QM QUARK MATTER
KRAKÓW
2022

29TH INTERNATIONAL
CONFERENCE ON ULTRARELATIVISTIC
NUCLEUS - NUCLEUS COLLISIONS
APRIL 4-10, 2022
KRAKÓW, POLAND

Experimental overview of electromagnetic probes

Klaus Reygers, Heidelberg University

Why electromagnetic probes?

Direct information about the medium, not affected by hadronization

figure credit: MADAI collaboration, Hannah Petersen and Jonah Bernhard

γ, γ*, W, Z: different information about the medium than from light-quark and heavy-quark observables

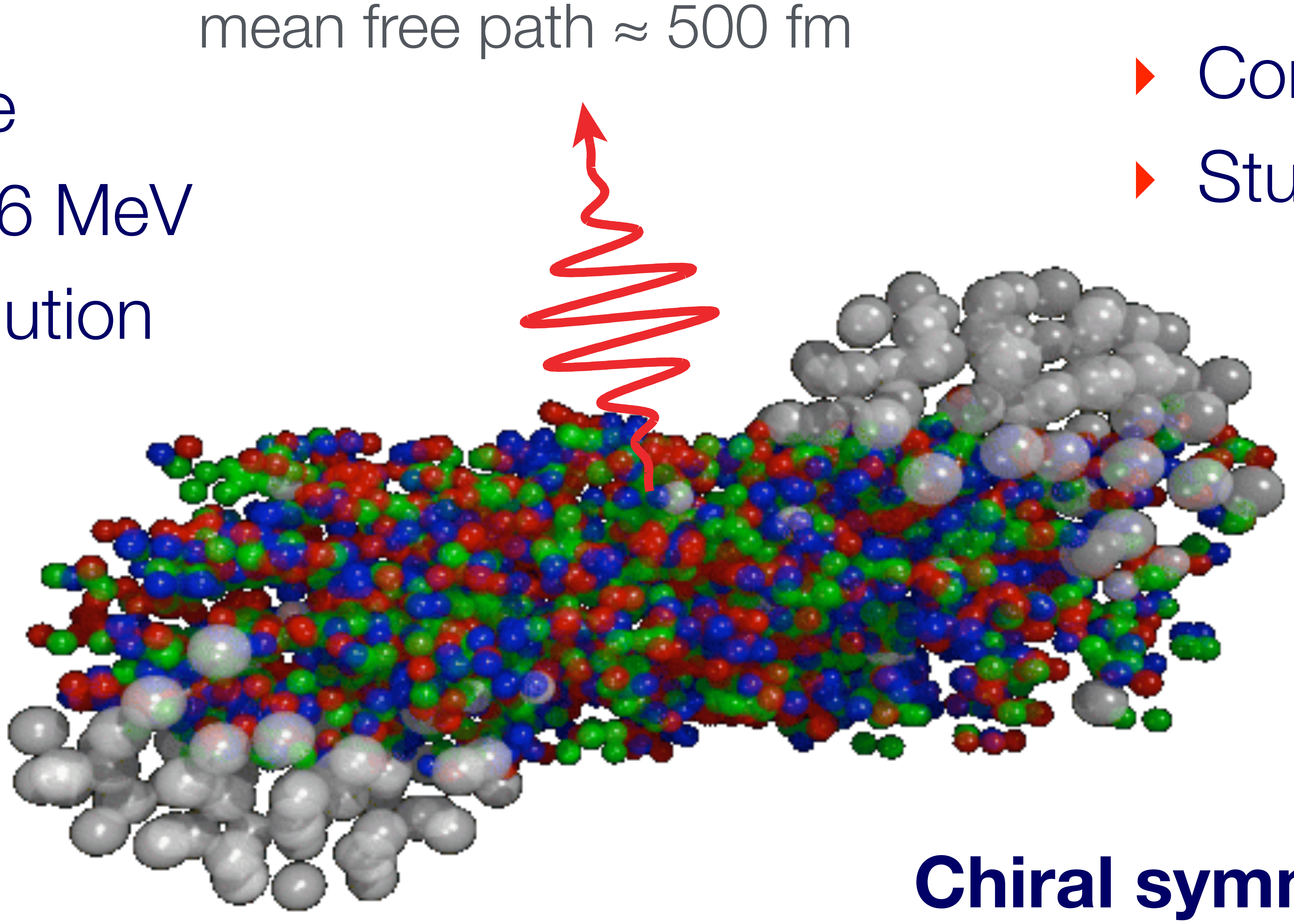
Different aspects of electromagnetic probes

Initial hard scattering

- Test N_{coll} scaling
- Constrain nuclear PDFs
- Study energy loss: γ/Z-tagged jets

Thermal radiation

- effective QGP temperature
- Demonstrate $T > T_{\mathrm{pc}} = 156$ MeV
- Constrain space-time evolution



Preequilibrium phase

- mechanism of equilibration
- transition to hydro phase

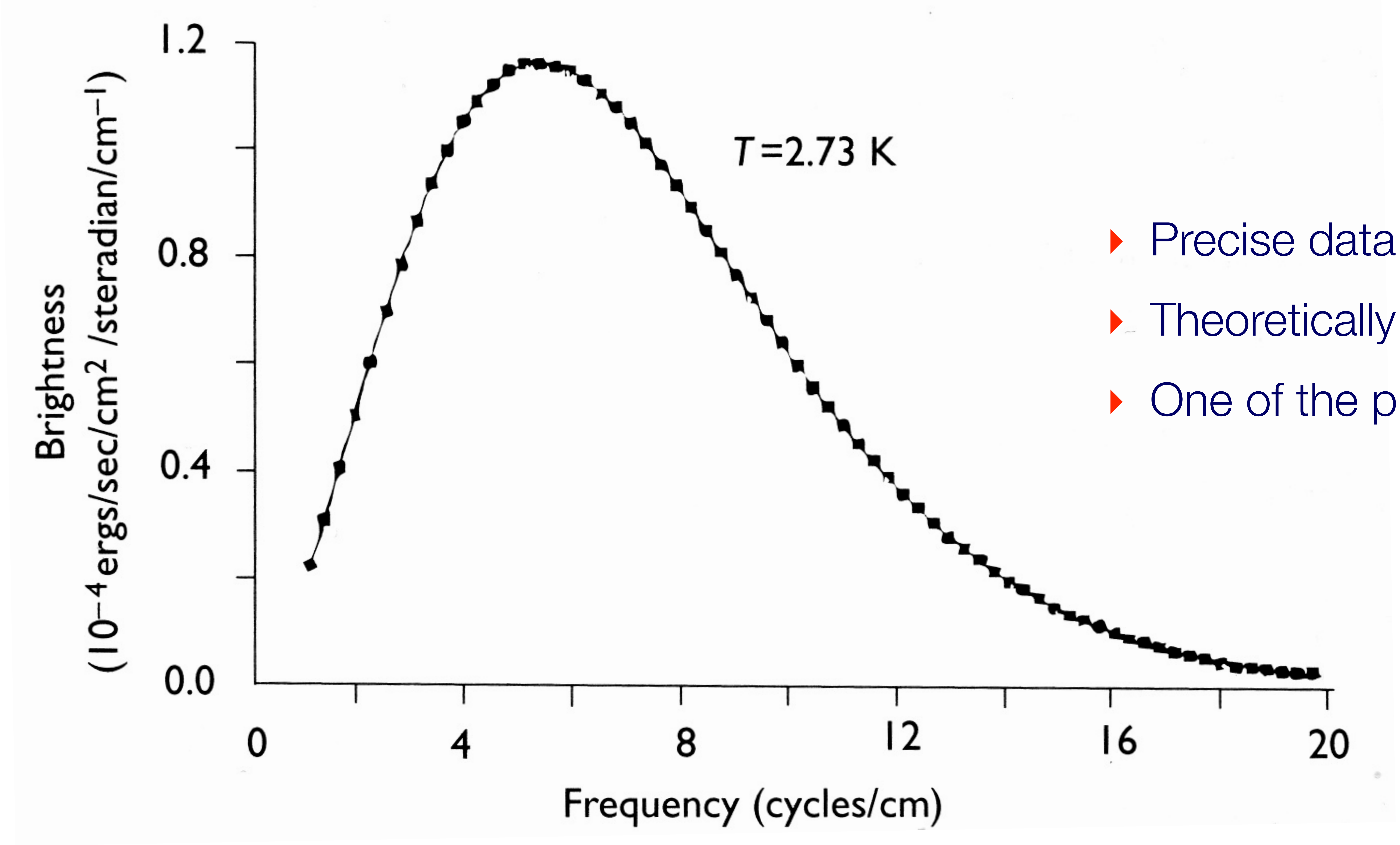
Chiral symmetry restoration (dileptons)

- ρ broadening
- constrain mechanism

A central goal …

Temperature through the measurement of thermal radiation

CMB black-body spectrum (COBE)



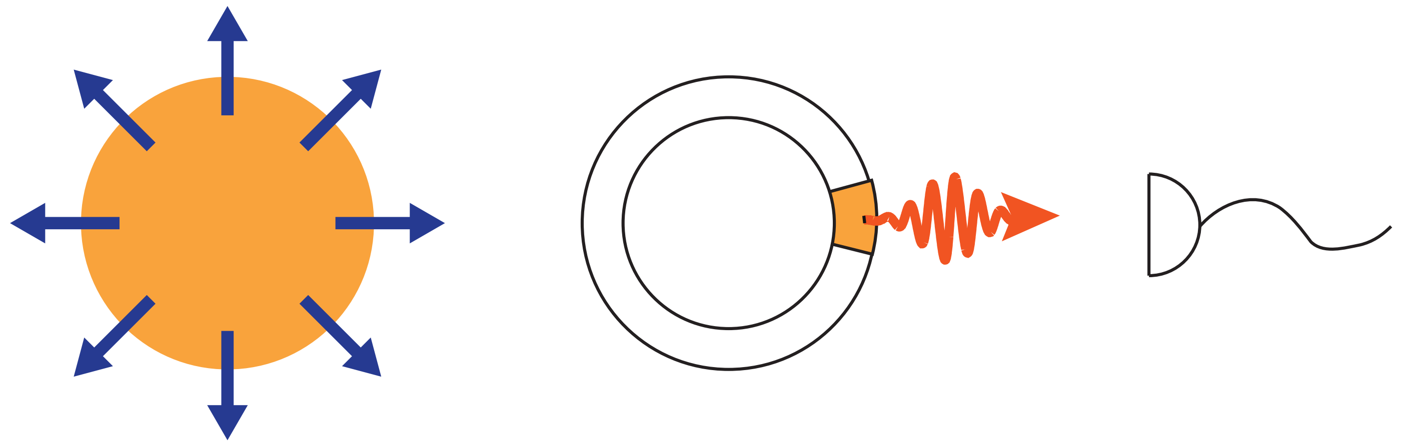
- Precise data
- Theoretically understood
- One of the pillars of cosmology

Thermal radiation

Basic expectations: direct photons

Thermal radiation expected to dominate for p_T < 2–3 GeV/c

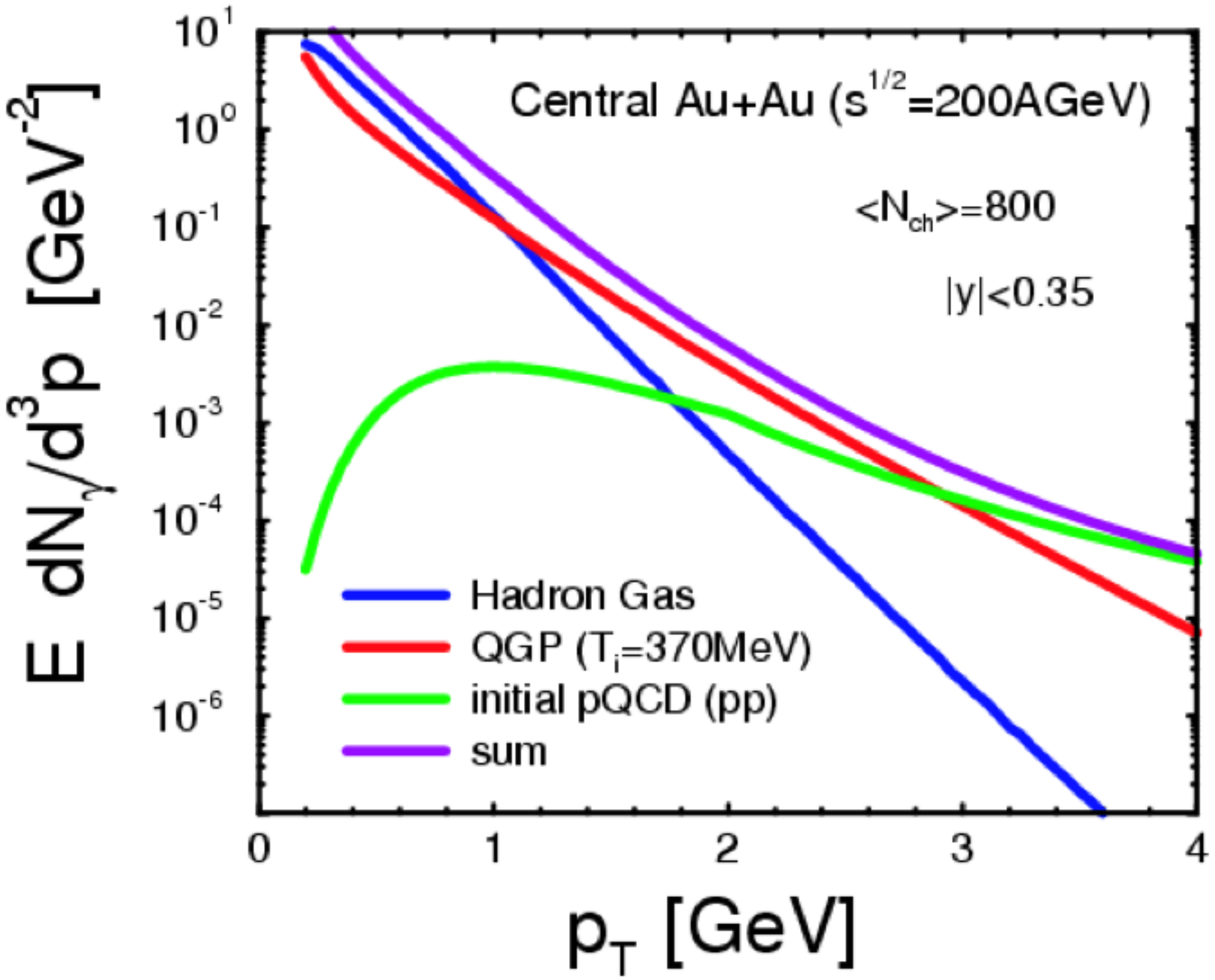
Inverse slope parameter T_eff affected by blueshift: $T_\mathrm{eff} > T_{pc}$ does not necessarily indicate QGP formation



$$E_\gamma \frac{d^3 N_\gamma}{d^3 p_\gamma} \propto e^{-E_\gamma / T_\mathrm{eff}} \qquad T_\mathrm{eff} = \underbrace{\sqrt{\frac{1+\beta_\mathrm{flow}}{1-\beta_\mathrm{flow}}}}_{2 \text{ for } \beta_\mathrm{flow}=0.6} \times T$$

Possibly significant contribution of preequilibrium photons for $p_T \gtrsim$ 3 GeV/c

Turbide, Rapp, Gale,
Phys. Rev. C 69 (014902), 2004



late → early

probed time scale

G. David, Rept.Prog.Phys. 83 (2020) 4, 046301
A. Monnai, 2203.13208

Basic expectations: dileptons

ρ meson sensitive to surrounding medium (τ_ρ = 1.3 fm/c < τ_fireball)

ρ broader in hot baryon-rich medium

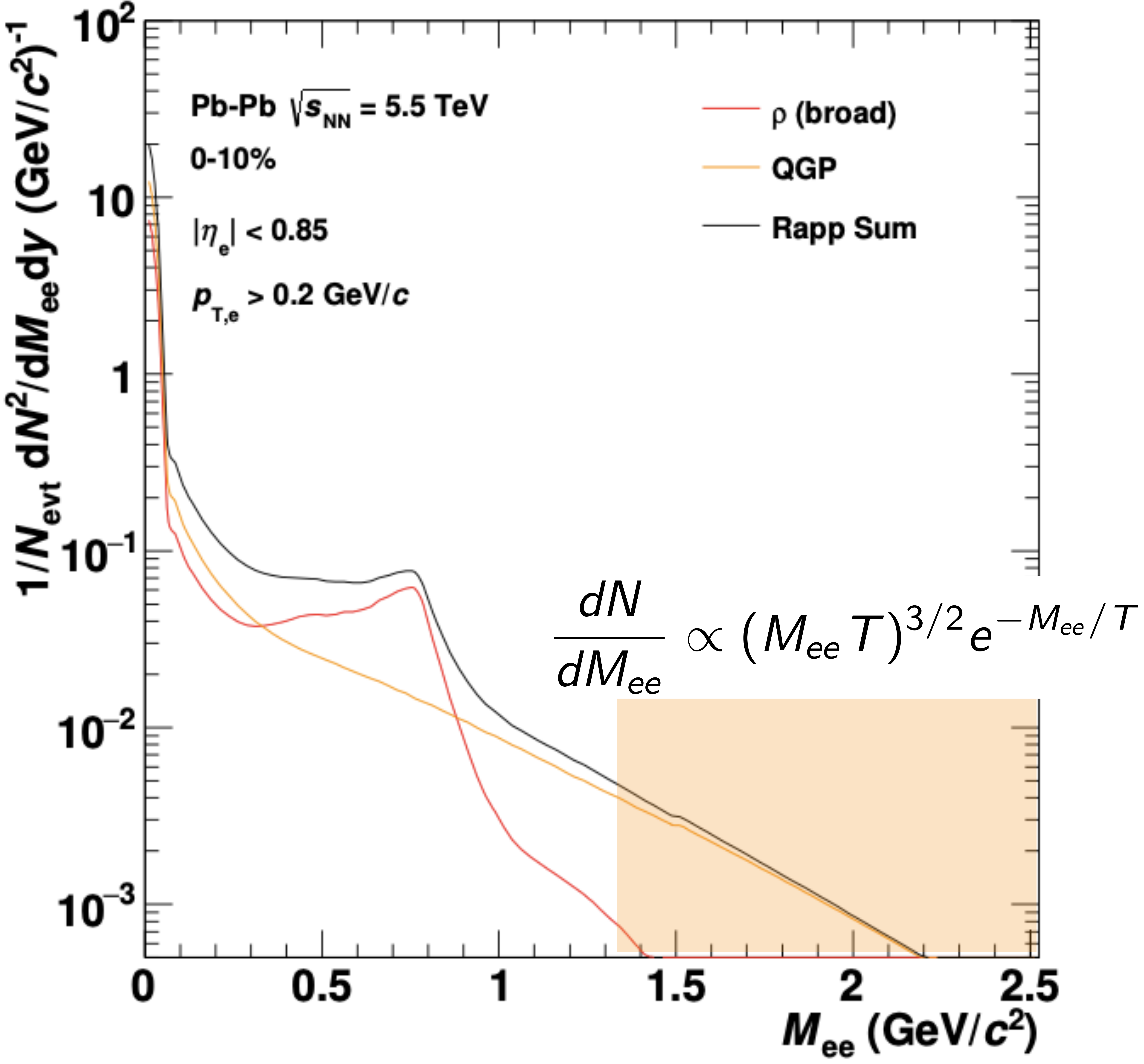
Connection between chiral symmetry restoration and ρ melting

Mass region 1.5 < M_ee < 2.5 GeV sensitive to effective QGP temperature T (not affected by blueshift)

NA60: T = 205 ± 12 MeV
In-In, fit range 1.2–2.0 GeV, AIP Conf.Proc. 1322 (2010)

Preequilibrium contribution could affect temperature extraction in 1.5 ≲ M_ee ≲ 2.5 GeV

CERN Yellow Rep.Monogr. 7 (2019) 1159

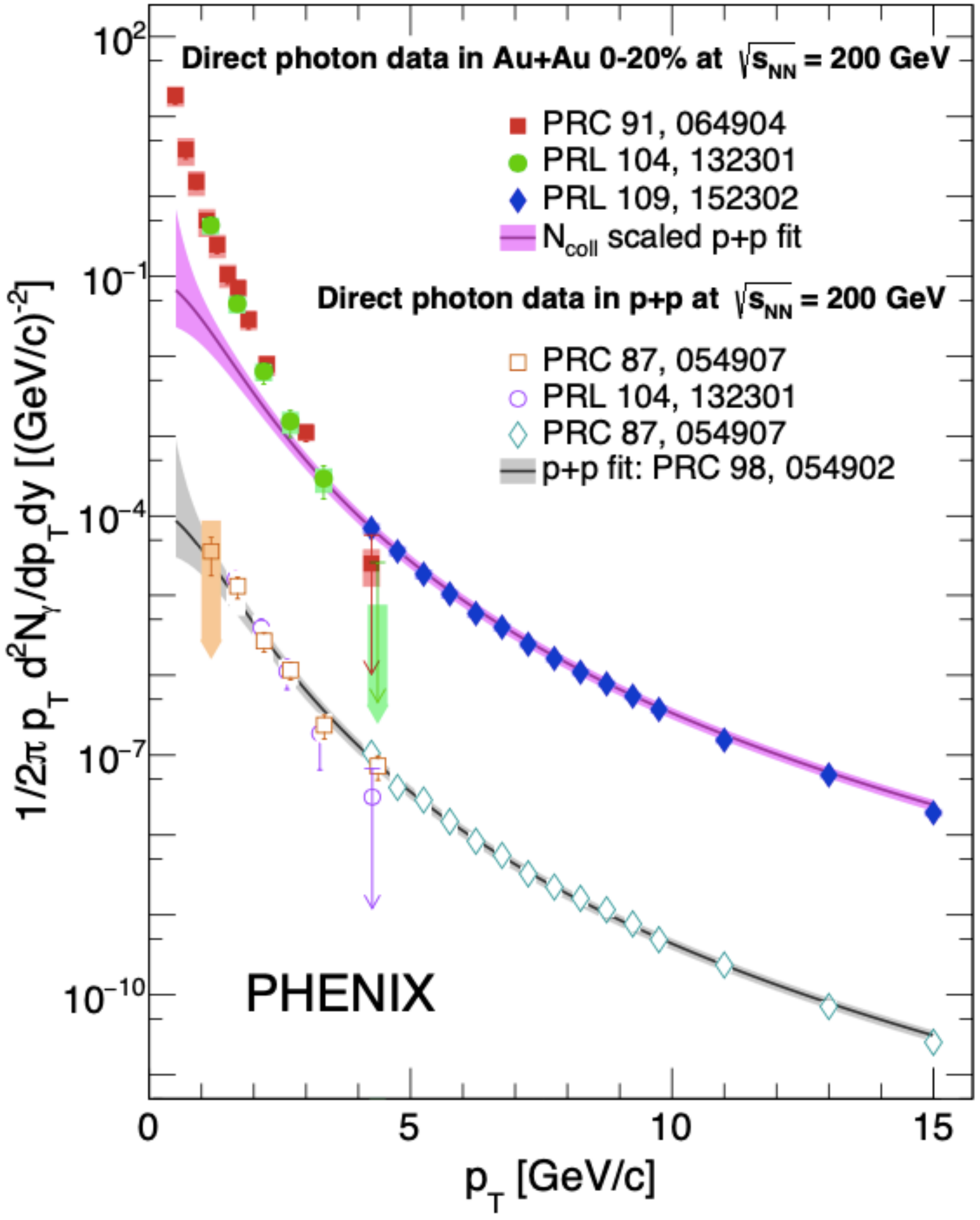


$$\frac{dN}{dM_{ee}} \propto (M_{ee}T)^{3/2} e^{-M_{ee}/T}$$

Low-p_T direct photons

Low-p_T direct photon spectra: status at RHIC (pre-QM 2022)

