Multiplicities in Pb-Pb collisions at the LHC from running coupling evolution and RHIC data

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Heavy Ion Collisions at the LHC
Last Call for Predictions

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OUTLINE

@ Balitsky-Kovchegov evolution equation with running coupling

⇒ Recent developments

⇒ Strong reduction of the speed of evolution

@ Phenomenological consequences:

⇒ Energy dependence of multiplicity densities in A-A collisions

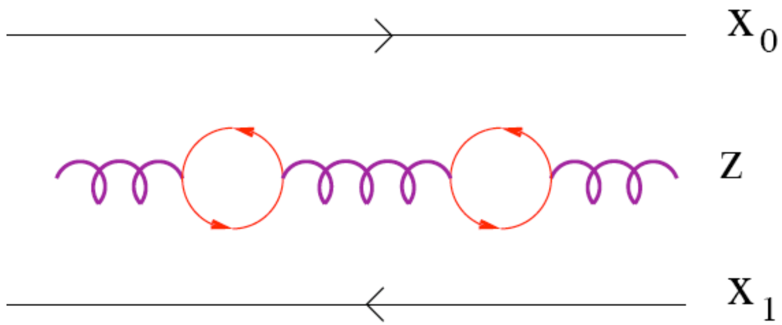
⇒ Determining initial conditions: RHIC @ $\sqrt{s}$=130 and 200 GeV

⇒ Extrapolation to central Pb-Pb collisions @ $\sqrt{s}$=5.5 TeV

BK with running coupling

- Balitsky (2006)
- Kovchegov and Weigert (2006)
- E. Gardi et. al. (2006)

- The quark contribution to the BK equation has been calculated recently resumming $\alpha_s N_f$ contributions to all orders, and then completing $N_f \to -6\Pi\beta_2$ to determine the scale for the running of the coupling:



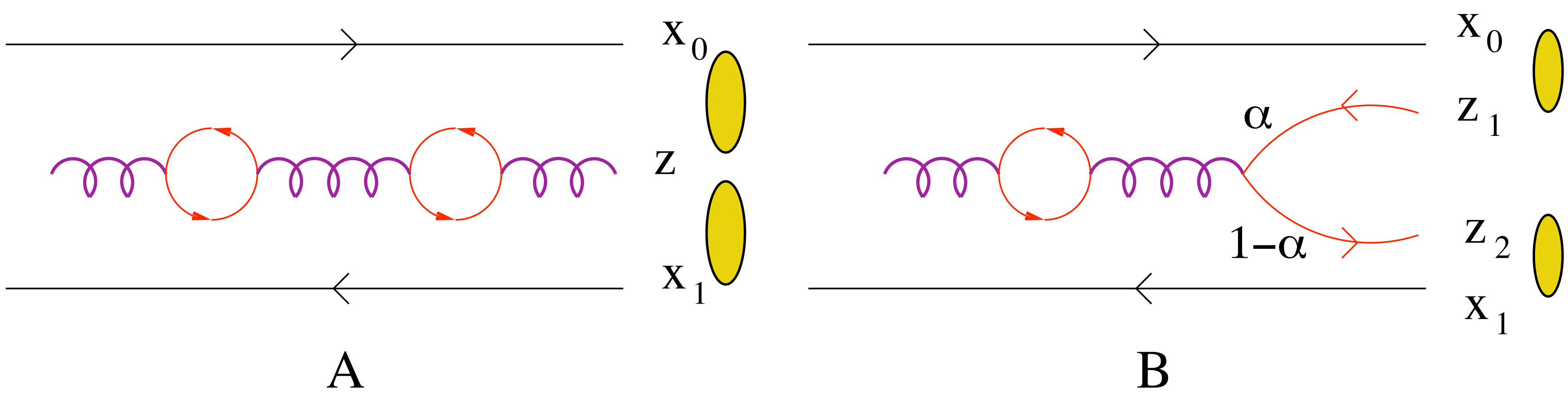
- However, the two calculations yield different results:

$$\frac{\partial S(\underline{r};Y)}{\partial Y} = \int d^2z\,\tilde{K}(\underline{r},\underline{r}_1,\underline{r}_2)\,[S(\underline{r}_1;Y)\,S(\underline{r}_2;Y) - S(\underline{r};Y)]$$

- KW $$\tilde{K}^{\mathrm{KW}}(\underline{r},\underline{r}_1,\underline{r}_2) = \frac{N_c}{2\pi^2}\left[\alpha_s(r_1^2)\frac{1}{r_1^2} - 2\,\frac{\alpha_s(r_1^2)\,\alpha_s(r_2^2)}{\alpha_s(R^2)}\,\frac{\underline{r}_1\cdot\underline{r}_2}{r_1^2\,r_2^2} + \alpha_s(r_2^2)\frac{1}{r_2^2}\right]$$

- Bal $$\tilde{K}^{\mathrm{Bal}}_{run}(\underline{r},\underline{r}_1,\underline{r}_2) = \frac{N_c\,\alpha_s(r^2)}{2\pi^2}\left[\frac{r^2}{r_1^2\,r_2^2} + \frac{1}{r_1^2}\left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1\right) + \frac{1}{r_2^2}\left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1\right)\right]$$

@ **Why?**: The inclusion of all orders $\alpha_s N_f$ contributions brings in new physical channels that modify the interaction structure of the equation:



$$\frac{\partial S(x,y,;Y)}{\partial Y} = \mathcal{R}[S] - \mathcal{S}[S]$$

JLA and Y. Kovchegov (07)

- "Running" term:

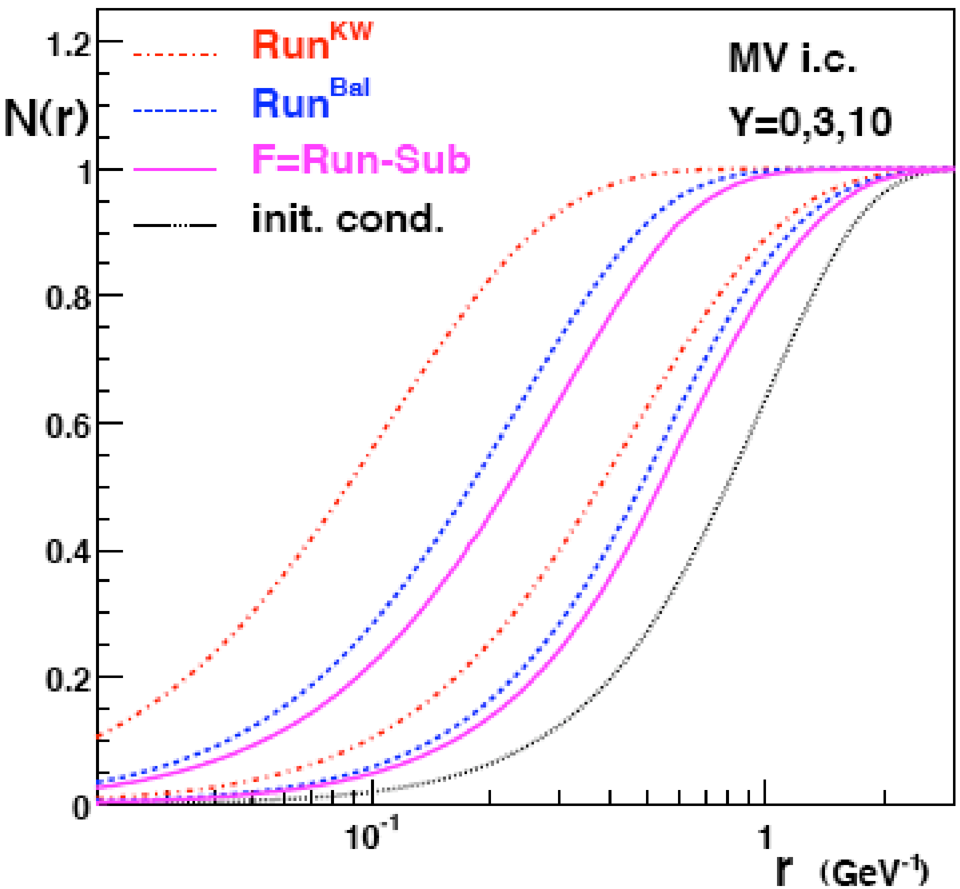
$$\mathcal{R}\,[S] = \int d^2z\, \tilde{K}^{run}(\underline{x}_0, \underline{x}_1, \underline{z})\, [S(\underline{x}_0, \underline{z}; Y)\, S(\underline{z}, \underline{x}_1; Y) - S(\underline{x}_0, \underline{x}_1; Y)]$$

