The Direct Photon Puzzle

EMMI Physics Day 2018

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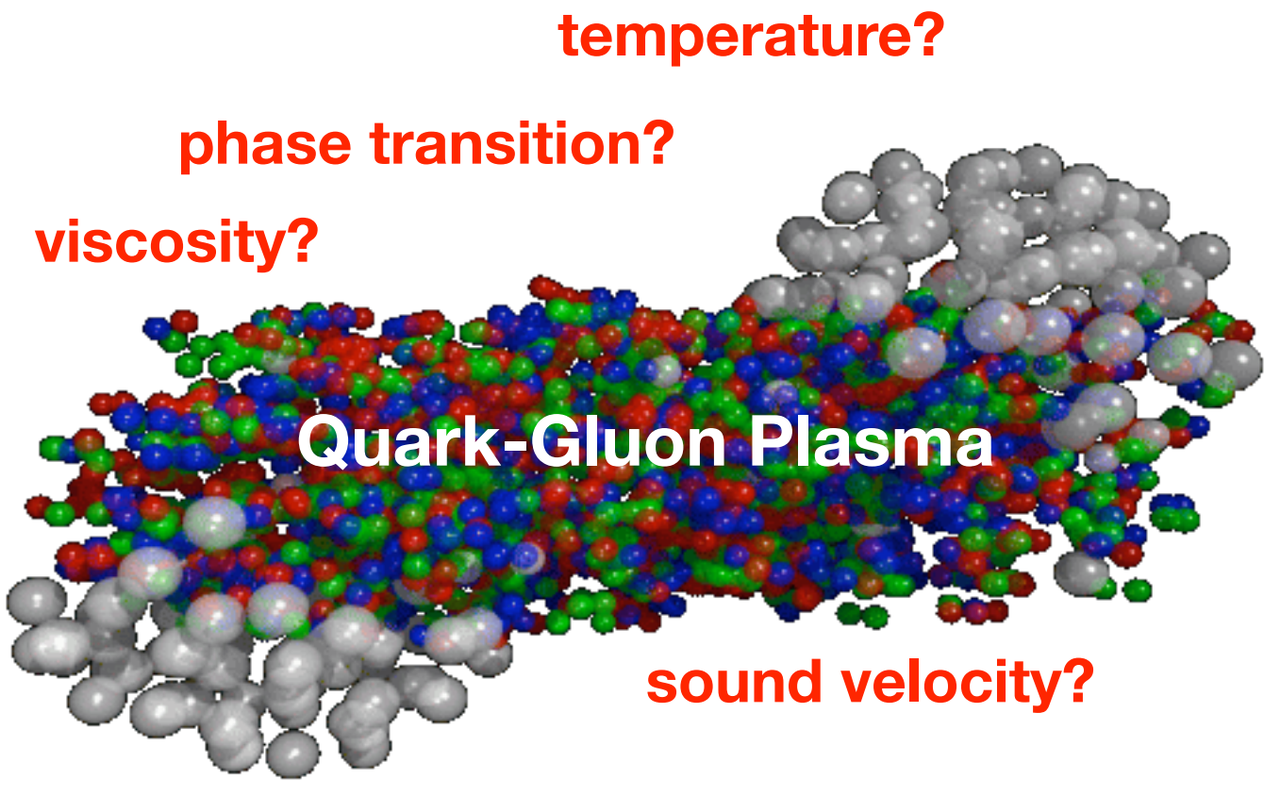
Heidelberg University
20 November 2018

Why Heavy-Ion Collisions?

- Particle physics: reductionism
- Heavy-ion physics:
  Emergent properties of QCD

More precisely:
"Material properties" of the QGP?

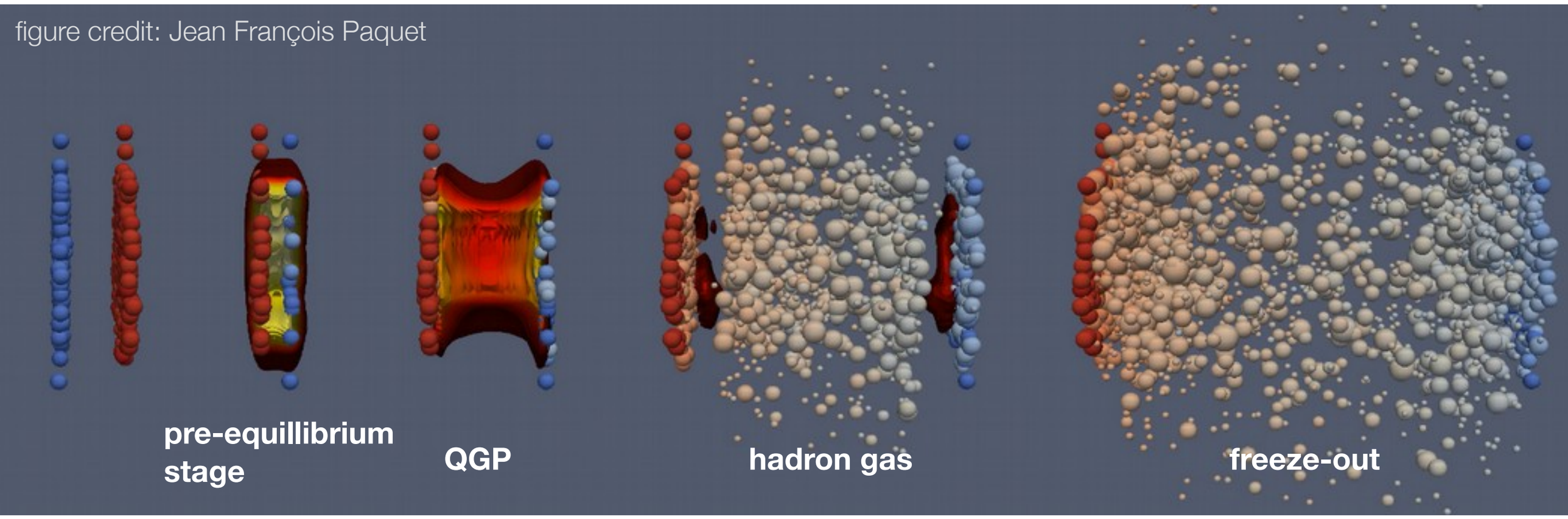


source: urqmd.org

„More is different“

Philip W. Anderson,
Science, 177, 1972, p. 393

figure credit: Jean François Paquet

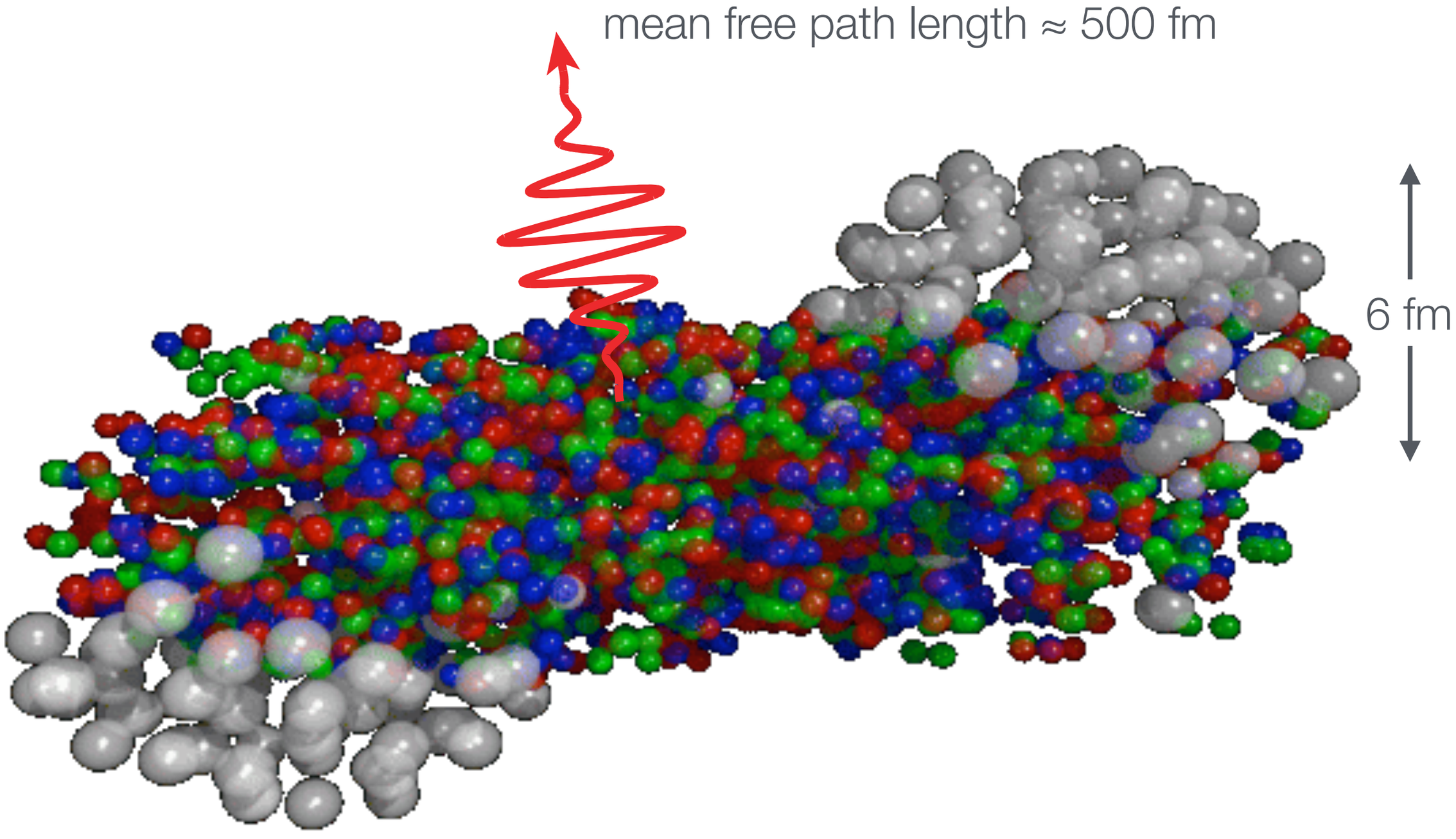


thermalization: $\tau_{\mathrm{th}} = 1\text{–}2\,\mathrm{fm}/c$

hadronization: $\tau_c \approx 10\,\mathrm{fm}/c$ (LHC)

QGP → hadron gas at $T \approx 155\,\mathrm{MeV}$

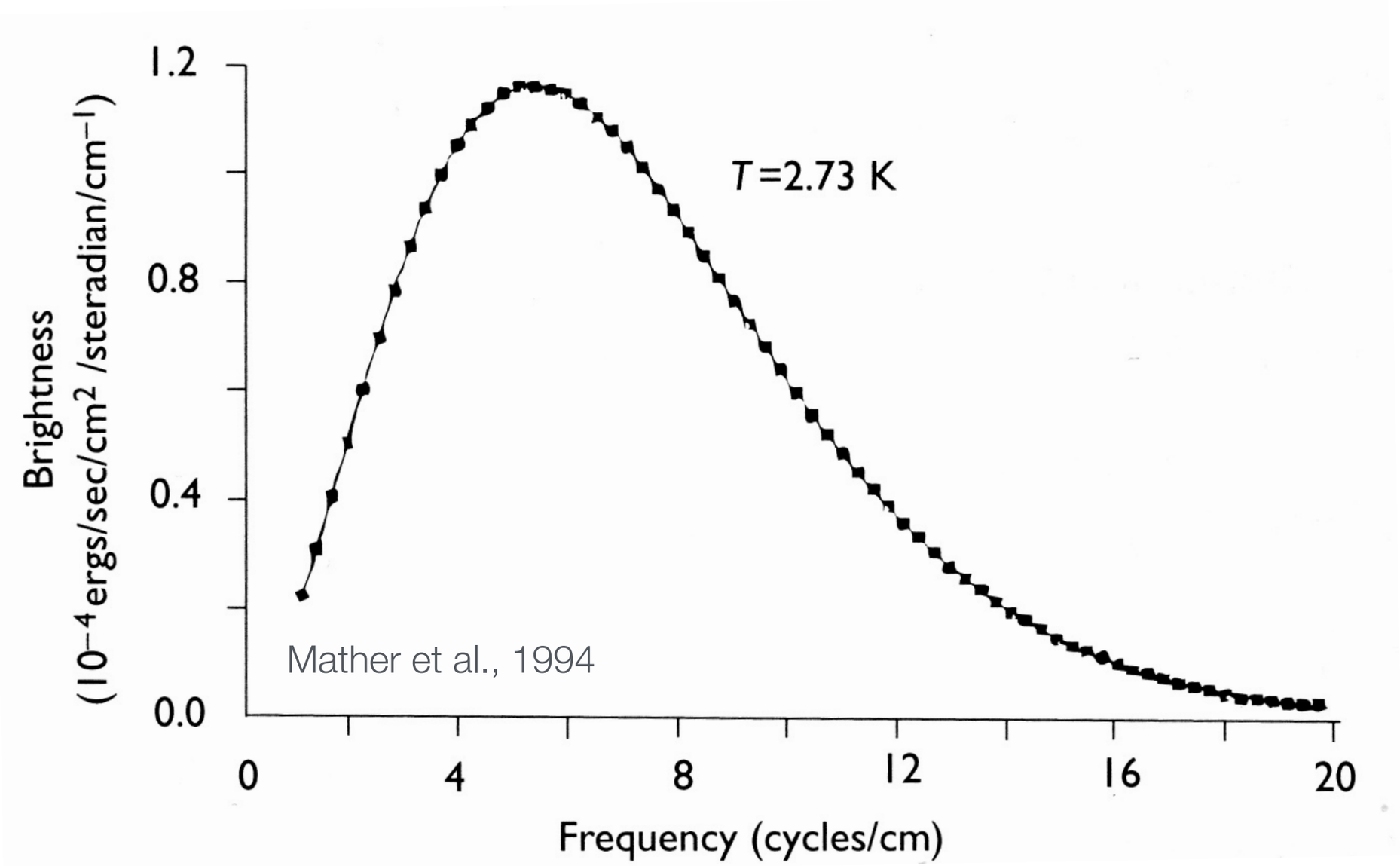
Why Photons?



