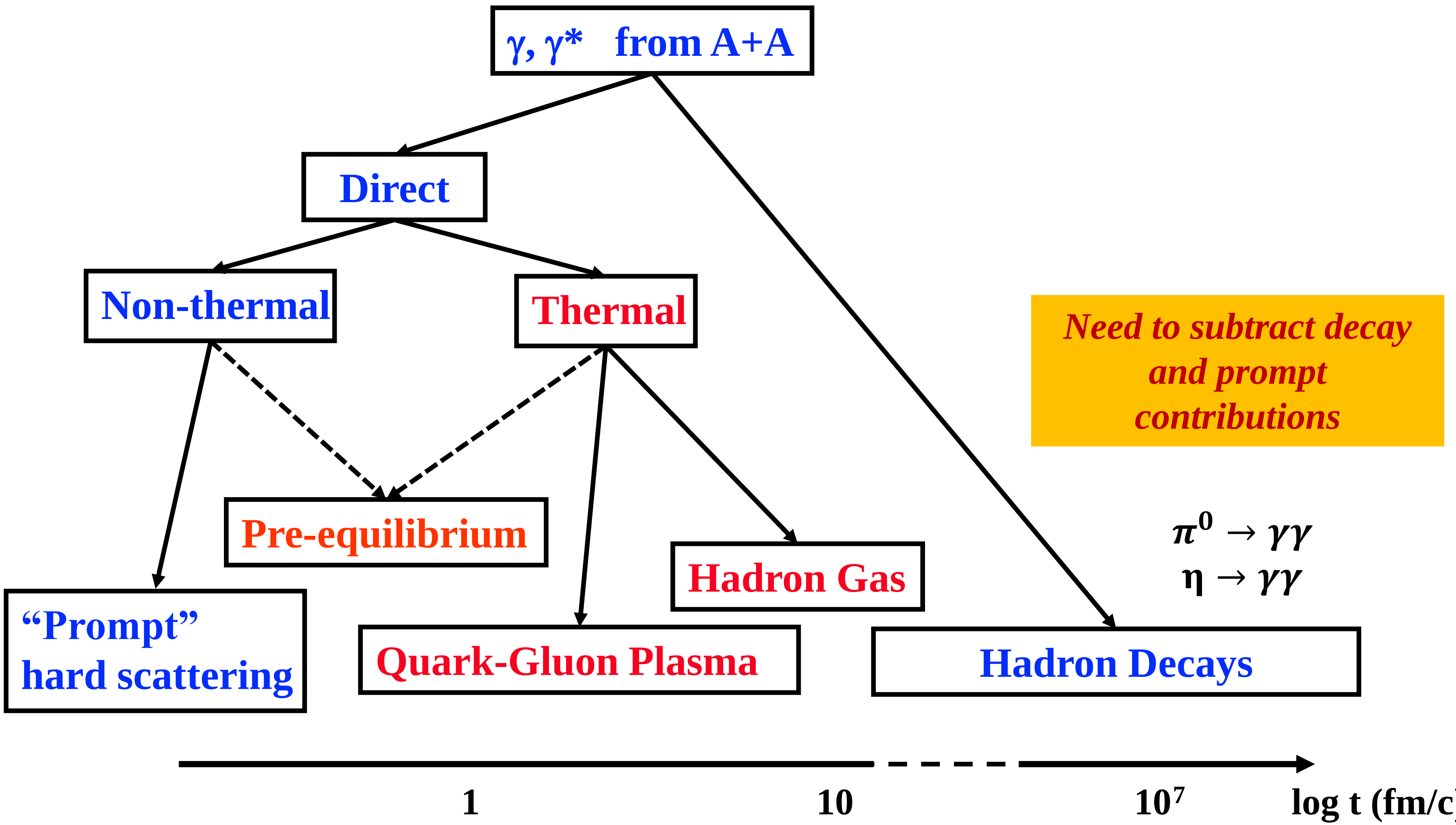
hadron gas:



low mass lepton pairs

Need realistic model simulation for rates and space-time evolution for quantitative comparison with data

Experimental Issue: Isolate Thermal Radiation



Using γ^* to Measure Direct Photons

- **Searches for thermal photons ongoing since late 1980's at SPS**
  - **WA80 & successors, HELIOS, CERES …**
  - **Established mostly upper limits in relevant range p_T < few GeV**

- **Breakthrough at RHIC: Measuring direct photons via virtual photons – published 2010** *PHENIX Phys.Rev.Lett 104 (2010) 132301*
  - **Method originally proposed by UA1 for prompt photons**

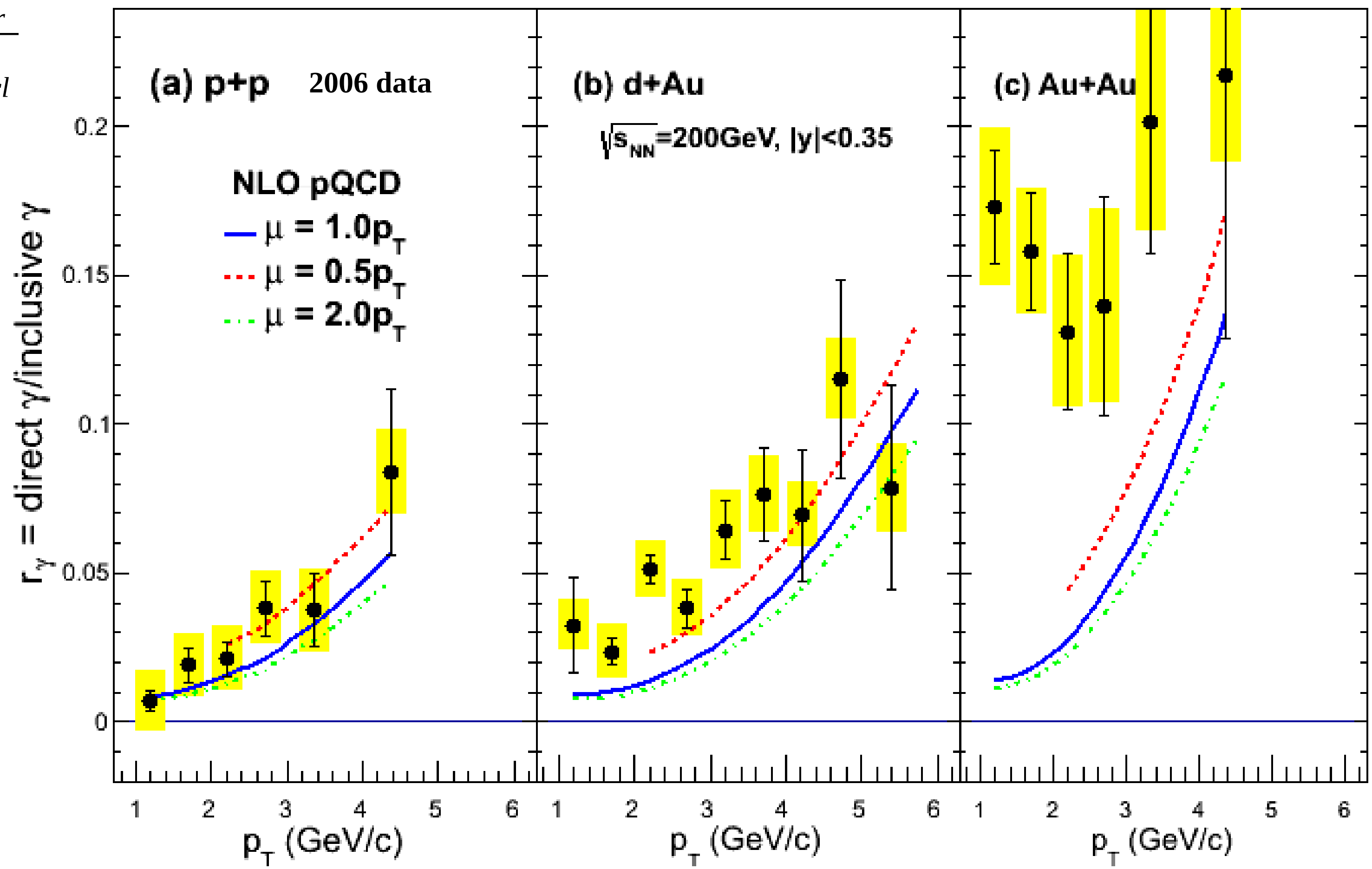
- **Using virtual photons:**
  - **any process that radiates γ will also radiate γ^***
  - **for $m \ll p_T$ γ^* are "almost real"**
  - **extrapolate $\gamma^* \to e^+e^-$ yield to $m = 0$ → direct γ yield**
  - **$m > m_\pi$ cut removes 90% of hadron decay background**
  - **S/B improves by factor 10 so that 10% direct γ → 100% direct γ^***
  - **measure ratio $\gamma^*_{direct}/\gamma^*_{inclusive}$ for sys. uncertainty cancelation**

PHENIX: Direct Photons from Virtual Photons

PHENIX Phys.Rev.C87 (2013) 054907

PHENIX PRL104 (2010) 132301

$$r = \frac{\gamma^*_{dir}}{\gamma^*_{incl}} = \frac{\gamma_{dir}}{\gamma_{incl}}$$



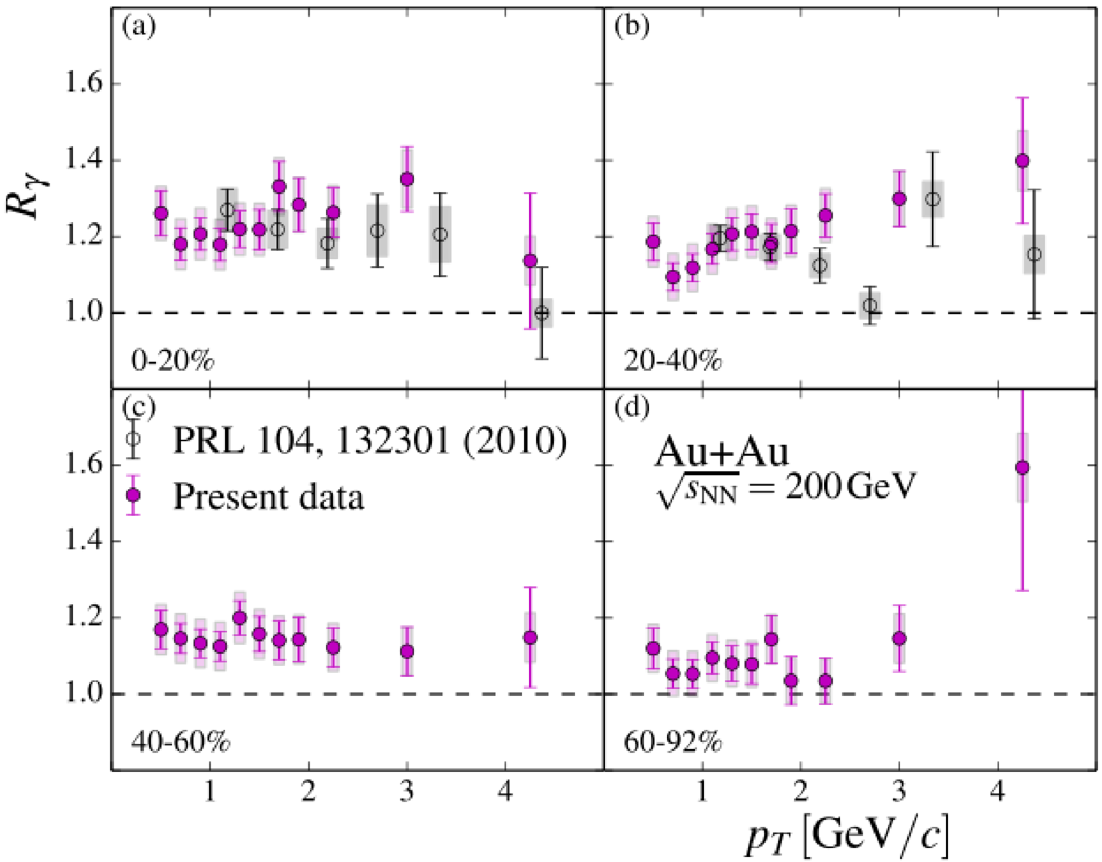
Prompt photon consistent with pQCD in p+p
Significant additional yield in Au+Au

