Physics Opportunities at the Largest Heavy Ion Collider (LHC)

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Quark Matter 2006
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Shanghai

Main goal:

- to produce the Quark Gluon Plasma and to determine its properties.
- How do collective phenomena and macroscopic properties of dense matter emerge from 1st principles in QCD?

The medium:

- its properties or their dynamical manifestations may change significantly with $\sqrt{s_{NN}}$ (complementarity of RHIC and LHC)

⇒ Novel opportunities for **soft physics**

The tools:

- improve significantly in variety and accuracy with $\sqrt{s_{NN}}$
  - rates
  - p_T -range
  - x_{Bj} -range

} Large quantitative/qualitative gains

⇒ Novel opportunities for **hard physics**

<u>The soft</u>

Agnostic starting point:

<u>If</u> generic trends in the data persist over wide $\sqrt{s_{NN}}$ - range,

<u>then</u> - do not discard them as numerical coincidence

- look for explanation in terms of fundamental theory.

<u>Here</u>: - consider generic trends in SPS and RHIC data

- what do we learn if these trends persist or break down at the LHC?

Day 1 @ LHC: event multiplicity at y=0

- generic trends in $dN^{ch}/d\eta$
  - extended longitudinal scaling
  - self-similar trapezoidal shape

$$\Rightarrow \quad dN^{ch}/d\eta\Big|_{\eta=0} \propto \ln\sqrt{s_{NN}}$$

- Saturation models predict

Armesto, Salgado, Wiedemann, PRL94 (2005) 022002

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

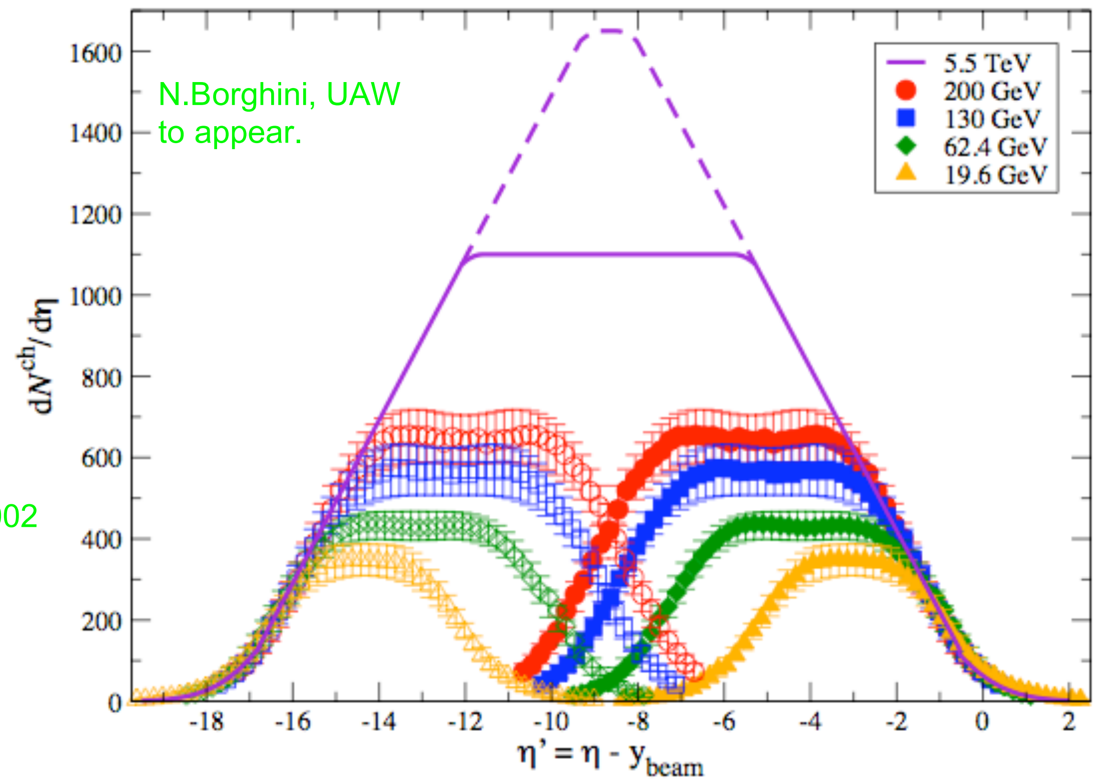
$$\Rightarrow \quad dN^{ch}_{LHC}/d\eta\Big|_{\eta=0} \approx 1650$$

or Kharzeev, Levin, Nardi, NPA747 (2005) 609.

$$\Rightarrow \quad dN^{ch}_{LHC}/d\eta\Big|_{\eta=0} \approx 1800-2100$$

Both consistent with main trends at RHIC, but …

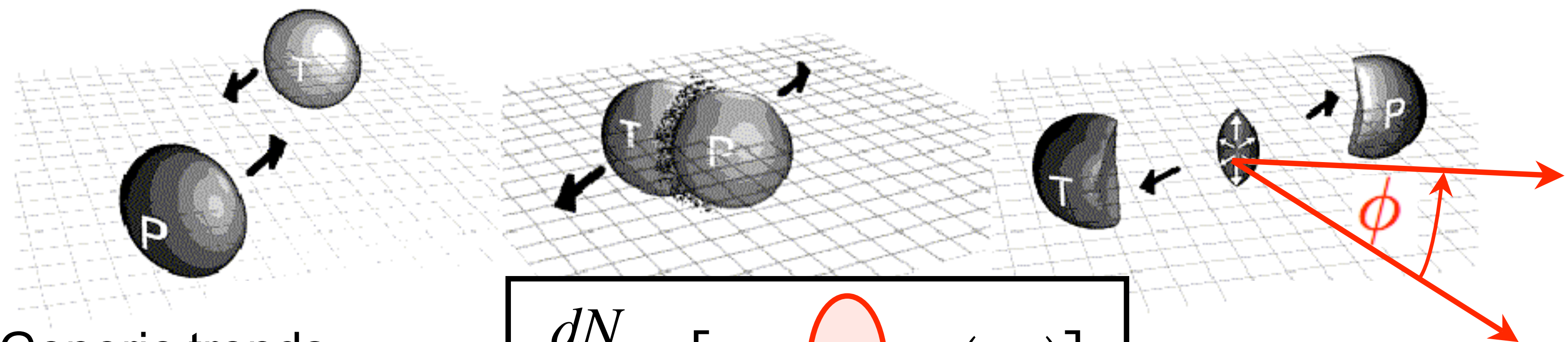
PHOBOS, PRC74 (2006) 021901; W. Busza .



Extrapolations to LHC deviate from so-far generic trends in data

$\Rightarrow$ Impact for understanding the dynamical origin of soft physics at RHIC and LHC.

