Measurements of direct virtual photon in Au+Au collision at $\sqrt{s_{\mathrm{NN}}}$ = 27 and 54.4 GeV

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2024年10月10-15日，重庆，STAR区域研讨会

Outline

Part I: Direct virtual photon production

Part II: Direct virtual photon mass spectrum shape

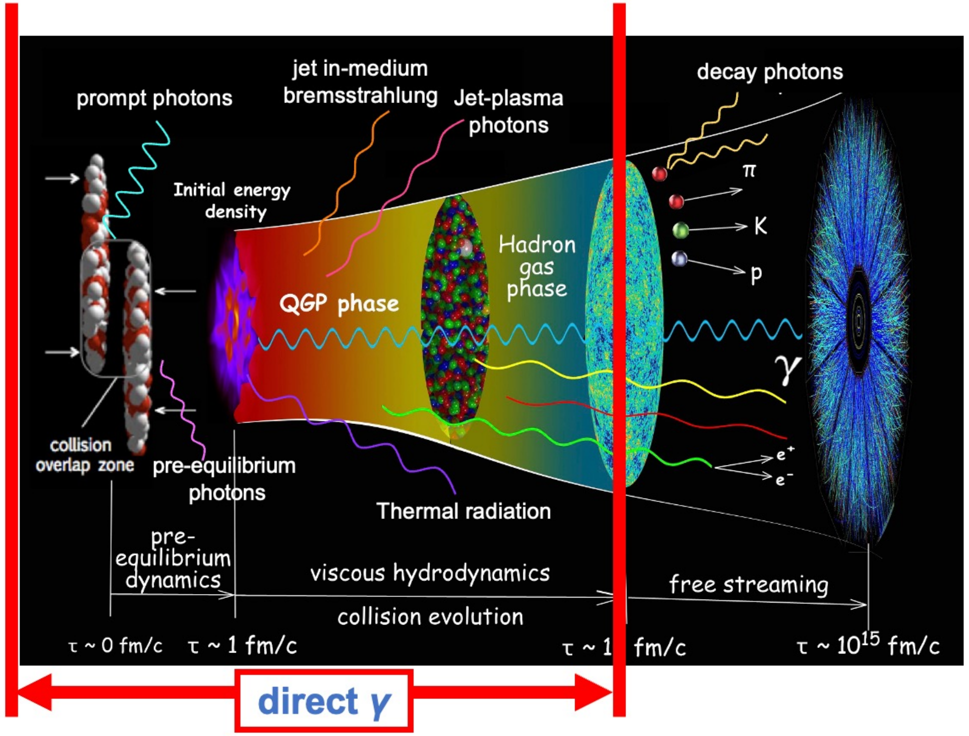
Why direct virtual photon?

- Do not participate in strong interaction
- Probe energy density, effective temperature, collective motion of QGP

What affect direct virtual photon yield?

- Emission time
- Volume ∝ $dN_{ch}/d\eta$
- Temperature and total chemical potential

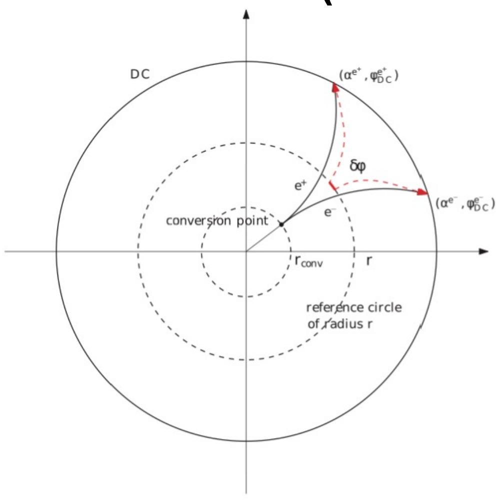
Comput. Phys. Commun., 199:61–85, 2016

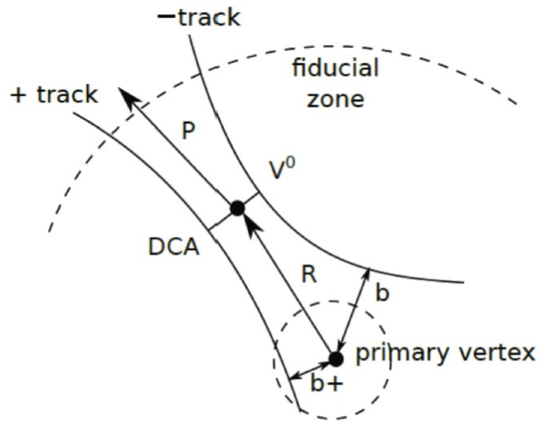


Au+Au collision at RHIC		
$\sqrt{s_{NN}}$ (GeV)	27	54.4
μ_B (MeV)	156	85
Use events (minimum bias)	~250M	~430M

How to extract direct photon?

(PHENIX, ALICE)





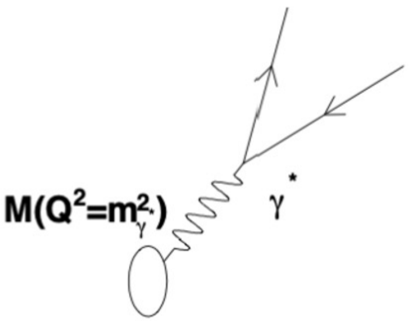
External method *Phys. Rev. C* 91, 064904 (2015)

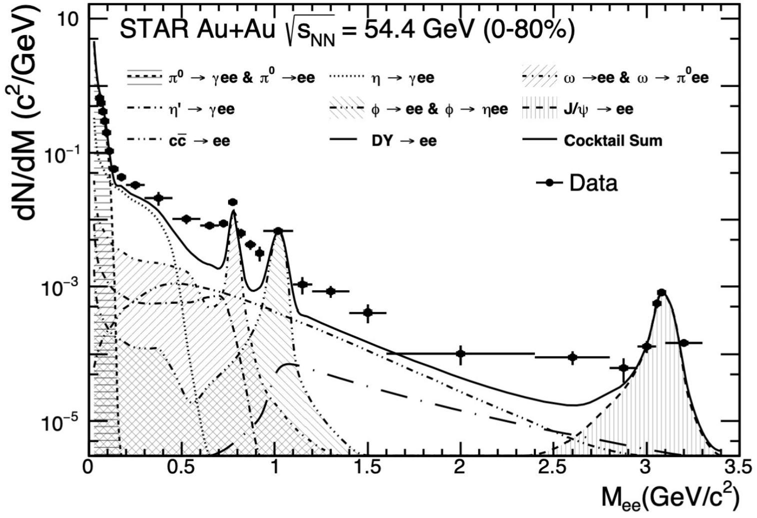
- Nearly background-free sample of photons down to p_T below 1 GeV/c
- BKG is dominated by η and π^0 two body decay
- Need good ability of photon identification

(STAR, PHENIX, ALICE)

Internal method *Phys. Rev. Lett.* 104, 132301 (2010)

- Virtual photon internally convert into e_+e_- pairs
- Used for low-momentum direct photon
- BKG is dominated by η dalitz decay
- Limitation: measurement to p_T > 1GeV/c

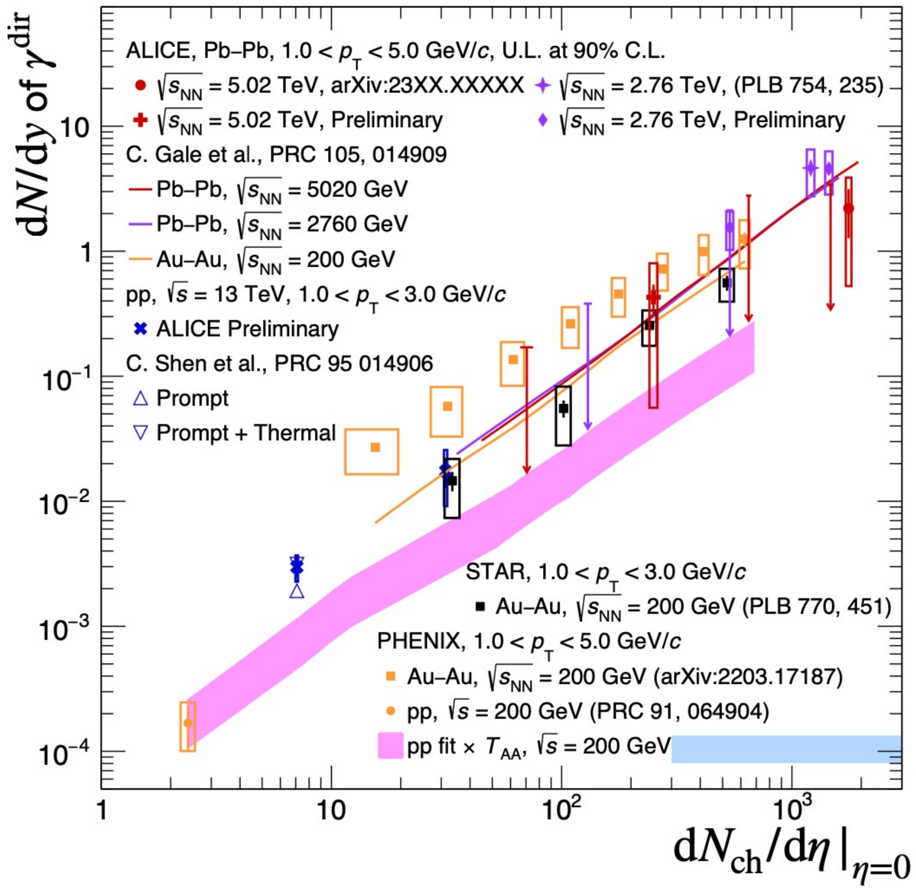




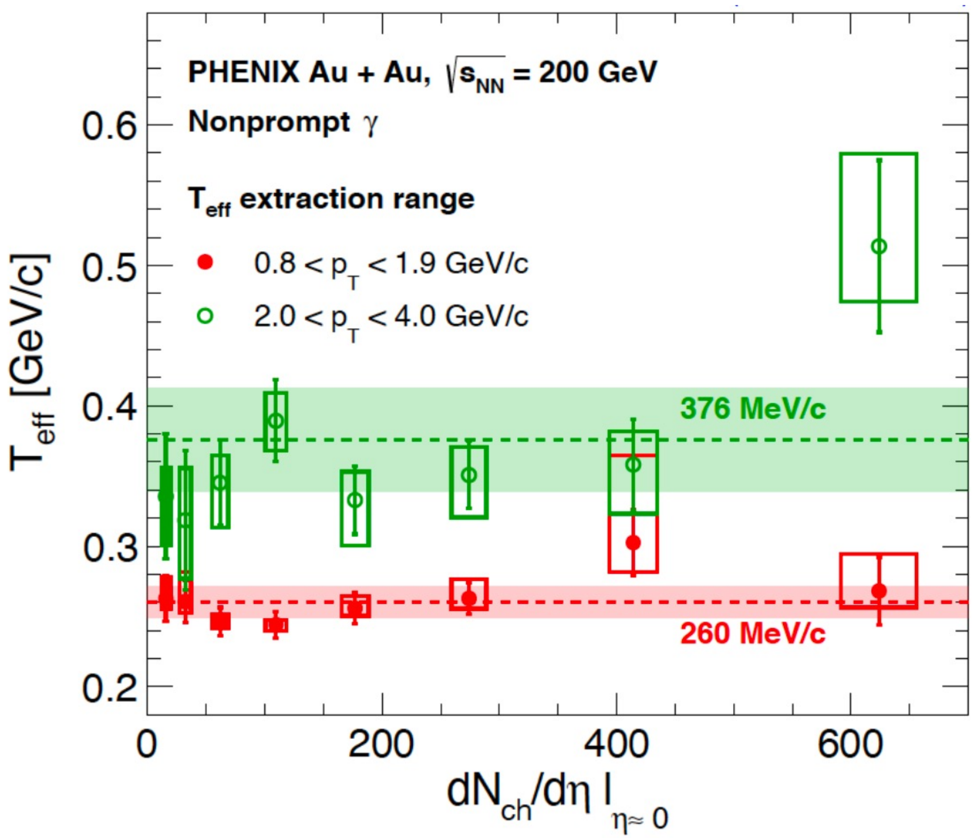
Current measurement

Au—Au $\sqrt{s_{NN}}$ = 200 GeV

Pb—Pb $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV and pp $\sqrt{s_{NN}}$ = 13 TeV



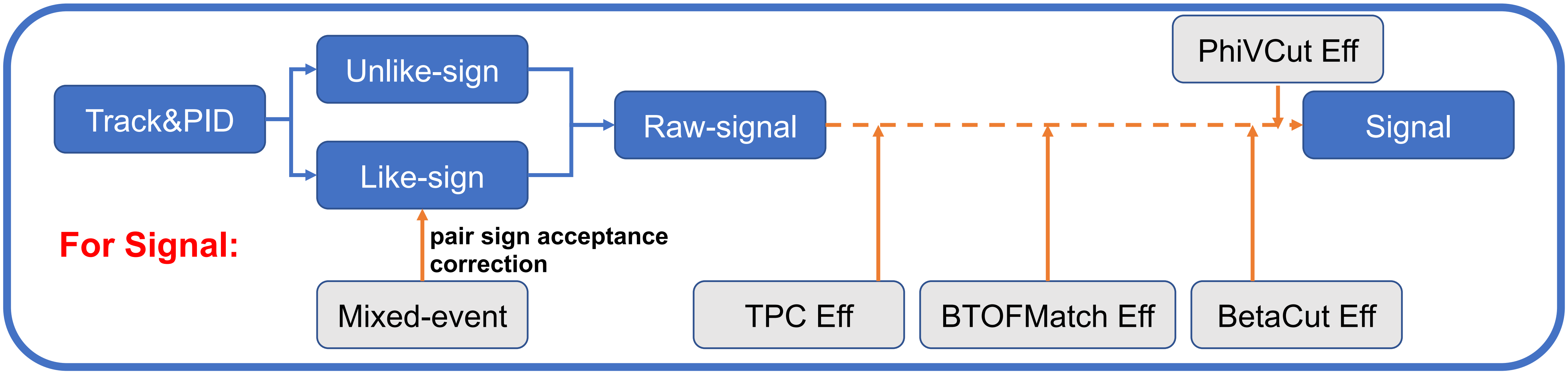
Phys. Rev. C 107, 024914 (2023)
Phys. Lett. B 754 (2016) 235-248

