Direct virtual photon measurements in Au+Au collisions with STAR BES-II data

Xianwen Bao (for the STAR collaboration)

(baoxianwen@mail.sdu.edu.cn)

Shandong University

Hot Quark, May. 11-17, 2025, Hefei, China

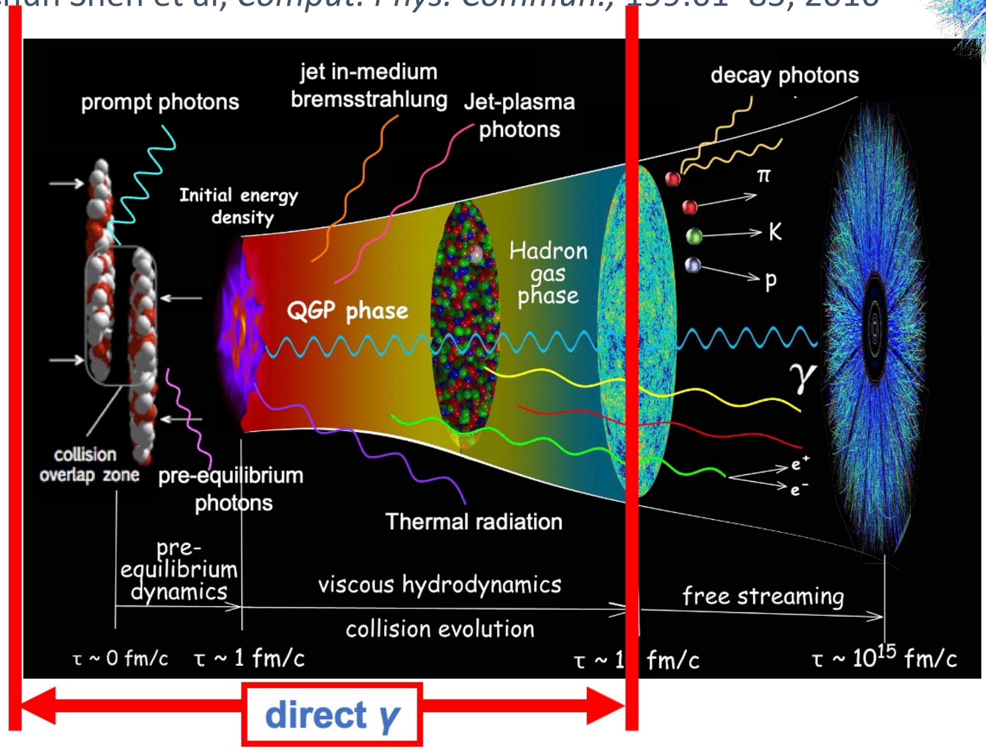
Supported in part by

U.S. DEPARTMENT OF ENERGY | Office of Science

NSFC National Natural Science Foundation of China

Introduction

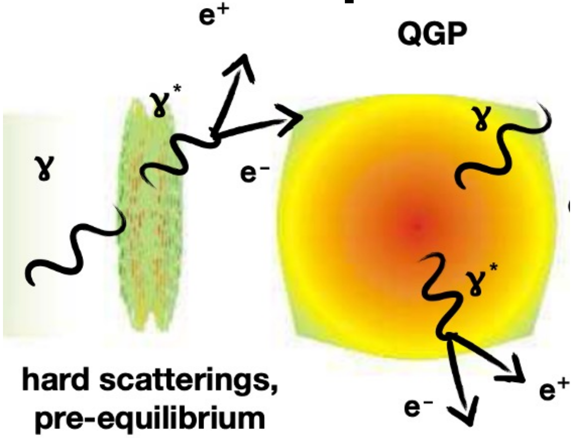
Chun Shen et al, *Comput. Phys. Commun.*, 199:61–85, 2016



Why direct virtual photon?

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

Direct virtual photon production

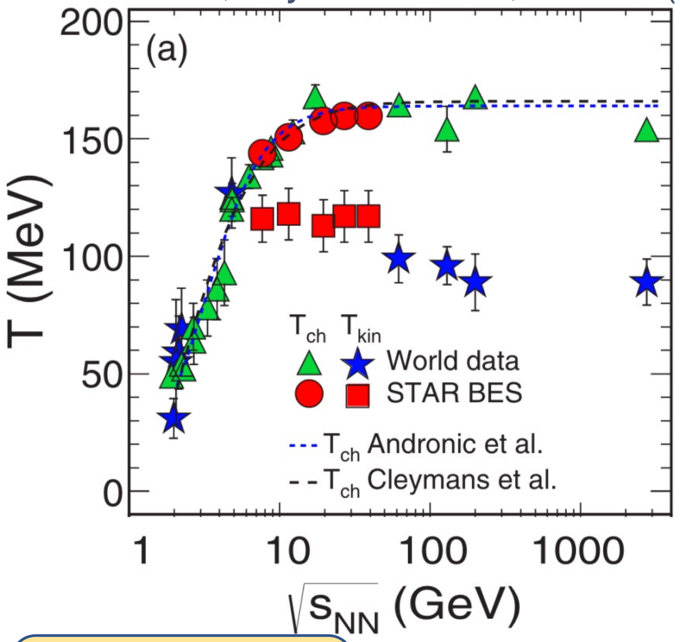


$$\frac{d^2N_{ee}}{dM^2} = \frac{\alpha}{3\pi}\frac{\mathrm{L(M)}}{M^2}S(M,q)dN_\gamma \qquad S(M,q) = dN_{\gamma^*}/dN_\gamma$$

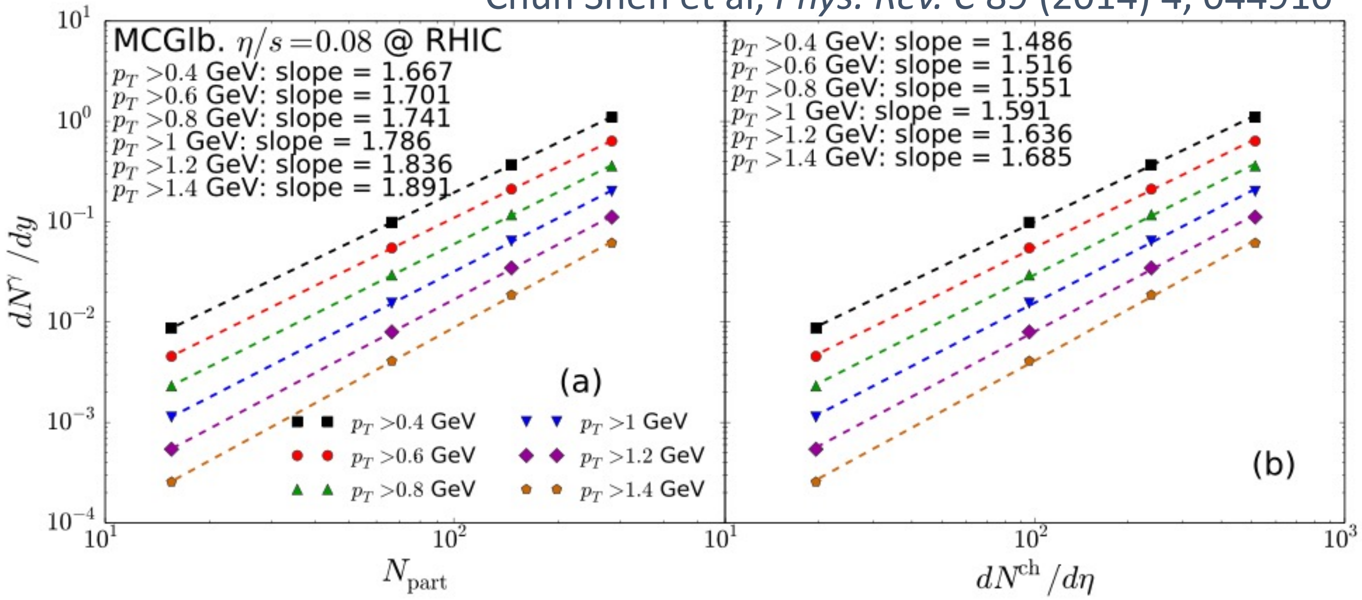
- ➢ High p_T: mainly **prompt photon** from **earlier stage**
- ➢ Low p_T: mainly **thermal photon** from **later stage**

