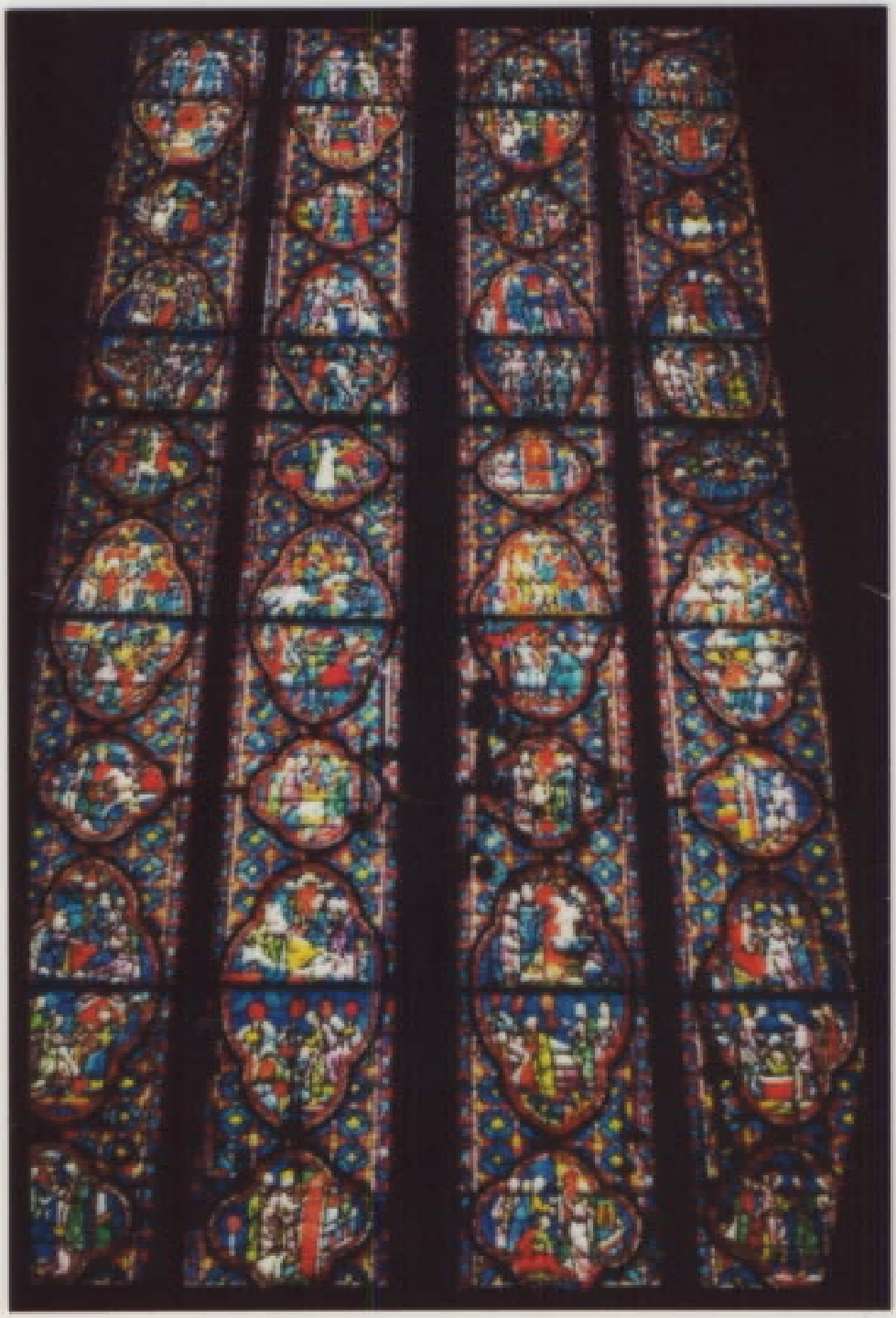
Shattering Colored Glass In Heavy Ion Collisions.

Raju Venugopalan
BNL & RIKEN-BNL

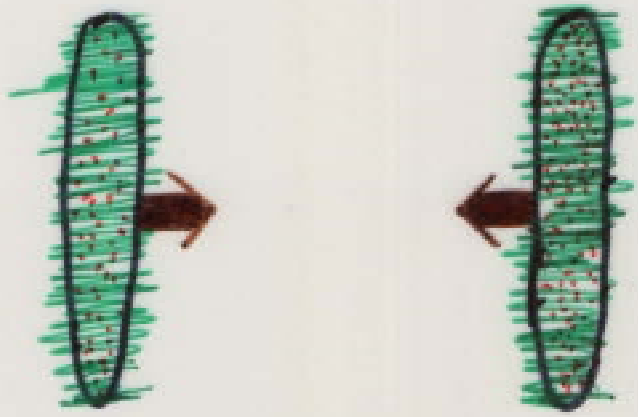


ST. CHAPPELLE, PARIS, FRANCE.

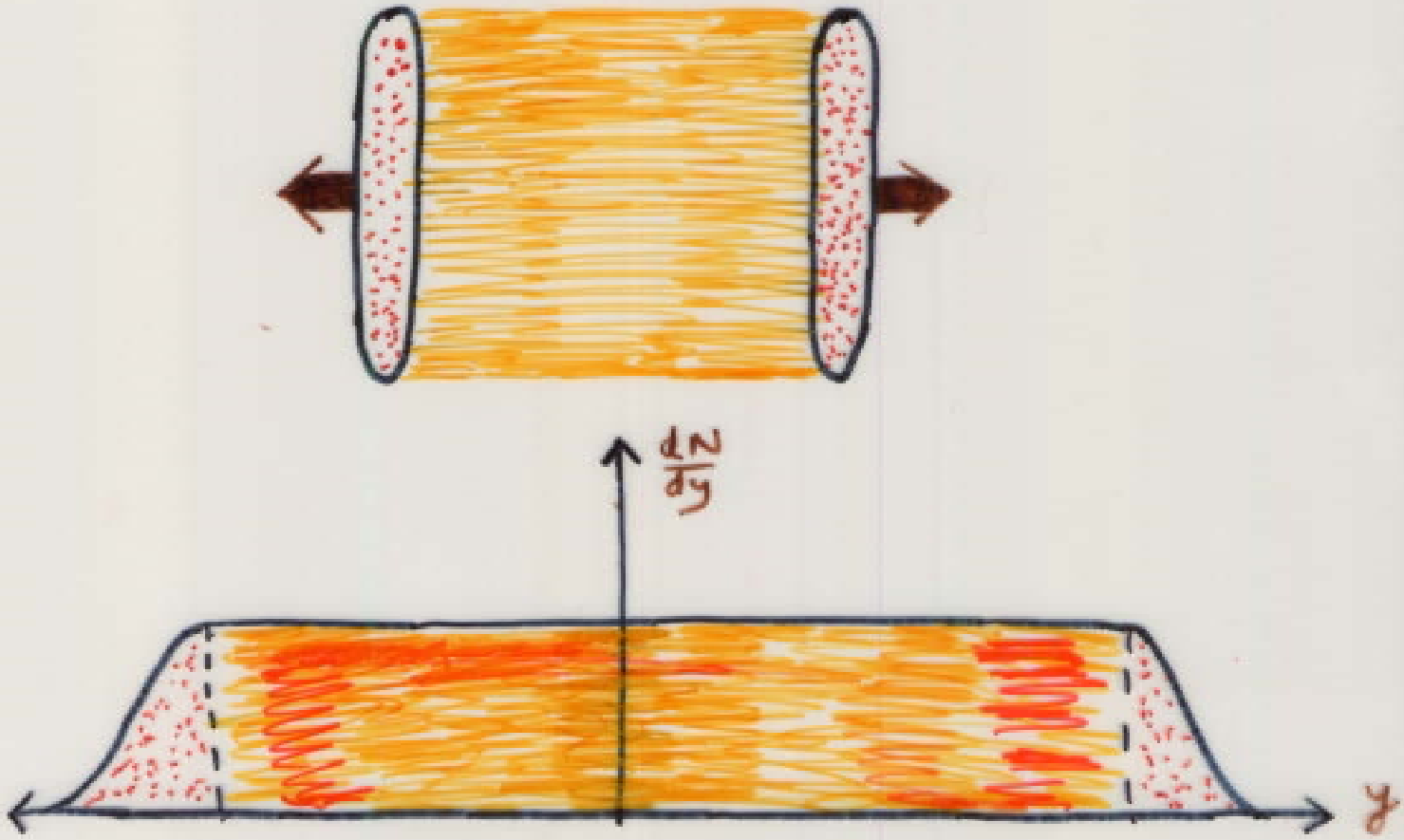
VALENCE: $x \sim 1/7$

WEE: $x \ll 1$

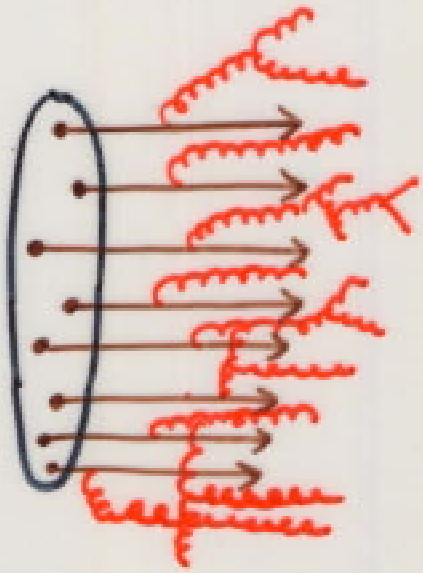
- BEFORE:



- AFTER:



- GLUON BREMSSTRAHLUNG:



$$\left| \underbrace{qqq\cdots q}_{3A \text{ VALENCE PARTONS}} \; \underbrace{gggg\cdots q\bar{q}ggq\bar{q}gg}_{\text{EACH "WEE" PARTON CARRIES A SMALL FRACTION } x \text{ OF MOMENTUM OF NUCLEUS.}} \right\rangle$$

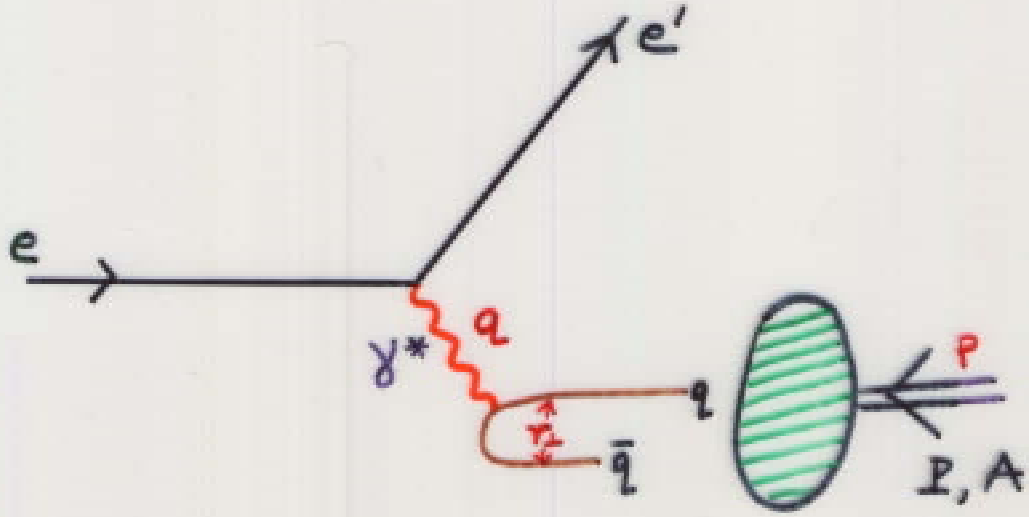
- PHYSICS OF MULTI-PARTICLE PRODUCTION AT HIGH ENERGIES IS THE PHYSICS OF SMALL x PARTONS.

• Small x Parton Distributions In DIS

$Q^2 = -q^2 > 0$

$x_{Bj} = \frac{Q^2}{2p\cdot q} \simeq x_F$

$$\boxed{x_{Bj} \simeq \frac{Q^2}{s}}$$



$$\sigma_{\gamma^* p} = |\psi|^2_{\gamma^* \to q\bar{q}} \otimes \hat{\sigma}_{q\bar{q}\, p/A}(x, r_\perp)$$

↦ Parton Distributions Grow Rapidly At Small x_{Bj} (HERA)

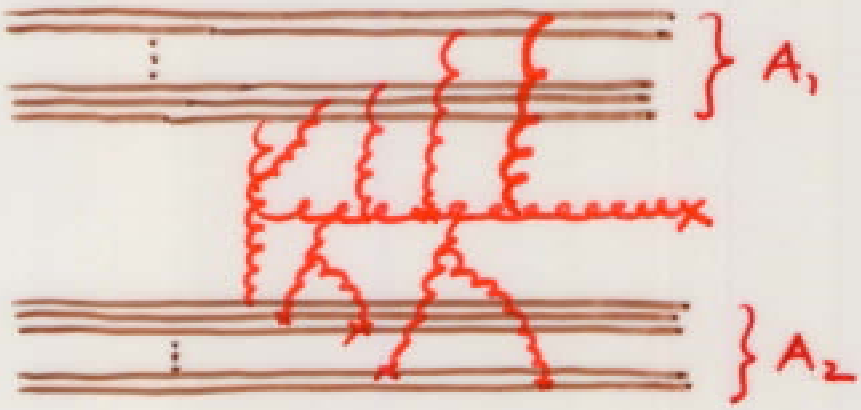
↦ QCD Linear Evolution Eqns.

"DGLAP" & "BFKL" Predict Rapid Rise For $x \ll 1$.

OUTLOOK

- $SU(2) \longrightarrow SU(3)$ – ~~IN PROGRESS~~ done!.
- RAPIDITY DEPENDENCE in progress.
- CONNECT TO TRANSPORT APPROACHES.
  - THERMALIZATION... interesting ideas of Son + A. Mueller.
- RG – FOR NUCLEAR COLLISIONS? The big kahuna.
- MORE DETAILED CONTACT WITH RHIC DATA.

- SHATTERING THE CGC IN HI-COLLISIONS



Krasnitz + R.V.
PRL 86 (2001)
PRL 84 (2000)
NPB

for SU(2) Yang-Mills.

- NON-PERTURBATIVE NUMERICAL SOLUTION.

ONLY PARAMETERS : Λ_s & R.

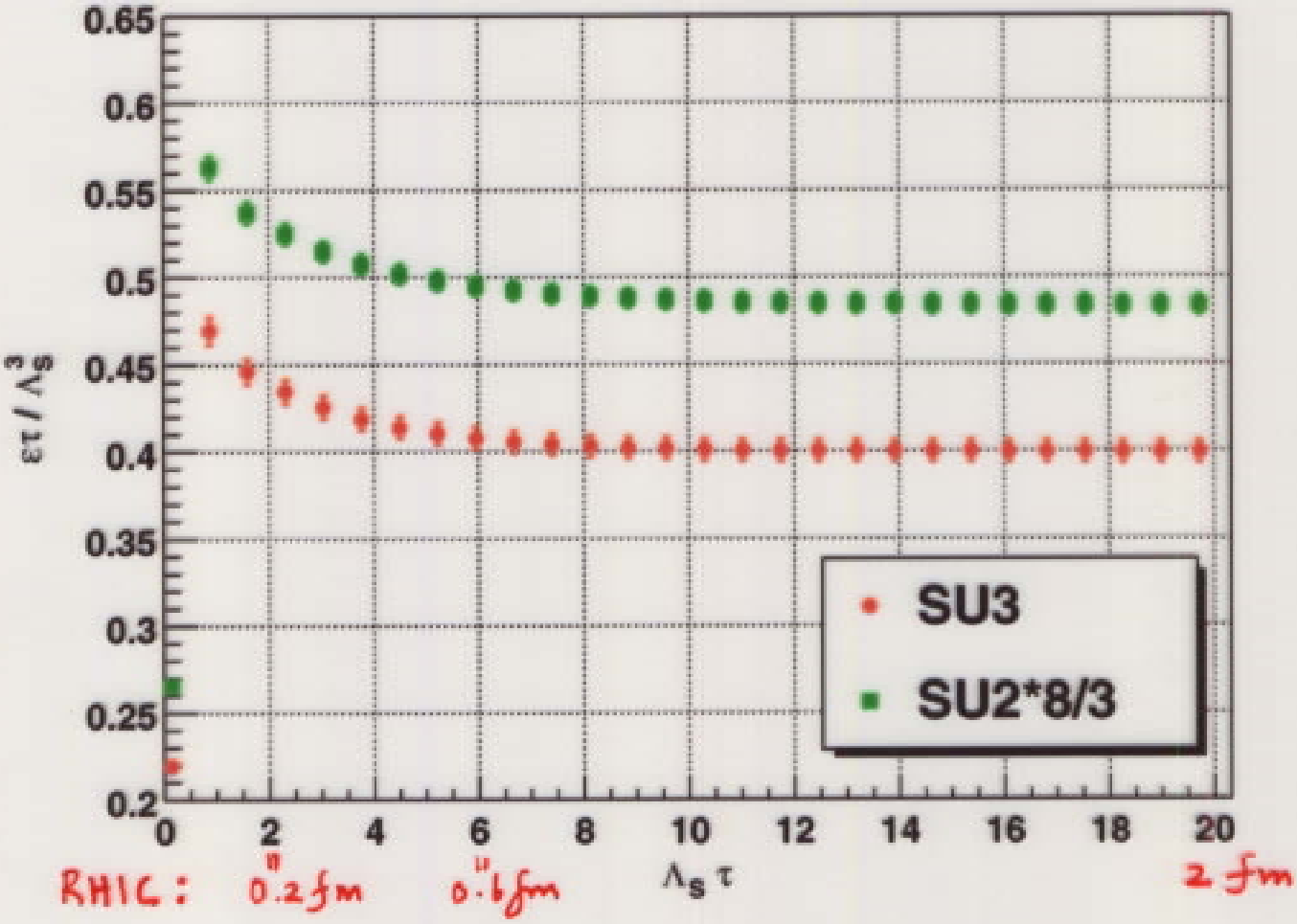
$\Lambda_s \simeq 2$ GeV for RHIC
$\simeq 4$ GeV for LHC

$R \simeq 6.5$ fm for Au.