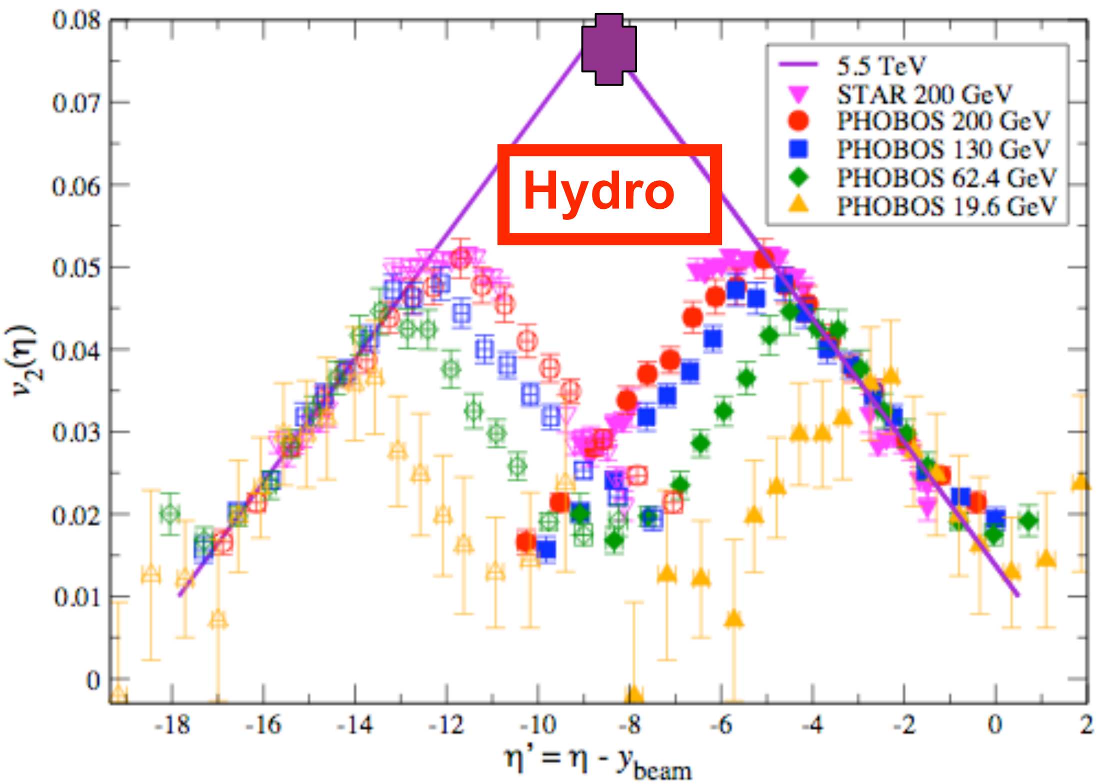
The soft Hallmark of Collectivity



Generic trends in the data:

$$\frac{dN}{d\phi} \propto \left[1 + 2v_2 \cos(2\phi)\right]$$

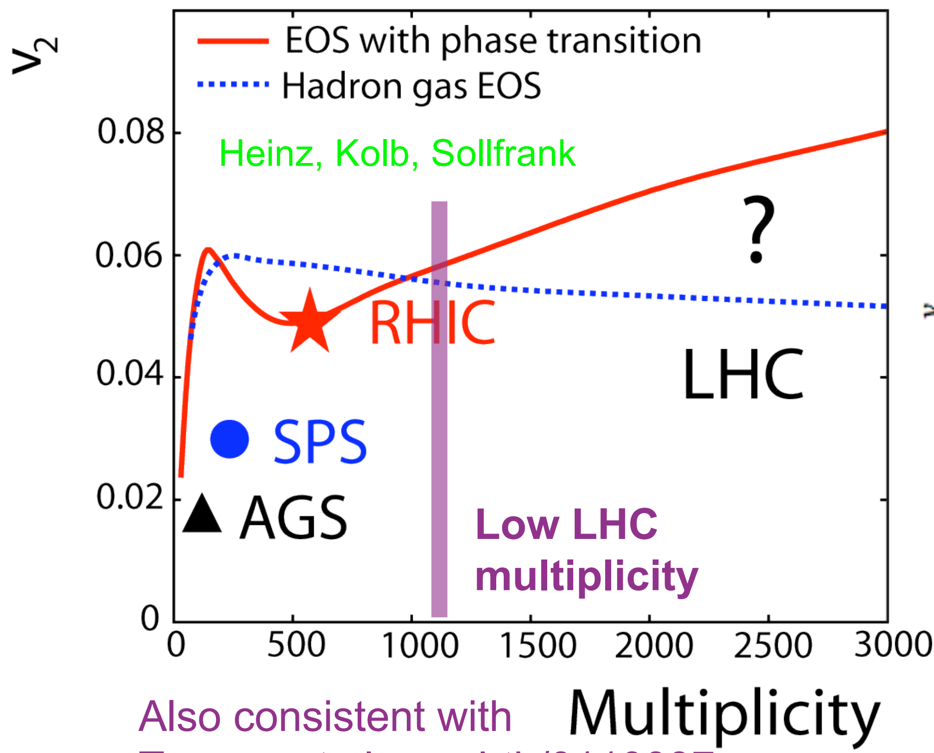
What if they **persist** or **fail**?



LHC tests the hydro-paradigm

- Hydro prediction for low LHC multiplicity

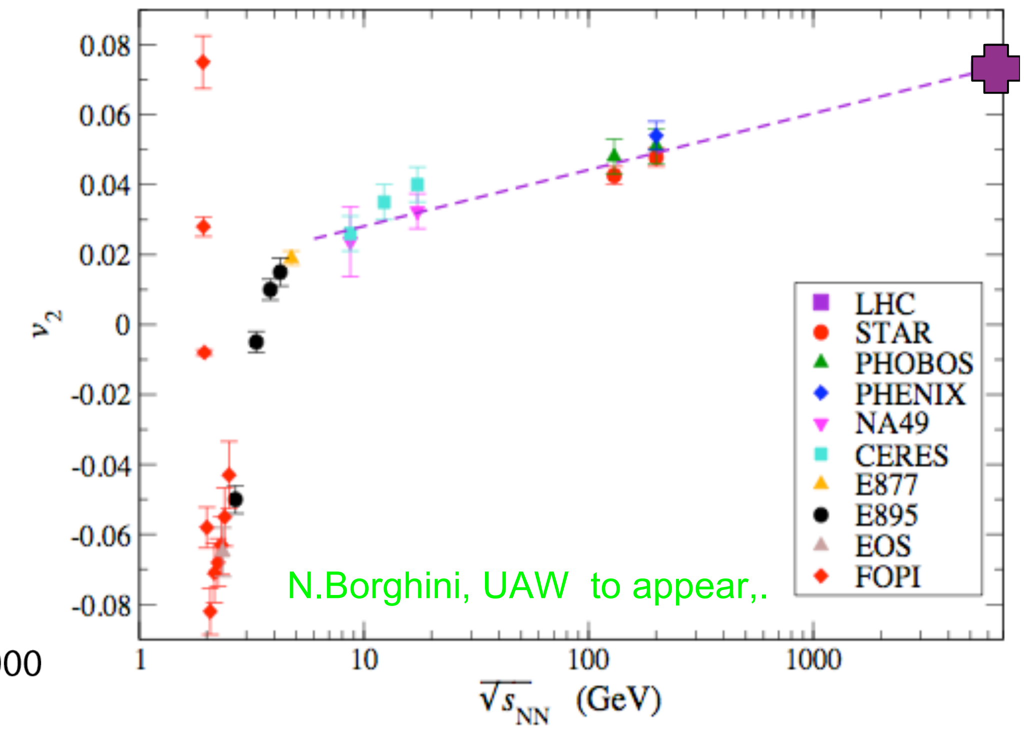
$$v_2 \approx 0.055$$



Also consistent with
Teaney et al., nucl-th/0110037

- Extrapolation of generic RHIC trend

$$v_2 \approx 0.075$$



(In)consistency with generic trend ⟷ Characterization of microscopic dynamics underlying collectivity

Hadrochemistry

- What is the **microscopic dynamics** underlying the success of thermal models?

Precise expectations ⟷ Good benchmarks for characterizing dynamics

Signatures of dynamics:

- Recombination?

