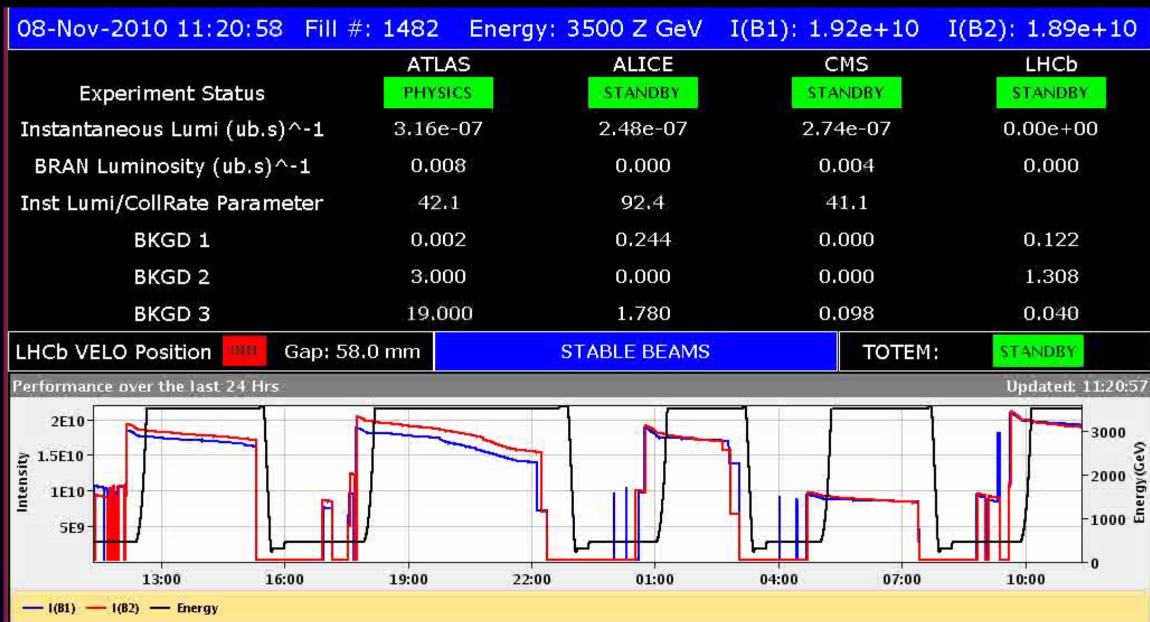
From Heavy Ions to Quark Matter

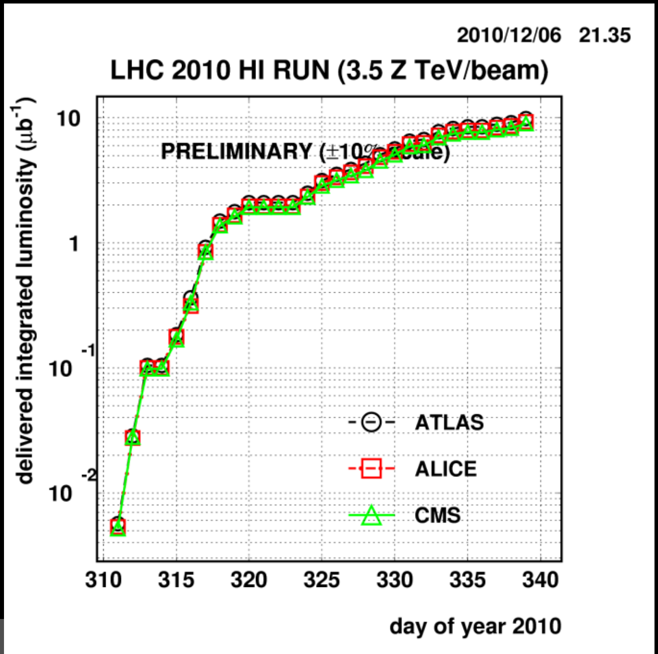
Episode 1

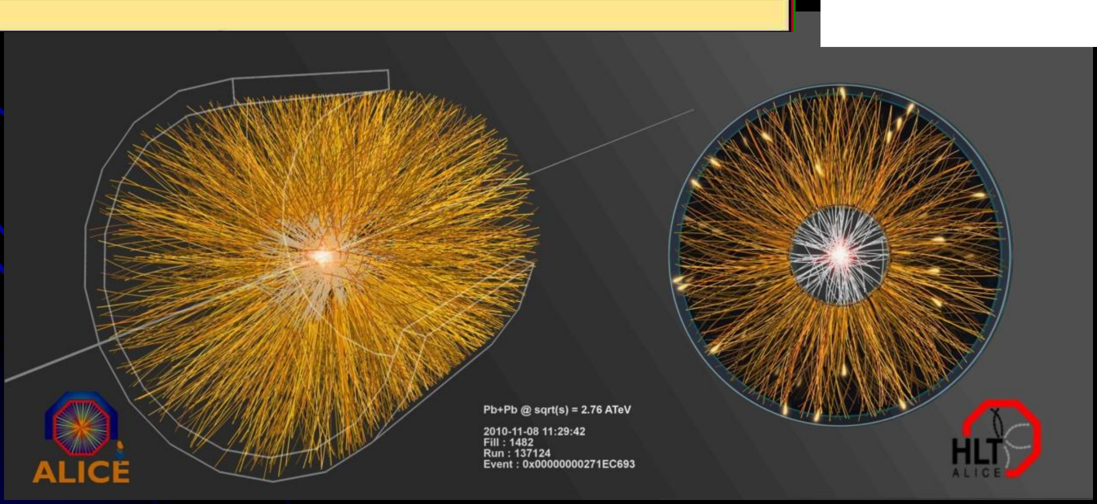
Federico Antinori
(INFN Padova, Italy & CERN, Geneva, Switzerland)

A-A collisions in the LHC!

- 8 November 2010: the beginning of a new era for Heavy Ion Physics







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- Introduction
  - two puzzles in QCD
  - confinement and deconfinement (an "intuitive" view)
  - Nucleus-Nucleus collisions
- Bulk observables: multiplicity & volume
- Strangeness enhancement
- Particle correlations
- High-p_T suppression
- Quark number scaling
- Identified particles
- Quarkonia
- Jets
- Heavy Flavours
- Conclusions

Two puzzles in QCD

The Standard Model and QCD

FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b beauty	4.3	−1/3

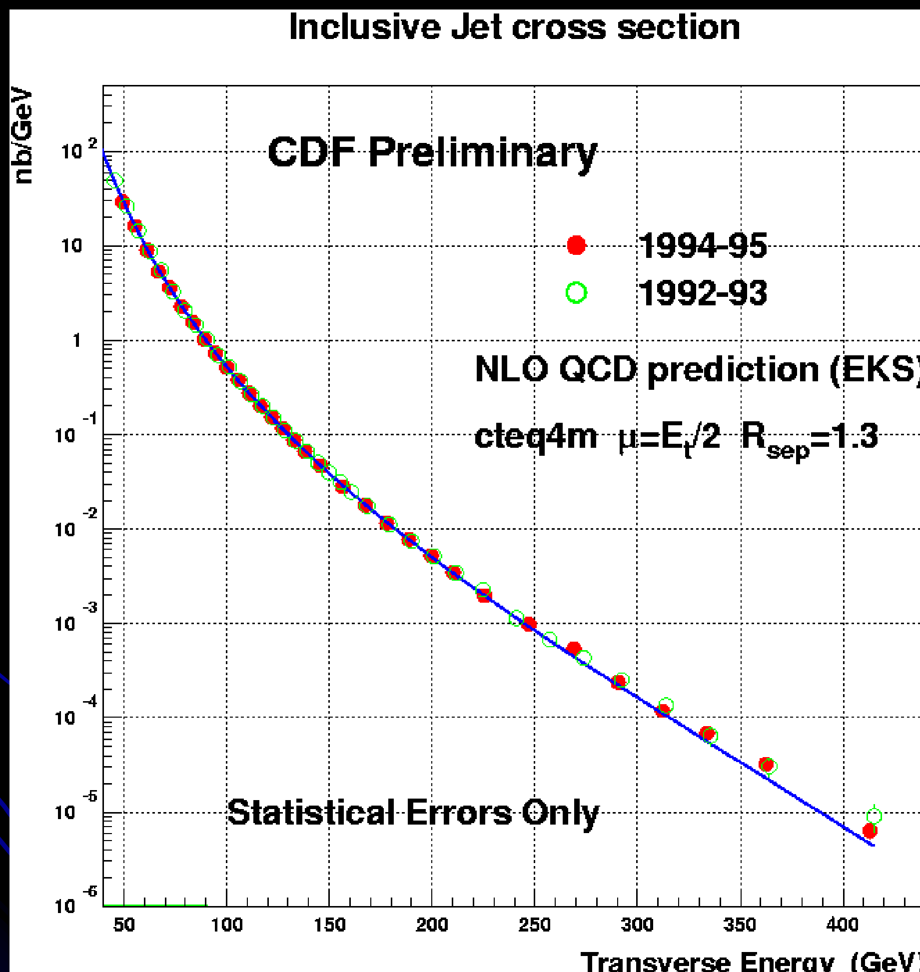
BOSONS
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W$^-$	80.4	−1
W$^+$	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

- strong interaction:
  - binds quarks into hadrons
  - binds nucleons into nuclei
- described by QCD:
  - interaction between particles carrying colour charge (quarks, gluons)
  - mediated by strong force carriers (gluons)
- very successful theory

- e.g.: pQCD vs production of high energy jets



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- very successful theory
  - jet production
  - particle production at high p_T
  - heavy flavour production
  - …
- … but with outstanding puzzles

Two puzzles in QCD: i) hadron masses

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- A proton is thought to be made of two u and one d quarks
- The sum of their masses is around 12 MeV
- ... but the proton mass is 938 MeV!
- how is the extra mass generated?

Two puzzles in QCD: ii) confinement

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- Nobody ever succeeded in detecting an isolated quark
- Quarks seem to be permanently confined within protons, neutrons, pions and other hadrons.
- It looks like one half of the fundamental fermions are not directly observable…

  how does this come about?

Confinement and deconfinement

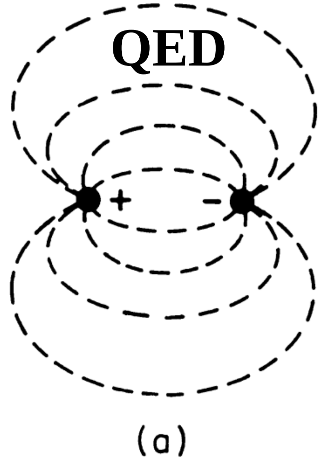
(an "intuitive" view)

Confinement

- At scales of the order of the hadron size (~ 1 fm) perturbative methods lose validity
- Calculations rely on approximate methods (such as lattice theory or effective theories)
- There are compelling arguments (but no rigorous proof) that the non-abelian nature of QCD is responsible for the confinement of colour

[see e.g. Gottfried-Weisskopf, p. 99]

Confining potential in QCD



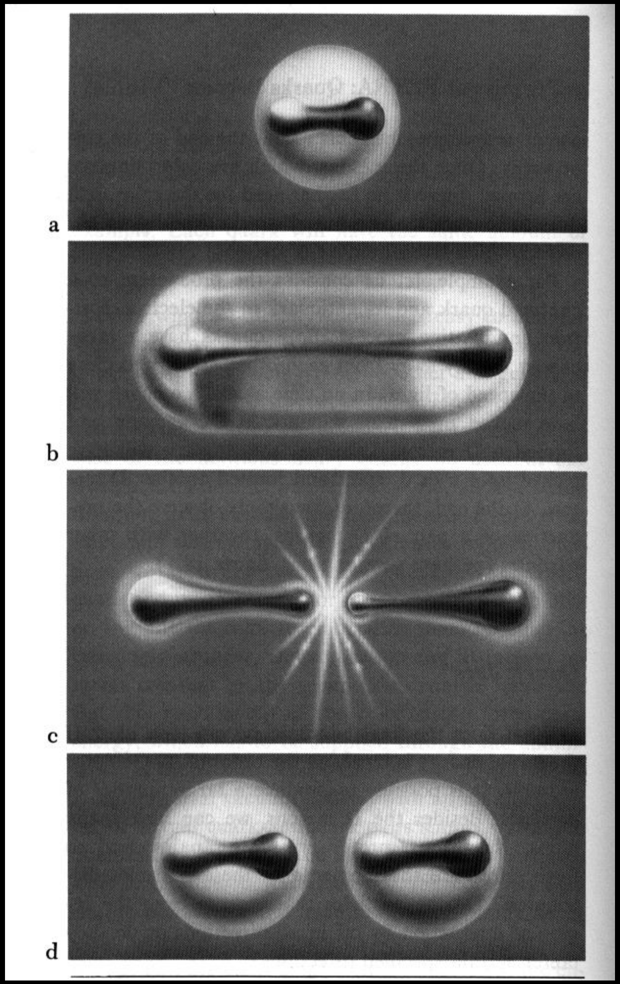
- In QCD, the field lines are compressed into a "flux tube" (or "string") of constant cross-section (~fm^2), leading to a long-distance potential which grows linearly with *r*:

$$V_{long} = kr$$

with k ~ 1 GeV/fm

String breaking

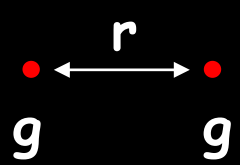
- If one tries to pull the string apart, when the energy stored in the string ($k\,r$) reaches the point where it is energetically favourable to create a $q\bar{q}$ pair, the string breaks…
- …and one ends up with two colour-neutral strings (and eventually hadrons)



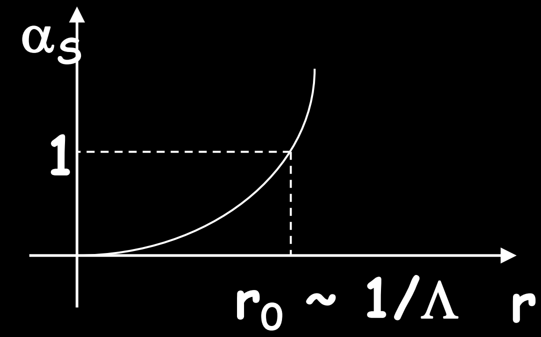
[illustration from Fritzsch]

QCD vacuum

- e.g.: 2 gluons in singlet state at a distance r



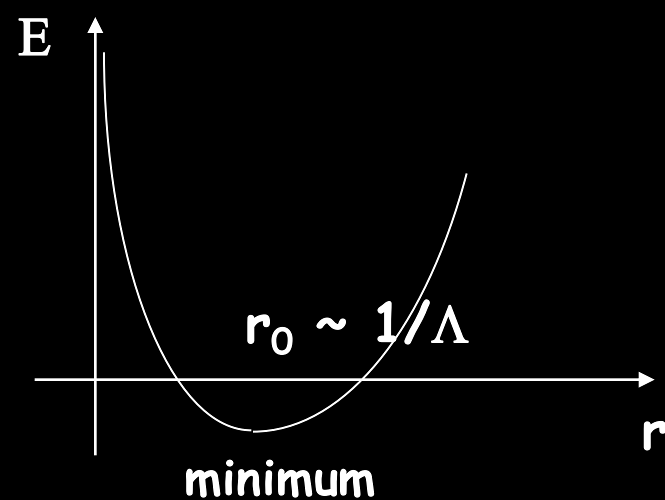
$$\Delta p \Delta r \sim \hbar = 1$$



$$r \sim \frac{1}{p} \sim \frac{1}{E_{KIN}} \quad \rightarrow \quad E_{KIN} \sim \frac{1}{r}$$

$$E = \frac{1}{r} - C\frac{\alpha_S}{r} = \frac{1 - C\alpha_S}{r}$$

$$\begin{array}{ll} r \rightarrow 0 & E \sim \frac{1}{r} \\ r \sim r_0 & E <\sim 0 \\ r \rightarrow \infty & E \sim kr \end{array}$$



QCD vacuum

- The "empty" vacuum is unstable. There is a state of lower energy that consists of cells, each containing a gluon pair in colour- and spin- singlet state. The size of these cells is of order r_0. We may speak of a "liquid" vacuum.

Gottfried-Weisskopf, IV C

Bag Model

- Due to the non-abelian nature of QCD and to the large value of the QCD coupling, the QCD vacuum is a rather complex object, behaving practically as a liquid

- The MIT bag model describes the essential phenomenology of confinement by assuming that quarks are confined within bubbles (bags) of perturbative (= empty) vacuum of radius *R* upon which the QCD vacuum exerts a confining pressure *B*

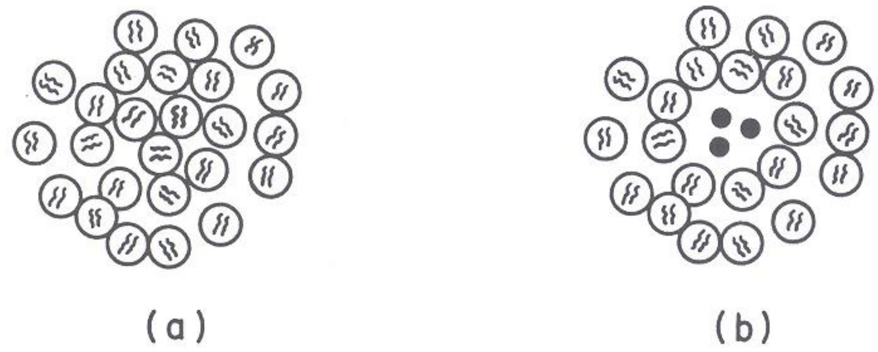


FIG. 9. The QCD vacuum state is depicted in (a). It is a random distribution of cells that contain a gluon pair in a color and spin singlet state. Quarks (in a color singlet configuration) displace these cells, creating a region (or "bag") of "empty" vacuum, as shown in (b).

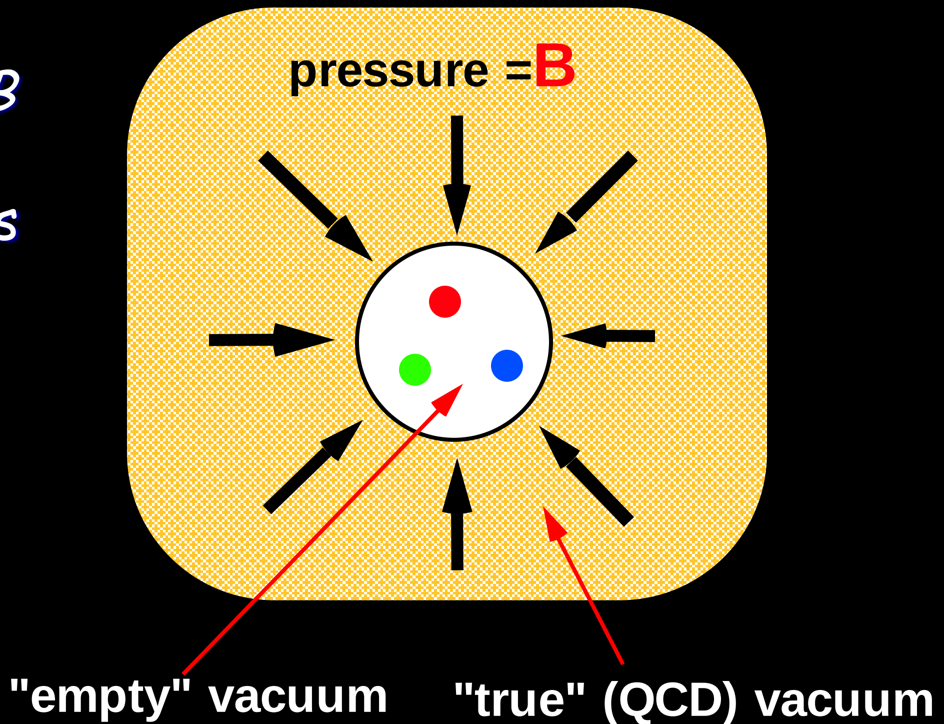
[see e.g. Gottfried-Weisskopf, p. 399]

- The bubble radius *R* is determined by the balance between the vacuum pressure *B* and the outward kinetic pressure exerted by the quarks

- From hadron spectra:

  $B \sim (200\ \text{MeV})^4$

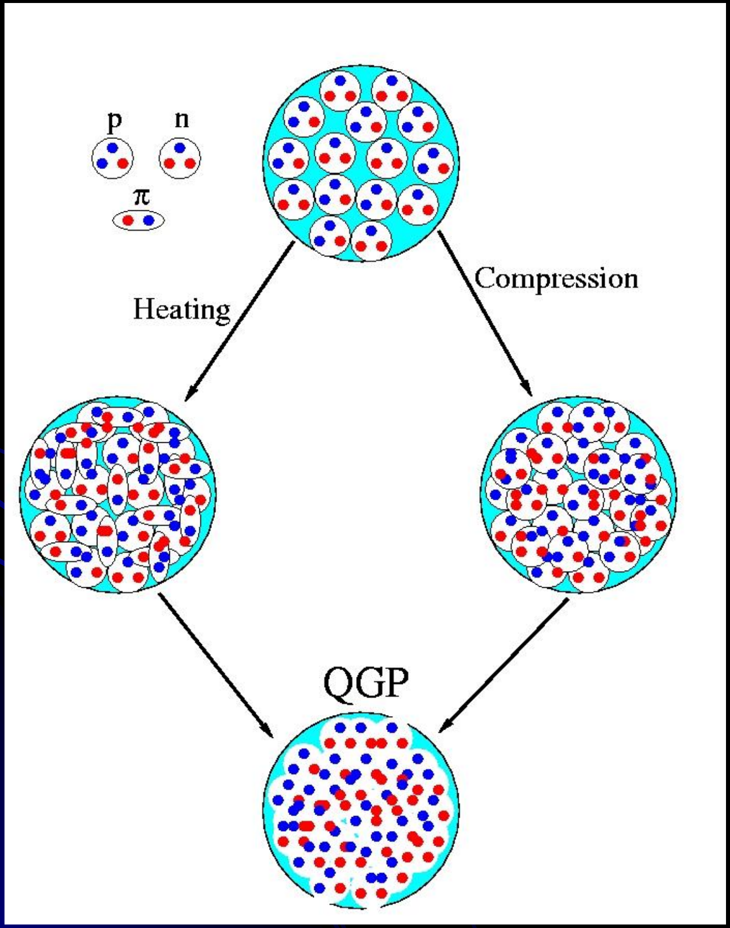
Bag model of a hadron



B = "bag constant" $B^{1/4} \sim$ **200 MeV**

Deconfinement

- What if we compress/heat matter so much that the individual hadrons start to interpenetrate?

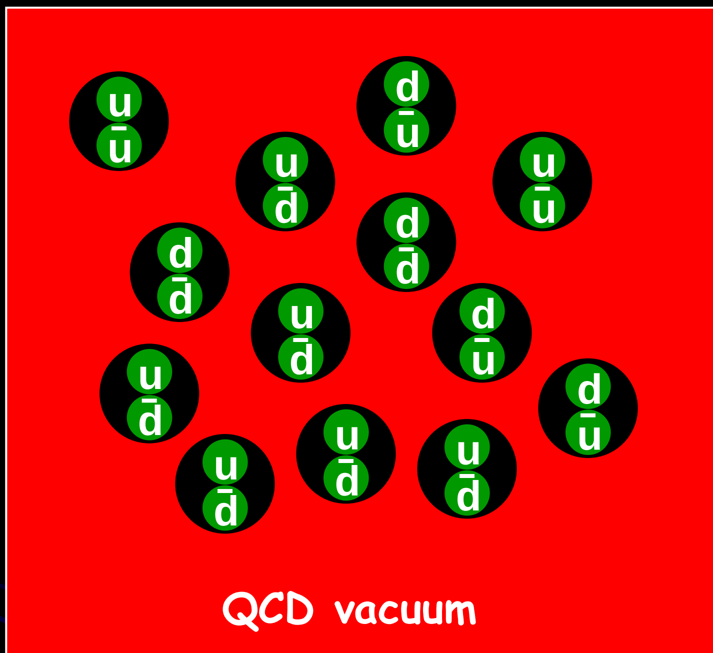


Lattice QCD predicts that if a system of hadrons is brought to sufficiently large density and/or temperature a deconfinement phase transition should occur

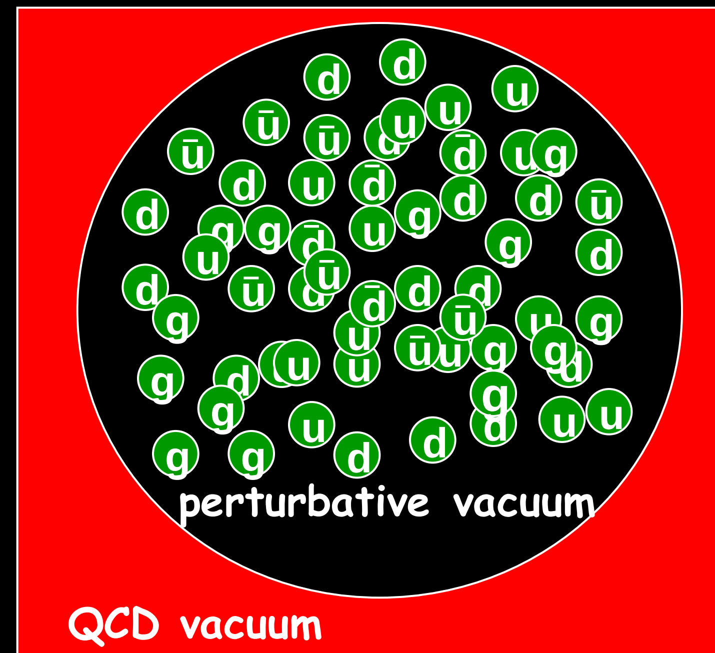
In the new phase, called Quark-Gluon Plasma (QGP), quarks and gluons are no longer confined within individual hadrons, but are free to move around over a larger volume

Deconfinement: a toy model

Hadron (pion) Gas



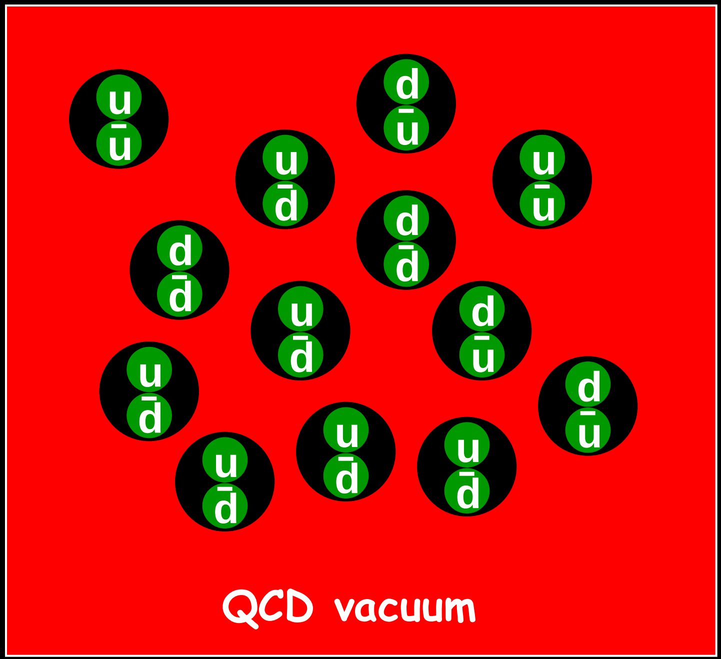
Quark-Gluon Plasma



- Gibbs' criterion: the stable phase is the one with the largest pressure
- From statistical mechanics: (for an ideal gas)

$$p = \frac{\varepsilon}{3} = \left(g_B + \frac{7}{8} g_F \right) \frac{\pi^2 T^4}{90}$$

