Heavy ion results from the LHC

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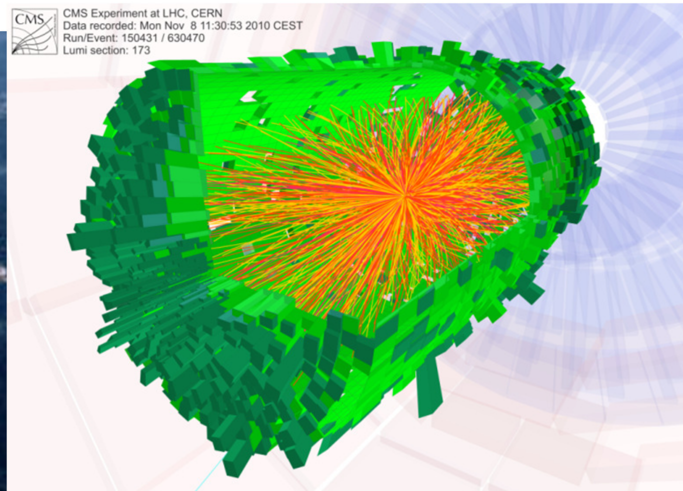
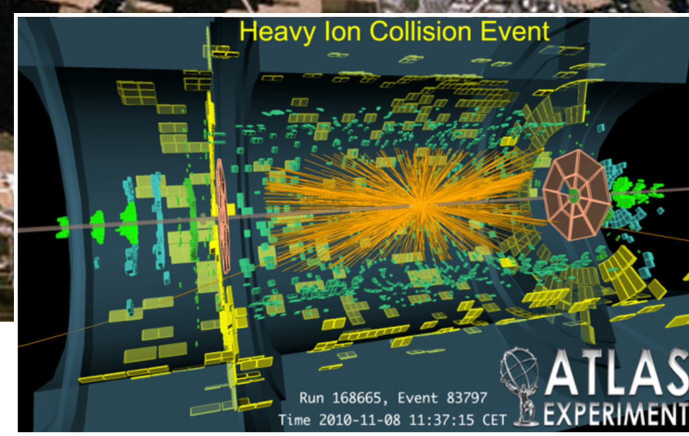
Physics in collisions, Vancouver, August 30th 2011

PbPb collisions at the LHC



- First Pb-Pb run at the LHC started on November 7th 2010
- $\sqrt{s_{NN}}$=2.76 TeV ($\approx$ 14x$\sqrt{s_{NN}}$ at RHIC)
- Delivered Integrated luminosity 10 μb^{-1}
- 3 experiments (ALICE, ATLAS, CMS)



2010 PbPb run

Beam conditions (PbPb 2010)	
√s / nucleon pair (TeV)	2.76
Peak luminosity (cm^{-2} s^{-1})	3×10^{25}
Number of colliding bunches	137
Bunch spacing (ns)	500
Ions per bunch	1.2×10^{8}

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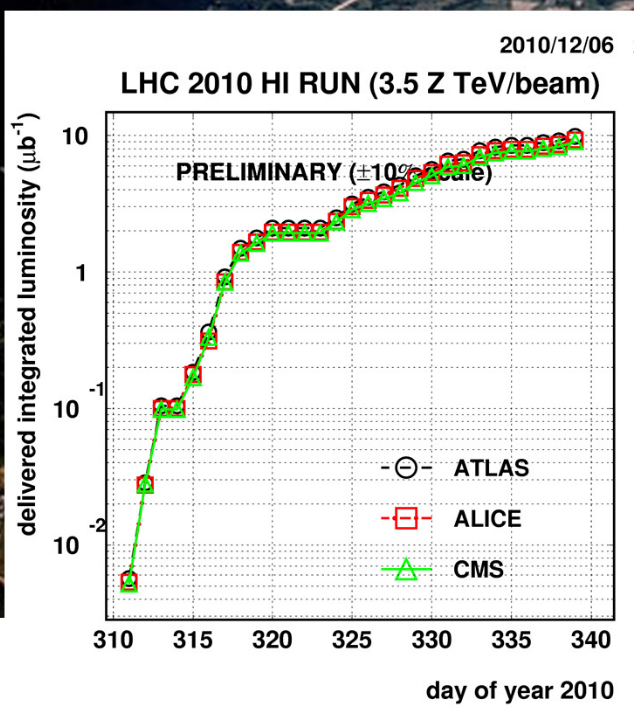
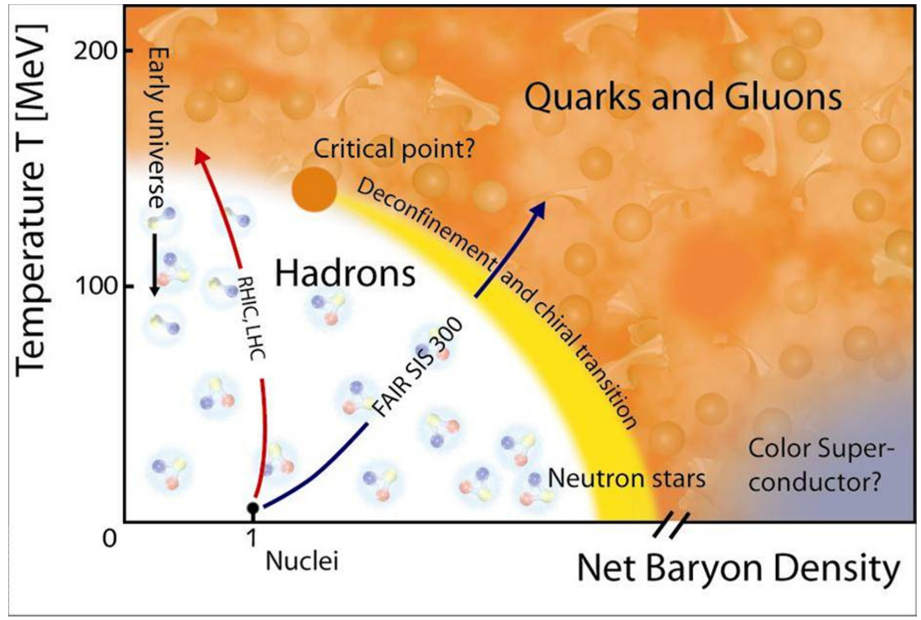
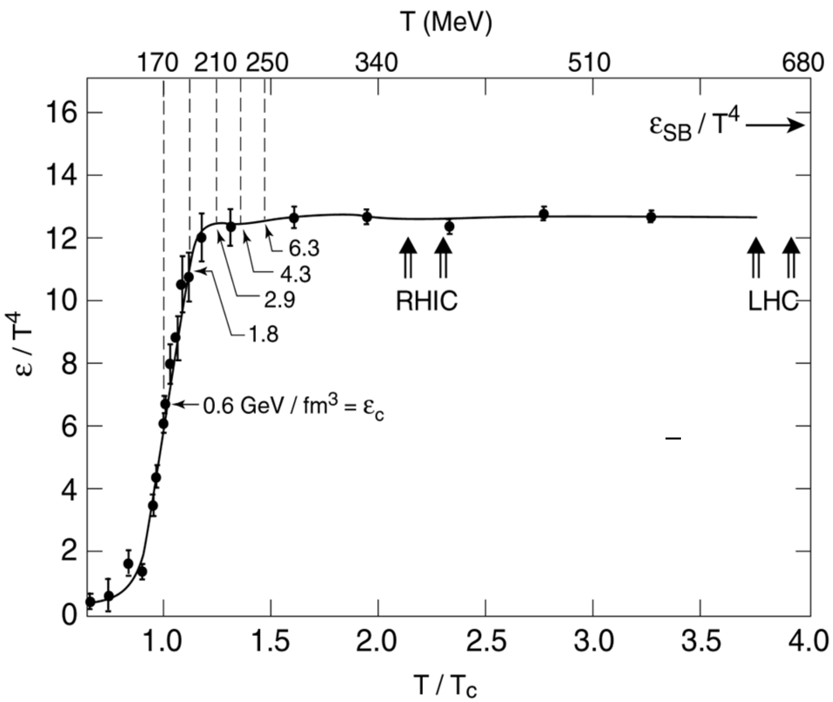


- In this talk: selection of results from the 2010 Pb-Pb run
  - ⇨ Global event properties from soft probes
    - ✓ *Particle multiplicity*
    - ✓ *Flow and Correlations*
  - ⇨ Studying the medium with hard probes
    - ✓ *High p_T hadron suppression*
    - ✓ *Heavy Flavours*
    - ✓ *Jets*
    - ✓ *Quarkonia*

Heavy Ion Collisions

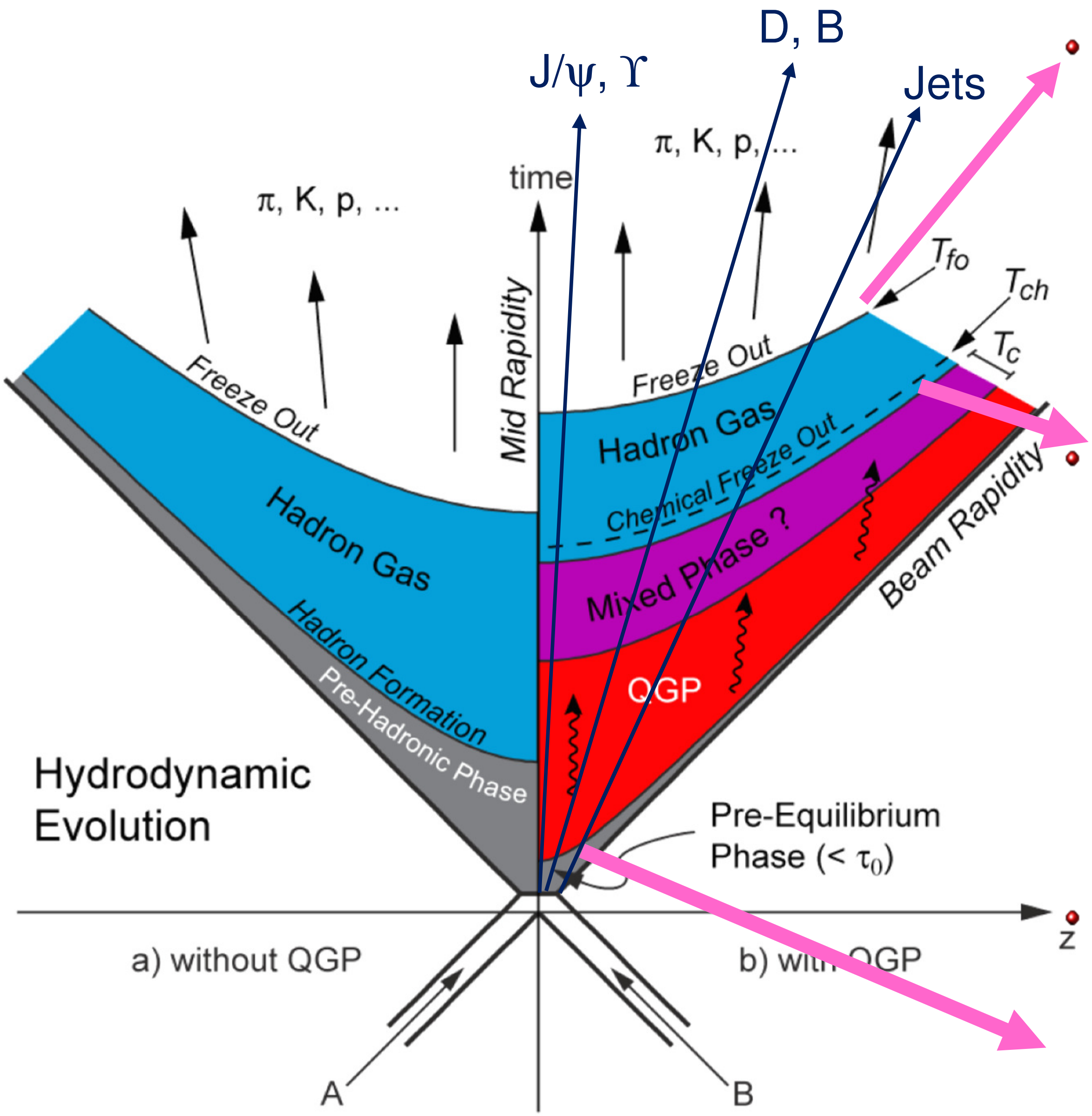
- Basic idea: compress large amount of energy in a very small volume
  - ⇨ produce a "fireball" of hot matter:
  - ⇨ temperature O(10^{12} K)
    - ✓ *~ 10^5 x T at centre of Sun*
    - ✓ *~ T of universe 10 μs after Big Bang*





- Study nuclear matter at extreme conditions of temperature and density
  - ⇨ Collect evidence for a state where quarks and gluons are deconfined (Quark Gluon Plasma) and study its properties
  - ⇨ Phase transition predicted by Lattice QCD calculations
    - ✓ $T_C \approx 170\ MeV \rightarrow \varepsilon_C \approx 0.6\ GeV/fm^3$

Space time evolution



- Thermal freeze-out
  - ⇨ Elastic interactions cease
  - ⇨ Particle dynamics ("momentum spectra") fixed

T_{fo} (RHIC) ~ 110-130 MeV

- Chemical freeze-out
  - ⇨ Inelastic interactions cease
  - ⇨ Particle abundances ("chemical composition") are fixed (except maybe resonances)

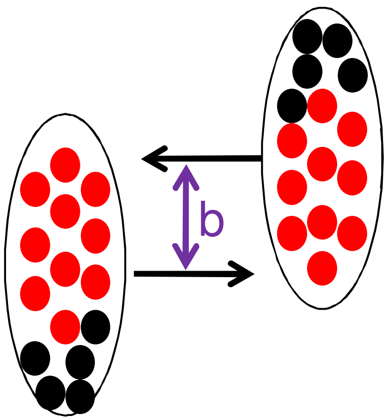
T_{ch} (RHIC) ~ 170 MeV

- Thermalization time
  - ⇨ System reaches local equilibrium

τ_{eq} (RHIC) ~ 0.6 fm/c

Geometry of the collision

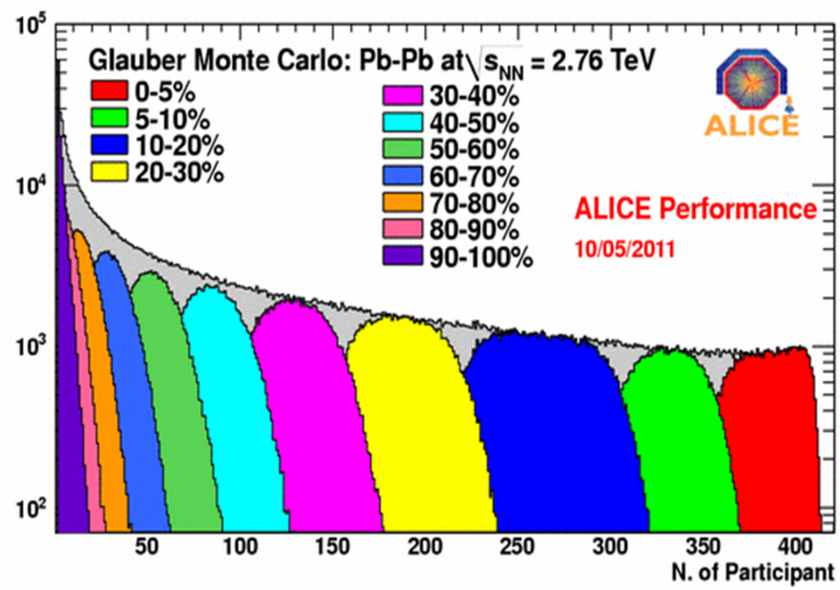
Centrality of the collision



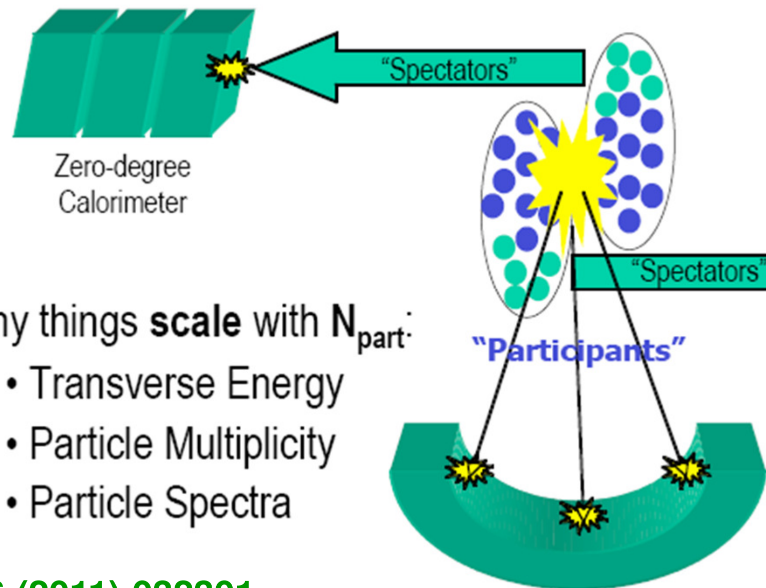
Centrality = degree of overlap of the 2 colliding nuclei

- Central collisions
  - ⇨ small impact parameter b
  - ⇨ high number of participant nucleons → high multiplicity
- Peripheral collisions
  - ⇨ large impact parameter b
  - ⇨ low number of participant nucleons → low multiplicity

- Geometrical picture of AA collisions with the Glauber model
  - ⇨ Random relative position of nuclei in transverse plane
  - ⇨ Woods-Saxon distribution of nucleons inside nucleus
  - ⇨ Straight-line nucleon trajectories
  - ⇨ N-N cross-section (σ_{NN}=64±5 mb) independent of the number of collisions the nucleons suffered before



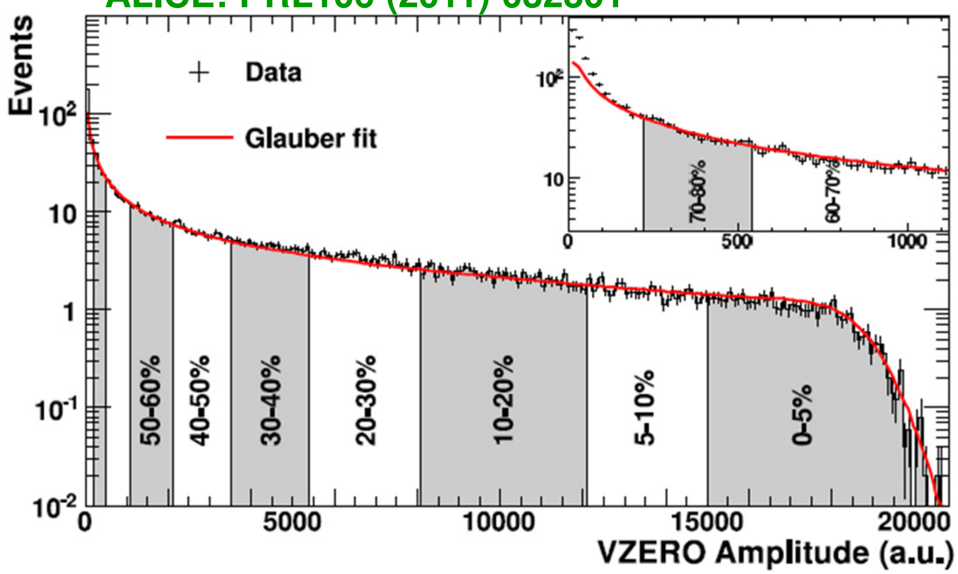
Experimentally



Many things **scale** with $\mathbf{N_{part}}$:
- Transverse Energy
- Particle Multiplicity
- Particle Spectra

$$N_{part} = A - N_{spec}$$

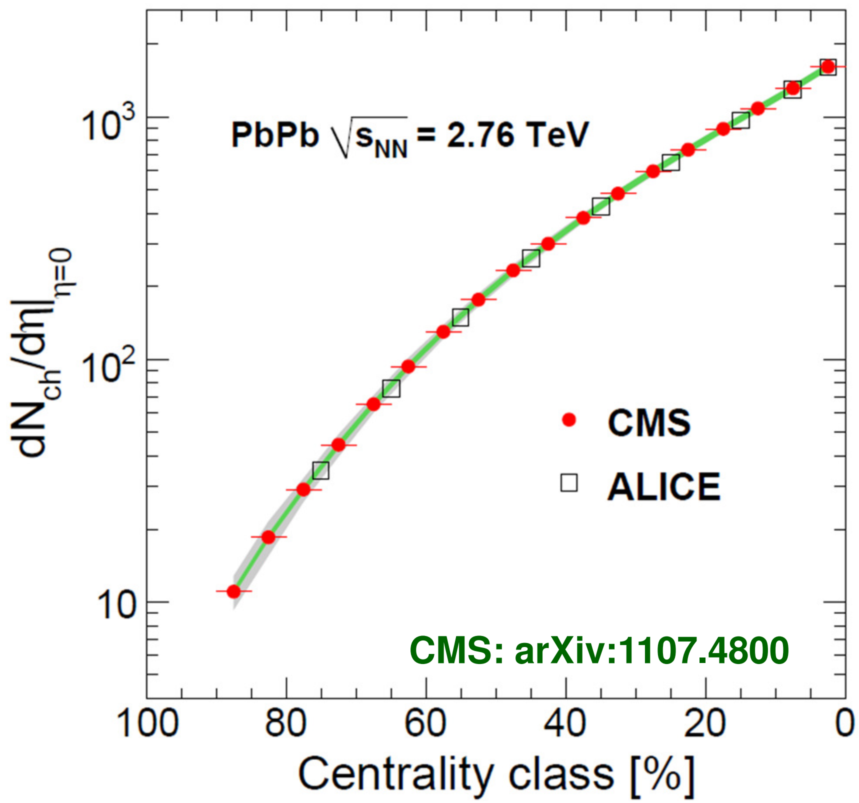
ALICE: PRL106 (2011) 032301

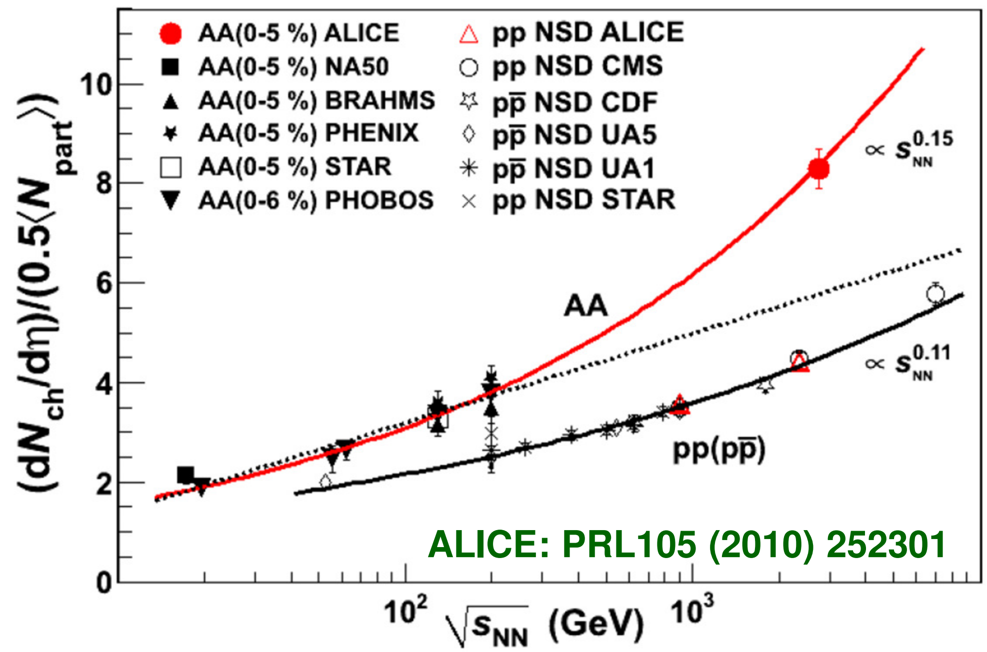


- For example: sum of the amplitudes in the ALICE V0 scintillators
  - ⇨ reproduced by Glauber model fit
  - ⇨ deviation at very low amplitude expected due to non-nuclear (electromagnetic) processes

Global event features

Charged particle multiplicity

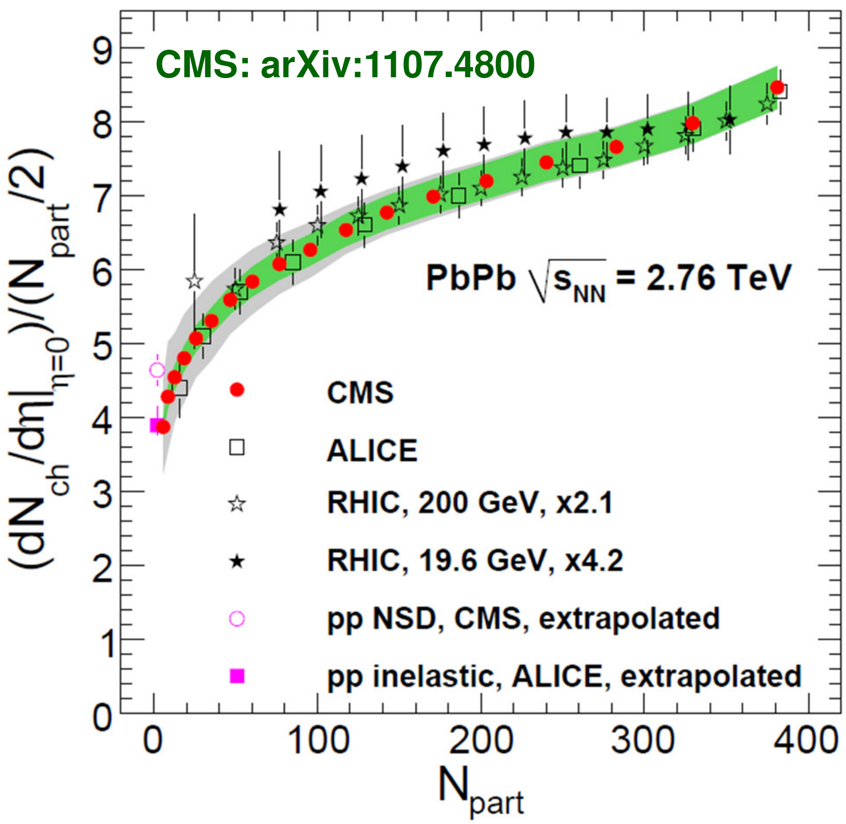




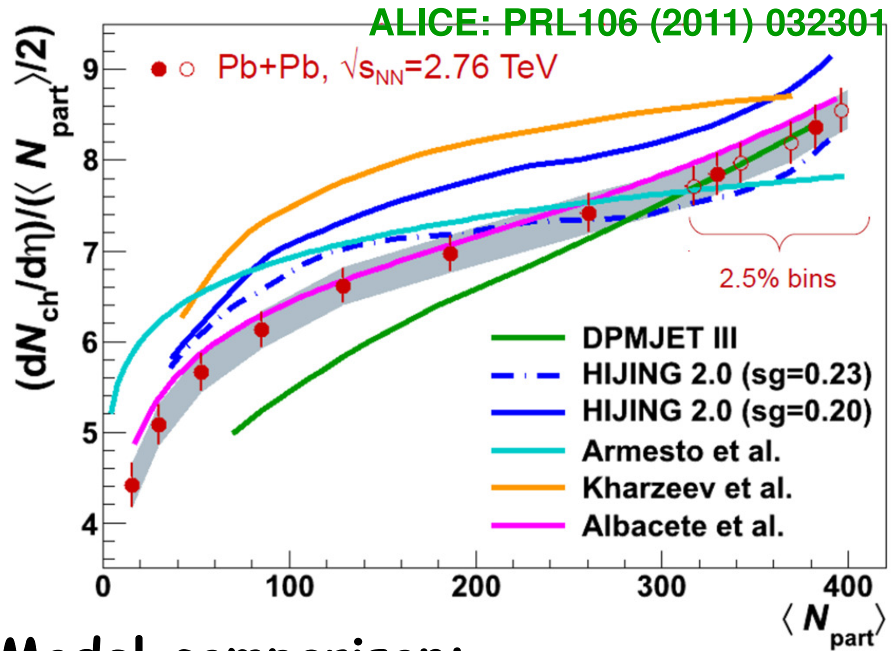
- $dN_{ch}/d\eta|_{\eta=0}$ for most central (0-5%) collisions ≈ 1600
- Measured particle densities constrain the QGP initial conditions in hydrodynamical calculations