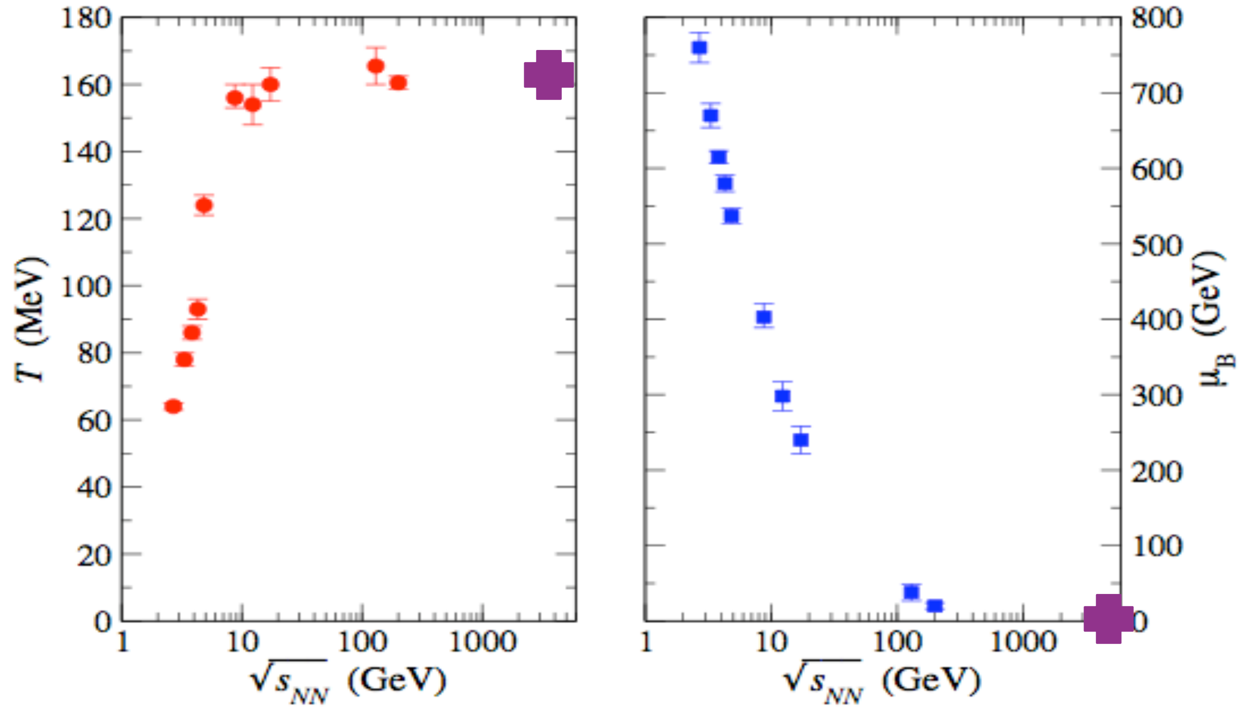
  Rates of J/Psi, D_s, …
  Exogamous pairing indicates randomization of momentum in medium

  Thews, Schroedter, Rafelski, PRC63 (2001) 054901

- strangeness oversaturation?

  Would be dramatic signal

- …?

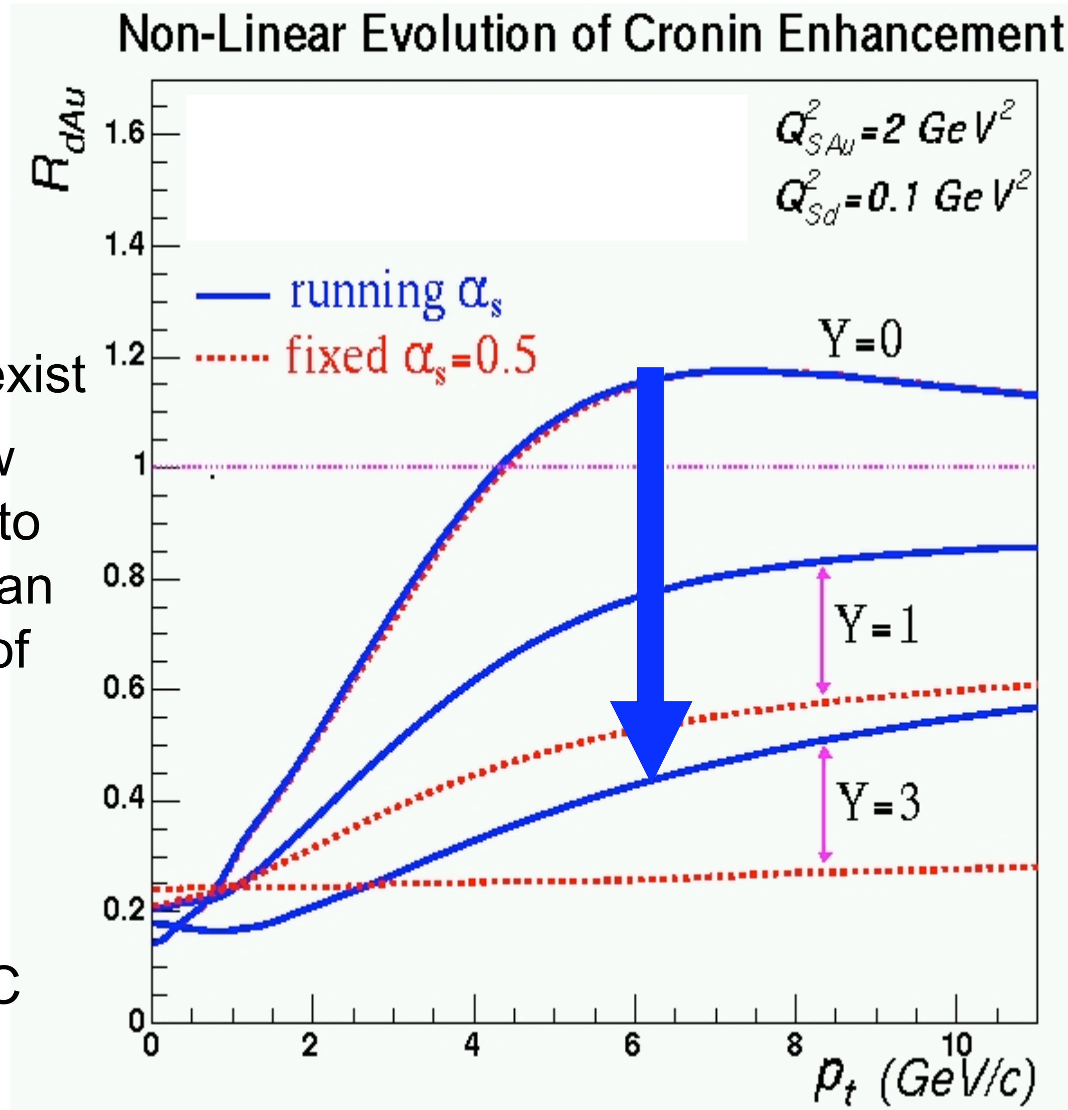


Andronic, Braun-Munzinger, Stachel, NPA772 (2006) 167

Is there a Y=0 Cronin peak in p+A@LHC?

- Saturation physics predicts **strong suppression** of Cronin peak $R_{pA}(p_t) << 1$ at high $\sqrt{s_{NN}}$ or at high rapidity Y.

