Workshop on physics performance studies at NICA(NICA 2024)

# Experiment result and method of direct virtual photon in Au+Au collision at $\sqrt{s_{NN}}$ = 27 and 54.4 GeV

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# Motivation

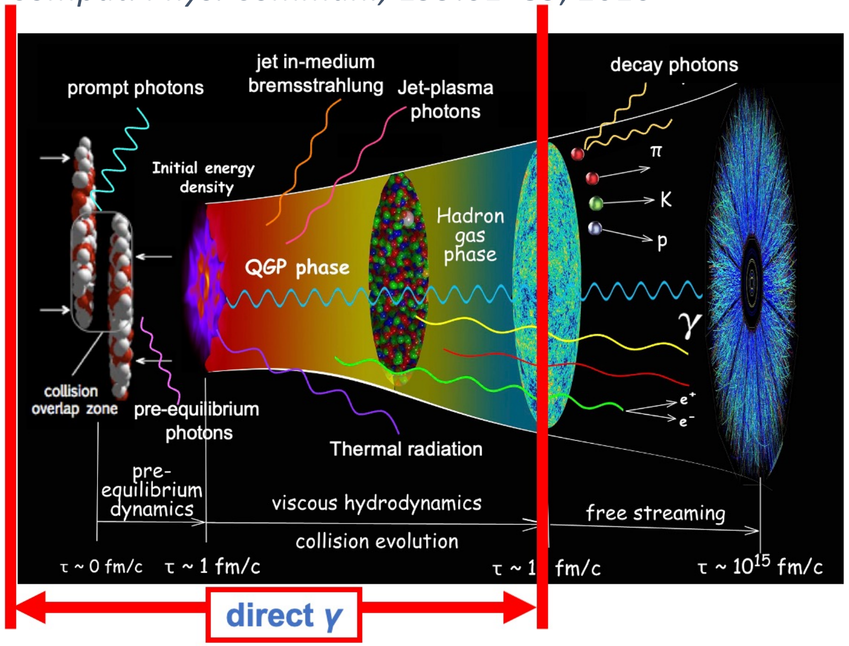
## Why choose direct virtual photon?

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

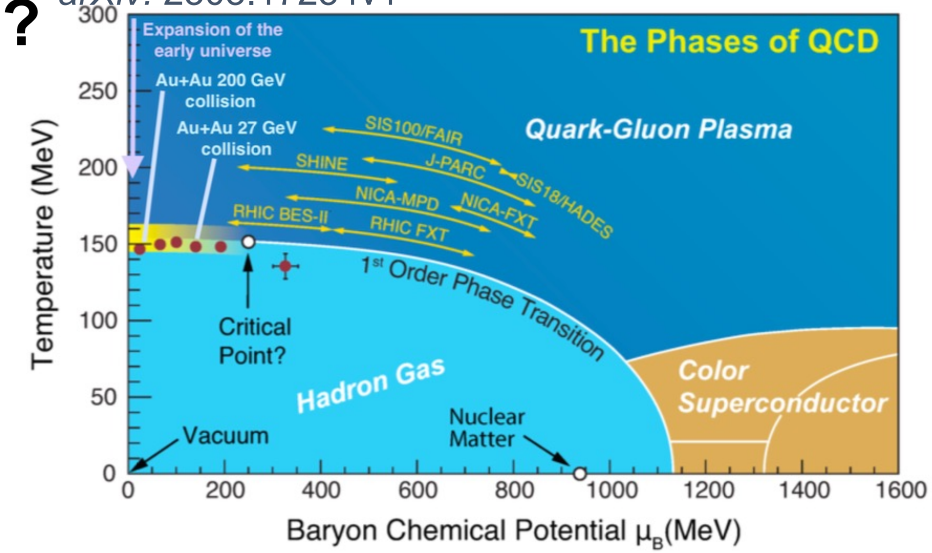
## What will affect direct virtual photon yield?

- Evolution time → $p_T$ integrated yield
- System size → $dN_{ch}/d\eta$
- $\mu_B$, T → collision energy

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



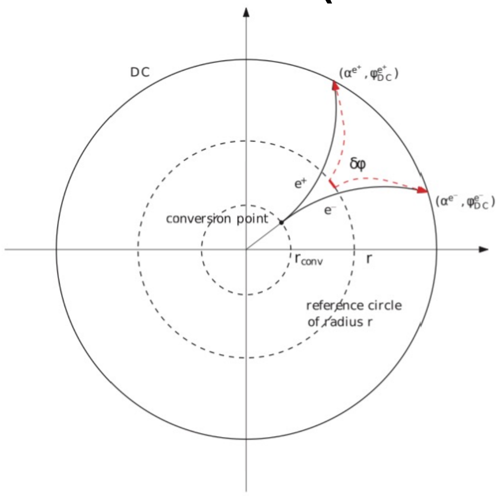

*arXiv:* 2303.17254v1

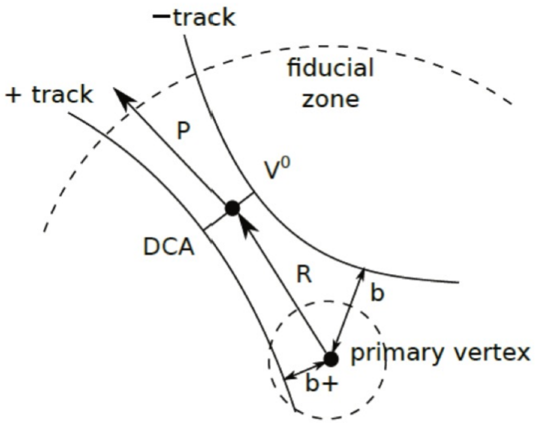


# How to extract direct photon?

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

(PHENIX, ALICE)



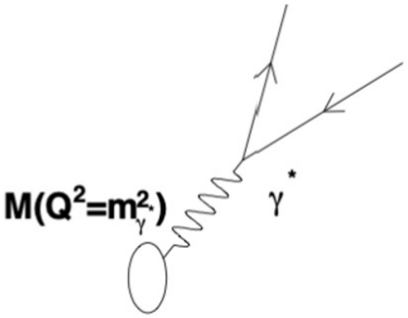



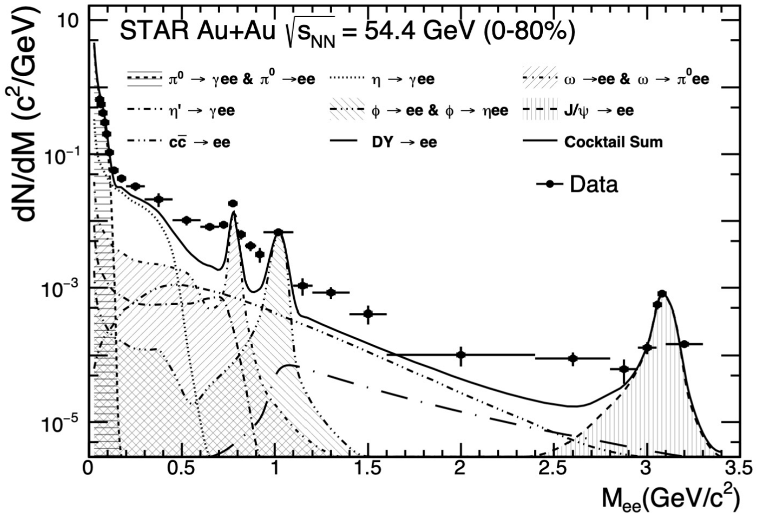

- Nearly background-free sample of photons down to $p_T$ below 1 GeV/c
- BKG is dominated by $\eta$ and $\pi^0$ two body decay
- Need good ability of photon identification

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

(STAR, PHENIX, ALICE)

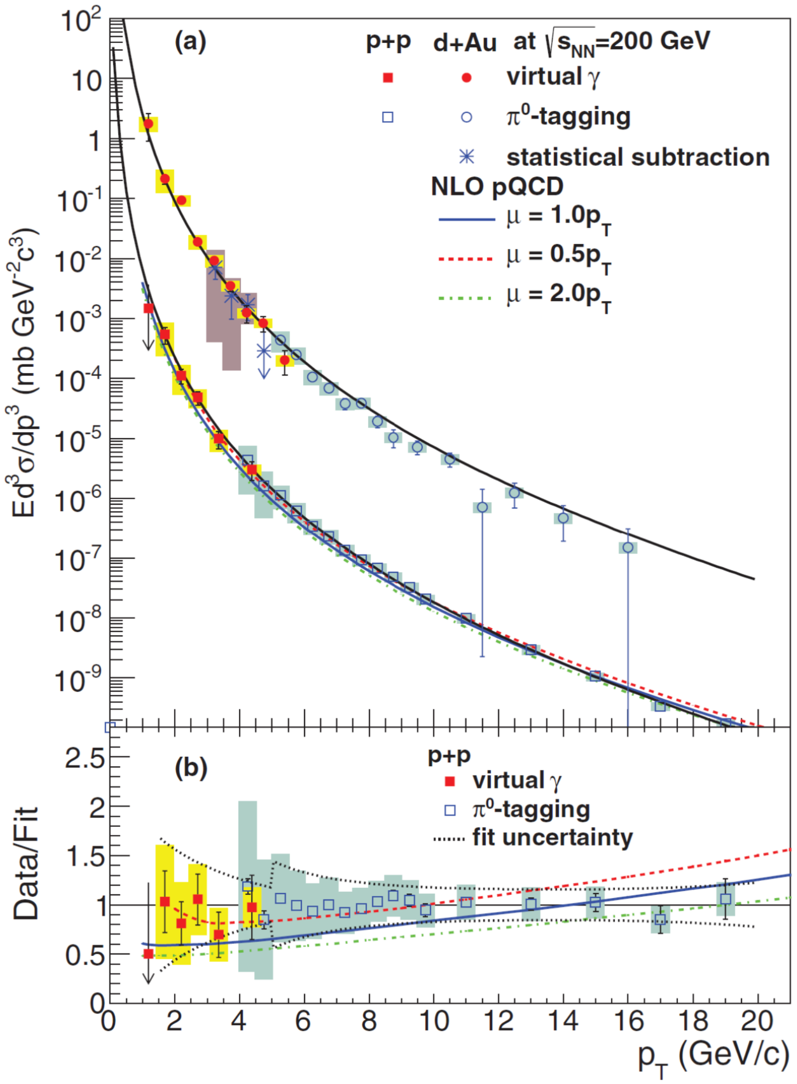
- Virtual photon internally convert into $e_+e_-$ pairs
- Used for low-momentum direct photon
- BKG is dominated by $\eta$ dalitz decay
- Limitation: measurement to $p_T$ > 1GeV/c

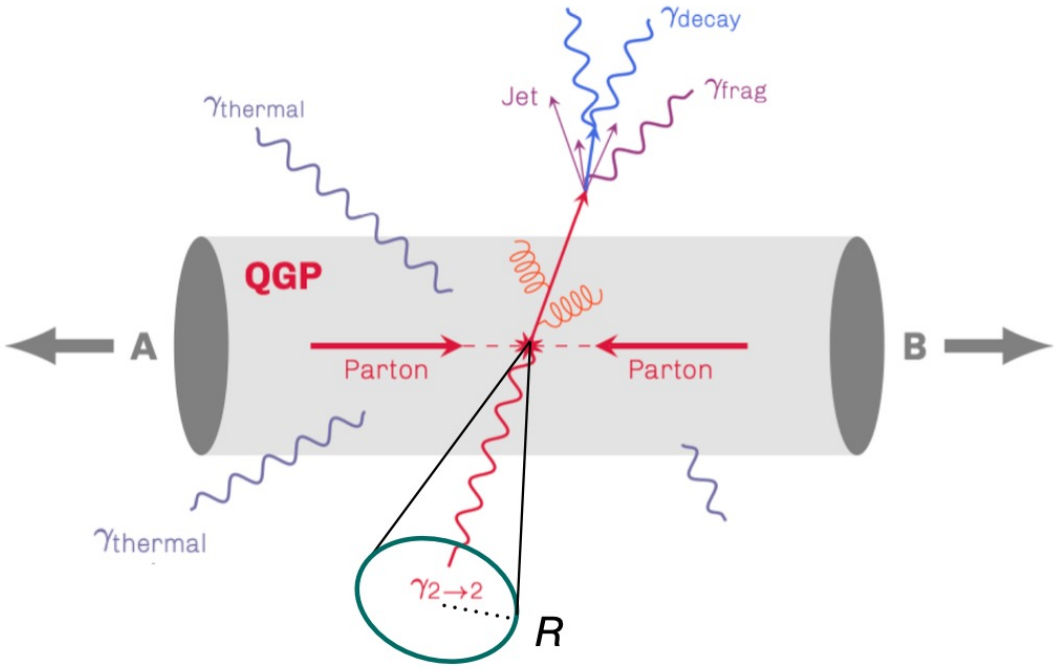


# Prompt photon

Phys.Rev.C 87 (2013) 054907



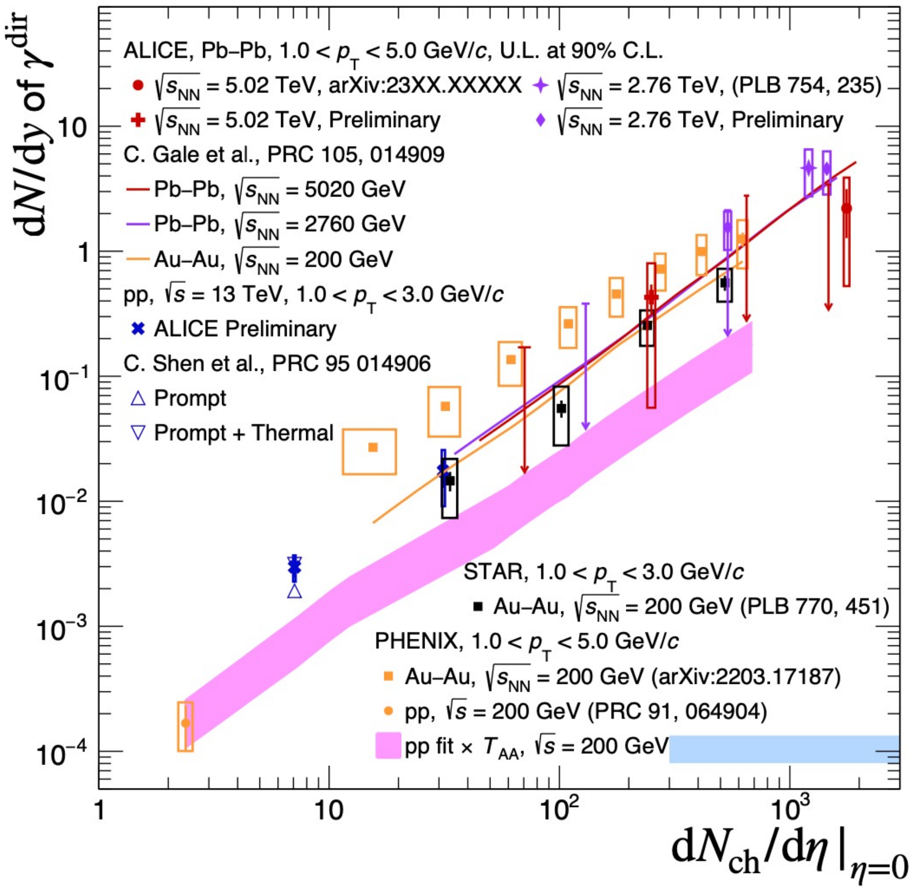

$\gamma_{2->2}$ from compton and annihilation processes:

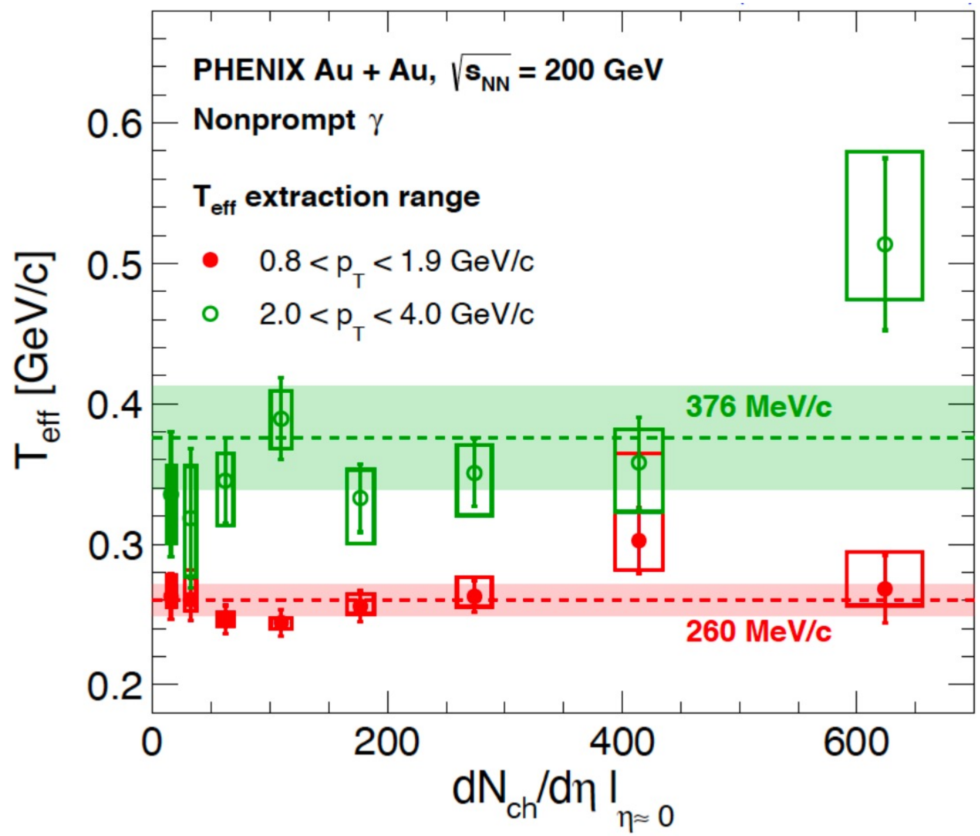
- Test pQCD and as a baseline in direct photon to extract thermal photon
- Tag the initial energy of the parton, $p_T^{\gamma} \approx p_T^{parton}$

