QCD

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Third IDPASC school

21Jan-2Feb Santiago de Compostela

---Introduction.QED and QCD differences
---Asymptotic freedom(Callan-Symanzyk equation, deep inelastic,jets)
---Confinement
---Symmetries.Isospin,Quiral symmetry, (spontaneus symmetry breaking,Goldtone bosons
Scale symmetry(trace anomaly,vacuum structure, instantons,topological charge
---QCD at high temperature.(Phase transitions, Confinement and quiral symmetry transitions
Elliptical flow.Little bang versus big-bang)

$$\mathcal{L} = \bar{\psi}(i\gamma^{\mu}\partial_{\mu} - m)\psi$$

$$\psi \;\longrightarrow\; \psi' = \exp\left[iq\alpha(x)\right]\psi,$$

$$\bar{\psi} \;\longrightarrow\; \bar{\psi}' = \exp\left[-iq\alpha(x)\right]\bar{\psi}.$$

$$A_{\mu} \longrightarrow A'_{\mu} = A_{\mu} - \partial_{\mu}\alpha(x),$$

$$D_{\mu} = \partial_{\mu} + iqA_{\mu},$$

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^{\mu}D_{\mu} - m)\psi = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi - q\bar{\psi}\gamma^{\mu}A_{\mu}\psi$$

$$\mathcal{L}_{QED} = \mathcal{L}_{0} - j^{\mu}A_{\mu}, \quad j^{\mu} = q\bar{\psi}\gamma^{\mu}\psi.$$

$$-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}, \quad F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}.$$

$$\mathcal{L} = \sum_q \bar{\psi}_q^j i\gamma^\mu \partial_\mu \psi_q^k - \sum_q m_q \bar{\psi}_q^j \psi_q^j,$$

el color, $j, k = 1, 2, 3$, y $q = d, u, s, c, b, t$

$$\psi_q(x) \longrightarrow \psi_q'(x) = \exp\left[ig_s\alpha_a(x)T_a\right]\psi_q(x),$$

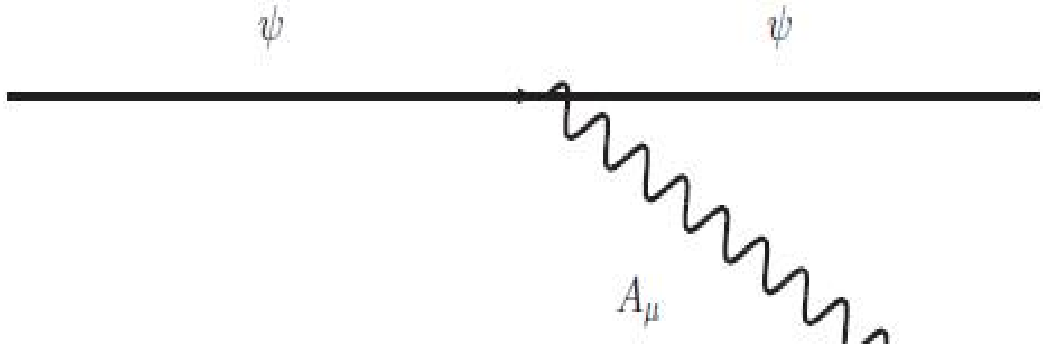
$$[T_a, T_b] = i f_{abc} T_c,$$

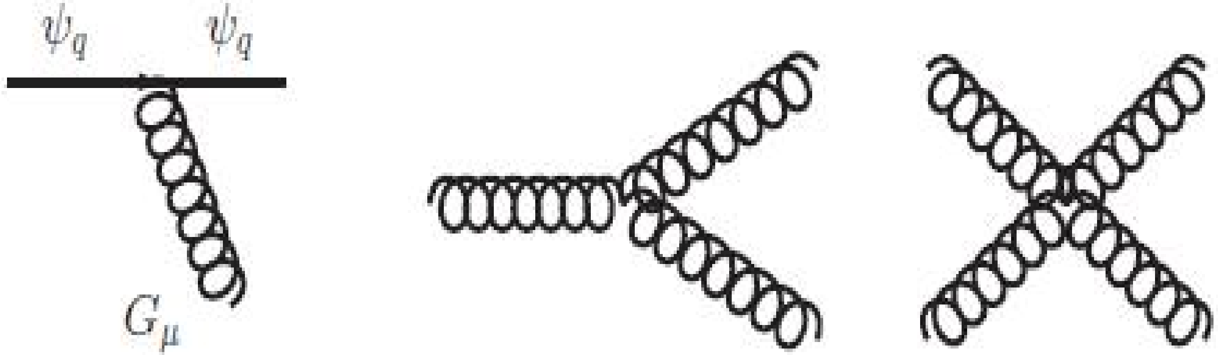
$$G_\mu^a \longrightarrow G_\mu^{a\prime} = G_\mu^a - \partial_\mu \alpha_a(x) - g_s f_{abc} \alpha_b(x) G_\mu^c,$$

$$D_\mu = \partial_\mu + i g_s T_a G_\mu^a$$

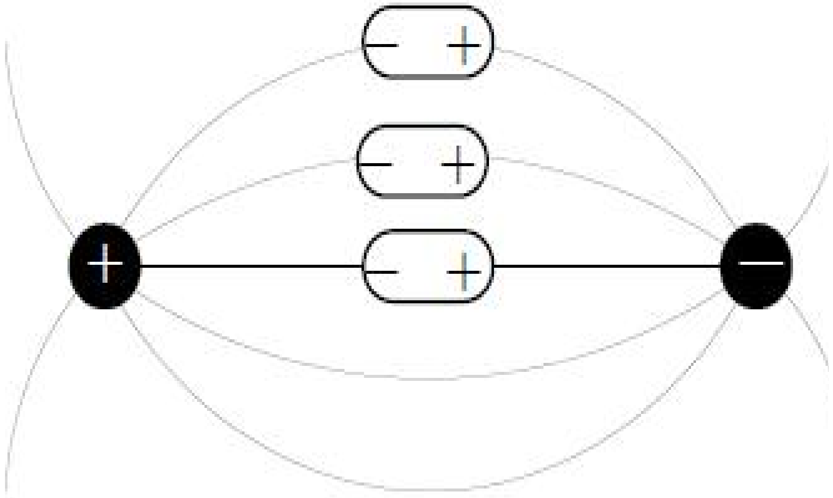
$$\mathcal{L}_{QCD} = \bar{\psi}_q i\gamma^\mu D_\mu \psi_q - m_q \bar{\psi}_q \psi_q = \bar{\psi}_q i\gamma^\mu \partial_\mu \psi_q - g_s \bar{\psi}_q i\gamma^\mu \psi_q T_a G_\mu^a - m_q \bar{\psi}_q \psi_q,$$

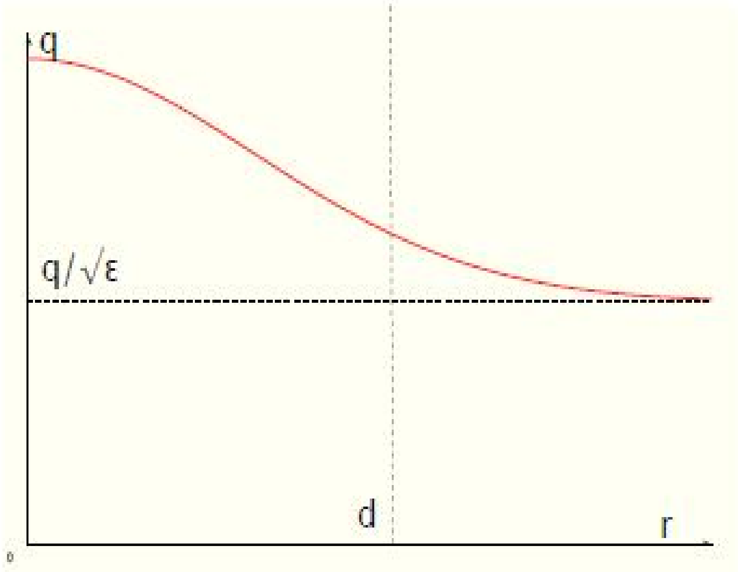
$$-\frac{1}{4} F_a^{\mu\nu} F_{\mu\nu}^a, \quad F_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - g_s f_{abc} G_\mu^b G_\nu^c.$$

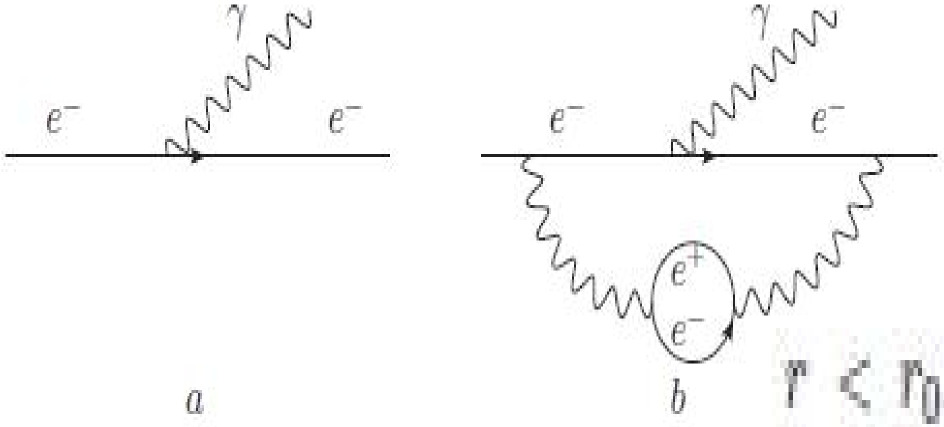

ψ
$\bar{\psi}$
A_μ


ψ_q
$\bar{\psi}_q$
G_μ

Charge screening in QED and in QCD.Asymptotic Freedom

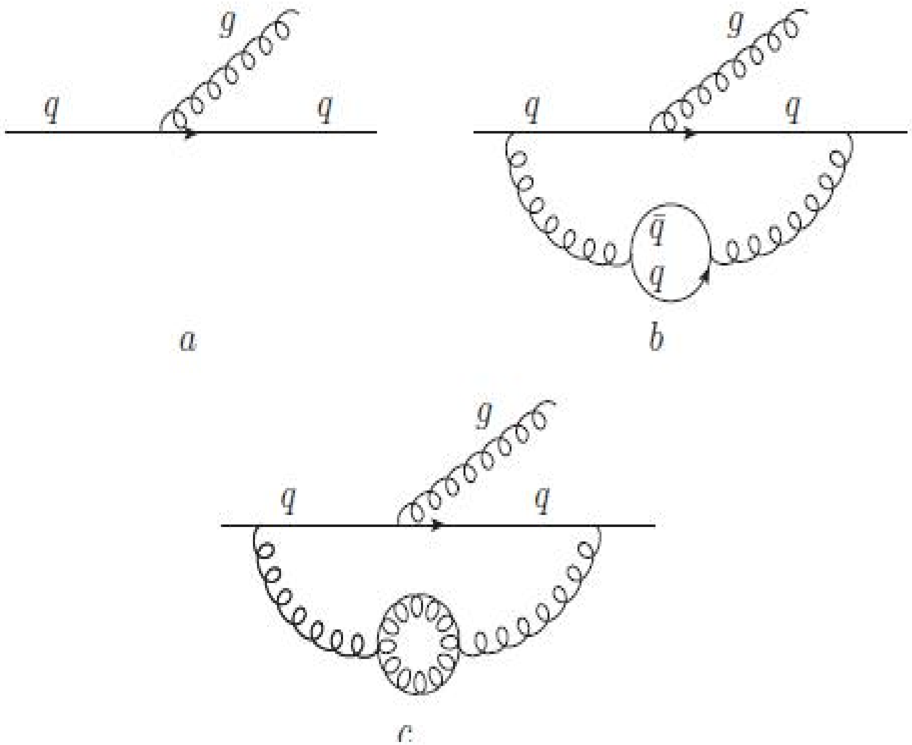






$$\alpha_{em}(r) = \frac{\alpha_{em}(r_0)}{1 + \frac{\alpha_{em}(r_0)}{3\pi}\ln(r^2/r_0^2)}$$

$$r < r_0,\ \alpha_{em}(r) > \alpha_{em}(r_0)$$



$$\alpha_s(r) = \frac{\alpha_s(r_0)}{1 - \frac{\alpha_s(r_0)}{12\pi}(11N_c - 2n_f)\ln(r^2/r_0^2)} .$$

$r \to 0,\ \alpha_s(r) \to 0,$

$\alpha_s = g_s^2/(4\pi)$

$$\Gamma_B(s, \alpha_0, \Lambda^2) = Z(\mu^2)^{-1}\Gamma(s, \alpha(\mu^2), \mu^2)$$

$$d\Gamma_B/d\mu^2 = 0$$

$$\mu^2 \frac{\partial \Gamma}{\partial \mu^2} + \mu^2 \frac{\partial \alpha}{\partial \mu^2}\frac{\partial \Gamma}{\partial \alpha} - \mu^2 \frac{\Gamma}{Z}\frac{\partial Z}{\partial \mu^2} = 0.$$

Defining $\beta(\alpha) = \mu^2 \frac{\partial \alpha}{\partial \mu^2}$ and $\gamma(\alpha) = -\frac{\mu^2}{Z}\frac{\partial Z}{\partial \mu^2}$

group equation (RGE),

$$\left[\mu^2 \frac{\partial}{\partial \mu^2} + \beta(\alpha)\frac{\partial}{\partial \alpha} + \gamma(\alpha)\right]\Gamma(s, \alpha(\mu^2), \mu^2) = 0.$$

Callan-Symanzyk Equation

$$\ln\left(\frac{\mu^2}{\mu_0^2}\right) = \int_{\alpha(\mu_0^2)}^{\alpha(\mu^2)} \frac{dx}{\beta(x)}$$

