Results from the ALICE Experiment on Heavy Ions and low x QCD physics

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For
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Aims of ALICE

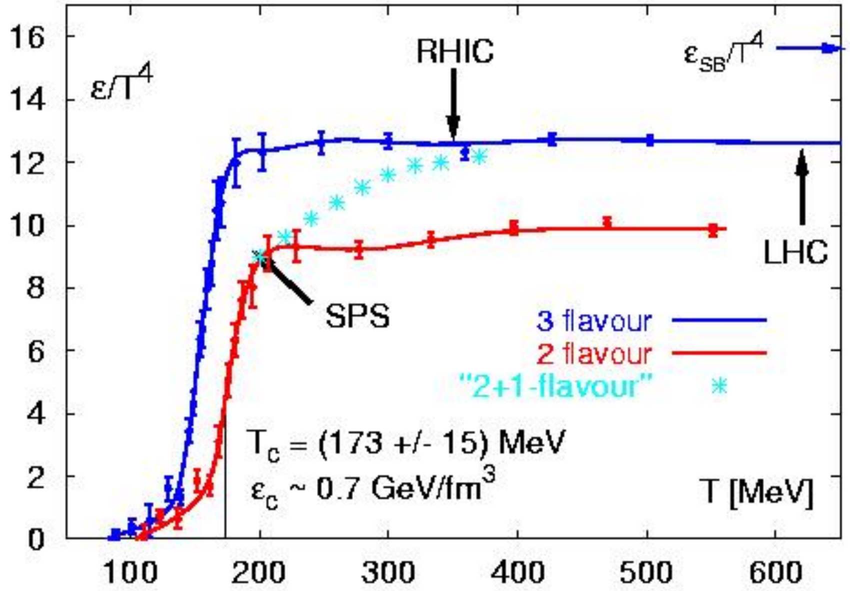
Study of strongly interacting matter under extreme conditions of temperature and energy densities

Study the QCD phase transition from hadronic matter to a deconfined state of quarks and gluons - The Quark-Gluon Plasma.

↓

Study the physics of the Quark-Gluon Plasma

Phases of Strongly Interacting Matter

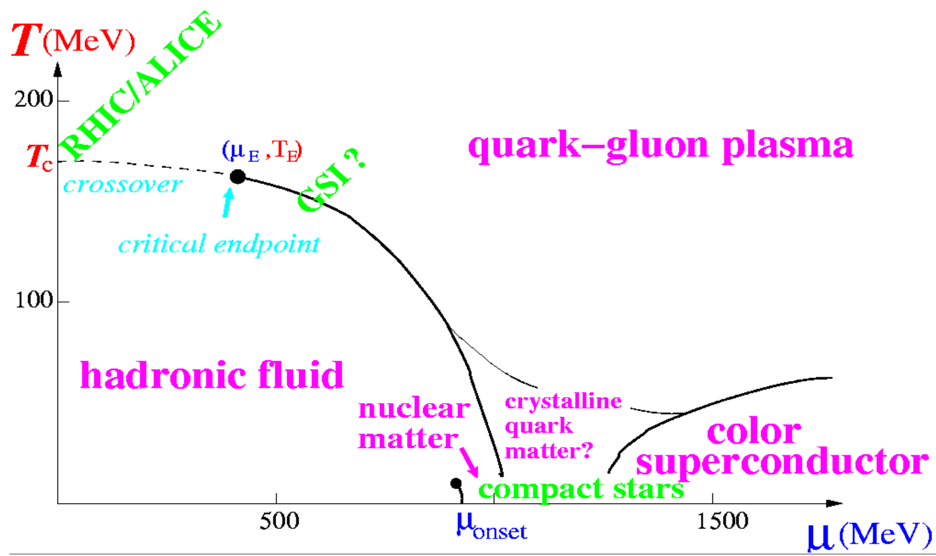


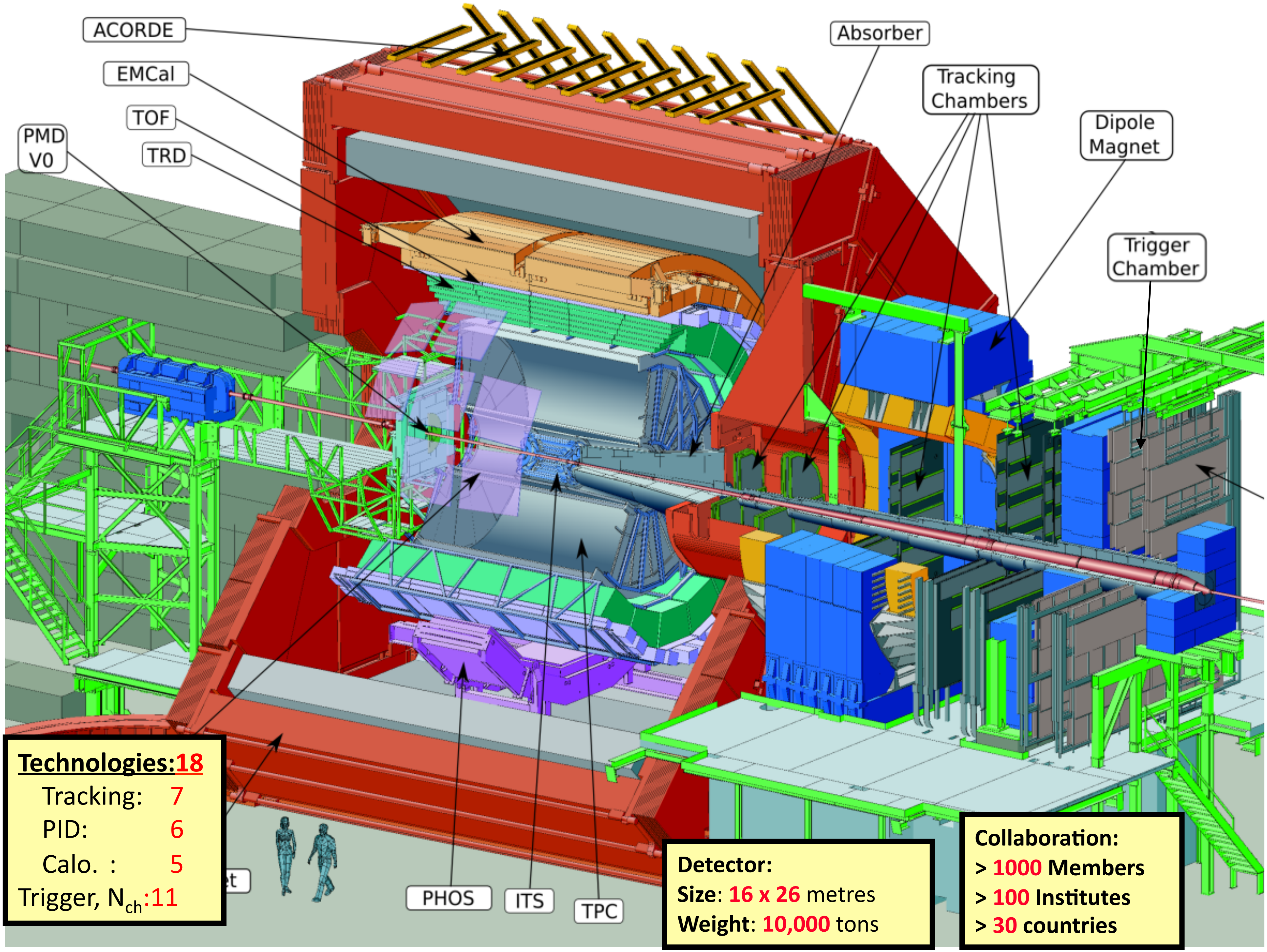
Lattice QCD, $\mu_B = 0$

Satisfied at LHC

ALICE will far exceed these temperatures & densities at the LHC.

Both statistical and lattice QCD predict that hadronic matter will undergo a phase transition, in to a deconfined state of quarks and gluons – a quark-gluon plasma, at a temperature of, $T \sim 170$ MeV and energy density, $\varepsilon \sim 1$ GeV/fm^3.





Technologies: 18

Tracking: 7

PID: 6

Calo. : 5

Trigger, N_{ch}: 11

Detector:

Size: **16 x 26** metres

Weight: **10,000** tons

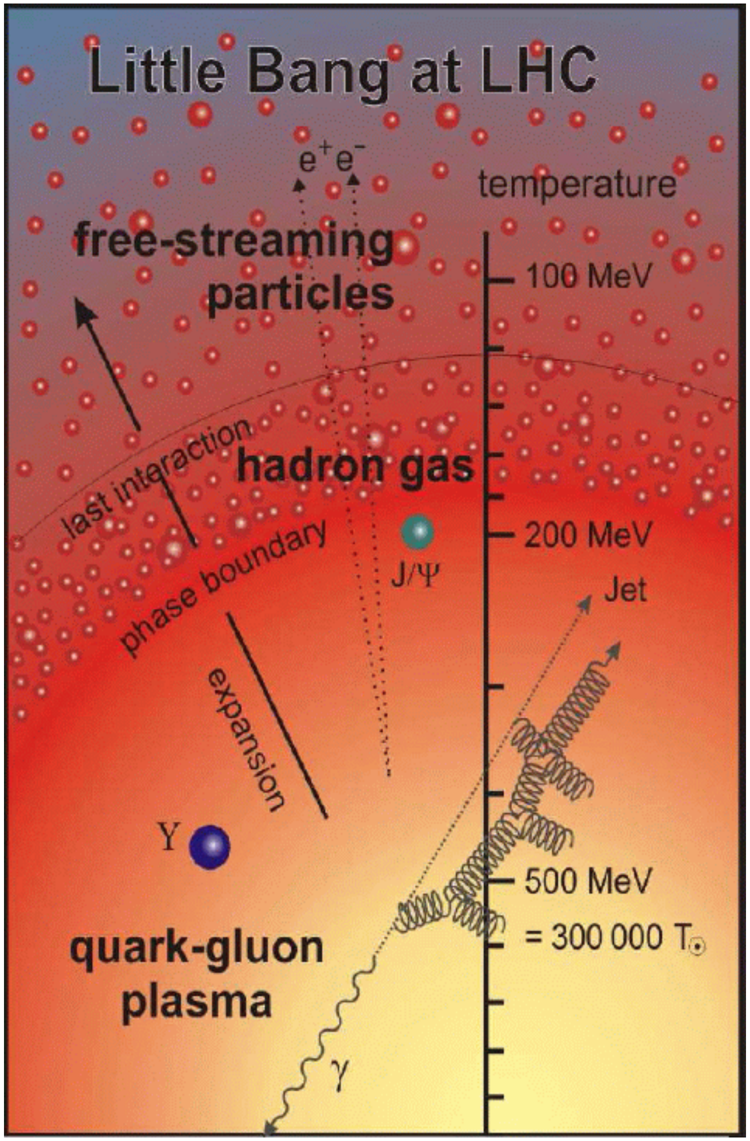
Collaboration:

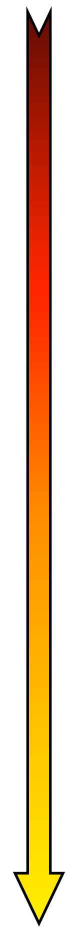
> 1000 Members

> 100 Institutes

> 30 countries

Heavy Ion Collisions - Evolution of the Fireball





- **global observables:**
  multiplicities, rapidity distributions
- **geometry of the emitting source:**
  HBT, impact parameter via zero-degree energy flow
- **early state collective effects:**
  collective flow
- **degrees of freedom as a function of T:**
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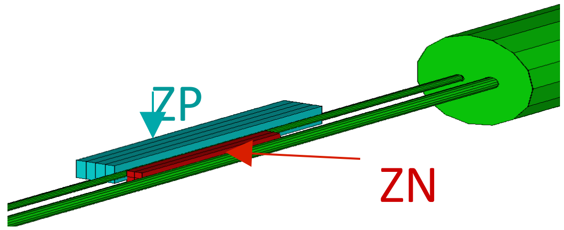
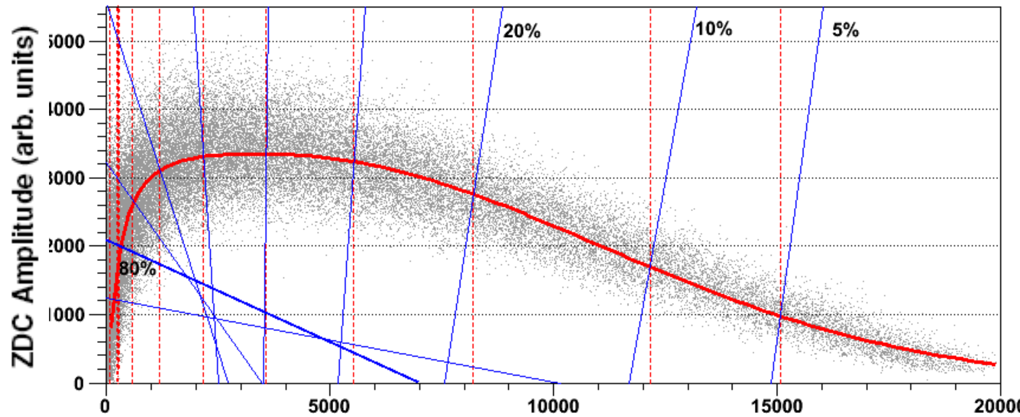
  jet quenching, high p_t spectra, open charm and open beauty

Centrality selection using Glauber Model



Zero Degree Calorimeters
~ 100m away from the interaction point

PRL 105, 252301 (2010)



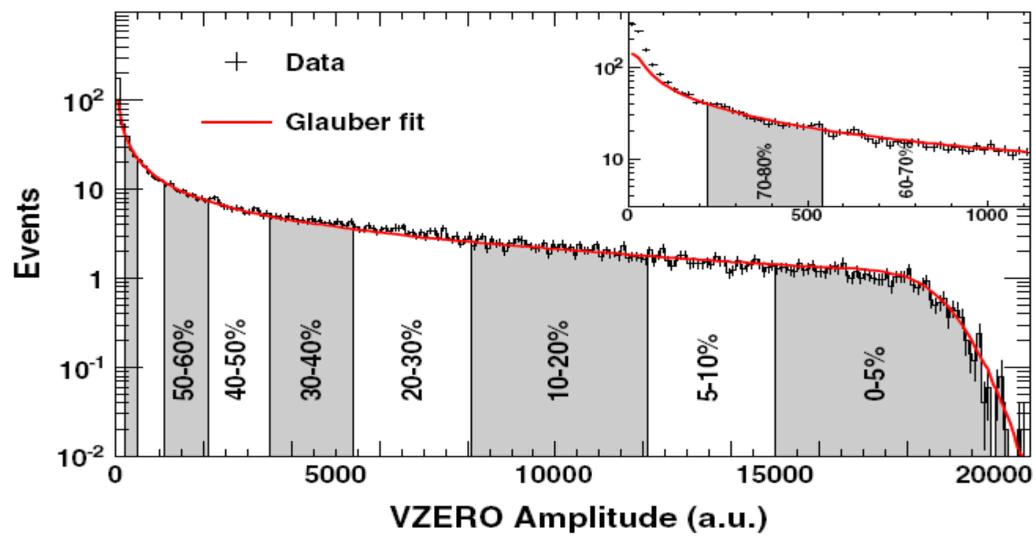
Two-source model for particle production according to negative binomial distribution

$$N_{ch} \sim f * N_{part} + (1-f) * N_{coll}$$

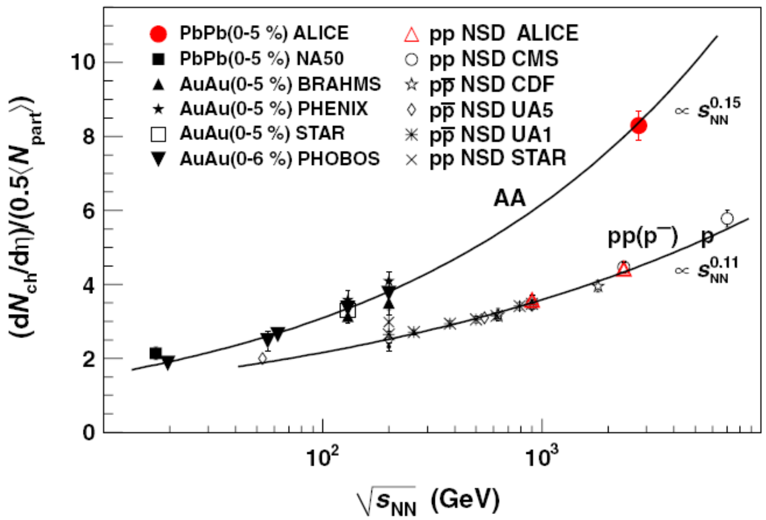
$$\sigma_{pp}^{inel} = 64 \pm 5 \text{ mb}$$

Centrality classes are determined by integrating the measured distribution above the cut.

PRL 106, 032301 (2011)



Charged Particle Multiplicity in most central collisions

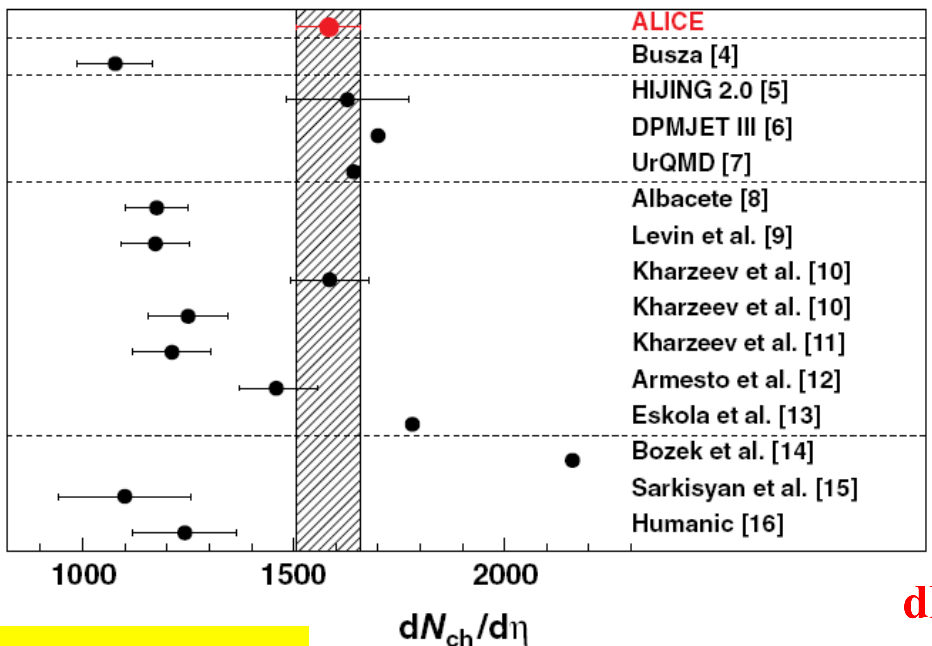


Increase of factor 1.9 compared to p-p collisions and about 2.2 to central Au-Au collisions at $\sqrt{S_{NN}}$ = 0.2 TeV

Energy dependence

p-p ~ $s_{NN}^{0.11}$

A-A ~ $s_{NN}^{0.15}$ (most central)



Empirical extrapolation of RHIC

Tuned to 7 TeV p-p data

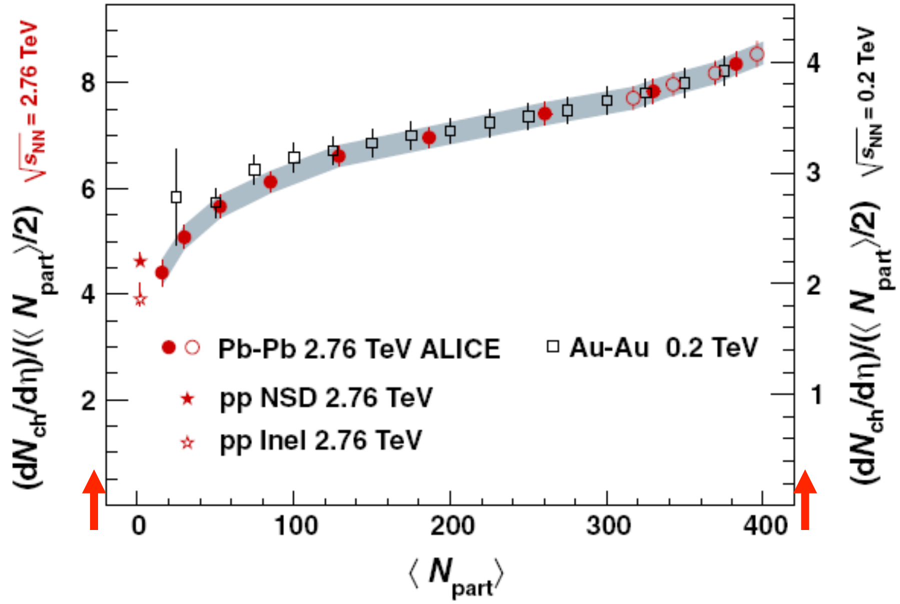
Initial state gluon saturation

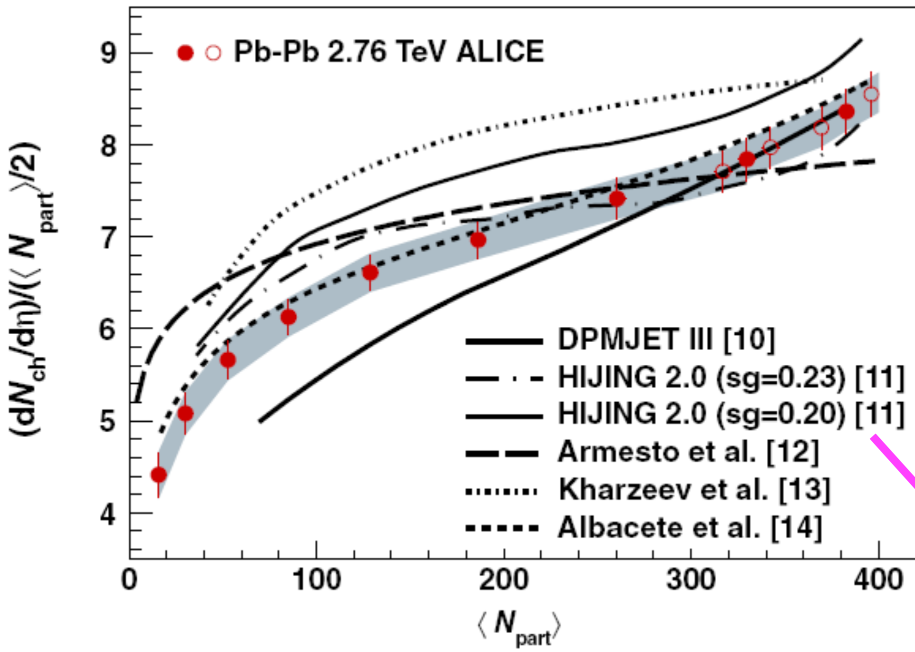
Hydrodynamic models

$dN_{ch}/d\eta = 1584 \pm 4$ (stat.) ± 76 (syst.)

PRL 105, 252301 (2010)

Centrality dependence of charged particle multiplicity density





Charge particle density per nucleon pair increases by factor of 2 from peripheral (70-80%) to central (0-5%).

Multiplicity increases by factor of 2 between $\sqrt{S_{NN}}$ = 0.2 and 2.76 TeV.

Dependence of multiplicity is very similar between $\sqrt{S_{NN}}$ = 0.2 and 2.76 TeV.