Photon excess above pp/pQCD at low p_T



Various direct photon measurements in different systems from PHENIX

Excess above pQCD / scaled pp reference for $p_T < 4$ GeV/c

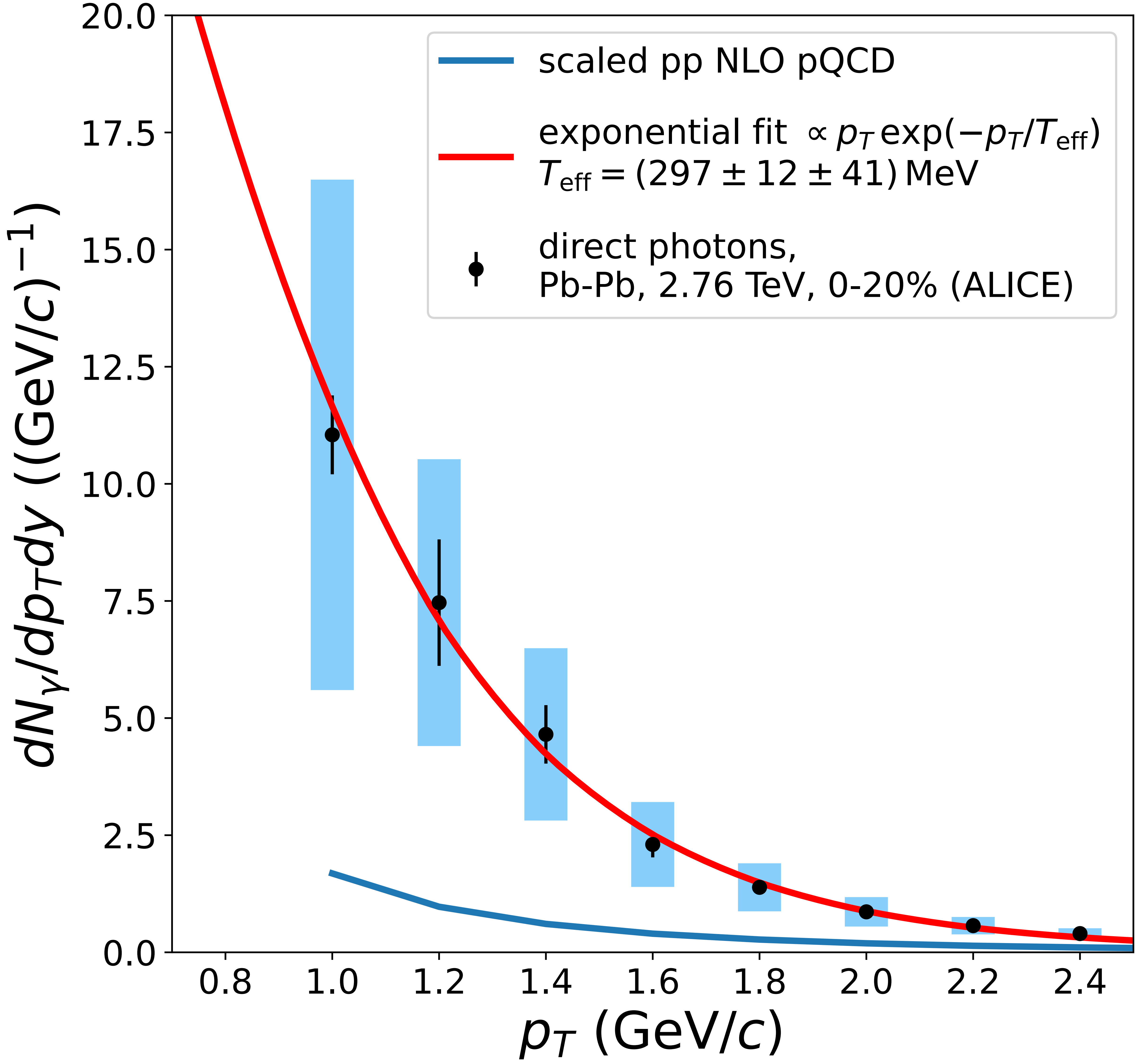
Excess above pQCD has exponential shape

T_{eff} ~ (240 ± 25) MeV in central Au-Au at 200 GeV
($0.6 < p_T < 2$ GeV/c)

PHENIX: PRC 91, 064904 (2015), 2203.12354

Low-p_T direct photon spectra: status at the LHC (pre-QM 2022)

Same trend as at RHIC, relatively large uncertainties



$T_{\mathrm{eff}} \sim (297 \pm 12^{\mathrm{stat}} \pm 41^{\mathrm{syst}})$ MeV
($0.9 < p_T < 2.1$ GeV/c, pQCD subtracted)

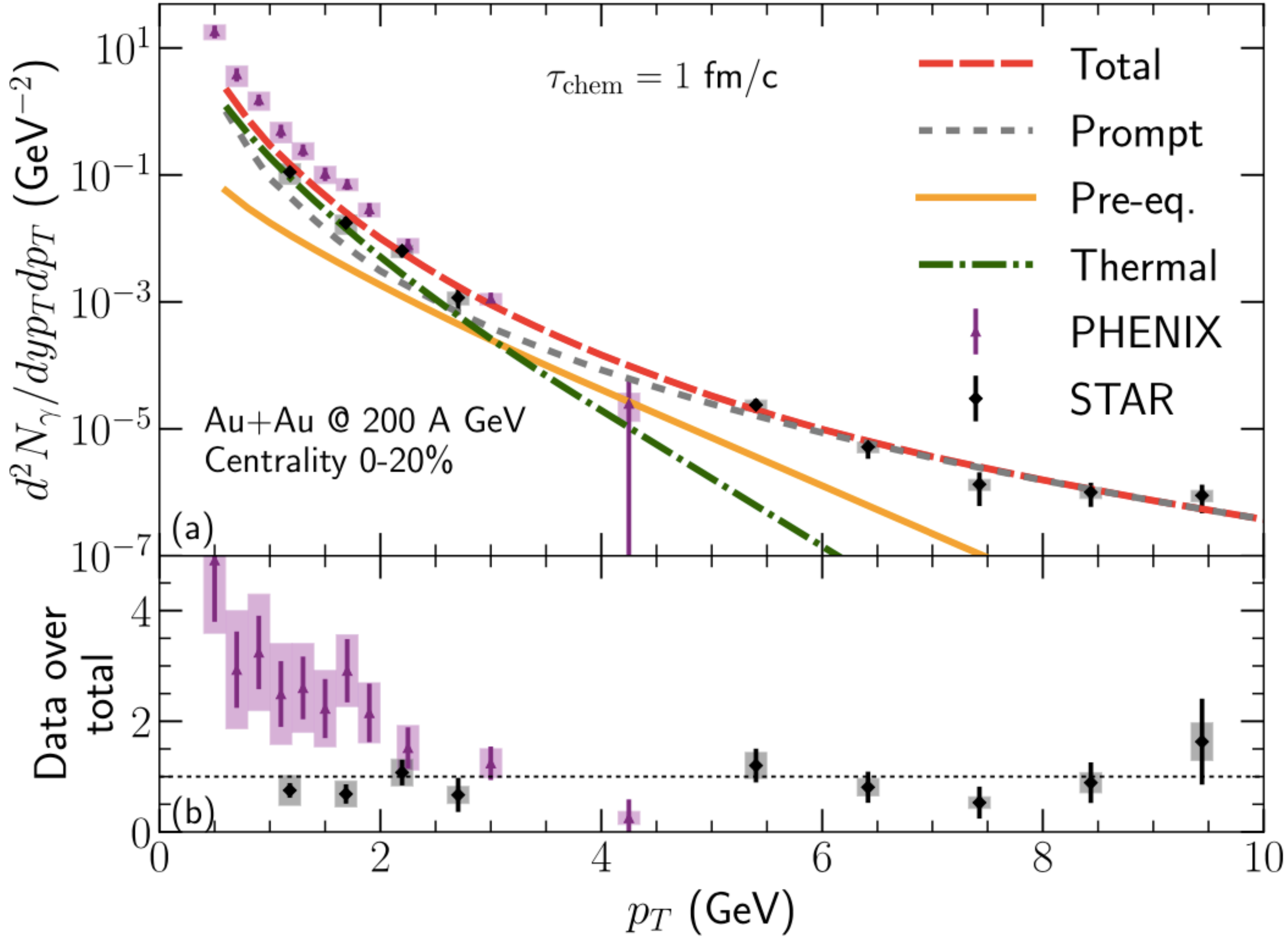
γ_{dir} significance < 3σ (a start …)

Smaller uncertainties highly desirable

ALICE, Phys. Lett. B 754 (2016) 235

Direct photon puzzle

Part I: Low-p_T yields not described by state-of-the-art models



Yield for $p_T < 2$ GeV/c factor 2–3 above model predictions

Discrepancy between PHENIX and STAR data

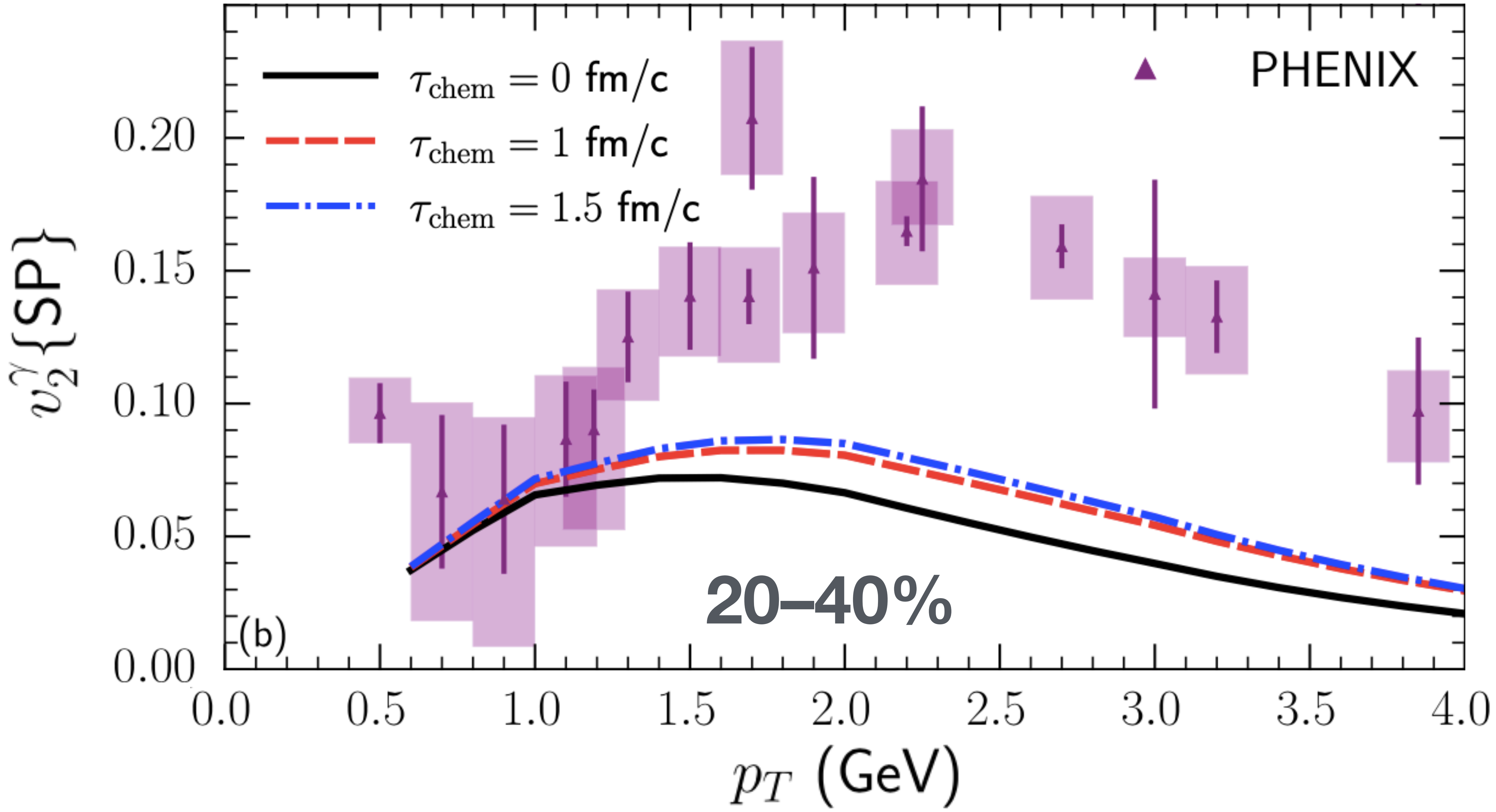
Yield at the LHC (ALICE, 2.76 TeV):

- similar trend as PHENIX
- but no puzzle within (large) exp. uncertainties

C. Gale, J-F. Paquet, B. Schenke, C. Shen
Phys.Rev.C 105 (2022) 1, 014909

Part II: Direct photon $v_2 \approx$ pion v_2, not described by models

C. Gale, J-F. Paquet, B. Schenke, C. Shen
Phys.Rev.C 105 (2022) 1, 014909



RHIC (PHENIX):
Large $v_{2,\mathrm{dir}}$ ($\approx v_{2,\pi}$) not reproduced by state-of-the-art hydro models

LHC (ALICE):
$v_{2,\mathrm{dir}} \approx v_{2,\pi}$, but no puzzle within (large) exp. uncertainties

Direct photon production dominated by late stage (cross over, hadron gas)?

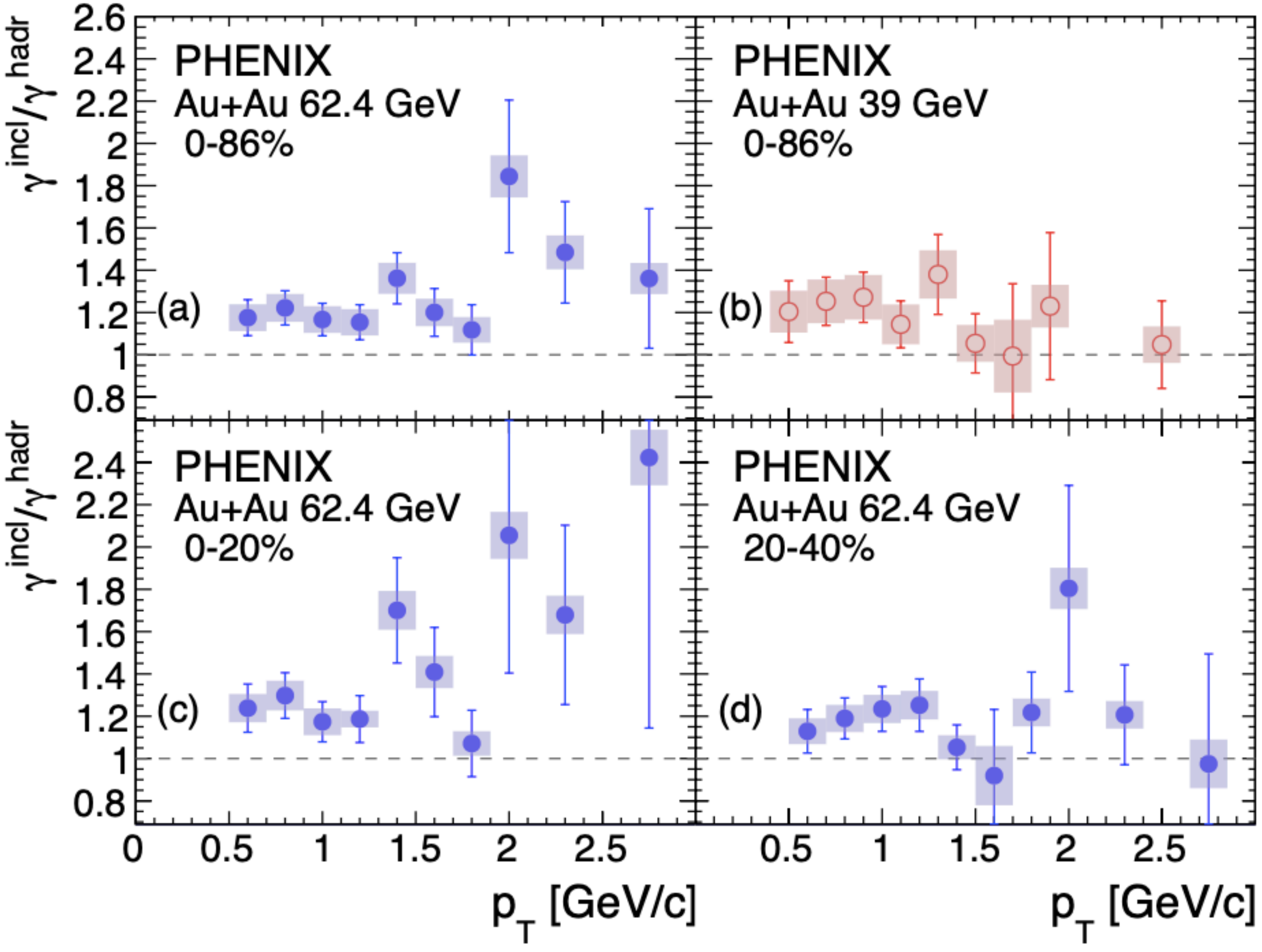
Particularly challenging:
Simultaneously description of yield and v_2

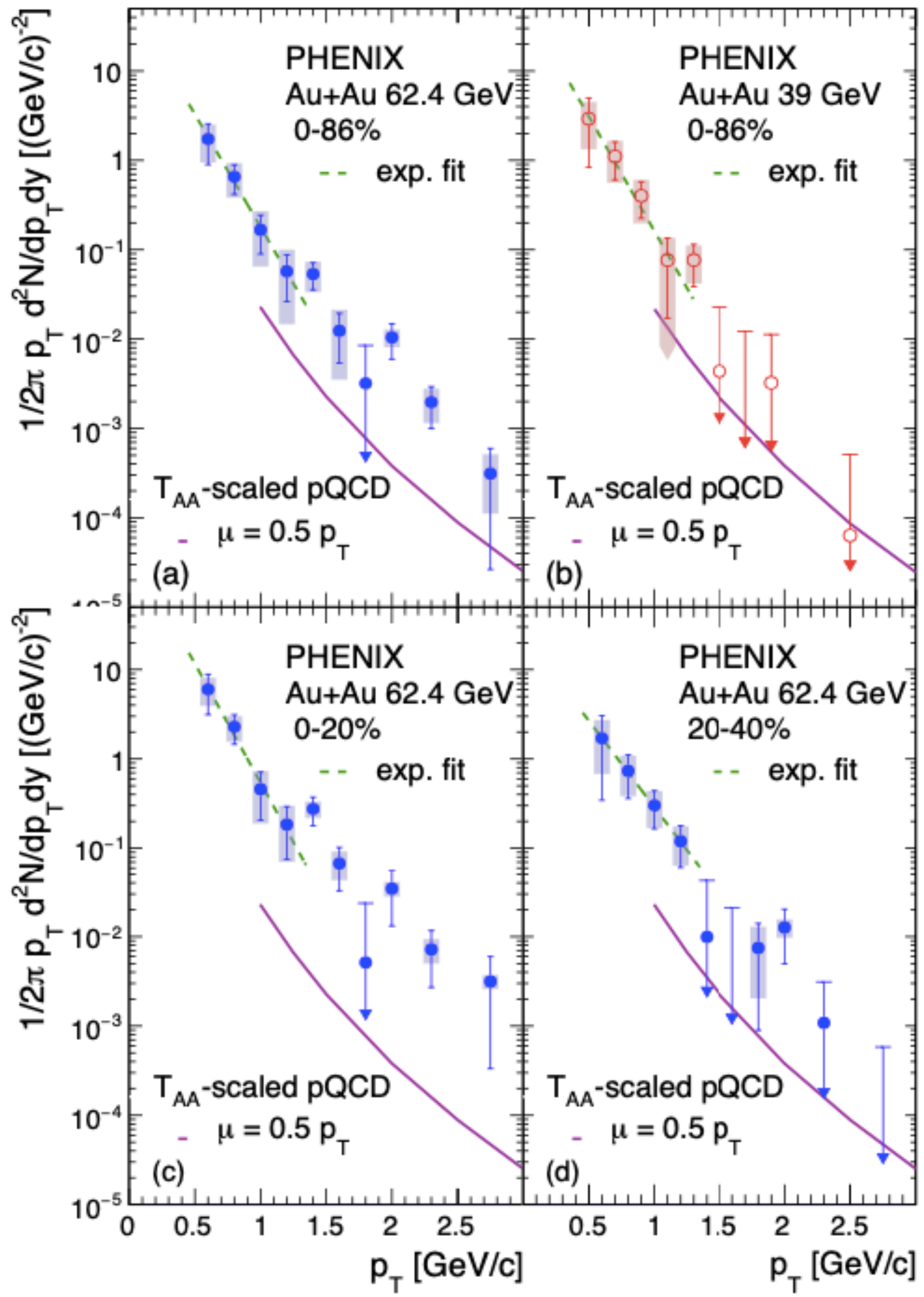
EMMI

"Direct photon puzzle" (2020, postponed)
EMMI Rapid Reaction Task Force (RRTF)
A. Marin, J.Stachel, K.R.

New PHENIX direct-photon data (1): Au-Au at 39 and 62.4 GeV

~20% direct photon excess above decay photon background





photon conversion method

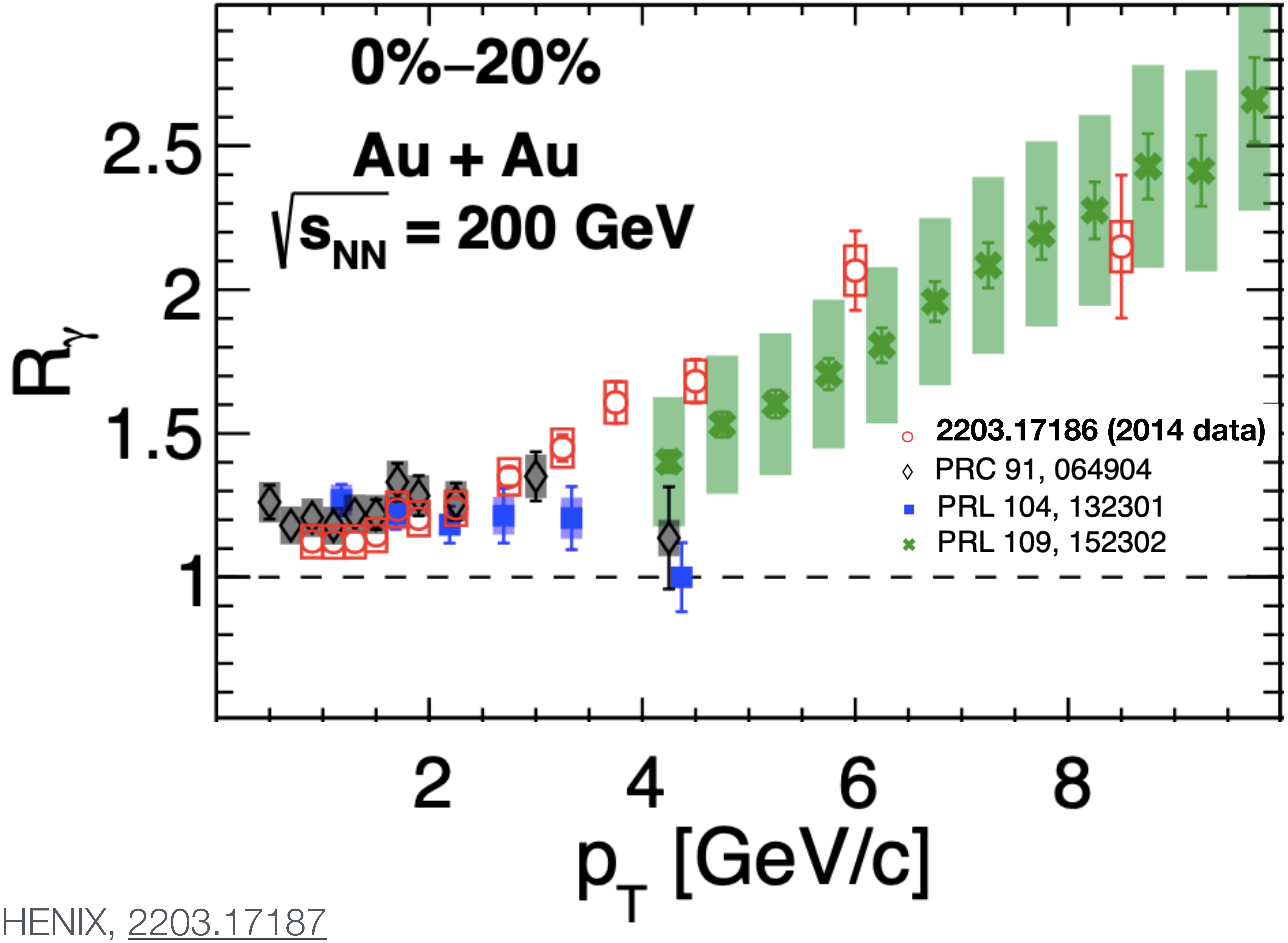
talk Roli Esha

PHENIX, 2203.12354

New PHENIX direct-photon data (2): Au-Au at 200 GeV (2014 data)

Different methods and results for different datasets agree

$$R_\gamma = \gamma_{\text{incl}}/\gamma_{\text{decay}} = 1 + \gamma_{\text{direct}}/\gamma_{\text{decay}}$$