# 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

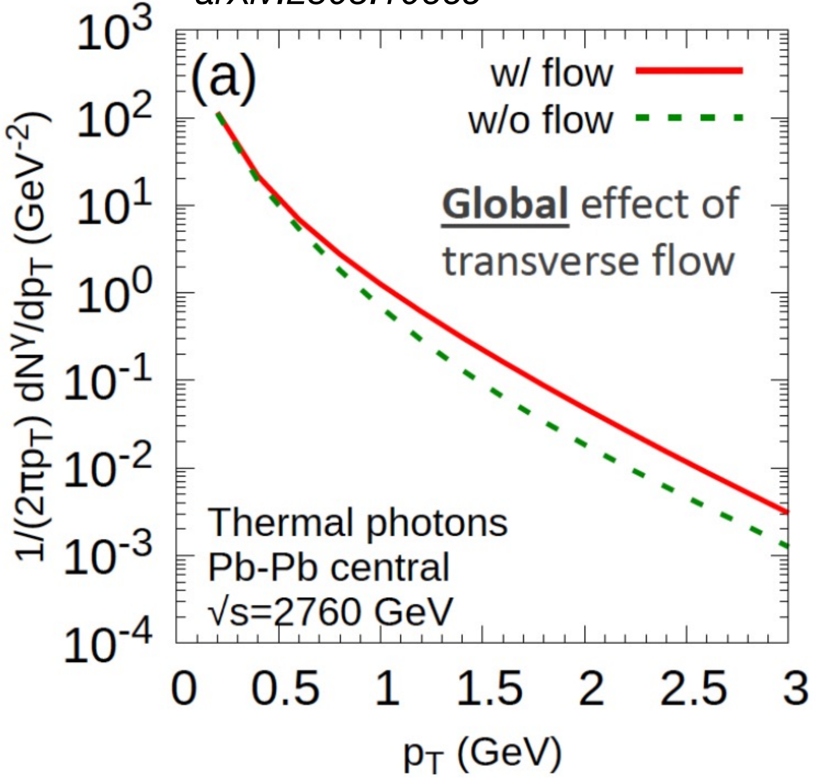



- ➢ Extract $T_{eff}$ from thermal photon
- ➢ Obvious strong dependence of yield with $dN_{ch}/d\eta|_{\eta=0}$
- ➢ No obvious variation of $T_{eff}$ with $dN_{ch}/d\eta|_{\eta=0}$

# Experiment vs. theoretical model

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

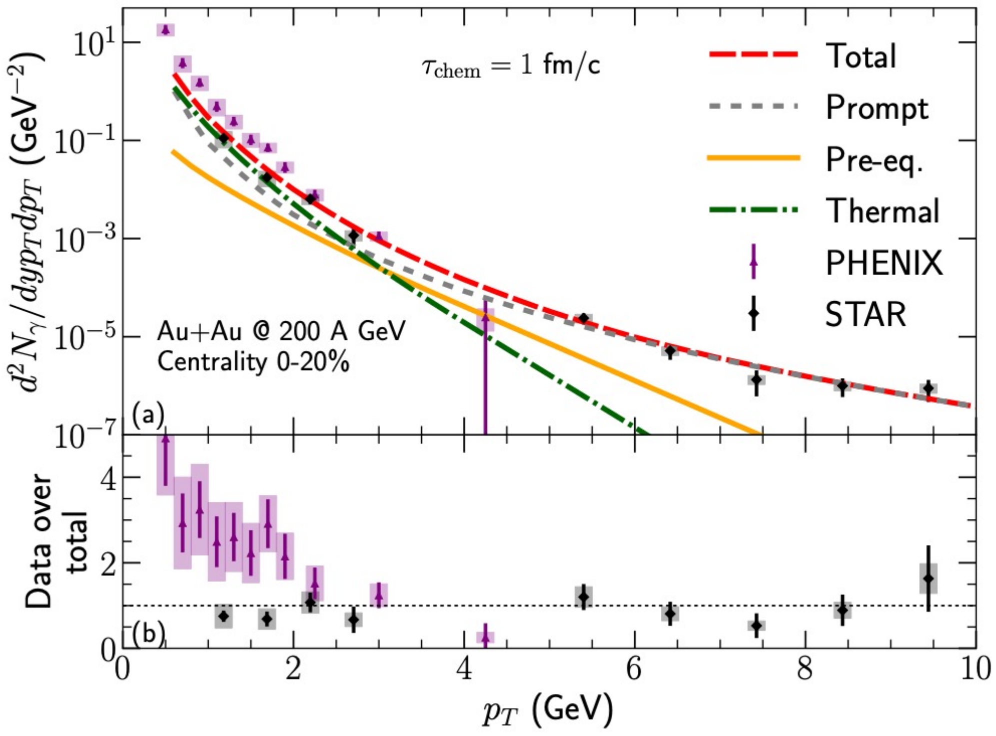



Inverse slope:

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

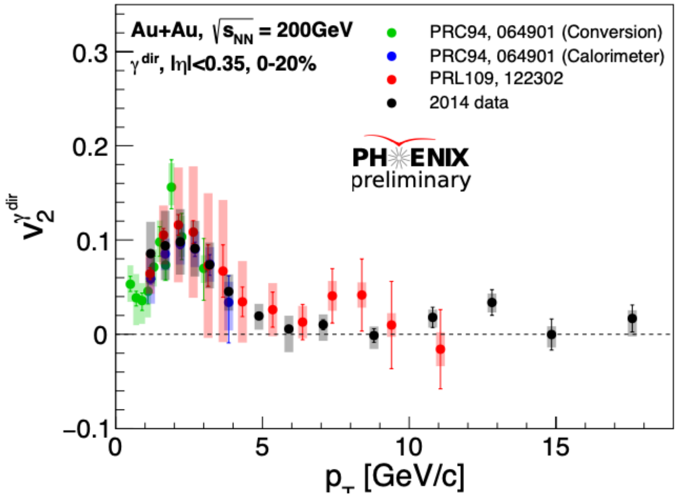
Initial maximum ***T*** of plasma

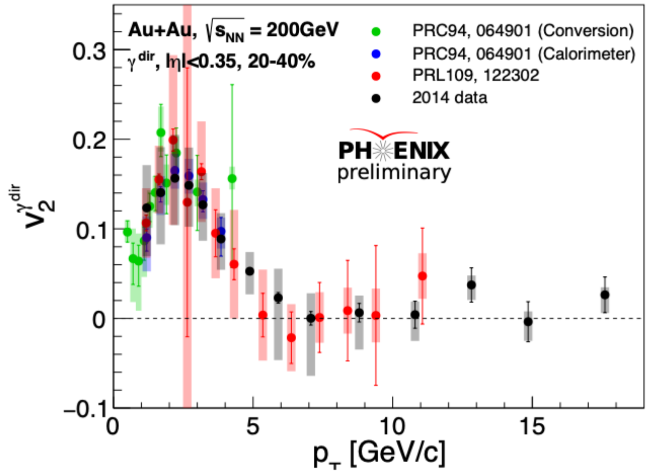
*Phys.Rev.C 105 (2022) 1, 014909*



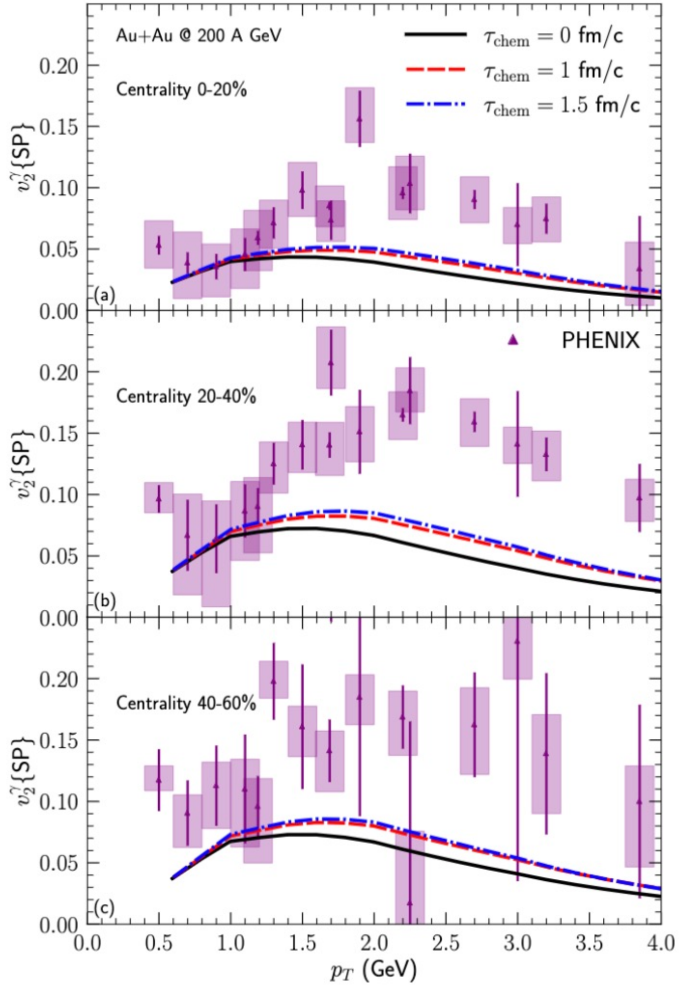

- ➢ Consider blue shift effect, theoretical model is consistent with STAR result better than PHENIX
- ➢ Acquire $T_0$ with simple hydro theoretical model

# Direct photon 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

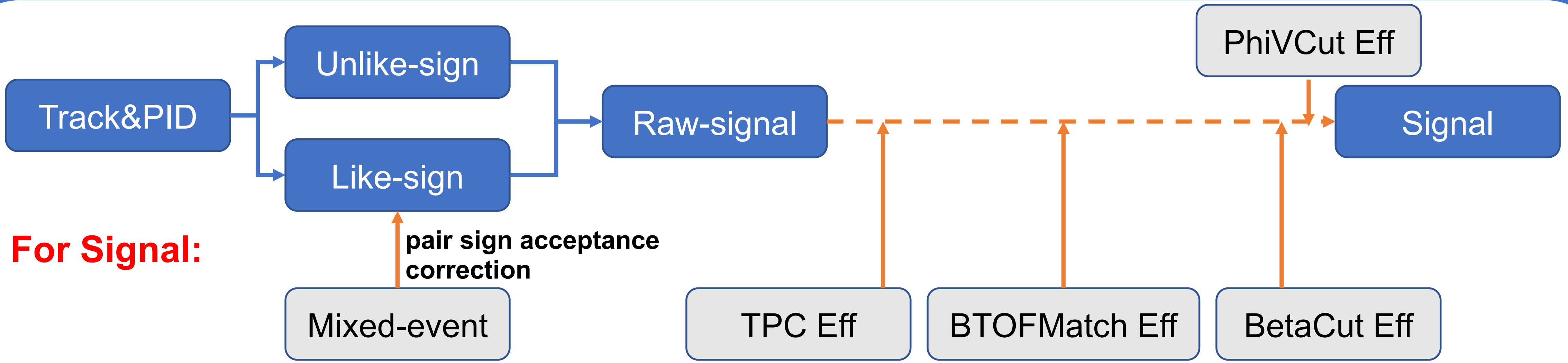
➢ Theoretical model:

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

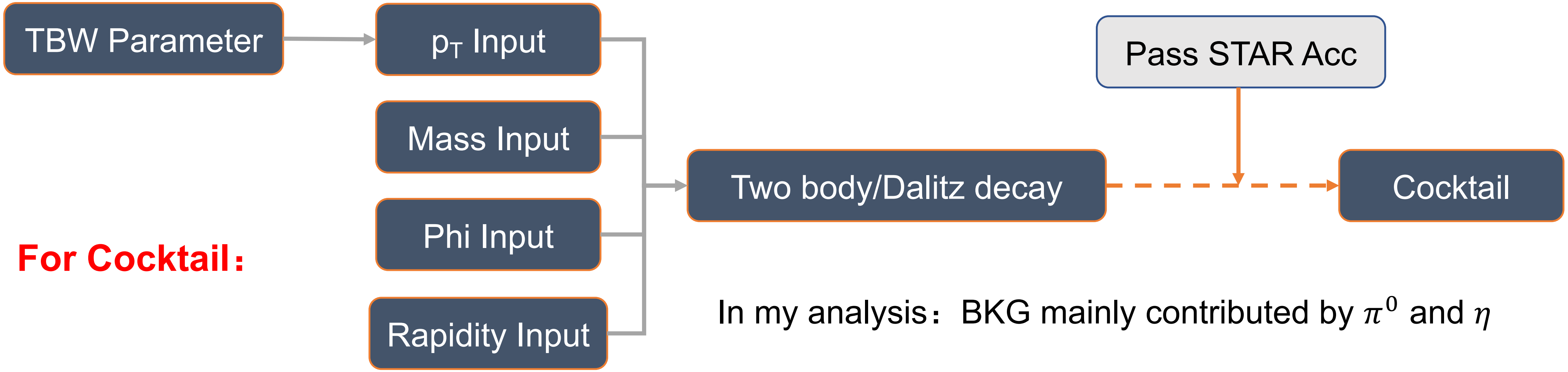
# Analysis procedure

Both in STAR Acceptance

**For Signal:**




**For Cocktail:**

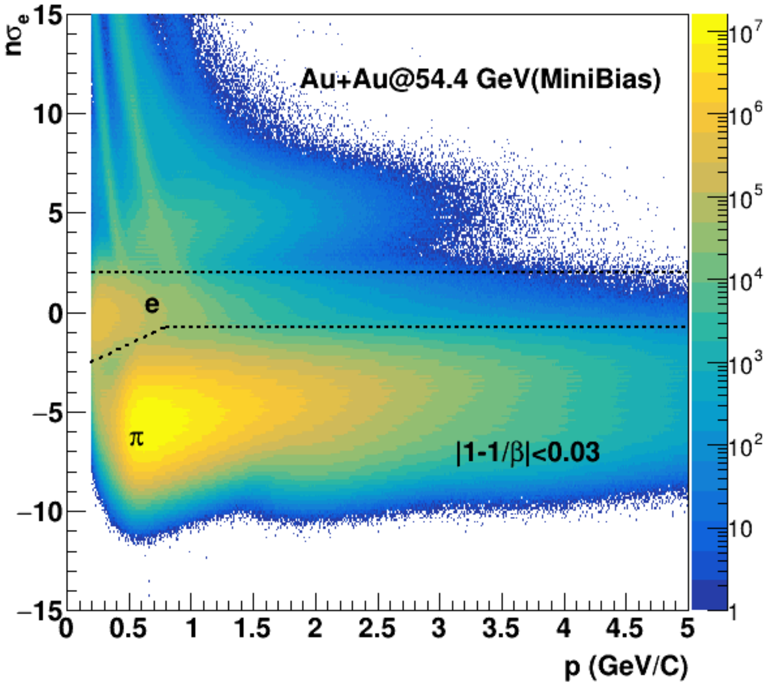



In my analysis：BKG mainly contributed by $\pi^0$ and $\eta$

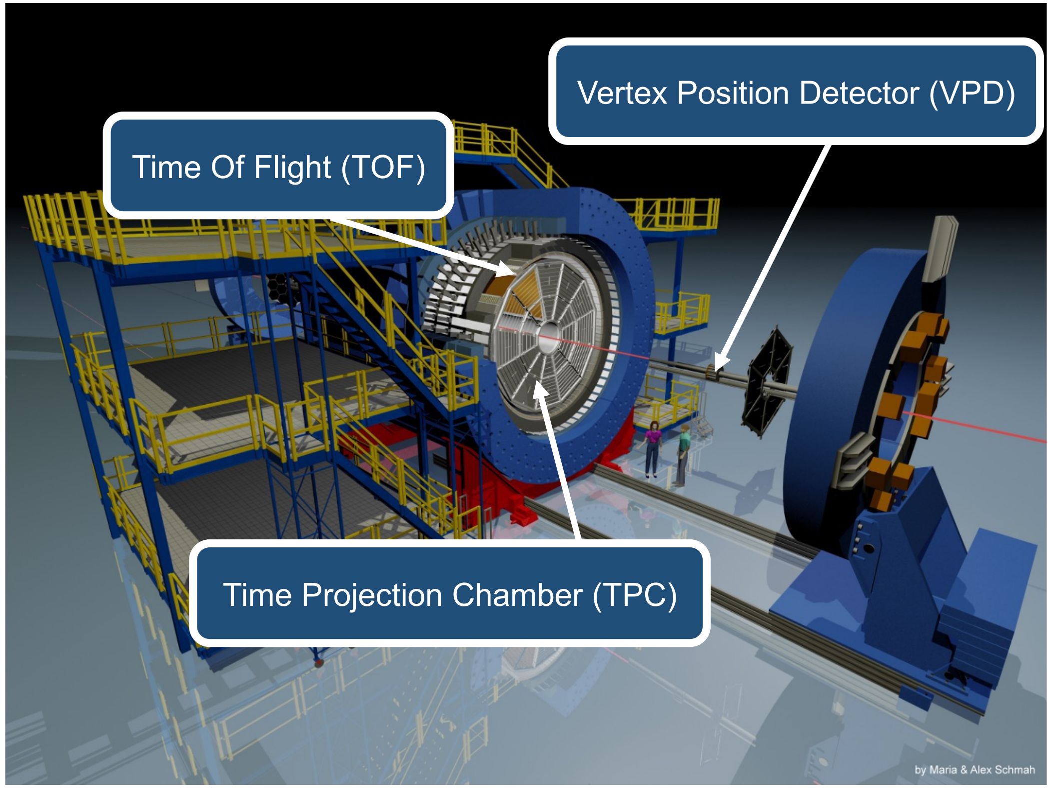
# Experiment setup and eID

- Au+Au collision at $\sqrt{s_{\rm NN}}$ = 27 and 54.4 GeV
- Used events:
  - 27 GeV: ~250M minimum bias events
  - 54.4 GeV: ~430M minimum bias events

