ALICE results on Heavy Ion Physics at the LHC

XXVI Rencontres de Physique de la Vallée d'Aoste

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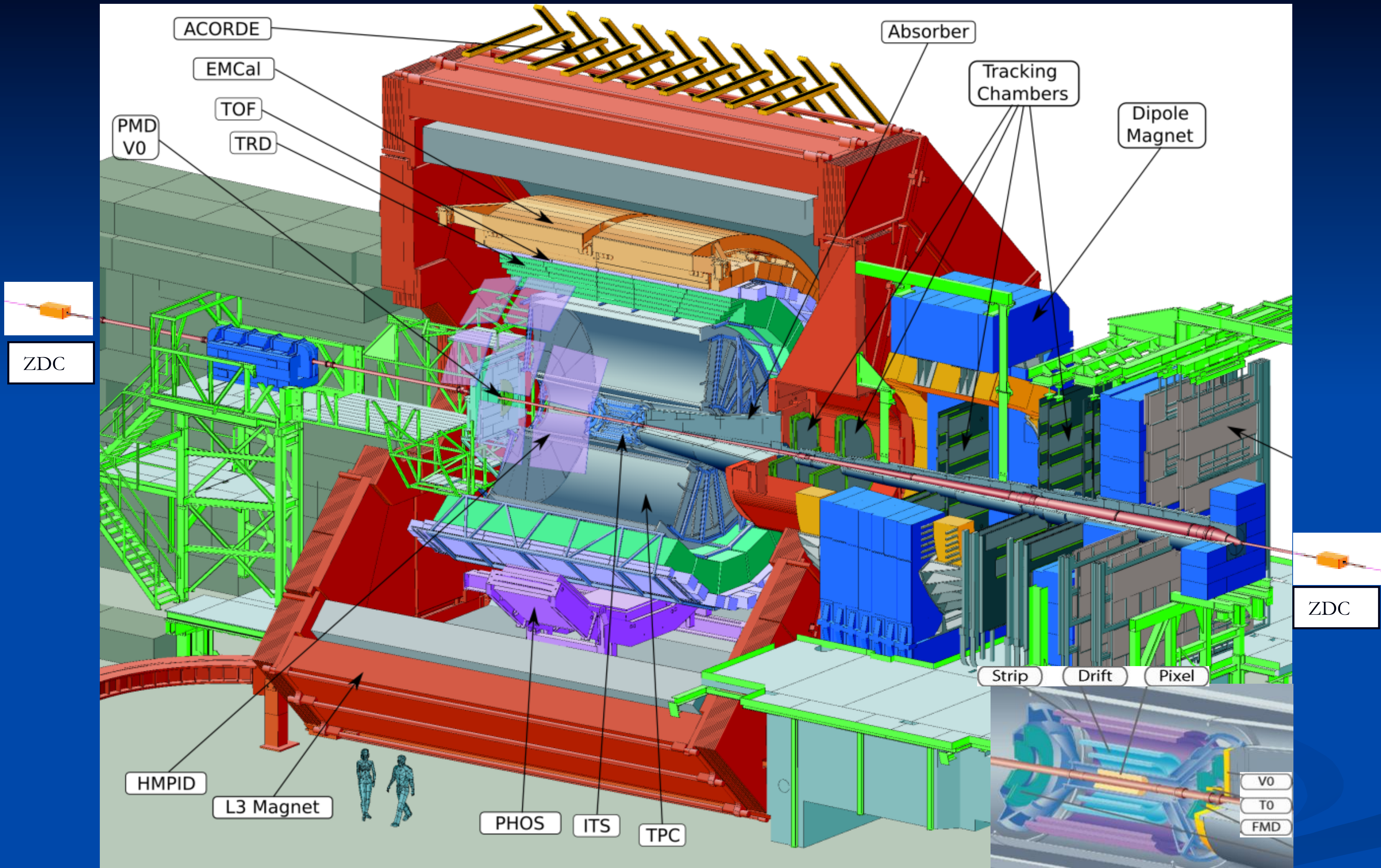
Outline

- ALICE at the LHC
- Pb-Pb (and pp) data at $\sqrt{s_{NN}}$=2.76 TeV
- Global event features
- Collective expansion and anisotropic flow
- Strangeness and chemical composition
- Parton energy loss in the medium
  - Light flavours
  - Heavy flavours
- Quarkonia dissociation/regeneration in the medium
- Conclusions and outlook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V0
T0
FMD
HMPID
L3 Magnet
PHOS
ITS
TPC

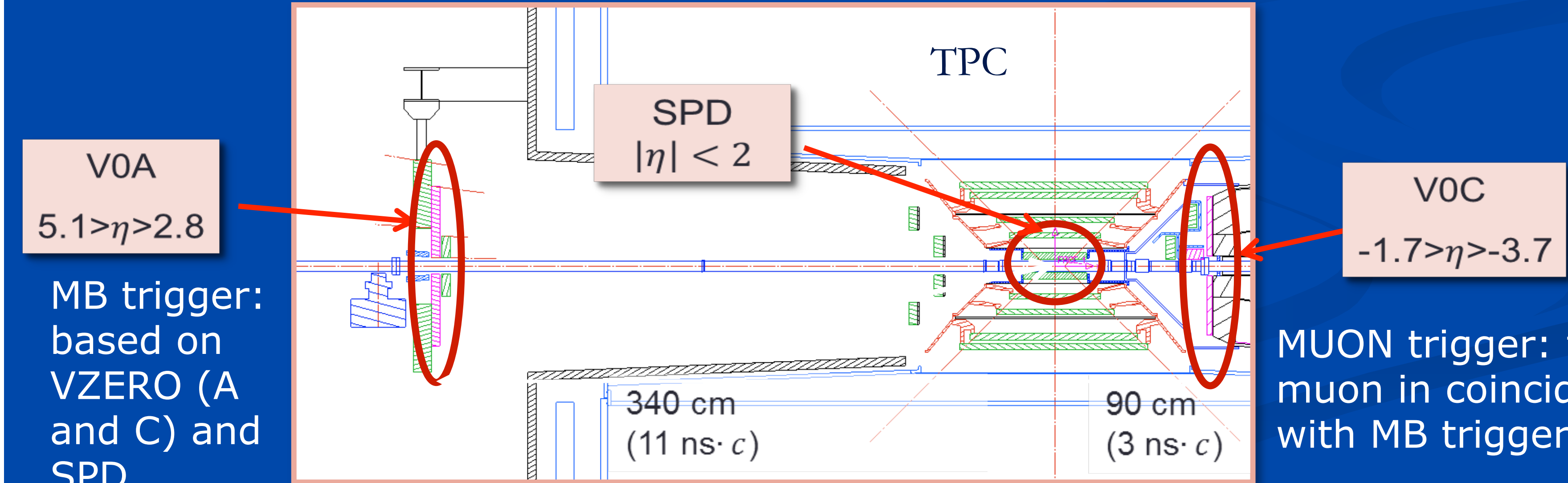
ALICE at LHC

Analyzed data samples

System	Energy (TeV)	Trigger	Analyzed events	∫Ldt
pp	7	MB MUON	300 M 130 M	5 nb^{-1} 16 nb^{-1}
PbPb	2.76	MB	17.7 M	2.9 μb^{-1}
pp	2.76	MB MUON	65 M ~9 M	1.1 nb^{-1} 20 nb^{-1}

} **2010**

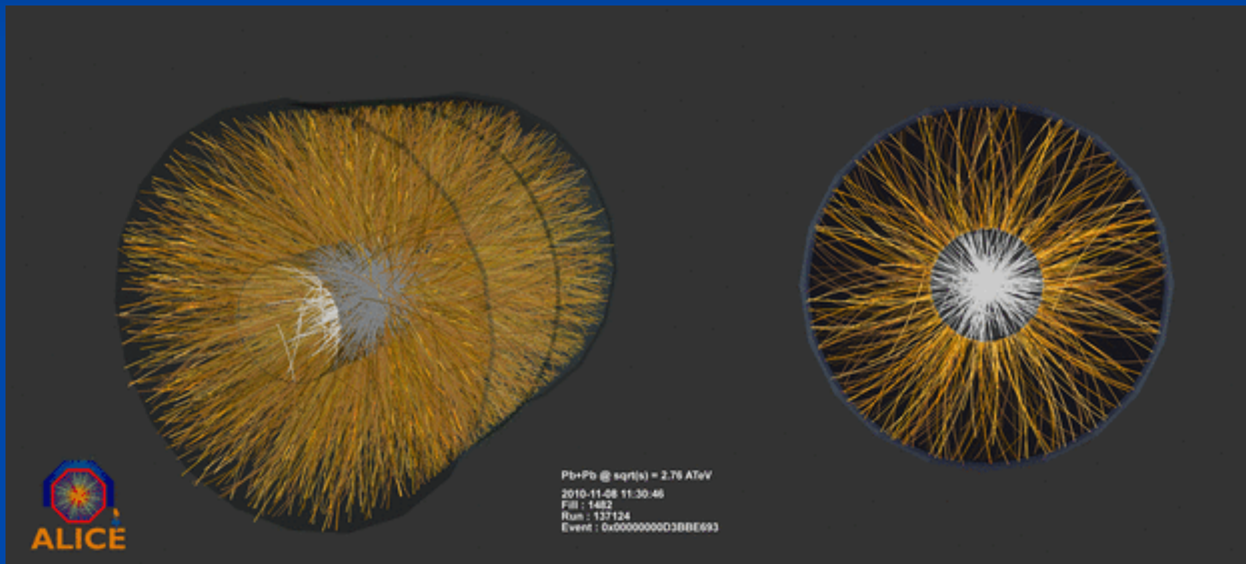
} **2011**



MB trigger: based on VZERO (A and C) and SPD

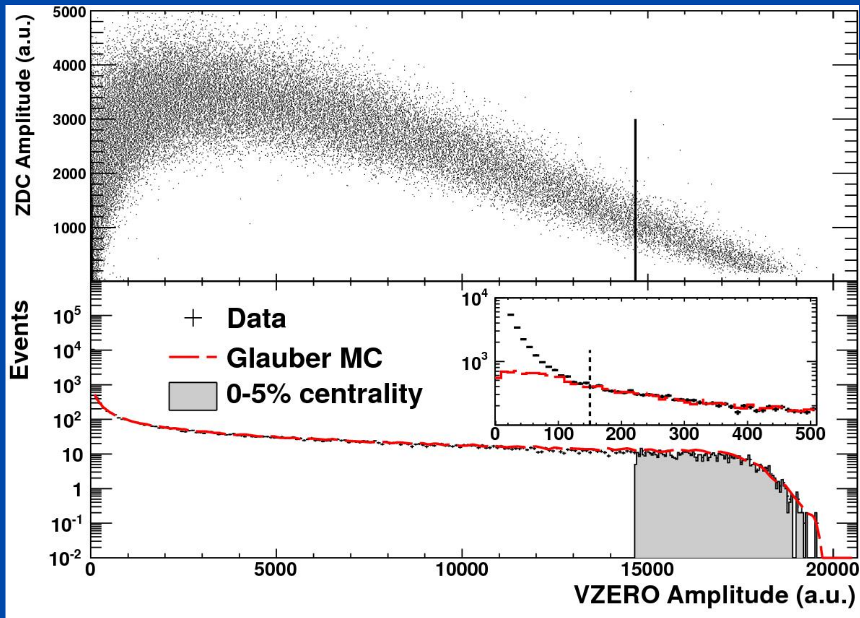
MUON trigger: forward muon in coincidence with MB trigger

Global features: centrality, system size, charged multiplicity



Centrality estimate

- Centrality observables: charged particle multiplicity (VZERO scintillator array), forward energy (zero-degree calorimeters)
- Glauber model fits to cross-section
- Define centrality classes corresponding to fractions of the inelastic Pb-Pb cross section



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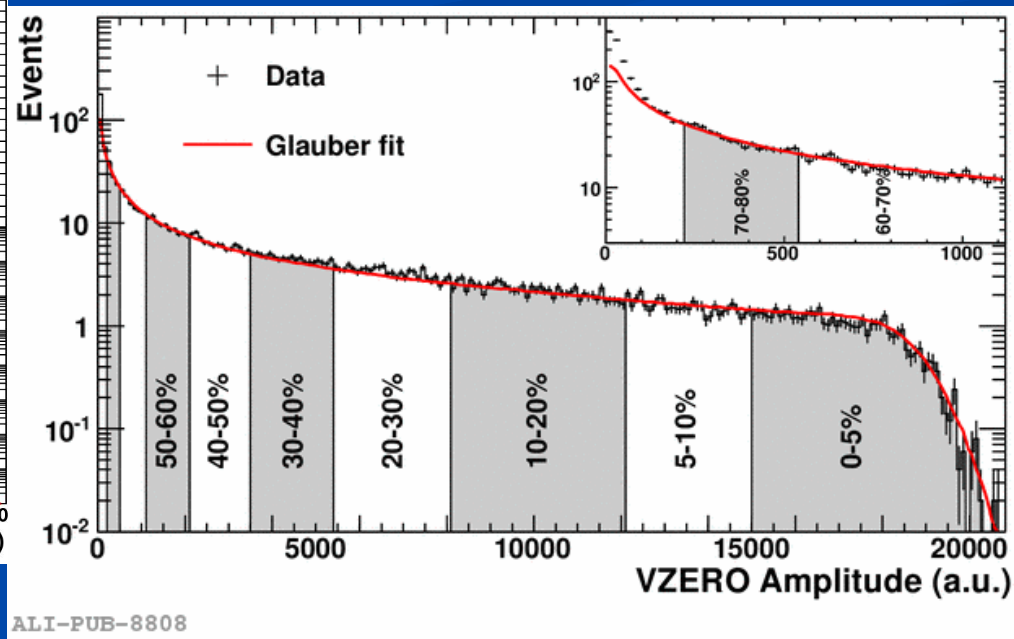
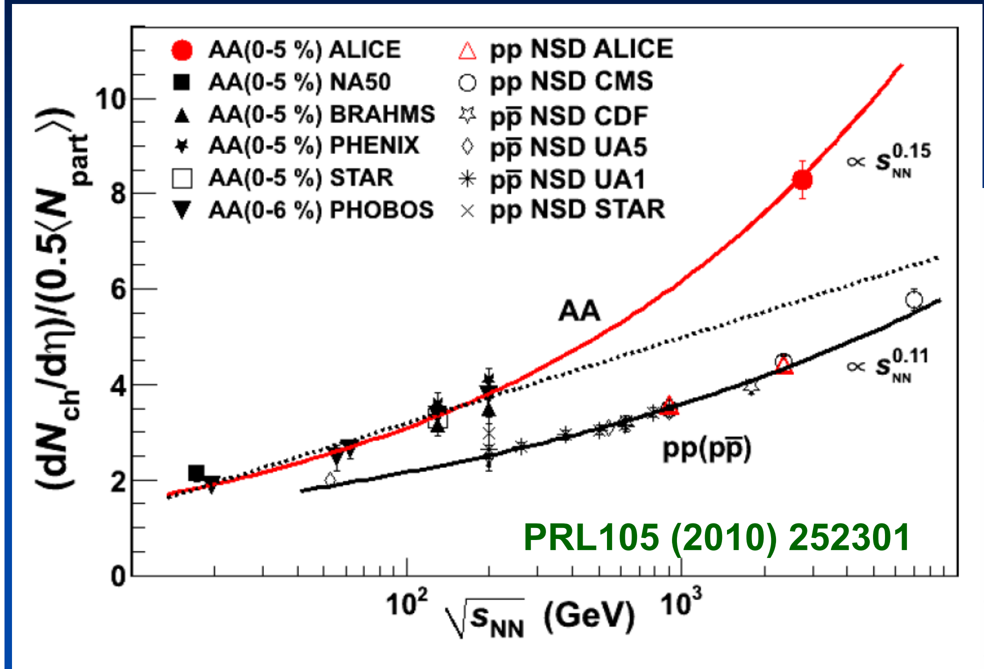
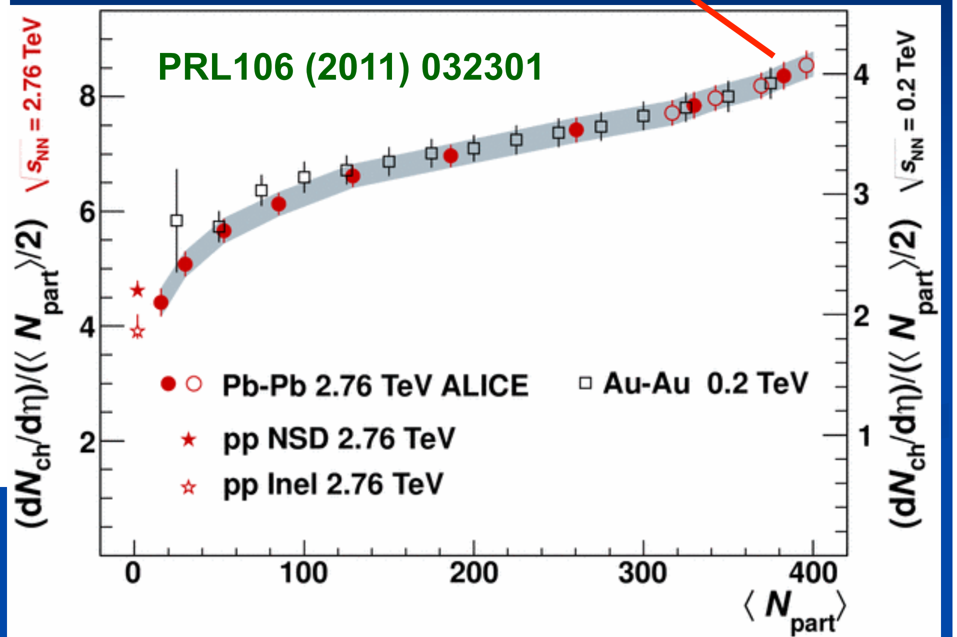
PRL106 (2011) 032301



Charged multiplicity



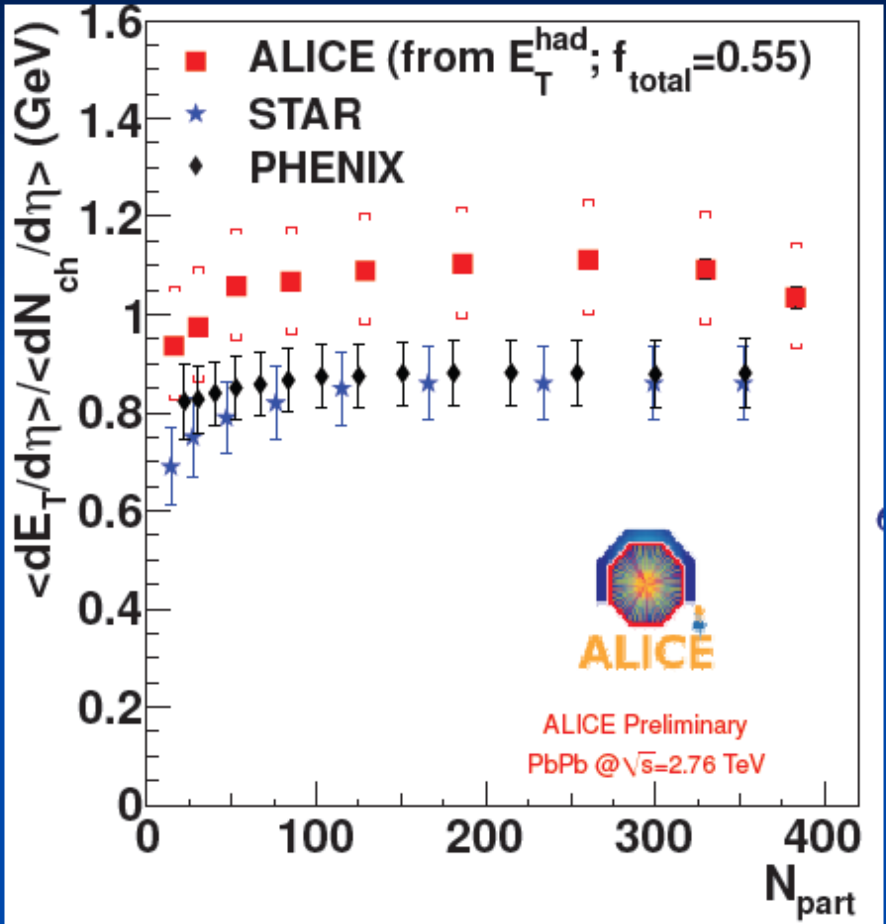
$\varepsilon_{Bj}\tau \cong 15\ \mathrm{GeV/(fm^2c)}$