PHENIX: Direct Photons from Photon Conversions

note: $1 - r_\gamma = \frac{1}{R_\gamma}$

$$R_\gamma = \frac{N_\gamma^{incl}}{N_\gamma^{hadr}} = \frac{\langle \varepsilon f \rangle \times \left(\frac{Y_\gamma^{incl}}{Y_\gamma^{\pi^0 tag}} \right)^{Data}}{\left(\frac{N_\gamma^{hadr}}{N_\gamma^{\pi^0}} \right)^{MC}}$$

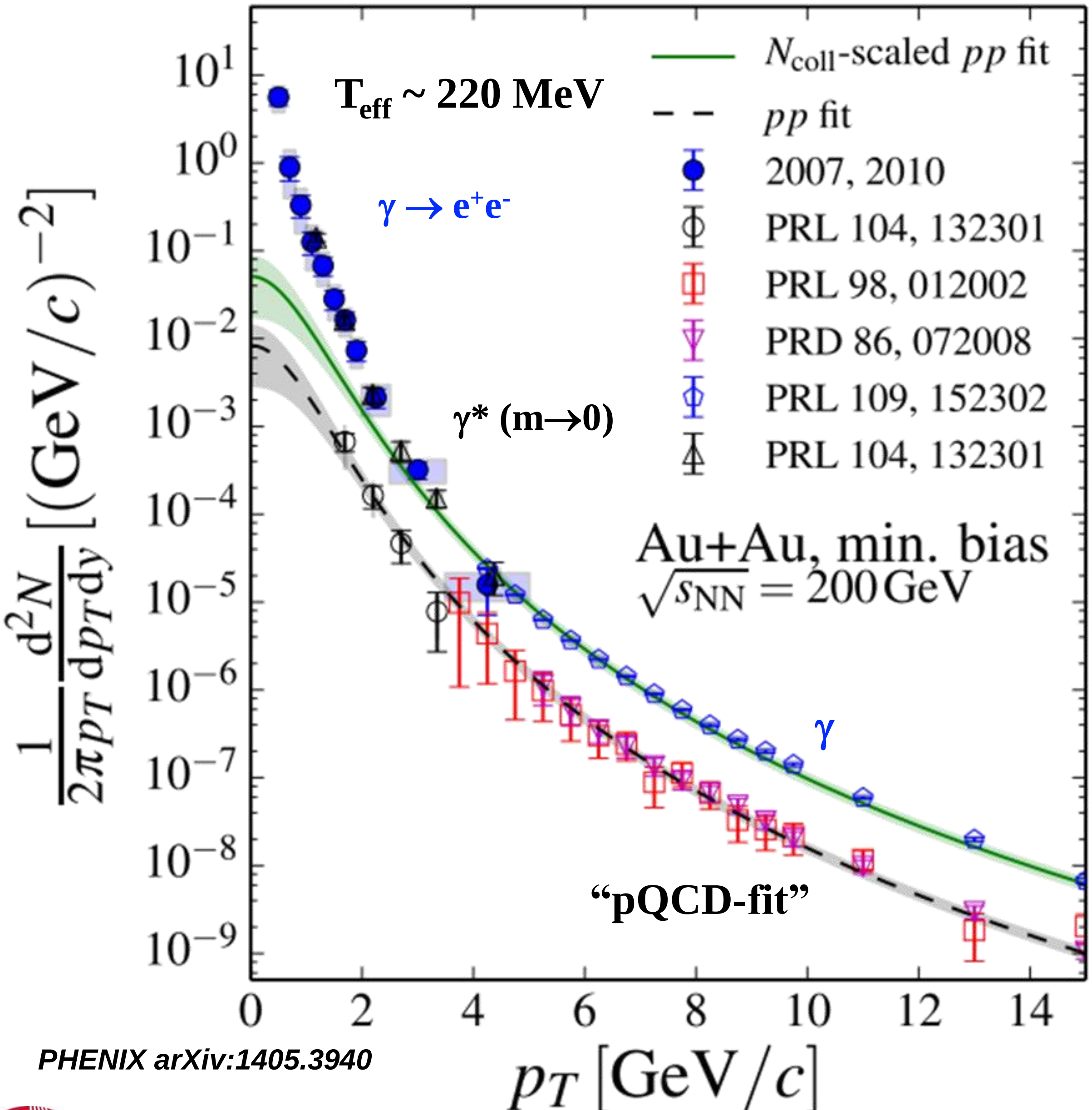
PHENIX arXiv:1405.3940



- **Double ratio tagging method**
  - Clean photon sample with photon conversion
  - Explicit cancelation of systematic uncertainties
  - Combined result from 2 analyses
- **Direct photons**
  - Well established in AuAu at RHIC
  - Real and virtual photons consistent
  - Full centrality dependence

Almost 20% direct photons in central Au+Au!
Approx. independent of p_T from 0.4 to 4 GeV

PHENIX: Direct Photons Au+Au Collisions



PHENIX arXiv:1405.3940

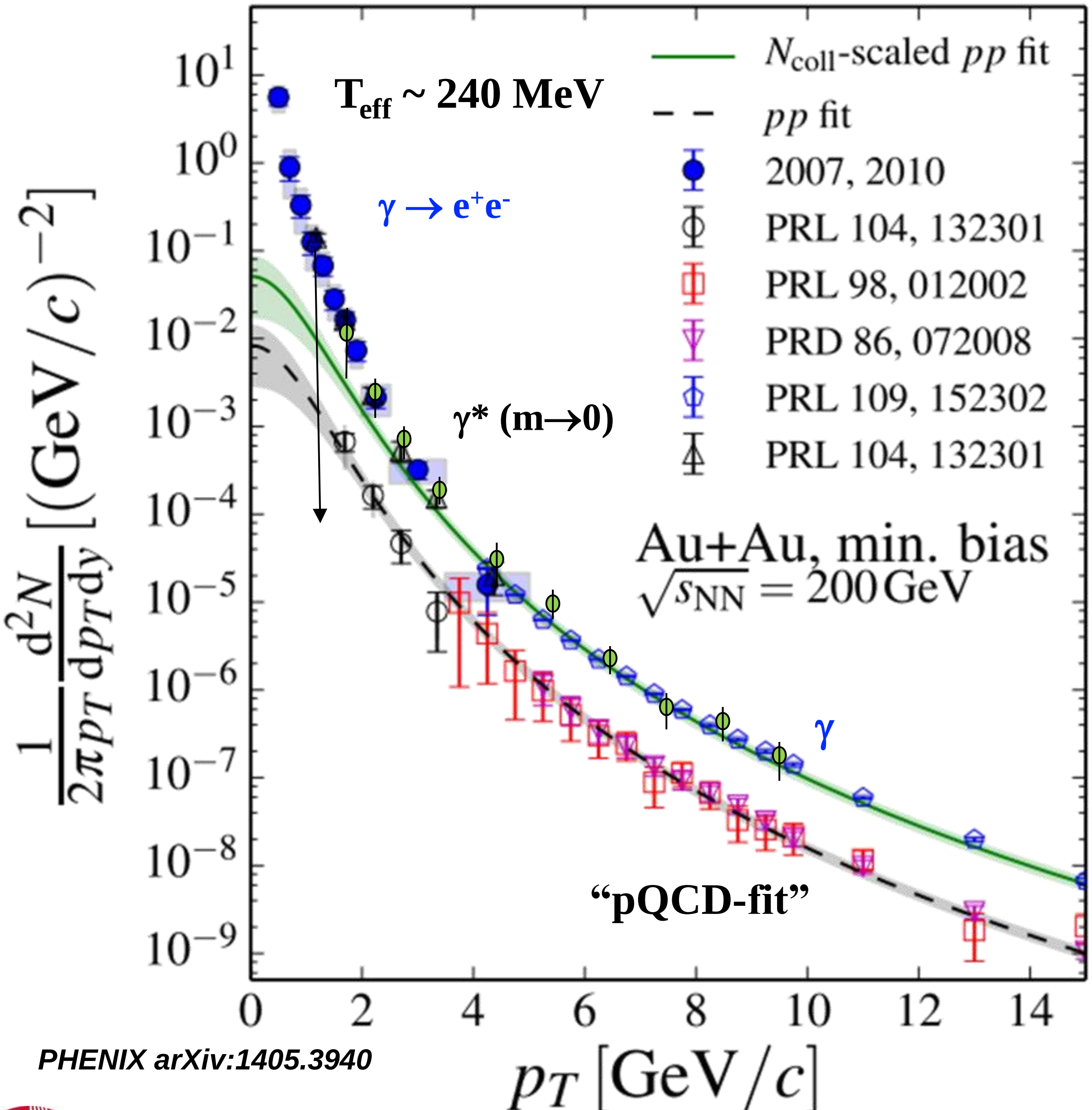
PHENIX arXiv:1405.3940

- **Direct photon yield well established**
  - **pp consistent with pQCD**
  - **AuAu follows N_{coll} scaled pp above 4 GeV**
  - **Significant excess below 3 GeV in AuAu**
  - **Excess has nearly exponential shape**

thermal photons:
T_{ini} > 240 MeV > T_C

large photon yield!

