Understanding the Physics of Heavy Ion Collisions

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Rencontres de Blois 2011

[Including news from Quark Matter 2011 - Last week]

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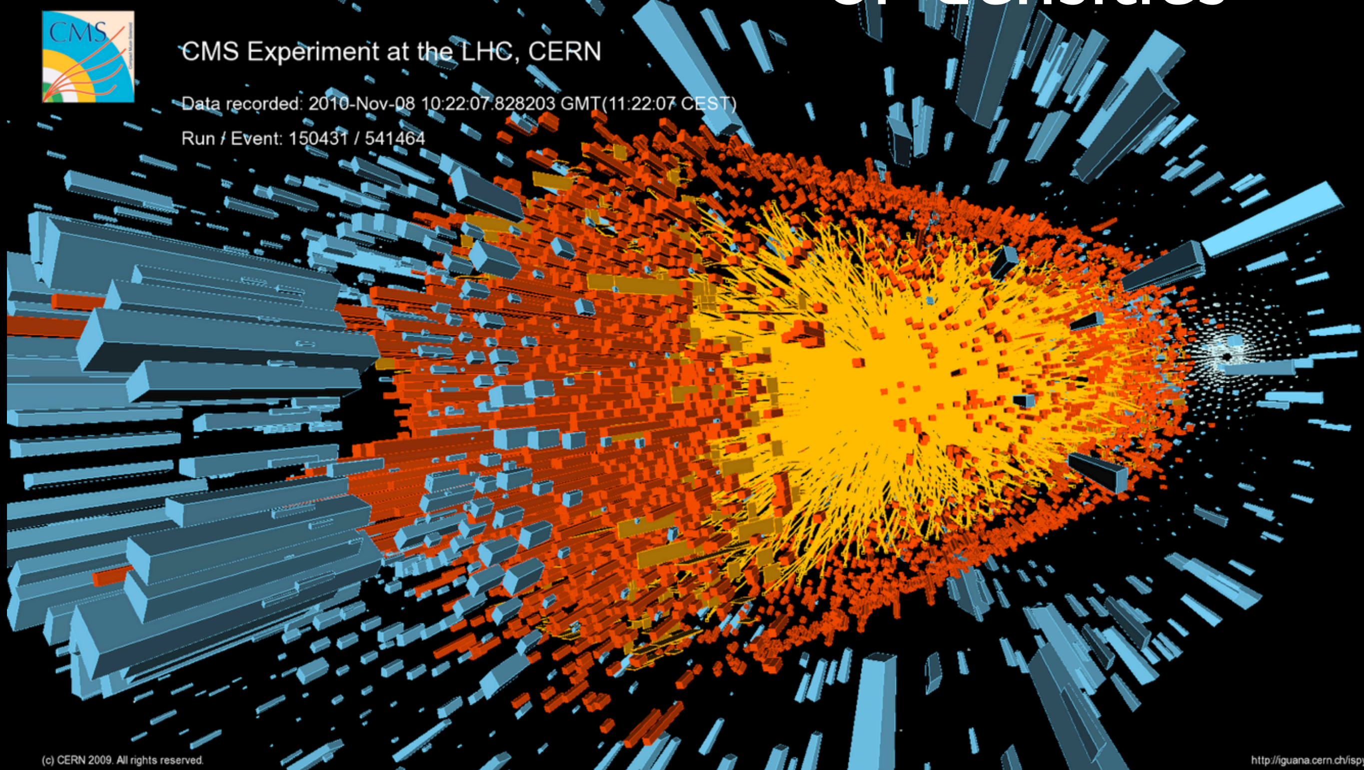
QCD: An apparently simple lagrangian hides a plethora of **emerging phenomena**

Asymptotic freedom; confinement; chiral symmetry breaking; mass generation; new phases of matter; a rich hadronic spectrum; etc

Some of these properties appear at high-temperatures or densities



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

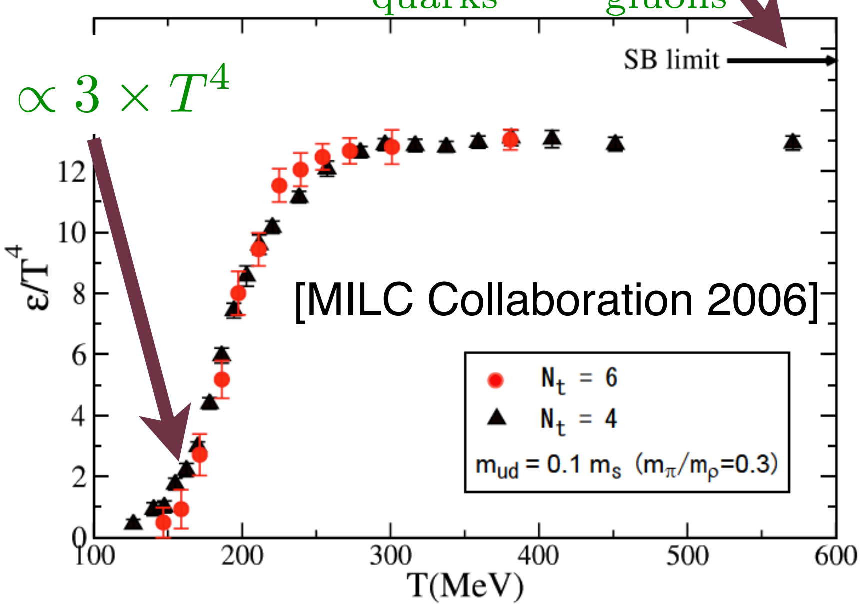
QCD at high-temperatures

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

Equation of state

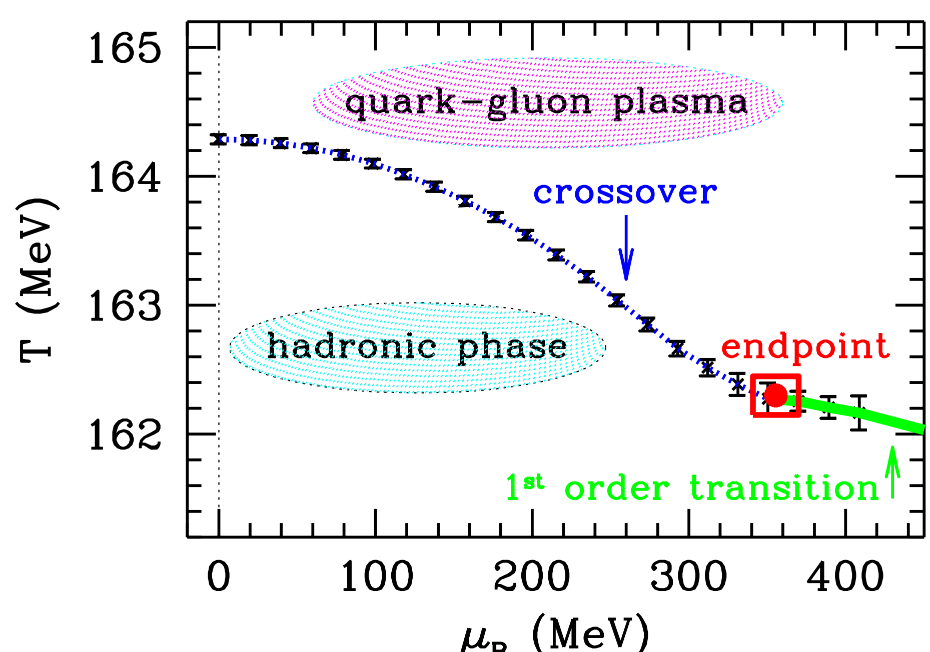
$$P_{QGP} \propto (\underbrace{2 \times 2 \times 3}_{\text{quarks}} + \underbrace{2 \times 8}_{\text{gluons}}) \times T^4$$

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



Phase diagram

[Fodor, et al. 2004]



Towards the highest energies

SPS@CERN - Fixed target

pA, SU, PbPb - 90's

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

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x10

RHIC@BNL - Collider

CuCu, AuAu, dAu
2000 - ...

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

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CuCu, AuAu, dAu
2000 - ...

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

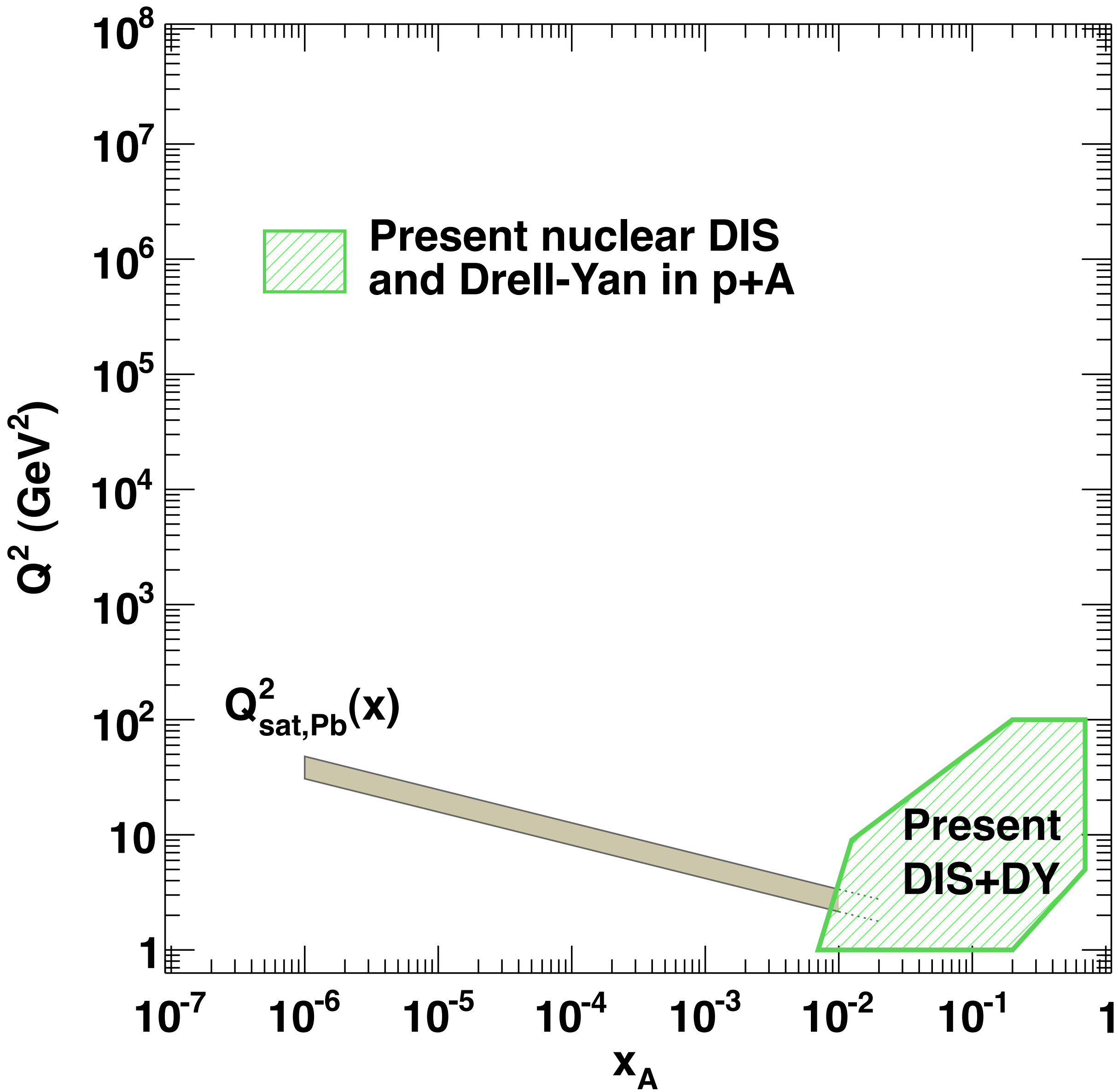
x30

(pp), PbPb, pPb
Energy frontier of HI
Starting November 2010

LHC@CERN - Collider

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

Kinematical reach in nuclear collisions



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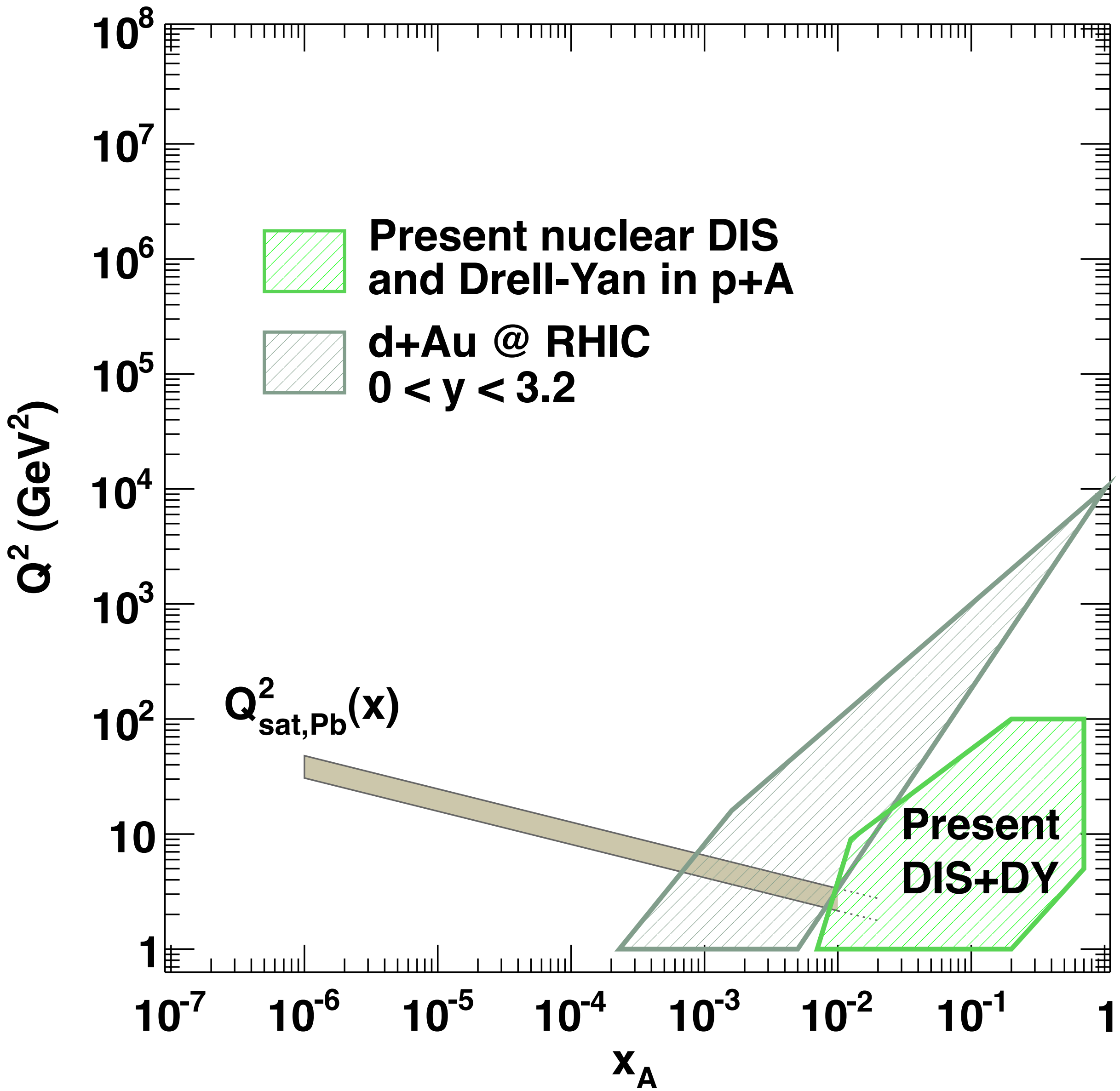

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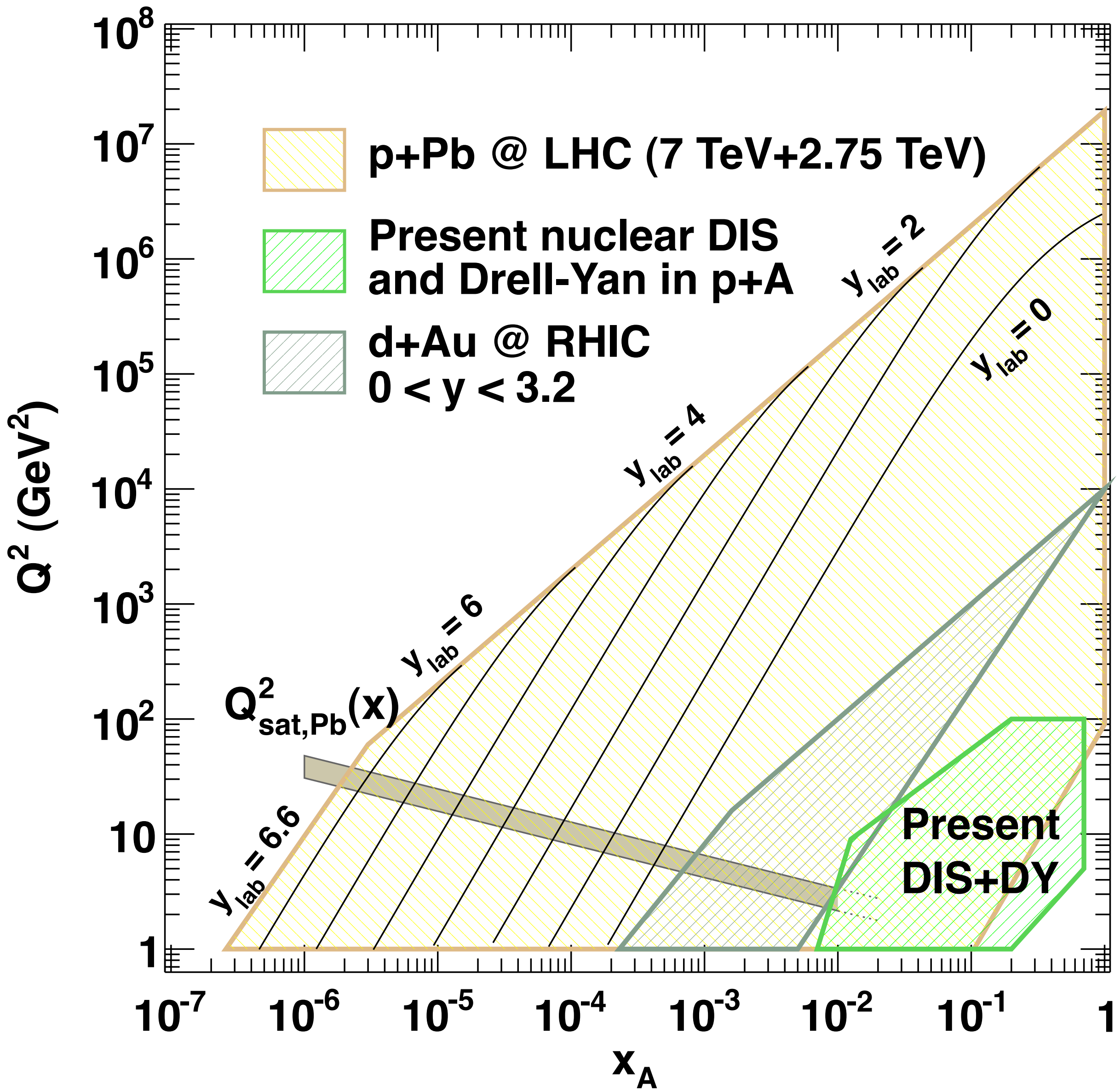

