From Heavy Ions to Quark Matter
(Episode 1)

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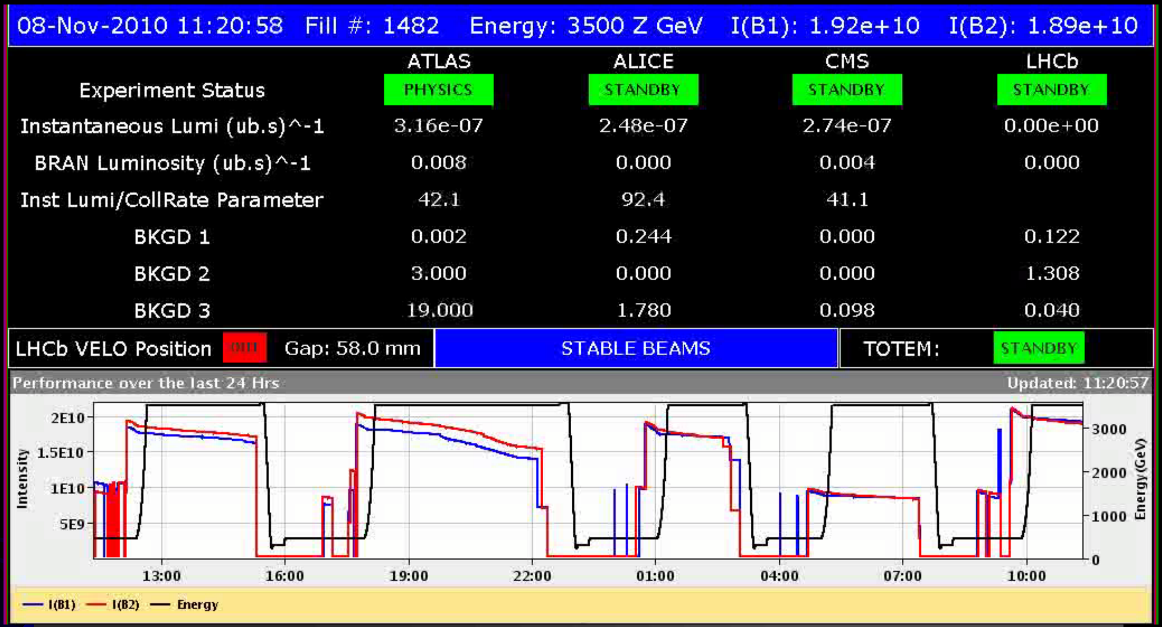
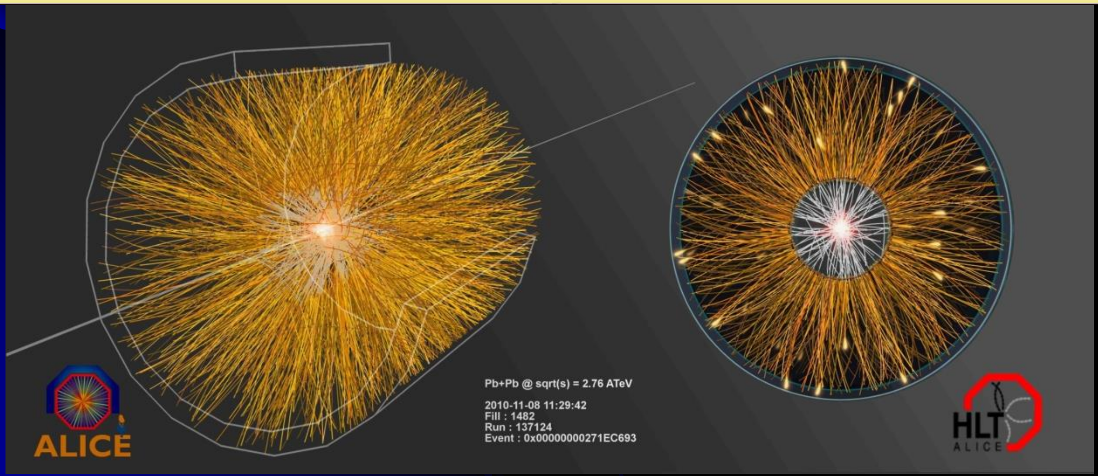
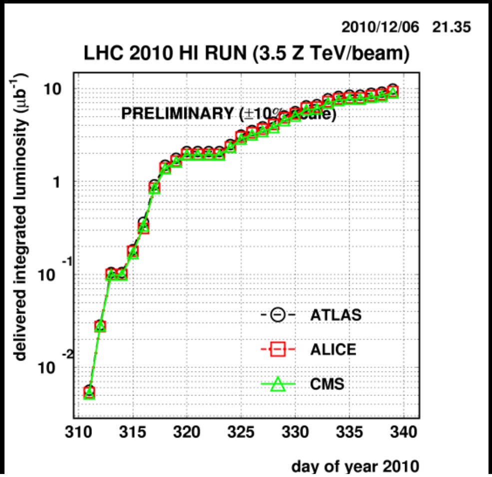
(INFN Padova, Italy & CERN, Geneva, Switzerland)

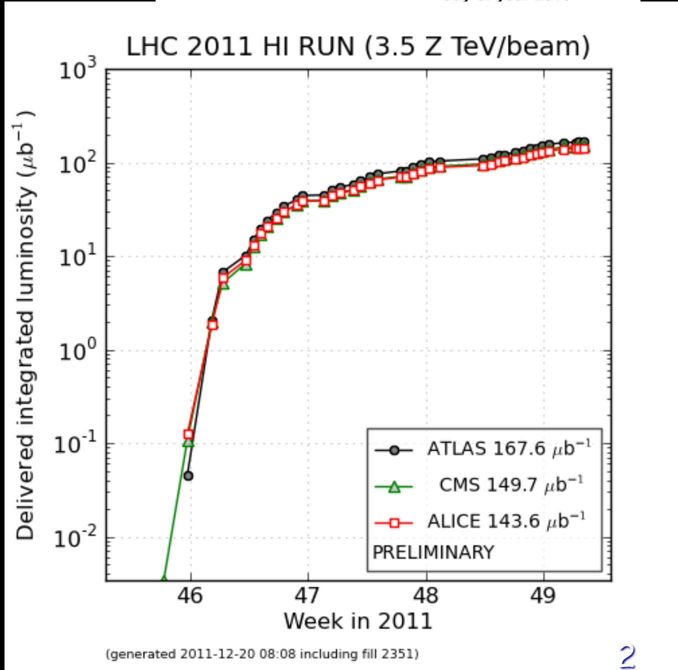
Pb-Pb collisions in the LHC!

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









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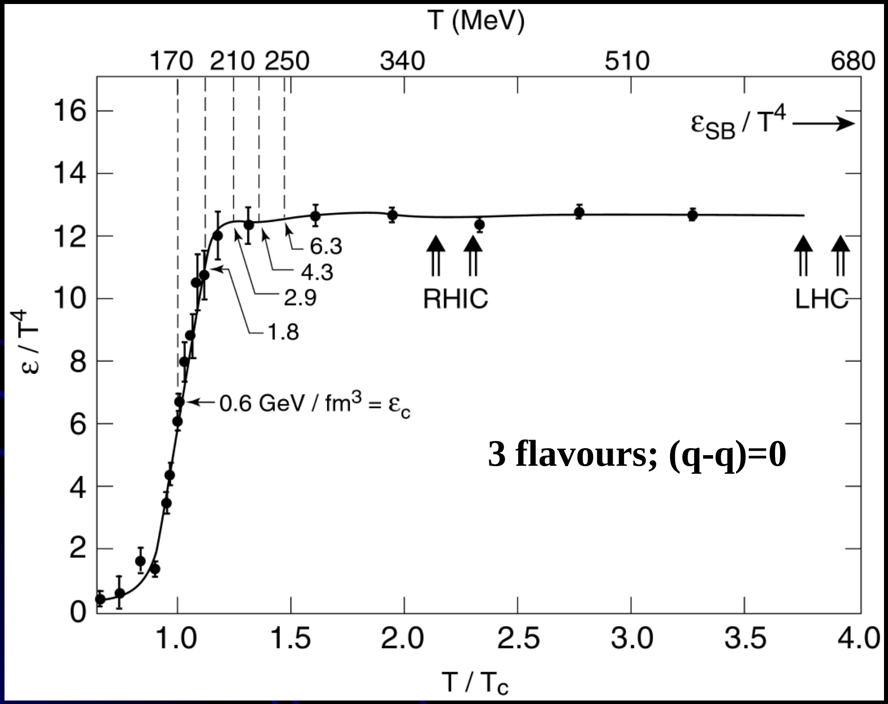
  - high p_T suppression
  - *(quarkonia production)*
  - *(jet production)*
  - heavy flavour production
  - first results from p-Pb collisions

Part 1: Introduction

Lattice QCD

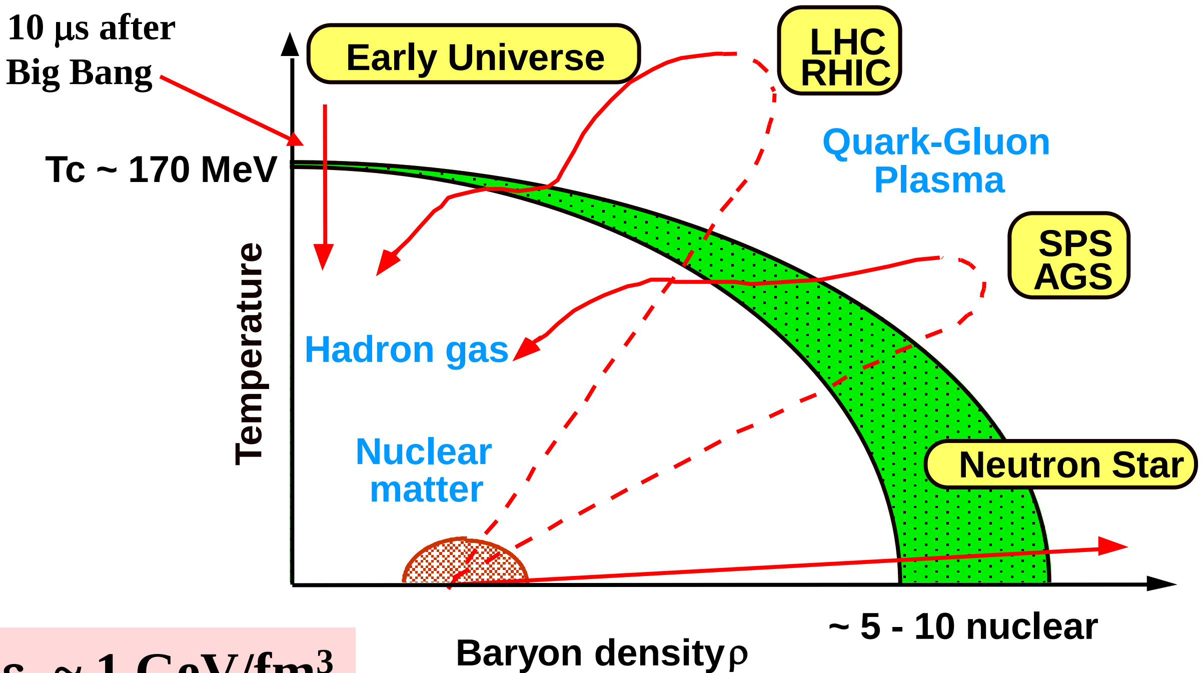
- rigorous way of doing calculations in non-perturbative regime of QCD
- discretization on a space-time lattice
  → ultraviolet (large momentum scale) divergencies can be avoided



- 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"...



$\varepsilon_c \sim 1$ GeV/fm^3

→ experimental access to phase transitions in non-abelian QFT!

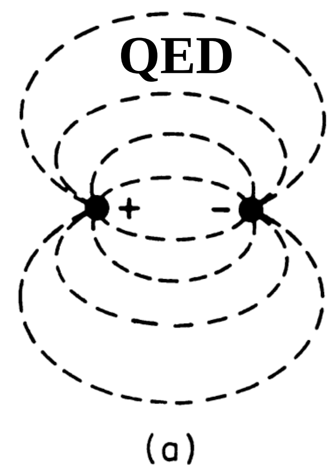
Confinement and deconfinement: an "intuitive" view

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



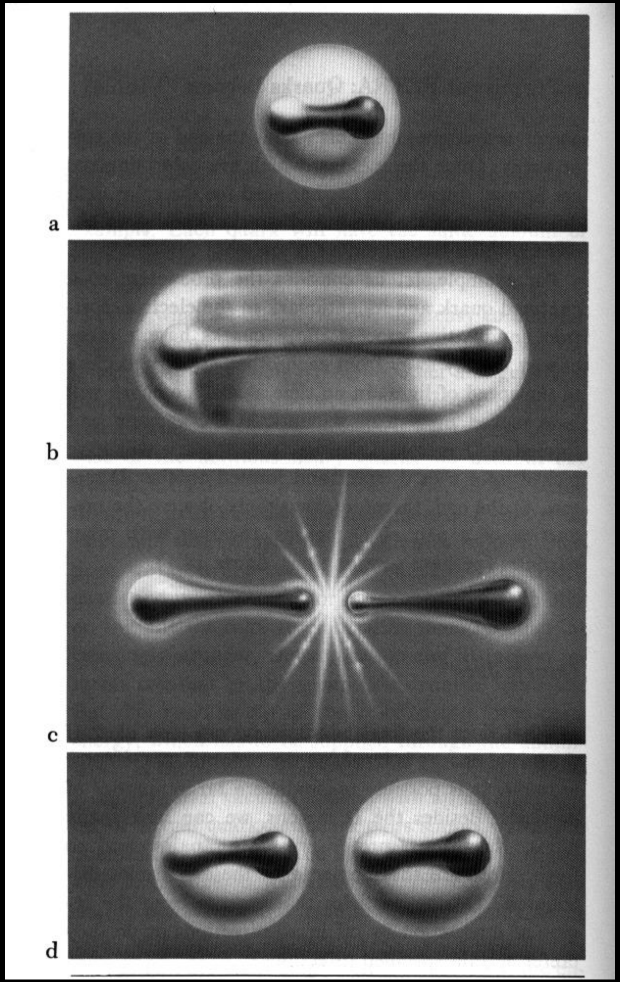
- In QCD, the field lines are compressed into a "flux tube" (or "string") of constant cross-section (~fm^2), leading to a long-distance potential which grows linearly with *r*:

$$V_{long} = kr$$

with k ~ 1 GeV/fm

String breaking

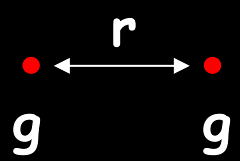
- If one tries to pull the string apart, when the energy stored in the string ($k\,r$) reaches the point where it is energetically favourable to create a $q\bar{q}$ pair, the string breaks…
- …and one ends up with two colour-neutral strings (and eventually hadrons)



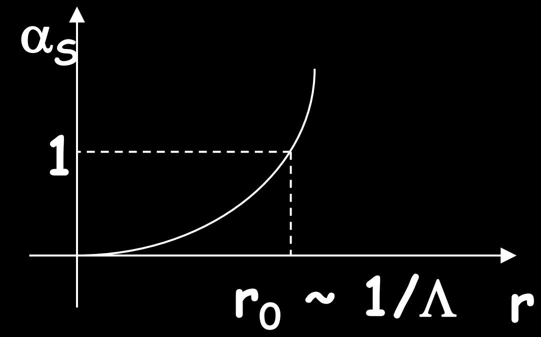
[illustration from Fritzsch]

QCD vacuum

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



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



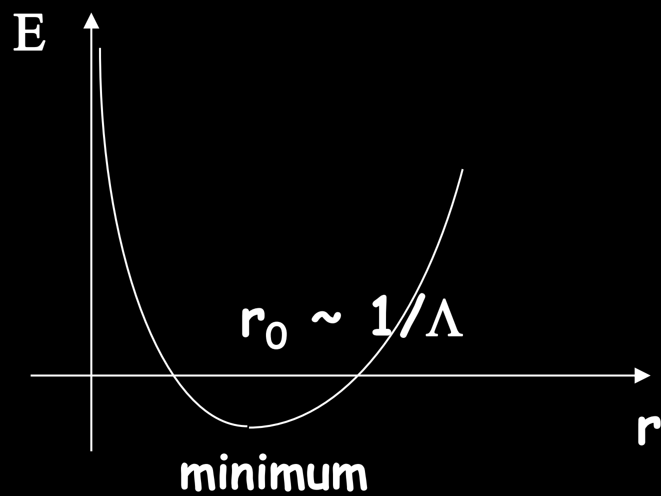
$$r \sim \frac{1}{p} \sim \frac{1}{E_{KIN}} \quad \rightarrow \quad E_{KIN} \sim \frac{1}{r}$$

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

$$r \rightarrow 0 \qquad E \sim \frac{1}{r}$$

$$r \sim r_0 \qquad E <\sim 0$$

$$r \rightarrow \infty \qquad E \sim kr$$



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

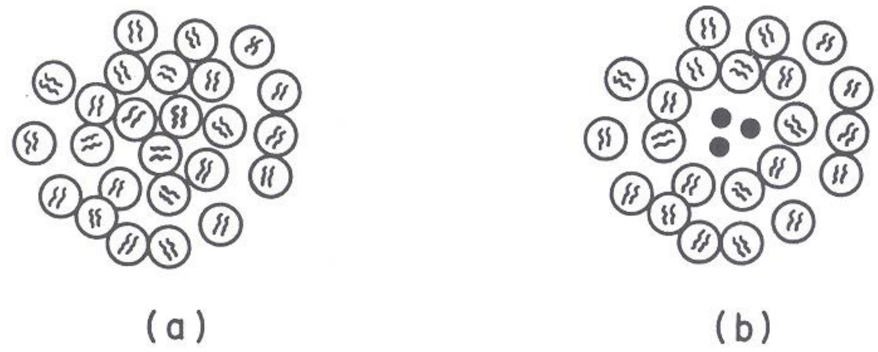


FIG. 9. The QCD vacuum state is depicted in (a). It is a random distribution of cells that contain a gluon pair in a color and spin singlet state. Quarks (in a color singlet configuration) displace these cells, creating a region (or "bag") of "empty" vacuum, as shown in (b).

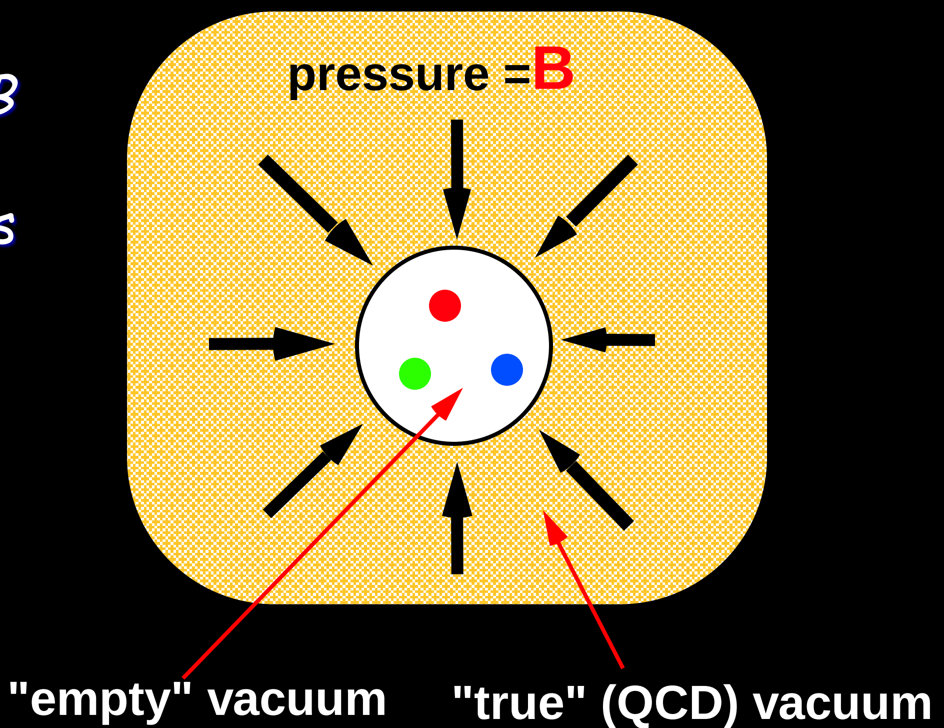
[see e.g. Gottfried-Weisskopf, p. 399]

- 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:

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

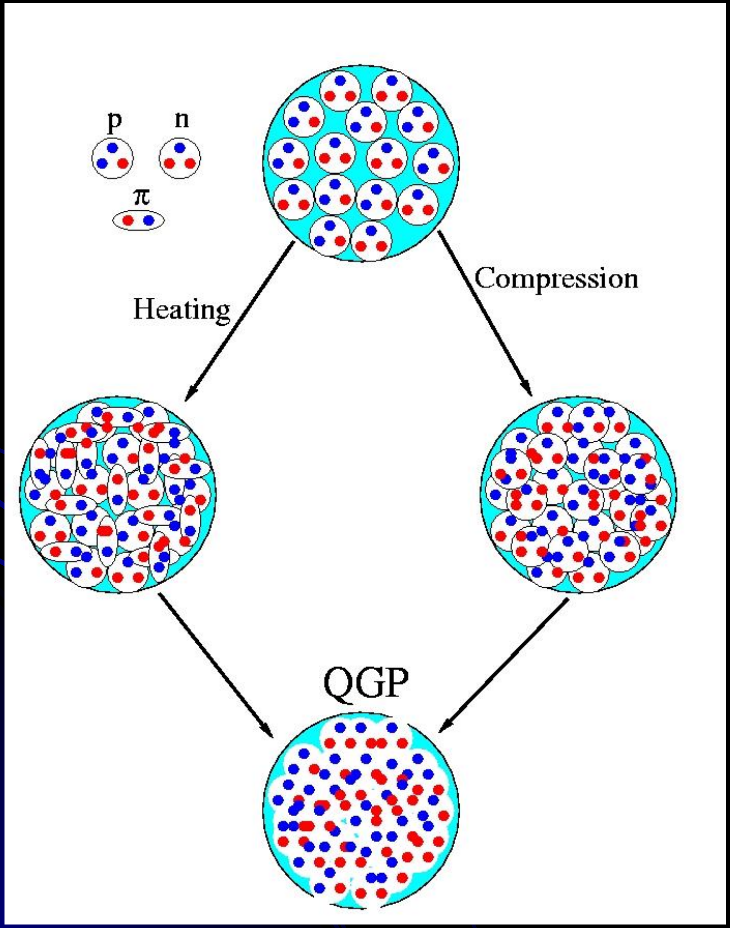
Bag model of a hadron



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?

