Scaling properties of direct photons in heavy ion collisions

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(Jagiellonian University)

based on a common work arXiv:1907.03815 [nucl-th]
with

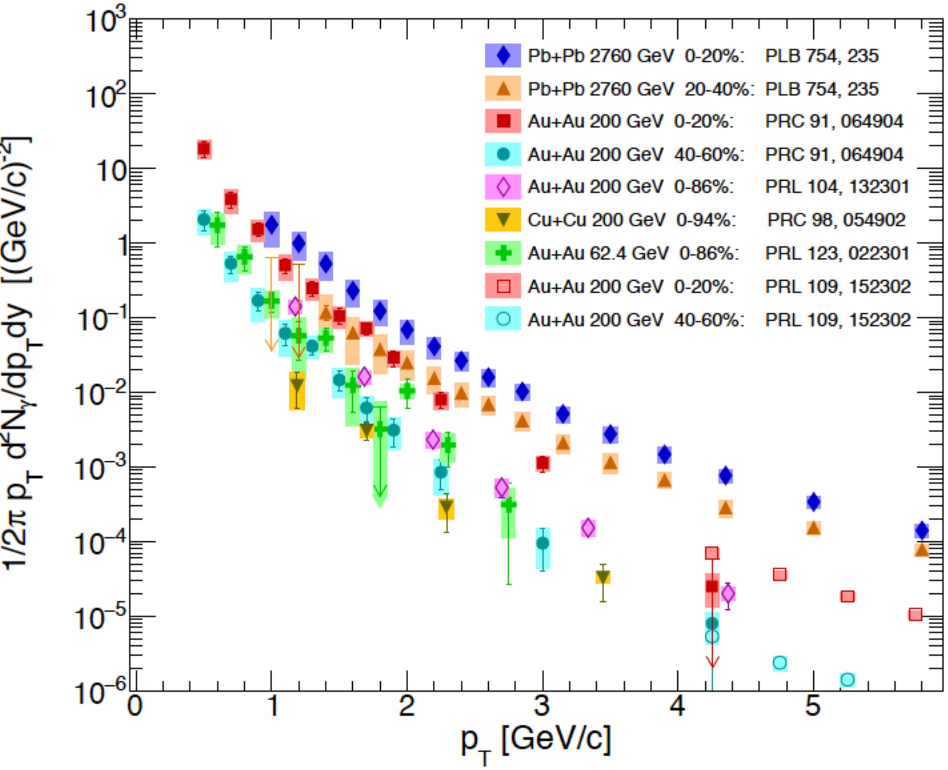
Vlad Khachatryan (Stony Brook & Duke)

Białasówka, 3 kwiecień, 2020

Goal

Direct photon spectra in HI collisions exhibit:

- geometrical scaling (MP Kawiory 2018)
- multiplicity scaling (VK WPCF 2018)



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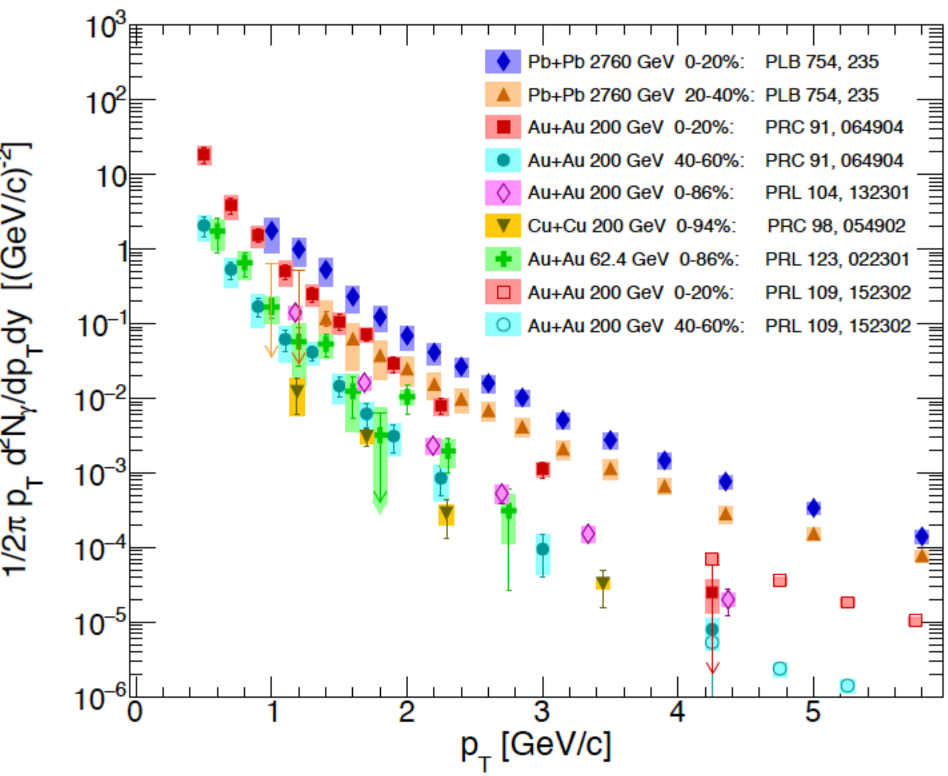

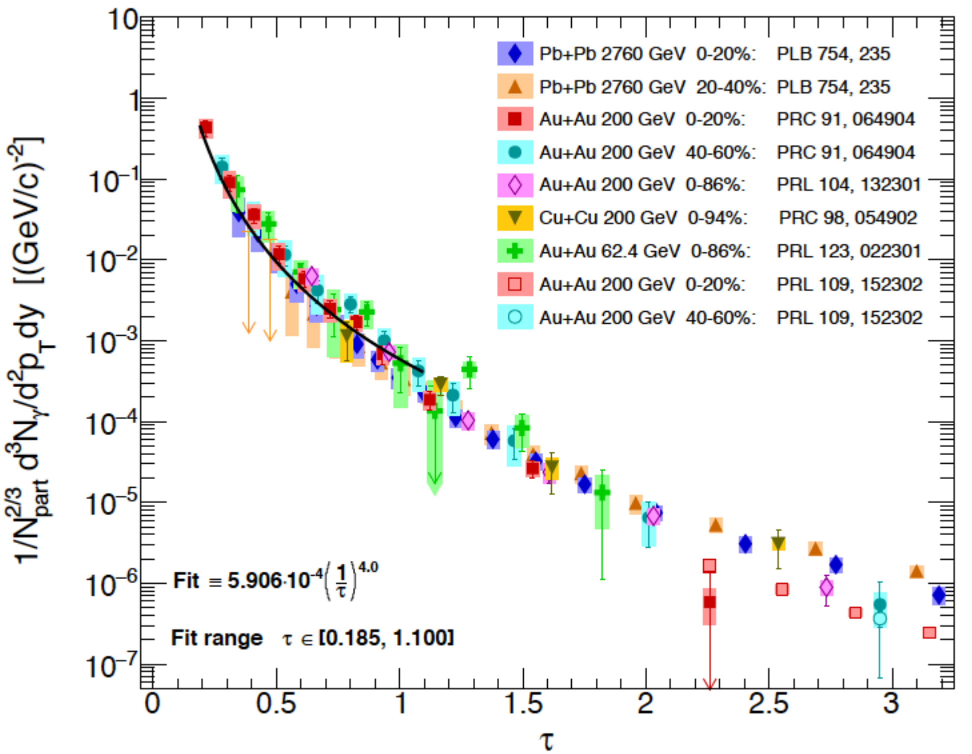

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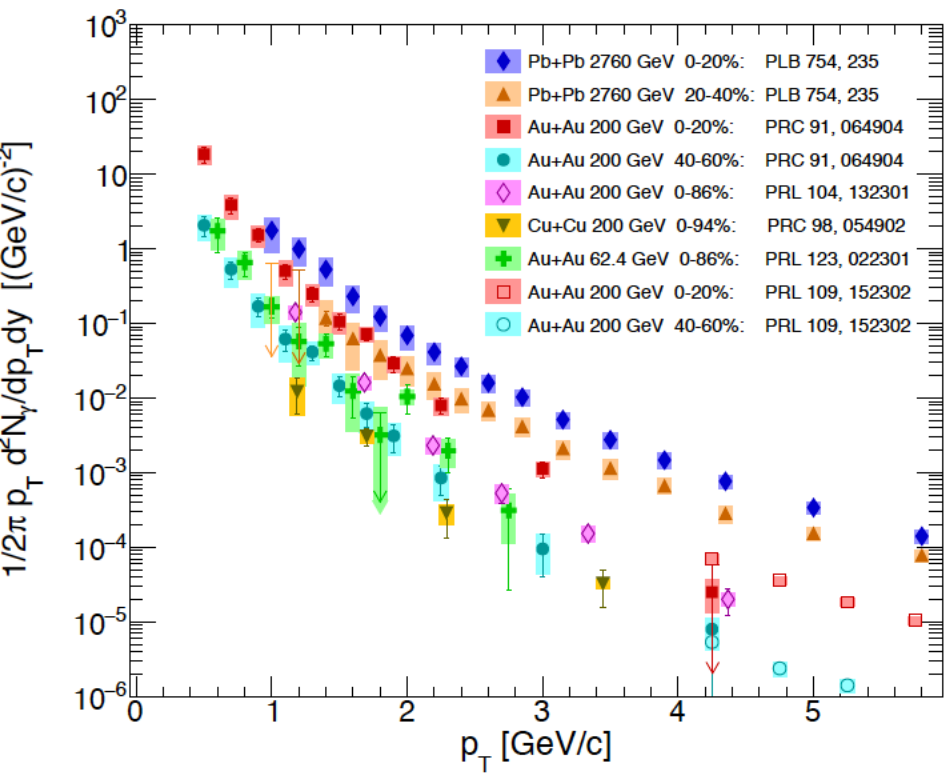
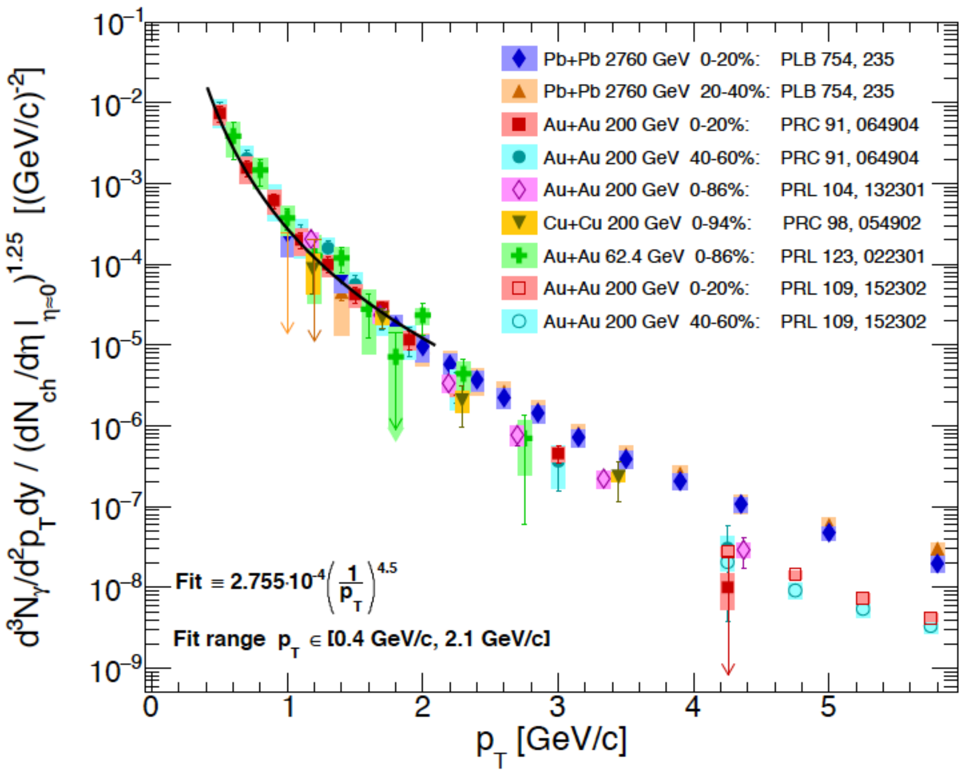