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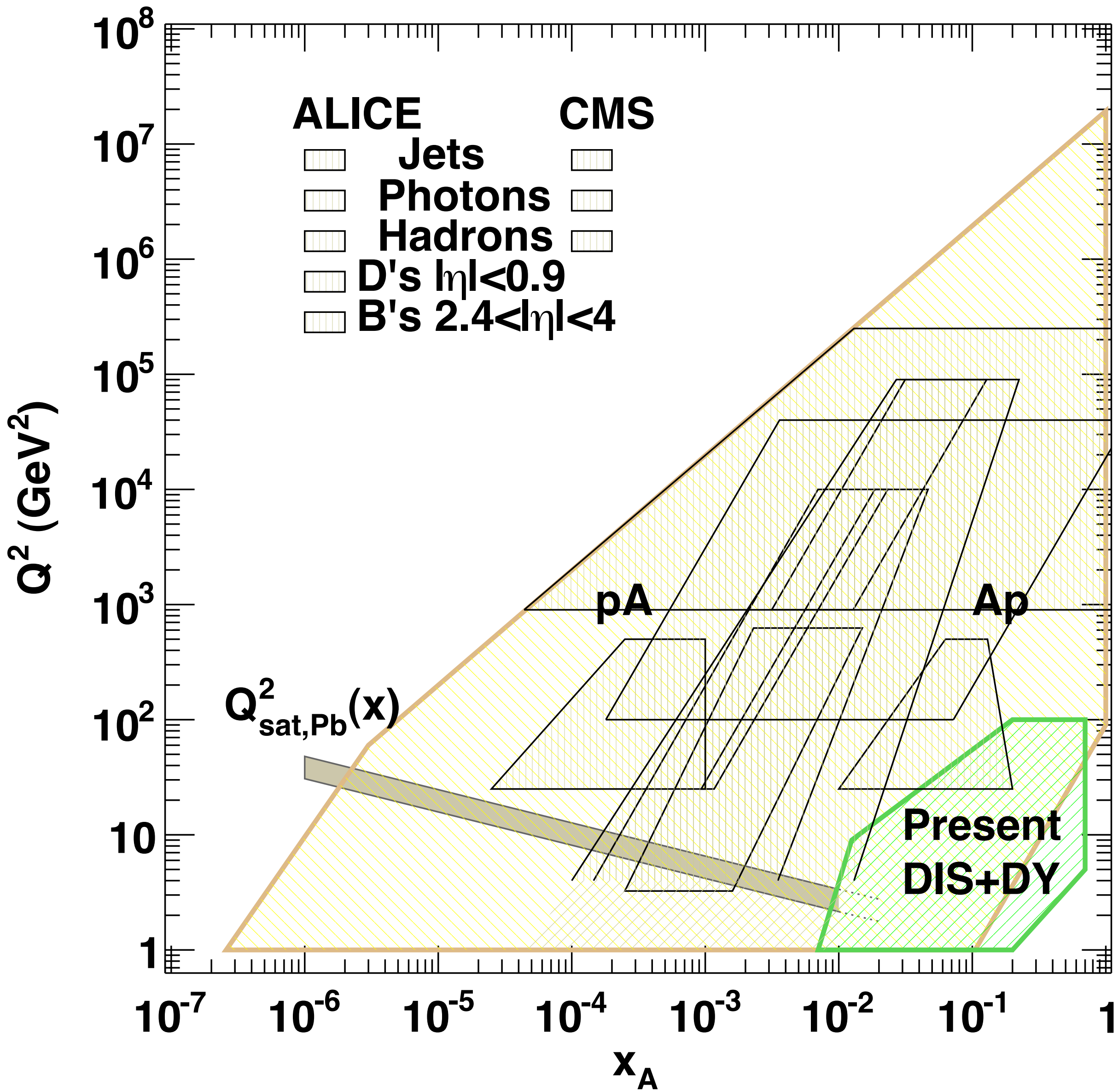

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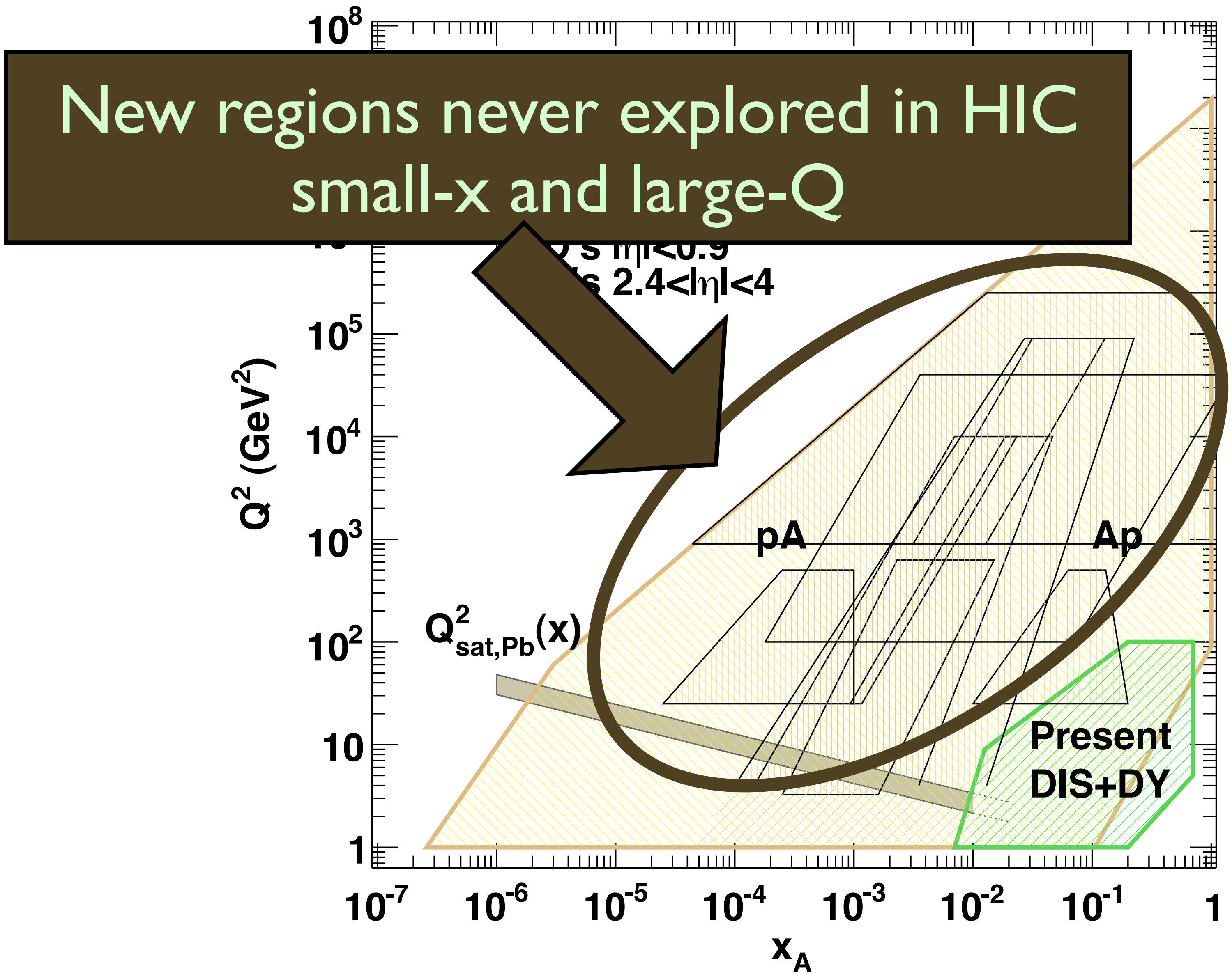
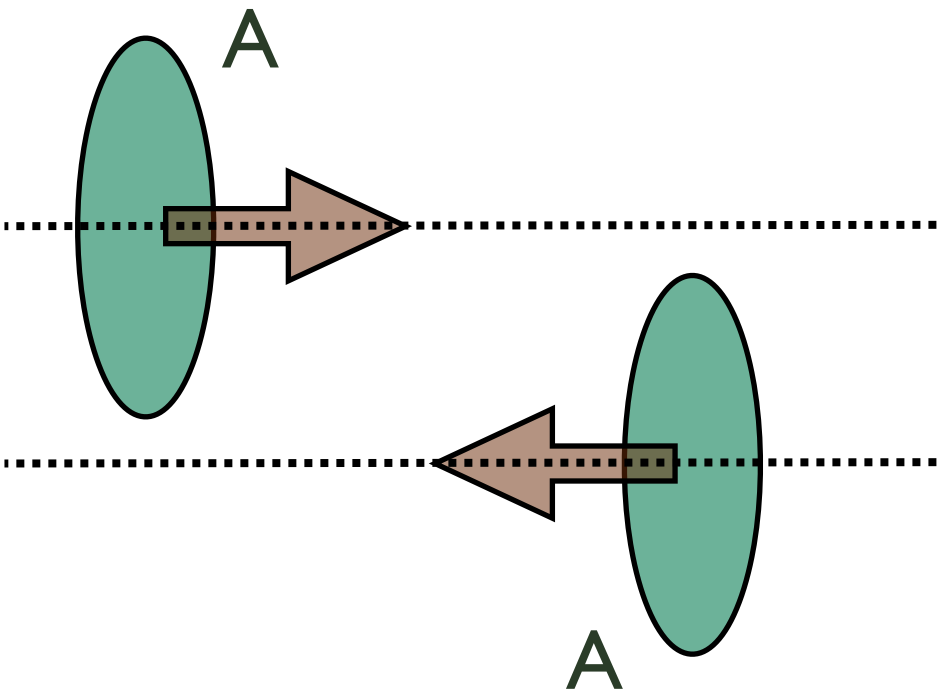
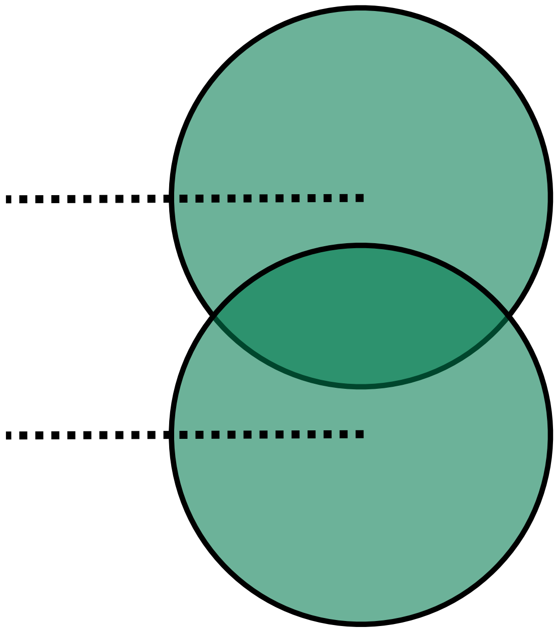


Some jargon... centrality of the collision



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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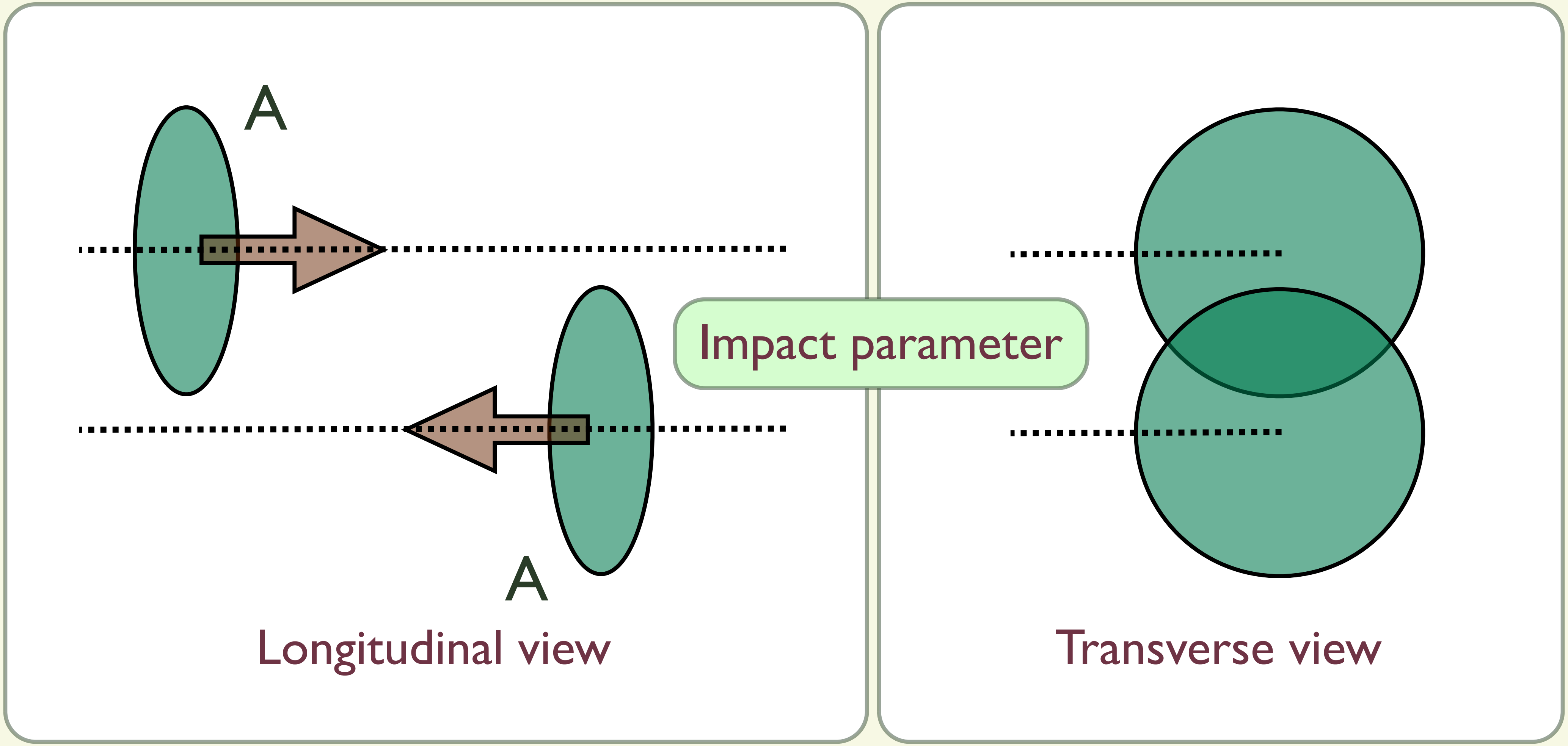

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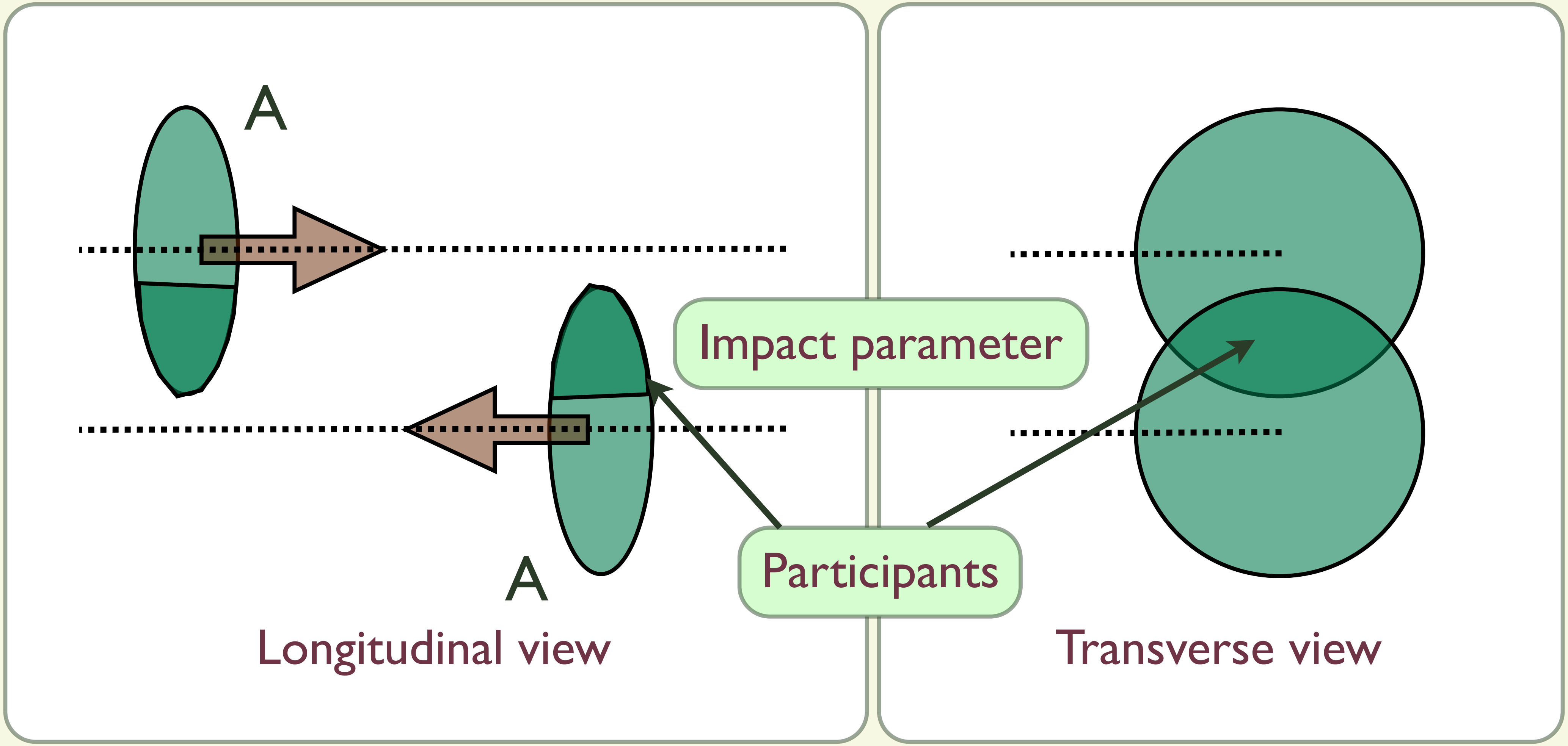

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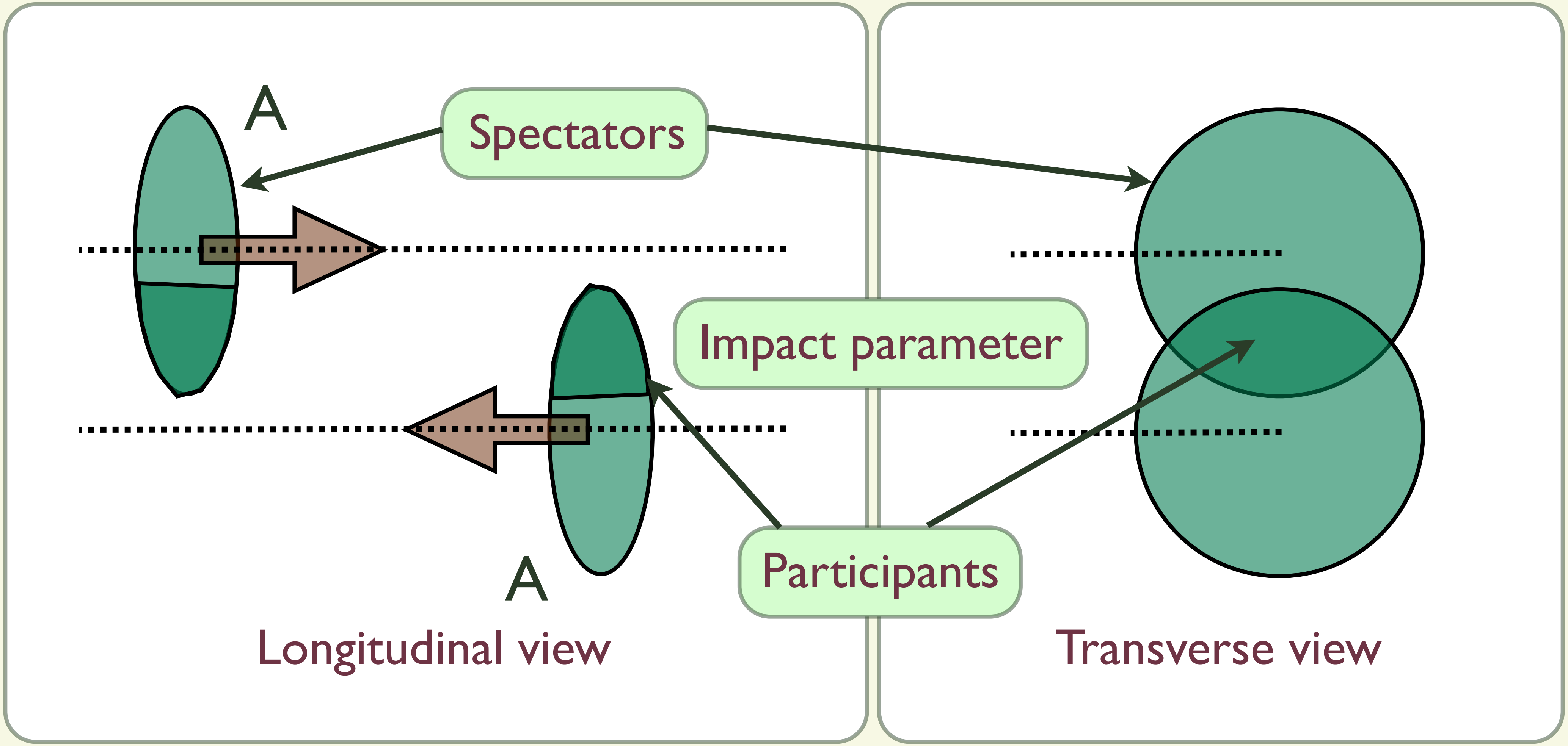

