A new look at heavy ion collisions: preparing for the LHC

Carlos A. Salgado
Universitá di Roma "La Sapienza"

carlos.salgado@cern.ch http://csalgado.web.cern.ch/

Fundamental Interactions

Searches – Higgs, SUSY, extra-dimensions...

pp @ LHC, LC??

Increase energy density

Fundamental Interactions

Searches – Higgs, SUSY, extra-dimensions...

pp @ LHC, LC??

Increase energy density

Increase <u>extended</u> energy density

AA @ RHIC and LHC

Collective properties
of the fundamental interactions

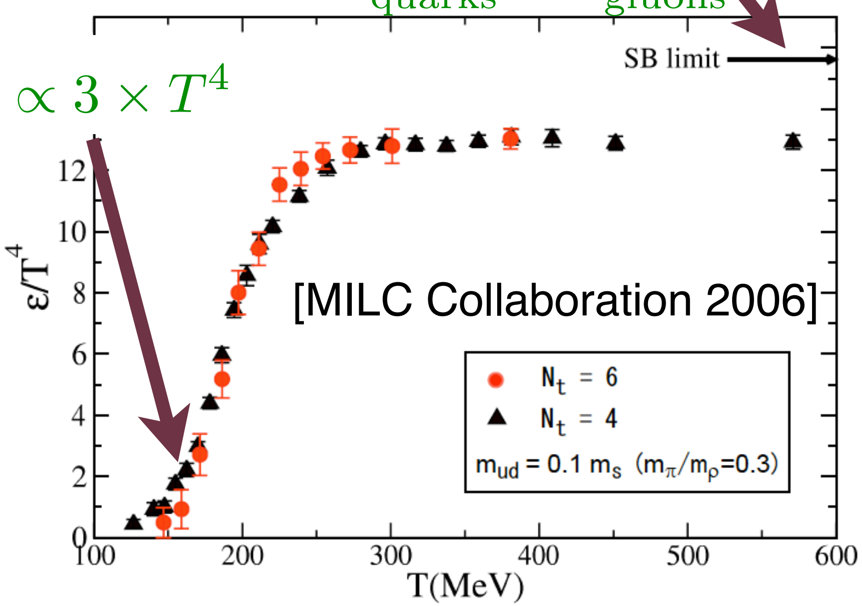
QCD has a rich dynamical structure

- ⇛ Two broken symmetries in the QCD vacuum
  - confinement
  - chiral symmetry is broken
- ⇛ Restored at high-temperatures ⟵ asymptotic freedom

Equation of state

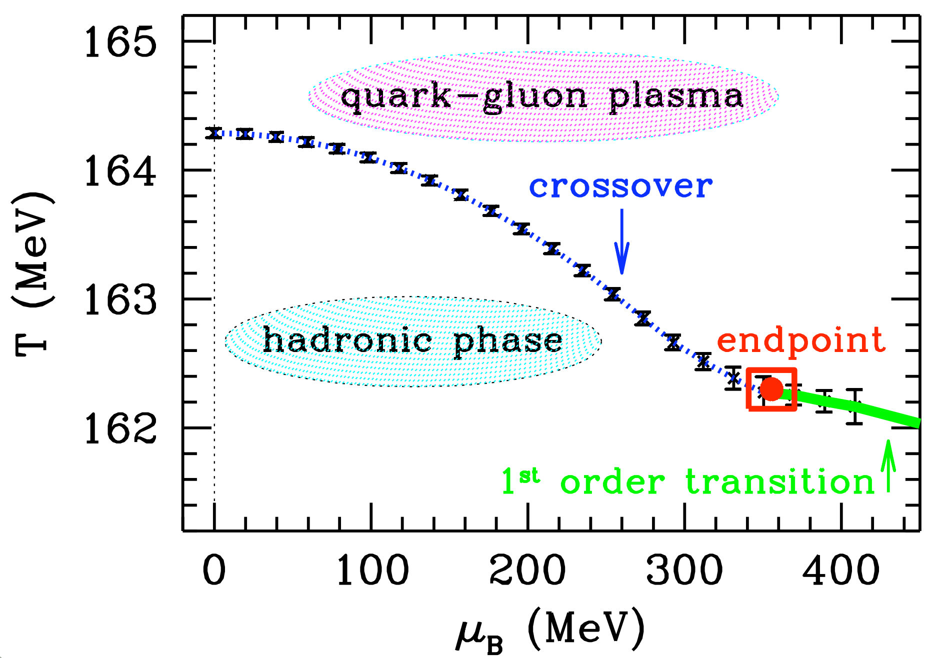
$$P_{QGP} \propto (\underbrace{2\times 2\times 3}_{\text{quarks}} + \underbrace{2\times 8}_{\text{gluons}}) \times T^4$$

$$P_\pi \propto 3 \times T^4$$



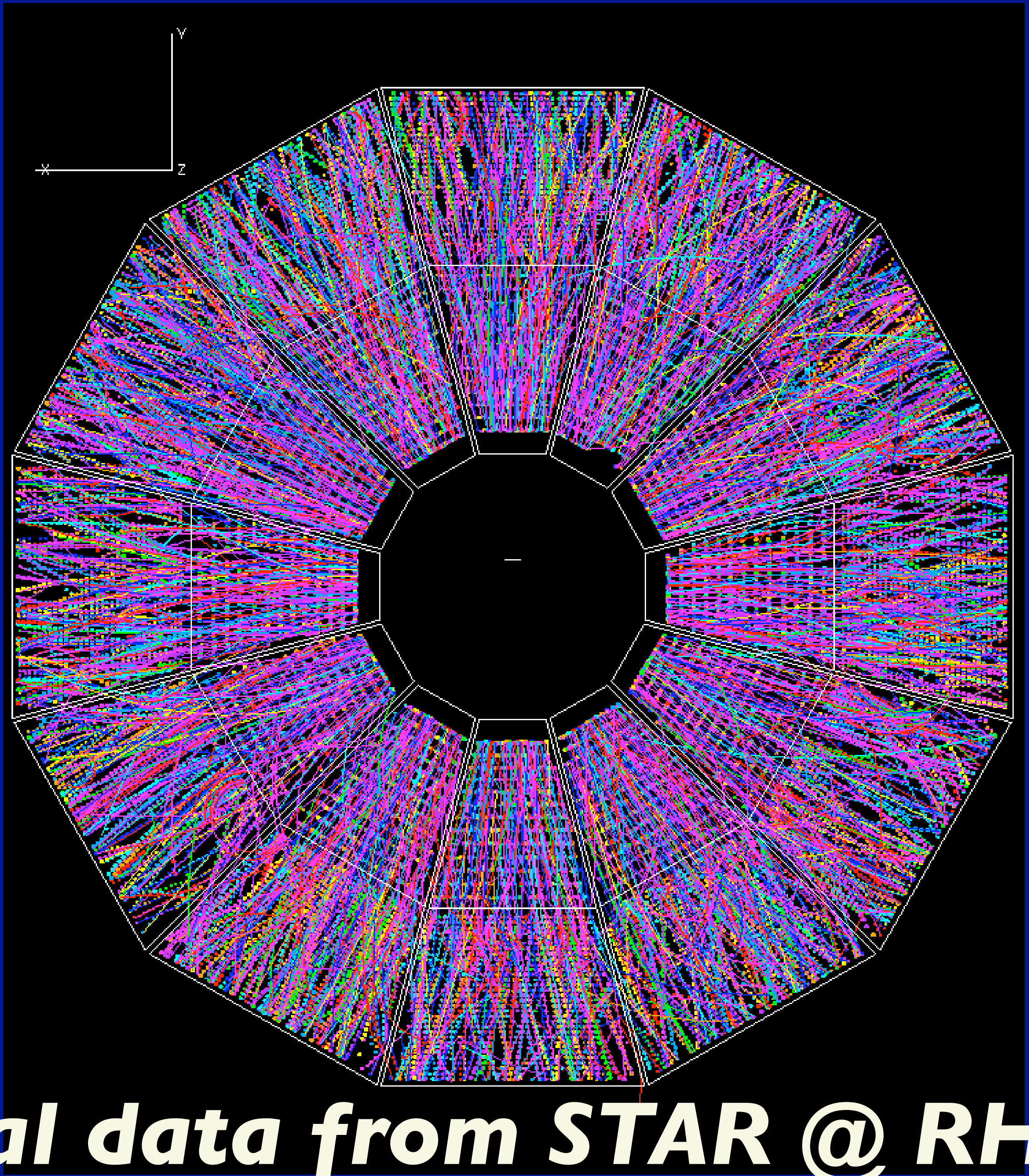
Phase diagram

[Fodor, et al. 2004]



Where?

- SPS at CERN.
  - Have collided pA at $p_{\rm lab} = 450$ GeV/c, SU at $p_{\rm lab} = 200$ AGeV/c and PbPb at $p_{\rm lab} = 158$ AGeV/c.
  - The program is almost finished now
- RHIC at BNL
  - pp, dAu, AuAu and CuCu at $\sqrt{s} = 20 \dots 200$ AGeV
  - RHIC II will improve detectors for rare processes and enhance statistics
- LHC at CERN
  - Will collide PbPb at $\sqrt{s} = 5500$ AGeV also pPb or dPb (under discussion) at $\sqrt{s} = 8200$
  - ALICE is a dedicated HI experiment
  - CMS and ATLAS have own programs of heavy ion collisions



real data from STAR @ RHIC

What do we expect to learn?

<u>Specific questions in heavy-ion collisions</u>

- ⇒ What is the initial state of the system and how is it produced?
  - What is the structure of the colliding objects?
  - What is the asymptotic limit of QCD?
- ⇒ What is the mechanism of thermalization?
  - How is thermal equilibrium reached?
  - What is the temperature of the created system?
- ⇒ What are the properties of the produced medium?
  - How to measured them? – signals
  - What is the relation with lattice QCD?

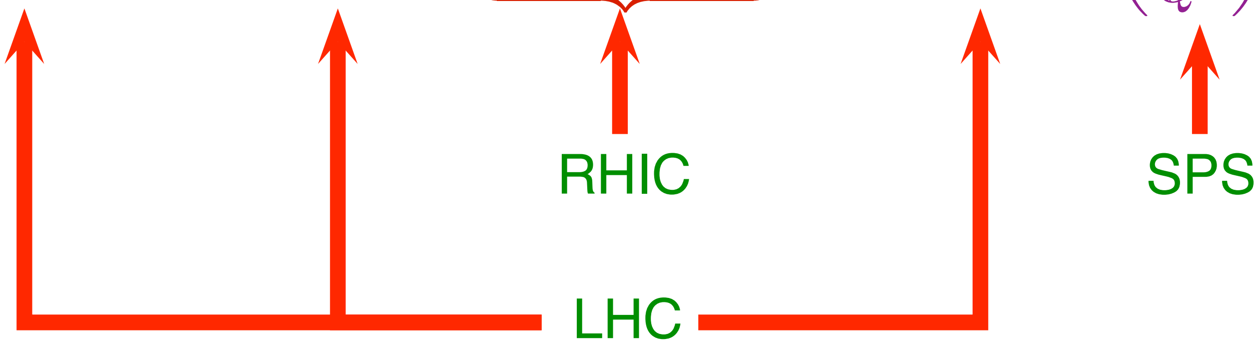
Hard probes

Provide a general framework to address these questions

Hard probes in heavy-ion collisions

- SPS $\sqrt{s}=20$ GeV ($Q\sim 1$ GeV) $\longrightarrow$ marginal access to HP
- RHIC $\sqrt{s}=200$ GeV ($Q\sim 10$ GeV) $\longrightarrow$ access to HP
- LHC $\sqrt{s}=5500$ GeV ($Q\gtrsim 100$ GeV) $\longrightarrow$ HP and QCD evolution

$$\sigma^{pp\to h}=f_p(x_1,Q^2)\otimes f_p(x_2,Q^2)\otimes \underbrace{\sigma(x_1,x_2,Q^2)}\otimes D(z,Q^2)+\left(\frac{1}{Q^2}\right)^n$$



- The extension of the medium modifies the long-distance terms
  - New evolution equations for $f_A(x,Q^2);D(z,Q^2)$
- Kinematical access to evolution: large-Q^2, small-x $\longrightarrow$ LHC

Experimental strategy

- ⇛ Simple collisions fix no-medium benchmark
  - lepton-proton DIS, e^+e^-, proton-proton
- ⇛ Fix cold-nuclear matter benchmark
  - lepton-nucleus DIS, proton-nucleus
- ⇛ Nucleus-Nucleus to create hot-matter
  - Change geometry of the medium - centrality

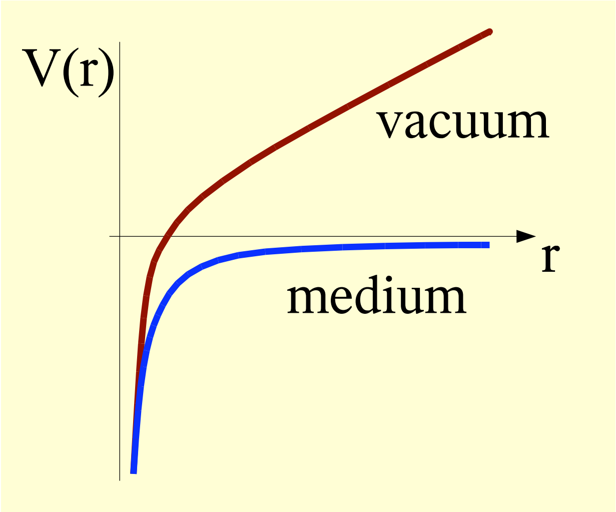
- ⇛ Probes of the medium (ideally)
  - Easy to measure and well calibrated
  - Theoretical control on the dynamical process
  - Theoretical control on the relation with a medium property

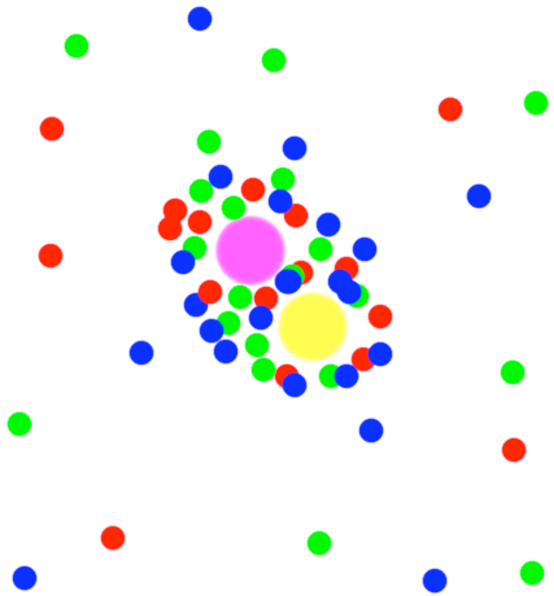
A ‘simple’ example, J/Ψ suppression

- A J/Ψ is a $c\bar{c}$ bound state.

$$\sigma^{hh\to J/\Psi} = f_i(x_1,Q^2)\otimes f_j(x_2,Q^2)\otimes\sigma^{ij\to[c\bar{c}]}(x_1,x_2,Q^2)\langle\mathcal{O}([c\bar{c}]\to J/\Psi)\rangle$$

- The potential is screened by the medium
  - The long-distance part is modified $\langle\mathcal{O}([c\bar{c}]\to J/\Psi)\rangle \to 0$
- The J/Ψ production is suppressed [Matsui, Satz 1986]



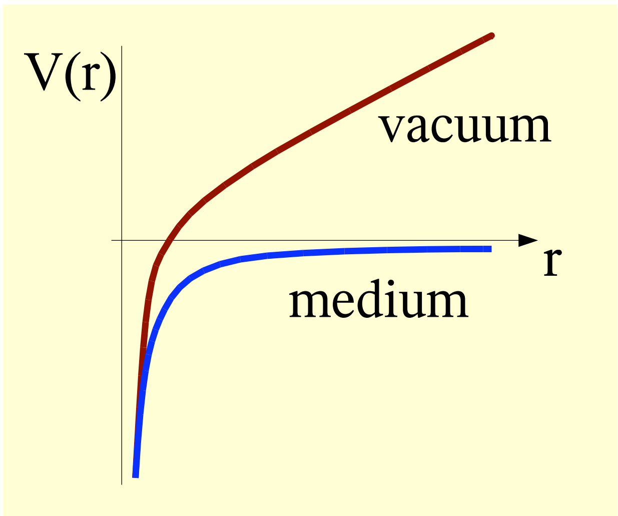


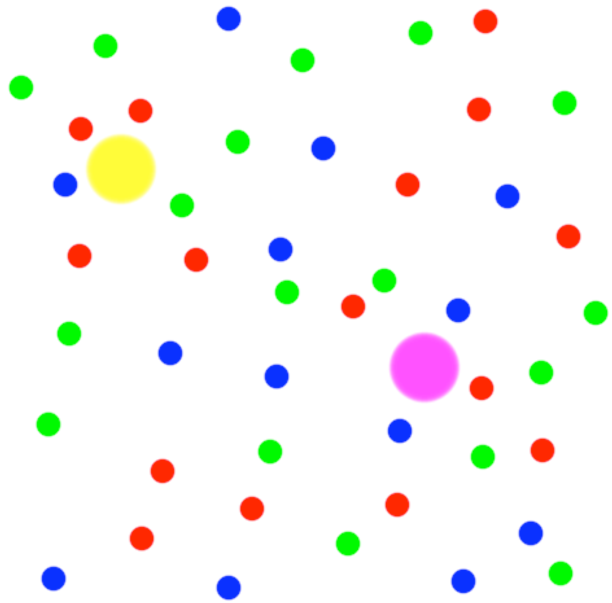
A 'simple' example, J/Ψ suppression

- A J/Ψ is a $c\bar{c}$ bound state.

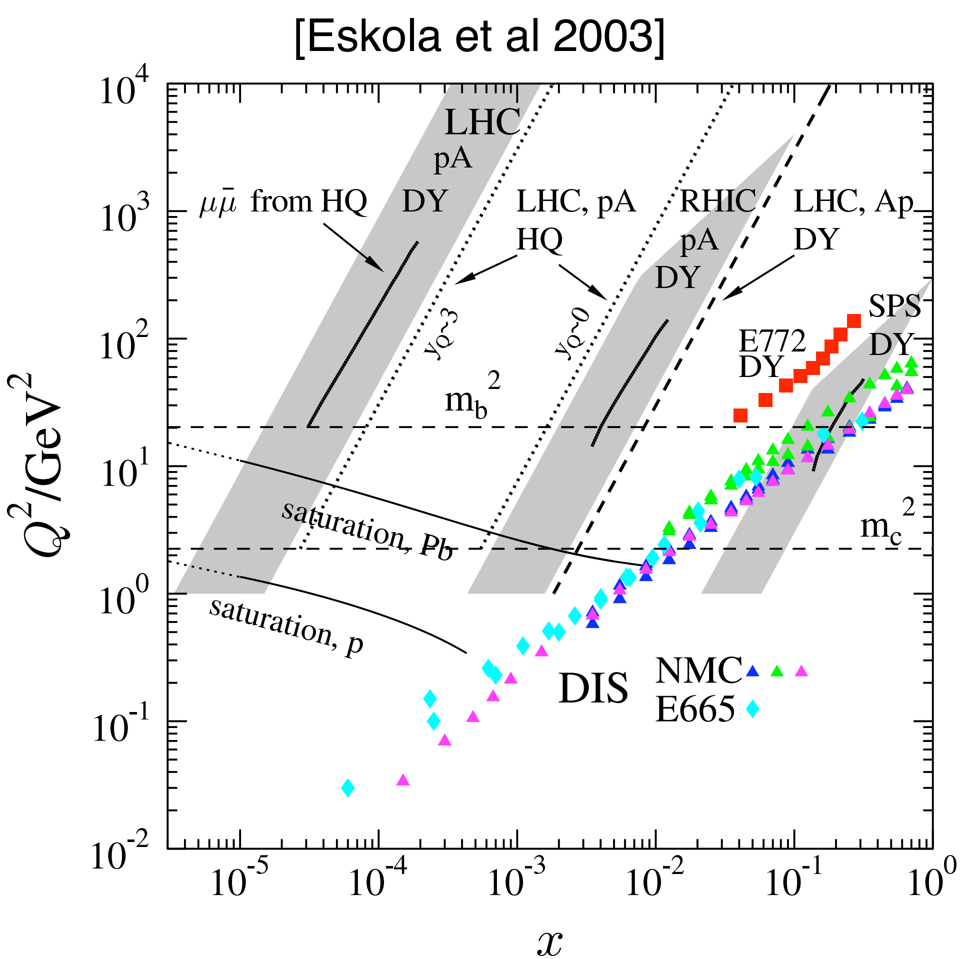
$$\sigma^{hh\to J/\Psi} = f_i(x_1,Q^2)\otimes f_j(x_2,Q^2)\otimes\sigma^{ij\to[c\bar{c}]}(x_1,x_2,Q^2)\langle\mathcal{O}([c\bar{c}]\to J/\Psi)\rangle$$

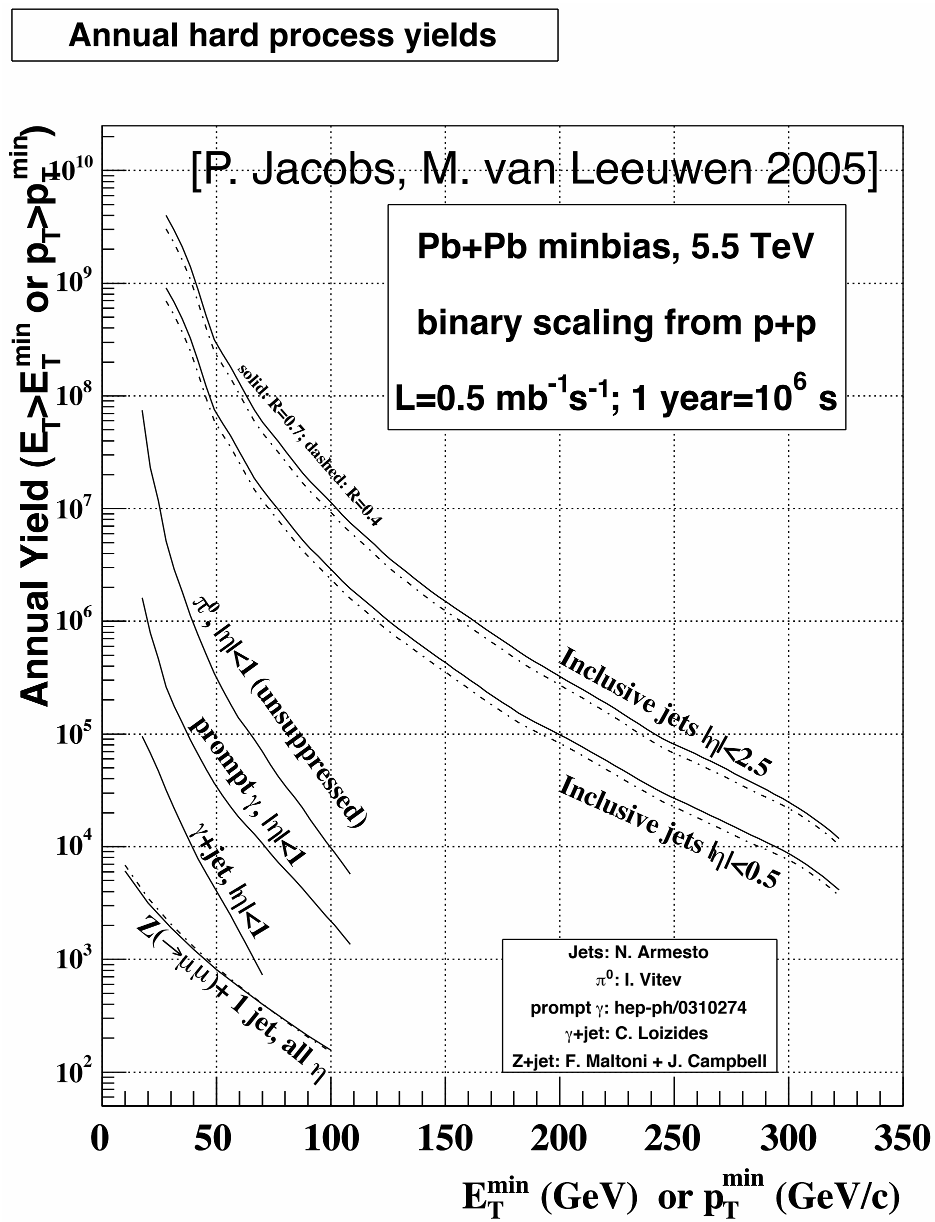
- The potential is screened by the medium
  - The long-distance part is modified $\langle\mathcal{O}([c\bar{c}]\to J/\Psi)\rangle\to 0$
- The J/Ψ production is suppressed [Matsui, Satz 1986]



