The future of heavy-ion collisions at RHIC and RHIC II

Peter Jones

University of Birmingham

(and for the STAR collaboration)

New opportunities in high temperature QCD

1. **Hard scattering and the Quark-Gluon Plasma (QGP)**
2. **Gluon saturation and the Colour Glass Condensate (CGC)**

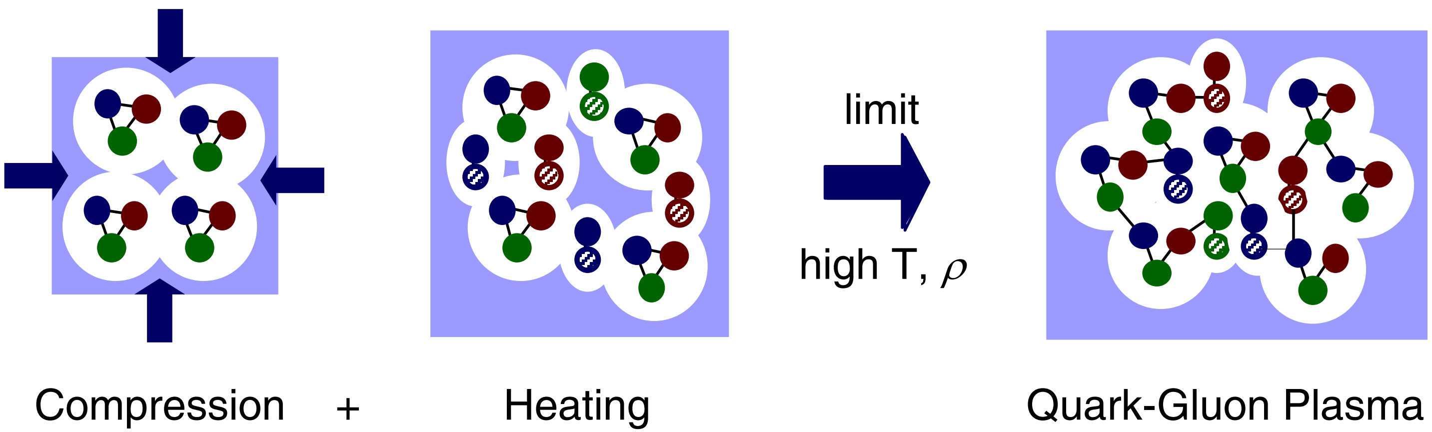
Quark deconfinement and the QGP

- **Expectations for a new state of matter in RHI collisions**
  - QCD is an asymptotically free theory.

$$V = -\frac{\alpha_s(r)}{r} + kr \qquad \alpha_s(r) \to 0 \text{ as } r \to 0$$

  - Charges are screened in a dense medium → Debye screening.

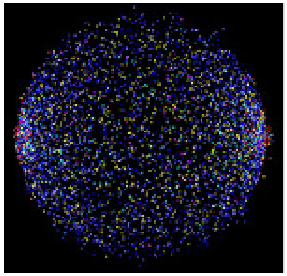
$$V = -\frac{\alpha_s(r)}{r}\exp\left(\frac{-r}{r_D}\right) \qquad \text{where} \qquad r_D \propto \frac{1}{\sqrt[3]{n}}$$

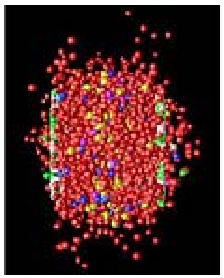


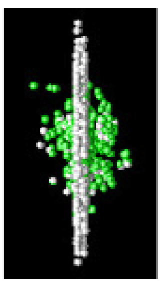
  - Estimates of critical parameters from Lattice QCD calculations.

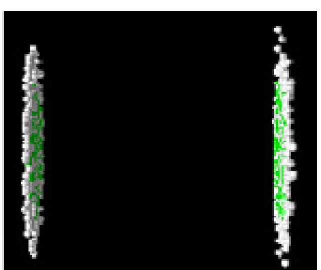
$\varepsilon_c \sim 1$ GeV/fm^3, $T_c \sim 170$ MeV   2-flavour QCD   F. Karsch, hep-ph/0103314