Hadron (pion) Gas



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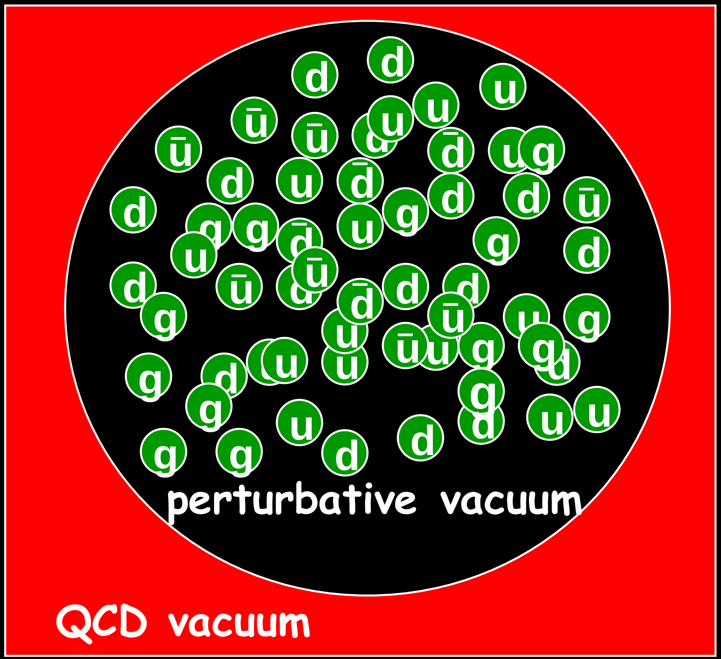


$$g_B = 3 \quad g_F = 0$$

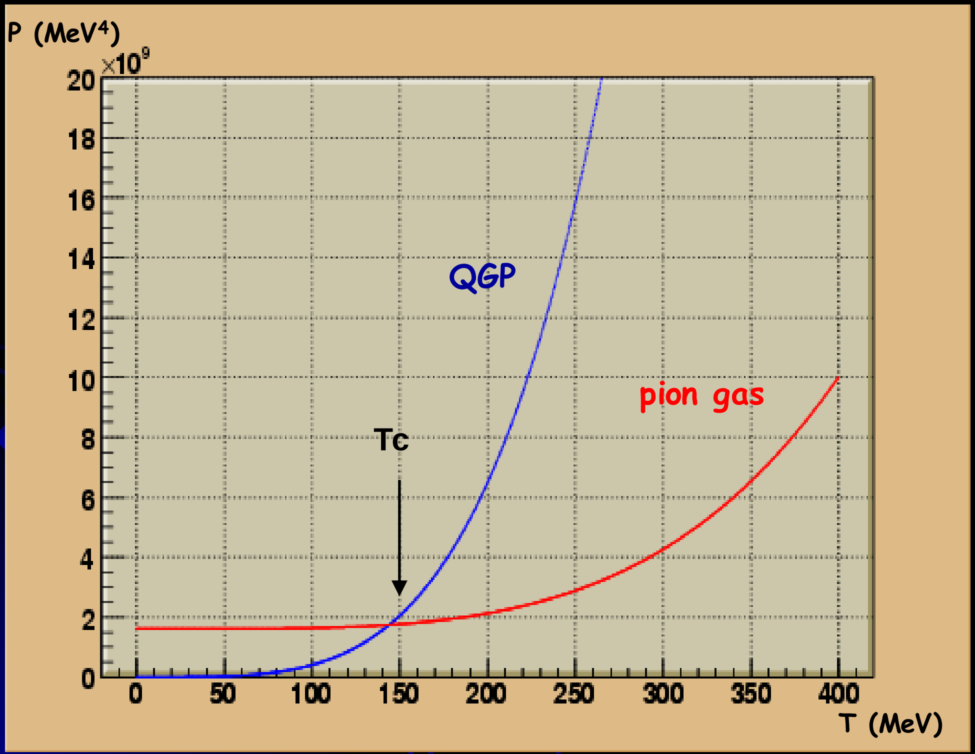
$$p = \frac{\varepsilon}{3} = \left(g_B + \frac{7}{8} g_F \right) \frac{\pi^2 T^4}{90}$$

$$g_B = 16 \quad g_F = 24$$

$$p = \frac{3}{90} \pi^2 T^4 + B$$

$$p = \frac{37}{90} \pi^2 T^4$$

- At low temperature the hadron gas is the stable phase
- There is a temperature T_C above which the QGP "wins", thanks to the larger number of degrees of freedom



$$T_C = \left(\frac{90}{34\,\pi^2} \right)^{1/4} B^{1/4}$$

$$\approx\ 150\,\mathrm{MeV}$$

- very simplified calculation…
  - more refined estimates:

    → Tc ≈ 170 MeV

- 170 MeV?

  recall: T_{room} (300 K) ~ 25 meV

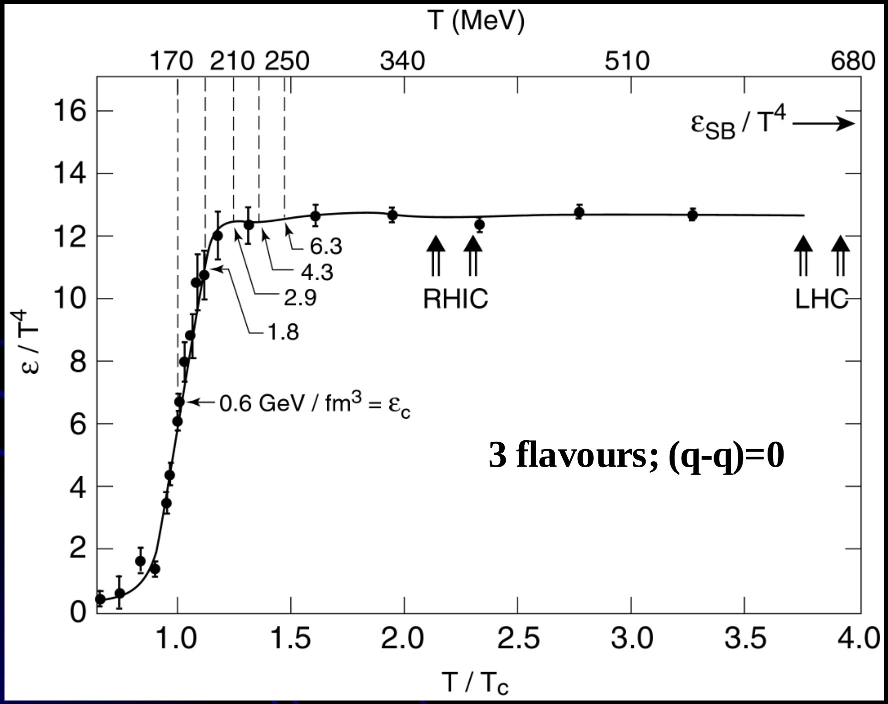
  (of course, lowercase m)

→ Tc ≈ 170 MeV ≈ 2000 billion K

(compare Sun core: 15 million K)

Lattice QCD

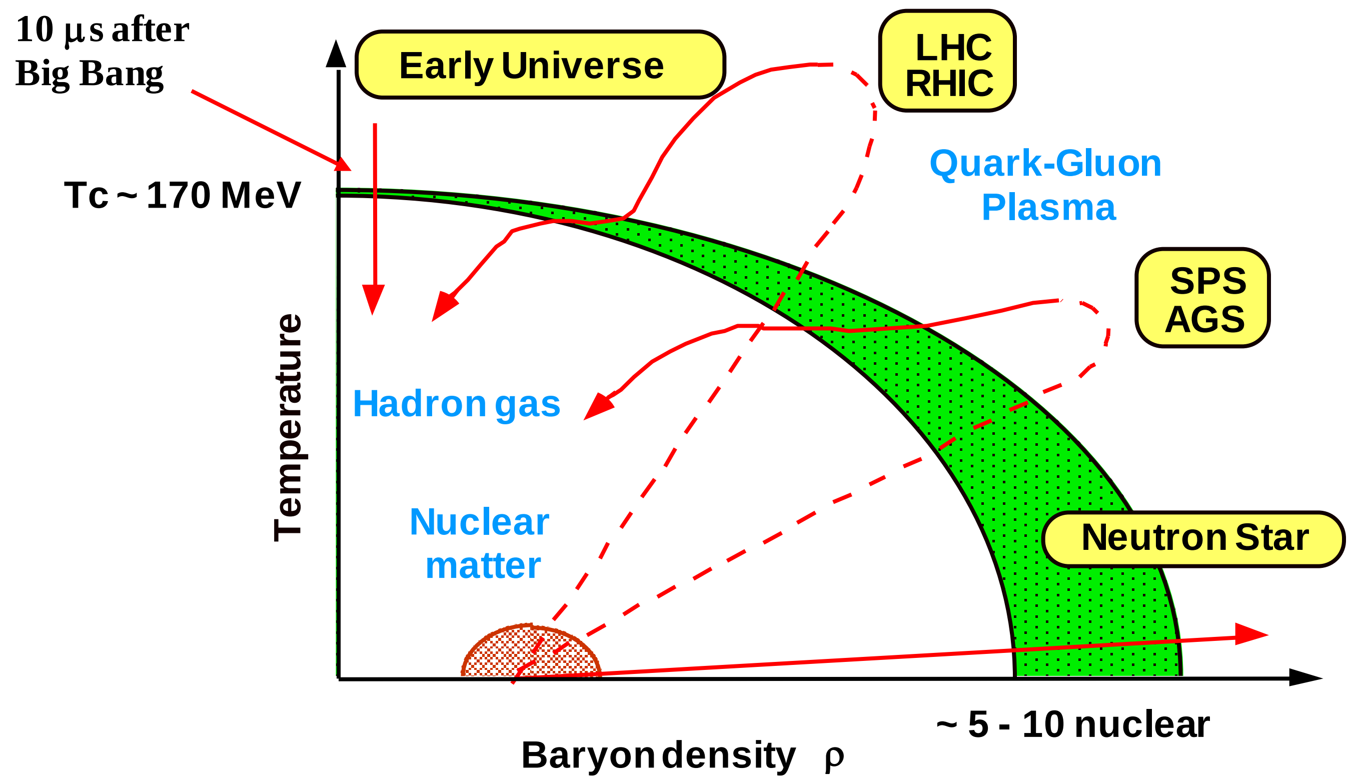
- rigorous way of doing calculations in non-perturbative regime of QCD
- discretization on a space-time lattice
  → ultraviolet (large momentum scale) divergencies can be avoided



- zero baryon density, 3 flavours
- ε changes rapidly around T_c
- T_c = 170 MeV:
  → ε_c = 0.6 GeV/fm^3
- at T~1.2 T_c ε settles at about 80% of the Stefan-Boltzmann value for an ideal gas of q,$\bar{q}$ g (ε_{SB})

QCD phase diagram

- an "artist's view"...



$$\varepsilon_c \sim 1\ \mathrm{GeV/fm^3}$$

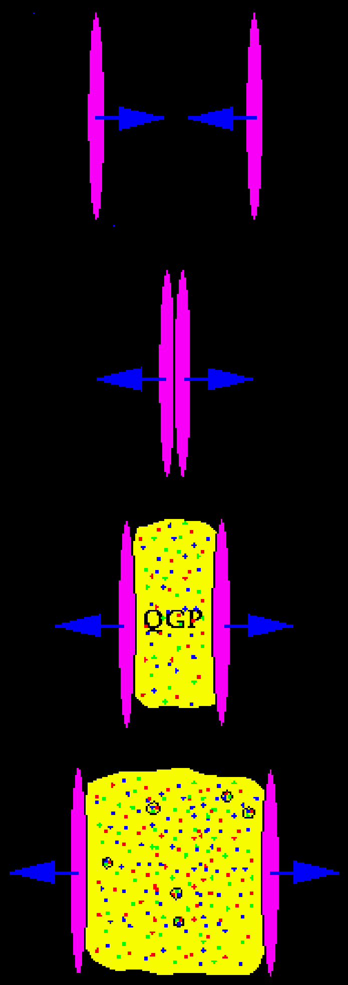
Restoration of bare masses

- Confined quarks acquire an additional mass (~ 350 MeV) dynamically, through the confining effect of strong interactions
  - M(proton) ≈ 938 MeV; m(u)+m(u)+m(d) = 10÷15 MeV
- Deconfinement is expected to be accompanied by a restoration of the masses to the "bare" values they have in the Lagrangian
- As quarks become deconfined, the masses go back to the bare values; e.g.:
  - m(u,d): ~ 350 MeV → a few MeV
  - m(s): ~ 500 MeV → ~ 150 MeV
- (This effect is usually referred to as "Partial Restoration of Chiral Symmetry". Chiral Symmetry: fermions and antifermions have opposite helicity. The symmetry is exact only for massless particles, therefore its restoration here is only partial)

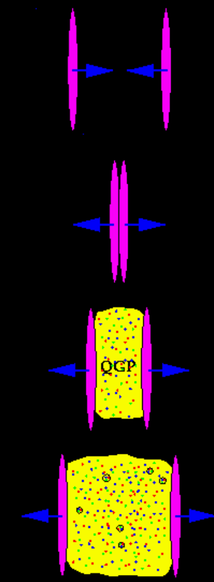
Nucleus - Nucleus collisions

Nucleus-nucleus collisions

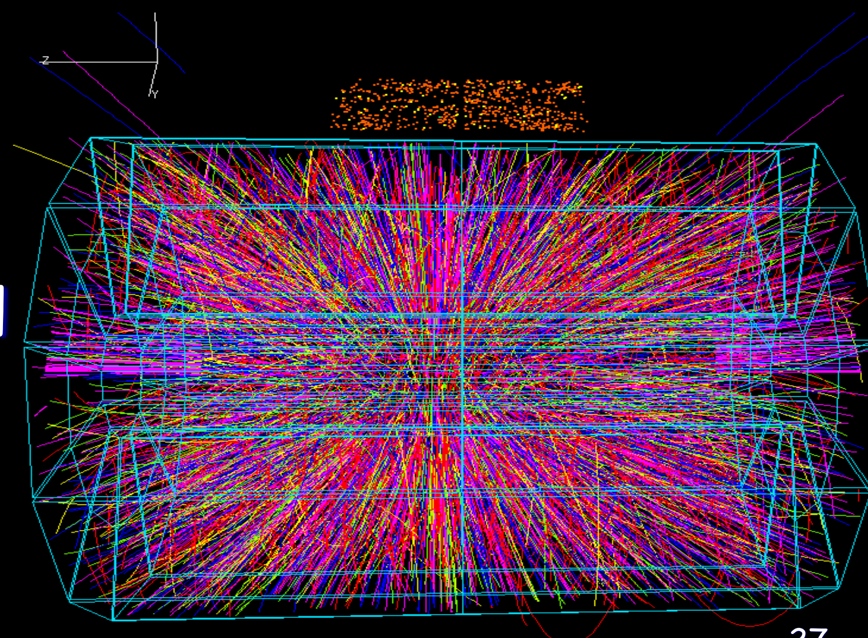
- How do we test this theory in the lab?
- How can we compress/heat matter to such cosmic energy densities?
- By colliding two heavy nuclei at ultrarelativistic energies we hope to be able to recreate, for a short time span (about 10^{-23}s, or a few fm/c) the appropriate conditions for deconfinement



- Even if a QGP is formed, as the system expands and cools down it will hadronize again, as it did at the beginning of the life of the Universe: we end up with confined matter again
  - QGP lifetime ~ a few fm/c



- The properties of the medium must be inferred from the properties of the hadronic final state

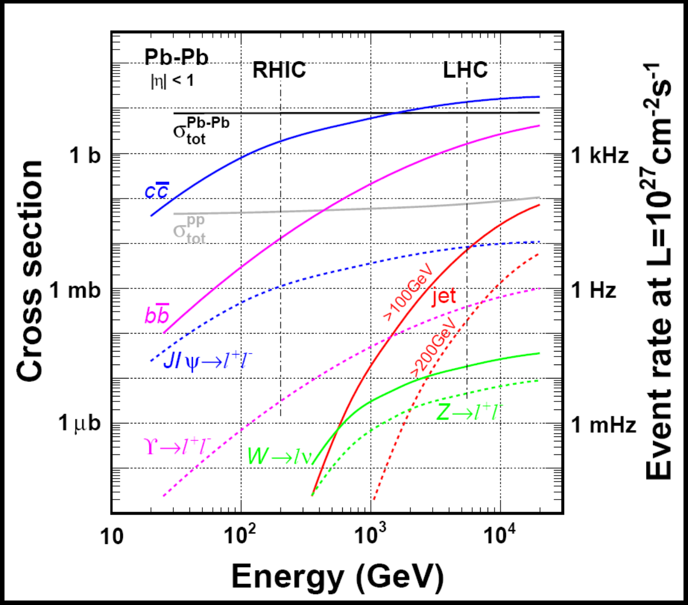


Collisions of Heavy Nuclei at SPS and RHIC

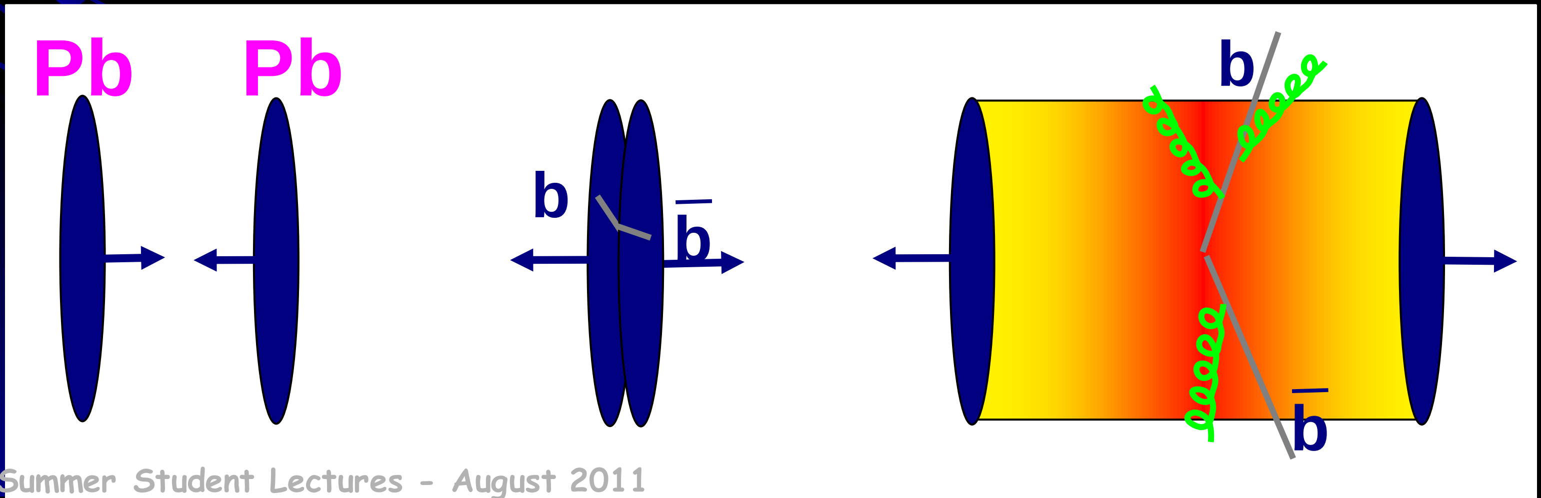
- Super Proton Synchrotron (SPS) at CERN (Geneva):
  - Pb-Pb fixed target, p = 158 A GeV → $\sqrt{s_{NN}}$ = 17.3 GeV
  - 1994 - 2003
  - 9 experiments:
    - WA97 (silicon pixel telescope spectrometer: production of strange and multiply strange particles)
    - WA98 (photon and hadron spectrometer: photon and hadronn production)
    - NA44 (single arm spectrometer: particle spectra, interferometry, particle correlations)
    - NA45 (e^+e^- spectrometer: low mass lepton pairs)
    - NA49 (large acceptance TPC: particle spectra, strangeness production, interferometry, event-by-event , …)
    - NA50 (dimuon spectrometer: high mass lepton pairs, J/ψ production)
    - NA52 (focussing spectrometer: strangelet search, particle production)
    - NA57 (silicon pixel telescope spectrometer: production of strange and multiply strange particles)
    - NA60 (dimuon spectrometer + pixels: dileptons and charm)
- Relativistic Heavy Ion Collider (RHIC) at BNL (Long Island)
  - Au-Au collider, $\sqrt{s_{NN}}$ = 200 GeV
  - 2000 - …
  - 4 experiments:
    - STAR (multi-purpose experiment: focus on hadrons)
    - PHENIX (multi-purpose experiment: focus on leptons, photons)
    - BRAHMS (two-arm spectrometer: particle spectra, forward rapidity)
    - PHOBOS (silicon array: particle spectra)

Nucleus-Nucleus collisions at the LHC!

		SPS	RHIC	LHC
$\sqrt{s_{NN}}$	[GeV]	17.3	200	5500
dN_{ch}/dy		450	800	1600
ε	[GeV/fm^3]	3	5.5	~ 10



- large ε → deeper in deconfinement region
  - → closer to "ideal" behaviour?
- large cross section for "hard probes" !
  - → a new set of tools to probe the medium properties e.g.:



LHC as a HI accelerator

- Fully ionised ^{208}Pb nucleus accelerated in LHC (configuration magnetically identical to that for pp)

$$E_{\mathrm{Pb}} = Z\, E_{\mathrm{p}} = 82 \cdot 7\ \mathrm{TeV} = 574\ \mathrm{TeV} \longrightarrow \sqrt{s_{\mathrm{PbPb}}} = 1.15\,\mathrm{PeV}$$

- the relevant figure is $\sqrt{s}$ per nucleon-nucleon collision: $\sqrt{s_{NN}}$

$$\sqrt{s_{\mathrm{NN}}} = \frac{2E_{\mathrm{Pb}}}{A} = \frac{Z}{A}\sqrt{s_{\mathrm{pp}}} = 0.39\sqrt{s_{\mathrm{pp}}} = 5.5\,\mathrm{TeV}$$

- … of course, real life is more complicated…
  - ion collimation
  - sensitivity of LHC instrumentation
  - injection chain
  - …

Luminosity limitations

- Bound-Free Pair Production (BFPP):

$$^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \rightarrow ^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{81+} + e^{+}$$

with subsequent loss of the $^{208}Pb^{81+}$

  - creates a small beam of $^{208}Pb^{81+}$, with an intensity $\propto$ Luminosity
  - impinging on a superconducting dipole (that you don't want to quench…)
  - cross section $\propto Z^7$ (!) ~ 280 b for PbPb at LHC (hadronic cross section ~ 8 b…)

- Collimation losses
  - collimation for ions (which can break up into fragments) is harder than for protons
  - limitation on the total intensity

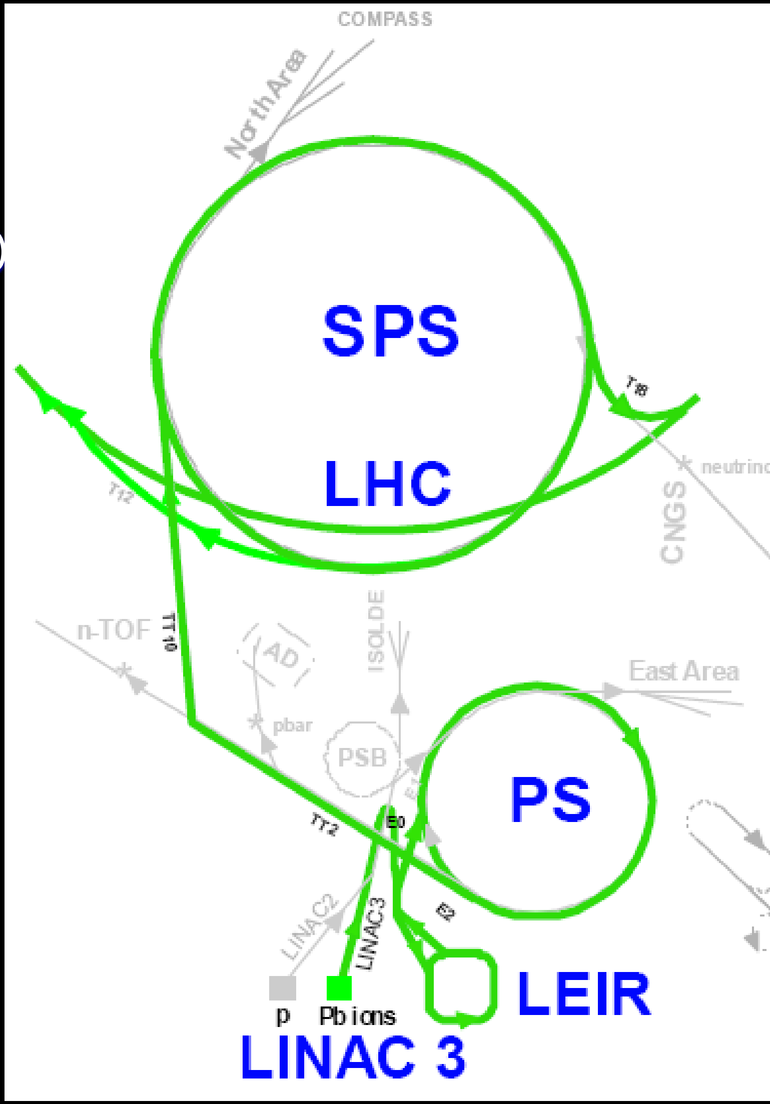
→ luminosity limited to ~ 10^{27} $cm^{-2}s^{-1}$

Pb nuclei in the LHC

- "Nominal" configuration:
  - 592 bunches (for protons: 2808)
  - 7 10^7 ions/bunch (for protons: ~ 10^{11})
  - L ~ 10^{27} $cm^{-2}s^{-1}$ (for protons: 10^{34} $cm^{-2}s^{-1}$)
  - 8 kHz interaction rate

- "Early scheme" configuration:
  - → for first heavy-ion run (2010)
  - 7 10^7 ions/bunch
  - 62 bunches
  - ½ energy → x 2 transverse emittance
  - ¼ less focussing
    - β*: 0.5 m → 2 m
  - L ~ 1.3 10^{25} $cm^{-2}s^{-1}$
  - ~ 100 Hz interaction rate

→ a dedicated AA experiment: ALICE and AA capability in ATLAS and CMS



From Heavy Ions to Quark Matter

Episode 2

Federico Antinori
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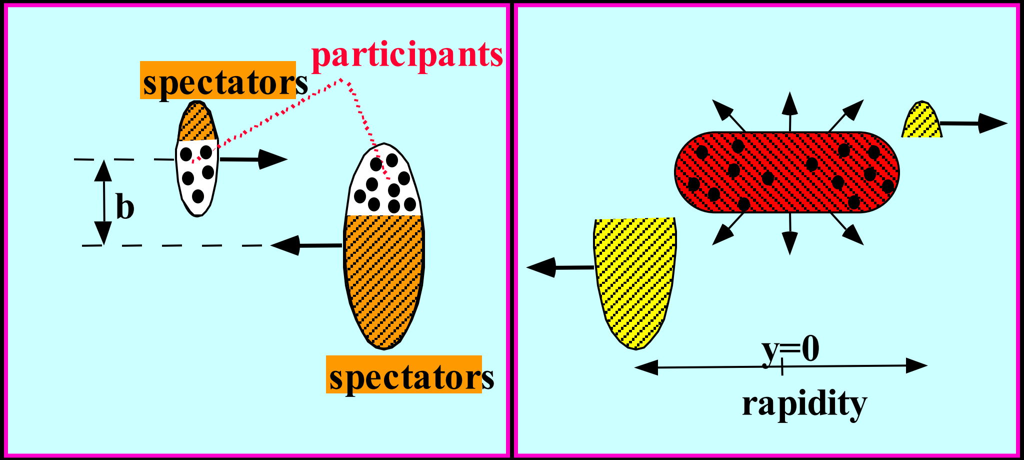
Contents

Collision centrality

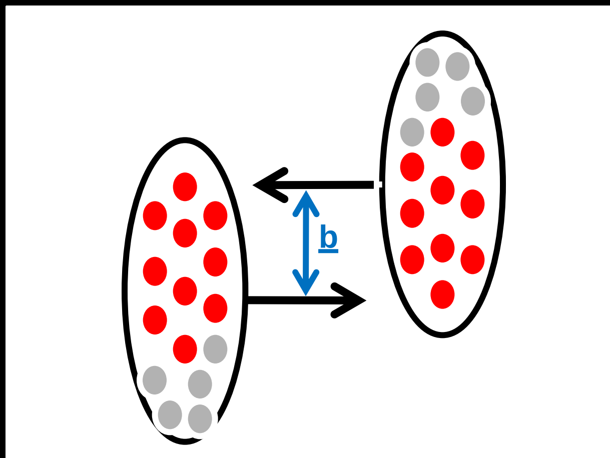
- How far do the centers of the two colliding nuclei pass one another?