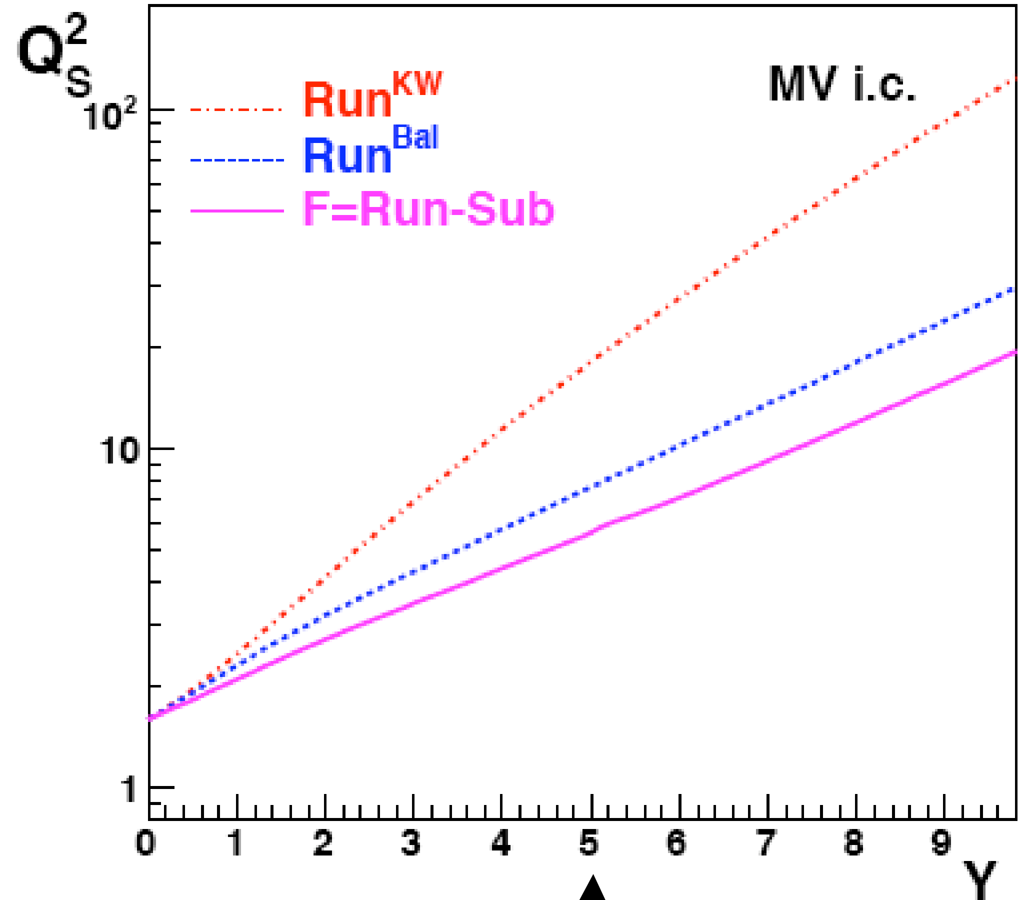
- "Subtraction" term:

$$\mathcal{S}[S] = \int d^2z_1\, d^2z_2\, K^{sub}\, [S(\underline{x}_0, \underline{\mathbf{w}}, Y)\, S(\underline{\mathbf{w}}, \underline{x}_1, Y) - S(\underline{x}_0, \underline{z}_1, Y)\, S(\underline{z}_2, \underline{x}_1, Y)]$$

Once the two terms are included the two calculations agree with each other!!

@ The extra "subtraction" term is numerically important and considerably reduces the speed of the evolution:





• Speed reduction due to subtraction term:
~ 30% w.r.t. only running in KW's scheme
~ 10% w.r.t. only running in Balitsky's scheme

Caution!!: A particular definition of Q_s

$$\mathcal{N}(r = 1/Q_s; Y) = 0.5$$

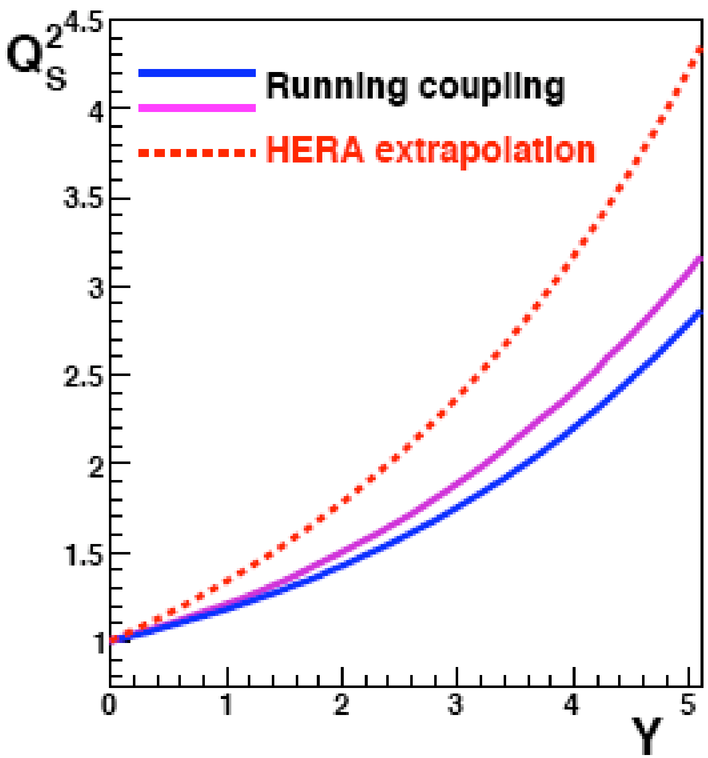
@ The energy dependence of the saturation scale from running coupling evolution is milder than the one extracted from fits to HERA DIS data

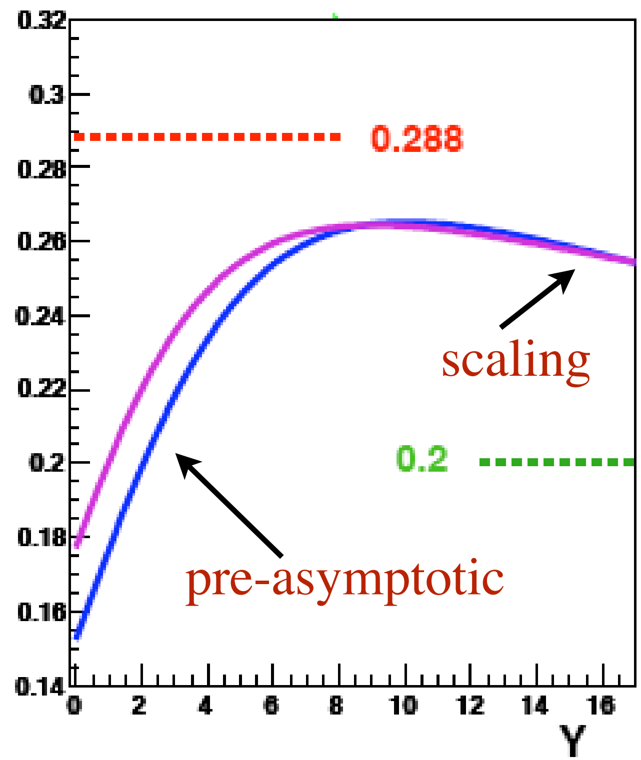
- Fits to HERA : $Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^{\lambda}$; $\lambda \approx 0.288$ Golec-Biernat Wüsthoff (98)

- Energy dependence of multiplicity in saturation models for particle production:

$$\left.\frac{dN_{AA}}{dy}\right|_{\eta=0} \sim \sqrt{s}^{\,\lambda}$$

Kharzeev-Levin-Nardi
Armesto-Salgado-Wiedemann (05)





$$\lambda = \frac{d \ln Q_s^2(Y)}{dY}$$

CGC
+hydrodynamics
at RHIC
favours λ=0.2

Hirano-Nara (04)

@ Particle production in A-A collisions :

• k_t-factorization 'a la KLN'

$$\frac{dN_{AA}}{d\eta} \propto \frac{4\pi N_c}{N_c^2-1} \int^{p_m} \frac{d^2p_t}{p_t^2} \int^{p} d^2k_t\, \alpha_s(Q)\, \varphi_A\left(x_1; \frac{|p_t+k_t|}{2}\right) \varphi_A\left(x_2; \frac{|p_t-k_t|}{2}\right)$$

• 2→1 kinematics

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

or

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

• rapidity ↔ pseudorapidity: gluon mass

$$y(\eta, p_t, m) = \frac{1}{2} \ln \left[\frac{\sqrt{\frac{m^2+p_t^2}{p_t^2} + \sinh^2\eta} + \sinh\eta}{\sqrt{\frac{m^2+p_t^2}{p_t^2} + \sinh^2\eta} - \sinh\eta} \right]$$

• Running coupling: $Q = \max\left\{ \frac{|p_t \pm k_t|}{2} \right\}$

+

$\varphi(x,k) \Rightarrow$ Solutions of BK with running coupling $\times (1-x)^4$

$$\varphi(x,k) = \int \frac{d^2r}{2\pi^2\, r^2}\, \exp^{i\underline{k}\cdot\underline{r}}\, \mathcal{N}(x,r)$$

+

Local Hadron Parton Duality

@ Initial conditions for evolution: Au-Au central collisions at RHIC at $\sqrt{s}$ =130 and 200 GeV

• McLerran-Venugopalan i.c. $\mathcal{N}_A(r, Y_{ev} = 0) = 1 - \exp\left\{-\frac{r^2 Q_0^2}{4} \ln\left(\frac{1}{|r\Lambda|} + e\right)\right\}$

$$\varphi(x, k) = \int \frac{d^2 r}{2\pi^2\, r^2}\, e^{i\underline{k}\cdot\underline{r}}\, \mathcal{N}(x, r)$$

Things to fix:

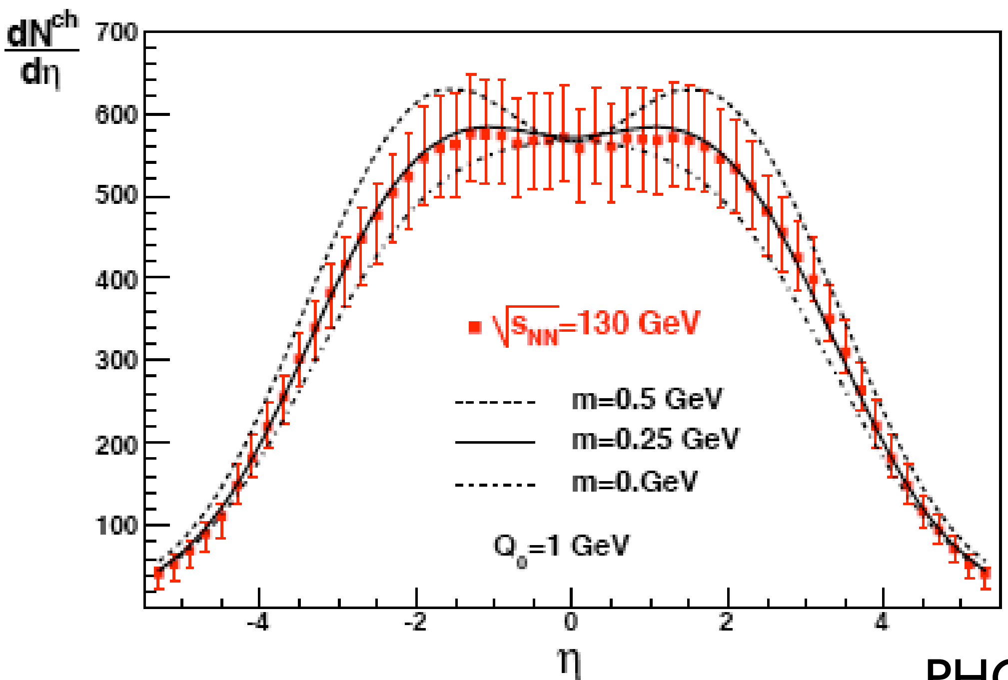
⇒ effective gluon mass, m

⇒ Initial saturation scale Q_0

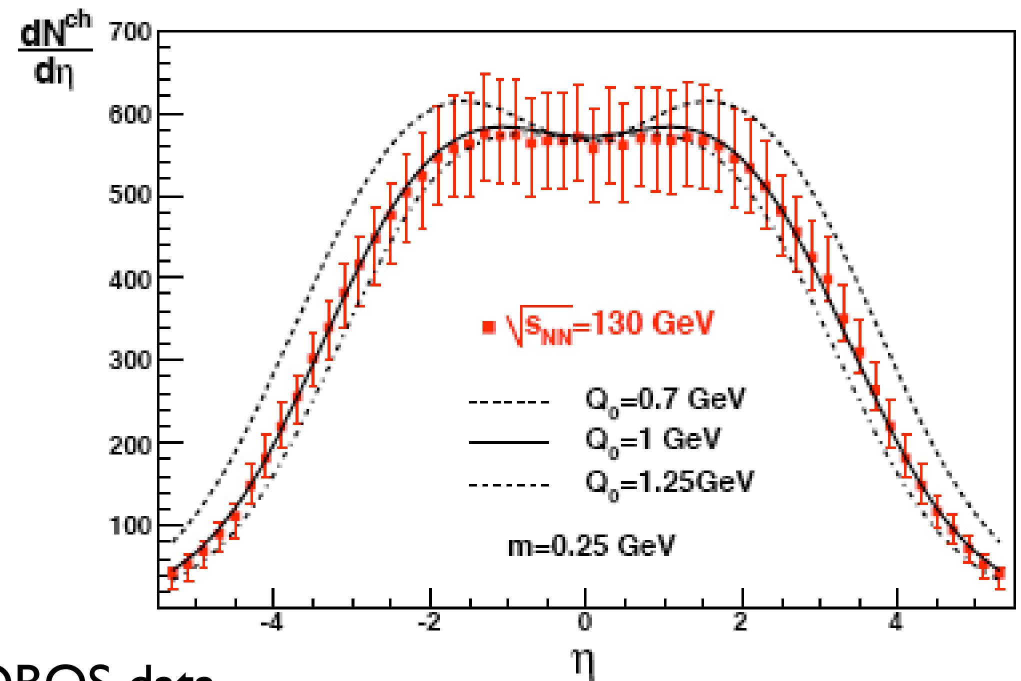
⇒ Is there significant evolution prior to $\sqrt{s}$ =130 ?

@ Initial conditions for evolution:
Au-Au central collisions at RHIC at $\sqrt{s}$ =130

Gluon mass ~ 0.25 GeV



Initial saturation scale
Q_0 ~ 1 GeV

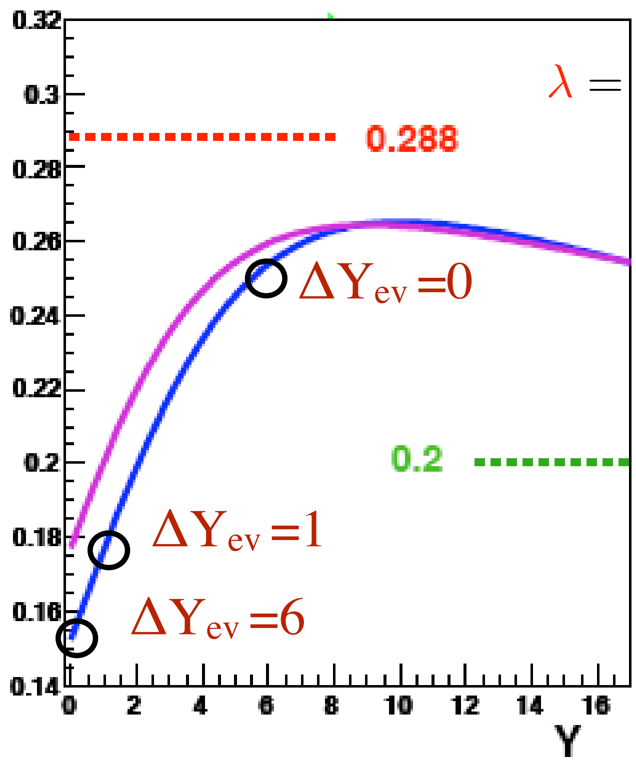


PHOBOS data

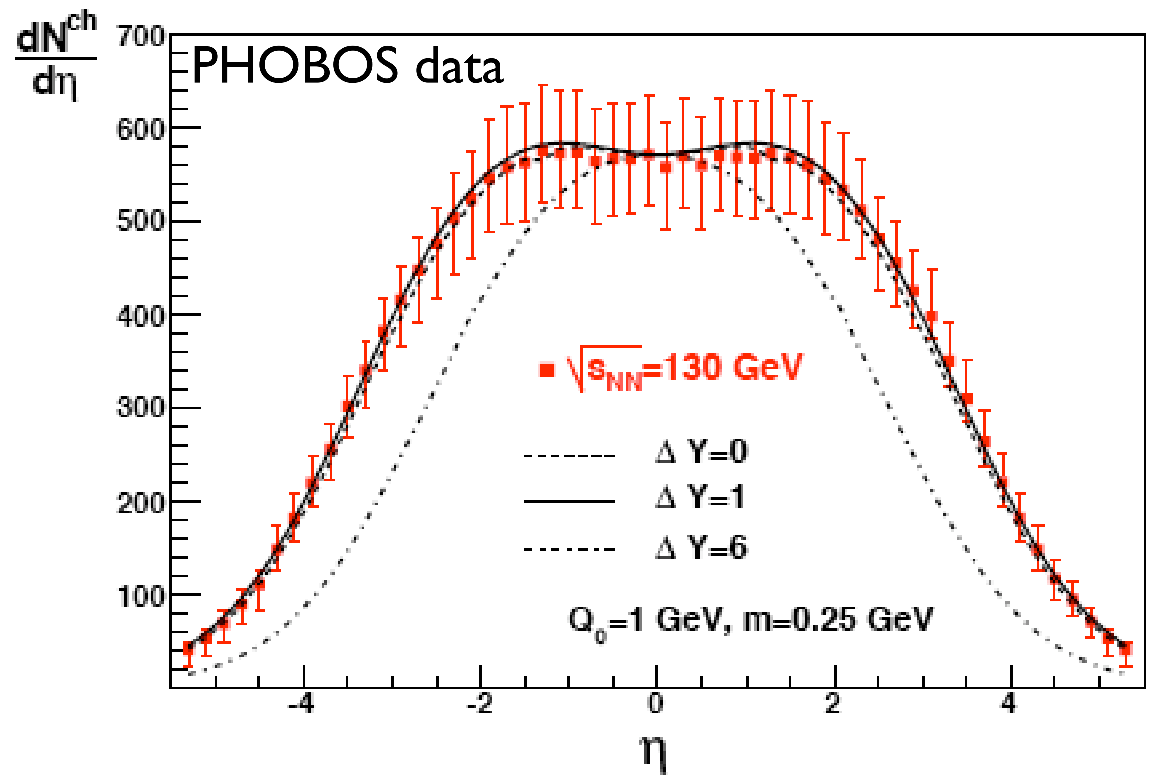
@ Is there significant evolution prior to $\sqrt{s}$ =130 at central rapidity?: NO!

$$Y = \ln\left(\frac{x_0}{x}\right) + \Delta Y_{ev}\,, \qquad x_0 = 0.1\,, \qquad x(\eta=0) = \frac{p_t}{\sqrt{s}}$$