The space-time collision picture

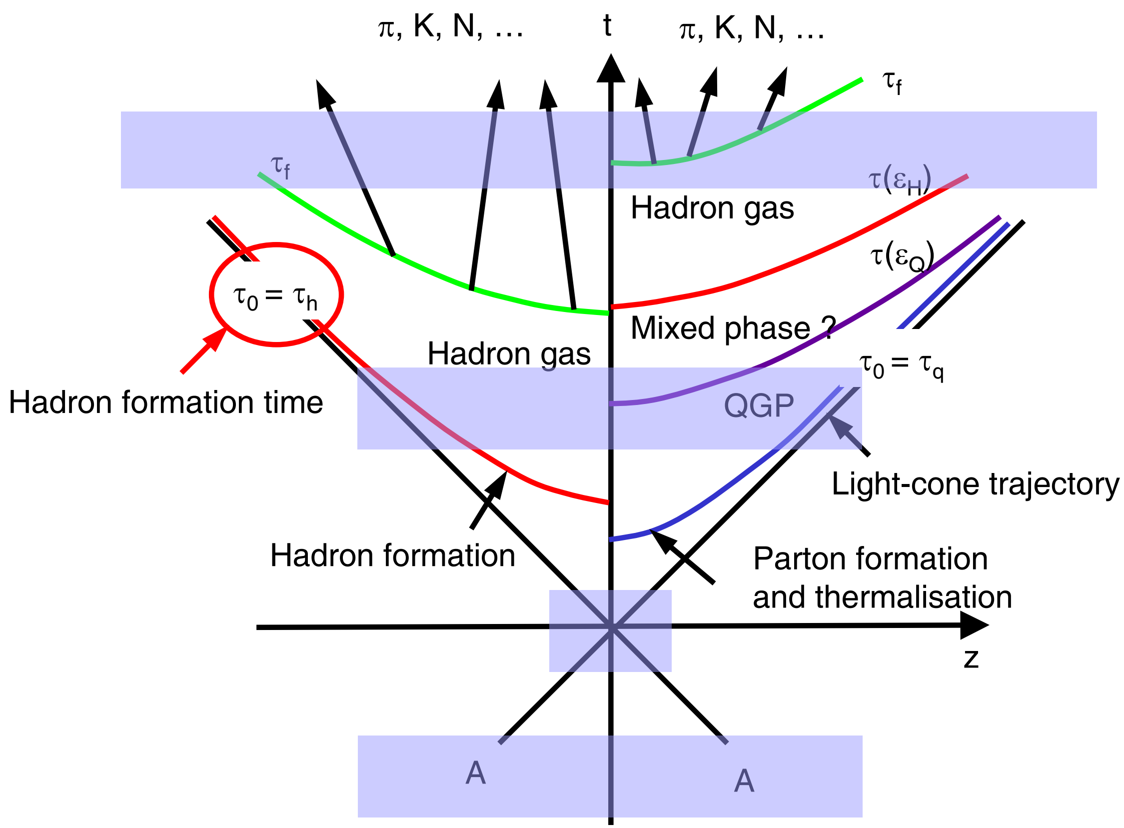








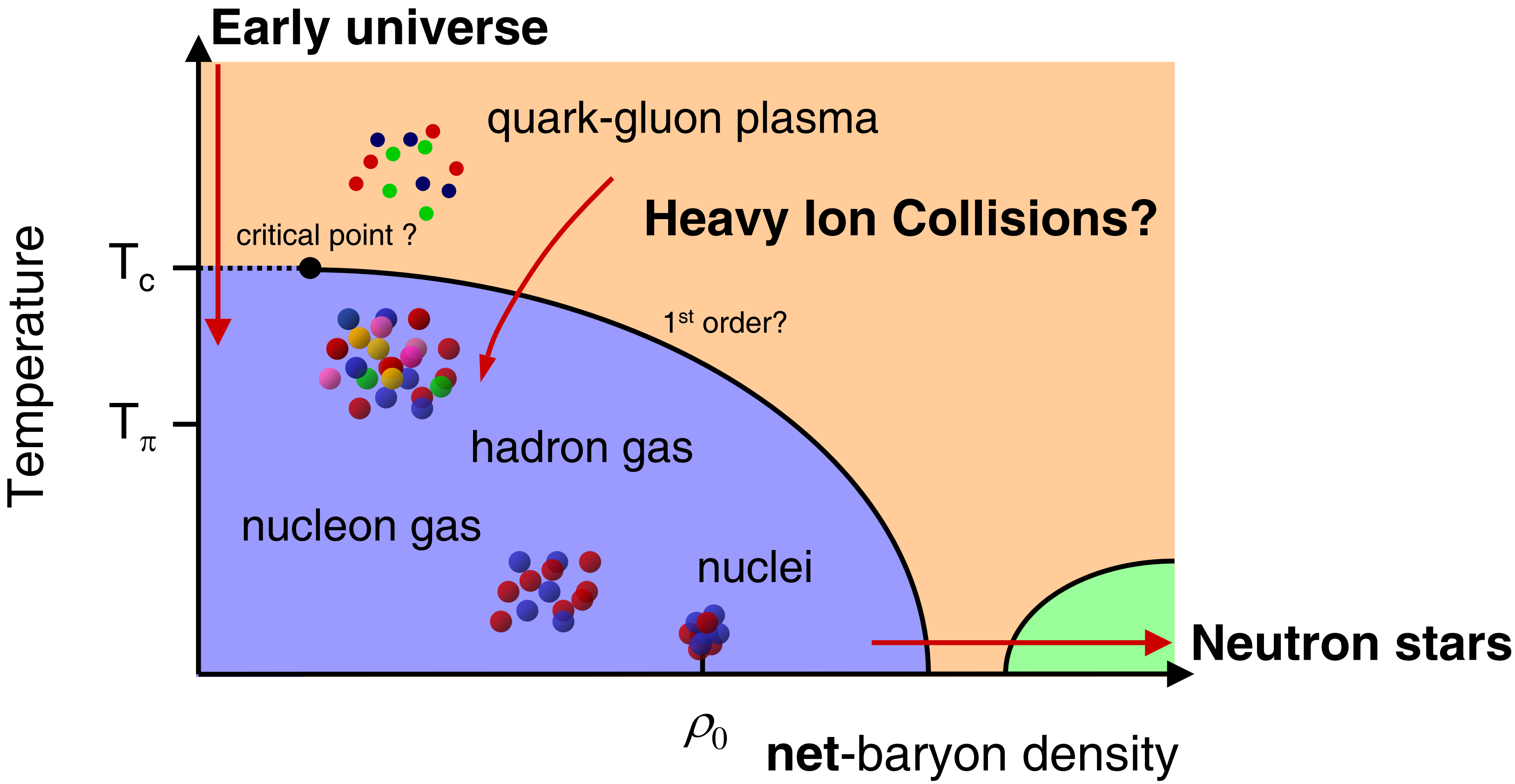
This is what the detectors "see"



a) Without QGP   b) With QGP

Define 'proper' time = $\tau = \sqrt{t^2 - z^2}$

Exploring the nuclear phase diagram



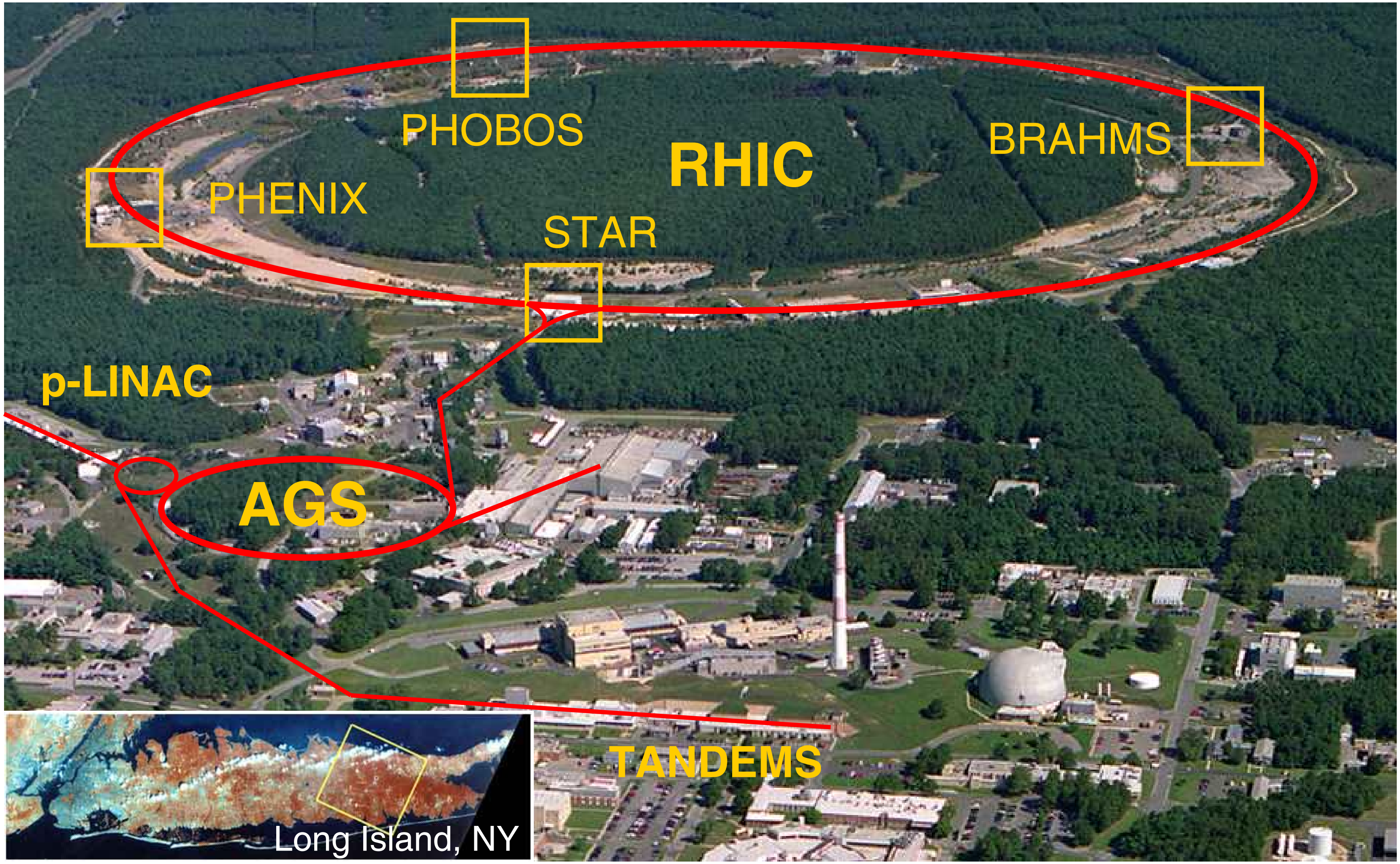
The possible phases of nuclear matter

Experimental facilities

Facility	Beam	Beam Energy (GeV/A)	CMS Energy $\sqrt{s}$	
AGS	^{28}Si	14.6	5.4	1986
	^{197}Au	11.6	4.8	1994
SPS	^{16}O	200	19	1986
	^{32}S	200	19	1987
	^{208}Pb	158	17	1994
RHIC	**^{197}Au**	**100**	**200**	**2000**
LHC	^{208}Pb	3000	6000	2007

