Direct Photon Flow at the LHC

ECT* workshop:
Electromagnetic Radiation from
Hot and Dense Hadronic Matter

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28 November 2018

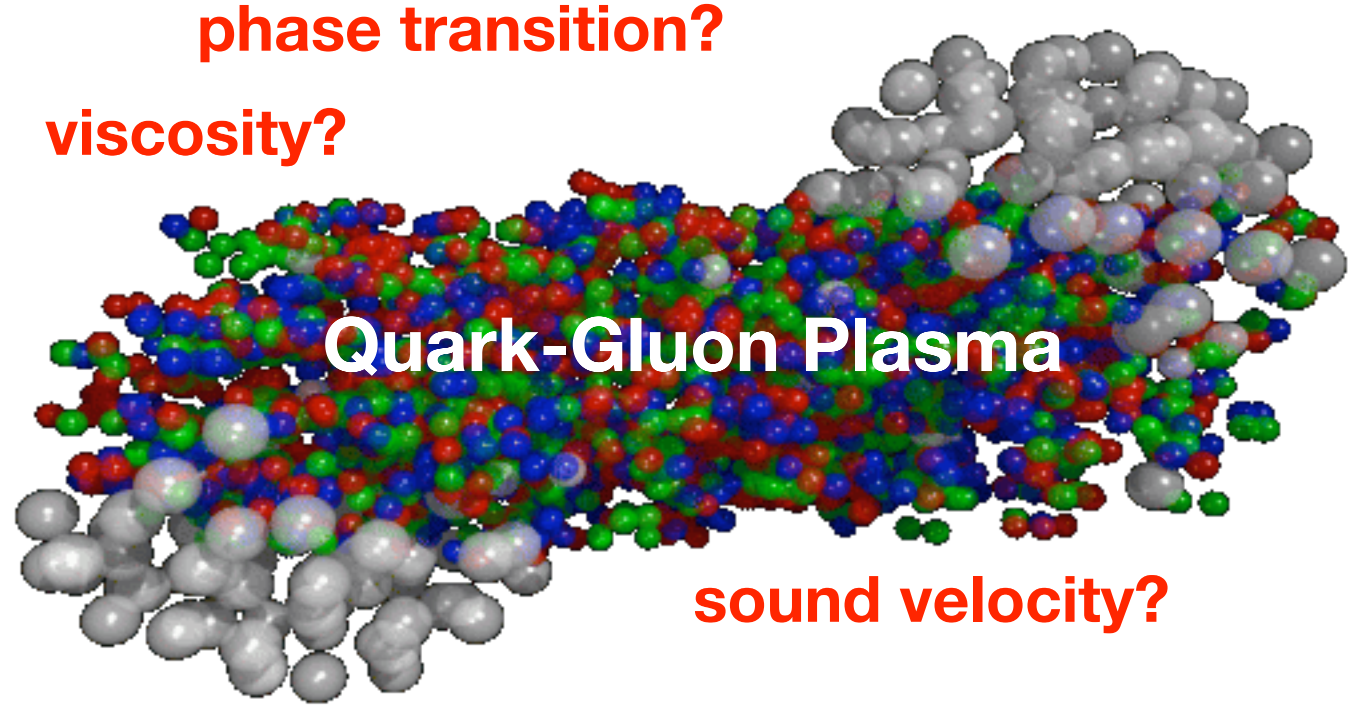
Outline

- Direct-photon v_2 at the LHC
- Statistical Methods (correlated uncertainties, Bayesian approach)
- Towards quantifying the statistical significance of the direct-photon puzzle
- Reducing systematic uncertainties
- Thoughts on the puzzle

Why Heavy-Ion Collisions?

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

More precisely:
"Material properties" of the QGP?



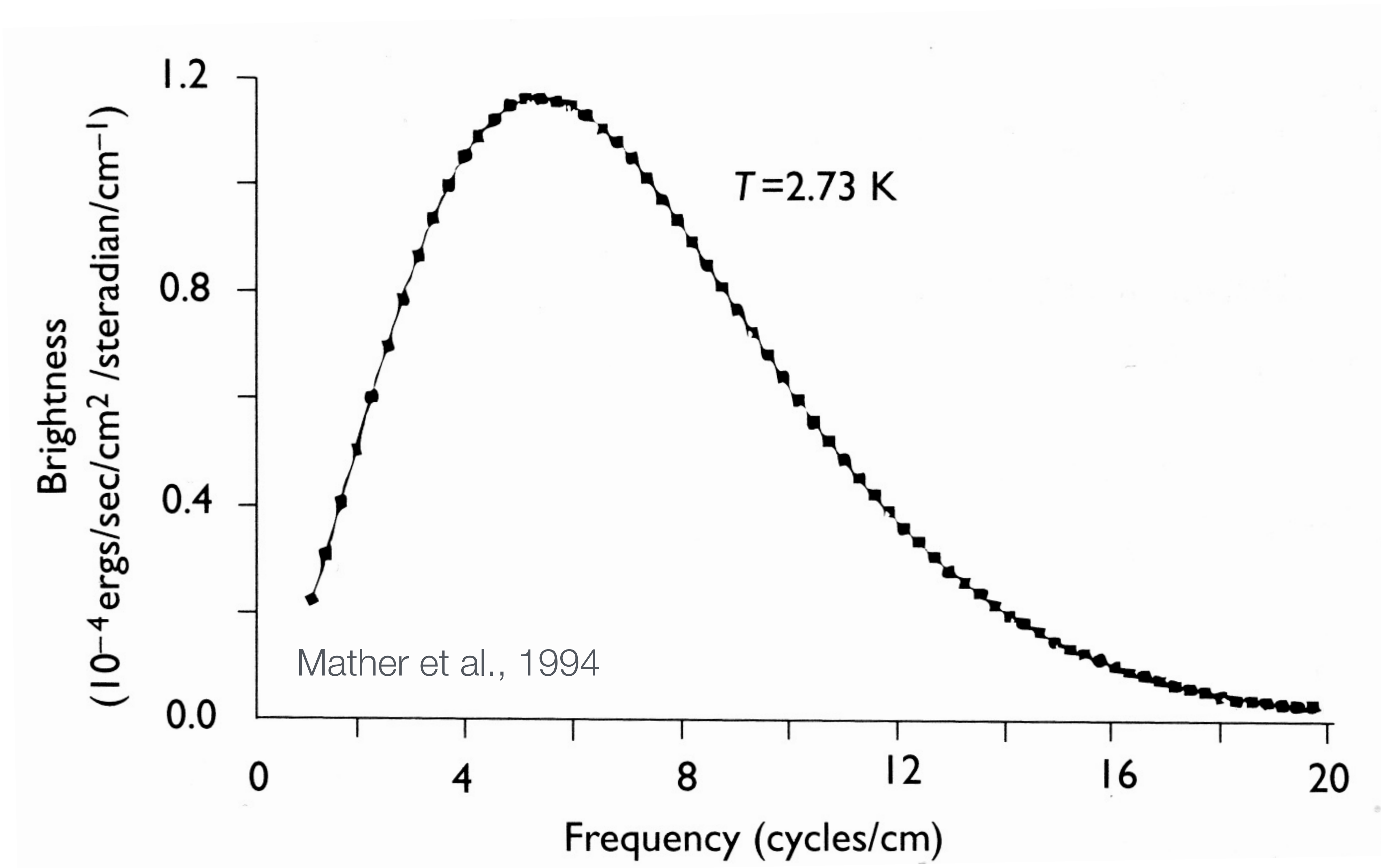
source: urqmd.org

„More is different“

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

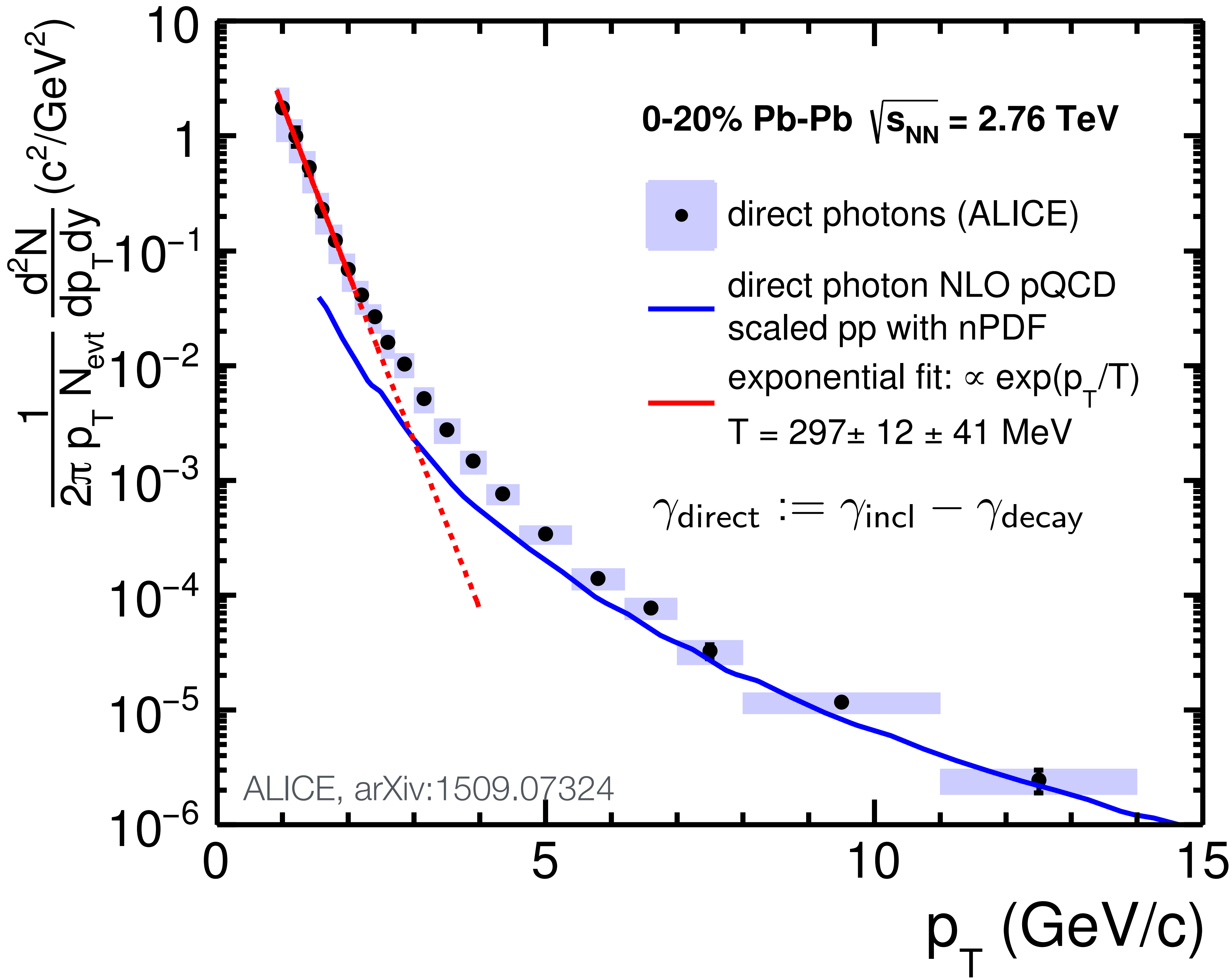
An Iconic Figure from Another Field

CMB black-body spectrum (COBE)



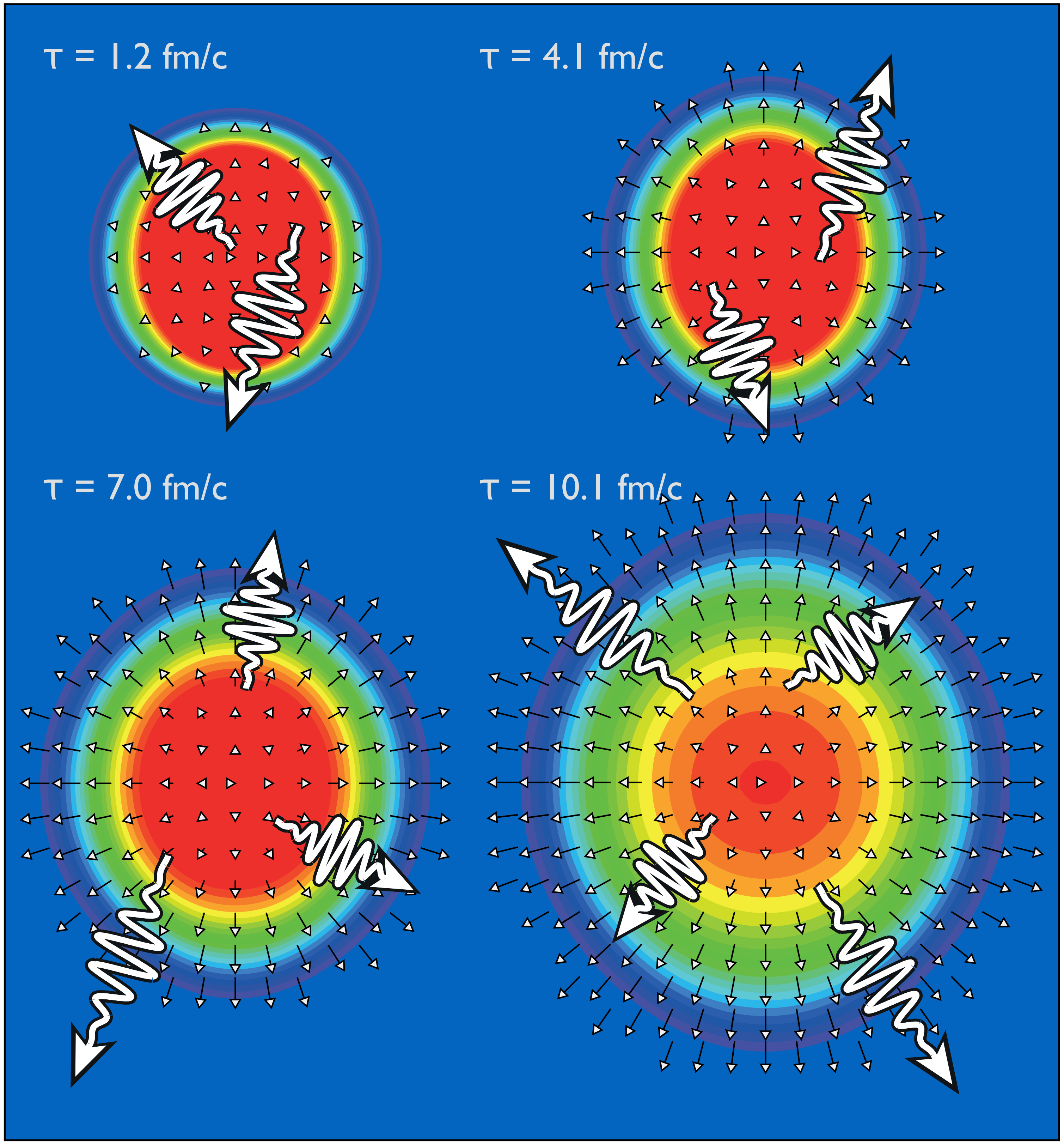
Recipe: Good data + well understood theory

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

Direct-Photon v_n: An additional Handle to Check Our Understanding of Photon Production



- Photons produced over the entire duration of the collision
  - Test understanding of the space-time evolution and production mechanisms
  - 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:

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

Total emission rate:

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

Direct-photon v_2 at the LHC

The Master Formula

v_2 of all photons
("inclusive photons")

calculated v_2 of
decay photons

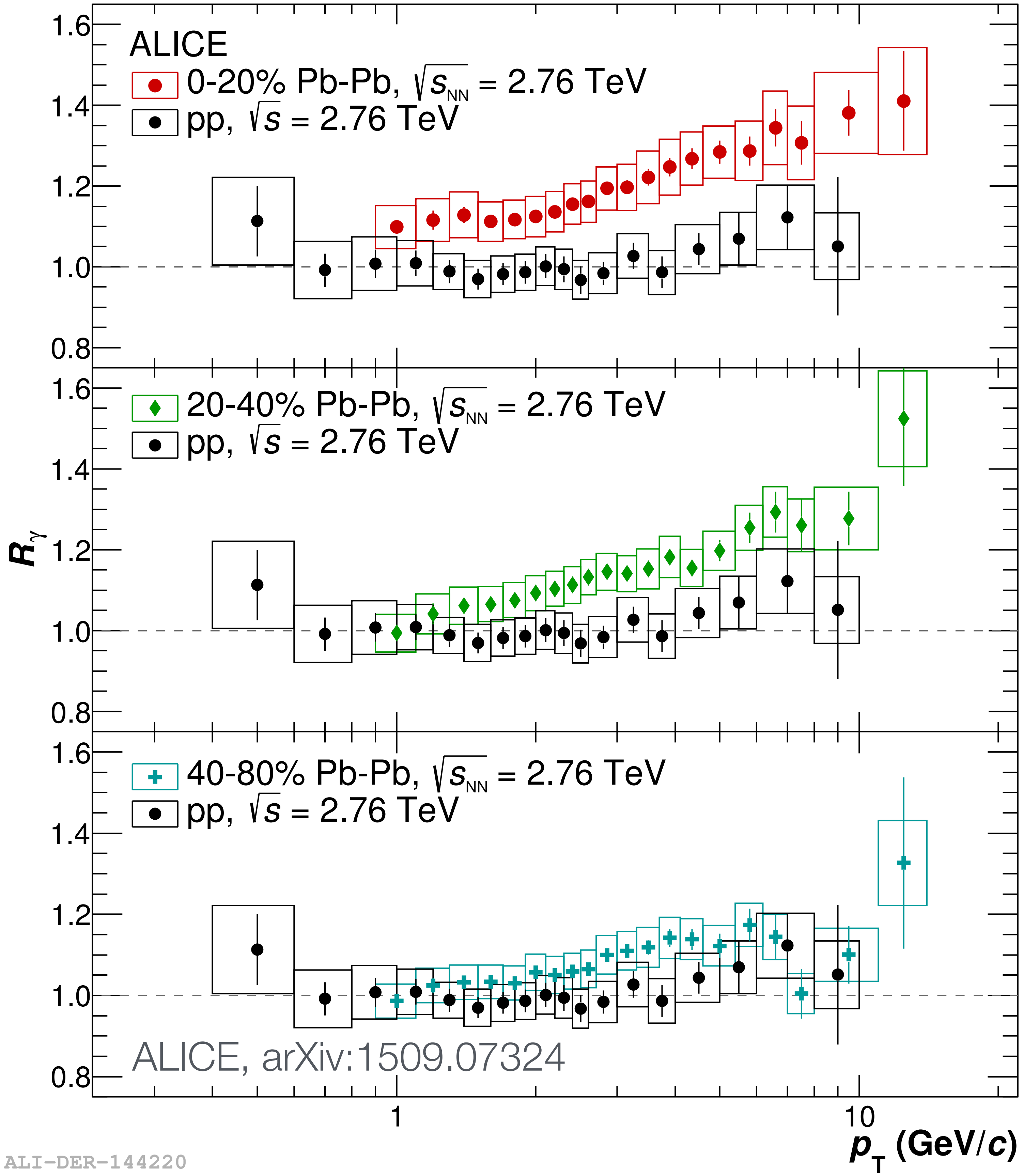
$$v_2^{\gamma,\mathrm{dir}} = \frac{R_\gamma \; v_2^{\gamma,\mathrm{inc}} - v_2^{\gamma,\mathrm{dec}}}{R_\gamma - 1}$$

photon excess:

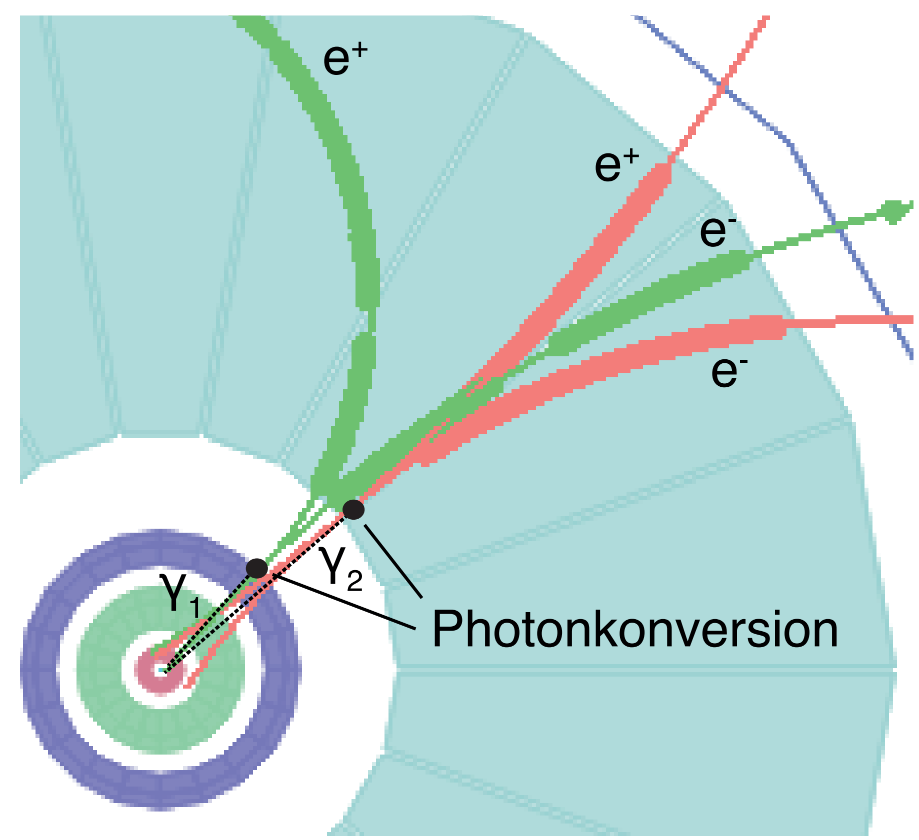
$$R_\gamma = \frac{\gamma_{\mathrm{incl}}}{\gamma_{\mathrm{decay}}} = 1 + \frac{\gamma_{\mathrm{dir}}}{\gamma_{\mathrm{decay}}}$$

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

$$R_\gamma = \frac{\gamma_{\mathrm{incl}}}{\gamma_{\mathrm{decay}}}$$



- Low-p_T excess in Pb-Pb
- No low-p_T excess in pp
- But: Low significance of R_γ makes extraction $v_{2,\mathrm{dir}}$ challenging

