Hot QCD matter
what has been learned at the LHC?

European Research Council

Jean-Paul Blaizot, IPhT-Saclay

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Many phenomenological issues (heavy ions are complex systems !)

Colliding heavy nuclei

Little Bang(s)

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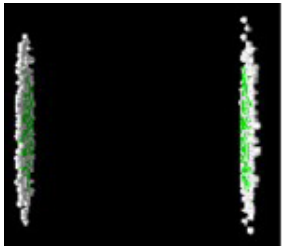

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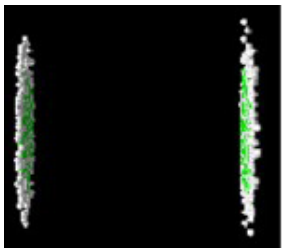

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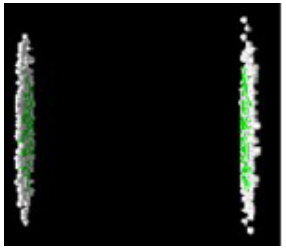

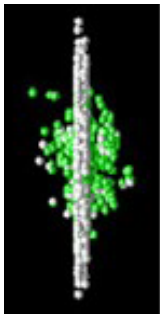

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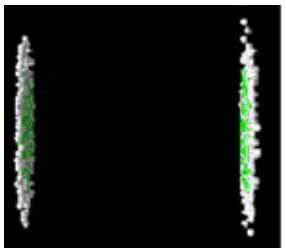

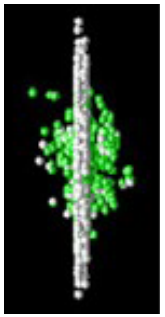

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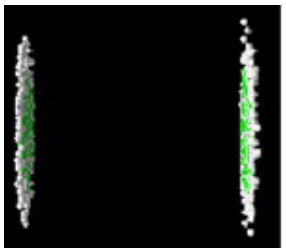

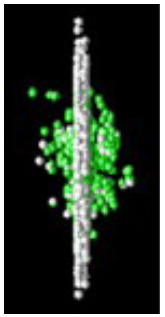

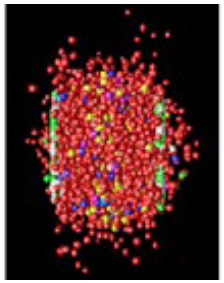

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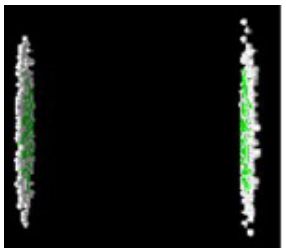

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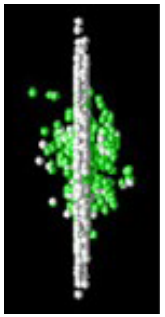

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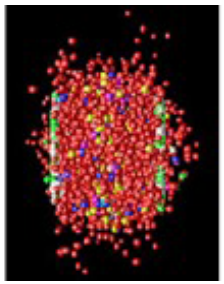

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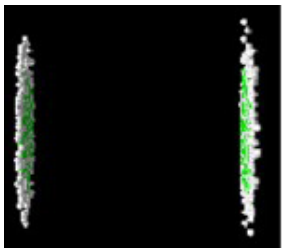

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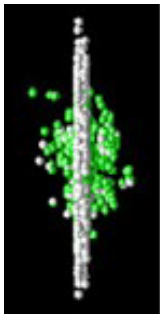

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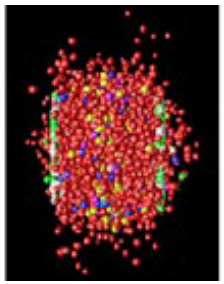

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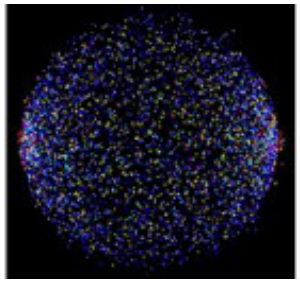

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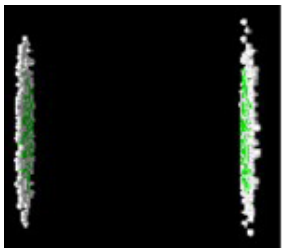

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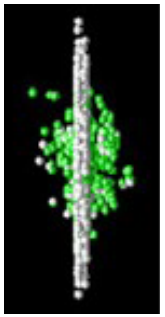

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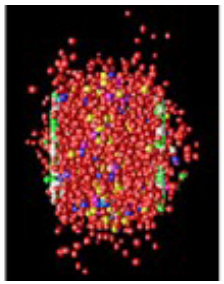

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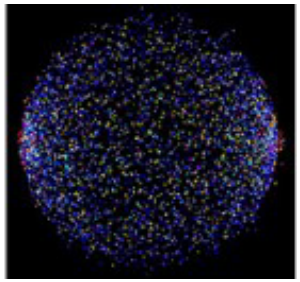
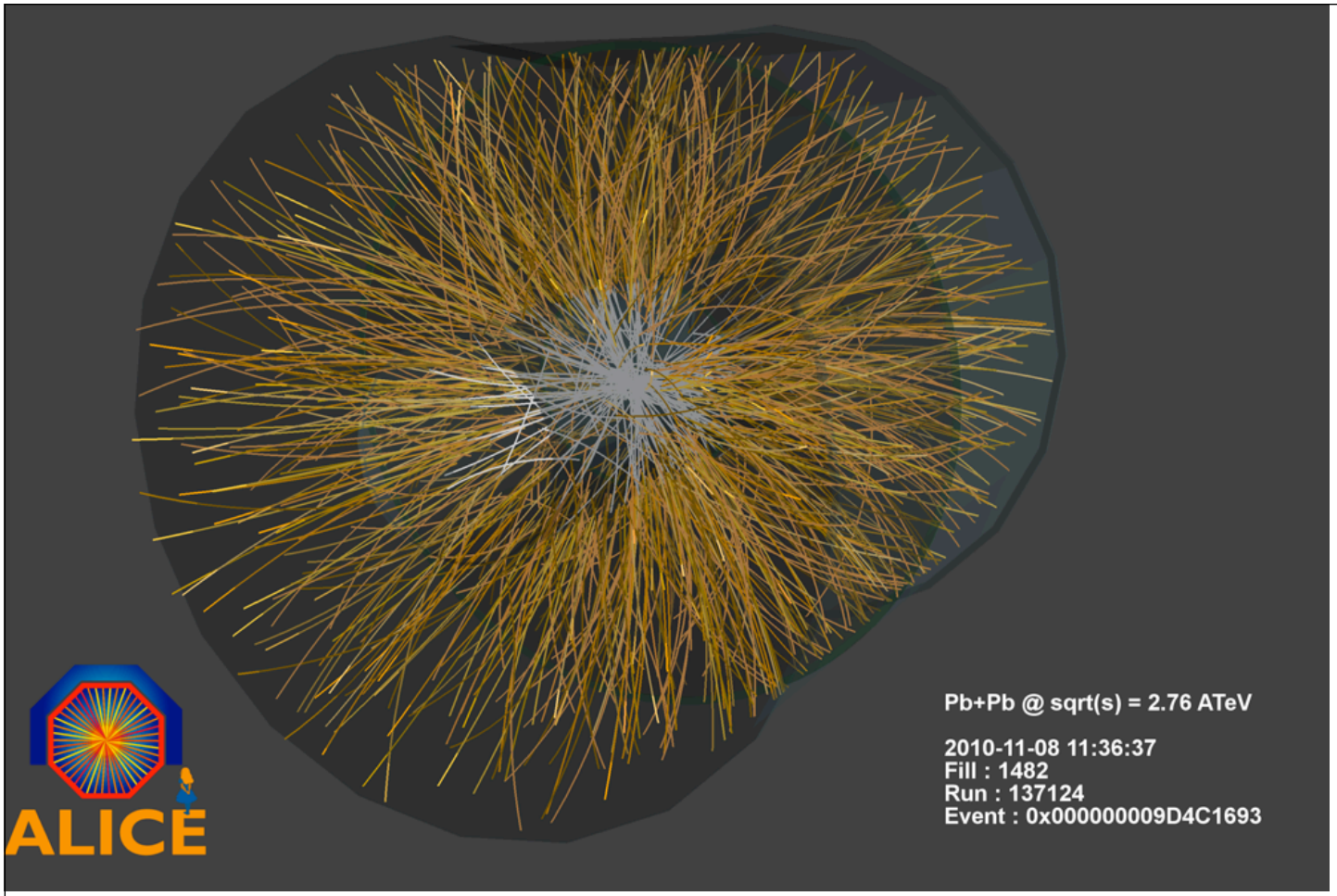