$\Rightarrow \Lambda_s R \simeq 65$ for RHIC
$\simeq 130$ for LHC.

CAN WE EXTRACT Λ_s FROM DATA?

Formation time of gluons

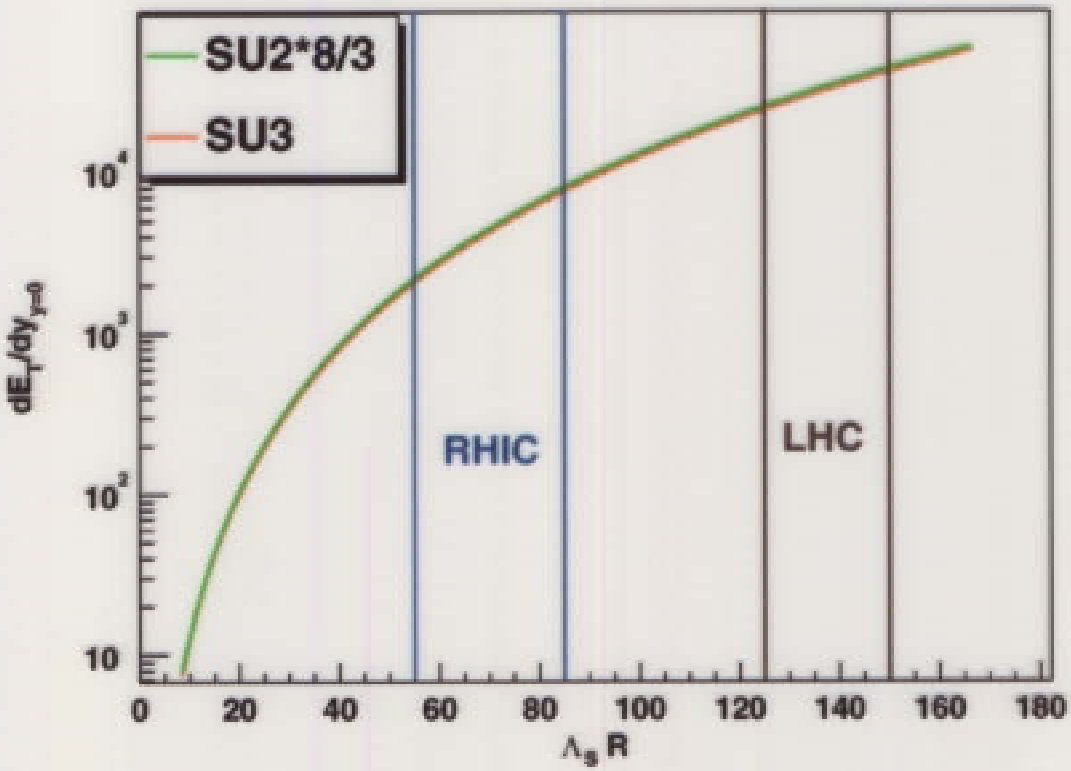


$$\tau_D = 1/(\Lambda_S \gamma), \qquad \epsilon\tau/\Lambda_S^3 = \alpha + \beta \exp(-\gamma\tau).$$

Formation time of SU2 and SU3 is the same. $\Rightarrow \tau_D^{RHIC} \simeq 0.3$ fms

$\tau_D^{LHIC} \simeq 0.13$ fms.

$dE_\perp/d\eta$ at $\eta = 0$ as a function of gluon density



$$\boxed{\frac{dE_\perp}{d\eta} = \pi R^2 \frac{1}{g^2} f_e(\Lambda_S R)\Lambda_S^3}$$

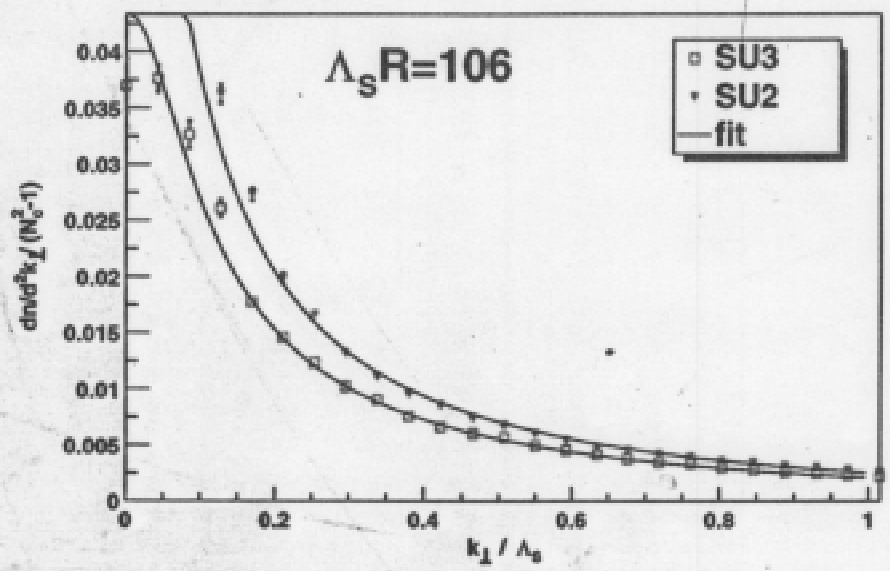
$f_e^{SU3}(83.8) = 0.52$, while $f_e^{SU2}(83.8) = 0.21$

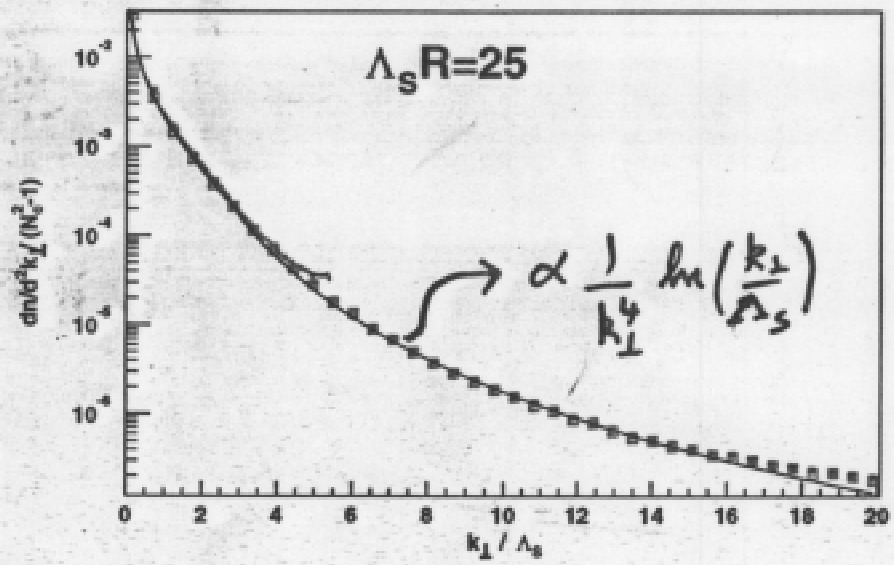
Non-perturbative formula for energy density

$$\boxed{\epsilon_{initial} = \frac{1}{4\pi\alpha_s} 0.18\Lambda_S^4}$$

$\epsilon^{RHIC}_{initial}$ $(\Lambda_s = 2\,GeV)$ $= 90\ GeV/fm^3$.

$\epsilon^{LHC}_{initial}$ $(\Lambda_s = 4\,GeV)$ $= 1.44\ TeV/fm^3$.