Goal

Direct photon spectra in HI collisions exhibit:

- geometrical scaling (MP Kawiory 2018)
- multiplicity scaling (VK WPCF 2018)

Both scaling laws describe the same data
in the same kinematic range with similar accuracy,
so that there must exist a relation between them.
Goal:
finding such relation
and understanding the physics behind it

so far rather mixed success

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 in tension with PHENIX data 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).

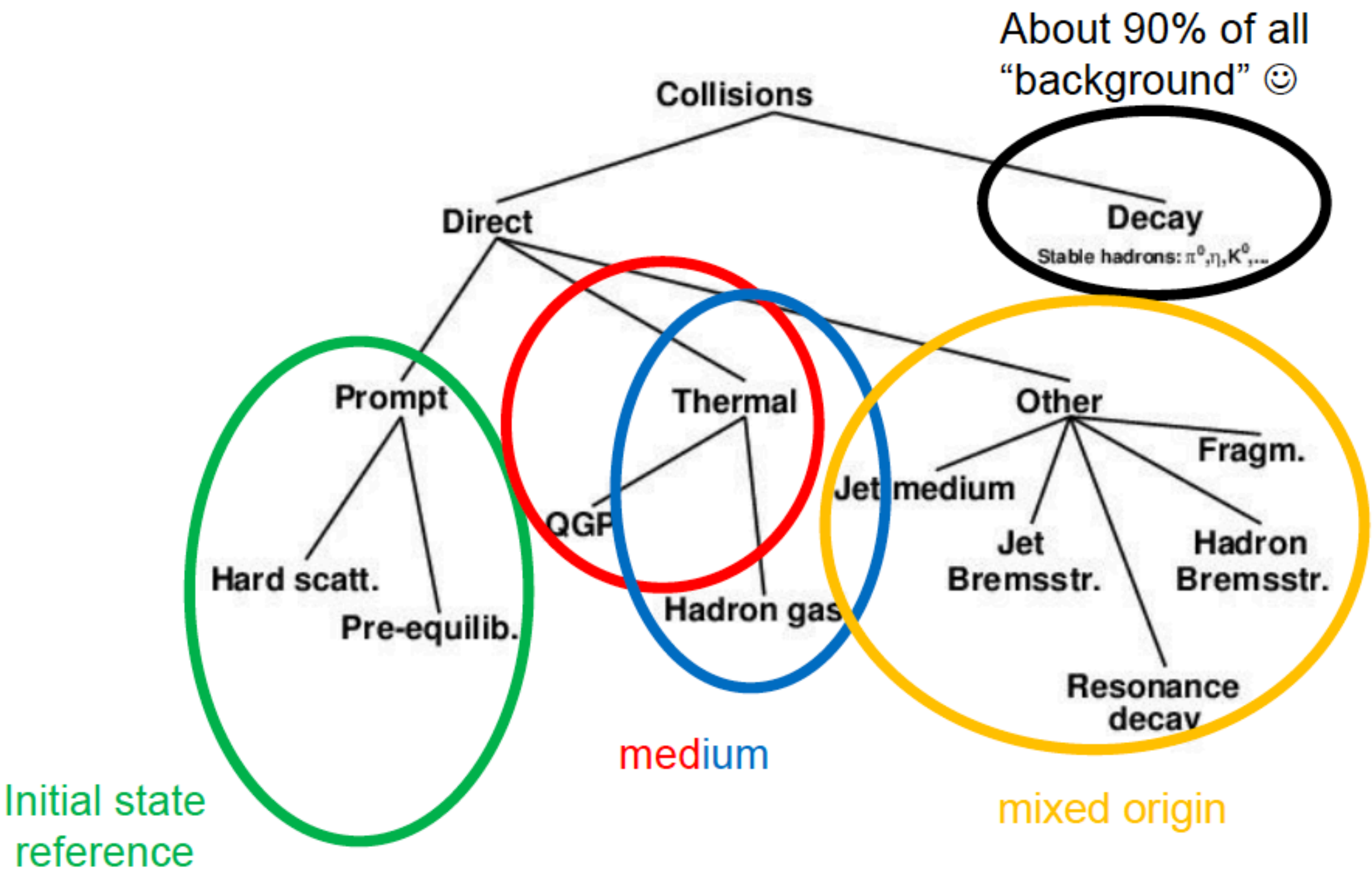
[32] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. C **87**, 054907 (2013).

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.

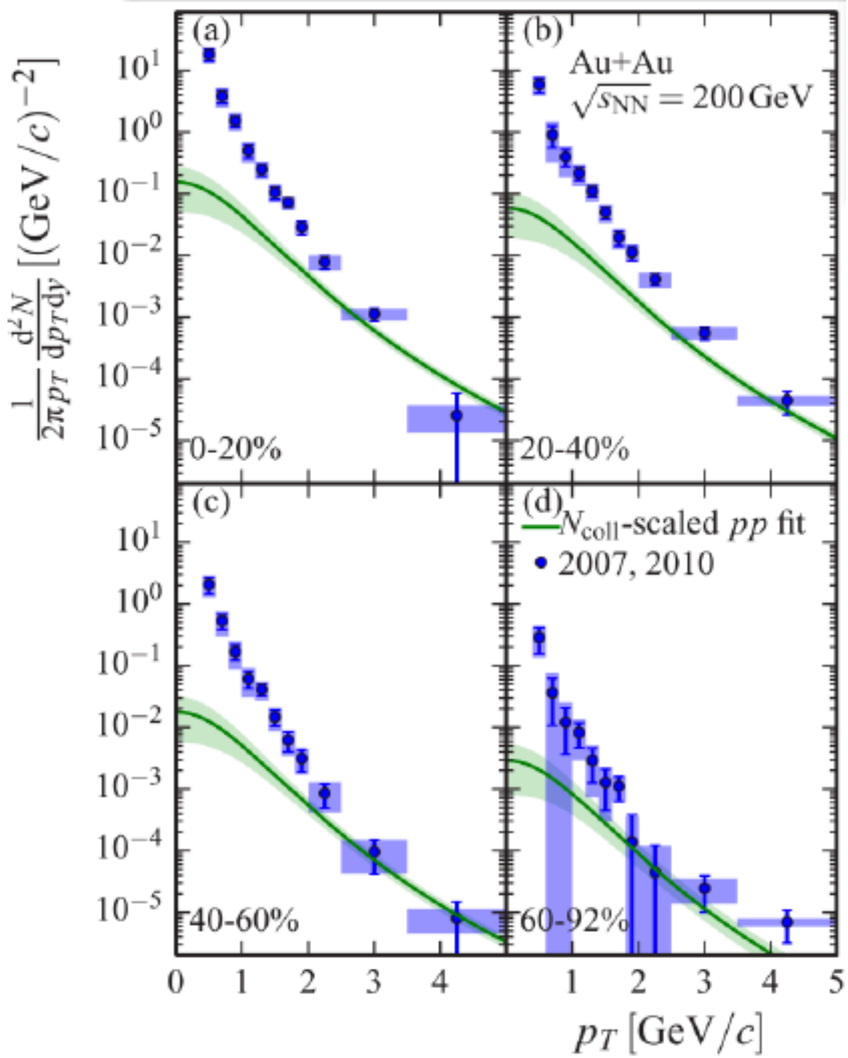
G. David, [arXiv:1907.08893 [nucl-ex]]