Thermal radiation

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



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

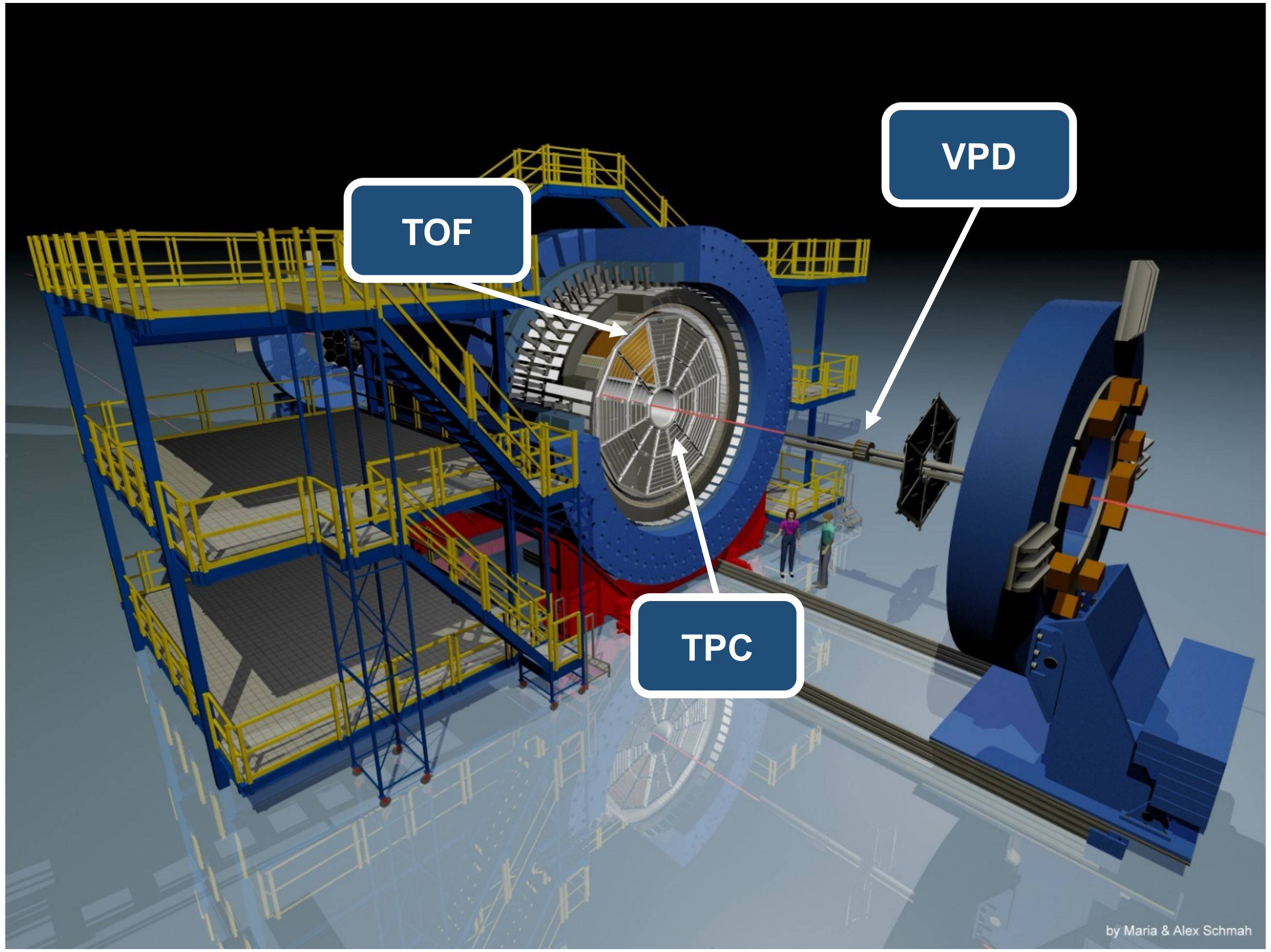


Hadrons (Yield, p_T) → **Statistical thermal model / Hydrodynamics-inspired model** → **Chemical freeze-out T_{ch} / Kinetic freeze-out T_{kin}**

Direct photon:

- **Thermometer**: extract $T_{effective}$ from p_T spectra (affected by blue shift effect)
- **Chronometer**: integrated yield is sensitive to lifetime

The Solenoidal Tracker At RHIC

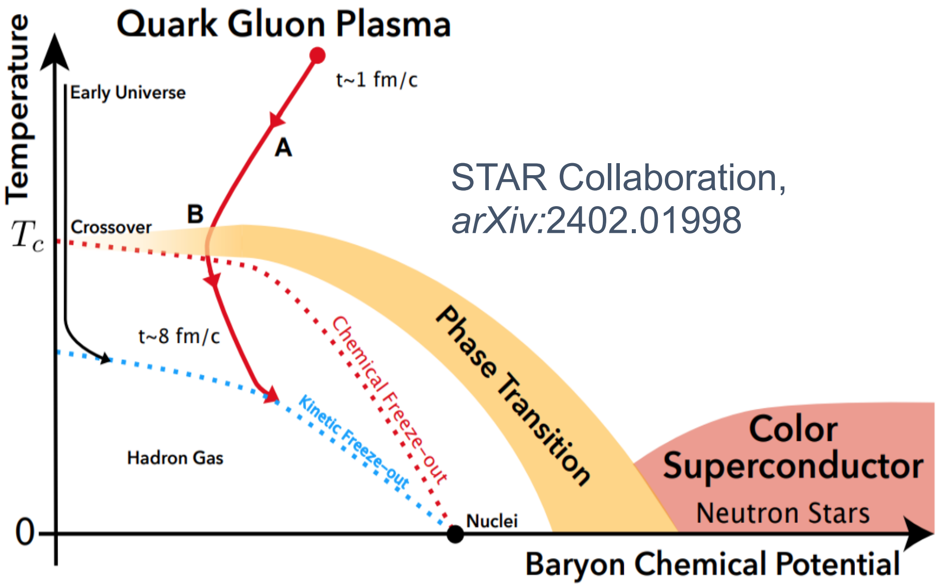


Time Projection Chamber
- Tracking
- Momentum and energy loss
- Acceptance: $|\eta| < 1;\ 0 \leq \varphi \leq 2\pi$

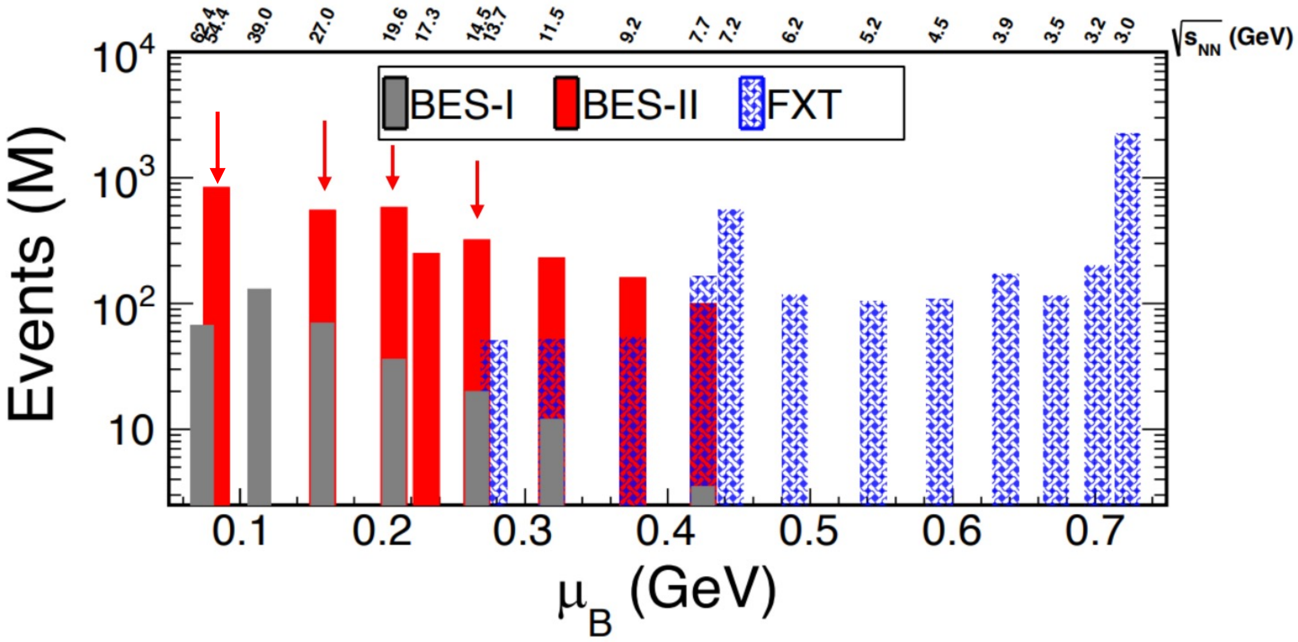
Time Of Flight
- Time of flight
- Particle identification
- Acceptance: $|\eta| < 1;\ 0 \leq \varphi \leq 2\pi$

Collision energies (Au+Au)
- $\sqrt{s_{\mathrm{NN}}}$ = 54.4 GeV (~430M events)
- $\sqrt{s_{\mathrm{NN}}}$ = 27 GeV (~250M events)
- $\sqrt{s_{\mathrm{NN}}}$ = 19.6 GeV (~213M events)
- $\sqrt{s_{\mathrm{NN}}}$ = 14.6 GeV (~110M events)

