포화 그리고 기하학적 스케일링

미할 프라샬로비츠

야게로냔 대학, 크라코프, 폴란드

제주도, 1.9.2016.

Saturation and geometrical scaling

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M. Smoluchowski Inst. of Physics

Jagiellonian University, Kraków, Poland

Jeju Island 1.9.2016.

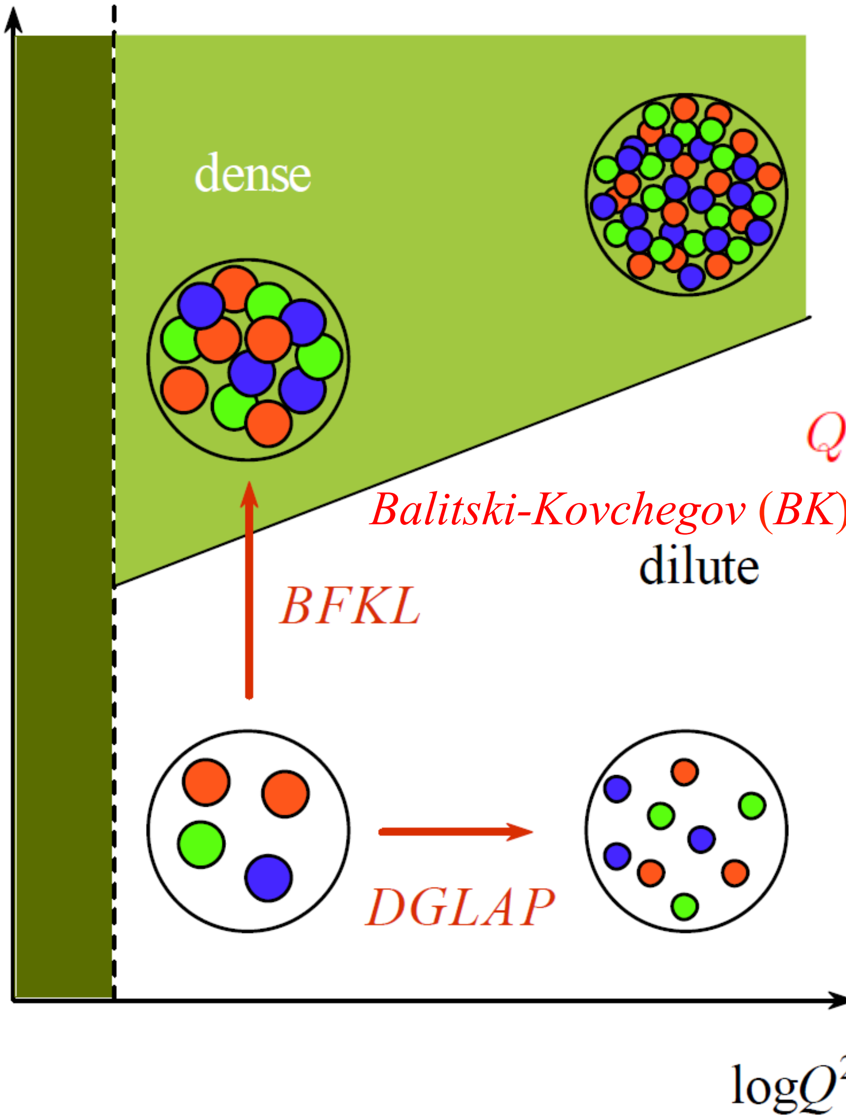
DGLAP vs BFKL Evolution

small x $Y = \log 1/x$
large W

Balitsky, Fadin,
Kuraev, Lipatov

Balitsky, Kovchegov

large x
small W

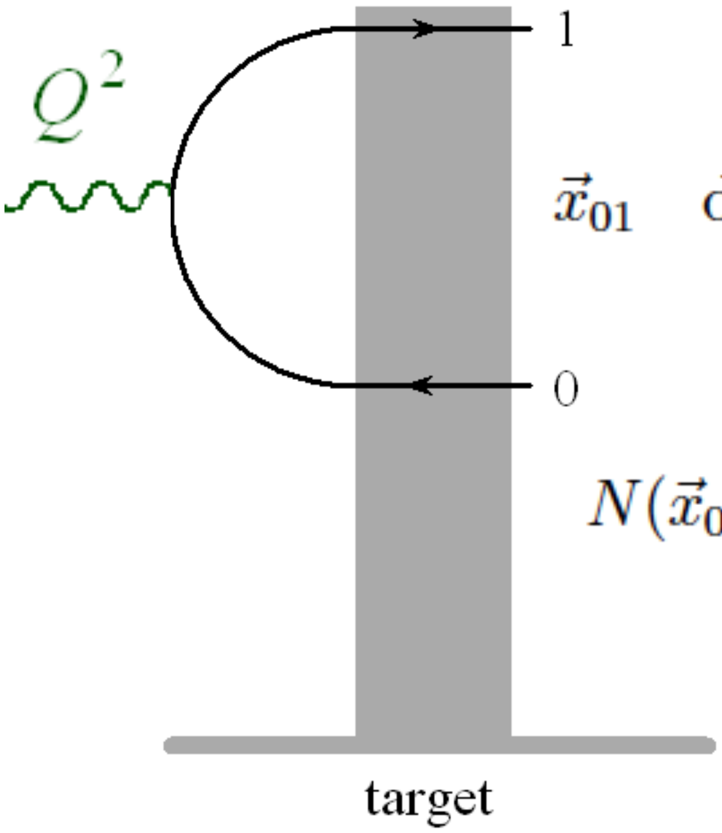


$$Q_s(x) = Q_0 \left(\frac{x_0}{x}\right)^{\lambda/2}$$

Dipole Picture

BFKL equation has very simple form and interpretation in the dipole picture of A. Mueller

A.H. Mueller and J.-w. Qiu,
Nucl. Phys. B 268 (1986) 427



$\vec{x}_{01}$ dipole transverse size $Y = \log 1/x$

$N(\vec{x}_{01}, Y)$ dipole-target forward amplitude

BK Equation

in terms of a Fourier transform: $$N(x,Y) = x^2 \int \frac{d^2\vec{k}}{2\pi} e^{i\vec{k}\cdot\vec{x}}\, \tilde{N}(k,Y)$$

$$\frac{\partial}{\partial Y}\tilde{N}(k,Y) = \overline{\alpha}_s\, \chi(-\partial/\partial \ln k^2)\, \tilde{N}(k,Y) - \overline{\alpha}_s\, \tilde{N}^2(k,Y)$$

here χ is a BFKL characteristic function

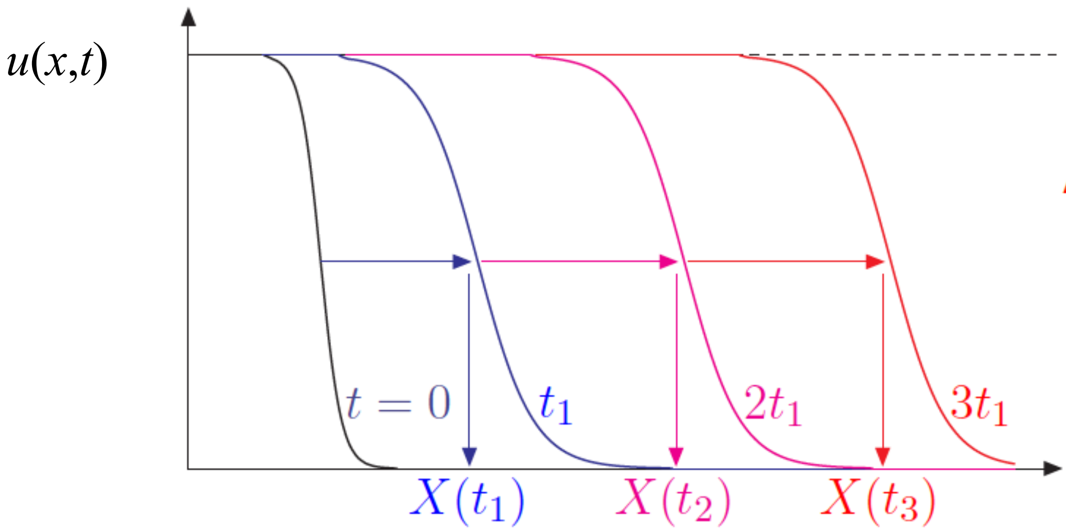
$$\chi(\gamma) = 2\psi(1) - \psi(\gamma) - \psi(1-\gamma)$$

there exists a theorem from the '30 (Fisher, Kolomogorov, Petrovsky, Piscounov) that non-linear equations of this sort have asymptotically travelling wave solutions

S. Munier, R.B. Peschanski
PRL 91 (2003) 232001
PRD 69 (2004) 034008

Travelling waves

identify time : $t = Y$, position : $x = \ln k^2$



Asymptotic solution:
travelling wave
$u(x,t) = u(x - v_c t)$

Position: $X(t) = X_0 + v_c t$ © G. Soyez

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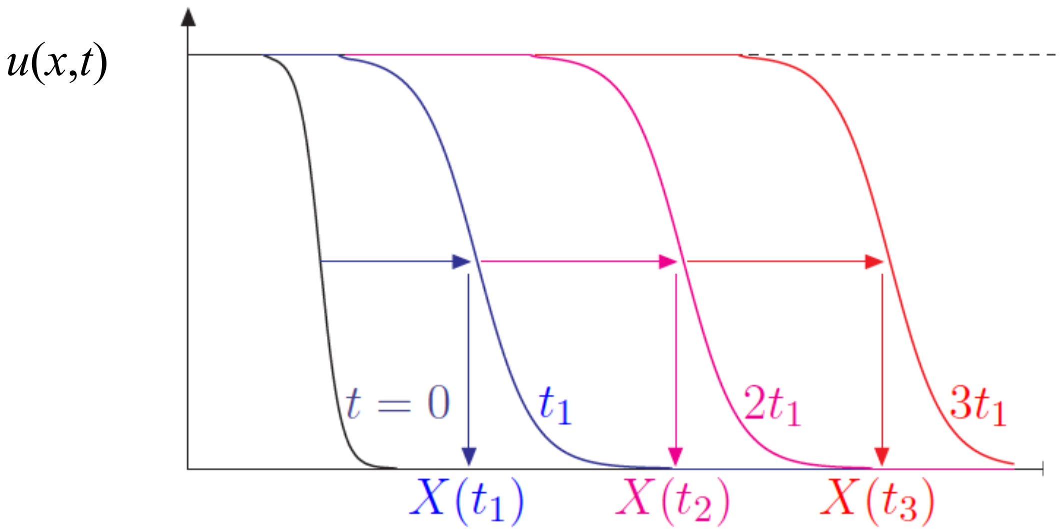