Hadronization in apparent chemical equilibrium. Hadronic cascade till freeze-out. Measurements.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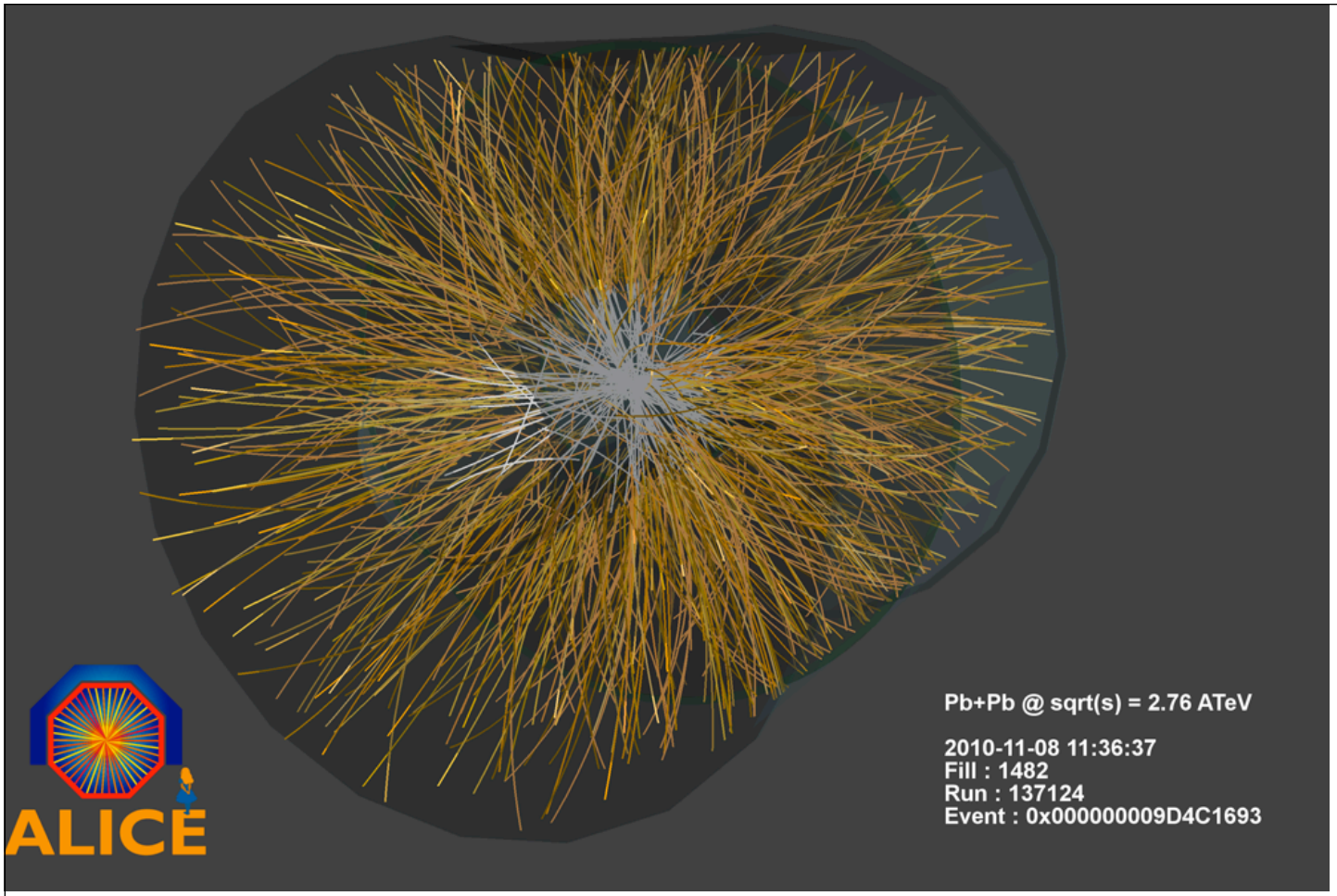
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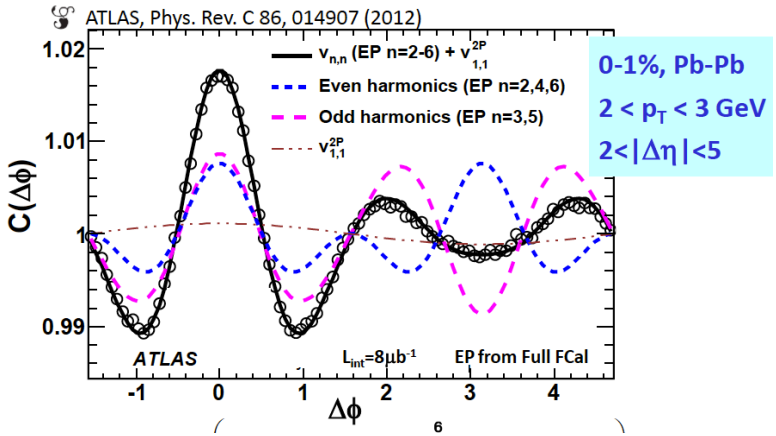
ATLAS, Phys. Rev. C 86, 014907 (2012)
$v_{n,n}$ (EP n=2-6) + $v_{1,1}^{2P}$
Even harmonics (EP n=2,4,6)
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0-1%, Pb-Pb
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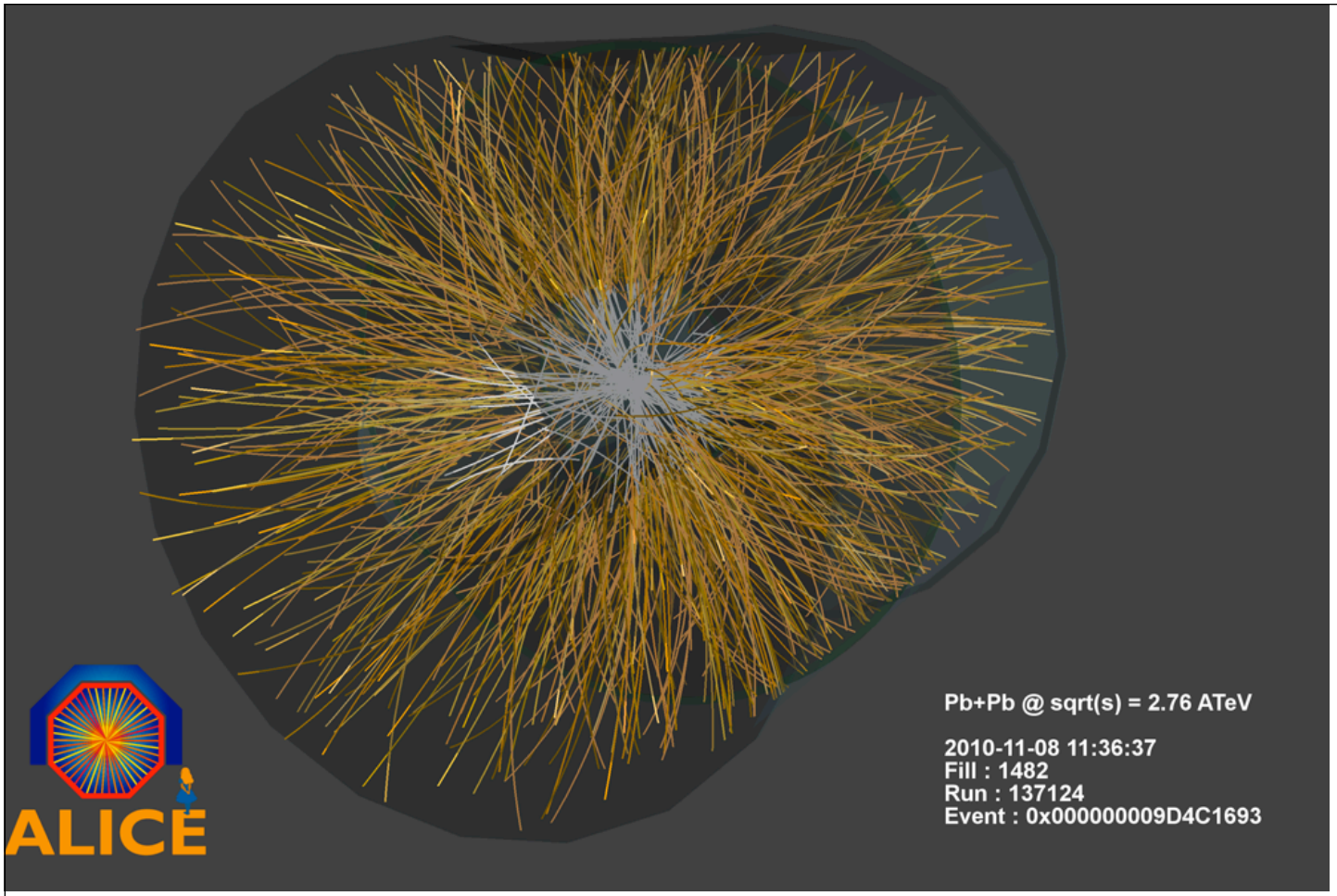
2<|Δη|<5
C(Δφ)
1.02
1.01
1
0.99
ATLAS
L_{int}=8μb^{-1}
EP from Full FCal
-1
0
1
2
3
4
Δφ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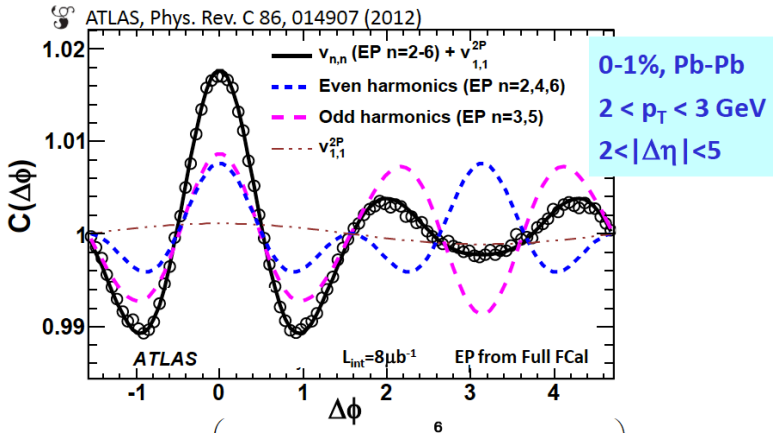
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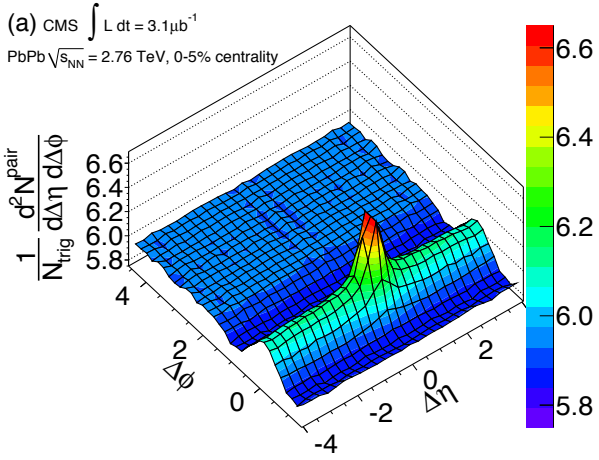
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Δφ
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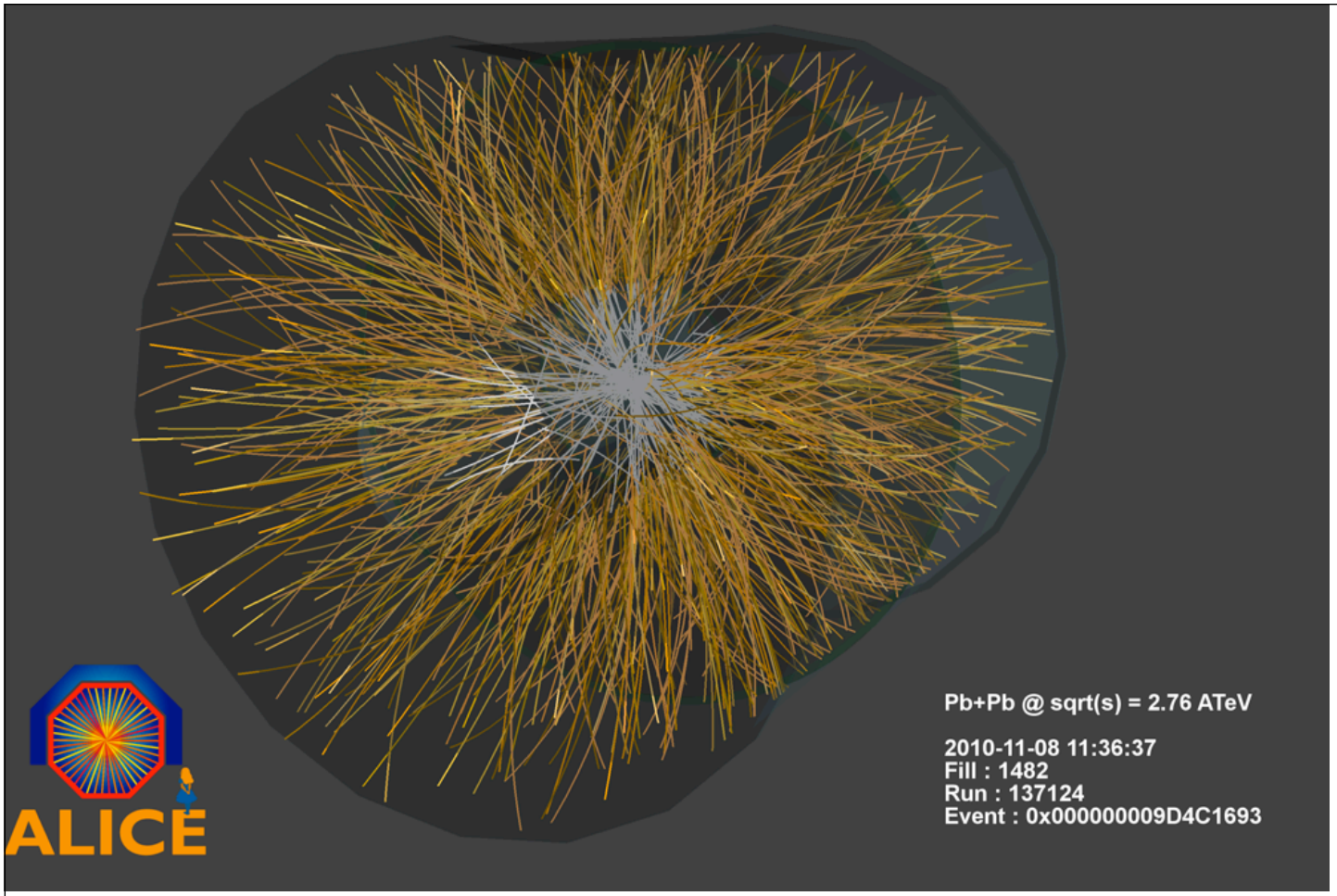
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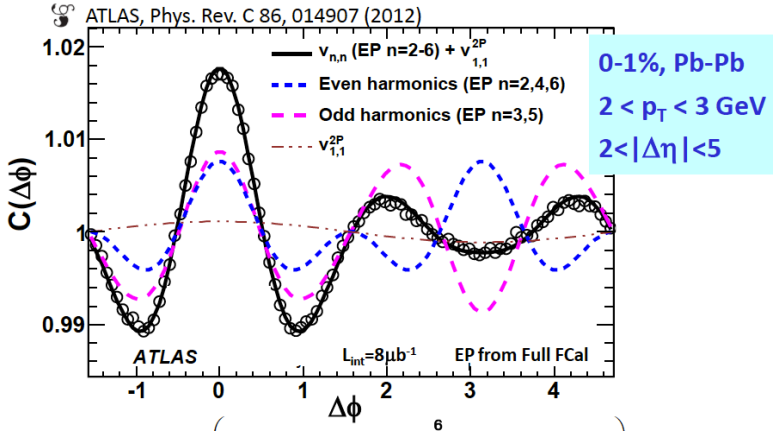
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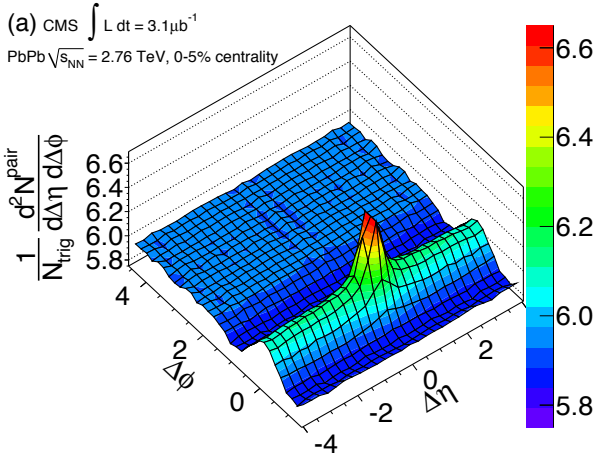
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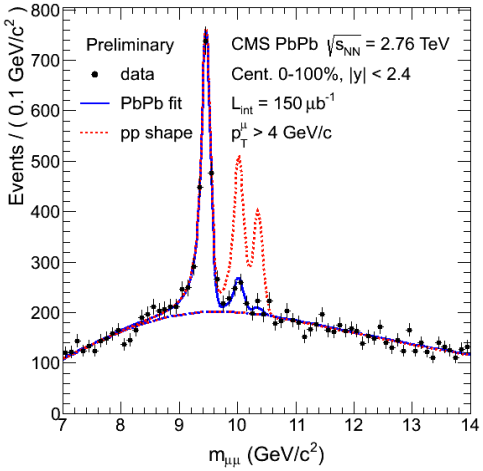
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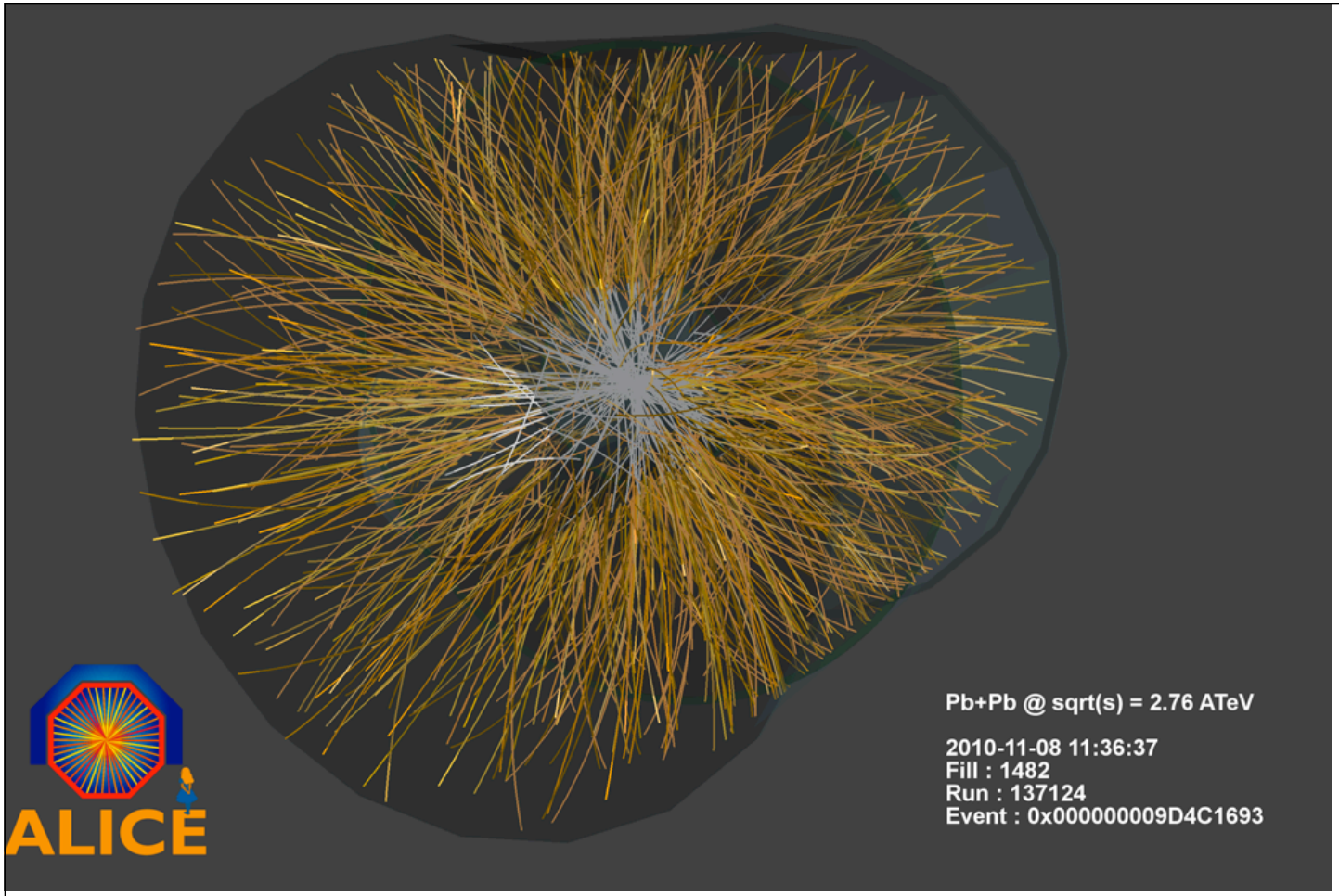
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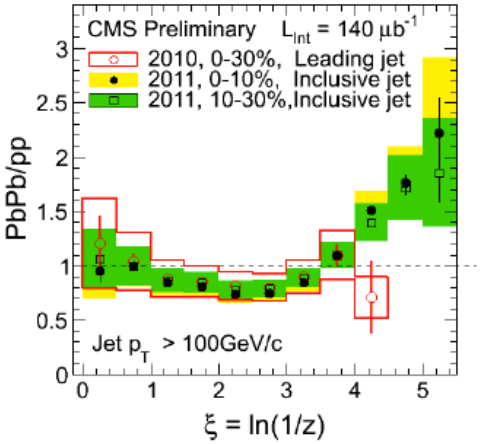
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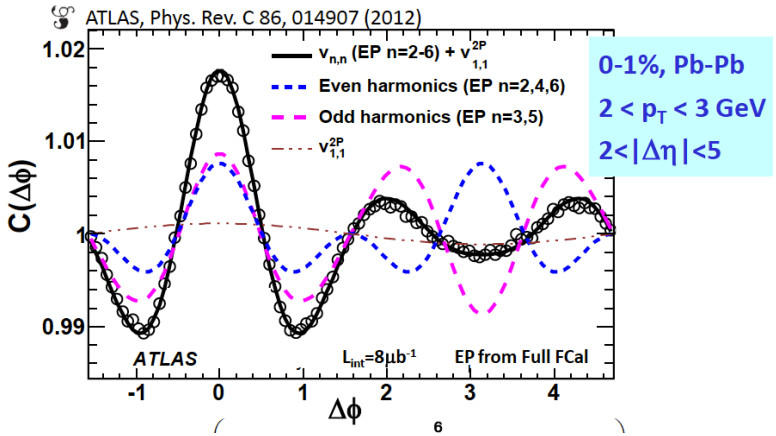
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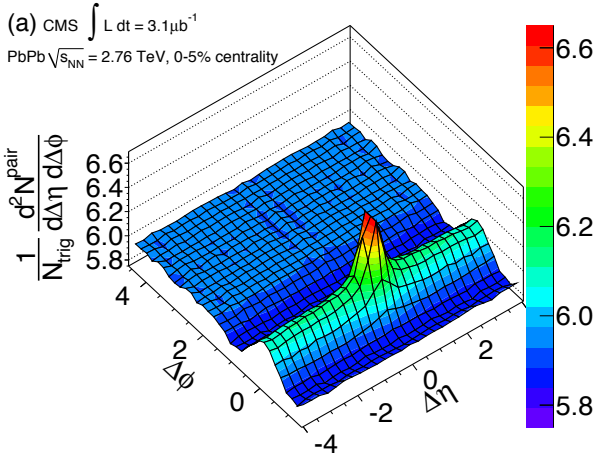
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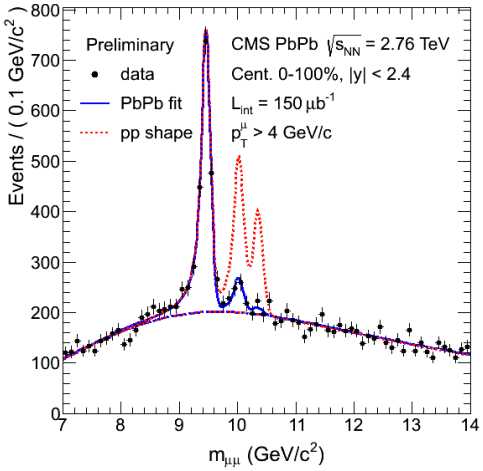
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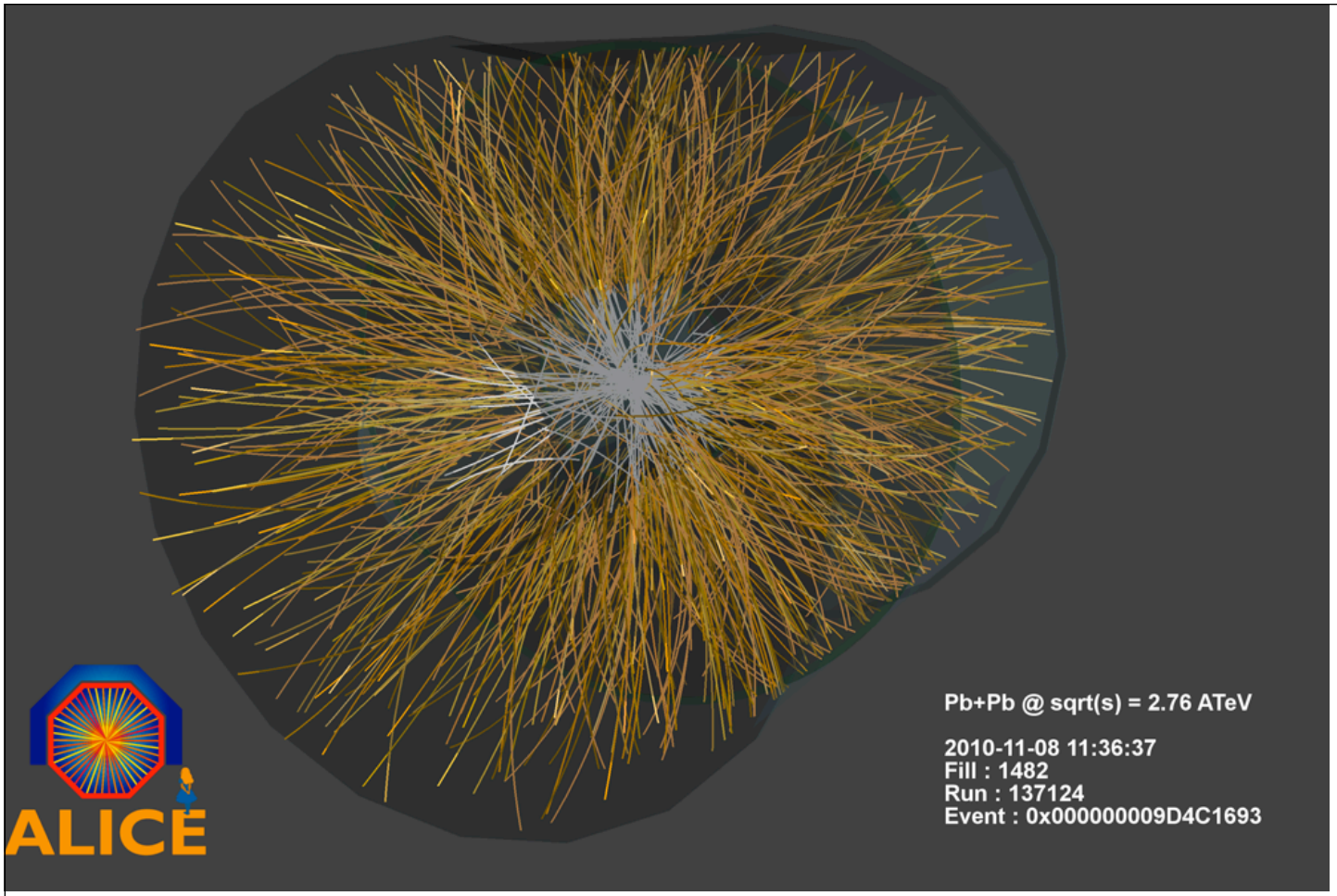
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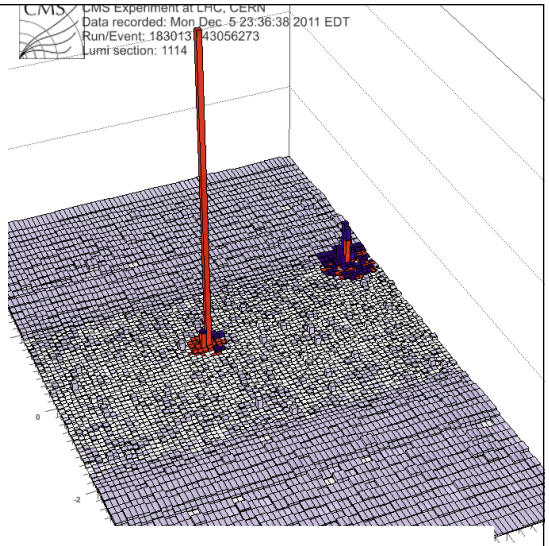
CMS Experiment at LHC, CERN
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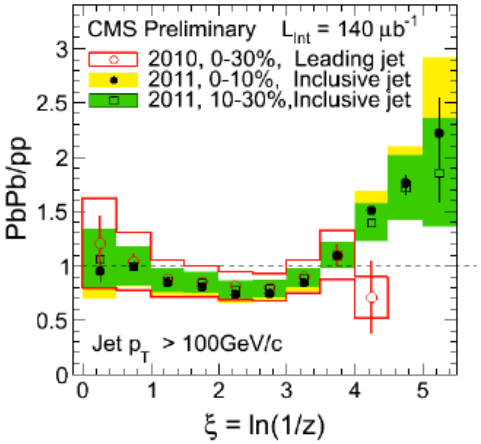
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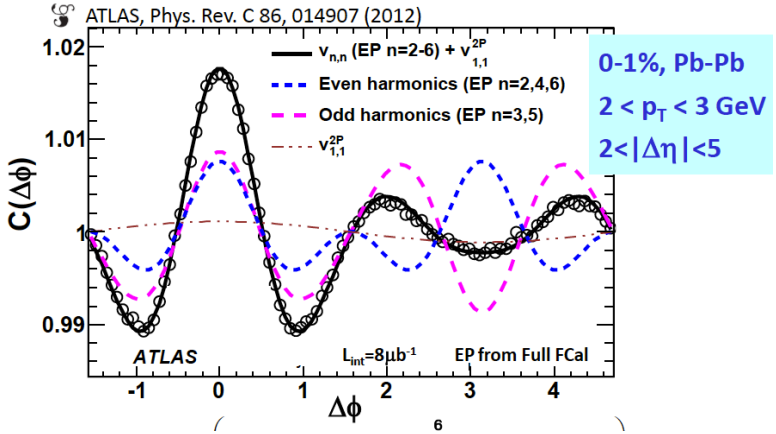
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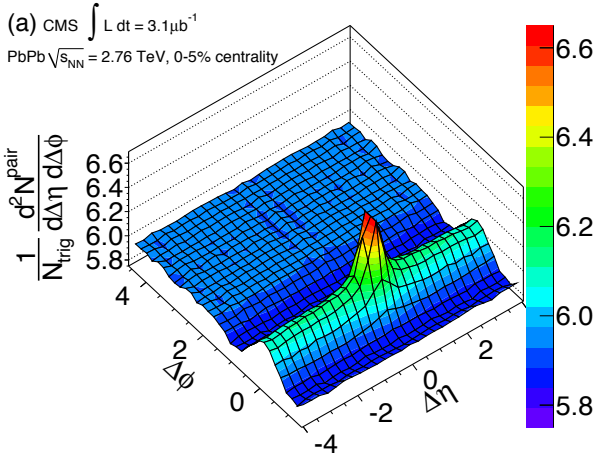
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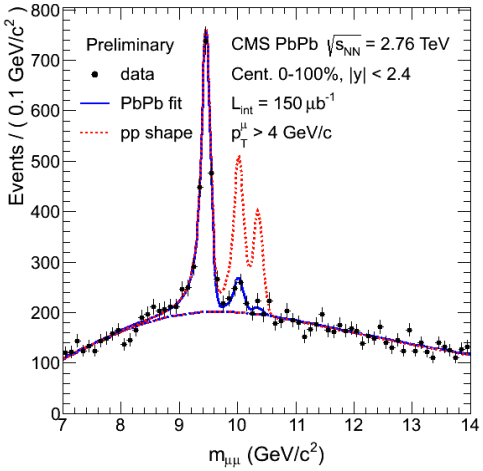
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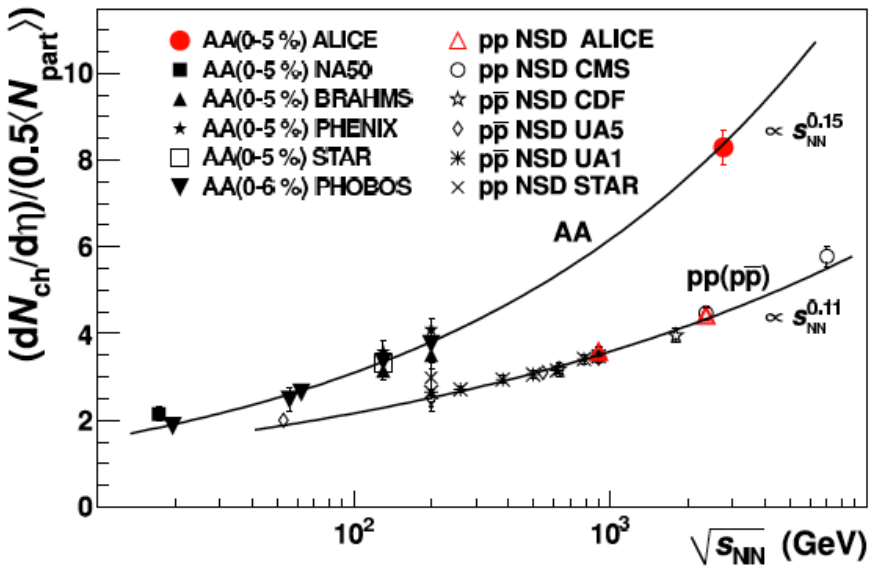
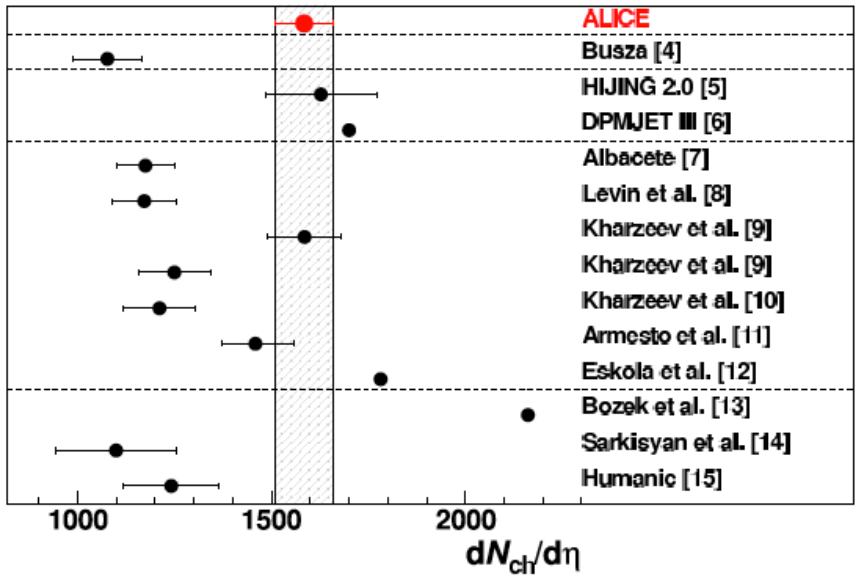
Moving backward in time

