Matter at Extreme Conditions

from to RHIC to LHC

European Research Council

Jean-Paul Blaizot, IPhT- Saclay

IPhT SACLAY

From AGS to SPS to RHIC to LHC

Bevalac

SPS-LHC

Why colliding heavy nuclei at high energy ?

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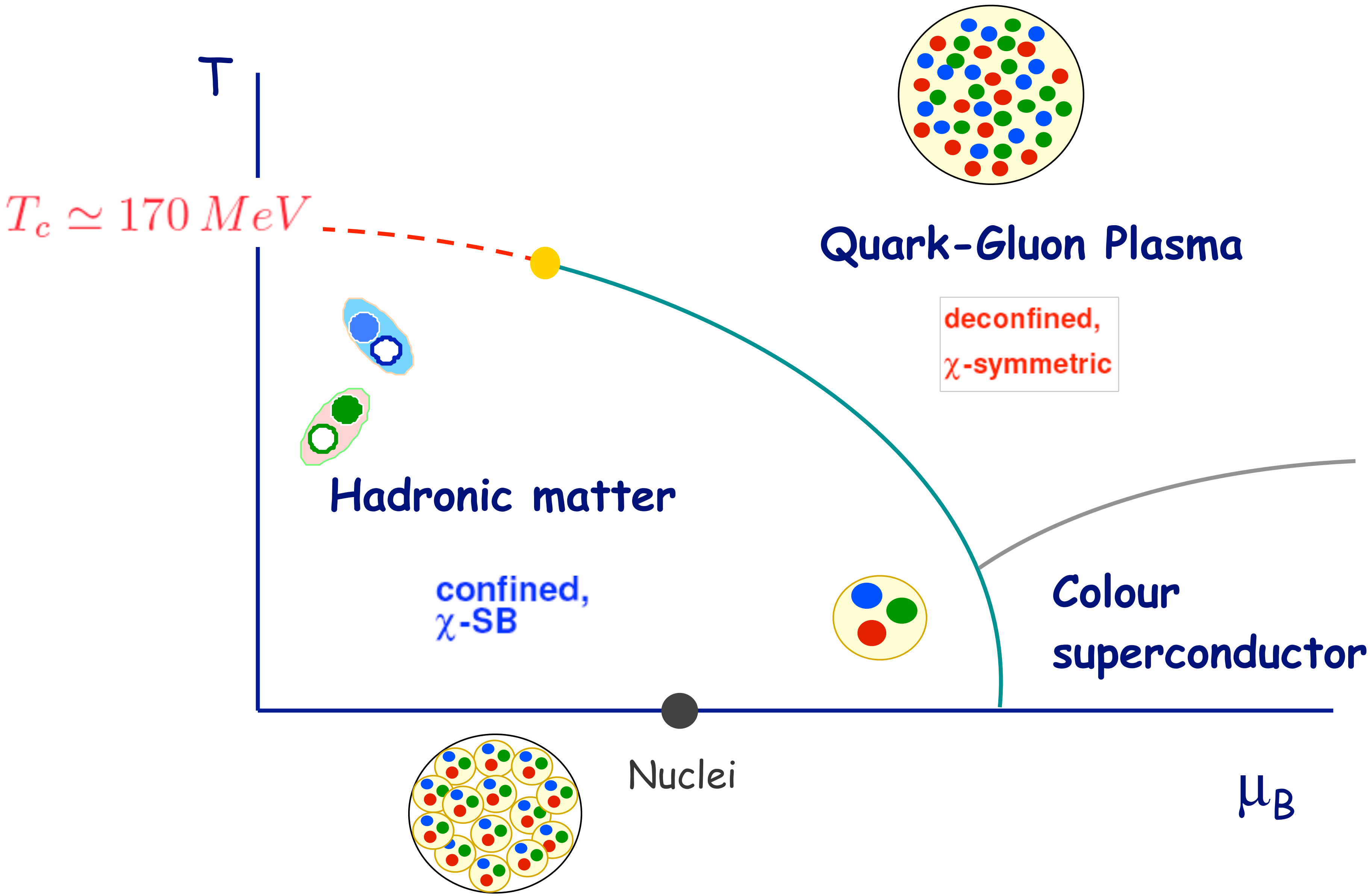
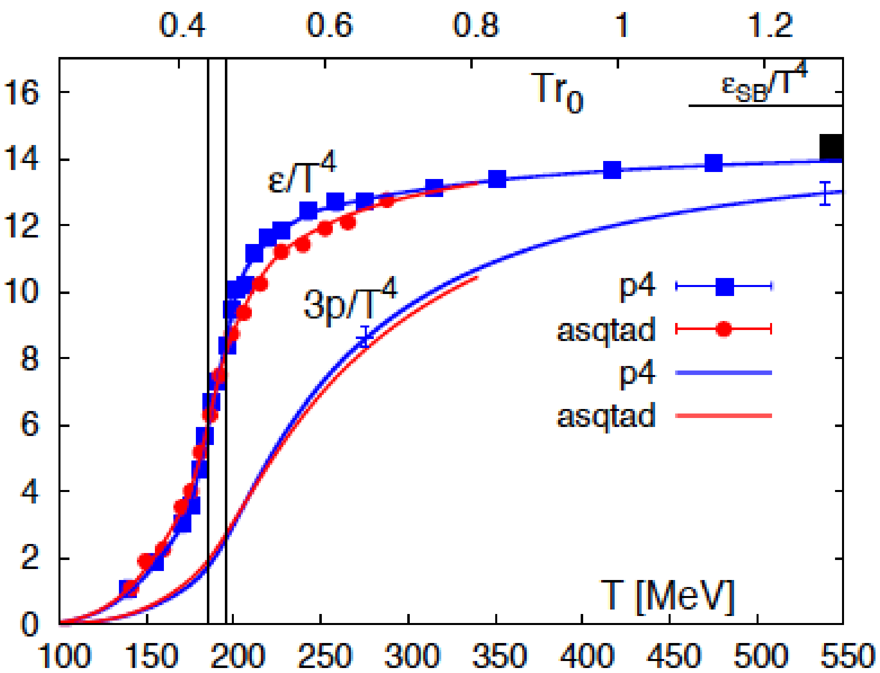
Simplicity may emerge in asymptotic situations

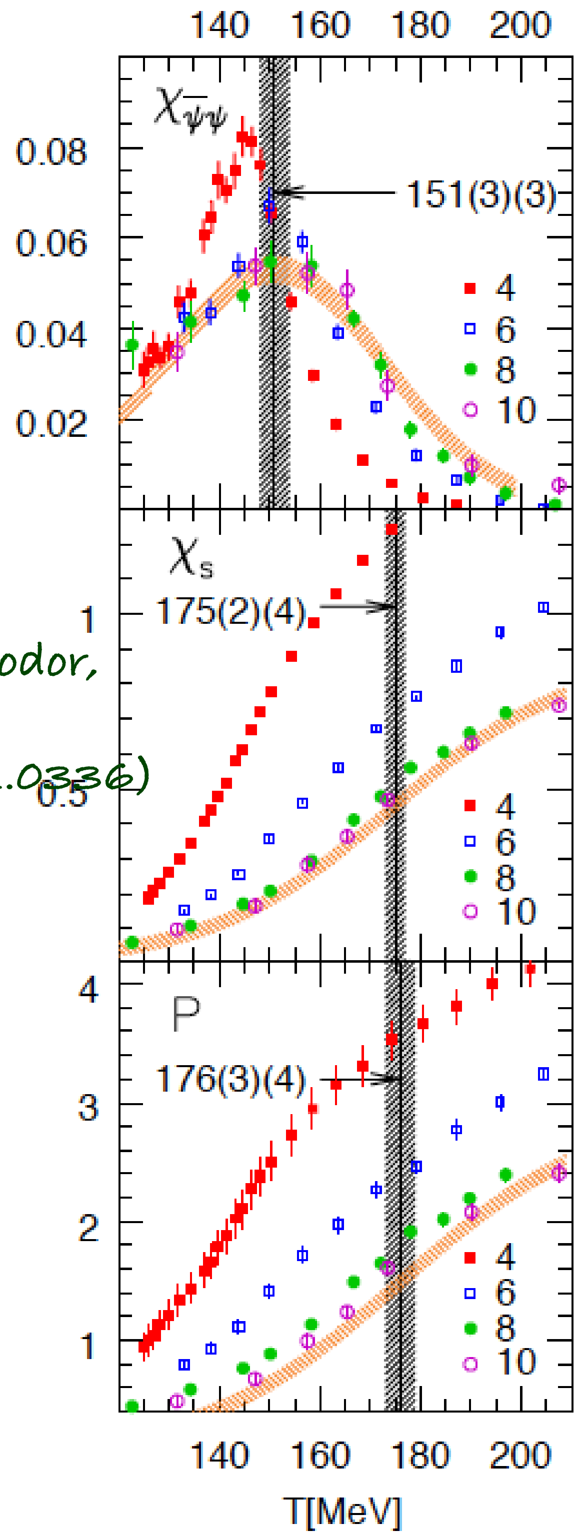
The QCD phase diagram



Crossover from hadrons to quarks and gluons



(from M. Bazavov et al, arXiv:0903.4379)



(from Z. Fodor,

arXiv:0711.0336)

The accelerated nucleus

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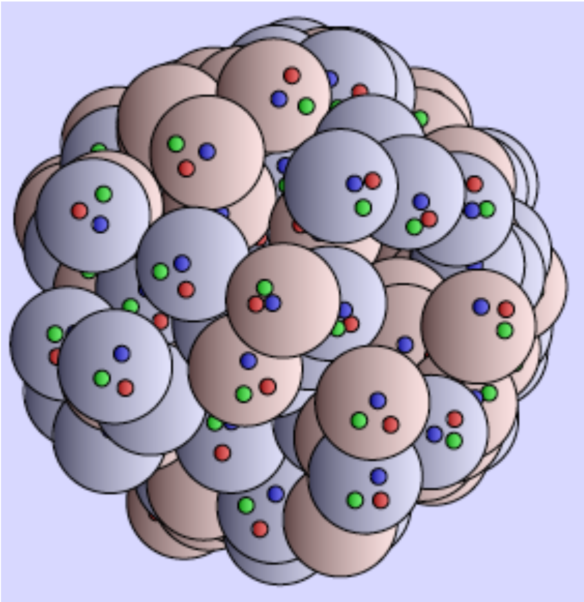

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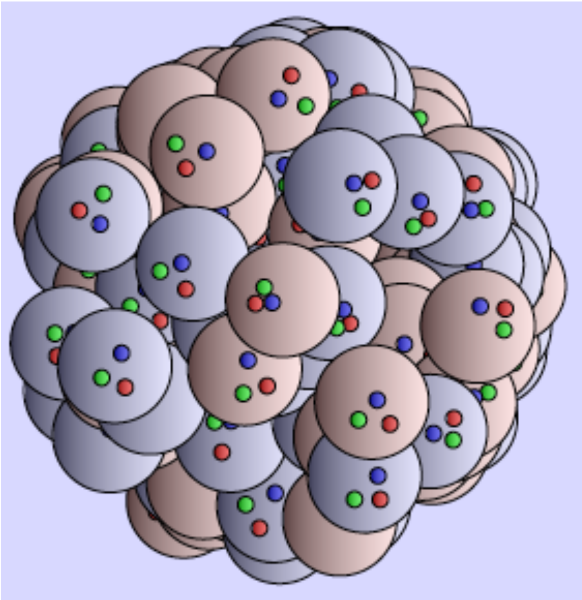 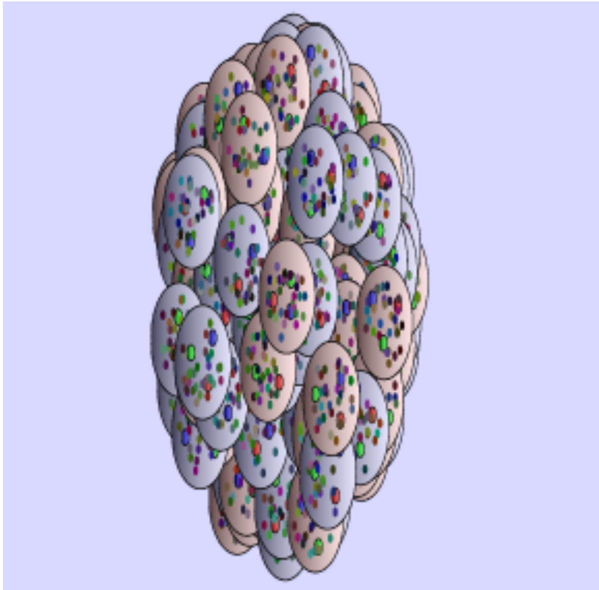

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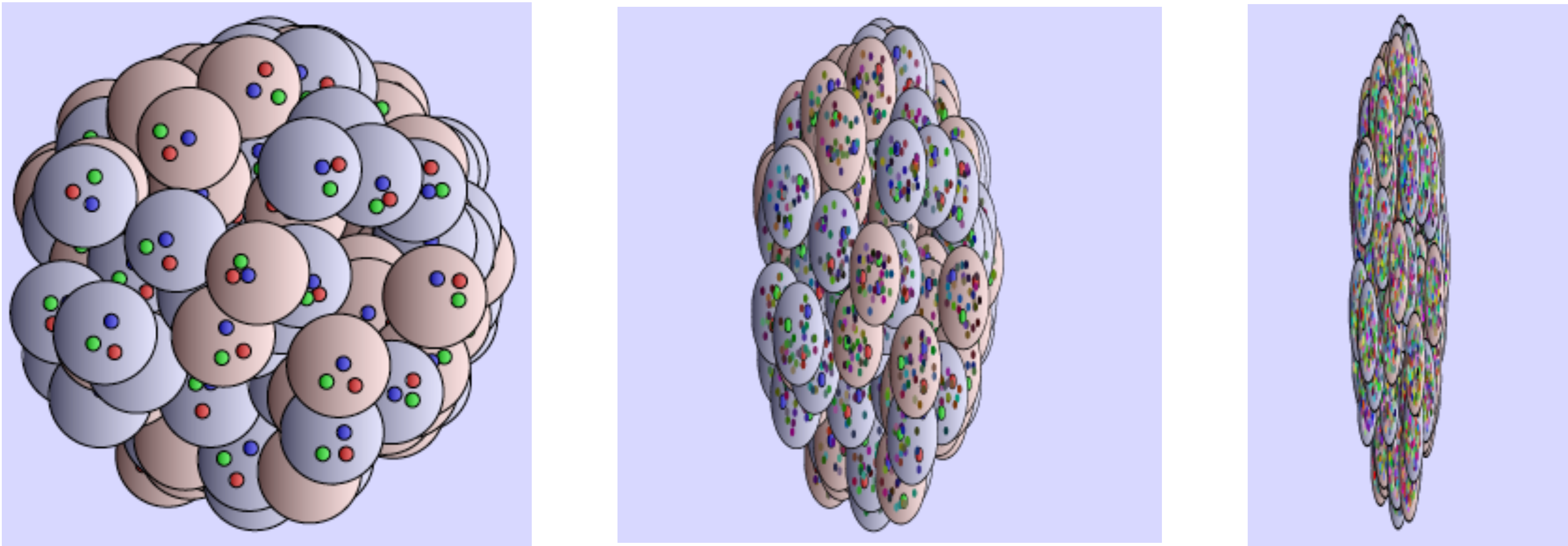

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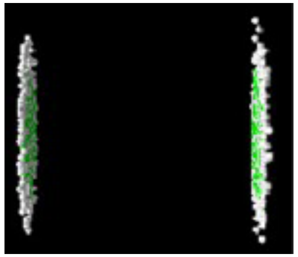
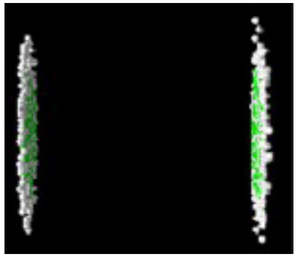


Fluctuations into multi-gluon configurations look frozen during collision (Lorentz time dilation)



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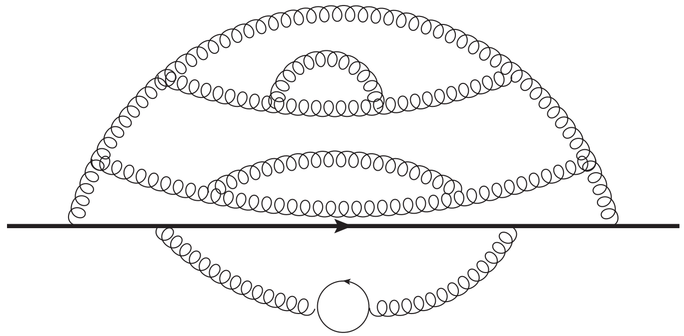

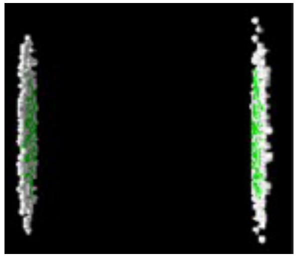

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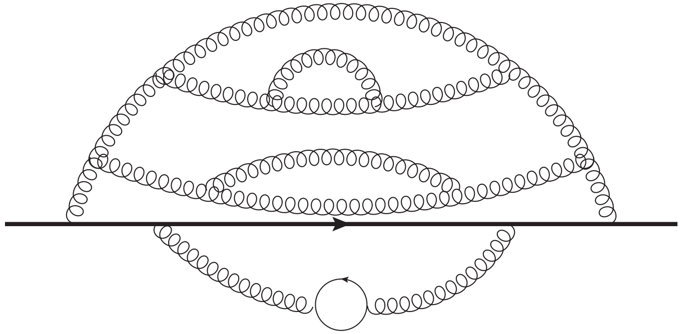

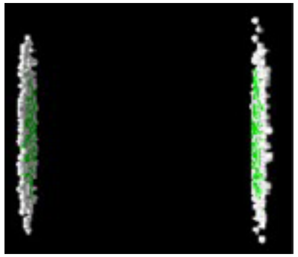

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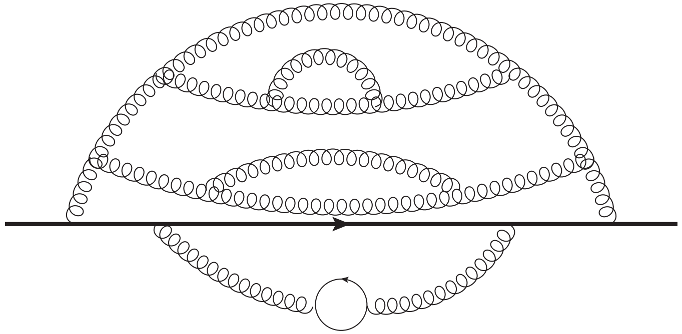