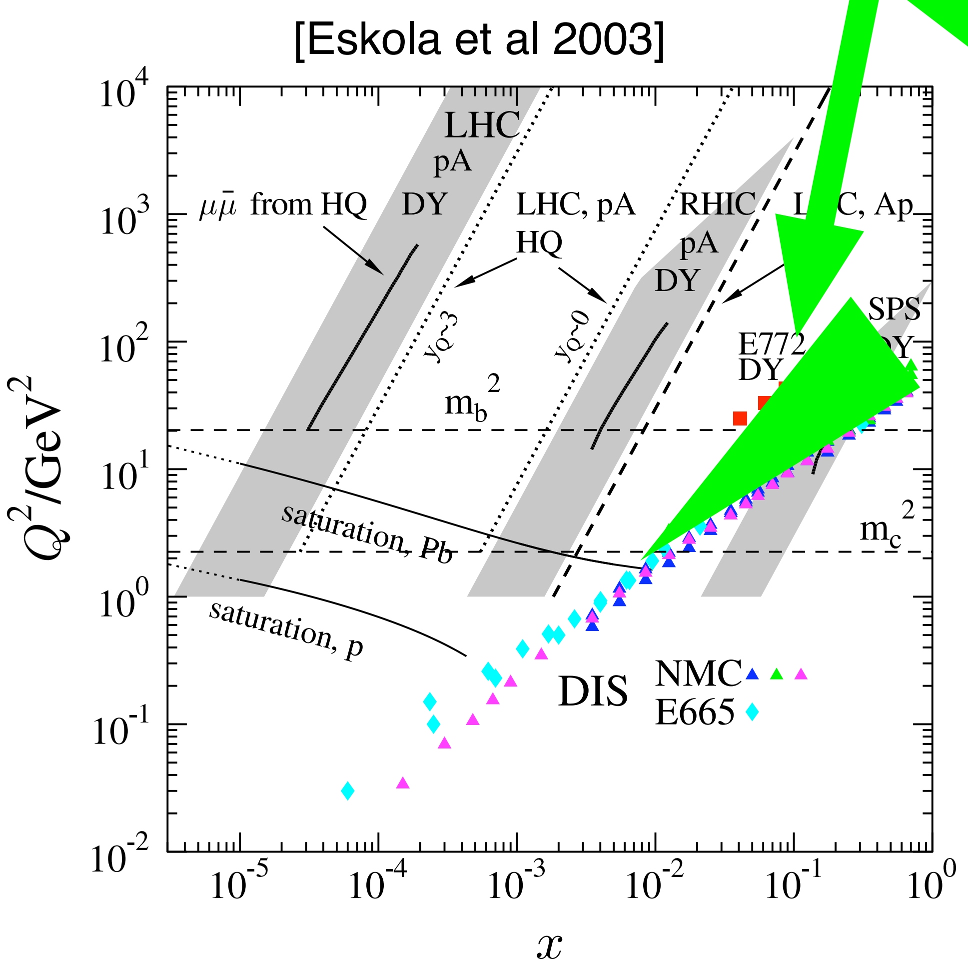


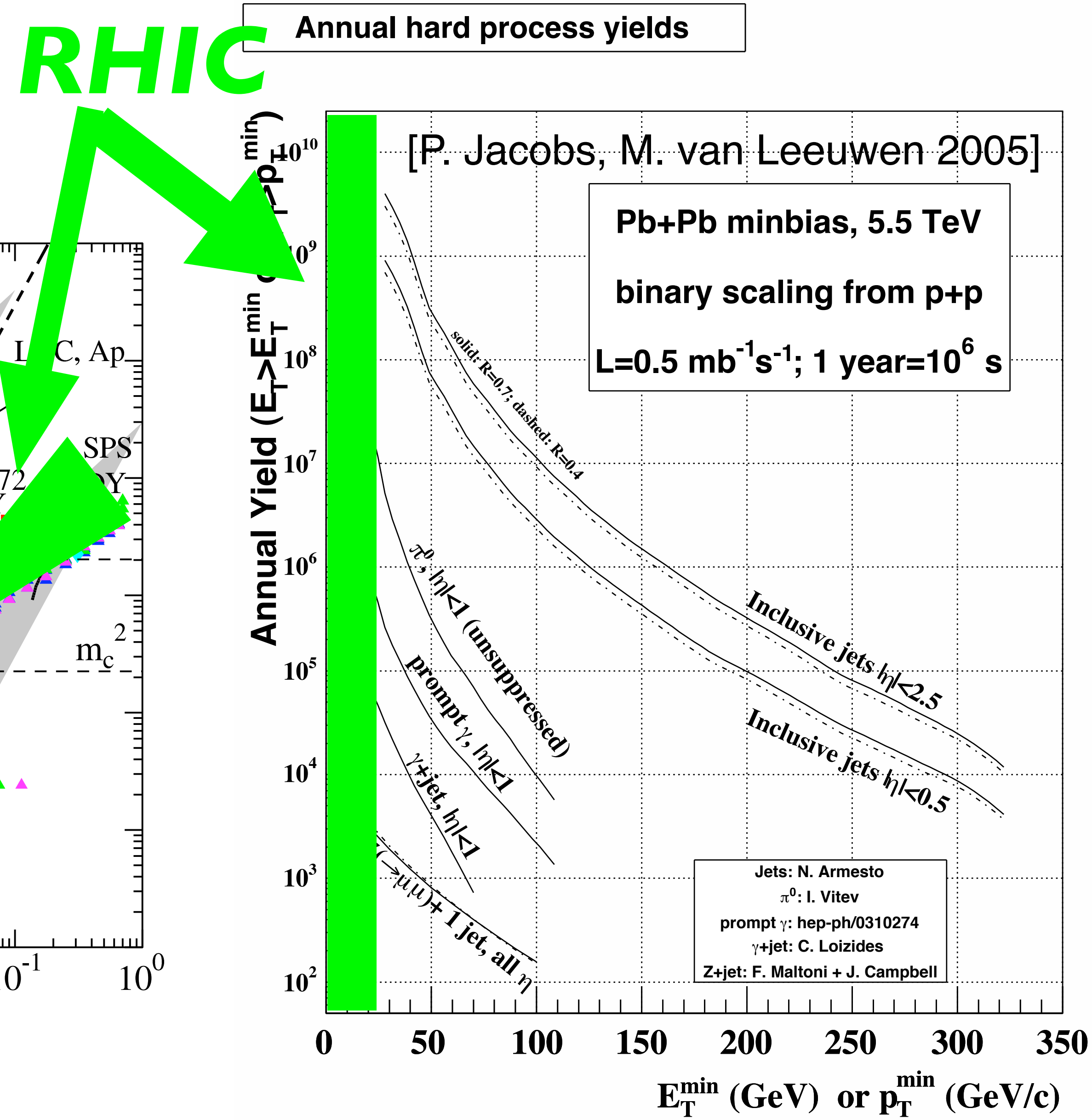
New regimes at the LHC



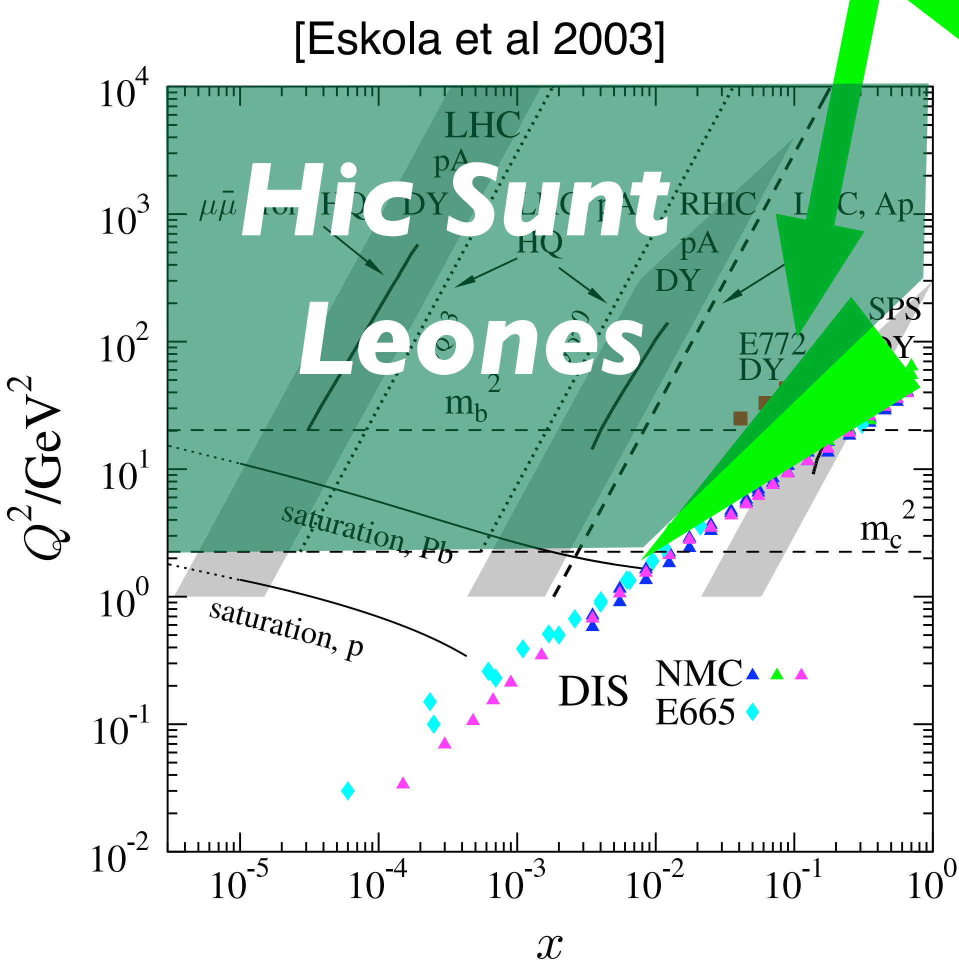


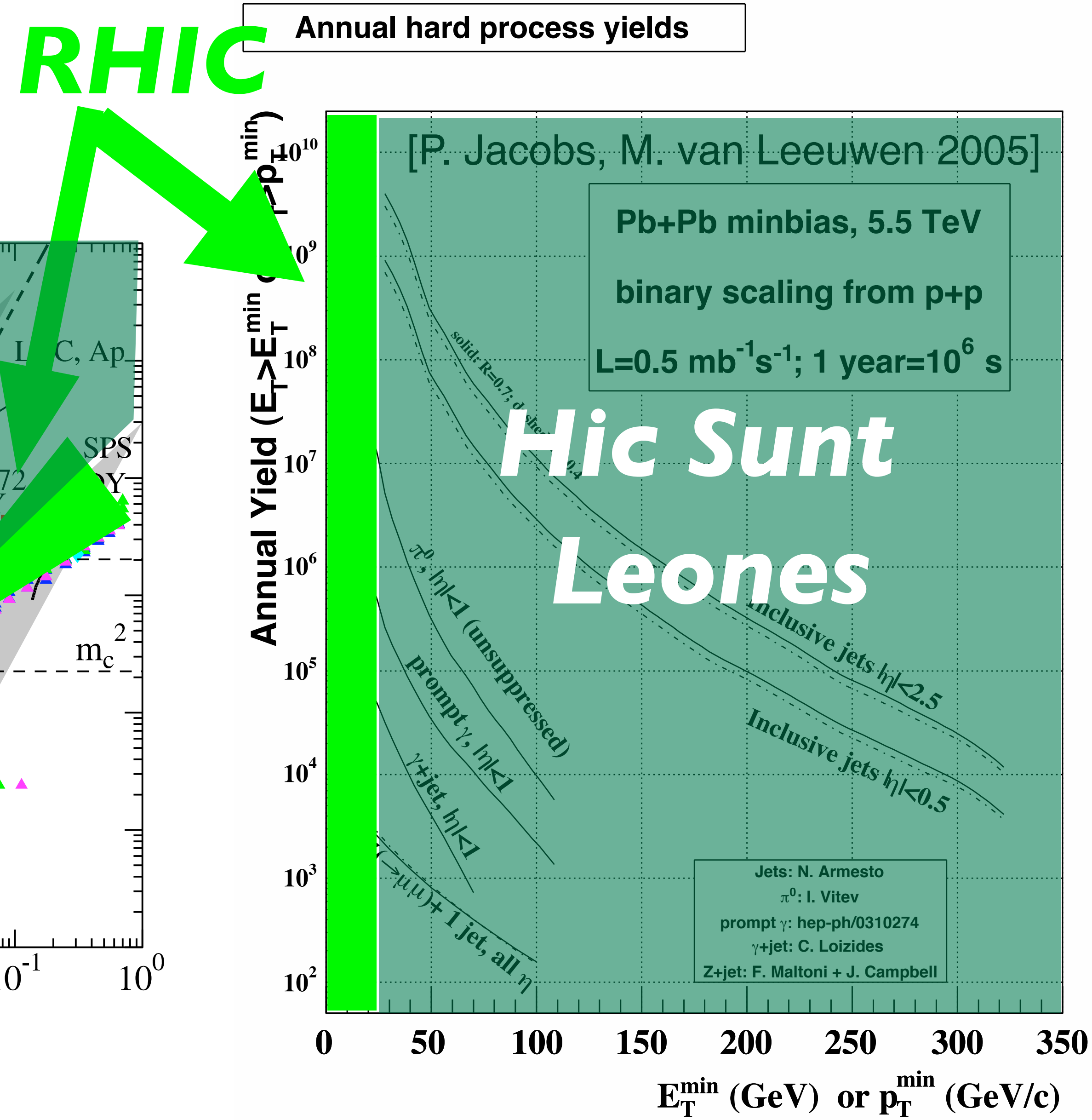
New regimes at the LHC



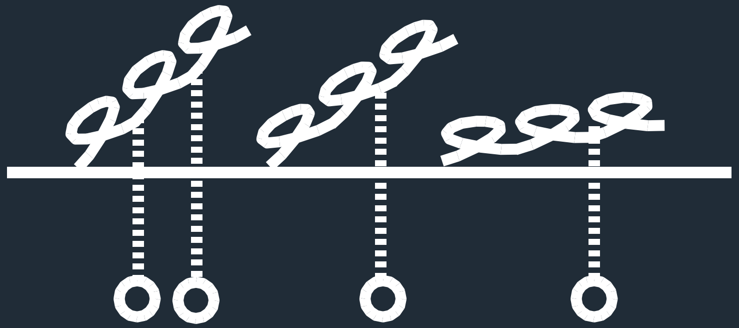


New regimes at the LHC



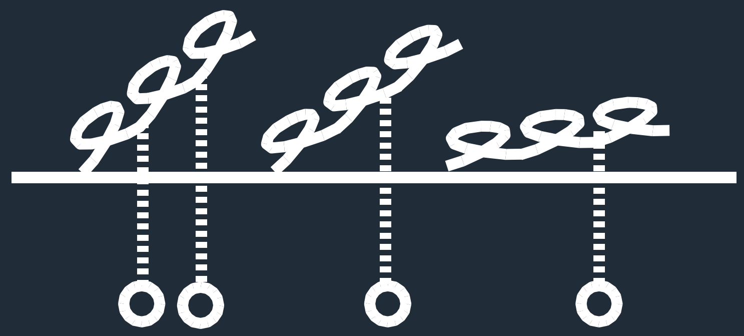


QCD at high densities



- *Modification of the PDFs*
- *Modification of the jet evolution*

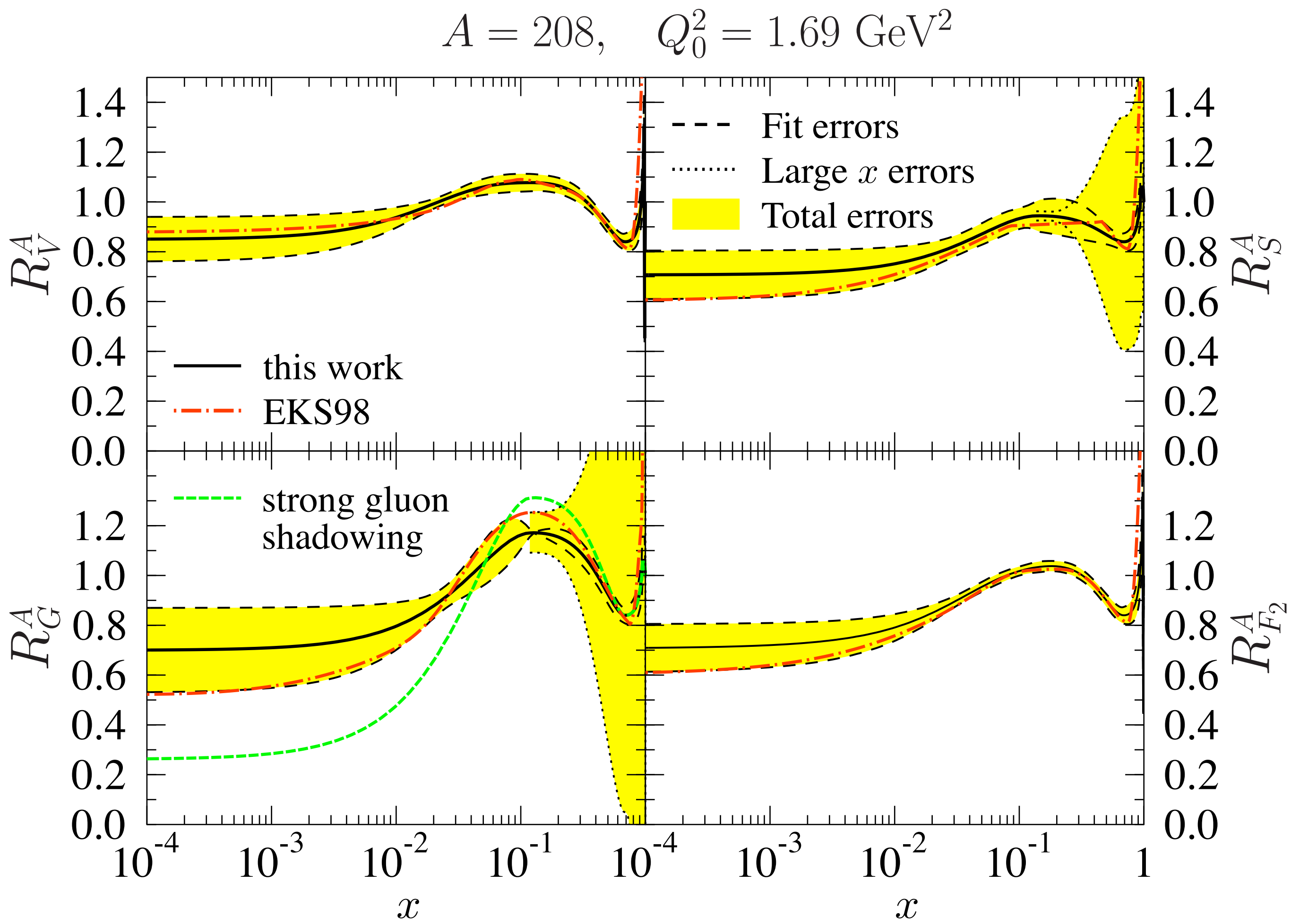
QCD at high densities



- *Modification of the PDFs*
- *Modification of the jet evolution*

Nuclear PDFs: uncertainties

PDFs determined by a global (linear) DGLAP fit



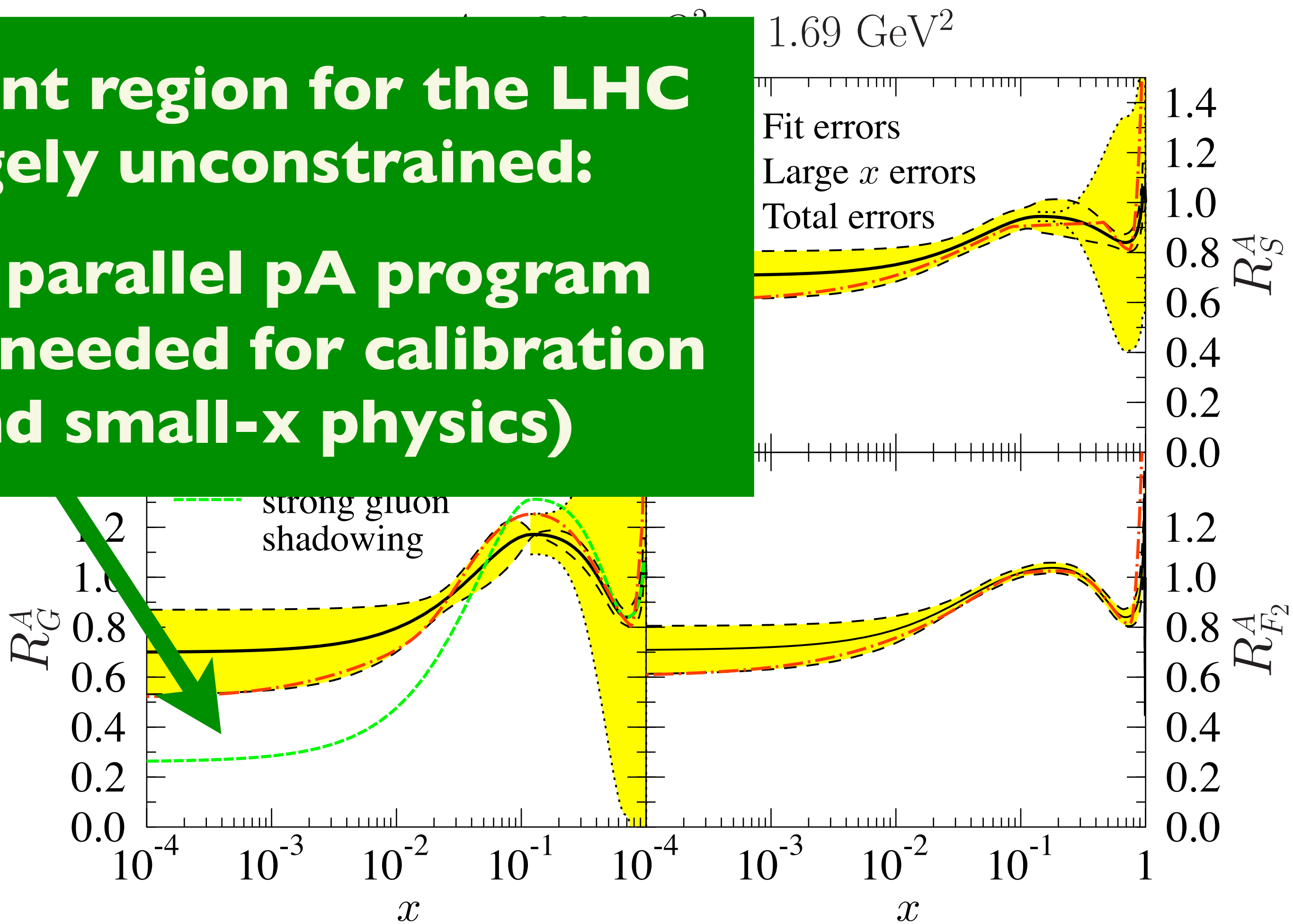
[Eskola, Kolhinen, Paukkunen, Salgado 2007]

Nuclear PDFs: uncertainties

PDFs determined by a global (linear) DGLAP fit

Relevant region for the LHC largely unconstrained:

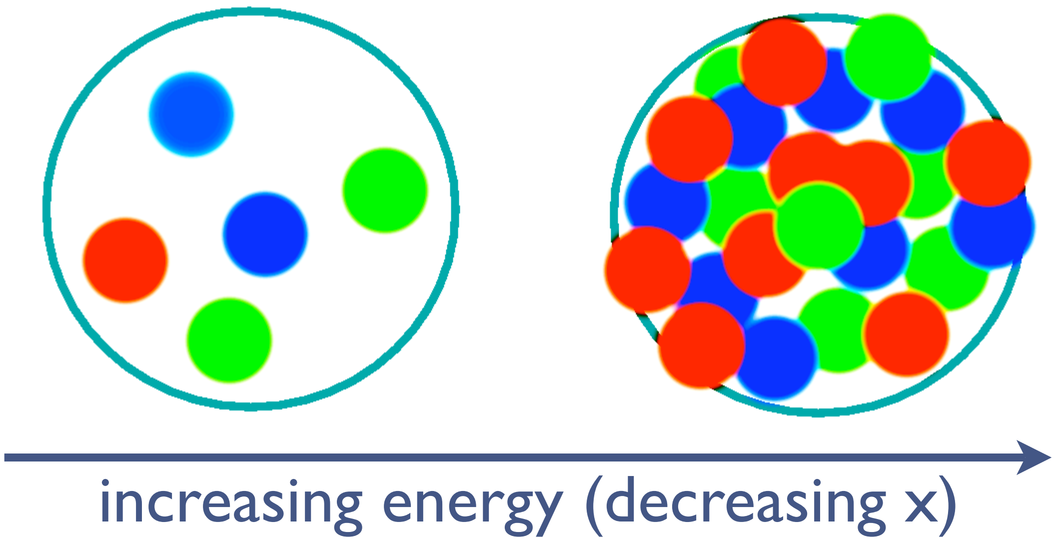
$\longrightarrow$ a parallel pA program will be needed for calibration (and small-x physics)