Ideal tool to study the early hot QGP

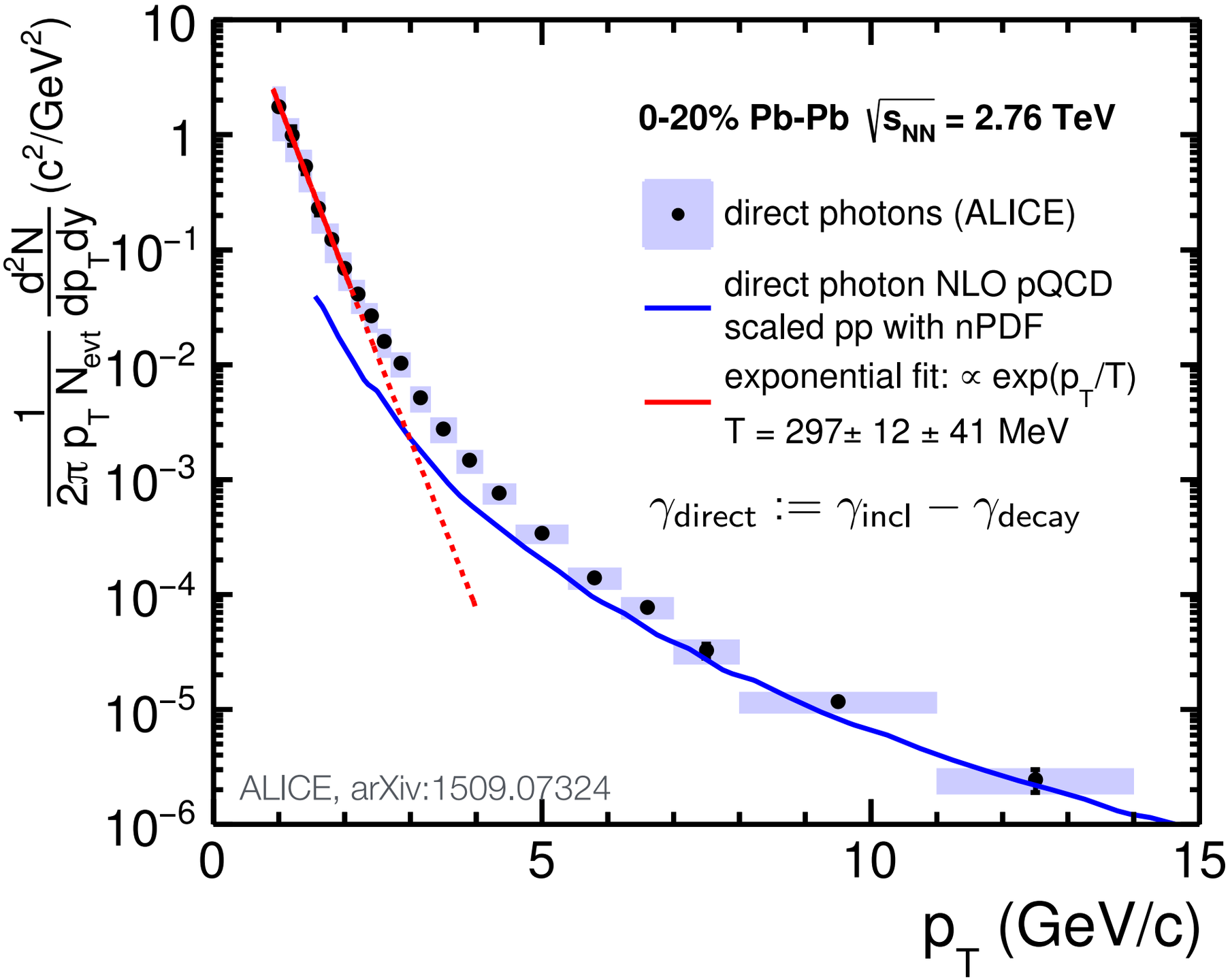
An Iconic Figures from another Field

CMB black-body spectrum (COBE)



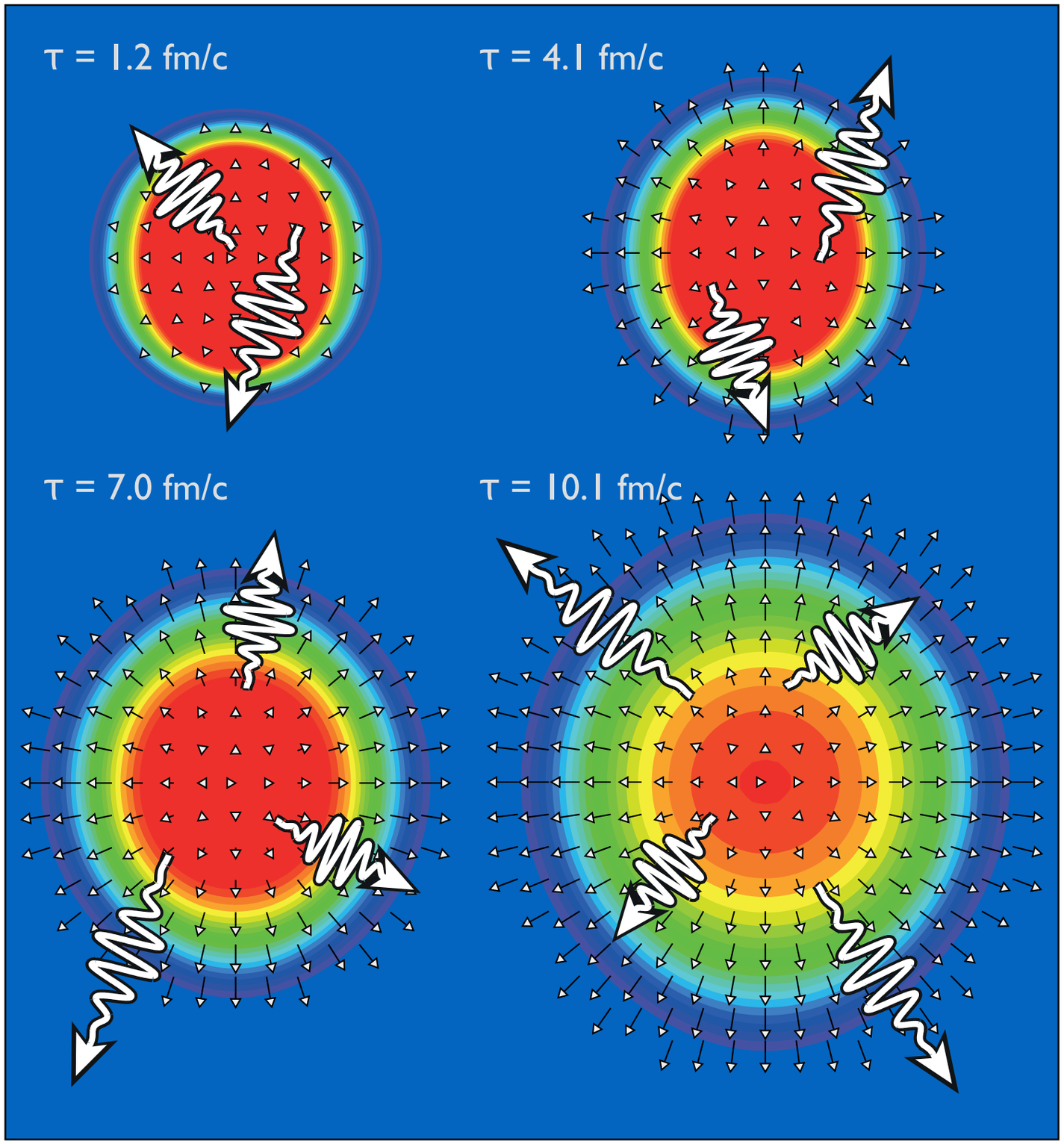
Recipe: Good data + well understood theory

A Candidate for an Iconic Figure from Heavy Ions: Planck-like Photon Spectrum



Current proxy (here from the LHC) looks already OK, but statistical significance needs to be improved

Promise: T_{QGP} from QGP photons



- Produced over the entire duration of the collision
  - Tests our understanding of the space-time evolution
  - Access to initial T_{QGP}
  - Expect more photons per pion at low p_T than in pp
- But: Slope $T_{eff} > T_{QGP}$ due to blue shift

QGP photon rate r_γ (lowest order):

$$E_\gamma \frac{\mathrm{d}r_\gamma}{\mathrm{d}^3 p} \propto \alpha\alpha_s T^2 e^{-E_\gamma/T} \log \frac{E_\gamma T}{k_c^2}$$

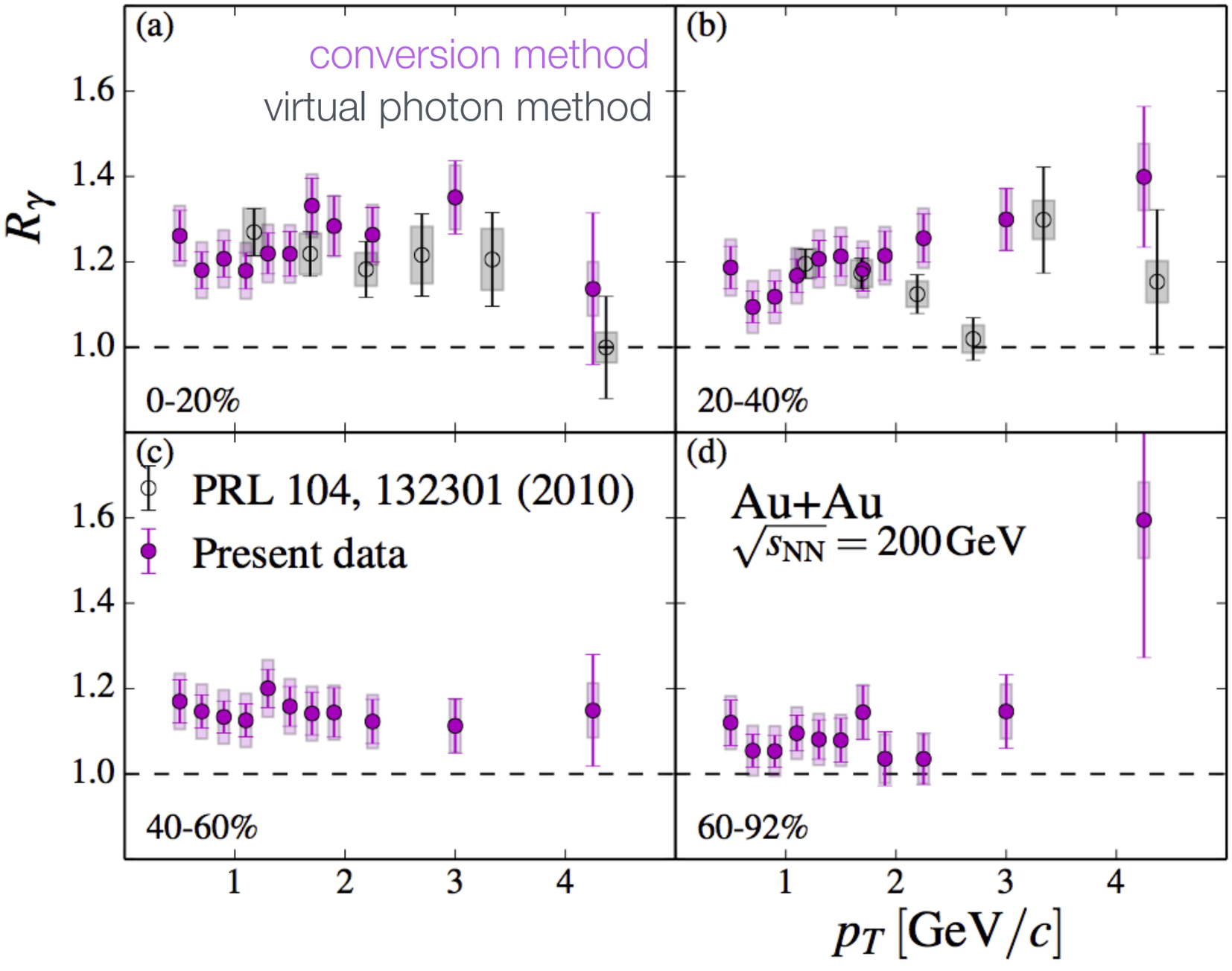
Total emission rate:

$$r_\gamma \propto T^4$$

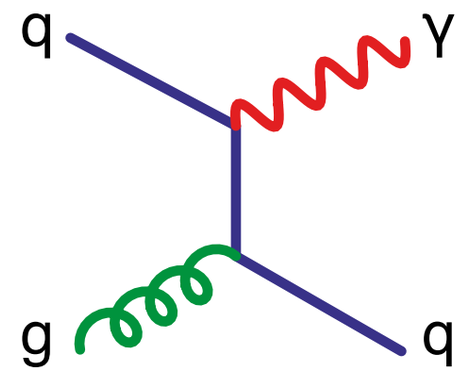
Direct Photons at RHIC (Au-Au at $\sqrt{s_{NN}} = 200$ GeV)

$$R_\gamma = \frac{\gamma_{incl}}{\gamma_{decay}} = 1 + \frac{\gamma_{dir}}{\gamma_{decay}}$$

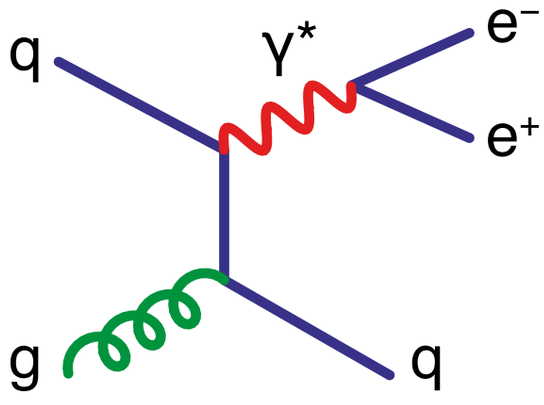
PHENIX, arXiv:1405.3940



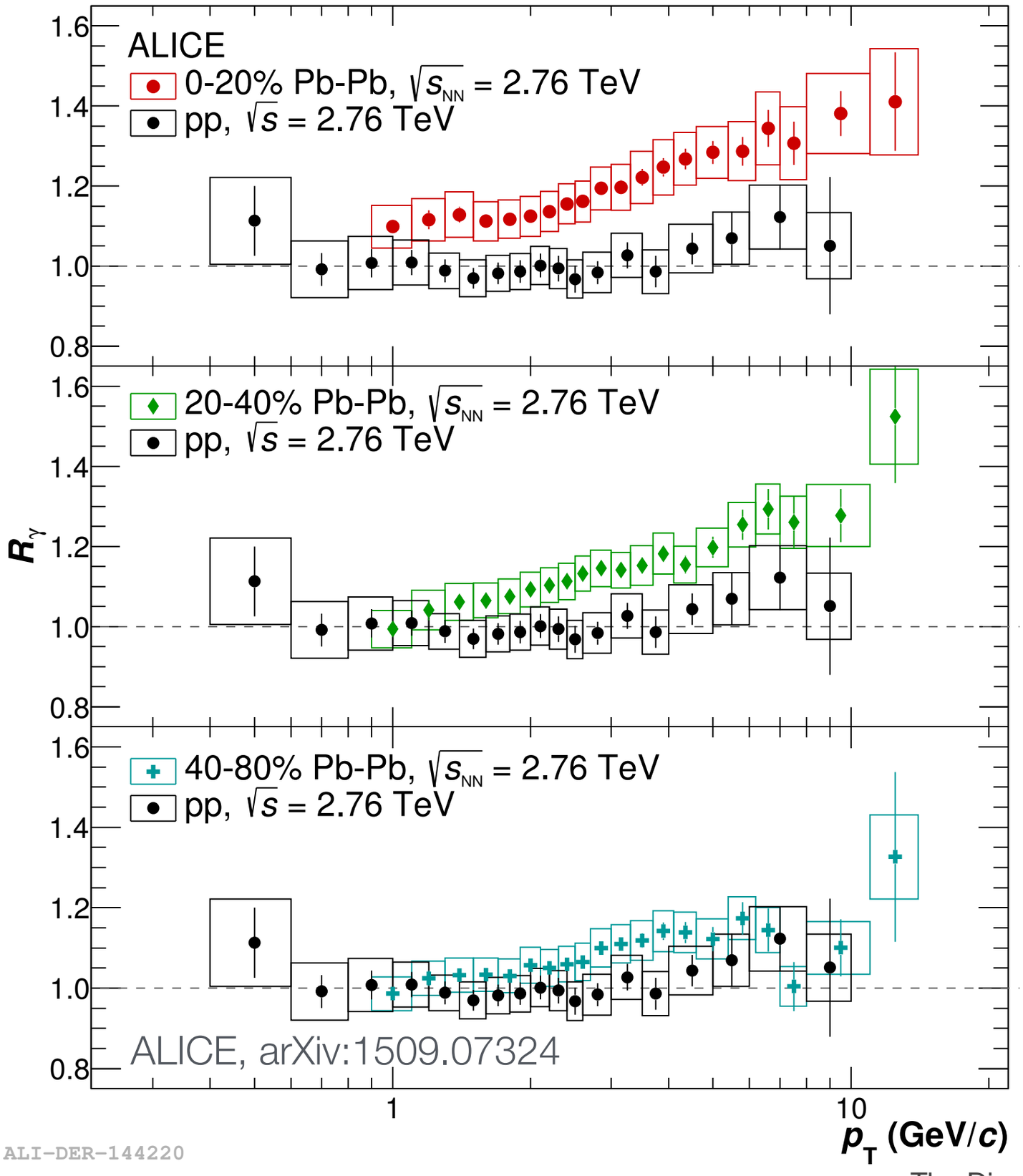
Real photons (through conversion):