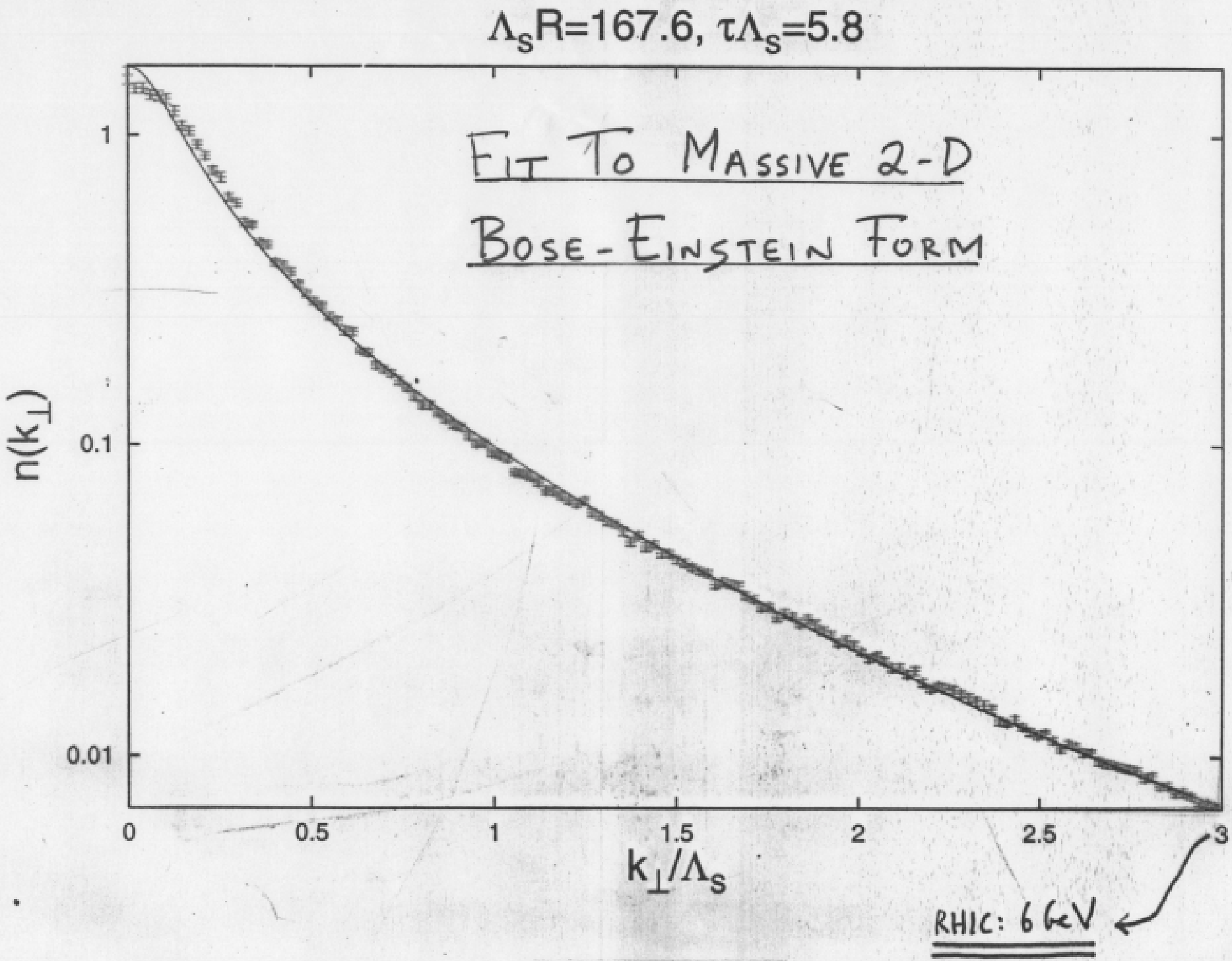




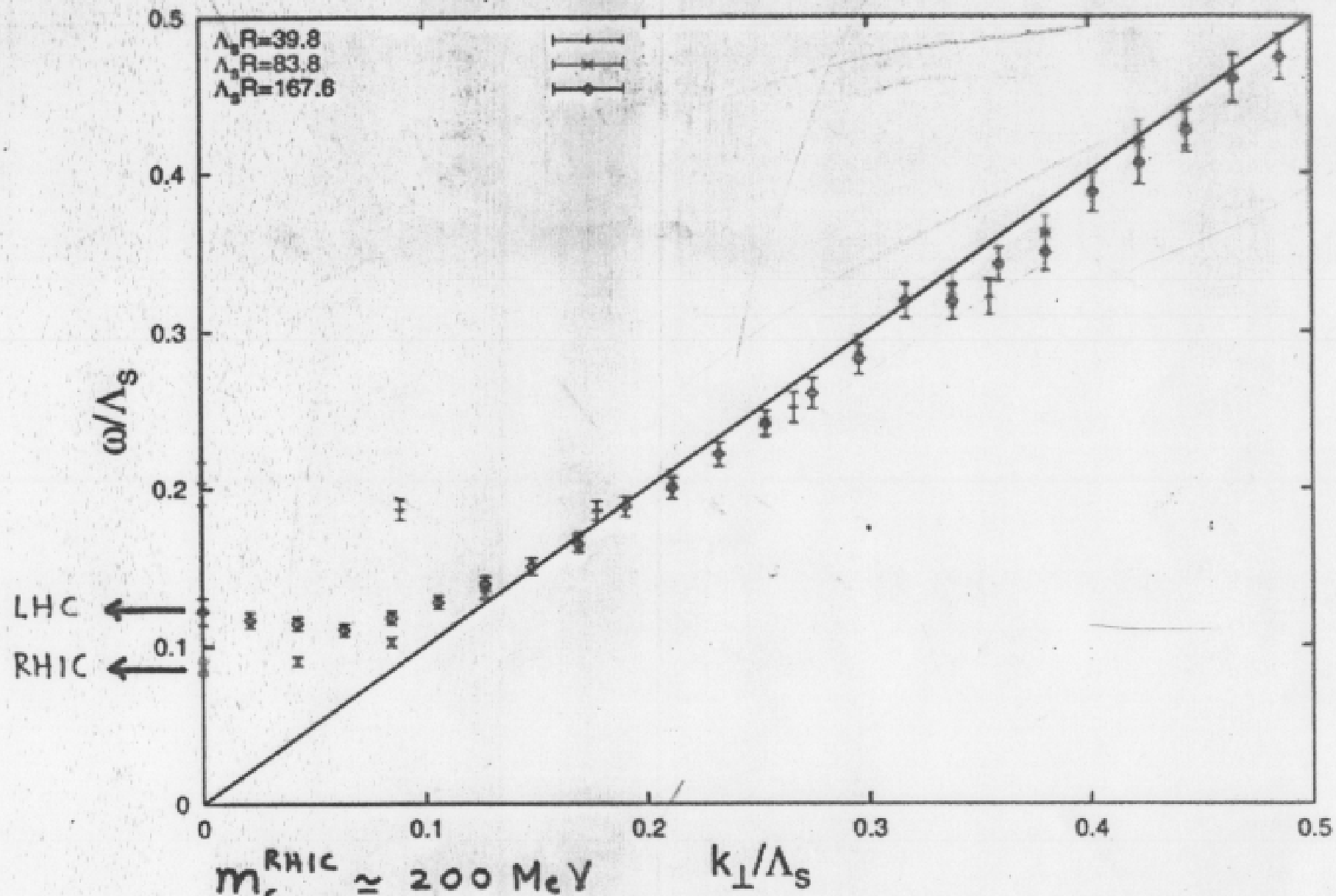
Suppression at nonperturbative region.

$SU(2)/SU(3) = 3/8$ at perturbative region.

SU(2)


$\Lambda_s R=167.6$, $\tau\Lambda_s=5.8$
FIT TO MASSIVE 2-D
BOSE-EINSTEIN FORM
$n(k_\perp)$
1
0.1
0.01
0
0.5
1
1.5
2
2.5
3
$k_\perp/\Lambda_s$
RHIC: 6 GeV

SU(2)

