The Color Glass Condensate

QCD at modern collider facilities

Heribert Weigert

University of Cape Town
CTMP
Centre for Theoretical and Mathematical Physics

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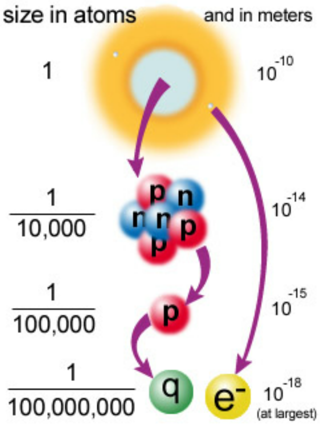
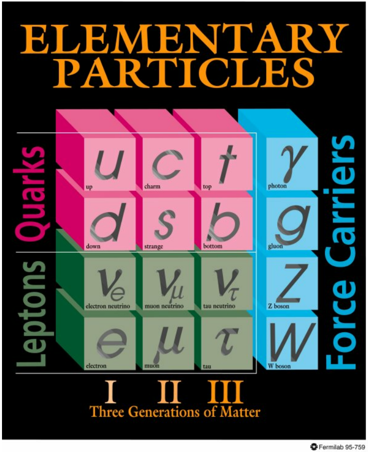
Outline

Outline

From atoms to the standard model





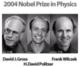
+Higgs

QCD: the strong interaction

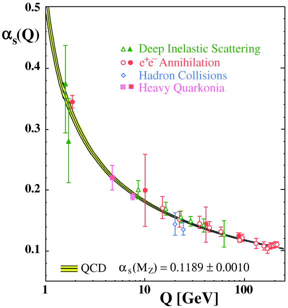
- Focus on QCD:

+Higgs

- Running coupling

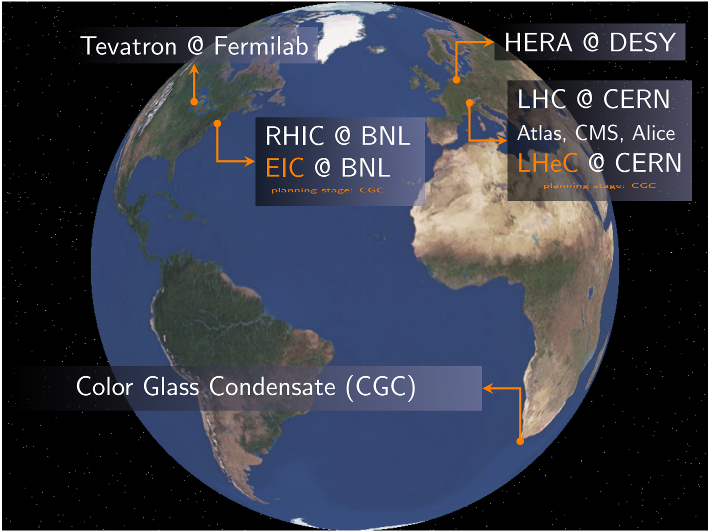


confinement

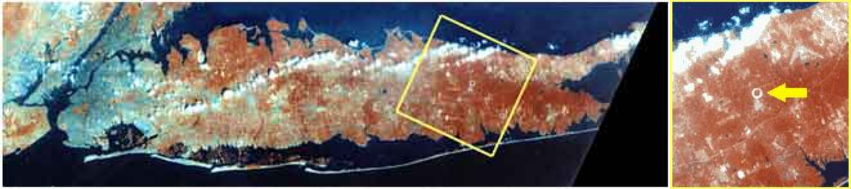


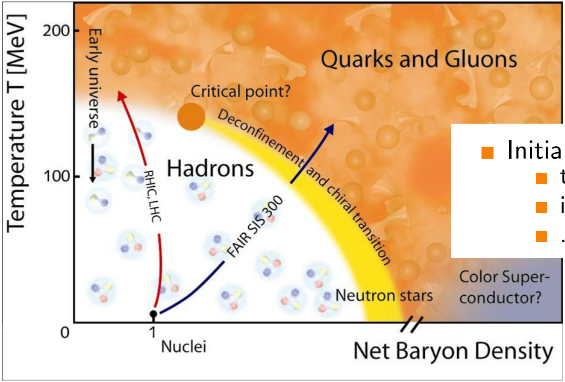
asymptotic freedom

High energy physics viewed from UCT



The Quark Gluon Plasma at RHIC and LHC





- Initial to final state via
  - thermalization (times!)
  - initial hard particle production
  - . . .

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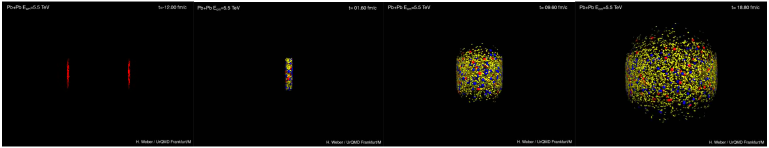

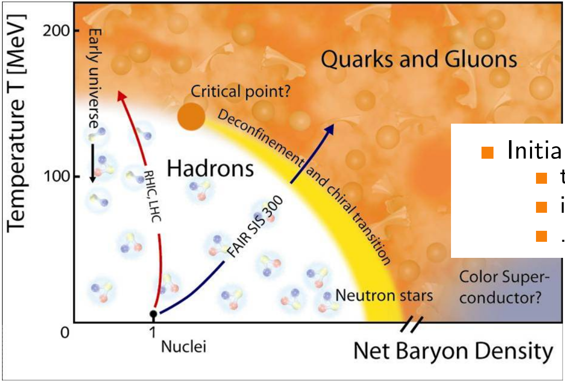

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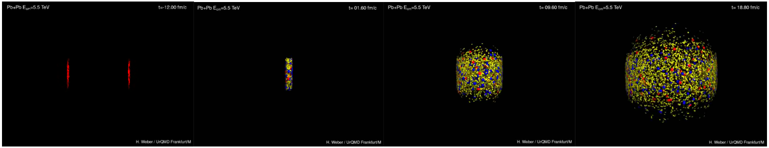
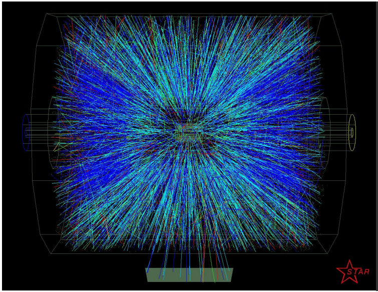
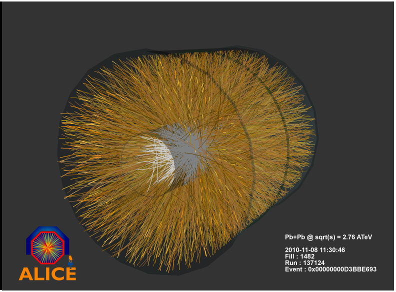