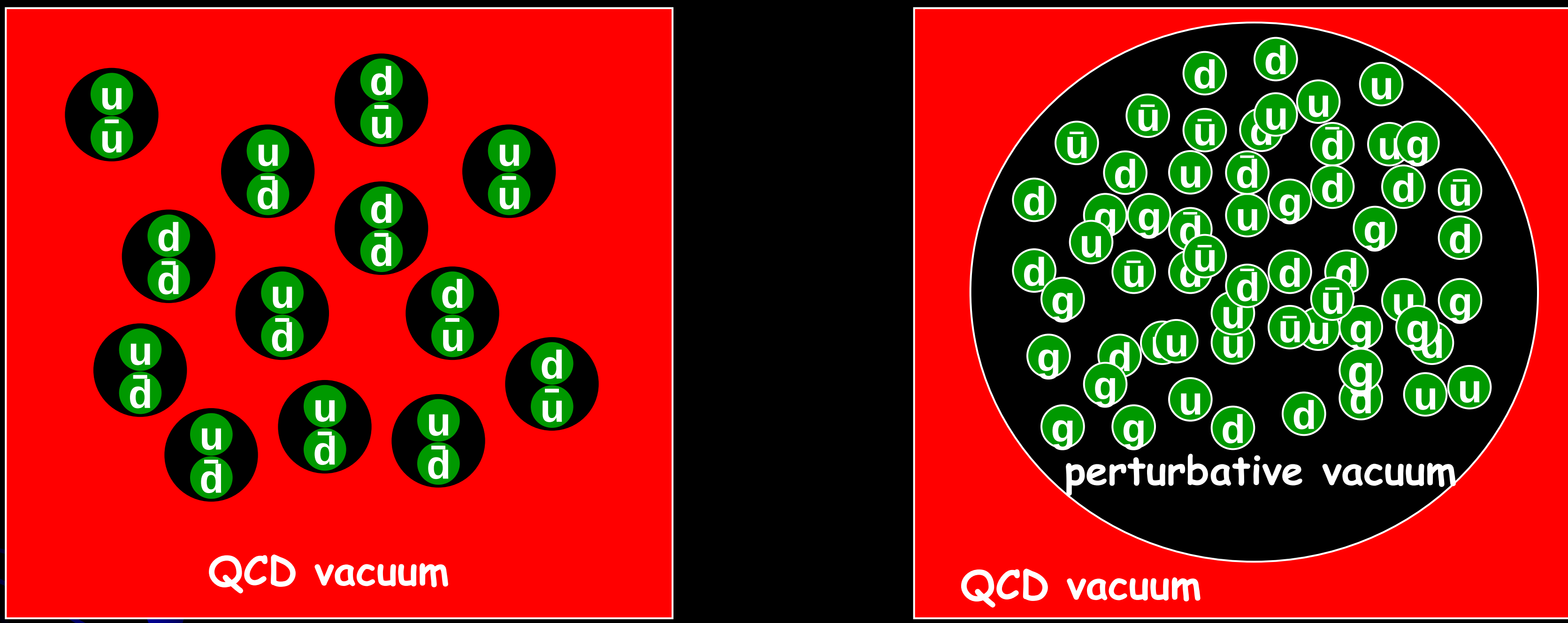


Lattice QCD predicts that if a system of hadrons is brought to sufficiently large density and/or temperature a deconfinement phase transition should occur

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

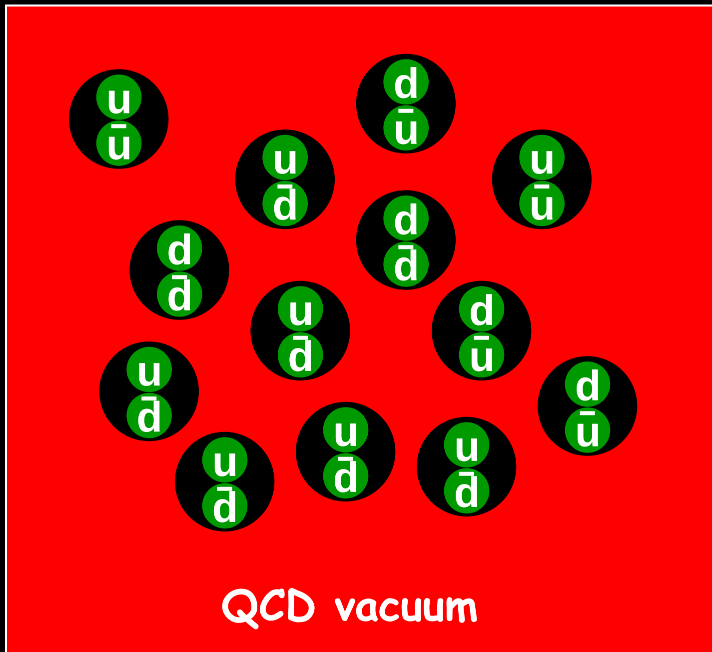
Hadron (pion) Gas | Quark-Gluon Plasma



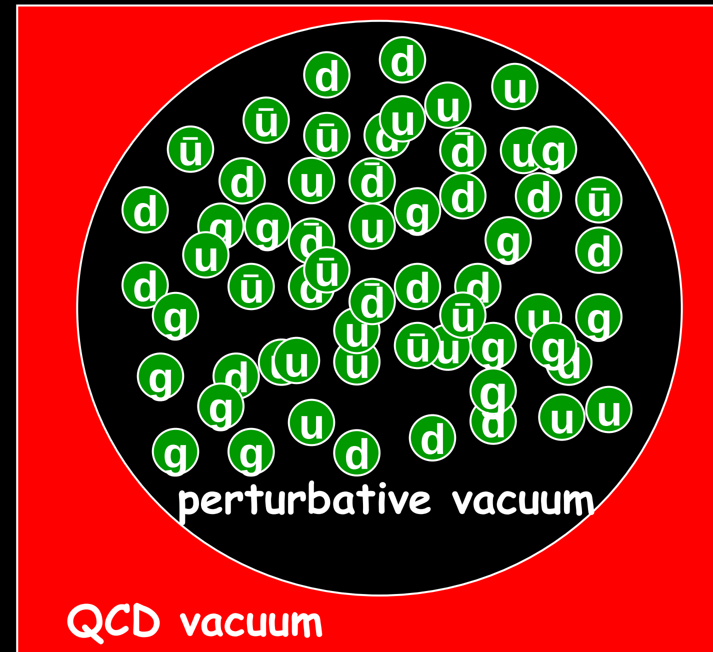
- Gibbs' criterion:the stable phase is the one with the largest pressure
- From statistical mechanics: (for an ideal gas)

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

Hadron (pion) Gas



Quark-Gluon Plasma



$g_B = 3 \quad g_F = 0$

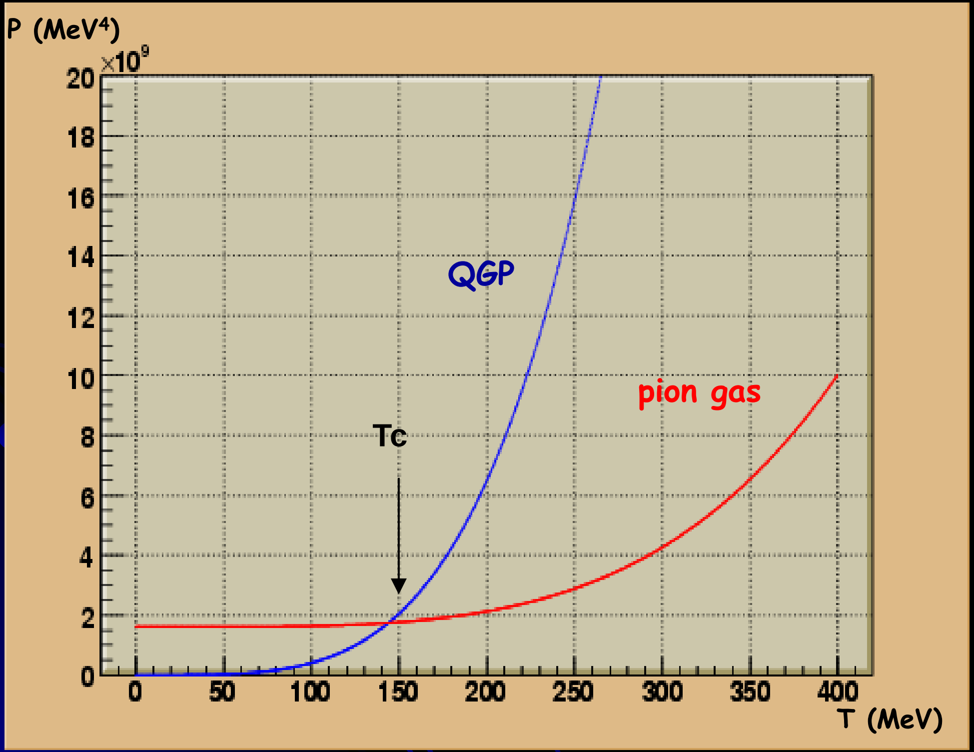
$$p = \frac{\varepsilon}{3} = \left(g_B + \frac{7}{8} g_F \right) \frac{\pi^2 T^4}{90}$$

$g_B = 16 \quad g_F = 24$

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

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

- 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



$$T_C = \left(\frac{90}{34\,\pi^2} \right)^{1/4} B^{1/4}$$
$$\approx \; 150\,\text{MeV}$$

- 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)

Restoration of bare masses

- Confined quarks acquire an additional mass (~ 350 MeV) dynamically, through the confining effect of strong interactions
  - M(proton) $\approx$ 938 MeV; m(u)+m(u)+m(d) = 10$\div$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 $\rightarrow$ a few MeV
  - m(s): ~ 500 MeV $\rightarrow$ ~ 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)

From Heavy Ions to Quark Matter (Episode 2)

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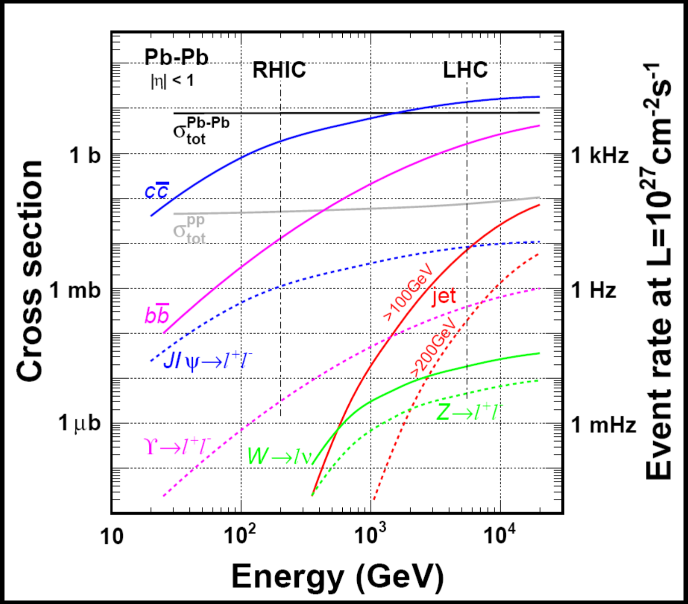
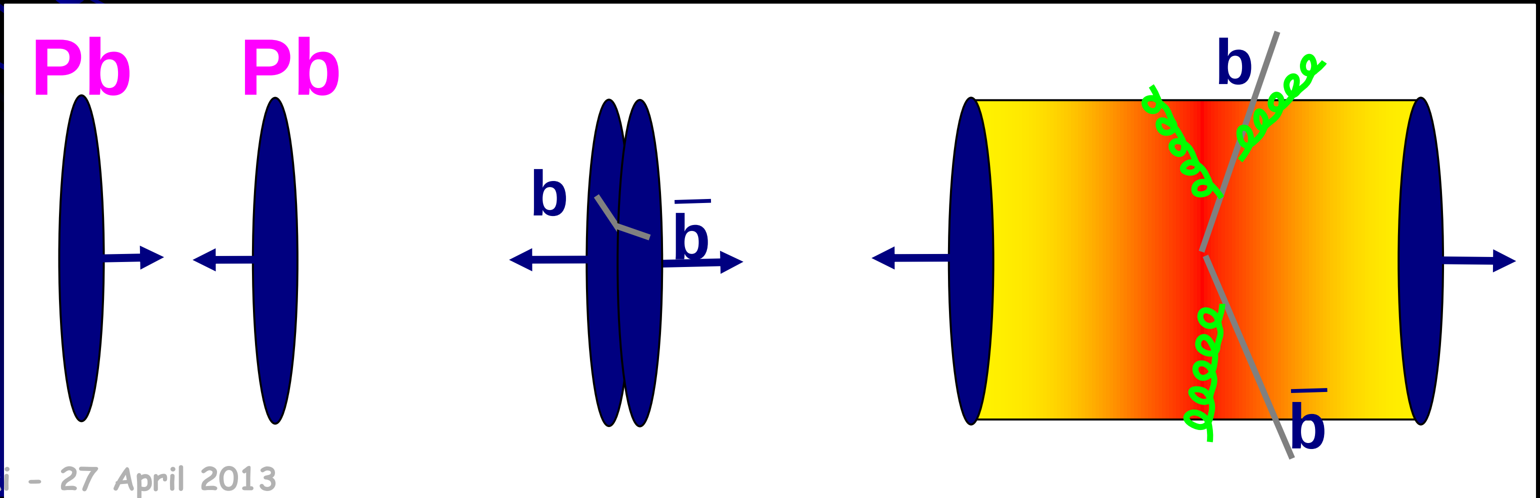
Nucleus-Nucleus collisions at the LHC!

		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



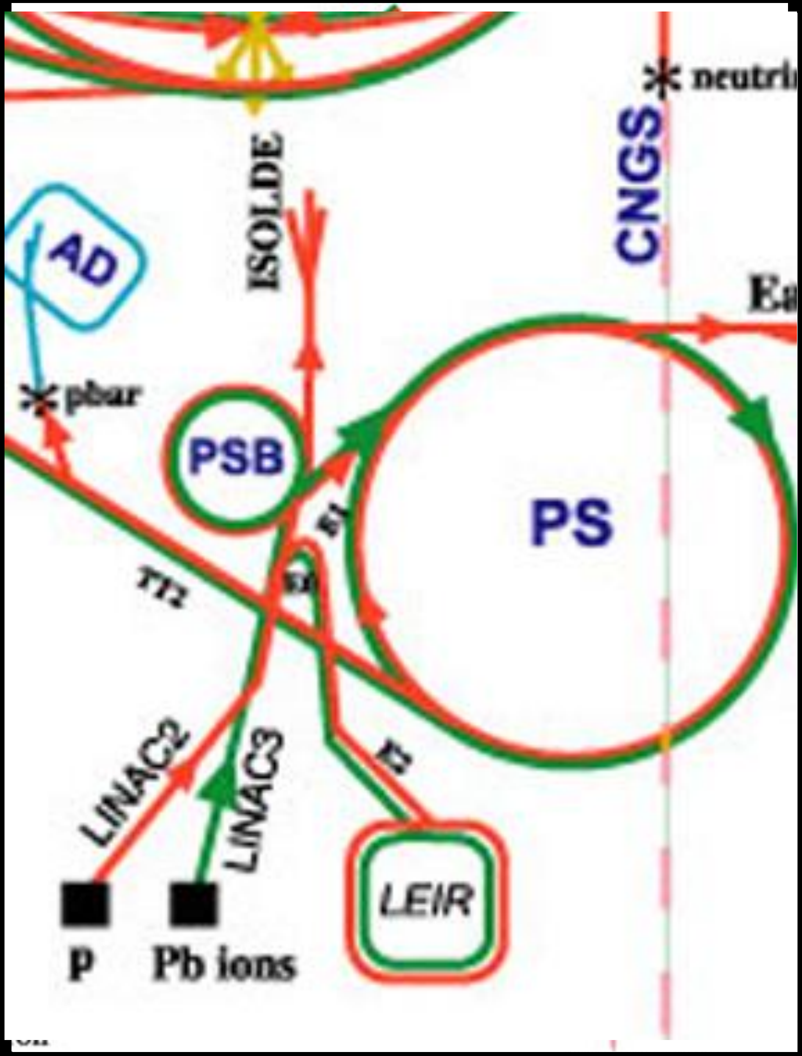
- large ε → deeper in deconfinement region
  → closer to "ideal" behaviour

- large cross sections for "hard probes" !
  → a new set of tools to probe the medium properties
  e.g.:



Heavy Ions at CERN

- Acceleration of Pb ions:
  - ECR source: Pb^{27+} (80 μA)
  - RFQ: Pb^{27+} to 250 A keV
  - Linac3: Pb^{27+} to 4.2 A MeV
  - Stripper: Pb^{53+}
  - PS Booster: Pb^{53+} to 95 A MeV
  - PS: Pb^{53+} to 4.25 A GeV
  - Stripper: Pb^{82+} (full ionisation)
  - SPS: Pb^{82+} to 158 A GeV
  - LHC: Pb^{82+} to 2.76 A TeV)



Luminosity limitations

- Bound-Free Pair Production (BFPP):

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

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…)

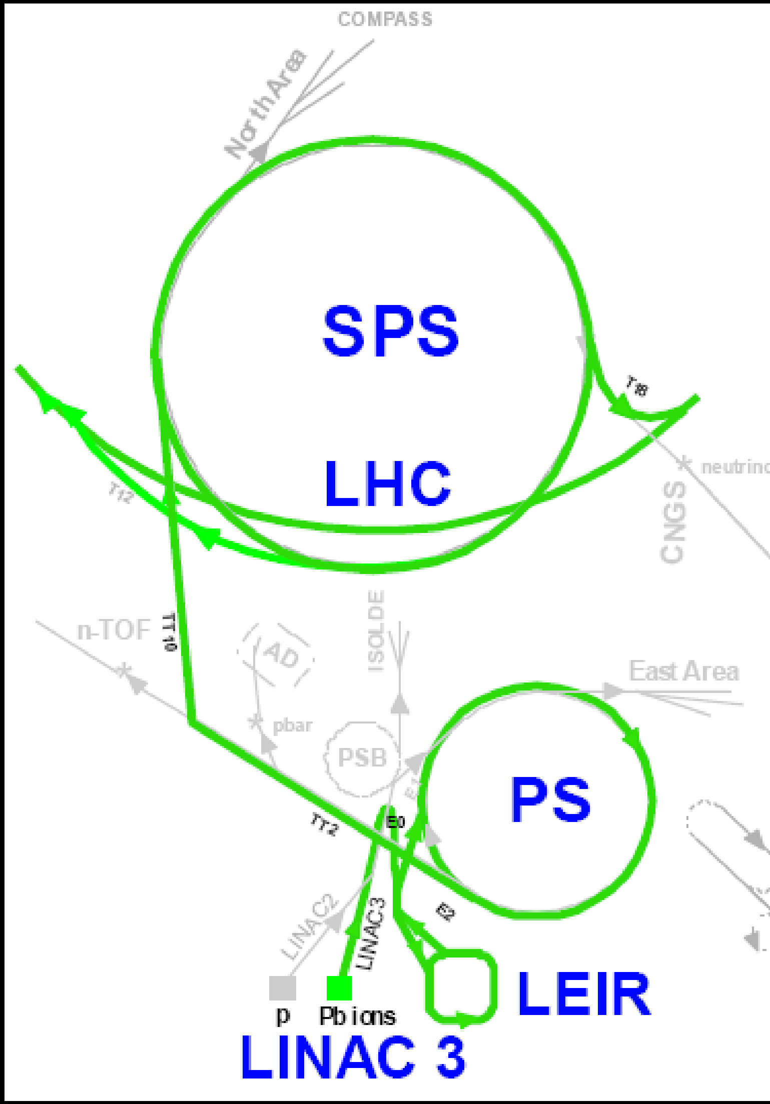
- Collimation losses
  - collimation for ions (which can break up into fragments) is harder than for protons
  - limitation on the total intensity

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

Pb nuclei in the LHC

- For 2011 Pb-Pb run:
  - ~ 1.1 10^8 ions/bunch
  - 358 bunches (200 ns basic spacing)
  - $\beta^* = 1$ m
  - L ~ 5 10^{26} $cm^{-2}s^{-1}$
  - → ~ 4000 Hz interaction rate

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



Bulk observables: multiplicity and volume

Particle multiplicity

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

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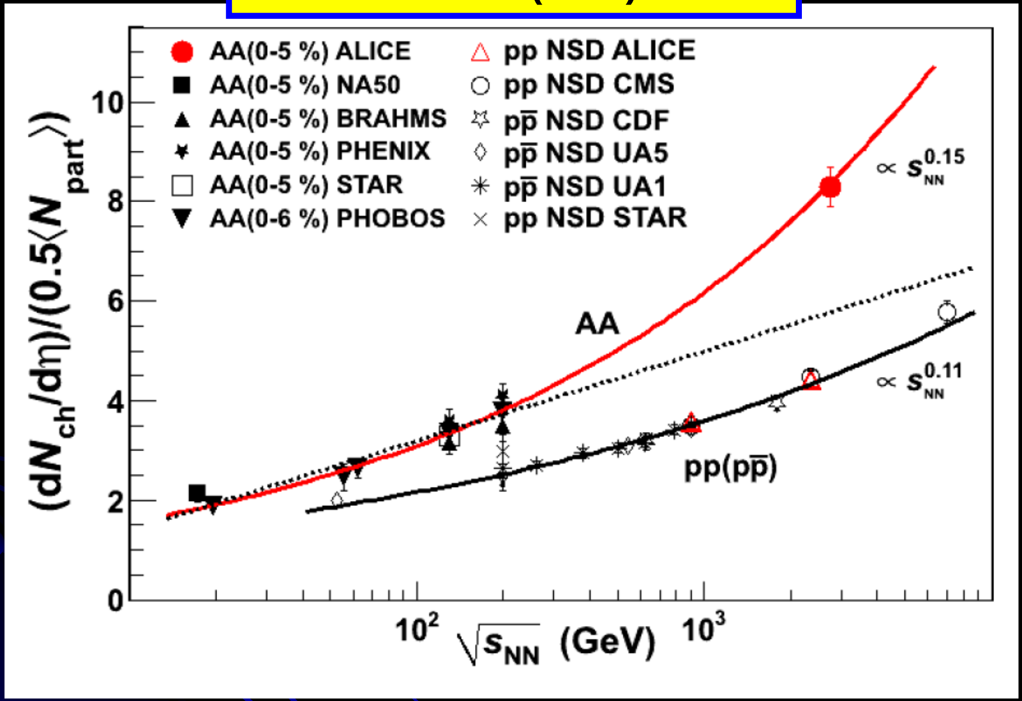


- log extrapolation:
  - OK at lower energies
  - finally fails at the LHC

$\sqrt{s_{NN}}$=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:

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

S = transverse dimension of nucleus
τ_0 = "formation time" ~ 1 fm/c

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

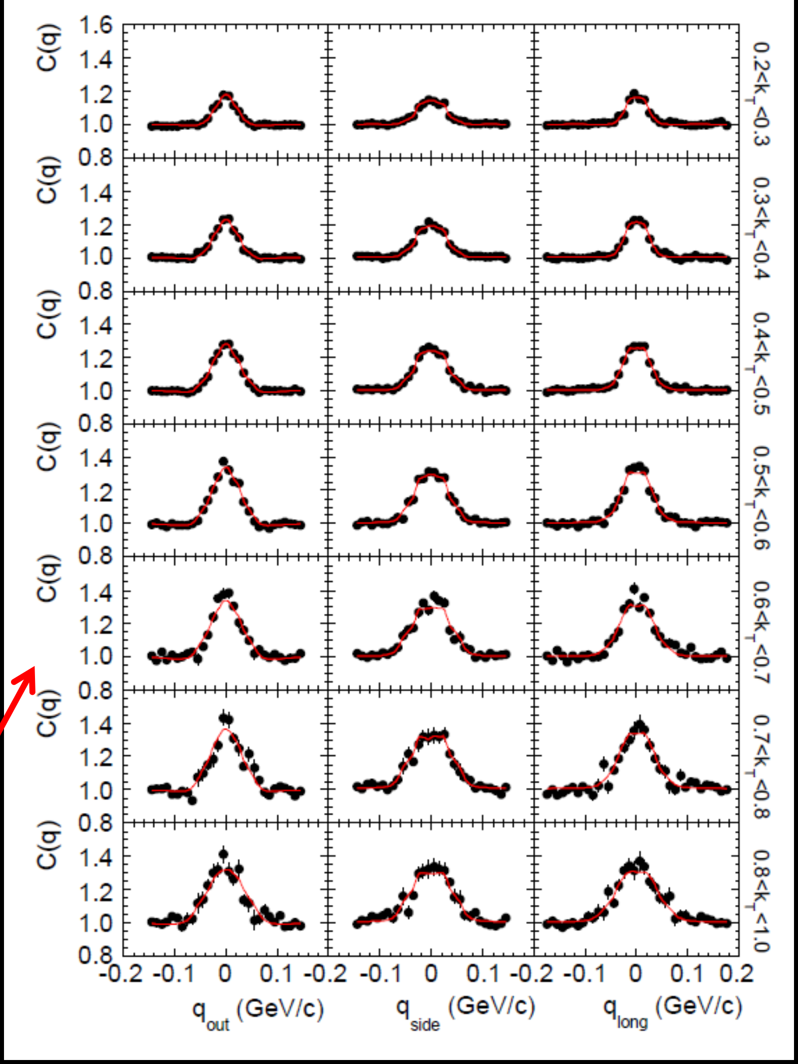
- Initial time τ_0 normally taken to be ~ 1 fm/c
  - i.e. equal to the "formation time": the time it takes for the energy initially stored in the field to materialize into particles

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

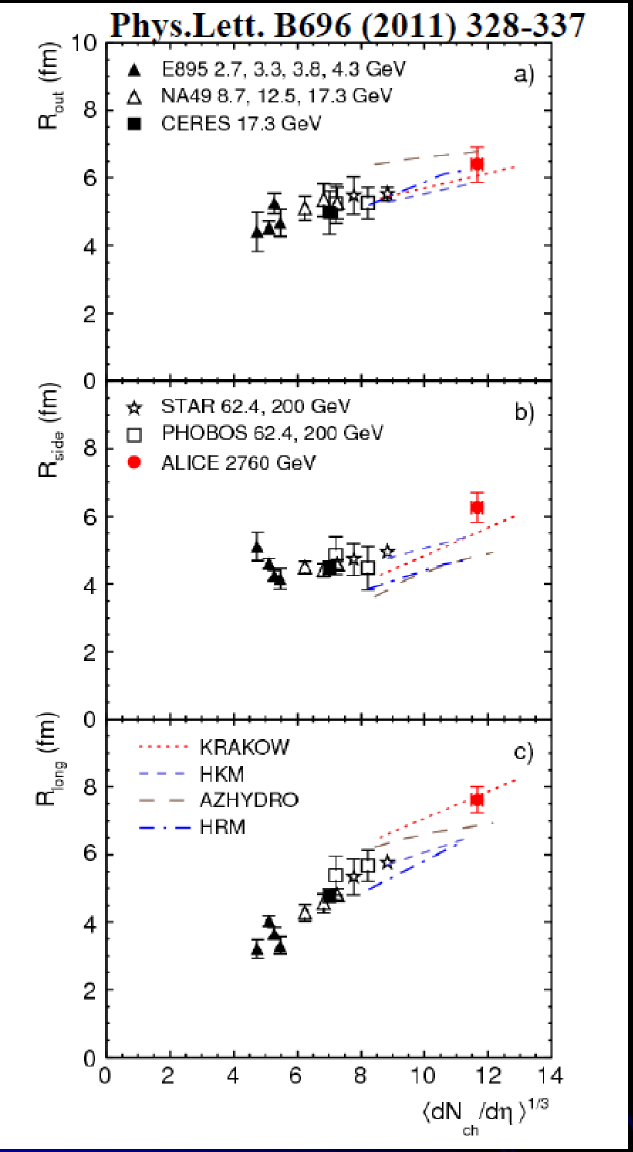
→ $\varepsilon \sim (1800\,/\,160)\ \mathrm{GeV/fm}^3 \sim 10\ \mathrm{GeV/fm}^3$ → **More than enough for deconfinement!**

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)

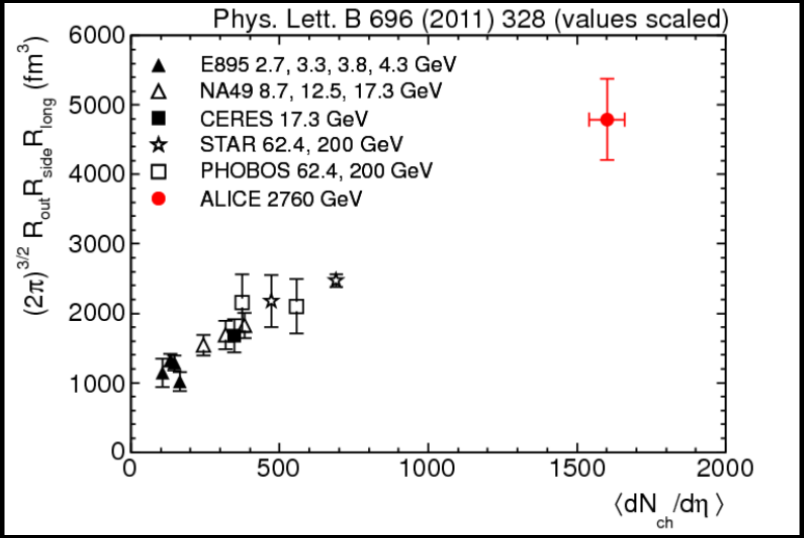


HBT interferometry



from RHIC to LHC:

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



- for comparison: R(Pb) ~ 7 fm → V ~ 1500 fm^3

→ substantial expansion!

