Physics at Extreme Temperatures and Energy Densities

APS Meeting

Jacksonville, April 14, 2007

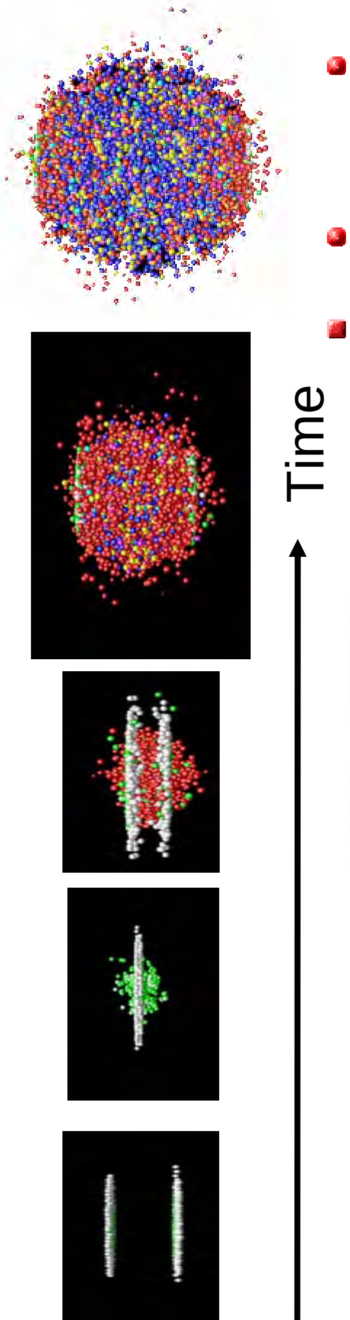
Bolek Wyslouch

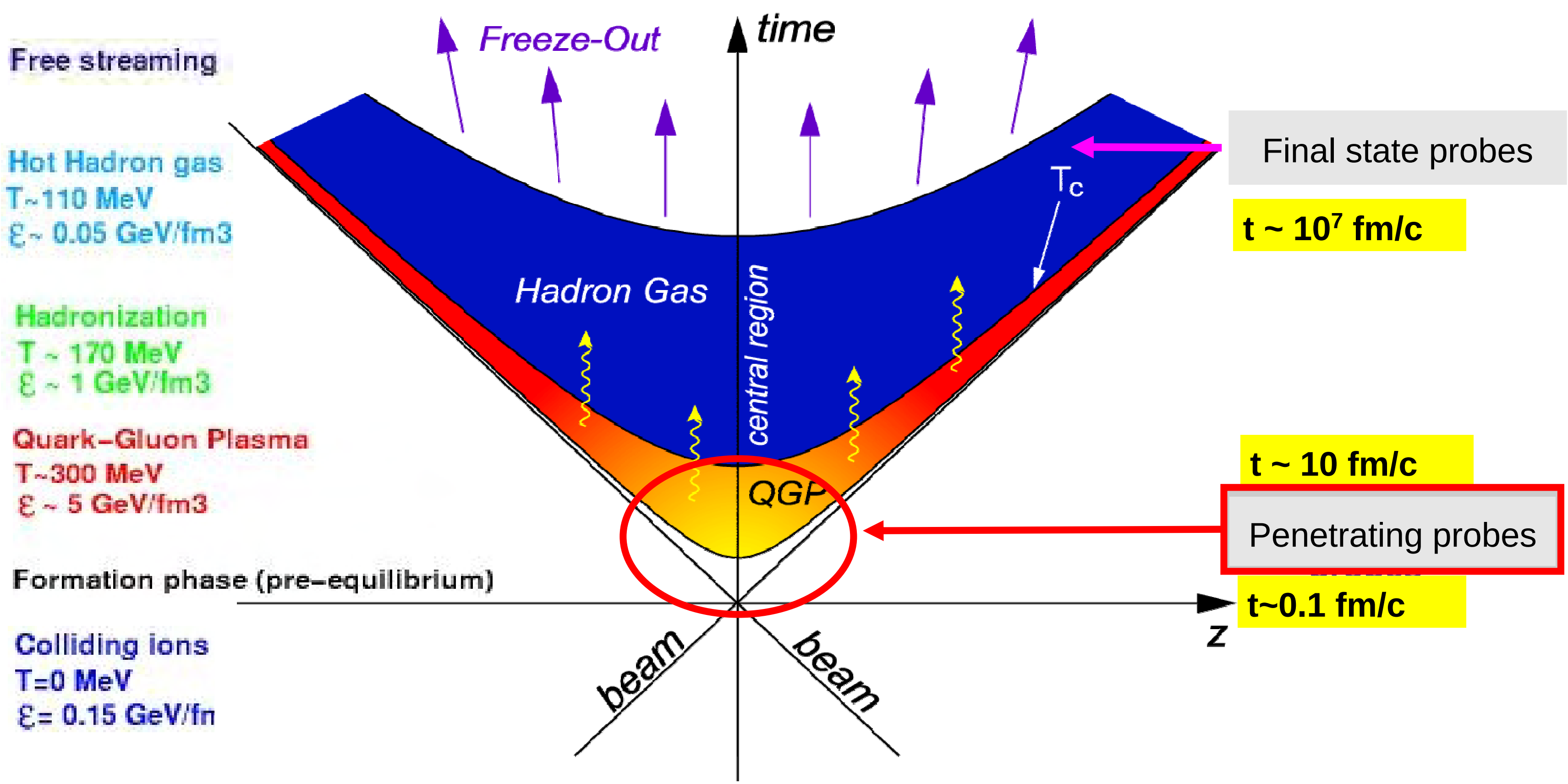
MIT

Special thanks to David d'Enterria, CERN

The "Little Bang" in the laboratory: Heavy-Ion Collisions

- ***High-energy nucleus-nucleus collisions: fixed-target ($\sqrt{s}$=20 GeV, SPS) or colliders ($\sqrt{s}$=200 GeV, RHIC; $\sqrt{s}$=5.5 TeV, LHC)***
- ***QGP formed in tiny region (~10^{-14} m) for very short times (~10^{-23} s)***
- ***Collision dynamics: Different observables sensitive to different reaction stages***

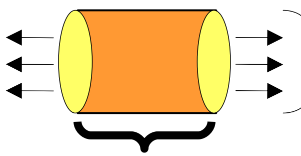




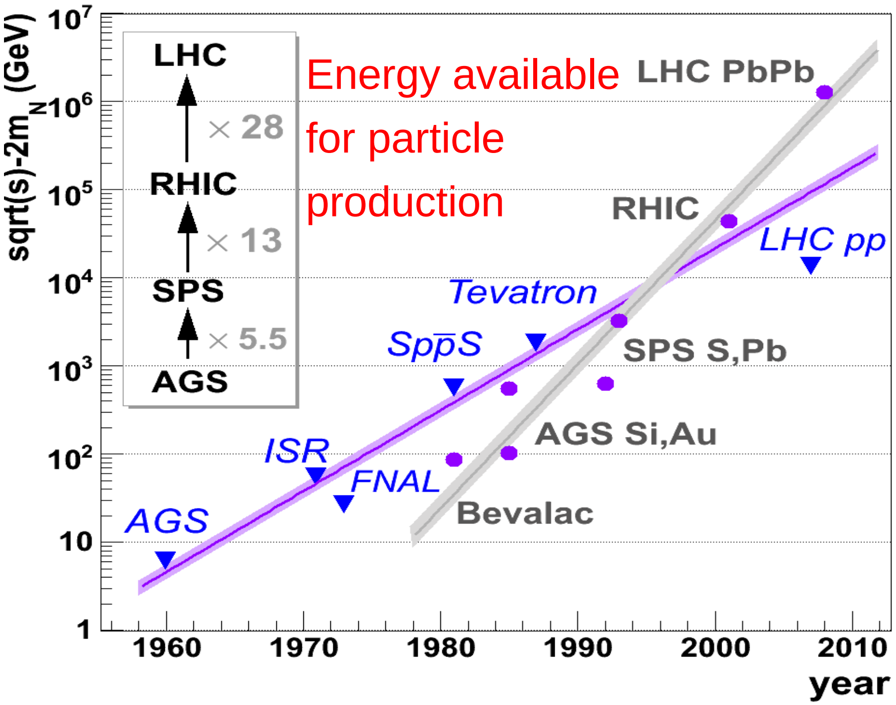
Energy densities in central AA collisions

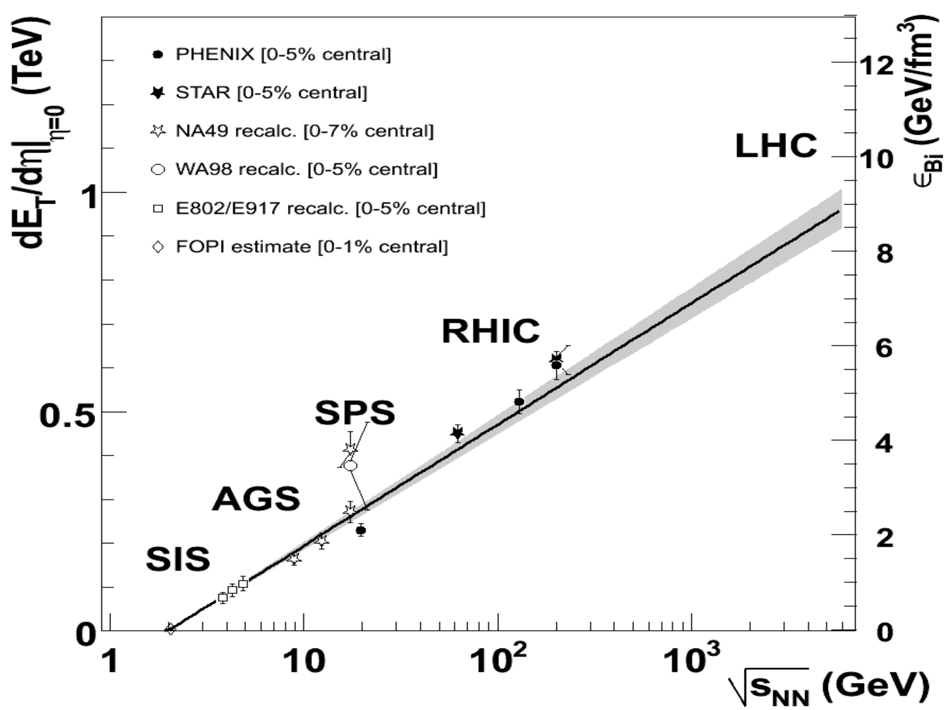
- T.D. Lee: *"In HEP we have concentrated on experiments in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions. In order to study the question of 'vacuum', we must turn to a different direction; we should investigate 'bulk' phenomena by distributing high energy over a relatively large volume."* [Rev.Mod.Phys.47(1975)267]
- Energy density: "Bjorken estimate" (for a longitudinally expanding plasma):

$$\epsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{\tau_0 \pi R^2}$$



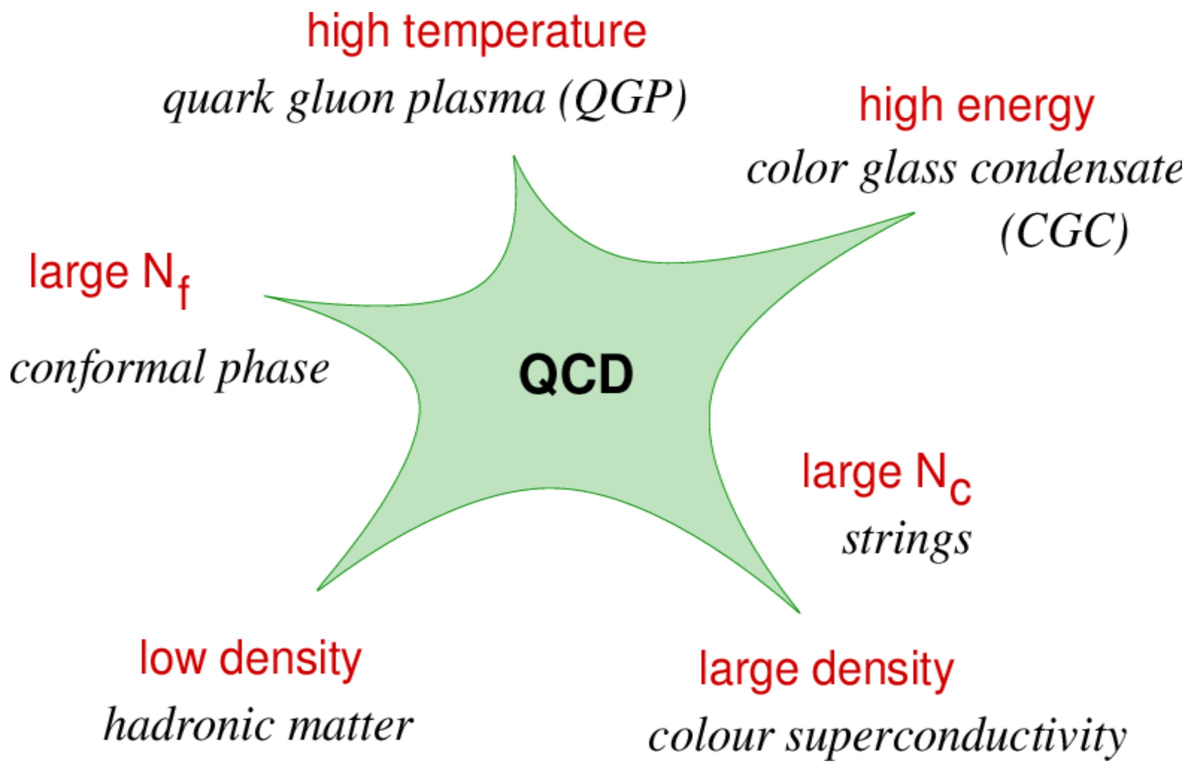
$\tau_0 \sim 1$ fm/c $> \tau_{cross} = 2R/\gamma \sim 0.15$ fm/c



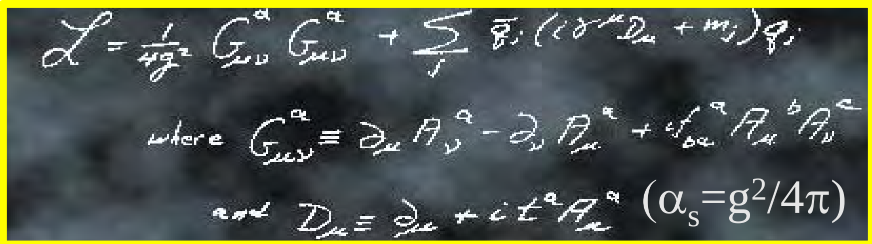


QCD: Strong force

- QCD is a QFT with very rich dynamical content: asymptotic freedom, confinement, (approx.) chiral symmetry, non-trivial vacuum, ...
- The only sector of the SM whose collective behaviour can be studied in the laboratory: phase transition(s), thermalization of fundamental fields, ...
- QCD has a very diverse many-body phenomenology at various limits:



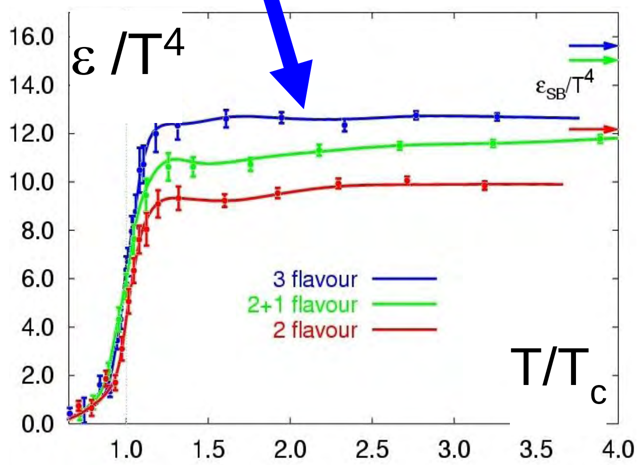
High-energy heavy-ion physics programme (in 4 plots)

