Hot and dense QCD at the beginning of the LHC

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II CPAN Days - Valencia - November 2010

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Disclaimer: LHC is performing so well in PbPb mode that
I ended up with a very optimistic talk. First results are just exciting

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QCD defined as our most perfect physical theory

[Wilczek 2000]

An apparently simple lagrangian hides a plethora of **emerging phenomena**

[Confinement; chiral symmetry breaking and mass generation; new phases of matter; a rich hadronic spectrum; a non-trivial vacuum structure; asymptotic freedom, etc]

High-energy heavy-ion collisions are experimental tools to access (some of) these properties

Towards the highest energies

SPS@CERN - Fixed target

pA, SU, PbPb - 90's

$\sqrt{s} \simeq 20\mathrm{AGeV}$

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RHIC@BNL - Collider

CuCu, AuAu, dAu
2000 - ...

$\sqrt{s} = 20...200\mathrm{AGeV}$

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2000 - ...

$\sqrt{s} = 20...200\mathrm{AGeV}$

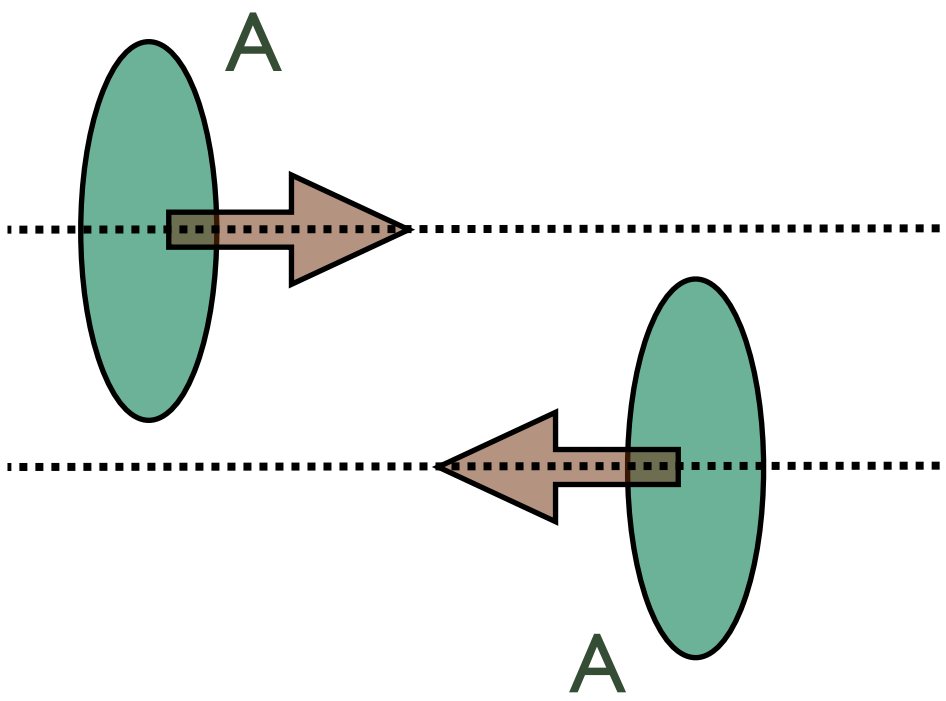
x30

(pp), PbPb, pPb
Energy frontier of HI
Starting three weeks ago

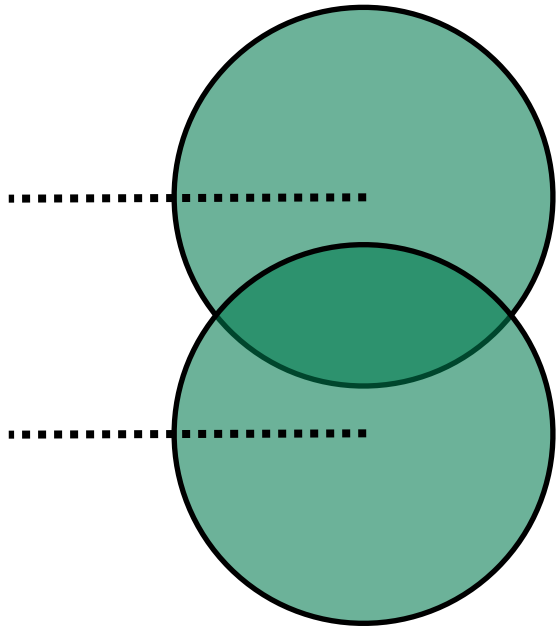
LHC@CERN - Collider

$\sqrt{s} = 2.76...5.5ATeV$

Some jargon... centrality of the collision



Longitudinal view



Transverse view

⇒ Experimental access to different medium densities and geometries

⇒ Normally computed in a (probabilistic) geometrical model by Glauber

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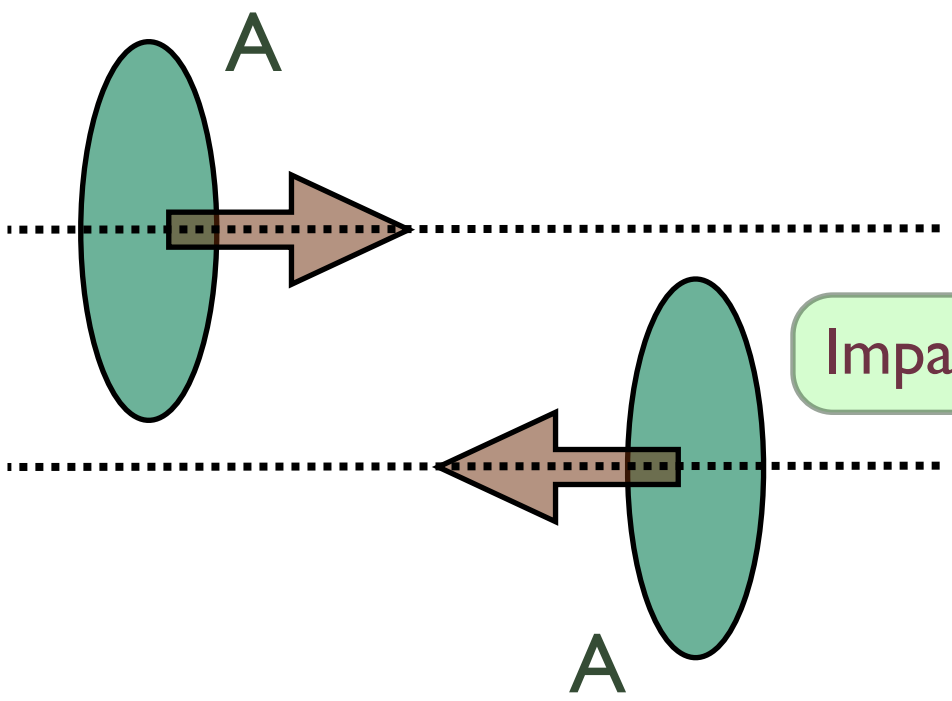
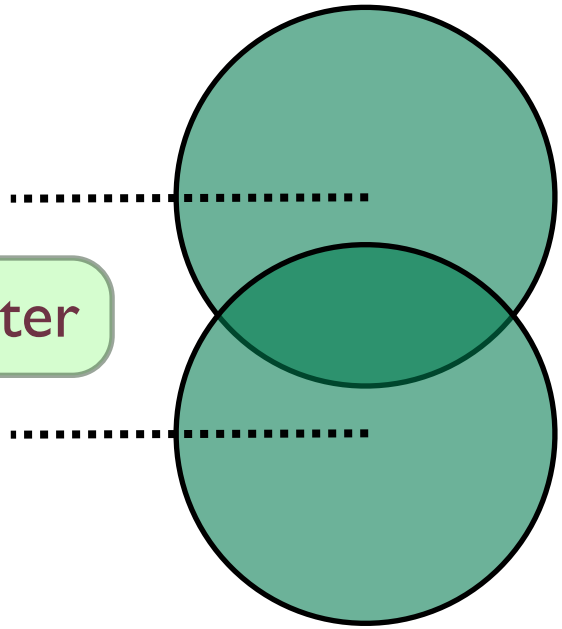


Longitudinal view

Impact parameter



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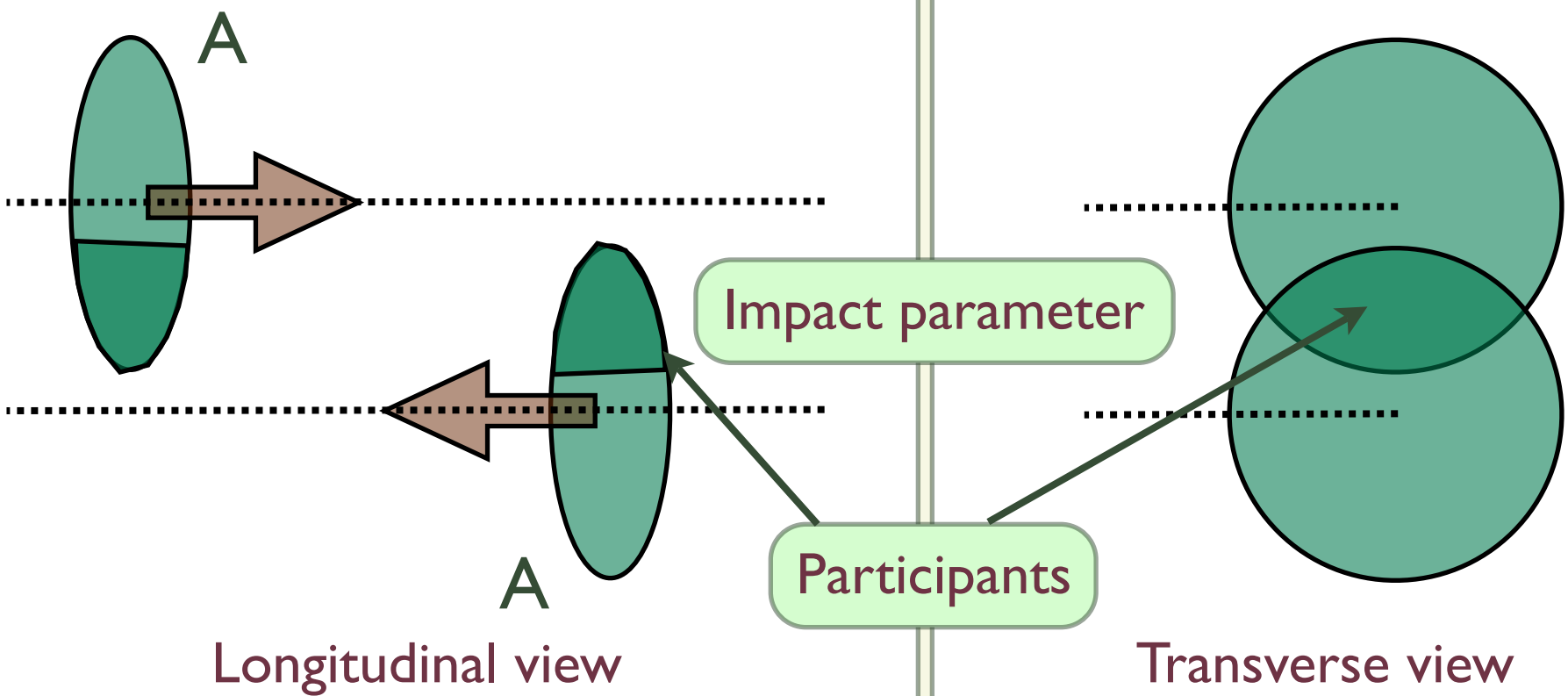

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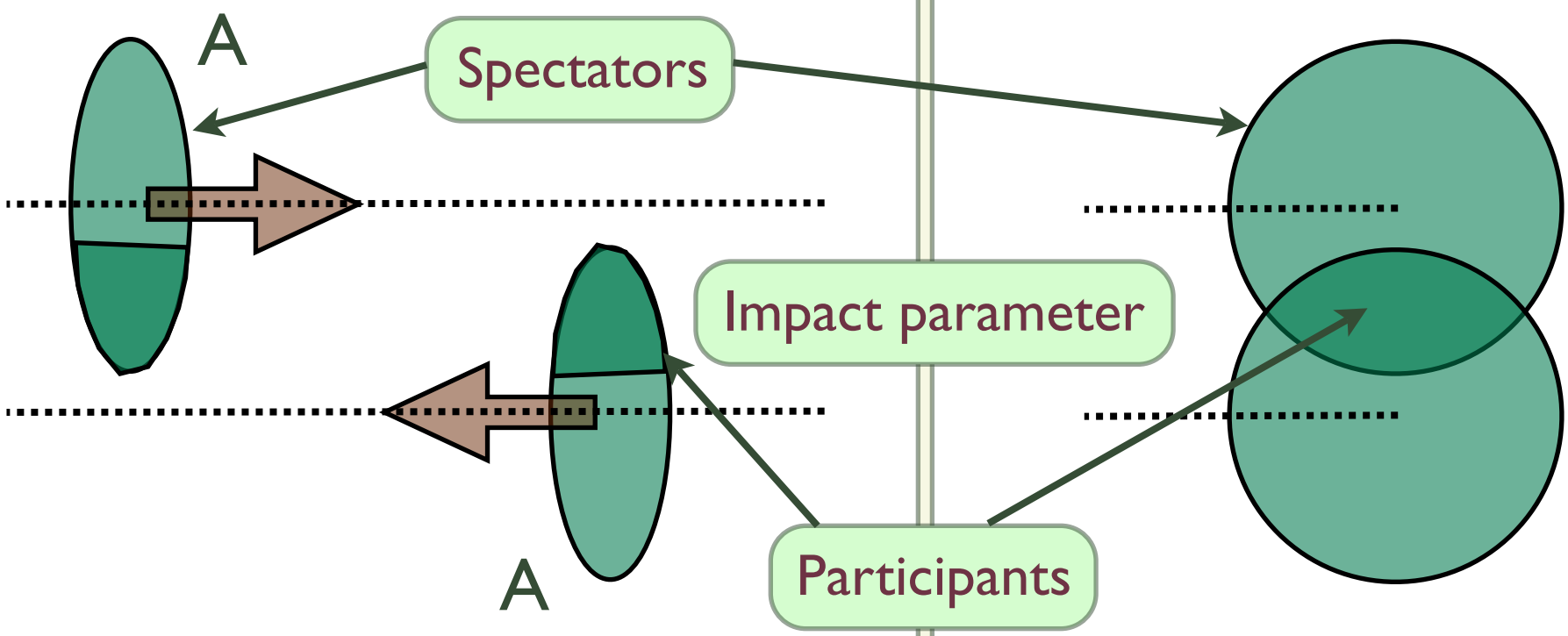