[Eskola, Kolhinen, Paukkunen, Salgado 2007]

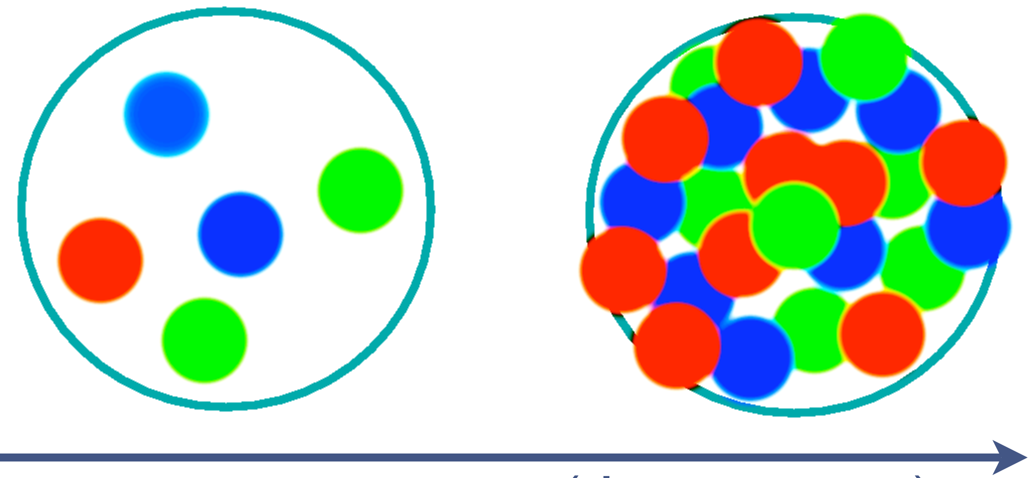
Saturation of partonic densities: picture

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



Saturation of partonic densities: picture

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



increasing energy (decreasing x)

transverse area of the gluon

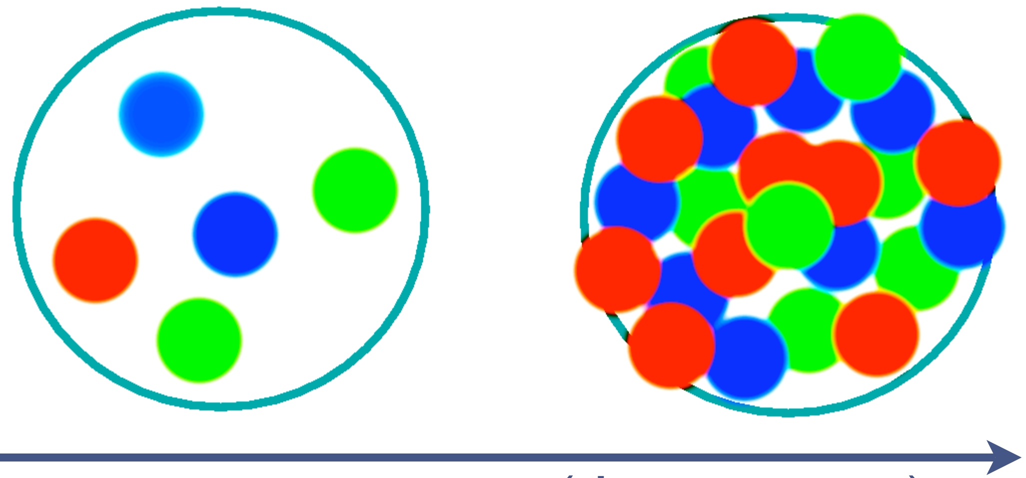
$$\alpha_s \frac{1}{Q_{\rm sat}^2} A N_g(x, Q_{\rm sat}^2) \sim \pi R_A^2$$

transverse area of the nucleus

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

Saturation of partonic densities: picture

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



increasing energy (decreasing x)

transverse area of the gluon

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

transverse area of the nucleus

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

⇛ Strong fields and large occupation numbers

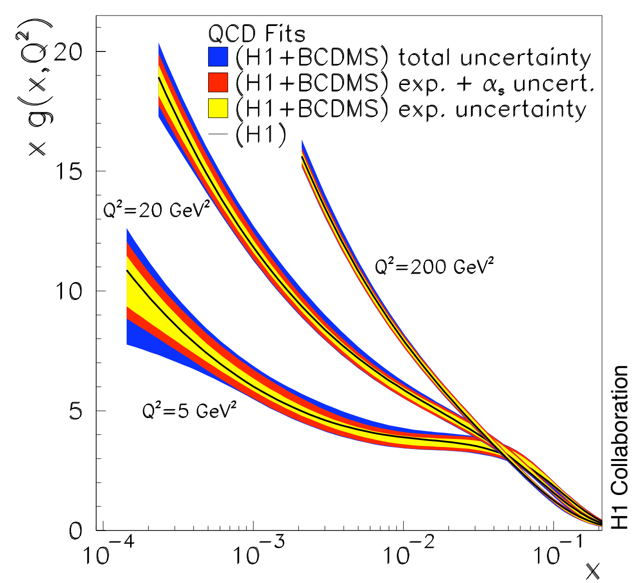
⇛ Semiclassical approach possible:

Color Glass Condensate

⇛ Weak coupling $\alpha_S(Q_{\rm sat}^2)$, $Q_{\rm sat} \gg \Lambda_{\rm QCD}$

⇛ New ev. equations B-JIMWLK, Kovchegov

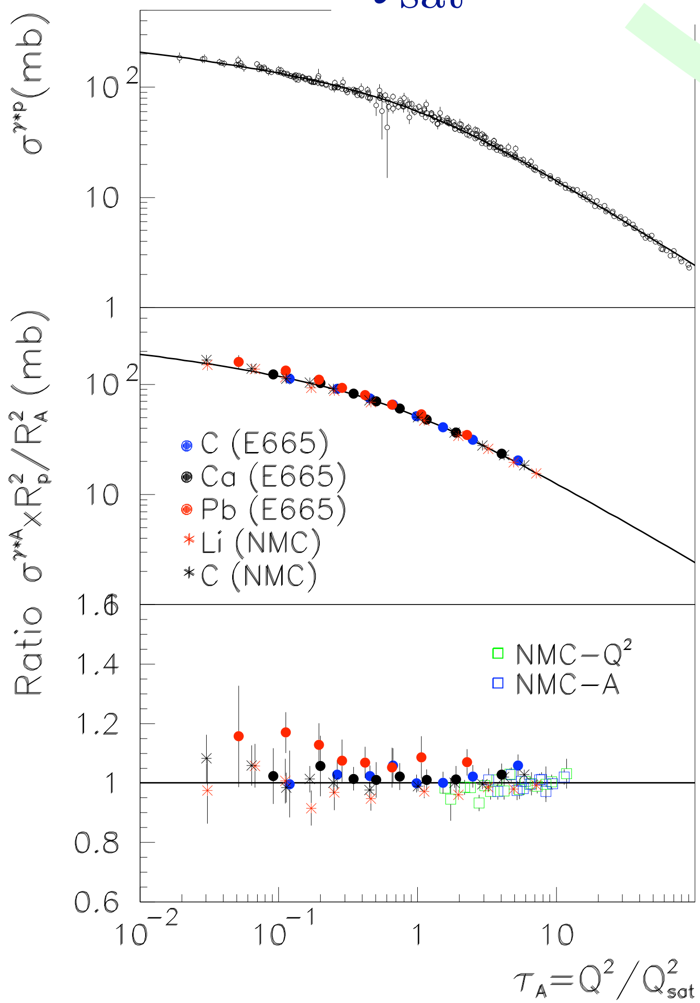
↘ Geometric scaling



Geometric scaling and data

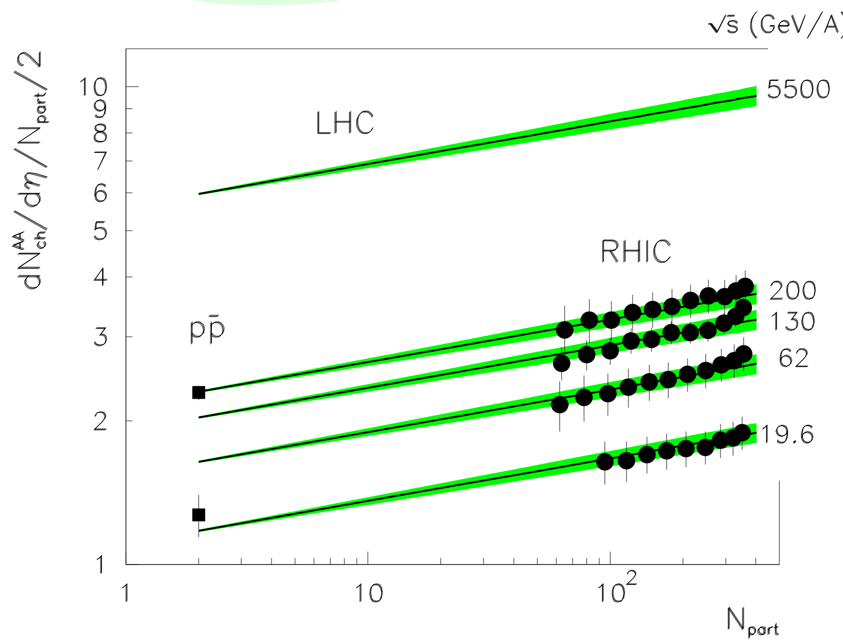
$$Q^2_{\rm sat} \propto x^{-\lambda} A^{1/3\delta}$$

$$\frac{1}{N_{\rm part}} \frac{dN^{AA}}{d\eta}\bigg|_{\eta\sim 0} = N_0 \sqrt{s}^{\lambda} N_{\rm part}^{\frac{1-\delta}{3\delta}}$$



Stasto, Golec-Biernat, Kwiecinski 2001

Armesto, Salgado, Wiedemann 2004



Kharzeev, Levin, McLerran, Nardi 2000...

Armesto, Salgado, Wiedemann 2004

Saturation and data

- Main properties of the CGC compatible with experimental data
  - saturation scale
  - scaling solution
  - suppression at forward rapidity (small-x)
- Accident??

++ Provides a general framework

- Initial conditions for the dense medium $\longrightarrow$ strong fields
- Fast thermalization? $\tau_0 \sim \frac{1}{Q_{\rm sat}} \sim$ 0.2 fm at RHIC
  - Strong fields $\Longrightarrow$ Unruh (thermal) radiation [Kharzeev and Tuchin (2005)]
- Other approaches predict slower thermalization times:
  - bottom-up thermalization [Baier, Mueller, Schiff and Son (2001)]
  - Plasma instabilities [Mrowczynski 1994; Arnold, Lenaghan, Moore 2003; Romatschke, Strickland 2003; Manuel, Mrowczynski 2005...]

The soft bulk

Checks of hydrodynamical evolution (thermalization)

Hydrodynamics and hadronic collisions

Landau (1953) applies hydrodynamics to hadronic collisions.

<u>Assumptions</u>

⇛ Large amount of the energy deposited in a short time in a small region of space (little fireball) with the size of a Lorentz-contracted nucleus

⇛ Created matter is treated as a relativistic (classical) ideal fluid

Equation of state $P = \epsilon/3$

⇛ The hydrodynamical flow stops when the mean free path becomes of the order of the size of the system: freeze out

⇛ Normally, the condition is $T \sim m_\pi$

⇛ Bjorken in the 80's proposes a boost-invariant version

More on hydrodynamics

⇛ Equations of motion of a relativistic fluid

$$\partial_\mu T^{\mu\nu} = 0$$

⇛ Where, the energy-momentum tensor for an ideal fluid is

$$T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu - p g^{\mu\nu}$$

here ϵ is the energy density, p the pressure and u^μ the flow velocity

⇛ The system is closed with an equation of state, ex. $P = \epsilon/3$

⇛ The initial conditions need to be fixed → e.g. by the CGC

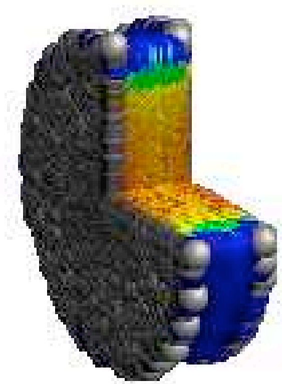
Hydrodynamics is one of the most active field of research in HIC

Main goal: check the degree of thermalization of the system

PbPb @ the LHC in hydro

Evolution of the temperature with time

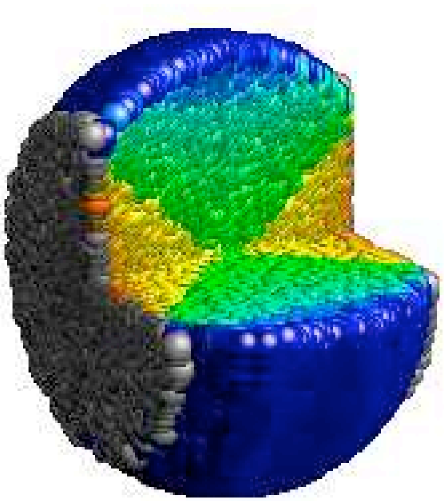
[simulations by V. Ruuskanen and H. Niemi]



time: 2.0000

Evolution of the temperature with time

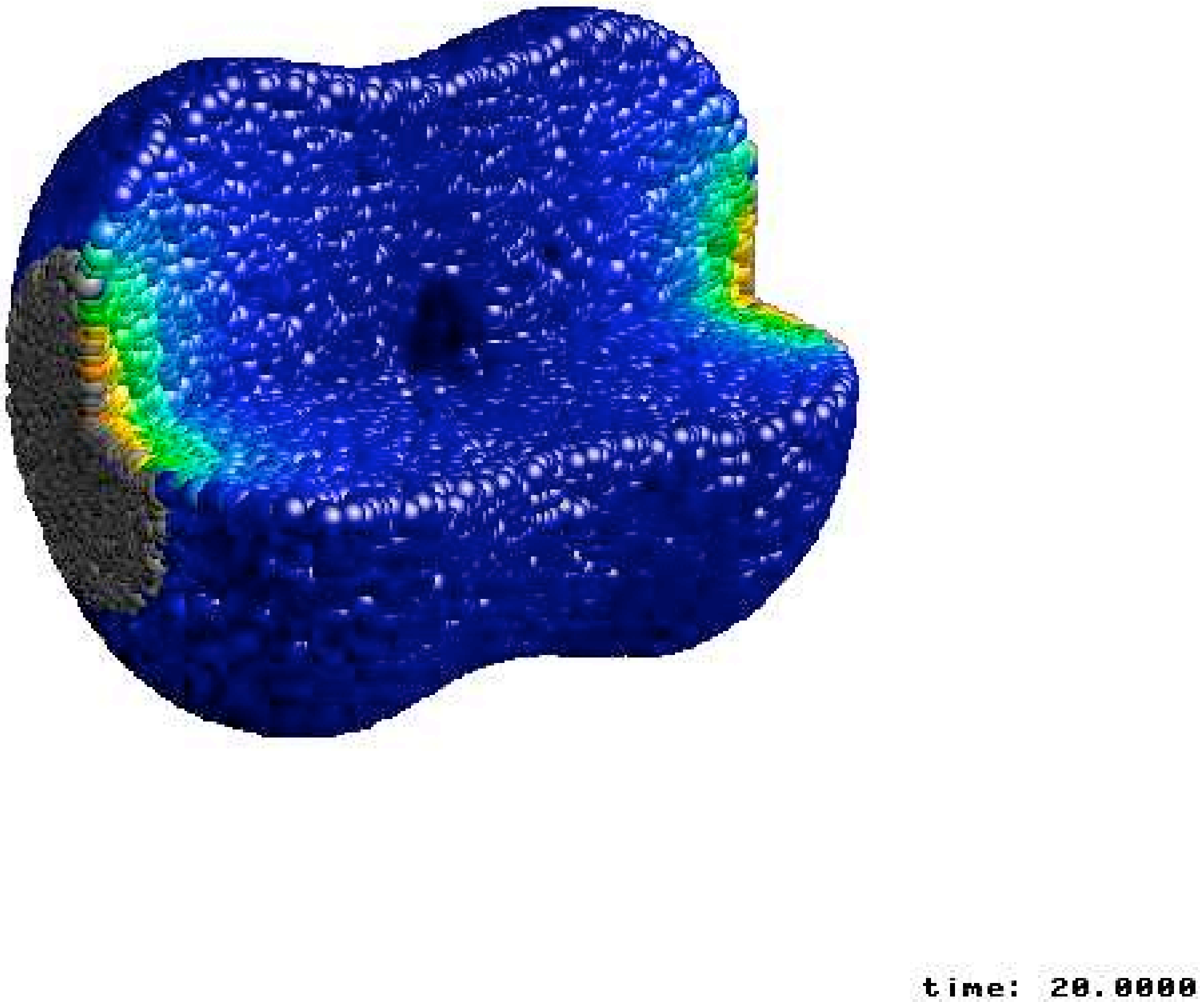
[simulations by V. Ruuskanen and H. Niemi]



PbPb @ the LHC in hydro

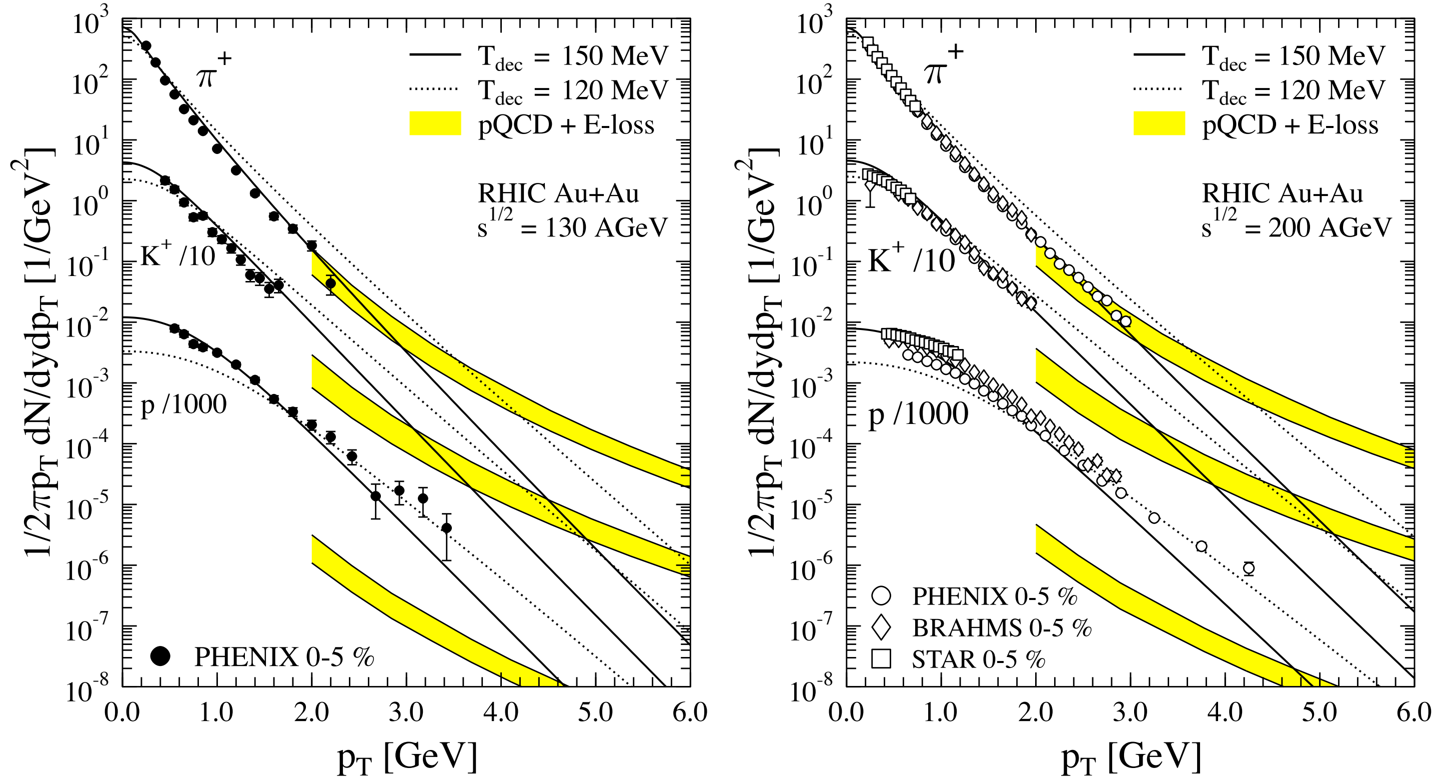
Evolution of the temperature with time

[simulations by V. Ruuskanen and H. Niemi]



Transverse-momentum spectra

Example of a hydrodynamical calculation in comparison with RHIC data



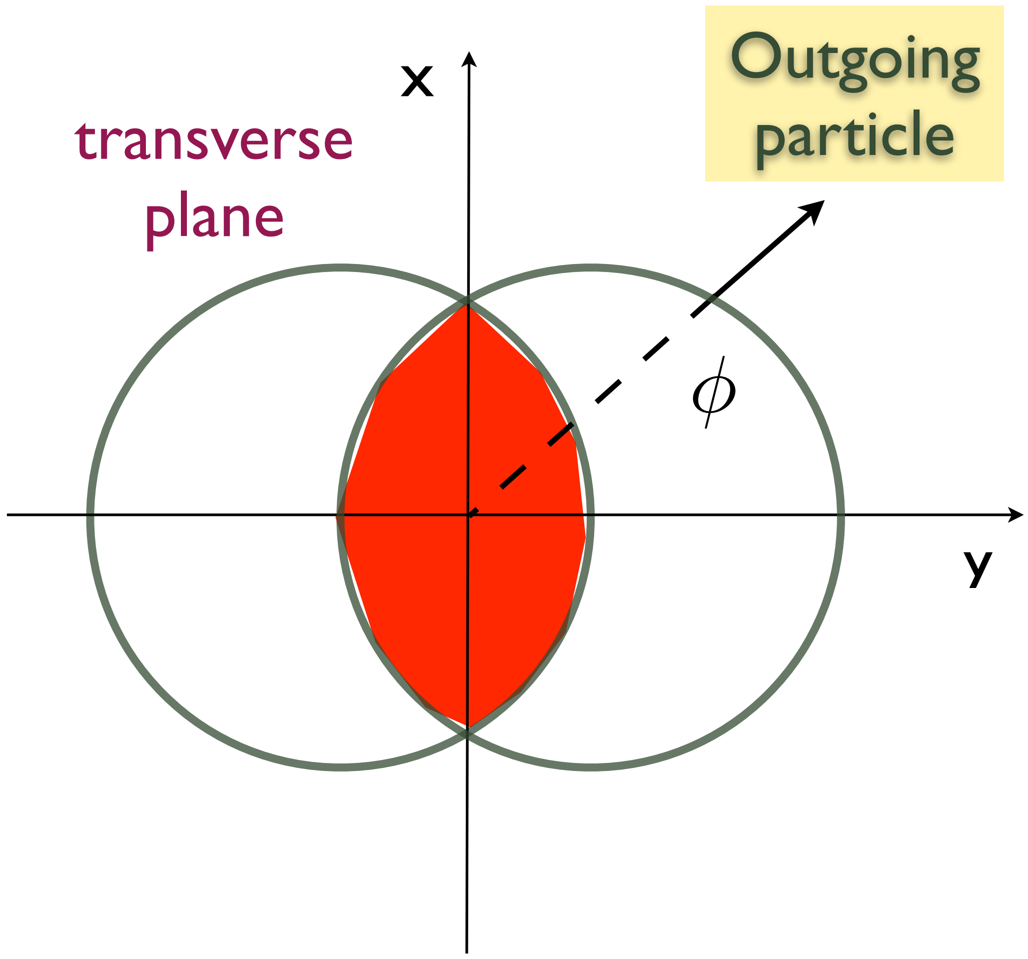
[Eskola et al 2006]

The essential measurement for hydro

Gradients are more easily produced (and studied) in asymmetric media, changing the centrality of the collision