- $dN_{ch}/d\eta$ = 1584 ± 76
- $(dN_{ch}/d\eta)/(N_{part}/2)$ = 8.3 ± 0.4
  - ≈ 2.1 x central AuAu at $\sqrt{s_{NN}}$=0.2 TeV
  - ≈ 1.9 x pp (NSD) at √s=2.36 TeV
- Stronger rise with √s in AA w.r.t. pp
- Stronger rise with √s in AA w.r.t. log extrapolation from lower energies

- Very similar centrality dependence at LHC & RHIC, after scaling RHIC results (x 2.1) to the multiplicity of central collisions at the LHC

Energy density



$dE_T/d\eta$:

- Same centrality dependence as at RHIC
- accounting for undetected fraction, LHC ~2.5 RHIC

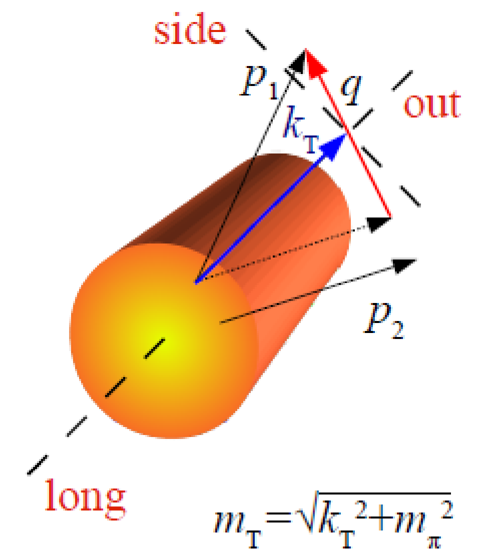
$$\epsilon_{Bj}(\tau) = \frac{1}{\tau \pi R^2} \frac{dE_T}{d\eta}$$

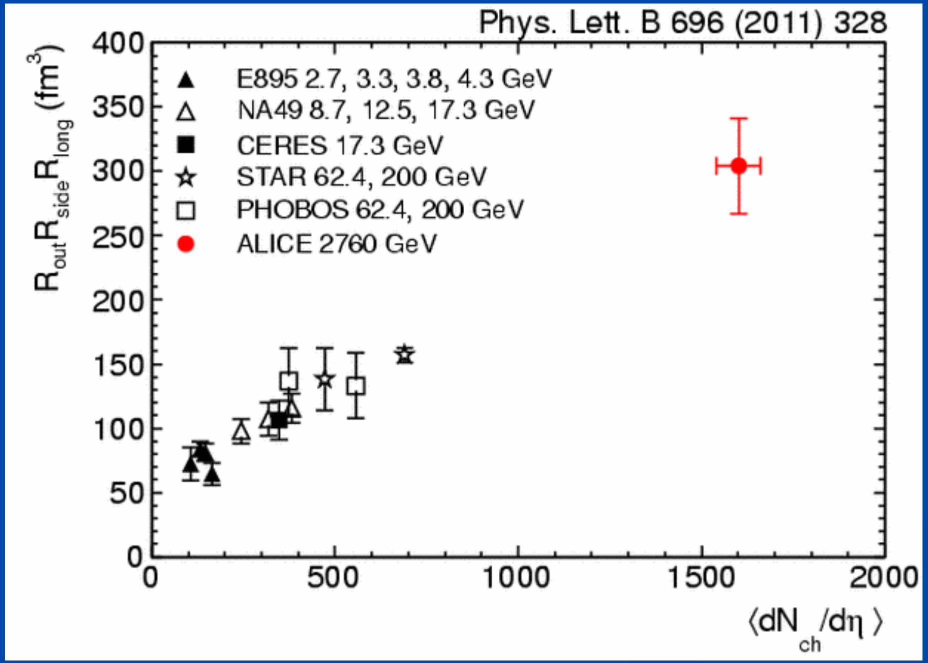
Bjorken energy density:

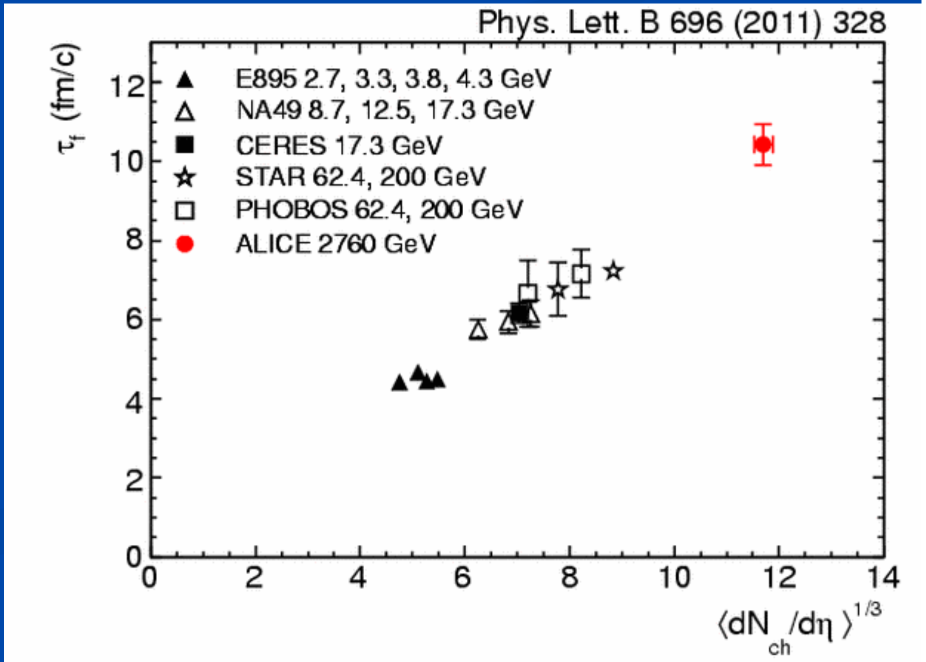
- Unknown (but likely < 1 fm/c) formation time
- ετ: LHC ~2.5 RHIC

System size

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

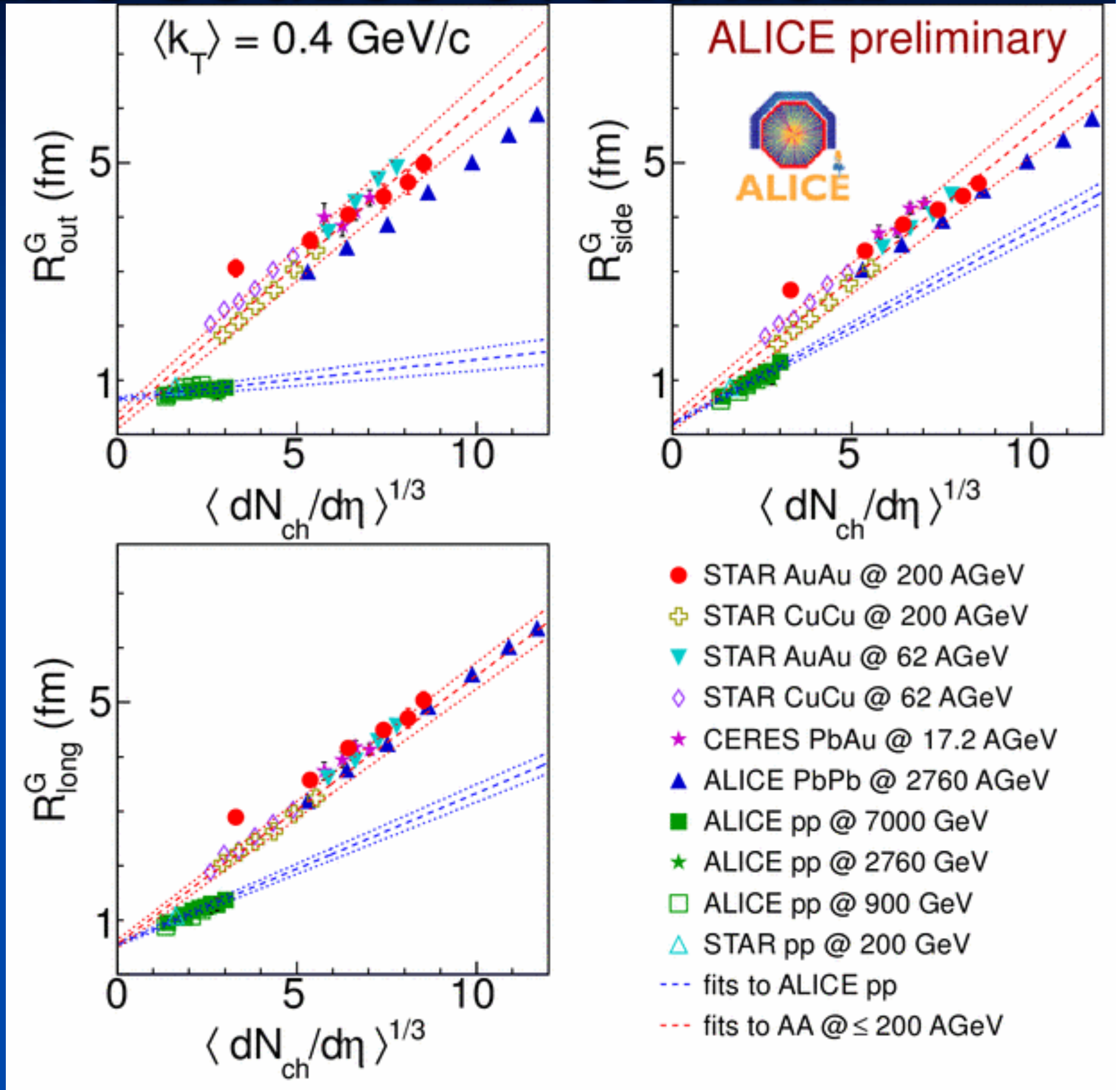




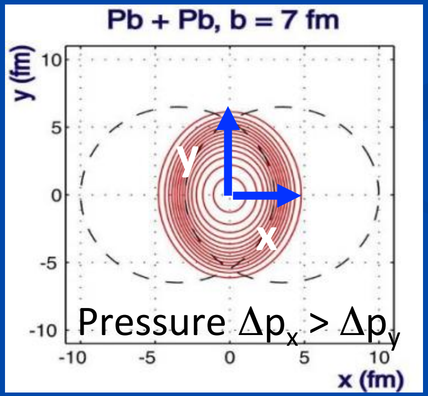


Space-time source evolution

- Decoupling (freezeout) time $\tau_f \propto R_{long}$
  - τ_f = 10-11 fm/c at LHC
- A-A and pp scale differently
- R_{out} at LHC cleary below the A-A trend:
  - qualitative agreement with hydrodynamic calculations
  - R_{out}/R_{side} in A-A (from 2 top plots) decreases with increasing √s (higher initial temperature at LHC)



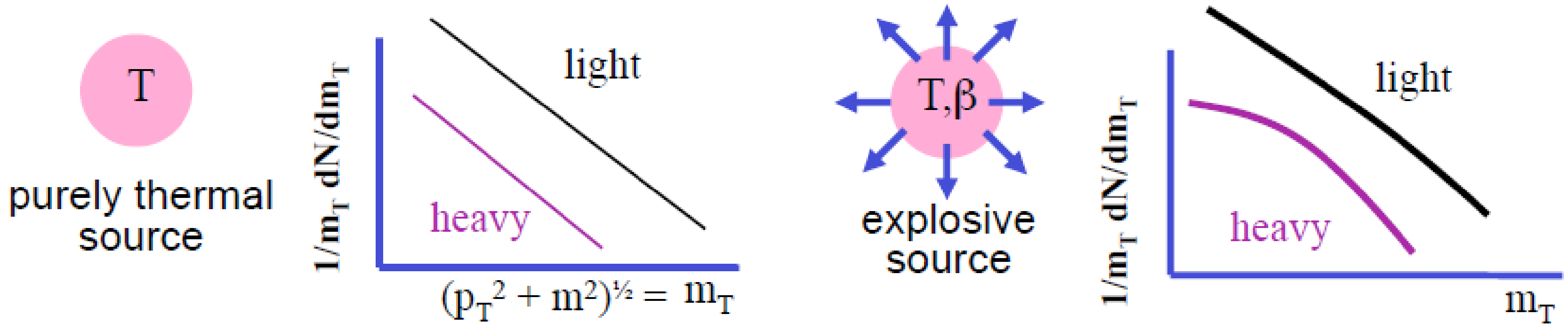
Collective expansion and anisotropic flow



'Temperature' from p_T spectra

Thermal source emits "Blackbody" radiation

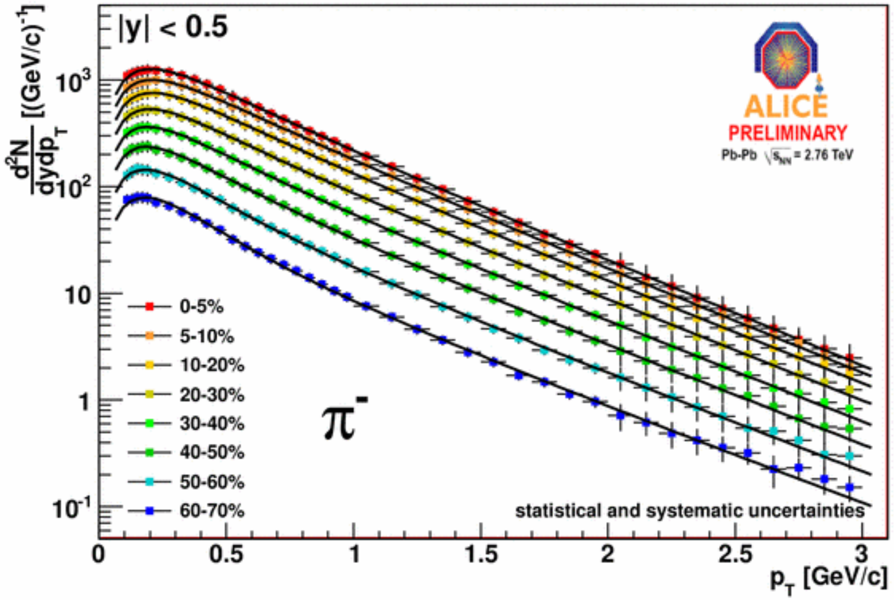
→ p_T spectra reveal temperature of QGP

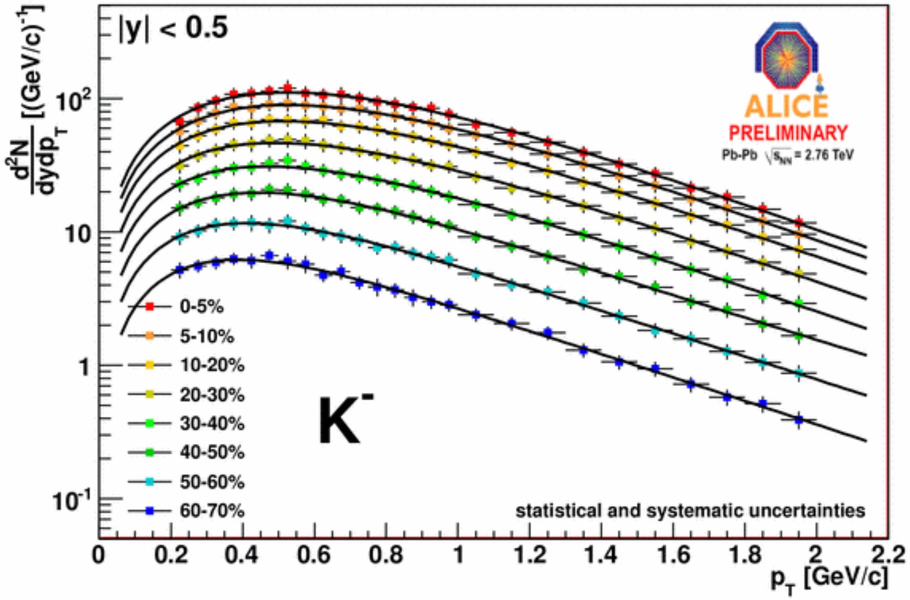


Different spectral shapes for particles of differing mass
→ strong collective radial flow

π light so not/hardly affected by flow

Identified hadron spectra in Pb-Pb

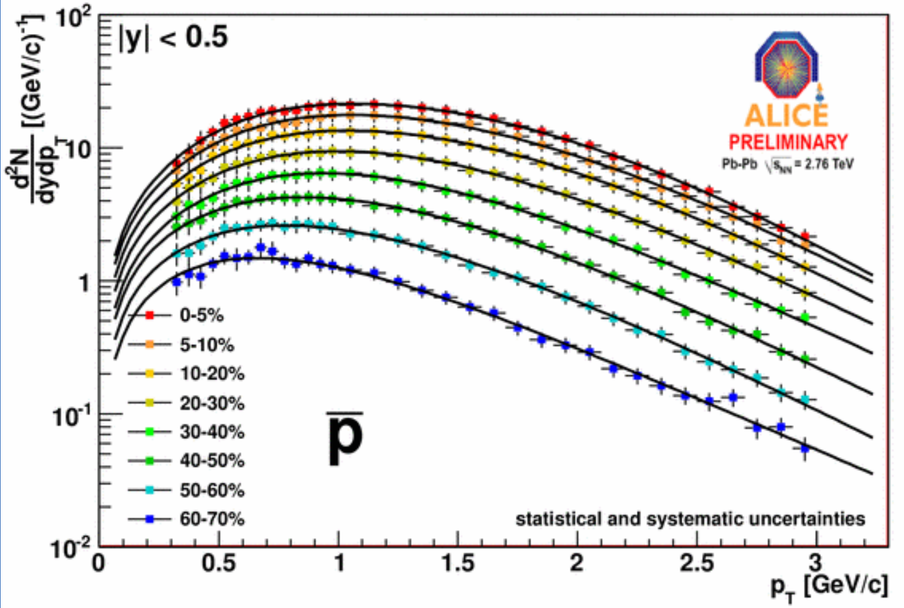




Lines = blast-wave* fits, extract:

- Integrated yields dN/dy
- Average p_T
- parameters of system at thermal freeze-out: T_{fo}, β (radial flow velocity)

(*) E. Schnedermann et al., PRC 48, 2462 (1993)