Nomenclature

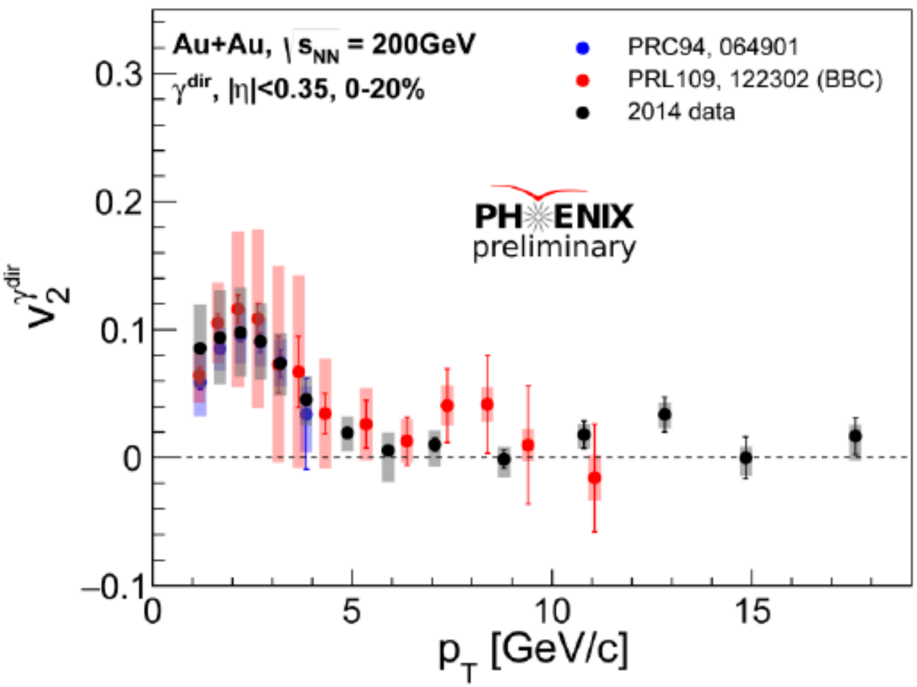


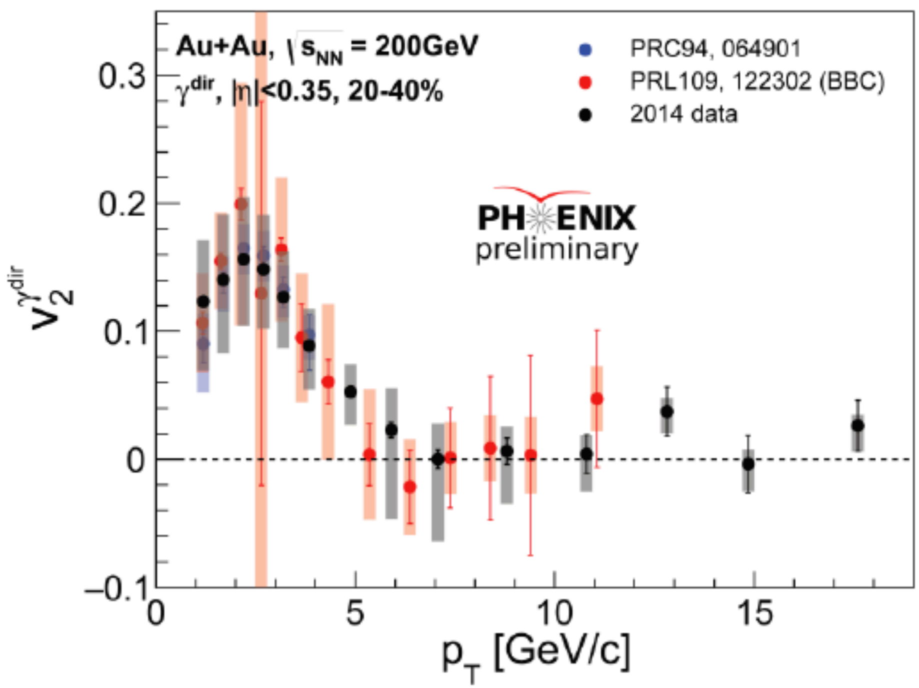
Direct photon spectra

The plots are from PRC 91, 064904



Direct photon flow





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)
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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)

Direct photon puzzle

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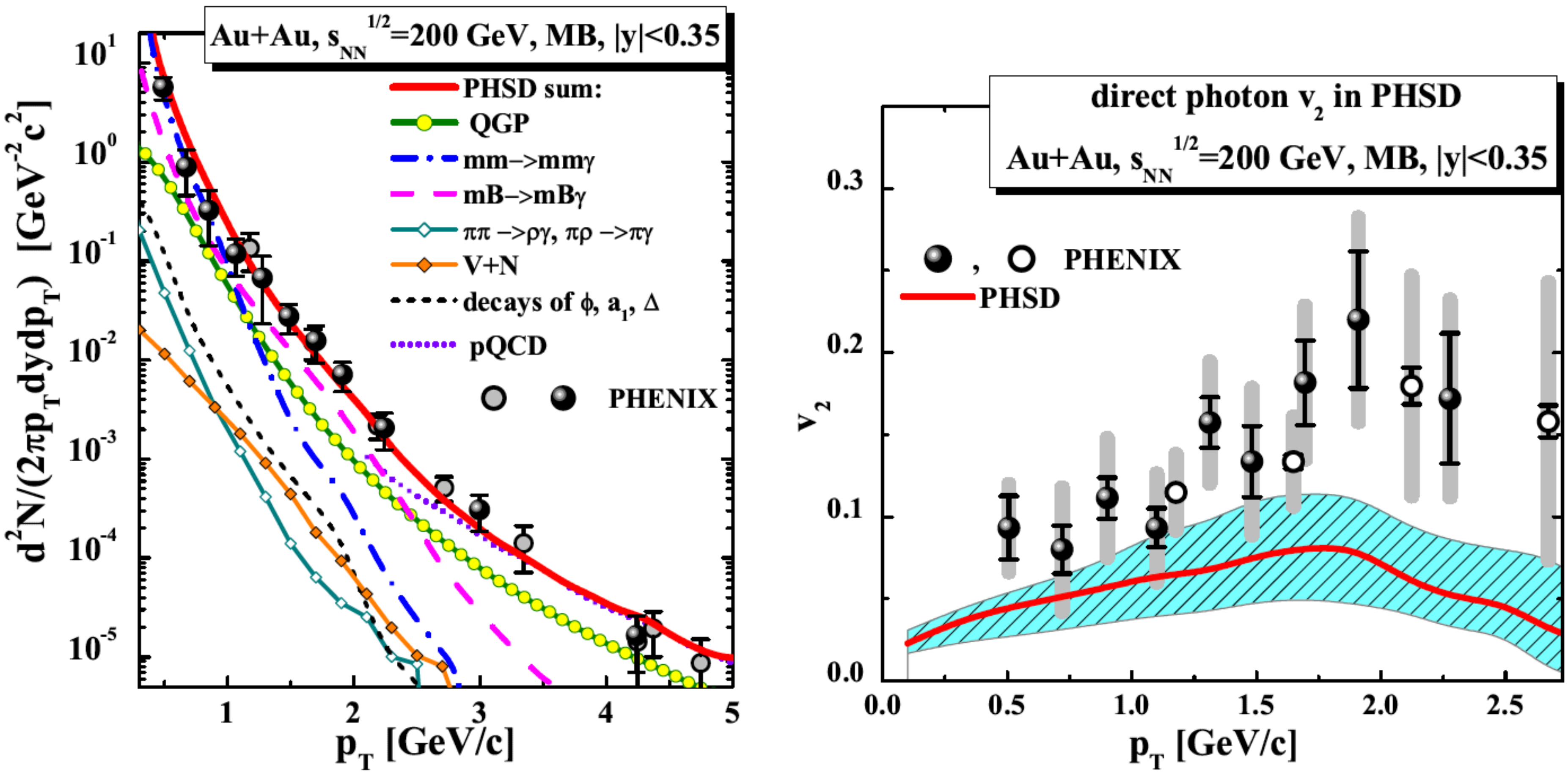
C.Shen, NPA 956, 184 (2016)

early emission?

late stages?

Direct photon puzzle

O.Linnyk, V.Konchakovski, T.Steinert, W.Cassing, E.L.Bratkovskaya, PRC 92, 054914 (2015)



Initial state models

Typically address only yields, no flow

Initial state models have been used both
as a part of hydrodynamic evolution

J.-F.Paquet, C.Shen, G.S.Denicol, M.Luzum, B.Schenke, S.Jeon , C.Gale, PRC 93, 044906 (2016)

and in a bottom-up thermalization scenario

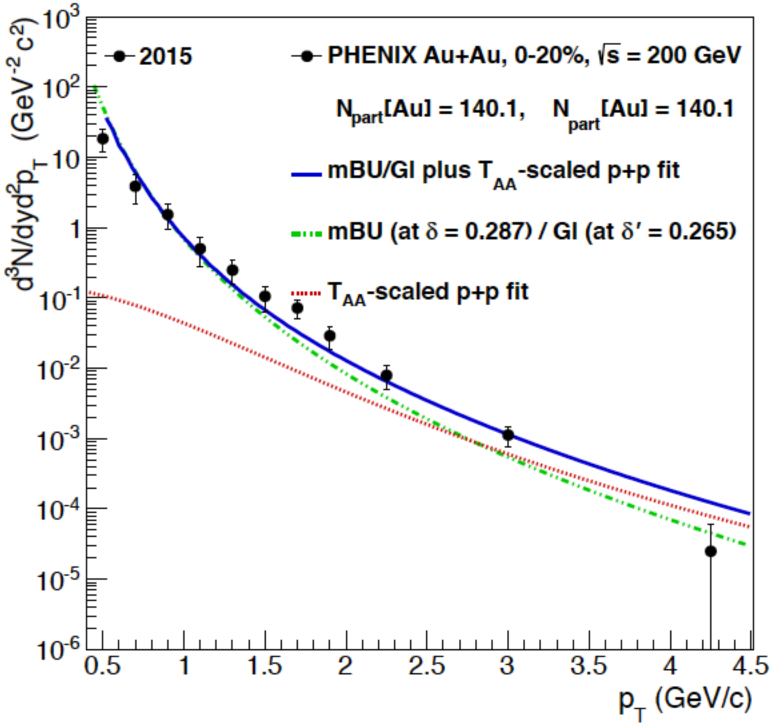
J.Berges, K.Reygers, N.Tanji and R.Venugopalan, PRC 95, 054904 (2017)

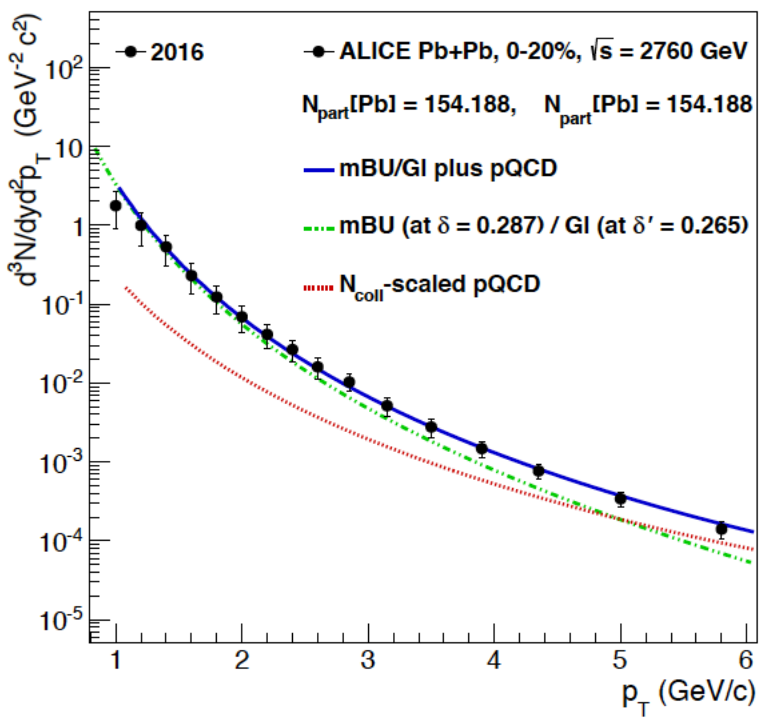
In the latter case good fits for the photon yields have been obtained for PHENIX and ALICE data