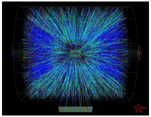
RHIC event (STAR), side view

LHC event (ALICE)

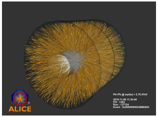
Particle production at modern colliders

- Large amounts of energy available: 200-14000 m_{proton}
- heavy ions @ RHIC & LHC: QGP

RHIC @ 200GeV/nucleon pair



LHC @ 2.76TeV/nucleon pair



LHC @ 4TeV/nucleon pair

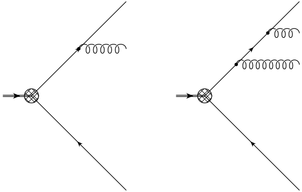
??

- QCD drives particle production
  - serious backgrounds for particle searches
  - new physics phenomena

copious gluon production → Color Glass Condensate CGC

Energy dependence: from photons to gluons

- **photon-like contributions**



- enhanced by phase space integrals $\frac{dE}{E}\frac{d\theta}{\theta}$ ➡ $\alpha_s \ln E \ln\theta$
- all orders calculation needed $\sum_{n=0}^{\infty}(\alpha_s \ln E)^n \ldots$

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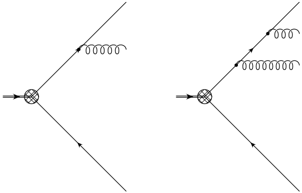
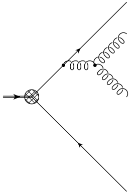


- **QCD: charged gluons**



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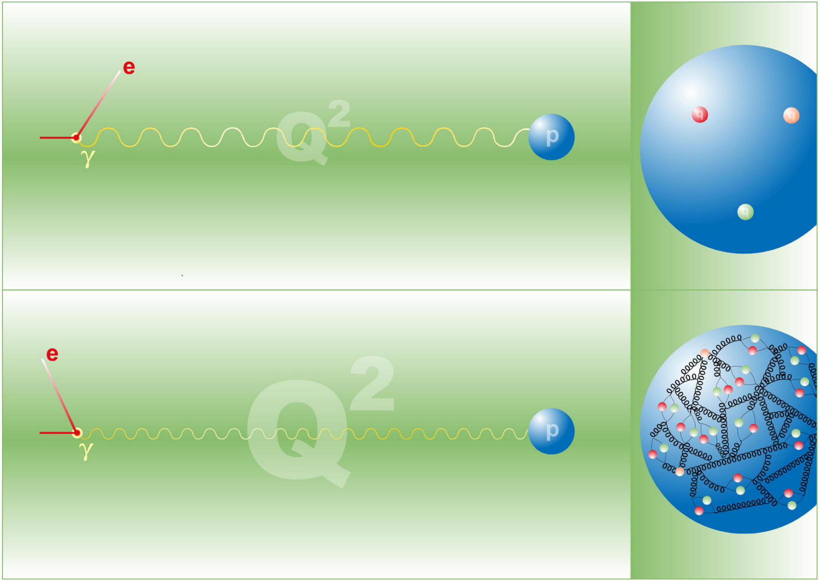
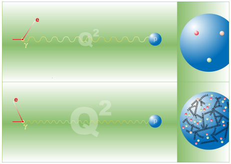
- all orders calculation needed $\sum_{n=0}^{\infty}(\alpha_s \ln E)^n \ldots$
- gluons charged ➡ radiation nonlinear in QCD

Example: ep at HERA



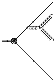
Example: ep at HERA

- Q^2 determines the resolution



$Q^2 := -q^2 \gg 0$
spacelike!
transverse resolution
$\Delta \boldsymbol{r} \sim \frac{1}{Q}$

- $\ln E$ comes with many aliases:

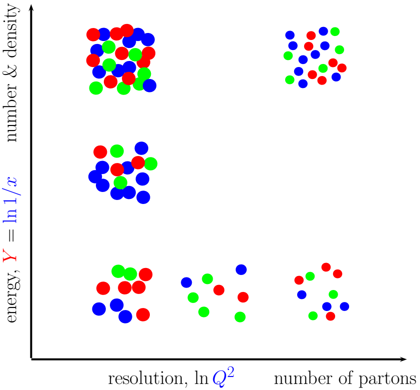


$$Y = \ln \frac{1}{x} = \ln E$$

all used synonymously

- Y rapidity
- $x = x_{\text{Bj}} := \frac{Q^2}{2p.q} = \frac{Q^2}{2m\ E}$ Bjorken x

Large energies mean large densities



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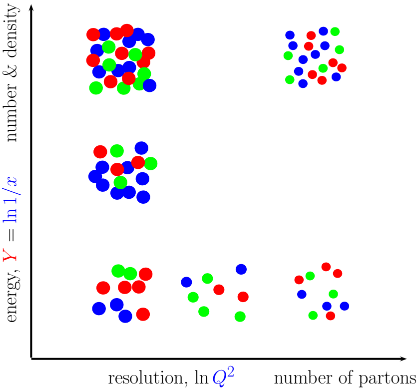

- density ➡ nonlinear effects
- finite correlation length R_s

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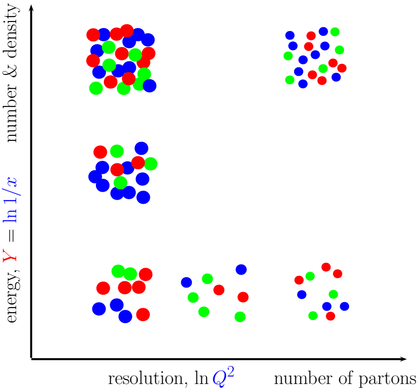