⇛ Recall the Euler equation

$$\frac{d\beta}{dt} = -\frac{c^2}{\epsilon + P}\nabla P$$



The essential measurement for hydro

Gradients are more easily produced (and studied) in asymmetric media, changing the centrality of the collision

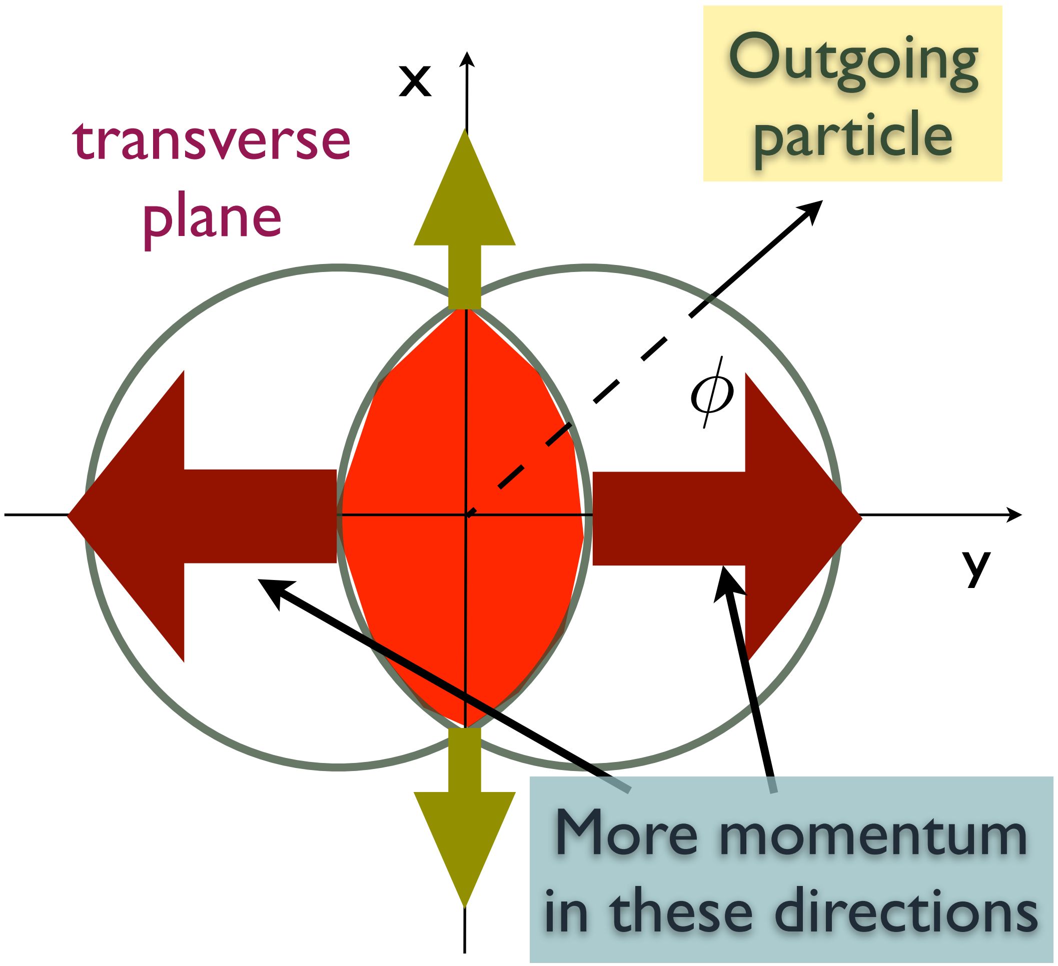
⇛ Recall the Euler equation

$$\frac{d\beta}{dt} = -\frac{c^2}{\epsilon + P}\nabla P$$

$$\epsilon = 3P \quad \Longrightarrow \quad \nabla_x P < \nabla_y P$$

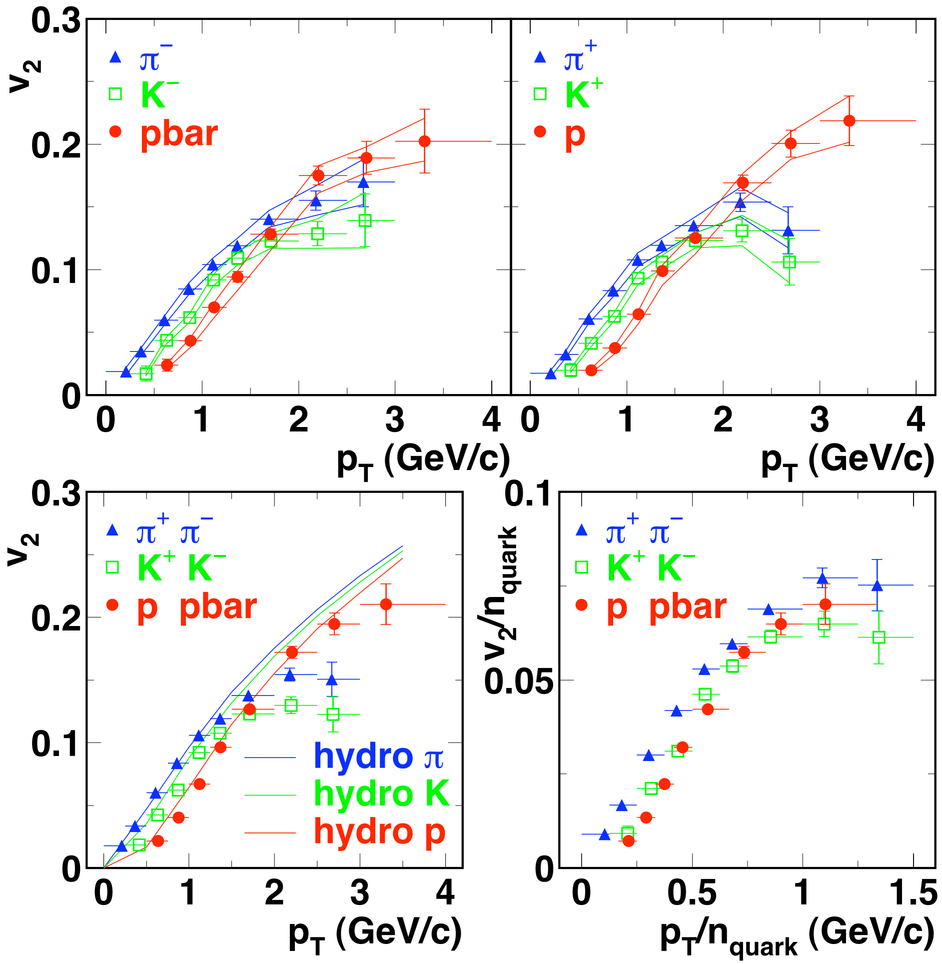
⇛ Elliptic flow normally measured by the second term in the Fourier expansion

$$\frac{dN}{d\phi} \propto 1 + 2\, v_2 \cos(2\phi)$$



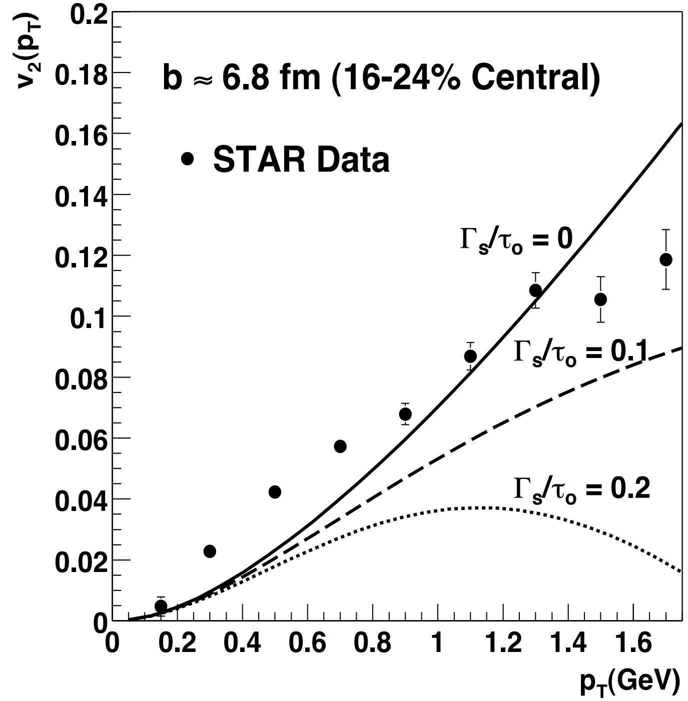
One of the first measurements at RHIC

Large momentum anisotropy compatible with ideal hydrodynamics



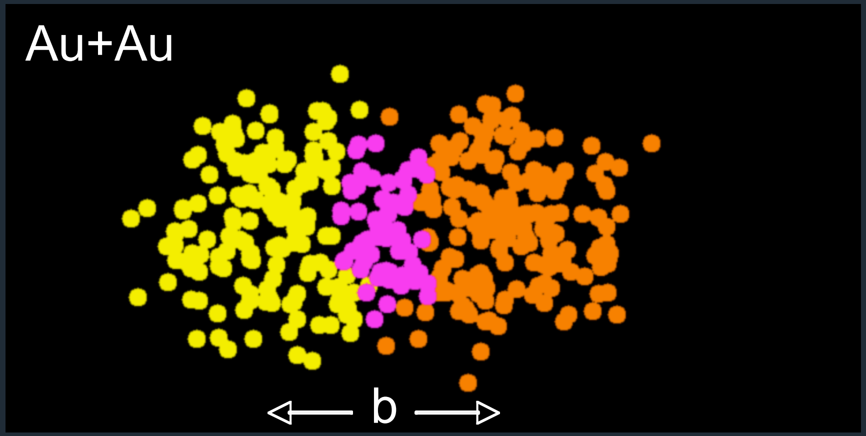
[data: STAR]

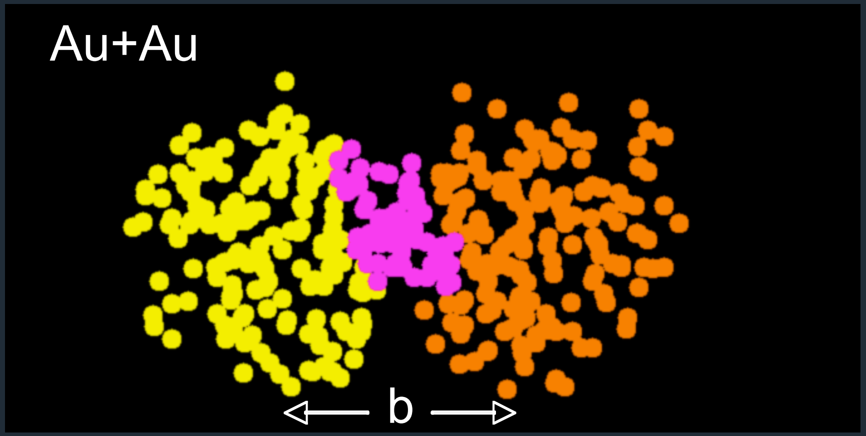
The effect of viscosity



[Teaney 2003]

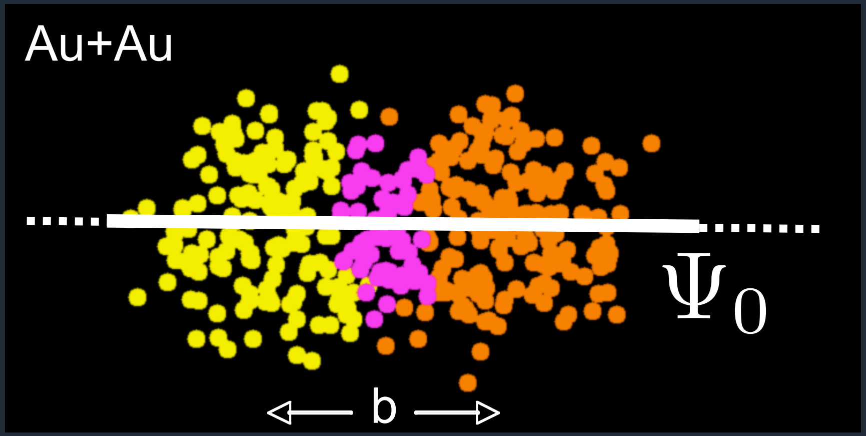
Geometry fluctuations → v_2 fluctuations

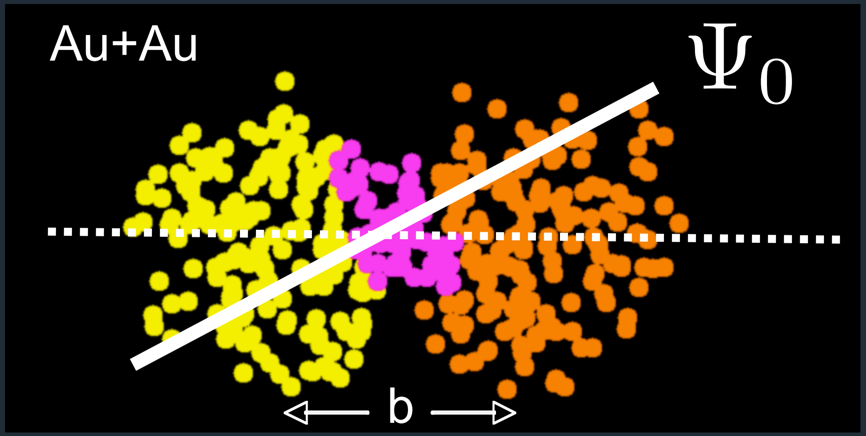




[David Hofman QM06]

Geometry fluctuations → v_2 fluctuations

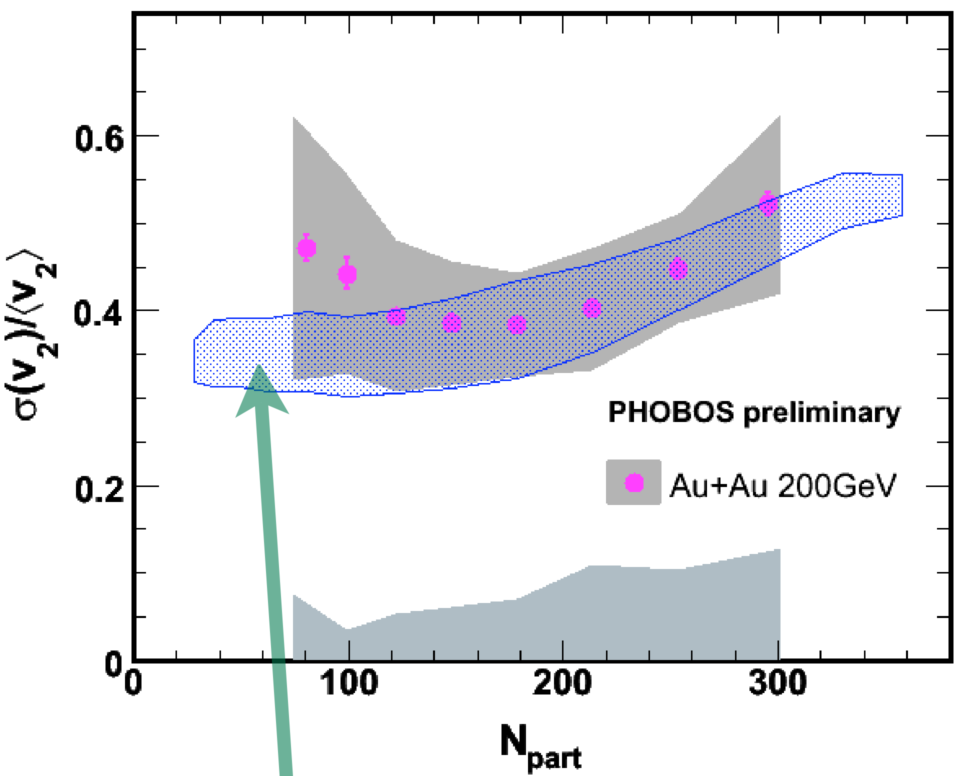




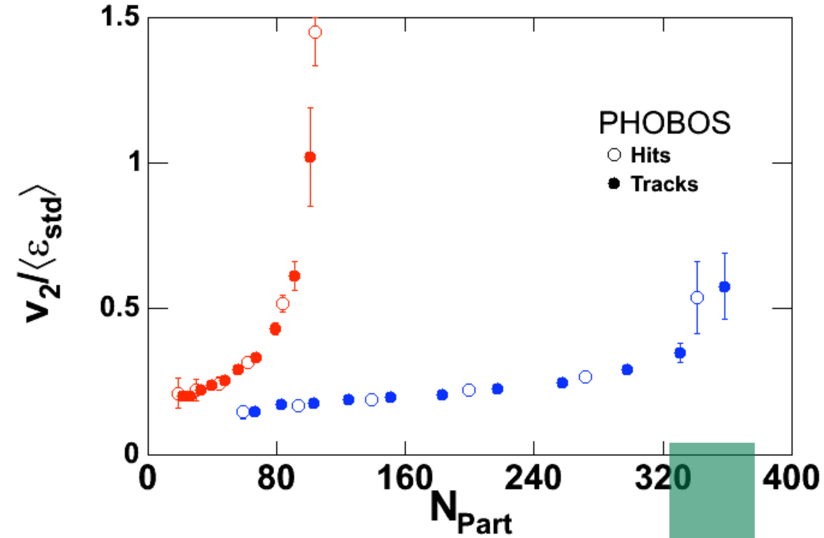
[David Hofman QM06]

v_2 fluctuations by PHOBOS

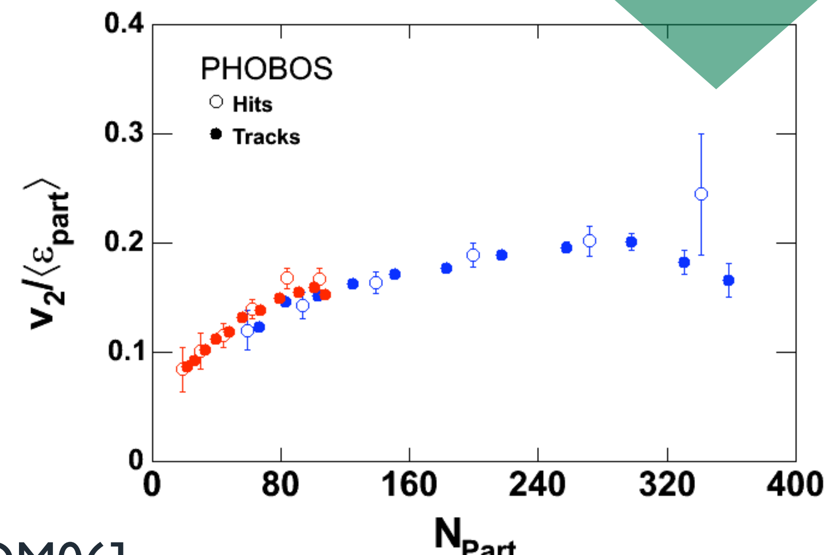
⇛ v_2 dominated by <u>initial</u> geometry



PHOBOS prediction



w/ geometry fluctuations



[David Hofman QM06]

Present view:

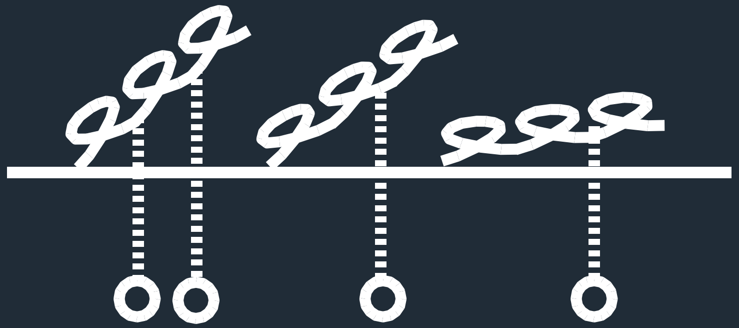
- Initial time for the evolution is very small
- Viscosity (non-perfect fluid behavior) is small

On-going discussion:

- Role of different initial conditions
- Size of viscosity corrections

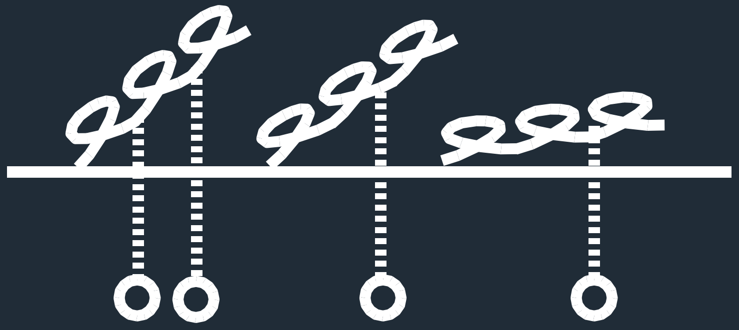
[Miklos Gyulassy: last week Colloquium;
Ulrich Heinz yesterday's talk]

QCD at high densities



- *Modification of the PDFs*
- *Modification of the jet evolution*

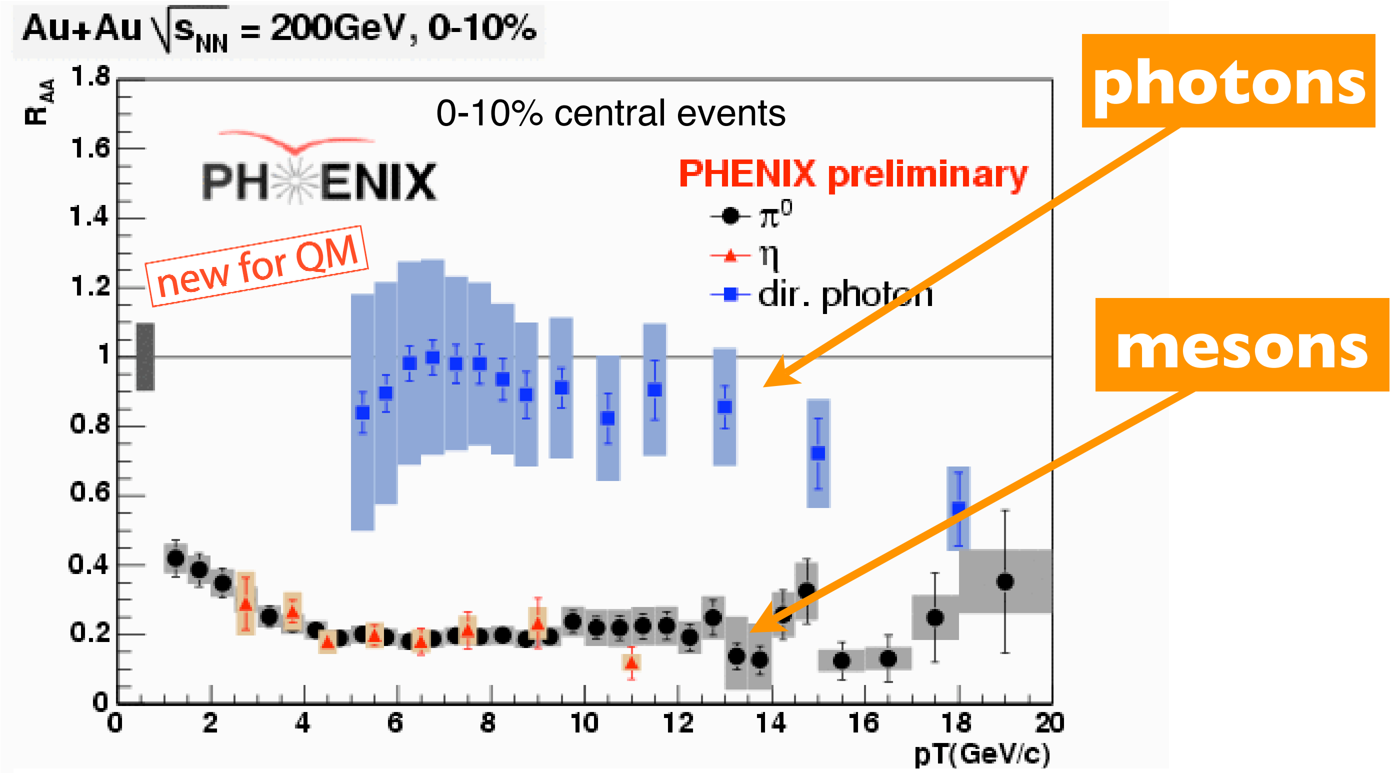
QCD at high densities



- Modification of the PDFs
- Modification of the jet evolution

Effects on high-p_t particles

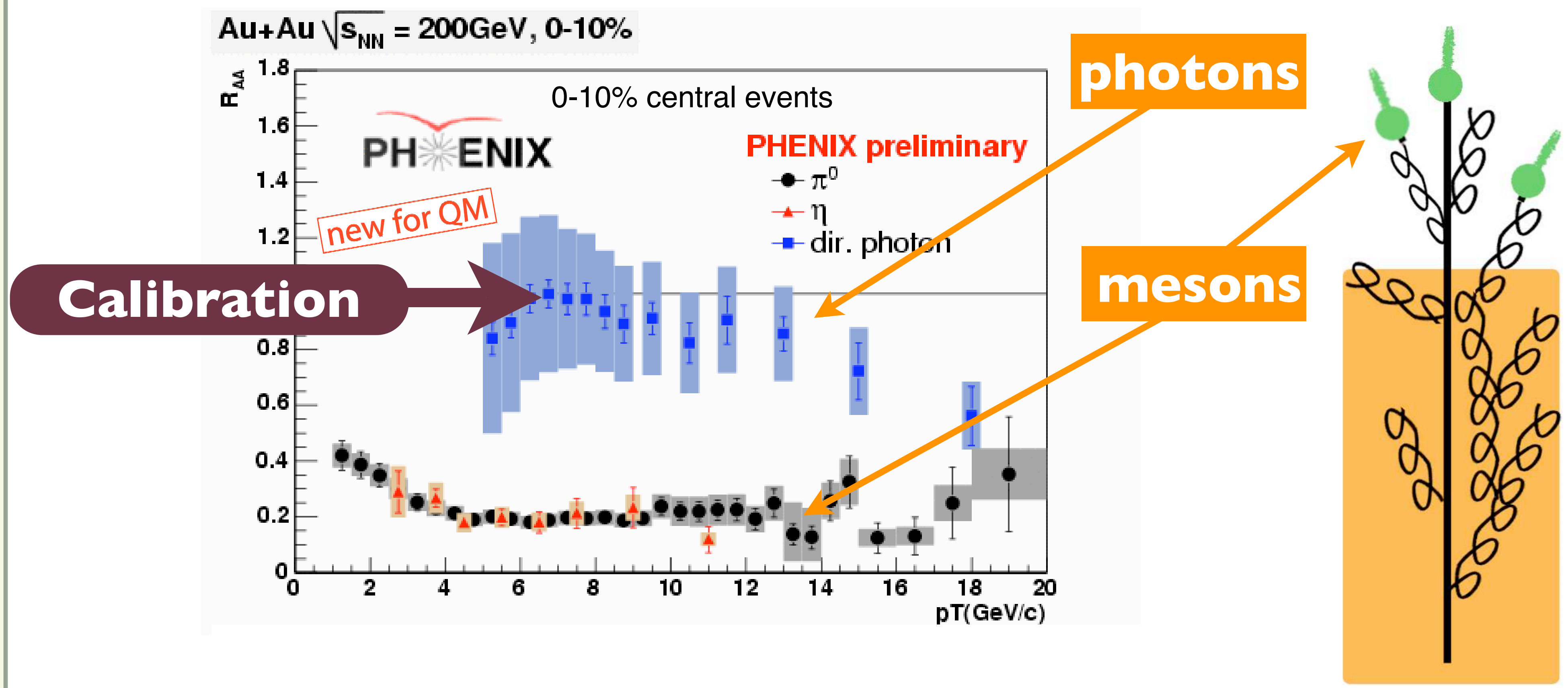
$$R_{AA} = \frac{dN^{AA}/dp_t}{N_{\rm coll} dN^{pp}/dp_t}$$