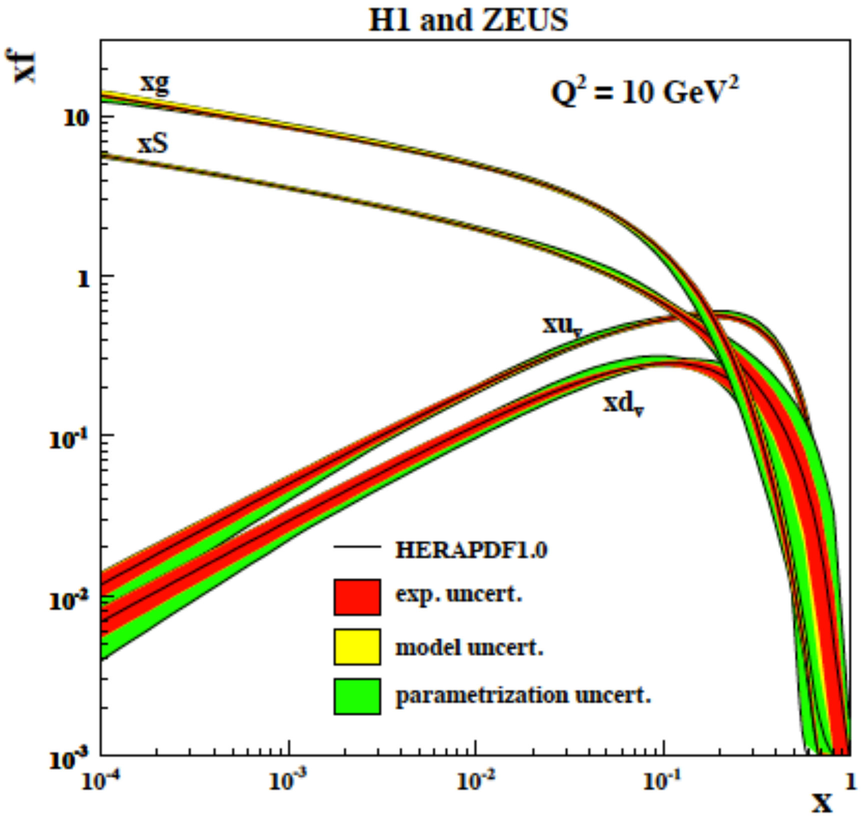

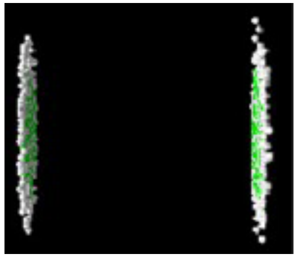

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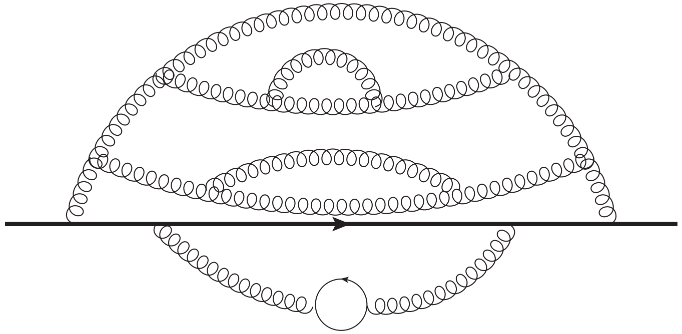
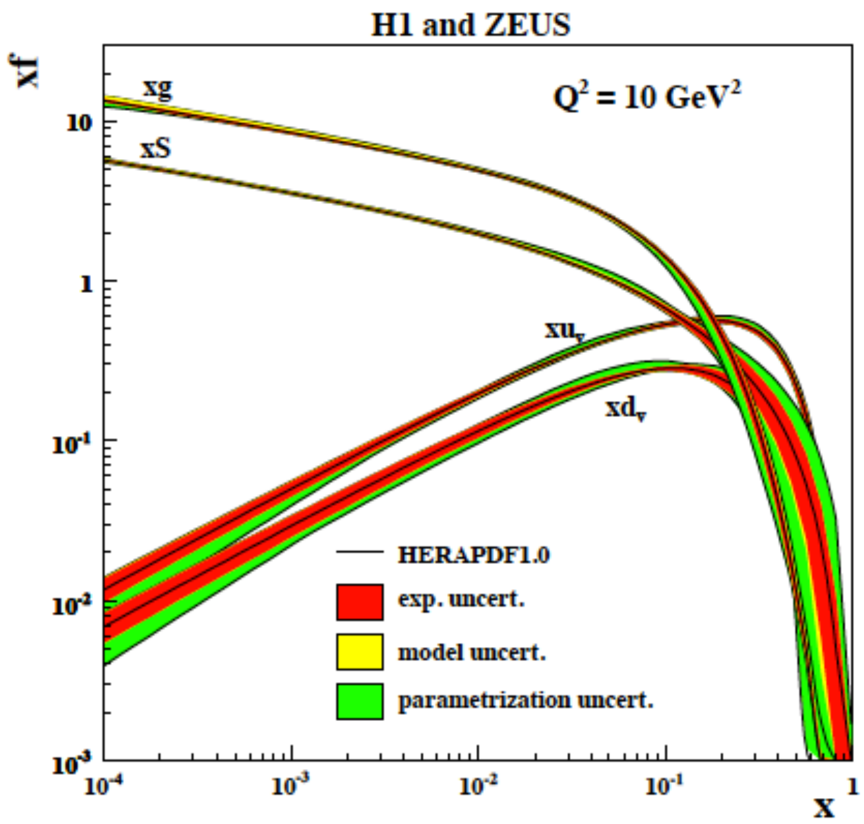
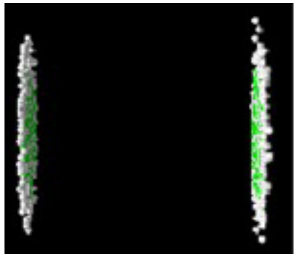
Gluon density increases with energy (with decreasing x, increasing Q)







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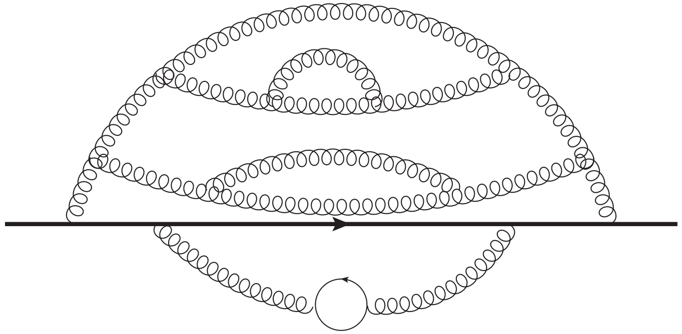

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Bulk of particle production $(p_T \lesssim 2$ GeV $)$

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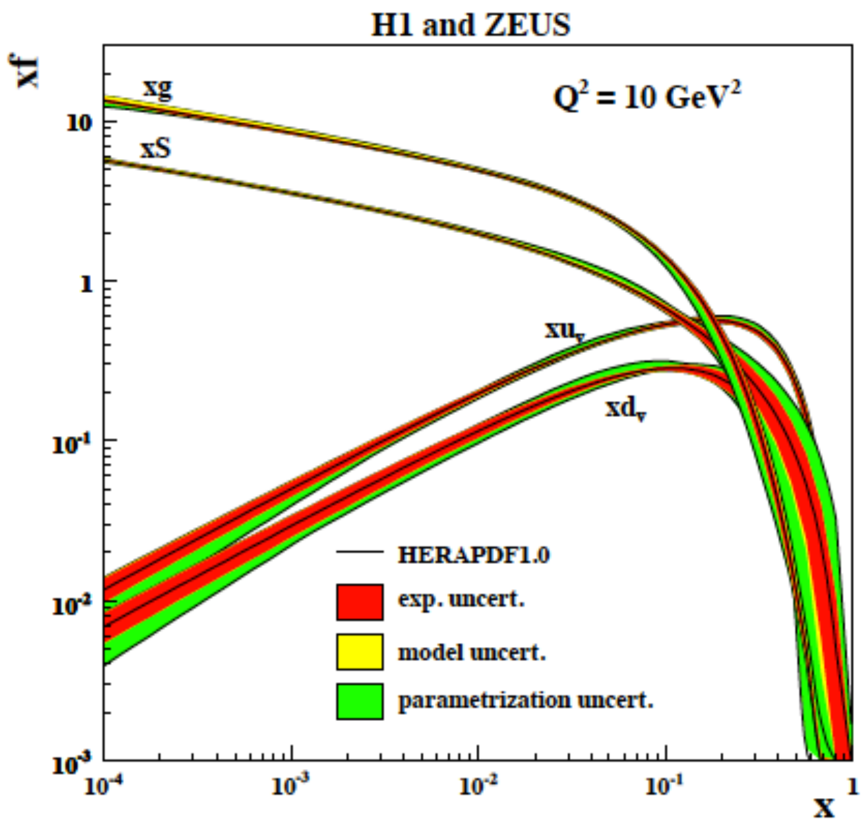

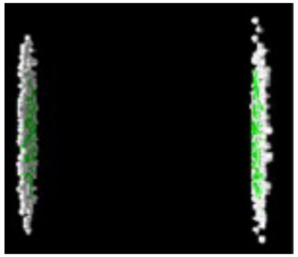

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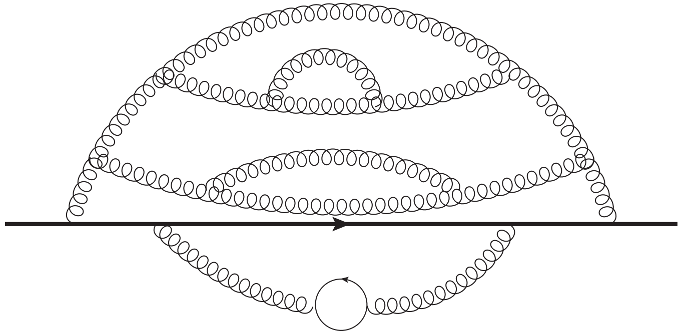

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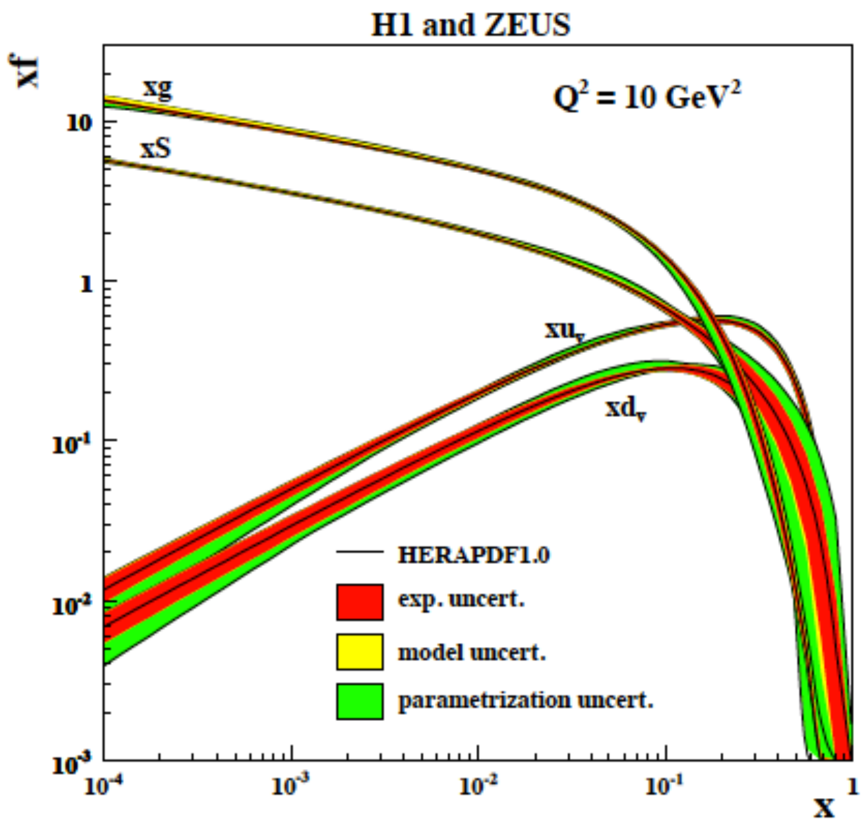

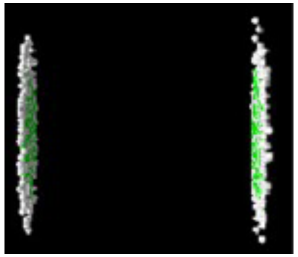

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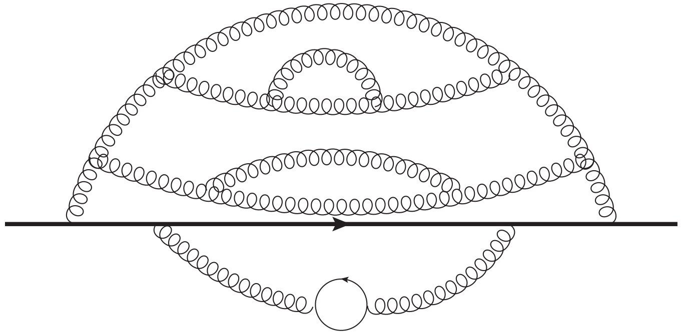

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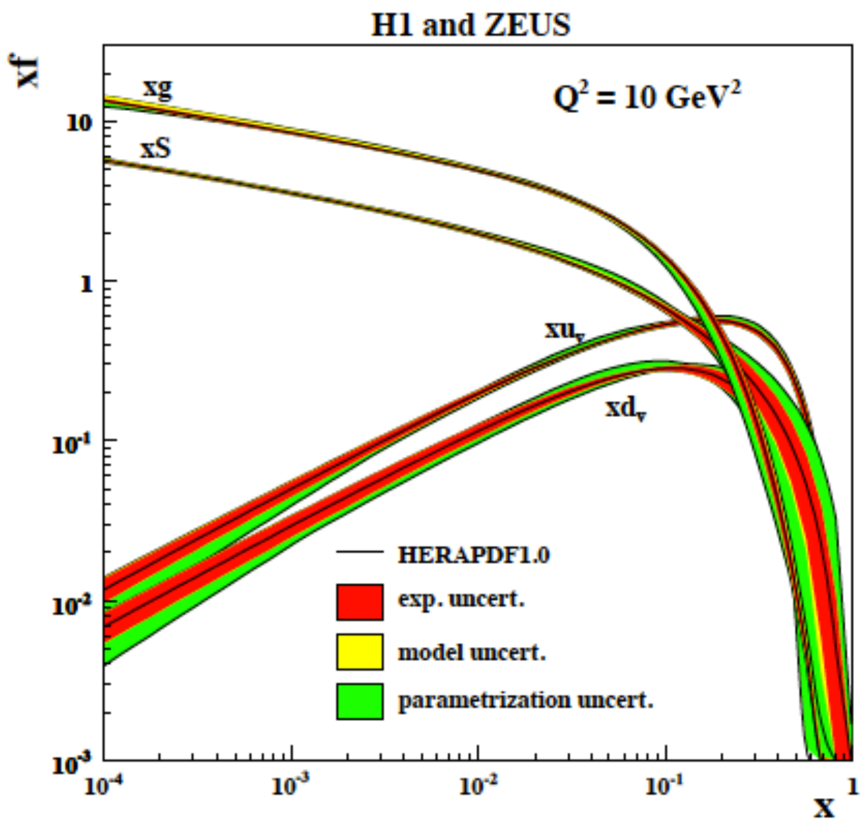
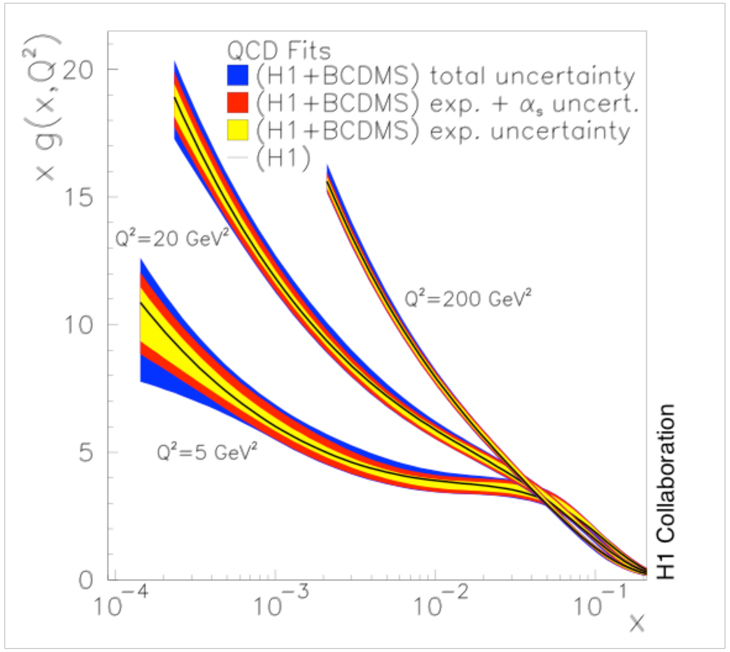
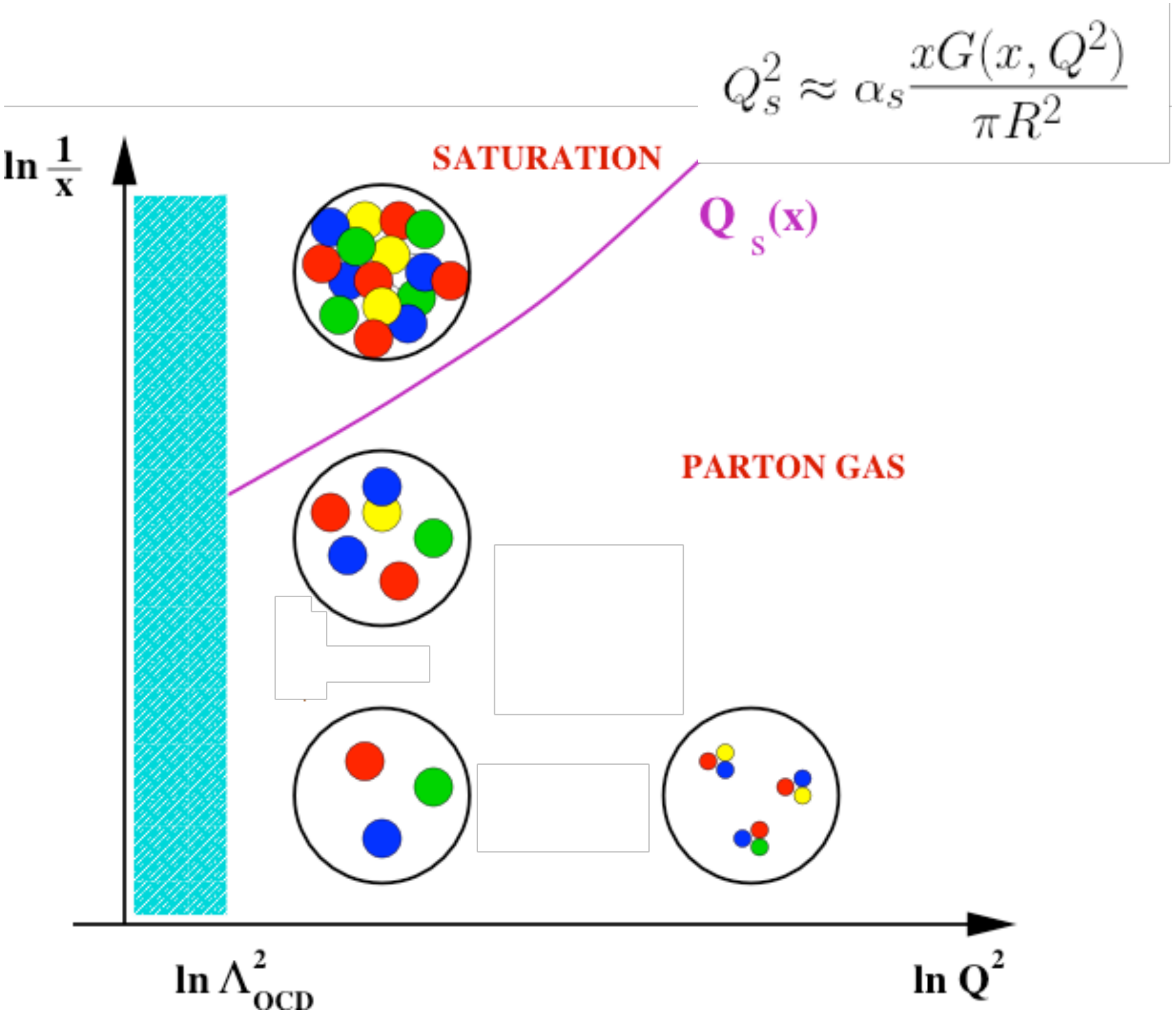
The growth eventually saturates