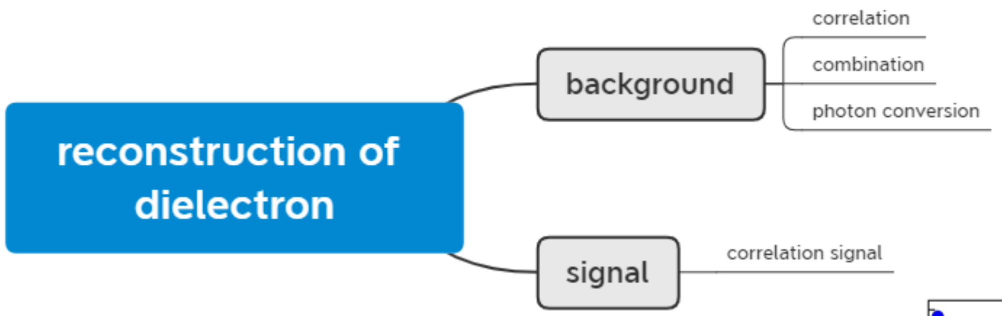
| EID cuts: |
|---|
| $p_T > 0.2$ GeV$/c$ |
| $n\sigma_e < 2$ |
| $n\sigma_e$ lower boundary for 54.4 GeV: |
| $n\sigma_e > 3.0p - 3.6$ for $p < 0.8$ GeV$/c$ |
| $n\sigma_e > -1.2$ for $p >= 0.8$ GeV$/c$ |
| $n\sigma_e$ lower boundary for 27 GeV: |
| $n\sigma_e > 1.6p - 2.6$ for $p < 1$ GeV$/c$ |
| $n\sigma_e > -1.0$ for $p >= 1$ GeV$/c$ |
| $\|1. - 1/\beta\| < 0.03$ |




- **Large acceptance:**
  - $p_T^e > 0.2$ GeV/c, $|\eta| < 1$,
  - $-\pi < \phi < \pi$
- **TPC:**
  - Momentum
  - Energy loss
- **TOF+VPD:**
  - Velocity

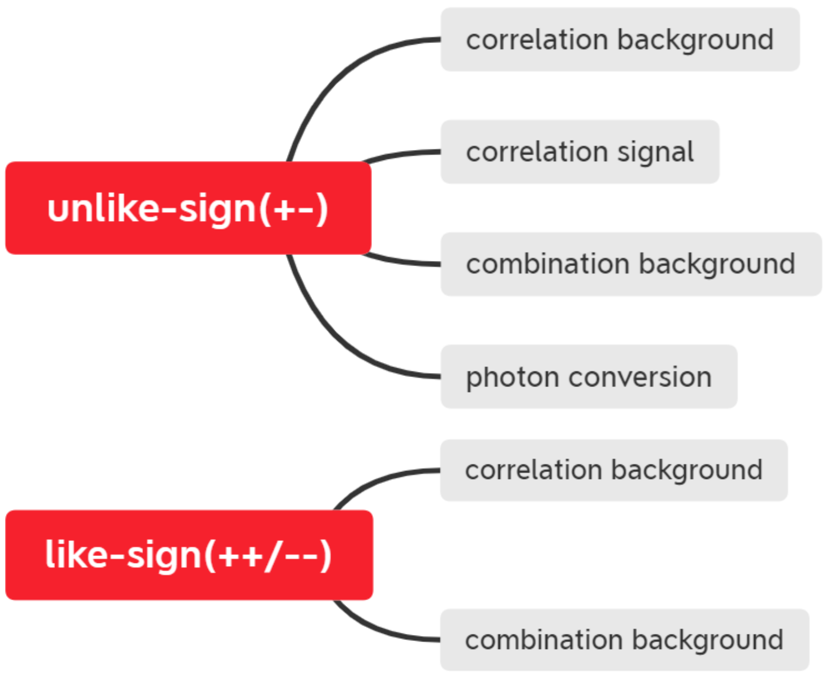


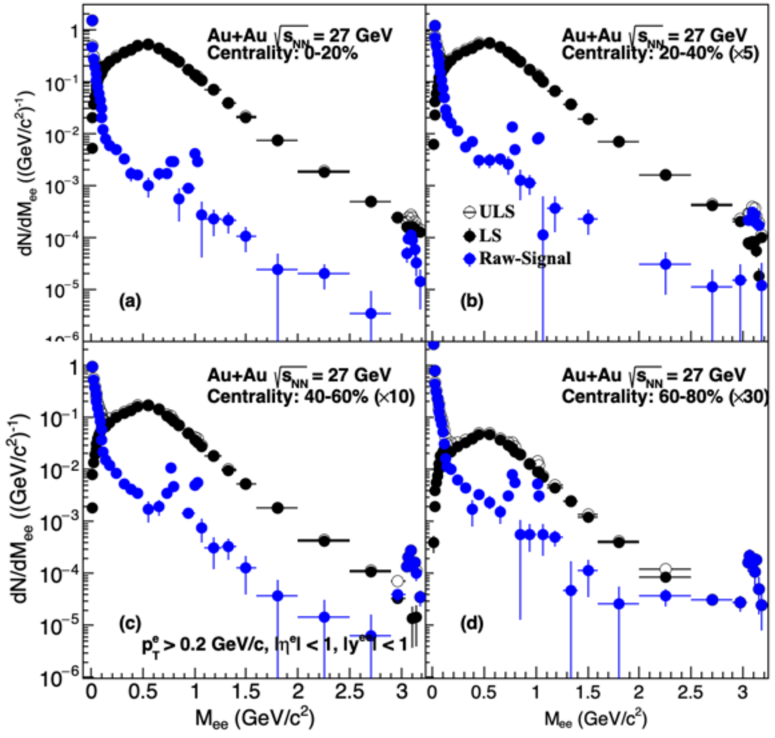
# Raw signal

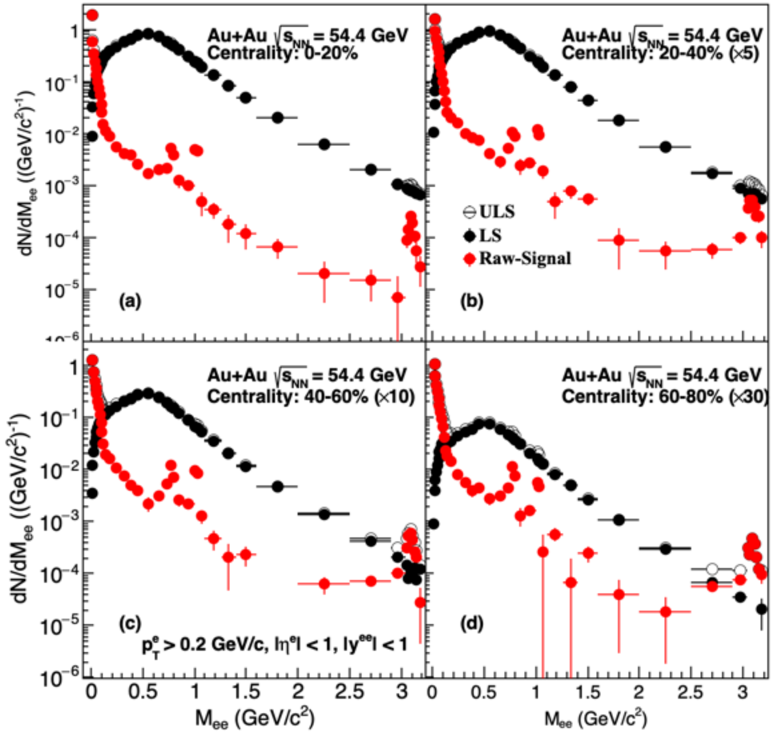



$$M_{e+e-} = \sqrt{(E_+ + E_-)^2 - (\vec{p_+} + \vec{p_-})^2}$$

$$E_{+/-} = \sqrt{m_e^2 + \vec{p}_{+/-}^{\,2}}$$



# Efficiency correction

## TPC Efficicency:

- Apply track cut and embedding to get the efficiency
- Use 3D($p_T, \eta, \phi$) TPC tracking efficiency for efficiency correction

## $n\sigma_e$ Cut Efficiency:

➢ **For 27GeV $n\sigma_e$ Cut Eff:**
- p<1.0, 1.6*p-2.6< $n\sigma_e$ <2
- p>1.0, -1.0< $n\sigma_e$ <2

Select pure electron sample:
- $M_{ee}$<0.015 (GeV/$c^2$)
- Loose $n\sigma_e$ cut: | $n\sigma_e$ |<2

➢ **For 54.4GeV $n\sigma_e$ Cut Eff:**
- p<0.8, 3.6*p-3< $n\sigma_e$ <2
- p>0.8, -1.2< $n\sigma_e$ <2

Select pure electron sample:
- $M_{ee}$<0.015 (GeV/$c^2$)
- Loose $n\sigma_e$ cut: | $n\sigma_e$ |<2

## BTOFMatch + β Cut Efficiency:

➢ **Pure electron select:**
- p<1.0, 1.6*p-2.6< $n\sigma_e$ <2
- p>1.0, -1.0< $n\sigma_e$ <2
- PairMass<0.015
- $\beta > 0$
- TOFMatchFlag>0
- |TOFLocalY|<1.8

➢ **Pure electron select:**
- p<0.8, 3.6*p-3< $n\sigma_e$ <2
- P>0.8, -1.2< $n\sigma_e$ <2
- PairMass<0.015
- $\beta > 0$
- TOFMatchFlag>0
- |TOFLocalY|<1.8

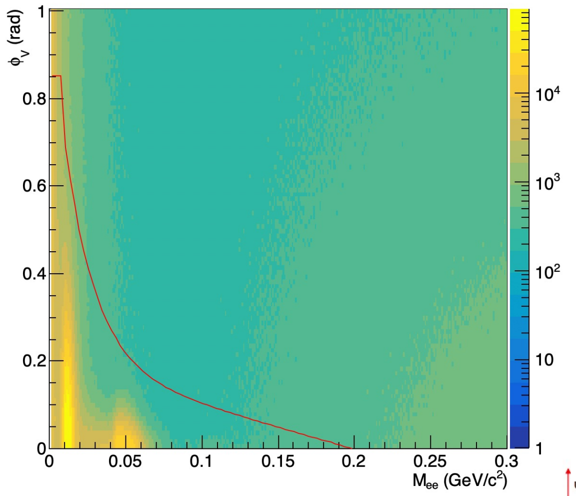
Beta Cut: $\left|{}^{1}/_{\beta} - 1\right| < 0.03$

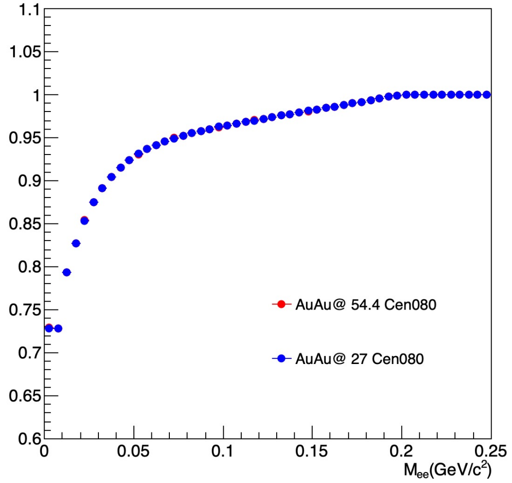
## $\phi_V$ Cut Efficiency:

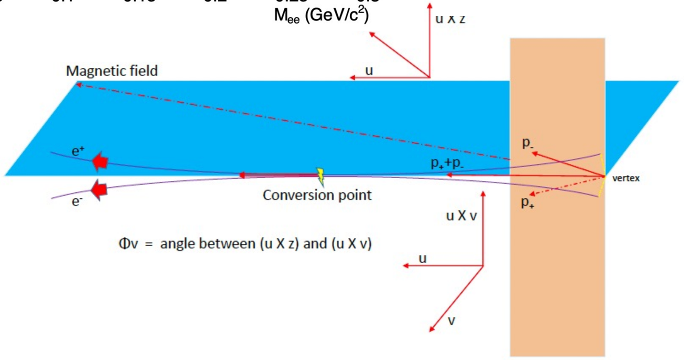
$$\phi_v = A * e^{B*M_{ee}} + C * M_{ee} + D$$

*From Jie Zhao Thsis*

| Par | A | B | C | D |
|---|---|---|---|---|
| Value | 0.84326 | -49.4819 | -0.996609 | 0.19801 |



# Cocktail component

interested signal：
- QGP radiation
- In-medium ρ decays
- Direct photon

➕

uninterested signal(cocktail)：
$Drell-Yan, c\bar{c}$
$\pi^0, \eta, \eta', \omega, \varphi, j/psi$

**Decay Process：**

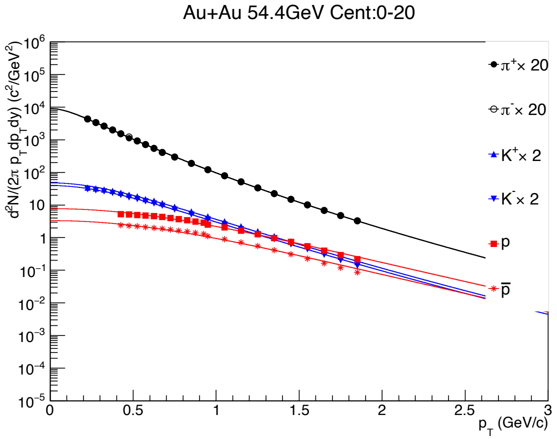
| | |
|---|---|
| two-body decay | $\omega \rightarrow e^+e^-, \phi \rightarrow e^+e^-, J/\psi \rightarrow e^+e^-, \psi' \rightarrow e^+e^-$ |
| dalitz decay | $\pi^0 \rightarrow \gamma e^+e^-, \eta \rightarrow \gamma e^+e^-, \eta' \rightarrow \gamma e^+e^-, \omega \rightarrow \pi^0 e^+e^-,$<br>$\phi \rightarrow \eta e^+e^-$ |
| heavy-flavor decay | $c\bar{c} \rightarrow e^+e^-$ |
| Drell-Yan process | $DY \rightarrow e^+e^-$ |

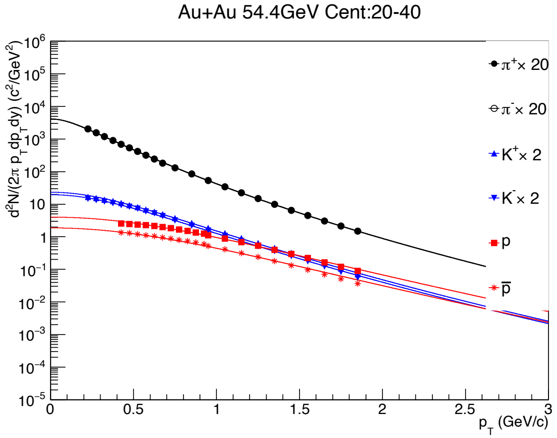
**Simulation method (for each mother particle)：**

- Particle properties input($p_T$ ,mass, rapidity, φ)
- Particle decay
- $p_T$ smearing
- Acquire electron information and reconstruct dielectron pair

# $p_T$ input for cocktail

**For 54.4GeV:** TBW estimate meson $p_T$ shape



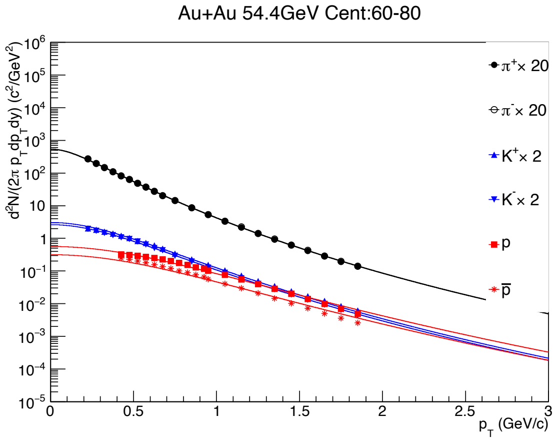



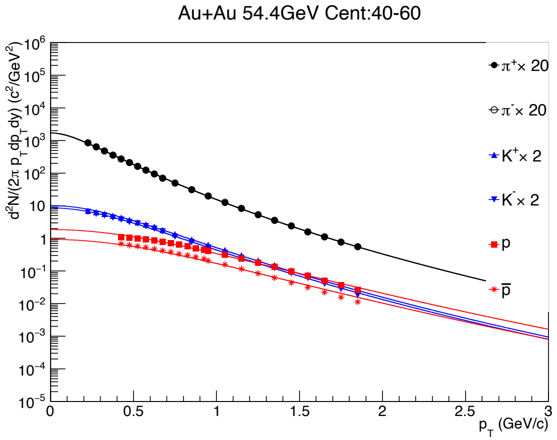

Data from 54.4 π/k/p preliminary result

| Centrality | T | q | β | $\chi^2/ndf$ |
|---|---|---|---|---|
| 0-20% | 0.0965+-0.0006 | 1.0442+-0.0012 | 0.4348+-0.0036 | 364.5/121 |
| 20-40% | 0.0979+-0.0007 | 1.0580+-0.0014 | 0.3726+-0.0059 | 207.54/121 |
| 40-60% | 0.0984+-0.0007 | 1.0745+-0.0014 | 0.2554+-0.0110 | 290.97/121 |
| 60-80% | 0.0981+-0.0006 | 1.0860+-0.0006 | 0.0001+-0.6398 | 413.06/121 |