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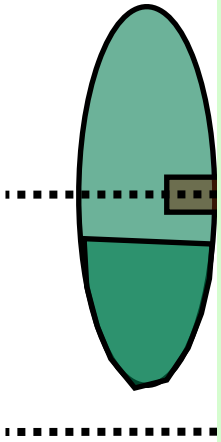
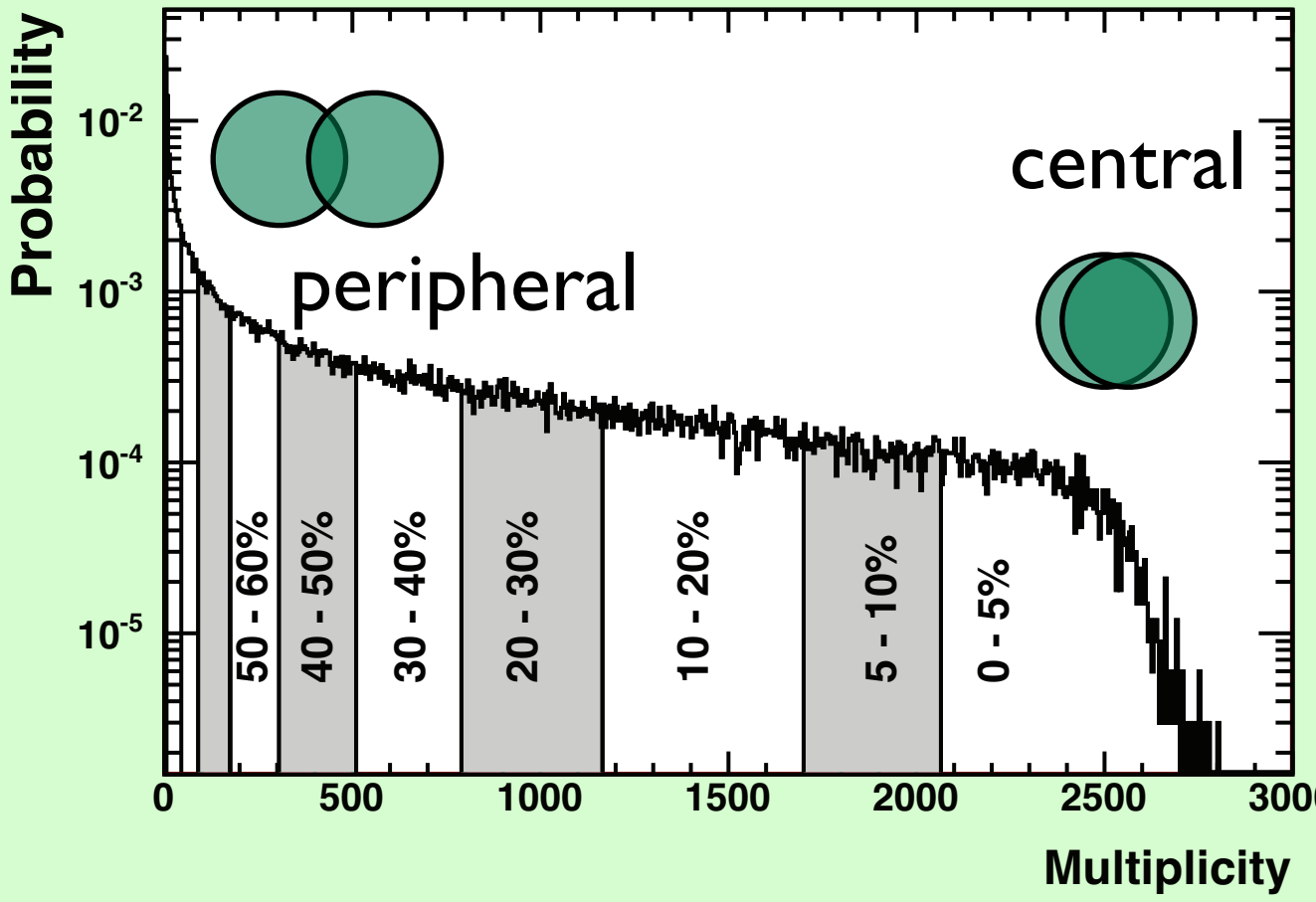
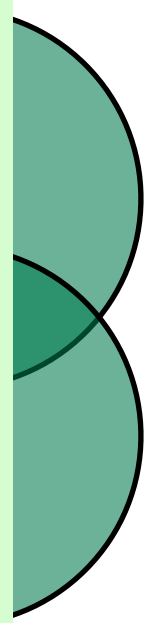






- Experimental access to different medium densities and geometries
- Normally computed in a (probabilistic) geometrical model by Glauber

Three main observations at RHIC

[RHIC experiments white papers]

- Strong screening in the nuclear wave functions

  → *color coherence effects in particle production.*

- Data compatible with low viscosities

  → *ideal fluid behavior.*

- Large effects on jets - jet quenching

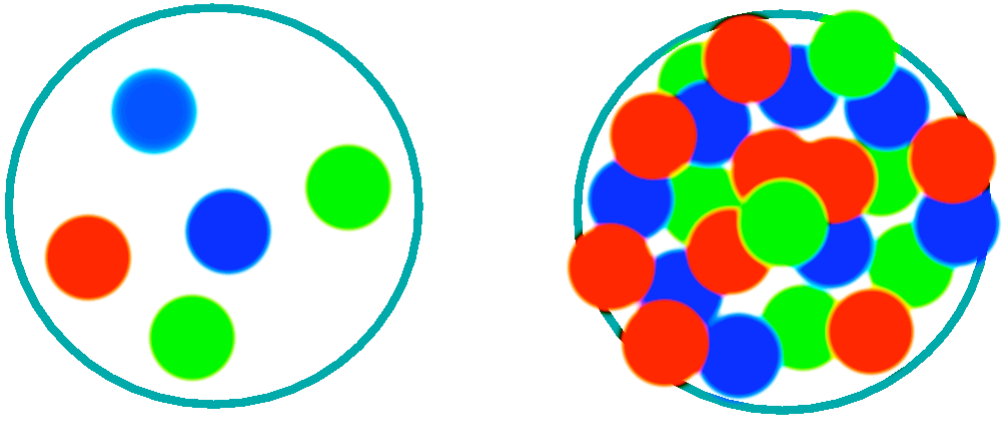
  → *dense partonic system.*

1. High-density initial state

Color screening in the small-x region

Color screening in partonic densities: picture

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



increasing energy (decreasing x)

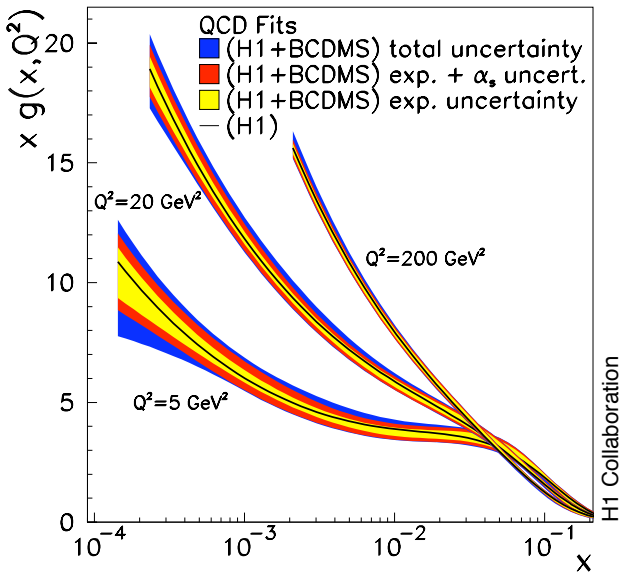
transverse area of the gluon

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

transverse area of the nucleus

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

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



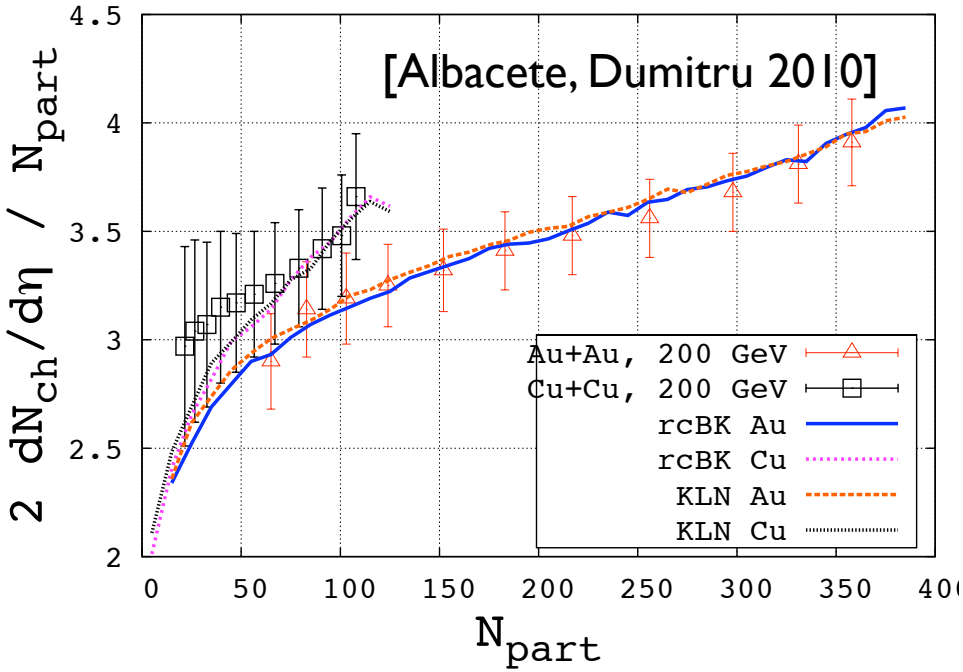
Strong fields and large occupation numbers.
Semiclassical approach: Color Glass Condensate
Geometric scaling

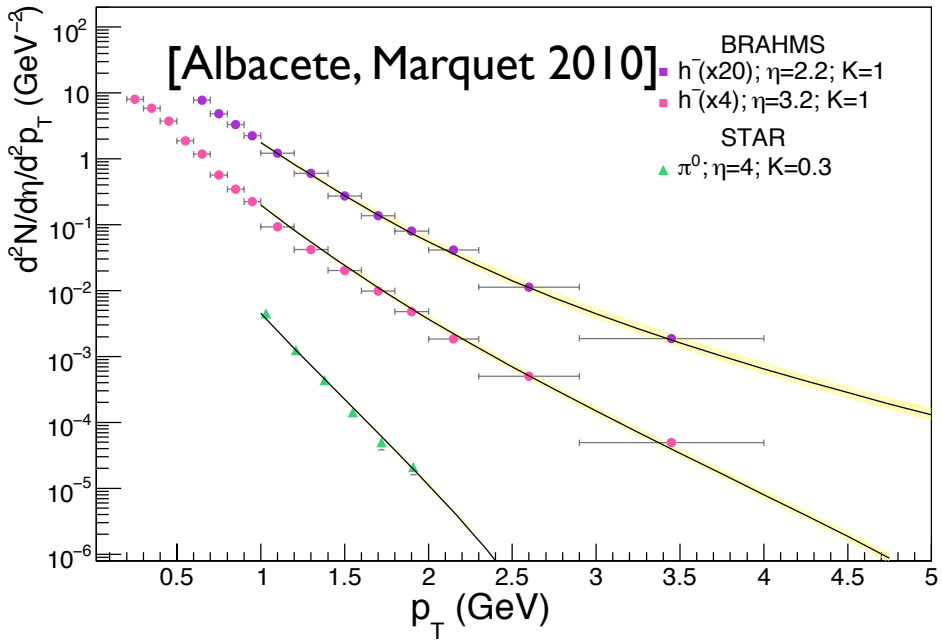
New (non-linear) evolution equations

- Technically, screening translates into non-linearities in evolution eqs.

$$\frac{\partial N(r,x)}{\partial \log(x_0/x)} = \int d\mathbf{r_1}\, K(\mathbf{r},\mathbf{r_1},\mathbf{r_2})\,[N(r_1,x)+N(r_2,x)-N(r,x)-N(r_1,x)N(r_2,x)]$$

- Balitsky-Kovchegov eqs. [New NLO: Balitsky, Chirilli, Kovchegov, Weigert, Albacete]
- Provides a solid theoretical framework to do phenomenology





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Linear: Balitsky-Fadin-Kuraev-Lipatov — Non-linear term

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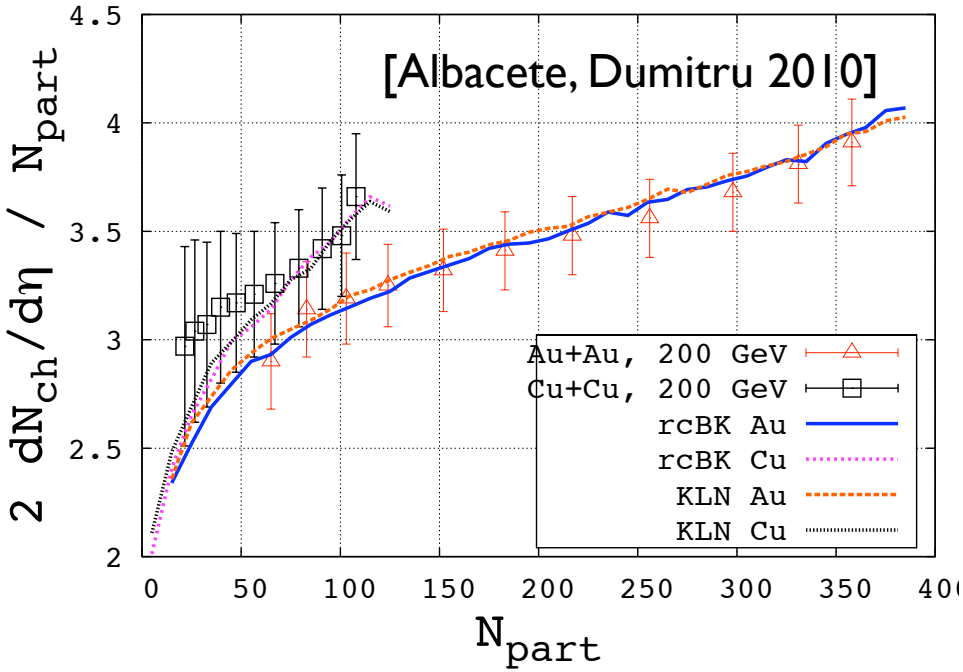
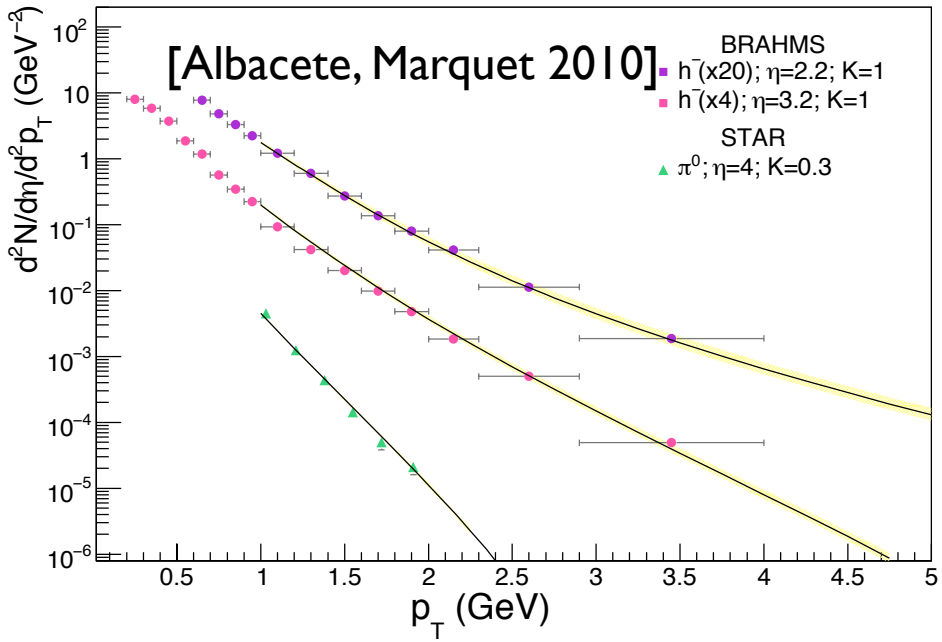


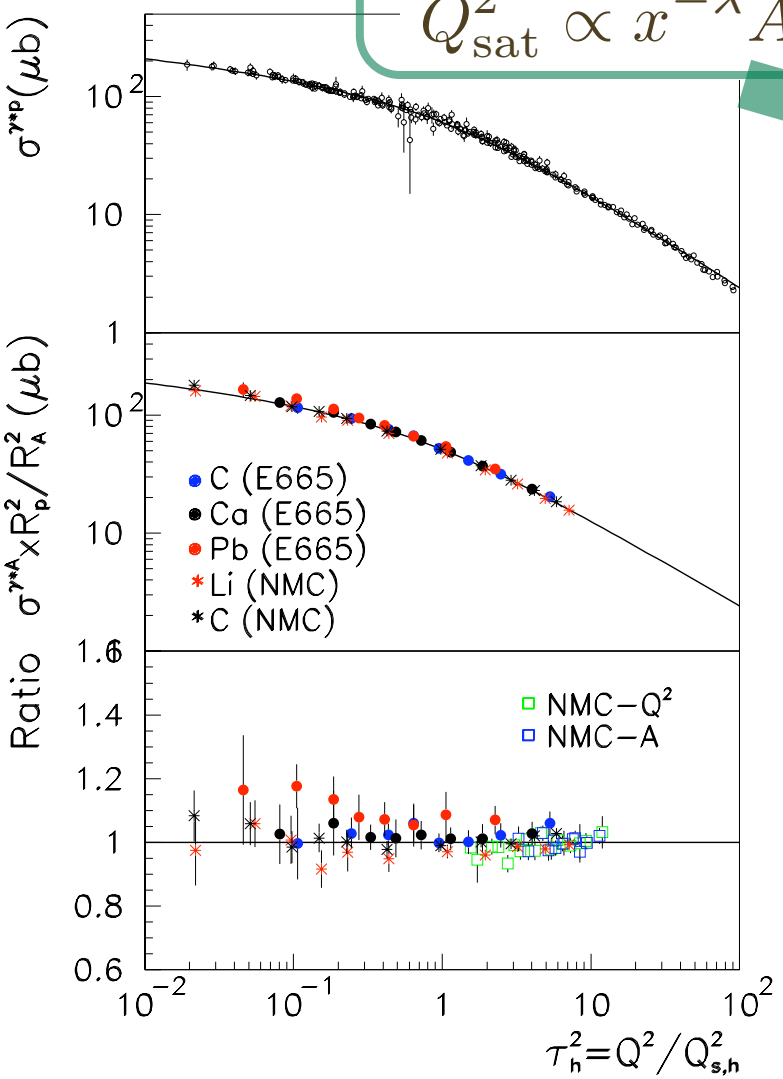


Geometric scaling and data

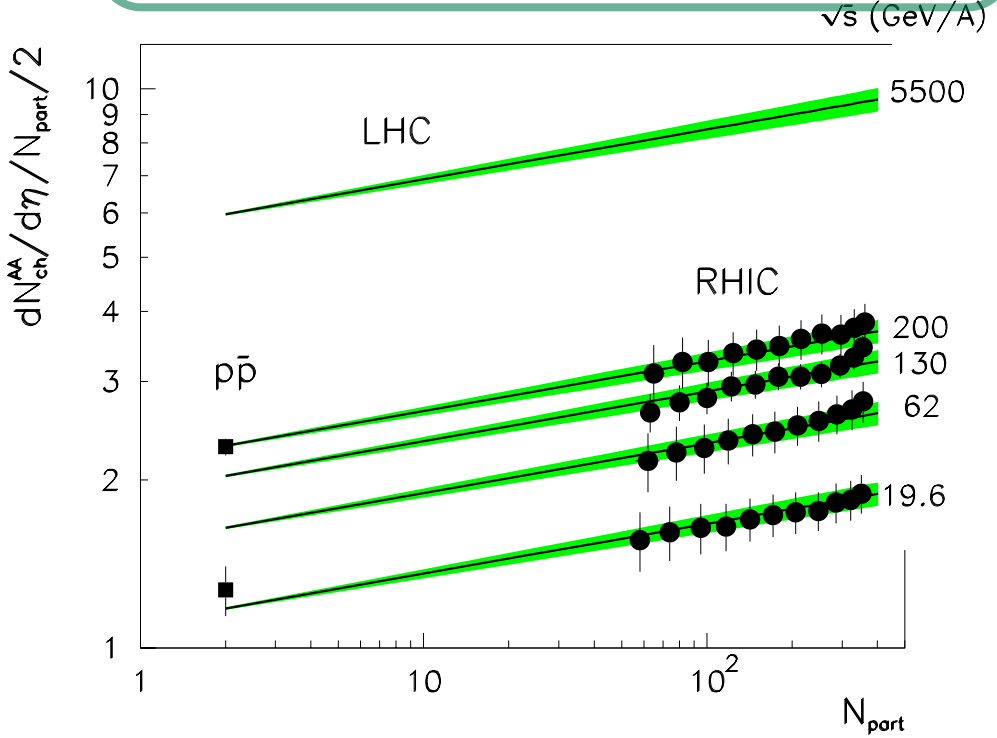
$$Q^2_{\rm sat} \propto x^{-\lambda} A^{1/3\delta}$$