Virtual photons (at $m_{ee} \gtrsim m_\pi$ extrapolated to $m_{ee} = 0$):

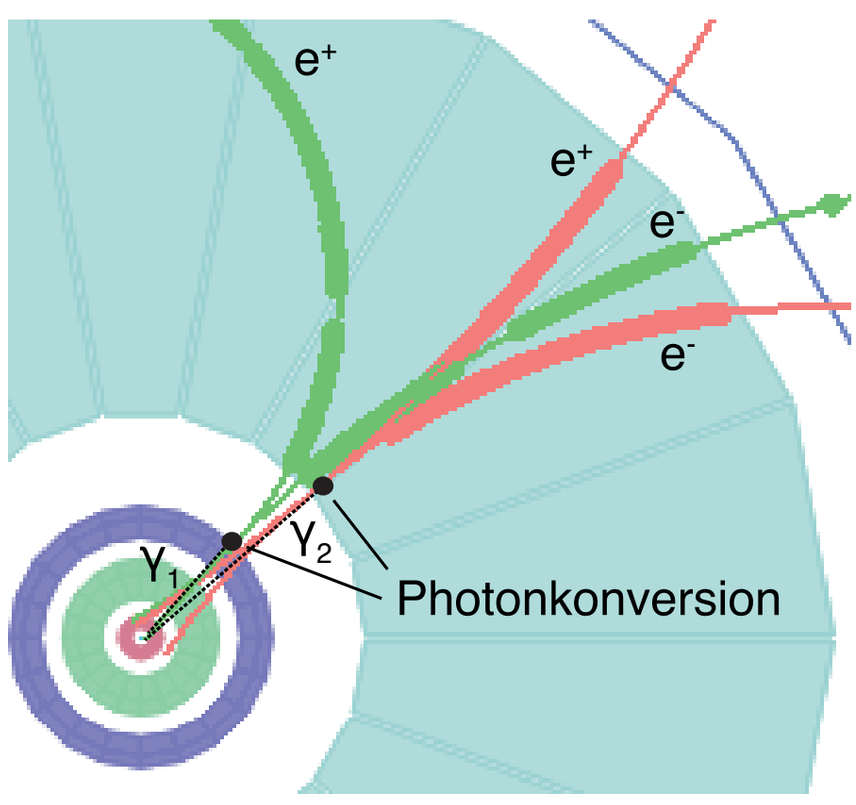


Direct Photons at the LHC (Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV)



$$R_\gamma = \frac{\gamma_{\text{incl}}}{\gamma_{\text{decay}}} = 1 + \frac{\gamma_{\text{dir}}}{\gamma_{\text{decay}}}$$

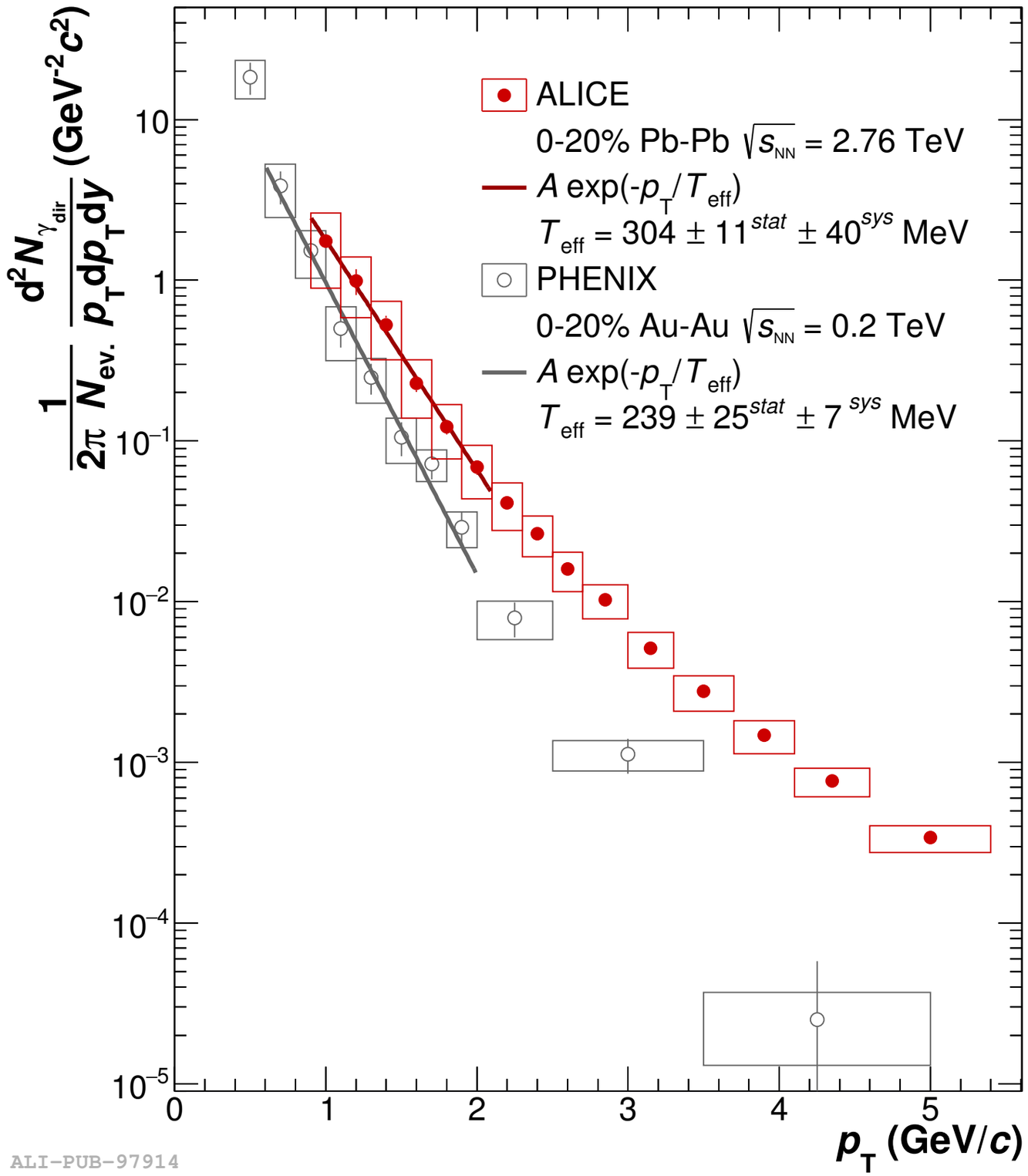
- Excess in Pb-Pb
- No low-p_T excess in pp
- Consistent with thermal radiation



+ PHOS calorimeter measurement

ALI-DER-144220

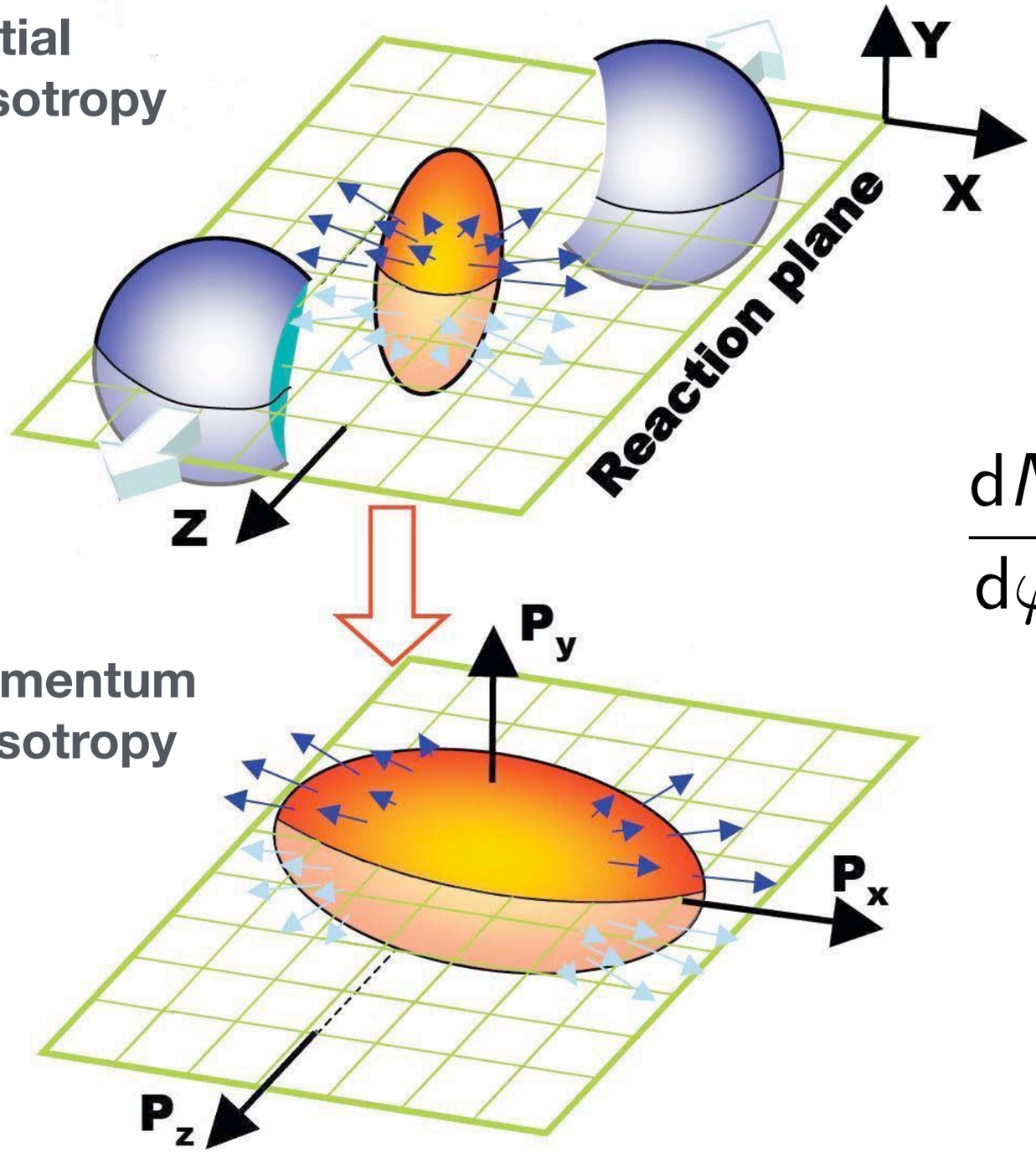
Larger T_{eff} at the LHC



- T_{eff} LHC
  - 0-20% Pb-Pb@2.76 TeV
  - without pQCD subtraction: $T_{eff} = 304 \pm 11^{stat} \pm 40^{sys}$ MeV
  - with pQCD subtraction: $T_{eff} = 297 \pm 12^{stat} \pm 41^{sys}$ MeV
- T_{eff} RHIC
  - 0-20% Au-Au@0.2 TeV
  - $T_{eff} = 239 \pm 25^{stat} \pm 7^{sys}$ MeV (pp parameterization subtracted)