54.4GeV dn/dy through extrapolate:

| Centrality | 0-20% | 20-40% | 40-60% | 60-80% |
|---|---|---|---|---|
| pi0 dndy | 170.76 | 78.82 | 32.22 | 10.38 |
| High | +7.73 | +4.43 | +1.79 | +0.38 |
| Low | -9.38 | -5.18 | -2.08 | -0.63 |



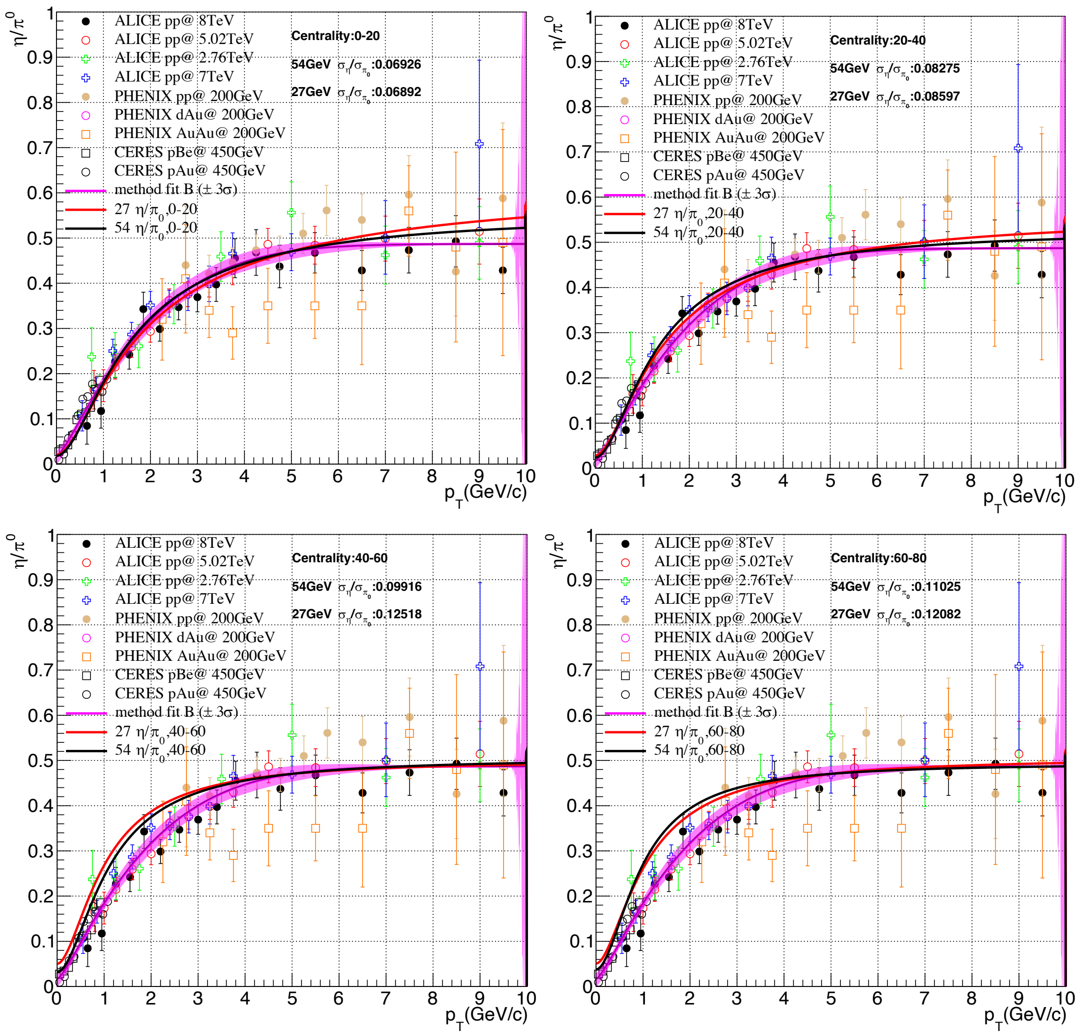



# Background——η contribution

- Fit method:

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

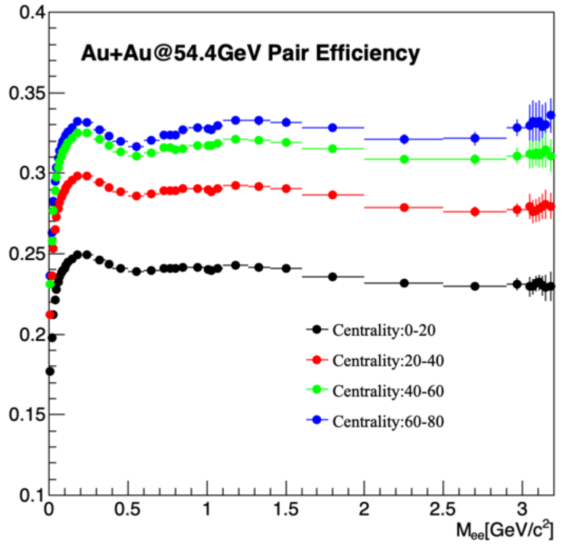
*Fit method form(Phys.Rev.C 104 (2021) 5, 054902)*

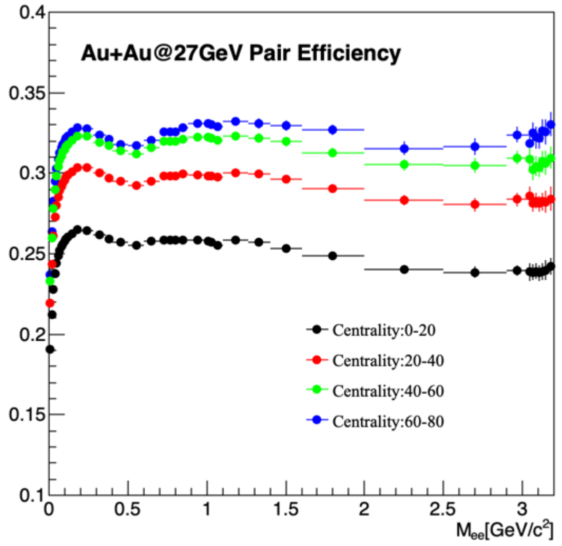


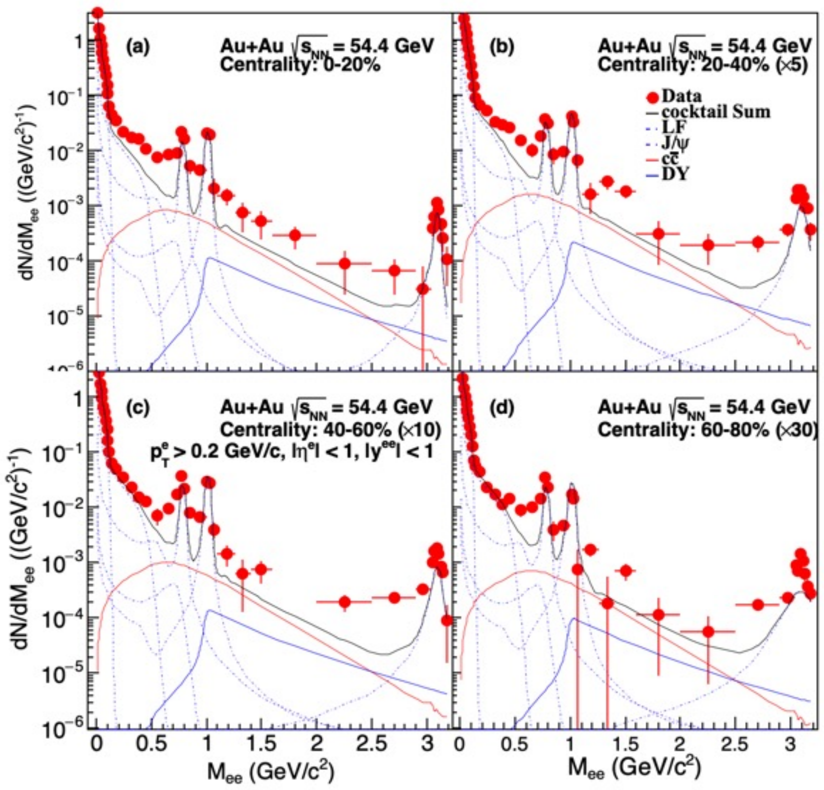

- $\eta/\pi^0$ ratio no significant dependence with energy, collision system and centrality at high $p_T$
- **Cocktail simulation**: using Monte Carlo simulation to acquire background (within STAR acceptance) and apply it to signal
  - Fix η yield with $\eta/\pi^0$= 0.4704 at $p_T$ = 5GeV/c

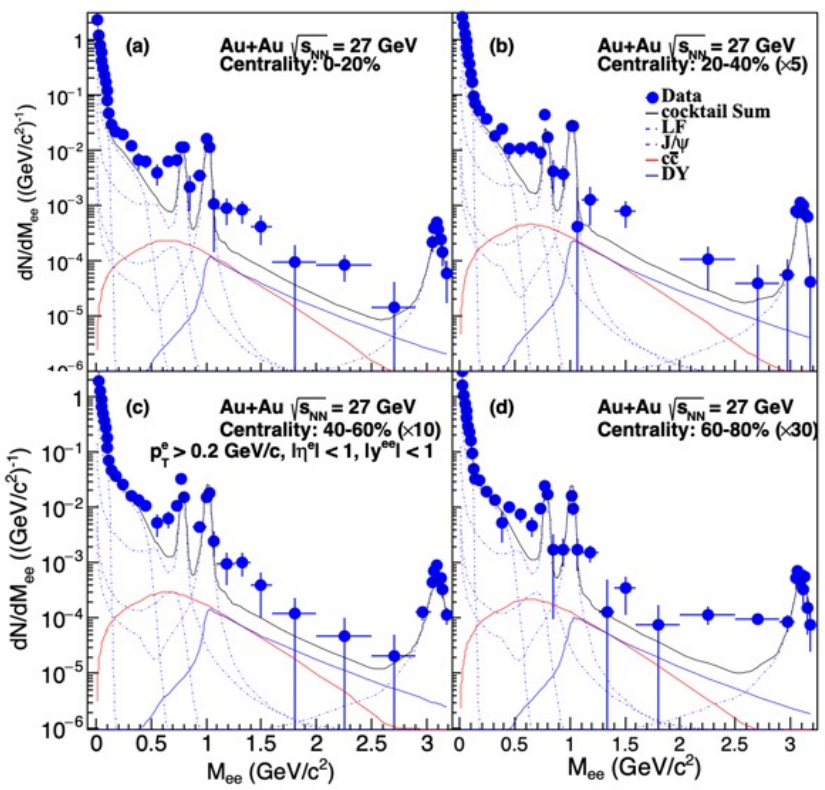
# Dielectron vs. Cocktail

Both in STAR Acceptance with efficiency correction



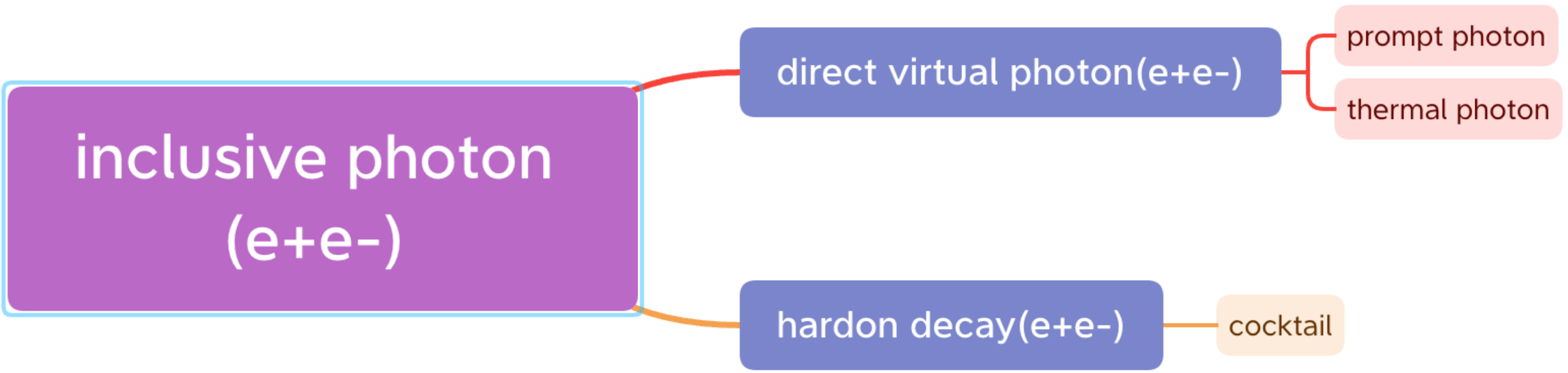




- Dielectron signal can be consistent with cocktail at $\pi^0$ mass region
- Observe significant excess yield contributed by direct virtual photon, in-medium rho at **LMR** and thermal dielectron at **IMR**

# 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 direct photon weight in inclusive photon**

$if: p_T \gg M_{ee}$

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

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

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

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**

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

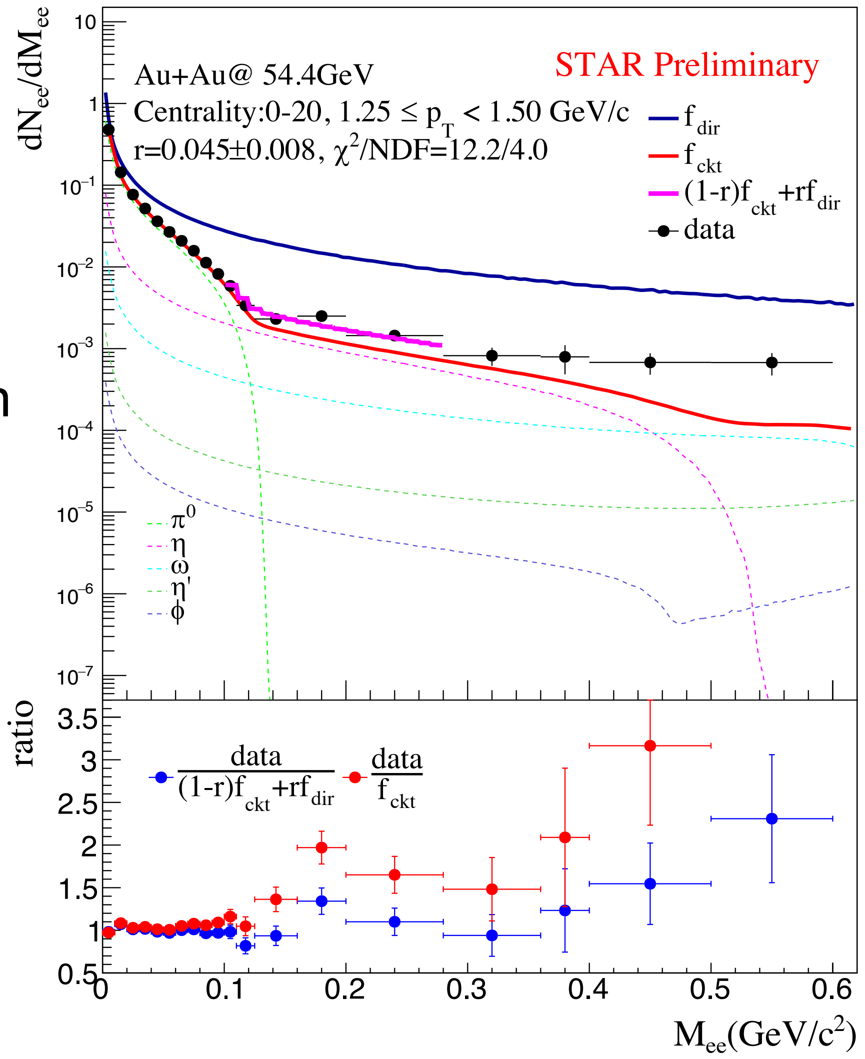
**two component fit**

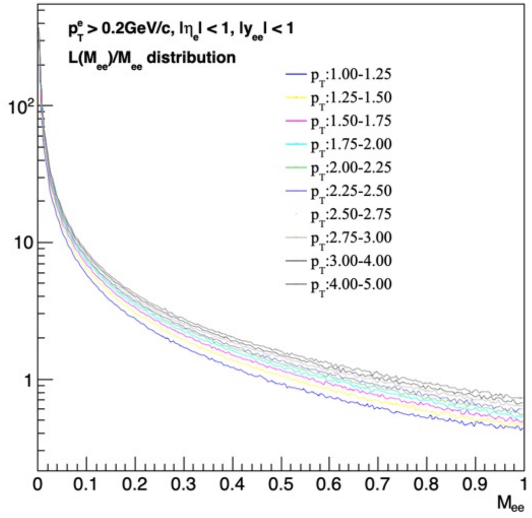
# Internal conversion method: two-component fit

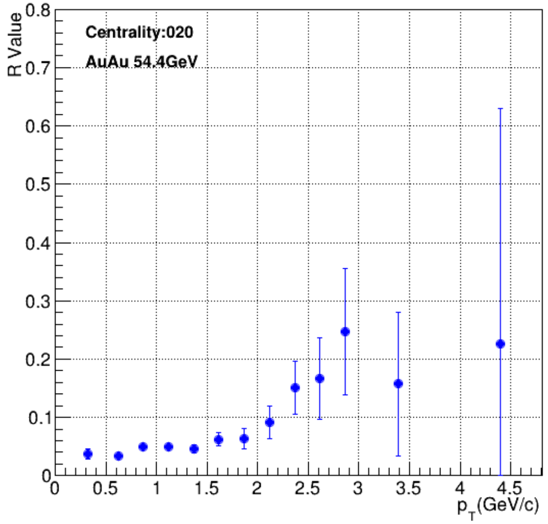
$$\frac{d^2N_{ee}}{dM} = r * f_{dir} + (1-r) * f_{cocktail} \qquad r = \frac{\gamma^{direct}}{\gamma^{inclusive}}$$