Impact parameter dependent gluon shadowing (s_g) limits the rise of particle production with centrality

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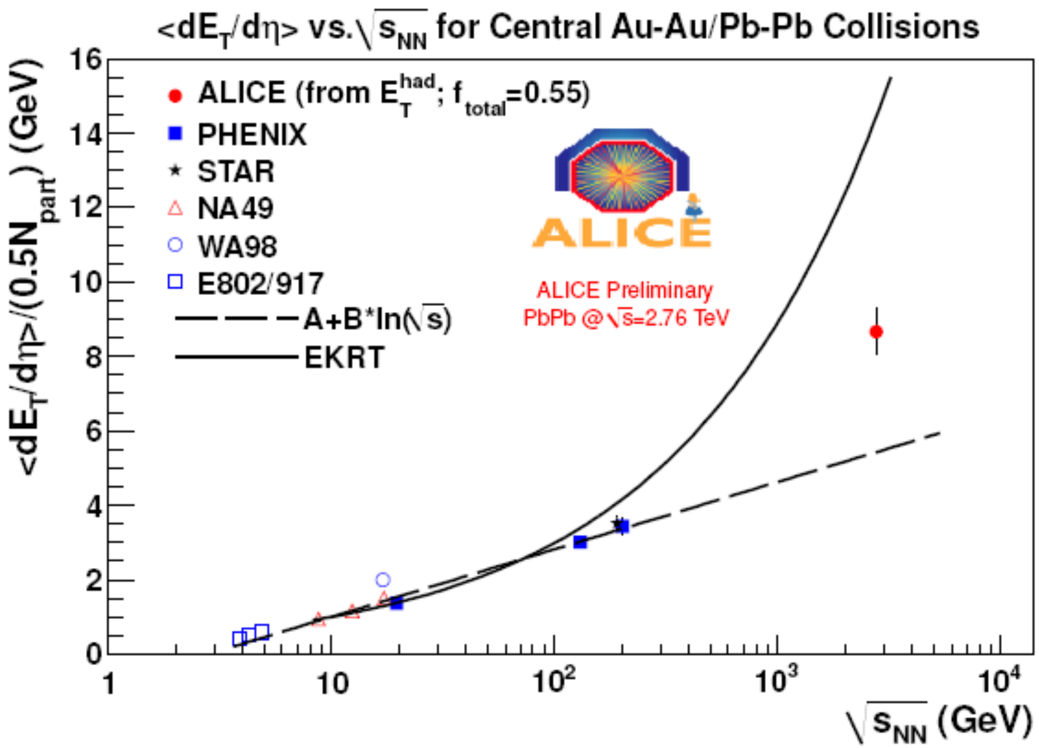
Energy Density



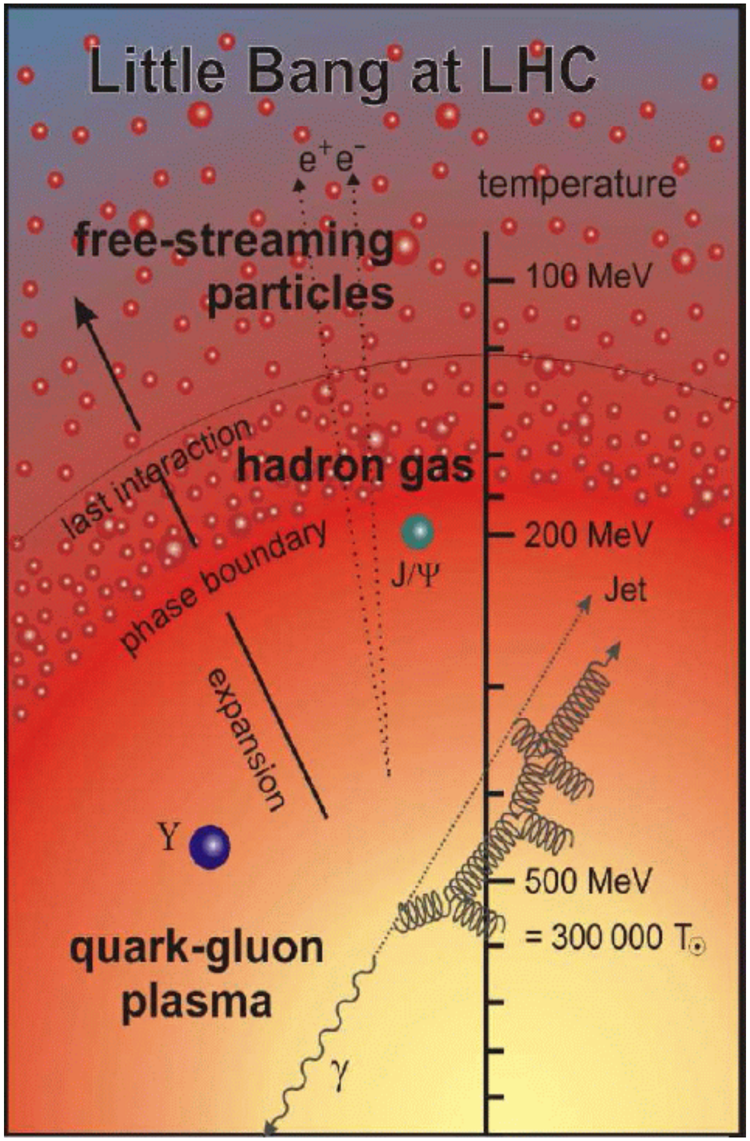
$$\varepsilon_{Bj}(\tau) = \frac{1}{\pi R^2 \tau} \frac{dE_T}{dy}$$

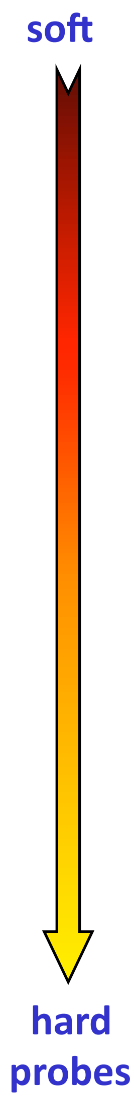
$dE_T/d\eta$ per participant pair is up by 3 times from RHIC.

$\varepsilon.\tau \sim 16$ GeV/fm^{2}c

Energy Density at LHC is at least 3 times more than that at RHIC

Heavy Ion Collisions - Evolution of the Fireball





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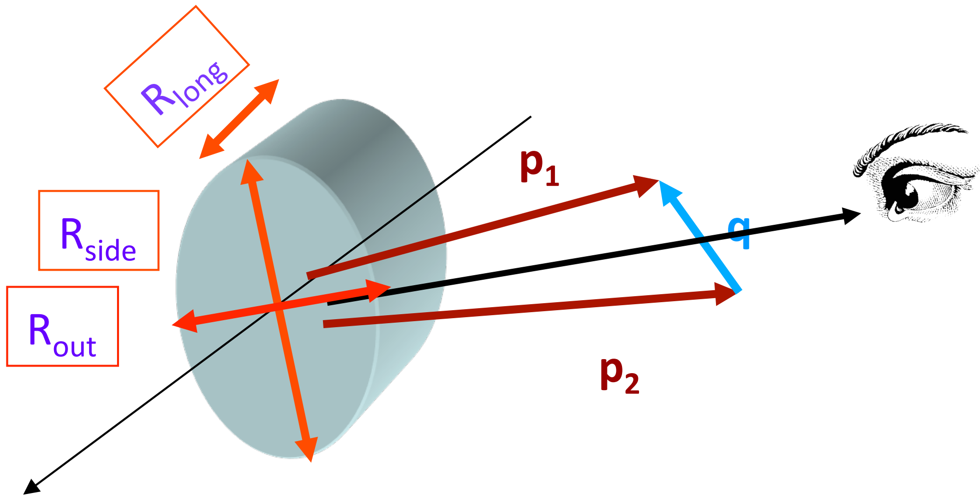
HBT - Correlation



R_{long} – along beam direction

R_{out} – along "line of sight"

R_{side} – ⊥"line of sight"

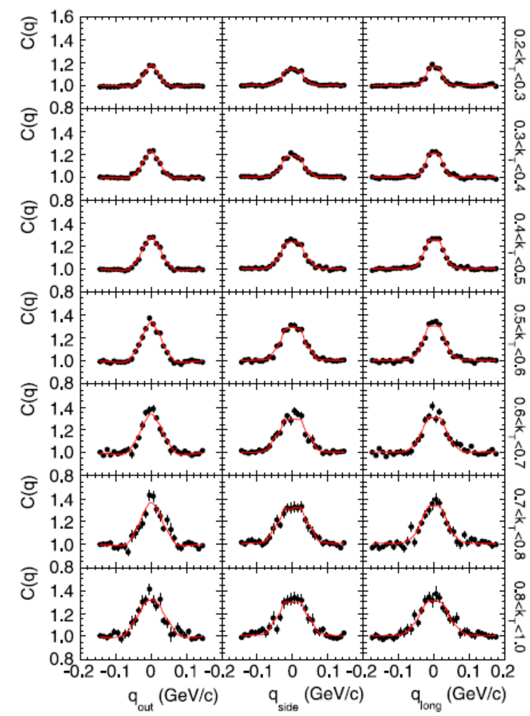
Correlation Function

$\mathbf{q} = \mathbf{p_2} - \mathbf{p_1}$; $k_T = |\mathbf{p}_{T,1} + \mathbf{p}_{T,2}|/2$

$C(\mathbf{q}) = N[(1-\lambda) + \lambda^* K(q_{inv})^*(1 + G(\mathbf{q}))]$

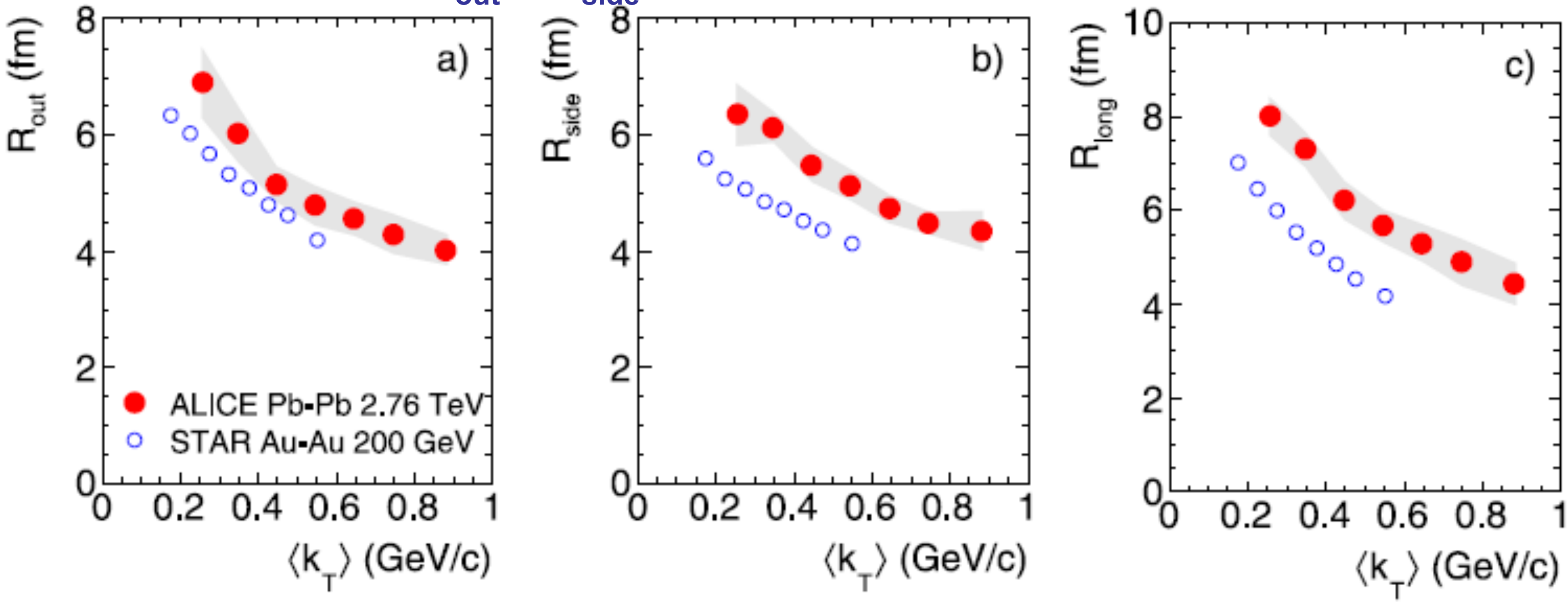
$G(\mathbf{q}) = \exp(-(R^2_{out}q^2_{out} + R^2_{side}q^2_{side} + R^2_{long}q^2_{long}))$

Cross term between q_{long} and q_{out} is zero for symmetric systems



Pion HBT radii at 5% central

$R_{out} \sim R_{side}$



The radii of are significantly larger compared to RHIC

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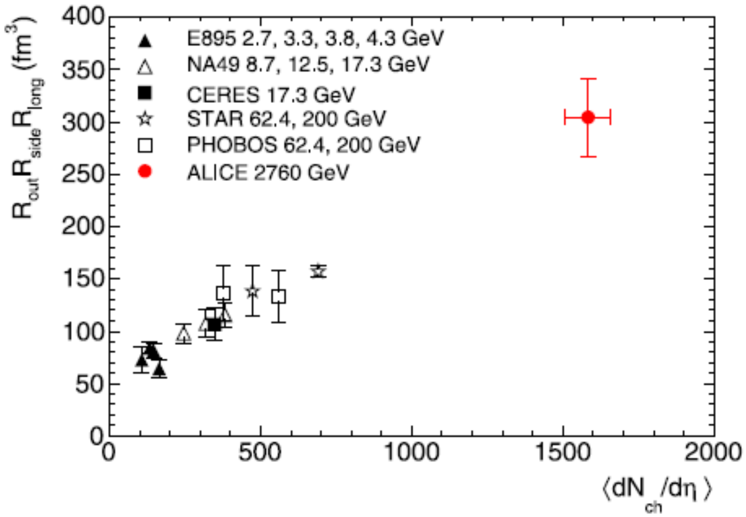
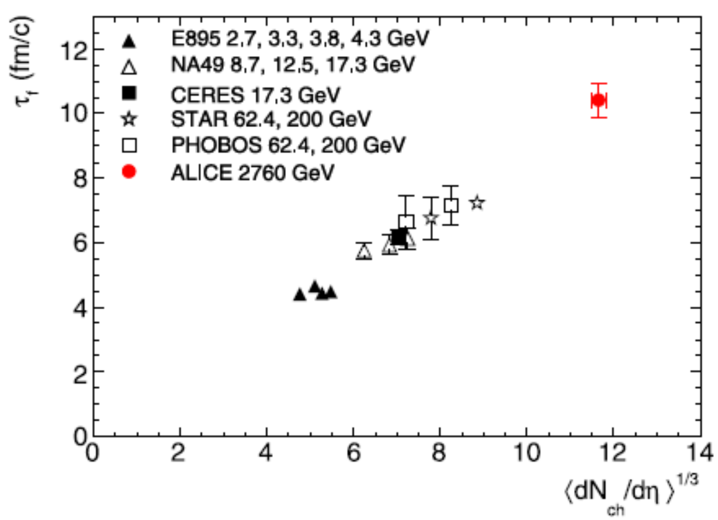
The Fireball



Volume at decoupling: ~ 5000 fm^3

R ~ 7 fm

X2 of RHIC



Lifetime from collision to freeze out

~ 10 fm/c

30% longer

Hotter bigger and longer-lived

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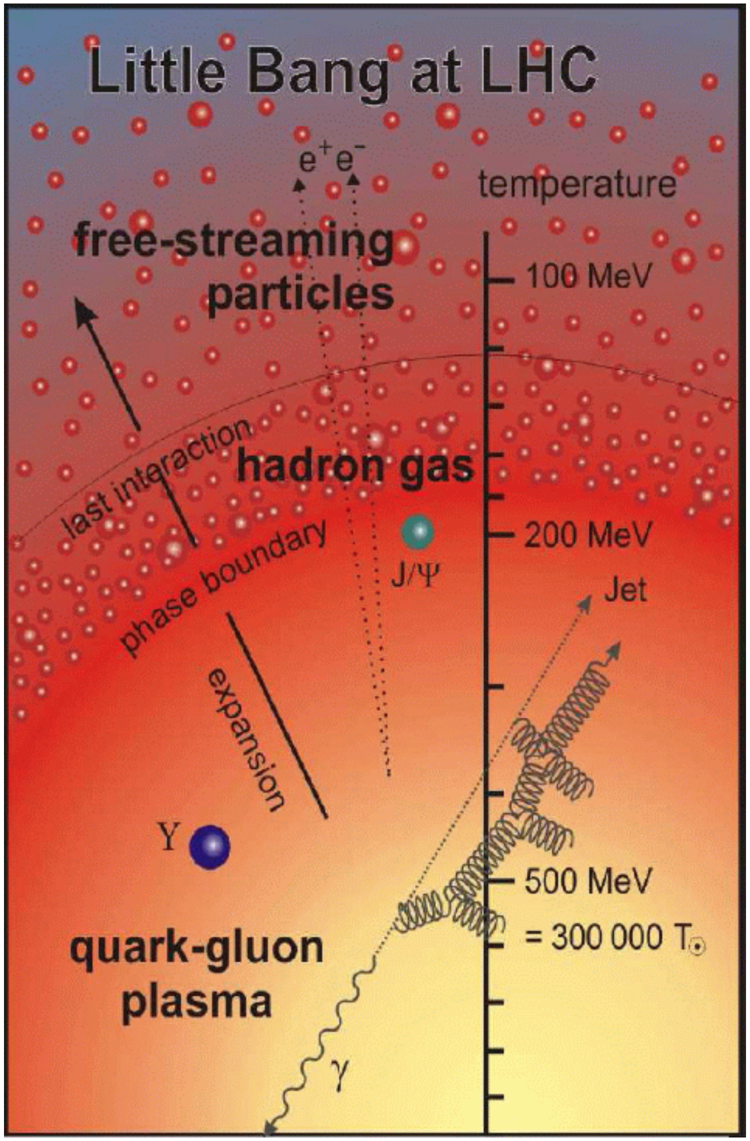

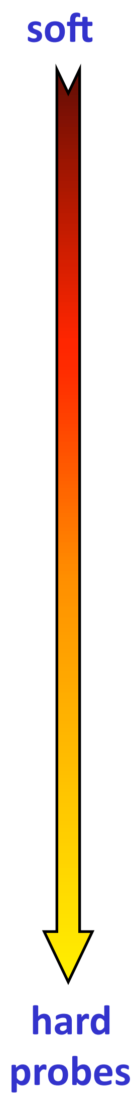

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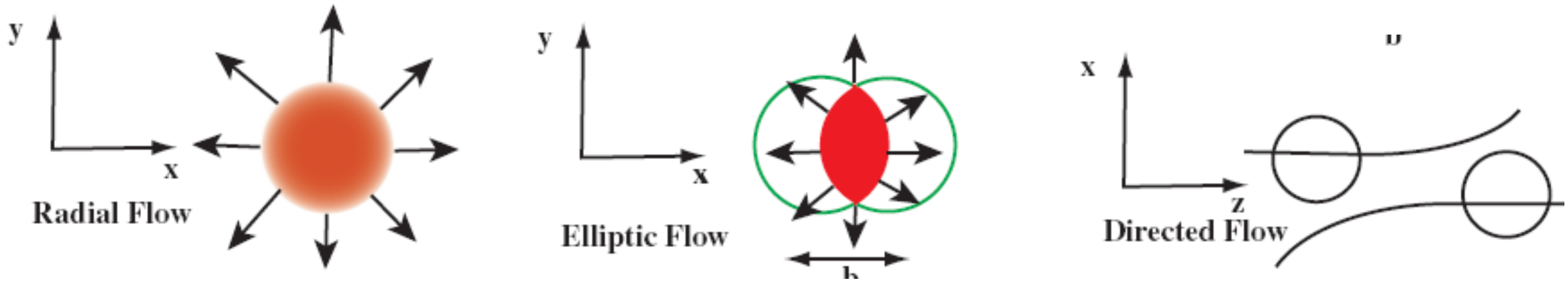
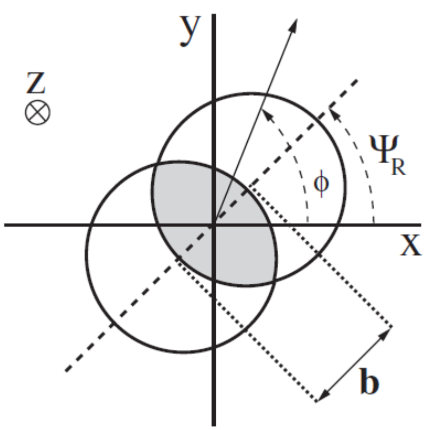
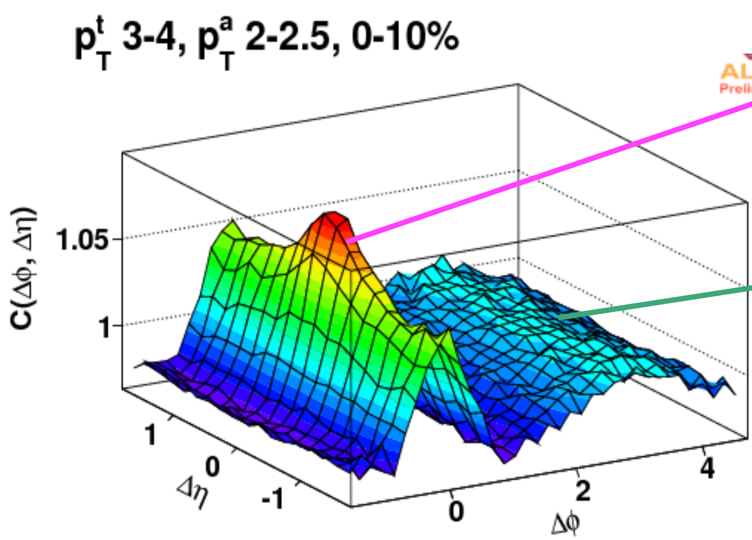
Collective expansion - Flow

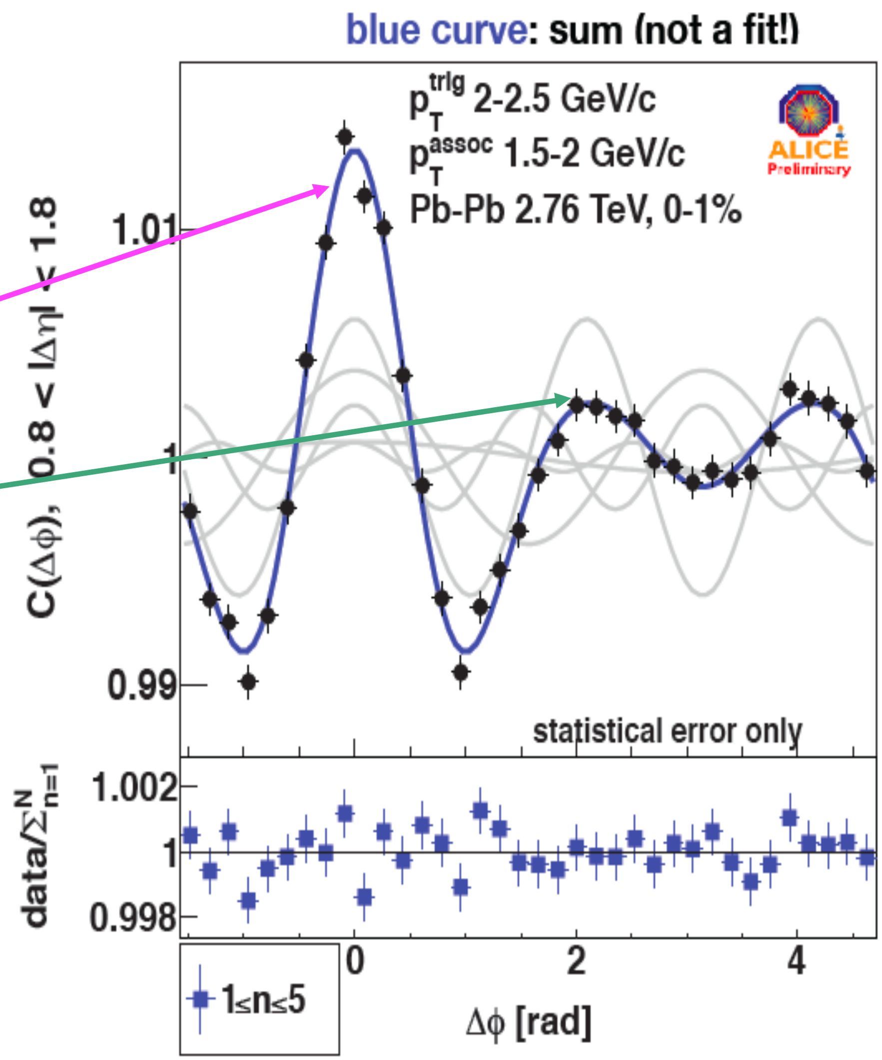




$$E\frac{d^3N}{d^3\mathbf{p}} = \frac{1}{2\pi}\frac{d^2N}{p_t\,dp_t\,dy}\left\{1+2\sum_{n=1}^{+\infty} v_n(p_t,y)\cos[n(\varphi-\Psi_R)]\right\},$$

Fluctuations & Fourier Decomposition of $dN_{pairs}/d\Delta\phi$





Odd terms become negative at large p_T (influence of away-side jet)

V_3 is necessary !