Elliptic Flow

spatial anisotropy

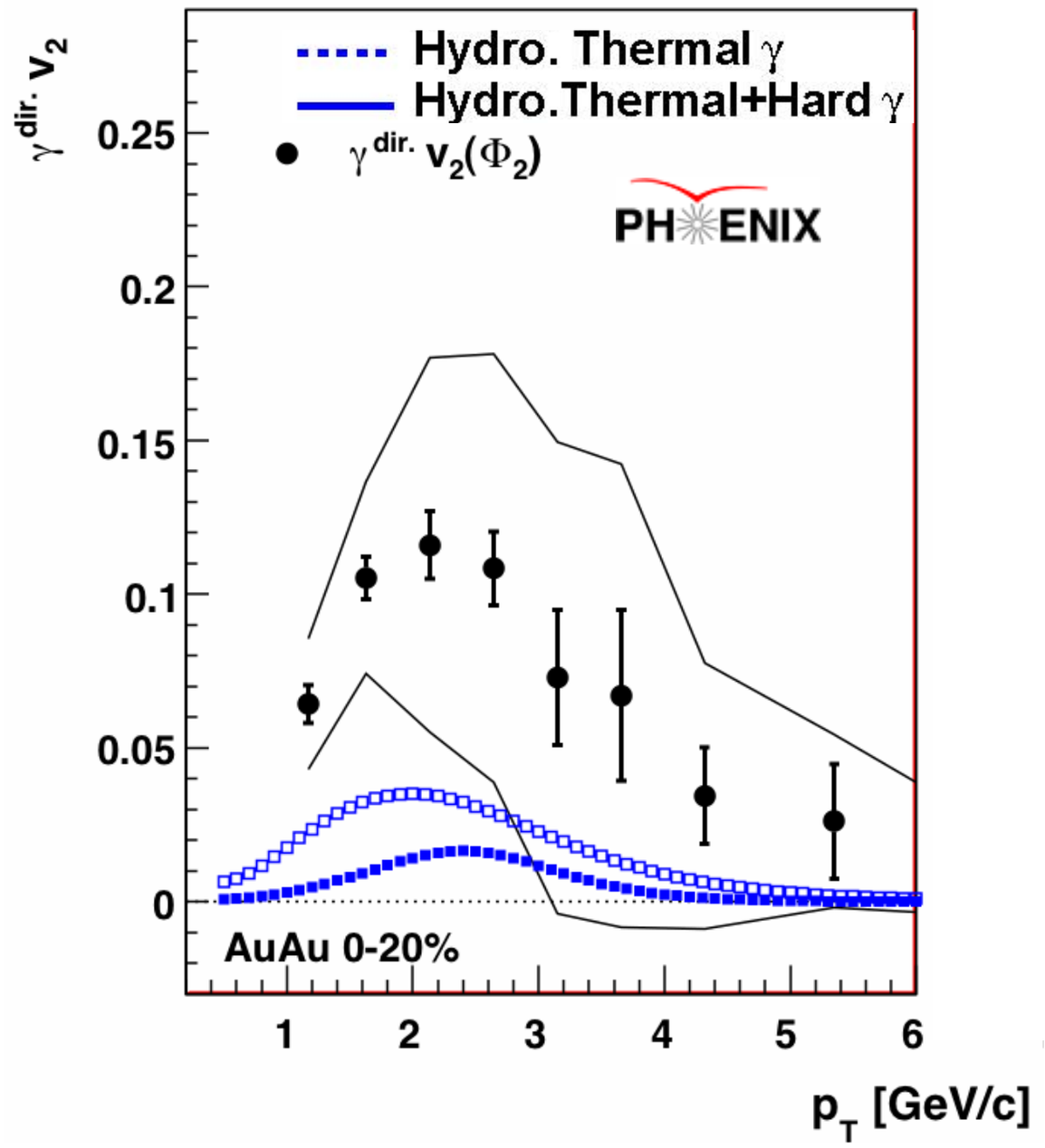


momentum anisotropy

$$\frac{dN}{d\varphi} = N_0 \left(1 + 2v_2 \cos(2\varphi)\right)$$

Direct Photon Puzzle

PHENIX, Quark Matter 2011

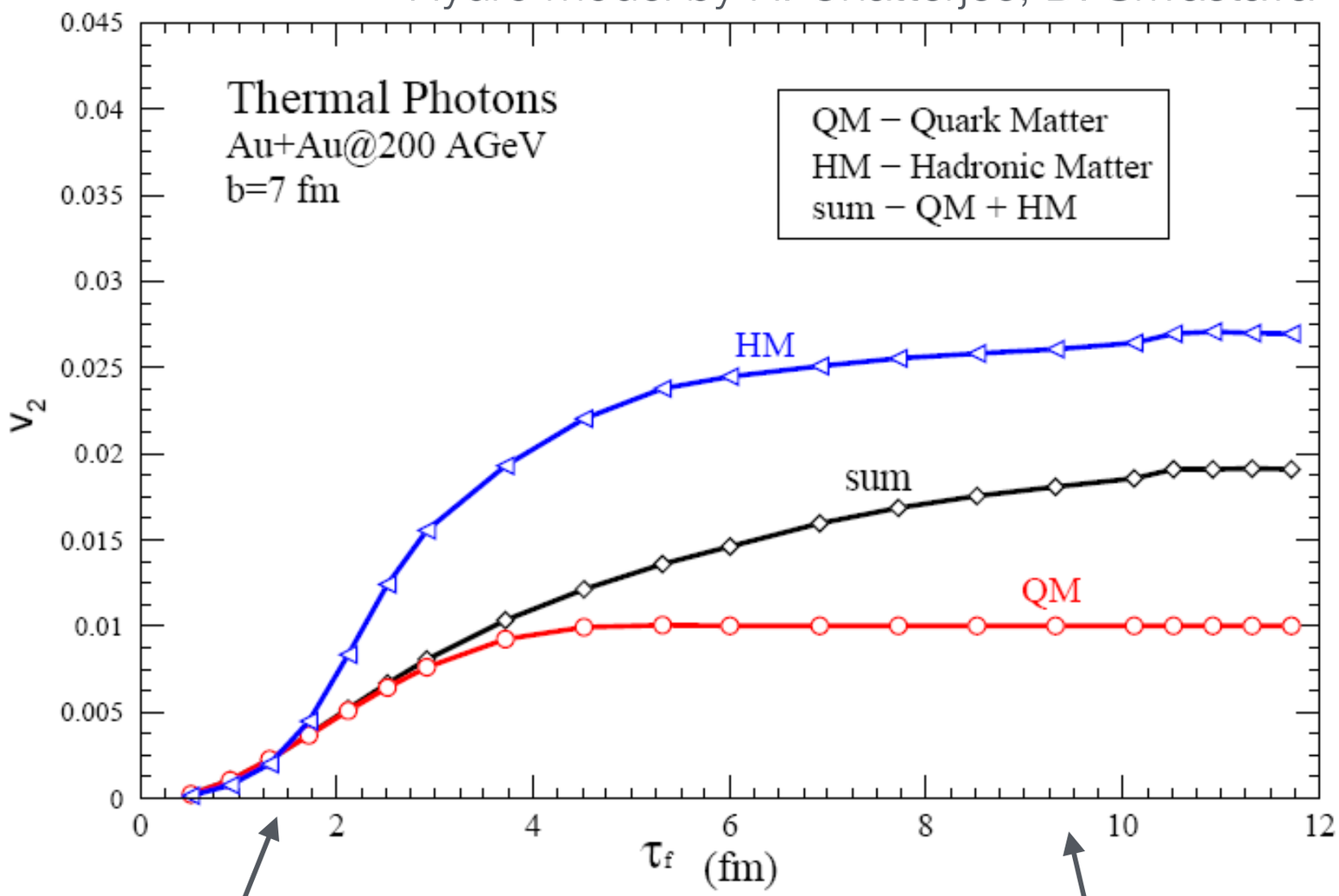


- Around since 2011
- PHENIX:
  "Data a challenge to theory"
- Theorist (Ch. Gale):
  "Theory a challenge to the data"

What's actually so puzzling?

Elliptic flow builds up gradually with time in hydro models:

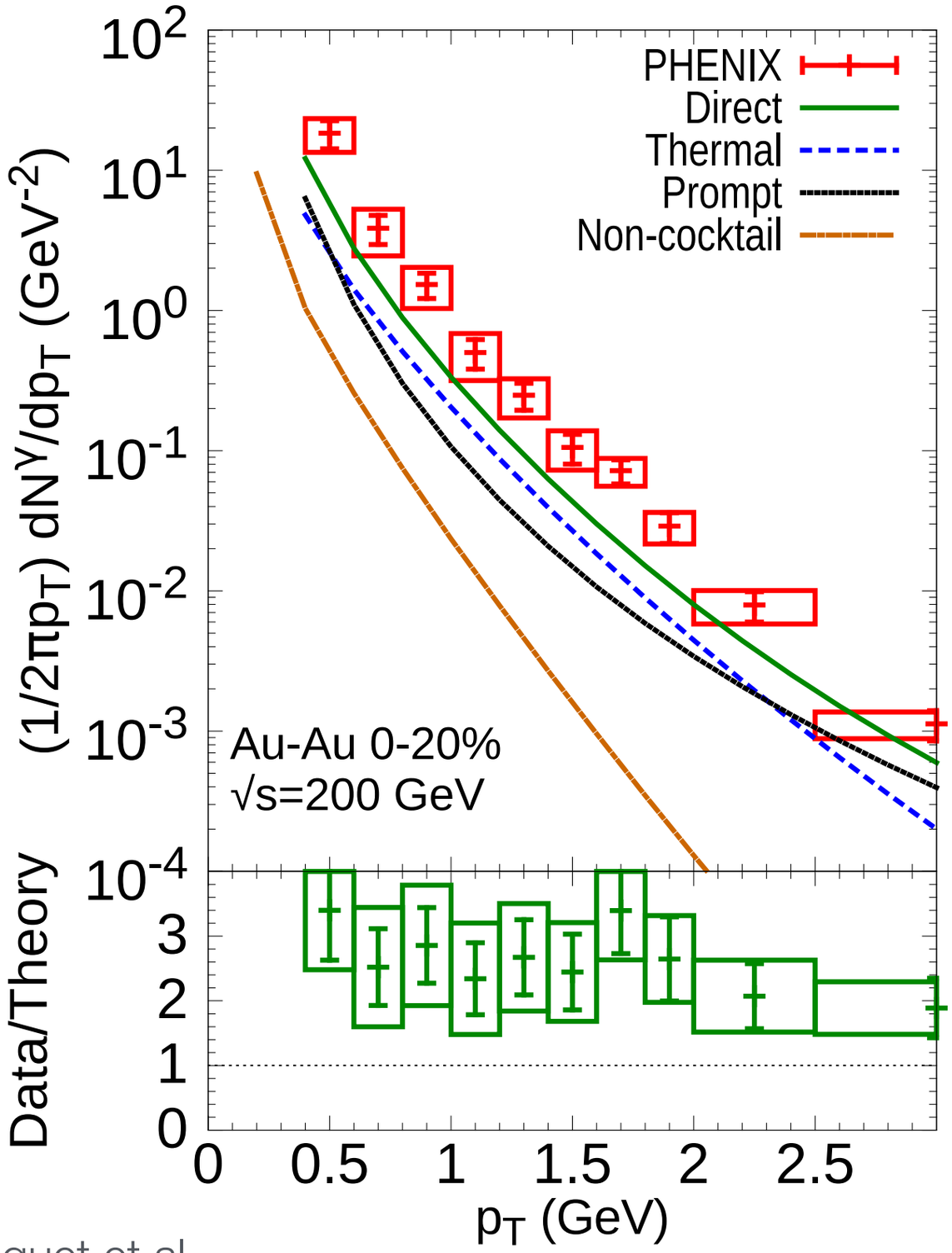
Hydro model by R. Chatterjee, D. Srivastava

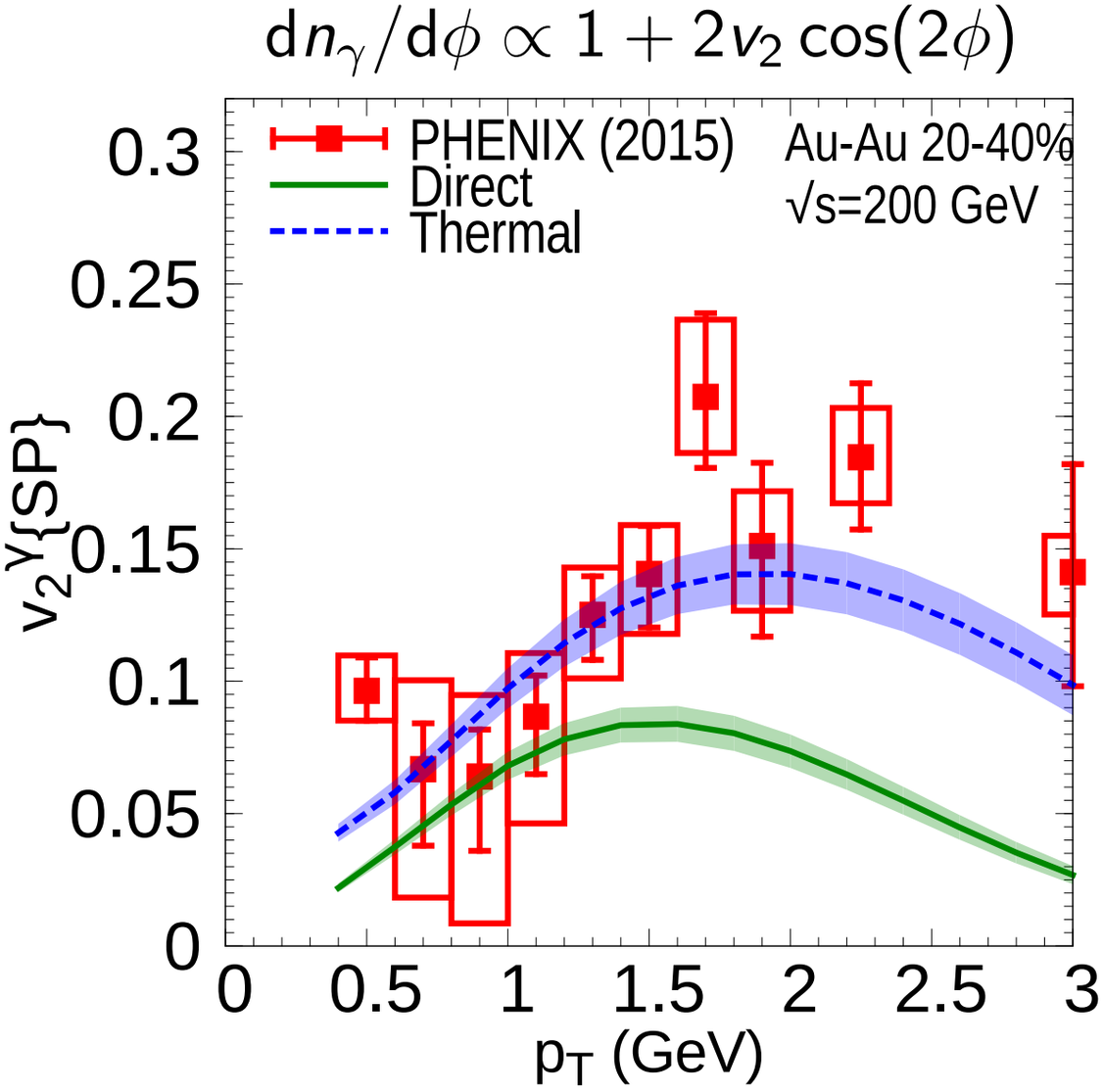


Expect large fraction of thermal photons from early times

Expect bulk of hadrons to be produced at late times

Direct-Photon Puzzle: Status

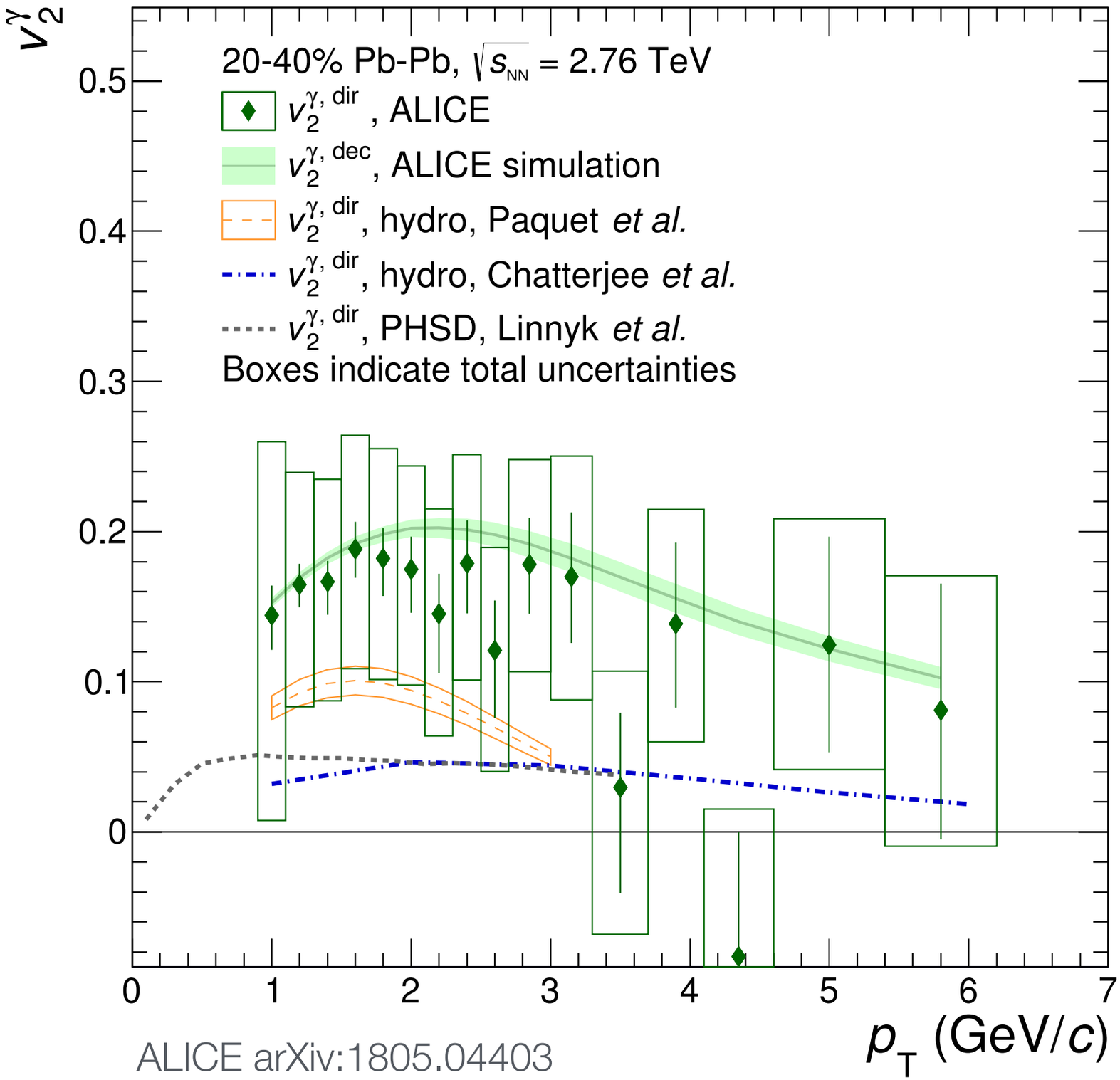




- Challenging for hydro models to describe v_2 and yield
- ALICE γ_{dir} and v_2:
  "No puzzle within current errors"

