Scaling of direct photons in heavy ion collisions

Michał Praszałowicz

(Jagiellonian University)

based on

EPJ Web Conf. 206 (2019) 02002 • ISMD 2018

PoS DIS2015 (2015) 084 • DIS 2015

Acta Phys.Pol. B Supp. 8 (2015) 2, 399 • "Excited QCD" 2015

and common work

Nucl.Phys.A 1034 (2023) 122655

Eur.Phys.J.C 80 (2020) 7, 670

with Vlad Khachatryan (Stony Brook & Duke)

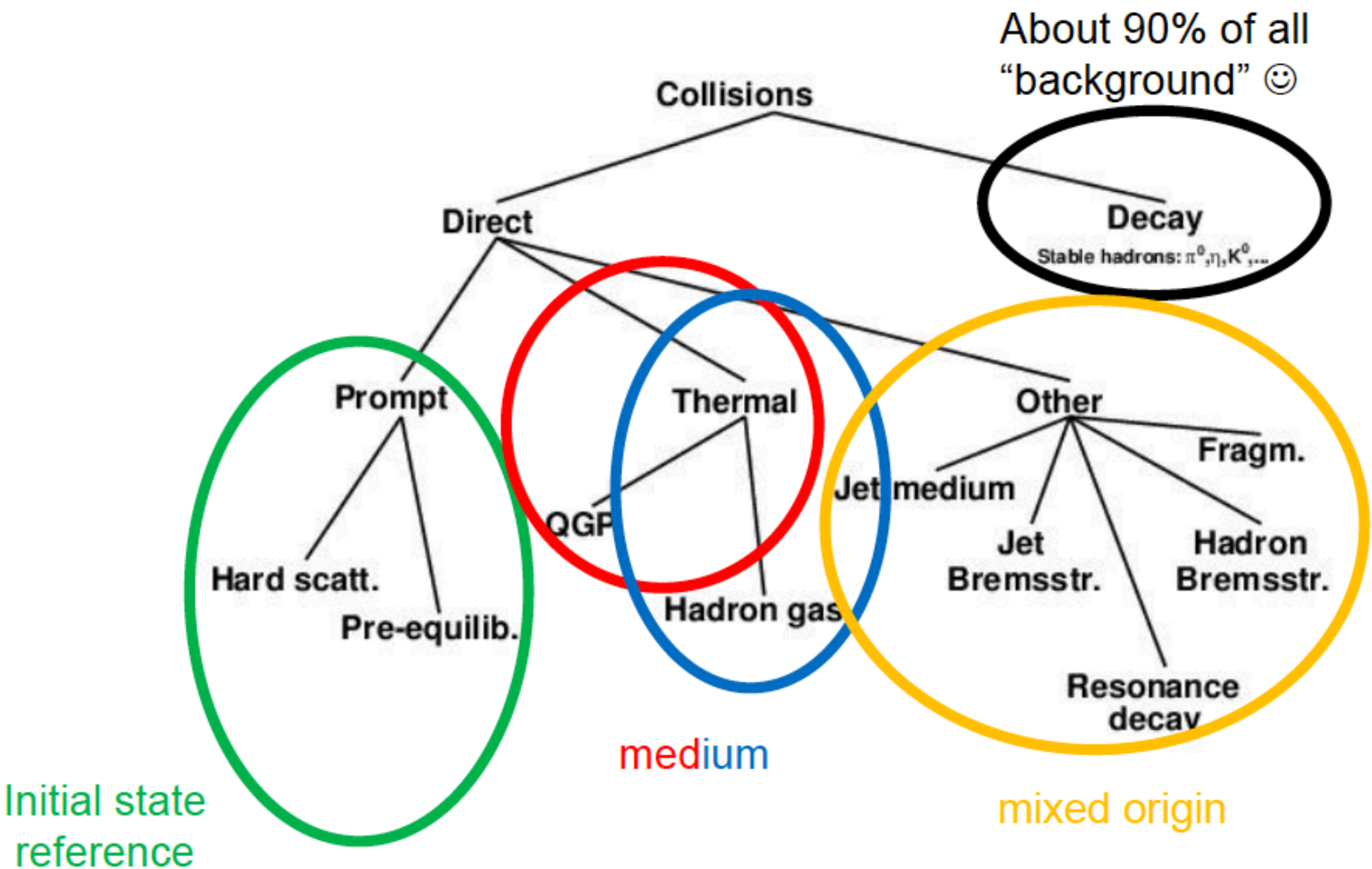
XVI Polish Workshop on Relativistic Heavy-Ion Collisions, Kielce, December 2, 2023

Why photons?

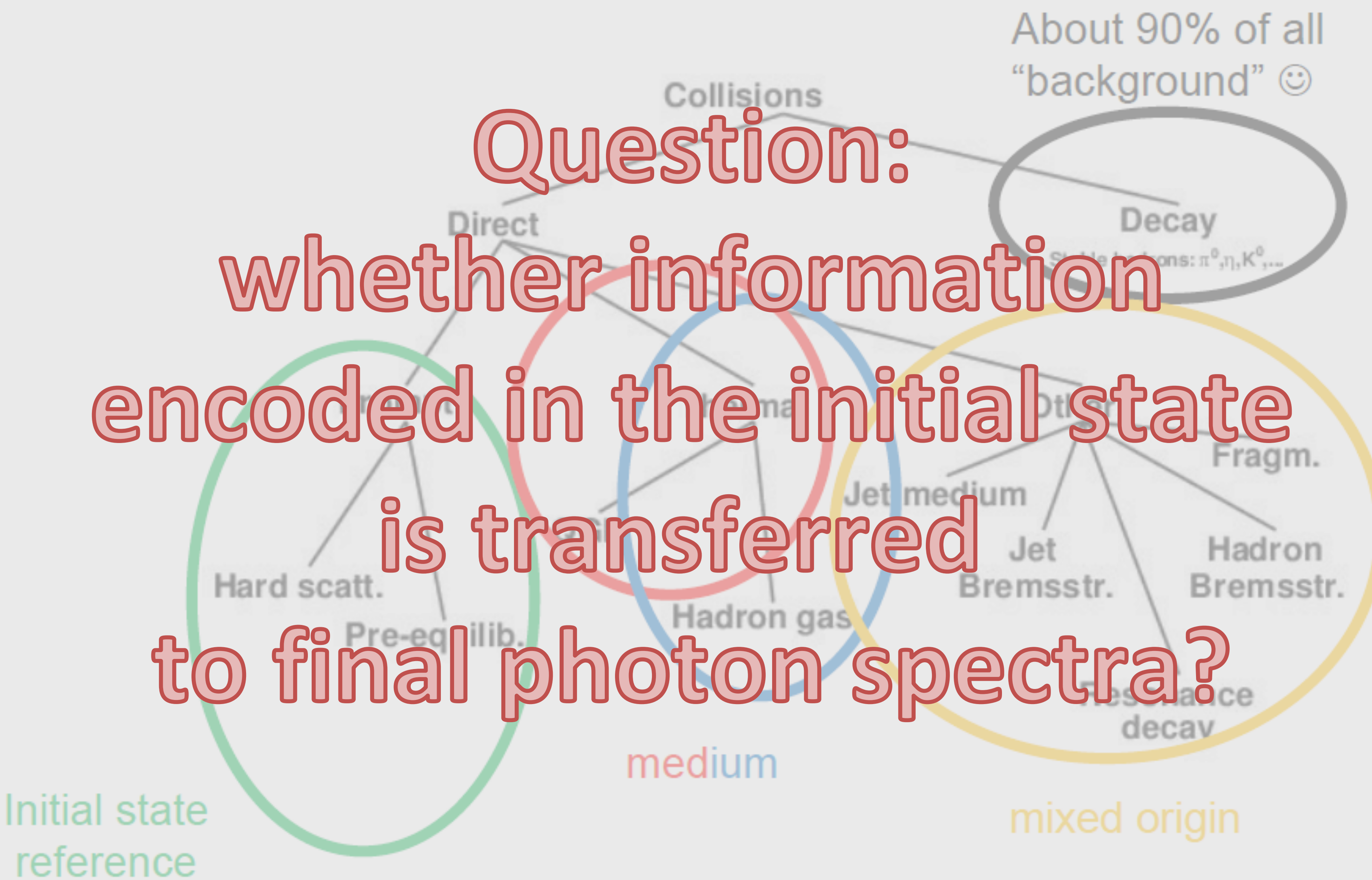
Photons, being colorless, most the time escape without further interaction, i.e. they are **penetrating probes**.
This makes them rich in information,
but hard to decypher and interpret.