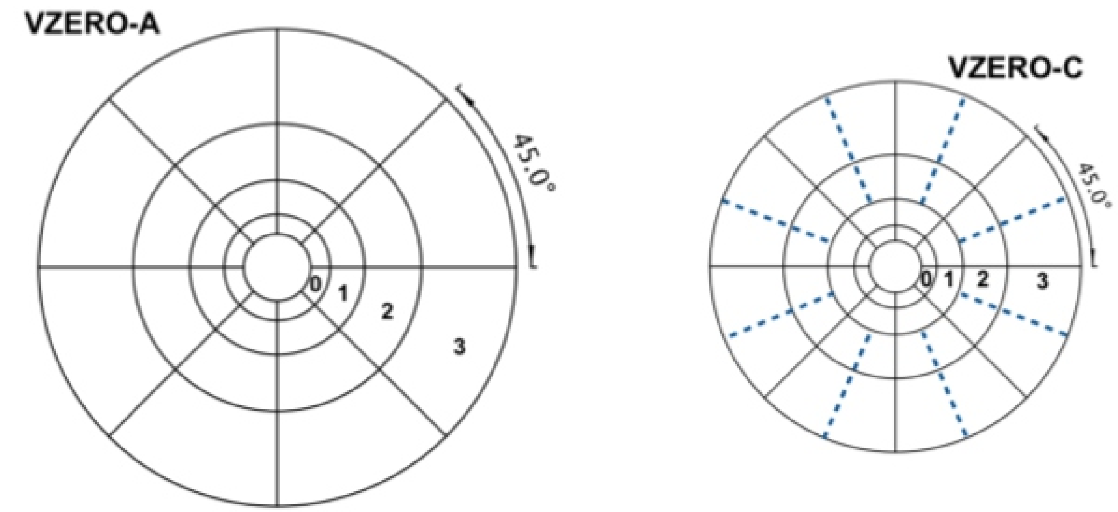


+ PHOS calorimeter measurement

Inclusive Photon v_2: Scalar Product Method

Reference particles in VZERO-A and VZERO-C:

$$\vec{Q}_n = \sum_{i \in \mathrm{RFP}} w_i e^{in\varphi_i}$$



$2.8 < \eta < 5.1$ $-3.7 < \eta < -1.7$

For each photon:

$$\vec{\mathrm{u}}_2 = e^{i2\varphi}$$

$$v_2 = \sqrt{\frac{\left\langle\left\langle \vec{\mathrm{u}}_2 \cdot \frac{\vec{Q}_2^{\mathrm{A}*}}{M_\mathrm{A}} \right\rangle\right\rangle \left\langle\left\langle \vec{\mathrm{u}}_2 \cdot \frac{\vec{Q}_2^{\mathrm{C}*}}{M_\mathrm{C}} \right\rangle\right\rangle}{\left\langle \frac{\vec{Q}_2^{\mathrm{A}}}{M_\mathrm{A}} \cdot \frac{\vec{Q}_2^{\mathrm{C}*}}{M_\mathrm{C}} \right\rangle}}$$

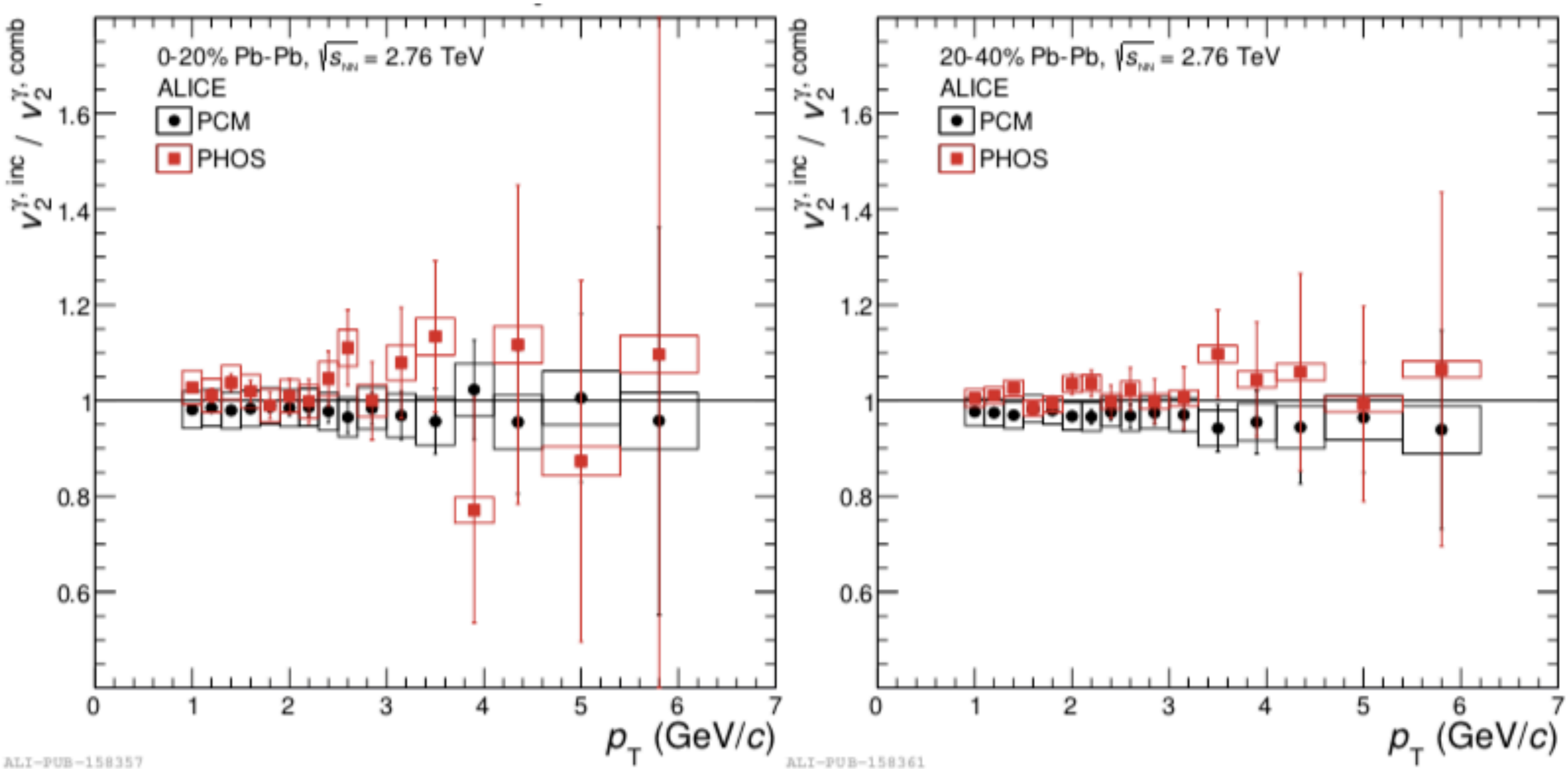
Advantage over event plane method: result not sensitive to event plane resolution

$v_{2,\mathrm{inc}}$ and $v_{2,\mathrm{dec}}$ Systematic Uncertainties

Centrality	0–20%		20–40%	
p_{T} (GeV/c)	2.0	5.0	2.0	5.0
PCM				
Photon selection	2.4	4.2	2.1	4.0
Energy resolution	1.0	1.0	1.0	1.0
Efficiency	3	3	1.9	1.9
Total	4.0	5.3	3.0	4.5
PHOS				
Efficiency & contamination	3.0	3.0	0.7	0.7
Event plane flatness	2.0	2.0	1.4	1.4
Total	3.5	3.5	1.6	1.6
Decay photon calculation				
Parameterization of v_2^{π}	1.3	3.6	0.8	2.2
η/π^0 normalization	1.7	3.2	1.7	2.4
Total	2.2	4.8	1.9	3.3

Agreement between $v_{2,\mathrm{inc}}$ from PCM and PHOS

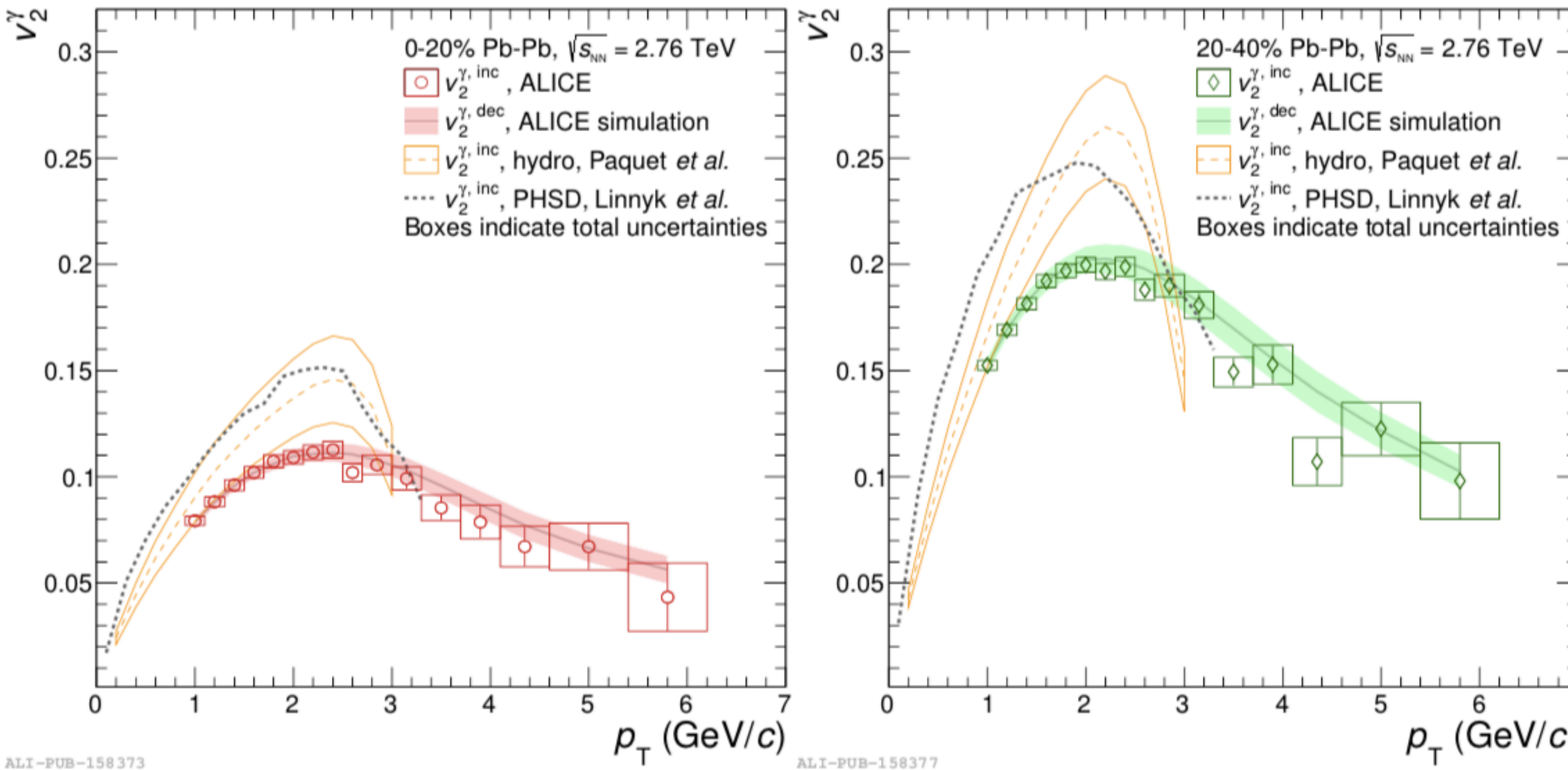
ALICE arXiv:1805.04403



Statistical uncertainty starts to be dominant for $p_T > 2$ GeV/c

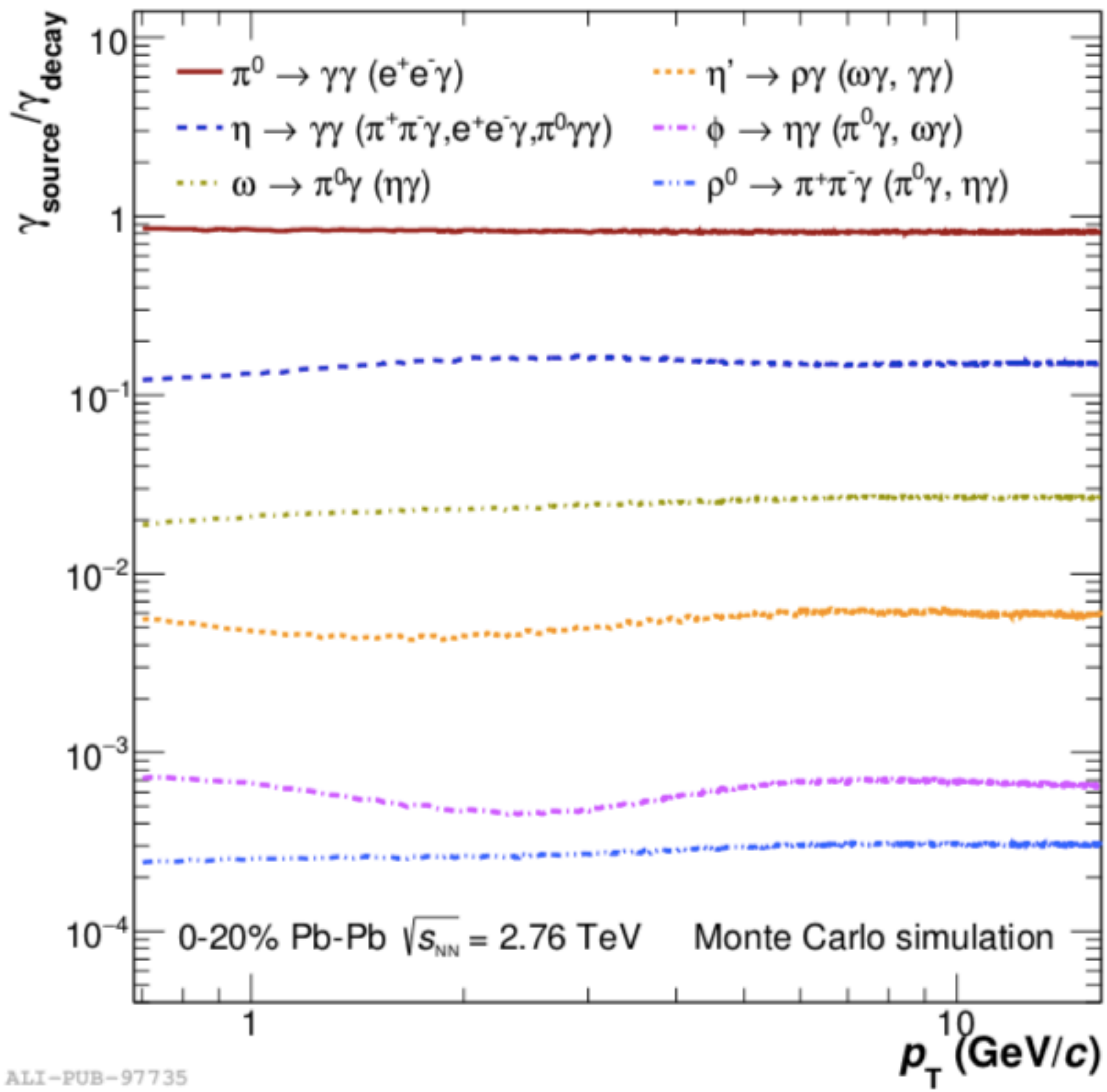
Inclusive Photons: $v_{2,\mathrm{inc}} \approx v_{2,\mathrm{dec}}$

ALICE arXiv:1805.04403



- Either R_γ small or $v_{2,\mathrm{dir}} \approx v_{2,\mathrm{inc}} \approx v_{2,\mathrm{dec}}$
- Model comparison: important two compare inclusive *and* direct photon v_2

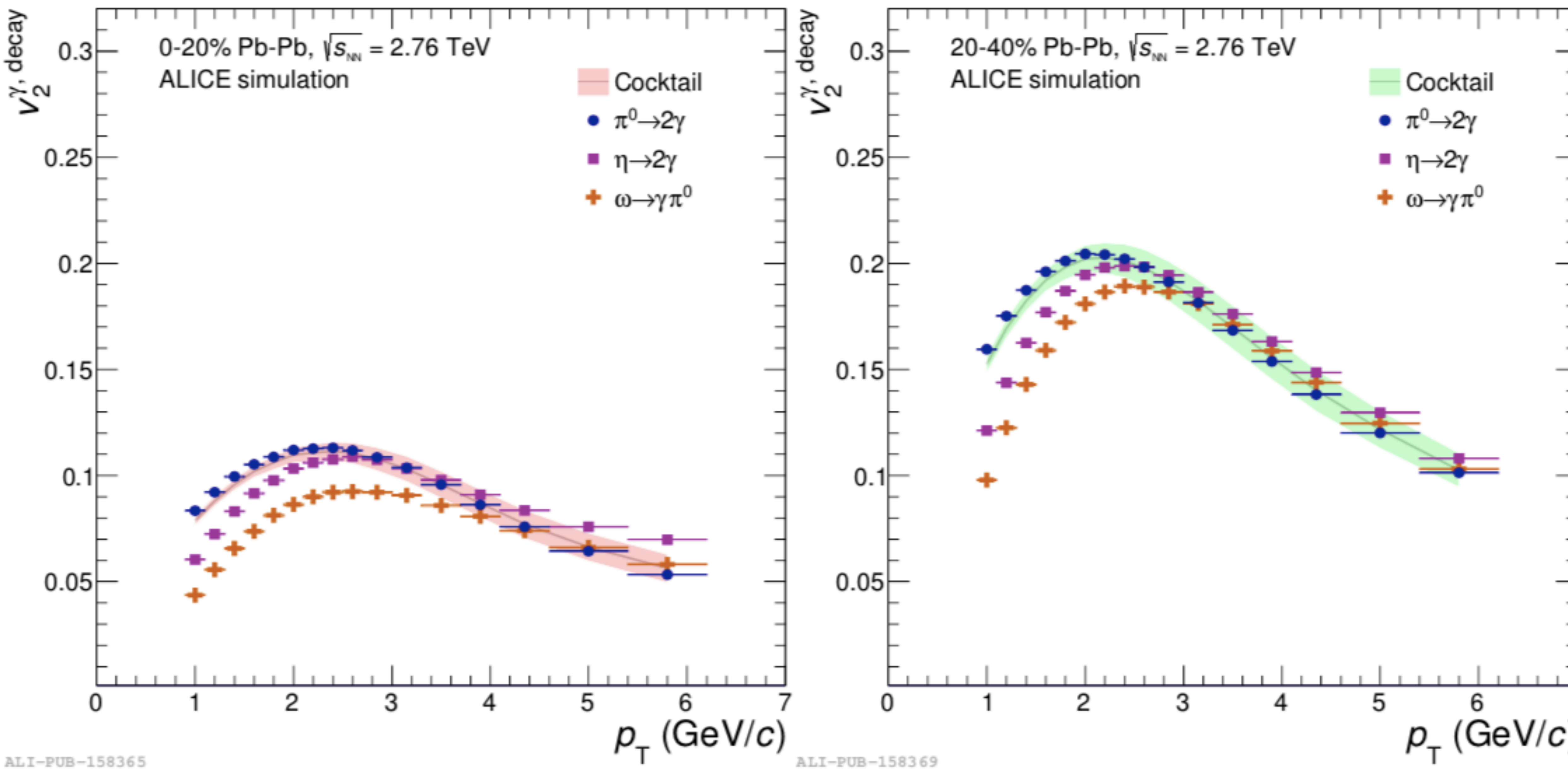
Decay Photon Cocktail: π^0, η, ω relevant



ALICE, 1509.07324

Calculated Decay Photon v_2

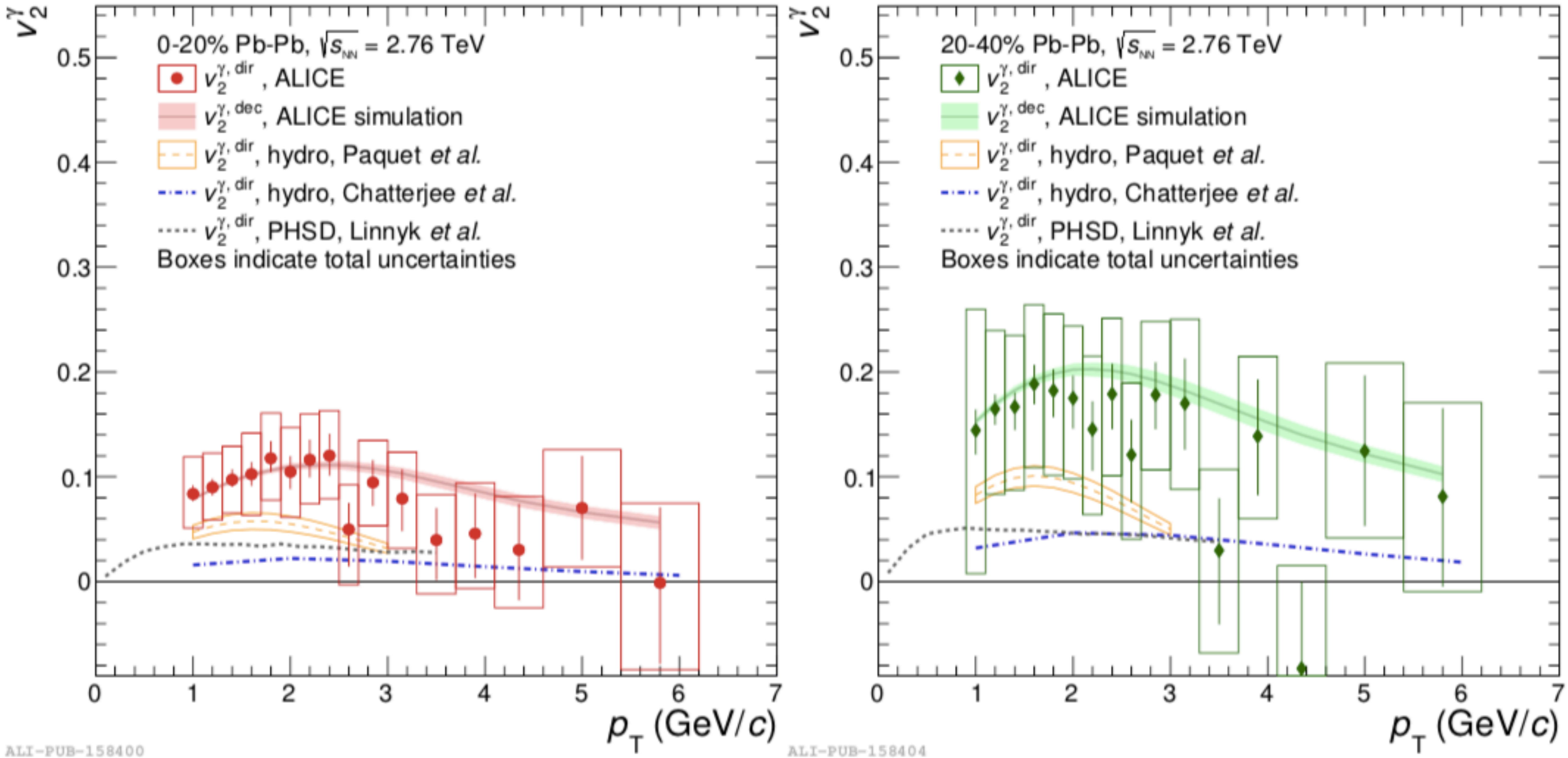
ALICE arXiv:1805.04403



- Input: Measured $\pi^{\pm}$, $K^{\pm,0}$ v_2
- Scaling of v_2 in transverse kinetic energy $m_T - m$ for η and ω

Large Direct Photon v_2 (but take error bars seriously)