[Armesto, Salgado, Wiedemann 2004]

$$\left.\frac{2}{N_{\rm part}}\frac{dN^{AA}}{d\eta}\right|_{\eta\sim 0} = N_0 \sqrt{s}^{\lambda} N_{\rm part}^{\frac{1-\delta}{3\delta}}$$



[Stasto, Golec-Biernat, Kwiecinski 2001; Armesto, Salgado, Wiedemann 2004]



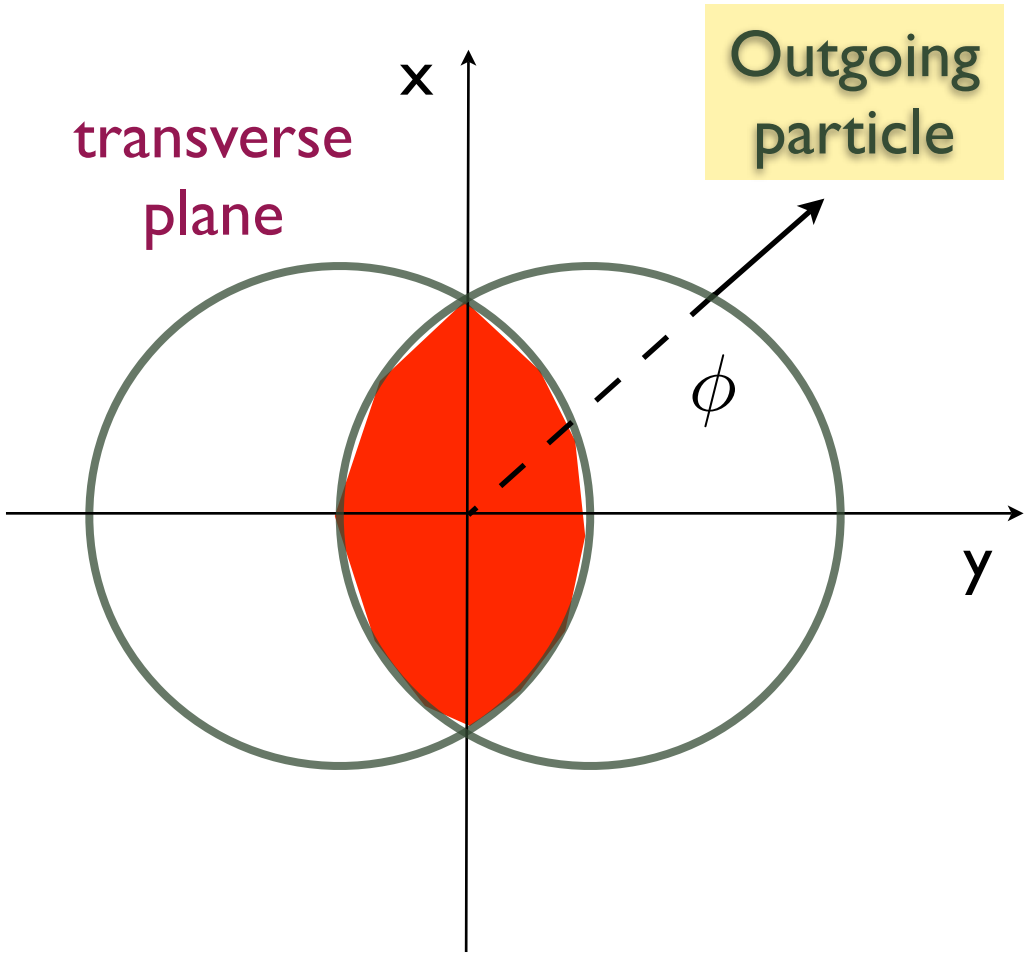
Energy and centrality dependences fixed by lepton-nucleus data

2. Checks of hydrodynamics (thermalization)

The essential measurement for hydro

⇛ Recall the Euler equation

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



The essential measurement for hydro

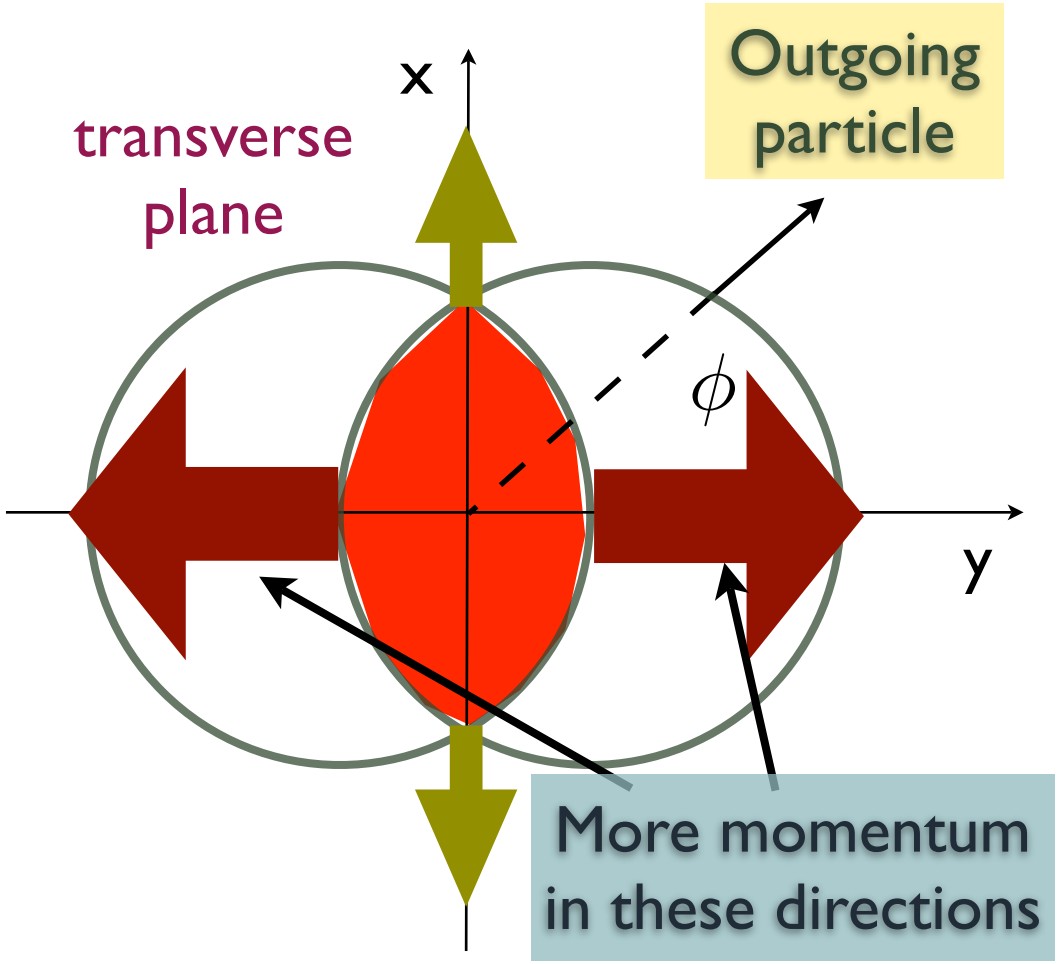
⇛ Recall the Euler equation

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

$$\epsilon = 3P \implies \nabla_x P < \nabla_y P$$

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

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

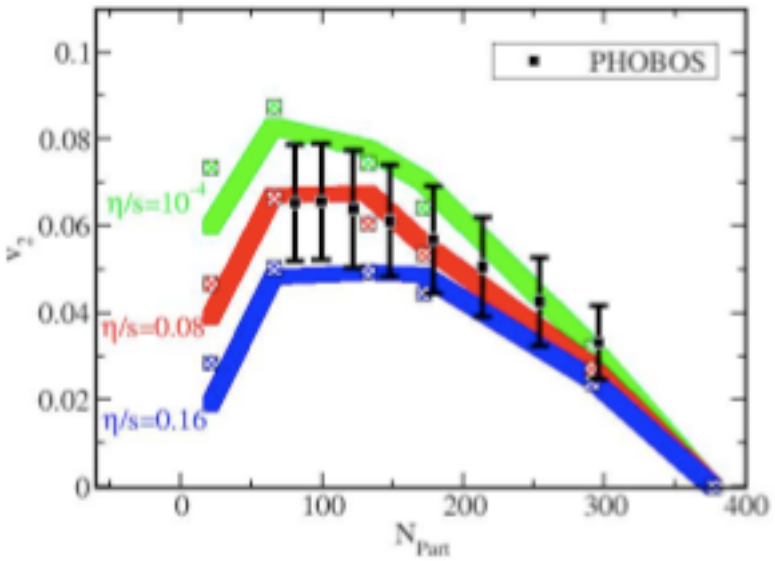


Initial conditions at thermalization time need to be given (ex. CGC)

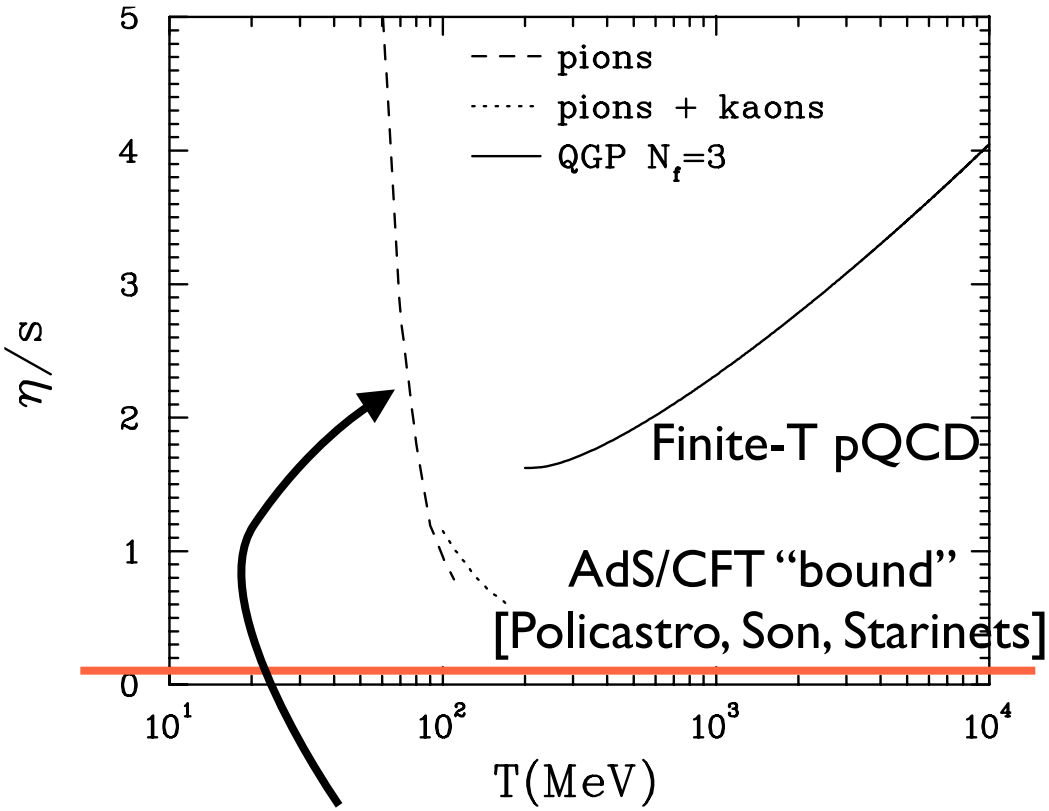
One of the first measurements at RHIC

Large elliptic flow compatible with hydrodynamics

[Luzum, Romatschke 2008]



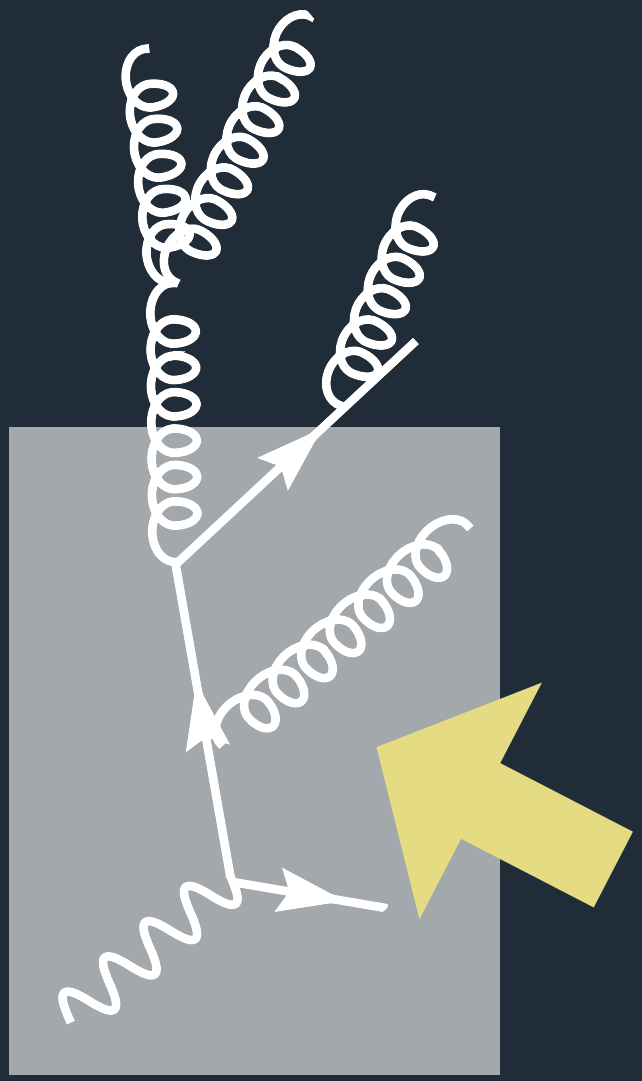
[Csernai, Kapusta, Mclerran 2006]



[New estimates: Fernandez-Fraile, Gomez-Nicola 2009, 2010]

⇛ **Lowest viscosity known**

- Ideal fluid behavior
- "perfect liquid"



