Geometrical scaling of direct photons in heavy ion collisions

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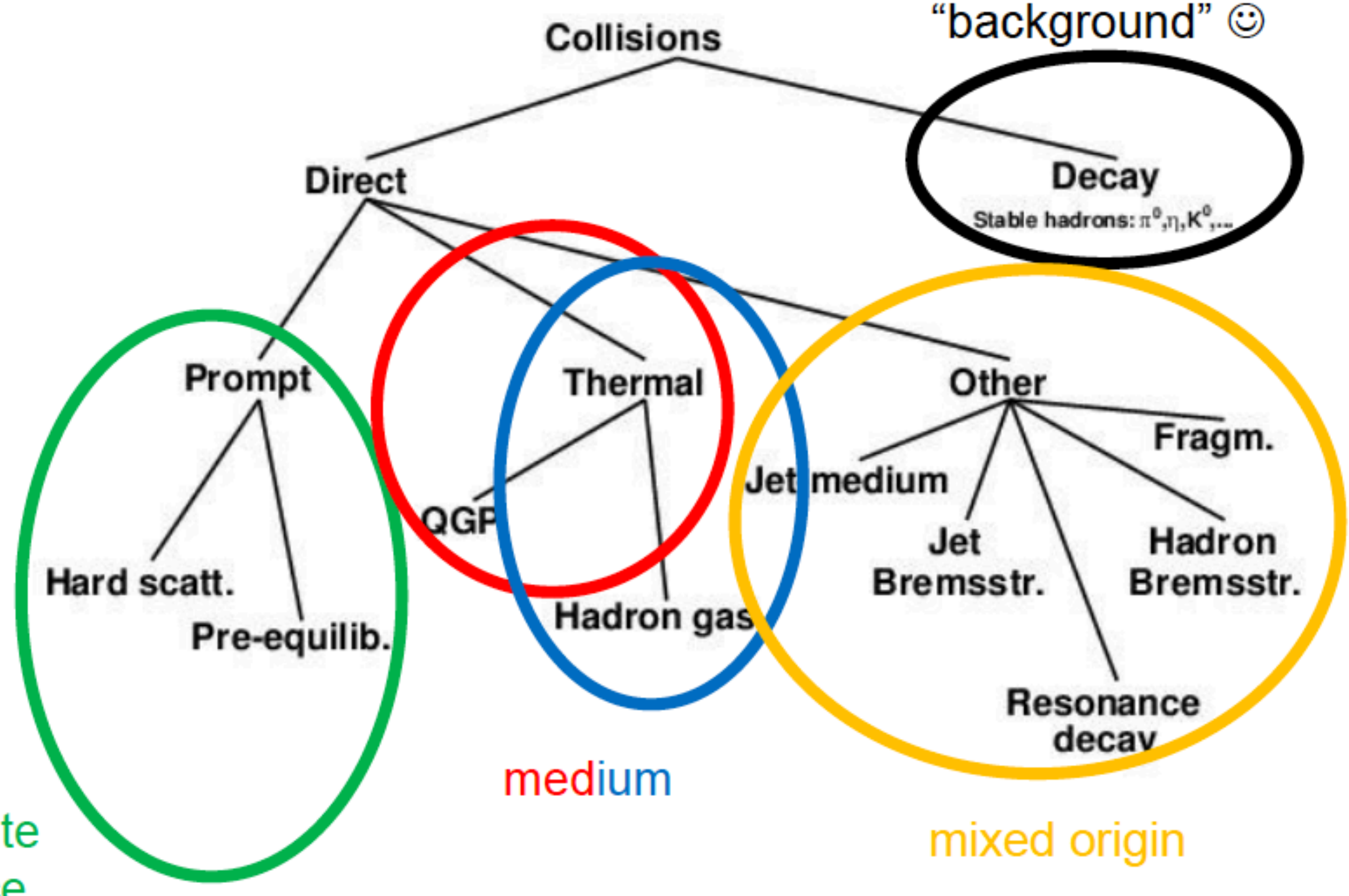
Introduction

1. Direct photons, general overview
2. Direct photon puzzle
3. Examples of GS: DIS and pp
4. GS in Heavy Ions - charged particles
5. Photons: advantages and disadvantages
6. Photons and Glasma
7. Data
8. GS for photons
9. End

Nomenclature

About 90% of all "background" ☺



Collisions

Direct

Decay

Stable hadrons: $\pi^0, \eta, K^0, \ldots$

Prompt

Hard scatt.

Pre-equilib.

Thermal

QGP

Hadron gas

Other

Jet medium

Jet Bremsstr.

Fragm.

Hadron Bremsstr.

Resonance decay

Initial state reference

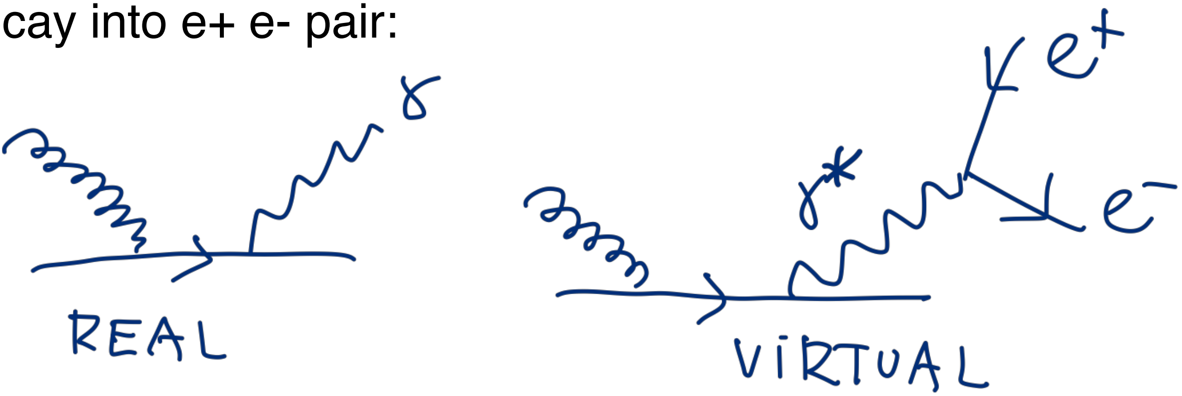
medium

mixed origin

Measurement principle

- virtual photon method

any real production process has an associated virtual photon production with subsequent decay into e+ e- pair:



$$\frac{d^2 n_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)\boxed{S}\,dn_\gamma$$

Measurement principle

- virtual photon method

any real production process has an associated virtual photon production with subsequent decay into e+ e- pair.

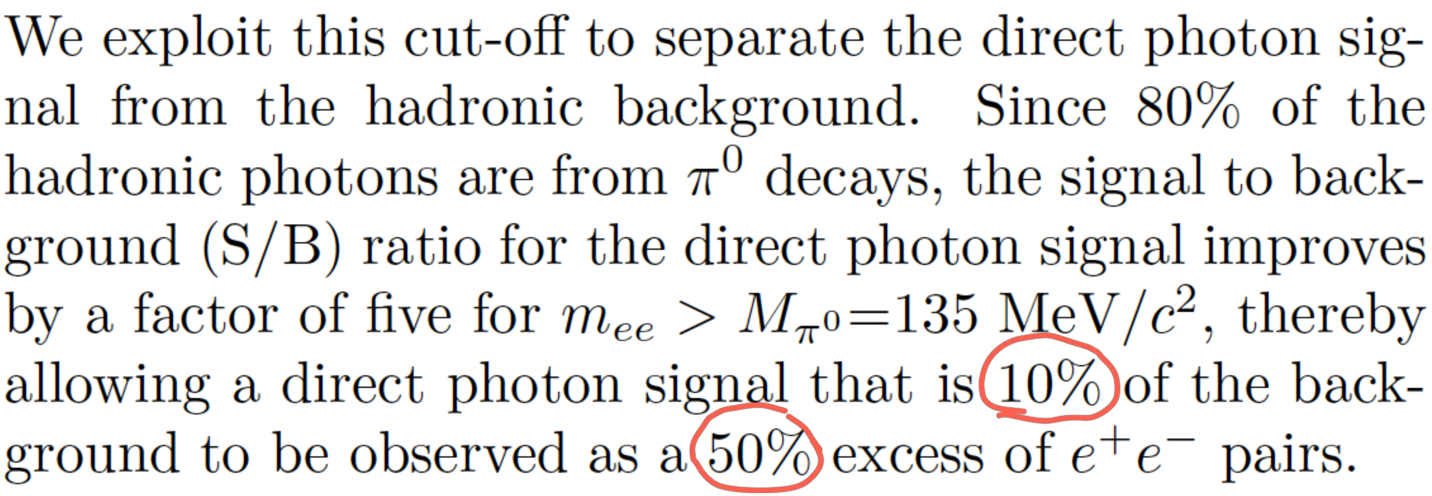
S is process dependent, helps to distinguish photons from meson decays (mostly pions):

$$S = |F(m_{ee}^2)|^2 (1 - \frac{m_{ee}^2}{M_h^2})^3$$

$$\frac{d^2 n_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi} \frac{1}{m_{ee}} \sqrt{1 - \frac{4m_e^2}{m_{ee}^2}} \left(1 + \frac{2m_e^2}{m_{ee}^2}\right) \boxed{S} dn_\gamma$$

Measurement principle

- virtual photon method



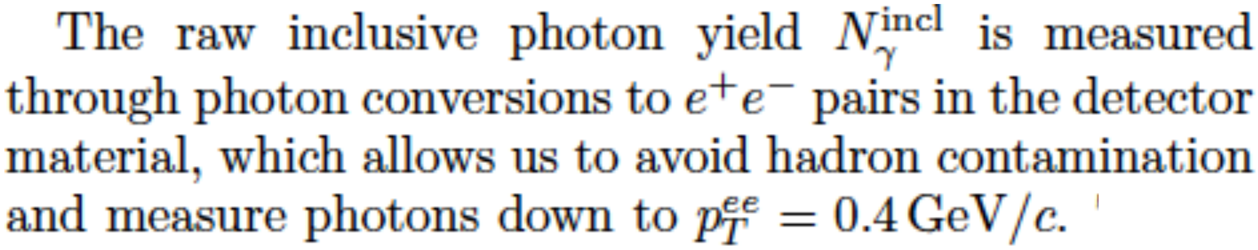
We exploit this cut-off to separate the direct photon signal from the hadronic background. Since 80% of the hadronic photons are from π^0 decays, the signal to background (S/B) ratio for the direct photon signal improves by a factor of five for $m_{ee} > M_{\pi^0}$=135 MeV/c^2, thereby allowing a direct photon signal that is 10% of the background to be observed as a 50% excess of e^+e^- pairs.