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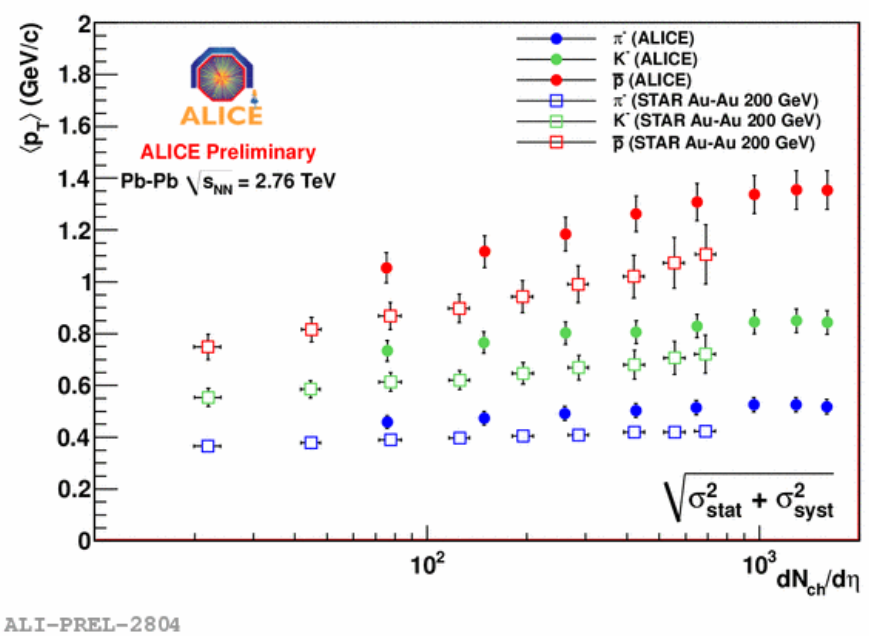
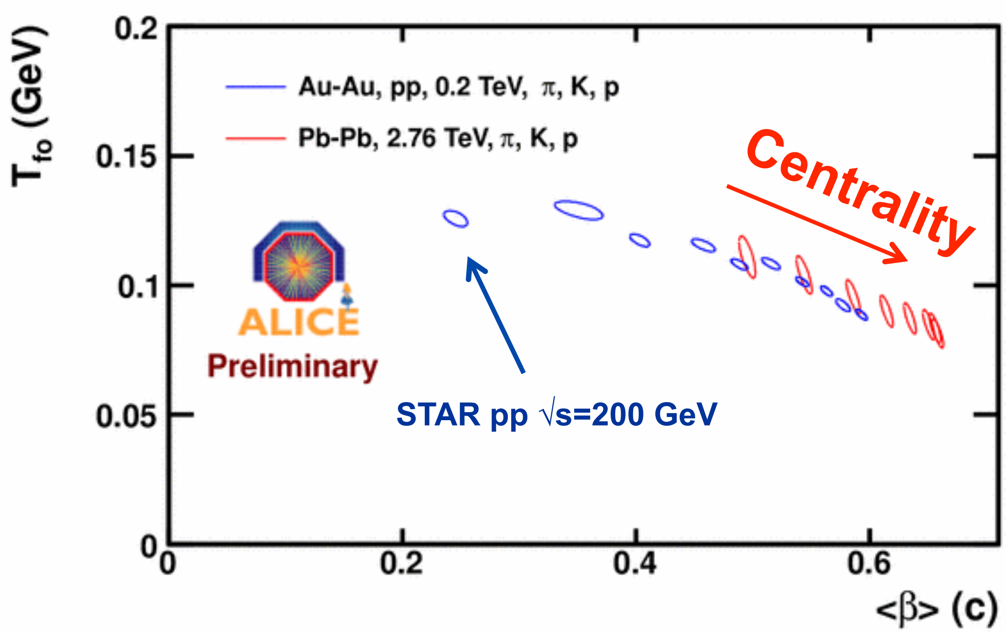
Radial expansion

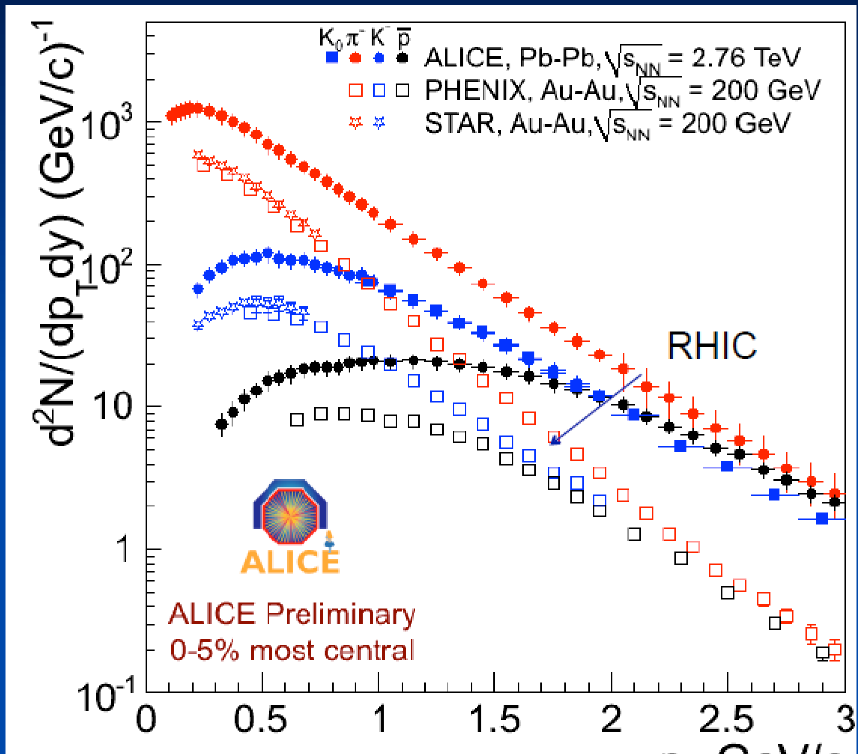




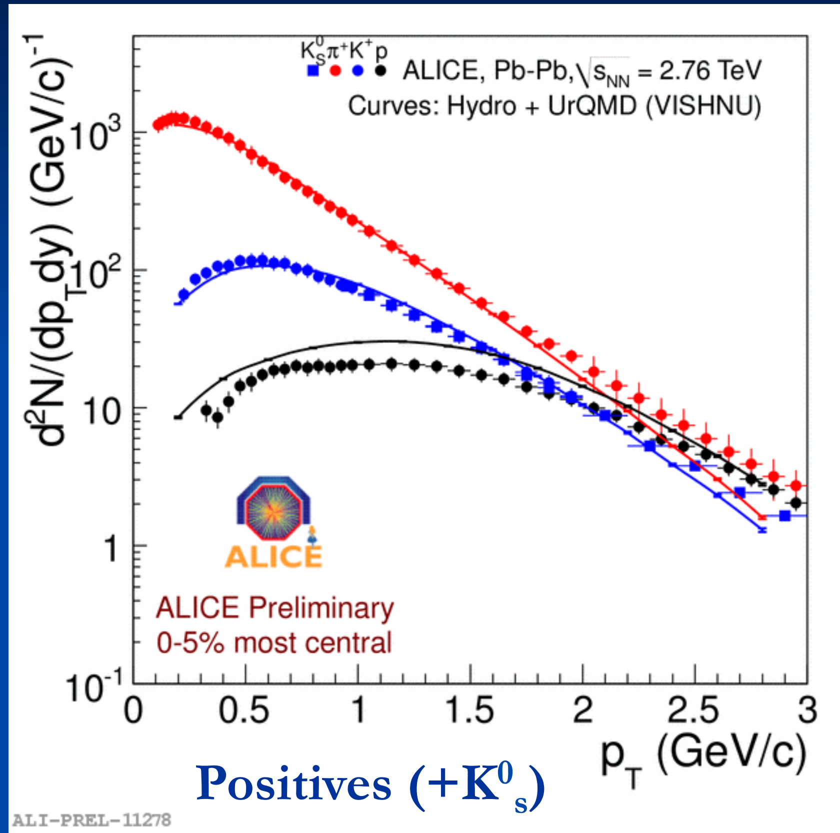
- Significant change in mean p_T between $\sqrt{s_{NN}}$=200 GeV and 2.76 TeV → harder spectra
- For the same dN/dη higher mean p_T than at RHIC

- Common blast-wave fit to π, K and p
- Strong radial flow: β≈ 0.66 for most central collisions, 10% higher than at RHIC
- Freeze-out temperature below 100 MeV

Compare to RHIC, hydrodynamics



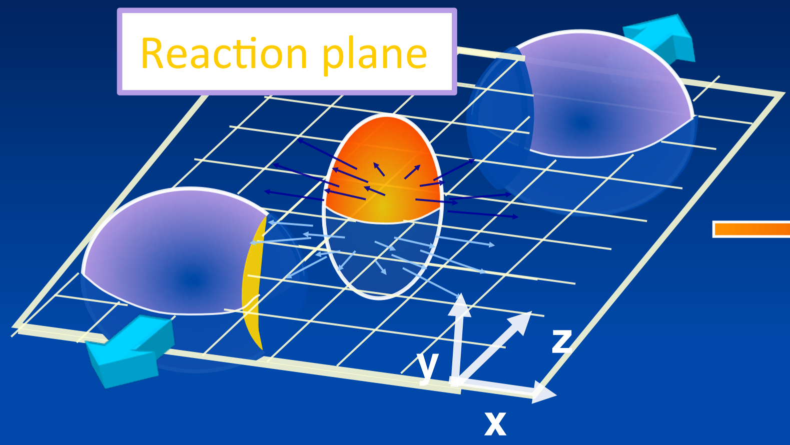
Negatives ($+K^0_s$)

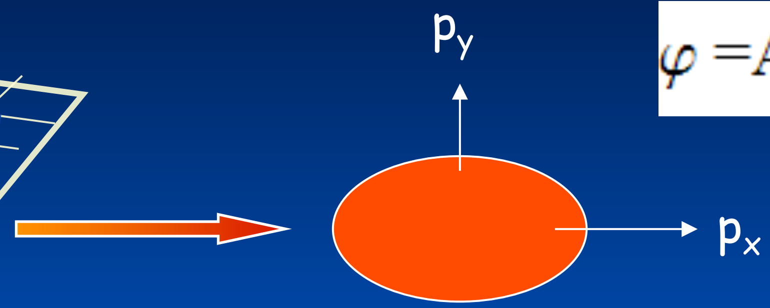


Positives ($+K^0_s$)

- Spectra much harder, yields higher than at RHIC
- Radial flow higher at LHC
- Hydro calculations with intial temperature ~420 MeV
- Proton yield overestimated by hydro

Azimuthal Anisotropy – Elliptic Flow





$$\varphi = \mathrm{ArcTan}\left(\frac{p_y}{p_x}\right)$$

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

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 (RP) defined by “soft” (low p_T) particles

$$\Delta\varphi = \varphi - \Psi_{RP}$$

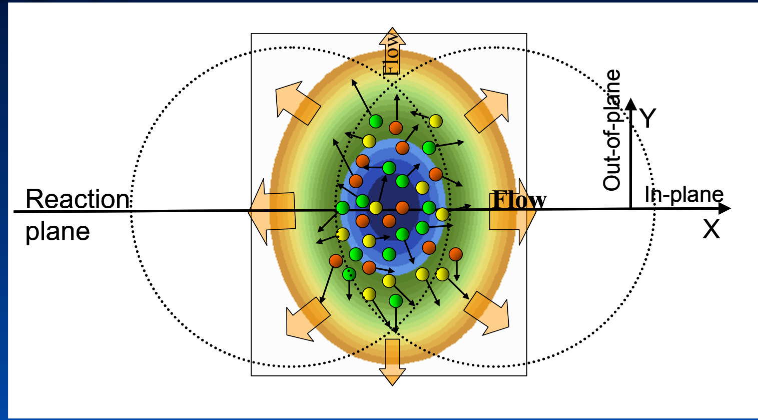
Elliptical flow

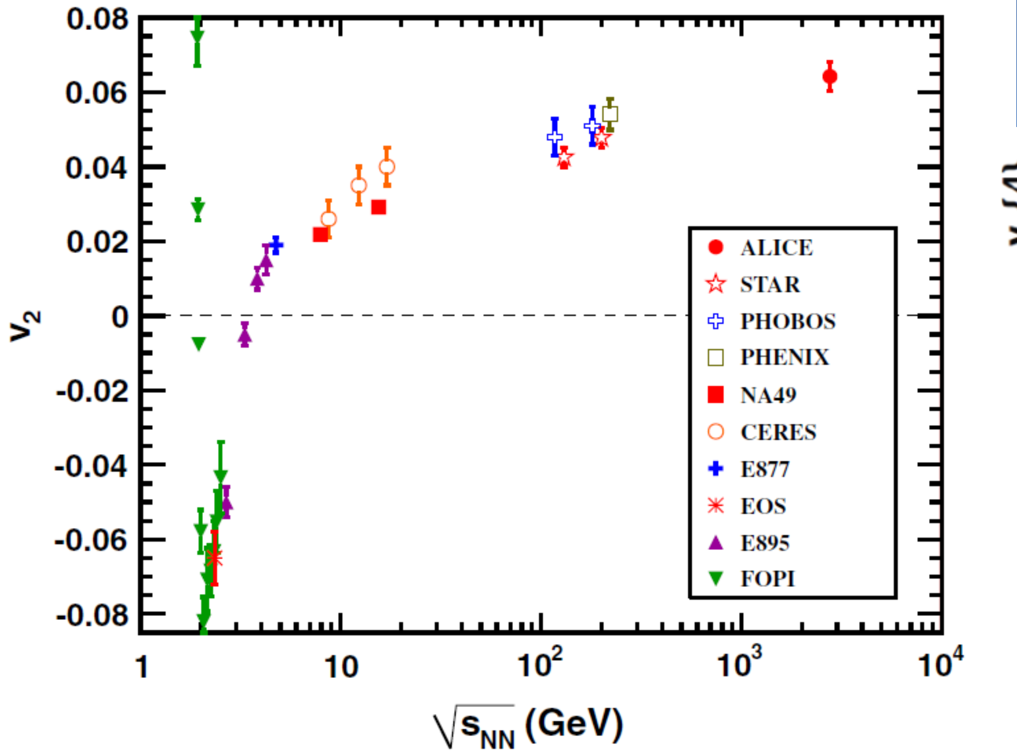
$$\frac{dN}{d\Delta\varphi} = \propto 1 + 2 v_2 \cos(2\,\Delta\varphi)$$

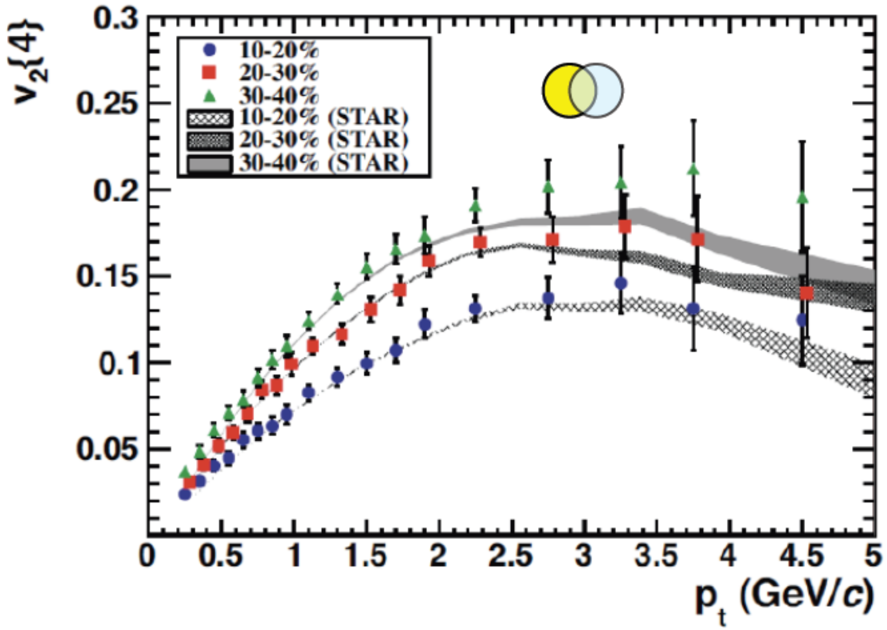
Elliptic flow

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

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

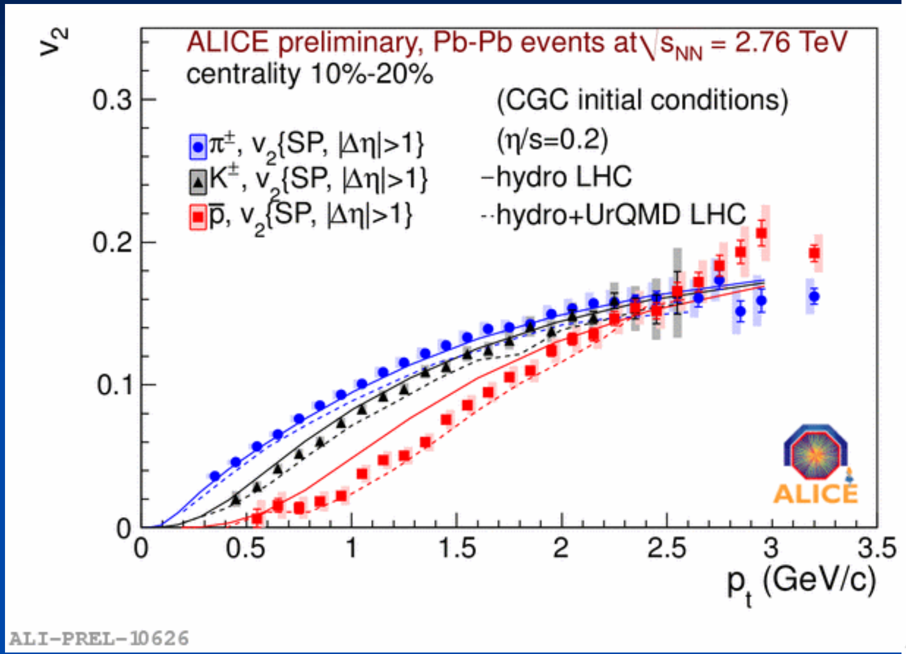


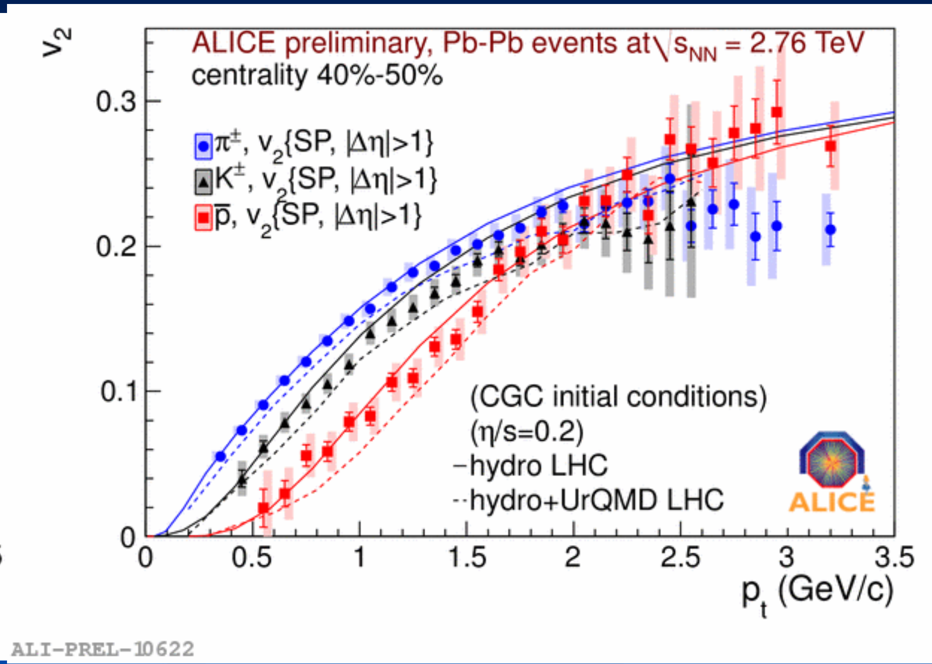




- v_2 (LHC) ~ 1.3 v_2 (RHIC) (p_T integrated), increase consistent with increased radial expansion (higher $\langle p_T \rangle$)