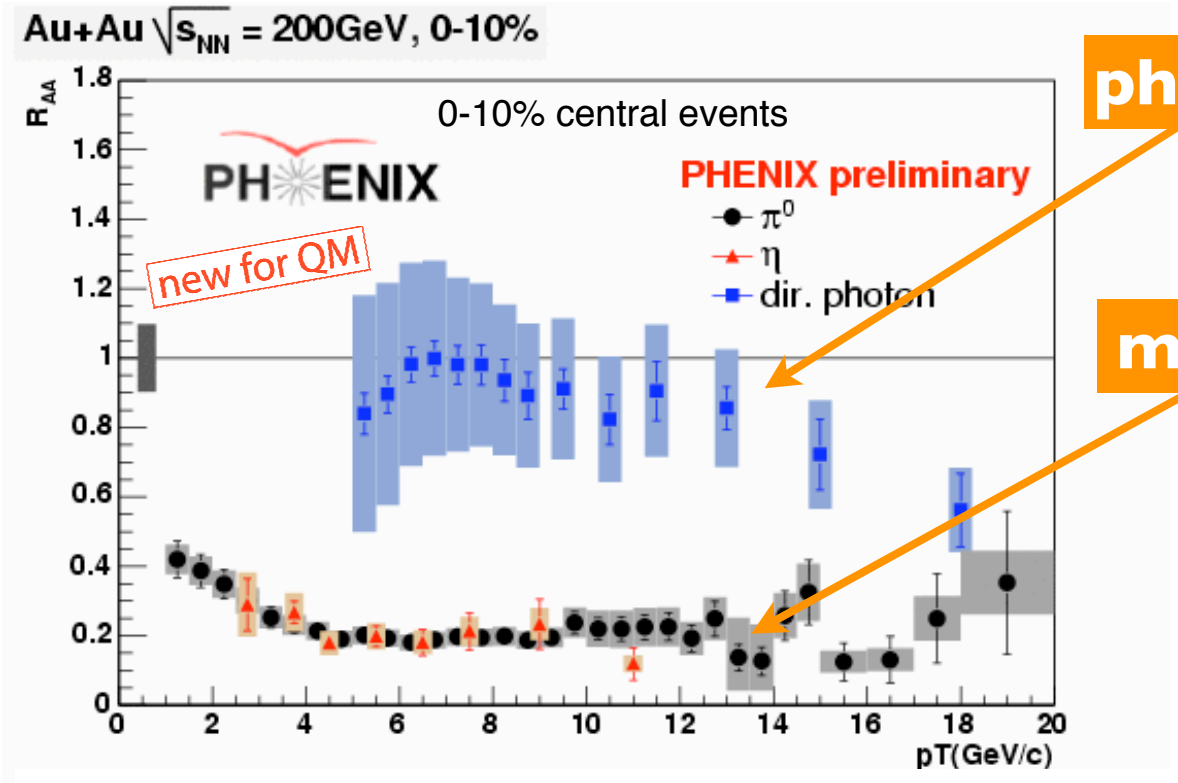
3. Jet quenching

- *Jets are extended objects*
- *In HIC the hard process takes place at very early times*
- *Energy loss of fast parton*

How does the extension of the jet interfere with the extension of the medium?

Jet quenching at RHIC

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



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

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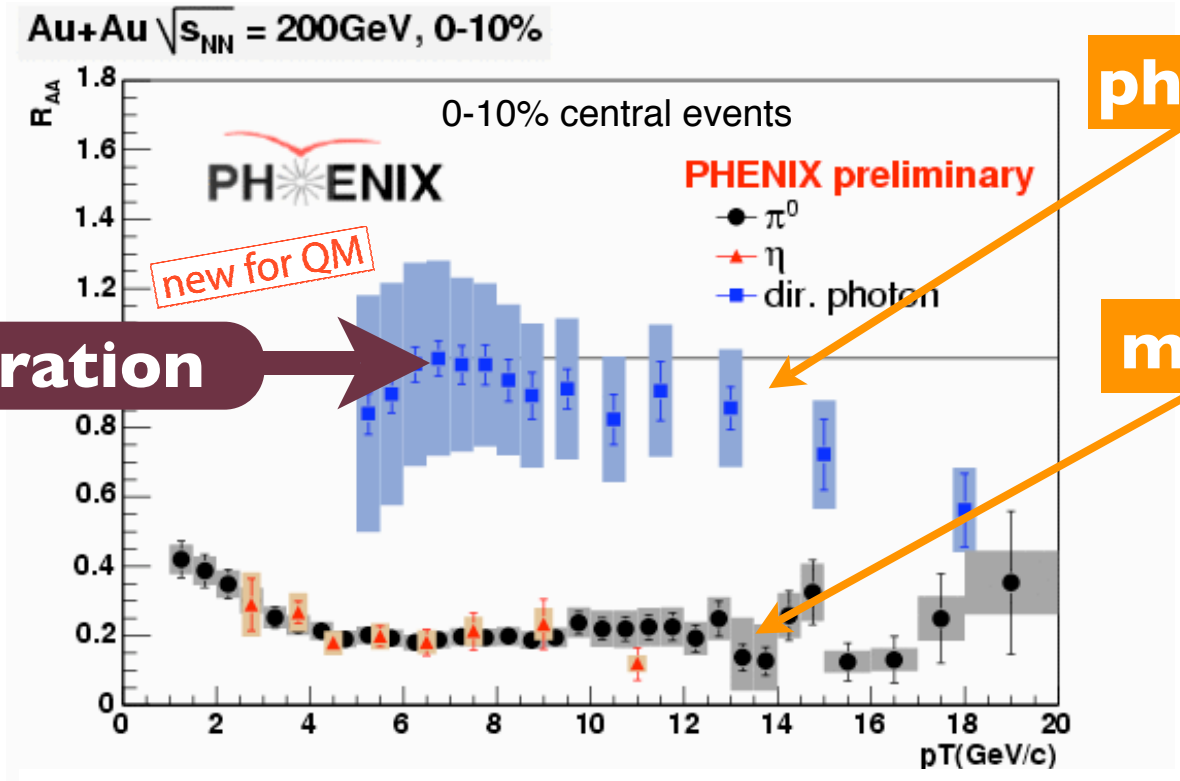
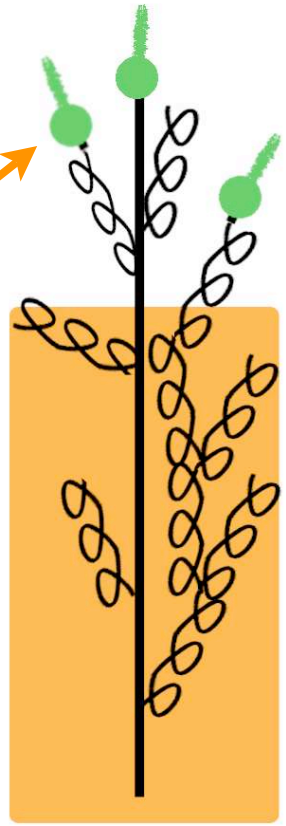


Calibration

photons

mesons



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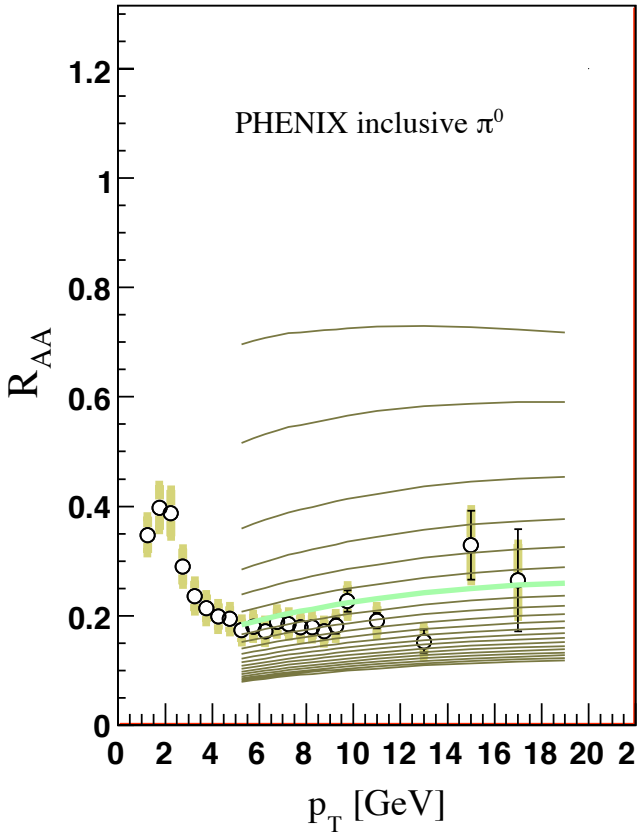
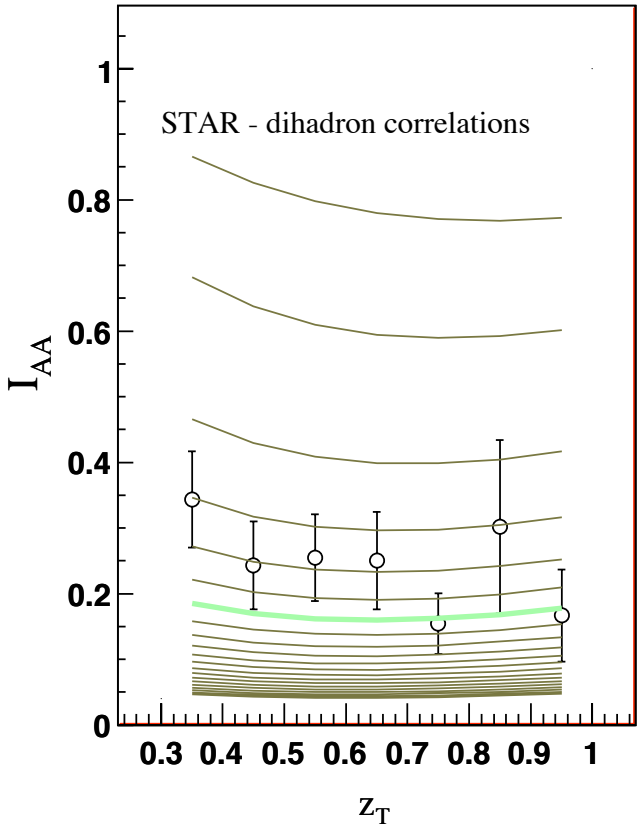
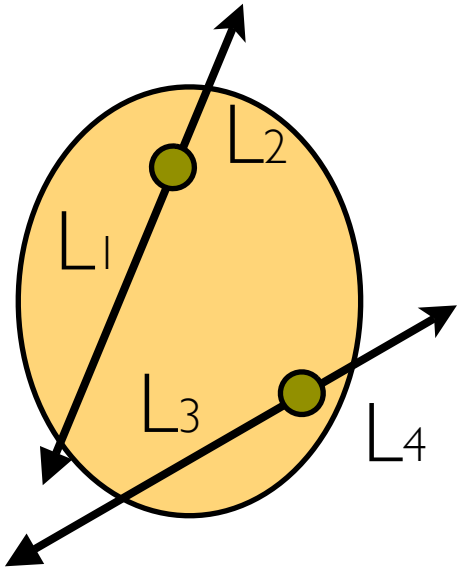
Global fit to data using a hydrodynamical medium

⇛ Fit several observables to obtain the jet quenching parameter

[Armesto, Cacciari, Hirano, Nagle, Salgado, 2009]





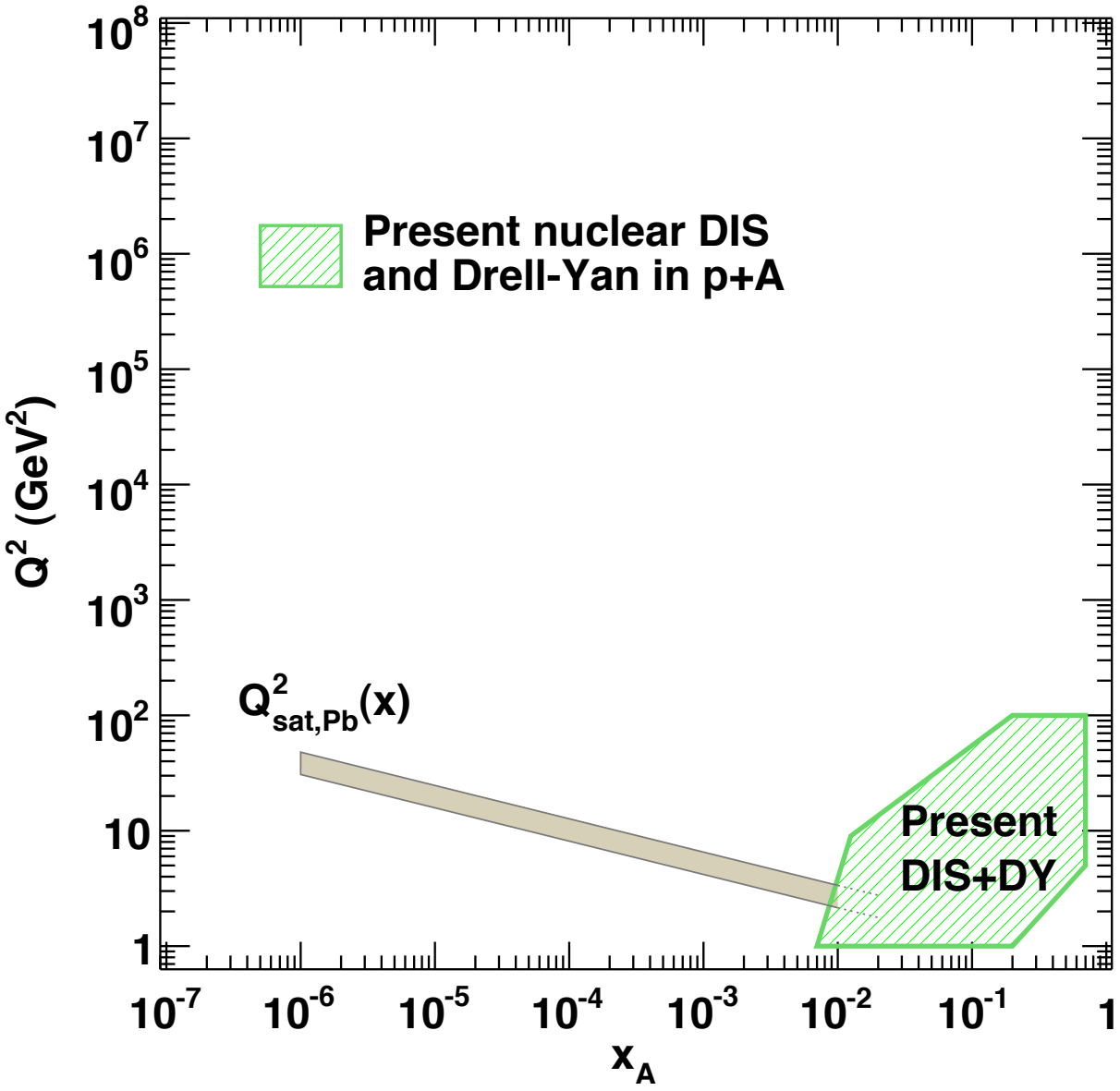


⇛ Very large energy loss - **large jet quenching parameter**

dense partonic system

LHC

Kinematical reach in nuclear collisions at the LHC



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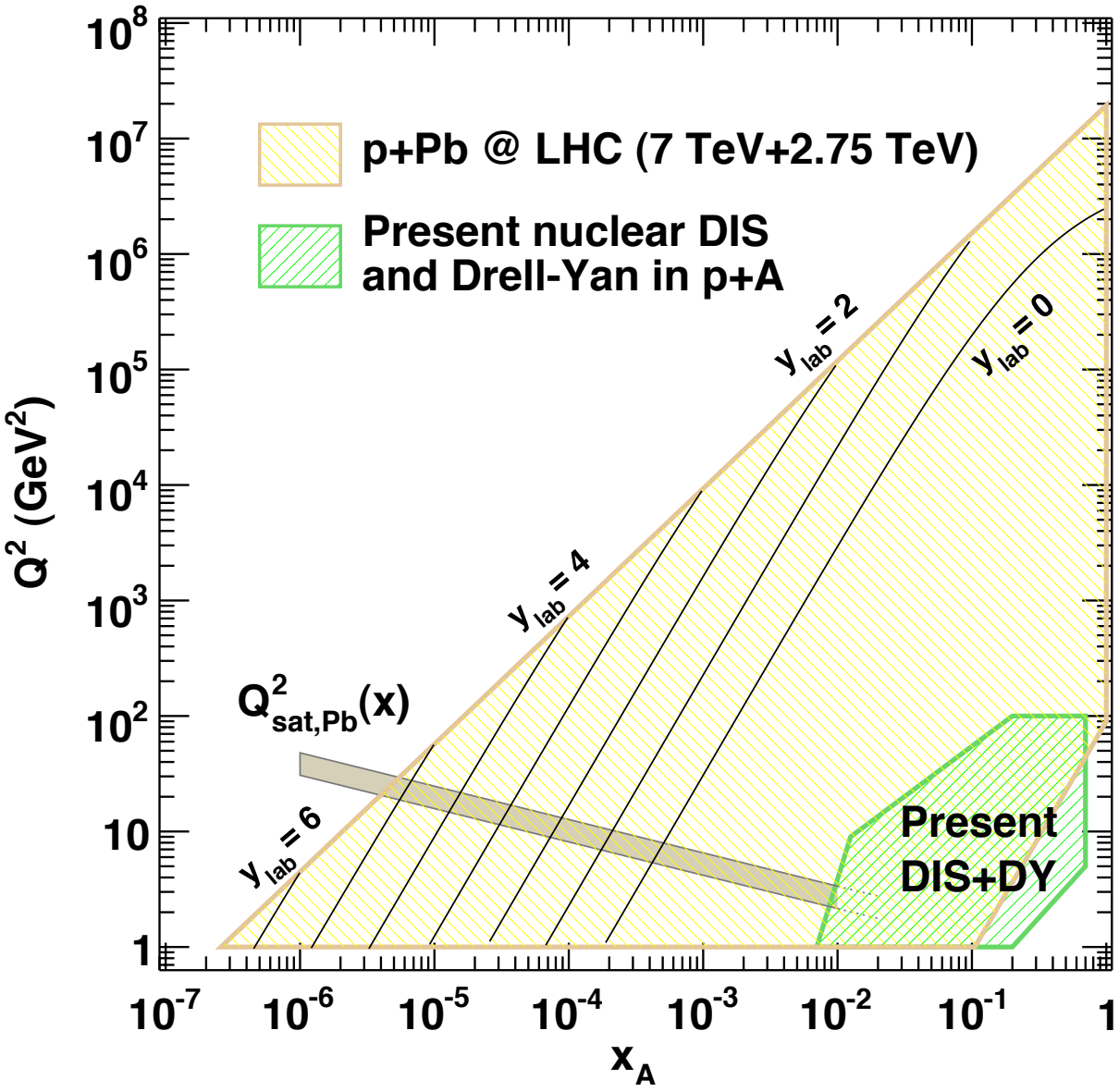