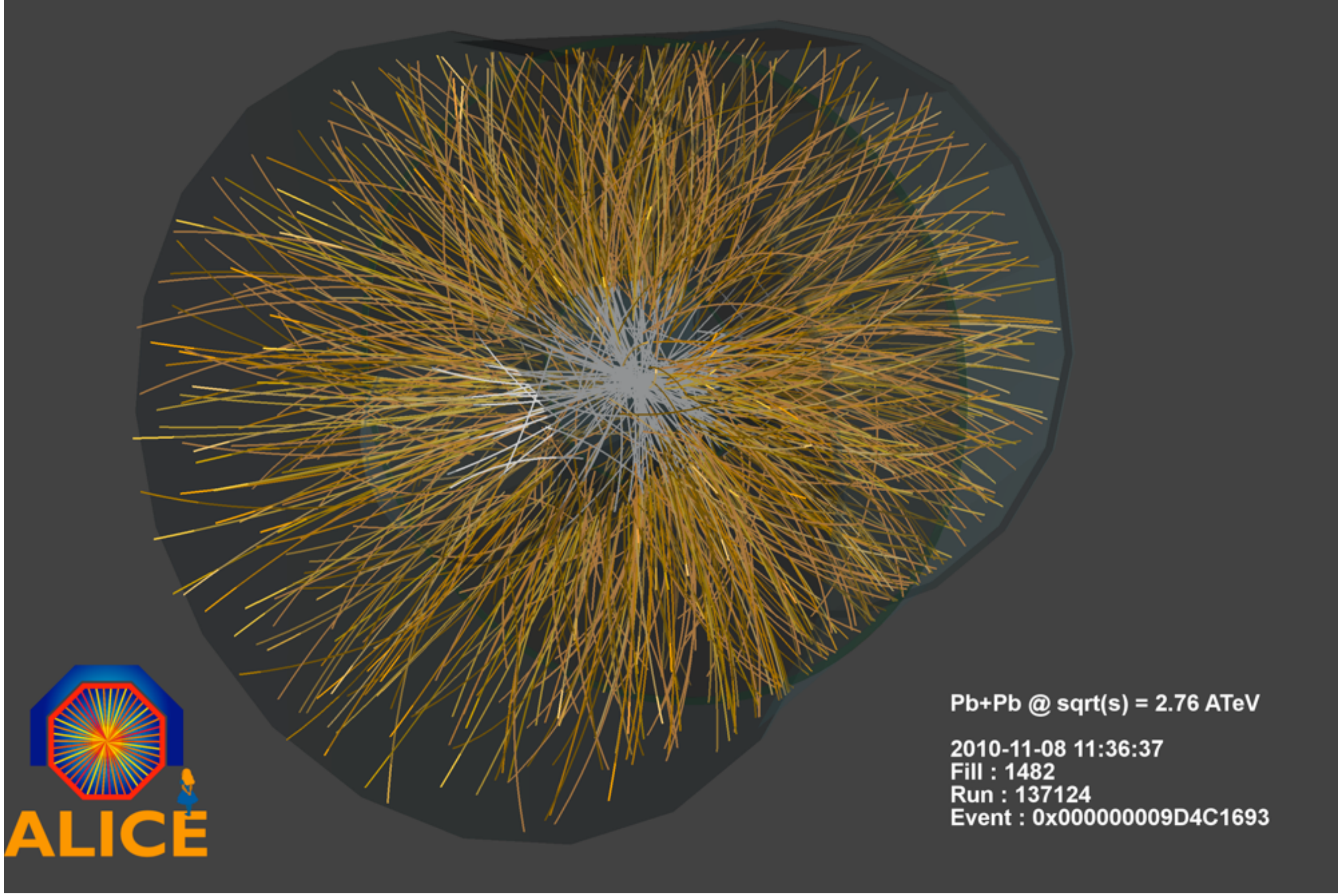
High density partonic systems

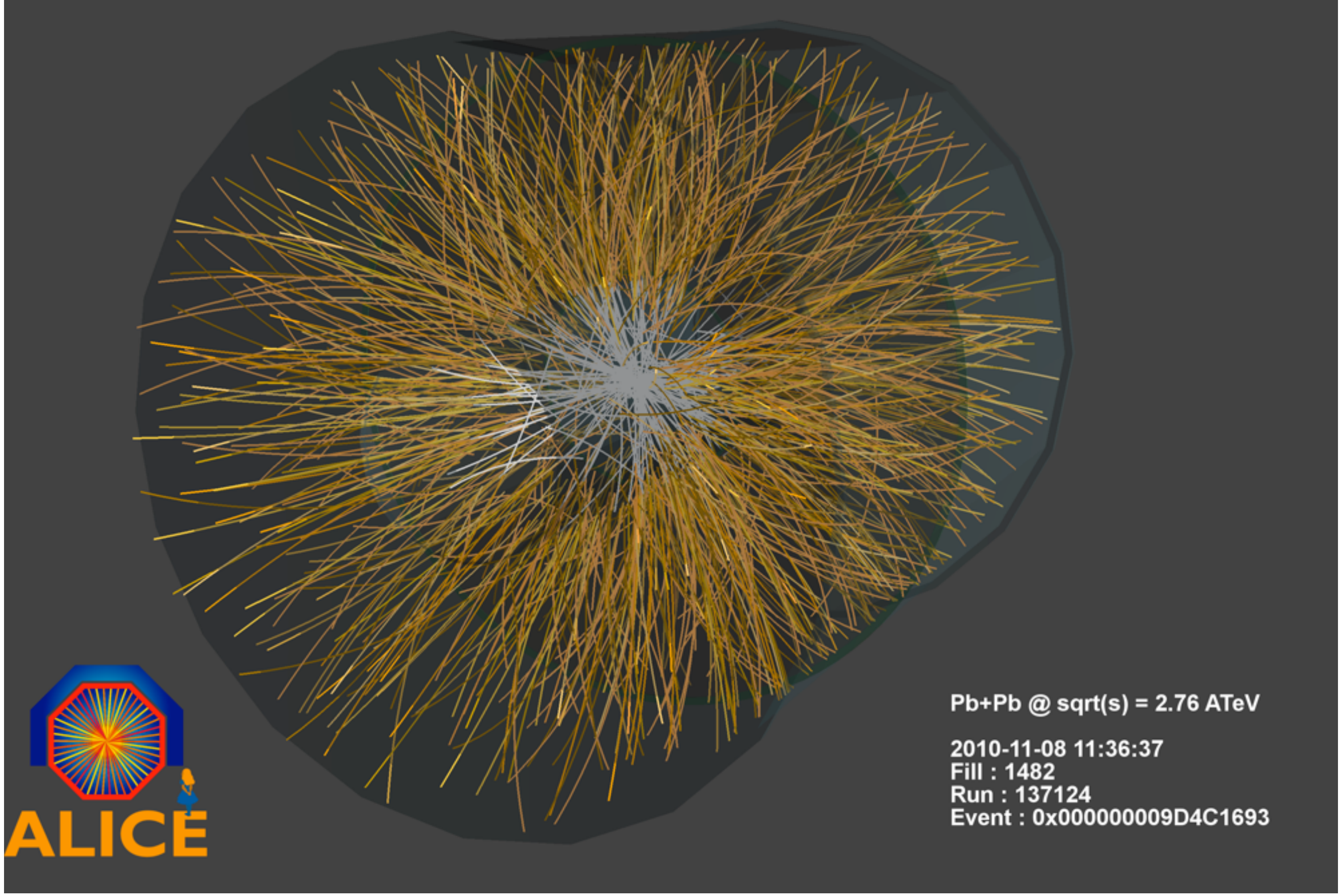


Large occupation numbers

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

Colliding heavy nuclei


Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:36:37
Fill : 1482
Run : 137124
Event : 0x000000009D4C1693
ALICE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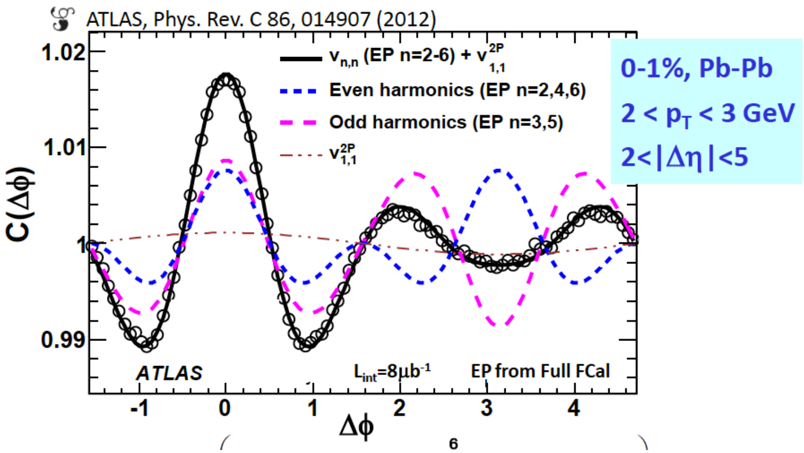
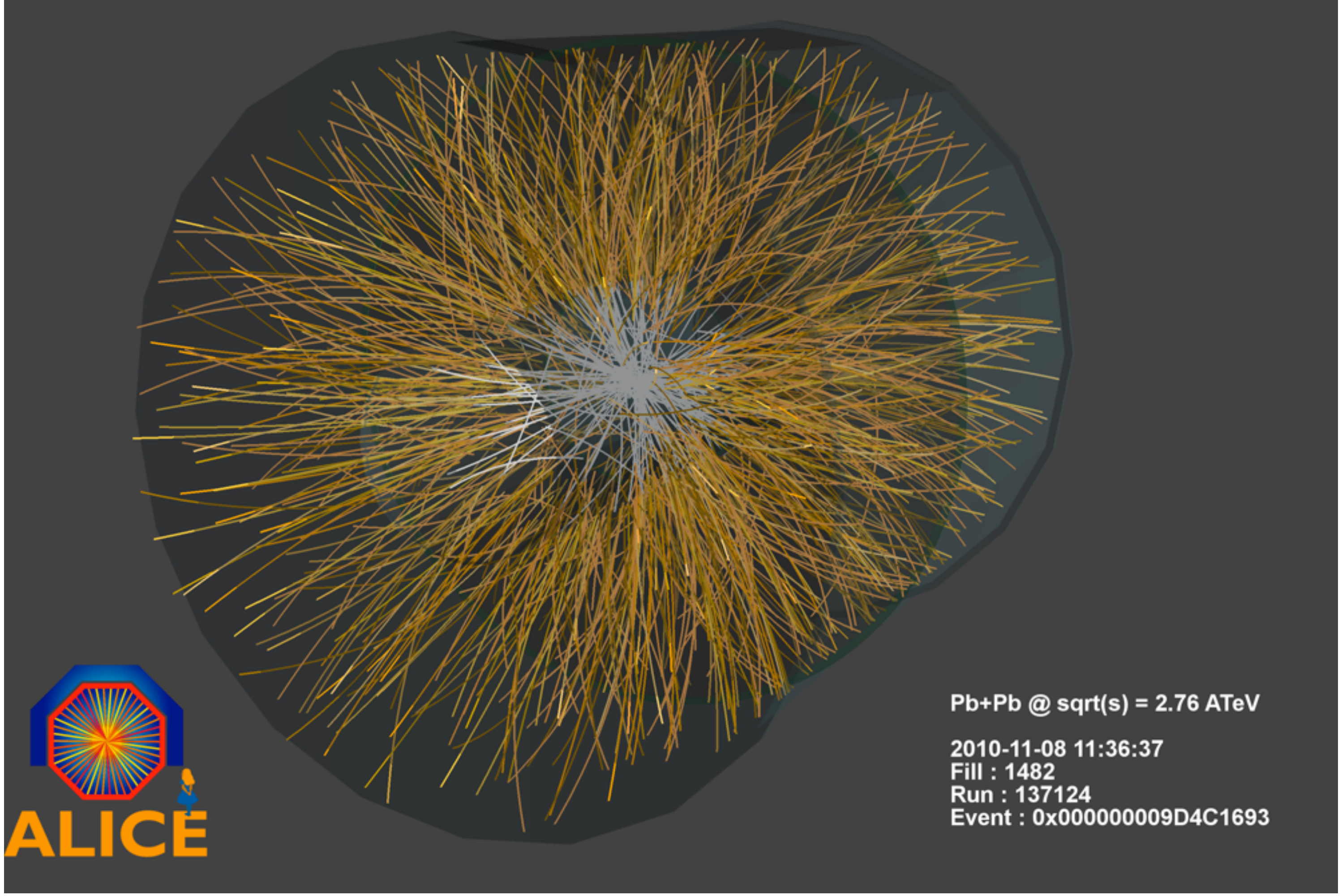

ATLAS, Phys. Rev. C 86, 014907 (2012)
$v_{n,n}$ (EP n=2-6) + $v_{1,1}^{2P}$
Even harmonics (EP n=2,4,6)
Odd harmonics (EP n=3,5)
$v_{1,1}^{2P}$
0-1%, Pb-Pb
$2 < p_T < 3$ GeV
$2<|\Delta\eta|<5$
C(Δϕ)
Δϕ
ATLAS
$L_{int}=8\mu b^{-1}$
EP from Full FCal
1.02
1.01
1
0.99
-1
0
1
2
3
4



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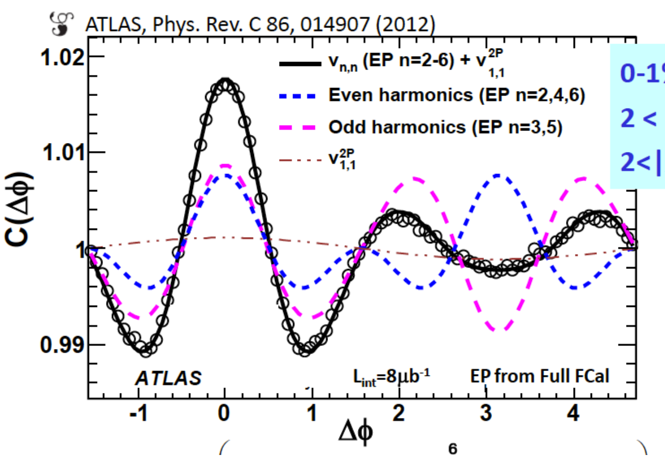

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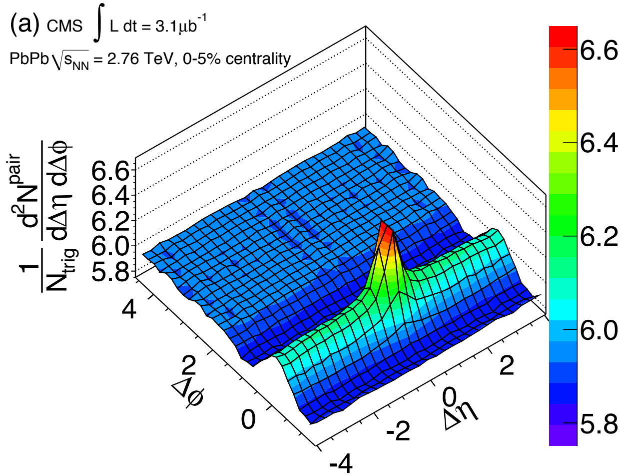
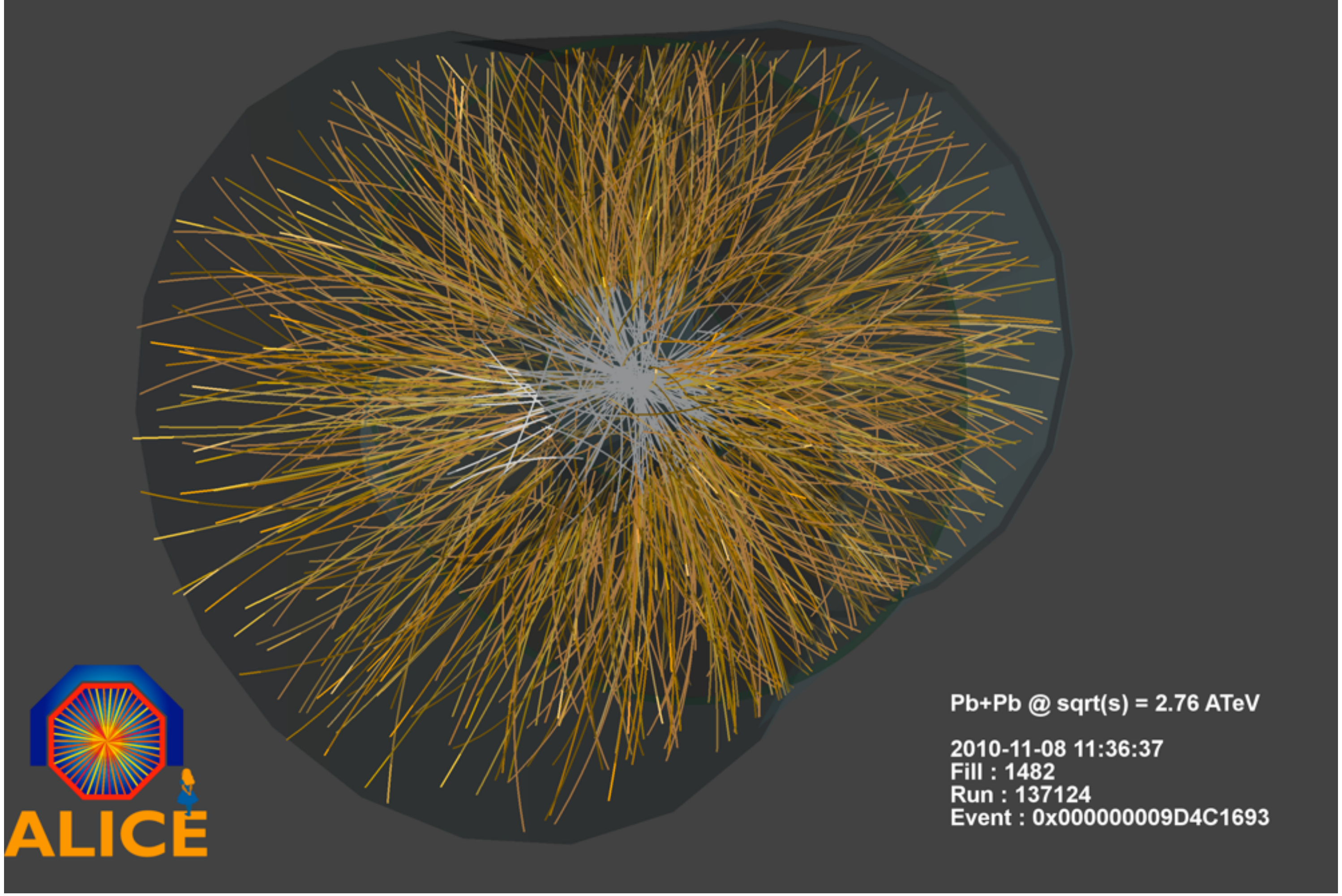


(a) CMS $\int L\,dt = 3.1\mu b^{-1}$
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV, 0-5% centrality
$\frac{1}{N_{trig}} \frac{d^2N^{pair}}{d\Delta\eta\, d\Delta\phi}$
Δϕ
Δη



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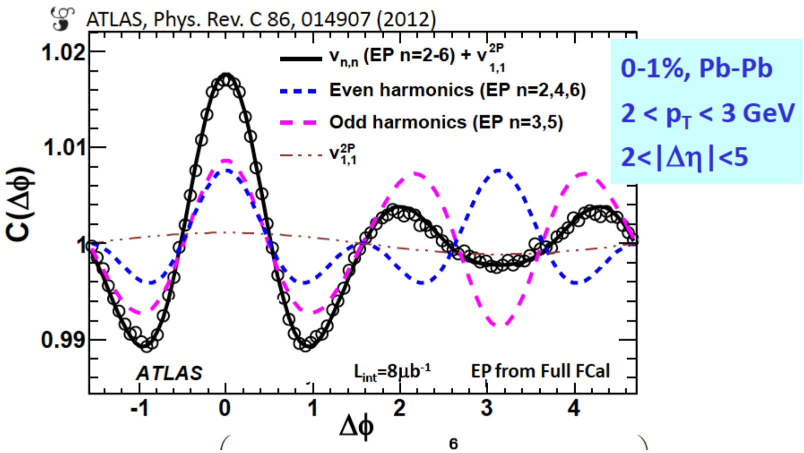

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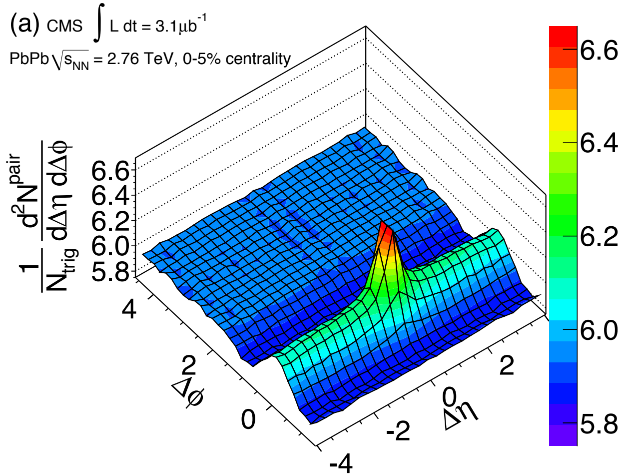

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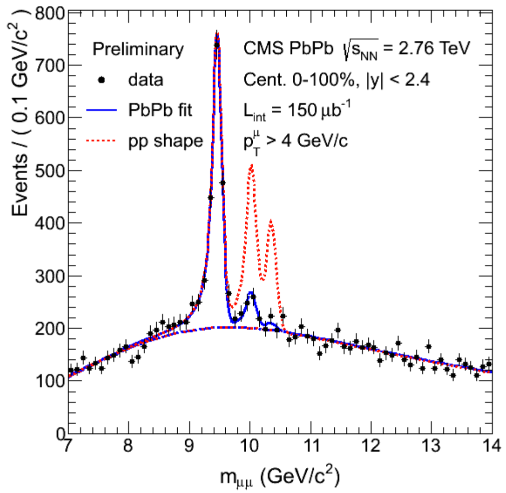