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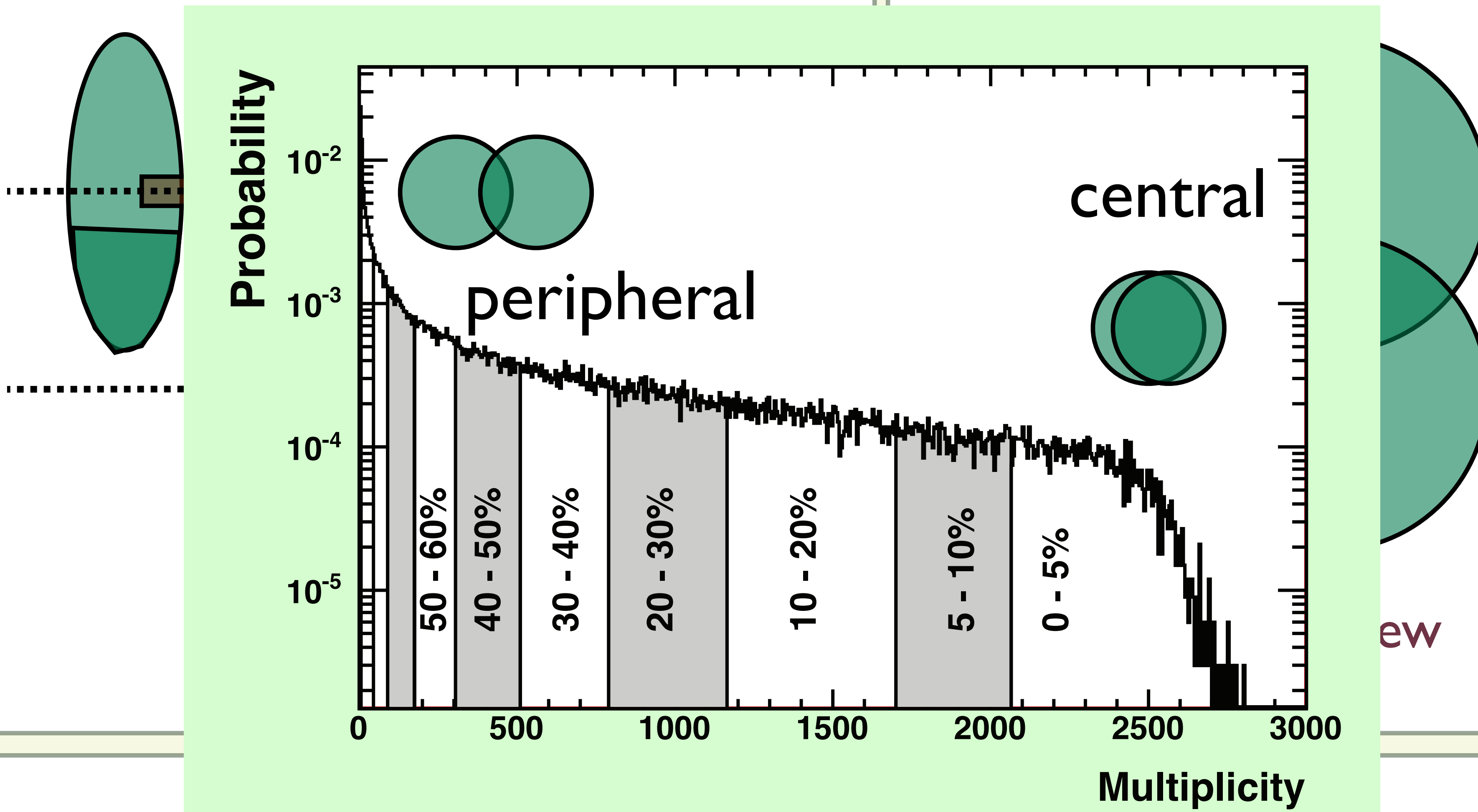

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What do we expect to learn?

- What is the structure of the hadrons at high energy?

  → *color coherence effects in particle production.*

- Is the created medium thermalized? How?

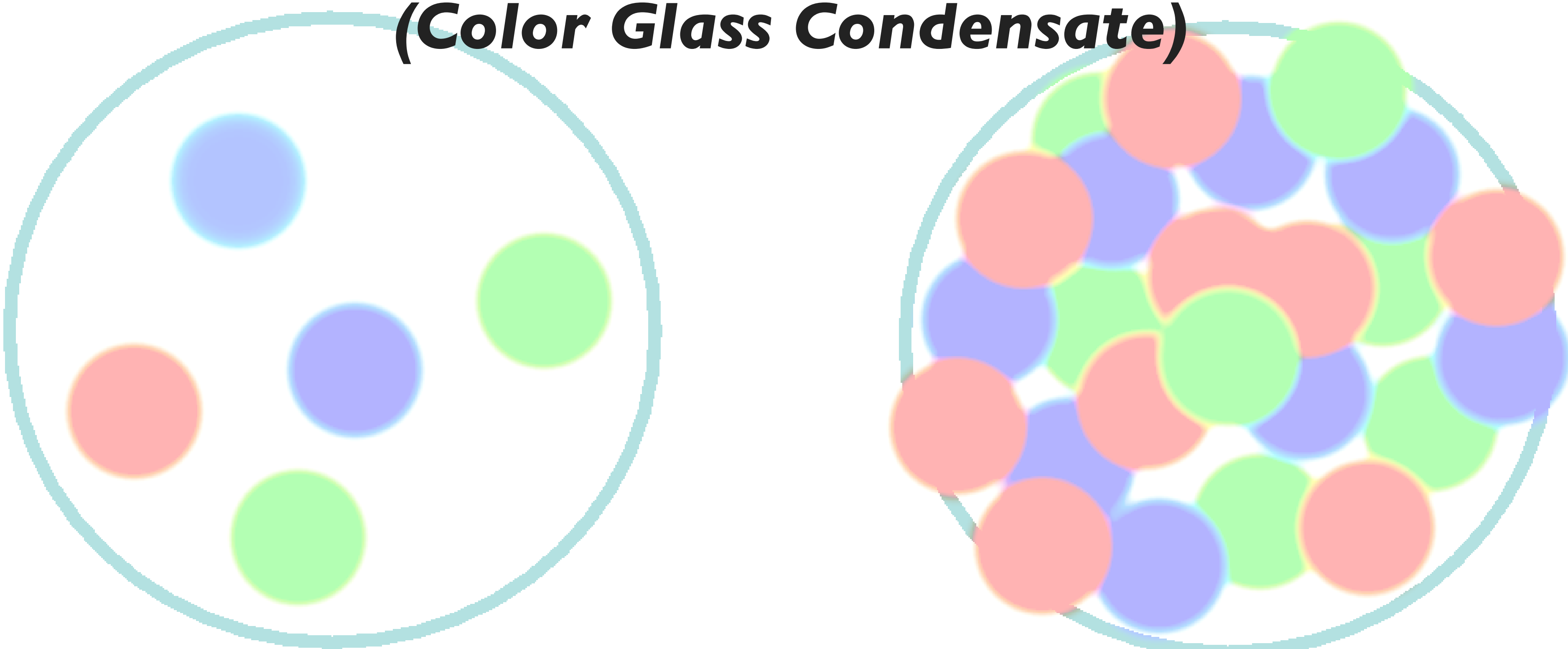
  → *presence of a hydrodynamical behavior.*

- What are the properties of the produced medium?

  → *identify signals of the presence of a medium in well-controlled observables.*

Initial state: Saturation of partonic densities

(Color Glass Condensate)



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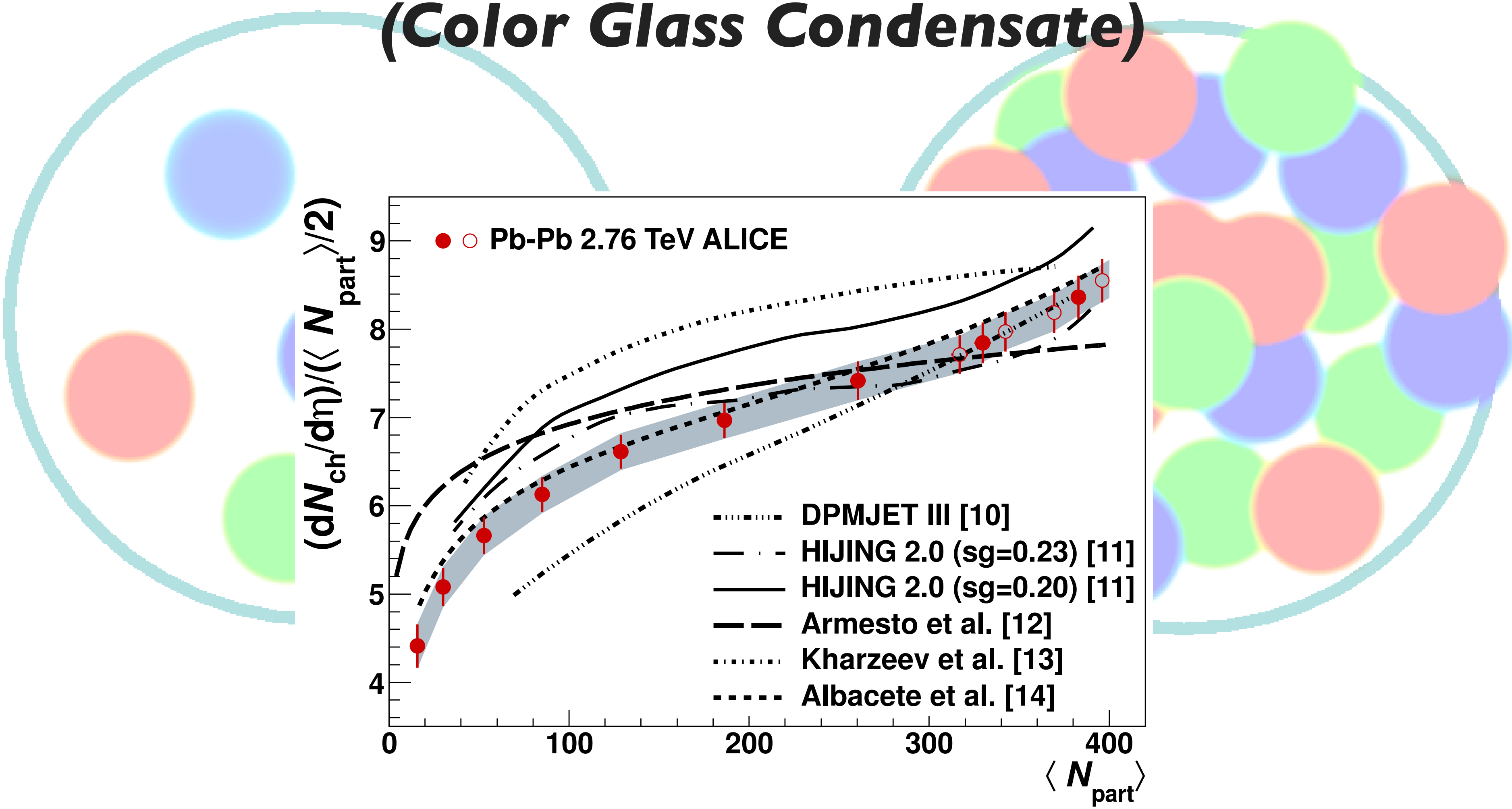


Checks of hydrodynamics (thermalization)

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

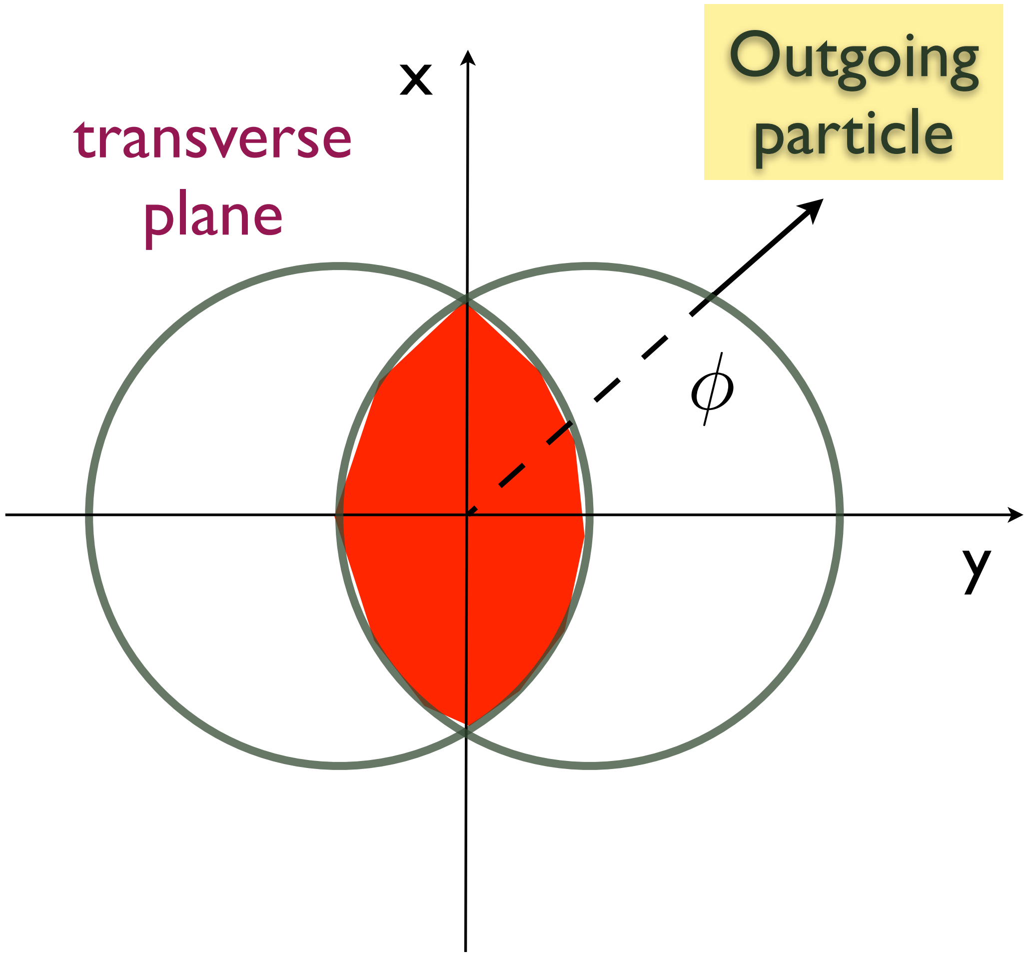
$$T^{\mu\nu} = (\varepsilon + p)u^\mu u^\nu - pg^{\mu\nu} + \text{viscosity corrections}$$

+ Equation of state

The essential measurement for hydro

⇛ Recall the Euler equation

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



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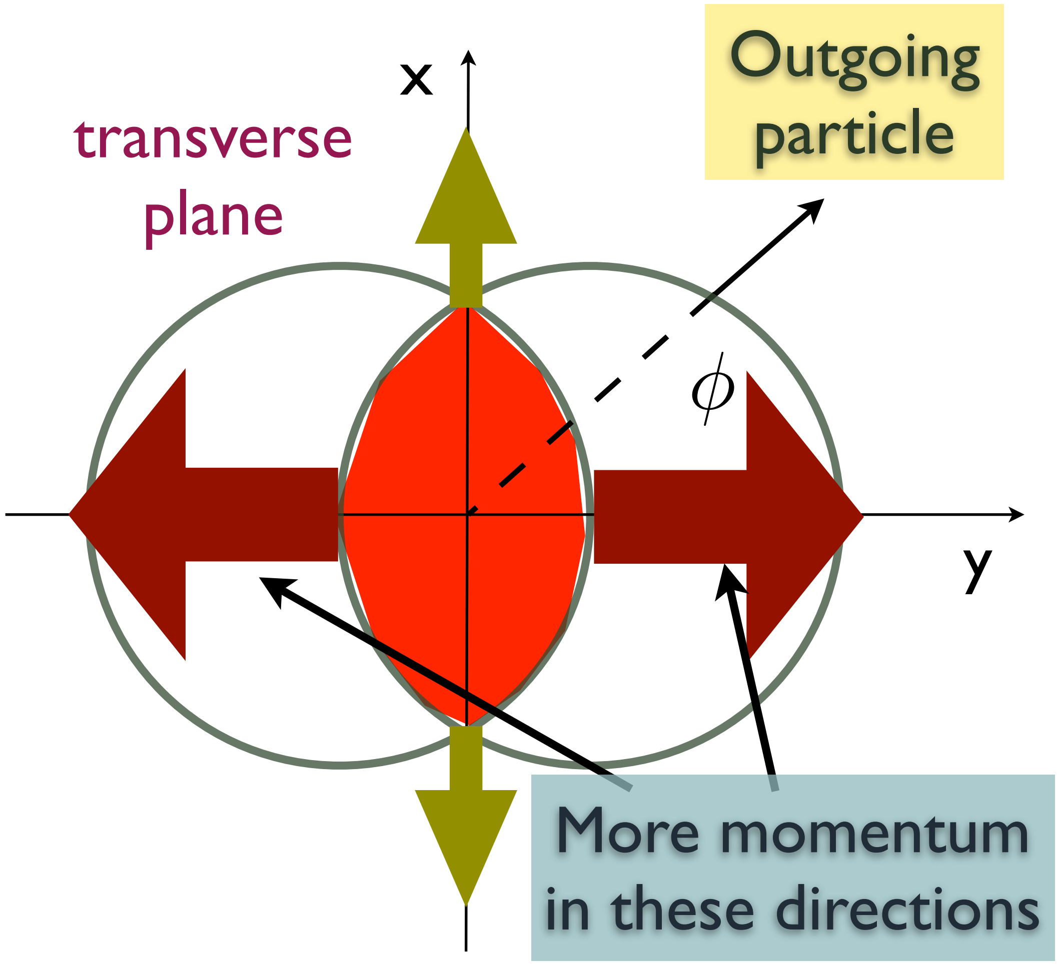
⇛ Recall the Euler equation