Photons don't interact (no effect) quarks and gluons do (suppression)

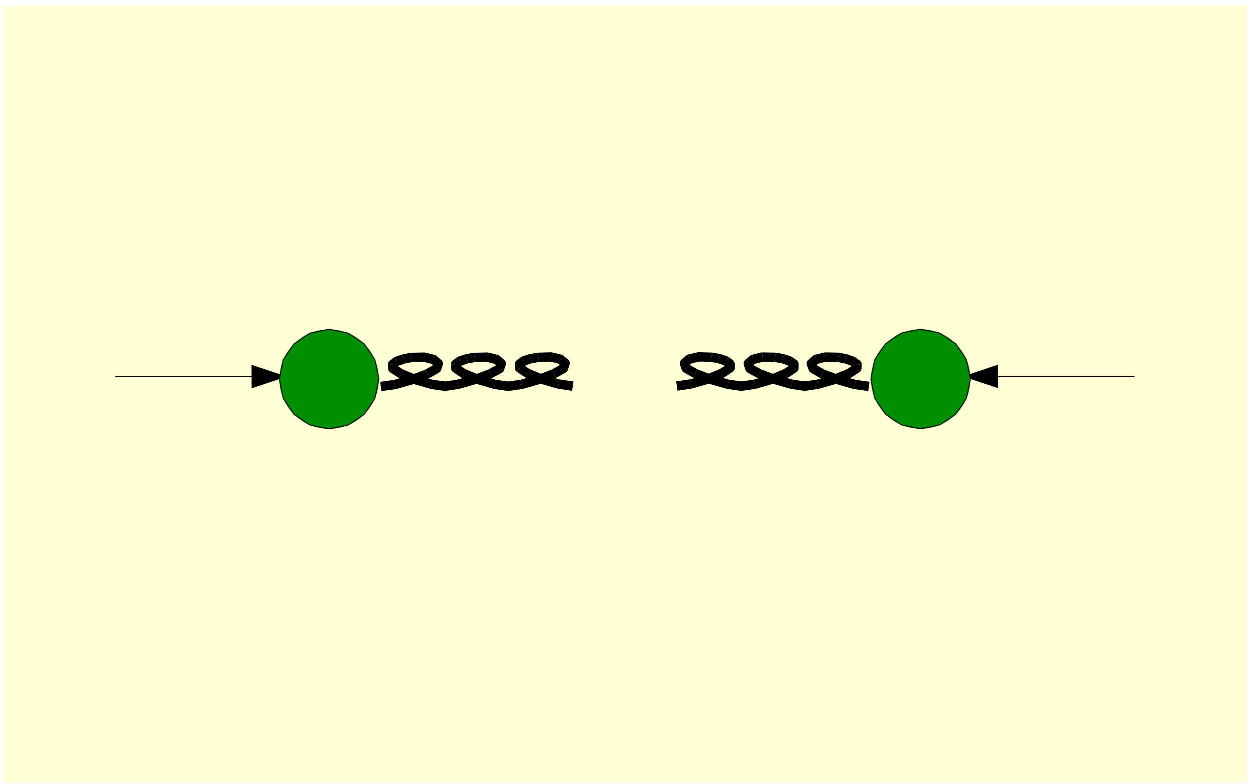
Effects on high-p_t particles

$$R_{AA} = \frac{dN^{AA}/dp_t}{N_{\text{coll}}dN^{pp}/dp_t}$$

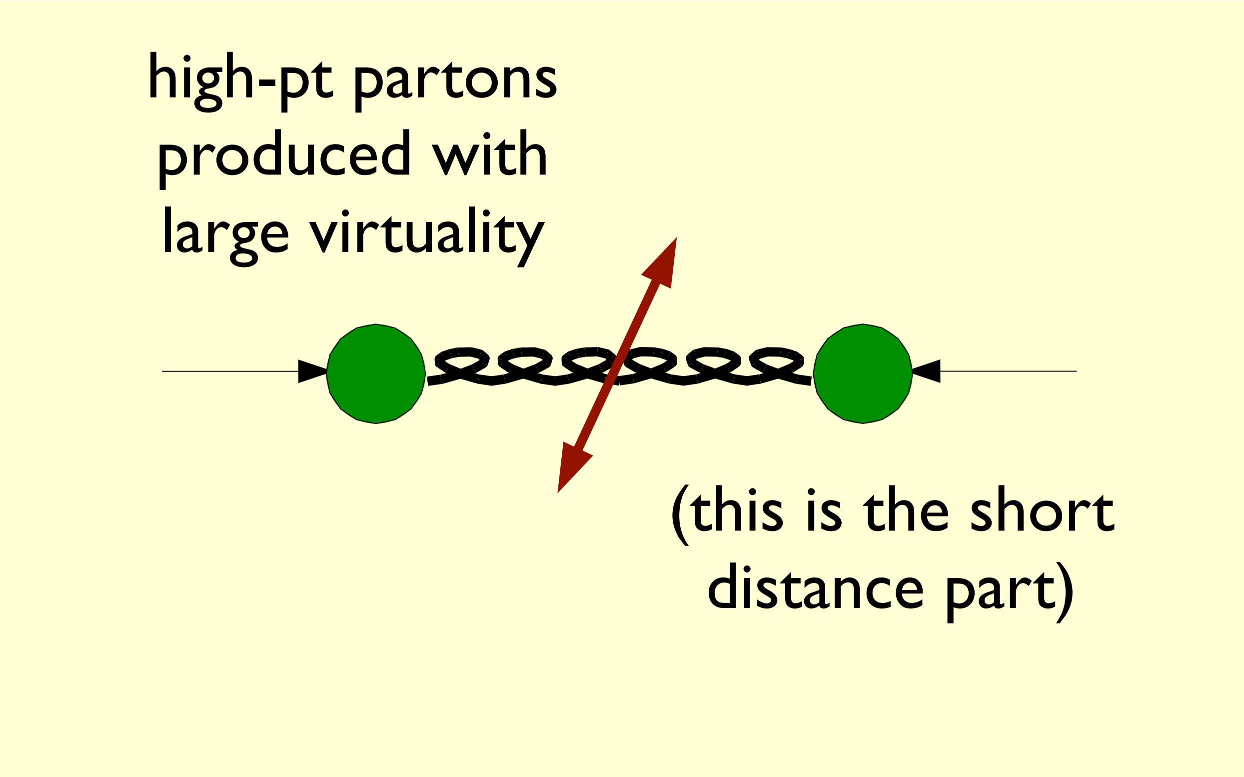


Photons don't interact (no effect) quarks and gluons do (suppression)

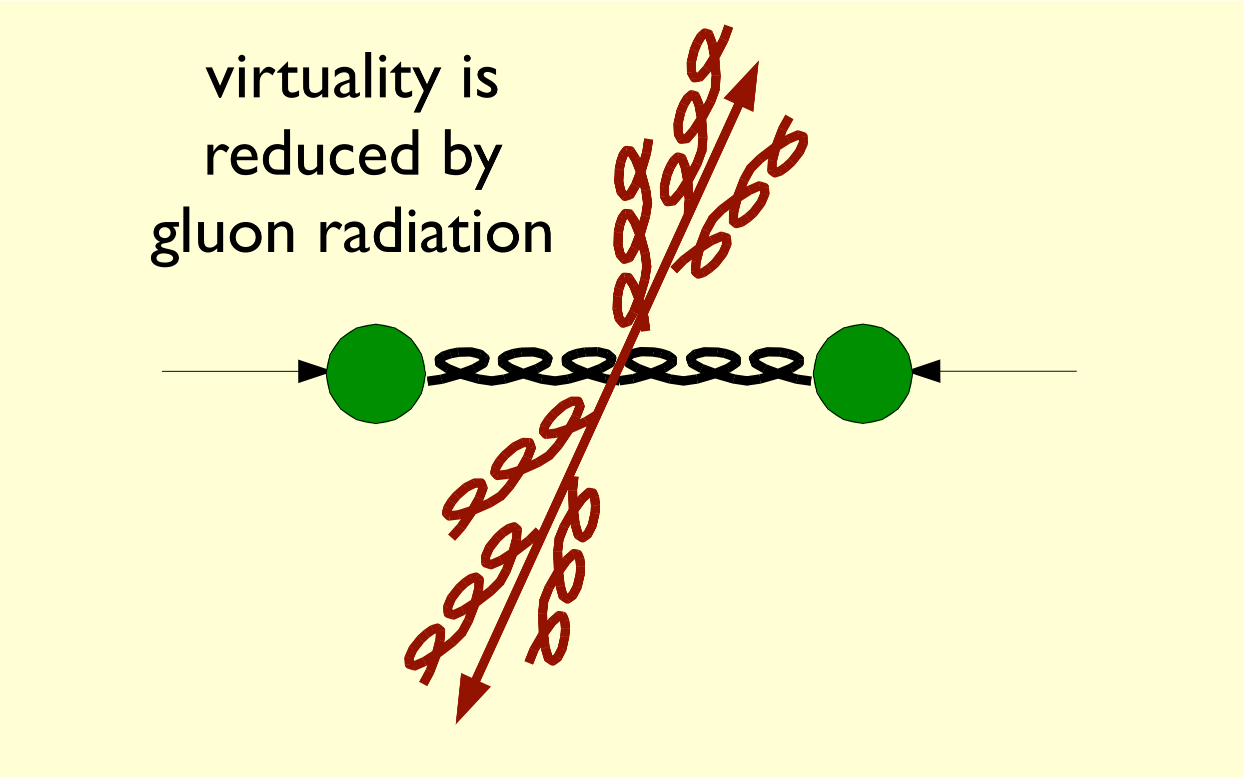
What is a jet (naively)



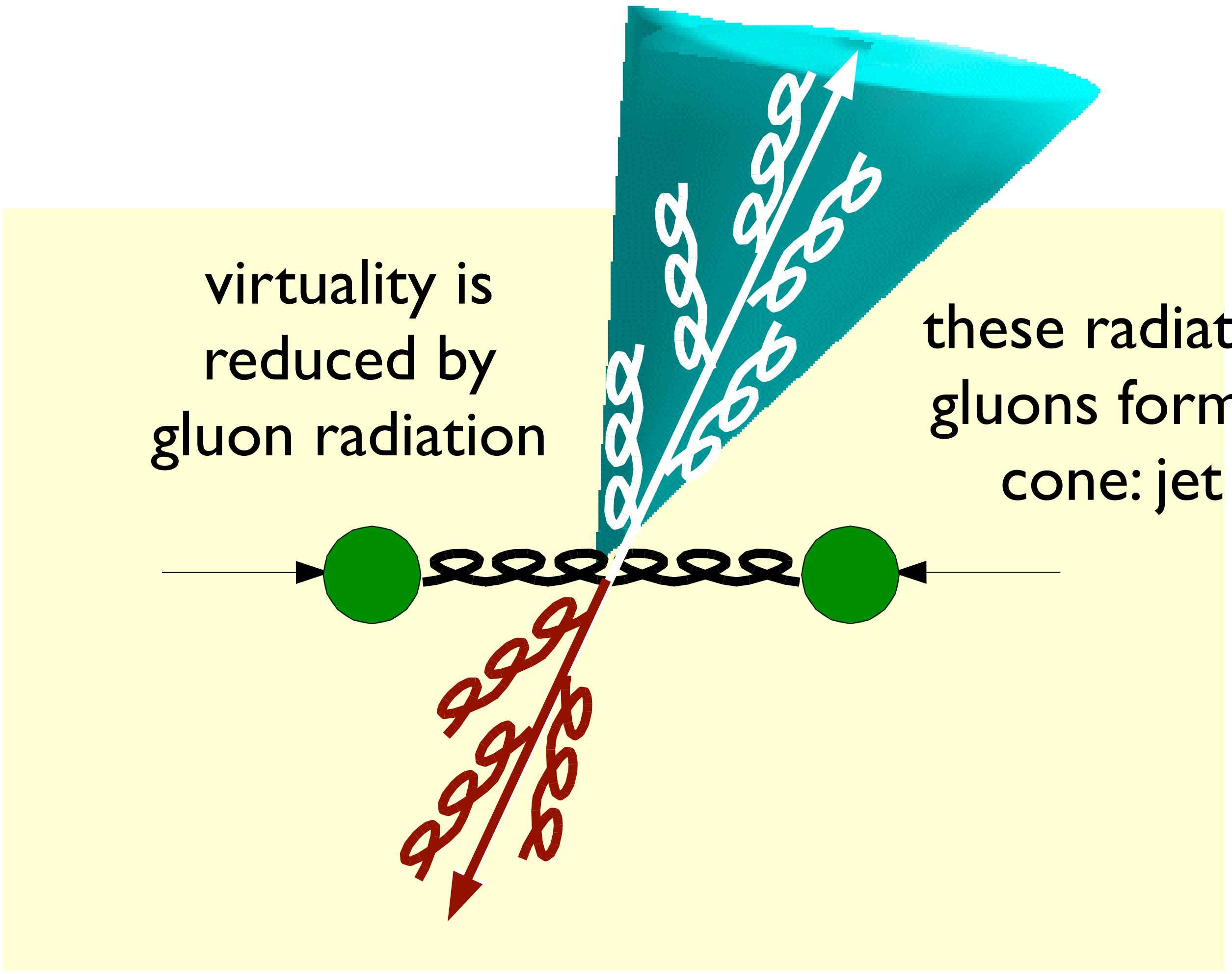
What is a jet (naively)



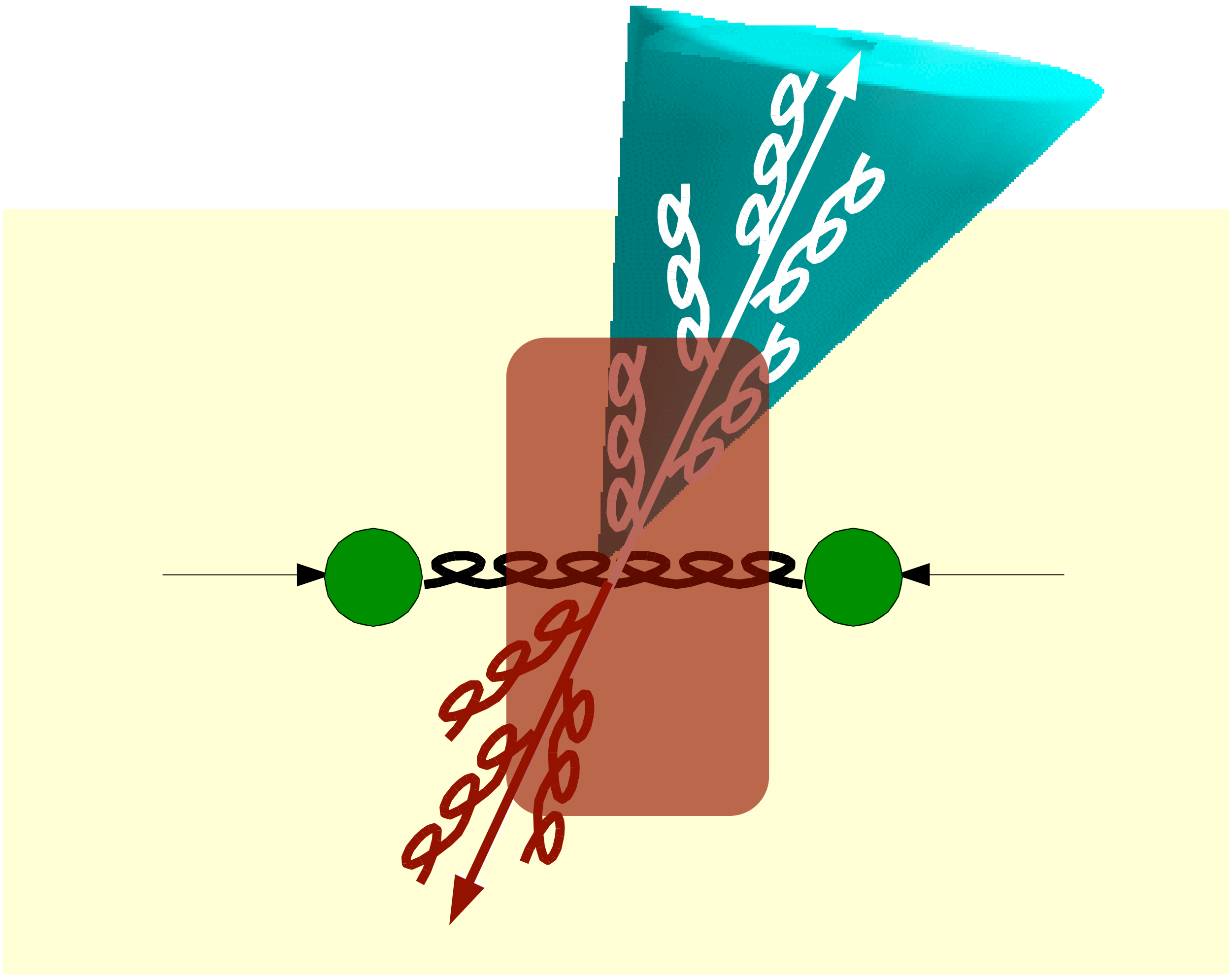
What is a jet (naively)



What is a jet (naively)



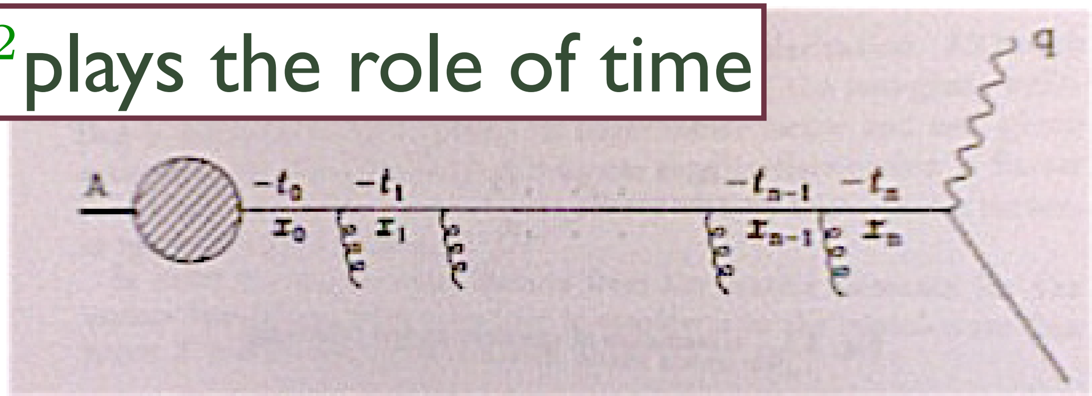
Jet quenching



What happens when this evolution takes place
in the medium created in the collision??