- Log extrapolation from lower energies fails
- Stronger rise with $\sqrt{s}$ in AA w.r.t. pp
- $(dN_{ch}/d\eta)/(N_{part}/2)$
  - ≈ 2.2 x central Au+Au at $\sqrt{s_{NN}}$=0.2 TeV
  - ≈ 1 .9 x pp (NSD) at $\sqrt{s}$=2.36 TeV

dN/dη per participant pair vs. centrality



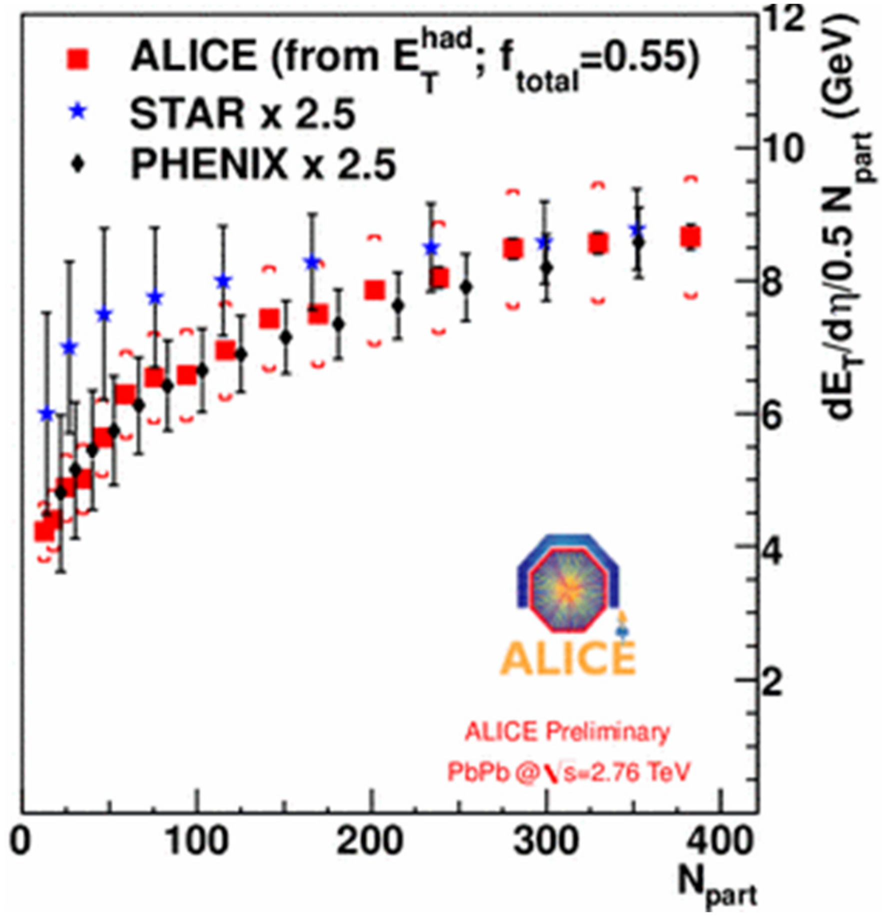
- Very similar centrality dependence at LHC & RHIC
  - ⇨ After scaling RHIC results to the multiplicity of central collisions at the LHC



Model comparison:

- Saturation models
  - ⇨ Reduction of the number of soft gluons due to nonlinear interactions and recombination
- Two-component models (= soft interactions + minijet fragmentation)
  - ⇨ HIJING 2.0 features:
    - ✓ *centrality-dependent gluon shadowing*
    - ✓ *tuned to multiplicity in 0-5%*

Energy density



- From RHIC to LHC:
  - ⇨ increase in $dE_T/d\eta$ per participant pair by a factor 2.5
  - ⇨ Similar centrality dependence
- Energy density of the medium from Bjorken formula

$$\varepsilon_{Bj} = \frac{1}{\tau \pi R^2} \frac{dE_T}{dy} \qquad R = 1.12 A^{1/3}\ fm$$

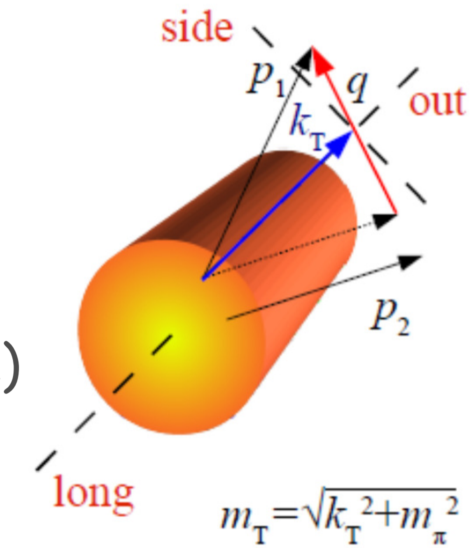
  - ⇨ Where τ = (unknown) formation time

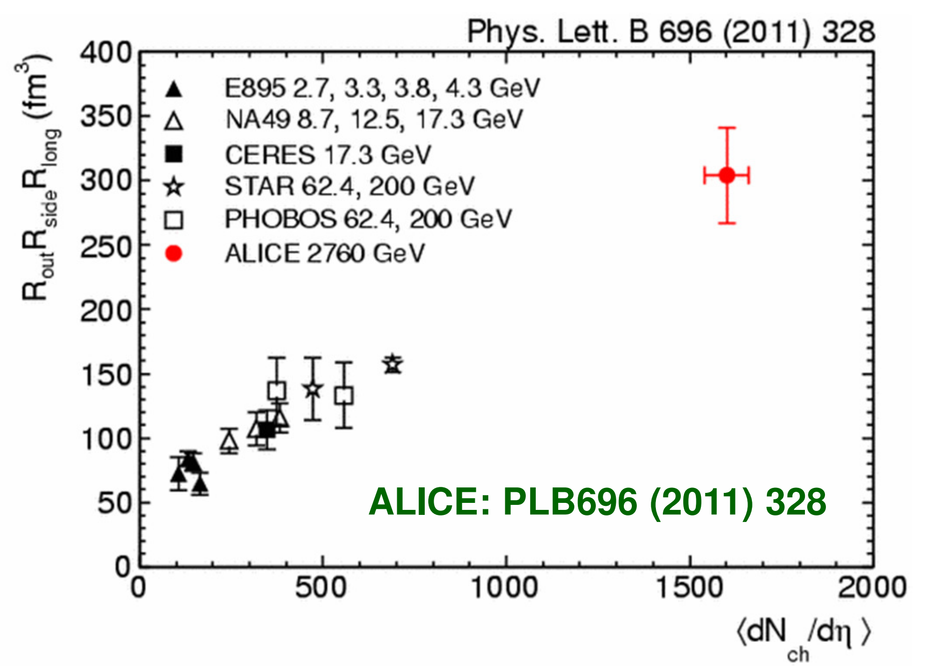
$$\varepsilon_{Bj}\tau \cong 16\ \mathrm{GeV/(fm^2c)}$$

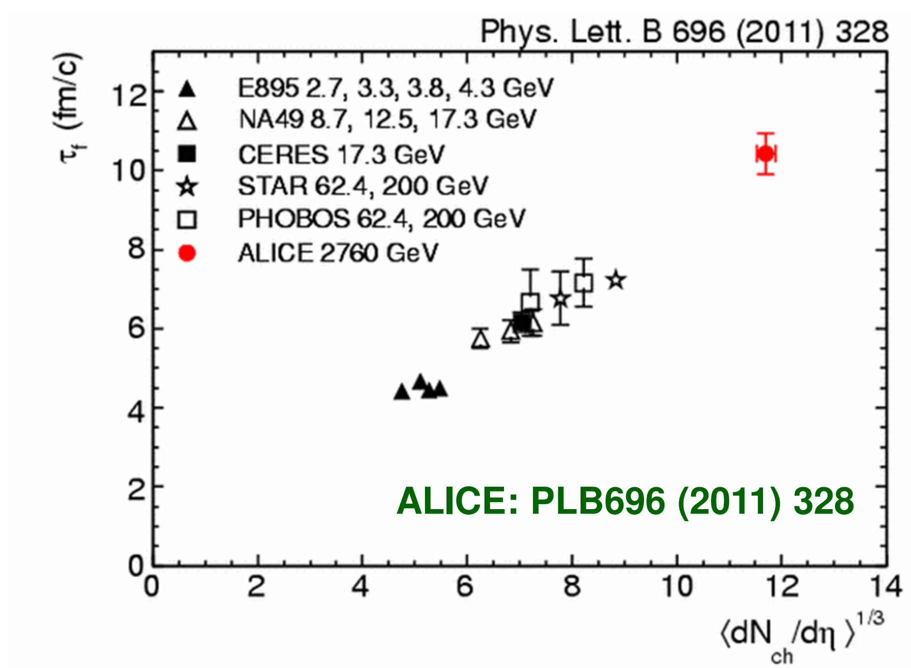
✓ *$\approx 3\times\varepsilon_{Bj}\tau$ at RHIC*

System size

- Spatial extent of the particle emitting source extracted from interferometry of identical bosons
  - ⇨ Two-particle momentum correlations in 3 orthogonal directions -> HBT radii (R_{long}, R_{side}, R_{out})
  - ⇨ Size: twice w.r.t. RHIC
  - ⇨ Lifetime: 40% higher w.r.t. RHIC



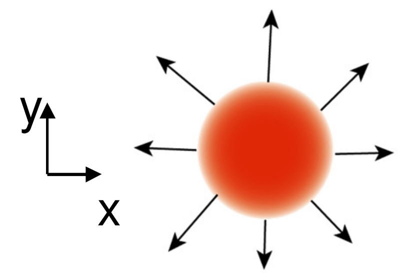




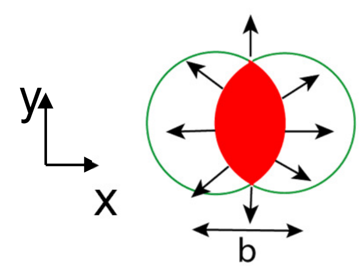
Collective expansion

Flow in heavy ion collisions

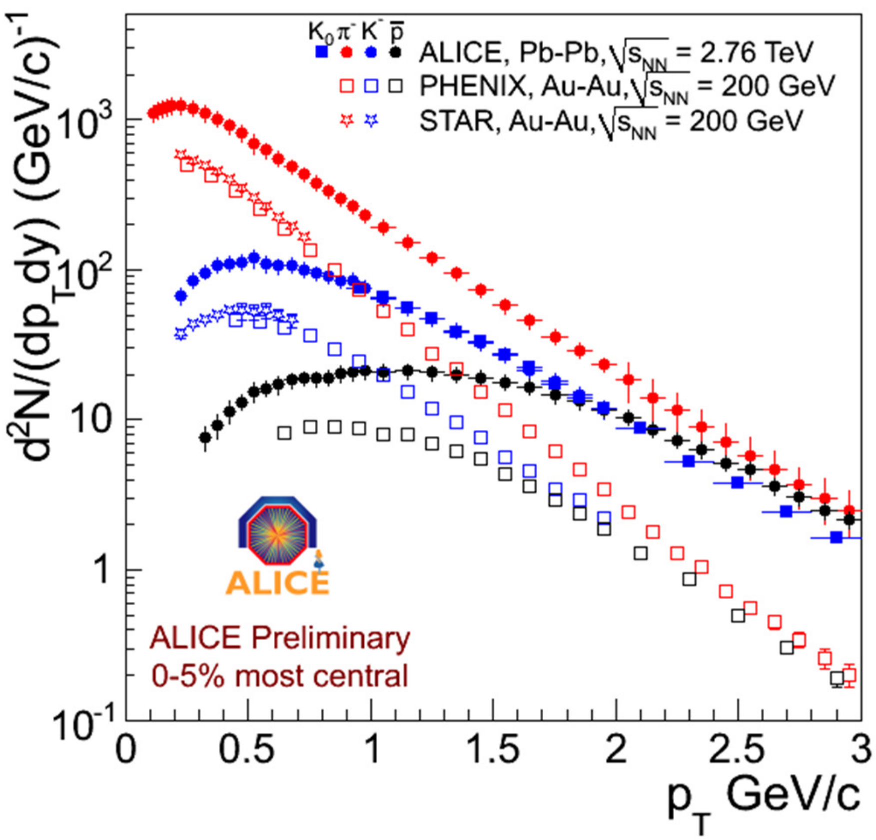
- **Flow = collective motion** of particles superimposed on top of the thermal motion
  - ⇨ Collective motion is due to high pressure arising from compressing and heating of nuclear matter.
- Radial flow = isotropic (i.e. independent of azimuthal angle φ) expansion of the fireball in the transverse plane
  - ⇨ Due to large pressures created in the fireball by matter compression
  - ⇨ Integrated over whole period of fireball evolution
  - ⇨ Experimental observables: p_T (m_T) spectra

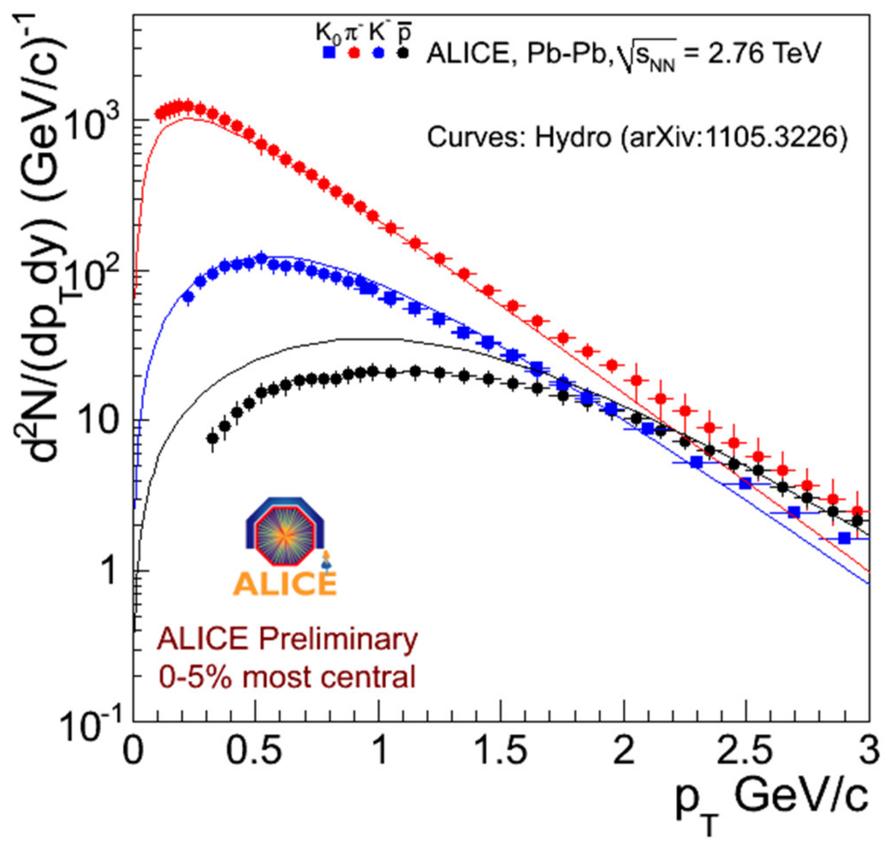


- Anisotropic transverse flow = anisotropy present in particle azimuthal distributions in collisions with impact parameter b≠0
  - ⇨ Due to pressure gradients arising from the geometrical anisotropy of the overlap region of the colliding nuclei
  - ⇨ Develop at relatively early times in the system evolution
  - ⇨ Experimental observables: particle azimuthal distributions, particle correlations



Identified particle spectra and collective radial expansion

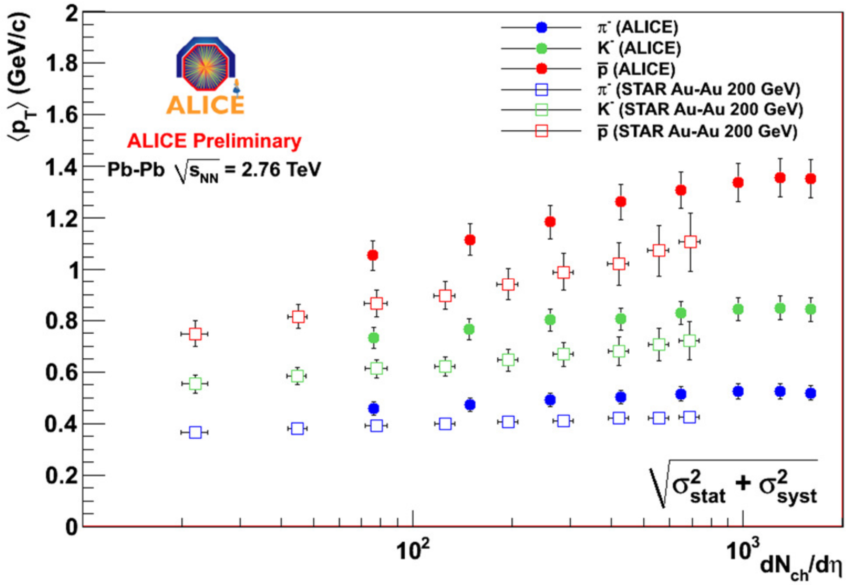


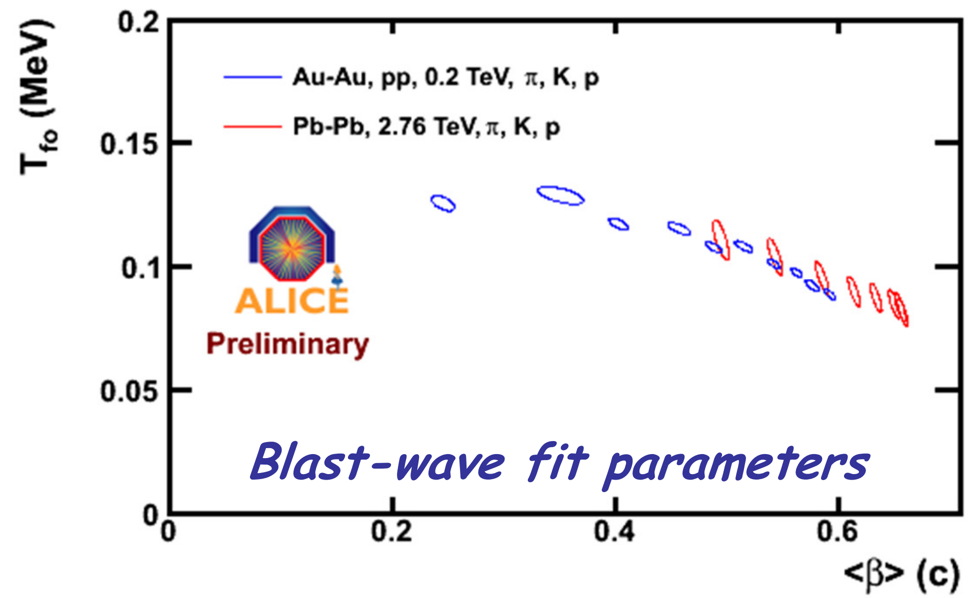


- Spectra harder than at RHIC energies
  - ⇨ Protons flatter at low p_T
- Indicate stronger radial flow

- Comparison with hydro predictions
  - ⇨ OK for pions and kaons, disagreement for (anti)protons

Identified particle spectra and collective radial expansion



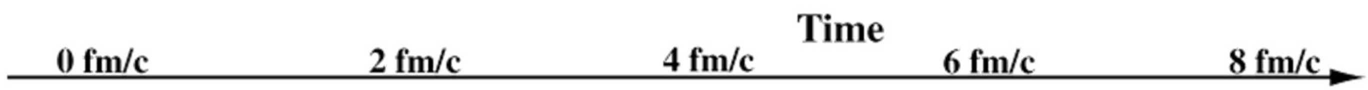


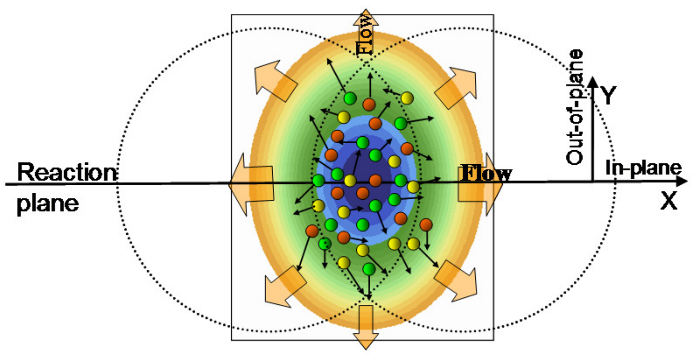
- Significant change in mean p_T between $\sqrt{s_{NN}}$=200 GeV and 2.76 TeV
  - ⇨ Harder spectra. Due to stronger flow?
- For the same dN/dη higher mean p_T than at RHIC

- Quantify the parameters of the system at the thermal freeze-out with a common blast-wave fit to π, K and p
  - ⇨ T_{fo} = thermal freeze-out temperature
  - ⇨ <β> = mean radial flow velocity
- Strong radial flow (β≈ 0.66)
  - ⇨ Larger w.r.t. hydro predictions

Anisotropic transverse flow

- In heavy ion collisions with b≠0 the impact parameter selects a preferred direction in the transverse plane
- Re-scatterings among produced particles convert the initial geometrical anisotropy into an observable momentum anisotropy
  - ⇨ Large mean free path
    - ✓ ***Particles stream out isotropically, no memory of the initial eccentricity***
  - ⇨ Small mean free path:
    - ✓ ***Larger density gradient "in plane" -> larger pressure gradient "in plane"***

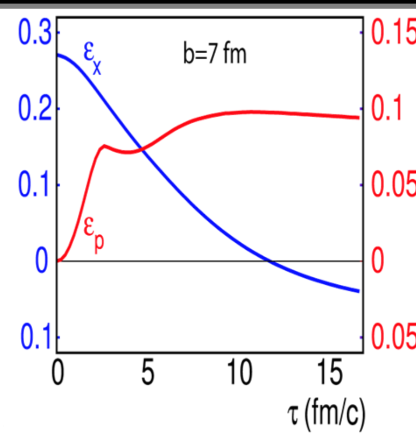


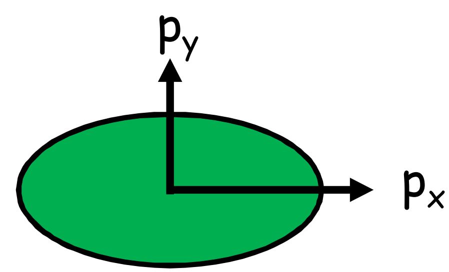


Initial geometrical anisotropy

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

Re-scatterings among produced particles (hydrodynamics)





Observable momentum anisotropy of final state particles

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

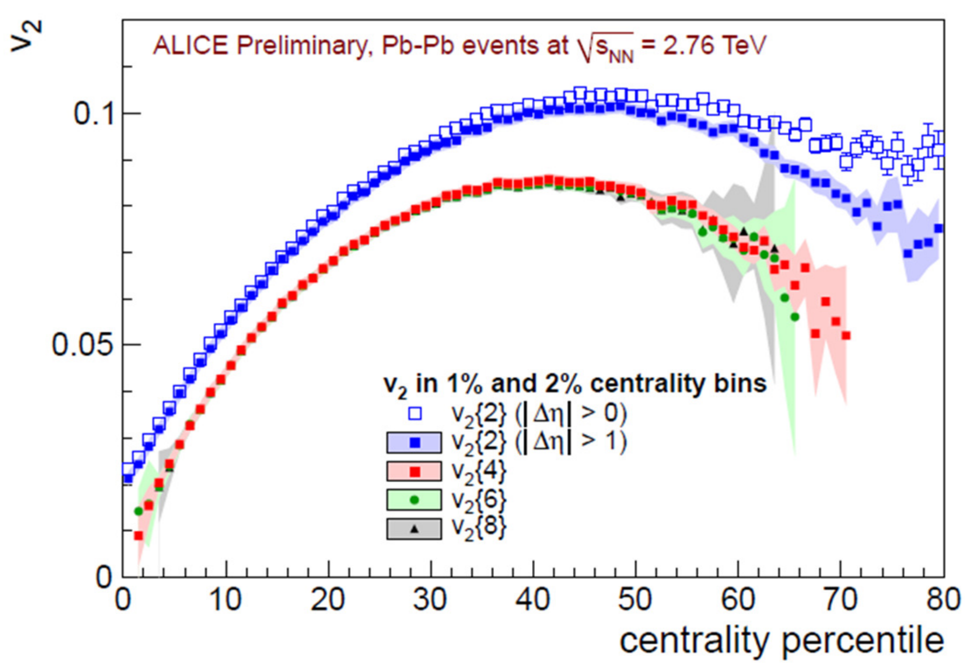
Elliptic flow

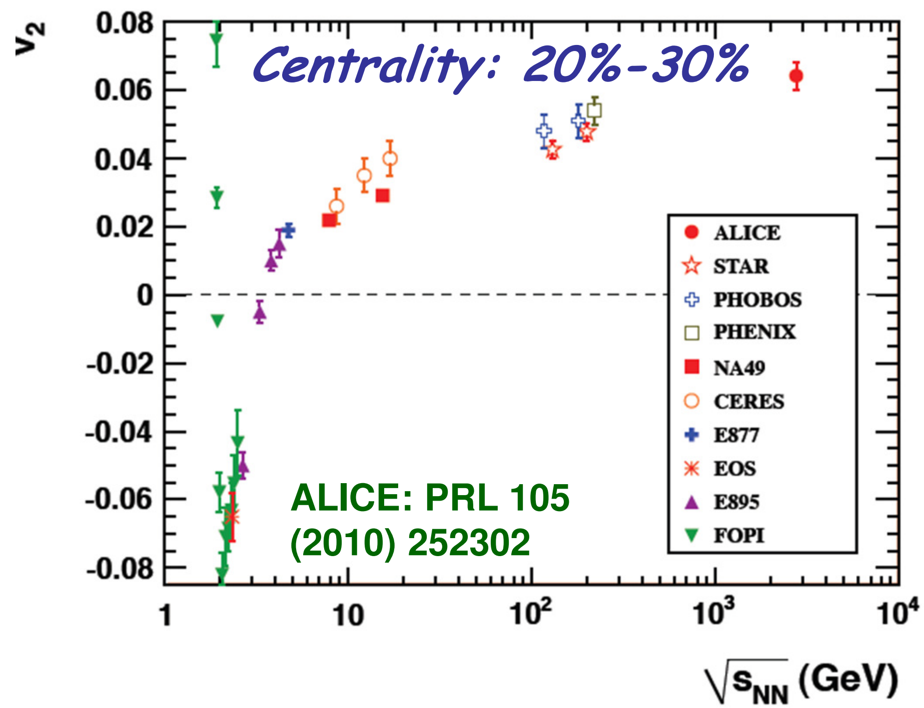
- Elliptic flow (v_2) = 2nd harmonic coefficient in the Fourier decomposition of particle azimuthal distributions w.r.t. the reaction plane (RP)

$$\frac{dN}{d(\varphi-\psi_{RP})} \propto 1+2\sum_{n=1} v_n \cos(n[\varphi-\psi_{RP}])$$