Conditions are reached for the formation of a quark-gluon plasma

Matter at freeze-out is in chemical equilibrium

Counting particles

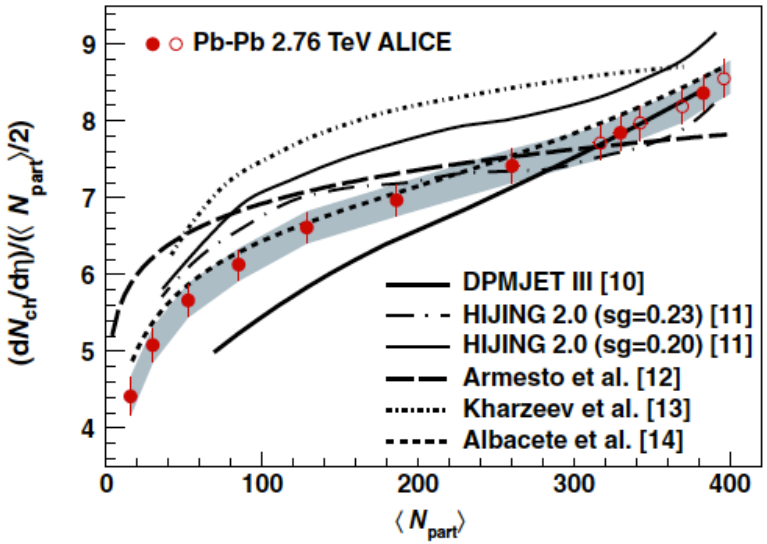




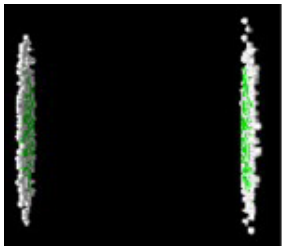
ALICE PRL 105 (2010)

Compatible with theoretical expectations, but large (theoretical) uncertainties remain...