Preliminary
data
PbPb fit
pp shape
CMS PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
Cent. 0-100%, |y| < 2.4
L_{int} = 150 μb^{-1}
p_T^μ > 4 GeV/c
Events / (0.1 GeV/c^2)
800
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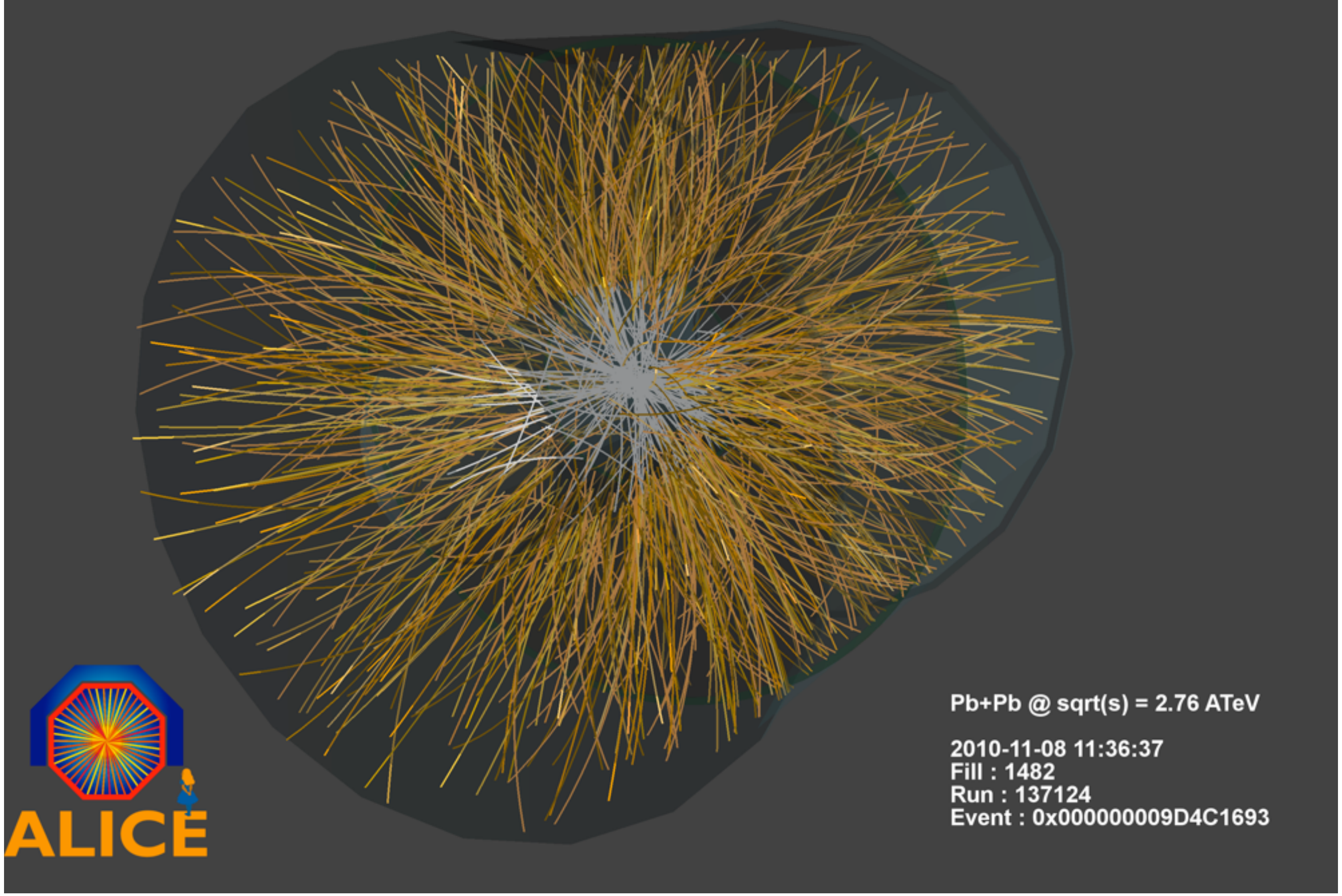
10
11
12
13
14
$m_{\mu\mu}$ (GeV/c^2)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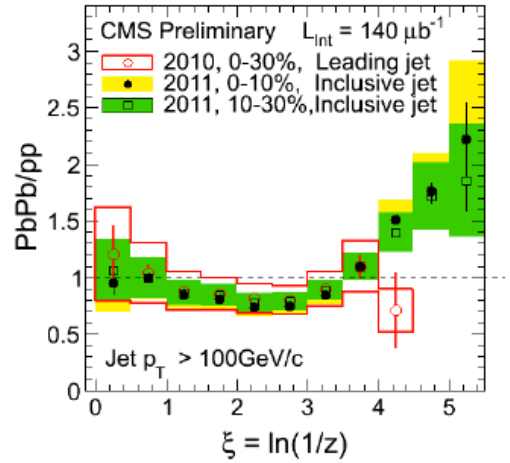
CMS Preliminary L_{int} = 140 μb^{-1}
2010, 0-30%, Leading jet
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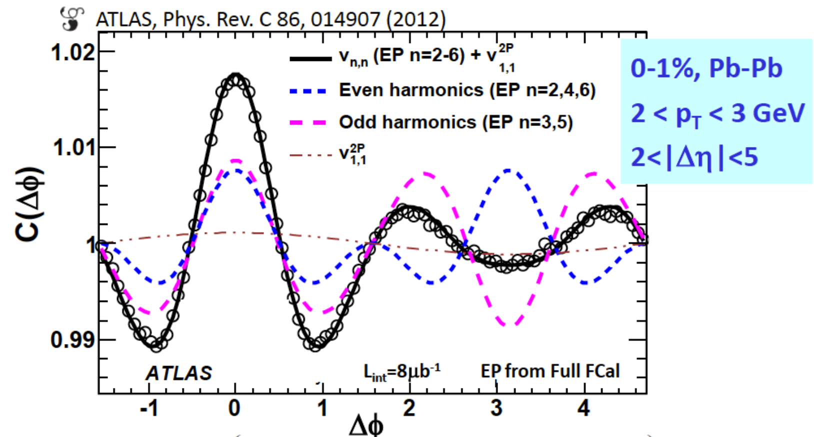
Jet p_T > 100GeV/c
PbPb/pp
$\xi = \ln(1/z)$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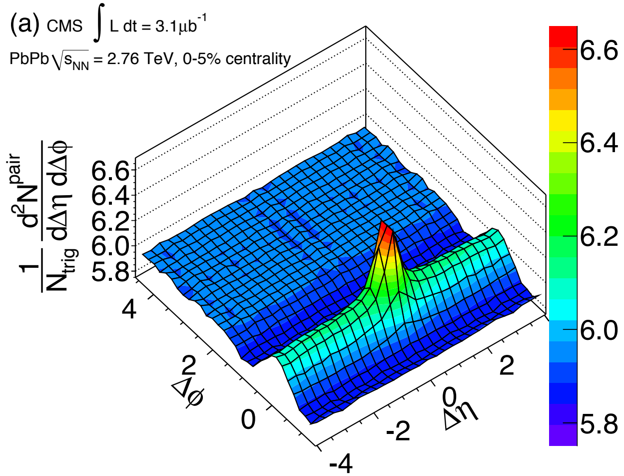
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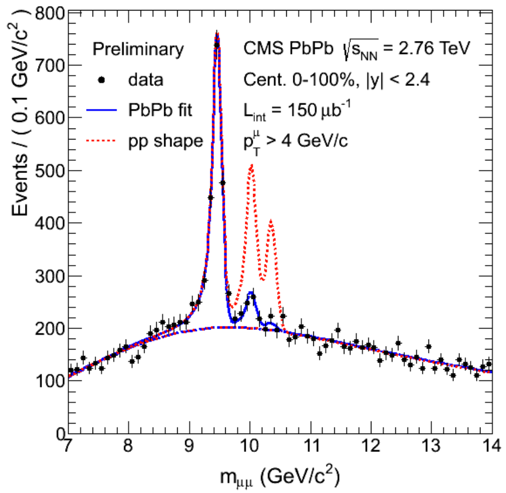
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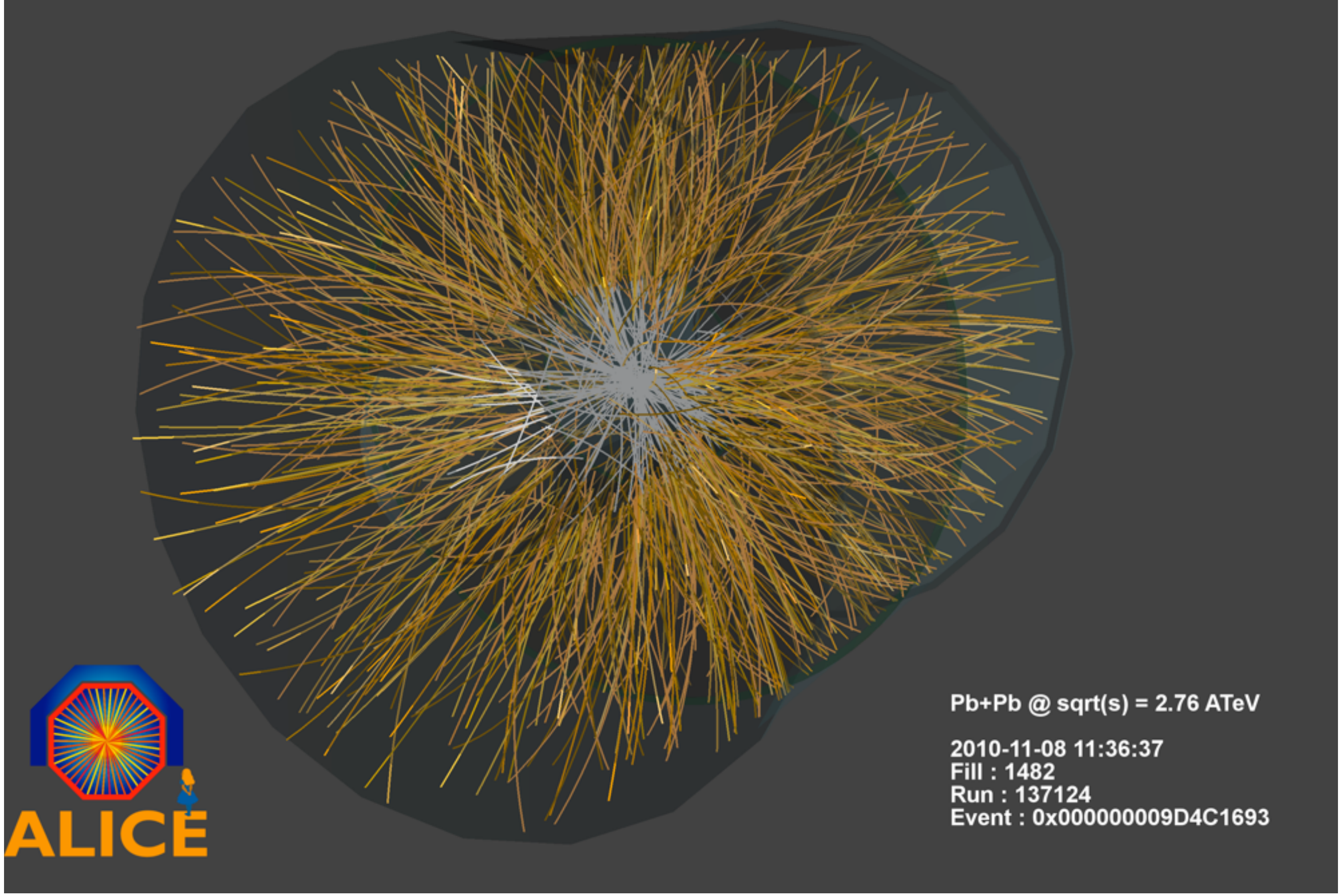
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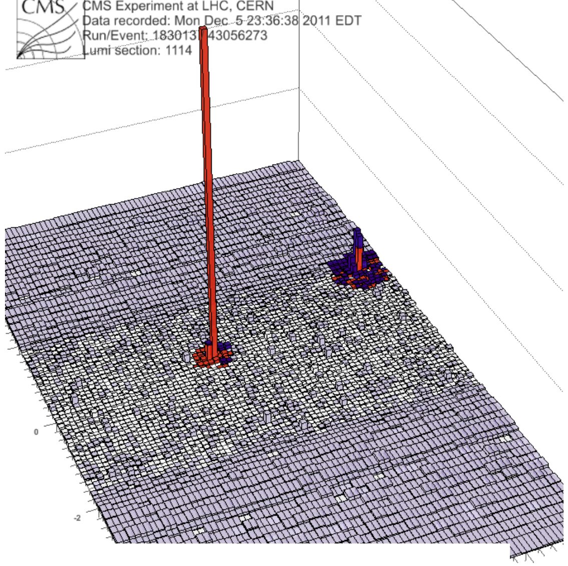
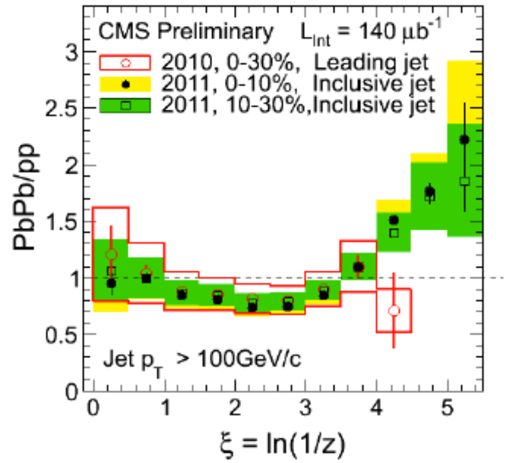

CMS Experiment at LHC, CERN
Data recorded: Mon Dec 5 23:36:38 2011 EDT
Run/Event: 183013 / 43056273
Lumi section: 1114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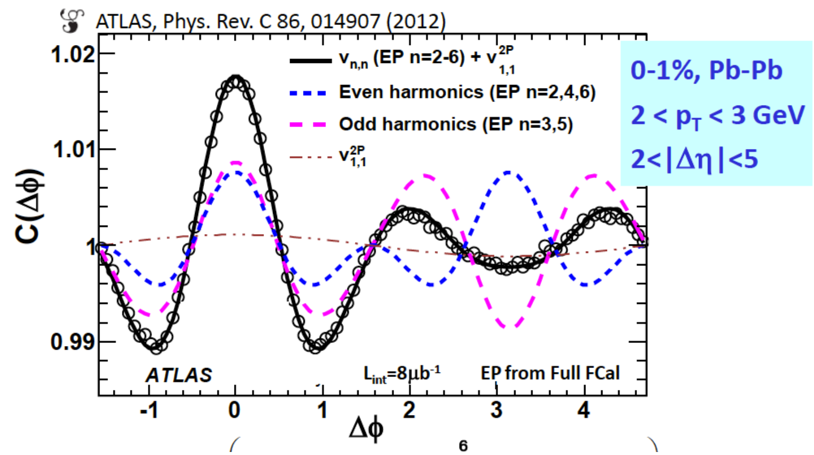
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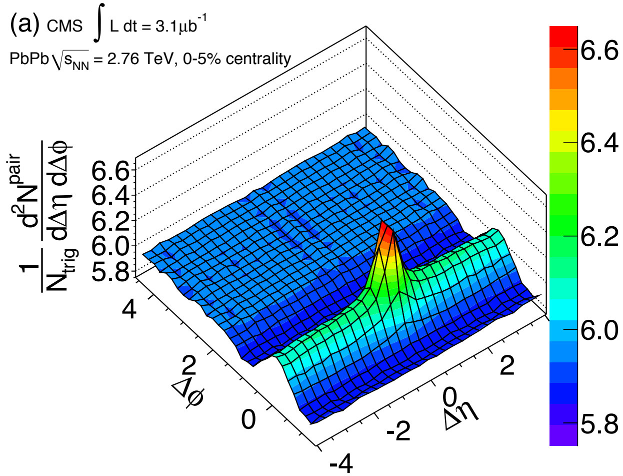
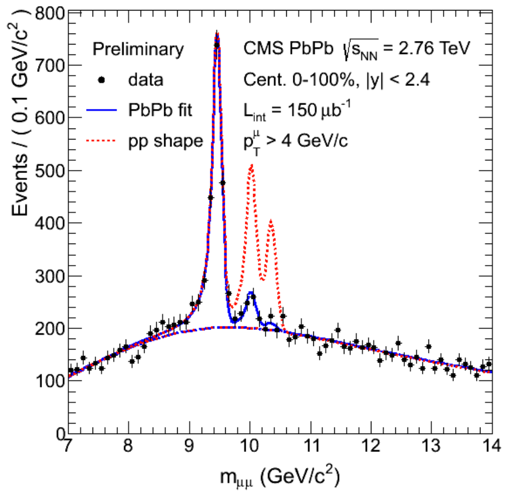
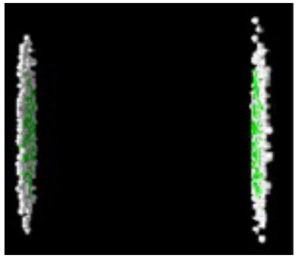
EP from Full FCal
Δϕ

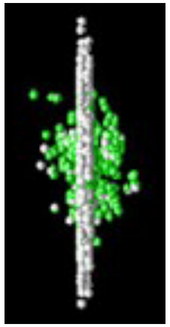

(a) CMS ∫ L dt = 3.1μb^{-1}
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV, 0-5% centrality
$\frac{1}{N_{trig}} \frac{d^2N^{pair}}{d\Delta\eta\, d\Delta\phi}$
Δϕ
Δη


Preliminary
data
PbPb fit
pp shape
CMS PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
Cent. 0-100%, |y| < 2.4
L_{int} = 150 μb^{-1}
p_T^{μ} > 4 GeV/c
Events / (0.1 GeV/c^2)
$m_{\mu\mu}$ (GeV/c^2)

Stages of nucleus-nucleus collisions

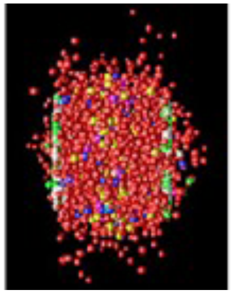


Initial conditions. Fluctuations (geometry, nucleus wave function and its parton content)

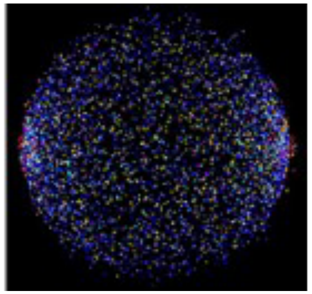


Particle (entropy) production. Involves mostly small x partons $(x = p_\perp / \sqrt{s} \sim 10^{-2} - 10^{-4} \quad \text{for} \quad p_\perp \simeq 2\text{GeV})$

One characteristic scale: saturation momentum Q_s



Thermalization. Quark-gluon plasma.
Hydrodynamical expansion



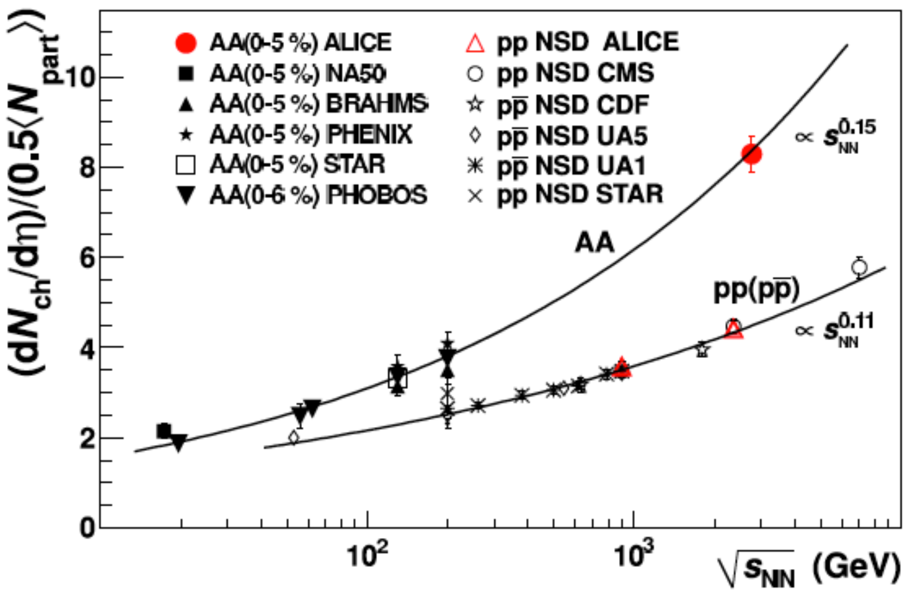
Hadronization in apparent chemical equilibrium.
Hadronic cascade till freeze-out.