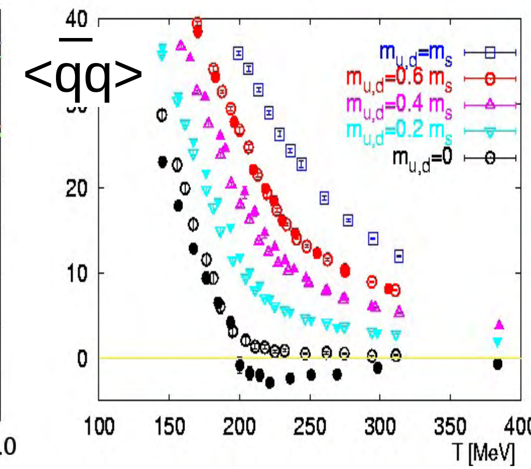


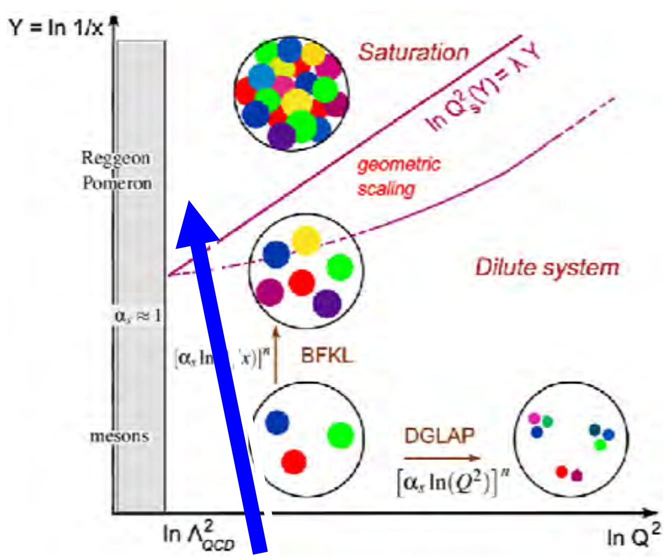
$\alpha_s(Q^2) \sim 1/\ln(Q^2/\Lambda^2)$, $\Lambda \sim 200$ MeV

1. Understand 2 basic properties of strong interaction: (de)confinement, chiral symm. breaking/restoration

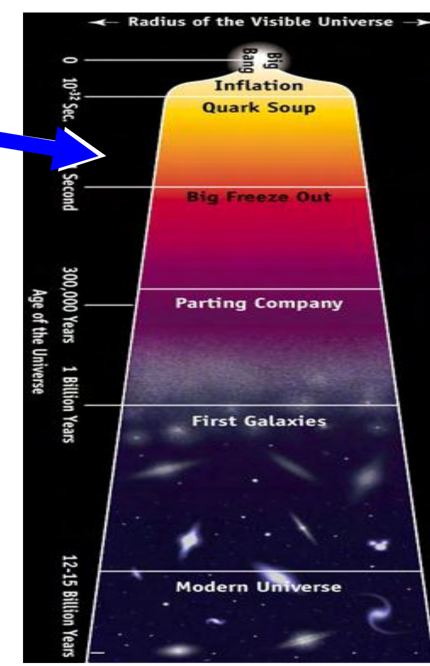
2. Study the phase diagram of QCD matter: produce & study the QGP







3. Probe conditions quark-hadron phase transition in primordial Universe (few µsec after the Big Bang)



4. Study the regime of non-linear (high density) many-body parton dynamics at small-x (CGC)

Relativistic Heavy-Ion Collider (RHIC) @ BNL

3.83 km circumference – 2 independent rings:

- 120 bunches/ring,106 ns crossing time
- 400 superconducting dipoles, 500 quadrupoles

A+A,p(d)+A collisions @ $\sqrt{s_{NN}}$ = 200 GeV

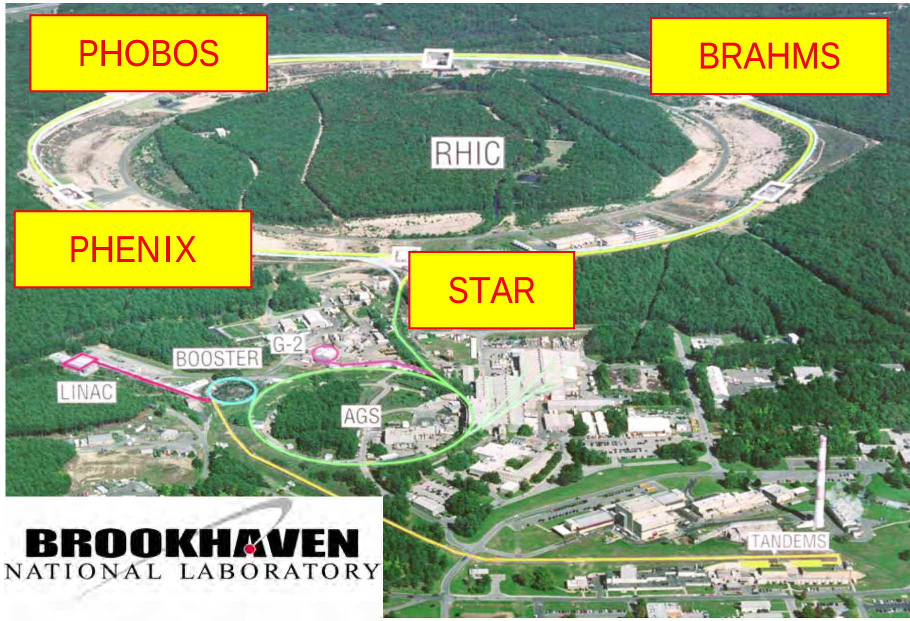
(polarized) p+p colls @ $\sqrt{s}_{max}$ = 500 GeV

$\mathcal{L}$ =1.5 10^{31} cm^{-2} s^{-1} = 15 $\mu b^{-1} s^{-1}$ (~0.6 MHz)

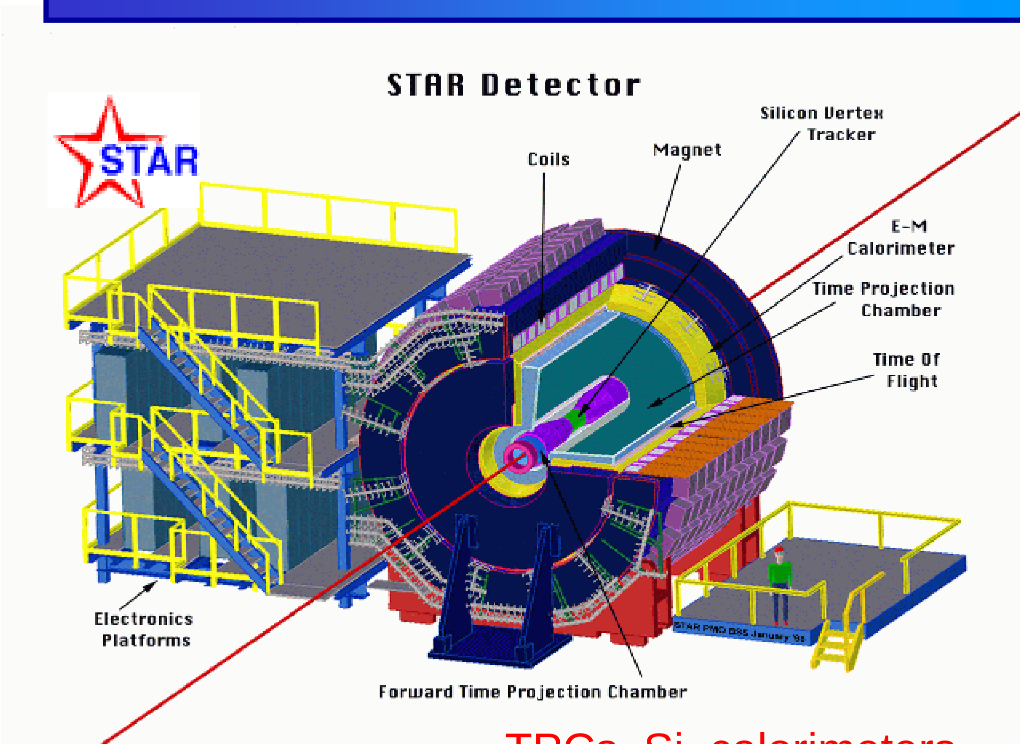
Experiments: **PHENIX,STAR,PHOBOS,BRAHMS**

Runs 1 - 6 (2000 – 2006):

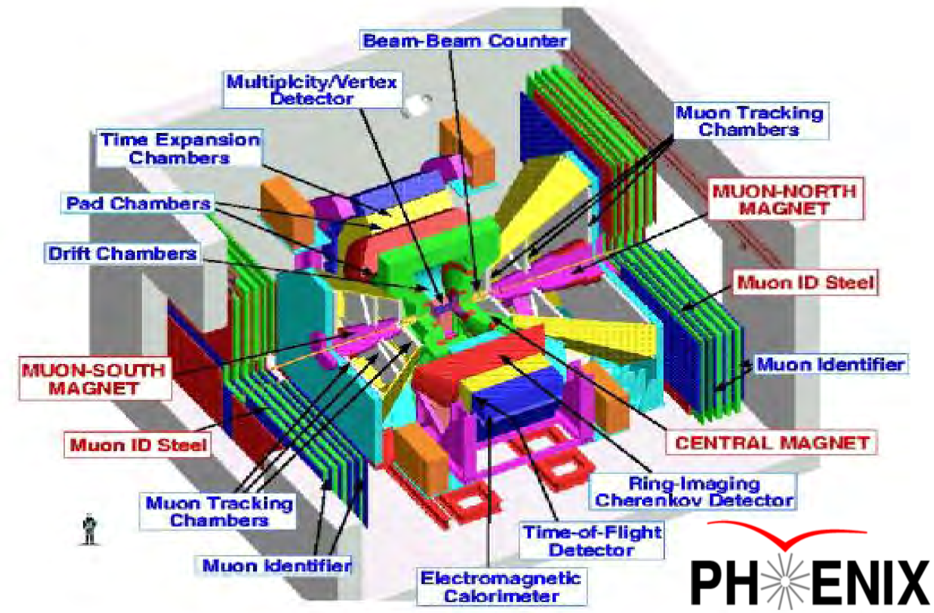
Au+Au @ 200, 130, 62.4, 22 GeV
Cu+Cu @ 200, 62.4 GeV
d+Au @ 200 GeV
p+p (polarized) @ 200, 62, 22 GeV



4 RHIC experiments



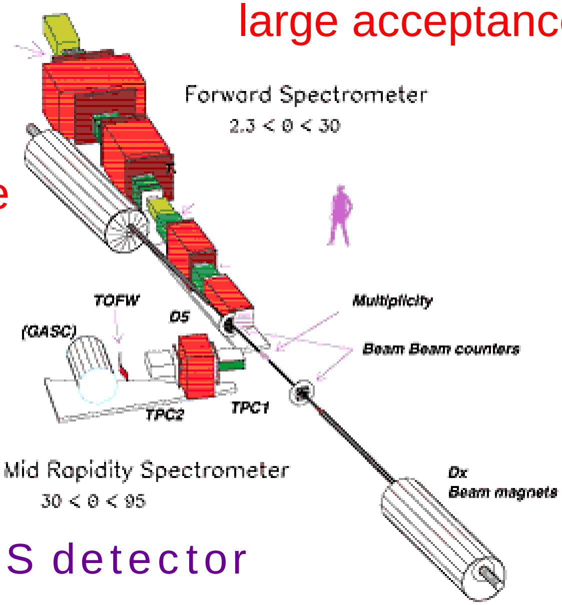
TPCs, Si, calorimeters, large acceptance



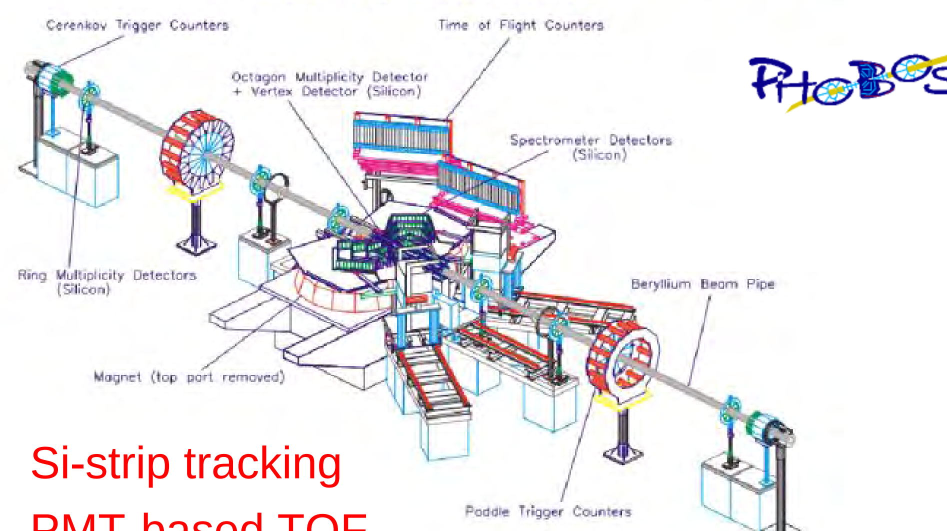
Hadrons, $e^{\pm}$, $\mu^{\pm}$, γ. High-rate DAQ.

Hard & penetrating probes

2 magn. dipole spectrometers in “fix-target” config.



BRAHMS detector



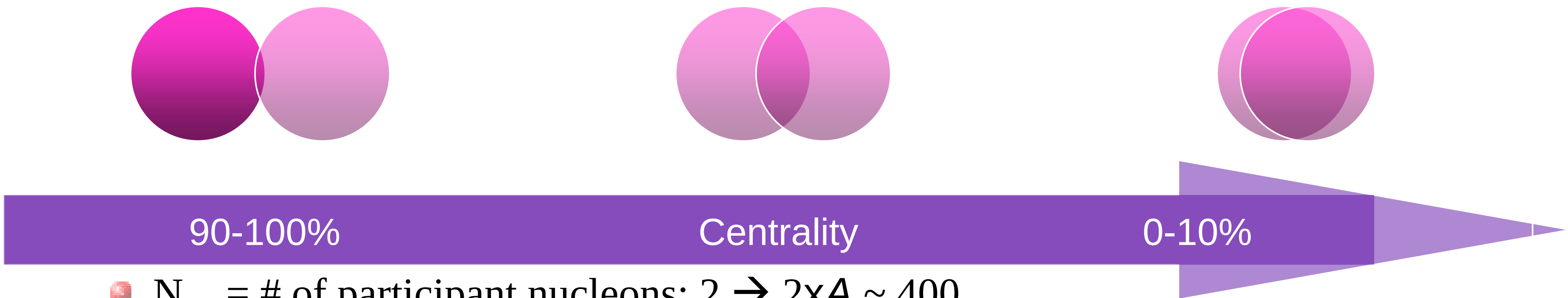
Si-strip tracking

PMT-based TOF

Collision Geometry

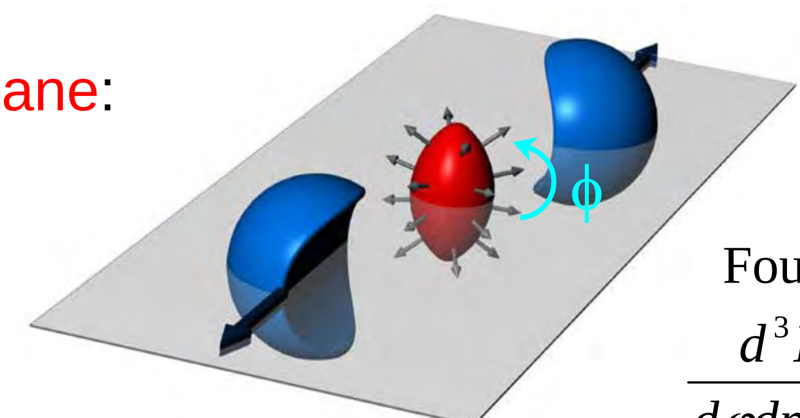
➢ Centrality:

Peripheral collision | Semi-Central collision | Central collision



- N_{part}= # of participant nucleons: 2 → 2xA ~ 400
- N_{coll}= # of binary nucleon-nucleon collisions: 1 → ~1200

➢ Reaction plane:



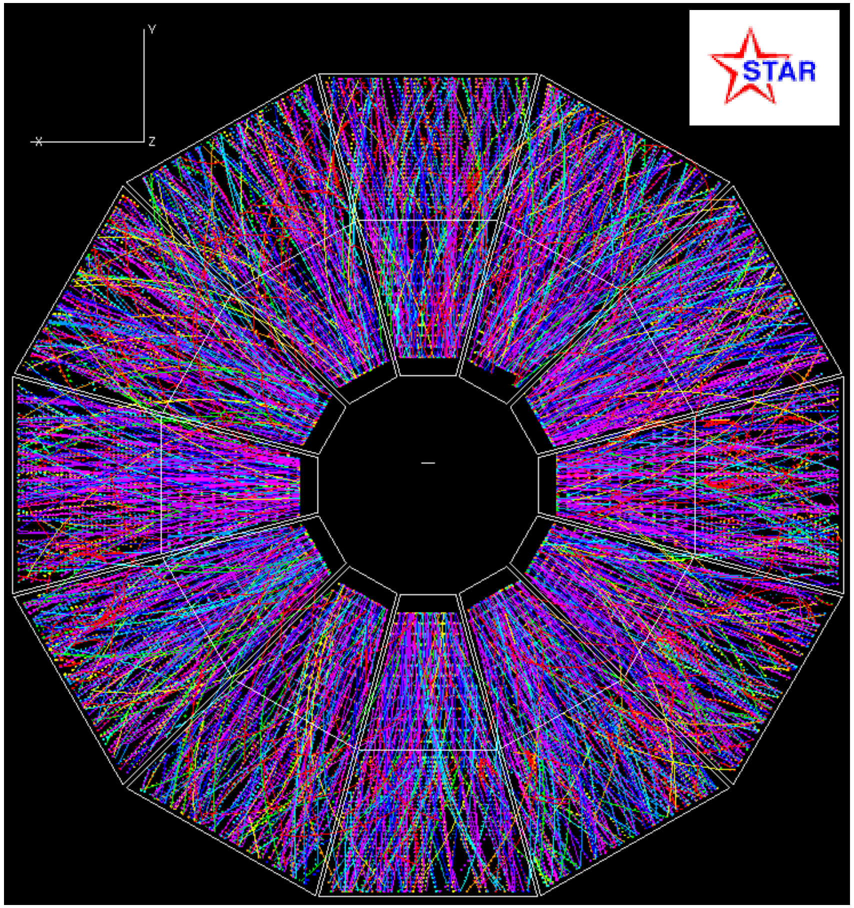
Fourier decompose azimuthal yield:

$$\frac{d^3N}{d\varphi dp_T dy} \propto \left[1 + 2v_1\cos(\varphi) + 2v_2\cos(2\varphi) + \ldots\right]$$

➢ Centrality and reaction plane determined on event-by-event basis.

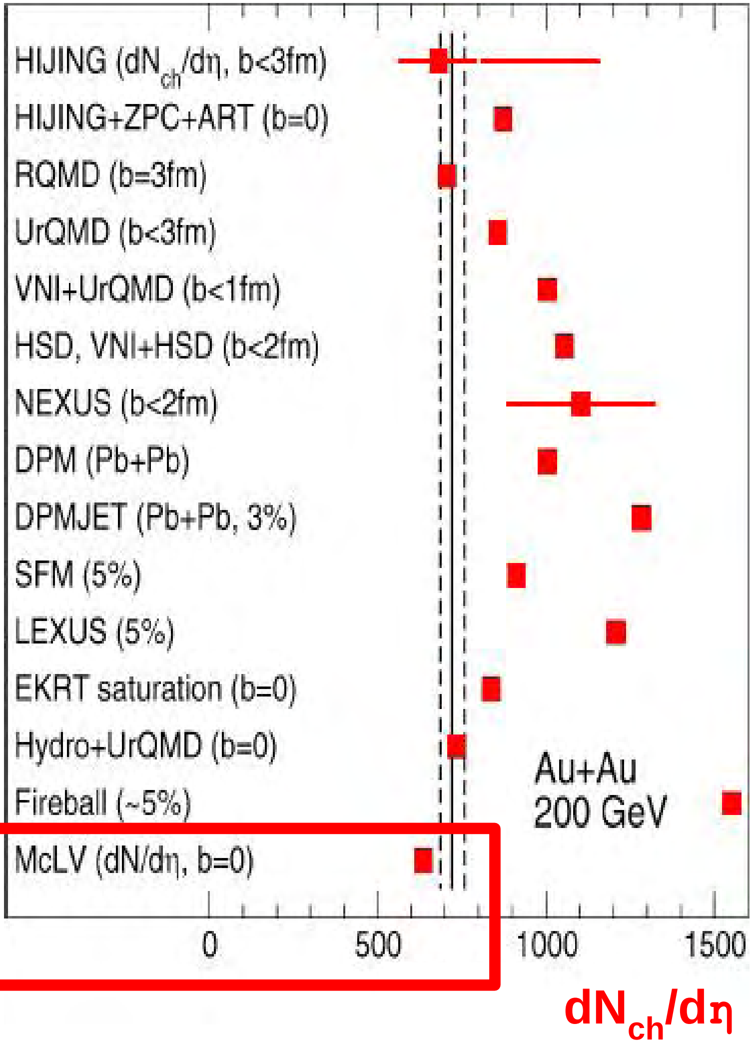
Total AA hadron multiplicity at RHIC (I)

- AuAu (200 GeV) 0-5% central collisions:



~ 700 charged particles per unit rapidity at y=0

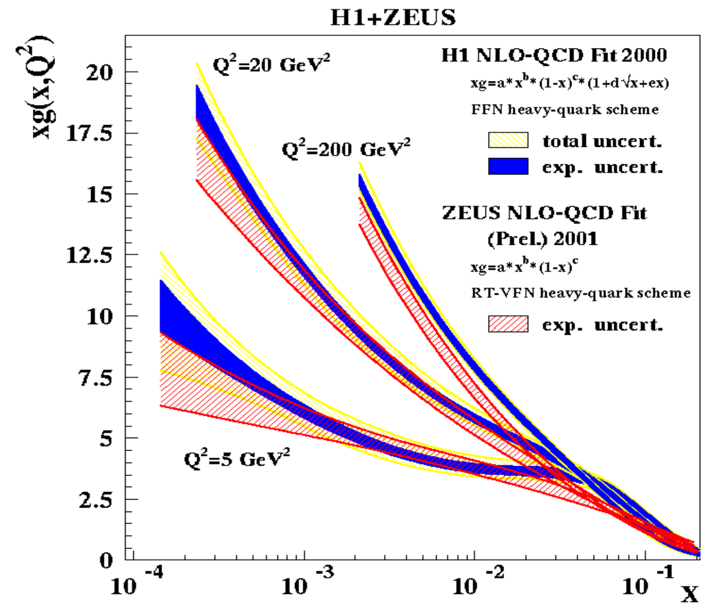
Predicted multiplicites:



- "Reduced" multiplicity predicted by saturation models (reduced parton flux).

Gluon saturation – Color Glass Condensate

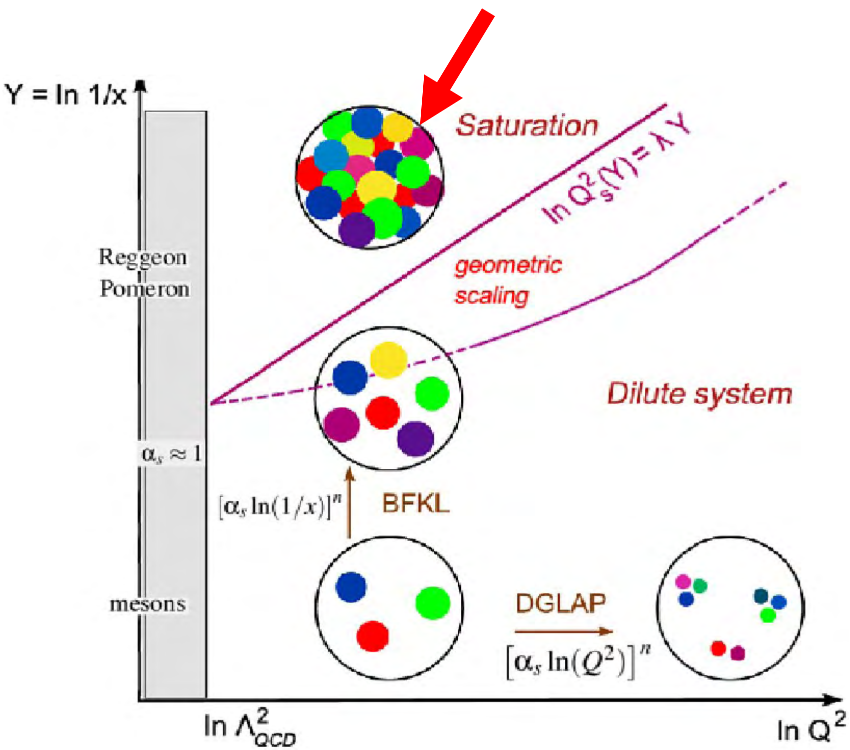
Strong rise at low-x of gluons observed at HERA:



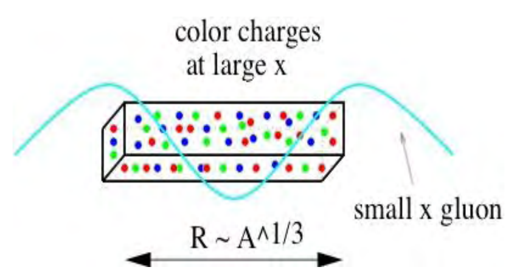
Radiation controlled by QCD evolution eqs.:

- **Q^2 - DGLAP:** $F_2(Q^2) \sim \alpha_s \ln(Q^2/Q_0^2)^n$, $Q_0^2 \sim 1$ GeV^2
- **x - BFKL:** $F_2(x) \sim \alpha_s \ln(1/x)^n$

Linear equations (single parton radiation/splitting) cannot work at low-x: Unitarity violated (even for $Q^2 >> \Lambda^2$), collinear & k_T factorization break



- Gluons overlap below "saturation scale" $Q_s(x)$
- Color Glass Condensate = effective-field theory describes hadrons as classical fields below Q_s (non-linear JIMWLK, BK evolution eqs.).
- Saturation effects enhanced in nuclear targets:



$$Q_s^2 \sim \alpha_s \frac{xG_A(x,Q_s^2)}{\pi R_A^2}$$

$$Q_s^2 \sim A^{1/3} \sim 6$$

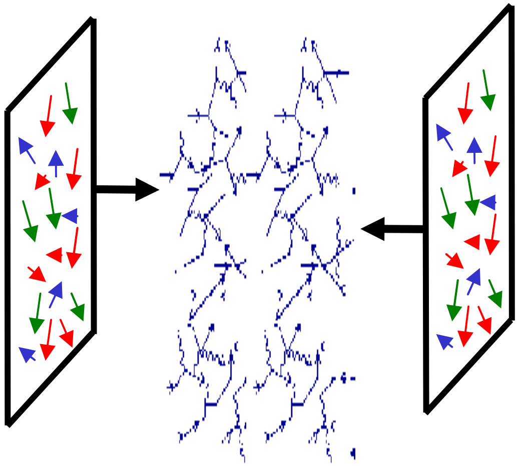
Total AA hadron multiplicity at RHIC (II)

Color Glass Condensate: Final hadron multiplicity ∝ Initial multiplicity of released gluons ∝ Q_s^2

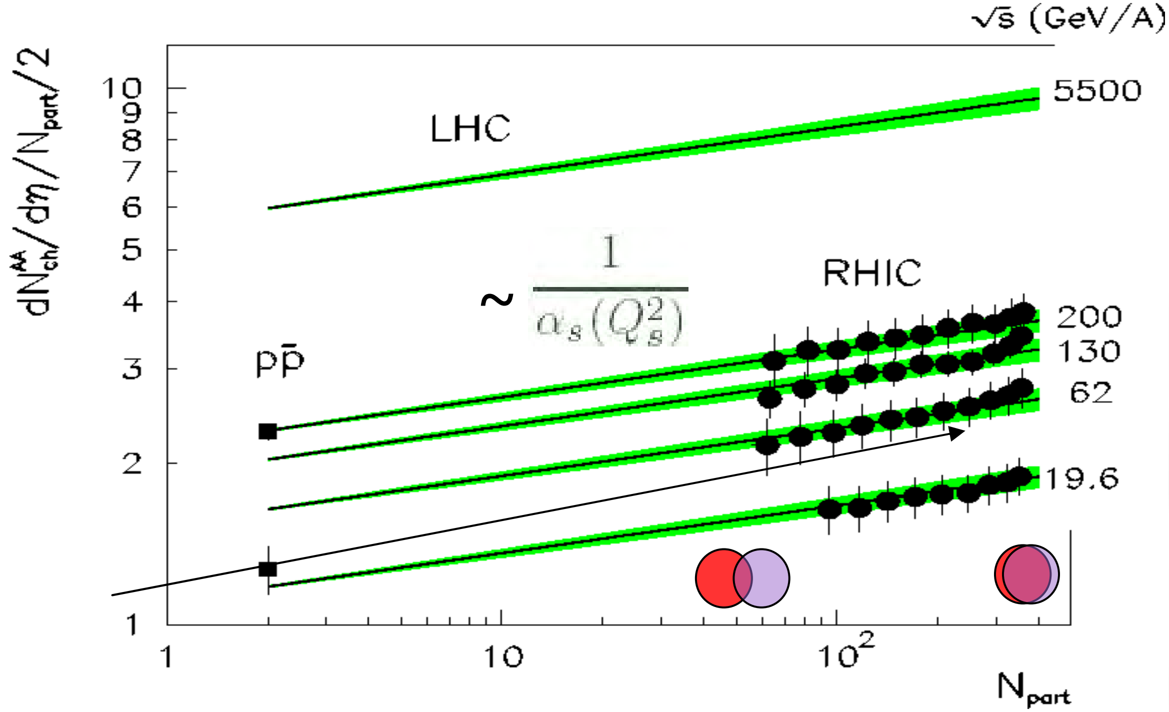
$$\frac{dN}{d^2b\,d\eta} \propto \frac{1}{\alpha_s(Q_s^2)} Q_s^2 \propto xG(x,Q_s^2)\cdot A^{1/3}$$

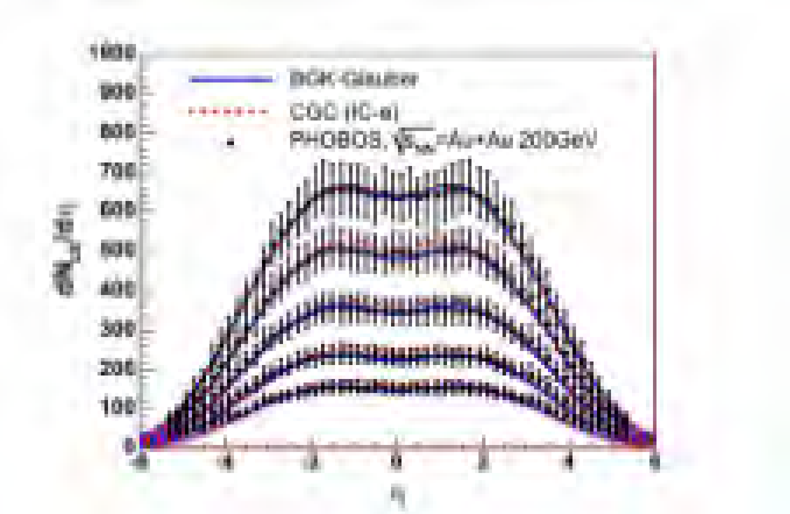
+ “local parton-hadron duality” (*1 gluon = 1 final hadron*)