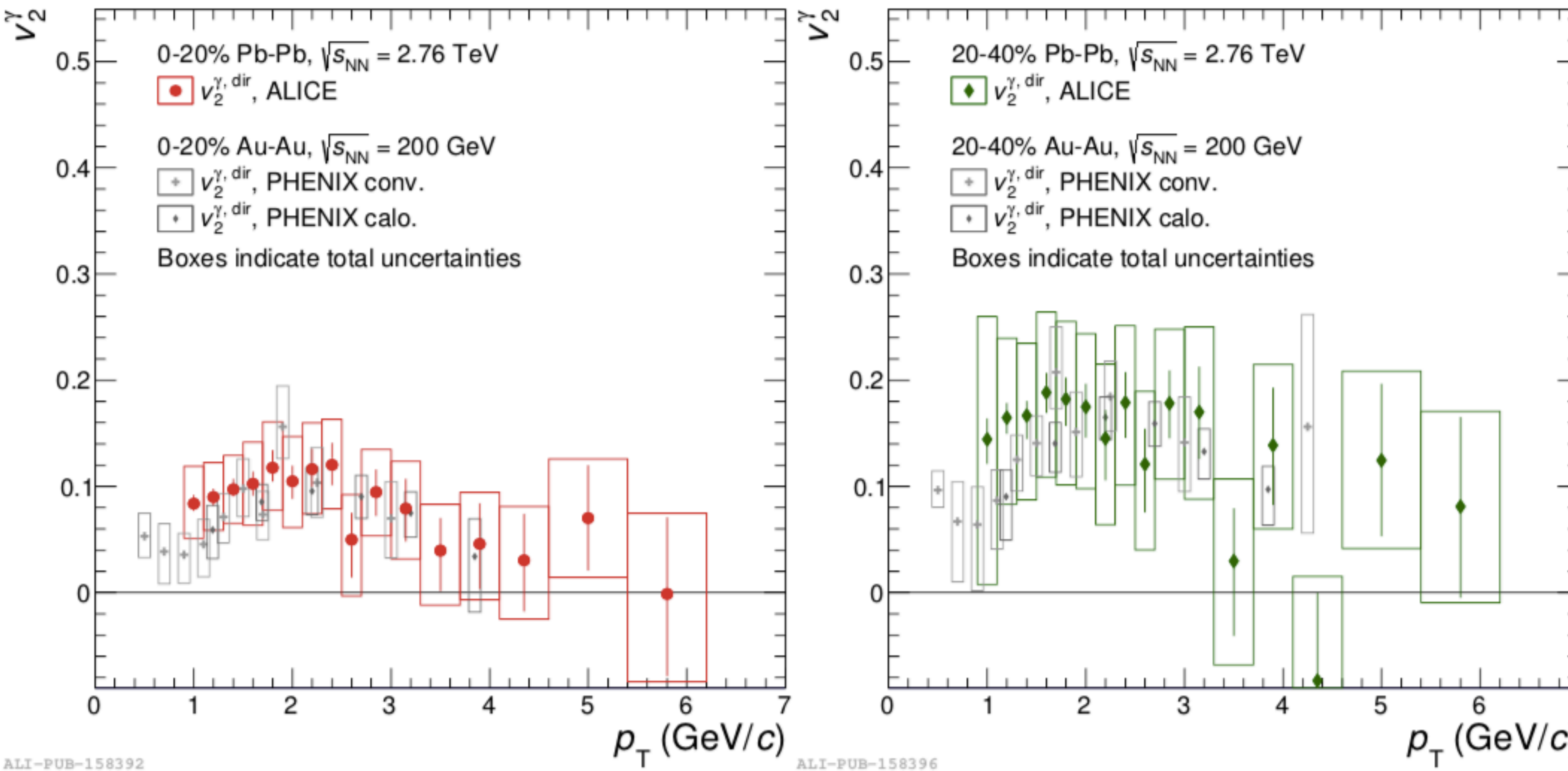
ALICE arXiv:1805.04403 error bars = statistical uncertainties, boxes = total uncertainties



- $v_{2,dir}$ larger than models predictions (in qualitative agreement with PHENIX)
- But: null hypothesis $v_{2,dir}$ = 0 not inconsistent with the data

$v_{2,dir}$(LHC) ≈ $v_{2,dir}$(RHIC)

ALICE arXiv:1805.04403



Statistical Methods

Correlated Systematic Uncertainties

"PHENIX system":

Uncertainties categorized as

$\sigma_{i,\mathrm{stat}}$, $\sigma_{i,A}$, $\sigma_{i,B}$, $\sigma_{C,rel}$,

A - point-by-point uncorrelated
B - correlated, size of relative error varies point-by-point
C - constant fractional error

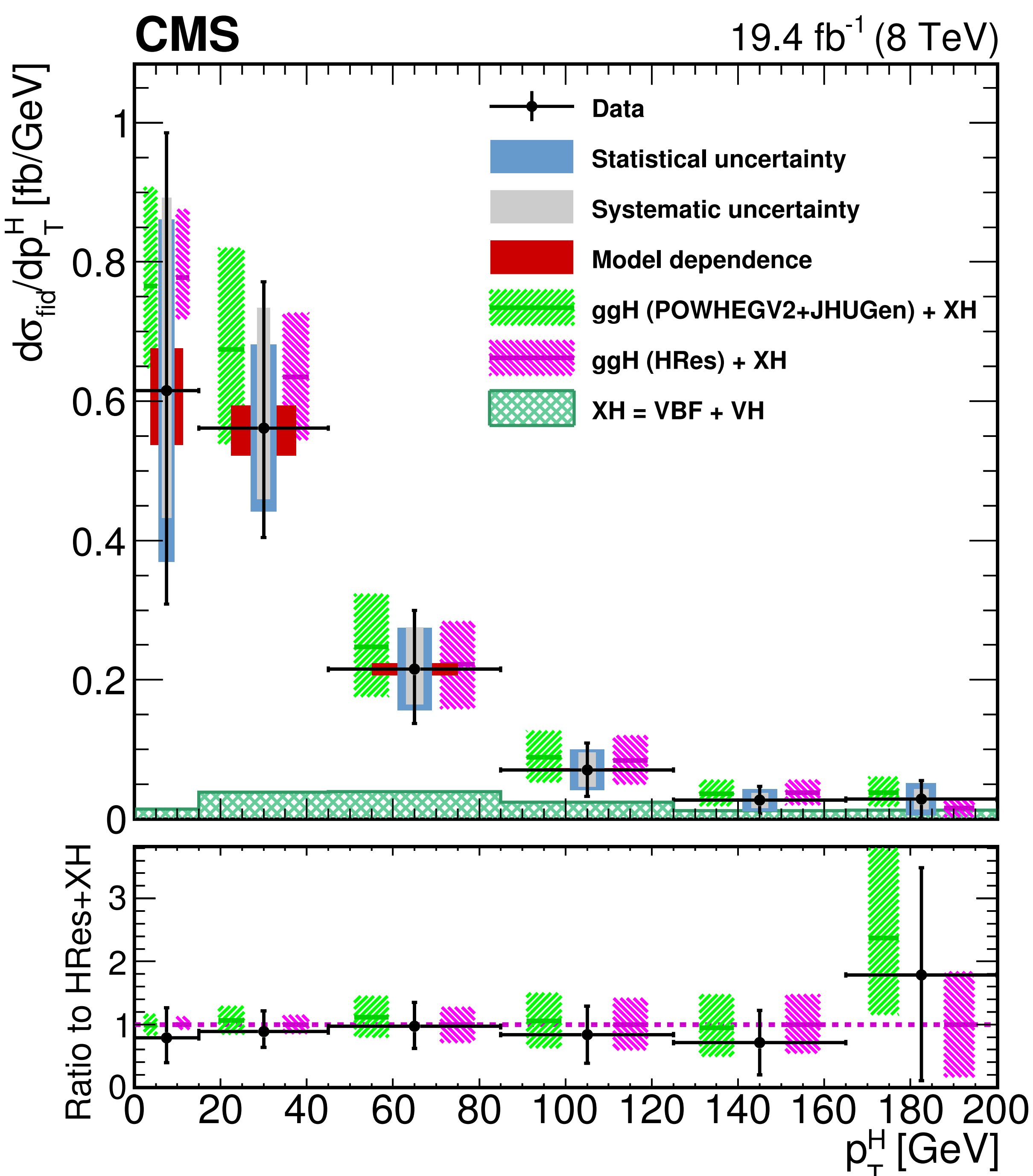
$$\chi^2 = \sum_{i=1}^{n} \frac{(\tilde{y}_i - \mu_i)^2}{\tilde{\sigma}_i^2} + \varepsilon_B^2 + \varepsilon_C^2$$

$$\tilde{y}_i = y_i + \varepsilon_\mathrm{B}\sigma_{B,i} + \varepsilon_C \sigma_{C,\mathrm{rel}} y_i$$

$$\tilde{\sigma}_i^2 = \frac{\sigma_{i,\mathrm{stat}}^2 + \sigma_{i,\mathrm{A}}^2}{y_i^2} \cdot \tilde{y}_i^2$$

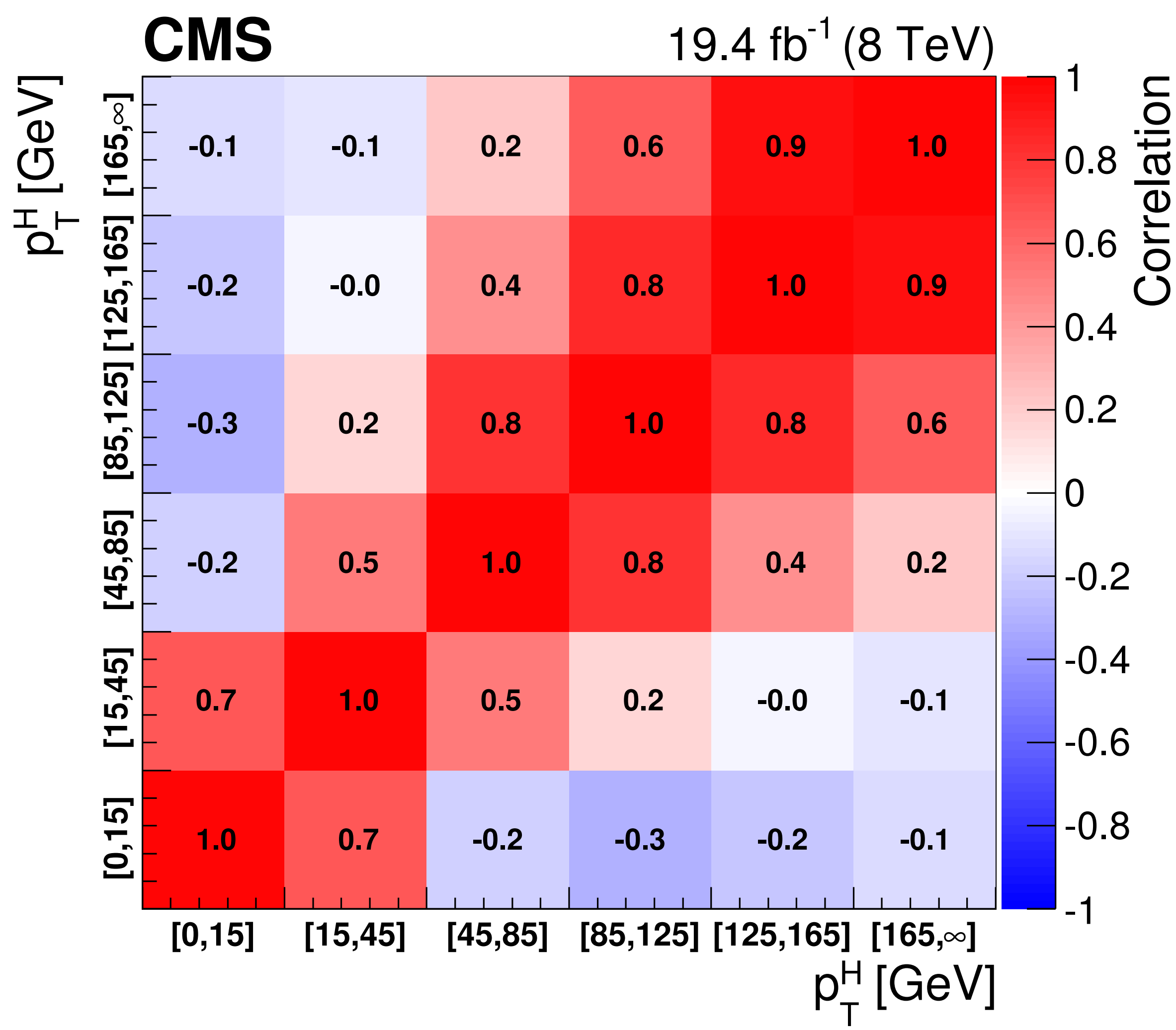
Quite useful, but often more flexibility needed

Correlated Uncertainties: Covariance Matrix



arXiv:1606.01522v1

Correlation matrix ρ_{ij} of the p_T bins:



Covariance matrix:

$$V_{ij} = \begin{cases} \sigma_i^2 & i = j \\ \rho_{ij}\sigma_i\sigma_j & i \neq j \end{cases}$$

Significances from Covariance Matrix

My preference: full covariance matrix V

$$\chi^2 = (\vec{x} - \vec{\mu})^\mathsf{T} V^{-1} (\vec{x} - \vec{\mu})$$

data model prediction

Translating statistical and type A, B, C systematic uncertainties into a covariance matrix:

$$V_{i,j} = V_{i,j}^{\mathrm{stat}} + V_{i,j}^{\mathrm{A}} + V_{i,j}^{\mathrm{B}} + V_{i,j}^{\mathrm{C}} = \begin{cases} \sigma_{i,\mathrm{stat}}^2 + \sigma_{i,\mathrm{A}}^2 + \sigma_{i,\mathrm{B}}^2 + y_i^2 \sigma_{\mathrm{C,rel}}^2, & \text{if } i = j. \\ \sigma_{i,\mathrm{B}} \sigma_{j,\mathrm{B}} + y_i y_j \sigma_{\mathrm{C,rel}}^2, & \text{if } i \neq j. \end{cases}$$

The other way round (e.g. for plotting purposes) is not straightforward
→ That's why ALICE error boxes = total errors

Combining PCM and PHOS $v_{2,\mathrm{inc}}$

Correlated uncertainties in p_T for PCM and PHOS, but no correlation between PCM and PHOS;

$$\vec{v}_2^{\gamma,\mathrm{inc}} = (V_{v_2,\mathrm{PCM}}^{-1} + V_{v_2,\mathrm{PHOS}}^{-1})^{-1}(V_{v_2,\mathrm{PCM}}^{-1}\vec{v}_2^{\gamma,\mathrm{inc,PCM}} + V_{v_2,\mathrm{PHOS}}^{-1}\vec{v}_2^{\gamma,\mathrm{inc,PHOS}})$$

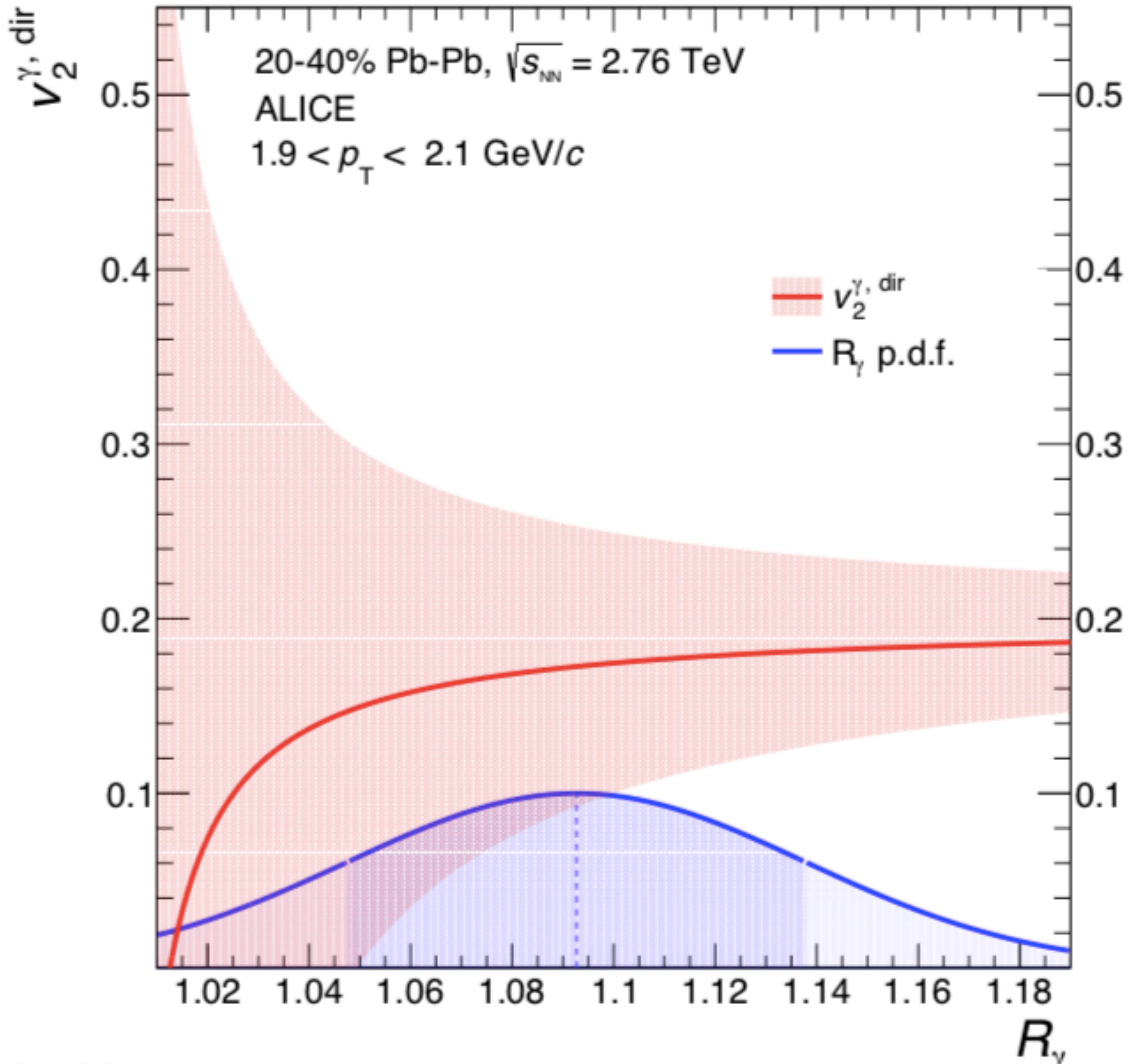
$$V_{ij} = V_{\mathrm{stat},ij} + V_{\mathrm{syst},ij}, \text{ where } V_{\mathrm{syst},ij} = \rho\,\sigma_{\mathrm{syst},i}\sigma_{\mathrm{syst},j}$$

(linear combination with the smallest χ^2)

Covariance matrices from estimating the correlations coefficient.

Better, but more work: covariance matrices from toy Monte Carlo studies

Error Propagation:
Small measured R_γ Requires Special Consideration



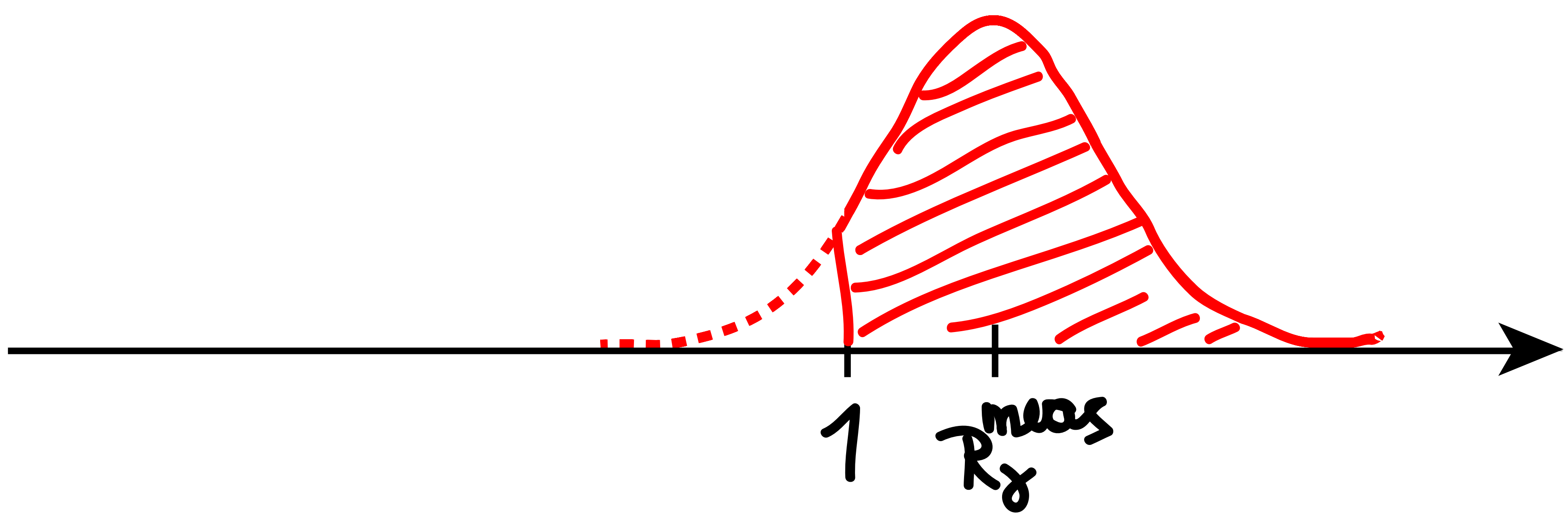
ALICE arXiv:1805.04403

Bayesian Approach

Bayes:

$$P(R_{\gamma,\mathrm{t}}|R_{\gamma,\mathrm{m}}) \propto L(R_{\gamma,\mathrm{m}}|R_{\gamma,\mathrm{t}})\pi(R_{\gamma,\mathrm{t}}), \qquad \pi(R_{\gamma,\mathrm{t}}) = \Theta(R_{\gamma,\mathrm{t}} - 1)$$

Posterior distribution of R_γ:



$v_{2,\mathrm{dir}}$ Calculation: One p_T bin

- The formula for $v_{2,\mathrm{dir}}$ is only defined for $R_\gamma > 1$: $$v_{2,\mathrm{dir}} = \frac{R_\gamma v_{2,\mathrm{incl}} - v_{2,\mathrm{decay}}}{R_\gamma - 1}$$
- The measured value of R_γ can be below unity. Same problem in MC error propagation for R_γ slightly larger than 1. How to handle this case?
- Bayes: $$P(\vec{\theta}|\vec{m}) \propto L(\vec{m}|\vec{\theta})\,\pi(\vec{\theta})$$
- In our case: $$\vec{\theta} = (v_{2,\mathrm{inc,t}}, v_{2,\mathrm{dec,t}}, R_{\gamma,\mathrm{t}}) \qquad \vec{m} = (v_{2,\mathrm{inc,m}}, v_{2,\mathrm{dec,m}}, R_{\gamma,\mathrm{m}})$$ $$\pi(R_{\gamma,\mathrm{t}}) = \Theta(R_{\gamma,\mathrm{t}} - 1)$$ $$L(\vec{m}|\vec{\theta}) = L(v_{2,\mathrm{inc,m}}|v_{2,\mathrm{inc,t}})\,L(v_{2,\mathrm{dec,m}}|v_{2,\mathrm{dec,t}})L(R_{\gamma,\mathrm{m}}|R_{\gamma,\mathrm{t}})$$
  Likelihoods modeled as Gaussians, e.g.: $$L(R_{\gamma,\mathrm{m}}|R_{\gamma,\mathrm{t}}) = G(R_{\gamma,\mathrm{m}}; R_{\gamma,\mathrm{t}}, \sigma(R_{\gamma,\mathrm{t}}))$$
- We obtain a posterior distribution for $v_{2,\mathrm{inc,t}}$, $v_{2,\mathrm{dec,t}}$, and $R_{\gamma,\mathrm{t}}$ from which we obtain a posterior distribution for $v_{2,\mathrm{dir,t}}$