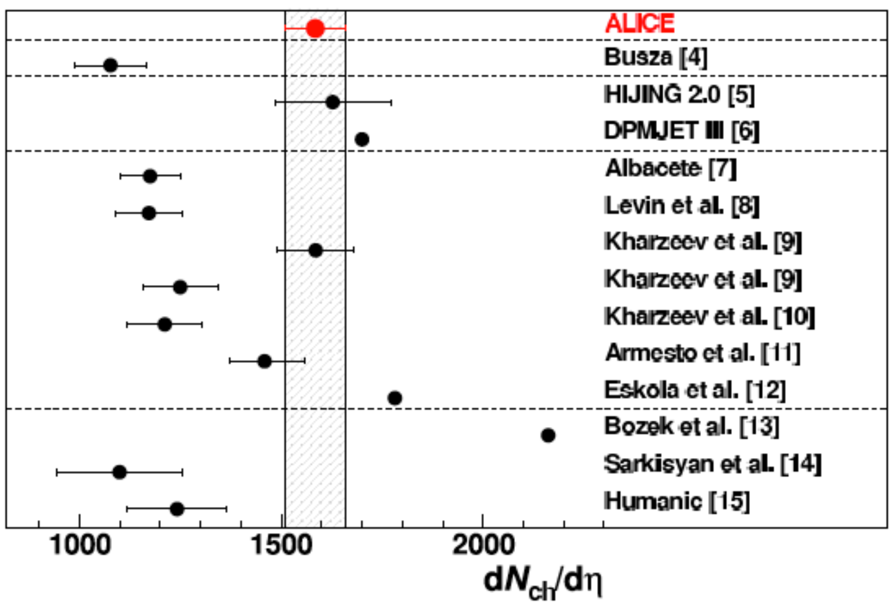
Moving backward in time

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

Matter at freeze-out is in chemical equilibrium

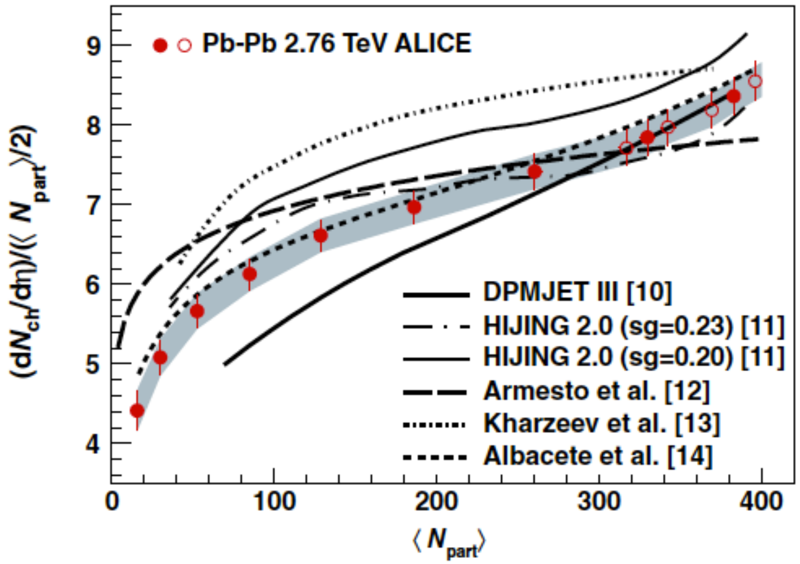
Counting particles





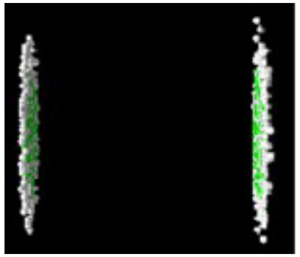
ALICE PRL 105 (2010)

ALICE PRL 106 (2011)



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

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

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

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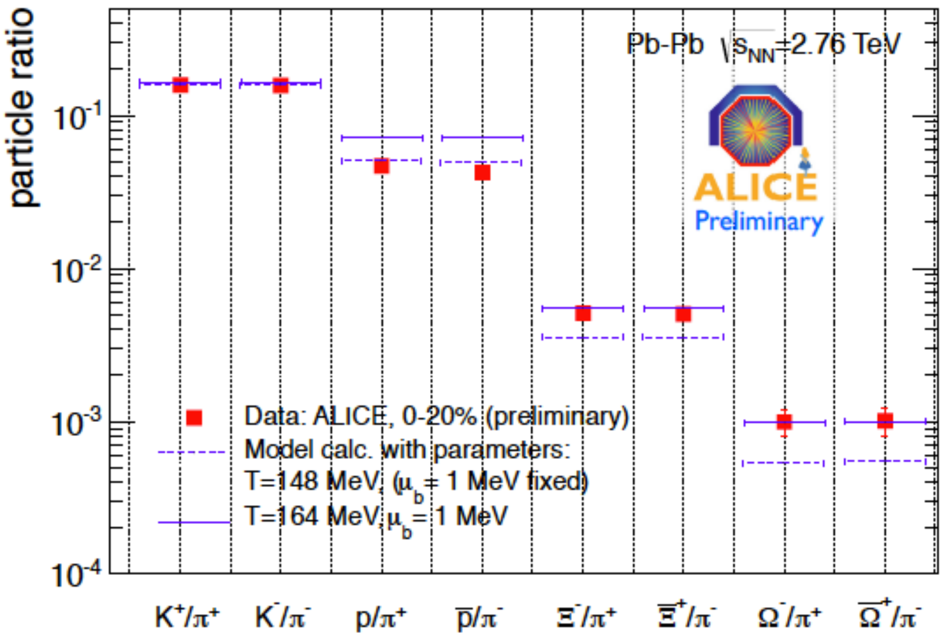

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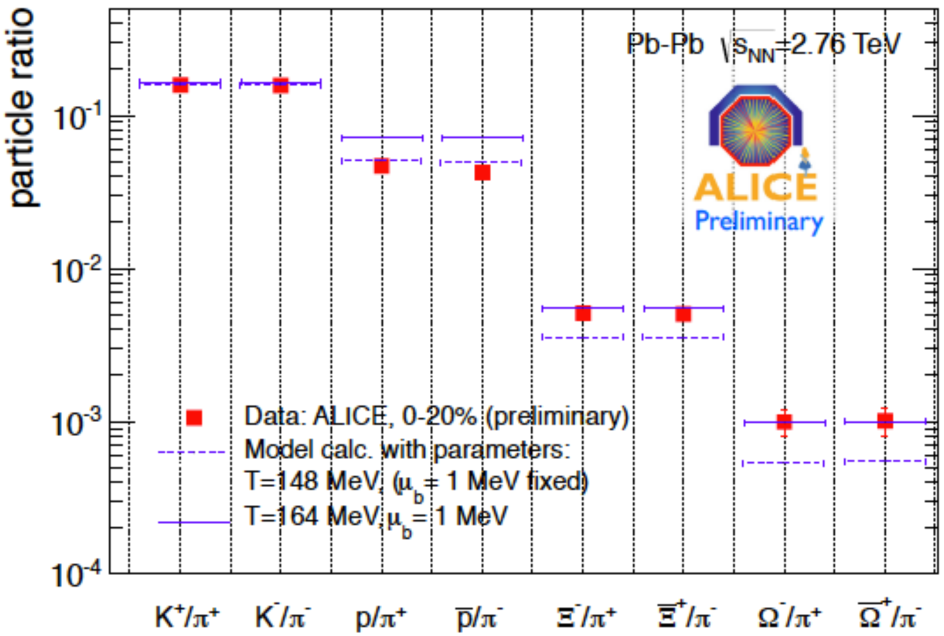

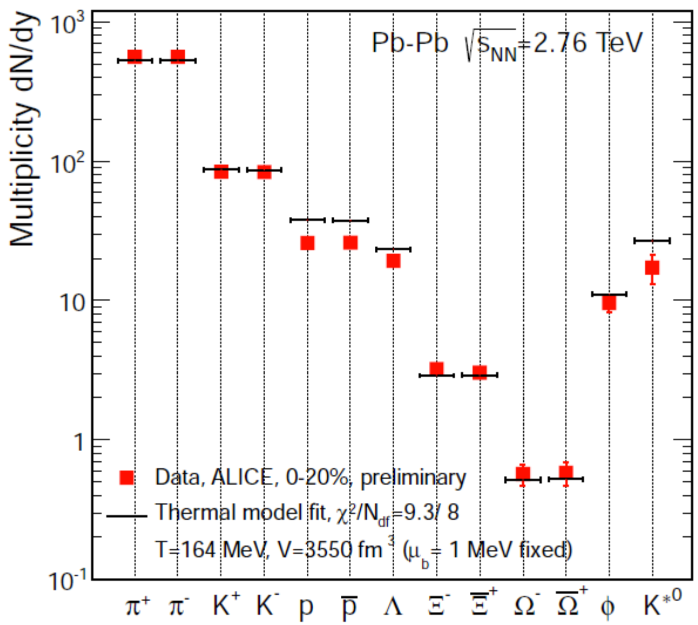

Matter at freeze-out

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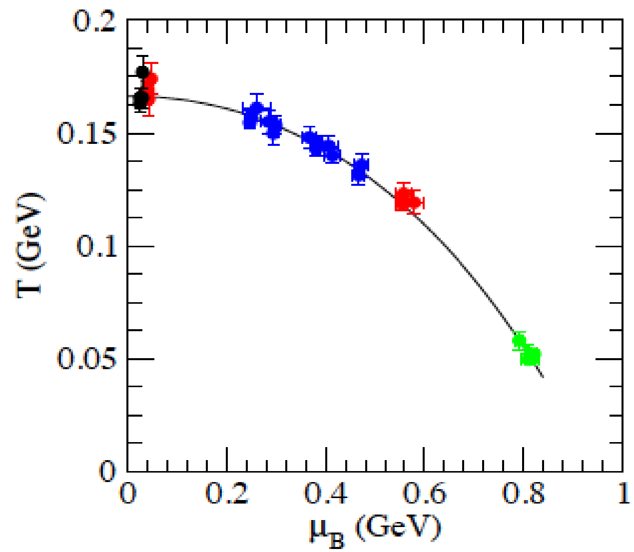
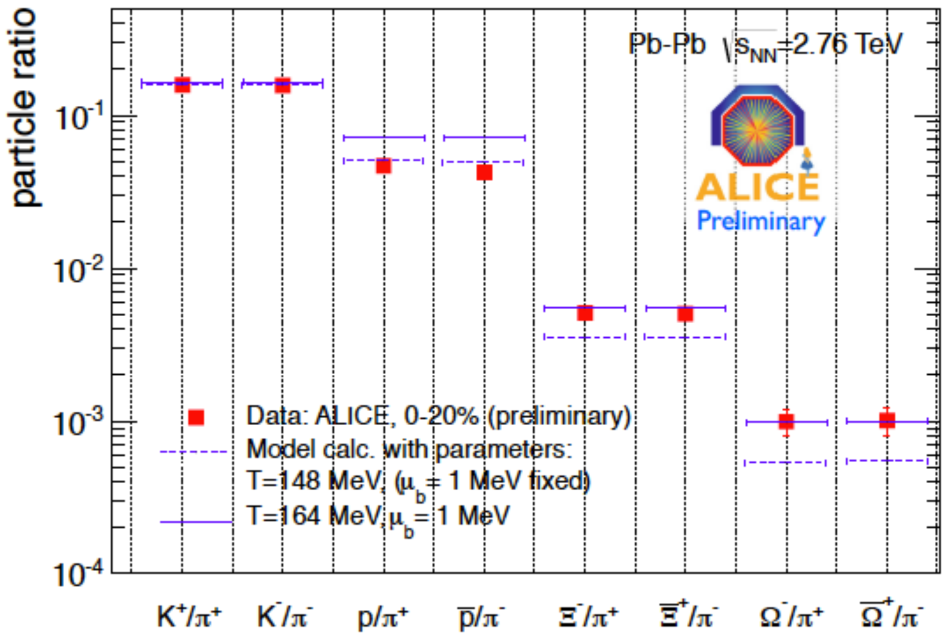
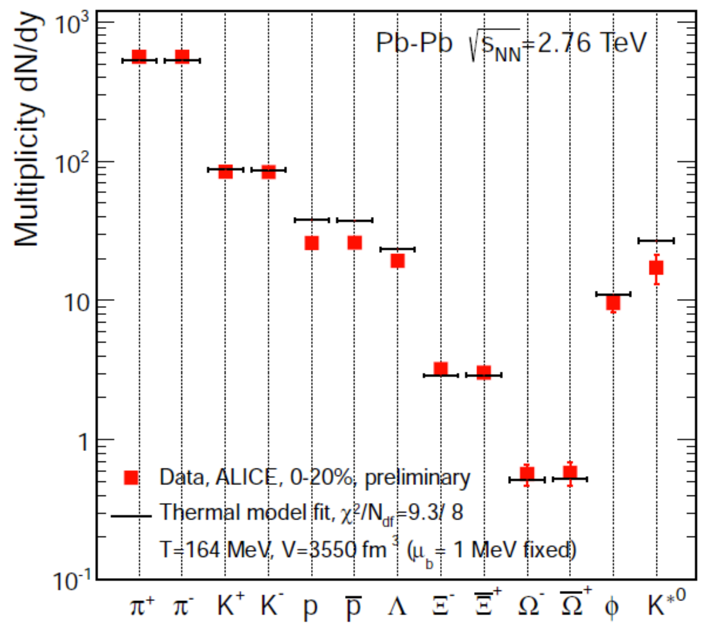


(from J. Cleymans et al, hep-ph/0511094)





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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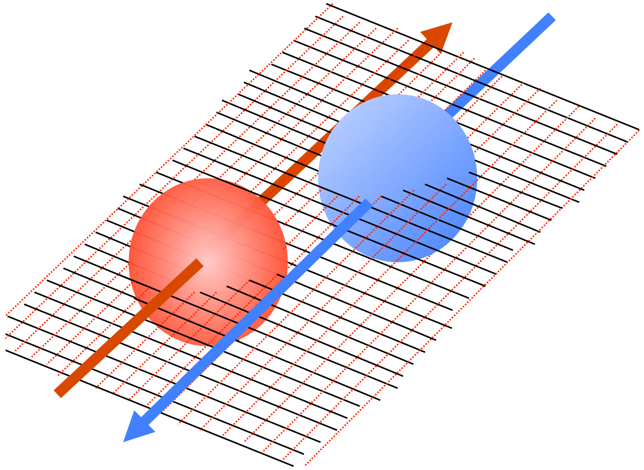

Flow is best seen in azymuthal distributions of produced particles.

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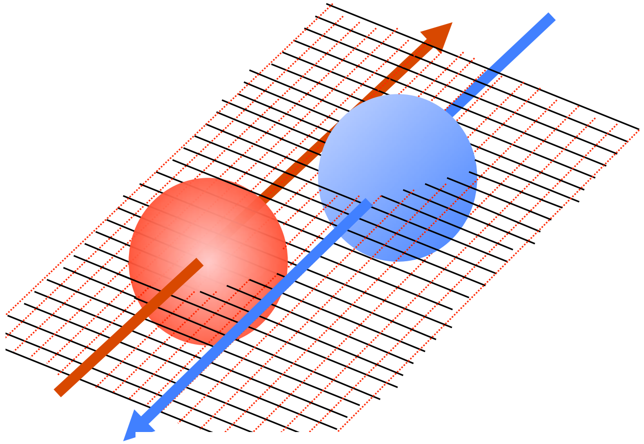

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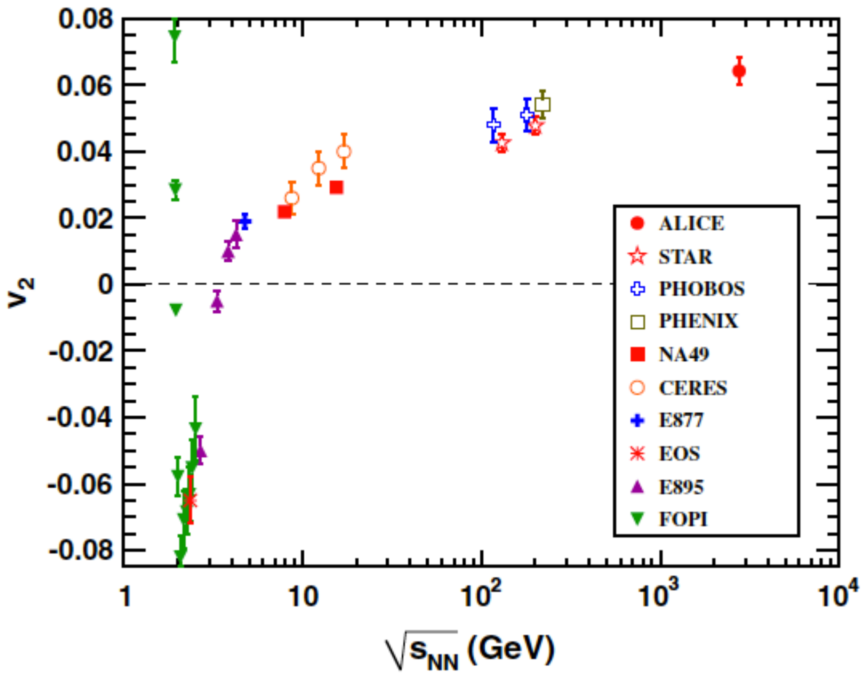
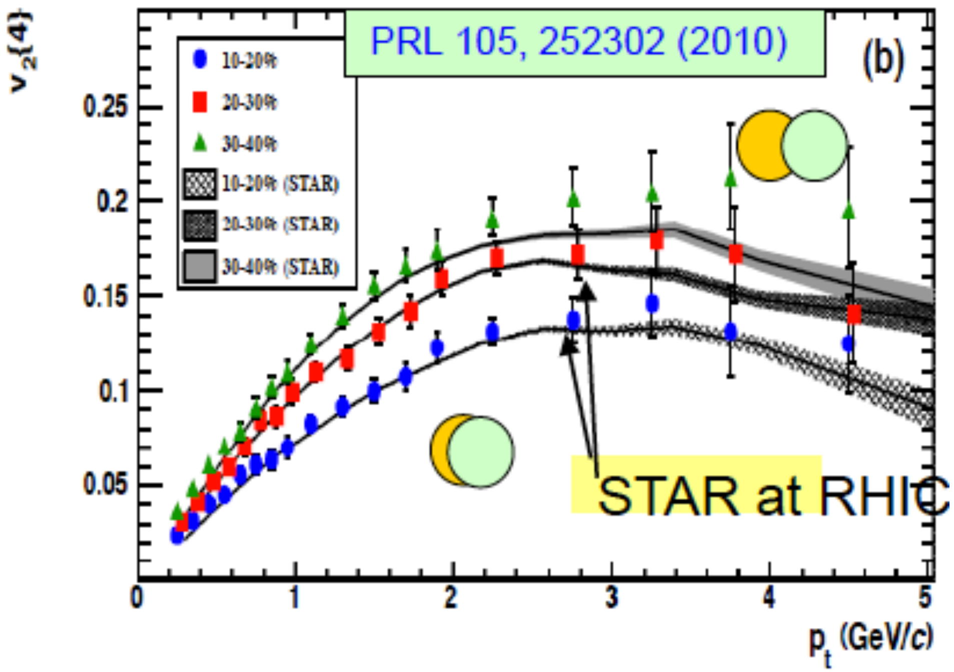
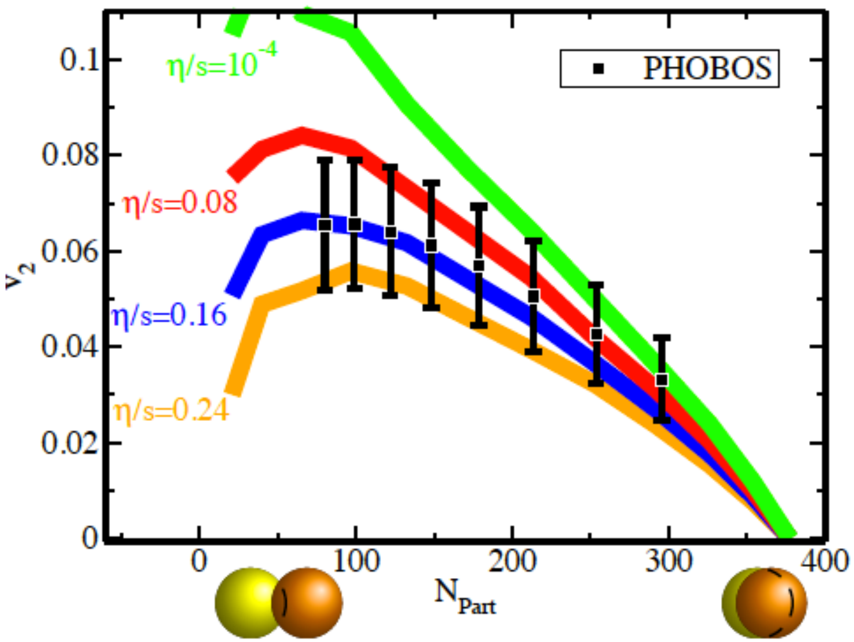