PHENIX, 2203.17187

Methods

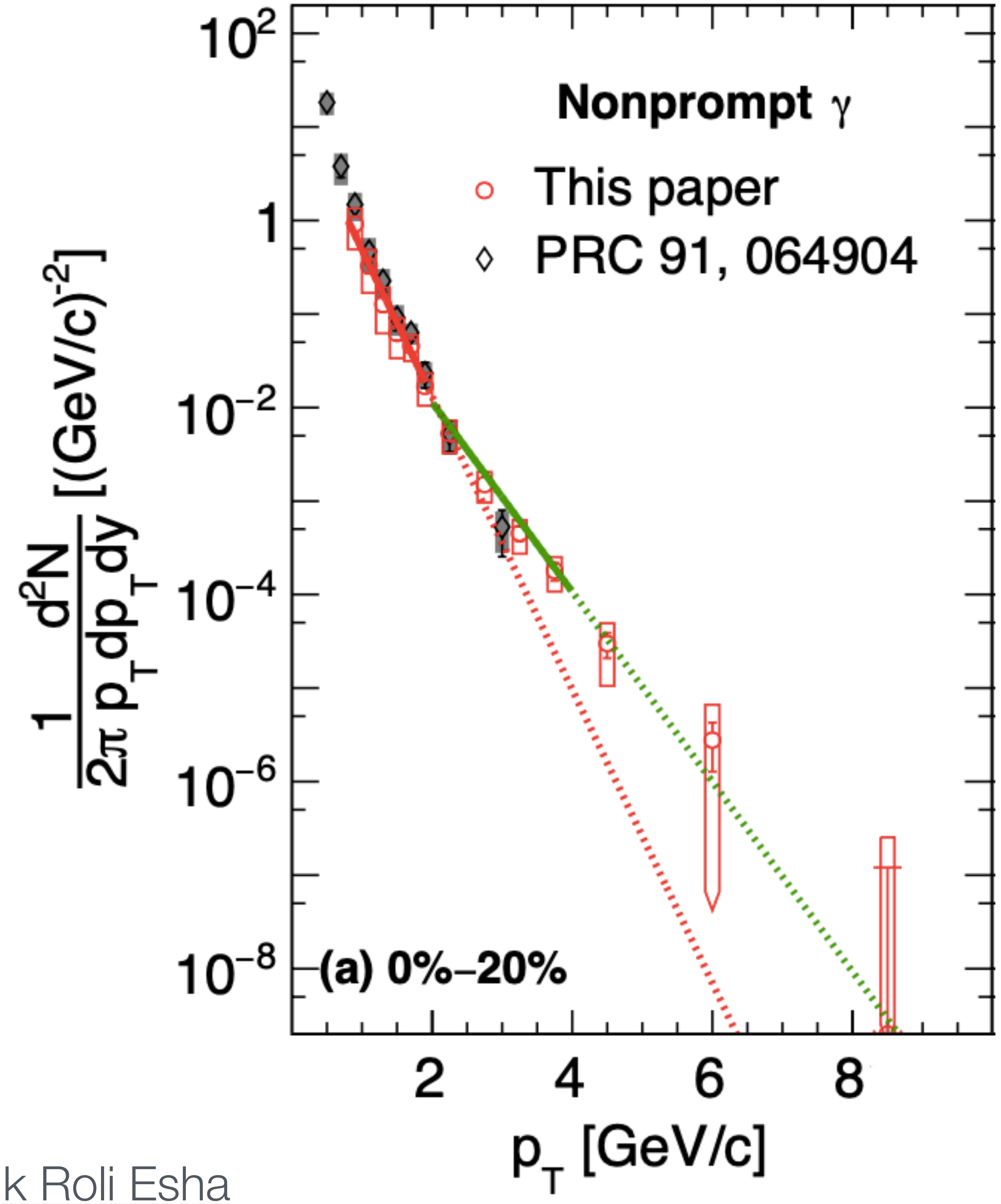
- calorimeter´
- virtual photon method
- conversions

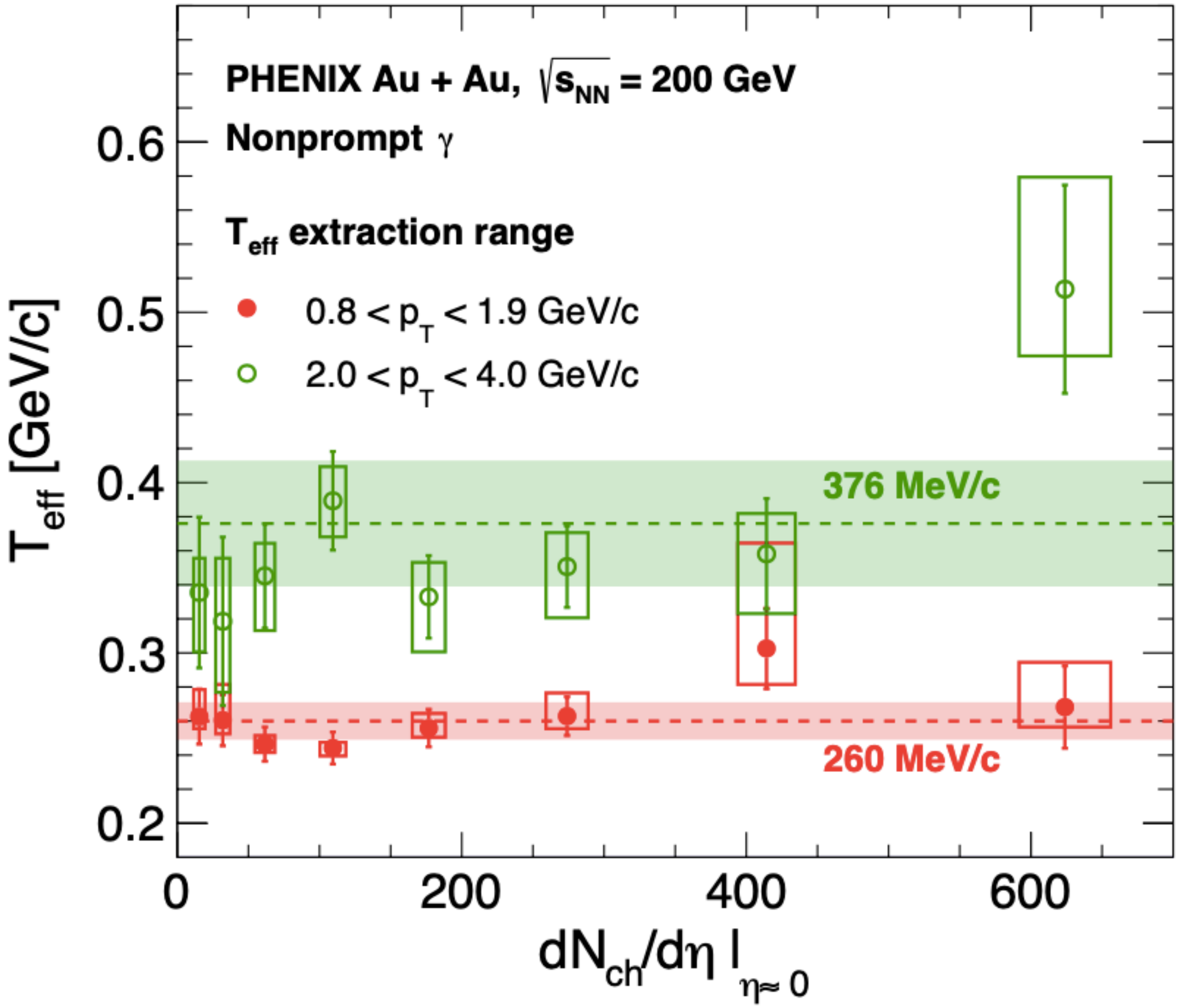
2014 data

- conversion method
- ×10 more statistics

T_{eff} from fit with exponential

T_{eff} increases with p_T: in line with a larger early-time contribution at higher p_T





“nonprompt" = direct – N_{coll} × pp

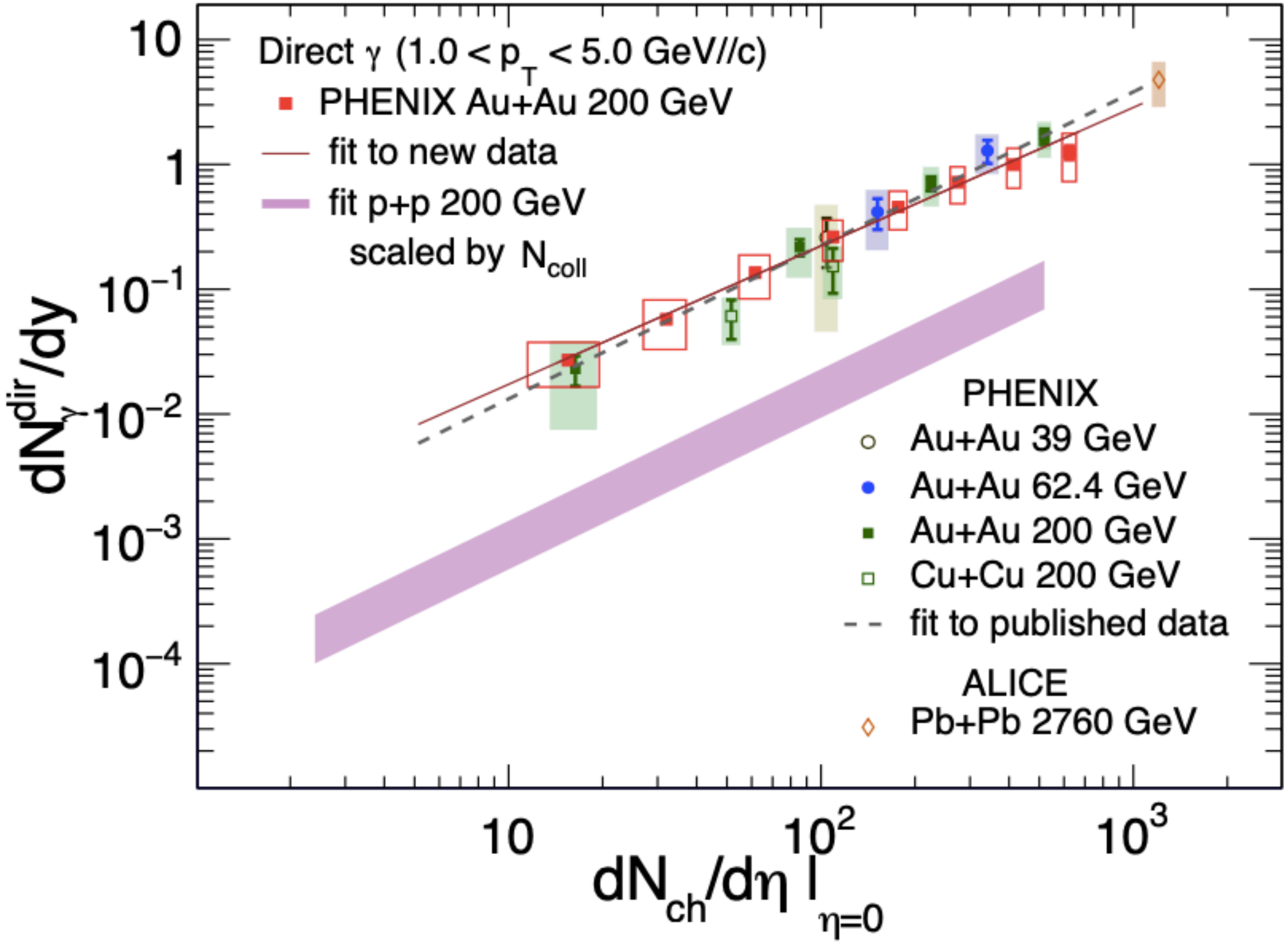
talk Roli Esha

PHENIX, 2203.17187

Constraining production mechanisms by studying scaling patterns (1)

Universal scaling of d$N_{\gamma,\mathrm{dir}}$/dy with dN_{ch}/dη

talk Roli Esha
PHENIX, 2203.17187
PHENIX, 2203.12354



$$\frac{dN_\gamma}{dy} = A \left(\frac{dN_{\mathrm{ch}}}{d\eta} \right)^{\alpha}$$

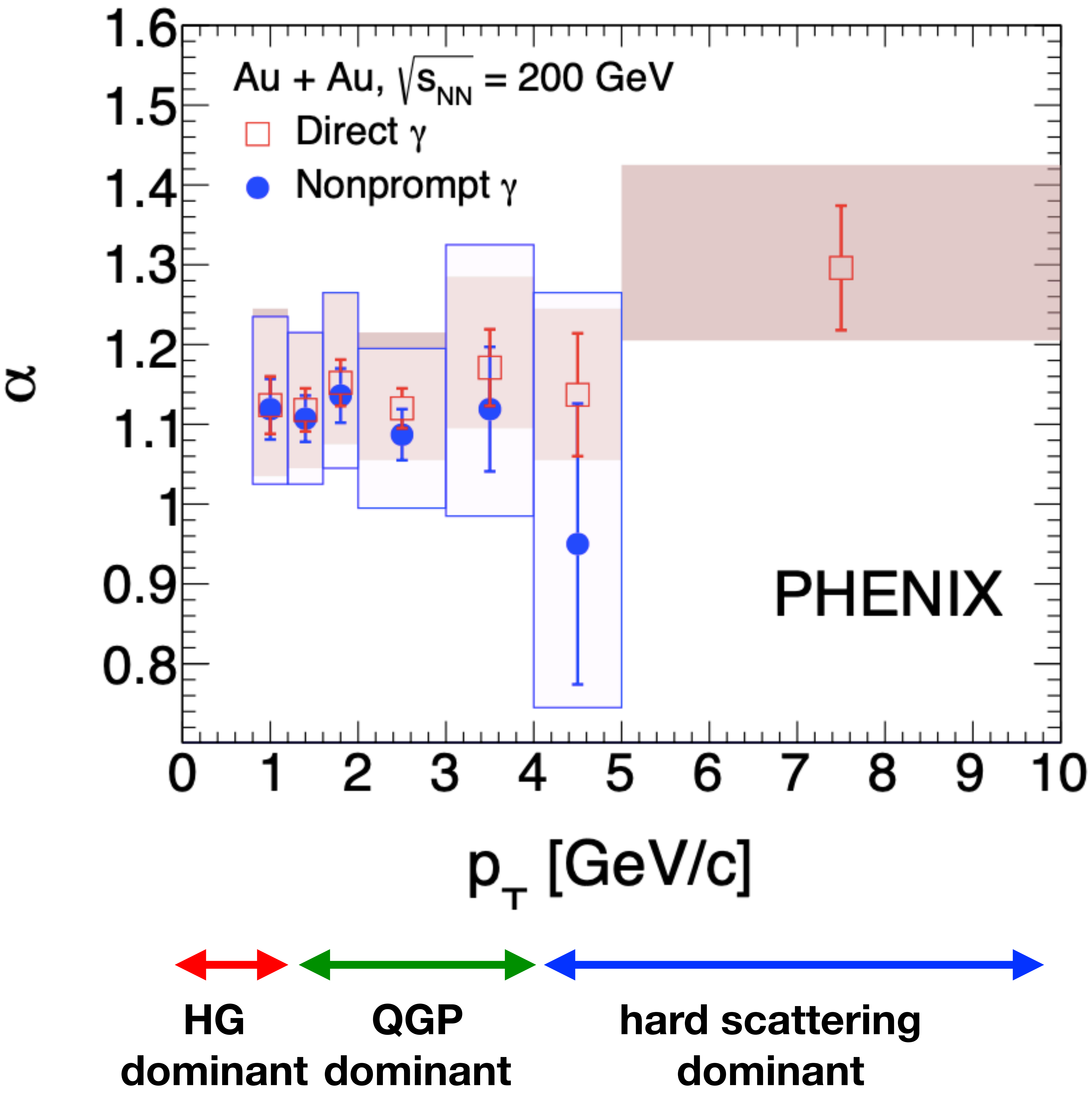
$$\alpha = 1.11 \pm 0.02\,(\mathrm{stat})^{+0.09}_{-0.08}\,(\mathrm{syst})$$

Hydro prediction for thermal photons:
$\alpha \approx 1.6$

Shen, Heinz, Paquet, Gale,
PRC 89, 044910 (2014)

Constraining production mechanisms by studying scaling patterns (2)

$\alpha(p_T) \approx$ constant: Expected p_T dependence of α not observed



$$\frac{dN_\gamma}{dy} = A(p_T)\left(\frac{dN_{ch}}{d\eta}\right)^{\alpha(p_T)}$$

photon sources:

Shen, Heinz, Paquet, Gale,
PRC 89, 044910 (2014)

HG	**QGP**	**pQCD**
$\alpha_{HG} \approx 1.23$	**$\alpha_{QGP} \approx 1.83$**	**$\alpha_{pQCD} \approx 1.25$**

relative contribution varies with p_T

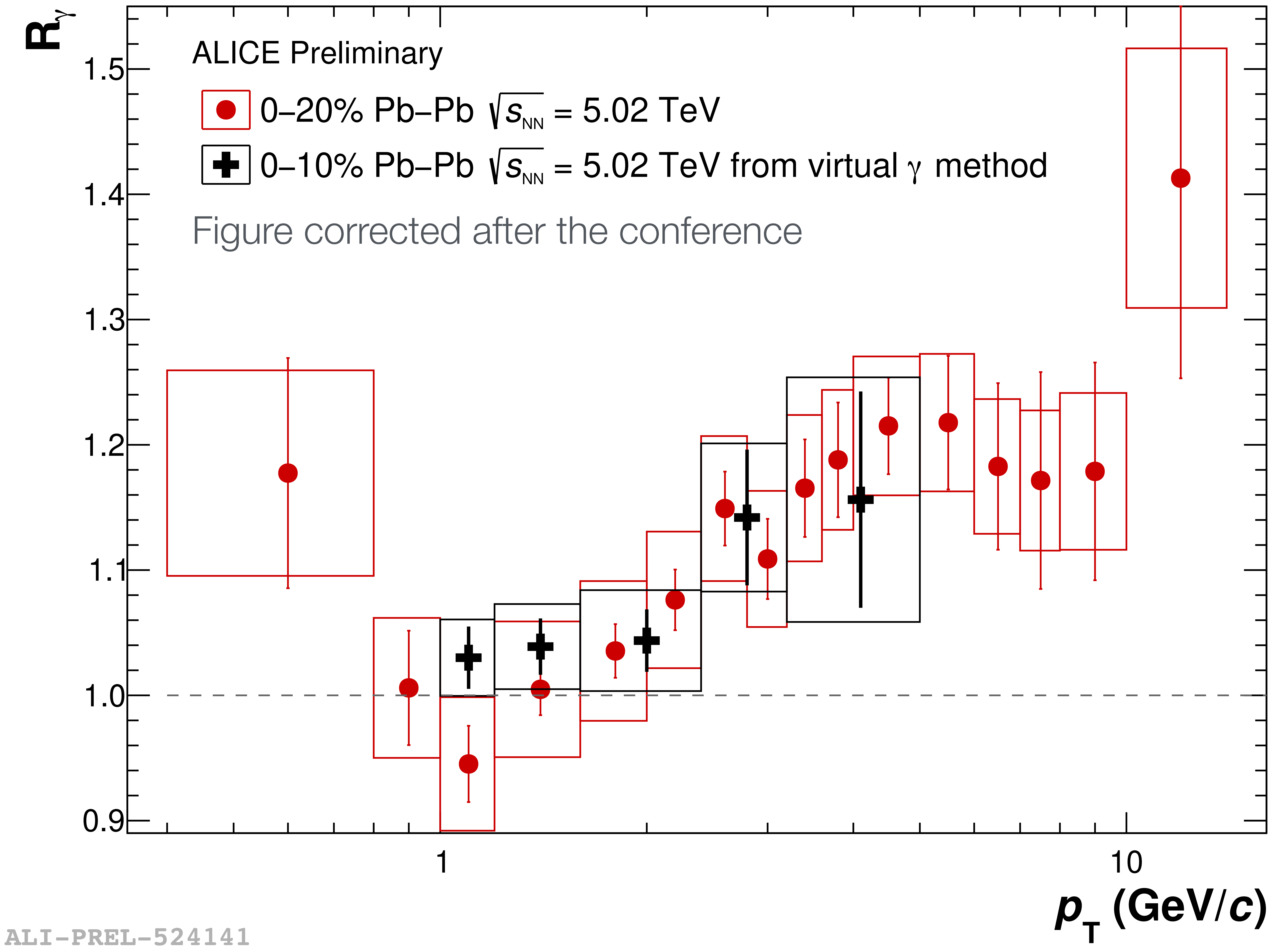
poster Wenqing Fan
PHENIX, 2203.17187

Pb-Pb at 5.02 TeV: New direct photon spectra from ALICE

talk Meike Danisch
talk Jerome Jung

Conversion method and virtual photon method agree

$$R_\gamma = \gamma_{\mathrm{incl}}/\gamma_{\mathrm{decay}} = 1 + \gamma_{\mathrm{direct}}/\gamma_{\mathrm{decay}}$$



Photon conversion method

- New data-driven approach to "measure" the material budget
- Material budget uncertainty reduced from **4.5% to 2.5%**

Virtual photon method

- Dielectron excess measured above pion mass
- Extrapolated to $m = 0$ with Kroll-Wada formula

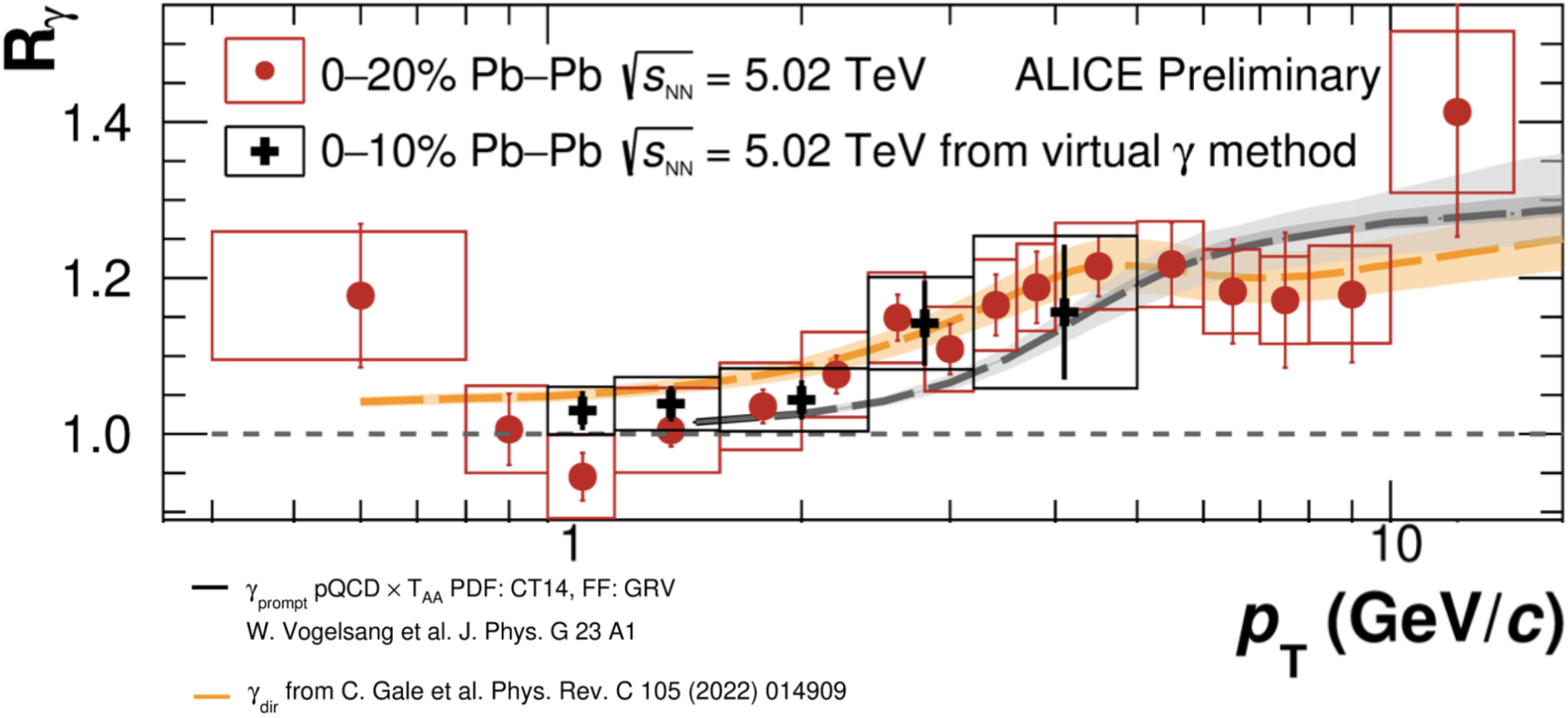
Comparison: pQCD and pQCD + preequilibrium (PE) + thermal

talk Meike Danisch

Both pQCD and pQCD+PE+thermal consistent with the data

$R_\gamma^{\text{theory}} = (\gamma_{\text{dir}}^{\text{theory}} + \gamma_{\text{decay}}^{\text{ALICE}})/\gamma_{\text{decay}}^{\text{ALICE}}$