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

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

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

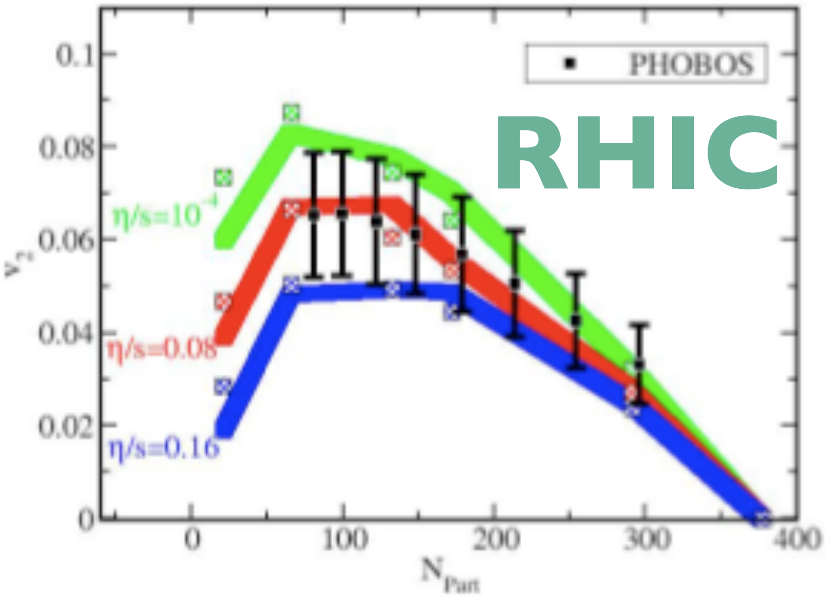
$$\frac{dN}{d\phi} \propto 1 + 2\, v_2 \cos(2\phi)$$

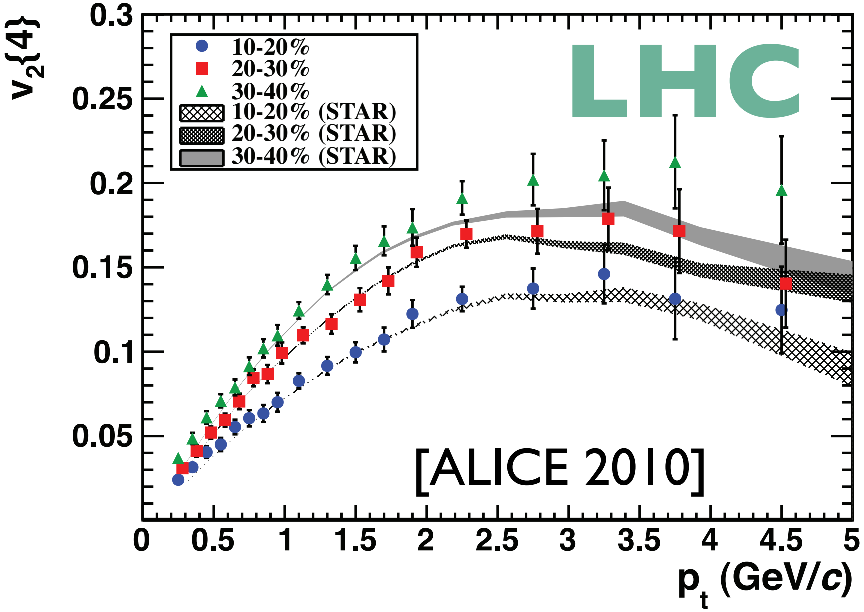


Initial conditions at thermalization time need to be given (ex. CGC)

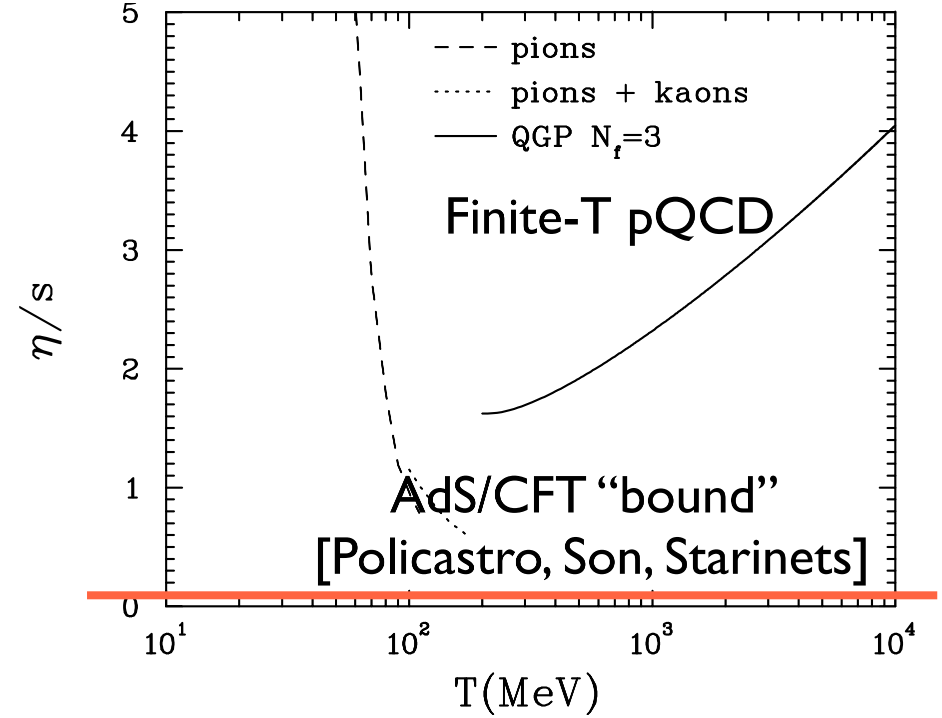
Ideal fluid behavior

[Luzum, Romatschke 2008]





[Csernai, Kapusta, Mclerran 2006]



⇛ **Lowest viscosity known**

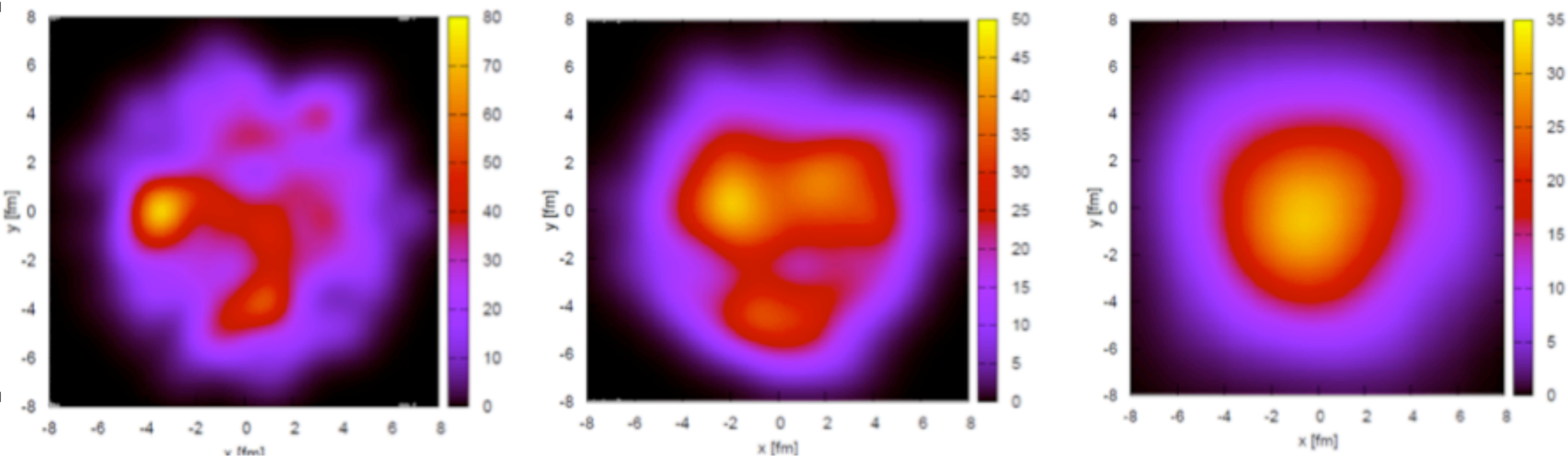
- Ideal fluid behavior
- "perfect liquid"

Higher harmonics

- With high precision data, higher terms in the expansion identified
  - For a symmetric medium odd terms are 0
  - Even-by-event fluctuations make them finite

[More in the talk by C. Loizides]

[H. Petersen, QM2011]



$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2\, v_n \, \cos\left[n\left(\phi - \phi_n\right)\right]$$

- Will allow precise tests of hydro

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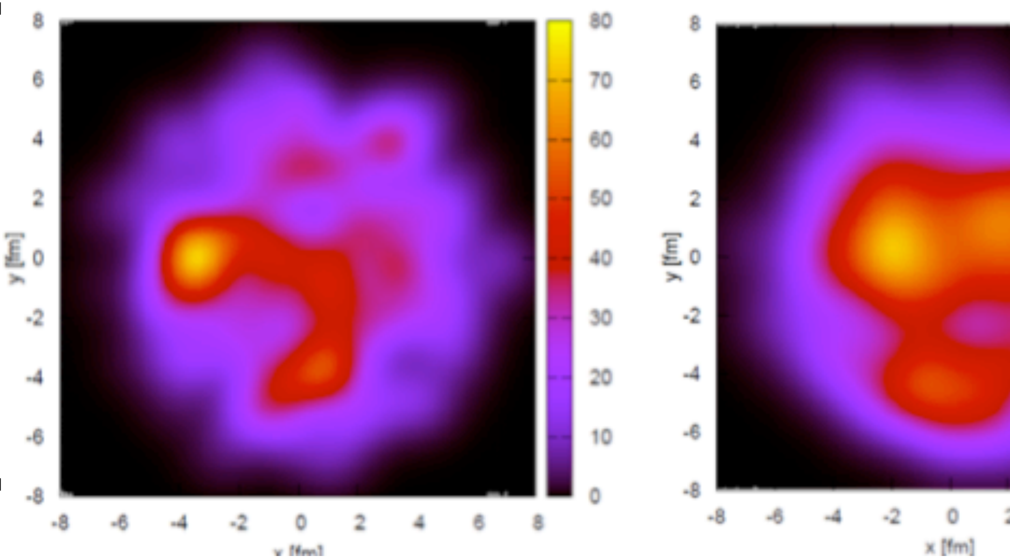

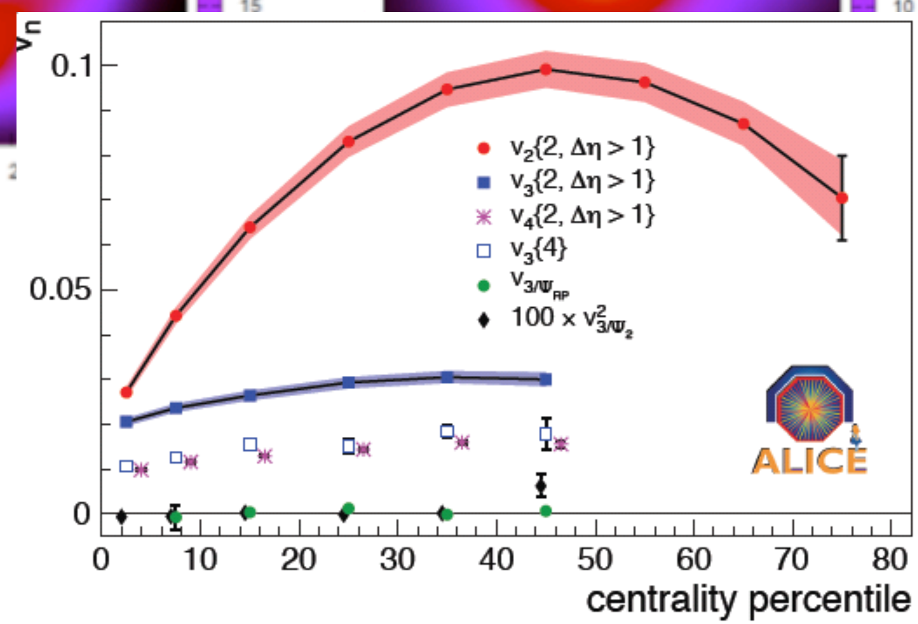

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Hard Probes

- ***Long distance terms modified by the presence of medium***
  - Nuclear PDFs and new (non-linear) evolution equations
  - Probes of hot matter created in the interaction
  - EW processes (no hadronization) used as benchmark

$$\sigma^{AB\to h} = \boxed{f_A^i(x_1,Q^2)\otimes f_B^j(x_2,Q^2)}\otimes\sigma(ij\to k)\otimes \boxed{D_{k\to h}(z,Q^2)}$$

Nuclear PDFs

Hadronization

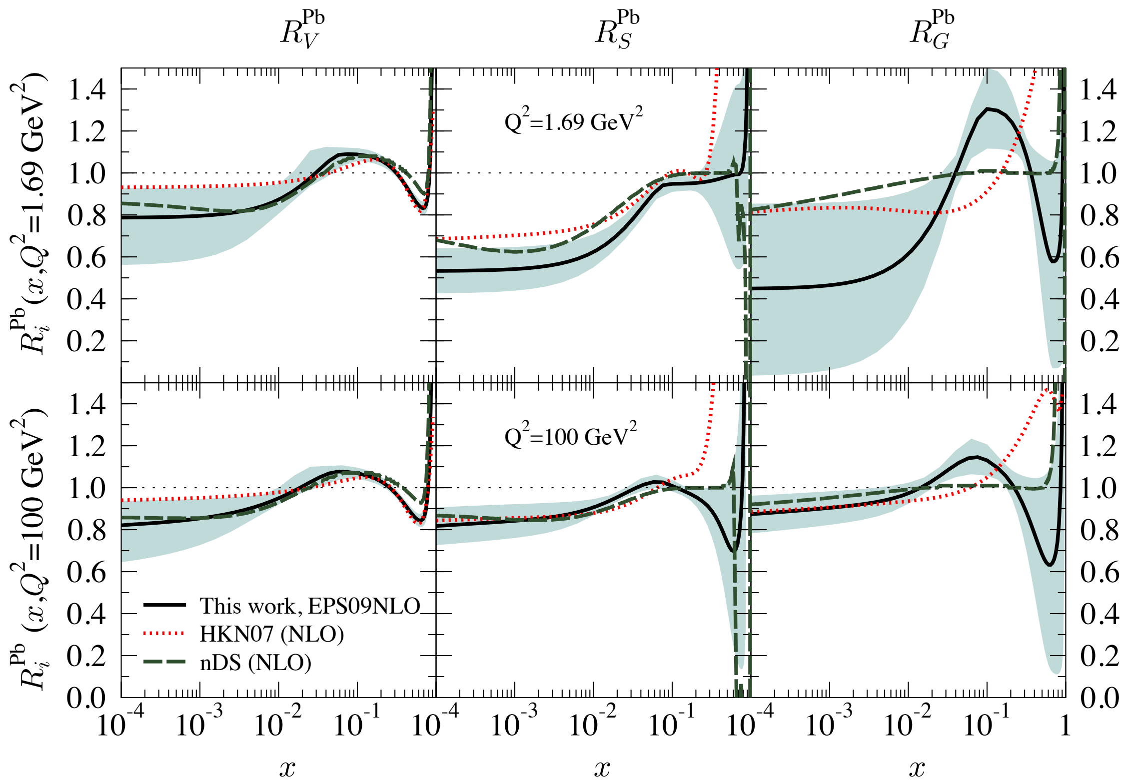
J/Ψ paradigmatic example

- ***If you know two ingredients you can extract the other***

[Tom LeCompte yesteday's talk]

Nuclear PDFs

⇛ Initial conditions and error analysis for different NLO sets



	Chi^2/dof
EPS09	0.79
HKN	1.58
nDS	0.76

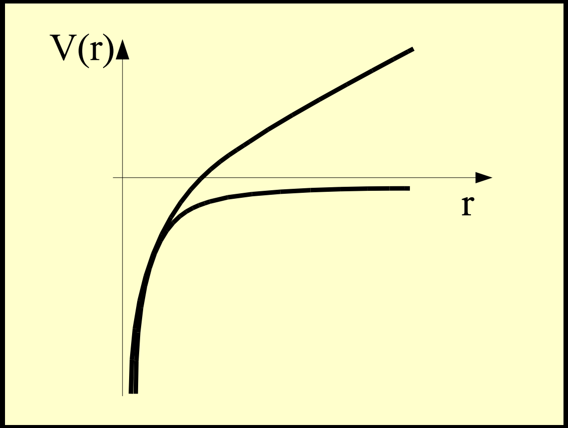
⇛ Large uncertainties especially for gluons - smaller at large virtuality

⇛ Notice that parametrization bias effects are present

- Bands to be considered as lower bounds

Quarkonia suppression

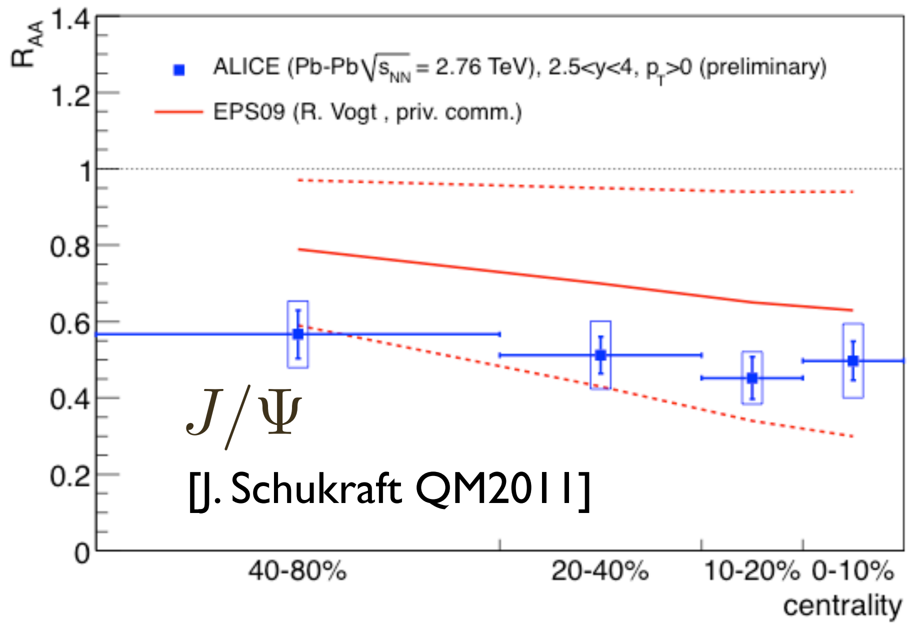
- ***Simple intuitive picture*** [Matsui & Satz 1986]
  - Potential screened at high-T
  - Bound states not possible
  - Suppression of J/Psi in nuclear collisions



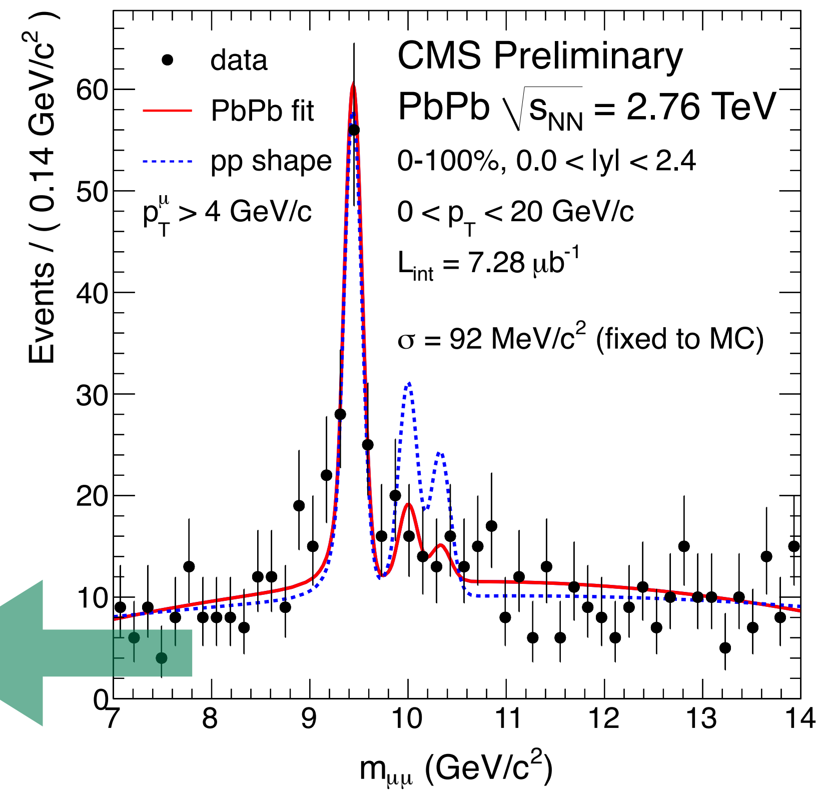
- ***However, interpretation of the data is not clear***
  - J/Psi suppressed also in pA (on top of nPDFs)
  - Not good theoretical control over the suppression
  - (Already J/Psi suppression not well understood in pp)
  - Could LHC improve the situation?