Strangeness enhancement

Historic QGP predictions

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Strangeness Production in the Quark-Gluon Plasma

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(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

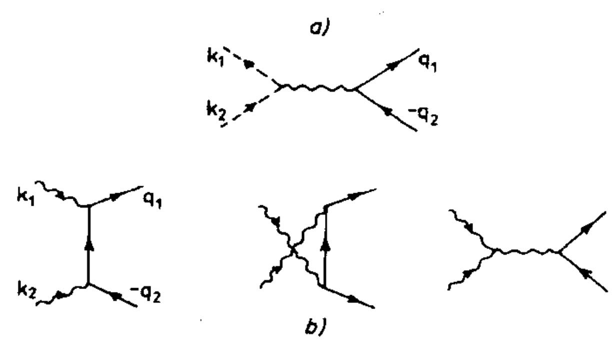
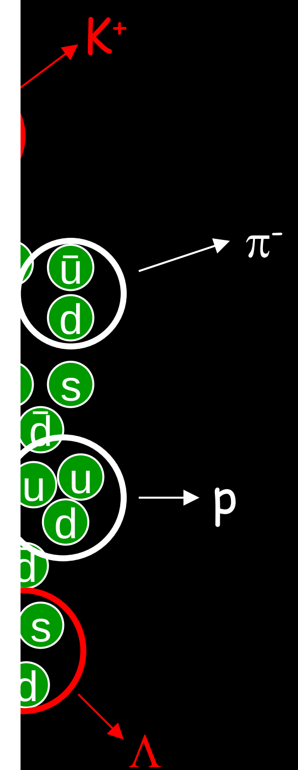
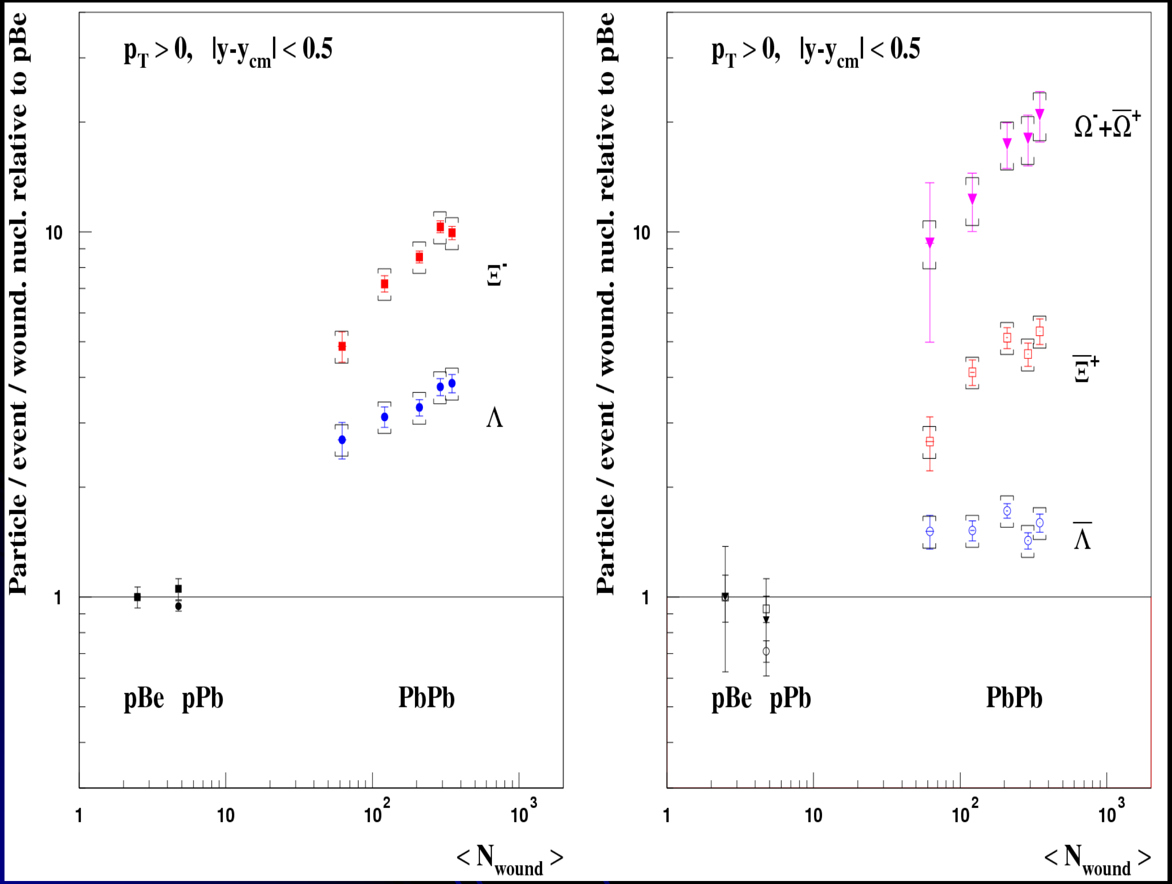


FIG. 1. Lowest-order QCD diagrams for $s\bar{s}$ production: (a) $q\bar{q} \to s\bar{s}$, (b) $gg \to s\bar{s}$.



Strangeness enhancement at the SPS

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

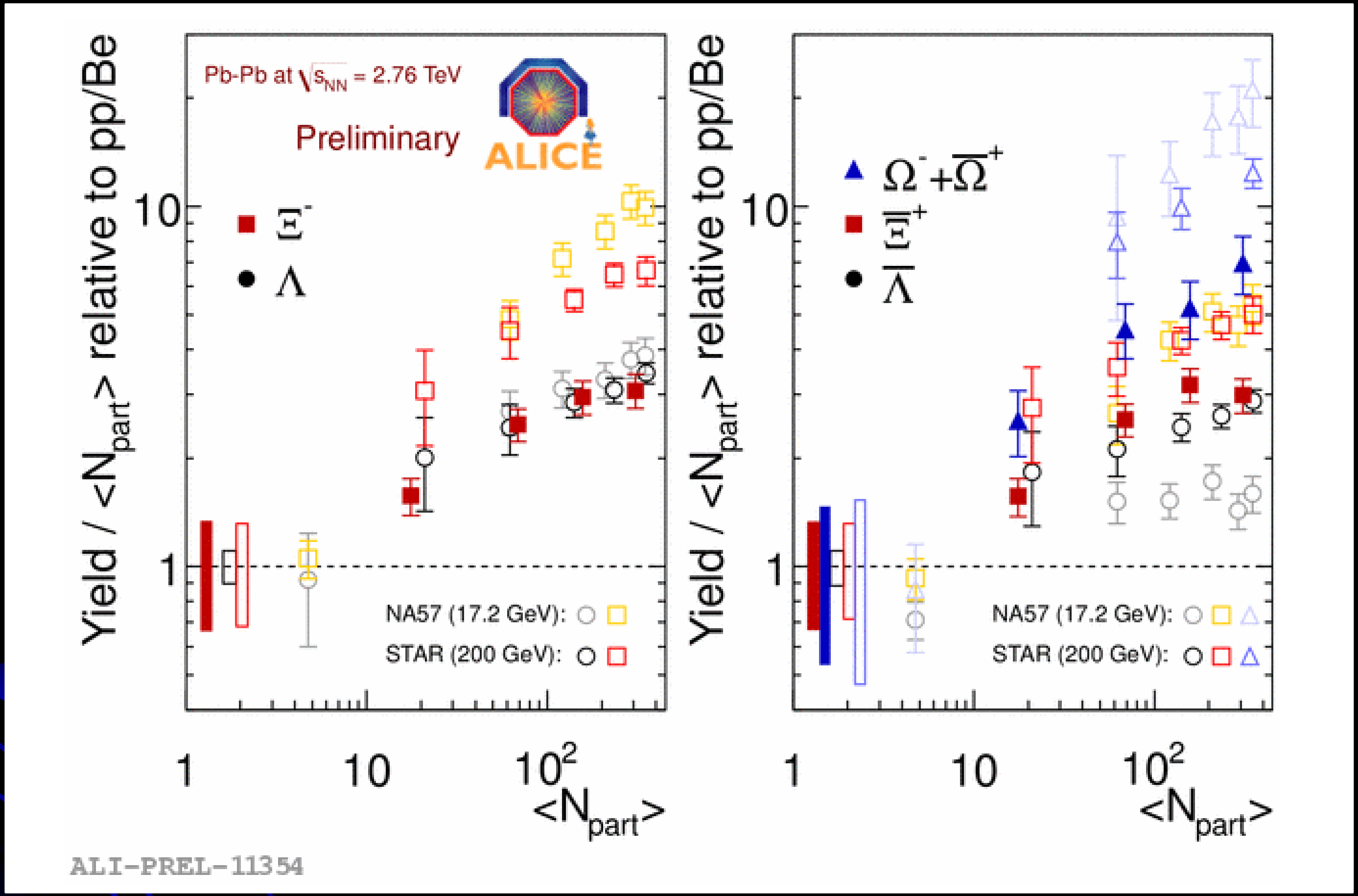


Enhancement is larger for particles of higher strangeness content (QGP prediction!)
up to a factor ~ 20 for Ω

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

Strangeness enhancement: SPS. RHIC. LHC

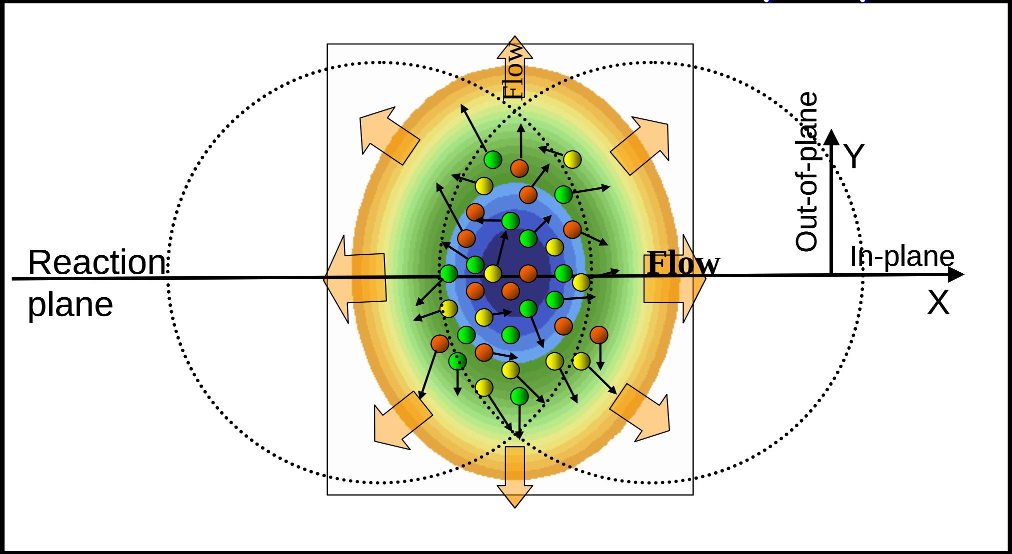


- enhancement still there at RHIC and LHC
  - effect decreases with increasing √s
  - → strange/non-strange increases with √s in pp

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:

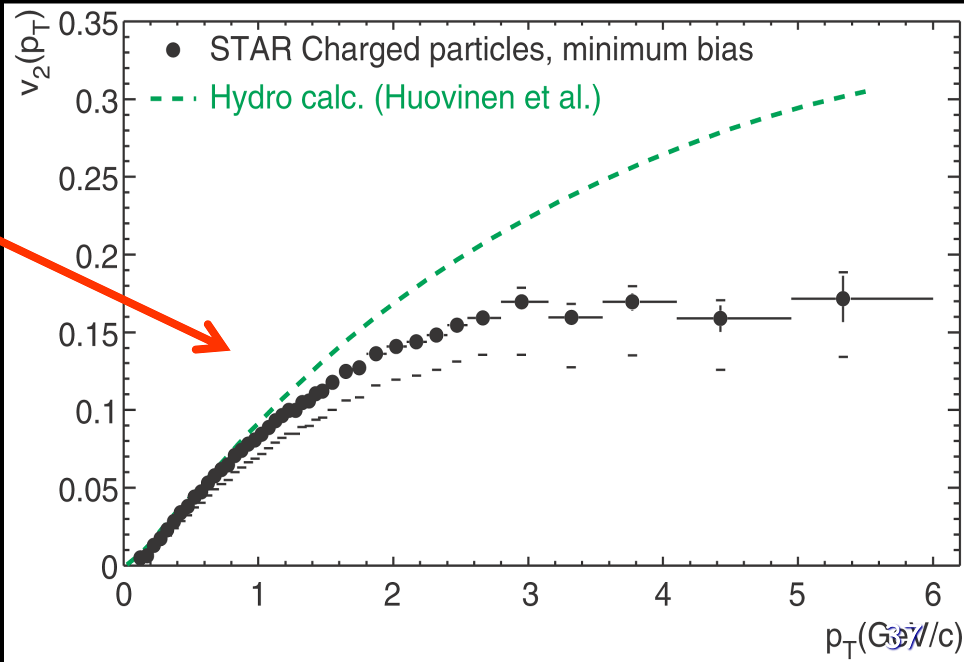
$$\frac{dN}{p_T dp_T dy d\varphi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}\left(1 + 2v_1\cos(\varphi) + 2v_2\cos(2\varphi) + \ldots\right)$$

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

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

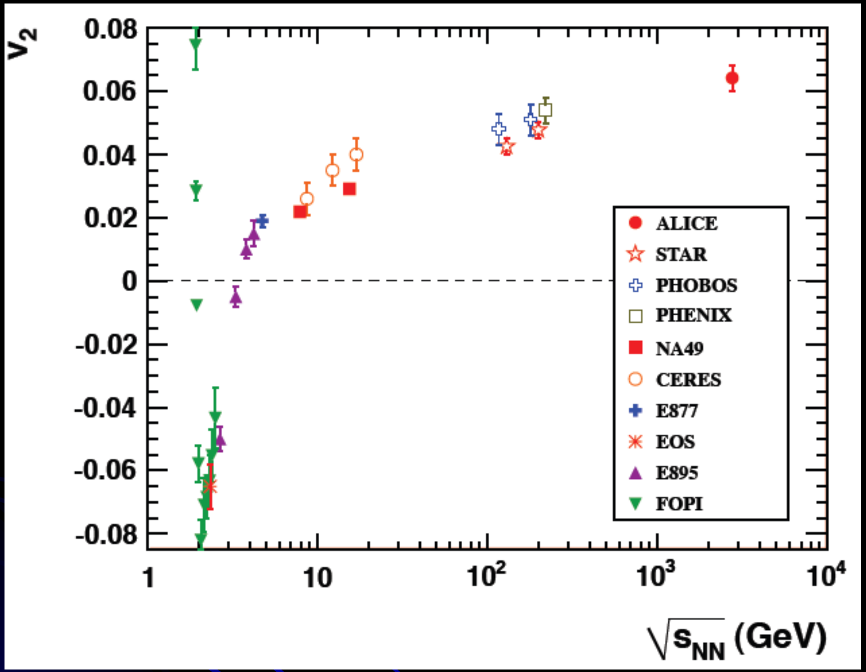
@RHIC:

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



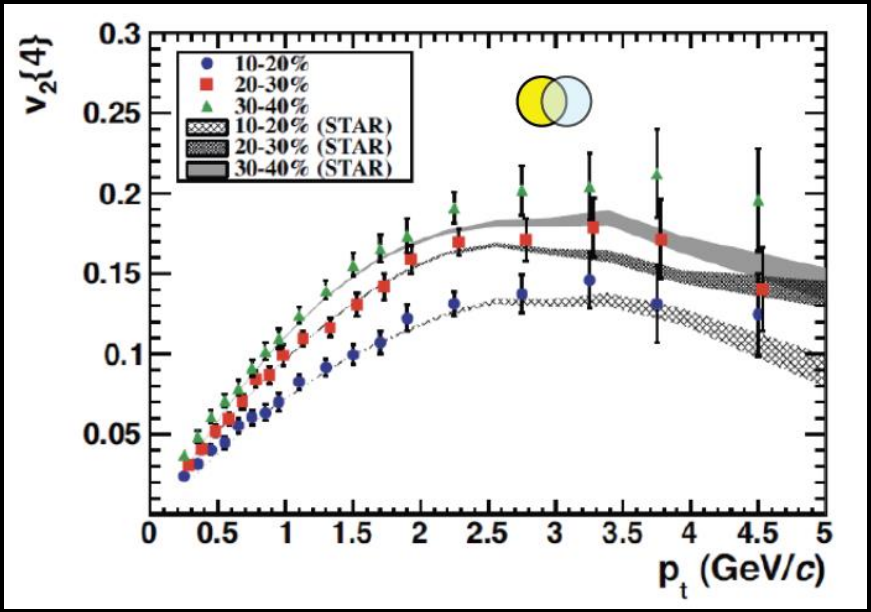
v_2 at the LHC

- 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?

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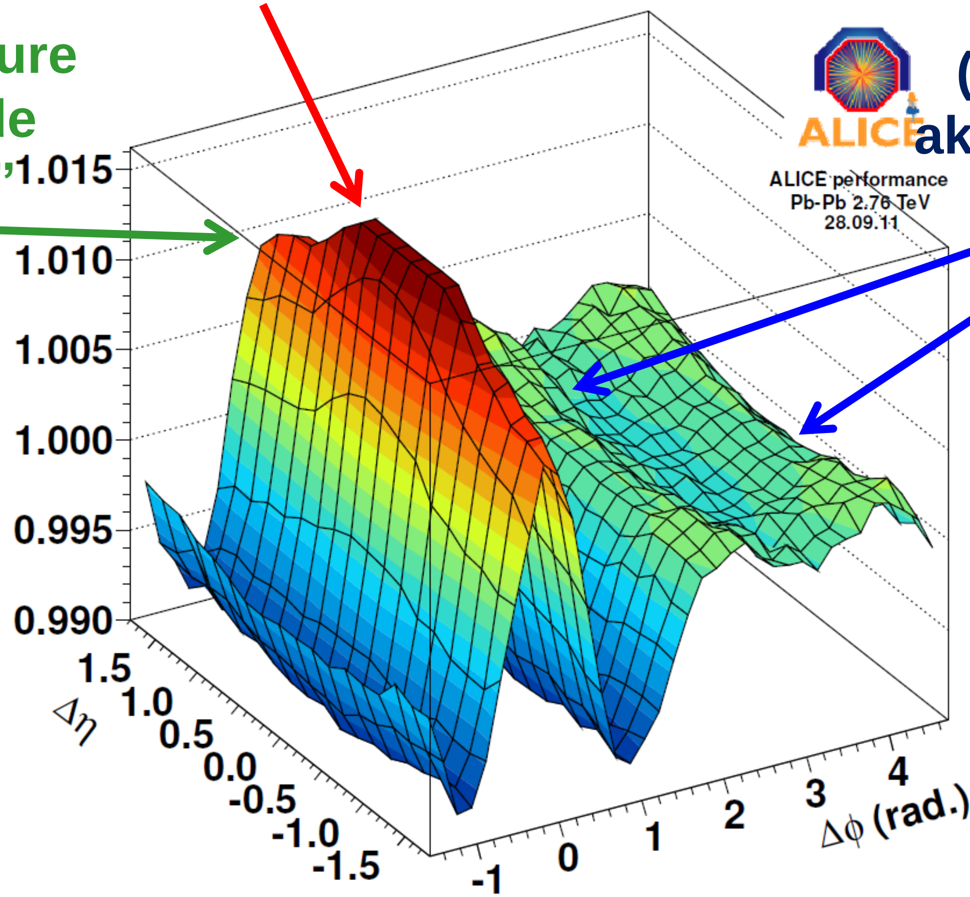
Structures in (Δη,Δφ)

near side jet peak

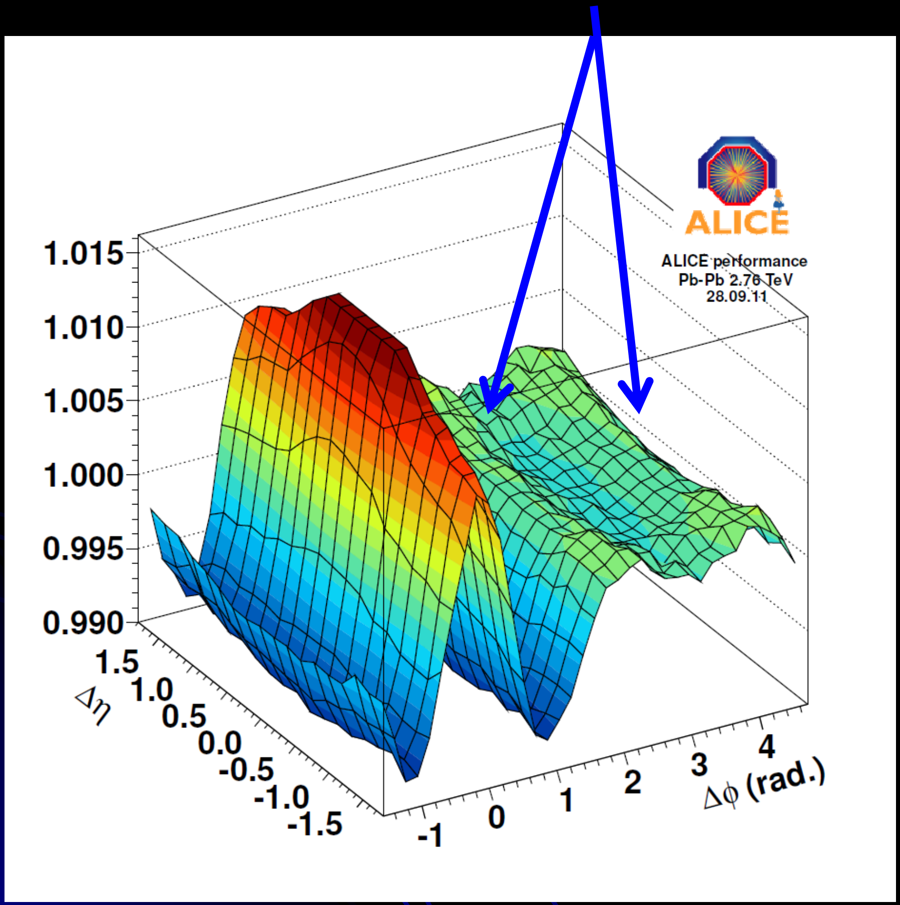
long range structure
in η on near side
aka “the ridge”

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



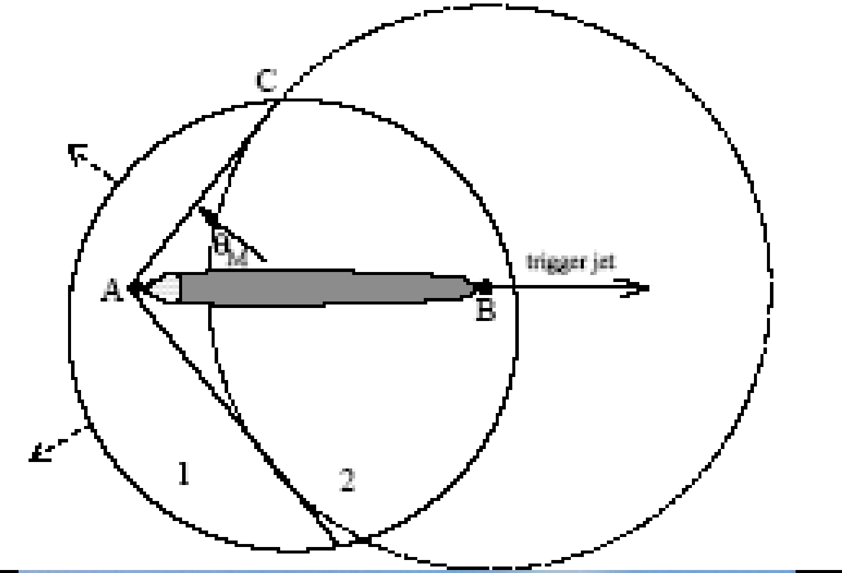
Mach cone?