- RHIC energies are governed by pre-asymptotics effects (MV model: good i.c.)
- Solutions close to the scaling region fail to reproduce RHIC data: No universality



$$\lambda = \frac{d\ln Q_s^2(Y)}{dY}$$

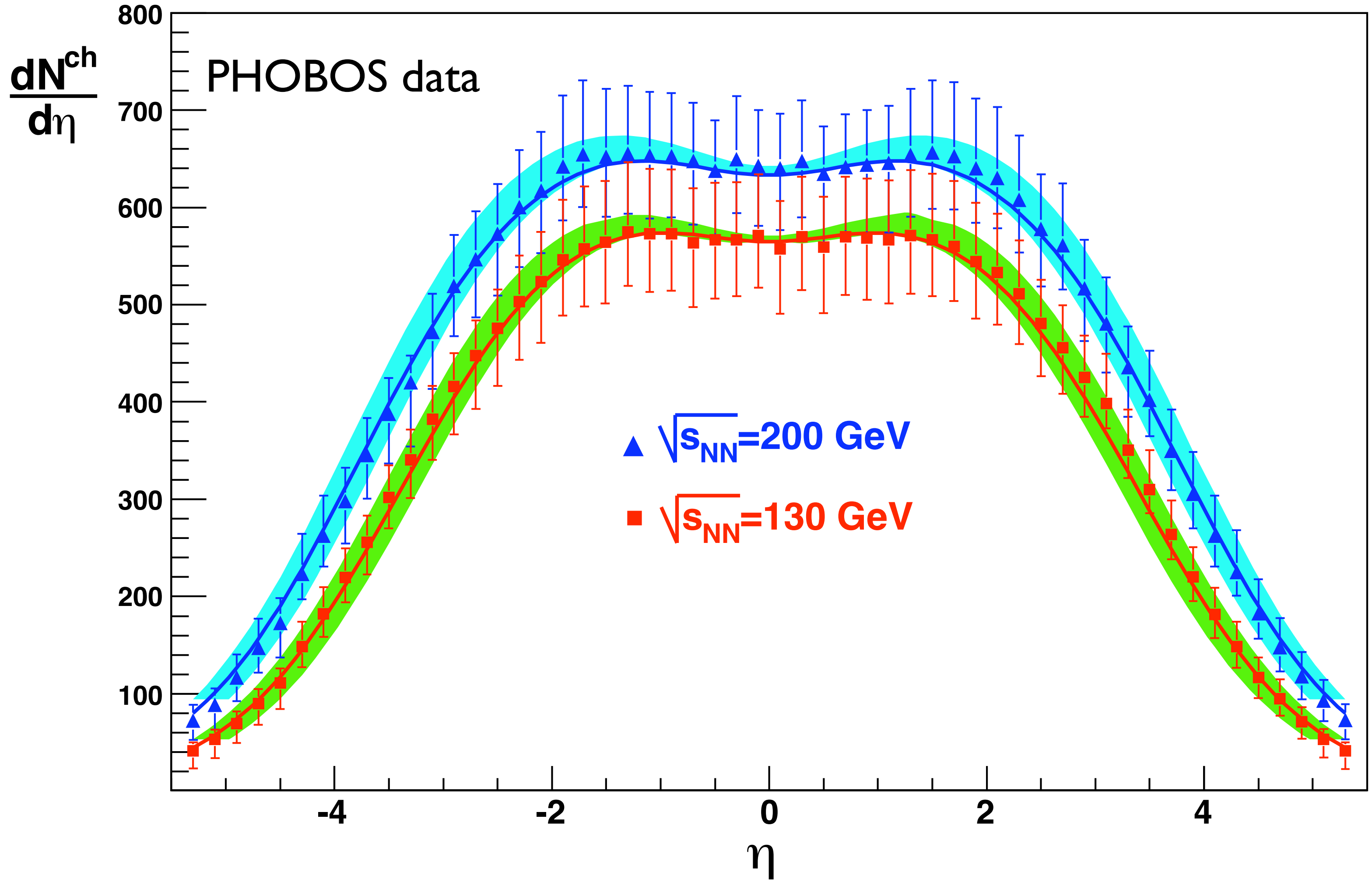


Very good agreement with RHIC data with:

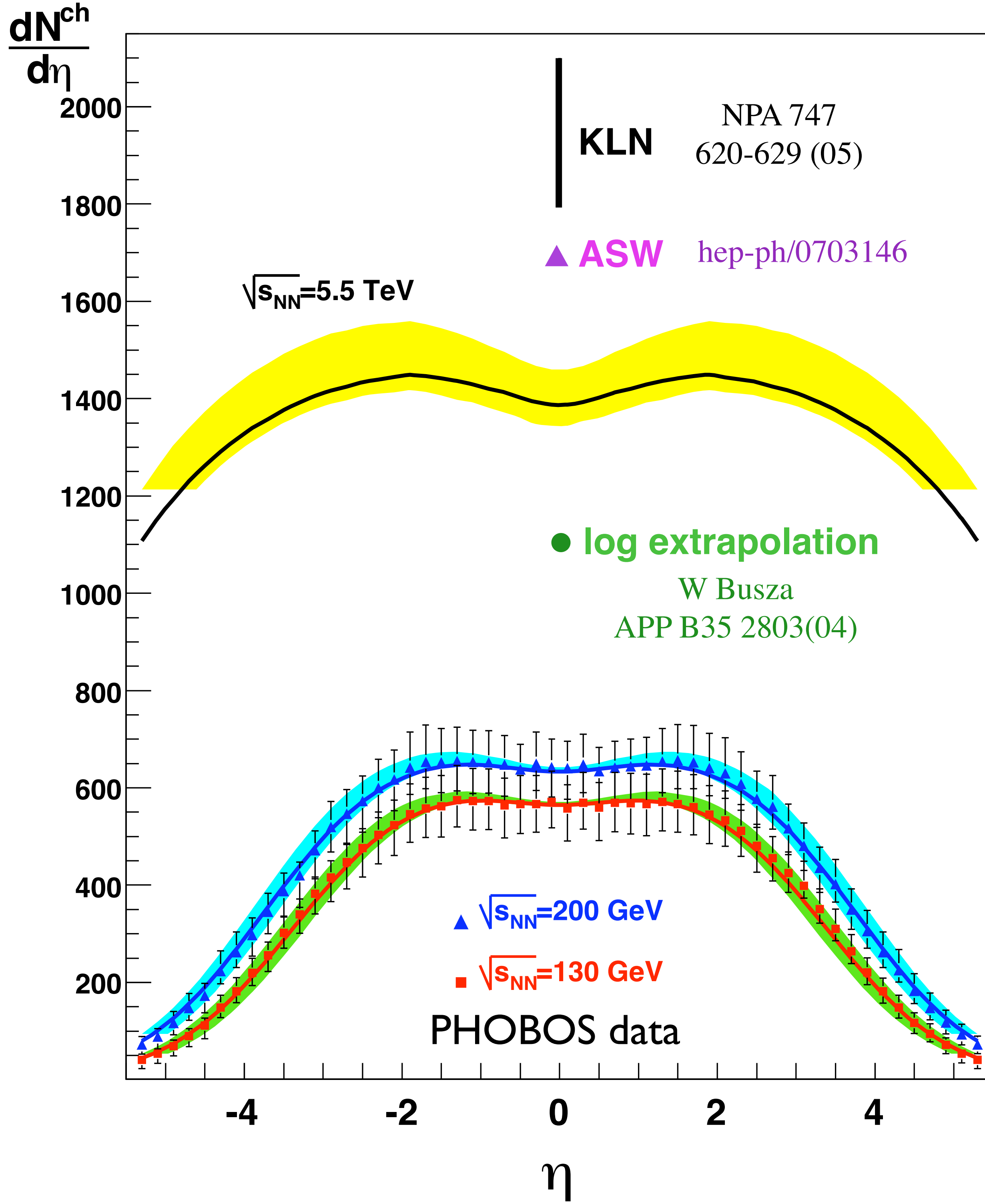
⇒ Gluon mass: m= 0.2 ÷ 0.3 GeV

⇒ Initial saturation scale: $Q_s(\sqrt{s}=130\text{ GeV}, \eta=0) = 0.9 \div 1.1$ GeV