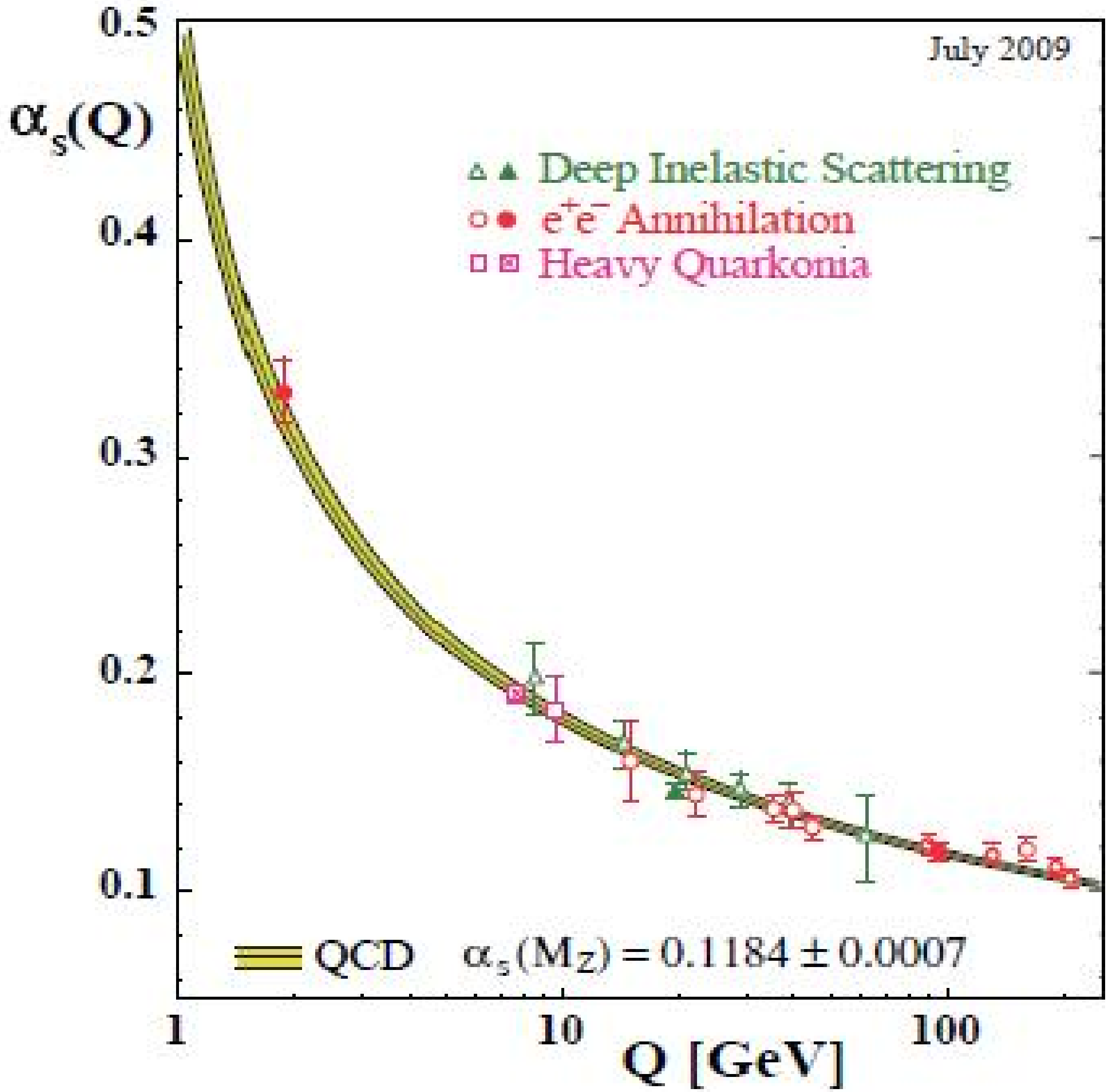
$$\beta(\alpha_s) = -b_0\alpha_s^2 - b_1\alpha_s^3 - b_2\alpha_s^4 + O(\alpha_s^5)$$

$$b_0 = \frac{33 - 2n_f}{12\pi},$$

$$b_1 = \frac{153 - 19n_f}{24\pi^2},$$

$$b_2 = \frac{77139 - 15099n_f + 325n_f^2}{3456\pi^3}$$

$$\alpha_s(\mu^2) = \frac{\alpha_s(\mu_0^2)}{1 + \alpha_s(\mu_0^2) b_0 \ln(\mu^2/\mu_0^2)}$$



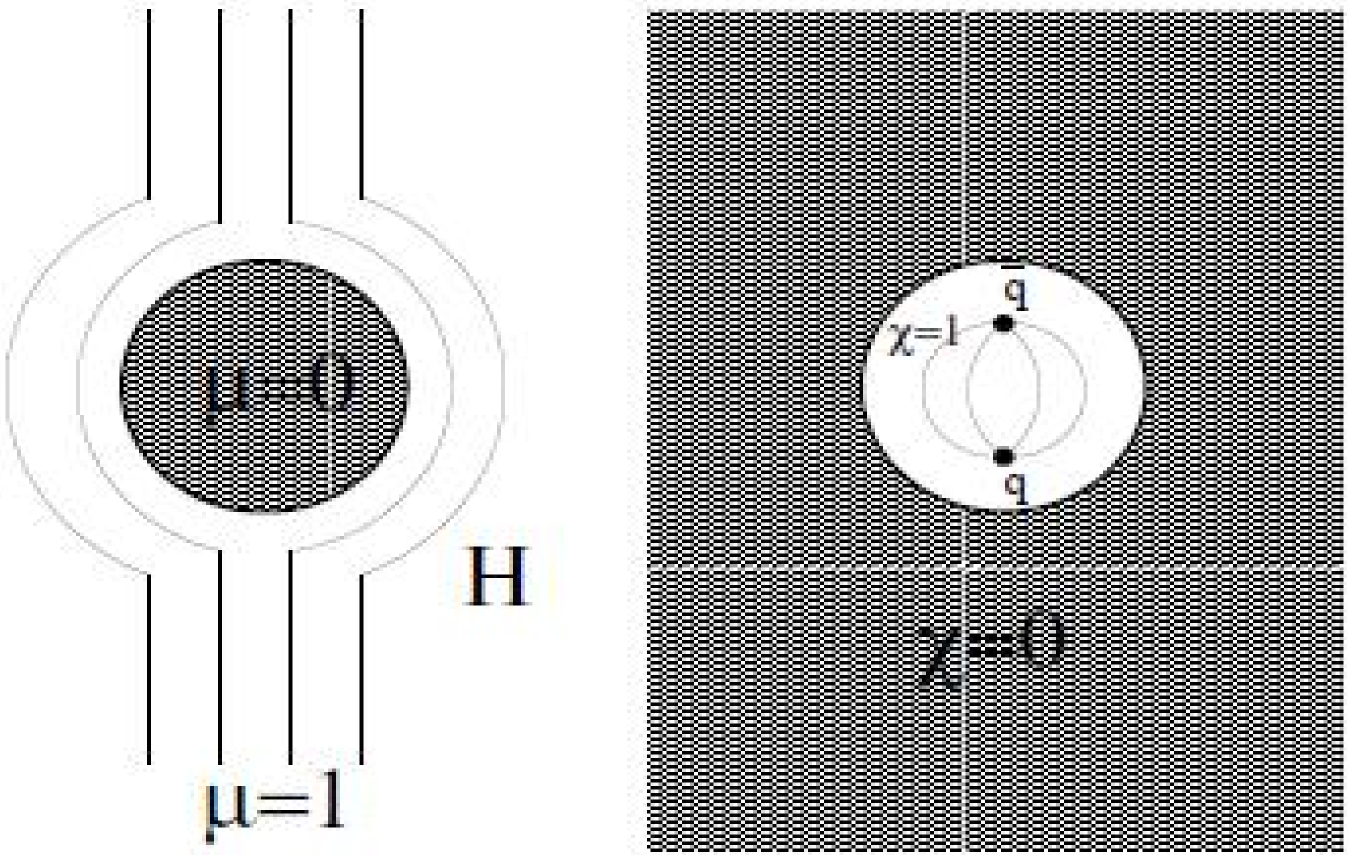
July 2009
$\alpha_s(Q)$
0.5
0.4
0.3
0.2
0.1
Deep Inelastic Scattering
e^+e^- Annihilation
Heavy Quarkonia
QCD $\alpha_s(M_Z) = 0.1184 \pm 0.0007$
1
10
100
Q [GeV]

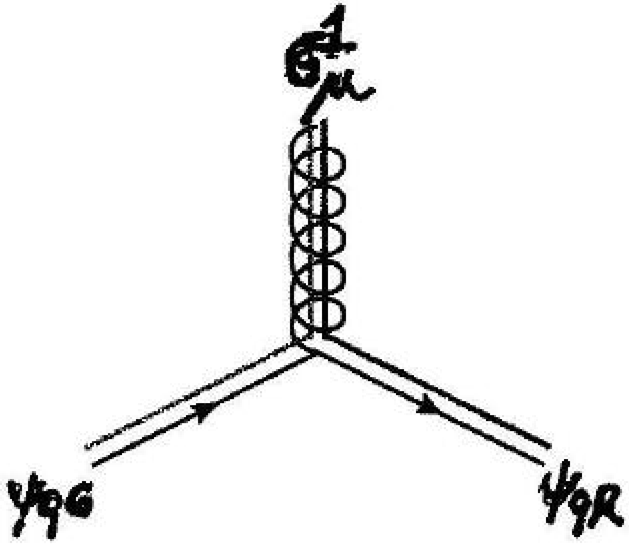
CONFINEMENT

Analogy superconductor QED-Vacuum QCD perfect color dielectric conductor

-Superconductor is perfect diamagnet with zero magnetic susceptibility(electron pairs in BCS).Repels the magnetic field

-Vacuum in QCD is a perfect color dielectric, zero dielectric constant,done by condensate qqbar and gluons.Repels the cromoelectric field, keeping it inside hadrons


μ=0
H
μ=1
q
χ=1
q
χ=0



$$\propto \quad -\tfrac{i}{2}g_s \quad \bar{\psi}_{qR} \quad \lambda^1 \quad \psi_{qG}$$

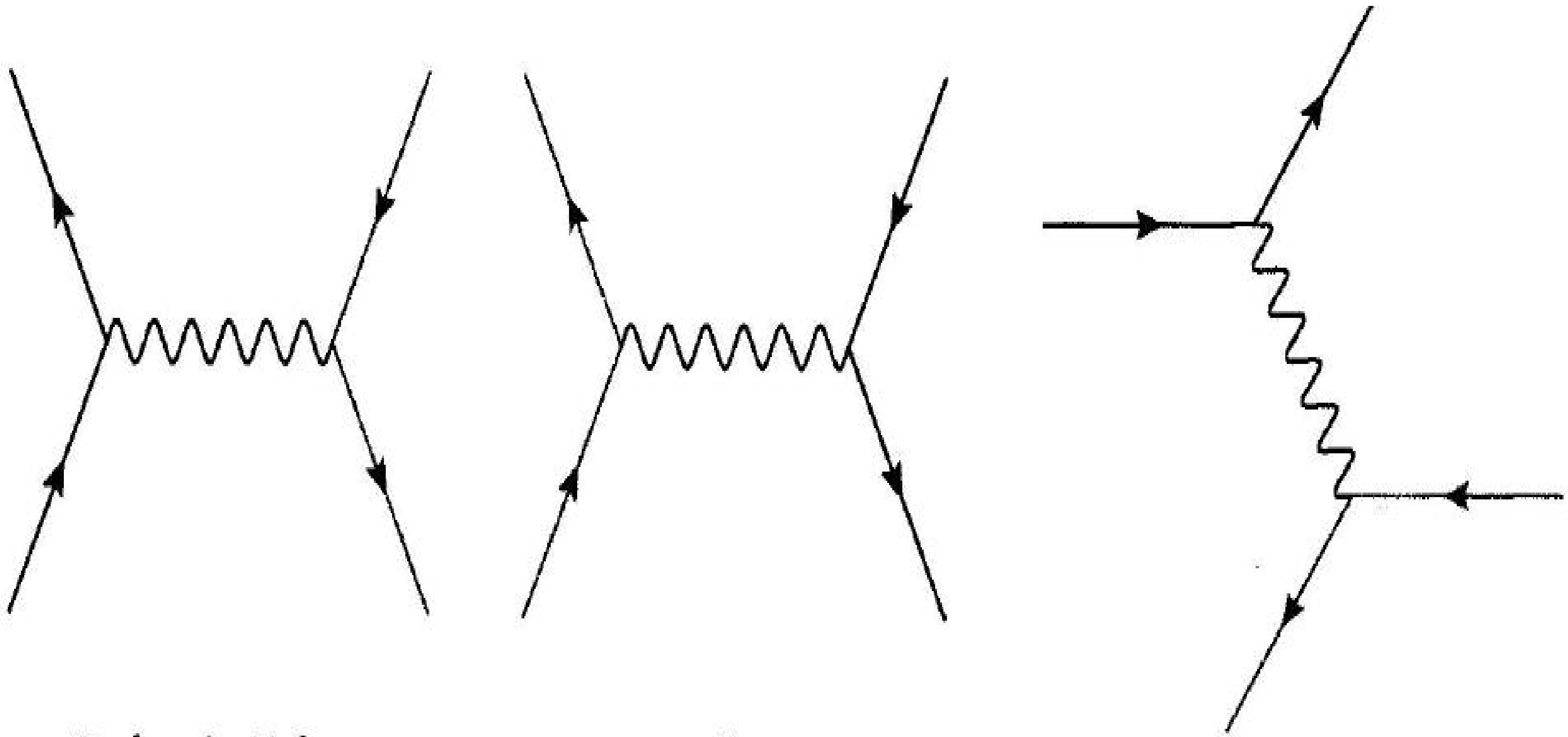
$$= \quad -\tfrac{i}{2}g_s \begin{pmatrix} 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$$

$$e^+e^- \to Z \to q\bar{q} \quad : \quad \sum_{\text{colors}} |M|^2 \propto \delta_{ij}\delta^*_{ji} = \mathrm{Tr}\{\delta\} = N_C = 3$$

Drell-Yan proce

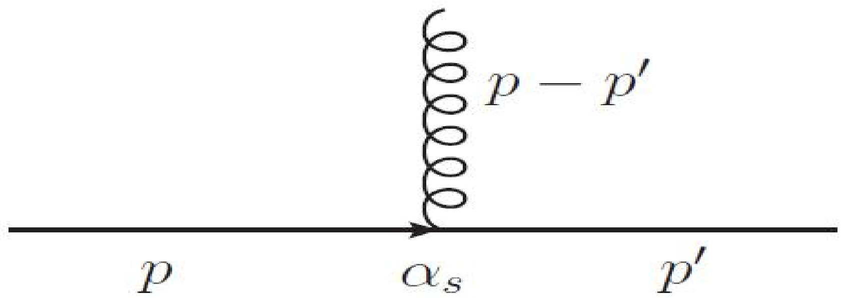
$$q\bar{q} \to Z \to e^+e^- \quad : \quad \frac{1}{9}\sum_{\text{colors}} |M|^2 \propto \frac{1}{9}\delta_{ij}\delta^*_{ji} = \frac{1}{9}\mathrm{Tr}\{\delta\} = \frac{1}{3}$$