Quarkonia at the LHC

- Different quarkonia states have different suppression



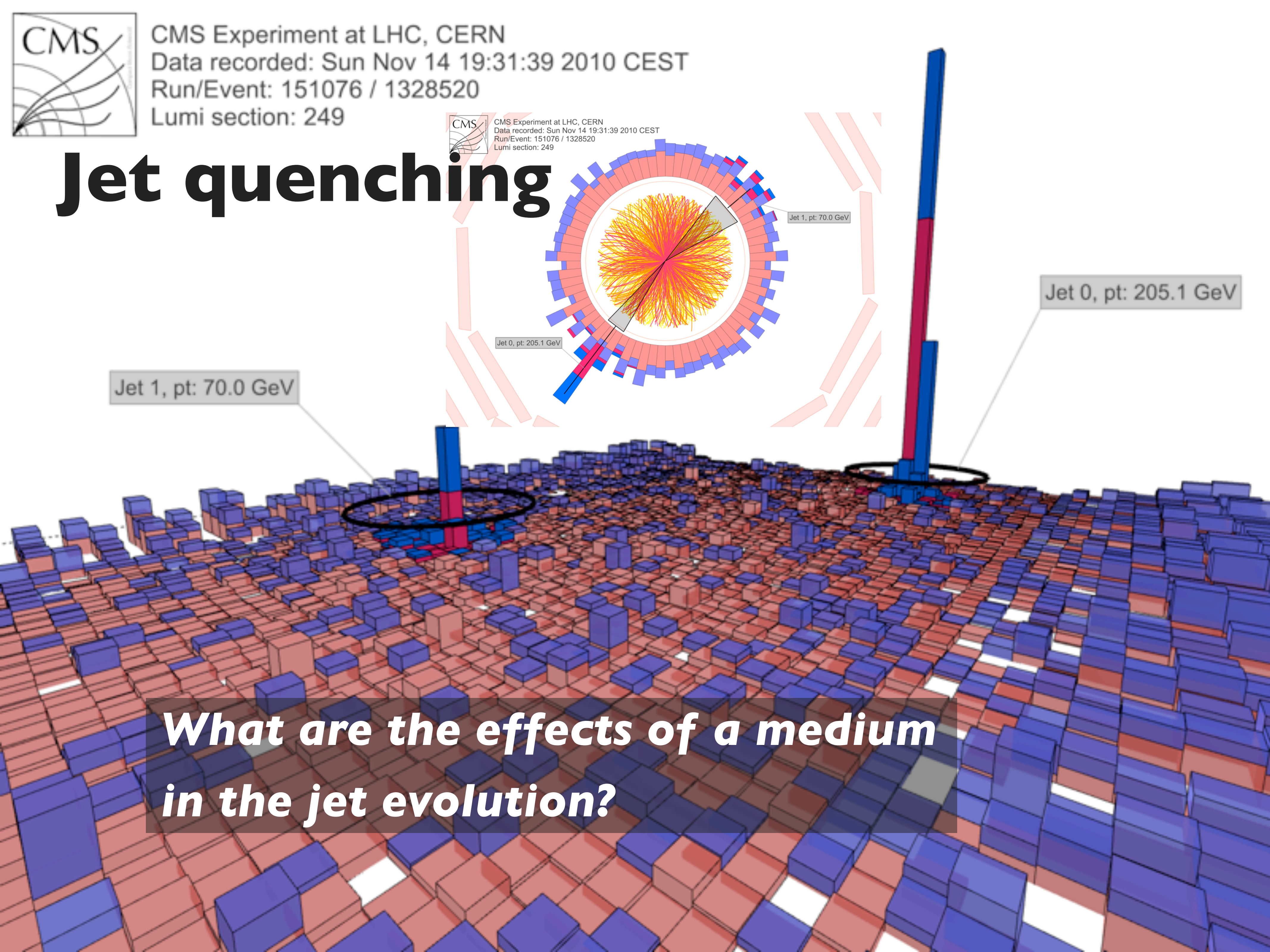
$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$



[C. Silvestre QM2011]

- Sequential suppression?
  - Lattice QCD suggest that 1S quarkonia states melt at $T \sim 2T_c$
  - Excited states melt at $T \sim T_c$

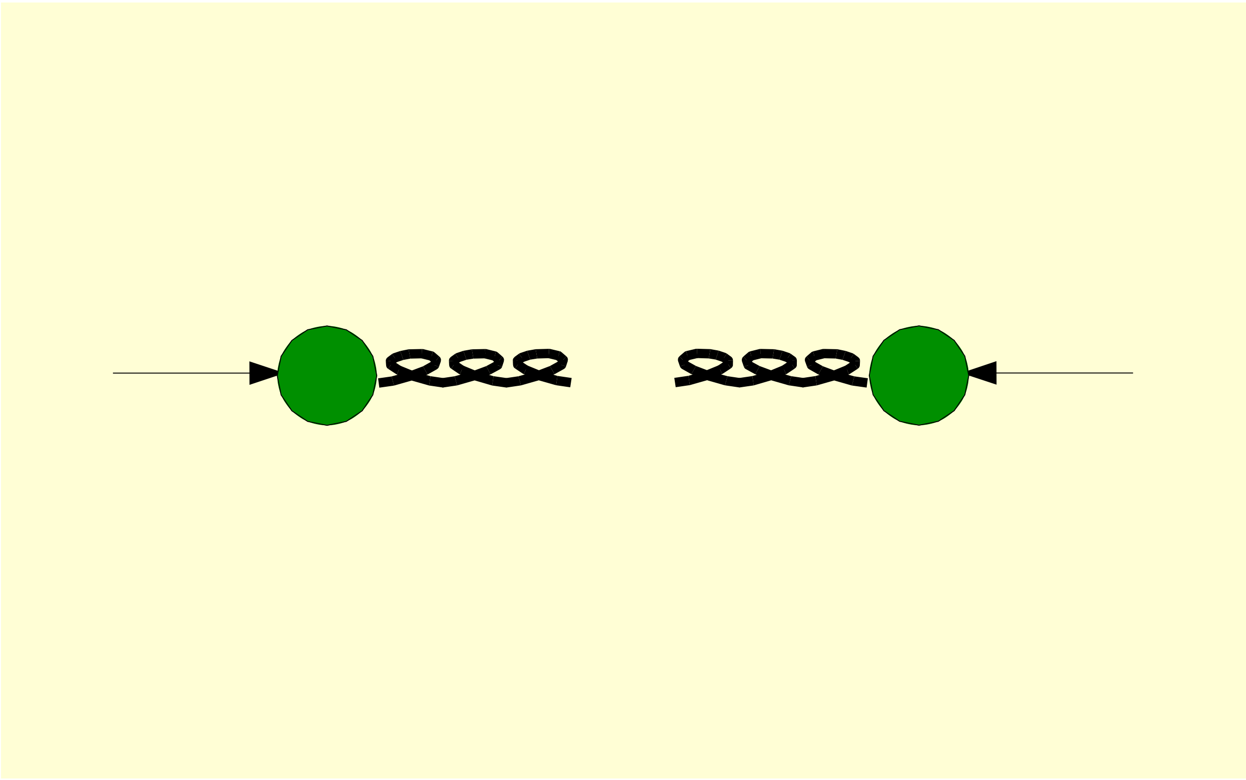
Jet quenching

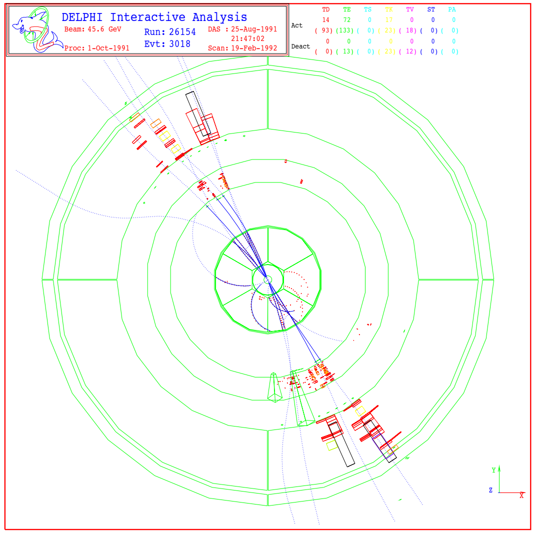


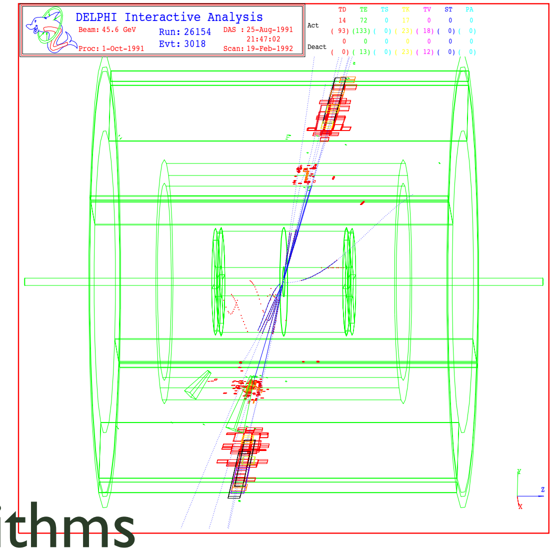
What are the effects of a medium in the jet evolution?

What is a jet (naively)

[Nigel Glover yesterday's talk]







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  - Ideally all the energy of the primary is reconstructed by the algo

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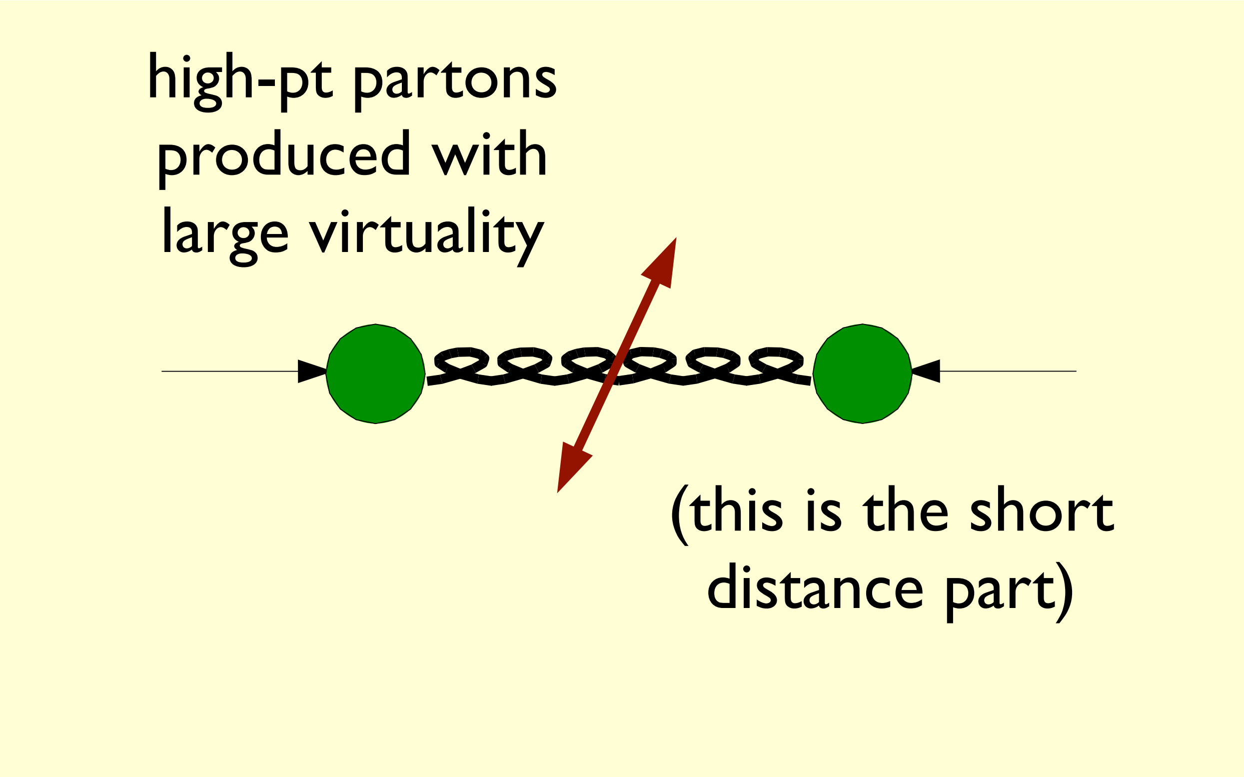

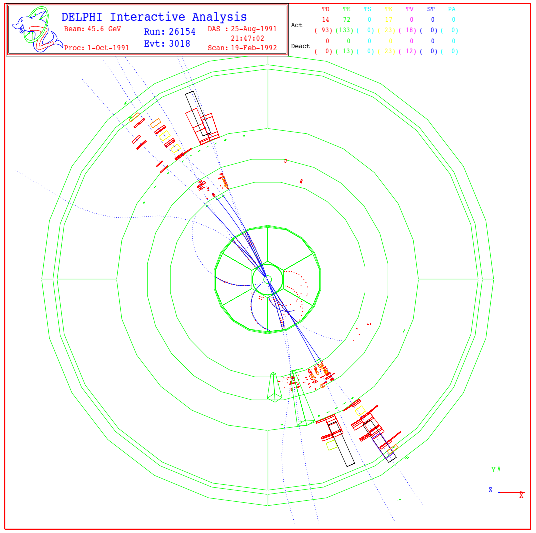

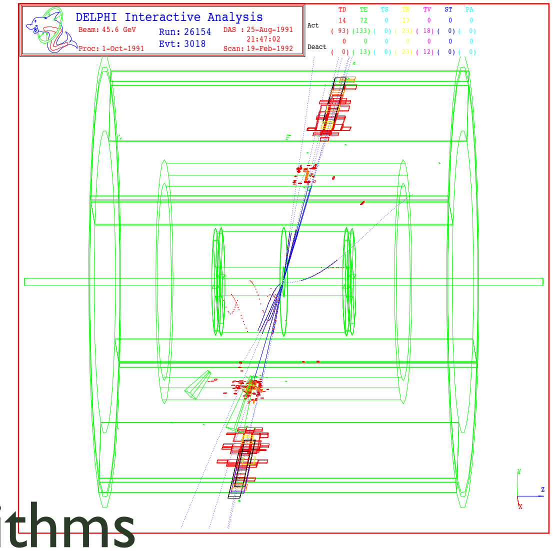

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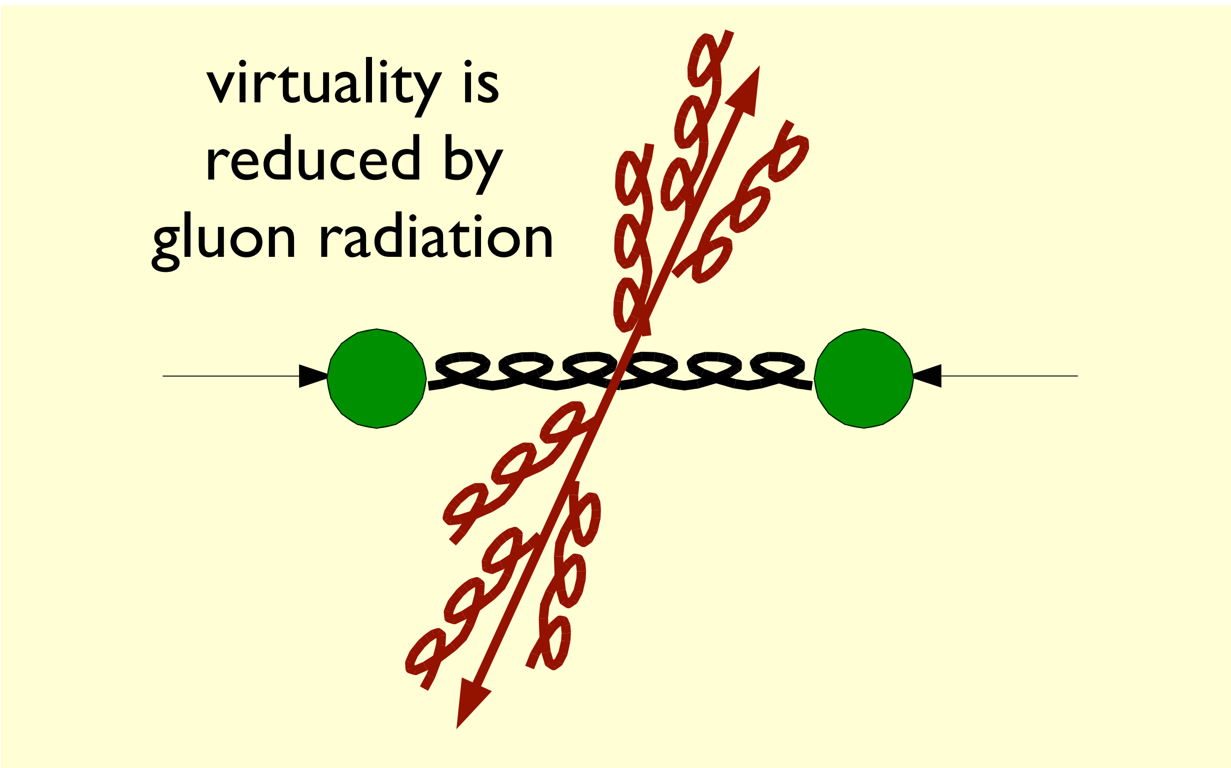