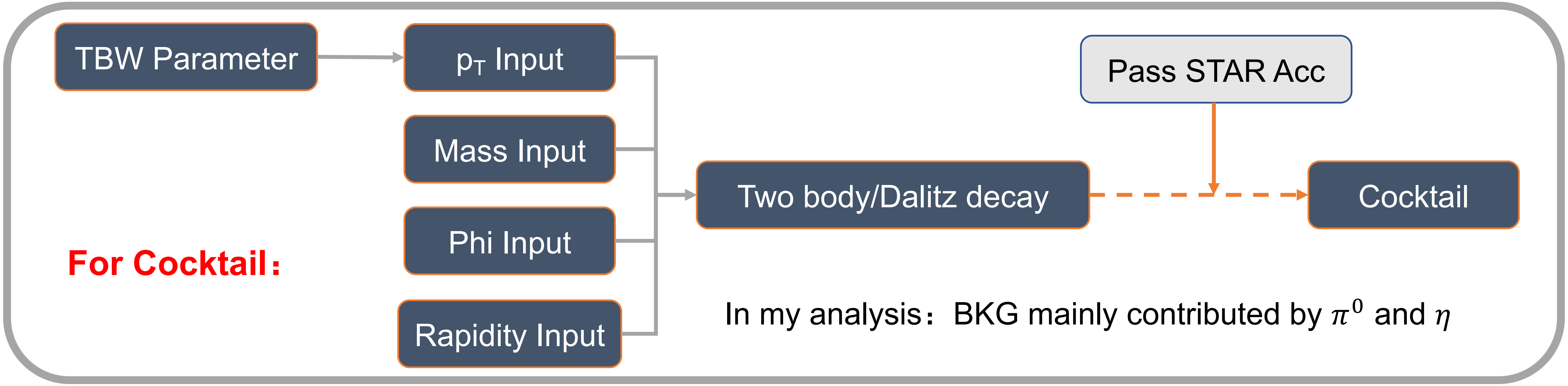


- Extract T_{eff} from thermal photon
- Obvious strong dependence of yield with $dN_{ch}/d\eta|_{\eta=0}$
- No obvious variation of T_{eff} with $dN_{ch}/d\eta|_{\eta=0}$

Analysis procedure

Both in STAR Acceptance

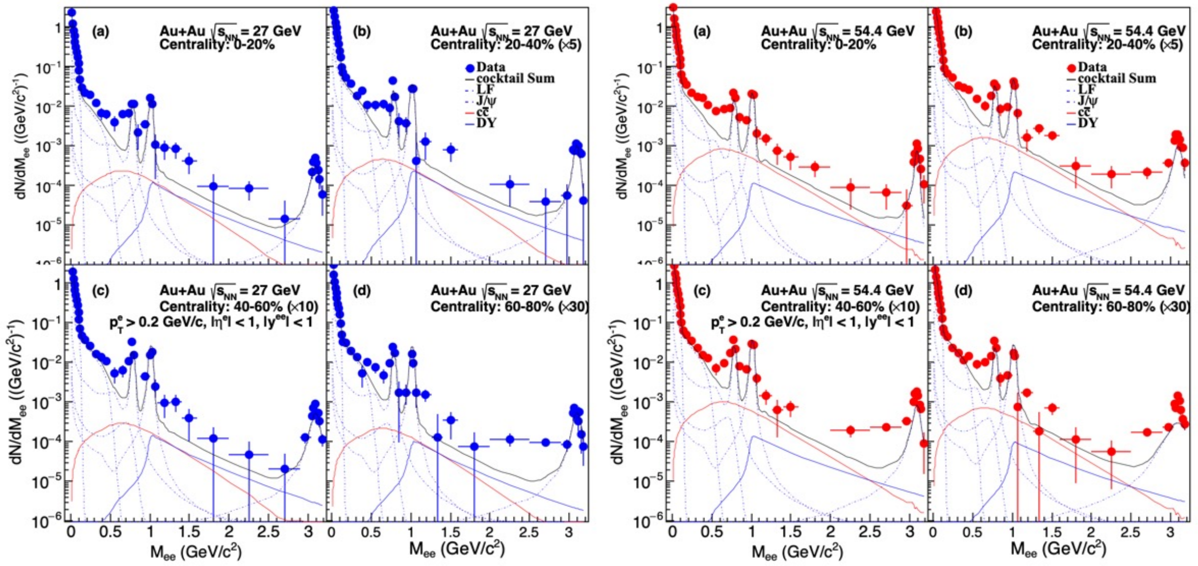




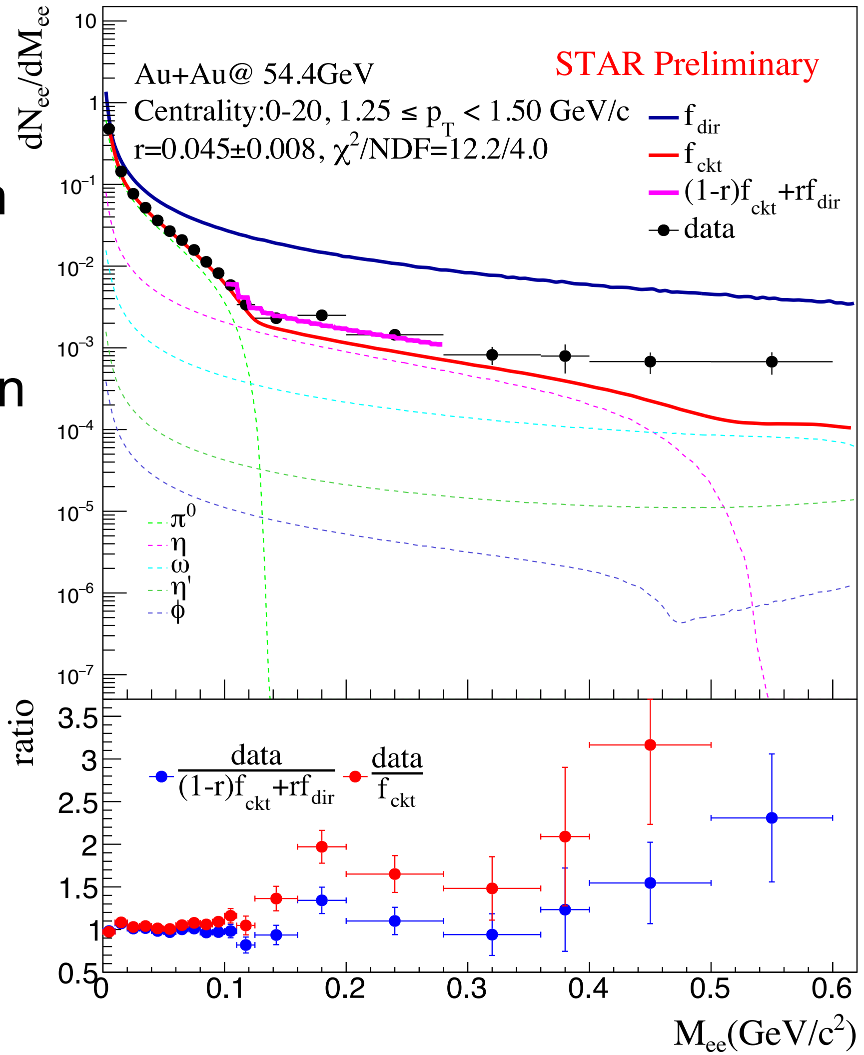
Internal conversion method: two-component fit

$$\frac{d^2N_{ee}}{dM} = r * f_{dir} + (1-r) * f_{cocktail} \qquad r = \frac{\gamma^{direct}}{\gamma^{inclusive}}$$

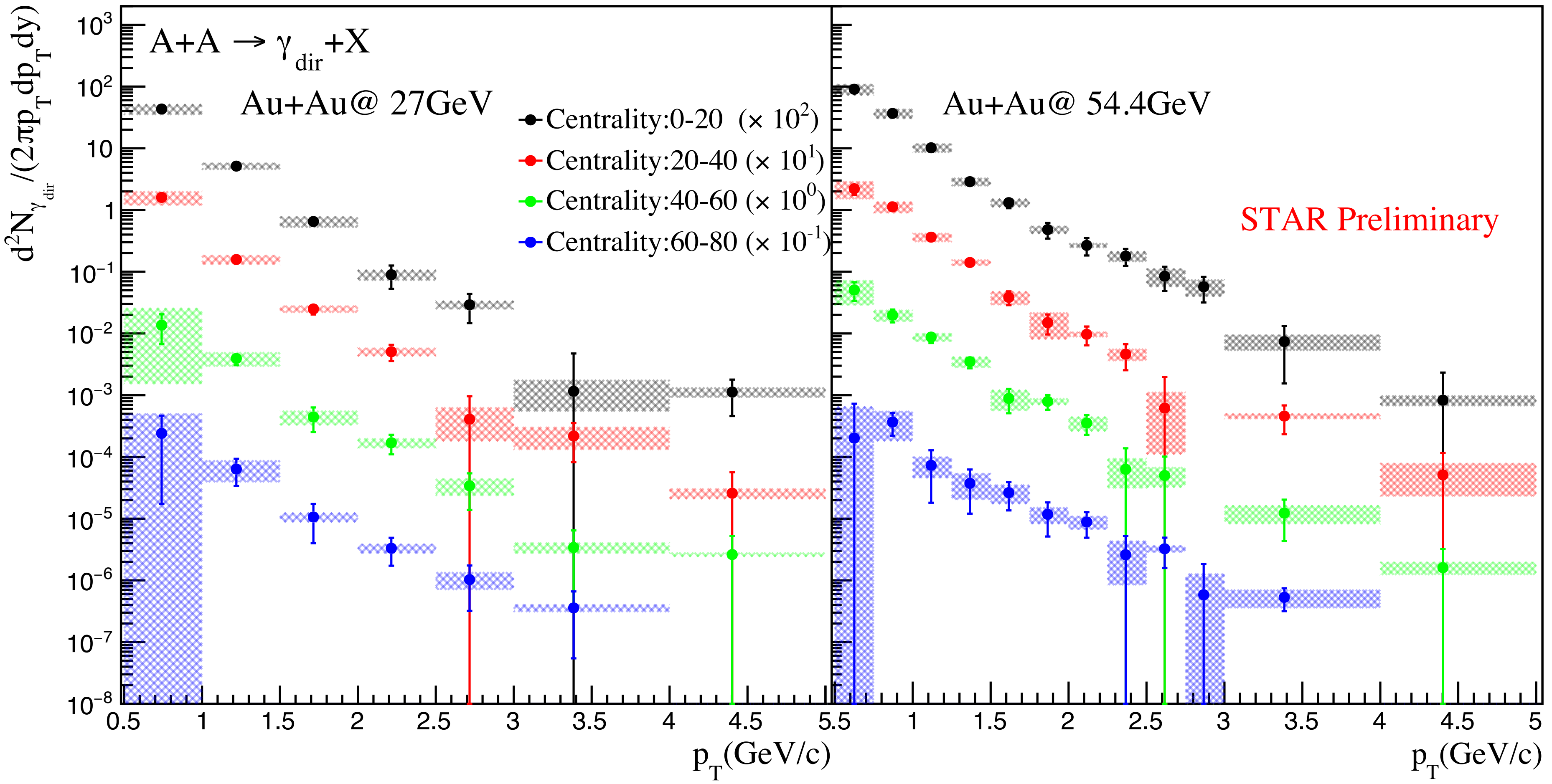
- Clear enhancement compared to cocktail contribution in η mass region
- Signal is consistent with cocktail at very low mass region
- Two-component fit region: 0.1-0.28 GeV/c^2



Both in STAR Acceptance



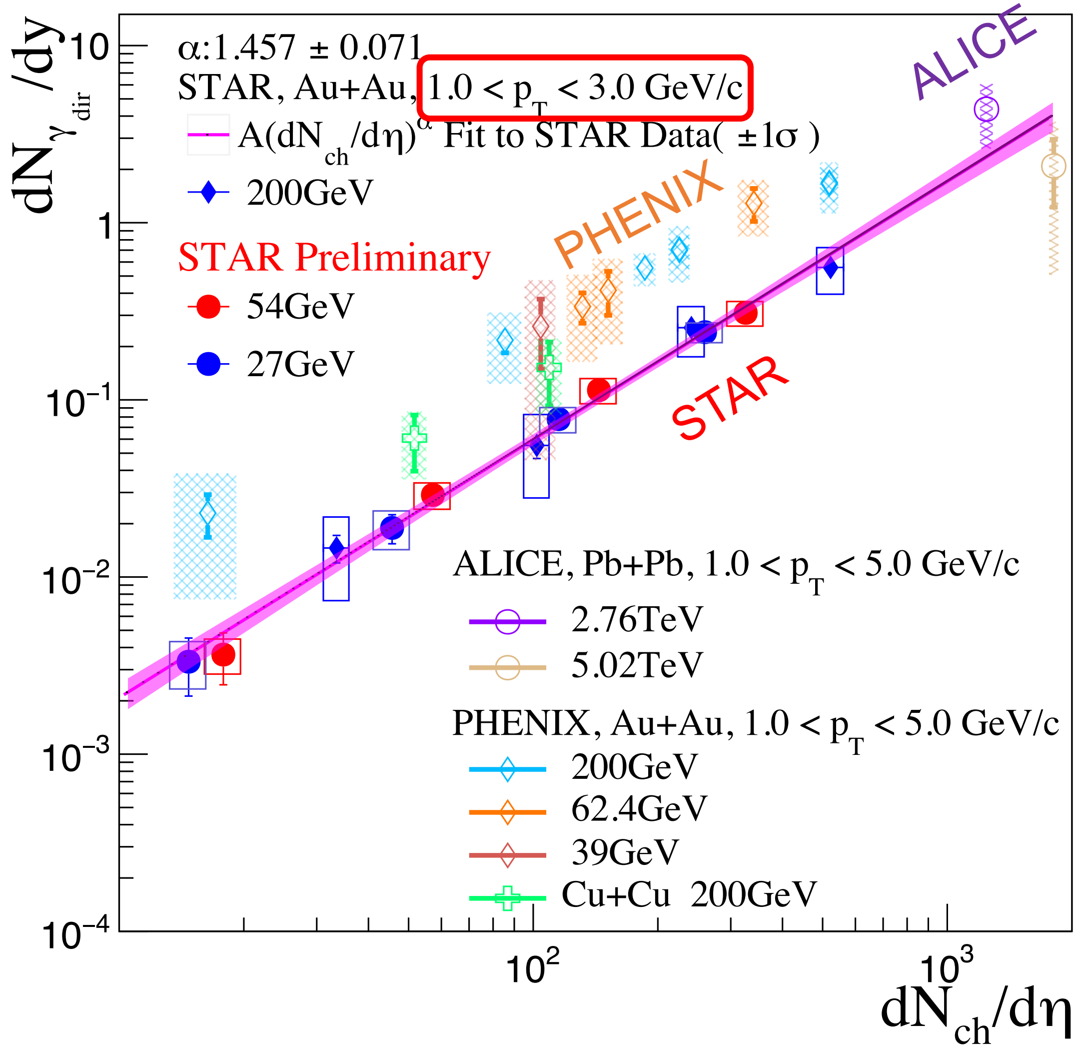
Direct virtual photon p_T spectrum



First direct virtual photon measurements in Au+Au collisions at $\sqrt{s_{NN}}$ = 27, 54.4 GeV