Figure corrected after the conference



γ_{prompt} pQCD × T_{AA} PDF: CT14, FF: GRV
W. Vogelsang et al. J. Phys. G 23 A1

γ_{dir} from C. Gale et al. Phys. Rev. C 105 (2022) 014909

Pb-Pb at 5.02 TeV: Resulting direct-photon spectra

talk Meike Danisch
talk Jerome Jung

All considered models in fair agreement with the data

virtual photon method

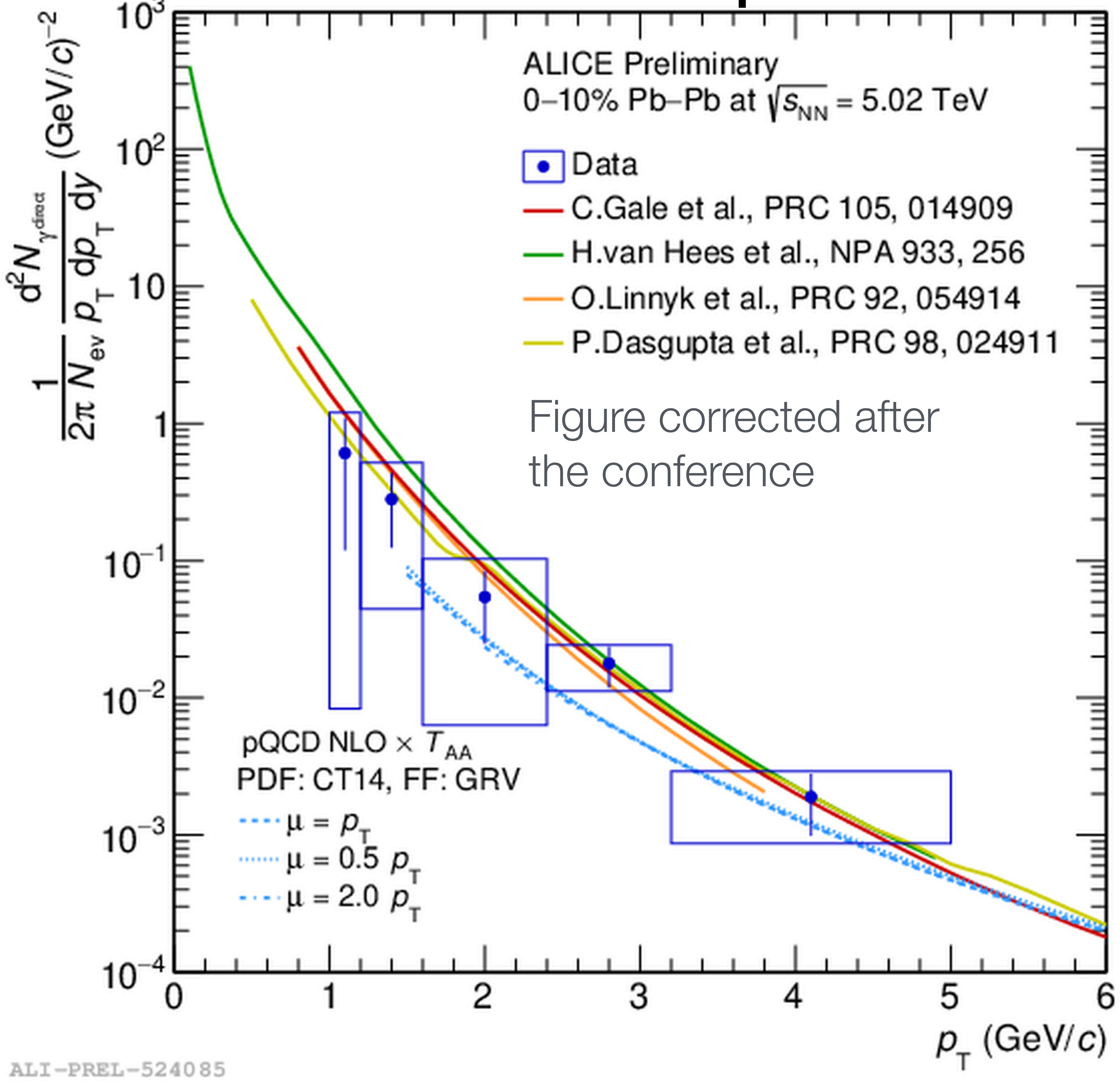
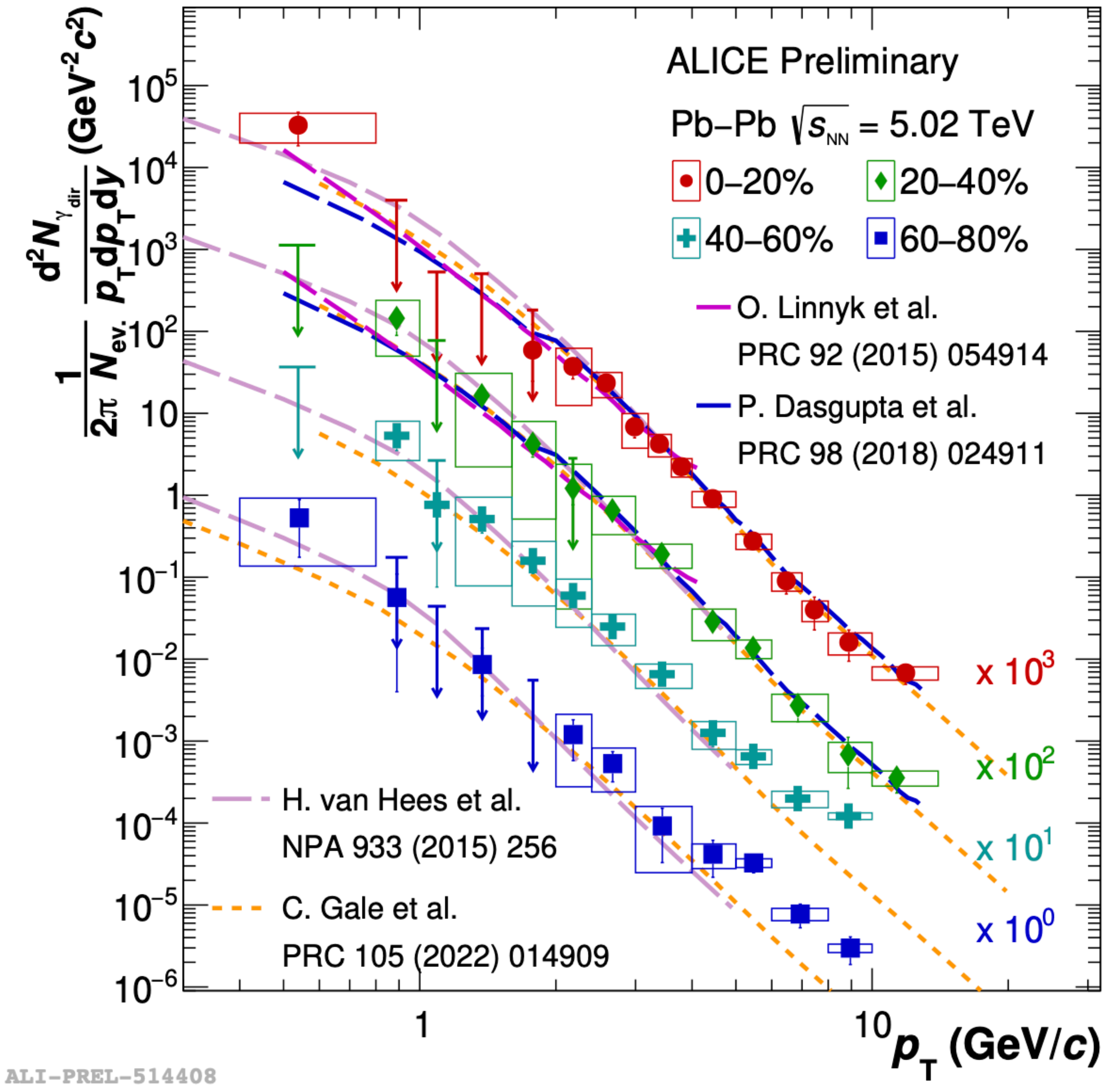


Figure corrected after the conference

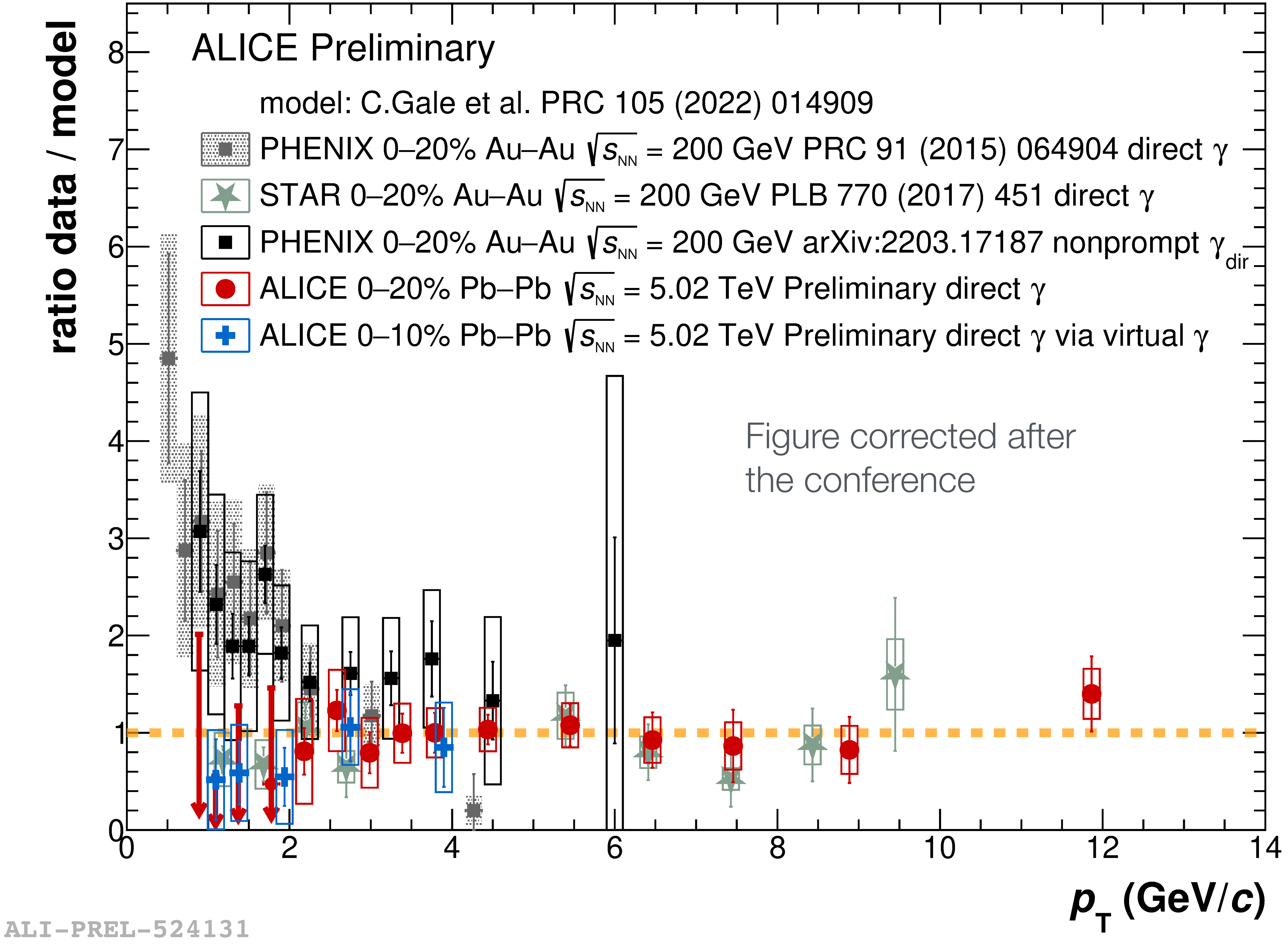
conversion method



Data / (prompt + PE + thermal): PHENIX, STAR, ALICE

talk Meike Danisch

Direct photon puzzle: Not too much of a puzzle left for yields



New PHENIX data:
no big puzzle for yields

New ALICE data:
fair agreement with theory

Level of agreement with theory appears similar for PHENIX and ALICE virtual photon result

ratio data / model 2.76 TeV 🔗

LHC direct photon yields consistent with PHENIX scaling

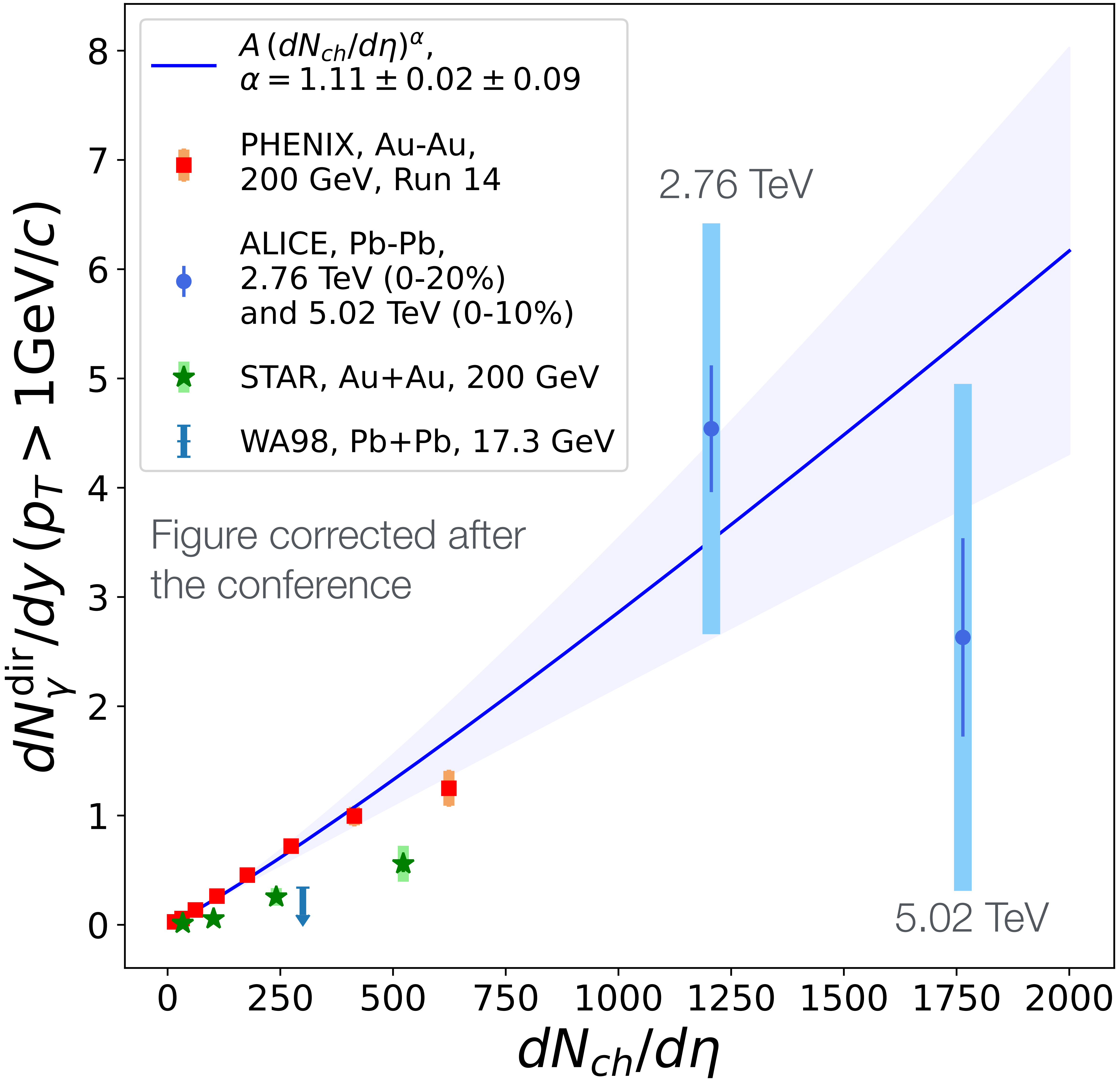
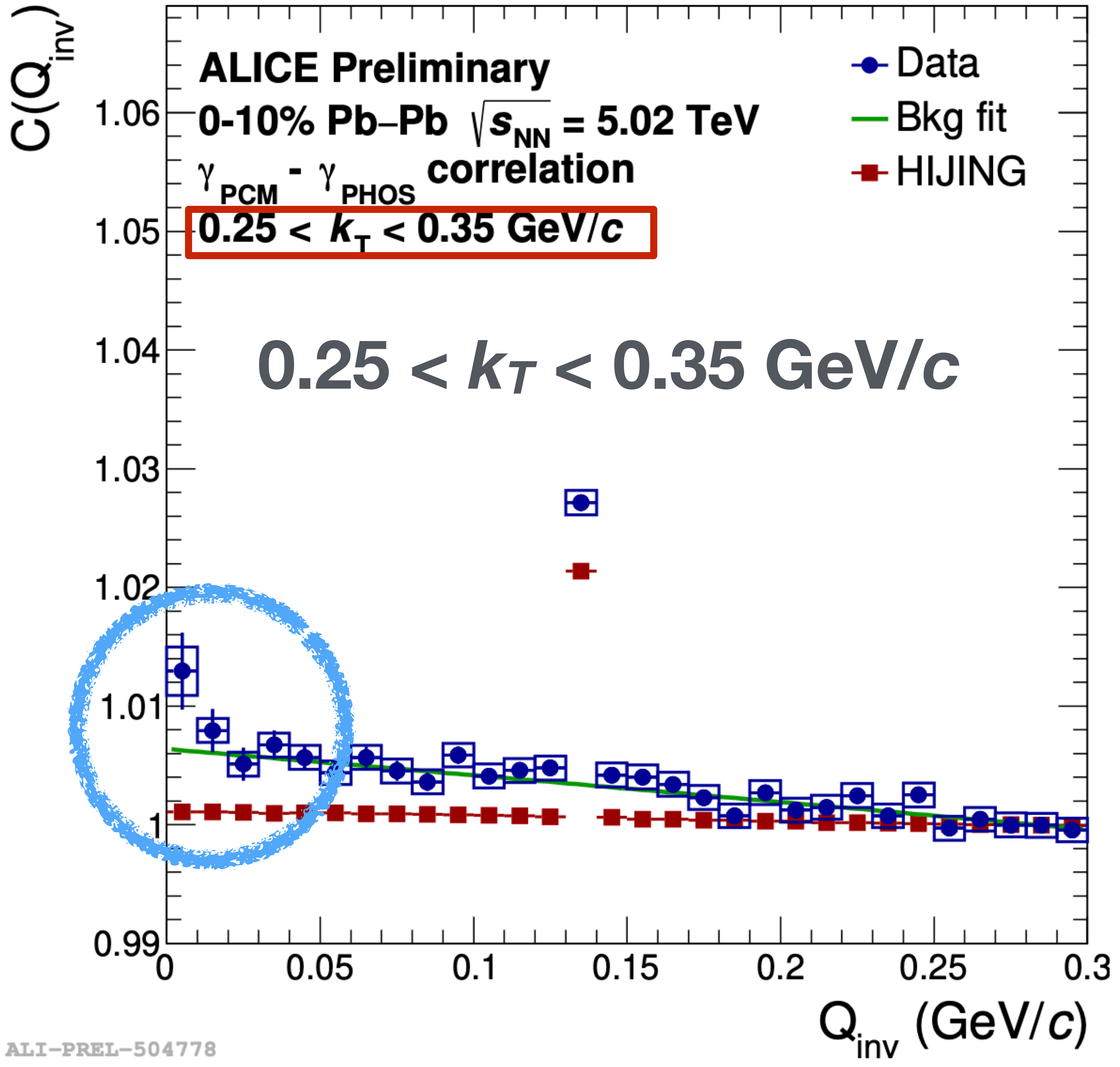


Figure corrected after the conference

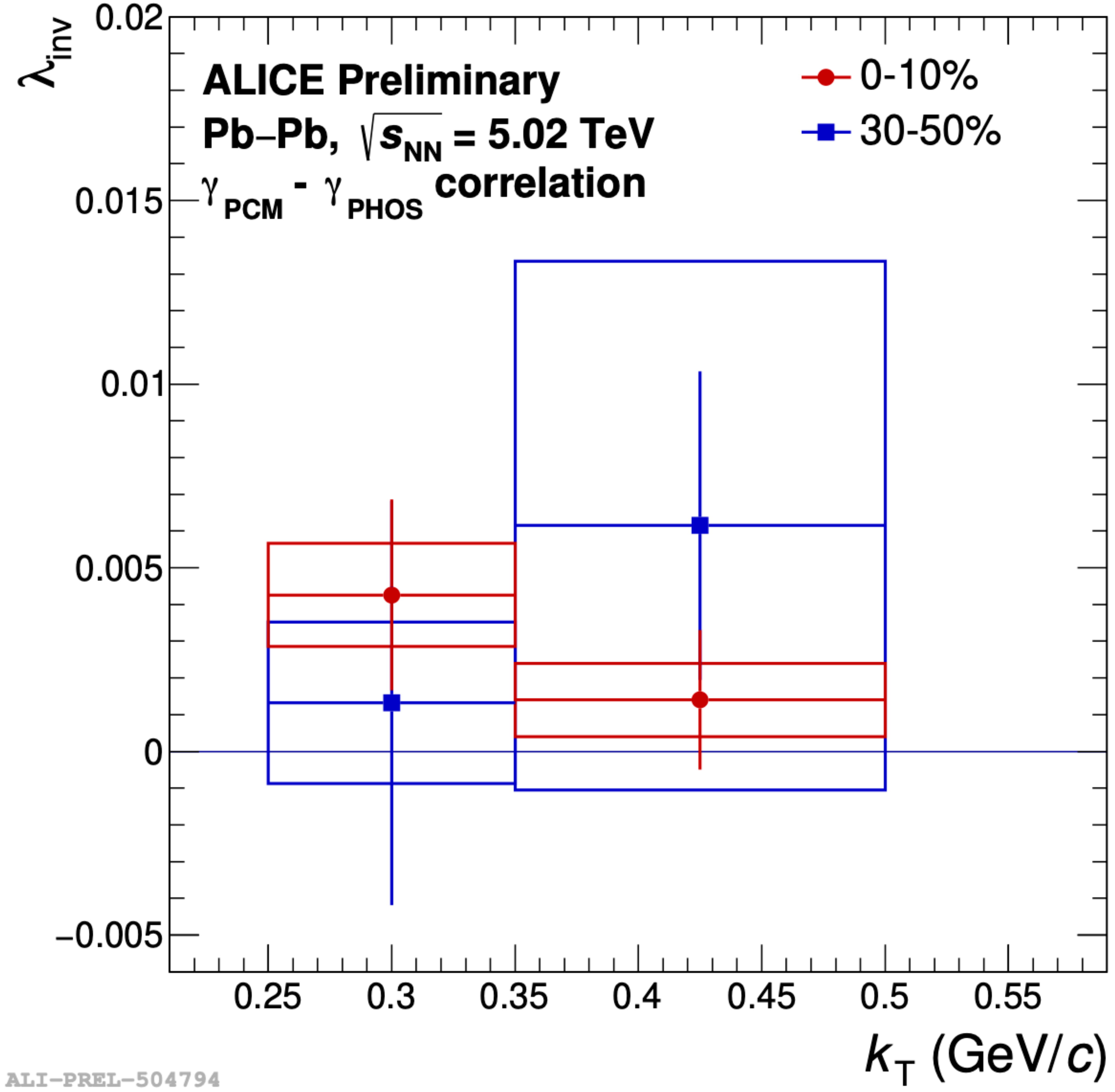
LHC points appear to be consistent with extrapolation of STAR data as well

Towards low-p_T direct photons: quest for photon HBT correlations with γ_{conv}-$\gamma_{calorimeter}$ pairs