- Clear enhancement compared to cocktail contribution in $\eta$ 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

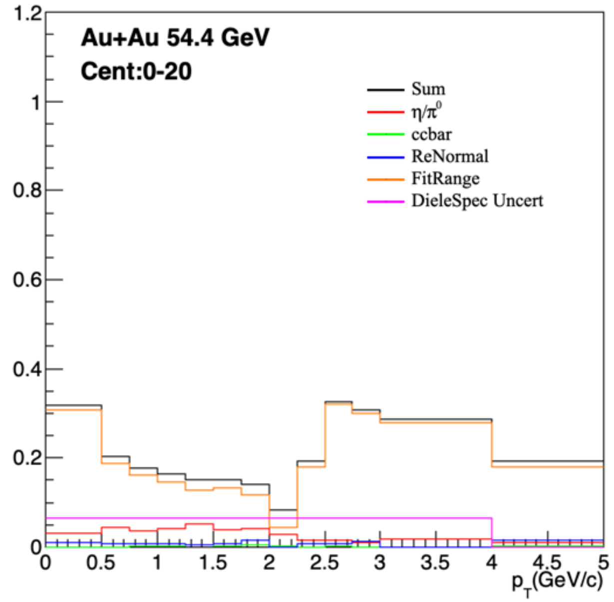


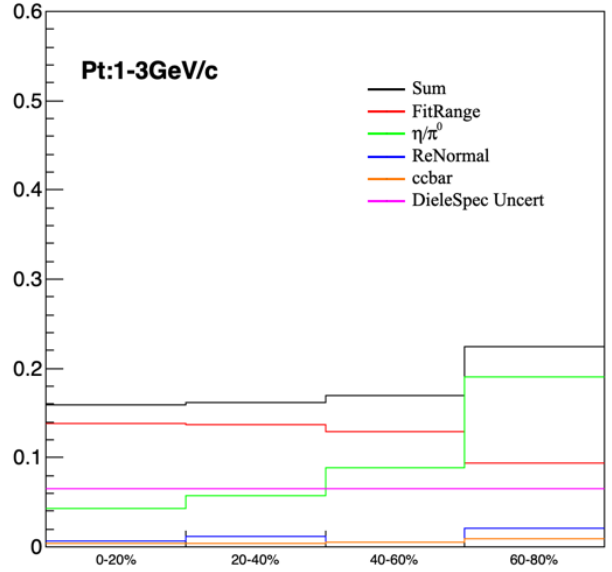



# Systematic Uncertainty

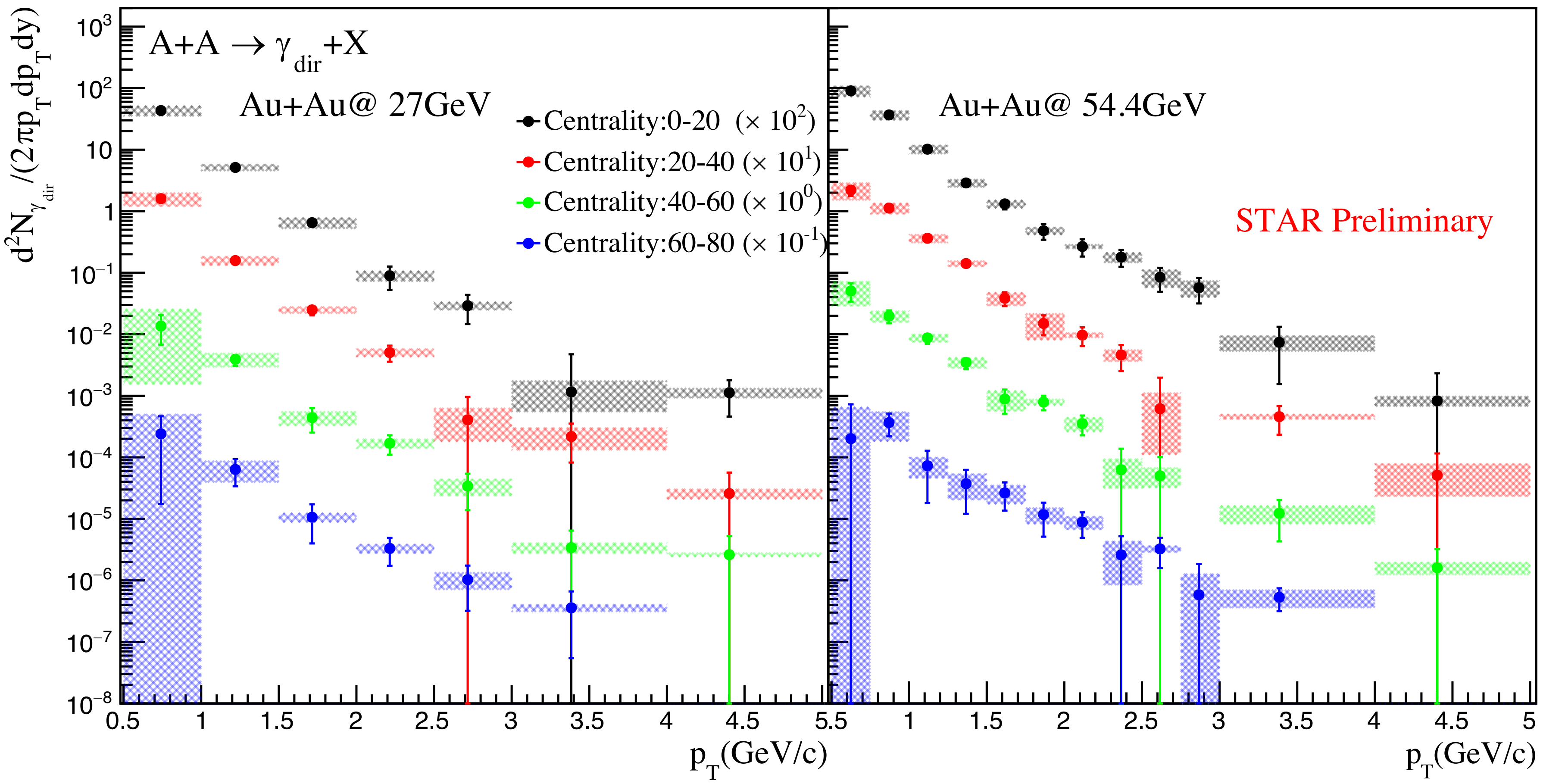
| Systematic Uncertainty Setting | | Default |
|---|---|---|
| Re-Normalization | 0-0.05 | 0-0.03 |
| Fit Range | 0.08-0.28 | 0.10-0.28 |
| | 0.125-0.36 | |
| | 0.08-0.36 | |
| $\eta/\pi^0$ | Fix：0.4706+3σ @5GeV/c | Fix : 0.4706 @5GeV/c |
| | Fix：0.4706-3σ @5GeV/c | |
| c-cbar | Random phi input | Back to back |
| Dielectron Spec Sys-Uncertainty | arXiv:2402.01998 | / |



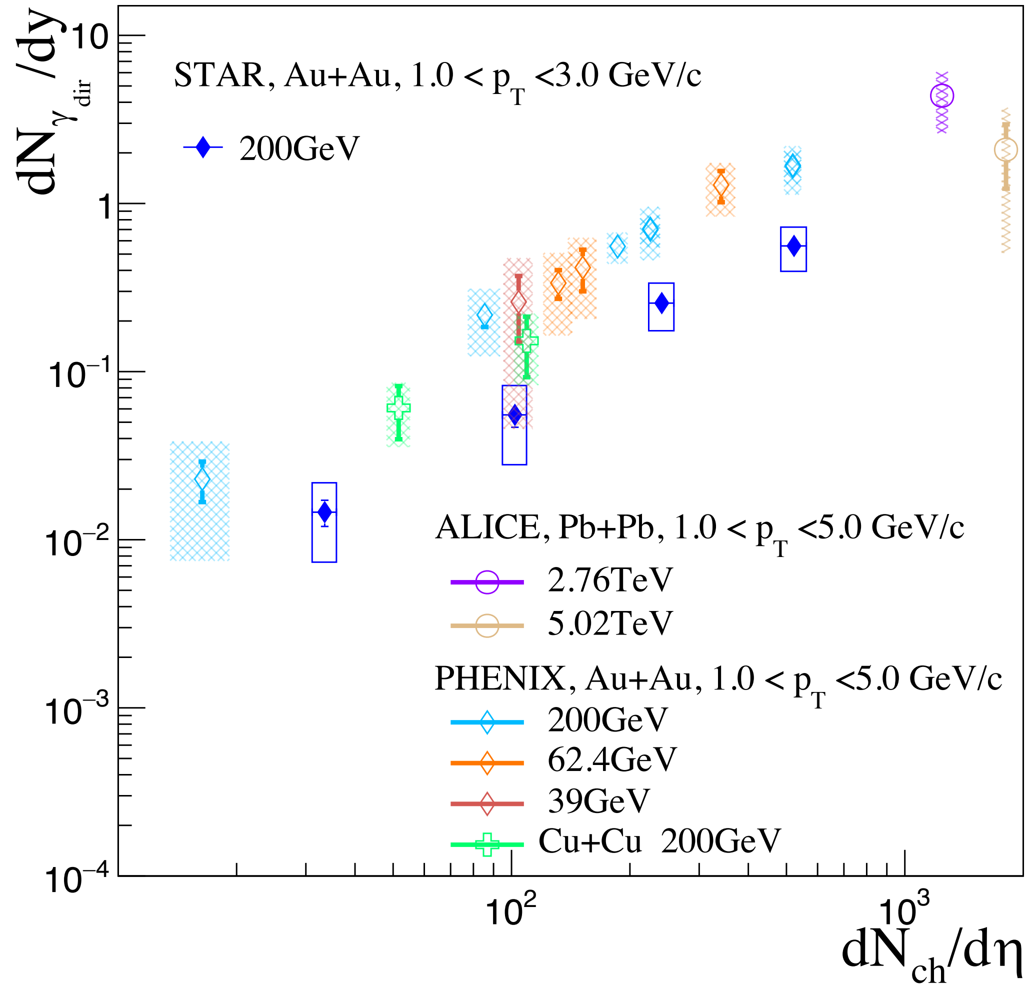
# Direct virtual photon $p_T$ spectrum

Need theoretical calculations for these results !




- First measurement of direct virtual photons in Au+Au collisions at $\sqrt{s_{NN}}$ = 27 and 54.4 GeV in different centrality regions

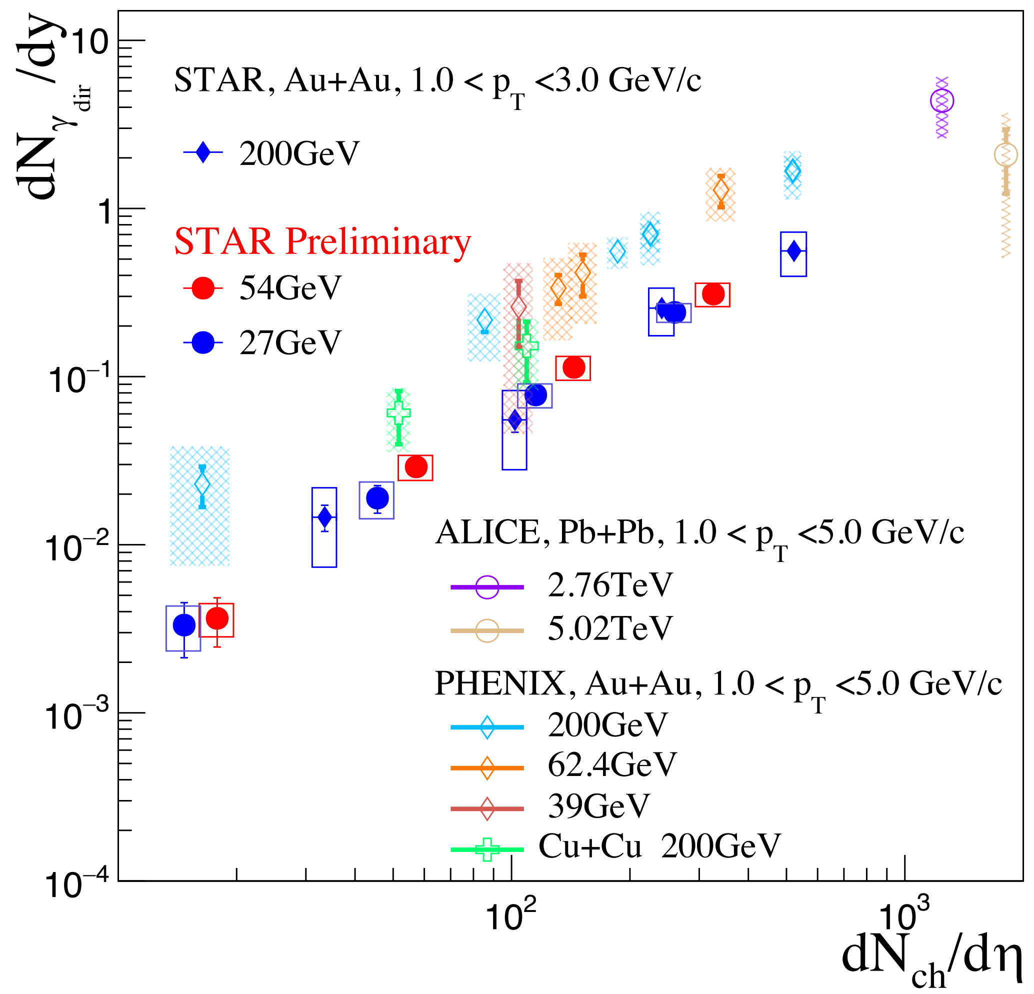
# dN/dy vs. $dN_{ch}/d\eta$




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

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

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




- New measurements of $dN_{\gamma_{dir}}/dy$ at STAR
- Strong $dN_{ch}/d\eta$ dependence

STAR Collaboration, *Phys.Lett.B* 770 (2017) 451-45
PHENIX Collaboration, *Phys.Rev.Lett*. 123 (2019) 022301
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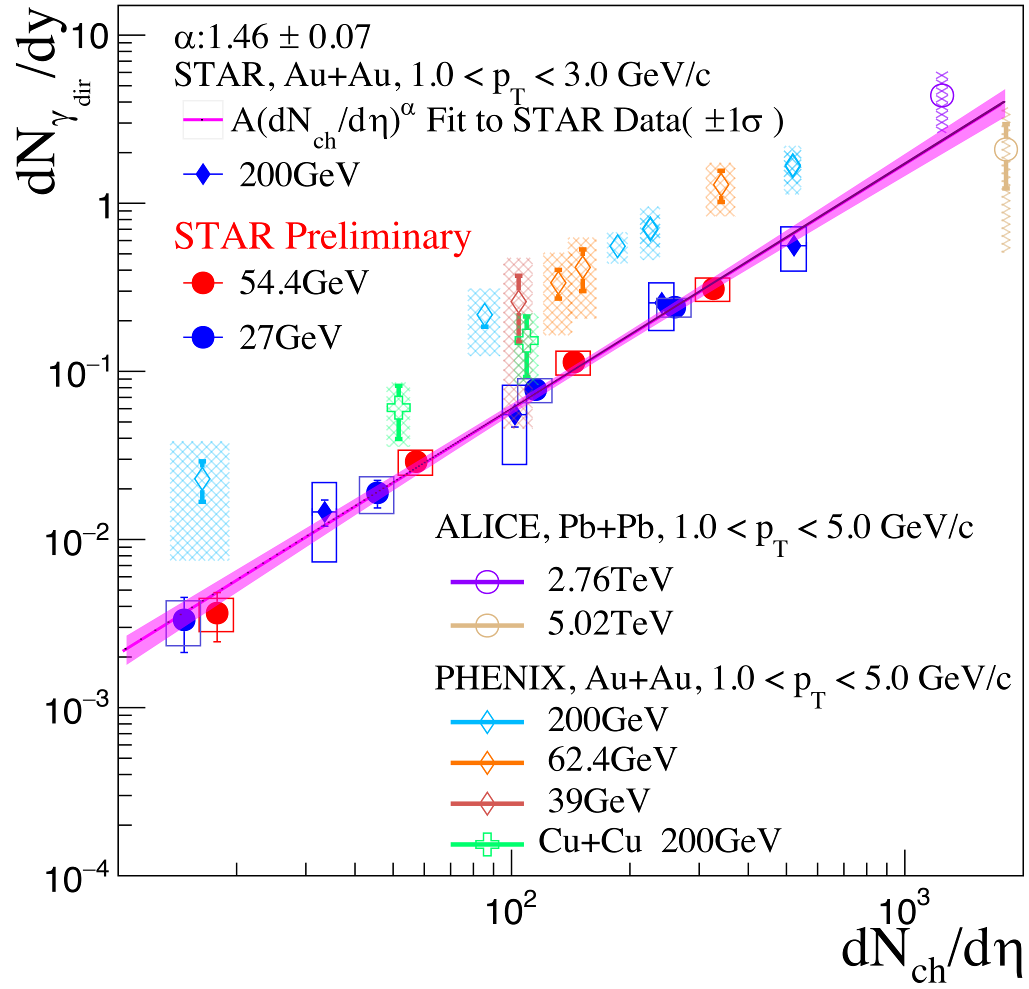
# dN/dy vs. $dN_{ch}/d\eta$