ALICE PRL 106 (2011)



The conditions for the formation of a quark-gluon plasma are reached in the early stages of the collisions



$\longleftarrow \tau_0 \longrightarrow$

order of magnitude estimate

$$\frac{dN_{ch}}{d\eta} \simeq 1600$$

$$\epsilon\,\tau_0 \simeq 15\mathrm{GeV/fm}^2$$

$$T_0 \simeq 300\,\mathrm{MeV}$$

Matter at freeze-out

well described by a statistical picture

$$n \sim \frac{1}{\mathrm{e}^{(\varepsilon_k - \mu)/T} \pm 1}$$

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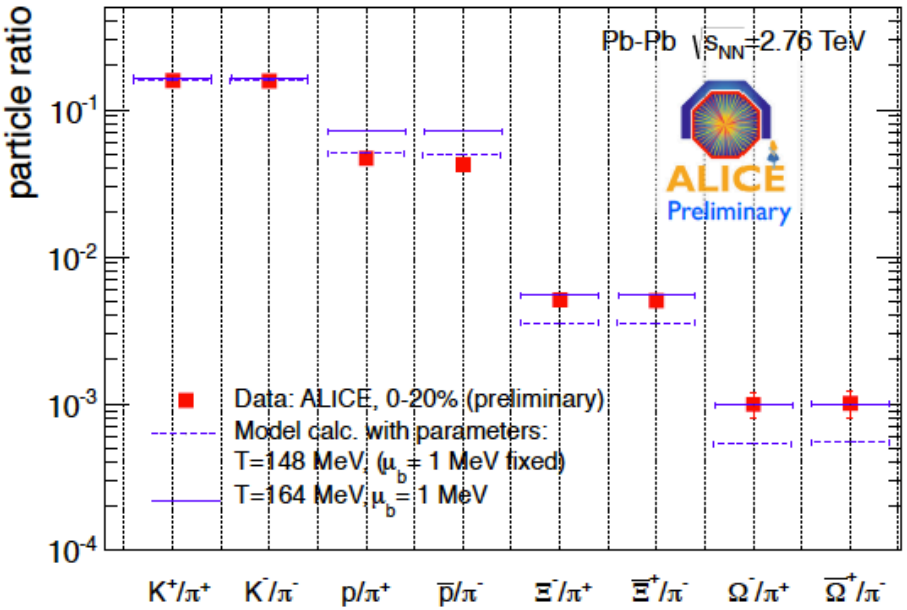

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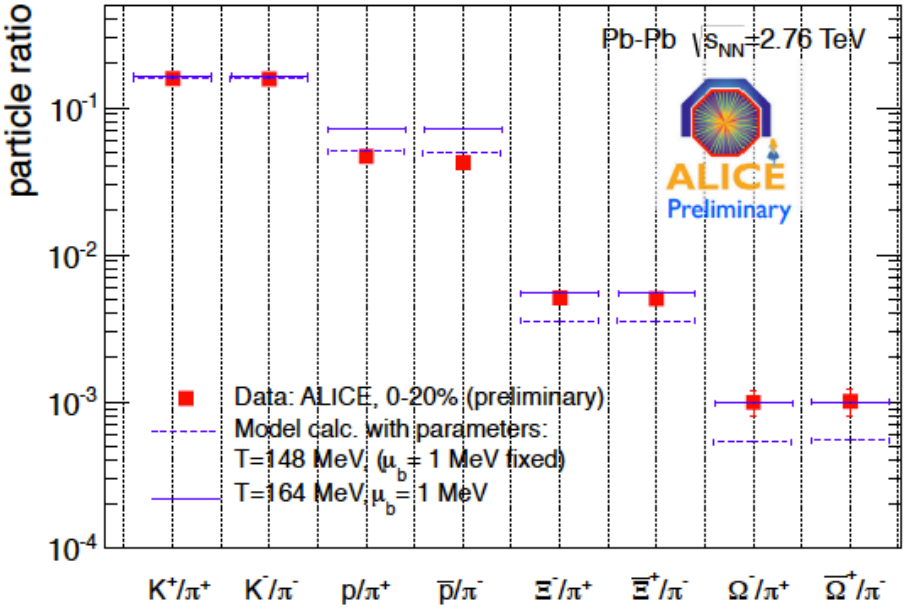

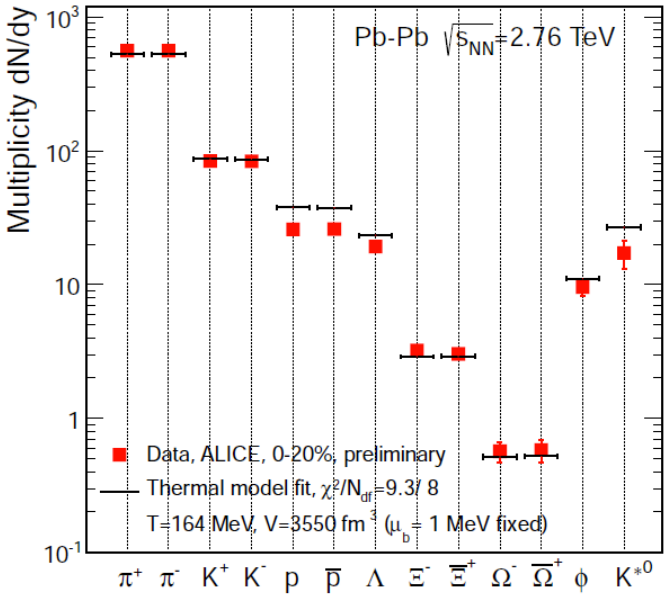

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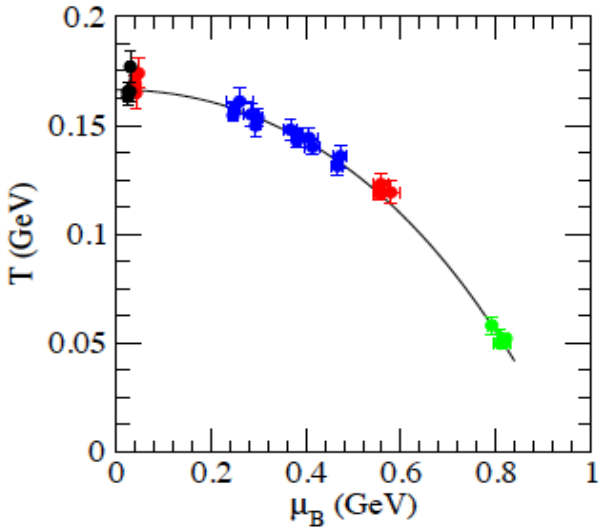
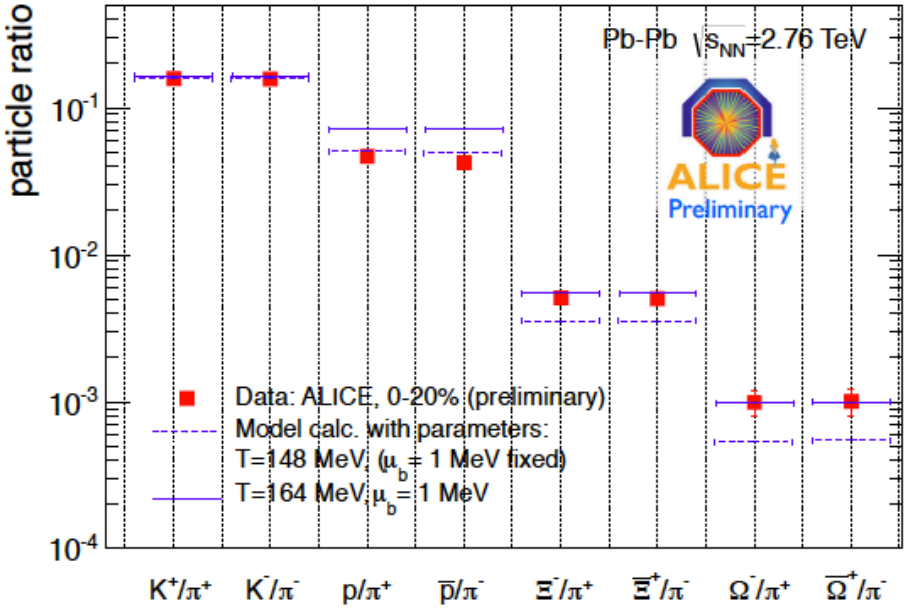
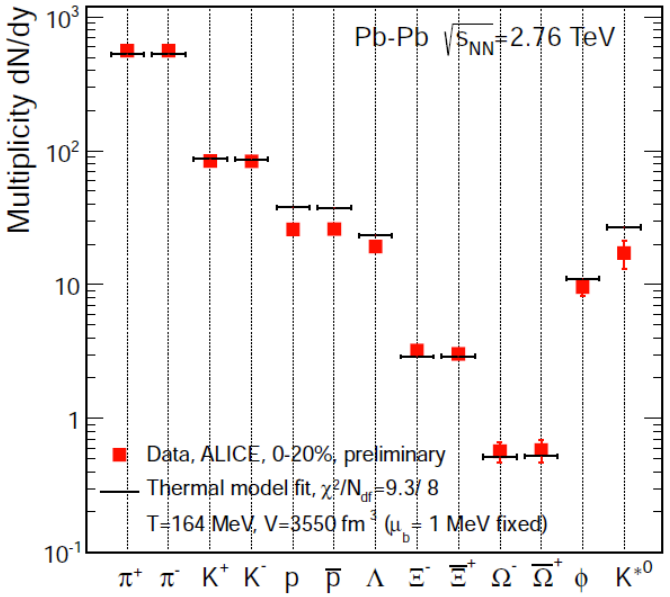


(from J. Cleymans et al, hep-ph/0511094)





Moving backward in time

Matter flows like a fluid

The quark-gluon plasma as a nearly perfect fluid

Puzzles : viscosity, thermalization

Collective flow

Matter flows like a fluid and is well described by relatvistic hydrodynamics

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

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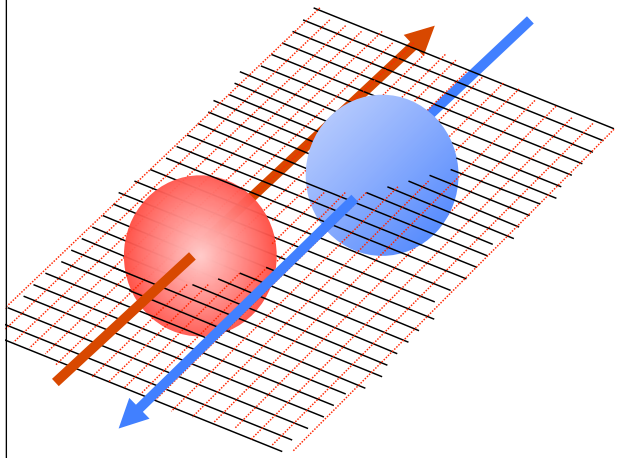

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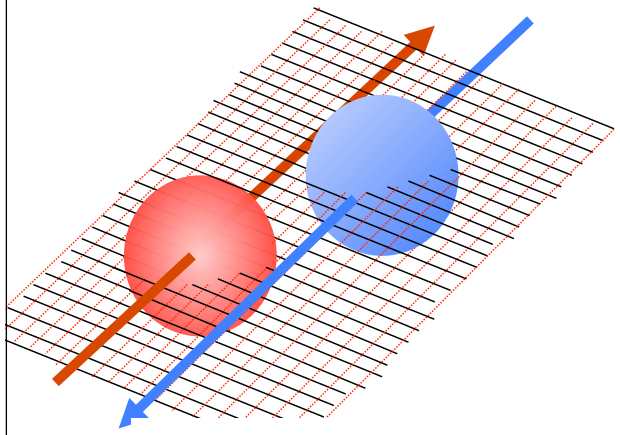