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



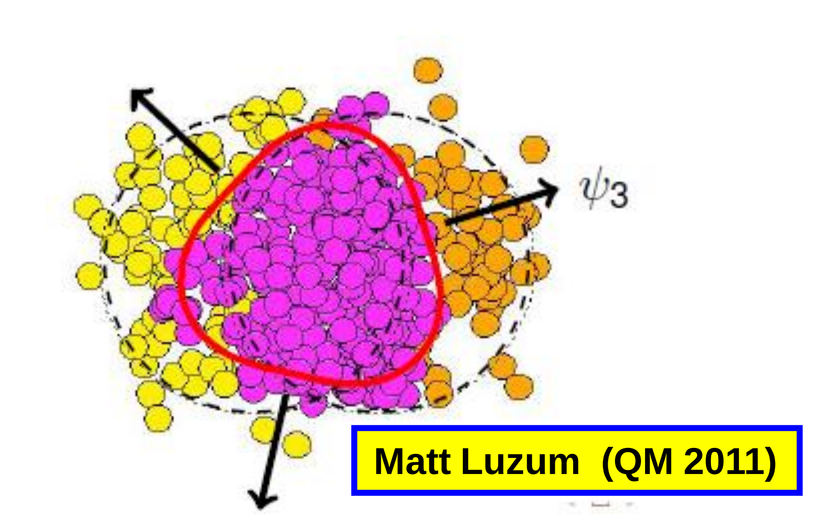
- a proposed explanation:
  - shock wave (sonic boom) : propagation through medium of recoiling parton

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

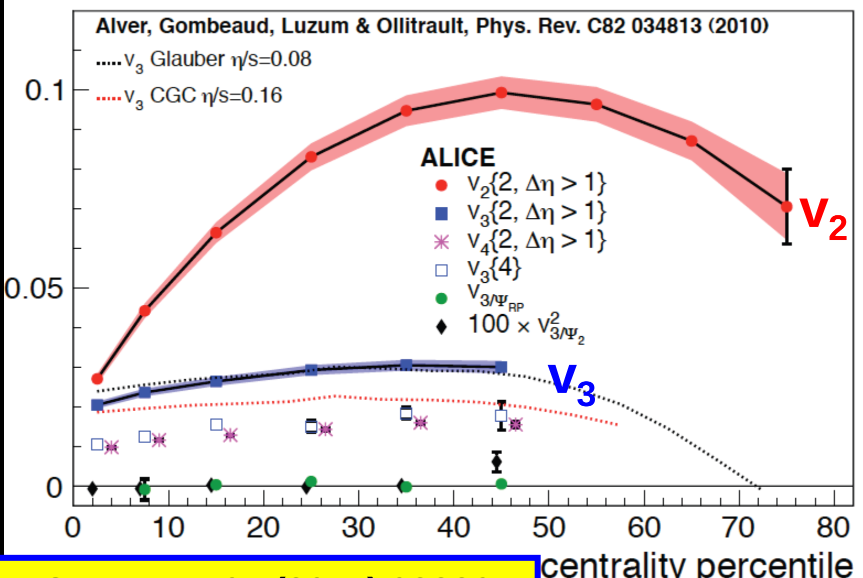


Fluctuations → v_3

- "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 ≠ 0 !
- v_3 has weaker centrality dependence than v_2
- when calculated wrt participants plane, v_3 vanishes
  - as expected, if due to fluctuations…



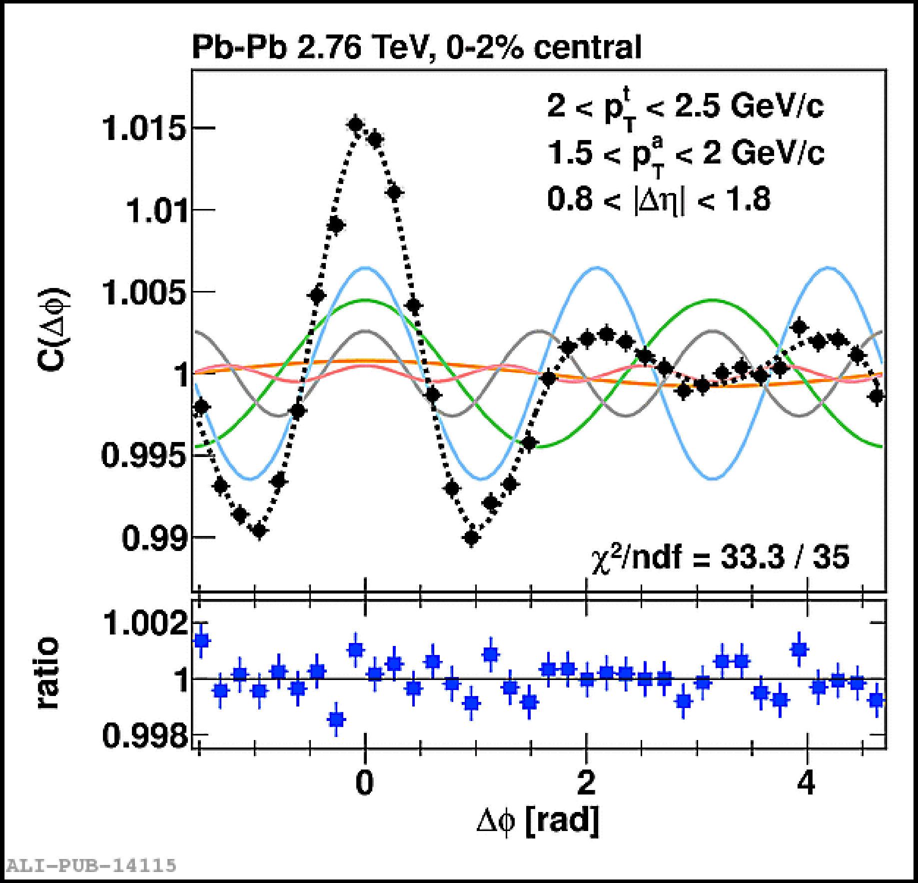
Matt Luzum (QM 2011)



ALICE: PRL 107 (2011) 032301

Long-η-range correlations

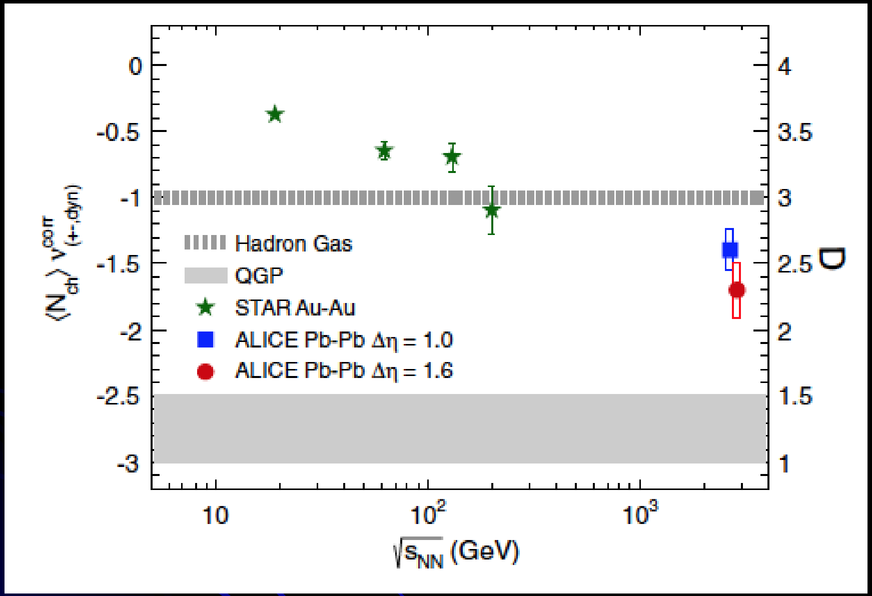
- "ultra-central" events: dramatic shape evolution in a very narrow centrality range
- double hump structure on away-side appears on 1% most central
  - visible without any need for v_2 subtraction!
- first five harmonics describe shape at 10^{-3} level
  → "ridge" and "Mach cone"
  - explanations based 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



ALICE: Phys. Lett. B 708 (2012) 249

Net charge fluctuations

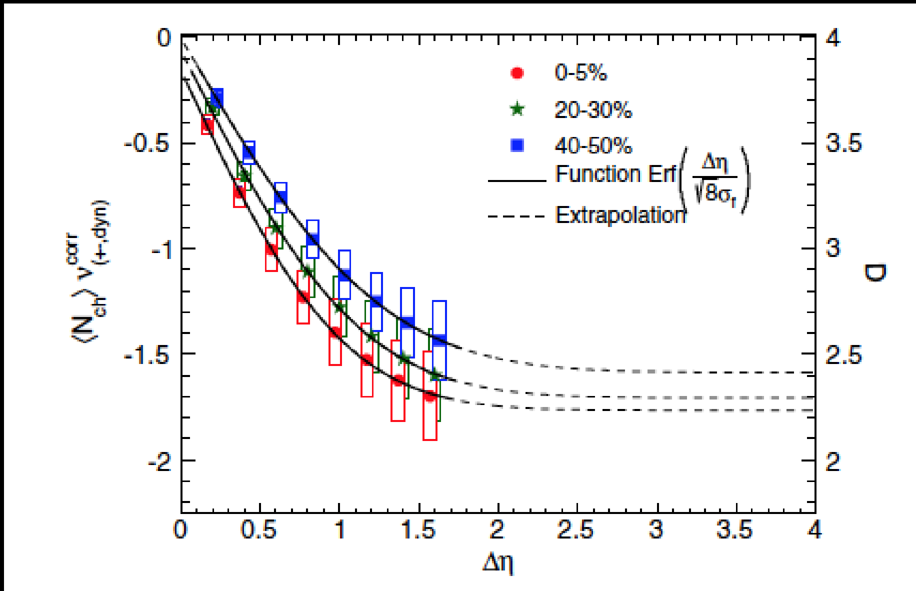
- first time fluctuations observed below the hadron gas limit



Phys. Rev. Lett. 110, 152301 (2013)

- fluctuations decrease
  - with increasing centrality
  - with increasing Δη

  (diffusion of hadrons in y?)



→ S Jena, BK Nandi, T Nayak & Co.

Correlations: outlook

- is there any residual room for medium response effects?

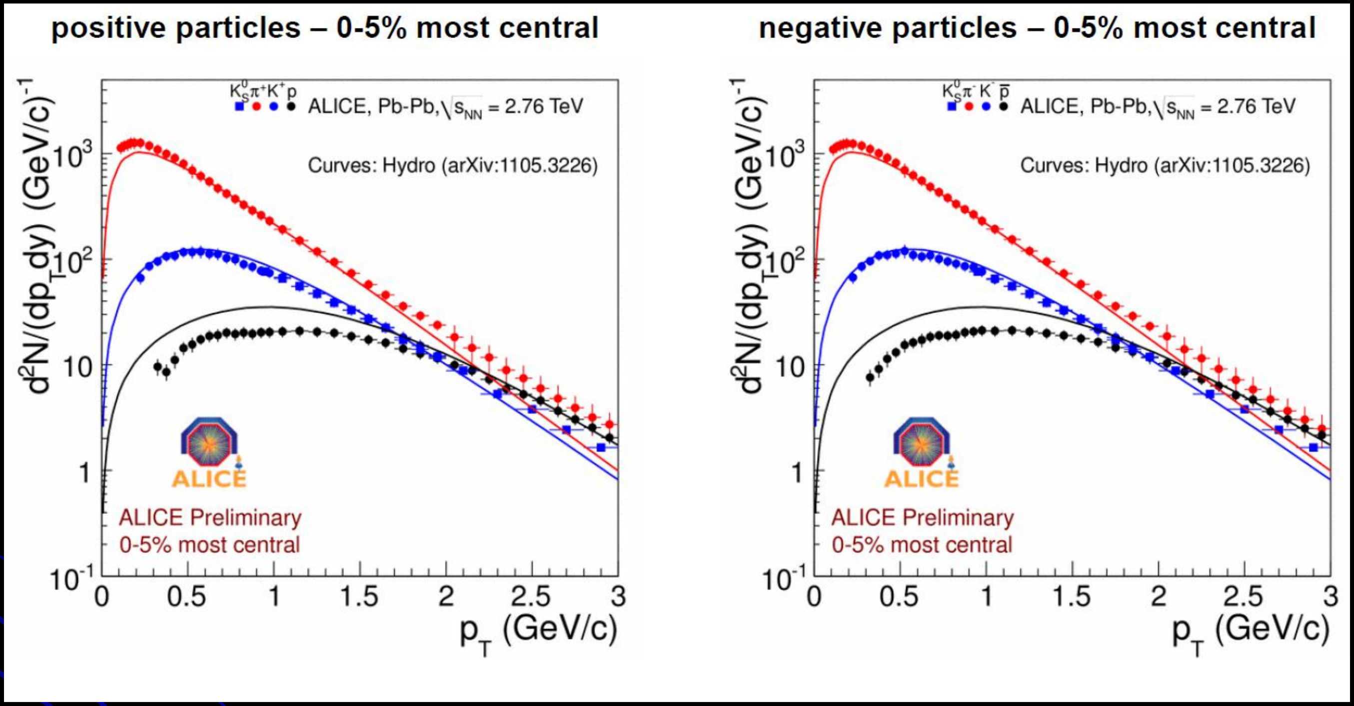
→ look at the "small print" on the away side

- quantitative comparisons with full hydrodynamic calculations

Identified particles and hydrodynamics

p_T spectra vs hydrodynamics

- identified particle spectra and hydrodynamics predictions

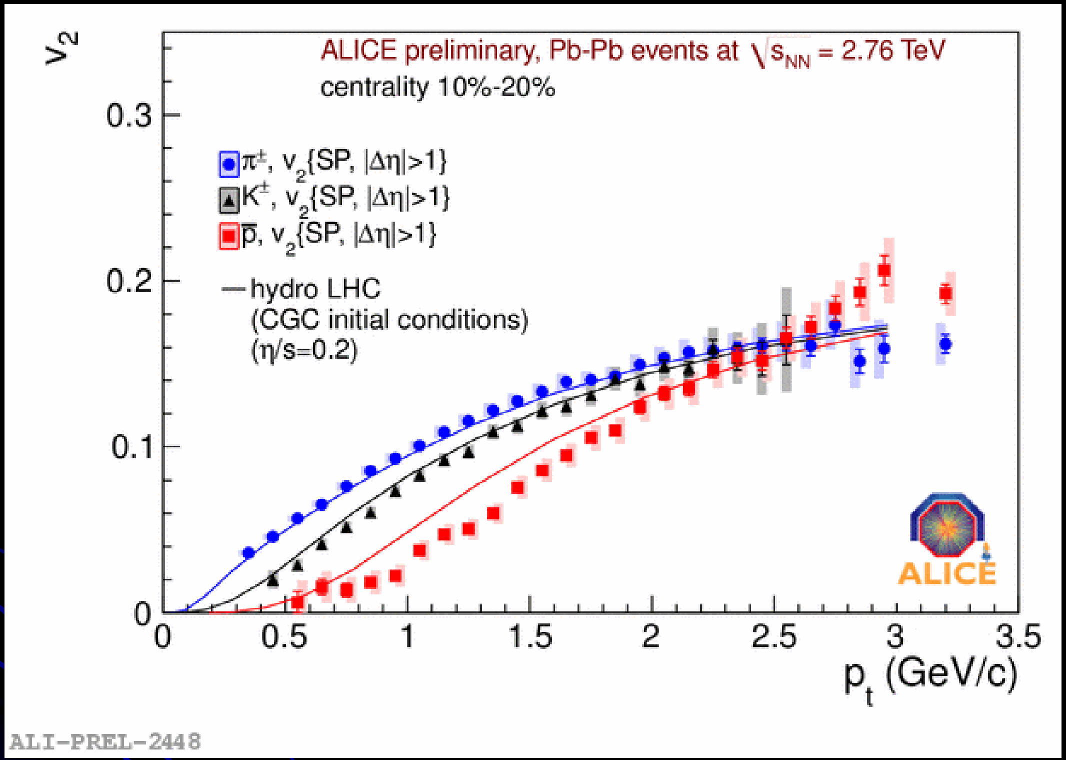


  - (calculations by C Shen et al.: arXiv:1105.3226 [nucl-th])

→ 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



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

→ again, protons are off… → what's going on with protons? rescattering/annihilation in the hadronic phase?

High-p_T suppression

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}

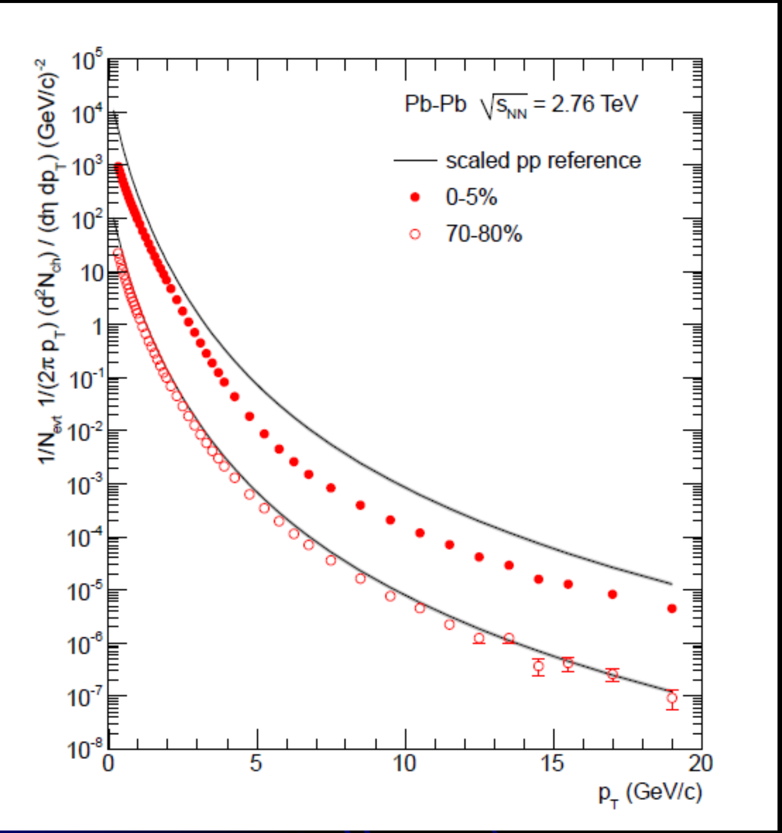
$$R_{AA} = \frac{\text{Yield}_{AA}}{\text{Yield}_{pp}} \cdot \frac{1}{\langle Nbin \rangle_{AA}}$$

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

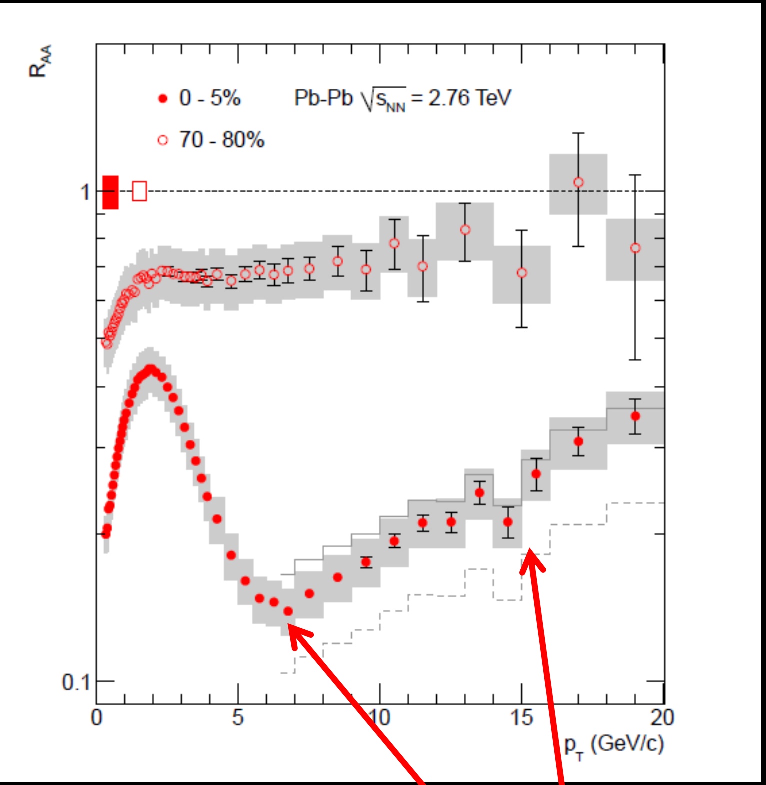
$$R_{cp} = \frac{\text{Yield}_{AA,central}}{\text{Yield}_{AA,periph}} \cdot \frac{\langle Nbin \rangle_{AA,periph}}{\langle Nbin \rangle_{AA,central}}$$

Strong quenching!