Position: $X(t) = X_0 + v_c t$ © G. Soyez

Asymptotic solution:
travelling wave

$u(x,t) = u(x - v_c t)$

$$x - v_c t = \log\left(\frac{k^2}{k_0^2}\right) - v_c \log\left(\frac{1}{x}\right)$$

$$= \log\left[k^2 \times \frac{1}{k_0^2}\left(\frac{1}{x}\right)^{-v_c}\right]$$

$$= \log\left(\frac{k^2}{Q^2_{\rm sat}(x)}\right)$$

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Travelling waves

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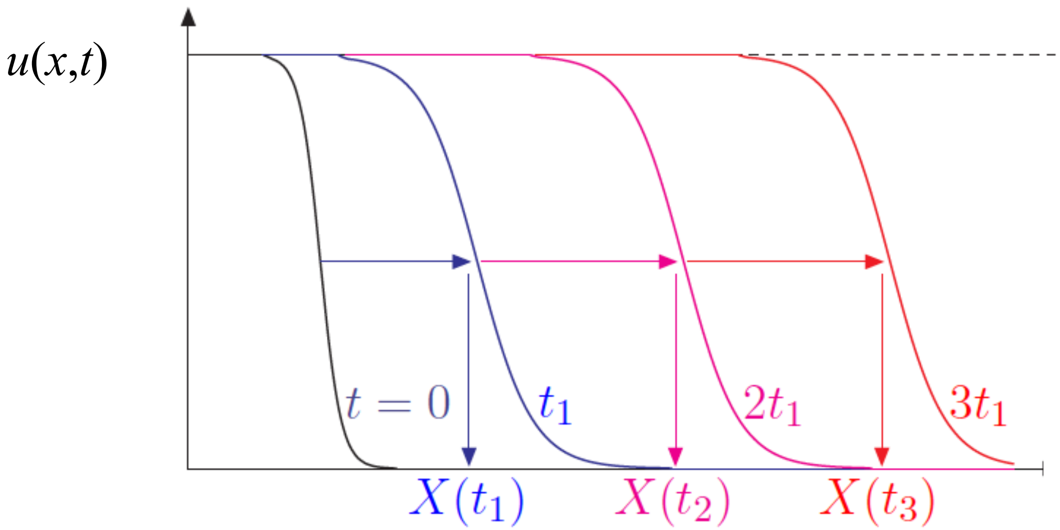


Position: $X(t) = X_0 + v_c t$ © G. Soyez

Asymptotic solution:
travelling wave

$$u(x,t) = u(x - v_c t)$$

$$Q^2_{\text{sat}}(x) = Q_0^2 \left(\frac{x_0}{x}\right)^\lambda$$

$$x - v_c t = \log\left(\frac{k^2}{k_0^2}\right) - v_c \log\left(\frac{1}{x}\right)$$

$$= \log\left[k^2 \times \frac{1}{k_0^2}\left(\frac{1}{x}\right)^{-v_c}\right]$$

$$= \log\left(\frac{k^2}{Q^2_{\text{sat}}(x)}\right)$$

Conlusions

- Nonlinear BK equation generates sauration scale $Q_s(x)$

Travelling waves in QCD imply Geometrical Scaling

$$f(x,k^2) = \mathcal{F}\left(\frac{k^2}{Q_s^2(x)}\right)$$

$$Q_s(x) = Q_0\left(\frac{x_0}{x}\right)^{\lambda/2}$$

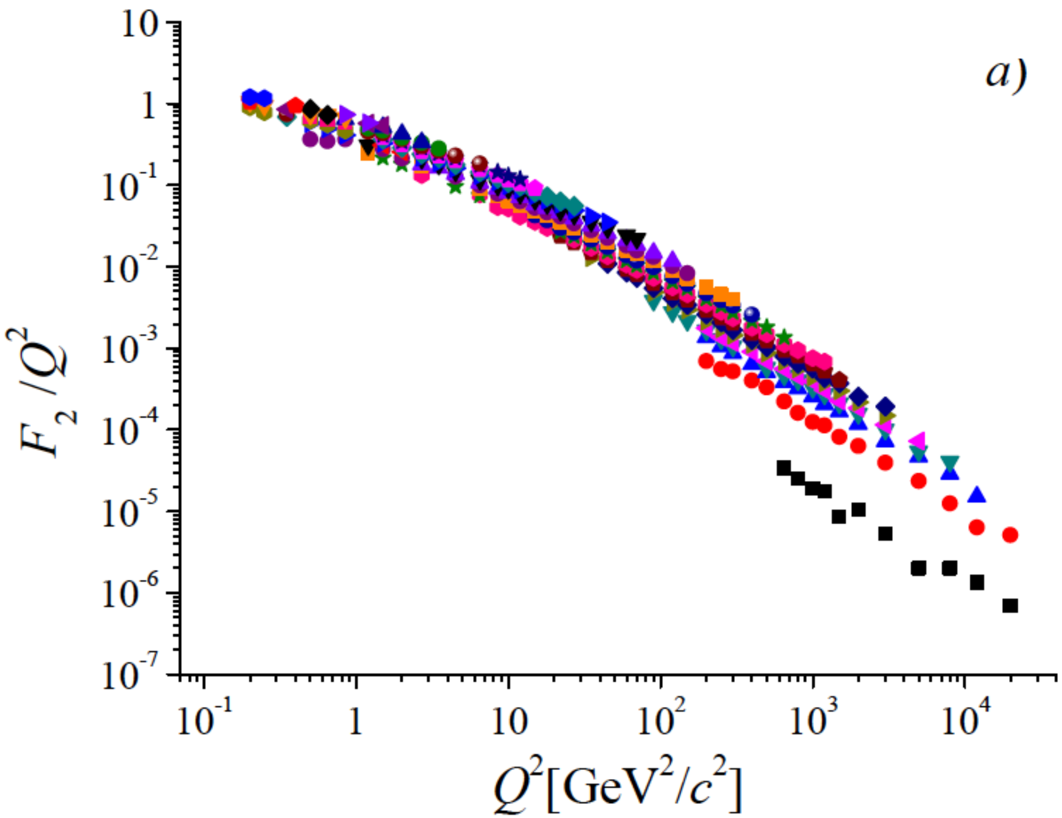
Conlusions

- Nonlinear BK equation generates sauration scale $Q_s(x)$
- In the region with no other scales Geometrical Scaling emerges

Deep Inealstic Scattering

Saturation scale: energy and x dependence

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

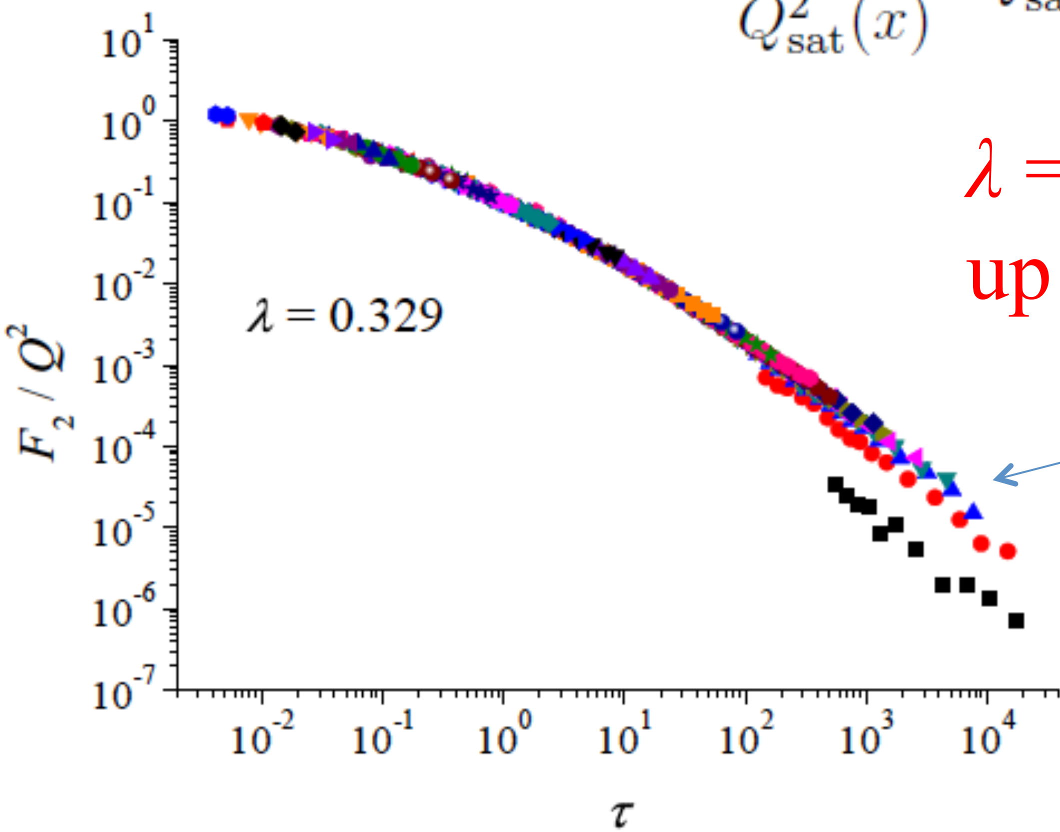


A.M. Stasto, K. J. Golec-Biernat, J. Kwiecinski
PRL 86 (2001) 596-599

M.Praszalowicz and T.Stebel
JHEP 1303, 090 (2013)
arXiv:1211.5305 [hep-ph]
and
JHEP 1304, 169 (2013)
arXiv:1302.4227 [hep-ph]

Saturation scale: energy and x dependence

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



$\lambda = 0.329 \pm 0.005$

up to $x = 0.08$ (!)

large x

more "sophisticated" scaling variables do not work well


Workshop on QCD
and Diffraction
saturation 1000+
5-7 December 2016
Cracow, Poland
qcdworkshop.ifj.edu.pl
Organising Committee:
Wojciech Broniowski
Janusz Chwastowski
Krzysztof Kutak
Michał Praszałowicz
Christophe Royon
Anna Staśto
Rafał Staszewski
PAN
POLSKA AKADEMIA NAUK
KRK 2B
Krakow to business
KRAKÓW
krakow.pl
photo: flickr.com/arekolek

Conlusions

- Nonlinear BK equation generates sauration scale $Q_s(x)$
- In the region with no other scales Geometrical Scaling emerges
- GS works well in DIS up to relatively large $x \sim 0.08$ with $\lambda \sim 0.33$