- Usually expressed in terms of:
  - b (impact parameter)
  - number of participants $N_{part}(b)$
    - [sometimes one speaks of "number of wounded nucleons": $N_W(b)$]
  - percentage of cross section $\sigma(b)$

- Experimentally, the centrality is evaluated by measuring one or more of these variables:
  - N_{ch}: number of charged particles produced in a given rapidity interval (near mid-rapidity)
    - increases (~ linearly) with N_{part}
  - E_T: transverse energy = $\Sigma\, E_i \sin\theta_i$
    - increases (~ linearly) with N_{part}
  - E_{ZDC}: energy collected in a "zero degree" calorimeter
    - increases (~ linearly) with $N_{spectators}$

Geometry of a Pb-Pb collision

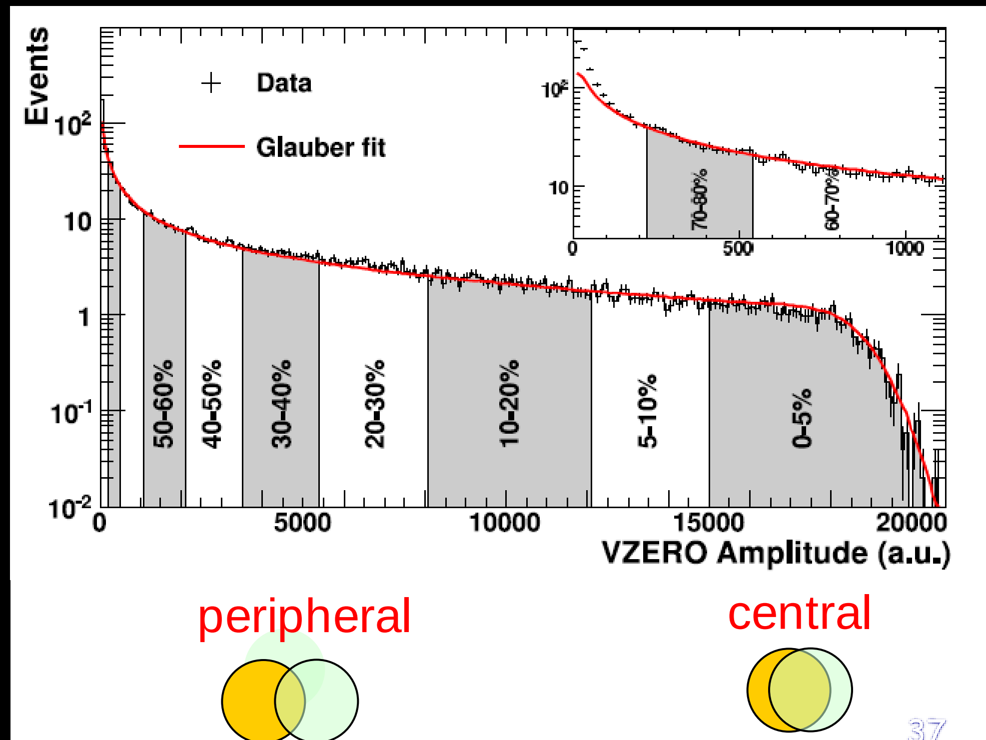


- central collisions
  - small impact parameter b
  - high number of participants → high multiplicity
- peripheral collisions
  - large impact parameter b
  - low number of participants → low multiplicity

for example: sum of the amplitudes in the ALICE V0 scintillators ⟶

reproduced by simple model (red):

- random relative position of nuclei in transverse plane
- Woods-Saxon distribution inside nucleus
- deviation at very low amplitude expected due to non-nuclear (electromagnetic) processes

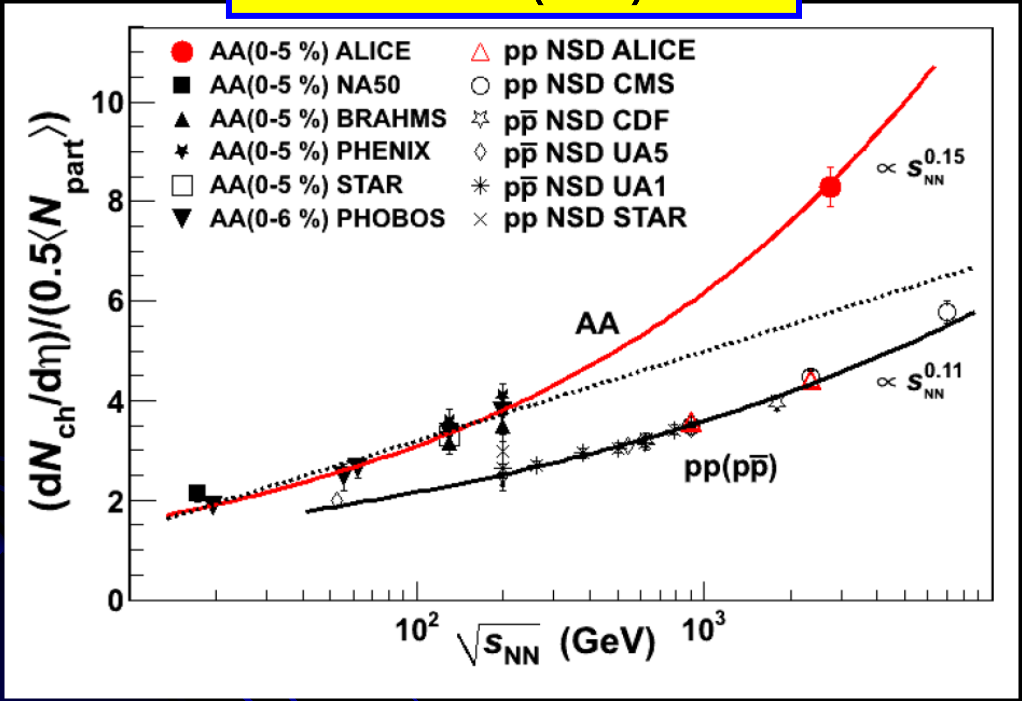


Bulk observables: multiplicity and volume

Particle multiplicity

most central collisions at LHC: ~ 1600 charged particles per unit of η

ALICE: PRL105 (2010) 252301



- log extrapolation:
  - OK at lower energies
  - finally fails at the LHC

$\sqrt{s_{NN}}$=2.76 TeV Pb+Pb, 0-5% central, |η|<0.5

$dN_{ch}/d\eta$ / (<Npart>/2) = 8.3 ± 0.4 (sys.)

Bjorken's formula

- To evaluate the energy density reached in the collision:

$$\varepsilon = \frac{1}{S c \tau_0} \left. \frac{dE_T}{dy} \right|_{y=0}$$

S = transverse dimension of nucleus

τ_0 = "formation time" ~ 1 fm/c

- for central collisions at LHC: $\left. \frac{dE_T}{dy} \right|_{y=o} \approx 1800\,\mathrm{GeV}$

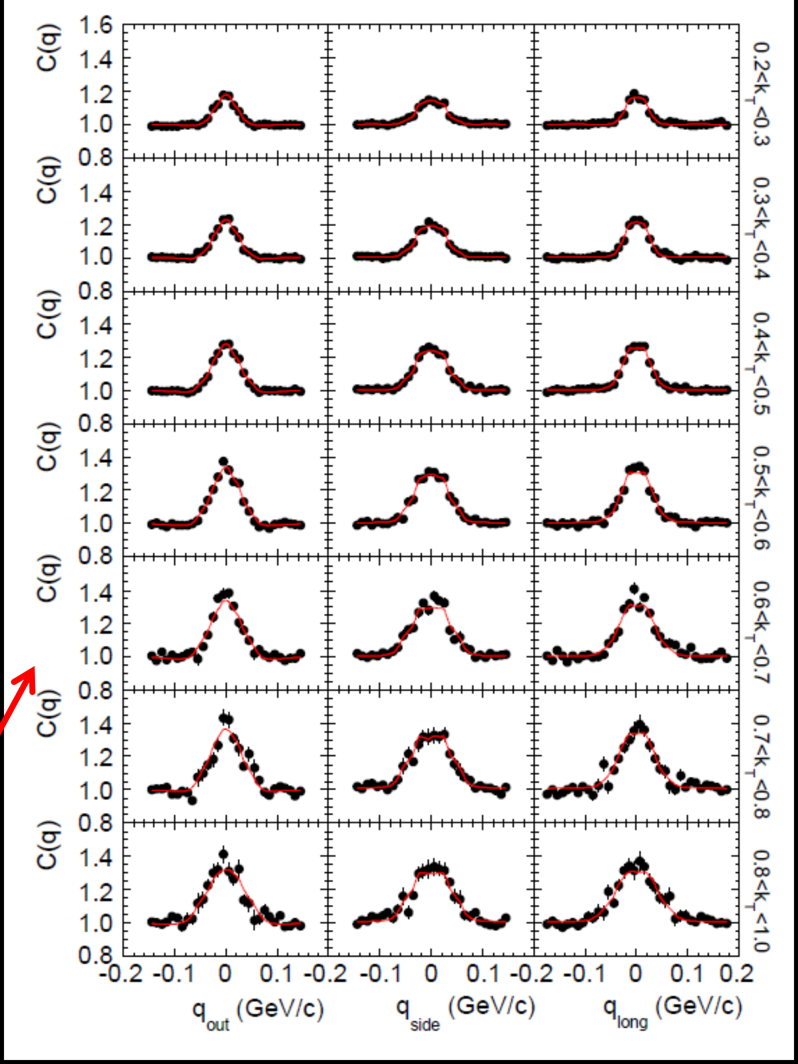
- Initial time τ_0 normally taken to be ~ 1 fm/c
  - i.e. equal to the "formation time": the time it takes for the energy initially stored in the field to materialize into particles

- Transverse dimension: $S \approx 160\ \mathrm{fm}^2 \qquad (R_A \approx 1.2 A^{1/3}\ \mathrm{fm})$

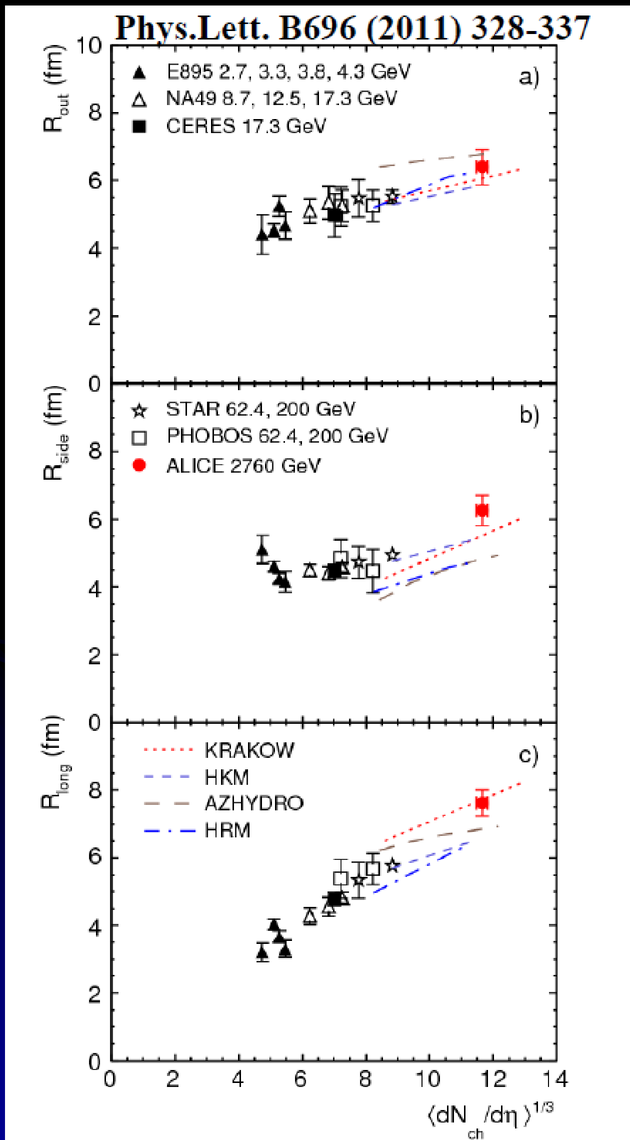
→ $\varepsilon \sim (1800\,/\,160)\ \mathrm{GeV/fm}^3 \sim 10\ \mathrm{GeV/fm}^3$ → **More than enough for deconfinement!**

Hanbury Brown - Twiss interferometry

- quantum phenomenon: enhancement of correlation function for identical bosons
- from Heisenberg's uncertainty principle:
  - $\Delta p \cdot \Delta x \sim \hbar$ (Planck's constant)
  - → (width of enhancement) · (source size) ~ $\hbar$
  - → extract source size from correlation function
- first used with photons in the 1950s by astronomers Hanbury Brown and Twiss
  - measured size of star Sirius by aiming at it two photomultipliers separated by a few metres
- e.g.: three components of correlation function C(q = momentum difference) for pairs of pions for eight intervals of pair transverse momentum (k_T)

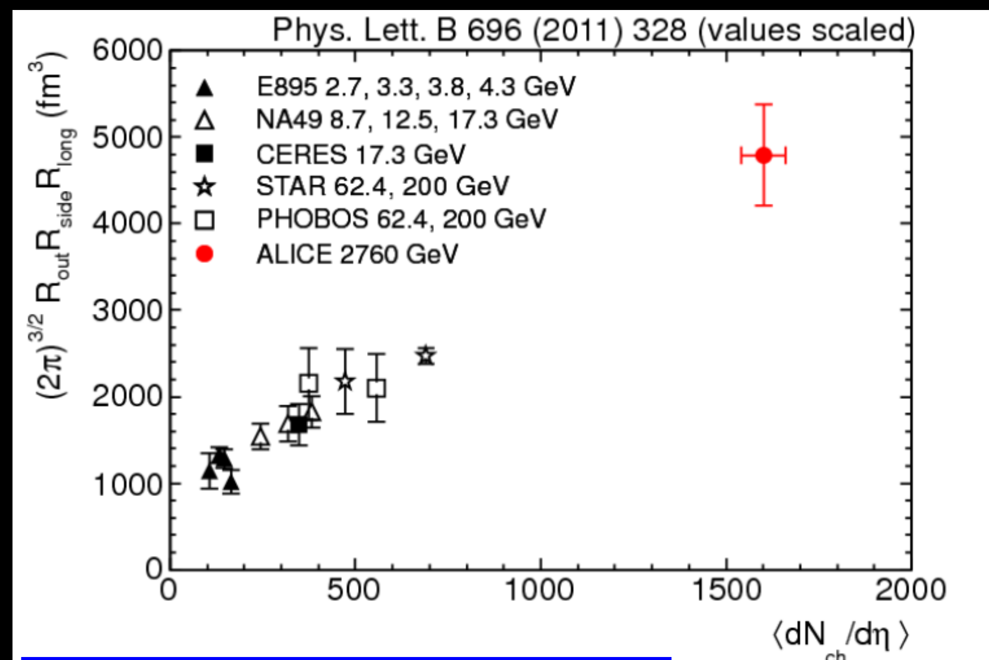


HBT interferometry



from RHIC to LHC:

- increase of size in the 3 dimensions
  - out, long, and (finally!) side
- "homogeneity" volume ~ x 2



ALICE: Phys Lett B 696 (2011) 328

Strangeness enhancement

Historic QGP predictions

- res... of s
  - n... ent value

→ c...
[Rafe...
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- dec...
  for...
  - c...

→ s...
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[Koch...

Strangeness Production in the Quark-Gluon Plasma

Johann Rafelski and Berndt Müller
Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, D-6000 Frankfurt am Main, Germany
(Received 11 January 1982)

Rates are calculated for the processes $gg \to s\bar{s}$ and $u\bar{u}, d\bar{d} \to s\bar{s}$ in highly excited quark-gluon plasma. For temperature $T \geq 160$ MeV the strangeness abundance saturates during the lifetime ($\sim 10^{-23}$ sec) of the plasma created in high-energy nuclear collisions. The chemical equilibration time for gluons and light quarks is found to be less than 10^{-24} sec.

PACS numbers: 12.35.Ht, 21.65.+f

Given the present knowledge about the interactions between constituents (quarks and gluons), it appears almost unavoidable that, at sufficiently high energy density caused by compression and/or excitation, the individual hadrons dissolve in a new phase consisting of almost-free quarks and gluons.[1] This quark-gluon plasma is a highly excited state of hadronic matter that occupies a volume large as compared with all characteristic length scales. Within this volume individual color charges exist and propagate in the same manner as they do inside elementary particles as described, e.g., within the Massachusetts Institute of Technology (MIT) bag model.[2]

It is generally agreed that the best way to create a quark-gluon plasma in the laboratory is with collisions of heavy nuclei at sufficiently high energy. We investigate the abundance of strangeness as function of the lifetime and excitation of the plasma state. This investigation was motivated by the observation that significant changes in relative and absolute abundance of strange particles, such as $\bar{\Lambda}$,[3] could serve as a probe for quark-gluon plasma formation. Another interesting signature may be the possible creation of exotic multistrange hadrons.[4] After identifying the strangeness-producing mechanisms we compute the relevant rates as functions of the energy density ("temperature") of the plasma state and compare them with those for light u and d quarks.

In lowest order in perturbative QCD $s\bar{s}$-quark pairs can be created by annihilation of light quark-antiquark pairs [Fig. 1(a)] and in collisions of two gluons [Fig. 1(b)]. The averaged total cross sections for these processes were calculated by

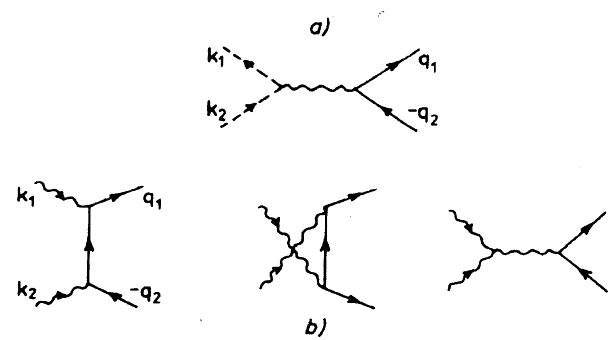
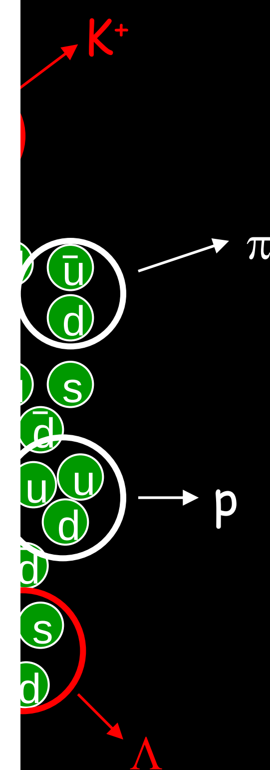


FIG. 1. Lowest-order QCD diagrams for $s\bar{s}$ production: (a) $q\bar{q} \to s\bar{s}$, (b) $gg \to s\bar{s}$.

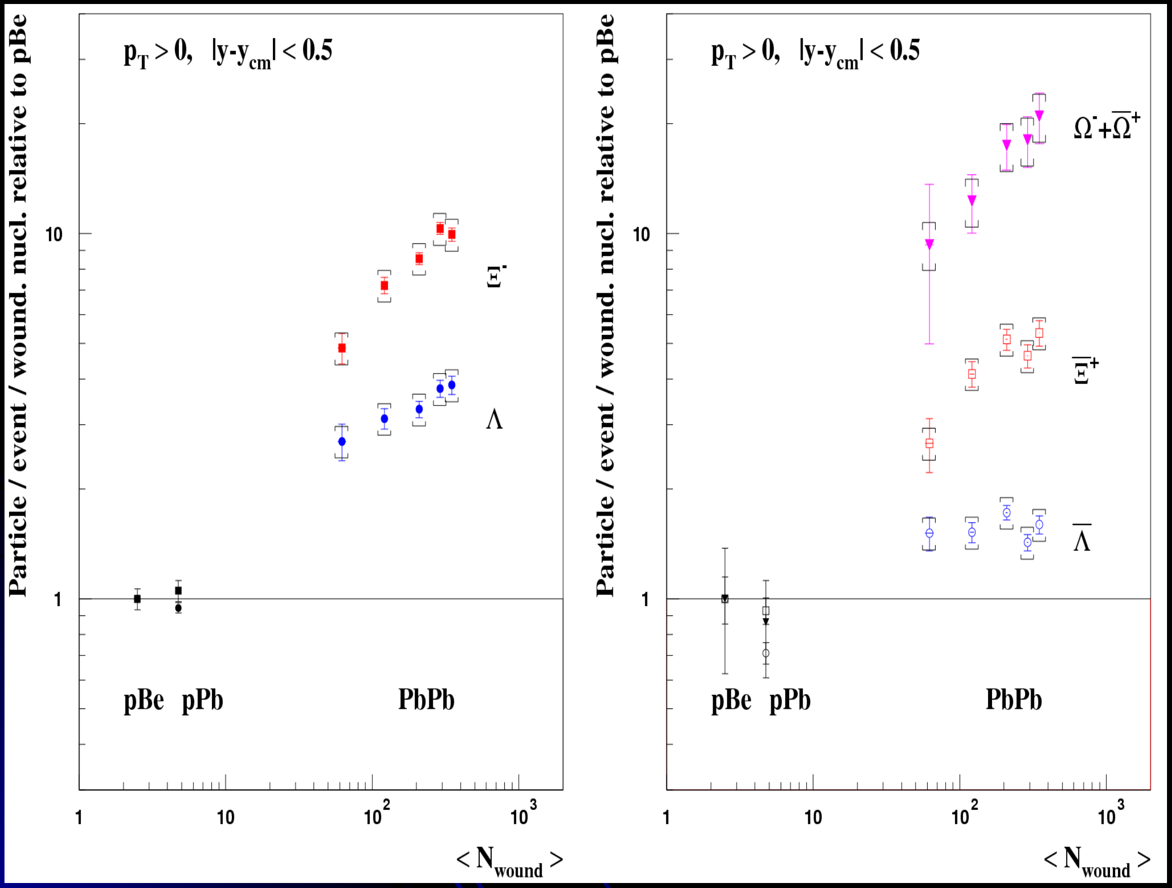


- The QGP strangeness abundance is enhanced
- As the QGP cools down, eventually the quarks recombine into hadrons ("hadronization")
- The abundance of strange hadrons should also be enhanced
- The enhancement should be larger for particles of higher strangeness content, e.g.:

$E(\Omega^-)$ >	$E(\Xi^-)$ >	$E(\Lambda)$
(sss)	(ssd)	(sud)
$\|s\| = 3$	$\|s\| = 2$	$\|s\| = 1$

Strangeness enhancement at the SPS

- Enhancement relative to p-Be (WA97/NA57)



Enhancement is larger for particles of higher strangeness content (QGP prediction!)
up to a factor ~ 20 for Ω

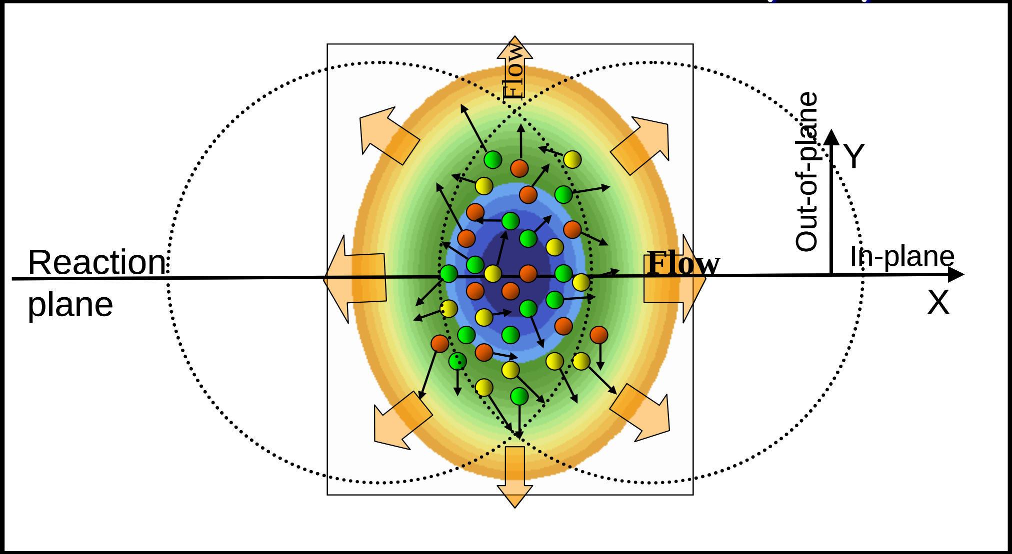
So far, no hadronic model has reproduced these observations (try harder!)

Actually, the most reliable hadronic models predicted an opposite behaviour of enhancement vs strangeness

Particle correlations

Elliptic Flow

- Non-central collisions are azimuthally asymmetric



→ The transfer of this asymmetry to momentum space provides a measure of the strength of collective phenomena

- Large mean free path
  - particles stream out isotropically, no memory of the asymmetry
  - extreme: ideal gas (infinite mean free path)
- Small mean free path
  - larger density gradient -> larger pressure gradient -> larger momentum
  - extreme: ideal liquid (zero mean free path, hydrodynamic limit)

Azimuthal Asymmetry

- Fourier expansion of azimuthal distribution:

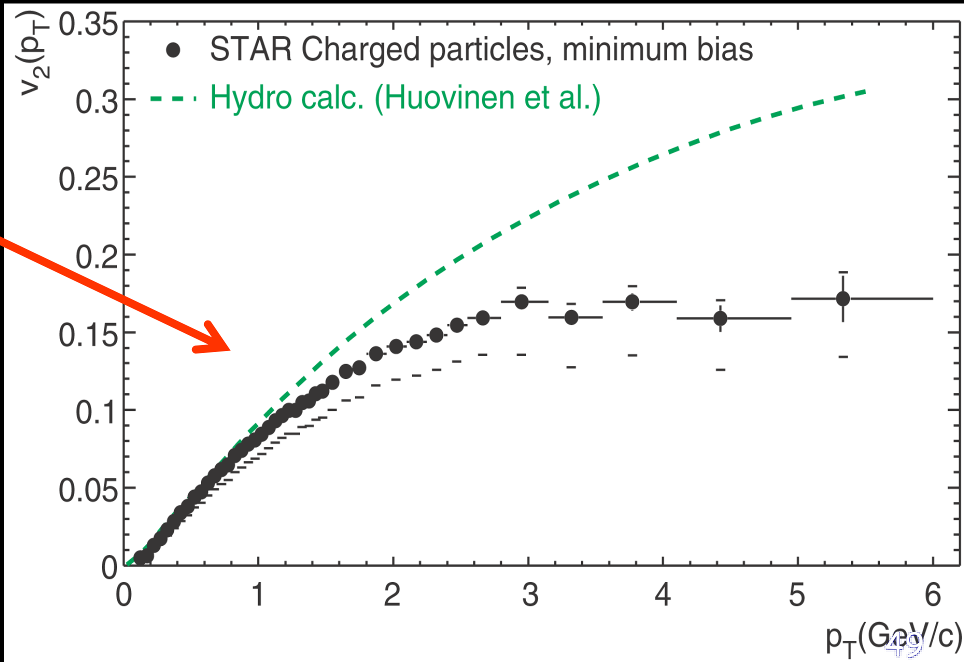
$$\frac{dN}{p_T dp_T dy d\varphi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}\left(1 + 2v_1\cos(\varphi) + 2v_2\cos(2\varphi) + \ldots\right)$$

$v_1 = \langle \cos\varphi \rangle$ "directed flow"

$v_2 = \langle \cos 2\varphi \rangle$ "elliptic flow"

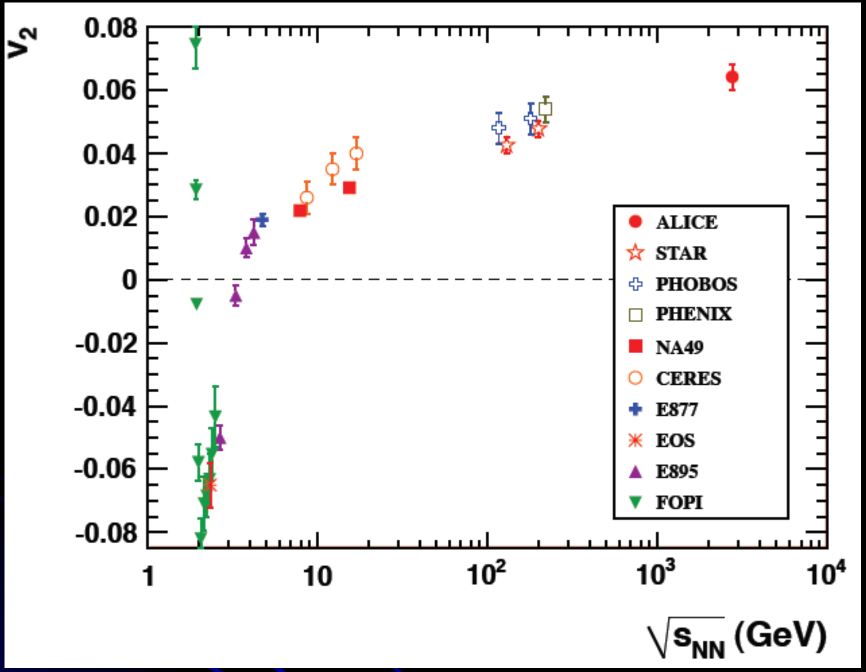
@RHIC:

- at low p_T: azimuthal asymmetry almost as large as expected at hydro limit!
  - "perfect liquid"?
- very far from "ideal gas" picture of plasma



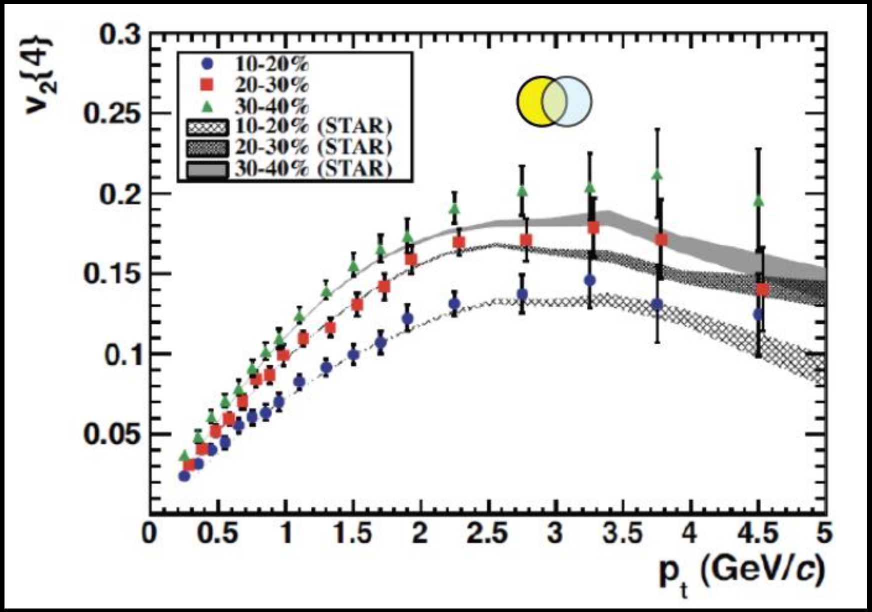
v_2 at the LHC

- v_2 still large at the LHC



→ system still behaves very close to ideal liquid (low viscosity)

- $v_2(p_T)$ very similar at LHC and RHIC



→ similar hydrodynamical behaviour?