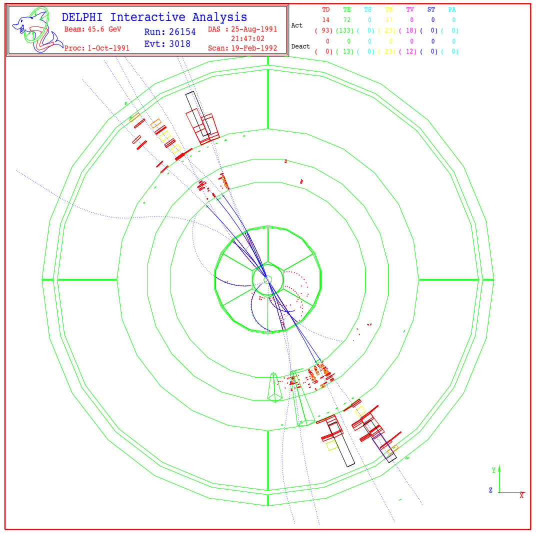

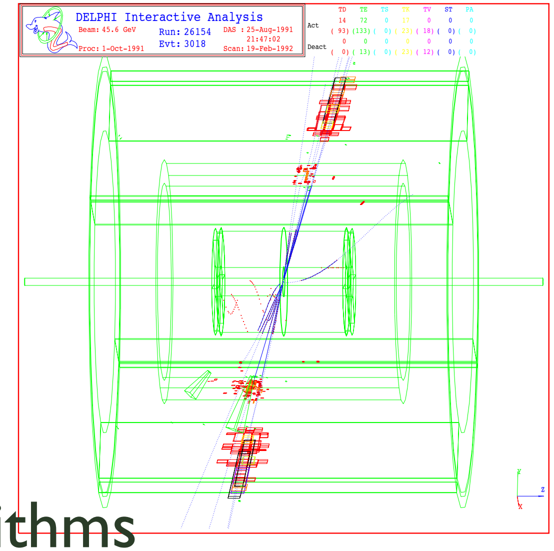

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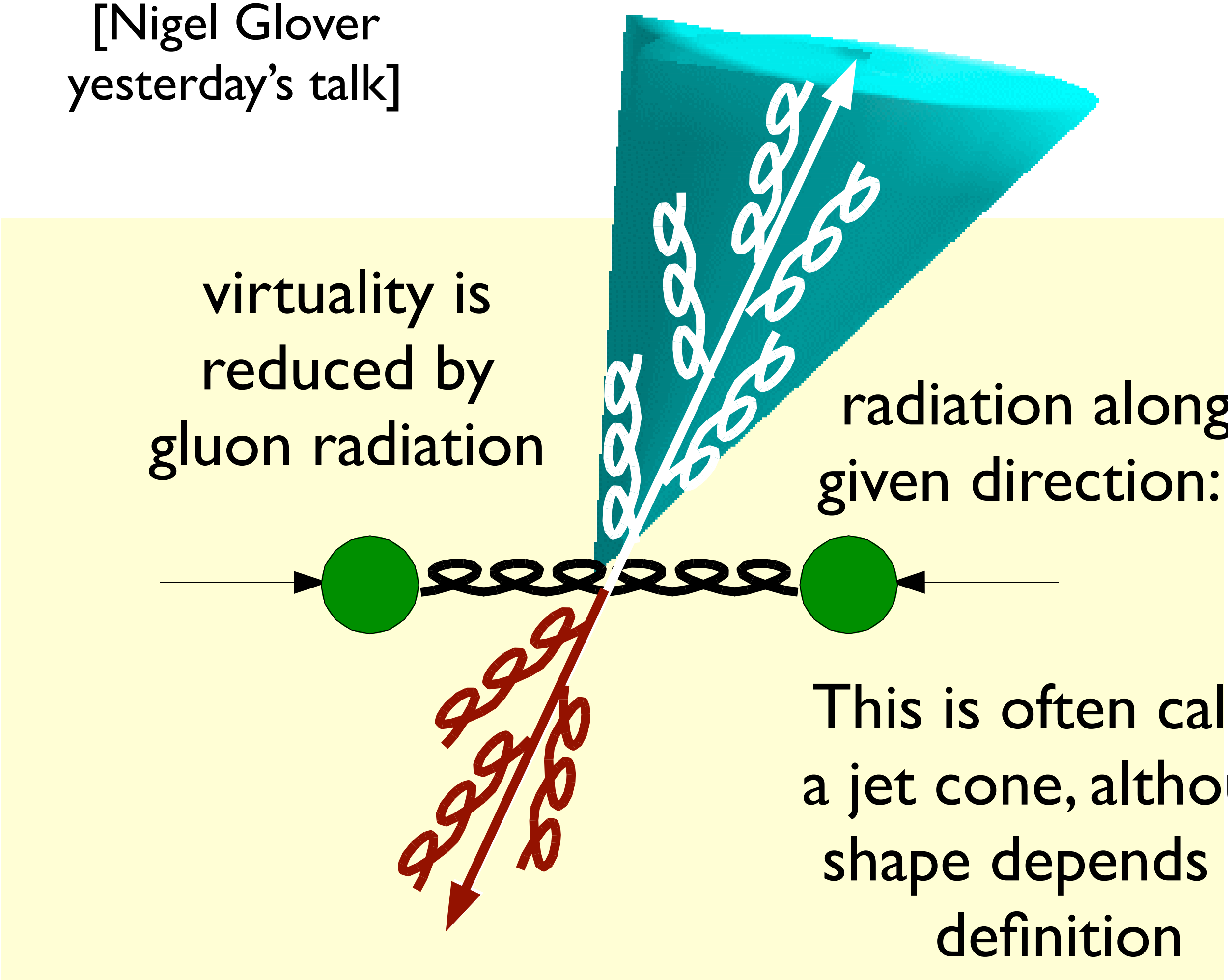

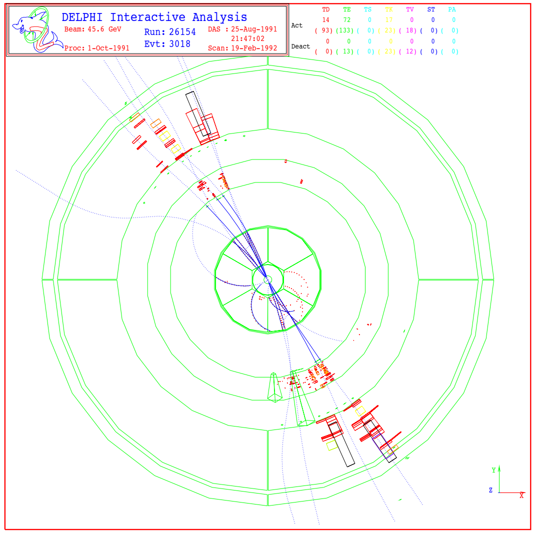

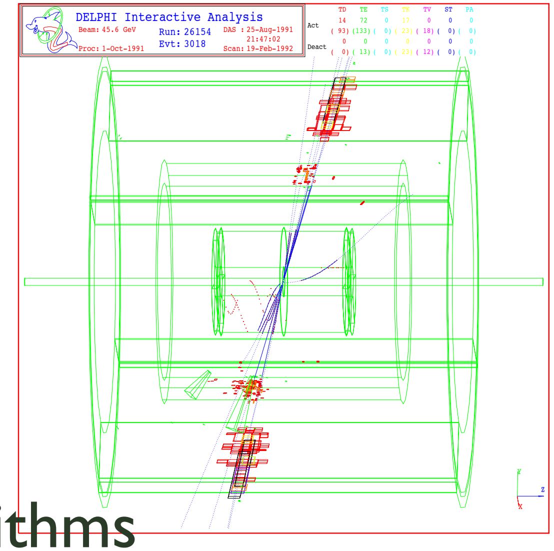

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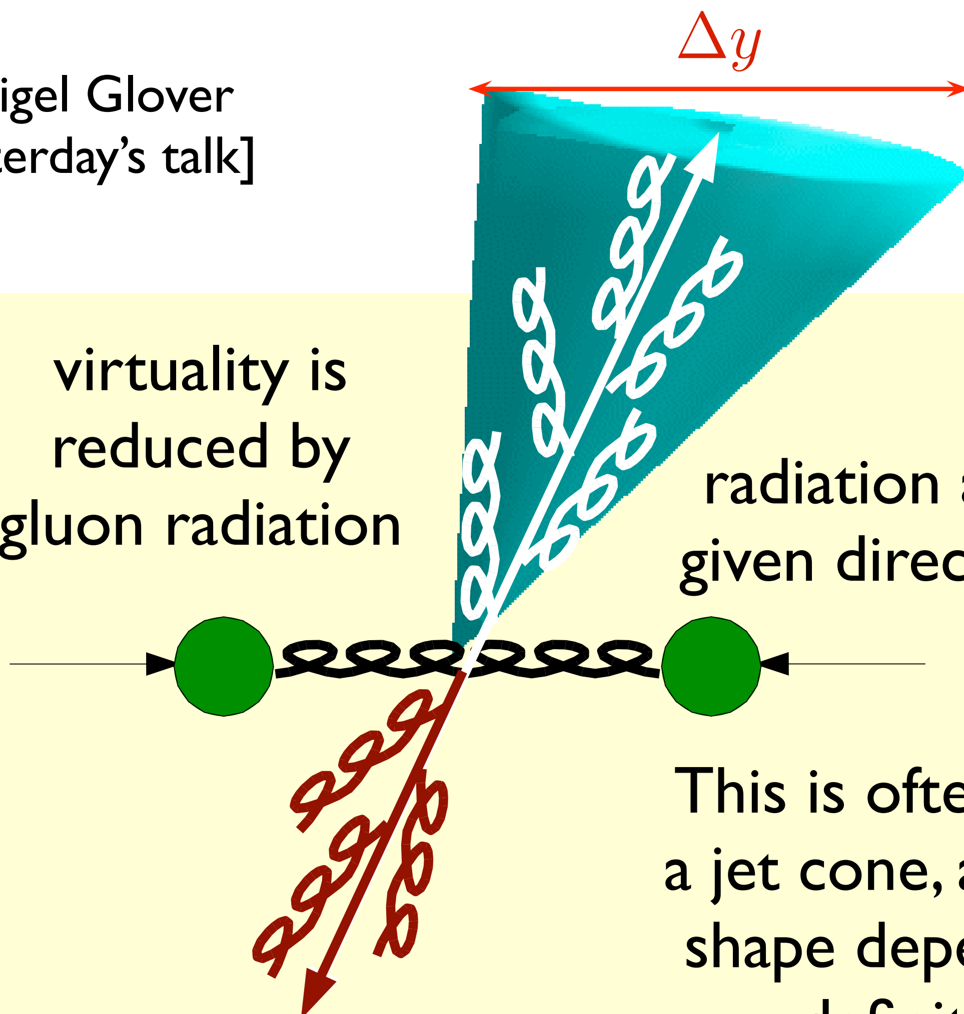
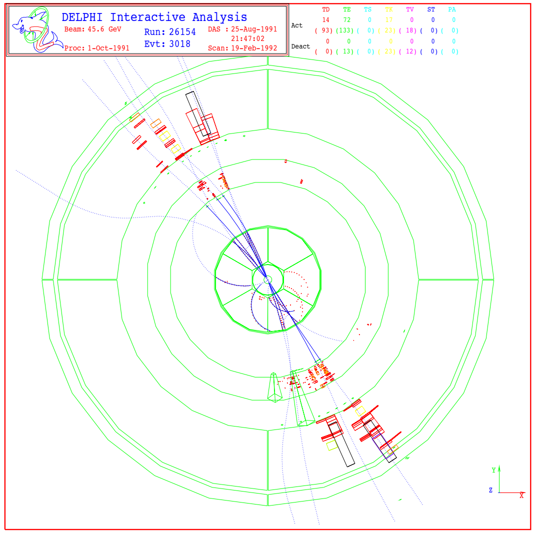
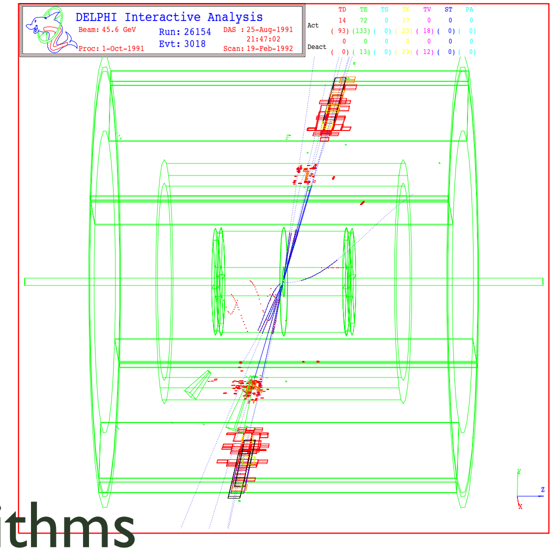


virtuality is reduced by gluon radiation

radiation along a given direction: jet

This is often called a jet cone, although shape depends on definition





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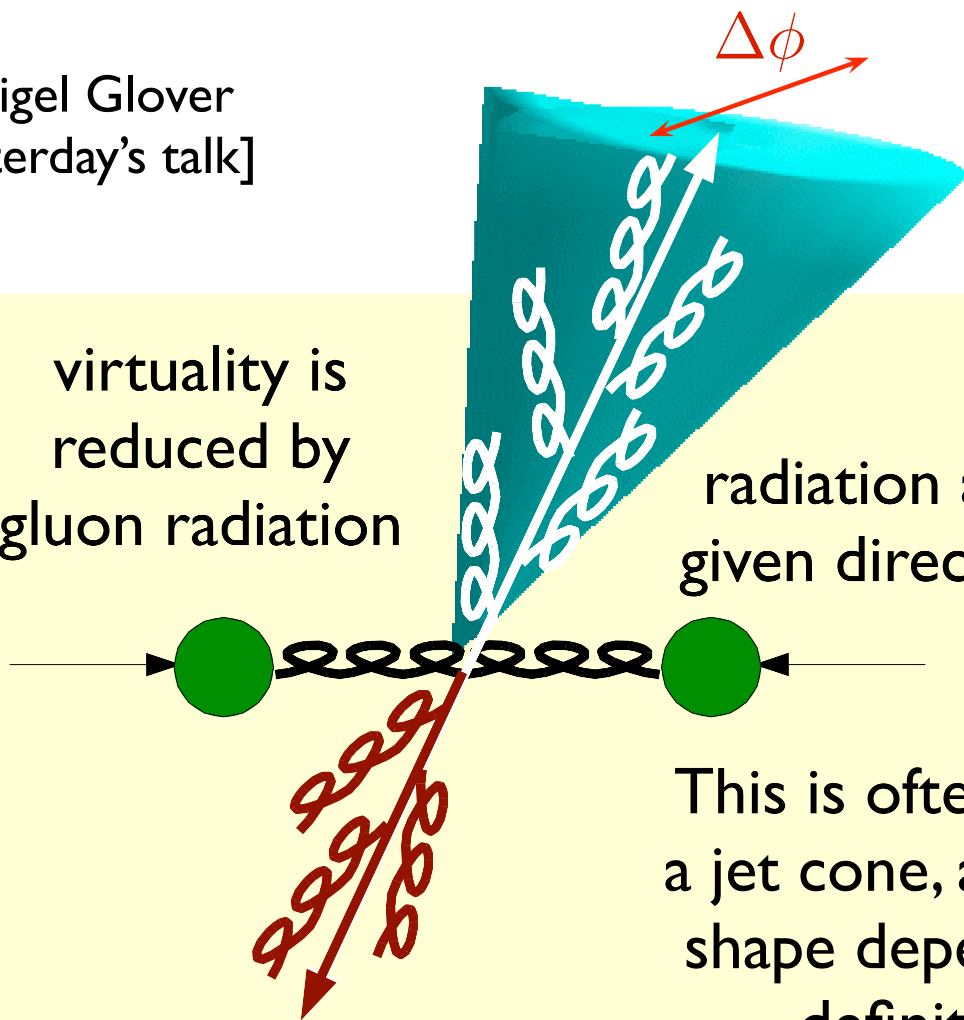

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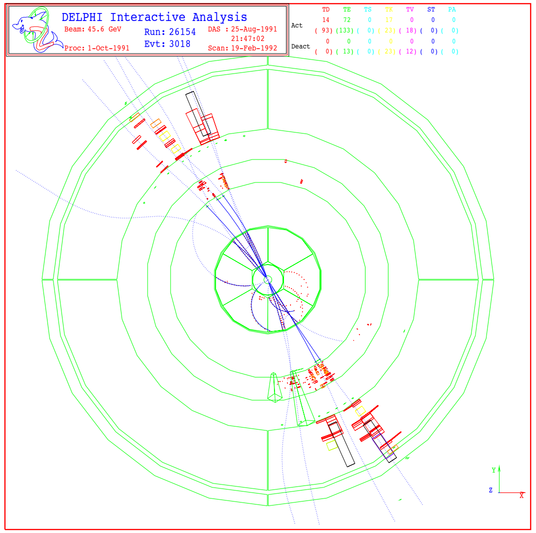

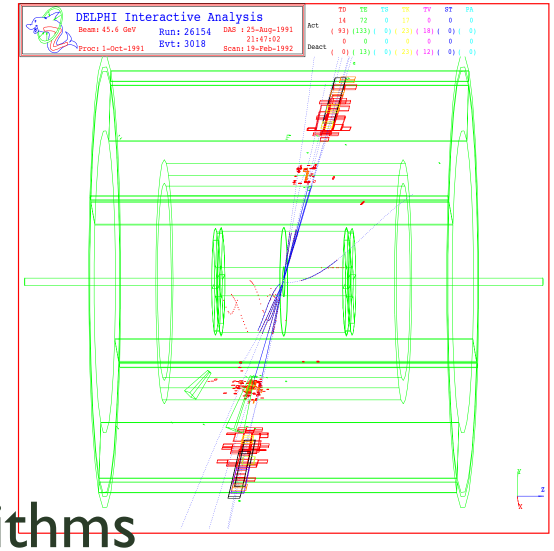

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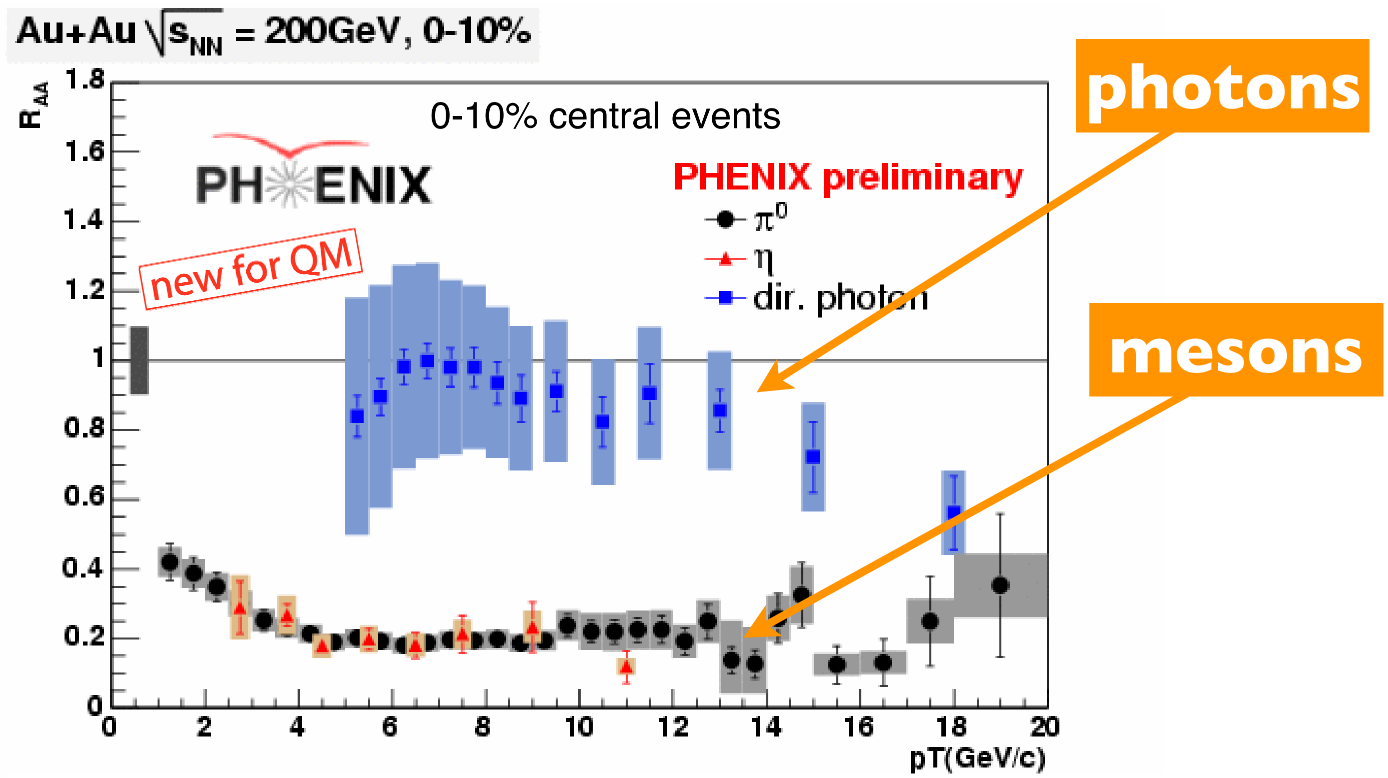
Jet quenching at RHIC