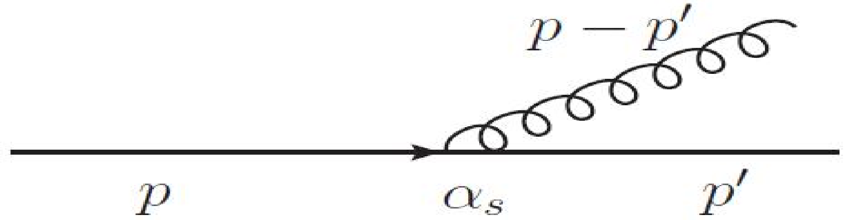
$$1/N_C$$

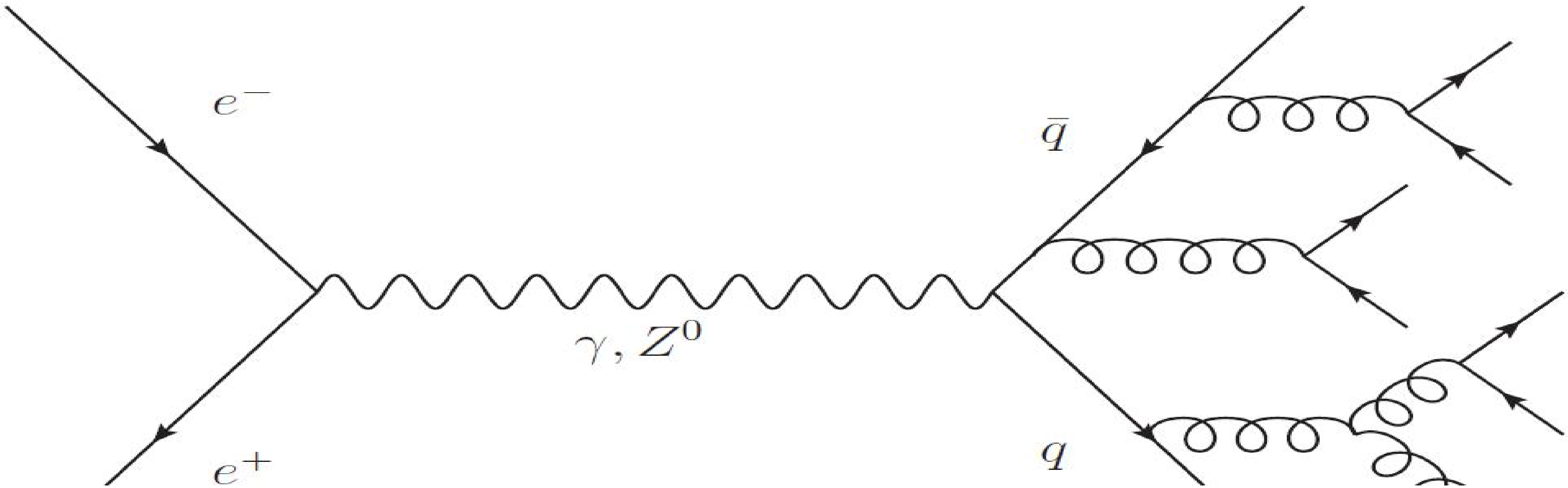


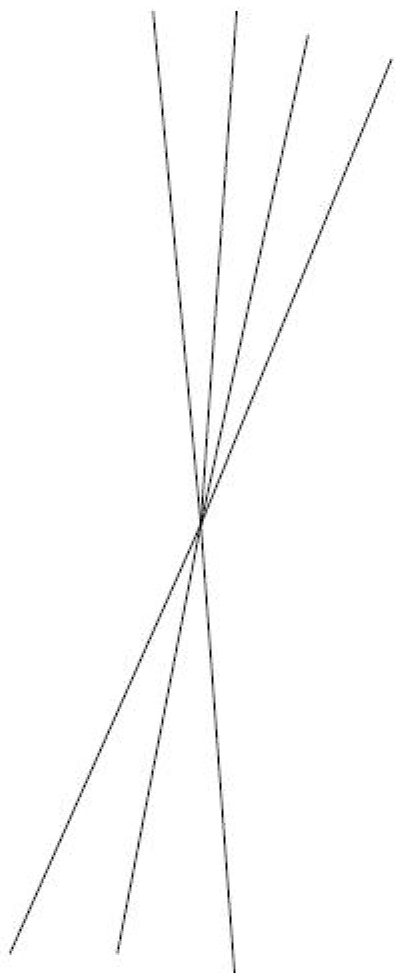
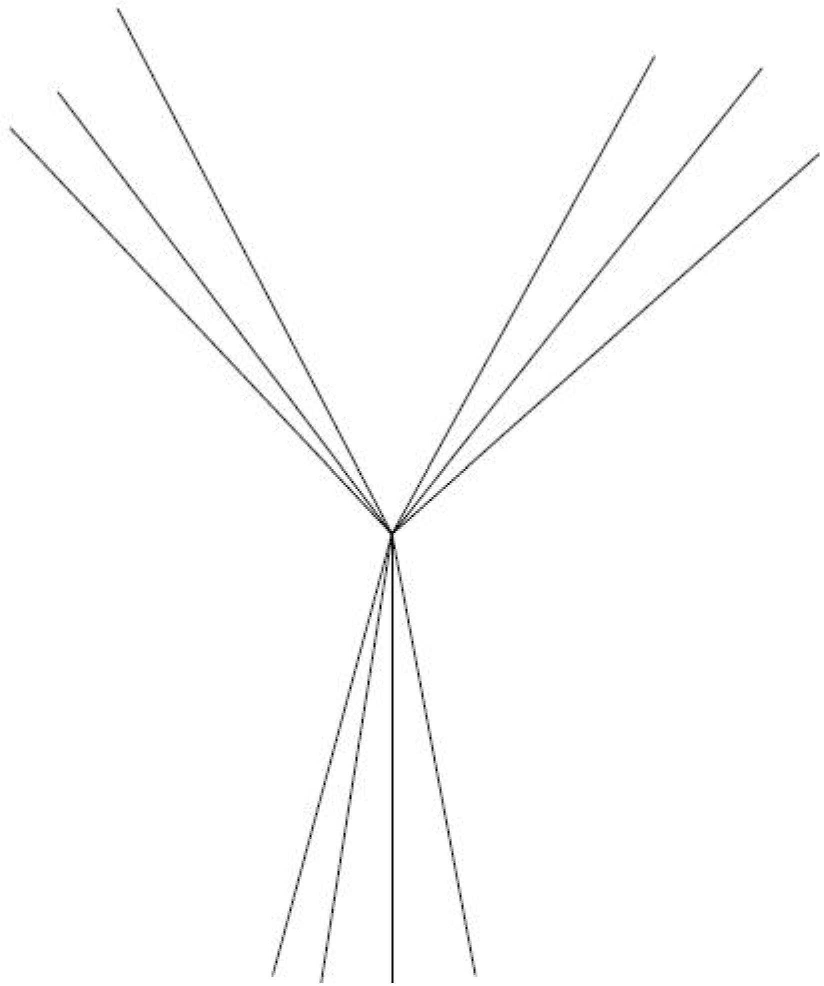
Hadronic Z decay	Drell-Yan	DIS
$e^- e^+ \to \gamma^*/Z^0 \to q\bar{q}$	$q\bar{q} \to \gamma^*/Z^0 \to \ell^+\ell^-$	$\ell\bar{q} \overset{\gamma^*/Z^*}{\to} \ell\bar{q}$
$\propto N_C$	$\propto 1/N_C$	$\propto 1$

Jets



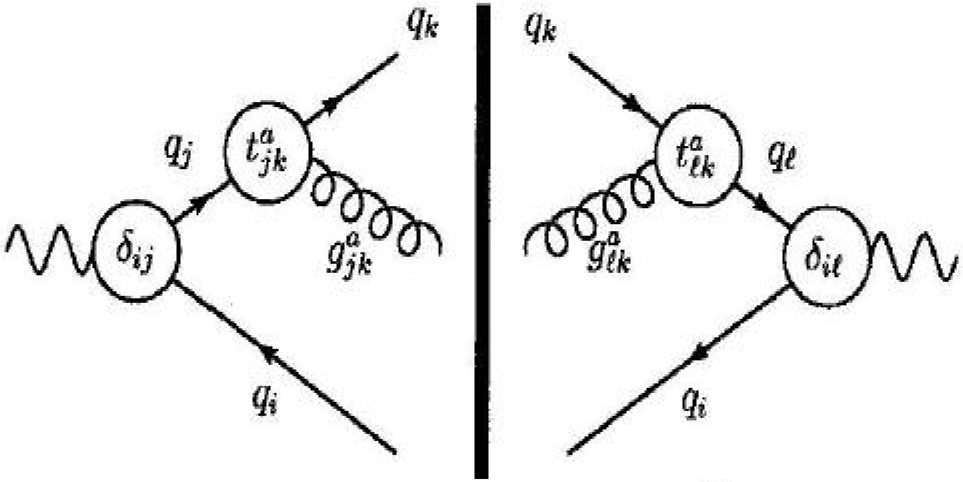




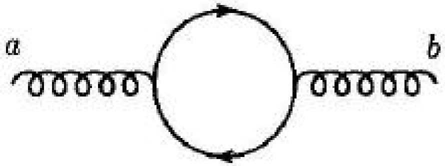



$Z \to qg\bar{q}$:

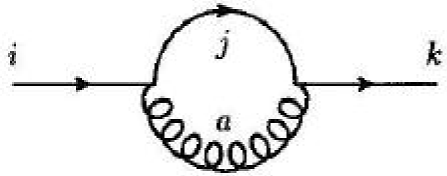
$$\sum_{\text{colors}} |M|^2 \propto \delta_{ij} t^a_{jk} (t^a_{\ell k} \delta^*_{i\ell})^* = \mathrm{Tr}\{t^a t^a\} = \frac{1}{2}\mathrm{Tr}\{\delta\} = 4\,,$$



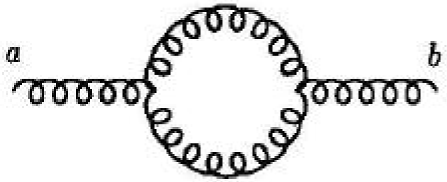
$\mathrm{Tr}\{t^a t^b\} = T_R\,\delta^{ab}$ $a, b \in [1, \ldots, 8]$



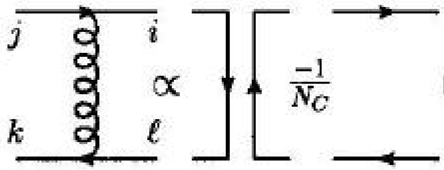
$\sum_a t^a_{ij} t^a_{jk} = C_F\,\delta_{ik}$ $a \in [1, \ldots, 8]$, $i, j, k \in [1, \ldots, 3]$



$\sum_{c,d} f^{acd} f^{bcd} = C_A\,\delta^{ab}$ $a, b, c, d \in [1, \ldots, 8]$



$t^a_{ij} t^a_{k\ell} = T_R \left(\delta_{jk}\delta_{i\ell} - \frac{1}{N_C}\delta_{ij}\delta_{k\ell}\right)$ $i, j, k, \ell \in [1, \ldots, 3]$



(Fierz)

$T_R = \frac{1}{2}$ $C_F = \frac{4}{3}$ $C_A = N_C = 3$

Symmetries

- Isospin $m_u = m_d$

$$\begin{aligned} u &\longrightarrow \alpha u + \beta d, \\ d &\longrightarrow \gamma u + \delta d, \end{aligned} \quad V = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix}, \quad \det V = 1 \qquad V \in SU(2)$$

$m_u < m_d$

$$m_u \bar{u} u + m_d \bar{d} d = \frac{1}{2}(m_u + m_d)(\bar{u}u + \bar{d}d) + \frac{1}{2}(m_d - m_u)(\bar{d}d - \bar{u}u)$$

Quiral

$$m_u = m_d = 0.$$

$$\begin{pmatrix} u_R \\ d_R \end{pmatrix} \longrightarrow V_R \begin{pmatrix} u_R \\ d_R \end{pmatrix}, \quad \begin{pmatrix} u_L \\ d_L \end{pmatrix} \longrightarrow V_L \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad V_R, V_L \in SU(2)$$

$$SU(2)_L \times SU(2)_R$$

$$\vec{I}(I^+, I^-, I^3) \quad \vec{I}_5(I_5^+, I_5^-, I_5^3)$$

$$I^+ = \int d\vec{x}\, \bar{u}\gamma^0 d = \int d\vec{x}\, u^+ d,$$

$$I_5^+ = \int d\vec{x}\, \bar{u}\gamma^0\gamma_5 d = \int d\vec{x}\, u^+\gamma_5 d$$

$$\partial_\mu(\bar{u}\gamma^\mu d) = i(m_u - m_d)\bar{u}d, \qquad \partial_\mu(\bar{u}\gamma^\mu\gamma_5 d) = i(m_u + m_d)\bar{u}\gamma_5 d$$

Spontaneus symmetry breaking (fundamental state is not symmetrical)

- No particle multiplets with opposite parity

If the vacuum is invariant under any S of a group G $S|\Omega\rangle = |\Omega\rangle$

$$S|\Omega\rangle = e^{i\epsilon Q}|\Omega\rangle \simeq (1 + i\epsilon Q)|\Omega\rangle = |\Omega\rangle \qquad Q|\Omega\rangle = 0.$$

$$\vec{I}|\Omega\rangle = 0 \qquad \vec{I}_5|\Omega\rangle \neq 0.$$

- The three states $\vec{I}_5|\Omega\rangle$ have the same vacuum energy,and the same spin, therefore we have three massless bosons (Golstone bosons) negative parity and I=1. It is natural the identification:

$$I_5^+|\Omega\rangle = |\pi^+\rangle, \quad I_5^3|\Omega\rangle = |\pi^0\rangle, I_5^-|\Omega\rangle = |\pi^-\rangle.$$

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{sb}, \;\; \mathcal{H}_{sb} = \int d\vec{x}\,(m_u\bar{u}u + m_d\bar{d}d),$$

$$[\mathcal{H}_0, \vec{I}] = 0 = [\mathcal{H}_0, \vec{I}_5].$$

Scale Symmetry and Trace Anomaly

- For massless, QCD is invariant under

$$x \longrightarrow \lambda x, \ \ \psi_q \longrightarrow \lambda^{3/2}\psi_q, \ \ G^a_\mu \longrightarrow \lambda G^a_\mu,$$

$$s^\mu = T^{\mu\nu} x_\nu,$$

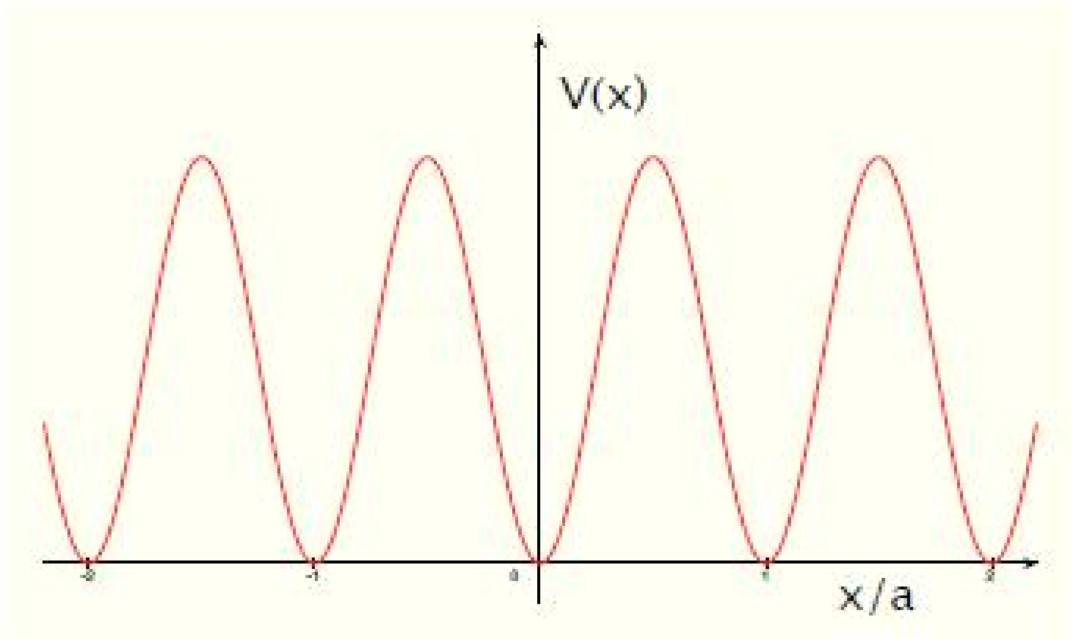
$$\partial_\mu s^\mu = T^\mu_\mu = \frac{\beta(g_s)}{2g_s} F^a_{\mu\nu} F^{\mu\nu a} + [1+\gamma(g_s)] m_q \bar{\psi}_q \psi_q,$$

$$T^\mu_\mu = \epsilon - 3P \qquad\qquad \beta(g_s) = -\frac{g_s^3}{3(4\pi)^2}(11N_c - 2n_f)$$