⇒ Pre-asymptotic regime: $\Delta Y_{ev} \leq 2$



Extrapolation to LHC Pb-Pb central collisions at $\sqrt{s}$=5.5 TeV



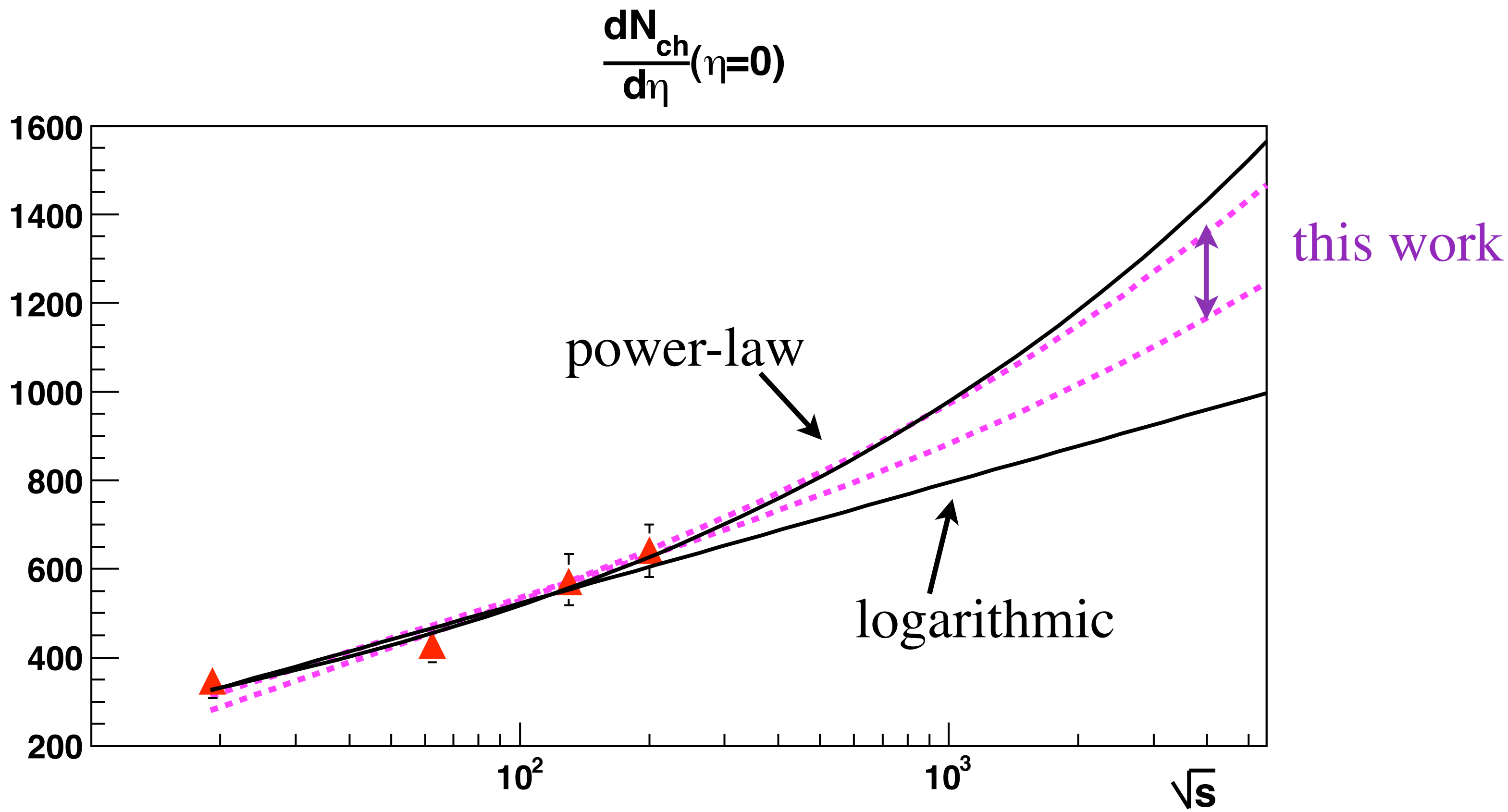
$\approx 2100 \div 1800$

≈ 1700

≈ 1400

≈ 1100

@ Au-Au data at RHIC energies is compatible with both logarithmic and power-law behaviour wrt collision energy



@ Logarithmic trend seems to be dictated from lower energies data

SUMMARY

- Higher order corrections considerably reduce the speed of non-linear evolution
- Multiplicity densities at RHIC can be reproduced using kt-factorization + solutions of the evolution

  ⇒ gluon mass ≈ 0.2 ÷ 0.3 GeV

  ⇒ $Q_s(\sqrt{s}=130\ \text{GeV}, \eta=0) \approx 0.9 \div 1.1$ GeV

  ⇒ Pre-asymptotic regime: strong scaling violations

- Extrapolation to Pb-Pb central collisions at $\sqrt{s}$=5.5 TeV yields a central value:

$$\frac{dN^{\text{evol}}}{d\eta}(\sqrt{s} = 5.5\,\text{TeV})\Big|_{\eta=0} \approx 1400$$

- Smaller than predictions based on HERA information

$$\frac{dN^{\lambda=0.288)}}{d\eta}(\sqrt{s} = 5.5\,\text{TeV})\Big|_{\eta=0} \approx 2100 \div 1700$$

- Larger than empiric extrapolations from lower energies data

$$\frac{dN^{\text{log ext}}}{d\eta}(\sqrt{s} = 5.5\,\text{TeV})\Big|_{\eta=0} \approx 1100$$

What's next?

@ Evolution equation:

⇒ Gluon contribution to high order corrections

⇒ Beyond mean field: Pomeron loops, fluctuations

⇒ Impact parameter dependence

⇒ Energy conservation

They all point to a even stronger reduction of the speed of evolution!!

@ Particle Production:

⇒ Factorization breaking terms (Classical YM EOM?)

⇒ NLO calculation

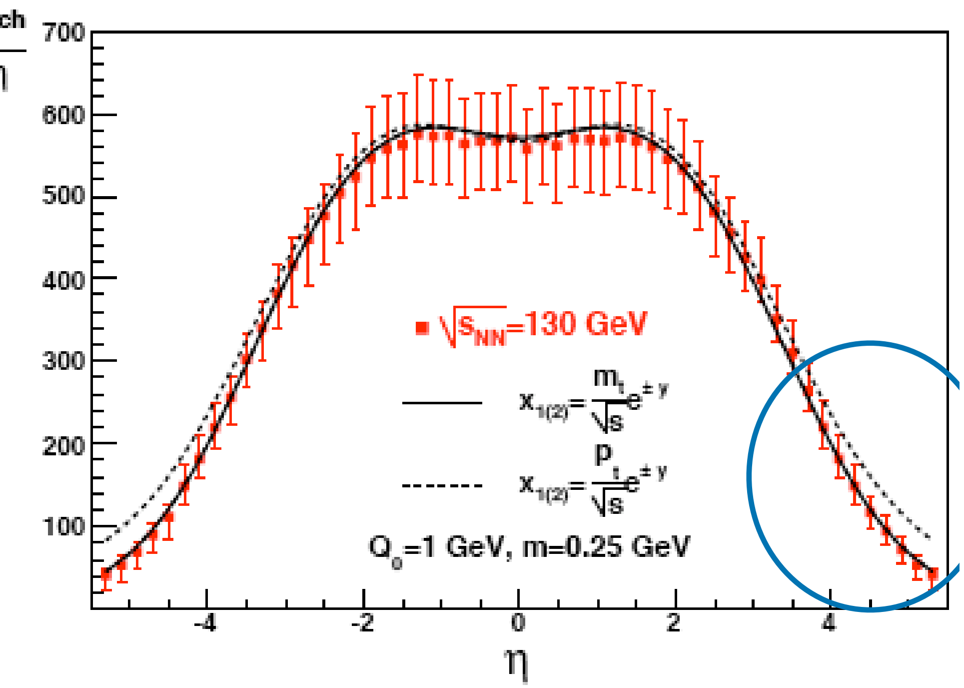
⇒ Large-x effects

⇒ Proper inclusion of non-perturbative effects (CGC + Hydro?)