Kharzeev, Levin, McLerran (2004)
Albacete, Armesto, Kovner, Salgado, Wiedemann, (2004)
Kharzeev, Kovchegov, Tuchin (2004) …



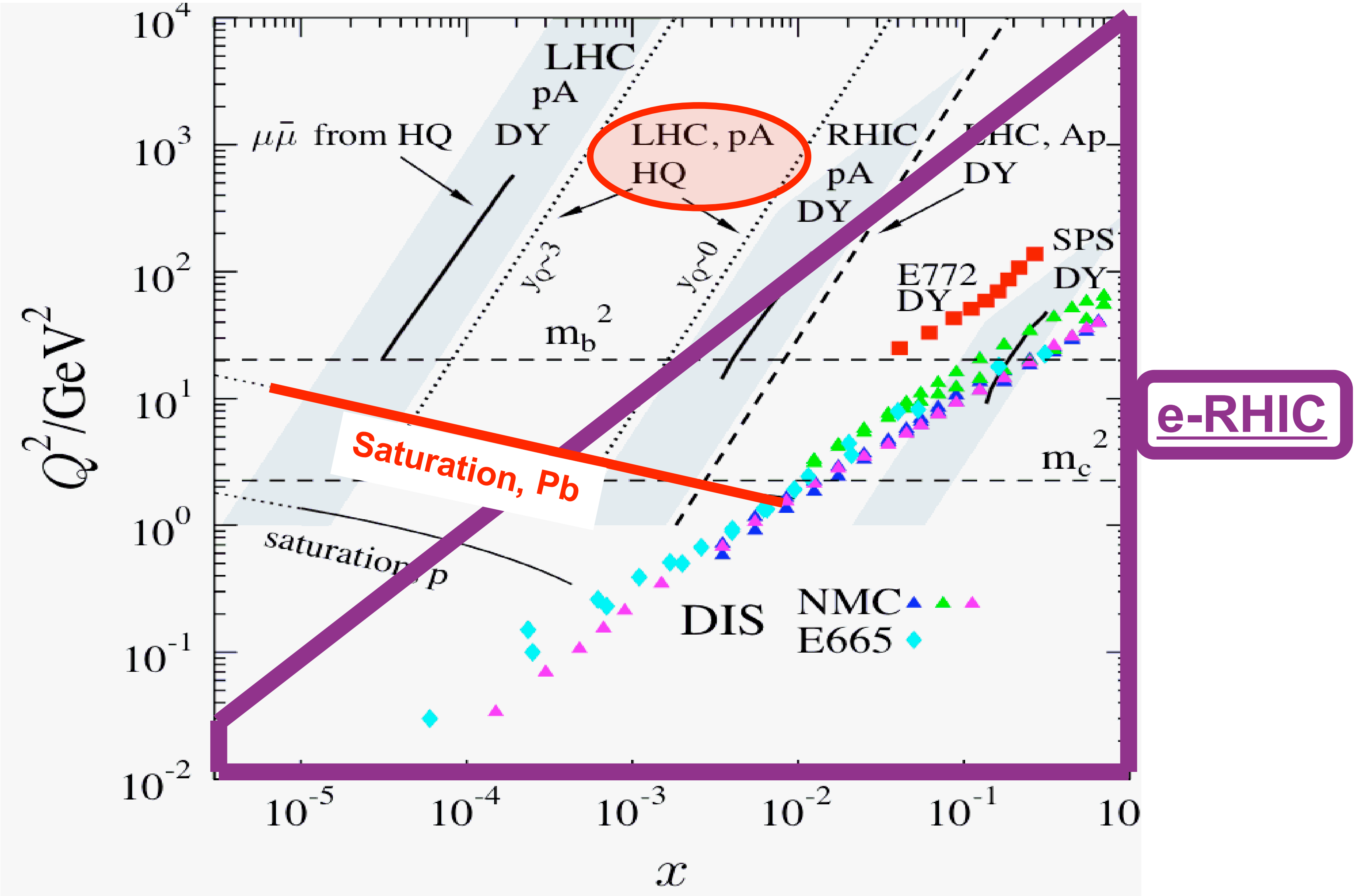
- RHIC data @ forward rapidity qualitatively consistent with non-linear small-x evolution **BUT:** alternative explanations exist

- Understanding whether and how $\sqrt{s_{NN}}$-dependence corresponds to Y-dependence is a key tool for an unambiguous characterization of saturation physics effects.

➡ **RHIC/LHC complementarity**

- Many more observables @ LHC forward rapidity

p+A@LHC adds to physics case for e-RHIC



Eskola et al. Hard Probes in Heavy Ion Collisions at the LHC:
PDFs, Shadowing and pA, hep-ph/0308248

Soft physics@LHC: Expecting the Unexpected

Extrapolating naively to LHC **generic trends** in RHIC data

Extrapolating to LHC the **dynamical models** advocated to underlie multi-particle production at RHIC

- LHC is a discovery machine for soft physics

- Soft physics discoveries @ LHC likely to extend over many years

  - forward physics is not day1 (additional instrumentation?)
  - p+A@LHC will come after several years of running

- Soft physics discoveries @ LHC likely to prompt reassessment of our understanding of RHIC A+A and d+A

  - potential to trigger 2nd generation measurements
  - significant potential to support the case for e-RHIC

- Major tests of QCD come from testing QCD evolution

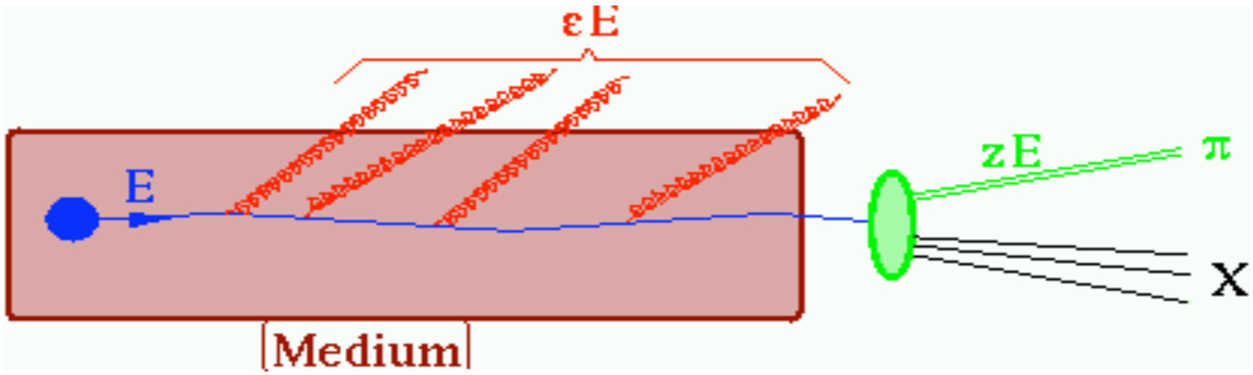
  - novel opportunities with wide rapidity range of LHC
  - only RHIC and LHC together provide sufficiently large $\sqrt{s}$-range

The hard

Abundant yield of hard probes + robust signal (medium sensitivity >> uncertainties) = detailed understanding of dense QCD matter

Which physics becomes newly accessible by extending the p_T-range by a factor 10?