Hints of a correlation peak, somewhat narrower than expected



0.25 < k_T < 0.35 GeV/c

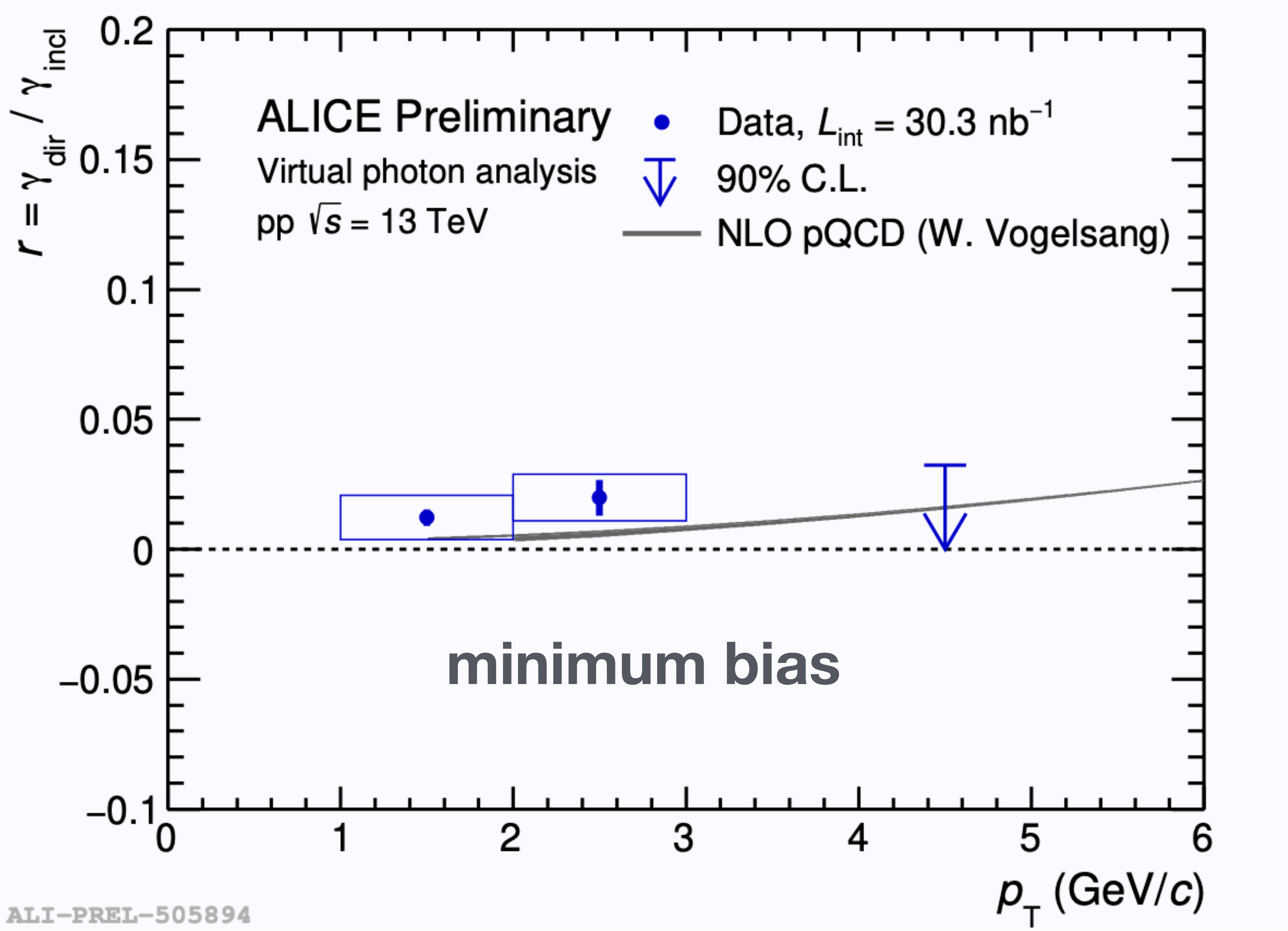


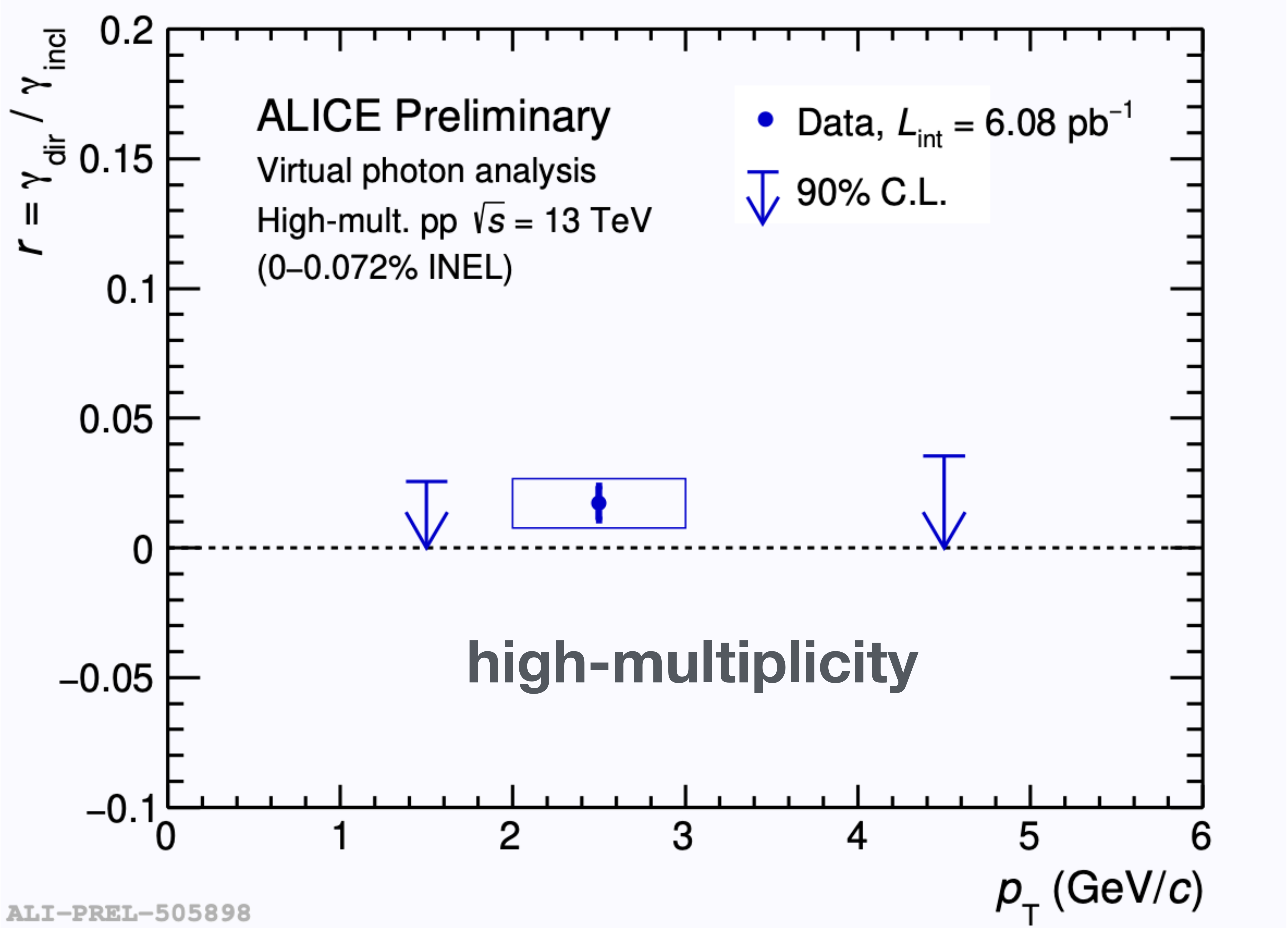
λ_{inv} → direct photon yield … but uncertainties currently large

poster Mike Sas

Direct photons in min. bias and high-multiplicity pp collisions 13 TeV from ALICE

No indications for thermal photons in pp collisions





poster Hikari Murakami

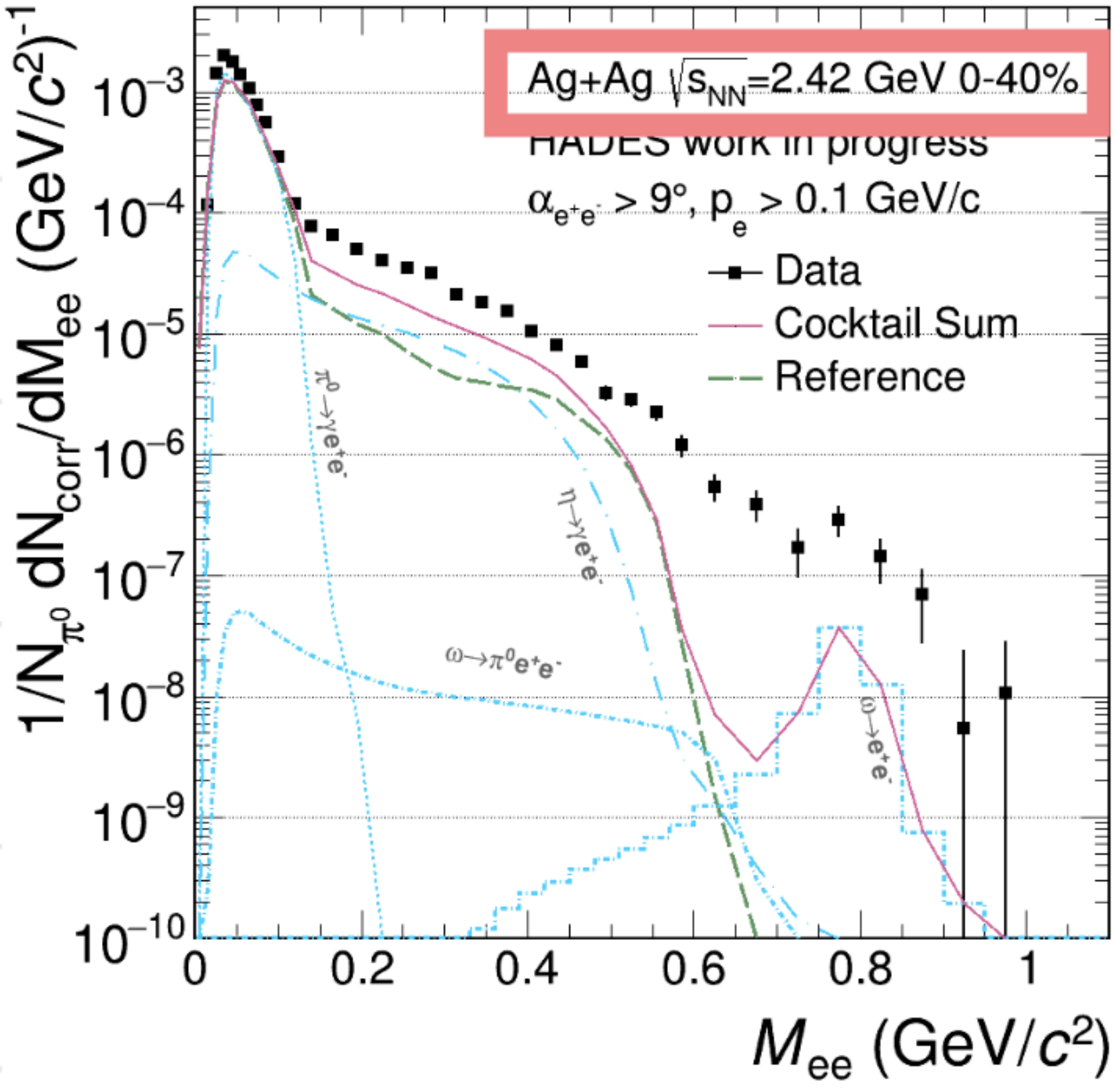
previous publication: ALICE PLB 788 (2019) 505

Dileptons

HADES: system size and energy dependence of medium properties at high μ_B

Clear dielectron excess above cocktail also in Ag-Ag

*HADES, Nature Phys. 15 (2019) 10, 1040

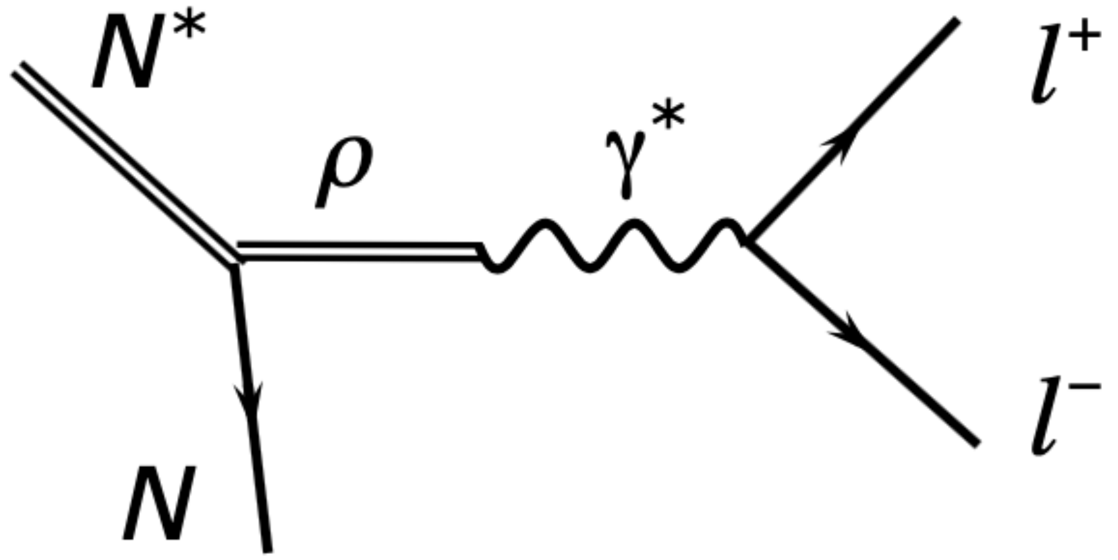


2012 Au-Au at $\sqrt{s_{NN}}$ = 2.42 GeV*

2019 Ag-Ag at $\sqrt{s_{NN}}$ = 2.42 GeV and 2.55 GeV

^{197}Au: $Z/A = 0.40$, ^{107}Ag: $Z/A = 0.44$

Understanding of e^+e^- production via resonances crucial

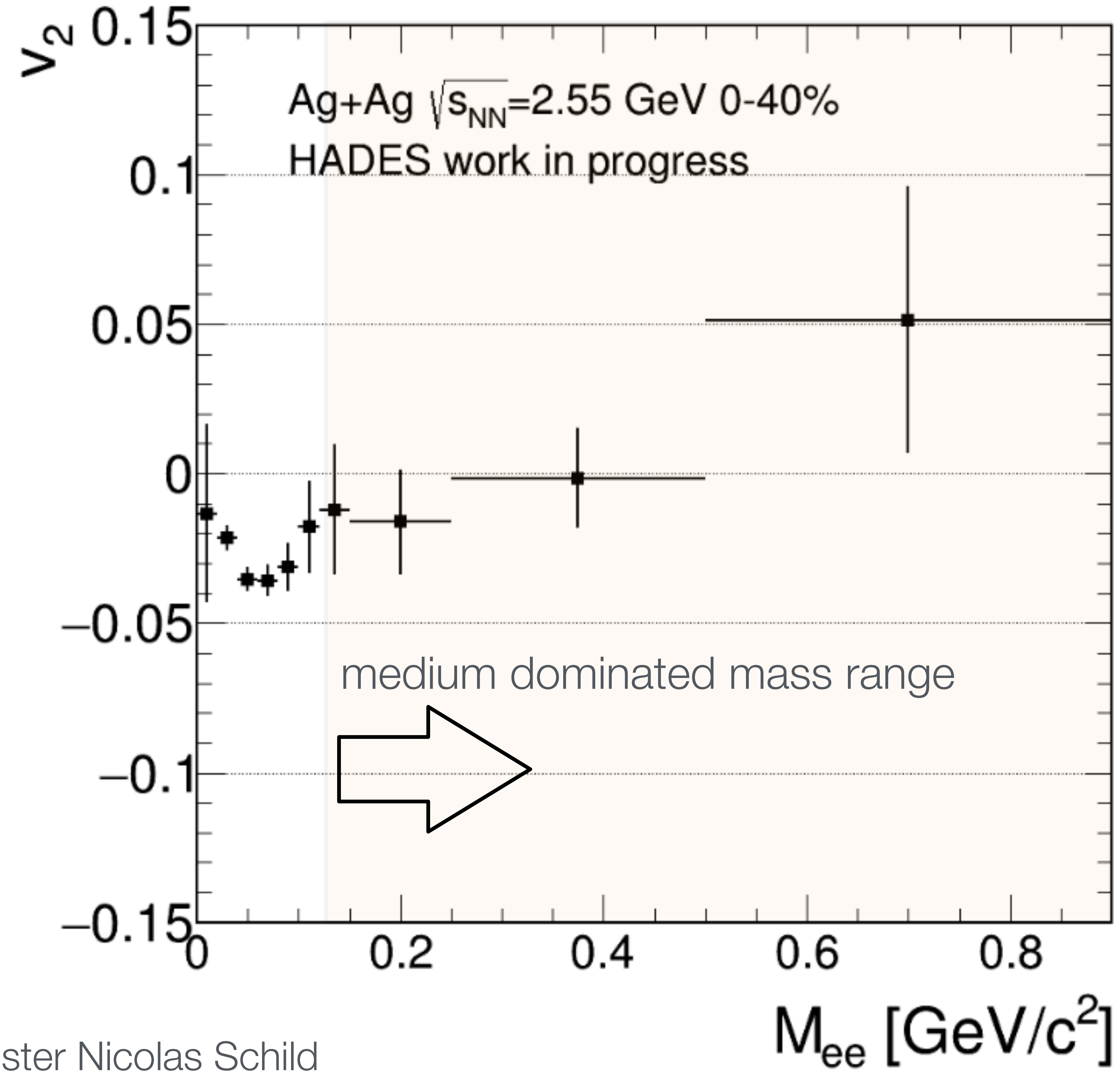


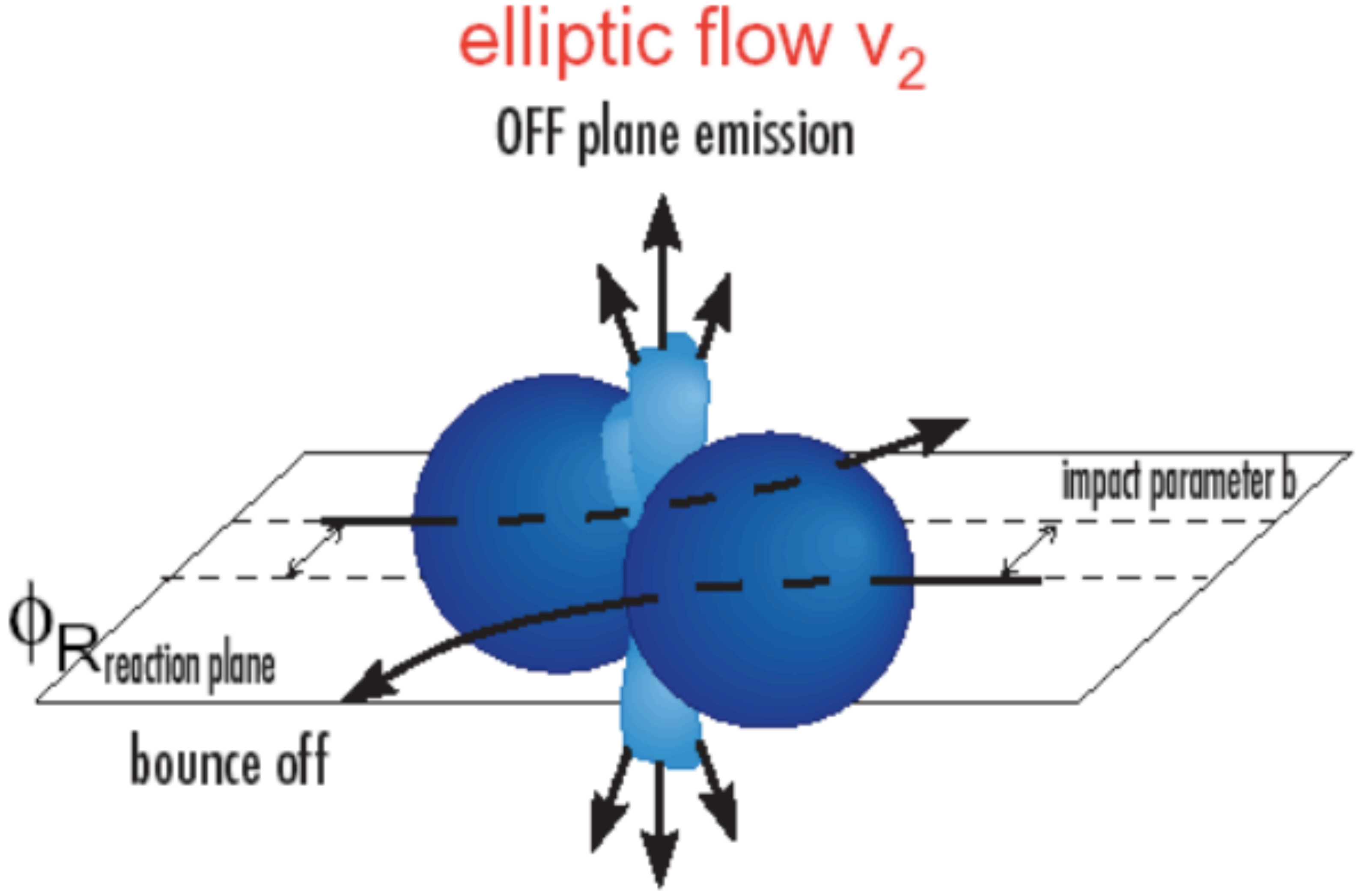
HADES measured effective transition form factor in $\pi^- p \to n e^+ e^-$. Important role of N*(1520). 🔗

Excess yield for same energy and N_{part} larger in Au-Au than in Ag-Ag. Why? 🔗

Dielectron elliptic flow consistent with zero in medium dominated mass range

Confirms dileptons as penetrating probes of hot and dense medium



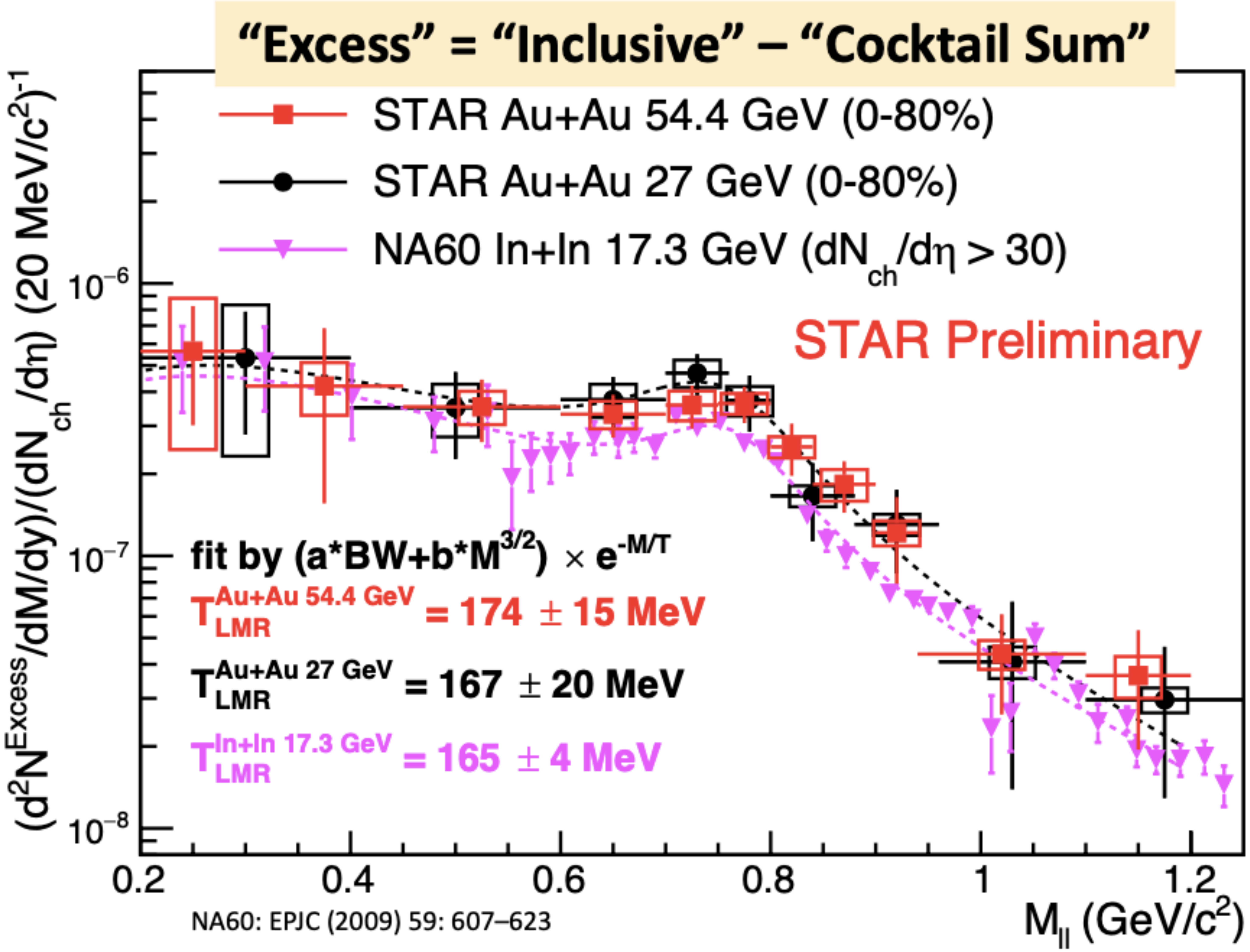


v_2 due to spectator shadowing at SIS energies (“squeeze-out”)

poster Nicolas Schild

New dielectron spectra in 27 GeV and 54.4 GeV Au-Au from STAR (1)

Temperature from excess dielectron mass spectrum: 1. LMR



NA60: EPJC (2009) 59: 607–623

Clear enhancement w.r.t. cocktail in both low mass region (LMR) and intermediate mass region (IMR)

Fit to excess yield:
ρ lineshape (Breit-Wigner) + thermal

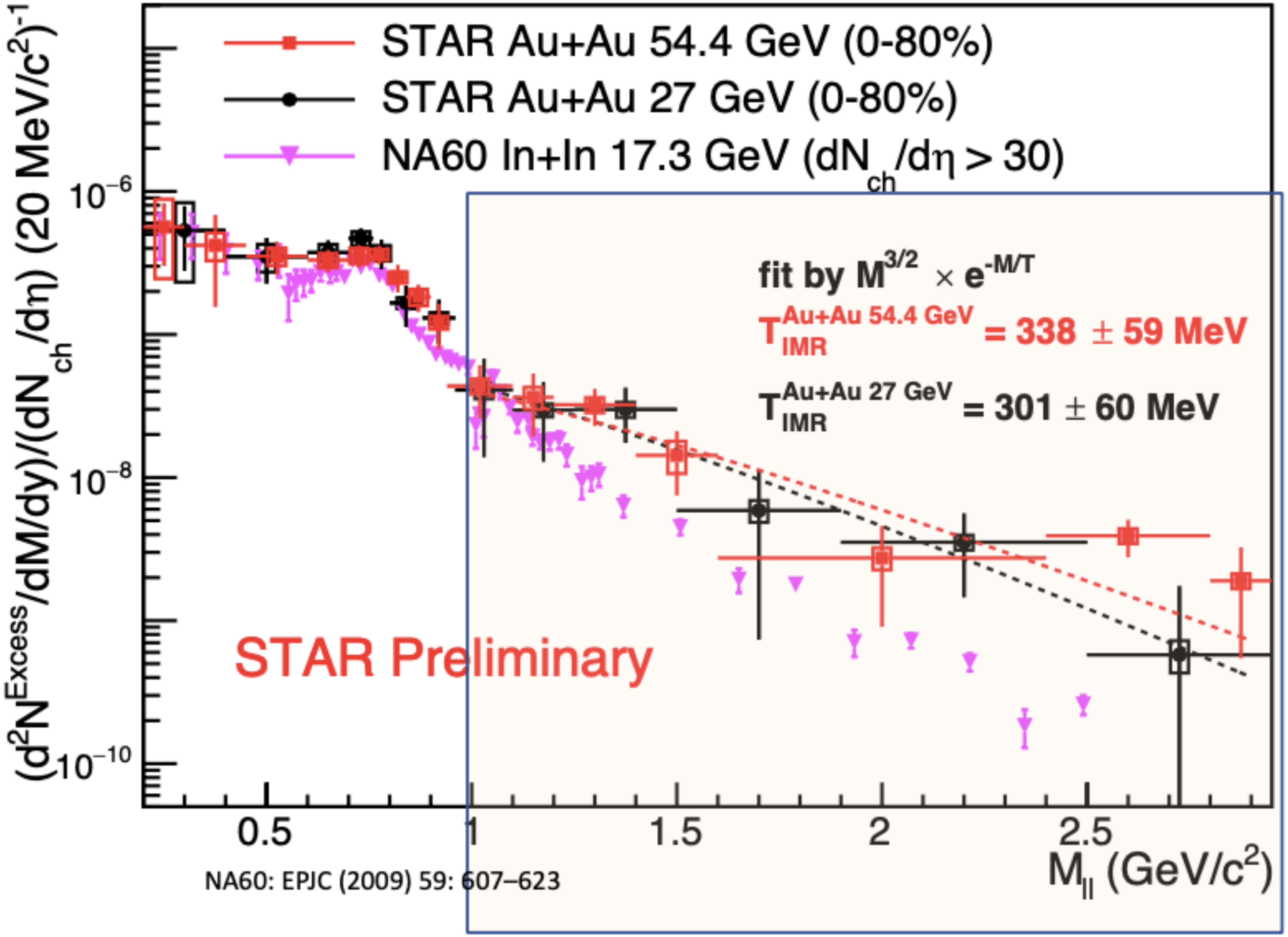
Fit also done for NA60 data

Extracted temperatures close to
T_{pc} = 156 MeV

talk Zaochen Ye

New dielectron spectra in 27 GeV and 54.4 GeV Au-Au from STAR (2)