G. David, [arXiv:1907.08893 [nucl-ex]]

Nomenclature



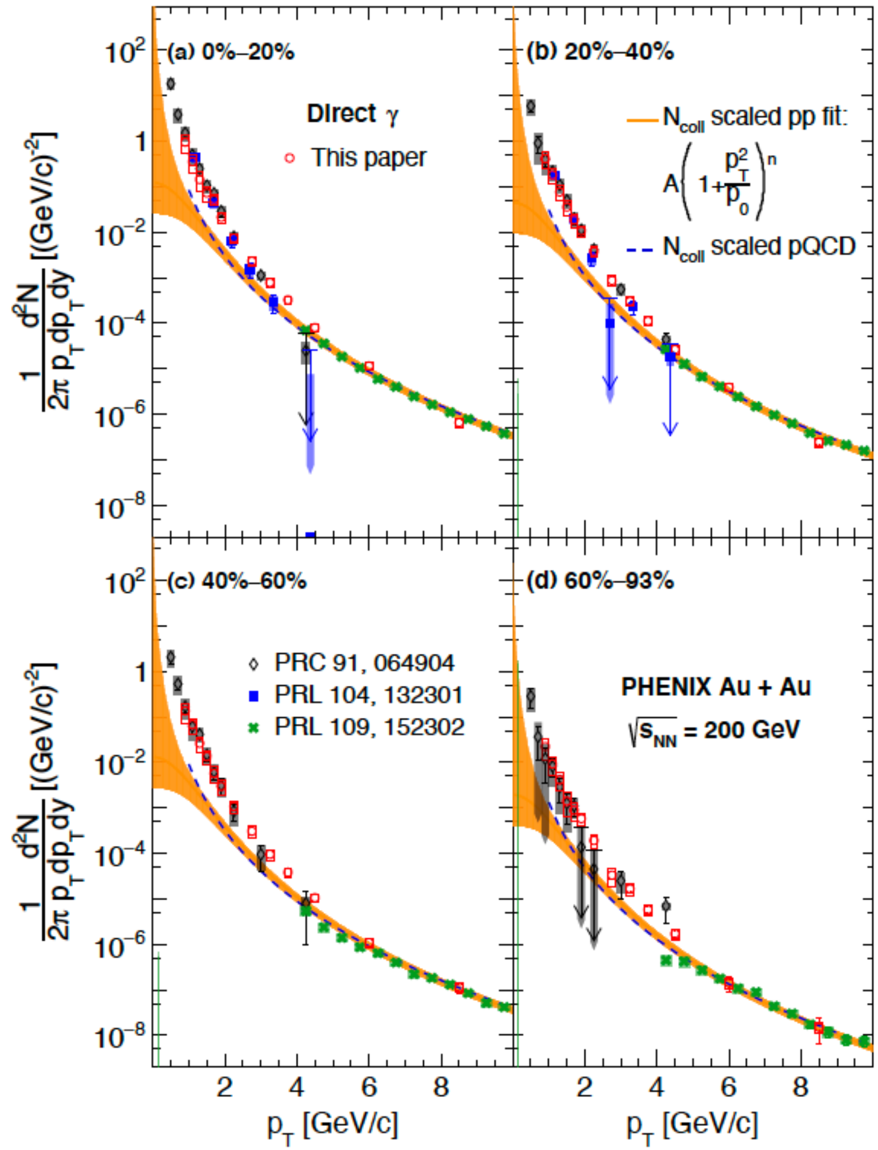
Nomenclature



Question:
whether information encoded in the initial state is transferred to final photon spectra?

Direct photon spectra

PHENIX Collaboration,
arXiv:2203.17187 [nucl-ex]
QM 2022



Is there really any enhancement?

APP B
proceedings
QM 2022

th model:
Gale et al.
PRC 105 (22) 014909

exp:
STAR – 2017
ALICE – 2022

1-A19.6 K. Reygers

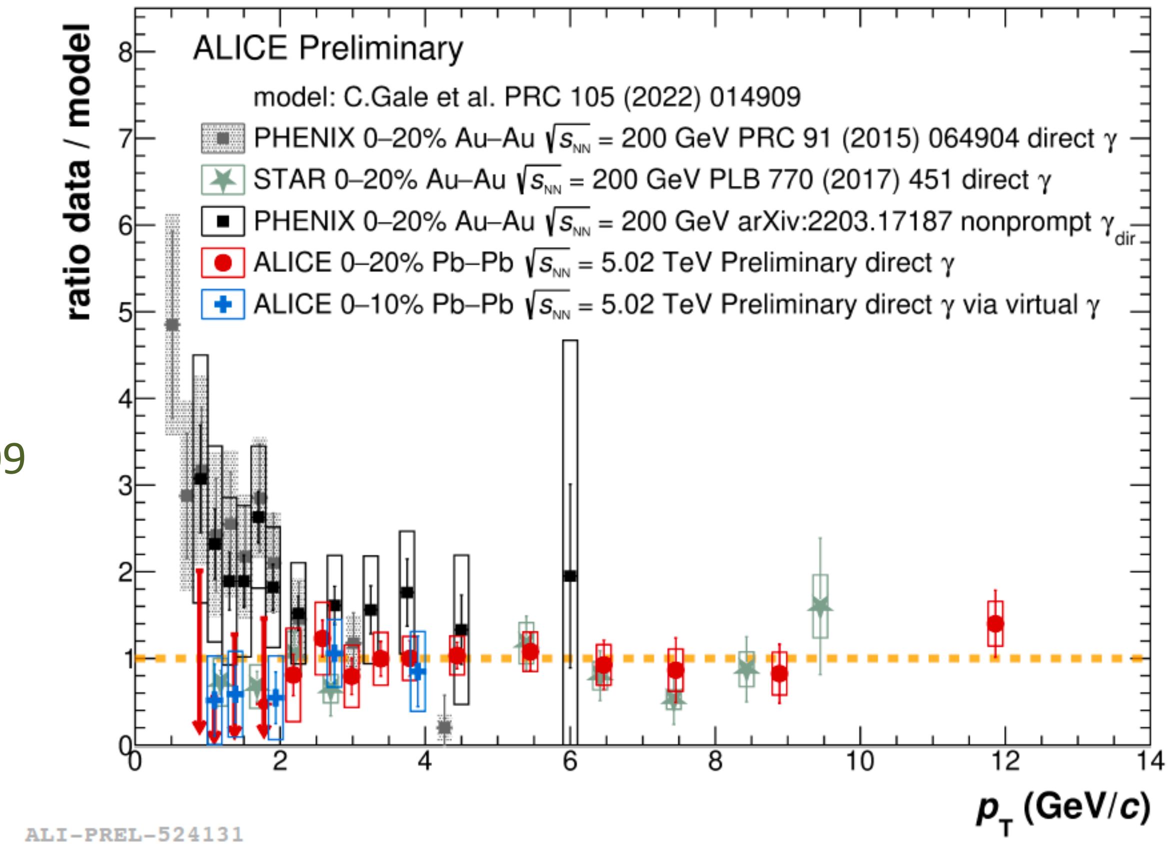
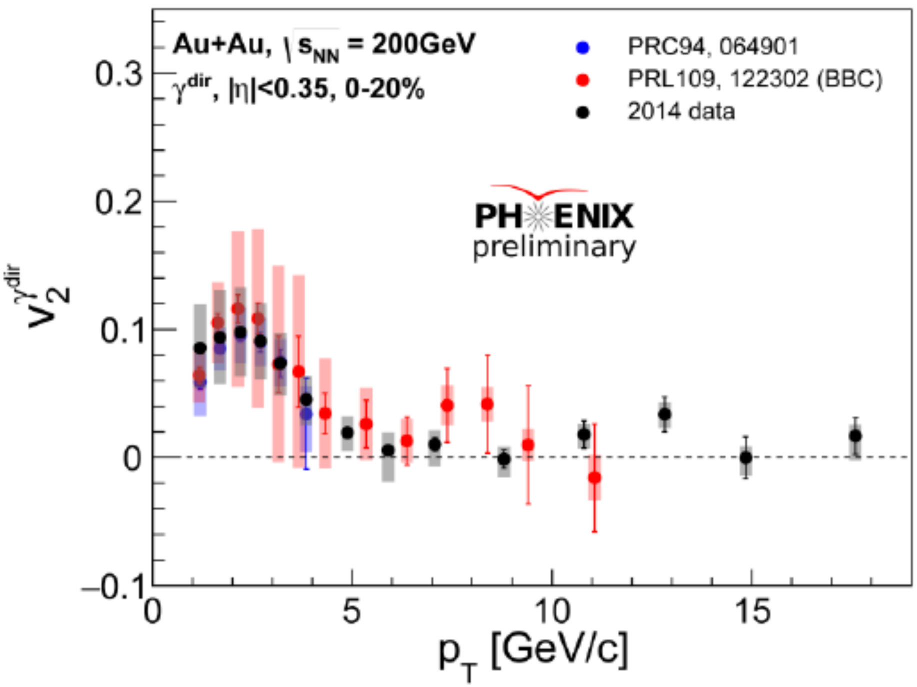
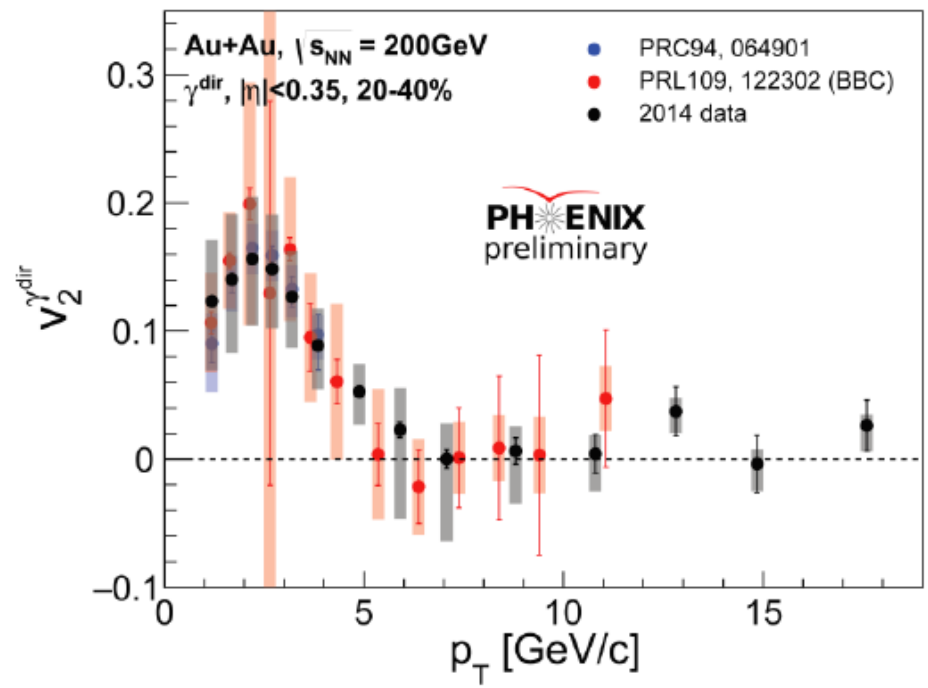