$1 \le n \le 5$ describe shape

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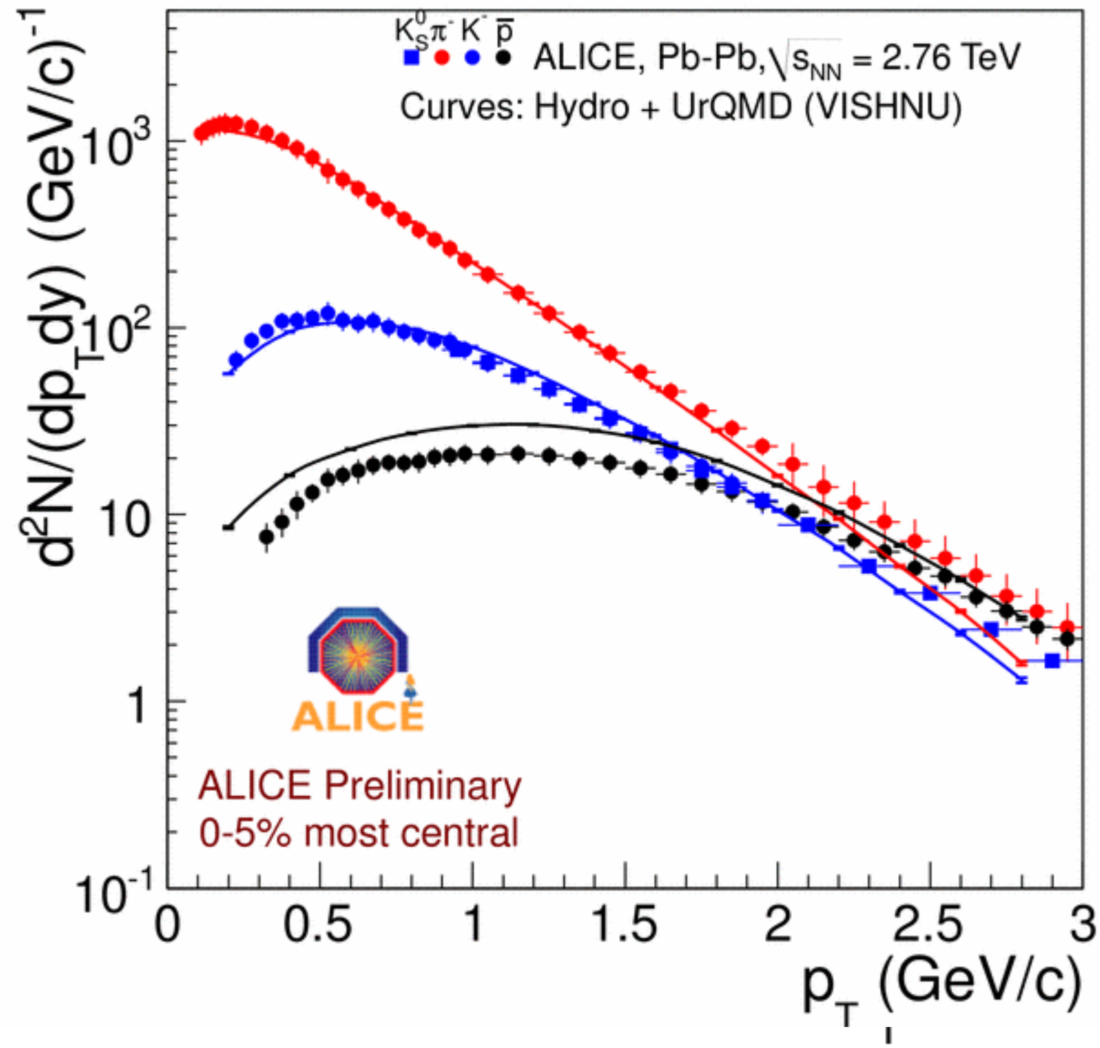
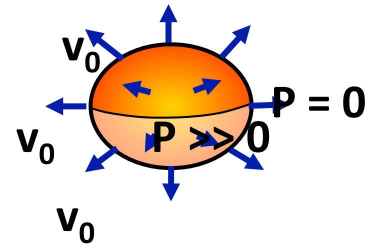
Effect of radial flow for π, K, p





Slope changes at LHC vs RHIC

Very strong radial flow
$\beta \approx 0.66$ at LHC

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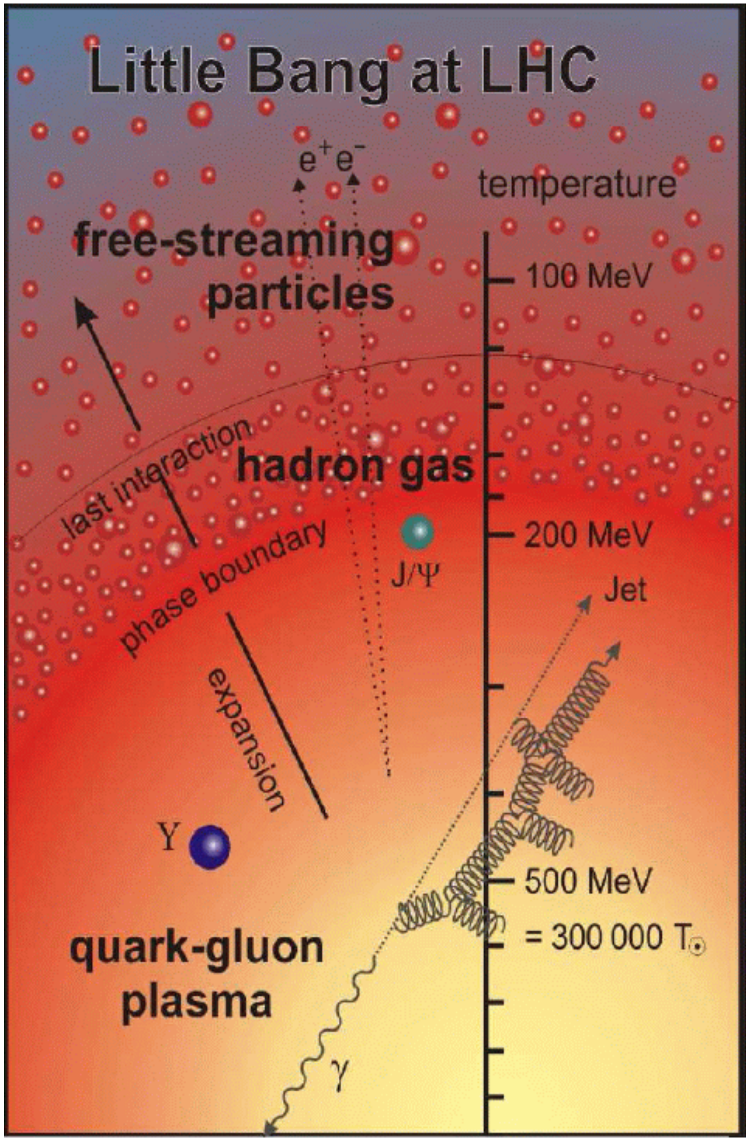

soft

hard probes

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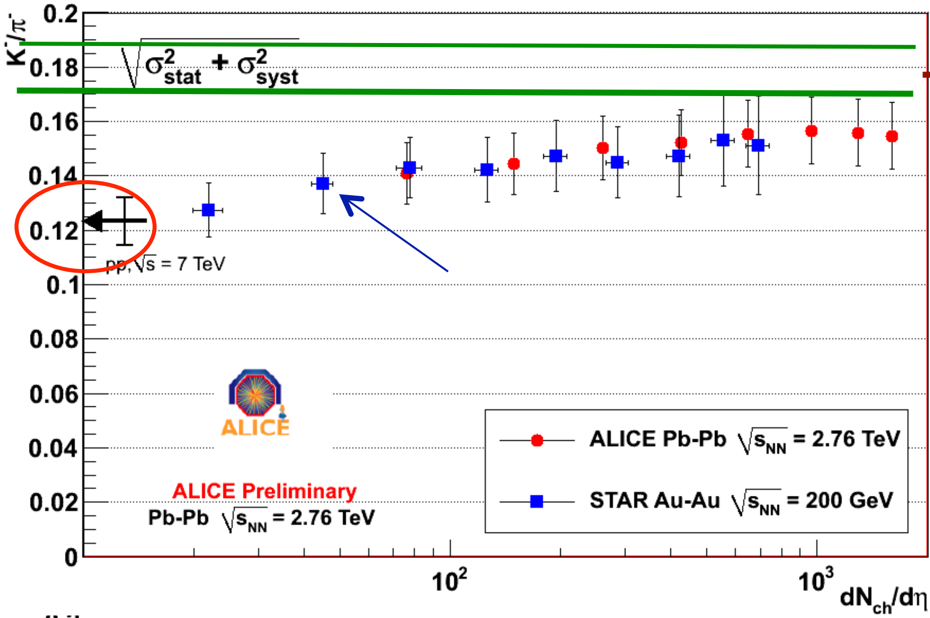
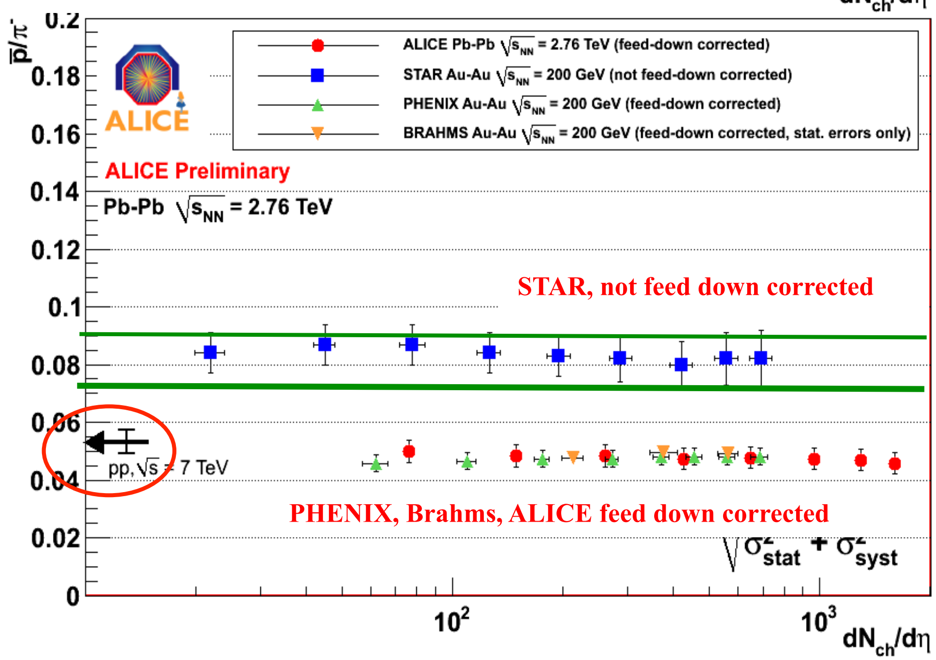
Particle Ratios in PbPb collisions



Range of Thermal model prediction

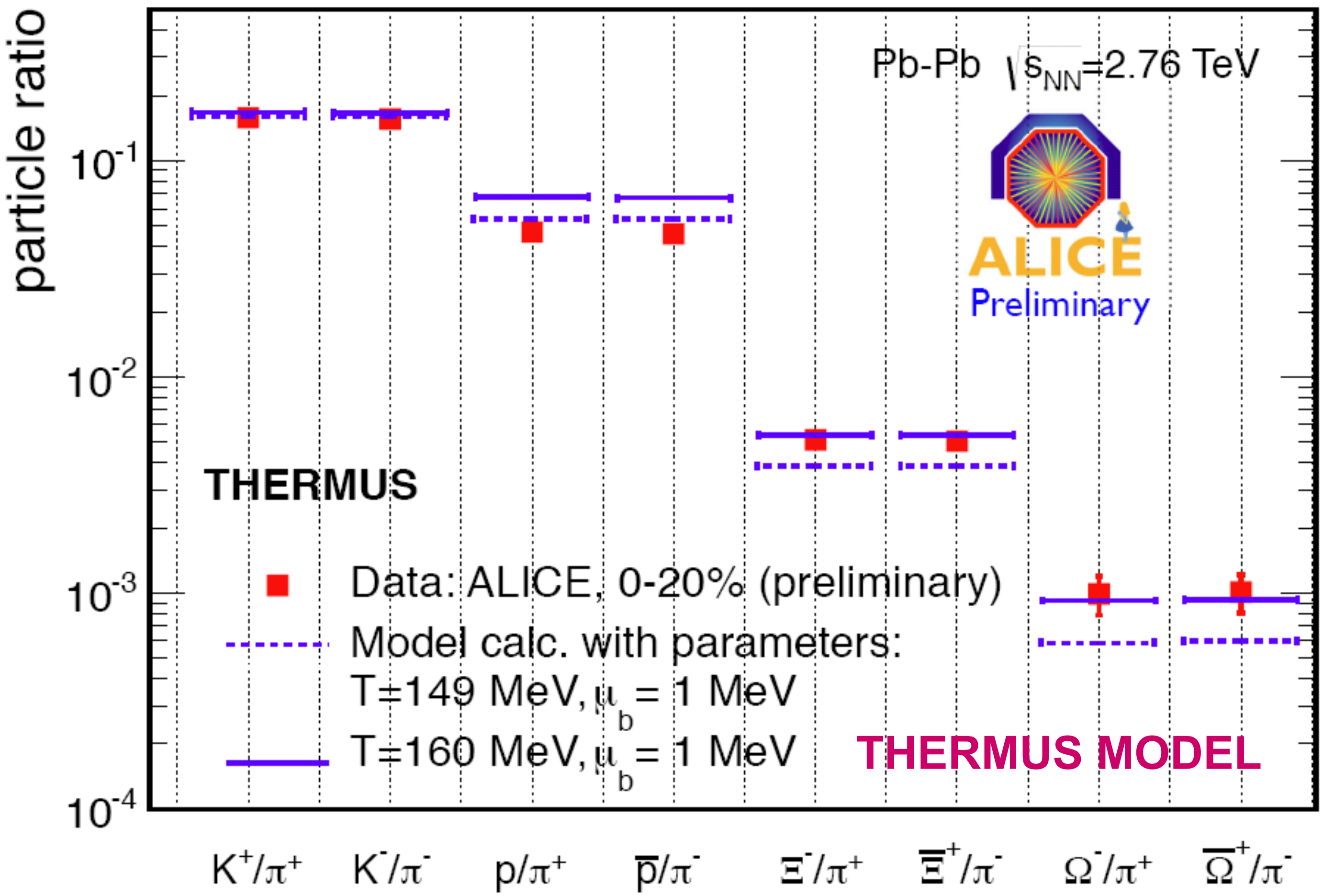
Agreement at LHC energies better



$\bar{p}/\pi^-$ ratio off by factor > 1.5 from predictions !

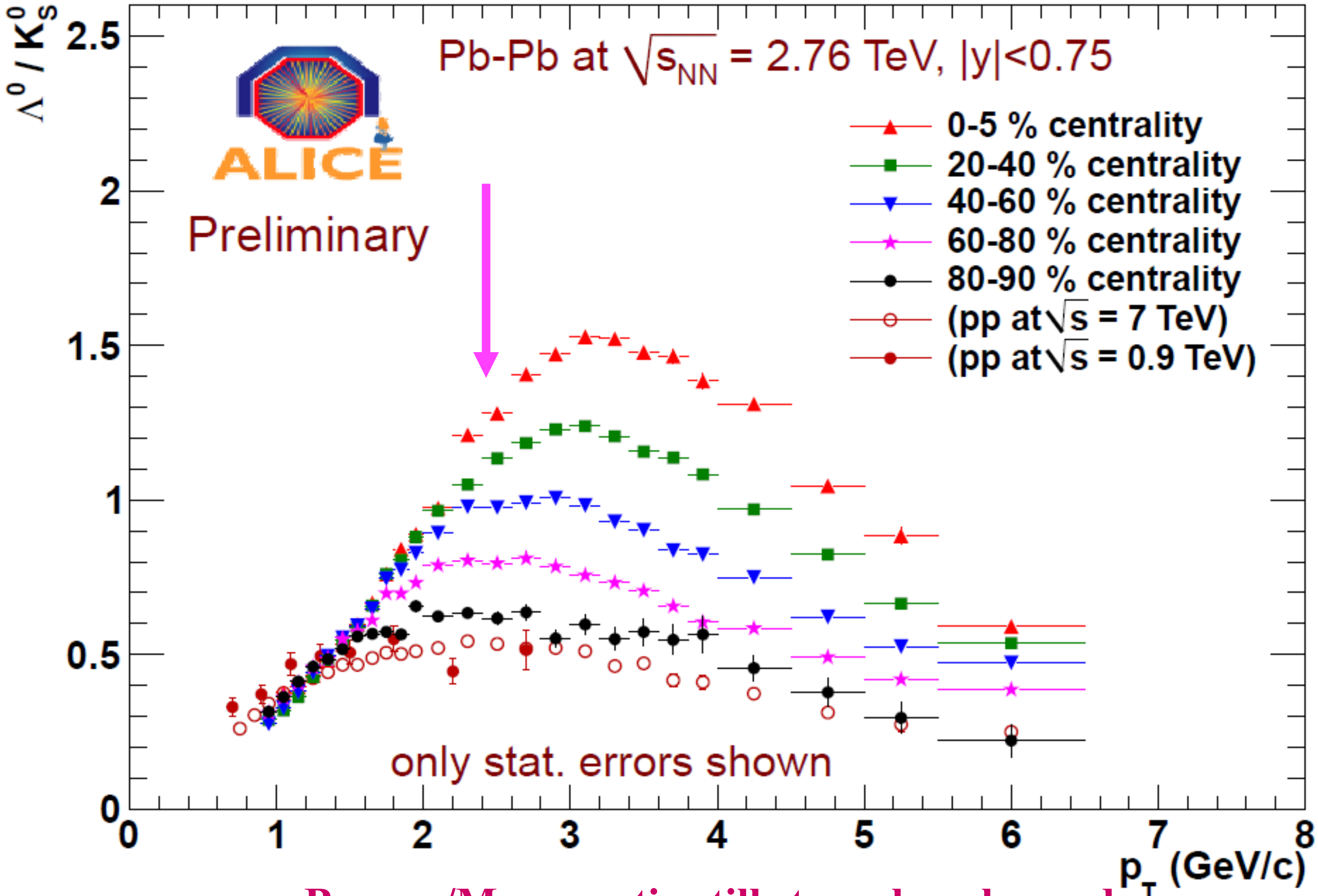
similar to RHIC (where pbar/p = 0.8) ?

Particle ratios and Temperature



Consistent with T = 160 MeV and vanishing baryo-chemical potential
except for protons

'Baryon anomaly': Λ/K_0



Baryon/Meson ratio still strongly enhanced

x 3 compared to pp at 3 GeV

- Enhancement slightly larger than at RHIC 200 GeV

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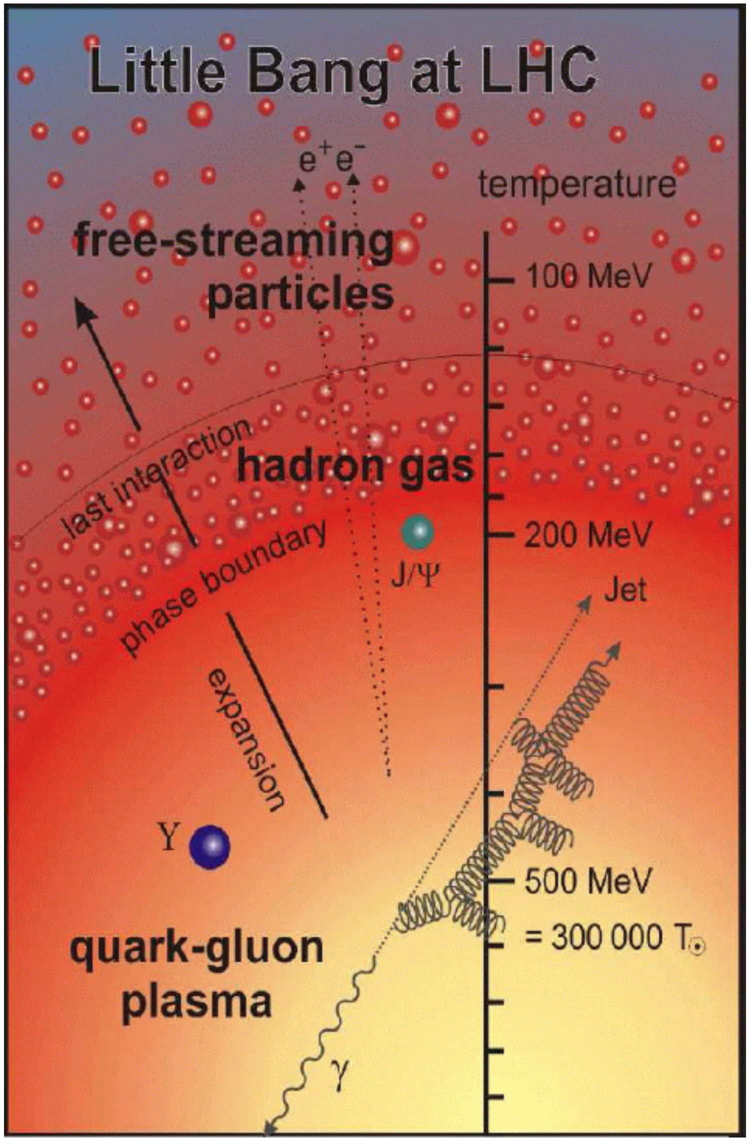

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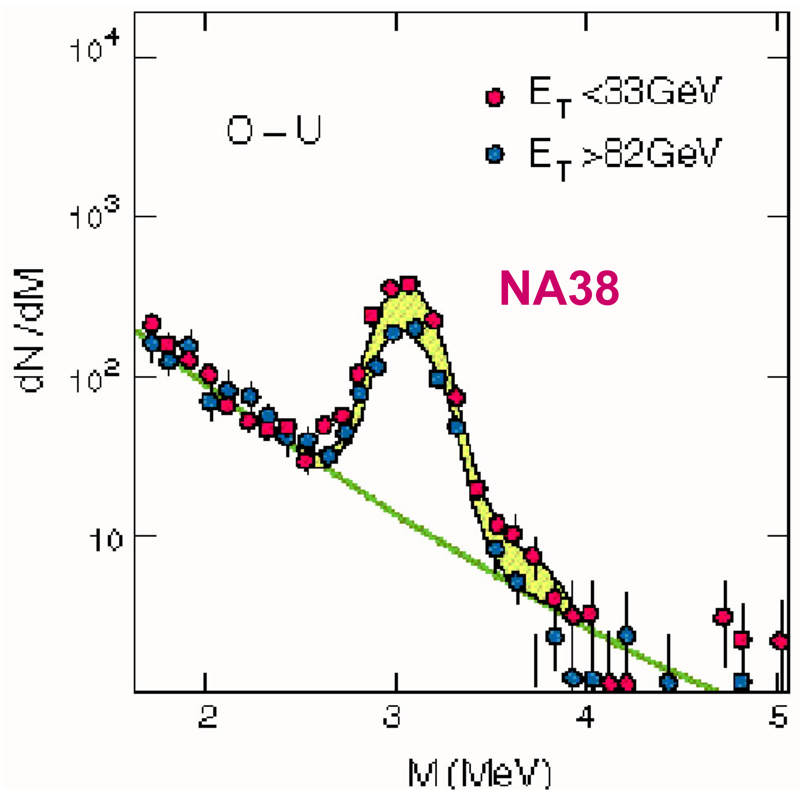
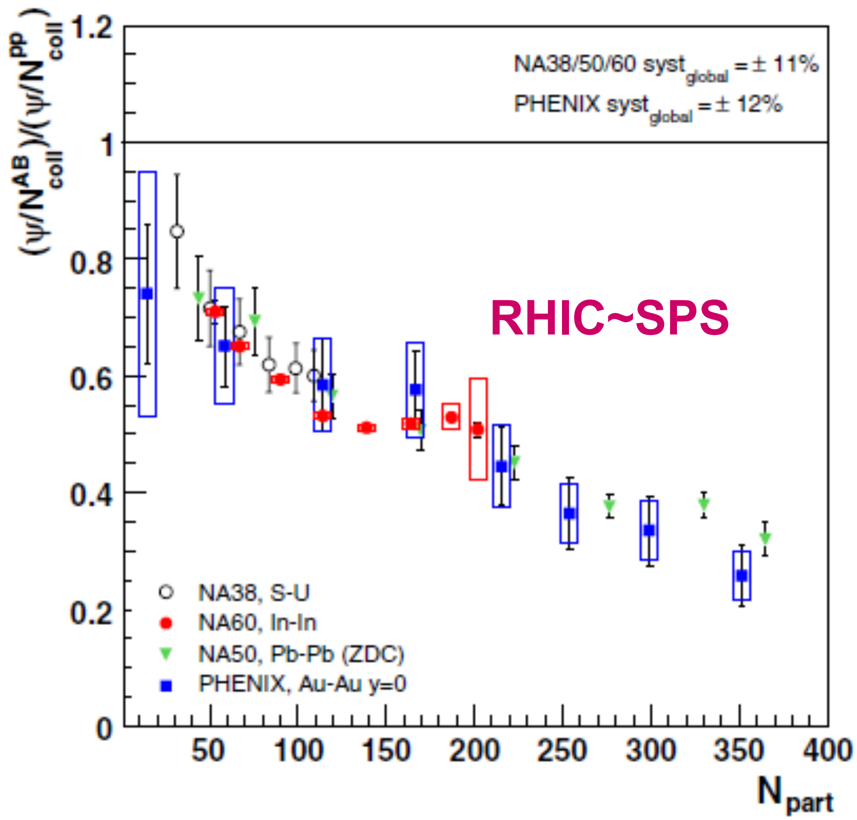
J/Ψ – classical case of deconfinement