Collision of 2 classical (saturated) fields



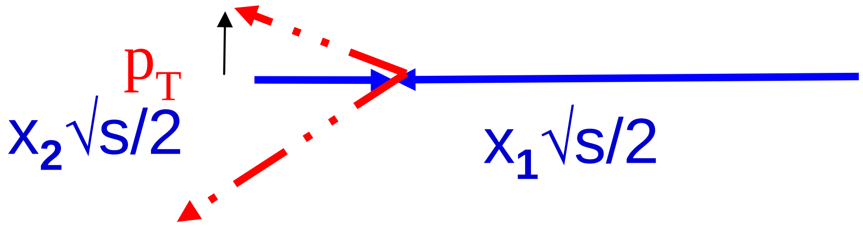
Centrality & √s dependence well described:





Suppressed forward dAu p_T spectra

➢ Particle production at forward rapidities sensitive to small-x in the "target"



$$x_2^{min} \sim p_T/\sqrt{s} \cdot e^{-y} = x_T \cdot e^{-y}$$

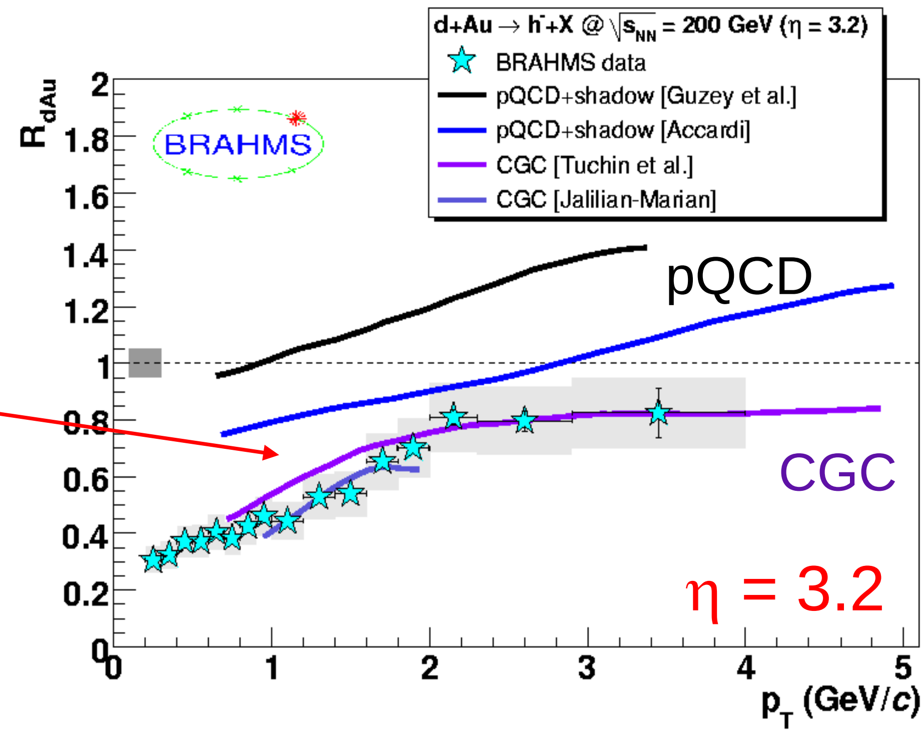
Every 2-units of y, x^{min} decreases by ~10

➢ Suppression of hadron spectra:

p_T ~ 2 – 4 GeV/c at forward rapidities sensitive to partons at $x_2 \sim 10^{-3}$

Ratio dAu/pp < 1

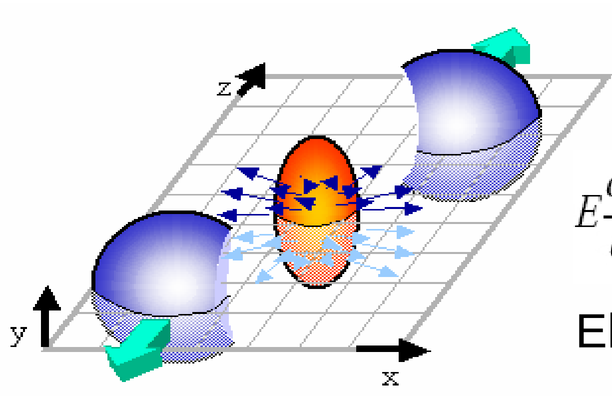
consistent w/ reduced # of partonic scattering centers in Au at low-x



➢ However: RHIC (& HERA) saturation "evidences" too close to non-perturbative regime (Q_s^2~1-2 GeV). Much better conditions at LHC (Q_s^2 ~ 5 GeV, lower x, larger y)

Collective elliptic flow

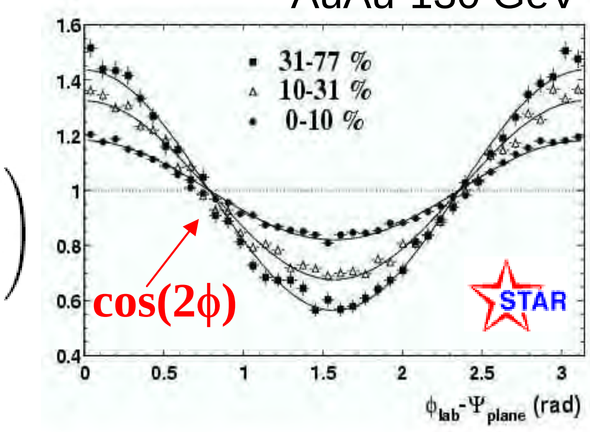
- **Lens-shaped spatial anisotropy (overlap) in non-central collisions translates into boosted momentum emission along reaction plane:**



$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \Phi_{RP})]\right)$$

Elliptic flow v_2 = 2nd Fourier coefficient

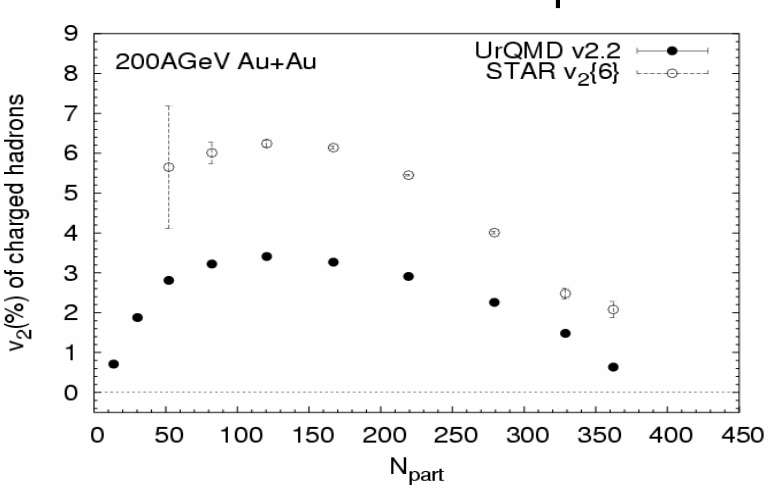
AuAu-130 GeV

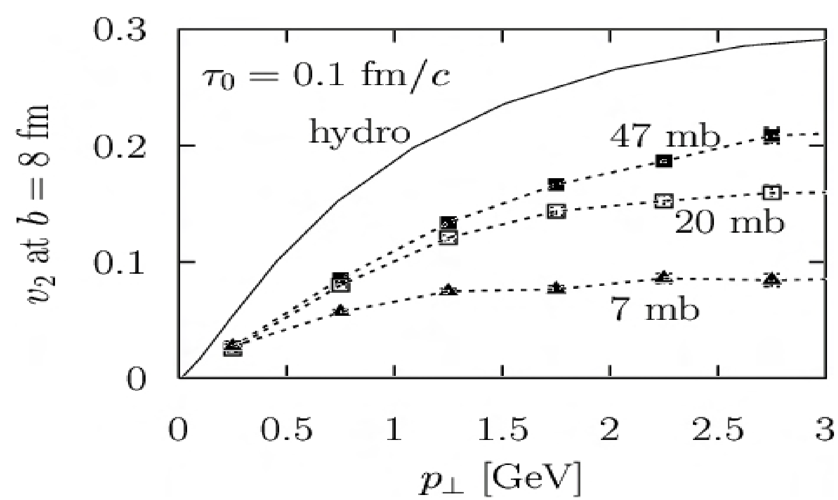


1) Truly collective effect (absent in pp): pressure grads. in partonic phase (τ < 5 fm/c)

2) Note: Pure hadronic models predict small v_2 (~4%)

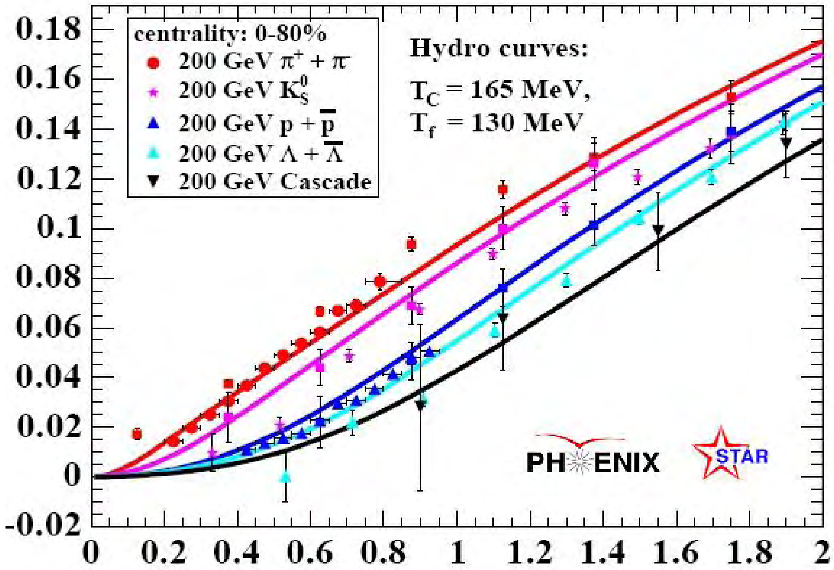
3) Note: Parton cascade w/ perturbative parton-parton σ ~3 mb predicts small v_2 (~5%)

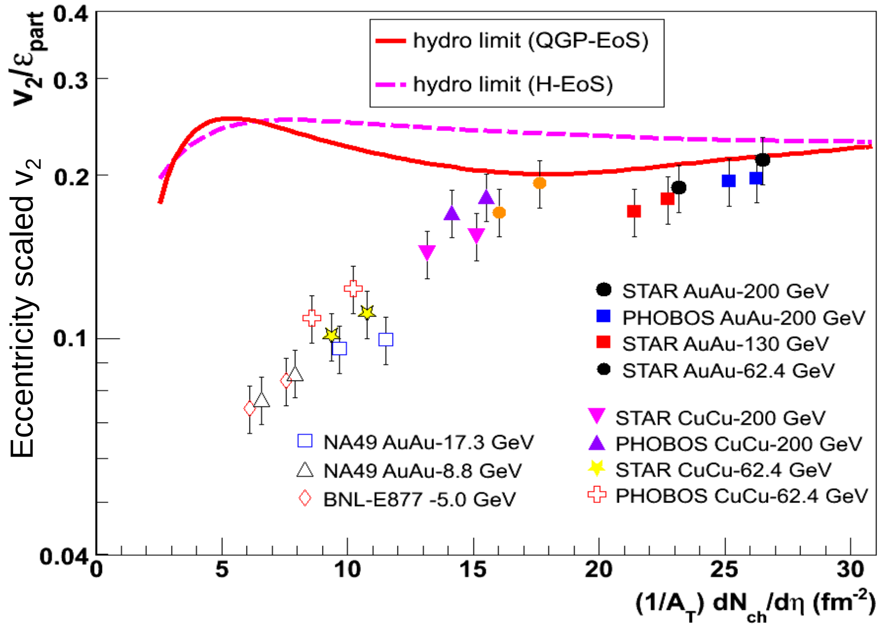




Strong elliptic flow at RHIC !

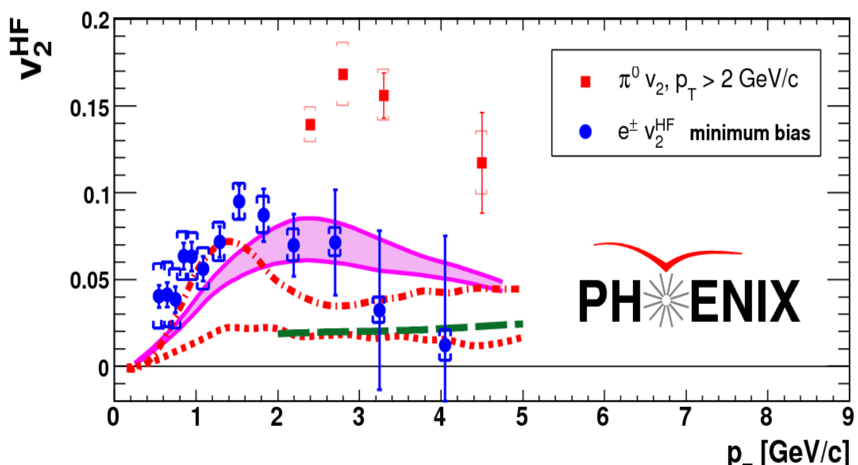
- **Large v_2 signal (~20%) for all hadrons: Reaches "hydro limit" (full thermalization)**





(much larger than CERN-SPS)

- **All hadron species, even heavy-flavor mesons (D,B), flow with the medium:**



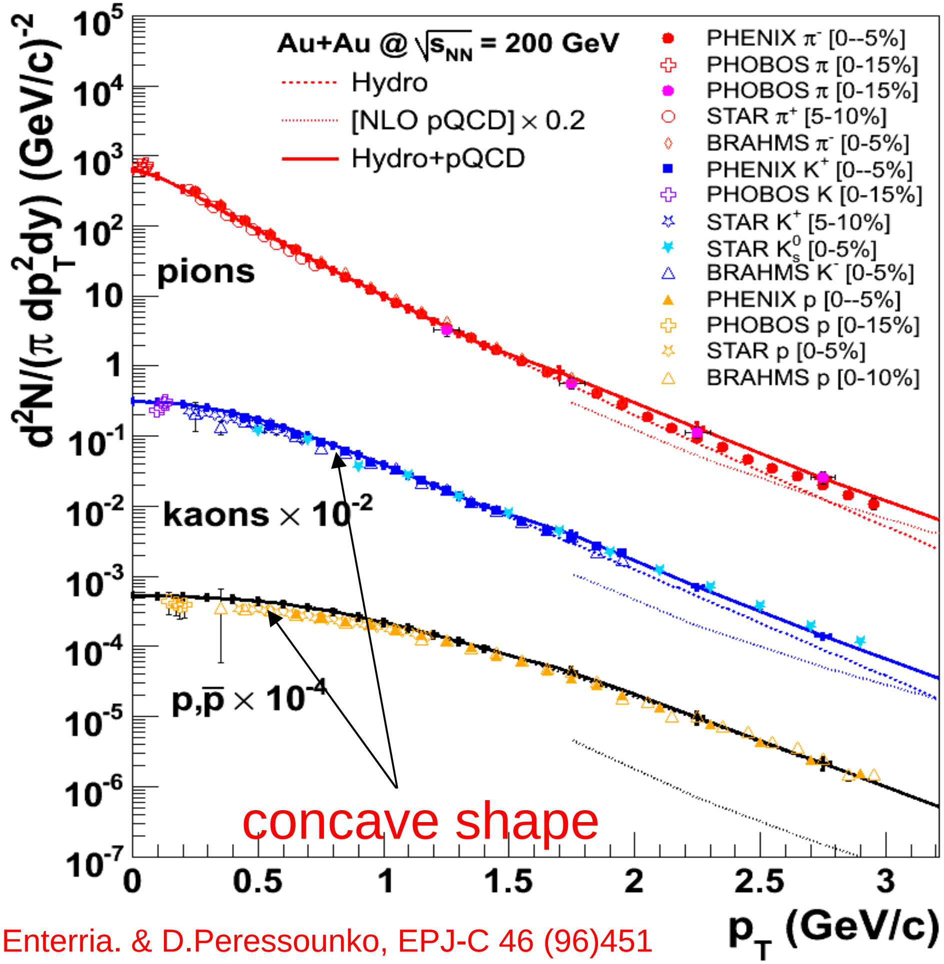
⇒ Strong partonic pressure grads.