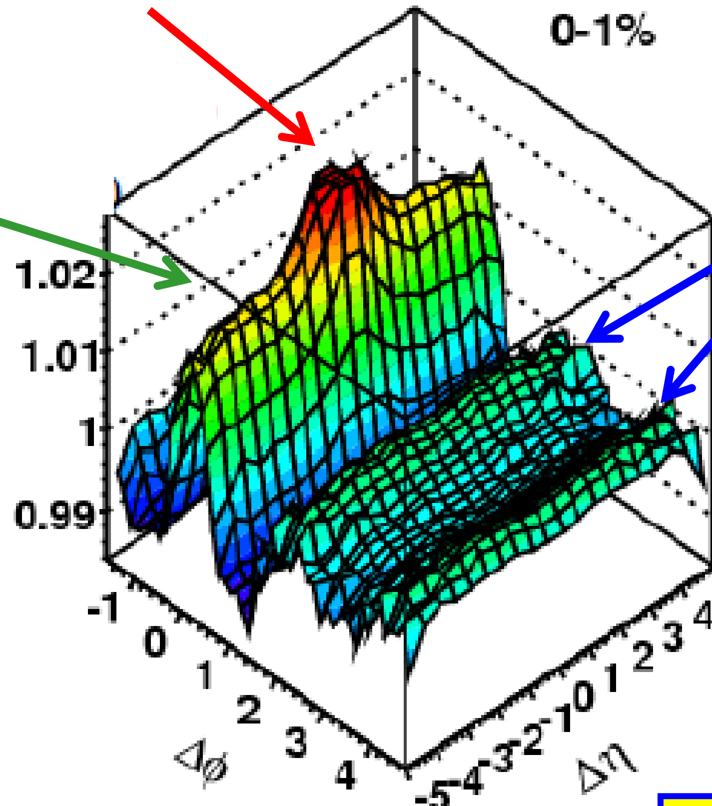
ALICE: PRL 105 (2010) 252302

Structures in (Δη,Δφ)

near side jet peak

long range structure in η on near side aka "the ridge"

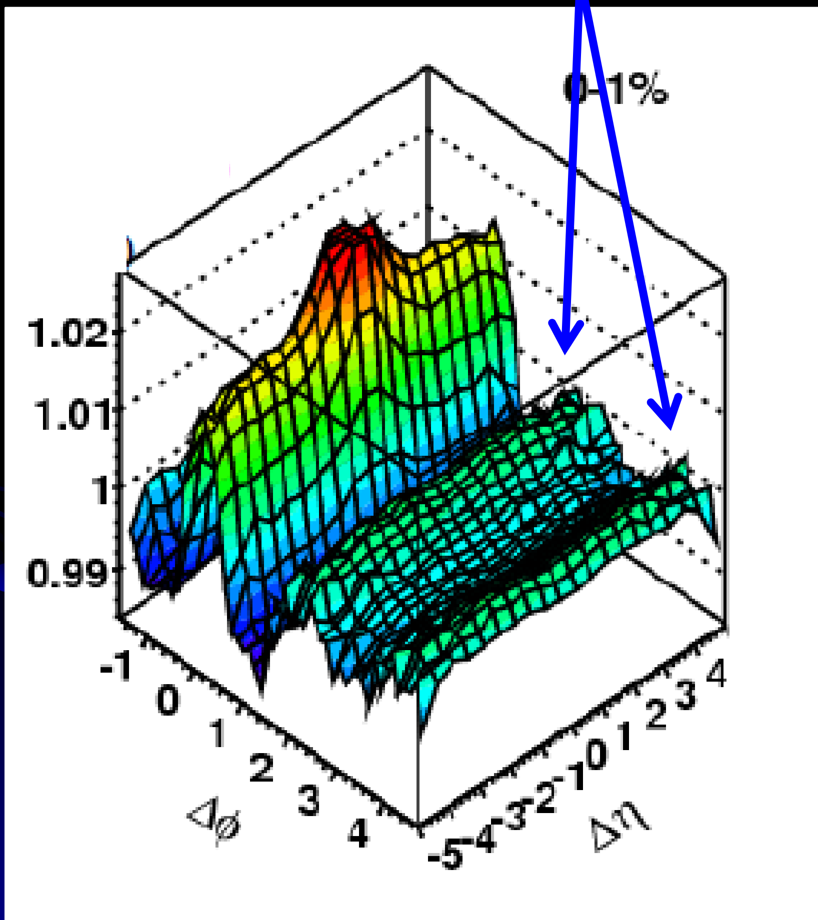
two shoulders on away side (at 120° and 240 °) aka "the Mach cone"



ATLAS-CONF-2011-074

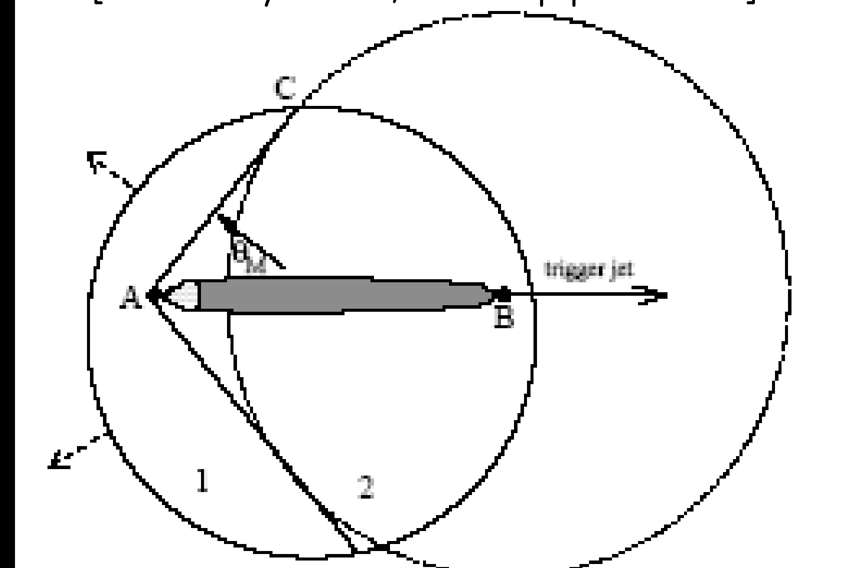
Mach cone?

- double-hump structure on away-side, at 120° and 240°



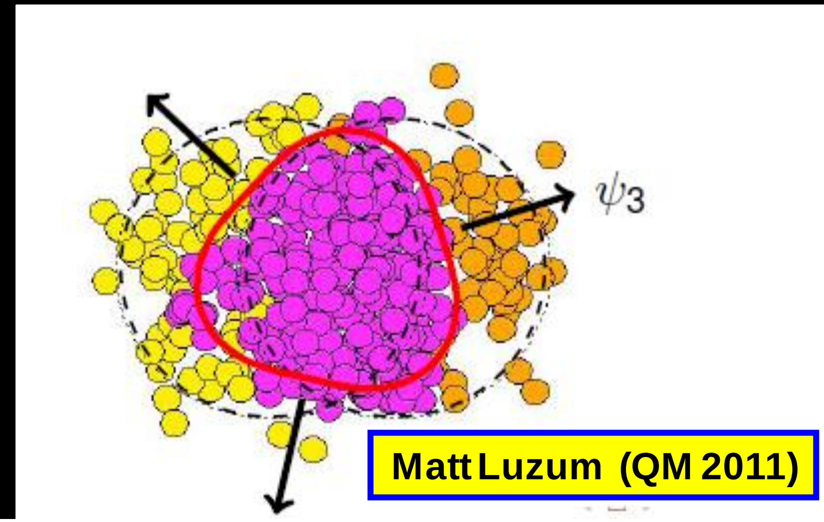
- a proposed explanation:
  - shock wave (sonic boom) : propagation through medium of recoiling parton

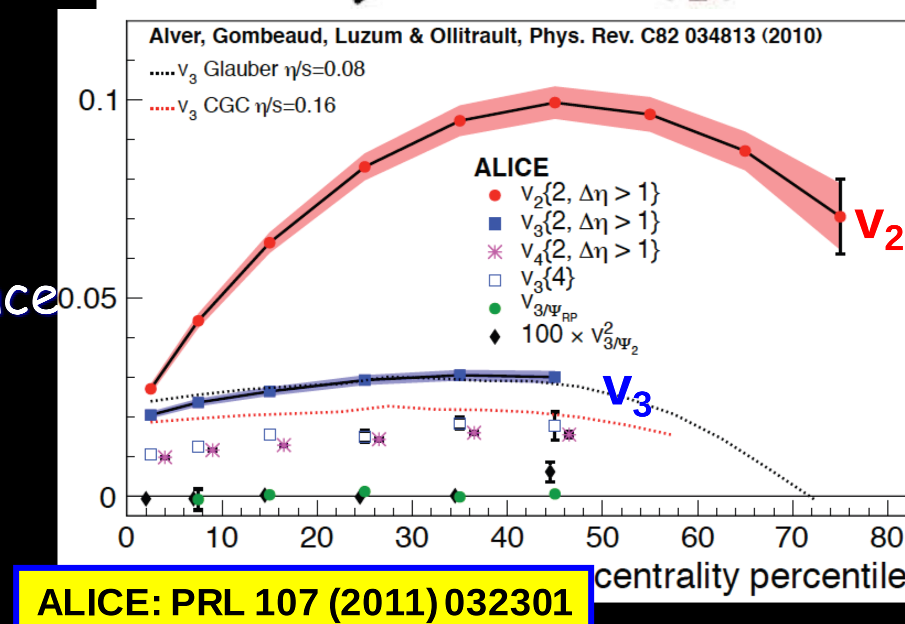
[Casalderrey-Solana, et al.: hep-ph/0411315]



Fluctuations → v_3

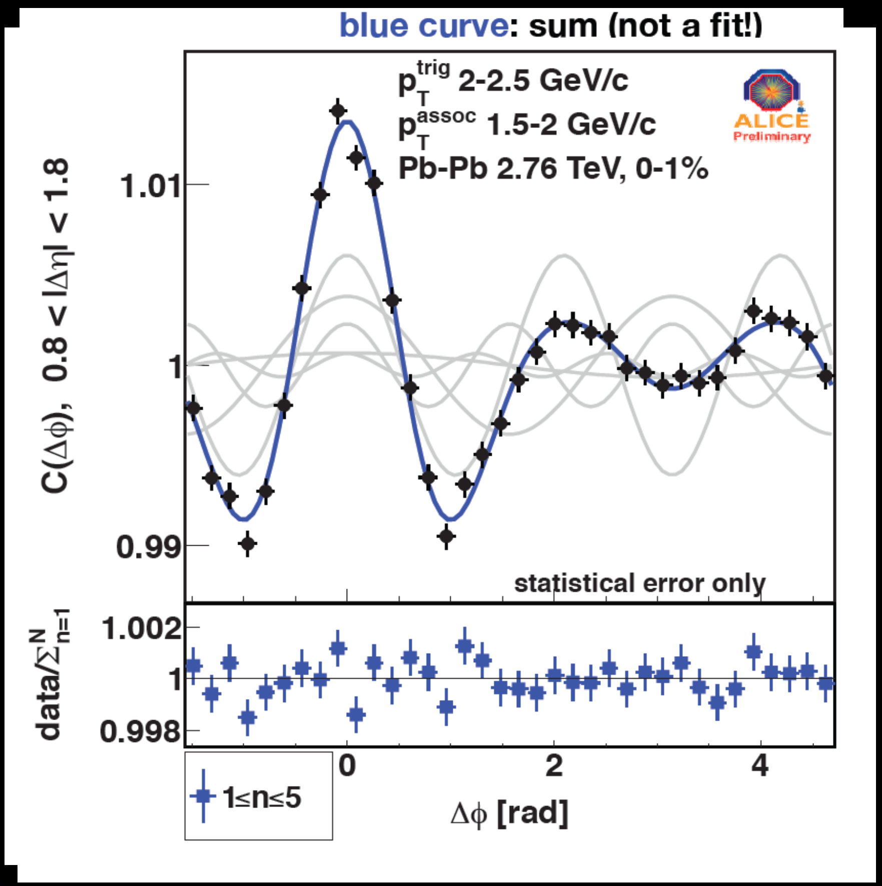
- "ideal" shape of participants' overlap is ~ elliptic
  - in particular: no odd harmonics expected
  - participants' plane coincides with event plane
- but fluctuations in initial conditions:
  - participants plane ≠ event plane
  - → v_3 ("triangular") harmonic appears [B Alver & G Roland, PRC81 (2010) 054905]
- and indeed, $v3 \neq 0$!
- v_3 has weaker centrality dependence than v_2
- when calculated wrt participants plane, v_3 vanishes
  - as expected, if due to fluctuations…





Long-η-range correlations

- "ultra-central" events: dramatic shape evolution in a very narrow centrality range
- double hump structure on away-side appears on 1% most central
  - visible without any need for v_2 subtraction!
- first five harmonics describe shape at 10^{-3} level
  - → "ridge" and "Mach cone"
  - explanations based on medium response to propagating partons were proposed at RHIC
  - Fourier analysis of new data suggests very natural alternative explanation in terms of hydrodynamic response to initial state fluctuations



Andrew Adare – ALICE (QM2011)

Flow vs non-flow correlations

- collective flow effects generate two-particle correlations via a global event-wide correlation

→ expect a factorisation relation between single-particle azimuthal asymmetry v_n and two-particle correlation $V_{n\Delta}$:

$$V_{n\Delta} = v_n^{trig} v_n^{assoc}$$

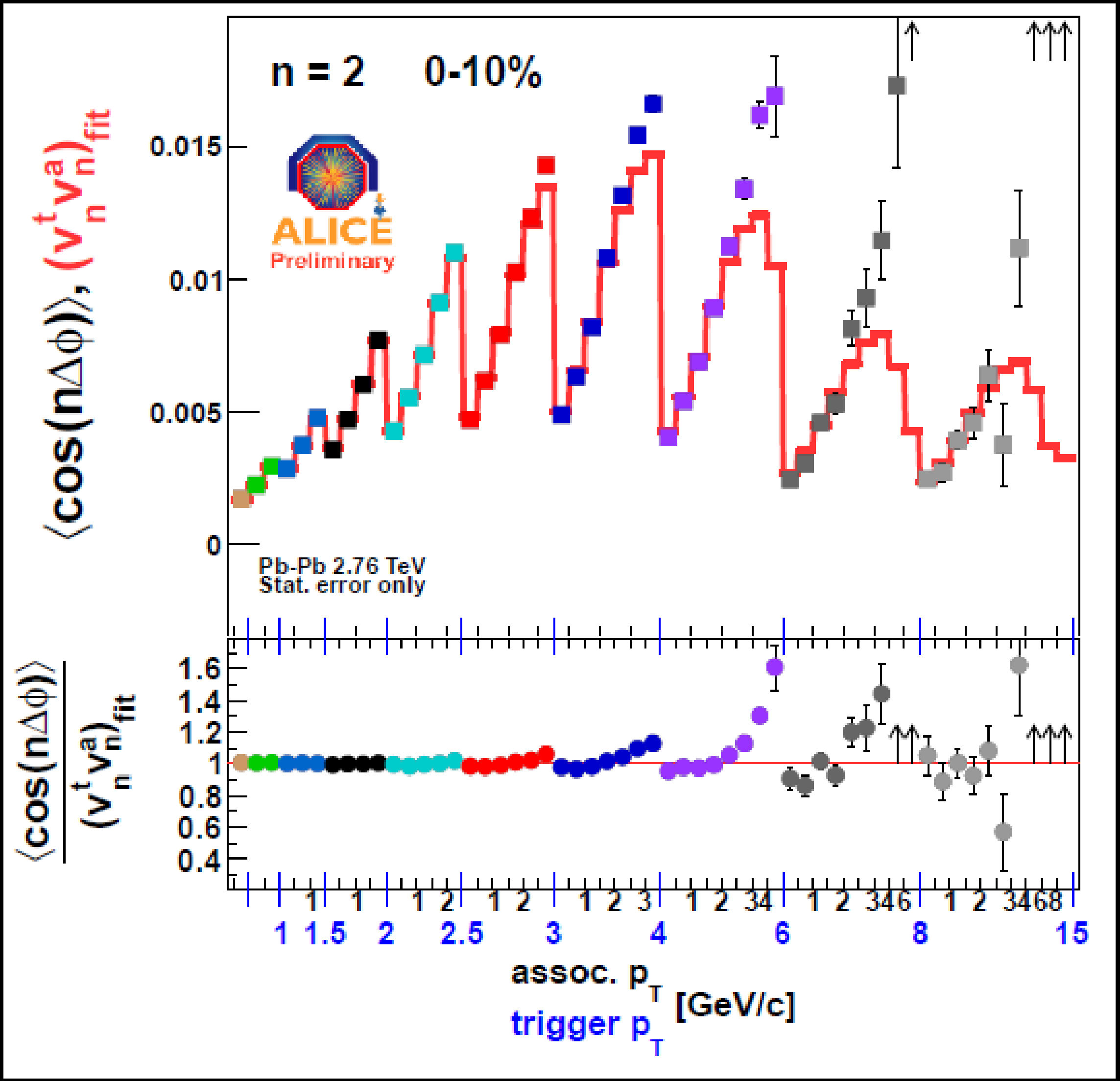
- jets or resonance decays cause correlations of a few energetic particles

→ assess flow vs. non-flow by testing the above factorisation relation

Flow vs non-flow correlations

- compare single particle values with global fit
- v_2 to v_5 factorize until $p_T \sim$ 3-4 GeV/c, then jet-like correlations strat to dominate
- v_1 factorization problematic, influenced by away-side jet (momentum conservation)

Andrew Adare – ALICE (QM2011)



Correlations: outlook

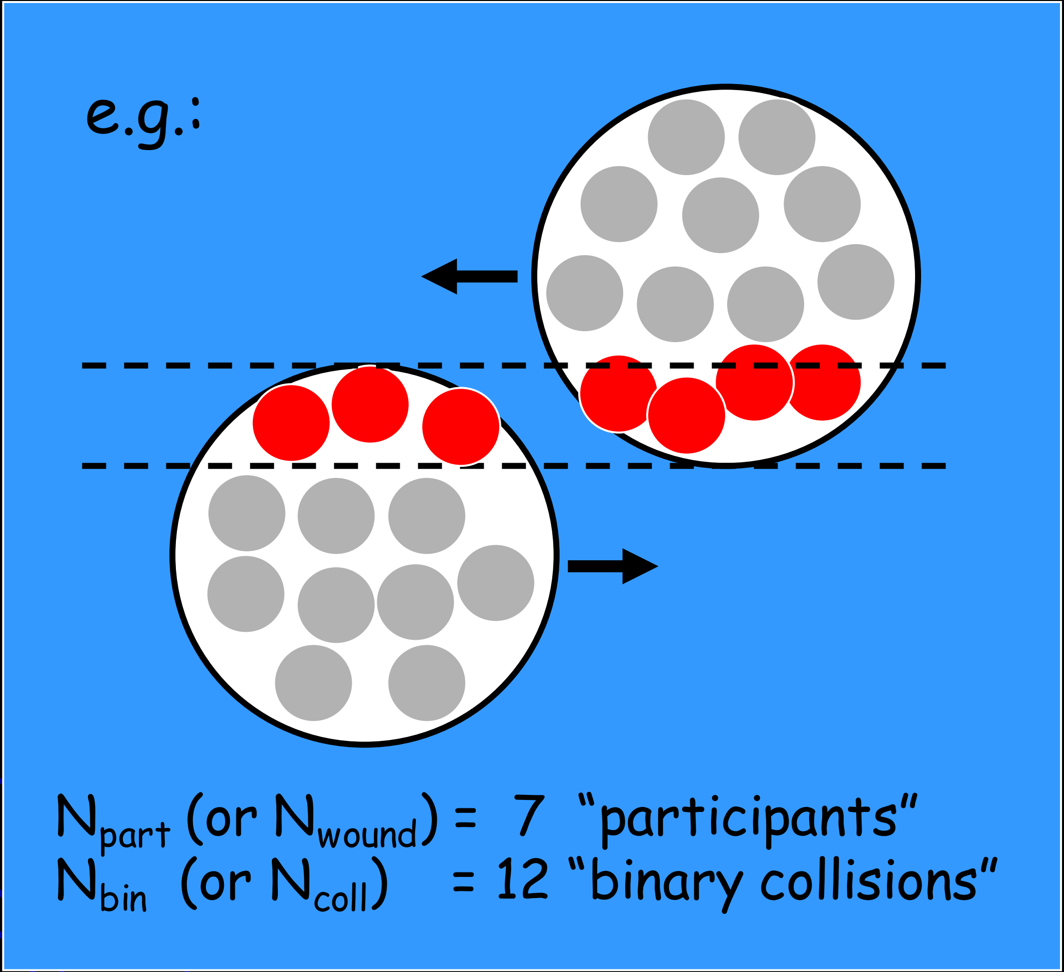
- is there any residual room for medium response effects?

→ look at the "small print" on the away side

- quantitative comparisons with full hydrodynamic calculations

High-p_T suppression

Participants Scaling vs Binary Scaling



- "Soft", large cross-section processes expected to scale like N_{part}
- "Hard", low cross-section processes expected to scale like N_{bin}

The nuclear modification factor

- quantify departure from binary scaling in AA

→ ratio of yield in AA versus reference collisions

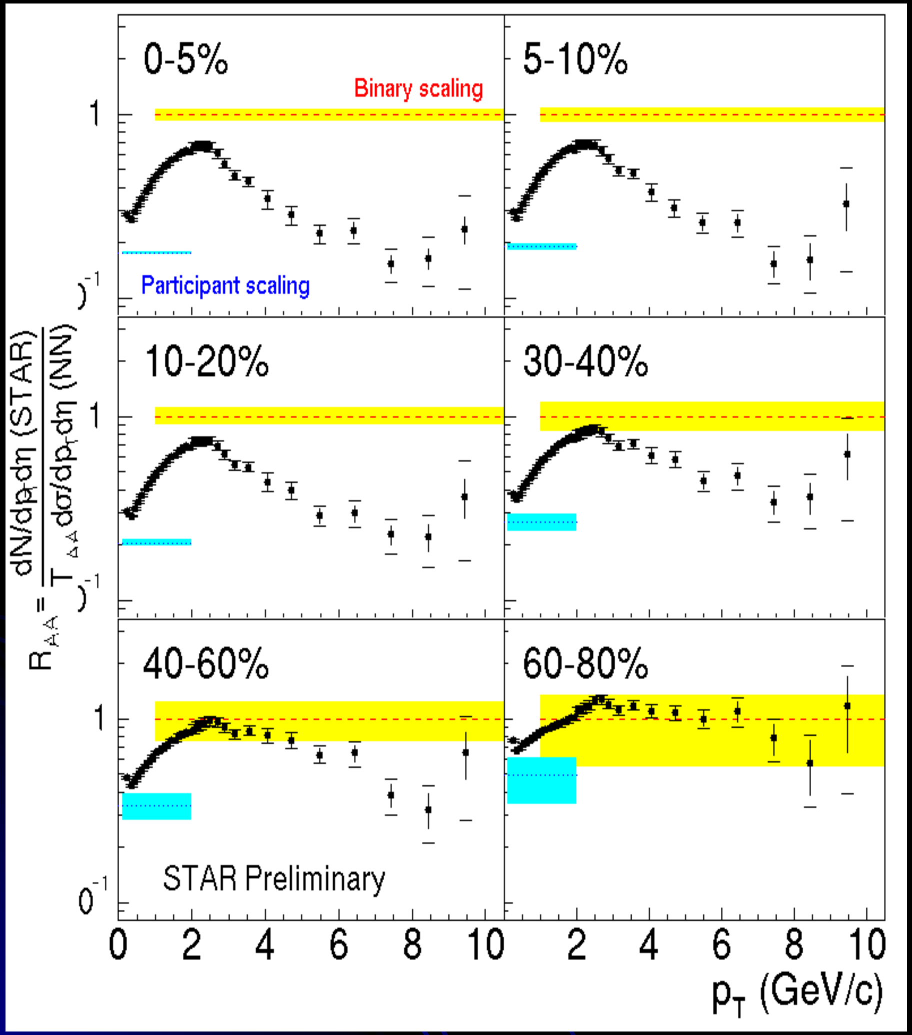
- e.g.: reference is pp → R_{AA}

$$R_{AA} = \frac{\text{Yield}_{AA}}{\text{Yield}_{pp}} \cdot \frac{1}{\langle Nbin \rangle_{AA}}$$

- …or peripheral AA → Rcp ("central to peripheral")

$$R_{cp} = \frac{\text{Yield}_{AA,central}}{\text{Yield}_{AA,periph}} \cdot \frac{\langle Nbin \rangle_{AA,periph}}{\langle Nbin \rangle_{AA,central}}$$

High p_T suppression: R_{AA} at RHIC



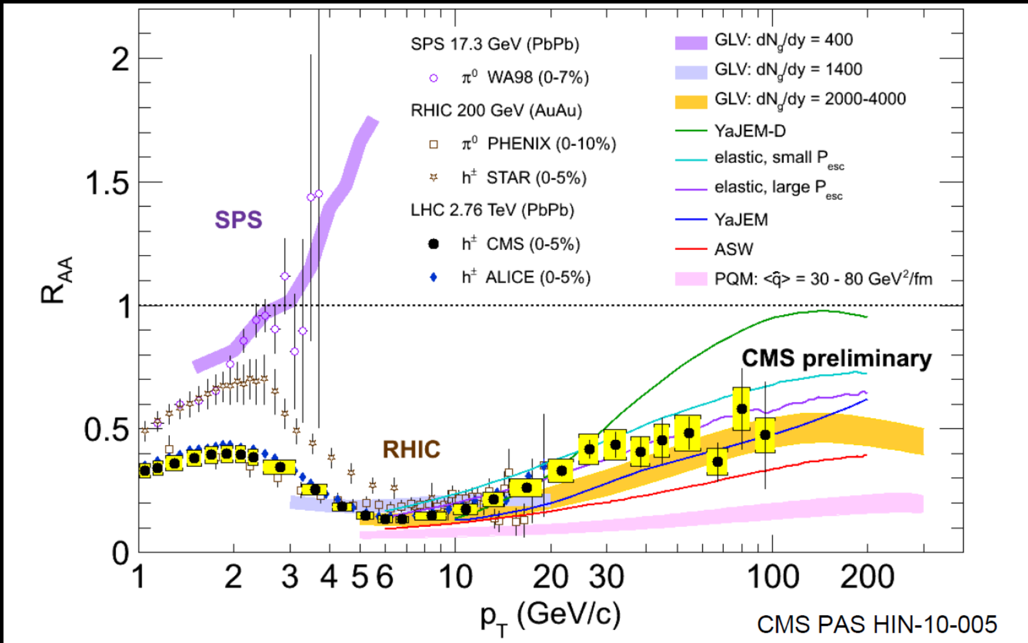
- High p_T particle production expected to scale with number of binary NN collisions if no medium effects
- Clearly does not work for more central collisions
- Interpreted as due to loss of energy of partons propagating through medium

R_{AA} at the LHC

- Suppression even larger than @ RHIC

$$R_{AA}(p_T) = \frac{\text{Yield}_{AA}(p_T)}{\langle Nbin \rangle_{AA}\,\text{Yield}_{pp}(p_T)}$$

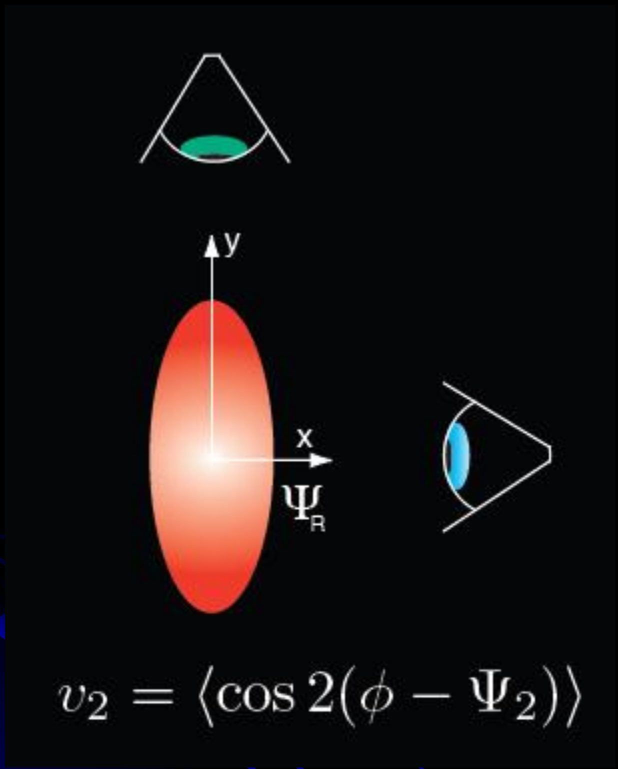
- $R_{AA}(p_T)$ for charged particles produced in 0-5% centrality range
  - minimum (~ 0.14) for p_T ~ 6-7 GeV/c
  - then slow increase at high p_T
  - still significant suppression at p_T ~ 100 GeV/c !