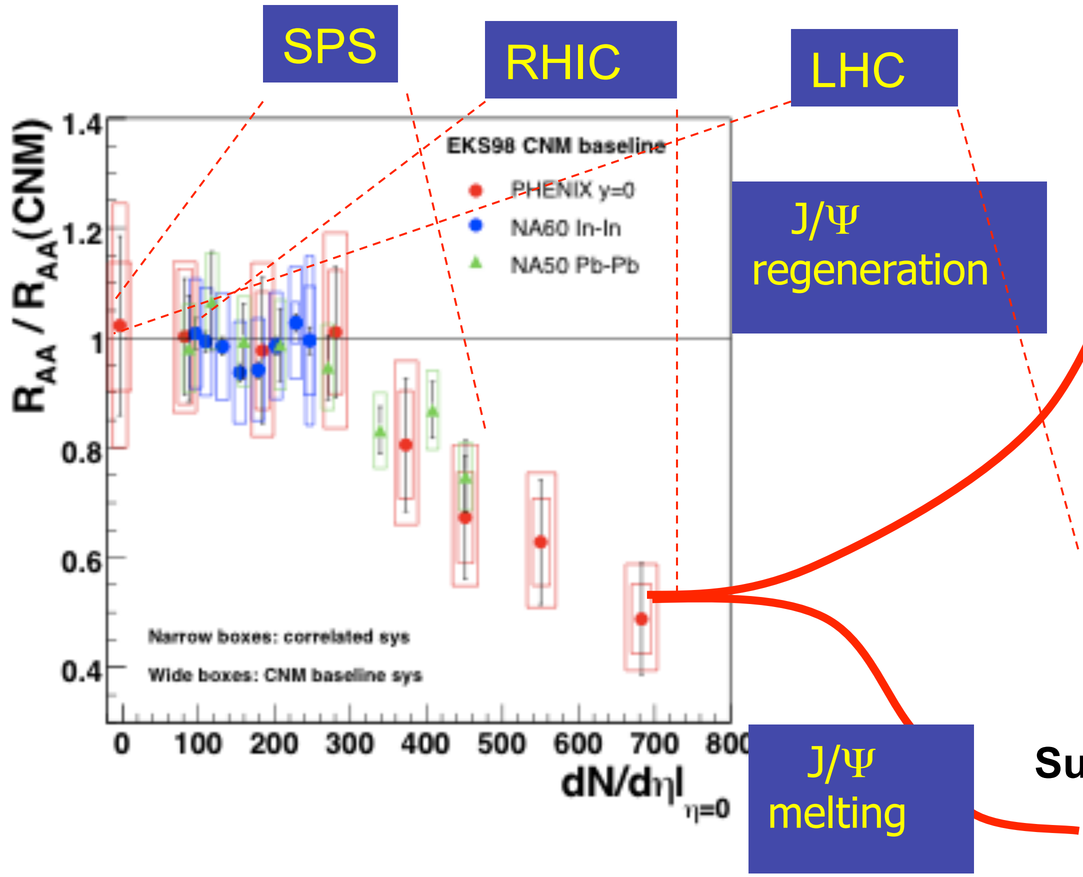


J/Ψ not suppressed at all only χ_c

OR

J/Ψ suppression is compensated by coalescence of charm quarks

Quarkonium at LHC

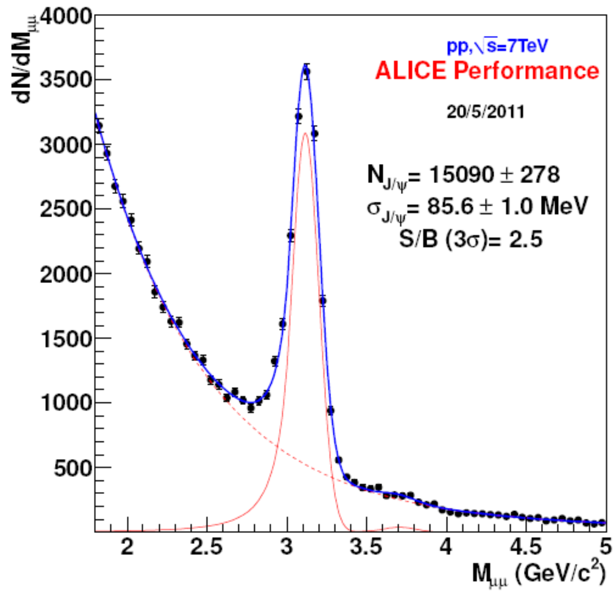


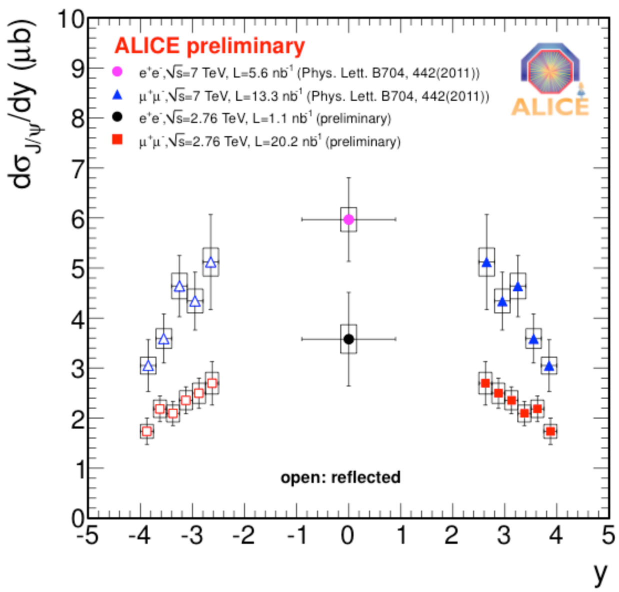
Suppression + regeneration =>
Υ', Υ'' ~unaffected, J/Ψ less suppression than @ RHIC

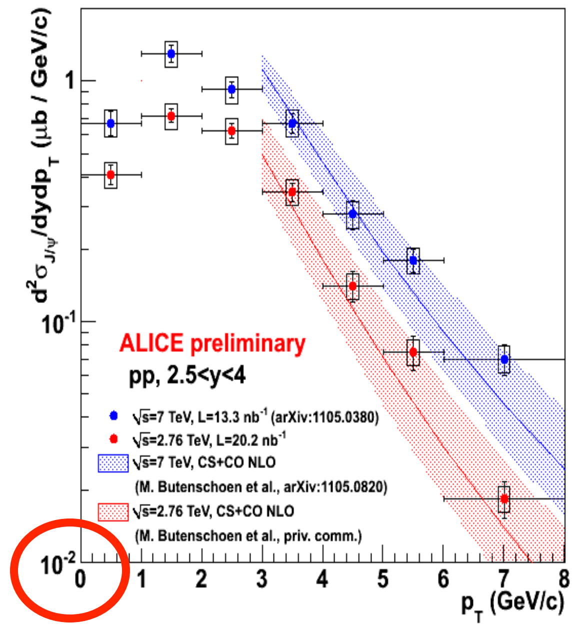
Suppression => Υ'(2S) ≈ J/Ψ , Υ''(3S) ≈ Ψ',

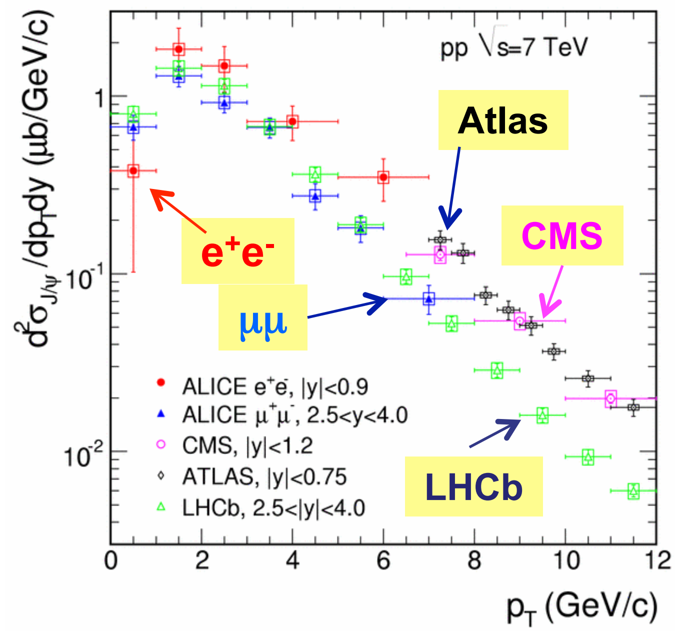
	Ψ'	χ	Υ''(3)	Υ'(2S)	J/Ψ	Υ
T_d/T_c	1-1.2	1-1.2	1.1-1.3	1.2-2	1.5-2.5	3-5

J/Ψ in p-p









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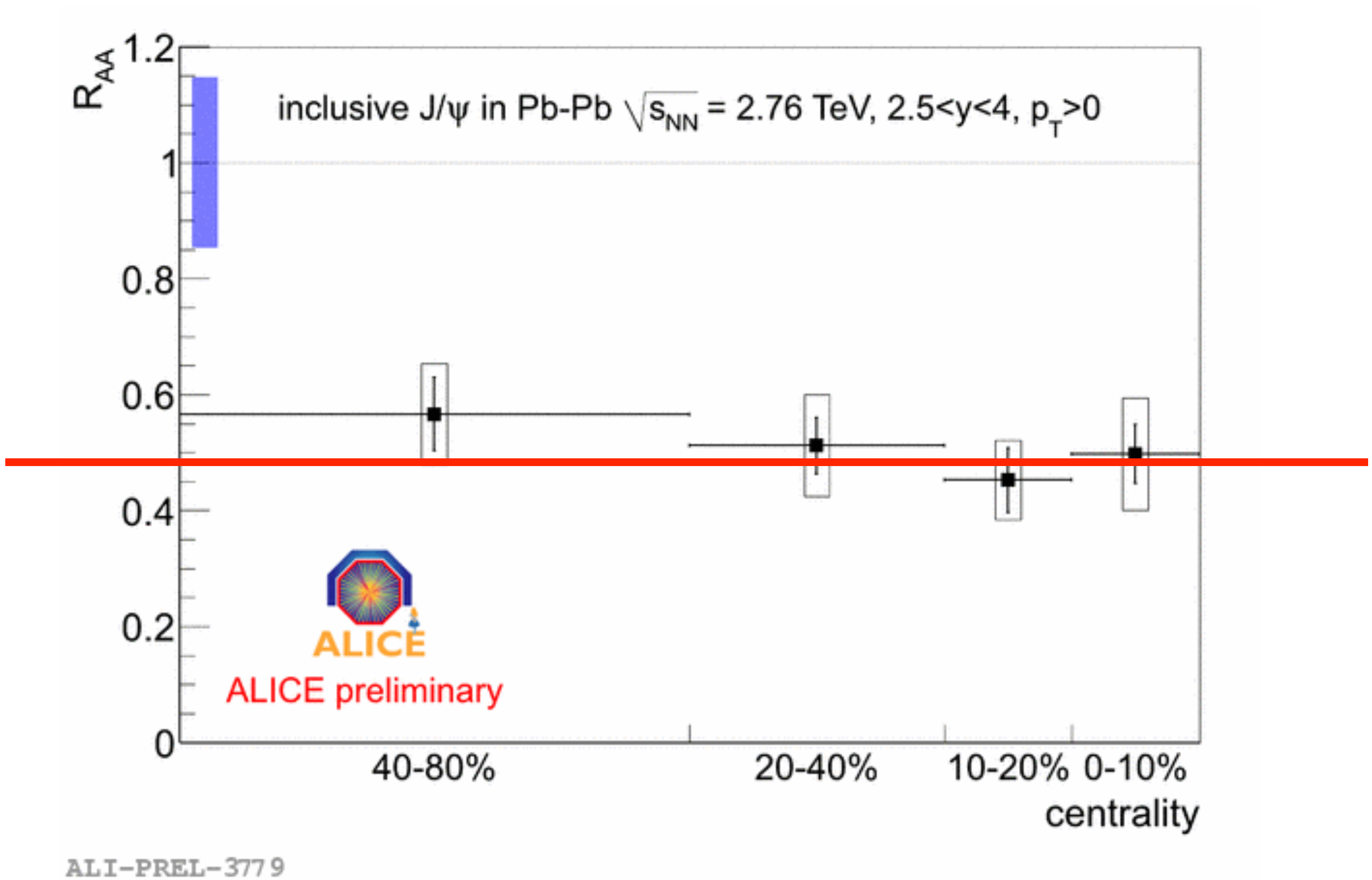
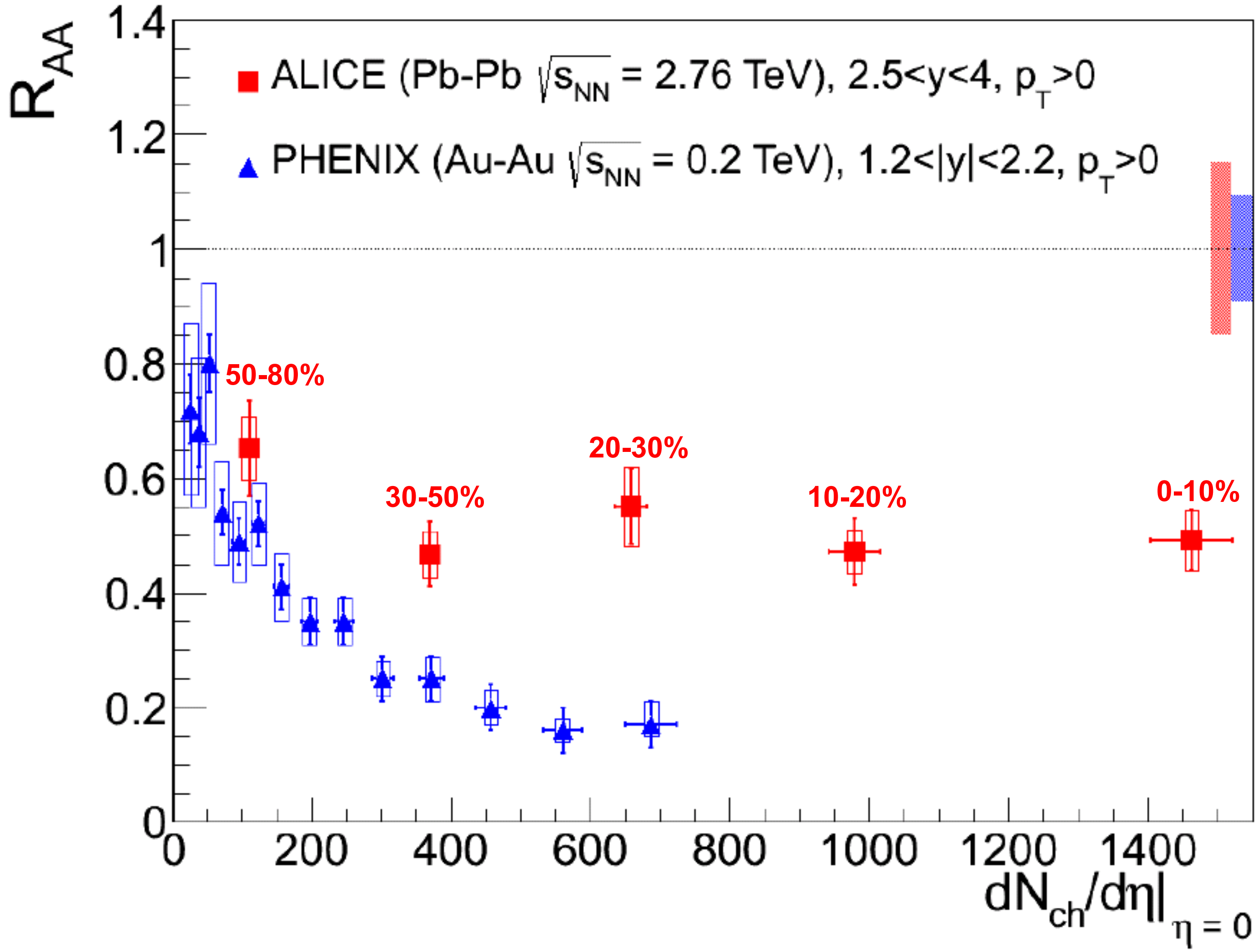
J/Ψ suppression: Results

Inclusive J/ψ $R_{AA}^{0\text{-}80\%}$ = 0.49 ± 0.03 (stat.) ± 0.08 (sys.)



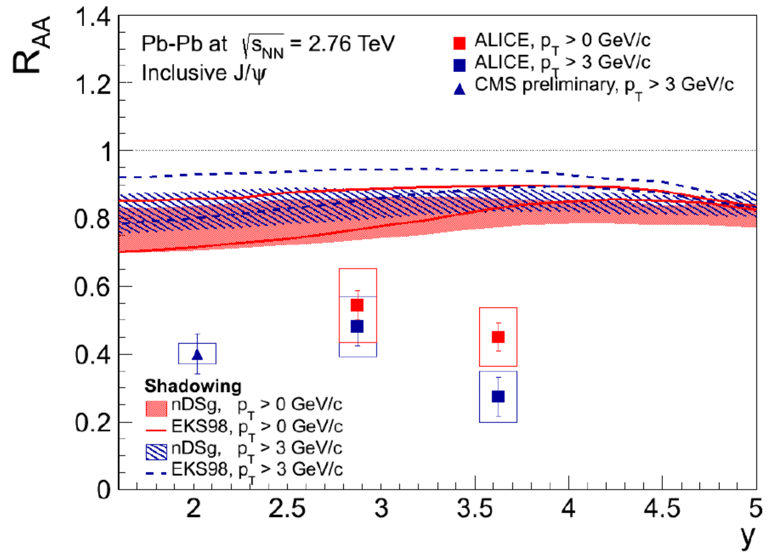
Rather small suppression & centrality dependence

J/Ψ suppression: Comparisons



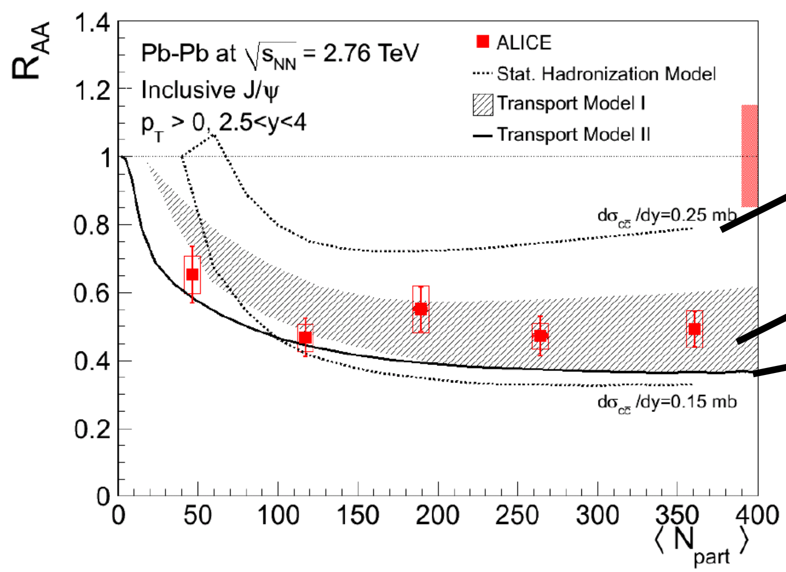
Less suppression than RHIC!

Comparison with models



Nuclear Shadowing models – CSM at LO shadowing calculated with EKS98 and nDSg parameterization for PDF

R_{AA} ~ 0.7 => medium induced suppression is stronger



Recombination models

SHM – deconfinement + thermal equilibration of cc pairs

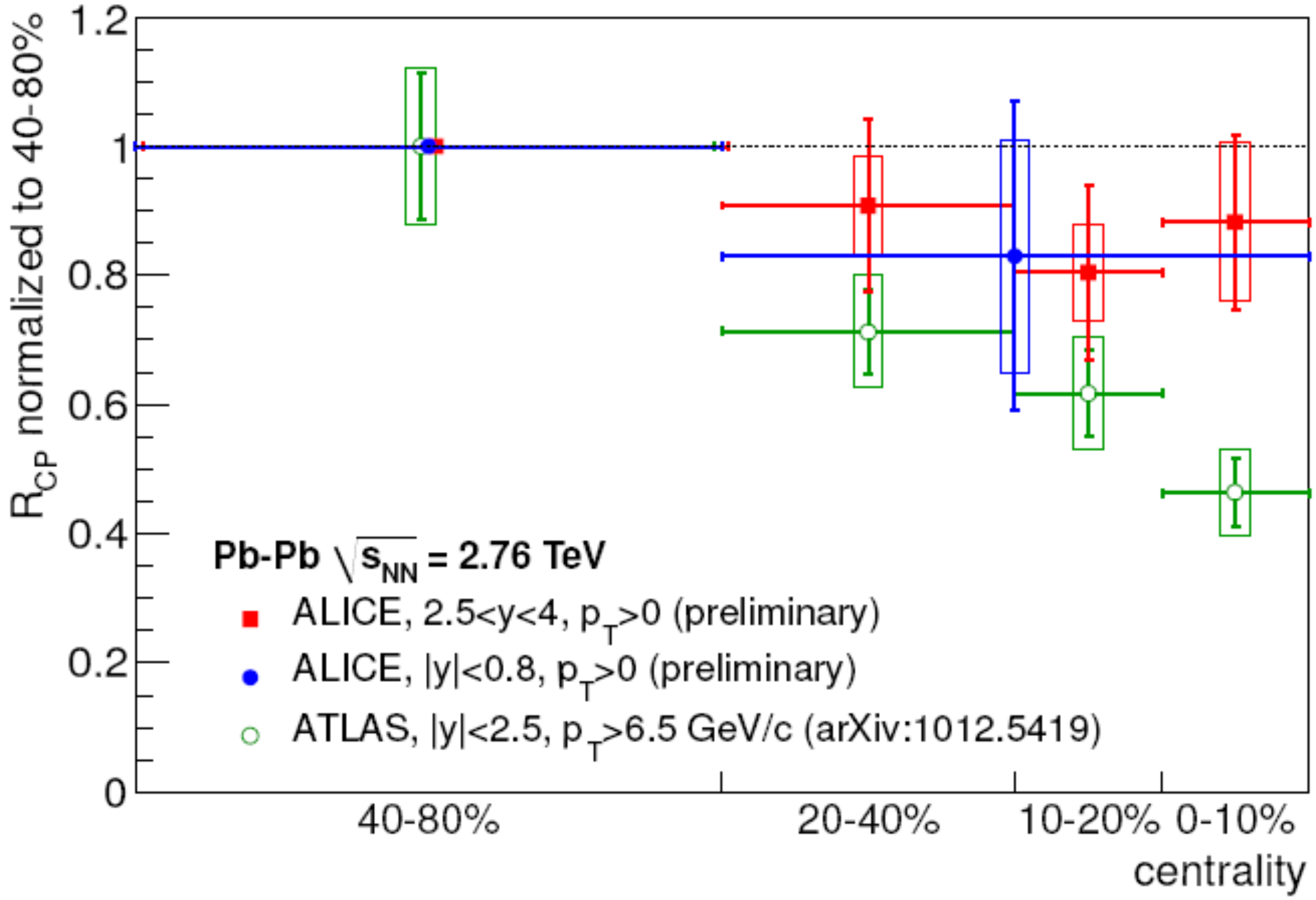
TM – rate of production & suppression with and without shadowing

shadowing + Cronin effect – can be tuned further

On of Recombination ?

Thermalization - J/Ψ elliptic flow
Knowledge of shadowing – p+Pb data.

J/Ψ suppression: Comparisons



Larger suppression observed at ATLAS

BUT

Different p_T and y

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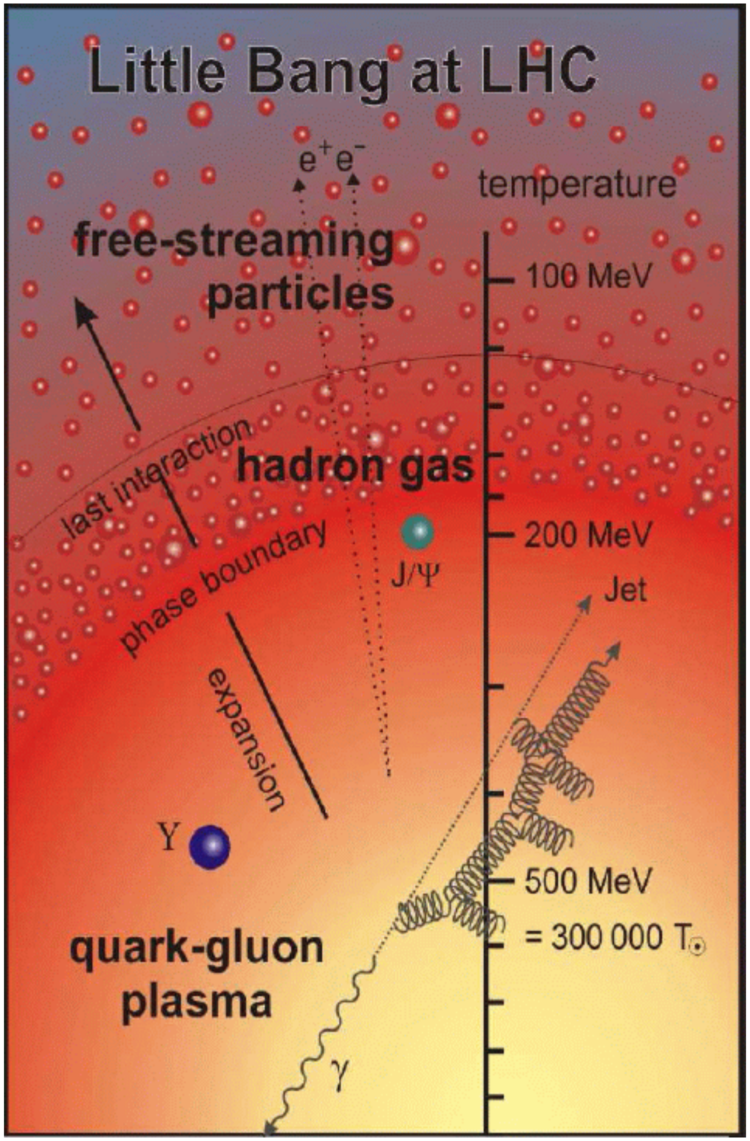

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Nuclear Modification Factor

- Production cross section of hard probes in Pb-Pb collisions is expected to scale with the number of binary nucleus-nucleus collisions (Pb-Pb is superposition of pp)
- Medium affects initially produced (colored) probes
- Departure from binary scaling expectation quantifies medium effects
- Study in-medium energy loss by measuring inclusive particle spectrum (dN_{ch}/dp_T)

Compare Pb-Pb and pp collisions scaled with number of binary
collisions (from Glauber calculation)

$$R_{AA} = \frac{d^2N^{AA}/dp_T d\eta}{\langle N_{coll}\rangle d^2N^{pp}/dp_T d\eta}$$