V.Khachatryan, B.Schenke, M.Chiu, A.Drees, T.K.Hemmick and N.Novitzky, NPA 978, 123 (2018)

Initial state models

V.Khachatryan, B.Schenke, M.Chiu, A.Drees, T.K.Hemmick and N.Novitzky, NPA 978, 123 (2018)



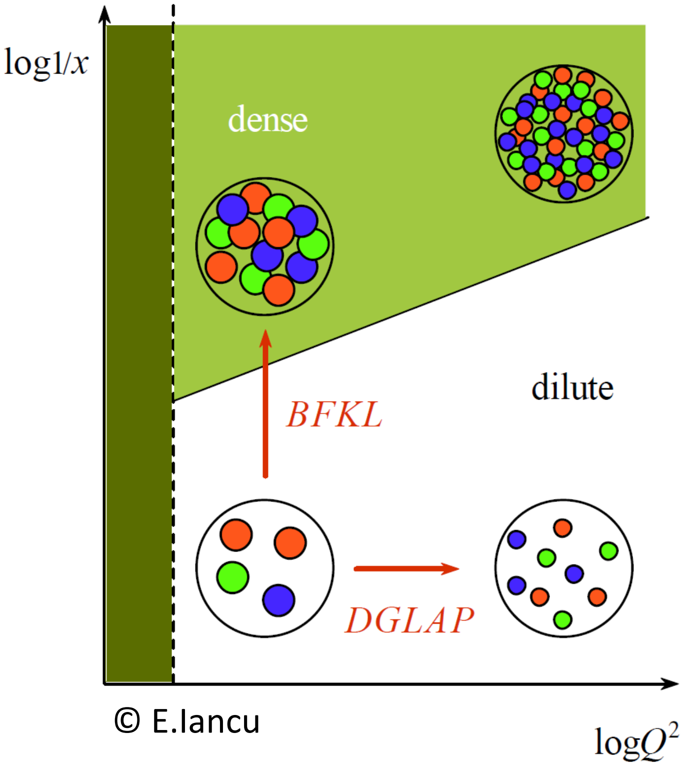


Direct photons do exhibit geometrical scaling

C. Klein-Bsing and L. McLerran, Phys. Lett. B 734 (2014) 282

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



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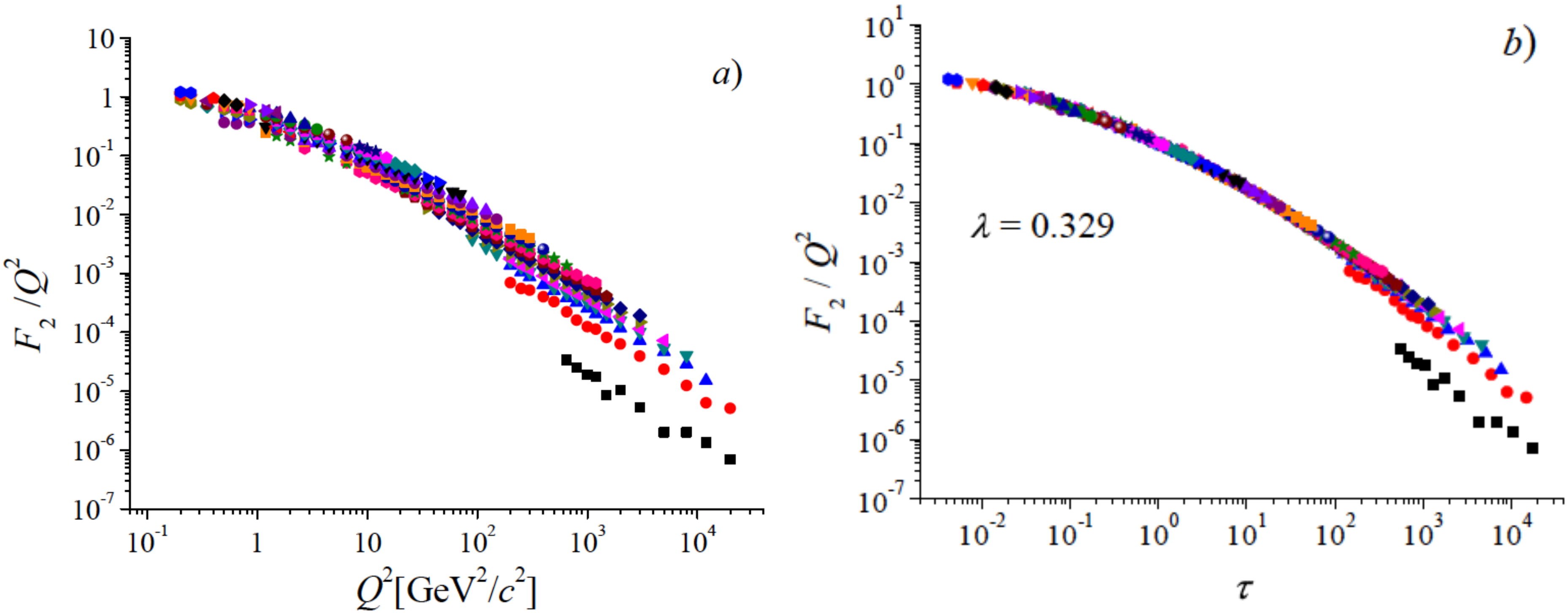
$$Q_s(x) = Q_0 \left(\frac{1}{x}\right)^{\lambda/2}$$

It has been for the firs time observed in DIS

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

GS at DIS



$$\tau = \frac{Q^2}{Q^2_{\rm sat}(x)} \quad Q^2_{\rm sat}(x) = Q_0^2 \left(\frac{x}{x_0}\right)^{-\lambda}$$

M.Praszalowicz and T.Stebel JHEP 1303, 090 (2013) and JHEP 1304, 169 (2013)

What scales in hadronic collisions?

Gribov, Levin Ryskin, *High p_T Hadrons In The Pionization Region In QCD*. Phys.Lett.B100:173-176,1981.

$$x_{1,2} = \frac{p_T}{\sqrt{s}} e^{\pm y}$$

$$\frac{d\sigma}{dy d^2 p_T} = \frac{3\pi\alpha_s}{2p_T^2} \int d^2\vec{k}_T \, \varphi_1(x_1, \vec{k}_T^2)\varphi_2(x_2, (\vec{k}-\vec{p})_T^2)$$

$$A_\perp = \sigma_0$$

$$\varphi(x, \vec{k}_T^2) = A_\perp \phi(\vec{k}_T^2 / Q_{sat}^2(x))$$

gluon distribution

unintegrated glue

$$xG(x, Q^2) = \int^{Q^2} dk_T^2 \, \varphi(x, k_T^2)$$

Kharzeev, Levin Phys.Lett.B523:79-87,2001.

What scales in hadronic collisions?

for $y \sim 0$ (central rapidity) *i.e.* for $x_1 \sim x_2 = x$ and for symmetric systems

$$\frac{d\sigma}{dy d^2 p_{\mathrm{T}}} = A_\perp^{(1)} A_\perp^{(2)} \frac{3\pi\alpha_{\mathrm{s}}}{2} \frac{Q_s^2(x)}{p_{\mathrm{T}}^2} \int \frac{d^2 \vec{k}_{\mathrm{T}}}{Q_s^2(x)} \phi_1(\vec{k}_{\mathrm{T}}^2 / Q_s^2(x)) \phi_2((\vec{k} - \vec{p})_{\mathrm{T}}^2 / Q_s^2(x))$$

$$= A_\perp^{(1)} A_\perp^{(2)} \mathcal{F}\left(\frac{p_{\mathrm{T}}^2}{Q_{\mathrm{s}}^2}\right)$$

For multiplicity one has to divide this by inelastic cross-section

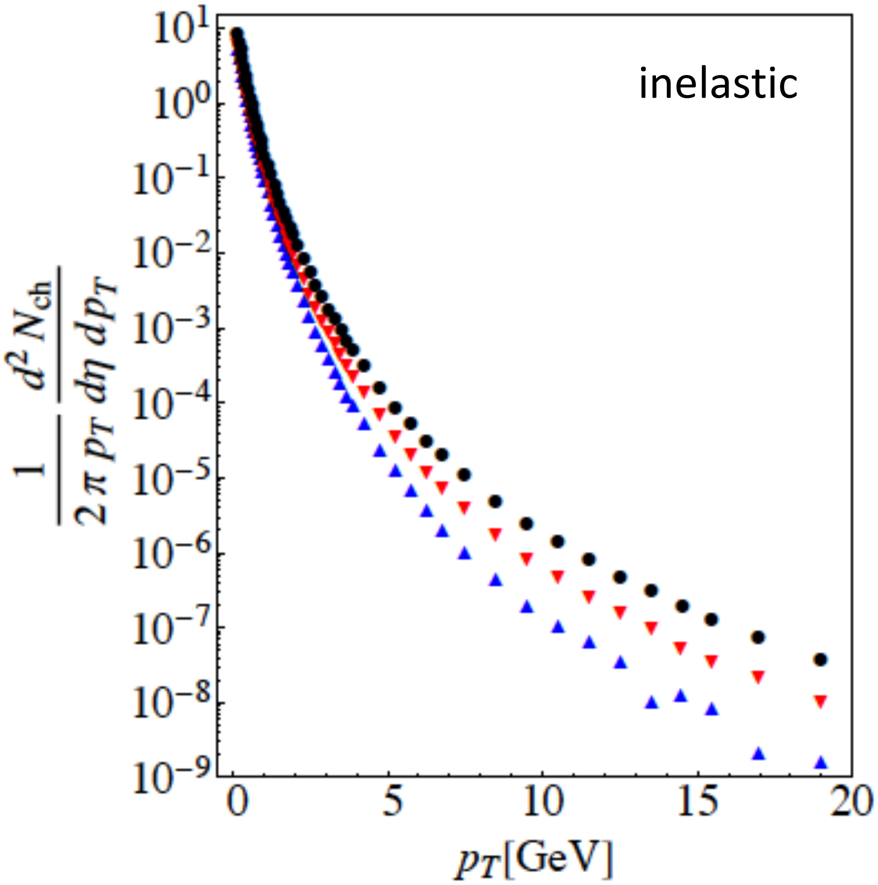
$$\frac{dN}{dy d^2 p_{\mathrm{T}}} = \frac{A_\perp^{(1)} A_\perp^{(2)}}{\sigma_{\mathrm{inel}}} \mathcal{F}\left(\frac{p_{\mathrm{T}}^2}{Q_{\mathrm{s}}^2}\right) = S_\perp \mathcal{F}\left(\frac{p_{\mathrm{T}}^2}{Q_{\mathrm{s}}^2}\right)$$