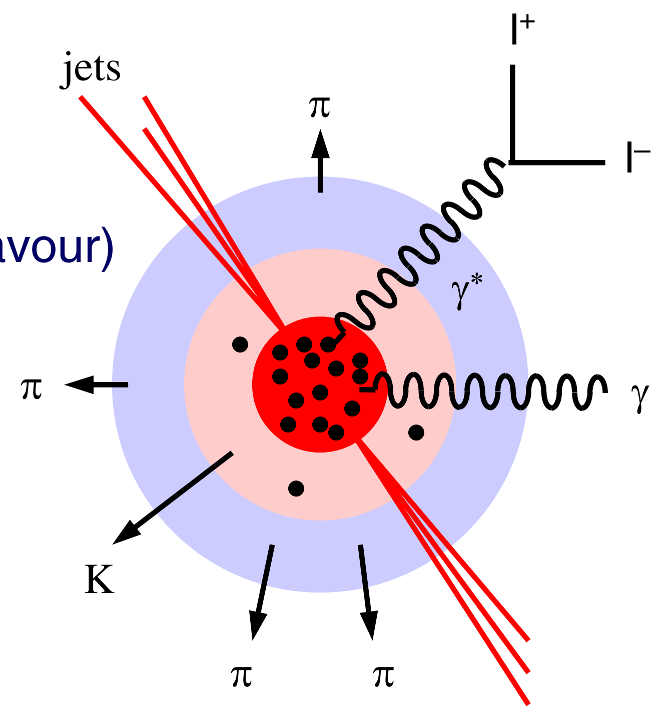
AGS Alternating Gradient Synchrotron (BNL)
SPS Super Proton Synchrotron (CERN)
RHIC Relativistic Heavy-Ion Collider (BNL)
LHC Large Hadron Collider (CERN)

Relativistic Heavy Ion Collider (RHIC)



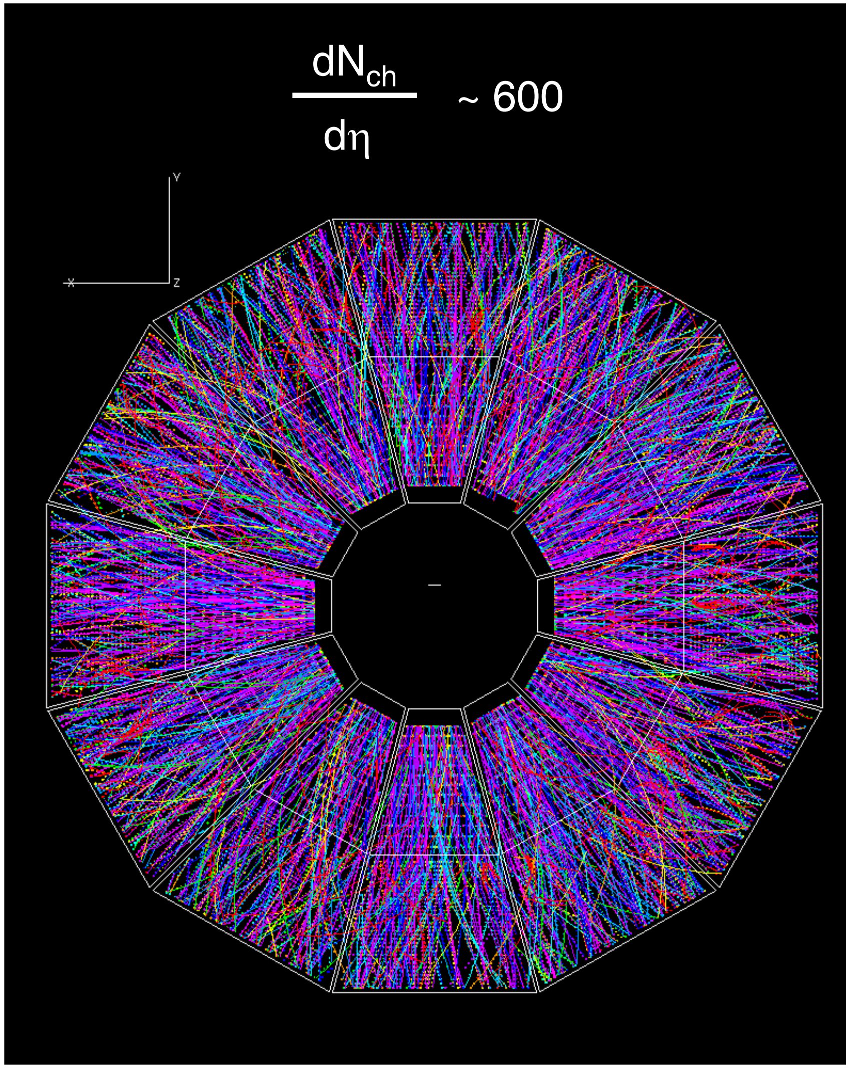
RHIC capabilities and RHIC II

- **RHIC I**
  - pp, dA, AA collisions ($\sqrt{s_{NN}}$ = 200 GeV)
  - Polarised pp collisions ($\sqrt{s_{NN}}$ = 500 GeV)
  - Design luminosity $L_0 = 2 \times 10^{26}$ cm^{-2} s^{-1} (ions)
  - Current performance $L = 2\ L_0$
  - $\int L\,dt$ per RHIC year (20 wks) ~ 2–3 nb^{-1}
- **RHIC II**
  - Luminosity upgrade $L = 40\ L_0$
  - Focus on rare probes (jets, photons, heavy flavour)



Status:
Community invited to make physics case.
R+D through 2007.
Available 2012+
Detector upgrades needed.
New detector proposal.

Challenges and opportunities



- **Questions**
  - Is the QGP formed at RHIC?
  - Can we test its properties?
  - What observables are sensitive to quark (and gluon) confinement?
  - Is there a way to understand multi-particle production in QCD?

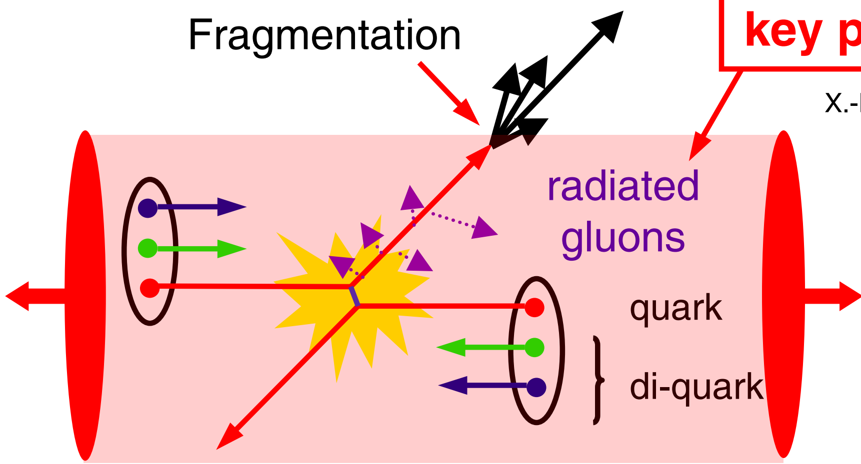
- **New opportunities**
  - Hard processes (e.g. jets, heavy flavour) are pQCD calculable.
  - These are rare probes – requiring high integrated luminosities.