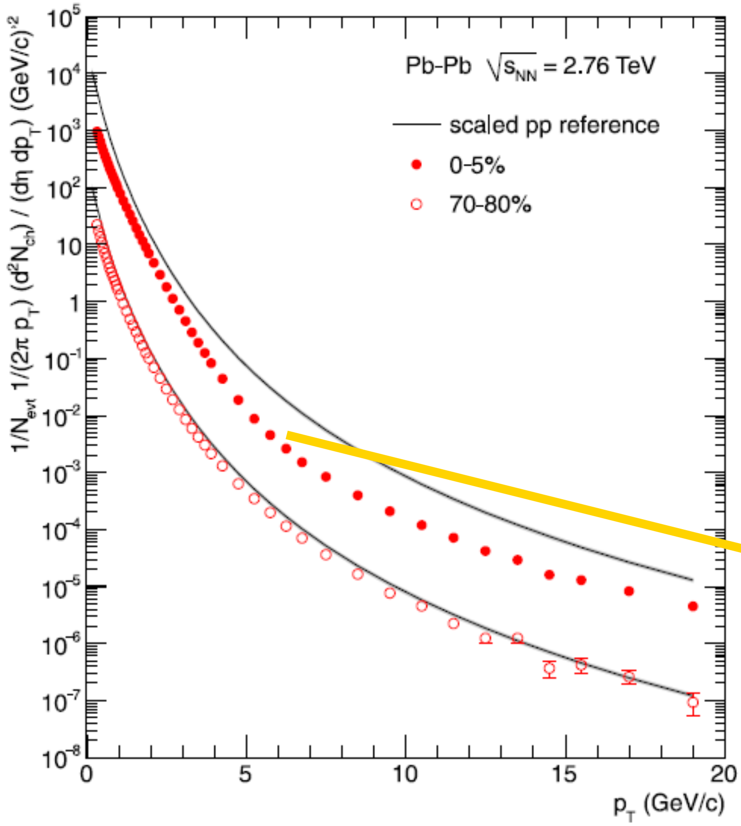
Particle production in Pb-Pb

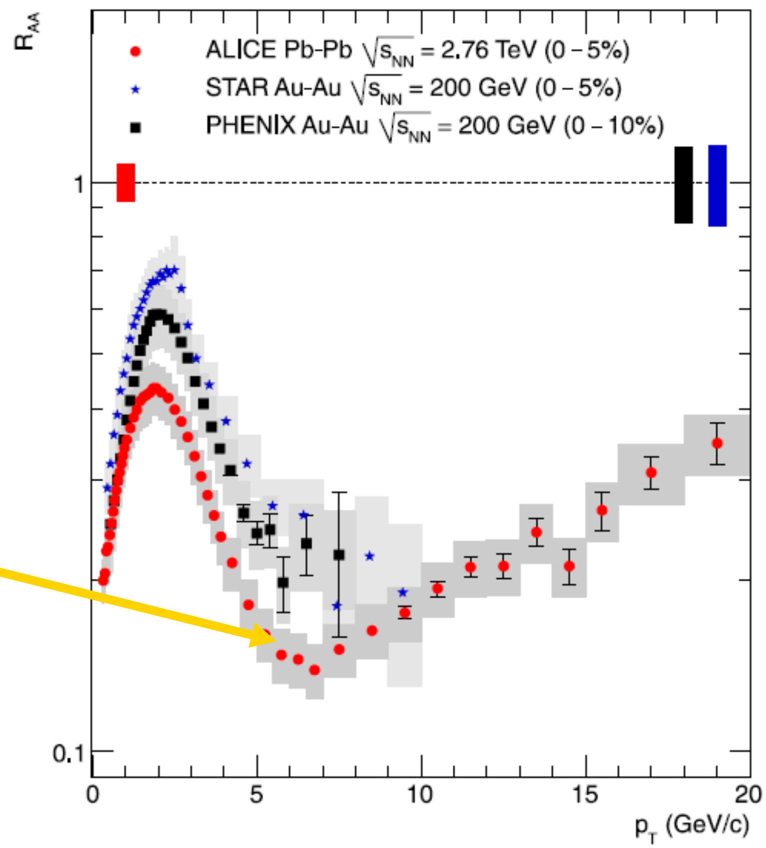
Particle production in pp

$$\langle N_{coll}\rangle = \langle T_{AA}\rangle \cdot \sigma_{pp}^{INEL}$$

Nuclear overlap function $<T_{AA}>$ from Glauber (corresponding to the number of binary collisions)

Charged Particle R_{AA}





No p_T dependence for peripheral

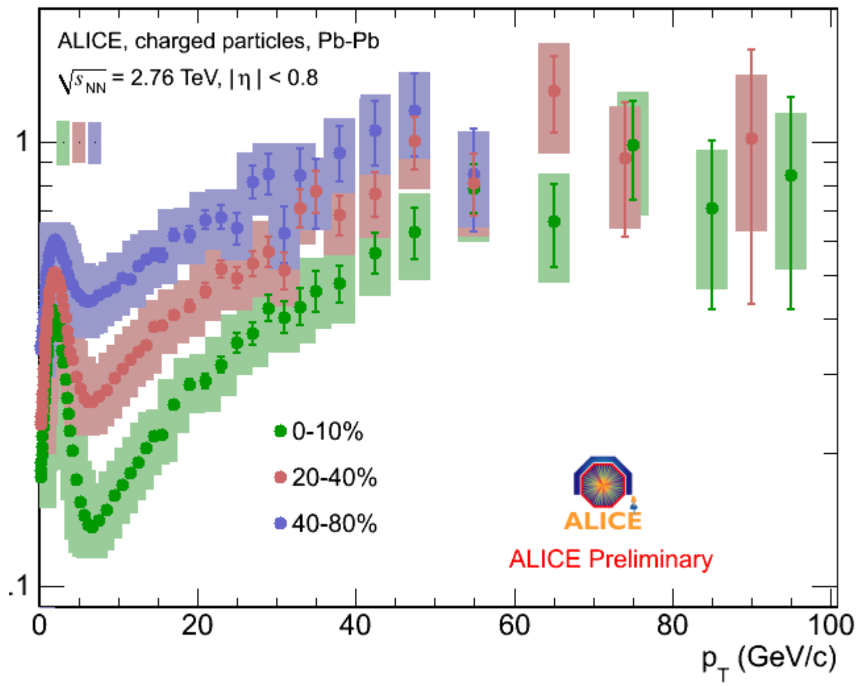
Stronger parton energy loss in central collisions compared to RHIC

Clear increase for p_T > 7 GeV/C !

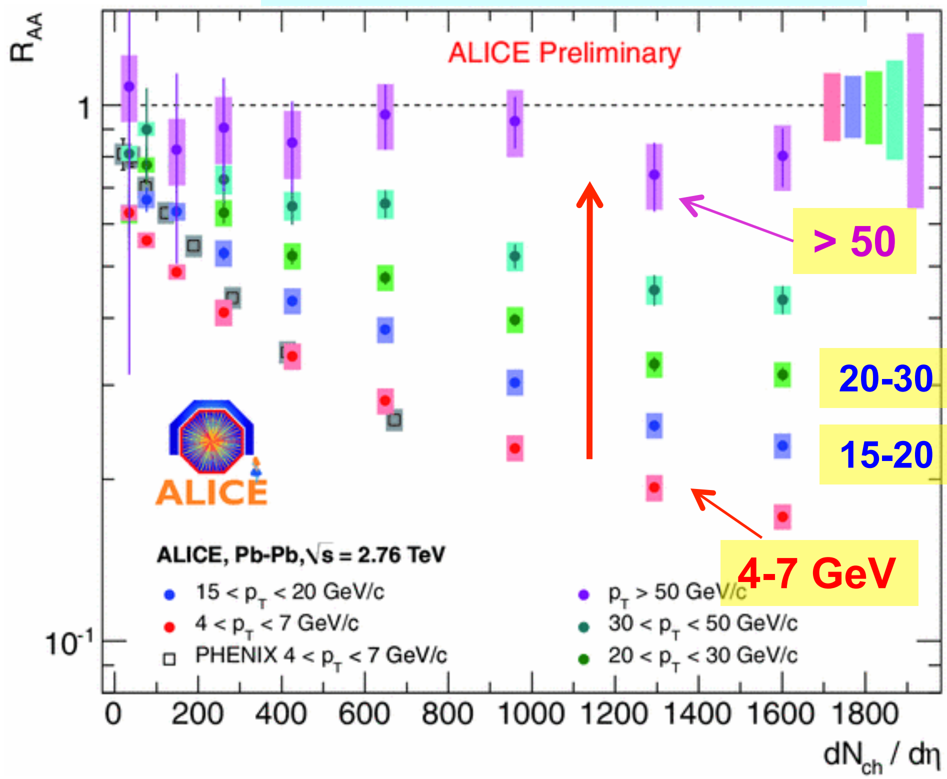
Not observed in RHIC

PLB 696, 30 (2011)

Centrality dependence



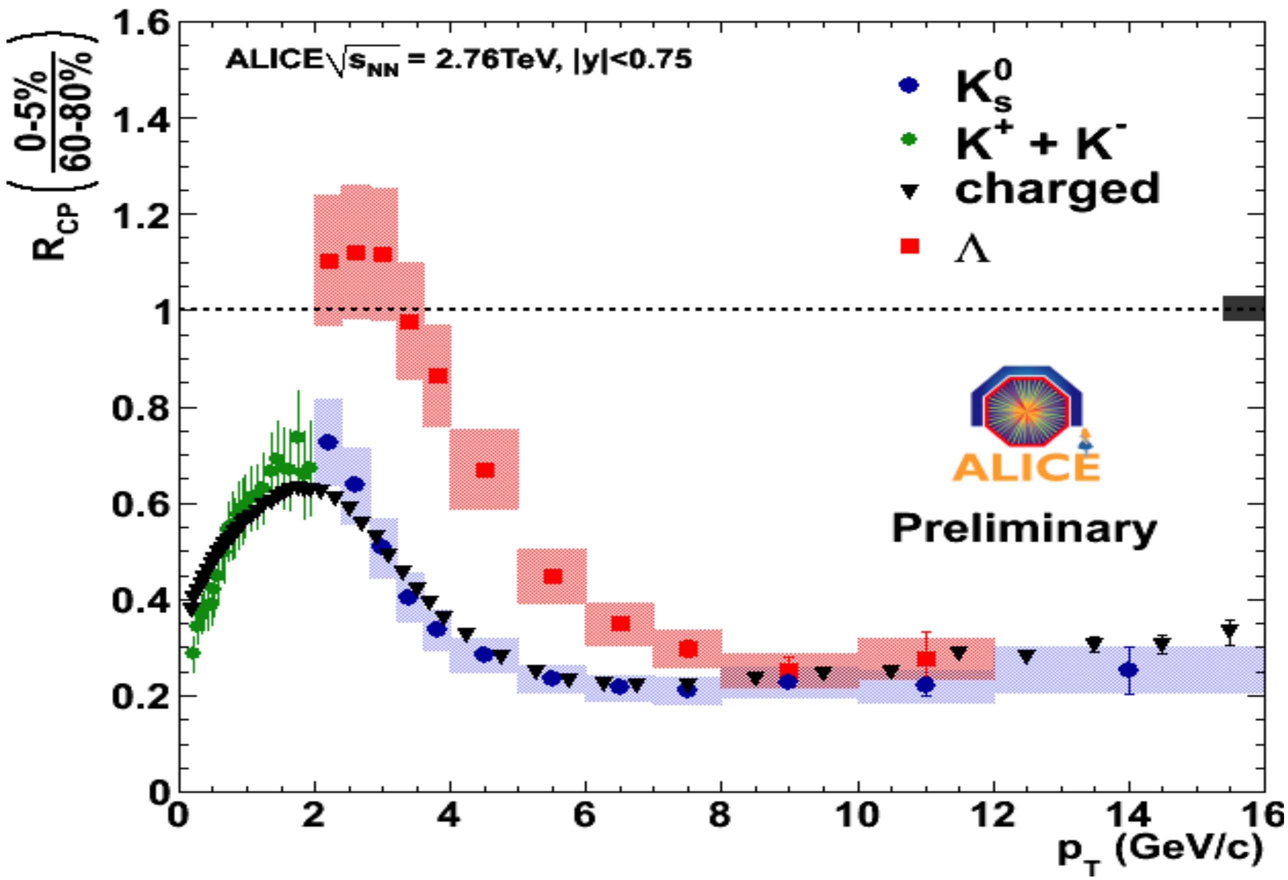
<R_{AA}> in p_T bins vers. N_{ch}



With increasing p_T

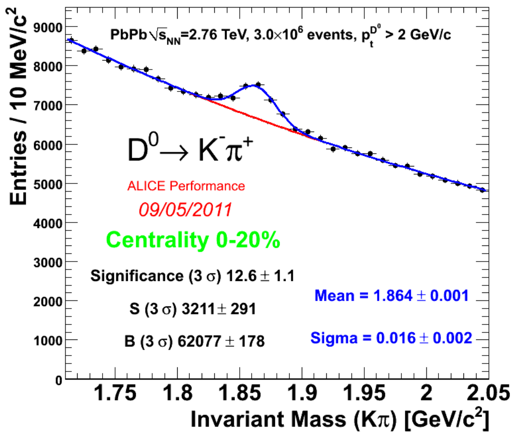
Less central => less R_{AA}

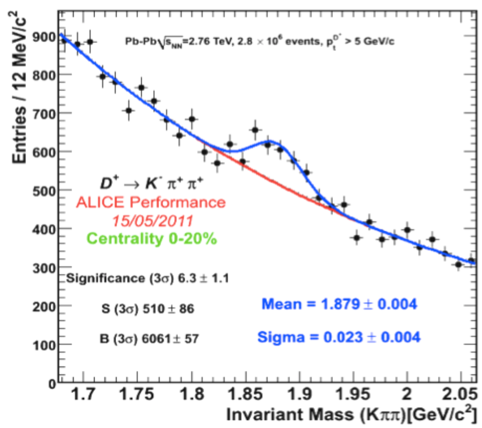
R_{CP} for Λ, K

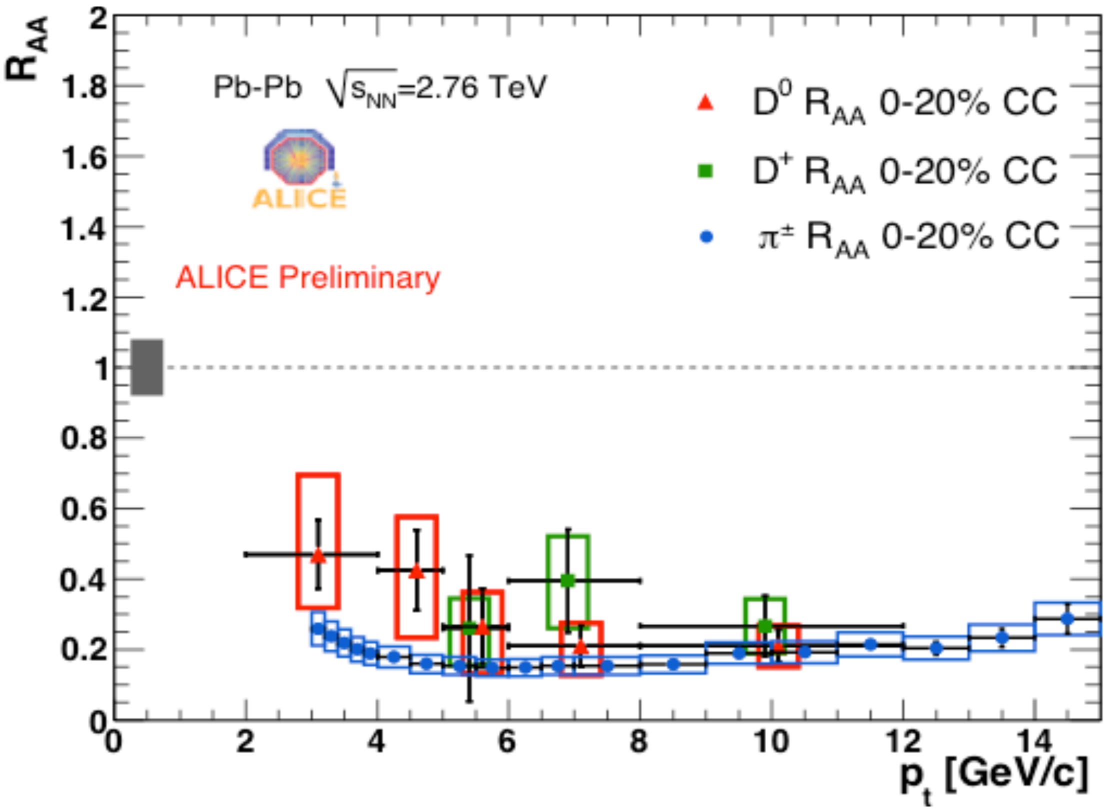


Universal R_{CP} for p_T > 7 GeV/C

Charm R_{AA}: D-Mesons

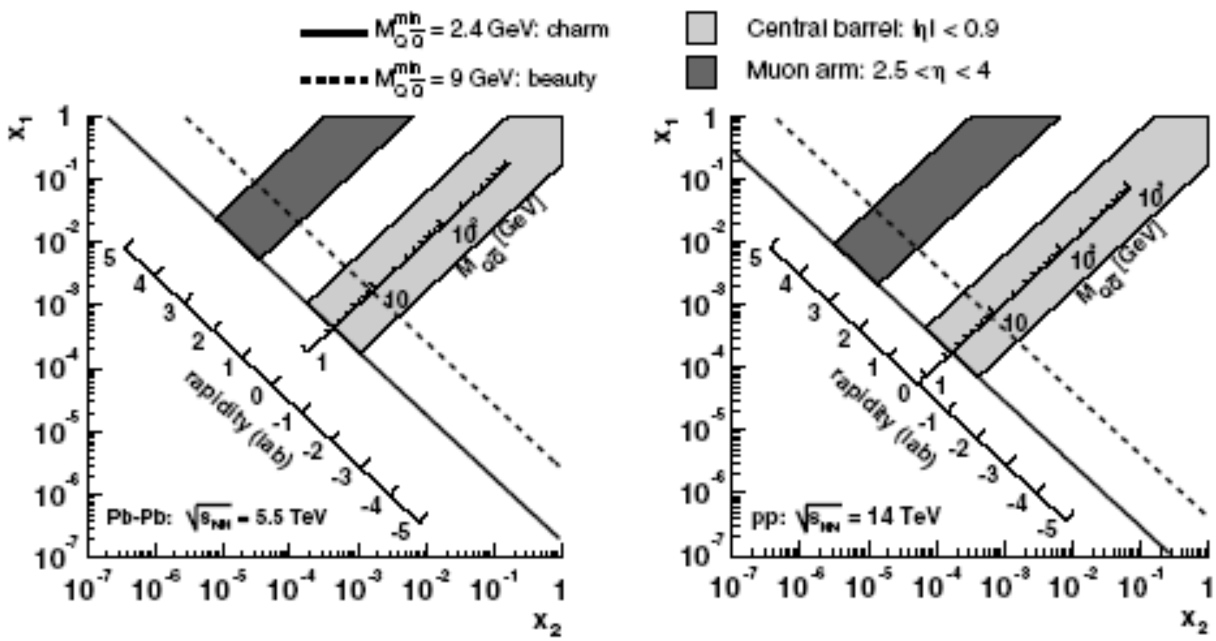






- R_{AA} prompt charm ≈ R_{AA} pions for p_T > 5-6 GeV
- R_{AA} charm > R_{AA} pion for p_T < 5 GeV ? – better error estimation
- Qualitative expectation: R_{AA} Charm > R_{AA} Mesons
  - ΔE gluon > ΔE quark (Casimir factor)
  - ΔE massless parton > ΔE massive quark ('dead cone')

Unprecedented low values of momentum fraction (Bjorken x)

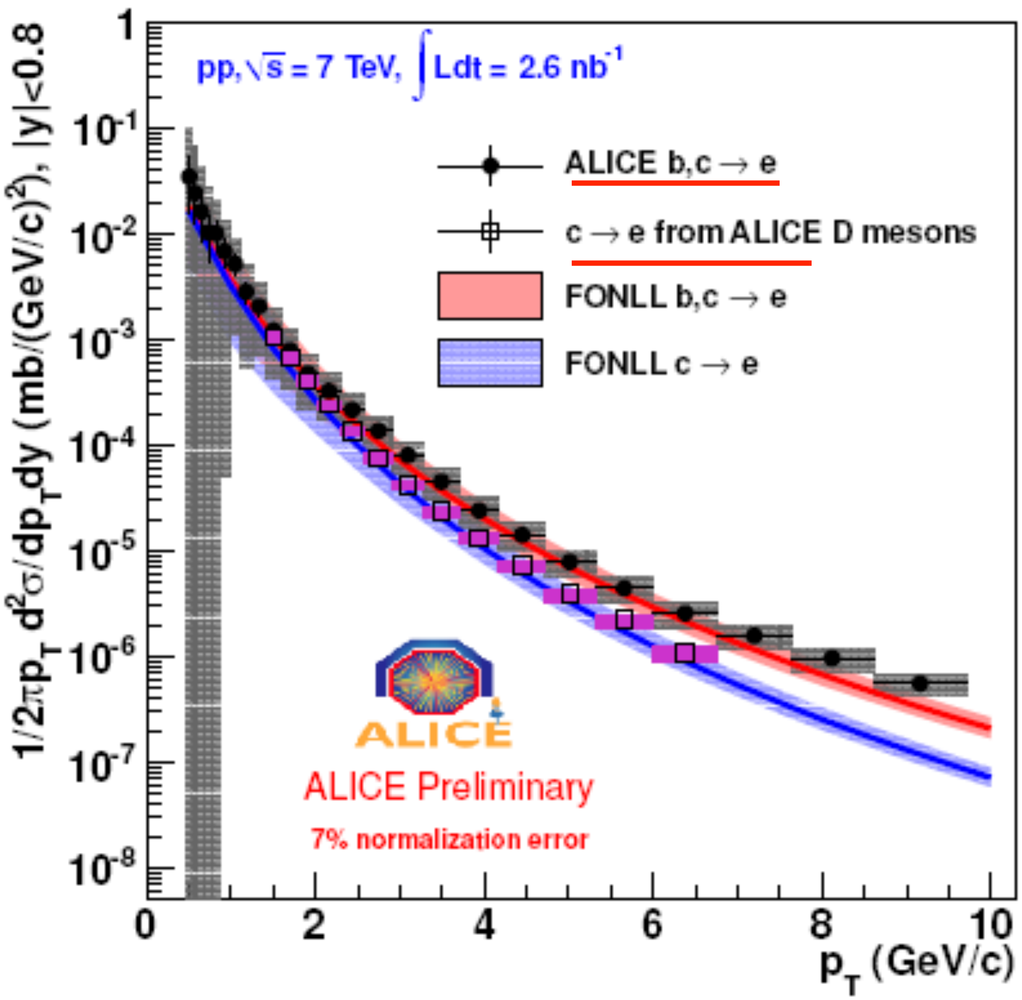


Very low X-range accessible to ALICE for heavy-flavour production

Suppression of Charm production > Beauty production

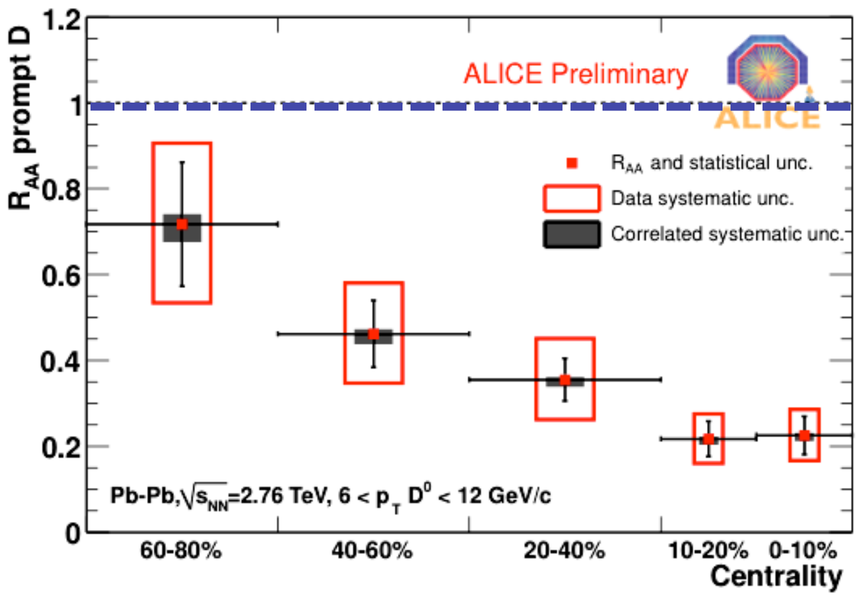
Separate the R_{AA}'s – In Central barrel