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

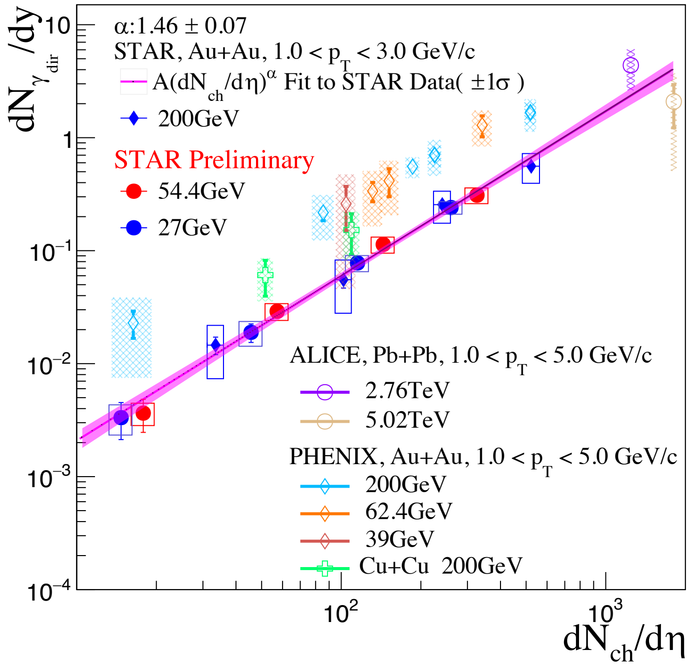
$$\alpha = 1.46 \pm 0.07$$

- The scaling trend is consistent with ALICE measurements

STAR Collaboration, *Phys.Lett.B* 770 (2017) 451-45
PHENIX Collaboration, *Phys.Rev.Lett*. 123 (2019) 022301
ALICE Collaboration, *arXiv:* 2308.16704
Jerome Jung, *Talk* 24/09 12:10 at HP2024

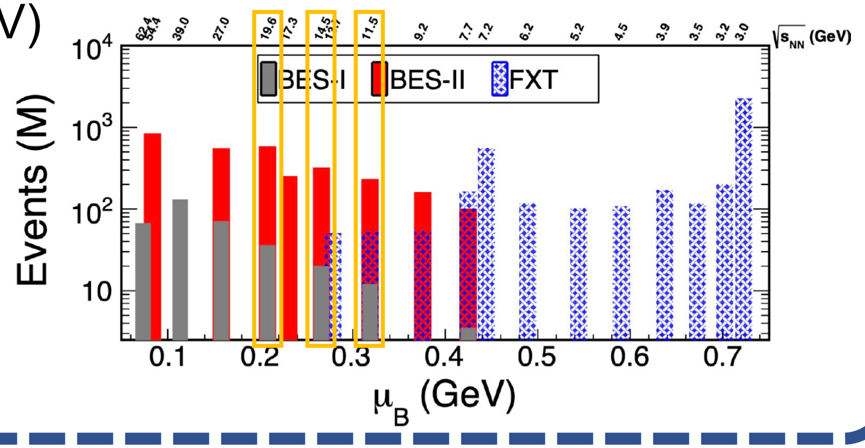
# Summary

- New measurements of direct virtual photon production in Au+Au collision at $\sqrt{s_{NN}}$ = 27 and 54.4 GeV, firstly extended to BES-II region
- The yields at $\sqrt{s_{NN}}$ = 27, 54.4 and 200 GeV measured by STAR follow a common scaling
  - Strong $dN_{ch}/d\eta$ dependence
  - $\alpha = 1.46 \pm 0.07$




## Outlook

- Extend the study to the interesting energy region near possible CEP
- Measure direct virtual photons at lower energies ($\sqrt{s_{NN}} = 11.5, 14.6, 19.6$ GeV)



# Summary

# Thanks for attention!

- ➢ New measurements of direct virtual photon production in Au+Au collision at $\sqrt{s_{NN}}$ = 27 and 54.4 GeV, firstly extended to BES-II region
- ➢ The yields at $\sqrt{s_{NN}}$ = 27, 54.4 and 200 GeV measured by STAR follow a common scaling
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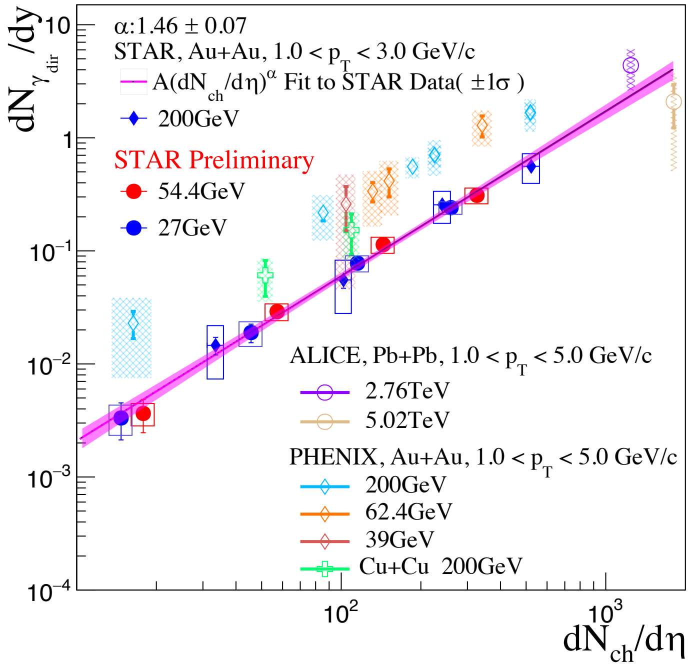


## Outlook

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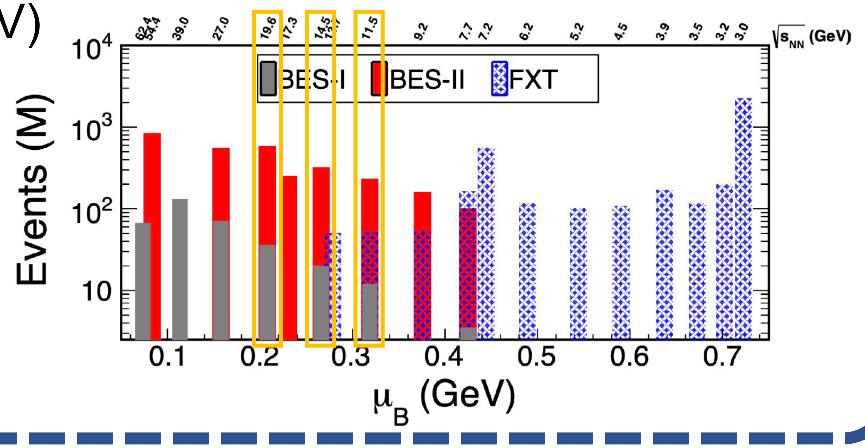
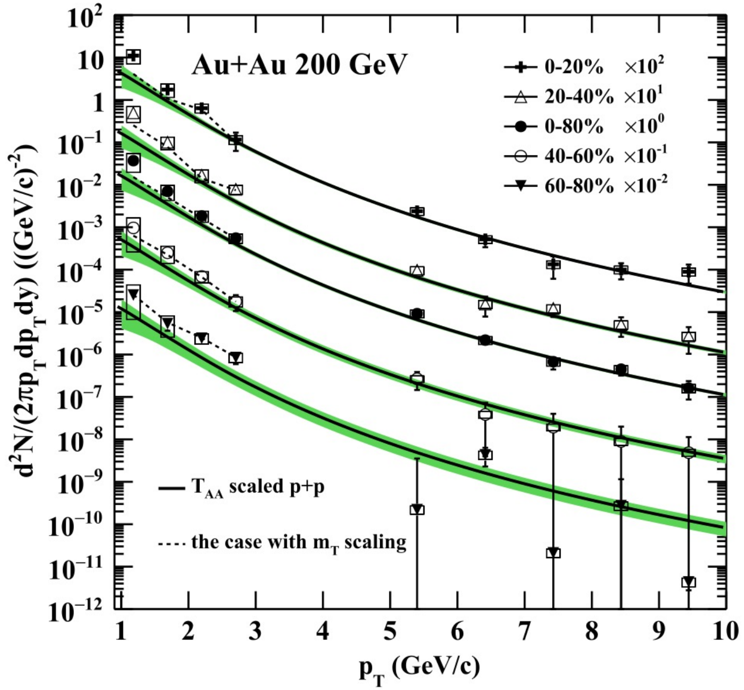
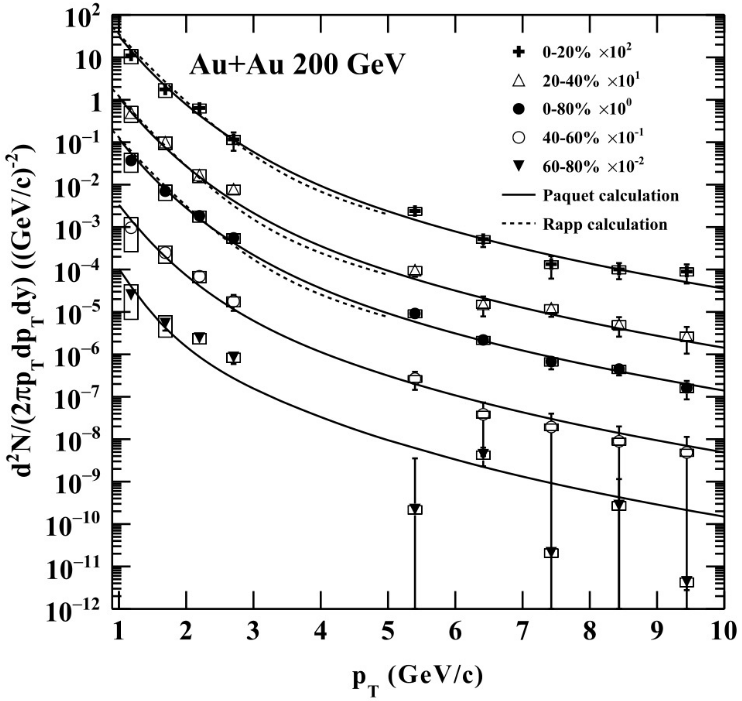


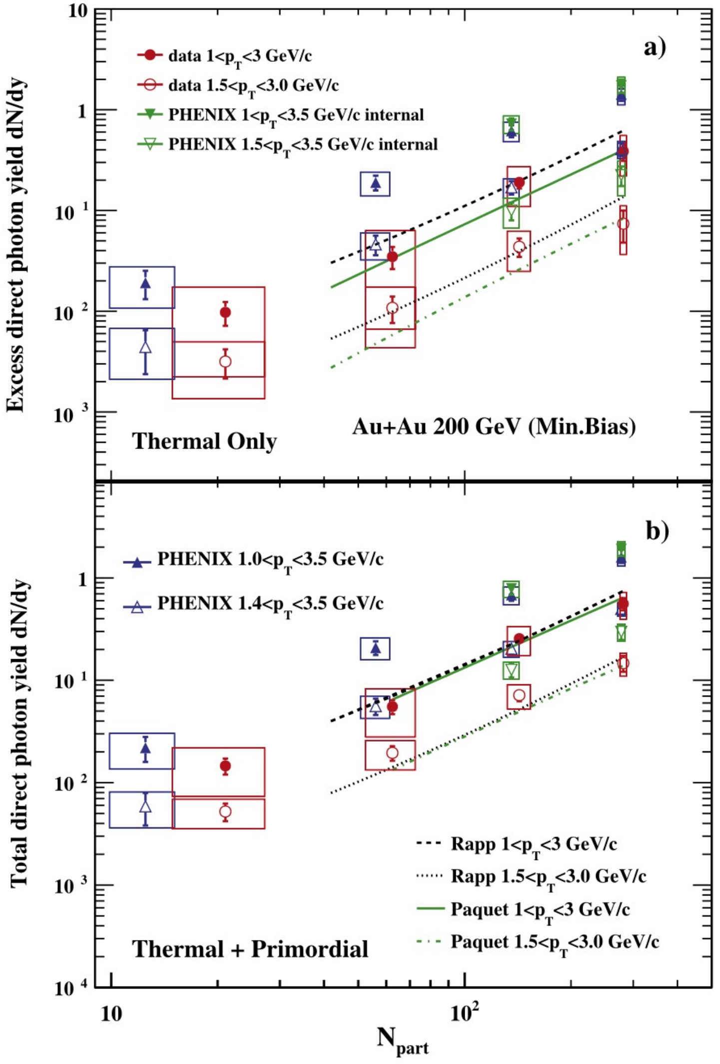
# Backup

# STAR 200 GeV result vs. Theory

*Phys.Lett.B* 770 (2017) 451-458

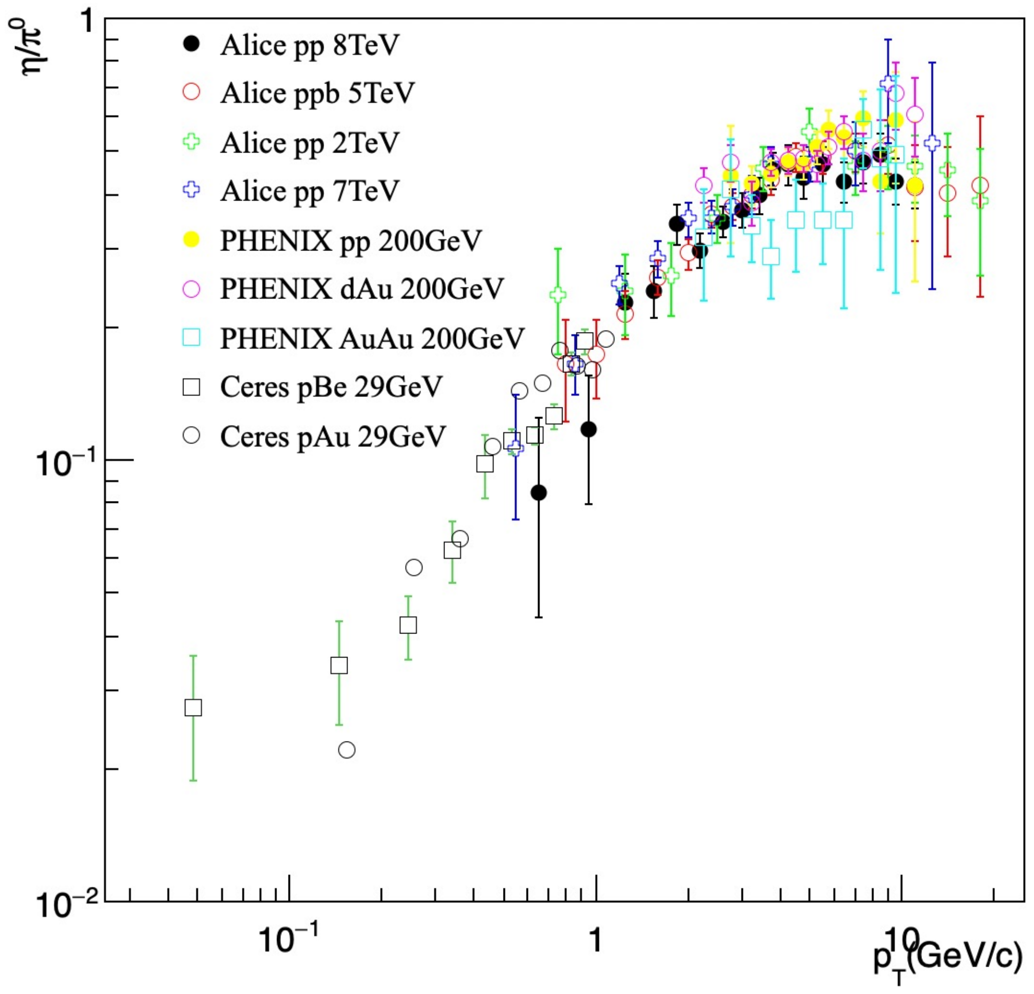


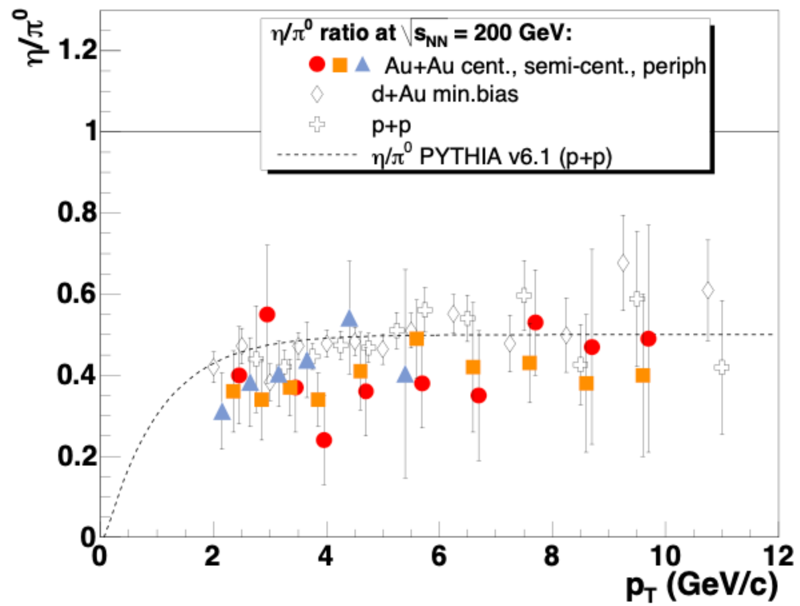




- High $p_T$: prompt photon be consistent with p+p results after $T_{AA}$ scaling
- Low $p_T$: Significant thermal photon enhancement
- Theory calculation can be consistent with direct photon $p_T$ spectrum and its yield