Particle production phenomenology

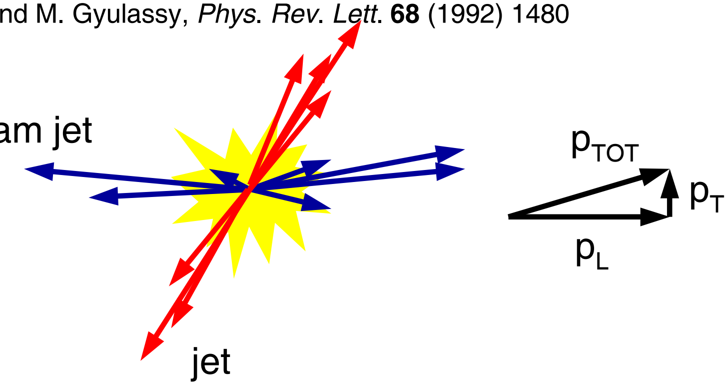
- **At high energy hadrons (nuclei) appear to be a beam of partons**

key pQCD prediction: jets are quenched

X.-N. Wang and M. Gyulassy, *Phys. Rev. Lett.* **68** (1992) 1480



Interaction at the quark (parton) level

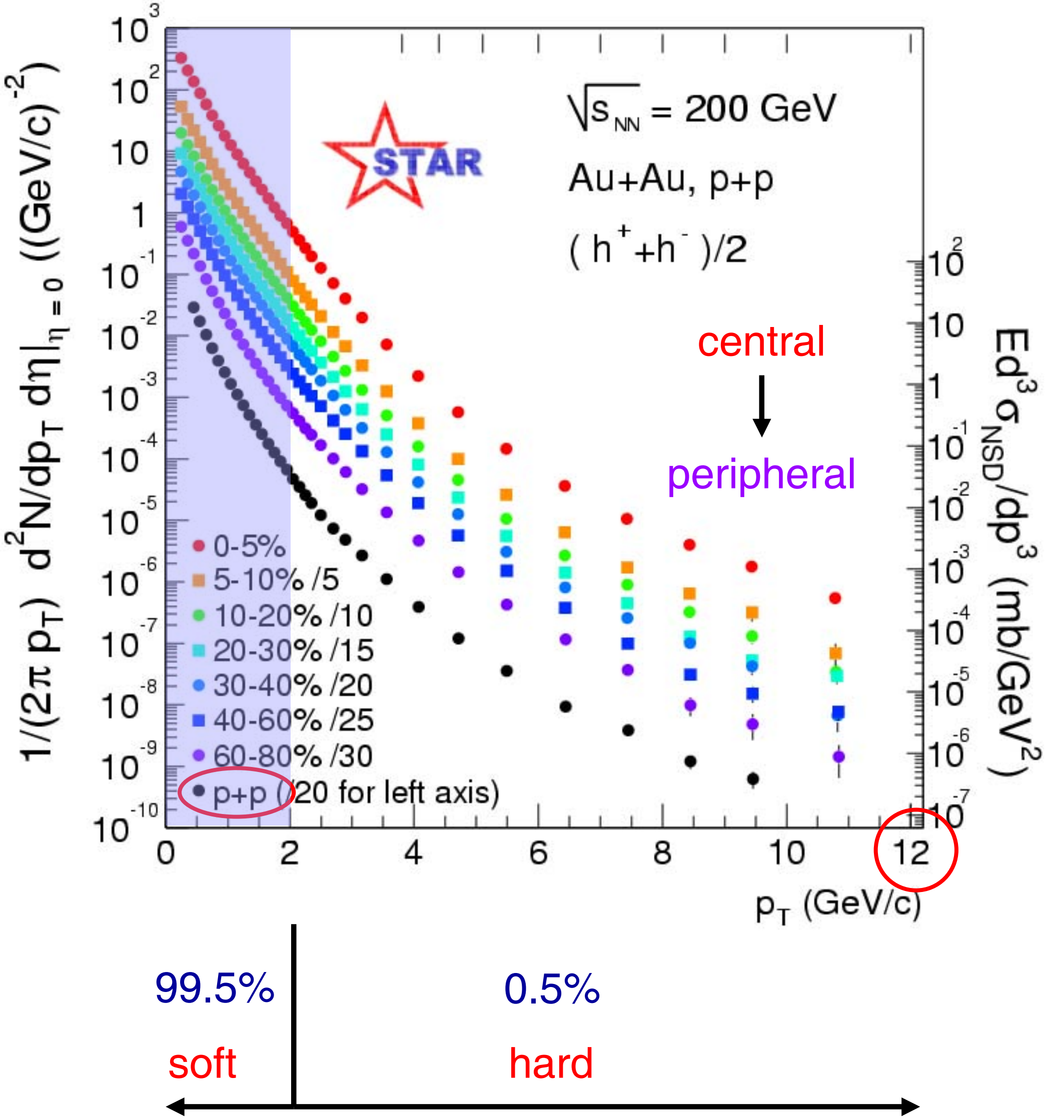


The same interaction at the hadron level

$$\frac{d\sigma^h_{pp}}{dy d^2 p_T} = K \sum_{abcd} \int dx_a dx_b \, f_a(x_a, Q^2) f_b(x_b, Q^2) \frac{d\sigma}{d\hat{t}}(ab \to cd) \frac{D^0_{h/c}}{\pi z_c}$$

Parton distribution functions	– known from DIS at HERA
Hard scattering cross-section	– pQCD calculable
Fragmentation function	– measured in e^+e^- and $pp(\bar{p})$ experiments

Charged hadrons in STAR



The inclusive p_T distribution

Transition from soft → hard scattering is expect above p_T > 2 GeV/c (pQCD valid?).

Nuclear modification factor

Hard scattering is an incoherent process. Therefore, the yield at high p_T should scale with the number of binary collisions.

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA}\, d^2\sigma^{NN}/dp_T d\eta}$$