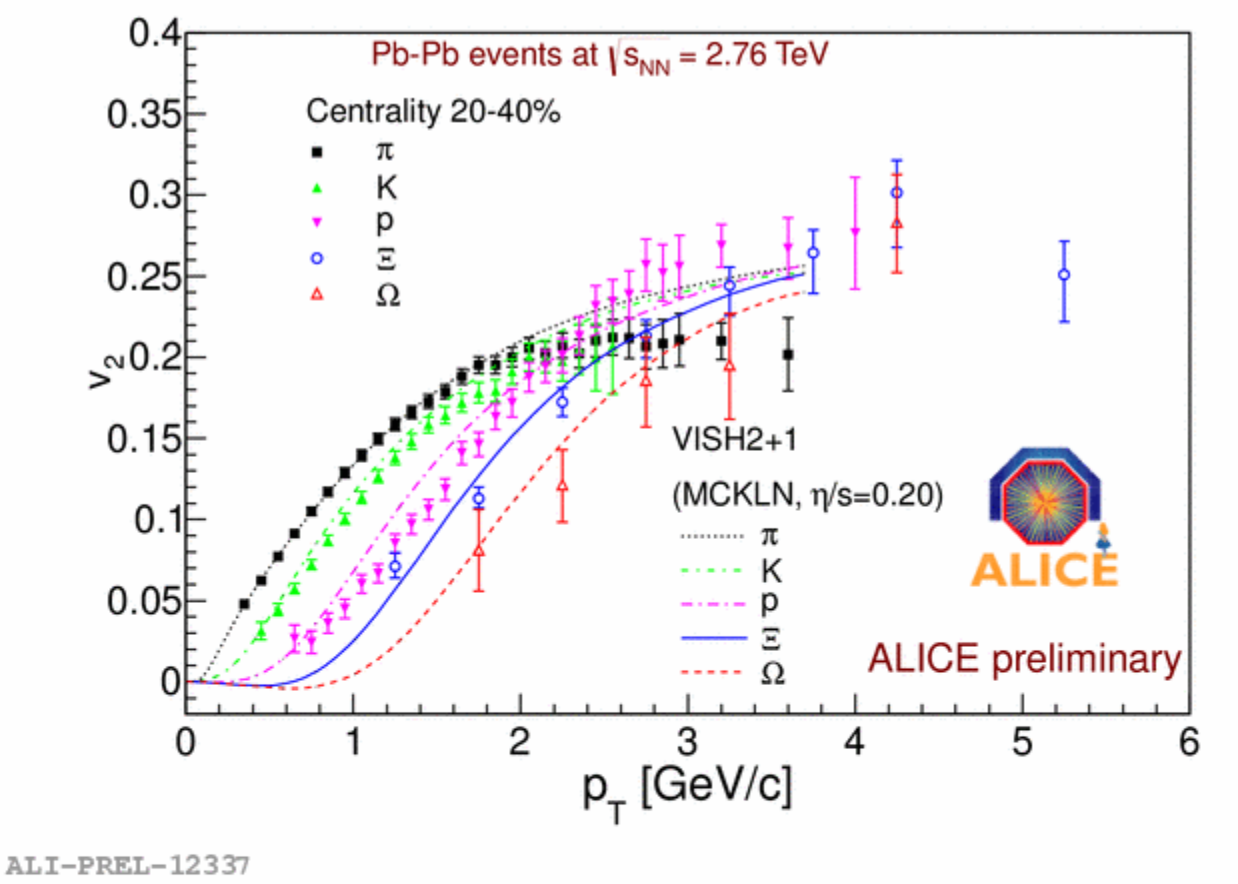
Flow of identified particles (I)





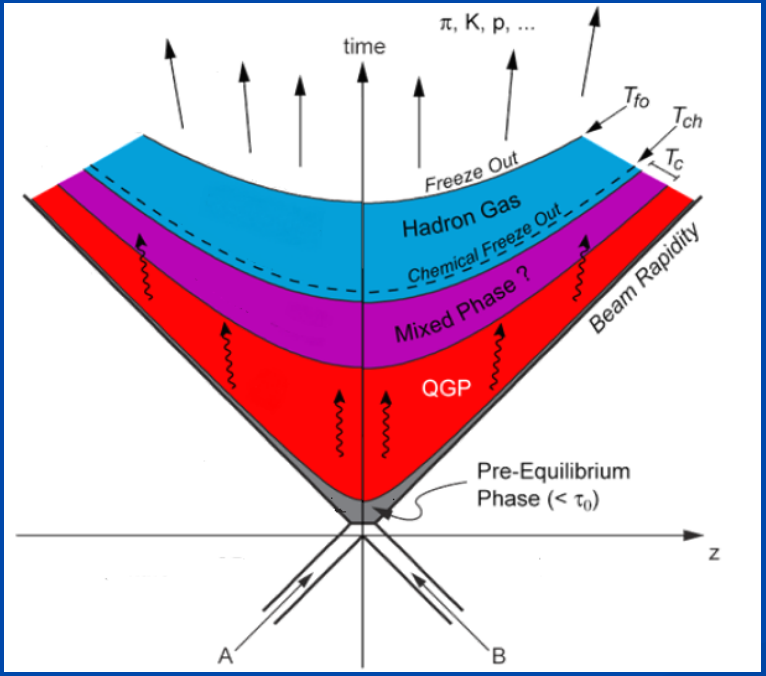
- Elliptic flow shows strong mass dependence, due to large radial flow
- Magnitude and mass splitting of $v_2(p_T)$ generally well predicted by hydrodynamics
- Hydro in disagreement for antiprotons in the more central bin, hydro +UrQMD does a better job

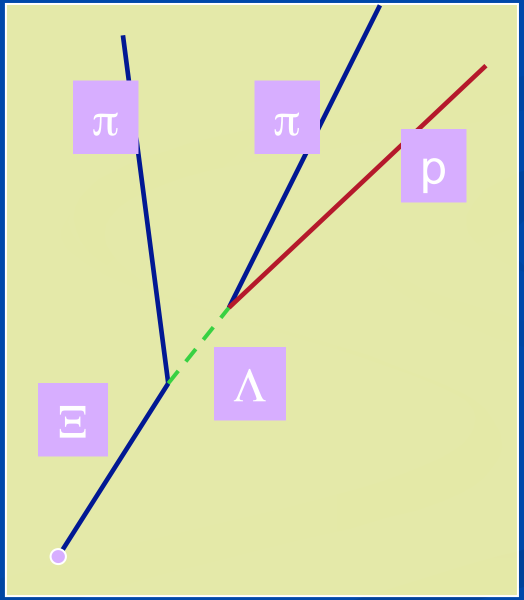
Flow of identified particles (II)



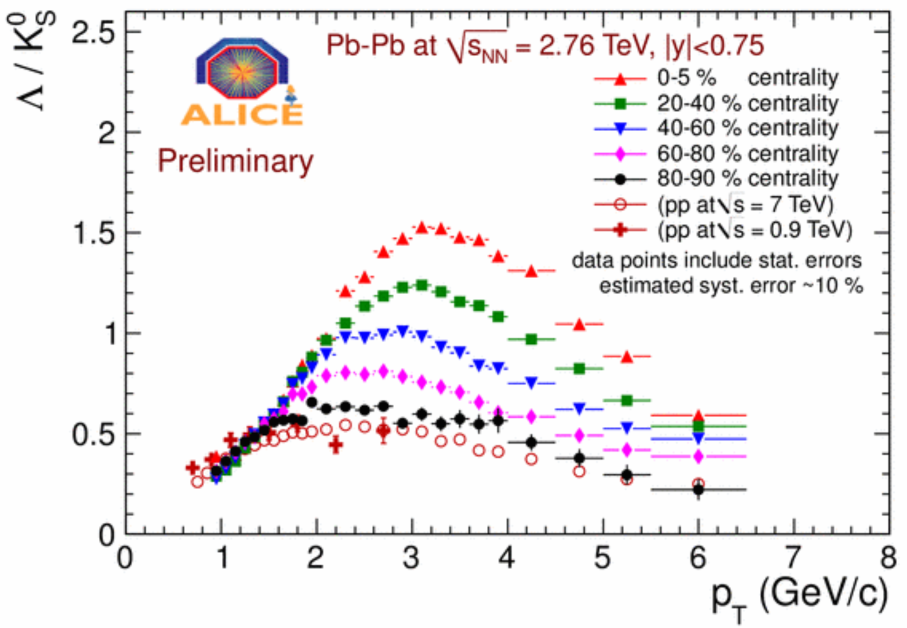
- More recent hydrodynamic calculations reproduce flow of multi-strange baryons as well

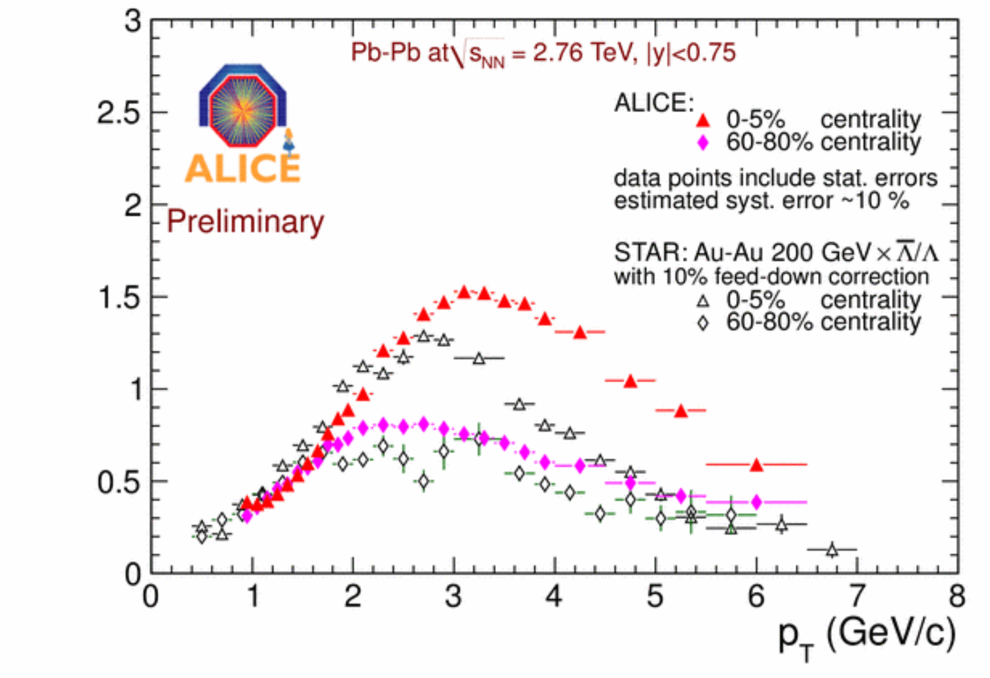
Strangeness and chemical composition





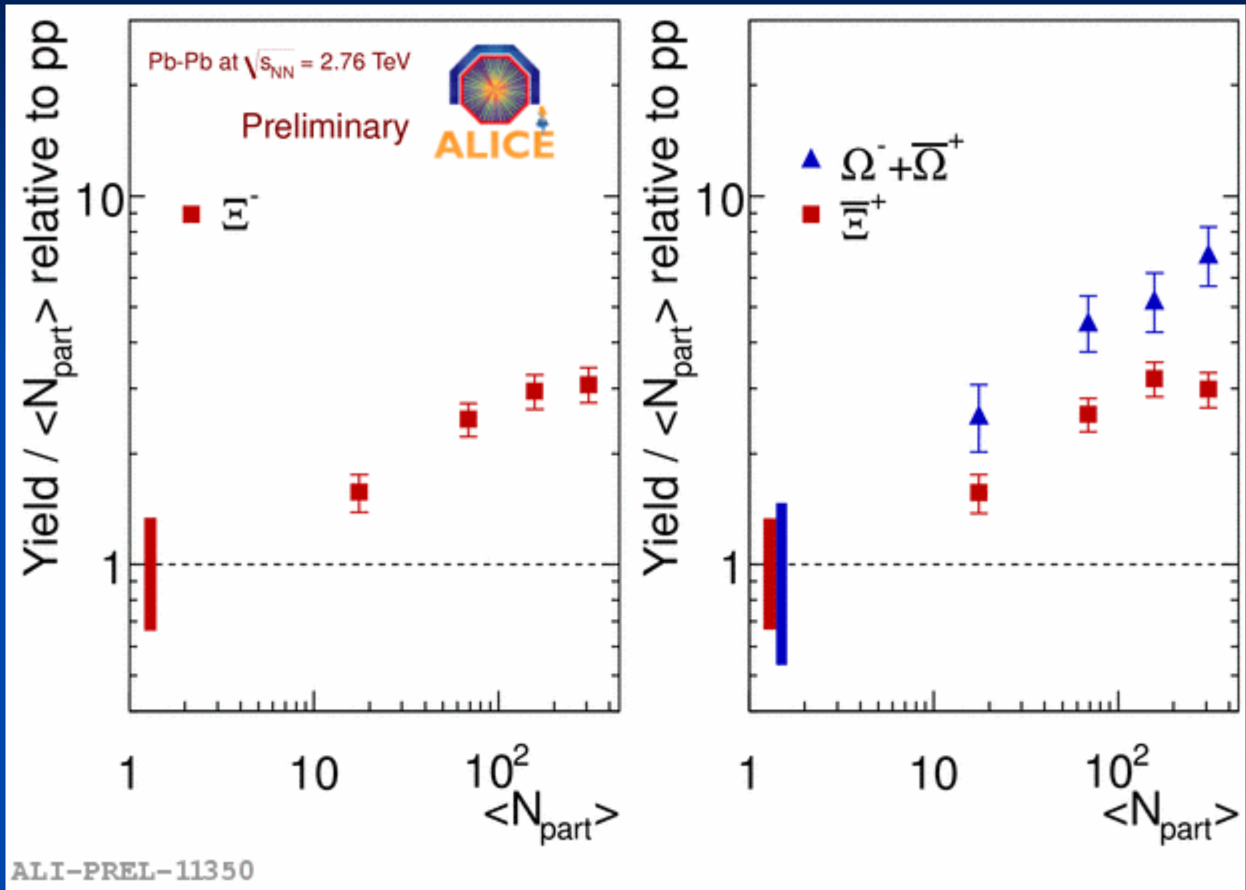
Strangeness in Pb-Pb





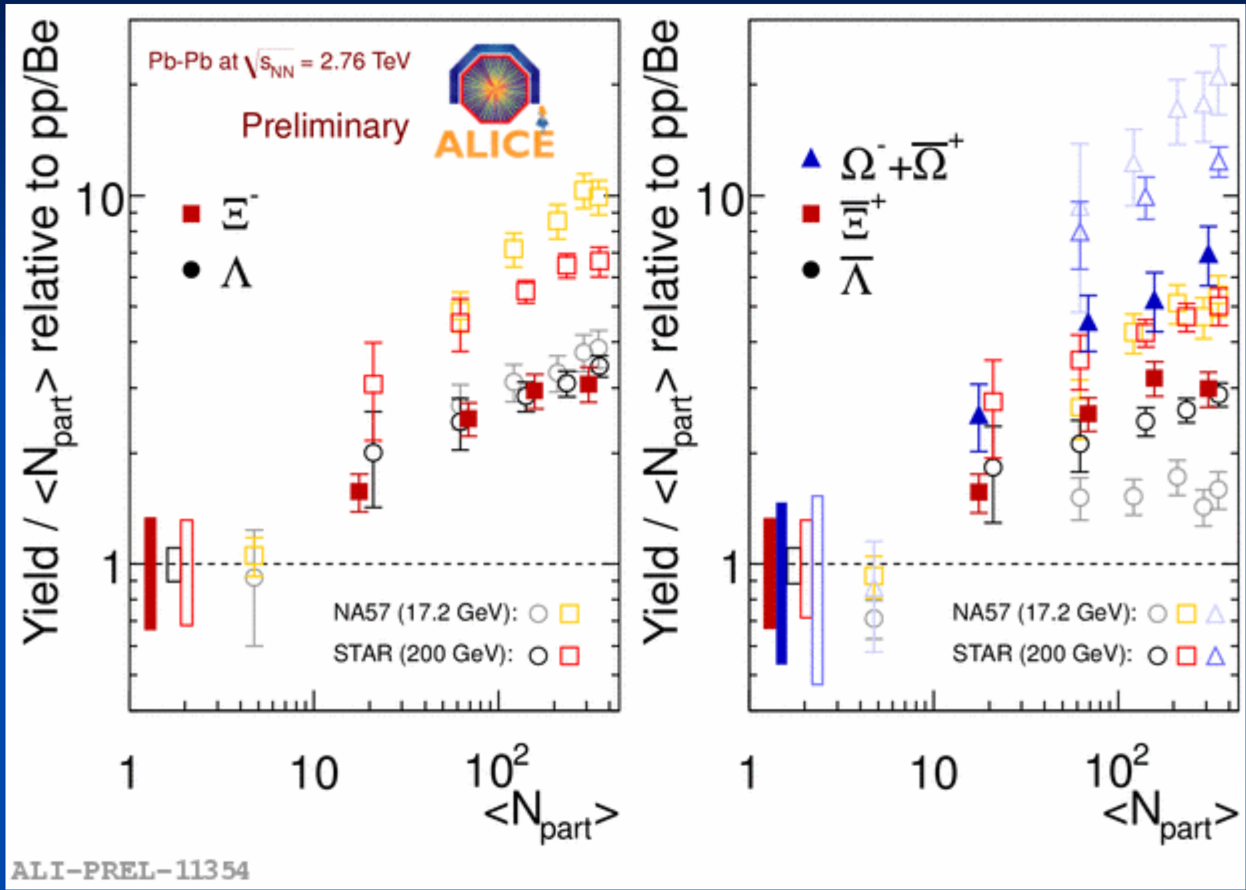
- Strange baryons are more abundant than mesons at higher p_T
- Baryon/Meson ratio increases with centrality, consistent with the quark recombination scenario
- The B/M ratio is higher at LHC than at RHIC
- The p_T where the maximum occurs is higher at LHC: due to higher radial flow?