RHIC: Direct Photons Au+Au Collisions



PHENIX arXiv:1405.3940

PHENIX arXiv:1405.3940

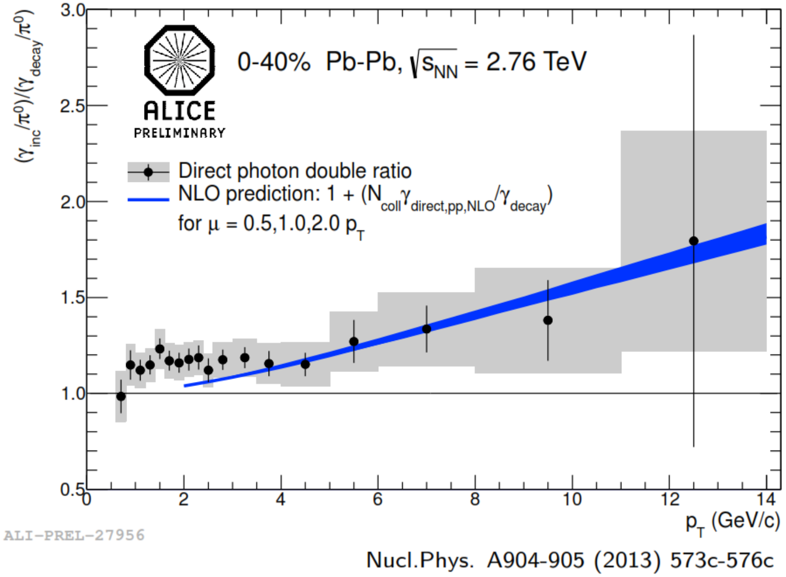
STAR preliminary γ^* (m → 0)
arXiv:1408.2371

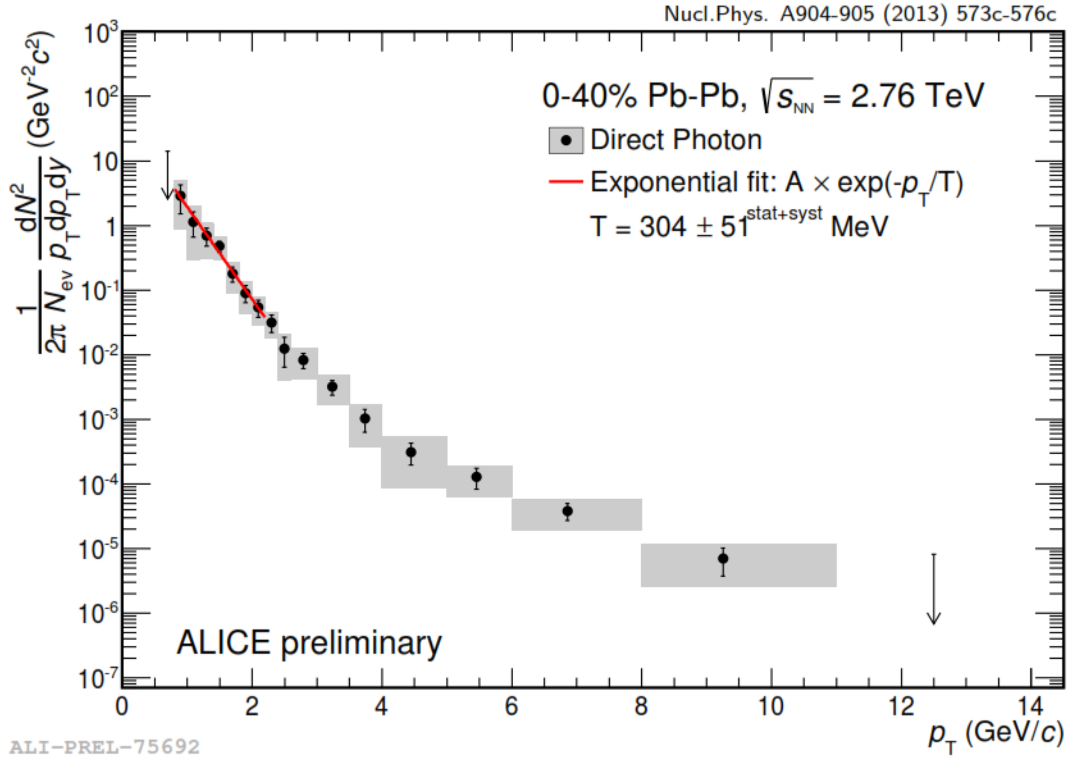
- **Direct photon yield well established**
  - **pp consistent with pQCD**
  - **AuAu follows N_{coll} scaled pp above 4 GeV**
  - **Significant excess below 3 GeV in AuAu**
  - **Excess has nearly exponential shape**

thermal photons:
T_{ini} > 240 MeV > T_C

large photon yield!

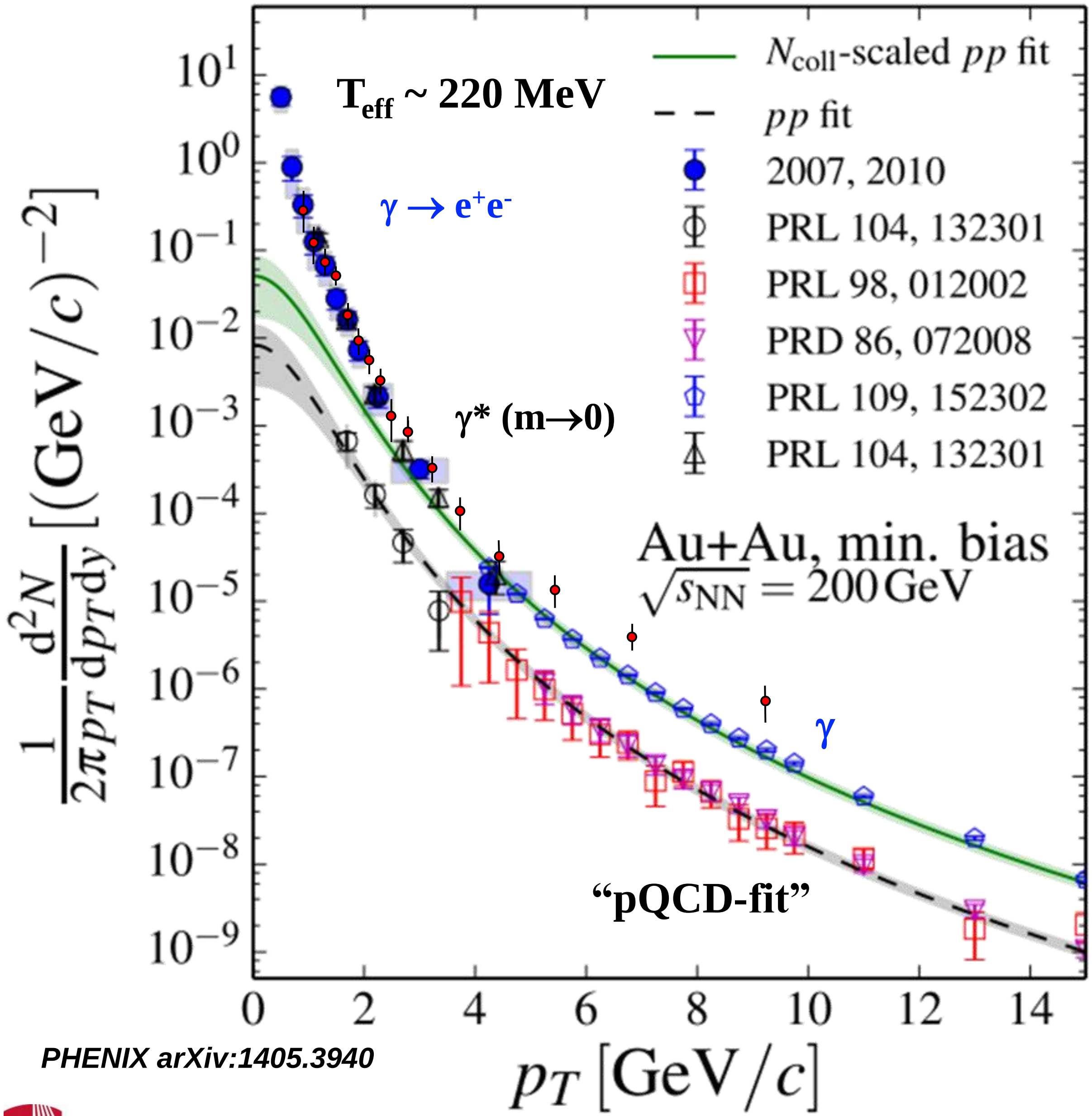
ALICE: Direct Photons Pb+Pb Collisions





- **Direct photon yield observed by ALICE at LHC**
  - **PbPb follows N_{coll} scaled NLO calculations above 4 GeV**
  - **20 ± 10% excess below 3 GeV with in AuAu**
  - **Excess has nearly exp. shape with inv. slope T_{eff} ~ 300 MeV**

PHENIX: Direct Photons Au+Au Collisions



PHENIX arXiv:1405.3940

PHENIX arXiv:1405.3940

ALICE preliminary $\gamma \to ee$
Nucl.Phys. A904-905 (2013) 573

- **Direct photon yield well established**
  - **pp consistent with pQCD**
  - **AuAu follows N_{coll} scaled pp above 4 GeV**
  - **Significant excess below 3 GeV in AuAu**
  - **Excess has nearly exponential shape**