Fig. 4. Comparison of direct-photon transverse momentum spectra measured at RHIC and the LHC to a model which includes thermal and preequilibrium photons in addition to pQCD photons.

Direct photon flow





Large flow at low p_T means that, contrary to expectations, these photons are produced at the later stages of evolution, making them a less usefule probe of QGP.

Direct photon puzzle

There have been many theoretical attempts to reproduce the photon yields and flow coefficients (with, however, mixed success):

Hydrodynamical simulations of the fireball evolution

M.Dion, J.-F.Paquet, B.Schenke, C.Young, S.Jeon and C. Gale, PRC 84, 064901 (2011)
C.Shen, U.W.Heinz, J.F.Paquet, I.Kozlov and C.Gale, PRC 91, 024908 (2015)
C.Shen, U.Heinz, J.-F.Paquet, and C.Gale, Phys. Rev. C 89, 044910 (2014)
J.-F.Paquet, C.Shen, G.S.Denicol, M.Luzum, B.Schenke, S.Jeon , C.Gale, PRC 93, 044906 (2016)

Calculations in the framework of the elliptic-fireball expansion scenario

H.van Hees, C.Gale, and R.Rapp, Phys. Rev. C 84, 054906 (2011)
R.Rapp, H.van Hees, M.He, NPA 931, 696 (2014)
H.van Hees, M.He, R.Rapp, NPA 933, 256 (2015)

Parton-Hadron-String Dynamics transport approach

E.L.Bratkovskaya, S.M.Kiselev and G.B.Sharkov, PRC 78, 034905 (2008)
E.L.Bratkovskaya, NPA 931, 194 (2014)
O.Linnyk, W.Cassing, E.Bratkovskaya, PRC 89, 034908 (2014)
O.Linnyk, V.Konchakovski, T.Steinert, W.Cassing, E.L.Bratkovskaya, PRC 92, 054914 (2015)

Spectral function approach

K.Dusling and I.Zahed, PRC 82, 054909 (2010)
C.-H.Lee and I.Zahed, PRC 90, 025204 (2014)
Y.M.Kim, C.-H. Lee, D.Teaney and I.Zahed, PRC 96, 015201 (2017)

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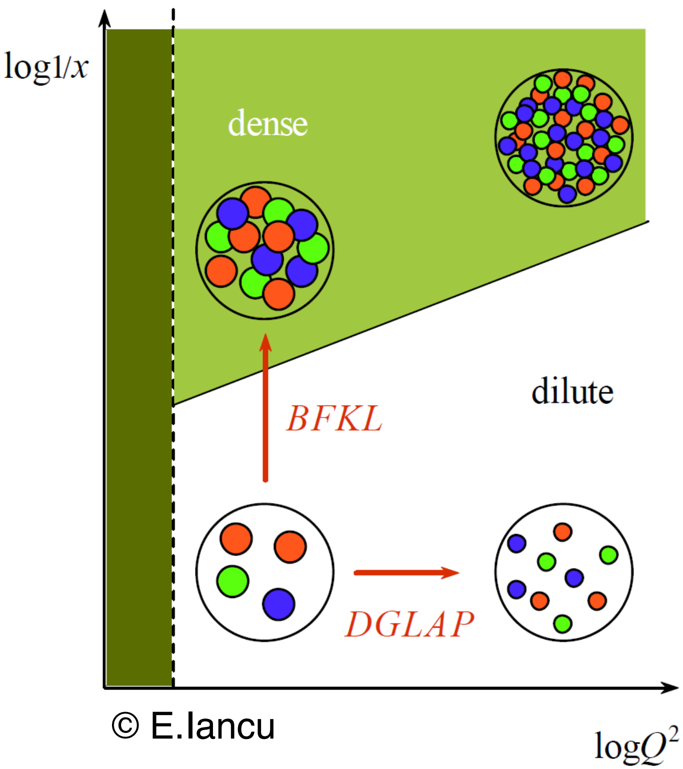
Failure to describe simultaneously large yields and large anisotropies has been dubbed as direct photon puzzle

C.Shen, NPA 956, 184 (2016)

What is Geometrical Scaling?

GS is a consequence of the nonlinear BK QCD evolution, which has travelling wave solutions characterized by a dynamical scale: saturation scale



$$Q_s(x) = Q_0 \left(\frac{1}{x}\right)^{\lambda/2}$$

A.M. Stasto, K. J. Golec-Biernat, J. Kwiecinski
PRL 86 (2001) 596-599

It has been for the first time observed in DIS

What is Geometrical Scaling?

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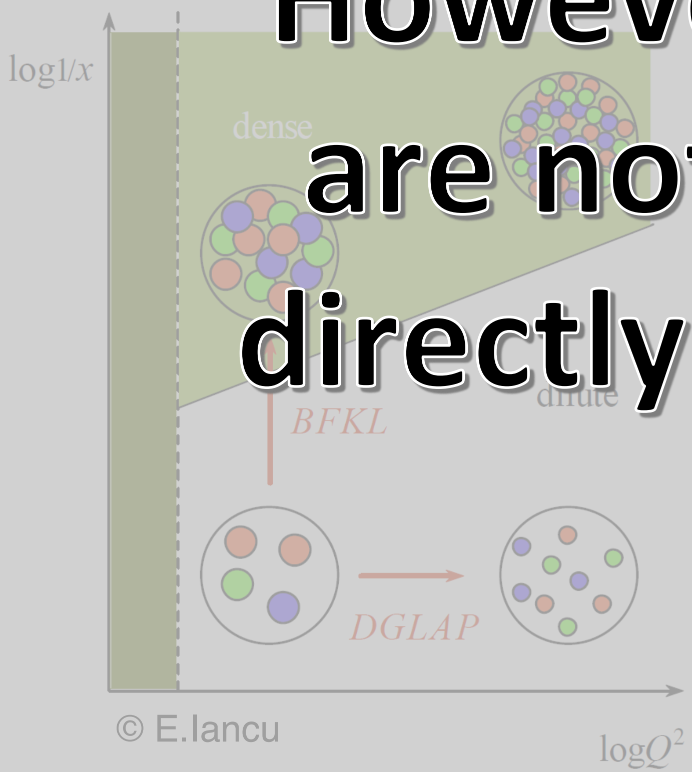
However, photons are not produced directly from gluons



A.M. Stasto, K. J. Golec-Biernat, J. Kwiecinski
PRL 86 (2001) 596-599

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Direct photons in HI

Photons carry information on the initial stages of the collisions.
Photons almost do not interact with medium.

But
photons do not couple to initial saturated gluon fields.
They are produced from quarks that themselves appear during the Glasma phase. Details of this process are not well quantitatively described, however the photon spectrum should exhibit GS.

A Phenomenological Model of the Glasma and Photon Production
Larry McLerran Acta Phys.Polon.B 45 (2014), 2307

First detailed analysis of the photon spectra has been performed assuming power-like p_T spectra.