Multi-strange baryons in Pb-Pb (I)



- Production of multi-strange baryons in Pb-Pb collisions at √s=2.76 TeV enhanced with respect to pp

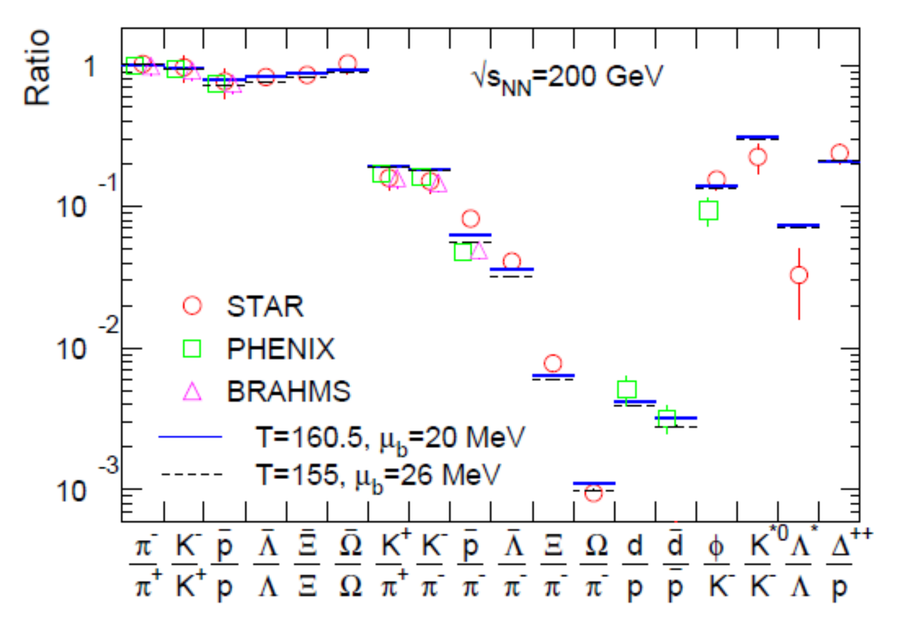
Multi-strange baryons in Pb-Pb (II)

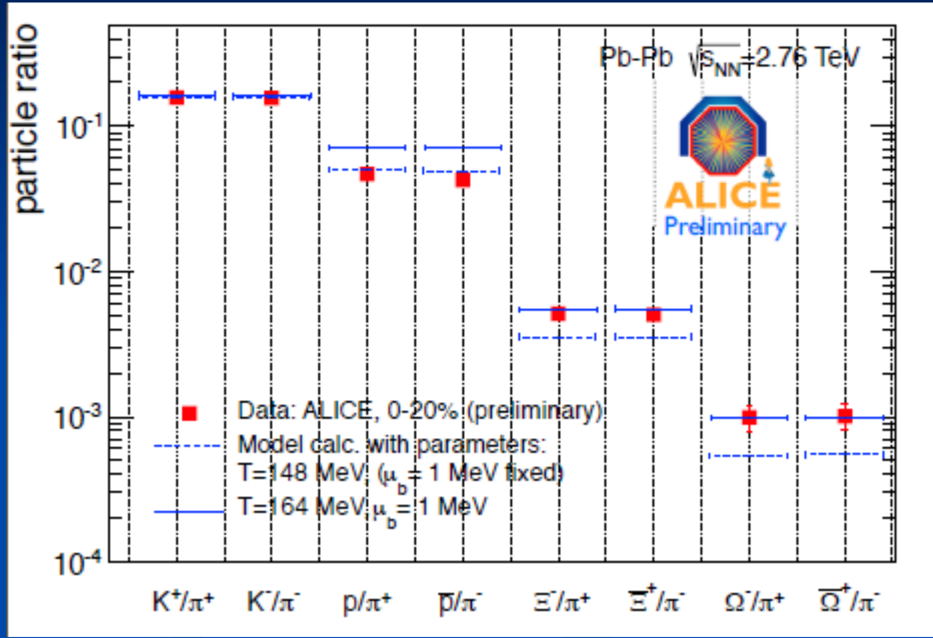


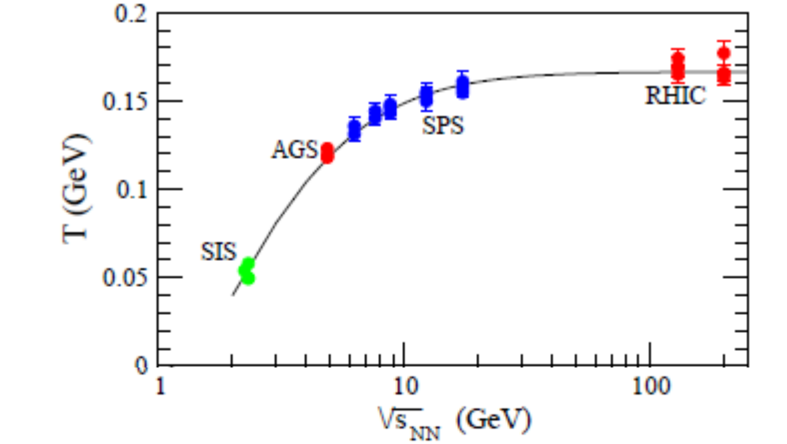
- The enhancement increases with the number of strange quarks and with centrality, confirming the SPS/RHIC trend
- The enhancement decreases with increasing √s

Chemical composition

Abundances of hadrons can be described by statistical distributions (T_{ch}, μ_B)



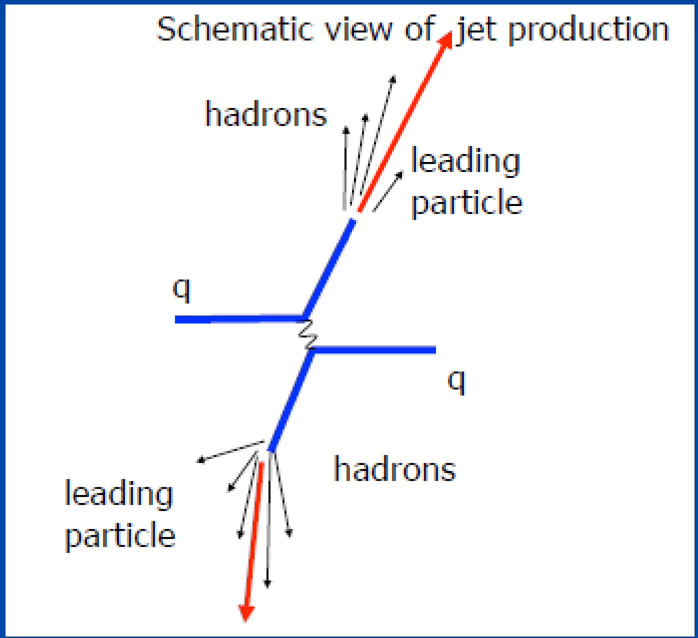


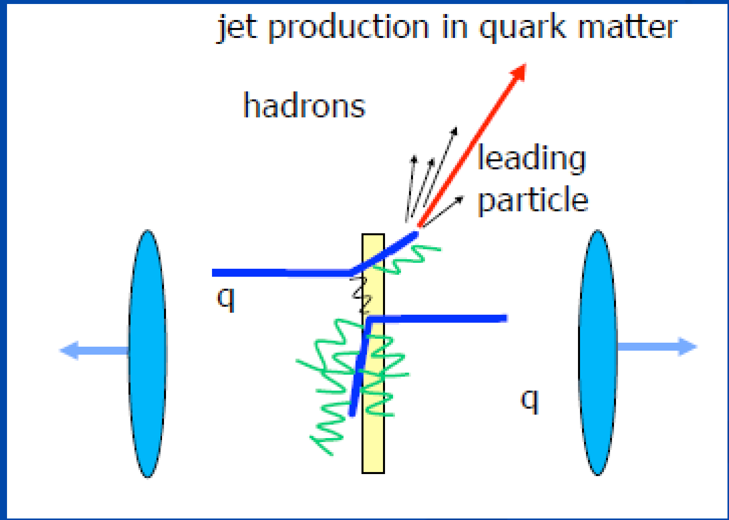


A. Andronic et al., Nucl. Phys. A772 (2006)

- Low T_{ch} suggested by p spectra, but excluded by Ξ and Ω
- If p excluded, T_{ch} = 164 MeV → T_{ch} (LHC) ~ T_{ch} (RHIC) ~ T_c

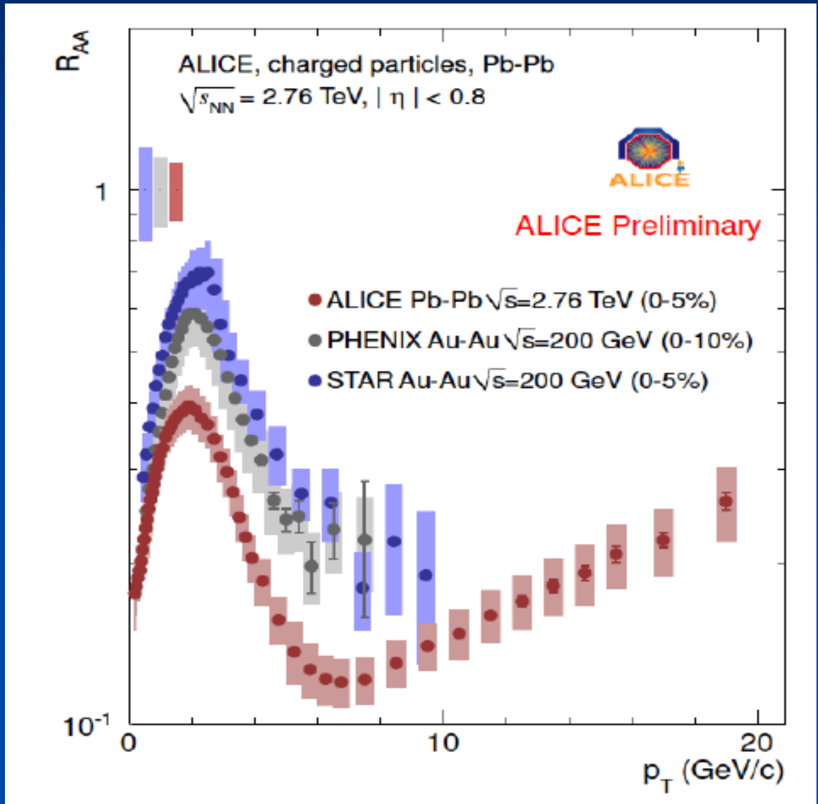
Parton energy loss in the medium

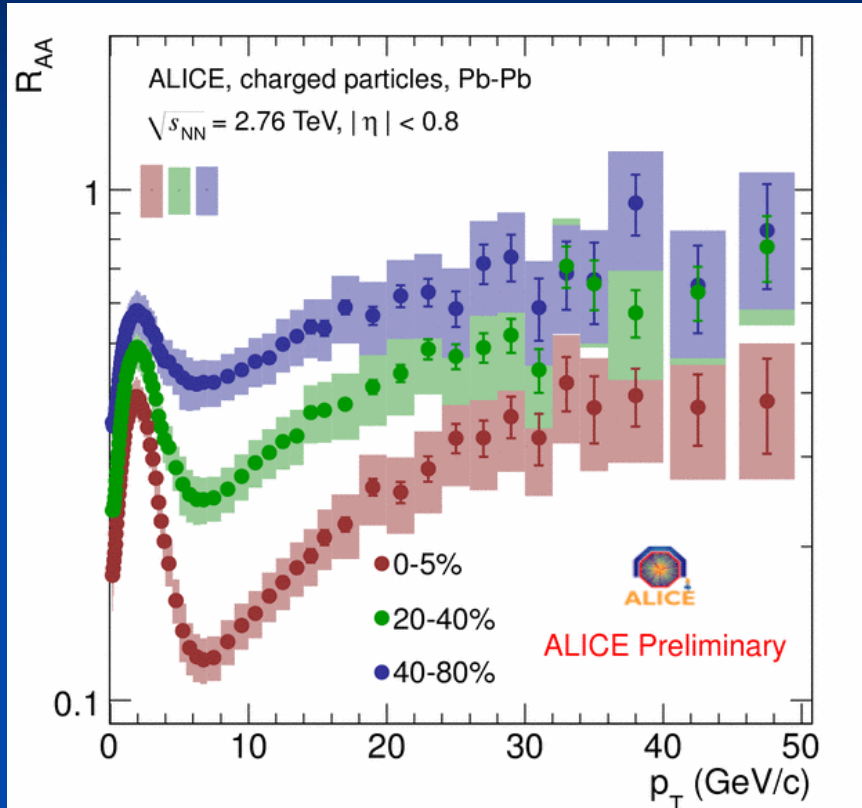




Charged hadron R_{AA}

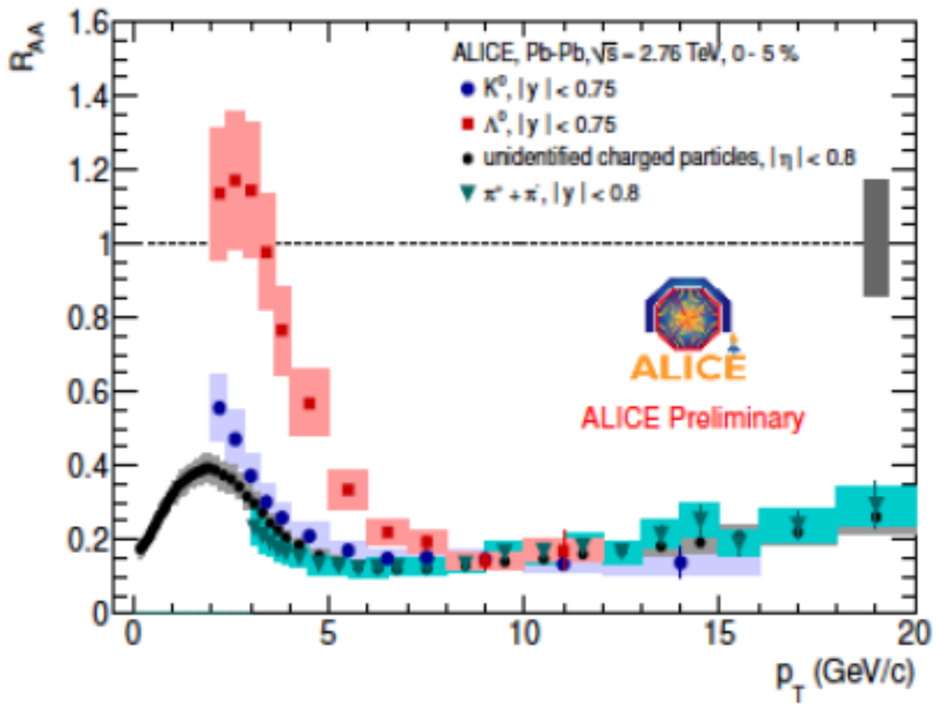
- $R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$ → parton energy loss (BDMPS) $\langle \Delta E \rangle \propto \alpha_s C_R \hat{q} L^2$

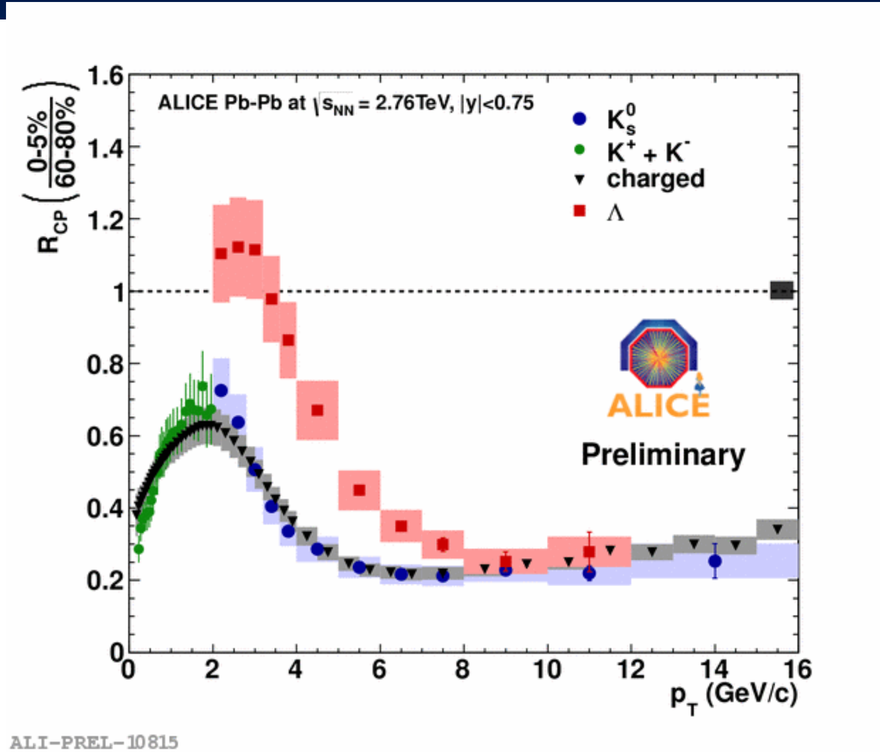




- Larger suppression wrt RHIC, suppr. increases with centrality (largest at pT ~ 6-7 GeV/c)
- R_{AA} increases for p_T > 10 GeV/c, hints of flattening above 30 GeV/c

R_{AA}, R_{CP} of identified hadrons

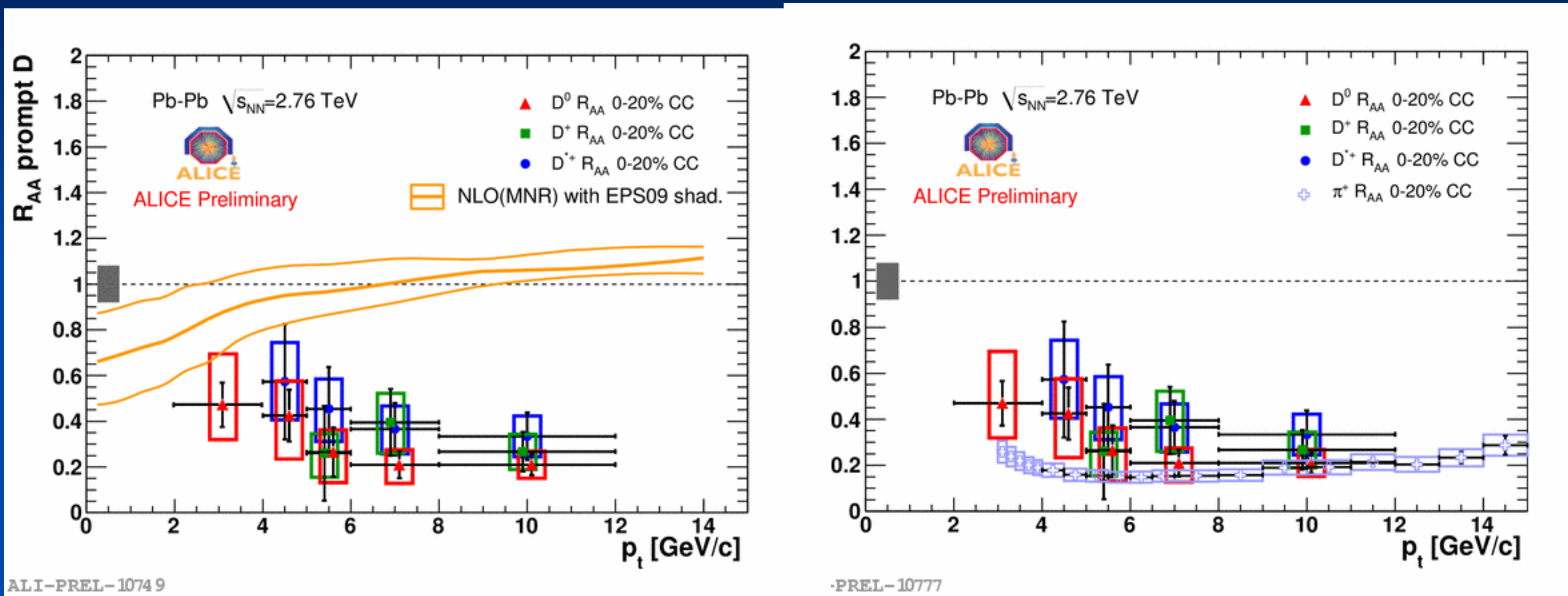




- Mesons vs. baryons, different R_{AA} at intermediate p_T : related to baryon enhancement, observed e.g. in Λ/K ratio
- At high p_T (>8-10 GeV/c) R_{AA} universality for light hadrons
- For hadrons containing heavy quarks, smaller suppression expected: dead cone effect, gluon rad. suppressed for $\vartheta < m_q/E_q$