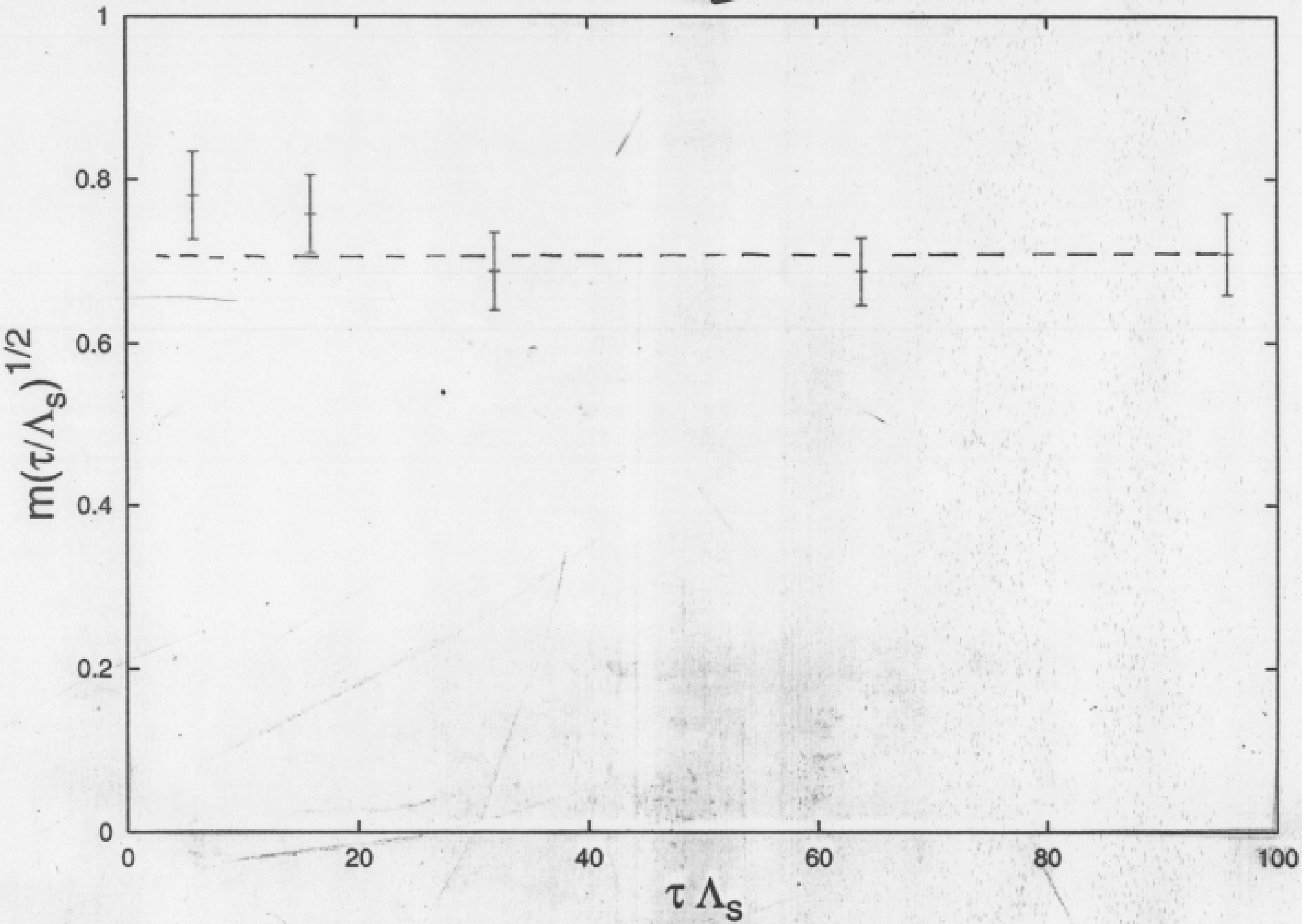


$m_s^{RHIC} \simeq 200$ MeV

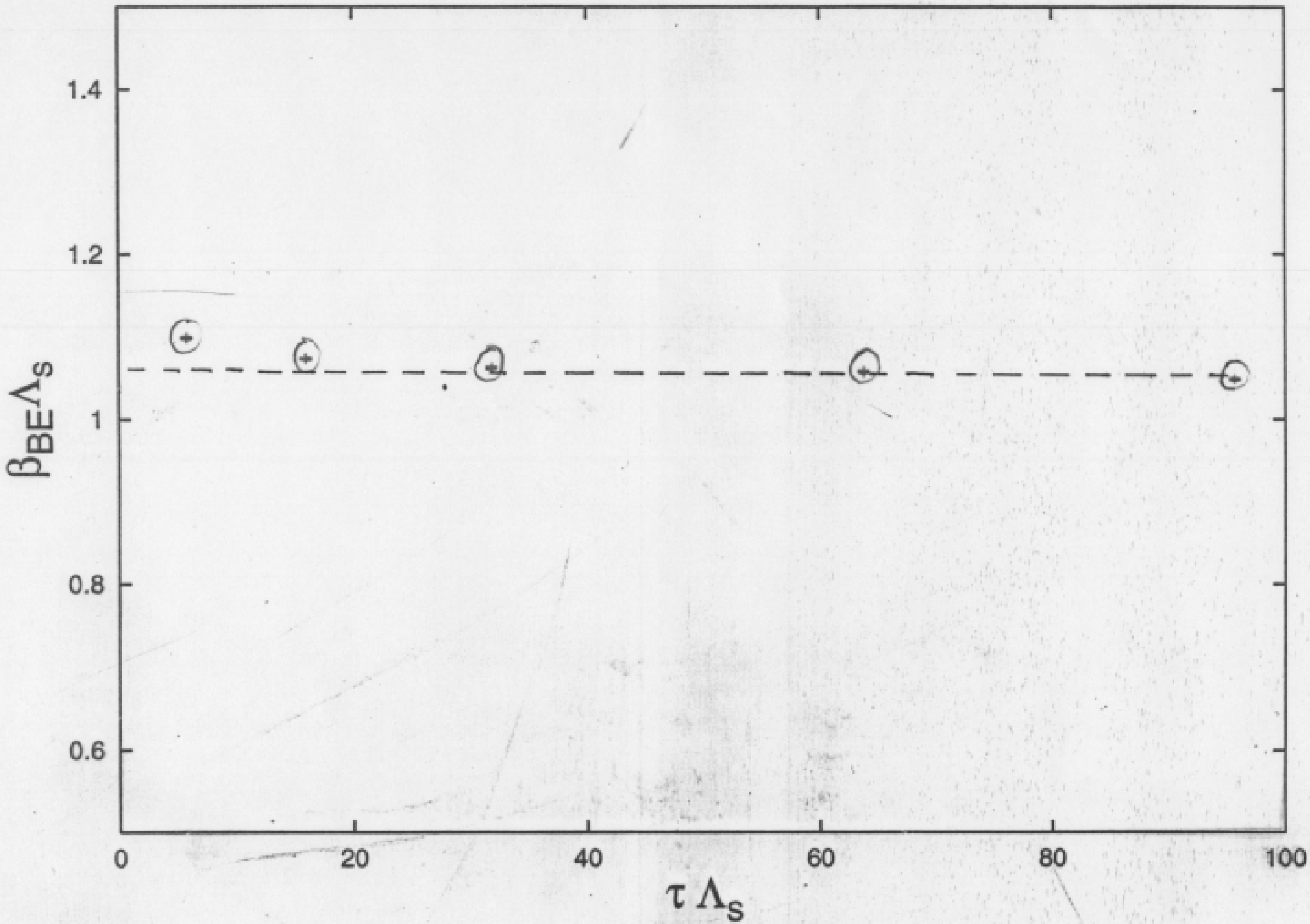
$m_s^{LHC} \simeq 400$ MeV

SU(2)

$m_s^2 \propto \frac{1}{\tau}$



INITIAL "TEMPERATURE": $T_{2D} \cong 0.9\,\Lambda_s$ $\left(T_{2D}^{RHIC} \simeq 1.8\,\mathrm{GeV}\right)$



- <u>INITIAL $P_\perp$ DISTRIBUTIONS:</u>

$\longmapsto \propto \dfrac{\Lambda_s^4}{k_\perp^4}$ for $\Lambda_s \ll k_\perp$

agrees with lattice pert. theory.

$\longmapsto$ DISTRIBUTION IS <u>INFRARED</u> <u>FINITE</u>! for $\Lambda_s \gg k_\perp$

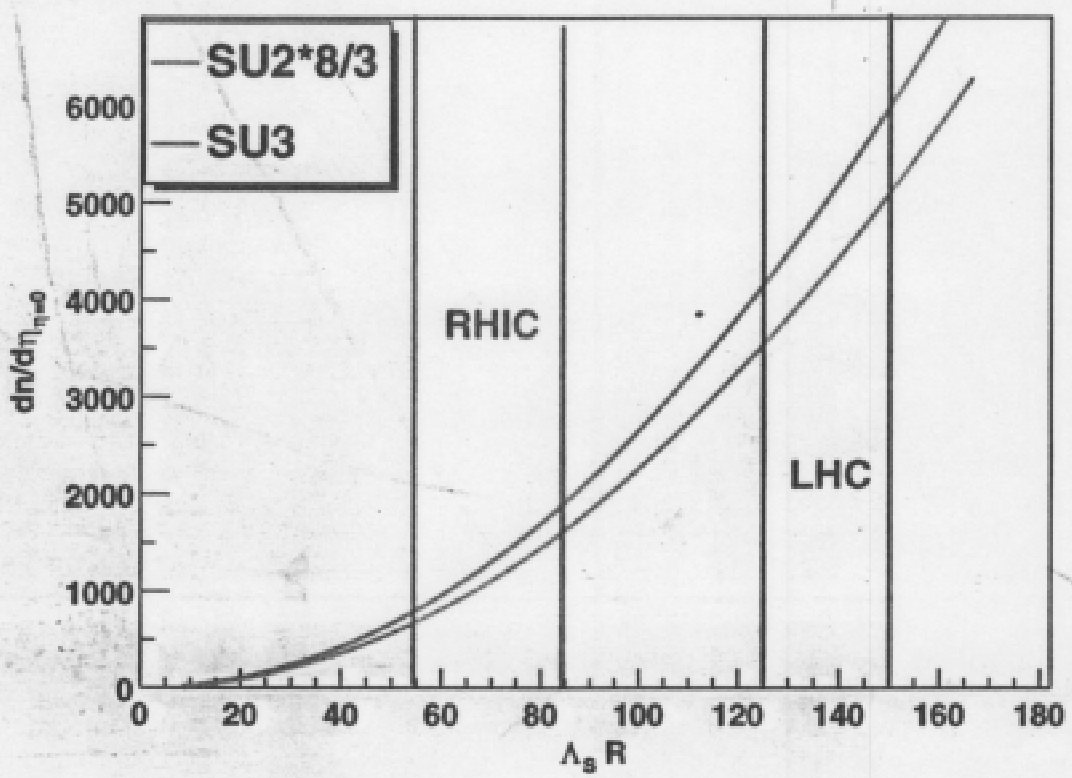
$\longmapsto$ <u>MASS GAP</u> IN DISPERSION RELATION

$- \; m \propto 1/\sqrt{\tau}$

$\longmapsto$ BEST FIT: <u>MASSIVE</u> <u>BOSE-EINSTEIN</u> <u>IN</u> <u>2-D</u> + POWER LAW TAIL.