⇒ Large & fast parton rescattering: early thermalization.

⇒ Low viscosity (no "internal dissipation")

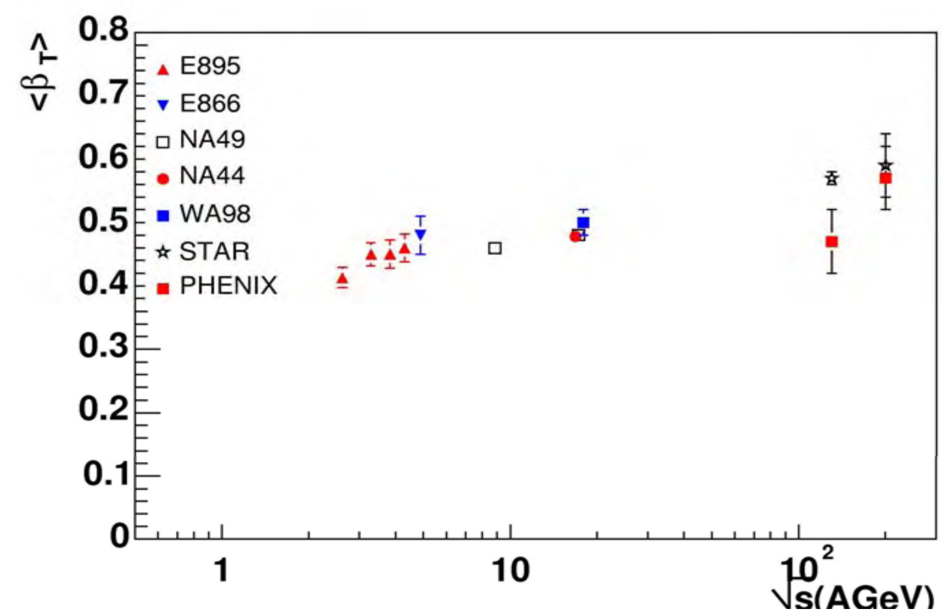
Collective radial flow

- Bulk hadron ($\pi^{\pm}$, $K^{\pm}$, p, pbar) p_T spectra up to ~2 GeV/c are boosted, for increasing centrality, with a (mass-dependent) collective radial flow:



D.d'Enterria. & D.Peressounko, EPJ-C 46 (96)451

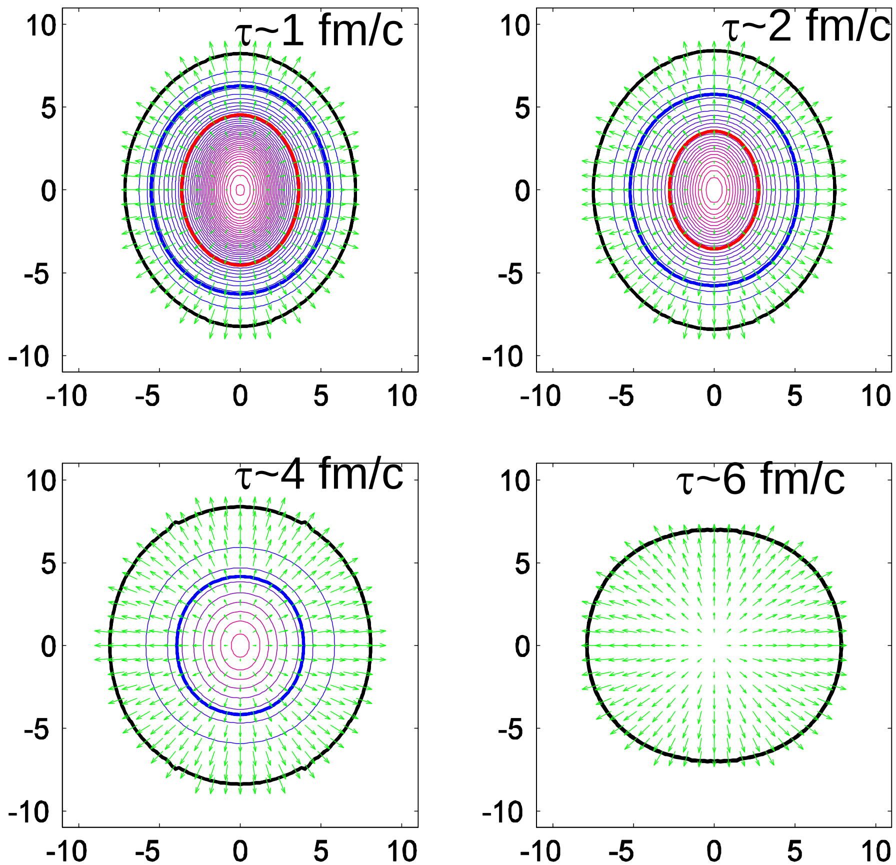
Large inverse slopes from outwards expansion built up in central AA: $\langle\beta_T\rangle$ ~0.6



- "Explosive" behaviour well reproduced by hydrodynamics calculations w/ QGP Equation-of-State and fast thermalization times

sQGP: most ideal fluid known

- "Perfect fluid" (non-viscous) relativistic hydrodynamics w/ QGP (ε_0~30 GeV/fm^3) & very fast thermalization times (τ_0= 0.6 fm/c) reproduces radial & elliptic flows:



$$\partial_\mu T^{\mu\nu} = 0$$
$$\partial_\mu N_i^\mu = 0, \quad i = B, S, \ldots$$

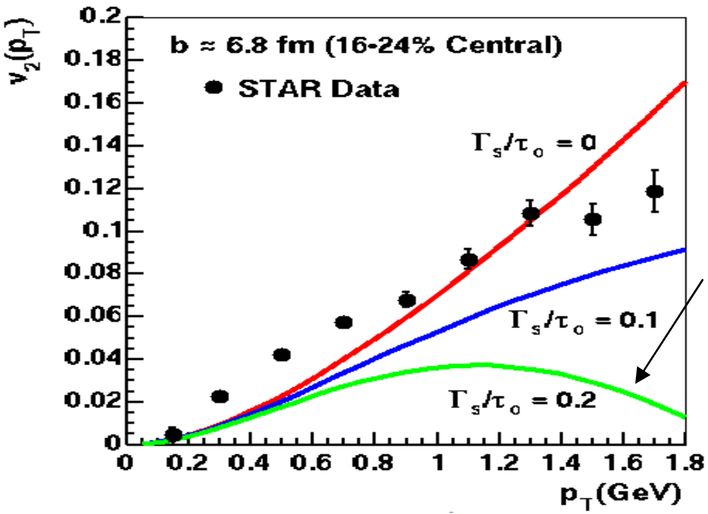
$T^{\mu\nu}$ is energy-momentum tensor

N_i^μ is charge 4-current , u^μ : collective 4-veloc. field

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$$ (ideal fluid form)

$$N^\mu = n u^\mu$$, $P = P(\varepsilon,n)$ ➡ QGP EoS

- Inclusion of viscosity η term (shear stress) modifies expansion rate:



v_2 strongly reduced

The "AdS/QGP" connection, heavy ions and string theory

- **The argument goes as follows ...**

(1) "Anti-deSitter/ConformalFieldTheory correspondence" (Maldacena): Strongly coupled gauge theories (N=4 SUSY Yang-Mills, $\lambda=g^2N_c>>1$) dual to (weakly coupled) 10-D gravity

(2) The sQGP at RHIC is "strongly coupled" (it flows) $\Rightarrow$ AdS/CFT applicable

(3) Non-static QGP properties: η/s, <q> quenching parameter, heavy-Q diffusion coeffic, photon emission rates ... calculable from black-hole thermodynamics.

In particular: strong heavy-Q flow consistent with very low viscosity/entropy: (η/s ~ 1/4π conjectured universal lower bound).

- **Caveat: QCD ≠ (N=4) SUSY Yang-Mills ! conformal, no running coupling constant, different degrees of freedom (no chiral-symmetry, spartners), ...**

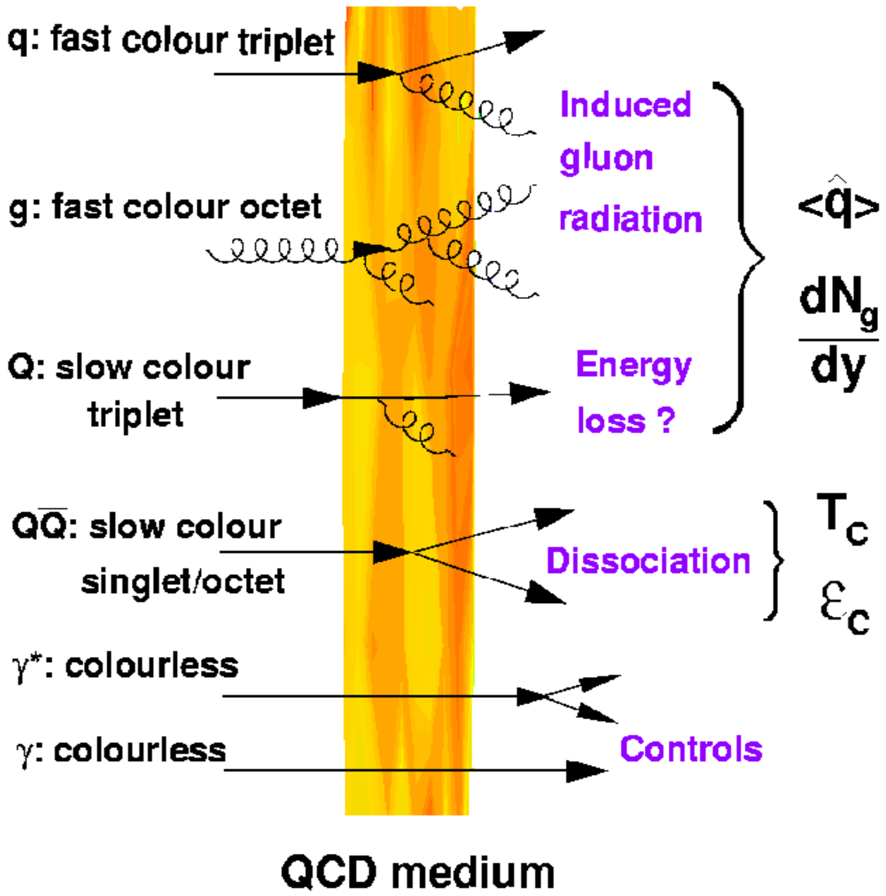
- **Yet: "details" washed out at finite T and interesting phenomenological/ empirical insights gained from string-theory methods.**

Hard probes of QCD matter

Use high-p_T hadrons, jets, prompt γ, heavy-quarks to probe the medium:

1. Early production ($\tau \sim 1/p_T < 0.1$ fm/c) in parton-parton scatterings with large Q^2
2. Calculable in pQCD. *(If no medium effects, simply: $dN^{hard}_{AA} = N_{coll} \times d\sigma^{hard}_{pp}$)*
3. *"Calibrated" in reference measurements: pp (QCD "vacuum"), p(d)A (cold medium)*
4. Measure medium properties:

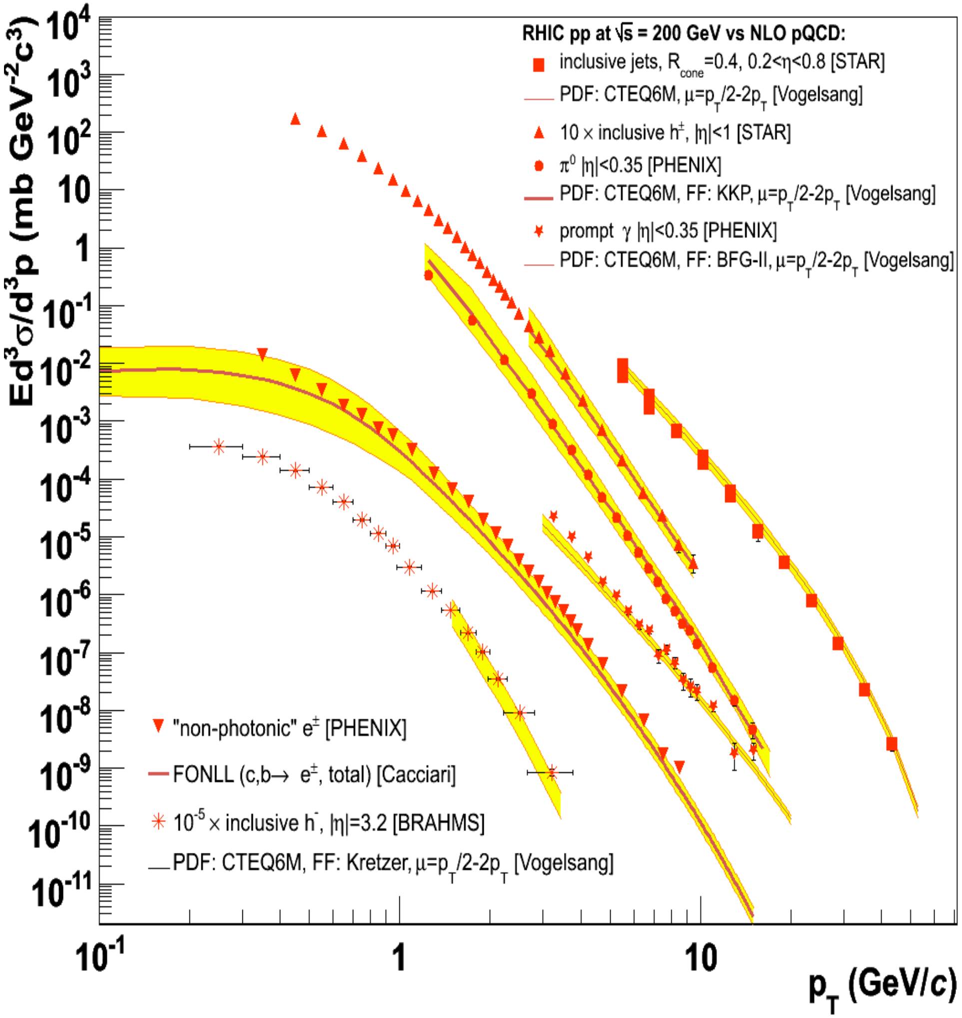
- Thermodynamical: density, temperature, # degrees of freedom, ...
- Dynamical: viscosity, transport coefficient, quark diffusion parameter, ...