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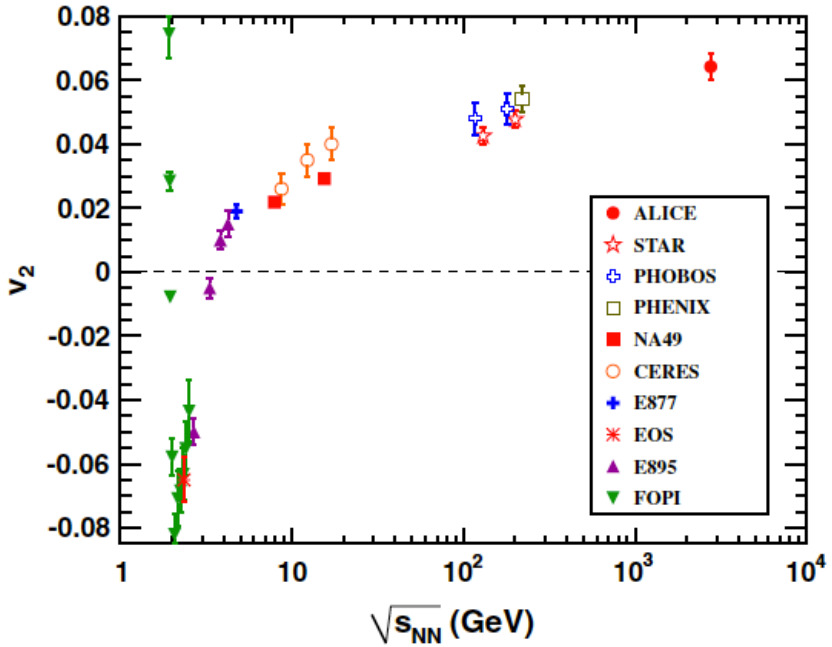
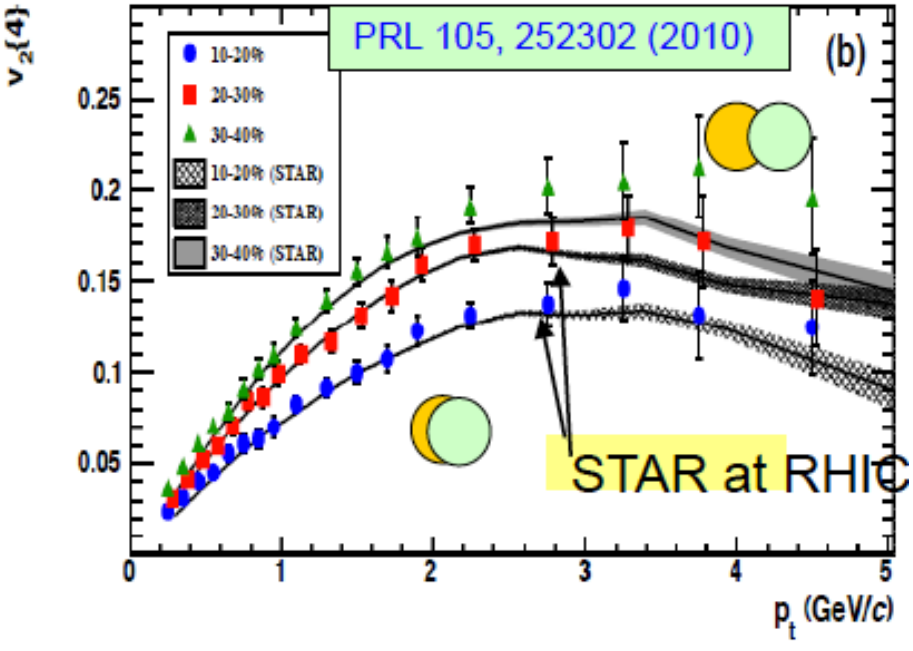
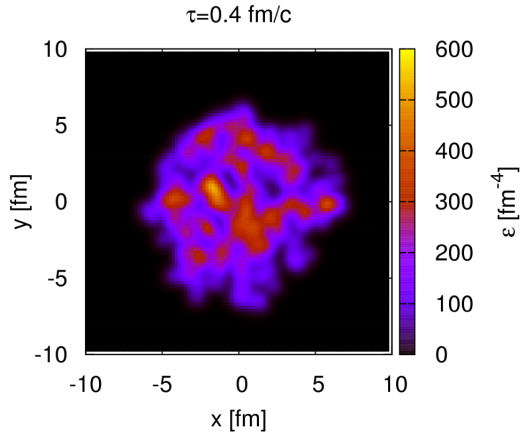




The flow is sensitive to initial density fluctuations



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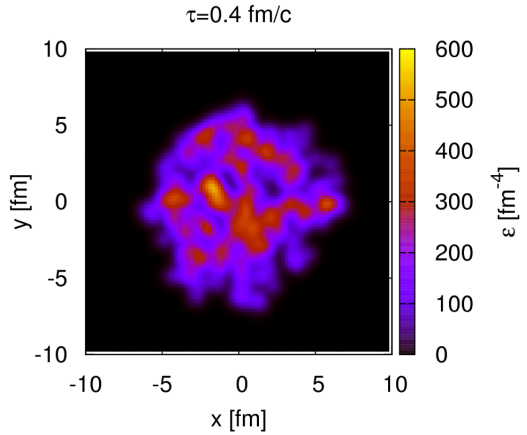

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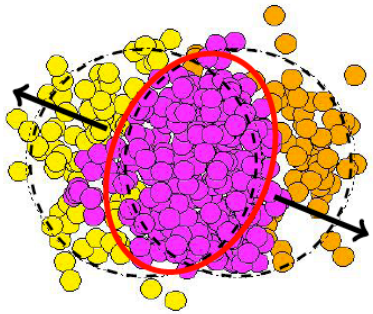

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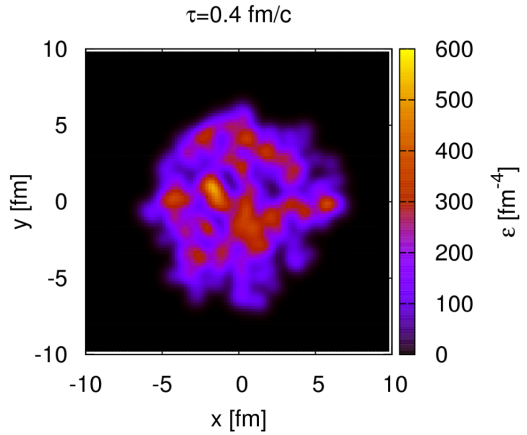

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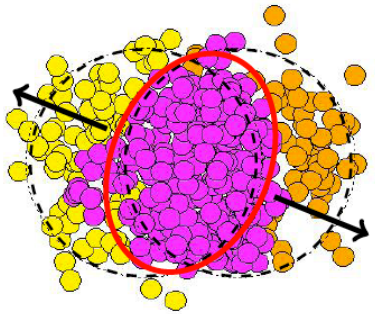

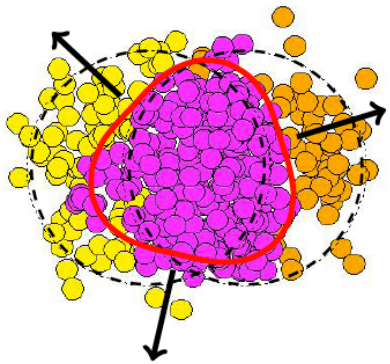

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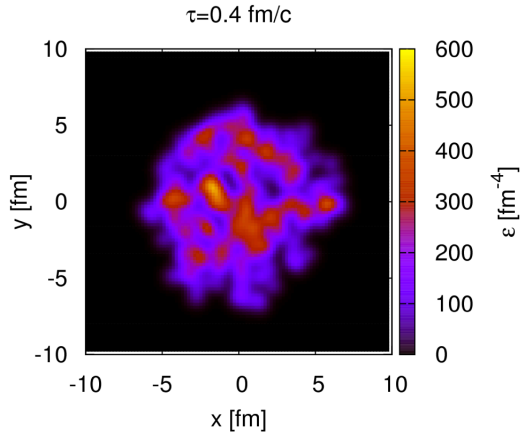

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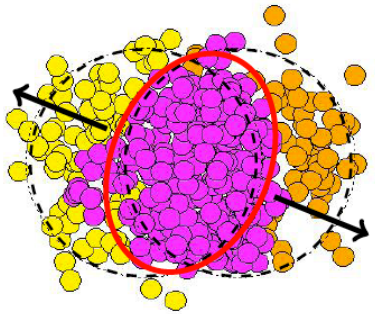
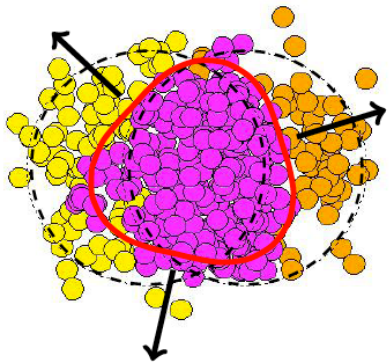
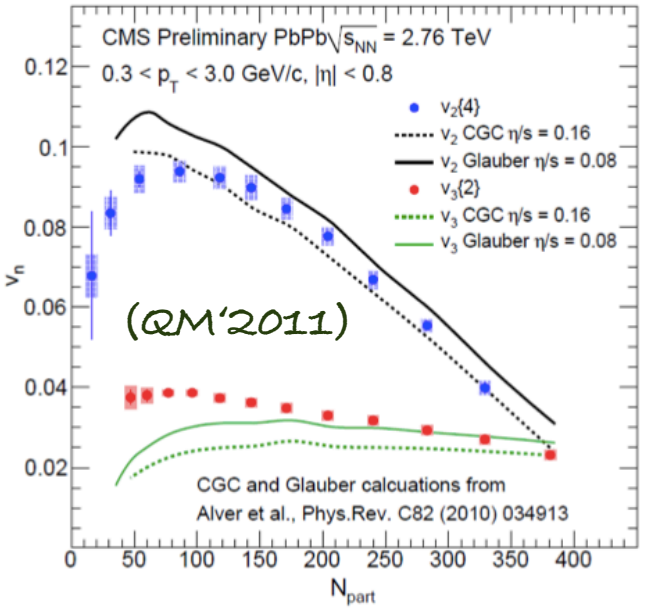
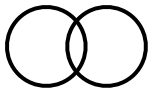
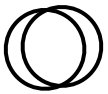








peripheral



central

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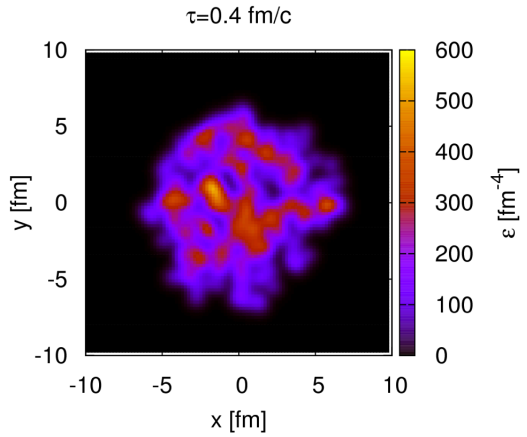

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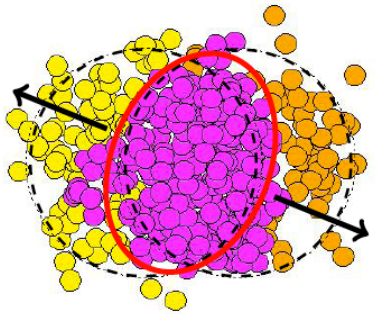

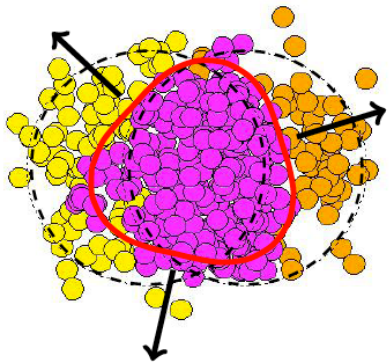

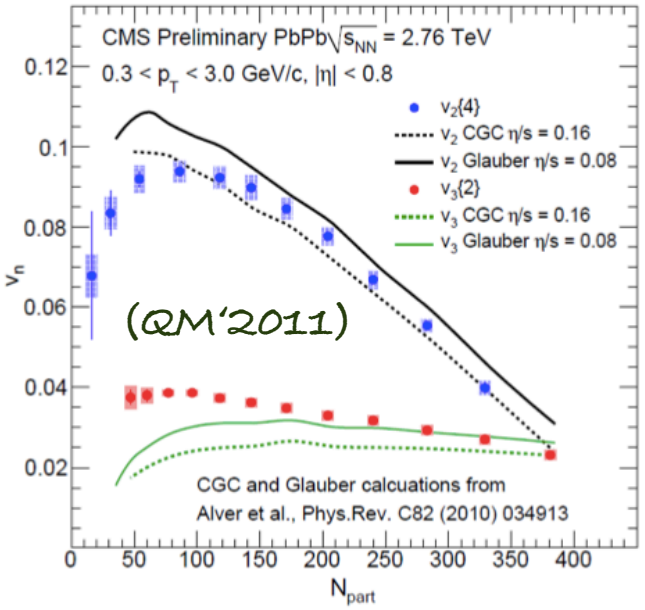

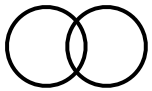

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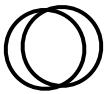

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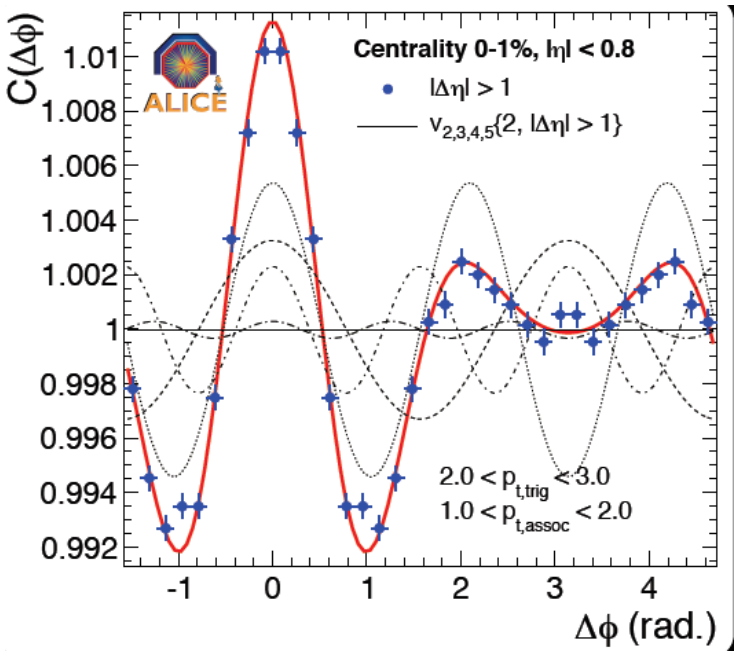

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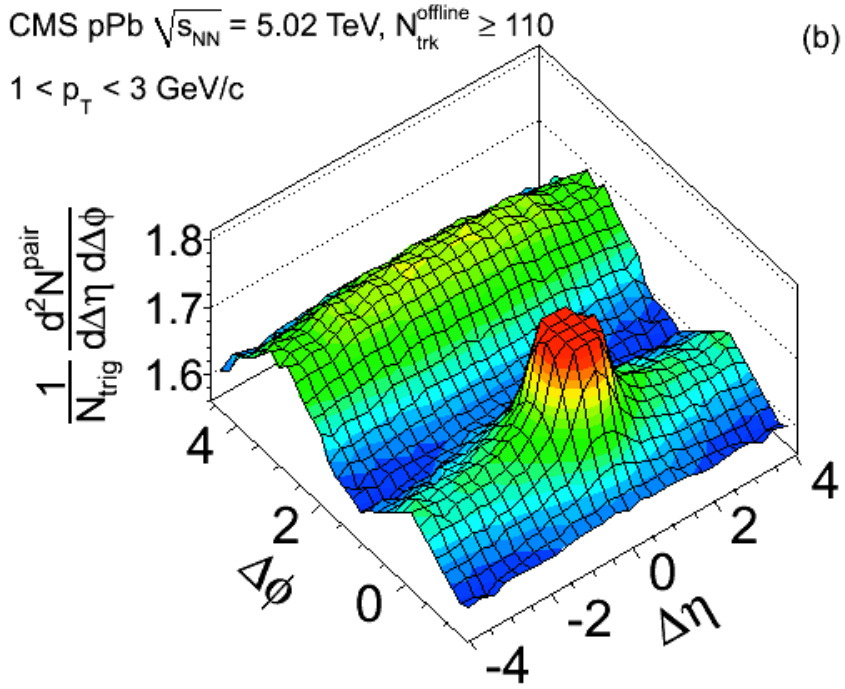
Plasma: *soft and hard modes, particles and fields*. Long wavelength modes can remain strongly coupled....