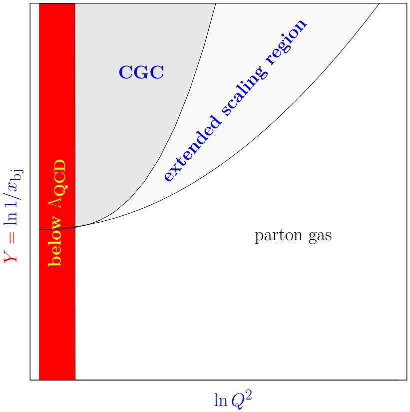

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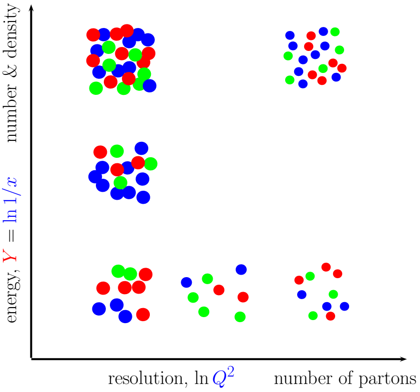
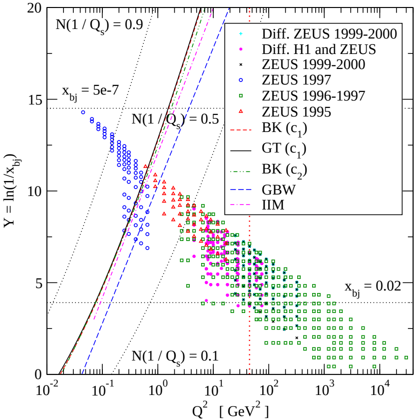




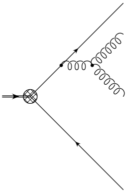
- density ➡ nonlinear effects
- finite correlation length R_s

- Real world example: HERA ep

Why the name?

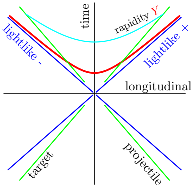
Color

- QCD
- and QCD only!
  quarks and gluons



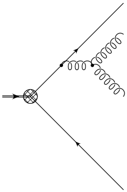
Glass

- fields evolve slowly compared to natural time scales
- time scales
  energy, time dilation



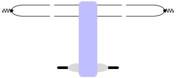
Condensate

- phase space densitiy $\sim \frac{1}{\alpha_s}$ & saturates
- density
  energy, gluons charged



Outline

Total cross section (zeroeth order in $\alpha^m(\alpha_s \ln(1/x))^n$)

$\sigma_{\text{DIS}}(Y, Q^2) = 2\text{Im}$ 

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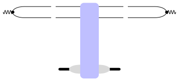
photon wave functions/impact factor

$\sigma_{\mathrm{DIS}}(Y, Q^2) = 2\mathrm{Im}$  $= \int d^2 r \; |\psi^2|(r^2 Q^2)$

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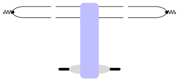
$\sigma_{\mathrm{DIS}}(Y, Q^2) = 2\mathrm{Im}$  $= \int d^2r \; |\psi^2|(r^2 Q^2) \; 2\int d^2b \, \langle \frac{\mathrm{tr}(1 - U_{\boldsymbol{x}} U_{\boldsymbol{y}}^\dagger)}{N_c} \rangle (Y)$

σ_{dipole}

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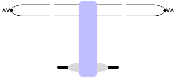
$\sigma_{\mathrm{DIS}}(Y, Q^2) = 2\mathrm{Im}$  $= \int d^2r \; |\psi^2|(r^2 Q^2) \; 2\int d^2b \; \langle \frac{\mathrm{tr}(1 - U_{\boldsymbol{x}} U^\dagger_{\boldsymbol{y}})}{N_c} \rangle (Y)$

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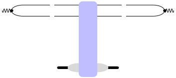
$\sigma_{\text{DIS}}(Y, Q^2) = 2\text{Im}$  $= \int d^2r\ |\psi^2|(r^2 Q^2)\ 2\int d^2b\ \langle \frac{\text{tr}(1 - U_{\boldsymbol{x}} U^\dagger_{\boldsymbol{y}})}{N_c} \rangle(Y)$

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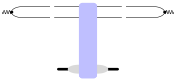

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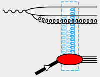
$\frac{d}{dY} \langle \ldots \rangle(Y)$



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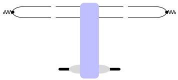

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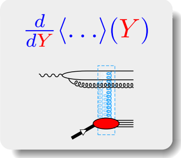
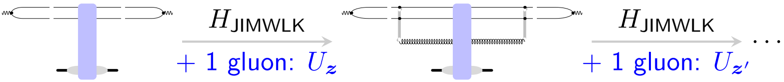


- Bookkeeping device: $\langle \ldots \rangle(Y) = \int \hat{D}[U]\ \ldots \hat{Z}_Y[U]$

The JIMWLK evolution equation



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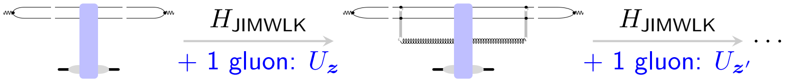
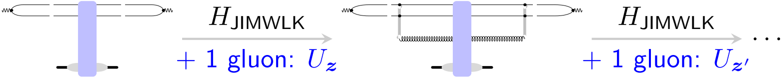


- $$\frac{d}{dY} Z_Y[U] = -H_{\text{JIMWLK}}[U] \; Z_Y[U]$$

Heribert Weigert **Nucl. Phys. A703**, 2002, 823

explicit form

The JIMWLK evolution equation



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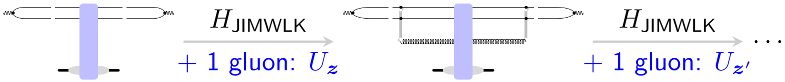

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Heribert Weigert **Nucl. Phys. A703**, 2002, 823 ▸ explicit form

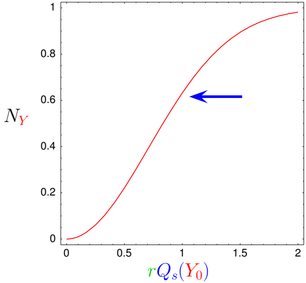
- resums all $\sim [\alpha_s \ln(1/x)]^n$ (at LO)
- ➡ energy dependence of $\langle \ldots \rangle (Y)$