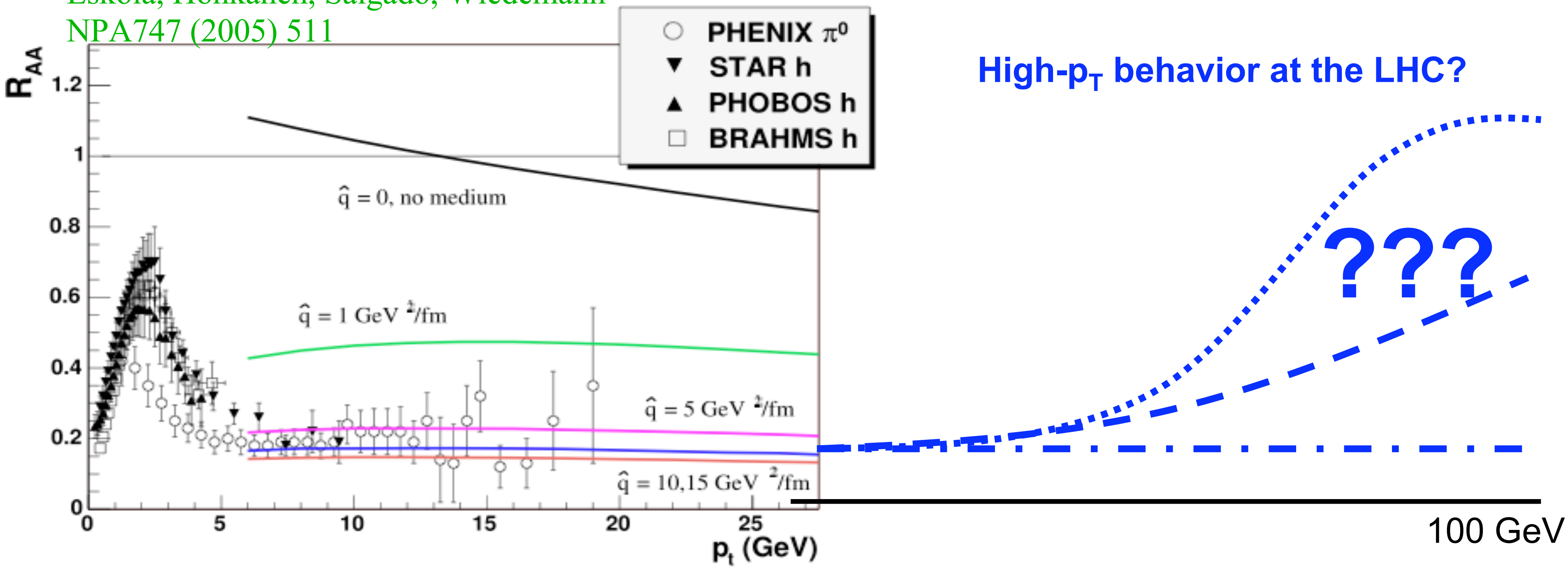
High p_T Single Inclusive Spectra



$$R_{AA}(p_T,\eta) = \frac{dN^{AA}/dp_T d\eta}{n_{coll}\; dN^{NN}/dp_T d\eta}$$

Light-flavored hadron modification factor

Eskola, Honkanen, Salgado, Wiedemann
NPA747 (2005) 511



Extended p_T-range provides novel physics opportunities, e.g.::

- Overcoming the surface bias

$$P_{e-loss}(\Delta E) = p_0 \delta(\Delta E) + p_{tot} \delta(E - \Delta E) + p_{cont}(\Delta E)$$

Continuous piece becomes gradually important at high-p_T
R_{AA} increases with p_T

→ Thorsten Renk

- Becoming sensitive to Q^2- evolution

  Testing Q^2- ordered parton shower in medium requires logarithmically large p_T-range.

→ Borghini,UAW, hep-ph/0506218
Polosa, Salgado, hep-ph/0607295
More to come …

Parton energy loss depends on parton identity

- Vacuum and medium radiation is suppressed due to **quark mass**

Dokshitzer, Kharzeev, PLB 519 (2001) 199

$$\frac{1}{k_T^2} \Rightarrow \frac{k_T^2}{\left(k_T^2 + \frac{m^2}{E^2}\omega^2\right)^2}$$

- Color charge dependence dominates

$$R_{D/h} = R_{AA}^{D} / R_{AA}^{h}$$

$$\Delta E_{gluon} > \Delta E_{quark}$$

- Mass dependence dominates

$$R_{B/h}$$

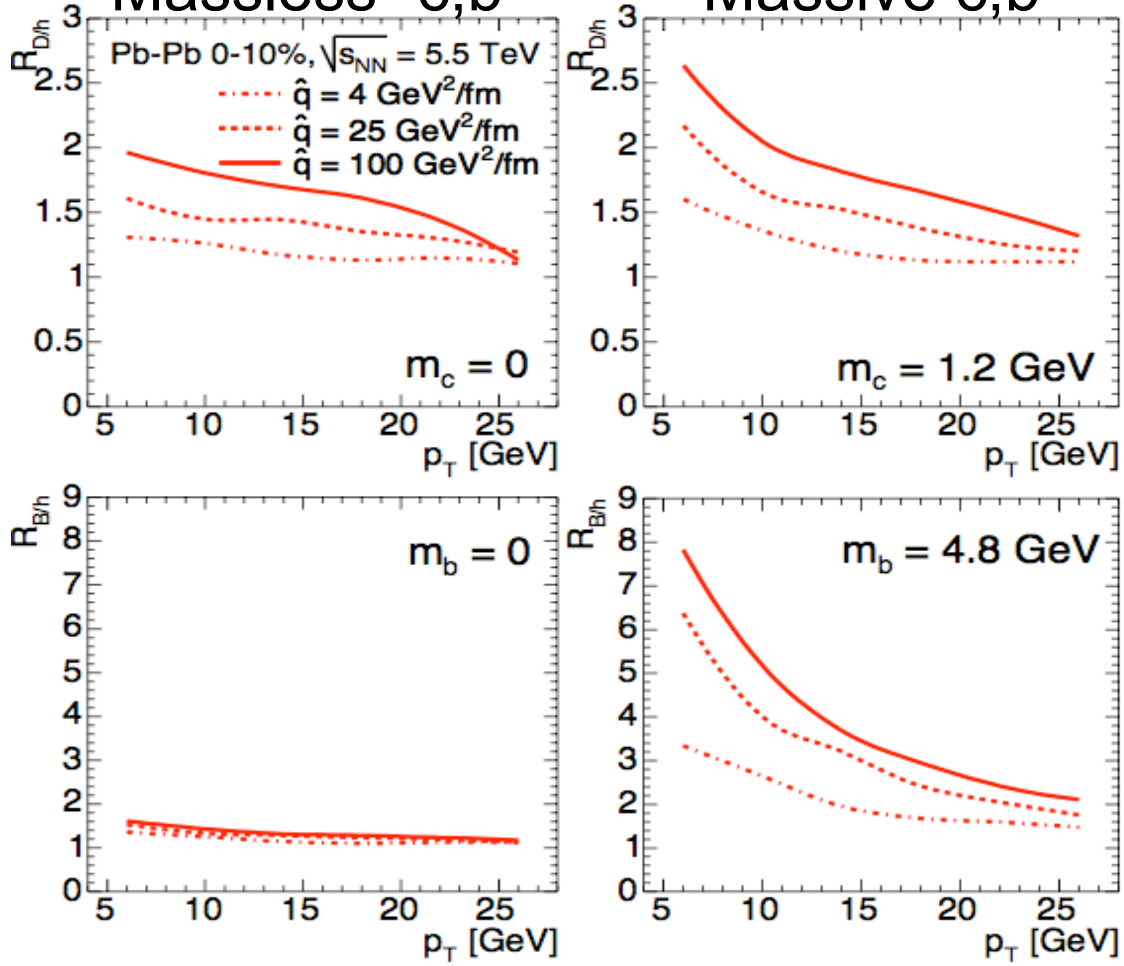
$$\Delta E_{quark,m=0} > \Delta E_{quark,m>0}$$

- To test this at the LHC, exploit:

light-flavored mesons - gluon parents
D - mesons - quark parents (m_c~0)
B - mesons - quark parents (m_b>0)