# $\eta/\pi^0$ at high $p_T$ region

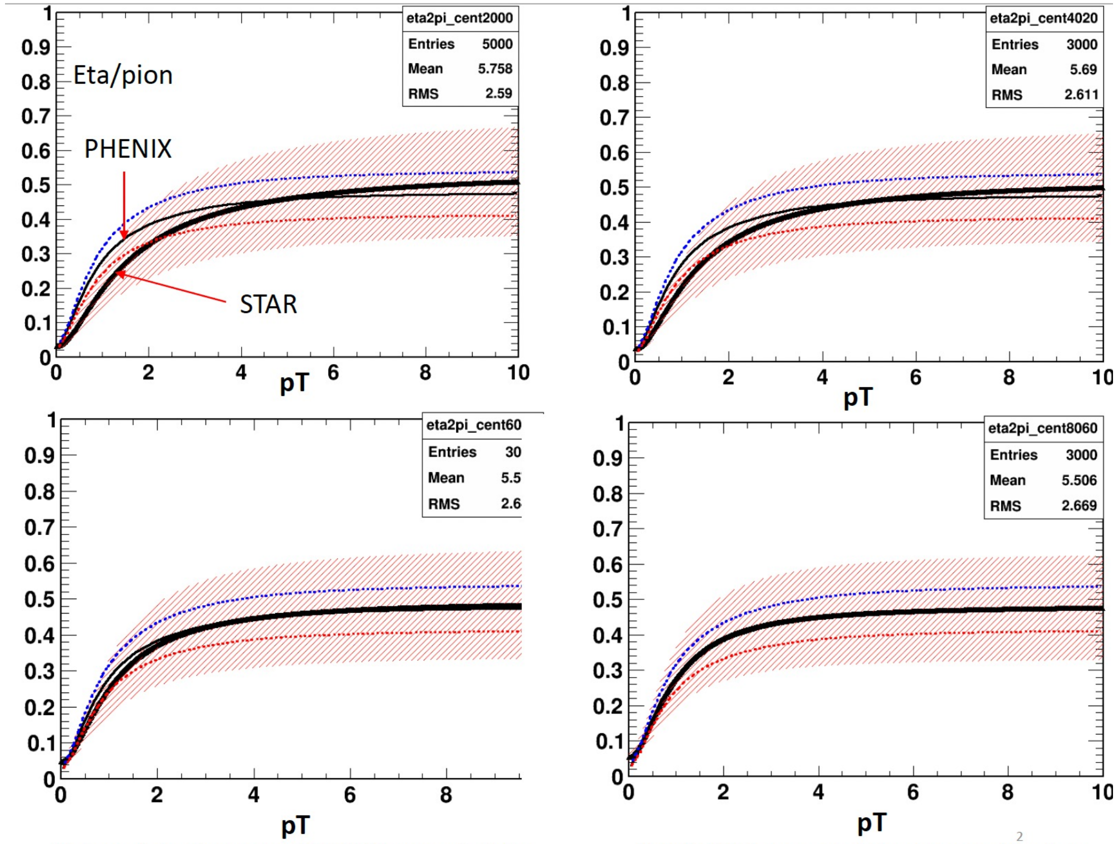



*Phys.Rev.C* 75 (2007) 024909



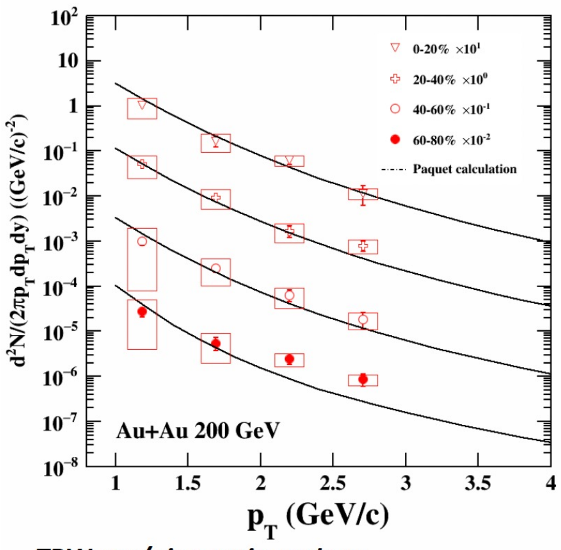

Eta/pi0 at different centrality in AuAu collision have a large error and no data at low pT

# $m_T$ scaling for η yield estimation



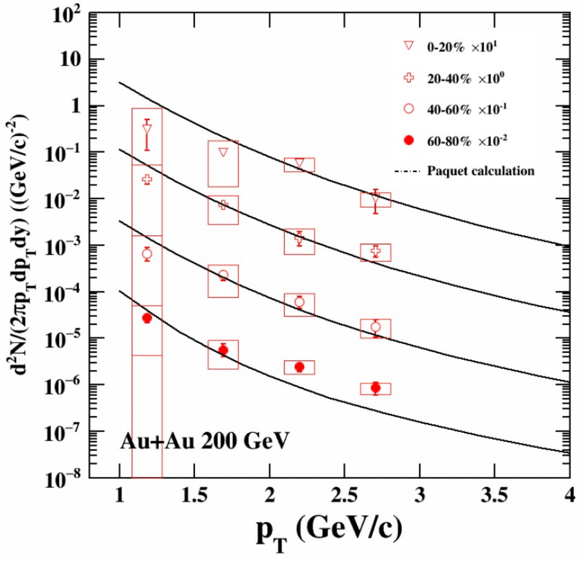

Colored dush curve: PHENIX uncertainty

Band: 30% uncertainty we used before




***TBW eta/pion ratio scale to 0.46@5GeV/c (PHENIX value)***

(use ratio uncertainty 13%, same as PHENIX)




***Use PHENIX eta/pion ratio***

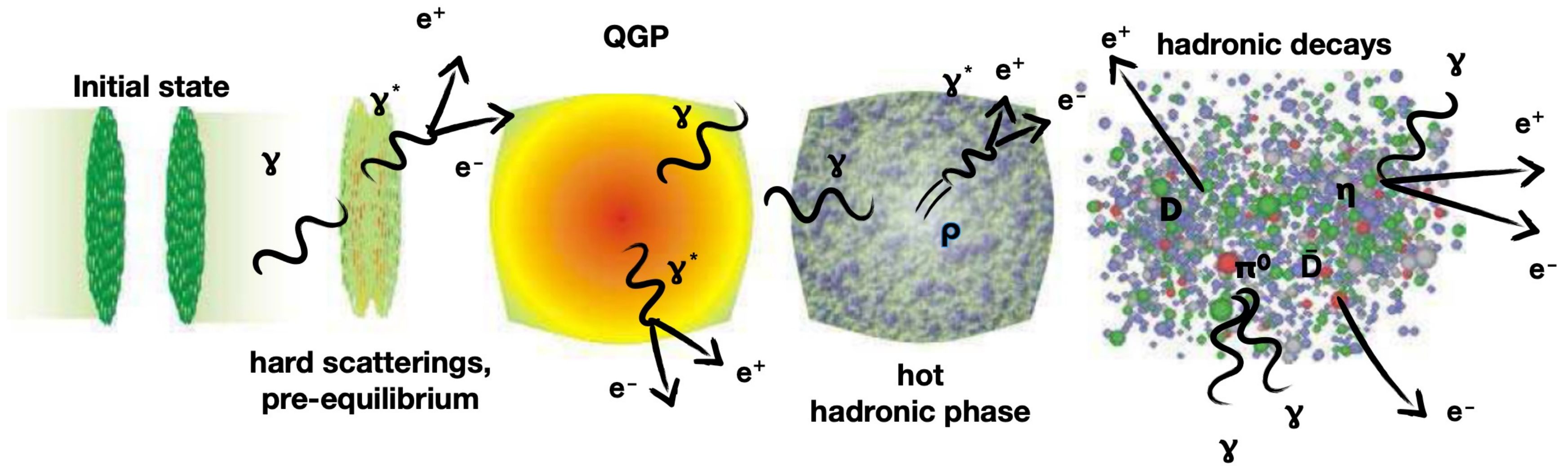
Use ratio uncertainty ~13%, used by PHENIX

- PHENIX **η** spectrum: $m_T$ scaling
- STAR **η** spectrum : TBW fit

- STAR eta/pi0 shape have strong centrality dependence
- PHENIX don't observe this dependence because flow effect will be ignored in $m_T$ scaling

# Production mechanism

Most interesting ones (Direct γ, γ*)




**1.Initial hard scattering**

- Test Ncoll scaling
- Constrain nuclear PDFs
- Candle for energy loss(γ-tagged jets)

**2.Pre-equilibrium phase**

- Mechanism of equilibration

**3.Thermal radiation**

- Effective QGP temperature
- Constrain space-time evolution

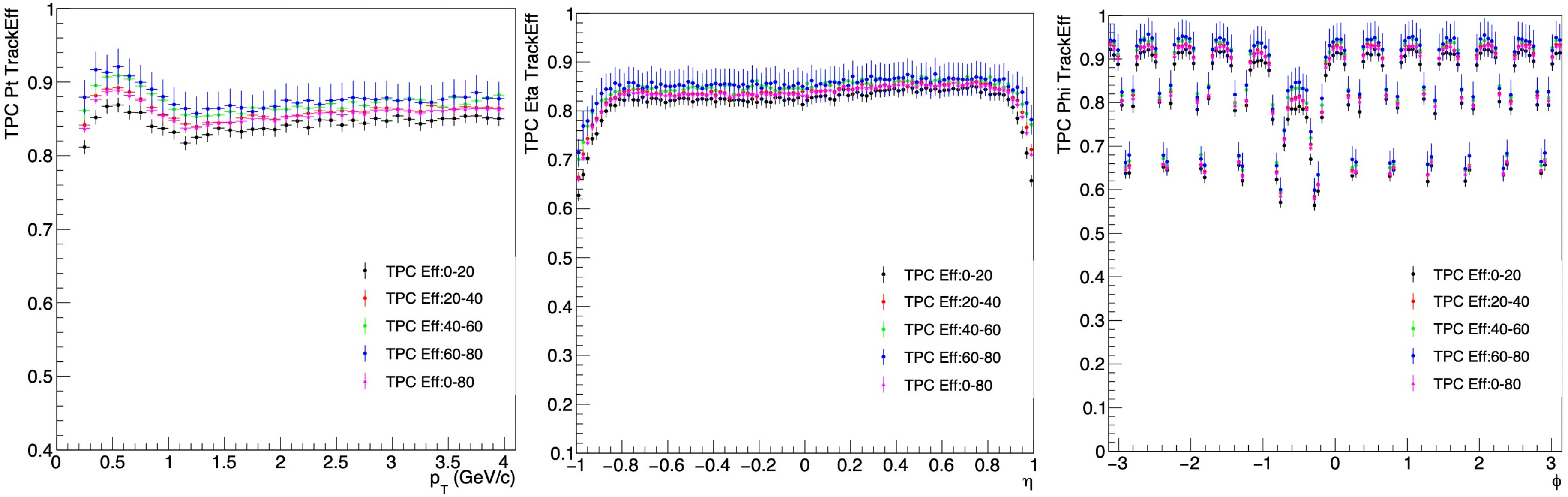
**4.Chiral symmetry restoration with dileptons**

- ρ boarding
- ρ-$\alpha_1$ mixing

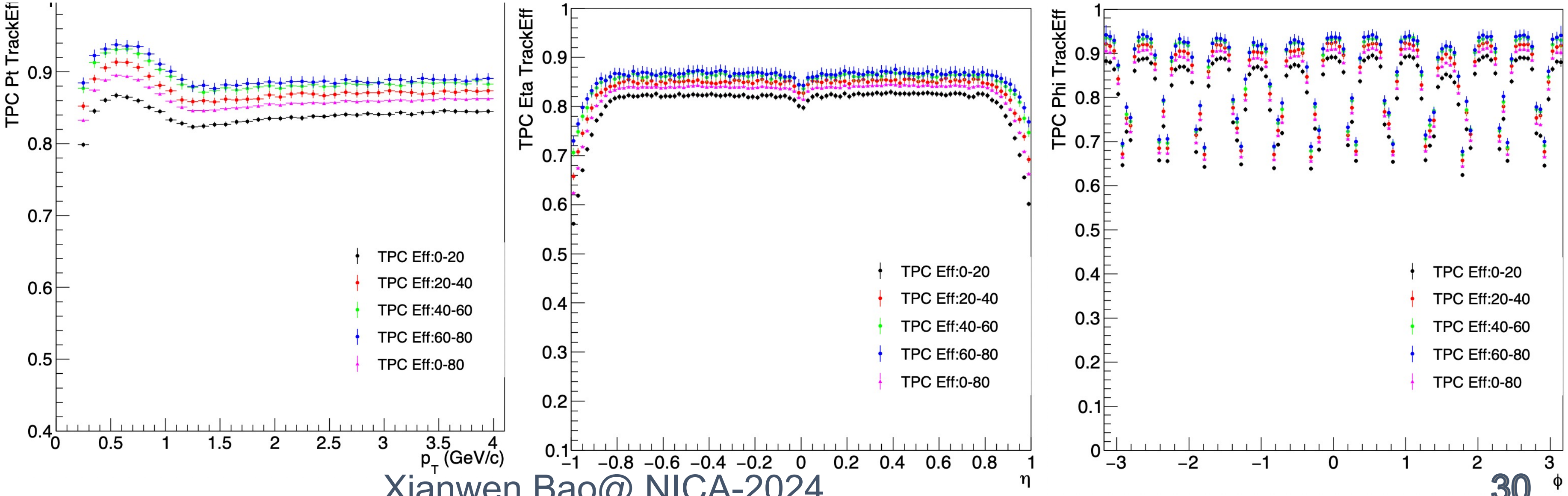
# TPC Efficiency

- Apply track cut and embedding to get the efficiency
- Use 3D($p_T, \eta, \phi$) TPC tracking efficiency for efficiency correction

**For 27GeV:**




**For 54.4GeV:**



# NSigmaE Cut Efficiency

## ➢ For 27GeV NSigmaE Cut Eff:

- p<1.0, 1.6*p-2.6< $n\sigma_e$ <2
- p>1.0, -1.0< $n\sigma_e$ <2

Select pure electron sample:

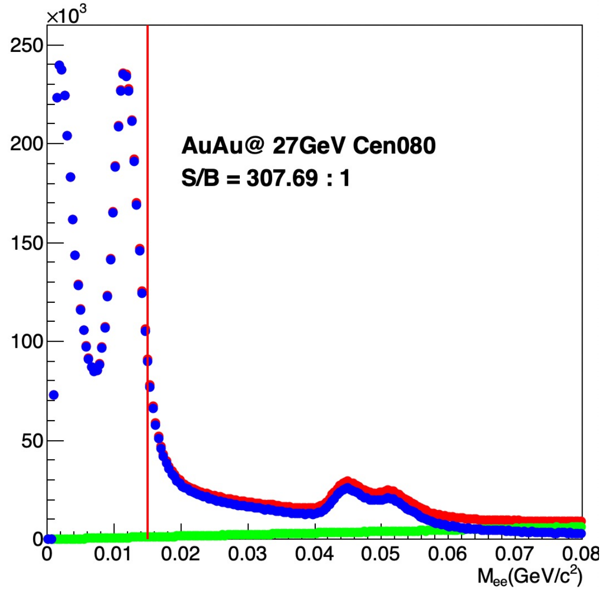
- $M_{ee}$<0.015 (GeV/$c^2$)
- Loose $n\sigma_e$ cut: | $n\sigma_e$ |<2

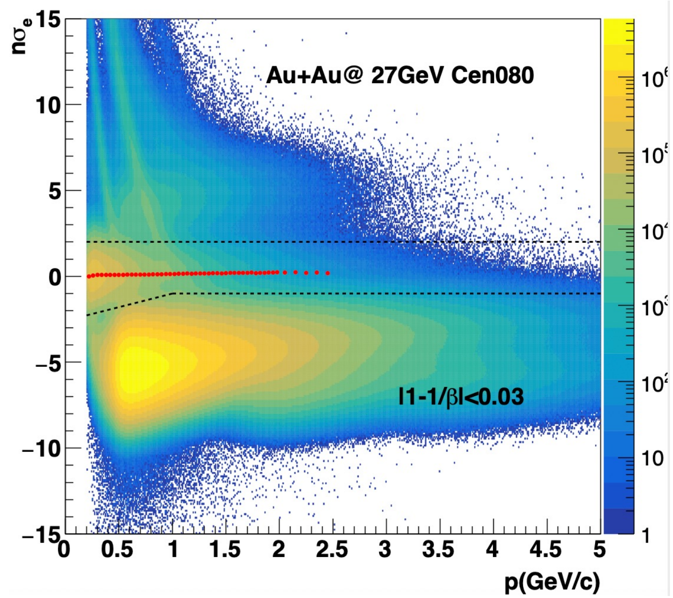
## ➢ For 54.4GeV NSigmaE Cut Eff:

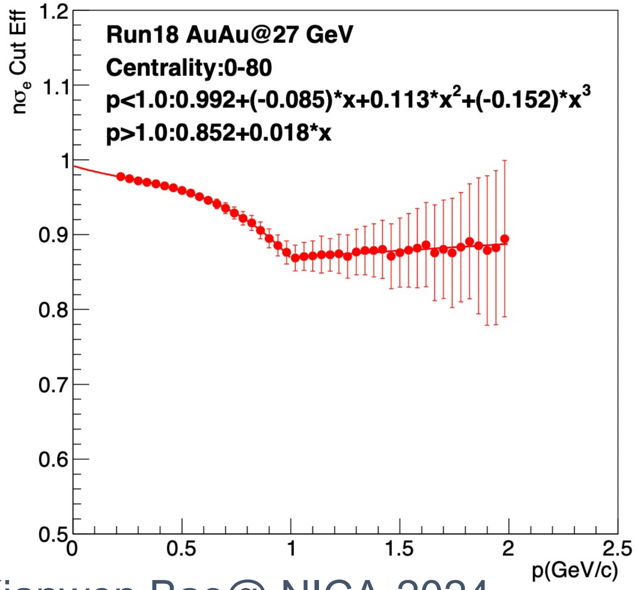
- p<0.8, 3.6*p-3< $n\sigma_e$ <2
- p>0.8, -1.2< $n\sigma_e$ <2