Saturation scale and cross section

- $\langle \ldots \rangle(Y)$ ➡ $\langle \frac{\mathrm{tr}(1 - U_{\boldsymbol{x}} U^\dagger_{\boldsymbol{y}})}{N_c} \rangle(Y) =: N_Y(\boldsymbol{r})$

Saturation scale and cross section

- $\langle \ldots \rangle(Y) \quad \longrightarrow \quad \langle \frac{\text{tr}(1 - U_{\boldsymbol{x}} U^\dagger_{\boldsymbol{y}})}{N_c} \rangle(Y) =: N_Y(\boldsymbol{r})$
- qualitative expectation:



$$R_s(Y) \sim \frac{1}{Q_s(Y)}$$

$R_s(Y) \equiv$ correlation length
$Q_s(Y) \equiv$ saturation scale

Saturation scale and cross section

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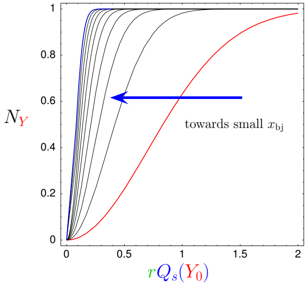
- qualitative expectation:

  correlation length shrinks:



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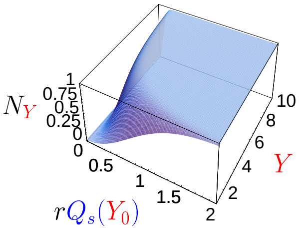
JIMWLK: IR safety and scaling

- Activity (new gluon production) near $Q_s(Y)$



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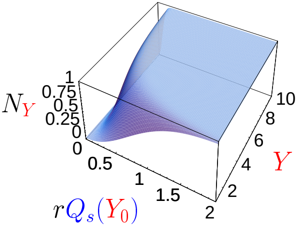

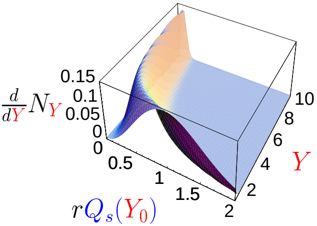

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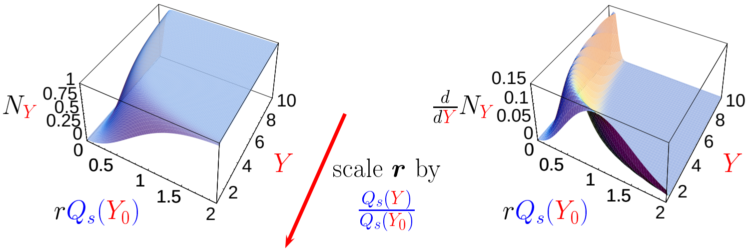

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Detailed analysis:

scaling with $Q_s(Y)$
[persists approximately @ NLO]

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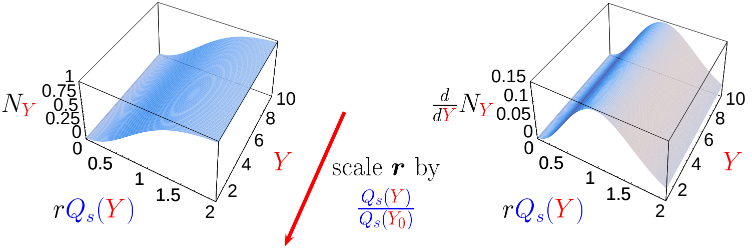

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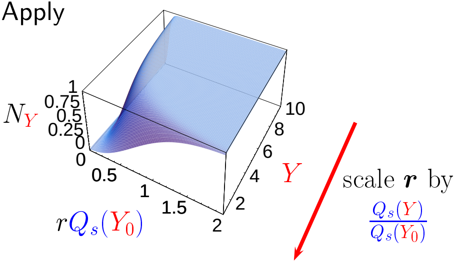
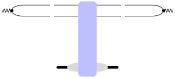
Geometric scaling @ HERA

Apply



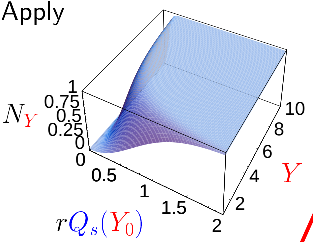
to Hera

$\sigma_{\text{DIS}}(Y, Q^2) = 2\text{Im}$ 

Golec-Biernat, Wüsthoff; PRD **60** (1999) 114023 [hep-ph/9903358]

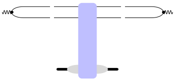
Geometric scaling @ HERA

Apply



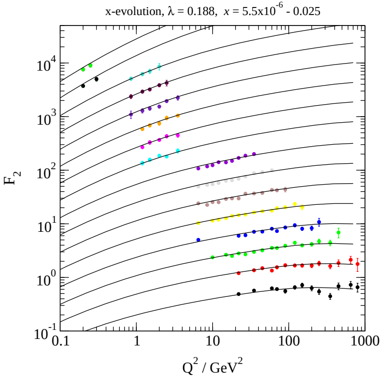
scale $\boldsymbol{r}$ by $\frac{Q_s(Y)}{Q_s(Y_0)}$

to Hera

$\sigma_{\rm DIS}(Y, Q^2) = 2\mathrm{Im}$ 

- scaling fit to HERA:

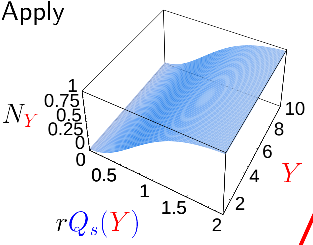
$$\sigma(Y, Q^2) \sim F_2(Y, Q^2) \cdot Q^2$$



Golec-Biernat, Wüsthoff; PRD 60 (1999) 114023 [hep-ph/9903358]

Geometric scaling @ HERA

Apply



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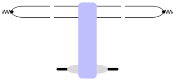
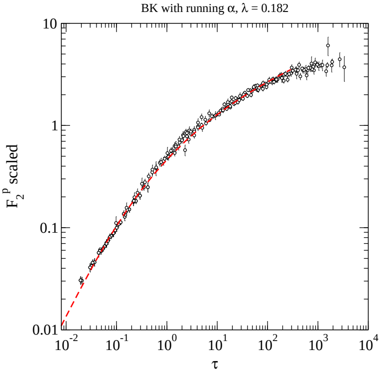
$\sigma_{\mathrm{DIS}}(Y, Q^2) = 2\mathrm{Im}$ 