Armesto, Dainese, Salgado, Wiedemann, PRD71:054027, 2005

Massless "c,b" | Massive c,b



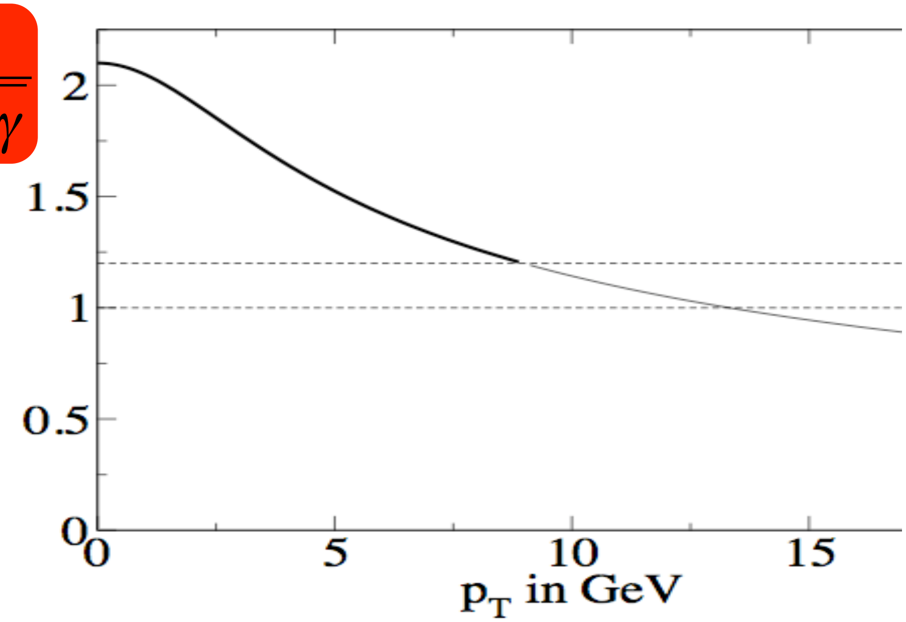
J/Psi as a high-p_T probe

- In AdS/CFT establishes velocity scaling of screening length

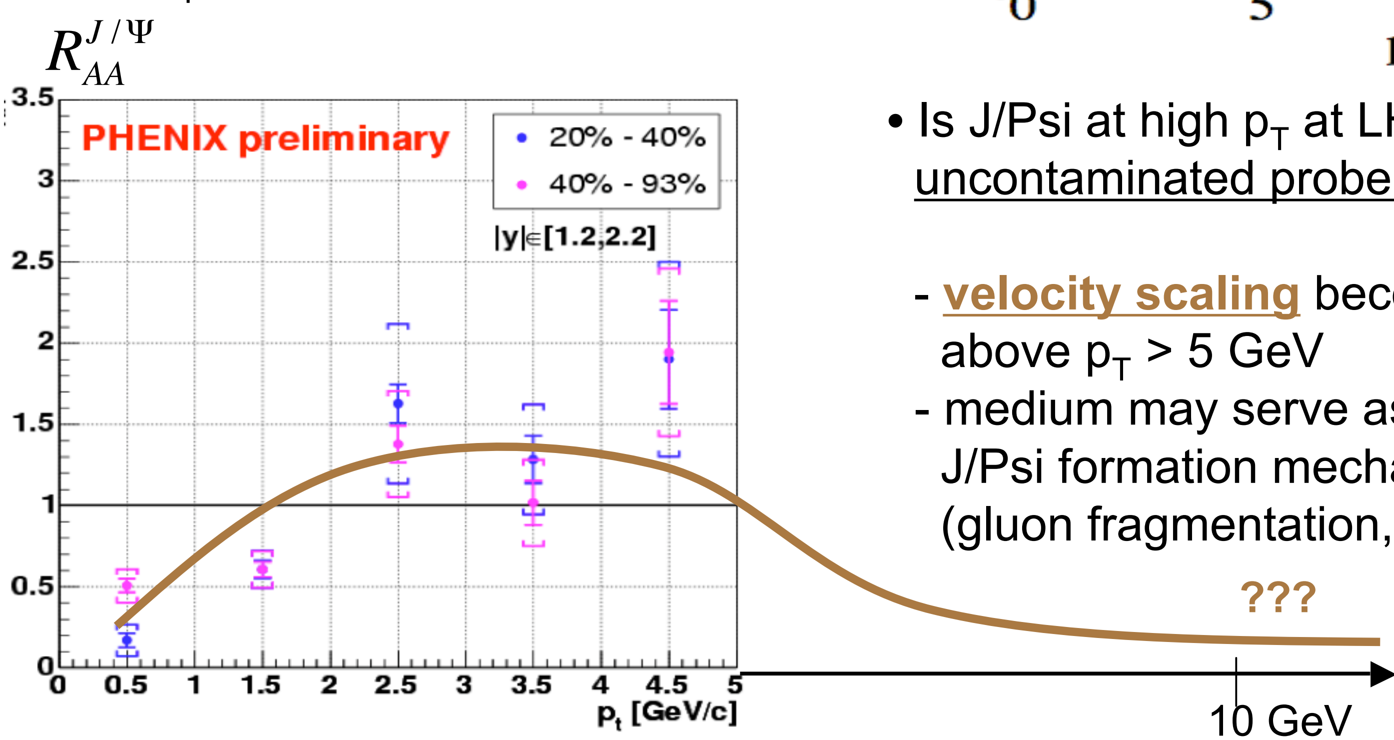
$$L_{screening}^{Q\bar{Q}} \propto \frac{1}{T\sqrt{\gamma}}$$

Hong, Rajagopal, Wiedemann, hep-ph/0607062

$$\frac{T_{diss}}{T_{crit}\sqrt{\gamma}}$$



- LHC determines J/Psi production up to p_T = 20 GeV

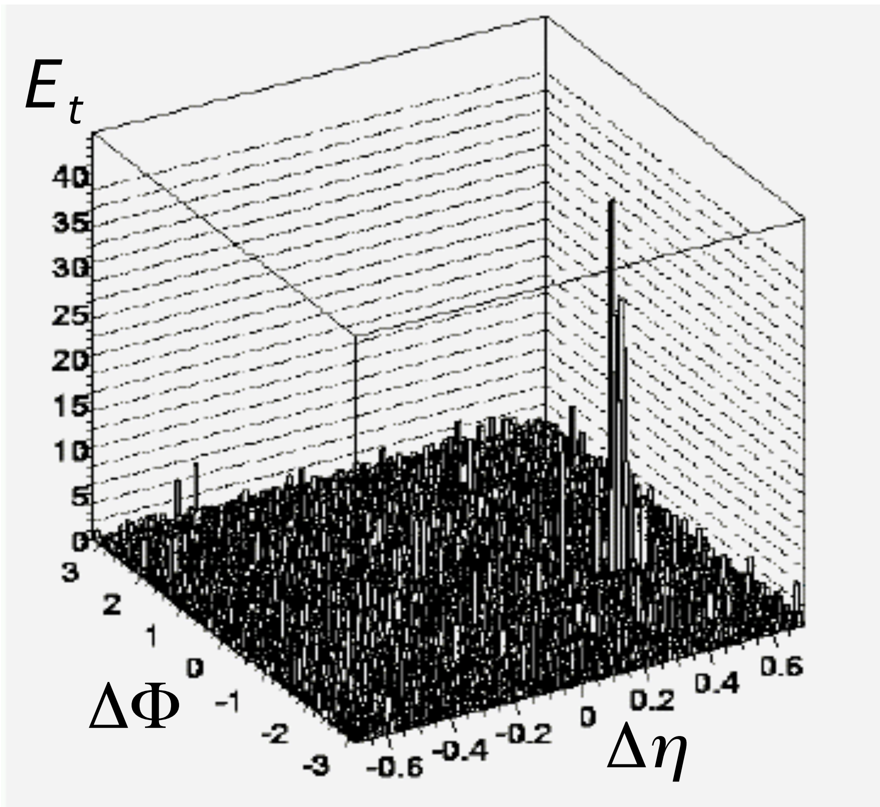


(Hand-drawn sketch)

- Is J/Psi at high p_T at LHC a clean, <u>uncontaminated probe of color screening</u>?