C. Klein-Bosing and L. McLerran, Phys. Lett. B 734, 282 (2014)
V. Khachatryan, B. Schenke, M. Chiu, A. Drees, T.K. Hemmick, N. Novitzky, Nucl. Phys. A 978, 123 (2018)

Geometrical scaling

Spectra depend only on a dimensionless variable τ

$$\tau = \frac{p_{\mathrm{T}}^2}{Q_s^2(x)} \quad Q_{\mathrm{s}}^2(x) = Q_0^2 \left(\frac{1}{x}\right)^{\lambda} \quad x = \frac{p_{\mathrm{T}}}{\sqrt{s}}$$

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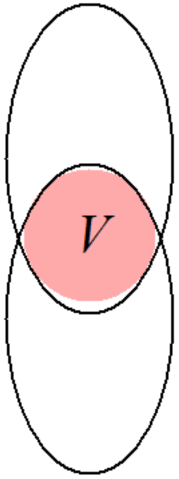
In HI, however, Q_0^2 depends on collision geometry:



$N_{\mathrm{part}} \sim V$

$$Q_0^2 \rightarrow Q_0^2 \times N_{\mathrm{part}}^{1/3}$$

Geometrical scaling in HI

Multiplicity: $$\frac{dN}{dy\,dp_{\mathrm{T}}^2} = S_\perp \mathcal{F}(\tau) \qquad S_\perp \sim N_{\mathrm{part}}^{2/3}$$

Scaling: $$\frac{Q_0^2}{N_{\mathrm{part}}^{2/3}} \frac{dN}{dy\,dp_{\mathrm{T}}^2} = \mathcal{F}(\tau)$$

Function $\mathcal{F}(\tau)$ is universal: does not depend on energy, centrality and colliding systems

Geometrical scaling in HI

In fact two scalings: centrality scaling and energy scaling

$$\frac{Q_0^2}{N_{\rm part}^{\delta}} \frac{dN}{dy dp_{\rm T}^2} = \mathcal{F}(\tau) \qquad \tau = \frac{p_{\rm T}^2}{N_{\rm part}^{\delta/2} Q_0^2} \left(\frac{p_{\rm T}}{W}\right)^{\lambda}$$

Expectations:

$$\lambda \simeq 0.2 \div 0.3, \qquad \delta \simeq 2/3$$

- fixed energy: test value of δ
- fixed centrality: test value of λ

Data

W [GeV]	system	centrality	N_{part}	experiment	references
200	Au+Au	0–20 %	277.5	PHENIX	[26] 2014
		20–40 %	135.6		
		0–92 %	106.3		
200	Au+Au	0–20 %	277.5	PHENIX	[27] 2015
		20–40 %	135.6		[28] 2012
		40–60 %	56.0		
		60–92 %	12.5		
62.4	Au+Au	0–86 %	114.5	PHENIX	[29] 2019
39.0	Au+Au	0–86 %	113.3	PHENIX	[29] 2019
200	Cu+Cu	0-40 %	66.4	PHENIX	[30] 2018
		0–94 %	34.6		
2760	Pb+Pb	0–20 %	308.0	ALICE	[31] 2016
		20–40 %	157.0		
		40–80 %	45.7		
200	d+Au		7.0	PHENIX	[32] 2013
	p+p		–		

STAR data and new ALICE data in tension with PHENIX are not taken into account

Data

[26] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **104**, 132301 (2010).

[27] A. Adare *et al.* [PHENIX Collaboration], "Centrality dependence of low-momentum direct-photon production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV," Phys. Rev. C **91**, 064904 (2015).

[28] S. Afanasiev *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **109**, 152302 (2012).

[29] A. Adare *et al.* [PHENIX Collaboration], [arXiv:1805.04084 [hep-ex]].

[30] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. C **98**, no. 5, 054902 (2018).

[31] J. Adam *et al.* [ALICE Collaboration], Phys. Lett. B **754**, 235 (2016).

[32] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. C **87**, 054907 (2013).

Photons: centrality scaling

PHENIX $\tau \to \tau = \sqrt{\tau_{\rm old}}$ ALICE

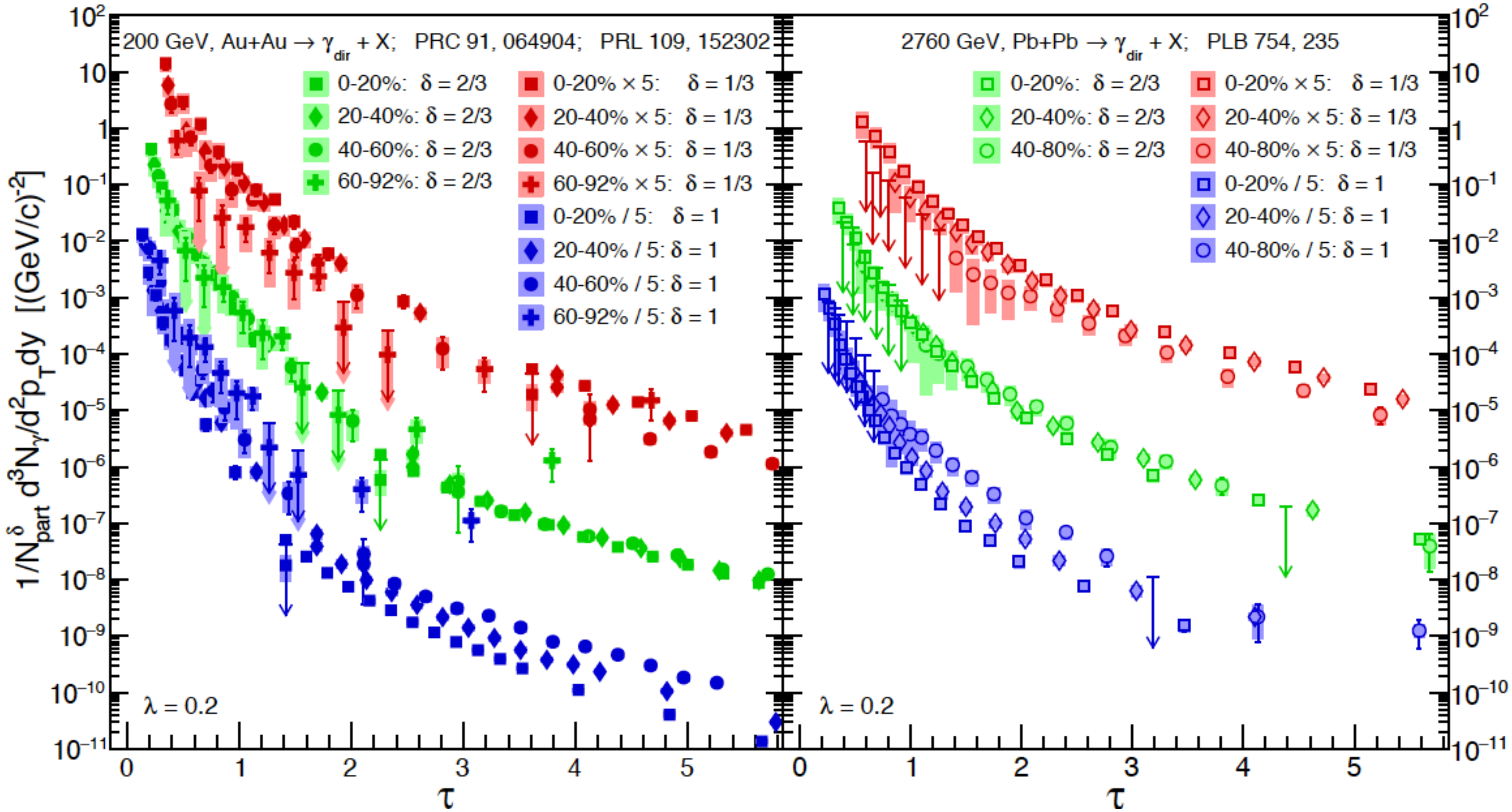


Figure 2: Direct photon spectra scaled according to Eq. (3) with $S_\perp$ and τ given by Eqs. (14) and (15) respectively, plotted – from top to bottom – for $\delta = 1/3$ (red points), 2/3 (green points) and 1 (blue points). Left panel corresponds to PHENIX $Au + Au$ data at 200 GeV, right panel to $Pb + Pb$ ALICE data at 2.76 TeV. Exponent $\lambda = 0.2$ does not play any role here since we compare data at the same energies.