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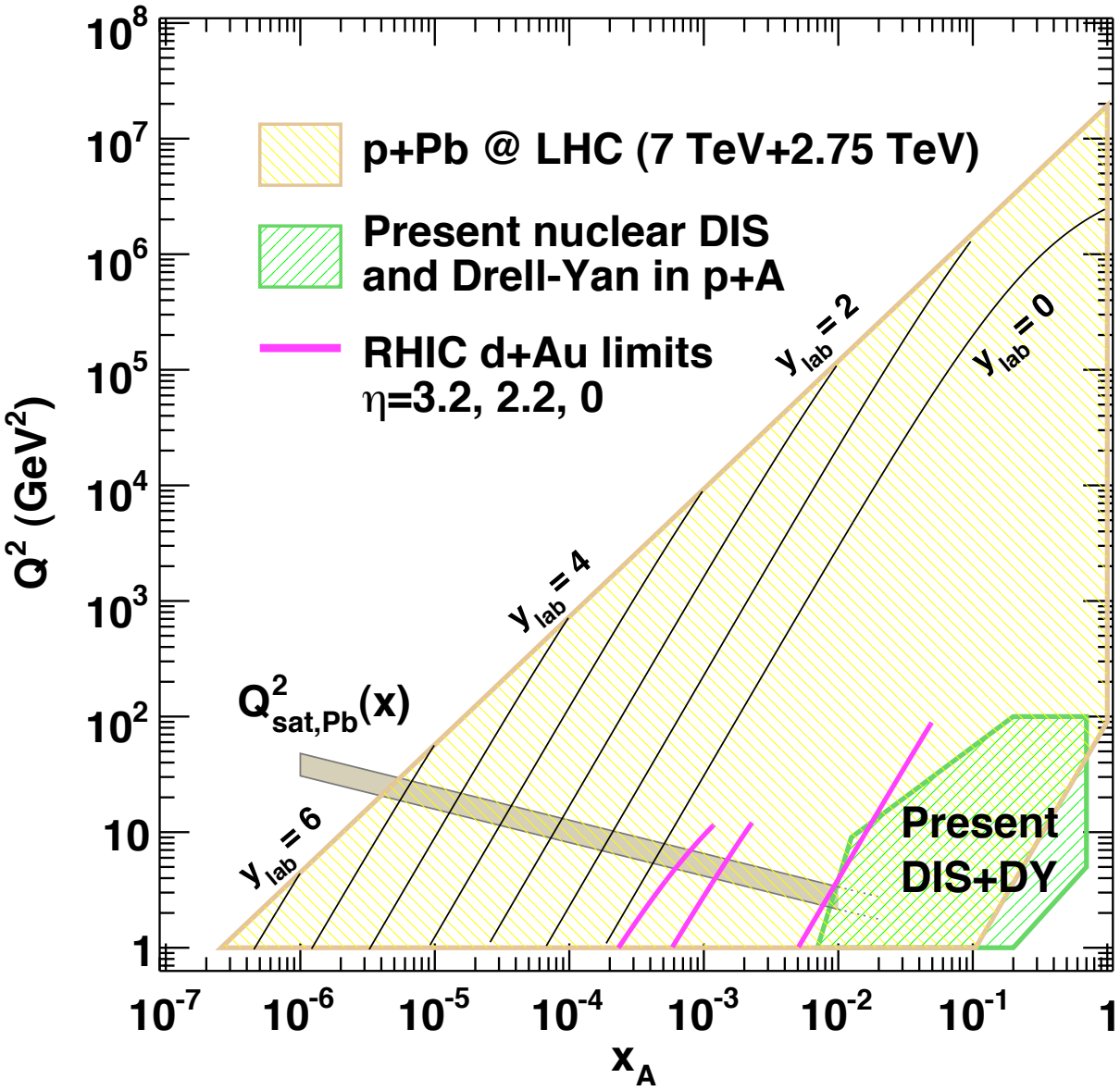

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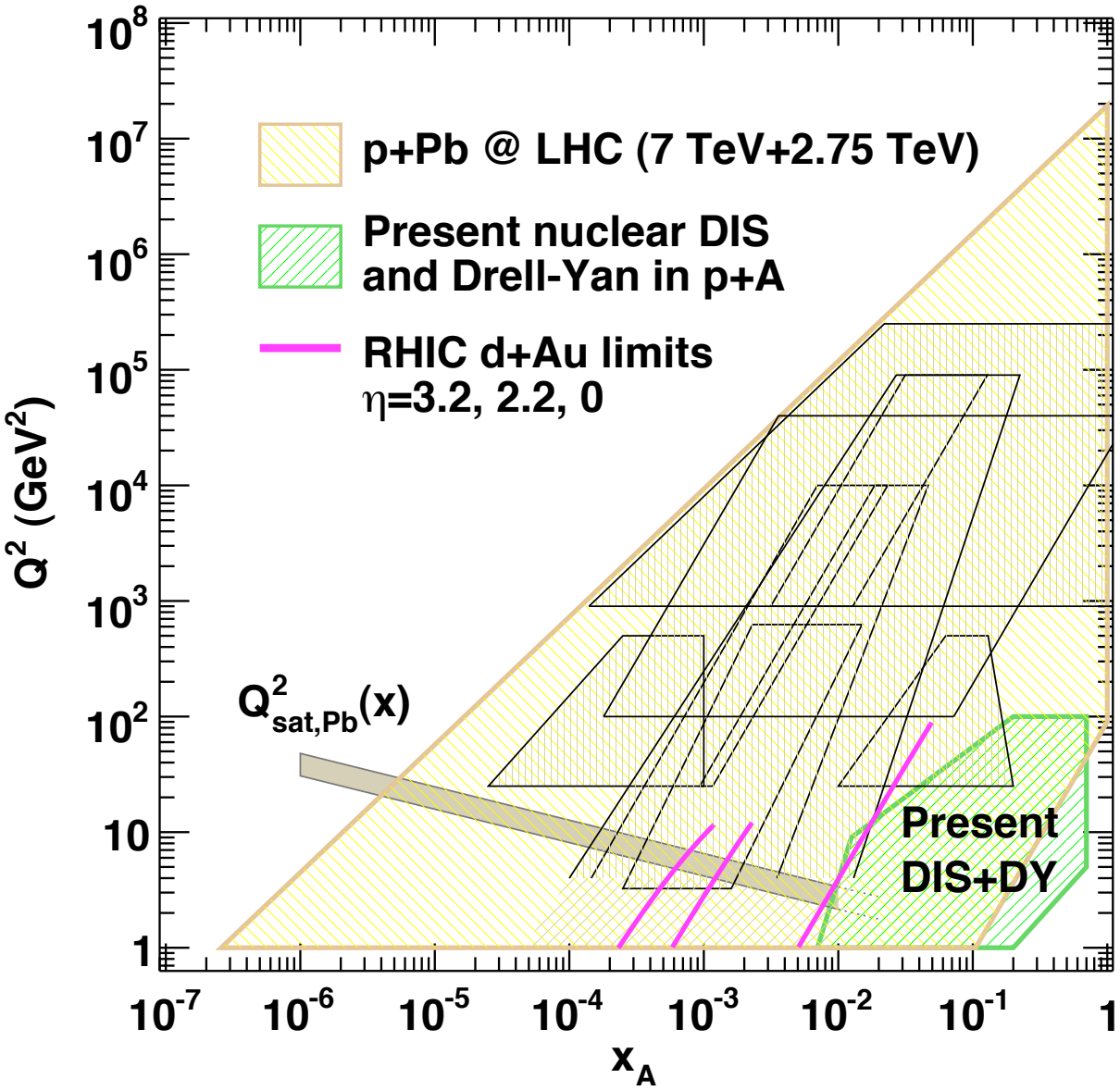

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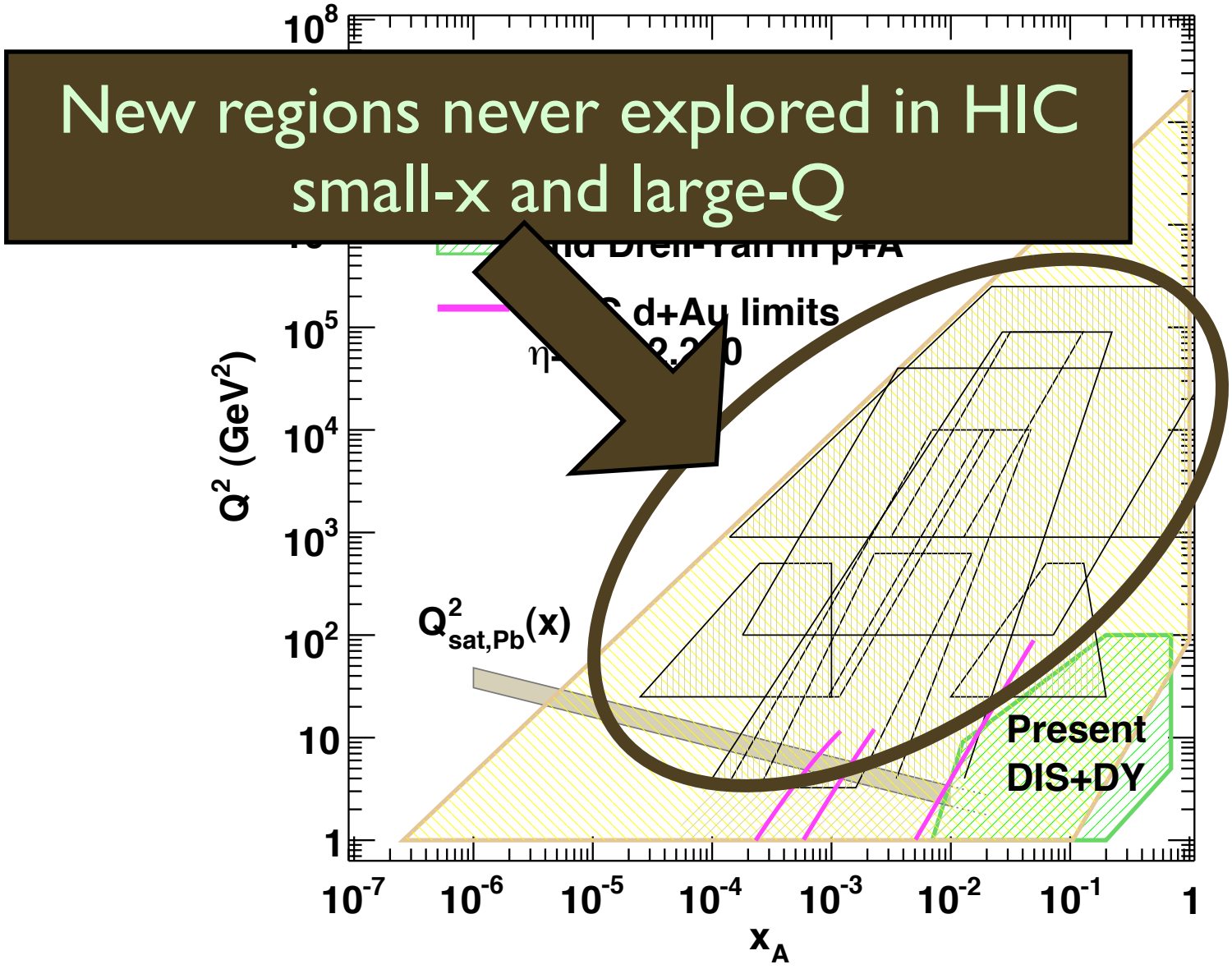

First results

Rediscovering the "Standard Model" of HIC + much more

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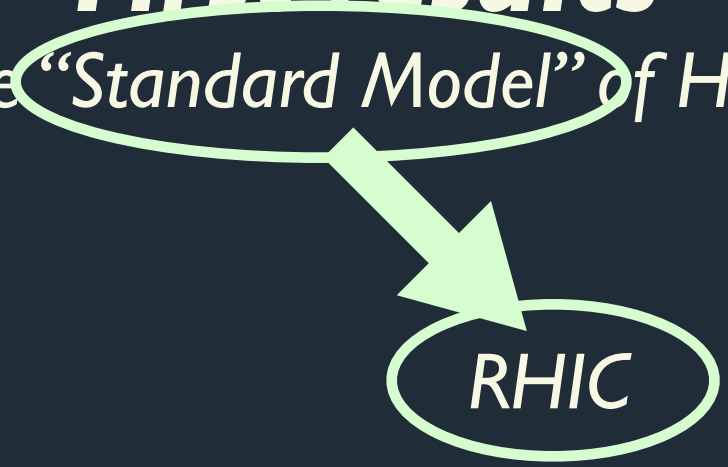
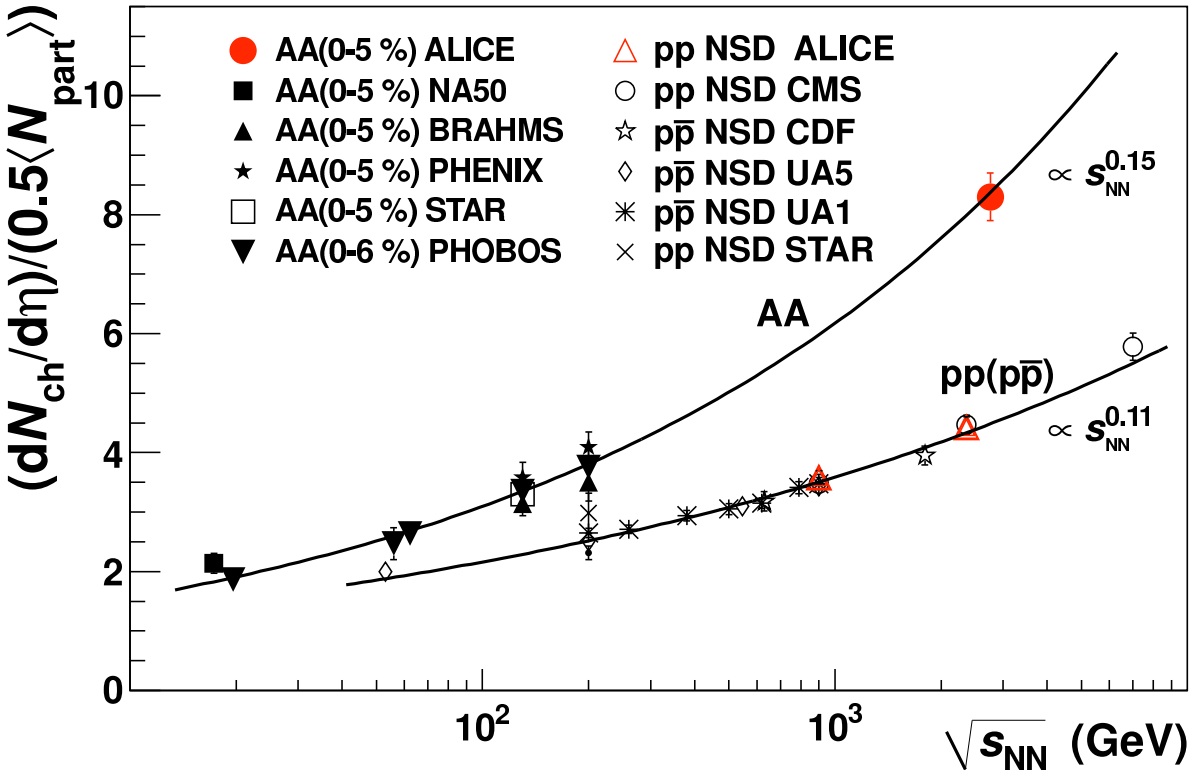