PHENIX Collaboration Apr 2008. 6 pp.
Published in Phys.Rev.Lett**. 104 (2010) 132301**

$$S = |F(m_{ee}^2)|^2(1 - \frac{m_{ee}^2}{M_h^2})^3$$

Measurement principle

- external conversion method

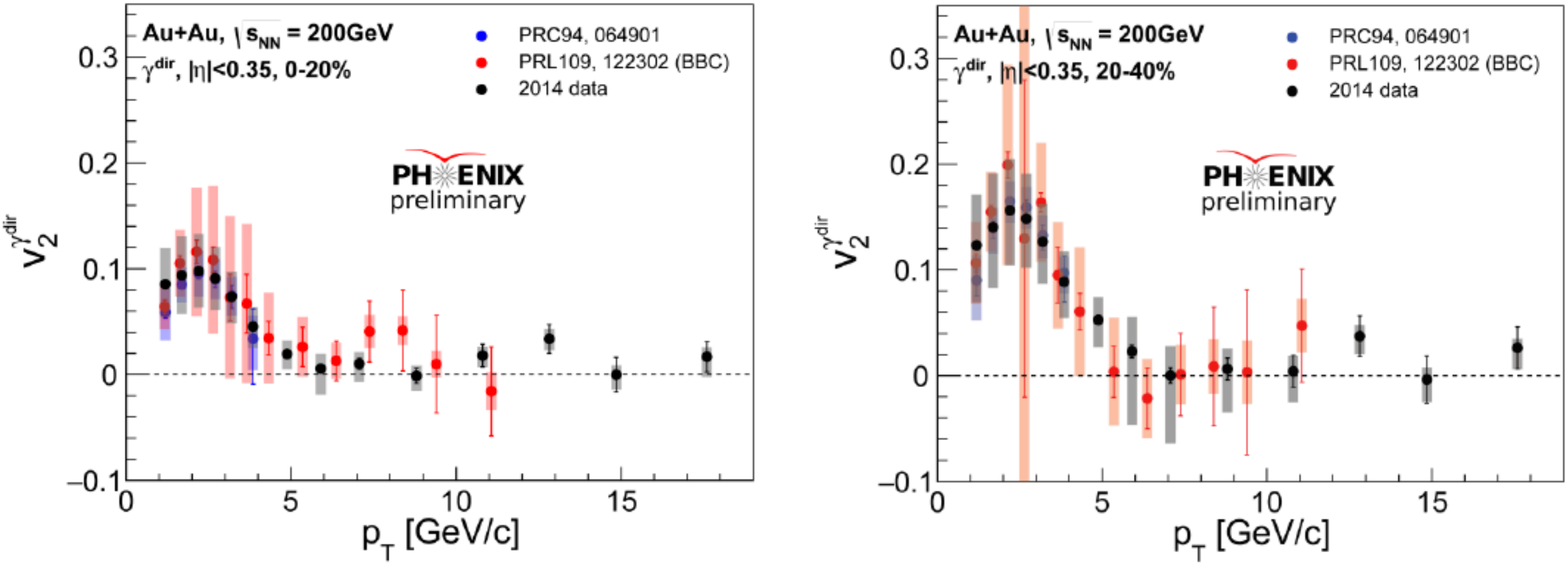


The raw inclusive photon yield N_γ^{incl} is measured through photon conversions to e^+e^- pairs in the detector material, which allows us to avoid hadron contamination and measure photons down to $p_T^{ee} = 0.4\,\text{GeV}/c$.

PHENIX Collaboration
Published in Phys.Rev. C91 (2015) no.6, 064904

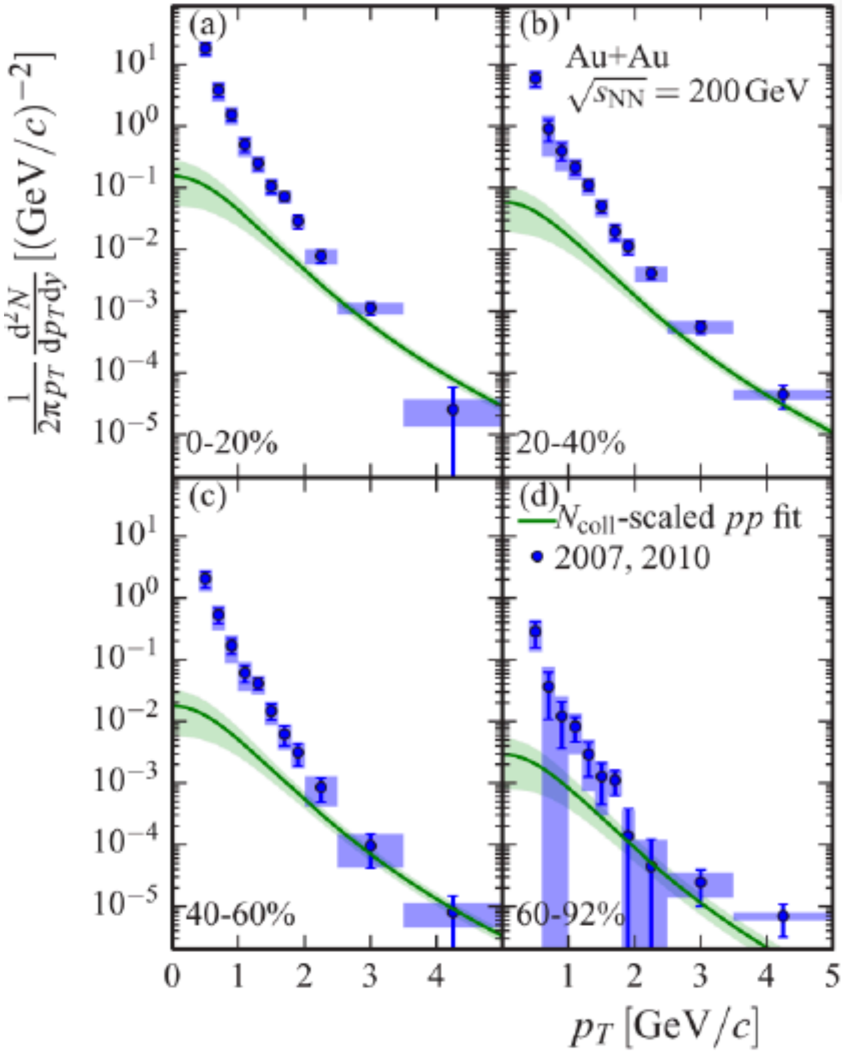
Distinction between direct photons and photons from hadron decays (mainly from pions) is done by different cuts with the help of MC simulations