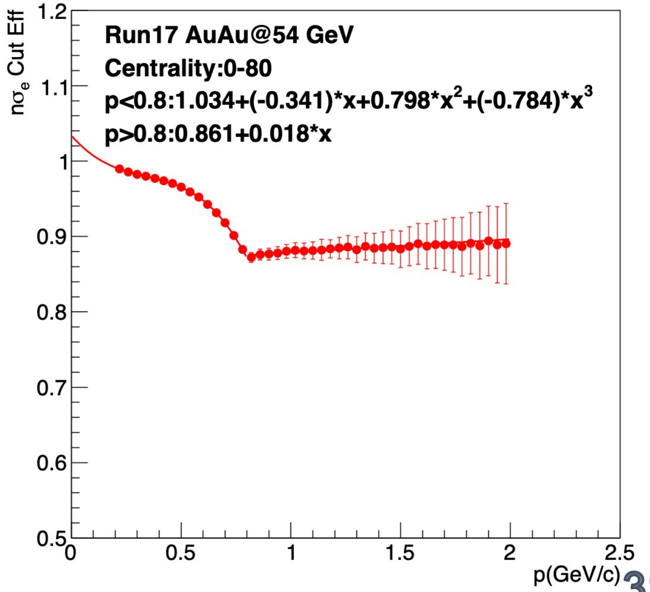
Select pure electron sample:

- $M_{ee}$<0.015 (GeV/$c^2$)
- Loose $n\sigma_e$ cut: | $n\sigma_e$ |<2



# BTOFMatch Efficiency

Use same pion cut for two dataset

➢ **Pure pion select:**

- $m^2 = 0.019 \pm 0.003 (GeV/c^2)$
- $|n\sigma_\pi|$<4
- $\beta > 0$
- TOFMatchFlag>0
- |TOFLocalY|<1.8

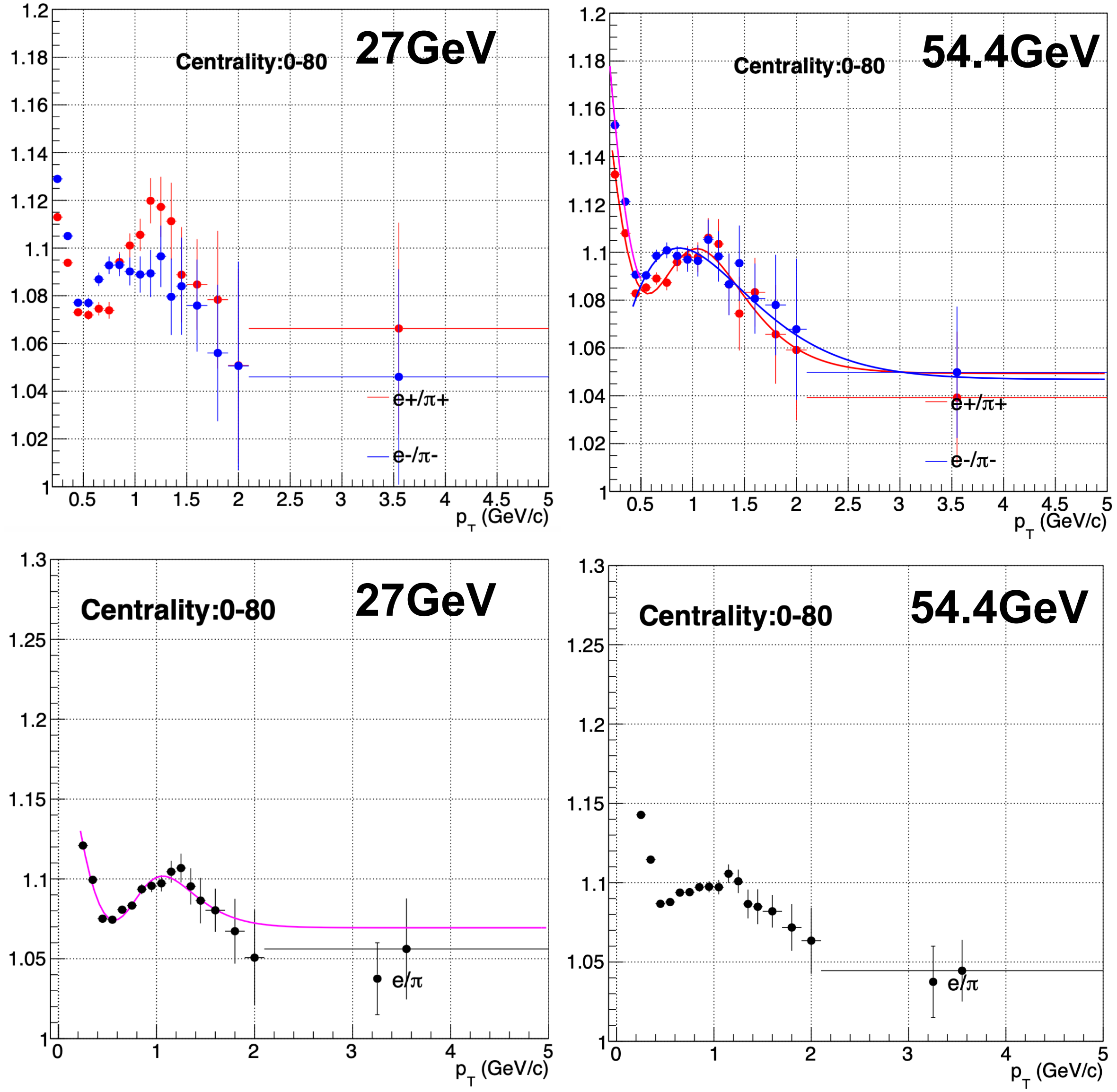
➢ **Pure electron select:**

- p<1.0, 1.6*p-2.6< $n\sigma_e$ <2
- p>1.0, -1.0< $n\sigma_e$ <2
- PairMass<0.015
- $\beta > 0$
- TOFMatchFlag>0
- |TOFLocalY|<1.8

➢ **Pure electron select:**

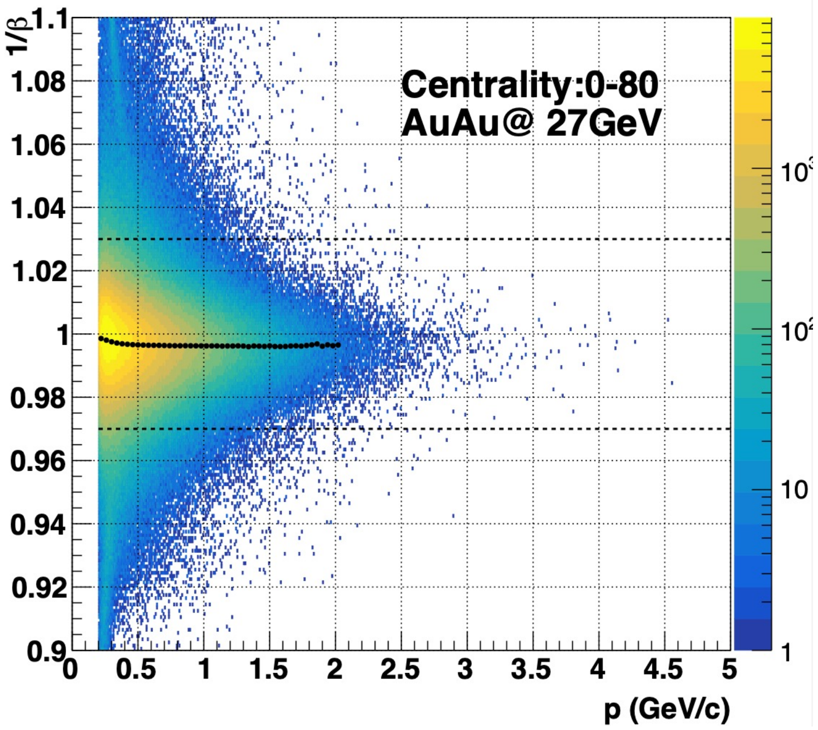
- p<0.8, 3.6*p-3< $n\sigma_e$ <2
- P>0.8, -1.2< $n\sigma_e$ <2
- PairMass<0.015
- $\beta > 0$
- TOFMatchFlag>0
- |TOFLocalY|<1.8

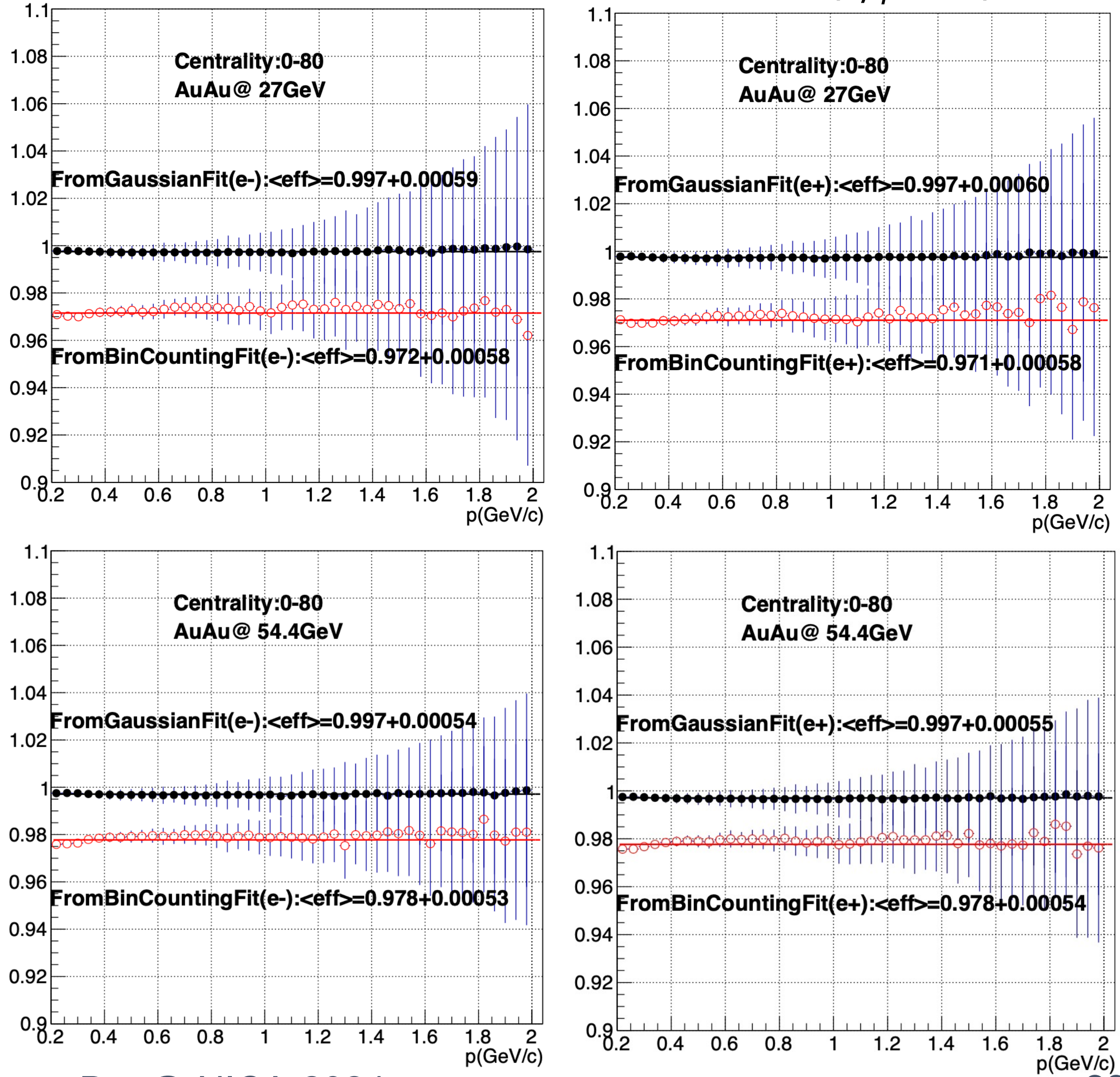
- Use e+/pi+ e-/pi- for efficiency correction at 54.4GeV
- Use e/pi for efficiency correction at 27.7GeV due to limitation of data statistic



# Beta Cut Efficiency

Beta Cut: $\left|{}^{1}/_{\beta} - 1\right| < 0.03$



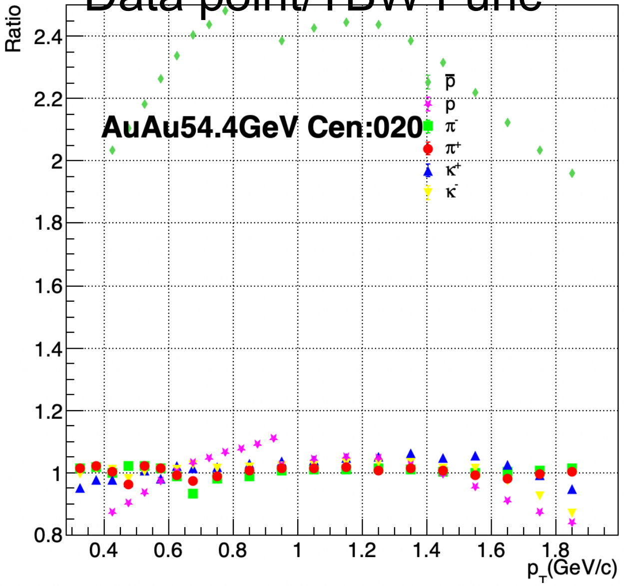

- Two methods: Gaus fit 1/β distribution and counting each momentum bin
- The difference between two method is taken into account for systematic uncertainty

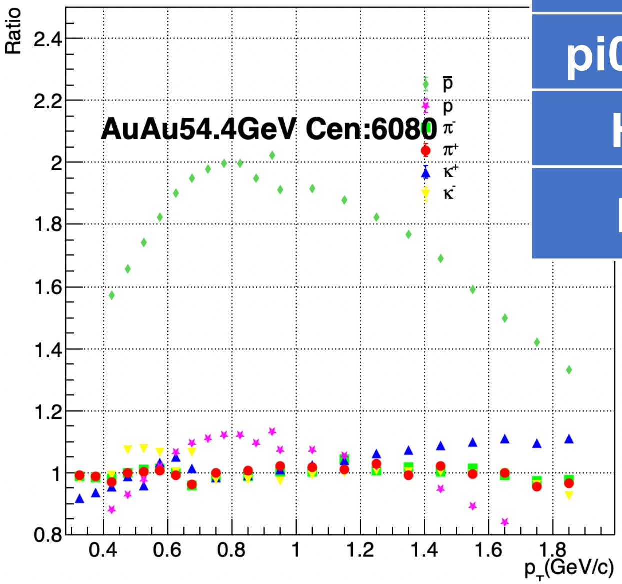
  Default: Bin Counting

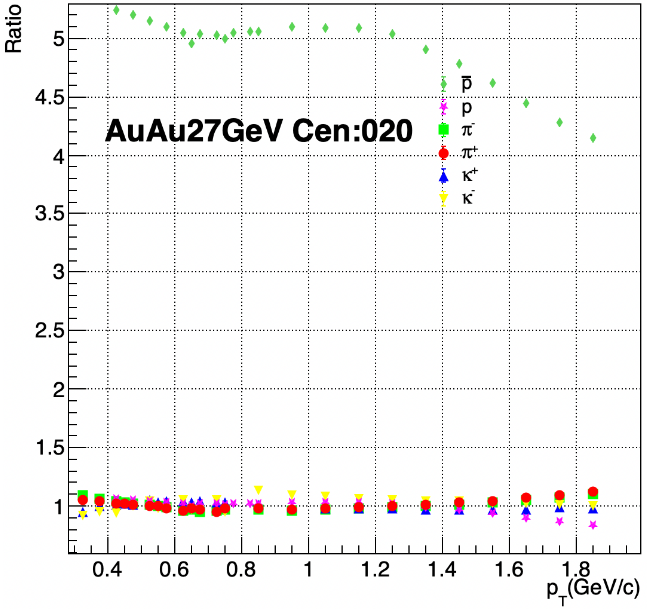
  Systematic Uncertainty: Gaus Fitting

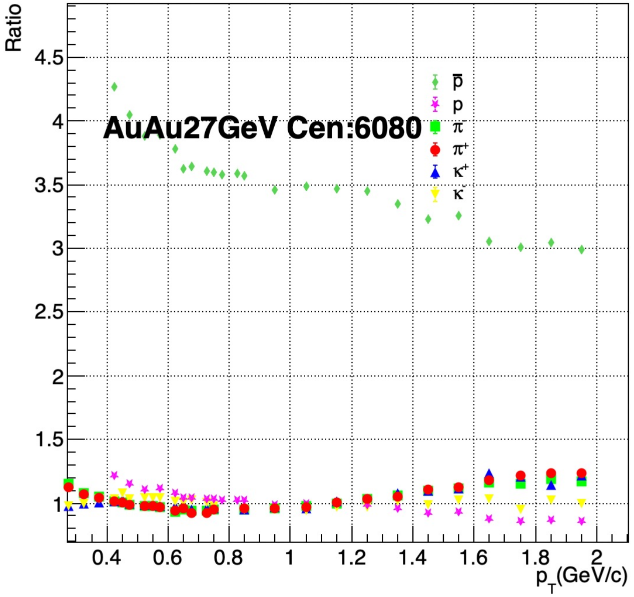
# CKT $p_T$ Spectrum estimation

Data point/TBW Func




54.4GeV dn/dy through extrapolate:

| Centrality | 0-20% | 20-40% | 40-60% | 60-80% |
|---|---|---|---|---|
| pi0 dndy | 170.76 | 78.82 | 32.22 | 10.38 |
| High | +7.73 | +4.43 | +1.79 | +0.38 |
| Low | -9.38 | -5.18 | -2.08 | -0.63 |

27GeV dn/dy from *Phys.Rev.C* 96 (2017) 4, 044904

Dielectron signal not consistent with CKT at Centrality 60-80% may caused by pi0 dn/dy. Maybe we should pi0 dn/dy at rapidity -1 – 1 instead of rapidity -0.1– 0.1