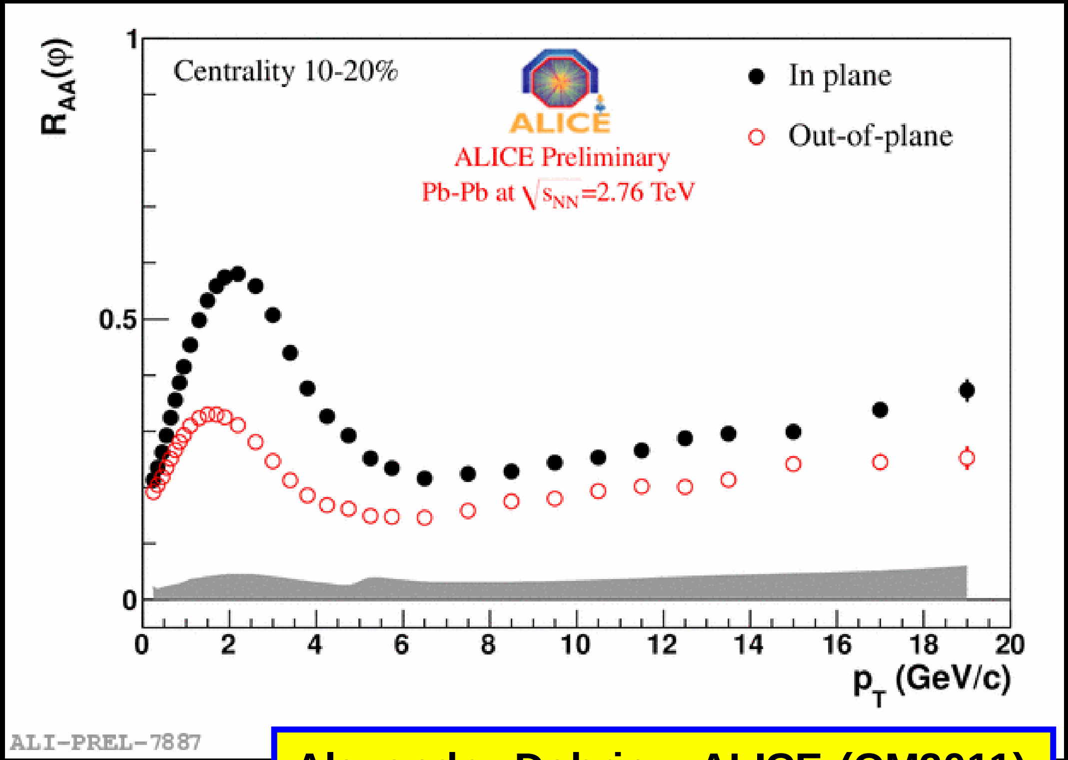


CMS: PAS HIN-10-005

- essential quantitative constraint for parton energy loss models!

Suppression vs event plane





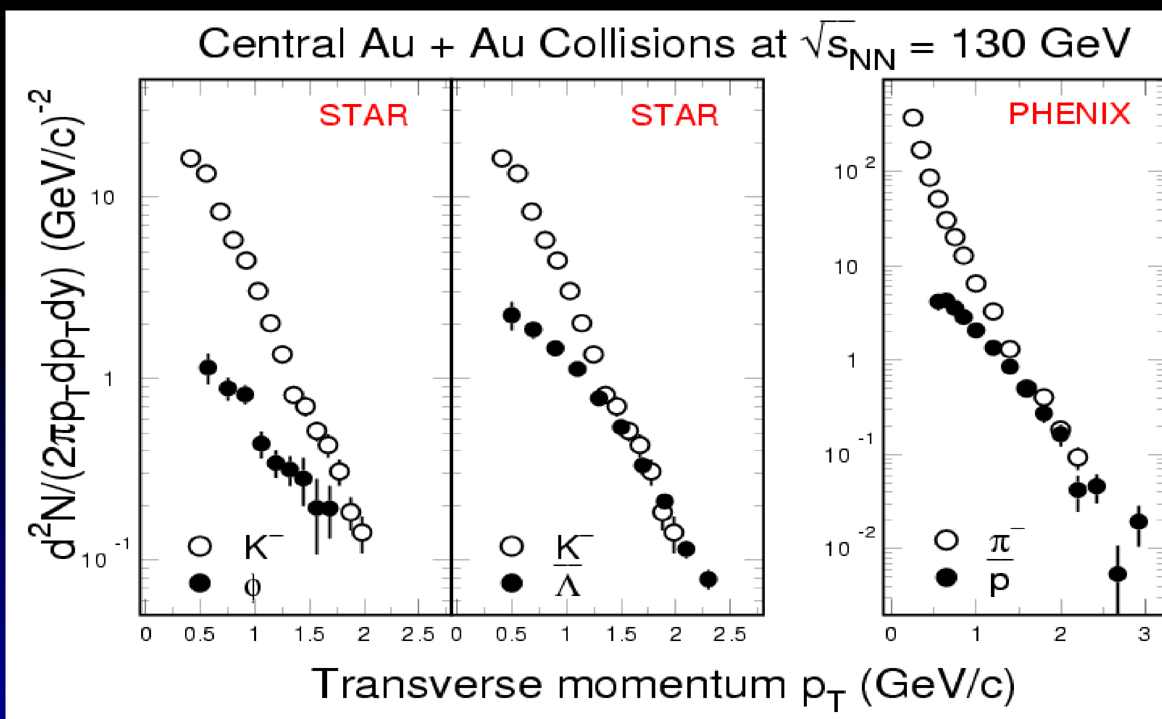
Alexandru Dobrin – ALICE (QM2011)

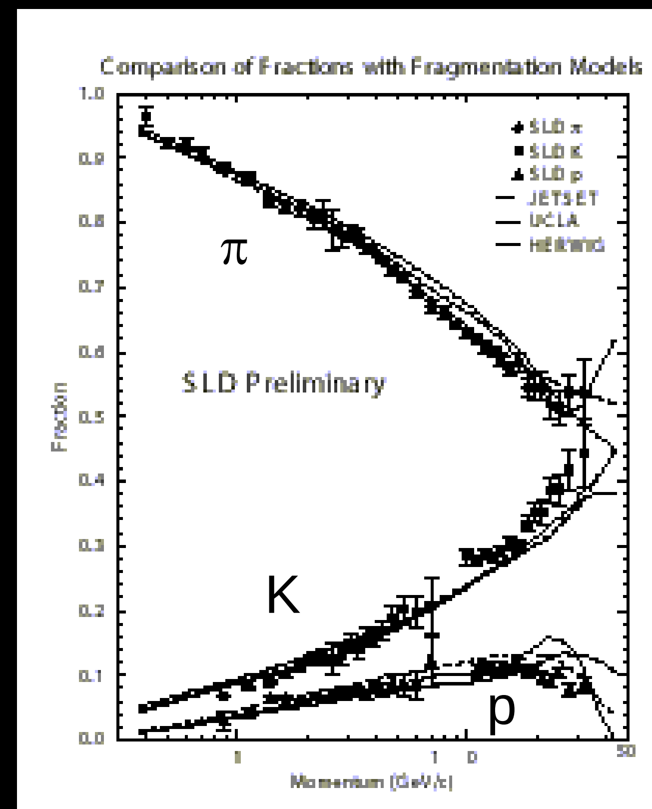
- significant effect, even at 20 GeV!
- further constraints to energy loss models
  - → path-length dependence of energy loss (L^2, L^3, ...)

Quark number scaling

Baryon puzzle @ RHIC

- Central Au-Au: as many π^- (K^-) as $\bar{p}$ ($\bar{\Lambda}$) at $p_T \sim 1.5 \div 2.5$ GeV
- $e^+e^- \rightarrow$ jet (SLD)
  - very few baryons from fragmentation!

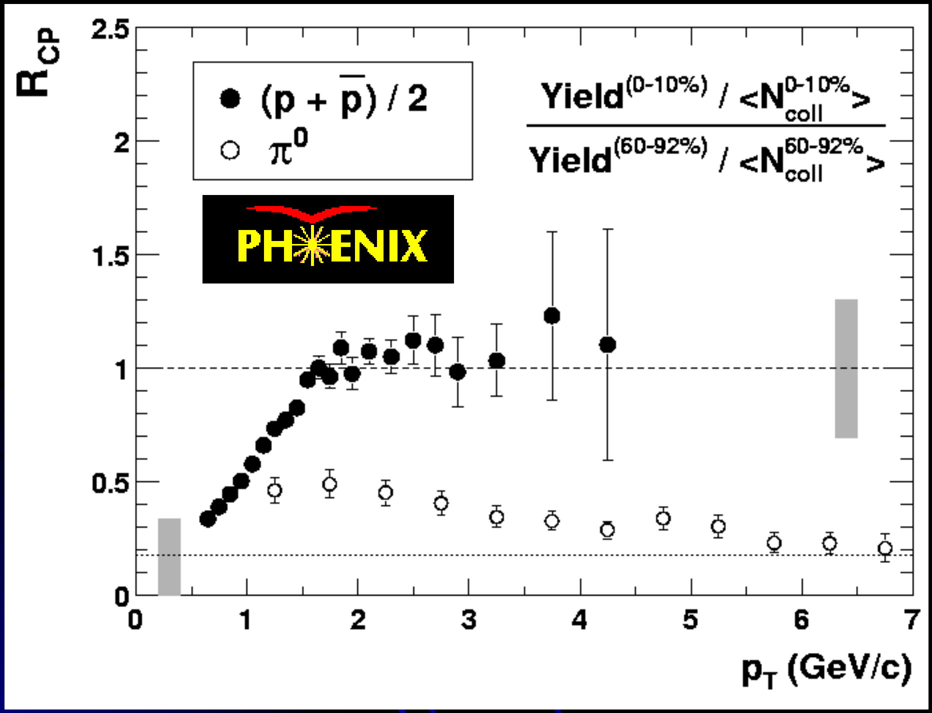




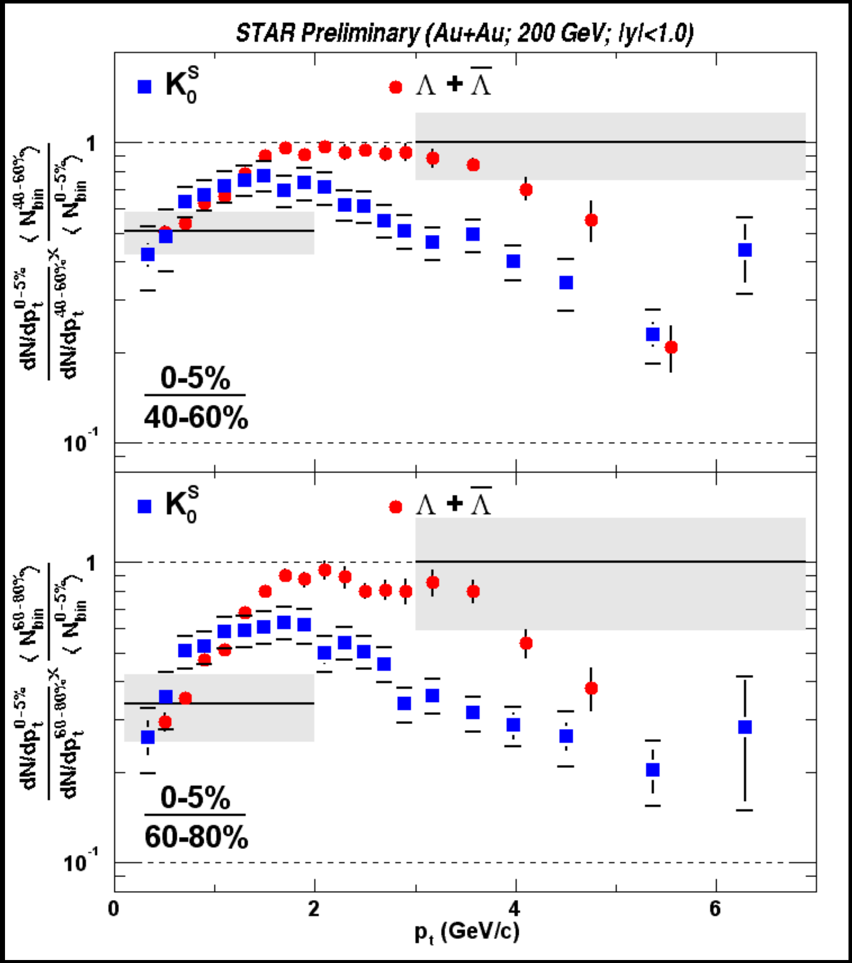
H.Huang @ SQM 2004

Rcp

$$R_{cp} = \frac{\text{Yield}_{\text{AA,central}}}{\text{Yield}_{\text{AA,periph}}} \cdot \frac{\langle Ncoll \rangle_{\text{AA,periph}}}{\langle Ncoll \rangle_{\text{AA,central}}}$$



- at higher p_T, Rcp of baryons also comes down!

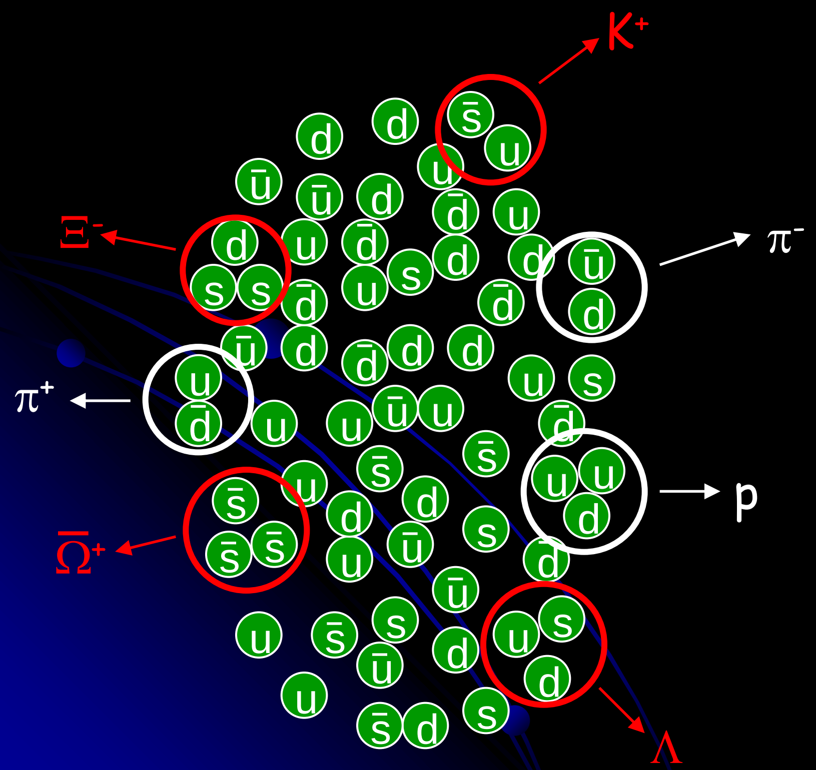


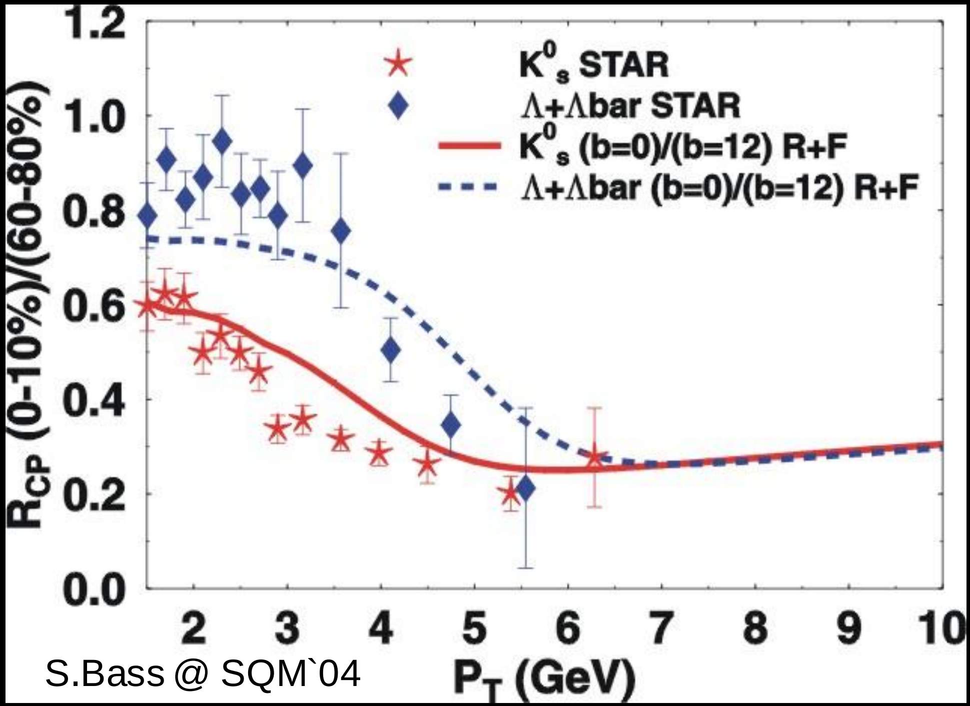
- if loss is partonic, shouldn't it affect p and π in the same way?

Quark Recombination?

- if hadrons are formed by recombination, features of the parton spectrum are shifted to higher p_T in the hadron spectrum, <u>in a different way for mesons and baryons</u>

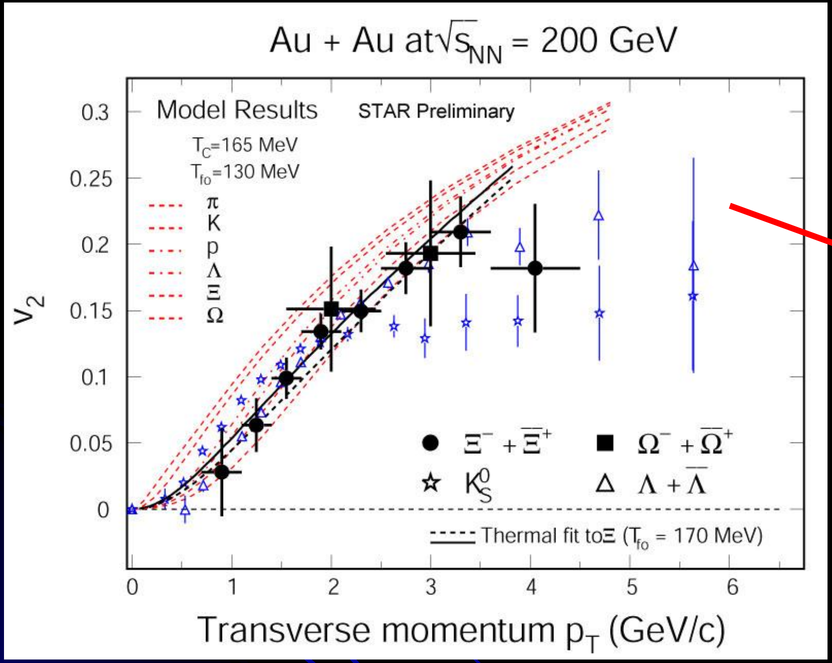
  → quark number scaling





Quark number scaling and v_2

- Recombination also offers an explanation for v_2 baryon puzzle...

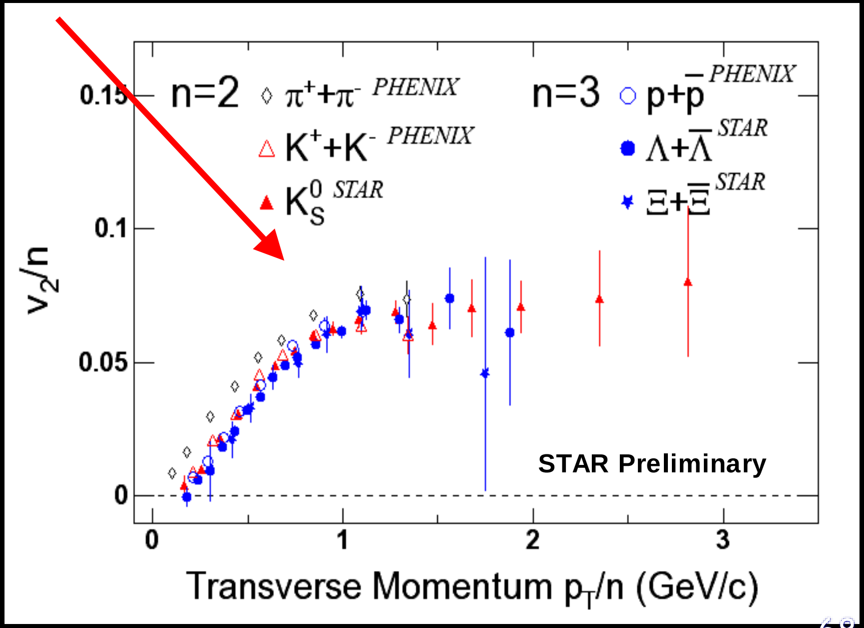


$$\frac{dN}{p_T dp_T dy d\varphi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}\left(1 + 2v_1\cos(\varphi) + 2v_2\cos(2\varphi) + \ldots\right)$$

$$v_1 = \langle \cos\varphi \rangle \quad \text{"direct flow"}$$

$$v_2 = \langle \cos 2\varphi \rangle \quad \text{"elliptic flow"}$$

scaled with n(quarks)



From Heavy Ions to Quark Matter

Episode 3

Federico Antinori
(INFN Padova, Italy & CERN, Geneva, Switzerland)

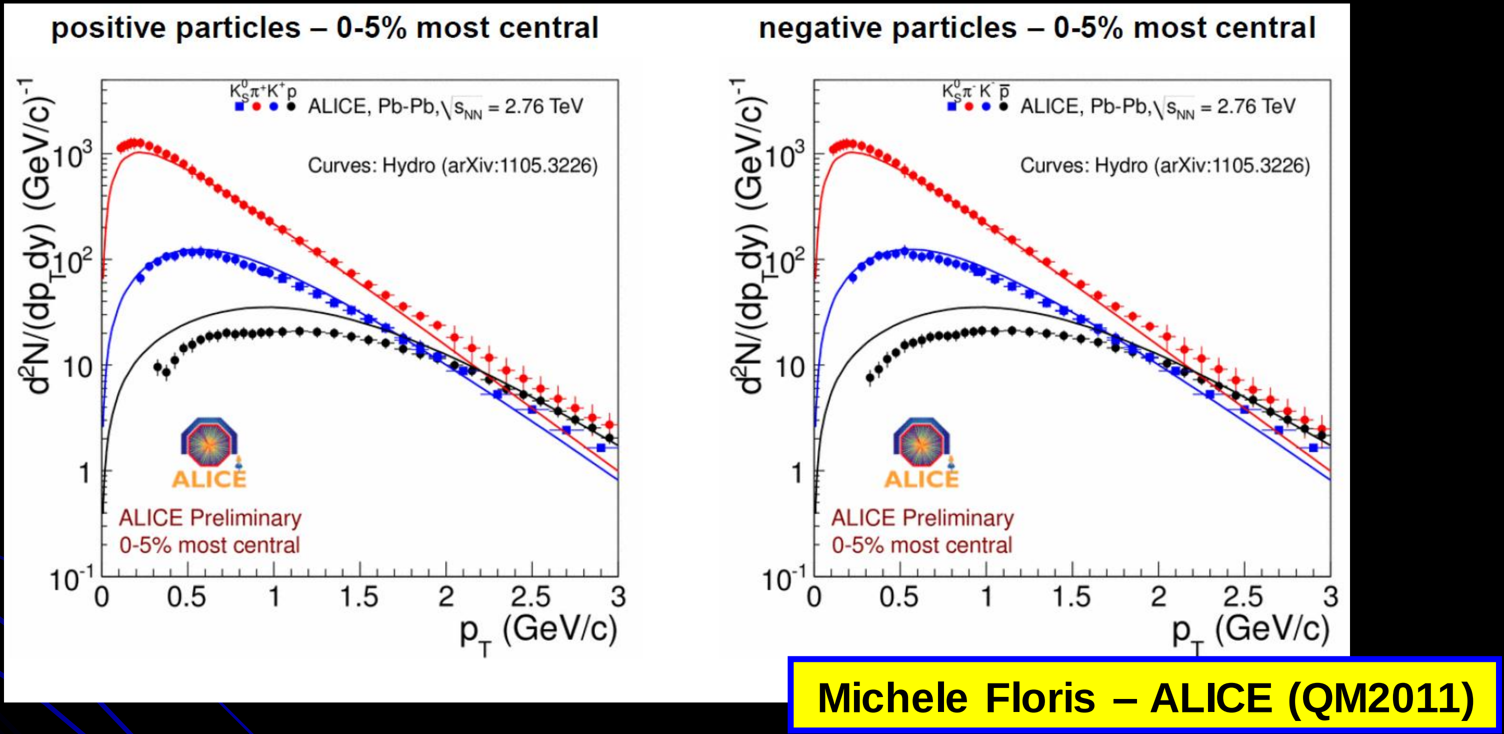
Contents

- Introduction
  - two puzzles in QCD
  - confinement and deconfinement (an "intuitive" view)
  - Nucleus-Nucleus collisions
- Bulk observables: multiplicity & volume
- Strangeness enhancement
- Particle correlations
- High-p_T suppression
- Quark number scaling
- Identified particles
- Quarkonia
- Jets
- Heavy Flavours
- Conclusions

Identified particles

p_T spectra vs hydrodynamics

- comparison of identified particle spectra with hydro predictions

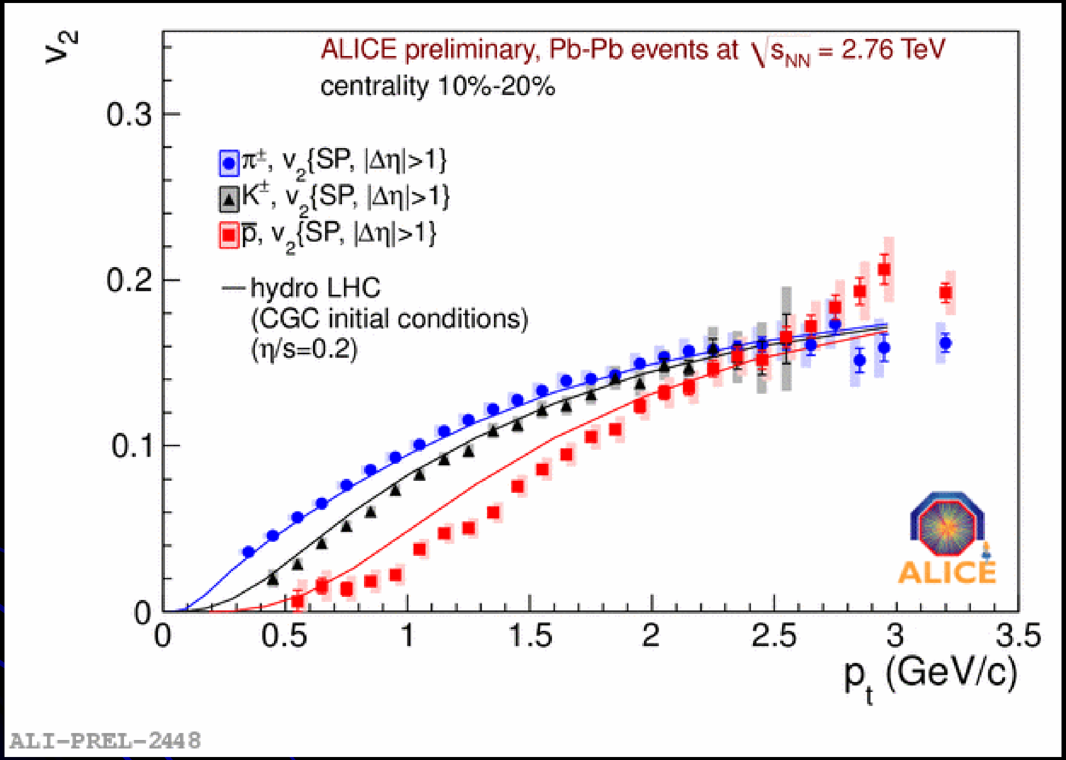


  - (calculations by C Shen et al.: arXiv:1105.3226 [nucl-th])