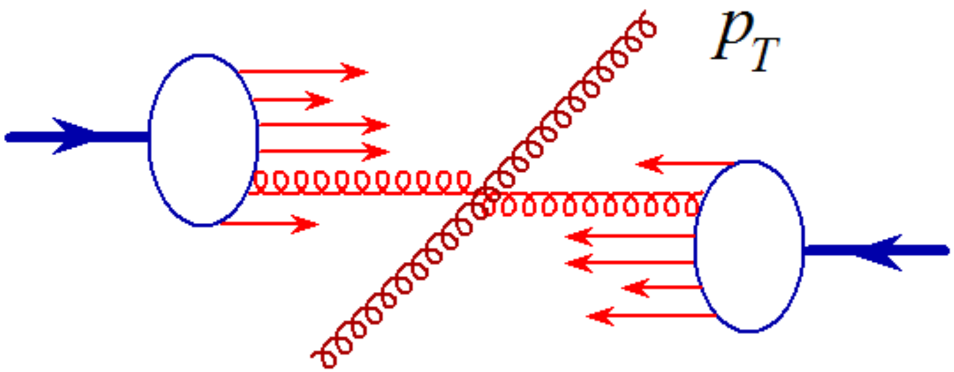
proton-proton @ LHC

Basics of geometrical scaling

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

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

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



gluon distribution

unintegrated glue

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

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

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)

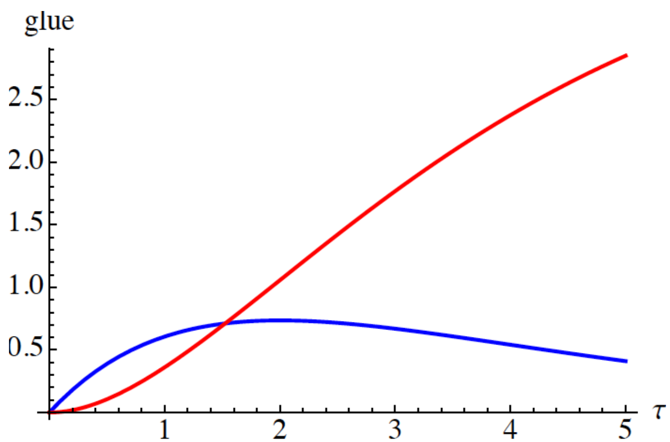
$$\varphi(x,k_{\mathrm{T}}^2) = S_{\perp} \frac{3}{4\pi^2} \frac{k_{\mathrm{T}}^2}{Q_{\mathrm{s}}(x)^2} \exp\left(-k_{\mathrm{T}}^2/Q_{\mathrm{s}}(x)^2\right)$$

$$S_{\perp} = \sigma_0$$

Kharzeev – Levin (AA)

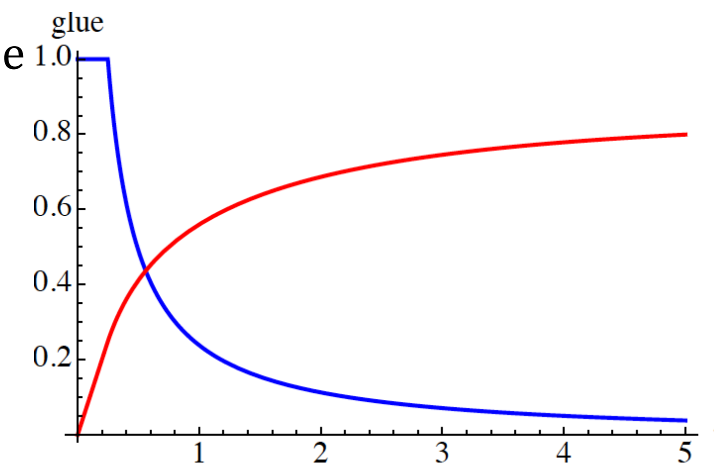
$$\varphi(x,k_{\mathrm{T}}^2) = S_{\perp} \begin{cases} 1 & \text{for} \quad k_{\mathrm{T}}^2 < Q_{\mathrm{s}}(x)^2 \\ Q_{\mathrm{s}}(x)^2/k_{\mathrm{T}}^2 & \text{for} \quad Q_{\mathrm{s}}(x)^2 < k_{\mathrm{T}}^2 \end{cases}$$

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



scaling variable

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



Basics of geometrical scaling

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

$$\frac{d\sigma}{dyd^2p_{\rm T}} = \frac{3\pi\alpha_{\rm s}}{2}\frac{Q_s^2(x)}{p_{\rm T}^2}\int \frac{d^2\vec{k}_{\rm T}}{Q_s^2(x)}\varphi_1\left(\vec{k}_{\rm T}^2/Q_s^2(x)\right)\varphi_2\left((\vec{k}-\vec{p})_{\rm T}^2/Q_s^2(x)\right)$$

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$$\frac{d\sigma}{dyd^2p_{\rm T}} = S_\perp^2\mathcal{F}(\tau) \quad \tau = \frac{p_{\rm T}^2}{Q_s^2(x)} \quad Q_s(x) = Q_0\left(\frac{x_0}{x}\right)^{\lambda/2}$$

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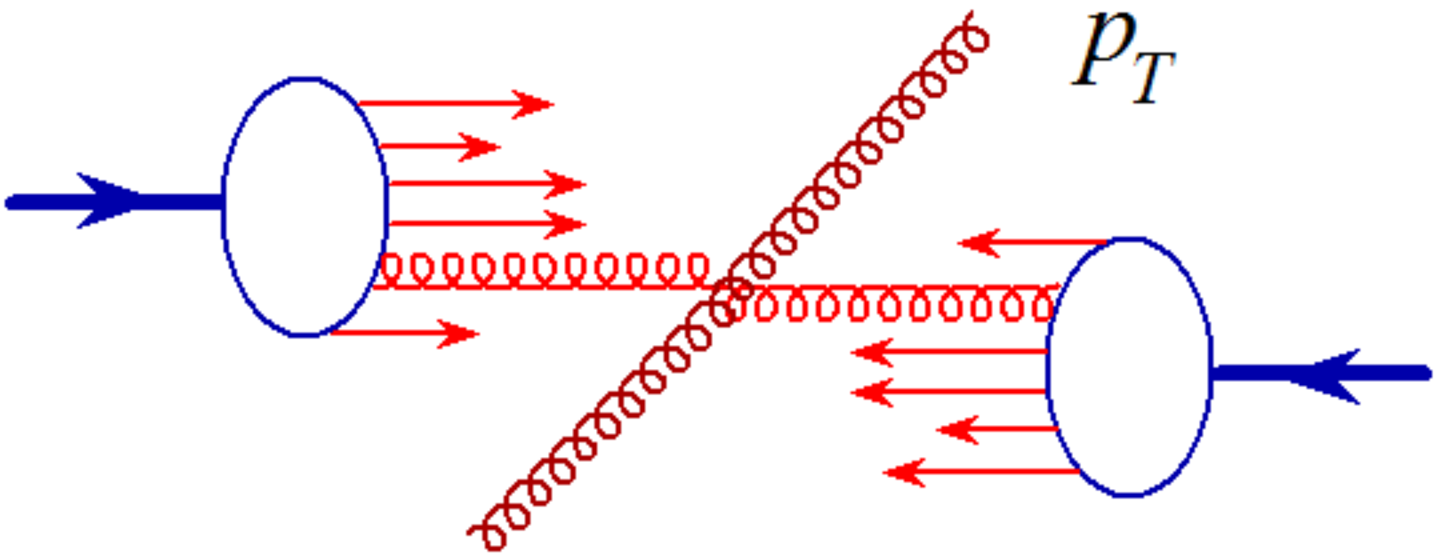
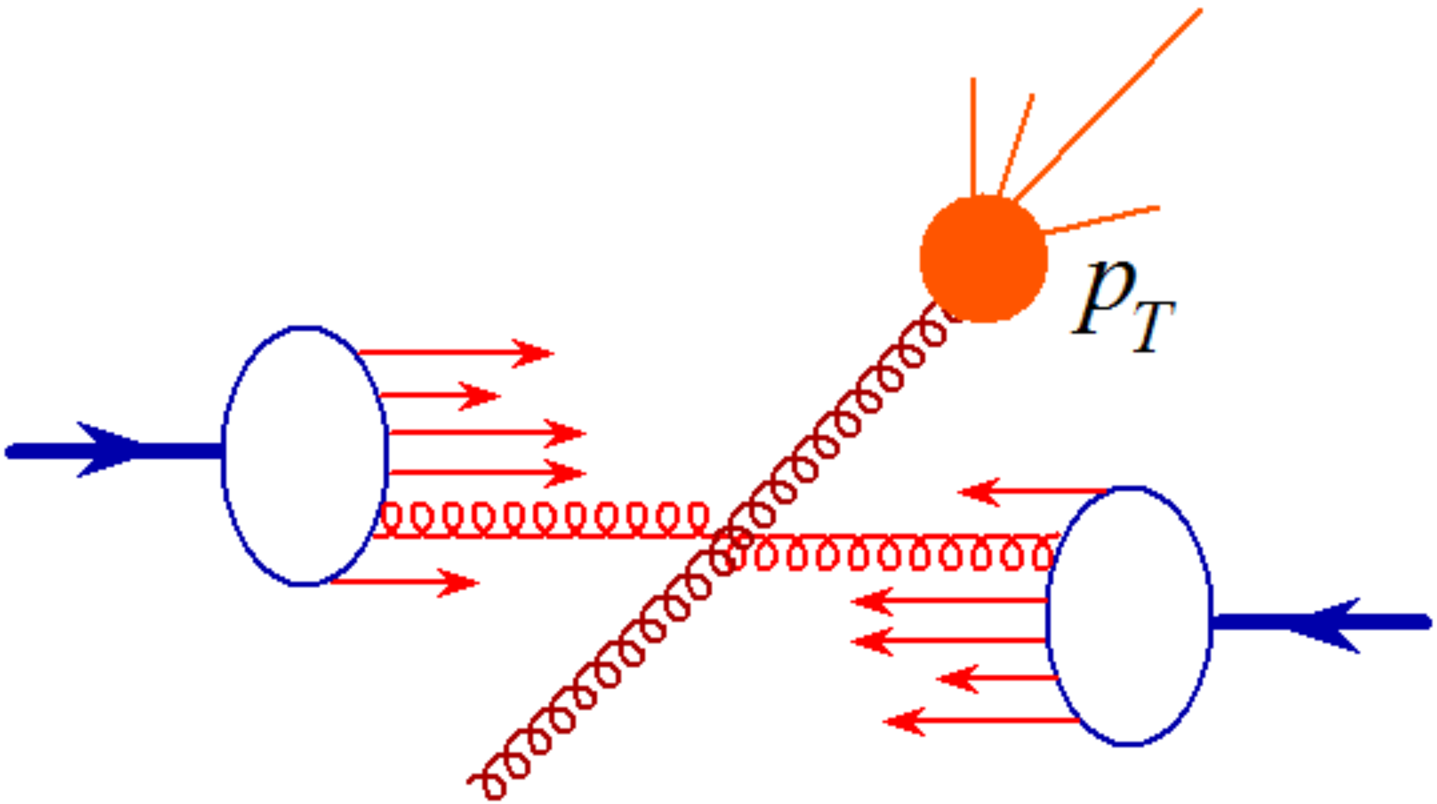
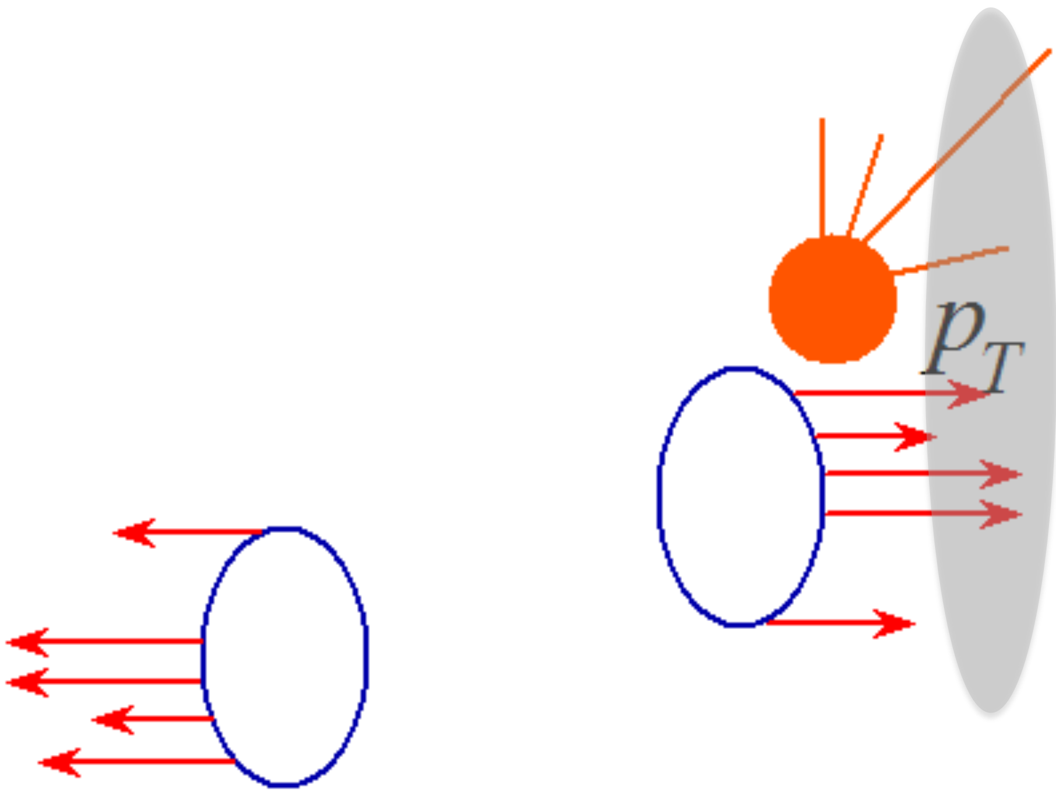
parton – hadron duality: power-like growth of particle multiplicity