New data: multiplicities

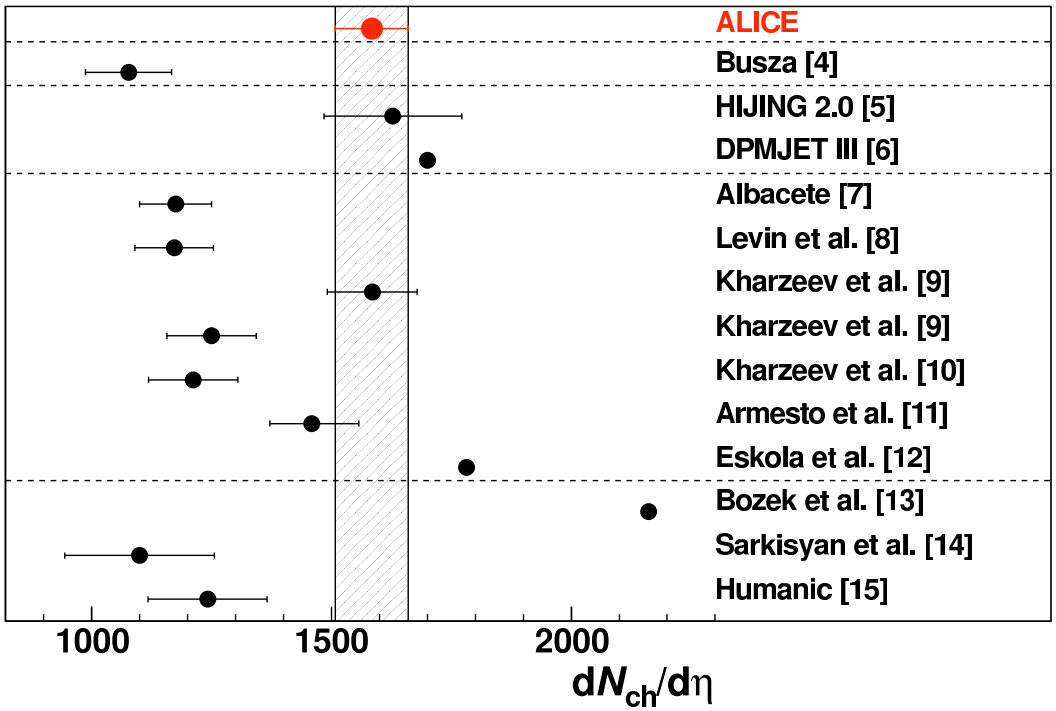
[ALICE: arxiv:1011.3916]



⇒ Multiplicities is a "day-1" measurement extremely relevant for HIC

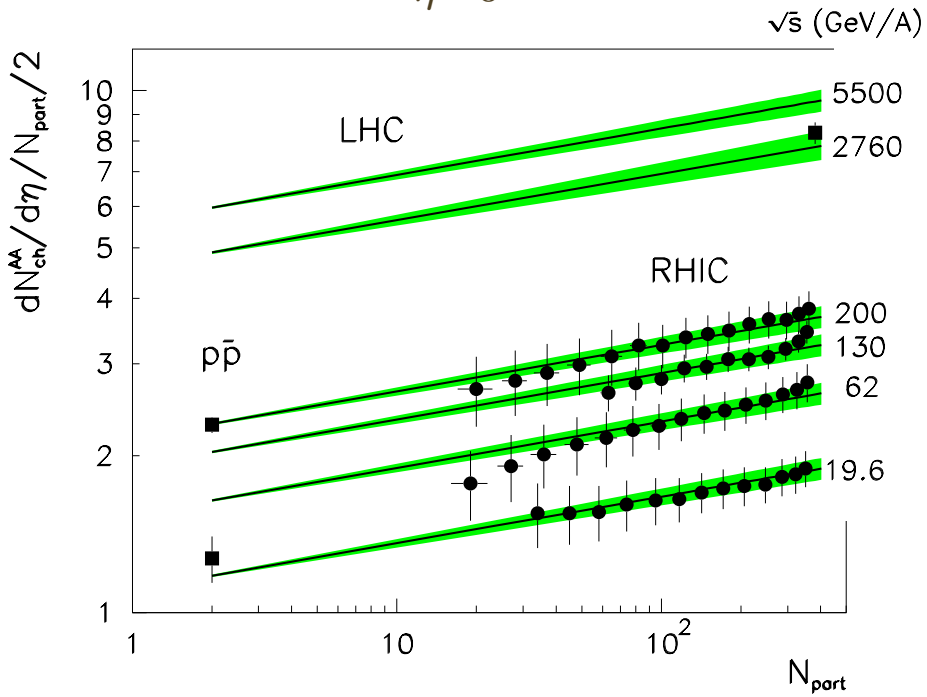
It constrains initial conditions, as energy density, of the medium

New data: multiplicities



- Most expectations were ~30% low
- **Strong screening confirmed**
- Compatible with geometric scaling

$$\left.\frac{2}{N_{\rm part}}\frac{dN^{AA}}{d\eta}\right|_{\eta\sim 0} = N_0\sqrt{s}^{\lambda} N_{\rm part}^{\frac{1-\delta}{3\delta}}$$

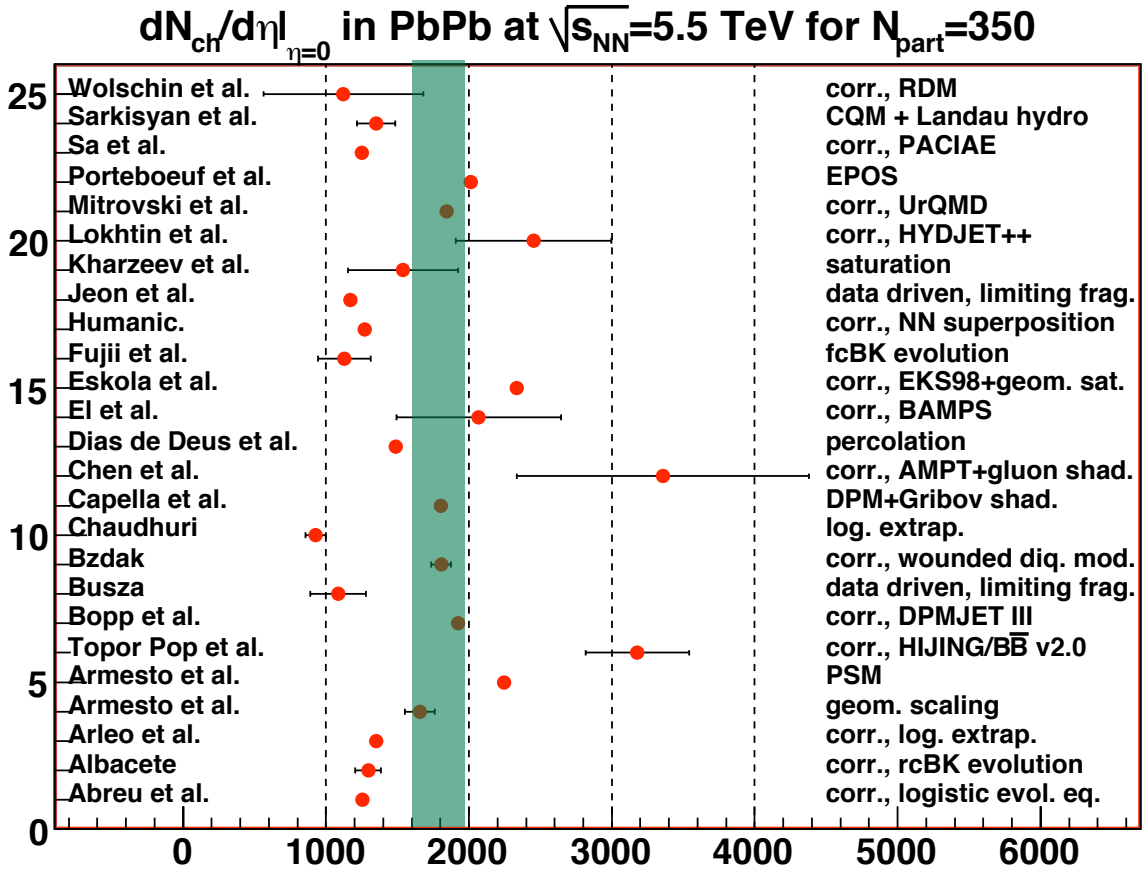


[Armesto, Salgado, Wiedemann 2004]

Surprising accuracy of such a simple formula... Why?

Approximate extrapolation to 5.5 TeV

⇛ Most of the predictions done at 5.5 TeV. Extrapolating using ALICE



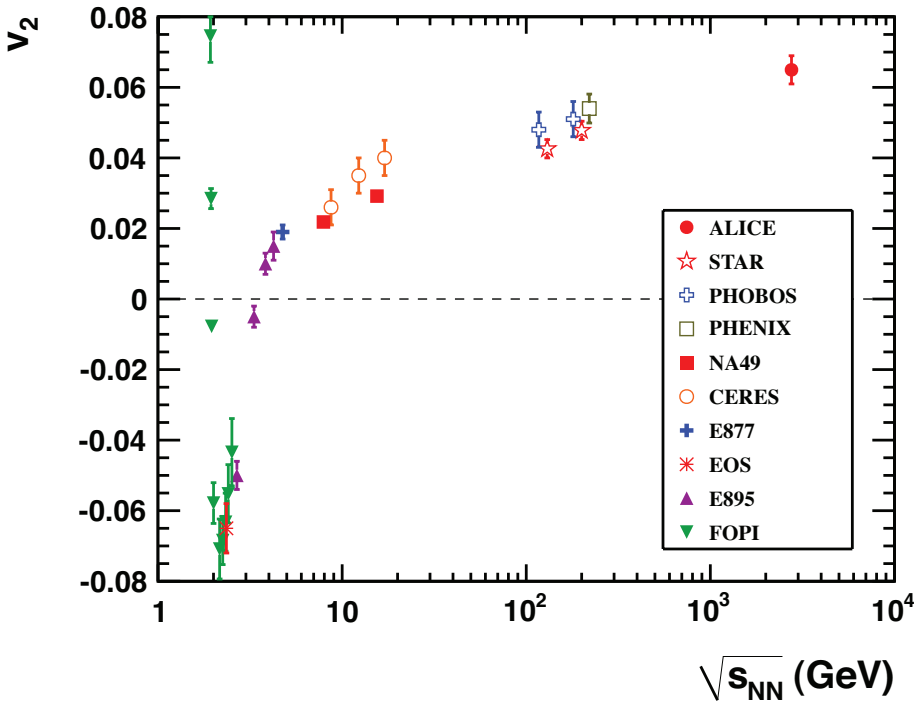
Compilation by N. Armesto, arxiv:0903.1330

⇛ Extrapolation agrees with medium-large multiplicity predictions

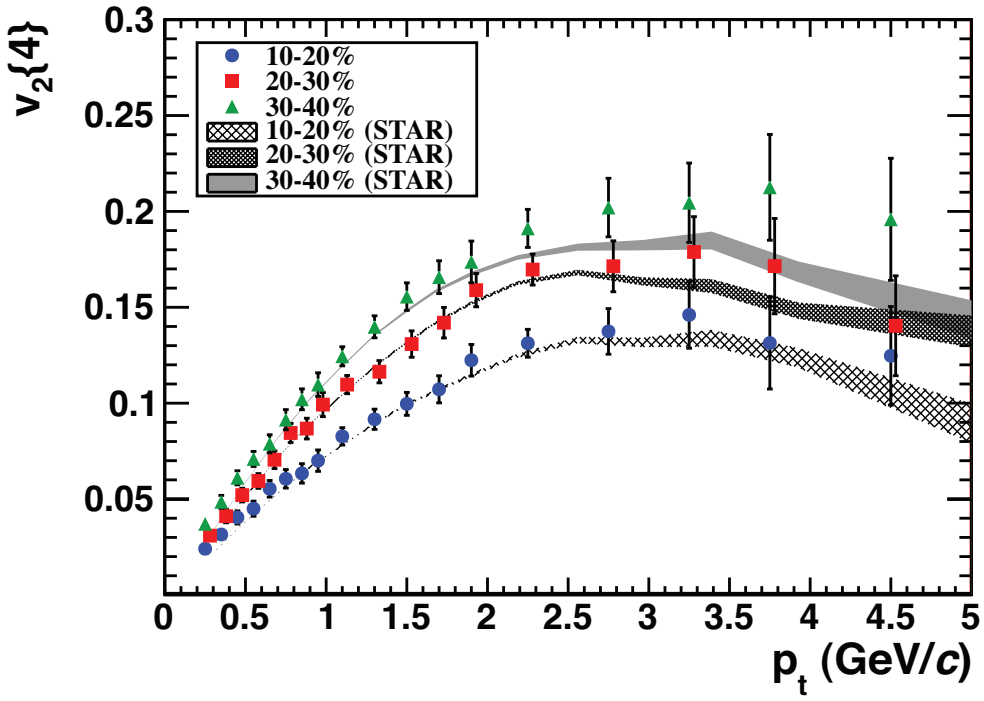
⇛ But we will need to wait till the data is measured at 5.5TeV....

New data: elliptic flow

⇛ ALICE released already data on elliptic flow [arxiv:1011.3914]