Call for theoretical calculations on thermal photons

The scaling behavior in $dN_{\gamma_{dir}}/dy$ vs. $dN_{ch}/d\eta$

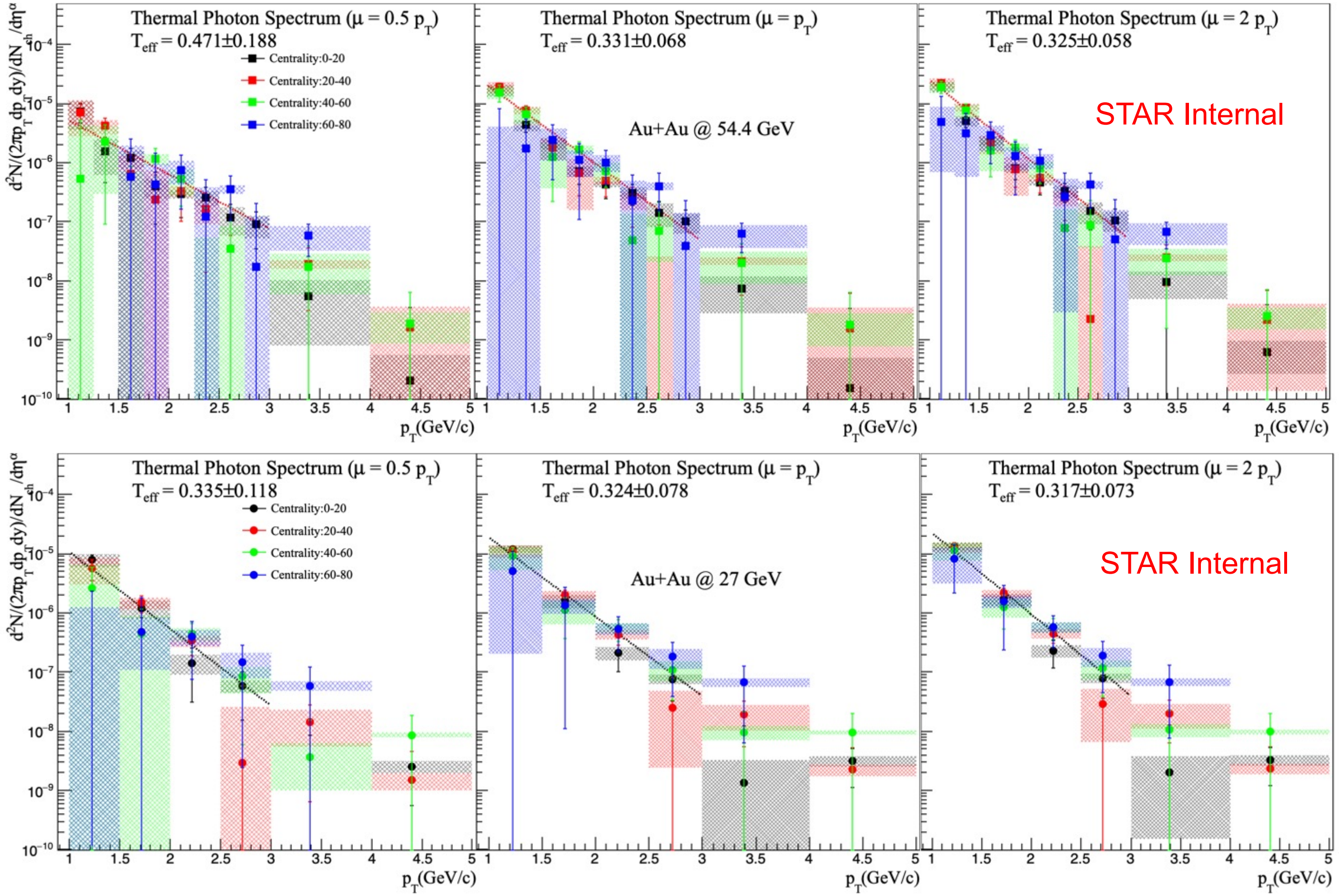


- New measurements of $dN_{\gamma_{dir}}/dy$ at STAR
- Yield dominated by thermal photon
- Strong $dN_{ch}/d\eta$ dependence
- The yields at $\sqrt{s_{NN}}$ **= 27, 54.4, 200** GeV measured by STAR follow **a common scaling**, with $\alpha = 1.457 \pm 0.071$

STAR Collaboration, *Phys.Lett.B* 770 (2017) 451-45
PHENIX Collaboration, *Phys.Rev.Lett*. 123 (2019) 022301
ALICE Collaboration, *arXiv:* 2308.16704

Direct thermal photon p_T spectrum

JHEP 0205:028,2002
Phys.Rev. D73:094007,2006
PHENIX Collaboration, *Phys.Rev.C* 81 (2010) 034911

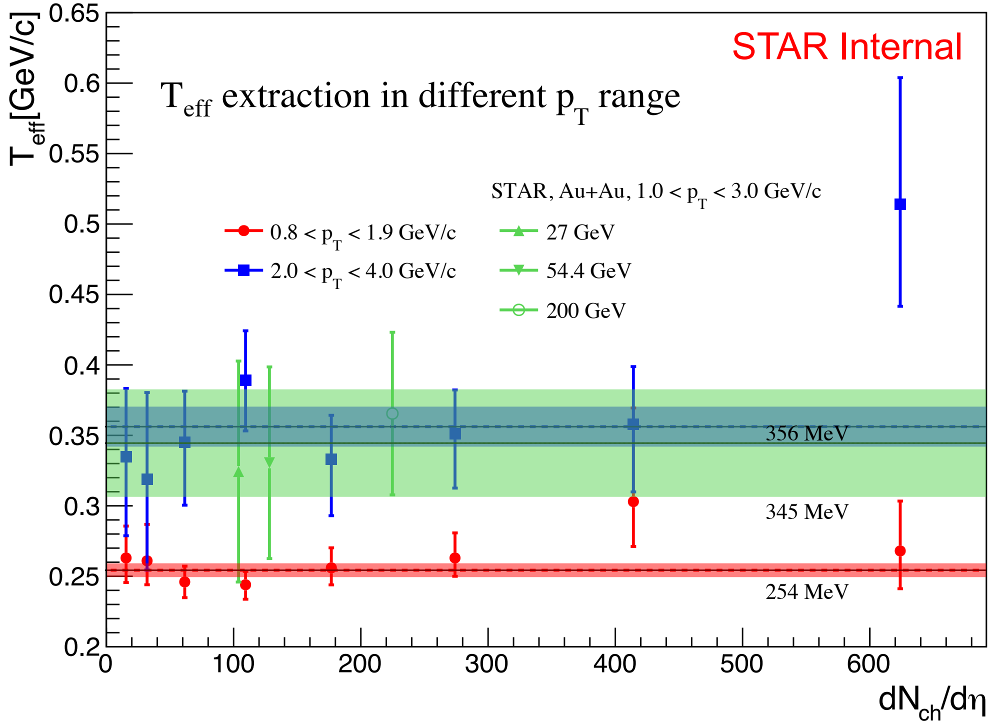


$$Ae^{-p_T/T} + \frac{N_{coll}^{STAR}}{\sigma_{inel}^{pp}} * A_{pp}(1 + p_T^2/b)^{-n}$$

Scale	27GeV	54.4GeV
$\mu = 0.5p_T$	324 ± 78	471 ± 188
$\mu = p_T$	330 ± 68	331 ± 68
$\mu = 2p_T$	316 ± 73	325 ± 58

- Reject prompt photon contribution by JetPhoX in different scale
- Combine thermal photon spectrum in different centralities and normalized by $dN_{ch}/d\eta$
- Time-average effective temperature over fireball evolution

Effective temperature



- ➢ Effective temperature from 1 to 3GeV/c is consistent with results from other p_T region
- ➢ Effective temperature is consistent with temperature from dielectron spectra at **IMR**

Phys.Rev.C 109 (2024) 4, 044912

Scale	27GeV	54.4GeV
$\mu = 0.5p_T$	324 ± 78	471 ± 188
$\mu = p_T$	330 ± 68	331 ± 68
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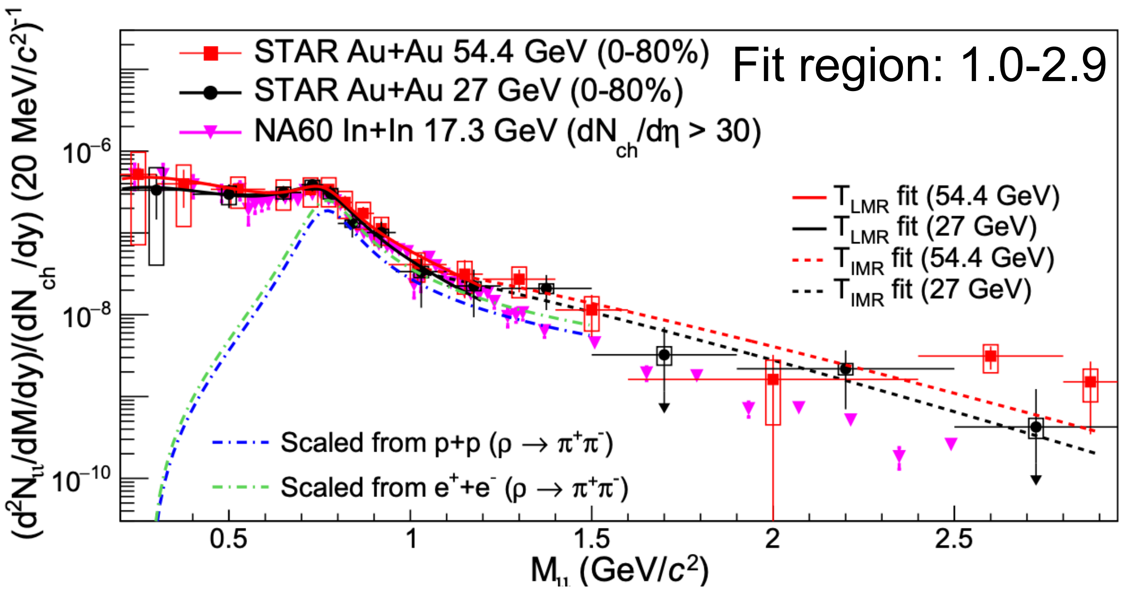


$$T_{IMR}^{54.4} = 303 \pm 59(stat.) \pm 28(sys.)$$
$$T_{IMR}^{27} = 280 \pm 64(stat.) \pm 10(sys.)$$

Direct virtual photon mass shape

$$dN_{direct\,\gamma*} = S_{direct\,\gamma} * dN_{direct\,\gamma}$$

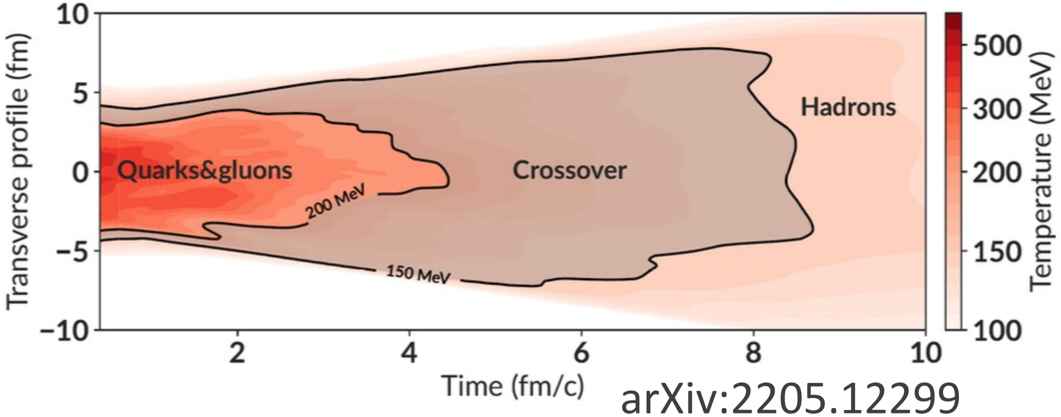
$if: p_T \gg M_{ee}$

$S \rightarrow 1, L(Mee) \rightarrow 1$

Phys.Rev.C 81 (2010) 034911
Phys. Rev. D 51, 6017–6035 (1995)
arXiv 2402.01998

we examine later the mass distribution for $p_T > 1$ GeV/c is consistent with the $1/m_{ee}$ shape expected for the electron pairs from internal conversion of virtual direct photons.

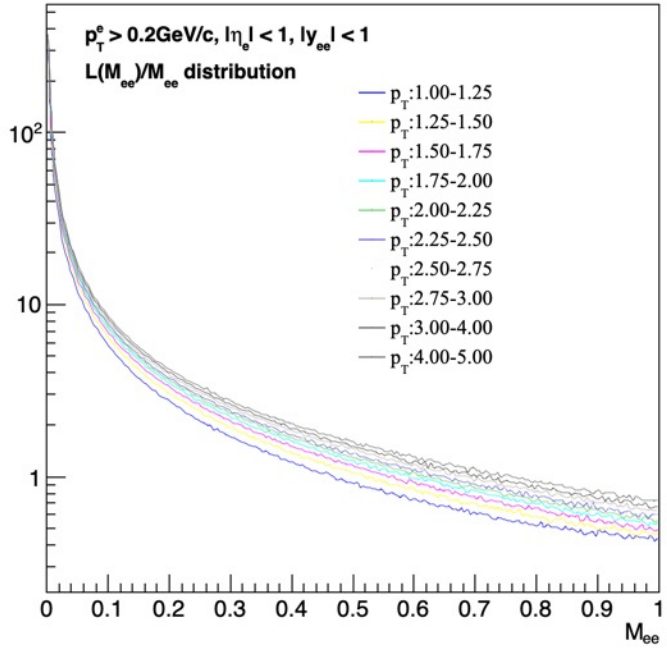
- Mass shape still follow $1/M_{ee}$ below p_T < 1GeV/c ?
- What is evolution stage and temperature for the excess yield at p_T < 1GeV and low mass?