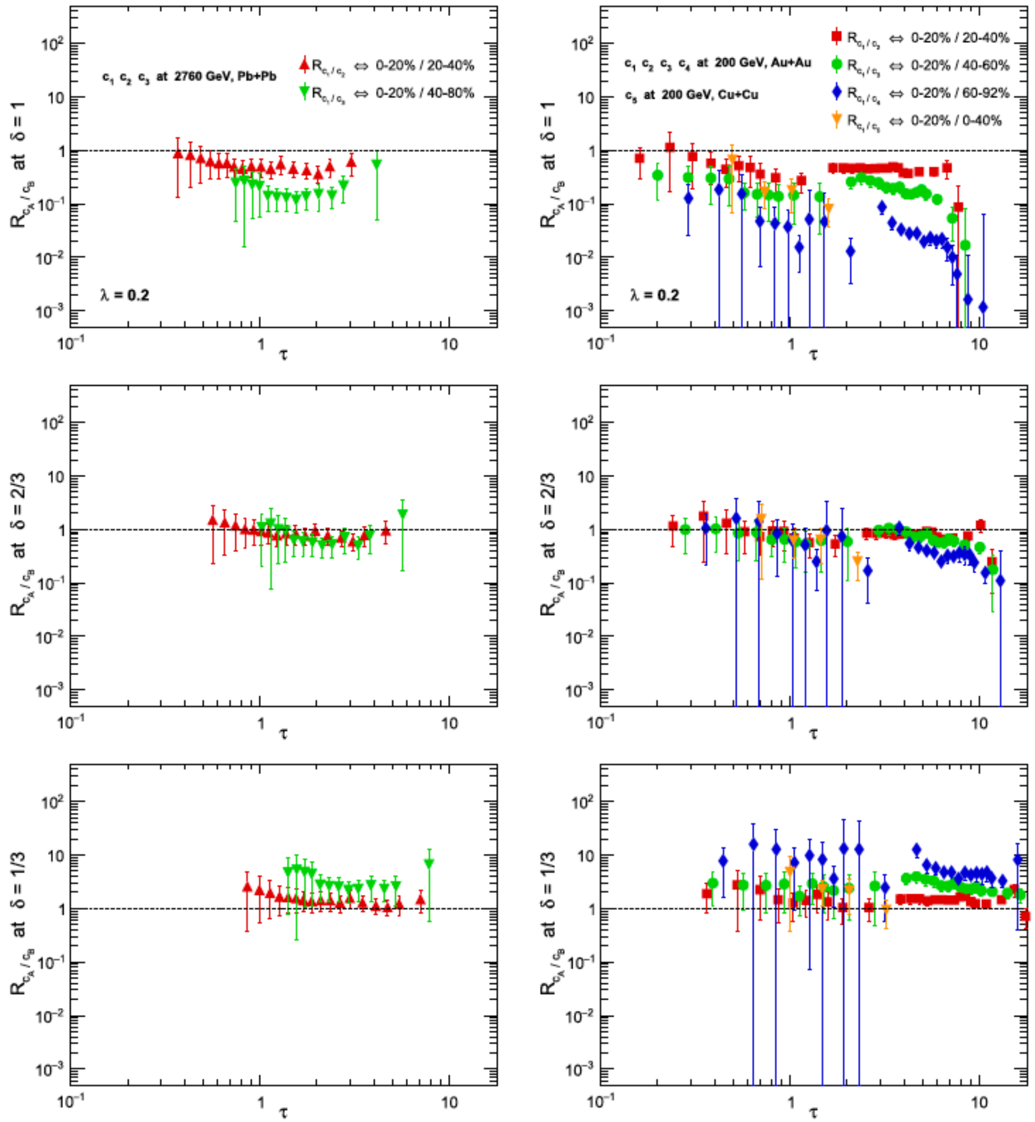
Centrality scaling: ratios

ALICE @ 2760 PHENIX @ 200

δ = 1/3

δ = 2/3

δ = 1

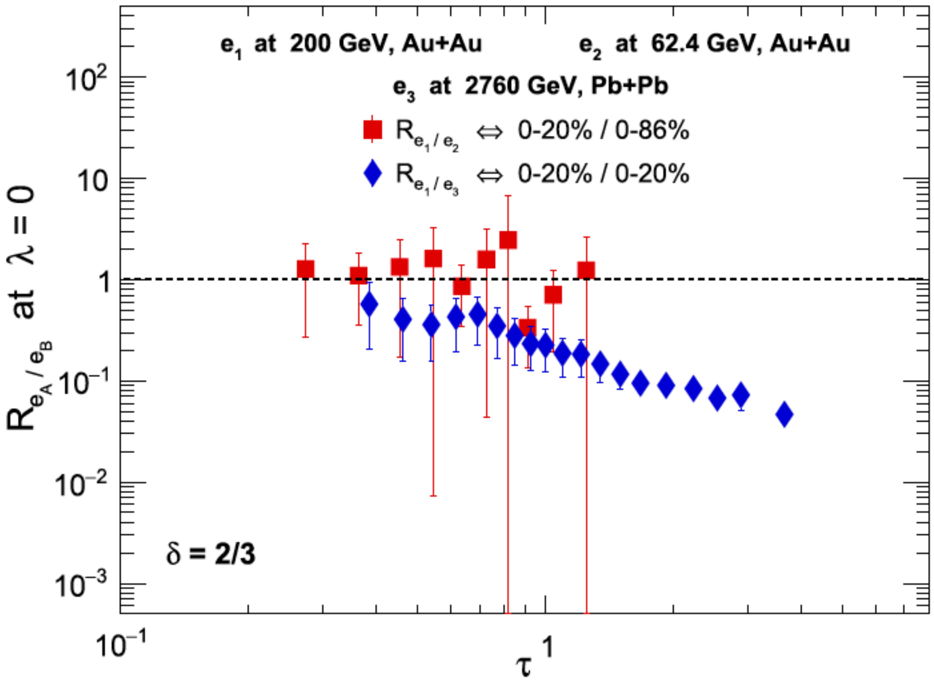


Energy scaling

$$R_1(\text{red squares}) = \frac{\text{AuAu@200 GeV} \quad 0-20\%}{\text{AuAu@62.4 GeV} \quad 0-86\%}$$

$$R_2(\text{blue diamonds}) = \frac{\text{AuAu@200 GeV} \quad 0-20\%}{\text{PbPb@2.76 TeV} \quad 0-20\%}$$

$\lambda = 0.0$



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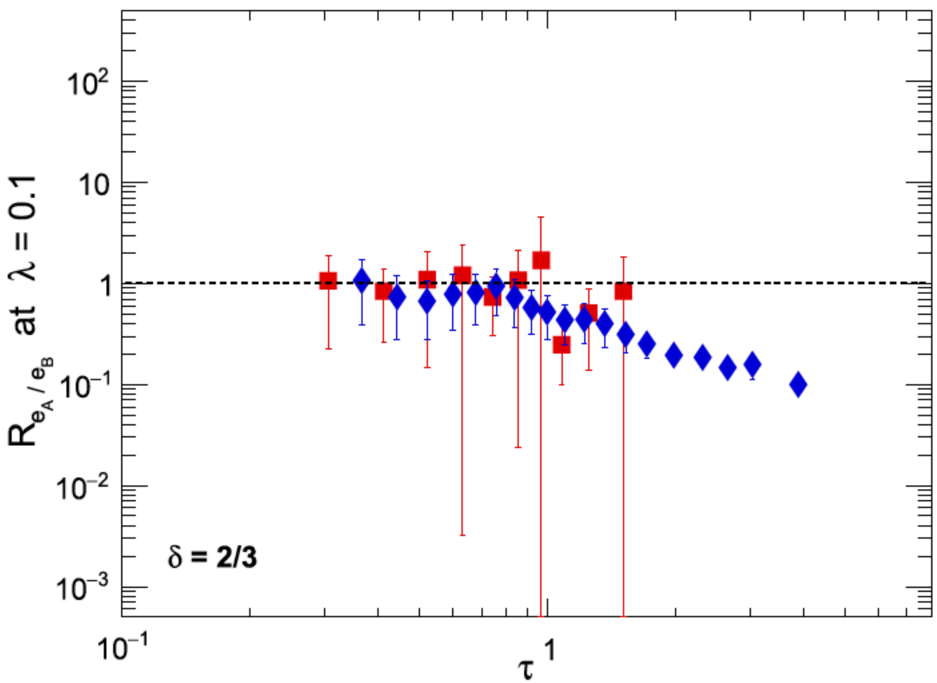
$$R_2(\text{blue diamonds}) = \frac{\text{AuAu@200 GeV} \quad 0-20\%}{\text{PbPb@2.76 TeV} \quad 0-20\%}$$

$\lambda = 0.1$



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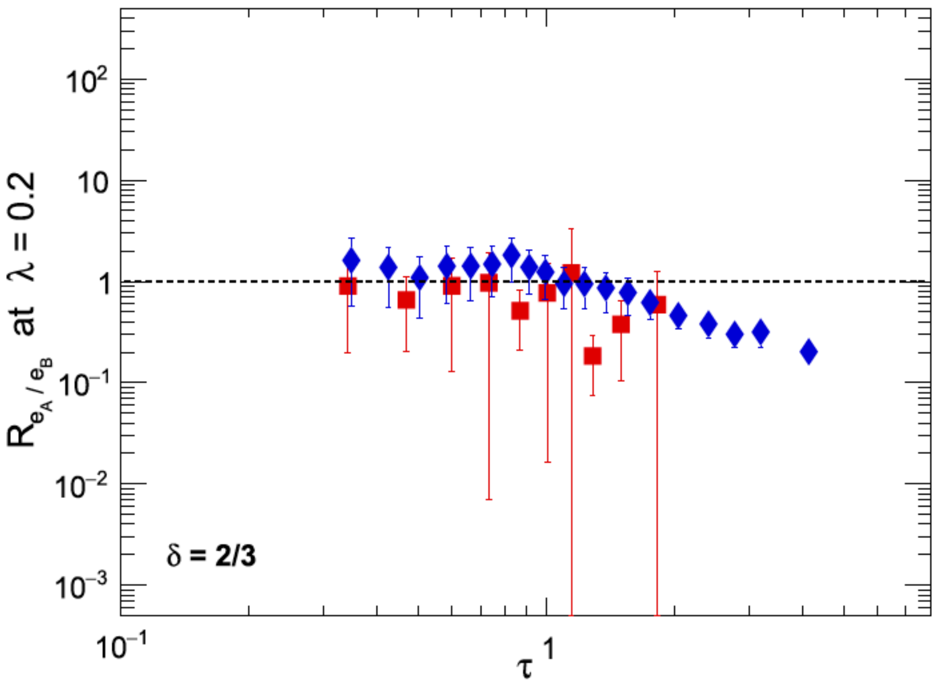
$\lambda = 0.2$