DGLAP evolution in vacuum

$t = Q^2$ plays the role of time



Ordered gluon splitting given by DGLAP

$$\frac{\partial f(x,t)}{\partial \log t} = \int_x^1 \frac{dz}{z} \frac{\alpha_s}{2\pi} P(z) f(x/z, t)$$

splitting function

f(x,t) are the PDFs or the FF

Sudakov prescription

⇛ The probability of no radiation between two scales

$$\Delta(t) \equiv \exp\left[-\int_{t_0}^{t} \frac{dt'}{t'} \int dz \frac{\alpha_s}{2\pi} P(z)\right]$$

⇛ The probability of one splitting

$$d\mathcal{P}(t,z) = \frac{dt}{t} dz \frac{\alpha_s}{2\pi} P(z) \Delta(t)$$

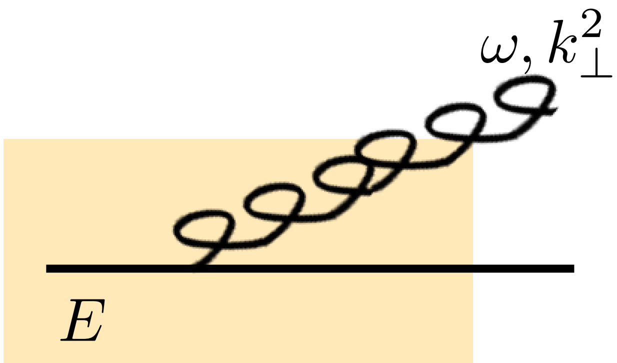
⇛ Iterating, an equivalent to DGLAP is obtained (at LO in α_s)

$$f(x,t) = \Delta(t) f(x,t_0) + \int \frac{dt'}{t'} \frac{\Delta(t)}{\Delta(t')} \int \frac{dz}{z} \frac{\alpha_s}{2\pi} P(z) f(x/z, t')$$

⇛ Probabilistic interpretation well suited for MC event generators

Medium-induced gluon radiation

Medium-modification of the jet evolution



⇛ Gluon formation time

$$t_{\text{form}} \sim \omega / k_\perp^2$$

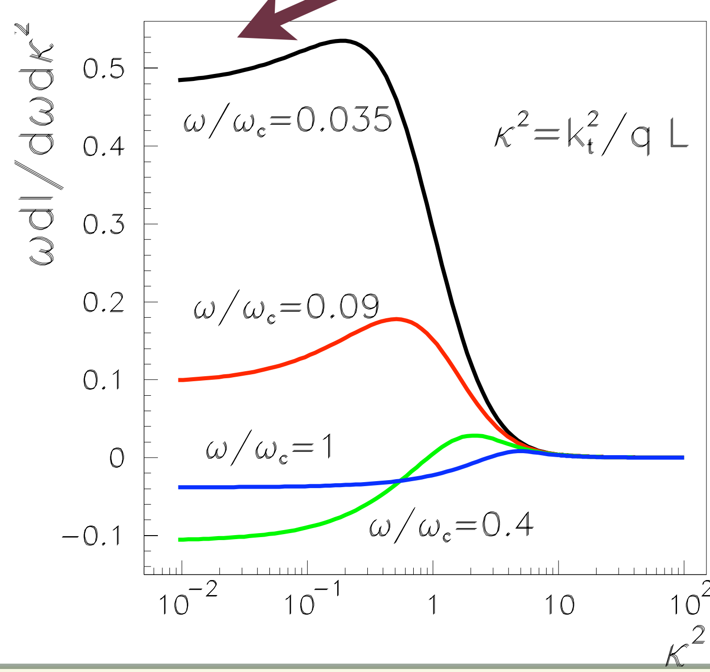
⇛ Radiation suppressed for $t_{\text{form}} \geq L$

⇛ Transport coefficient

$$\hat{q} \simeq \frac{\langle k_\perp^2 \rangle}{\lambda} \propto n(\xi)$$

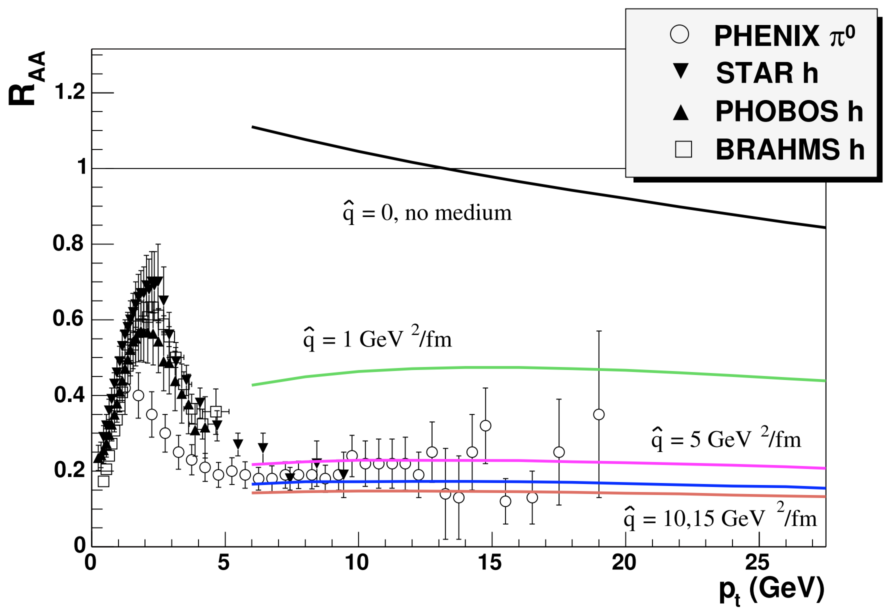
⇛ Two main predictions

- Energy loss $\Delta E \sim \alpha_s \hat{q} L^2$
- Jet broadening $\langle k_t \rangle \sim \hat{q} L$

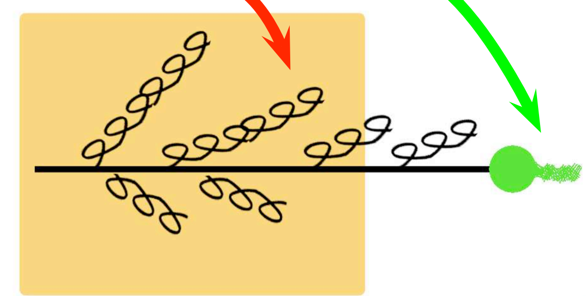


Description of the suppression

$$d\sigma^{AA\to h+X}_{(\mathrm{med})} = \sum_f d\sigma^{AA\to f+X}_{(\mathrm{vac})} \otimes \boxed{P_f(\Delta E, L, \hat{q})} \otimes D^{(\mathrm{vac})}_{f\to h}(z,\mu_F^2)\,.$$



[Eskola, Honkanen, Salgado, Wiedemann (2004)]



⇛ Virtuality neglected

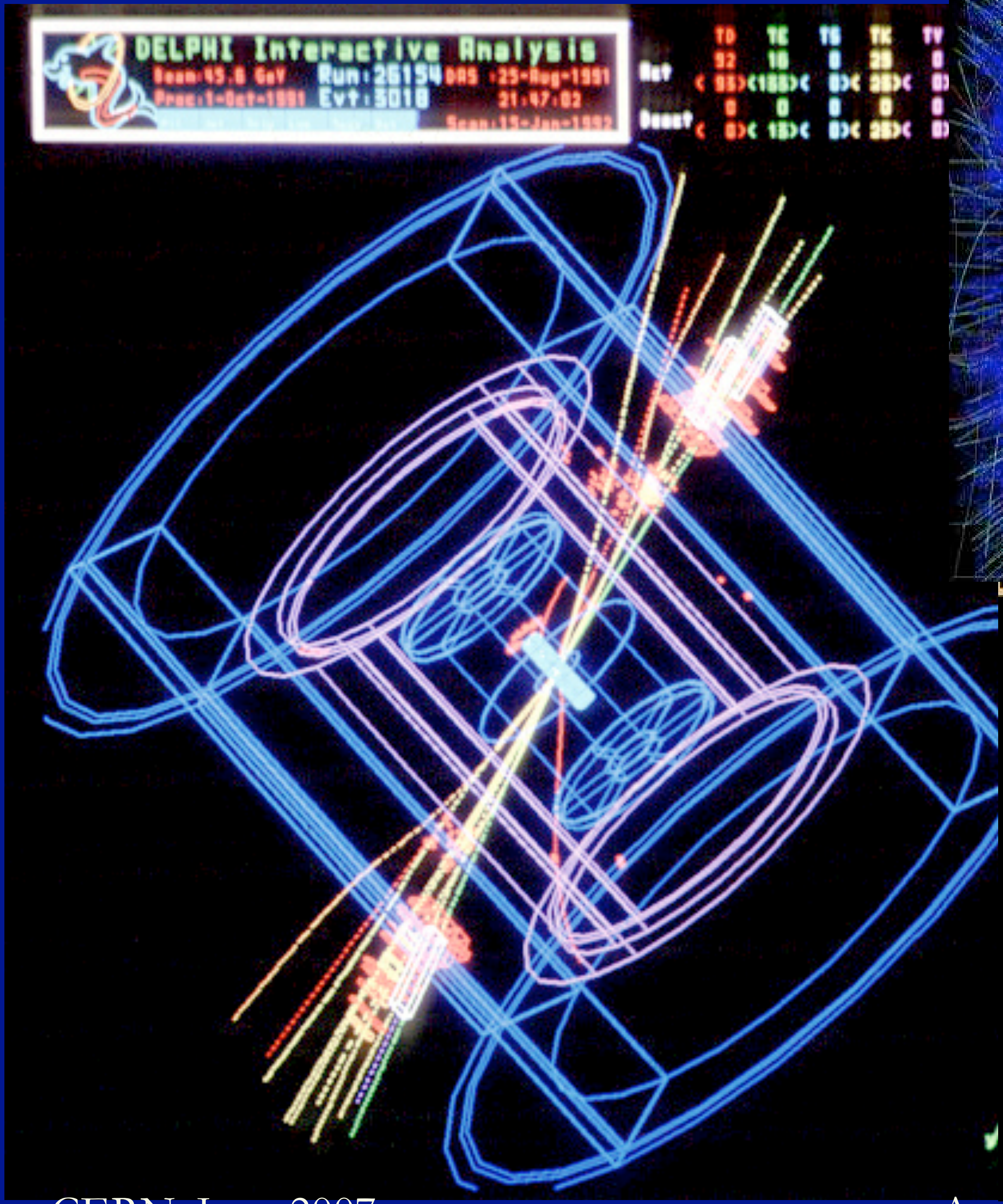
⇛ Poisson distribution for multiple gluon radiation

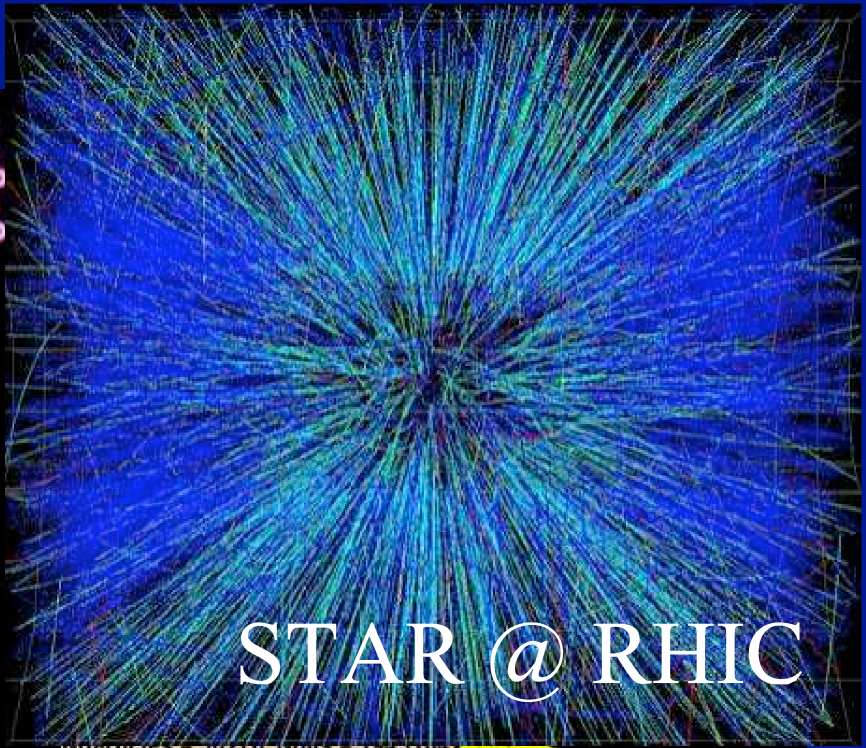
⇛ Data favors a large time-averaged transport coefficient

$$\boxed{\hat{q} \sim 5\dots 15 \frac{GeV^2}{fm}}$$

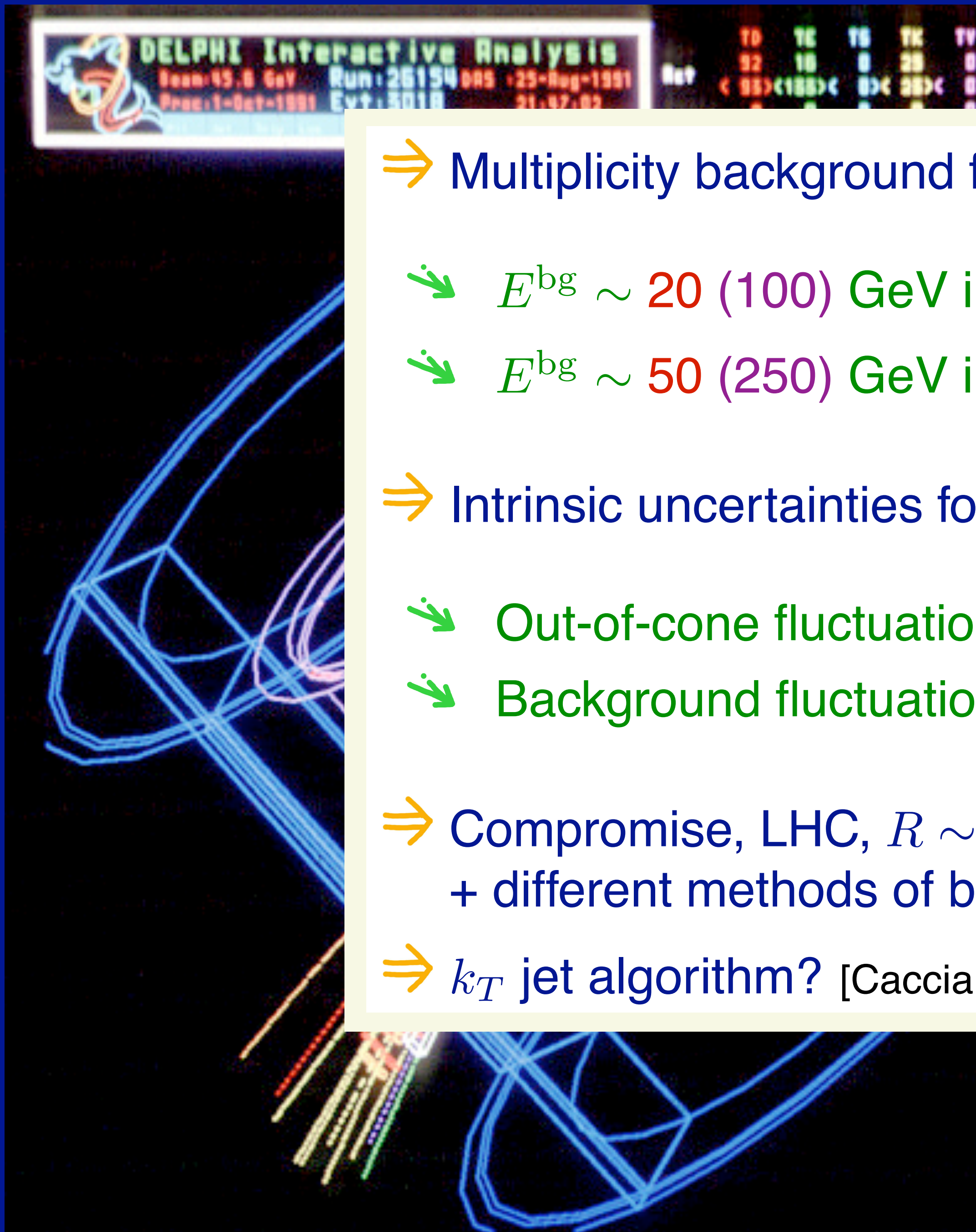
[Gyulassy, Levai, Vitev 2002; Arleo 2002; Dainese, Loizides, Paic 2004; Wang, Wang 2005; Drees, Feng, Jia 2005; Turbide, Gale, Jeon, Moore 2005...]

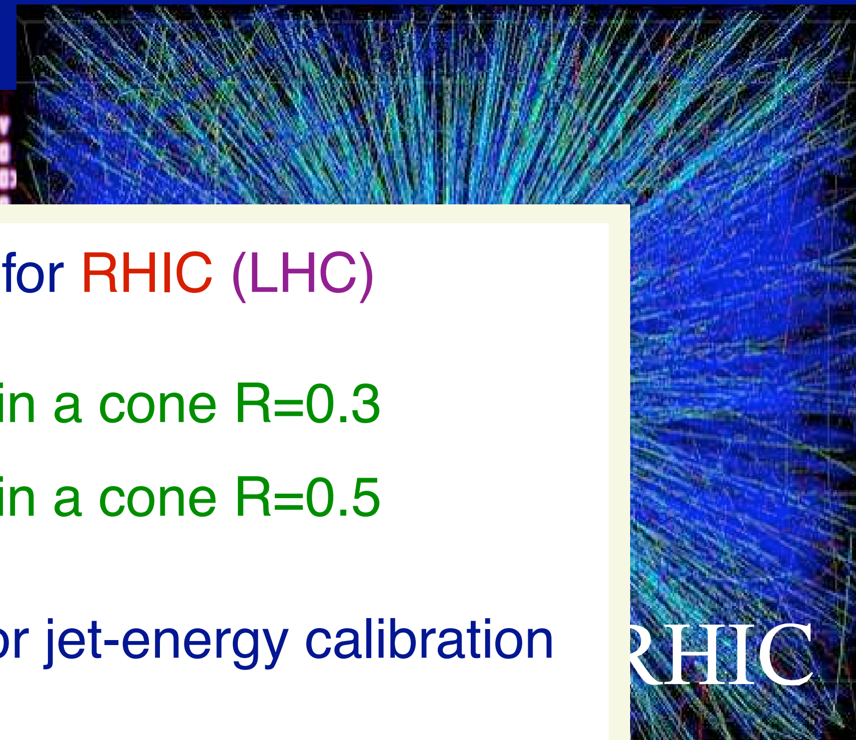
Jets in HIC

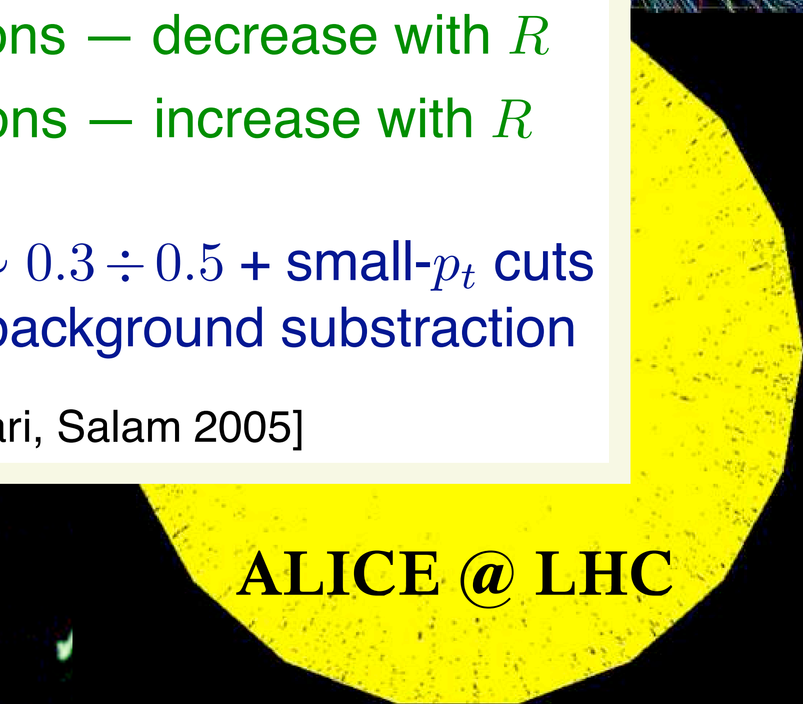




Jets in HIC



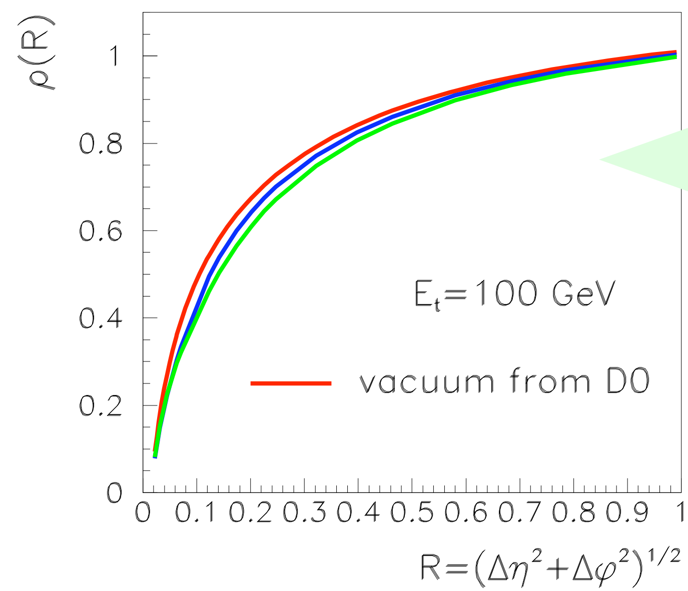




- ⇒ Multiplicity background for RHIC (LHC)
  - $E^{\rm bg} \sim$ 20 (100) GeV in a cone R=0.3
  - $E^{\rm bg} \sim$ 50 (250) GeV in a cone R=0.5
- ⇒ Intrinsic uncertainties for jet-energy calibration
  - Out-of-cone fluctuations — decrease with R
  - Background fluctuations — increase with R
- ⇒ Compromise, LHC, $R \sim 0.3 \div 0.5$ + small-p_t cuts + different methods of background substraction
- ⇒ k_T jet algorithm? [Cacciari, Salam 2005]

Medium-modification of jet shapes

Jet heating at the LHC, E_t=100 GeV [Salgado, Wiedemann 2004]



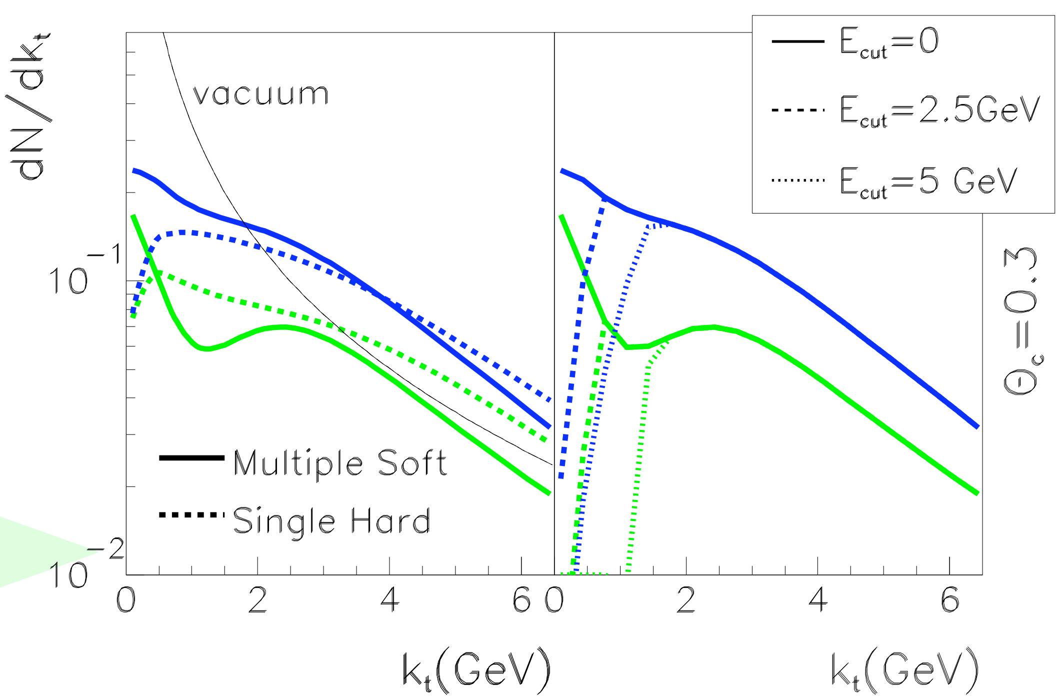
⇛ Fraction of the energy inside a cone $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

$$\rho(R) = \frac{1}{N_{\rm jets}} \sum_{\rm jets} \frac{E_t(R)}{E_t(R=1)}$$

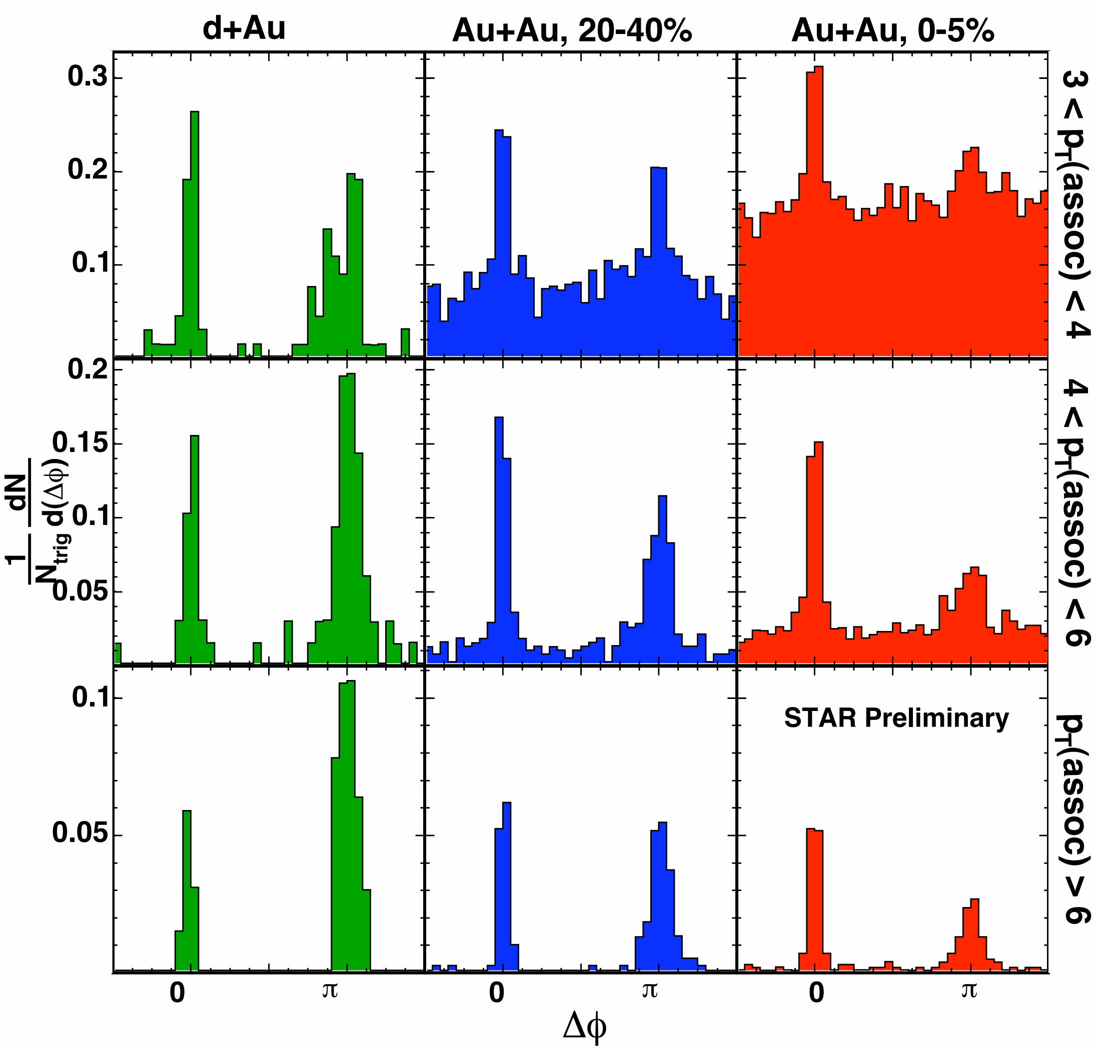
⇛ Jet energy calibration for $R \sim 0.3$