Vacuum Structure, Instantons, Topological Charge

$$\mathcal{L}_\theta = g_s^2 \frac{\theta}{32\pi^2} \epsilon^{\mu\nu\rho\sigma} F^a_{\mu\nu} F^a_{\rho\sigma} ;$$

$$\partial_\mu K^\mu = \text{traza}(\epsilon^{\mu\nu\rho\sigma} F^a_{\mu\nu} F^a_{\rho\sigma}), \quad K^\mu \equiv 2\epsilon^{\mu\nu\rho\sigma}\, \text{traza}\left(F^a_\nu \partial_\rho F^a_\sigma - \frac{1}{3} g_s f_{abc} F^a_\nu F^b_\rho F^c_\sigma \right).$$



$$\psi(x) = \sum_n c_n \psi(x - x_n) \quad x_n = na, \quad c_n = e^{in\theta}$$

$$|\theta\rangle = \sum_n e^{in\theta} |n\rangle$$

- The classical theory has degenerate vacua labelled by the winding number n(topological charge)

In the quantized theory

$$|\theta\rangle = \sum_n e^{in\theta} |\underline{\boldsymbol{A}}_n\rangle$$

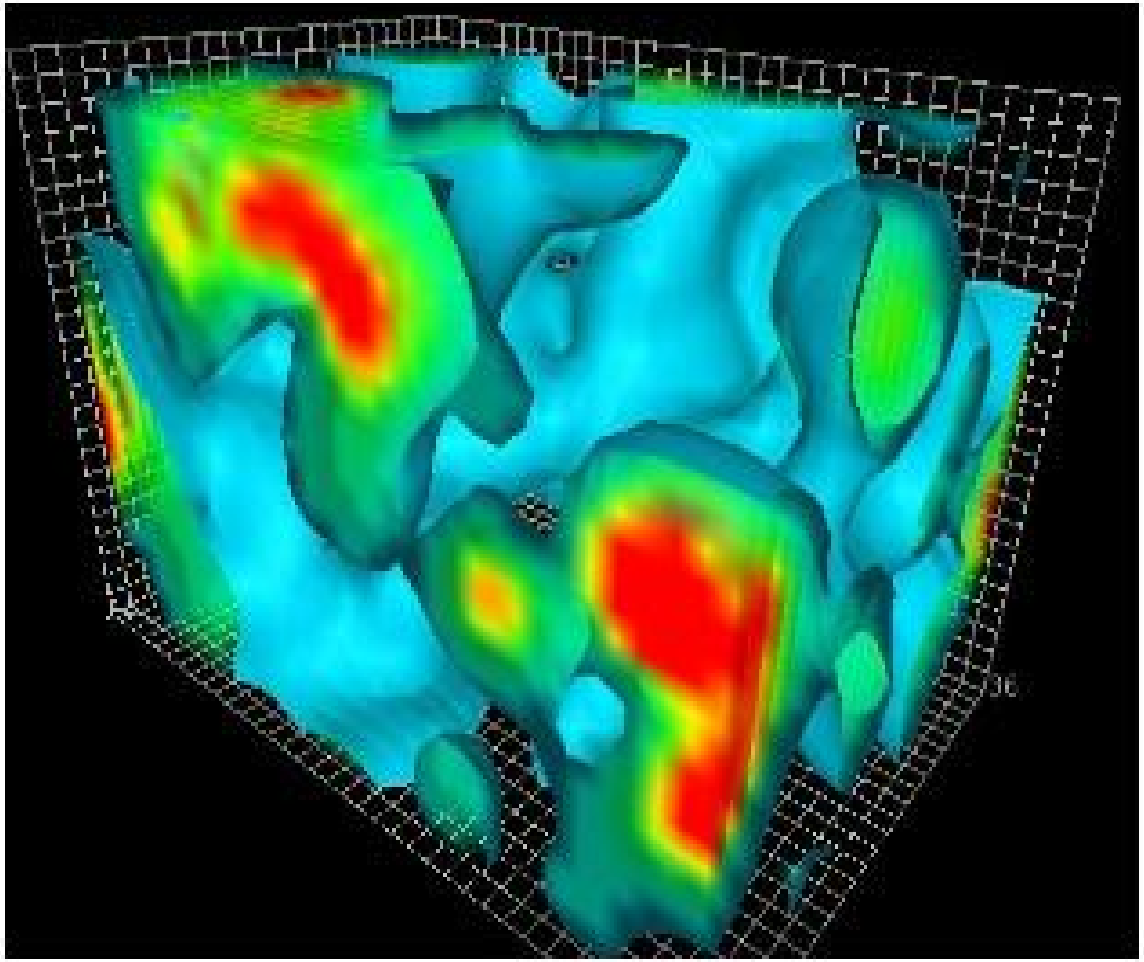
where the state $|\underline{\boldsymbol{A}}_n\rangle$ is an eigenstate of $\underline{\boldsymbol{A}}_n$ which satisfies

i) Finite euclidean action

ii) Solutions of the classical field equations with zero Euclidean energy

iii) Evolves from $\underline{\boldsymbol{A}}_n$ at it=-Infinite to $\underline{\boldsymbol{A}}_{n+\nu}$ at it=infinite

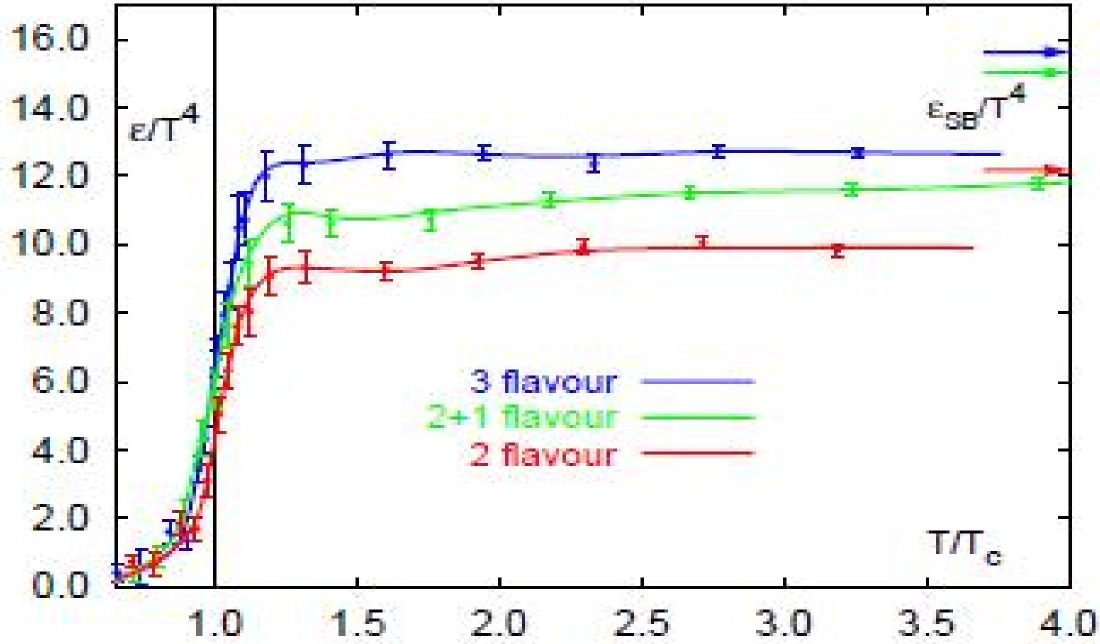
$$\begin{aligned} \nu &= -\frac{g^2}{16\pi^2}\int \mathrm{d}\tau\, \mathrm{d}^3\boldsymbol{r}\, \partial_\alpha^E K_\alpha^E \quad (\alpha = x, y, z, \tau) \\ &= -\frac{g^2}{16\pi^2}\int_{r=\infty} \mathrm{d}S_\alpha K_\alpha^E , \end{aligned}$$



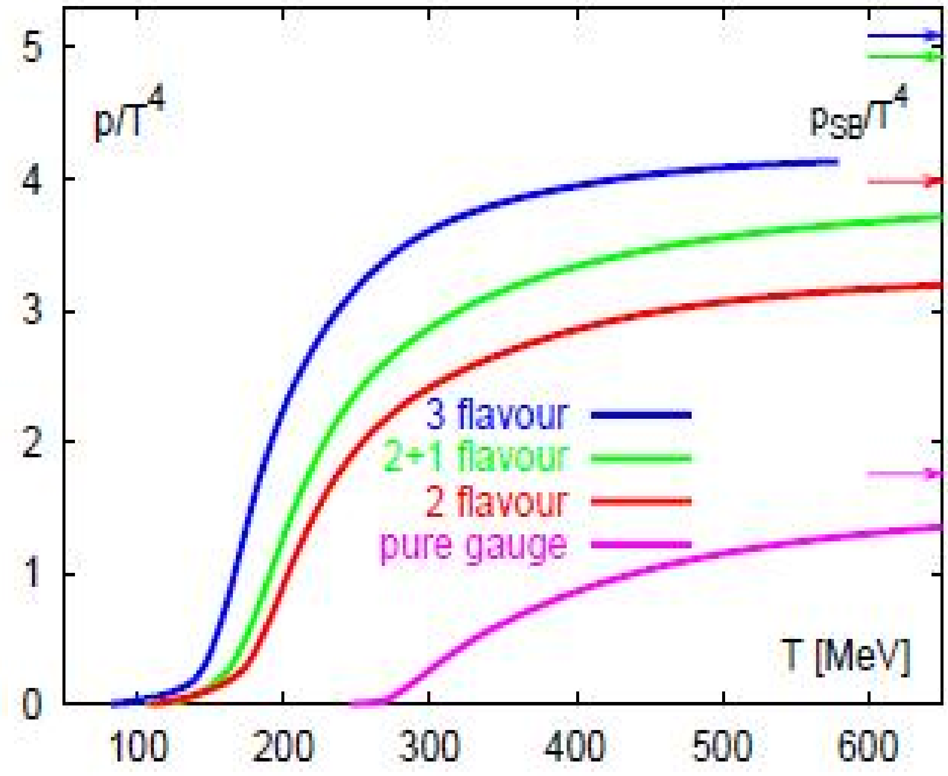
QCD at high temperature

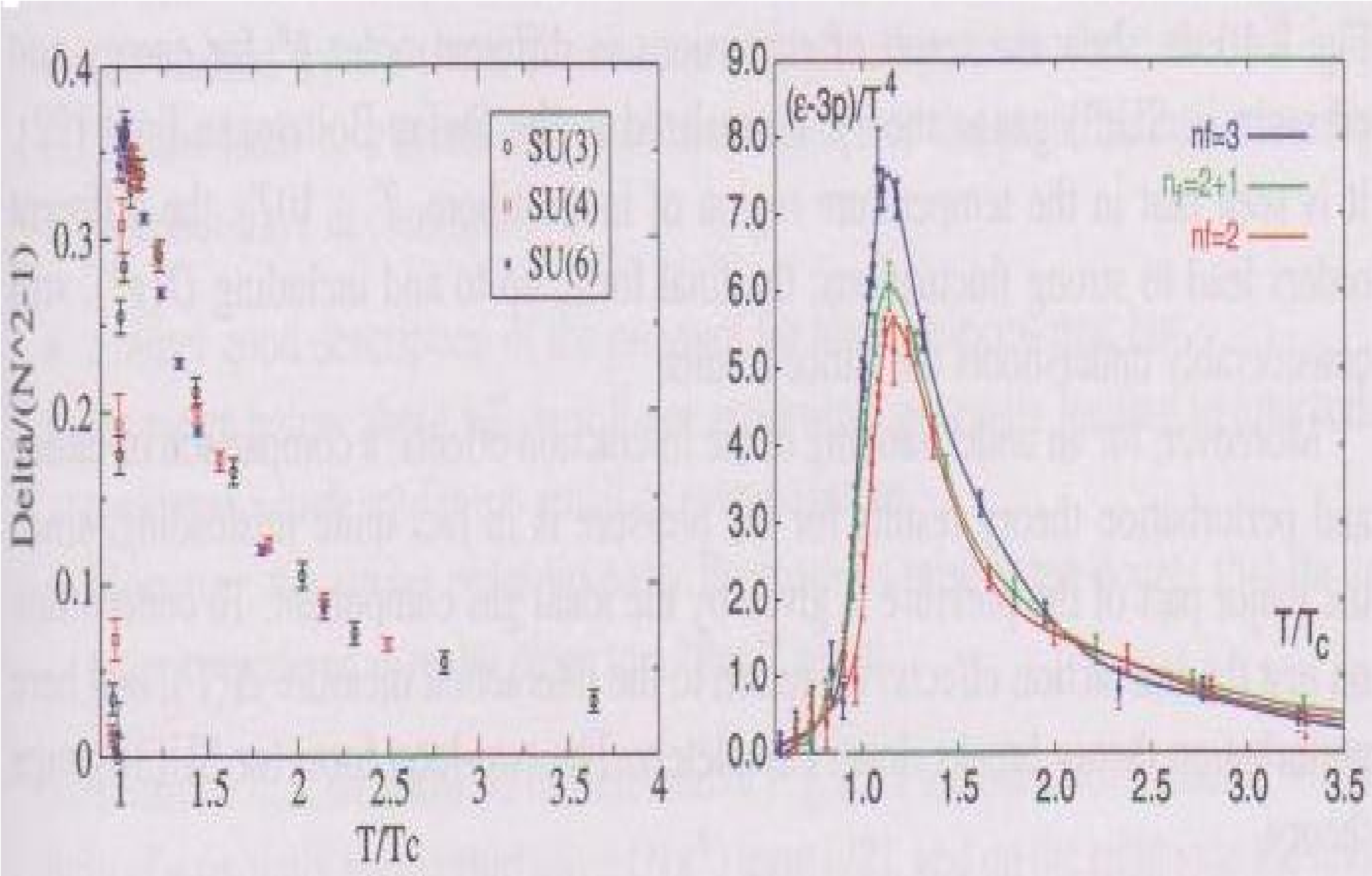
$$\epsilon_{\rm HG} = \frac{\pi^2}{30} 3 T^4 \simeq T^4,$$

$$\epsilon_{\rm QGP} = \frac{\pi^2}{30} \left[2 \times 8 + \frac{7}{8} \times 2(3) \times 2 \times 2 \times 3 \right] T^4 = \frac{\pi^2}{30} [16 + 21(31.5)] T^4,$$