Paquet et al.,
arXiv:1509.06738

ALICE Direct-Photon v_2



ALICE arXiv:1805.04403

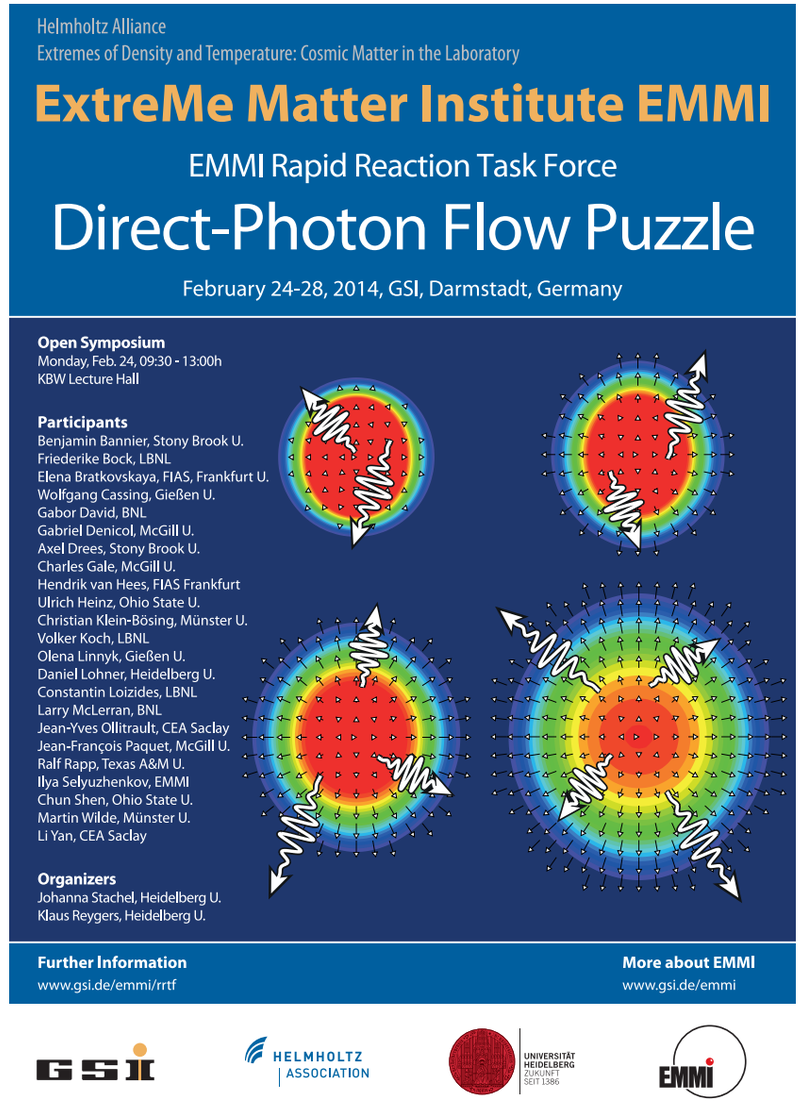
Large $v_{2,\mathrm{dir}}$:

$$v_{2,\mathrm{dir}} \approx v_{2,\mathrm{decay}}$$

But no puzzle within the current uncertainties

EMMI Rapid Reaction Task Force on the Direct Photon Flow Puzzle

- Feb. 2014, 25 participants (theory + experiment)
- Open Symposium:
  https://indico.gsi.de/conferenceDisplay.py?confId=2662
- Detailed discussions on
  - Averaging of v_n over large centrality bins, definition of v_n in models
  - Definition of decay photon cocktail in experiment and models, contribution from short-lived resonances
  - Comparison of the space-time evolution (hydro models, PHSD, parameterized fireball evolution)
  - pQCD contribution in various models
  - Initial flow, near T_c enhancement of photon rates, bremsstrahlung photons in the hadrons gas, Glasma photons, role of fragmentation photons, …
- Puzzle remains after checking various aspects of the data/theory comparison



Resolution of the direct photon puzzle

experiment

- decay photon cocktail?
- …

theory

early stage

- Glasma?
- transport models (e.g. BAMPS) [2]
- Initial *B* field?

late stage ($T \approx T_c$)

(→ large T_{eff} due to blue shift)

- π+π → π+π+γ (e.g. PHSD model [1])
- "radiative hadronization"?
- …

?

Possible paradigm shift concerning role of photons as QGP messengers?

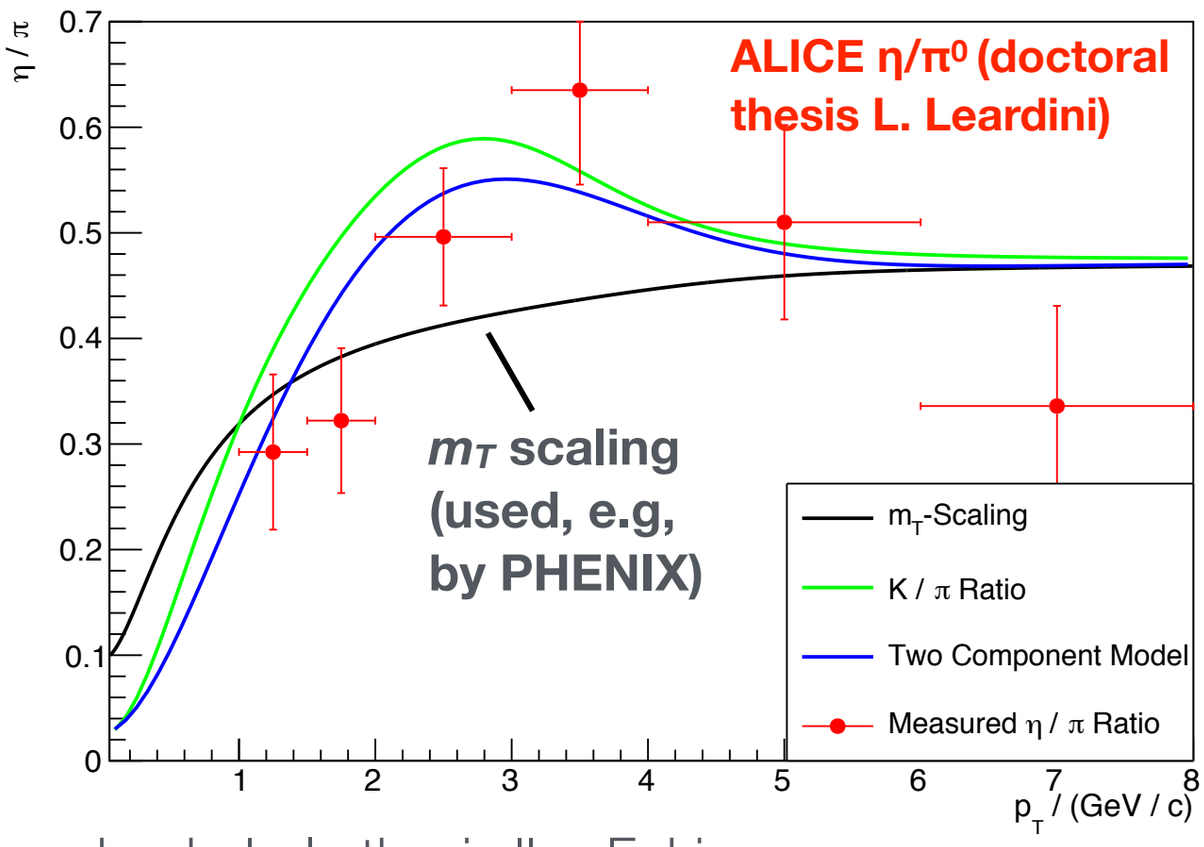
[1]: O. Linnyk et al, 1512.08126
[2]: M. Greif et al, 1612.05811

Decay Photon Cocktail: Beyond m_T scaling for η, ω, η', …

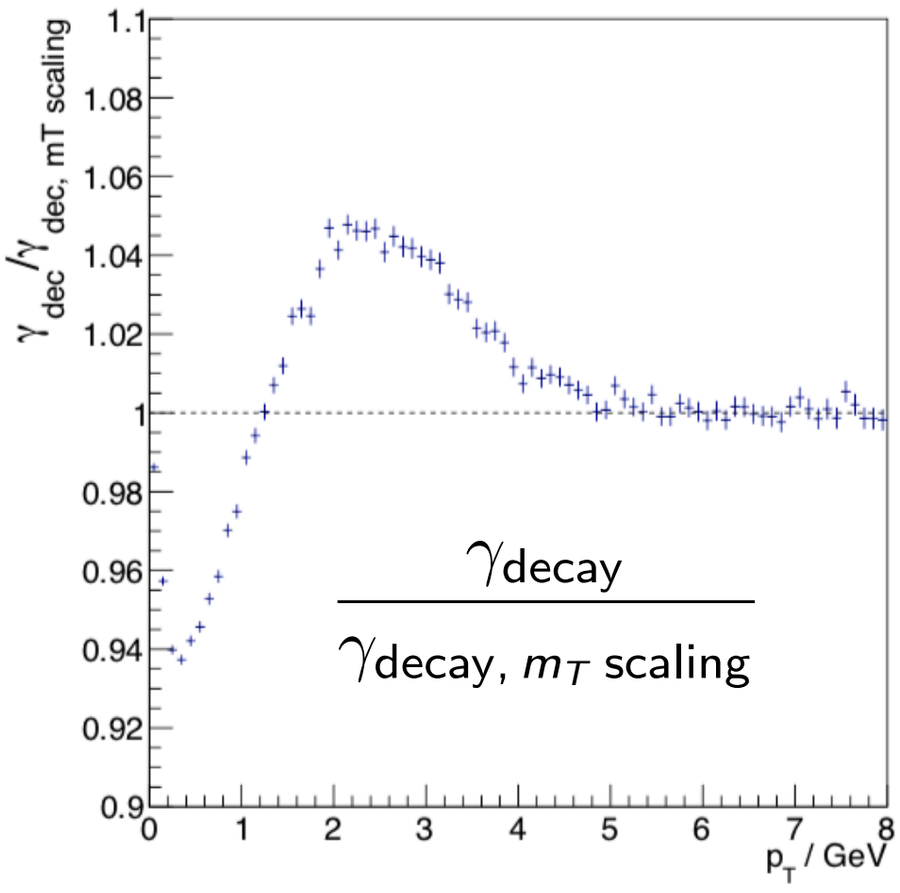
m_T scaling often used to model spectra of η, ω, …:

$$\frac{1}{p_T}\frac{\mathrm{d}n}{\mathrm{d}p_T} \propto f(m_T), \quad m_T = \sqrt{m^2 + p_T^2}$$

→ Include effect of radial flow (which breaks m_T scaling)

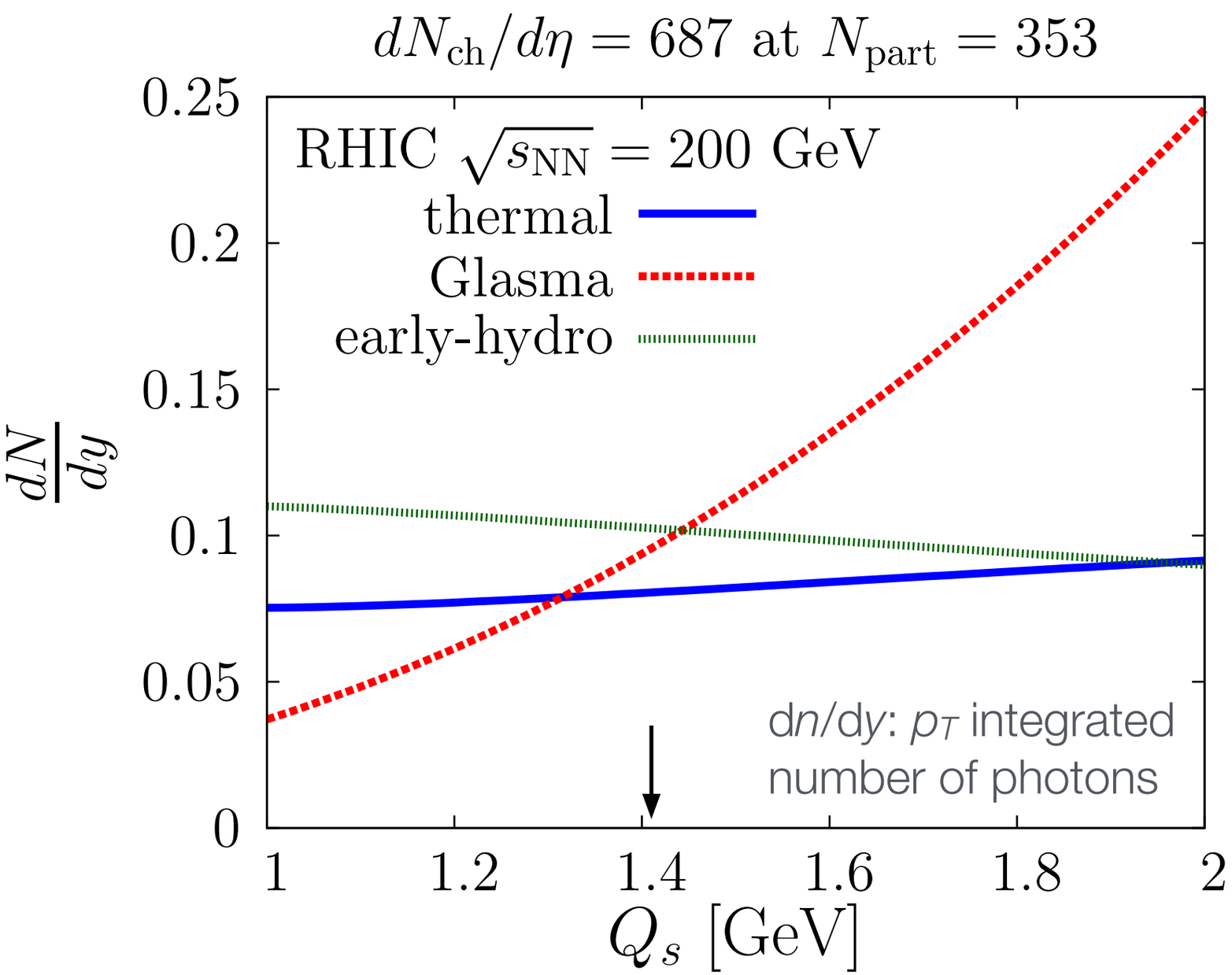


bachelor's thesis Ilya Fokin



Know your baseline!