- Pb-Pb significantly below scaled pp for central collisions



- RAA: intriguing modulation:

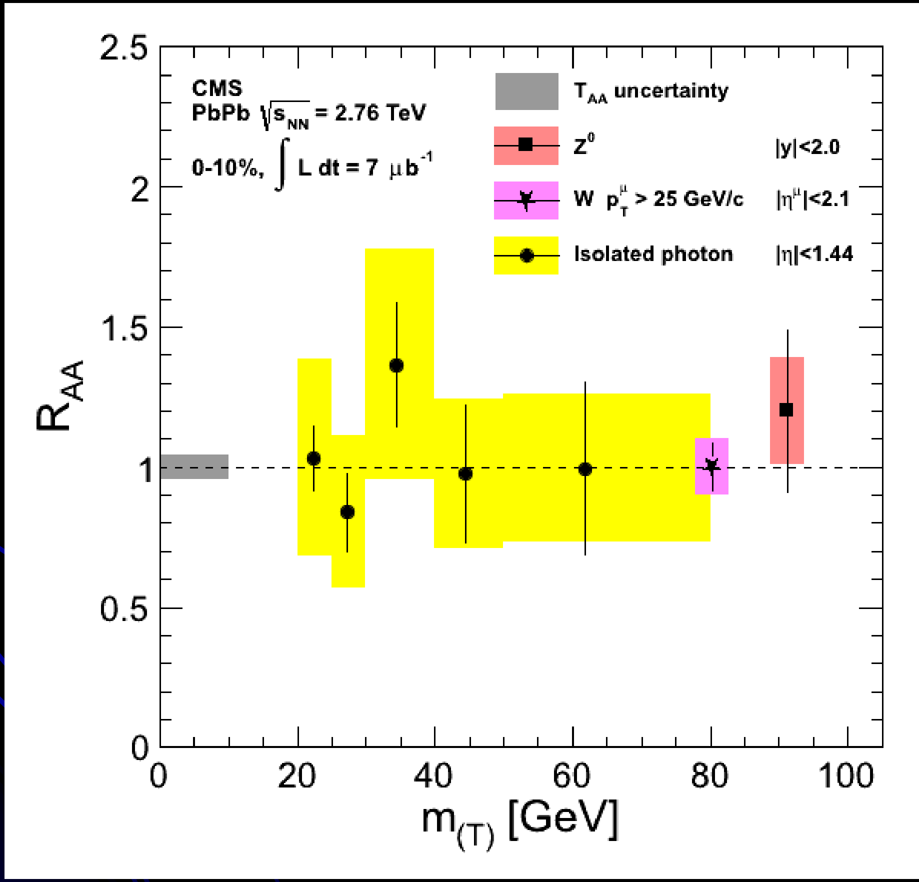


- minimum around 6-7 GeV (R_{AA} ~ 0.14)
- clear increase at higher p_T → not yet fully understood

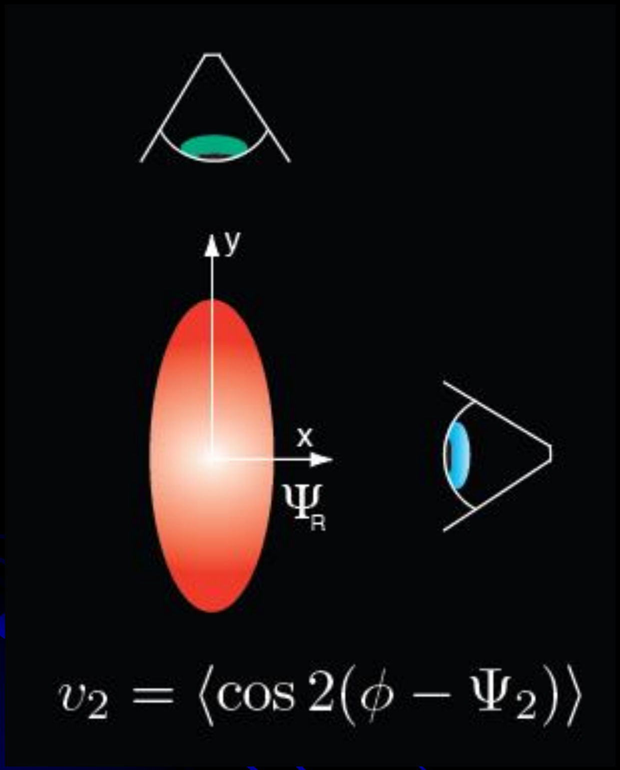
R_{AA} for vector bosons

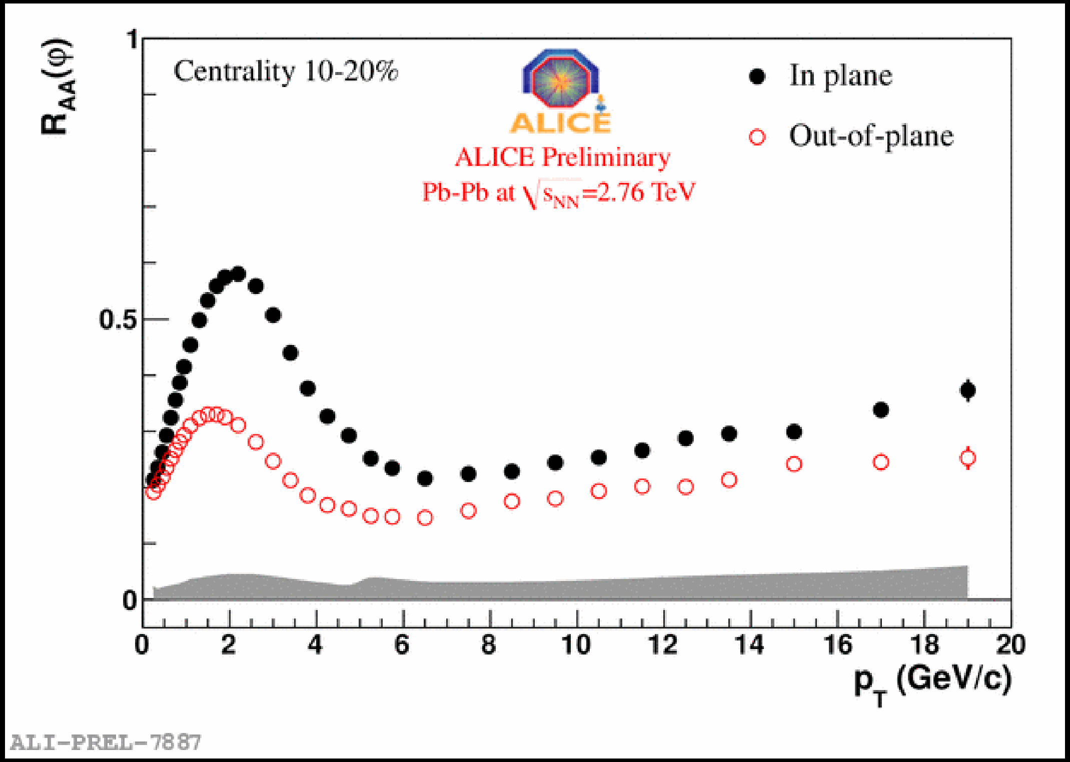
- electroweak probes, on the other hand, are unmodified

→ (essential cross check!)



Suppression vs event plane

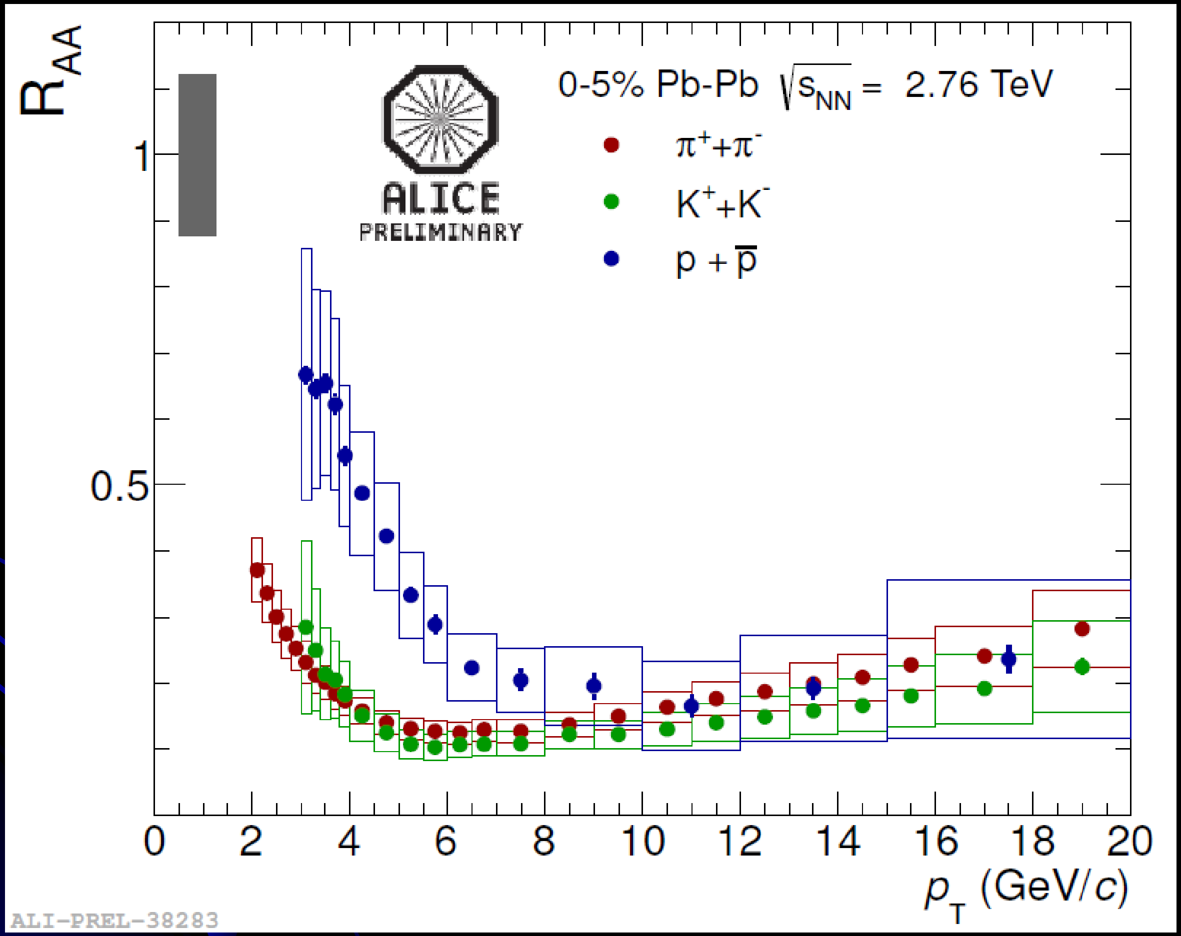




- significant effect!
- further constraints to energy loss models
  - → path-length dependence of energy loss

Baryon/Meson effect

→ sensitivity to medium hadronisation



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:

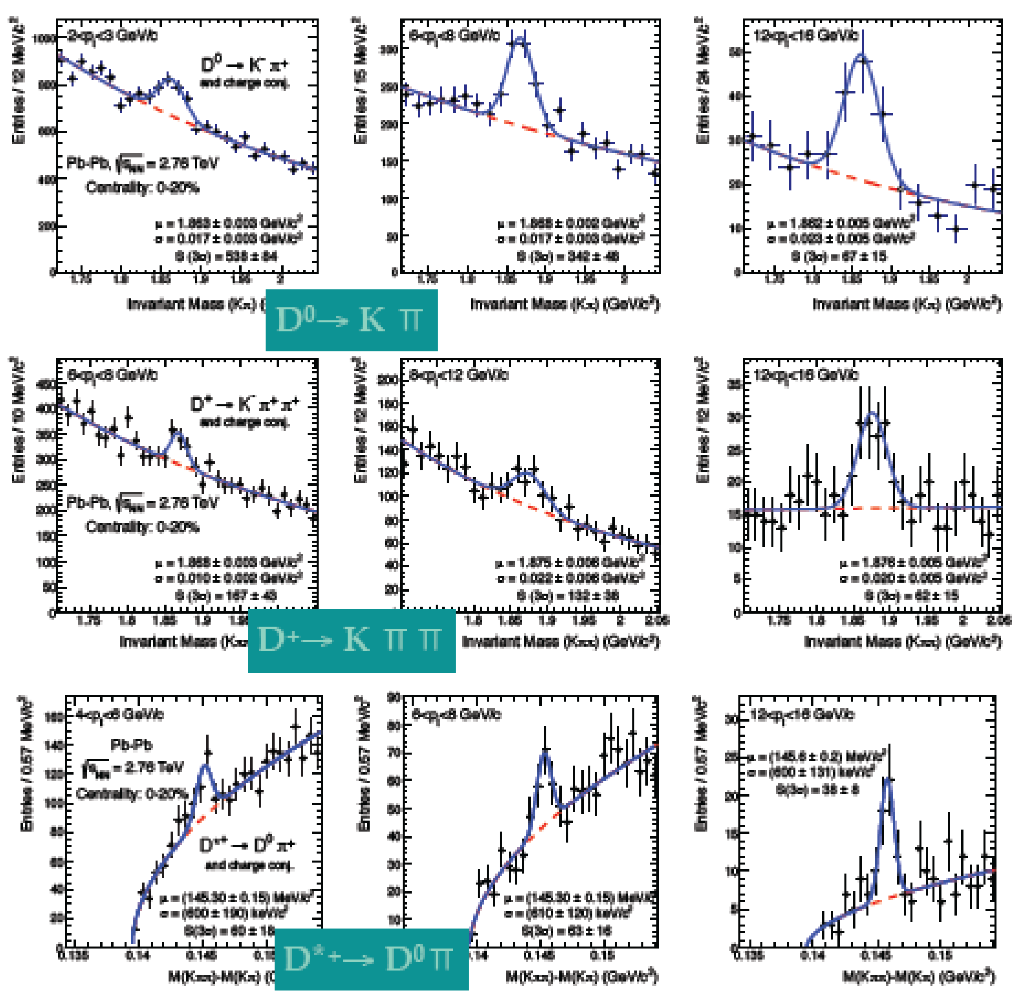
i) Casimir factor

- 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

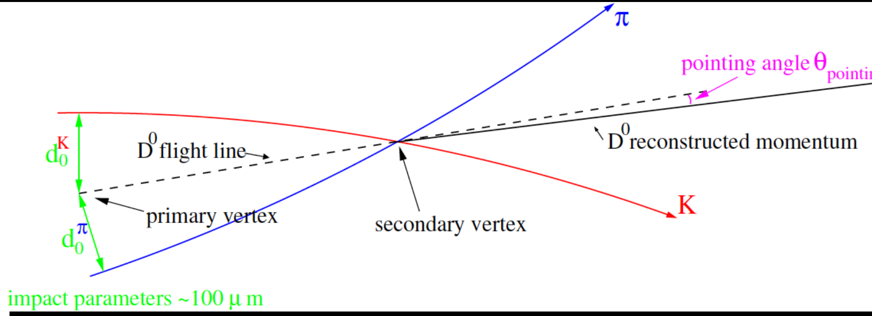
ii) dead-cone effect

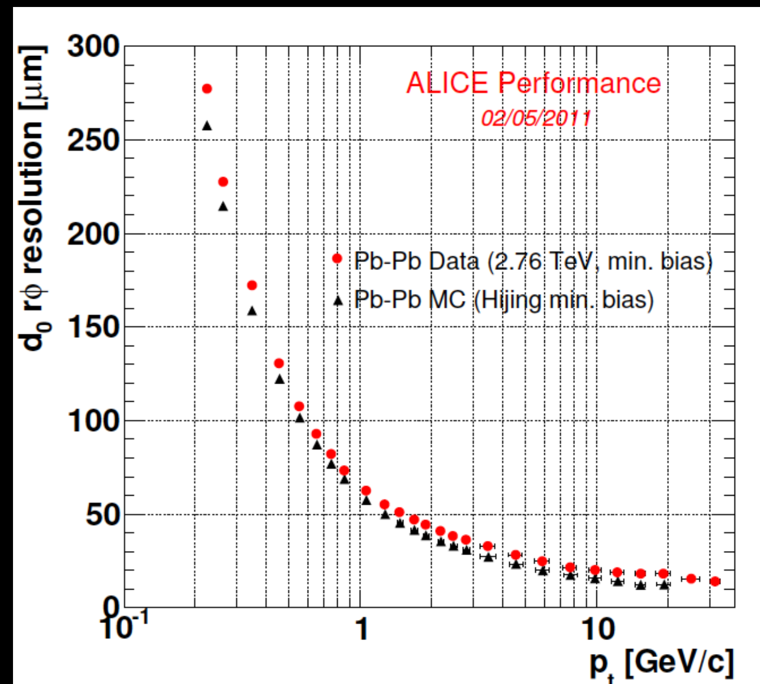
- gluon radiation expected to be suppressed for $\theta < M_Q/E_Q$
  [Dokshitzer & Karzeev, Phys. Lett. **B519** (2001) 199]
  [Armesto et al., Phys. Rev. D69 (2004) 114003]

Reconstructed D mesons!

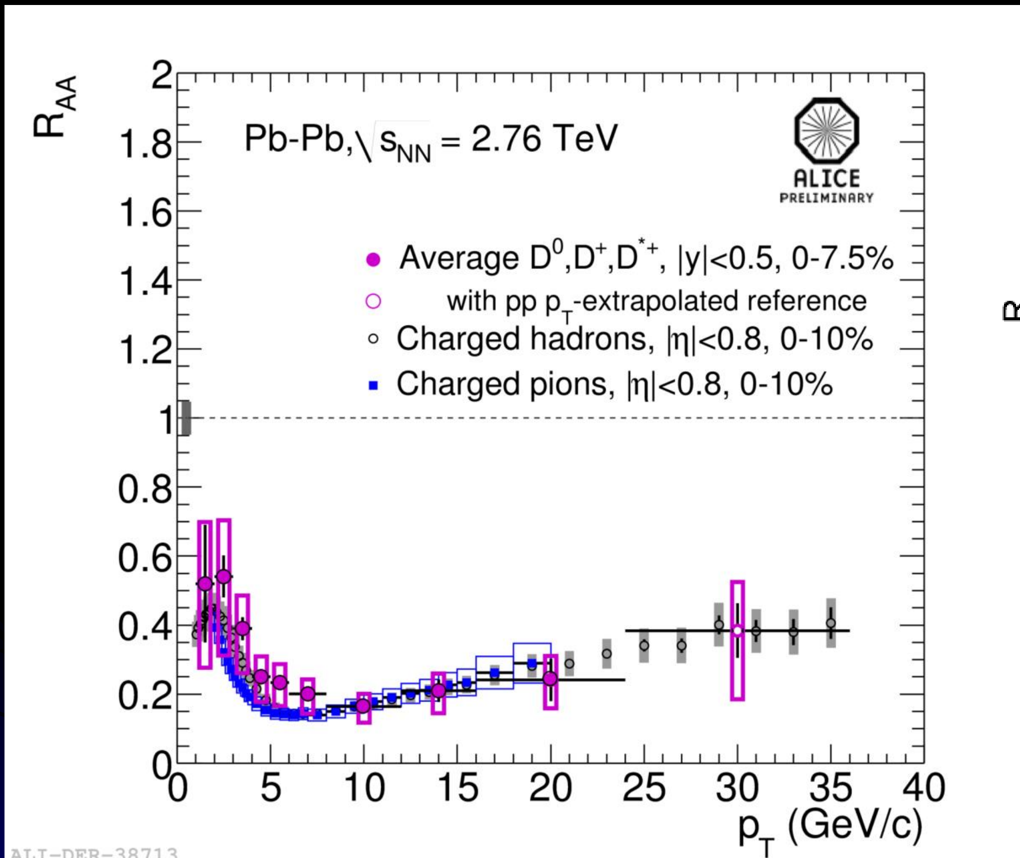


D^0, D^+ and D^{*+} signals in p_t bins for 0-20%CC

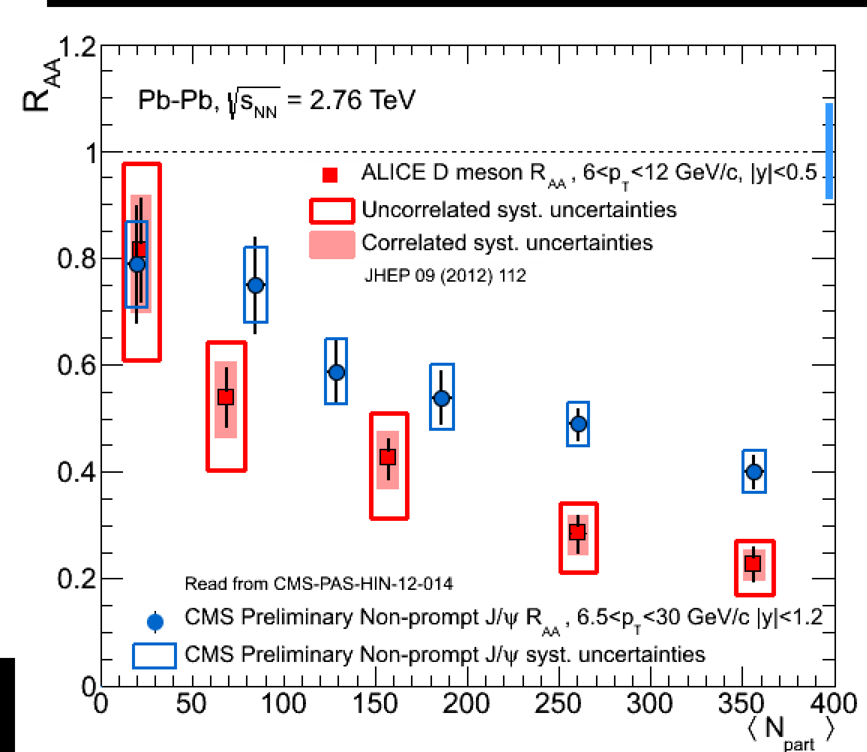




Heavy Flavours R_{AA}



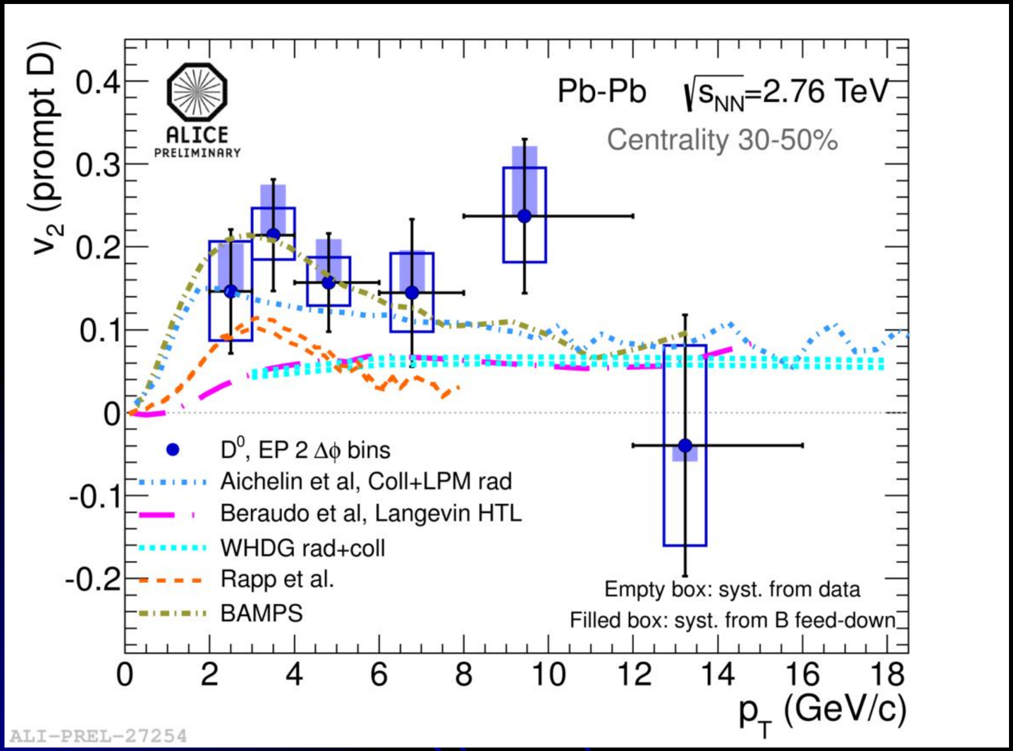
+ indication of less suppression for beauty?

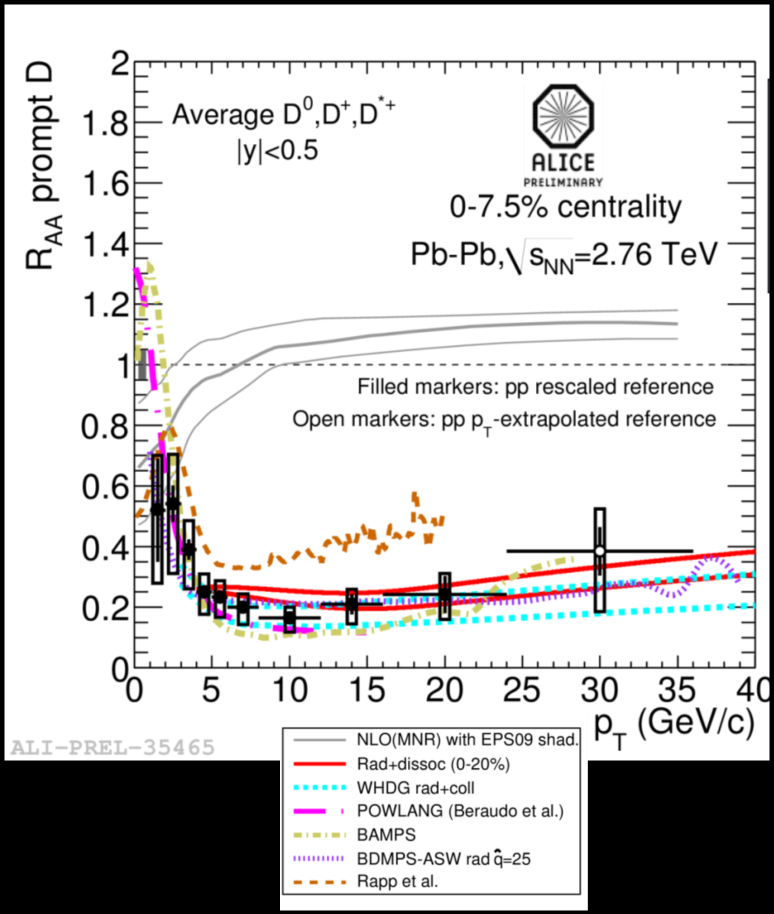


- p_T < 8 GeV/c:
  - hint of less suppression than for π ?
- p_T > 8 GeV/c
  - same suppression as for π…

D meson v_2

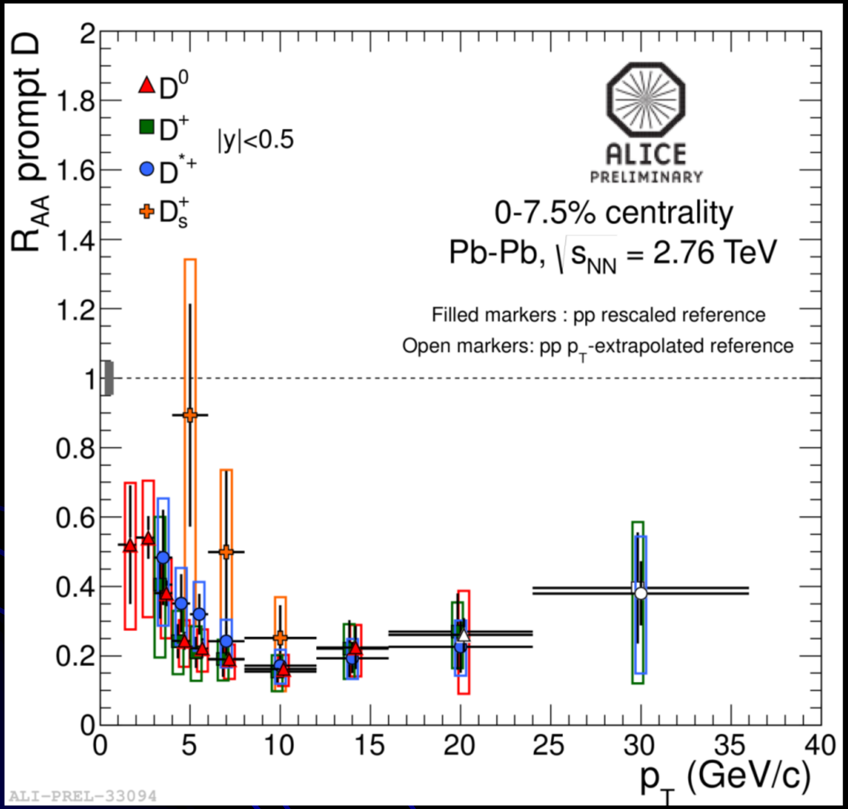
- Hint of non-zero v_2
  - consistent with strong coupling of c to medium
- theory must describe simultaneously v_2 and R_{AA} ...