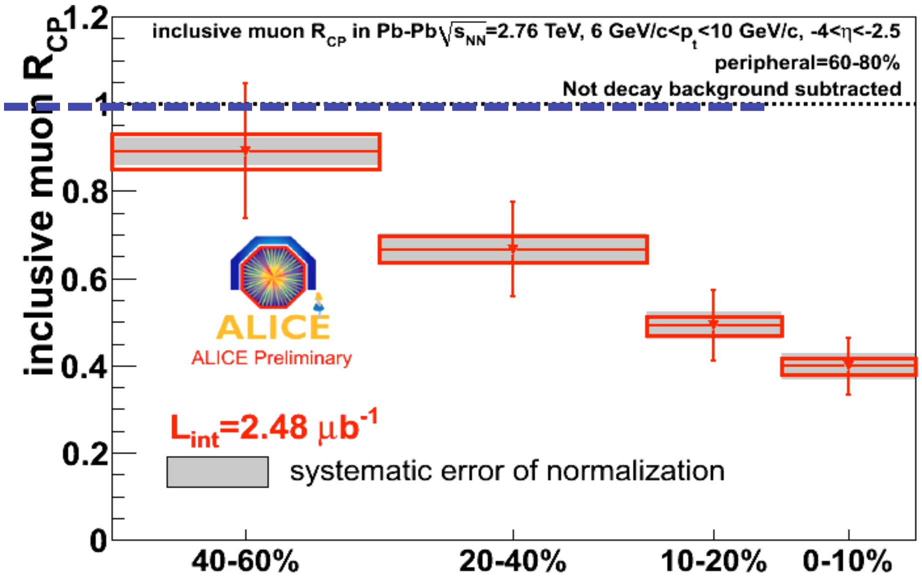
Status in p-p data



Charm contribution from D2h data compared with total HF electon yield

HF Electrons and D meson R_{AA}

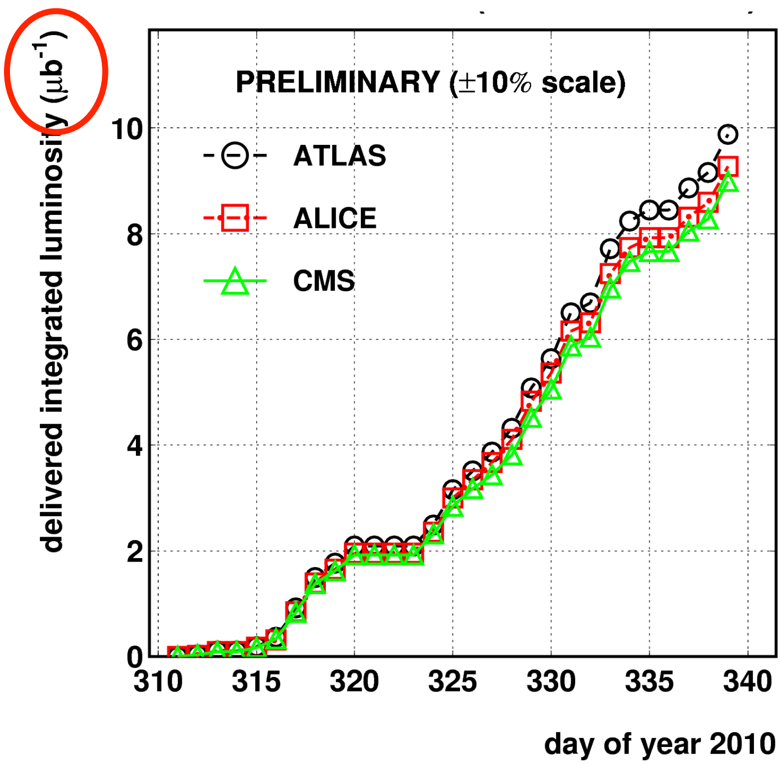


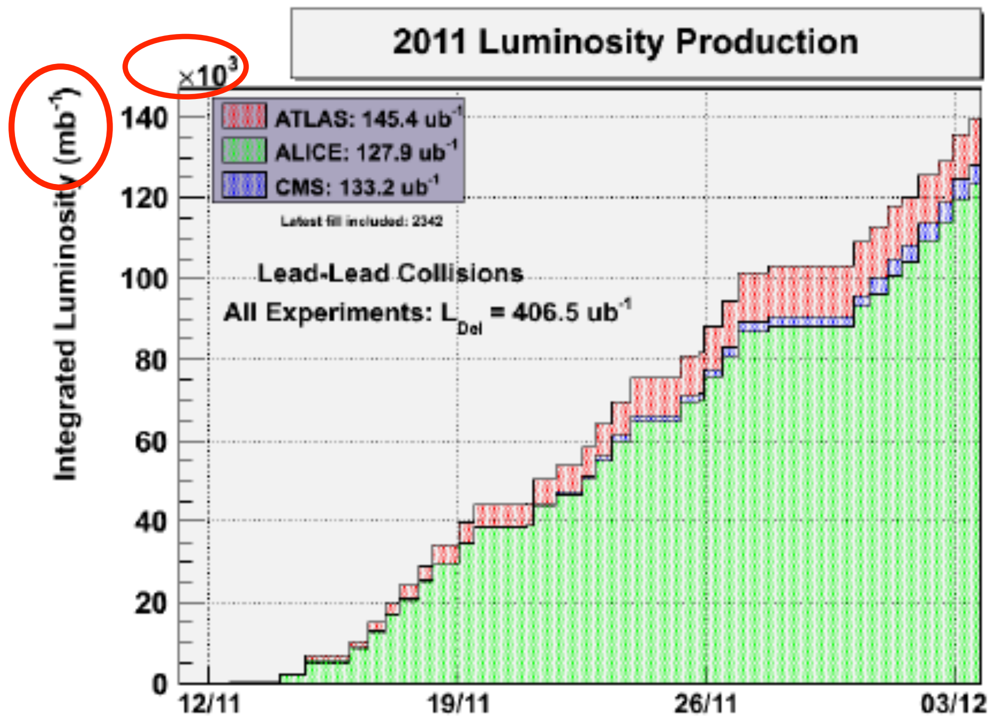


- **D^0 seems more suppressed than HF electrons (inclusive-cocktail)**
- **Similar results for HF muons (inclusive – π+κ)**
- **More energy loss for charm than for beauty?**
  Very large systematic errors
  Better knowledge of gluon shadowing – pA collisions

FUTURE

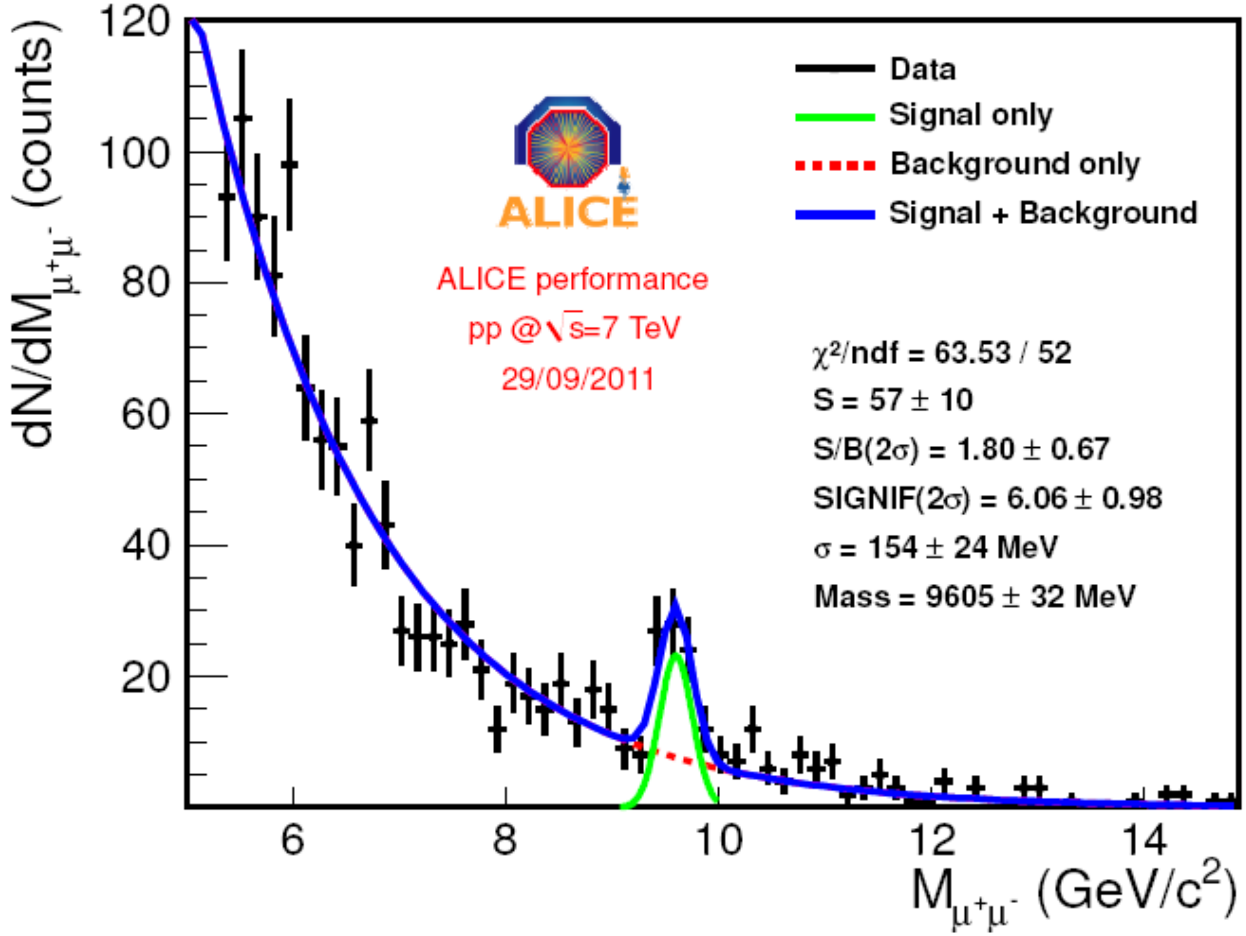
Luminosity in Pb-Pb 2010 & 2011





~20 times more data!

Upsilon



Υ peak (not resolved) observed in p-p at forward rapidity – experimentally difficult

Υ physics

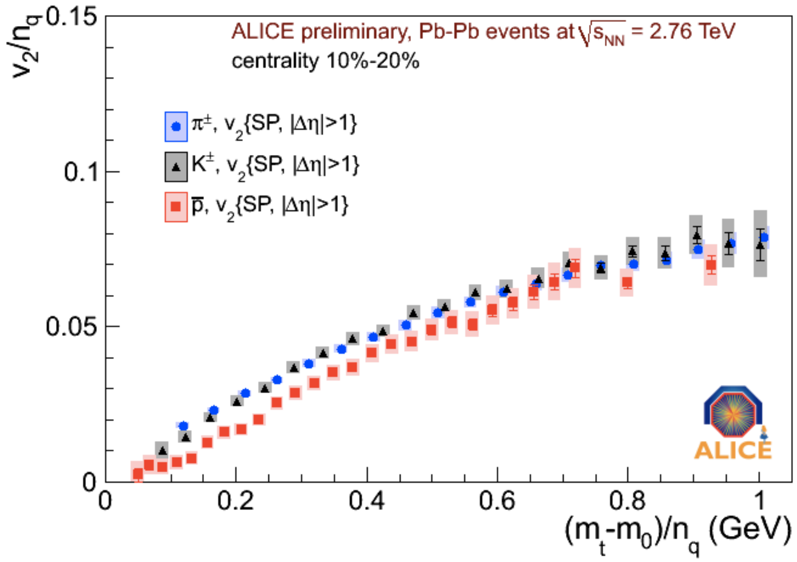
Summary

- First Pb-Pb data of 2010– 3 weeks of low luminosity run ~ 30 M MB!
- ALICE & RHIC results are consistent in the regions of overlap e.g V_2, fluctuations, baryon/meson enhancement.
- The bigger&hotter&longer-lived fireball is expected to lead to better quantitative results e.g η/s.
- Already some surprises!
  - Larger mass spltting for V_2
  - Strong radial flow
  - Necessity of V_3
  - Increase of charged particle R_{AA} at high p_T
  - Small and centrality independent R_{AA} for J/Ψ at high p_T
  - Universal R_{CP} at high p_T
  - R_{AA} Charm ~ R_{AA} mesons at high p_T
- Newer ideas with 2011 data.


Thank you

Backup slides

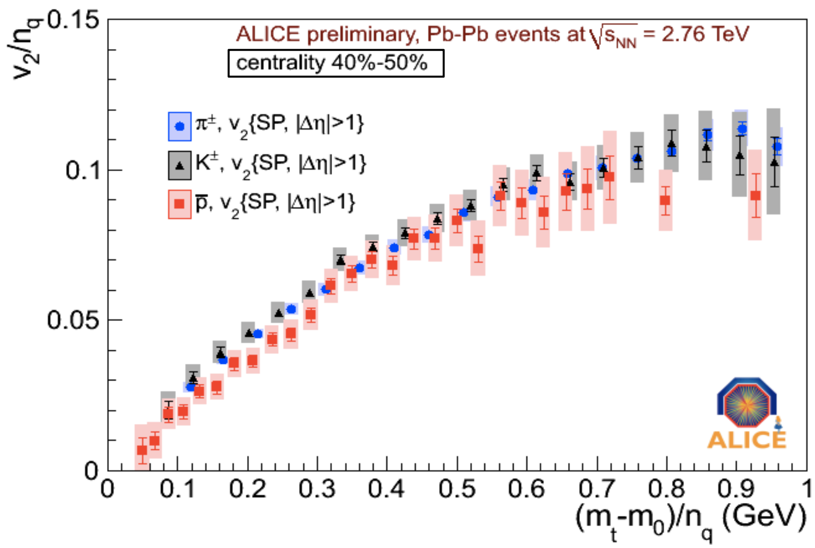
Quark Scaling



For Central collisions:

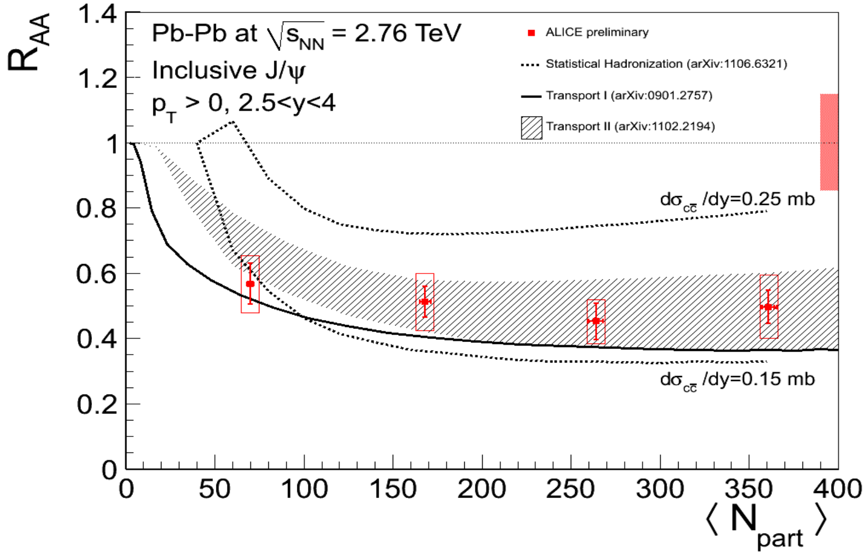
Quark scaling appears to work for π and K at low pT

Quark scaling does NOT work for protons at low pT



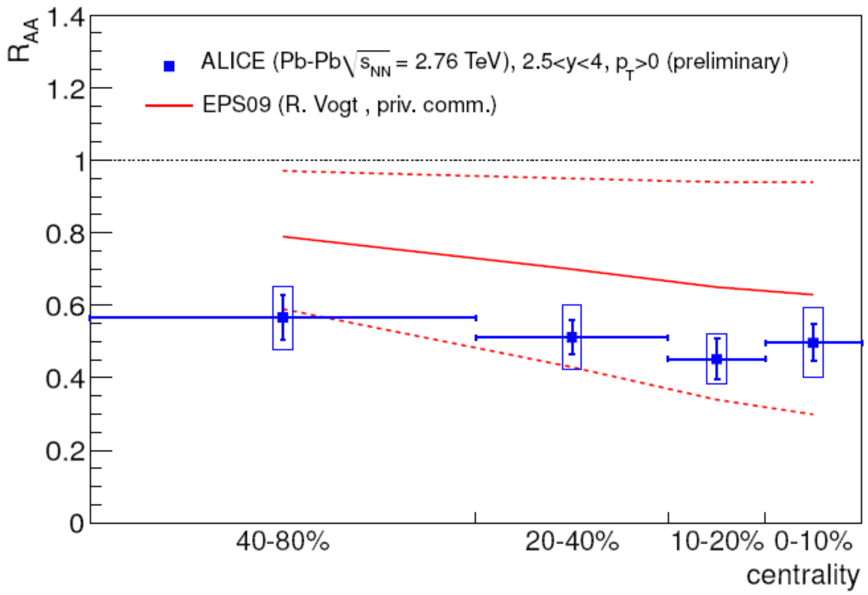
Quark scaling may work (large errors) for π, K, p at high pT for peripheral collisions

J/Ψ suppression: Comparisons



Statistical model (successful at RHIC and SPS) would suggest less suppression at LHC, but large uncertainties

- Needs a precise charm cross-section
- Needs better knowledge of gluon shadowing (pA collisions)



J/Ψ (B) ≈ 10% (LHCb) => R_{AA}(prompt) lower by ≈ 0.05

shadowing(LHC) > shadowing(RHIC) ? => R_{AA} goes up !

cold nuclear matter suppression ?

Net Charge Fluctuations

Net charge: $\delta Q = N^{+} - N^{-}$

Hadron Gas: $q = \pm 1$; $q^2 = 1$

QGP: $q = \pm\frac{1}{3}, \pm\frac{2}{3}$; $q^2 = 1/9, 4/9$

=> Fluctuation of net charge is sensitive to charge state: hadron gas or QGP

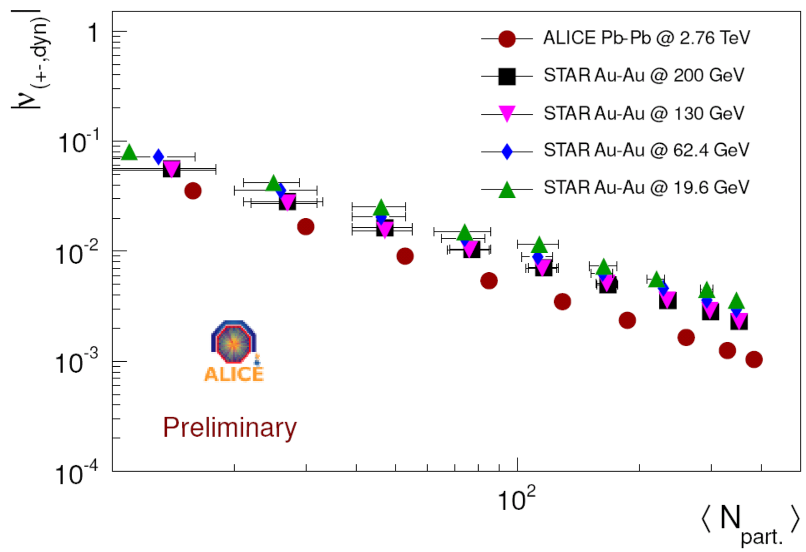
$$D = 4\frac{\langle \delta Q^2 \rangle}{N_{\mathrm{ch}}}$$

≈1 for QGP and
3 for hadron gas

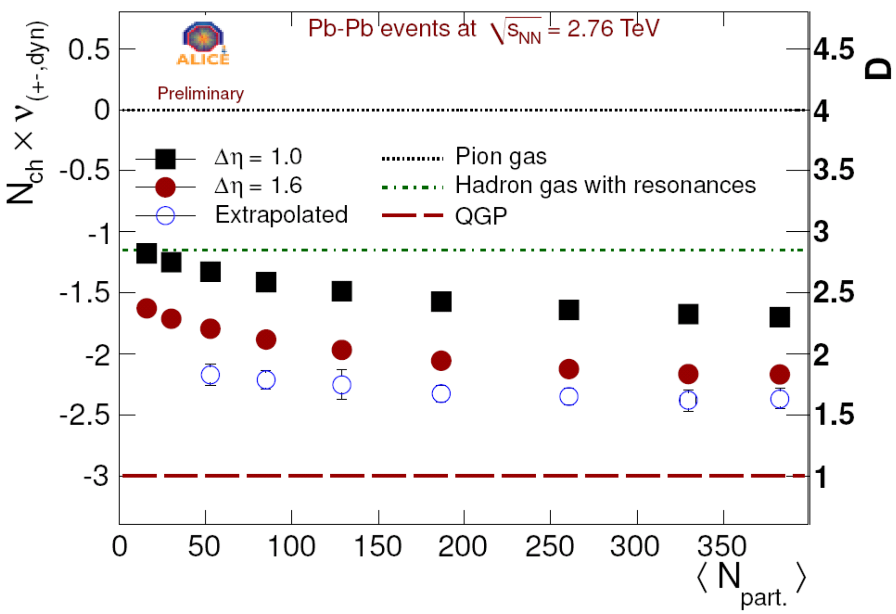
Measure of Dynamical Net Charge fluctuations:

$$\nu_{(dyn)} = \nu_{(+-)} - \nu_{(stat)}$$

Charge Fluctuations

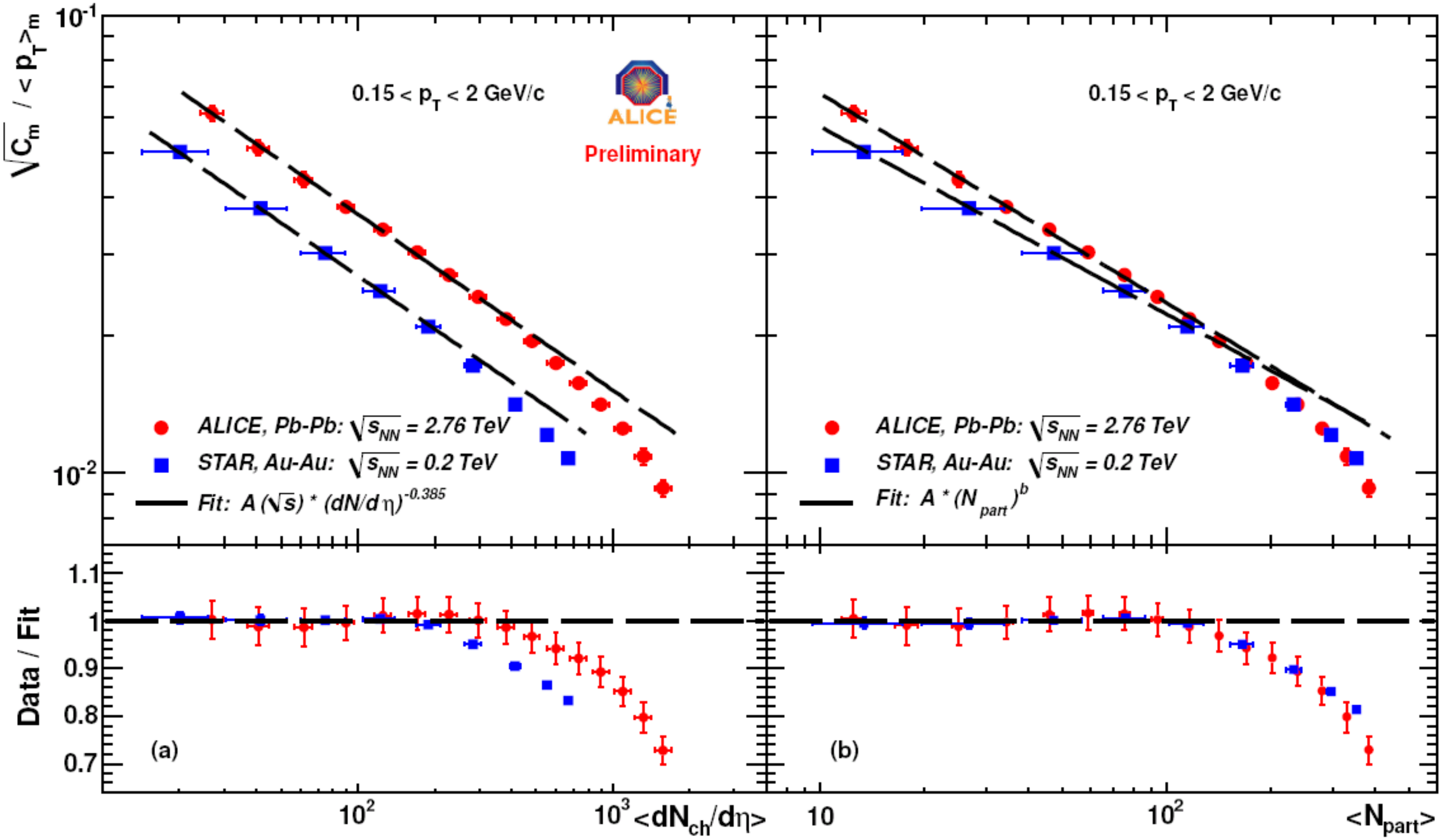


Fluctuations decrease with increase of energy

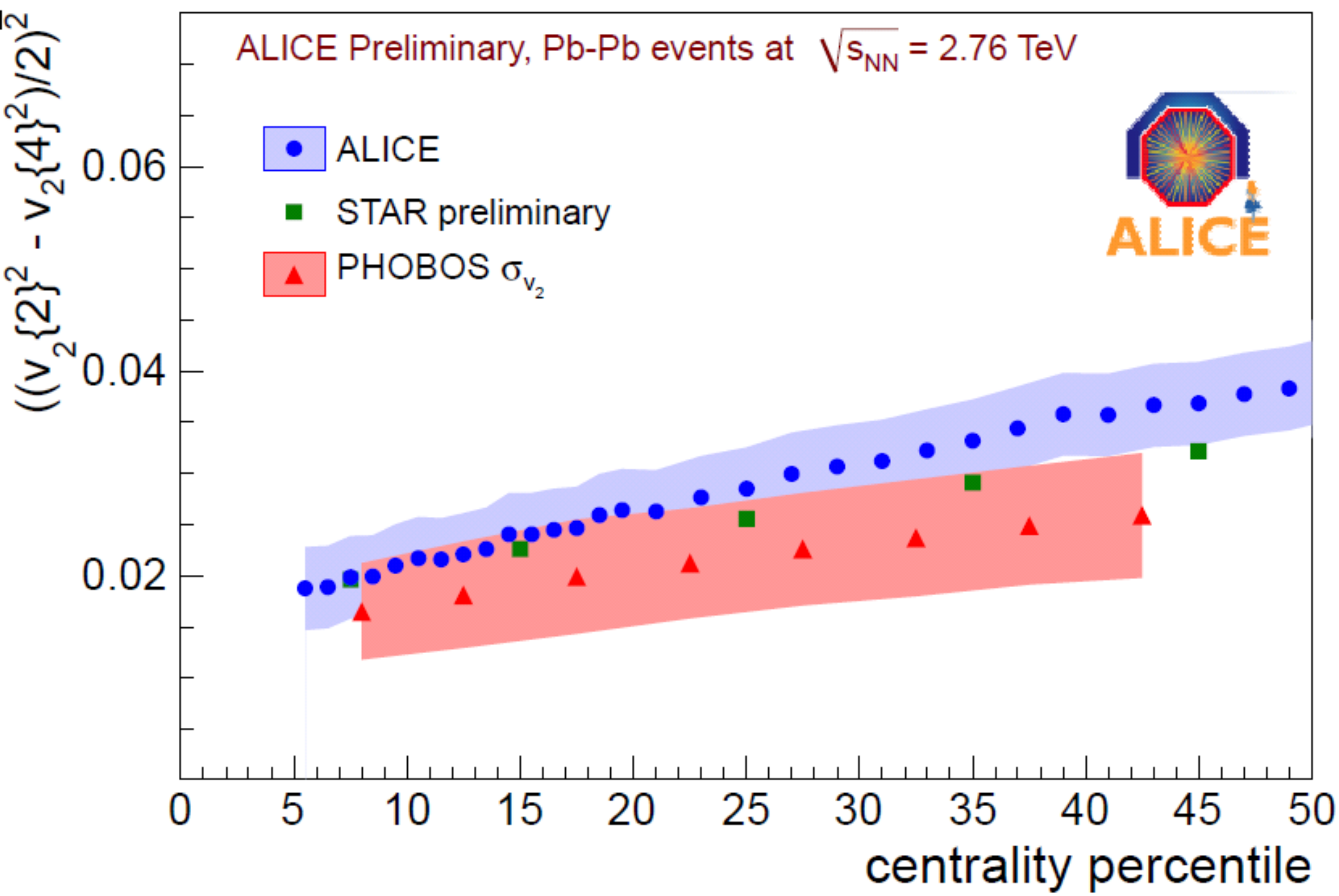


Data between hadron-gas and QGP predictions

p_T Fluctuations

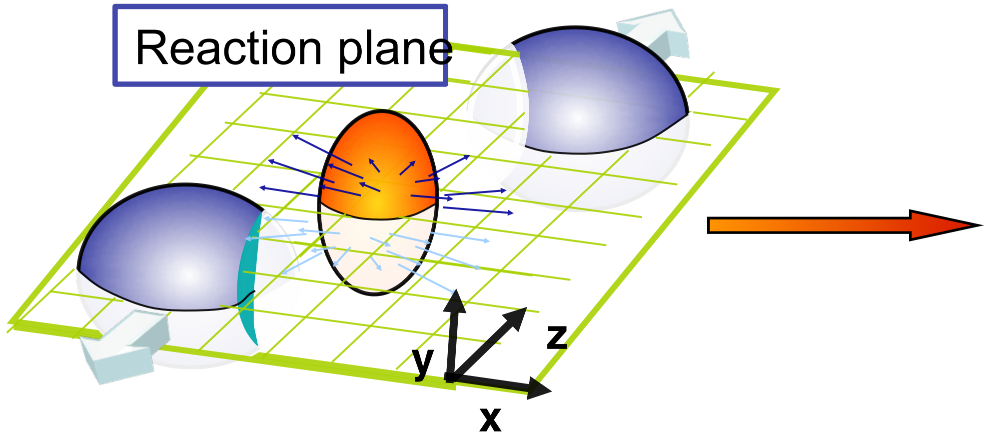


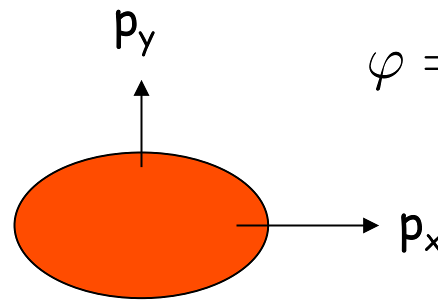
V_2 Fluctuations



Fluctuation dependence on centrality – same as RHIC

Azimuthal Anisotropy – Elliptical Flow





$$\varphi = \arctan \frac{p_y}{px}$$

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

Initial spatial anisotropy

$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

Final momentum anisotropy

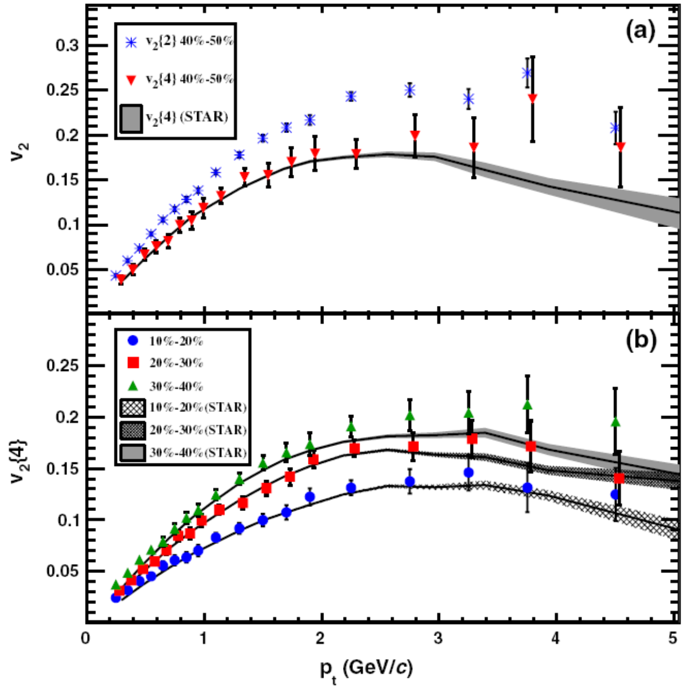
Reaction plane defined by "soft" (low p_T) particles

$$\Delta\varphi = \varphi - \varphi^{Reaction\ \ Plane}$$

Elliptical flow

$$\frac{dN}{d\Delta\varphi} \propto 1 + 2 v_2 \cos(2\Delta\varphi)$$

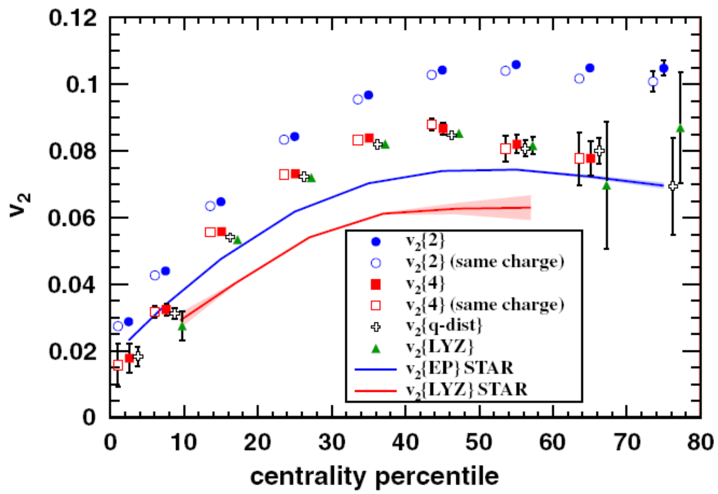
Elliptic Flow



v_2 as function of p_t

practically no change with energy !

extends towards larger centrality/ higher p_t



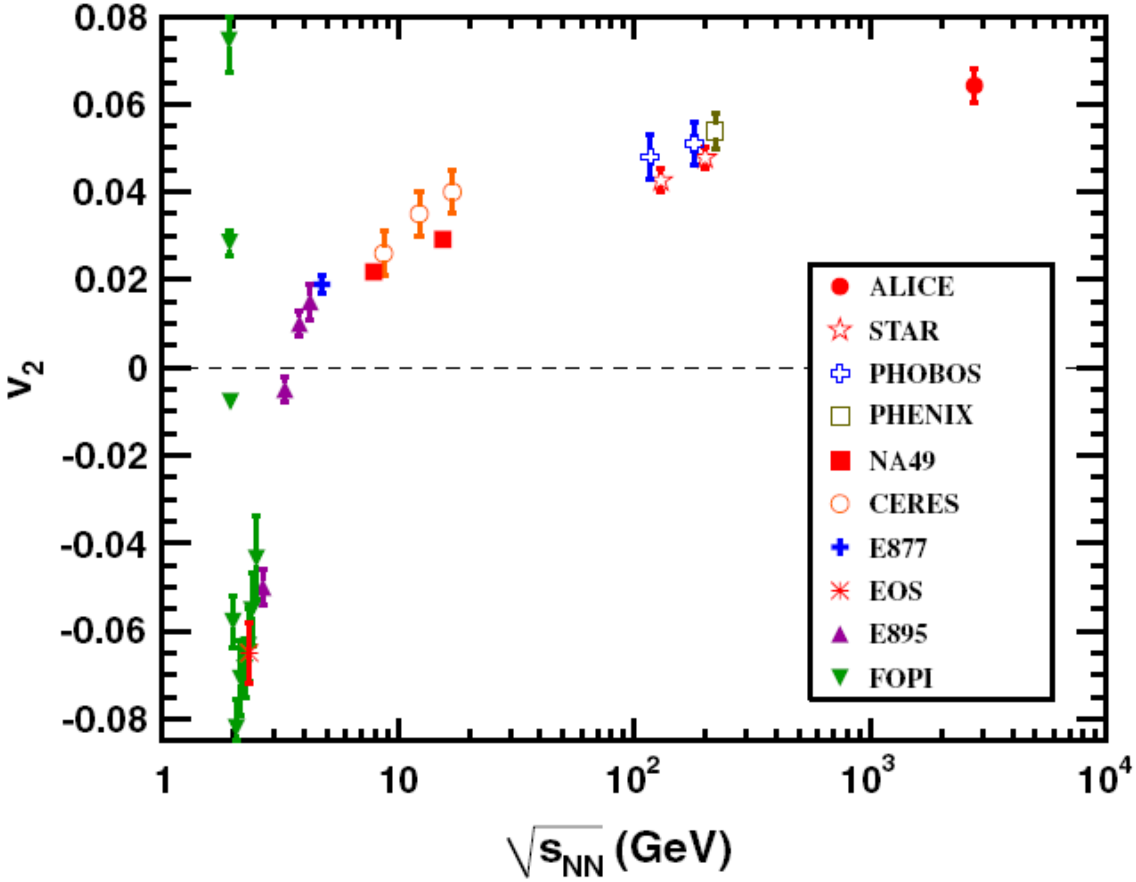
v_2 integrated over pt

expected increases from Central to peripheral

PRL 105, 252302 (2010)

Integrated Elliptic flow at 20-30% centrality

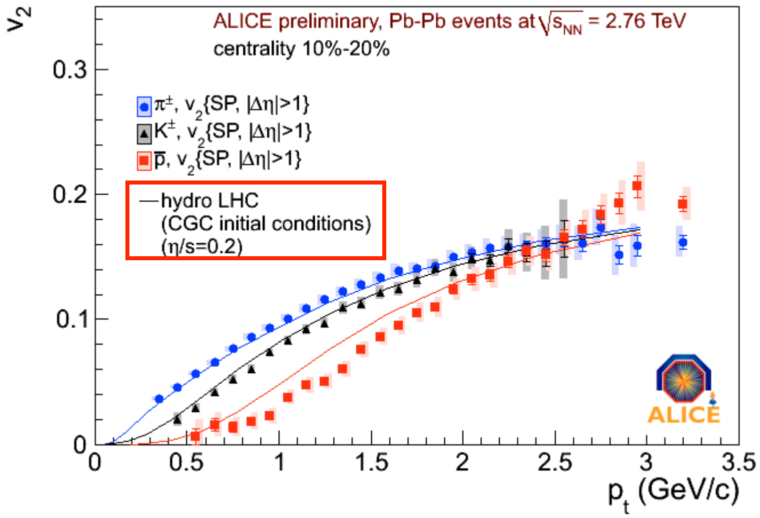
PRL 105, 252302 (2010)



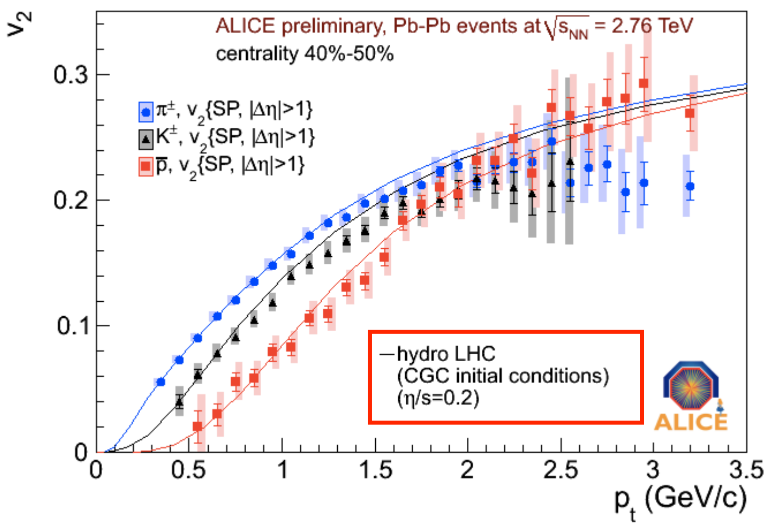
30% increase in magnitude compared to Au-Au collisions at $\sqrt{S_{NN}}$ = 0.2 TeV caused by increase in mean pt

The system produced at the LHC behaves as a very low viscosity fluid (departure from a perfect fluid behaviour as compared to RHIC observation - $\eta/s = 1/4\pi = 0.08$).

V_2 for identified particles

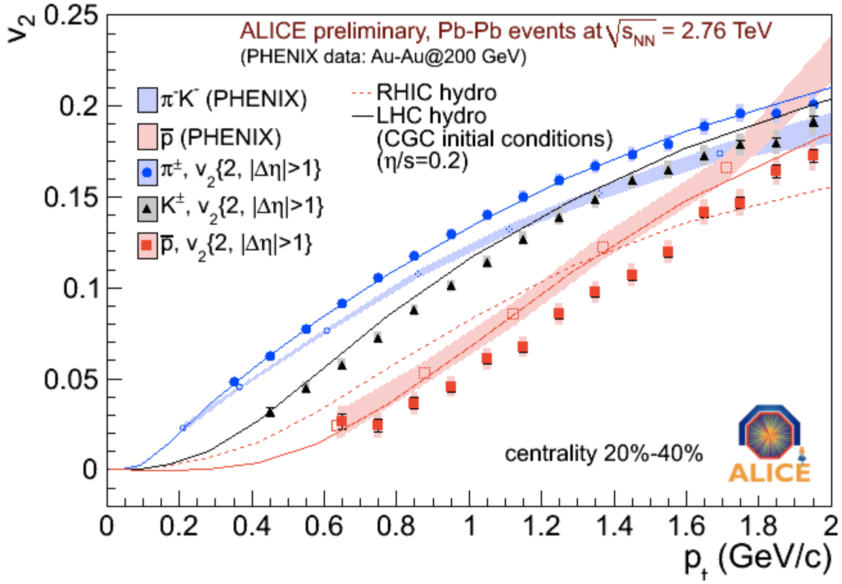


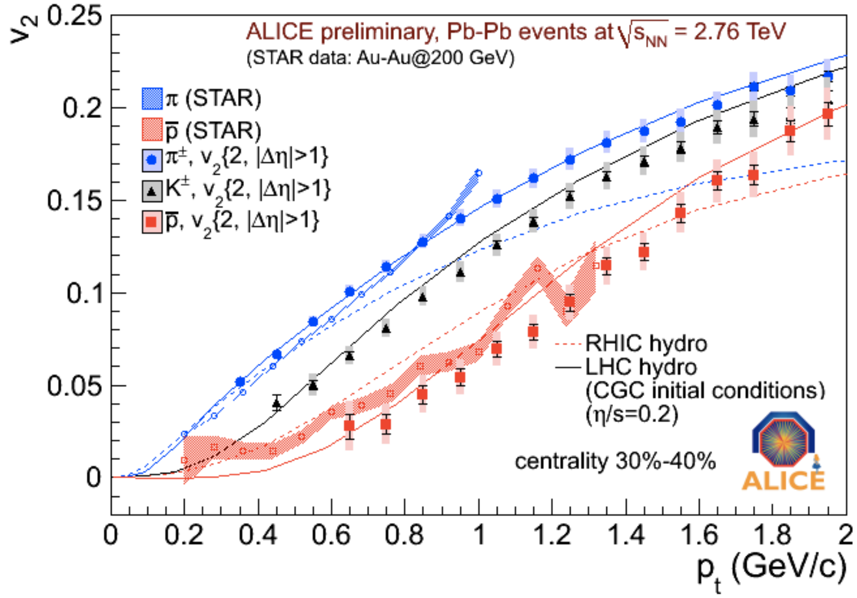
Significant departure for protons in Central collisions



Reasonable agreement with Hydro for peripheral collisions.

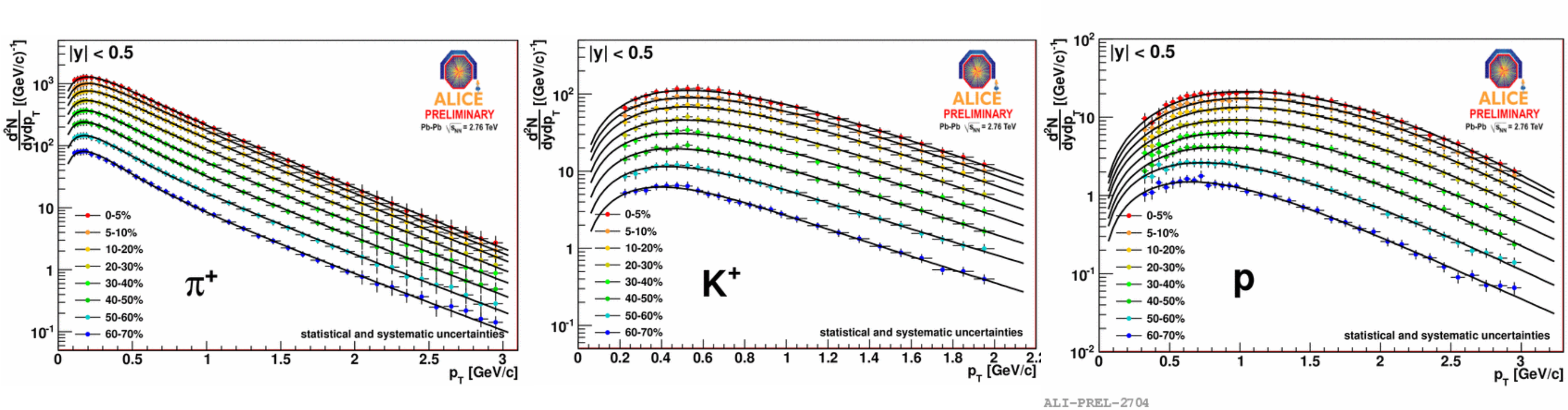
V_2 for identified particles – LHC & RHIC





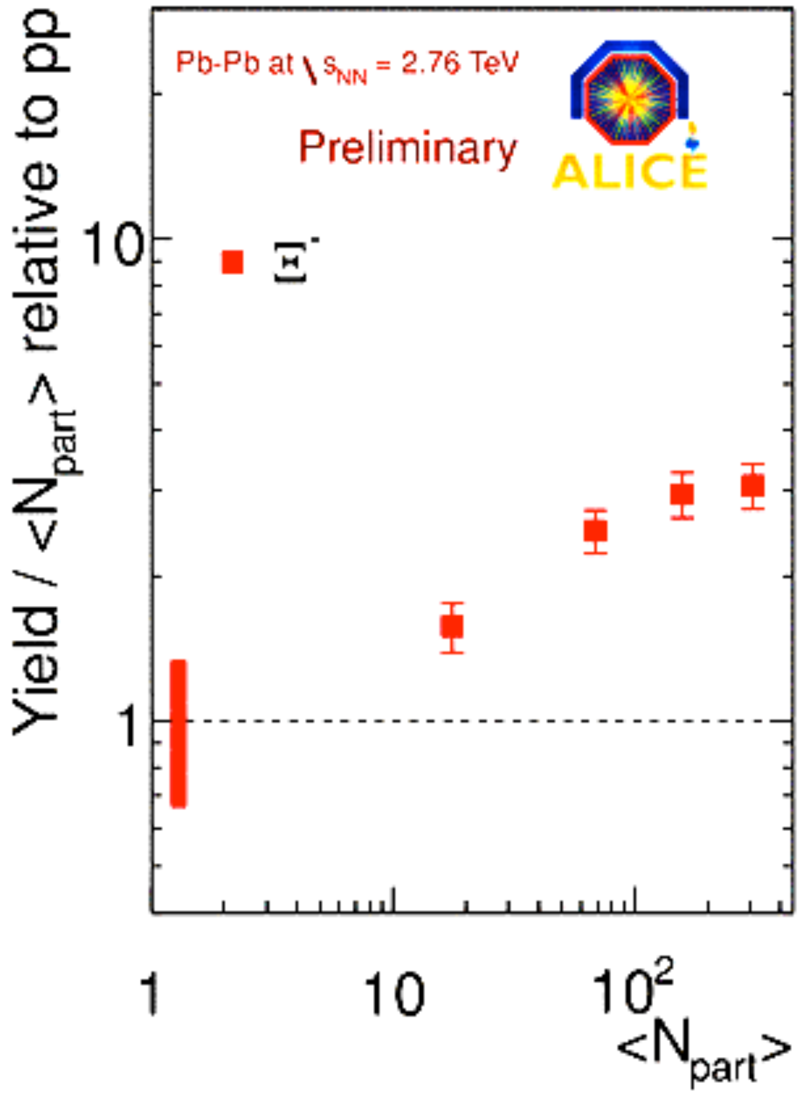
Larger mass splitting at LHC than RHIC

Identified particle yields



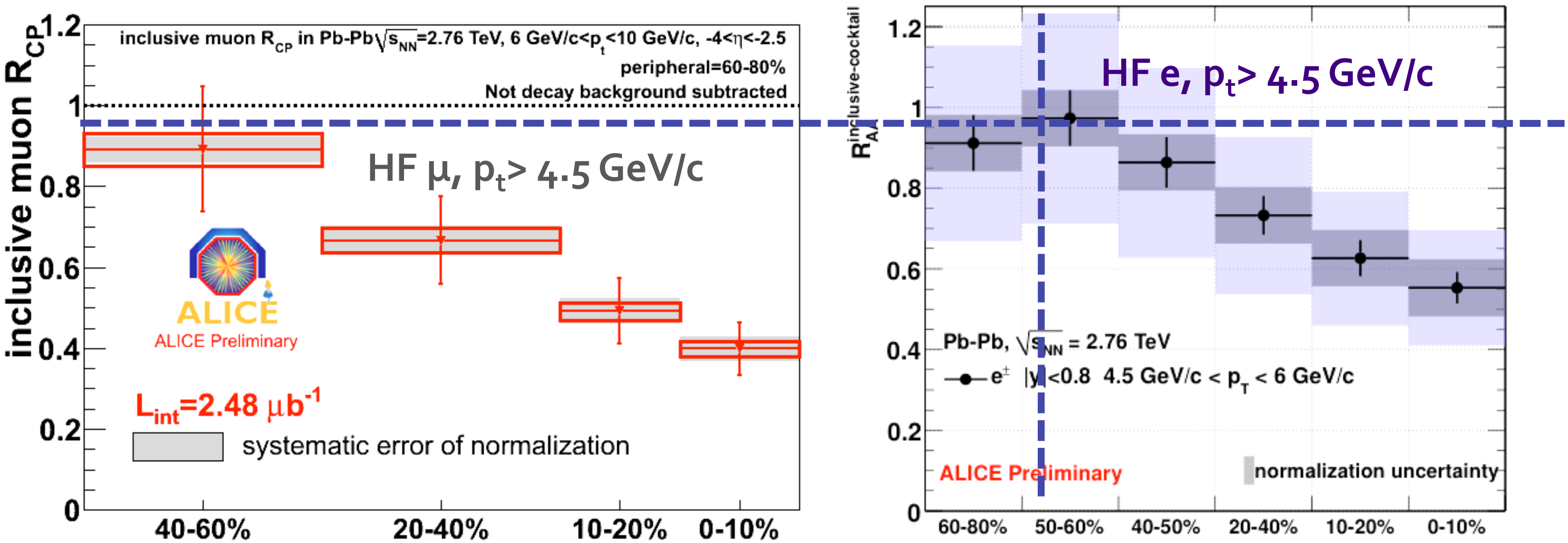
Blast wave model fits to the observed yields and <p_T>

Multi-strange Baryon Production



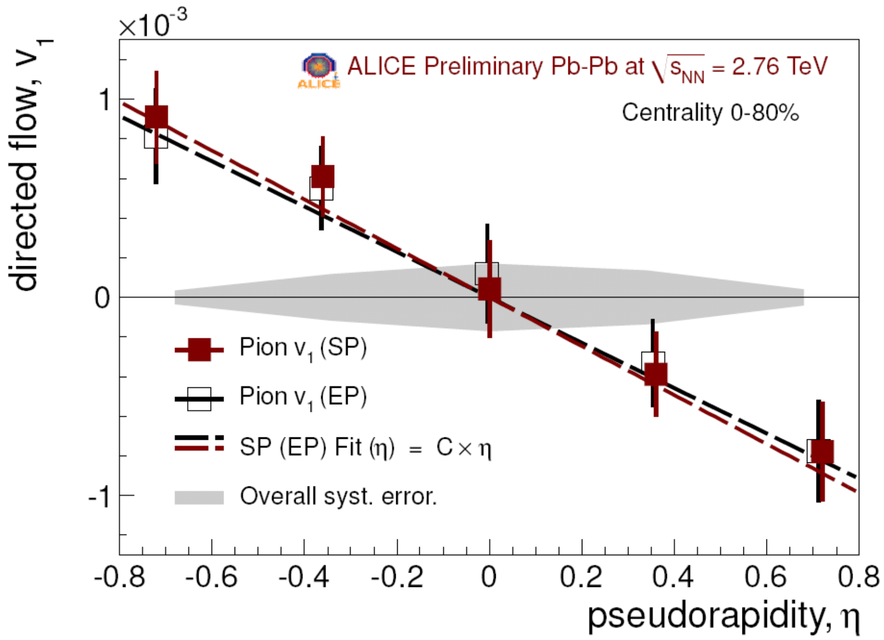
Multi-strange baryon production increases in Pb-Pb collisions at $\sqrt{S_{NN}}$ = 2.76 TeV with respect to p-p