$v_{2,\mathrm{dir}}$ Calculation: Several p_T Bins

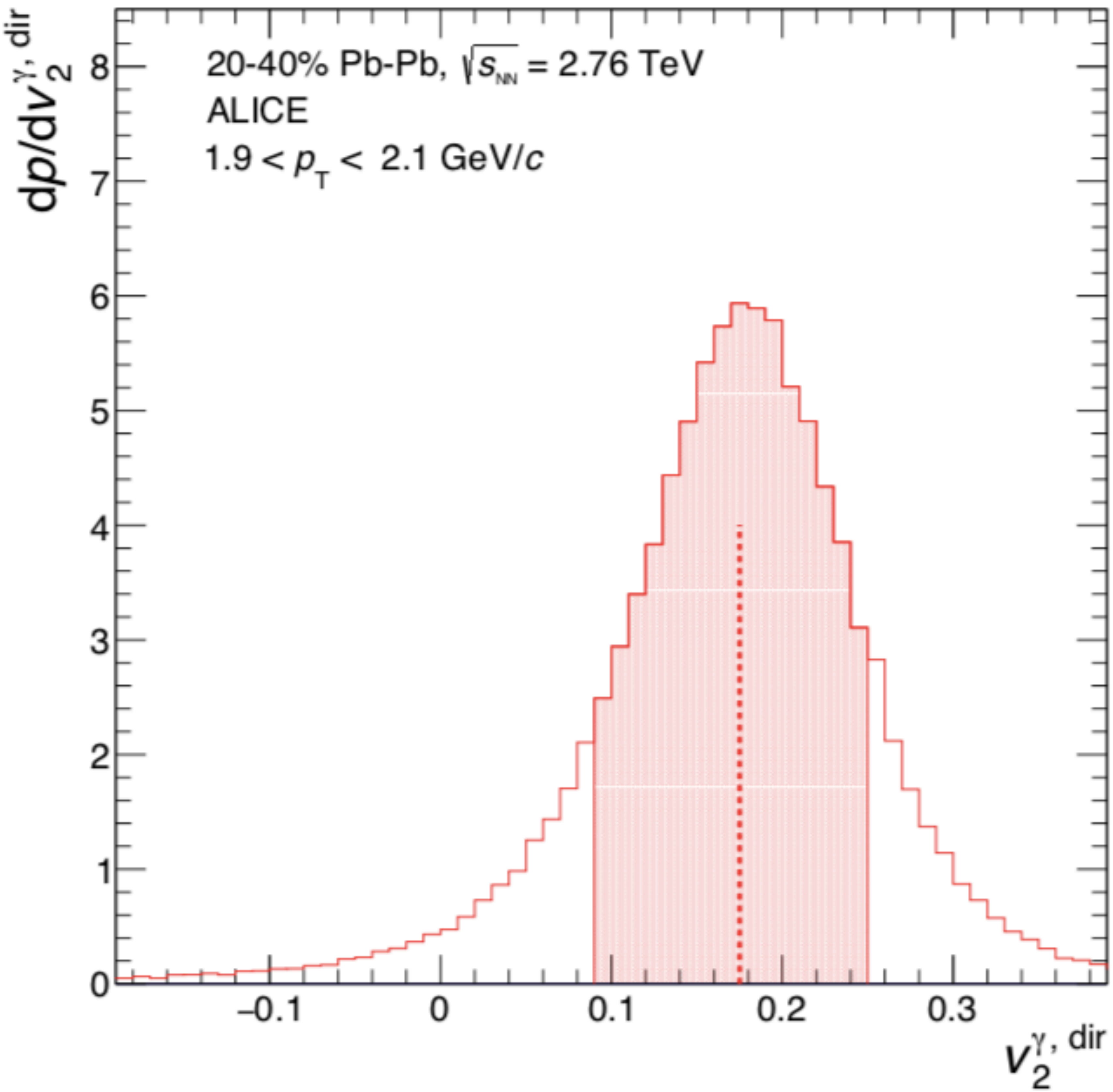
$$\vec{m} = (\vec{R}_{\gamma,\mathrm{m}}, \vec{v}_2^{\,\gamma,\mathrm{inc,m}}, \vec{v}_2^{\,\gamma,\mathrm{dec,m}}) \qquad \vec{\vartheta} = (\vec{R}_{\gamma,\mathrm{t}}, \vec{v}_2^{\,\gamma,\mathrm{inc,t}}, \vec{v}_2^{\,\gamma,\mathrm{dec,t}})$$

$$P(\vec{\vartheta}|\vec{m}) \propto P(\vec{m}|\vec{\vartheta})\pi(\vec{\vartheta})$$

$$\pi(\vec{\vartheta}) \equiv \pi(\vec{R}_{\gamma,\mathrm{t}}) = \Theta(R_{\gamma,\mathrm{t},1} - 1, \ldots, R_{\gamma,\mathrm{t},n} - 1)$$

$$\underbrace{P(\vec{m}|\vec{\vartheta})}_{\text{likelihood}} = \prod_{x=R_\gamma, v_2^{\gamma,\mathrm{inc}}, v_2^{\gamma,\mathrm{dec}}} \underbrace{G}_{\text{multivariate Gaussian}}(\vec{x}_\mathrm{m}; \vec{x}_\mathrm{t}, \underbrace{V_x}_{\text{covariance matrix}})$$

$v_{2,dir}$ Posterior Distribution for One p_T Bin



Towards quantifying the statistical significance of the direct-photon puzzle

Hypothesis Testing / Significance

Q: Significance of the difference between data and a certain $v_{2,\mathrm{dir}}$ hypothesis?

Need a test statistic t that quantifies deviation/difference between a hypothesis and the data.

Often used test statistics: likelihood $L(x;\theta)$ and χ^2

$$p\text{-value} = \int_{t_{\mathrm{obs}}}^{\infty} p(t|H)\,\mathrm{d}t \qquad \text{(frequentist concept)}$$

One way to handle nuisance parameters: marginal likelihoods

prior knowledge about ν:

integrate over nuisance parameter ν:

$$t := L_{\mathrm{m}}(x|s) = \int L(x|\nu, s)\pi_\nu(\nu)\,\mathrm{d}\nu$$

Further information: lecture G. Cowan (especially p. 88ff.):

- http://www.ippp.dur.ac.uk/~ross/invisibles13/school/talks/GlenCowanStatisticalandDataAnalysis.pdf
- 1307.2487 (section 5.2)

Likelihood Function (One p_T bin)

Likelihood function (note that we use $v_{2,\mathrm{dir}}^{\mathrm{t}}$ as parameter):

$$
\begin{aligned}
L(v_{2,\mathrm{inc}}^{\mathrm{m}}, v_{2,\mathrm{dec}}^{\mathrm{m}}, R_\gamma^{\mathrm{m}}; v_{2,\mathrm{dir}}^{\mathrm{t}}, v_{2,\mathrm{dec}}^{\mathrm{t}}, R_\gamma^{\mathrm{t}}) = {} & G(v_{2,\mathrm{inc}}^{\mathrm{m}}; v_{2,\mathrm{inc}}^{\mathrm{t}}, \sigma_{v_{2,\mathrm{inc}}}) \cdot \\
& G(v_{2,\mathrm{dec}}^{\mathrm{m}}; v_{2,\mathrm{dec}}^{\mathrm{t}}, \sigma_{v_{2,\mathrm{dec}}}) \cdot \\
& G(R_\gamma^{\mathrm{m}}; R_\gamma^{\mathrm{t}}, \sigma_{R_\gamma})
\end{aligned}
$$

G(x; μ, σ): 1d Gaussians

Here $v_{2,\mathrm{inc}}^{\mathrm{t}}$ is a function of the other three parameters:

$$
v_{2,\mathrm{inc}}^{\mathrm{t}} \equiv v_{2,\mathrm{inc}}^{\mathrm{t}}(v_{2,\mathrm{dir}}^{\mathrm{t}}, v_{2,\mathrm{dec}}^{\mathrm{t}}, R_\gamma^{\mathrm{t}}) = \frac{(R_\gamma^{\mathrm{t}} - 1) v_{2,\mathrm{dir}}^{\mathrm{t}} + v_{2,\mathrm{dec}}^{\mathrm{t}}}{R_\gamma^{\mathrm{t}}}
$$

Marginalized Likelihood (I)

Treat $v_{2,\mathrm{dec}}^{\mathrm{t}}$ and R_γ^{t} as nuisance parameters:

$$L_{\mathrm{m}}(v_{2,\mathrm{inc}}^{\mathrm{m}} | v_{2,\mathrm{dir}}^{\mathrm{t}}) = \int \mathrm{d}v_{2,\mathrm{dec}}^{\mathrm{t}} \mathrm{d}R_\gamma^{\mathrm{t}}\, L(v_{2,\mathrm{inc}}^{\mathrm{m}} | v_{2,\mathrm{dir}}^{\mathrm{t}}, v_{2,\mathrm{dec}}^{\mathrm{t}}, R_\gamma^{\mathrm{t}}) \pi(v_{2,\mathrm{dec}}^{\mathrm{t}}) \pi(R_\gamma^{\mathrm{t}})$$

$$\pi(v_{2,\mathrm{dec}}^{\mathrm{t}}) \propto G(v_{2,\mathrm{dec}}^{\mathrm{t}}; v_{2,\mathrm{dec}}^{\mathrm{m}}, \sigma_{v_{2,\mathrm{dec}}}), \qquad \pi(R_\gamma^{\mathrm{t}}) \propto G(R_\gamma^{\mathrm{t}}; R_\gamma^{\mathrm{m}}, \sigma_{R_\gamma}) \theta(R_\gamma^{\mathrm{t}} - 1)$$

This gives:

$$v_{2,\mathrm{inc}}^{\mathrm{t}} \equiv v_{2,\mathrm{inc}}^{\mathrm{t}}(v_{2,\mathrm{dir}}^{\mathrm{t}}, v_{2,\mathrm{dec}}^{\mathrm{t}}, R_\gamma^{\mathrm{t}}) = \frac{(R_\gamma^{\mathrm{t}} - 1) v_{2,\mathrm{dir}}^{\mathrm{t}} + v_{2,\mathrm{dec}}^{\mathrm{t}}}{R_\gamma^{\mathrm{t}}}$$

$$L(v_{2,\mathrm{inc}}^{\mathrm{m}} | v_{2,\mathrm{dir}}^{\mathrm{t}}) = \int_{-0.5}^{0.5} \mathrm{d}v_{2,\mathrm{dec}}^{\mathrm{t}} \int_{1}^{\infty} \mathrm{d}R_\gamma^{\mathrm{t}}\, G(v_{2,\mathrm{inc}}^{\mathrm{m}}; v_{2,\mathrm{inc}}^{\mathrm{t}}, \sigma_{v_{2,\mathrm{inc}}}) \cdot G(v_{2,\mathrm{dec}}^{\mathrm{t}}; v_{2,\mathrm{dec}}^{\mathrm{m}}, \sigma_{v_{2,\mathrm{dec}}}) \cdot$$
$$G(R_\gamma^{\mathrm{t}}; R_\gamma^{\mathrm{m}}, \sigma_{R_\gamma})$$

Marginalized Likelihood (II)

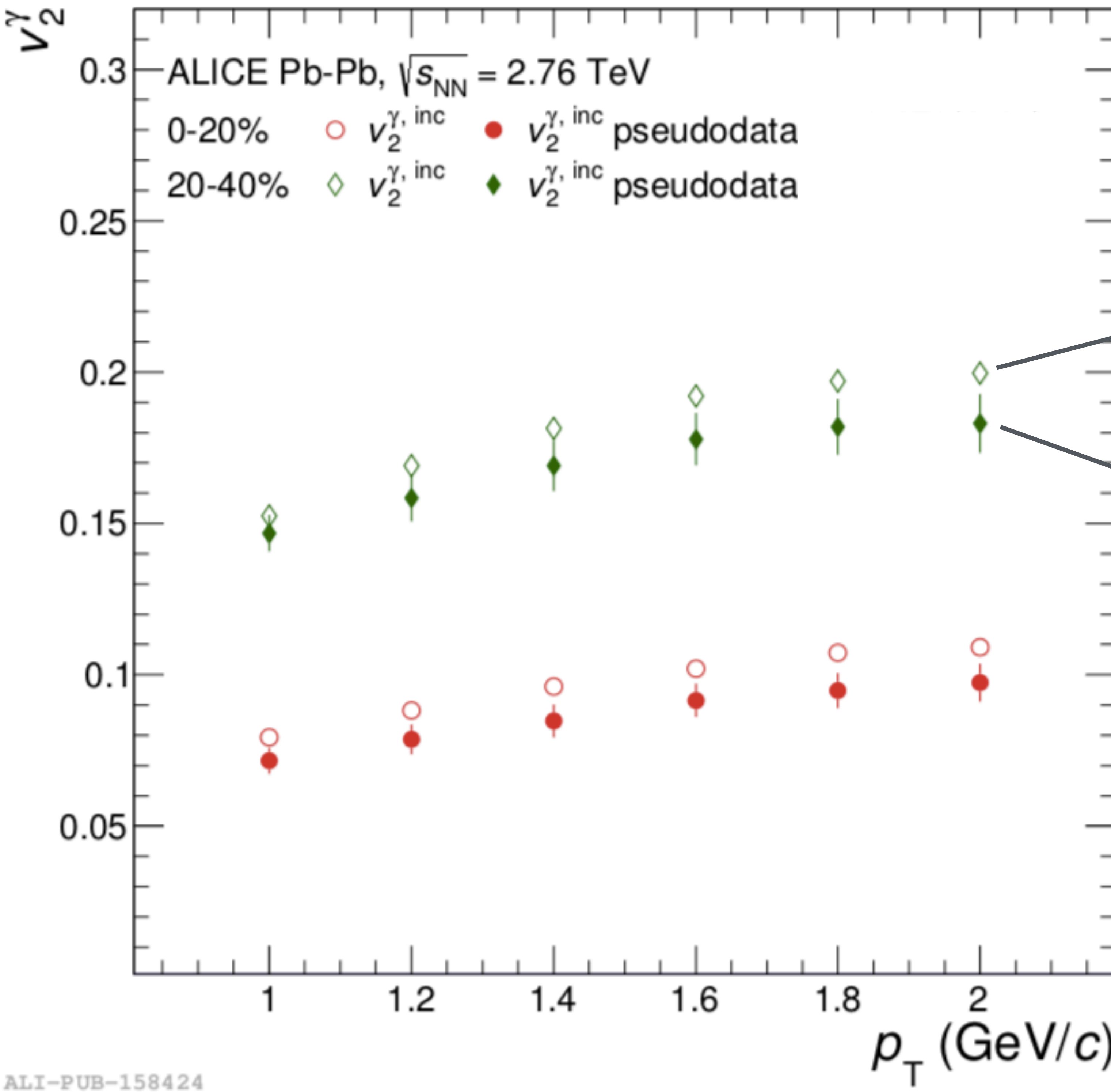
From previous slide:

$$L(v_{2,\mathrm{inc}}^{\mathrm{m}} | v_{2,\mathrm{dir}}^{\mathrm{t}}) = \int\limits_{-0.5}^{0.5} \mathrm{d}v_{2,\mathrm{dec}}^{\mathrm{t}} \int\limits_{1}^{\infty} \mathrm{d}R_{\gamma}^{\mathrm{t}}\, G(v_{2,\mathrm{inc}}^{\mathrm{m}}; v_{2,\mathrm{inc}}^{\mathrm{t}}, \sigma_{v_{2,\mathrm{inc}}}) \cdot G(v_{2,\mathrm{dec}}^{\mathrm{t}}; v_{2,\mathrm{dec}}^{\mathrm{m}}, \sigma_{v_{2,\mathrm{dec}}}) \cdot G(R_{\gamma}^{\mathrm{t}}; R_{\gamma}^{\mathrm{m}}, \sigma_{R_{\gamma}})$$

MC sampling instead of solving the integrals $\rightsquigarrow$ histogram of $v_{2,\mathrm{inc}}^{\mathrm{m}}$ values:

- Draw $v_{2,\mathrm{dec}}^{\mathrm{t}}$ and R_{γ}^{t} from the corresponding Gaussians
- Calculate $v_{2,\mathrm{inc}}^{\mathrm{t}}$ from these values and the given $v_{2,\mathrm{dir}}^{\mathrm{t}}$ hypothesis
- Generate $v_{2,\mathrm{inc}}^{\mathrm{m}}$ pseudo-data

Significance of the Deviation from the Null Hypothesis $v_{2,\mathrm{dir}} \equiv 0$



measured $v_{2,\mathrm{inc}}$

pseudodata for null hypothesis $v_{2,\mathrm{dir}} \equiv 0$

For both centralities:
Significance $O(1\sigma)$

Significance of Puzzles

Another example:

https://home.cern/news/news/experiments/lhcb-finds-new-hints-possible-standard-model-deviations

LHCb finds new hints of possible Standard Model deviations

The LHCb experiment finds intriguing anomalies in the way some particles decay

18 APRIL, 2017 | By Stefania Pandolfi

"While potentially exciting, the discrepancy with the Standard Model occurs at the level of **2.2 to 2.5 sigma**, which is not yet sufficient to draw a firm conclusion."

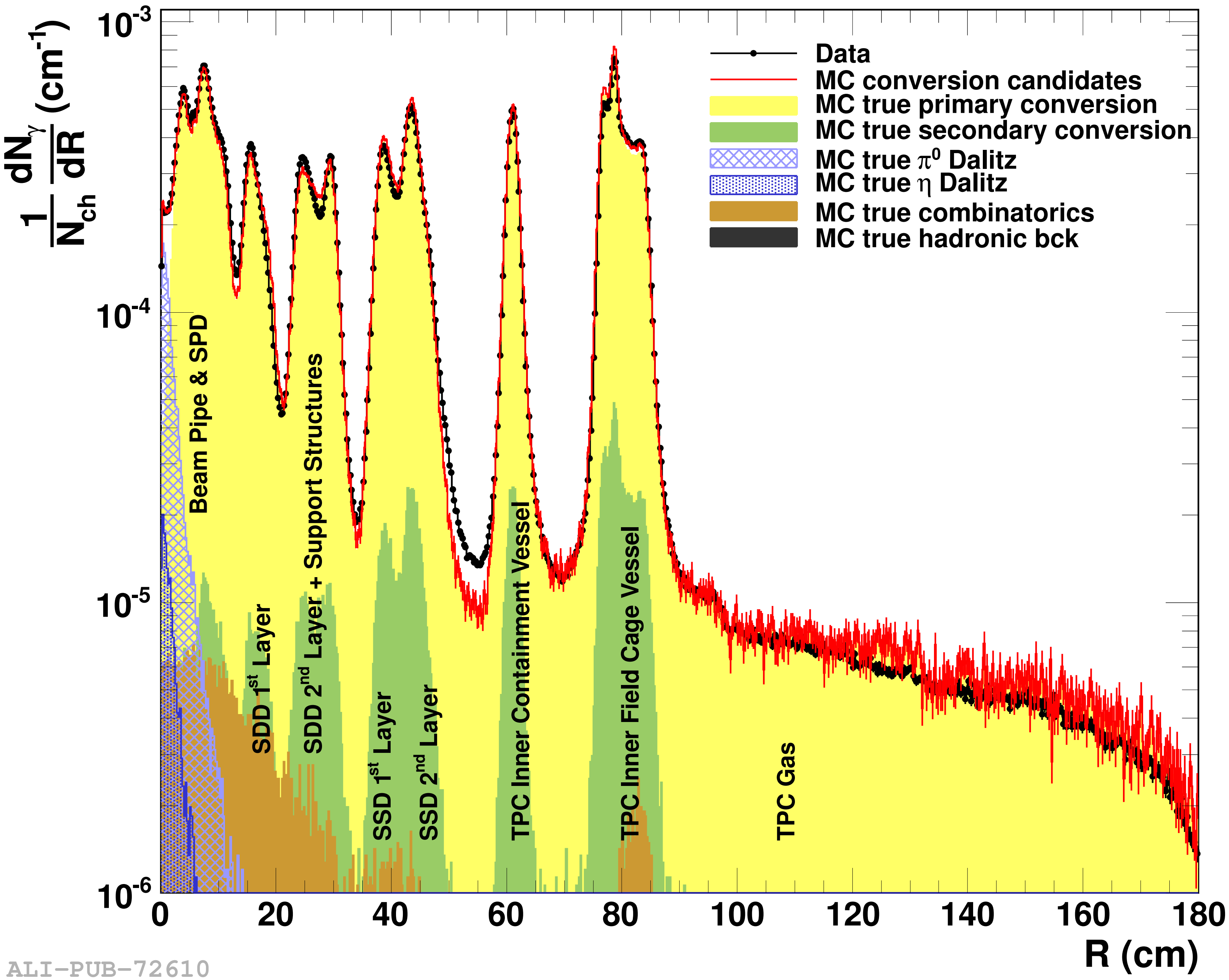
What is the statistical significance of the direct-photon puzzle?

In a joint effort, we could come up with a statement.