p_T


p_T


p_T

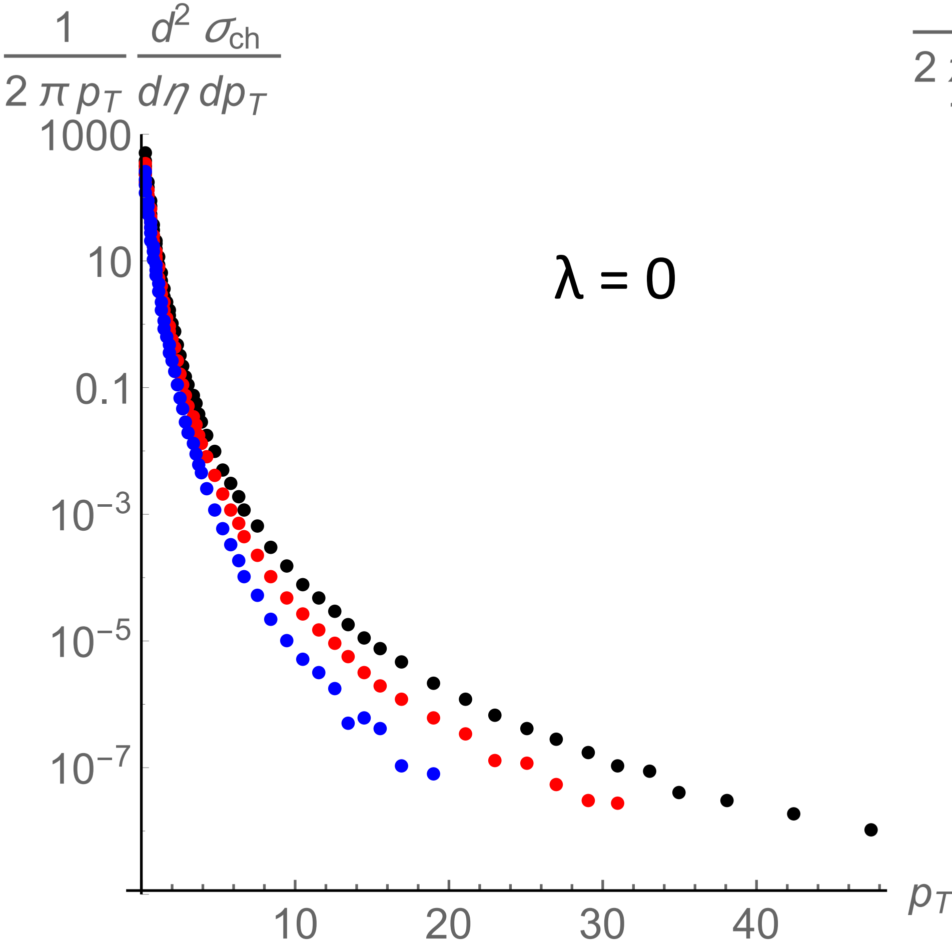
Geometrical scaling of p_T distributions

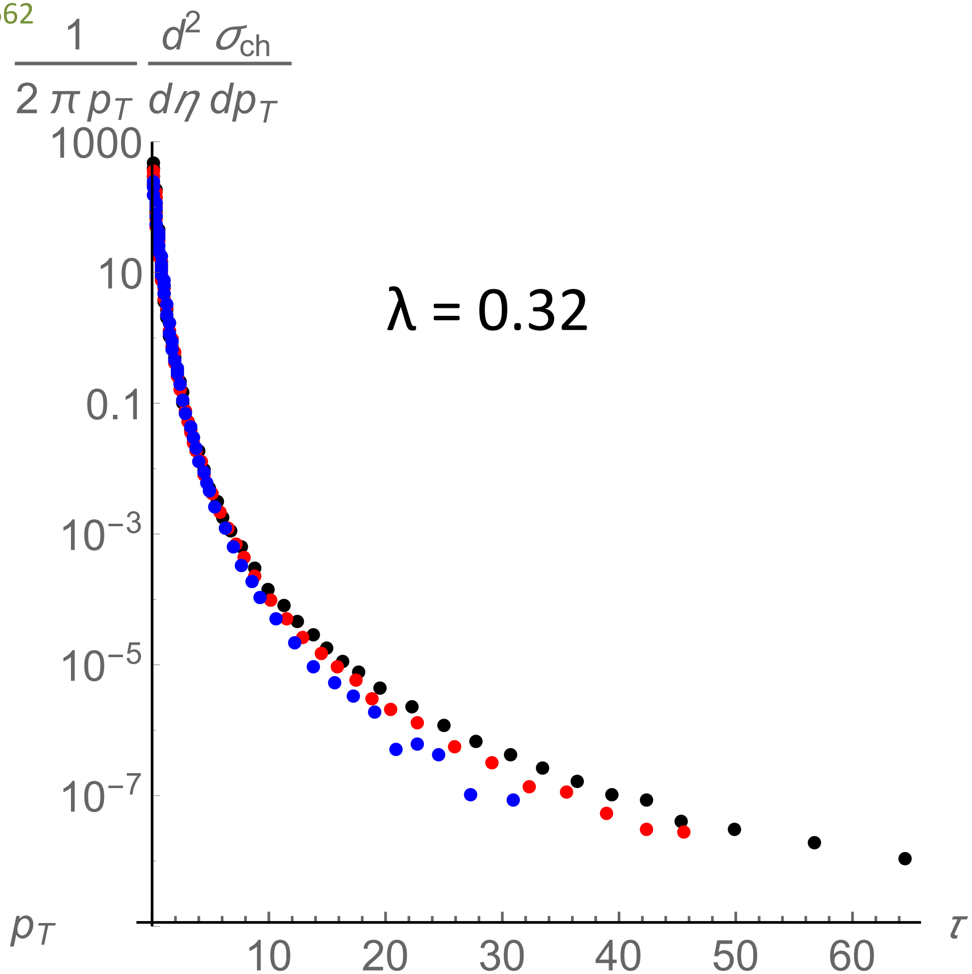
L. McLerran, M. P. Acta Phys.Polon.B41:1917,2010, B42:99,2011
M. P. Phys.Rev.Lett.106:142002,2011, Acta Phys.Pol. B42 (2011) 1557-1566
Phys.Rev. D87 (2013) 071502(R)

$$\tau = \frac{p_{\mathrm{T}}^2}{Q_{\mathrm{sat}}^2(p_{\mathrm{T}}/\sqrt{s})} = \frac{p_{\mathrm{T}}^2}{1\,\mathrm{GeV}^2}\left(\frac{p_{\mathrm{T}}}{\sqrt{s}\times 10^{-3}}\right)^{\lambda}$$