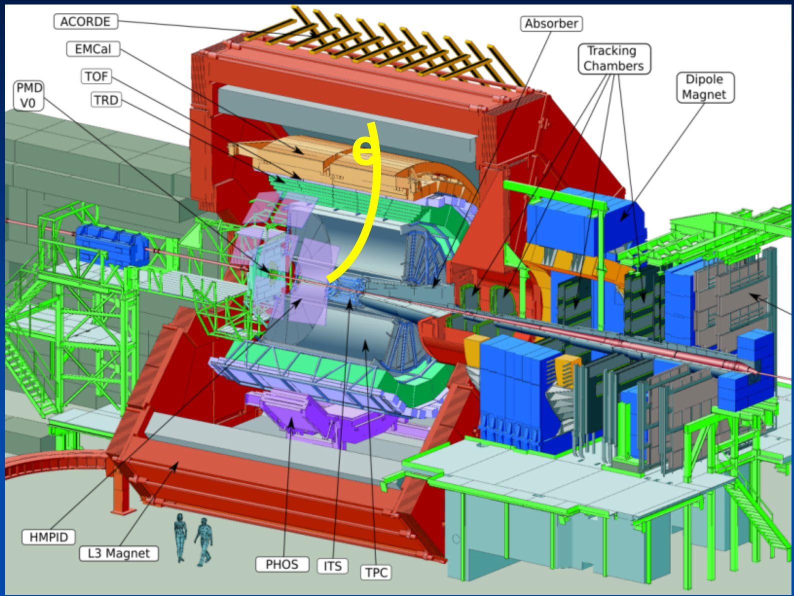
D-meson R_{AA}

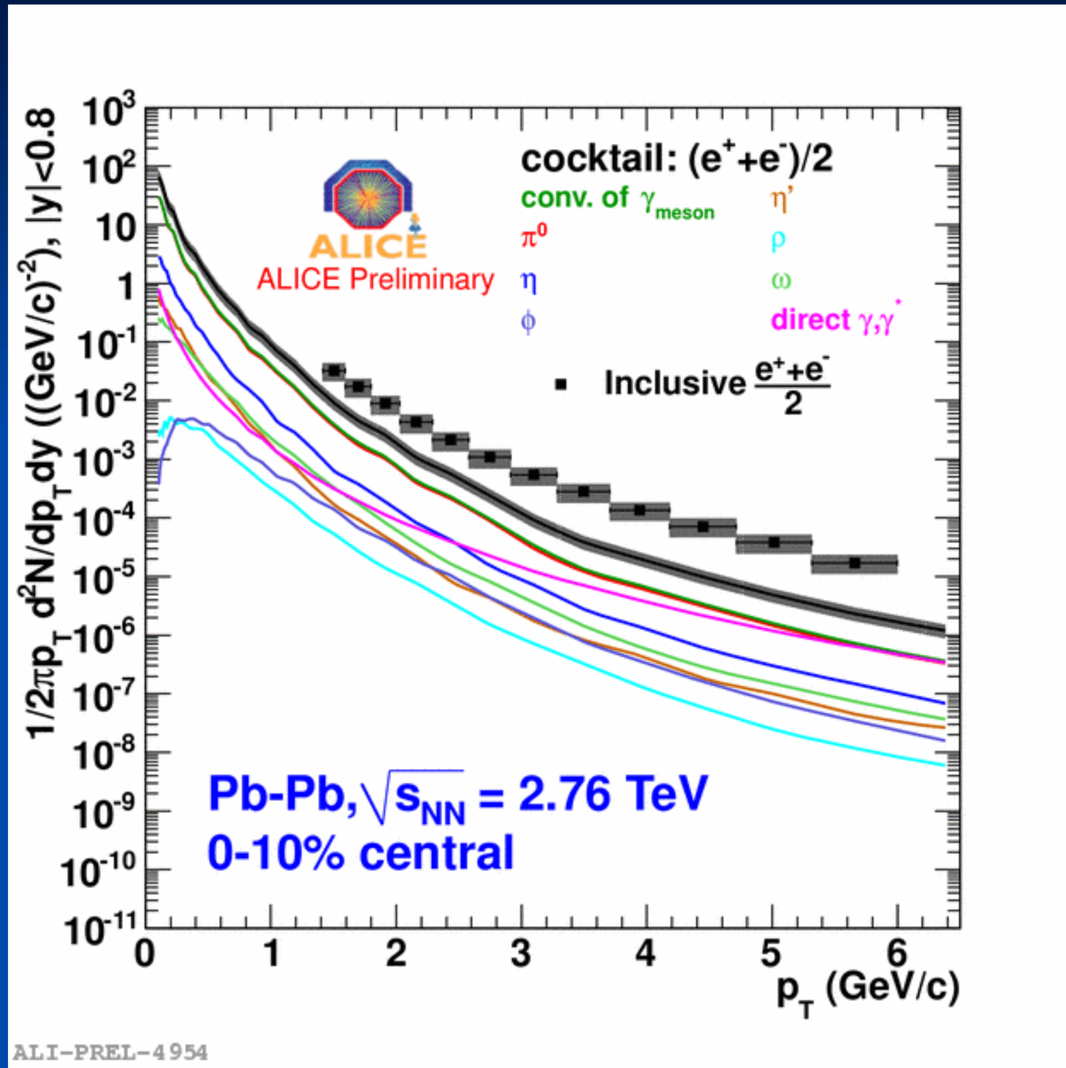
• pp reference: measured D^0, D^+ & D^* $d\sigma/dp_T$ @ 7 TeV → 2.76 TeV (FONLL)



- Suppression of prompt D mesons in central (0-20%) Pb-Pb collisions by a factor 4-5 for p_T>5 GeV/c
  - Little shadowing at high p_T → suppression comes from hot matter
  - Similar suppression for D mesons and pions, hint of $R_{AA}^D > R_{AA}^{\pi}$ at low p_T

Electrons from heavy flavours

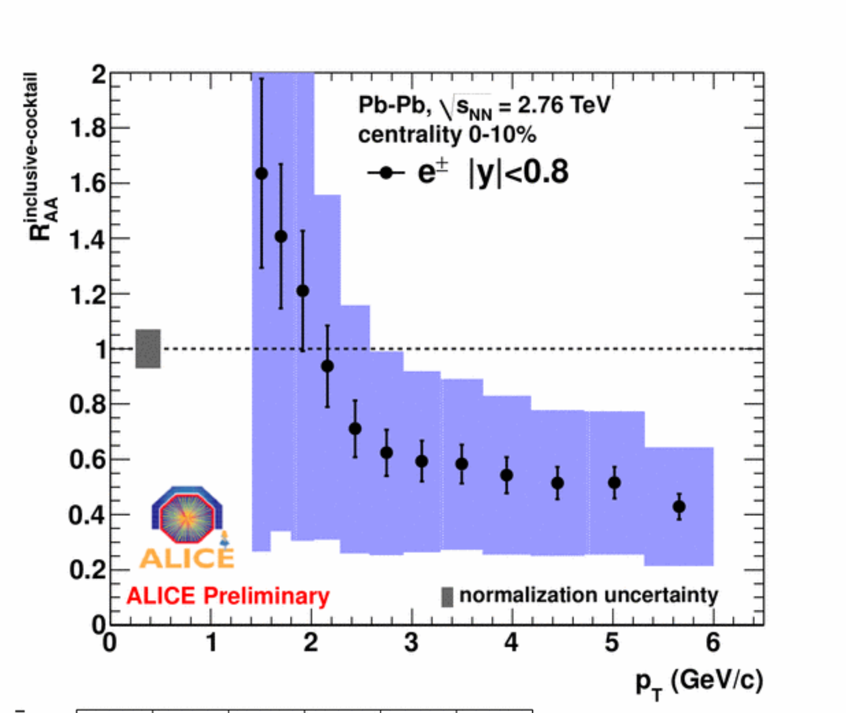


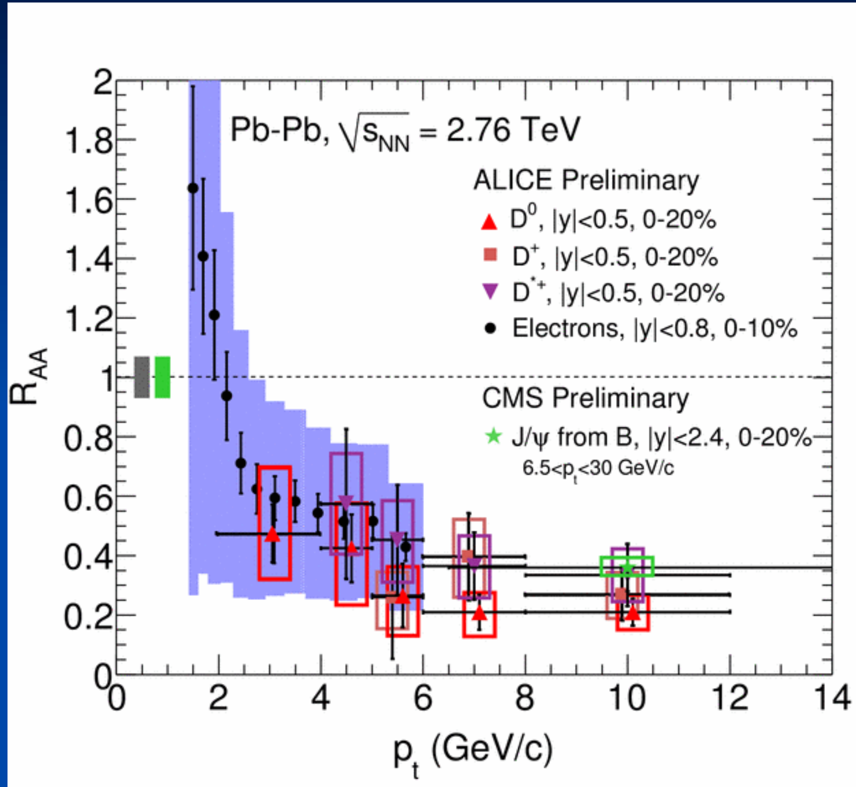


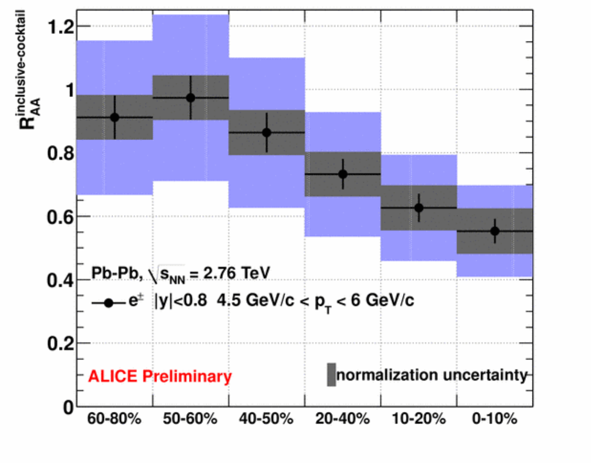
- Cocktail method: inclusive e^+, e^- p_T spectrum
- Subtract known sources (decays of mesons)

- **Impact parameter method** (pp only by now) to select electrons from beauty

R_{AA} of cocktail-subtracted electrons

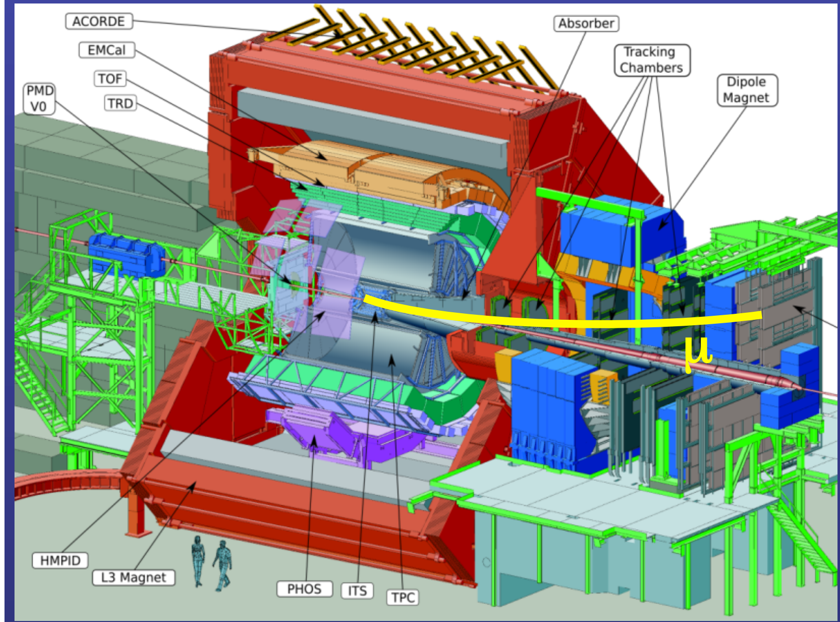


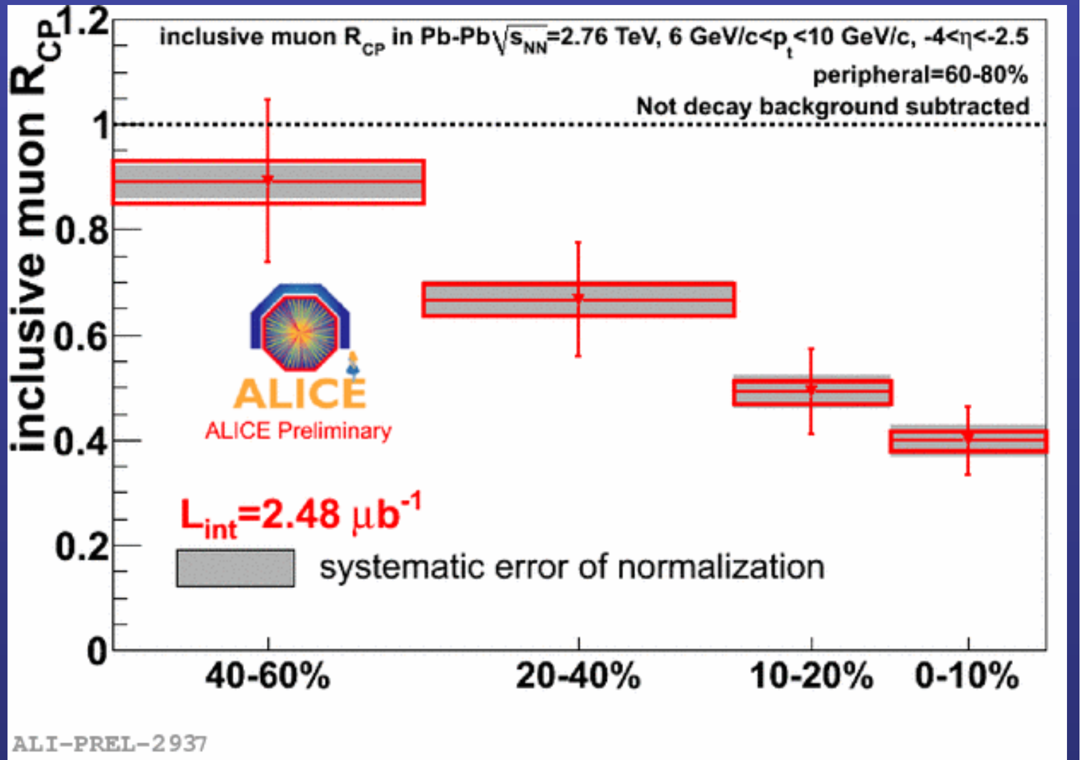




- Factor 1.5 - 4 suppression for p_T>3.5 GeV/c in the most central (0-10%) events
- Suppression increasing with centrality
- Electrons' R_{AA} coherent with charmed hadrons' R_{AA}

Heavy-flavor decay muons

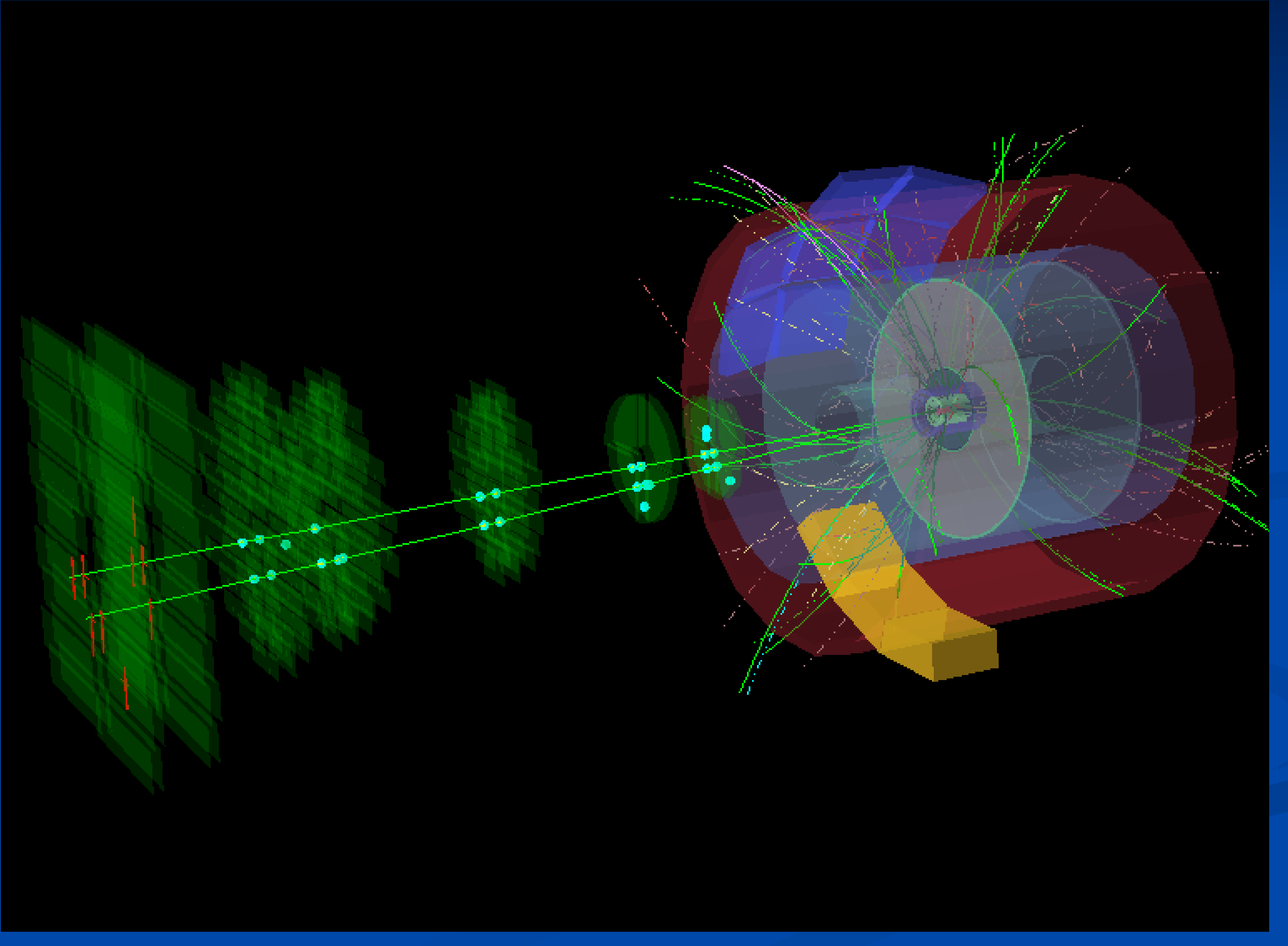




- Single muons at forward rapidity (-4<η<-2.5)
- Background from primary π/K decay not subtracted
  - estimated with HIJING to be 9% in the most central class (0-10%) for p_T>6 GeV/c

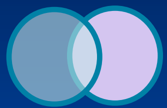
- R_{CP} for inclusive muons in 6<p_T<10 GeV/c
  - suppression increases with increasing centrality