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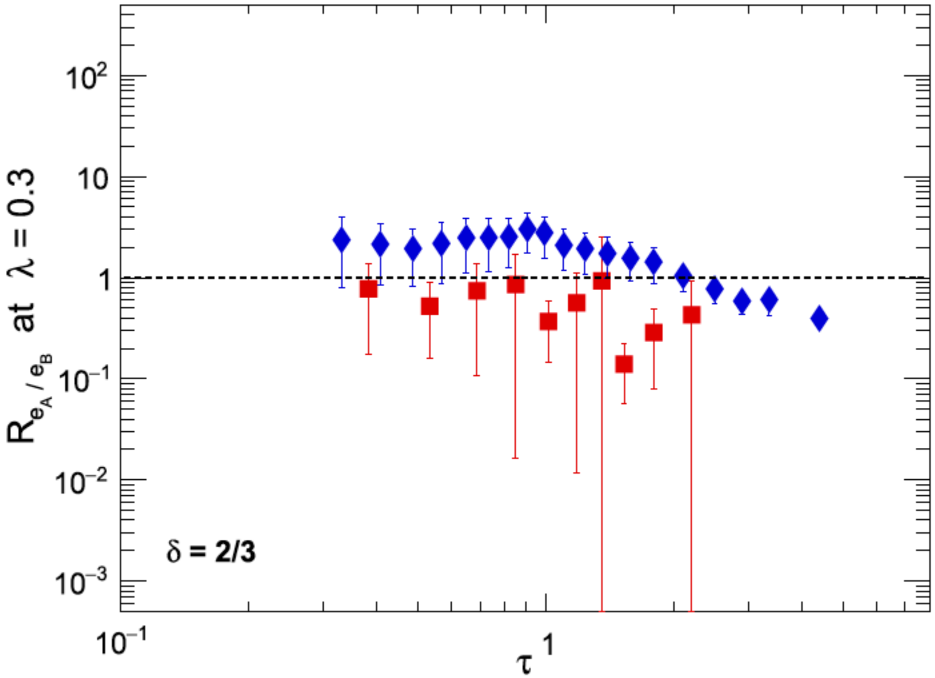
$\lambda = 0.3$



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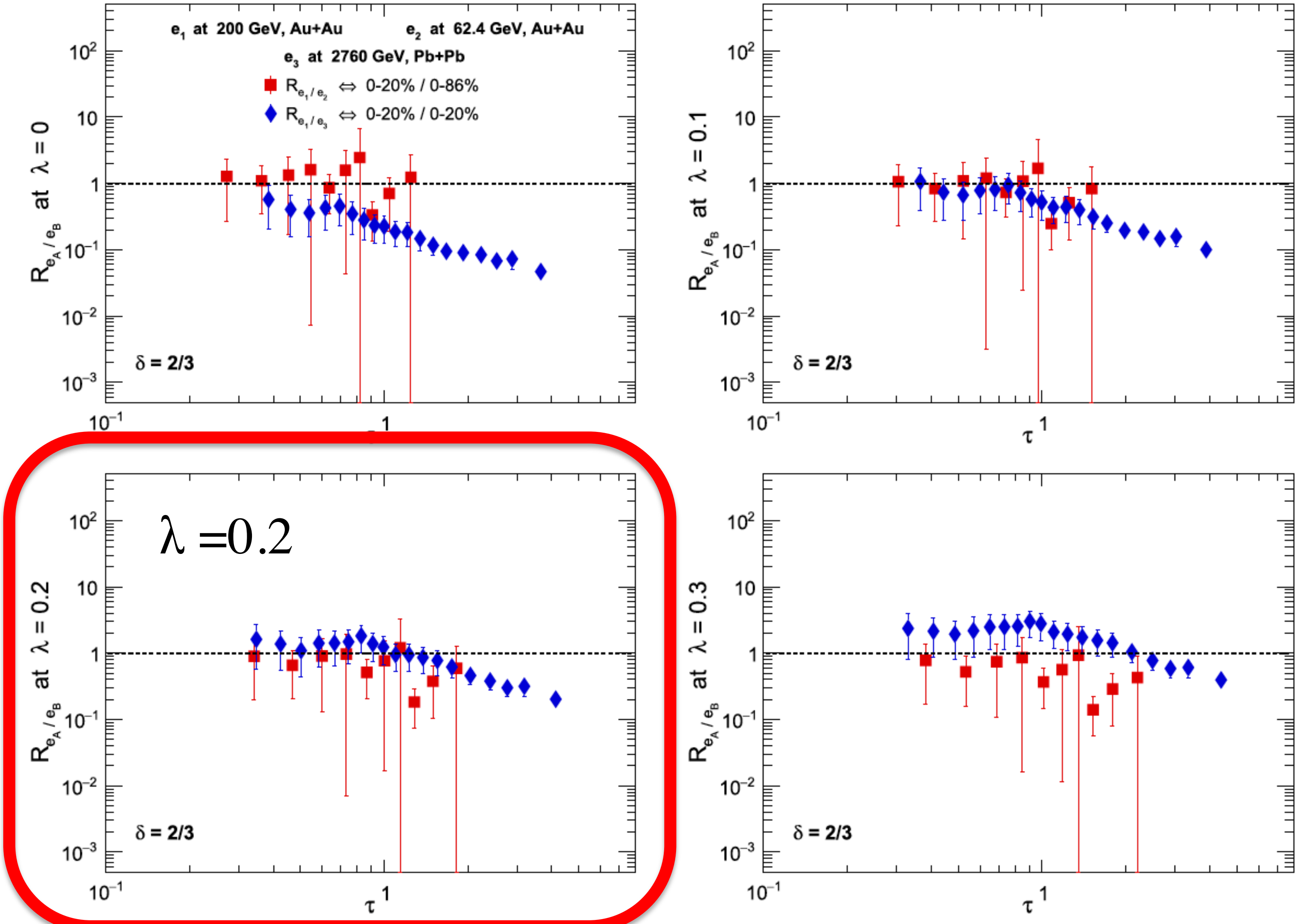
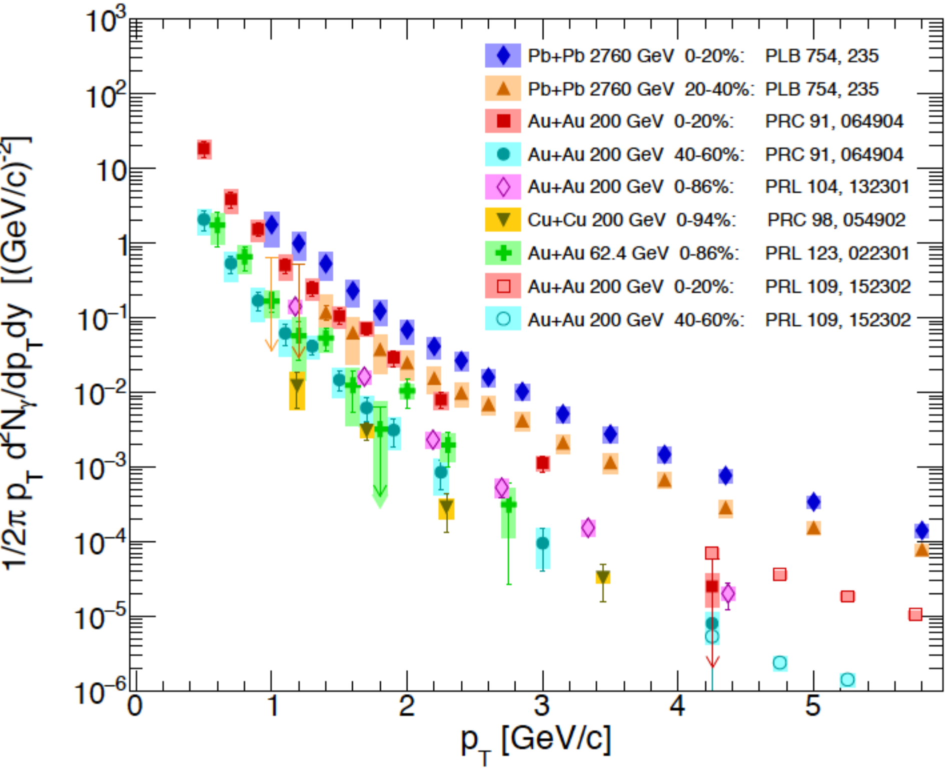
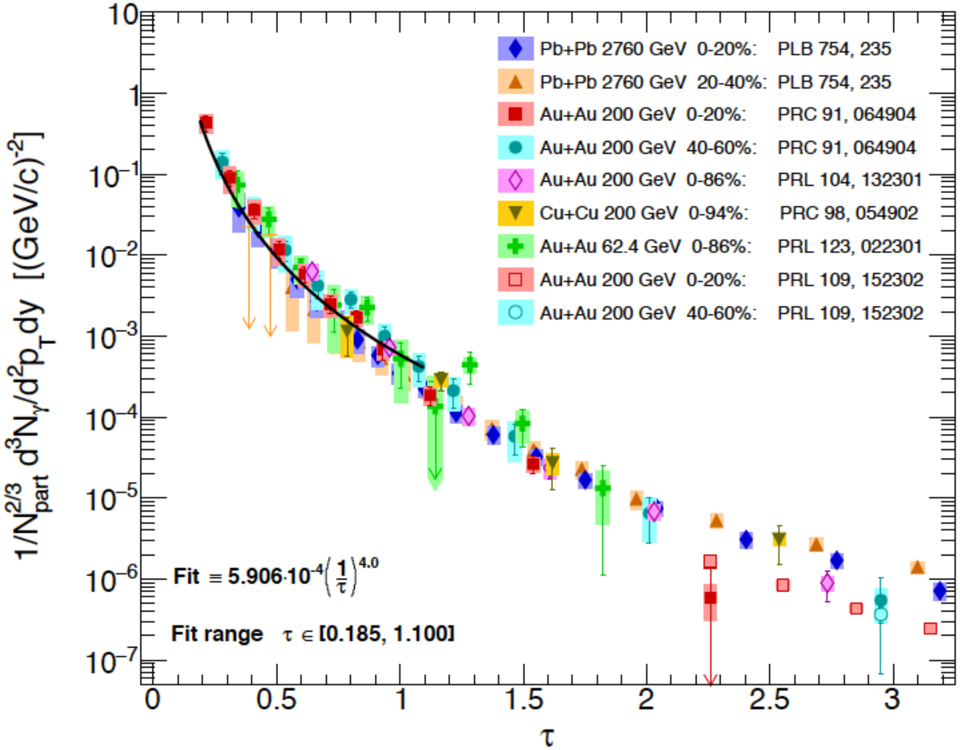