Temperature from excess dielectron mass spectrum: 2. IMR



NA60: EPJC (2009) 59: 607–623

$T_{IMR} > T_{pc} = 156$ MeV

T_{IMR} (STAR) > T_{IMR} (NA60)

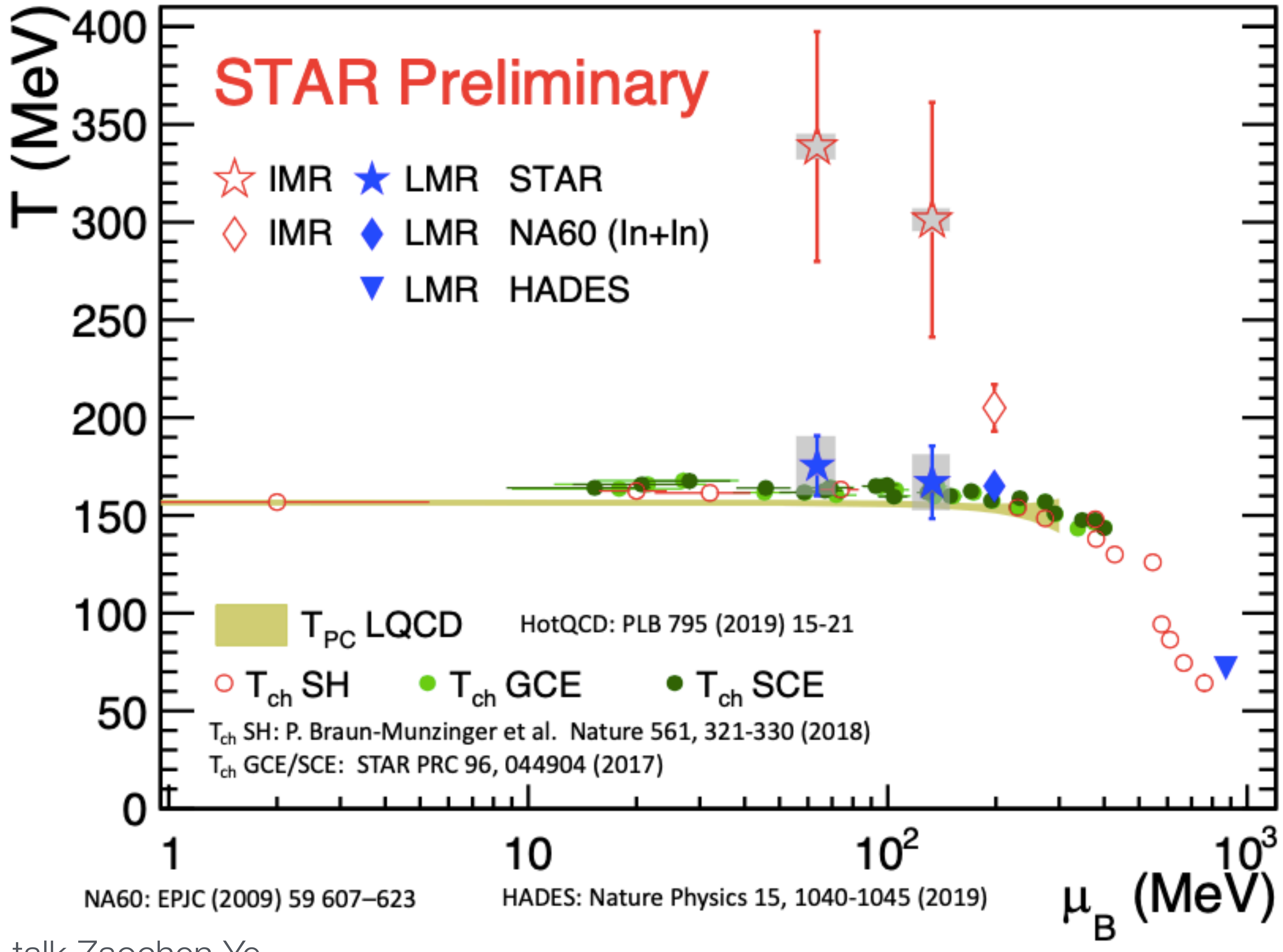
└ 205 ± 15 MeV

Statistical uncertainties dominant

talk Zaochen Ye

New dielectron spectra in 27 GeV and 54.4 GeV Au-Au from STAR (3)

$T_{\text{eff}} > T_{\text{pc}}$ = 156 MeV in intermediate mass range



Interpreted as space-time averaged QGP temperature of $T \approx 300$ MeV

Back-on-the-envelope estimate

- multiplicity $\propto s^{0.155}$
- initial temperature $T^3 \propto dN/dy$

Expected temperature increase from $\sqrt{s_1} = 17.3\,\text{GeV},\ T_1 \approx 200\,\text{MeV}$:

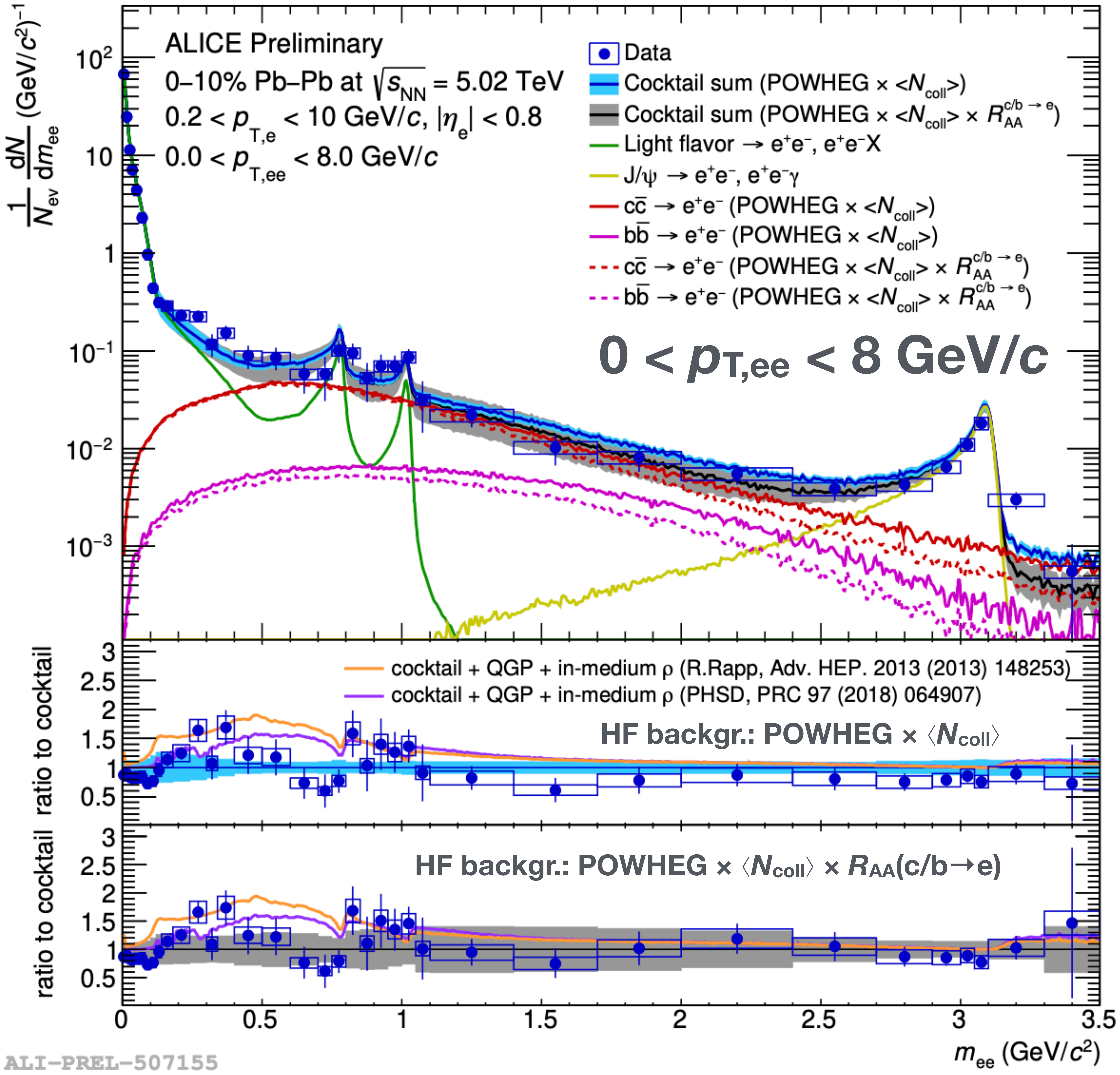
- 4% at 27 GeV
- 13% at 54.4 GeV

Measured T surprisingly large

talk Zaochen Ye

Dielectrons at 5.02 TeV Pb-Pb from ALICE

No significant excess within uncertainties



Handling of $c\bar{c}, b\bar{b} \to e^+e^-$ background is key for measuring thermal dielectrons from the QGP

Two different cocktails

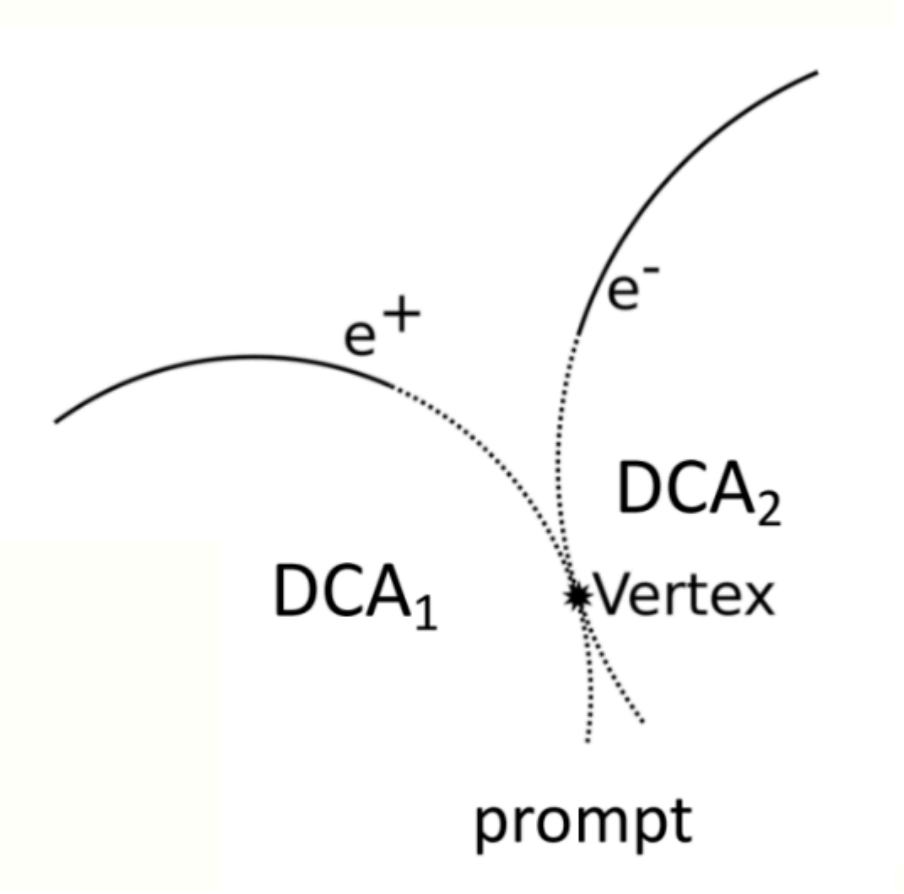
- N_{coll}-scaled HF in pp
- Include R_{AA} of c/b → $e^{+/-}$

talk Jerome Jung

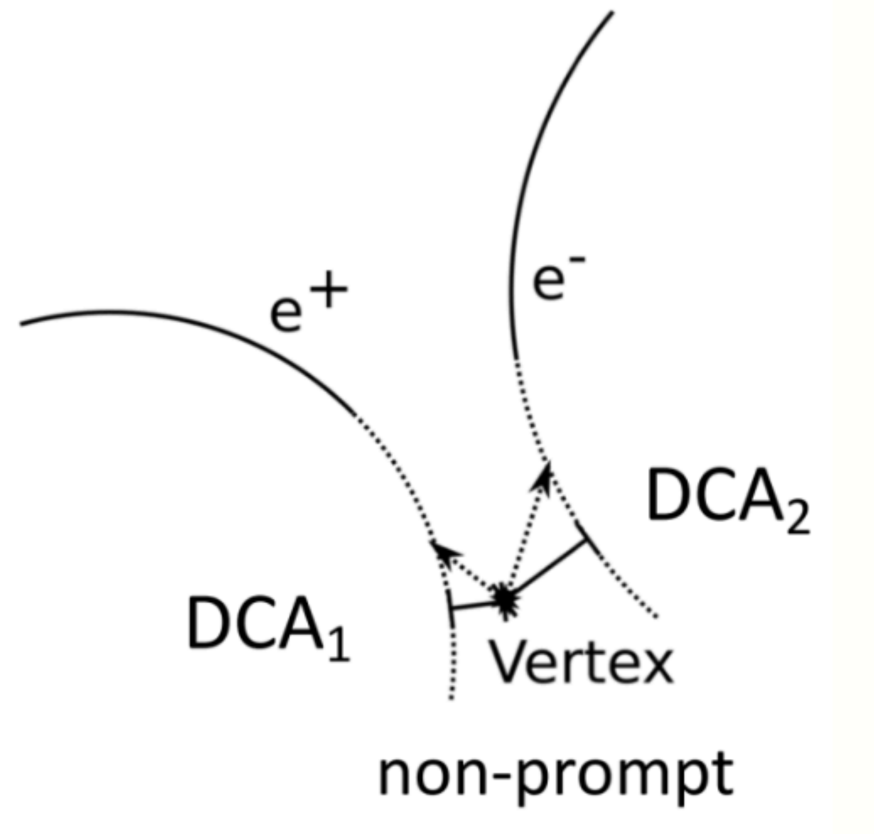
Data-driven way of handling charm background: DCA template fits

talk Jerome Jung

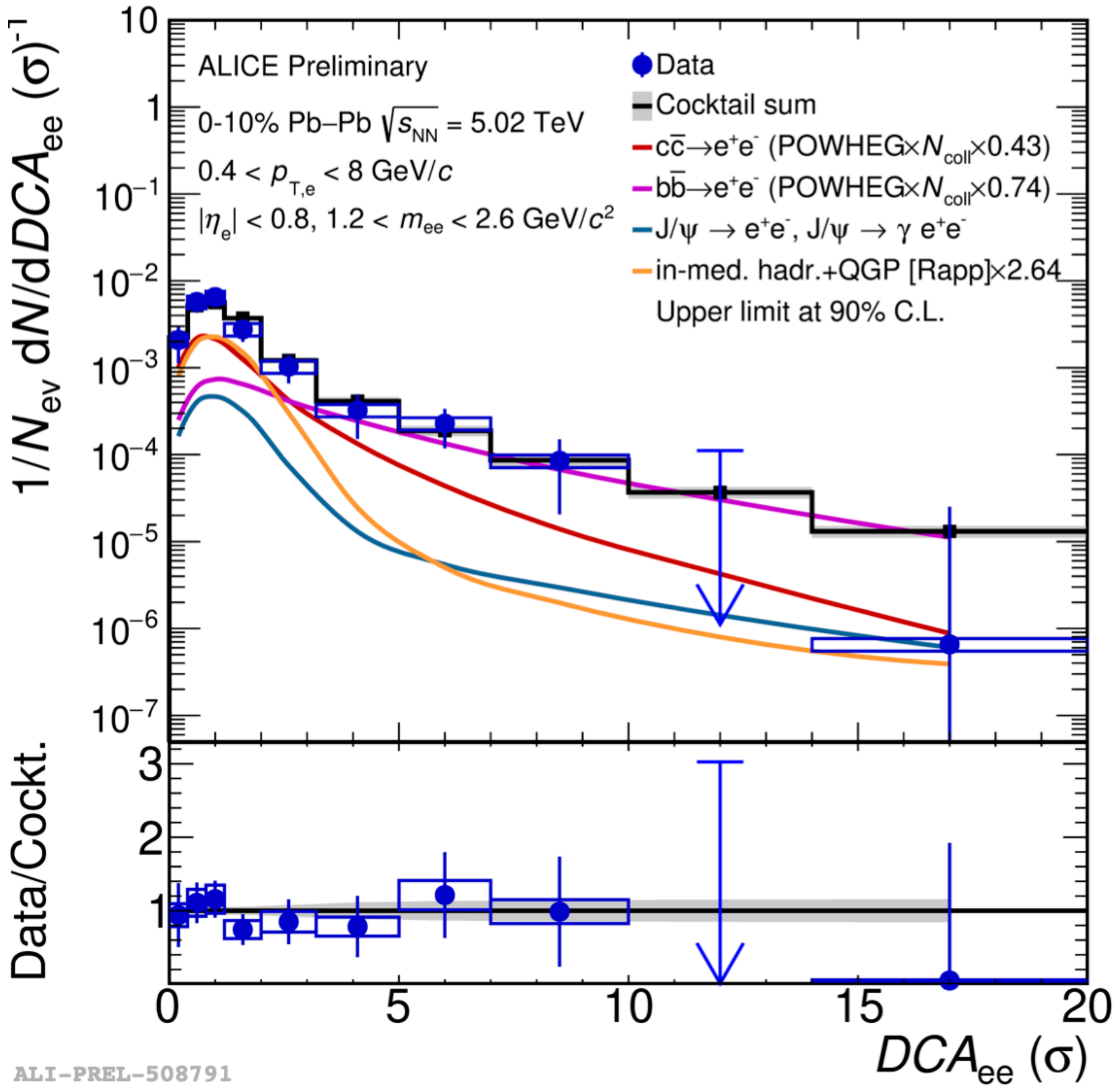
High statistics and very good DCA resolution crucial



prompt



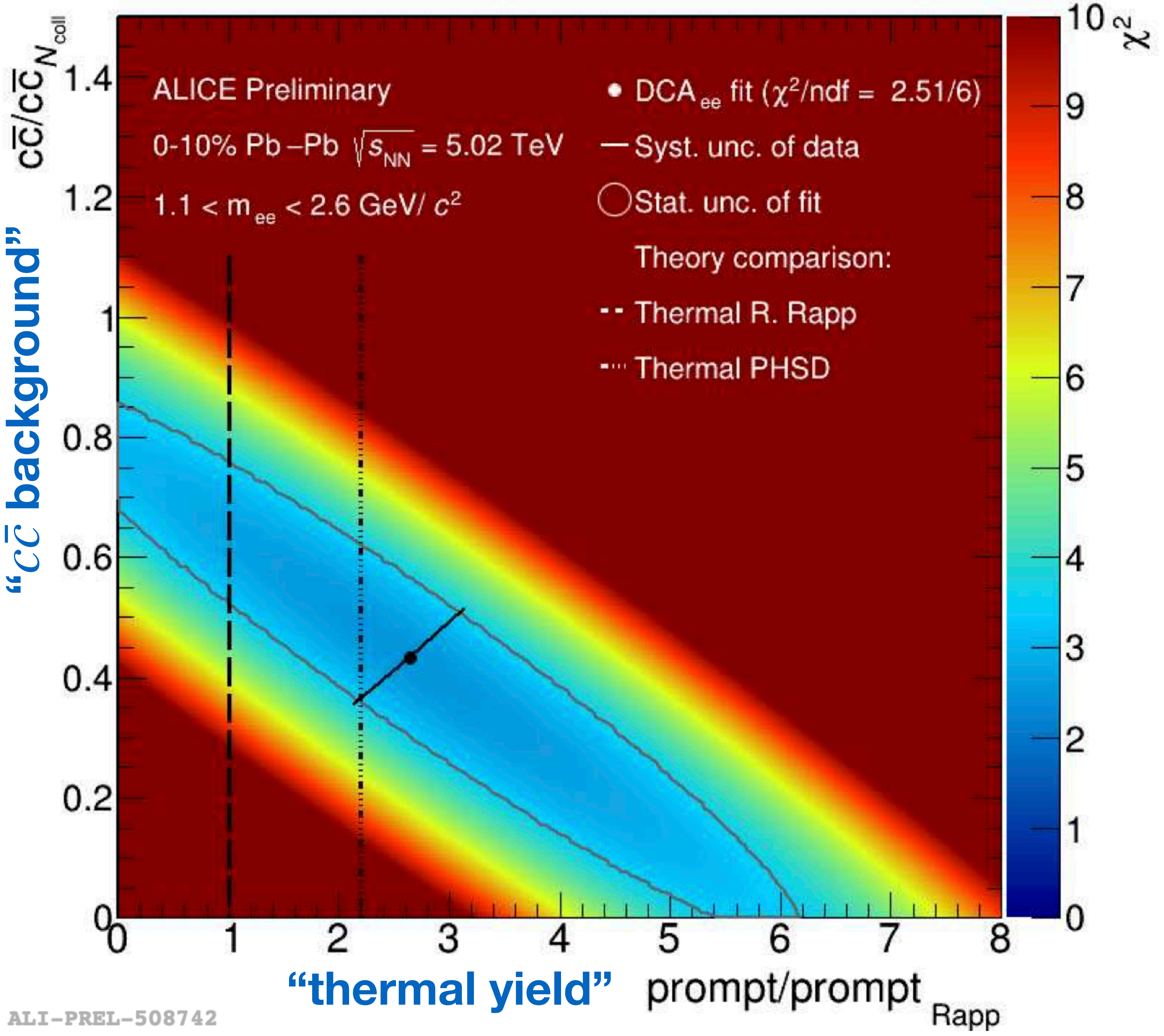
non-prompt



ALI-PREL-508791

templates:

$c\bar{c} \rightarrow e^+e^-$, $b\bar{b} \rightarrow e^+e^-$, prompt



ALI-PREL-508742

Currently limited by statistics and DCA resolution:

→ **ALICE 2** (Run 3 & 4, **ITS2**, **ITS3**)

→ **ALICE 3** (Run 5+)