→ OK for π and K, but p seem to "misbehave" (less yield, flatter spectrum)

v_2 vs hydrodynamics

- comparison of identified particles $v_2(p_T)$ with hydro prediction



Raimond Snellings ALICE (QM2011)

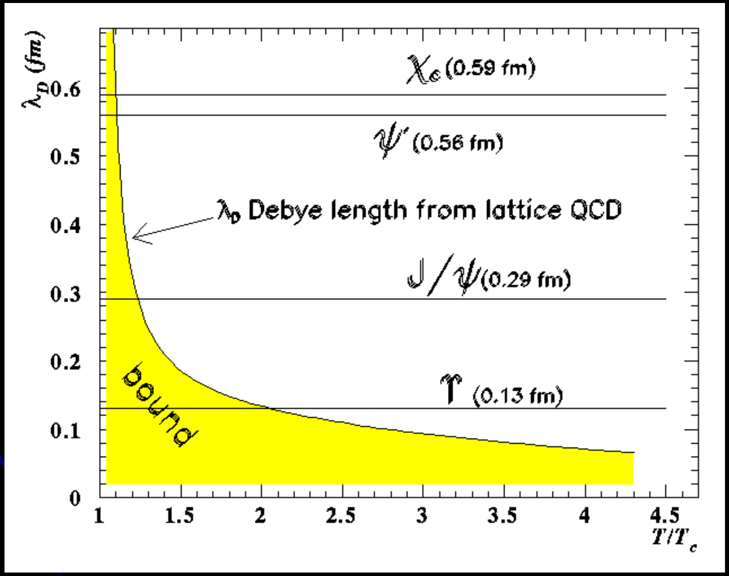
  - (calculation by C Shen et al.: arXiv:1105.3226 [nucl-th])

→ again, protons are off… → what's going on with protons?
to be continued…

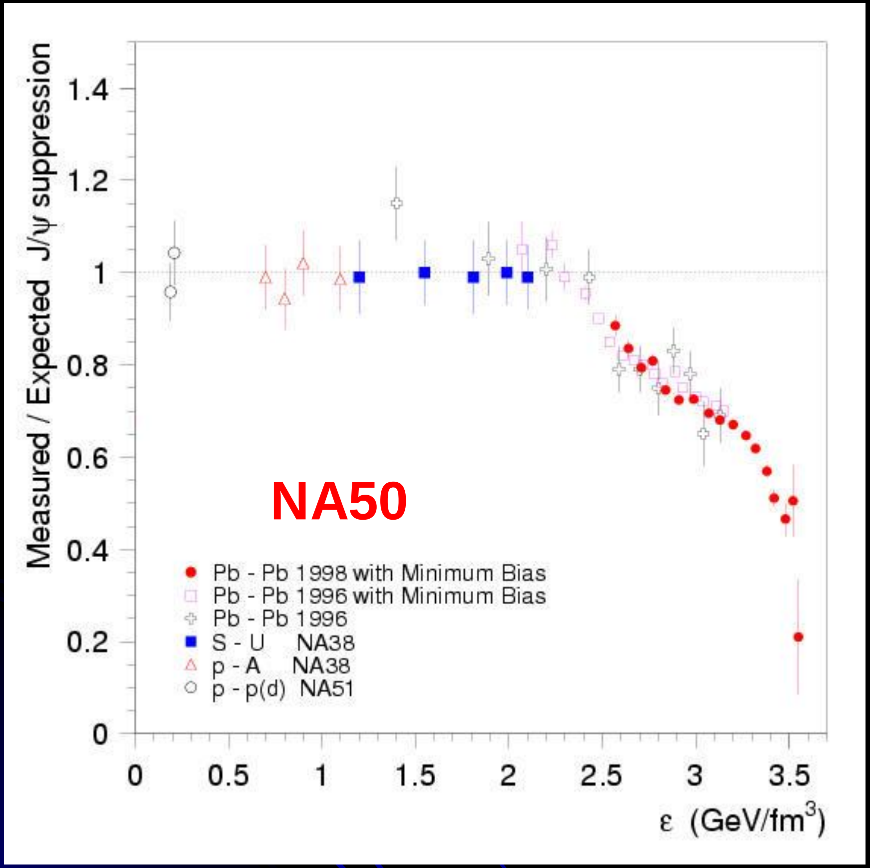
Quarkonia

Charmonium suppression

- QGP signature proposed by Matsui and Satz, 1986
- In the plasma phase the interaction potential is expected to be screened beyond the Debye length λ_D(analogous to e.m. Debye screening):
- Charmonium ($c\bar{c}$) and bottonium ($b\bar{b}$) states with r > $\lambda_D$will not bind; their production will be suppressed

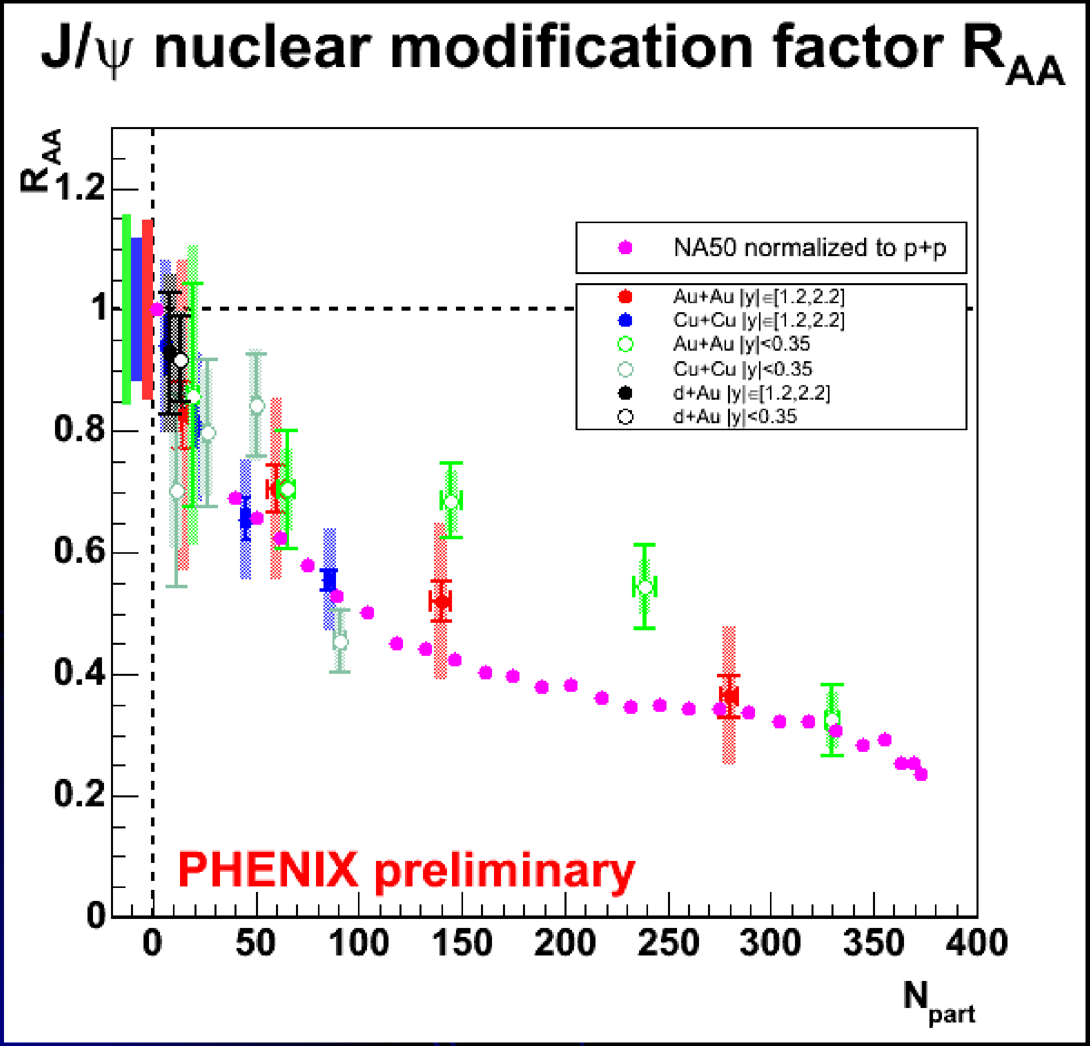


J/ψ suppression pattern at the SPS



- measured/expected J/ψ suppression vs estimated energy density
  - anomalous suppression sets in at $\varepsilon \sim 2.3$ GeV/fm^3 ($b \sim 8$ fm)
  - effect seems to accelerate at $\varepsilon \sim 3$ GeV/fm^3 ($b \sim 3.6$ fm)
  - this pattern has been interpreted as successive melting of the χ_c and of the J/ψ

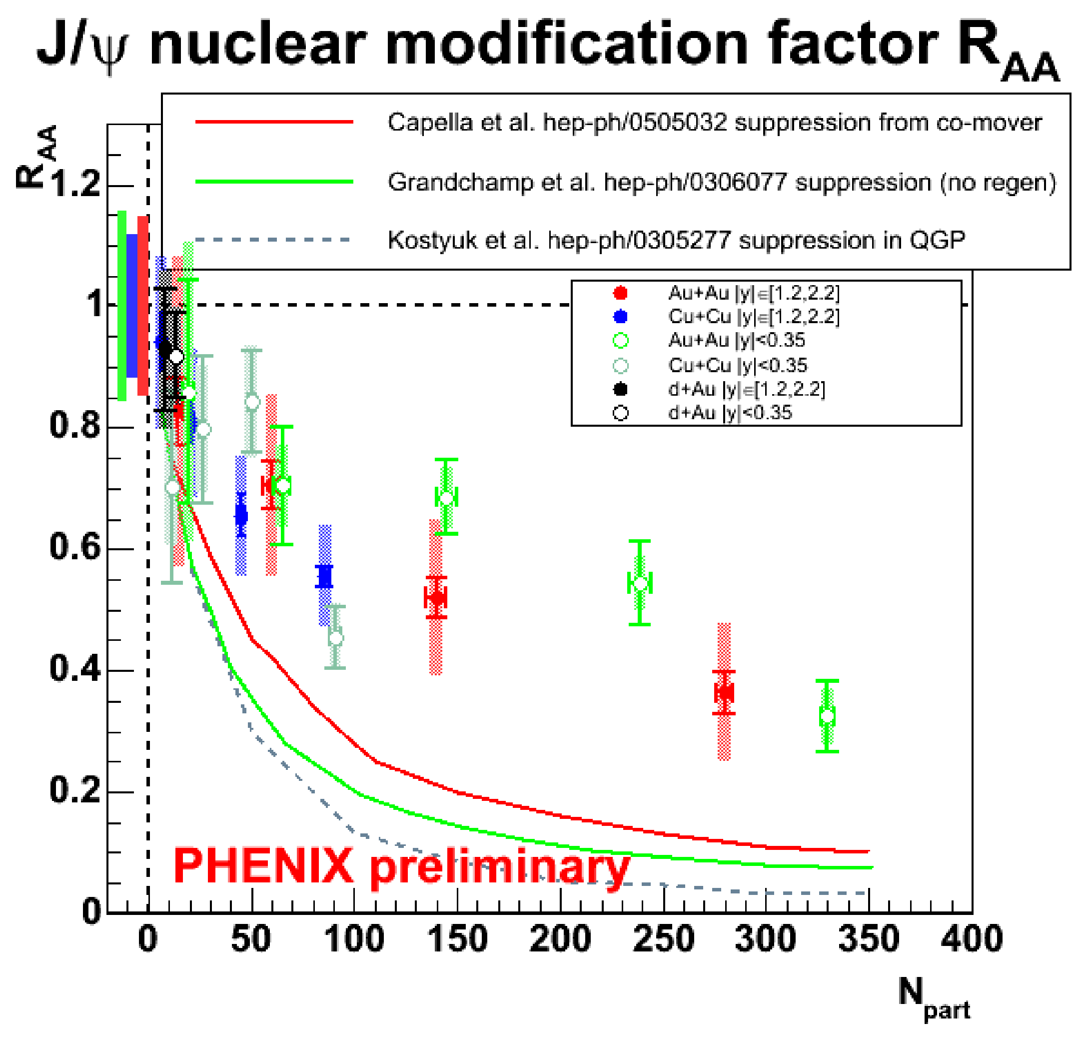
J/ψ suppression at RHIC



[Hugo Pereira (PHENIX), QM05]

- J/ψ ~ as suppressed as at SPS (NA50)

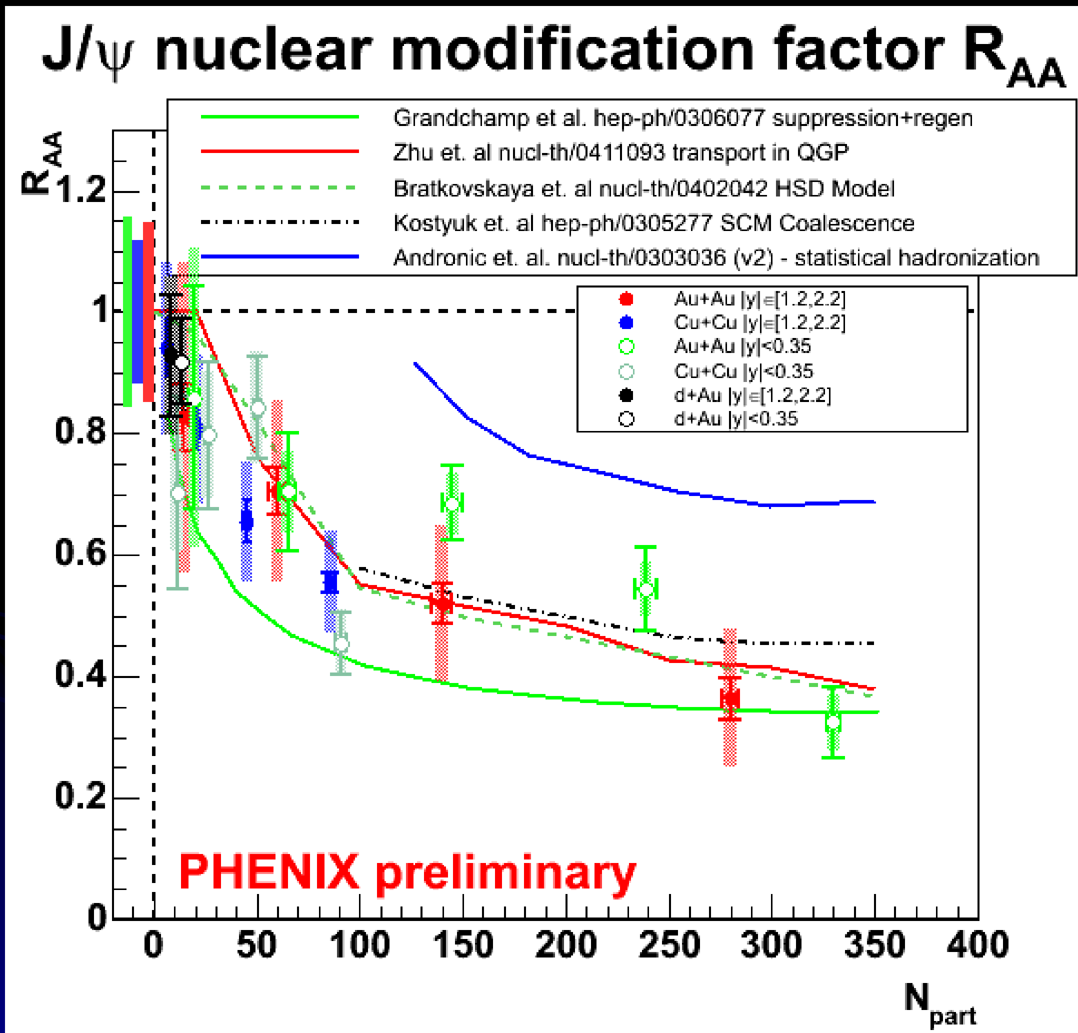
J/ψ suppression at RHIC



[Hugo Pereira (PHENIX), QM05]

- all models reproducing magnitude of J/ψ suppression at SPS predicted larger suppression at RHIC

J/ψ suppression at RHIC

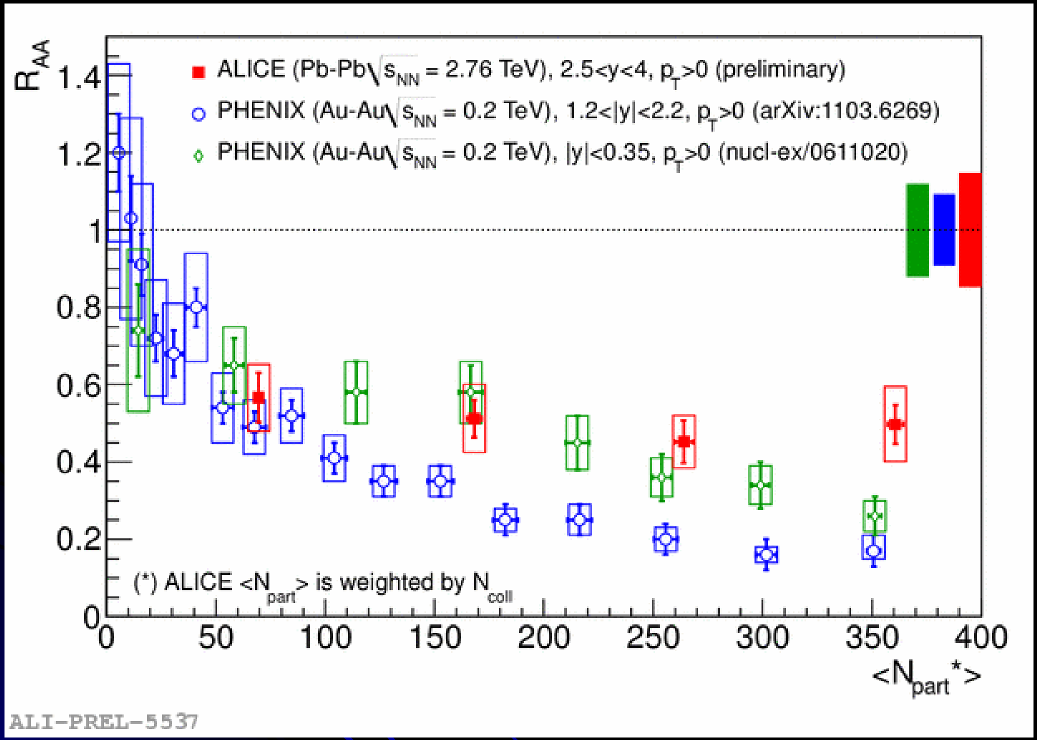


[Hugo Pereira (PHENIX), QM05]

- Models including recombination of c and $\bar{c}$ produced in different initial parton-parton collisions do better…

J/ψ @ LHC: forward y, low p_T

- LHC: $2.5 < y < 4$, $p_T > 0$ (ALICE)



→ less suppression than

RHIC: $1.2 < y < 2.2$, $p_T > 0$ (PHENIX)

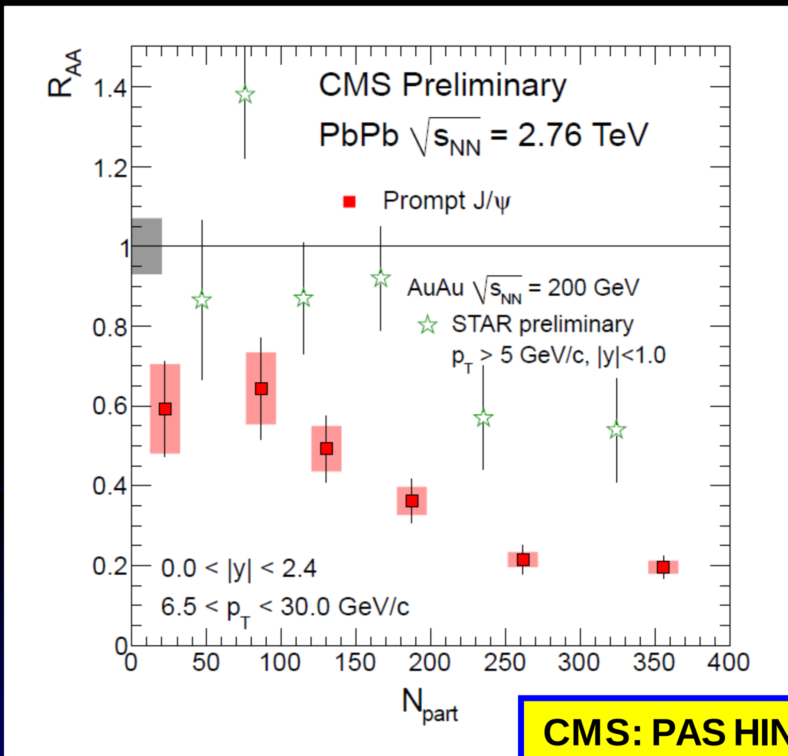
→ ~ as suppressed as

RHIC: $|y| < 0.35$. $pT > 0$ (PHENIX)

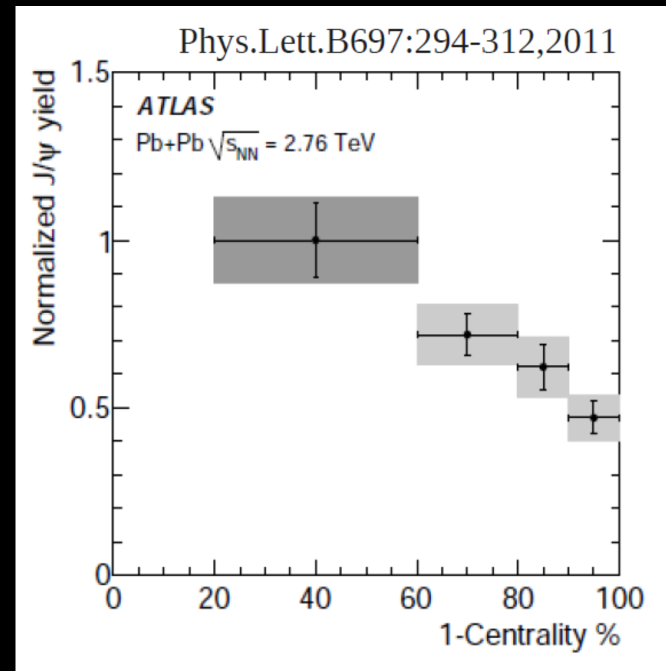
Ginés Martínez – ALICE (QM2011)

J/ψ @ LHC: central y, high p_T

- LHC: $|y| < 2.4$, $p_T > 6.5$ GeV/c (CMS)
  prompt J/ψ
- LHC $|y| < 2.5$, $pT > 3$ GeV/c (ATLAS)



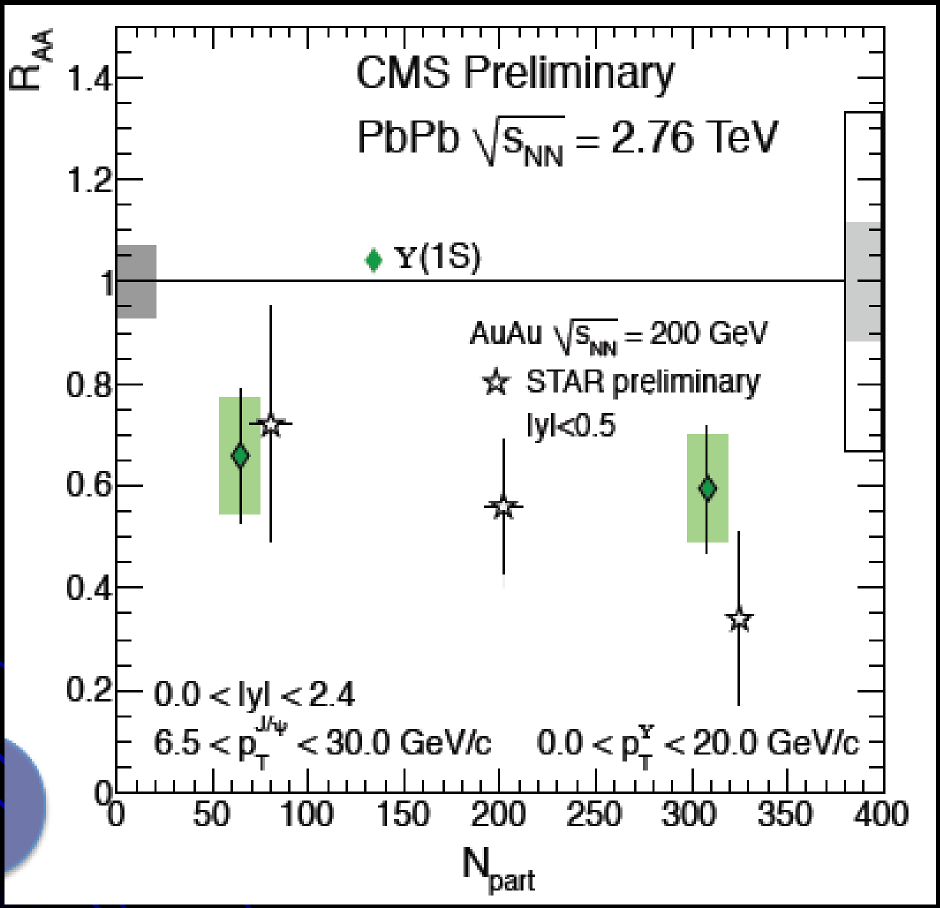
CMS: PAS HIN-10-006



ATLAS: PLB 697 (2011) 294

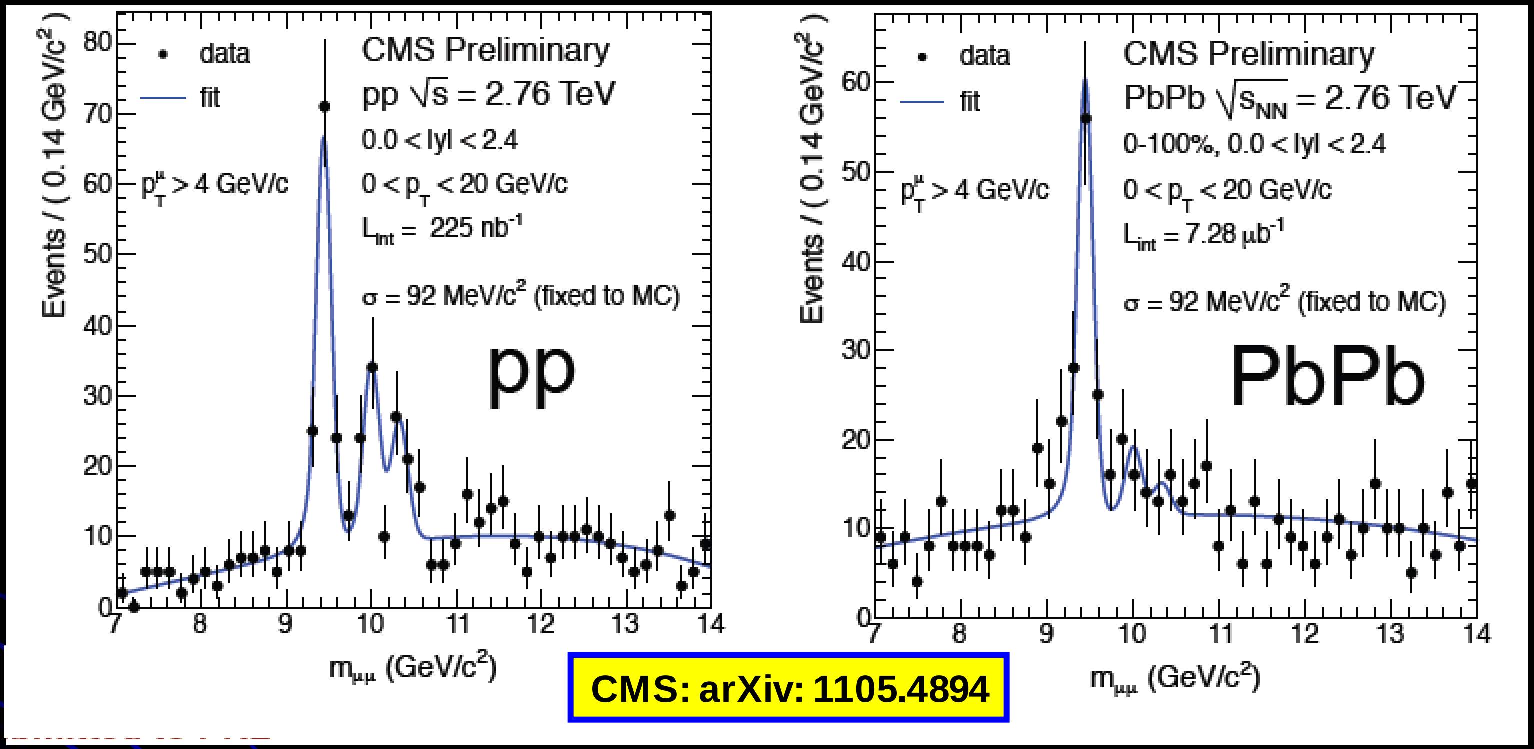
→ more suppressed than
RHIC: $|y| < 1$. $pT > 5$ GeV/c (STAR)
inclusive J/ ψ

Υ(1S) suppression



CMS: PAS HIN-10-006

ϒ(2S+3S) suppression!