Direct photon flow



Direct photon spectra

The plots are from PRC 91, 064904

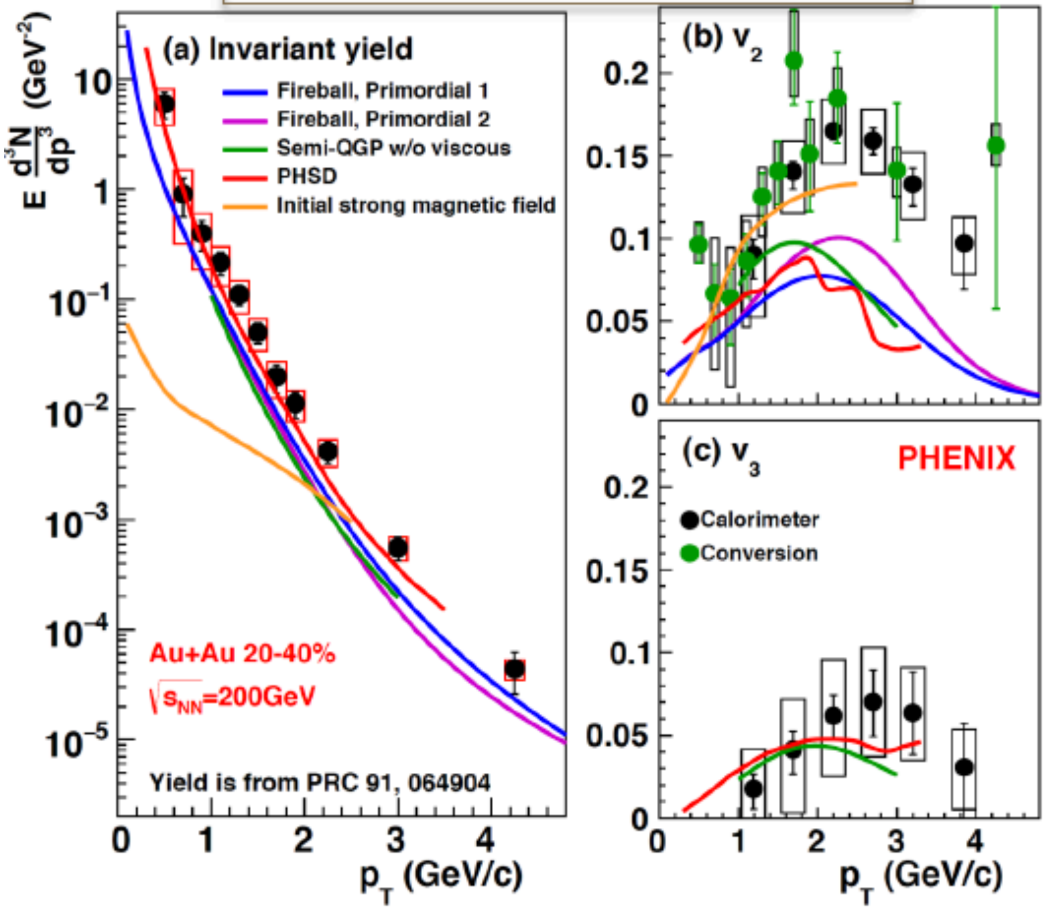


Direct photon puzzle

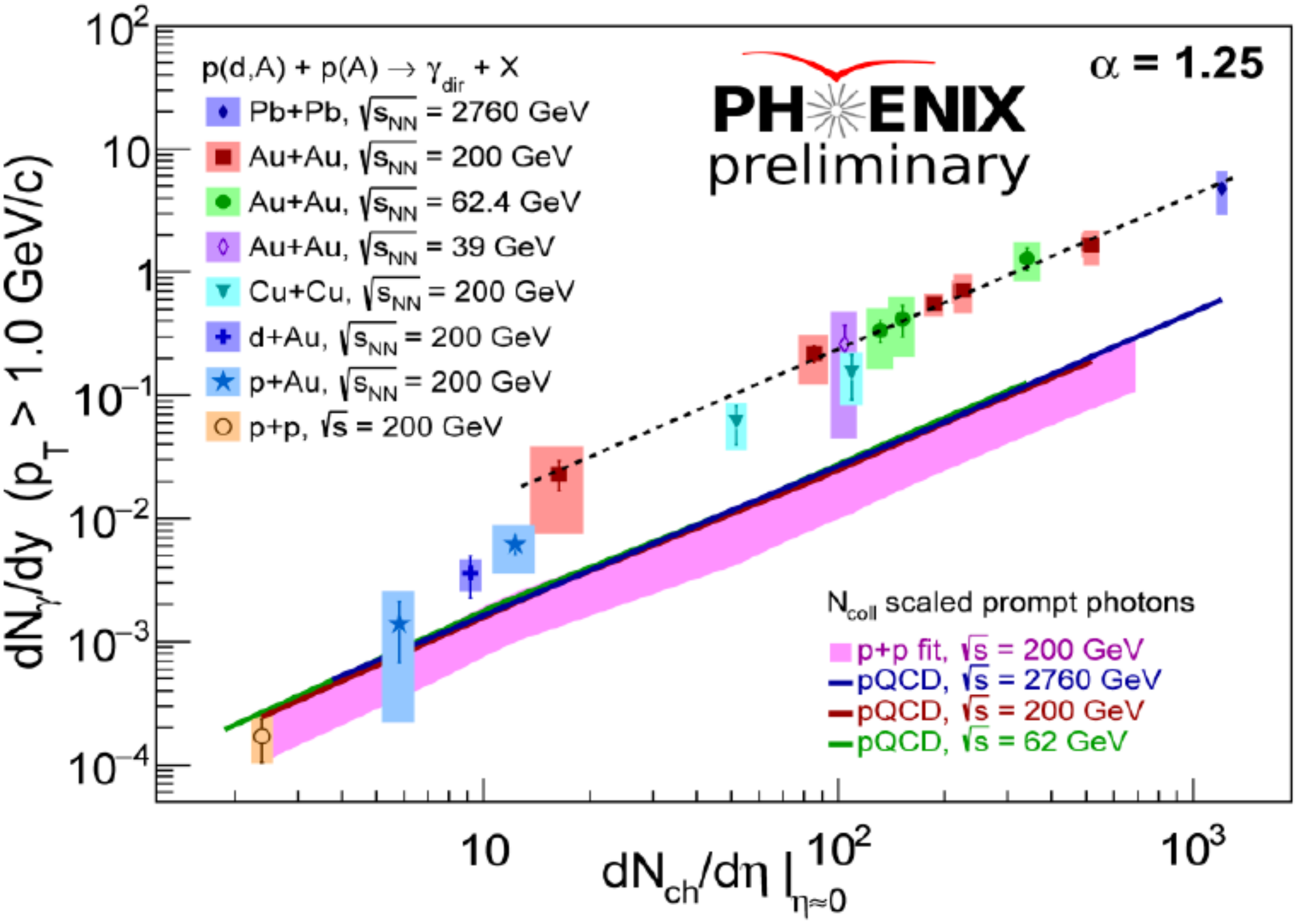
Large yield from early emission ?

Large v_2 from late emission ?

The plots are from PRC 94, 064901 (2016)



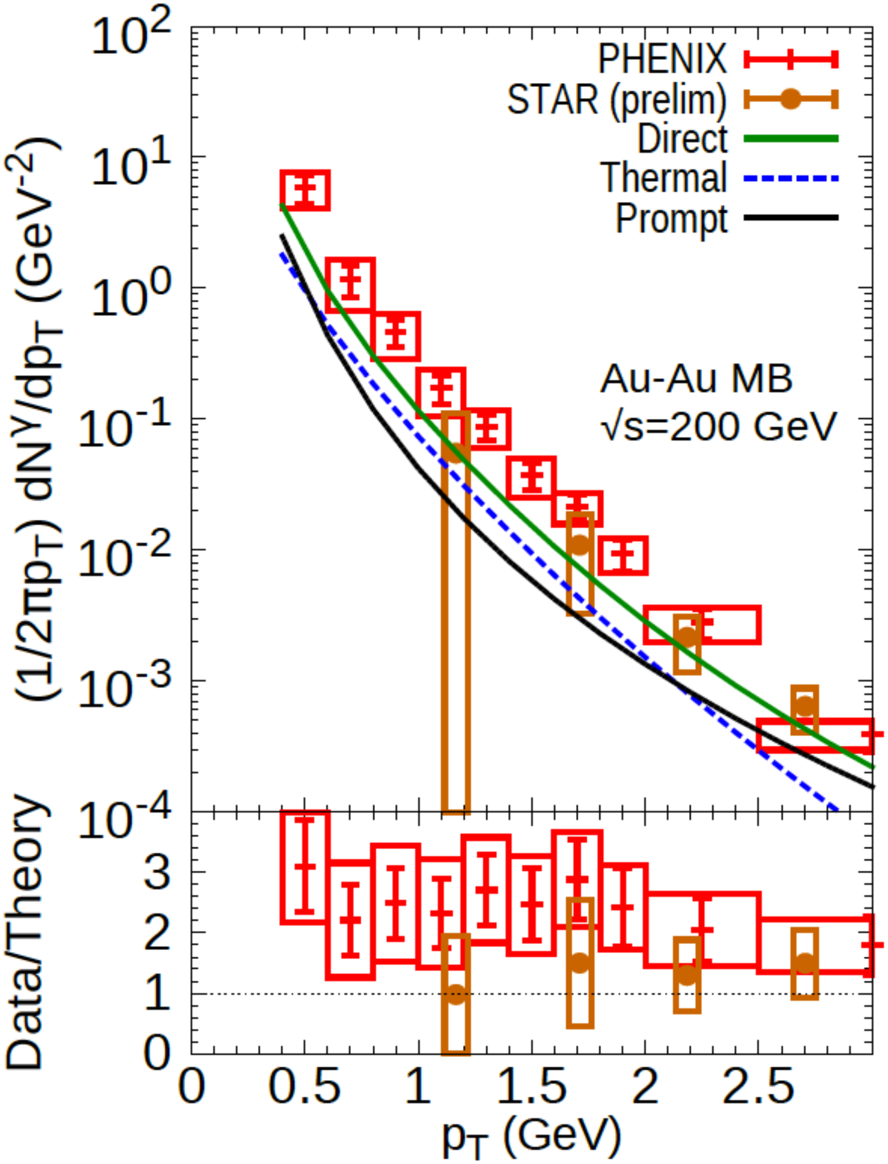
Direct photon scaling with centrality



PHENIX vs. STAR

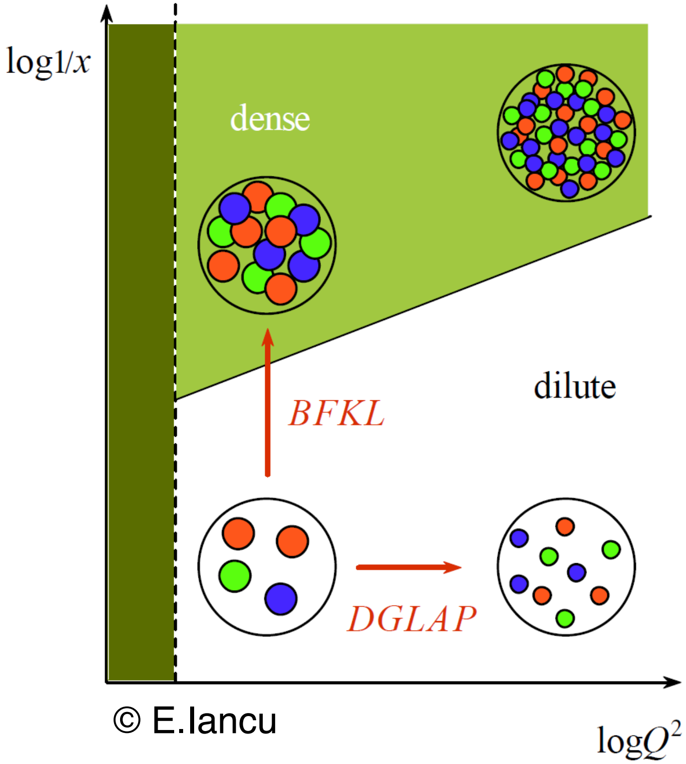
STAR and PHENIX photons are currently incompatible, even considering uncertainty bounds