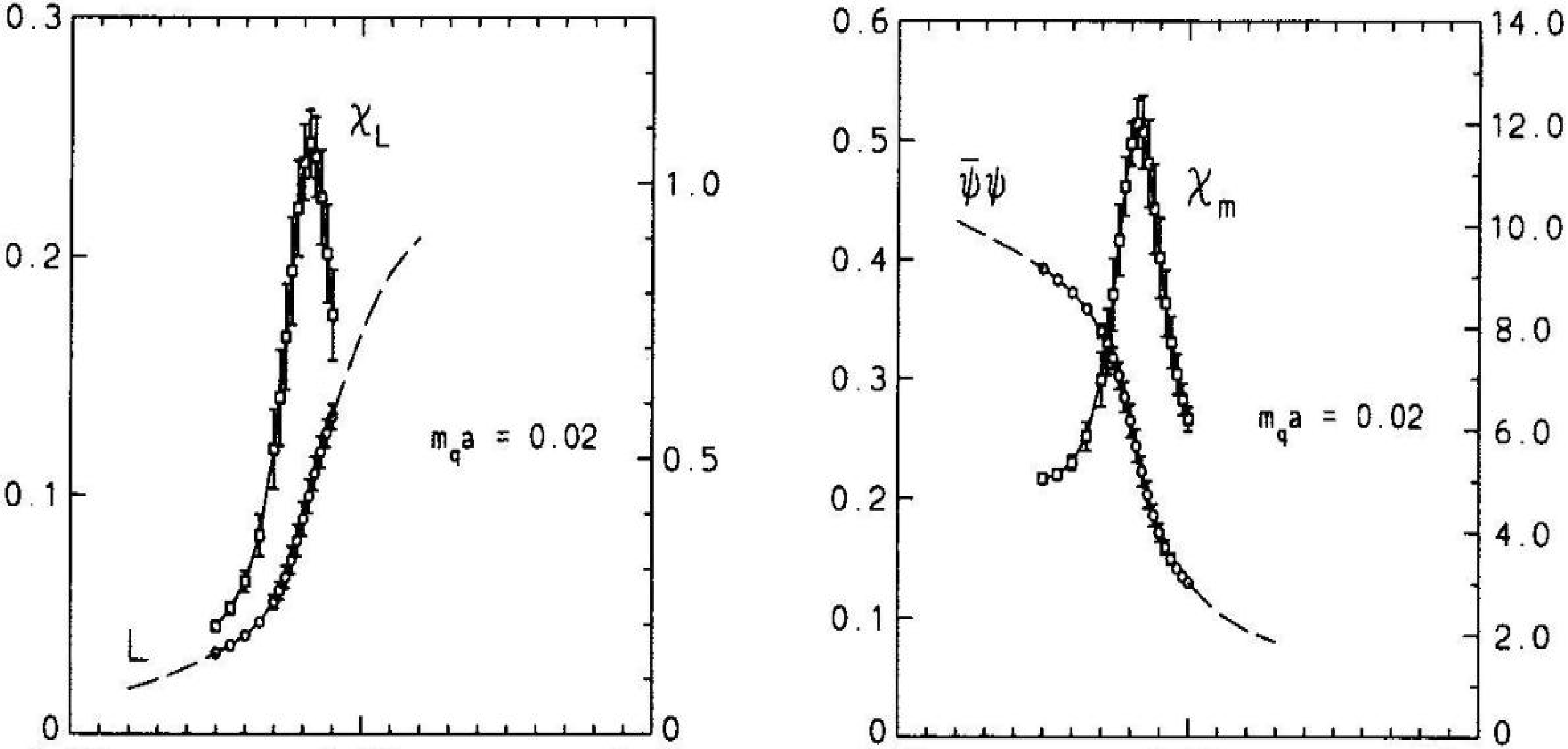


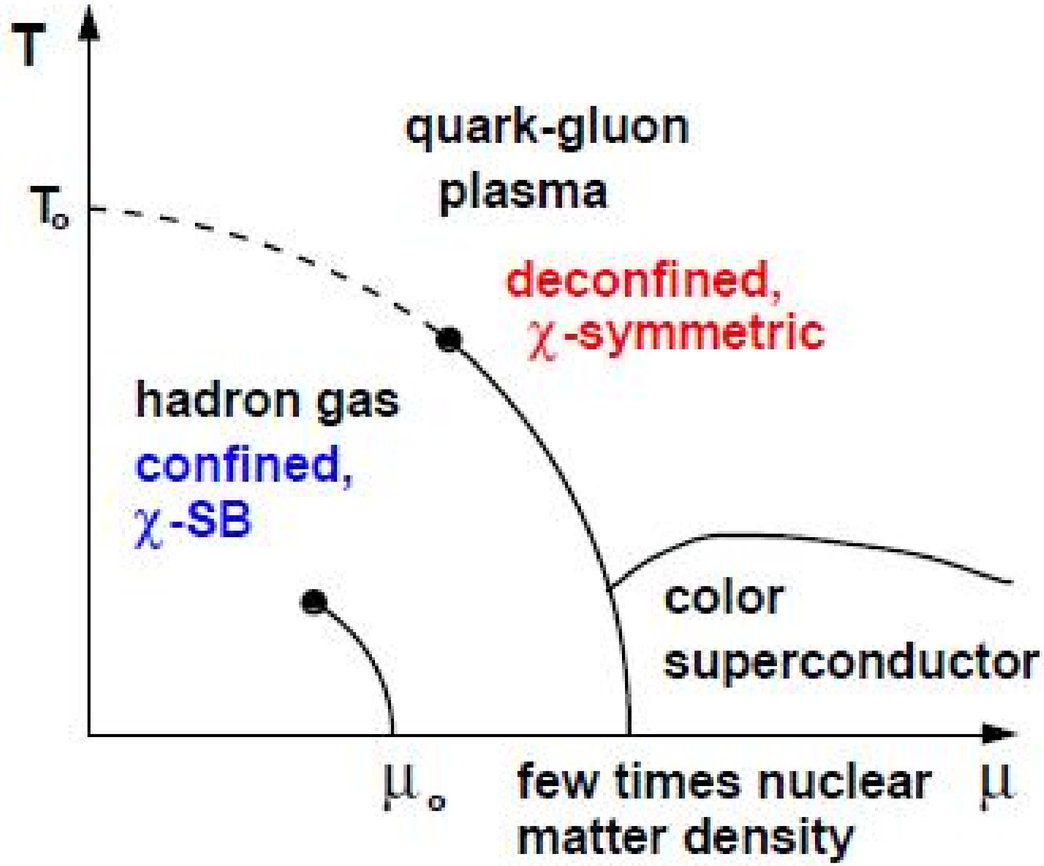
$$\epsilon = \frac{\langle p_T \rangle \left. \frac{dN}{dy} \right|_{y=0}}{\tau_0 \pi R_p^2 A^{2/3}}$$



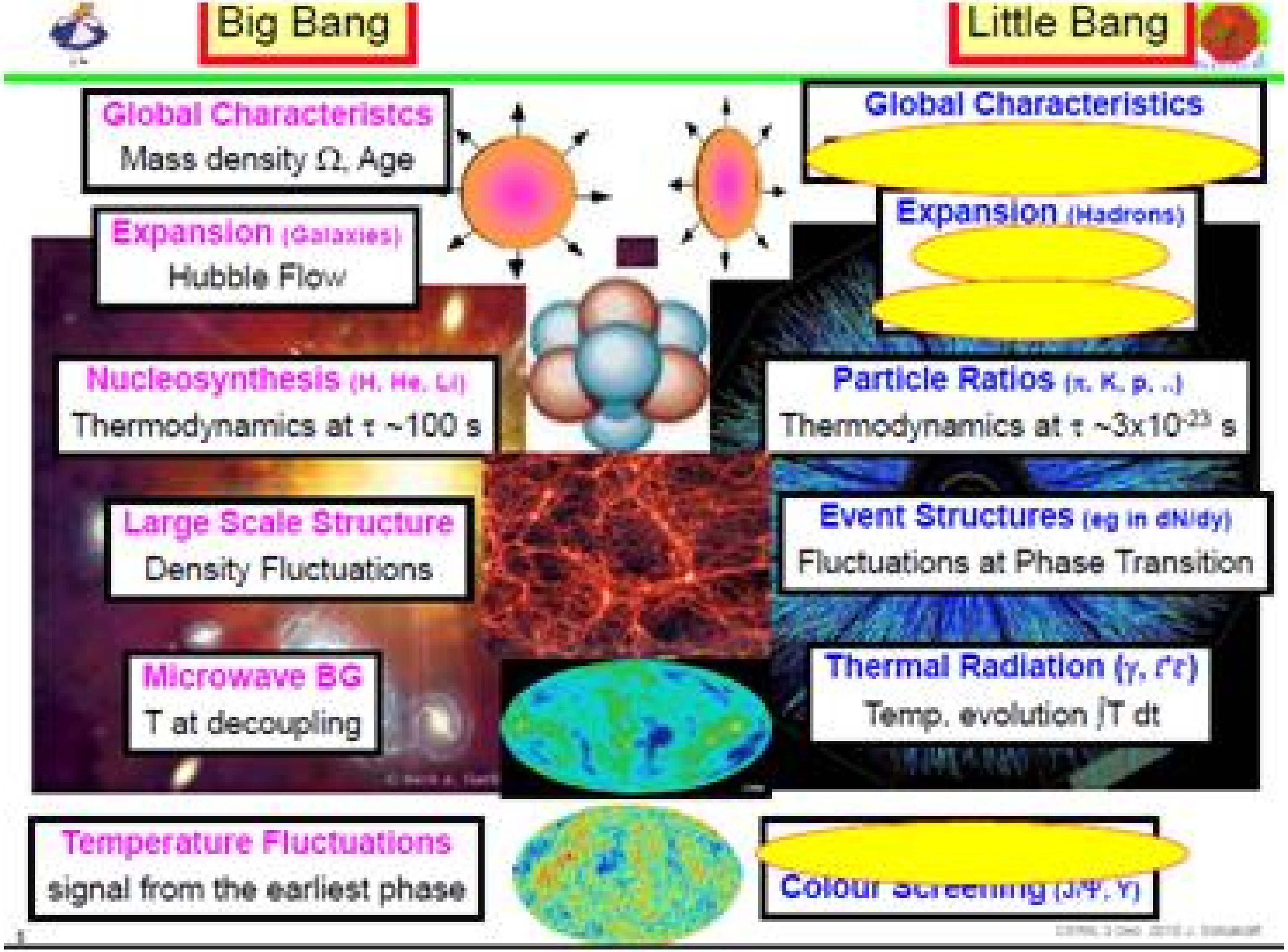


0.4
0.3
0.2
0.1
0
Delta/(N^2-1)
SU(3)
SU(4)
SU(6)
1
1.5
2
2.5
3
3.5
4
T/Tc
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
(ε-3p)/T^4
nf=3
nf=2+1
nf=2
T/Tc
1.0
1.5
2.0
2.5
3.0
3.5


0.3
0.2
0.1
0
1.0
0.5
0
χ_L
L
$m_q a = 0.02$
0.6
0.5
0.4
0.3
0.2
0.1
0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0
$\bar{\psi}\psi$
χ_m
$m_q a = 0.02$



T
quark-gluon
plasma
T₀
deconfined,
χ-symmetric
hadron gas
confined,
χ-SB
color
superconductor
μ₀
few times nuclear
matter density
μ



Big Bang
Little Bang
Global Characteristics
Mass density Ω, Age
Global Characteristics
Expansion (Galaxies)
Hubble Flow
Expansion (Hadrons)
Nucleosynthesis (H, He, Li)
Thermodynamics at τ ~100 s
Particle Ratios (π, K, p, ..)
Thermodynamics at τ ~3x10^-23 s
Large Scale Structure
Density Fluctuations
Event Structures (eg in dN/dy)
Fluctuations at Phase Transition
Microwave BG
T at decoupling
Thermal Radiation (γ, l⁺l⁻)
Temp. evolution ∫T dt
Temperature Fluctuations
signal from the earliest phase
Colour Screening (J/Ψ, Υ)

Characterizing the Little Bang (1)

- Particle Production and Energy density ε:
  - ⇨ Produced Particles: $dN_{ch}/d\eta$ ~ 1600 ± 76 (syst)
    - ~ 30,000 particles in total, ~ 400 times p
    - somewhat on high side of expectations
    - growth with energy faster in AA than pp
  - ⇨ Energy density ε > 3 x RHIC (fixed τ_0)
  - ⇨ Temperature + 30%
    - lower limit, likely τ_0

Particle production at RHIC (BNL)

1666: First documented use of the word 'Annus Mirabilis'

Matter under extreme conditions:

ε > 15 GeV/fm³

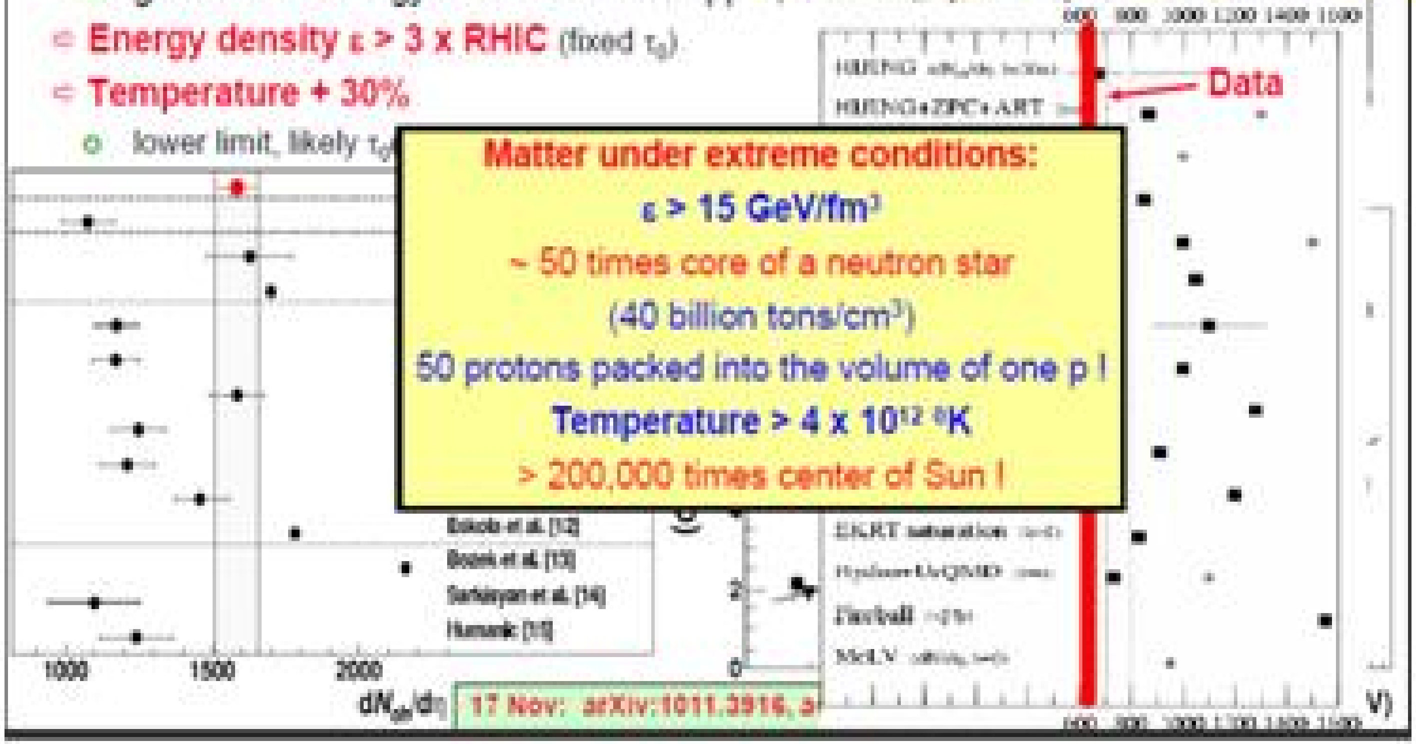
~ 50 times core of a neutron star

(40 billion tons/cm³)

50 protons packed into the volume of one p !