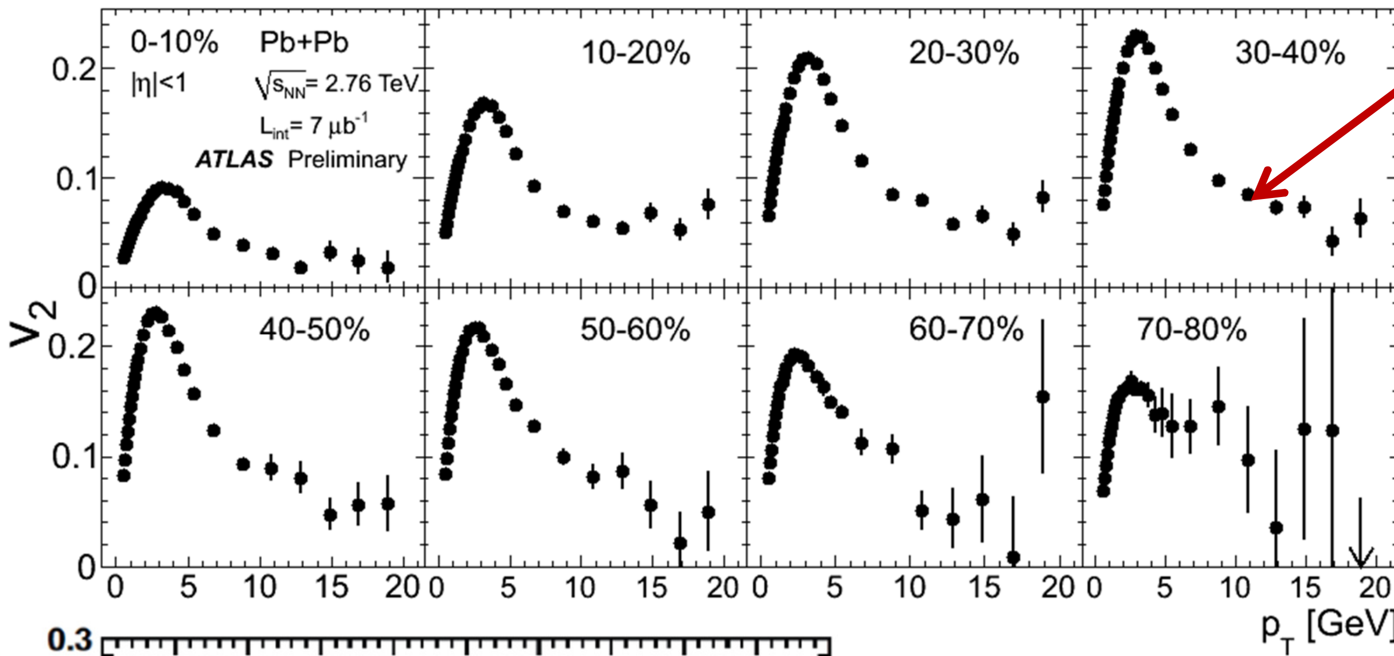
$$v_2 = \langle \cos[2(\varphi-\Psi_{RP})] \rangle$$

- Large elliptic flow observed at RHIC
  - ⇨ Consistent with strongly coupled medium with low shear viscosity (ideal fluid)
- At LHC, integrated v_2 increases by 30% w.r.t RHIC data at $\sqrt{s_{NN}}$=200 GeV



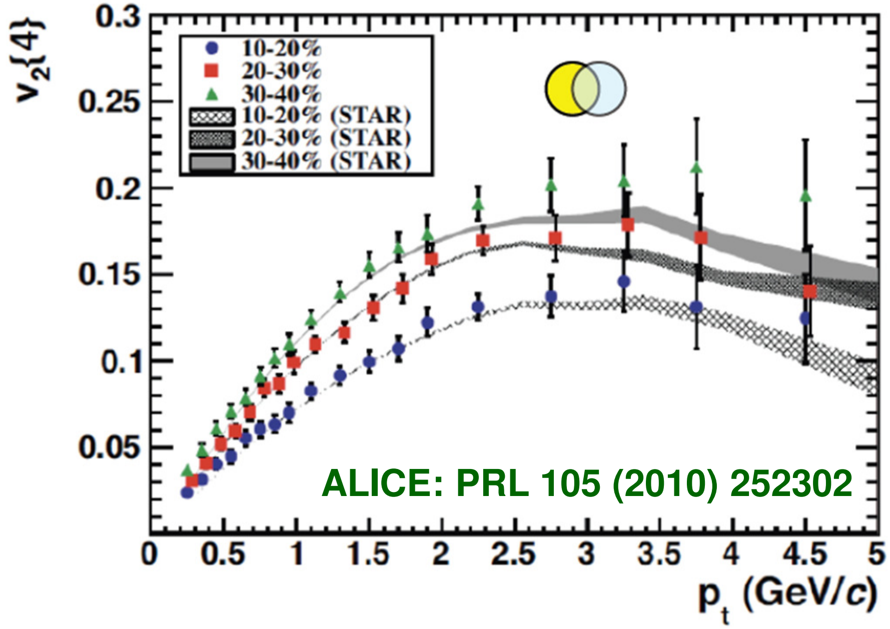


p_t differential elliptic flow



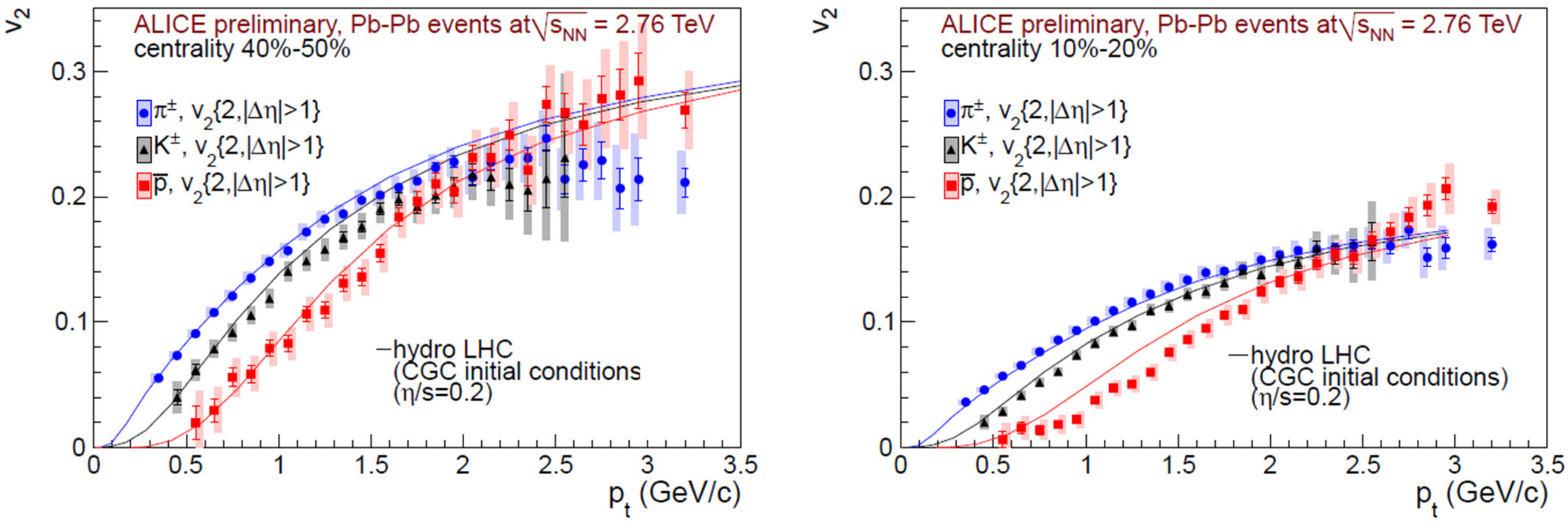
Significant values of v2 for p_T>8 GeV/c

- Due to path length dependence of parton energy loss
- More on this in the following



- v_2 vs. p_T does not change within uncertainties between $\sqrt{s_{NN}}$=200 GeV and 2.76 TeV
  - 30% increase of p_T integrated flow explained by higher mean p_T due to stronger radial flow at higher energies

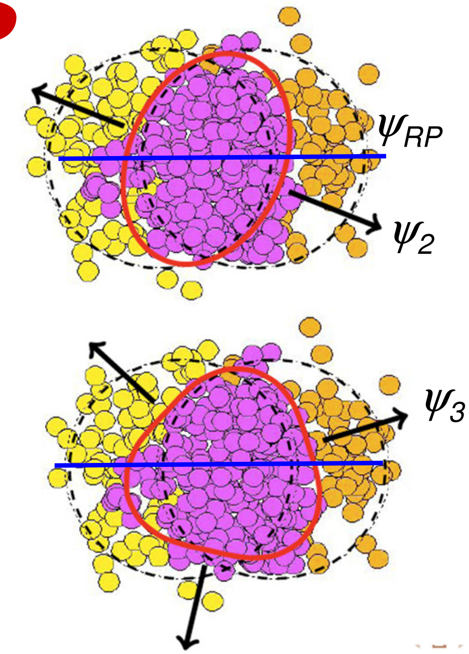
Identified particle v_2

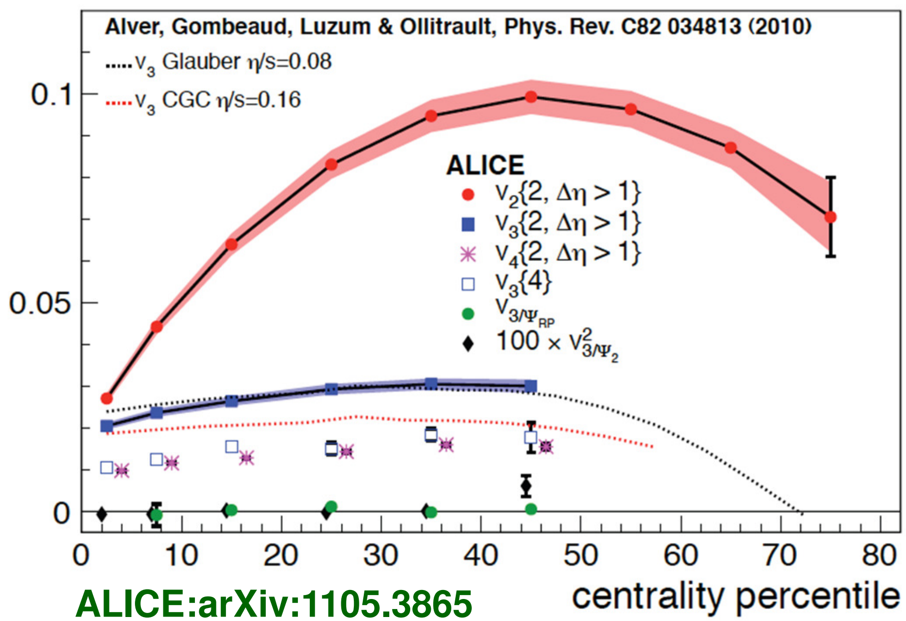


- Stronger radial flow at LHC energy -> more pronounced mass dependence of elliptic flow
  - ⇨ Hydrodynamics predictions describe well the measured $v_2(p_T)$ for π and K for semiperipheral (40%-50%) and semi-central (10%-20%) collisions
  - ⇨ Mismatch for anti-protons in the more central bin
    - ✓ ***Due to larger radial flow in the data than in the Hydro model?***
    - ✓ ***Rescatterings in the hadronic phase?***

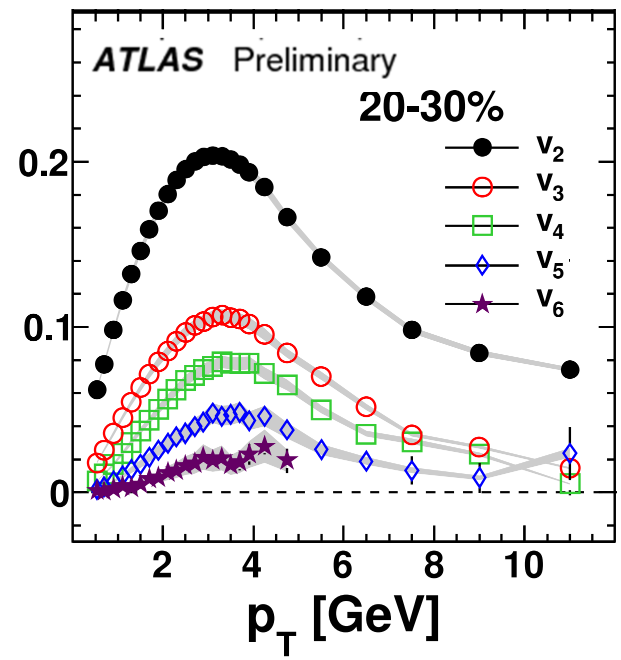
Higher harmonics

- Fluctuations in the initial nucleon distribution
  - ⇨ Event-by-event fluctuation of the symmetry plane Ψ_n w.r.t. Ψ_{RP}
- Odd harmonics are not null
- In particular, v_3 ("triangular") harmonic appears
  - ⇨ v_3 has weaker centrality dependence than v_2
  - ⇨ When calculated w.r.t. participant plane, v_3 vanishes (as expected, if due to fluctuations)
- Similar p_T dependence for all harmonics





ALICE:arXiv:1105.3865

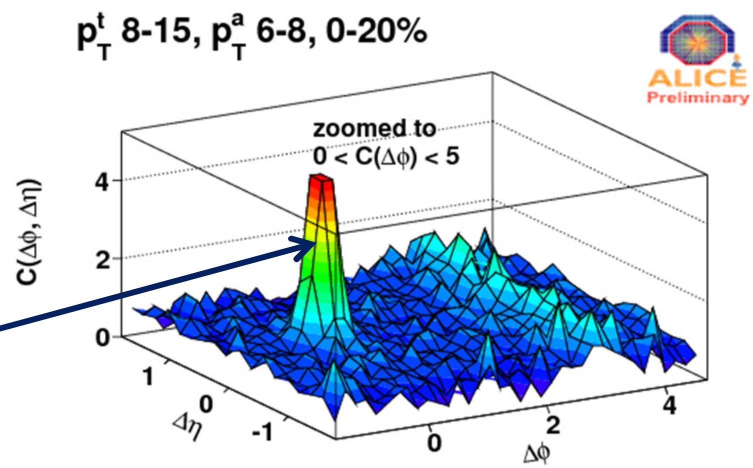


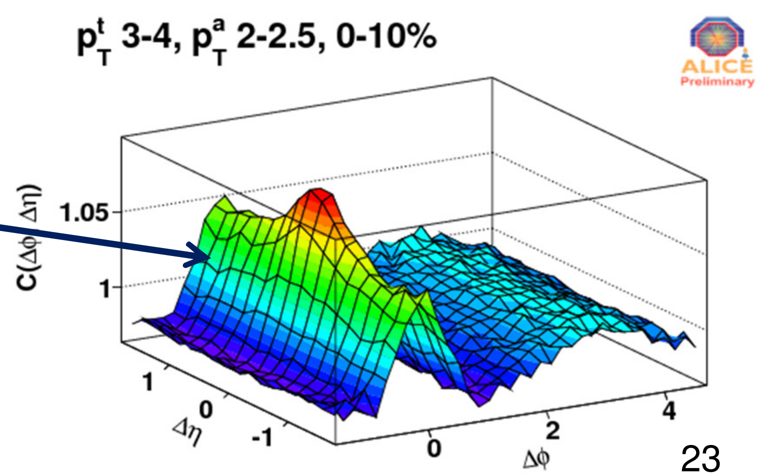
Di-hadron correlations

- Choose a particle from one p_T region ("trigger particle") and correlate with particles from another p_T region ("associated particles")
  - ⇨ Where $p_{T,assoc} < p_{T,trig}$
  - ⇨ Done in bins of $p_{T,trig}$ and $p_{T,assoc}$

$$C(\Delta\eta,\Delta\varphi) = \frac{N^{pairs}_{mixed}}{N^{pairs}_{same}} \frac{\left(d^2 N_{assoc} / d\Delta\varphi\, d\Delta\eta\right)_{same}}{\left(d^2 N_{assoc} / d\Delta\varphi\, d\Delta\eta\right)_{mixed}}$$

- Higher p_T
  - ⇨ Near-side jet dominates
  - ⇨ Quenching/suppression and broadening of the away side jet
- Lower p_T
  - ⇨ Near-side ridge
    - ✓ *First observed at RHIC*
    - ✓ *Observed also by CMS in high multiplicity pp collisions at $\sqrt{s}$=7 TeV*
  - ⇨ Broad away-side
  - ⇨ Dominated by hydrodynamics and flow



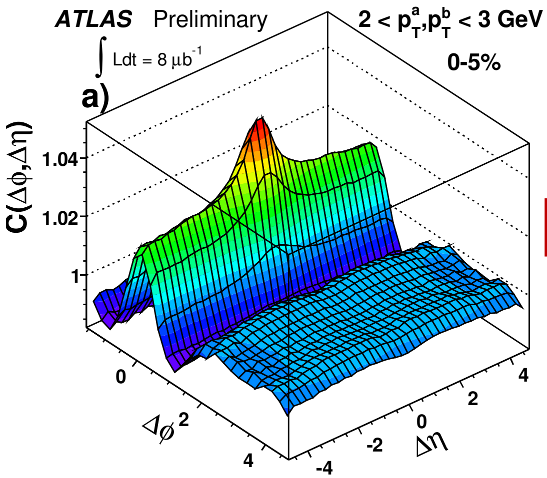


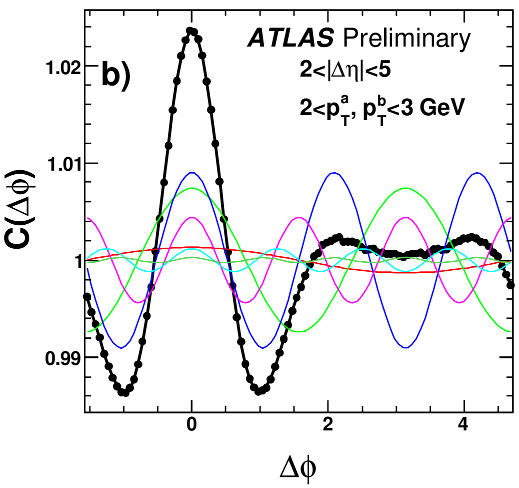
Fourier analysis

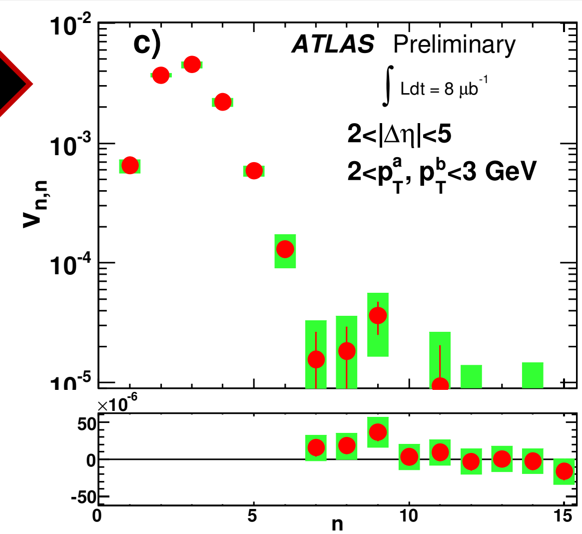
- Extract 1D Δφ correlations by integrating the C(Δη,Δφ) in a given Δη range and do a Fourier decomposition

$$C(\Delta\varphi) = \frac{1}{\Delta\eta_{\max} - \Delta\eta_{\min}} \int_{\Delta\eta_{\min}}^{\Delta\eta_{\max}} C(\Delta\eta,\Delta\varphi) \propto 1 + 2\sum_{n=1} v_{n,n}\cos(n\Delta\varphi)$$

$$v_{n,n} = \langle \cos(n\Delta\varphi) \rangle = \frac{\int C(\Delta\varphi)\cos(n\Delta\varphi)d(\Delta\varphi)}{\int C(\Delta\varphi)d(\Delta\varphi)}$$







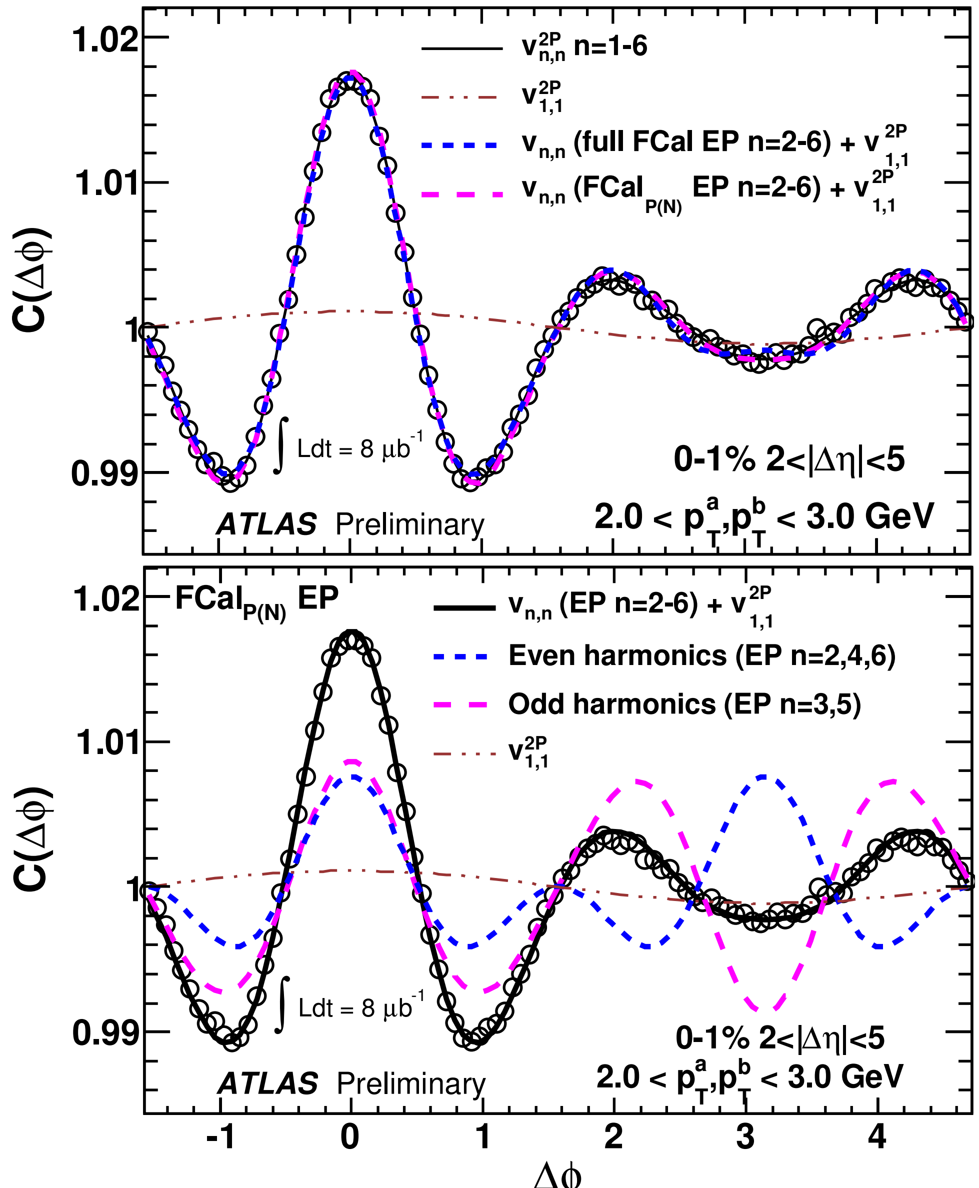
- 5 components describe completely the correlations at large Δη and low p_T
  - ⇨ Strong near-side ridge + double-peaked structure on away side

Due to collective flow?