Beam Energy Scan II



STAR Collaboration,
*arXiv:*2402.01998



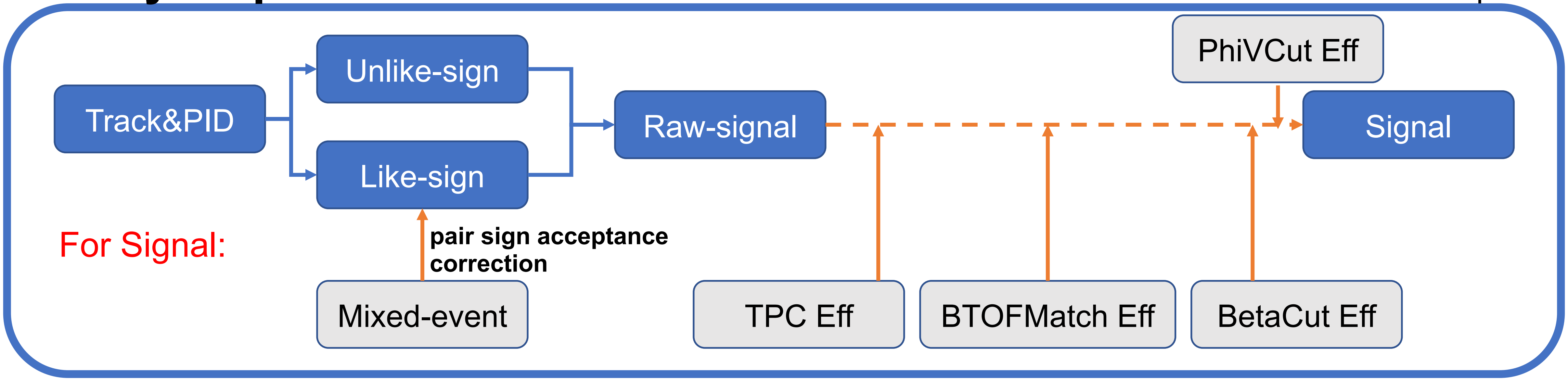
γ_{direct}: a possible probe of Critical End Point (CEP)

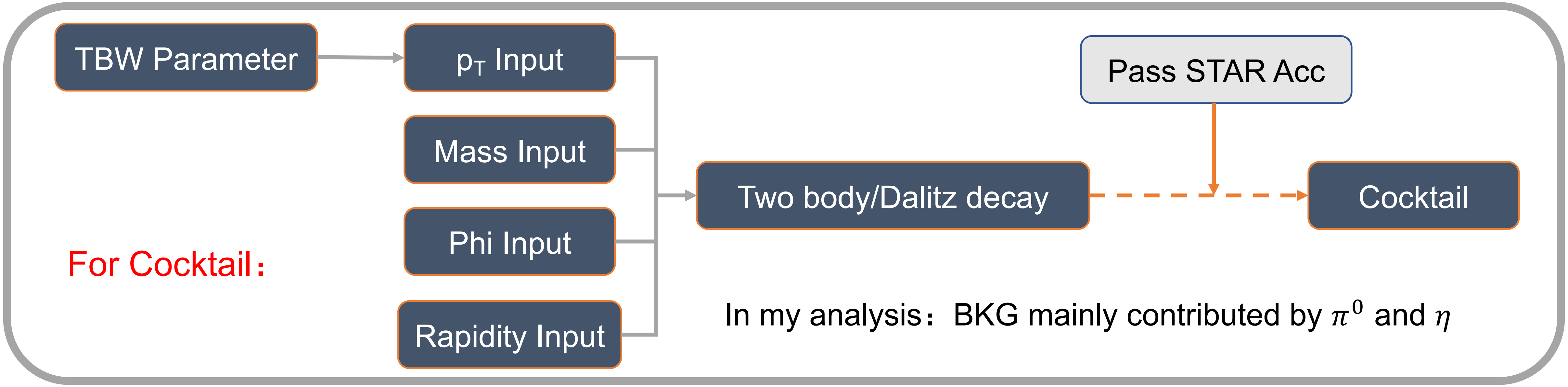
- Expect more thermal radiation close to CEP
- Need high statistics at lower collision energies

- BES-II: 10-20 times higher statistics than BES-I

Analysis procedure

Both in STAR Acceptance





Signal and Hadronic cocktail

signals:
QGP radiation
In-medium ρ
Prompt photon

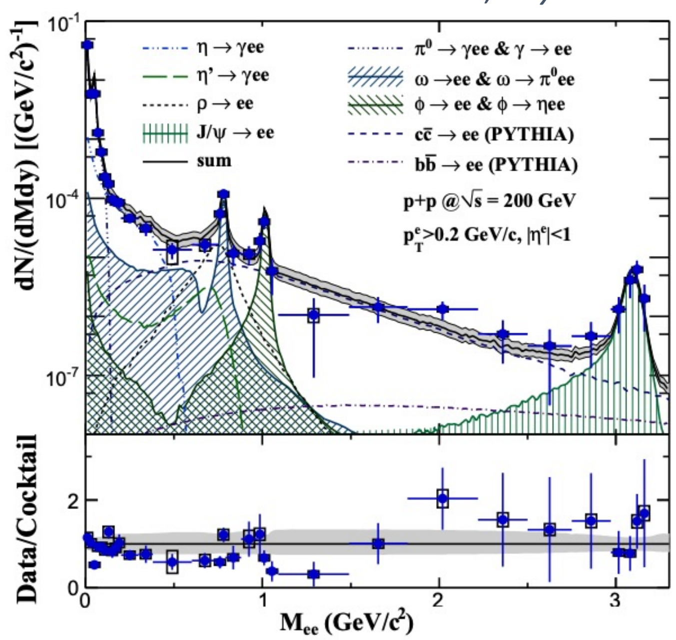
➕

background sources (cocktail):
$Drell-Yan, c\bar{c}$
$\pi^0, \eta, \eta', \omega, \varphi, J/\psi$

Hadronic cocktail :

two-body decay	$\omega \to e^+e^-, \phi \to e^+e^-, J/\psi \to e^+e^-, \psi' \to e^+e^-$
Dalitz decay	$\pi^0 \to \gamma e^+e^-, \eta \to \gamma e^+e^-, \eta' \to \gamma e^+e^-, \omega \to \pi^0 e^+e^-,$ $\phi \to \eta e^+e^-$
heavy-flavor decay	$c\bar{c} \to e^+e^-X$
Drell-Yan process	$DY \to e^+e^-$

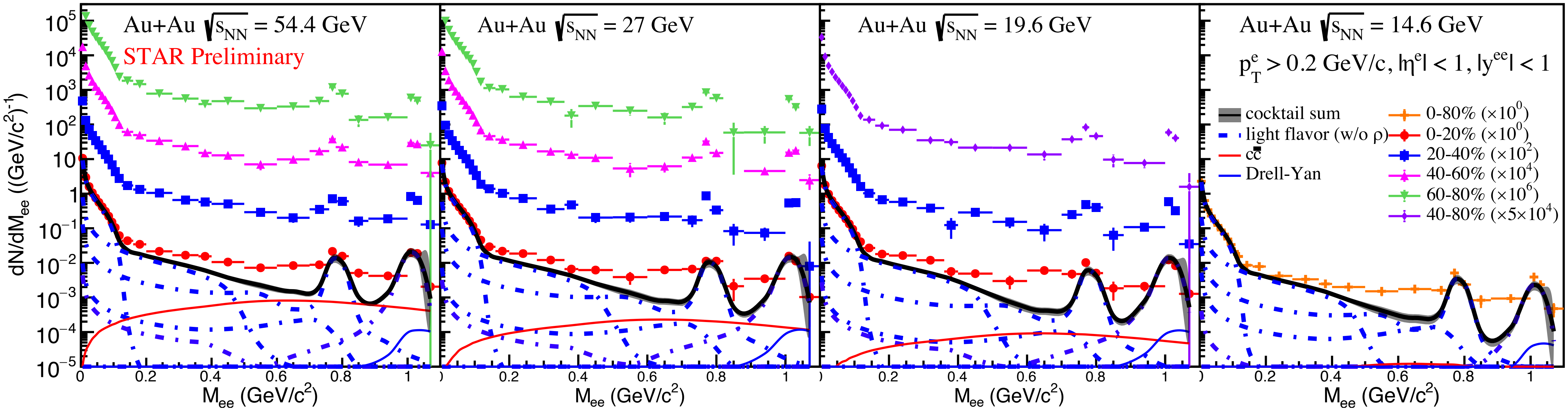
STAR, *Phys.Rev.C* 86 (2012) 024906



- ➢ Hadronic cocktail was examined in previous dielectron spectra studies in p+p collisions