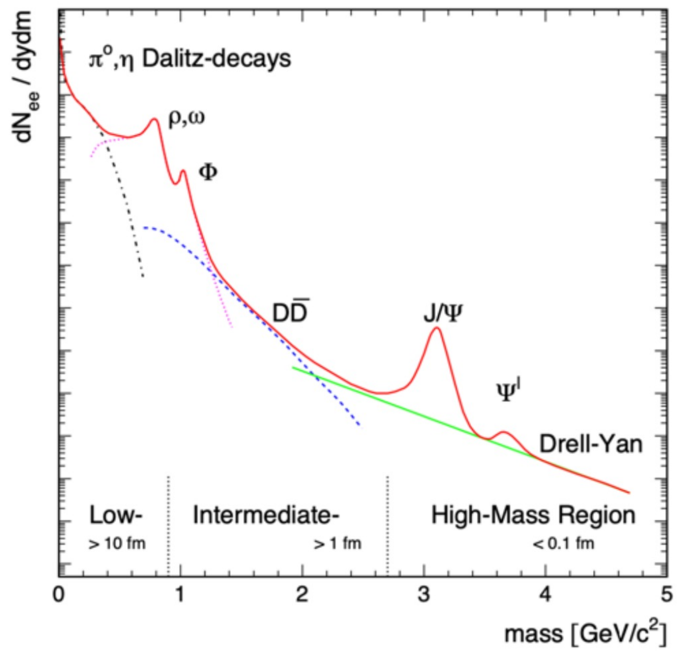
arXiv:2205.12299

Excess yield at low mass from virtual photon or dilepton radiation, the mass shape should follow exponent like dilepton mass spectrum in **IMR**

(Focus on virtual photon at whole LMR)



Extract Background and method



Background：

- π^0， η contribution → TBW predict p_T shape
- in-medium had. contribution → Rapp model calculation
- ω, ϕ contribution → muti-round fit to extract its yield

4 component Fit:

$$\frac{dN_{ee}}{dM_{ee}} = A * \gamma^{direct} + B * CKT({}^{W}/_{O}\ \omega, \phi) + InMedium\ \text{Had.} + \omega\ , \phi$$

- Select one mass shape(power-law/ exponent) to fit dielectron mass spectrum
- 4 component Fit(3 round):
  - Fit region: 0.6-0.9 to get ω contribution
  - Fit region: 0.9-1.1 to get ϕ contribution
  - Fit region: 0.1-1.0 to constrain direct virtual photon mass shape and its yield

Which one ?
$e^{-T/M}$ or $M^{-(q-1)}$

Mass spectrum shape choose

$$\frac{dN}{m_T dm_T} \propto m_T \int_{-Y}^{+Y} \cosh(y) dy \int_{-\pi}^{+\pi} d\phi \int_0^R r dr (1 + \frac{q-1}{T}(m_T \cosh(y)\cosh(\rho) - p_T \sinh(\rho)\cos(\phi)))^{-1/(q-1)}$$

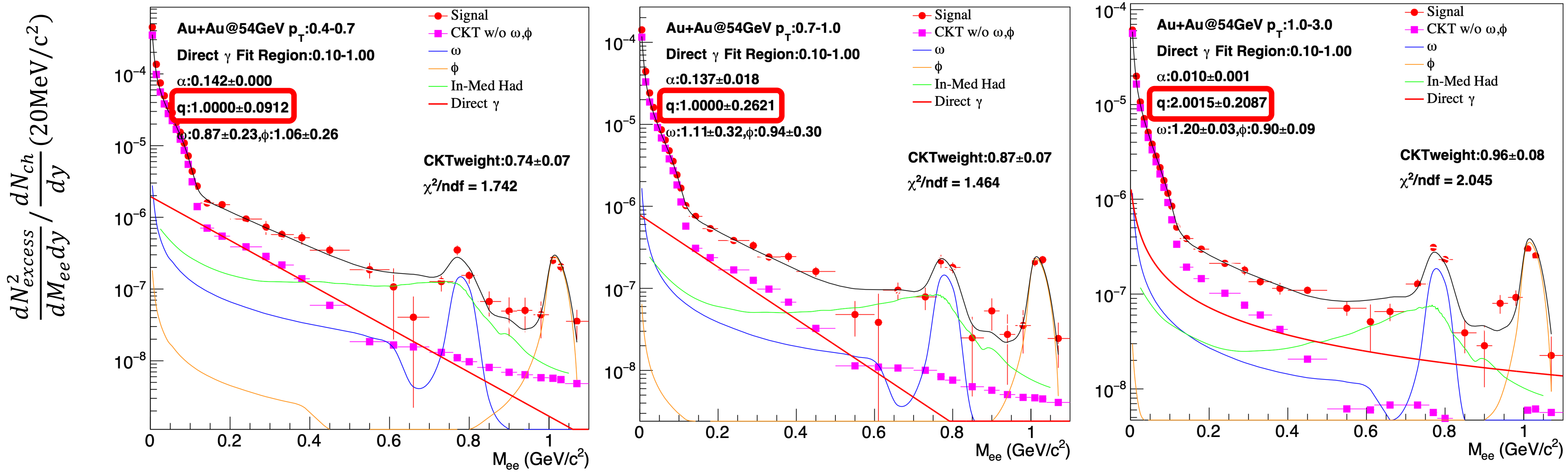
If q = 1, Mass shape : exponent

If q = 2, Mass shape : power-law

For Direct Photon:

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

$$\frac{dN_{ee}}{dM_{ee}} = A * \gamma^{direct} + B * CKT({}^{W}/_{O}\ \omega, \phi) + InMedium\ had. + \omega, \phi$$



- p_T: 0.4-0.7 GeV/c, its shape is more inclined to exponential
- p_T: 1.0-3.0 GeV/c, its shape is more inclined to power-law

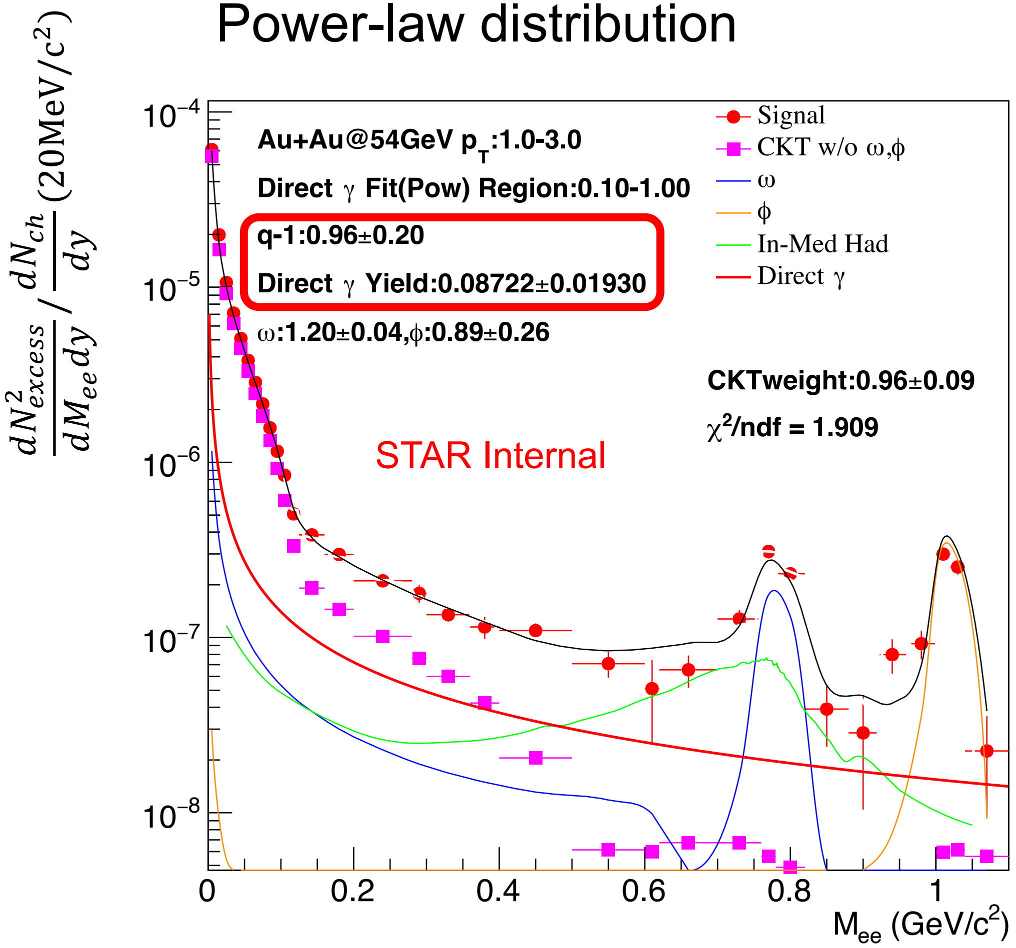
Consistent with previous results——Yield

- Virtual photon shape: $M^{-(q-1)}$
- Mass spectrum shape follow $1/M_{ee}$ at p_T: 1.0-3.0 GeV/c
- Yield is consistent with result from internal method

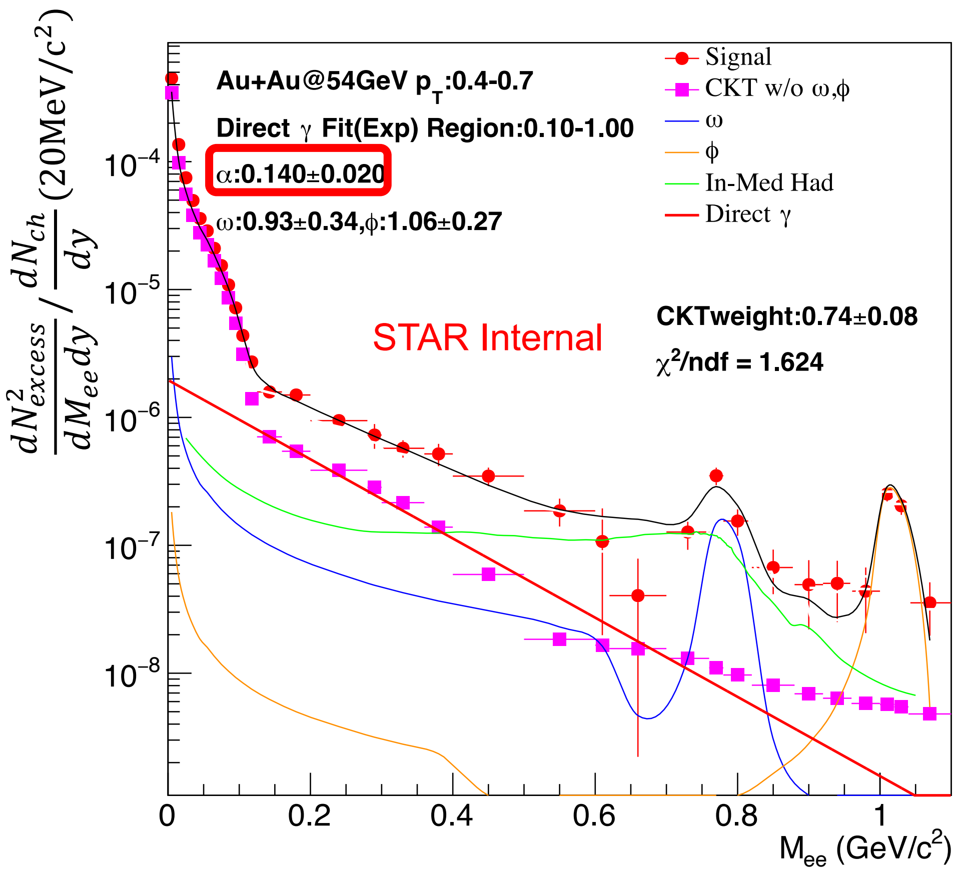
Internal conversion method:

Energy	Direct γ yield (w/o In-Med had.)
54.4 GeV	0.114 ± 0.007
Energy	**Direct γ yield (w/ In-Med had.)**
54.4 GeV	0.104 ± 0.006

Power-law distribution

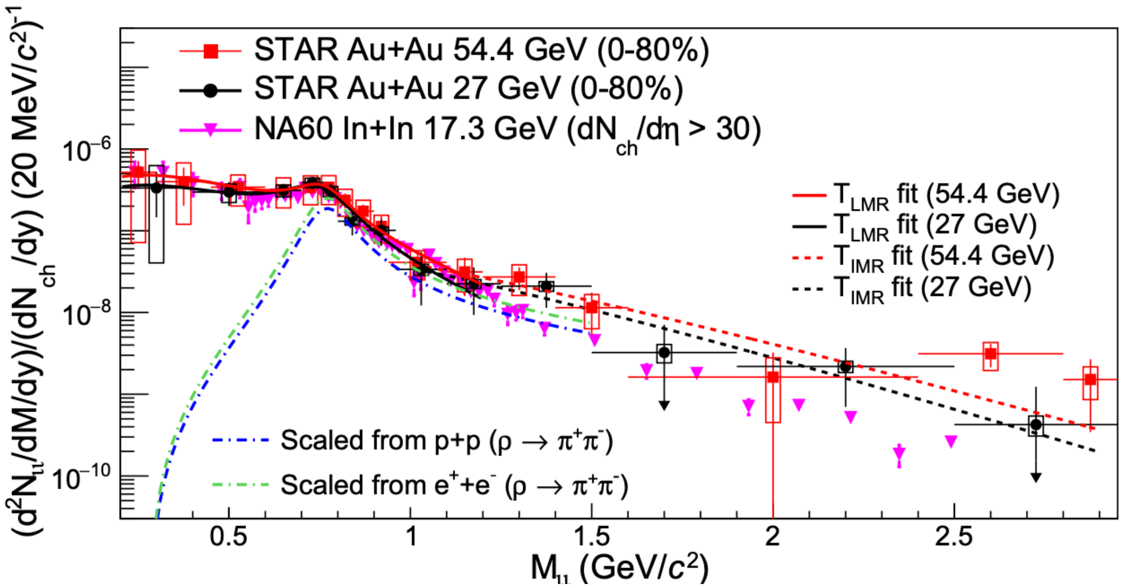


Consistent with previous results——Temperature



$T_{\gamma^*} = 140 \pm 20$ MeV

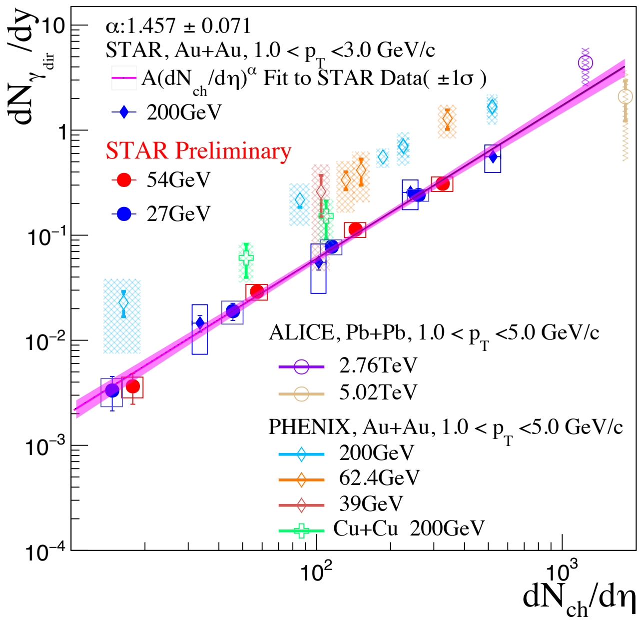
- Virtual photon shape: $e^{-\alpha/M}$
- Temperature extract from virtual photon mass spectrum can be consistent with result from dielectron at LMR