but sigma_inel
is energy dependent

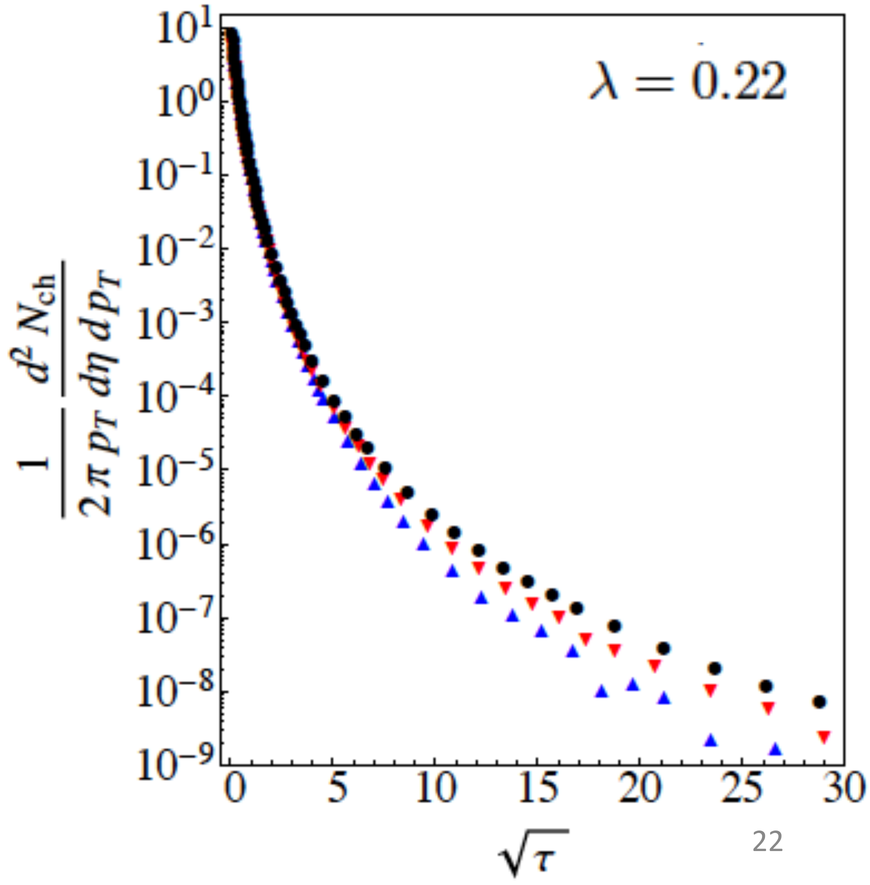
Determination of lambda in pp

$$\frac{dN_{\rm ch}}{dy\,dp_{\rm T}^2} = S_{\perp}\mathcal{F}(\tau) \qquad \tau = \frac{p_{\rm T}^2}{Q_{\rm sat}^2(p_{\rm T}/\sqrt{s})} = \frac{p_{\rm T}^2}{1\,{\rm GeV}^2}\left(\frac{p_{\rm T}}{\sqrt{s}\times 10^{-3}}\right)^{\lambda}$$

ALICE 1307.1093 [nucl-ex], Eur.Phys.J C73 (2013) 2662



M. Praszałowicz, A. Francuz Phys.Rev. D92 (2015) no.7, 074036

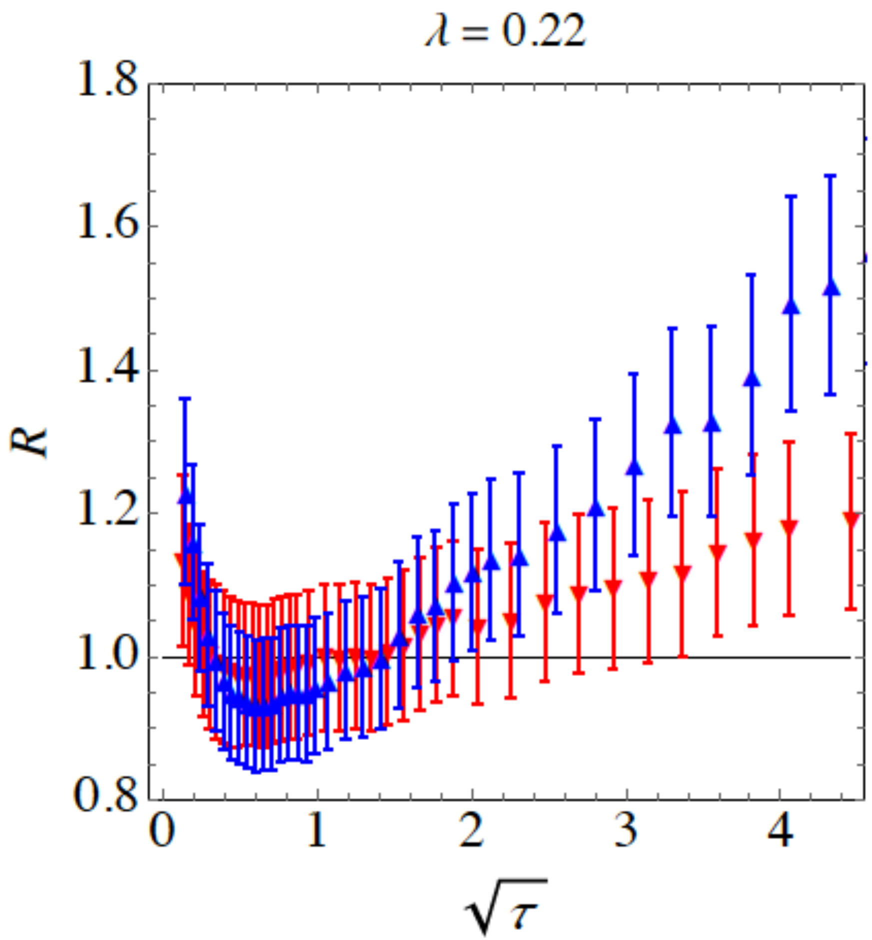


What should scale in pp?

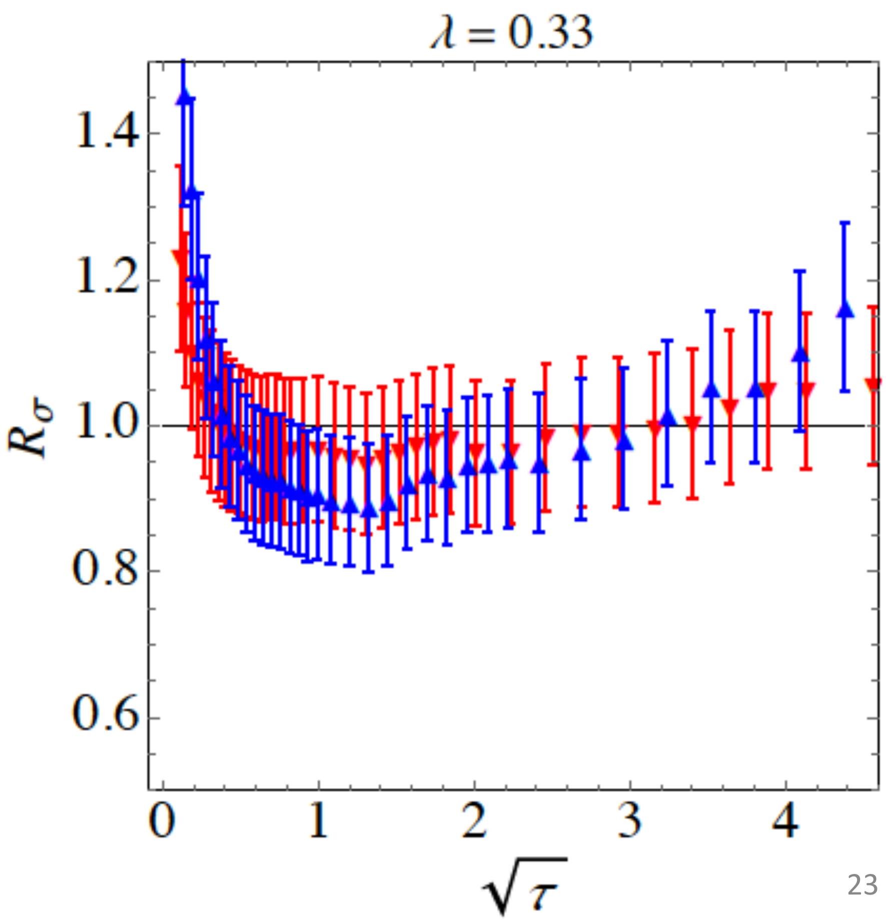
ALICE 1307.1093 [nucl-ex], Eur.Phys.J C73 (2013) 2662