- additional suppression for ϒ(2S+3S) w.r.t. ϒ(1S) ?

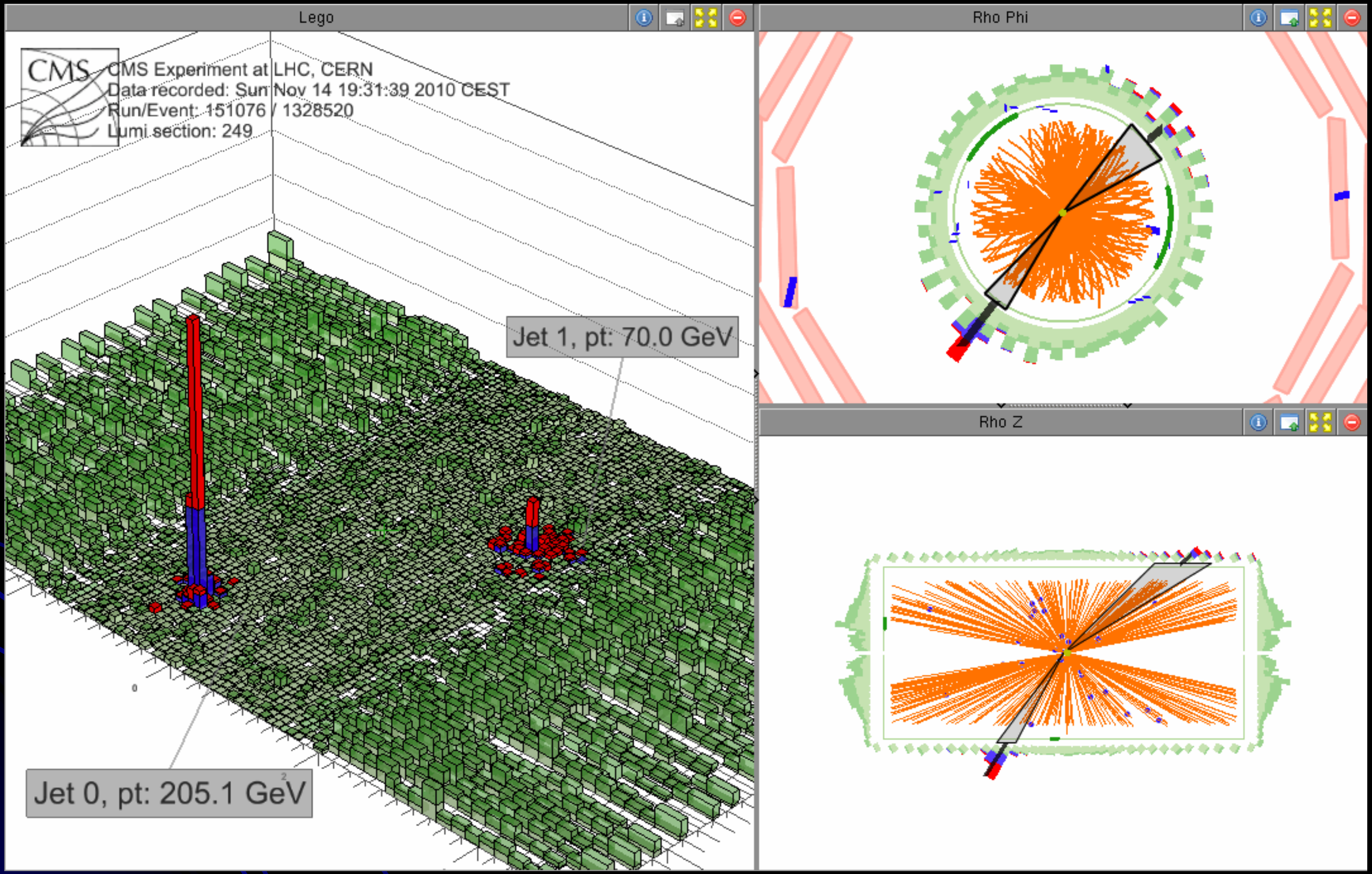
Quarkonia: outlook

- the future runs should allow us to establish quantitatively the complete quarkonium suppression(/recombination?) pattern
  - high statistic measurements
  - open flavour baseline / contamination
  - pA baseline

Jets

Di-jet imbalance

- Pb-Pb events with large di-jet imbalance observed at the LHC

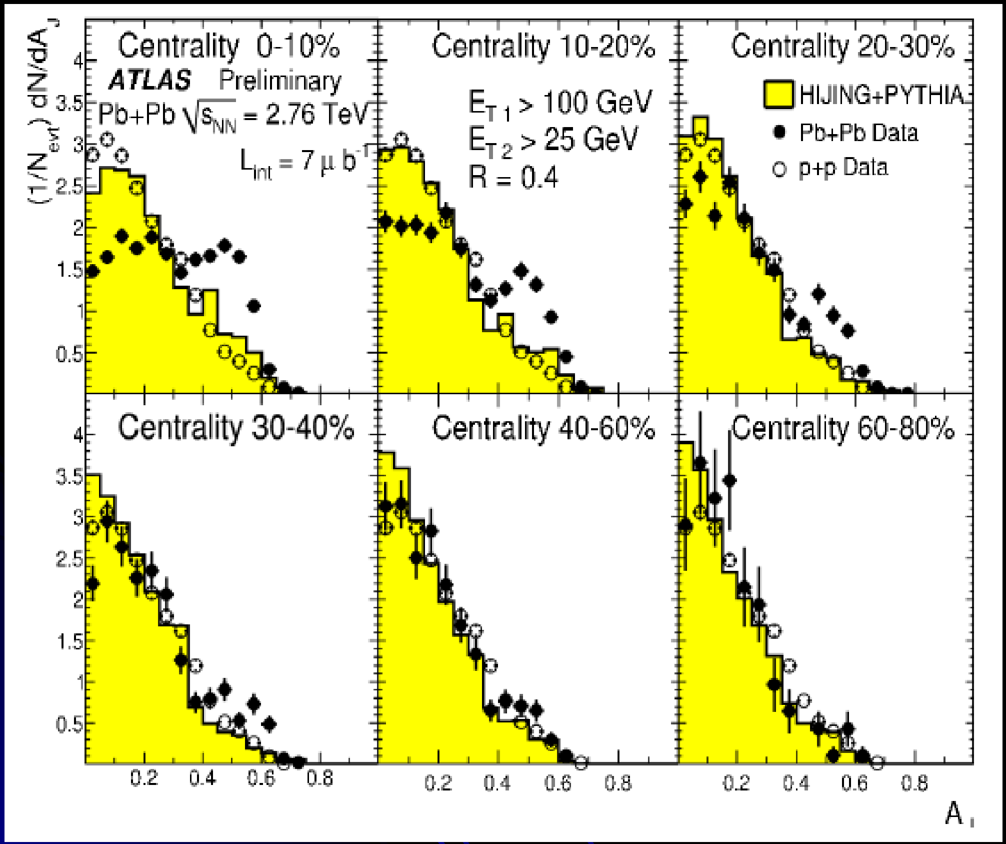


→ recoiling jet strongly quenched!

CMS: arXiv:1102.1957

A_J

- imbalance quantified by the di-jet asymmetry variable A_J:



$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \qquad E_{T1} > 100\,GeV \quad E_{T2} > 25\,GeV$$

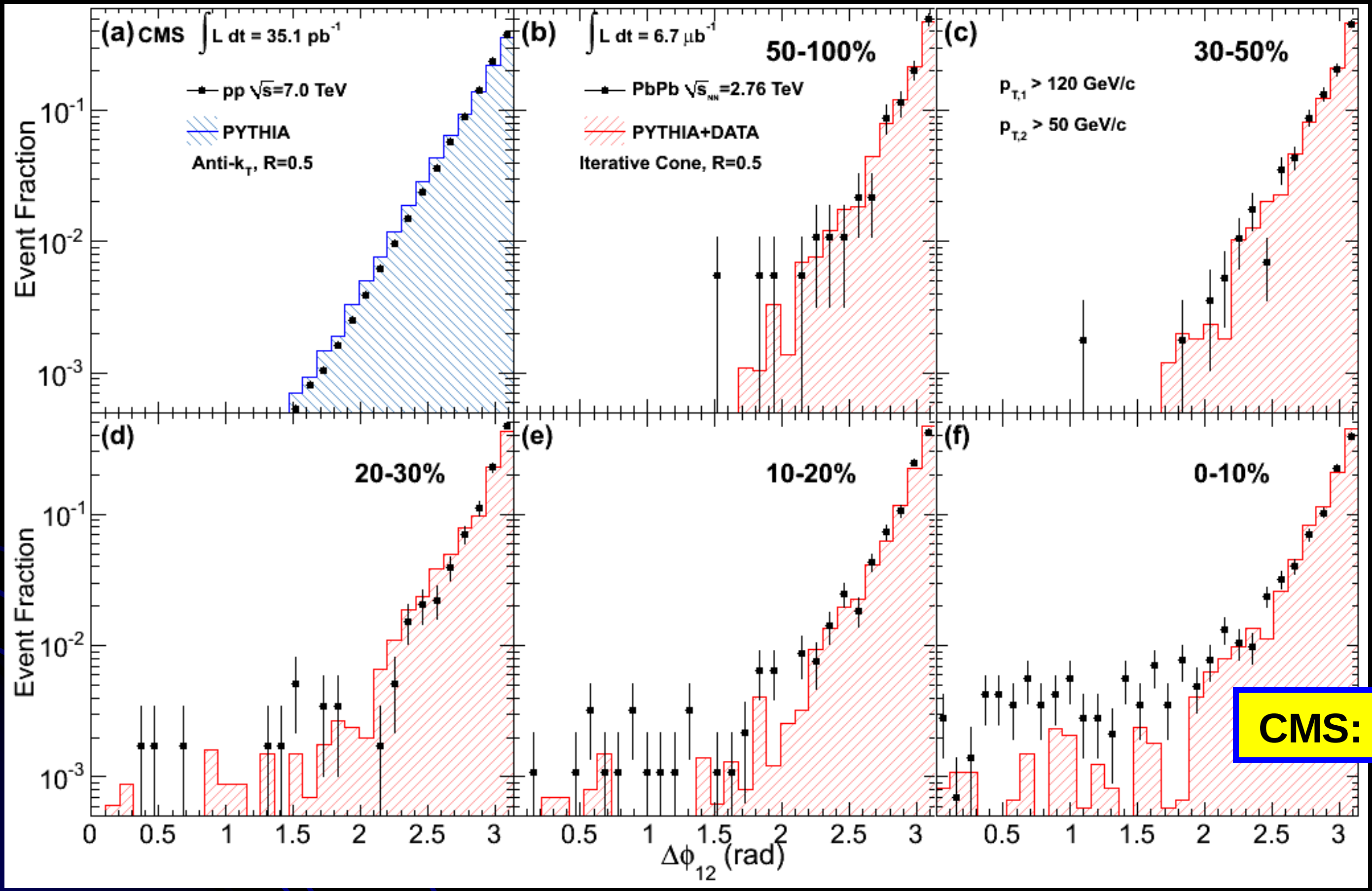
- with increasing centrality:

→ enhancement of asymmetric di-jets with respect to pp
  - & HIJING + PYTHIA simulation

ATLAS: PRL105 (2010) 252303

Di-jet Δφ

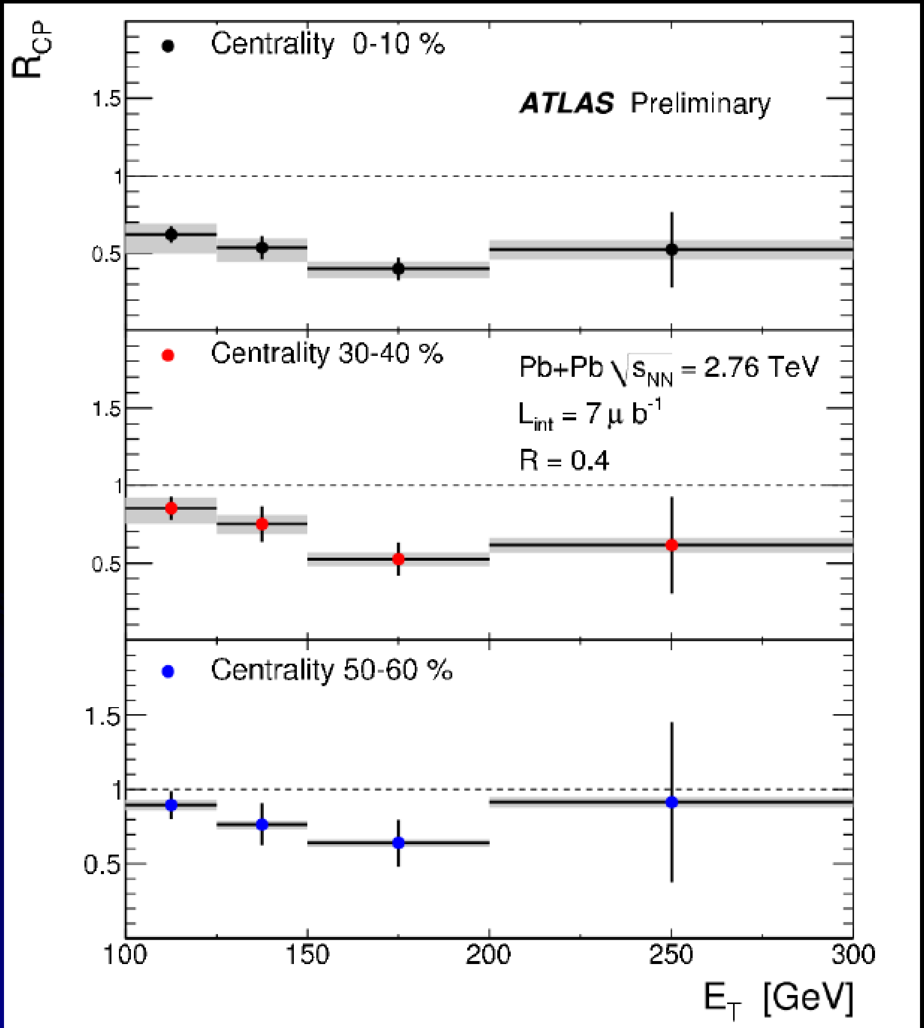
- no visible angular decorrelation in Δφ wrt pp collisions!



CMS: arXiv:1102.1957

→ large imbalance effect on jet energy, but very little effect on jet direction!

Jet nuclear modification factor



$$R_{CP} = \frac{<Nbin>_{Central} \ \text{Yield}_{\ Central}}{<Nbin>_{Peripheral} \ \text{Yield}_{\ Peripheral}}$$

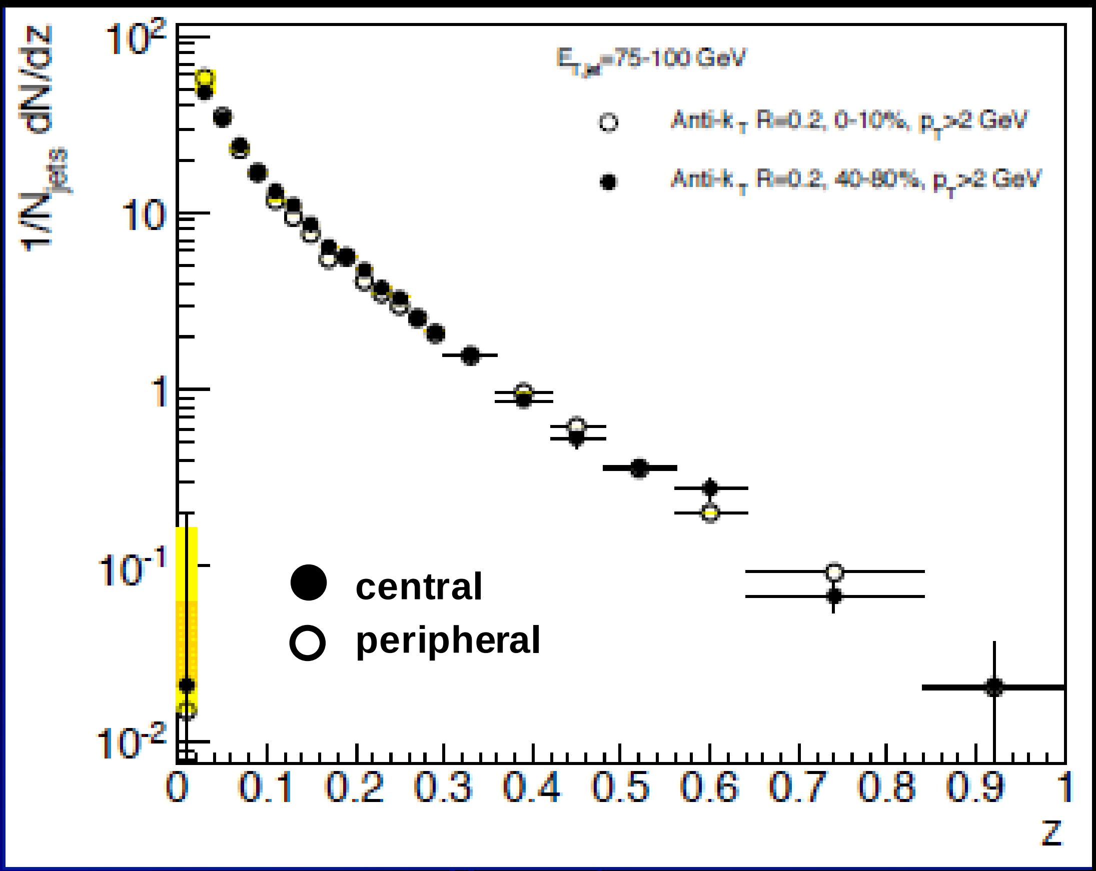
→ substantial suppression of jet production
- in central Pb-Pb wrt binary-scaled peripheral

→ out to very large jet energies!

Brian Cole – ATLAS (QM2011)

Jet fragmentation function

- distribution of the momenta of the fragments along the jet axis



Brian Cole – ATLAS (QM2011)

$$z = \frac{p_T^{hadron} \cdot \cos(\Delta R)}{E_T^{jet}}$$

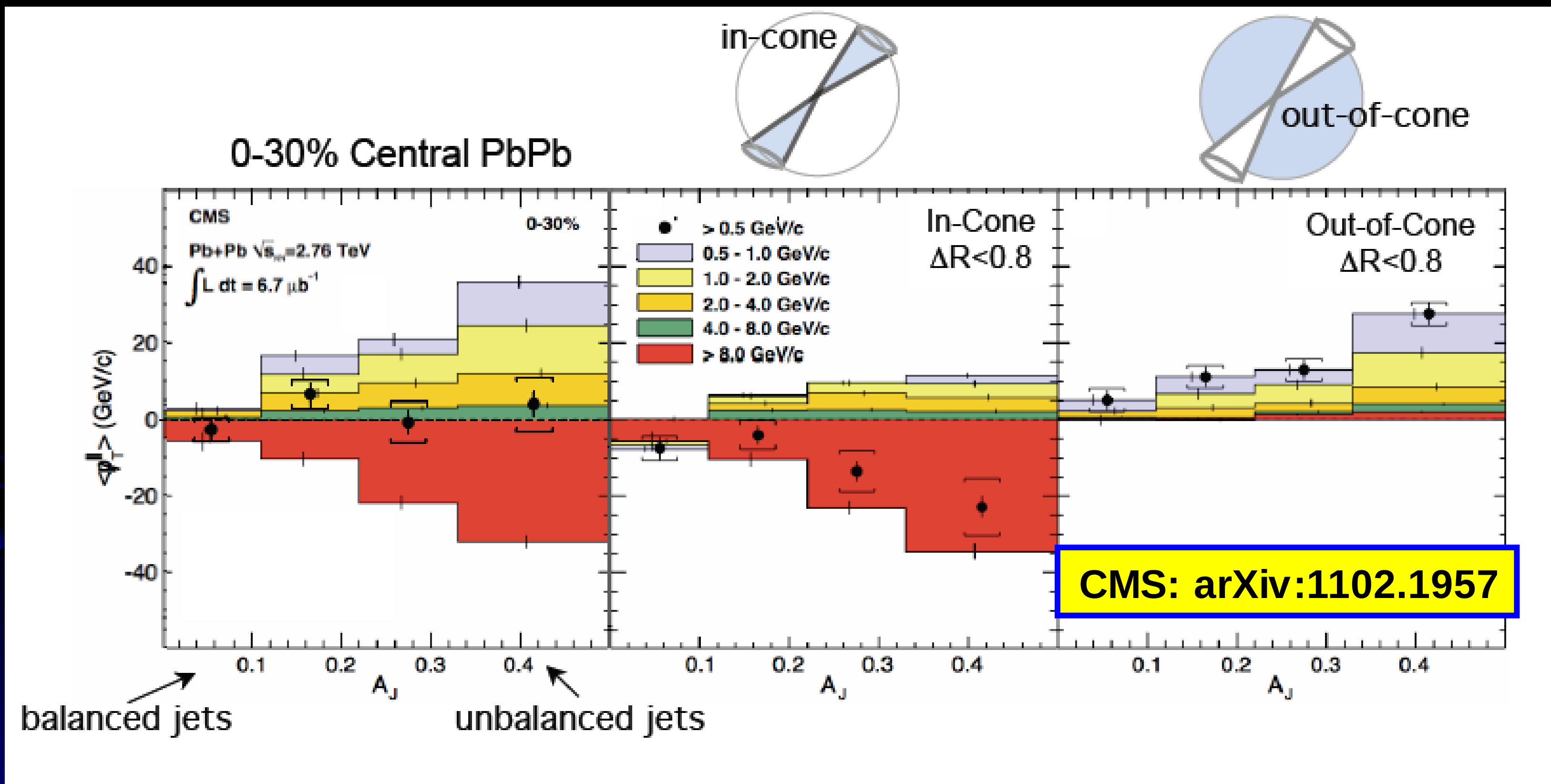
- distribution is very similar in central and peripheral events
  - although quenching is very different…

→ apparently no effect from quenching inside the jet cone…

→ another puzzle ?

Where does the energy end up?

- nice analysis by CMS using reconstructed tracks:



→ momentum difference is balanced by low momentum particles outside of the jet cone

What next?

- understand theoretically what is going on
  - strong di-jet asymmetry
  - no visible effects in fragmentation function, dijet angular correlations…
- γ/Z-jet fragmentation functions
  - measure fragmentation function of jets recoiling against vector bosons → low-bias estimate of jet energy before quenching
- explore the surroundings of away-side jets
  - broadening? softening? re-heating?
- in-medium fragmentation vs reaction plane
  - path length dependence!
- b-tagged jets (quark vs gluon jets)
- extreme suppression?
  - "mono-jet" events? what do they look like?

Heavy flavours

Charm and beauty: ideal probes

- study medium with probes of known colour charge and mass
  - → e.g.: energy loss by gluon radiation expected to be:
  - parton-specific: stronger for gluons than quarks (colour charge)
  - flavour-specific: stronger for lighter than for heavier quarks (dead-cone effect)
- study effect of medium on fragmentation (no extra production of c, b at hadronization)
  - → independent string fragmentation vs recombination
  - e.g.: D^{+}_{s}/D^{+}
- + measurement important for quarkonium physics
  - open $Q\bar{Q}$ production natural normalization for quarkonium studies
  - B meson decays non negligible source of non-prompt J/ψ

Theoretically…

$$\langle \Delta E \rangle \propto \alpha_s \, C_R \, \hat{q} \, L^2$$

average energy loss

Casimir coupling factor

transport coefficient of the medium

distance travelled in the medium

→ R.Baier et al., Nucl. Phys. **B483** (1997) 291 ("BDMPS")

Energy loss for heavy flavours is expected to be reduced:

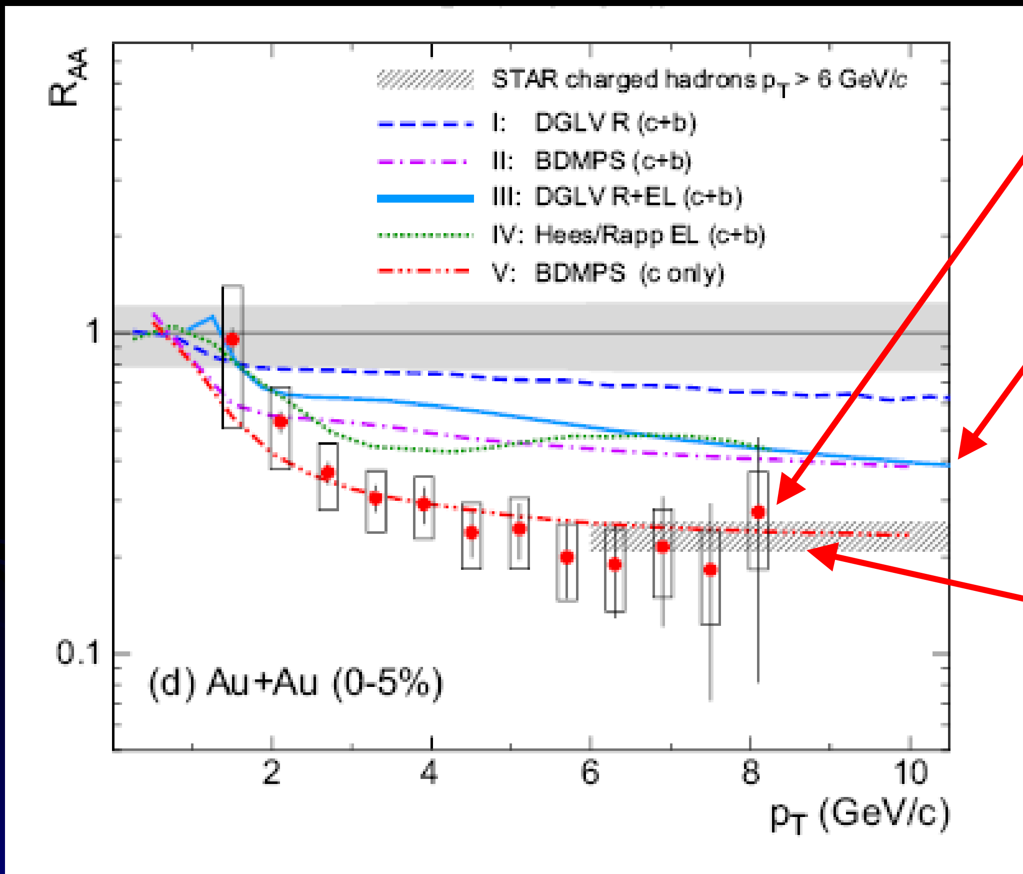
i) Casimir factor

- light hadrons originate from a mixture of gluon and quark jets, heavy flavoured hadrons originate from quark jets
- C_R is 4/3 for quarks, 3 for gluons

ii) dead-cone effect

- gluon radiation expected to be suppressed for $\theta < M_Q/E_Q$
  [Dokshitzer & Karzeev, Phys. Lett. **B519** (2001) 199]
  [Armesto et al., Phys. Rev. D69 (2004) 114003]

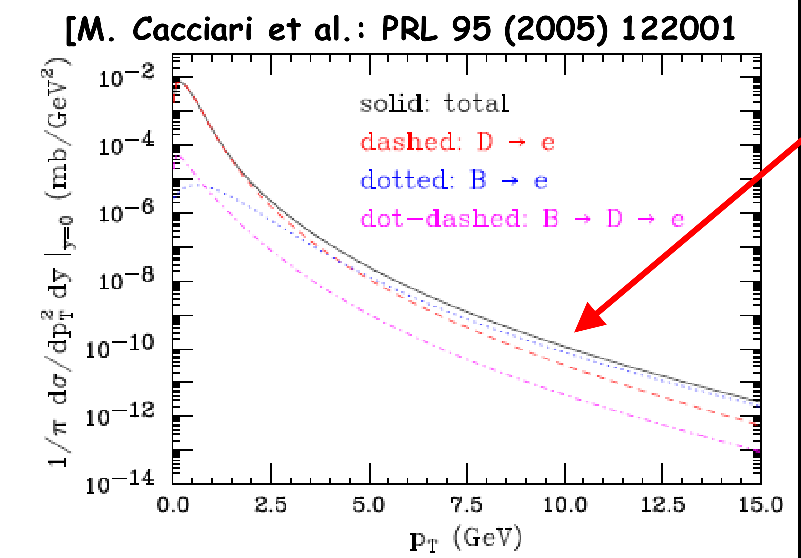
Experimentally: at RHIC



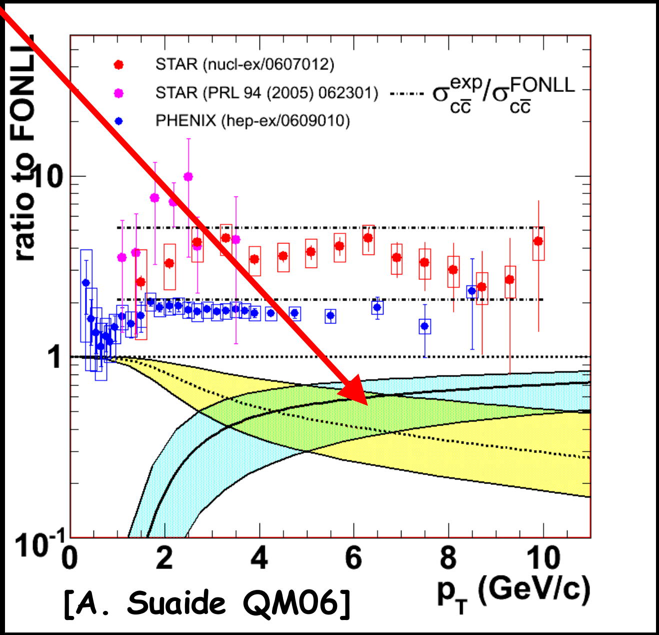
- HF e ~ as suppressed as light hadrons
- use of high density (qhat), introduction of elastic (in addition to radiative) energy loss... not enough
- high qhat and no beauty electrons does better

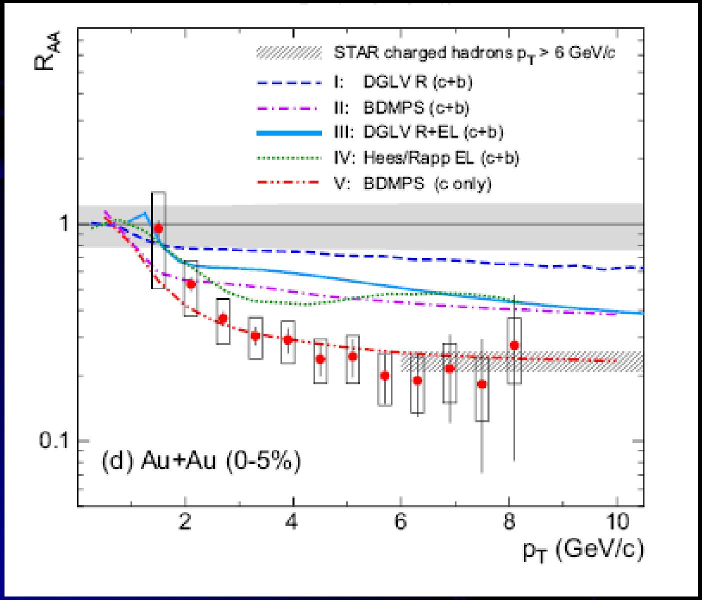
[B.I. Abelev et al (STAR): nucl-ex/0607012]

How much beauty?