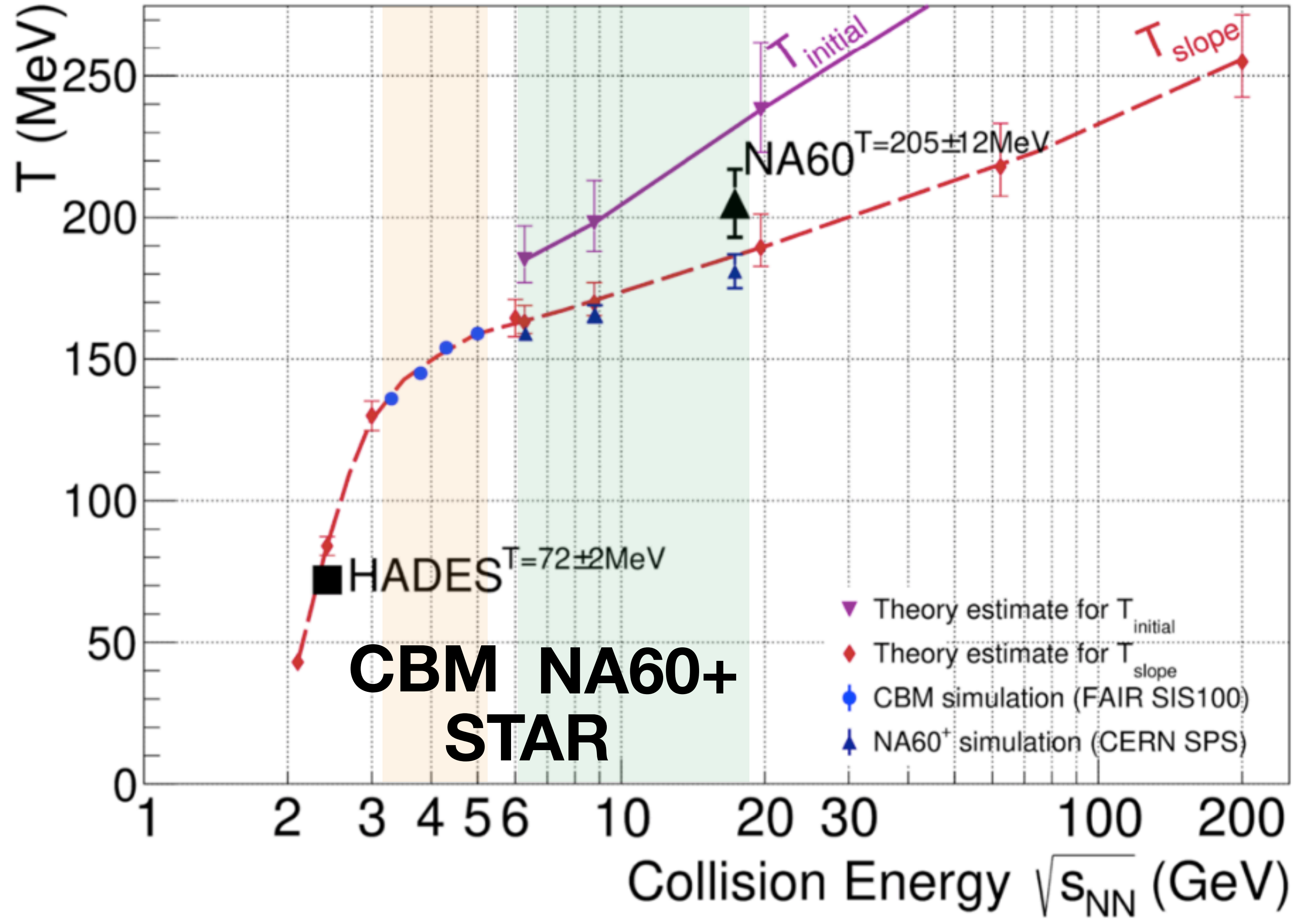
Future measurements

ALICE 3, CERN-LHCC-2022-009
NA60+, CERN-SPSC-2019-017

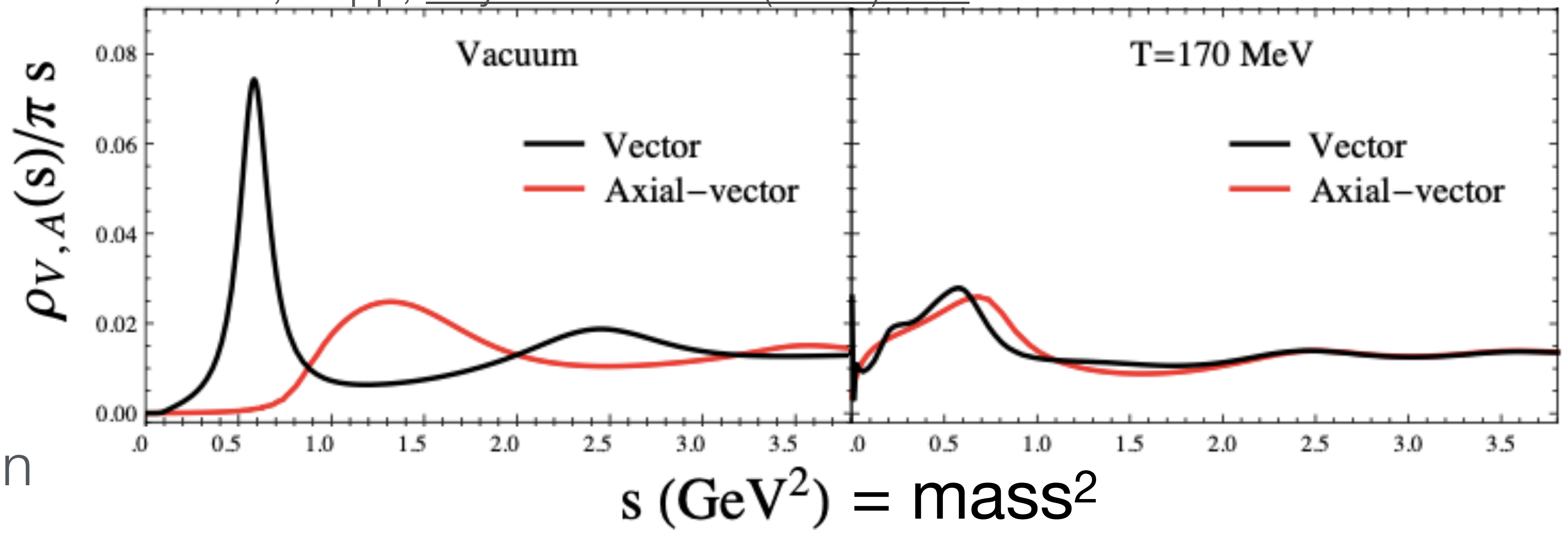
	High μ_B	**Vanishing μ_B**
Thermal radiation (γ, γ^* spectra)	**STAR, NA60+, CBM, NICA**	**PHENIX, STAR, ALICE 2, ALICE 3**
Caloric curve (T_{eff} in IMR vs. $\sqrt{s_{\text{NN}}}$)	**STAR, NA60+, CBM, NICA**	
Mechanism of CSR, ρ-a_1 mixing	**CBM, NA60+**	**STAR, ALICE 3**
Dilepton + direct photon v_n	**CBM, HADES, NA60+**	**STAR, (ALICE 2), ALICE 3**
Time dependence of T_{eff}, preequilibrium contribution		**ALICE 3**
Ultra-soft photons (test of Low's theorem)		**ALICE 3**
Electrical conductivity	**HADES**	**STAR, ALICE 3***

*under investigation

Tetyana Galatyuk et al.



Hohler, Rapp, Phys. Lett. B731 (2014) 103

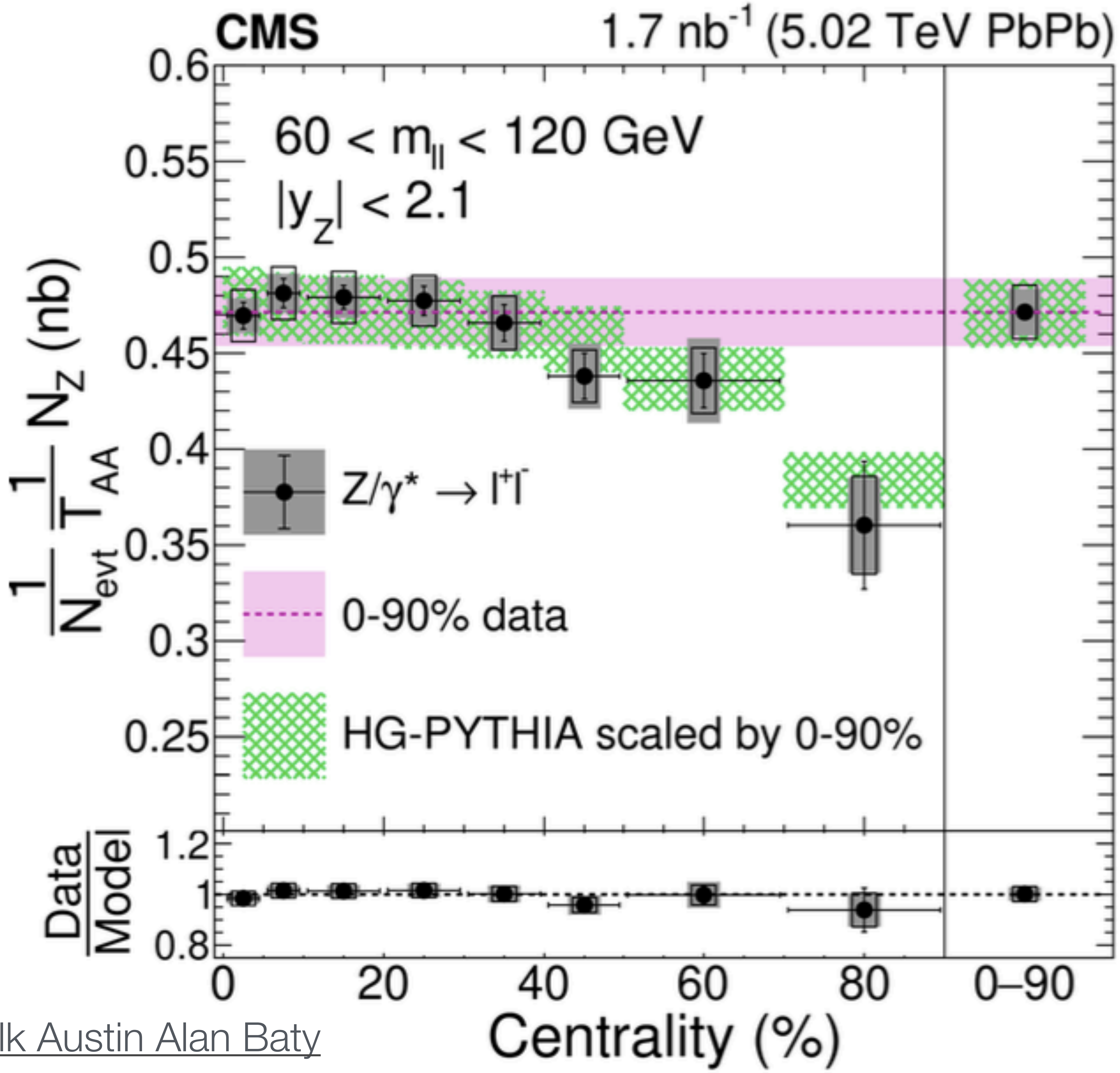


Initial state

Avoiding selection biases in T_{AA} from Glauber model with electroweak probes

Experimental T_{AA} from weak boson yield in CMS

HG-PYTHIA: C.Loizides, A. Morsch, PLB B773 (2017) 408



Deviation of Z boson yield from Glauber T_{AA} scaling reproduced by HG-PYTHIA
→ interpreted as selection bias

Replace Glauber T_{AA} with $T_{AA}^{\mathrm{exp}} = \frac{N_Z}{N_{\mathrm{evt}} \cdot \sigma_Z^{\mathrm{NN}}}$

Similar approach in PHENIX:
Long-standing puzzle of peripheral $R_{dAu}^{\pi^0} > 1$ for p_T > 10 GeV/c resolved by using direct γ's:

$$\langle N_{coll}^{exp} \rangle = \frac{\left(\frac{d^2 N^\gamma}{dp_T d\eta}\right)_{dAu}}{\left(\frac{d^2 N^\gamma}{dp_T d\eta}\right)_{pp}}$$

talk Niveditha Ramasubramanian

talk Austin Alan Baty
see also: talk Shingo Sakai

Conclusions

Low-p_T direct photons

PHENIX data qualitatively in line with thermal QGP radiation. Yield puzzle appears less puzzling with 2014 data.

Important aspects not fully understood (e.g., direct photon v_2, constant $\alpha(p_T)$)

ALICE: still no yield puzzle with new 5.02 TeV Pb-Pb data and improved analysis methods

Dileptons

So far only one measurement of QGP temperature from dileptons in IMR:
$T = 205 \pm 15$ MeV from NA60

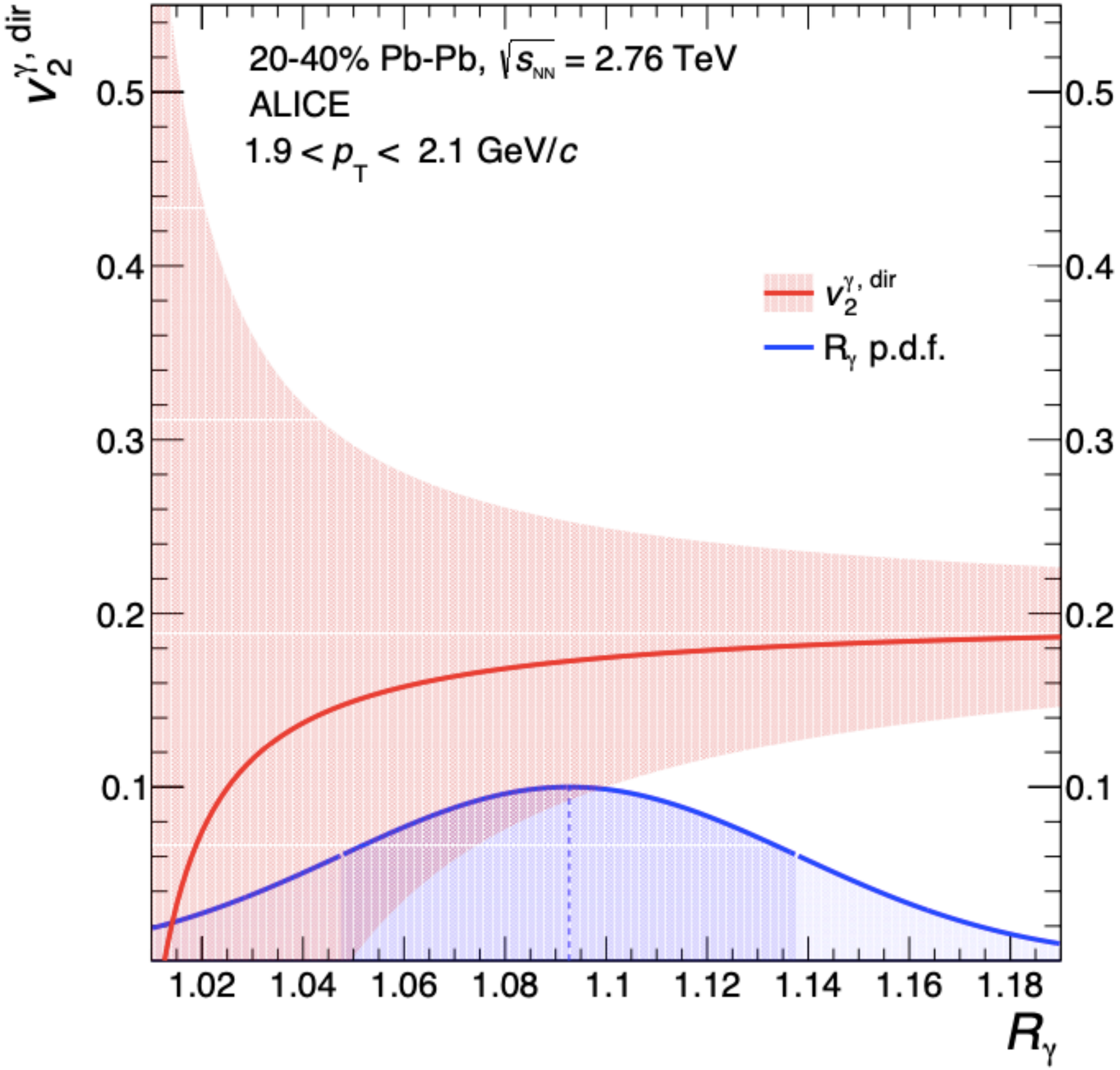
New STAR data:
Surprisingly large T_{eff} (~ 300 ± 60 MeV) from fit in IMR in Au-Au at 27 and 54.4 GeV

Many thanks to: 🙏🏻
Raphaëlle Bailhache, Peter Braun-Munzinger, Meike Danisch, Gabor David, Axel Drees, Tetyana Galatyuk, Frank Geurts, Szymon Harabasz, Christian Klein-Bösing, Aleksas Mazeliauskas, Norbert Novitzky, Jean-François Paquet, Mike Sas, Sören Schlichting, Daiki Sekihata, Johanna Stachel

Extra slides

Pb-Pb at 2.76 TeV

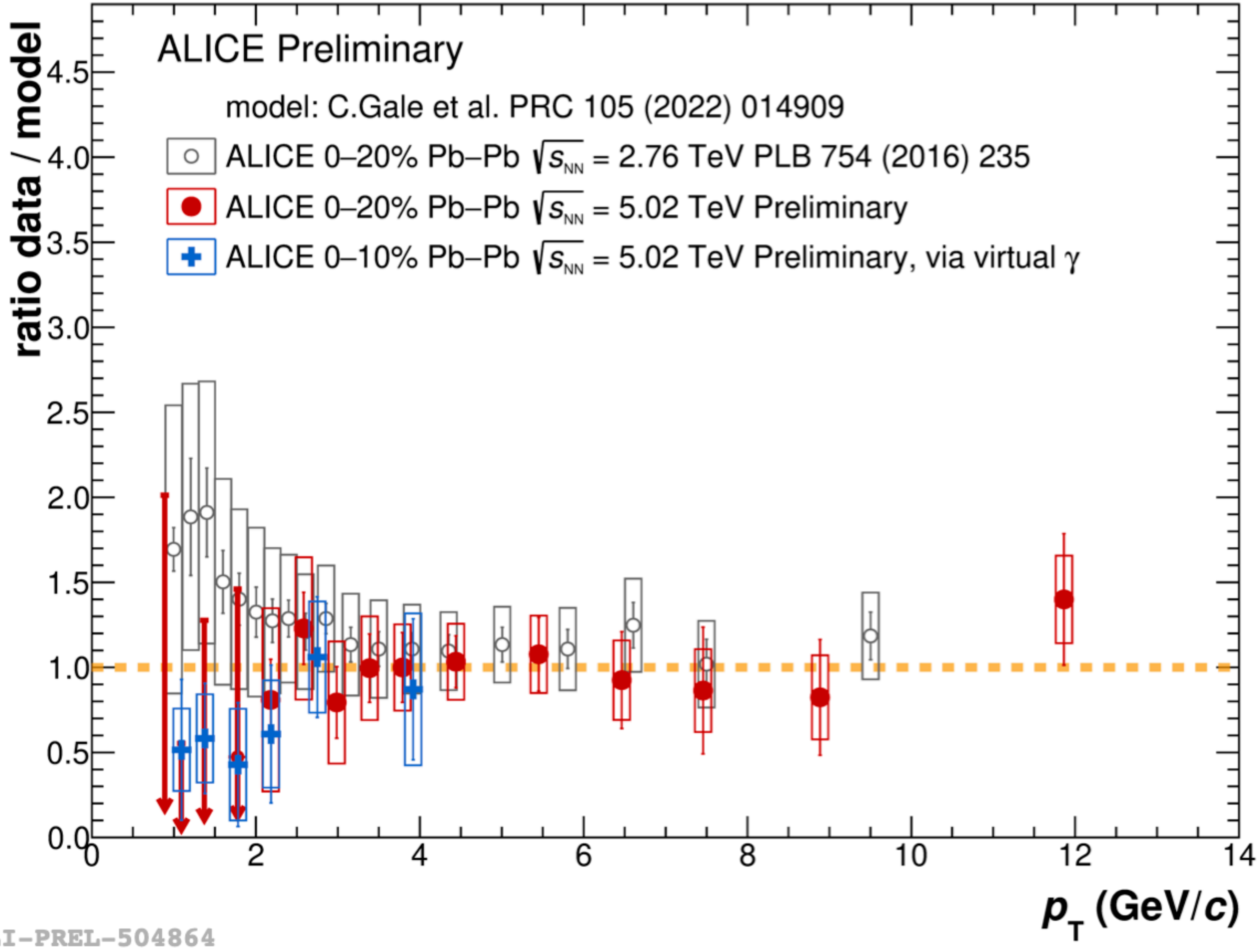
v_2 uncertainty vs R_γ



ALICE, Phys. Lett. B 789 (2019) 308

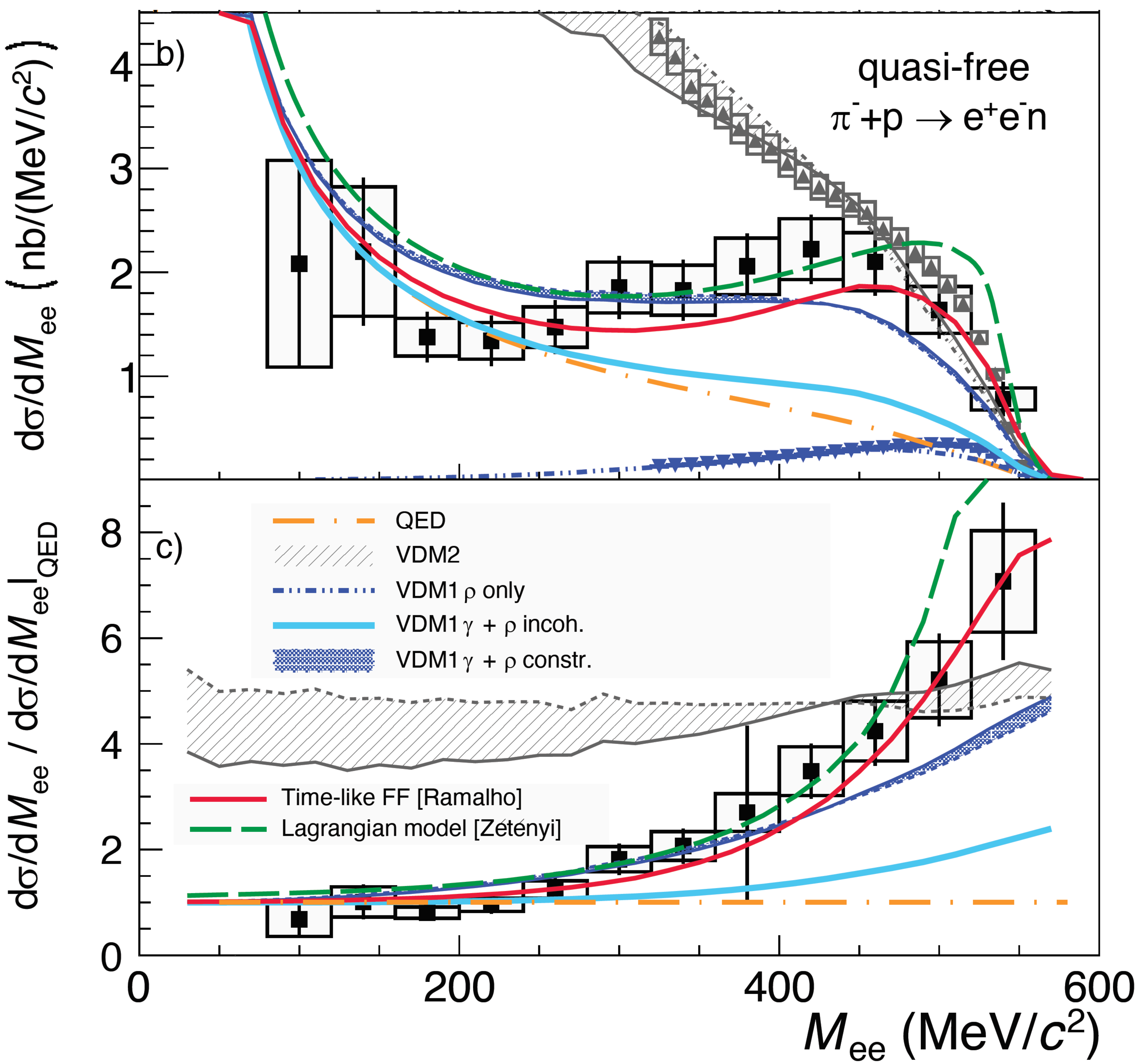
Data / (prompt + PE + thermal)