[reasonable timing: as spectra at v_2 at RHIC and the LHC are now published]

Reducing systematic uncertainties

Reducing the Material Budget Uncertainty in the Photon Conversion Method: Weights



$$w_i = \frac{(N_{\gamma}^{\mathrm{rec}}(r_i)/N_{\gamma}^{\mathrm{rec}}(r_{\mathrm{ref}}))_{\mathrm{data}}}{(N_{\gamma}^{\mathrm{rec}}(r_i)/N_{\gamma}^{\mathrm{rec}}(r_{\mathrm{ref}}))_{\mathrm{MC}}}$$

$$\varepsilon_{\gamma}^{\mathrm{rec}}(p_T) = \frac{\sum_i w_i N_{\gamma}^{\mathrm{rec}}(r_i, p_T)}{N_{\gamma}^{\mathrm{prod}}(r_i, p_T)}$$

Reference material:

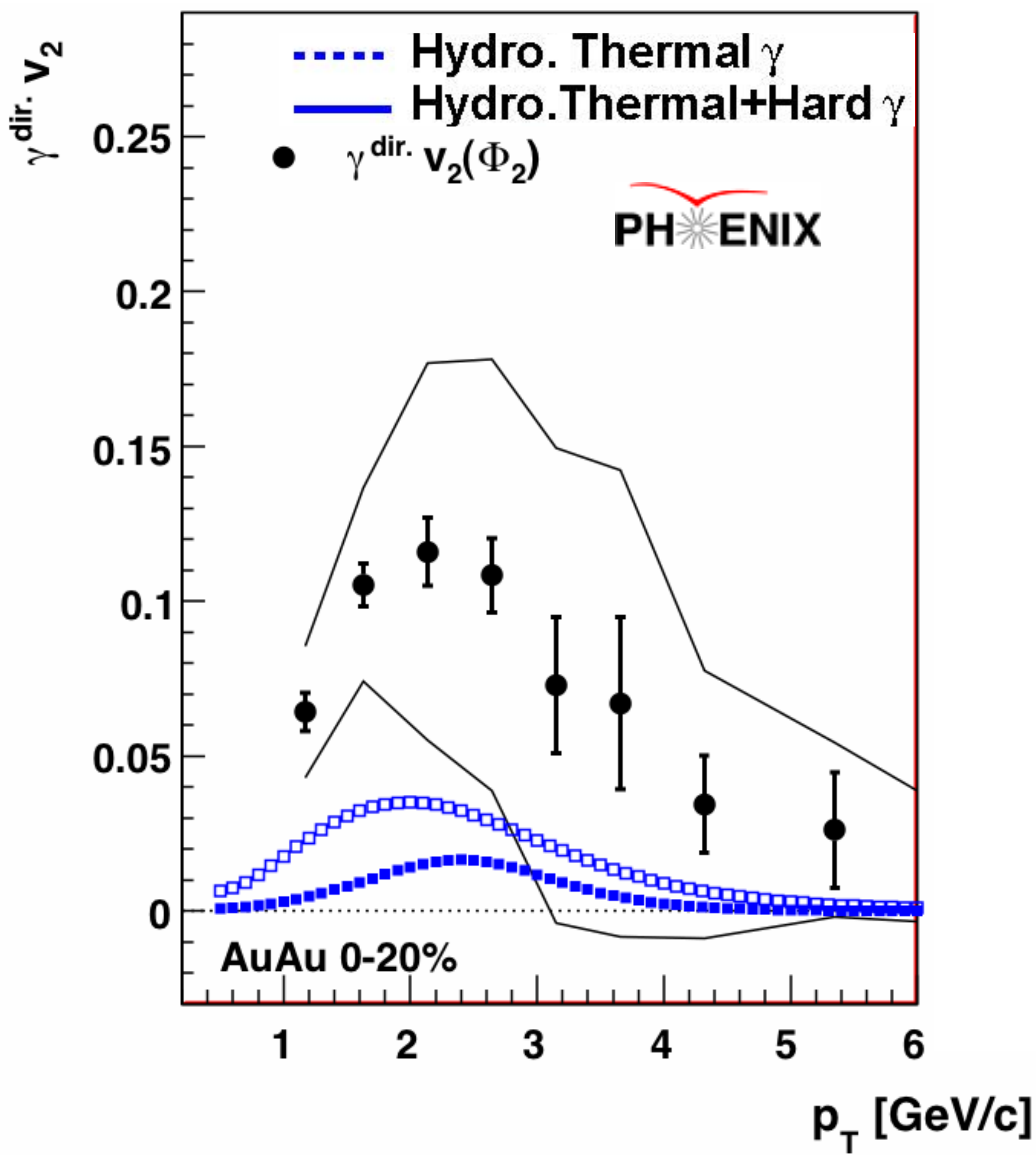
- TPC gas (need to keep track of pressure)
- tungsten wires (Run 3)

Might reduce current material budget uncertainty of 4.5% by more than a factor 2

Direct-Photon Puzzle

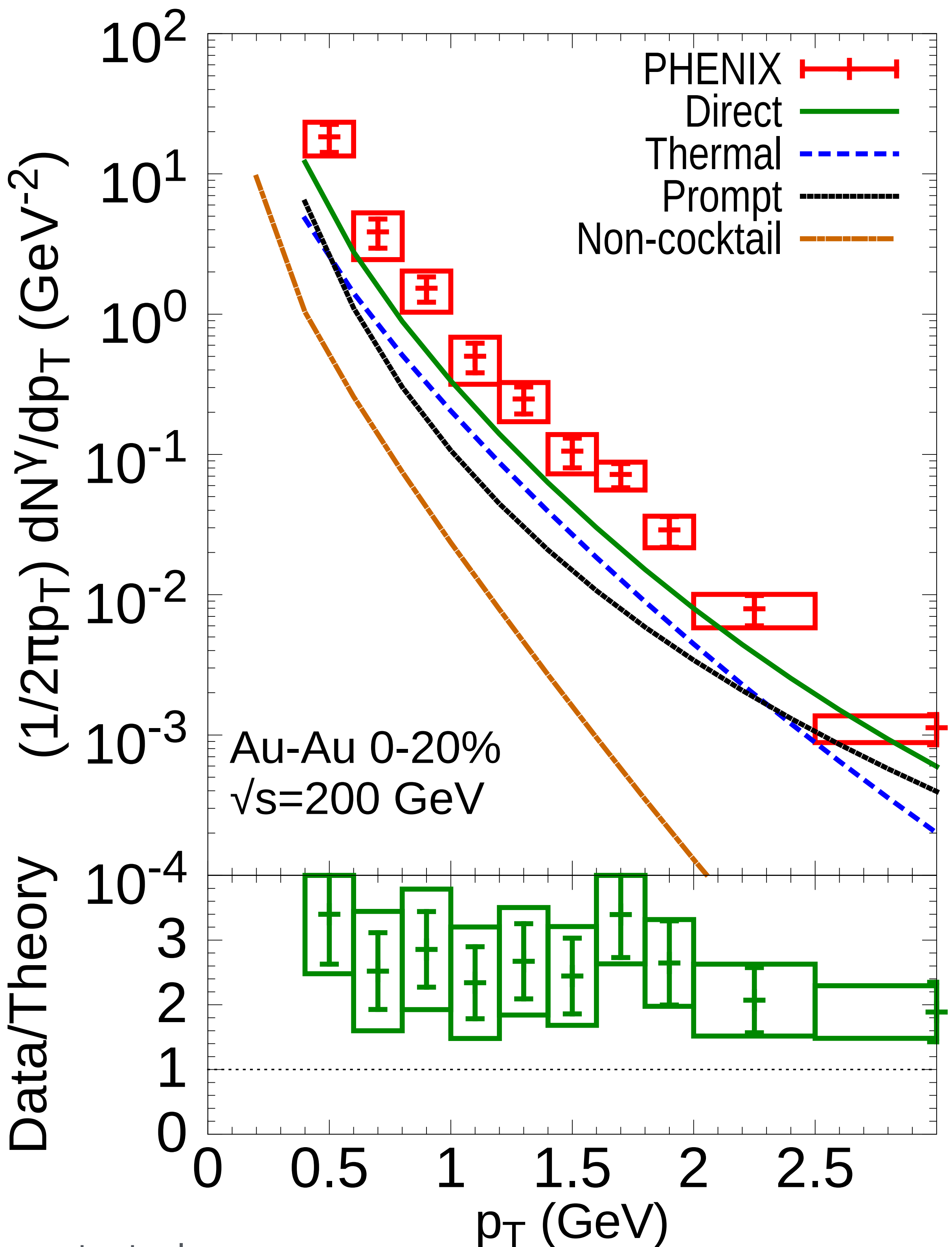
Birth of the Direct Photon Puzzle

PHENIX, Quark Matter 2011



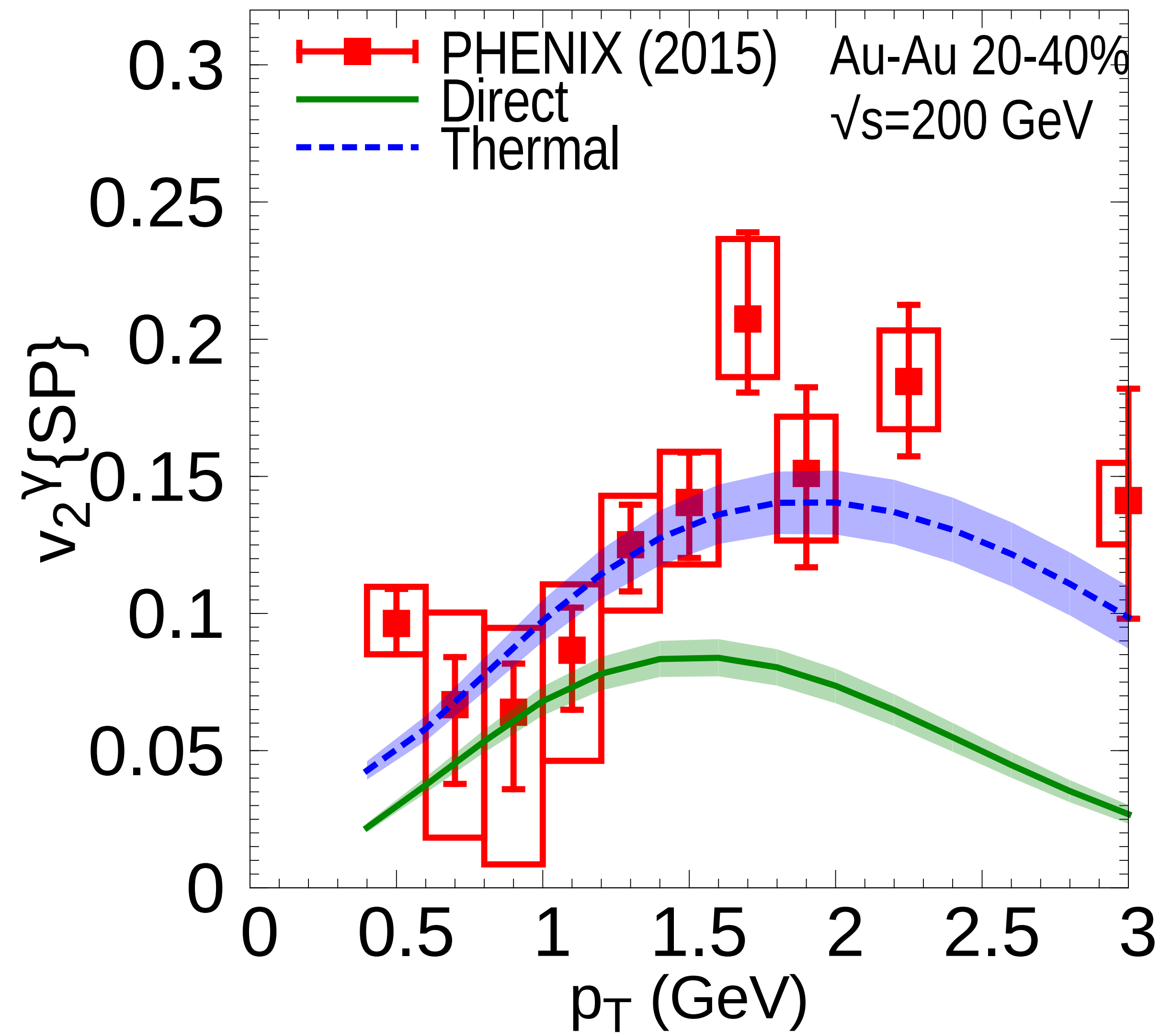
- Quark Matter 2011
- "Data a challenge to theory" or
- "Theory a challenge to the data"

Direct-Photon Puzzle: Status



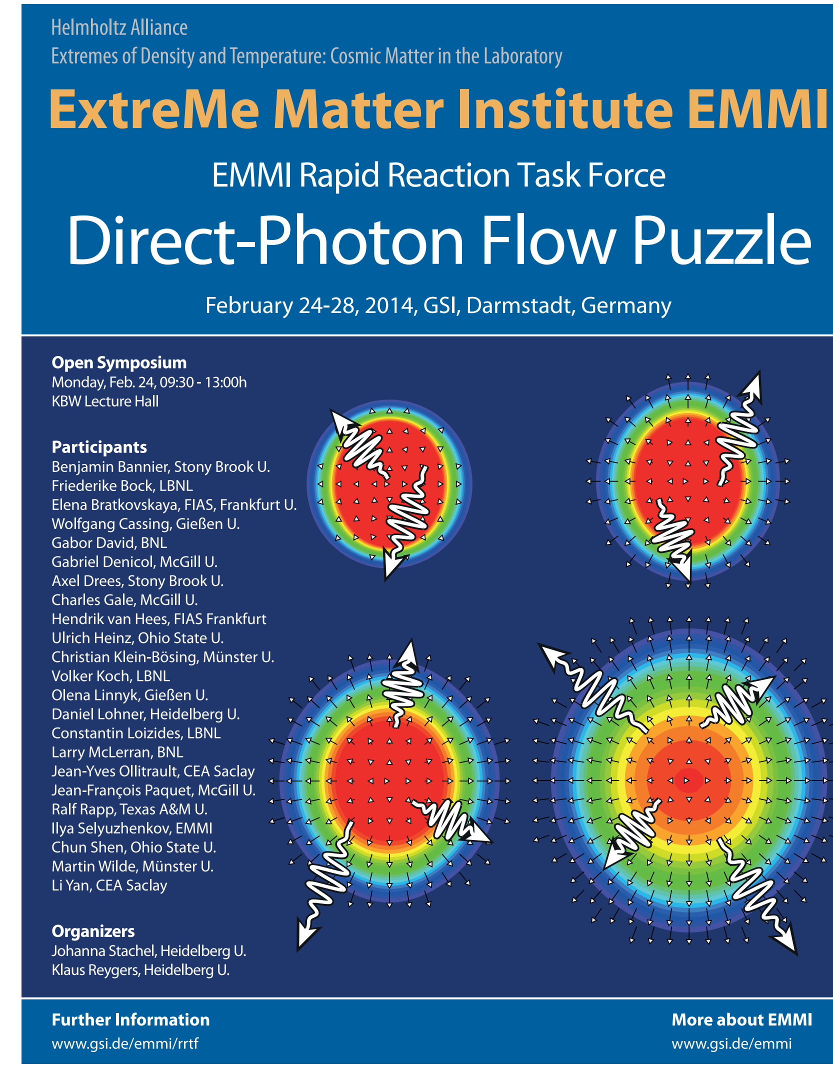
Paquet et al., arXiv:1509.06738

$$dn_\gamma/d\phi \propto 1 + 2v_2\cos(2\phi)$$



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

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)

- $\pi+\pi \rightarrow \pi+\pi+\gamma$ (e.g. PHSD model [1])
- "radiative hadronization"?
- …

?

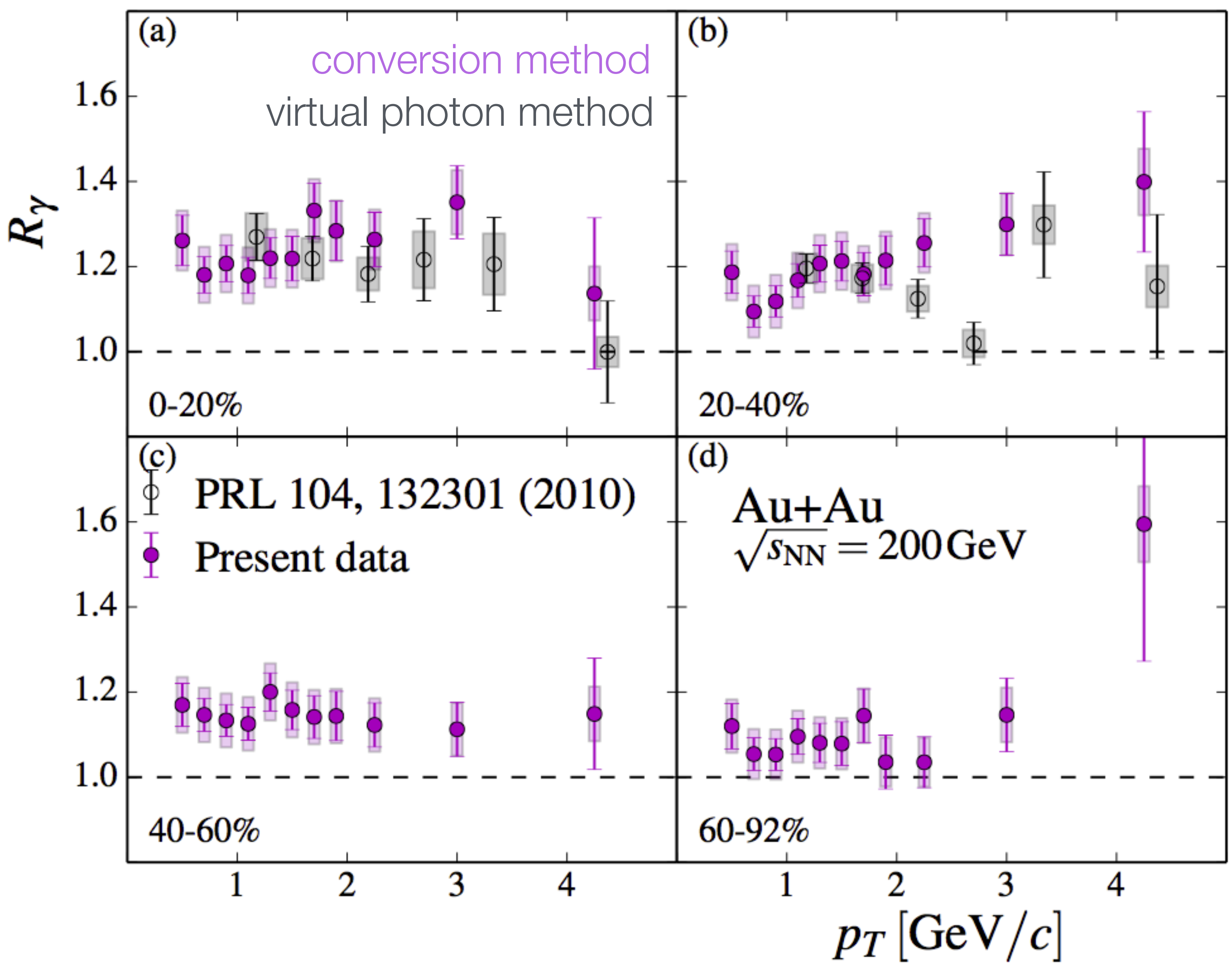
Possible paradigm shift concerning role of photons as QGP messengers?

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

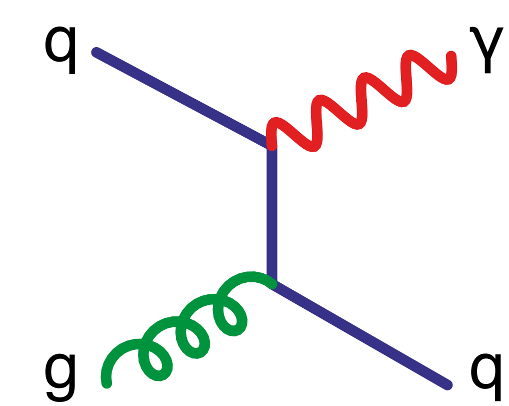
RHIC: Two Methods, Same Answer

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

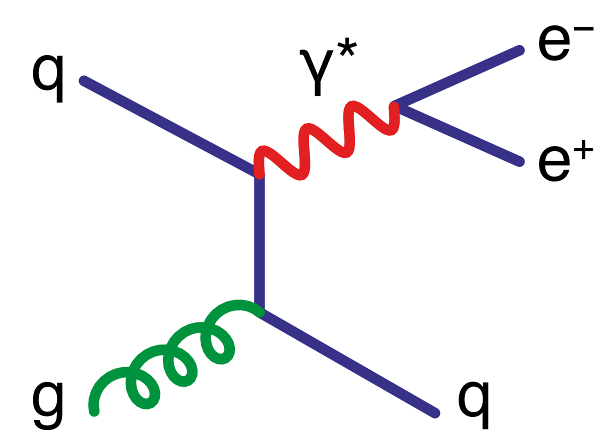
PHENIX, arXiv:1405.3940



Real photons (through conversion):



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

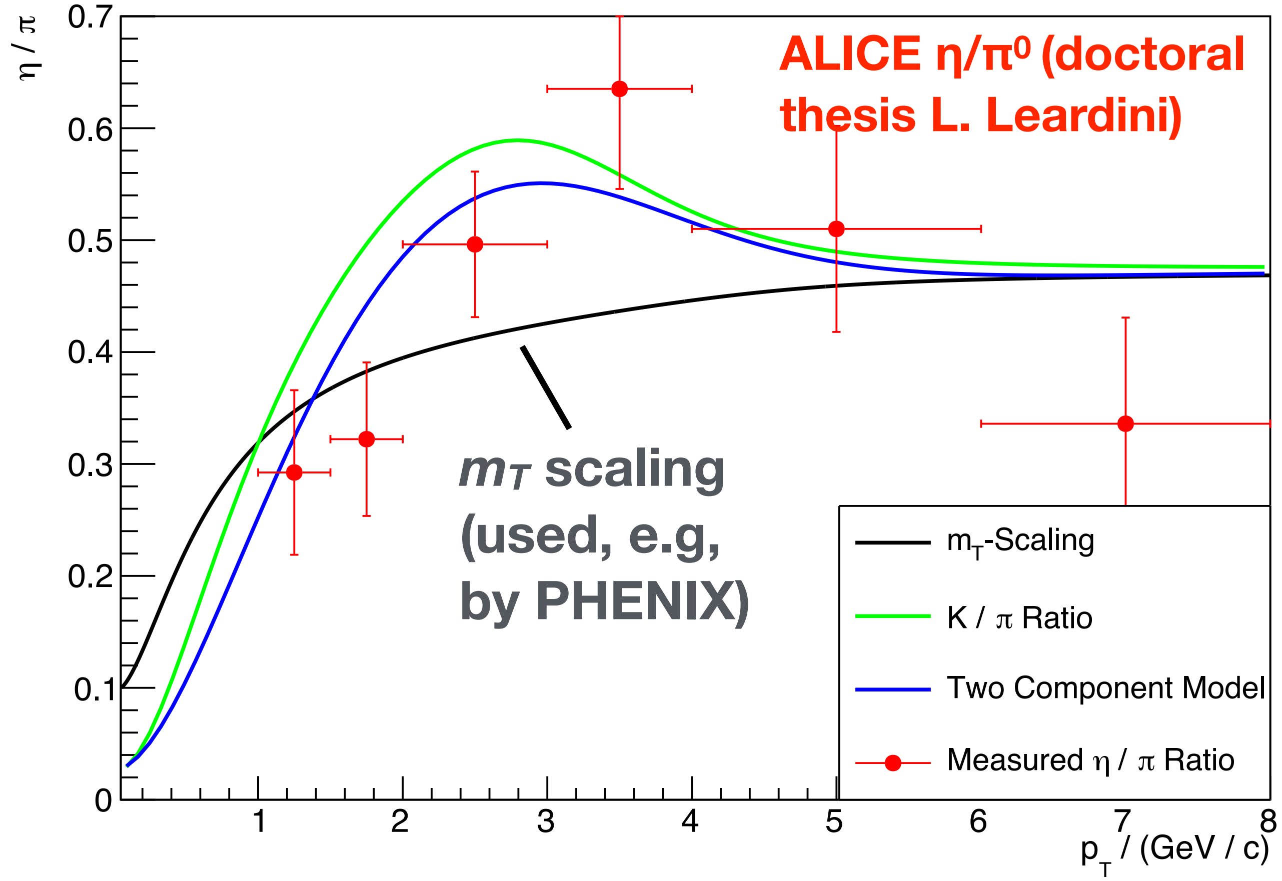


Decay Photon Cocktail: Beyond m_T scaling for η, ω, η', …

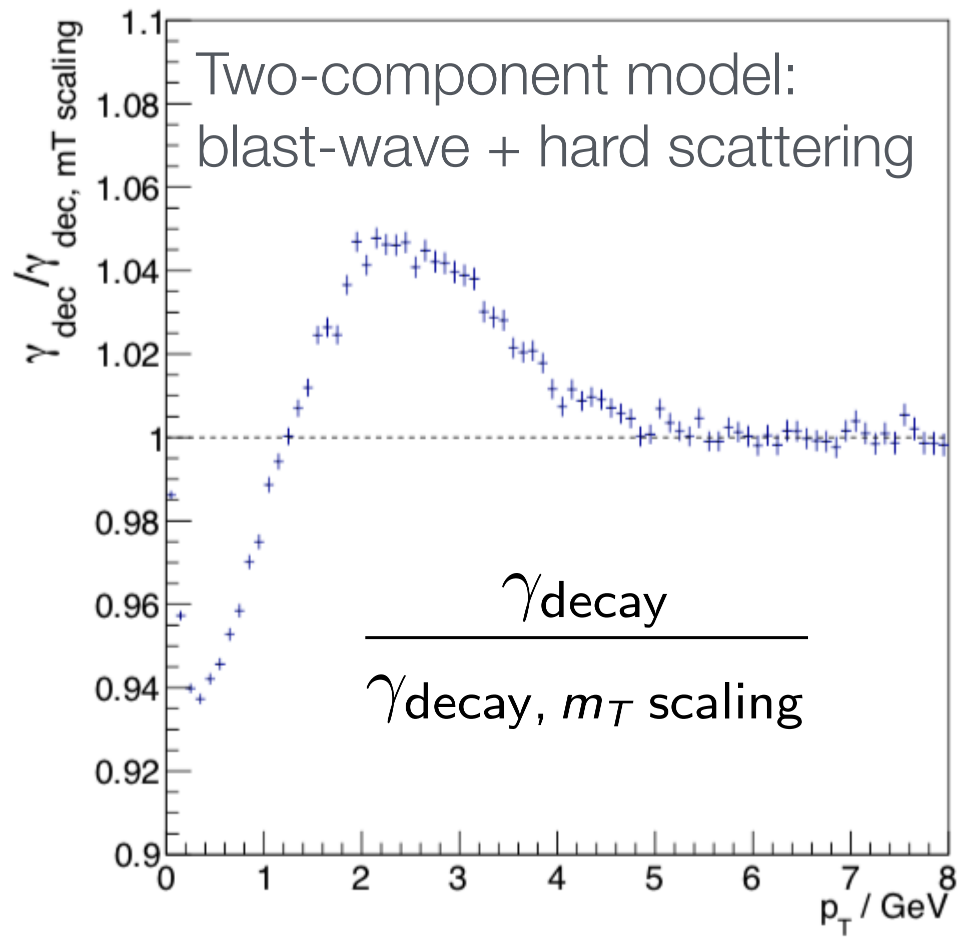
m_T scaling often used to model spectra of η, ω, …:

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

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

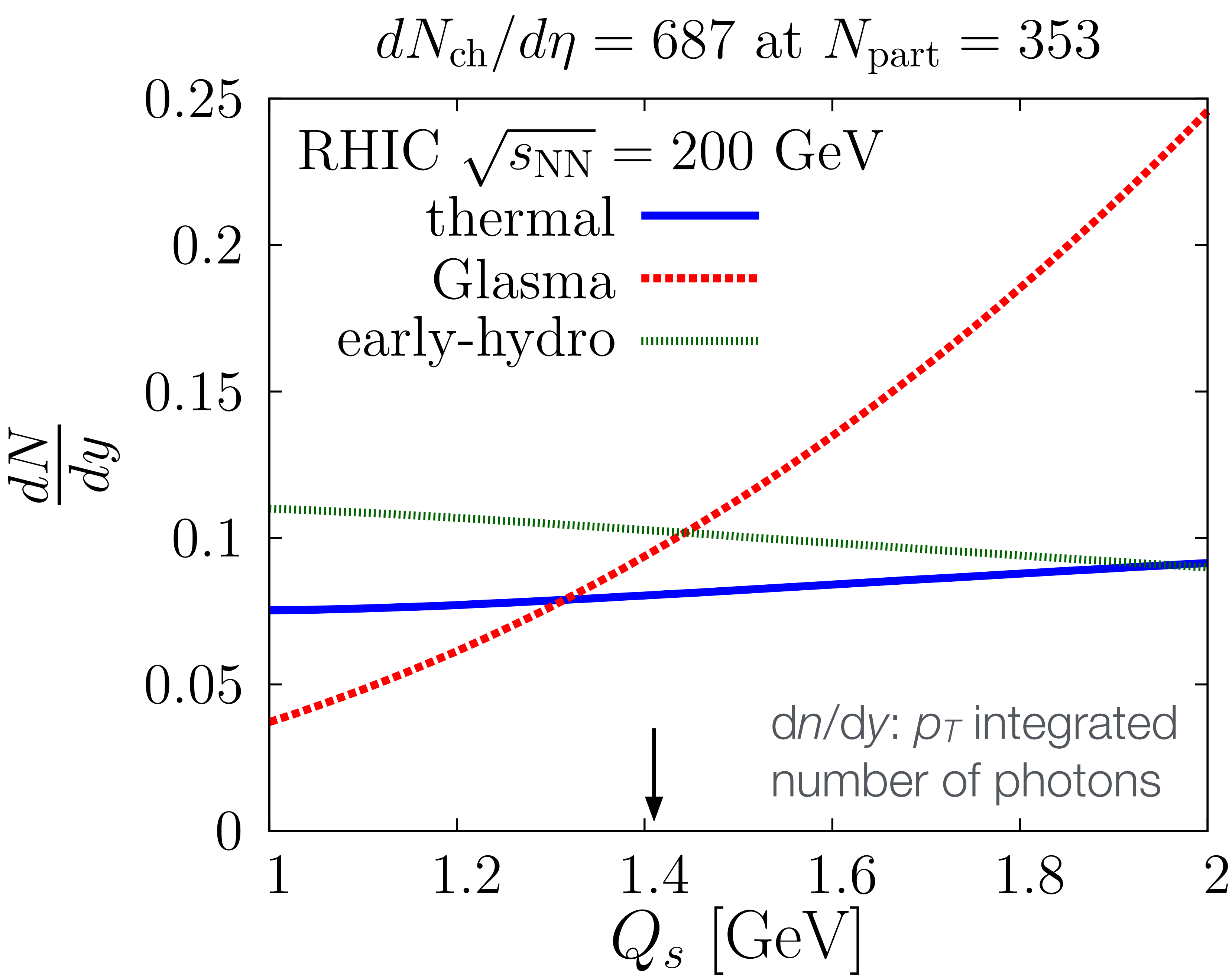


bachelor's thesis Ilya Fokin



Know your baseline!

Early Stage: Glasma Contribution to Total Photon Yield Might be Sizable



Parametric estimate

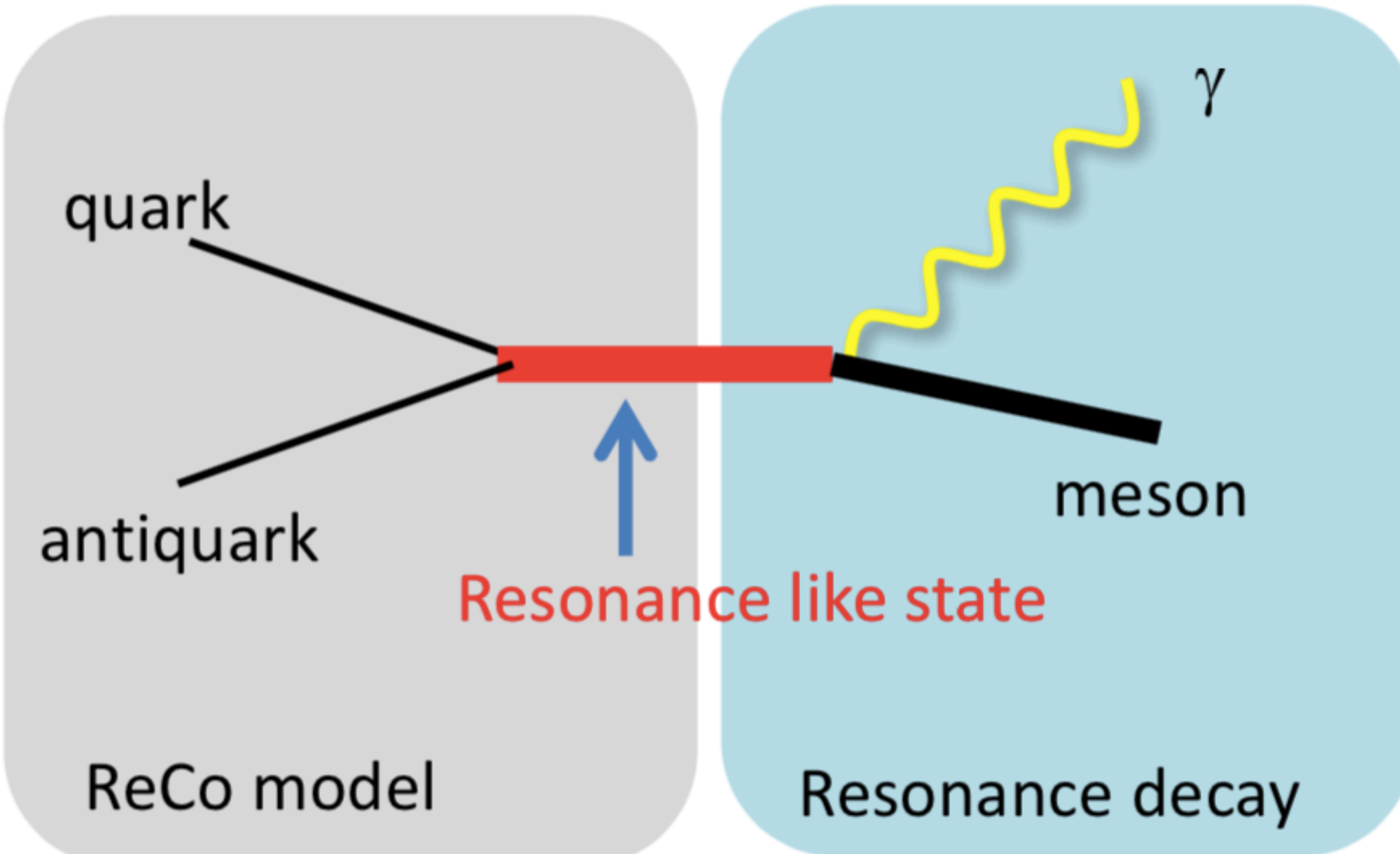
"bottom-up thermalization"
[R.Baier et al.]

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

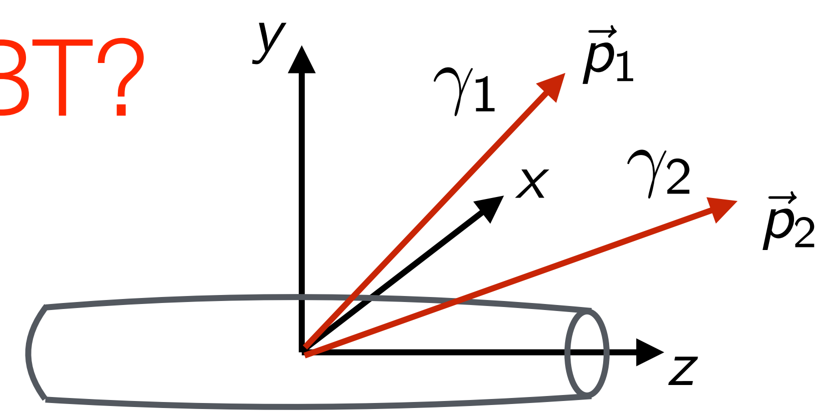
$$T_\text{eff} \approx \sqrt{\frac{1+\beta}{1-\beta}}\,T$$

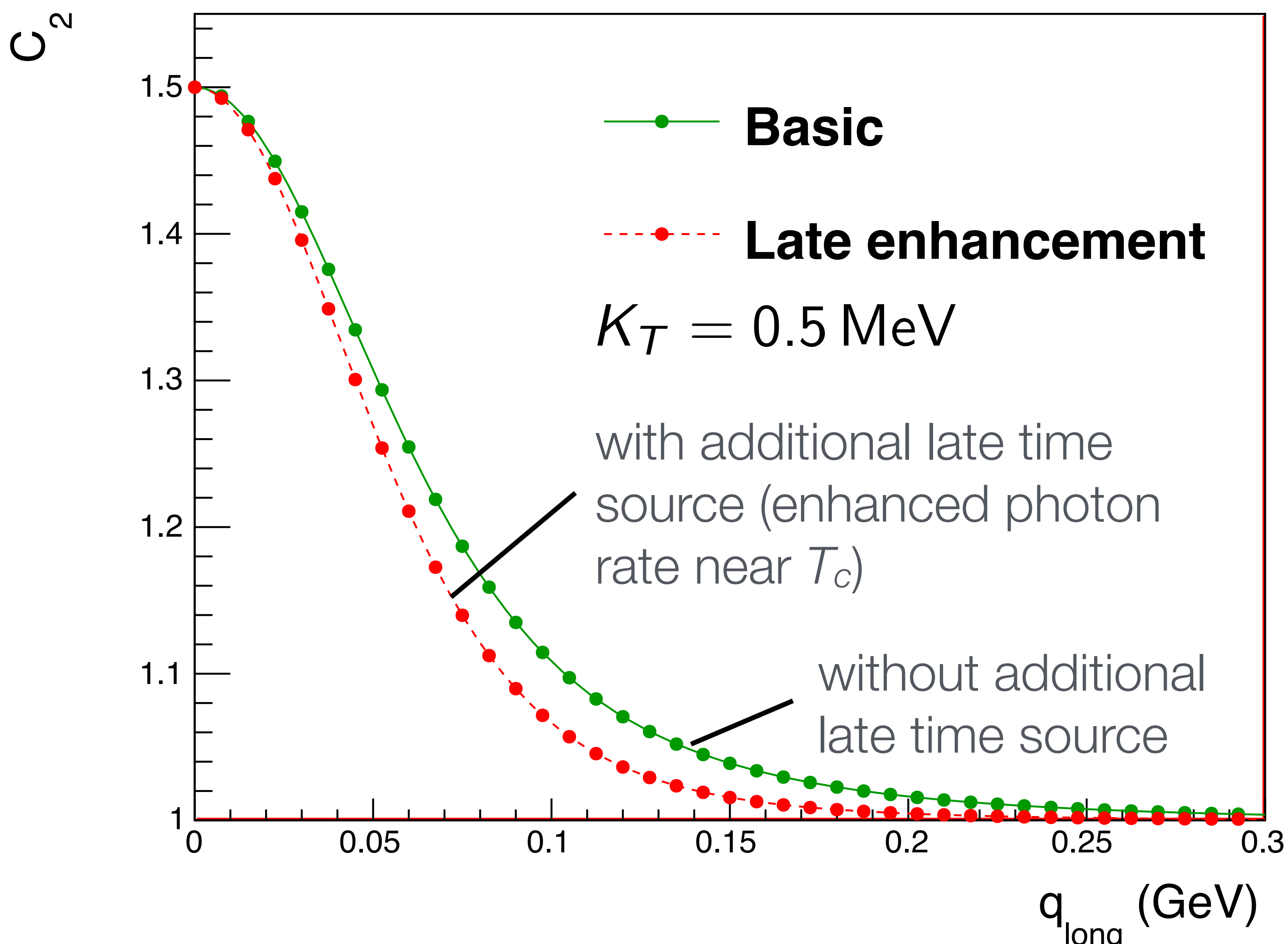
- "Saves" energy conservation in recombination models

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

Early or Late Stage Production: Constraints from Photon HBT?

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



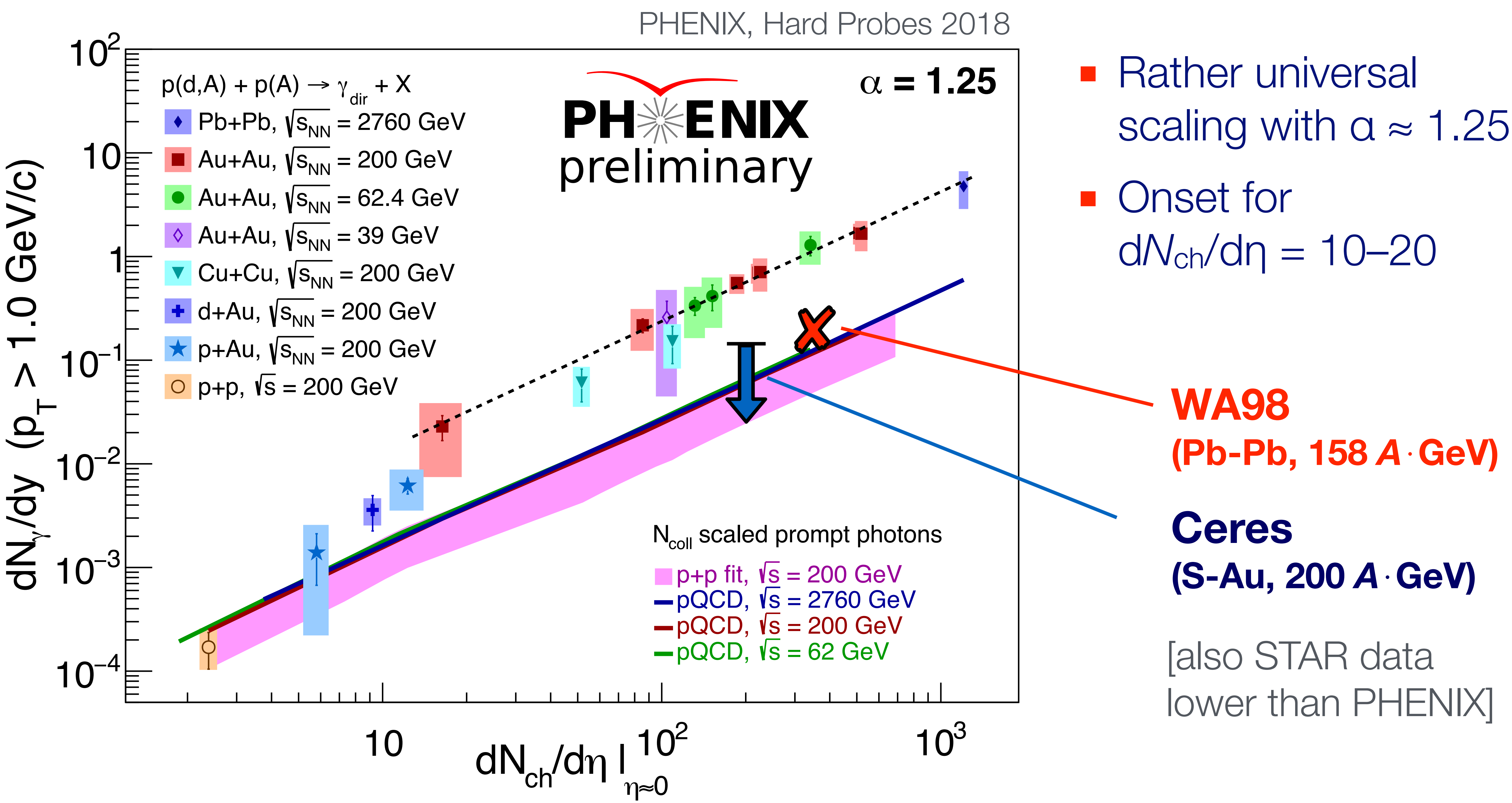


projection of momentum difference onto z axis

- 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?



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

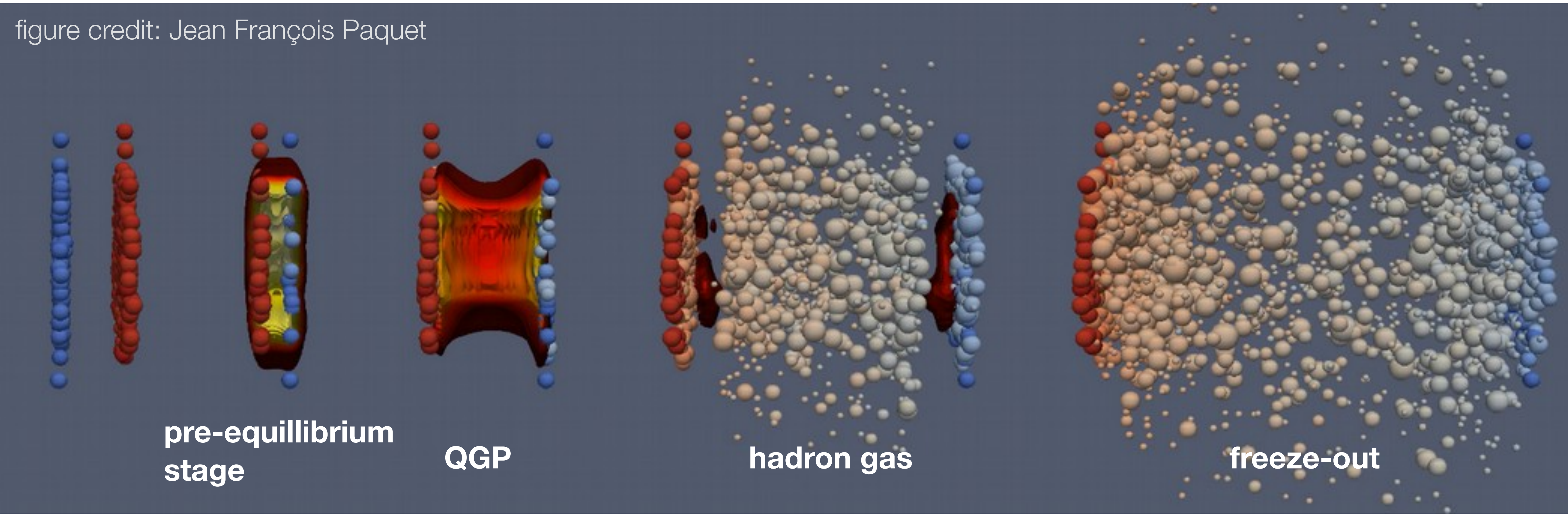
[also STAR data lower than PHENIX]

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

Conclusions

- ALICE: Large $v_{2,\mathrm{dir}}$ ($\approx v_{2,\mathrm{dec}}$), but also large uncertainties
- Direct photon puzzle mostly at RHIC
- Quantifying the statistical significance of the puzzle would be a nice joint project
- Possible paradigm shift:
  Photon production dominated by late stage around T_c?