  - <u>**velocity scaling**</u> becomes effective above p_T > 5 GeV
  - medium may serve as tool to characterize J/Psi formation mechanism (gluon fragmentation, formation time …)

"True" Jets



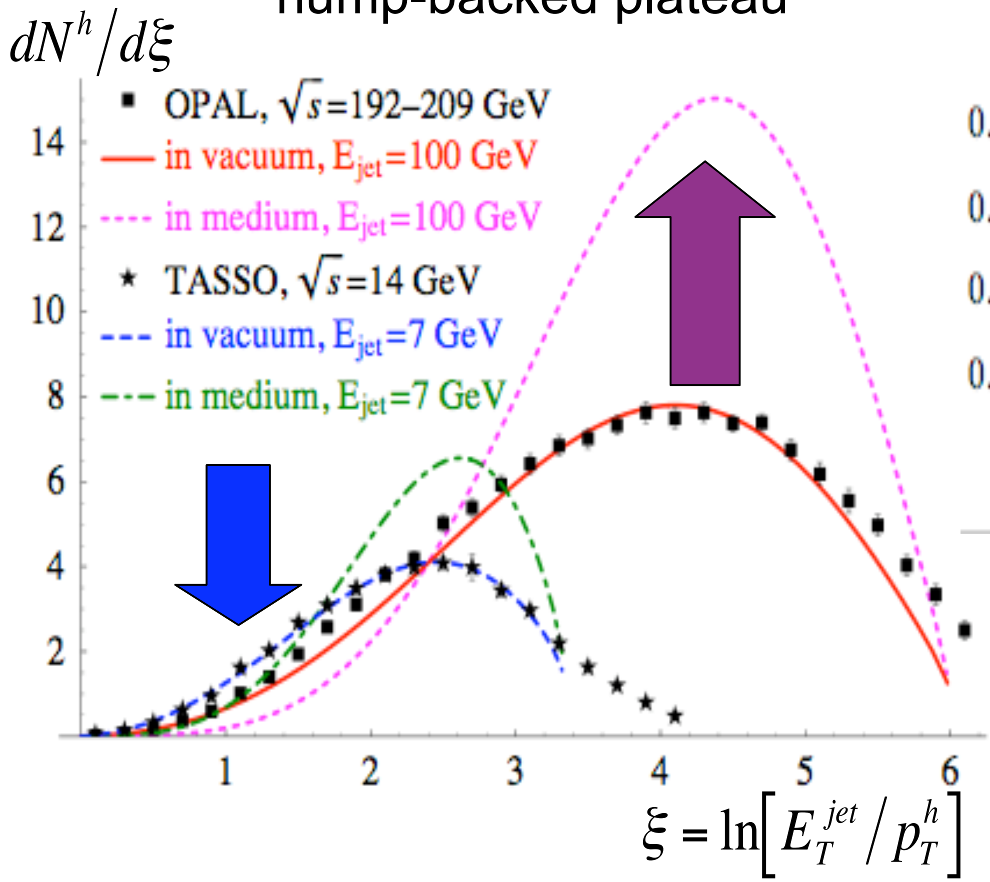
E_t
40
35
30
25
20
15
10
5
0
3
2
1
0
-1
-2
-3
$\Delta\Phi$
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
$\Delta\eta$

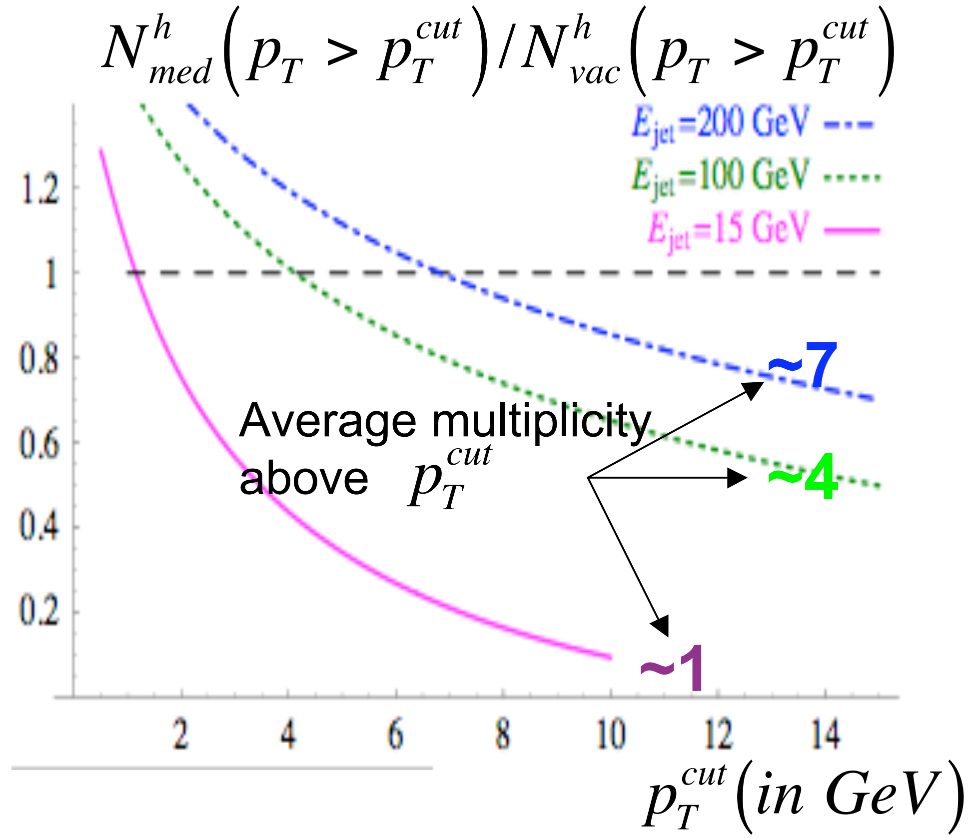
Longitudinal Jet Heating

Borghini, Wiedemann, hep-ph/0506218

- If **leading hadron** in jet is suppressed then **soft jet multiplicity** must increase

⇨ Medium-modification of hump-backed plateau





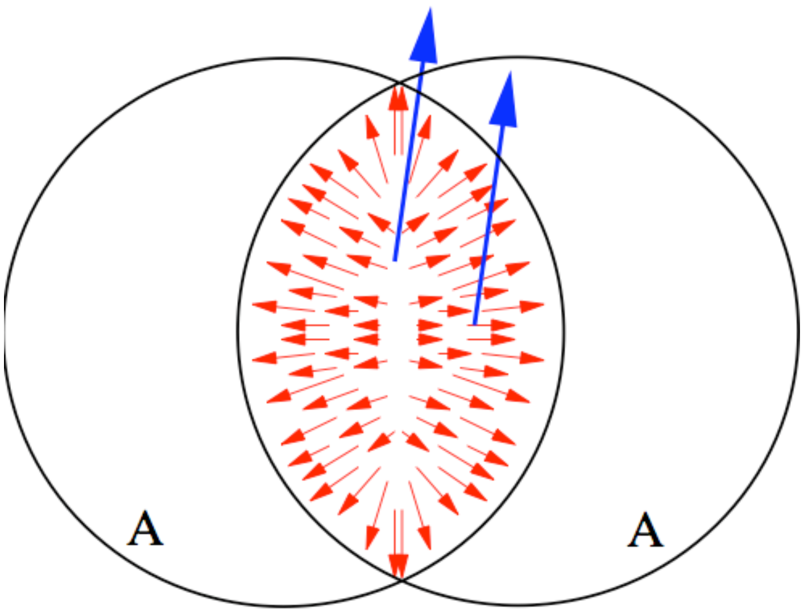
Quantitative improvement of tools ⟷ **Qualitatively** novel access to medium properties