- scaling fit to HERA:

$$\sigma(Y, Q^2) = \sigma(Y_0, \tau = Q^2 \frac{Q_s^2(Y_0)}{Q_s^2(Y)})$$



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Geometric scaling @ HERA

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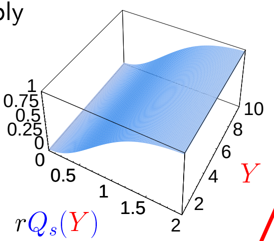

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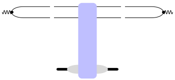
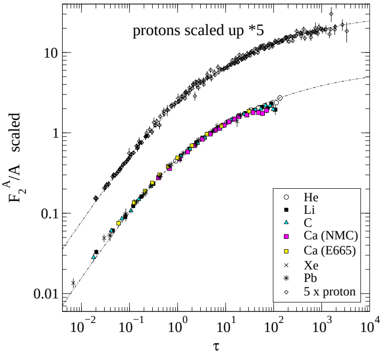
to Hera

$$\sigma_{\rm DIS}(Y, Q^2) = 2\text{Im}$$



- … & with nuclei:

$$\sigma(Y, Q^2) = \sigma(Y_0, \tau = Q^2 \frac{(Q_s^A(Y_0))^2}{(Q_s^A(Y))^2})$$



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Outline

NLO-corrections

LO: $[\alpha_s \ln(1/x)]^n$; NLO: $[\alpha_s]^n [\ln(1/x)]^{n-1}$

- Corrections to evolution:

- Corrections to wave functions/impact factors

NLO-corrections

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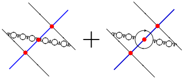

Gardi, Kuokkanen, Rummukainen, Weigert
Weigert, Kovchegov
Balitsky

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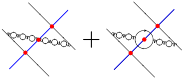
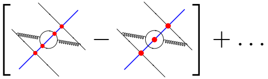


Gardi, Kuokkanen, Rummukainen, Weigert
Weigert, Kovchegov
Balitsky

  - new channels: quark/gluon-pair production ("conformal")



Gardi, Kuokkanen, Rummukainen, Weigert
Weigert, Kovchegov

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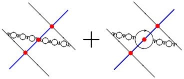

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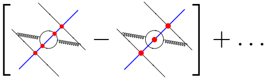

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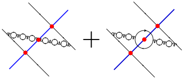

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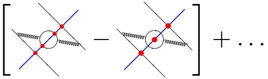

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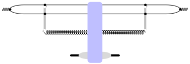

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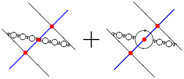

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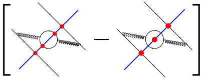
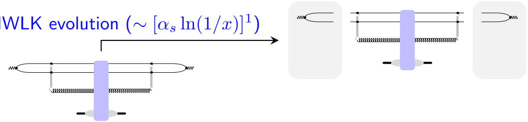


$+ \ldots$

Gardi, Kuokkanen, Rummukainen, Weigert
Weigert, Kovchegov

- Corrections to wave functions/impact factors

LO JIMWLK evolution ($\sim [\alpha_s \ln(1/x)]^1$)



✓

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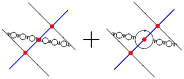

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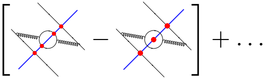

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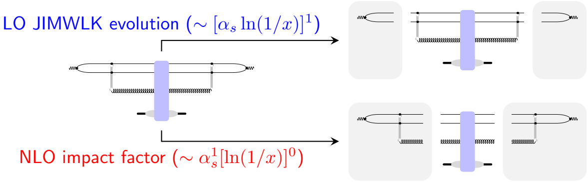


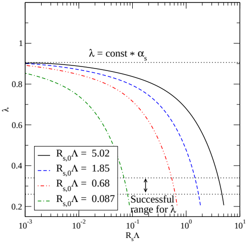
✓

Balitsky, Chirilli (2011)
not yet included

Effects of NLO-corrections

- NLO evolution: speed reduced

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



LO JIMWLK

- too fast

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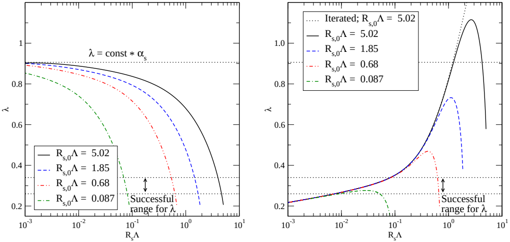

LO JIMWLK

- too fast

+ running coupling

- remarkable slowdown
- fits become possible

▸ large effect expected

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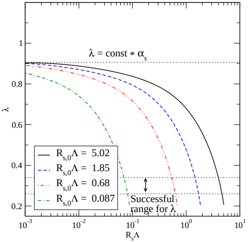

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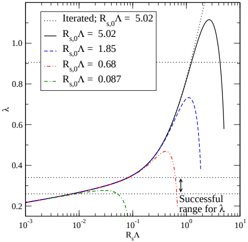

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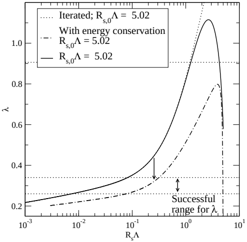

$+$ energy cons. corr.

- asymptotic fits preferred

large effect expected

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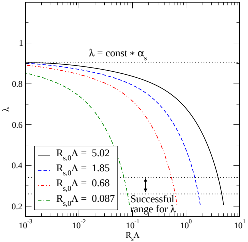

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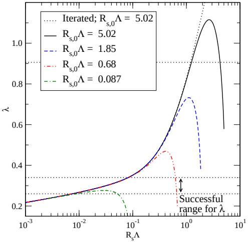
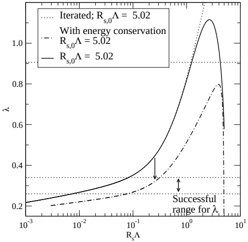


\+ running coupling

- remarkable slowdown
- fits become possible

▸ large effect expected



\+ energy cons. corr.