Extra Slides

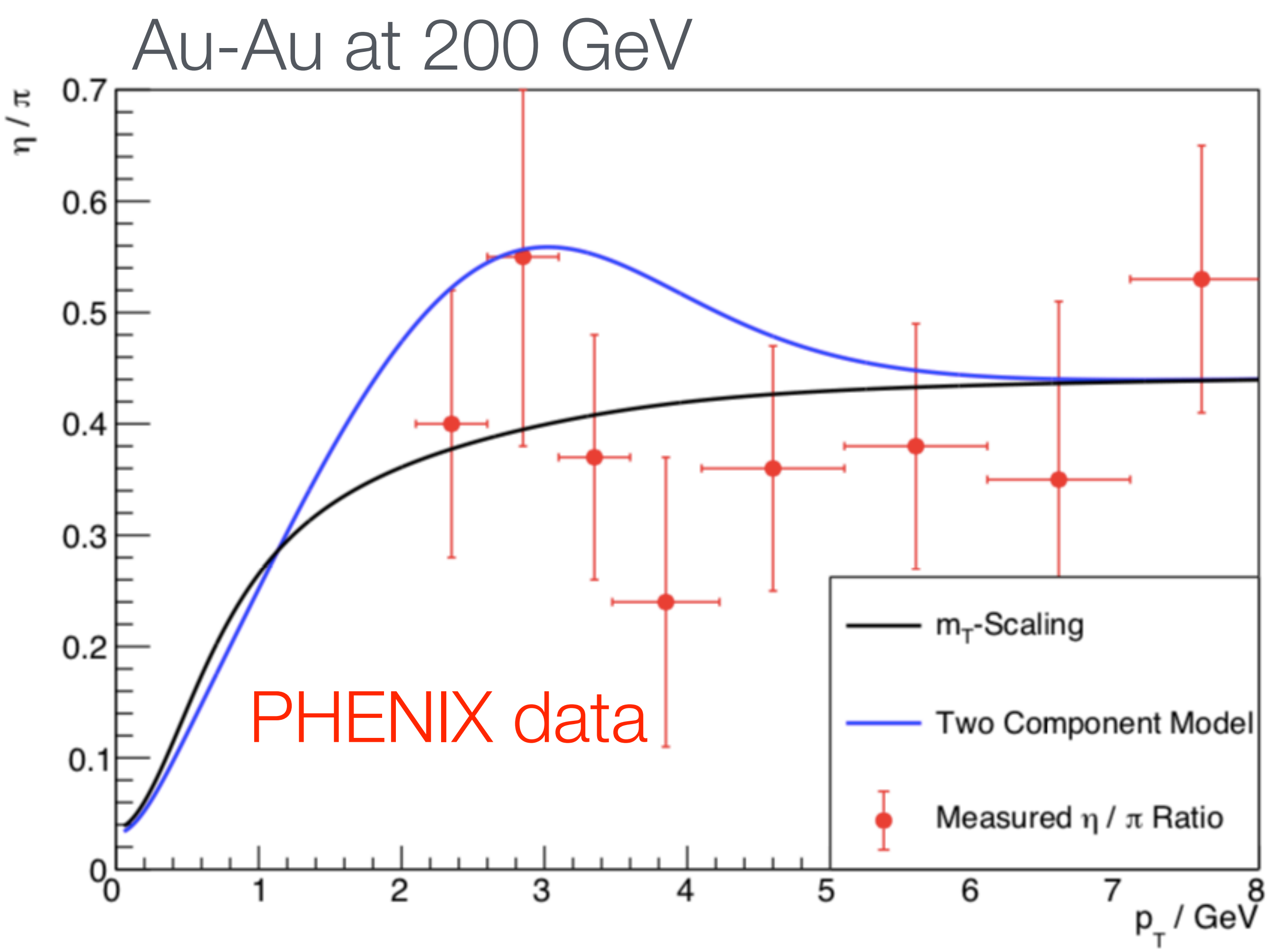


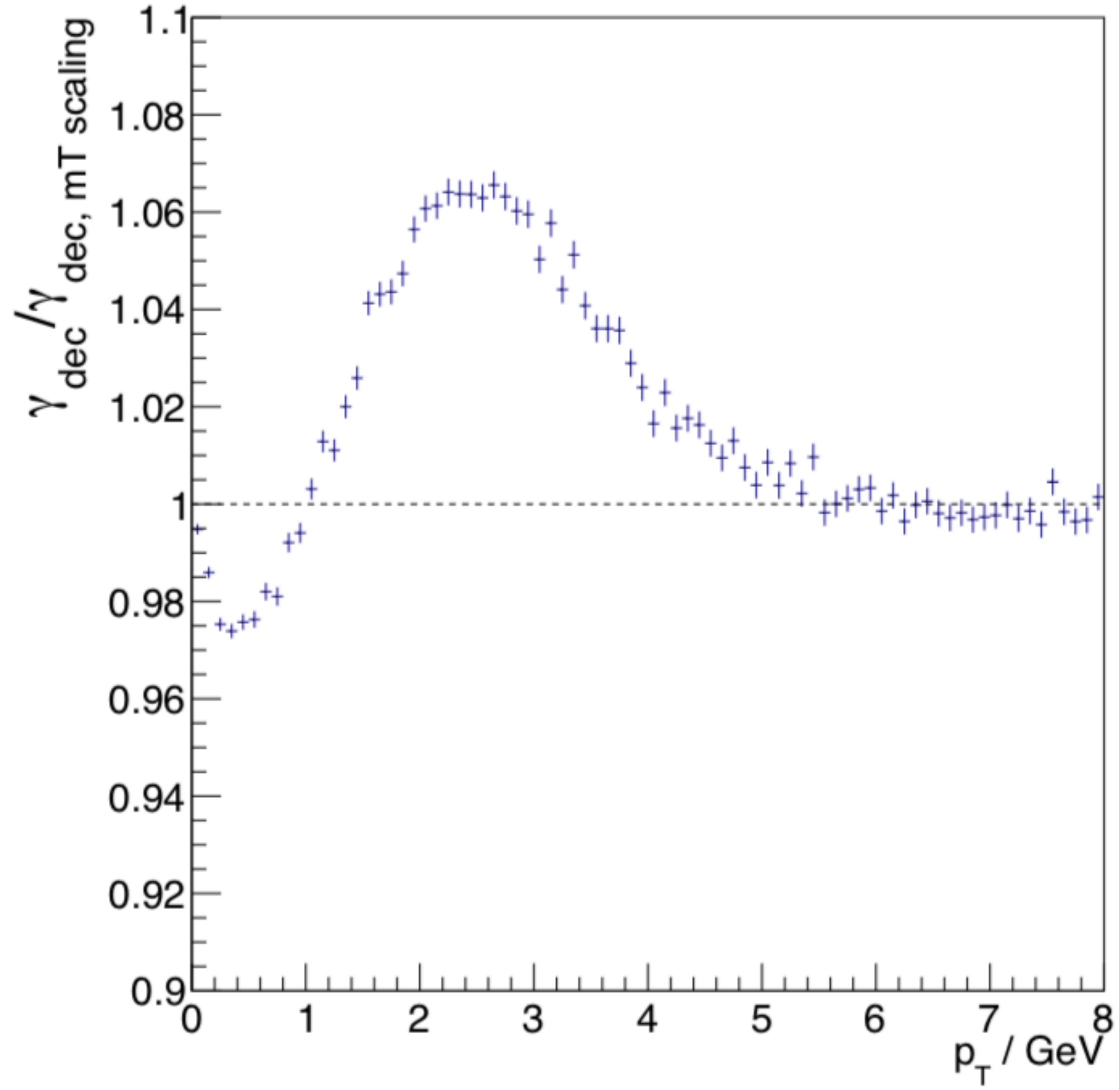
thermalization: $\tau_{\text{th}} = 1\text{–}2\,\text{fm}/c$

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

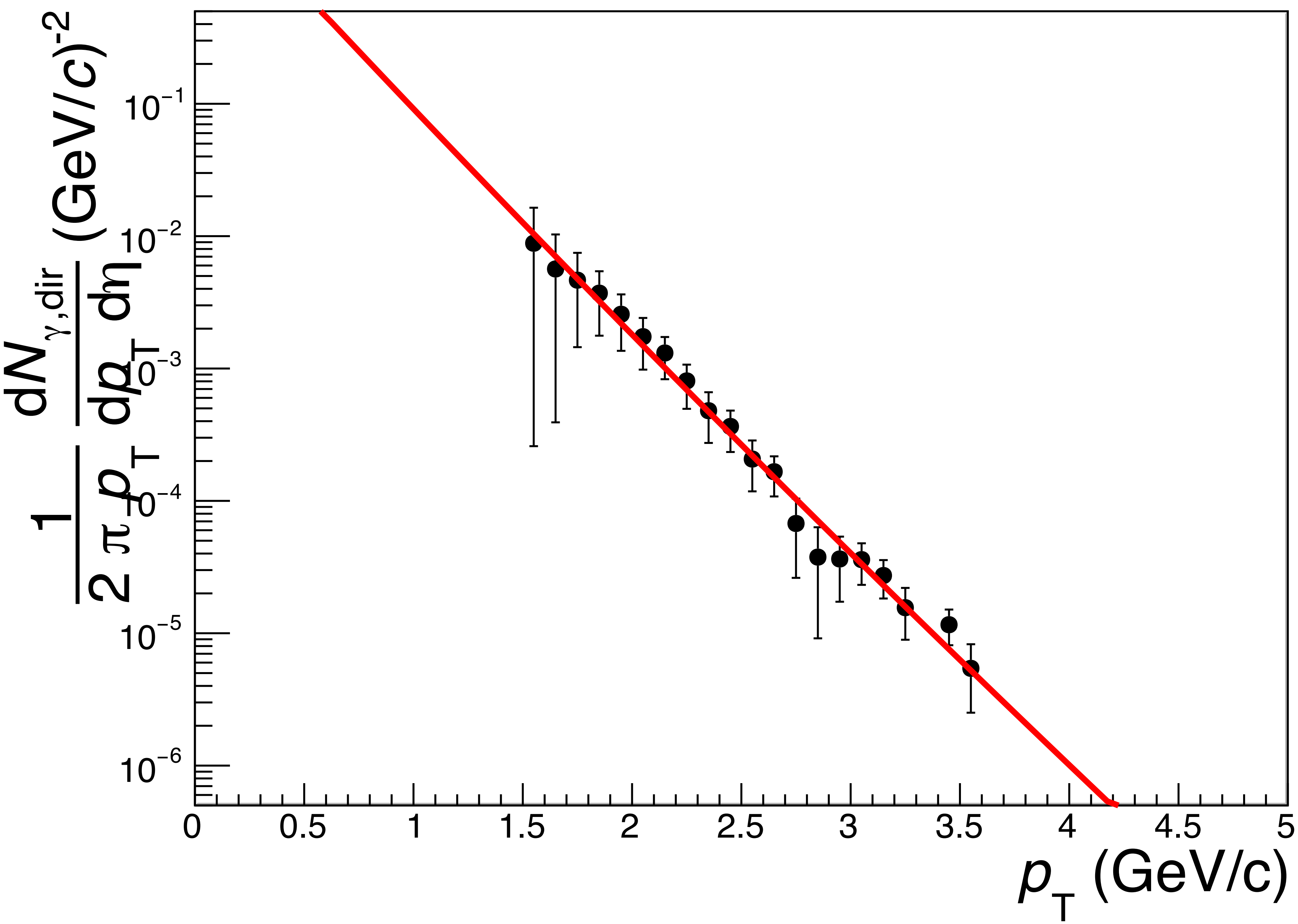
QGP → hadron gas at $T \approx 155\,\text{MeV}$

Improved Cocktail: Au-Au at 200 GeV



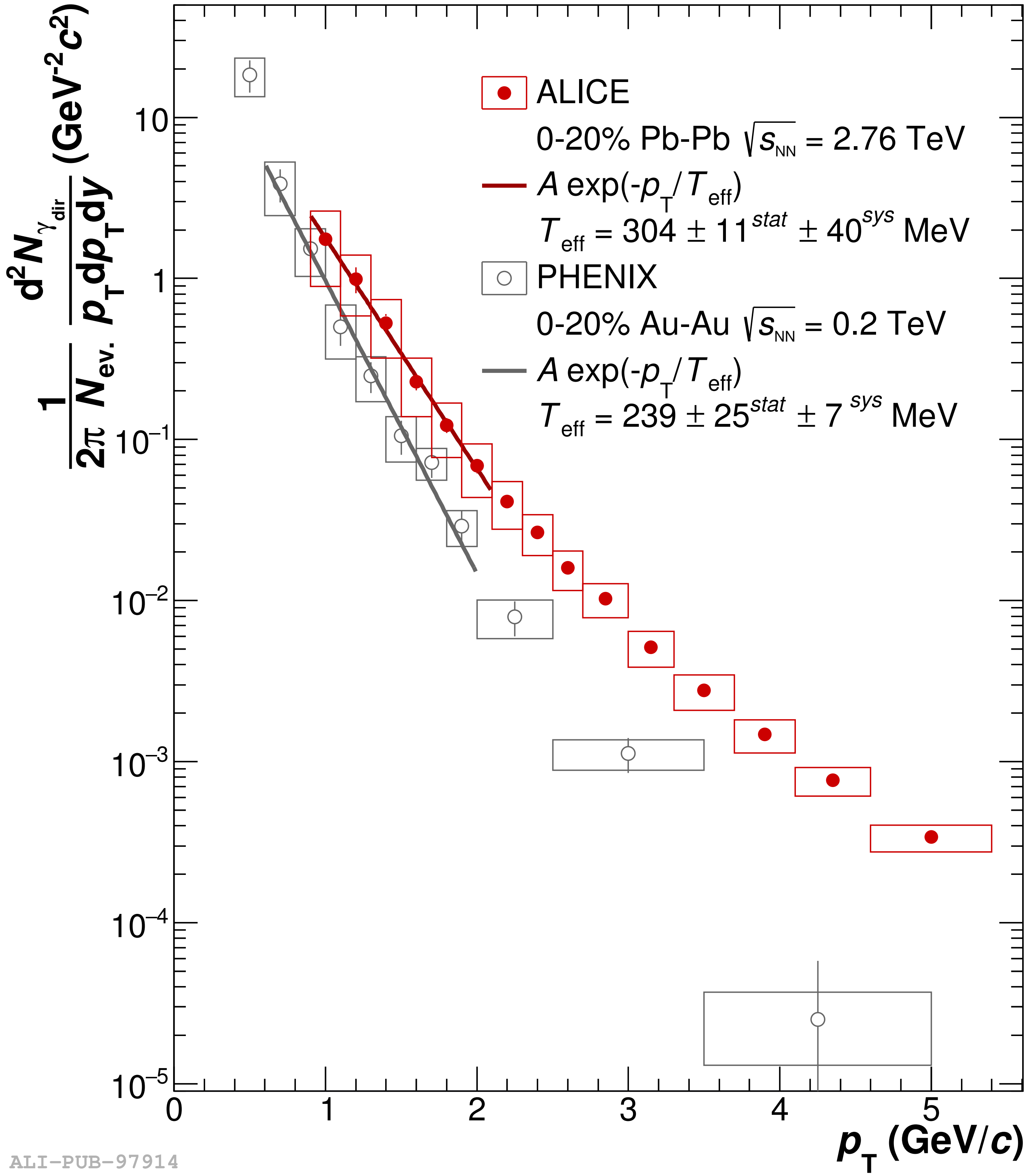


WA98 Data



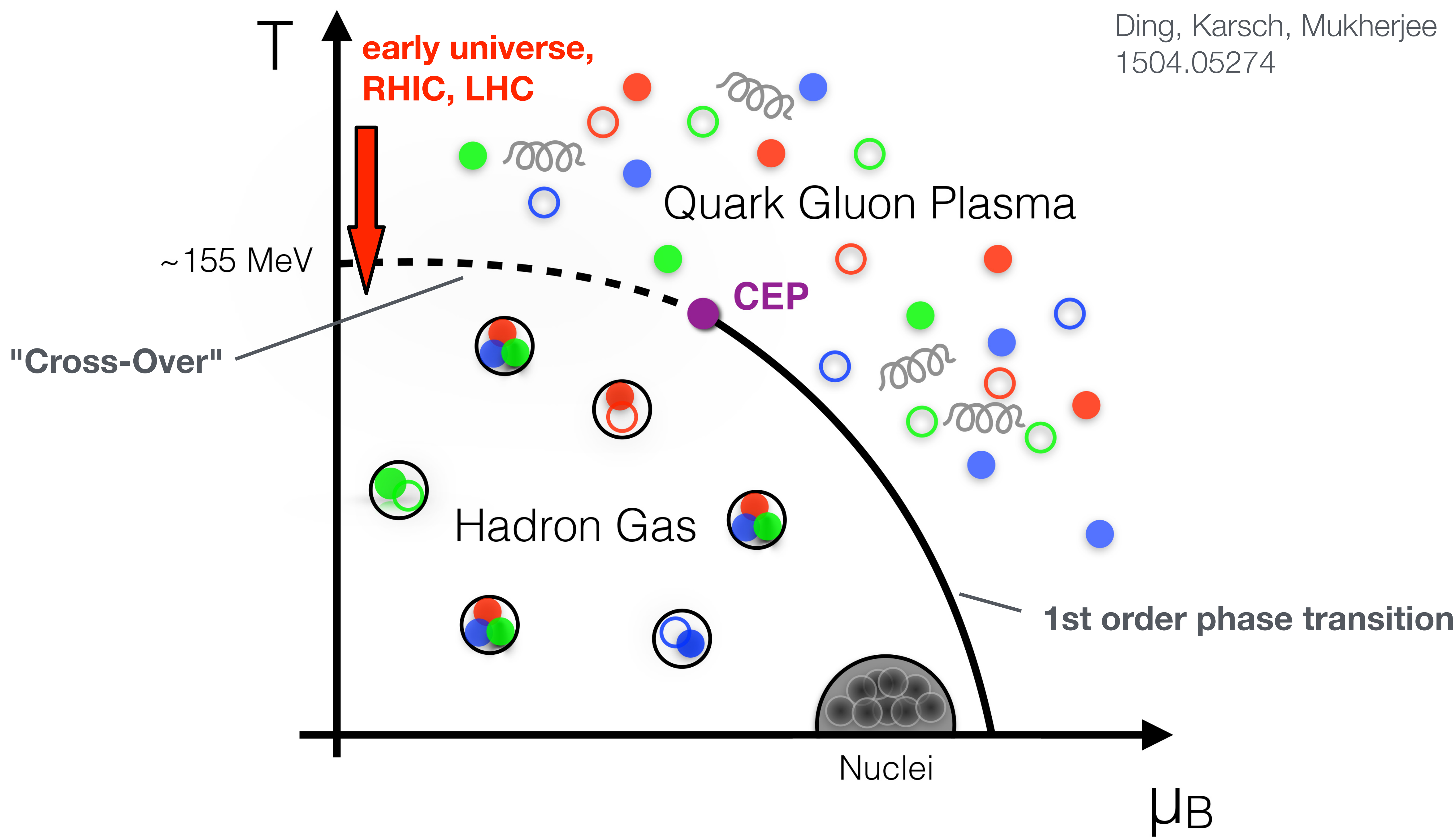
$\frac{1}{2\pi p_T} \frac{dN_{\gamma,dir}}{dp_T\, d\eta}$ (GeV/c)$^{-2}$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
p_T (GeV/c)

Larger T_{eff} at the LHC

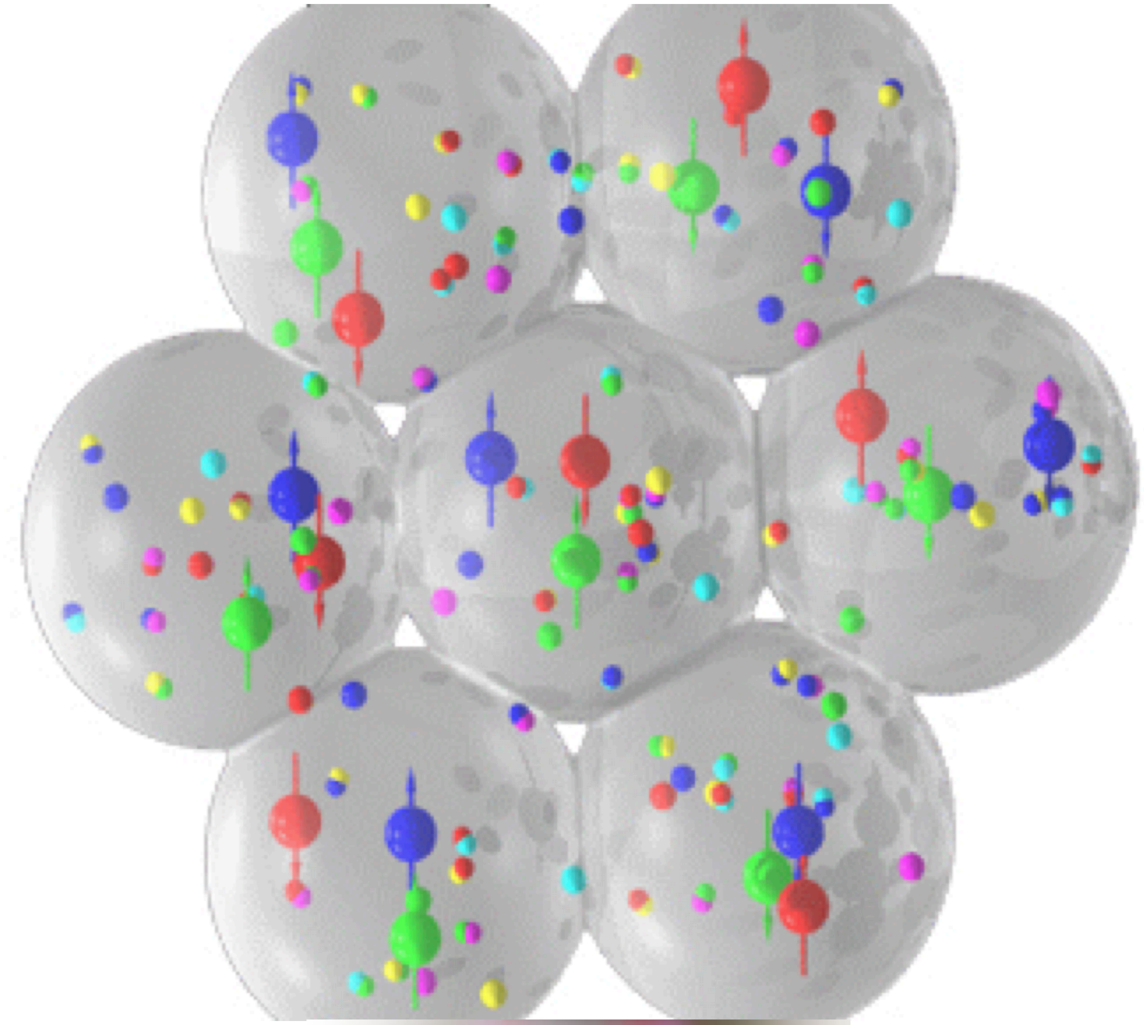


- T_{eff} LHC
  - 0-20% Pb-Pb@2.76 TeV
  - without pQCD subtraction: $T_{eff} = 304 \pm 11^{stat} \pm 40^{sys}$ MeV
  - with pQCD subtraction: $T_{eff} = 297 \pm 12^{stat} \pm 41^{sys}$ MeV
- T_{eff} RHIC
  - 0-20% Au-Au@0.2 TeV
  - $T_{eff} = 239 \pm 25^{stat} \pm 7^{sys}$ MeV (pp parameterization subtracted)

(Conjectured) QCD Phase Diagram



What is the question?