$\longmapsto$ "T" $\simeq 0.9\,\Lambda_s$

$dn/d\eta$ at $\eta = 0$ as a function of gluon density

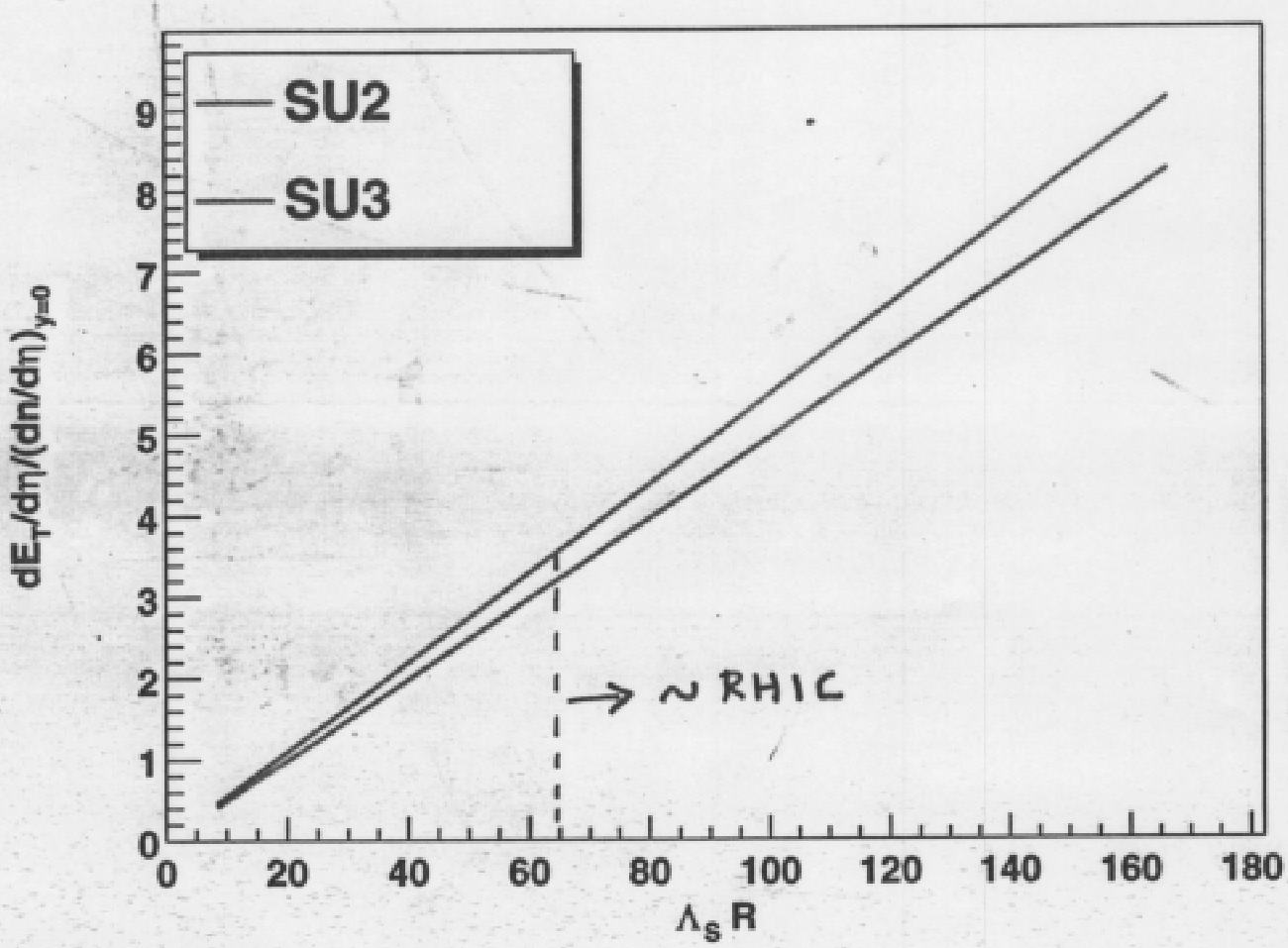


$\Lambda_S = g^2\mu$, R: nuclear size.

$$\boxed{\frac{dn}{d\eta} = \pi R^2 \frac{1}{g^2} f_n(\Lambda_S R)\Lambda_S^2}$$

$f_n^{SU3}(83.8) = 0.29$, while $f_n^{SU2}(83.8) = 0.126$

Transverse energy production per gluon



- MOMENTUM DISTRIBUTION IS NOT ISOTROPIC — SYSTEM IS <u>COMPLETELY</u> <u>OUT</u> <u>OF</u> <u>EQUILIBRIUM</u>

- INITIAL $\boxed{\frac{E_T}{N} \sim 1.5\,\Lambda_s \simeq 3\ \text{GeV}}$ - for RHIC

  → NOT CONSERVED QUANTITY!

  → DYNAMICS IS CRUCIAL

- TOWARDS THERMALIZATION...

  A.H. Mueller
  Bjorken + R.V.
  Dumitru - Gyulassy

  E_T DECREASES $(2 \to 2\,;\ 2 \to n)$

  N INCREASES $(2 \to 3\,;\ 2 \to n)$

  → Baier, Mueller, Schiff, Son.

  → ONCE IN EQUILIBRIUM FURTHER DECREASE DUE TO pdV WORK.

- 3-D SU(3) LATTICE SIMULATIONS...

  (Krasnitz, Nara, Venugopalan)

THE CGC AND RHIC DATA.

Schaffner-Bielich, Kharzeev, McLerran, Venugopalan.

- The CGC predicts a scaling function

$$\frac{1}{\sigma}\frac{dN}{dp_\perp^2} = f\left(p_\perp/\Lambda_s\right)$$

→ such a scaling seen in data

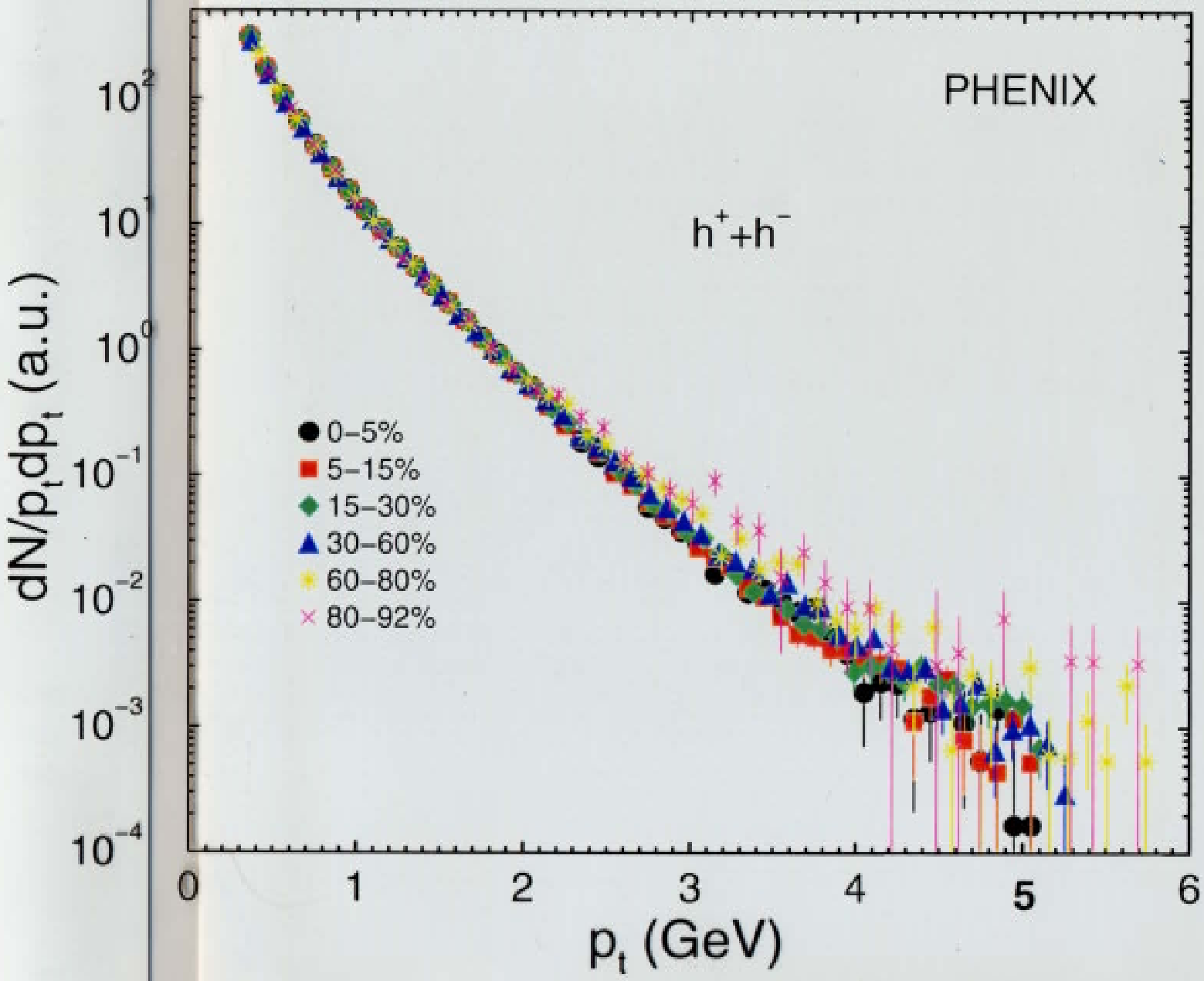
→ re-scaled Λ_s gives right $\frac{1}{N_{part}}\frac{dN}{dy}$ vs N_{part}