thermal photons:
T_{ini} > 240 MeV > T_C

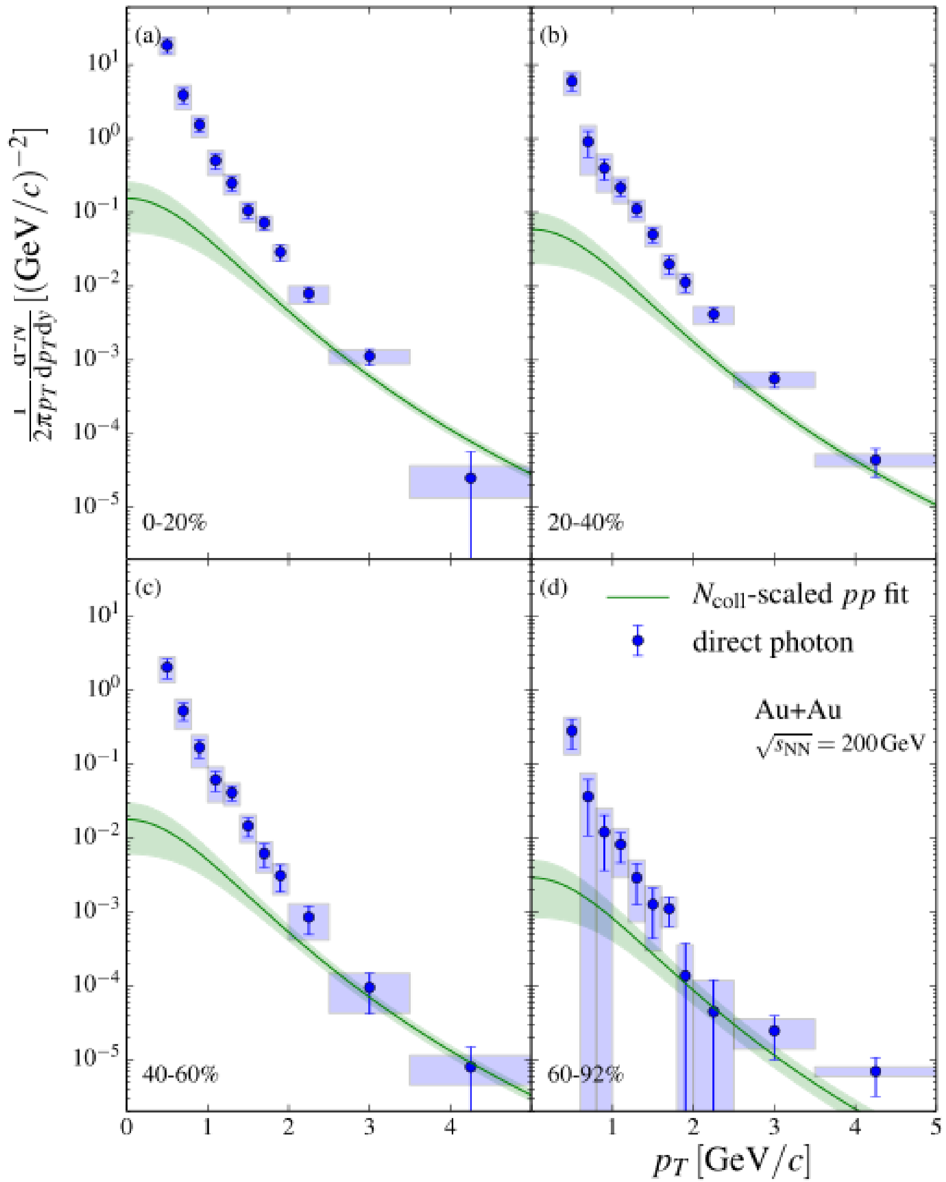
large photon yield!

Centrality Dependence of Thermal Component

PHENIX arXiv:1405.3940

- **No significant change in shape**
  - **Inverse slope ~ const.**
  - **Fit range 0.6-2.0 GeV: $Ae^{-p_T/T_{eff}}$**

Centrality	N_{part}	N_{coll}	T_{eff} (MeV/c)
0%–20%	279.9 ± 5.7	779.0 ± 75.2	239 ± 25 ± 7
20%–40%	140.4 ± 7.0	296.8 ± 31.1	260 ± 33 ± 8
40%–60%	59.9 ± 5.0	90.6 ± 11.8	225 ± 28 ± 6
60%–92%	17.6 ± 4.2	14.5 ± 4.0	238 ± 50 ± 6

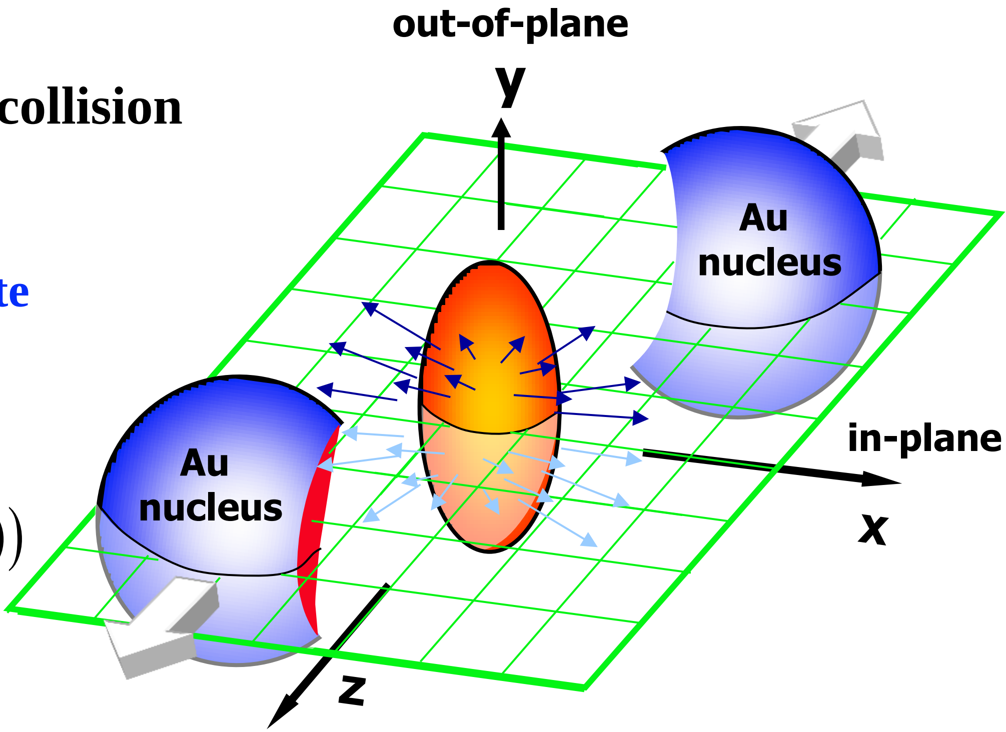


- **Rapidly increasing yield with centrality like N_{part}^{α}**
  - **Data α = 1.48±0.08±0.04**
  - **Faster than volume ~ N_{part}**
  - **Faster than prompt component**
    N_{coll} ~ $N_{part}^{4/3}$
  - **Slower than naïve expectation**
    Yield ~ N_{part}^{2}

Collective Behavior: Elliptic Flow

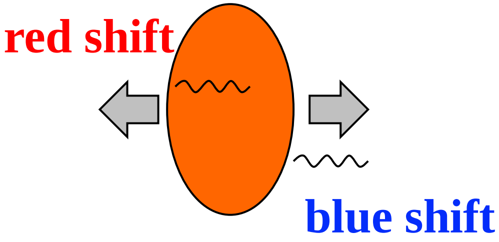
- **initial state of non-central Au+Au collision**
  - spatial asymmetry
  - asymmetric pressure gradients
  - momentum anisotropy in final state
  - expressed as elliptic flow "v_2"

$$E\frac{d^3N}{d^3p} = \frac{d^3N}{p_T d\varphi dp_T dy}\sum_{n=0}^{\infty} 2v_n \cos\left(n\left(\varphi - \Psi_R\right)\right)$$