- asymptotic fits preferred

- Effect of NLO impact factors? yet unknown

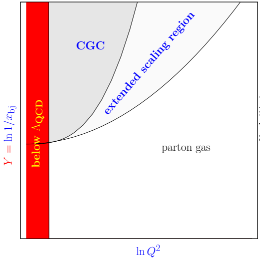
Fit to HERA data

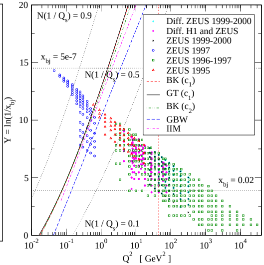
- Total cross section:

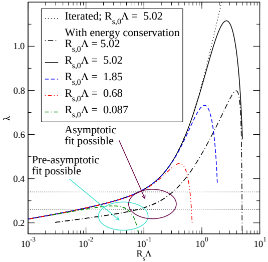
- Rapidity gap events (diffractive events):

Fit to HERA data

- Total cross section:



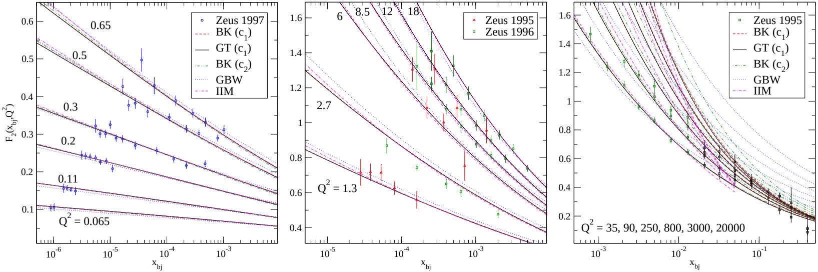




- Rapidity gap events (diffractive events):

Fit to HERA data

- Total cross section: $\chi^2/\text{dof} \sim .8$



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Fit to HERA data

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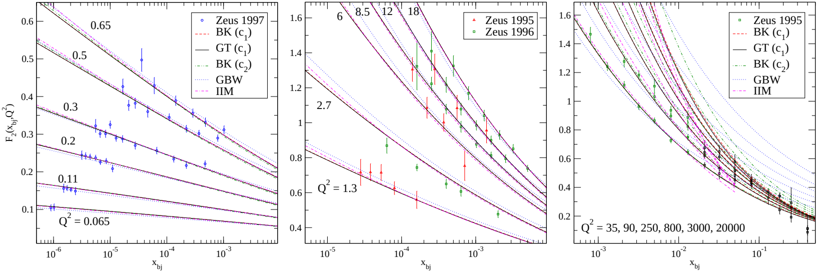
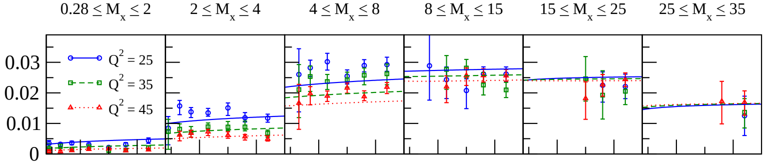


- Rapidity gap events (diffractive events): $\chi^2/\text{dof} \sim 1.3$

  ratios diffractive/total cross sections (sample only):

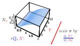


- Lack of NLO impact factors: predictive power down!

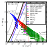
Outline

Applications

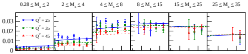
- Geometric scaling in $\gamma^* p$ & $\gamma^* A$
  Golec-Biernat Wüsthoff, Kwieczinski; Kuokkanen, Rummukainen, Weigert; Albacete, Salgado, Wiedemann



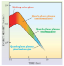

- Precision fits to HERA σ_{total}
  Kuokkanen, Rummukainen, Weigert




- almost precision fits for HERA $\sigma_{\text{diffractive}}$
  Kuokkanen, Rummukainen, Weigert



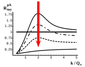
- Sets the initial conditions of heavy ion collisions
  Kovner, Weigert, McLerran; Venugopalan, Krasnitz; Lappi



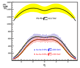
- qualitative only: BRAHMS (RHIC)
  Suppression of the Cronin peak at forward rapidities (large Y) Kovchegov; Kovner, Wiedemann

$$R^{pA} = \frac{\frac{d\sigma^{pA}}{d^2k\,dY}}{A\,\frac{d\sigma^{pp}}{d^2k\,dY}}$$

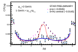
$p_t \sim Q_s(Y)$



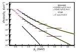
- Fit multiplicities at RHIC, predict LHC
  Albacete, partial NLO



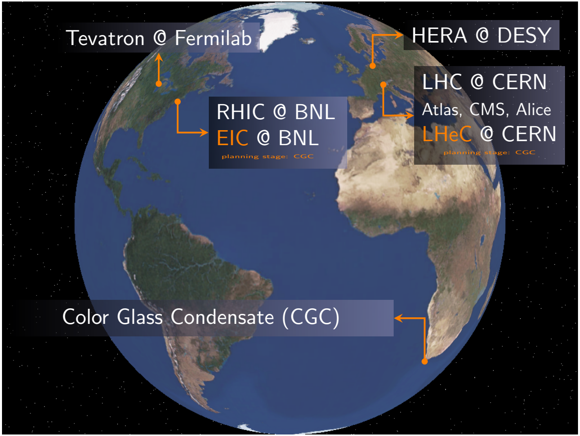
- Monojets at RHIC
  Albacete, Marquet, partial NLO



- Forward (exclusive) particle production at RHIC (predict LHC?)
  Albacete, Marquet, partial NLO



The Color Glass Condensate, a birds eye view



CGC in experiments @:

- RHIC, HERA
- Tevatron (new!)
- LHC
- EIC & LHeC (dedicated!)