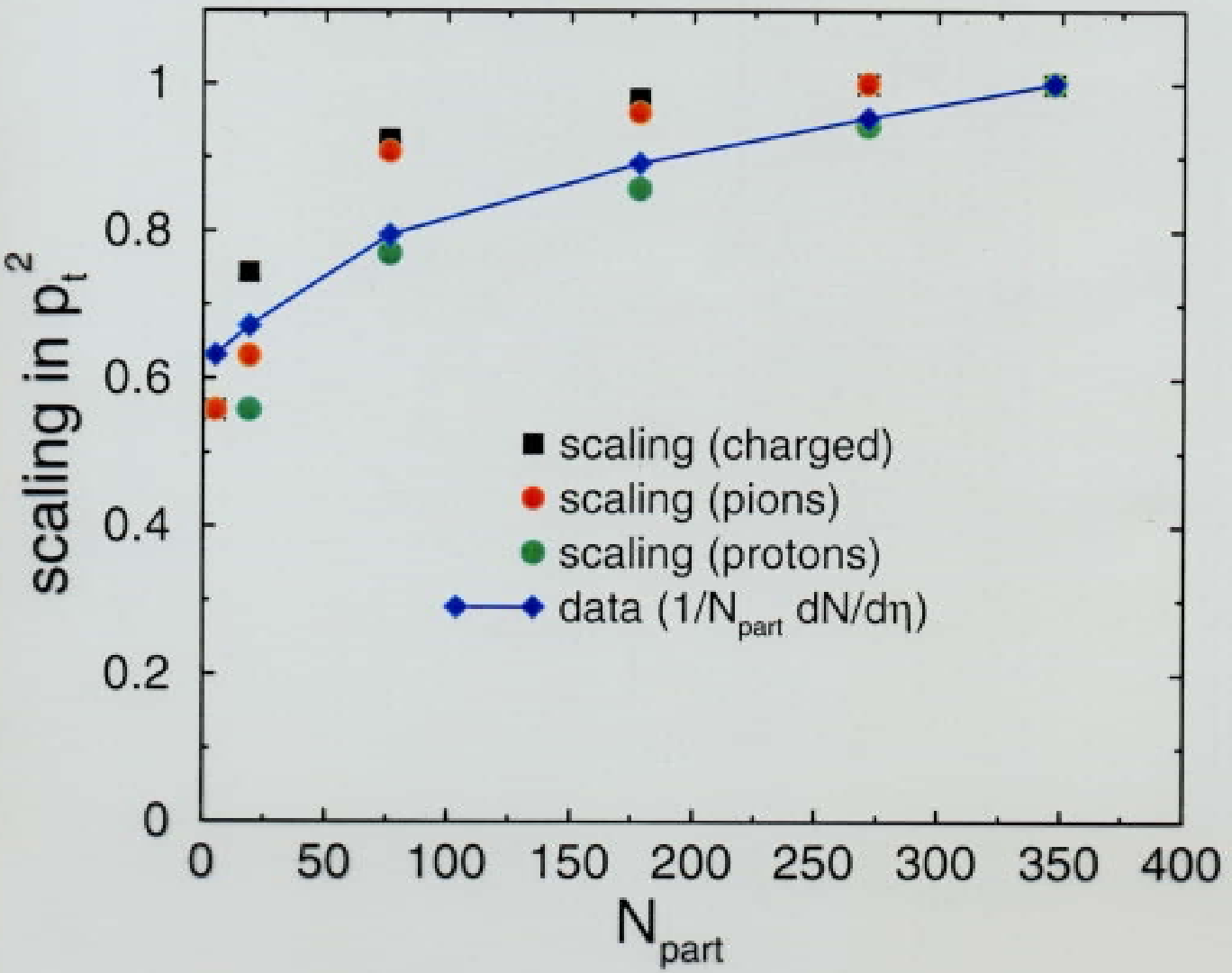
- Elliptic flow: In CGC, spatial anisotropy translates into mom-space anisotropy : $\langle p_x^2\rangle \propto L_x$; $\langle p_y^2\rangle \propto L_y$

Gupta, Krasnitz, Nara, Venugopalan.

- "Hard probes": Work of Geiß and Peshier indicate strong dependence of $Q\bar{Q}$-production on Λ_s.

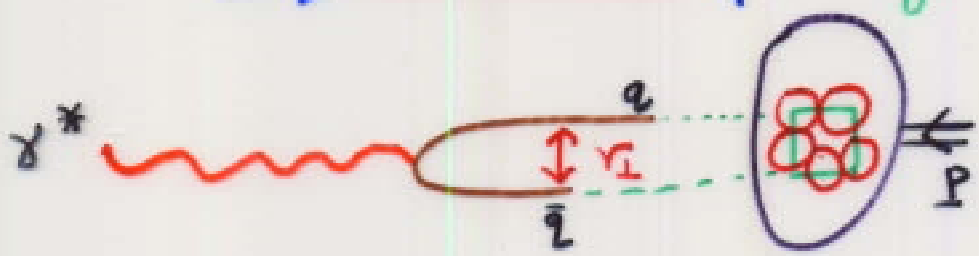
- pA Collisions: Dumitru & McLerran.


PHENIX
h⁺+h⁻
0–5%
5–15%
15–30%
30–60%
60–80%
80–92%
dN/p_t dp_t (a.u.)
p_t (GeV)
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
0
1
2
3
4
5
6


scaling in p_t^2
N_{part}
0
0.2
0.4
0.6
0.8
1
0
50
100
150
200
250
300
350
400
scaling (charged)
scaling (pions)
scaling (protons)
data ($1/N_{part}$ dN/dη)

Gribov, Levin, Ryskin
Mueller, Qiu.

- PARTONS IN TRANSVERSE PLANE OVERLAP WHEN DENSITY IS LARGE
  - THEY SATURATE (i.e., grow very slowly)



$$r_\perp \sim \frac{1}{Q} \ll 1\,\text{fm}$$

- $$\hat{\sigma}(x, r_\perp) = \sigma_0 \left(1 - e^{-r_\perp^2 Q_s^2/4}\right)$$

Golec-Biernat, Wusthoff.

$\mapsto$ SATURATION $\simeq \ln\left(\frac{Q_s^2}{Q^2}\right)$ for $Q_s^2 r_\perp^2 \gg 1$

DIS SCALING $\simeq Q_s^2/Q^2$ for $Q_s^2 r_\perp^2 \ll 1$

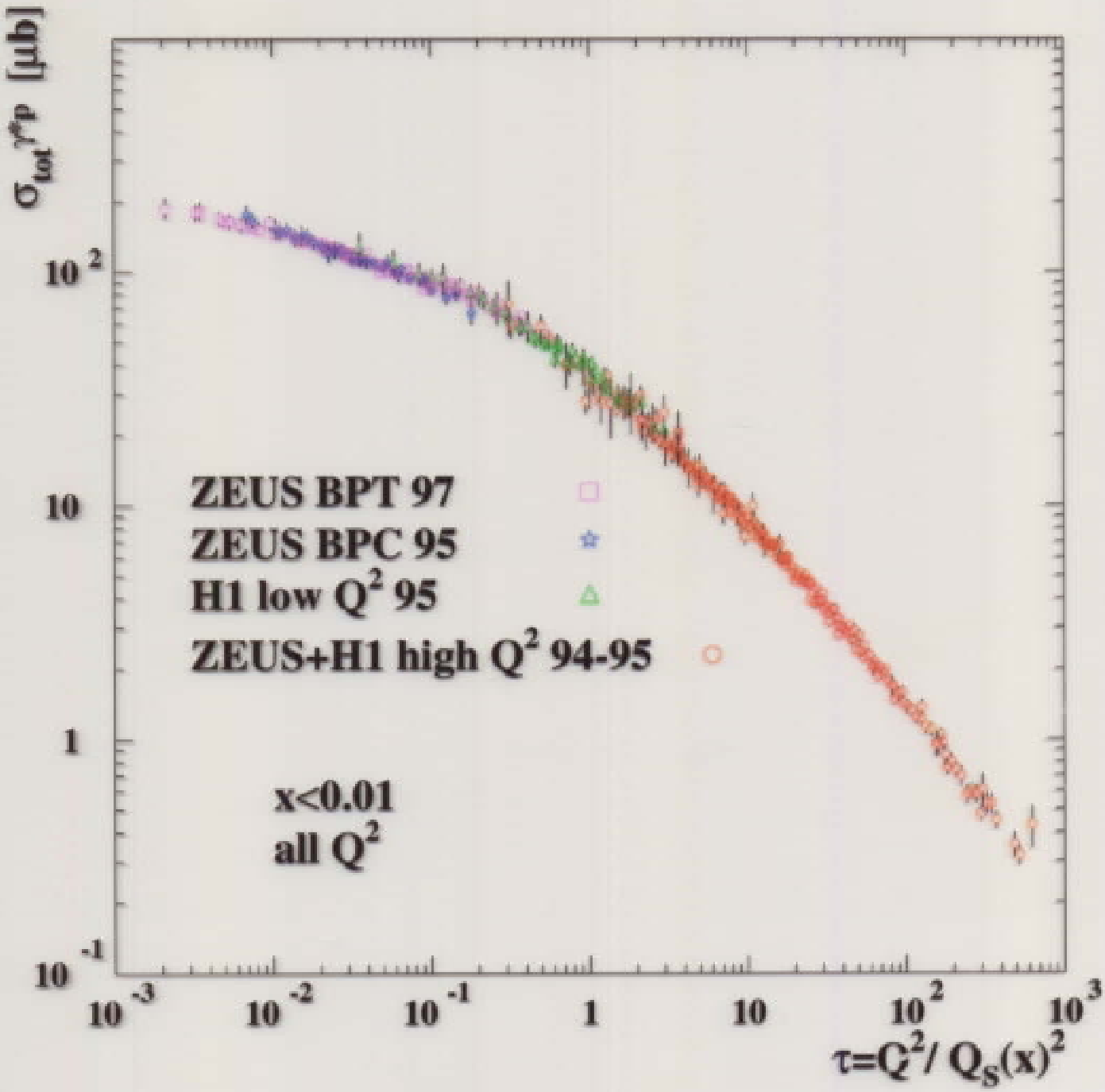
$$\boxed{Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^\lambda}$$