Photons: GS full





Multiplicty scaling

In 2018 PHENIX observed the following scaling:

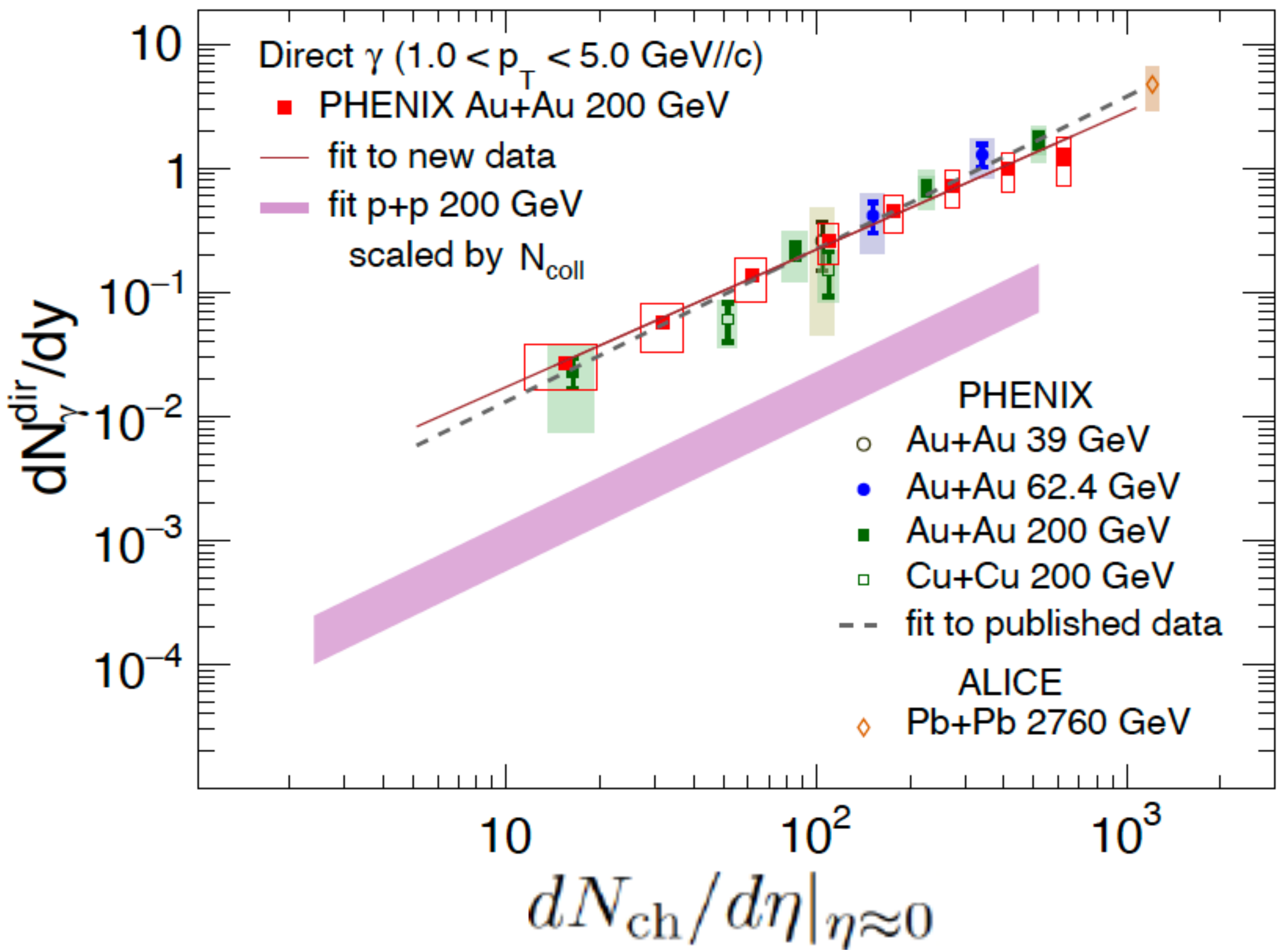
A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. C **98**, 054902 (2018).

$$\frac{1}{(dN_{\rm ch}/d\eta|_{\eta\approx 0})^{\alpha}}\frac{dN_{\gamma}}{d^2p_T dy} = \frac{1}{Q_0^2}G(p_T)$$

$\alpha = 1.25$ charged hadrons

Recent PHENIX data

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



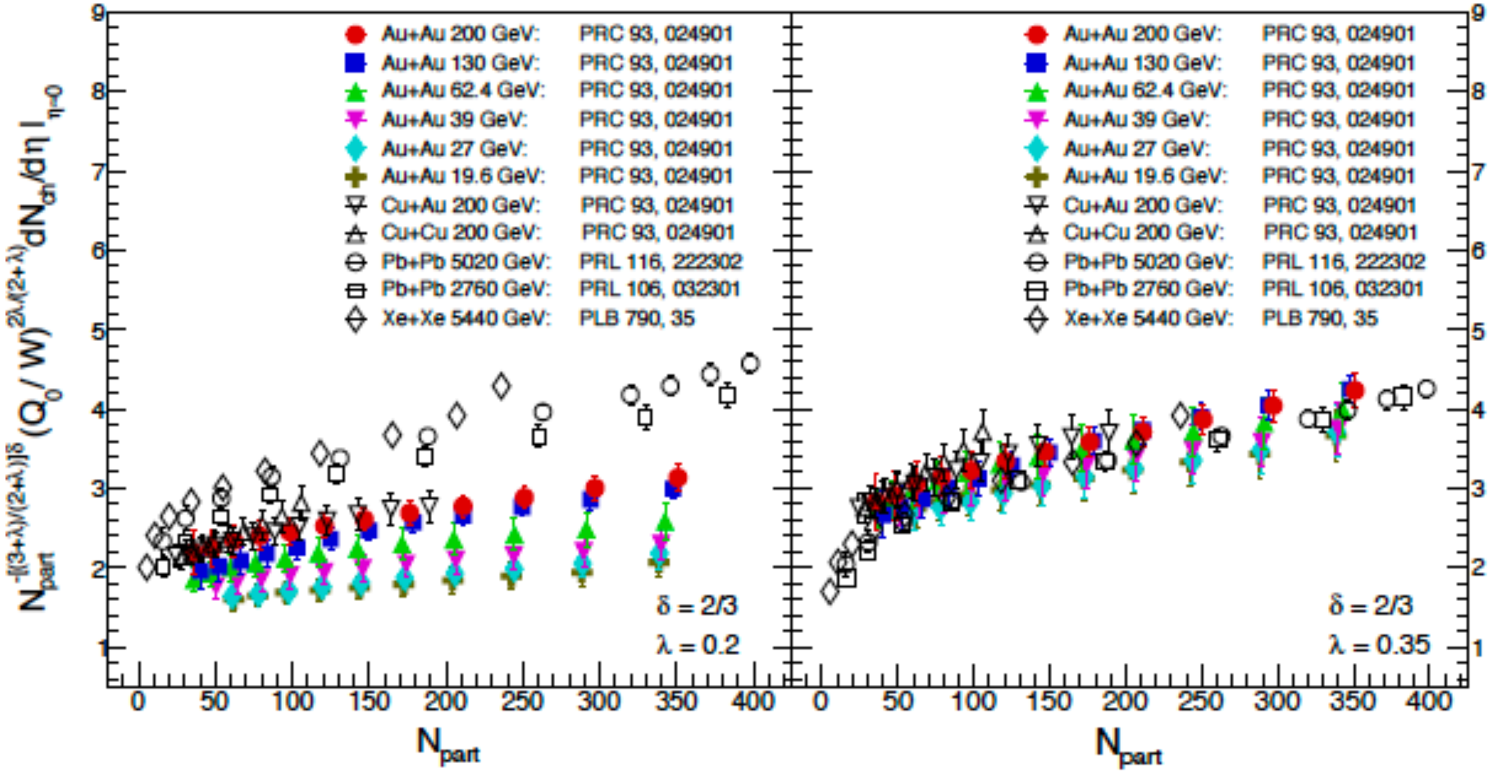
Direct γ (1.0 < p_T < 5.0 GeV//c)
PHENIX Au+Au 200 GeV
fit to new data
fit p+p 200 GeV
scaled by N_coll
PHENIX
Au+Au 39 GeV
Au+Au 62.4 GeV
Au+Au 200 GeV
Cu+Cu 200 GeV
fit to published data
ALICE
Pb+Pb 2760 GeV
dN_γ^{dir}/dy
$dN_{ch}/d\eta|_{\eta\approx0}$
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
10^2
10^3