Charles Gale (McGill)
12th International Workshop on High-pT Physics in the RHIC/LHC Era (HPT 2017)



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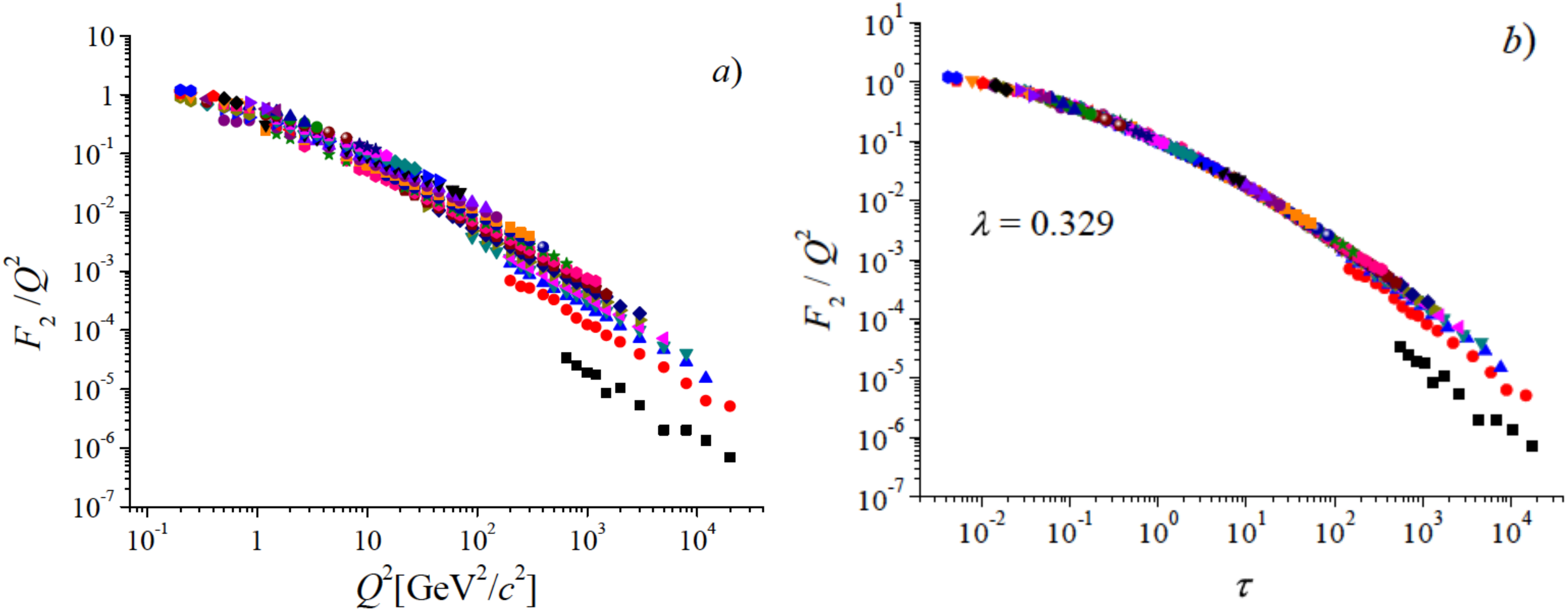
$$Q_s(x) = Q_0 \left(\frac{1}{x}\right)^{\lambda/2}$$

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

It has been for the firs time observed in DIS

GS at DIS



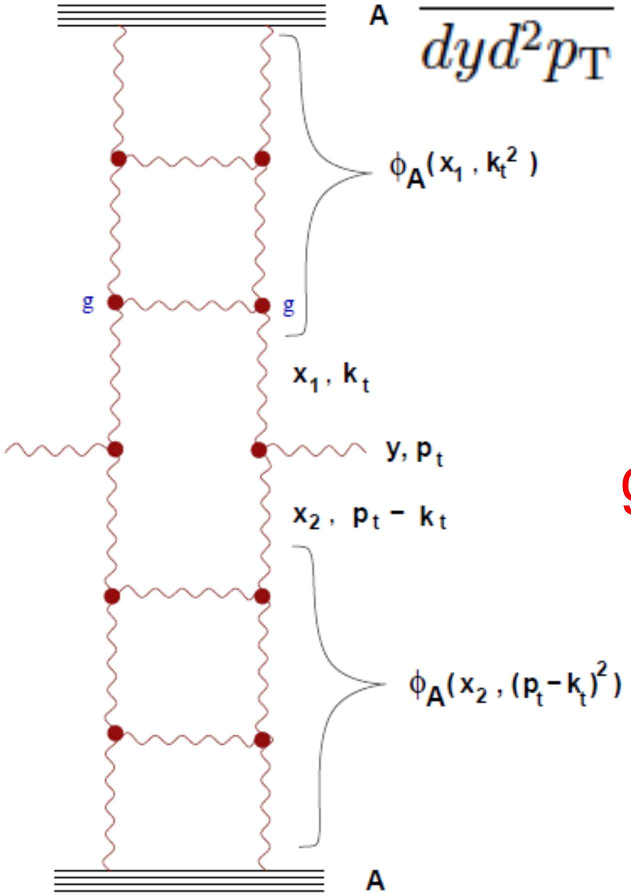
$$\tau = \frac{Q^2}{Q^2_{\rm sat}(x)} \quad Q^2_{\rm sat}(x) = Q_0^2 \left(\frac{x}{x_0}\right)^{-\lambda}$$

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

GS in pp

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

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



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

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.

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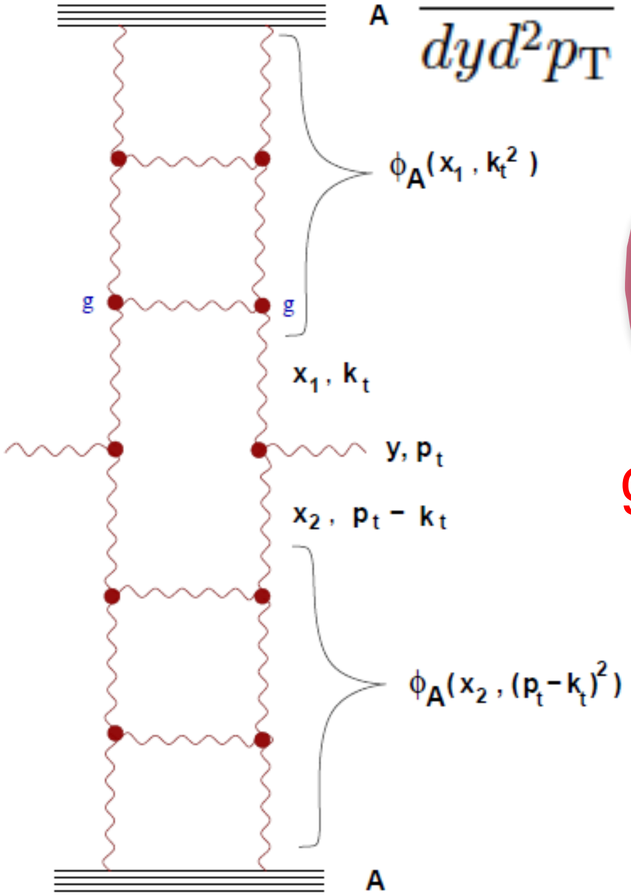

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$$\boxed{\varphi(x, \vec{k}_T^2) = \varphi(\vec{k}_T^2 / Q_{\rm sat}^2(x))}$$

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Basics of geometrical scaling

gluon distribution unintegrated glue

$$xG(x,Q^2) = \int^{Q^2} dk_{\mathrm{T}}^2\, \varphi(x,k_{\mathrm{T}}^2)$$

Golec-Biernat – Wuesthoff (DIS)