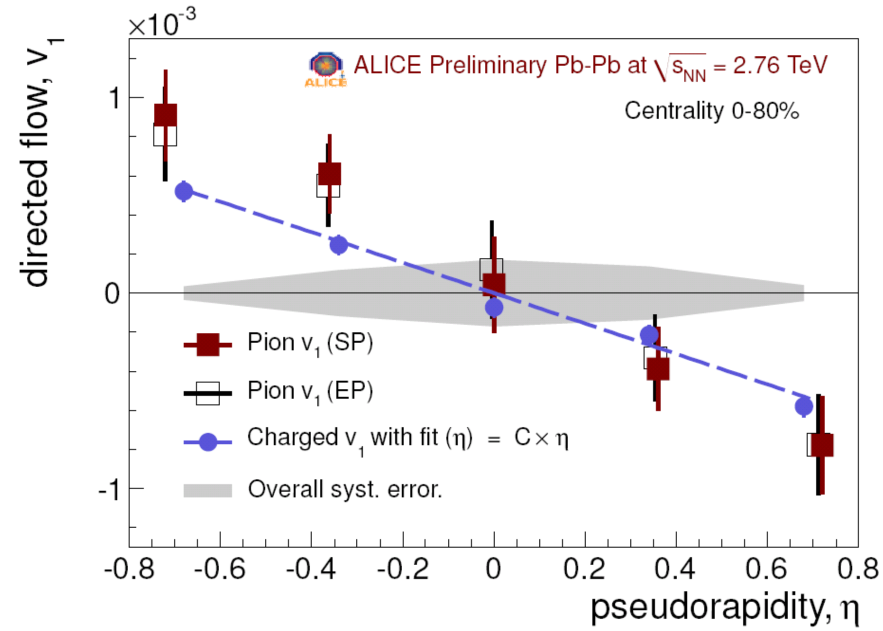
Heavy Flavour Muons



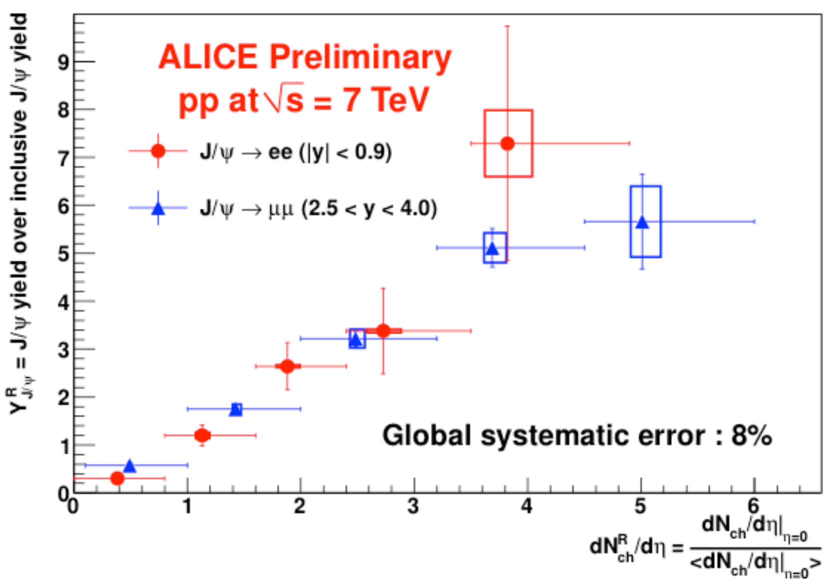
Muon R_{CP} at forward rapidity > Charm R_{AA} at central rapidity

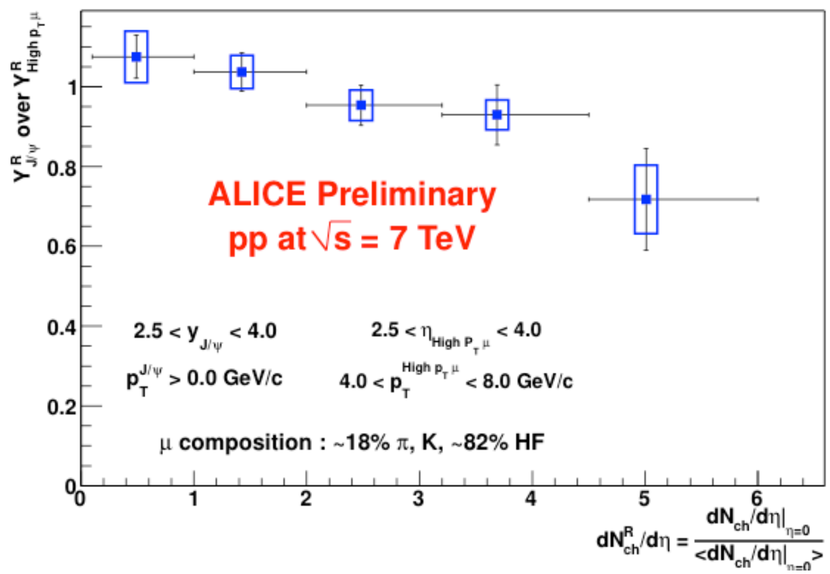
Directed Flow





J/ψ vs multiplicity pp, 7 TeV





J/ψ cross-section

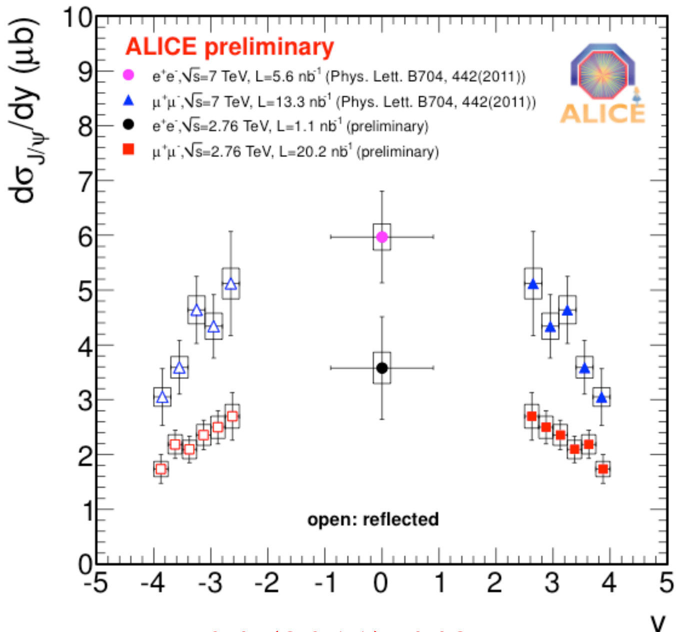
pp, 7 TeV

Inclusive J/ψ cross sections at 7 TeV

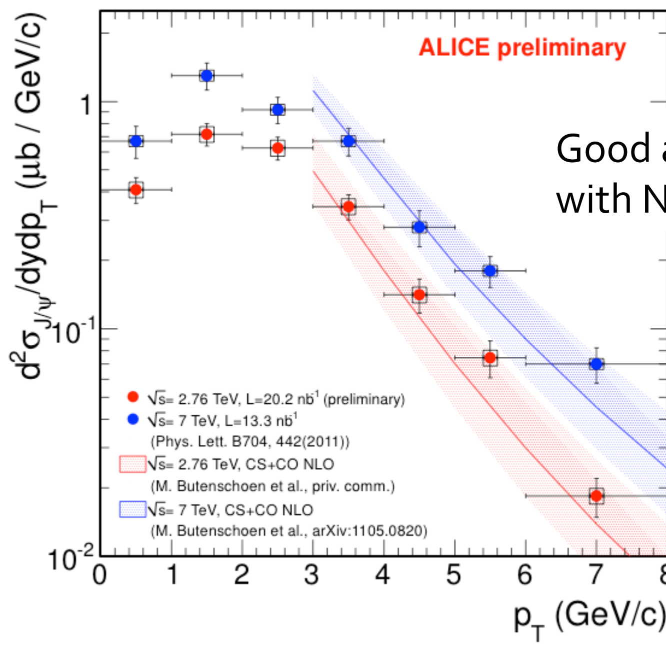
- $\sigma_{J/\psi}$ (|y|<0.9) = 10.7 ± 1.00 (stat) ± 1.70 (syst) + 1.60 (λHE=+1) -2.30 (λHE=-1) μb
- $\sigma_{J/\psi}$ (2.5<y<4) = 6.31 ± 0.25 (stat) ± 0.76 (syst) + 0.95 (λCS=+1) -1.96 (λCS=-1) μb

Inclusive J/ψ cross sections at 2.76 TeV

- $\sigma_{J/\psi}$ (|y|<0.9) = 6.44 ± 1.42 (stat) ± 0.88 (syst) ± 0.52 (lumi) + 0.64 (λHE=+1) -1.42 (λHE=-1) μb
- $\sigma_{J/\psi}$ (2.5<y<4) = 3.46 ± 0.13 (stat) ± 0.32 (syst) ± 0.28 (lumi) + 0.55 (λCS=+1) -1.11 (λCS=-1) μb

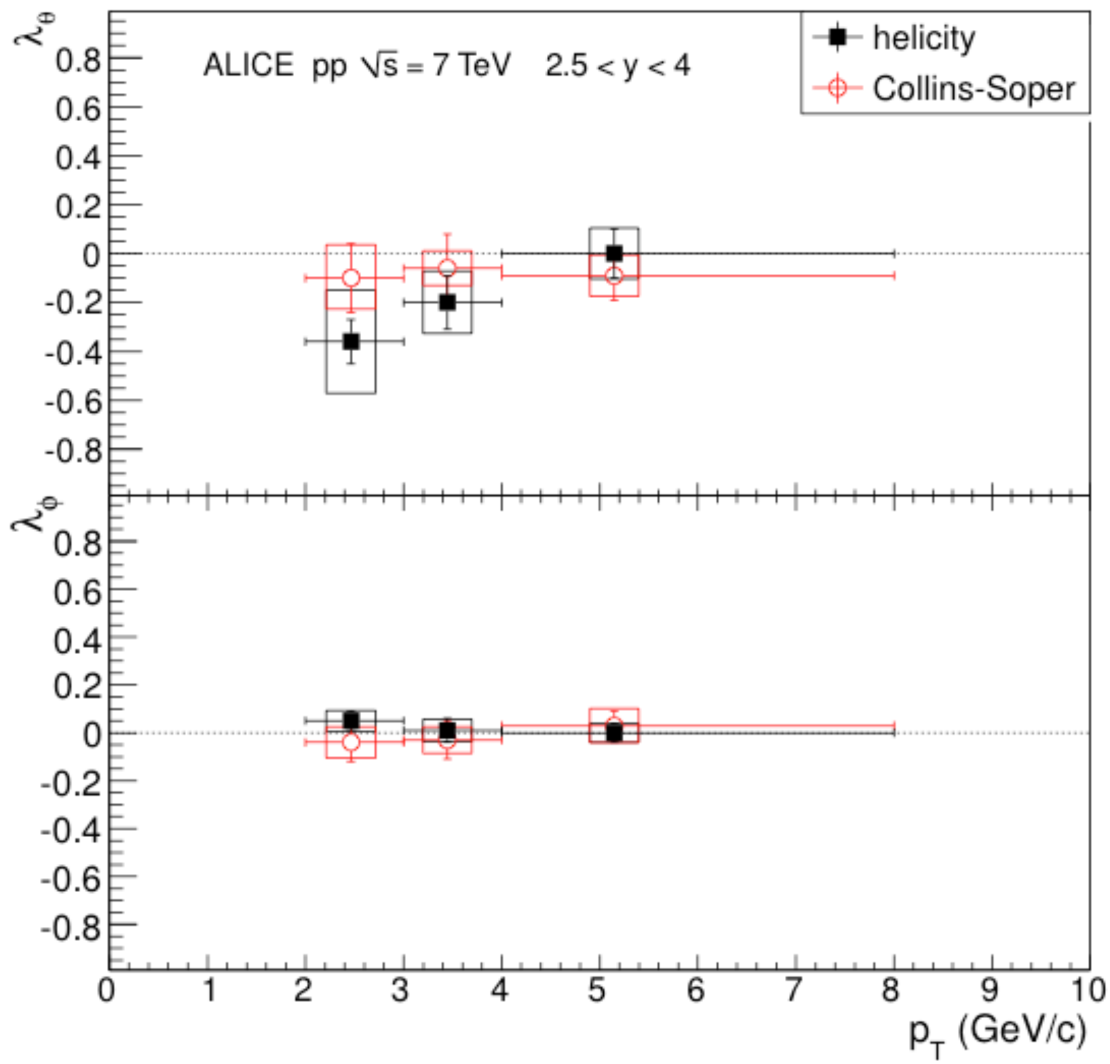


Phys. Lett. B704 (2011) 442



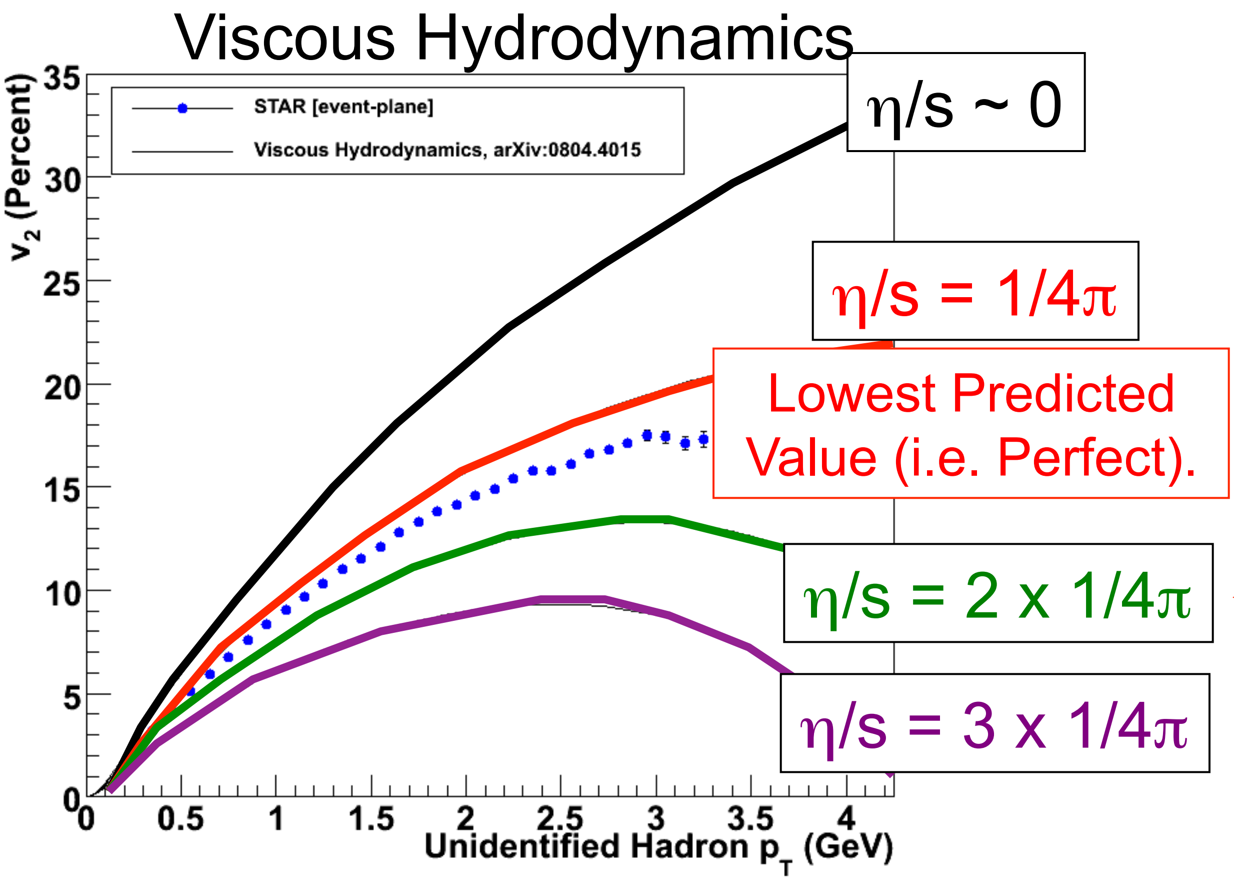
Good agreement with NRQCD

J/ψ polarization pp, 7 TeV



arXiv:1111.1630

The Perfect Fluid

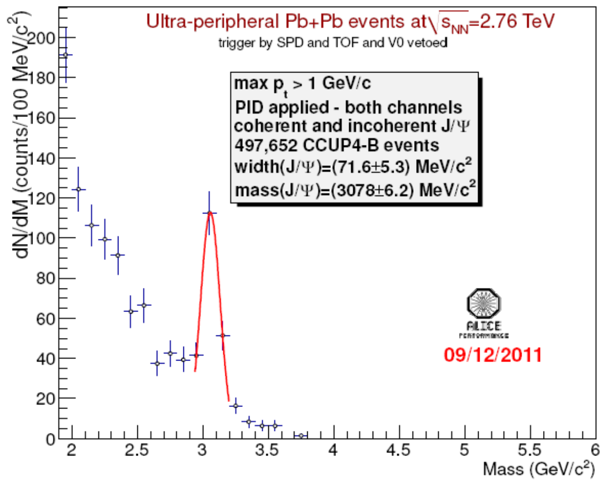


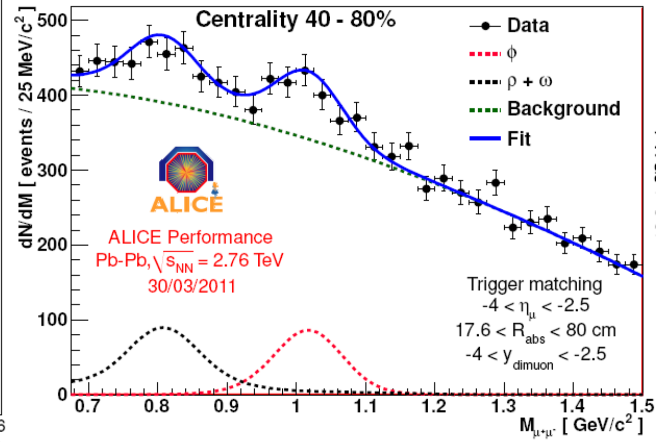
Hydro calculations, $\eta/s = 0.2$ for V_2 and that for identified particles

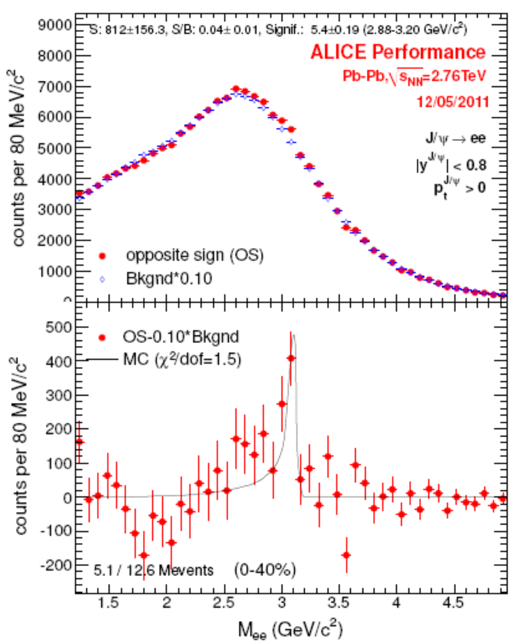
M.Luzum & R. Romatschke
PRC 78 034915 (2008)

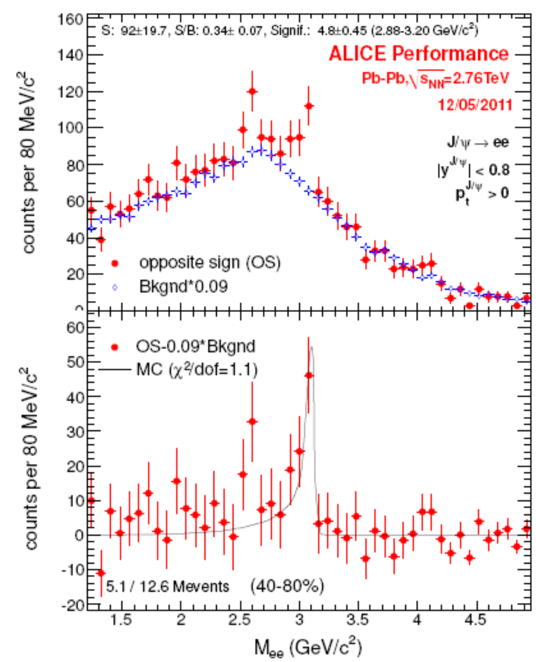
String Theory (AdS/CFT) predicted η/s Bound

Di-leptons - general

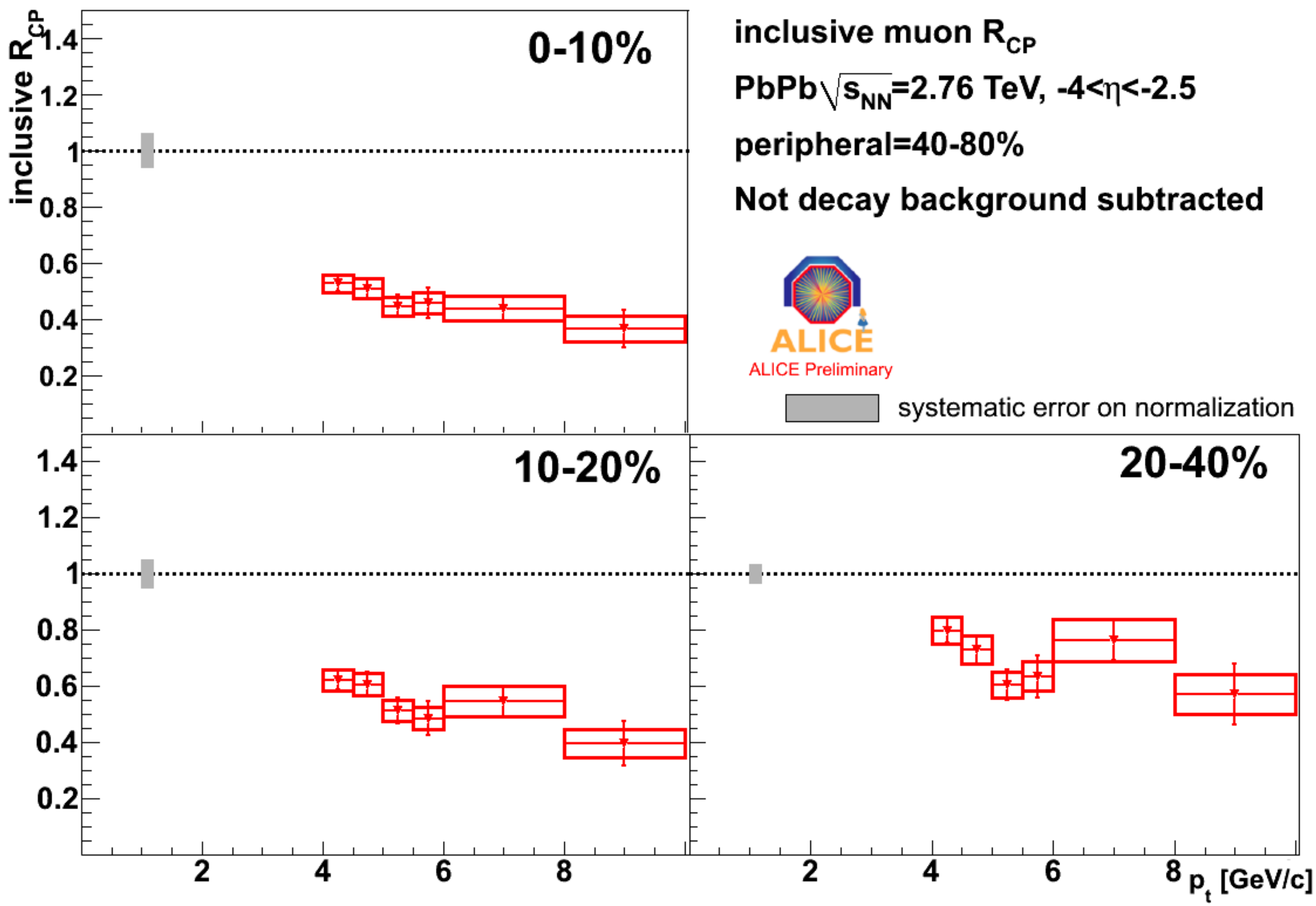








HFMuons



inclusive muon R_{CP}
PbPb $\sqrt{s_{NN}}$=2.76 TeV, -4<η<-2.5
peripheral=40-80%
Not decay background subtracted
ALICE
ALICE Preliminary
systematic error on normalization
0-10%
10-20%
20-40%
inclusive R_{CP}
1.4
1.2
1
0.8
0.6
0.4
0.2
2
4
6
8
p_t [GeV/c]

Data Samples of 2010

Beam	Energy	# of Events	
pp	900 GeV	300 k MB	2009, analysis finished
pp	900 GeV	~ 8 M MB	2010, partially analyzed
pp	2.36 TeV	~ 40 k MB	2009, only ITS, $dN_{ch}/d\eta$
pp	7 TeV	~ 800 M MB ~ 50 M muons ~ 20 M high N_{ch}	2010
PbPb	2.76 TeV/N	~ 30 M MB	2010