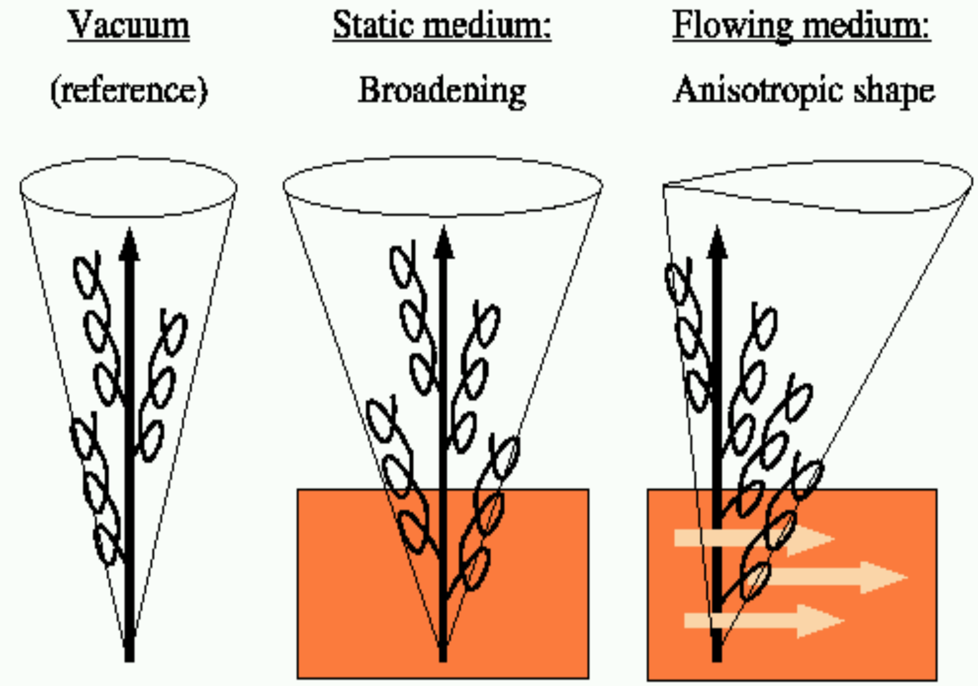
Jets in pionic winds and partonic storms

If **hard partons** are produced outside rest frame comoving with medium, then jets sensitive to **boost** and **orientation**

Hong, Rajagopal, Wiedemann, in preparation

$$\hat{q} = \left(\cosh\eta_f + \cos\theta \sinh\eta_f\right)\hat{q}_0$$





Armesto, Salgado, Wiedemann, PRL 93 (2004) 242301

Effects:

- broken $\Delta\eta \times \Delta\phi$ - symmetry of jet shapes and particle correlations.
- increased high-pt elliptic flow.

What can we learn from jets at the LHC?

- Jets as thermometer

$$\hat{q} \propto T^3$$

- Jets as recoil-meter
  - is the ability of a medium to accept recoil one of its properties?
  - can we gain information about constituents of the medium by kicking them out of the medium (collisional mechanism)

- Jets as flow-meter
  - independent characterization of the main collective phenomenon

- Jets as remnants of a non-equilibrium test particle
  - how does a parton equilibrate kinetically ?
    chemically ?

- Jets as viscosity-meter
  - see talk by Casalderrey-Solana

- …

Quantitative improvement of tools ⟷ **Qualitatively** novel access to medium properties

CERN TH Institute announces workshop

Heavy Ion Collisions at the LHC Last Call for Predictions

Nestor Armesto *(main organizer)*, ***Nicolas Borghini***, ***Sangyong Jeon***
Local contact: Urs A. Wiedemann

14 May - 8 June 2007
CERN, Geneva

- Review Predictions experimentally accessible in the LHC HI runs
- Document them in a proceedings article and discuss their implications

The abundance of scales and probes

The probes:
- Jets
- identified hadron specta
- D-,B-mesons
- Quarkonia
- Photons
- Z-boson tags

The range:

Q^2 ,x, A, luminosity

Abundant yield

of hard probes

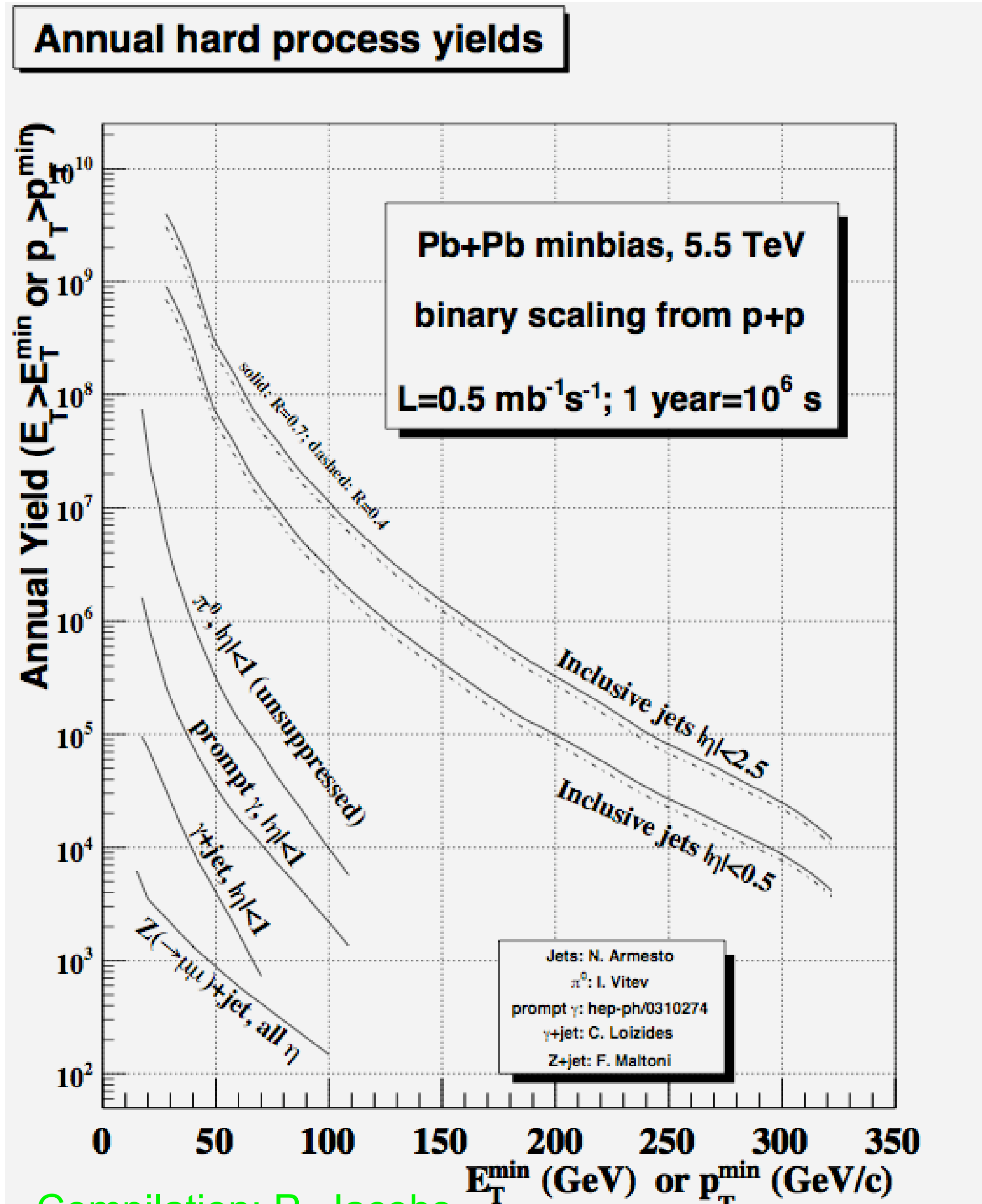
+ robust signal

(medium sensitivity

>> uncertainties)

= detailed understanding

of dense QCD matter



Compilation: P. Jacobs