Baseline hard QCD results (pp, dAu @ 200 GeV)

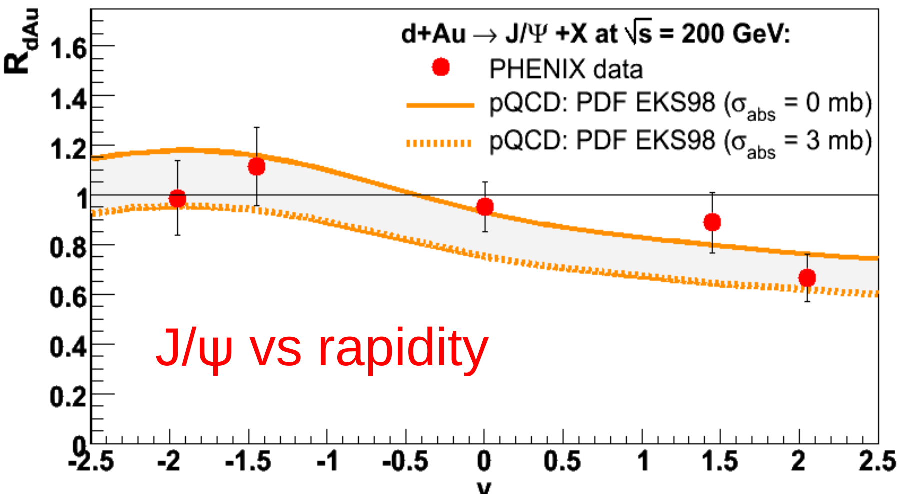
"QCD vacuum" (pp):

- Hard pp cross-sections under experimental & theoretical (NLO, NLL) control:

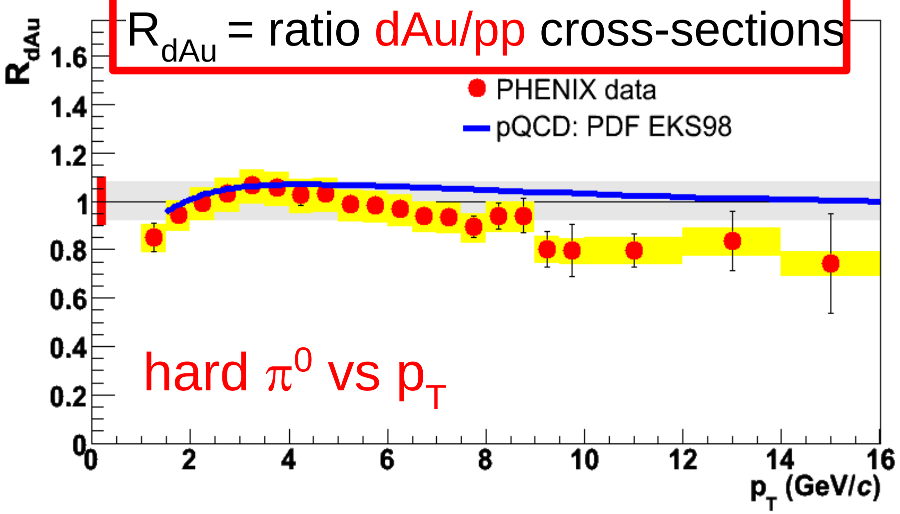


Cold QCD medium (dAu):

- Small (~20%) cold nuclear matter effects: PDF shadowing, k_T broadening

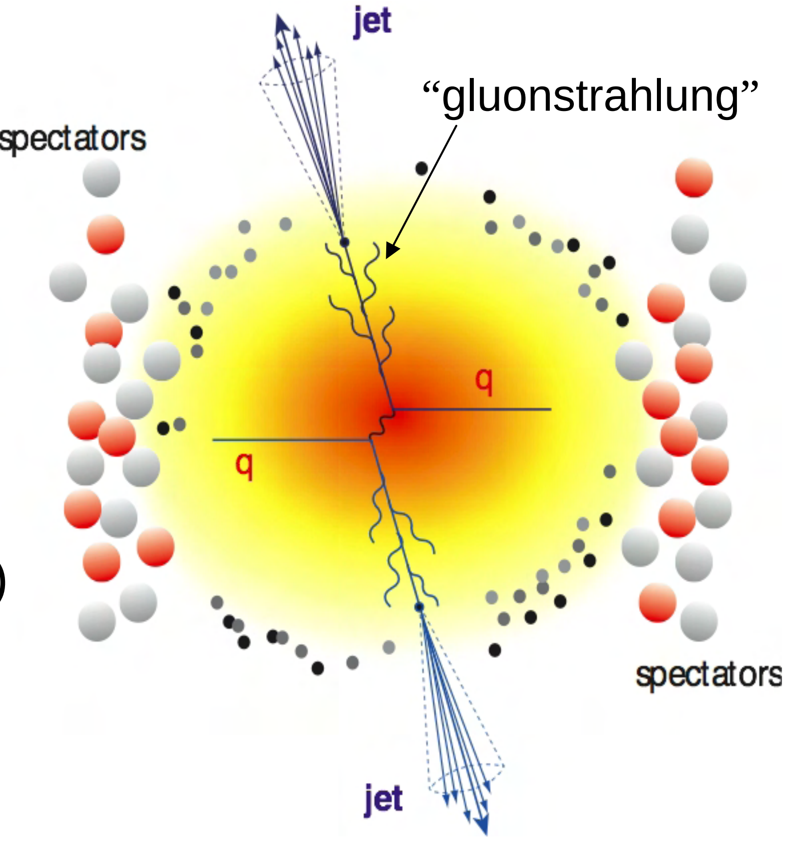


R_{dAu} = ratio dAu/pp cross-sections



"Jet quenching"

Produced hard partons lose energy by multiple final-state non-Abelian (gluon) radiation in the traversed dense medium



QCD energy loss ∝ medium properties:

GLV: $\Delta E \propto \alpha_S^3 C_R \frac{1}{A_\perp} \frac{dN^g}{dy} L \propto$ (gluon density)

BDMPS: $\langle \Delta E \rangle \propto \alpha_S C_R \langle \hat{q} \rangle L^2 \propto$ (transport coeffic.)

Flavor-dependent energy loss:

$\Delta E_{loss}(g) > \Delta E_{loss}(q) > \Delta E_{loss}(Q)$

(color factor) (mass effect)

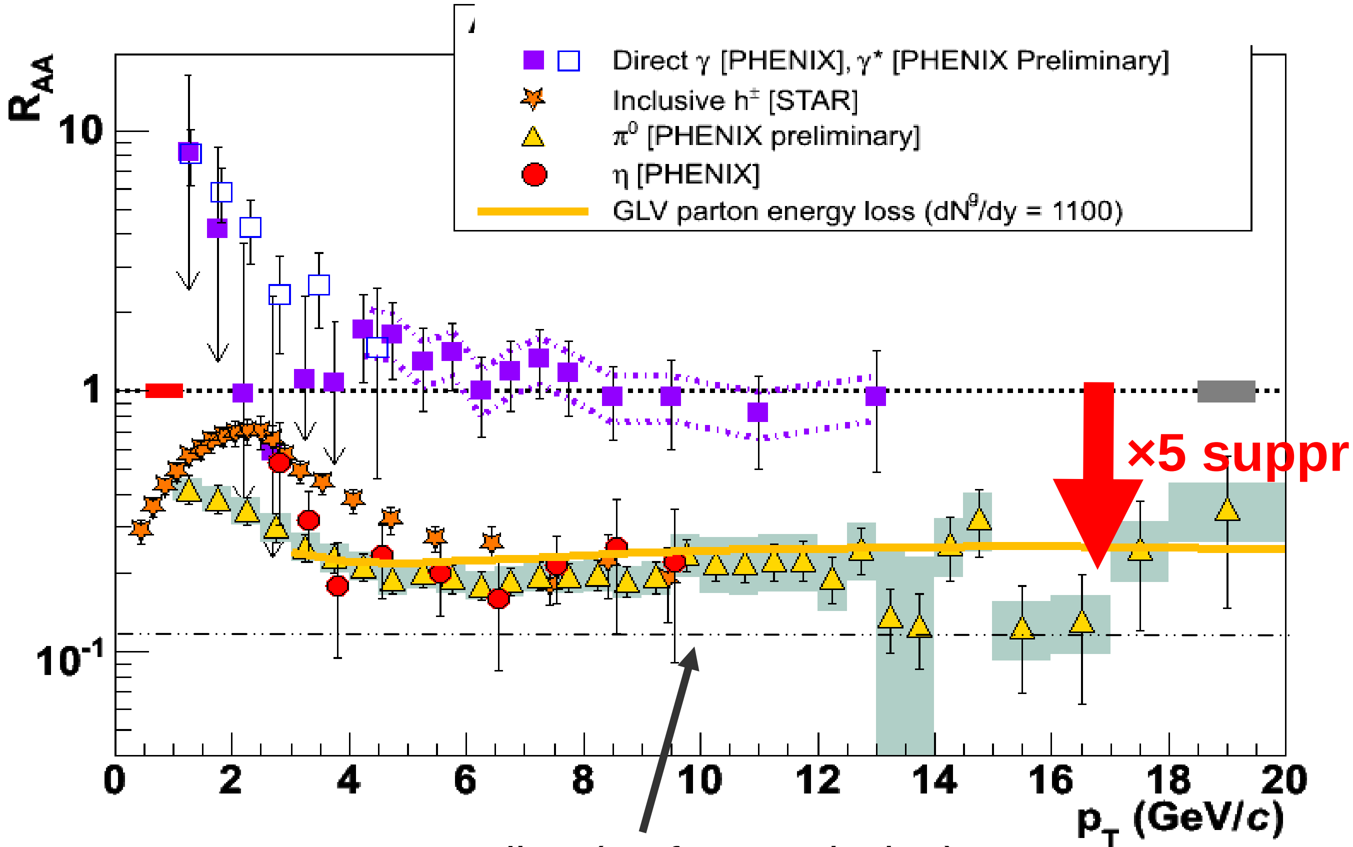
Energy carried away outside jet cone: dE/dx ~ $\alpha_s \langle k^2_T \rangle$

Phenomenological implications:

- Suppression of high p_T leading hadrons
- Disappearance of back-to-back (di)jet correlations ("monojets")

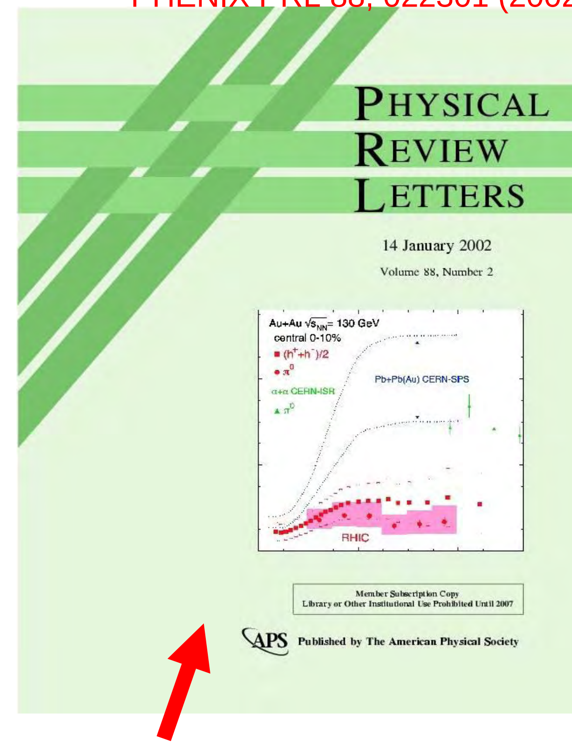
Suppressed high p_T hadroproduction in central AuAu

R_{AA} nuclear modification factor = “QCD medium”/ “QCD vacuum”



N_{part} scaling (surface emission)

PHENIX PRL 88, 022301 (2002)



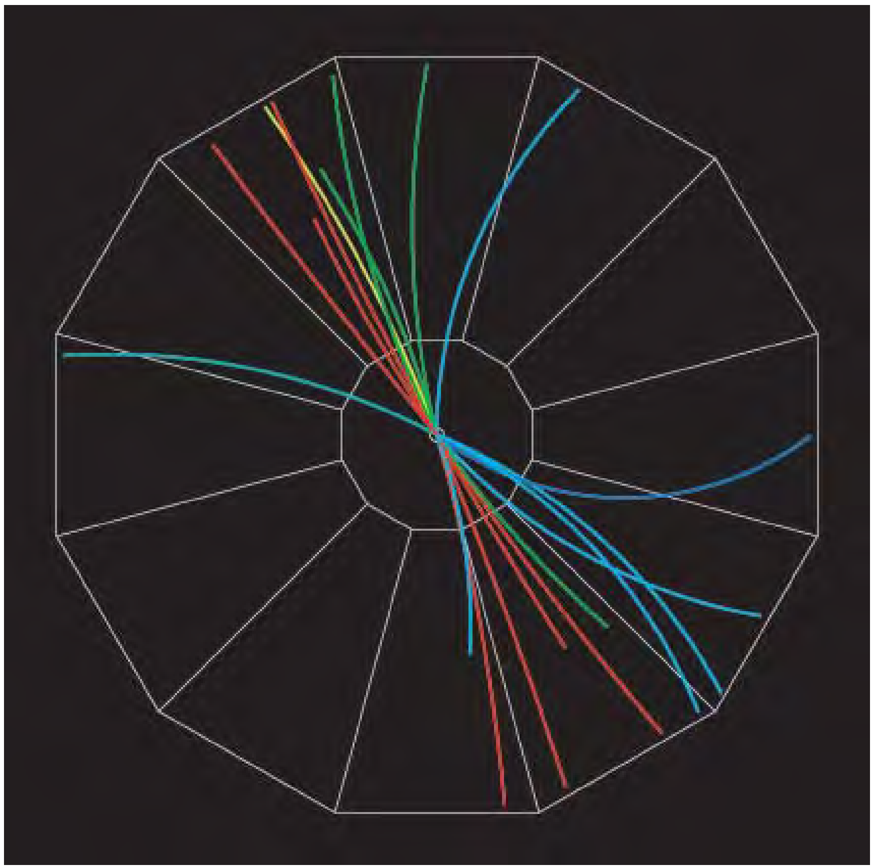
[2002] Discovery of high p_T suppression (one of most significant results @ RHIC so far: 350+ citations)

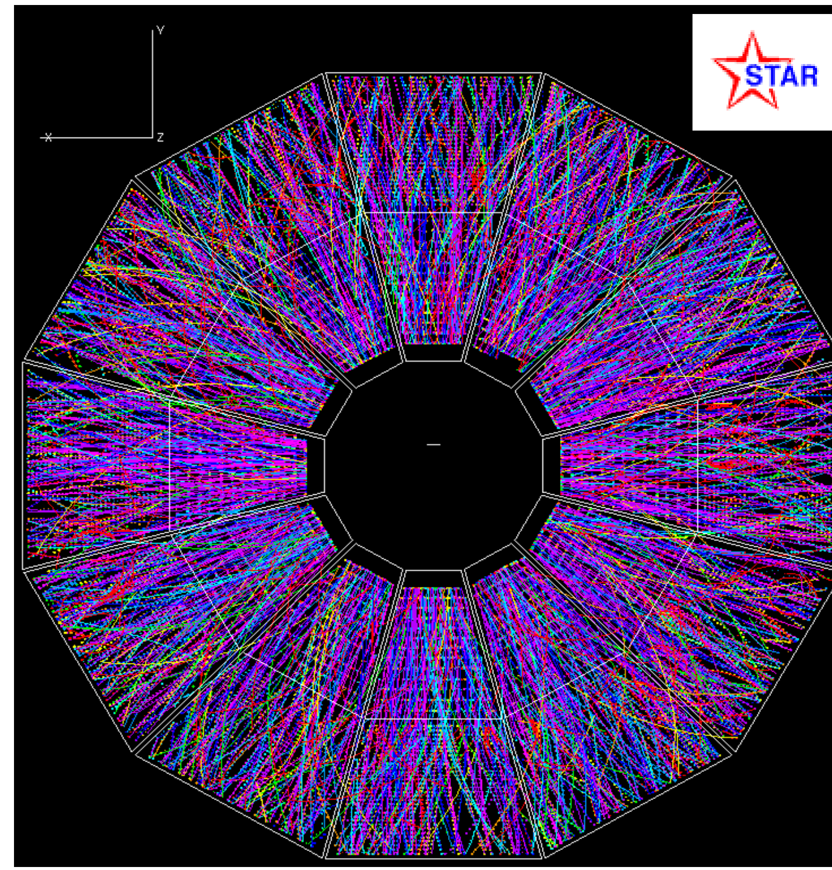
R_{AA}~ 1: Photon spectrum consistent with pQCD×N_{coll} (unaffected by FSI, AA = incoherent sum of pp)

R_{AA} << 1: Hadrons well below pQCD expectations. Energy-loss in dense medium: $dN^g/dy \sim 1100$, $\langle \hat{q} \rangle \sim 14$ GeV^2/fm

Jets in AA collisions at RHIC

Full jet reconstruction w/ standard algorithms is unpractical at RHIC due to huge soft background ("underlying event") and low large-E_T jet cross sections

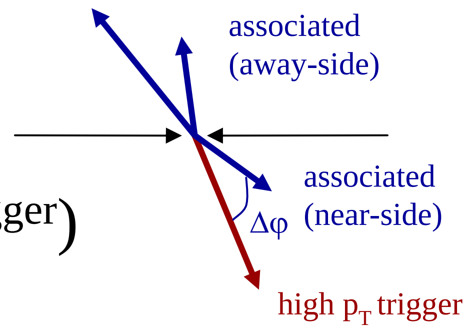




p+p $\rightarrow$jet+jet [$\sqrt{s}$ = 200 GeV]
STAR @ RHIC (2003)

Au+Au $\rightarrow$ X [$\sqrt{s_{NN}}$ = 200 GeV]
STAR @ RHIC (2003)

High p_T di-hadron $\Delta\varphi$ correlations in pp,dAu



Two-particle correlations: $h^{\pm}$ – $h^{\pm}$, $\pi^{0,\pm}$ – $h^{\pm}$.