M. Praszałowicz, A. Francuz Phys.Rev. D92 (2015) no.7, 074036

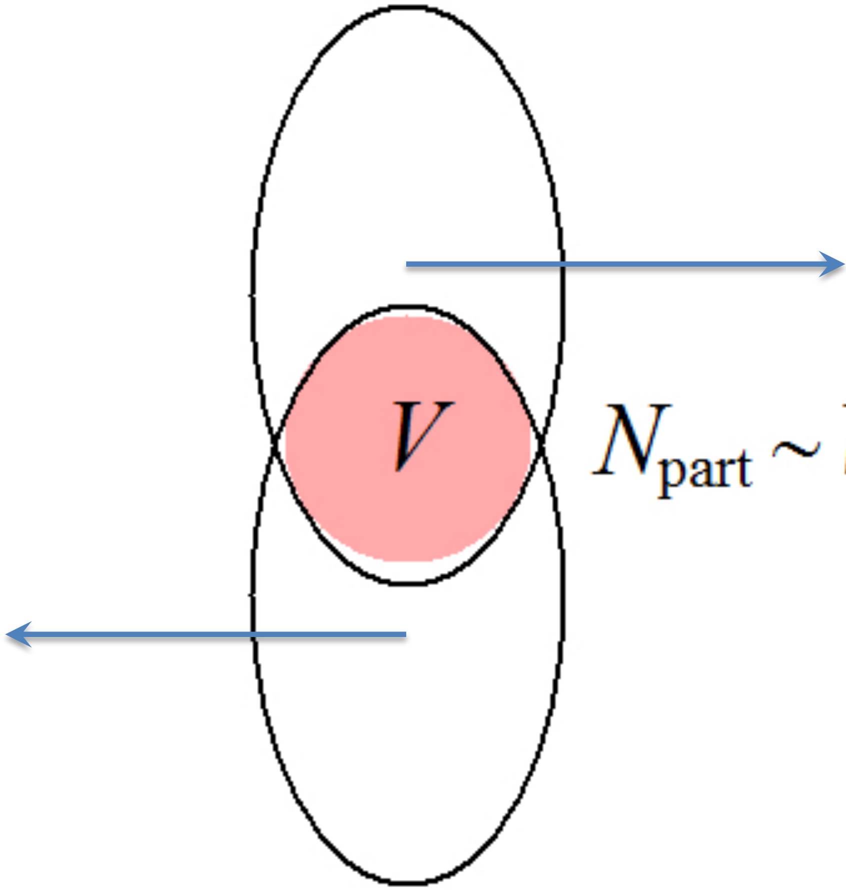
multiplicity



cross-section



GS in HI: centrality dependence



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

commonly assumed:

$$\frac{dN}{dy\,dp_T^2} = S_\perp \mathcal{F}(\tau)$$

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

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

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

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

GS in HI: *energy* and *centrality*

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

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

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

Photons: centrality scaling

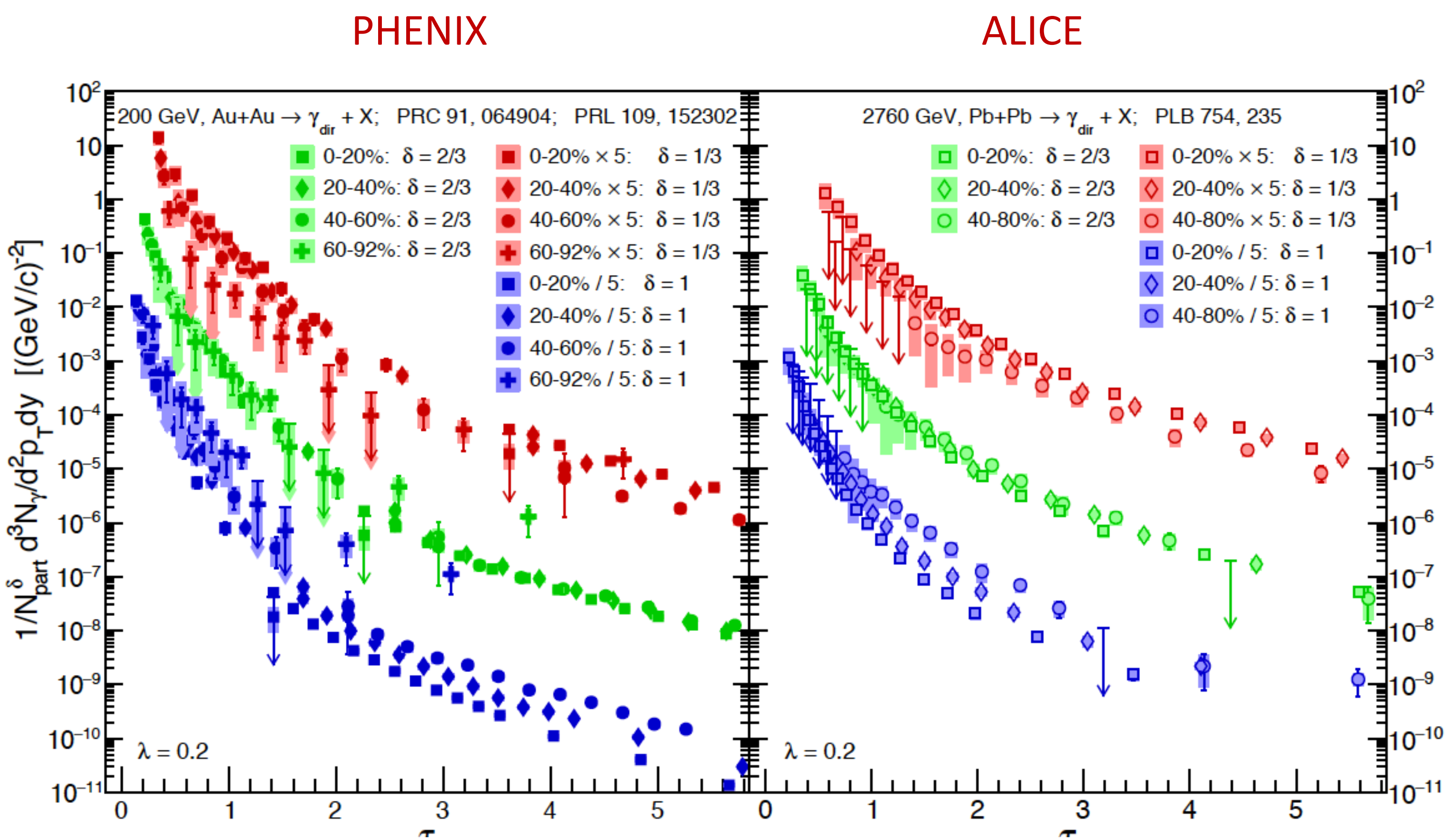
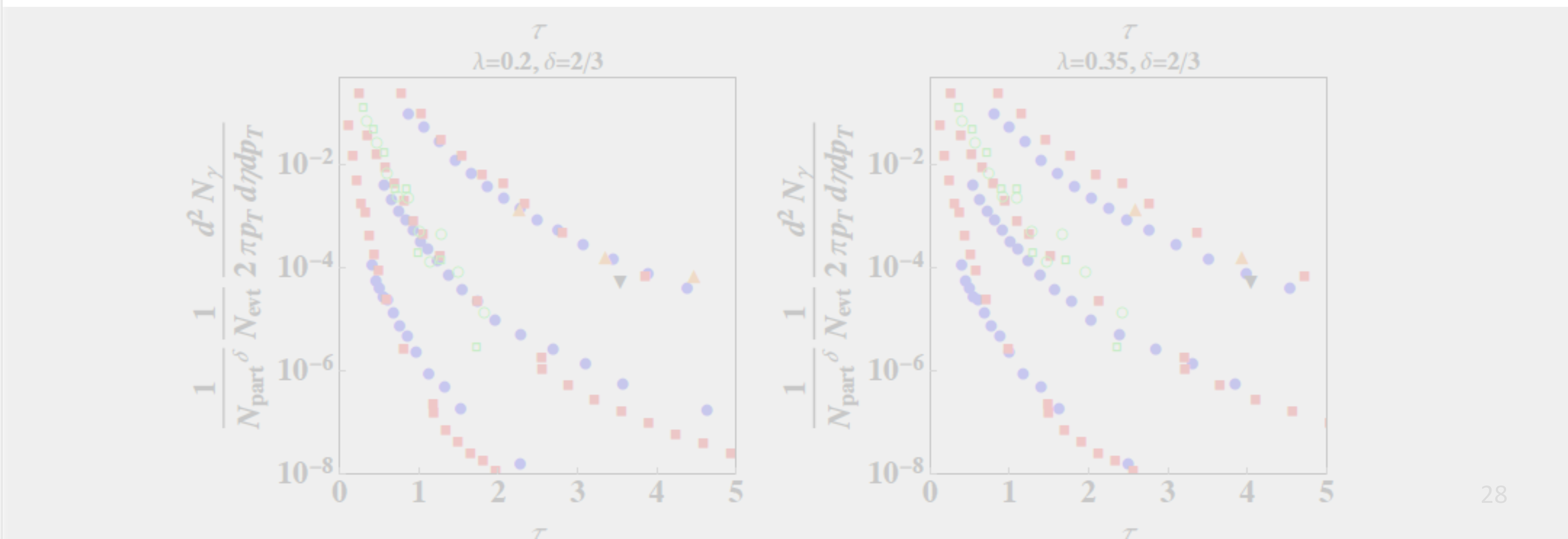