Energy systematics

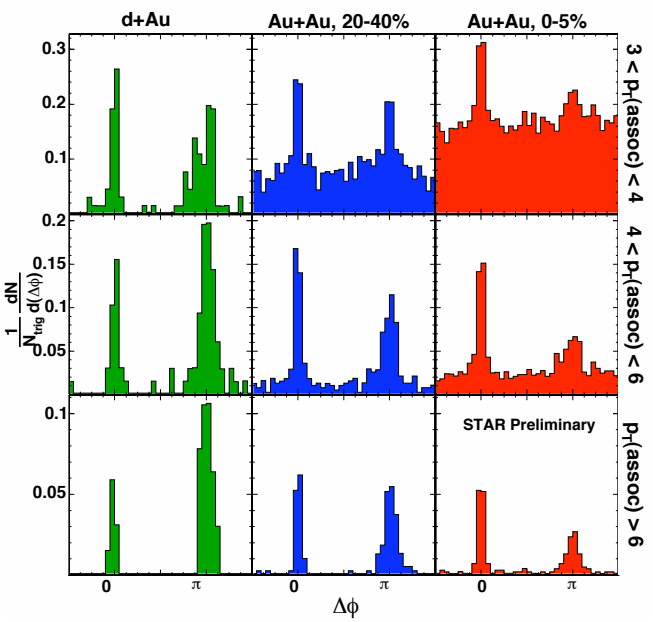


Transverse momentum dependence

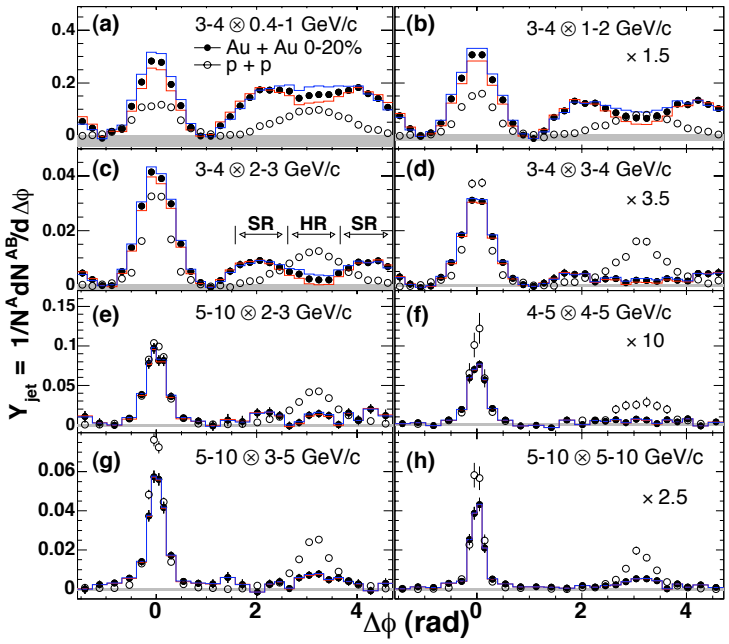
⇛ Elliptic flow of similar size as RHIC

Points to a **similar (very low) viscosity**

Jet studies in nuclear collisions

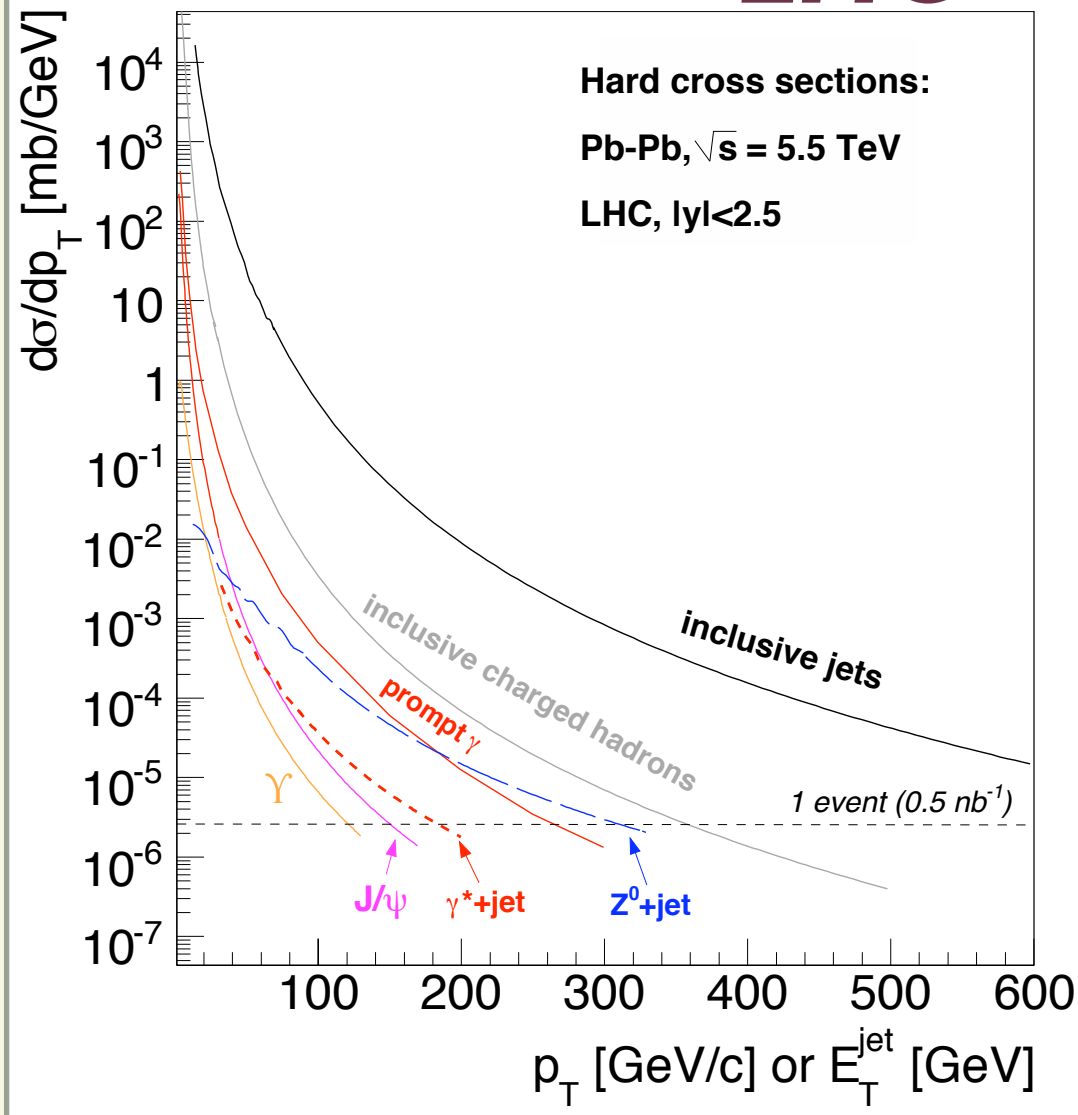


[STAR]



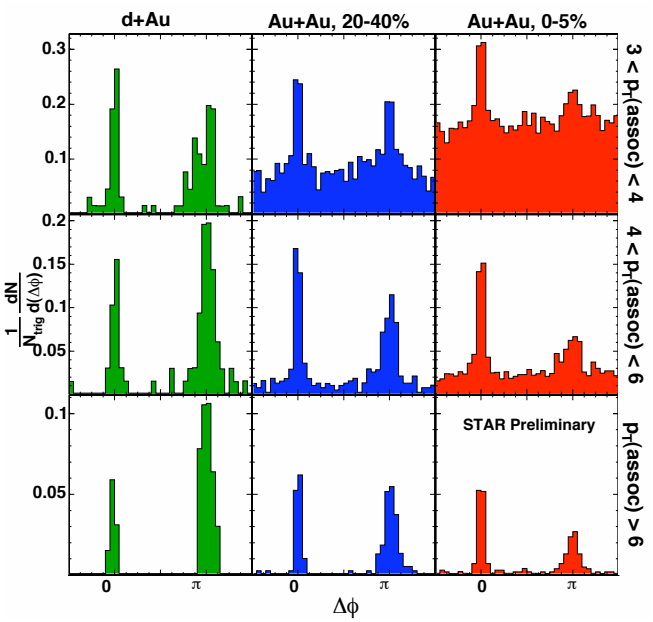
[PHENIX]

LHC

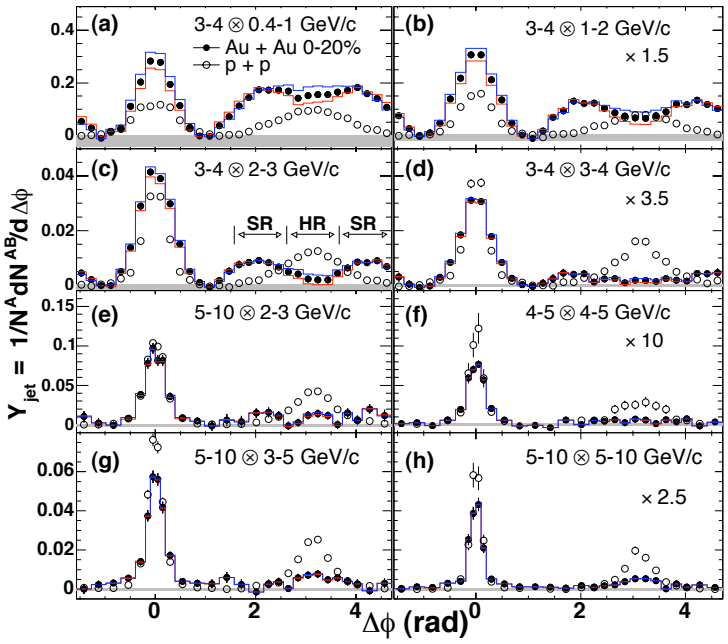


[D'Enterria 2008]

Jet studies in nuclear collisions

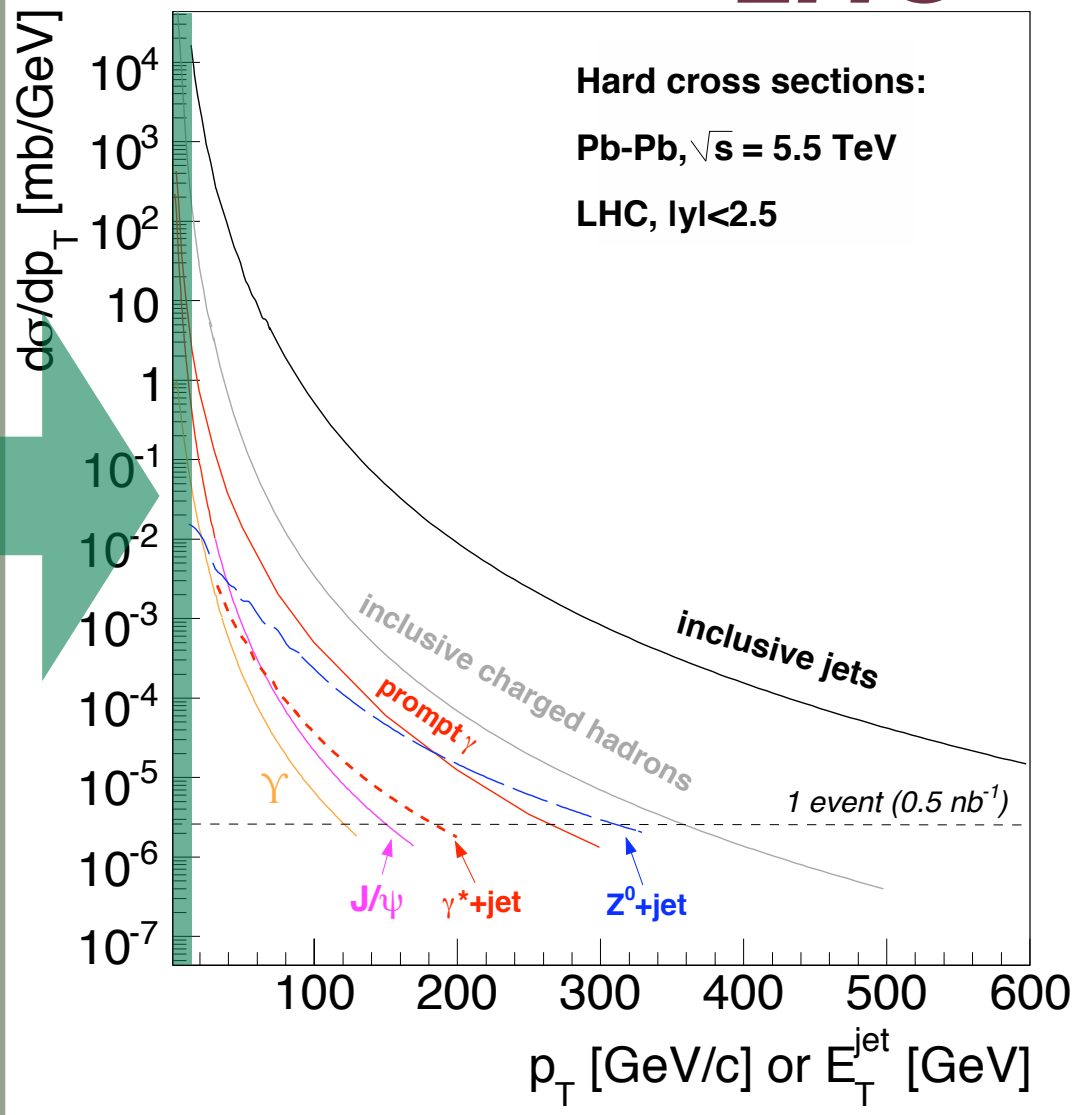


[STAR]



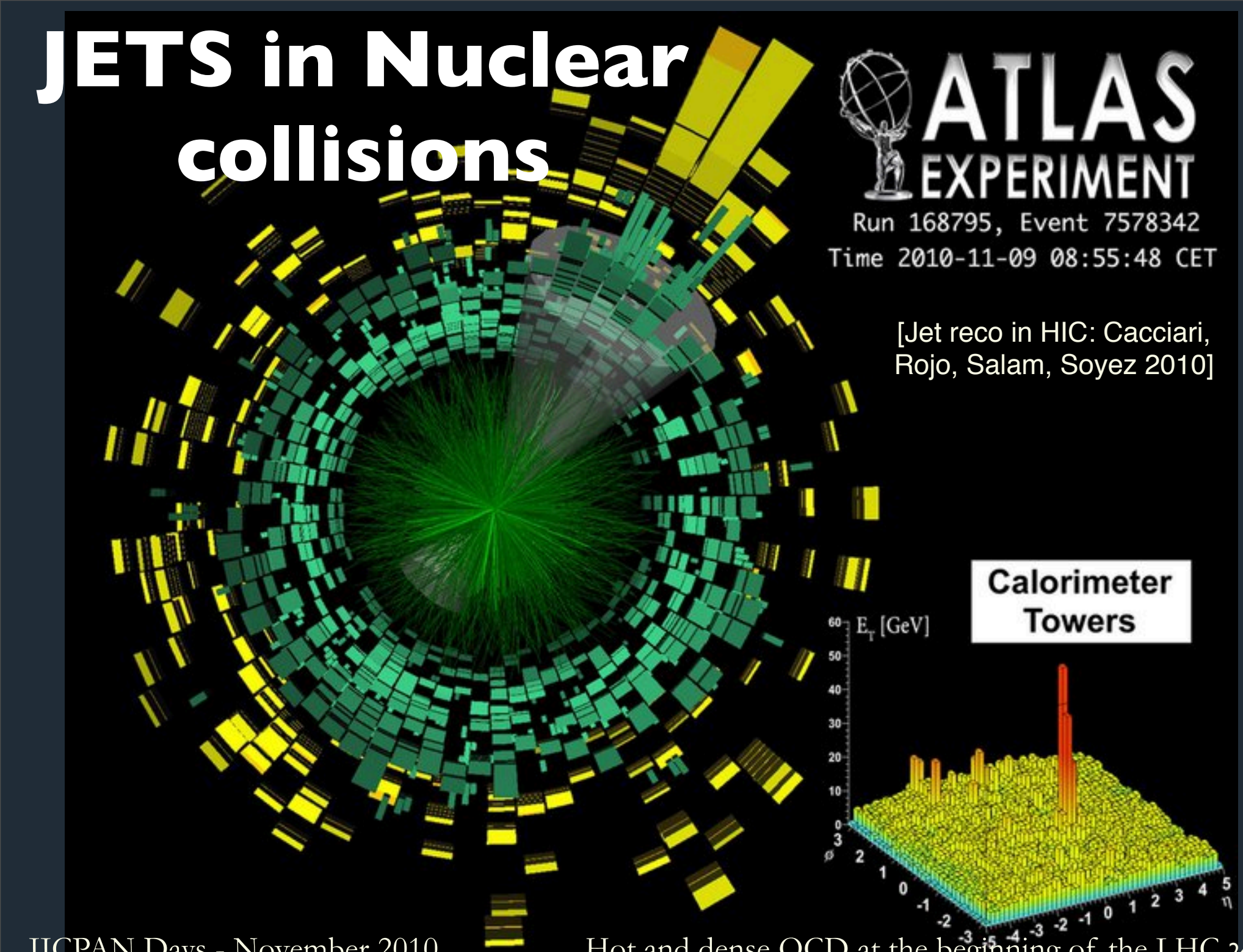
[PHENIX]

LHC



[D'Enterria 2008]