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



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

dense partonic system

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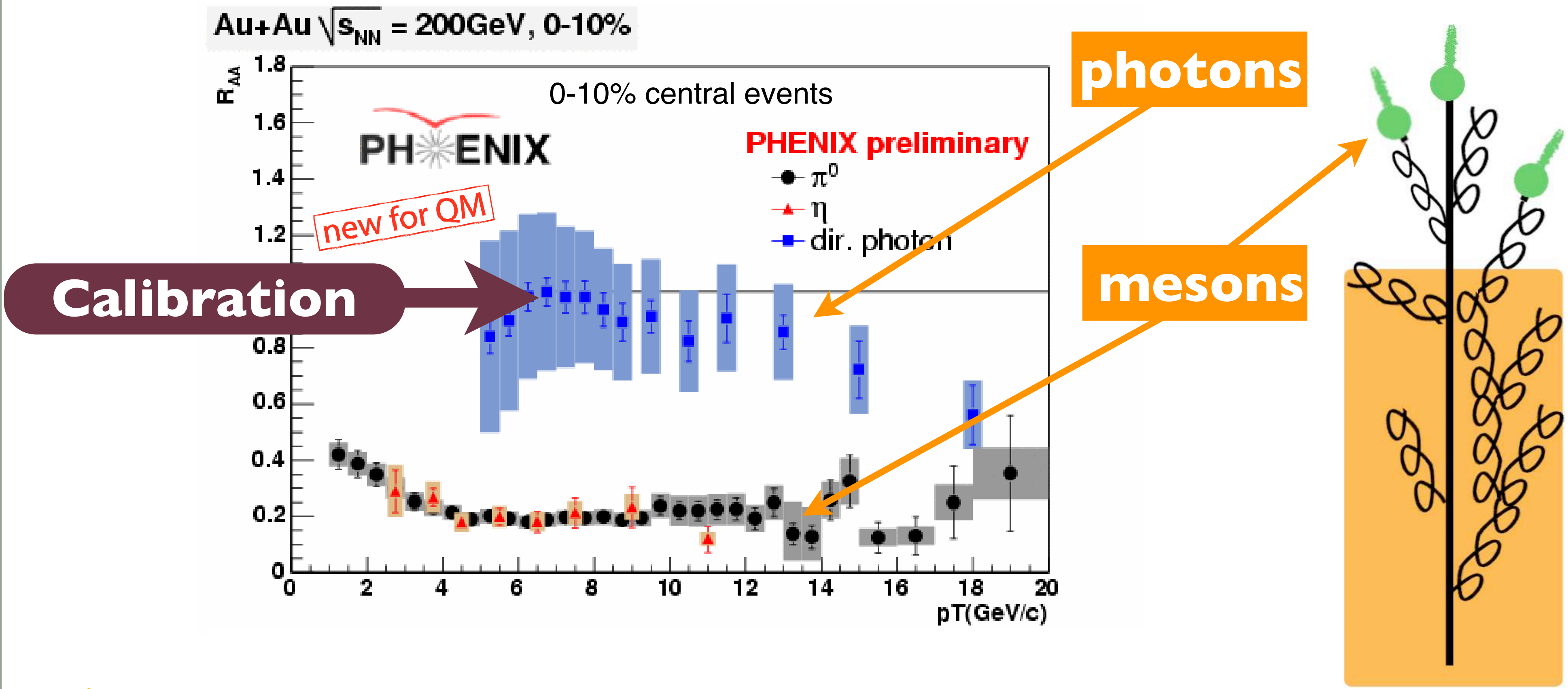

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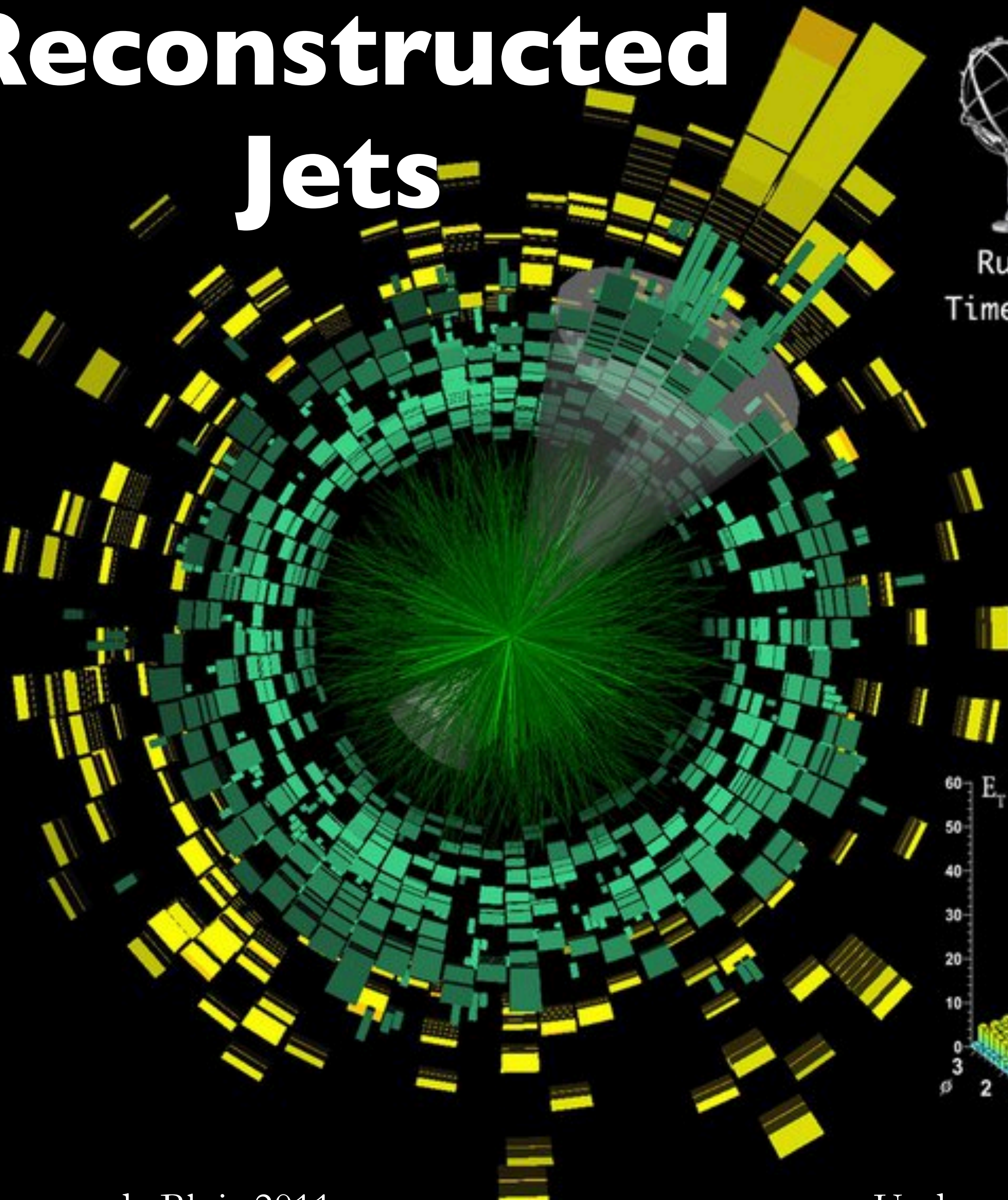
Reconstructed Jets

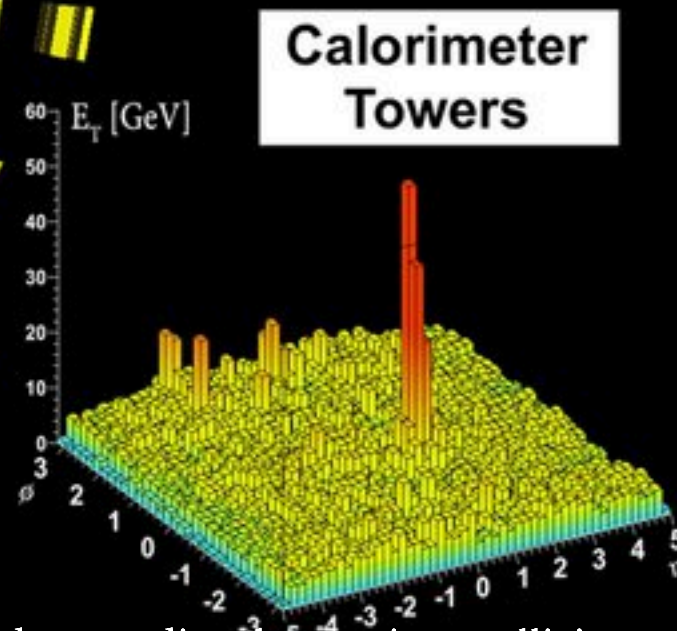


ATLAS EXPERIMENT

Run 168795, Event 7578342

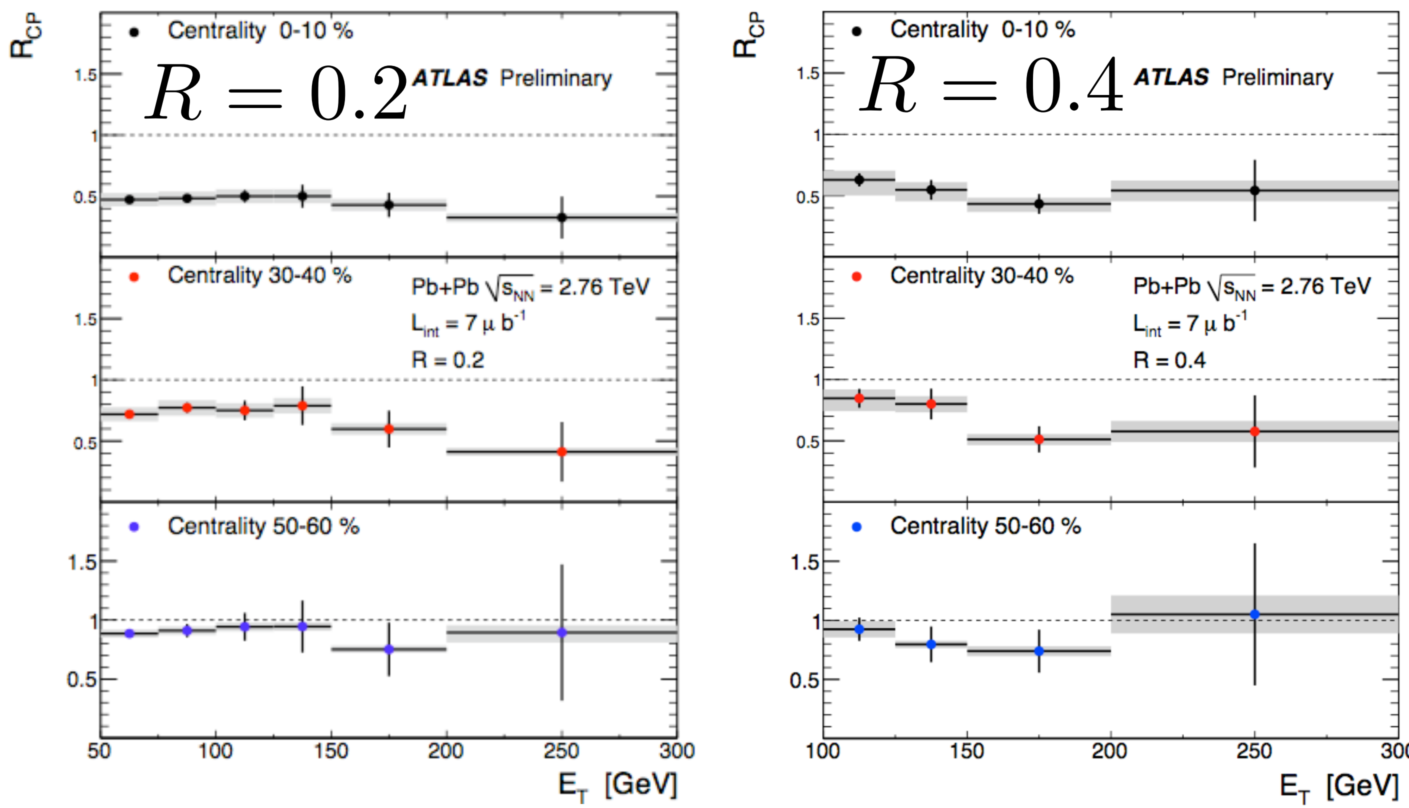
Time 2010-11-09 08:55:48 CET

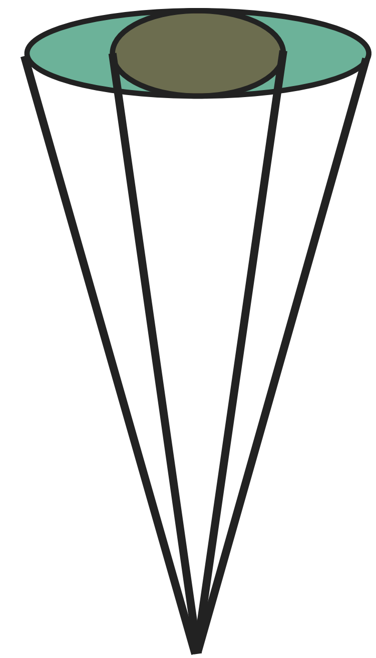
[Jet reco in HIC: Cacciari, Rojo, Salam, Soyez 2010]



Inclusive jets are suppressed

- In central collisions, only 1/2 of the jets are observed for two radius R [ATLAS 2010 - B. Cole QM2011]



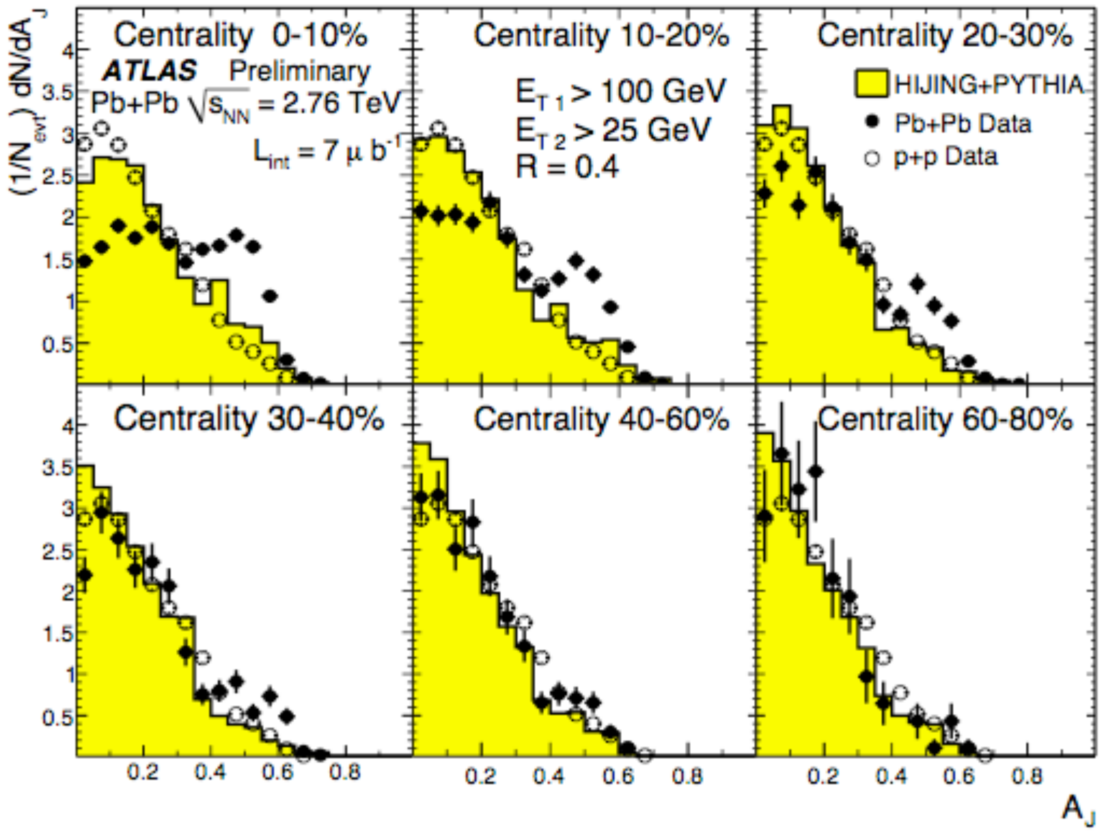


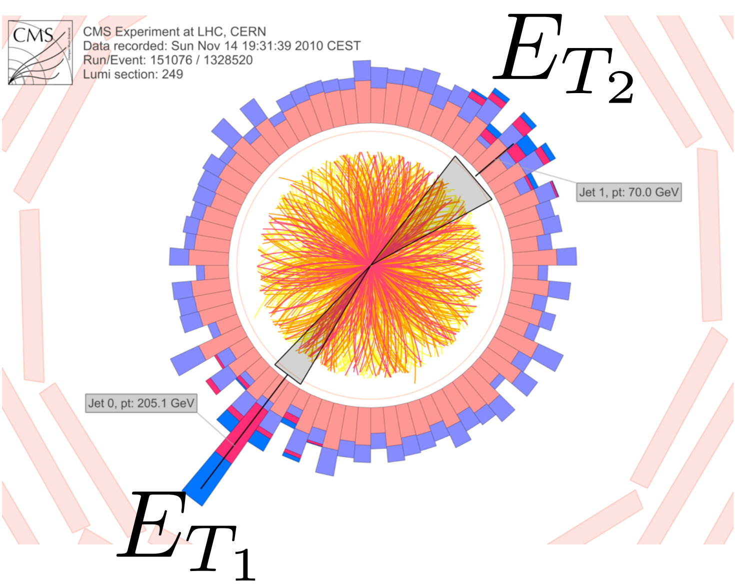
- Need to understand proton-proton reference
- Observed jets are biased - is an unbiased measurement possible in HI?