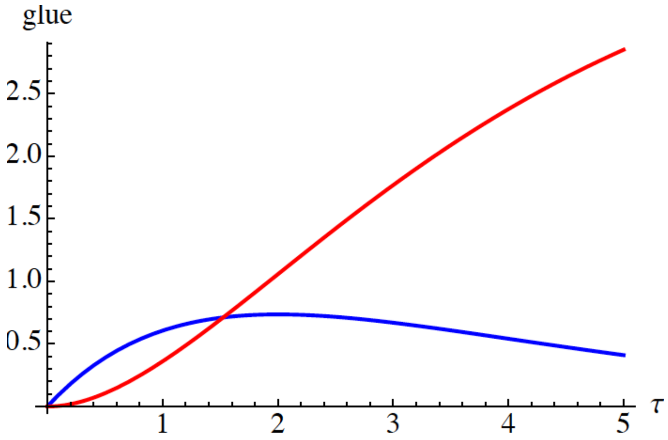
$$\varphi(x,k_{\mathrm{T}}^2) = S_\perp \frac{3}{4\pi^2}\frac{k_{\mathrm{T}}^2}{Q_{\mathrm{s}}(x)^2}\exp\left(-k_{\mathrm{T}}^2/Q_{\mathrm{s}}(x)^2\right)$$

$$S_\perp = \sigma_0$$

Kharzeev – Levin (AA)

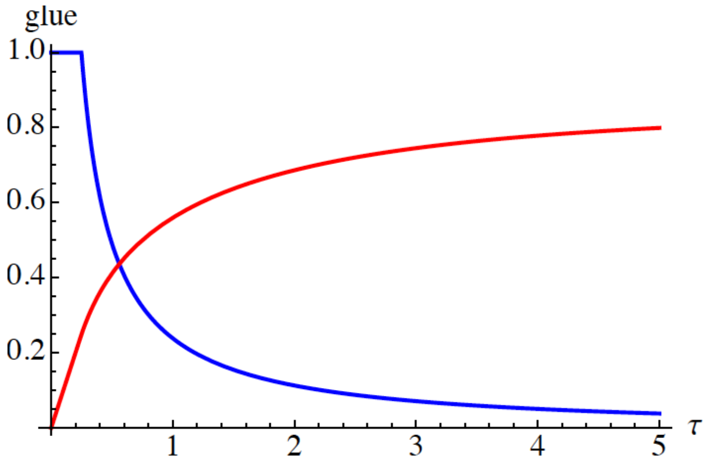
$$\varphi(x,k_{\mathrm{T}}^2) = S_\perp \begin{cases} 1 & \text{for} \quad k_{\mathrm{T}}^2 < Q_{\mathrm{s}}(x)^2 \\ Q_{\mathrm{s}}(x)^2/k_{\mathrm{T}}^2 & \text{for} \quad Q_{\mathrm{s}}(x)^2 < k_{\mathrm{T}}^2 \end{cases}$$

$S_\perp$ is the transverse size given by geometry



scaling variable

$$\tau = \frac{p_{\mathrm{T}}^2}{Q_s^2(x)}$$



Why there is GS in pp?

Strictly speaking GS is a property of unintegrated gluon distribution. This is why we see direct GS in inclusive DIS.

Gluons freed in a pp collision are expected to scale. However particles are produced by non-perturbative fragmentation, radiation, resonance decays, undergo final state interactions, which could in principle destroy GS.

Even more so in heavy ion collisions, where scaling of gluon distribution is a property of the initial state that is followed by glasma and plasma evolution, freezout, etc.

Nevertheless, GS has been observed in HI, however of lesser quality.

GS in HI: centrality dependence

$$\frac{dN_{\rm ch}}{dy\,dp_{\rm T}^2} = S_\perp \mathcal{F}(\tau)$$

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

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

Triggering off fixed transverse area by selecting centrality classes.

Scaling of the saturation scale:

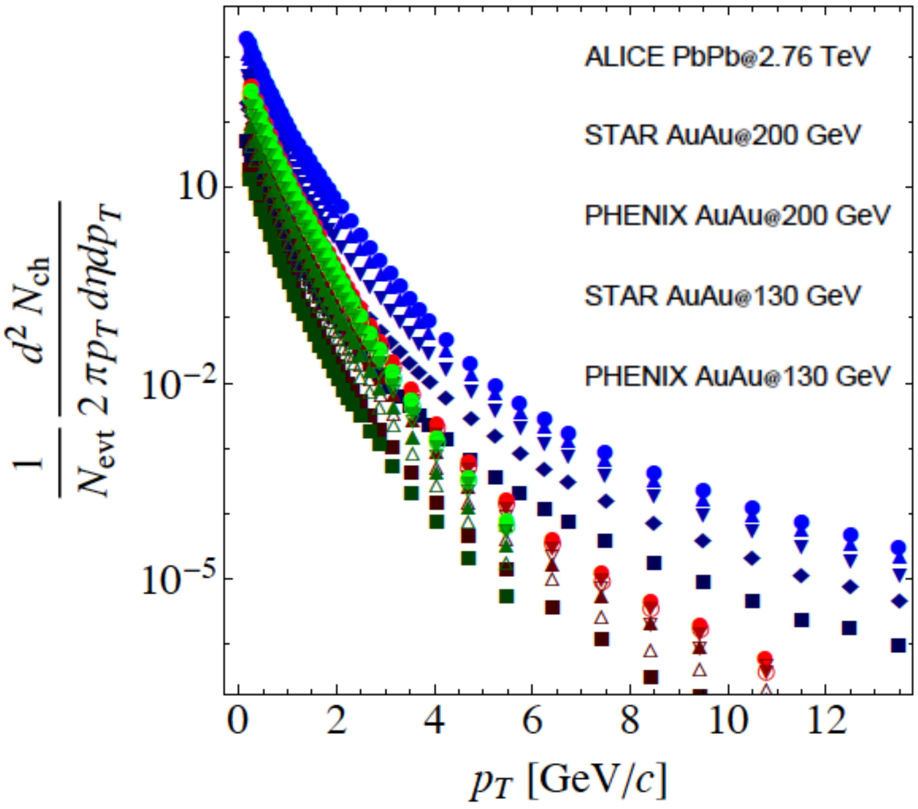
$$Q_s^2(x) = \frac{\kappa}{S_\perp}\frac{dN}{dy} \sim N_{\rm part}^{1/3}\left(\frac{\sqrt{s}}{p_{\rm T}}\right)^{\lambda}$$

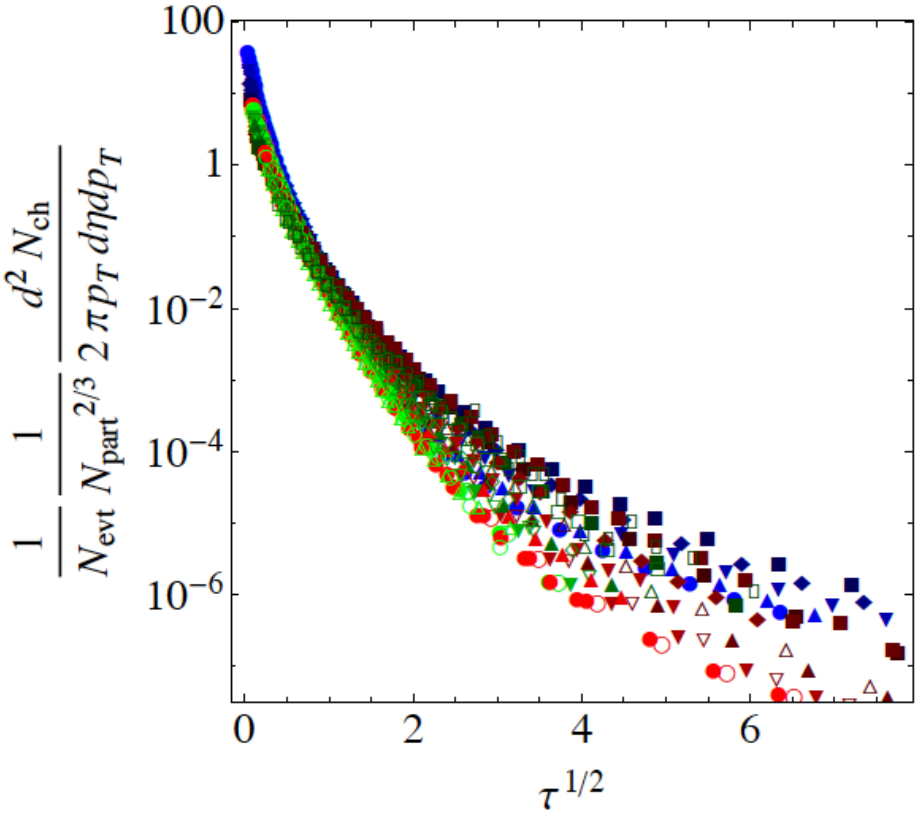
$$\boxed{\frac{Q_0^2}{N_{\rm part}^{2/3}}\,\frac{dN_{\rm ch}}{2\pi p_{\rm T}\,d\eta\,dp_{\rm T}} = F(\tau)}$$