Data vs. Cocktail

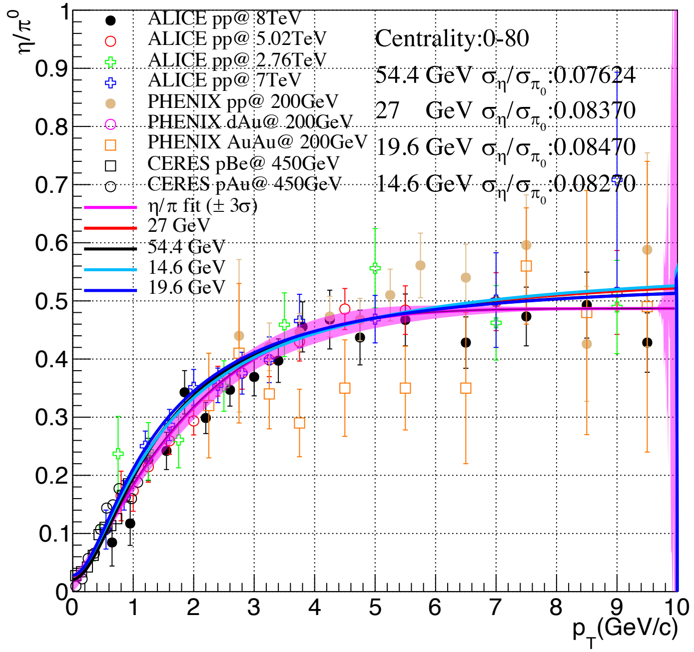
STAR, *Phys.Rev.C* 107 (2023) 6, L061901
STAR, *arXiv*:2402.01998



- Dielectron signal is consistent with cocktail in π^0 mass region
- Observed significant excess yield contributed by γ^*_{dir}, in-medium ρ at low mass region **(LMR, 0.1< M_{ee} < 0.76 GeV/c²)**

Extract direct virtual photon

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

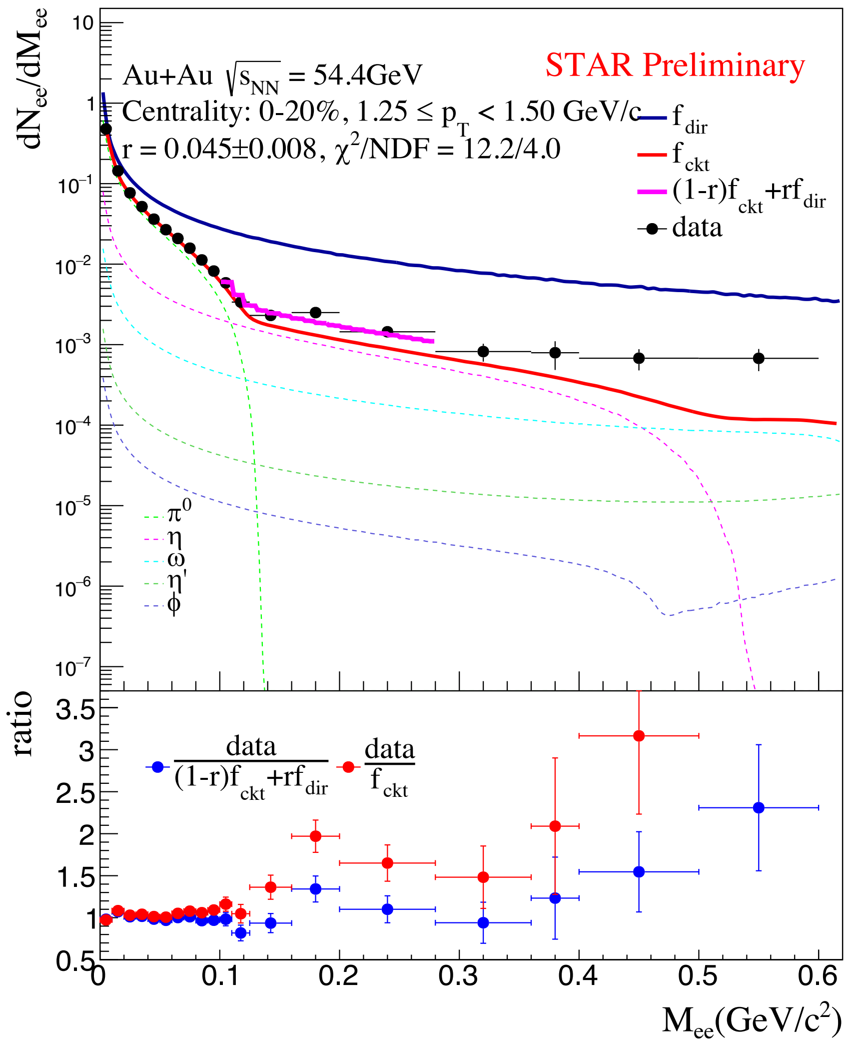


- Fit method:

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

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

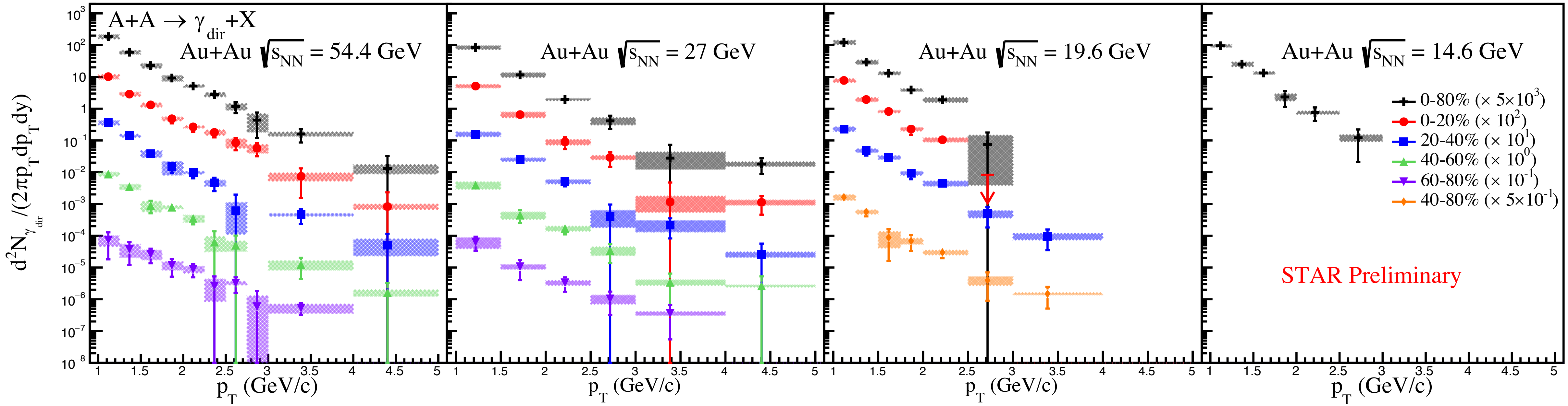
- η/π^0
  - Parametrized using Tsallis Blast Wave (TBW) function
  - Fixed to **0.470±0.017** at 5 GeV/c