2.76 TeV and 5.02 TeV

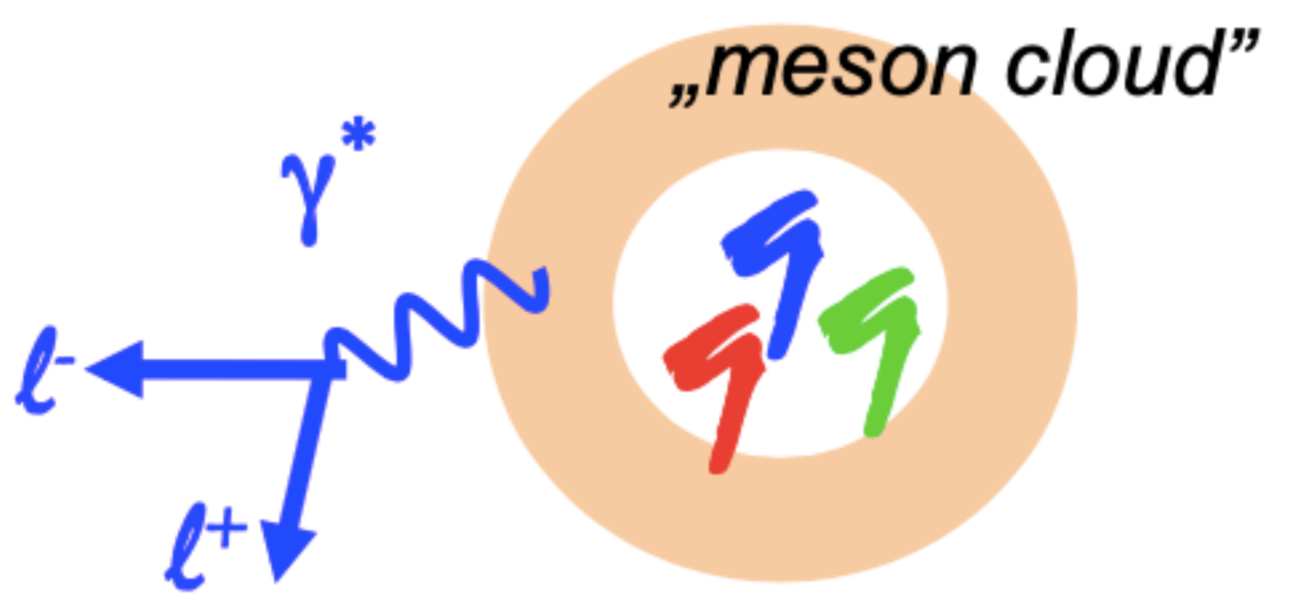


Meson cloud exclusive analysis of $\pi^- p \to n e^+ e^-$

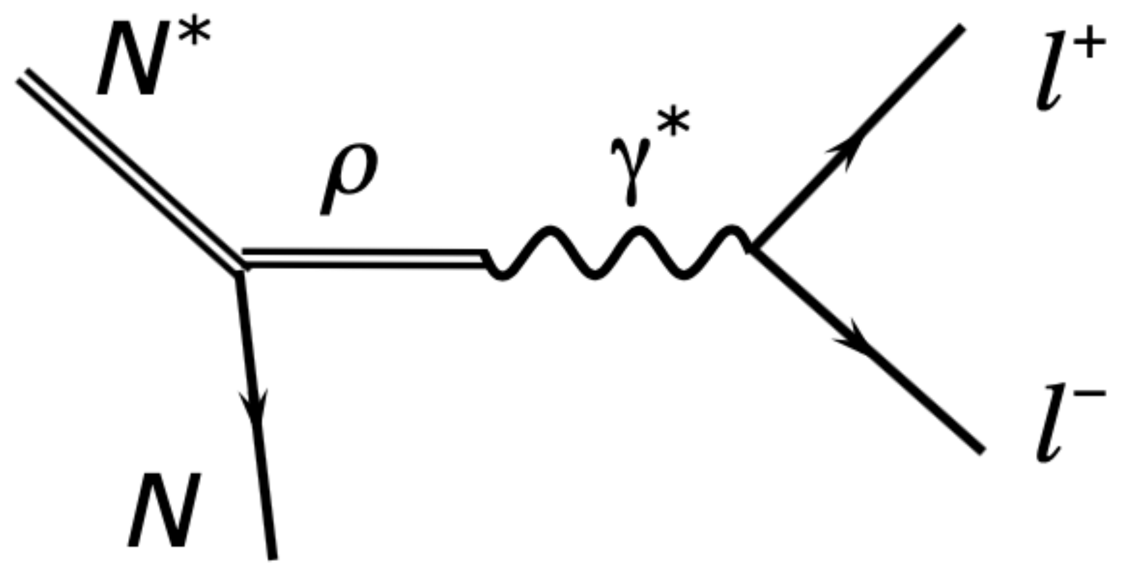
Dominance of the N*(1520) resonance



Excitation of a baryon can be carried by the meson cloud

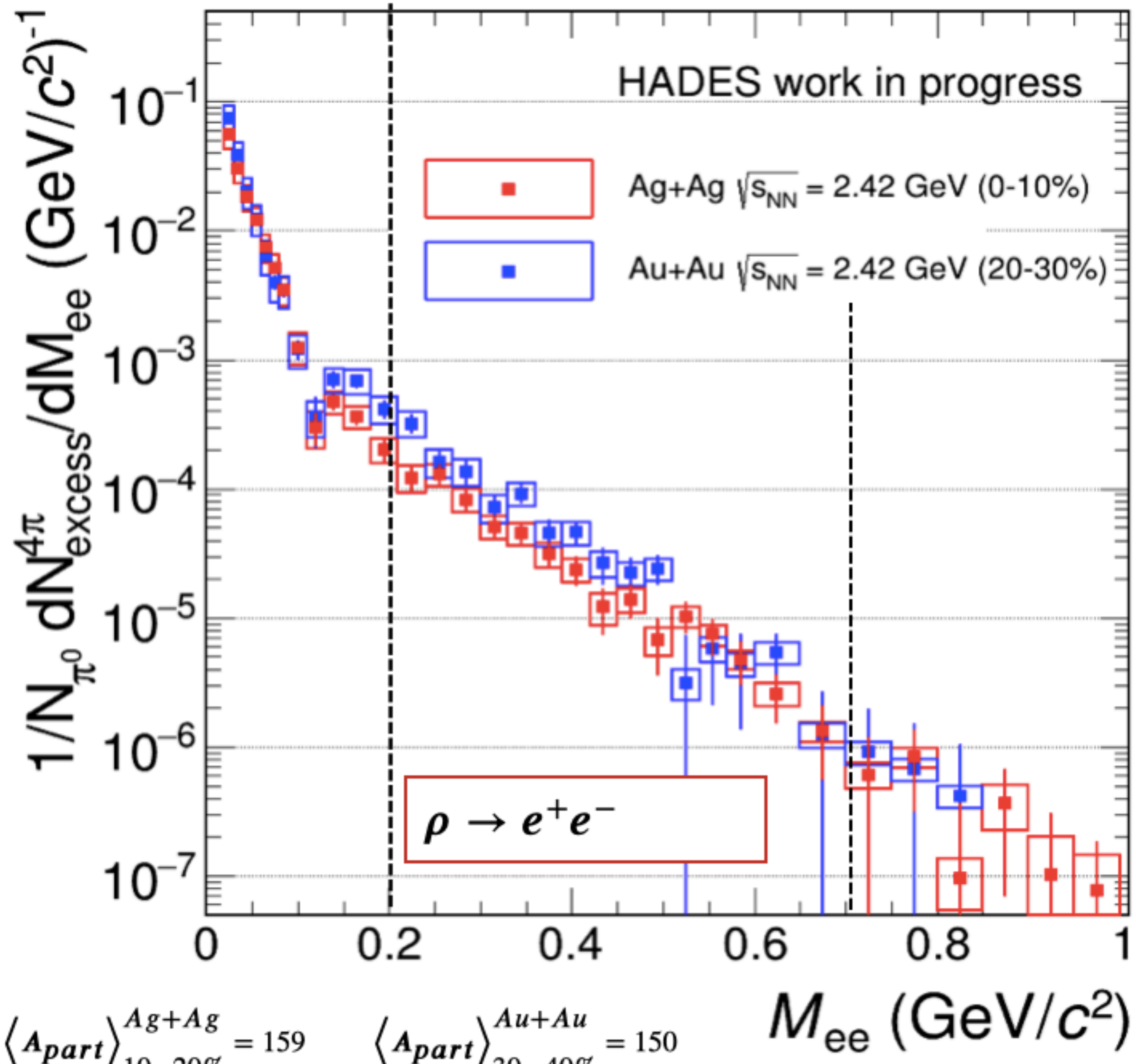


Vector Meson Dominance: the basis of emissivity calculations for QCD matter



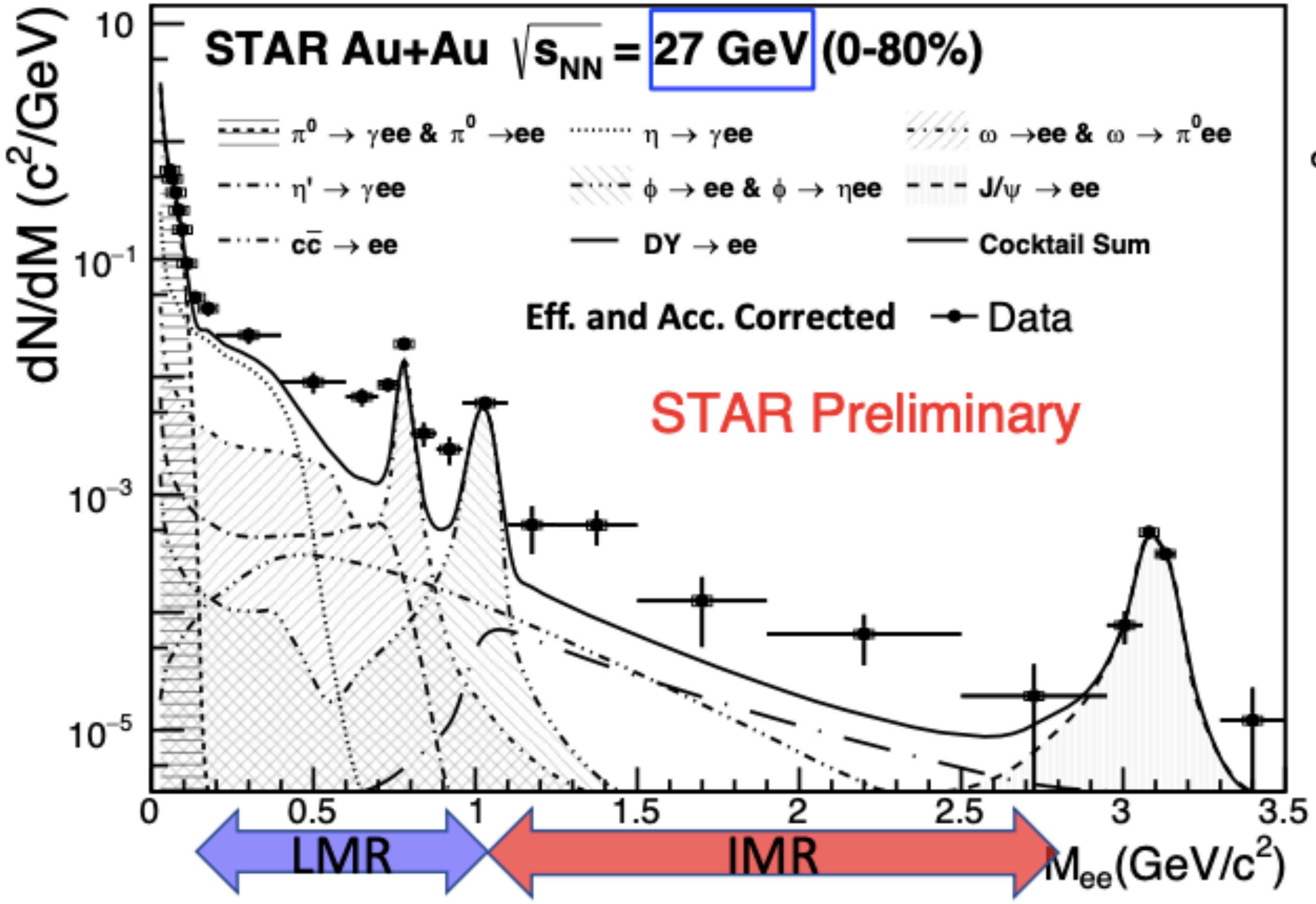
HADES: system size and energy dependence of medium properties at high μ_B

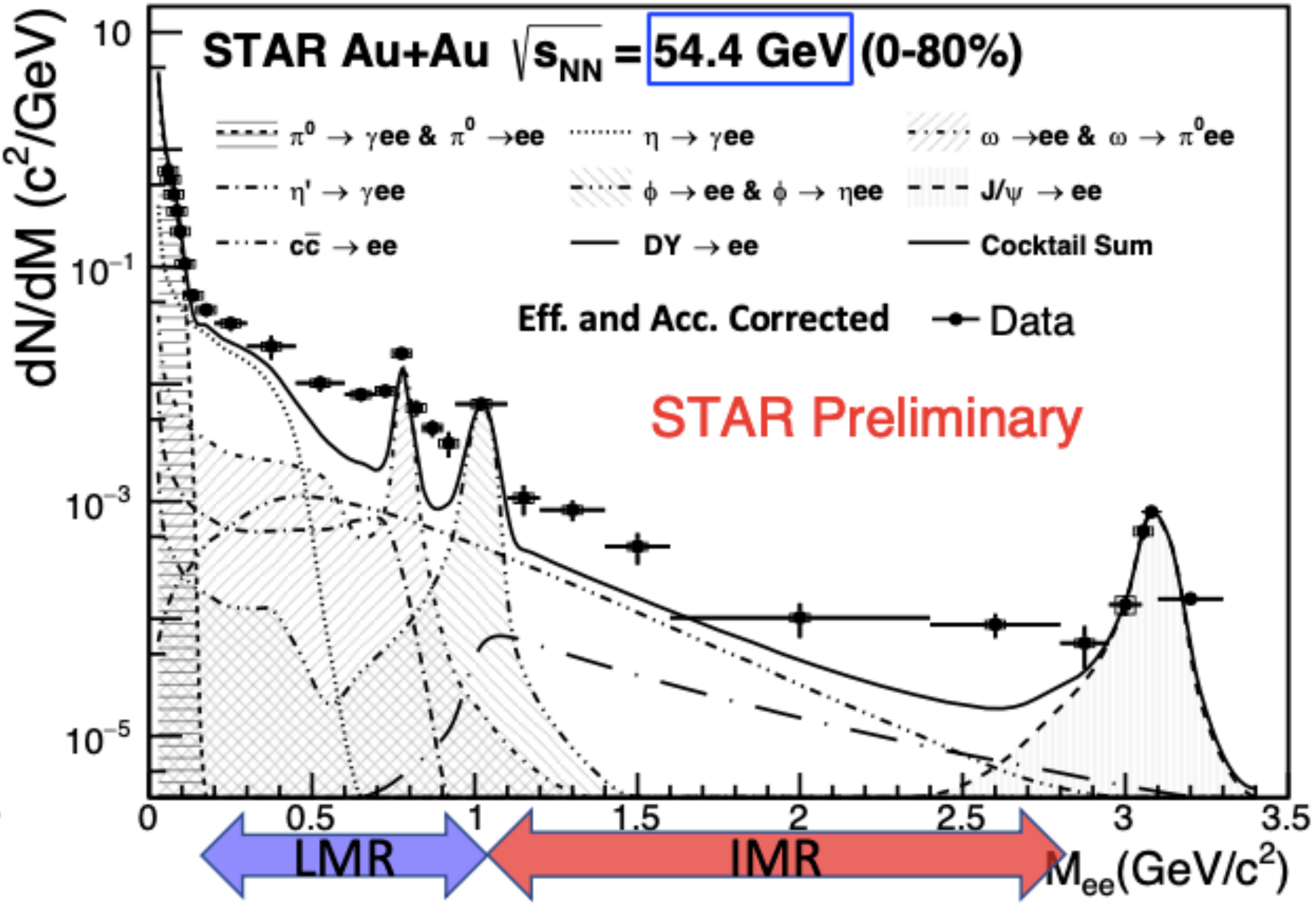
Excess yield for same energy and Npart larger in Au-Au than Ag-Ag. Why?



$\langle A_{part} \rangle^{Ag+Ag}_{10-20\%} = 159$ $\langle A_{part} \rangle^{Au+Au}_{30-40\%} = 150$

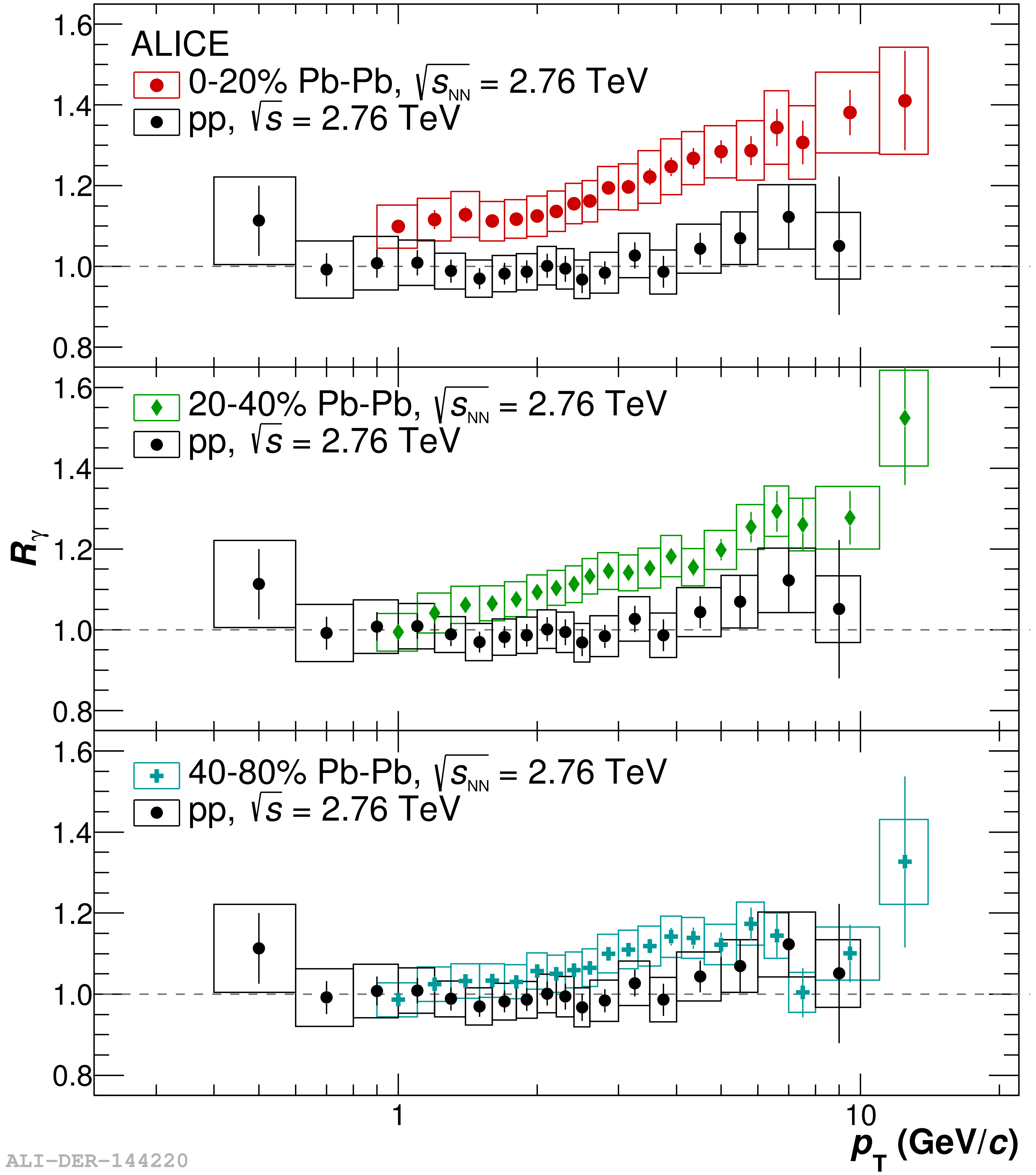
STAR dielectron spectra in Au-Au at 27 GeV and 54.4 GeV

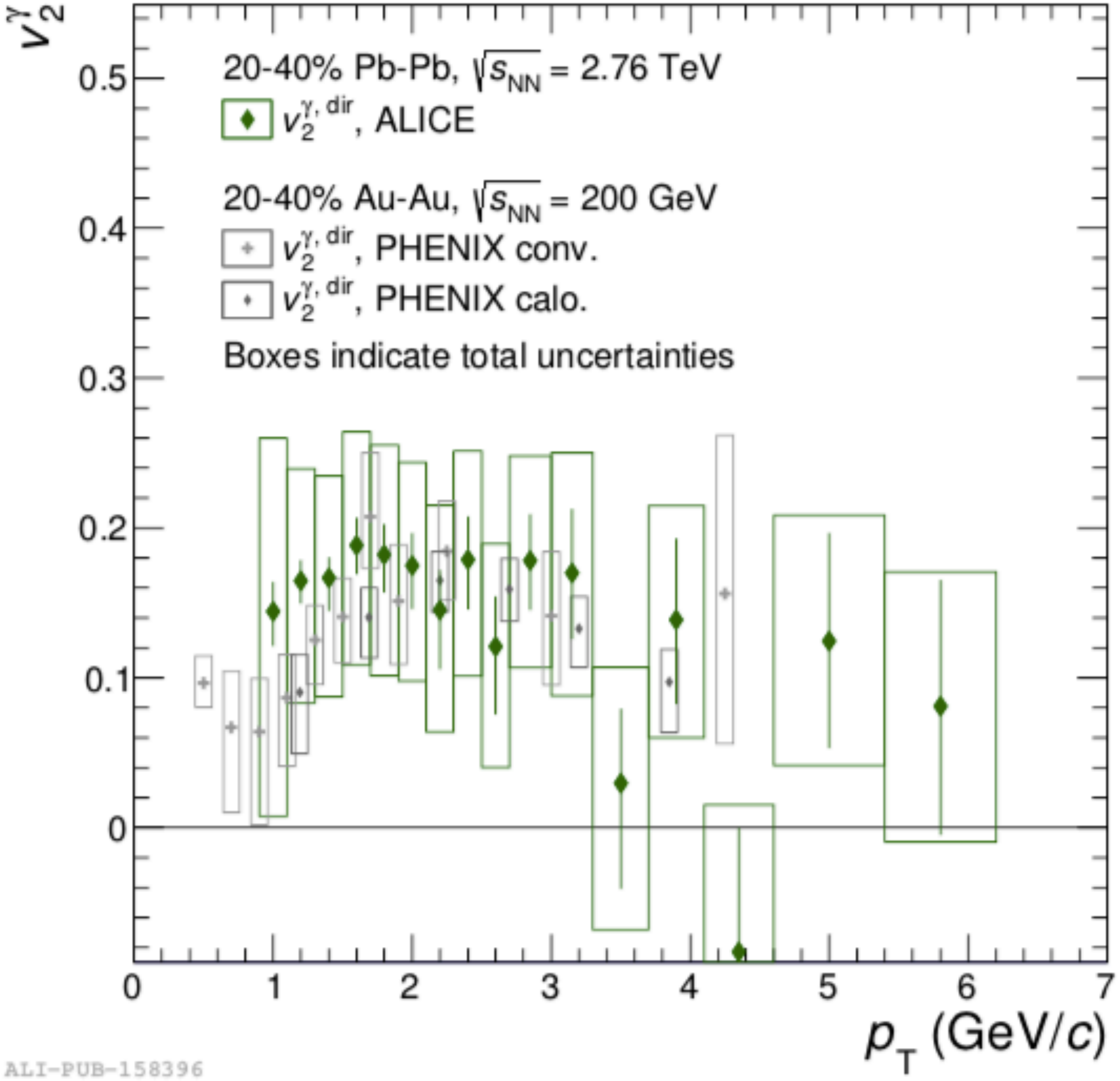




ALICE direct photon results in Pb-Pb at 2.76 TeV

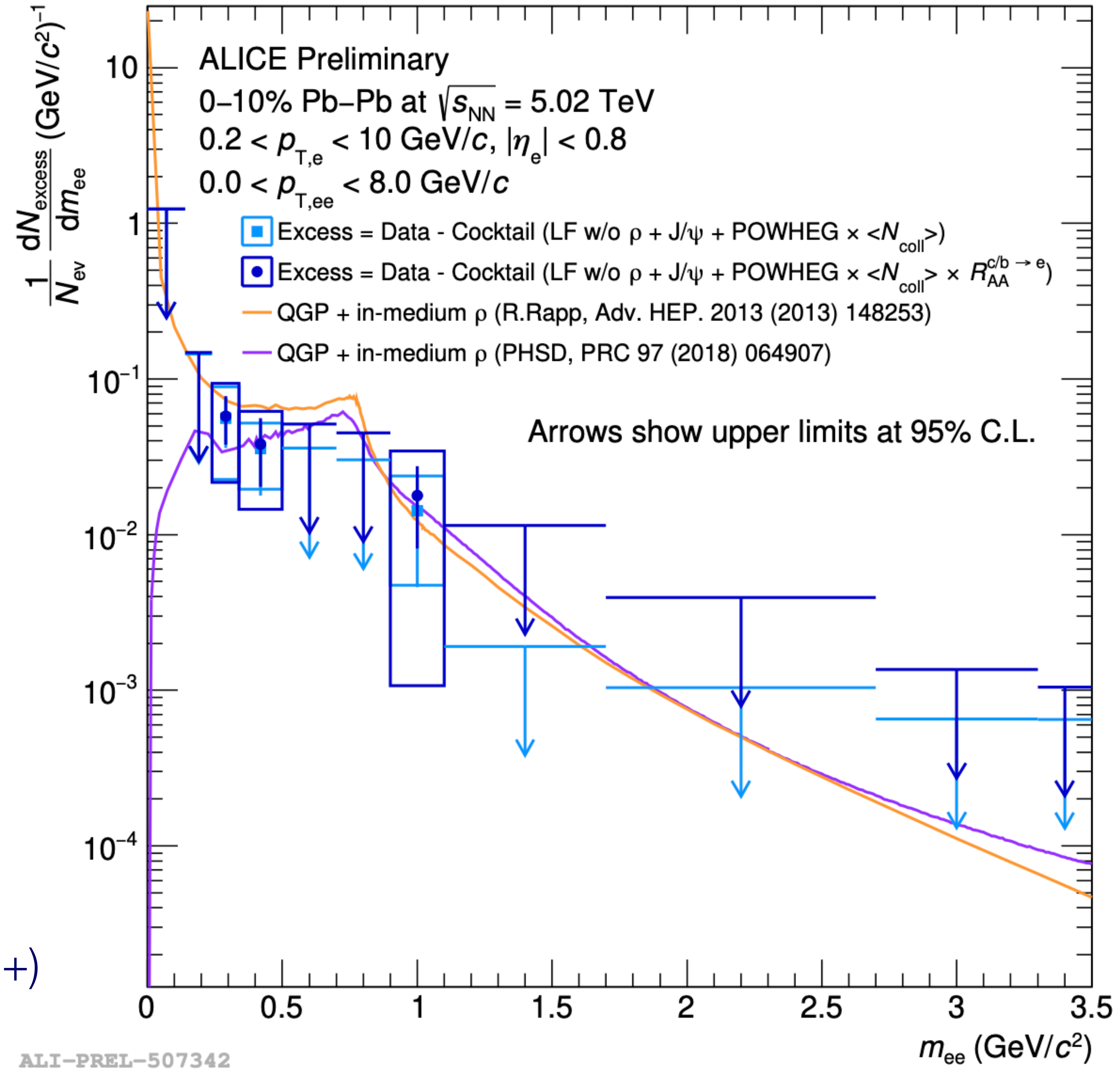
R_γ and v_2





Dielectrons at 5.02 TeV Pb-Pb from ALICE

Upper limits on dielectrons excess consistent with models



QGP radiation and ρ broadening consistent with the data

Expect temperature measurement via dielectrons from ALICE 2 (Run 3 + 4)

Time dependence of T from ALICE 3 (Run 5+)