Main characteristic:

- correlation length $R_s(Y) \sim \frac{1}{Q_s(Y)}$
- Q_s-scaling: Y dependence via $Q_s(Y)$

Outline

The JIMWLK Hamiltonian

back

$$H_{\text{JIMWLK}} = -\frac{1}{2}\frac{\alpha_s}{\pi^2}\,\mathcal{K}_{\boldsymbol{xzy}}\left[i\nabla^a_x i\nabla^a_y + i\bar\nabla^a_x i\bar\nabla^a_y + \tilde{U}^{ab}_z(i\bar\nabla^a_x i\nabla^b_y + i\nabla^a_x i\bar\nabla^b_y)\right]$$

$$\mathcal{K}_{\boldsymbol{xzy}} = \frac{(\boldsymbol{x}-\boldsymbol{z})\cdot(\boldsymbol{z}-\boldsymbol{y})}{(\boldsymbol{x}-\boldsymbol{z})^2(\boldsymbol{z}-\boldsymbol{y})^2}$$

[integration convention for x, z, y]

$i\nabla^a_{\boldsymbol{x}}$ and $i\bar\nabla^a_{\boldsymbol{x}}$ are functional derivatives:

$$i\nabla^a_{\boldsymbol{x}} := -[U_{\boldsymbol{x}}t^a]_{ji}\frac{\delta}{\delta U_{\boldsymbol{x},ij}} \qquad i\bar\nabla^a_{\boldsymbol{x}} := [t^a U_{\boldsymbol{x}}]_{ji}\frac{\delta}{\delta U_{\boldsymbol{x},ij}}$$

The JIMWLK Hamiltonian

back

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generate l. & r. inv vector fields, r & l rotations:

$$e^{-i\omega^a(i\nabla^a)}U = U e^{i\omega^a t^a} \qquad e^{-i\omega^a(i\bar\nabla^a)}U = e^{-i\omega^a t^a}U$$

reps of the algebras:

$$[i\nabla^a, i\nabla^b] = i f^{abc} i\nabla^c \qquad [i\bar\nabla^a, i\bar\nabla^b] = i f^{abc} i\bar\nabla^c \qquad [i\bar\nabla^a, i\nabla^b] = 0$$

The JIMWLK Hamiltonian

back

$$H_{\text{JIMWLK}} = -\frac{1}{2}\frac{\alpha_s}{\pi^2}\,\mathcal{K}_{\boldsymbol{xzy}}\left[i\nabla^a_x i\nabla^a_y + i\bar\nabla^a_x i\bar\nabla^a_y + \tilde U^{ab}_z(i\bar\nabla^a_x i\nabla^b_y + i\nabla^a_x i\bar\nabla^b_y)\right]$$

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[integration convention for x, z, y]

$i\nabla^a_{\boldsymbol{x}}$ and $i\bar\nabla^a_{\boldsymbol{x}}$ are functional derivatives:

$$i\nabla^a_{\boldsymbol{x}} := -[U_{\boldsymbol{x}}t^a]_{ji}\frac{\delta}{\delta U_{\boldsymbol{x},ij}} \qquad i\bar\nabla^a_{\boldsymbol{x}} := [t^a U_{\boldsymbol{x}}]_{ji}\frac{\delta}{\delta U_{\boldsymbol{x},ij}}$$

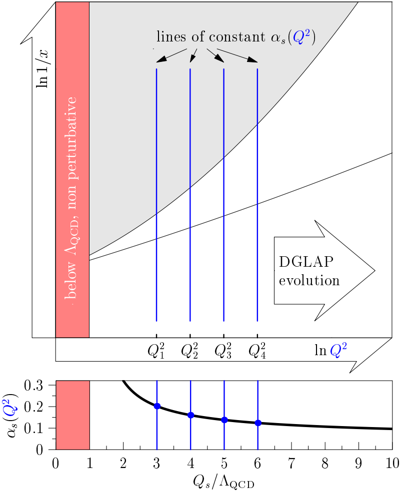
physics content:

- $\tilde U^{ab}_z(i\bar\nabla^a_x i\nabla^b_y + i\nabla^a_x i\bar\nabla^b_y)$ — real emission
- $i\nabla^a_x i\nabla^a_y + i\bar\nabla^a_x i\bar\nabla^a_y$ — virt. correction
- real emission term → nonlinear evolution

Outline

Running coupling is essential: Q^2 vs small x

- DGLAP: Q^2 evolution



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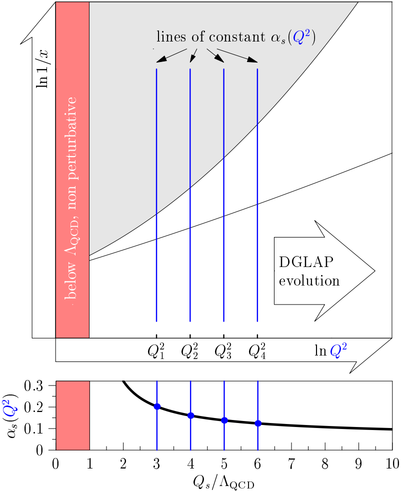
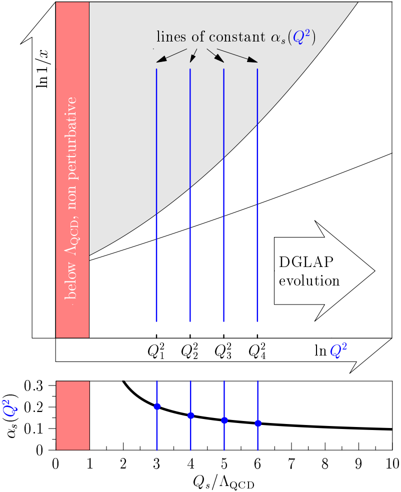


- no qualitative changes

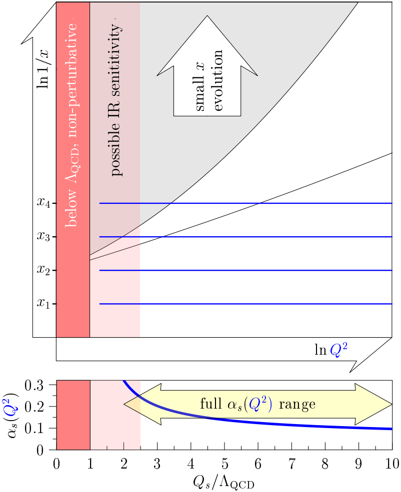
Running coupling is essential: Q^2 vs small x

- DGLAP: Q^2 evolution



- no qualitative changes

- JIMWLK, BK: small x evolution



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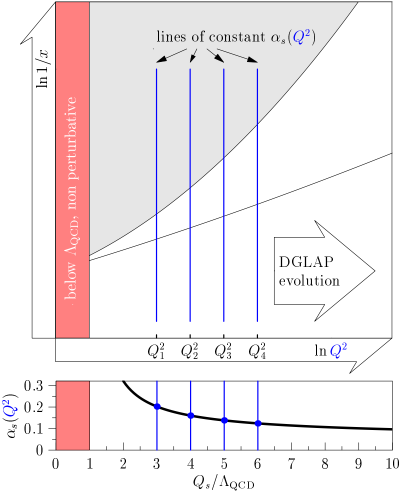
- DGLAP: Q^2 evolution