Two component fit PHENIX, *Phys.Rev.C* 81 (2010) 034911

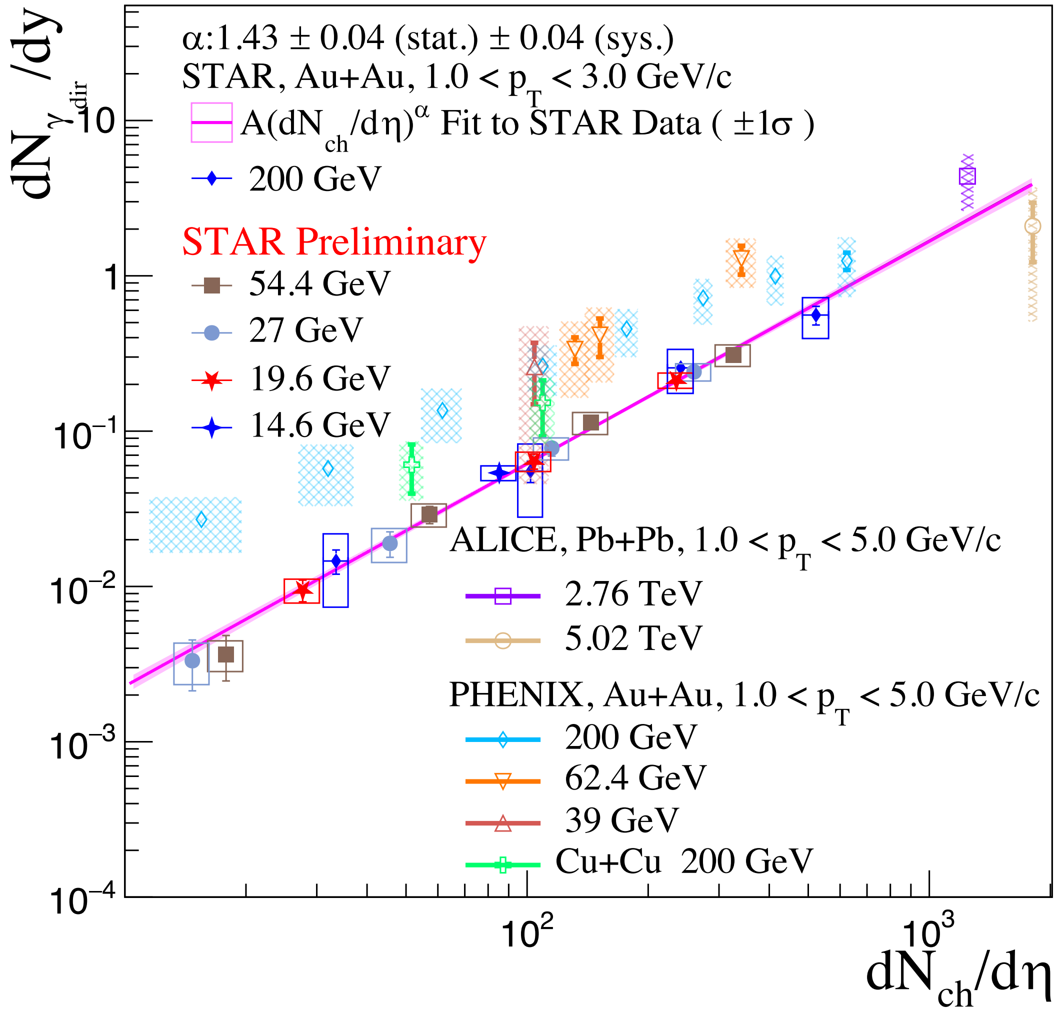
- A clear enhancement at η mass region contributed by γ^*_{dir}
- Extract direct virtual photon fraction r by fitting cocktail and γ^*_{dir} templates to the data in M_{ee} range **[0.10,0.28]** GeV/c²

Direct virtual photon p_T spectrum



➢ First measurement of γ^{*}_{dir} in Au+Au collisions at BES-II in different centrality intervals

Direct virtual photon dN/dy vs. $dN_{ch}/d\eta$



- New measurements of $dN_{\gamma_{dir}}/dy$ at STAR
- Strong $dN_{ch}/d\eta$ dependence
- The yields at $\sqrt{s_{NN}}$ = **14.6**, **19.6**, 27, 54.4, 200 GeV measured by STAR follow a common scaling, with

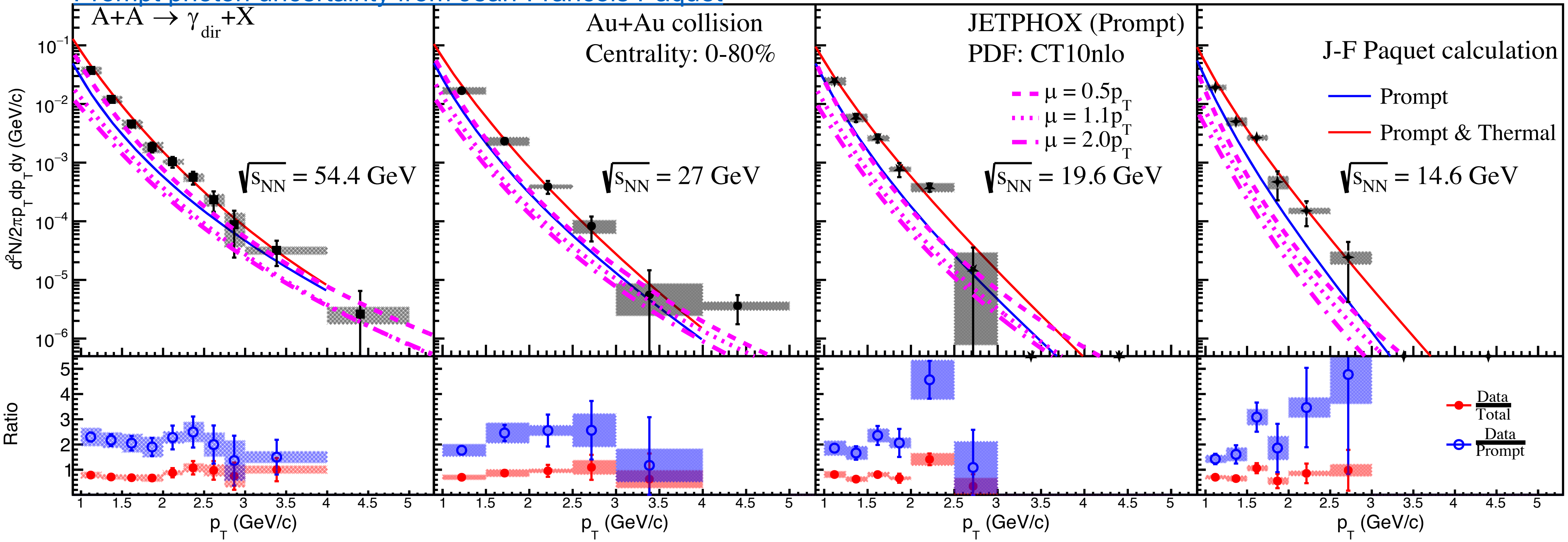
$$\alpha = 1.43 \pm 0.04 \pm 0.04$$

STAR, *Phys. Lett. B* 770 (2017) 451-45
PHENIX, *Phys.Rev.C* 109 (2024) 044912
ALICE, *arXiv:* 2308.16704
ALICE, Jerome Jung, Hard Probe 2024 presentation

Thermal photon enhancement

Patrick Aurebche et al, *Phys.Rev.* D73:094007,2006
PHENIX, *Phys.Rev.C 107 (2023) 2,024914*
Xiang-yu Wu, Quark Matter 2025 presentation

Prompt photon uncertainty from Jean-Francois Paquet



- Enhancement observed compared with prompt photon yield in 0-80% Au+Au at $\sqrt{s_{NN}}$ =14.6 - 54.4 GeV
- Indication of **thermal photon** contribution
- **Measured direct photon yield** can be well described by **theoretical calculation**

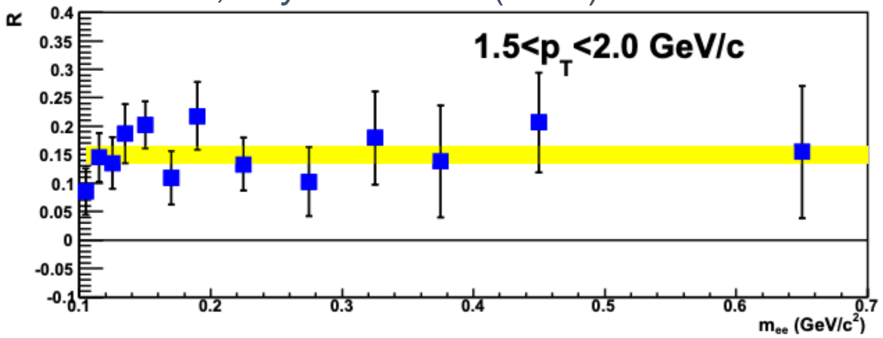
Direct virtual photon mass shape

STAR, *Phys.Lett.B* 770 (2017) 451-458
Peter Lichard, *Phys.Rev.D* 51 (1995) 6017-6035

For $p_T > 1.5$ GeV/c the fit gives good χ^2/NDF, demonstrating that the shape of the excess is consistent with $1/m_{ee}$ as expected for internal conversion.

Since the shape of $f_{\rm dir}(m_{ee})$ is $1/m_{ee}$ smeared by the detector effects, a fit of $R = ({\rm data} - {\rm cocktail})/f_{\rm dir}(m_{ee})$ to a constant can be used to test that the excess has the shape expected for internal conversion of direct photons.

PHENIX, *Phys.Rev.C* 81 (2010) 034911



- Mass Shape:
  - Power-law (1/M) ← dominated by internal conversion from **earlier stage**
  - Exponential (e^{-M}) ← dominated by thermal radiation from **later stage**
- Are the mass shapes in different p_T ranges sensitive to these contributions from different stages of evolution?