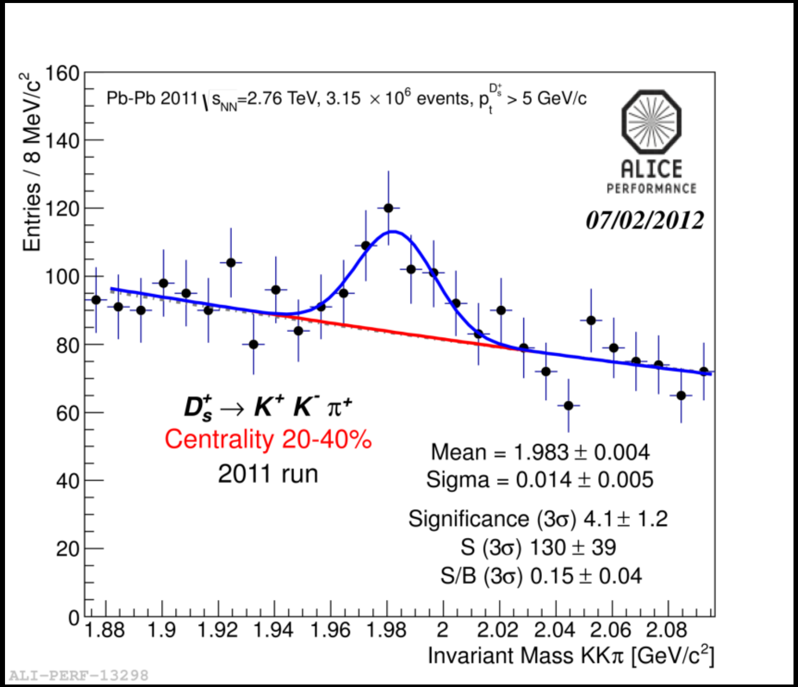




The D_s

- HF in-medium hadronisation!





- a hint of strangeness enhancement?
  - more stats needed!

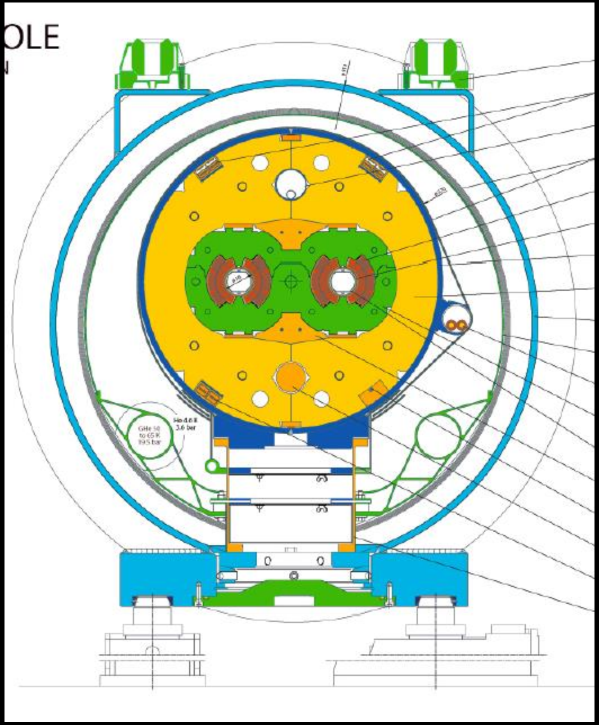
Heavy Flavour: outlook

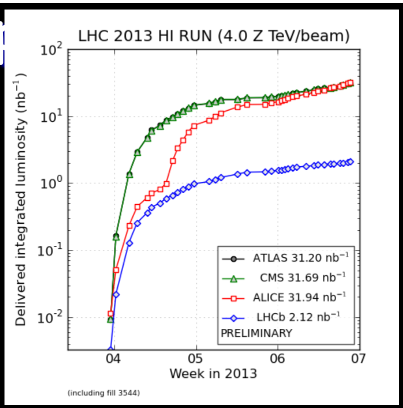
- high statistics D measurements
  → quantify difference between D and light hadrons
- charm thermalisation?
  → higher statistics measurement of D mesons v2
- subtract D background → pure B electron spectrum
  - beauty energy loss in wide p_T range
- in-medium fragmentation of b-tagged jets !

p-Pb collisions in the LHC!

- tricky, but can be done…
- 2-in-1 design…
  - → identical bending field in two beams
  - → locks the relation between the two beam momenta: p (Pb) = Z p(proton)
  - → different speeds for the two beams!
- adjust length of closed orbits!
  - to compensate different speeds
- different RF freq for two beams at injection and ram
- short low lumi pilot run (a few hours) on 12/9/2012
- first run in Jan-Feb 2013!

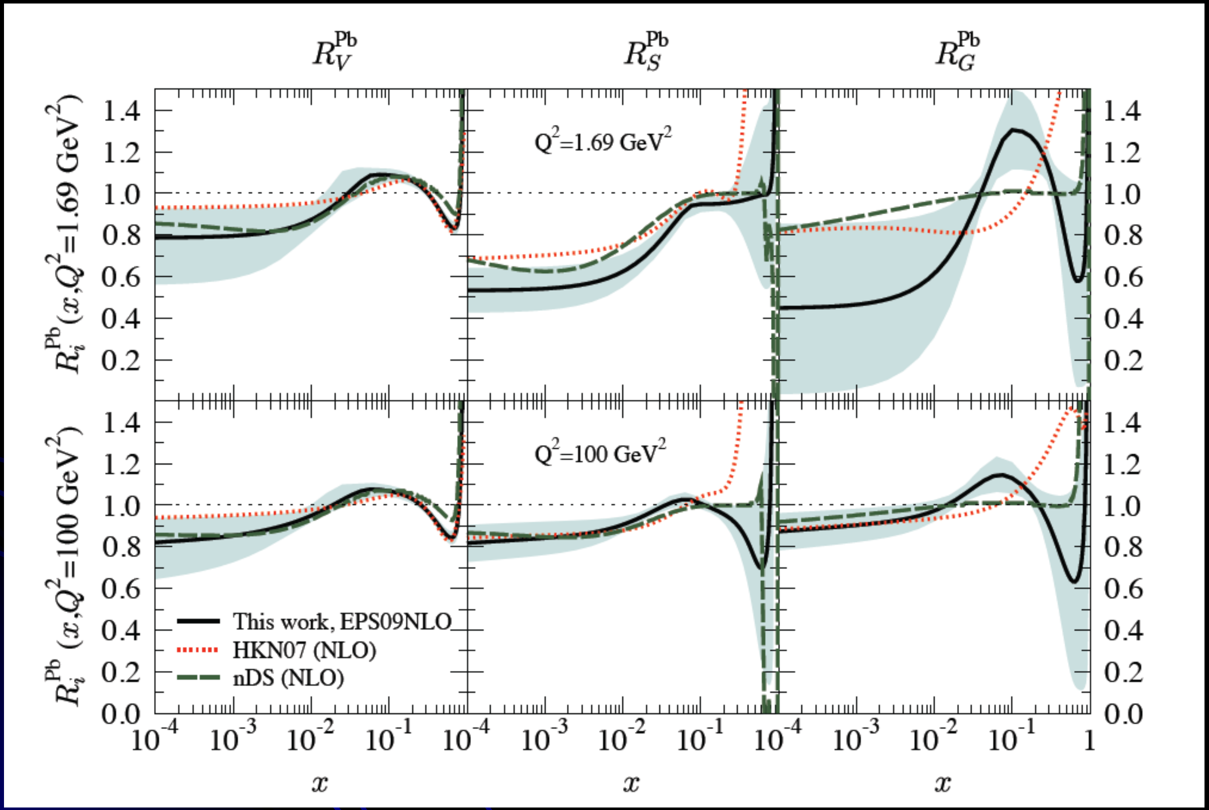
→ ~ 30/nb





Gluon shadowing…

- different parton distribution functions in protons and nuclei

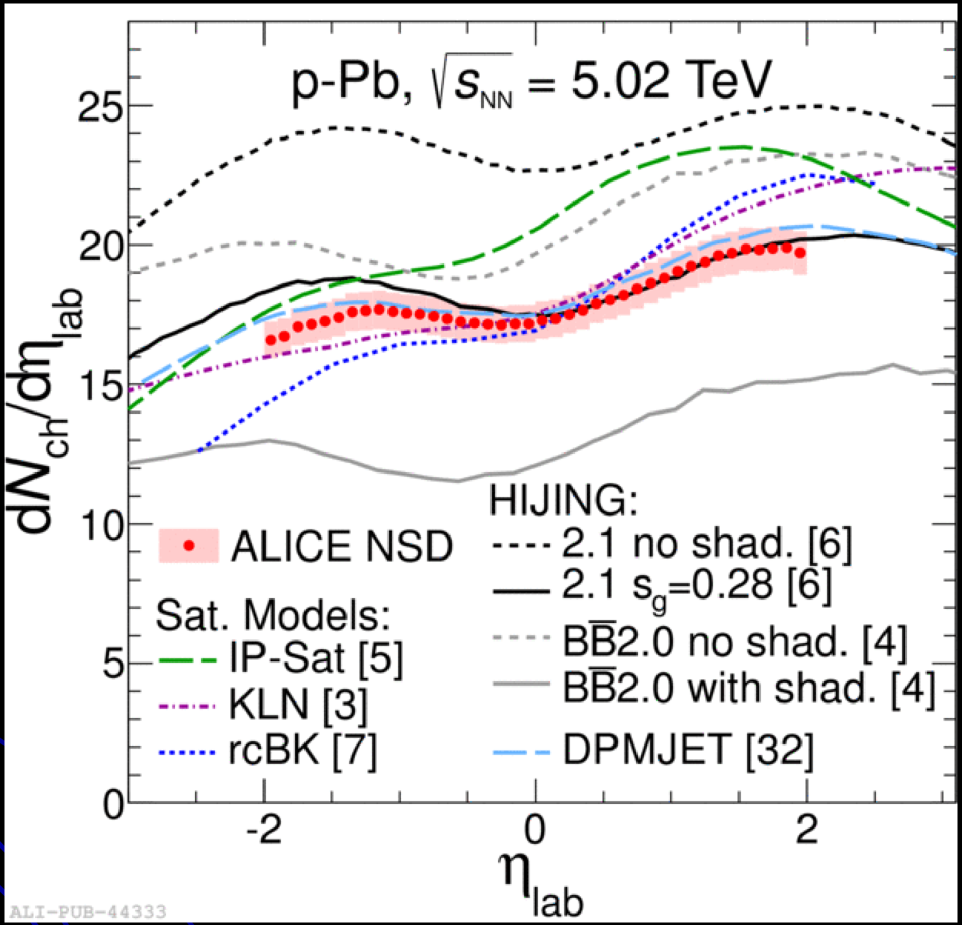


x = fraction of nucleon momentum carried by gluon

[K J Eskola et al: JHEP04(2009)065]

- a priori, large uncertainty
  → measure p-Pb collisions

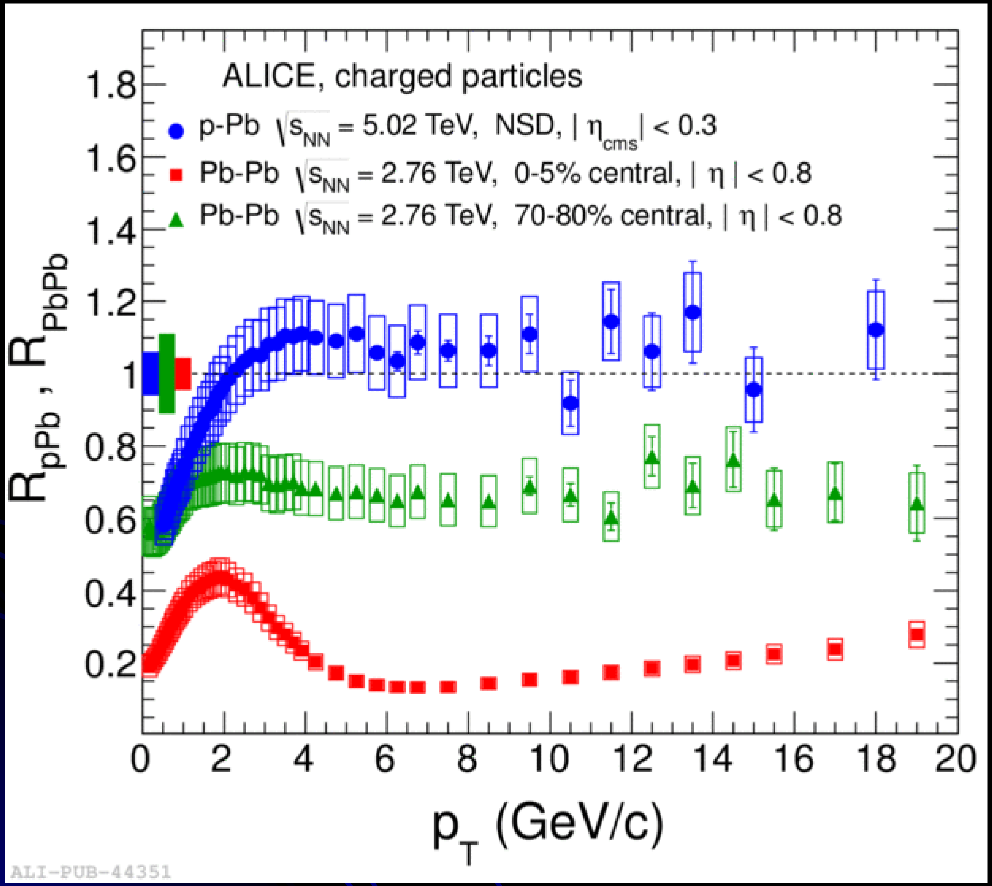
dN/dη in p-Pb

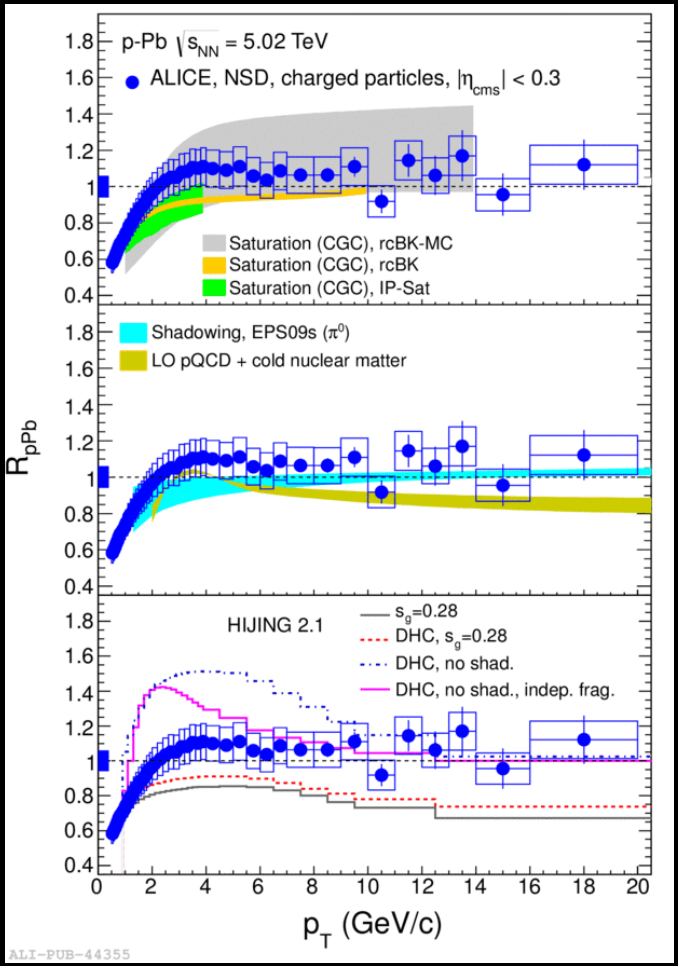


- essential model constraint
- too much p/Pb asymmetry in saturation models?

Control experiment: R_{pPb}

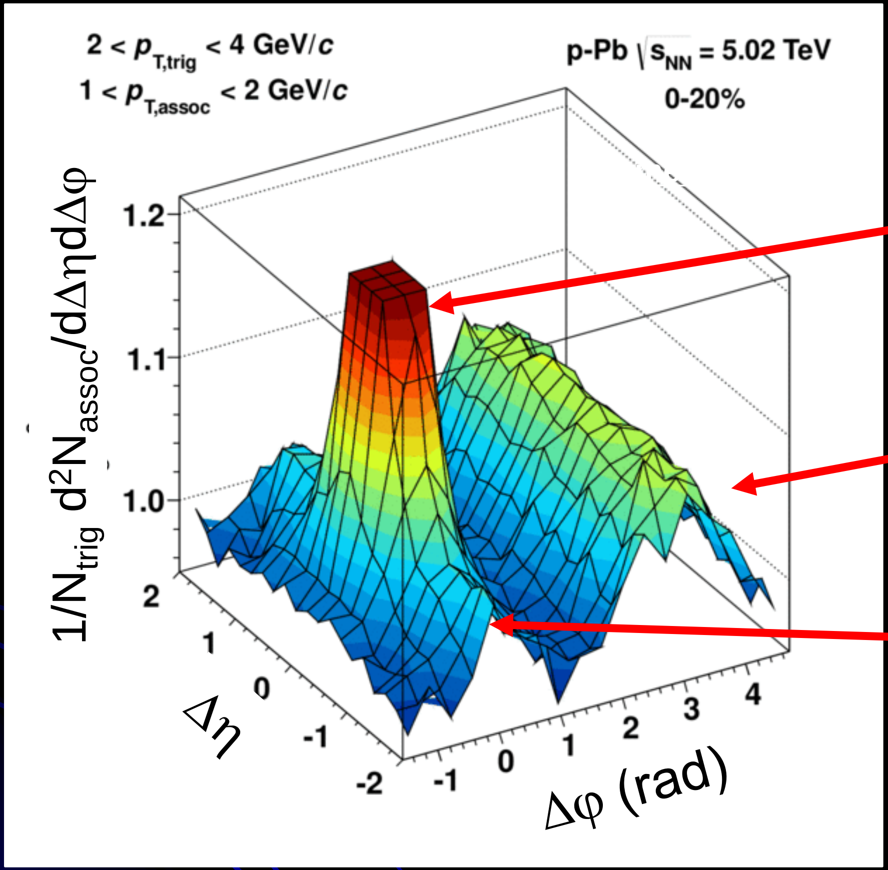
- measurement of nuclear modifications in initial state





- R_{pA} ~ 1 for p_T> 3 GeV/c → confirms quenching is due to QCD medium

The Ridge



2 < $p_{T,trig}$ < 4 GeV/c
1 < $p_{T,assoc}$ < 2 GeV/c
20% highest multiplicity

Near-side jet
($\Delta\varphi$ ~ 0, $\Delta\eta$ ~ 0)

Away-side jet
($\Delta\varphi$~ π, elongated in $\Delta\eta$)

Near-side ridge
($\Delta\varphi$ ~ 0, elongated in $\Delta\eta$)

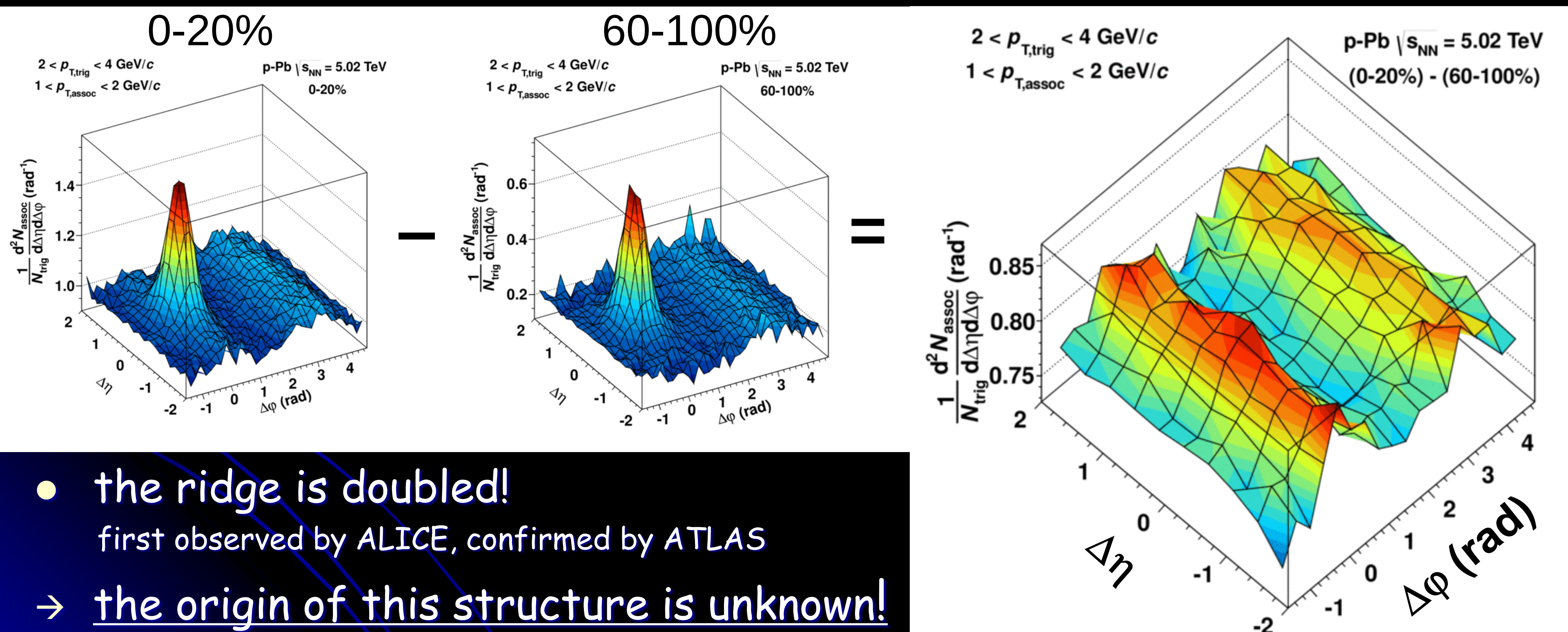
PLB719 (2013) 29

- in addition to near side peak and away-side recoil…
  … there's an additional near side ridge in p-Pb
  first observed by CMS [PLB718 (2013) 795]

The Double Ridge

- Can we separate the jet and ridge components?
  - no ridge seen in 60-100% and similar to pp
    → what remains if we subtract 60-100%?

PLB719 (2013) 29



- the ridge is doubled!
  first observed by ALICE, confirmed by ATLAS

→ <u>the origin of this structure is unknown!</u>
  (and currently under vigorous investigation… stay tuned…)
  a similar structure observed in Pb-Pb is attributed to hydrodynamic flow!

Conclusions

- exciting results already from "on-line" analysis of Run 1 data
  - death of ridge and Mach cone?
  - anomalies in proton yields & momentum distributions
  - pattern of jet and heavy flavour suppression → challenge to Eloss models
  - intriguing behaviour of J/ψ R_{AA} at low p_T
  - discovery of double ridge in p-Pb collisions, origin still unknown!
- bright future ahead
  - new, thorough look at Run 1 data during 2013/2014 shutdown
  - preparations for Run 2 have started
- we need you!
  - the Run 1 samples have just been "scratched on the surface"
    - mostly based on pre-existing approaches
  - we now need to look again at the data with fresh, creative eyes
  - energetic young people are essential to this programme!

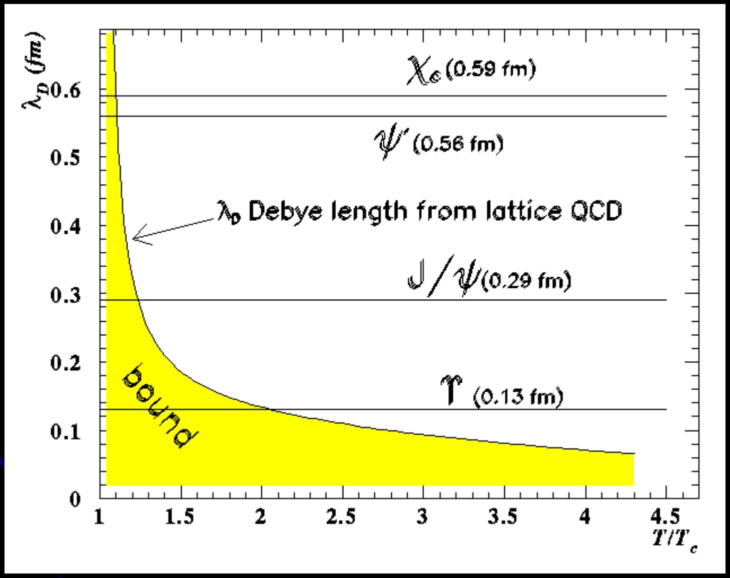
Thank you!