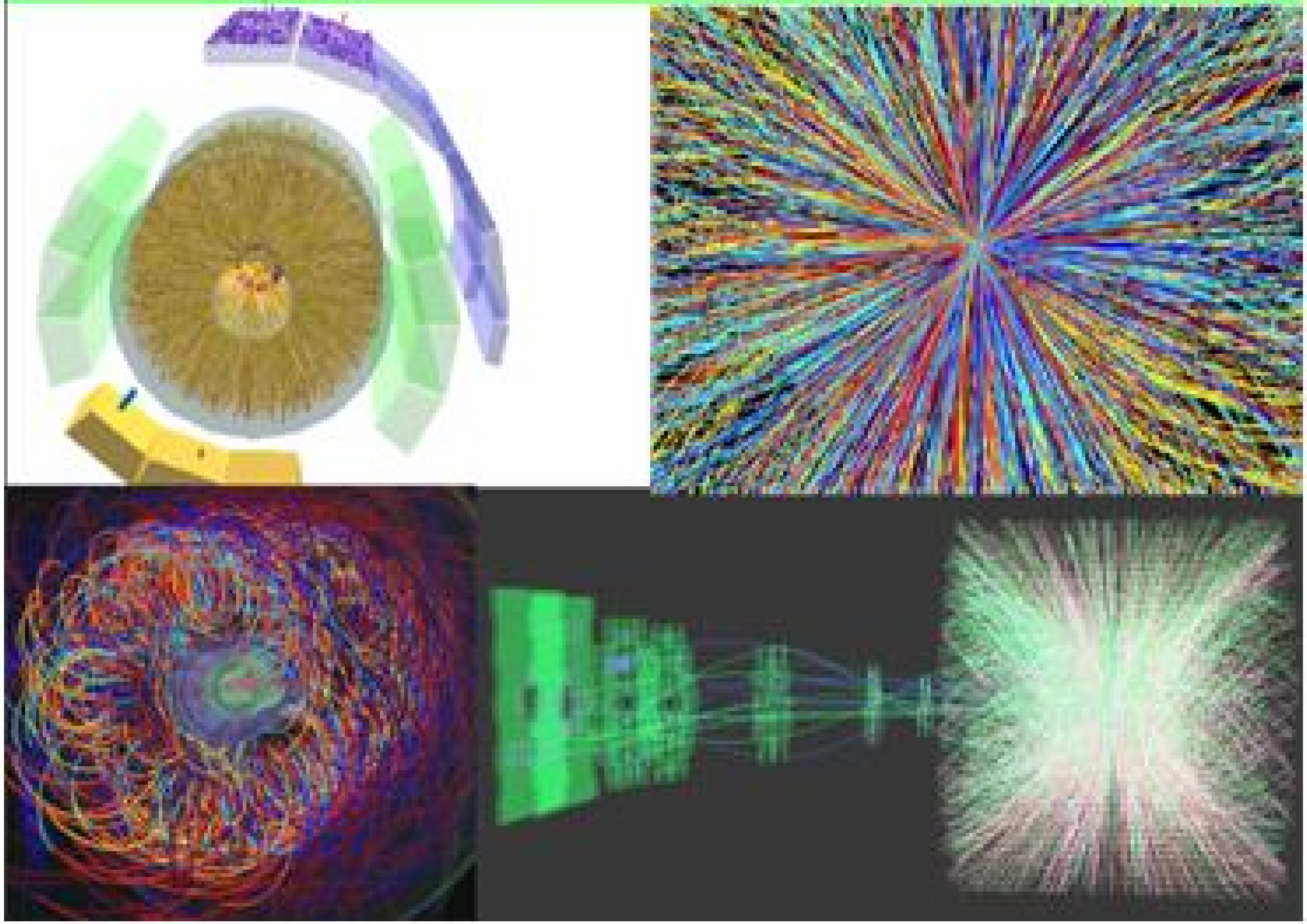
Temperature > 4 x 10^{12} °K

> 200,000 times center of Sun !



17 Nov: arXiv:1011.3916, a

Results from the Heavy Ion Run

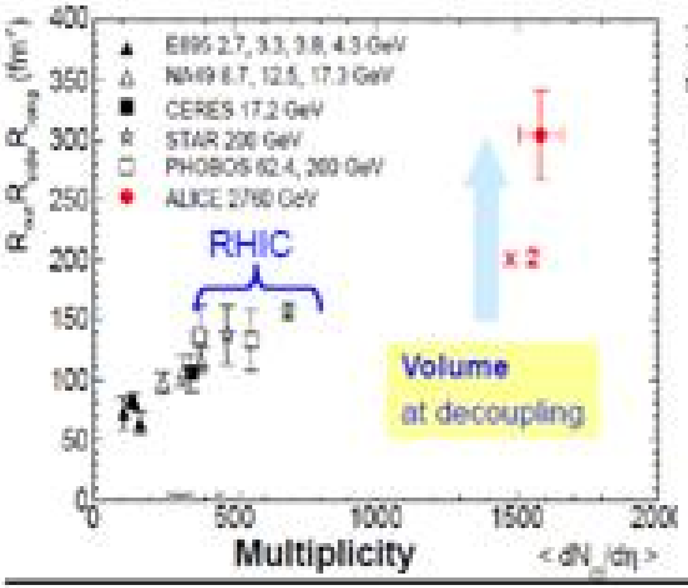


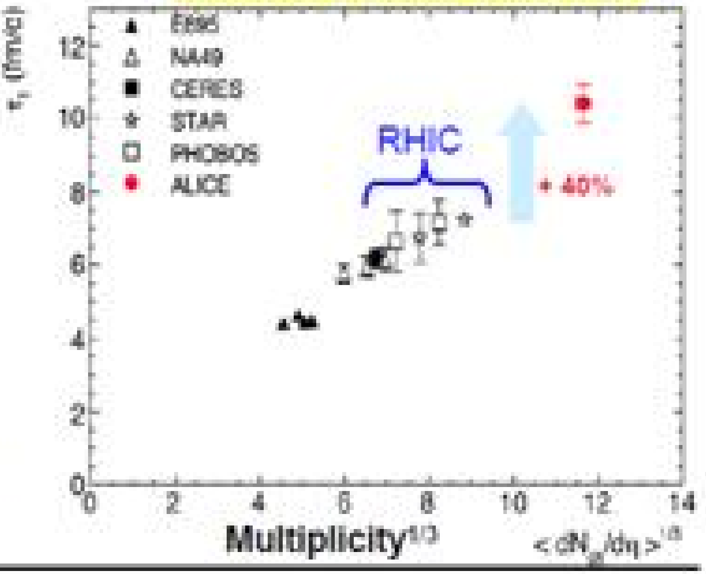
Characterizing the Little Bang (2)

- Volume and Lifetime:
  - ⇨ Identical particle interferometry
    - Quantum effect, leading to Bose Einstein Condensate at zero temperature
  - ⇨ **Volume ≈ 2 x RHIC** (≈ 300 fm^3)
    - observable 'comoving' volume !
  - ⇨ **Lifetime ≈ +30-40%** (> 10 fm/c ~ 3×10^{-23} s)

'Little Bang' lives some 10^{40} less than current age of Universe..

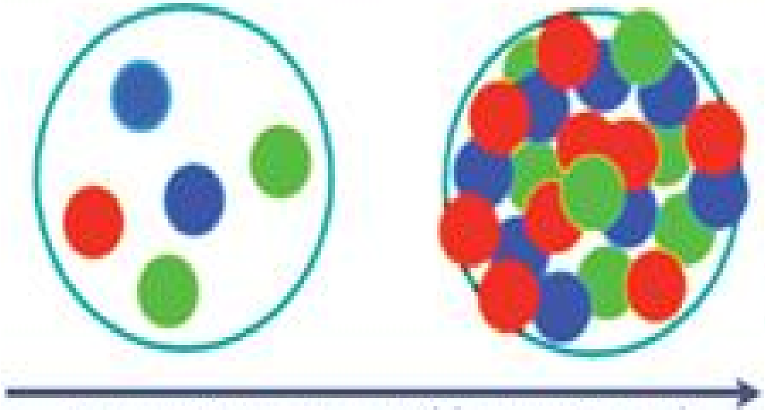
Lifetime: from collision to 'freeze-out' (hadron decoupling)





Color screening in partonic densities: picture

Saturation scale when interaction probability becomes $\mathcal{O}(1)$



increasing energy (decreasing x)

transverse area of the gluon

$$\alpha_s \frac{1}{Q^2_{\rm sat}} A N_g(x, Q^2_{\rm sat}) \sim \pi R_A^2$$

transverse area of the nucleus

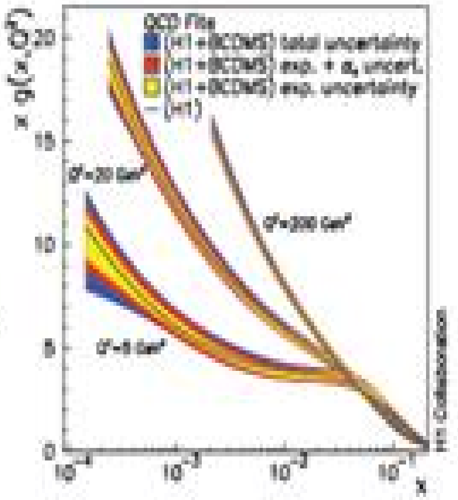
$$R_A \sim A^{1/3}$$

$$N_g \sim \frac{1}{x^\lambda} \quad \Longrightarrow \quad Q^2_{\rm sat} \sim \frac{A^{1/3}}{x^\lambda}$$

Strong fields and large occupation numbers.

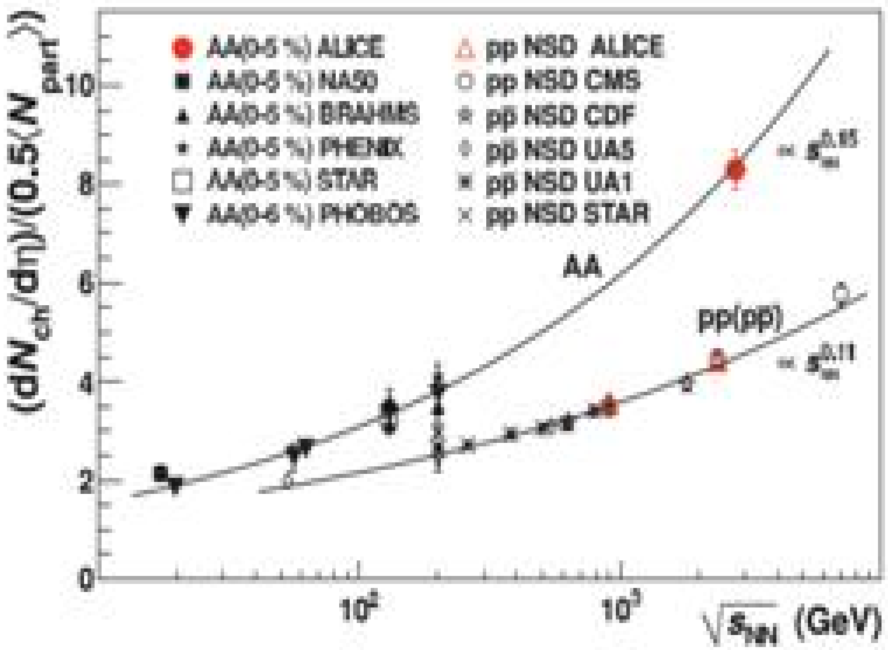
Semiclassical approach: Color Glass Condensate