Strategy:

For γ^*_{dir} mass:

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

- Apply one **unified** mass shape to fit dielectron mass spectrum **in different p_T ranges**
- **Different values of q parameter:**
  - **Power-law (1/M) : q~2**
  - **Exponential (e^{-M}): q~1**

Direct virtual photon production stage

For γ^*_{dir} mass:

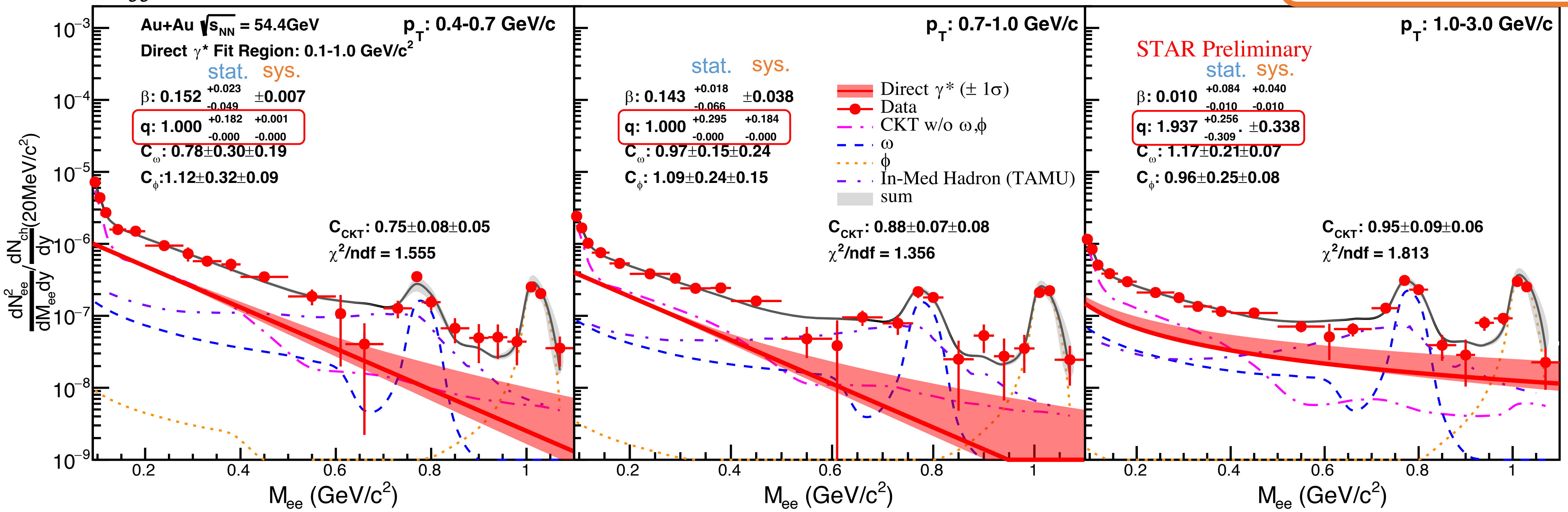
$$\frac{dN}{dM} = C * [1 + (q-1)\frac{M_{ee}}{\beta}]^{-\frac{1}{q-1}}$$

$q \in [1, 2.5]$
$\beta \in (0, 0.25]$

STAR

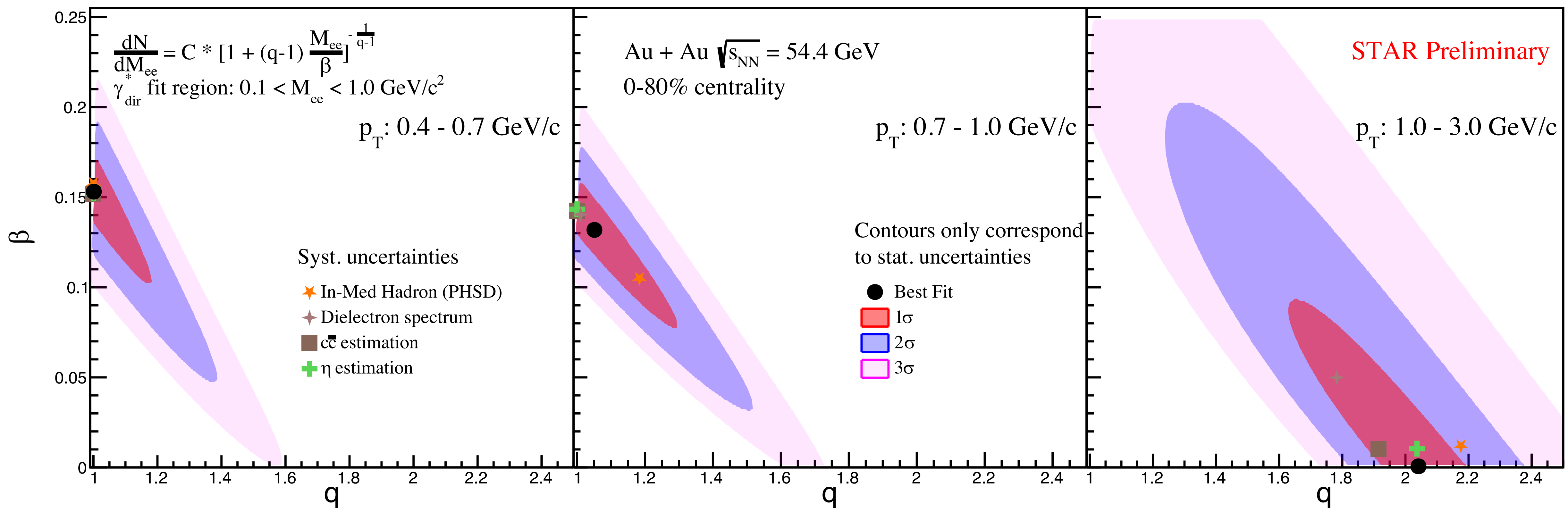
Exponential q ~ 1
Power-law q ~ 2

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



- As the transverse momentum increases, its shape changes from **exponential** to **power-law**, corresponding to the direct photon produced in **later** to **earlier** stages respectively

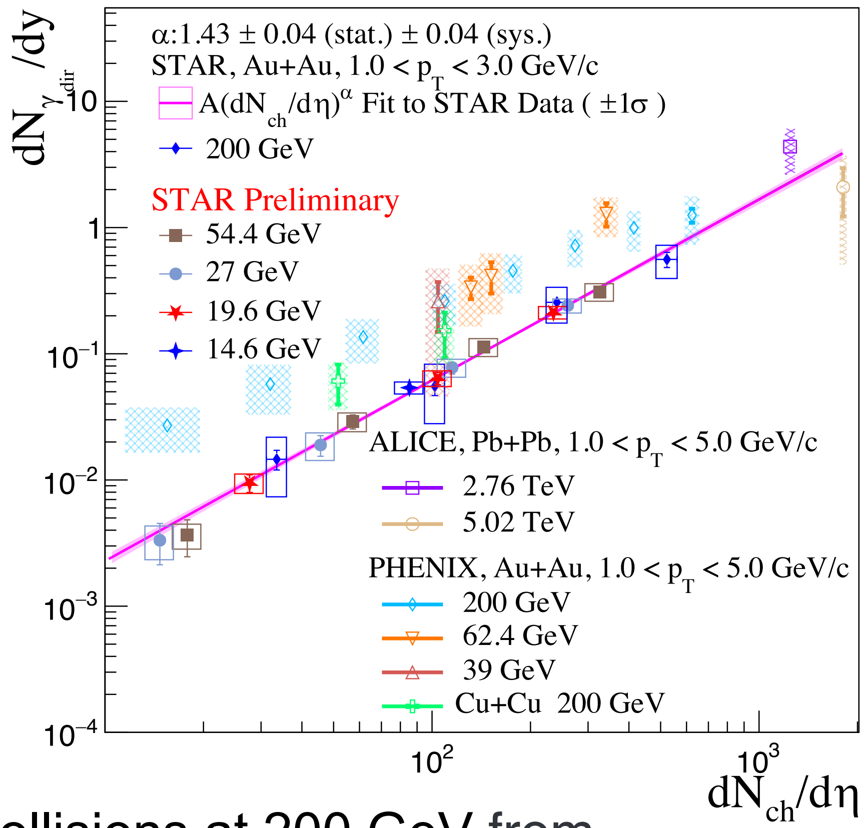
Direct virtual photon production stage



- Acquire 1, 2, 3σ contours by scanning different q and β
  - **$1 \le q \le 2.5$**
  - **$0 < \beta \le 0.25$**
- Transition from exponential to power-law is observed

Summary

- First measurements of direct virtual photons in Au+Au collisions with BES-II data at RHIC
- The measured yields from STAR follow a common scaling
  - Strong $dN_{ch}/d\eta$ dependence
  - Scaling power $\alpha = \mathbf{1.43 \pm 0.04}\ (\mathrm{stat.}) \pm \mathbf{0.04}\ (\mathrm{sys.})$
- Direct virtual photon mass spectrum shape:
  - High p_T (>1GeV/c)→ **power-law** → earlier production
  - Low p_T (<1GeV/c) → **exponential** → later production



Outlook:

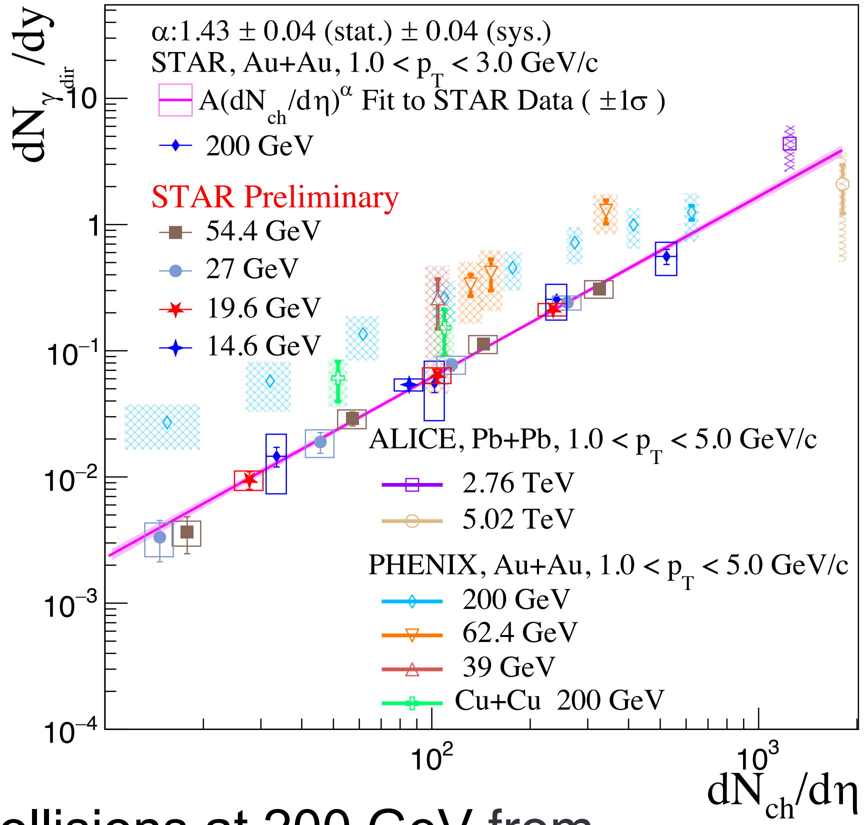
- Fixed-target data at lower collision energies
  - High η region
- Direct virtual photon polarization/v_2 in Au+Au collisions at 200 GeV from Run23 and Run25

Summary

Thanks for your attention!

Thanks for theoretical contribution by X. Wu, A. Alaoui, C. Gale, S. Jeon, J-F. Paquet, B. Schenke and C. Shen

- First measurements of direct virtual photons in Au+Au collisions with BES-II data at RHIC
- The measured yields from STAR follow a common scaling
  - Strong $dN_{ch}/d\eta$ dependence
  - Scaling power $\alpha = \mathbf{1.43 \pm 0.04}\ (\text{stat.}) \pm \mathbf{0.04}\ (\text{sys.})$
- Direct virtual photon mass spectrum shape:
  - High p_T (>1GeV/c)→ **power-law** → earlier production
  - Low p_T (<1GeV/c) → **exponential** → later production



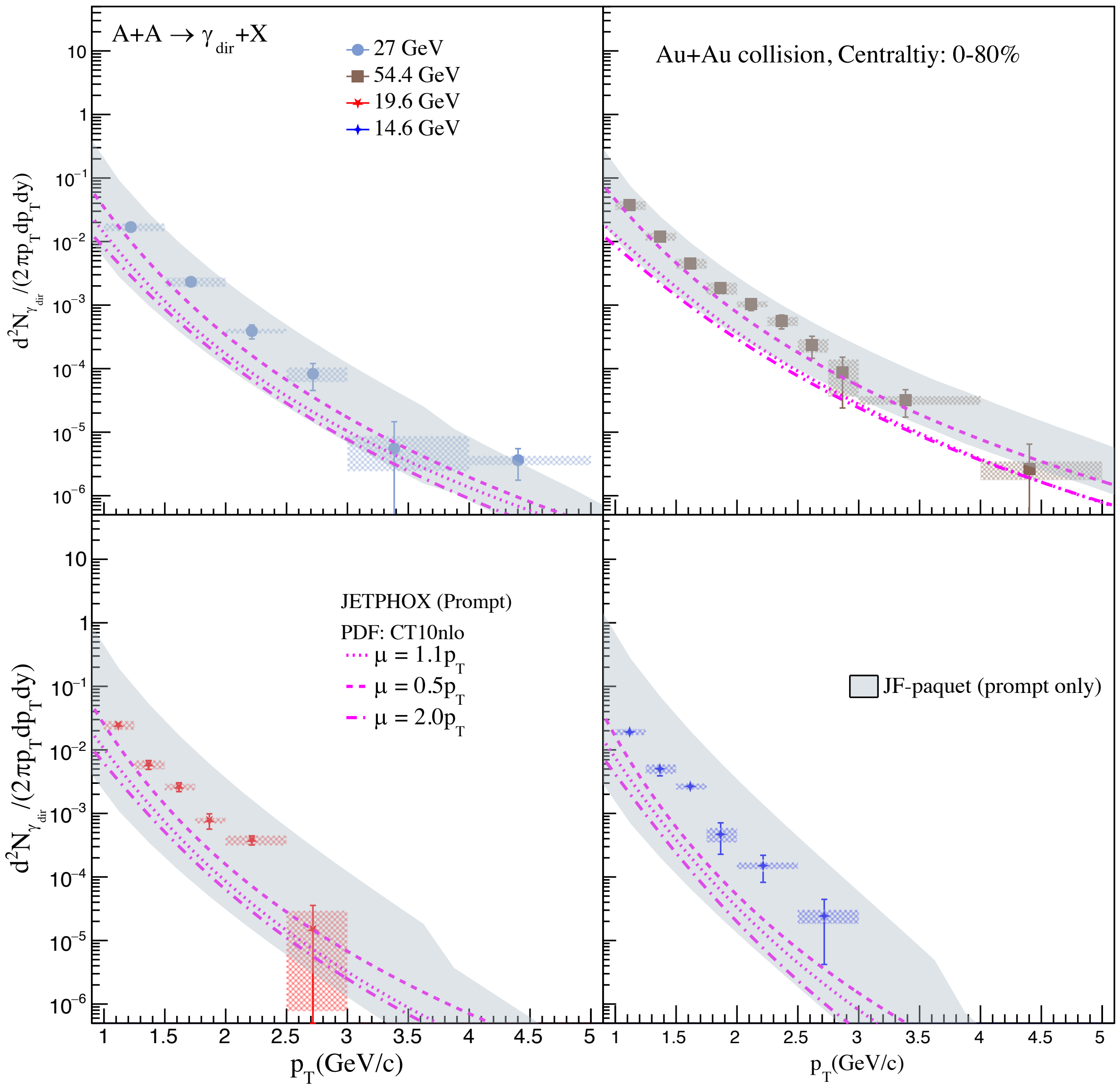
Outlook:

- Fixed-target data at lower collision energies
  - High η region
- Direct virtual photon polarization/v_2 in Au+Au collisions at 200 GeV from Run23 and Run25

Backup

Compared with theoretical calculation

The direct virtual photon p_T spectra compared with Jean-Francois Paquet theoretical calculation



Effective temperature based on Jetphox

Prompt photon distribution can be comparable with data in p+p collision at 200 GeV and 63 GeV when μ = 1.1p_T

μ : factorisation/renormalisation/fragmentation scale

Table 1: Effective temperature extraction after different prompt photon estimation by jetphox

μ	54.4 GeV	27 GeV	19.6 GeV	14.6 GeV
0.5 p_T	316±44±11	298±78±26	259±42±5	240±46±9
0.6 p_T	301±36±11	282±71±25	255±40±5	234±44±9
0.7 p_T	300±33±11	278±68±25	248±38±5	233±42±9
0.8 p_T	291±31±11	275±67±19	248±38±2	233±42±8
0.9 p_T	288±30±11	282±66±20	246±37±2	233±41±8
1.0 p_T	291±30±11	280±65±20	245±37±2	234±41±8
1.1 p_T	289±29±11	279±64±16	244±36±2	233±41±8
1.2 p_T	289±29±11	277±63±16	244±36±2	233±41±8
1.3 p_T	289±29±11	278±63±16	242±36±2	232±41±8
1.4 p_T	288±29±11	276±63±16	242±36±2	232±41±8
1.5 p_T	286±28±11	277±63±16	242±36±2	232±40±8
1.6 p_T	287±28±11	277±63±16	242±36±2	232±40±8
1.7 p_T	289±28±11	277±62±15	241±36±2	232±40±8
1.8 p_T	289±28±11	278±63±15	241±35±2	232±40±8
1.9 p_T	288±28±10	278±63±15	242±36±2	232±40±8
2.0 p_T	289±28±11	278±62±16	240±35±2	232±40±8