Early Stage: Glasma Contribution to total Photon Yield might be Sizable



Parametric estimate

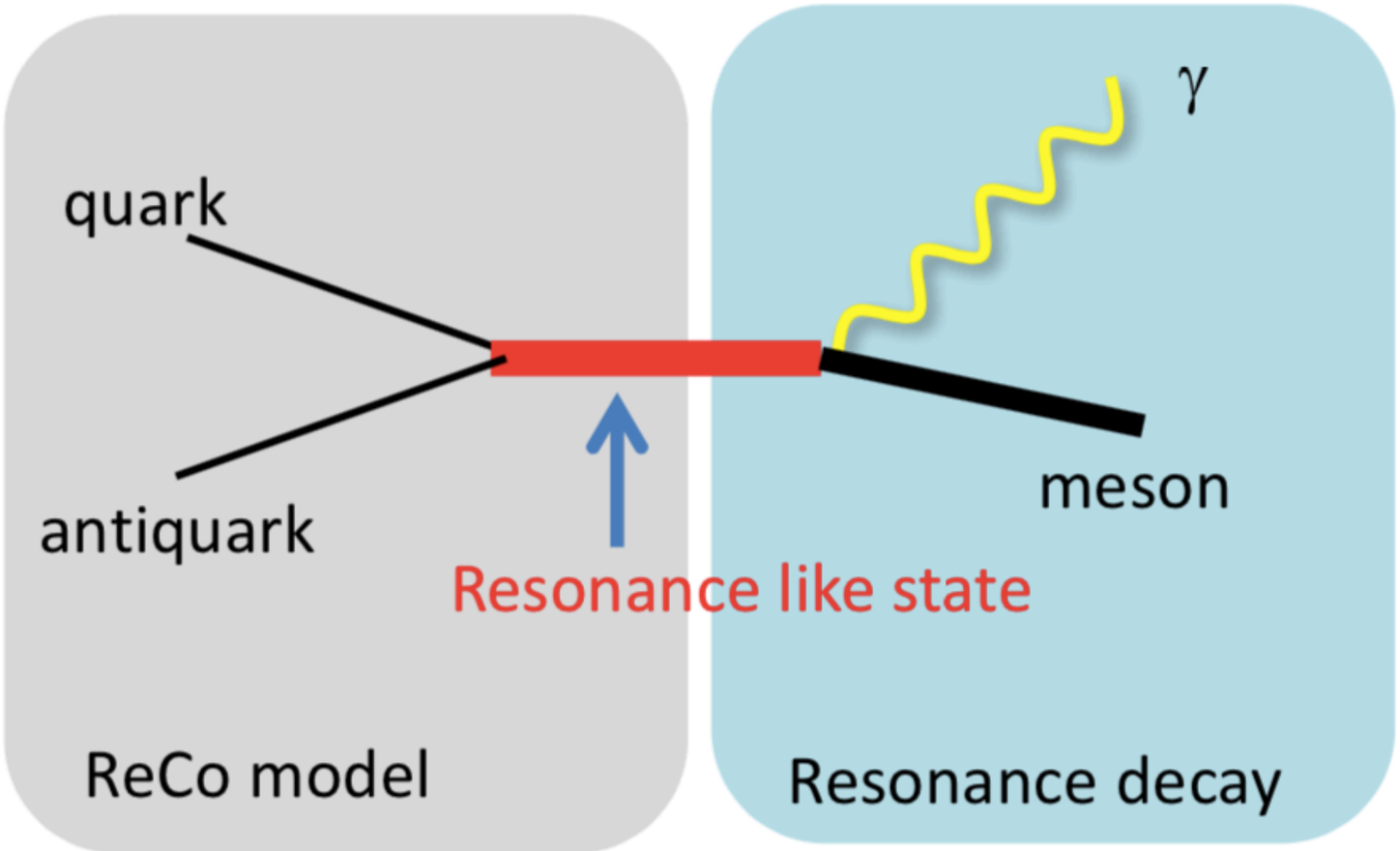
Modeling of pre-equilibrium stage: "bottom-up thermalization"

current hydro models: early-hydro + thermal

consistent weak coupling approach: Glasma + thermal

arXiv:1701.05064 (J. Berges, KR, N. Tanji, R. Venugopalan)

Late Stage: Radiative Recombination?



- Naturally:

$$v_2(\gamma) \approx v_2(\text{hadron})$$

- Large T_{eff} due to blue shift

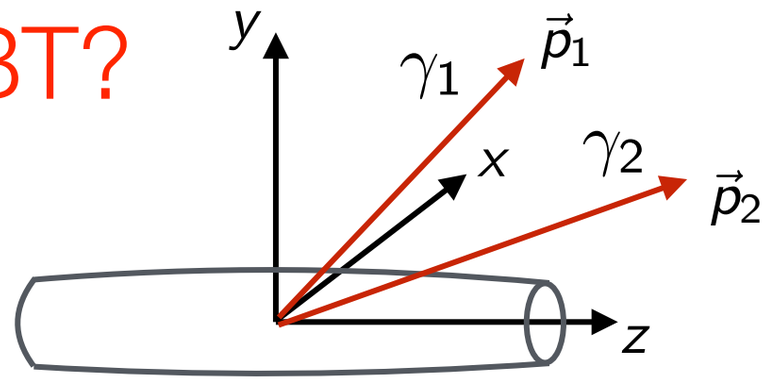
$$T_{\text{eff}} \approx \sqrt{\frac{1+\beta}{1-\beta}}\, T$$

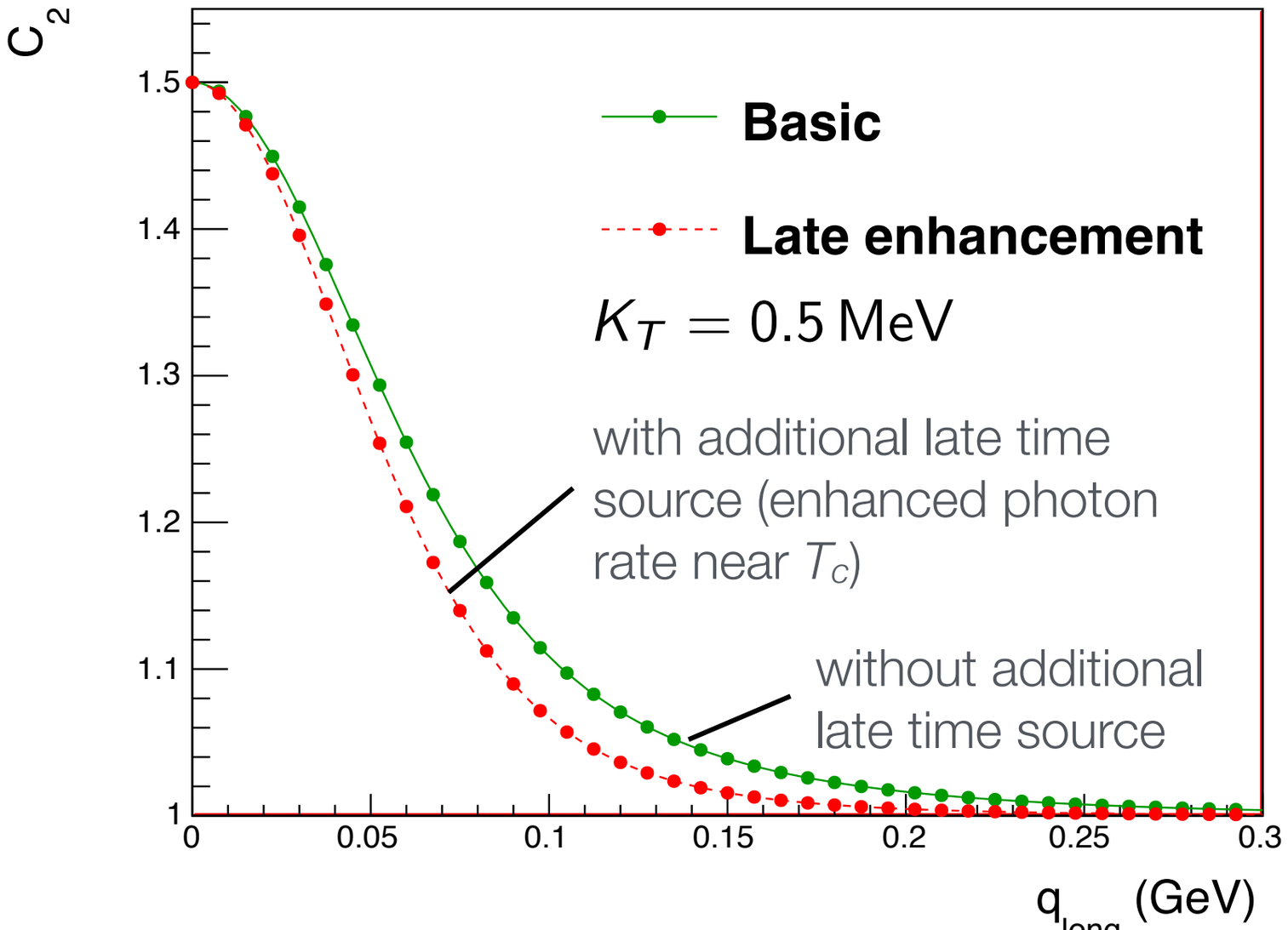
- "Saves" energy conservation in recombination models

Fujii, Itakura, Nonaka, Nucl.Phys. A967 (2017) 704-707
Young, Pratt, 1511.03147

Early or late stage production: Constraints from Photon HBT?

$$C_2 = \frac{f(\vec{p}_1, \vec{p}_2)}{f(\vec{p}_1) f(\vec{p}_2)}$$



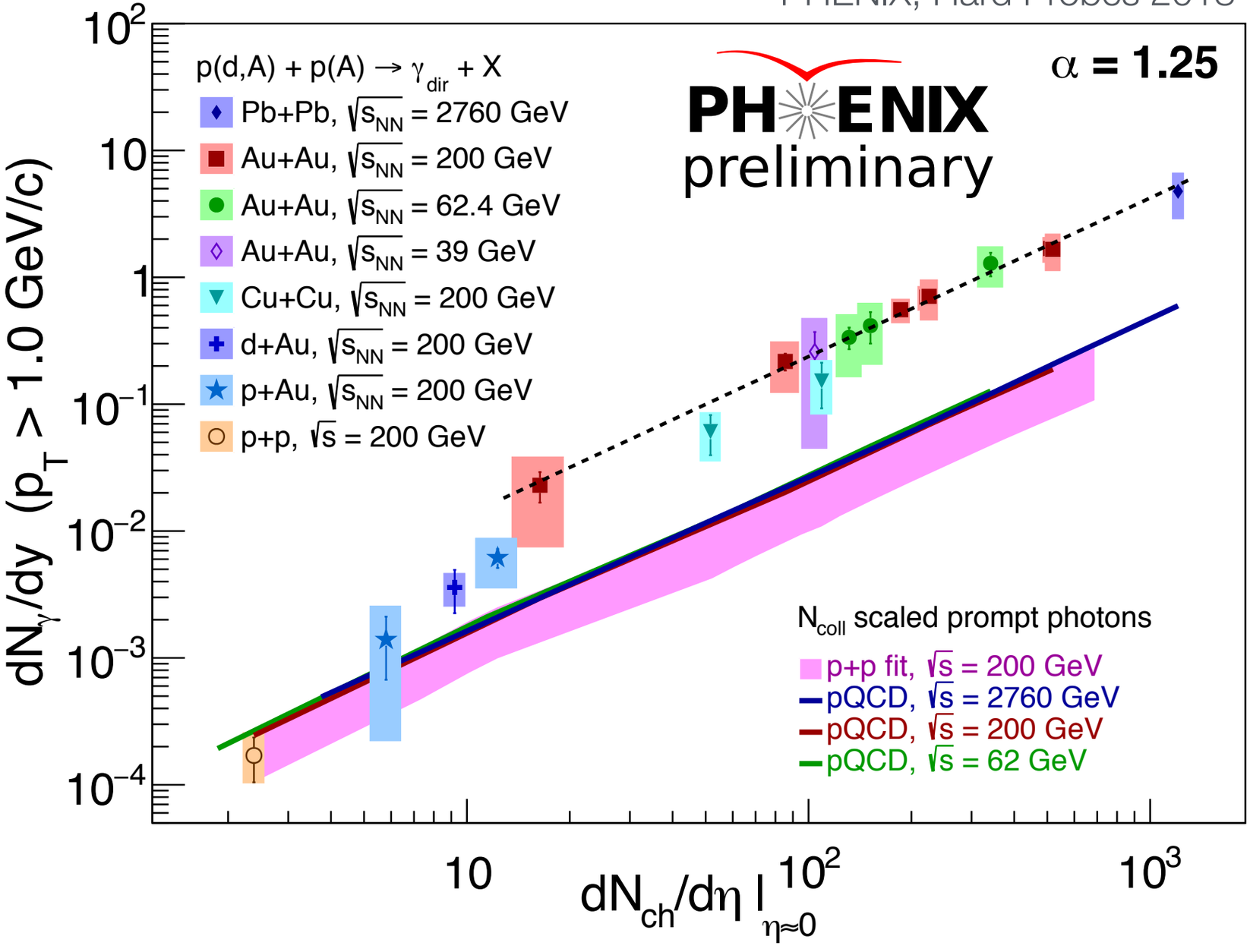


- Photon rate around T_c increased to describe data
- Narrower correlation for scenario with enhanced photon rate near Tc
- Will be hard to measure, even in future high-statistics runs at the LHC

N. Löher, O. Garcia-Montero, A. Mazeliauskas, J. Berges, KR, J. Stachel, in preparation

Do the Data Speak for Themselves? Universal Scaling?

PHENIX, Hard Probes 2018



- Rather universal scaling with $\alpha \approx 1.25$
- Onset for $dN_{ch}/d\eta = 10–20$

$\alpha = 1.25 \triangleq N_{coll}$ scaling $\Rightarrow$ photons related to initial parton scattering?

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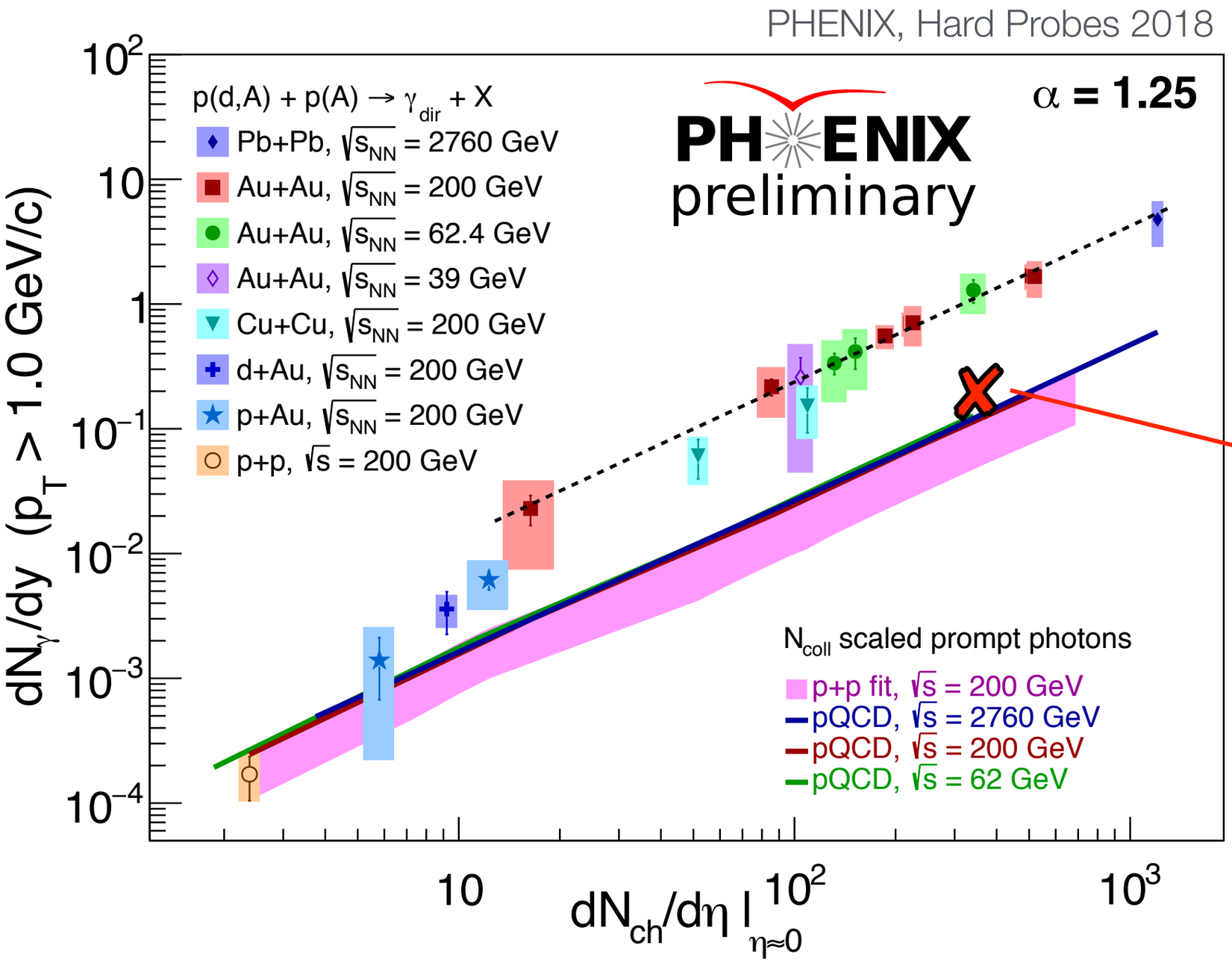