Cross-section scaling in pp

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

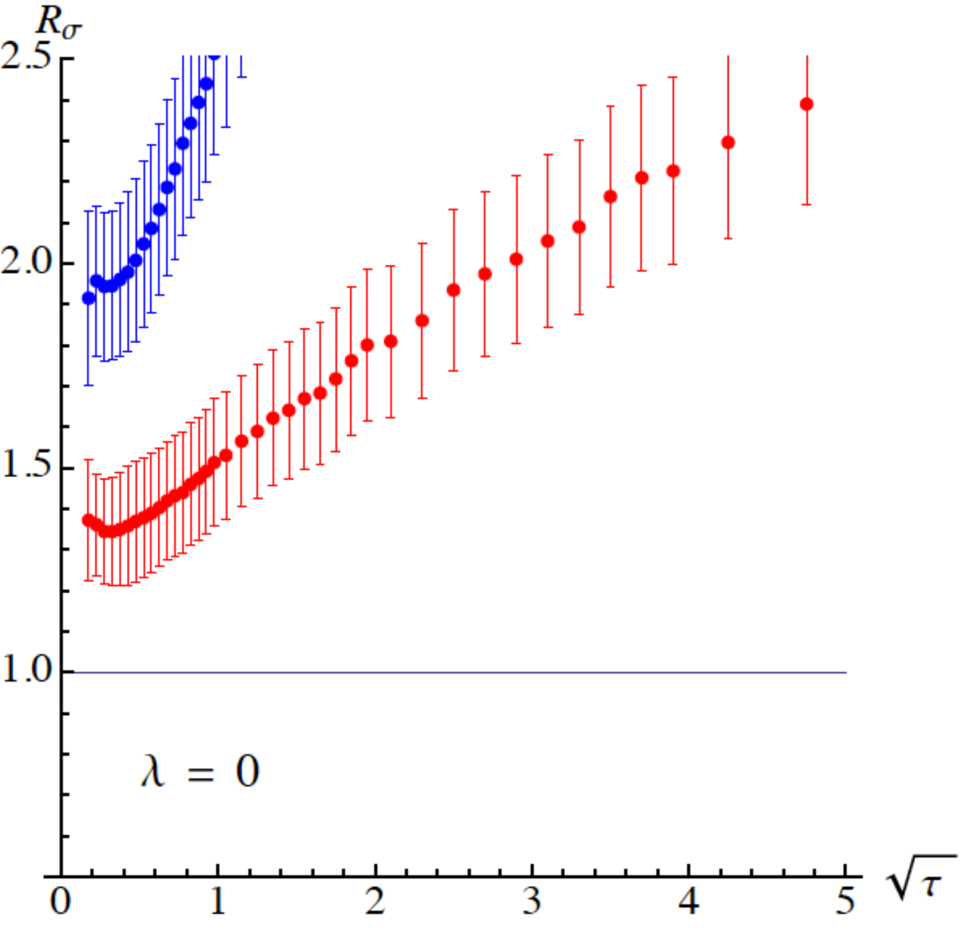




ALICE 1307.1093 [nucl-ex], Eur.Phys.J C73 (2013) 2662

Determination of lambda

$$\tau = \frac{p_T^2}{Q_{\text{sat}}^2(p_T/\sqrt{s})} = \frac{p_T^2}{1\,\text{GeV}^2}\left(\frac{p_T}{\sqrt{s}\times 10^{-3}}\right)^{\lambda}$$



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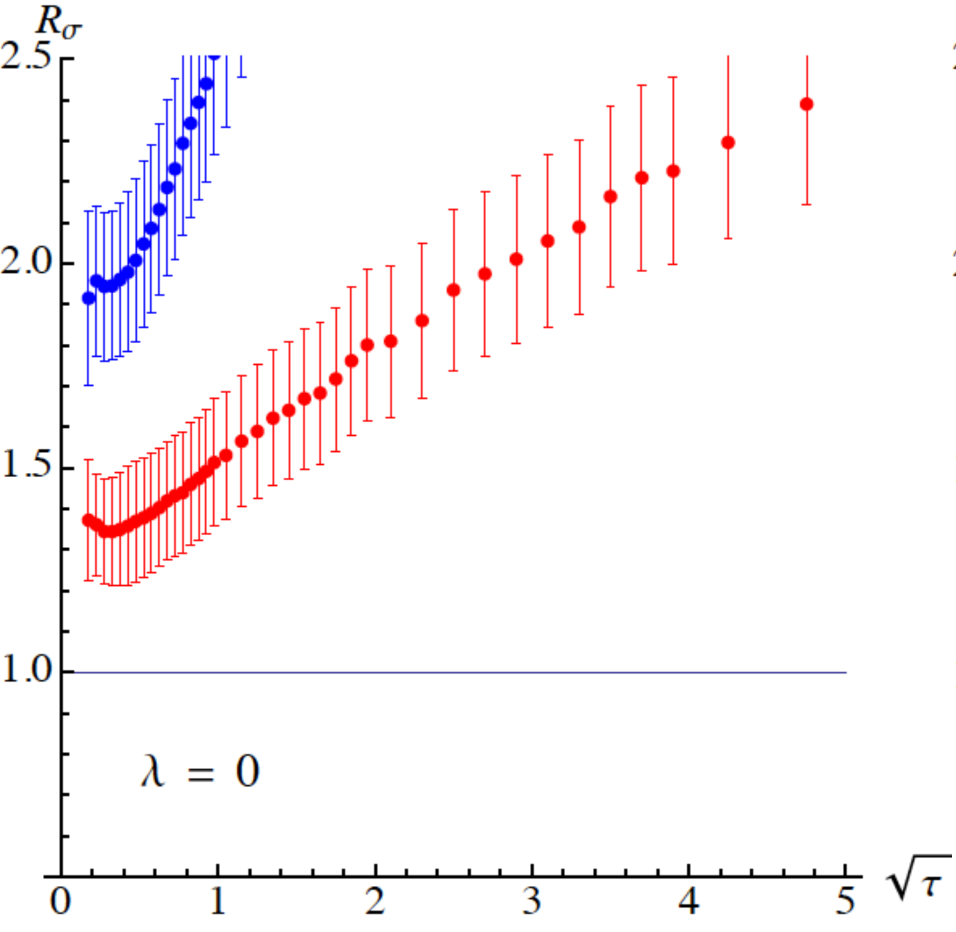

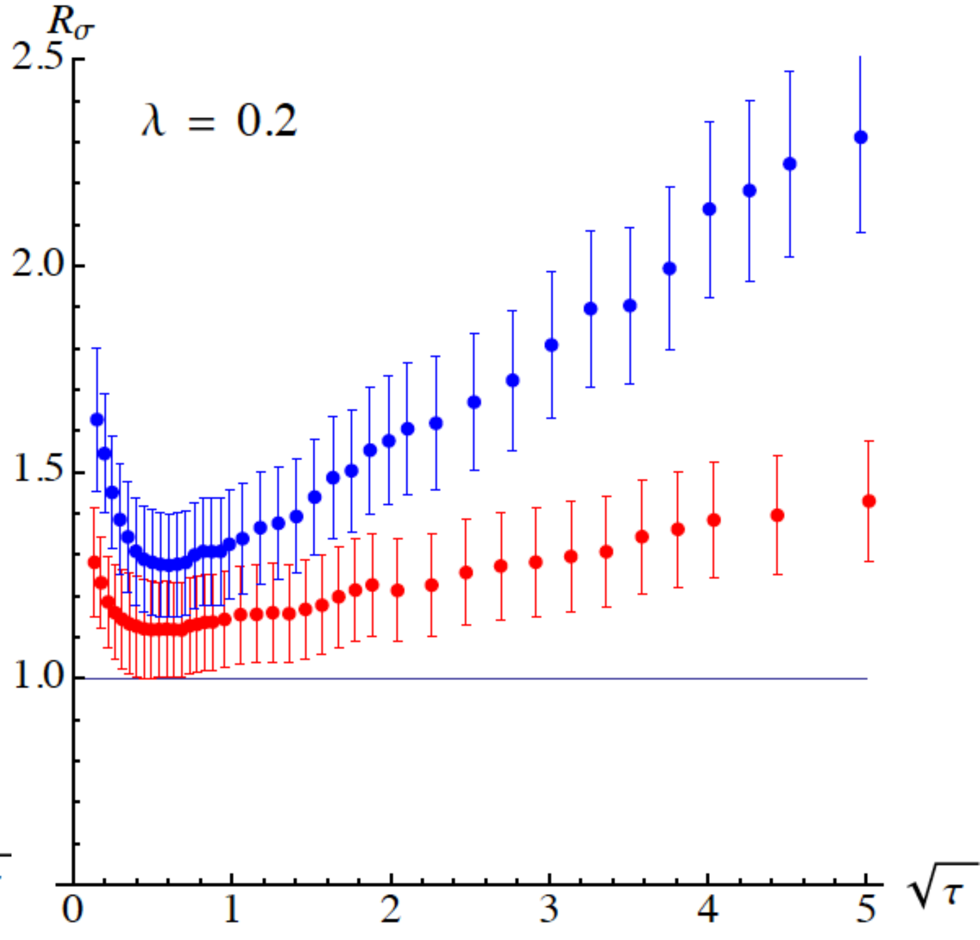

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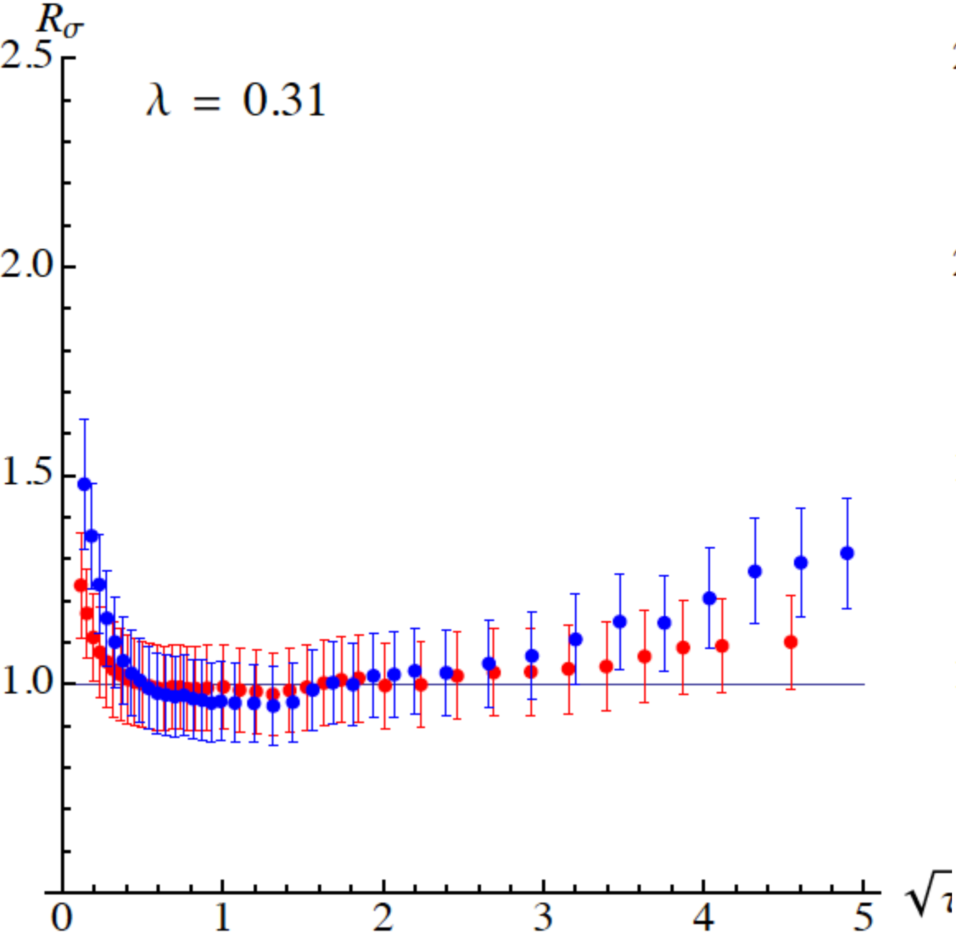