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

participant scaling
and
energy scaling

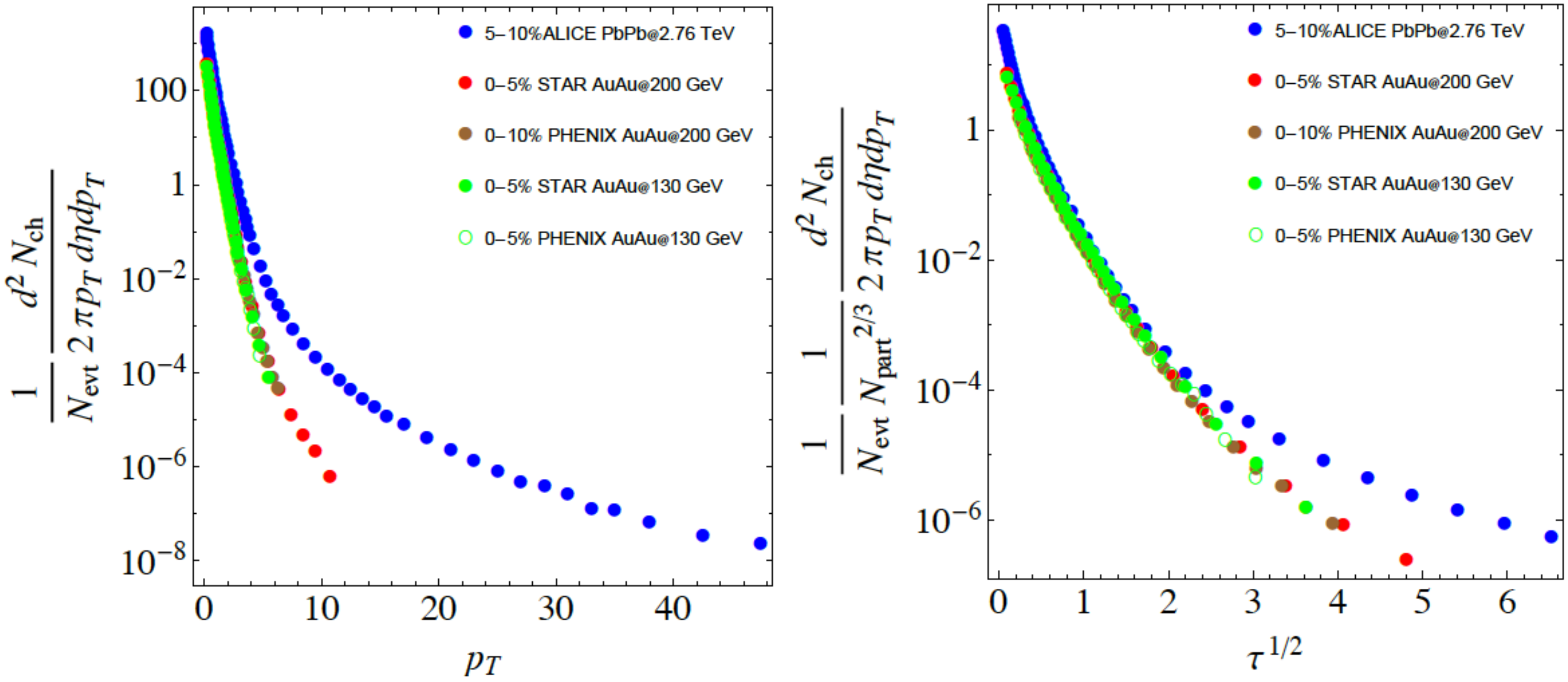
Charged particles GS in HI





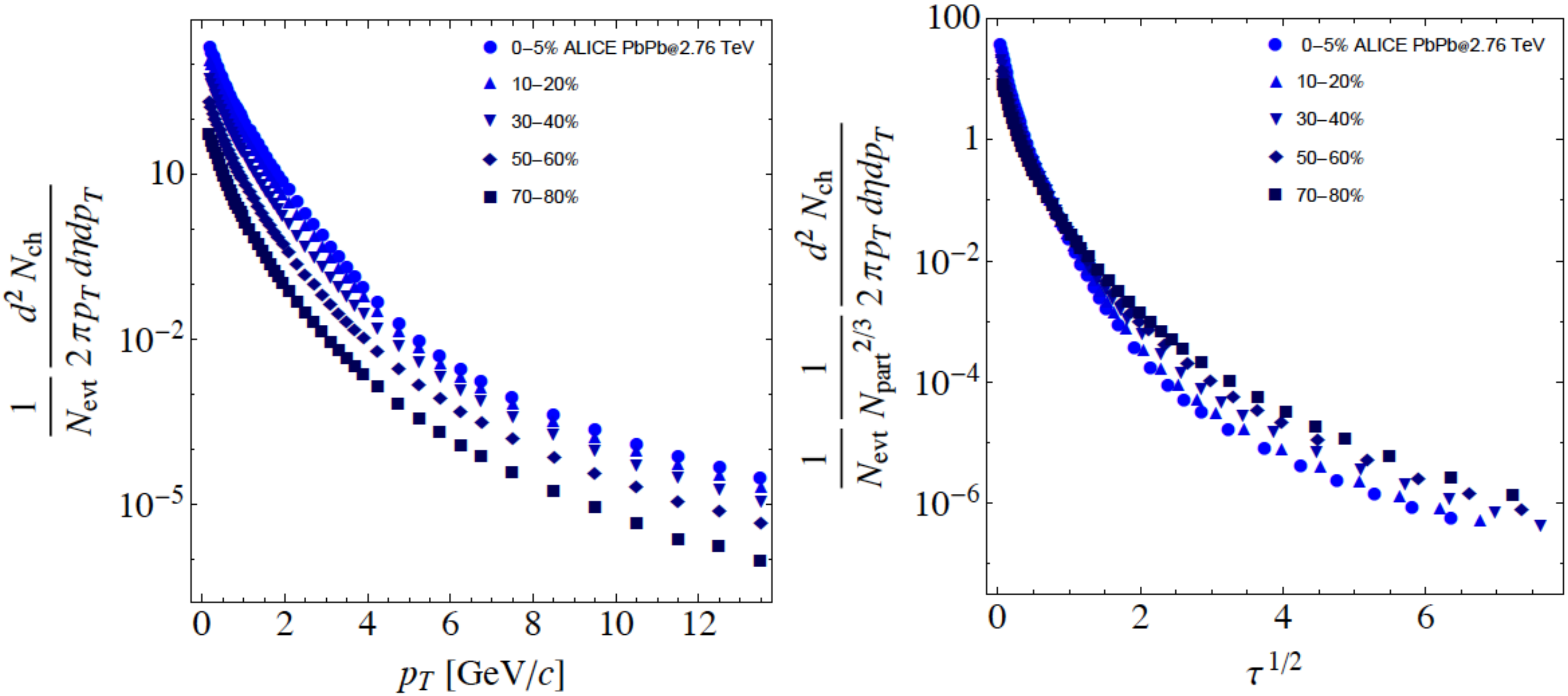
B. Abelev et al. [ALICE Collaboration], Phys. Lett. B 720, 52 (2013)
J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 91, 172302 (2003)
C. Adler et al. [STAR Collaboration], Phys. Rev. Lett. 89, 202301 (2002)
S. S. Adler et al. [PHENIX Collaboration], Phys. Rev. C 69, 034910 (2004)
K. Adcox et al. [PHENIX Collaboration], Phys. Rev. Lett. 88, 022301 (2002)

Energy Scaling in HI



energy scaling works quite well, why?

Centrality Scaling in HI



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.

So far 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)

CGC and photons

- Initially two sheets of CGC collide and produce Glasma
- Glasma is strongly interacting GP and in the course of time QGP
- Glasma is not thermalised
- Glasma evolves into a thermalised QGP

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Simple model of Glasma

gluon distribution: $f(p) = \frac{1}{\tau S_\perp} \frac{dN_G}{d^3p}$

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Simple model of Glasma

gluon distribution:

$$f(p) = \frac{\gamma(t)}{e^{E/\Lambda(t)} - 1} \underset{\text{small } E}{\sim} \frac{\gamma(t)\Lambda(t)}{E} = \frac{1}{\alpha_\mathrm{s}} \frac{\Lambda_\mathrm{IR}(t)}{E} \gg 1$$

$$\rightarrow \gamma(t) = \frac{1}{\alpha_\mathrm{s}} \frac{\Lambda_\mathrm{IR}(t)}{\Lambda(t)} = \frac{1}{\alpha_\mathrm{s}} \frac{\Lambda_\mathrm{IR}(t)}{\Lambda_\mathrm{UV}(t)}$$

CGC, Glasma and photons

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$$\text{initially: } \gamma(t_{\mathrm{in}}) = \frac{1}{\alpha_s} \rightarrow \Lambda_{\mathrm{IR}}(t_{\mathrm{in}}) = \Lambda_{\mathrm{UV}}\,(t_{\mathrm{in}}) \sim Q_{\mathrm{sat}}$$

$$\text{thermalization: } \gamma(t_{\mathrm{therm}}) = 1 \rightarrow \Lambda_{\mathrm{IR}}(t_{\mathrm{therm}}) = \alpha_s \Lambda_{\mathrm{UV}}\,(t_{\mathrm{therm}})$$

CGC, Glasma and photons

More generally at $E = \Lambda_{\mathrm{UV}}$: $f(\Lambda_{\mathrm{UV}}) \sim 1$

This means that Λ_{UV} is the momentum scale up to which $f(p)$ is substantially larger than zero. This corresponds to volume

$$V \sim \frac{1}{{\Lambda_{\mathrm{UV}}}^3}$$

Number density of gluons at early times

$$\rho \sim \frac{1}{\alpha_{\mathrm{s}}} \frac{\Lambda_{\mathrm{IR}}}{\Lambda_{\mathrm{UV}}} \times \frac{1}{V} = \frac{1}{\alpha_{\mathrm{s}}} \Lambda_{\mathrm{IR}} {\Lambda_{\mathrm{UV}}}^2$$

CGC, Glasma and photons

For quarks we assume that Λ_{UV} is the same as for gluons

$$f_{\mathrm{q}}(p) = \frac{1}{e^{E/\Lambda_{\mathrm{UV}}(t)} + 1}$$

Number density of quarks

$$\rho_{\mathrm{q}} \sim {\Lambda_{\mathrm{UV}}}^3$$

and we have

$$\frac{\rho_{\mathrm{q}}}{\rho} \sim \alpha_{\mathrm{s}} \frac{\Lambda_{\mathrm{UV}}}{\Lambda_{\mathrm{IR}}} \text{ changes with time as } \quad \alpha_{\mathrm{s}} \to 1$$

Photons 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.