Scale factor

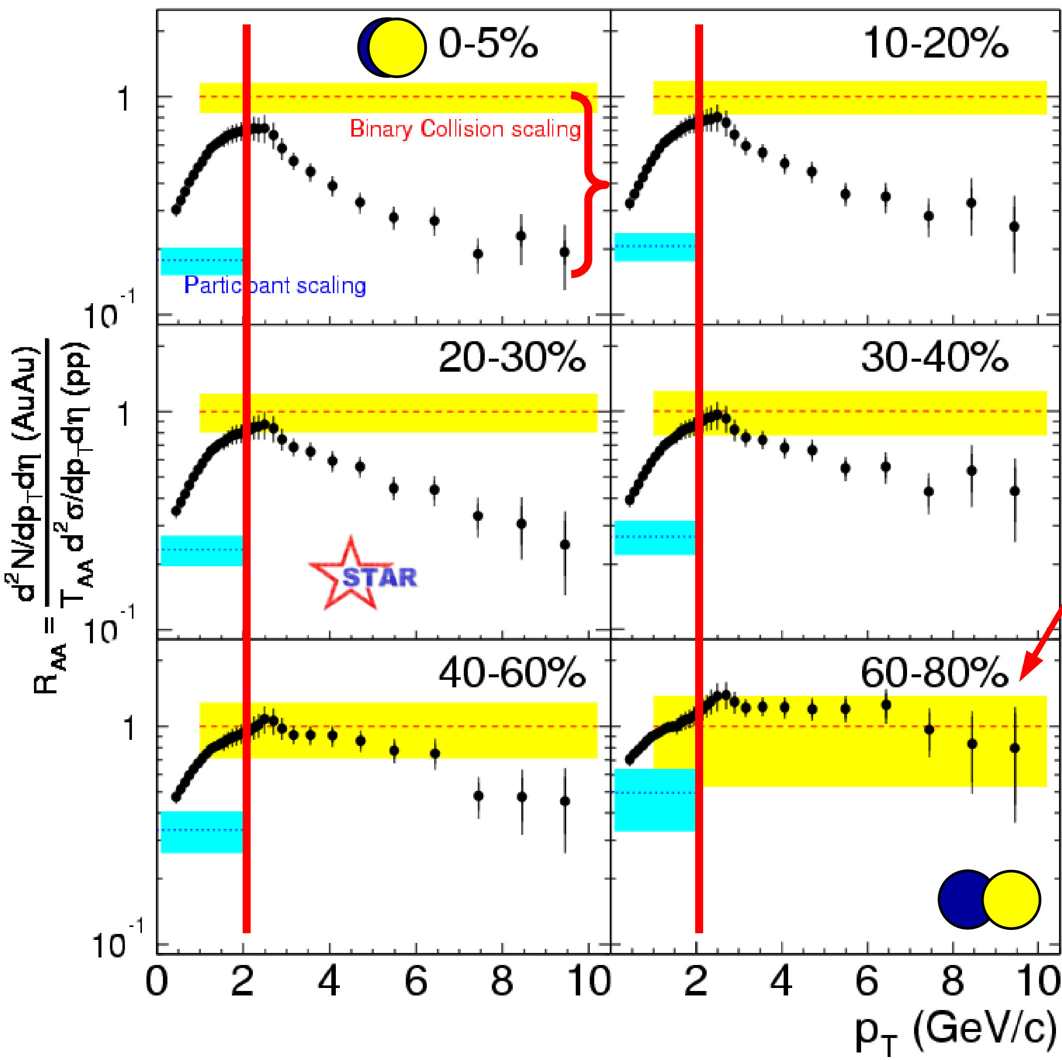
no. binary collisions

p+p reference

$$T_{AA} = \langle N_{binary} \rangle / \sigma^{pp}_{inelastic}$$

Suppression of high p_T hadrons

Central collisions



Peripheral collisions

Binary collision scaling?

Expect hard scattering to dominate above 2 GeV/c.

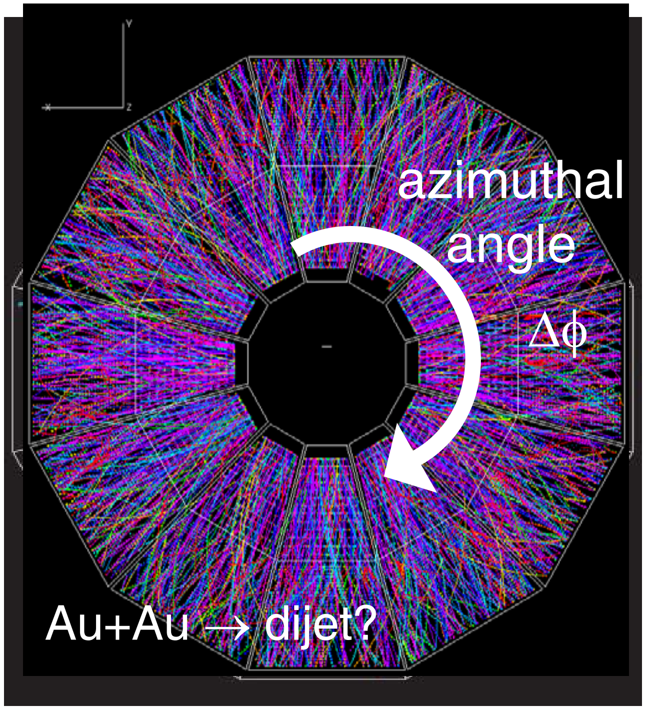
Binary collision scaling is observed only in the most peripheral collisions.

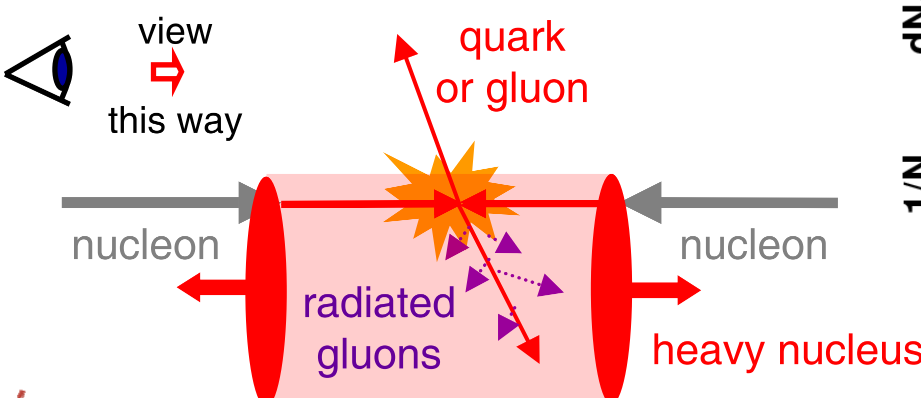
In central collisions the yield falls well below the binary scaling expectation.

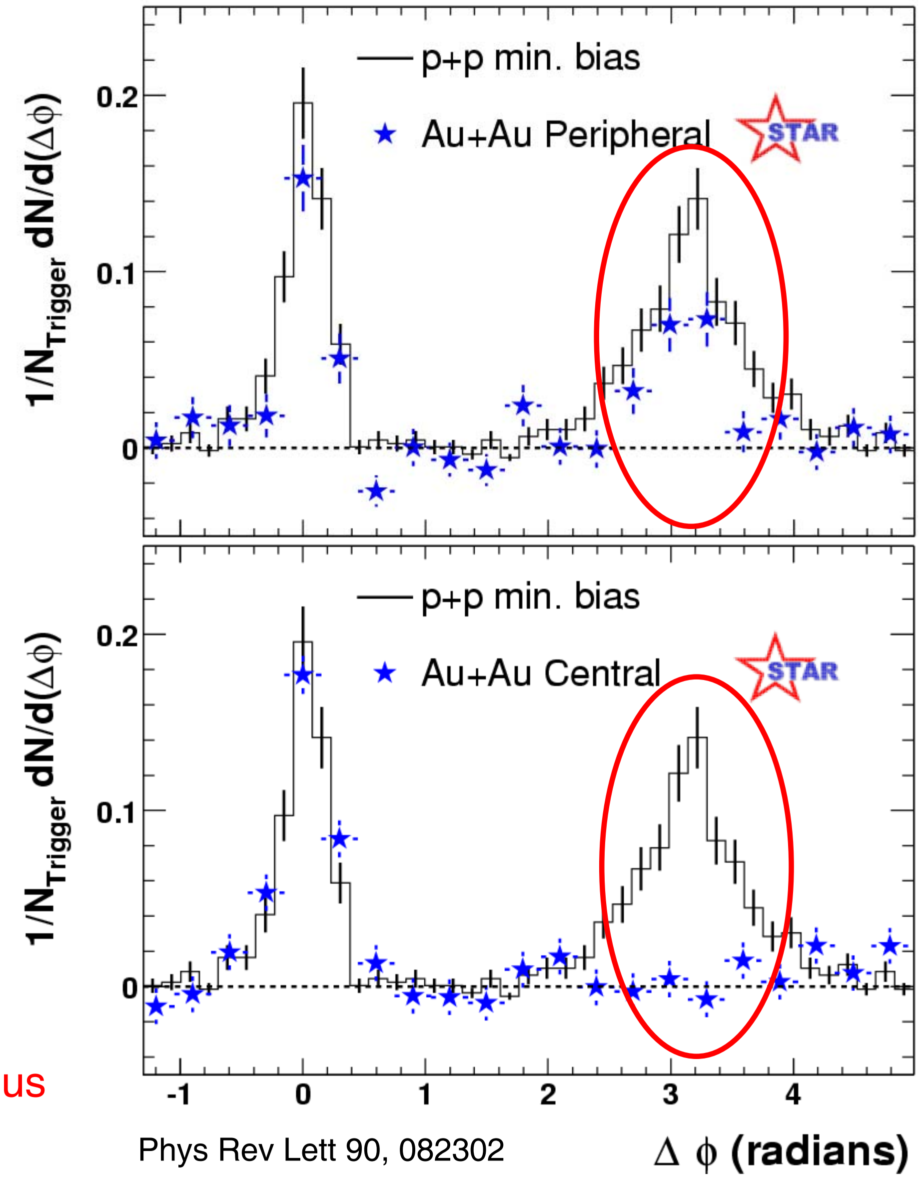
Consistent with increased partonic energy loss in the larger volume.