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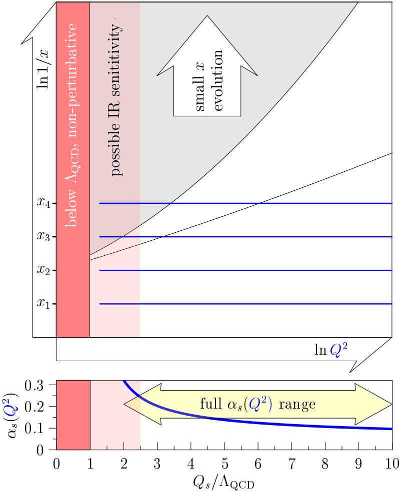


- qualitative changes

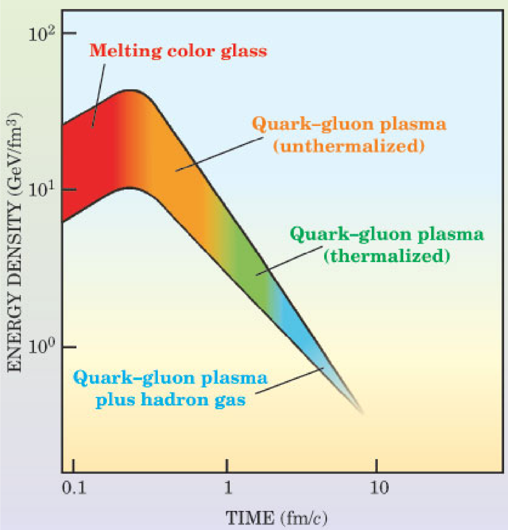
Outline

6 The JIMWLK Hamiltonian

7 Running coupling

8 Experiments
- From CGC to QGP
- Cronin effect BRAHMS
- Multiplicities
- Monojets RHIC
- Forward particle production RHIC

From Colored Glass to Quark Gluon Plasma



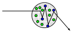
McLerran, Ludlam
Physics Today
Oct 2003

← core of neutron star

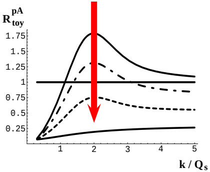
← nuclear matter

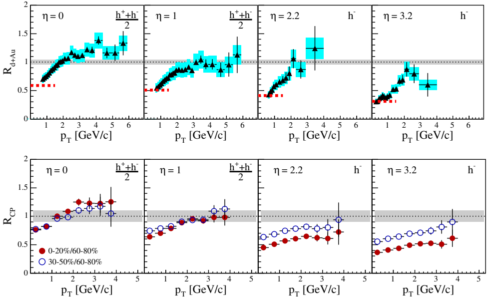
Erasing the Cronin effect on the parton level [BRAHMS]

$$R^{pA} = \frac{\frac{d\sigma^{pA}}{d^2k\,dY}}{A\,\frac{d\sigma^{pp}}{d^2k\,dY}}$$



$$p_t \sim Q_s(Y)$$





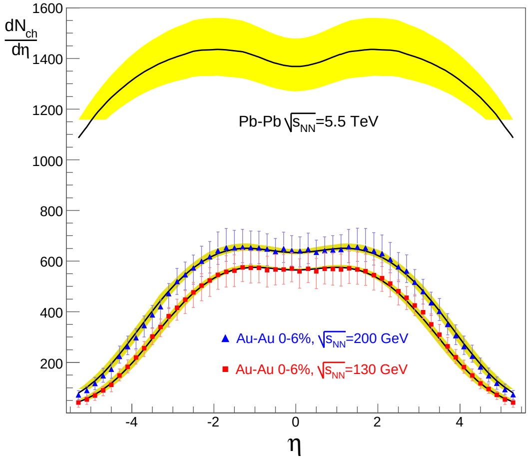
disappears at forward rapidities

disappears faster centrally

- qualitative only: no hadronization of partons, simulation only LO

Multiplicities at RHIC and LHC(?)

- Fit multiplicities at RHIC, predict LHC

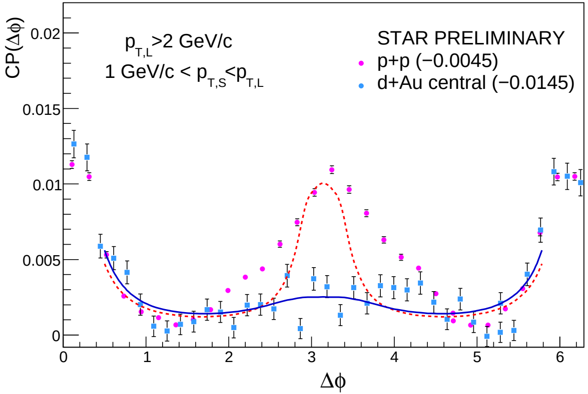


J. L. Albacete, Phys. Rev. Lett. **99** (2007) 262301 [arXiv:0707.2545 [hep-ph]]

Monojets at RHIC

- light nuclei: back to back jets

  not quantitative: energy too low centrally, see Cronin
- heavy nuclei: Monojets; back to back correlation is broken

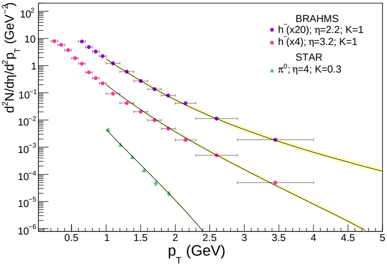


J. L. Albacete and C. Marquet, arXiv:1005.4065 [hep-ph].

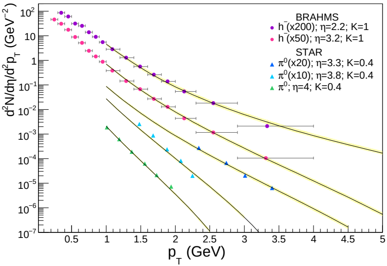
- partial NLO: running coupling only!

Forward particle production RHIC

- d Au



- p p



J. L. Albacete and C. Marquet, Phys. Lett. B **687** (2010) 174 [arXiv:1001.1378 [hep-ph]]

- partial NLO: running coupling only!