⇛ k_t-dependence of the multiplicity inside a cone

⇛ Large broadening

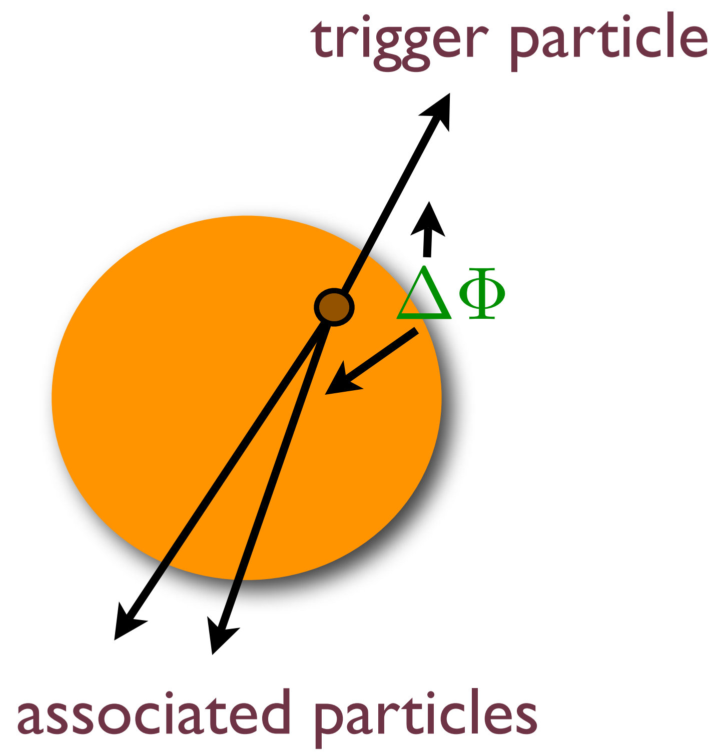


RHIC: two particle correlations

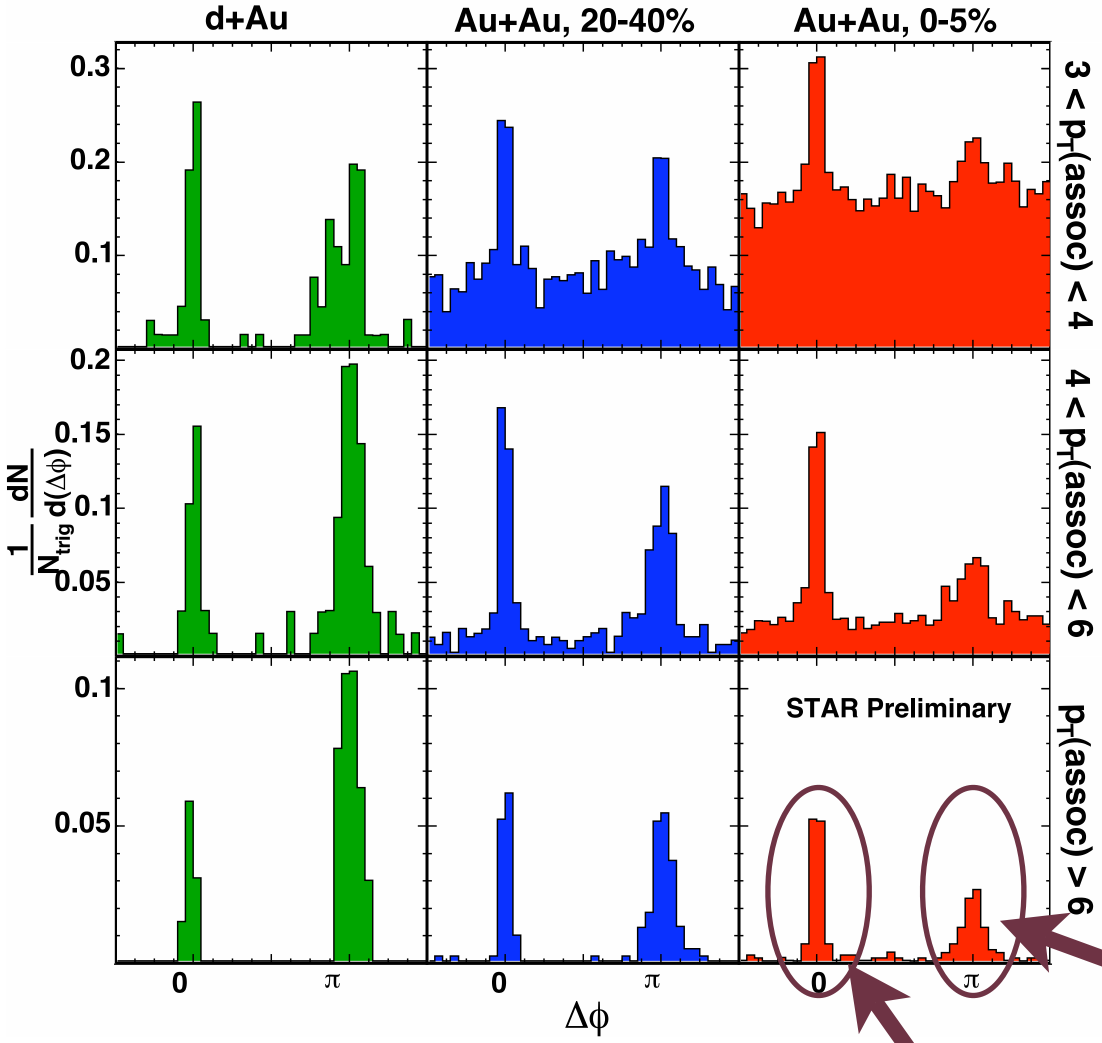


[STAR 2006]

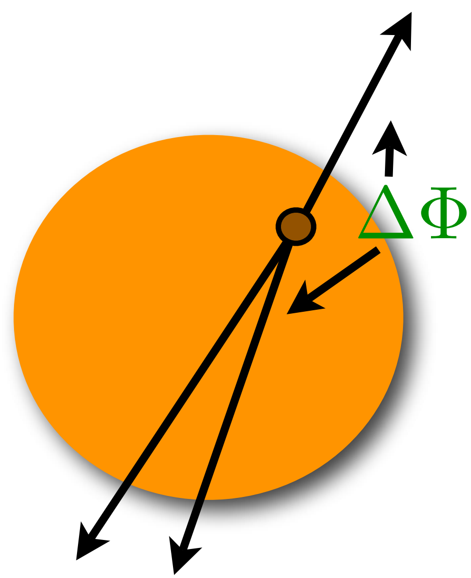
Transverse plane



RHIC: two particle correlations

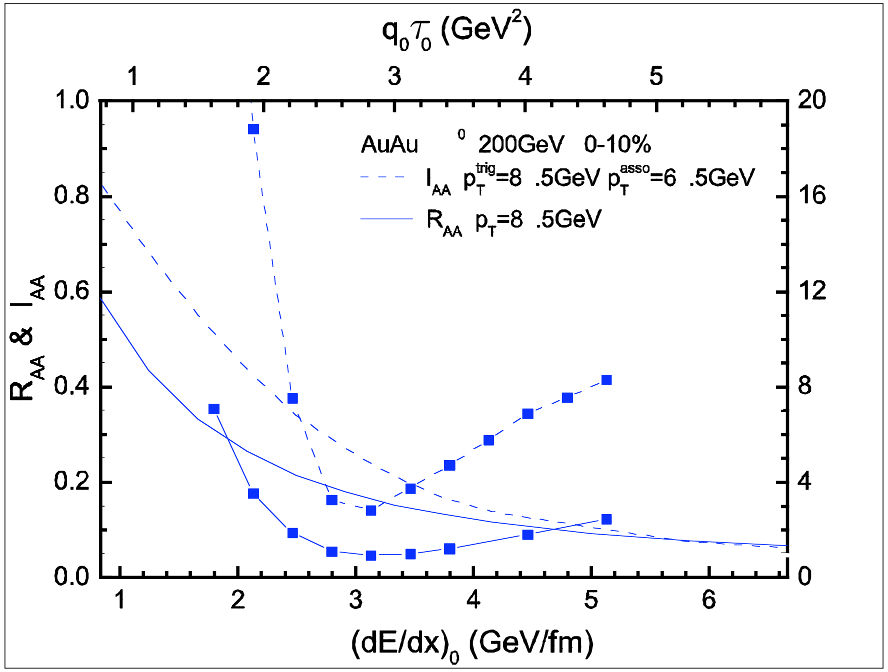


[STAR 2006]

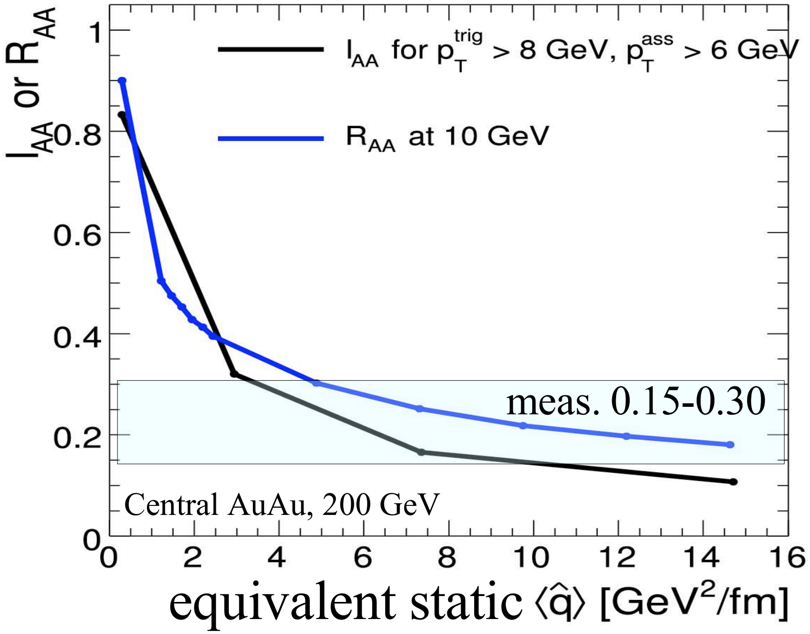


Constrains to $\hat{q}$

⇛ Simultaneous fit reduces the uncertainties



[Zhang, Owens, Wang, Wang 2007]

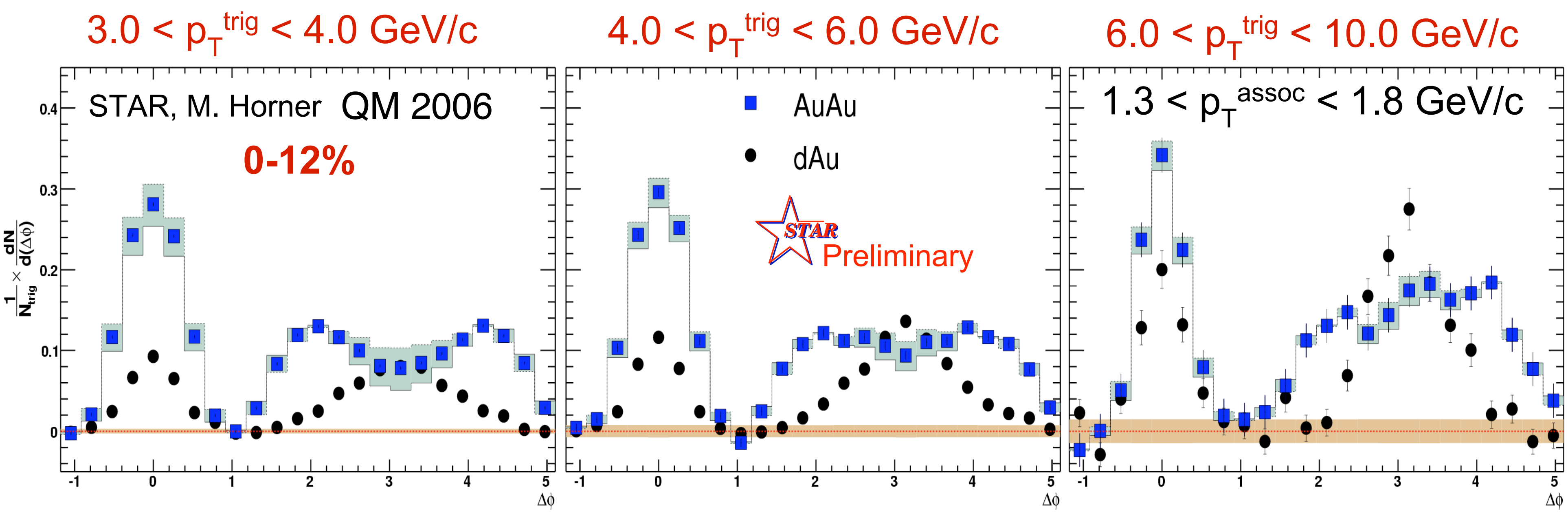


[C. Loizides HQ2006]

[Similar results by Eskola and Renk 2007]

Removing the cut-off at RHIC

[Similar results for PHENIX and also SPS (Ceres)]

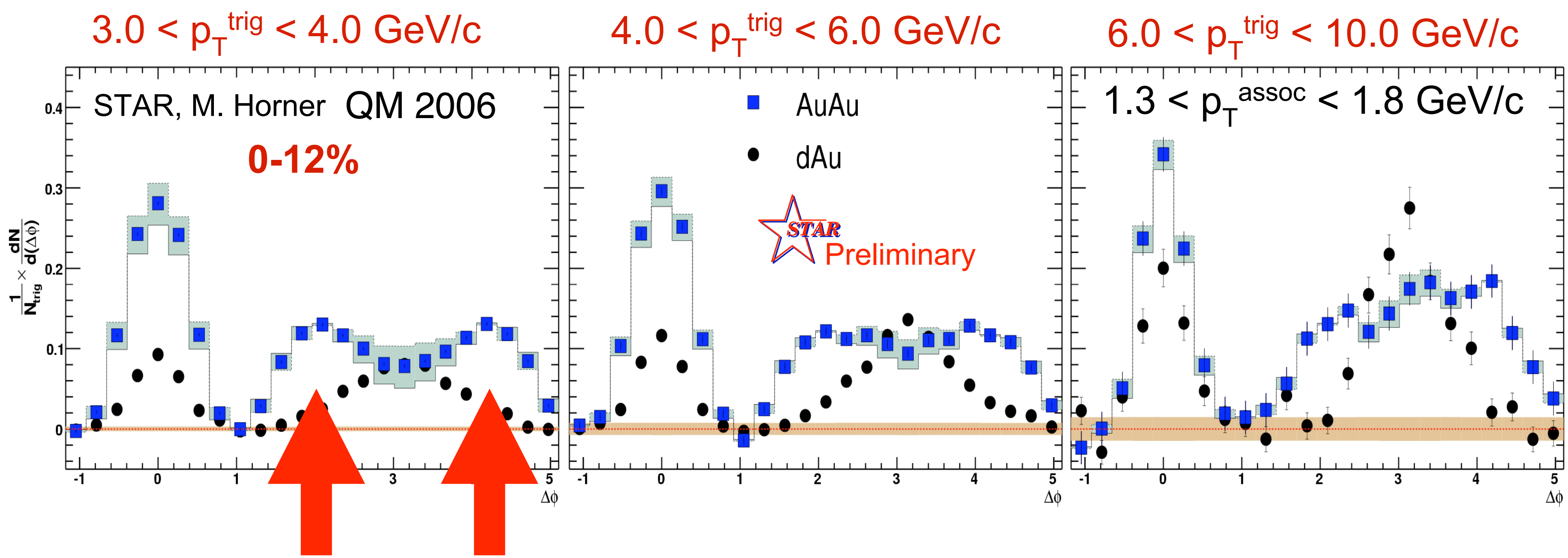


⇒ Nontrivial angular dependences in the away-side

- Large broadening
- Two-peaks when $p_t^{\rm trigg} \sim p_t^{\rm assoc}$

Removing the cut-off at RHIC

[Similar results for PHENIX and also SPS (Ceres)]



⇒ Nontrivial angular dependences in the away-side

- Large broadening
- Two-peaks when $p_t^{\rm trigg} \sim p_t^{\rm assoc}$

Two opposite assumptions:

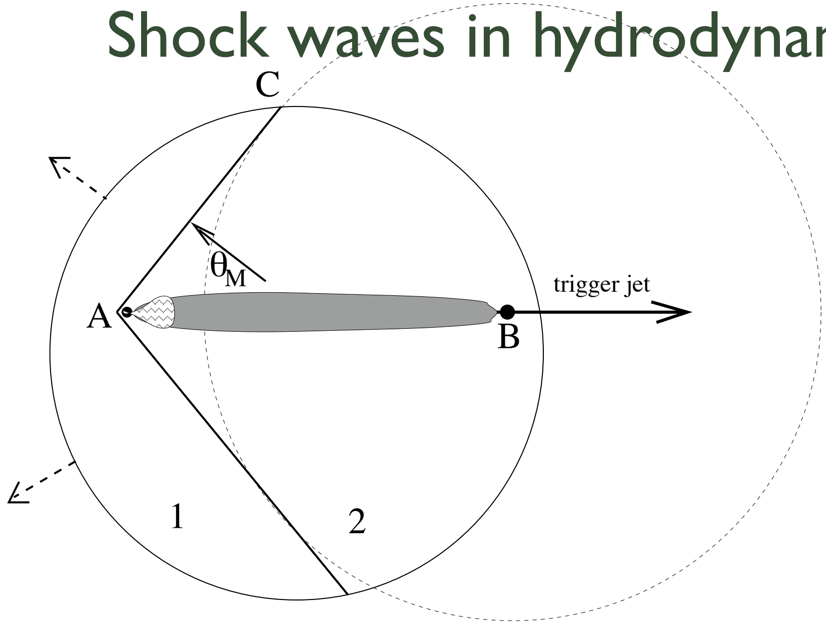
- All energy deposited in the medium +hydrodynamical evolution
- Recoil-less medium-induced radiation

Two opposite assumptions:

- All energy deposited in the medium +hydrodynamical evolution
- Recoil-less medium-induced radiation

A way to understand the energy deposition in the medium

Shock waves in hydrodynamical medium

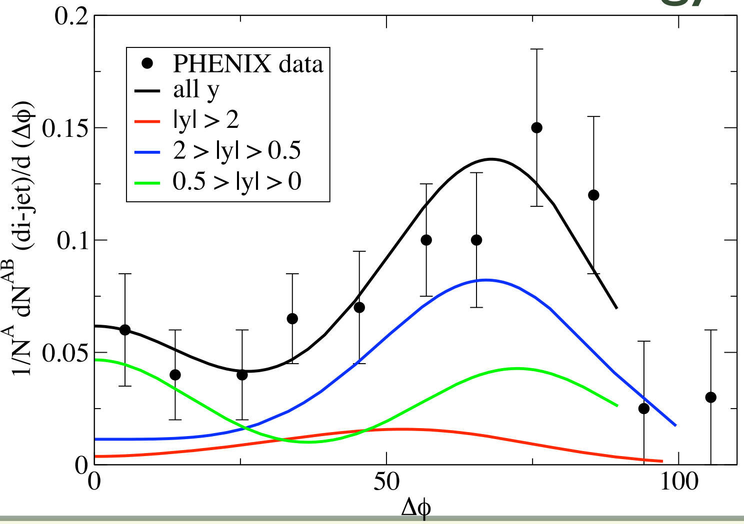


⇛ A hydrodynamical medium produces shock waves IF the energy is deposited fast enough

[Casalderrey-Solana, Shuryak, Teaney; Stoeker; Muller, Renk, Ruppert; Manuel, Mannarelli ...]