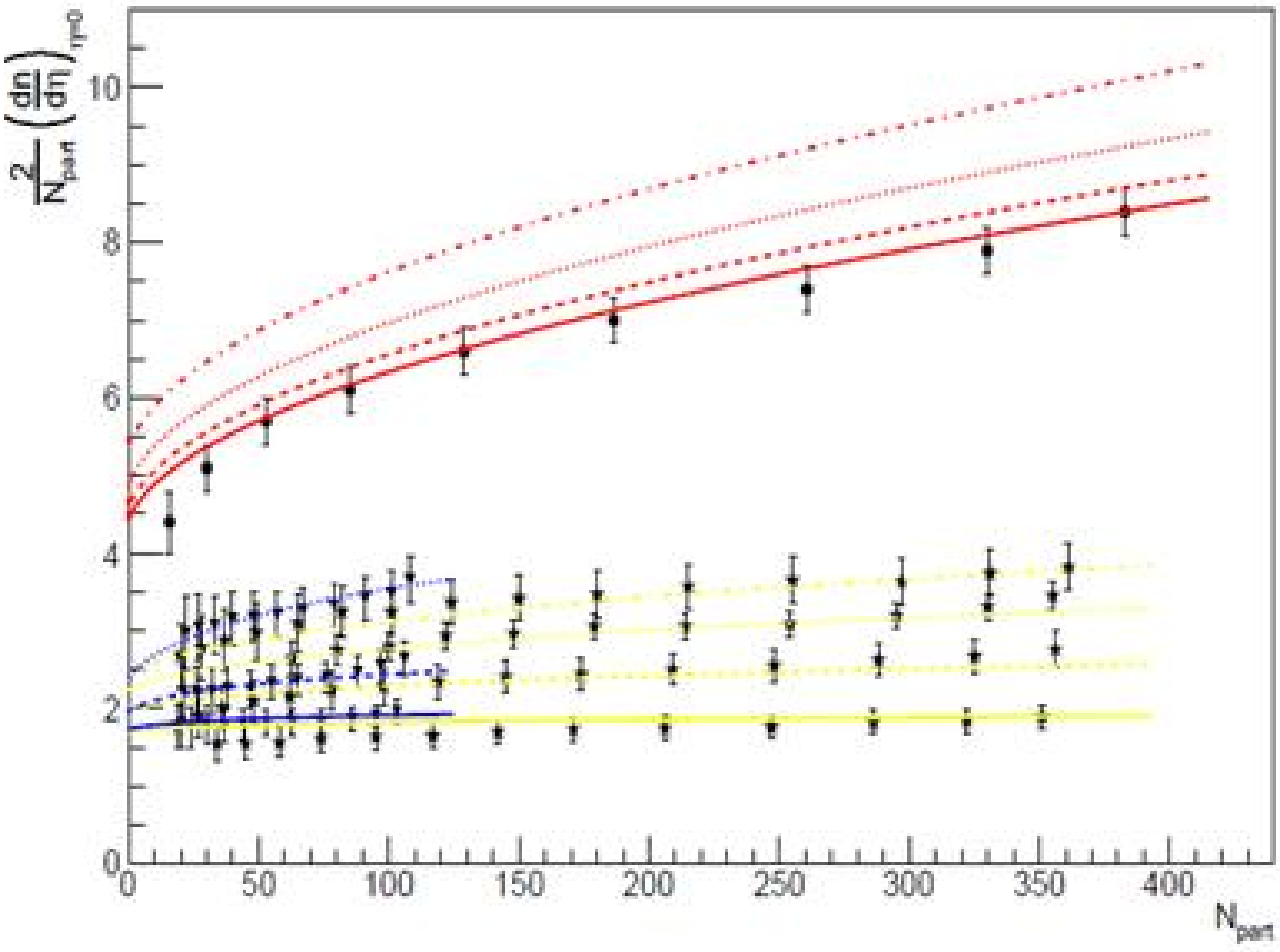
Geometric scaling



New data: multiplicities

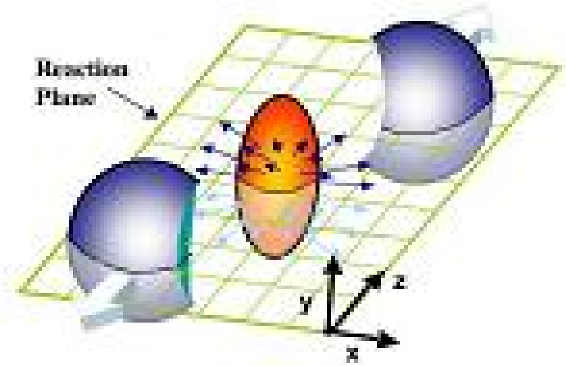
[ALICE: arxiv:1011.3916]

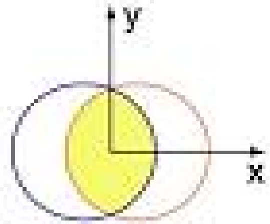


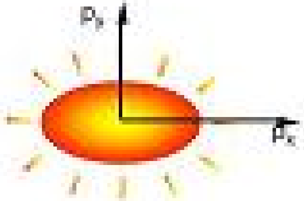


$\frac{2}{N_{part}}\left(\frac{dn}{d\eta}\right)_{\eta=0}$
0
2
4
6
8
10
0
50
100
150
200
250
300
350
400
N_{part}

ELLIPTIC FLOW







$$\frac{E d^3N}{dp^3} = \frac{d^3N}{p_T dp_T dy d\phi} = \frac{d^3N}{2\pi p_T dp_T dy}[1+2v_1\cos(\phi-\Phi_R)+2v_2\cos 2(\phi-\Phi_R)+\dots]$$

eccentricity $\epsilon = \left\langle \frac{\sigma_y^2-\sigma_x^2}{\sigma_y^2+\sigma_x^2} \right\rangle$ spatial anisotropy of the almond

$V_2 = \left\langle \frac{p_y^2-p_x^2}{p_y^2+p_x^2} \right\rangle$ momentum anisotropy

pressure gradient is mainly along the direction of impact parameter (x axis)

in fluid, the p_T distribution will reflect the fluid profile. Spatial distribution is carried over the momentum distribution. (partons or hadrons must interact each other)

We expect

$$v_2 \propto \varepsilon \text{ density of scatterings} = \varepsilon \frac{1}{\pi S}\frac{dn}{dy}$$

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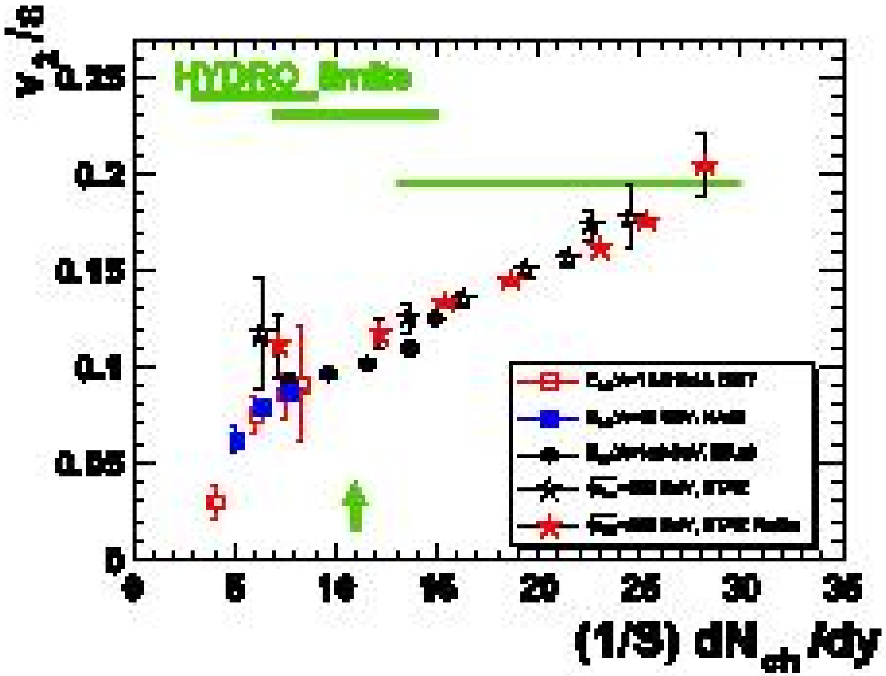
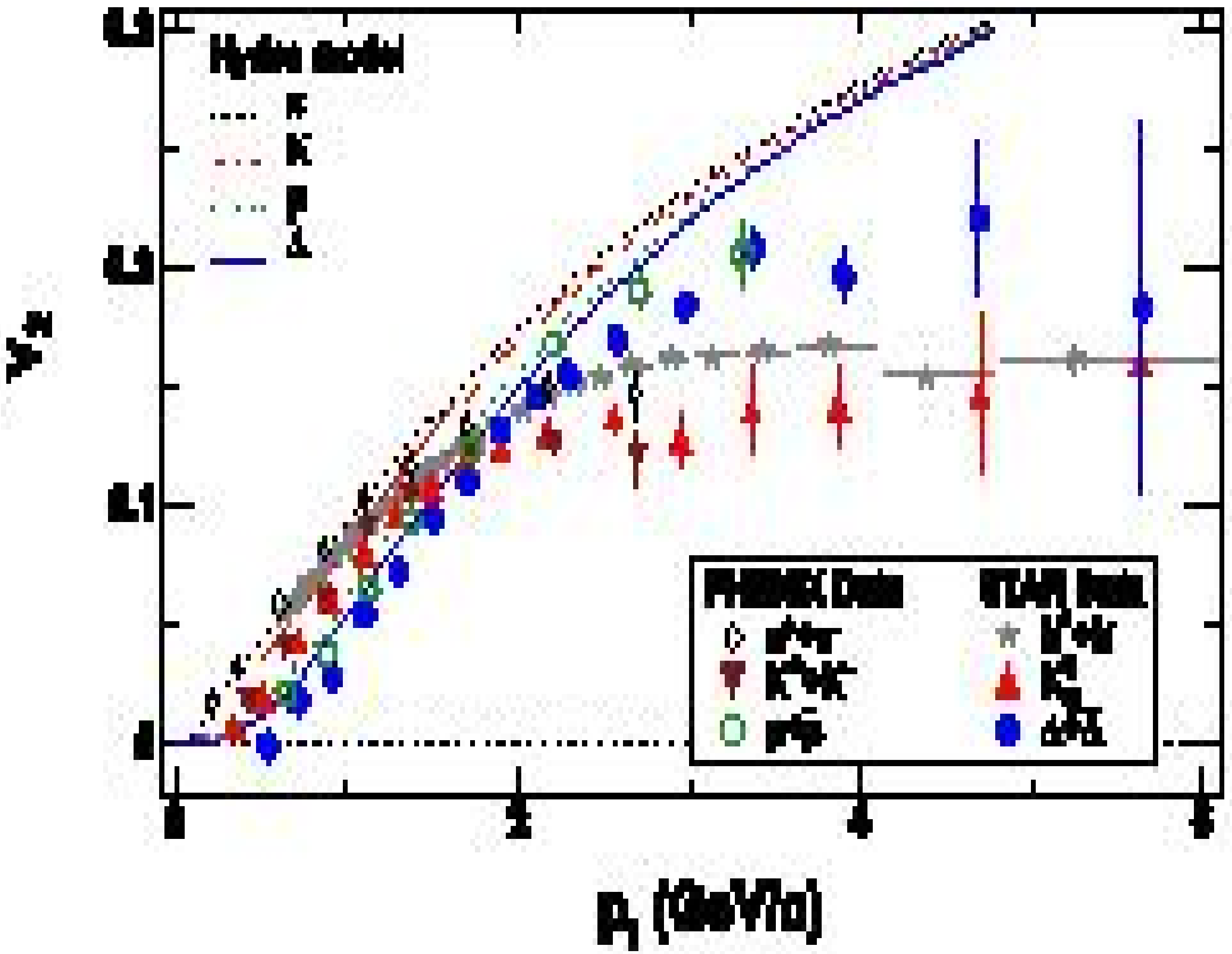


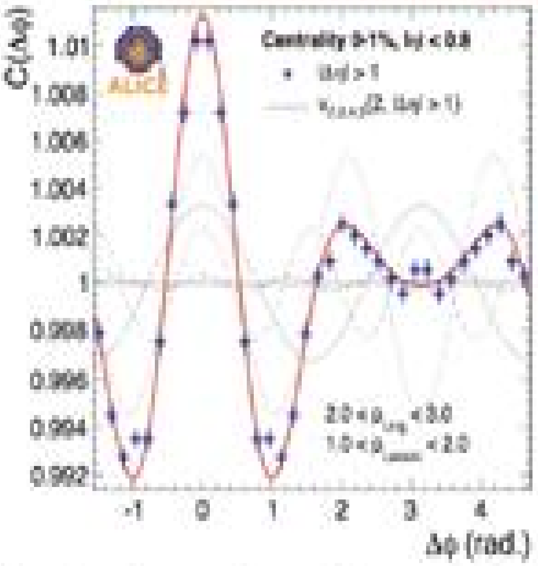
Hydrodynamics perfect fluid result is for full thermalized system and a soft EoS (e energy density cs speed sound)
Reynolds number Re=eLv/viscosity;Mach number Ma=v/cs, compresibility; Knudsen number Kn=lambda/L

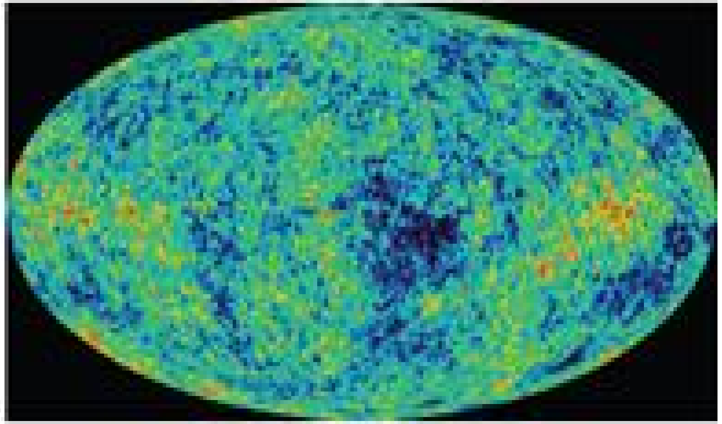
Viscosity=ecslambda Ma=Re x Kn Ma=1;Re=1/Kn



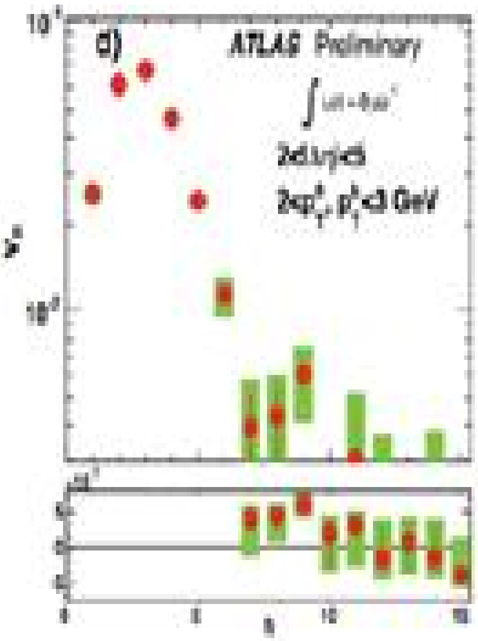
Hydro model
PHENIX Data
STAR Data
v2
pT (GeV/c)
0
2
4
6
0
0.1
0.2
0.3

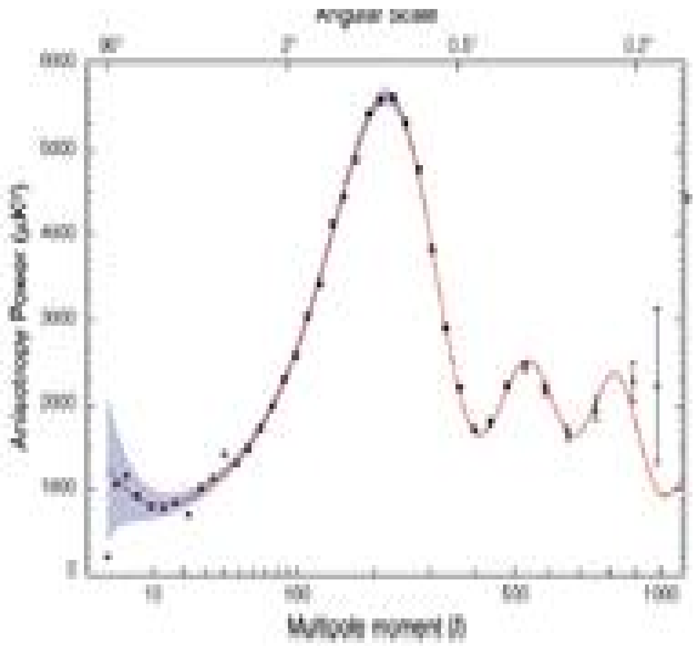
Little Bangs versus Big Bang





- Fluctuation analyzed since 2009
  ~ 100 % uncertainty on η/s
- After more than a decade of analysis and measurements,
  ~1 % accuracy on key parameter
- Improved measurements upcoming (future RHIC & LHC running)
- Improved measurements upcoming (PLANCK, ...)