- If the observed di-hadron correlation comes from the single particle azimuthal anisotropy due to the collective flow, the $v_{n,n}$ extracted from $C(\Delta\varphi)$ should be related with the flow coefficients v_n:

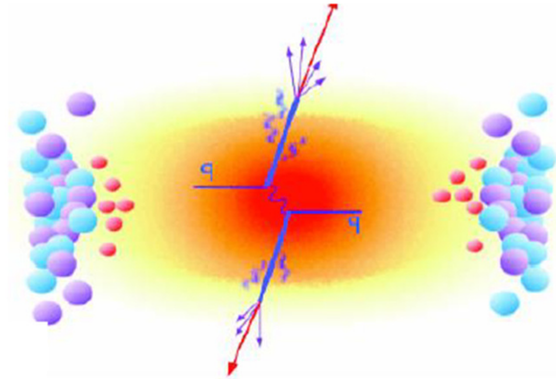
$$v_{n,n} = \langle \cos(n\Delta\varphi)\rangle = \langle \cos[n(\varphi_{trig} - \varphi_{assoc})]\rangle$$
$$= \langle \cos[n(\varphi_{trig} - \Psi_n)]\rangle \langle \cos[n(\varphi_{assoc} - \Psi_n)]\rangle =$$
$$= v_n(p_t^{trig}) \cdot v_n(p_t^{assoc})$$

  - ⇨ The two-particle correlation is due to the correlation with a common plane of symmetry
- Good description of $C(\Delta\varphi)$ for central collisions at low p_T with the single particle v_n
  - ⇨ Does not hold at high p_T where away-side jet dominates



Studying the medium with hard probes

Hard probes



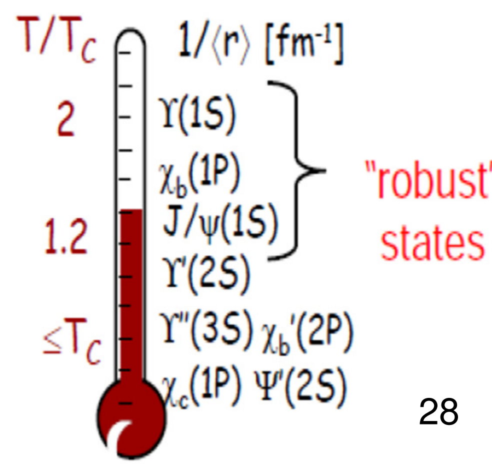
- Hard probes in nucleus-nucleus collisions:
  - ⇨ Produced at the very early stage of the collisions
  - ⇨ pQCD can be used to calculate initial cross sections
  - ⇨ Traverse the hot and dense medium
  - ⇨ Can be used to probe the properties of the medium
- Hard probes production in AA expected to scale with the number of nucleon-nucleon collisions N_{coll} (**binary scaling**)
- Observable: **nuclear modification factor** $$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$
- If no nuclear effects are present -> R_{AA}=1
- Effects from the hot and deconfined medium created in the collision -> breakup of binary scaling -> $R_{AA}\neq 1$
  - ⇨ **Parton energy loss** via gluon radiation and collisions in the medium
  - ⇨ **Quarkonia melting** in the QGP
- But also cold nuclear matter effects (e.g. shadowing, Cronin enhancement) give rise to $R_{AA}\neq 1$
  - ⇨ Need control experiments: medium blind probes (photons, Z) + pA collisions

Quarkonium suppression

- Quark-Gluon Plasma "signature" proposed in the 80's
  - ⇨ In the QGP, quarkonia with radius > Debye screening length are expected to melt due to colour screening of the $q\bar{q}$ potential.
  - ⇨ Quarkonia should melt above a given temperature, depending on their binding energy -> sequential suppression pattern

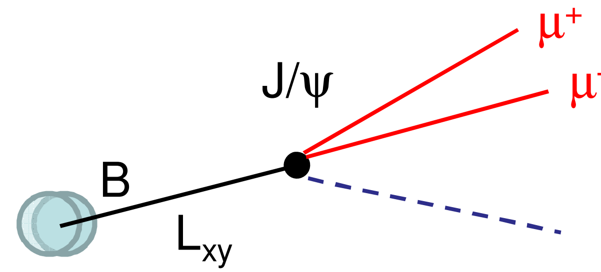
state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	>4.0	1.76	1.60	1.19	1.17

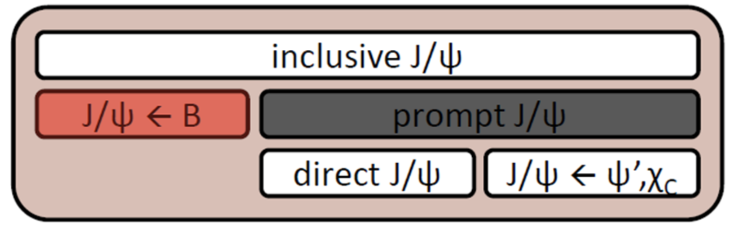
- Melting sequence of quarkonia as QGP thermometer
- But also:
  - ⇨ Feed-down from higher quarkonium states
    - ✓ *And (for charmonia) also from B-meson decays*
  - ⇨ Cold nuclear matter effects (also in pA)
    - ✓ *Shadowing, nuclear absorption (mainly at low $\sqrt{s}$)*
  - ⇨ J/Ψ's from $c\bar{c}$ recombination at hadronization
    - ✓ *Negligible at SPS, could be dominant at LHC*

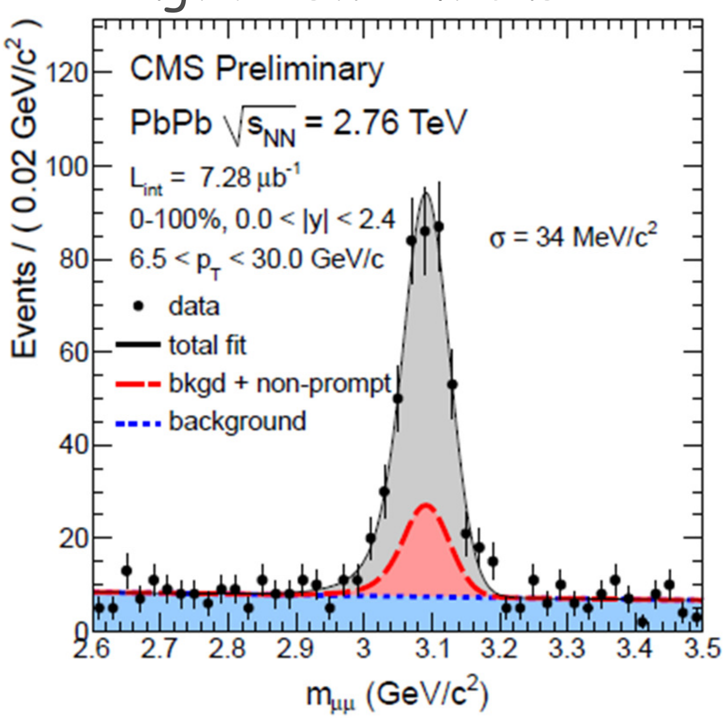


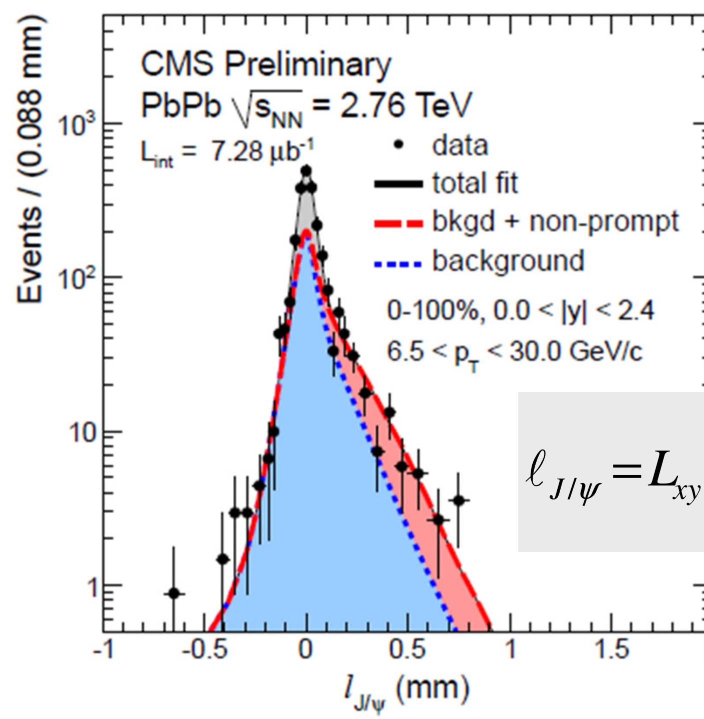
J/ψ from B feed-down

- At LHC B->J/ψ becomes significant
  - ⇨ up to 30% at p_T~15 GeV/c
  - ⇨ Long B-meson lifetime -> secondary J/ψ's from B feed-down feature decay vertices displaced from the primary collision vertex
  - ⇨ Fraction of non-prompt J/ψ from simultaneous fit to $\mu^+\mu^-$ invariant mass spectrum and pseudo-proper decay length distributions



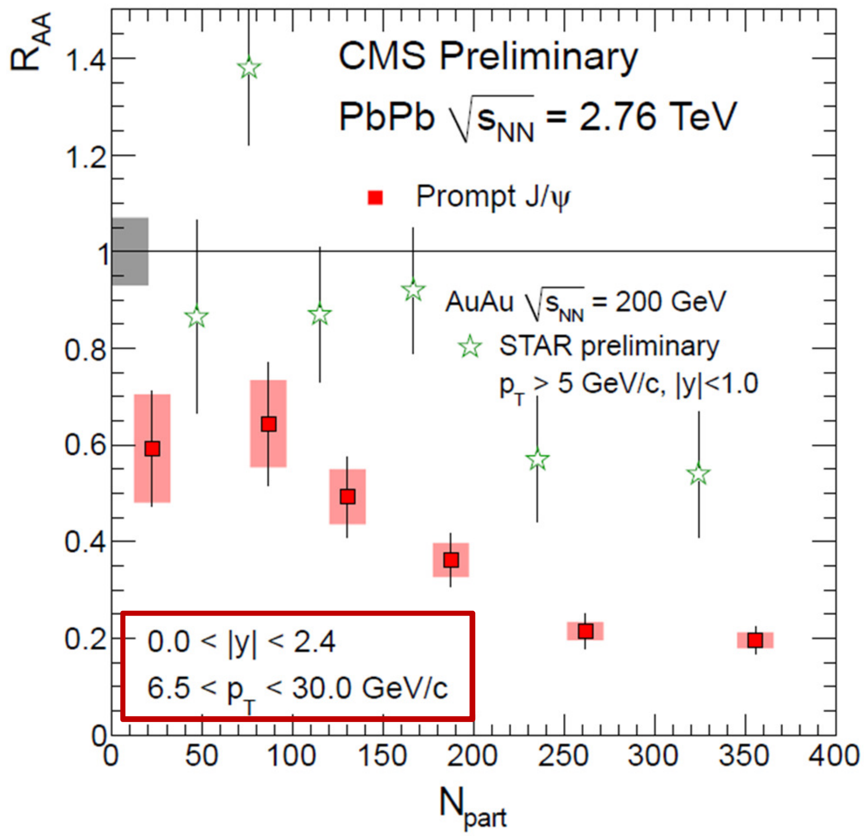




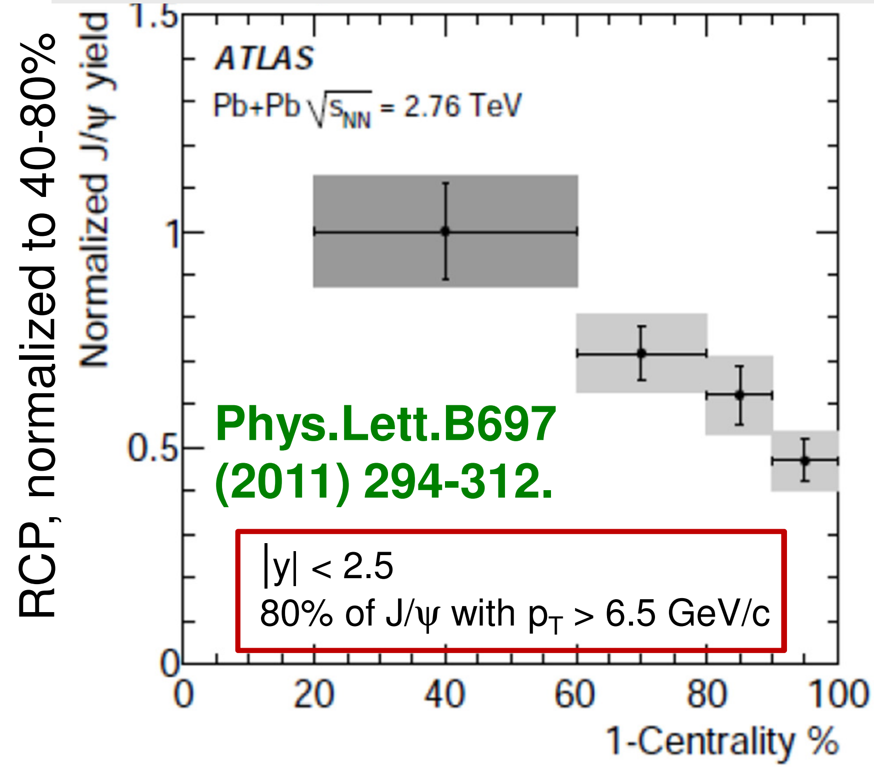


$$\ell_{J/\psi} = L_{xy}(J/\psi) \cdot \frac{M_{J/\psi}}{p_T(J/\psi)}$$

J/ψ at central rapidity, high p_T

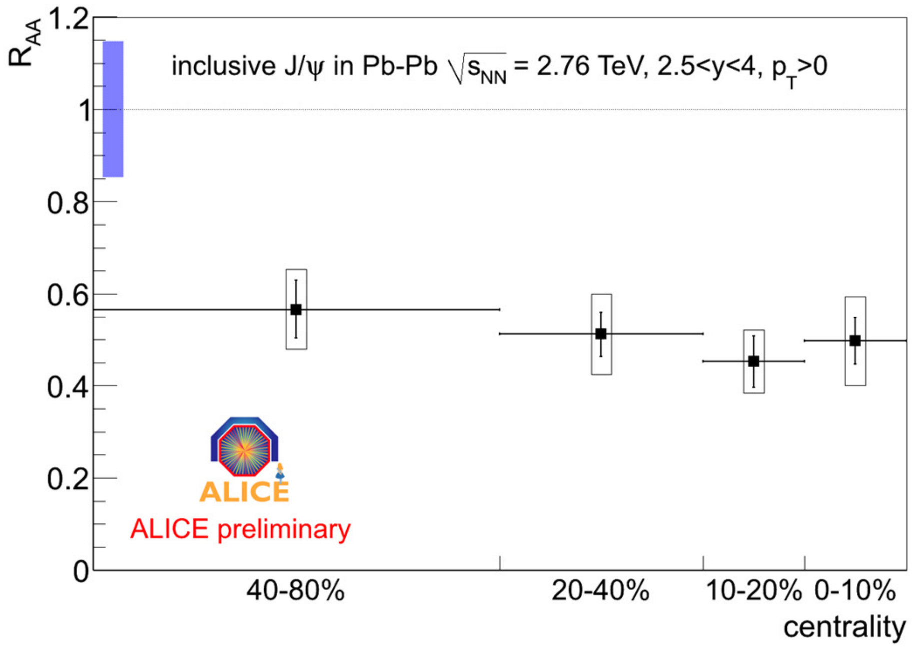


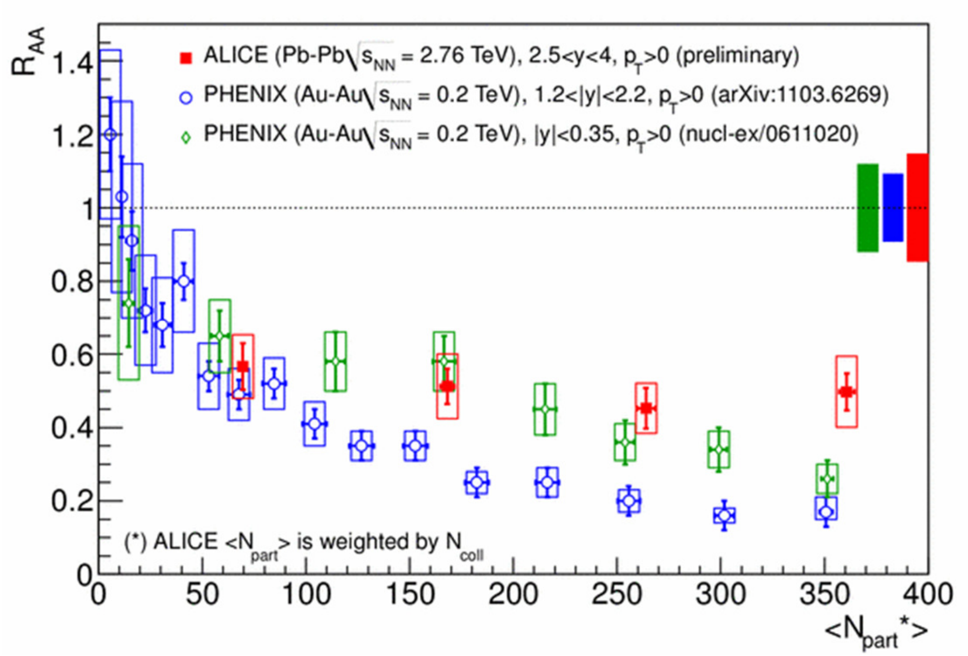
$$R_{CP}(p_T) = \frac{\langle N_{coll} \rangle^{Peripheral}}{\langle N_{coll} \rangle^{Central}} \frac{(dN_{AA} / dp_T)^{Central}}{(dN_{pp} / dp_T)^{Peripheral}}$$



- J/ψ are suppressed (R_{AA}<1)
- J/ψ yield normalized to N_{coll} significantly decreases from peripheral to central collisions
- More suppression at LHC than at RHIC: R_{AA}(CMS) < R_{AA}(STAR)
  - ⇨ Result from STAR is for inclusive J/ψ

J/ψ at forward rapidity, low p_T





- J/ψ are suppressed (R_{AA}<1)
- J/ψ R_{AA} almost independent of centrality
- Less suppression at LHC than at RHIC at forward rapidity:
  - ⇨ R_{AA}(ALICE) > R_{AA}(PHENIX, 1.2<y<2.2)
- Same suppression at LHC than at RHIC at midrapidity
  - ⇨ R_{AA}(ALICE) ≈ R_{AA}(PHENIX, |y|<0.35)
- Contribution from B feed-down not subtracted
- Cold nuclear matter effects different at RHIC and LHC
  - ⇨ Need for p-A collisions at LHC

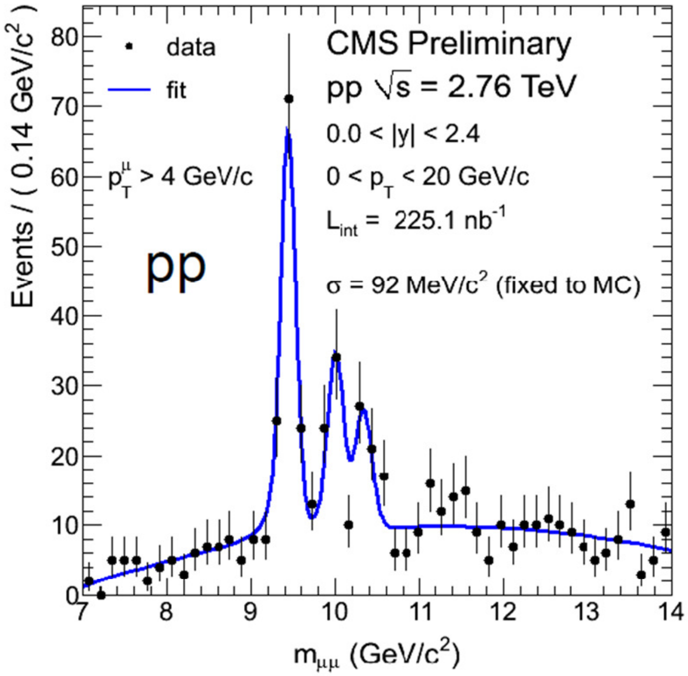
Suppression of Υ states

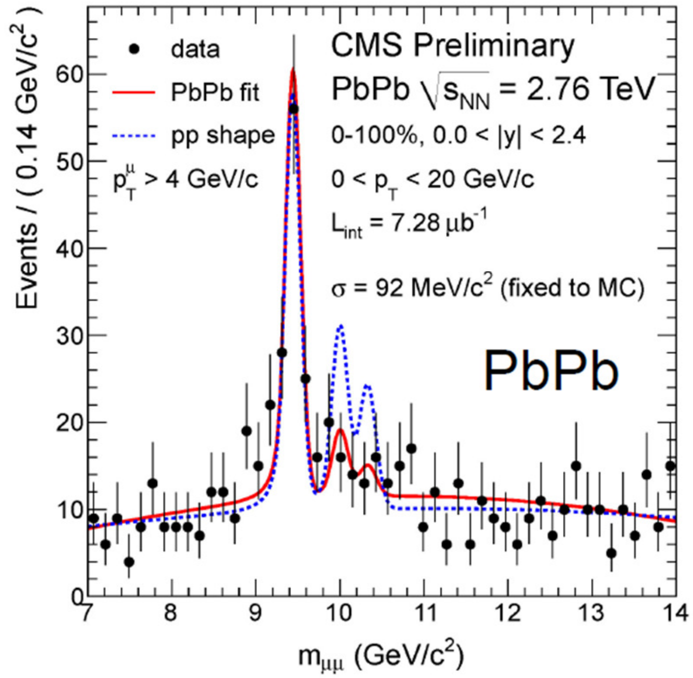
- $\Upsilon(1S)$ suppressed: $\boxed{R_{AA} = 0.62 \pm 0.11 \pm 0.10 \text{ (min.bias)}}$

CMS-PAS-HIN-10-006

- Excited states $\Upsilon(2S,3S)$ suppressed relative to $\Upsilon(1S)$

CMS: PRL 107 (2011) 052302





$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$$

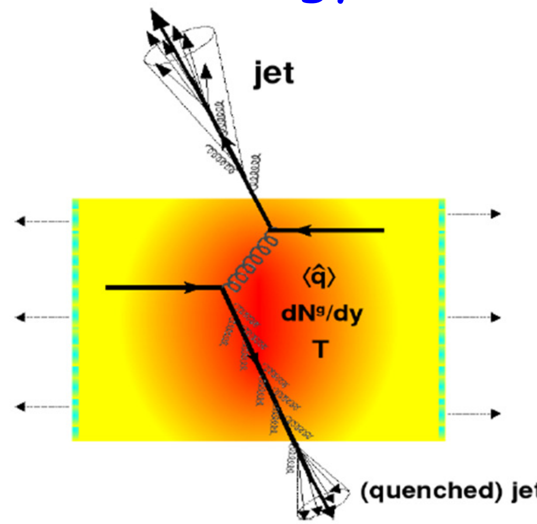
$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

$$\boxed{\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03}$$

⇨ Less than 1% probability of finding the measured value (0.31) for the double ratio if the real value is 1

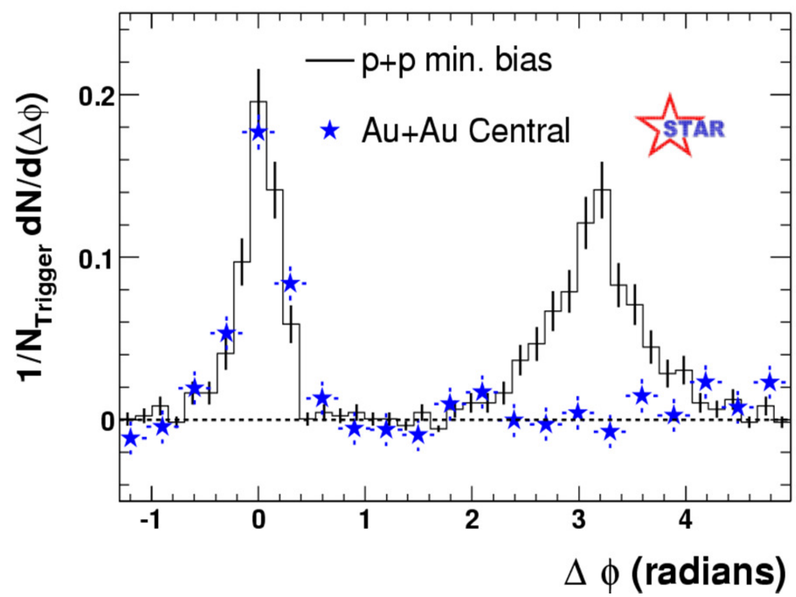
Parton energy loss

- A parton passing through the QCD medium suffers energy loss
  - ⇨ **Collisional** energy loss through elastic scatterings with the medium constituents
  - ⇨ **Radiative** energy loss through inelastic scatterings



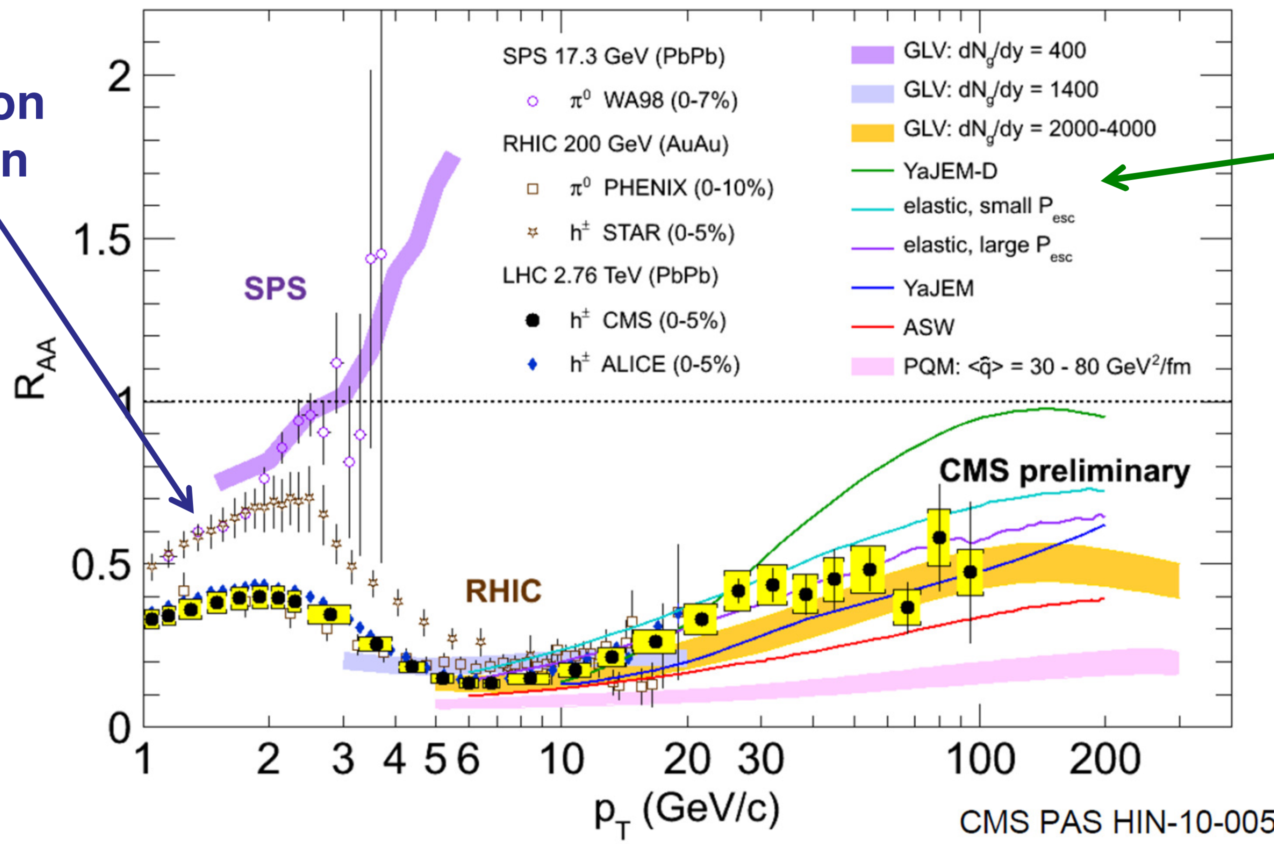
- The energy lost by a parton in the medium (ΔE) depends on:
  - ⇨ Properties of the medium (density, temperature, mean free path) and of the parton (Casimir factor, mass)
  - ⇨ Length of medium crossed by the parton

- Observed at RHIC:
  - ⇨ Suppression of high p_T hadron yields (R_{AA}<1)
  - ⇨ Suppression of the recoiling jet in di-hadron angular correlations



Charged hadron R_{AA}

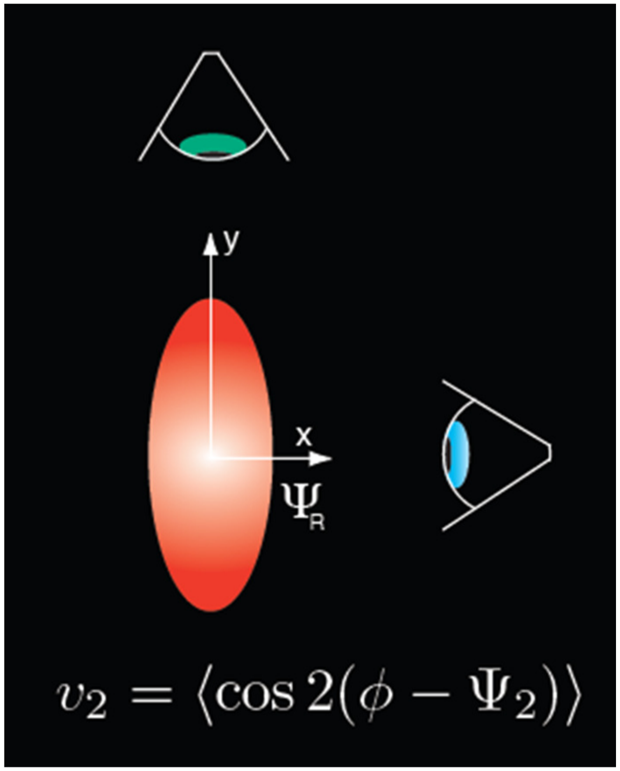
Stronger suppression at LHC than at RHIC

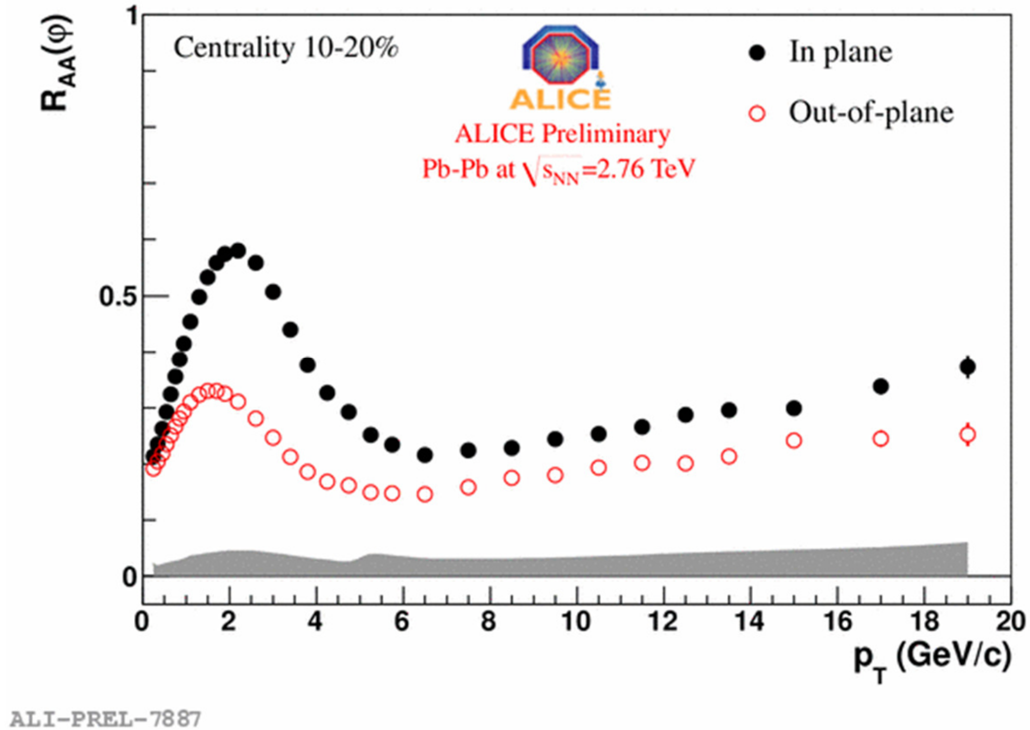


Essential quantitative constraint for parton energy loss models!