$T^{54.4}_{LMR} = 172 \pm 13(stat.) \pm 18(sys.)$

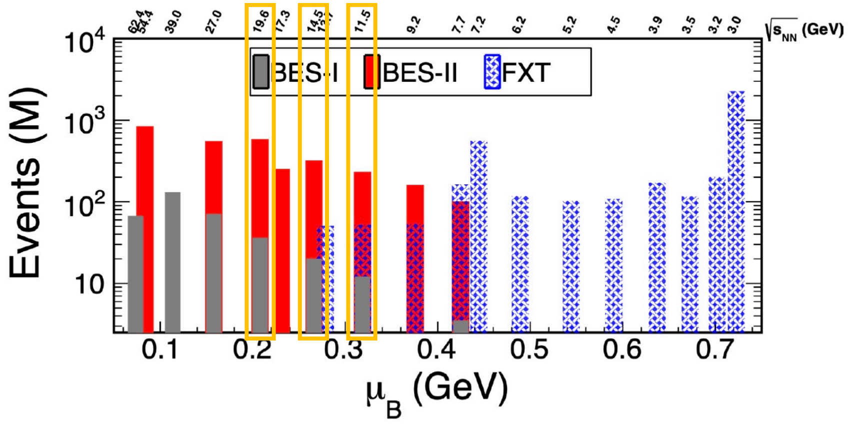
Summary

- New measurements of direct virtual photons in Au+Au collisions at $\sqrt{s_{NN}}$ = **27, 54.4** GeV, firstly extended to BES-II region
- The yields at $\sqrt{s_{NN}}$ **= 27, 54.4**, **200** GeV measured by STAR follow **a common scaling**
  - Strong $dN_{ch}/d\eta$ dependence
  - Scaling power α = 1.457 ± 0.071
- Direct virtual photon mass spectrum shape:
  - **High** p_T → **power-law**
  - **Low** p_T → **exponent**



Outlook

- Extend the study to the lower energies $\sqrt{s_{NN}} = 11.5, 14.6, 19.6$ GeV



Summary

Thanks for attention!

- New measurements of direct virtual photons in Au+Au collisions at $\sqrt{s_{NN}}$ = **27, 54.4** GeV, firstly extended to BES-II region
- The yields at $\sqrt{s_{NN}}$ **= 27, 54.4**, **200** GeV measured by STAR follow **a common scaling**
  - Strong $dN_{ch}/d\eta$ dependence
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- Direct virtual photon mass spectrum shape:
  - **High p_T → power-law**
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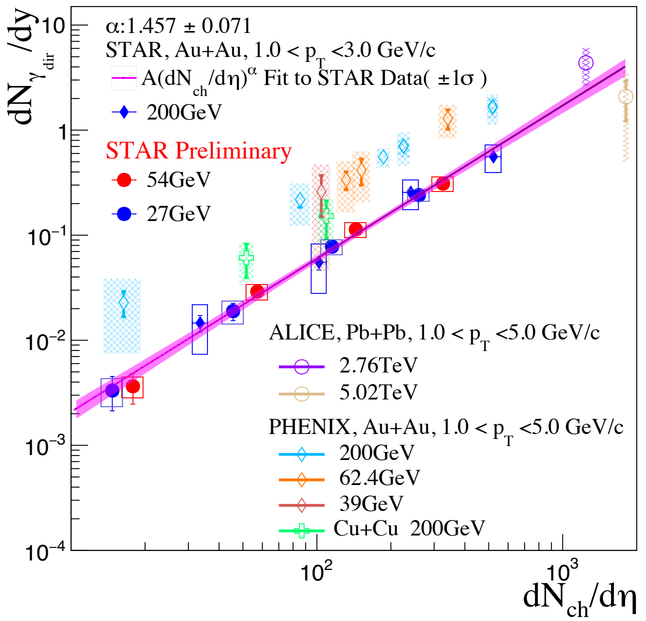

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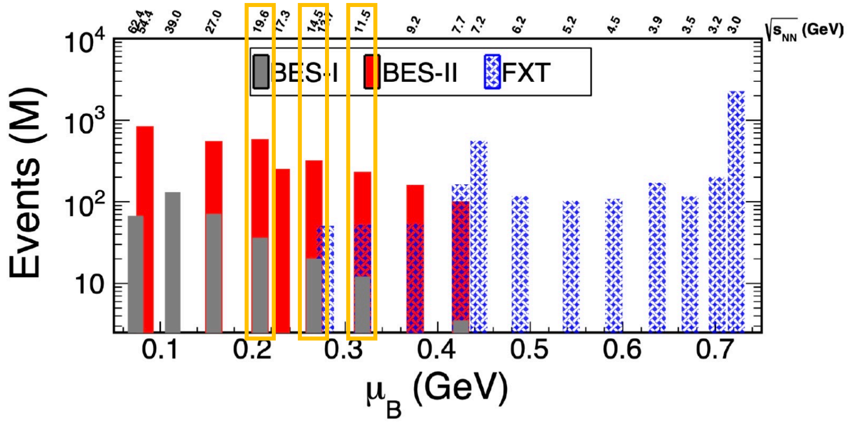
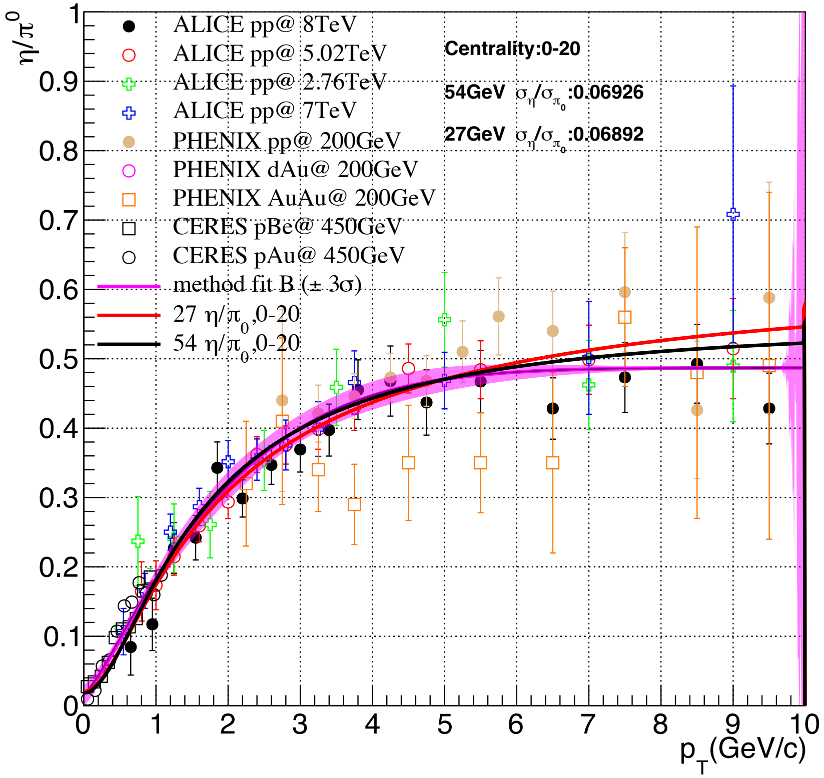
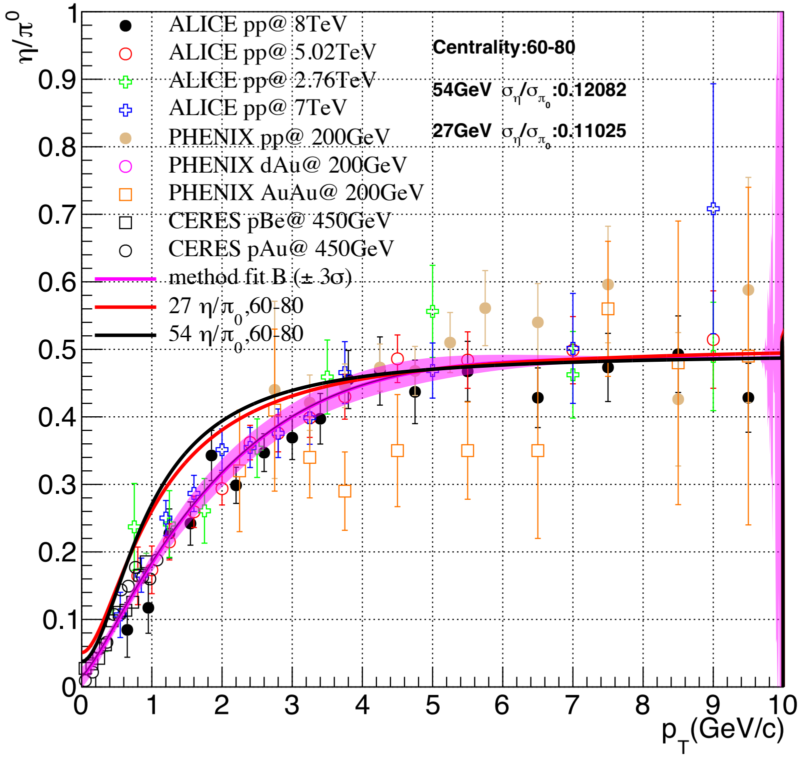


Backup

Background estimation

Phys.Rev.C 104 (2021) 5, 054902)
CERES Collaboration, *Eur.Phys.J.C* 4, 249–257 (1998)
ALICE Collaboration, *Eur.Phys.J.C* (2017) 77:339
ALICE Collaboration, *Eur.Phys.J.C* 78 (2018) 8, 624
PHENIX Collaboration, *Phys.Rev.C* 75 (2007) 024909





$f_{worldwide}$:

$$R^{\eta/\pi_0}(p_T) = A\frac{\left(e^{-a*p_T-bp_T^2}+\left(\frac{R^{\infty}}{A}\right)^{-\frac{1}{n}}\frac{p_T}{p_0}\right)^{-n}}{\left(e^{-a*p_T-bp_T^2}+\frac{p_T}{p_0}\right)^{-n}}$$

- No obvious energy and centrality dependence at high p_T
- η/π^0 are parametrized using Tsallis blast-wave function,

and η/π^0 (**p_T = 5 GeV/c**) is fixed to **0.470±0.017** obtained from global data