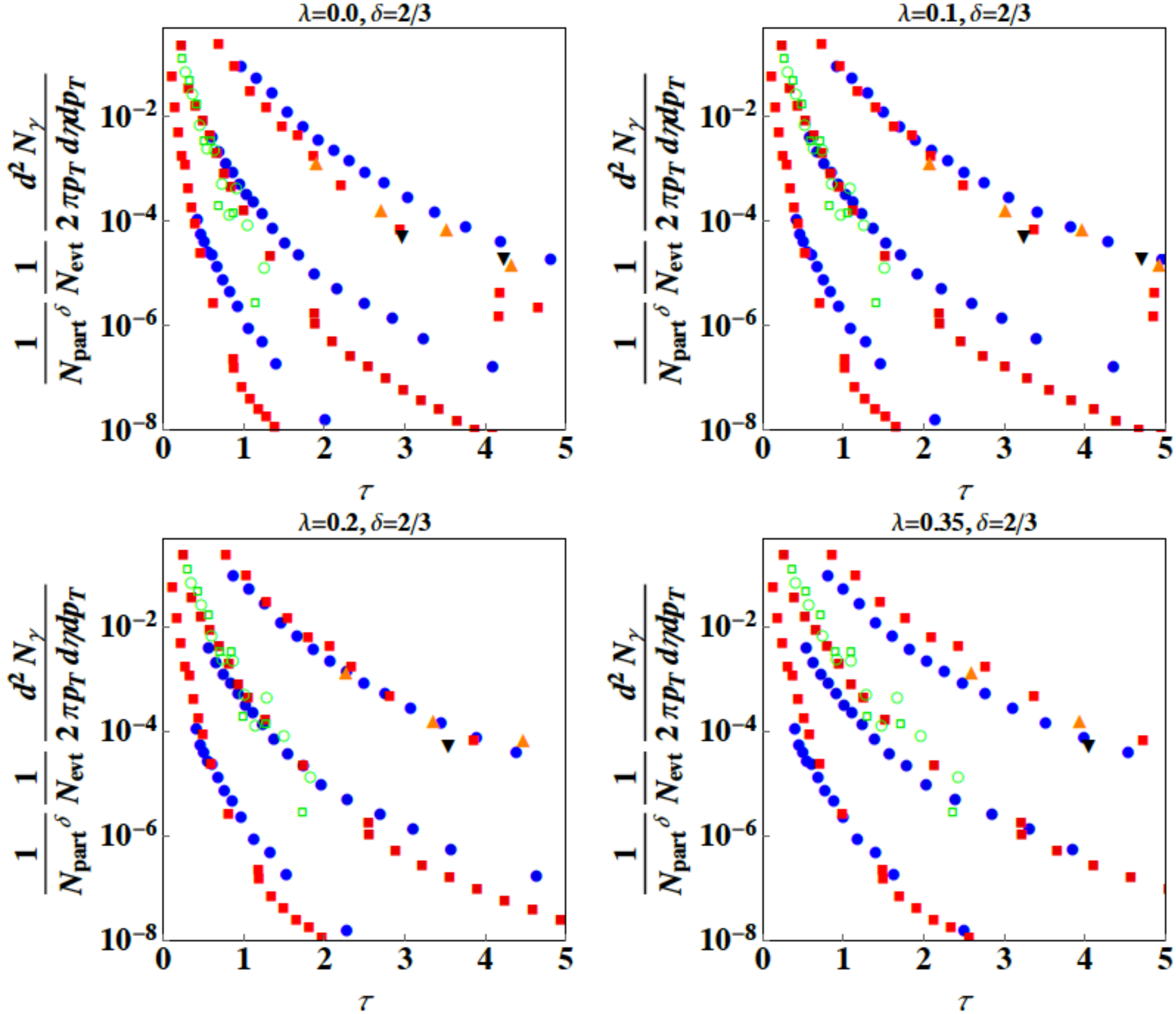
Figure 2: Direct photon spectra scaled according to Eq. (3) with $S_\perp$ and τ given by Eqs. (14) and (15) respectively, plotted – from top to bottom – for $\delta = 1/3$ (red points), 2/3 (green points) and 1 (blue points). Left panel corresponds to PHENIX $Au + Au$ data at 200 GeV, right panel to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

Photons: energy scaling

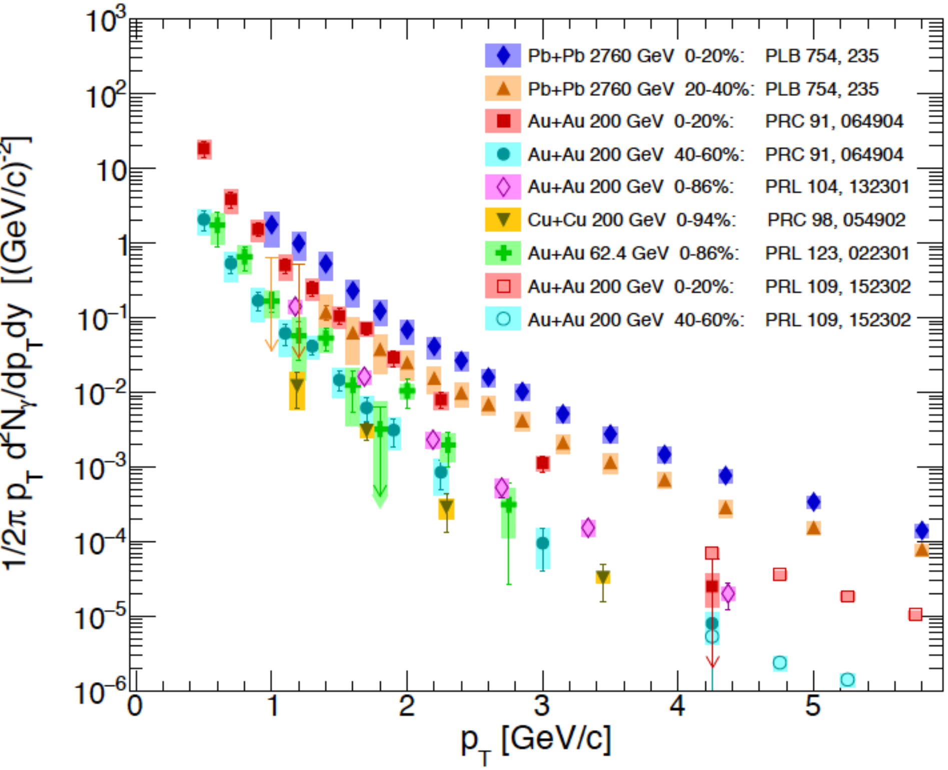
Figure 1: Scaled direct photon p_T-spectra for different systems and different energies plotted for four different choices of scaling exponent λ. Upper band (multiplied by 2.5): data for most central collisions, includes also dA and pp data, middle band: mid centralities, lower band (divided by 2.5) peripheral.