- $R_{AA}(p_T)$ for charged particles in 0-5% centrality range
  - ⇨ Minimum (~ 0.14) for p_T ~ 6-7 GeV/c
  - ⇨ Slow increase in the region p_T>10 GeV/c
  - ⇨ Still significant suppression at p_T ~ 100 GeV/c

Suppression vs. event plane

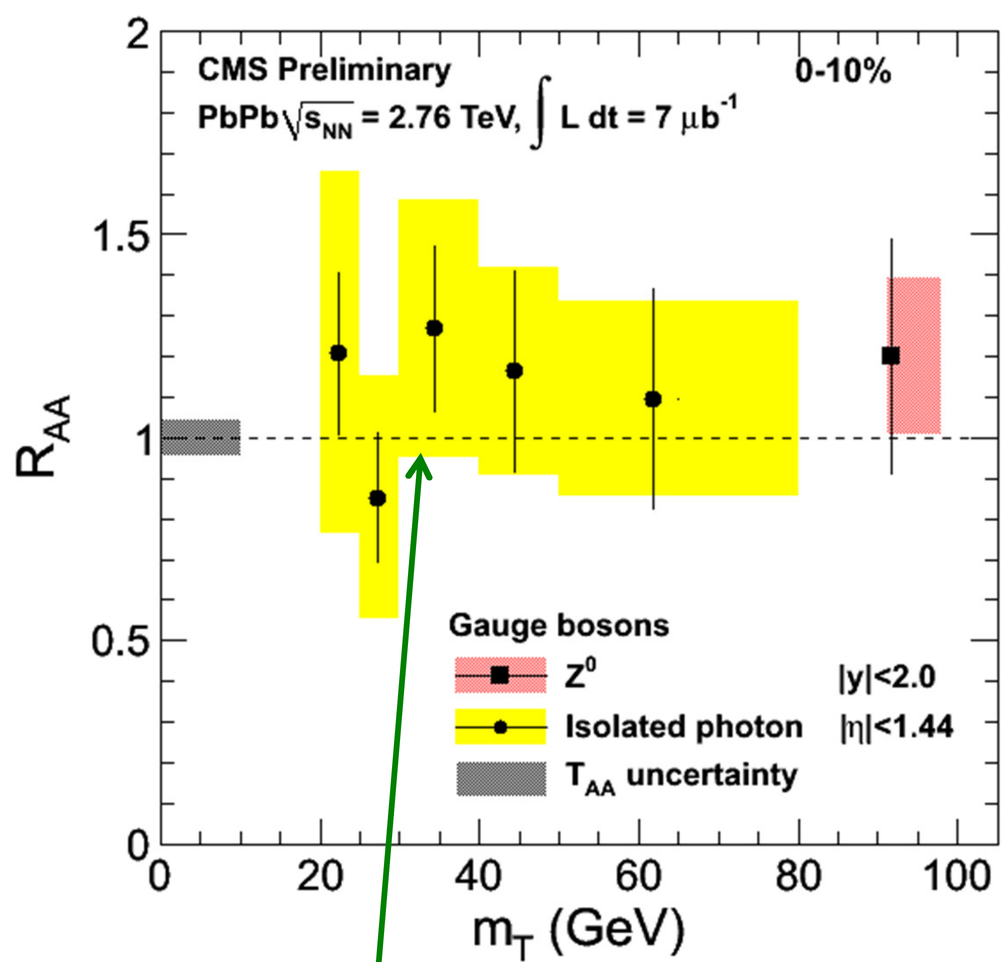




- More suppression for hadrons exiting out-of-plane (longer path length in the medium)
  - ⇨ Significant effect, even at 20 GeV/c
- Provide further constraints to energy loss models
  - ⇨ Path-length dependence of energy loss (L^2, L^3, …)

Colorless probes

- Colorless probes: photons and Z bosons
  - ⇨ No suppression expected (R_{AA}=1) since they do not interact strongly with the medium
  - ⇨ Test for initial state effects (nuclear pdf)
- Direct photons from hard scatterings
  - ⇨ Measured from isolated electromagnetic clusters + cut on transverse shower shape
    - ✓ *To remove background from decay and fragmentation photons*
- $Z \to \mu^+\mu^-$

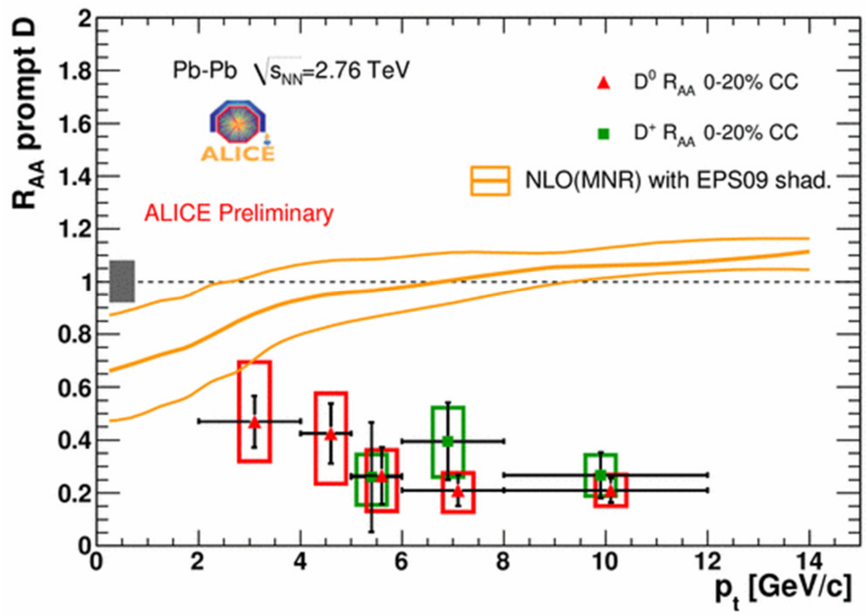


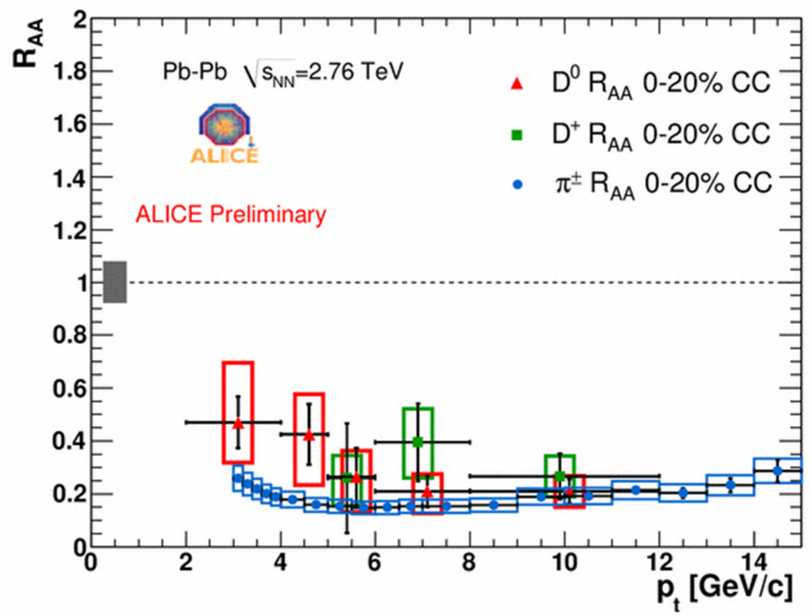
Confirmation of binary scaling for pQCD probes.
No nuclear modifications seen.

Open charm quenching

- Study parton mass and colour charge dependence of interaction with medium
  - ⇨ Expectation from radiative energy loss models:

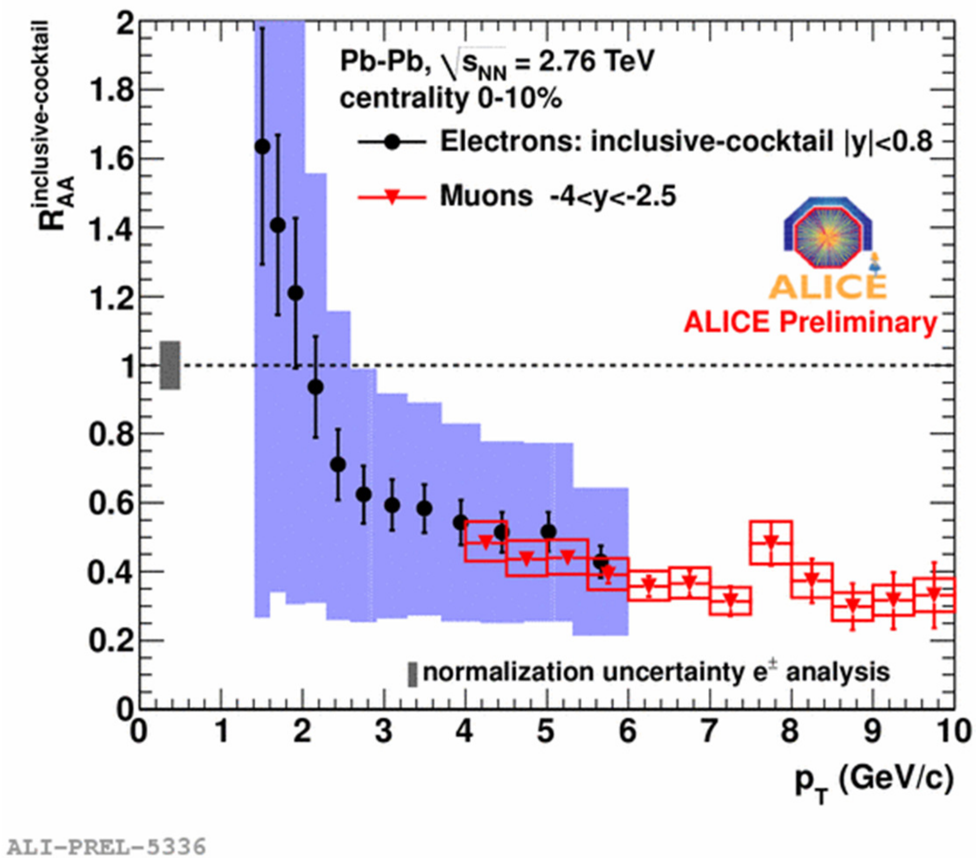
$$\begin{array}{c} \Delta E_{quark} < \Delta E_{gluon} \\ \Delta E_{massive\ quark} < \Delta E_{light\ quark} \end{array} \Rightarrow R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$$





- Suppression for prompt D mesons is a factor 4-5 for p_T>5 GeV/c
  - ⇨ Little shadowing at high p_T → suppression is a hot matter effect
  - ⇨ Similar suppression for D mesons and pions
  - ⇨ Maybe a hint of $R_{AA}^D > R_{AA}^\pi$ at low p_T

Heavy flavour leptons



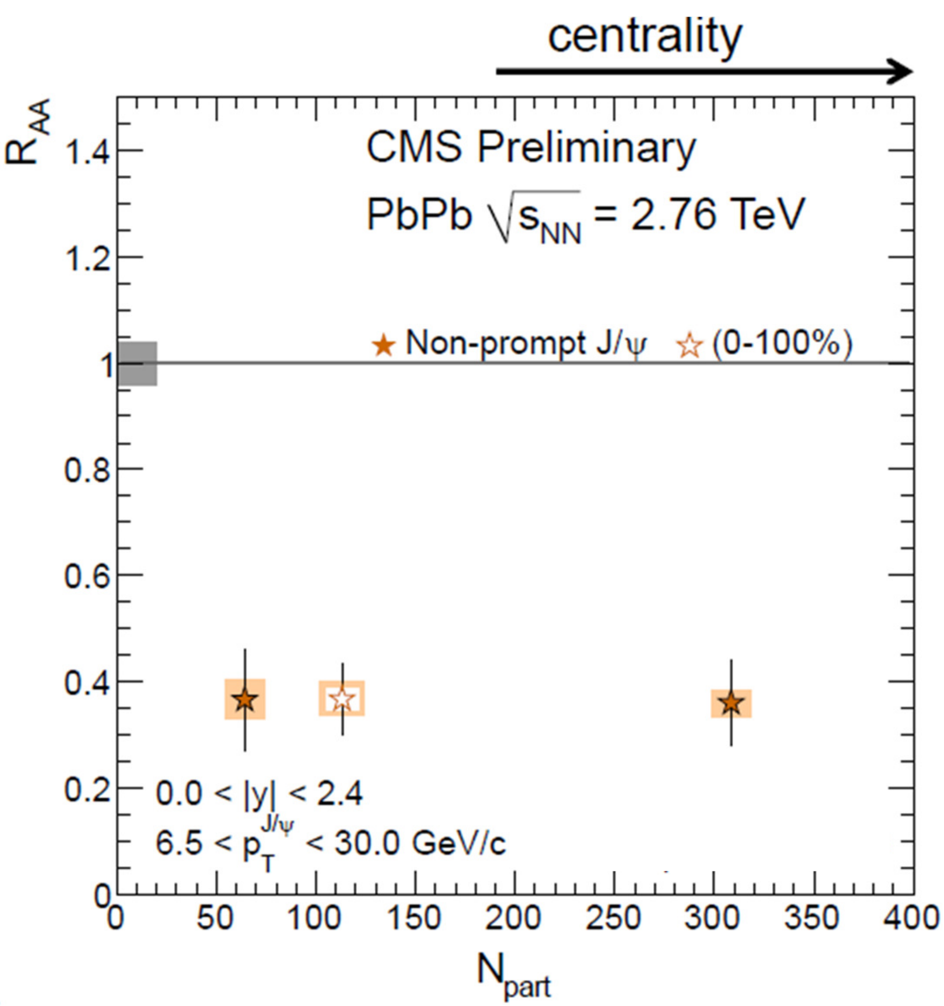
- Semileptonic decays of HF contribute to the electron and muon yields
- Electrons at central rapidity
  - (Inclusive electron spectra) – ("cocktail" of known sources) is dominated by HF for p_T>3-4 GeV/c
- Muons at forward rapidity
  - Yield is suppressed by a factor of ~3 for p_T>6 GeV/c, where is dominated by Beauty
- R_{AA} for muons and electrons compatible within the large electron signal systematic uncertainties
- R_{AA} for muons for p_T>5GeV/c higher than D meson R_{AA} (D mesons more suppressed)

B->J/Ψ suppression

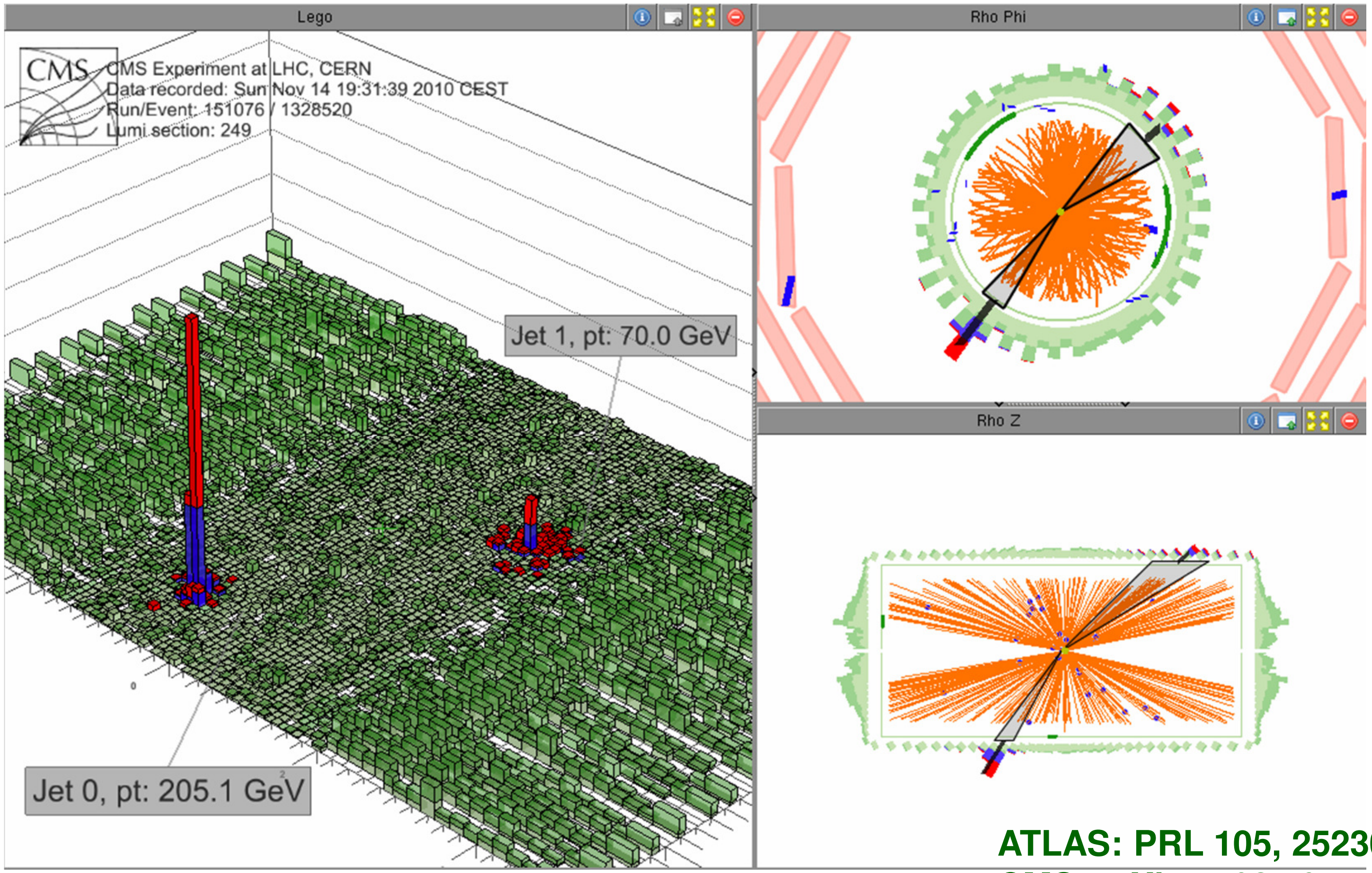
- Measured for the 1st time in PbPb collisions
- J/ψ coming from B decay are strongly suppressed

$R_{AA} = 0.37 \pm 0.07 \pm 0.03$ (min.bias)

- NOTE:
  - ⇨Not due to J/ψ melting in the QGP
    - ✓ ***B mesons decay outside the medium -> different physics behind this suppression and the quarkonia melting in the QGP***
  - ⇨Due to b quark energy loss?



Jet quenching



ATLAS: PRL 105, 252303 (2010)
CMS: arXiv:1102.1957

- Pb-Pb events with large di-jet imbalance observed by ATLAS & CMS
  - ⇨Recoiling jet strongly quenched

Di-jet imbalance

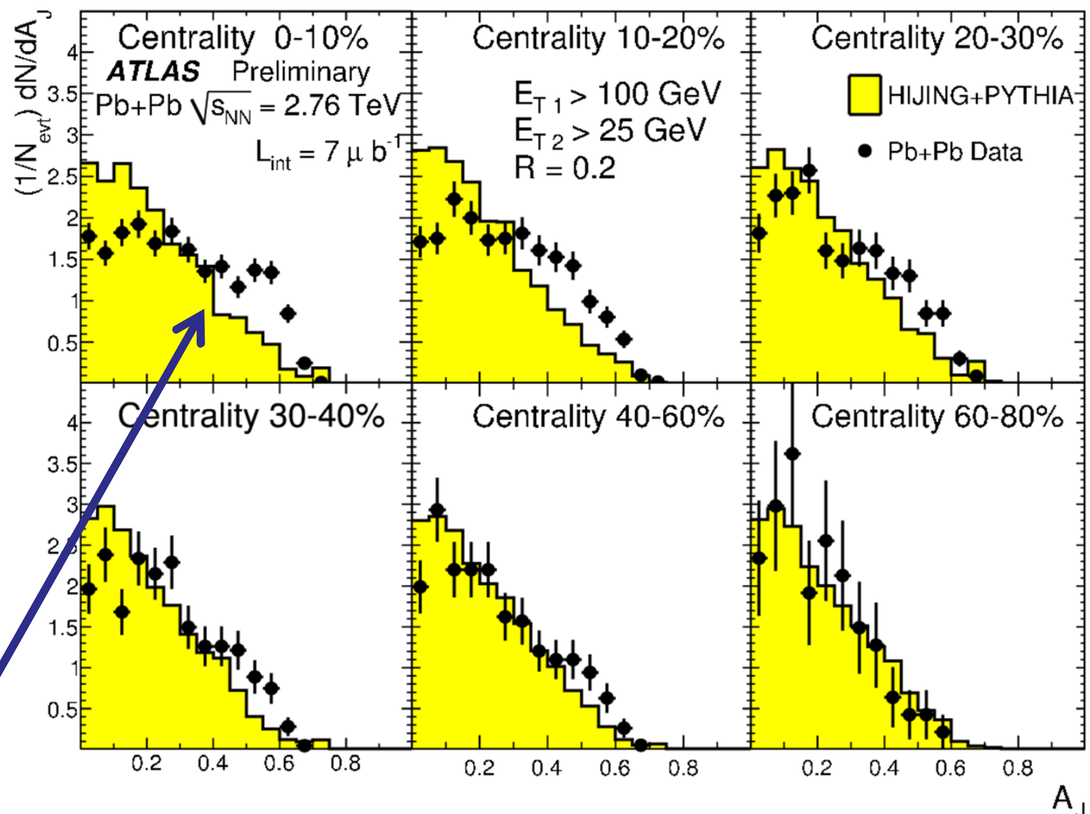
- Jet energy imbalance quantified by:

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \quad , \quad \Delta\varphi_{12} > \frac{\pi}{2}$$

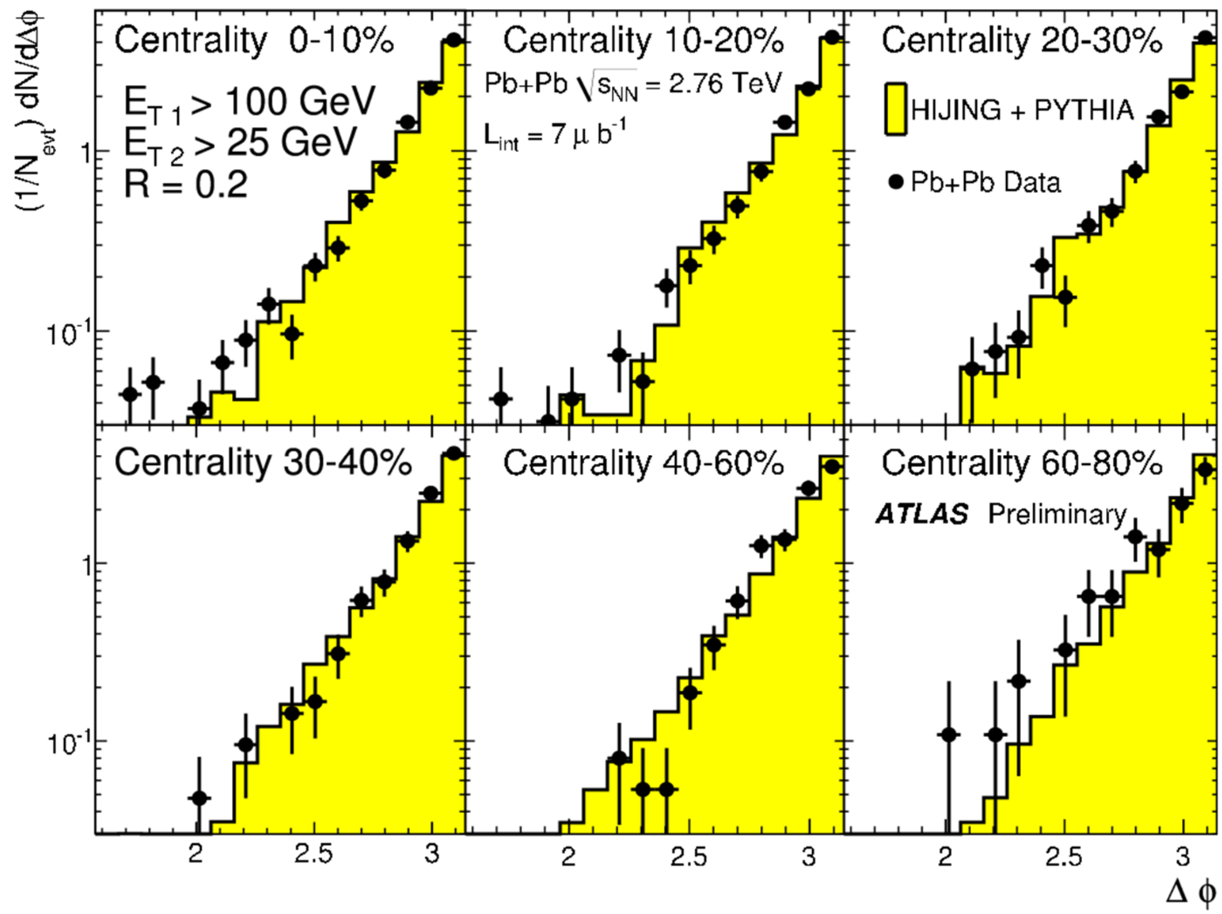
Di-jet events are expected to have $A_J \approx 0$