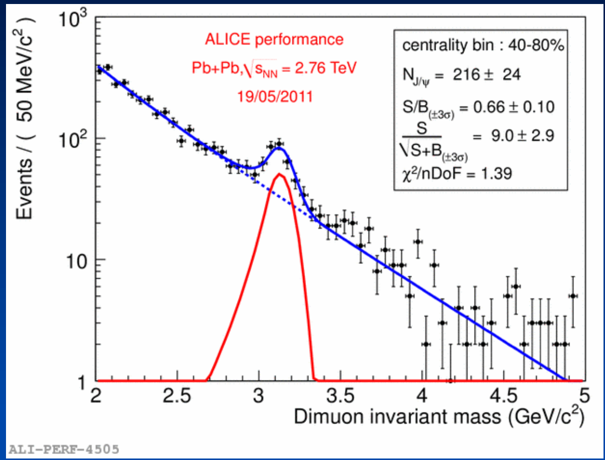
Quarkonia

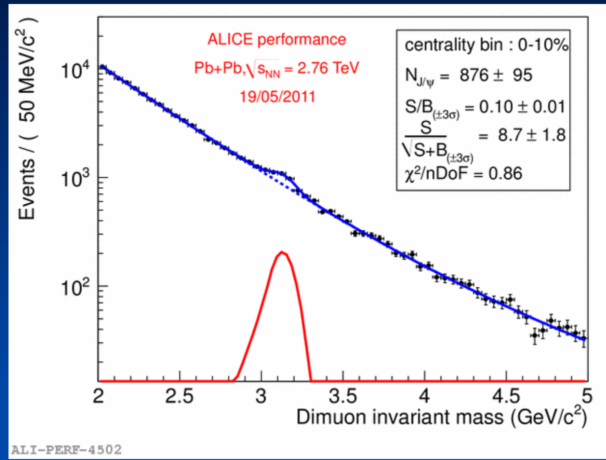


J/ψ suppression in Pb-Pb

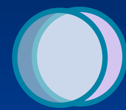
peripheral

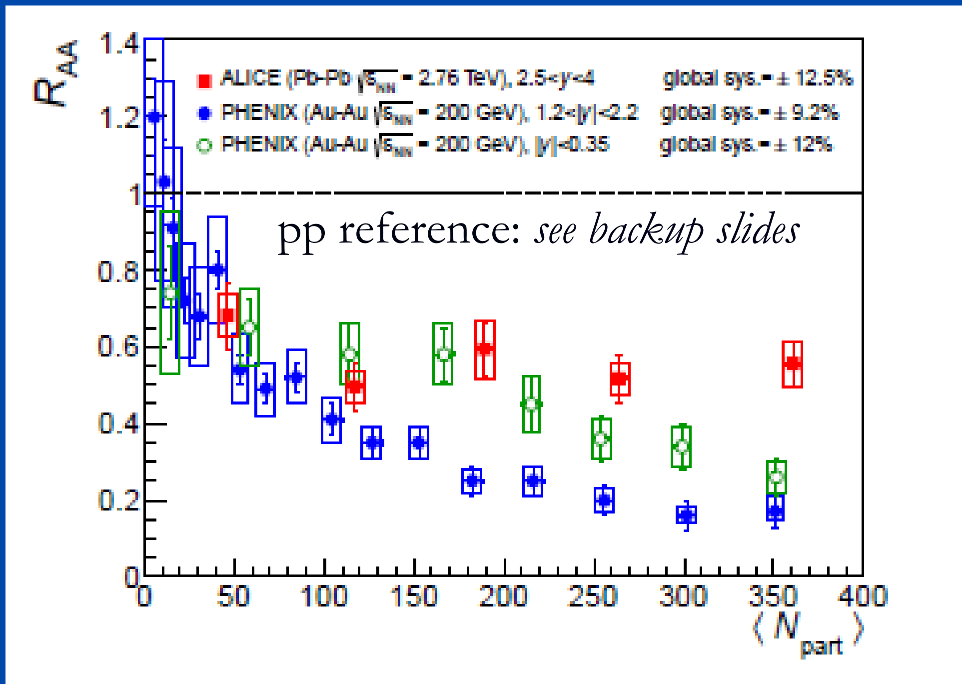






central

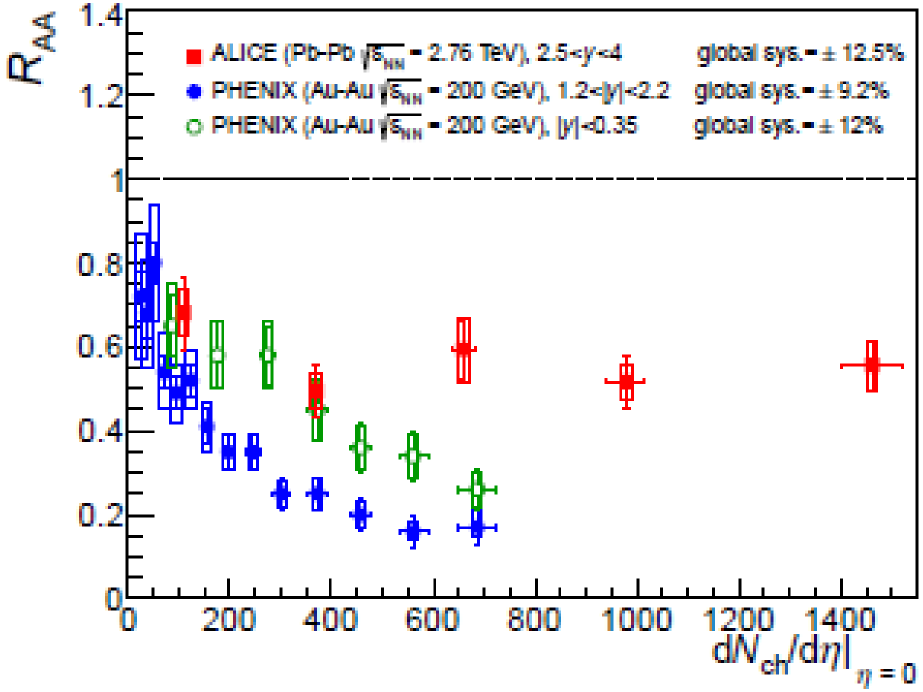




- ALICE: inclusive R_{AA} (small contribution from B feed-down not subtracted)
- J/ψ's are suppressed wrt pp collisions
- Suppression is almost independent of centrality

ALICE Pb-Pb: arXiv:1202.1383

J/ψ: comparison with RHIC



ALICE, LHC, forward rapidity

PHENIX, RHIC, mid-rapidity

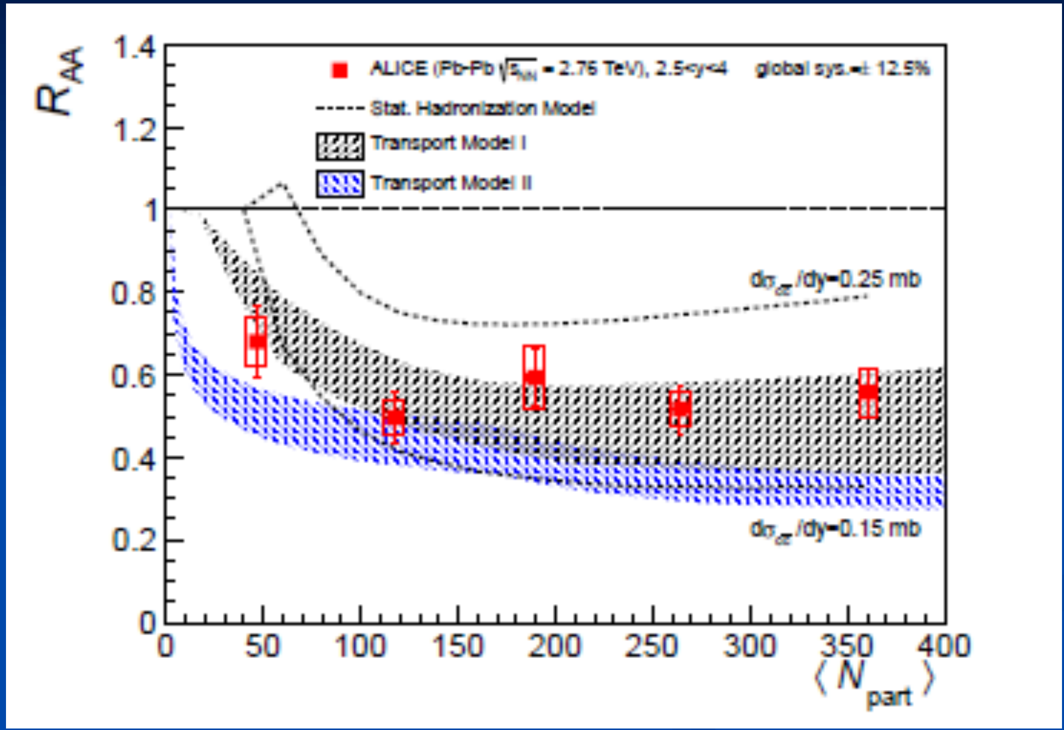
PHENIX, RHIC, forward rapidity

ALICE Pb-Pb: arXiv:1202.1383

- ALICE: less suppression than RHIC at forward rapidity
- Similar suppression (not for central collisions) as RHIC at midrapidity

Cold nuclear matter effects could be different: need p-Pb data

J/ψ in Pb-Pb: comparison to models



ALICE Pb-Pb: arXiv:1202.1383

A.Andronic et al., arXiv:1106.6321
P.Braun-Munzinger et al., PLB 490 (2000) 196

- Statistical hadronization model
- Screening by QGP of all J/ψ
- Charmonium production at phase boundary by statistical combination of uncorrelated c-quarks

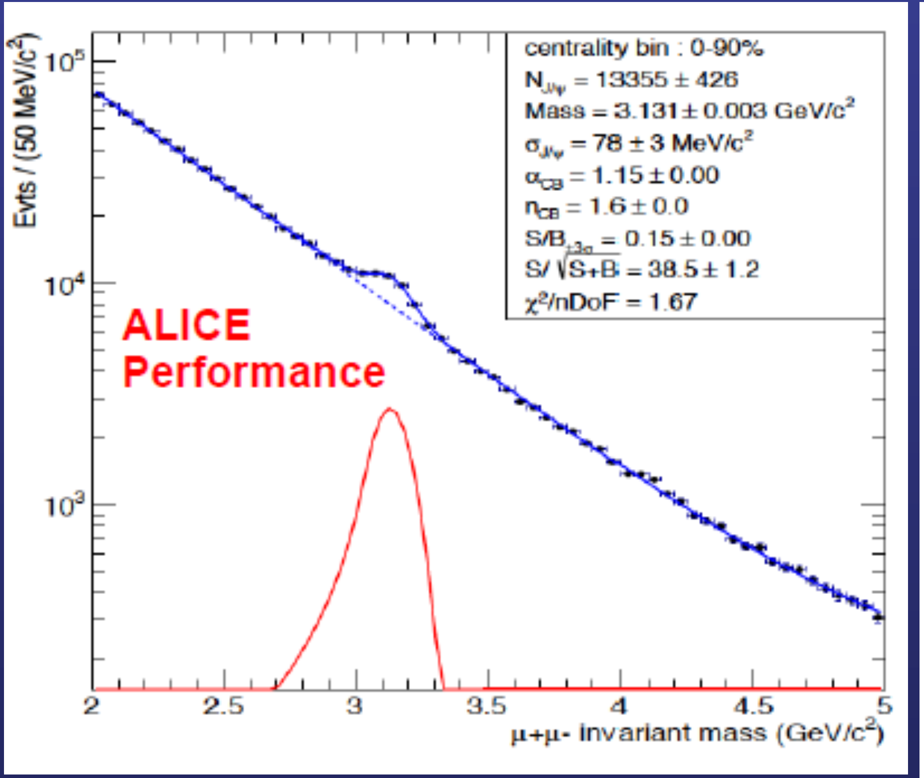
Y.-P. Liu et al., PLB 678 (2009) 72
R.Rapp & X.Zhao, NPA 859 (2011) 114

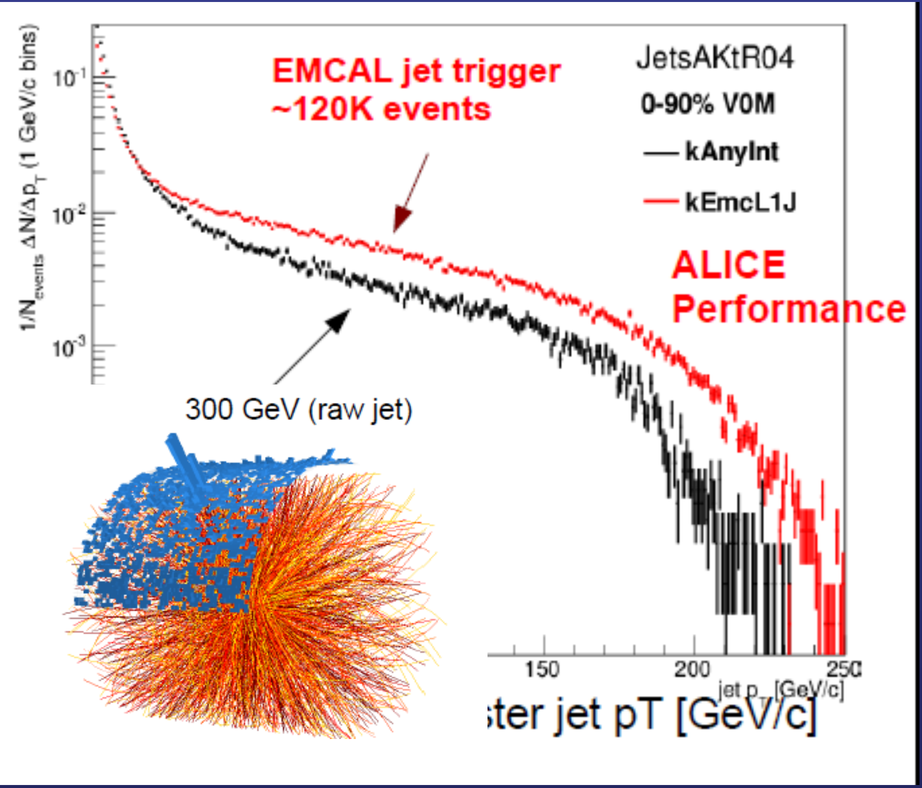
- Parton transport models
- J/ψ dissociation in QGP
- J/ψ regeneration by c-quark pair recombination
- Feed-down from B-decays
- Shadowing

Prospects, 2011 Pb-Pb data

- 2011 Pb-Pb data quite successful
- Smooth running, much higher luminosity → ~10 times more statistics (centrality and rare triggers) compared to 2010
- New, exciting results expected soon!

A couple of performance plots





Total 2011 statistics → 40000 J/ψ

Triggering on EMCAL

Conclusions

- ALICE focused in 2011 on analysis of first Pb-Pb run and on the vast amount of pp data (2.76 TeV & 7 TeV) collected in 2010 + early 2011
- Main results obtained:
  - Medium with 3 times higher energy density wrt RHIC
  - Abundant hard probes
  - Smooth evolution of global events observables, now looking more differentially (e.g. v2, v3, v4, ... with identified hadrons)
  - Strong suppression of high p_T hadrons
  - Light and heavy quarks R_{AA} similar
  - J/ψ less suppressed than at RHIC
- Second Pb-Pb run (2011) very successful, now focusing on analysis of new data and on the upgrade programme

The ALICE Collaboration

35 countries, 120 institutes, 1300 members

Thank you!

BACKUP

ALICE Pb-Pb papers

- Published:
  - PRL 105, 252301(2010)
  - PRL 105, 252302 (2010)
  - PRL 106, 032301 (2011)
  - PLB 696, 30 (2011)
  - PLB 696, 328 (2011)
  - PRL 107, 032301 (2011)
- Submitted:
  - arXiv:1109.2501 (angular correlations)
  - arXiv:1201.2423 (background fluctuations for charged particle jets)
  - arXiv:1202.1383 (J/ψ production)
- In preparation:
  - Measurement of the Cross Section for Electromagnetic Dissociation with Neutron Emission in Pb-Pb Collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
  - Suppression of high transverse momentum prompt D mesons in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
  - Centrality Dependence of Charged Particle Production at Large Transverse Momentum in Pb-Pb Collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

ALICE Detector Status (2010-11)

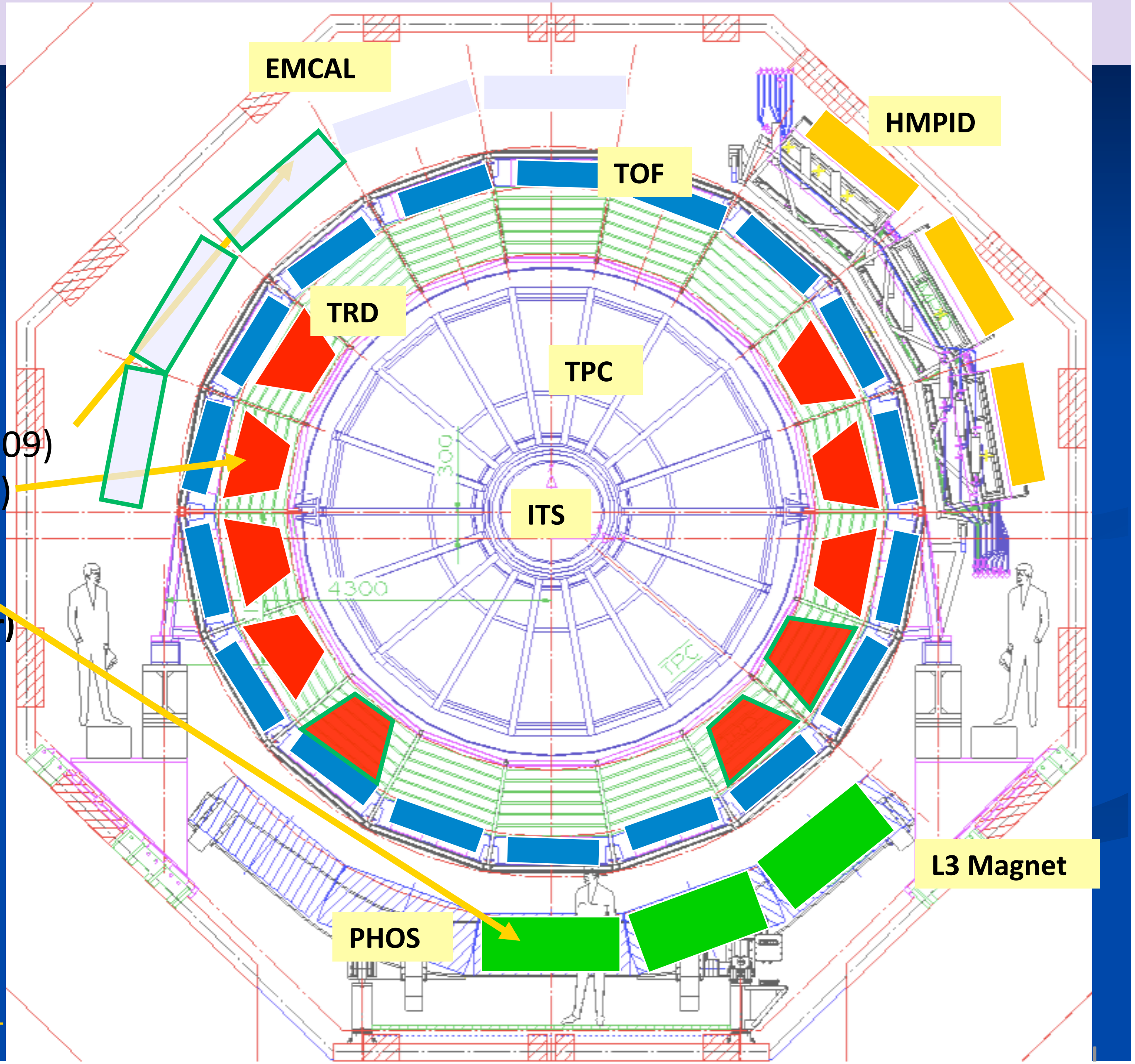
<u>Complete since 2008:</u>
ITS, TPC, TOF, HMPID,
FMD, T0, V0, ZDC,
Muon arm, Acorde
PMD , DAQ

<u>Partial installation (2010):</u>
4/10 **EMCAL*** (approved 2009)
7/18 **TRD*** (approved 2002)
3/5 **PHOS** (funding)

~ 60% **HLT (High Level Trigger)**

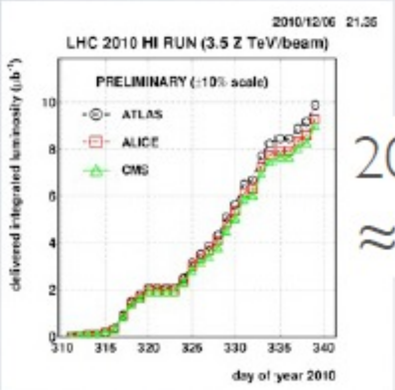
<u>2011</u>
10/10 **EMCAL**
10/18 **TRD**