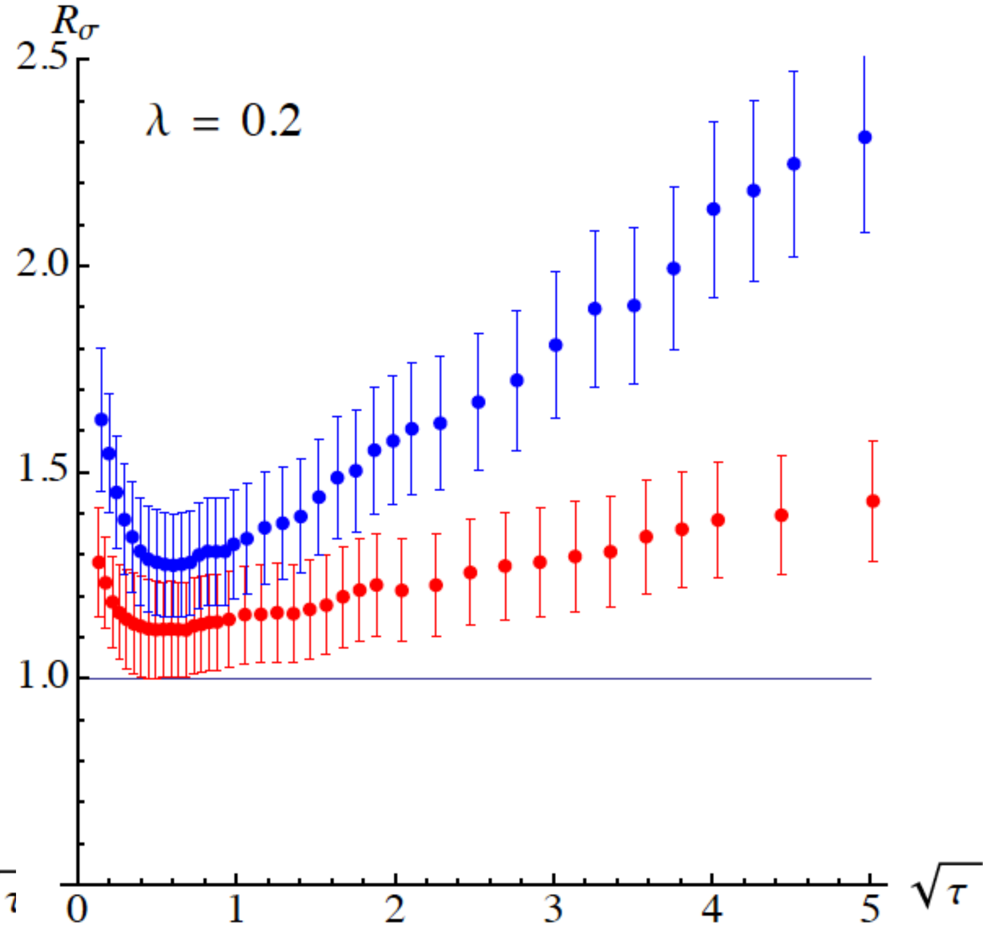

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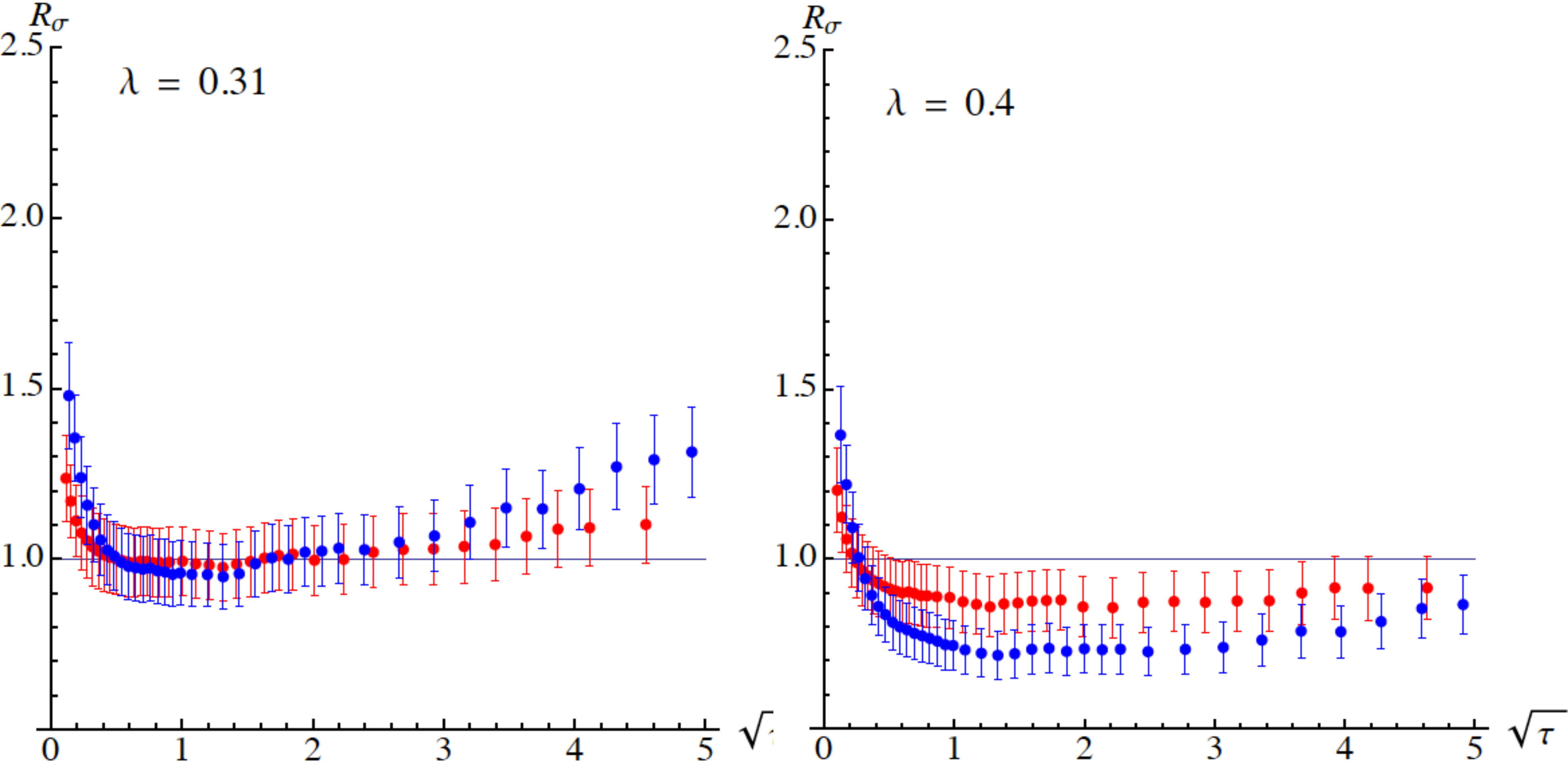

Conlusions

- Nonlinear BK equation generates sauration scale $Q_s(x)$
- In the region with no other scales Geometrical Scaling emerges
- GS works well in DIS up to relatively large $x \sim 0.08$ with $\lambda \sim 0.33$
- GS for the cross-section compatible with DIS

Basics of geometrical scaling

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

$$\frac{d\sigma}{dyd^2p_\mathrm{T}} = \frac{3\pi\alpha_\mathrm{s}}{2}\frac{Q_s^2(x)}{p_\mathrm{T}^2}\int\frac{d^2\vec{k}_\mathrm{T}}{Q_s^2(x)}\varphi_1\left(\vec{k}_\mathrm{T}^2/Q_s^2(x)\right)\varphi_2\left((\vec{k}-\vec{p})_\mathrm{T}^2/Q_s^2(x)\right)$$

$$\frac{d\sigma}{dyd^2p_\mathrm{T}} = S_\perp^2\mathcal{F}(\tau) \quad \tau = \frac{p_\mathrm{T}^2}{Q_s^2(x)} \qquad dp_\mathrm{T}^2 = \frac{2}{2+\lambda}\bar{Q}_\mathrm{s}^2(W)\,\tau^{-\lambda/(2+\lambda)}d\tau$$

$$\bar{Q}_s(W) = Q_0\left(\frac{W}{Q_0}\right)^{\lambda/(2+\lambda)}$$

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$$\frac{d\sigma}{dy} = S_\perp^2 \int \mathcal{F}(\tau) d^2 p_{\rm T} = S_\perp^2 \bar{Q}_s^2(W) \int \mathcal{F}(\tau) \ldots d\tau = \frac{1}{\kappa} S_\perp^2 \bar{Q}_s^2(W)$$

Basics of geometrical scaling

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$$\frac{d\sigma}{dy} = S_\perp \frac{dN}{dy} = \frac{1}{\kappa}S_\perp^2 \bar{Q}_s^2(W) \rightarrow \bar{Q}_s^2(W) = \frac{\kappa}{S_\perp}\frac{dN}{dy}$$

Basics of geometrical scaling

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$$\frac{d\sigma}{dyd^2p_{\rm T}} = \frac{3\pi\alpha_{\rm s}}{2}\frac{Q_s^2(x)}{p_{\rm T}^2}\int \frac{d^2\vec{k}_{\rm T}}{Q_s^2(x)}\varphi_1\left(\vec{k}_{\rm T}^2/Q_s^2(x)\right)\varphi_2\left((\vec{k}-\vec{p})_{\rm T}^2/Q_s^2(x)\right)$$