Uncertainties in initial conditions

Many observables

$$v_n(p_T),\ n=1,...,10$$

Many small events

- Uncertainties in initial condition
- Many observables

$$c_l,\ l=1,...,1000$$

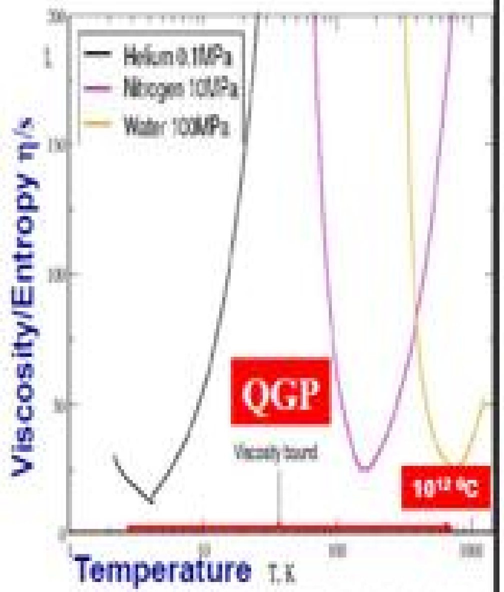
- One big event
  (additional uncertainty: cosmic variance)

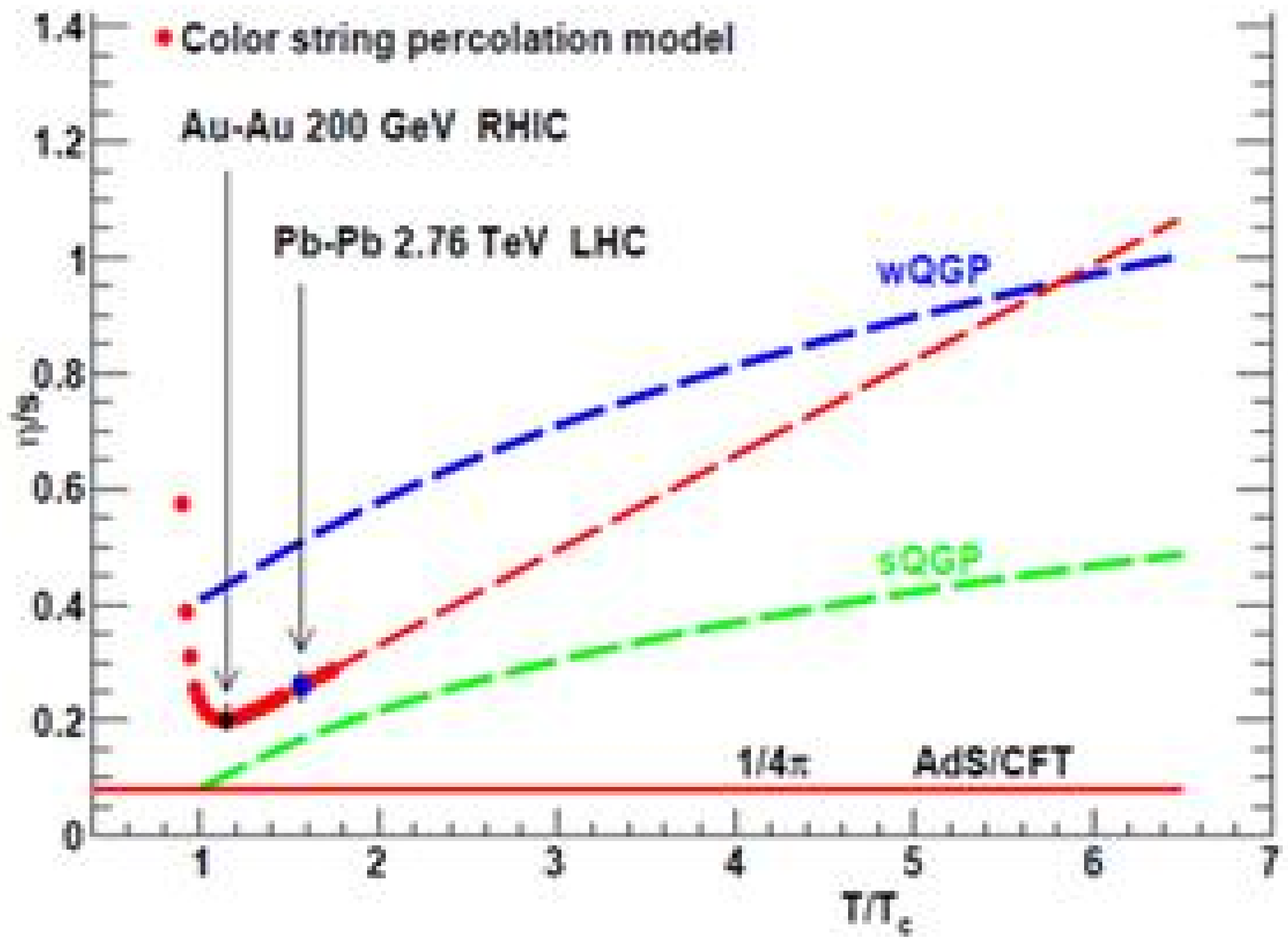
Characterizing the Matter (1)

- RHIC discovery in 2005: The QGP is a (almost) perfect liquid
  - ⇨ **perfect liquid → Viscosity $\eta = 0$** ('response to pressure gradients')
    (→ strong interactions in the liquid)
  - ⇨ QGP almost **ideal fluid**, η/S < 0.2 - 0.5
    - o usually use Viscosity/Entropy (η/S dimensionless number)
- unexpected result
  - ⇨ QGP though to behave like a gas (weakly interacting)
  - ⇨ closest Theory prediction **$\eta/S > 1/4\pi \approx 0.08$**
    - o AdS/CFT:

      SUSY string theory in 5 dimensions !

BNL Press release, April 18, 2005:
QGP = "Perfect" Liquid
New state of matter more remarkable than predicted – raising many new questions

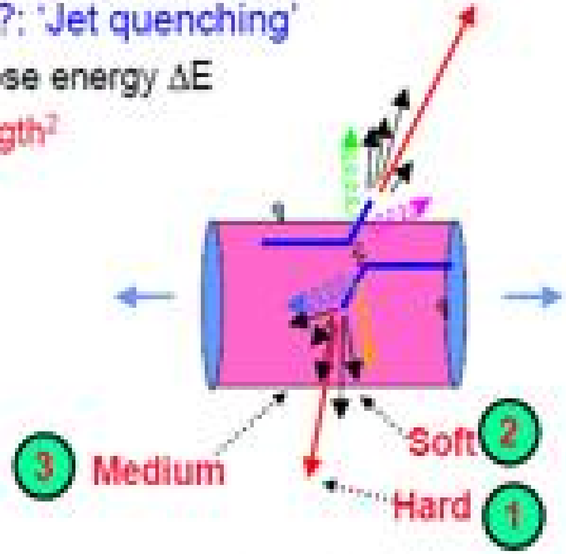




Color string percolation model
Au-Au 200 GeV RHIC
Pb-Pb 2.76 TeV LHC
wQGP
sQGP
1/4π
AdS/CFT
η/s
T/T$_c$
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1
2
3
4
5
6
7

Characterizing the Matter (2)

- How strongly interacting is the matter ?: 'Jet quenching'
  - ⇨ quarks/gluons traveling through QGP loose energy ΔE
    - some unusual properties, e.g. ΔE ~ Length[2] (not ΔE ~ L, as in normal matter !)

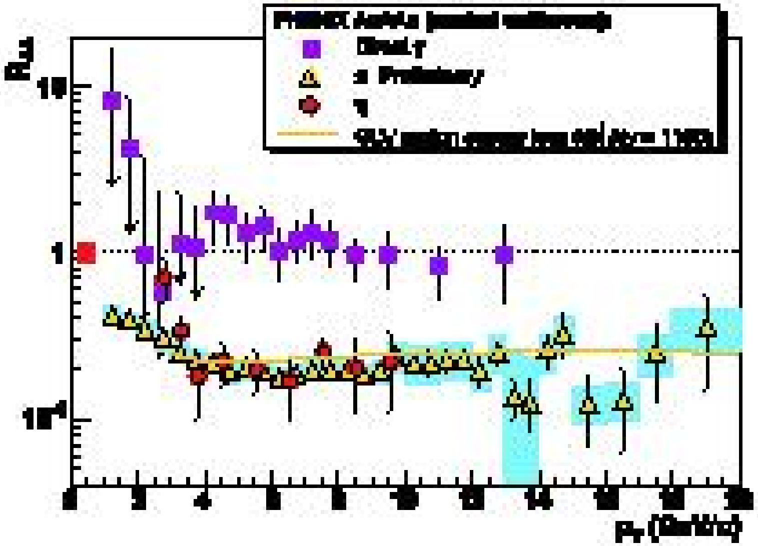


- ⇨ how much energy is lost ? (measures 'interaction strength' of QGP)
  - look at high momentum ('hard') part of jets
- ⇨ how is it lost ?
  - many **soft** or few **hard** scatterings
  - look at low momentum ('soft') part
- ⇨ 'response of QGP'
  - shock waves, Mach cones ??
  - look at average ('very soft') particles of the medium

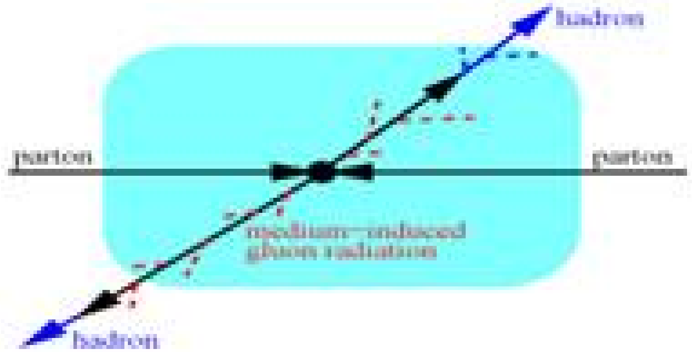

'Jet' breaking the sound barrier

Transverse Momentum Suppression

$$R_{AA}(p_T) = \frac{d^2N_{AA}/dp_T d\eta}{T_{AA}(b) d^2\sigma_{NN}/dp_T d\eta'}$$



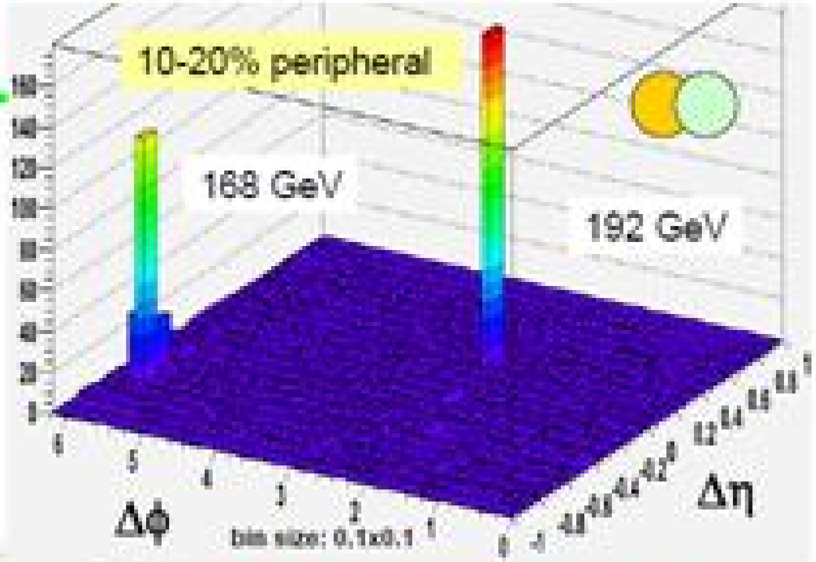
Photons in agreement with perturbative QCD

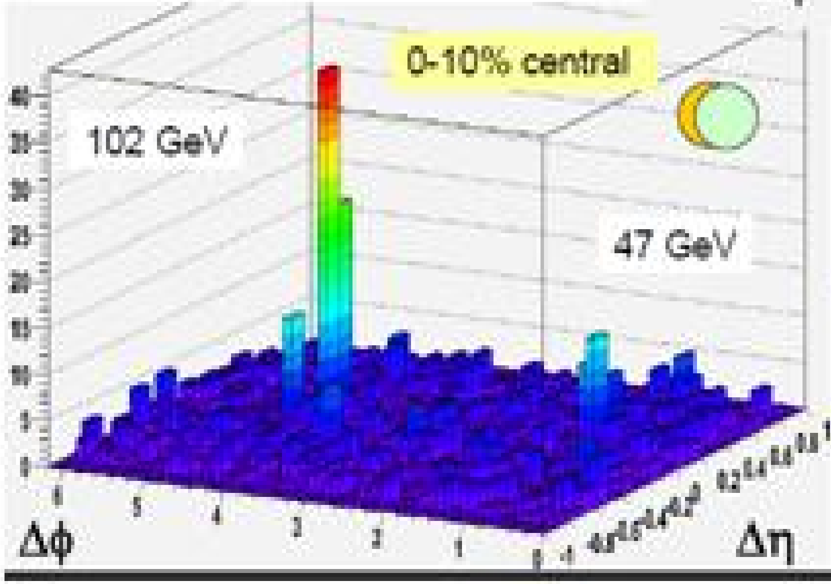


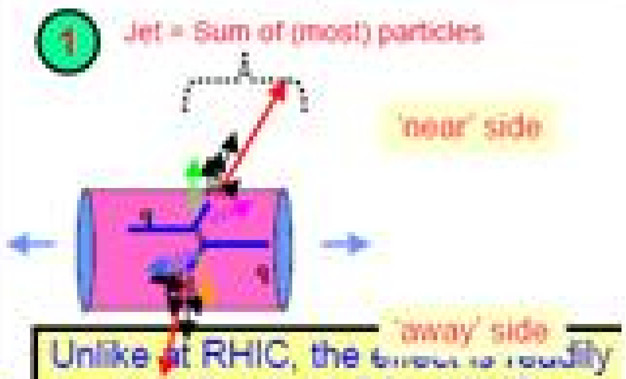
Energy loss by medium induced gluon radiation

Charged Jets

- Jets in ALICE (TPC)
  - ⇨ we see qualitatively a similar effect to Atlas/CMS







Unlike at RHIC, the effect is readily and directly visible at LHC.

Quantifying energy loss needs further analysys