THERMALIZATION

- How do we go from the intial nuclear wave-functions to the locally equilibrated fluid seen in experiments ?
- What are the initial d.o.f.'s : partons ? color fields (CGC)? mixture of both ?
- Initial fields are typically unstable (e.g. if anisotric momentum distributions of particles). Instabilities provide 'fast' isotropization of momentum distributions
- Amplification of soft modes is a generic feature
- CGC picture suggests an overpopulation of soft modes

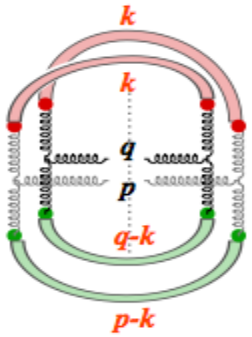
(for a summary see arXiv: 1203.2042)

Surprising p-Pb collisions



Is it hydrodynamics ?

Or evidence for CGC ?

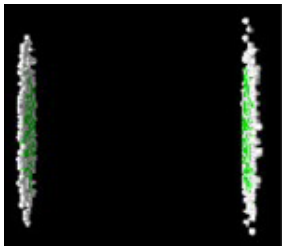


Dumitru, Dusling, Gelis, Jalilian-Marian, Lappi, Venugopalan : 1009.5295

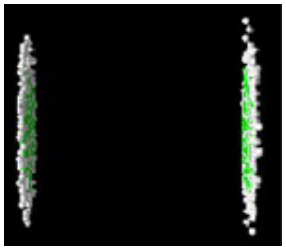
Dusling, Venugopalan:1211.3701

Moving backward in time

Nuclei are made of densely packed gluons



Fluctuations into multi-gluon configurations look frozen during collision (Lorentz time dilation)



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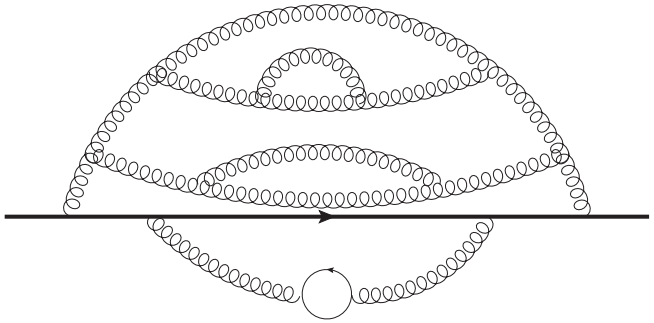

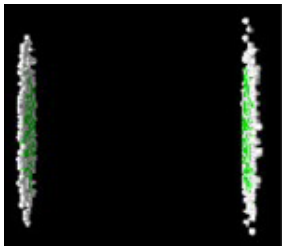

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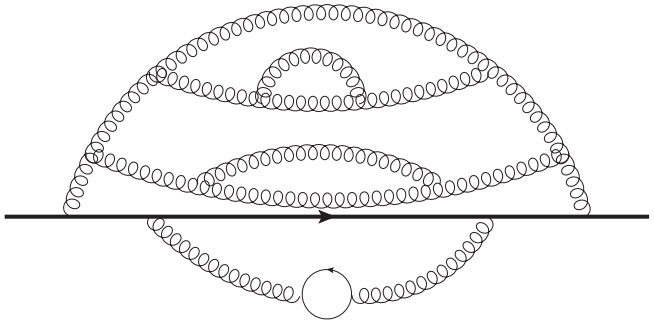
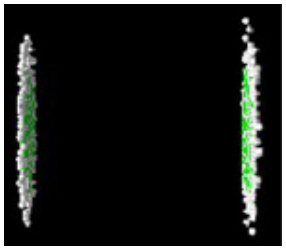
In a collision at high energy, one 'sees' mostly the gluons in the nuclei





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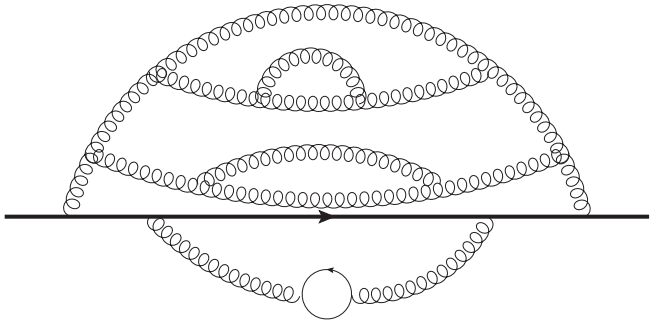

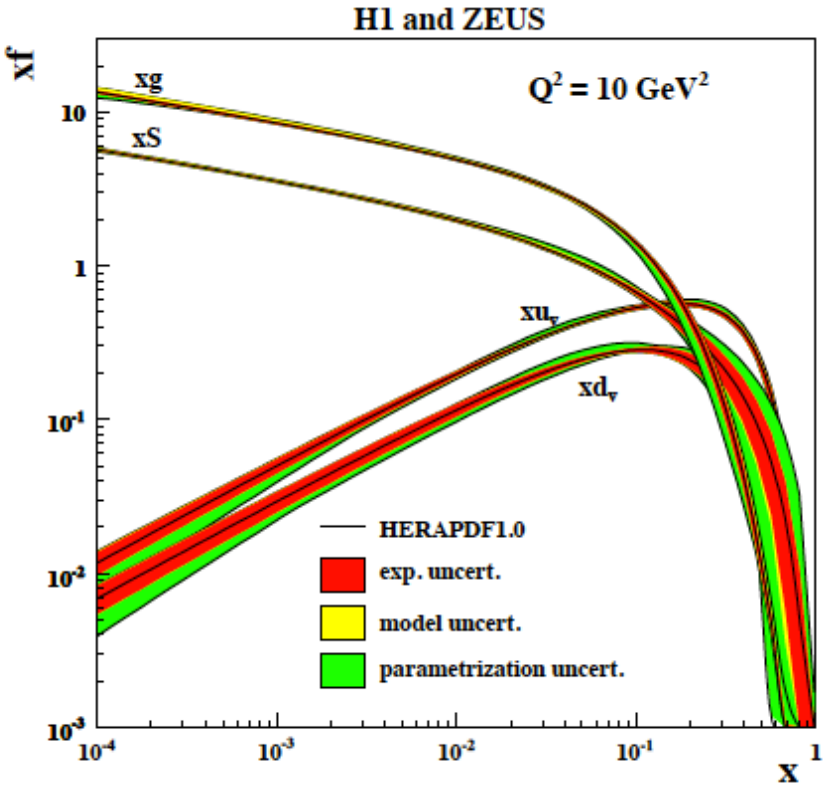

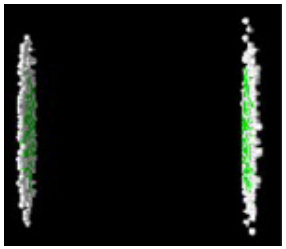

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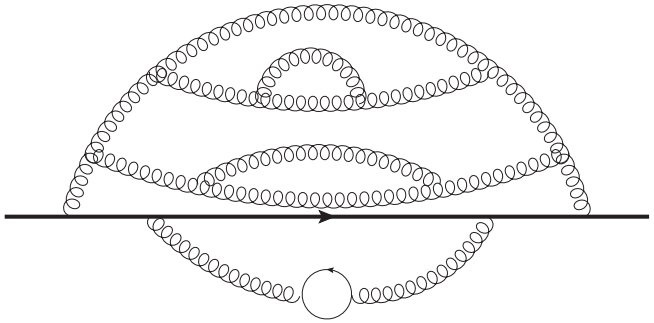

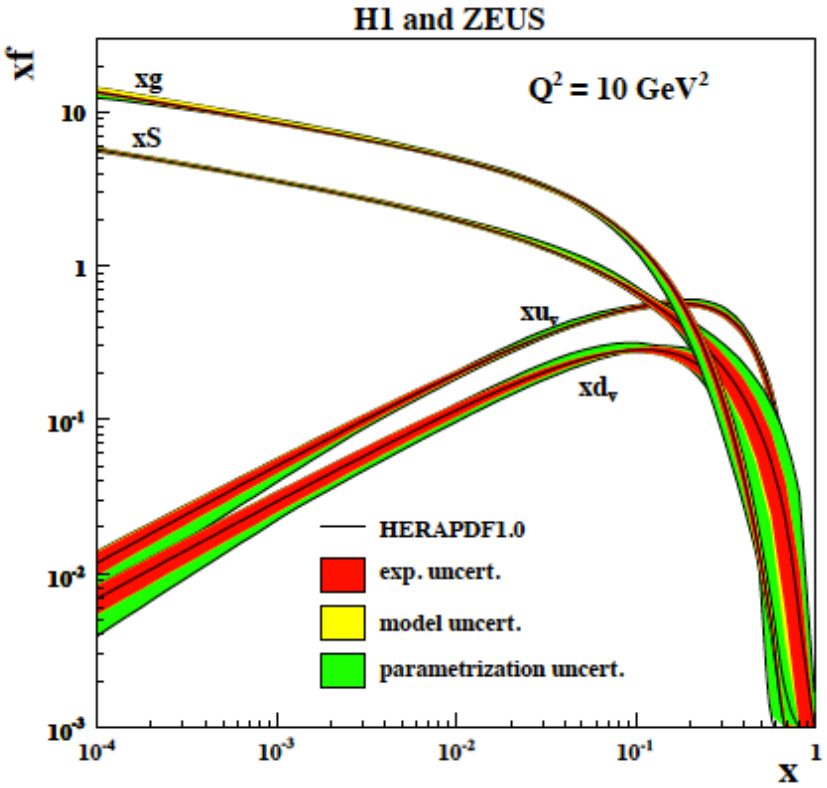

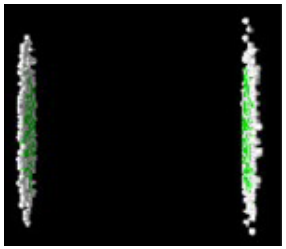

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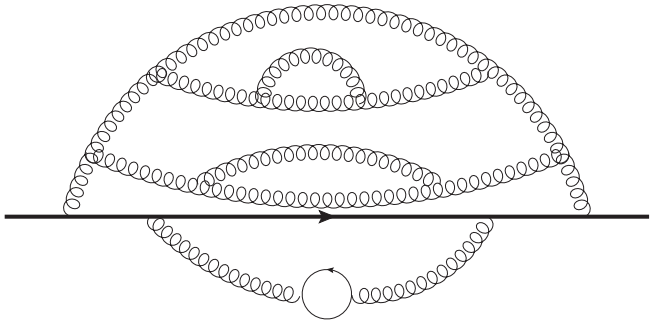
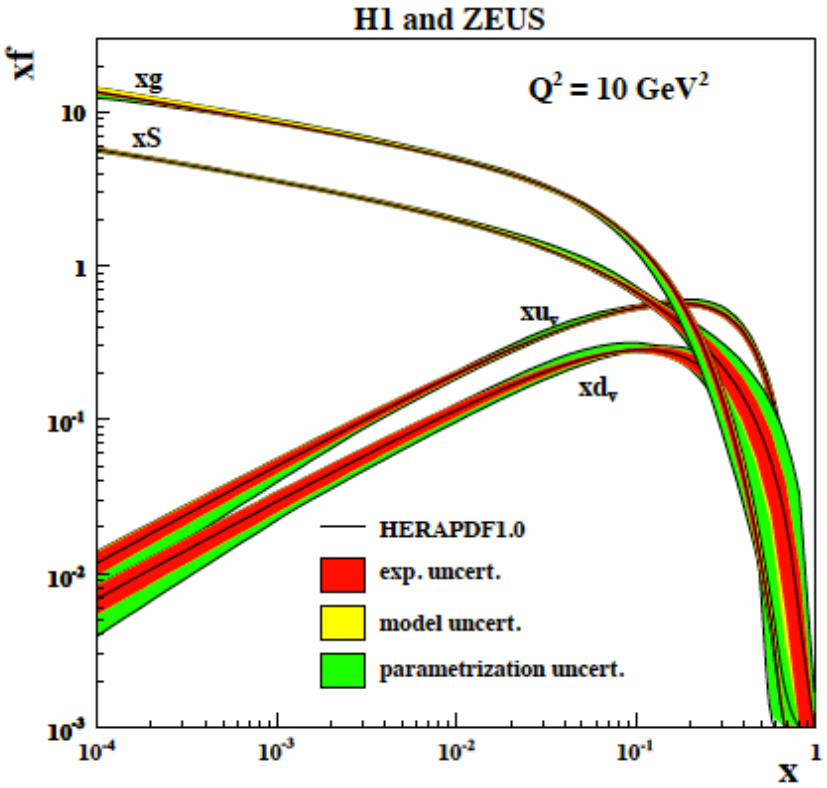
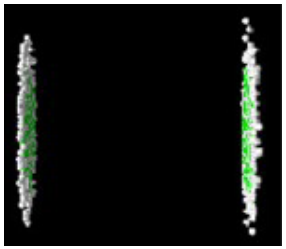
Bulk of particle production ($p_T \lesssim 2$ GeV)

RHIC ($\sqrt{s} = 200\,\mathrm{GeV}$) $x \sim 10^{-2}$

LHC ($\sqrt{s} = 5.5\,\mathrm{TeV}$) $x \sim 4 \times 10^{-4}$







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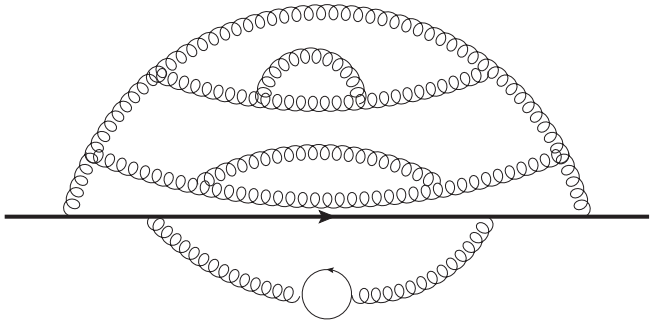
Gluon density increases with energy (with decreasing x, increasing Q)

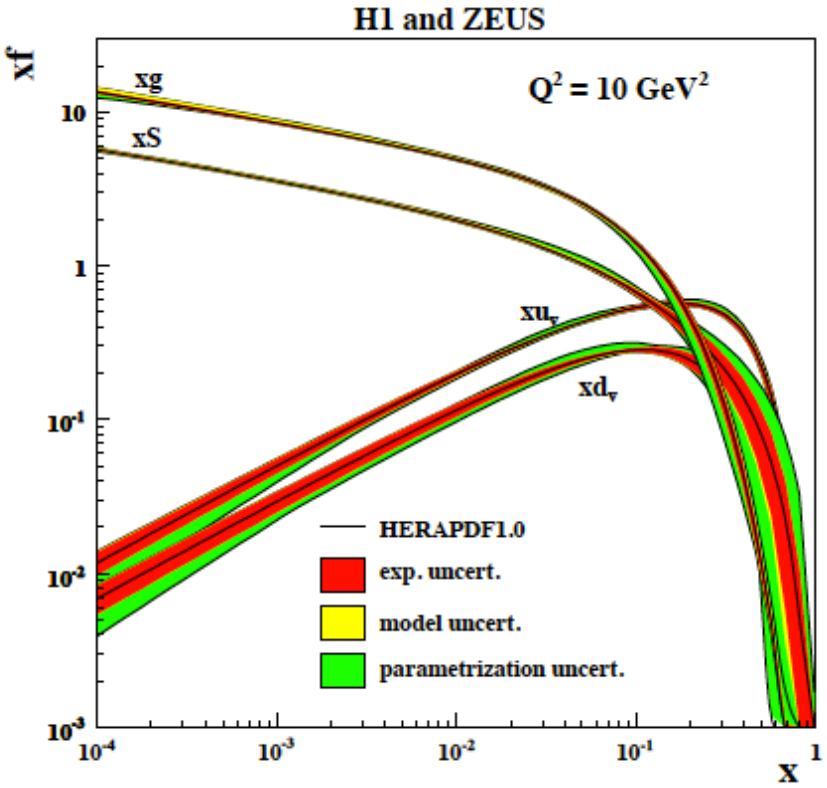
Bulk of particle production ($p_T \lesssim 2$ GeV)

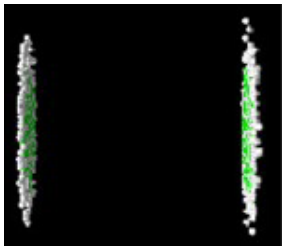
RHIC ($\sqrt{s} = 200\,\text{GeV}$) $x \sim 10^{-2}$

LHC ($\sqrt{s} = 5.5\,\text{TeV}$) $x \sim 4 \times 10^{-4}$

Evolution equations describe the evolution with energy of relevant configurations (DGLAP, BFKL, JIMWLK...)