Disappearance of back-to-back jets

- **A new probe of quark deconfinement**



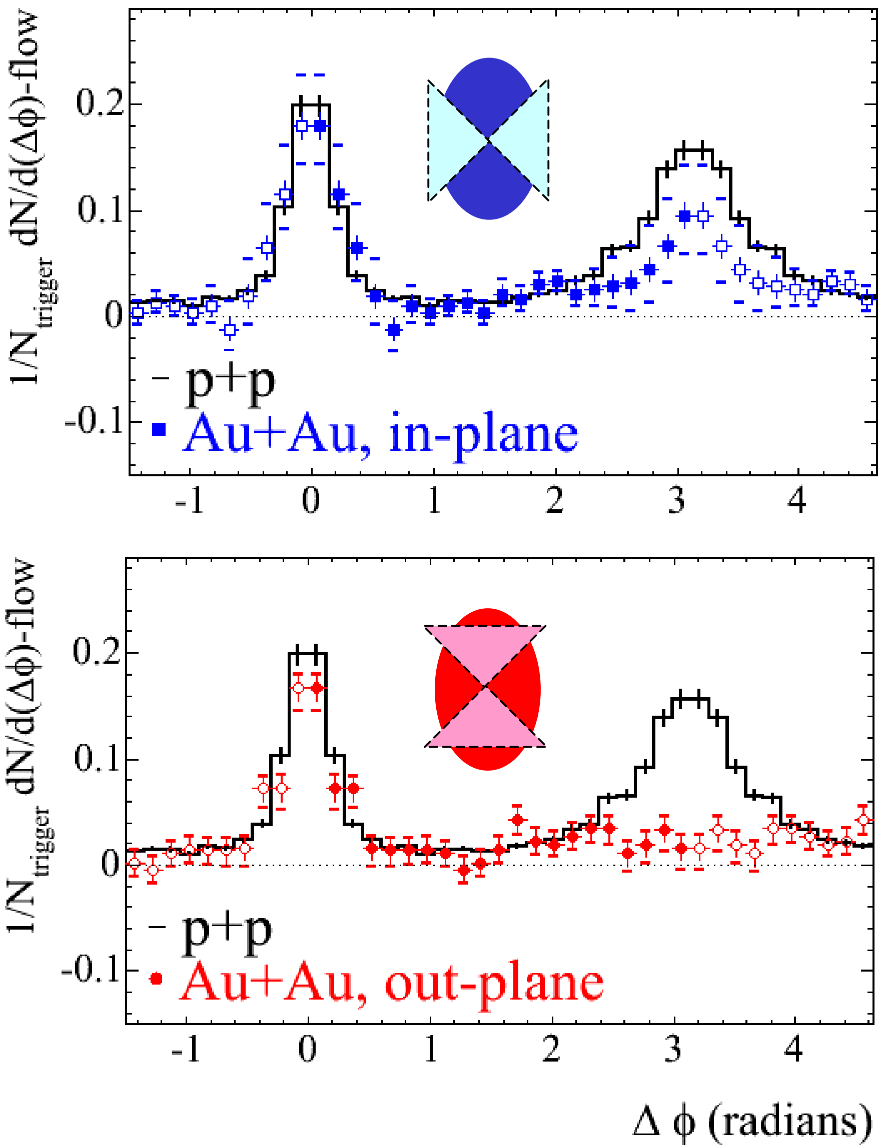




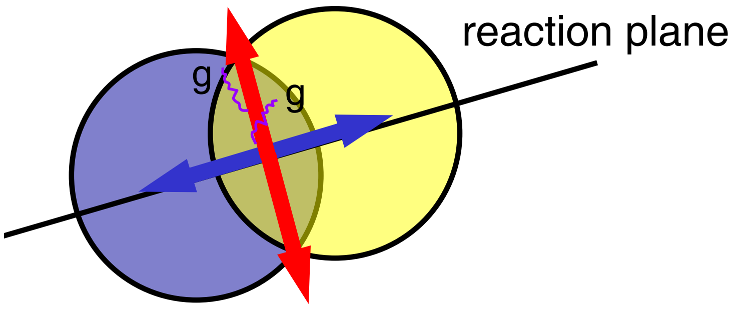
Phys Rev Lett 90, 082302

Towards jet-tomography

- **Correlating back-to-back jets with the reaction plane**



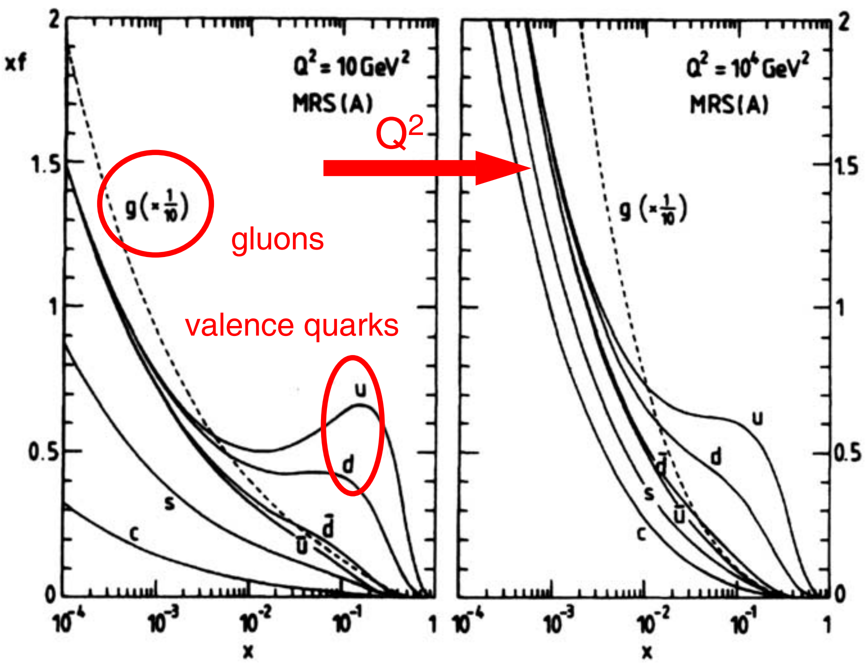
Non-central collisions



Evidence of stronger suppression when jet is emitted out of the reaction plane.