Direct photons in HI - data

1. PHENIX (preprint 2008, paper 2010) Au+Au @ 200 GeV, invariant yields in two centrality classes 0-20% and 20-40%, MB , and pp x-section for pT < 5 Gev/c. Superseded by 2.

2. PHENIX (2015) Au+Au @ 200 GeV, invariant yields in four centrality classes 0-20%, 20-40%, 40-60%, 60-92%.

3. PHENIX (2012) d+Au and also p+p @ 200 GeV, x-sections to be converted to multiplicities dividing with pp inel = 42 mb and dAu inel = 2:26 0:10 b.

4. Moriond 2018 talk by Y. Yamaguchi (PHENIX) includes new data: Cu+Cu @200 GeV, MB and 0-40%, Au+Au 39 GeV, MB, @ 62.4 GeV 0-20%, 20-40%, MB, arXiv:1805.04084 [hep-ex]

5. ALICE 2013 (preprint 2012) Pb+Pb @ 2.76 TeV: 0-40%, 40-80%, conference paper.

6. ALICE 2016 (preprint 2015) Pb+Pb @ 2.76 TeV: 0-20%, 20-40% and 40-80%.

Direct photons in HI - GS

$$S_{\perp} \sim N_{\text{part}}^{\delta}$$

From geometric considerations $\delta = 2/3$

Scaling multipicity spectra:

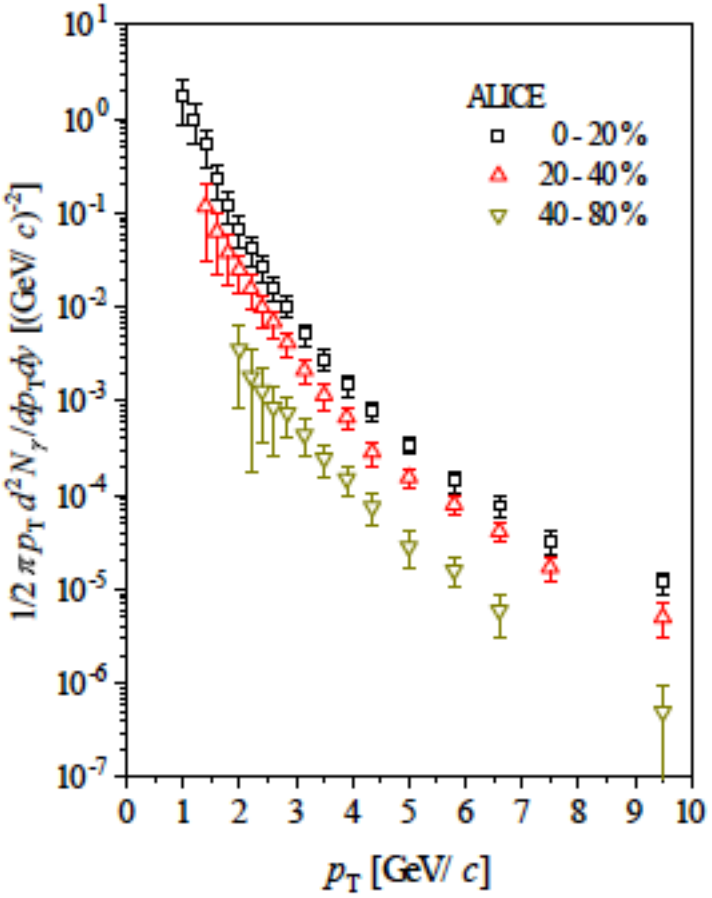
$$\frac{1}{N_{\text{part}}^{\delta}} \frac{dN_{\gamma}}{N_{\text{evt}}\, 2\pi p_{\text{T}}\, d\eta dp_{\text{T}}} = \frac{1}{Q_0^2} \mathcal{F}(\tau)$$

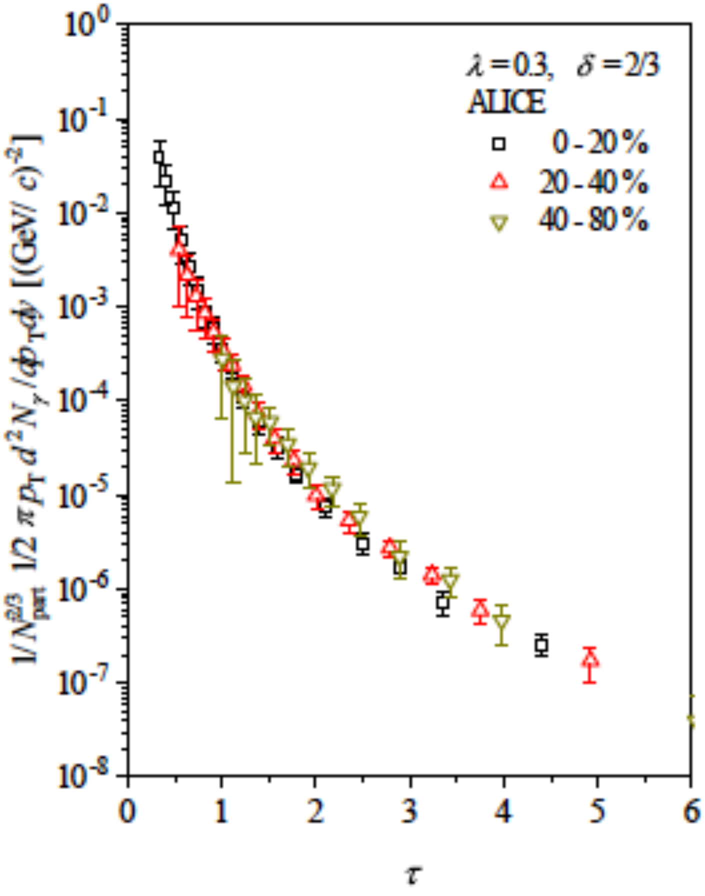
where scaling variable is:

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

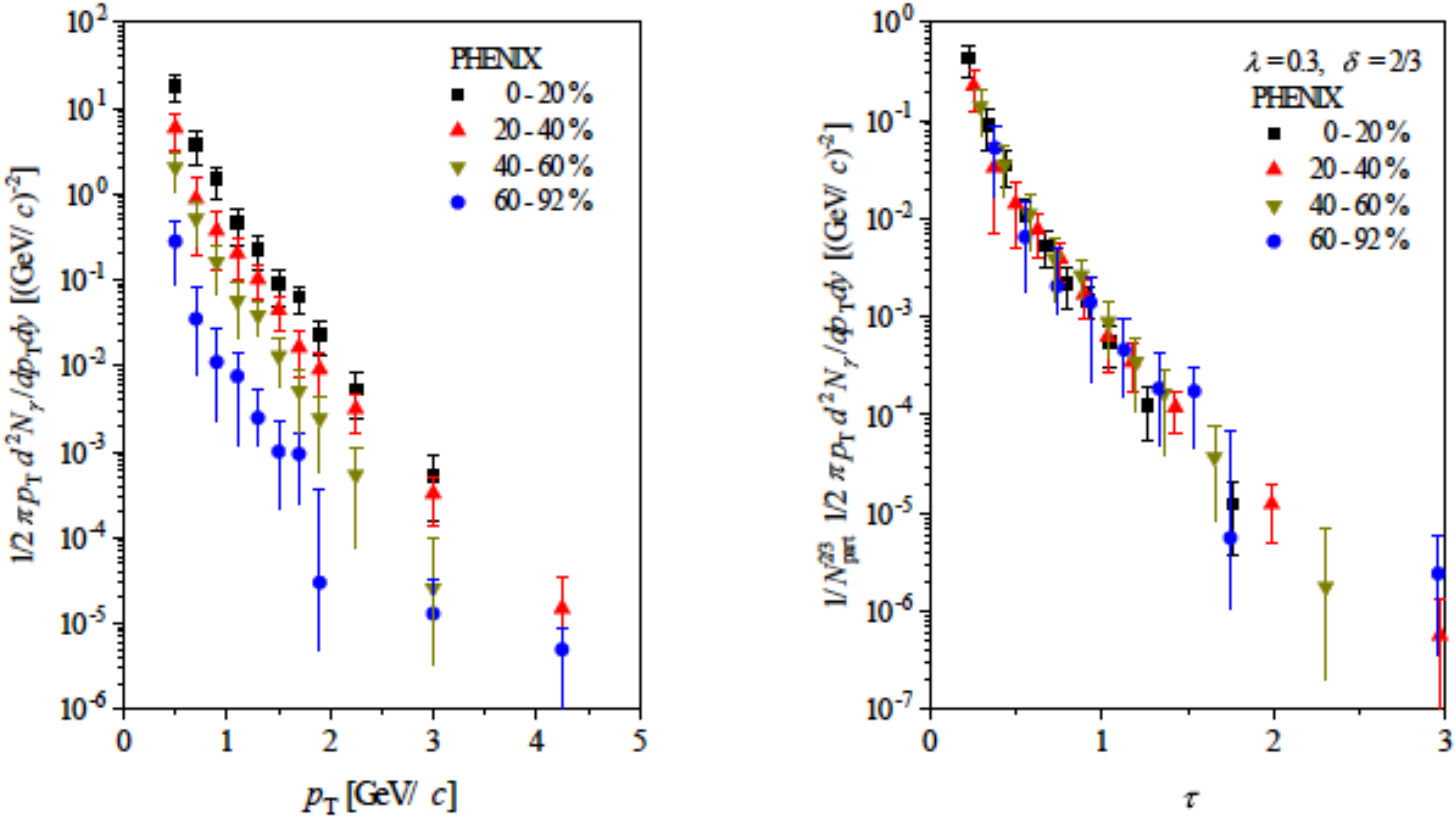
Again,
we can test N_{part} scaling (δ)
and
energy scaling (λ)