- Small deviation from gluon radiation outside jet cone
- Much stronger deviation from energy loss in the medium

- Jet reconstruction:
  - Leading jet with E_{T1}> 100 GeV
  - Second jet = highest transverse energy jet in the opposite hemisphere with E_{T2}>25 GeV
  - Jets reconstructed with anti-k_T clustering algorithm with R=0.2
  - Underlying event background subtracted
- **Pronounced energy imbalance observed in central PbPb collisions**



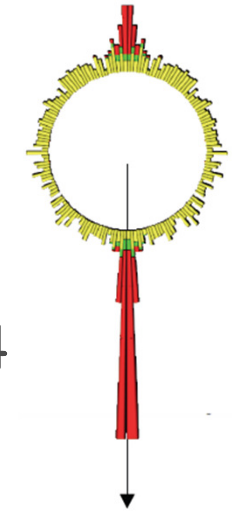
Di-jet angular correlation



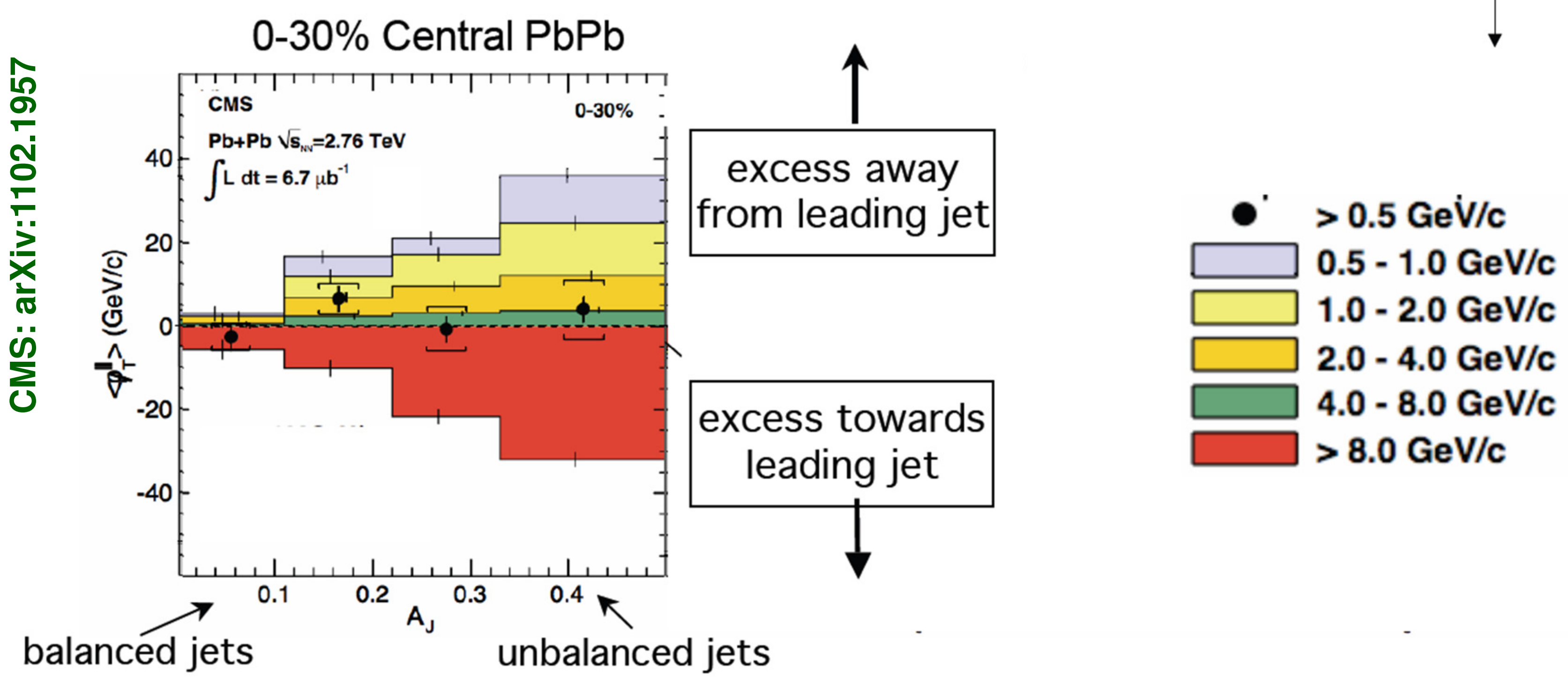
- No visible angular decorrelation in Δφ wrt pp collisions
  - ⇨ Propagation of partons in the dense medium does not lead to sizeable angular de-correlation

Where does the missing energy go?

- Missing $p_T^{||}$: $$\not{p}_T^{\parallel} = \sum_{Tracks} -p_T^{Track}\cos\left(\phi_{Track} - \phi_{Leading\ Jet}\right)$$



⇨ Leading jet defines direction
⇨ Sum the projections of track p_T on leading jet axis for all tracks with p_T>0.5 GeV/c and |η|<2.4



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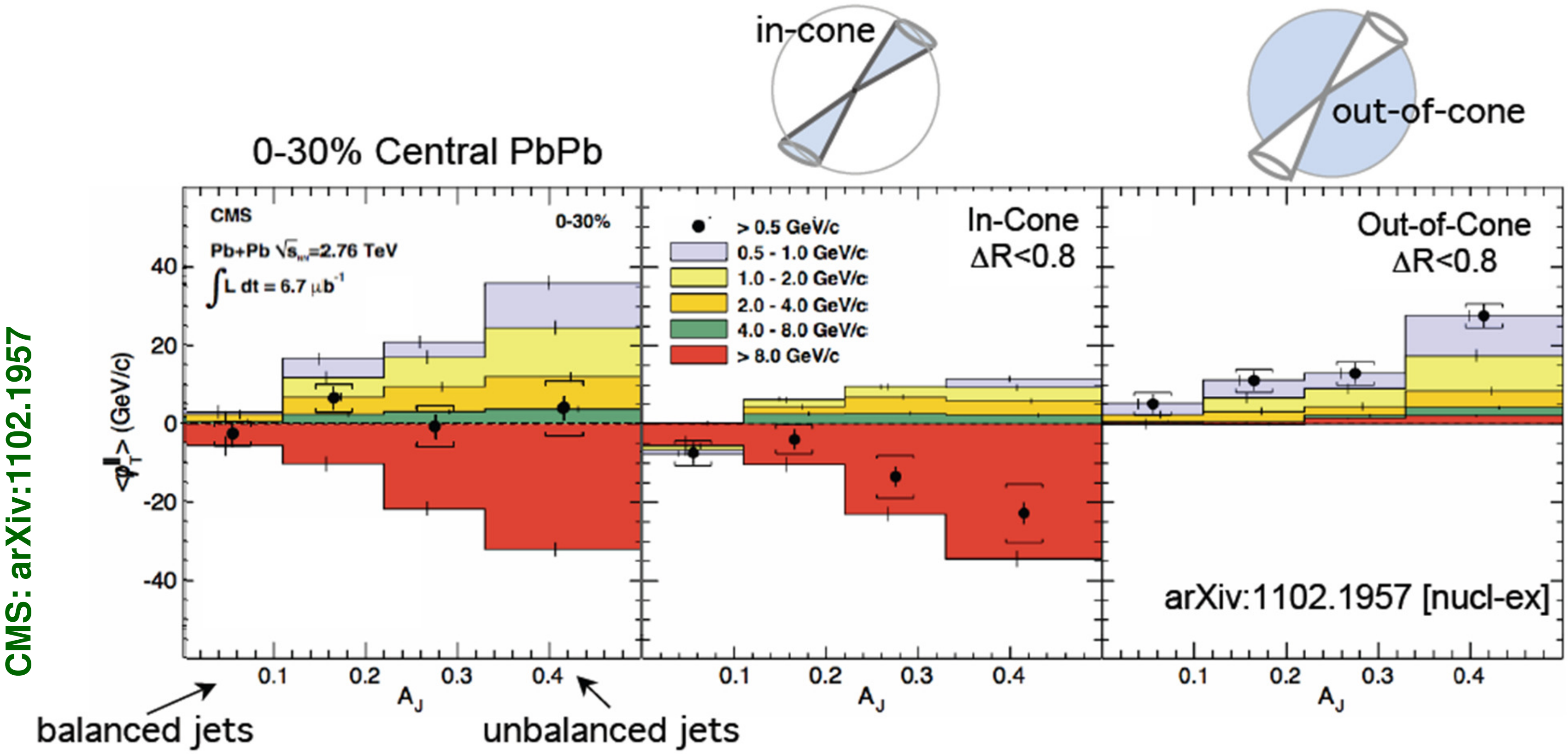


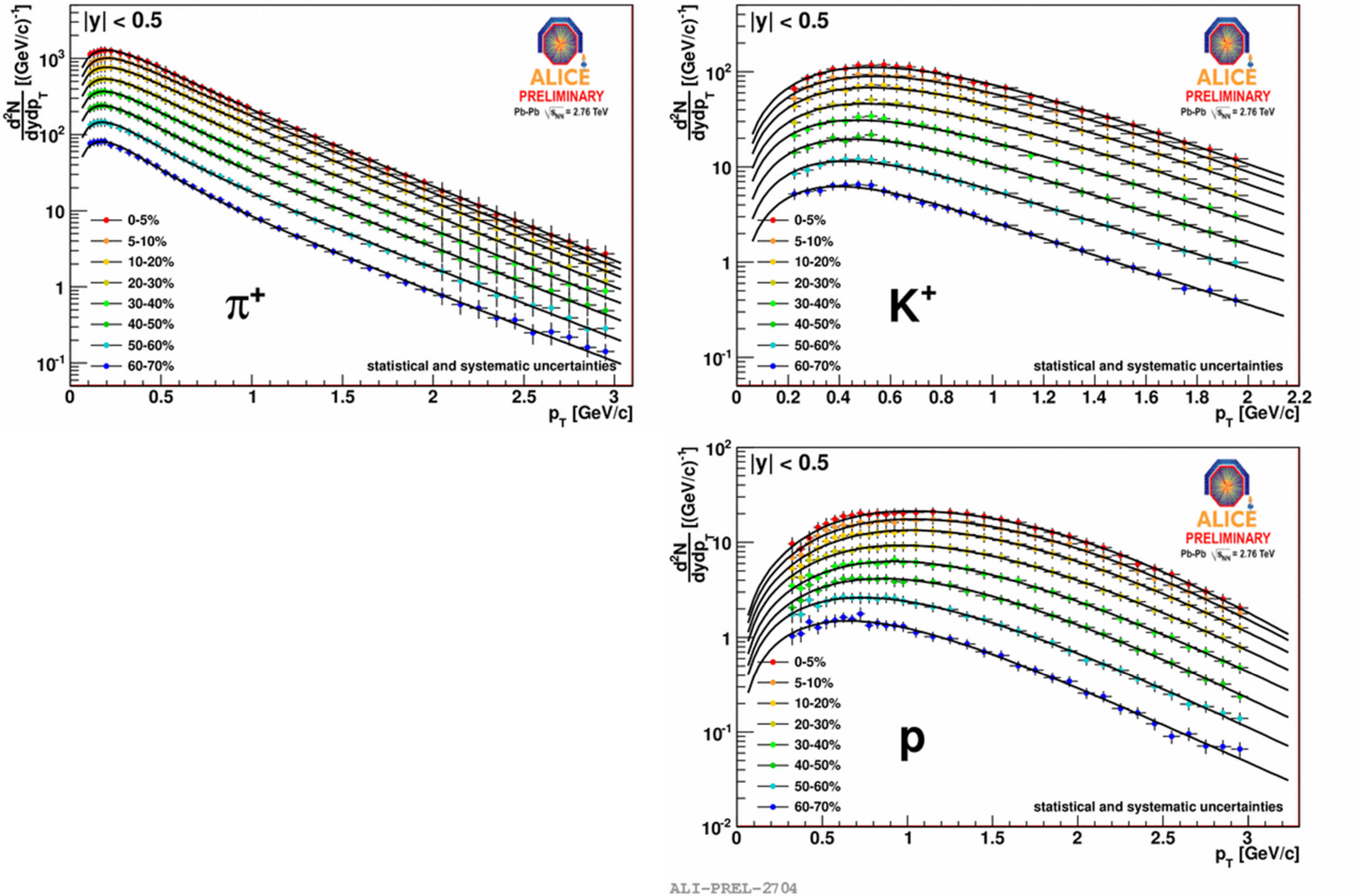
- **The momentum difference in the di-jet is balanced by low p_T particles emitted at large angles relative to the away side jet**

Conclusions

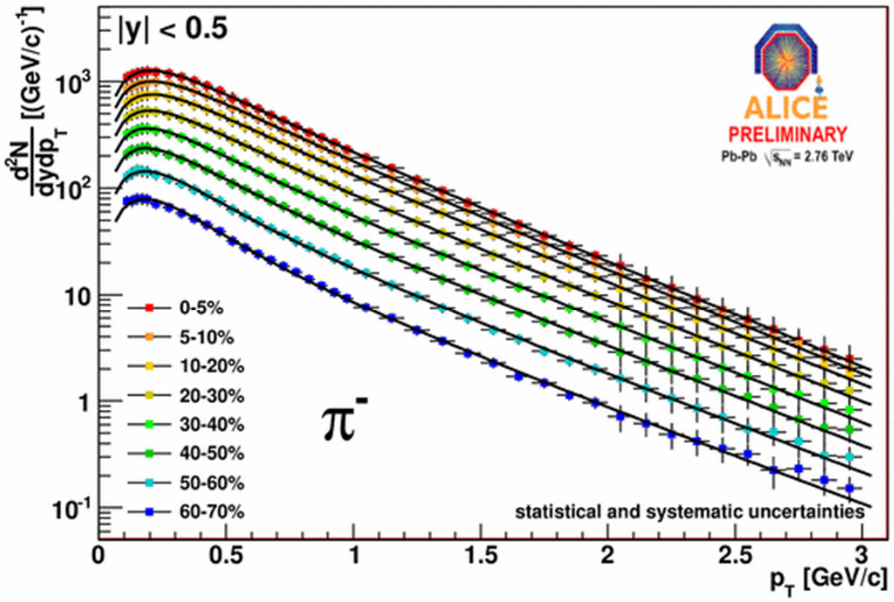
- In November 2010, heavy ion collisions entered a new era with the first of PbPb data sample at the LHC ($\sqrt{s}$=2.76 TeV)
  - ⇨ Medium with 3 times higher energy density than at RHIC
  - ⇨ Abundance of hard probes
- Smooth evolution of global (bulk) event characteristics from RHIC to LHC energies
  - ⇨ Precision measurements in the next future
    - ✓ ***Better constraints for existing models***
- Hard probes: novelties, surprises, challenges for theory
  - ⇨ High p_T hadrons
    - ✓ ***Strong suppression (factor 7 at p_T~7 GeV/c)***
    - ✓ ***Heavy quark R_{AA} similar to that of pions at high p_T***
  - ⇨ Jets
    - ✓ ***Large imbalance in di-jet energies compensated by low p_T particles at large angles***
  - ⇨ Quarkonia:
    - ✓ ***J/ψ are suppressed more than at RHIC at high p_T, but less at low p_T***
    - ✓ ***Υ excited states (first time accessible in heavy ion collisions) are suppressed***
- Look forward to 2011 PbPb run!

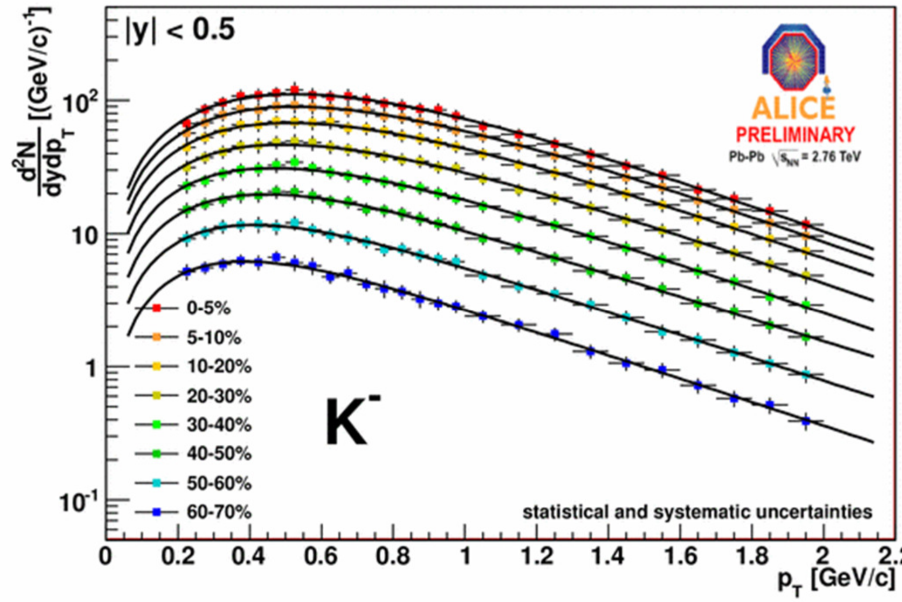
Backup

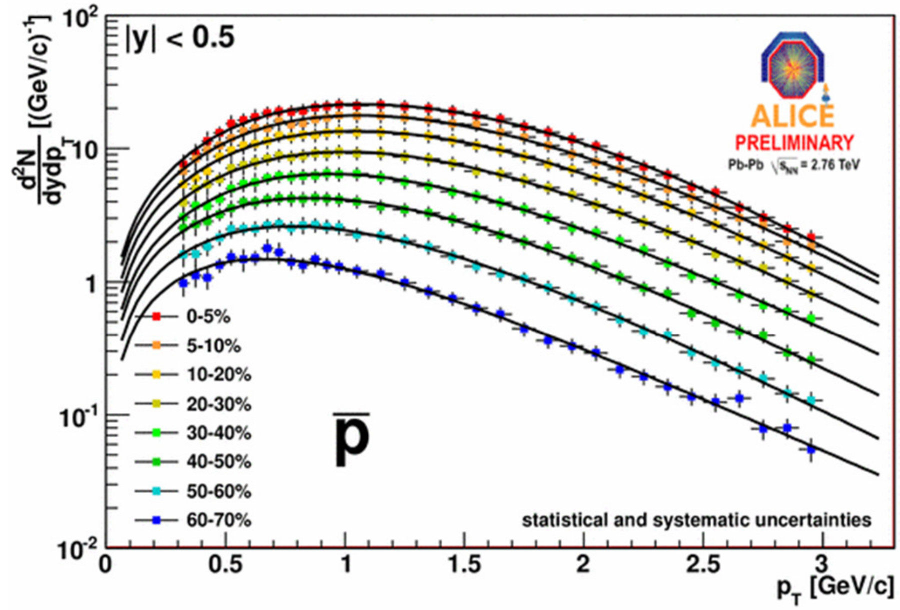
Identified hadron spectra



Identified hadron spectra

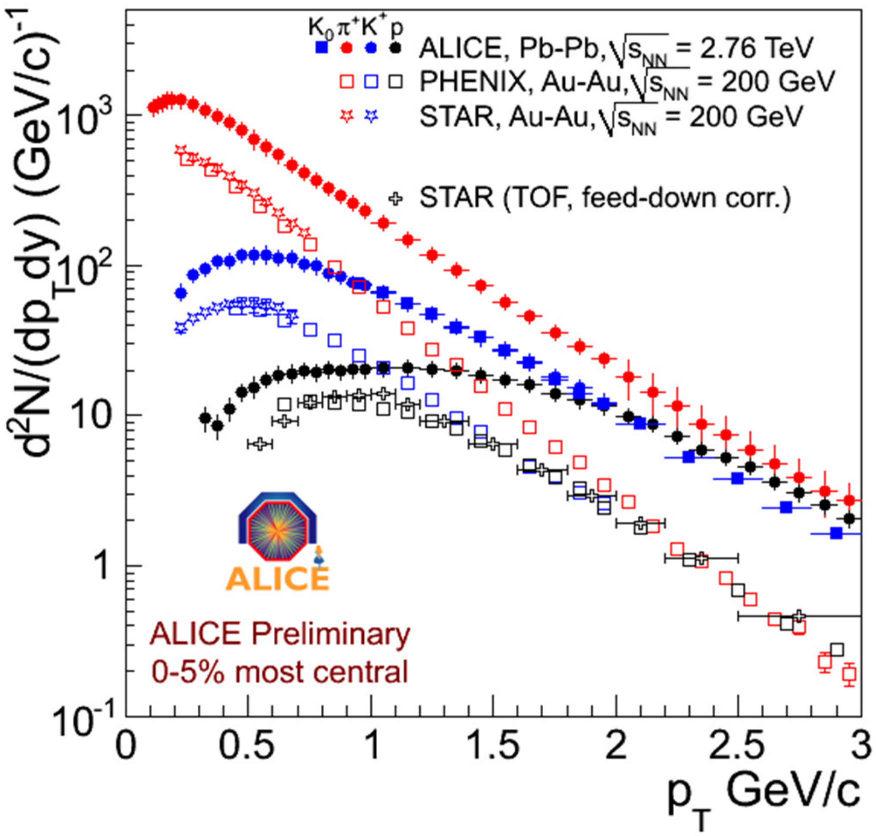


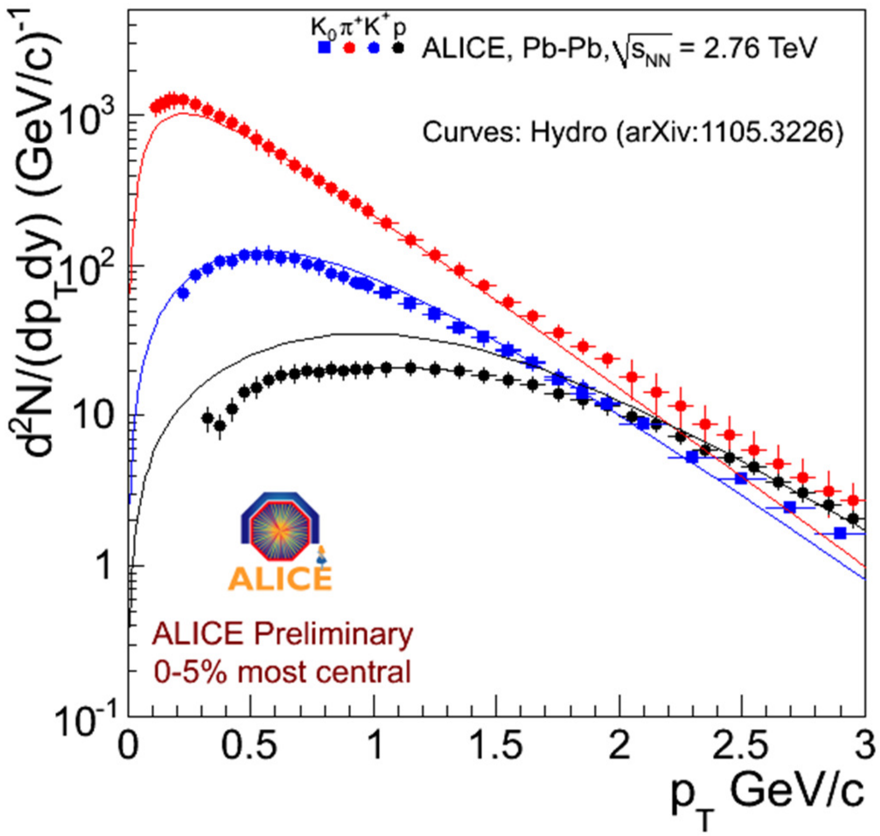




ALI-PREL-2713

Positive charged π, K, p spectra





- Spectra harder than at RHIC energies
  - ⇨Protons flatter at low pt
- Comparison with hydro predictions
  - ⇨OK for pions and kaons, protons are off

Blast wave

- E.Schnedermann, J.Sollfrank, and U.Heinz, Phys. Rev. C48, 2462(1993)

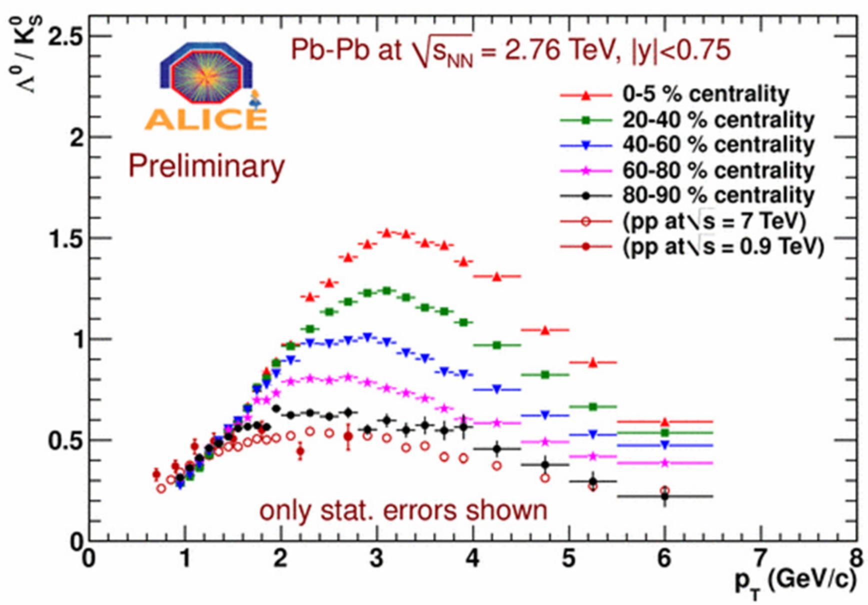
$$E\frac{d^3N}{dp^3} \propto \int_\sigma e^{-(u^\mu p_\mu)/T_{fo}} p d\sigma_\mu \Rightarrow$$

$$\frac{dN}{m_T dm_T} \propto \int_0^R r dr m_T K_1\left(\frac{m_T \cosh\rho}{T_{fo}}\right) I_0\left(\frac{p_T \sinh\rho}{T_{fo}}\right)$$

$$\rho = \tanh^{-1}\beta_T \qquad \beta_T = \beta_S\left(\frac{r}{R}\right)^\alpha \qquad \alpha = 0.5,\ \ 1,\ \ 2$$