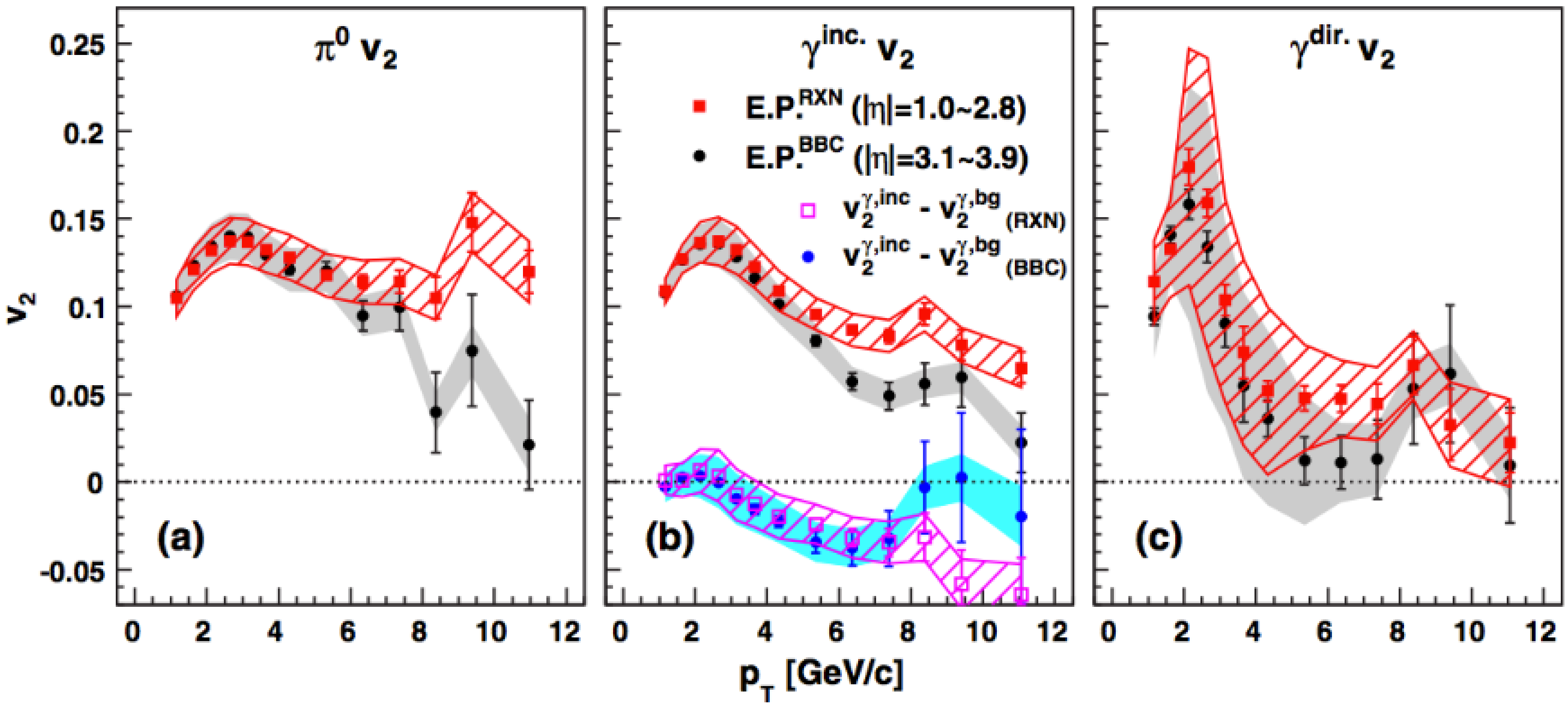
Non-central Collisions

Thermal radiation emitted from moving matter → Doppler Shift
→ Anisotropy



Thermal Photon Show Large Anisotropy

PHENIX Phys.Rev.Lett 109 (2012) 122302



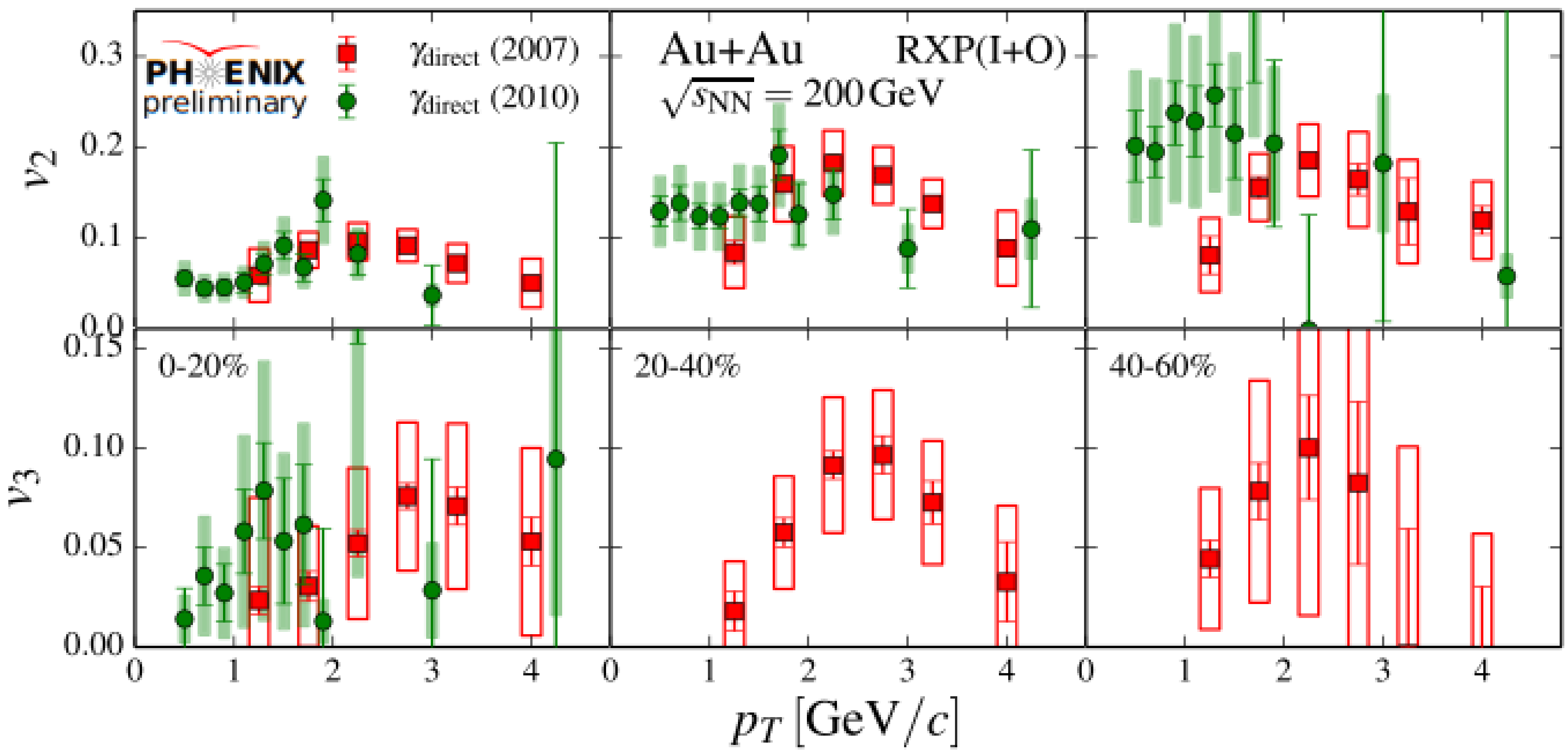
$$\nu_n^{dir.} = \frac{R_\gamma \nu_n^{inc.} - \nu_n^{dec.}}{R_\gamma - 1}$$

- R_γ (p_T) ~ constant > 1
- At 2 GeV $v_2^{inc} \sim v_2^{dec}$

} $v_2^{dir} \sim v_2^{inc}$

Large v_2~ 0.2 at 2 GeV/c
Insensitive to sys. uncertainty
IF there are direct photons

Thermal Photon Anisotropy Update



- **Two new independent analysis**
  - **Calorimeter measurement**
  - **photon conversions $\gamma \rightarrow e^+e^-$**

(also seen at LHC – see below)

Consistent with published results
Large v_2~ 0.2 at 2 GeV/c
Indication for const. v_2 at low p_T

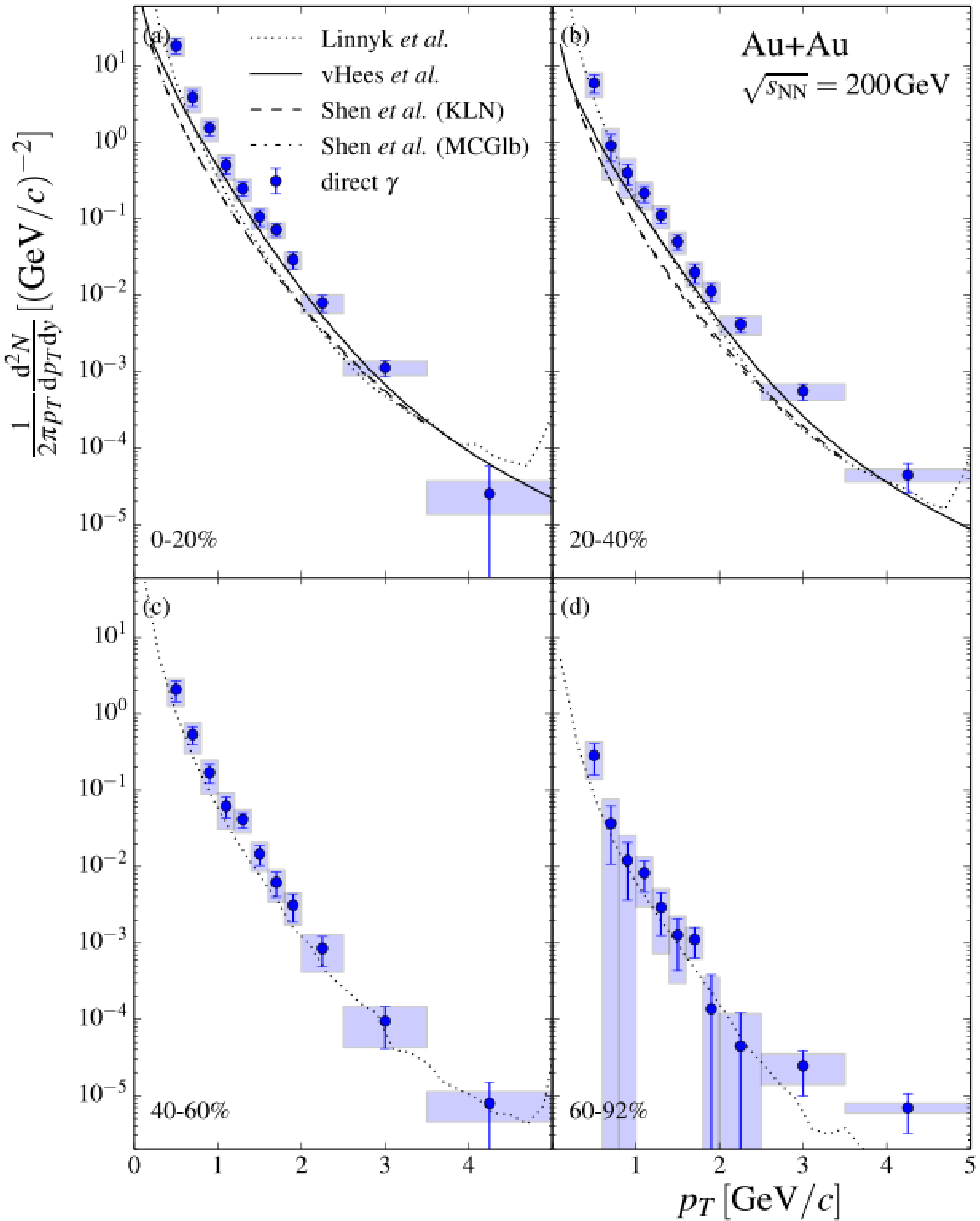
Theory Comparison: Thermal Photon Puzzle (I)

data: PHENIX arXiv:1405.3940

Transport model: Linnyk, Cassing, Bratkovskaya, PRC89 (2014) 0034908

Fireball model: van Hees, Gale, Rapp, PRC84 (2011) 054906

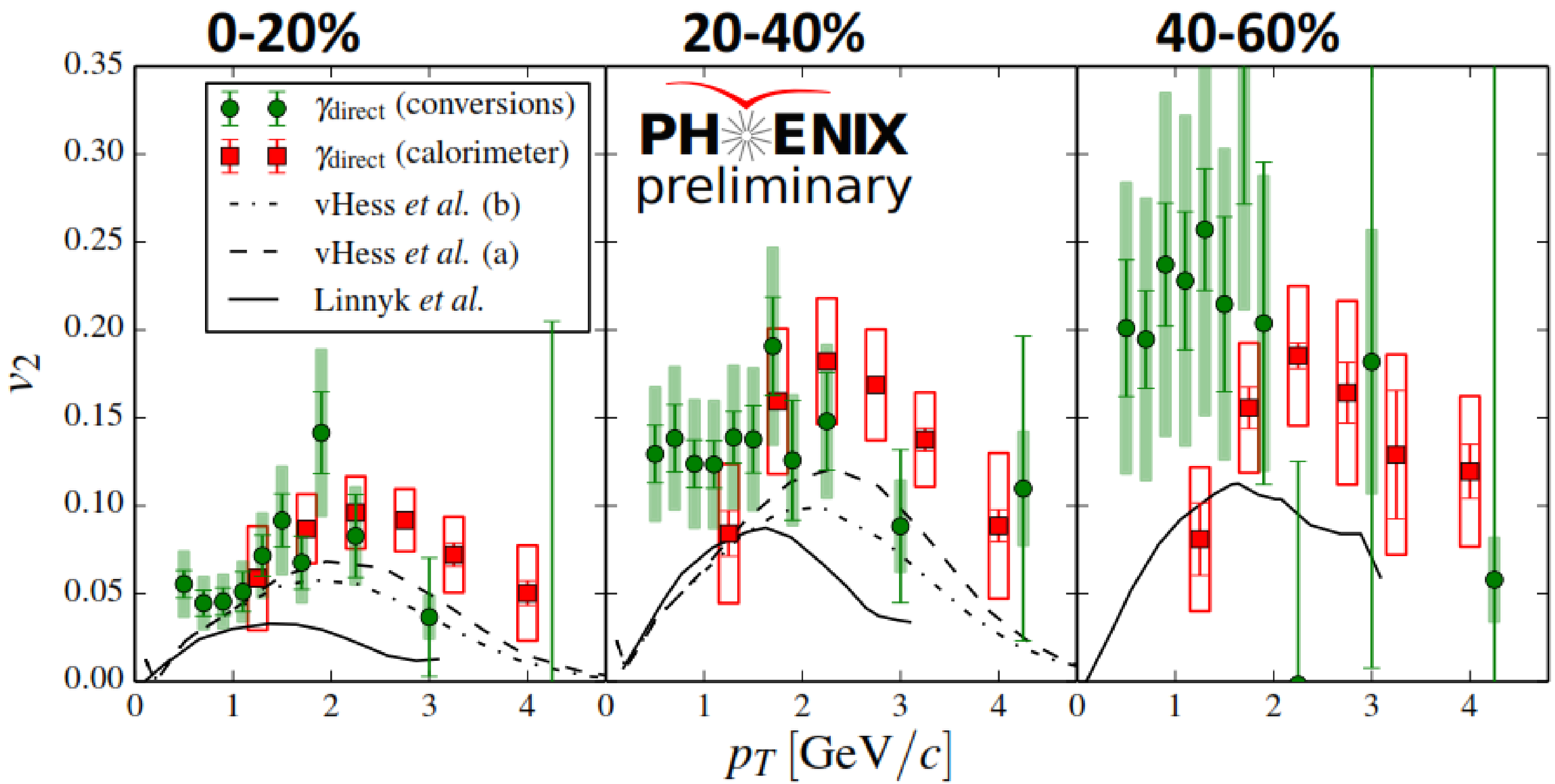
Hydrodynamic model: Shen, Heinz, Paquet, Gale, PRC89 (2014) 044910