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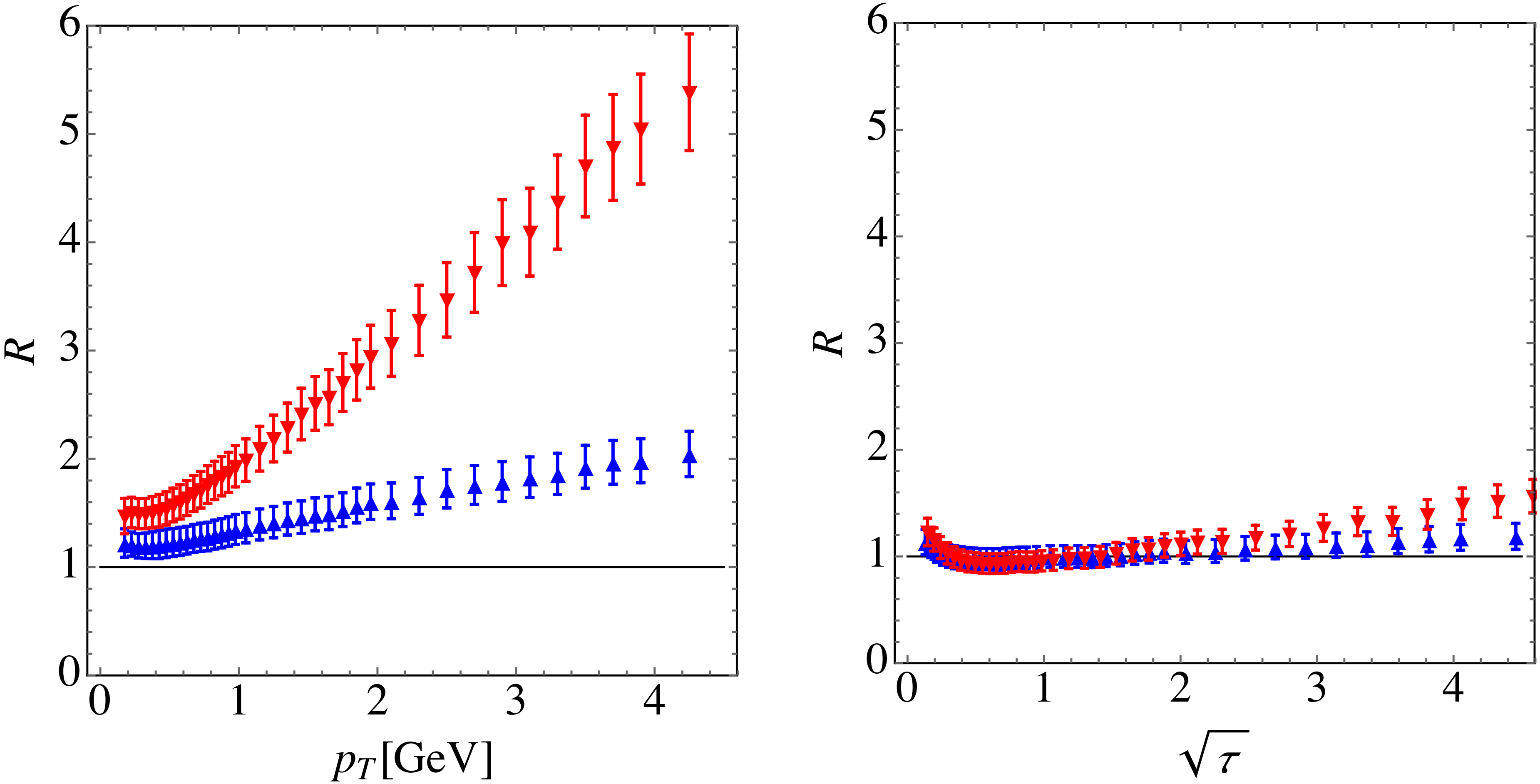
$$\frac{d\sigma}{dy} = S_\perp^2\int\mathcal{F}(\tau)d^2p_{\rm T} = S_\perp^2\bar{Q}_s^2(W)\int\mathcal{F}(\tau)\ldots d\tau = \frac{1}{\kappa}S_\perp^2\bar{Q}_s^2(W)$$

$$\frac{d\sigma}{dy} = \sigma^{\rm MB}(W)\frac{dN}{dy} = \frac{1}{\kappa}S_\perp^2\bar{Q}_s^2(W) \rightarrow S_\perp\frac{\bar{Q}_s^2(W)}{\sigma^{\rm MB}(W)} = \frac{\kappa}{S_\perp}\frac{dN}{dy}$$

Determination of lambda

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

$\lambda = 0$ $\lambda = 0.22$



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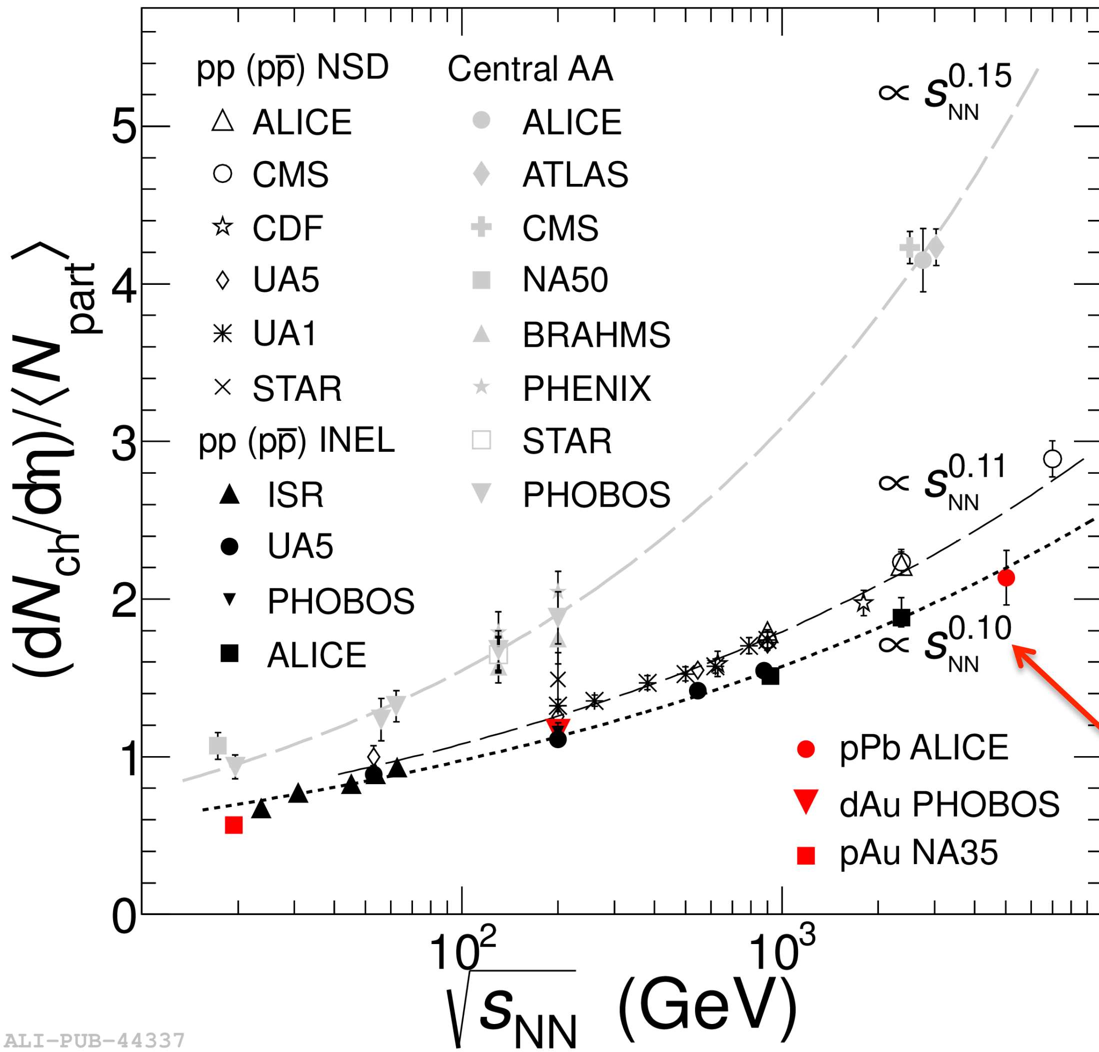
- In the region with no other scales Geometrical Scaling emerges
- GS works well in DIS up to relatively large $x \sim 0.08$ with $\lambda \sim 0.33$
- GS for the cross-section compatible with DIS
- In pp GS works for multiplicity distributions with with $\lambda \sim 0.22$ (!)

continue
with multiplicity scaling…

Power-like growth of multiplicity

http://th-www.if.uj.edu.pl/school/2014/talks/braun-munzinger_1.pdf



plot: P. Braun-Munzinger, 54 Cracow School of Theoretical Physics (from ALICE-PUB-44337)

$$\frac{dN_{ch}}{dy} \sim S_\perp \bar{Q}_s^2(W)$$

$$\sim S_\perp Q_0^2 \left(\frac{W^2}{Q_0^2}\right)^{\lambda/(2+\lambda)}$$

transverse area is energy indpendent

$$\lambda/(2+\lambda) \simeq 0.099$$

Conlusions

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- GS for the cross-section compatible with DIS
- In pp GS works for multiplicity distributions with with $\lambda \sim 0.22$ (!)
- As a consequence total multiplicity grows with energy as $s^{0.1}$