⇛ Also Cherenkov radiation proposed

[Dremin; Majumder, Wang]



Parton shower for opaque media

- When $\omega \lesssim \hat{q}^{1/3}$
  - totally coherent limit and large angle radiation

$$\frac{dI^{\rm med}}{d\omega\, dk_t^2} \simeq \frac{\alpha_s C_R}{16\pi}\, L\, \frac{1}{\omega^2} \quad \Longrightarrow \quad \frac{dI^{\rm med}}{dz\, dk_t^2} \simeq \frac{\alpha_s C_R}{16\pi}\, L\, \frac{1}{E\, z^2}$$

- The probability of only one splitting

$$d\mathcal{P} = dz\, d\theta\, \frac{\alpha_s C_R}{8\pi}\, E\, L\, \sin\theta\, \cos\theta\, \exp\left\{ -\frac{\alpha_s C_R}{16\pi}\, E\, L\, \cos^2\theta \right\}$$

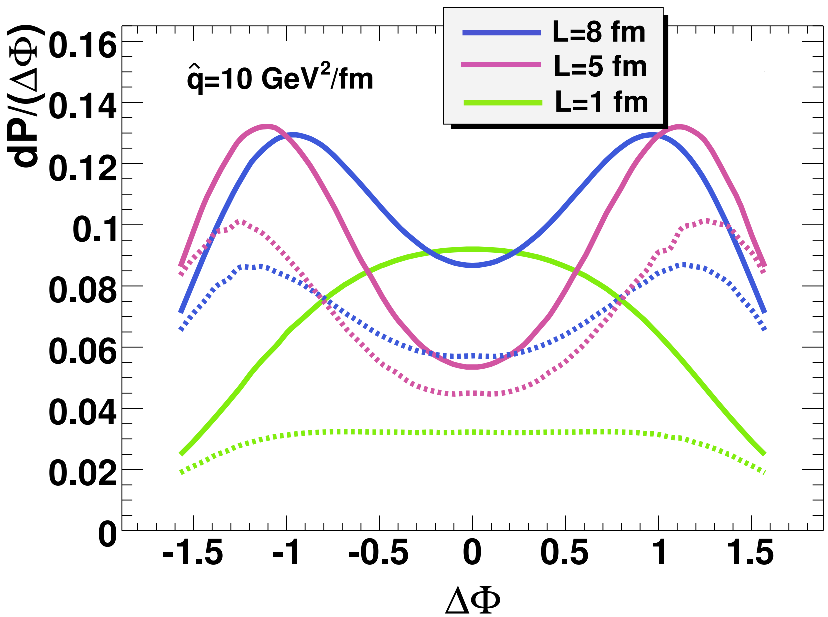
- Non-trivial angular dependence for the medium-induced gluon radiation. Two peaks in the laboratory variables η, Φ for ($\eta \simeq 0$)

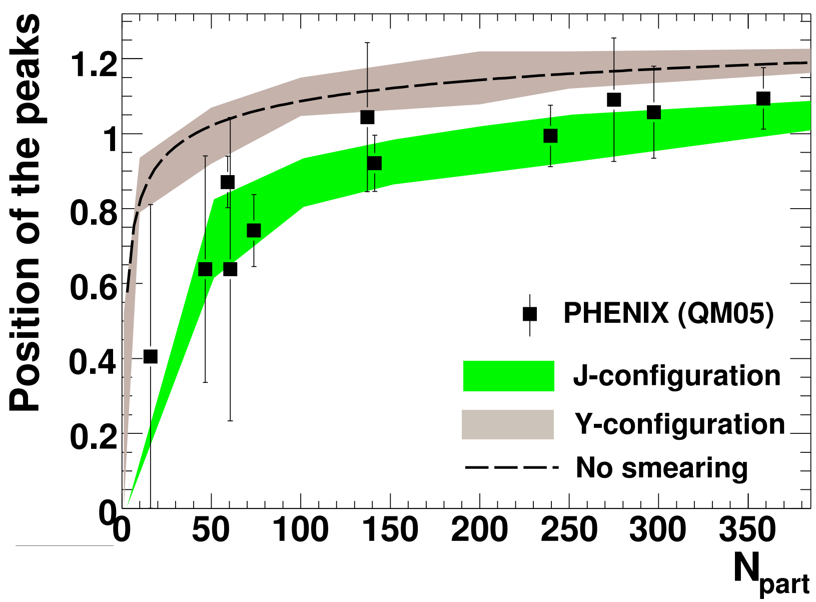
$$\Phi_{\rm max} = \pm \arccos \sqrt{\frac{8\pi}{E\, L\, \alpha_s\, C_R}}$$

A simple model to compare with data

⇛ Smearing in longitudinal (η) and transverse (Φ) variables

$$\frac{dP}{d\Delta\Phi dz} = \frac{1}{N}\int_{-\Delta\eta}^{\Delta\eta} d\eta \int d\Phi' \frac{d\mathcal{P}}{d\Phi' dz d\eta} e^{-\frac{(\Delta\Phi-\Phi')^2}{2\sigma^2}}$$

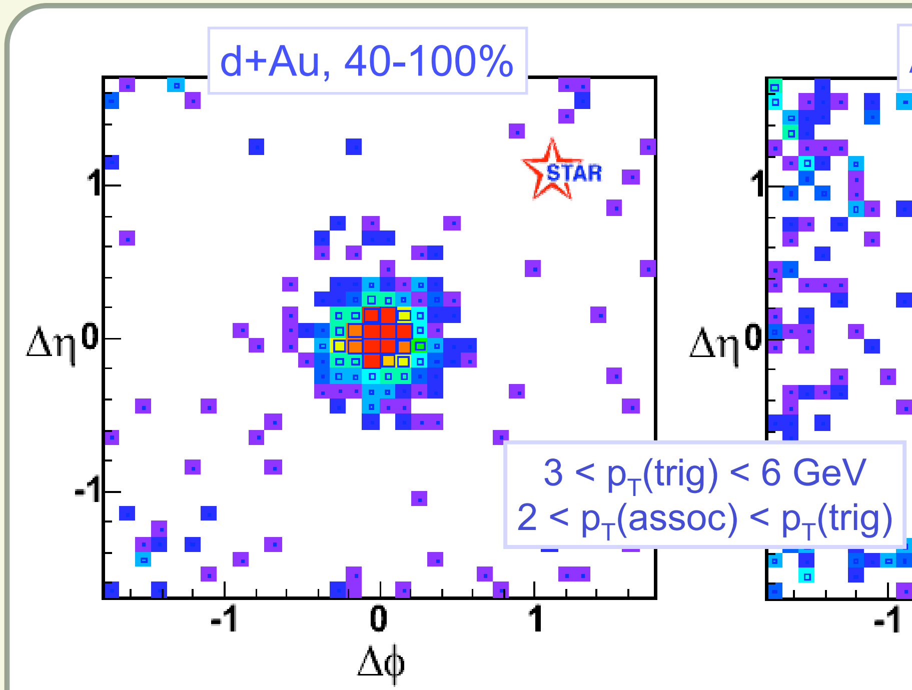




[Polosa, Salgado hep-ph/0607295]

⇛ A perturbative mechanism, the medium-induced gluon radiation, is able to reproduce the observed 2-peak structure in the away side jet.

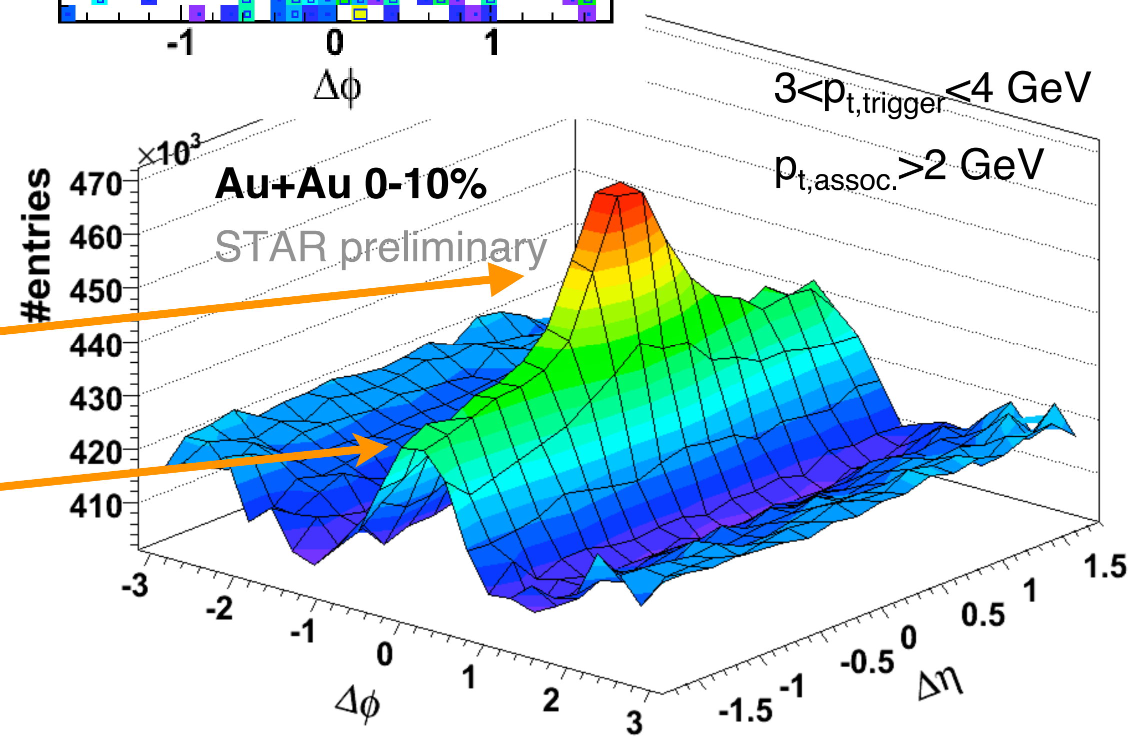
The ‘ridge’



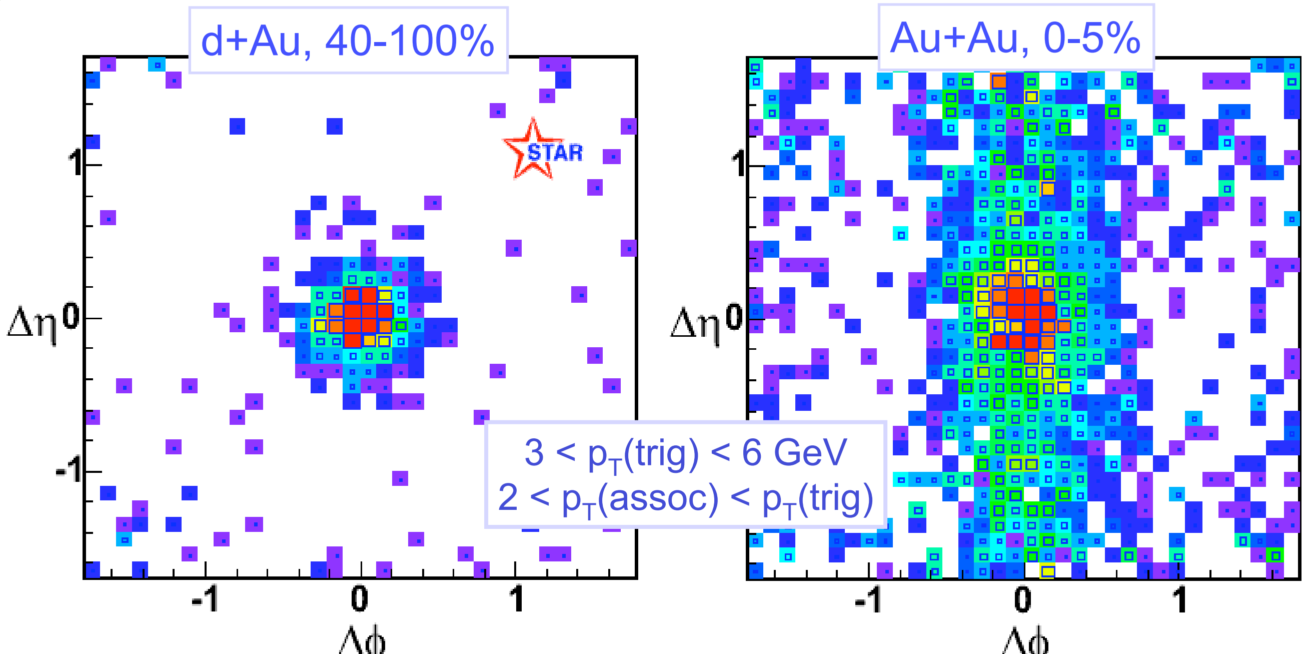
Near side correlations gaussian+ridge

[Dan Magestro HP04]

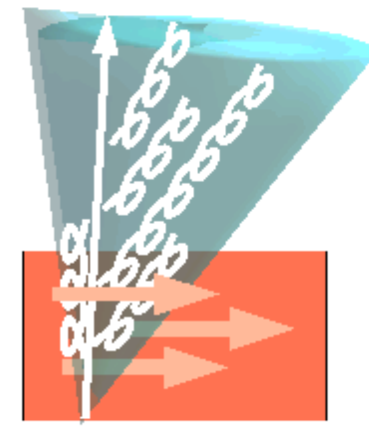
- ⇒ Gaussian similar to vacuum fragmentation
- ⇒ Ridge similar to bulk



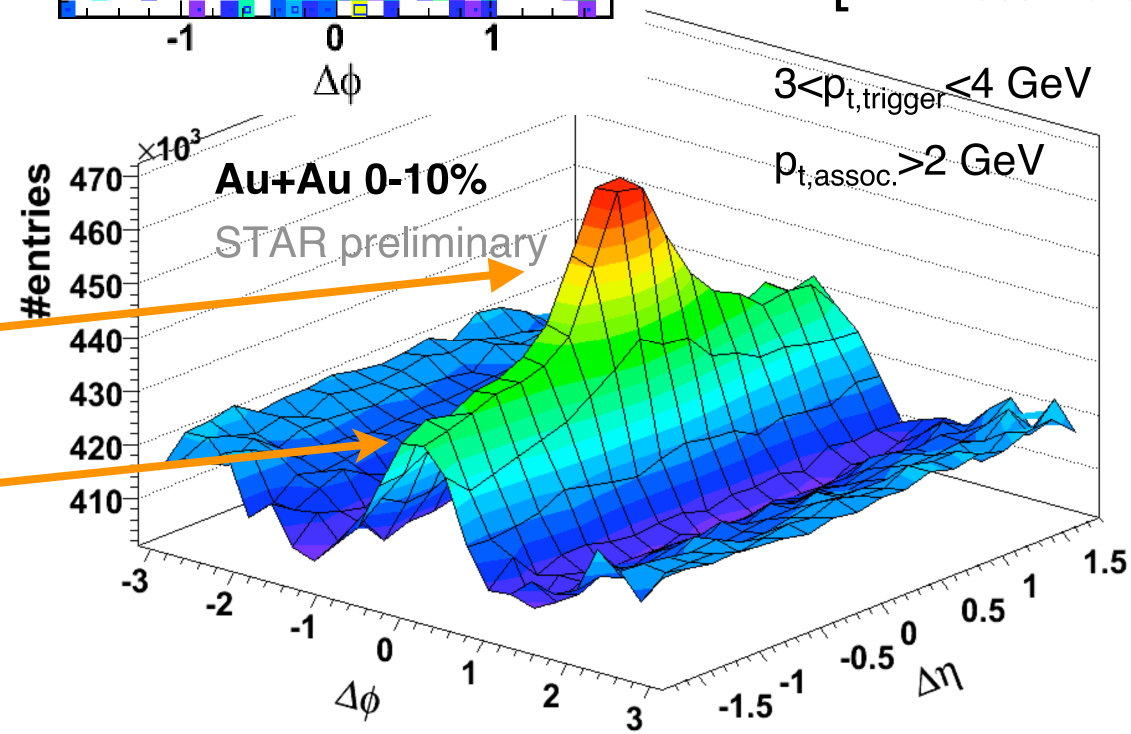
The ‘ridge’



[Dan Magestro HP04]

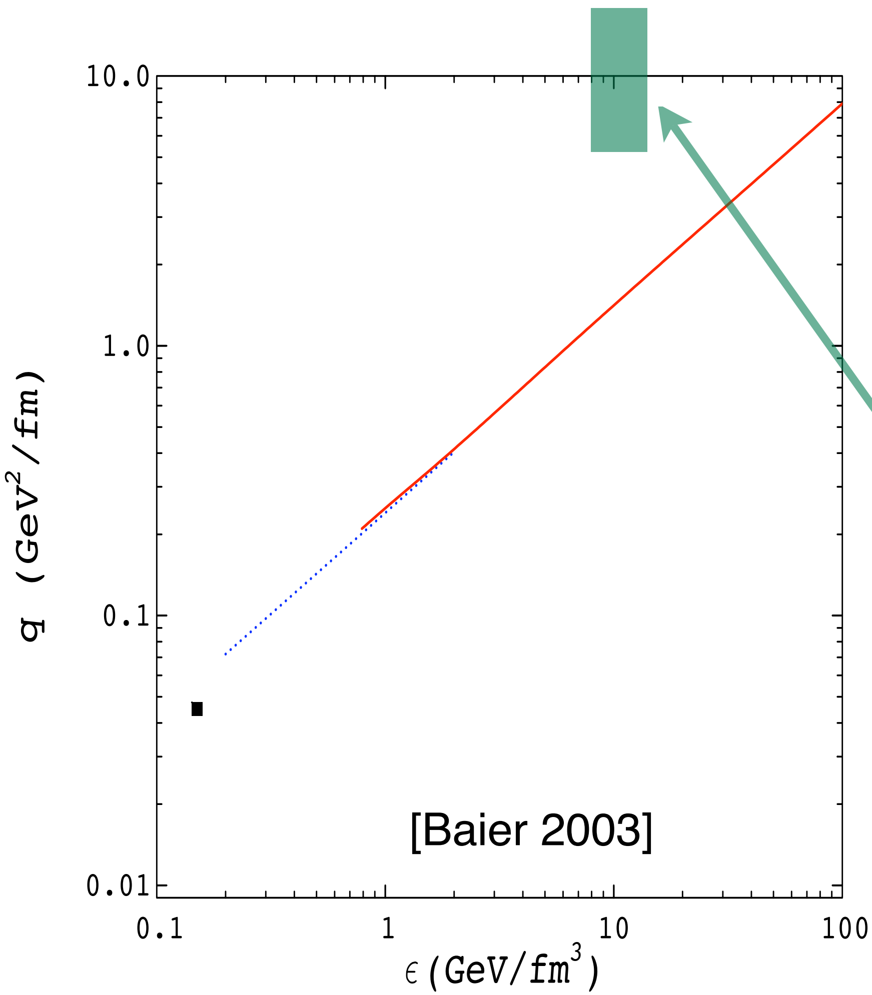


[Armesto et al 2004]



- ⇛ Gaussian similar to vacuum fragmentation
- ⇛ Ridge similar to bulk

Interpretation of the value of $\hat{q}$



⇛ Transport coefficient for an ideal qg gas

$$\hat{q}_{\rm ideal\ gas} \simeq \frac{72}{\pi}\xi(3)\alpha_s^2 T^3 \simeq 2\epsilon^{3/4}$$

[Baier and Schiff 2006]

⇛ Fits to the data

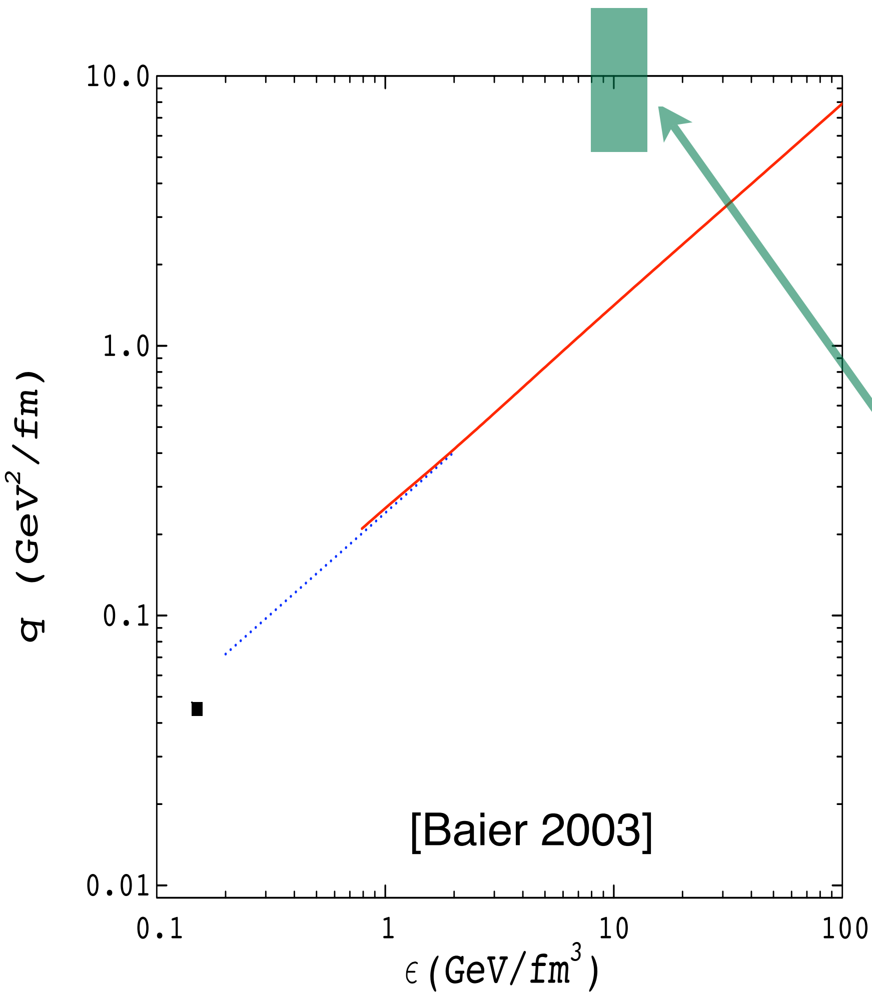
$\hat{q} > 5\ \hat{q}_{\rm ideal\ gas}$ [Eskola et al. 2004]

$\hat{q} \simeq 4.2\ \hat{q}_{\rm ideal\ gas}$ [Renk et al. 2007]

⇛ Geometry plays a crucial role

⇛ Model of the medium? sQGP?

Interpretation of the value of $\hat{q}$



⇛ Transport coefficient for an ideal qg gas

$$\hat{q}_{\rm ideal\ gas} \simeq \frac{72}{\pi}\xi(3)\alpha_s^2 T^3 \simeq 2\epsilon^{3/4}$$

[Baier and Schiff 2006]

⇛ Fits to the data

$\hat{q} > 5\ \hat{q}_{\rm ideal\ gas}$ [Eskola et al. 2004]

$\hat{q} \simeq 4.2\ \hat{q}_{\rm ideal\ gas}$ [Renk et al. 2007]

⇛ Geometry plays a crucial role

⇛ Model of the medium? sQGP?

Should we be worried that a LO calculation gives a K-factor of 5?

Jet quenching as a medium probe

Probes

Easy to measure and well calibrated

Control on dynamical process

Control on the relation with the medium properties

Improvements in the jet evolution

role of virtuality

recoil effects...

Improvements in the model of the medium

hydrodynamical medium

calculations of $\hat{q}$

Some new developments...

Some new developments...

The String Theory connection

The observables

⇛ Applied to the jet quenching parameter:

$$\langle W^A(\mathcal{C})\rangle \simeq \exp\left[-\frac{1}{4\sqrt{2}}\hat{q}r^2 L_-\right]$$

$$\hat{q} = 4.5,\ 10.6,\ 20.7\ \mathrm{GeV}^2/\mathrm{fm}$$

$$T = 300,\ 400,\ 500\,\mathrm{MeV}$$

[Liu, Rajagopalan, Wiedemann; Armesto, Edelstein, Mas...2006]

⇛ The viscosity-to-entropy ratio

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

$\eta \propto$ area of horizon
$s \propto$ area of horizon

Universal lower bound?

[Kovtun, Son, Starinets 2003]

⇛ The hydrodynamic behavior

↘ Bjorken hydrodynamics recovered (and more)

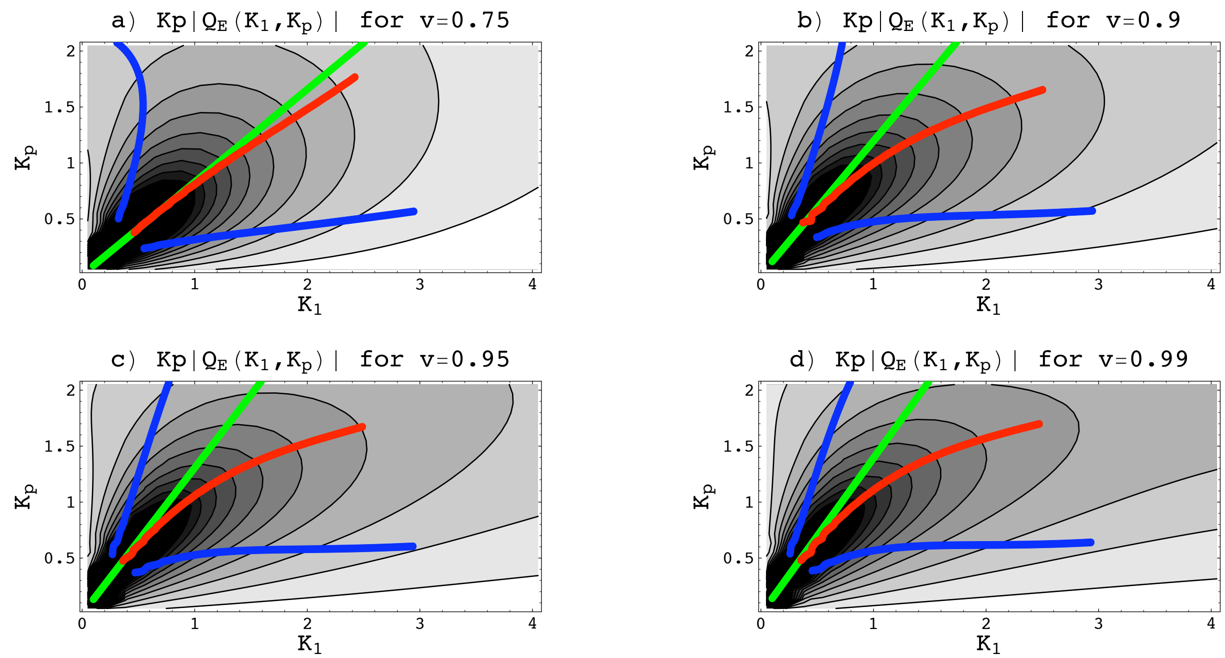
[Janik, Peschanski 2006; Kovchegov, Taliotis 2007...]

⇛ Shock waves; heavy quark energy loss; bound states....

[Gubser; Herzog, Karch, Kovtun, Kozcaz, Yaffe; Casalderrey-Solana, Teaney.... 2006]

Shock waves and AdS/CFT

$T^{\mu\nu}$ computed for a quark moving with constant velocity in a medium



Yet, despite the potential stumbling blocks, it is exciting to see a simple type IIB string theory construction approaching quantitative comparisons with a data-rich experimental field.

[Friess, Gubser, Michalogiorgakis, Pufu hep-th/0607022]

Summary of our present view

- Initial state dominated by saturated gluon distributions
- Developing paradigm from experimental data+theory
  - early themalization
  - ideal fluid behavior - negligible viscosity
  - very dense medium
  - properties 'very' different from asymptotic (gas) limit
- Different fields are contributing to these developments
  - String-theory computations (attempt to) face experimental data

- LHC: new regimes of QCD where in-medium evolution dominates
  - Hard probes are the best new tools available

Perspectives for the future

Perspectives for the future

- Is the initial state given by saturated PDFs? strong color fields
- Is the hydrodynamical behavior ideal at the LHC? viscous corrections?
- What are the medium modification of jets and how to compute them?
- Theoretical control on the medium properties