The perfect liquid

The perfect liquid

Viscous corrections are small



(Luzum, Romatschke, 2007)

The perfect liquid

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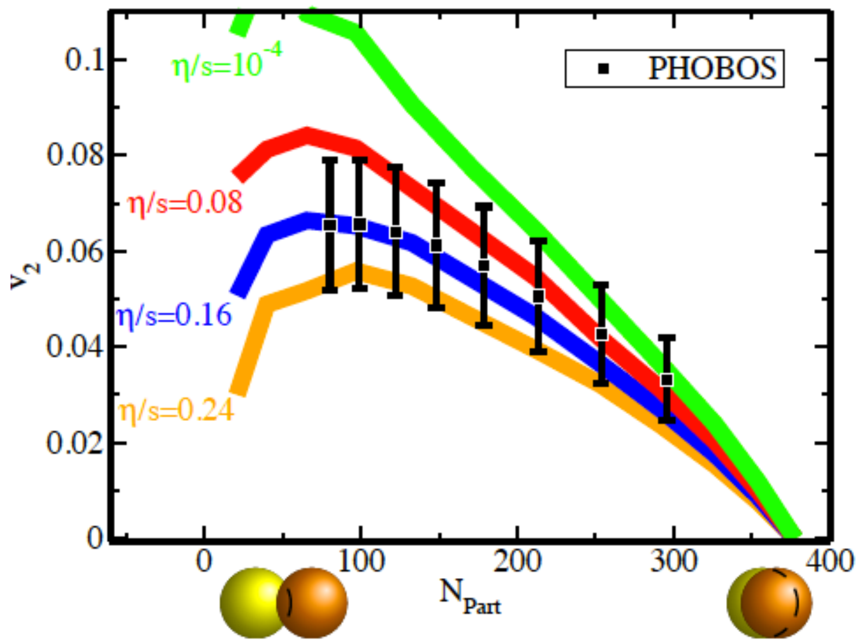

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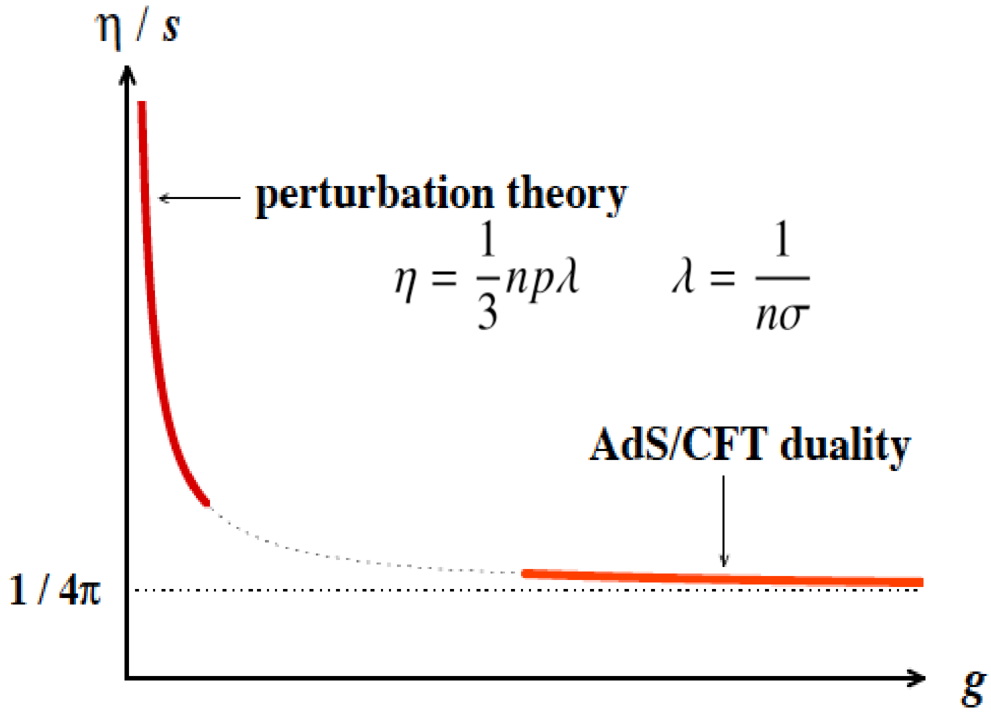
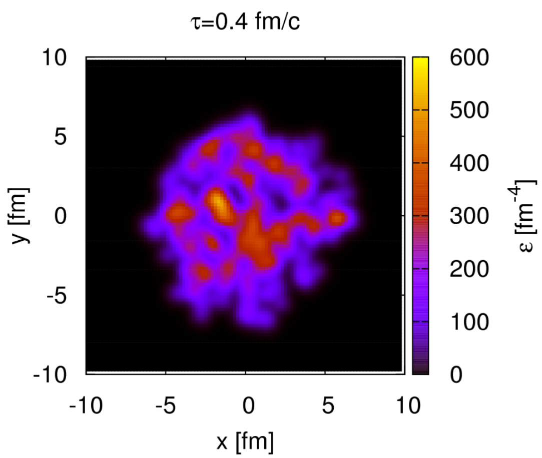


$$\eta = \frac{1}{3} n p \lambda \qquad \lambda = \frac{1}{n\sigma}$$

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

The small value of eta/s suggests a strongly coupled liquid...

The flow is sensitive to initial density fluctuations



$$v_n \sim \epsilon_n$$

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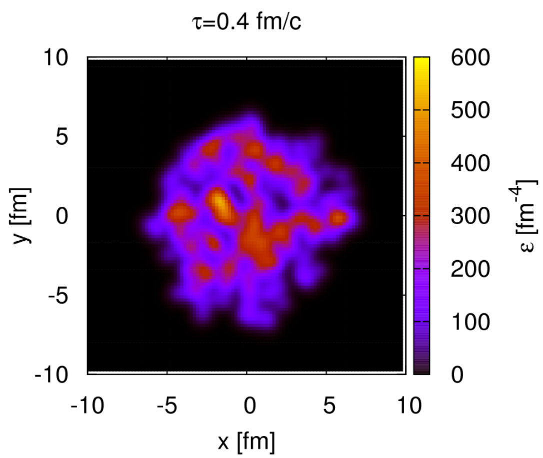

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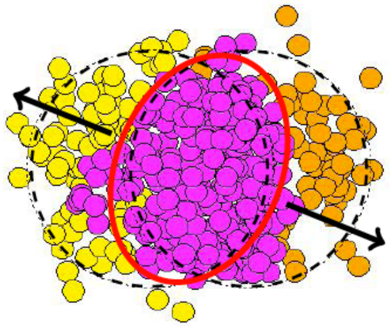

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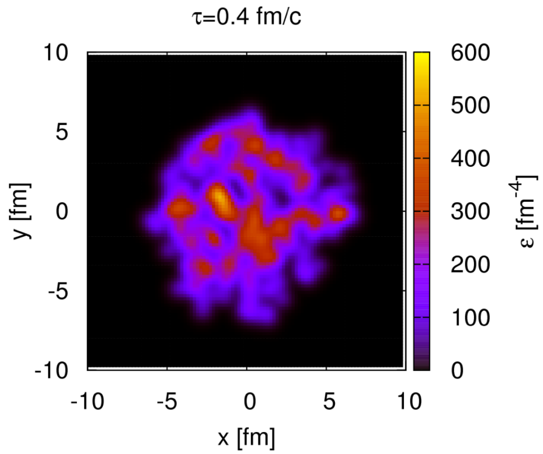

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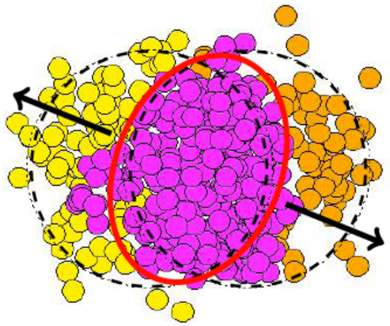

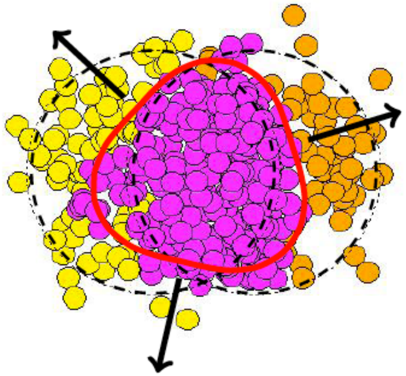

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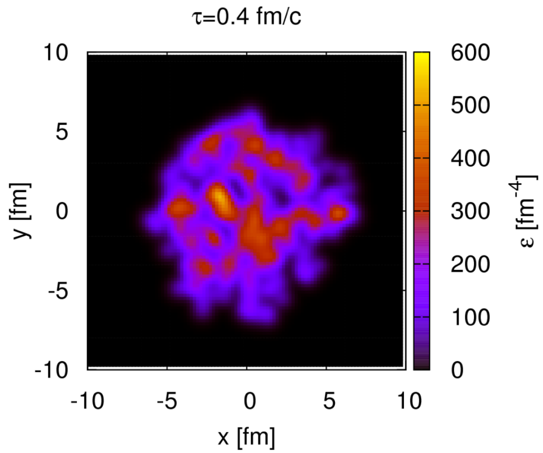

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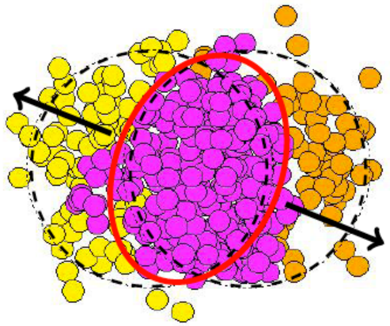
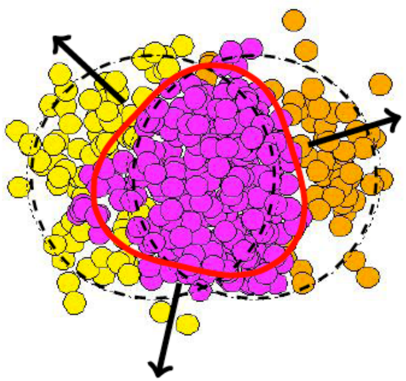
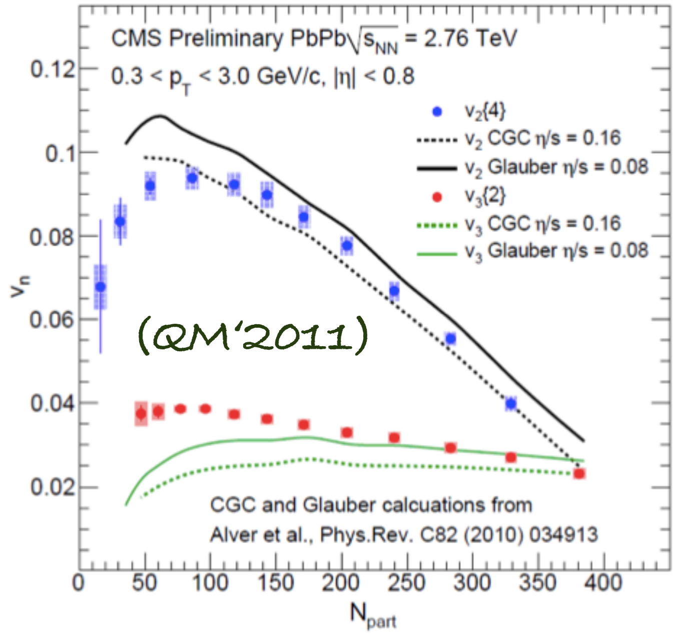
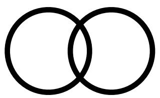
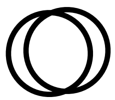




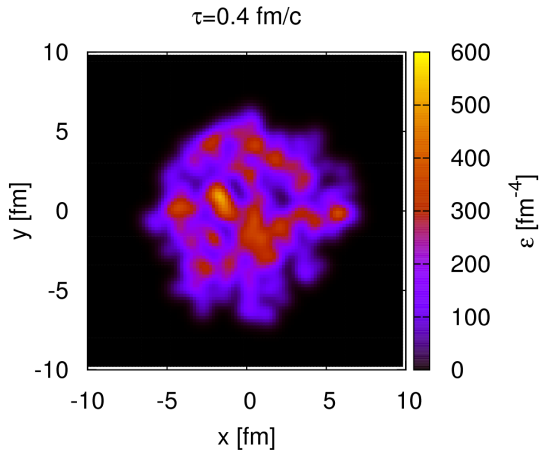




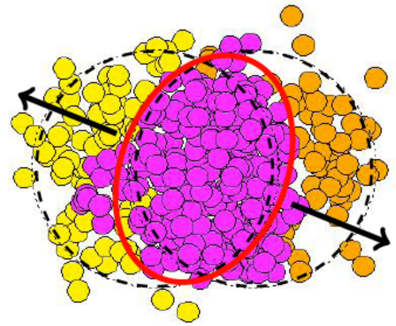


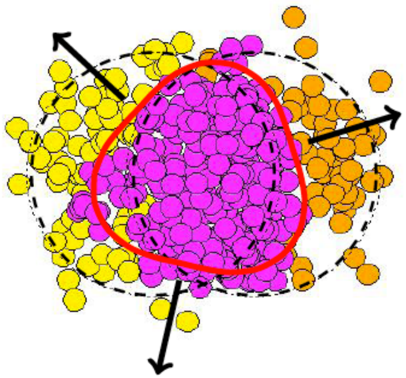
peripheral central

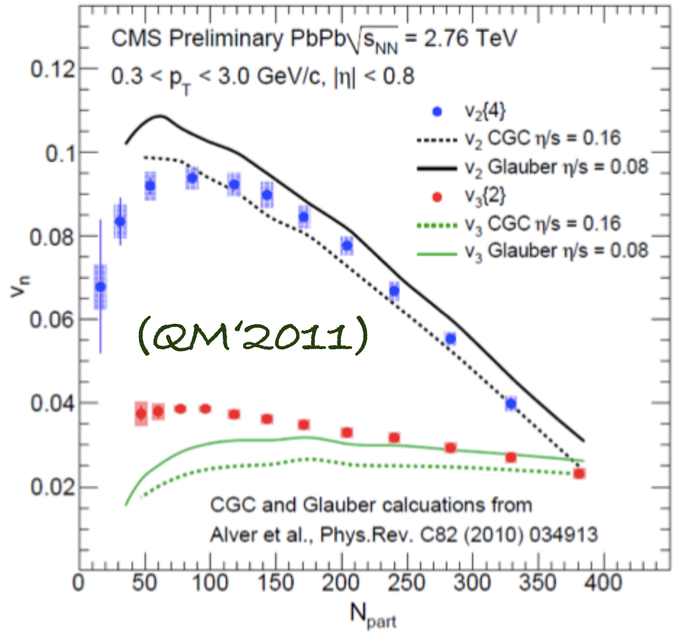
The flow is sensitive to initial density fluctuations

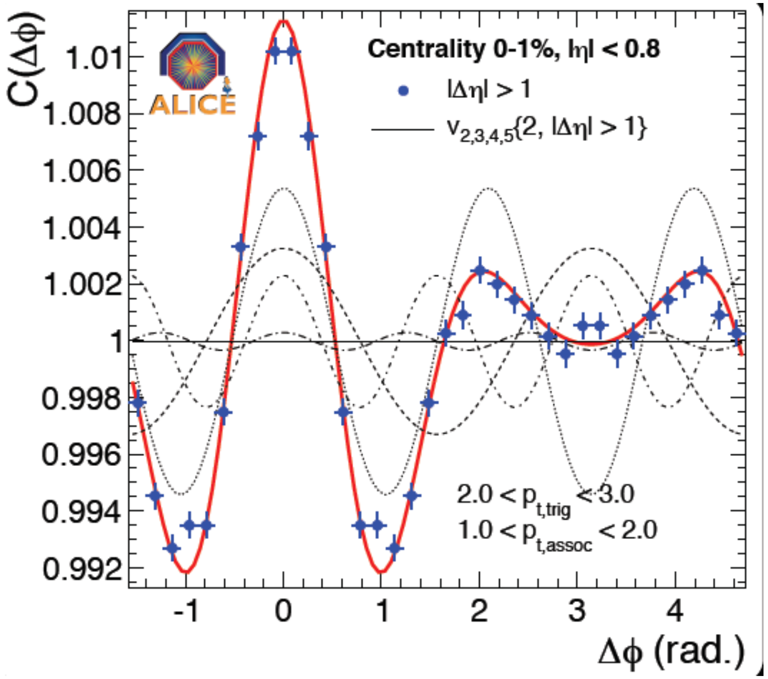


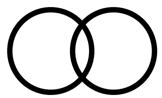
$$v_n \sim \epsilon_n$$



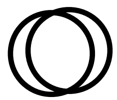






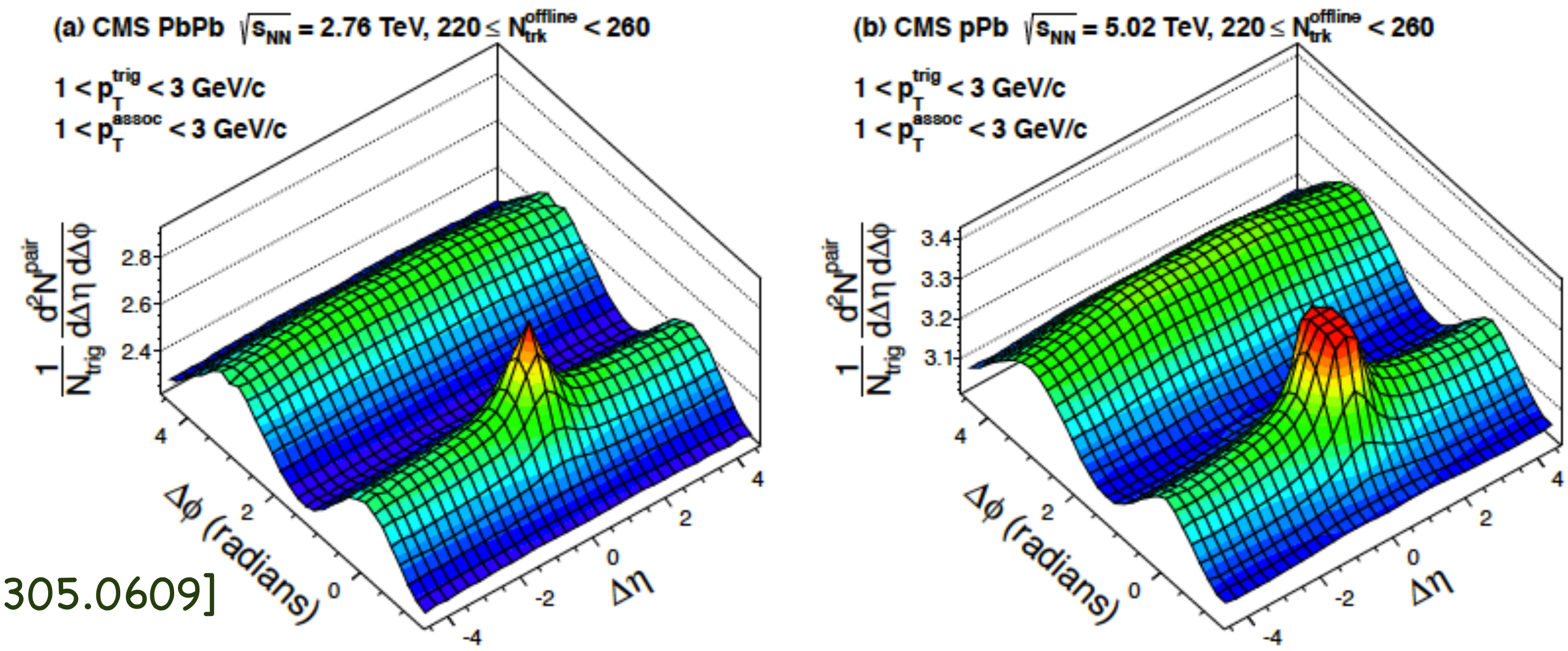


peripheral



central

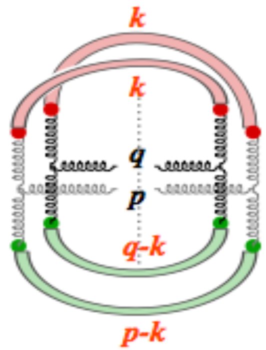
Surprising p-Pb collisions



[arXiv: 1305.0609]

Is it hydrodynamics ?