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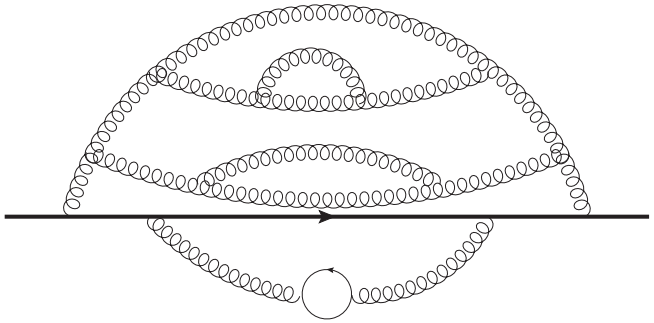

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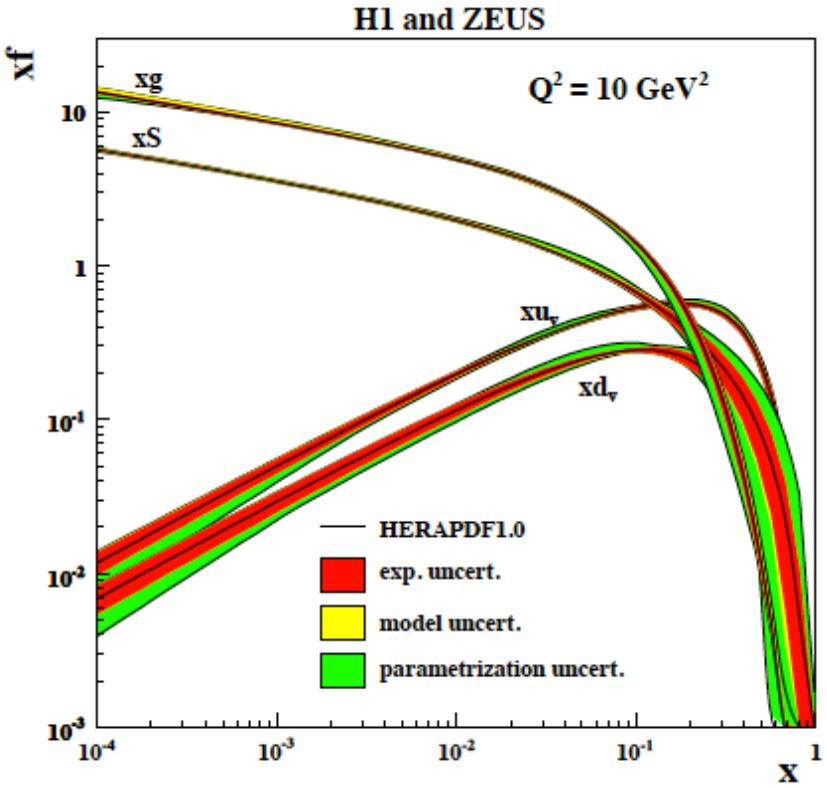

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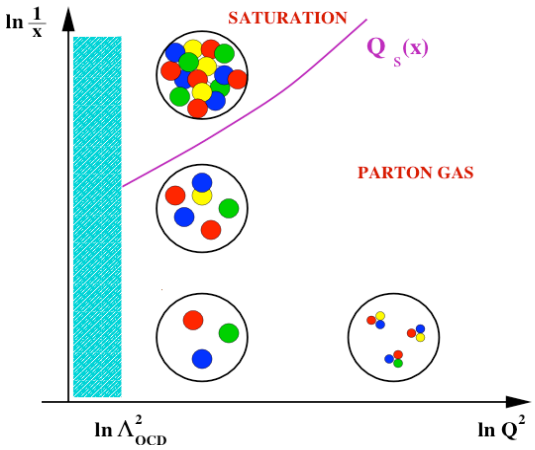
The growth eventually saturates

Saturation momentum

$$Q_s^2 \approx \alpha_s \frac{xG(x,Q^2)}{\pi R^2}$$



At saturation, occupation numbers are large

$$\frac{xG(x,Q^2)}{\pi R^2 Q_s^2} \sim \frac{1}{\alpha_s}$$

$$Q_s^2(x,A) \simeq Q_0^2 A^{1/3} \left(\frac{x_0}{x}\right)^{\lambda}$$

$$\lambda = 0.2 \div 0.3$$

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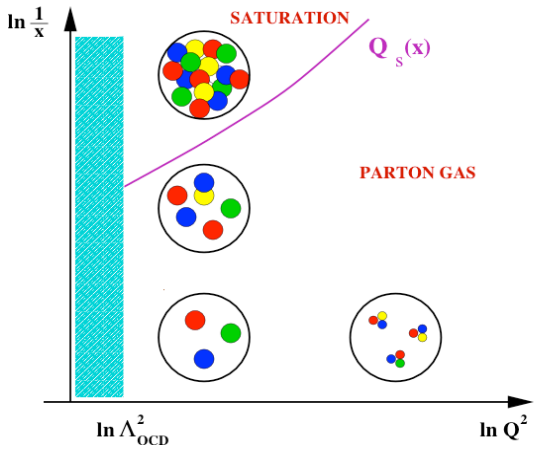

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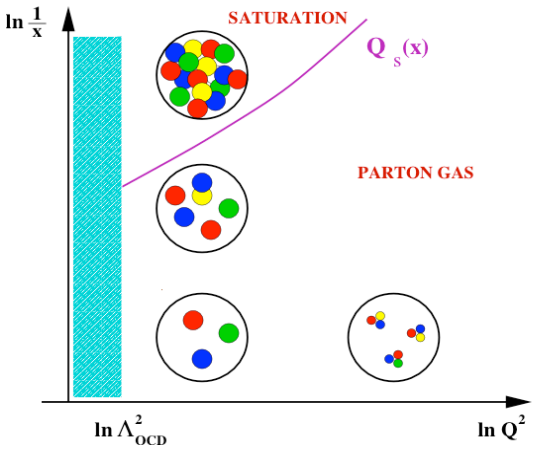

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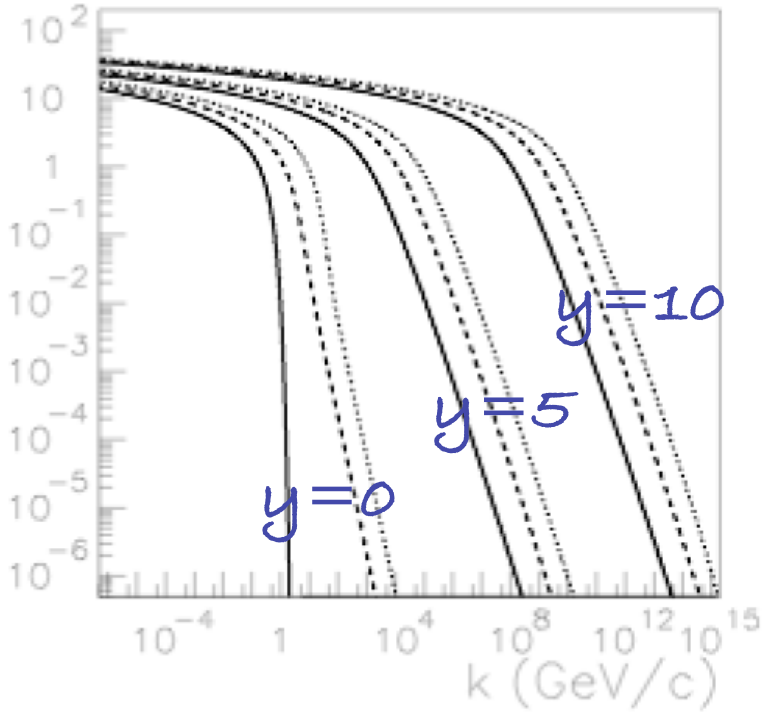

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$$f_A(k_\perp \gg Q_s) \approx \frac{1}{\alpha N_c} \frac{Q_s^2}{k_\perp^2}$$

Moving backward in time

Signals from the early stages

Hard probes

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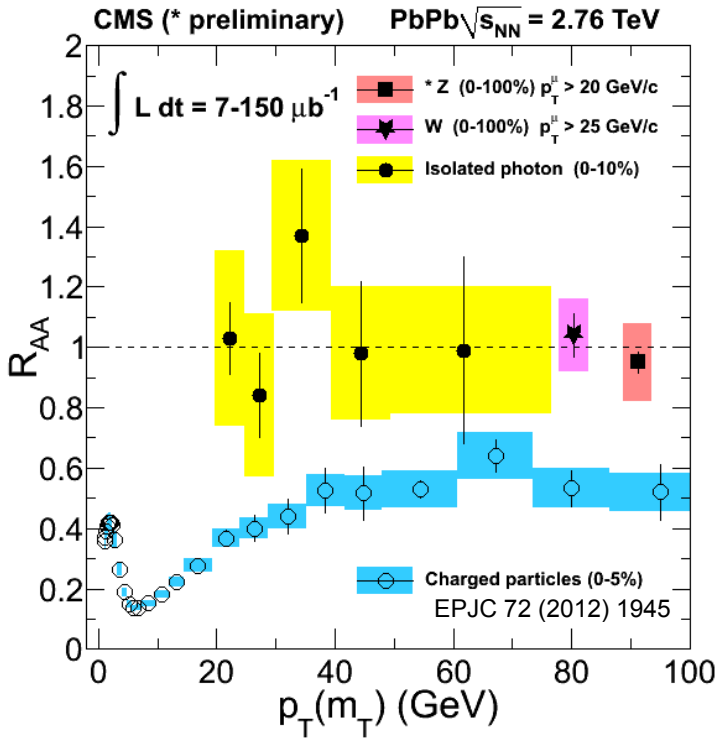
Prospects for hard probes at the LHC are truly fascinating

hard processes are under control



Hard processes are not affected by the nuclear environment, as expected.

J/Ψ suppression

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A long story....

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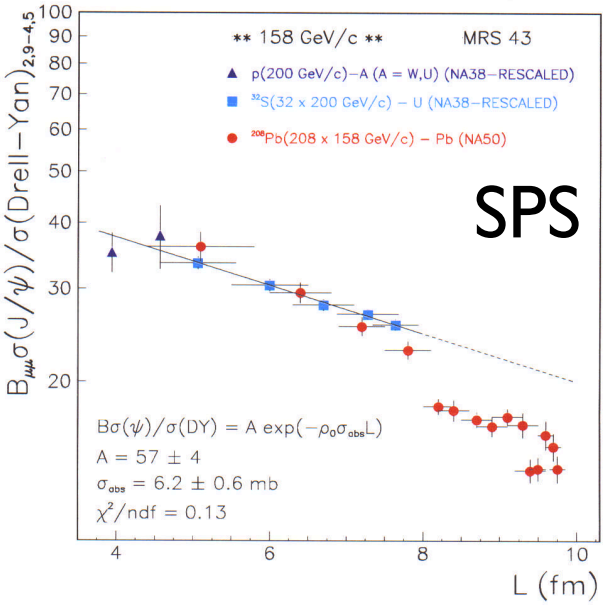

'anomalous' suppression

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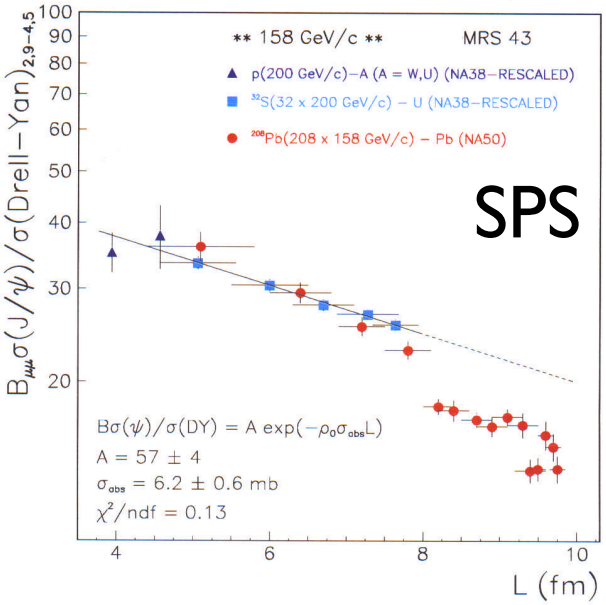

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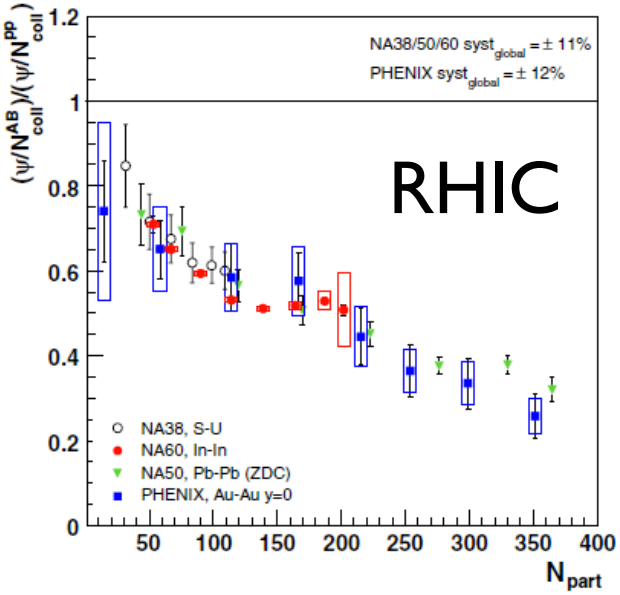