Prompt photon from JetPhoX

- Use JETPhox produce prompt photon

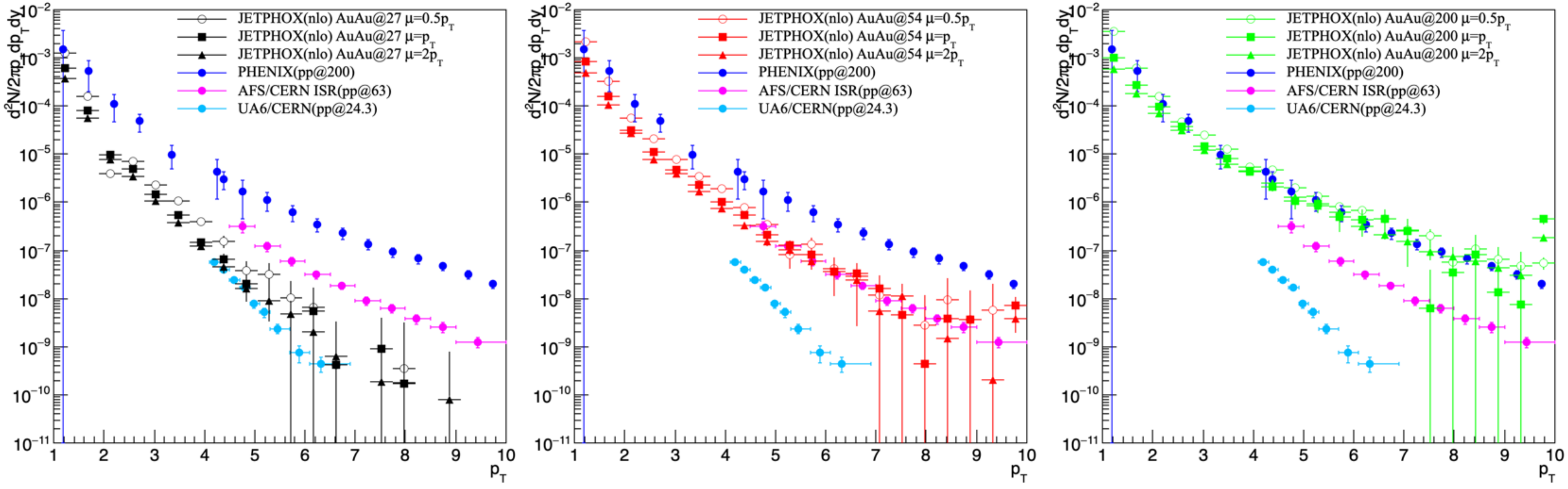
Model Setting：

1.pdf: CT10nlo

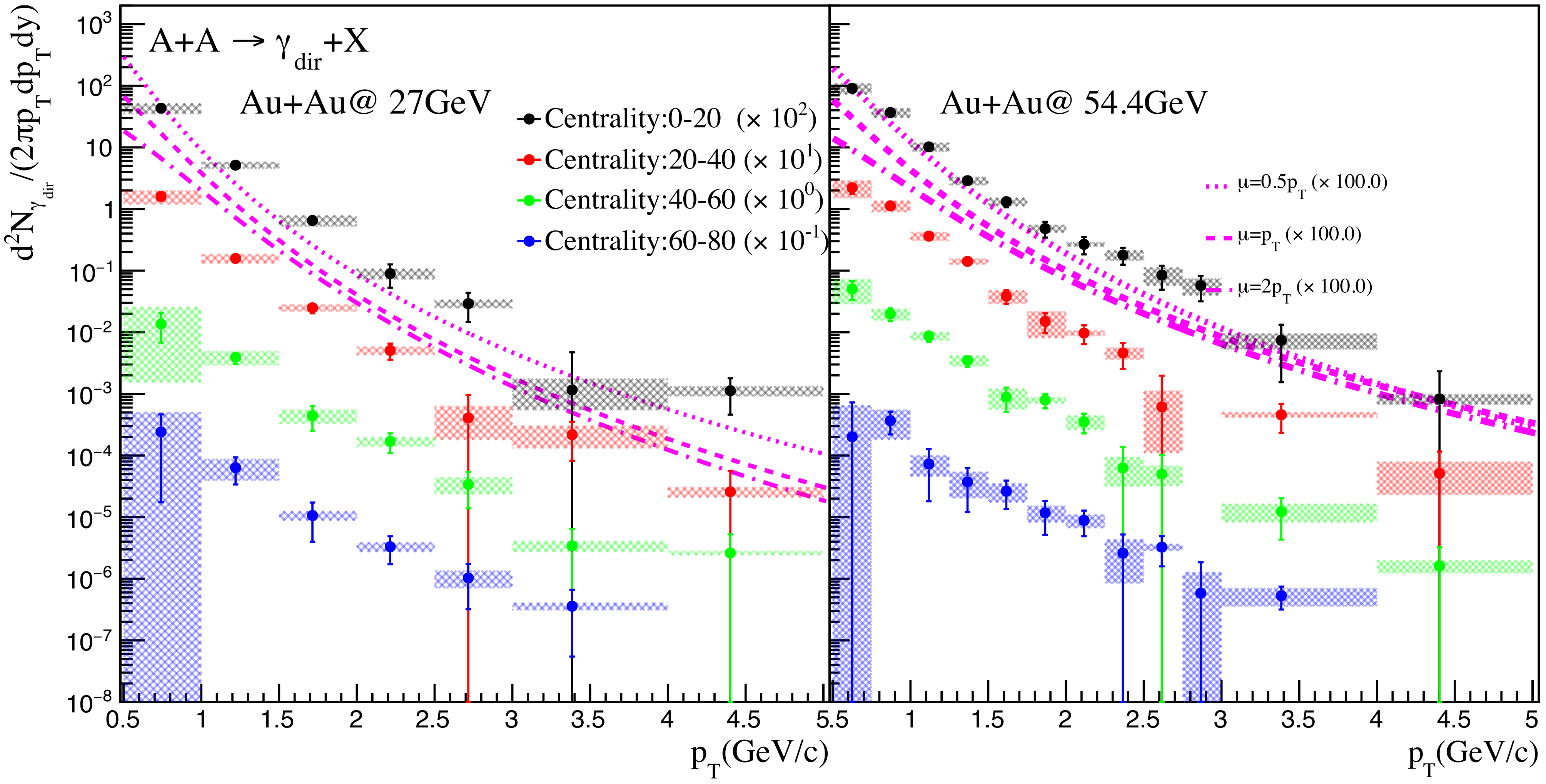
2.scale($\mu = 0.5p_T, \mu = p_T, \mu = 2p_T$)

- Prompt Photon cut:

- $-1 < y_\gamma < 1$
- $0.5 < p_T^\gamma < 10$

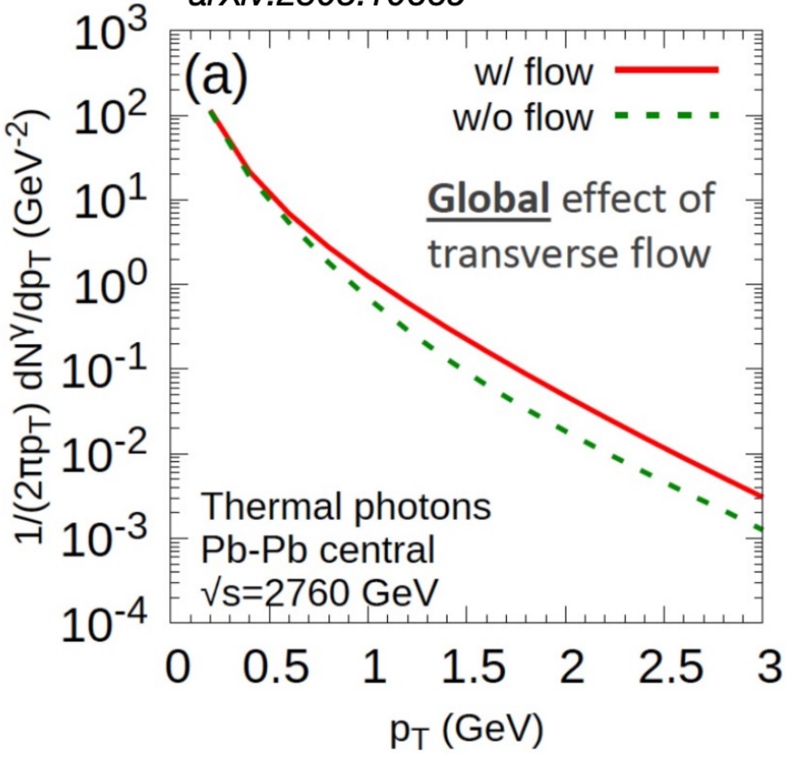


Direct photon vs. prompt photon



Experiment vs. Theory

Phys. Rev. C 89 (2014) 044910
arXiv:2305.10669

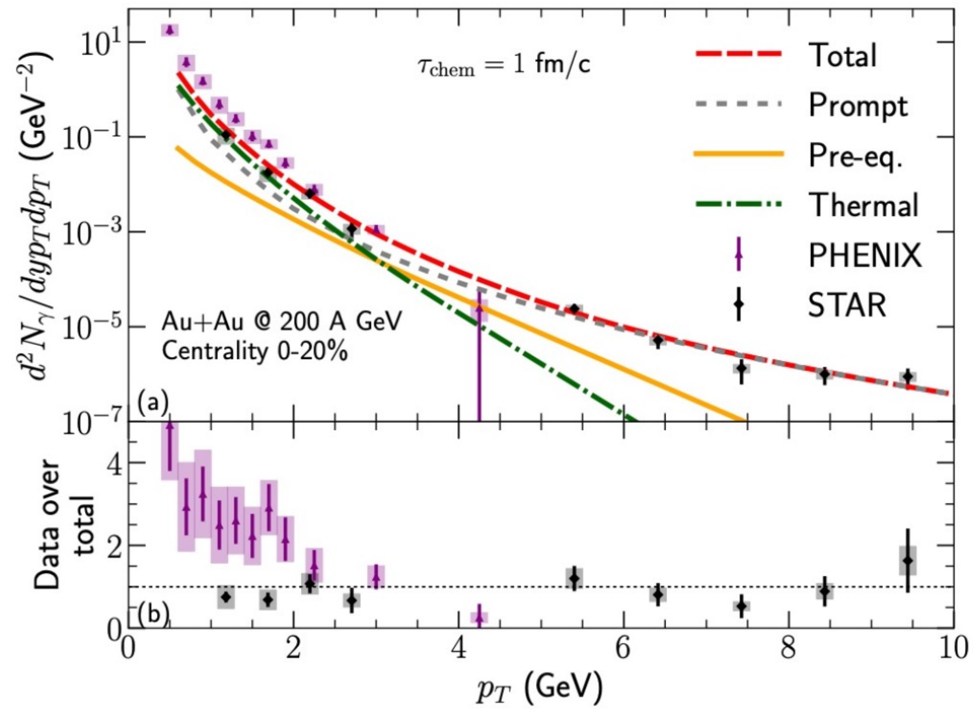


Inverse slope:

$$-\frac{1}{T_{eff}} \approx -\frac{1}{T_0} - \frac{5}{2}\frac{1}{p_T} + O\left(\frac{T_0}{p_T^2}\right)$$

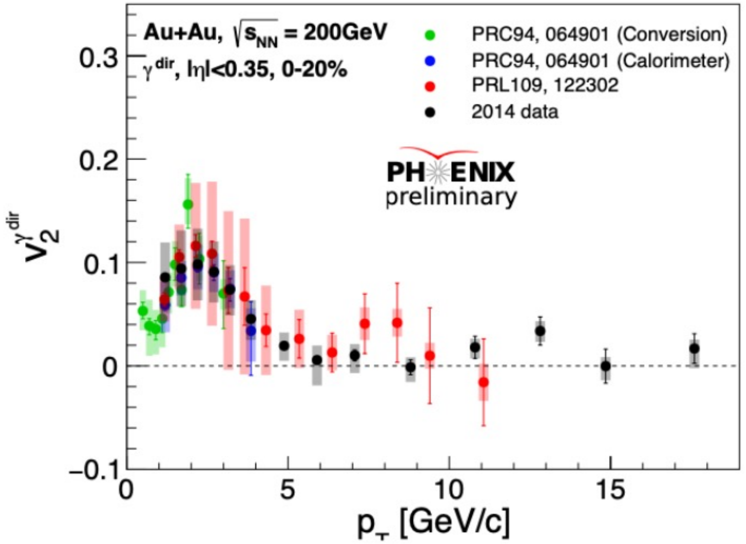
Initial maximum ***T*** of plasma

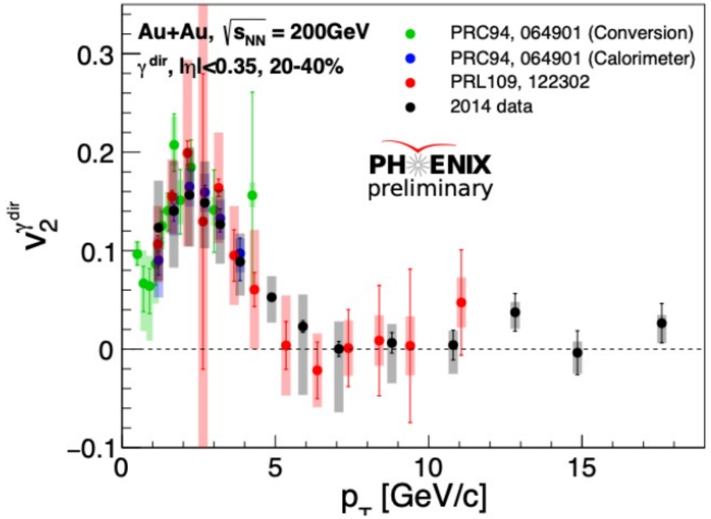
Phys.Rev.C 105 (2022) 1, 014909



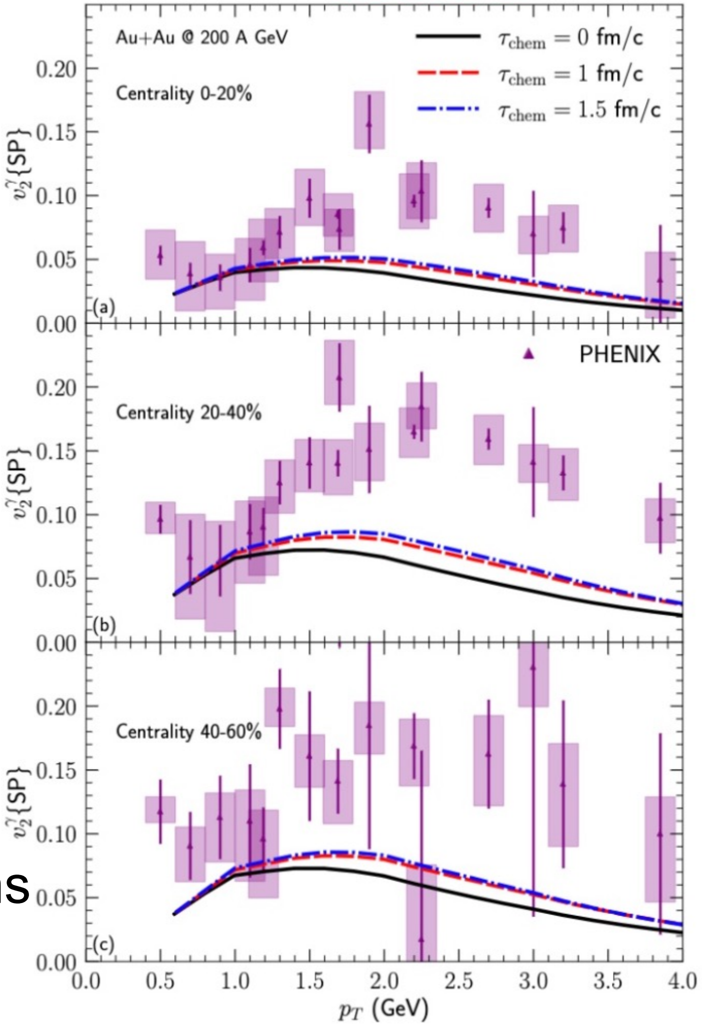
- Consider blue effect, theoretical model is consistent with STAR result better than PHENIX
- Acquire T_0 with simple hydro theoretical model

Direct photon v_2 puzzle





Phys. Rev. C 105 014909 (2022)
C. Gale et. al.