Application to pA scattering at the LHC

Color Glass Condensate in pPB

stolen from Bozek, Bzdak, Skokov

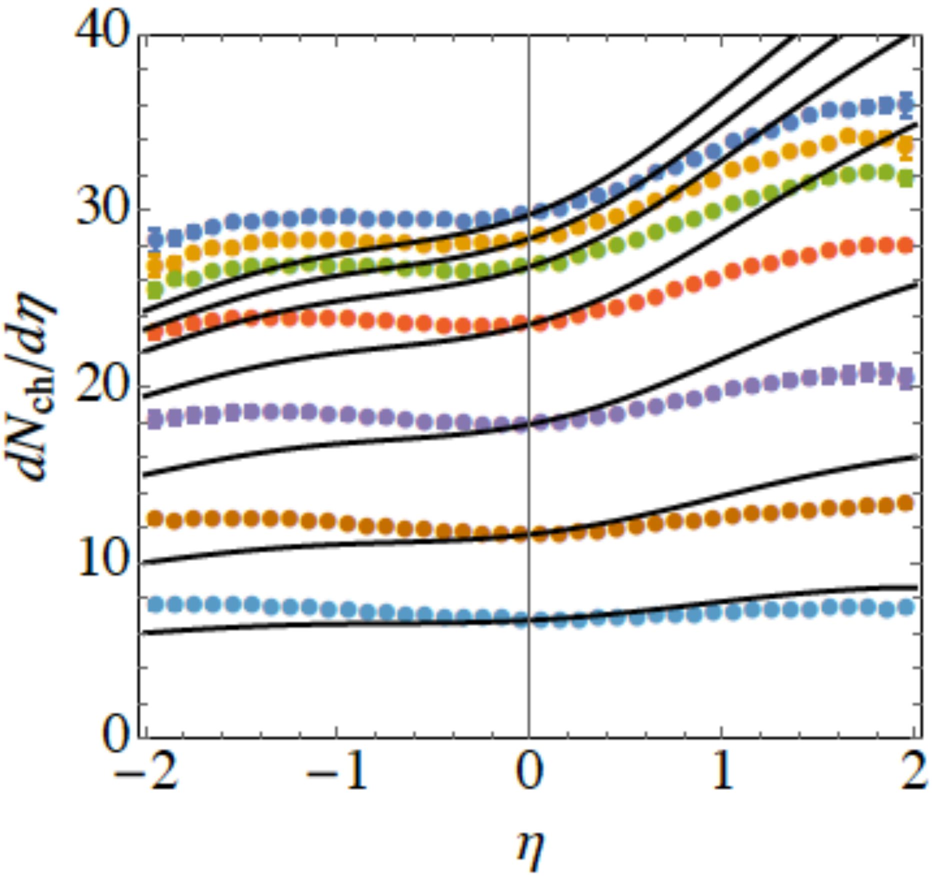
$$\frac{dN}{dy} = S_\perp Q_p^2 \left(2 + \ln \frac{Q_A^2}{Q_p^2} \right)$$

$$Q_p^2(W, y) = Q_0^2 \left(\frac{W}{W_0} \right)^\lambda \exp(\lambda y),$$

$$Q_A^2(W, y) = Q_0^2 N_{\text{part}} \left(\frac{W}{W_0} \right)^\lambda \exp(-\lambda y)$$

$$\lambda = 0.32$$

Multiplicity for pPb

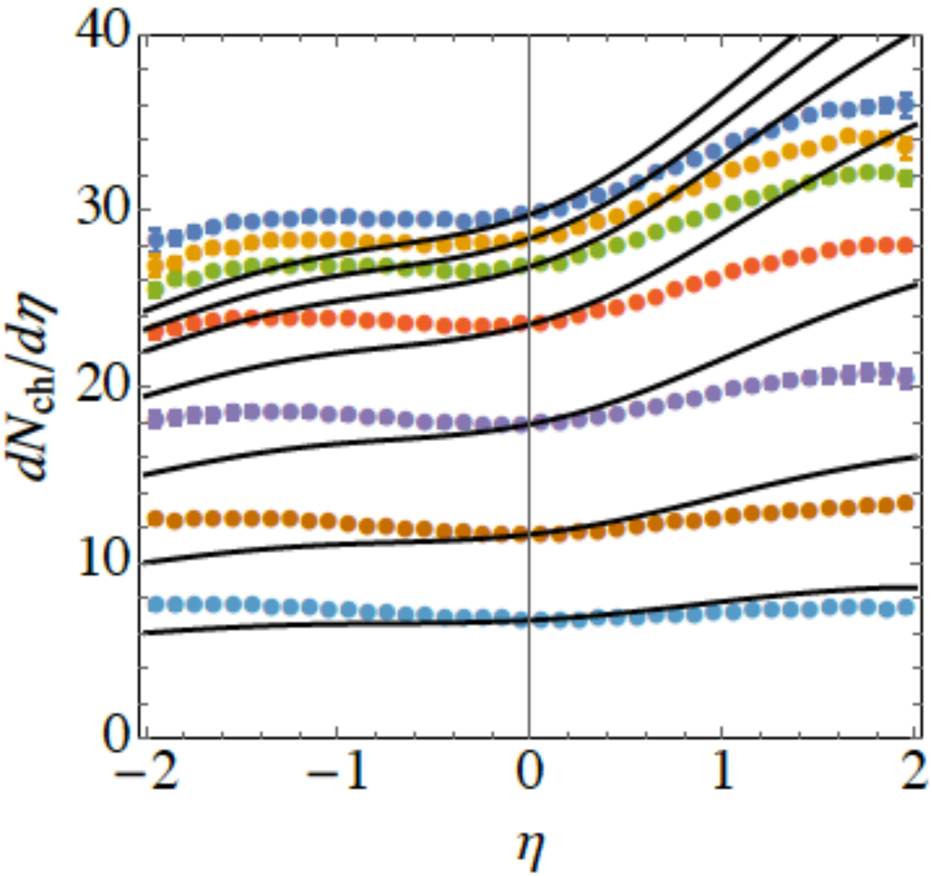


$$\frac{dN_{\mathrm{ch}}}{dy} = S_\perp Q_p^2 \left(2 + \ln \frac{Q_A^2}{Q_p^2} \right)$$

ZNA method

J. Adam *et al.* [ALICE Collaboration], Phys. Rev. C **91** (2015) 064905.

Multiplicity for pPb



$$\frac{dN_{\rm ch}}{dy} = S_\perp Q_p^2 \left(2 + \ln \frac{Q_A^2}{Q_p^2} \right)$$

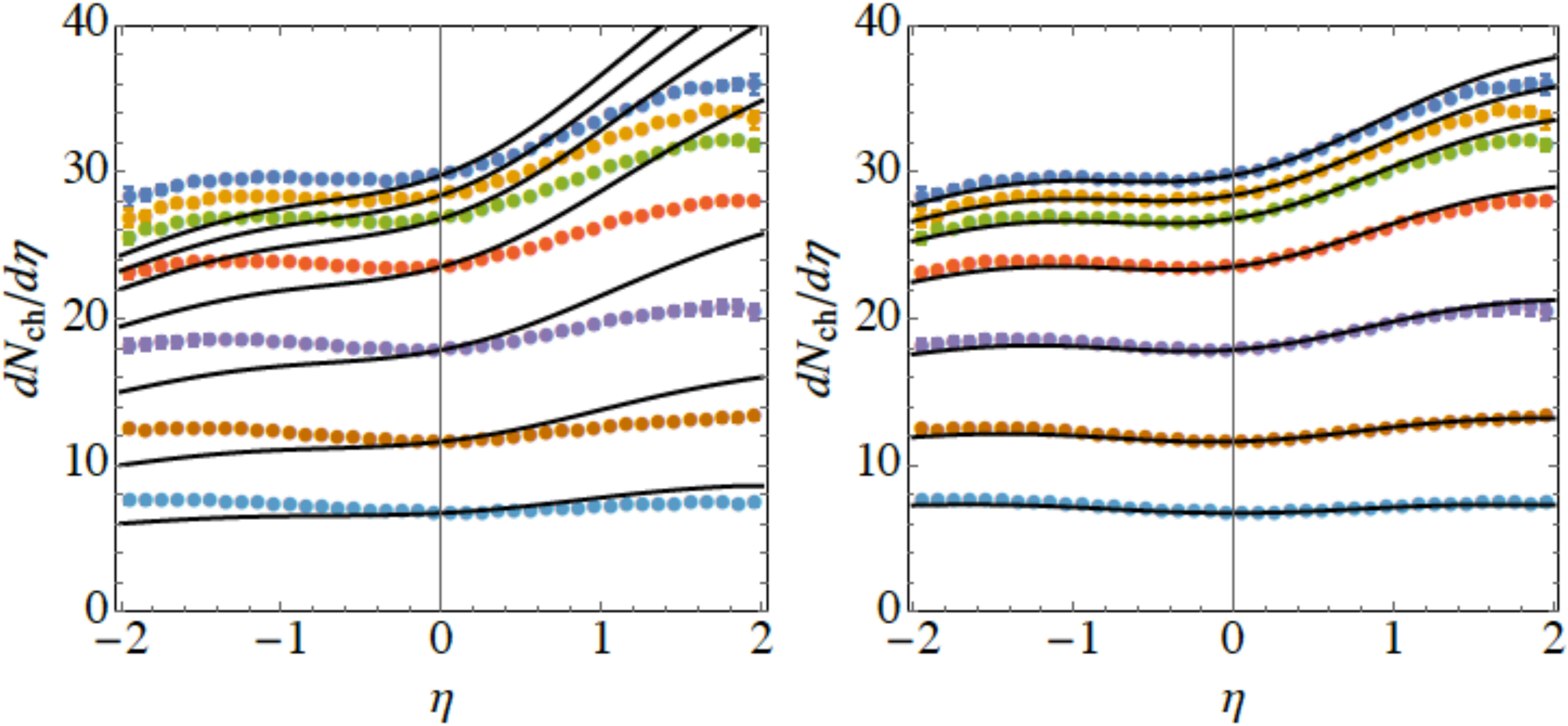
Allow Q_p to fluctuate:

$$\frac{1}{\sqrt{2\pi}\sigma} \exp\left(- \frac{(\ln {Q_p}^2/Q_0^2 - \ln \overline{Q}_p^2/Q_0^2)^2}{2\sigma^2} \right)$$

E. Iancu, A. H. Mueller, S. Munier Phys. Lett. B **606** (2005) 342

J. Adam *et al.* [ALICE Collaboration], Phys. Rev. C **91** (2015) 064905.

Fluctuations of Q_{sat} in pPb



rather large $\sigma \sim 1.55$

L. McLerran, M. Praszalowicz, Annals of Phys. **372** (2016) 215

Conlusions

- Nonlinear BK equation generates sauration scale $Q_s(x)$
- In the region with no other scales Geometrical Scaling emerges
- GS works well in DIS up to relatively large $x \sim 0.08$ with $\lambda \sim 0.33$
- GS for the cross-section compatible with DIS
- In pp GS works for multiplicity distributions with with $\lambda \sim 0.22$ (!)
- As a consequence total multiplicity grows with energy as $s^{0.1}$
- Fluctuations of the saturation scale may explain *dN/dy*

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Not discussed

- Consequences of GS for F_L
- Scaling violations in pp due to $y \neq 0$
- Scaling violations in pp due to $\lambda(Q^2)$
- Scaling in pp for identified particles
- Connection with Tsallis distribution
- $<p_T>(N)$ for identified particles
- geometrical scaling predicts energy dependence of $<p_T>$
- $<p_T>(N_{ch})$ difficult to describe by untuned MonteCarlos
- scaling of $<p_T>(N_{ch})$ induced by energy dependence of Q_{sat} + CGC
- GS in heavy ion collisions – scaling with energy and N_{part}
- 끝


감사합니다!

Workshop on QCD and Diffraction

saturation 1000+

5-7 December 2016
Cracow, Poland

qcdworkshop.ifj.edu.pl

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