JETS in Nuclear collisions

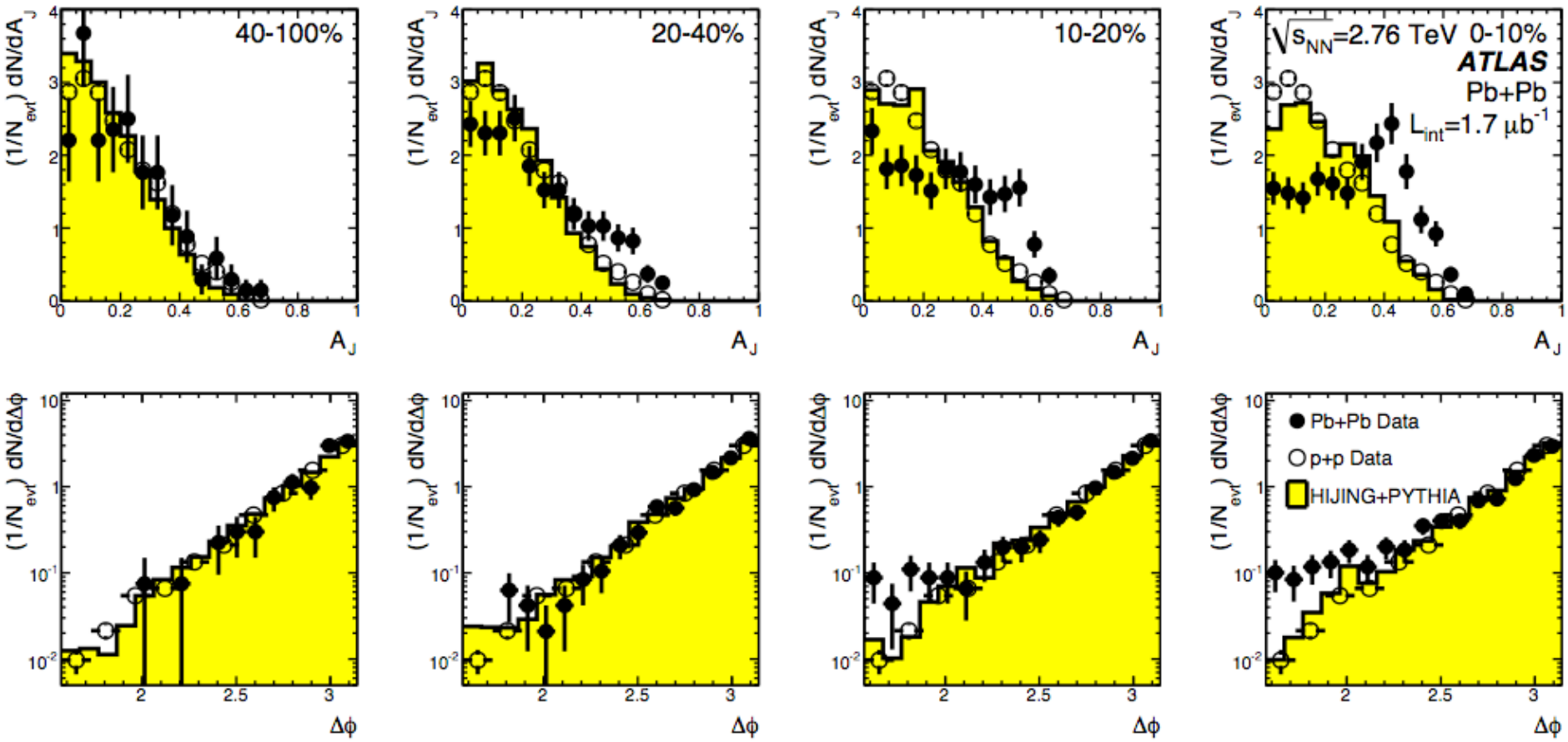


First jets in HIC at the LHC

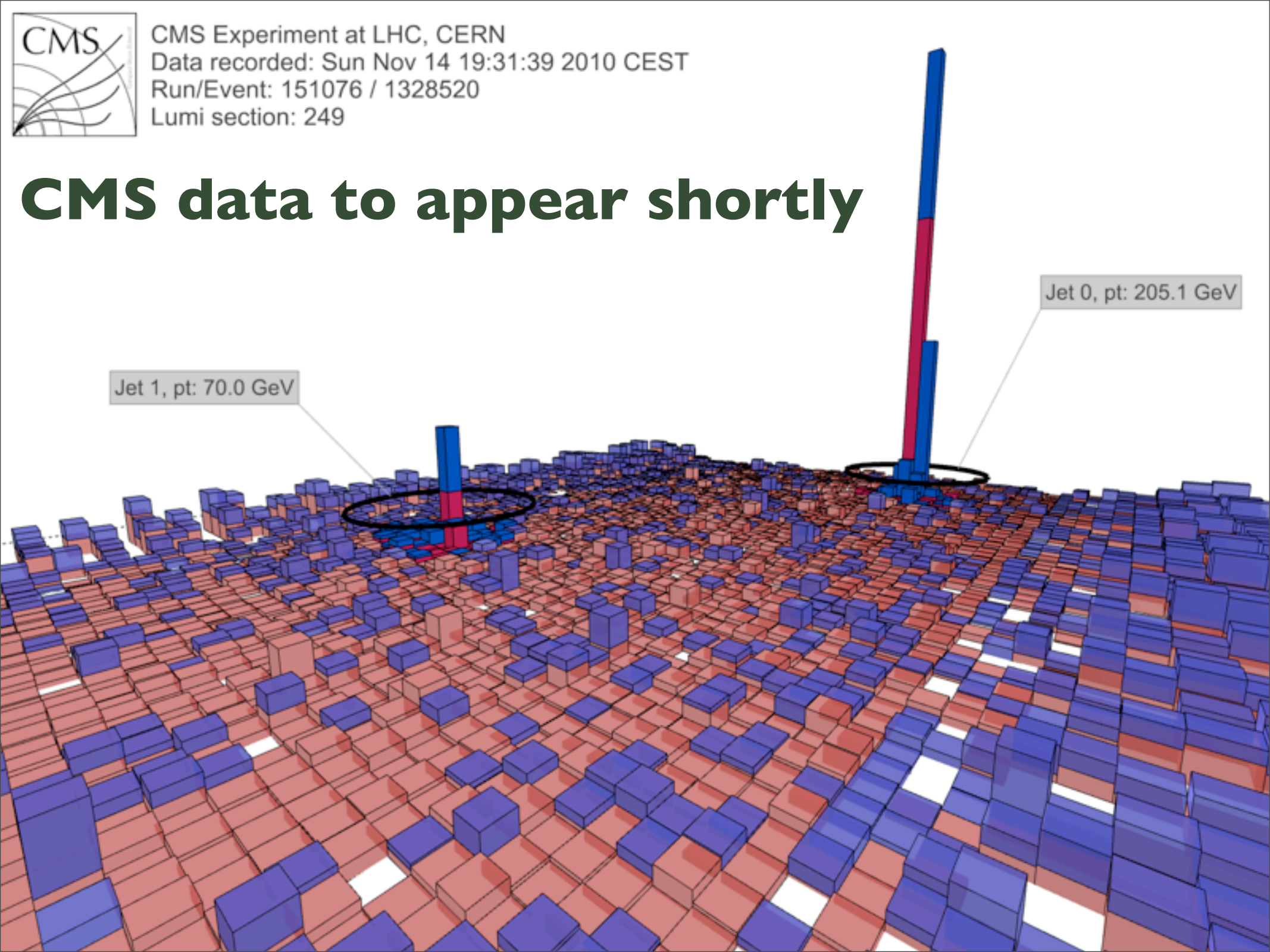
⇛ First reconstructed jet data from LHC - ATLAS

[PRL to appear]

$$A_j = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$



⇛ Strong energy loss - points to a **very dense partonic system**


CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
CMS data to appear shortly
Jet 0, pt: 205.1 GeV
Jet 1, pt: 70.0 GeV

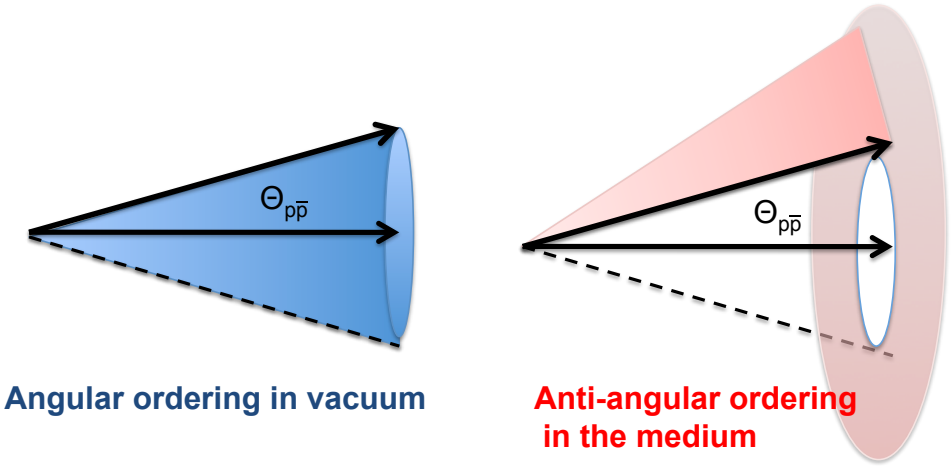
New theoretical developments

⇛ Coherent emission known to be a main ingredient in parton showers

⇛ Very striking result found in the medium

↘ Strict large angle emission - anti-angular ordering

$$dN_q = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{d\theta}{\theta}\left(\Theta\left(\cos\theta - \cos\theta_{q\bar{q}}\right) + A(\theta_{q\bar{q}}, L)\Theta\left(\cos\theta_{q\bar{q}} - \cos\theta\right)\right)$$

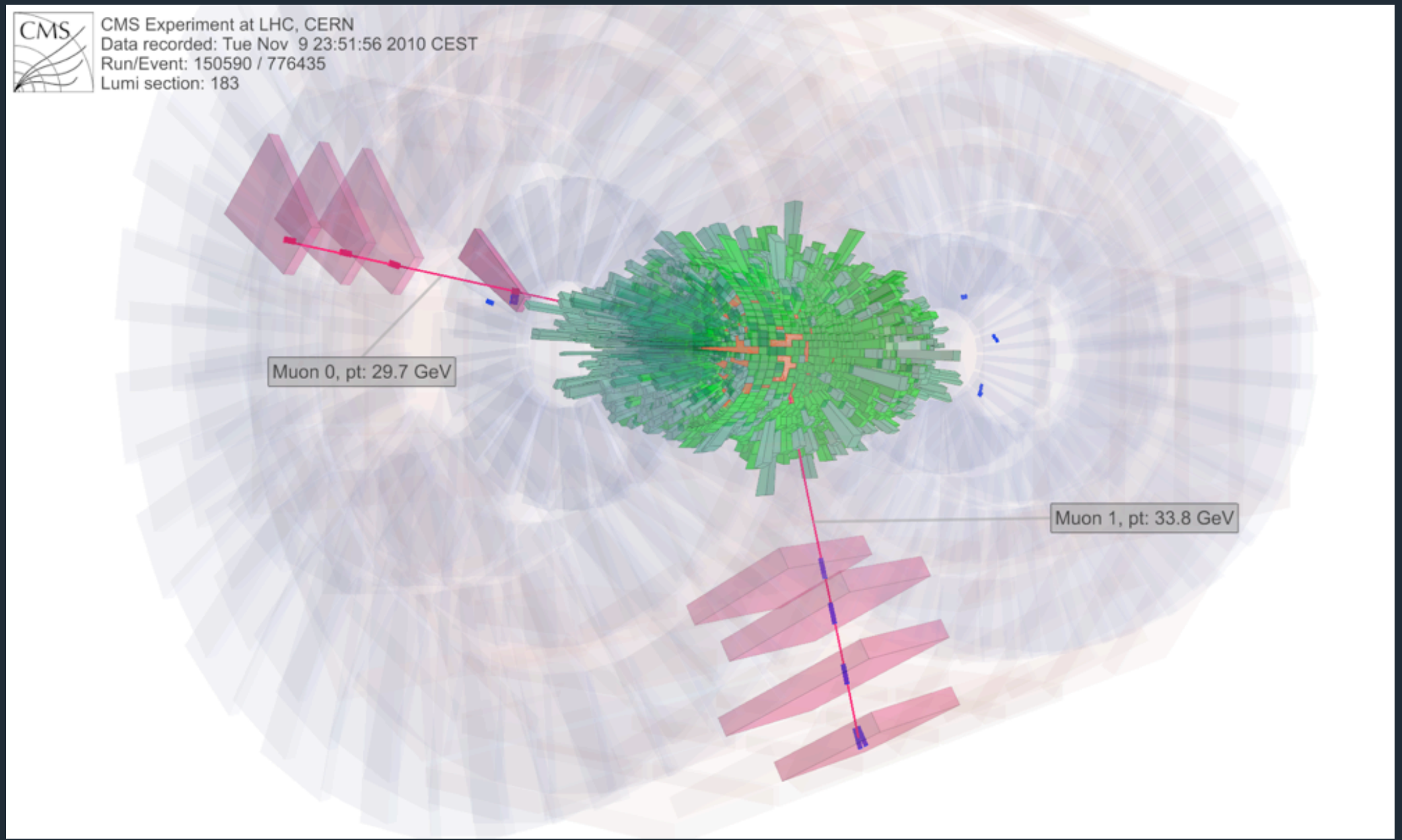


⇛ First step into a theoretically controlled in-medium parton shower

[Mehtar-Tani, Salgado, Tywoniuk 2010]

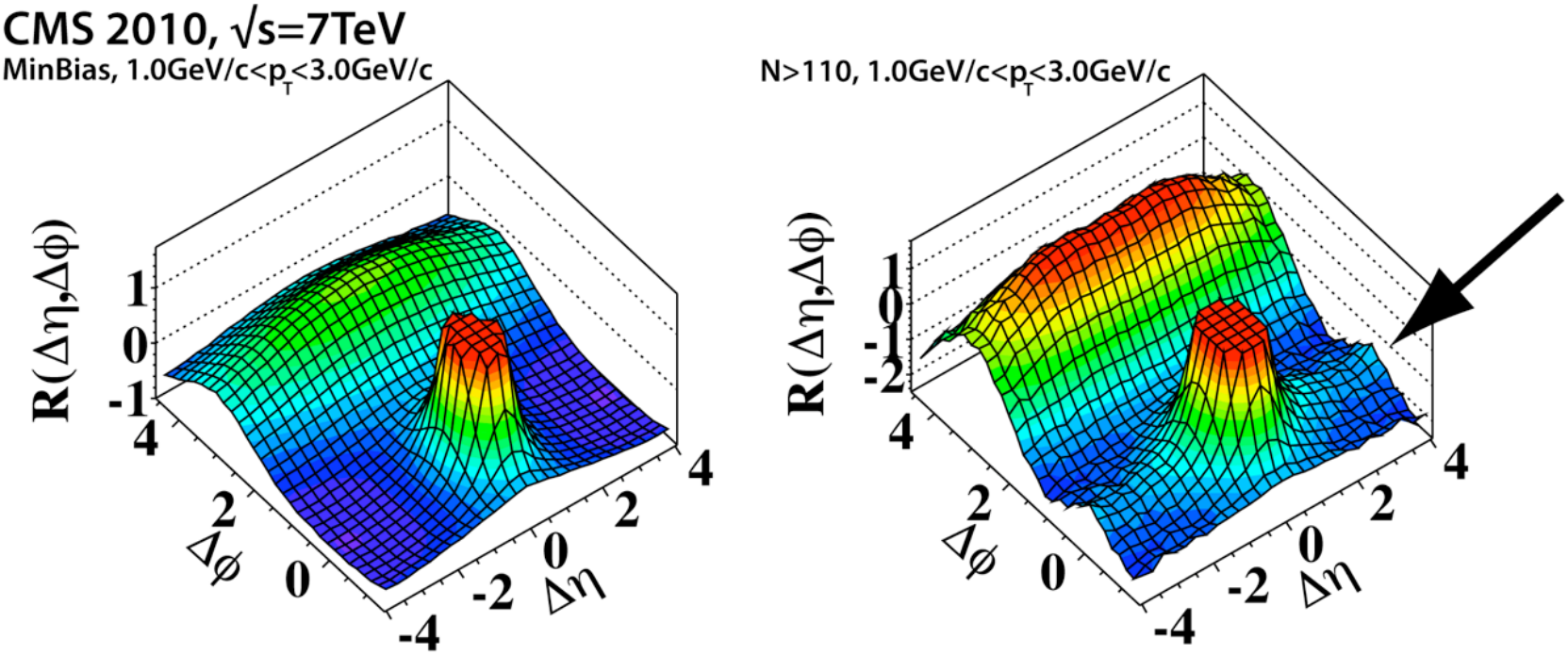
Collisions at the TeV scale
imply completely new opportunities

First Z's seen in nuclear collisions ever



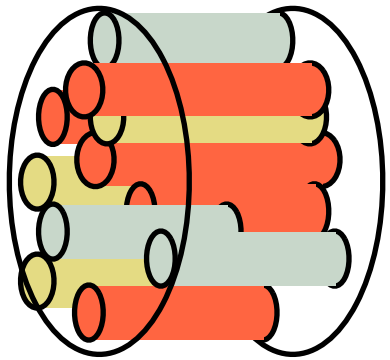
HI-like effects in proton-proton collisions

⇛ Long range rapidity correlations by CMS in **high-multiplicity pp**



⇛ The "ridge" first seen in AuAu collisions at RHIC

⇛ Compatible with CGC/percolation of flux tubes



[Bautista, Brogueira, Dias de Deus, Pajares 2009;
Dusling, Fernandez-Fraile, Lappi, Gelis, Venugopalan 2009-2010]

Some things I have not time to comment on

- **J/Psi suppression**
  - ALICE-CIEMAT; New theoretical developments [Ferreiro, Feuret, Lansberg, Rakotozafindrabe 2008-2010; Brambilla, Escobedo, Ghiglieri, Soto, Vairo 2010]
- **Nuclear Parton Distribution Functions** [Eskola, Paukkunen, Salgado]
- **C and P violation in heavy-ion collisions**
  - Formation of "exotic" condensates [Adrianov, Adrianov, Espriu, Planells 2010]
  - Chiral magnetic effect [Kharzeev, McLerran, Warringa 2008]
- **AdS/CFT connections**
  - Viscosity [PSS, Mas, Landsteiner 2006,2007]; Jet quenching parameter [Liu, Rajagopal, Wiedemann 2006; Armesto, Mas, Edelstein 2006...]; Drag force [Gubser 2006; Casalderrey-Solana, Teaney 2006]; New observables [Casalderrey-Solana, Matteos 2009-2010]...
  - Active groups in Barcelona, Madrid, Salamanca, Santiago

Summary

- LHC is performing better than expected in PbPb mode
  - Short setup period (4 days)
  - First physics results in ~1 week.
- RHIC physics re-discovered
- But much more (with just 3 weeks of running!)
  - Jet physics: jet quenching found in reconstructed jets
  - Gamma-jet; multijet; heavy bosons (Z's)....
- A new era of QCD at high densities and temperatures just started