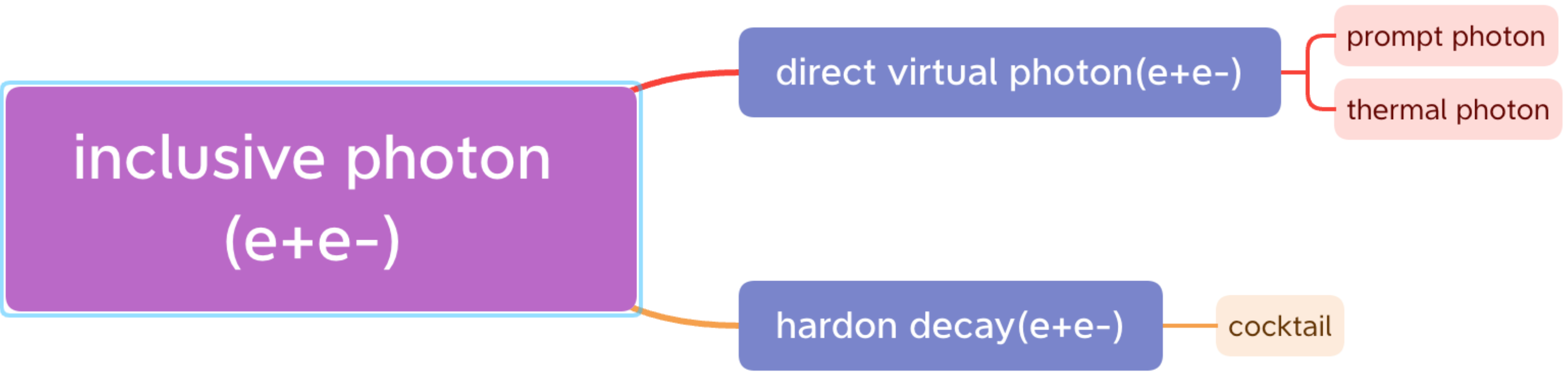


- ➢ Direct photon v_2 in high p_T region is consistent with 0
- ➢ The expectation of direct thermal photon v_2 should be close to 0

◆ Theoretical model:

- ➢ Hybrid model can describe all stages of relativistic heavy-ion collisions
- ➢ Effect of pre-equilibrium phase on both photonic and hadronic observables highlighted

Direct virtual photon analysis——Internal Conversion



Direct photon invariant yield:

$$d_{direct\,\gamma} = r * F * \frac{3\pi}{2\alpha}$$

$$\frac{d^2N}{2\pi p_T dp_T dy} = \frac{3 * r * F}{4\alpha p_T dp_T dy}$$

inclusive dielectron consist of:

- **From dalitz decay**
- **From direct photon decay**

Parameter r to measure the directphoton weight in inclusive photon

$if: p_T \gg M_{ee}$

$S \to 1, L(Mee) \to 1$

$$dN_{direct\,\gamma*} = S_{direct\,\gamma} * dN_{direct\,\gamma}$$

$$\frac{d^2N_{ee}}{dM} = \frac{d^2N_{ee}^{direct\,\gamma*}}{dM} + \frac{d^2N_{ee}^{dalitz\,\gamma*}}{dM}$$

$$= \frac{2\alpha}{3\pi}\frac{L(M)}{M} dN_{direct\,\gamma*} + \frac{2\alpha}{3\pi}\frac{L(M)}{M} dN_{dalitz\,\gamma*}$$

two-body decay process or Kroll–Wada

$$L(M) = \sqrt{1 - \frac{4M_e^2}{M_{ee}^2}}\left(1 + \frac{2M_e^2}{M_{ee}^2}\right)$$

$$S = \frac{dN_{\gamma*}}{dN_{\gamma}}$$

$$= \frac{2\alpha}{3\pi}\frac{L(M)*S_{direct\,\gamma}}{M} dN_{direct\,\gamma} + \frac{2\alpha}{3\pi}\frac{L(M)*S_{dalitz\,\gamma}}{M} dN_{dalitz\,\gamma}$$

$$= \frac{2\alpha}{3\pi}\frac{r}{M} dN_{inclusive\,\gamma} + \frac{2\alpha}{3\pi}\frac{1-r}{M} dN_{inclusive\,\gamma}$$

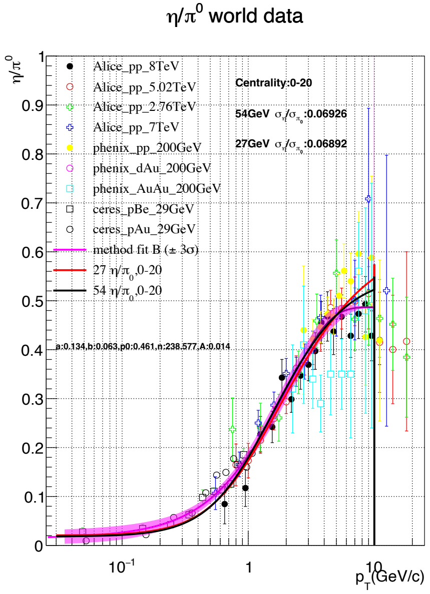
$$= r * f_{dir} + (1-r) * f_{cocktail}$$

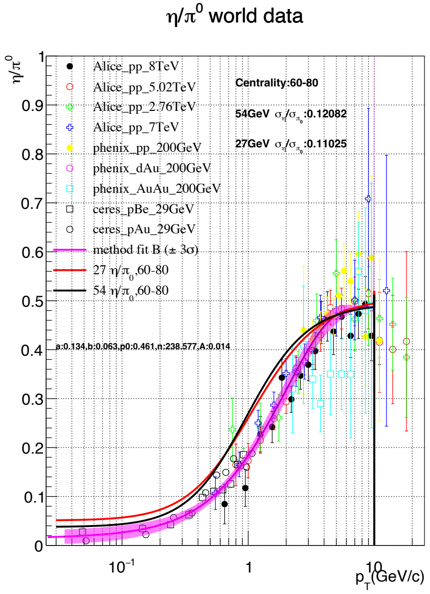
we interested **inclusive background**

$$= r * F * \frac{1}{M} + (1-r) * f_{cocktail}$$

two component fit

Eta/pi0 detail

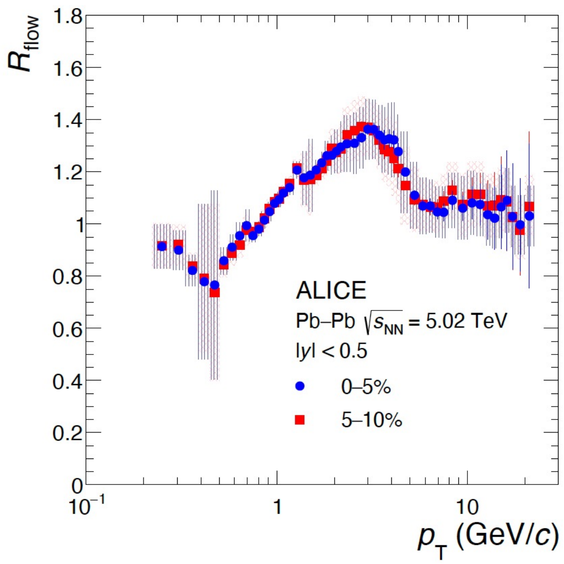


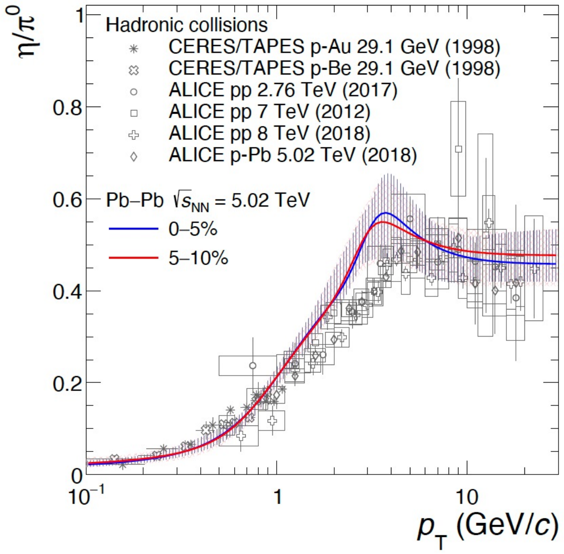


- Eta/pi0 affected by flow largely in AA collision
- High pT: No large flow effect
- Central collision: fireball close to round(not ellipse)

$$\left(\frac{\eta}{\pi^0}\right)_{\text{PbPb}} = \left(\frac{\eta}{\pi^0}\right)_{\text{pp}} \times R_{\text{flow}} = \left(\frac{\eta}{\pi^0}\right)_{\text{pp}} \times \frac{\left(\frac{K^\pm}{\pi^\pm}\right)^*_{\text{PbPb}}}{\left(\frac{K^\pm}{\pi^\pm}\right)^*_{\text{pp}}},$$

Eta/pi0	0-20	20-40	40-60	60-80
27GeV	0.0692567	0.0859706	0.125181	0.12082
Lower	0.0666966	0.0827927	0.120554	0.116354
Upper	0.0717959	0.0891226	0.129771	0.12525
54GeV	0.0689218	0.0827538	0.0991576	0.110253
Lower	0.066374	0.0796947	0.0954921	0.106177
Upper	0.0714487	0.0857878	0.102793	0.114295





HADES result

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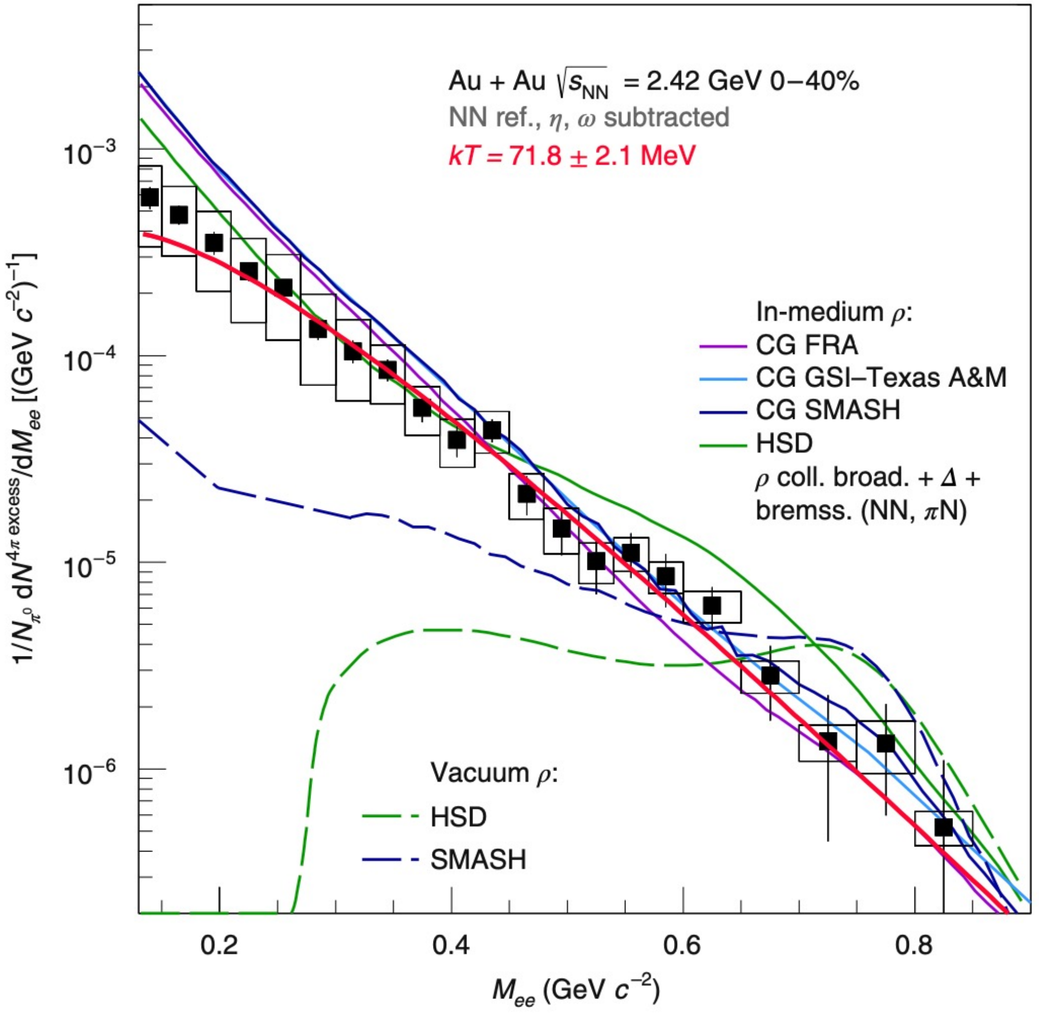
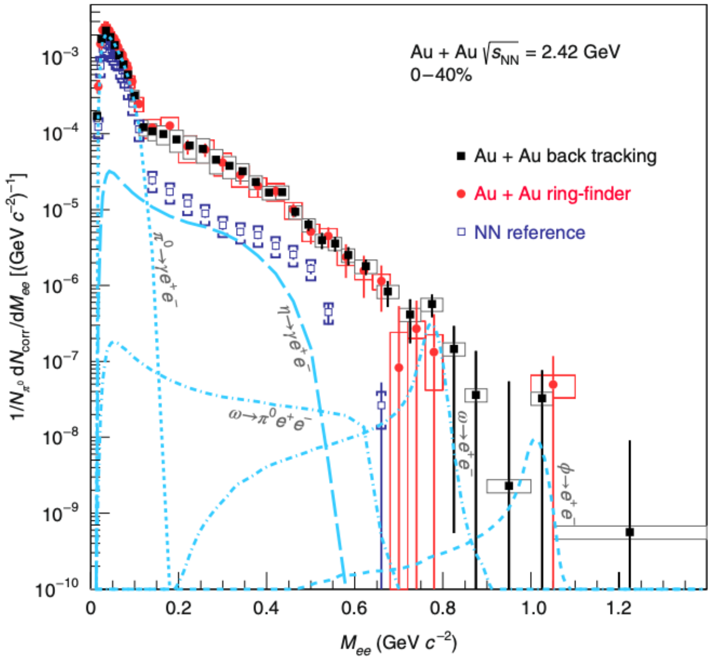