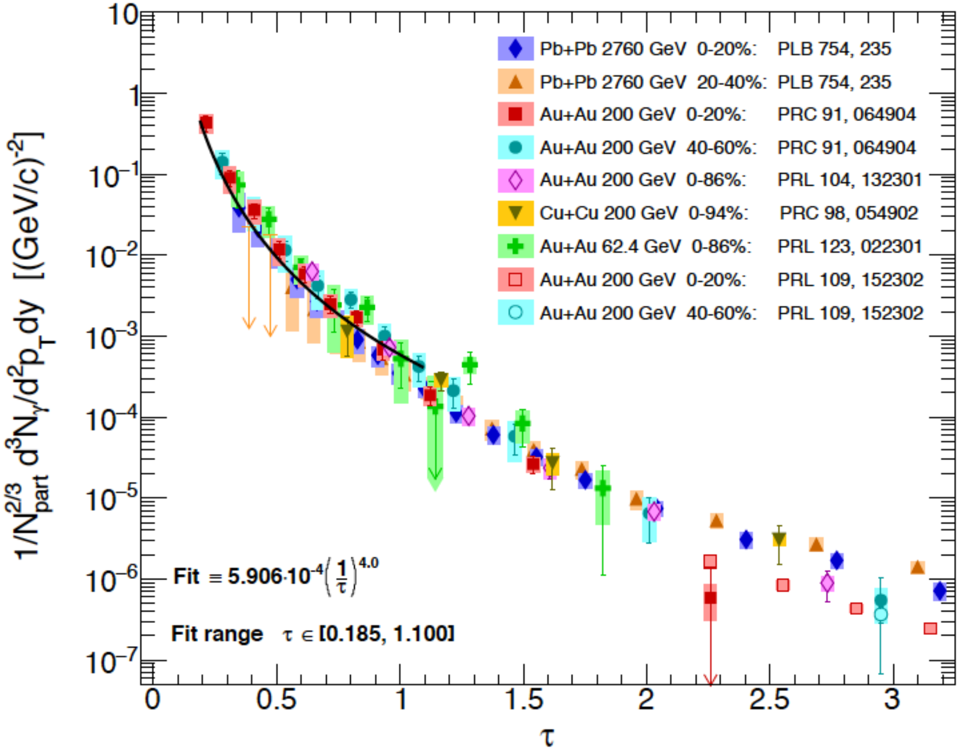


Photons: energy scaling



Photons: GS full

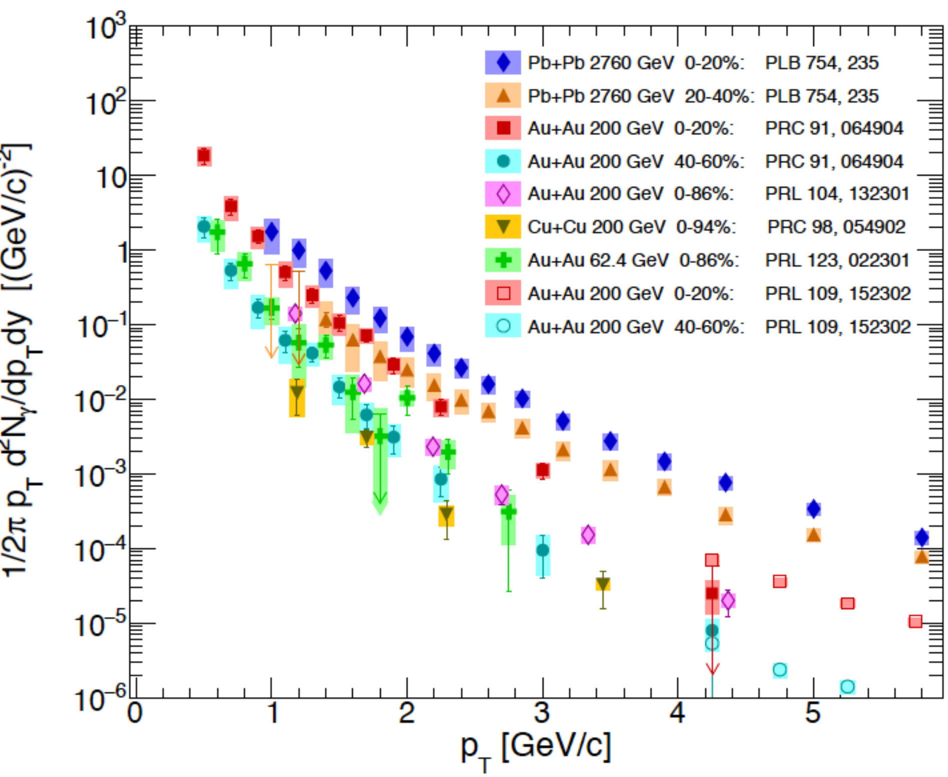


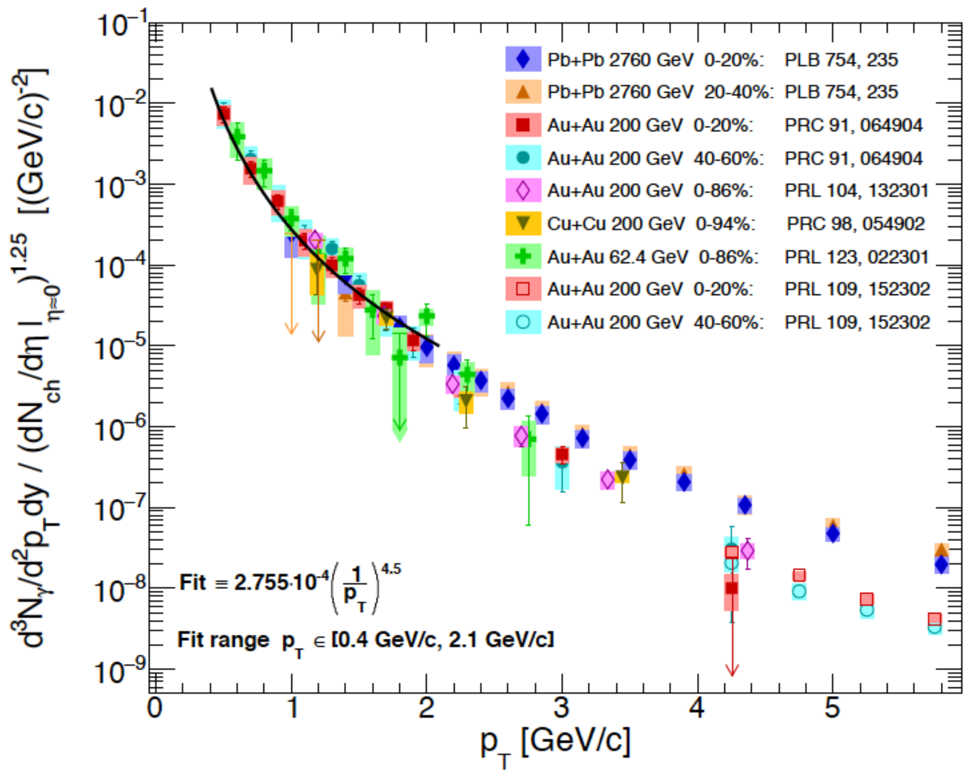


A.Adare PHENIX Collaboration,
Phys. Rev. Lett. 123, 022301 (2019)

Multiplicity scaling

Phenomenological obserervation, no theory:
take photon yeilds,
divide them by charged particles total multiplicity$^{\alpha}$
α=1.25





Relating scaling laws

Geometrical scaling:

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

Multiplicity scaling:

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

⇧ calculate charged particle multiplicity from GS

$$\frac{d\sigma}{dy\,d^2p_\mathrm{T}} = \frac{C}{p_T^2}\int d^2\vec{k}_T\,\alpha_\mathrm{s}(k_T^2)\varphi^{(1)}(x_1,\vec{k}_T^2)\,\varphi^{(2)}(x_2,(\vec{k}-\vec{p})_T^2)$$

Relating scaling laws

Geometrical scaling:

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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

$$\frac{dN_\mathrm{ch}}{d\eta} = \int d^2p_T\,\frac{dN_\mathrm{ch}}{d^2p_T\,d\eta} = N_\mathrm{part}^{\frac{3+\lambda}{2+\lambda}\delta}\left(\frac{W}{Q_0}\right)^{\frac{2\lambda}{2+\lambda}}\kappa$$

Relating scaling laws

$$S_T\, F_\gamma(\tau(p_T)) = \frac{dN_\gamma}{d^2p_T dy} = \left(\frac{dN_{\rm ch}}{d\eta}\right)^\alpha \frac{1}{Q_0^2} G(p_T)$$

one cannot proceed without some assumptions concerning functions *F* and *G*
power law seems to work rather well in some range of p_T
$n = 4$, $m = 4.5$

$$F_\gamma(\tau) \sim \frac{1}{\tau^n} \quad \text{and} \quad G(p_T) \sim \left(\frac{Q_0}{p_T}\right)^m$$

Energy and N_{part} depndence of both sides must be the same

Relating scaling laws

Geometrical scaling:

$$N_{\text{part}}^{\delta} \left(N_{\text{part}}^{\delta/4} \left(\frac{W}{Q_0} \right)^{\frac{\lambda}{2}} \left(\frac{Q_0}{p_T} \right)^{\frac{2+\lambda}{2}} \right)^{n}$$

Multiplicity scaling:

$$\left(N_{\text{part}}^{\delta} N_{\text{part}}^{\frac{1}{2+\lambda}\delta} \left(\frac{W}{Q_0} \right)^{\frac{2\lambda}{2+\lambda}} \right)^{\alpha} \left(\frac{Q_0}{p_T} \right)^{m}$$

Relating scaling laws

$$m = \frac{2+\lambda}{2} n, \quad \frac{4+n}{4}\delta = \frac{3+\lambda}{2+\lambda}\delta\alpha, \quad \frac{\lambda}{2} n = \frac{2\lambda}{2+\lambda}\alpha.$$

m > *n*

☺

Relating scaling laws

$$m = \frac{2+\lambda}{2} n, \qquad \frac{4+n}{4} \delta = \frac{3+\lambda}{2+\lambda} \delta\alpha, \qquad \frac{\lambda}{2} n = \frac{2\lambda}{2+\lambda} \alpha.$$

m > n centrality energy

$$\alpha = \left. \frac{4+n}{4} \frac{2+\lambda}{3+\lambda} \right|_{\substack{n=4 \\ \lambda=0.2}} = 1.375.$$

$$\alpha = \left. n \frac{2+\lambda}{4} \right|_{\substack{n=4 \\ \lambda=0.2}} = 2.2.$$

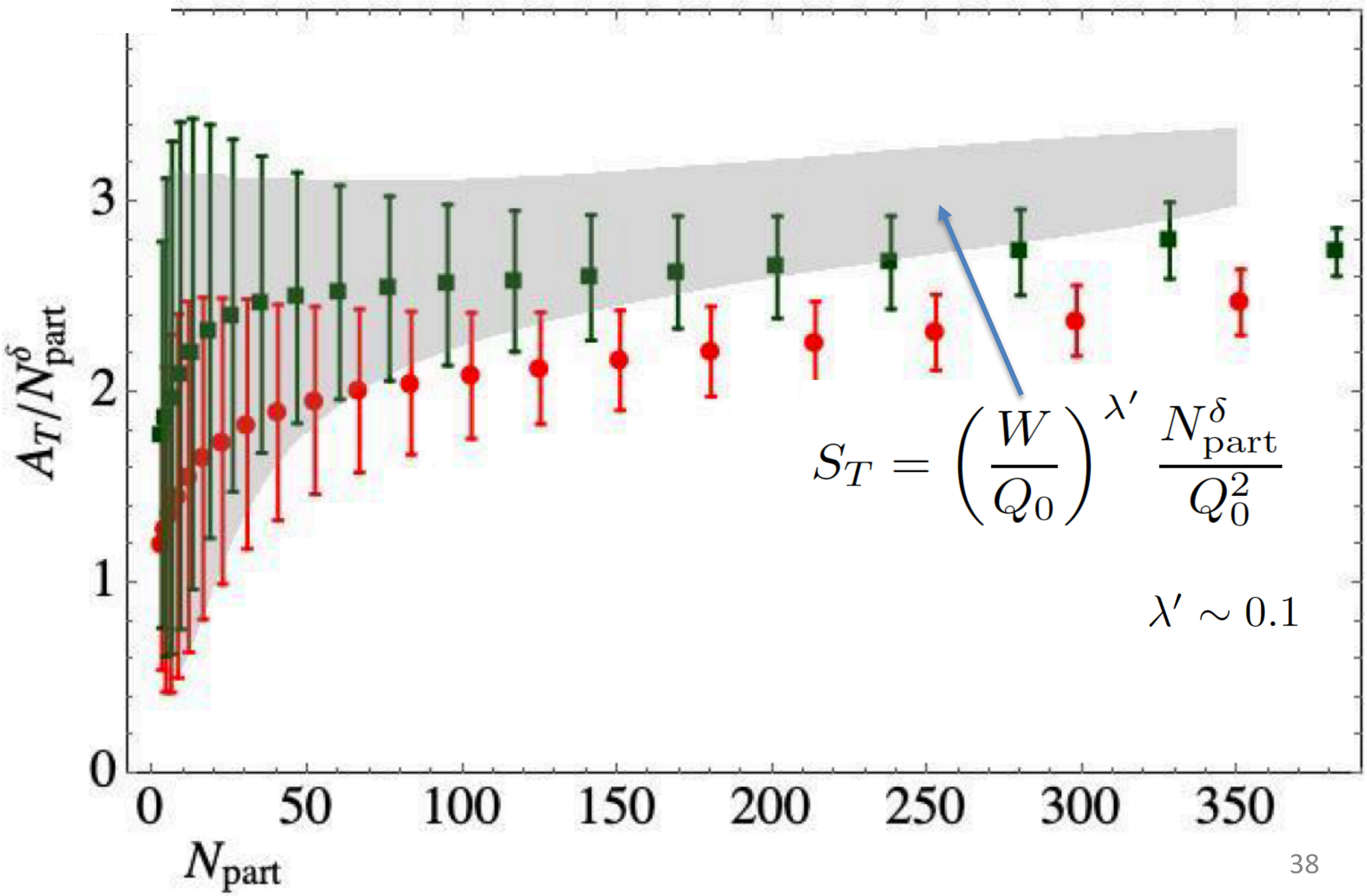
Correcting energy dependence

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

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



Adding violation of GS

$$\frac{\lambda}{2} n = \frac{2\lambda}{2+\lambda} \alpha. \quad \Rightarrow \quad \frac{\lambda n}{2} + \lambda' = \left(\frac{2\lambda}{2+\lambda} + \lambda' \right) \alpha$$

$$\alpha = n \frac{2+\lambda}{4} \Bigg|_{\substack{n=4 \\ \lambda=0.2}} = 2.2$$

$$\alpha = \frac{\lambda n + 2\lambda'}{2\left(\frac{2\lambda}{2+\lambda} + \lambda' \right)} \Bigg|_{\substack{n=4 \\ \lambda=0.2 \\ \lambda' \sim 0.1}} = 1.77$$

Possible way out

- Q^2 dependence of α_s
- non-factorization of gluon distribution: ~~$A_T \varphi(\tau)$~~
- correlation $\delta(N_{part})$
- better, data drvien parametrization instead of power law
- two component model of photon emission
- ?

Possible ways out

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Both scaling laws describe the same data
in the same kinematic range with similar accuracy,
so that there must exist a relation between them.