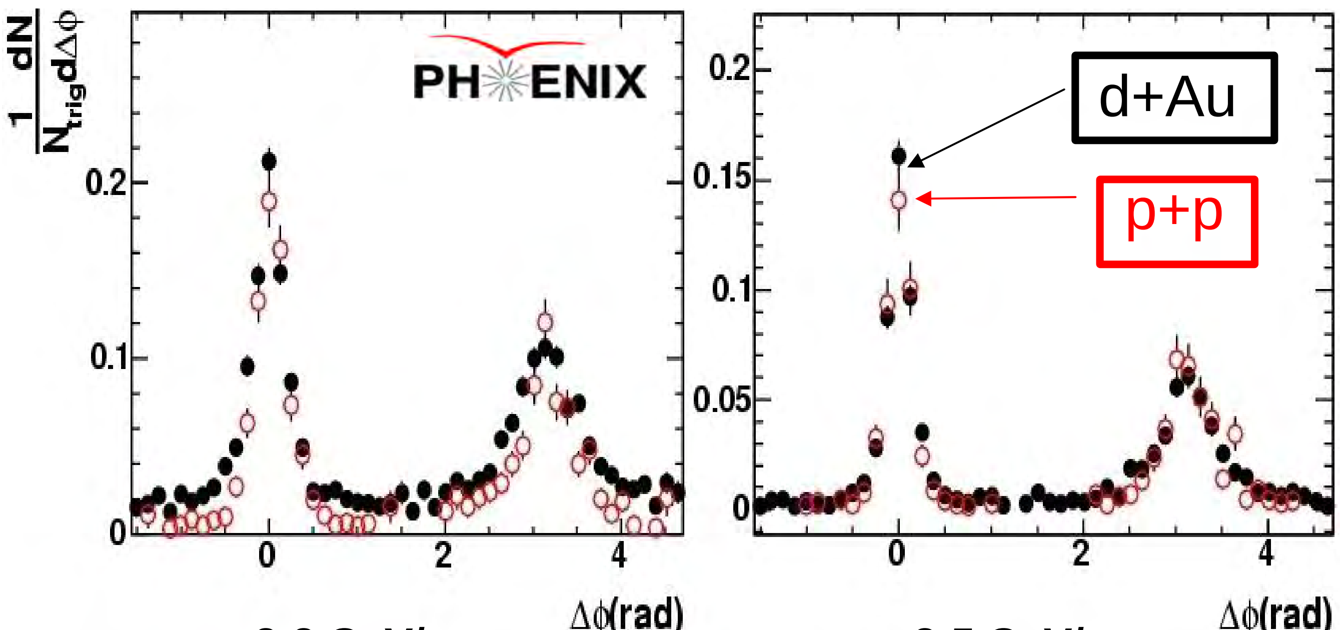
Trigger: highest p_T (leading) hadron.

Associated $\Delta\phi$ distribution (e.g. 2 GeV/c < p_T^{assoc} < $p_T^{trigger}$)

Correlation function normalized to number of triggers:

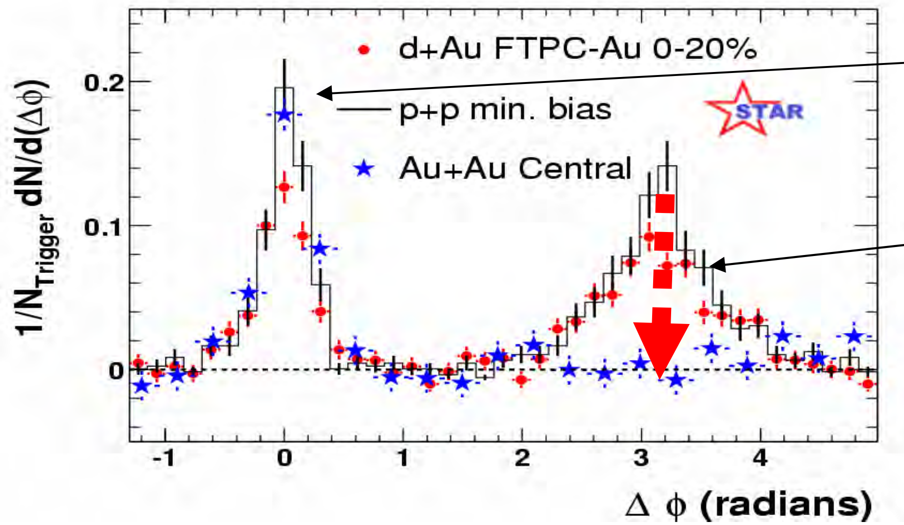
$$C(\Delta\phi, \Delta\eta) = \frac{1}{N_{trig}} \frac{d^2 N_{pair}}{d\Delta\phi d\Delta\eta}$$

Clear near- ($\Delta\phi \sim 0$) and away- ($\Delta\phi \sim \pi$) side jet signals:



p_T^{assoc} = 2-3 GeV/c p_T^{assoc} = 3-5 GeV/c

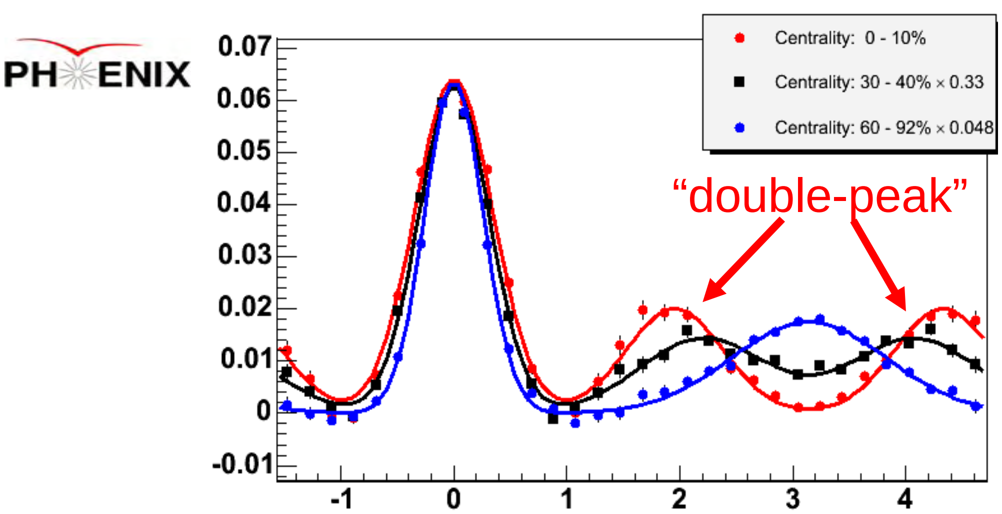
High p_T di-hadron Δφ correlations in central AuAu



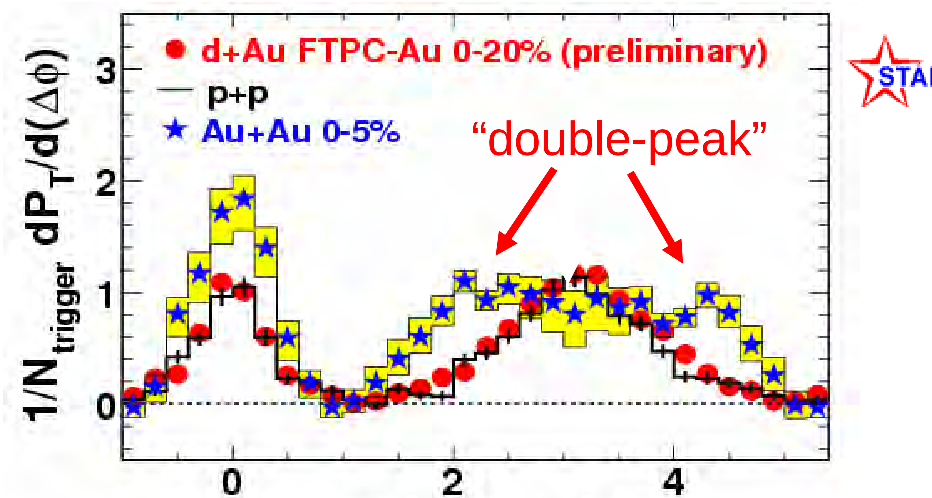
- Near-side jet-like Gaussian peak unmodified (AuAu ~ dAu ~ pp)
- Away-side peak disappears: "monojet"-like topology

$p_{T\ trigg}$ = 4 – 6 GeV/c
$p_{T\ assoc}$ > 2 GeV/c

"Lost" away-side energy dissipated at lower p_T values.
Away-side Δϕ peak splits in two with increasing centrality:



$p_{T\ trigg}$ = 2.5 – 4 GeV/c
$p_{T\ assoc}$ = 2 – 3 GeV/c

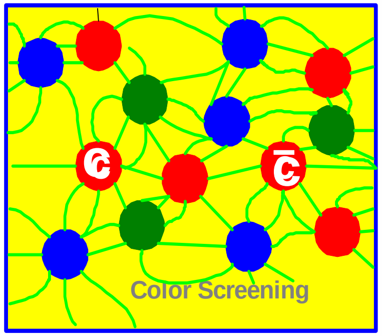


$p_{T\ trigg}$ = 4 – 6 GeV/c
$p_{T\ assoc}$ = 0.15 – 4 GeV/c

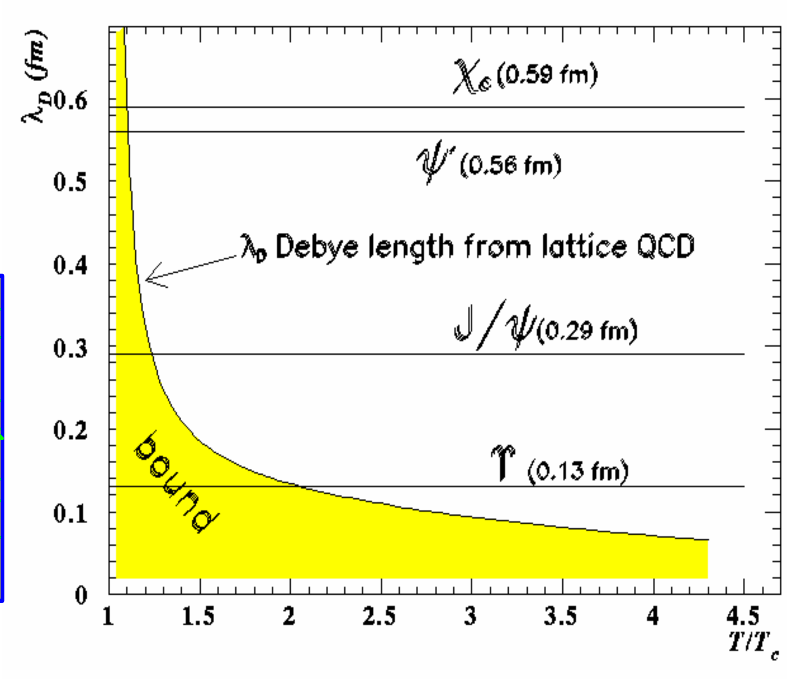
QQbar suppression = Colour screening

Heuristic argument (Matsui-Satz 1986):

- Colour screening in a deconfined plasma dissolves QQbar
- Different bound states "melt" at different temperatures due to their different binding radius: QQbar "thermometer"



Screening length λ_D vs. T:

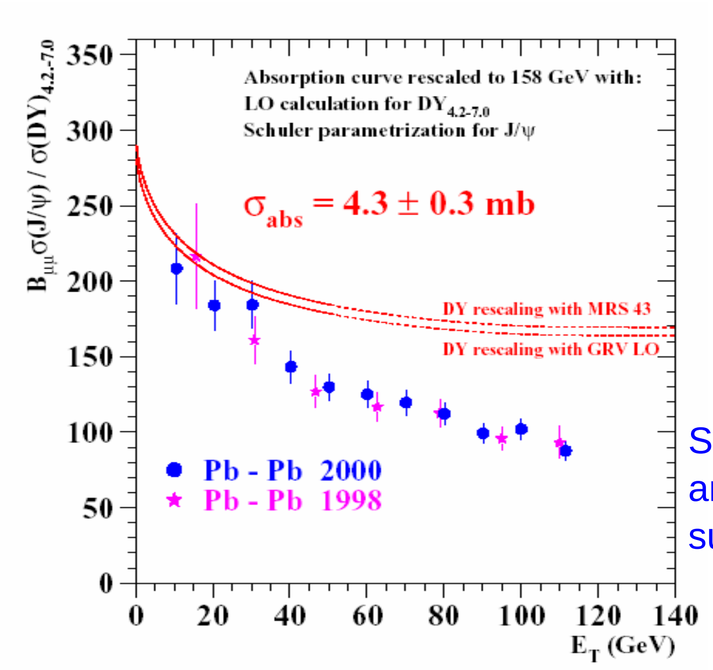


Lattice QCD calculations:

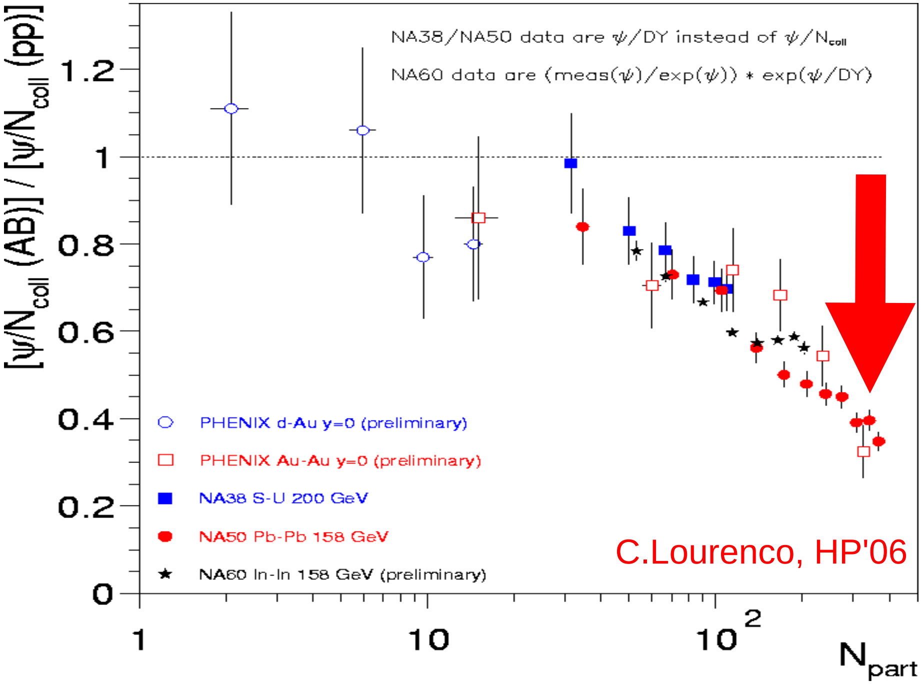
ψ' , χ_c dissolve arount T_c, J/ψ survives until $2T_c$, Υ may survive up to LHC energies

J/ψ suppression at SPS and RHIC

J/ψ suppression vs. centrality (N_{part}):



SPS NA50 anomalous suppression



Same suppression observed at RHIC (T~400 MeV) & SPS (T~200 MeV) !?