Reasonable agreement with:
T_{ini} = 300 to 600 MeV

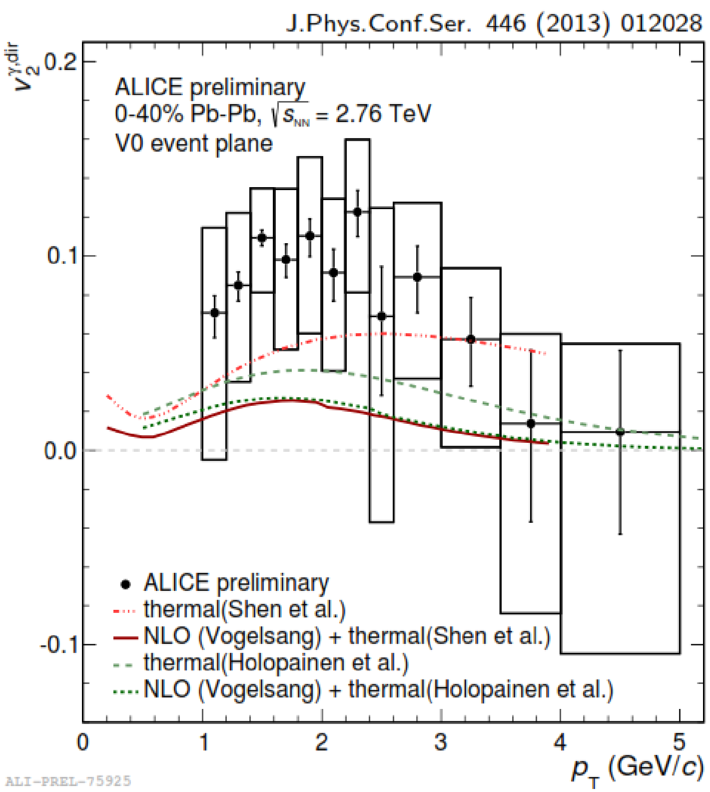
Shape similar, but yield is underestimated by factor 2-10

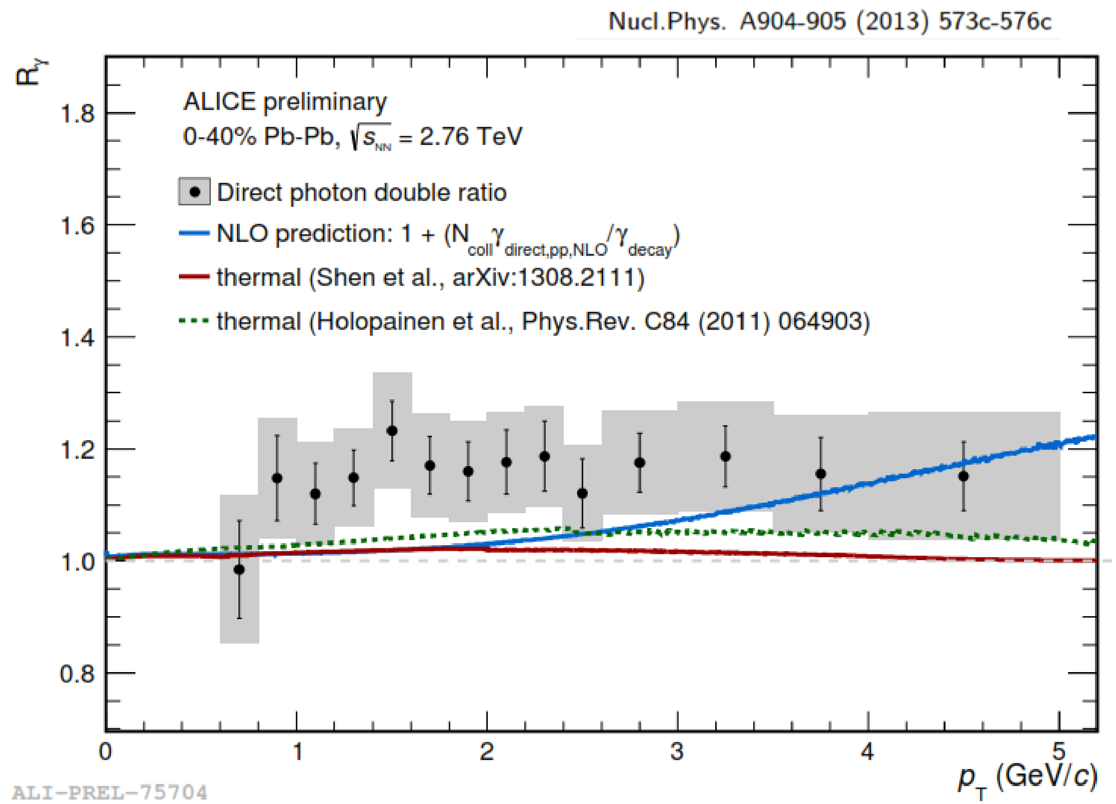
Theory Comparison: Thermal Photon Puzzle (II)



Difficult for models to describe simultaneously photon yield, T and v2 at RHIC!

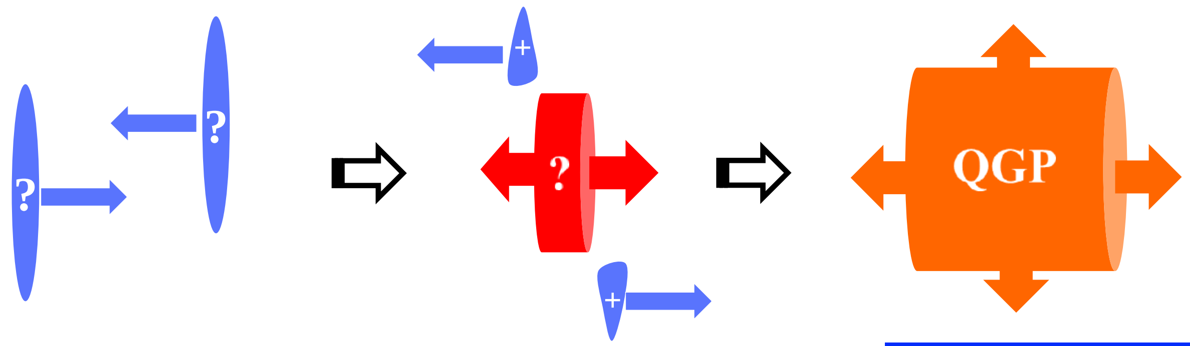
Theory Comparison: Thermal Photon Puzzle (III)





Difficult for models to describe simultaneously photon yield, T and v2 at LHC!

Thermal Photon Puzzle and Beyond

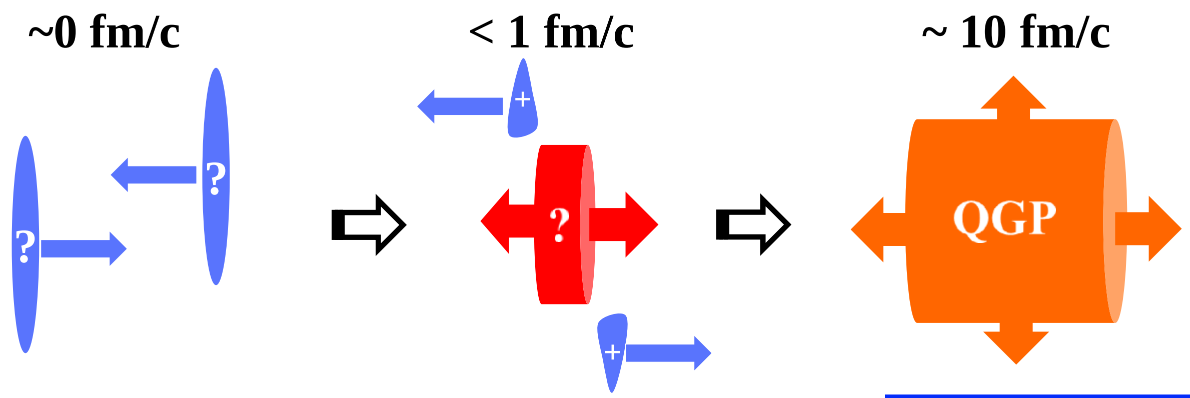


Interpretation as thermal photons seems incomplete

- **Experimental low momentum photon data shows:**
  - High yield → early emission
  - Large anisotropy → late emission
- **Theoretical models of thermal radiation based on:**
  - Standard rates
  - Hydro like space-time evolution

fail to describe the data

Thermal Photon Puzzle and Beyond



Interpretation as thermal photons seems incomplete

- Experimental low momentum photon data shows:
  - High yield → early emission
  - Large anisotropy → late emission
- Theoretical models of thermal radiation based on:
  - Standard rates
  - Hydro like space-time evolution

fail to describe the data

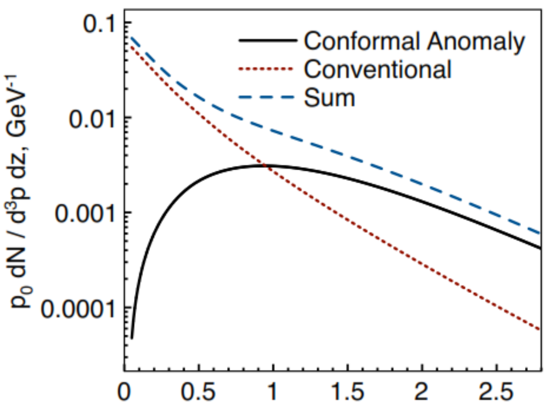
What are we missing?