N_{part} scaling in ALICE

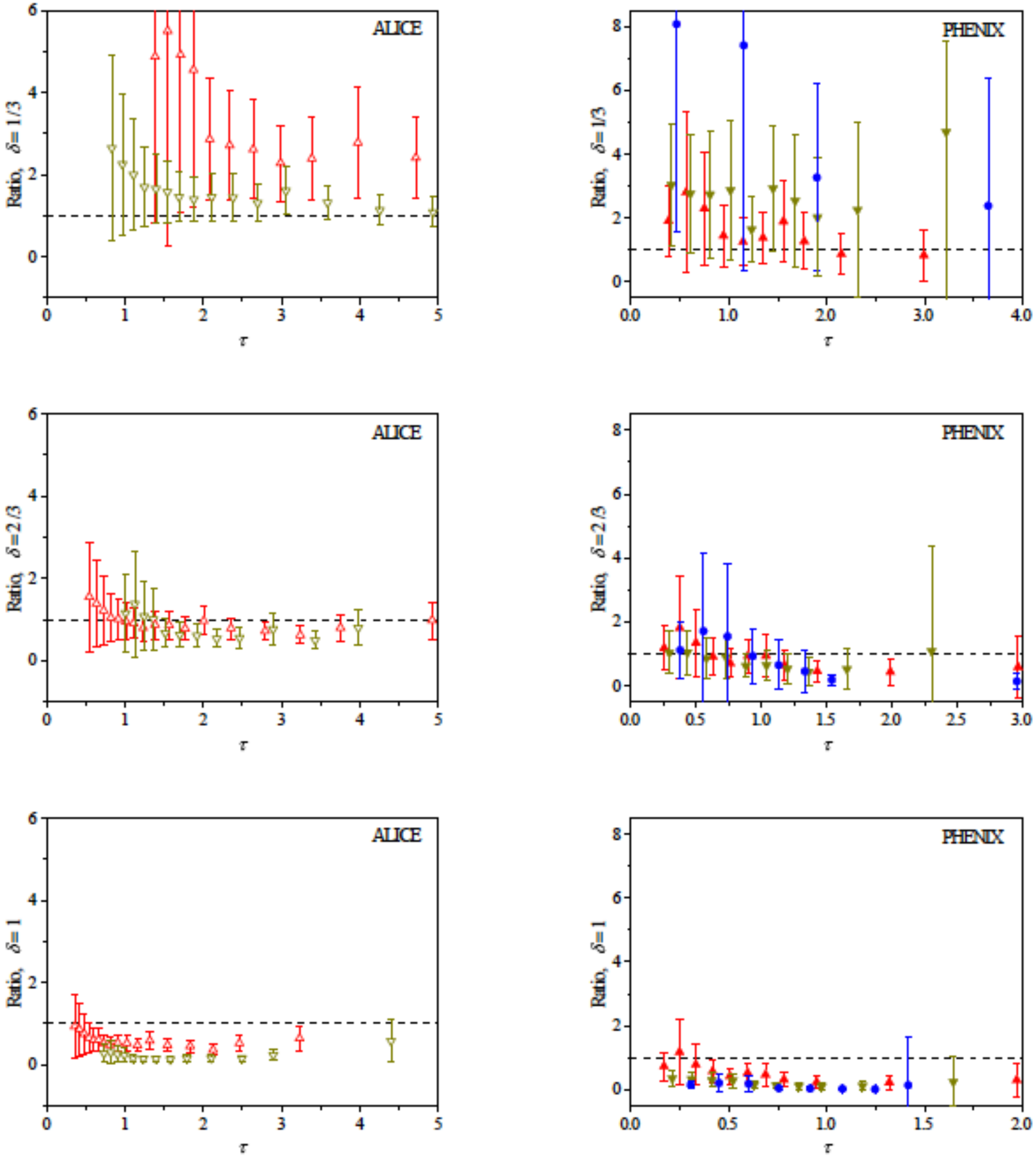




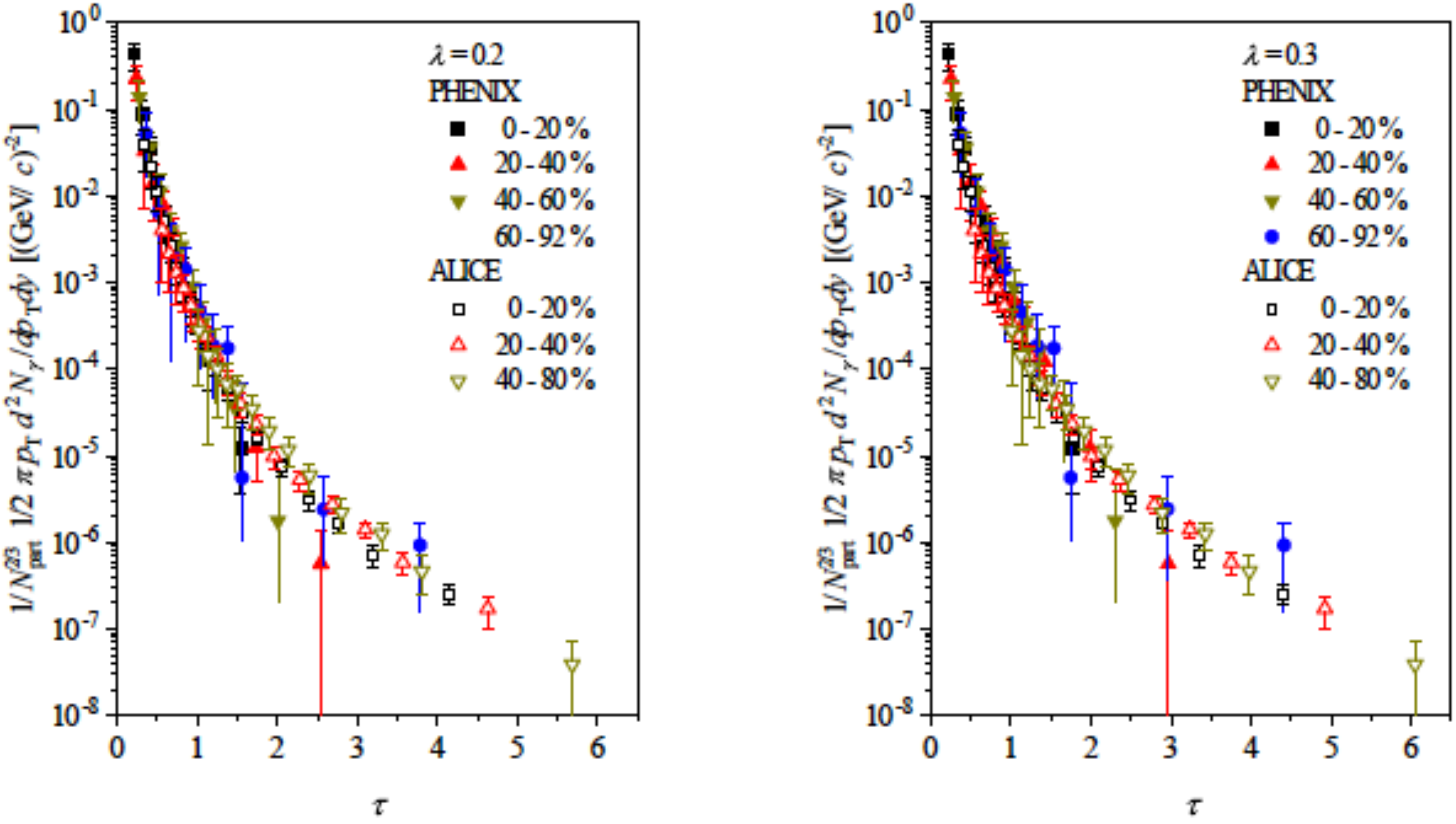
N_{part} scaling in PHENIX



Ratios of the highest centrality class to the available lower centrality classes for different values of δ



N_{part} and energy scaling



More data at different energies is needed to get meaaningful constraint on λ

Summary and outlook

- GS is the property of gluons due to the nonlinear evolution
- saturation scale emerges, GS holds when no other scales interfer
- in inclusive DIS GS is a direct consequence of NL evolution
- in hadronic collision gluon properties are transferred to particles
- ratios of of spectra are a good tool to look for GS
- in HI we can test scaling in energy (λ)
- in HI we can test scaling in #participants (δ)
- direct photons test initial stages in HI collisions and Glasma evolution
- direct photons come from quarks, nevertheless exhibit GS
- more data will be shortly analysed