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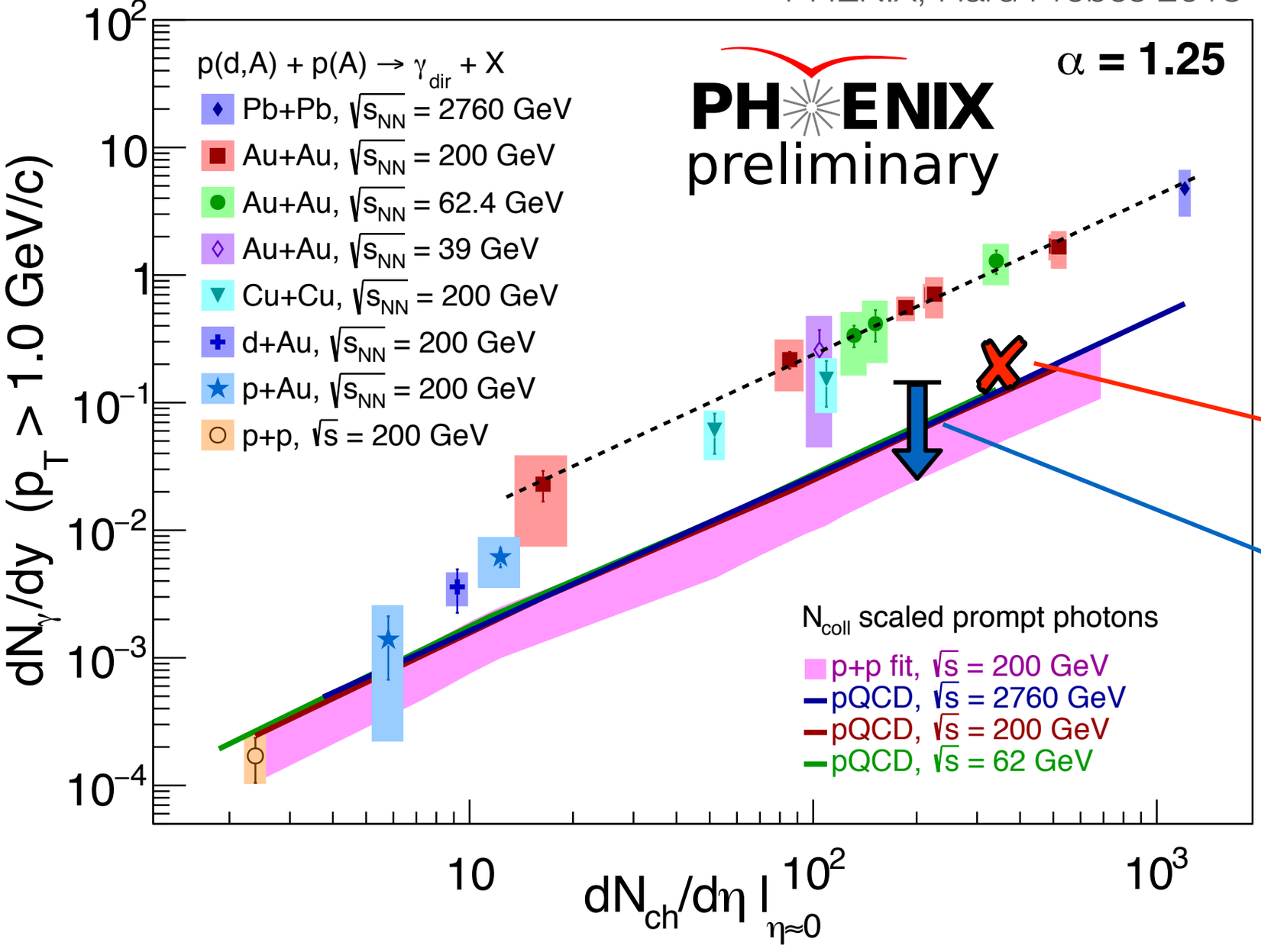
PHENIX, Hard Probes 2018



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WA98
(Pb-Pb, 158 *A*·GeV)

Ceres
(S-Au, 200 *A*·GeV)

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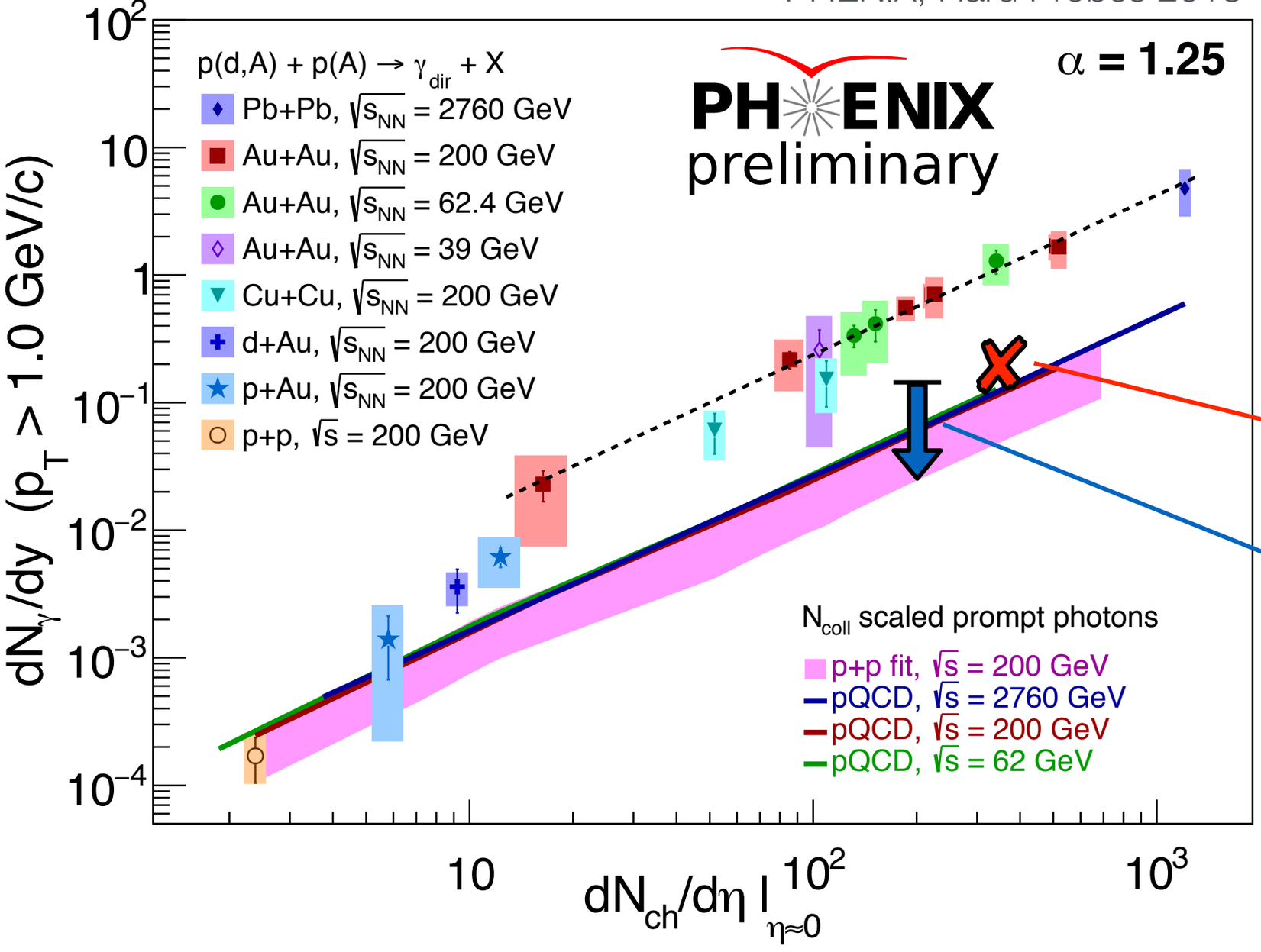
PHENIX, Hard Probes 2018



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(Pb-Pb, 158 *A*·GeV)

Ceres
(S-Au, 200 *A*·GeV)

[also STAR data lower than PHENIX]

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Conclusions

- Direct photon puzzle still with us
- Currently mostly at RHIC
- Something rather fundamental in heavy-ion collisions not fully understood
- Possible paradigm shift:
  Photon production dominated by late stage around T_C?
- High statistics LHC data will help solve the puzzle

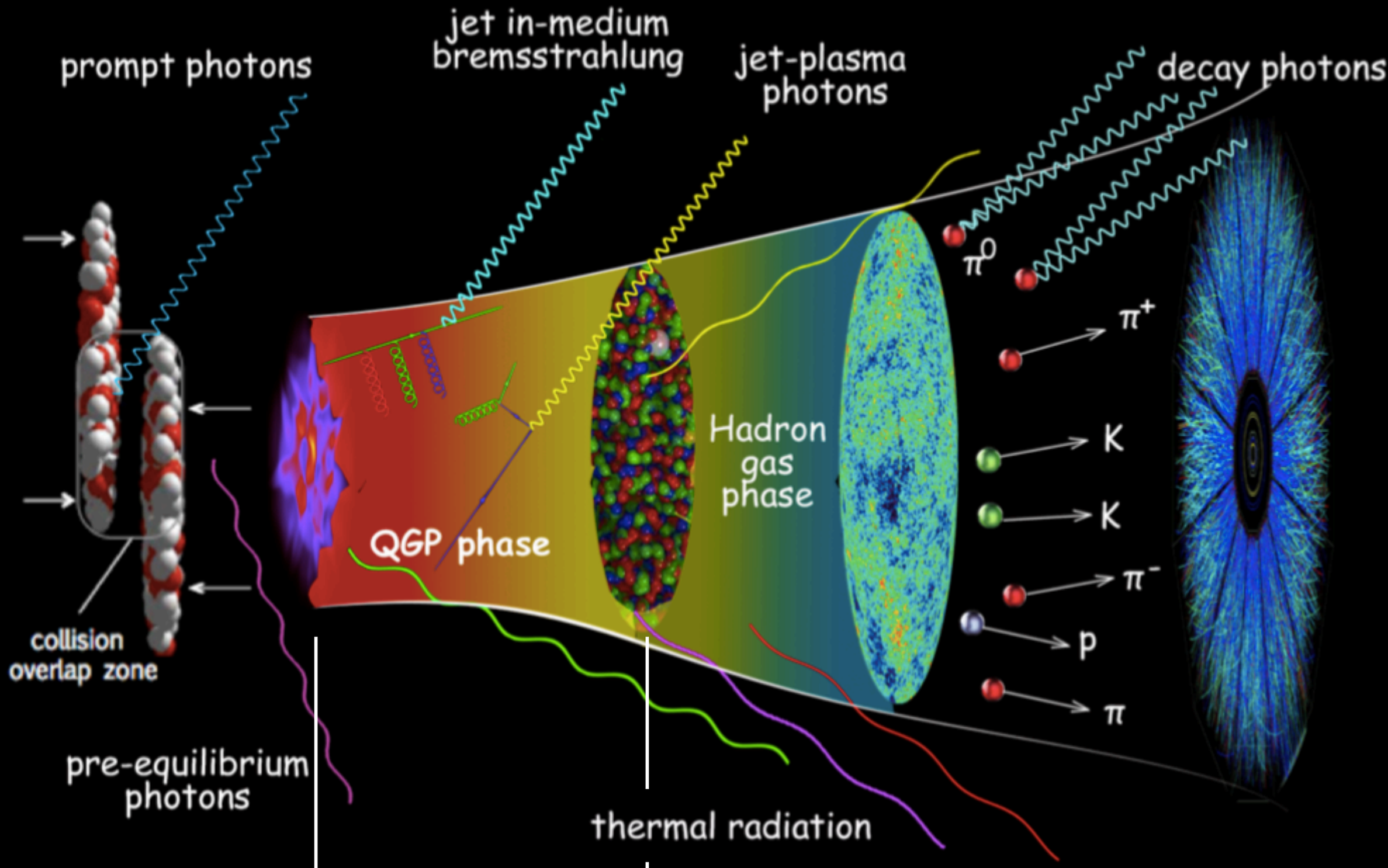
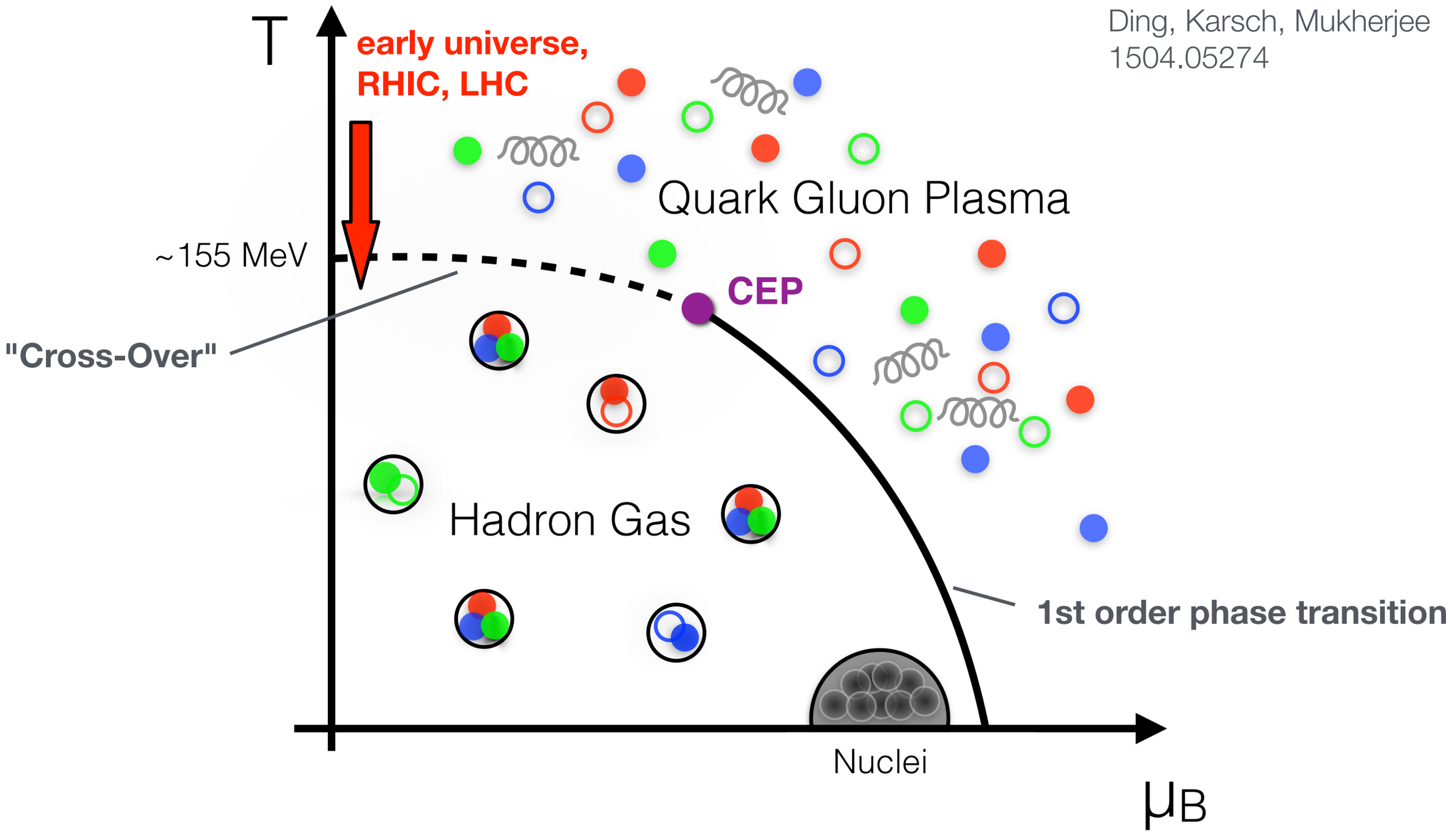