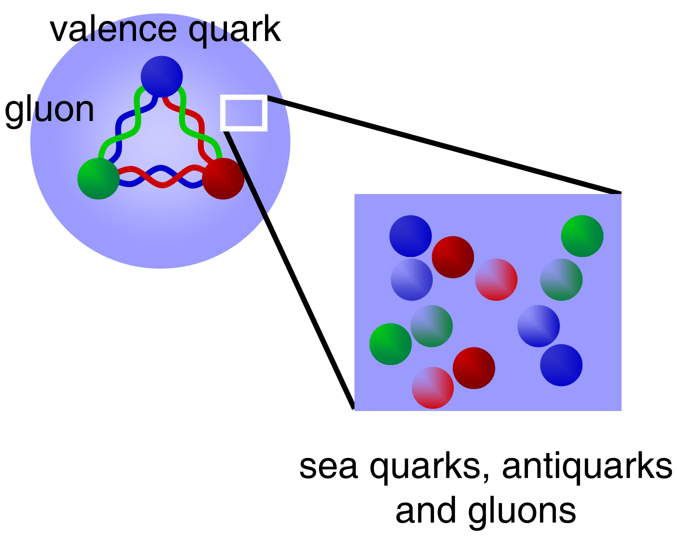
Multi-particle production in QCD

- **Can QCD tell us anything about the initial conditions?**
  – pQCD describes a very small part of the total inelastic cross-section.
- **Parton distributions from Deep Inelastic Scattering (DIS)**



Parton distributions in the proton

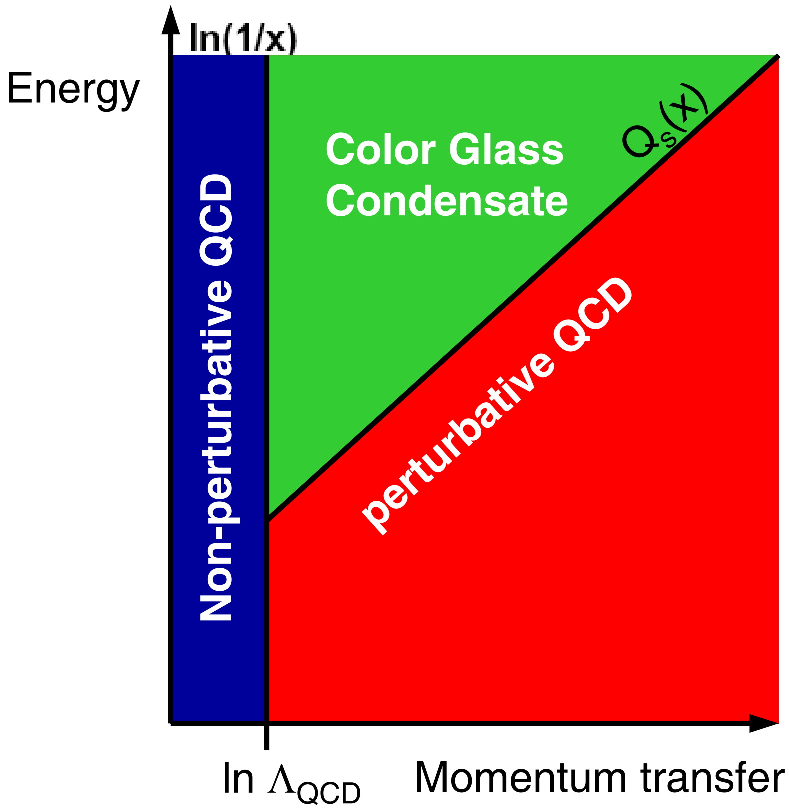
A.D. Martin et al, Phys. Rev. D 50 (1994) 6734

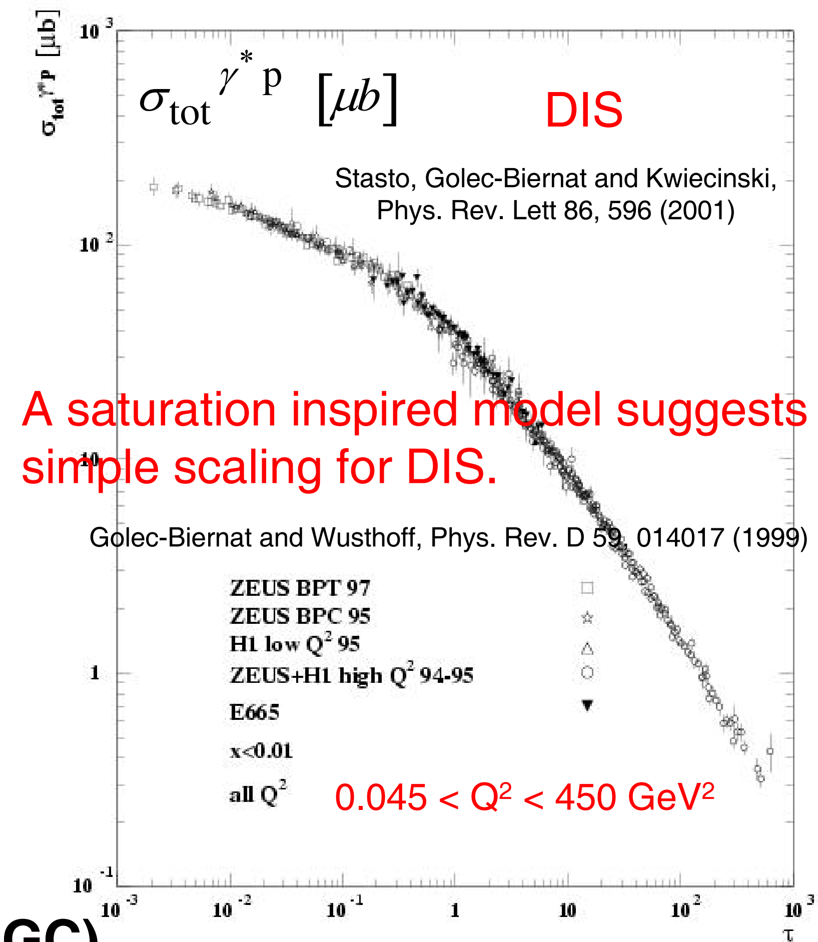


- **The low-x problem**
  – The parton distributions at low-x are dominated by gluons.
  – At high densities, gluons are no longer incoherent ⇒ saturation!

Saturation

- **When does saturation set in?**





A saturation inspired model suggests a simple scaling for DIS.

$$\tau = \frac{Q^2}{Q_S^2}$$

- **The Colour Glass Condensate (CGC)**

  Colour – because partons (gluons in particular) are coloured.

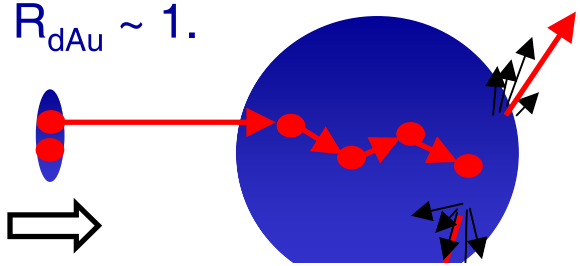
  Glass – disordered system; gluon distributions frozen on timescale of collision.

  Condensate – high phase-space occupancies.

An initial or final state effect?

- **Inclusive p_T distribution**

  If suppression is a final state effect, expect $R_{dAu} \sim 1$.

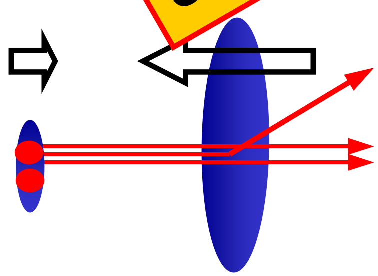


  If suppression is an initial state effect, expect $R_{dAu} < 1$.