Extras

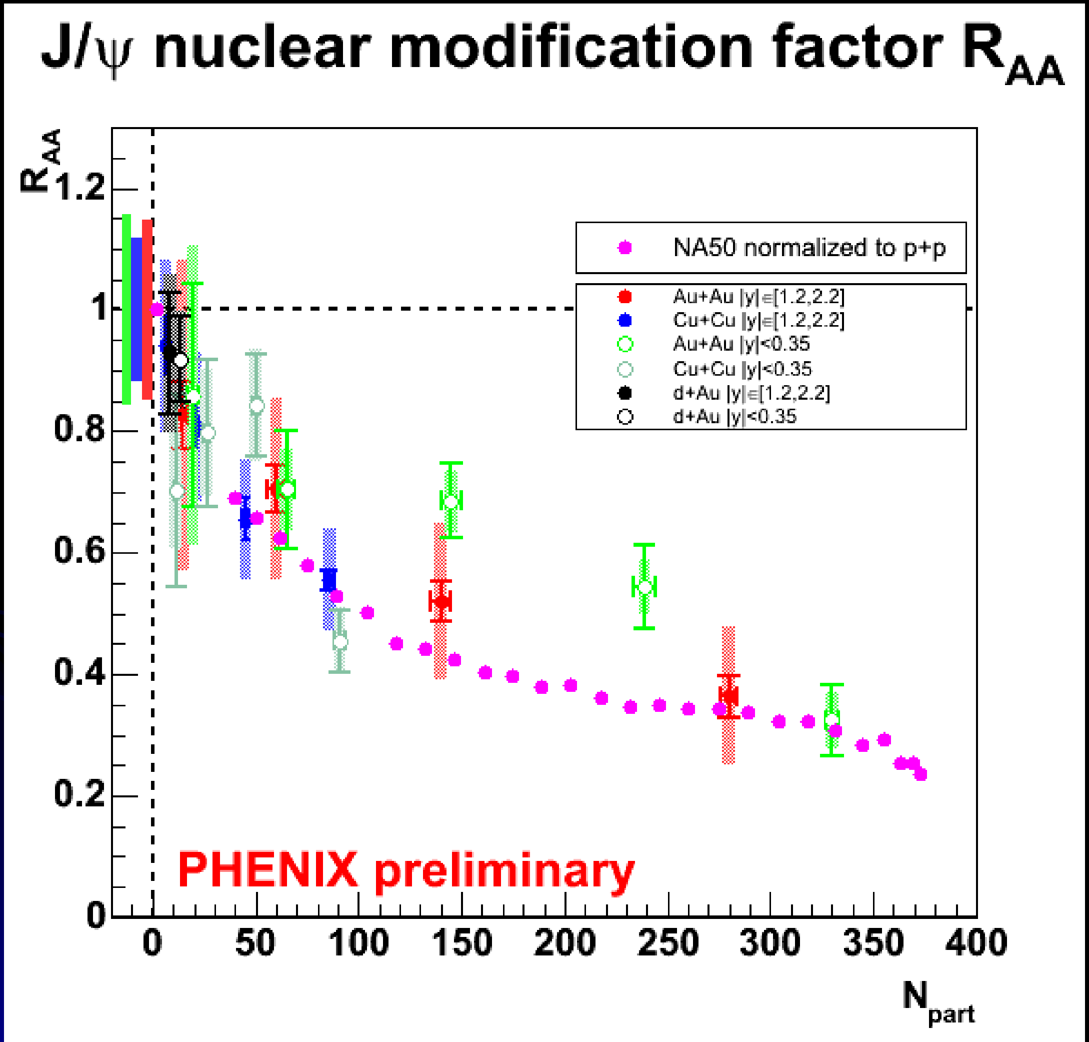
Quarkonia

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 > λ_D will not bind; their production will be suppressed



J/ψ suppression at SPS and RHIC



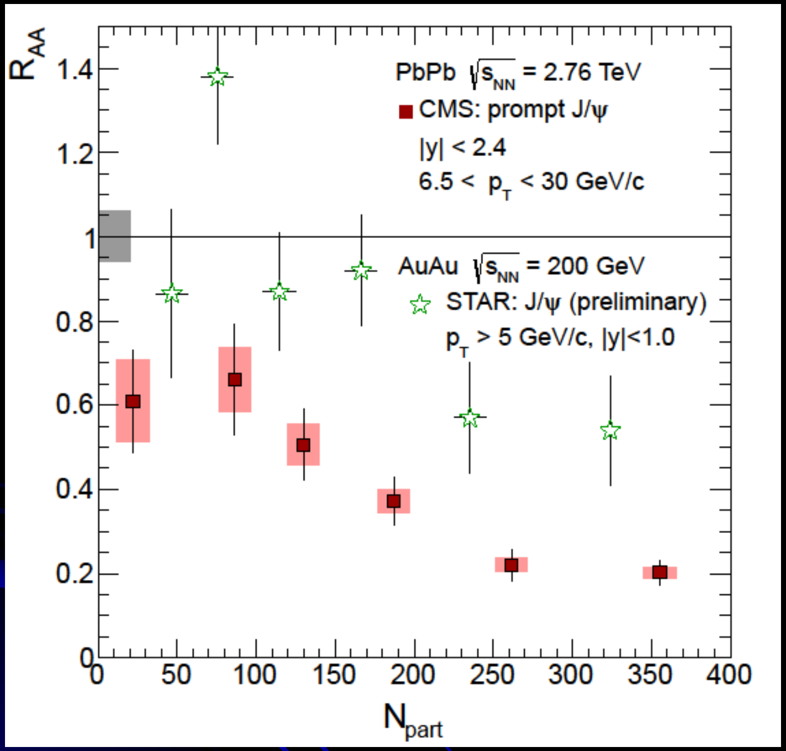
[Hugo Pereira (PHENIX), QM05]

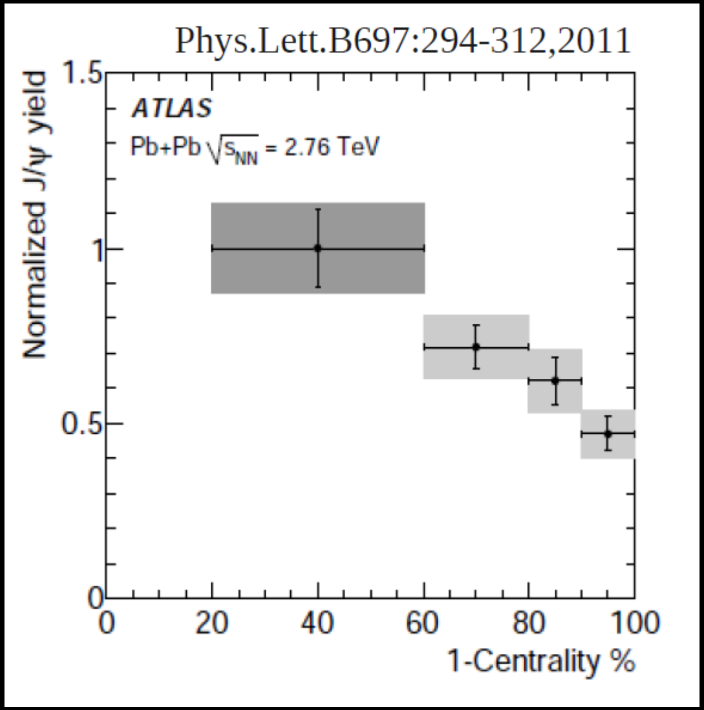
- substantial suppression of J/ψ production observed at SPS & RHIC
- ~ similar levels of suppression

J/ψ @ LHC: 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)





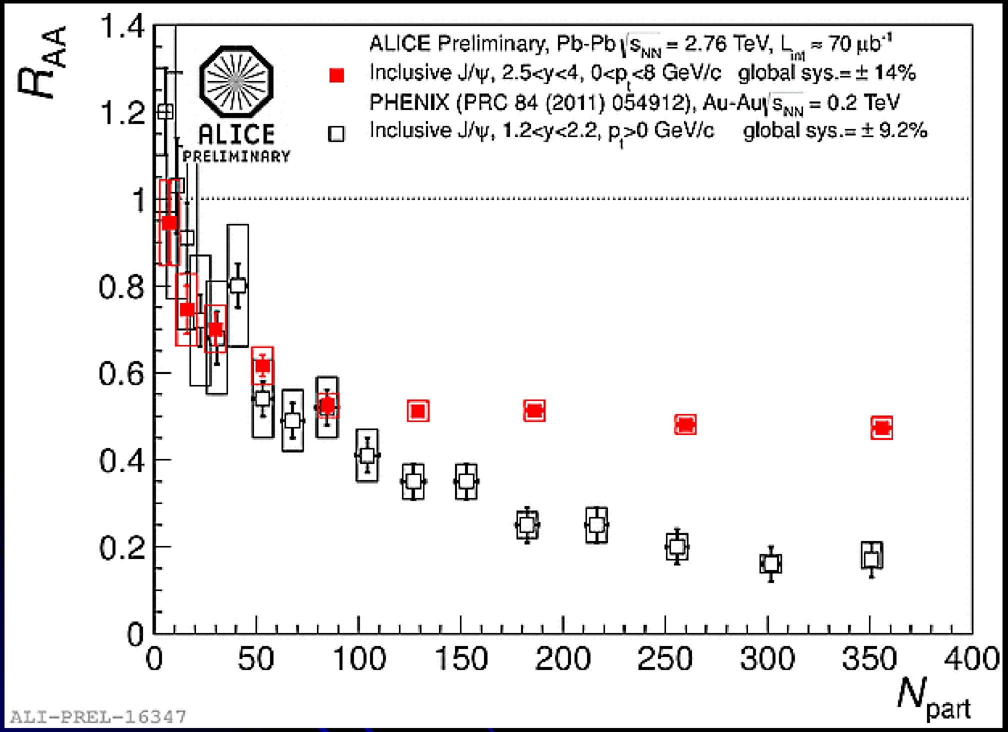
CMS: arXiv:1201.5069

ATLAS: PLB 697 (2011) 294

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

J/ψ @ LHC: 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)

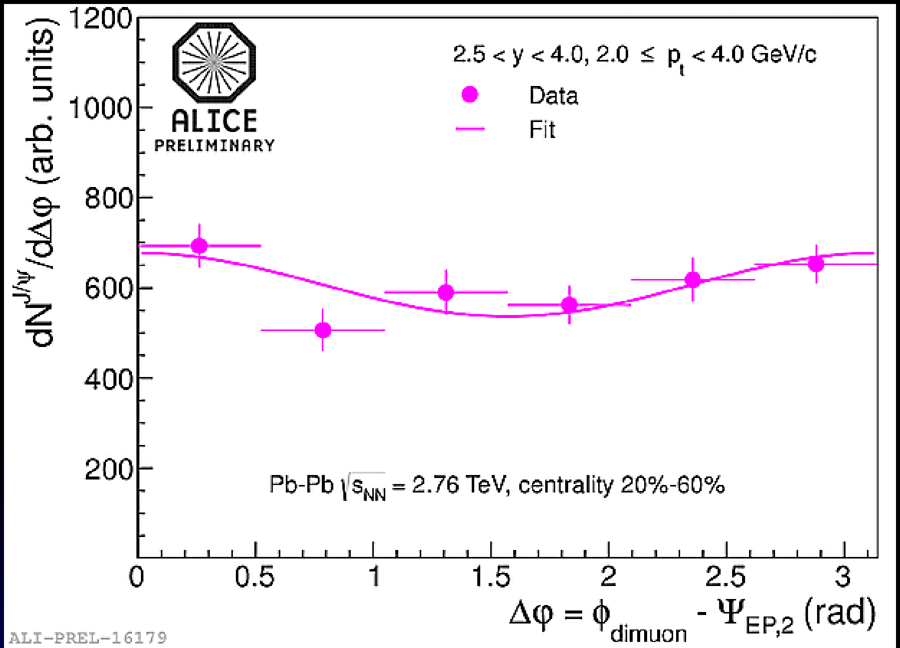
→ centrality dependence is much weaker!

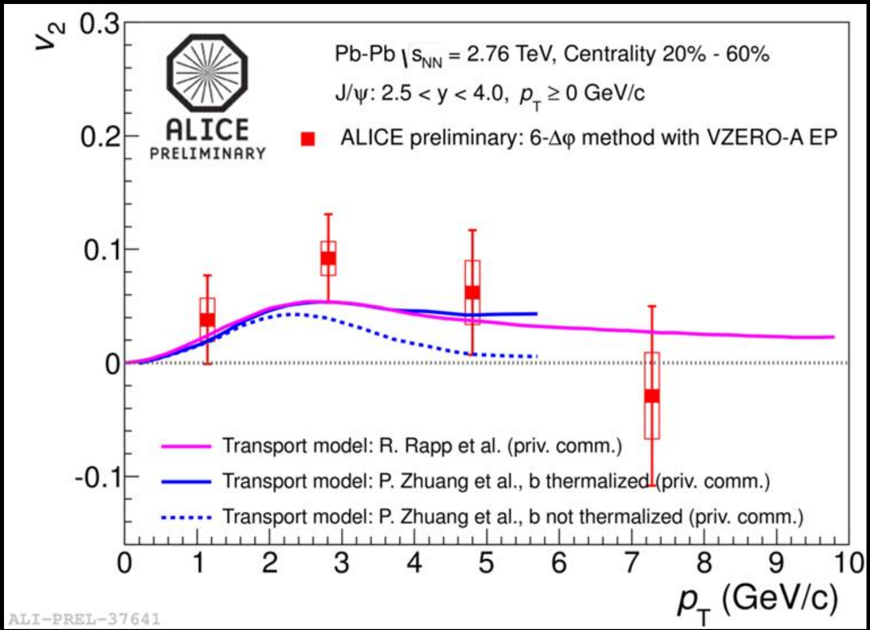
→ c-cbar coalescence?

- (suppression vs regeneration)

J/ψ flow?

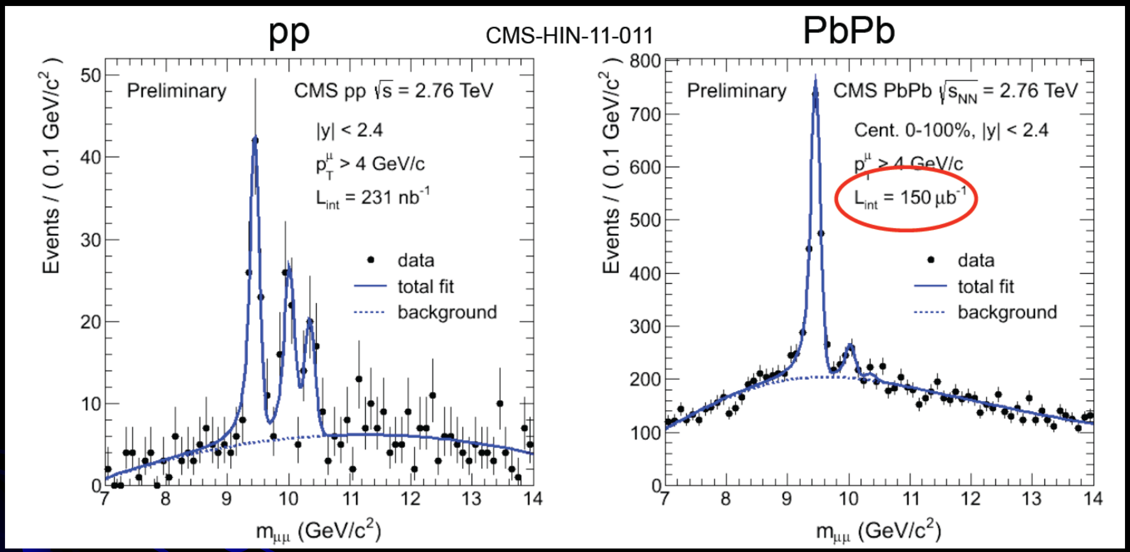
- some hint for a modulation…?

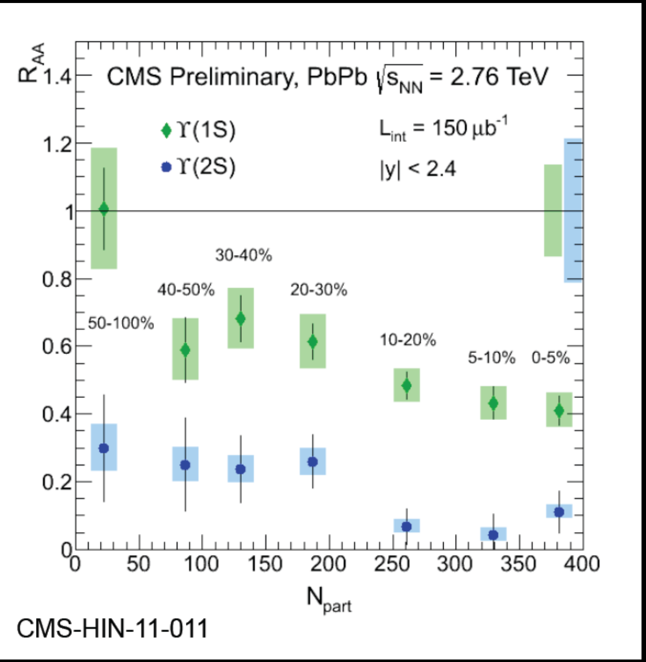




Bottomonia @ LHC

CMS: HIN-11-011





- ϒ(1S) significantly suppressed
- ϒ(2S) strongly suppressed
- ϒ(3S) not visible…

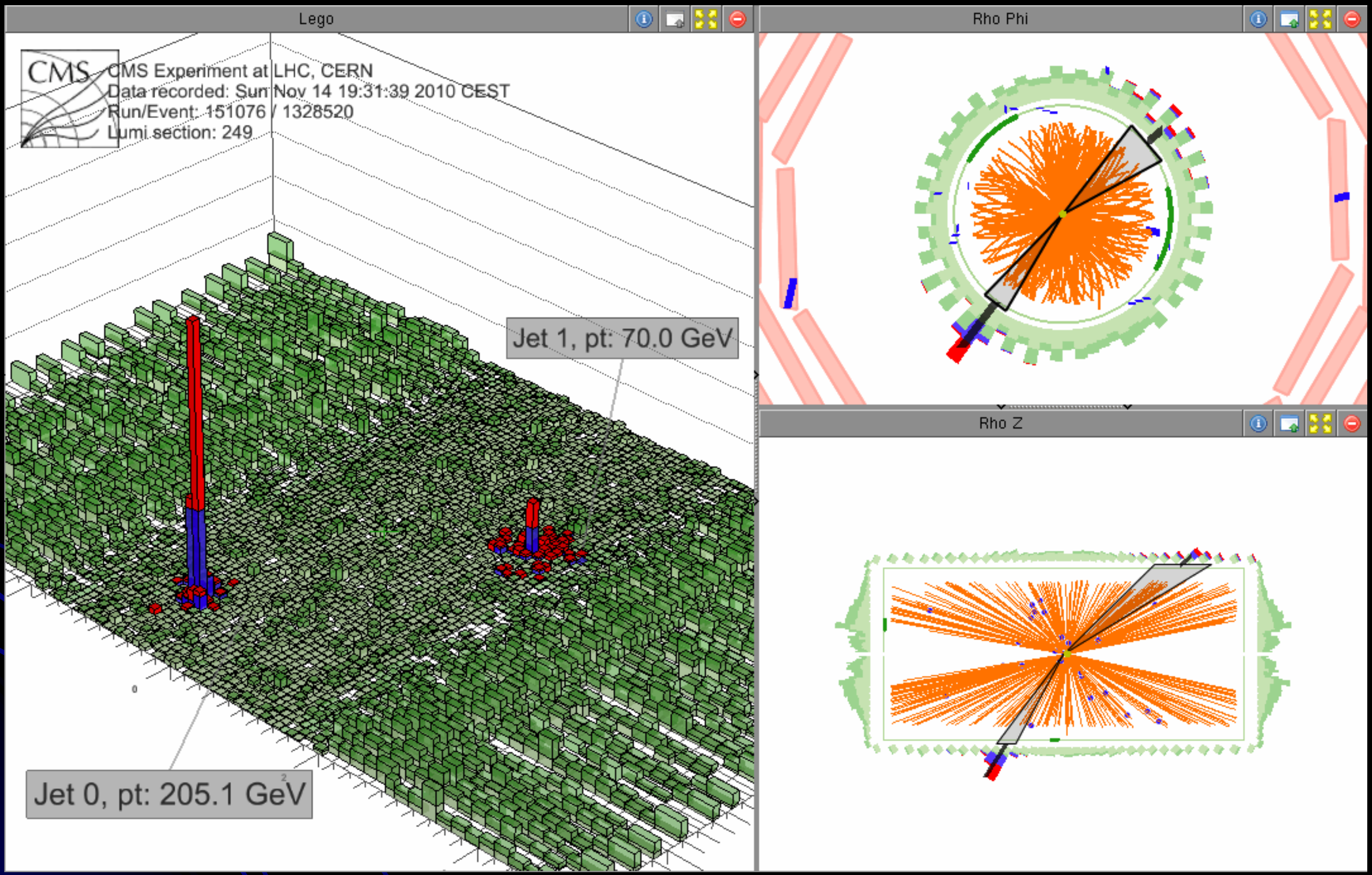
Quarkonia: outlook

- the pA baseline will be available soon!
- the future runs should allow us to establish quantitatively the complete quarkonium suppression (/recombination?) pattern
  - high statistic measurements → precision v_2
  - open flavour baseline / contamination

Jets

Di-jet imbalance

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

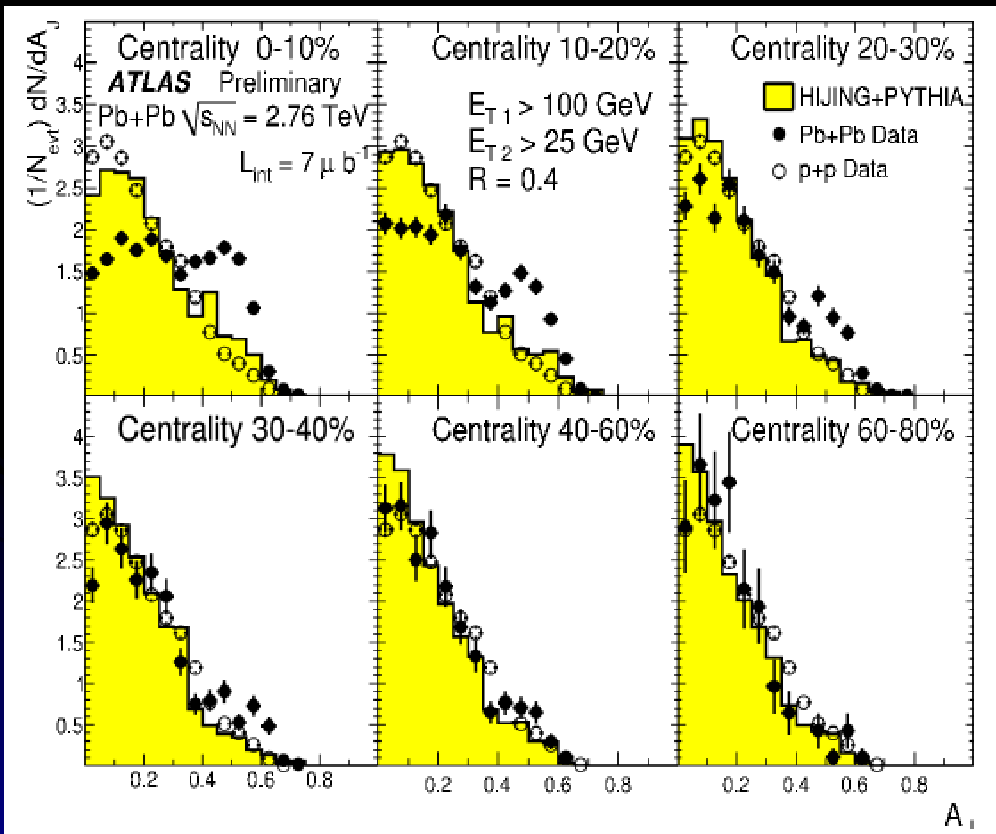


→ recoiling jet strongly quenched!