⇒ Better knowledge of pre-equilibrium / thermalization dynamics

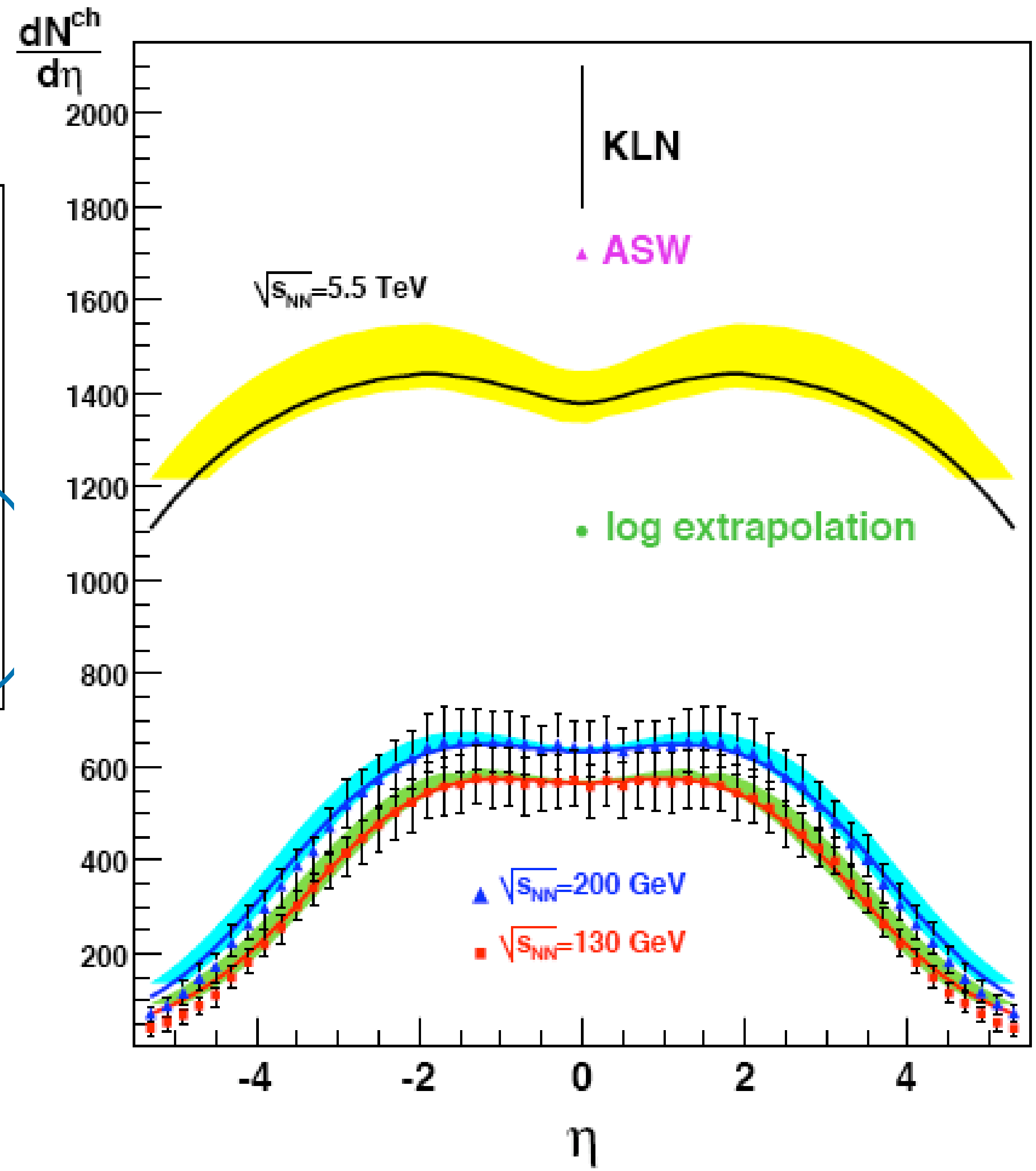
Back up slides

pt vs mt

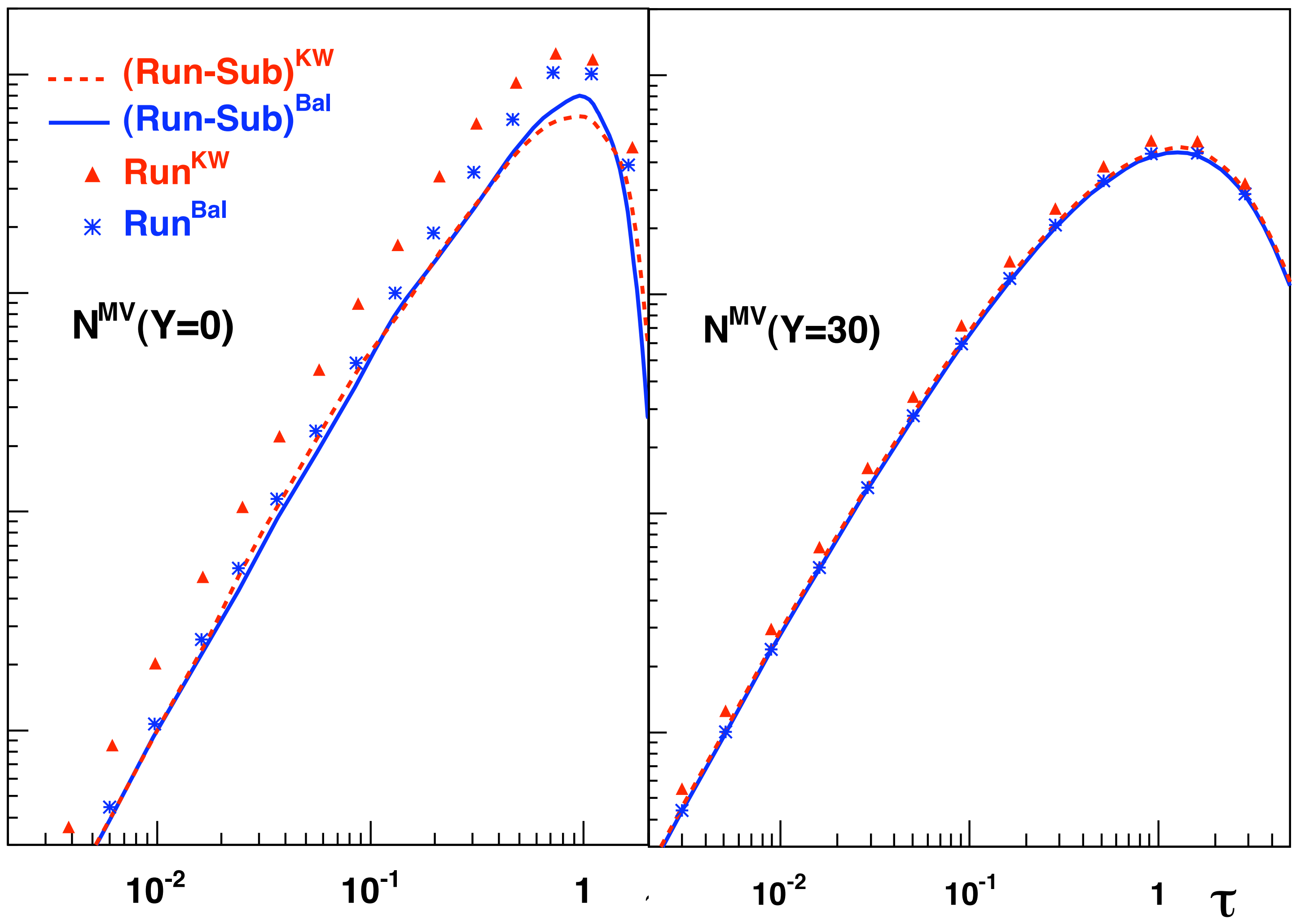


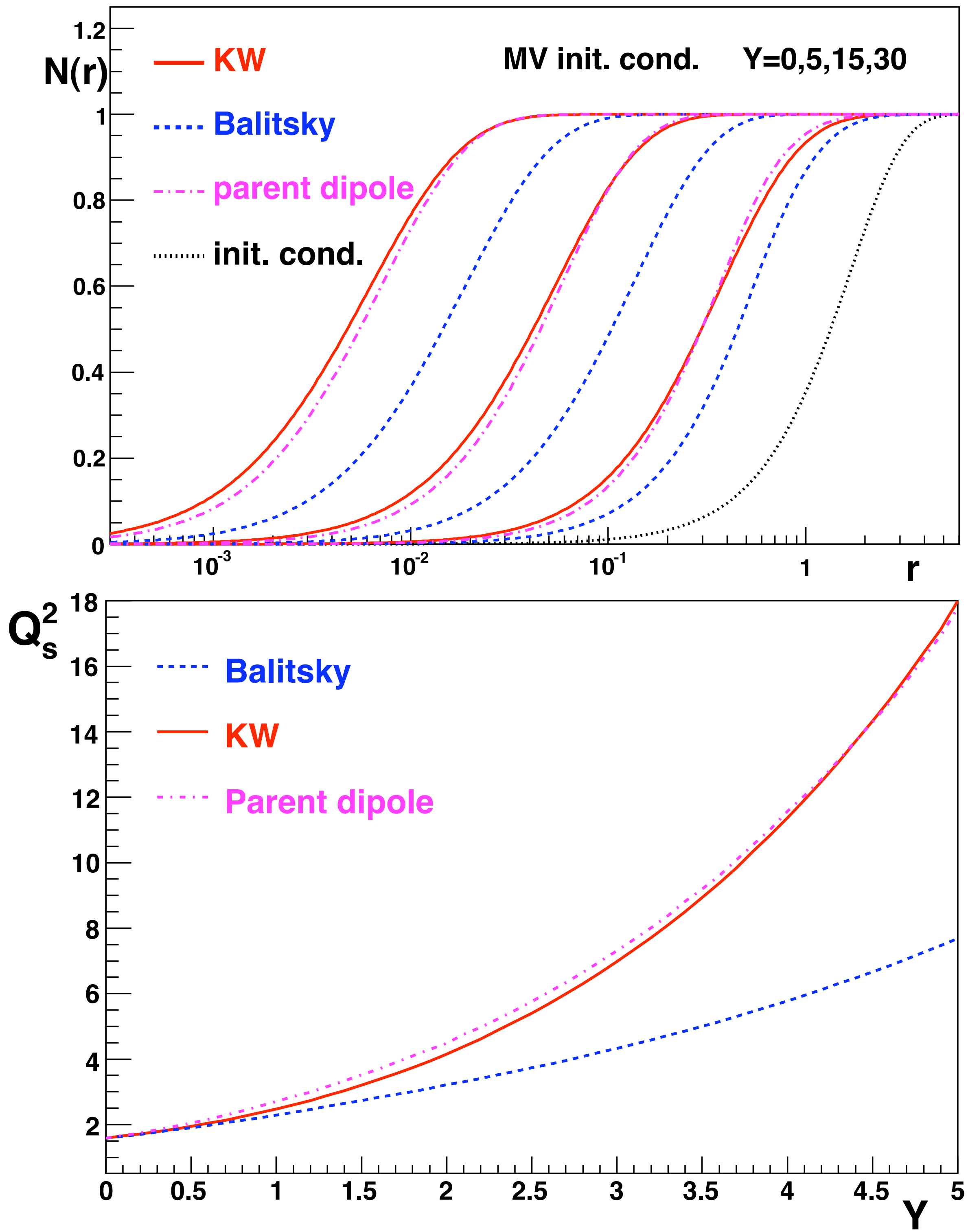
differences only in the
forward region

Extrapolation at η=0
unaffected



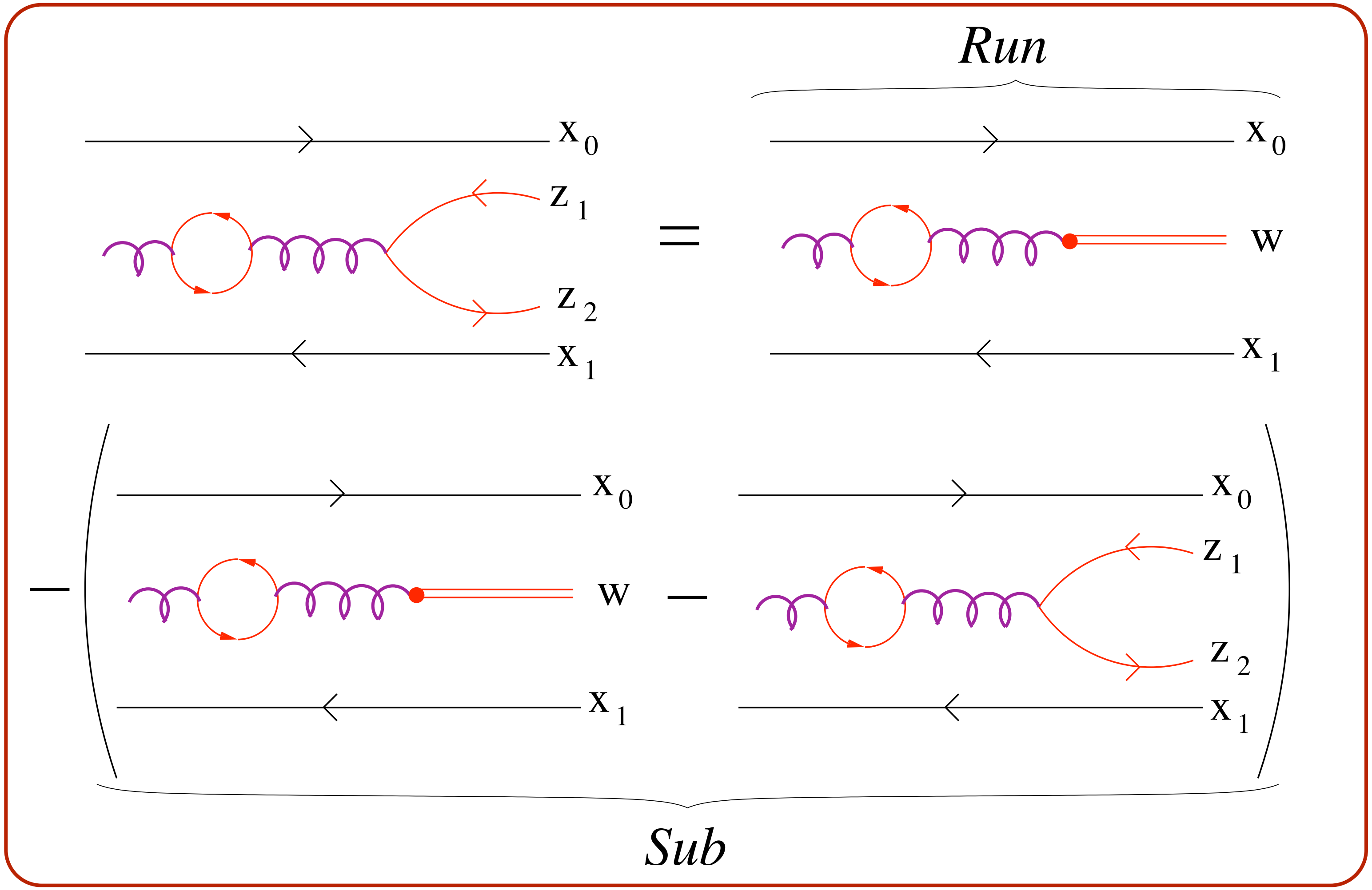
Once the subtraction term is added back, the two approaches agree:





N(r)
KW
Balitsky
parent dipole
init. cond.
MV init. cond.
Y=0,5,15,30
r
10^{-3}
10^{-2}
10^{-1}
1
0
0.2
0.4
0.6
0.8
1
1.2
Q_s^2
Balitsky
KW
Parent dipole
Y
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
2
4
6
8
10
12
14
16
18

- The separation procedure is similar in both calculations:



$$\mathcal{S}[S] = \int d^2 z_1\, d^2 z_2\, K^{sub}\, [S(\underline{x}_0, \underline{\mathbf{w}}, Y)\, S(\underline{\mathbf{w}}, \underline{x}_1, Y) - S(\underline{x}_0, \underline{z}_1, Y)\, S(\underline{z}_2, \underline{x}_1, Y)]$$

- The differences between the two approaches stem from the choice of the subtraction point, w

- In Balitsky's scheme: w = z_1 (or z_2), the quark's (anti-q) transverse position :

$$\mathcal{S}^{Bal}[S] = \int d^2z_1\, d^2z_2\, K^{sub}\,[S(\underline{x}_0, \underline{\mathbf{z_1}}, Y)\, S(\underline{\mathbf{z_1}}, \underline{x}_1, Y) - S(\underline{x}_0, \underline{z}_1, Y)\, S(\underline{z}_2, \underline{x}_1, Y)]$$

An expansion in term of N's result in just non-linear terms ($N^2 << N$ at small-r)

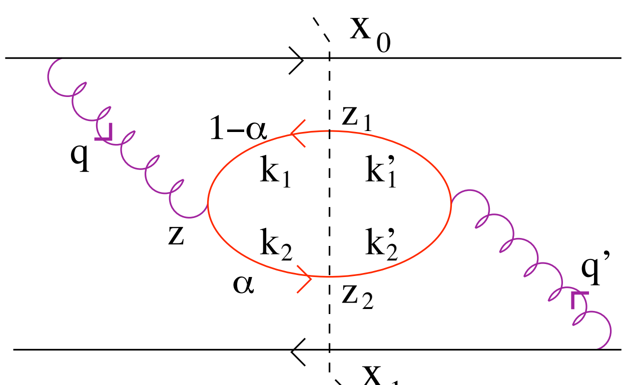
- In KW scheme: w = z =, the gluon's transverse position:

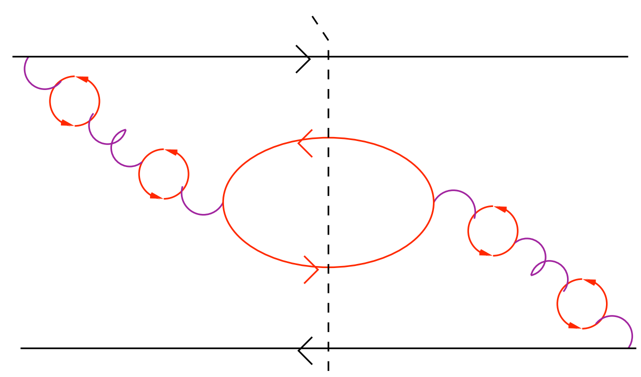