$Q_0 = 1$ GeV ; from fits: $\lambda = 0.29$; $x_0 = 3 * 10^{-4}$
$\sigma_0 = 23$ mb.

- FORM OF $\hat{\sigma}$ PREDICTED IN pQCD BASED MODELS

Nikolaev-Zakharov, Mueller, ...

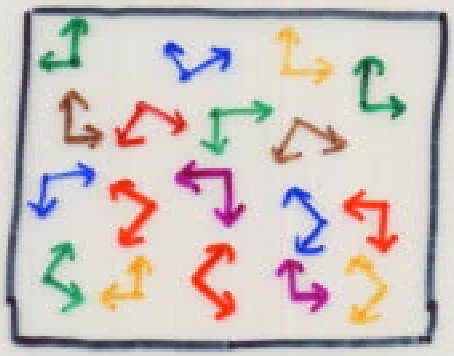
Golec-Biernat, Kwiecinski, Stasto.



- HERA DIFFRACTIVE DIS DATA EXPLAINED — NO ADDITIONAL PARAMETERS.

Golec-Biernat + Wusthoff.

COLORED GLASS CONDENSATE.



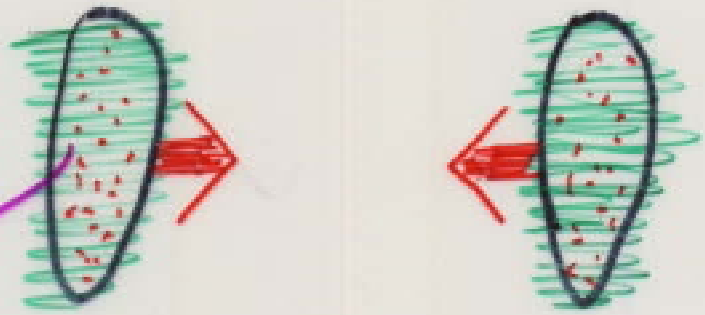
Why Colored Glass Condensate?

Colored : QCD

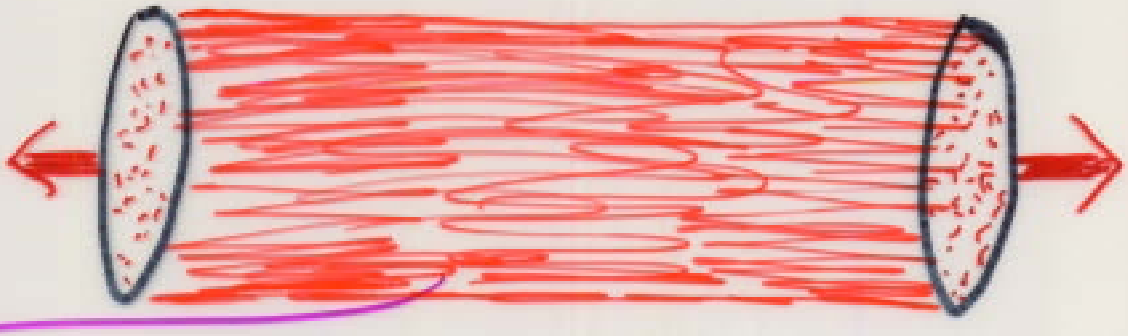
Glass : Strong analogy of the system to spin glasses in condensed matter physics.

Condensate: Large occupation # of gluons in system $\propto \frac{1}{\alpha_s}$ – peaked about saturation momentum scale Λ_s.

Probing The CGC In HI-Collisions



Bulk scale Λ_s controls the distribution of partons in incoming nuclei.

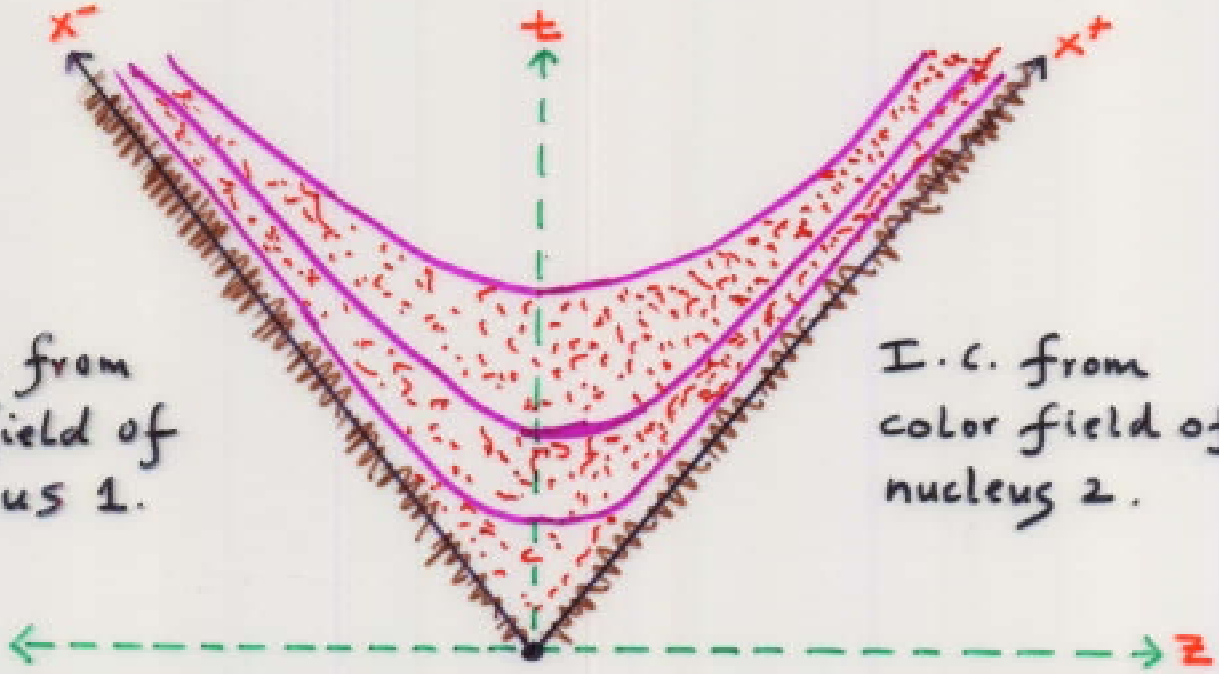


Λ_s also controls the initial multiplicity and transverse energy of produced glue.

$\Lambda_s \simeq 2$ GeV for RHIC

$\simeq 4$ GeV for LHC.

$$\tau = \sqrt{2x^+x^-}$$
$$\eta = \frac{1}{2}\ln\left(\frac{x^+}{x^-}\right)$$



Kovner, McLerran, Weigert

- NUCLEAR COLLISIONS – SOLVE YANG-MILLS EQUATIONS FOR TWO SOURCES.

$$D_\mu F^{\mu\nu,a} = \rho_1^a(x_\perp)\,\delta(x^-)\,\delta^{\nu+} + \rho_2^a(x_\perp)\,\delta(x^+)\,\delta^{\nu-}$$

color charge density of nucleus 1

color charge density of nucleus 2.

- GAUSSIAN AVERAGE (with weight Λ_s) OVER COLOR CHARGES OF DIFFERENT CONFIGS.

$$\int (2\pi) \frac{}{q_\perp^2 (q_\perp - k_\perp)^2}$$

In classical YM model: $\mathcal{L}(k_\perp, \Lambda) \to \ln\left(\frac{k_\perp}{\Lambda}\right)$

with $\Lambda \simeq \alpha_s \mu$.

Kovchegov-Rischke: $\mathcal{L}(k_\perp, \Lambda) \to k_\perp^2 a^2$

$\hookrightarrow$ nucleon radius

- Infra-red divergent!