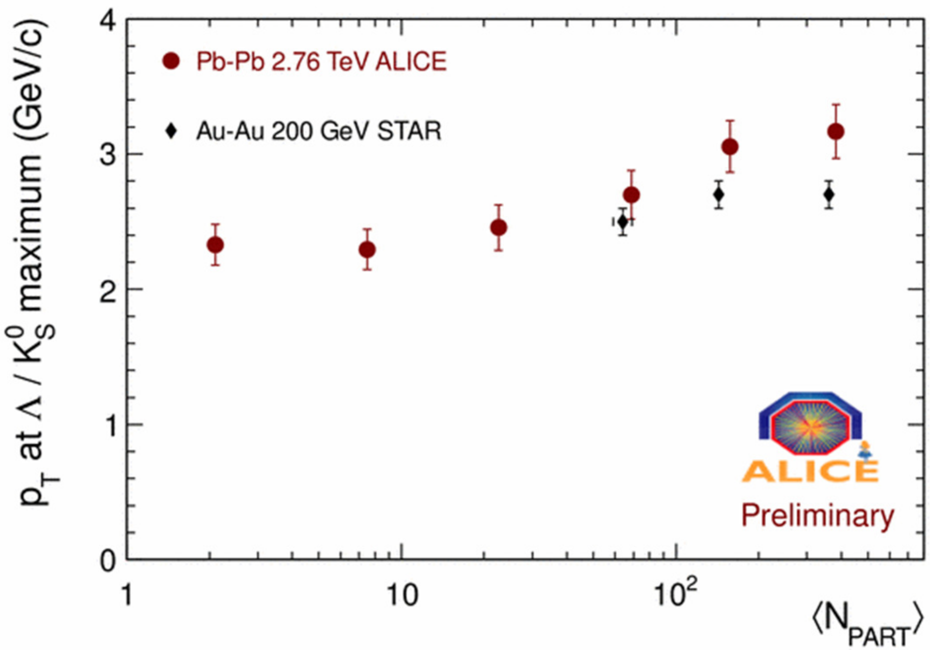
⇨ Free parameters: T_{fo}, β, α

Baryon to meson ratio: Λ/K_s^0

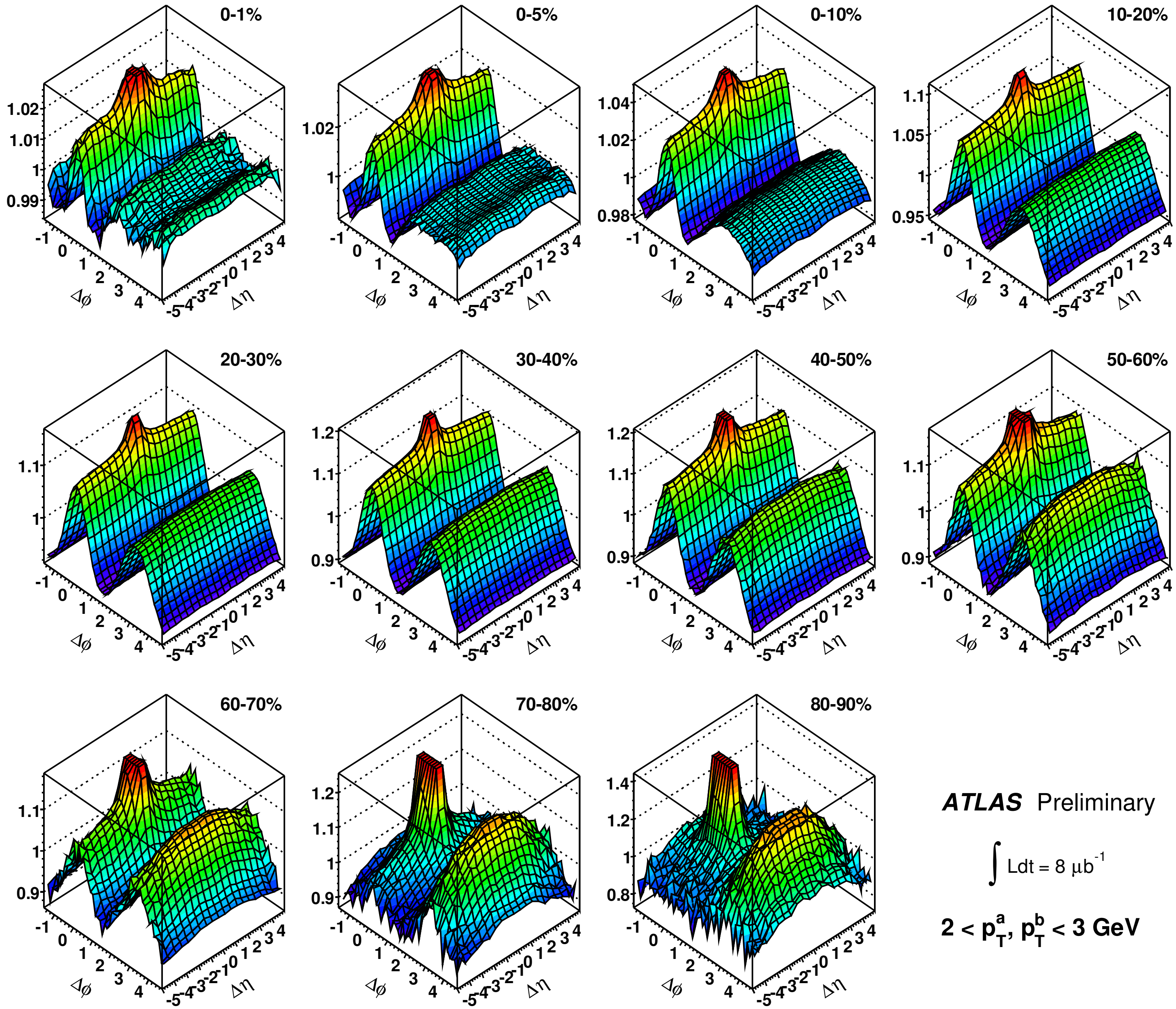


- Baryons produced more easily at intermediate p_T
- Baryon/meson ratio increases with centrality
  - ⇨Recombination?
- Enhancement stronger than at RHIC

- Maximum of Λ/K slightly pushed towards higher p_T than at RHIC:
  - ⇨higher radial flow?



Di-hadron correlations

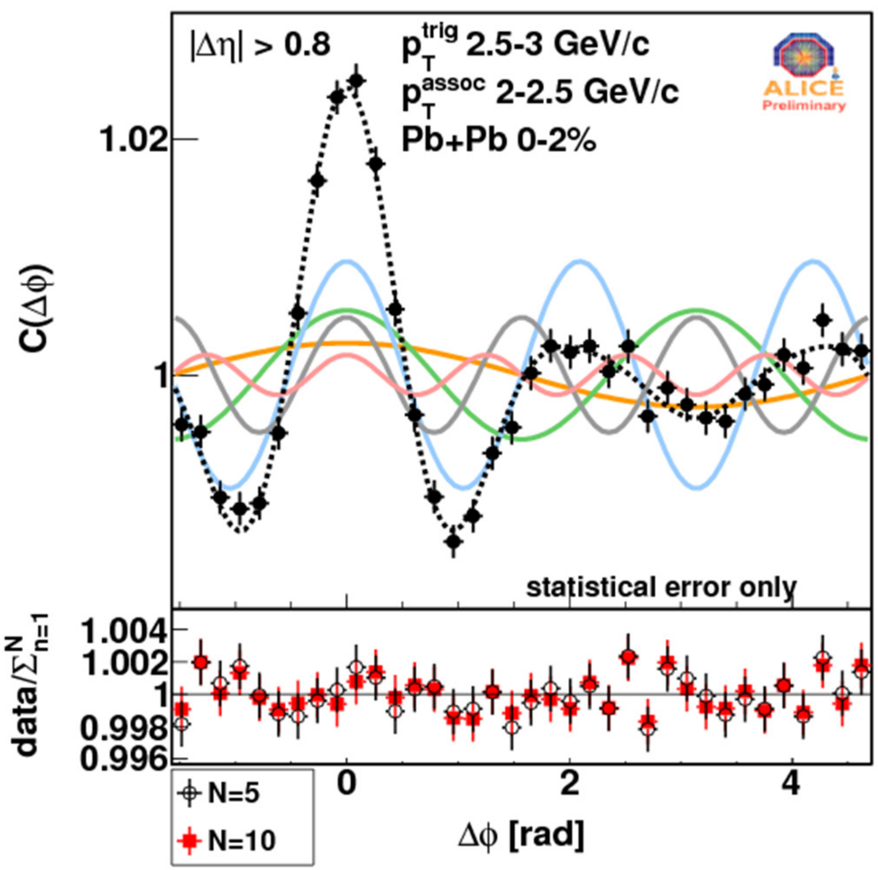


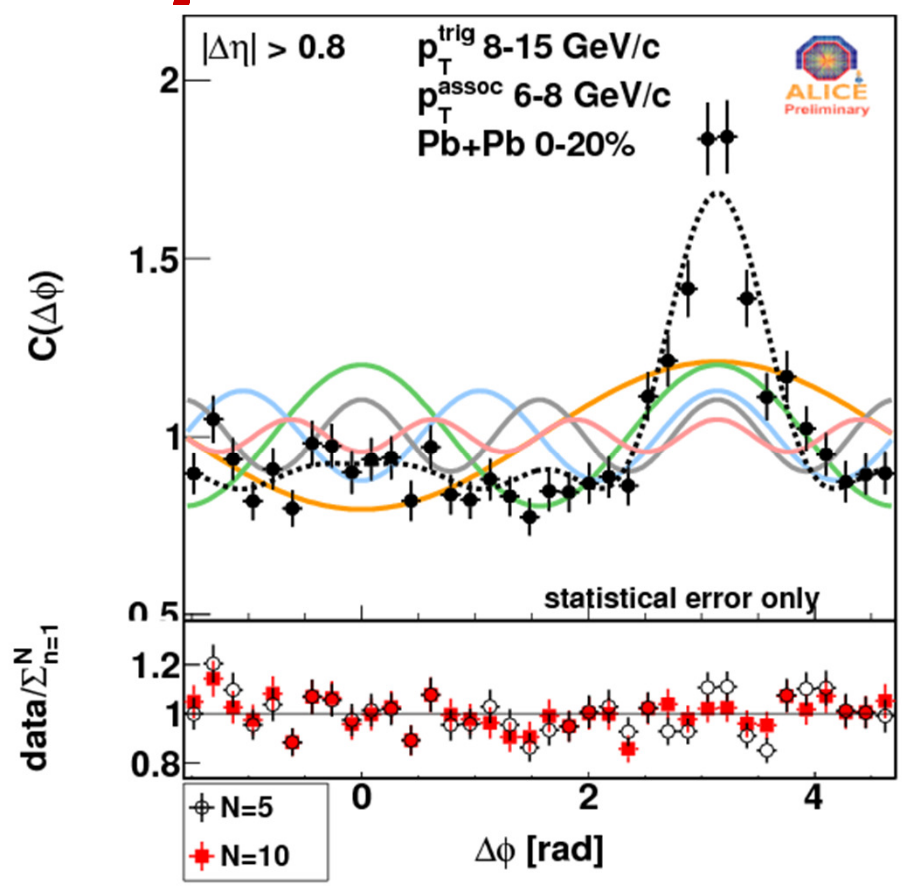
ATLAS Preliminary

$\int Ldt = 8\ \mu b^{-1}$

$2 < p_T^a, p_T^b < 3$ GeV

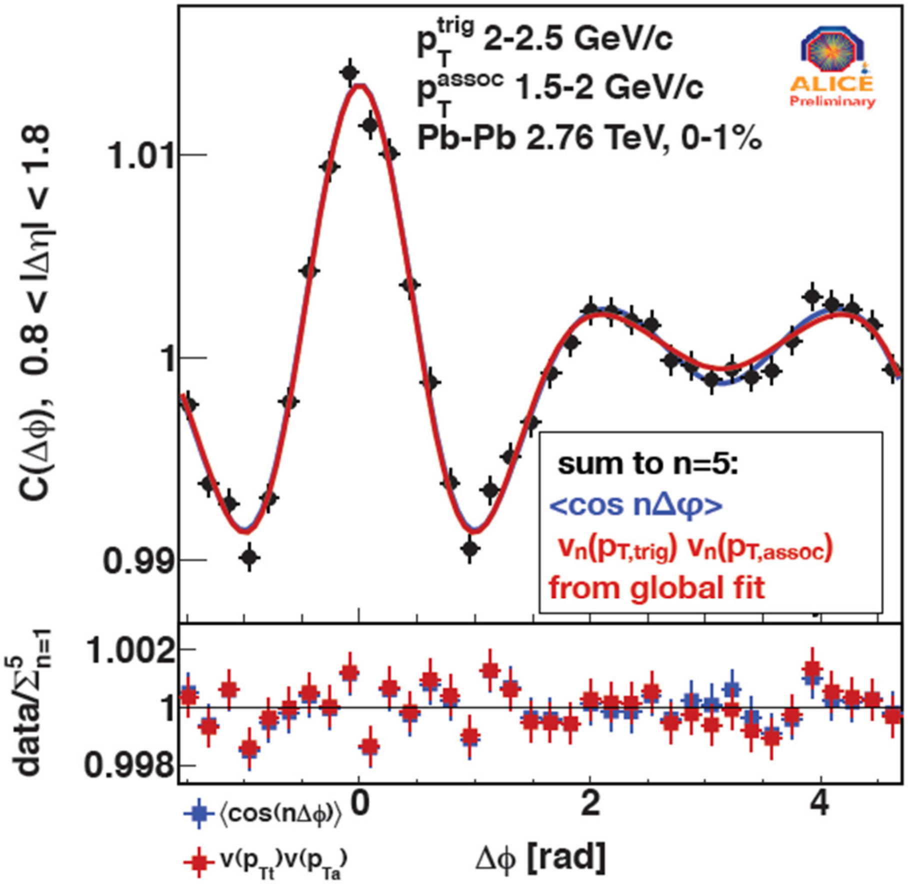
Fourier decomposition

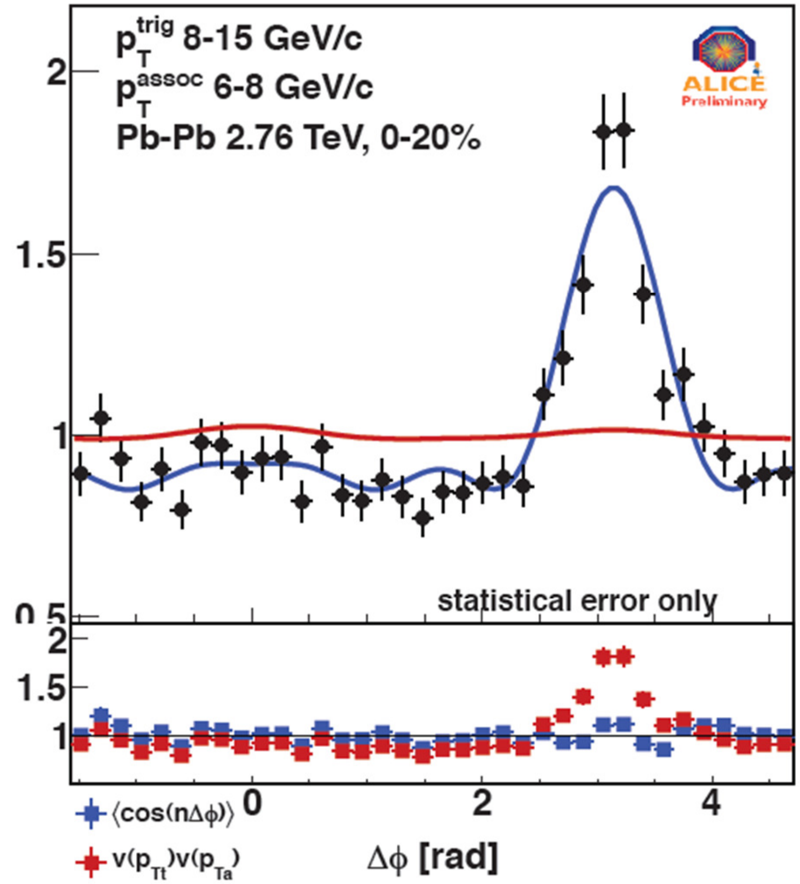




- Low p_t: 5 harmonics sufficient to describe completely the correlation spectrum
- High p_t: away side jet dominates, using 10 harmionics imporved the result

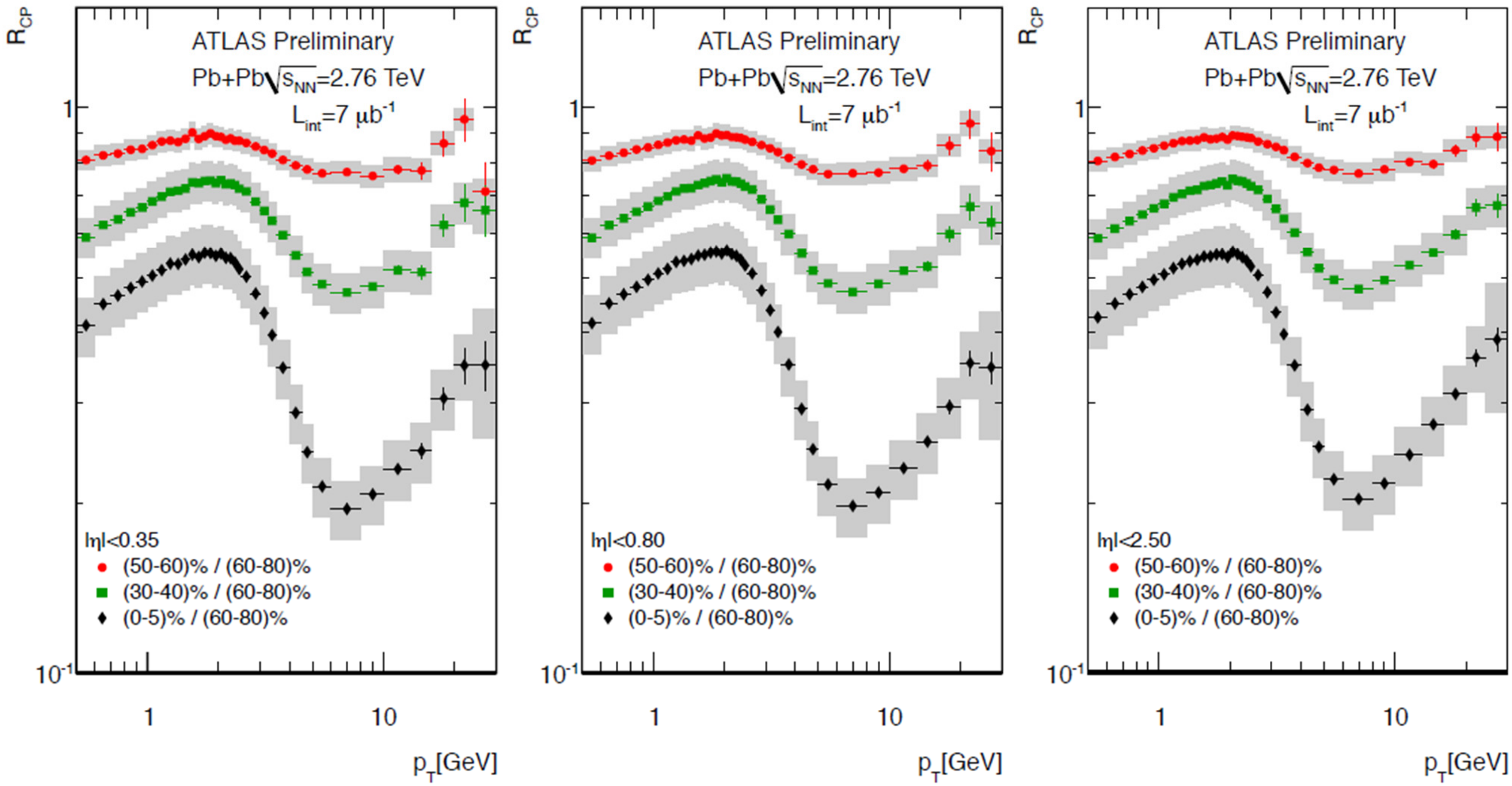
Flow vs. non flow correlations





- Single particle $v_n(p_t)$ provide a good description of long range di-hadron correlations for central events at low p_t
- Not good description at high p_t where away side jet dominates

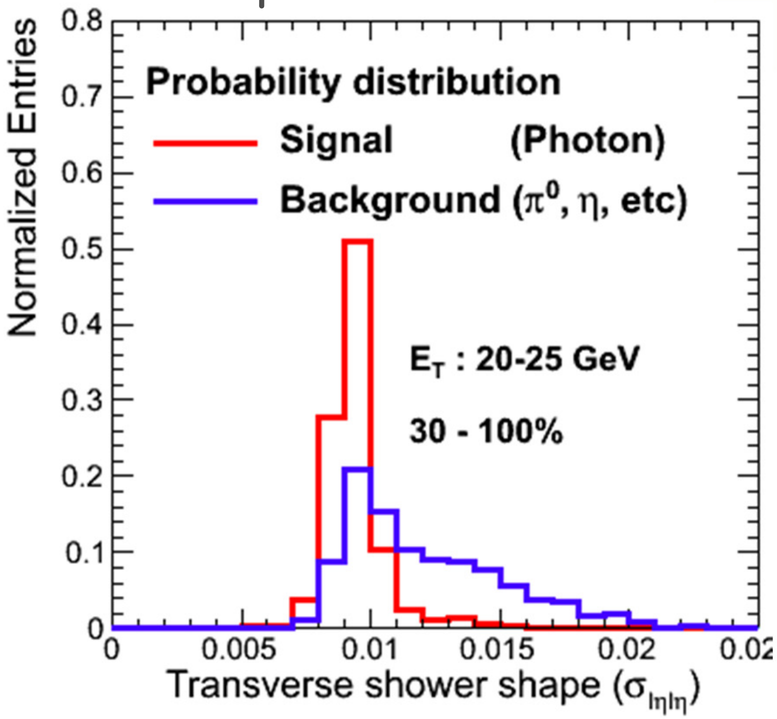
RCP in different η regions



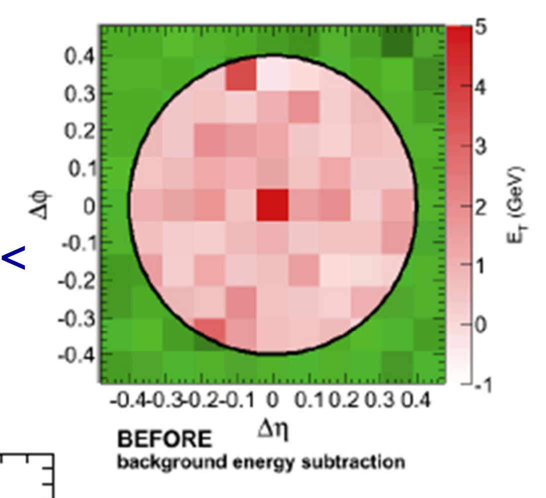
- No pseudorapidity dependence of nuclear modification within errors

Isolated photons

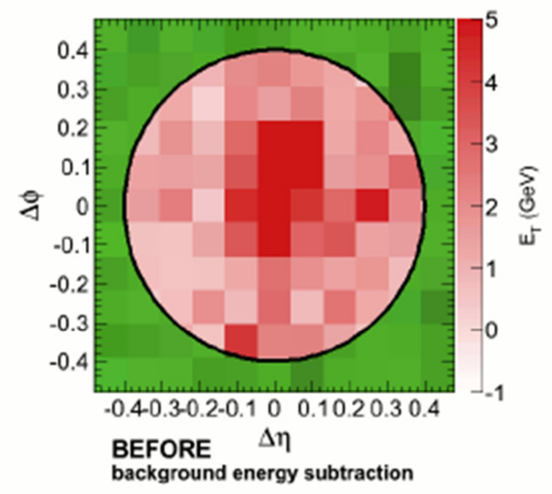
- Photon selection:
  - ⇨ Identify isolated electromagnetic clusters
    - ✓ $E_{HCAL}/E_{ECAL} < 0.2$
    - ✓ *Energy in cone (R=0.4) < 5 GeV*
  - ⇨ Transverse shower shape