$$\mathcal{S}^{KW}[S] = \int d^2z_1\, d^2z_2\, K^{sub}\,[S(\underline{x}_0, \underline{\mathbf{z}}, Y)\, S(\underline{\mathbf{z}}, \underline{x}_1, Y) - S(\underline{x}_0, \underline{z}_1, Y)\, S(\underline{z}_2, \underline{x}_1, Y)]$$

An expansion in term of N's also includes linear terms.

- The kernel of the subtraction contribution is the same in both cases:

Leading-Nf ⇒ All orders Nf (LCPT) ⇒ Fourier transform to coordinate space





$K_1 \Longrightarrow K_{①}$

SUBTRACTION TERM KERNEL:

$$\mathcal{K}_{①}(\underline{x}_0,\underline{x}_1;\underline{z}_1,\underline{z}_2) = \frac{N_f}{4\pi^4}\int_0^1 d\alpha \, \frac{1}{[\alpha\,(\underline{z}_1-\underline{x}_0)^2+\bar{\alpha}\,(\underline{z}_2-\underline{x}_0)^2]\,[\alpha\,(\underline{z}_1-\underline{x}_1)^2+\bar{\alpha}\,(\underline{z}_2-\underline{x}_0)^2]\,z_{12}^4}$$

$$\Bigg\{\Bigg[-4\,\alpha\,\bar{\alpha}\,\underline{z}_{12}\cdot(\underline{z}-\underline{x}_0)\,\underline{z}_{12}\cdot(\underline{z}-\underline{x}_1)+z_{12}^2\,(\underline{z}-\underline{x}_0)\cdot(\underline{z}-\underline{x}_1)\Bigg]$$

$$\times\left[1-\alpha_\mu\,\beta_2\,\ln\left(\frac{1}{R_T^2(\underline{x}_0)\,\mu_{\overline{\mathrm{MS}}}^2}\right)+o(\alpha_\mu^2)\right]\left[1-\alpha_\mu\,\beta_2\,\ln\left(\frac{1}{R_T^2(\underline{x}_1)\,\mu_{\overline{\mathrm{MS}}}^2}\right)+o(\alpha_\mu^2)\right]$$

$$+2\,\alpha\,\bar{\alpha}\,(\alpha-\bar{\alpha})\,z_{12}^2\left\{\underline{z}_{12}\cdot(\underline{z}-\underline{x}_0)\left[1-\alpha_\mu\,\beta_2\,\ln\left(\frac{1}{R_T^2(\underline{x}_0)\,\mu_{\overline{\mathrm{MS}}}^2}\right)+o(\alpha_\mu^2)\right]\right.$$