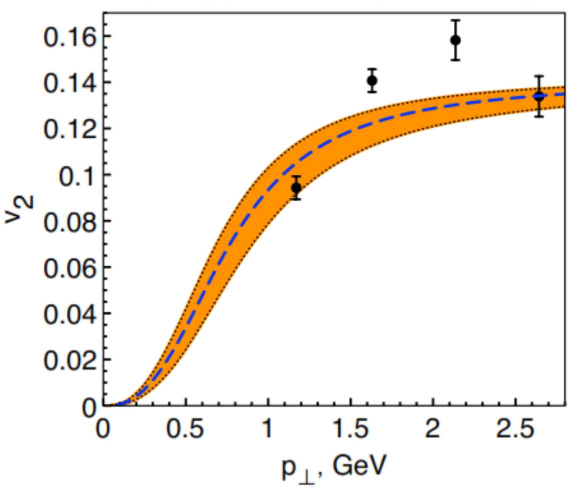
- Are the rates right?
- Impact of large B-fields?
- Pre-equilibrium dynamics?

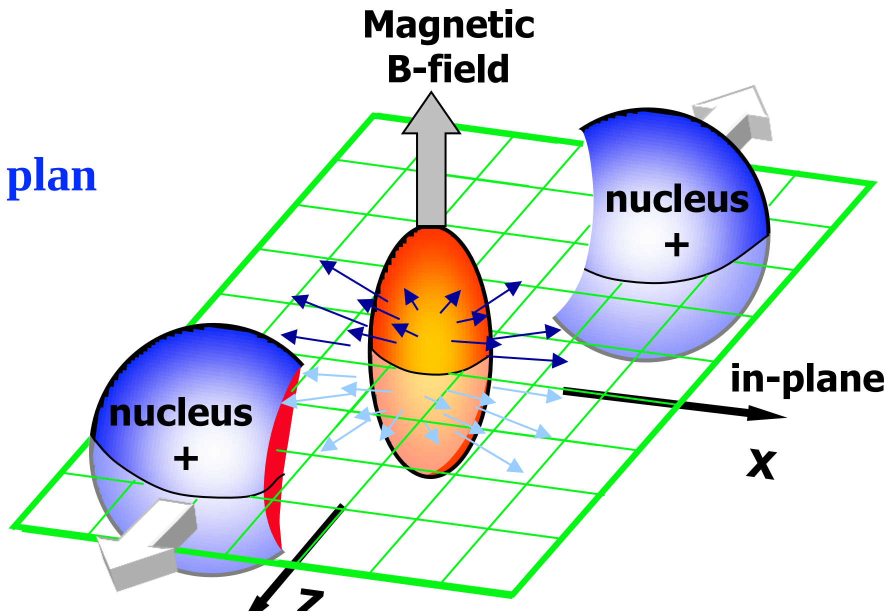
Large B-field Enhances Thermal Radiation

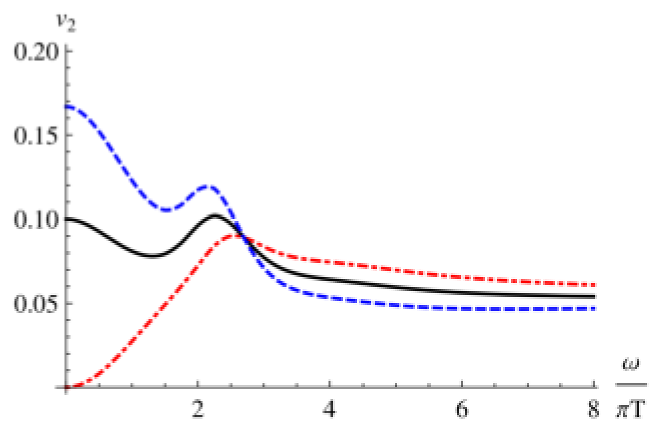
Basar, Kharzeev, Skokov PRL 109 (2012) 202303

- **Large magnetic field**
  - **Enhanced thermal emission**
  - **Anisotropy with respect to reaction plan**









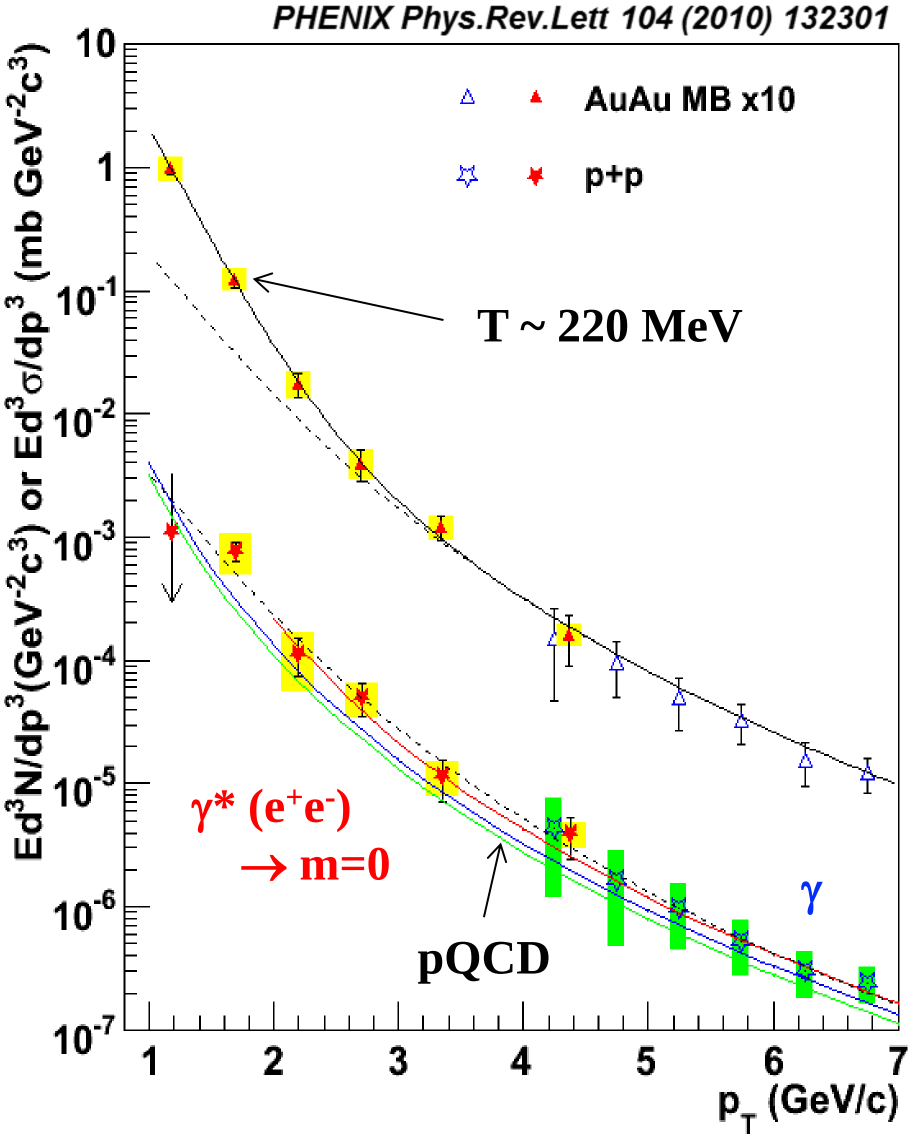
B.Müller, S.Y.Wu, D.LYang PRD 89 (2014) 026013

Summary and Outlook

- **Well established measurement of low momentum direct photon in Au+Au at 200 GeV at RHIC**
  - **Large yield above expected contribution from pQCD**
  - **Centrality dependence of yield ~ $N_{part}^{3/2}$**
  - **Large anisotropy v_2 with respect to reaction plan**
- **Consistent data from LHC in Pb+Pb at 2.76 TeV**
- **Thermal photon puzzle**
  - **Models based on standard rates and time evolution fail to describe simultaneously photon yield, T and v2**
  - **New additional sources early in collision?**
    - **Enhanced emission due to large B fields**
    - **Pre-equilibrium dynamics**
- **Expect additional experimental measurements from RHIC**
  - **Vary collision geometry → U+U, Cu+Au, p+A**
  - **62.4 (and 39 GeV) Au+Au**
  - **New large Au+Au data samples to measure v_n**

Backup slides

First Measurement of Thermal Radiation

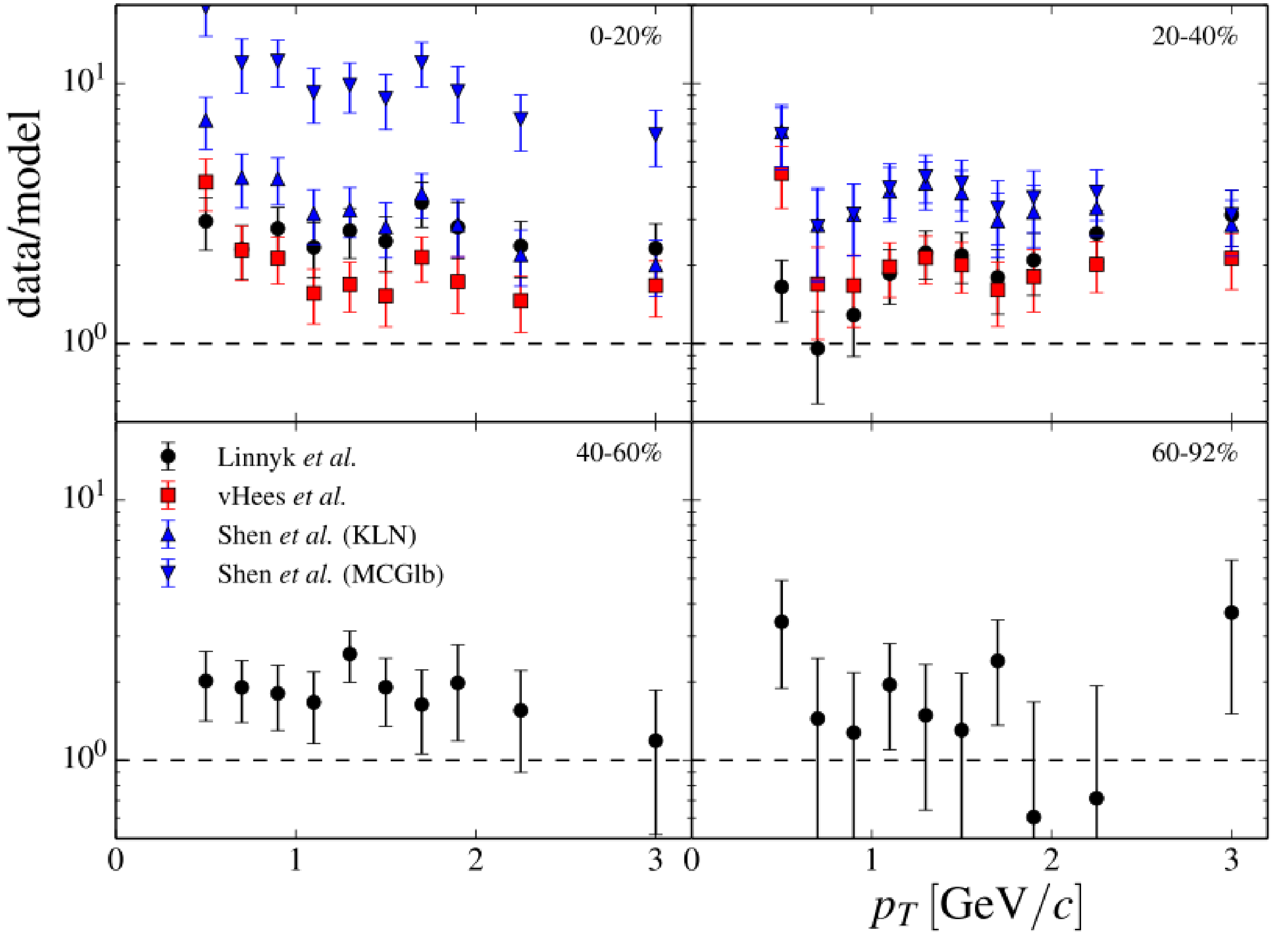


- **Direct photons from real photons:**
  - **Measure inclusive photons**
  - **Subtract π^0 and η decay photons at S/B < 1:10 for p_T<3 GeV**
- **Direct photons from virtual photons:**
  - **Measure e^+e^- pairs at $m_\pi < m << p_T$**
  - **Subtract η decays at S/B ~ 1:1**
  - **Extrapolate to mass 0**

First thermal photon measurement:
T_{ini} > 220 MeV > T_C

large photon yield!