Computing α from GS

Vladimir Khachatryan, Michał Praszałowicz Eur.Phys.J.C 80 (2020) 7, 670

To link both scalings one needs to use the fact, that charged hadron spectra also scale, however with $\lambda = 0.35$

Below plots show scaled multiplicity spectra



Relating scaling laws

Geometrical scaling:

$$\frac{1}{S_T}\frac{dN_{\gamma,\mathrm{ch}}}{d^2p_T\,d\eta} = F_{\gamma,\mathrm{ch}}(\tau) \qquad\qquad \tau = p_T/Q_\mathrm{s}(x)$$

Multiplicity scaling:

$$\frac{1}{\left(dN_{\mathrm{ch}}/d\eta|_{\eta\approx 0}\right)^{\alpha}}\frac{dN_{\gamma}}{d^2p_T\,dy} = \frac{1}{Q_0^2}G(p_T)$$

⇧ calculate charged particle multiplicity from GS

Computing α from GS

Vladimir Khachatryan, Michał Praszałowicz Eur.Phys.J.C 80 (2020) 7, 670

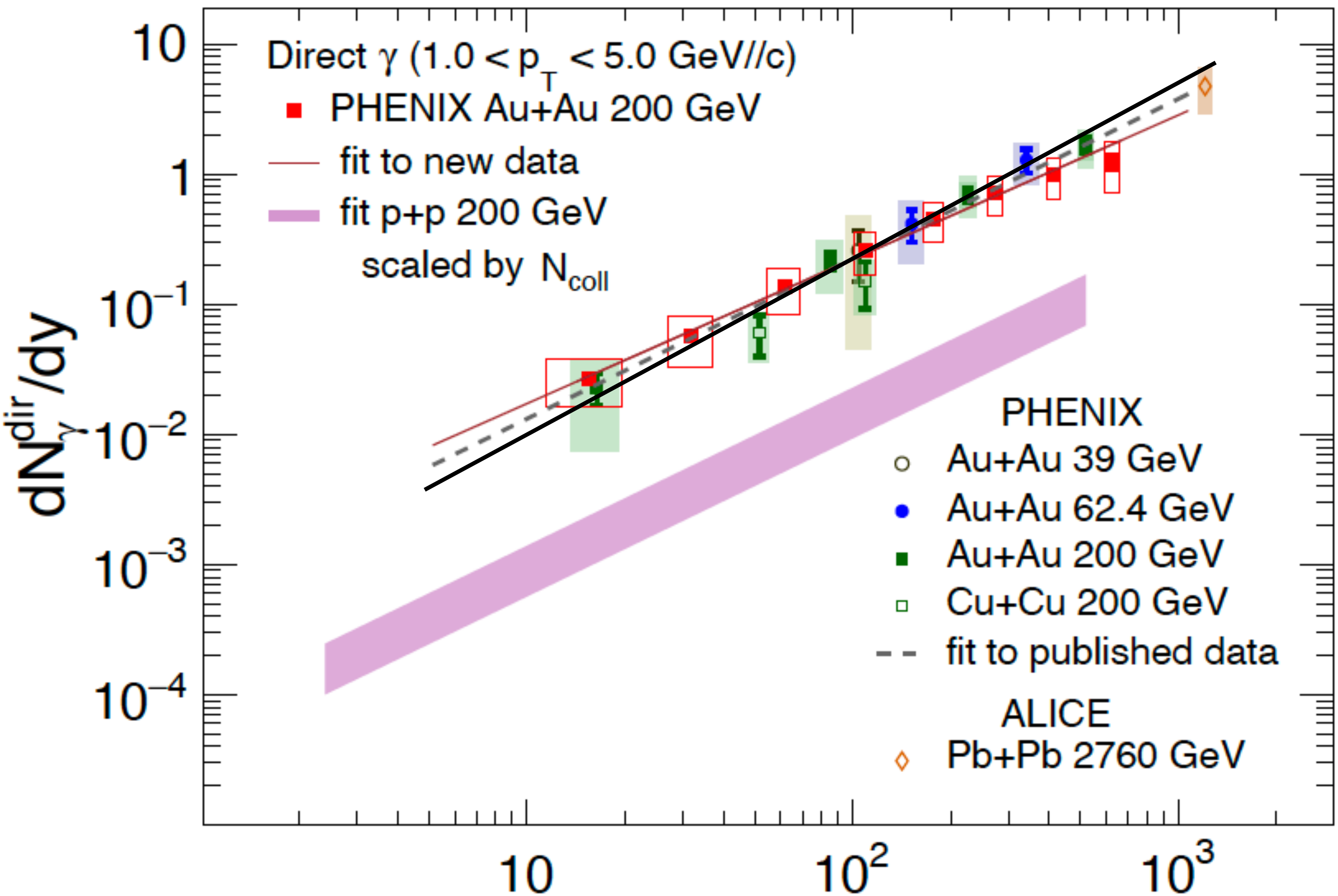
We obtain $\alpha = 1.34$

hadron gas: $\alpha_{\mathrm{HG}} \approx 1.23$

QGP: $\alpha_{\mathrm{QGP}} \approx 1.83,$

pQCD: $\alpha_{\mathrm{pQCD}} \approx 1.25$

Charles Gale,
Jean-François Paquet,
Björn Schenke,
Chun Shen
Phys. Rev. C **105** (2022) 014909



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PHENIX Au+Au 200 GeV
fit to new data
fit p+p 200 GeV
scaled by N_coll
PHENIX
Au+Au 39 GeV
Au+Au 62.4 GeV
Au+Au 200 GeV
Cu+Cu 200 GeV
fit to published data
ALICE
Pb+Pb 2760 GeV
dN_γ^dir/dy
10
1
10^−1
10^−2
10^−3
10^−4
10
10^2
10^3

Conclusions

- Reasonable quality GS is observed in direct photon spectra
- Centrality scaling agrees with expectations: $\delta = 2/3$
- Energy scaling gives lambda below expectations: $\lambda = 0.2$
- Multiplicity scaling can be roughly derived from GS

Outlook

- Is there any enhancement for small p_T ?
- Small systems
- GS breaking: S_T dependence on energy
- What should scale: multiplicity or cross-section?

backup slides

GS in HI: centrality dependence

$$S_\perp \sim N_{\rm part}^{2/3}$$

$$\frac{dN}{dy} \sim N_{\rm part}$$

Triggering on fixed transverse area by selecting centrality classes.

Scaling of the saturation scale: $Q_s^2(x) = \frac{\kappa}{S_\perp}\frac{dN}{dy} \sim N_{\rm part}^{1/3}\left(\frac{\sqrt{s}}{p_{\rm T}}\right)^\lambda$

$$\frac{Q_0^2}{N_{\rm part}^{2/3}}\frac{dN}{dy\,dp_{\rm T}^2} = \mathcal{F}(\tau)$$

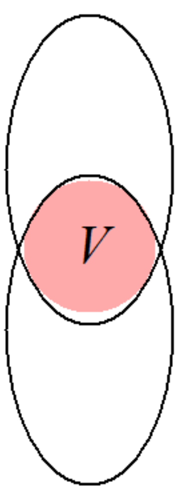
$$\tau = \frac{1}{N_{\rm part}^{1/3}}\frac{p_{\rm T}^2}{Q_0^2}\left(\frac{p_{\rm T}}{W}\right)^\lambda$$

Geometrical scaling

Spectra depend only on a dimensionless variable τ

$$\tau = \frac{p_{\mathrm{T}}^2}{Q_s^2(x)} \qquad Q_{\mathrm{s}}^2(x) = Q_0^2 \left(\frac{1}{x}\right)^{\lambda} \qquad x = \frac{p_{\mathrm{T}}}{\sqrt{s}}$$

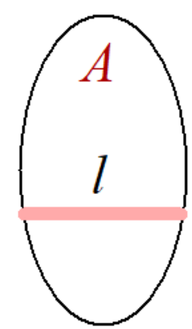
In HI, however, Q_0^2 depends on collision geometry:



$N_{\mathrm{part}} \sim V$

$$Q_0^2 \to Q_0^2 \times N_{\mathrm{part}}^{1/3}$$

$$Q_0^2 \to Q_0^2 \times \frac{N_{\mathrm{part}}[A]}{n_{\mathrm{part}}^{2/3}}$$



$V \sim l \times n_{\mathrm{part}}^{2/3}$

Correcting energy dependence

$$\frac{A_\perp^{(1)} A_\perp^{(2)}}{\sigma_{\text{inel}}} = A_\perp$$

C.Loizides, J.Kamin and D.d'Enterria,
``Improved Monte Carlo Glauber predictions at present and future nuclear colliders,'' PRC 97, 054910 (2018)

ALICE

PHENIX