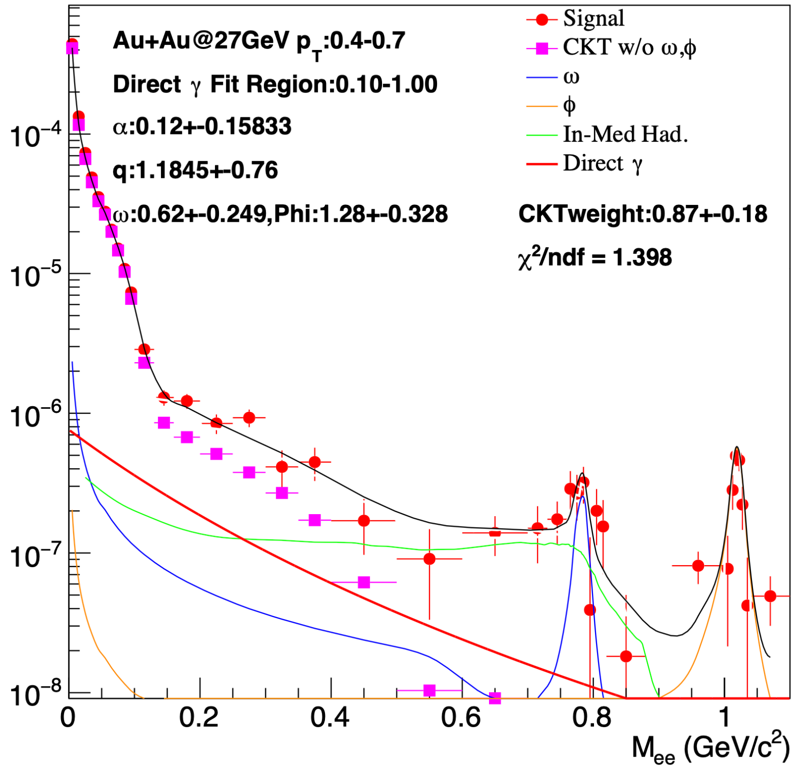


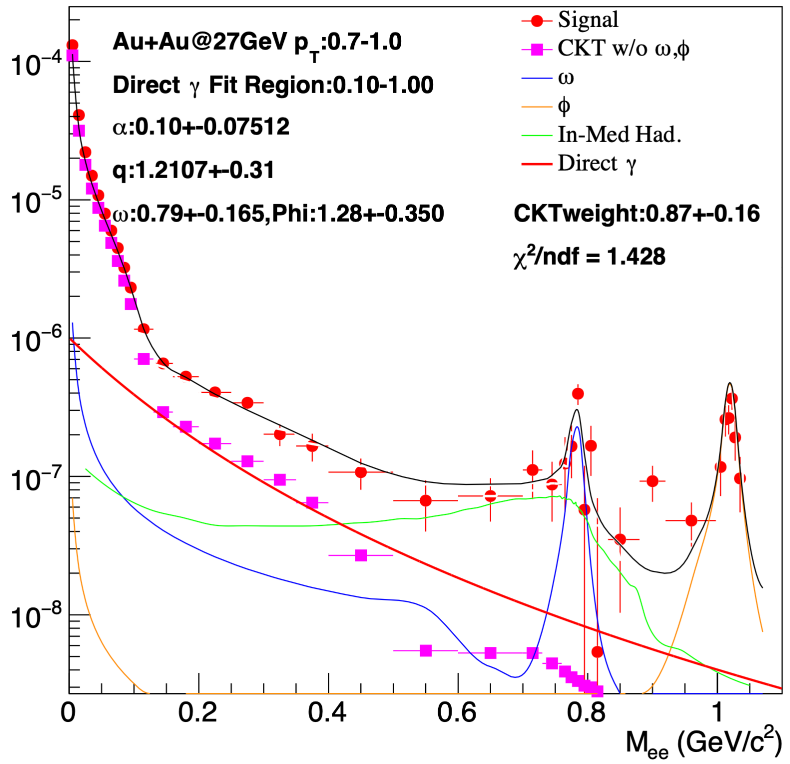
Fit region: 0.2-0.7 GeV/c^2

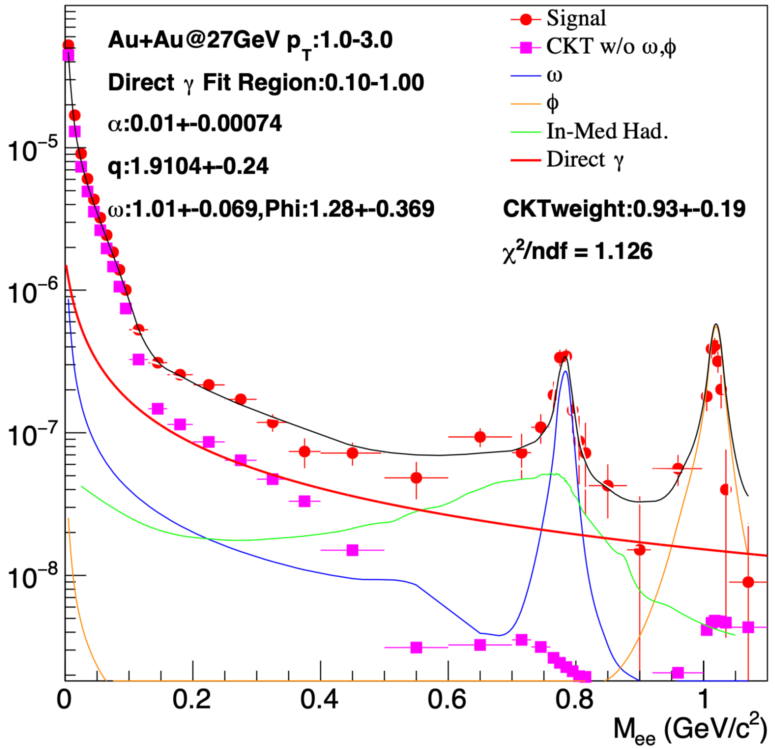
QGP contribution: B $*$ M$^{1.5}*\, e^{-T/M}$

Looks more like exponential

27 GeV result with large statistic error

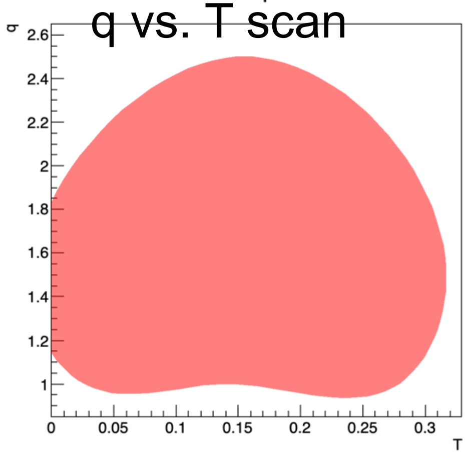


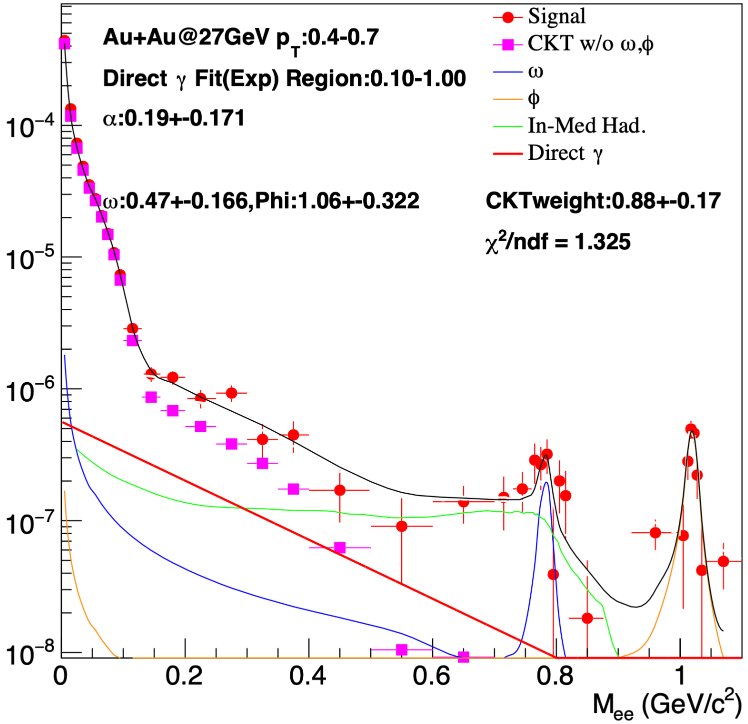


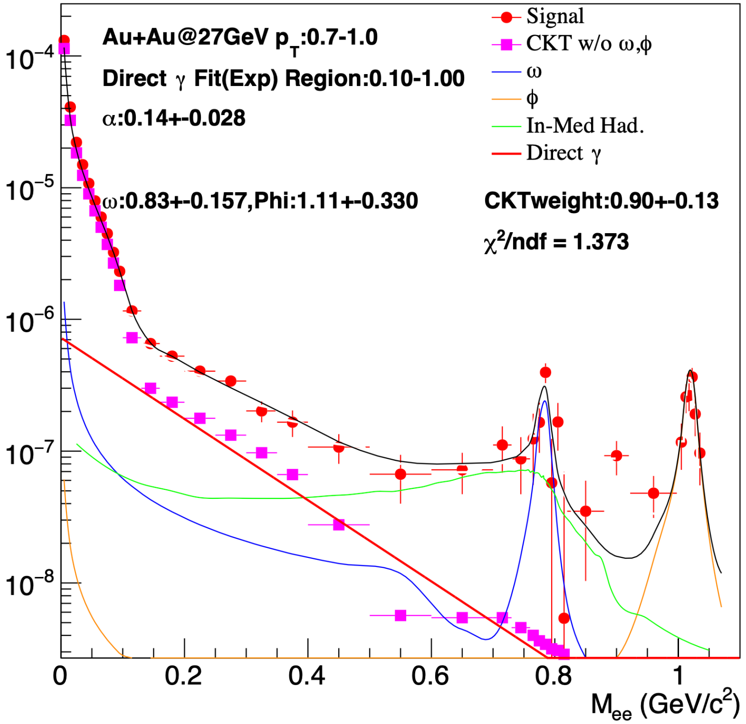


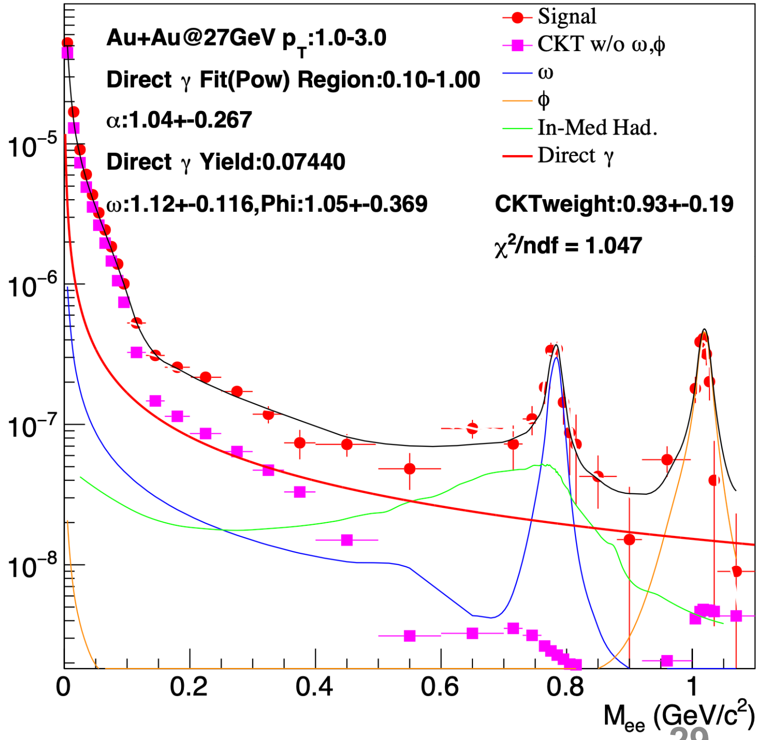
27 GeV result with large statistic error

AuAu 54.4 GeV 0.4-0.7 p_T
q vs. T scan

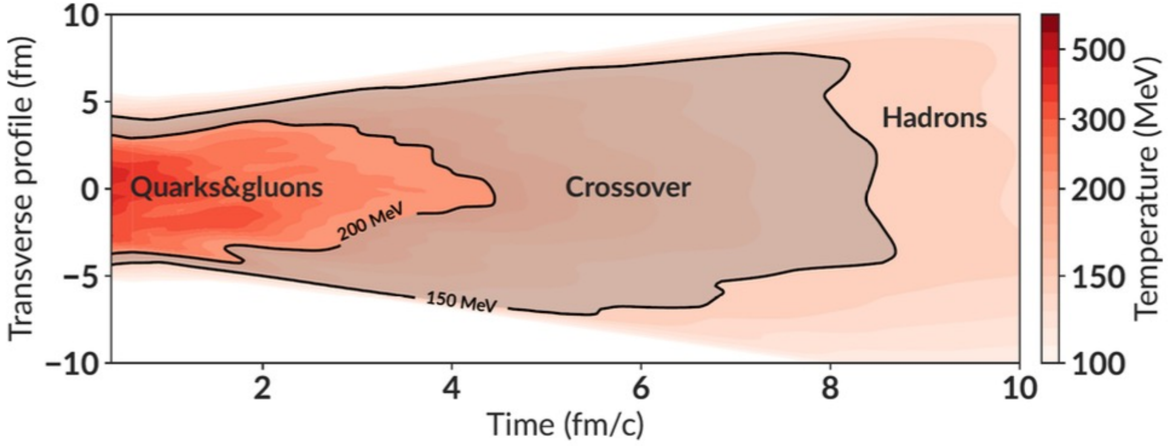






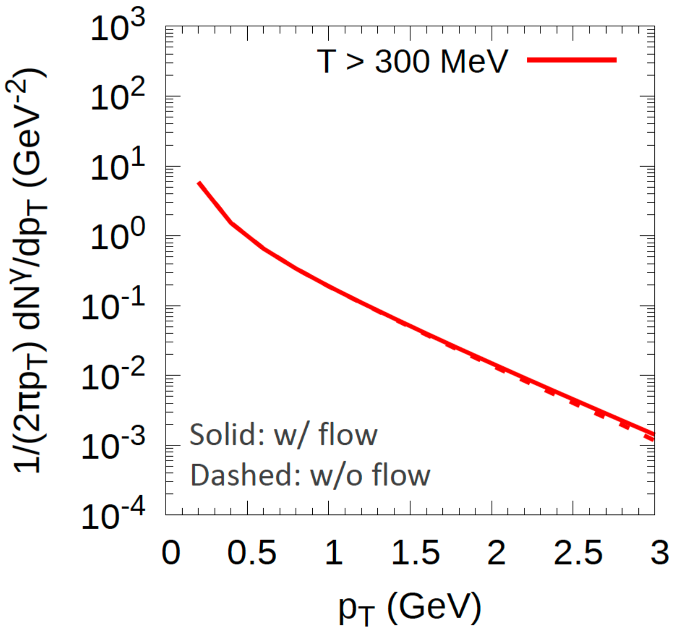


Direct photon p_T shape in different temperature

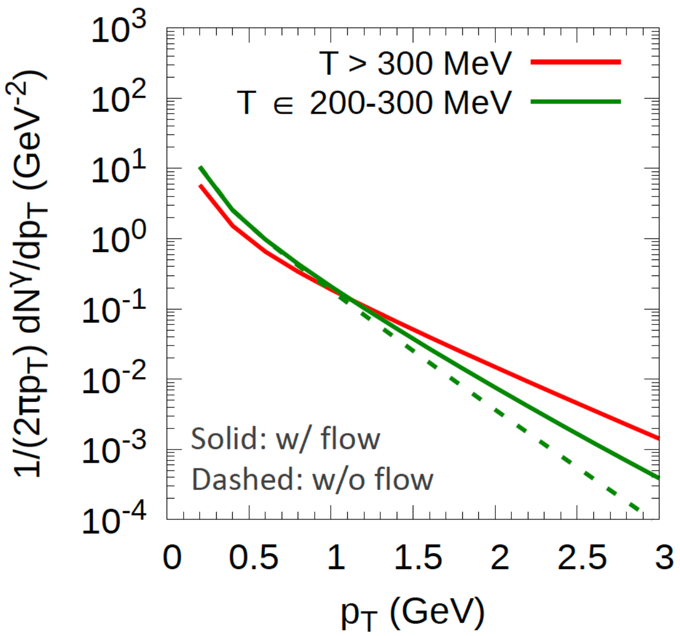


arXiv:2205.12299

Local effect of Doppler shift



Local effect of Doppler shift



Local effect of Doppler shift