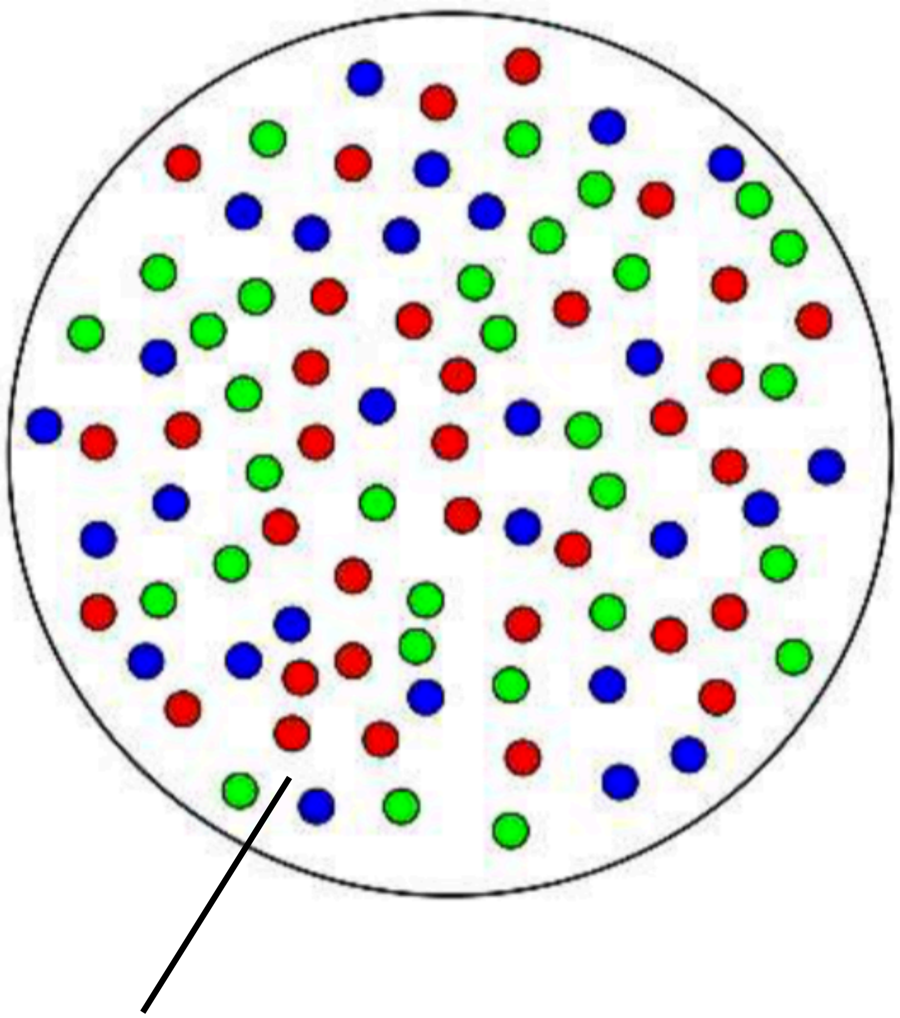


What happens if make nuclear matter

- 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: $n_\gamma \propto n_\mathrm{h}$

Parameterization: $n_\gamma \propto n_\mathrm{h}^\alpha$

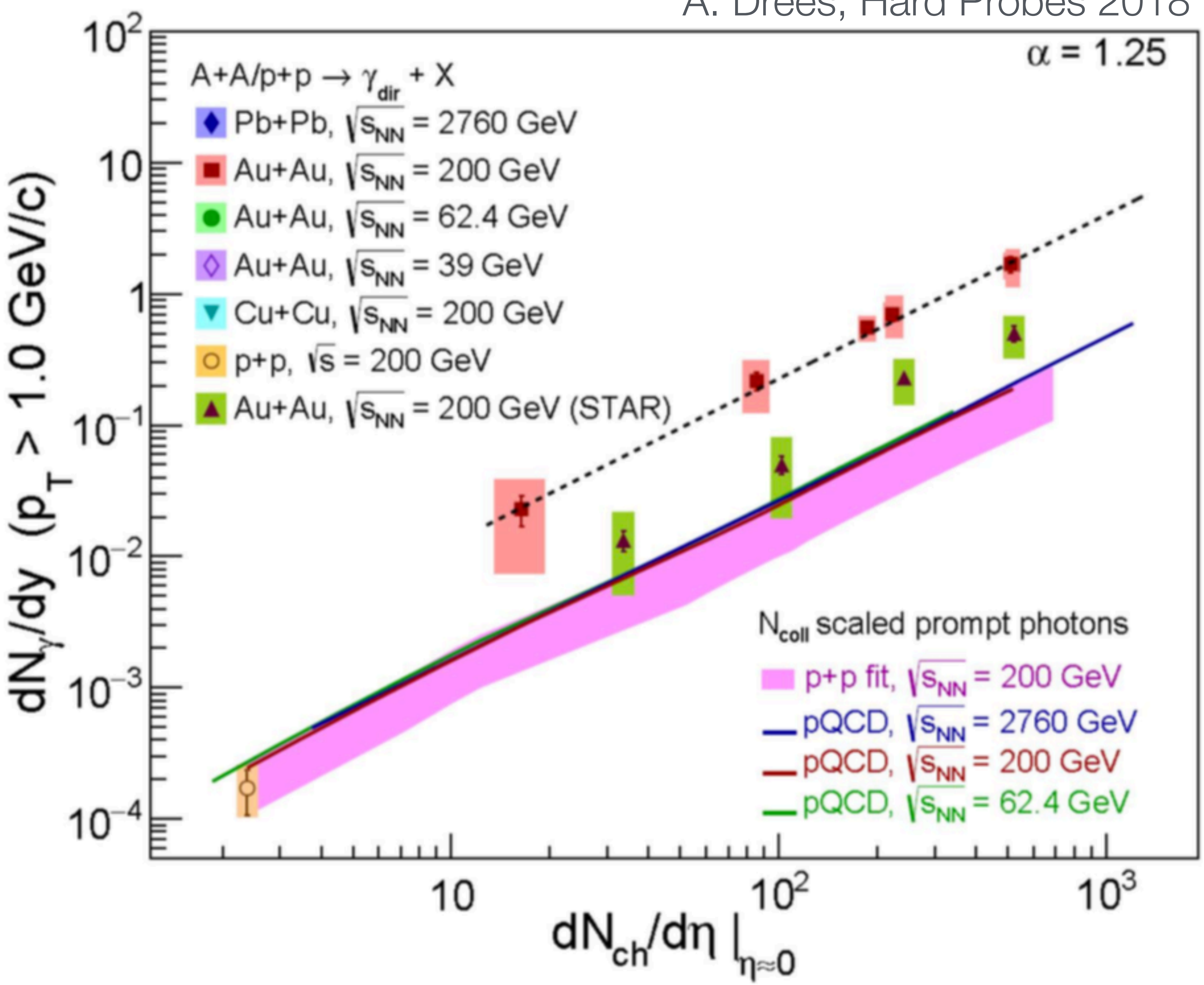
Bjorken expansion (only QGP): $\alpha \approx 2$

Realistic hydro model: ($p_{\mathrm{T},\gamma} > 1$ GeV/c) $\alpha \approx 1.6$–1.7

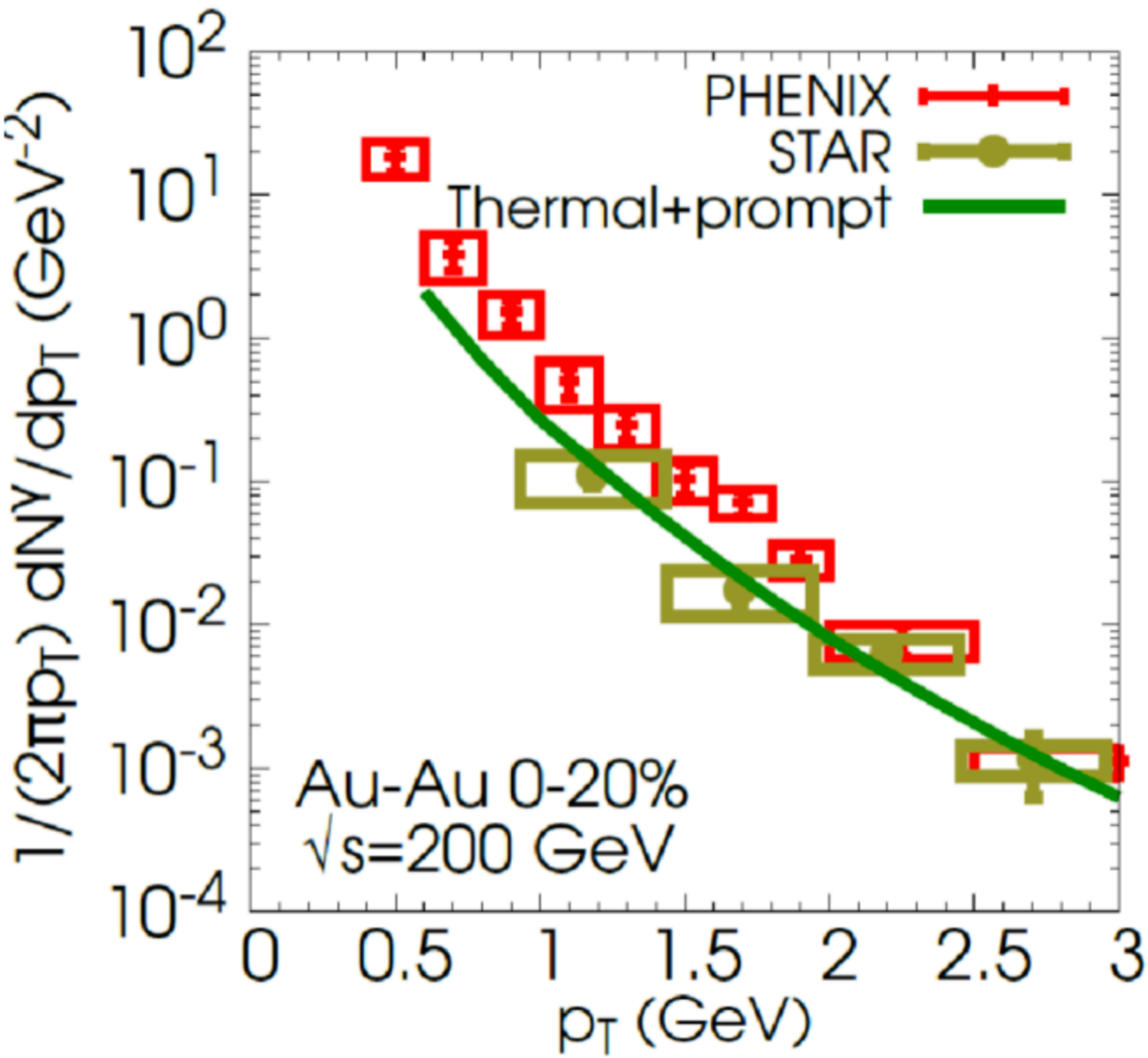
Jean-François Paquet, Hard Probes 2018

Direct Photons: PHENIX vs. STAR

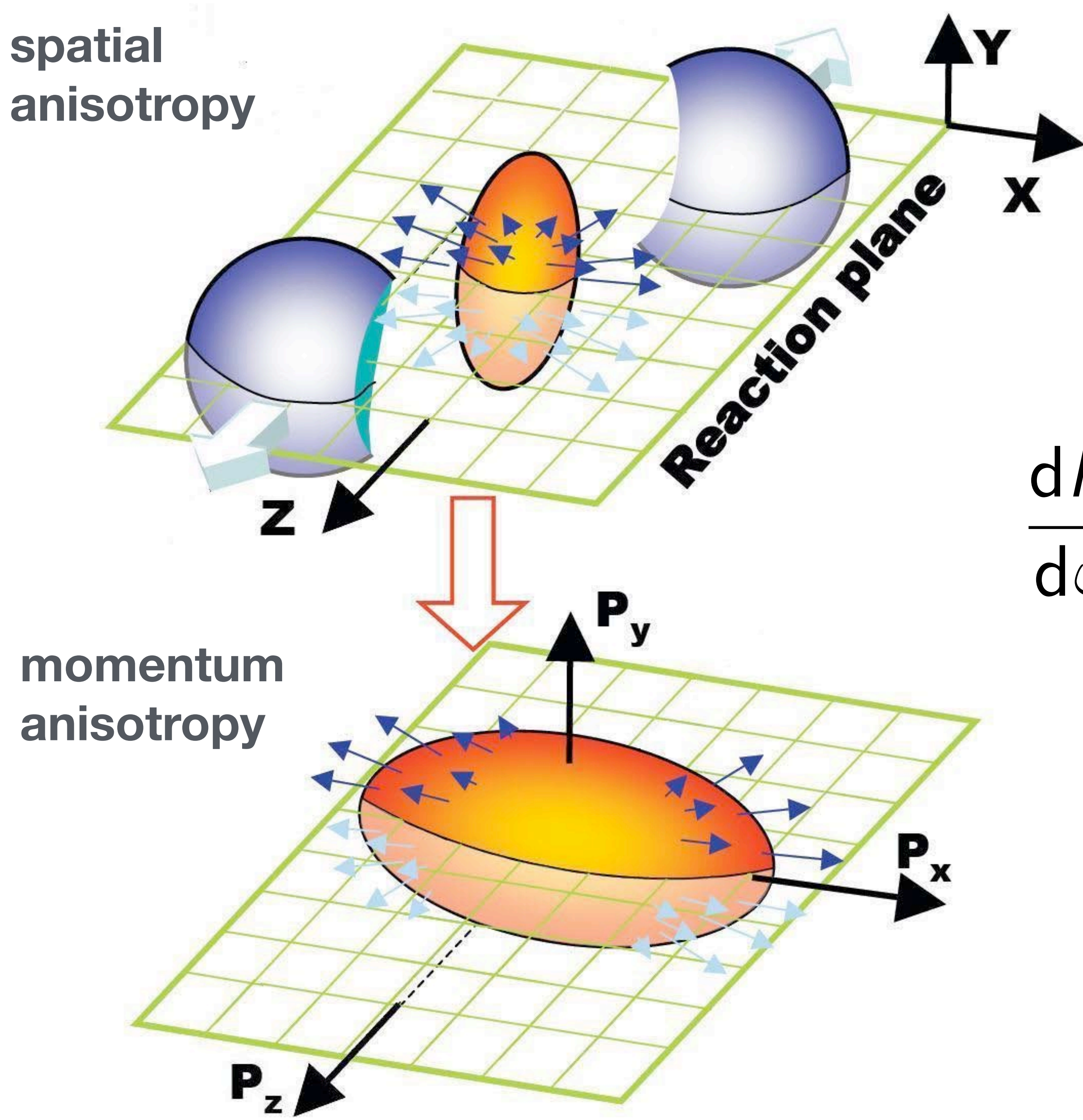
A. Drees, Hard Probes 2018



Direct Photons: PHENIX vs. STAR



Elliptic Flow

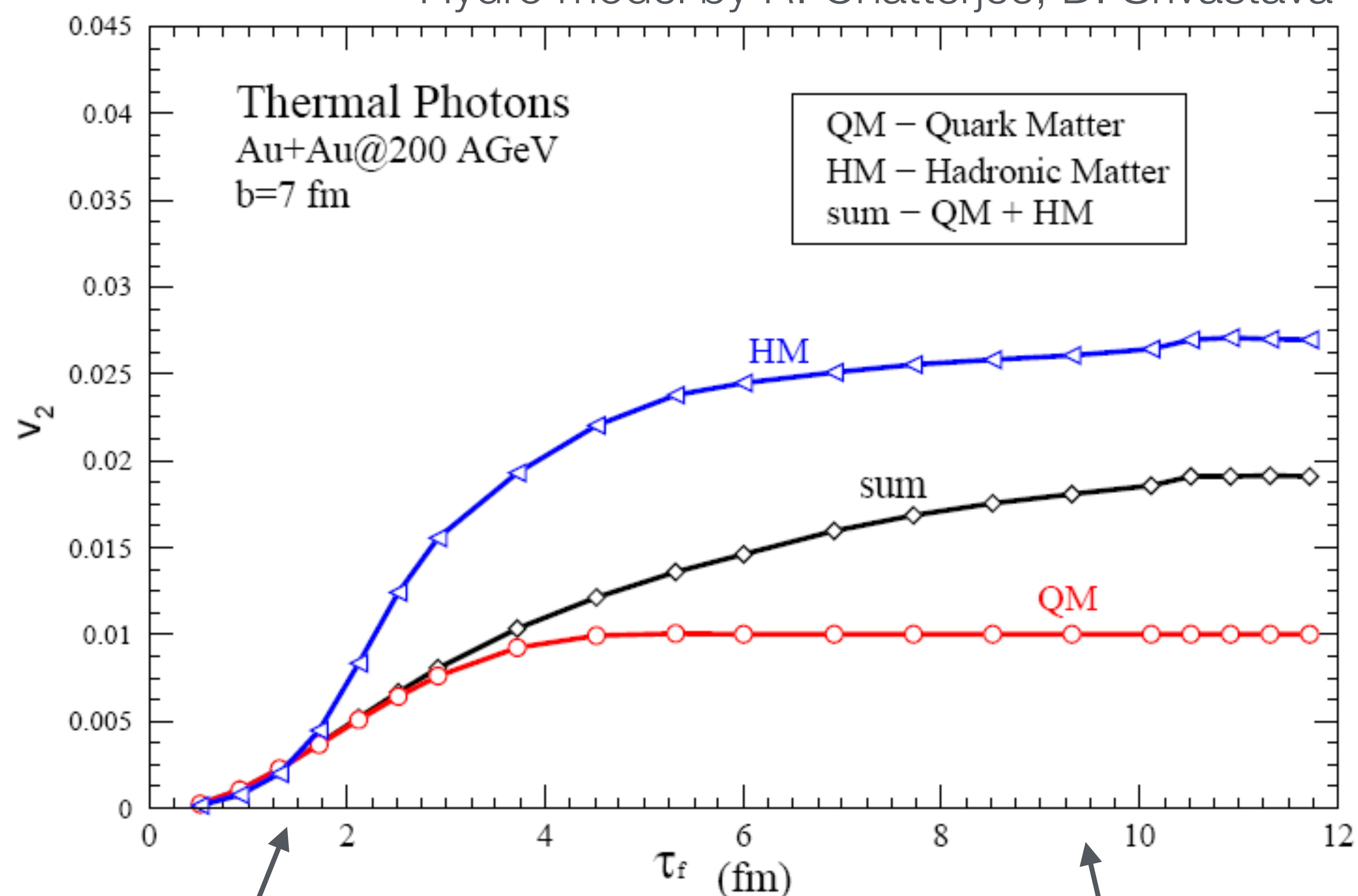


$$\frac{dN}{d\varphi} = N_0\,(1 + 2v_2\cos(2\varphi))$$

What's actually so puzzling?

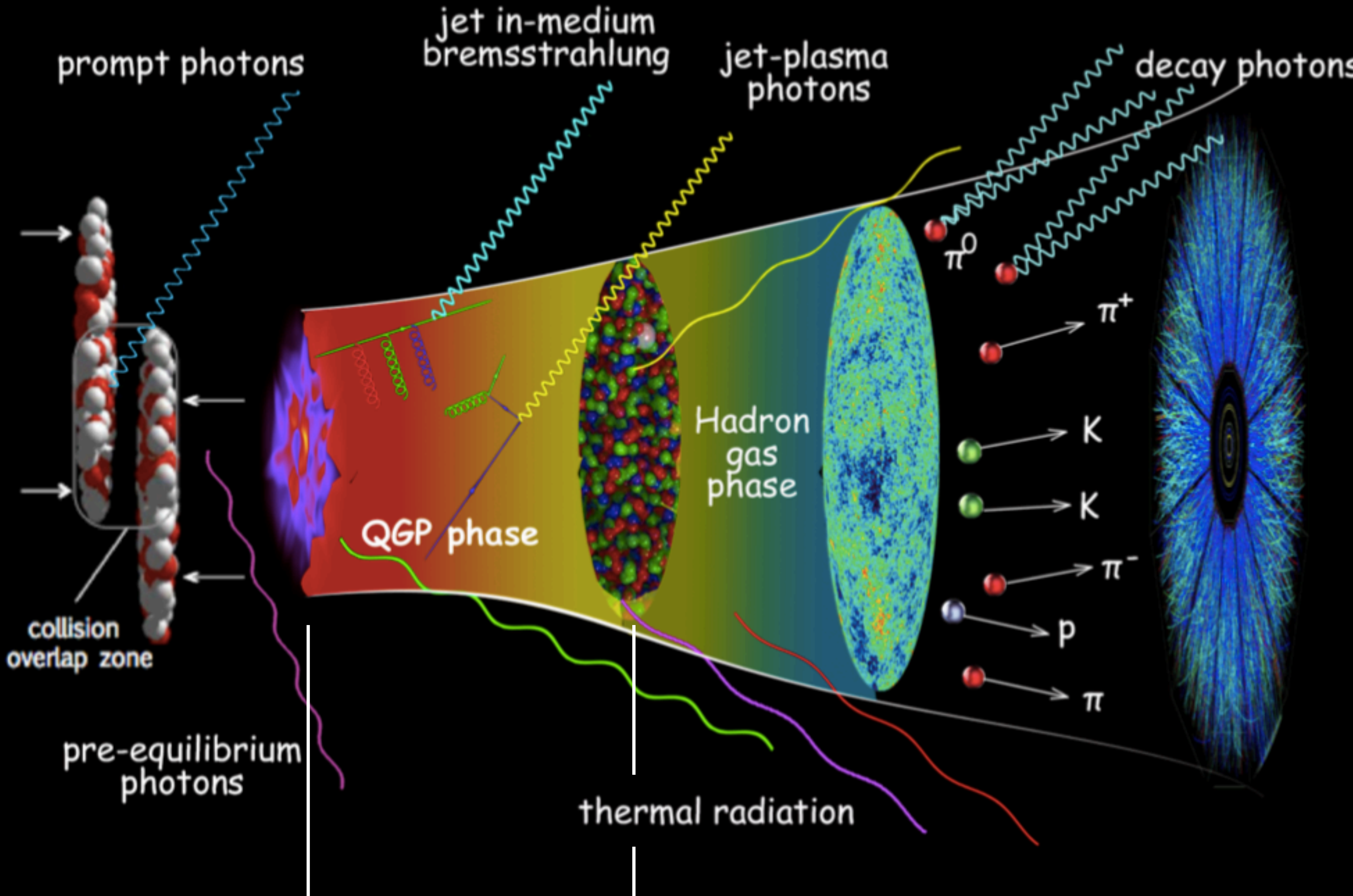
Elliptic flow builds up gradually with time in hydro models:

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



1–2 fm/c 10 fm/c

figure credit: Chun Shen