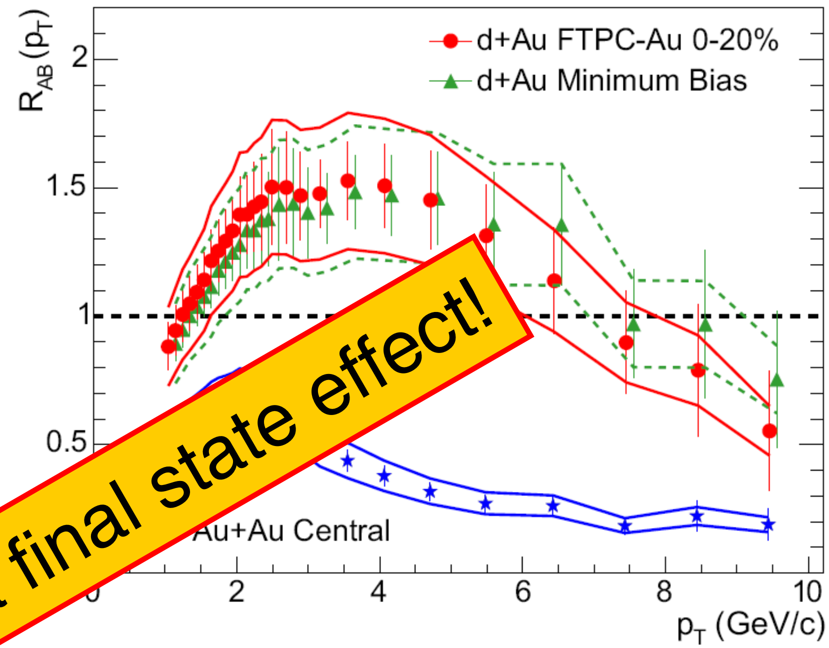
- **Two particle correlations (jet**

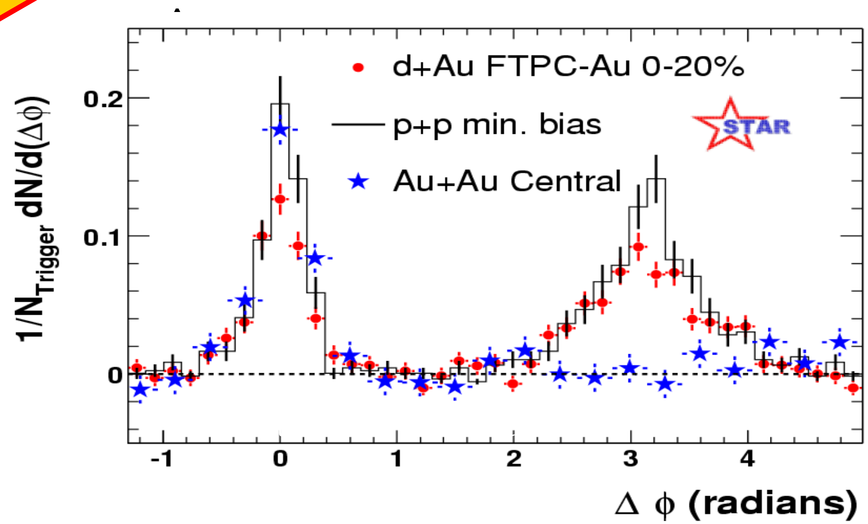
  pQCD: no suppression, sma broadening due to Cron

  Saturation mode ssion persists due t jets.



Jet suppression is a final state effect!

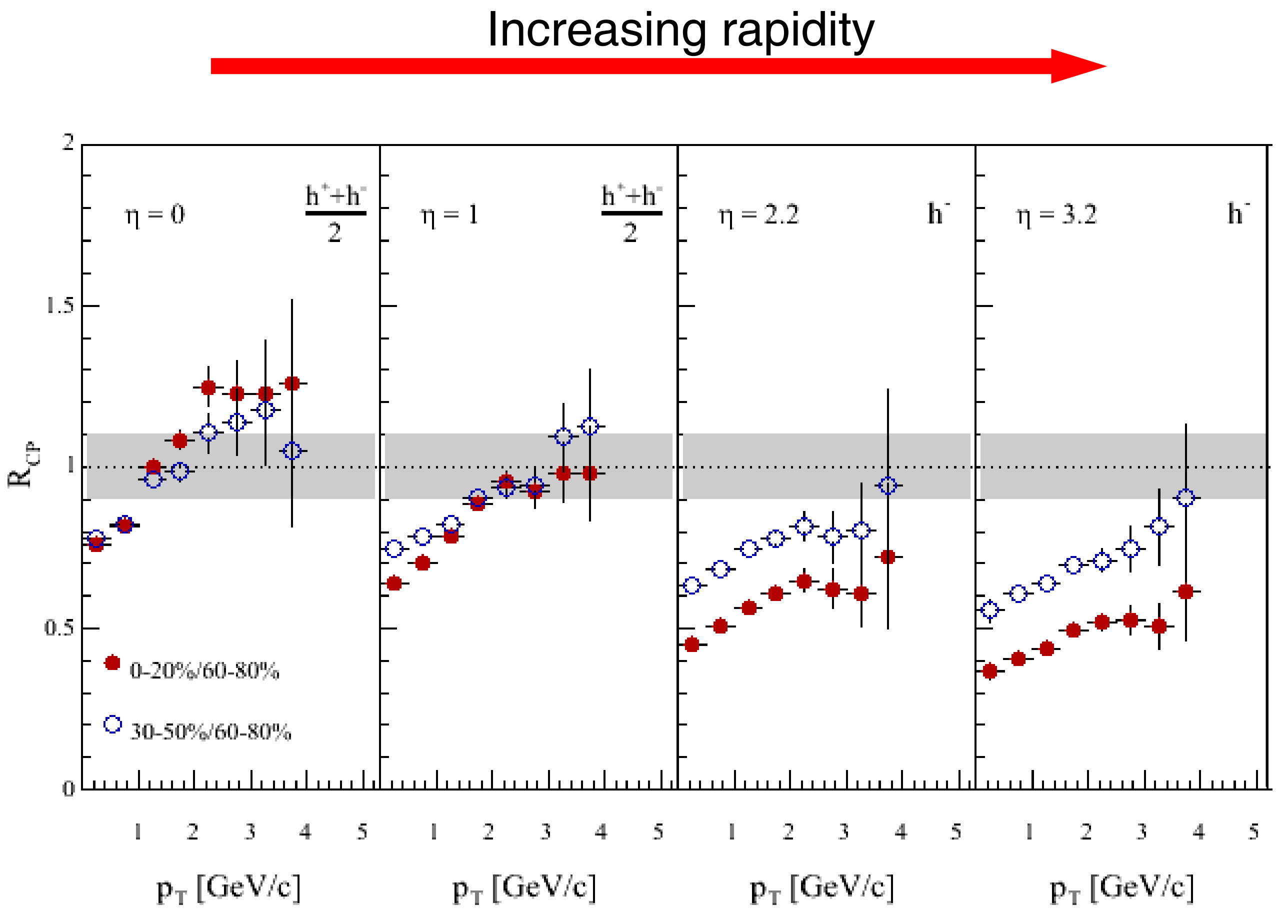




J. Adams et al., Phys. Rev. Lett. 91, 072304 (2003).

Forward particle production from BRAHMS

- **Higher rapidity probes lower x**



Outlook

- **Use hard probes to study the quark-gluon plasma**
  - Back-to-back jets (leading hadron correlations).

    Detailed study of jet-quenching.
  - Gamma+jet (quark-gluon compton processes: $g+q \rightarrow q+\gamma$).

    Use gamma to measure jet E_T.
  - Flavour tagged jets.

    Test prediction that heavy quarks are less quenched.
  - Quarkonium ($c\bar{c}$) and ($b\bar{b}$).

    Measure the initial energy density (Debye screening).
  - Direct (thermal) photons.

    Direct measure of plasma temperature?
- **Colour Glass Condensate links RHIC to HERA**
  - Explore forward region for evidence of gluon saturation in p(d)+Au.

    Perhaps more relevant for the LHC than RHIC.