Di-jet asymmetry at the LHC

⇛ Energy imbalance between two most energetic jets: $A_j = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$

[ATLAS 2010 - B. Cole QM2011; CMS similar results]



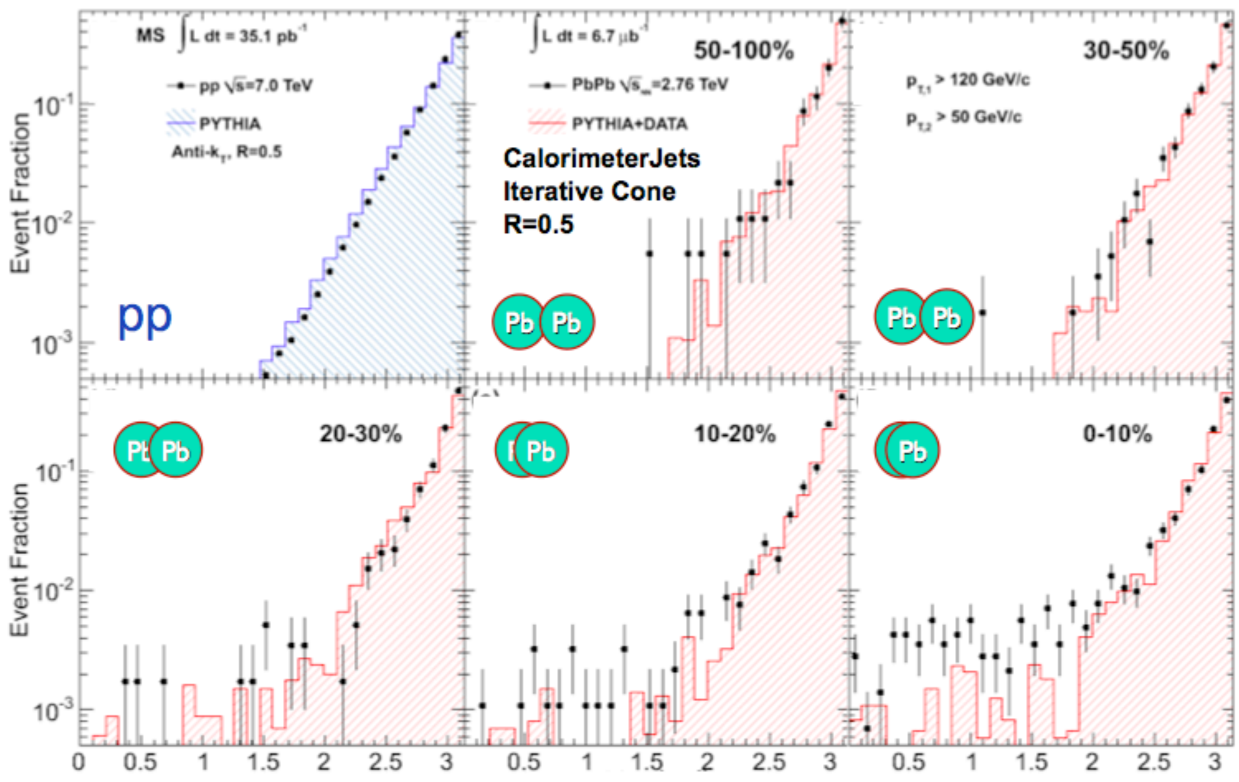


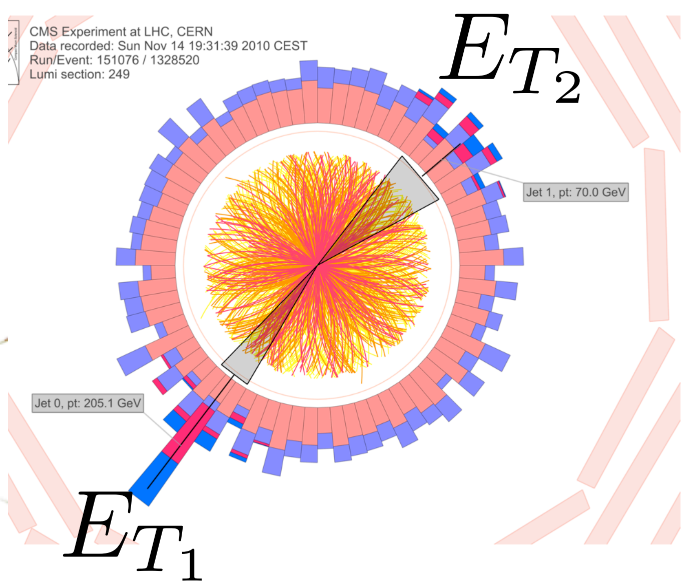
⇛ Strong energy loss - points to a **very dense partonic system**

Di-jet asymmetry at the LHC

⇛ Azimuthal distribution of two most energetic jets

[CMS 2011 - C. Roland QM2011; ATLAS similar results]



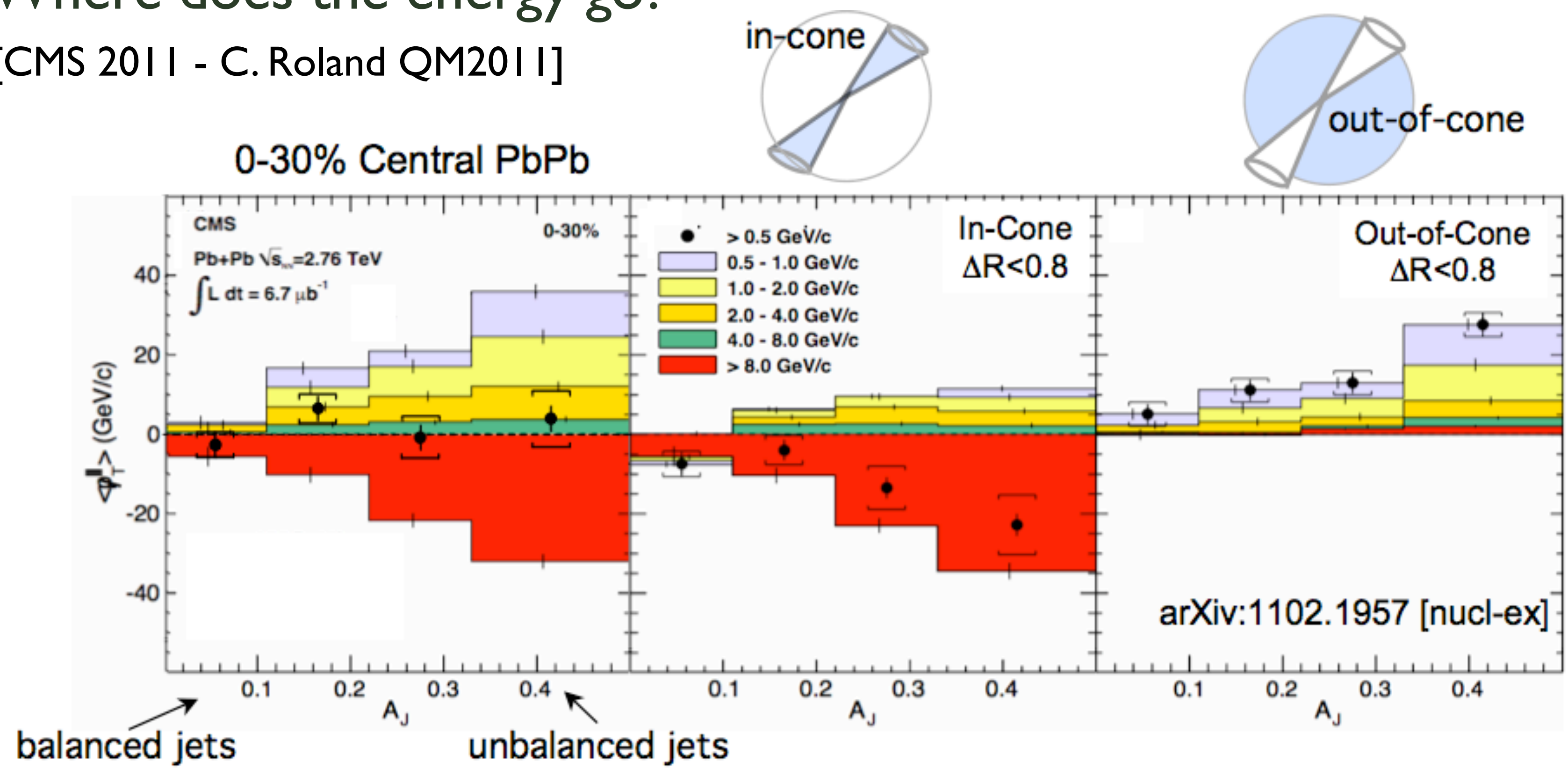


⇛ **No strong change with respect to the vacuum jets**

Di-jet asymmetry at the LHC

⇒ Where does the energy go?

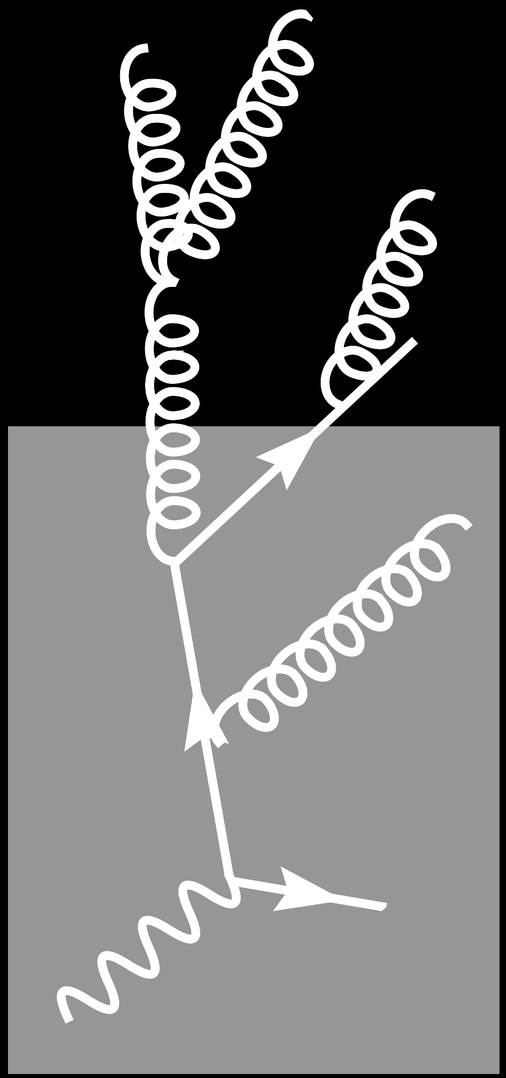
[CMS 2011 - C. Roland QM2011]



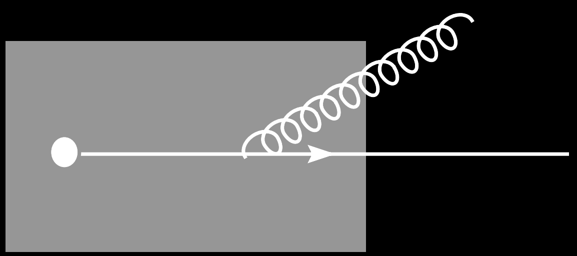
$$\not{p}_T^{\|} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

⇒ **Energy taken by soft particles at large angles**

A theory of jets in the medium



- In-medium parton shower **not known** from QCD
- Until recently only medium modification off **single emitter** computed

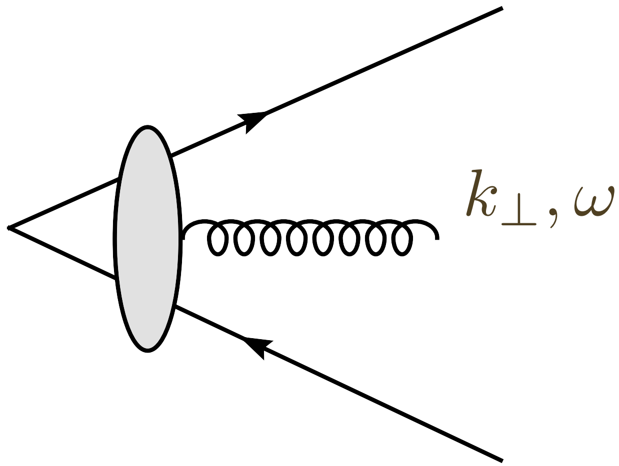


- But coherence among different emitters is essential in the vacuum case:

ordering variables

Antenna emission in vacuum (QCD or QED)

⇛ Building block of parton showers in vacuum. Taking quark as reference:



$$t_{\rm form} \simeq \frac{\omega}{k_\perp^2} \simeq \frac{1}{\theta_{q,g}^2 \omega}$$

⇛ The transverse wavelength

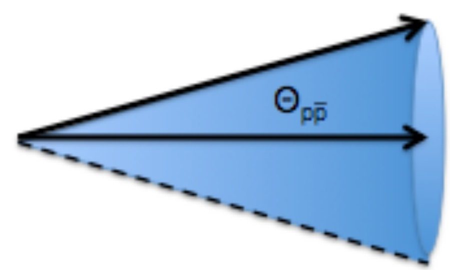
$$\lambda_\perp \simeq \frac{1}{k_\perp} \quad \Rightarrow \quad t_{\rm form} \simeq \frac{\lambda_\perp}{\theta_{q,g}}$$

⇛ The transverse size of the pair : $\theta_{q\bar{q}}\, t_{\rm form} \simeq \lambda_\perp \frac{\theta_{q\bar{q}}}{\theta_{q,g}}$

⇛ So, when $\theta_{q,g} \gg \theta_{q\bar{q}}$ the gluon/photon "sees" a **neutral** object

⇛ The spectrum integrated in azimuthal angle

$$\langle dN_q \rangle_\phi \propto \frac{d\omega}{\omega} \frac{d\theta_{pk}}{\theta_{pk}} \Theta\left(\theta_{p\bar{p}} - \theta_{pk}\right)$$



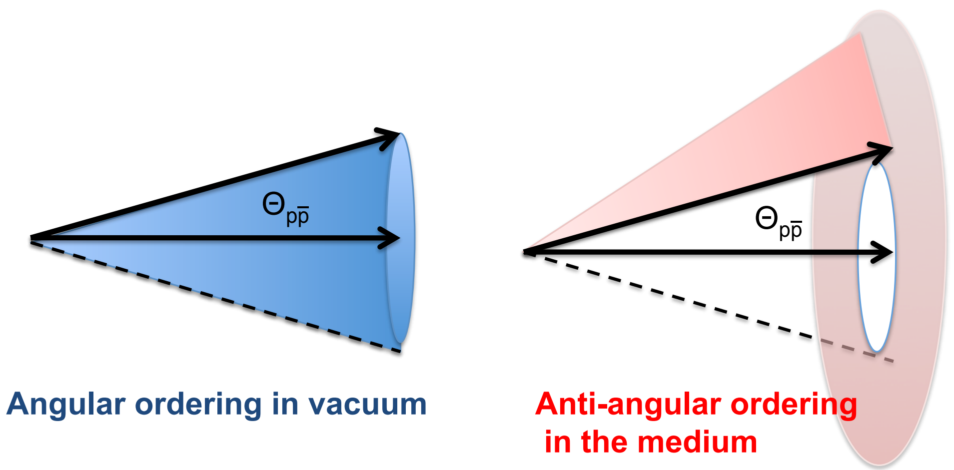
Angular ordering in vacuum

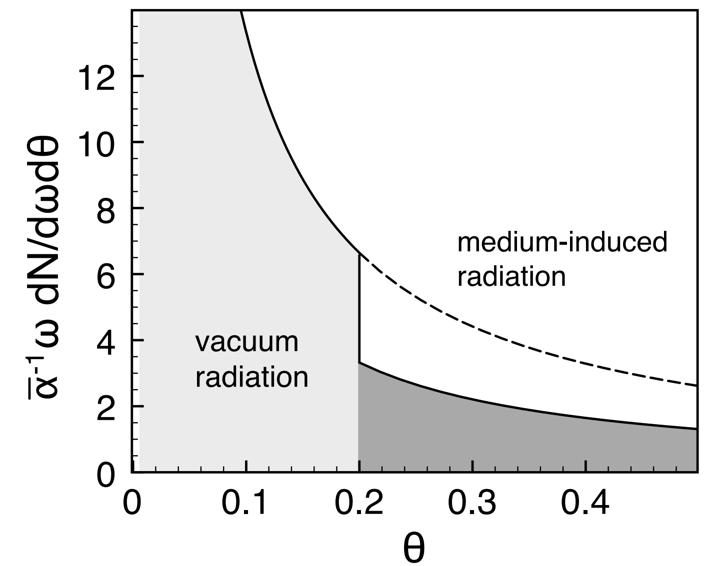
Antenna radiation in medium

⇛ Very striking result found in the medium [Mehtar-Tani, Salgado, Tywoniuk 2010]

- Strict large angle emission - anti-angular ordering in soft limit

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



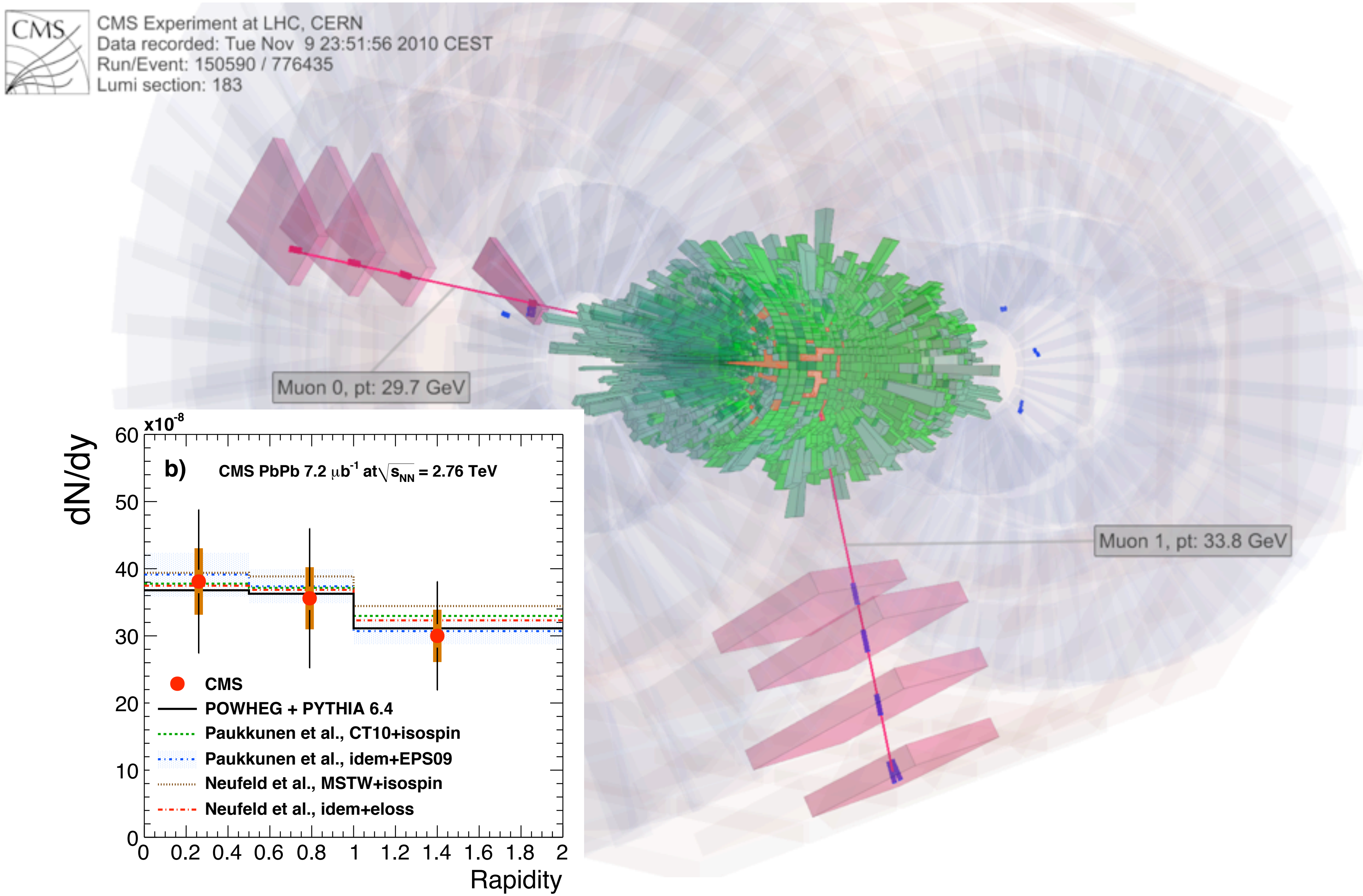


⇛ For an **opaque medium**, two vacuum-like **de-coherent** spectra

- Soft emission at large angle. Promising tool for in-medium shower
- Memory loss effect: radiation independent on initial color config.

Collisions at the TeV scale imply completely new opportunities

First Z's measured in nuclear collisions



Summary

- ***With LHC nuclear collisions at the TeV for the first time***
  - Access to the small-x region of the wave function
  - Large virtualities: jets, EW bosons, etc...
- ***Created medium (RHIC+LHC) very dense***
  - ***Ideal fluid behavior***
- ***Higher statistics and new tools***
  - Will allow to characterize the medium properties with unprecedented precision
  - **Is it a liquid? Strongly coupled? Are quasiparticles the relevant degrees of freedom?..**