figure credit: Chun Shen

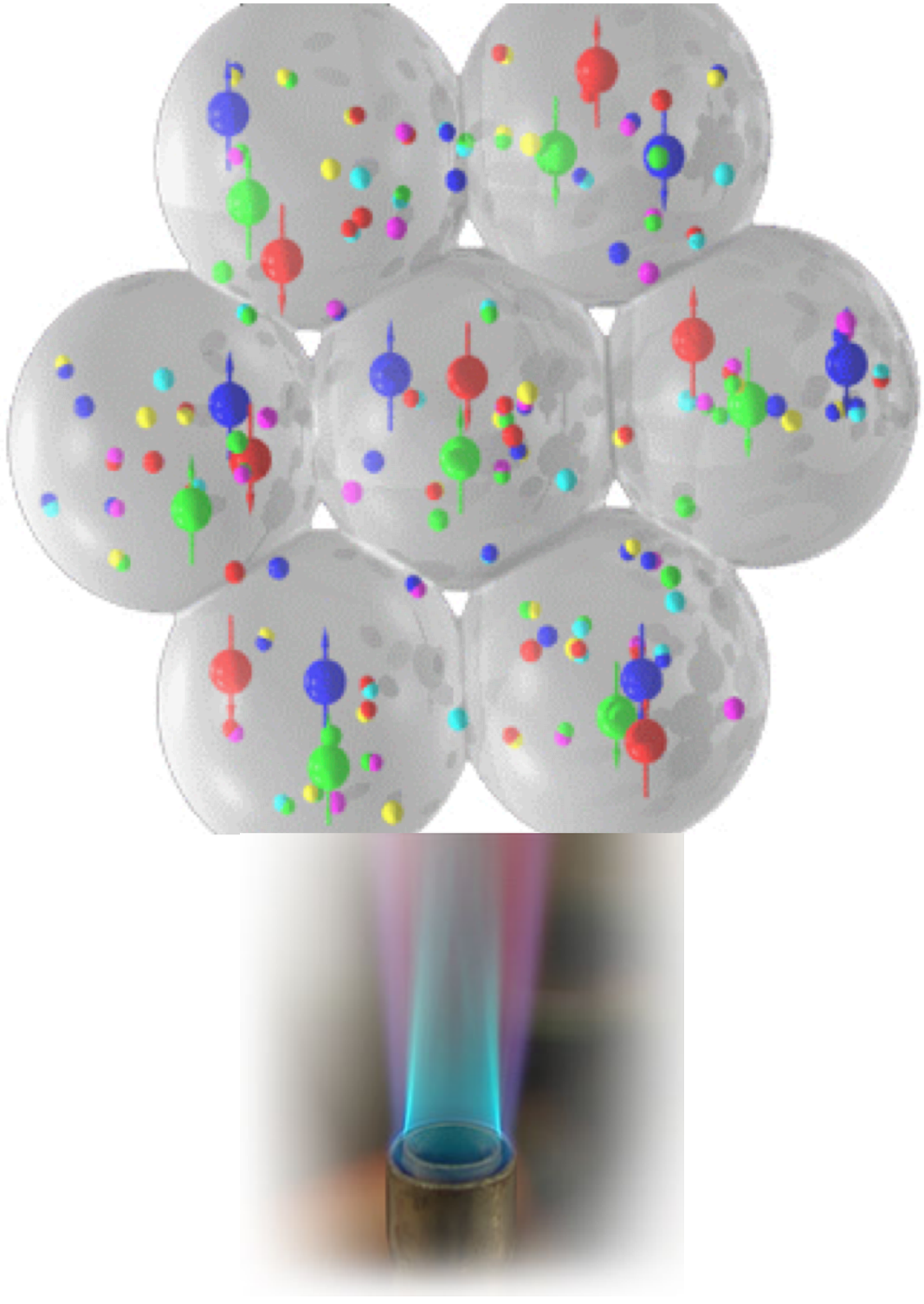
Extra Slides

(Conjectured) QCD Phase Diagram

Ding, Karsch, Mukherjee
1504.05274



What is the question?

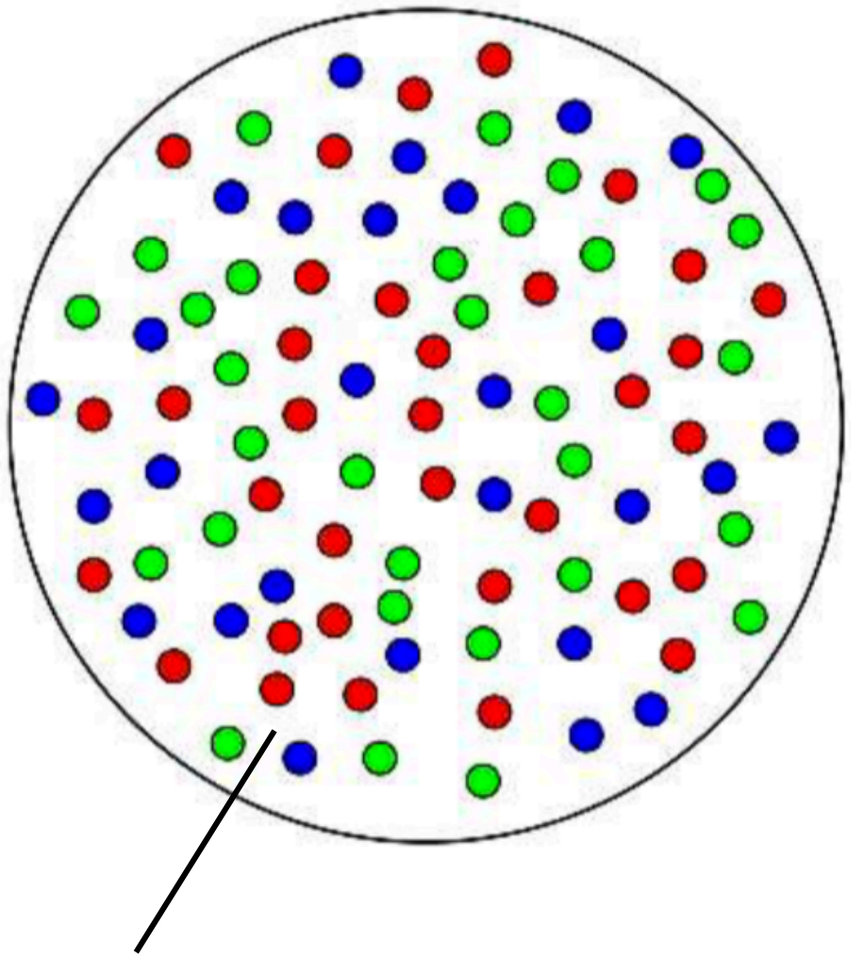


What happens if make nuclear matter

- hotter and hotter?
- denser and denser?

solid → liquid → gas → plasma → hadron gas → QGP

Let the data Speak:
Empirical Scaling Law for n_γ vs n_{hadron} ?



QGP at fixed temperature T

In recombination models:

$$n_\gamma \propto n_h$$

Parameterization:

$$n_\gamma \propto n_h^\alpha$$

Bjorken expansion (only QGP):

$$\alpha \approx 2$$

Realistic hydro model: ($p_{T,\gamma} > 1$ GeV/c)

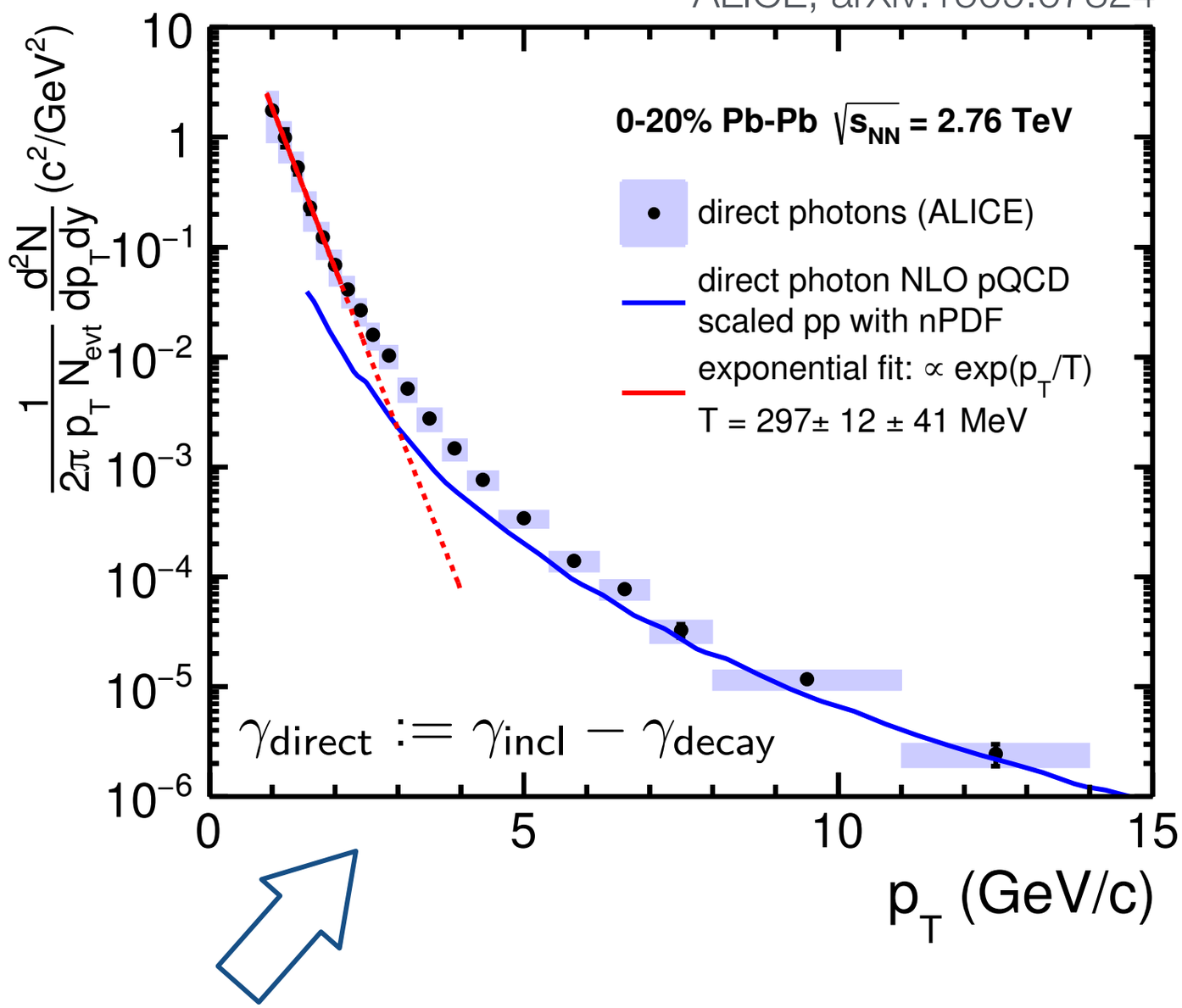
$$\alpha \approx 1.6\text{–}1.7$$

Jean-François Paquet, Hard Probes 2018

A Candidate for an Iconic Figure from Heavy Ions: Planck-like Photon Spectrum

- Will eventually belong to the set of few essential plots in heavy-ion physics
- Along with
  - R_{AA} (parton energy loss)
  - Elliptic flow
  - …

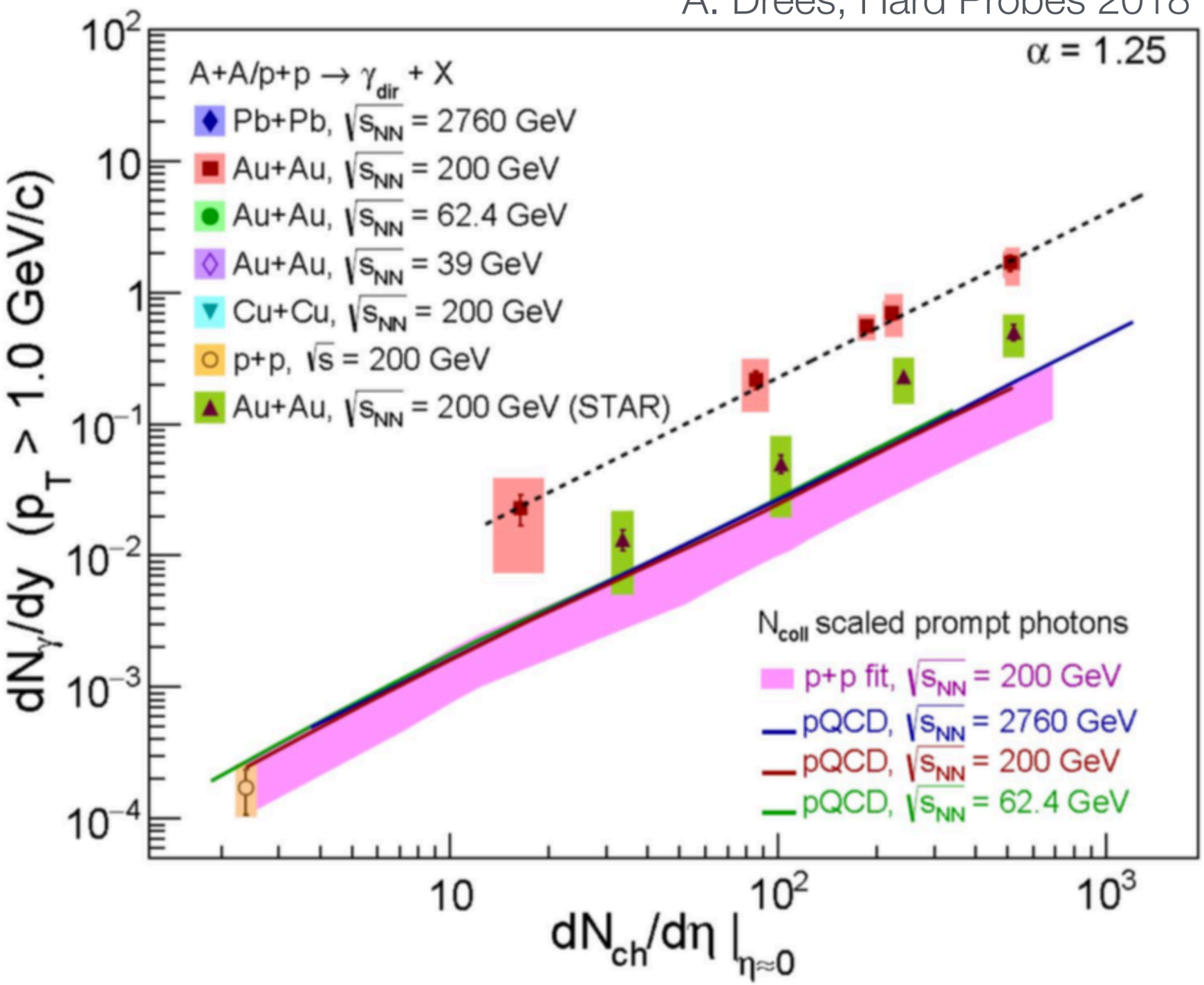
ALICE, arXiv:1509.07324



Current proxy (here from the LHC) looks already OK, but statistical significance needs to be improved

Direct Photons: PHENIX vs. STAR

A. Drees, Hard Probes 2018



Direct Photons: PHENIX vs. STAR