Recombination:

ccbar regeneration (10 ccbar pairs in central AuAu !) compensates for screening ?

Sequential dissociation:

Only ψ' and χ_c (~40% feed-down J/ψ) melt.

Direct J/ψ survives at RHIC $T_0 <\sim 2 \cdot T_c$

Large Hadron Collider (LHC) @ CERN

Specifications:

26.66 km circumference

1 ring:

- 8.33 T superconducting coils
- 25 ns crossing time (40 MHz)

pp luminosity: 10^{34} cm^{-2} s^{-1} (10^7 s/year)

AA luminosity: 10^{27} cm^{-2} s^{-1} (10^6 s/year)

3 heavy-ion experiments:

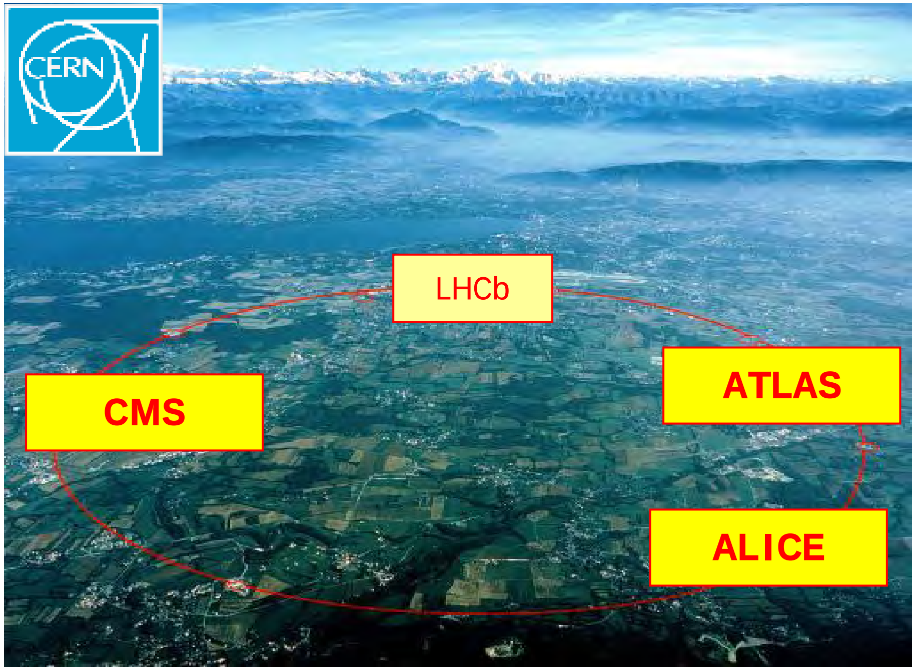
ALICE, ATLAS, CMS

First runs:

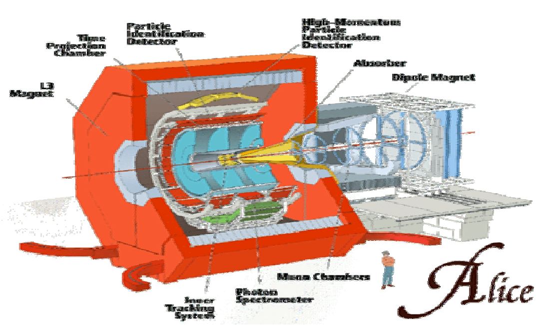
pp @ 14 TeV (2007 pilot, 2008)

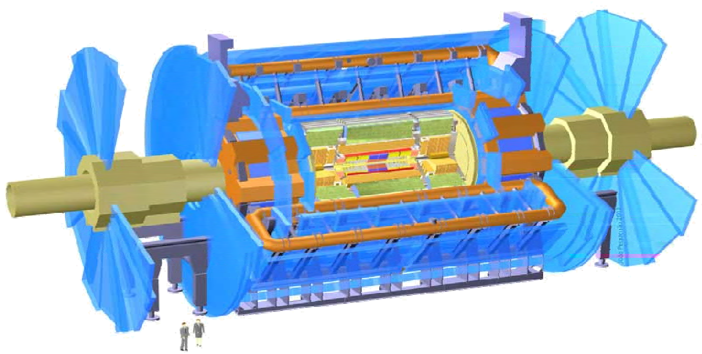
PbPb @ 5.5 TeV (2008: early cfg., 2009 std. cfg.)

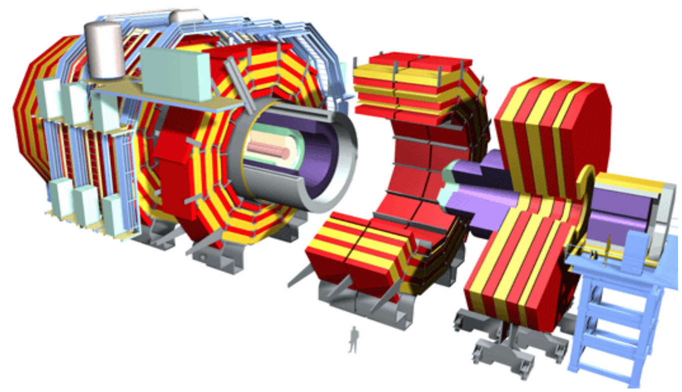
pPb @ 8.8 TeV (2010?)



The 3 LHC heavy-ion experiments







- ALICE: dedicated HI experiment
- Largest HI community (~1000)
- Tracking (|η|<1-2): TPC + ITS + TRD
- 0.5 T solenoid magnet
- EMCal under discussion
- Forward muon spectrometer

- Strongest capabilities: low-p_T, light-quark PID, ...

- ATLAS & CMS: multipurpose (pp) + HI program
- People: ~50/2000 (ATLAS), ~70/2300 (CMS)
- |η|<2.5: Full tracking, muons
- |η|<5: Calorimetry
- 4 T (CMS), 2 T (ATLAS) mag. field

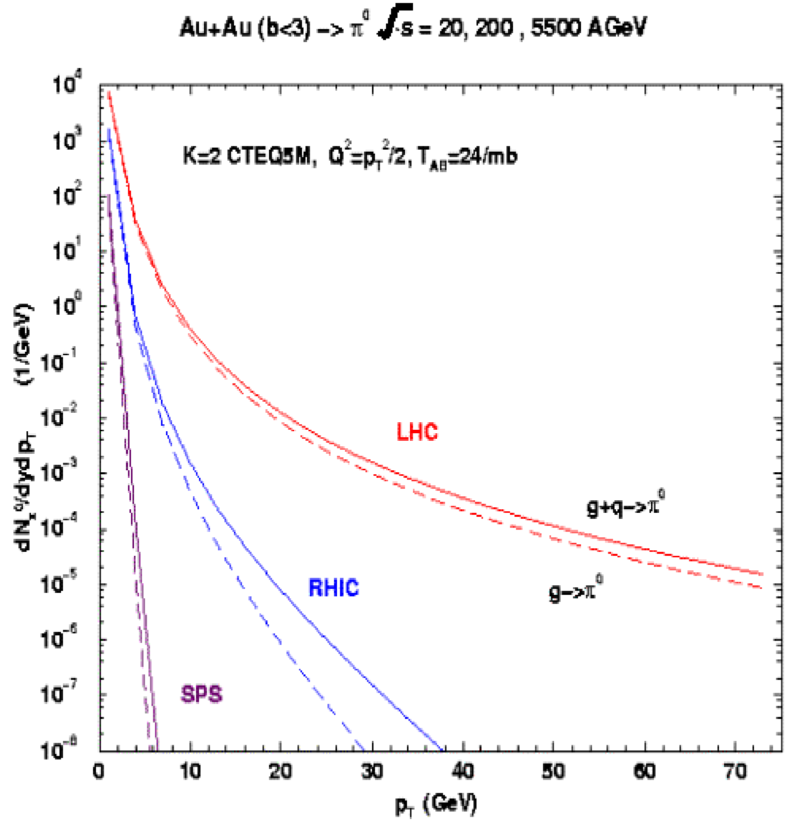
- Forward detectors (CMS)
- Strongest capabilities: hard-probes, Υ, full jet reco, heavy-Q jet PID, jet-Z,γ

LHC: new regime for QGP studies

- Produced quark-gluon matter:
  hotter, denser, bigger, longer lifetime

	SPS	RHIC	LHC	
$\sqrt{s_{NN}}$ (GeV)	17	200	5500	X 28
dN_{ch}/dy	500	850	1500-3000	x 2-3
τ^0_{QGP} (fm/c)	1	0.2	0.1	faster
T/T_c	1.1	1.9	3.0-4.2	hotter
ε (GeV/fm^3)	3	5	15-60	denser
τ_{QGP} (fm/c)	≤ 2	2-4	≥ 10	longer
τ_f (fm/c)	~10	20-30	30-40	
V_f(fm^3)	few 10^3	few 10^4	few 10^5	bigger

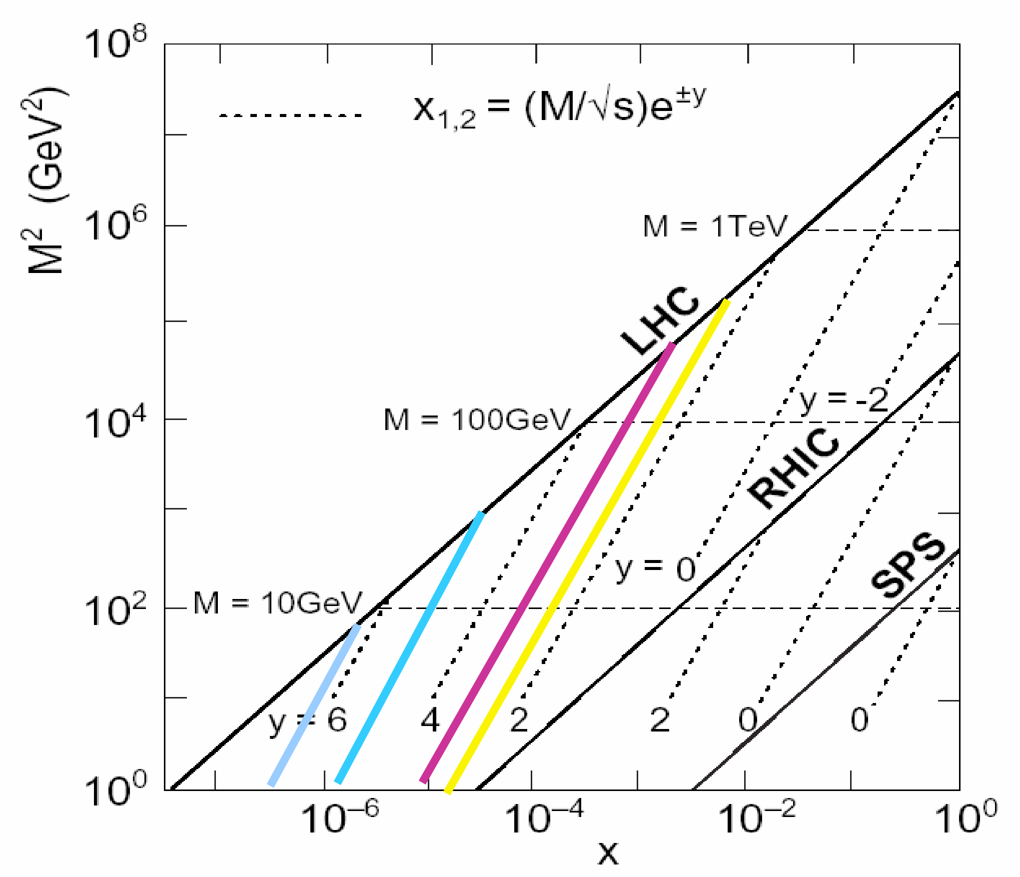
- Very large pQCD cross-sections: well calibrated probes of QCD medium.



- Different plasma ? Liquid- (RHIC) to gas-like (LHC) transition ?

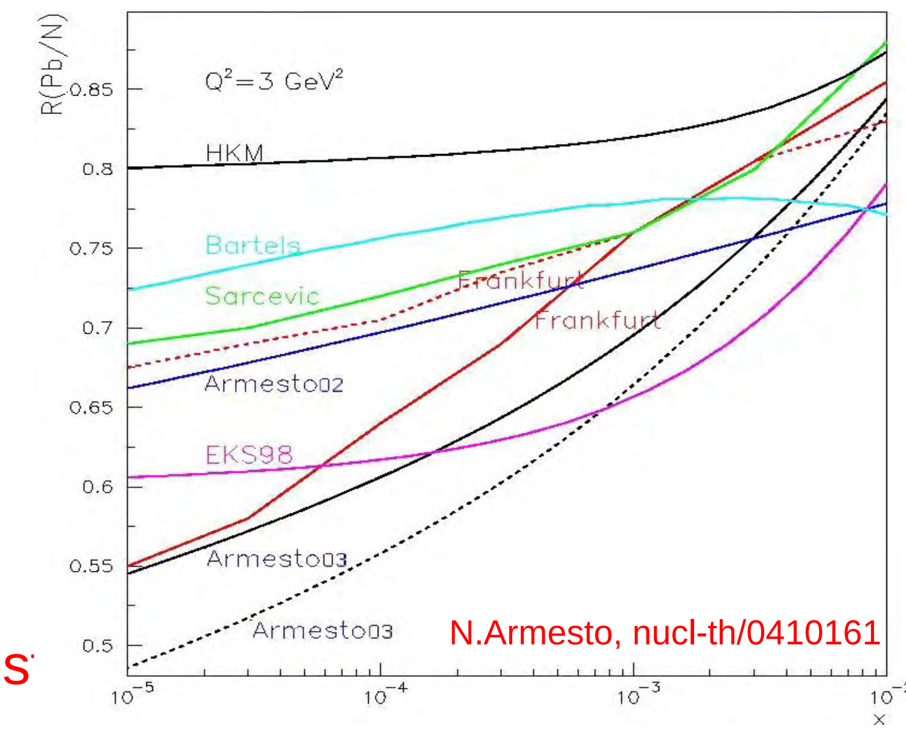
LHC: New low-x QCD regime

- PbPb @ 5.5 TeV, pPb @ 8.8 TeV:
  (i) Bjorken $x=2p_T/\sqrt{s}$, ~30-45 times smaller x than AuAu,dAu @ RHIC
  (ii) Very large perturbative (jets, QQbar, DY, high-p_T) cross-sections.
  (iii) Forward detectors allows for measurements down to $x\sim10^{-6}$!



S

Nuclear $xG(x,Q^2)$ currently unknown for $x<10^{-3}$



Summary

- High-energy colls. of heavy-ions study QCD in extreme conditions of Density, Temperature and small-x
- QCD phase diagram explored:
  - SPS: close to phase boundary (T_0~200 MeV)
  - J/Ψ suppressed, ρ broadened, ...
  - RHIC:
    - Initial-state = Color Glass Condensate (saturated *xG*)
    - Strongly coupled QGP (large partonic flows) viscosity/entropy~1/4p
    - Very dense system ("jet quenching"): dN_g/dy~1000, <q>~14 GeV^2/fm, $\langle c_s \rangle$~0.3 (?)
    - Hot medium (J/Ψ suppressed, thermal g ?) T_0~2·T_c~400 MeV
- LHC: weakly coupled QGP ? strong CGC effects ? ...