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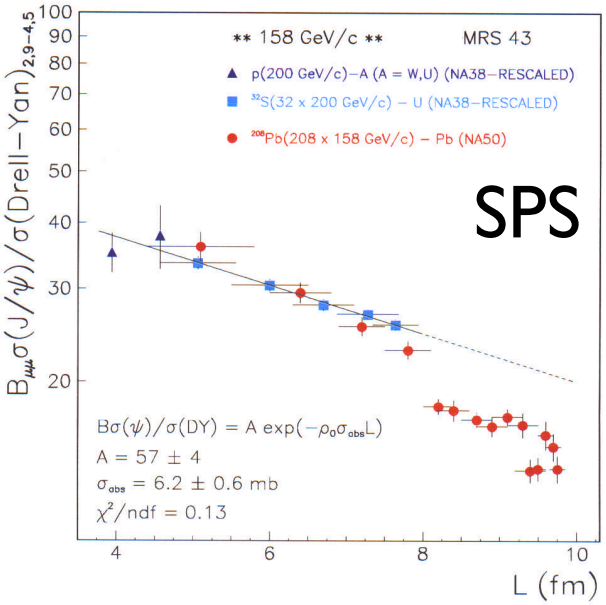

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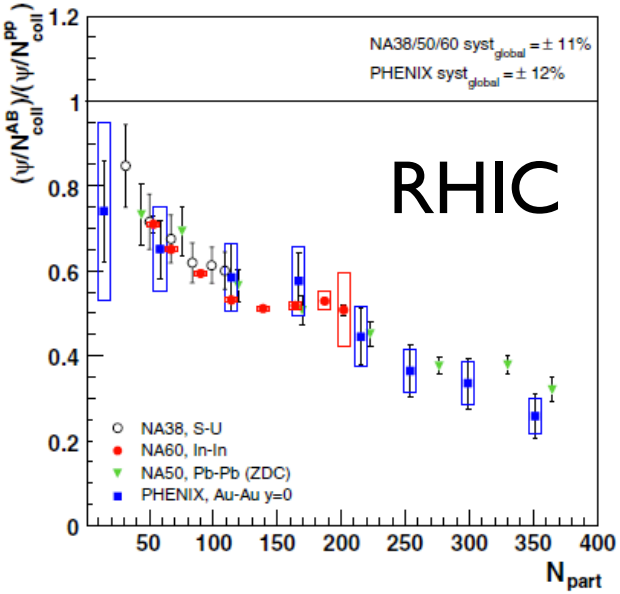
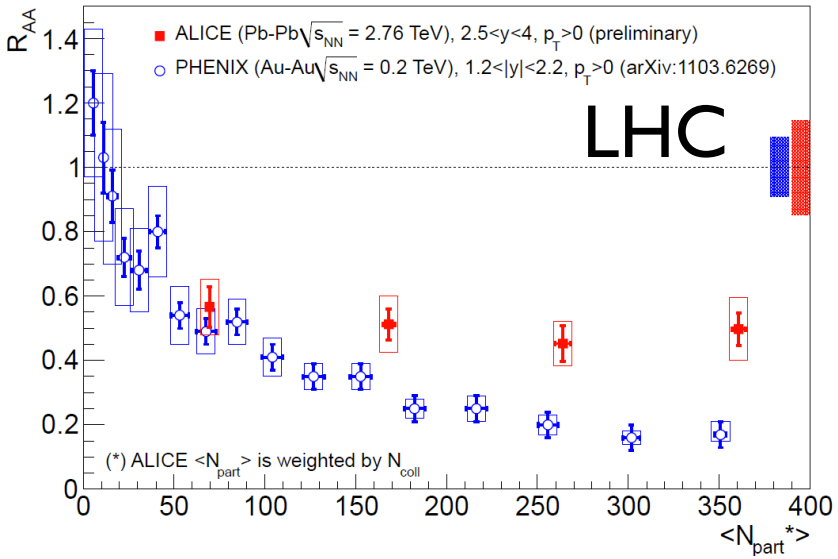
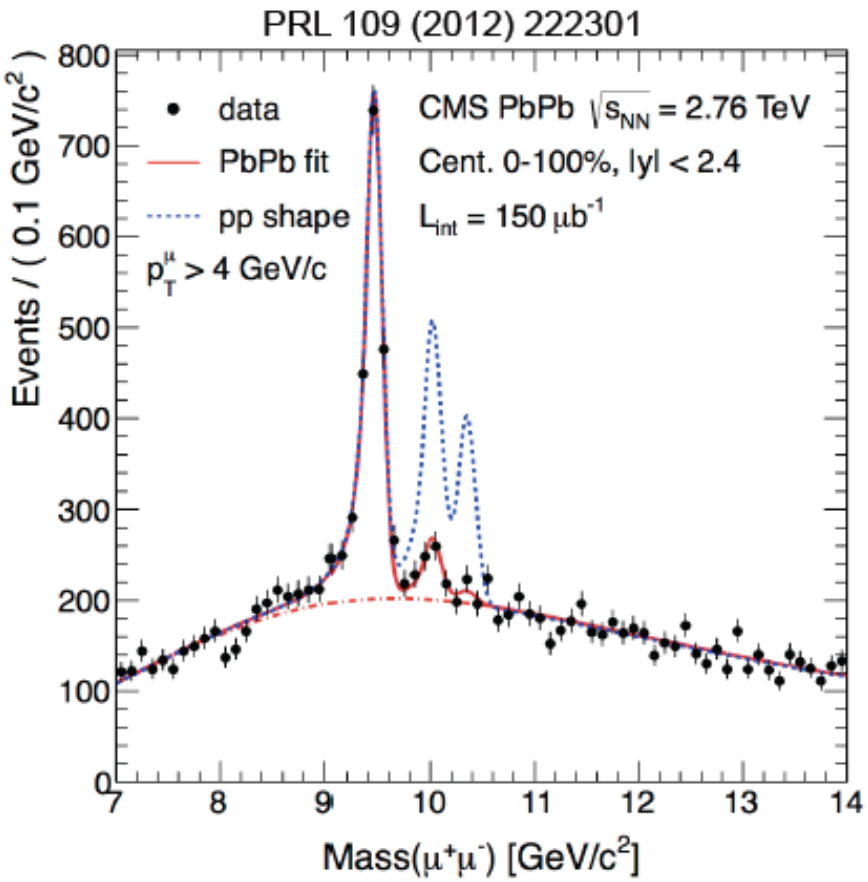




suppression / regeneration

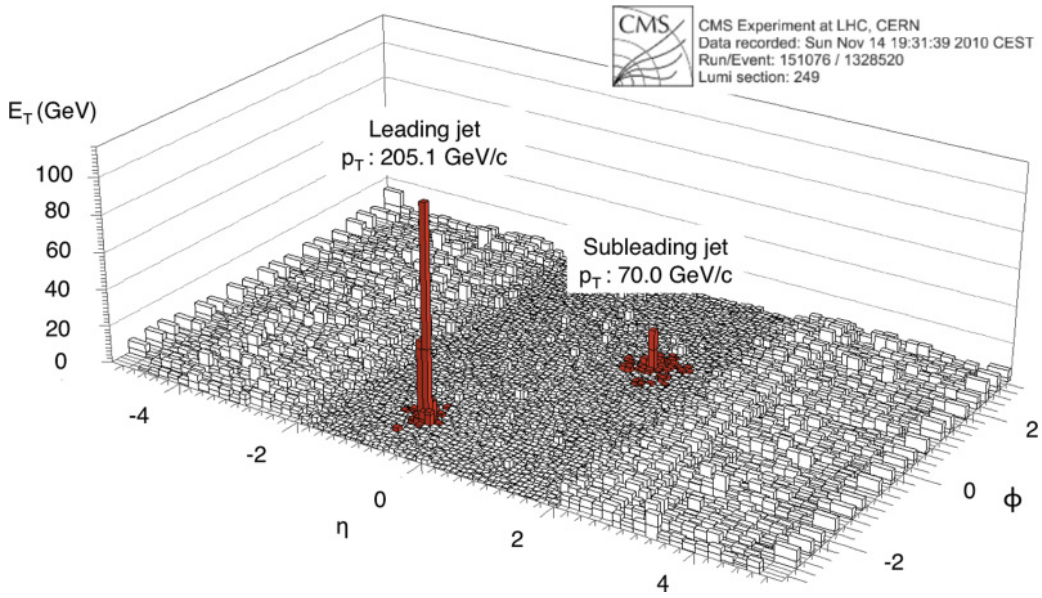
Υ suppression

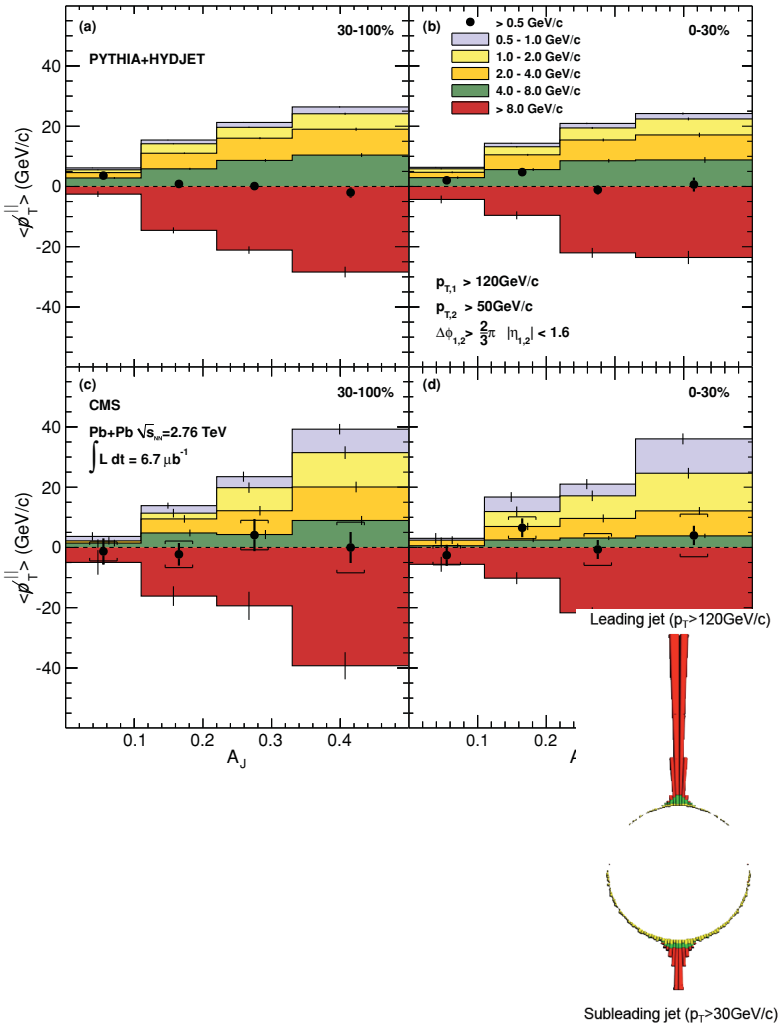


excited states are more 'fragile'....

Di-jet asymmetry

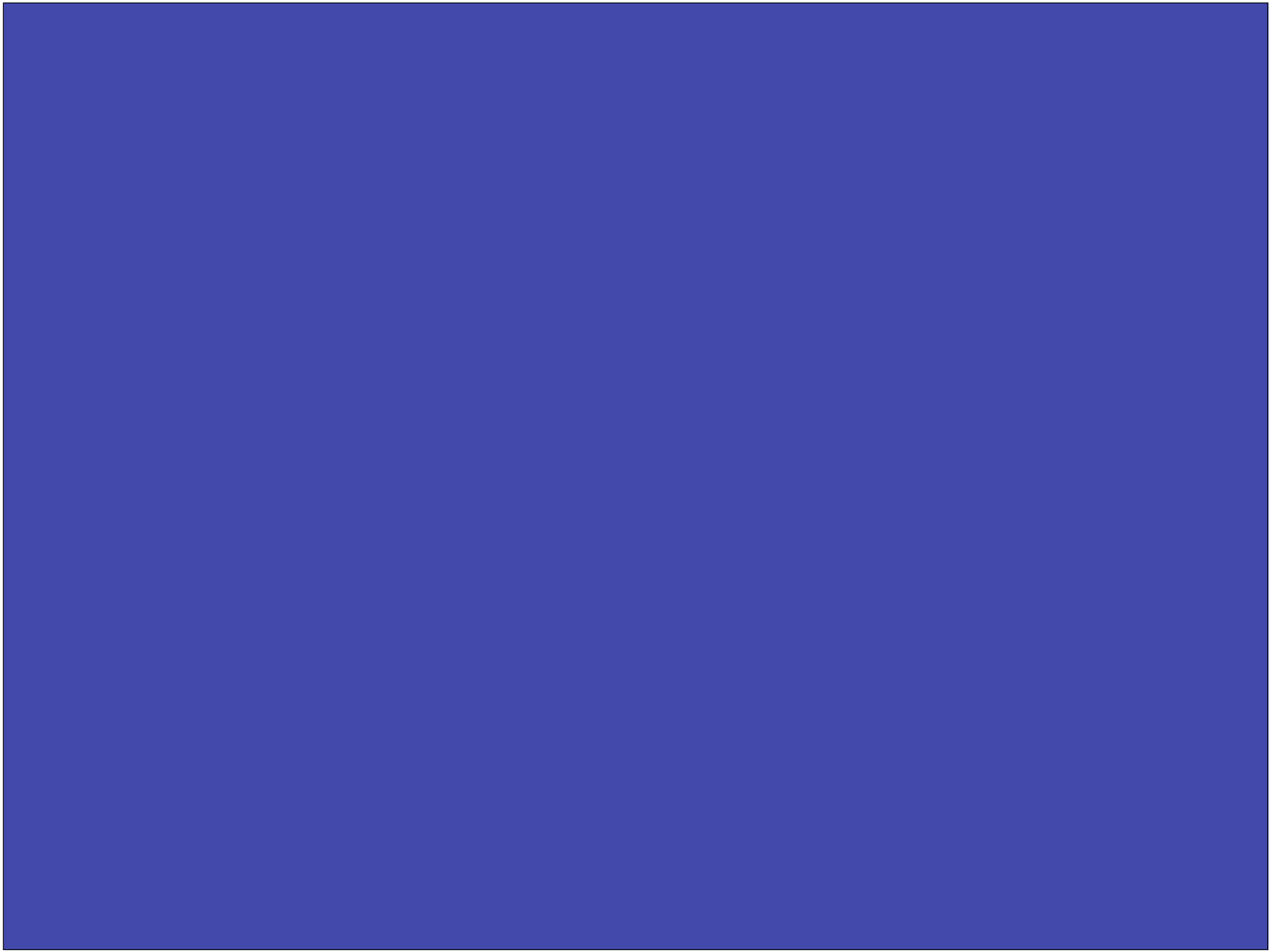
there is more to it than just 'jet quenching'...





Missing energy is associated with additional radiation of many soft quanta at large angles

Perhaps reflecting a new type of in-medium QCD cascade (see JPB, E. Iancu and Y. Mehtar-Tani, arXiv: 1301.6102)



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The field has never been so exciting as now !