Or evidence for CGC ?



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

Dusling, Venugopalan:1211.3701

A puzzling situation

A puzzling situation

Where is the apparent strongly coupled character of the QGP coming from ?

Is initial concept wrong ?

Is initial concept wrong ?

No...

QCD asymptotic freedom works !

Is initial concept wrong ?

No…

QCD asymptotic freedom works !

Is the coupling constant large ?

Is initial concept wrong ?

No…

QCD asymptotic freedom works !

Is the coupling constant large ?

Not really !

Is initial concept wrong ?

No...

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Is production of matter in heavy ion collisions compatible with strong coupling?

Is initial concept wrong ?

No...

QCD asymptotic freedom works !

Is the coupling constant large ?

Not really !

Is production of matter in heavy ion collisions compatible with strong coupling?

Not really (?)

- The strongly coupled character of the quark-gluon plasma does not seem related in any obvious way to a large value of the coupling constant.

- Non perturbative features may arise from the cooperation of many degrees of freedom, or strong classical fields.

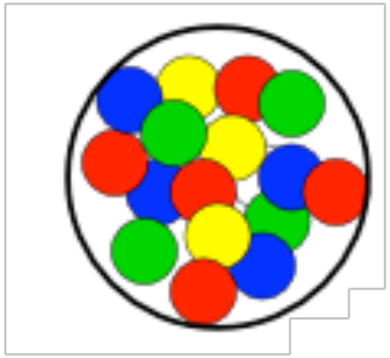
- The quark-gluon plasma is a multiscale system (no ideal plasma, neither weakly nor strongly coupled)

- Transport properties, thermalization remain challenging issues.

Moving backward in time

Nuclei are made of densely packed gluons

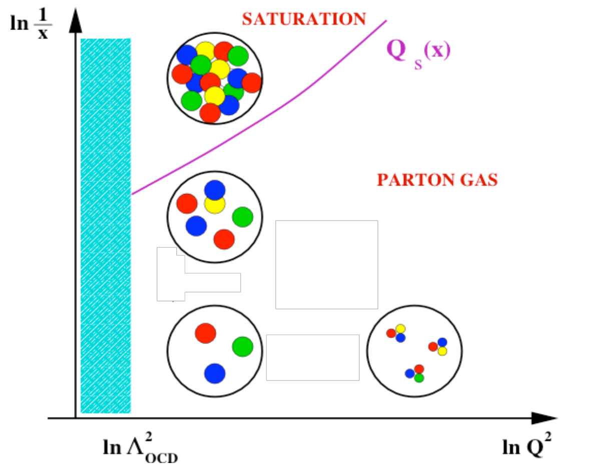
Saturation momentum



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

At saturation, occupation numbers are large

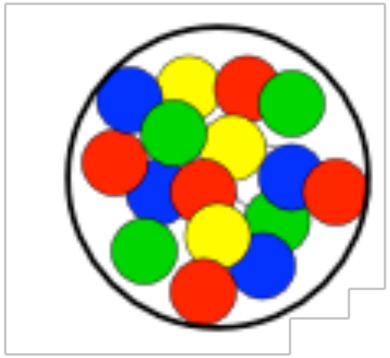
$$\frac{xG(x,Q^2)}{\pi R^2 Q_s^2} \sim \frac{1}{\alpha_s}$$



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

$$\lambda = 0.2 \div 0.3$$

Saturation momentum



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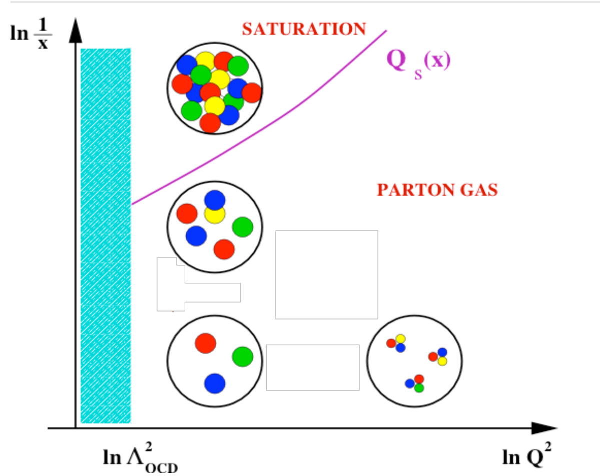

Most partons taking part in collision have $k_T \sim Q_s$

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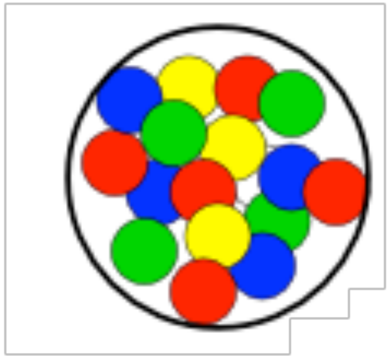

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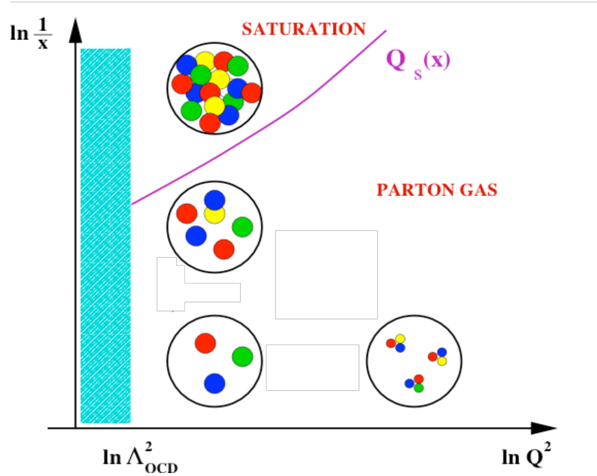
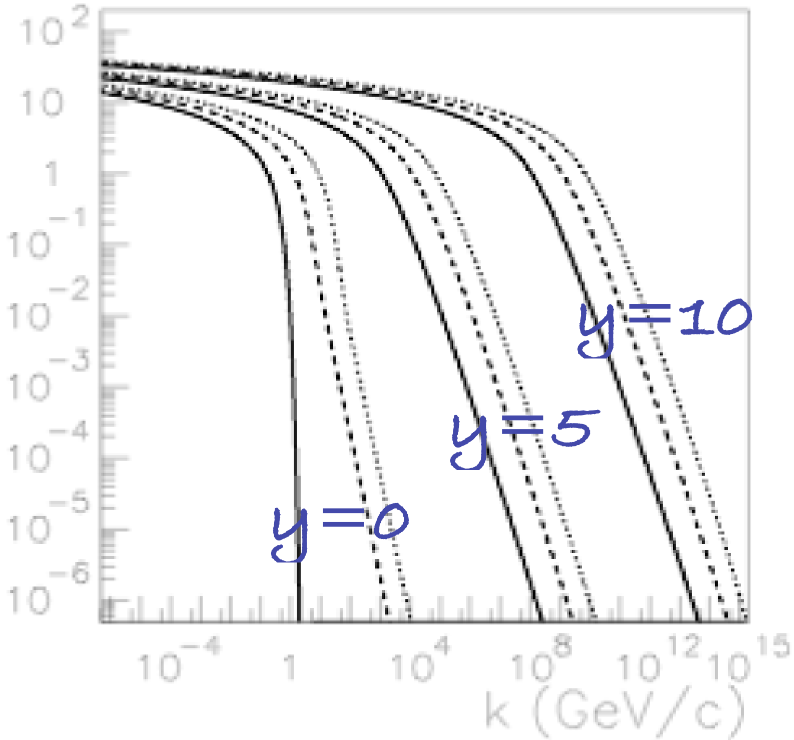


At saturation, occupation numbers are large

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

Most partons taking part in collision have $k_T \sim Q_s$

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

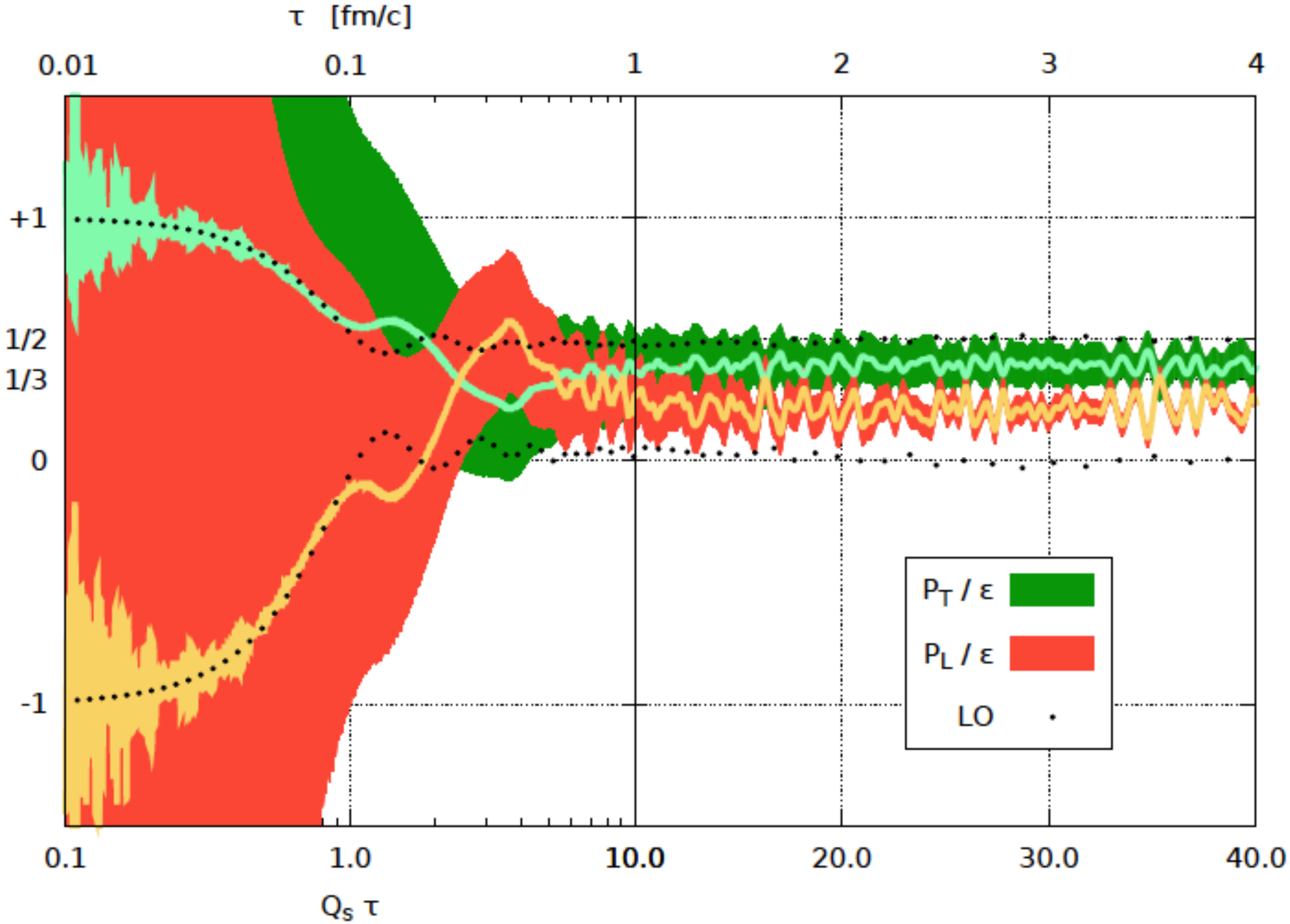


$$Q_s^2(x,A) \simeq Q_0^2\, A^{1/3} \left(\frac{x_0}{x}\right)^\lambda$$

$$\lambda = 0.2 \div 0.3$$

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

Statistical-classical field simulations



T. Epelbaum and F. Gelis, PRL (2013)

Moving backward in time

Signals from the early stages

Hard probes

Hard probes

Hard probes

Hard probes are produced on short space time scales, and their production rate can be calculated from pQCD

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Hard probes are like test particles. The study of their propagation provides much information about the medium in which they propagate.

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Examples of hard probes: heavy quarks, quarkonia, photons, Z and W, jets...

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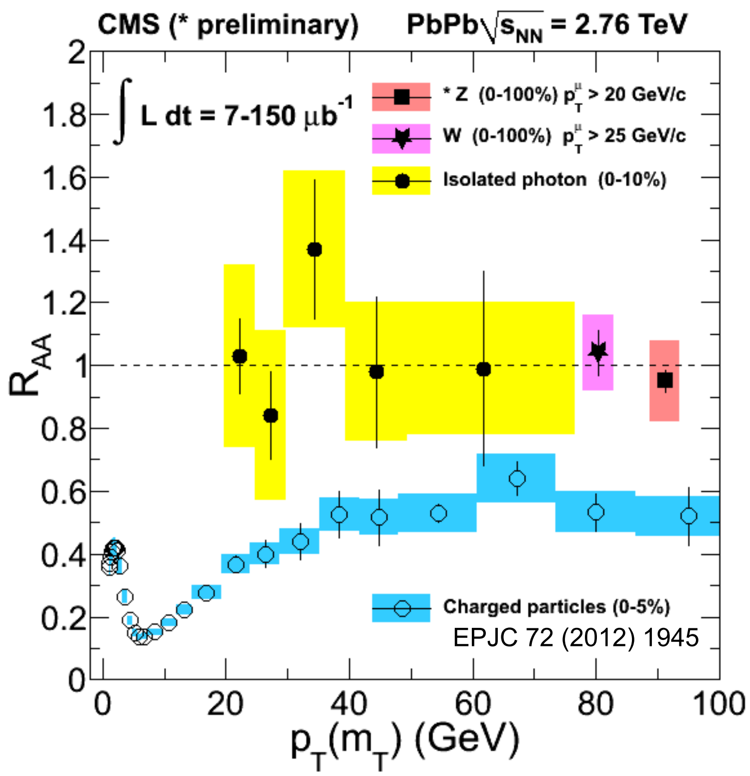
Examples of hard probes: heavy quarks, quarkonia, photons, Z and W, jets...

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.

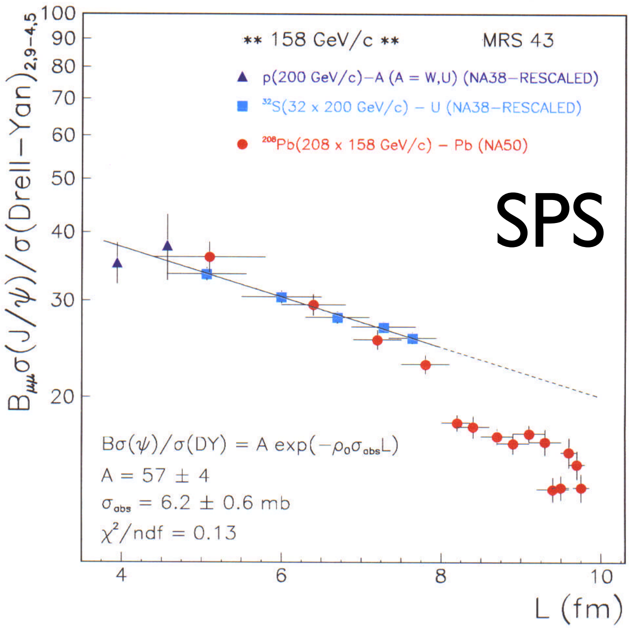
J/Ψ suppression

J/Ψ suppression

A long story....

J/Ψ suppression

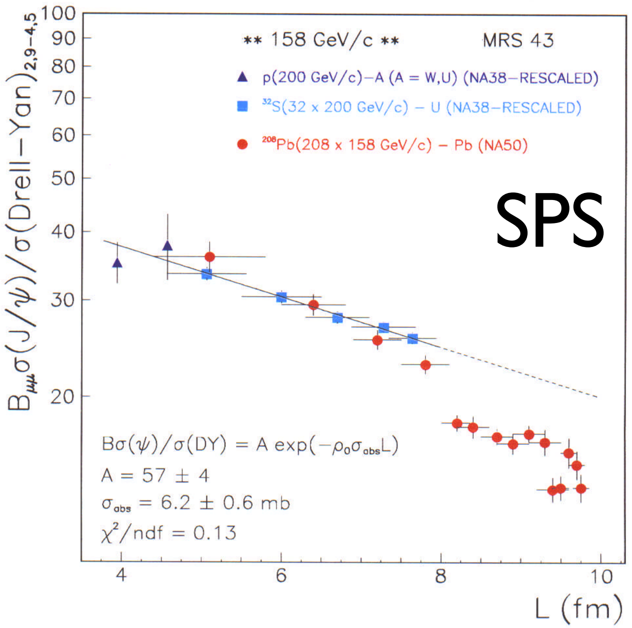
A long story....



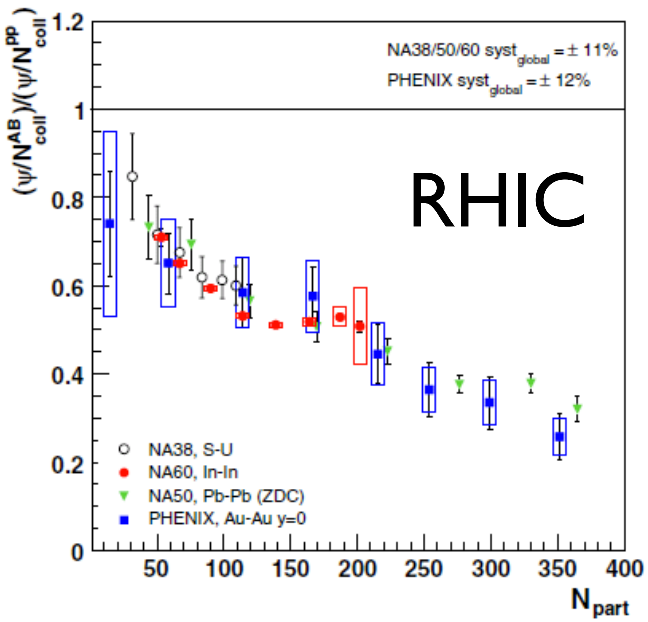
'anomalous' suppression

J/Ψ suppression

A long story....