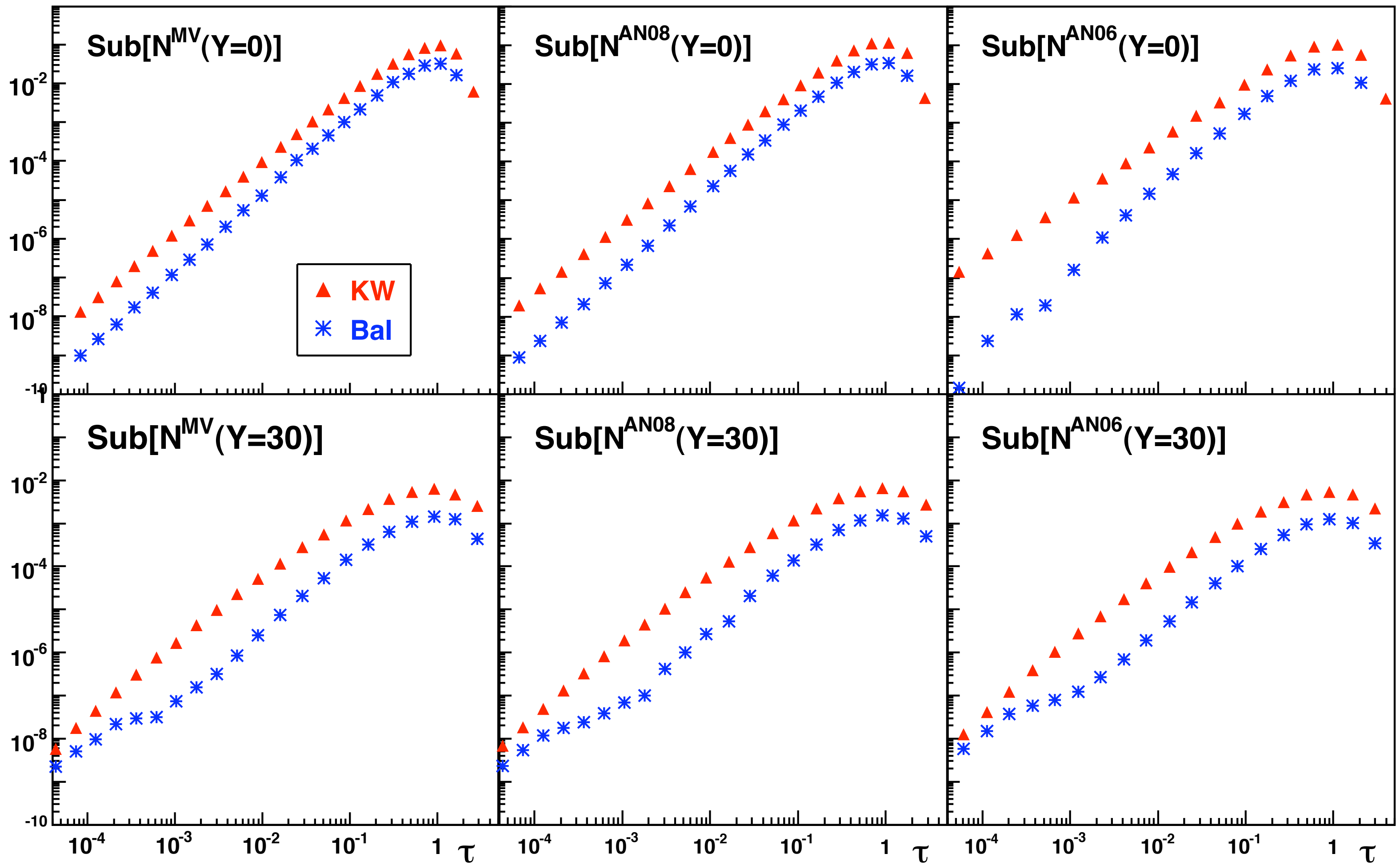
$$\times\left[1-\alpha_\mu\,\beta_2\,\ln\left(\frac{1}{R_L^2(\underline{x}_1)\,\mu_{\overline{\mathrm{MS}}}^2}\right)+o(\alpha_\mu^2)\right]+\underline{z}_{12}\cdot(\underline{z}-\underline{x}_1)$$

$$\left.\times\left[1-\alpha_\mu\,\beta_2\,\ln\left(\frac{1}{R_L^2(\underline{x}_0)\,\mu_{\overline{\mathrm{MS}}}^2}\right)+o(\alpha_\mu^2)\right]\left[1-\alpha_\mu\,\beta_2\,\ln\left(\frac{1}{R_T^2(\underline{x}_1)\,\mu_{\overline{\mathrm{MS}}}^2}\right)+o(\alpha_\mu^2)\right]\right\}$$

$$+4\,\alpha^2\,\bar{\alpha}^2\,z_{12}^4\left[1-\alpha_\mu\,\beta_2\,\ln\left(\frac{1}{R_L^2(\underline{x}_0)\,\mu_{\overline{\mathrm{MS}}}^2}\right)+o(\alpha_\mu^2)\right]\left[1-\alpha_\mu\,\beta_2\,\ln\left(\frac{1}{R_L^2(\underline{x}_1)\,\mu_{\overline{\mathrm{MS}}}^2}\right)+o(\alpha_\mu^2)\right]\Bigg\}.$$

- Here: $N_f \to -6\Pi\beta_2$ .Part of the gluon contribution is also taken into account

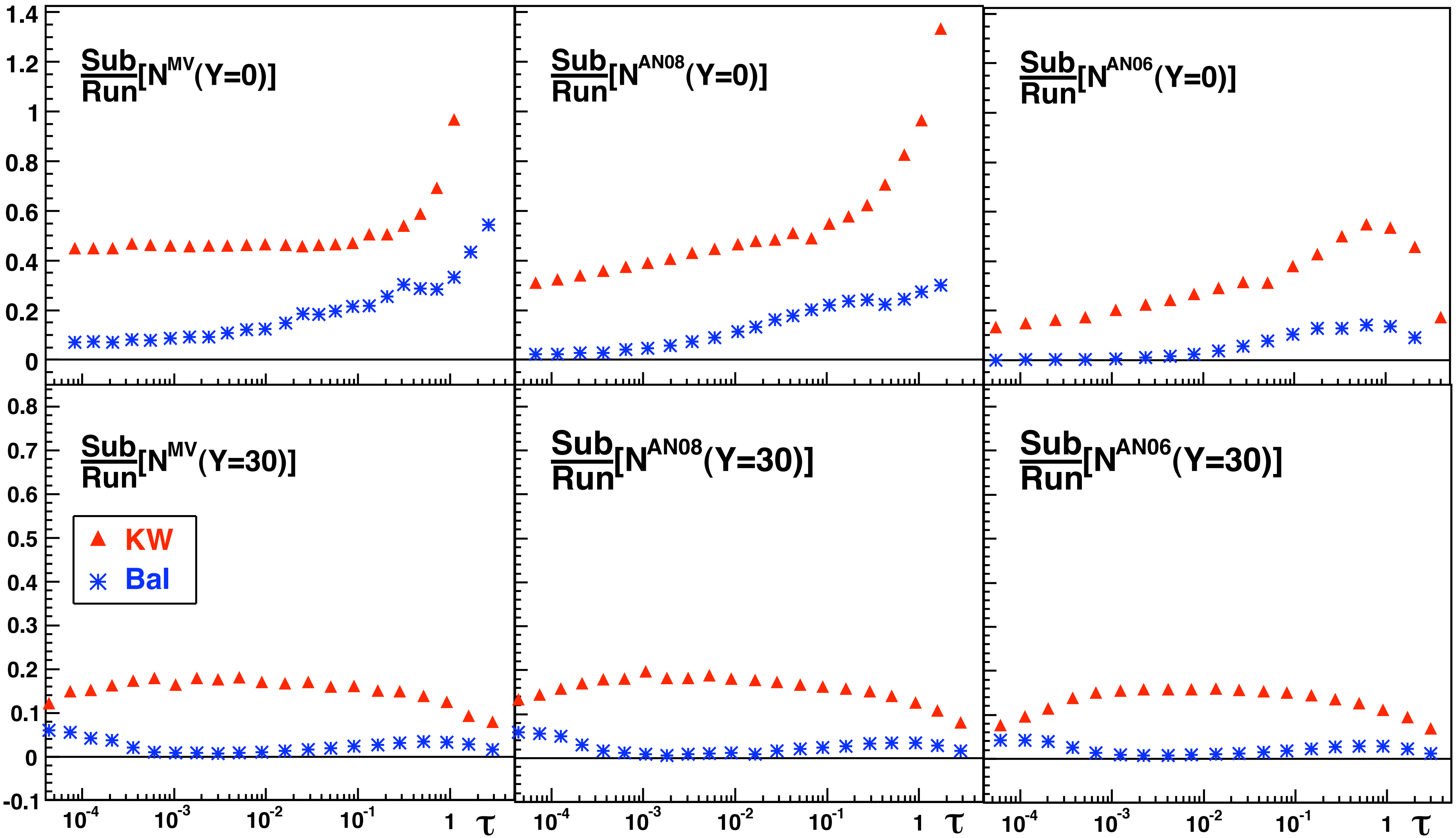
- The subtraction term is larger in KW's scheme than in Balitsky's:



- It has the same sign as the running term: It slows down the evolution

$$\mathcal{F} = \mathcal{R} - \mathcal{S}$$

- The subtraction term is larger in KW's scheme than in Balitsky's:



- The relative contribution of the subtraction term to the evolution fades away at large rapidity