- high p_T region expected to be beauty-dominated
- but how "high"?





- not easy to disentangle c/b contributions to RHIC HF e samples (no heavy flavour vertex detectors in RHIC experiments)

Vertex Detectors!

- need less indirect measurement

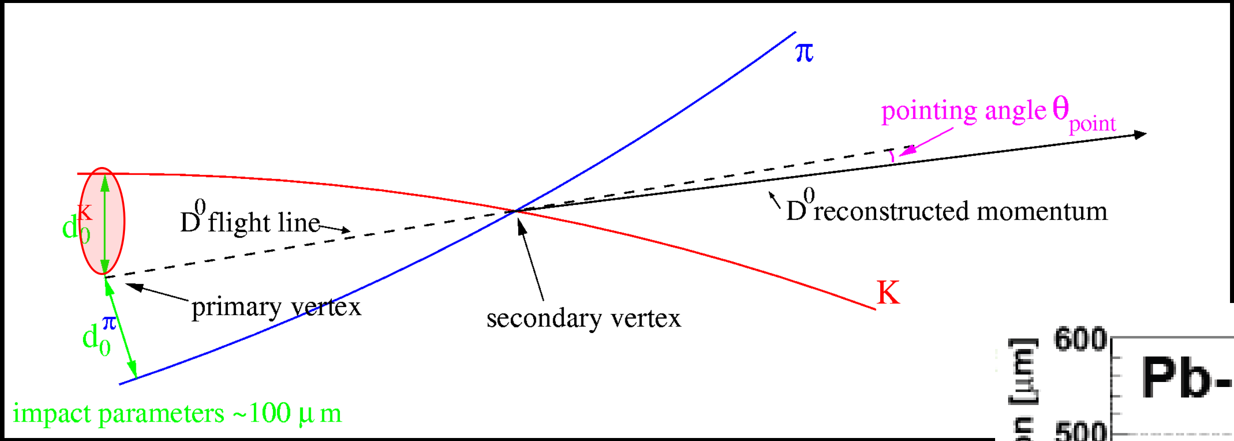
→ full reconstruction of charm decays!
  - get rid of b/c ambiguities
  - study relative abundances in charm sector

- Silicon Pixels in ALICE, ATLAS, CMS

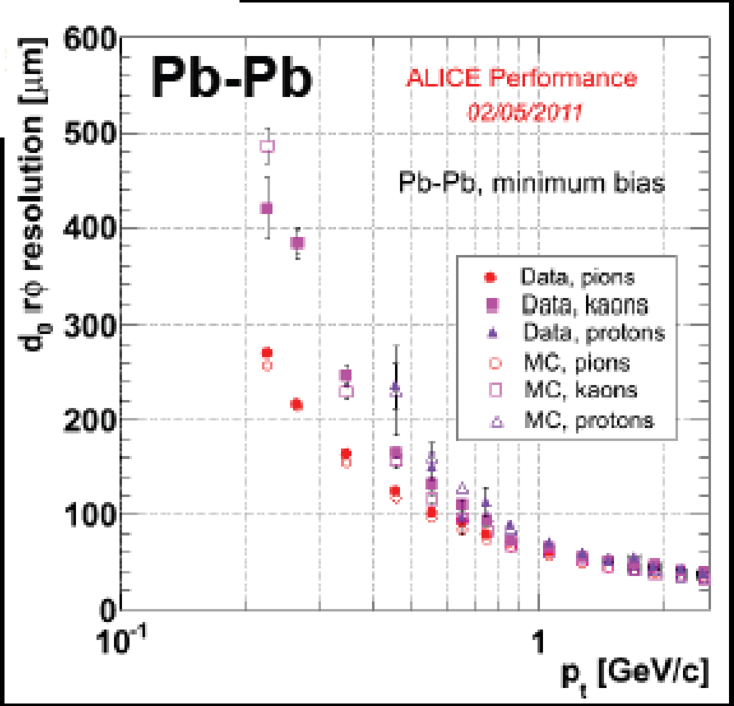
- + Silicon Vertex upgrades in STAR, PHENIX

Track Impact Parameter

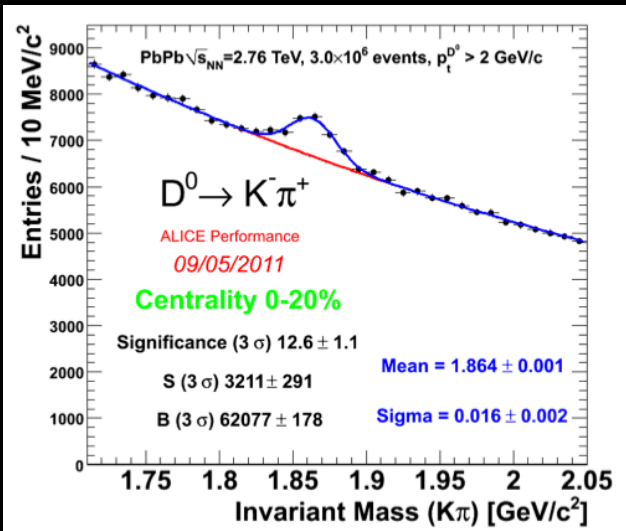
- track impact parameter (d_0): separation of secondary tracks from HF decays from primary vertex

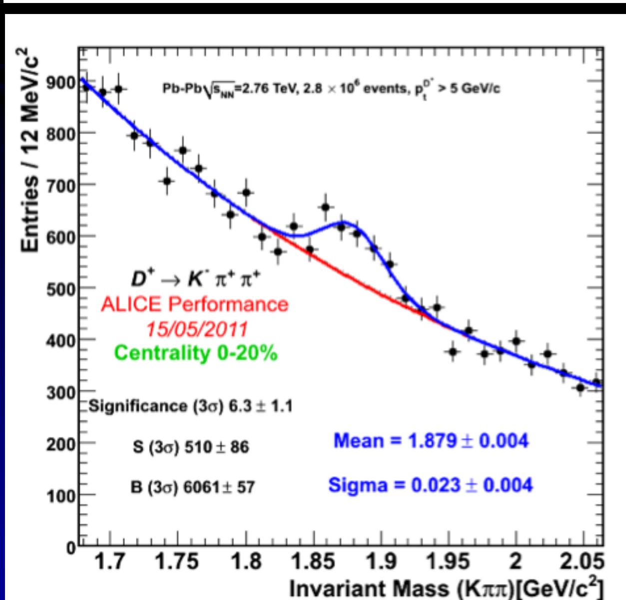


- e.g.: d_0 resolution in ALICE

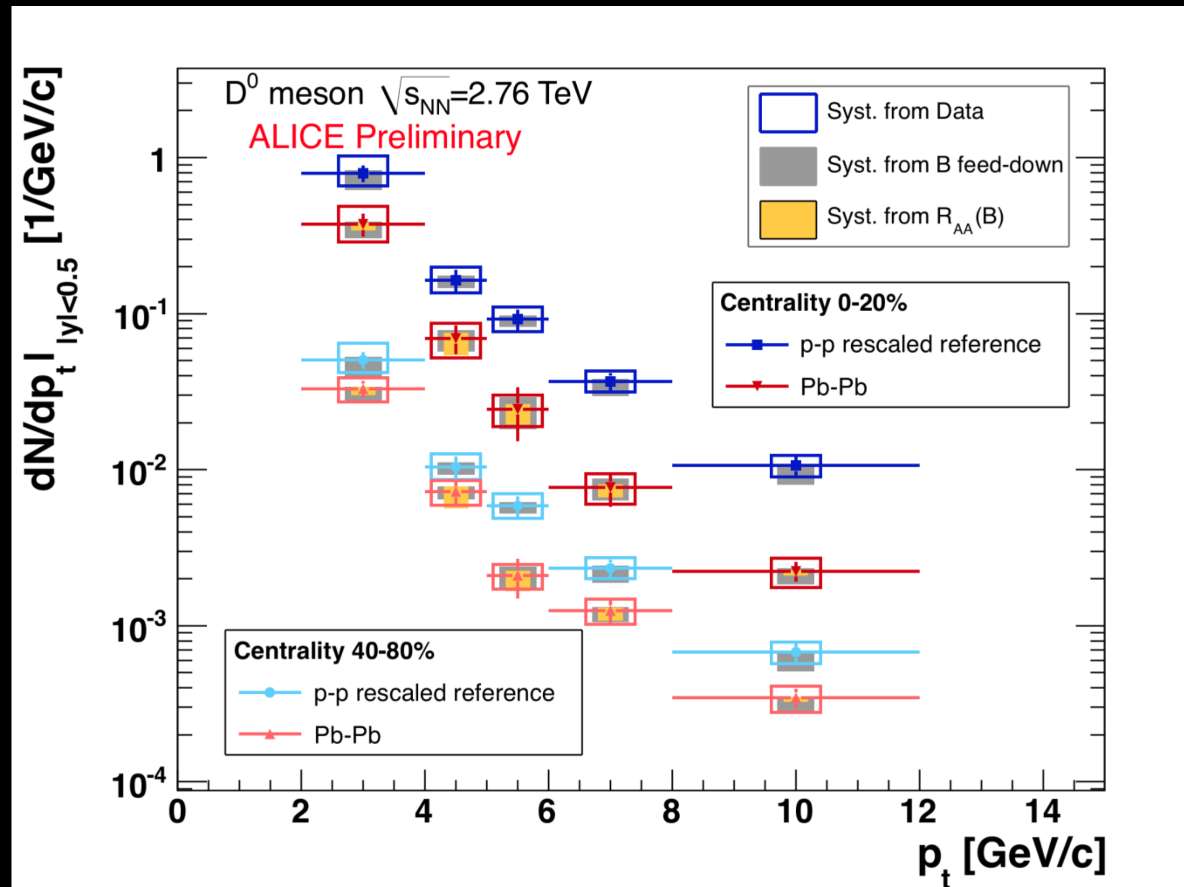


Reconstructed D decays

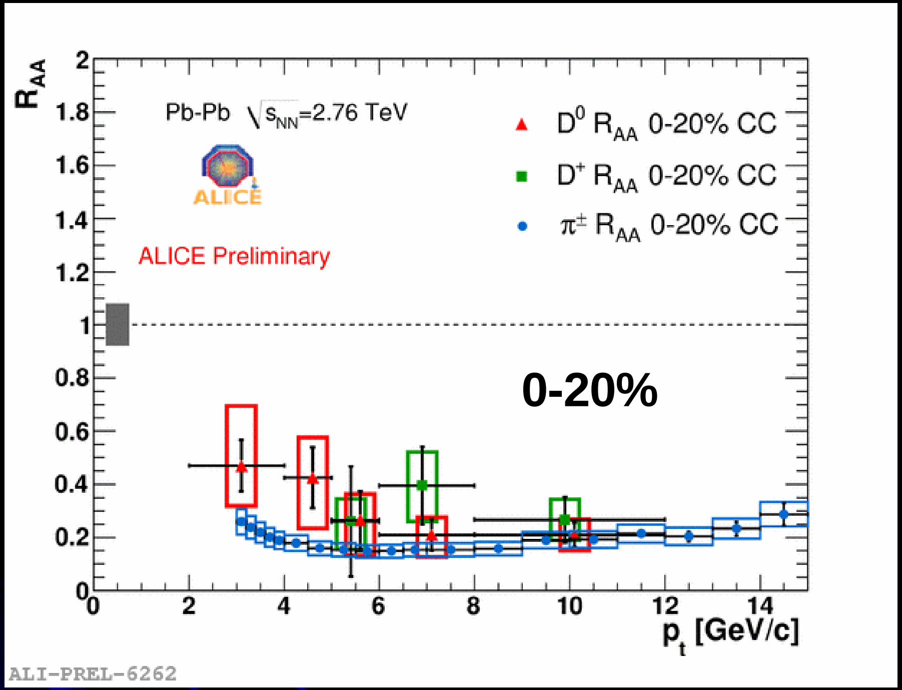


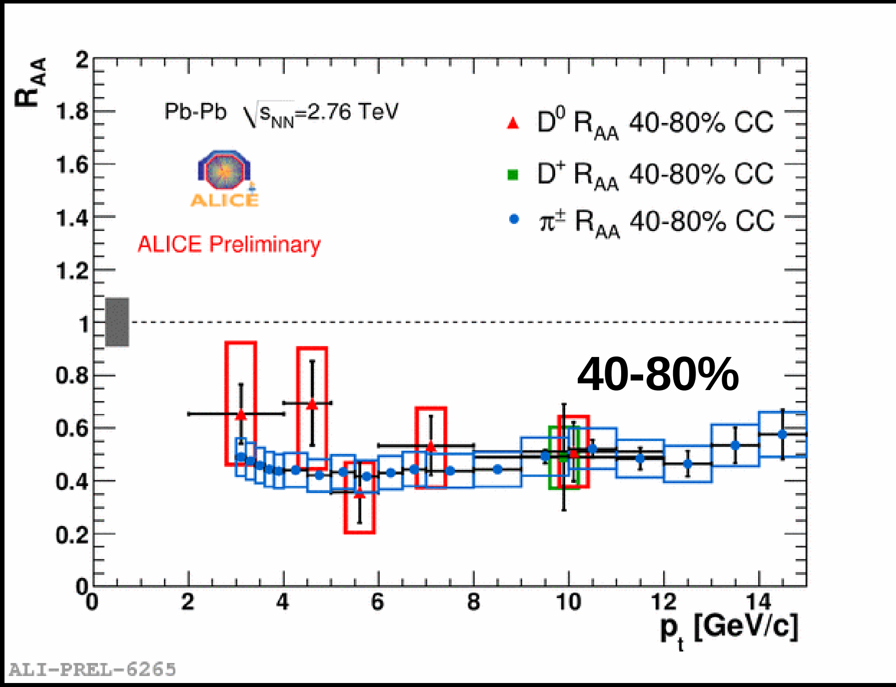


→ strong suppression observed in central Pb-Pb (0-20%) with respect to scaled pp reference



Comparison: D and $\pi^{\pm}$ suppression



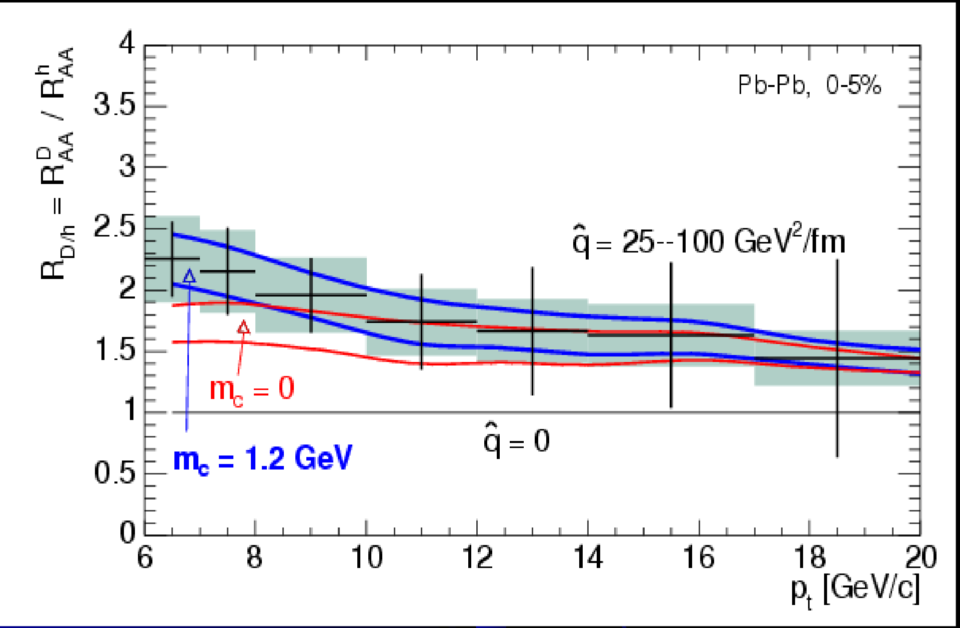


- charm is substantially suppressed:
  - in central collisions: ~ a factor 4-5 for $p_T > 5$ GeV/c
- D meson R_{AA} compatible with $\pi^{\pm}$ R_{AA}
  - slightly larger for $p_T < 5$ GeV/c

How about the colour factor?

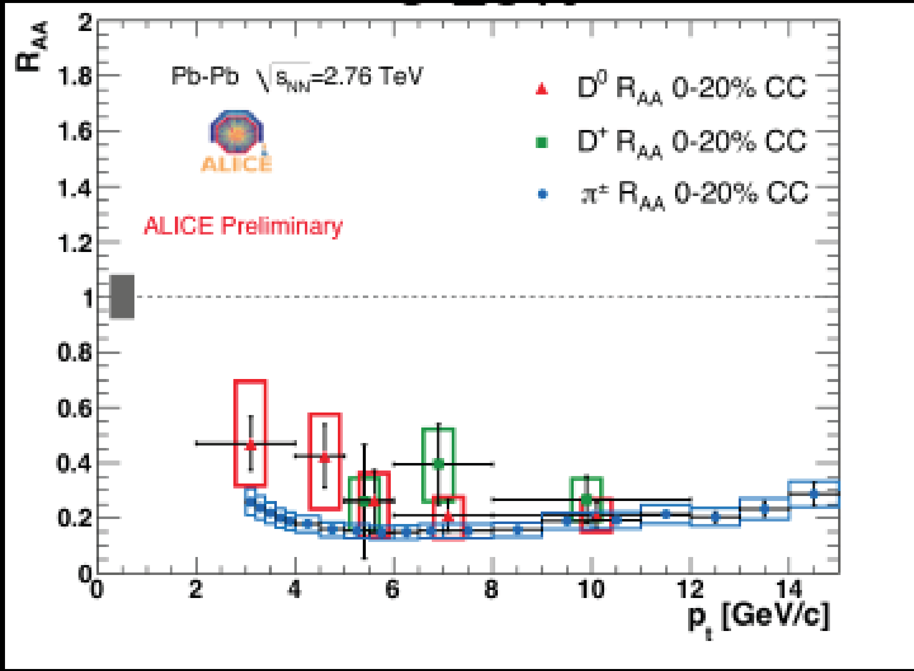
- quarks (C_R = 4/3) expected to couple weaker than gluons (C_R = 3)

→ at p_T ~ 8 GeV, factor ~ 2 less suppression expected for D than for light hadrons in gluon radiation energy loss prediction



N Armesto et al., Phys. Rev. D71 (2005) 054027

- data do show a hint of deviation ($R_{AA}^D > R_{AA}^\pi$), but at much lower p_T …

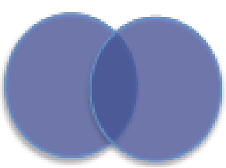


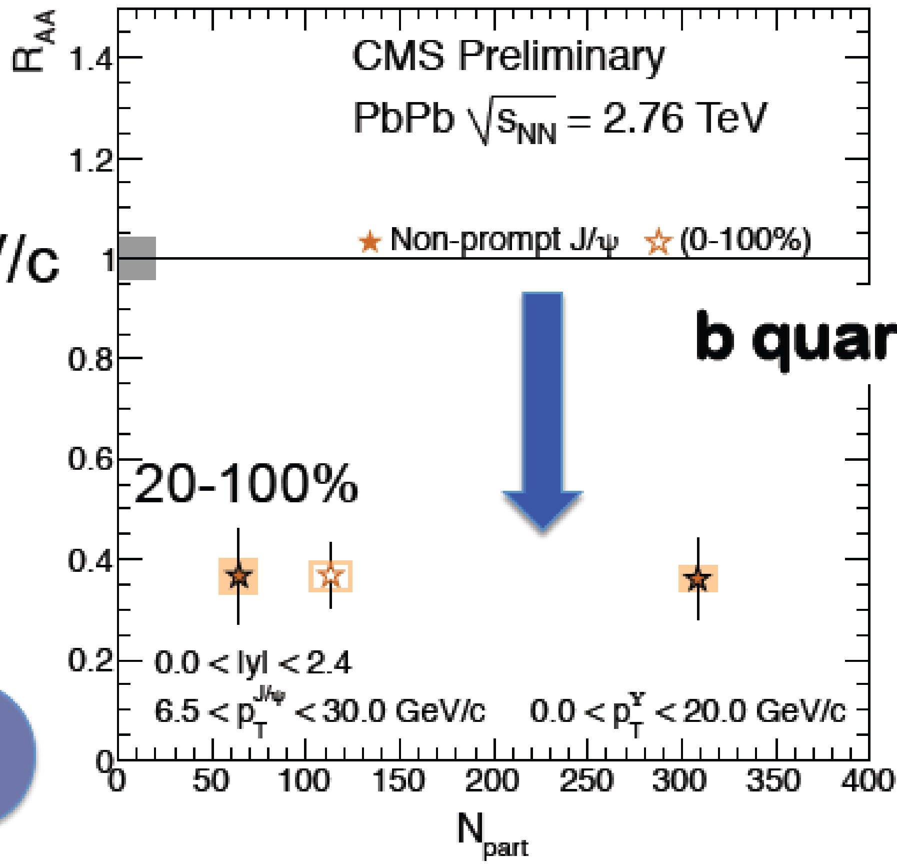
… to be continued with higher statistics…

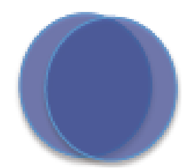
First B → J/ψ R_{AA}

PbPb
$\sqrt{s_{NN}}$=2.76 TeV

$p_T^{J/\psi}$ > 6.5 GeV/c





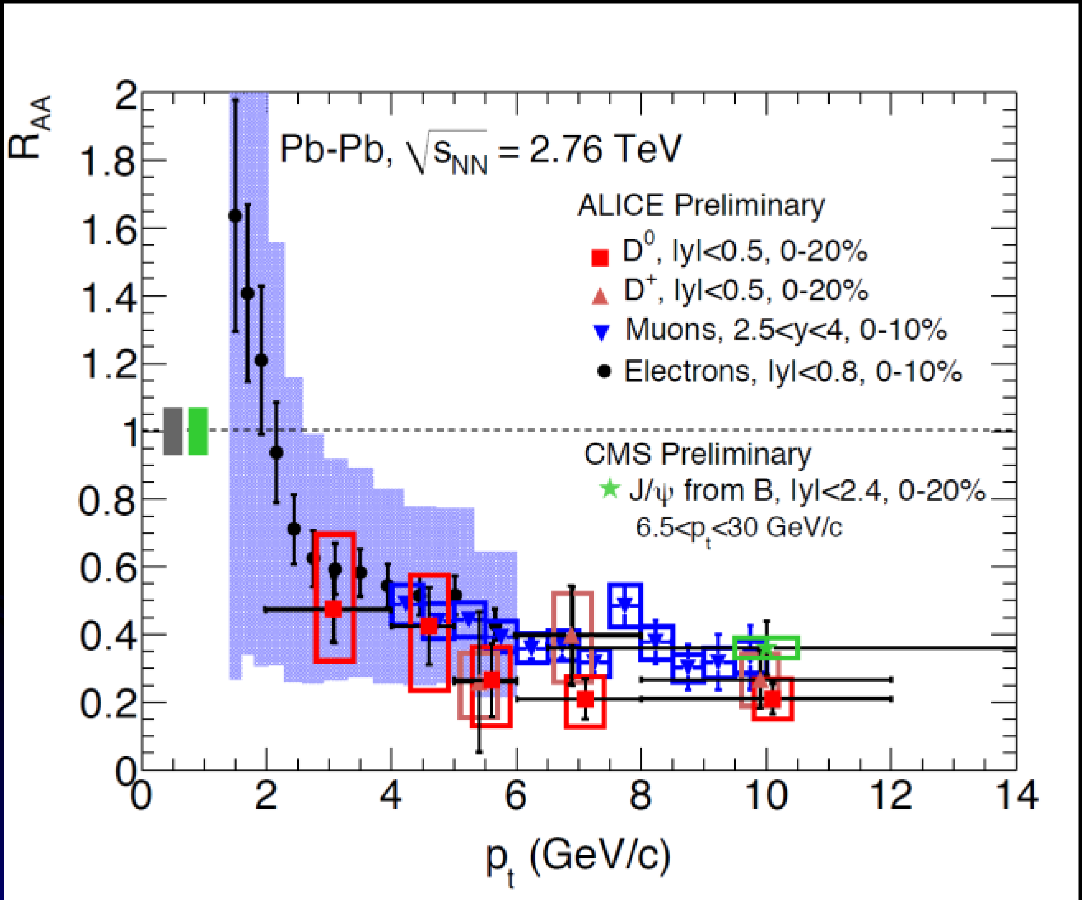


b quark energy loss ?

Minimum bias R_{AA} = 0.37 ± 0.07 ± 0.03

Central 0-20% R_{AA} = 0.36 ± 0.08 ± 0.03

c and b quenching @ LHC



→ substantial suppression of heavy flavour production
- beauty, too!

[compilation courtesy of Andrea Dainese]

→ with larger statustucs: study parton mass and colour charge dependence of interaction with medium!

Heavy Flavour: outlook

- high statistics D measurements
  → are D really as suppressed as light hadrons?
- charm thermalisation?
  → measure D mesons v2
- subtract D background → pure B electron spectrum
  - beauty energy loss in wide p_T range
- in-medium fragmentation of b-tagged jets !

Conclusions

- in November 2010, the field of ultrarelativistic nuclear collisions has entered a new era with the start of heavy ion collisions at the LHC
  - abundance of hard probes
  - state-of-the art collider detectors
- exciting results already from first, limited data samples
  - death of ridge and Mach cone?
  - anomalies in proton yields & momentum distributions
  - pattern of jet and heavy flavour suppression challenges energy loss models
- the future looks very bright
  - precision measurements → constrain dynamic and coupling properties of medium
  - look out for surprises!!!

Thank you!

(and stay tuned…)