Prompt photon in p+p collisions predicted by Jetphox

T_{AA} scale

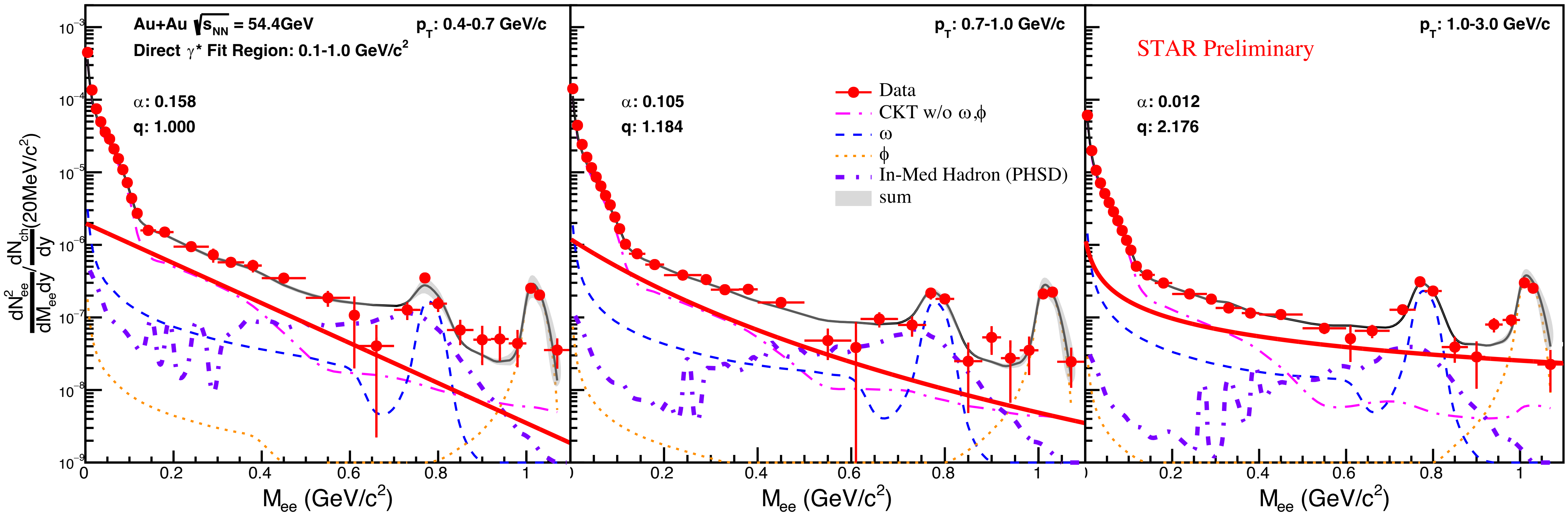
Prompt photon in AA collision

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

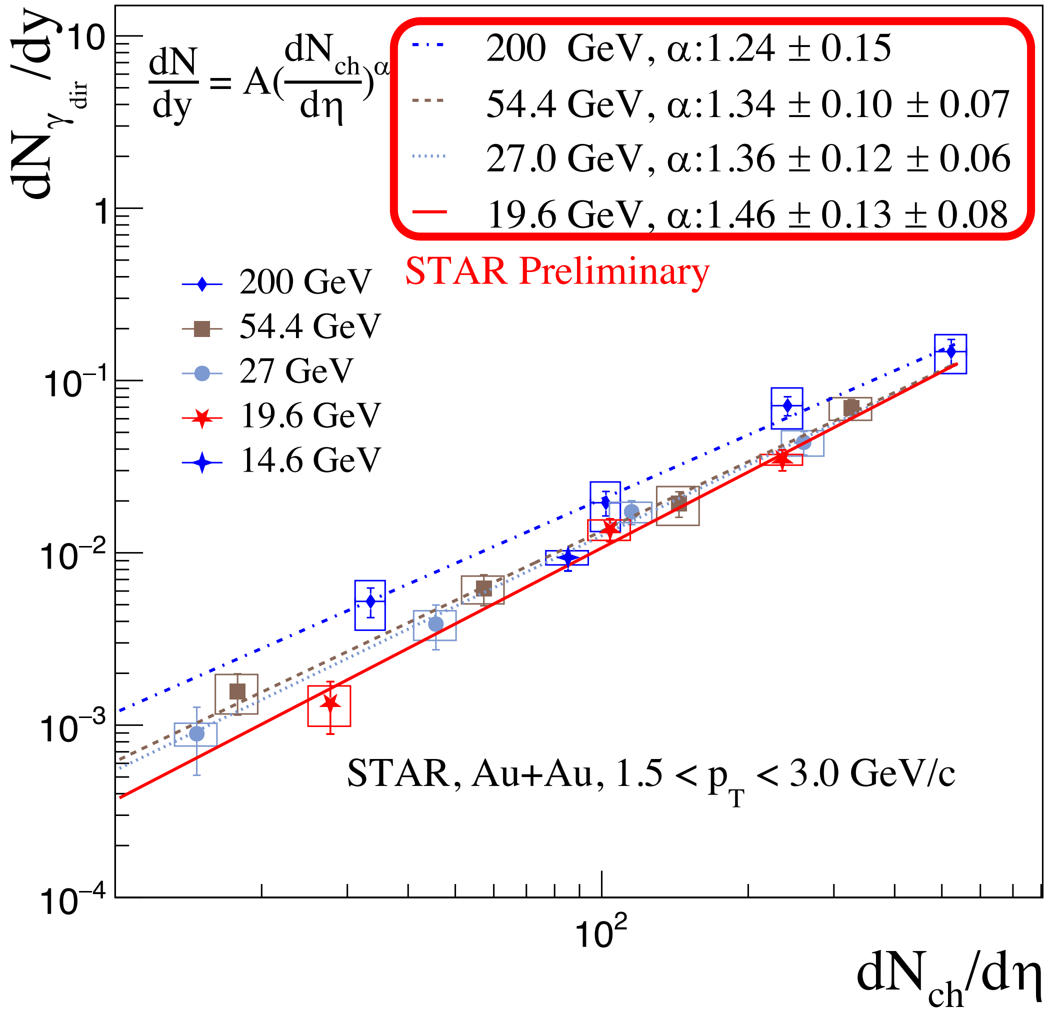
Thermal photon   Prompt photon

Observed that the effective temperature **decreases** as the energy **decreases** in different estimation of prompt photon by Jetphox

Direct virtual photon mass shape (In-Med Hadron, PHSD)



dN/dy vs. $dN_{ch}/d\eta$

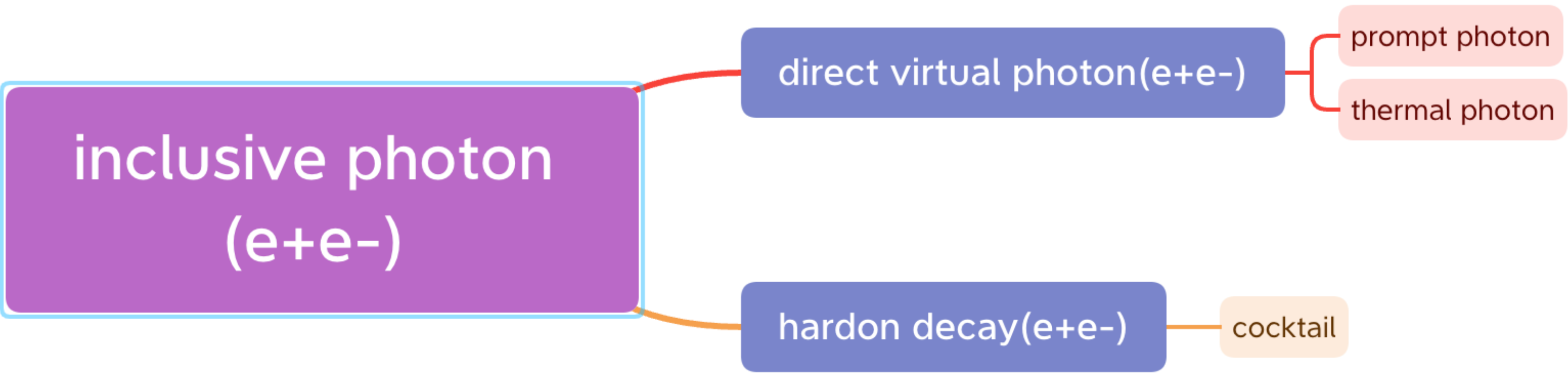


Energy(GeV)	200	54.4	27	19.6
A	6.81e-5	2.83e-5	2.37e-5	1.26e-5
error	5.45e-5	1.49e-5	1.41e-5	8.39e-6

- Obvious $dN_{ch}/d\eta$ dependence in energies from 200 to 19.6 GeV
- Hint of increasing α with decreasing collision 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**

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

$if: p_T \gg M_{ee}$

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

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

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

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

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

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

we interested **inclusive background**

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

two-body decay process or Kroll–Wada

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

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

two component fit