CMS: arXiv:1102.1957

A_J

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



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

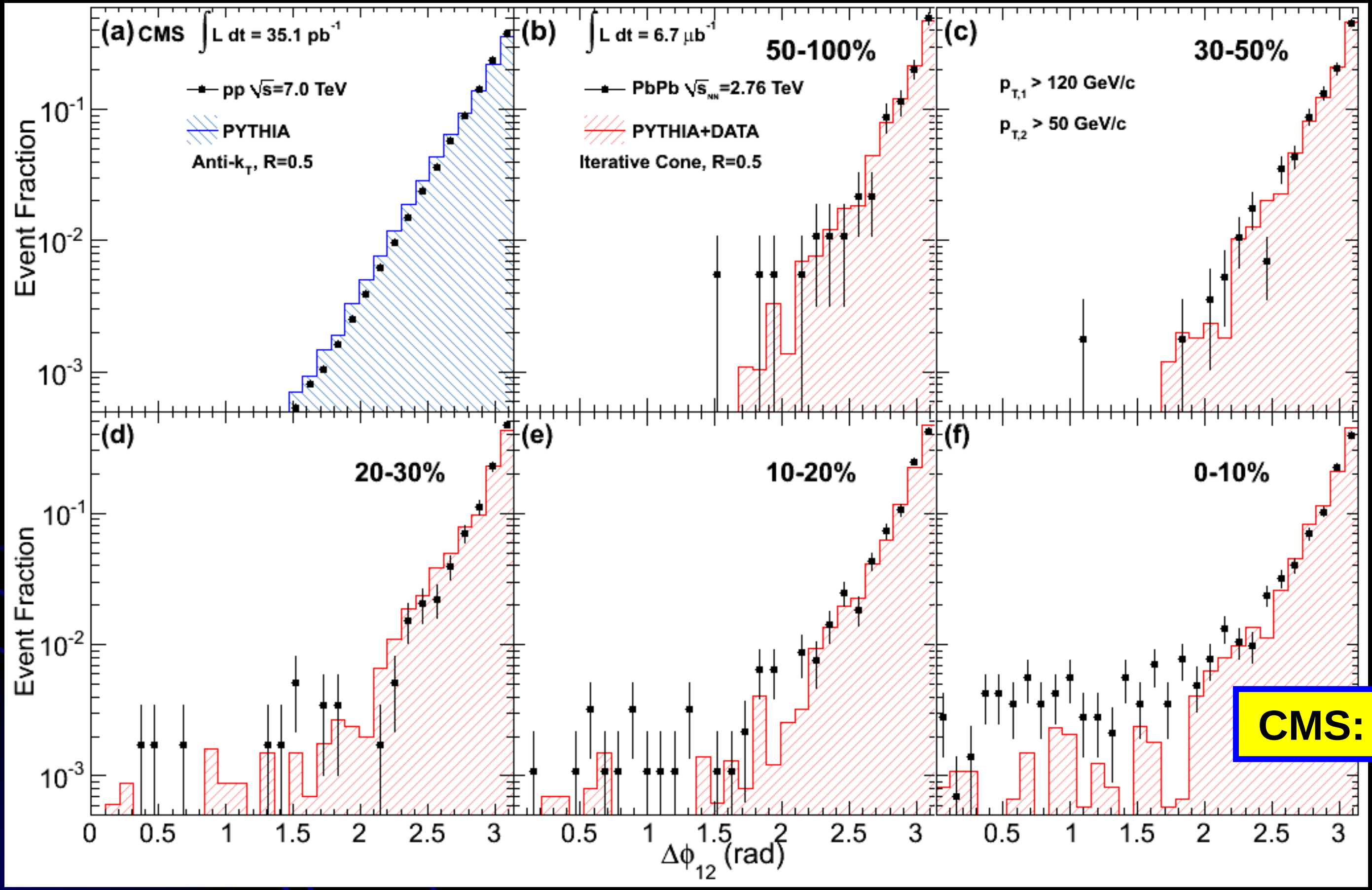
- with increasing centrality:

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

ATLAS: PRL105 (2010) 252303

Di-jet Δφ

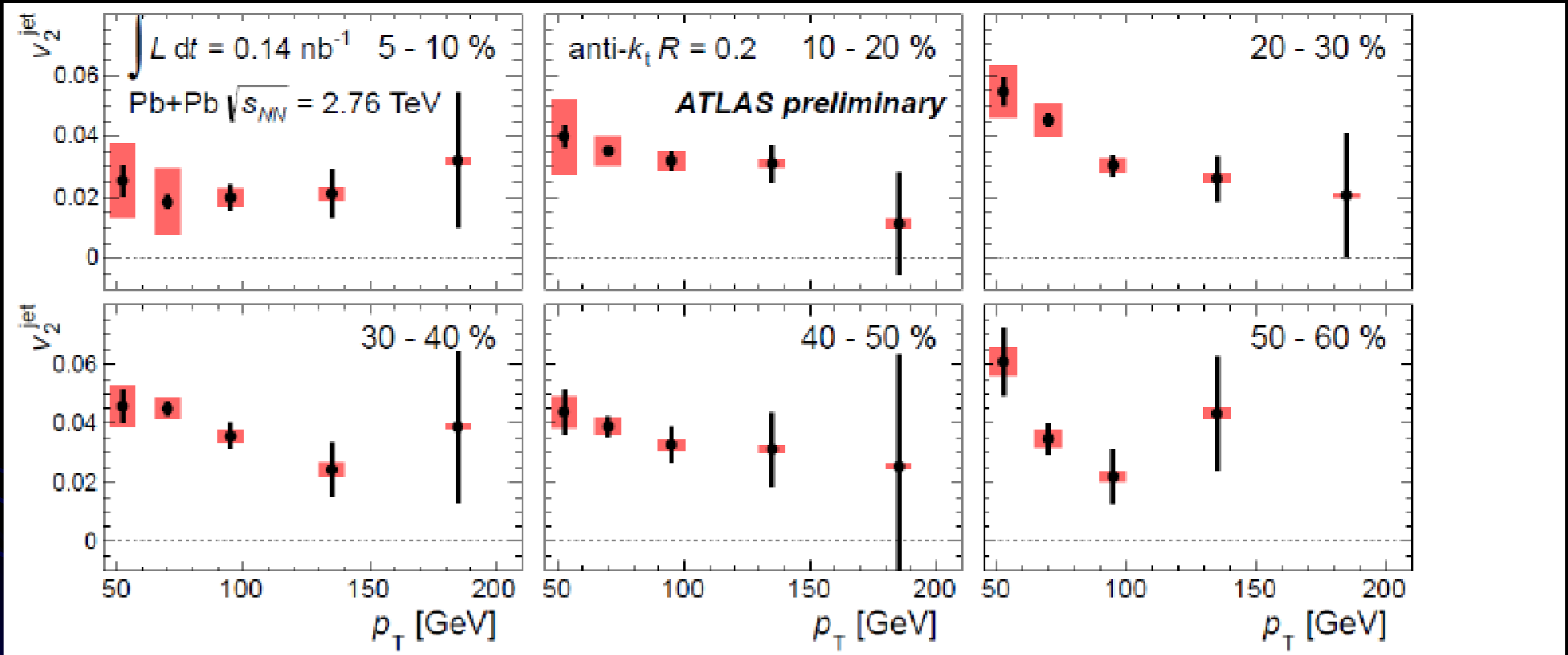
- no visible angular decorrelation in Δφ wrt pp collisions!



CMS: arXiv:1102.1957

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

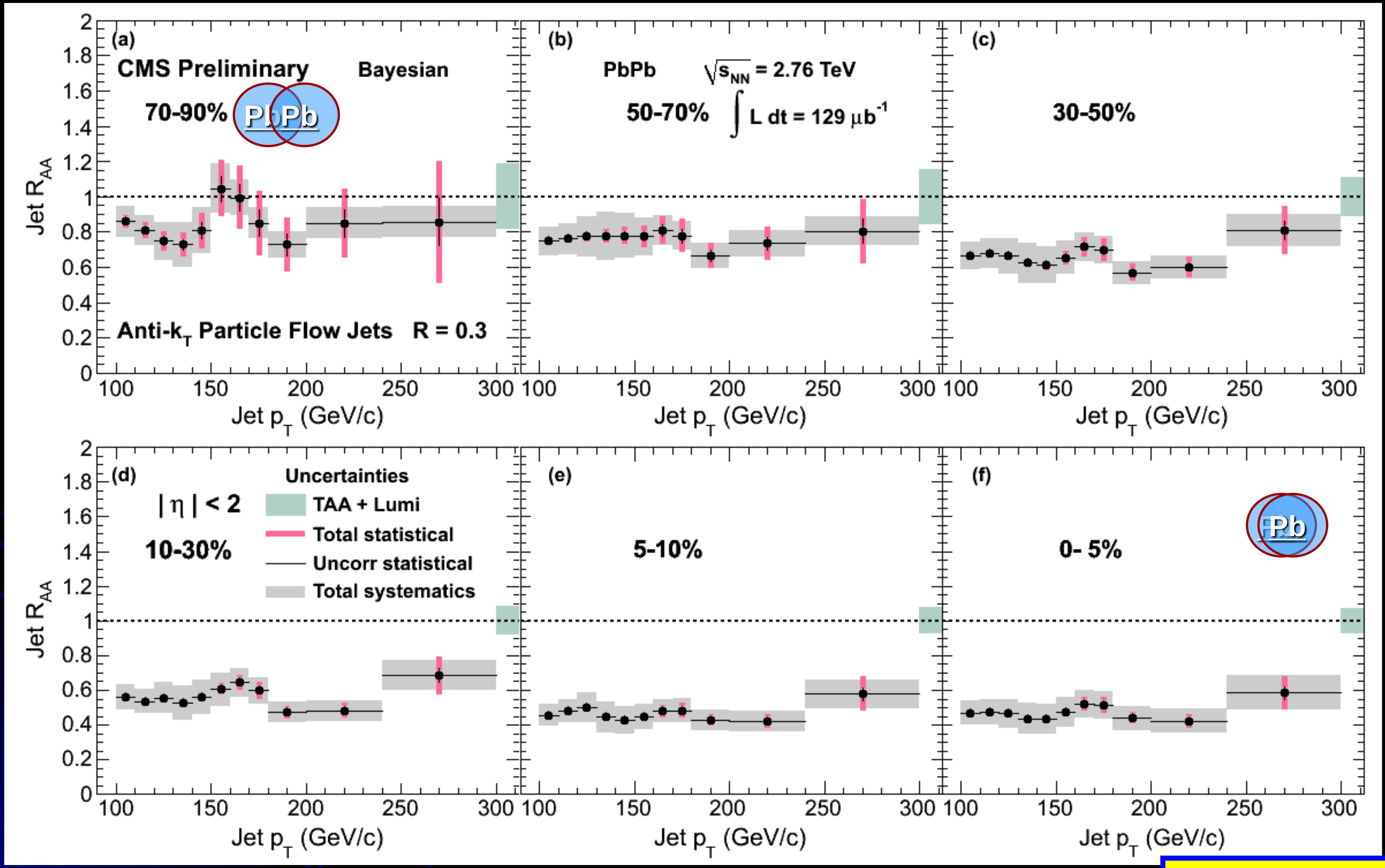
Jet v_2



ATLAS-CONF-2012-116

- substantial azimuthal asymmetry up to highest jet energies!

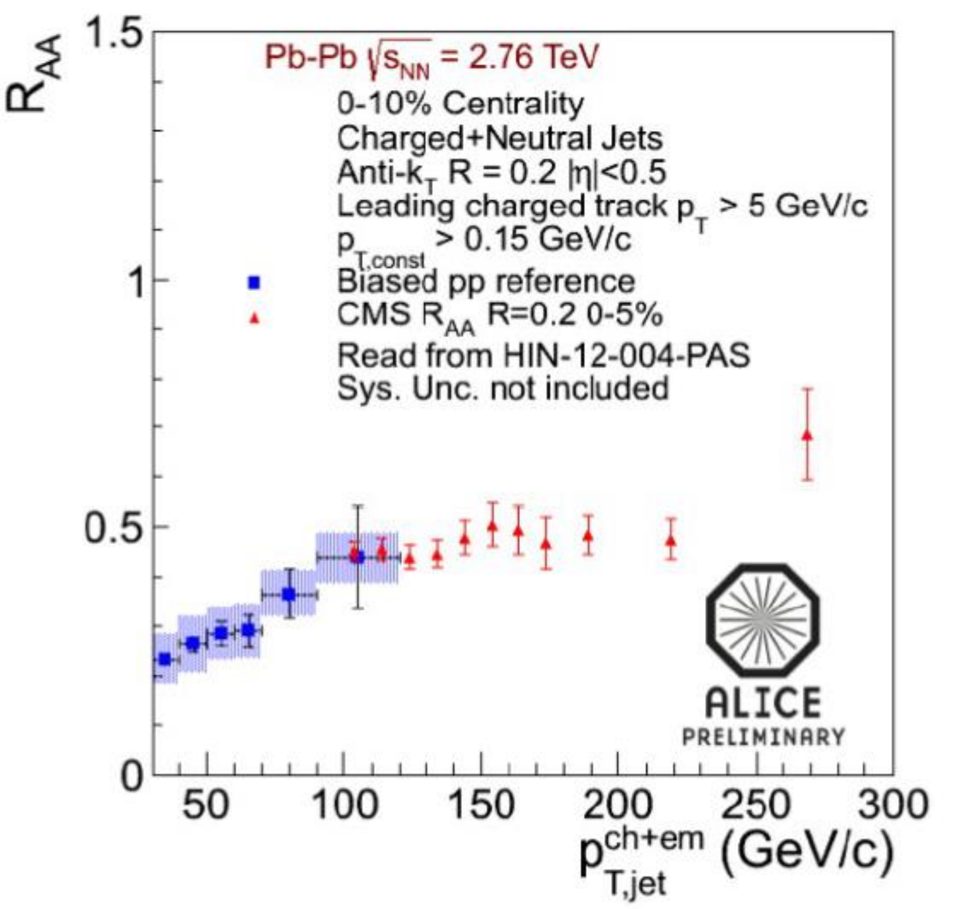
Jet R_{AA}



CMS PAS HIN-12-004

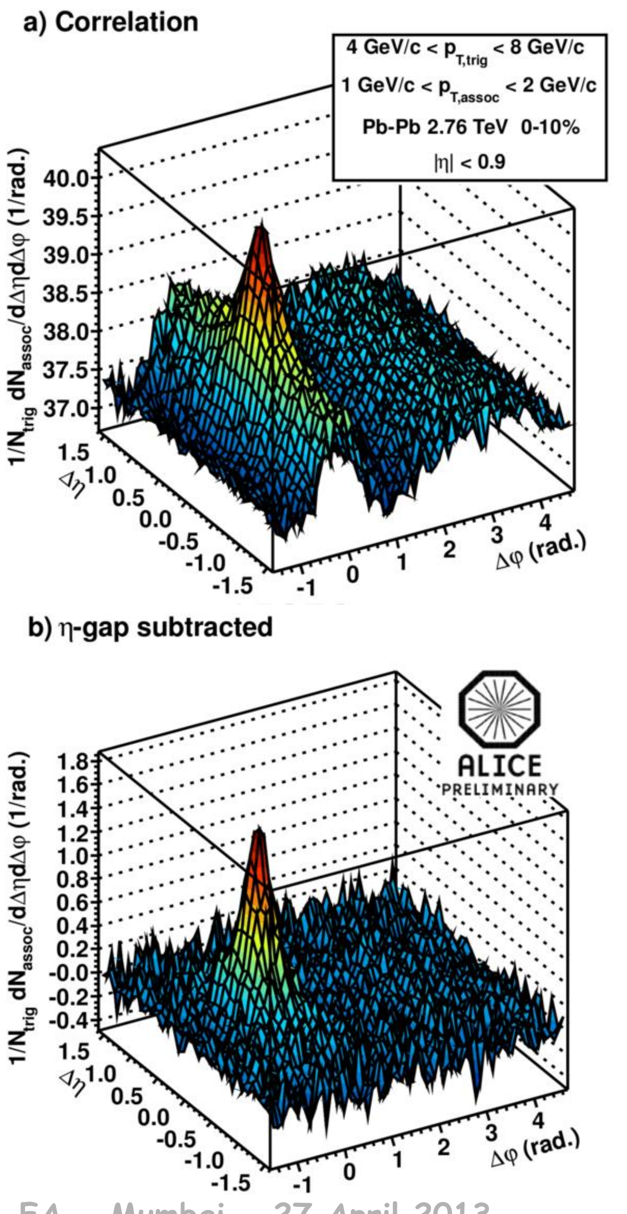
Jet R_{AA}, low p_T

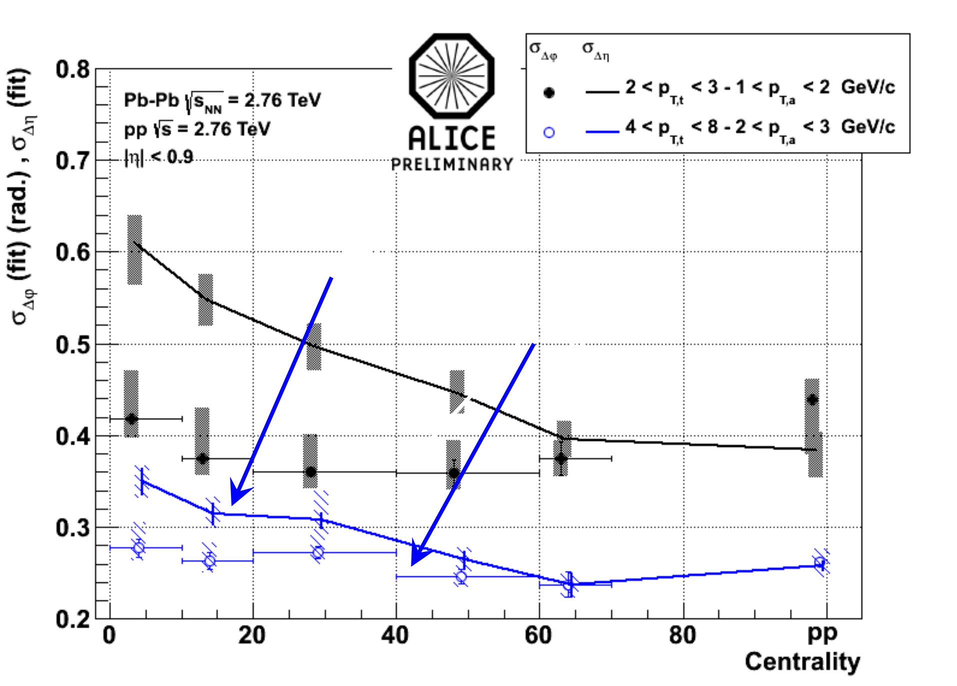
- change of behaviour at low p_T? it seems to decrease further…



- caveat: orange and mandarin…

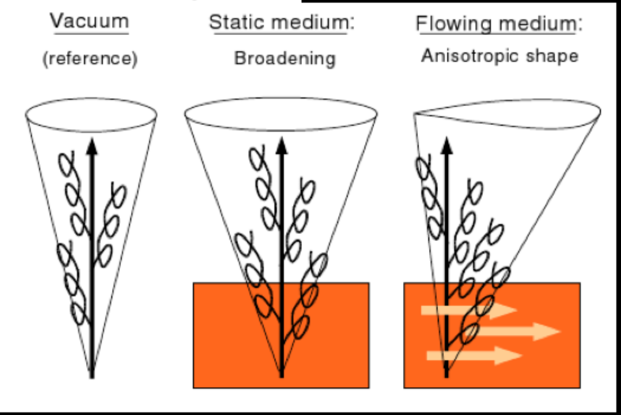
Near-side broadening





Evolution of near-side-peak s_h and s_φ with centrality:
Strong s_h increase for central collisions

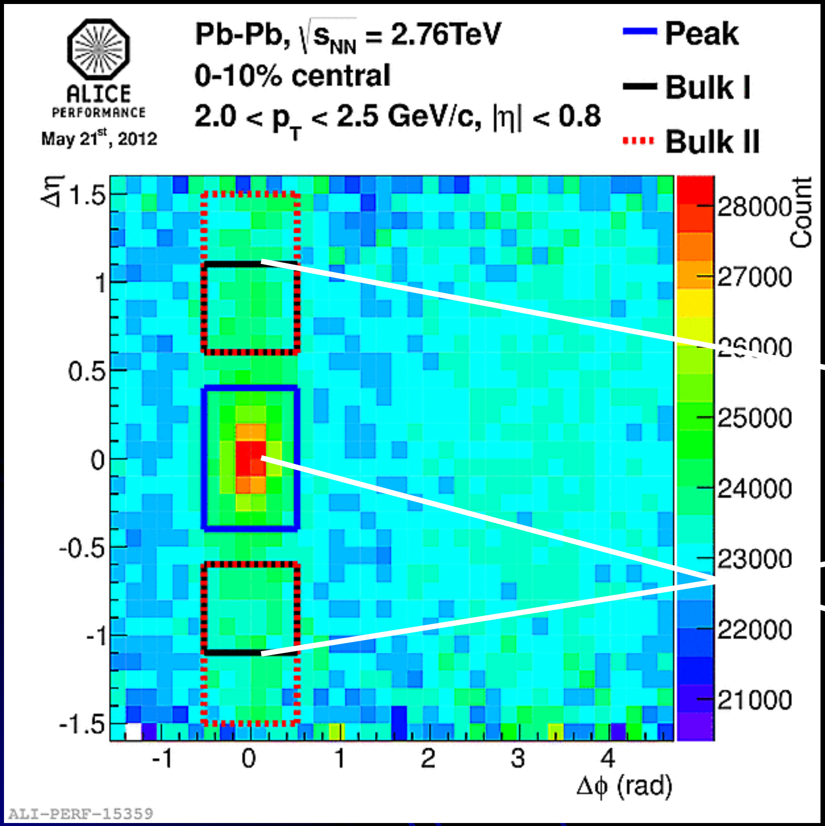
Interestingly: AMPT describes the data very well
Influence of flowing medium?

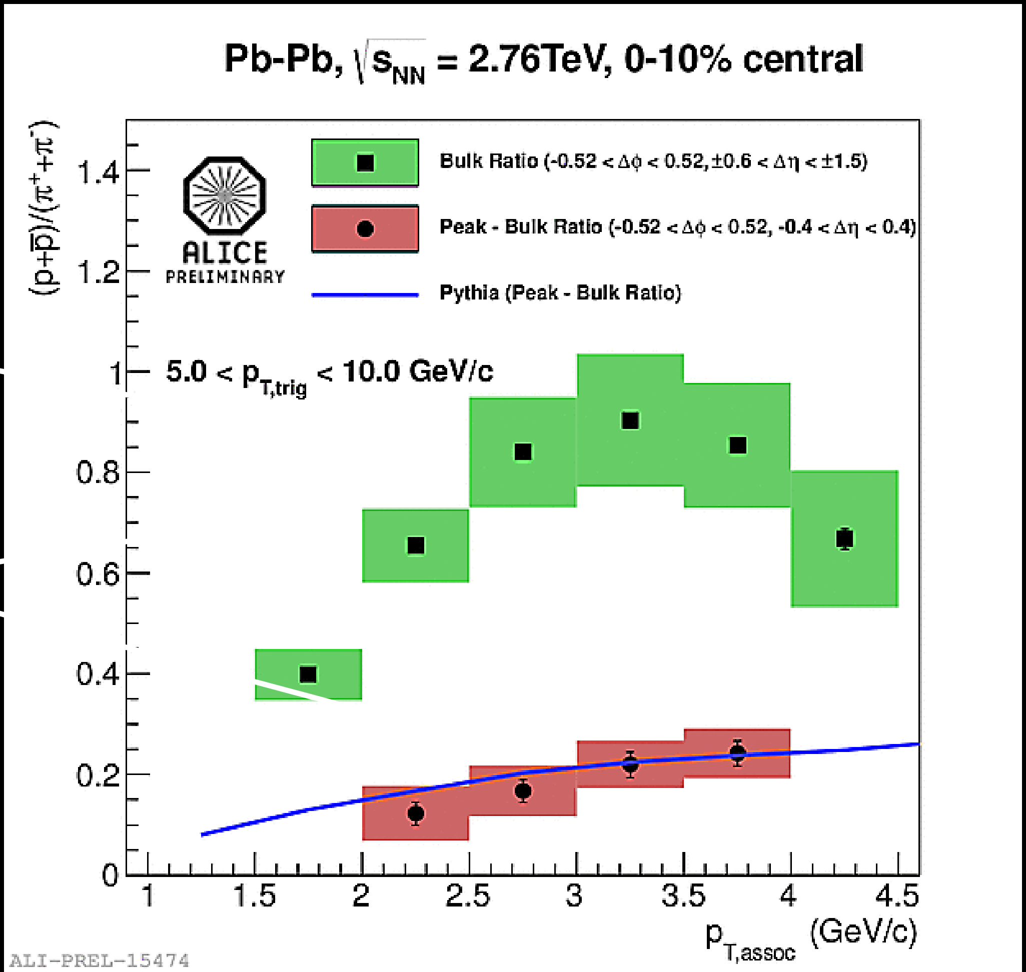


N.Armesto et al., PRL 93, 242301

Particle composition

- peak excess particle composition similar to pp!





What next?

- explore further the surroundings of away-side jets
  - broadening? softening? re-heating?
- b-tagged jets (quark vs gluon jets)
- extreme suppression?
  - “mono-jet” events? what do they look like?