'anomalous' suppression



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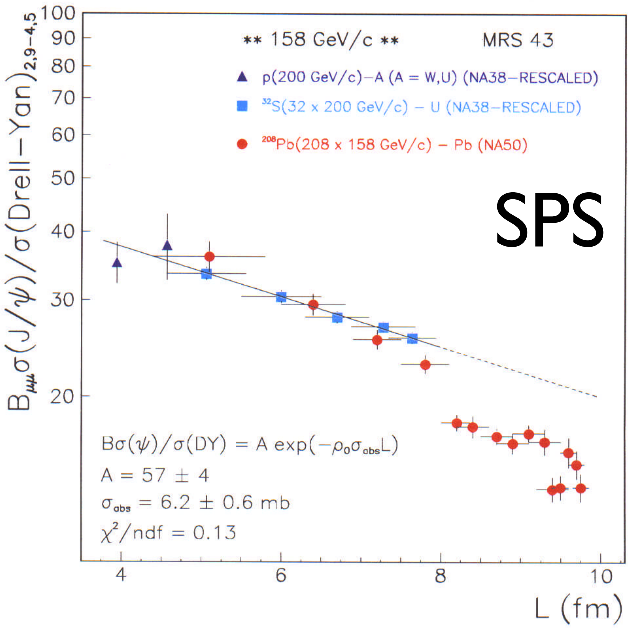

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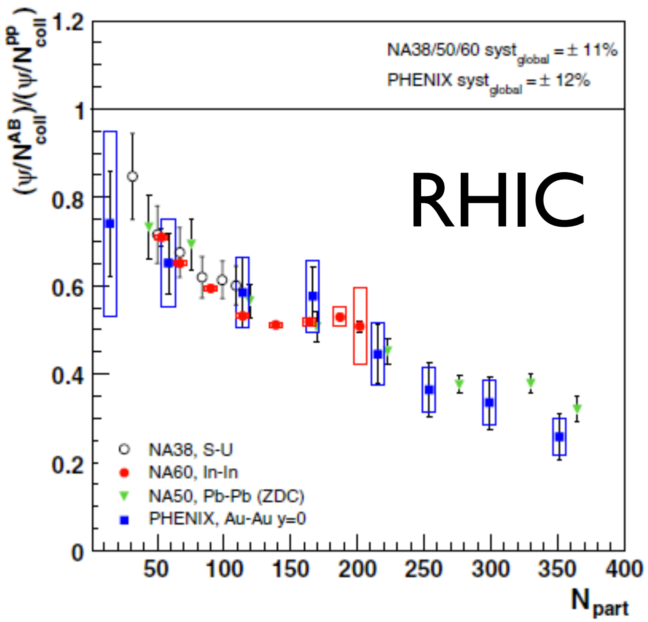
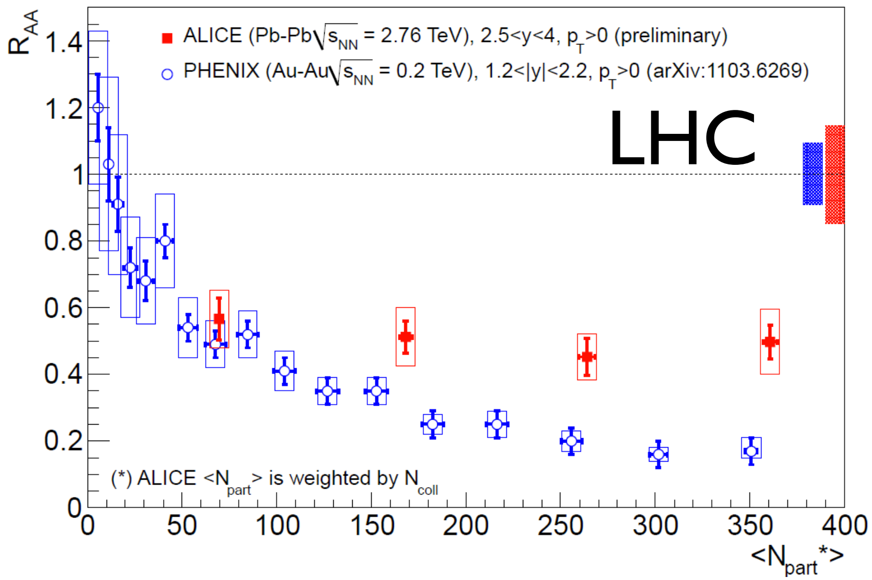
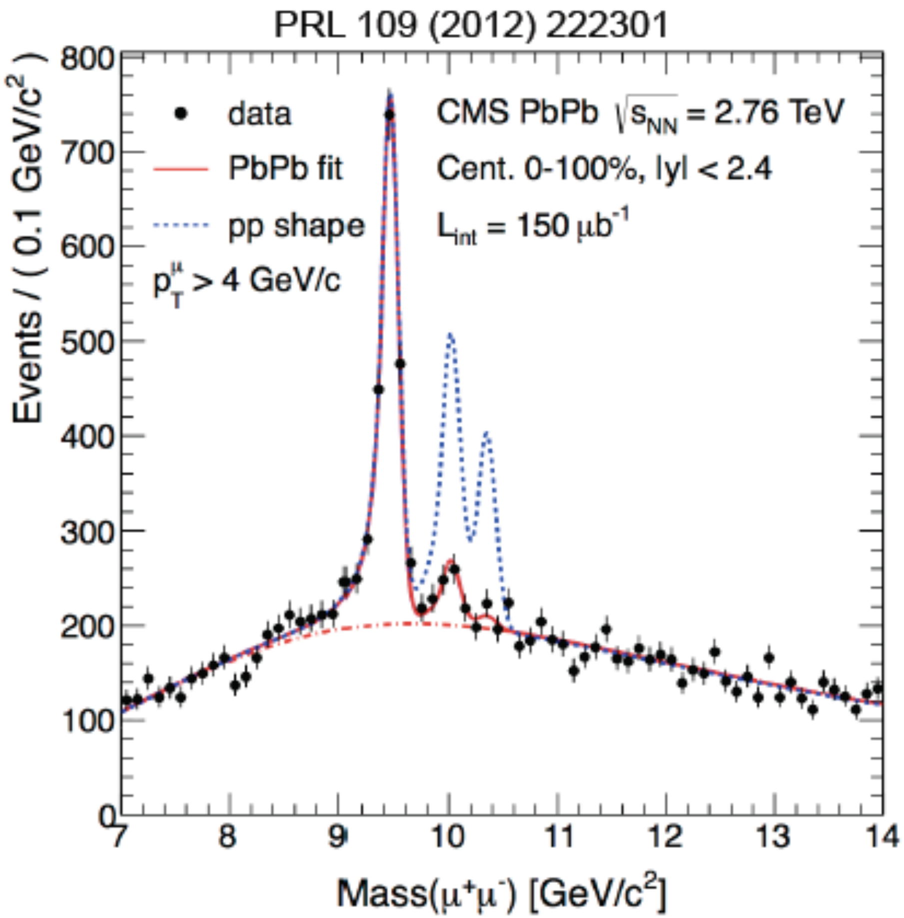




suppression / regeneration

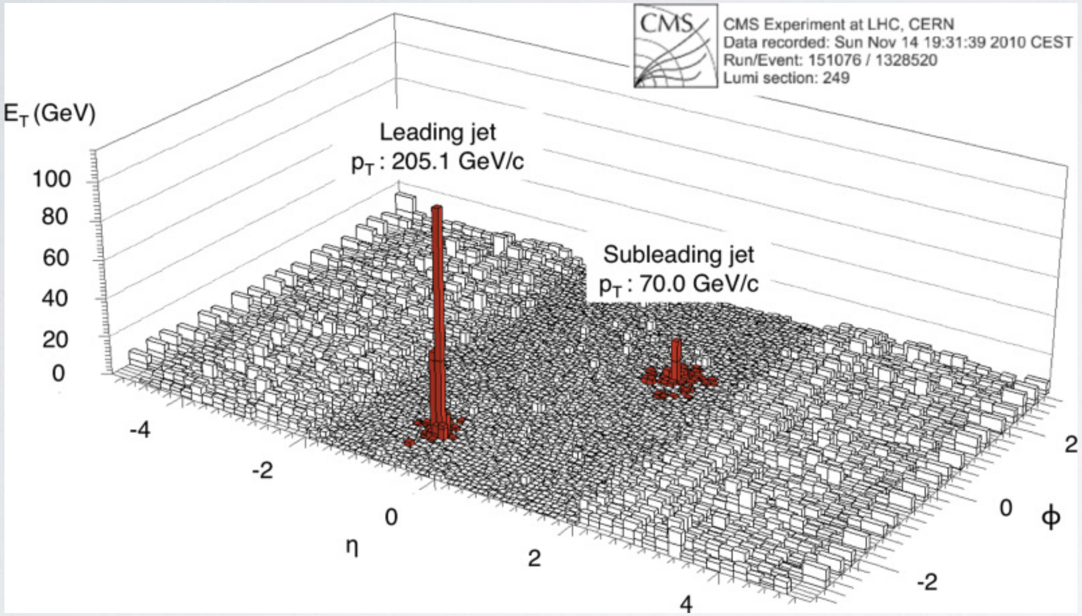
Υ suppression

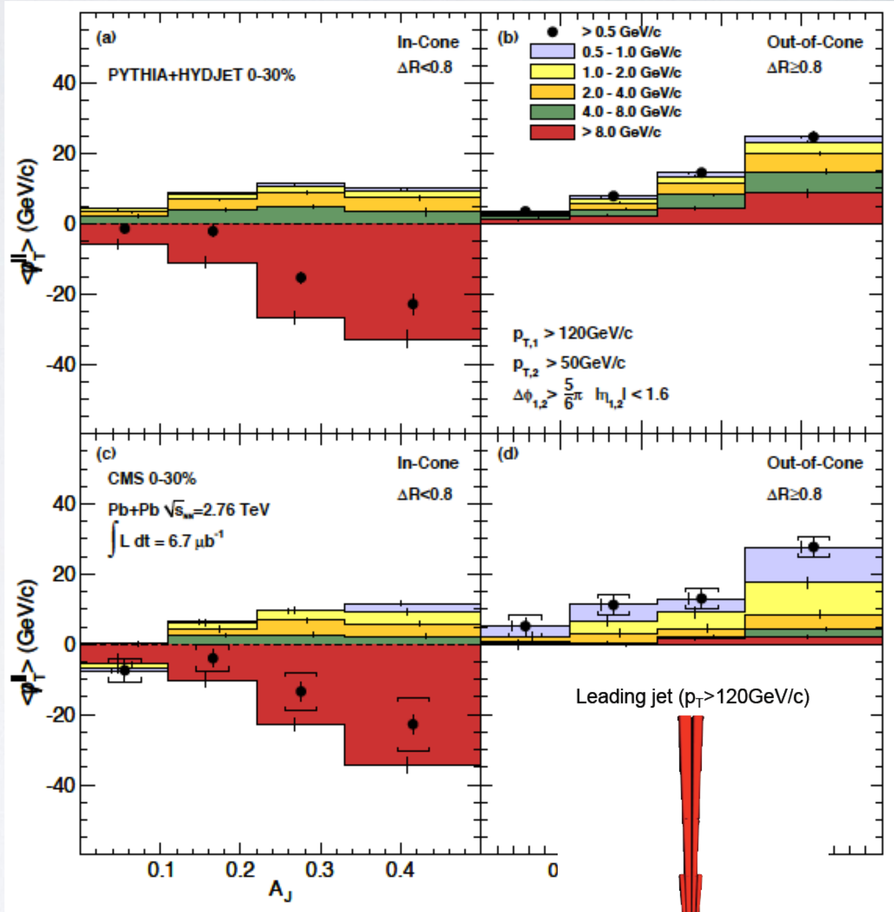


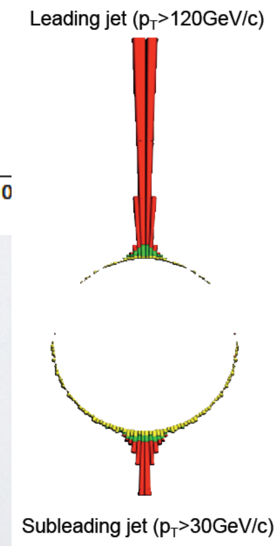
excited states are more 'fragile'....

Di-jet asymmetry

there is more to it than just ‘jet quenching’...





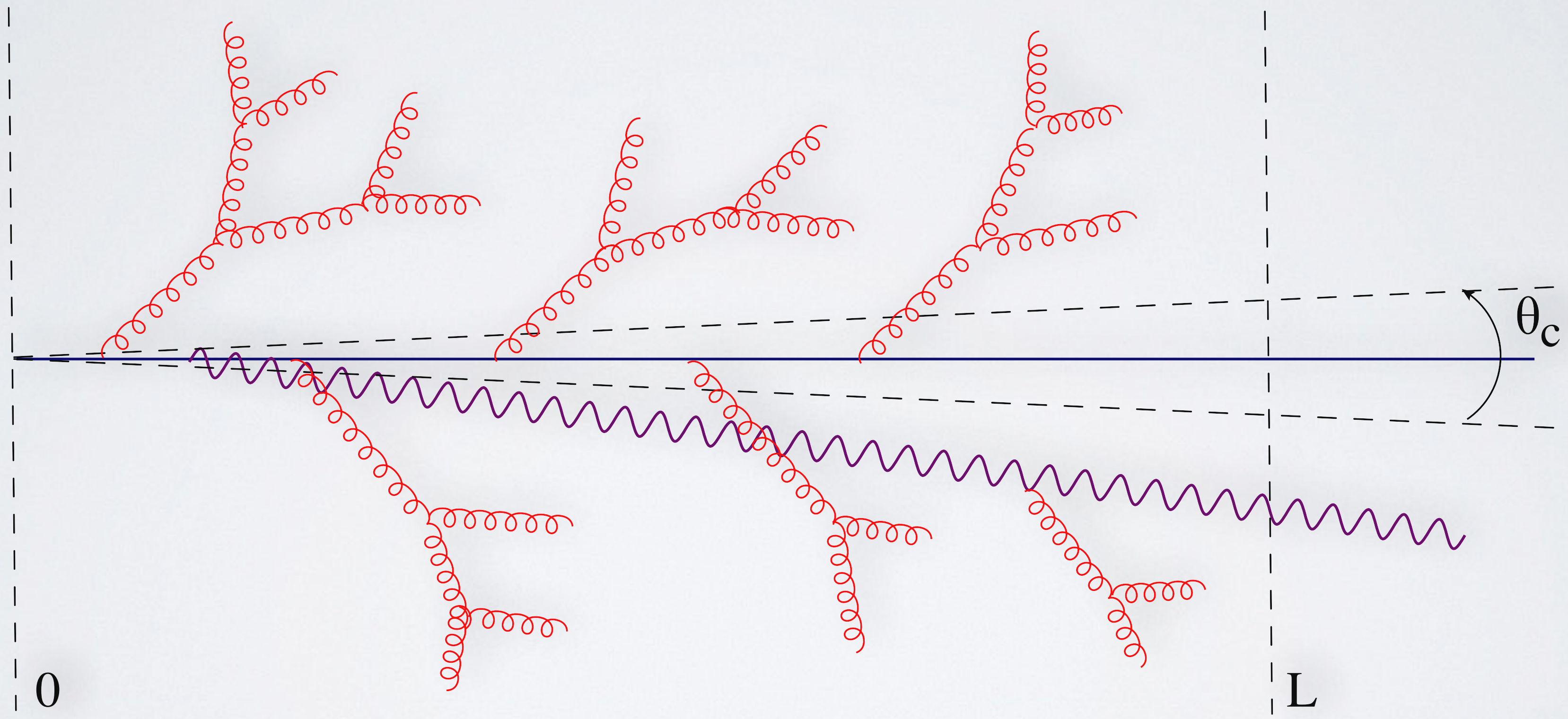


Missing energy is associated with additional **radiation of many soft quanta at large angles**

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

We argue that this reflects a **genuine feature of the in-medium QCD cascade** (JPB, E. Iancu and Y. Mehtar-Tani, arXiv: 1301.6102)

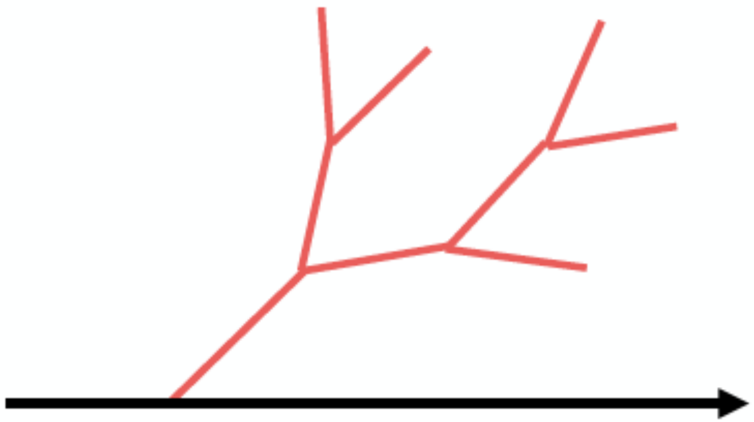
Multiple branchings (de)-coherence in-medium cascade



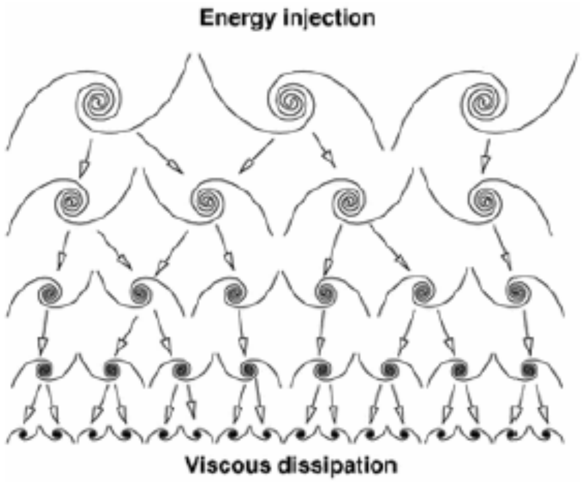
Work done in collaboration with F. Dominguez, E. Iancu and Y. Mehtar-Tani (arXiv:1209.4585, 1301.6102, 1311.5823)

The turbulent in-medium QCD cascade

soft particles / large angle



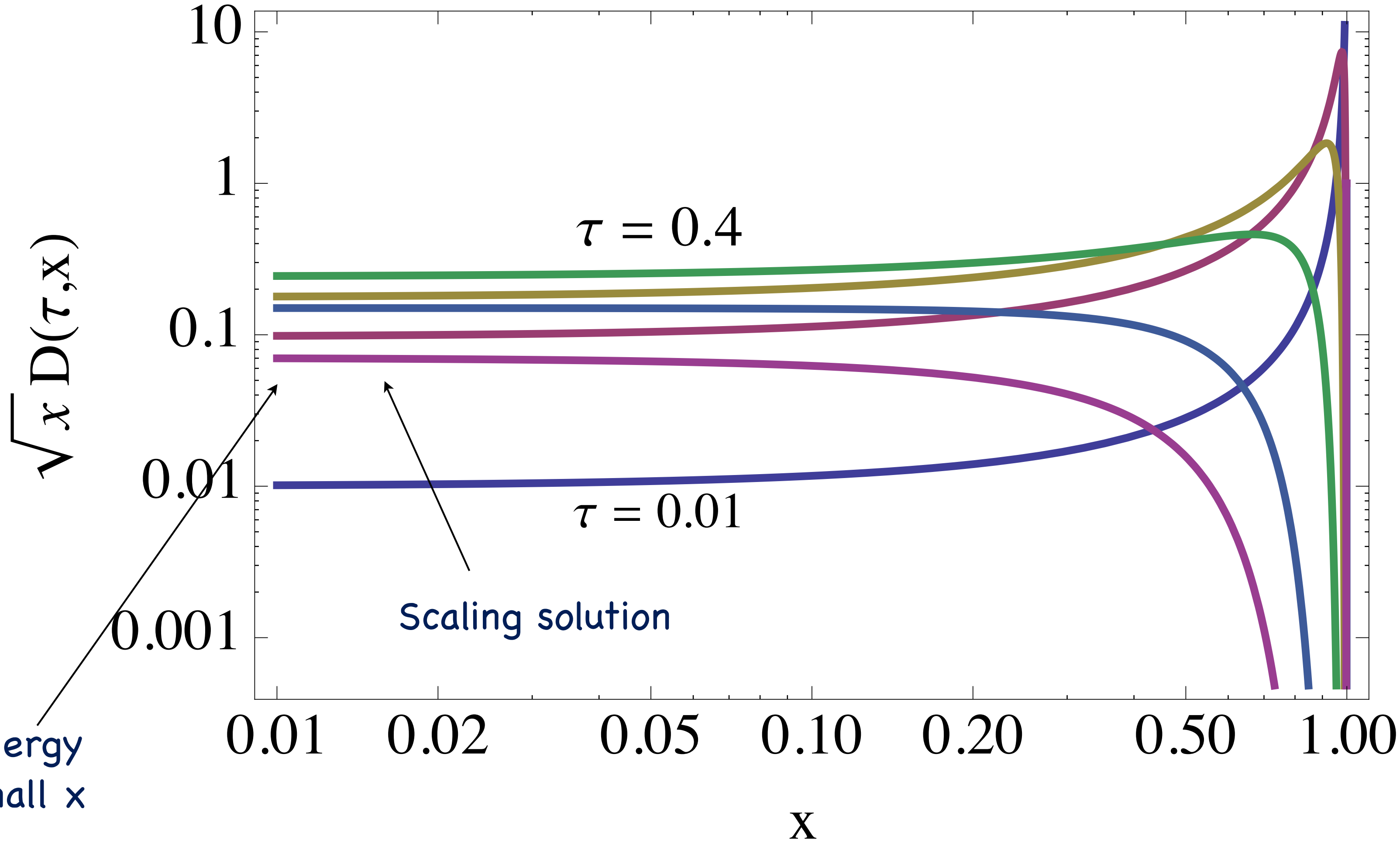
Richardson cascade 1921



Energy flows from large to low frequencies and large angles without accumulating (signature of wave turbulence)

Efficient mechanism for energy transport at large angles

Evolution of the inclusive spectrum



$$\mathcal{E}_{\rm flow} = E\frac{\upsilon\tau^2}{2} = \frac{\upsilon}{2}\,\bar{\alpha}^2\omega_c \qquad \omega_c \equiv \frac{\hat{q}L^2}{2} \qquad \upsilon \simeq 5$$

Estimate $\hat{q} = 1\,\mathrm{GeV}^2/\mathrm{fm}$ $\quad \omega_c \simeq 40$ Gev $\quad \bar{\alpha}^2 \simeq 0.1 \quad \mathcal{E}_{\rm flow} \simeq 15\ \mathrm{GeV}$

$L = 4$ fm

J.-P. B., E. Iancu, Y. Mehtar-Tani, arXiv: 1301.6102

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The field has never been so exciting as now !