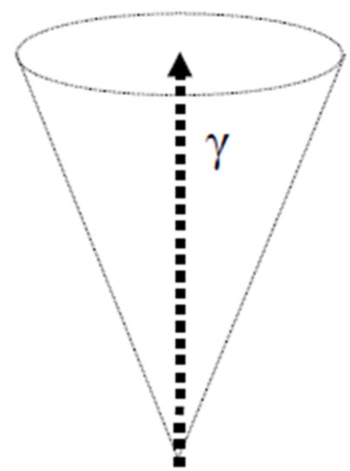


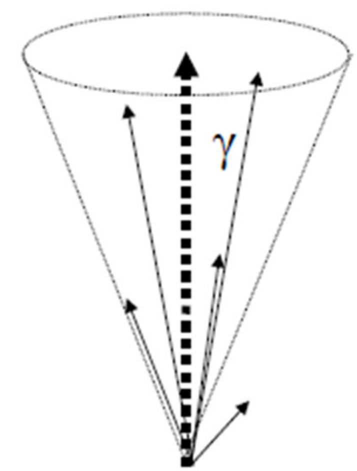
Isolated photon



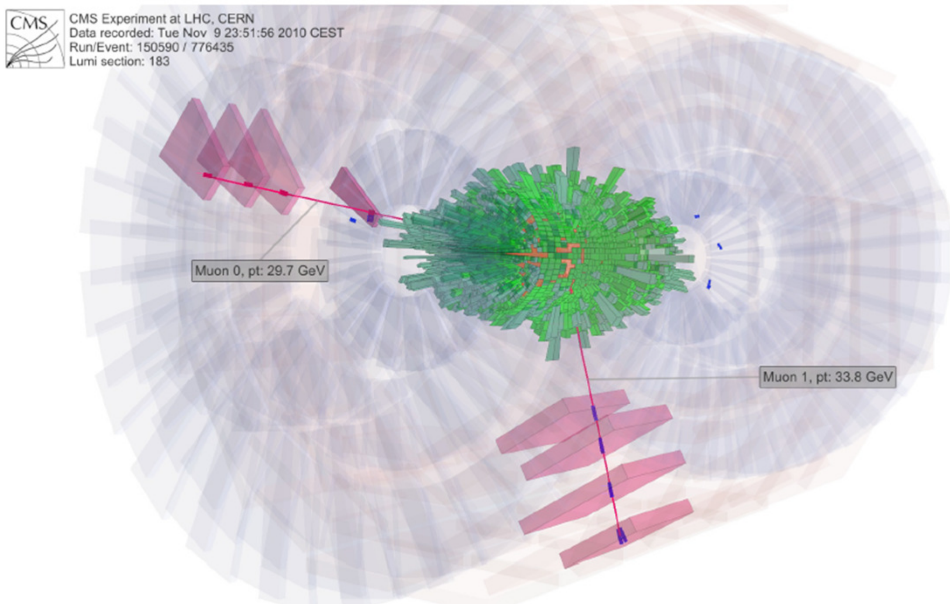
Photon candidate from jet

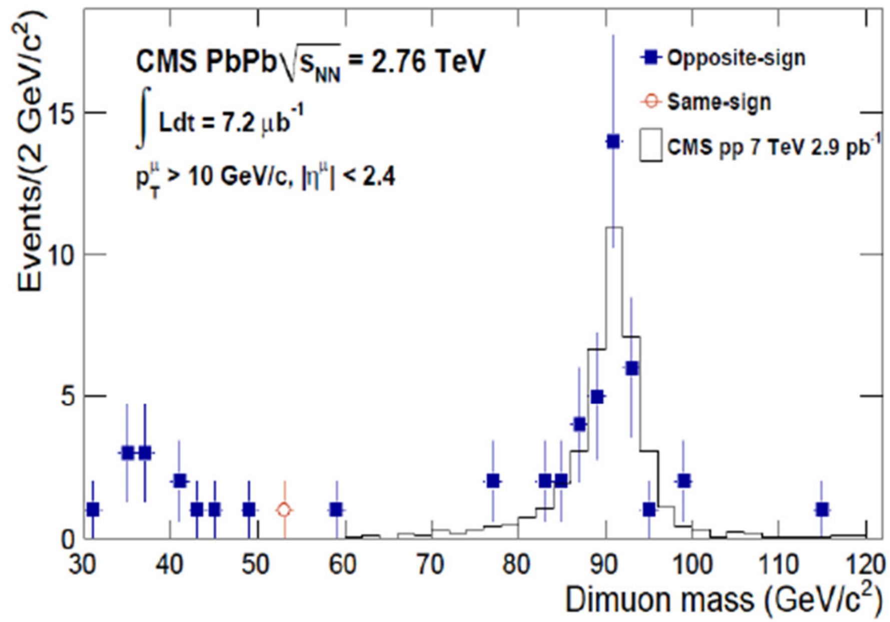


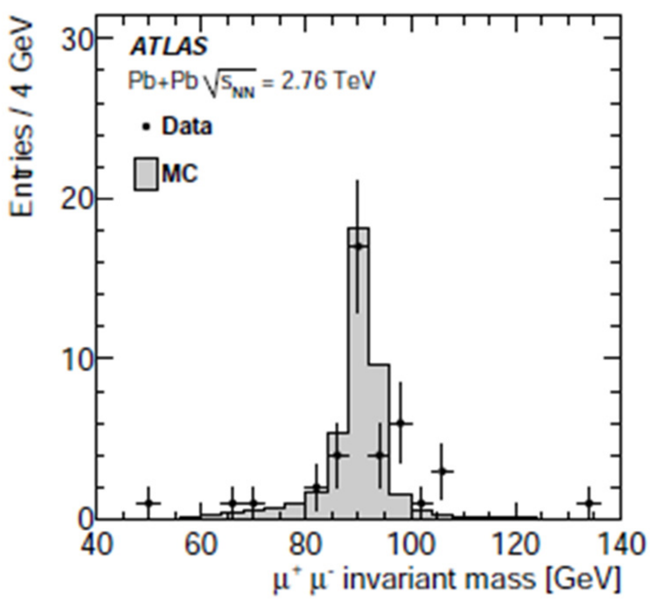


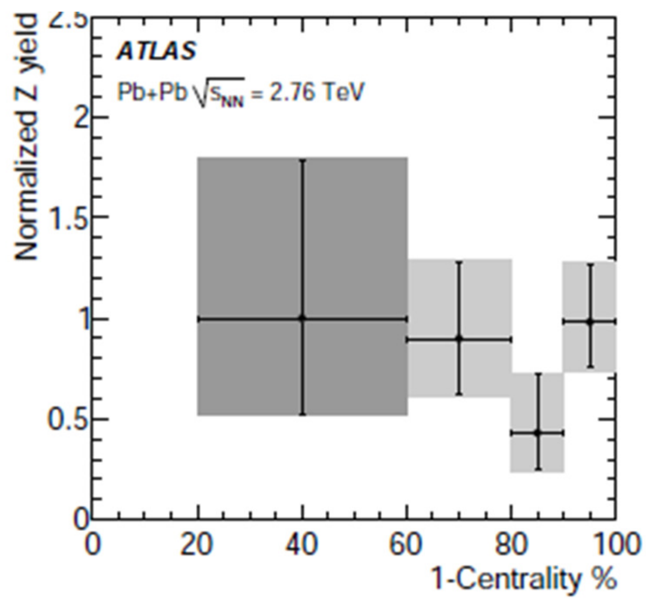


$Z \to \mu^+\mu^-$

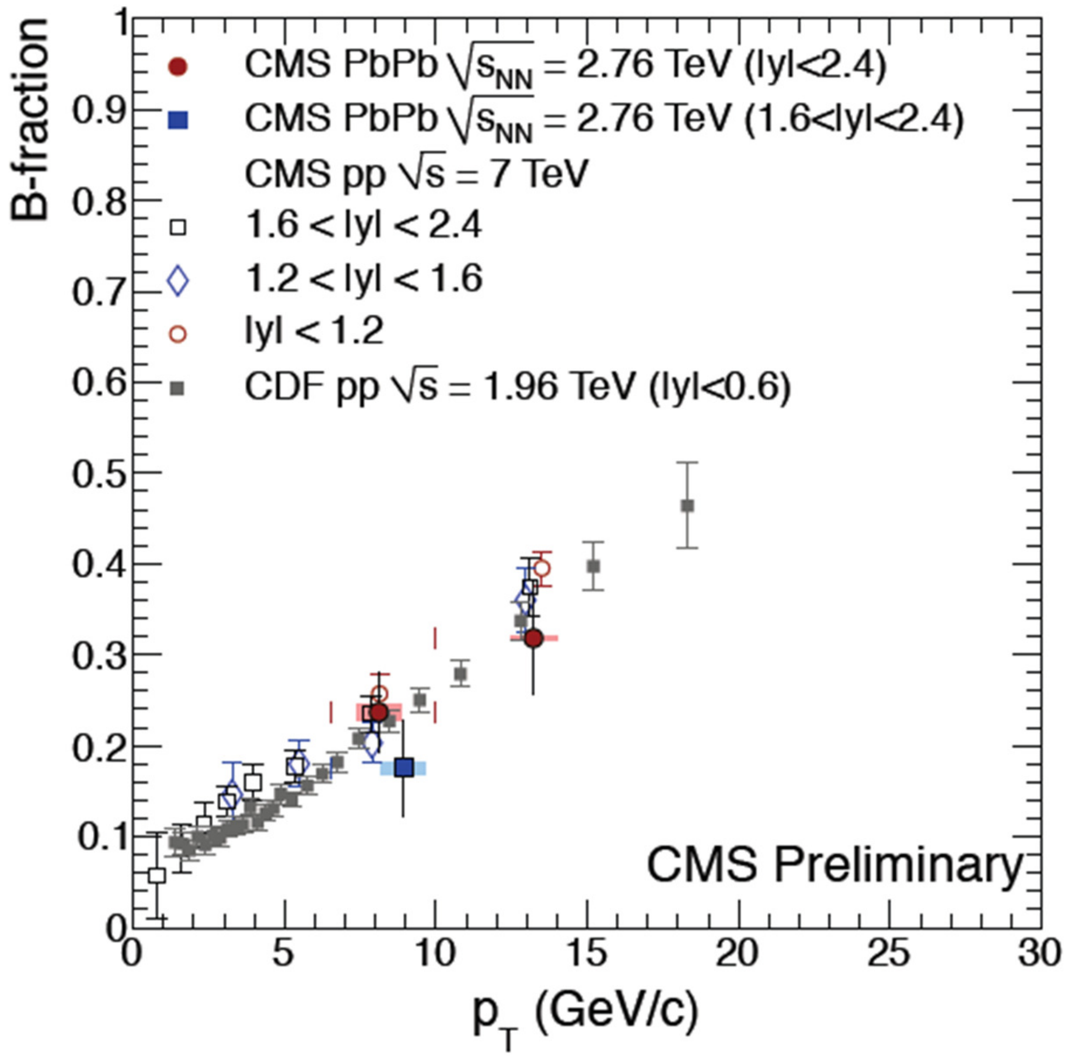

CMS Experiment at LHC, CERN
Data recorded: Tue Nov 9 23:51:56 2010 CEST
Run/Event: 150590 / 776435
Lumi section: 183
Muon 0, pt: 29.7 GeV
Muon 1, pt: 33.8 GeV


CMS PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
$\int$ Ldt = 7.2 μb^{-1}
p_T^μ > 10 GeV/c, $|\eta^\mu|$ < 2.4
Opposite-sign
Same-sign
CMS pp 7 TeV 2.9 pb^{-1}
Events/(2 GeV/c^2)
Dimuon mass (GeV/c^2)


ATLAS
Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV
Data
MC
Entries / 4 GeV
$\mu^+\mu^-$ invariant mass [GeV]

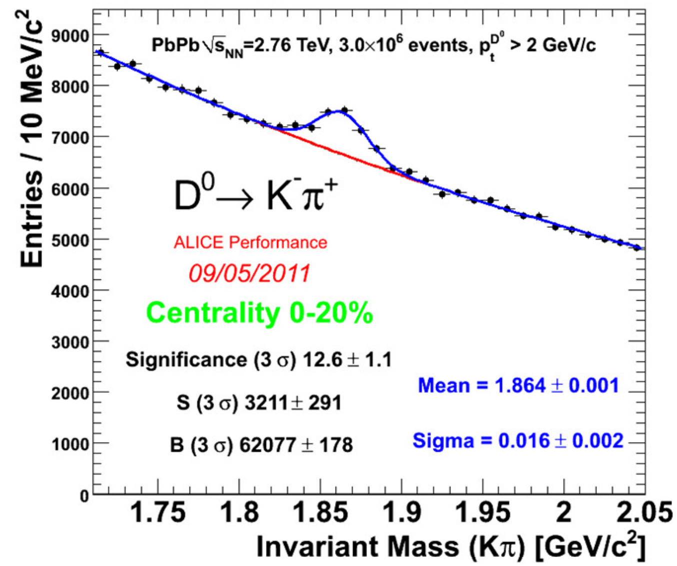

ATLAS
Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV
Normalized Z yield
1-Centrality %

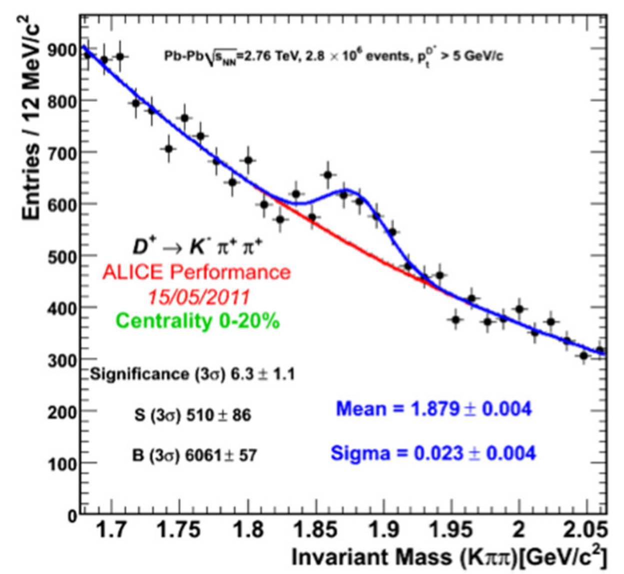
B->J/ψ fraction in pp and PbPb



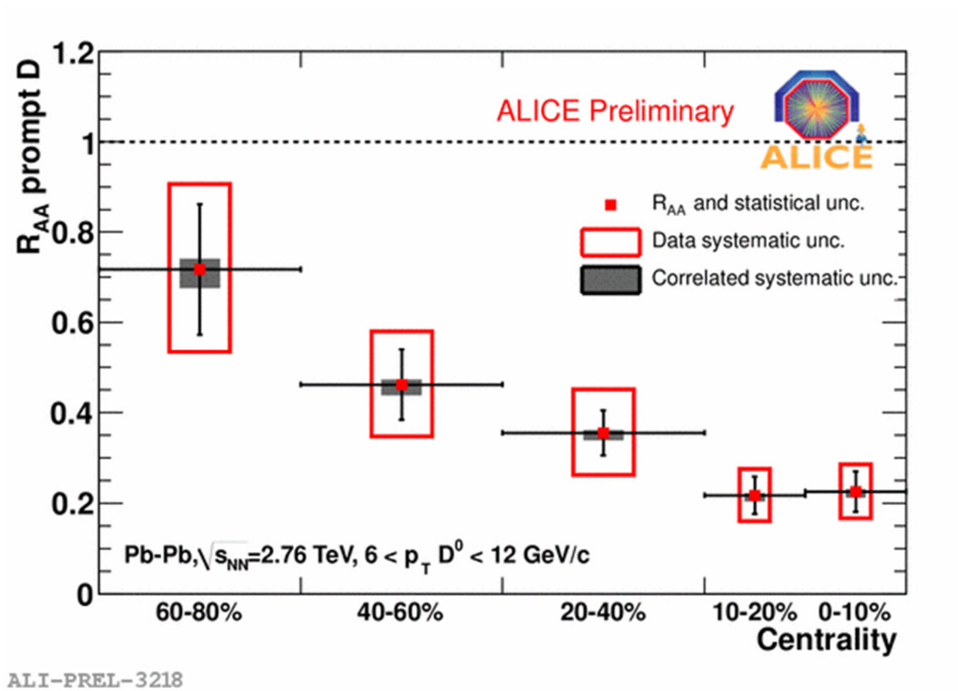
D mesons in PbPb

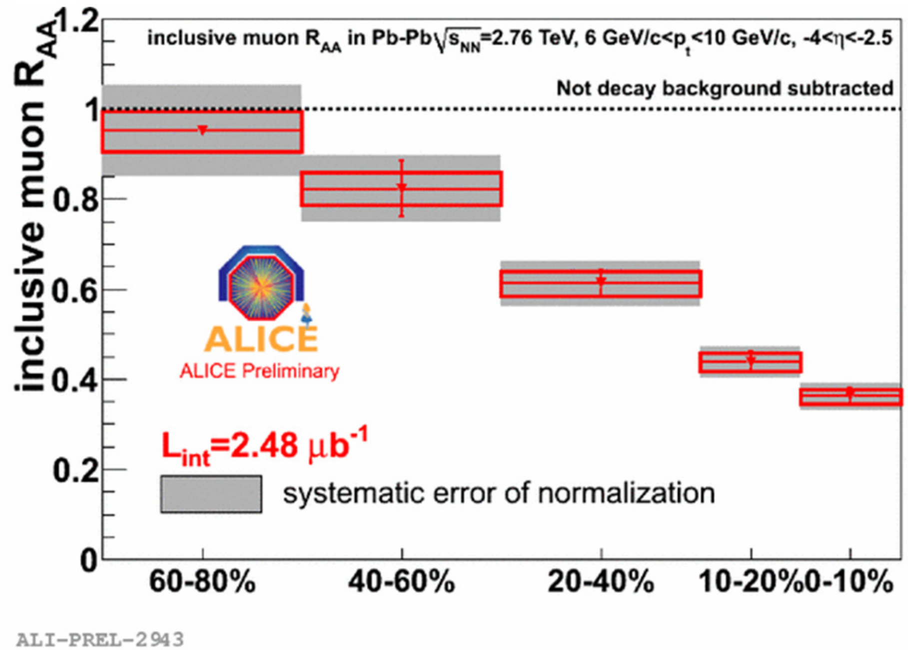
- Analysis strategy
  - ⇨ Invariant mass analysis of fully reconstructed decay topologies displaced from the primary vertex
- Central collisions (0-20%):
  - ⇨ $D^0 \to K\pi$: 5 p_T bins in 2-12 GeV/c
  - ⇨ $D^+ \to K\pi\pi$: 3 p_T bins in 5-12 GeV/c
- Reconstruction efficiency ~1-10 %
  - ⇨ From MC simulation
    - ✓ *Detector conditions described in MC at the level of few %*
    - ✓ *No centrality dependence*
- Feed down from B (10-15 % after cuts) subtracted using FONLL + hypothesis on B R_{AA}





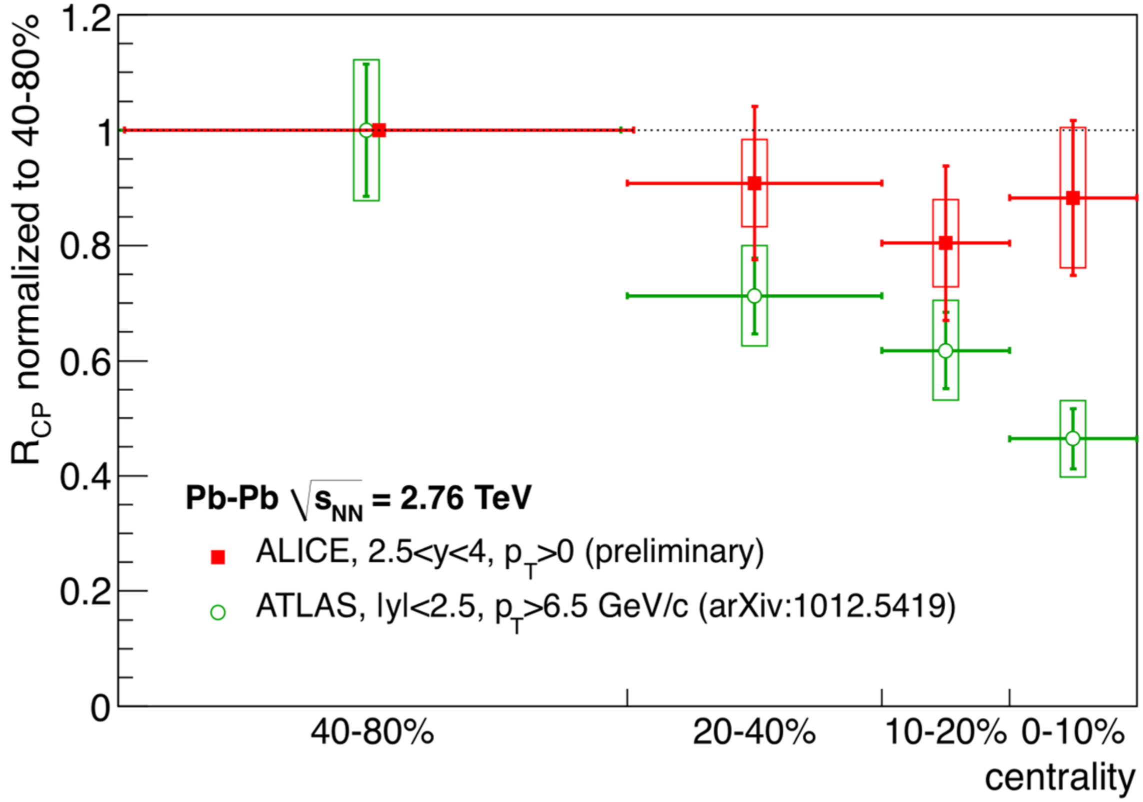
Heavy flavour R_{AA} vs. centrality





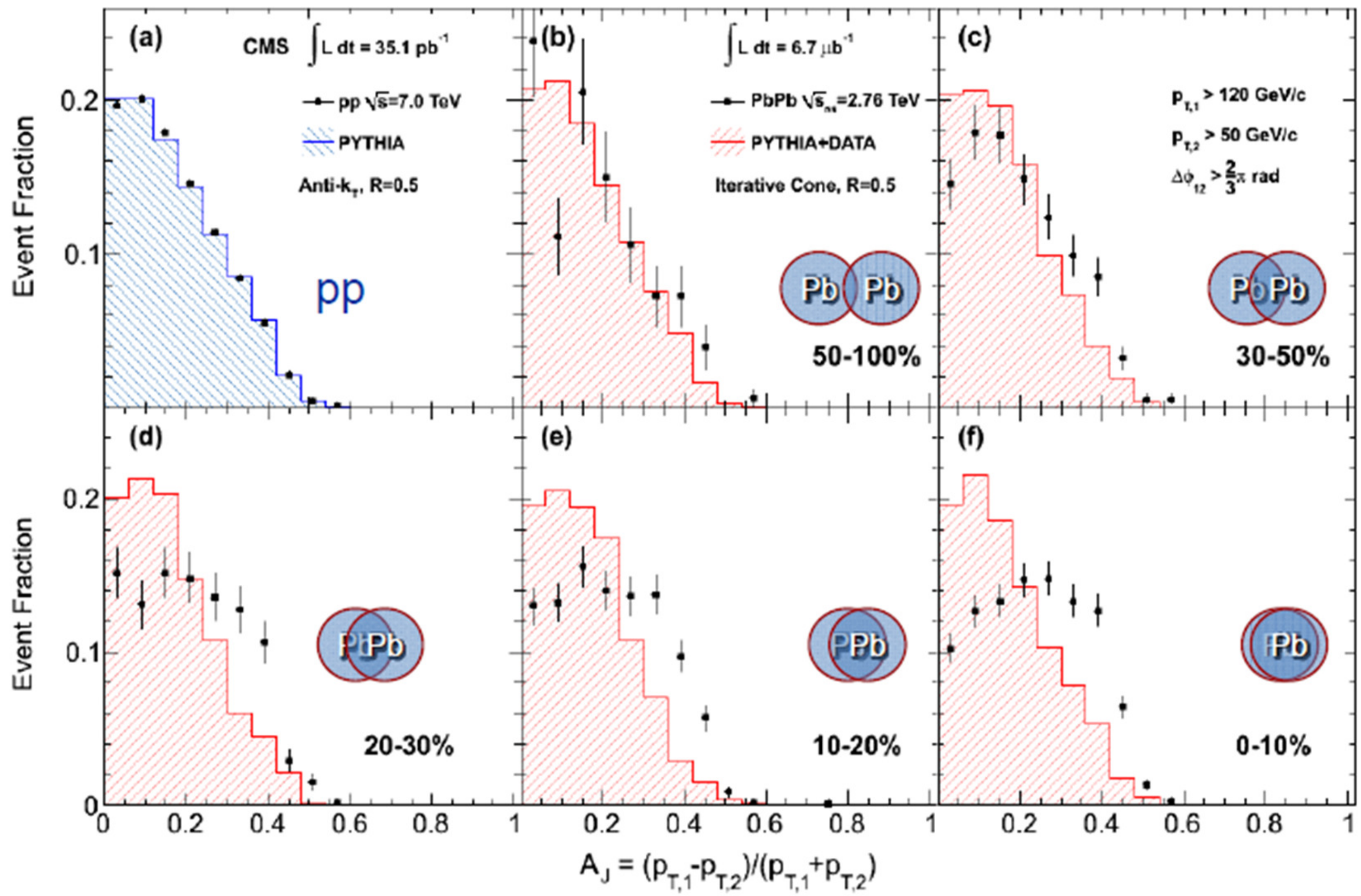
- Prompt D mesons at central rapidity more suppressed than heacy flavour muons (c+b) at forward rapidity

J/Ψ R_{CP}: ALICE vs ATLAS

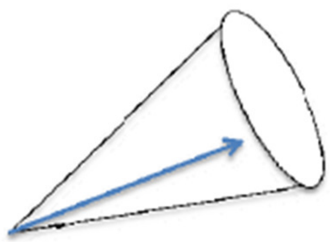


- Less suppression in ALICE than in ATLAS
  - ATLAS:
    - ✓ $|y|<2.5$
    - ✓ *80% of J/ψ with p_T>6.5 GeV/c*
    - ✓ *error in the 40-80% bin not propagated*
  - ALICE:
    - ✓ *2.5<y<4.0*
    - ✓ *p_T>0 GeV/c*

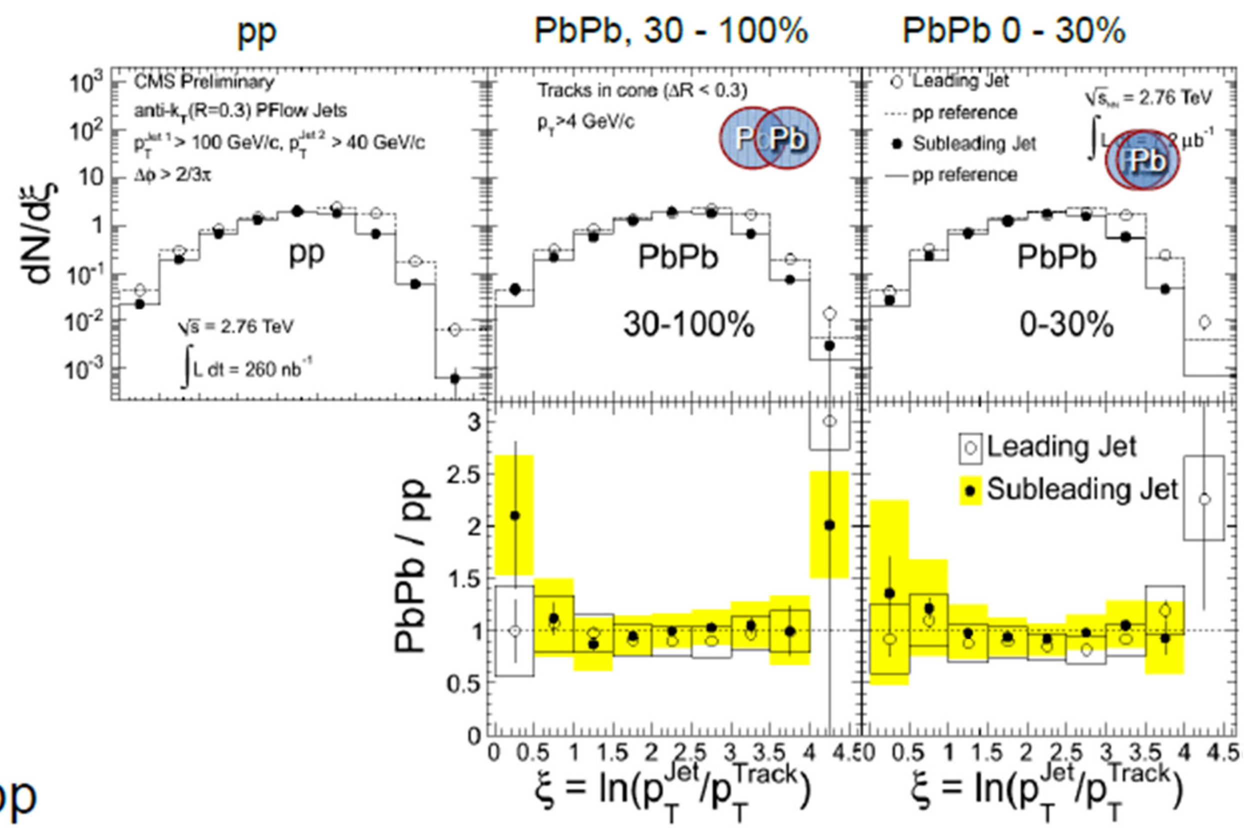
Jet imbalance: CMS



Jet fragmentation function: PbPb≈pp



$$\xi = \ln\left(\frac{p_T^{Jet}}{p_T^{Track}}\right)$$



- Compare PbPb to pp
  - Fragmentation function similar between PbPb and pp
  - Jets fragment in the vacuum

CMS PAS HIN-11-004