Theoretical Models Underestimate Yield



- **About factor of 2 at high pt – with large errors**
- **Factor 5-10 at lower pt (central collisions)**

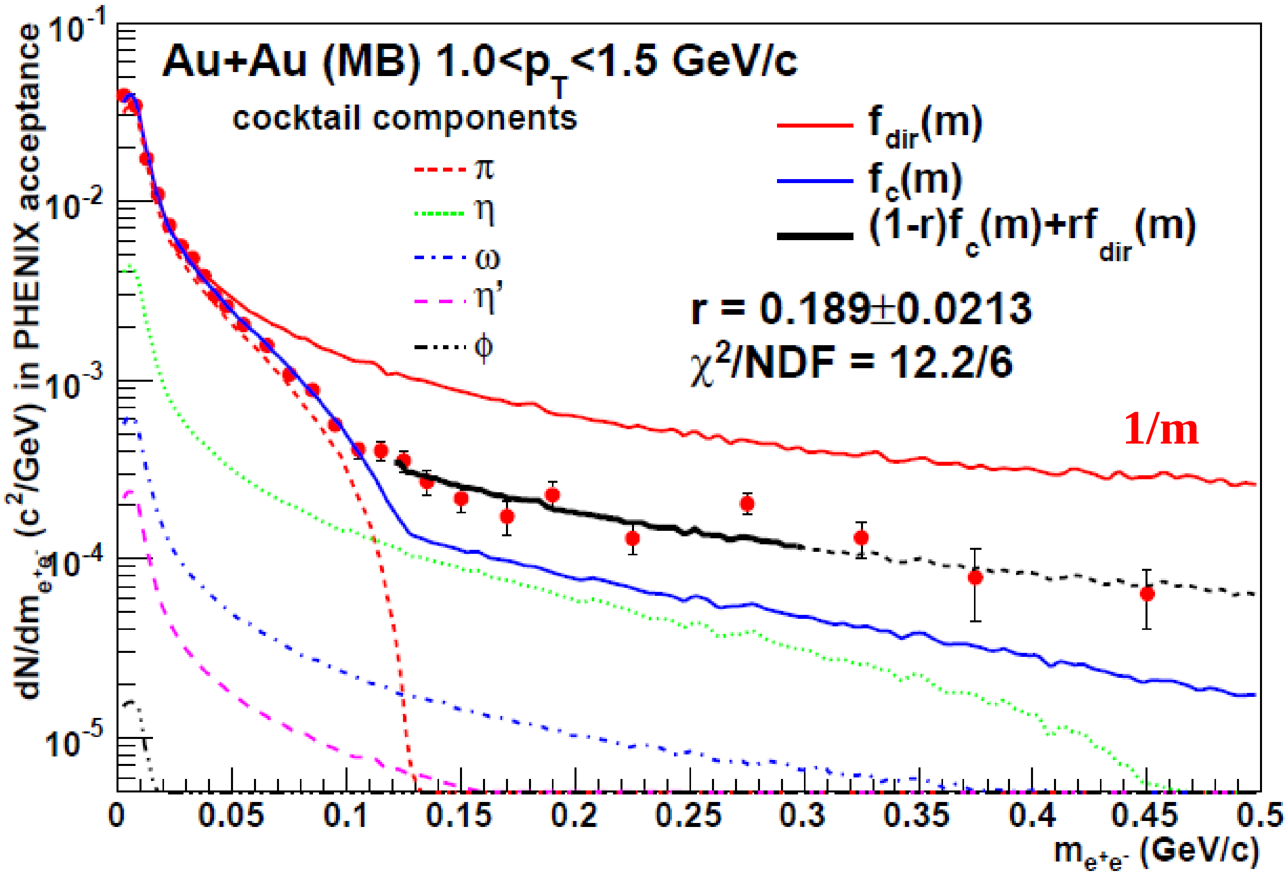
Fit e^+e^- Mass Distribution to Extract the Direct Yield:

- **Example: one p_T bin for Au+Au collisions**

$$\frac{d\sigma_{ee}}{dM^2 dp_T^2 dy} \cong \frac{\alpha}{3\pi}\frac{1}{M^2}L(M)\frac{d\sigma_\gamma}{dp_T^2 dy}$$

$f_c(m_{ee})$ and $f_{dir}(m_{ee})$ normalized to data for $m_{ee} < 30\,MeV$

$$r = \frac{\gamma^*_{dir}}{\gamma^*_{incl}} = \frac{\gamma_{dir}}{\gamma_{incl}}$$



Direct γ* yield fitted in range 120 to 300 MeV
Insensitive to π^0 yield

PHENIX: Direct Photons from Photon Conversions

- **Double ratio tagging method**
  - **Clean photon sample with photon conversion**
  - **Explicit cancelation of systematic uncertainties**

measured raw yields

$$\frac{Y_\gamma^{incl}}{Y_\gamma^{hadr}} = \frac{N_\gamma^{incl}\; p_{conv} a_{ee} \varepsilon_{ee}}{N_\gamma^{\pi^0 tag}\; p_{conv} a_{ee} \varepsilon_{ee} \langle \varepsilon f \rangle} = \frac{N_\gamma^{incl}}{N_\gamma^{\pi^0 tag} \langle \varepsilon f \rangle}$$

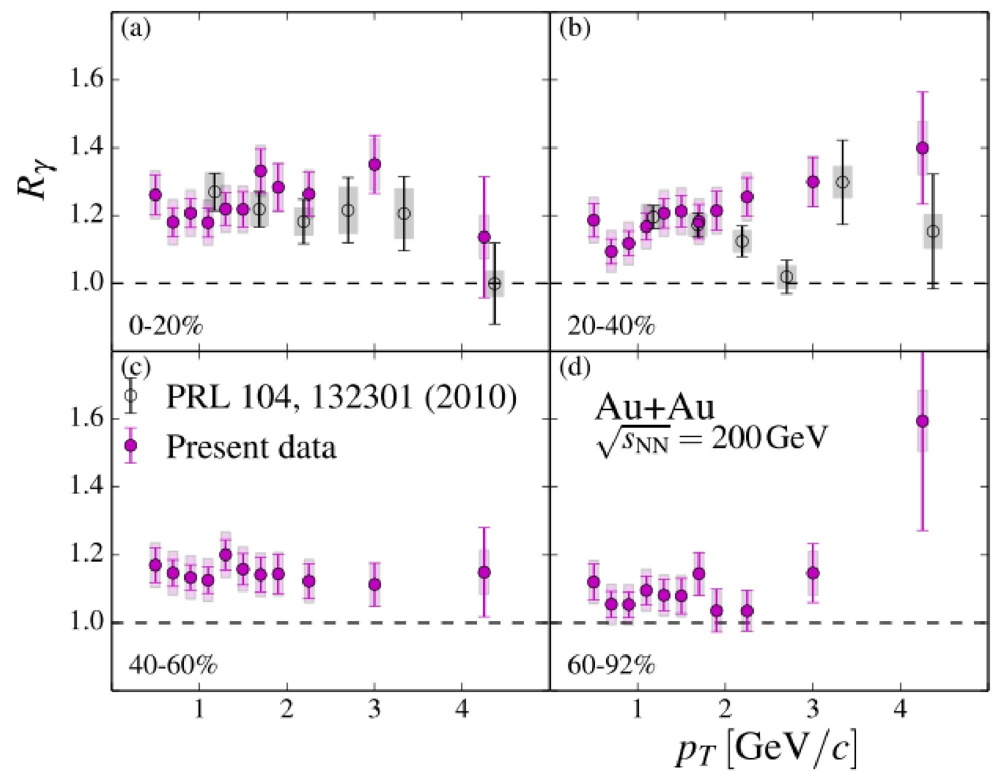
conditional tagging efficiency

measured raw yields

$$R_\gamma = \frac{N_\gamma^{incl}}{N_\gamma^{hadr}} = \frac{\langle \varepsilon f \rangle \times \left(\frac{Y_\gamma^{incl}}{Y_\gamma^{\pi^0 tag}} \right)^{Data}}{\left(\frac{N_\gamma^{hadr}}{N_\gamma^{\pi^0}} \right)^{MC}}$$

simulated based On hadron data

PHENIX arXiv:1405.3940

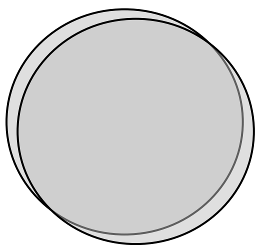


Almost 20% direct photons!
Approx. independent of p_T
from 0.4 to 4 GeV

Flow vs B Field Effect

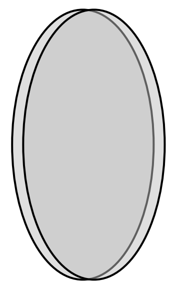
- **Look at different collision systems**

Au+Au
central



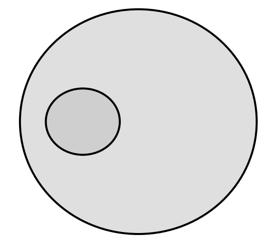
B = 0
$v_2 = 0$

U+U
central



B = 0
$v_2 \neq 0$

Cu+Au
semi-central



B ≠ 0
$v_2 = 0$

U+U and Cu+Au data sitting on tape waiting to be analysis