*upgrade to the original setup

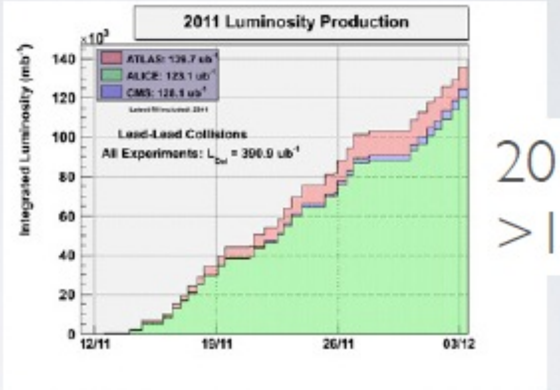


ALICE Pb-Pb data samples (2010, 2011)

- Heavy Ion Luminosity



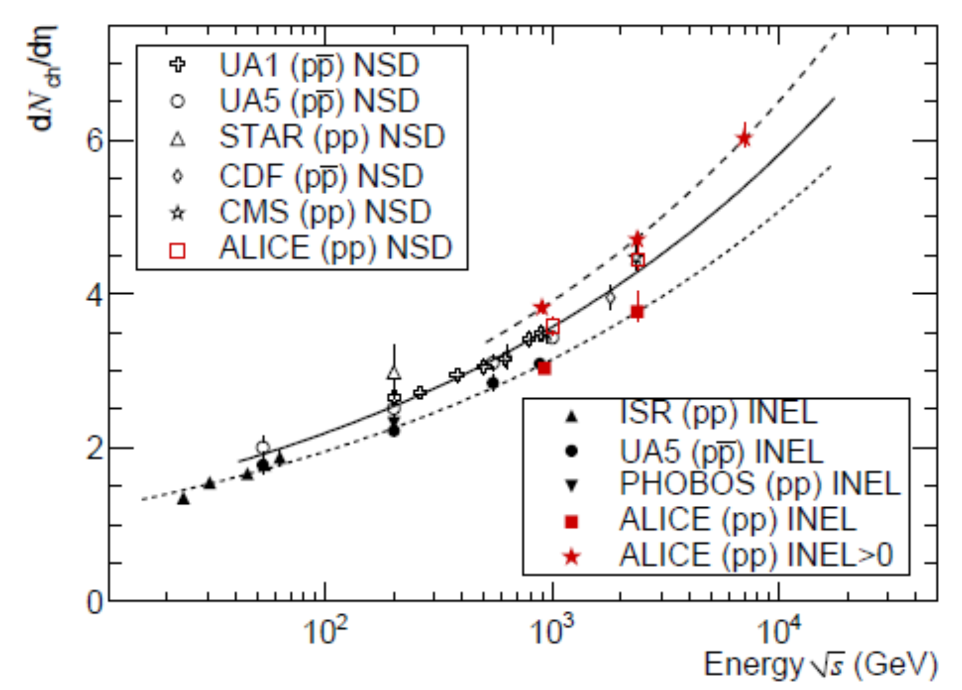
2010:
≈ 10 μb^{-1}

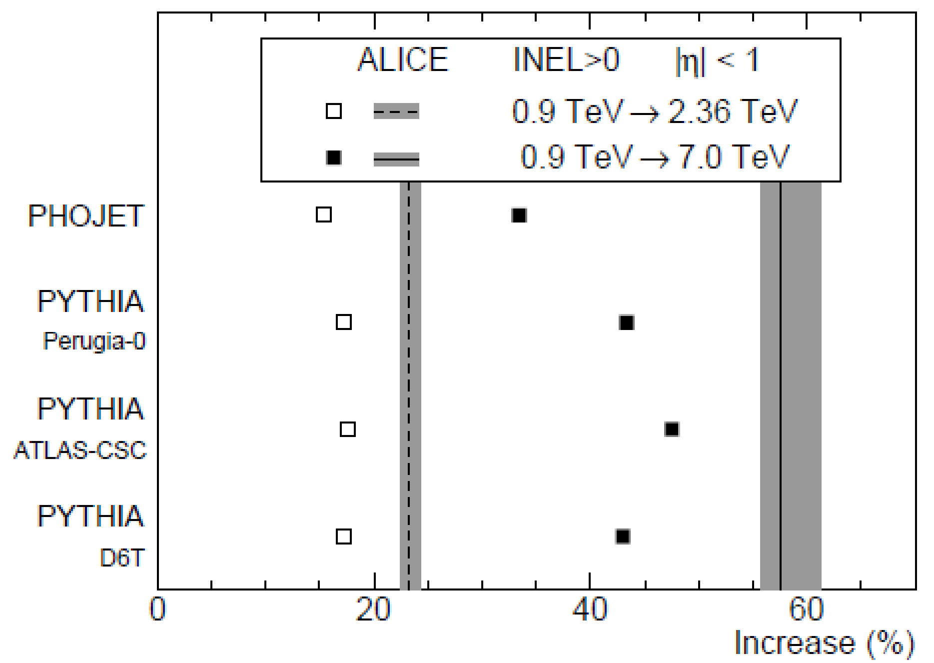


2011:
>120 μb^{-1}

- 10 times more data delivered (and taken)!
- improvement on "rare" triggers (EMCAL, DIMUON, PHOS,...)
  - crucial in p+p running
- data compression (3x) by TPC clustering in HLT
  - from ≈12 GB/s readout reduced to max. 4GB/s to storage

$dN_{ch}/d\eta$ in pp

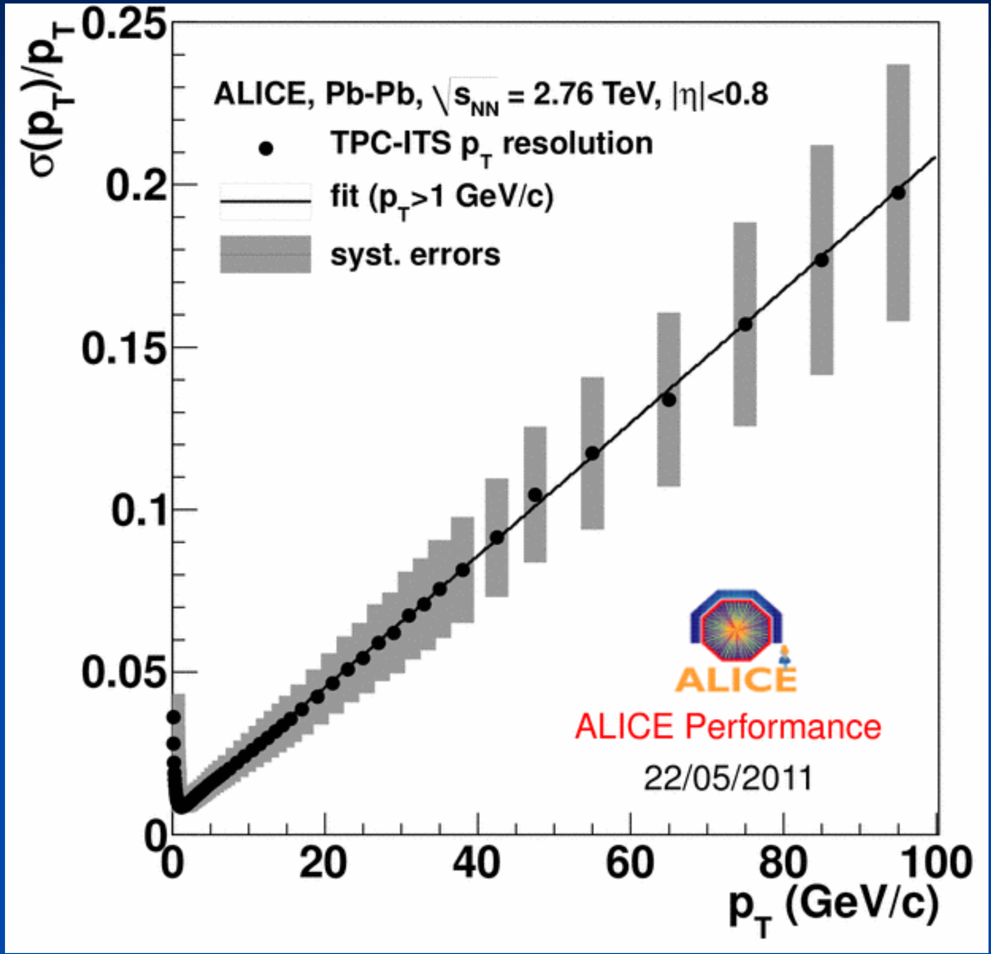




- - - INELastic >0 (at least 1 part. in $|\eta|<1$)
----- Non Single Diffractive
……. INELastic

Charged multiplicity at 7 TeV: Eur. Phys. Journal **C 68** (2010), 345
Charged multiplicity (900 GeV & 2.36 TeV): Eur. Phys. Journal **C 68** (2010), 89

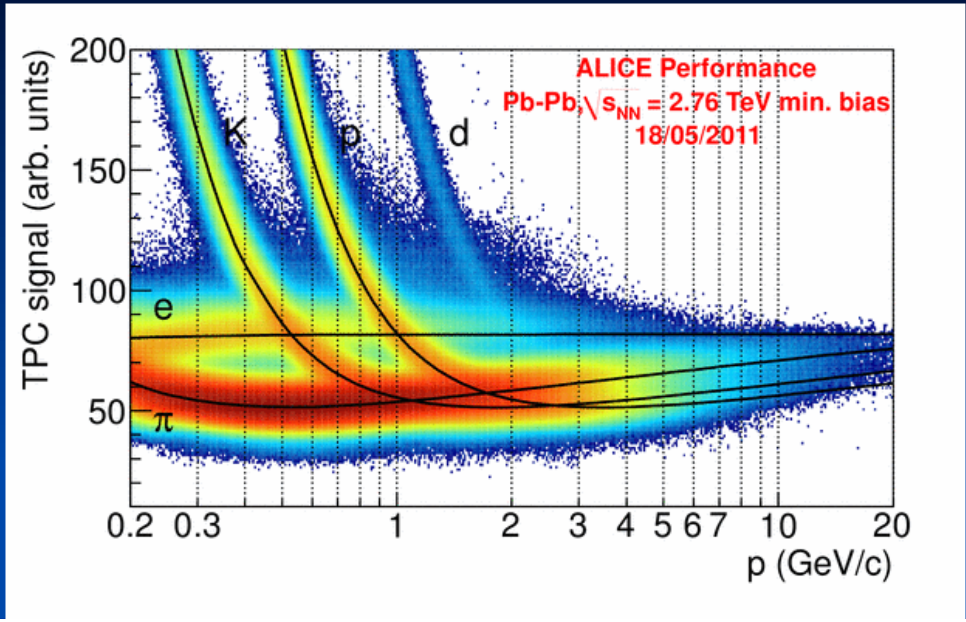
ALICE momentum resolution

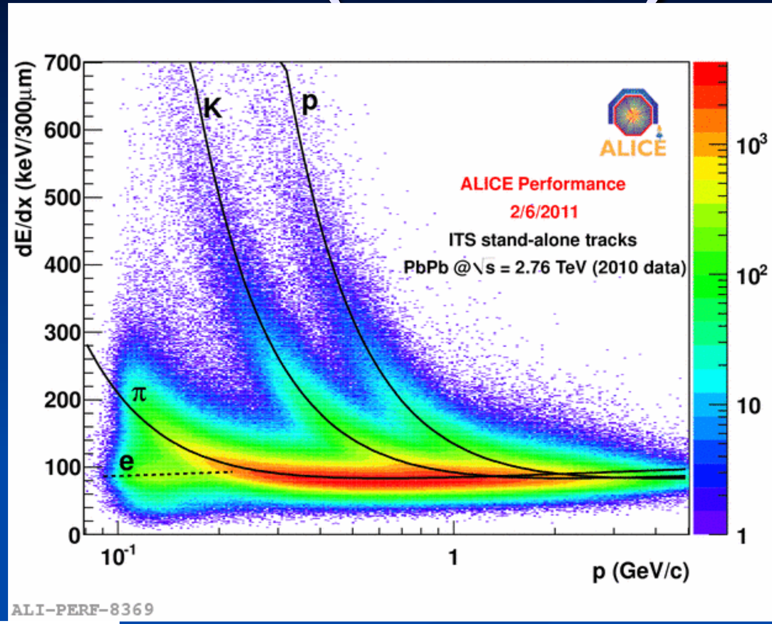


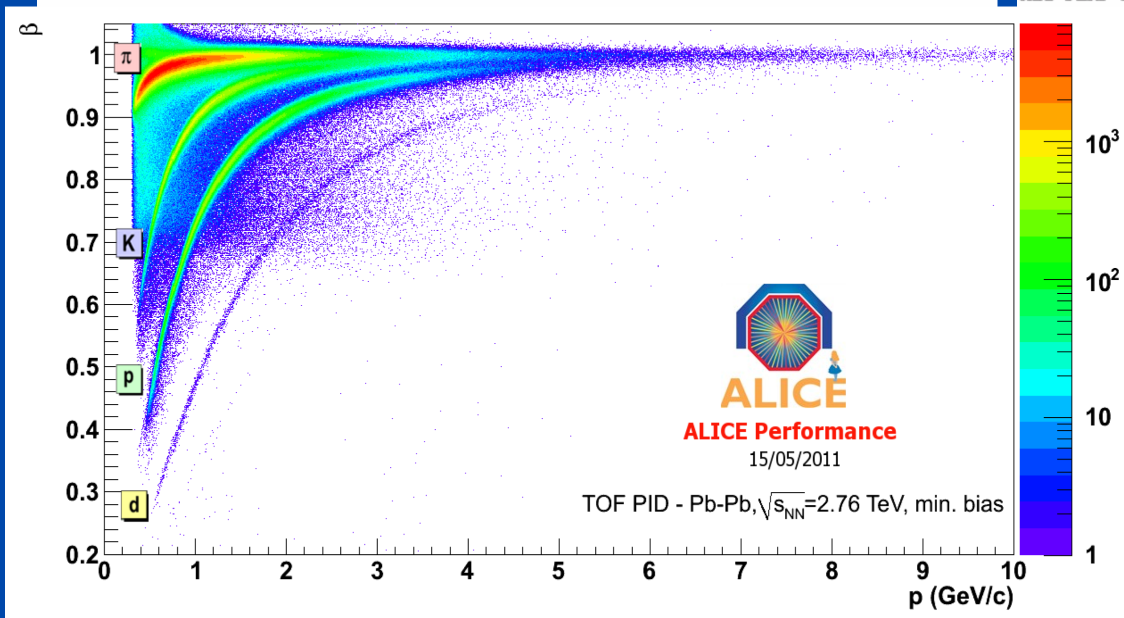
combined TPC-ITS momentum resolution:

$\sigma(p_T)/p_T$ = 20% at p_T = 100 GeV/c

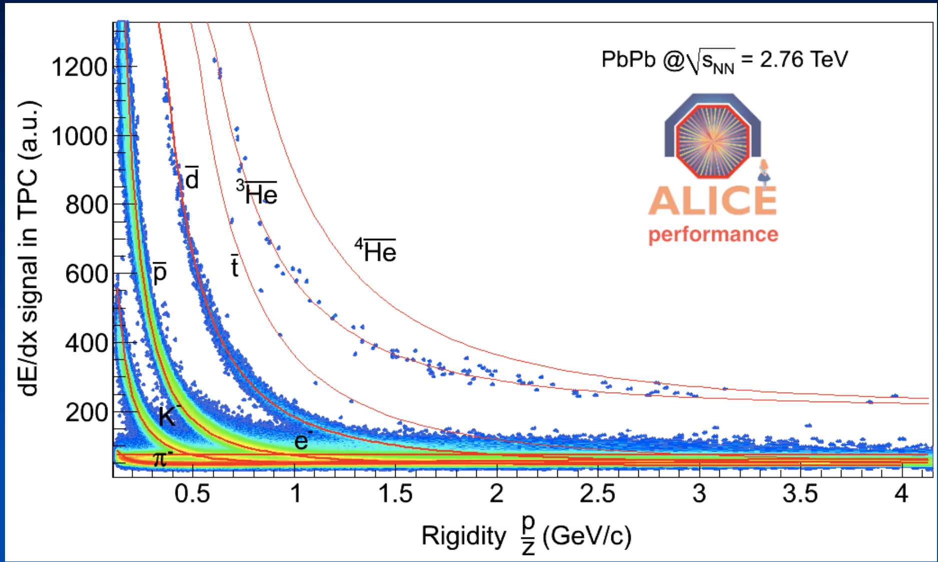
ALICE P.ID. Performance (Pb-Pb)

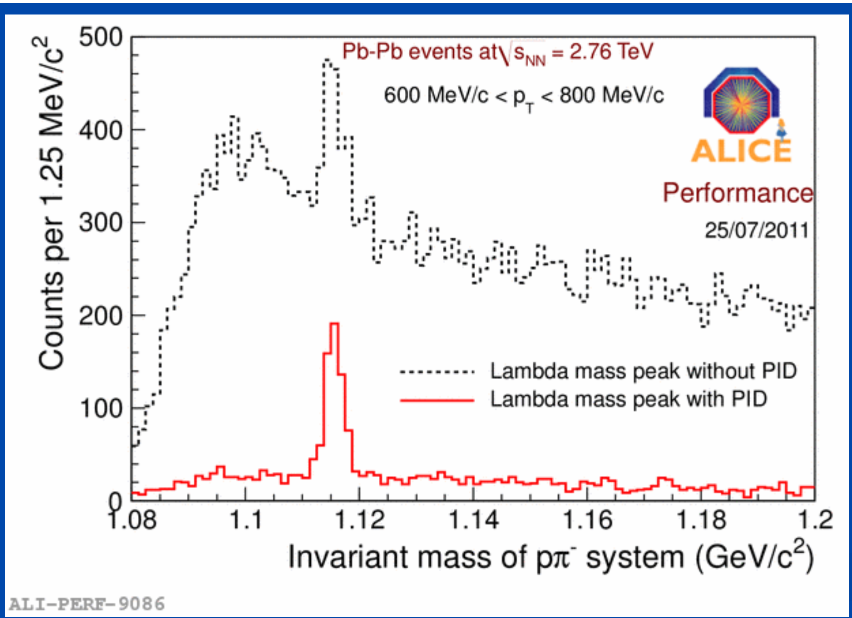


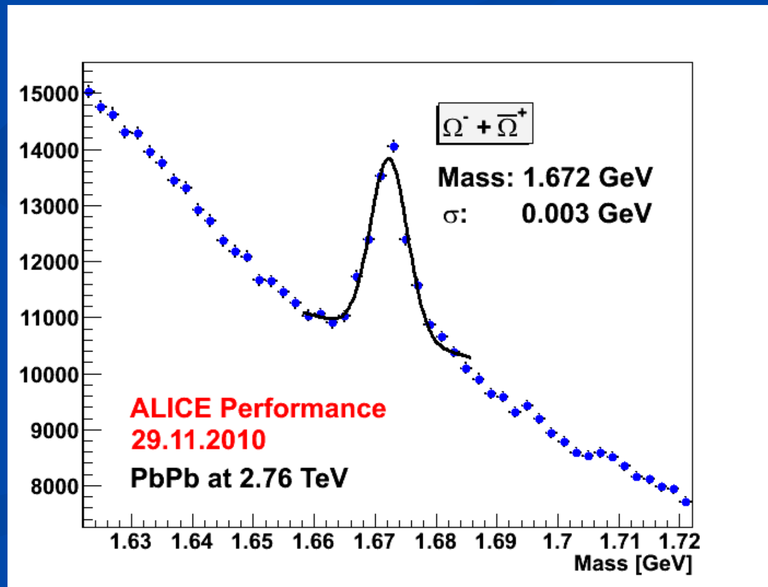




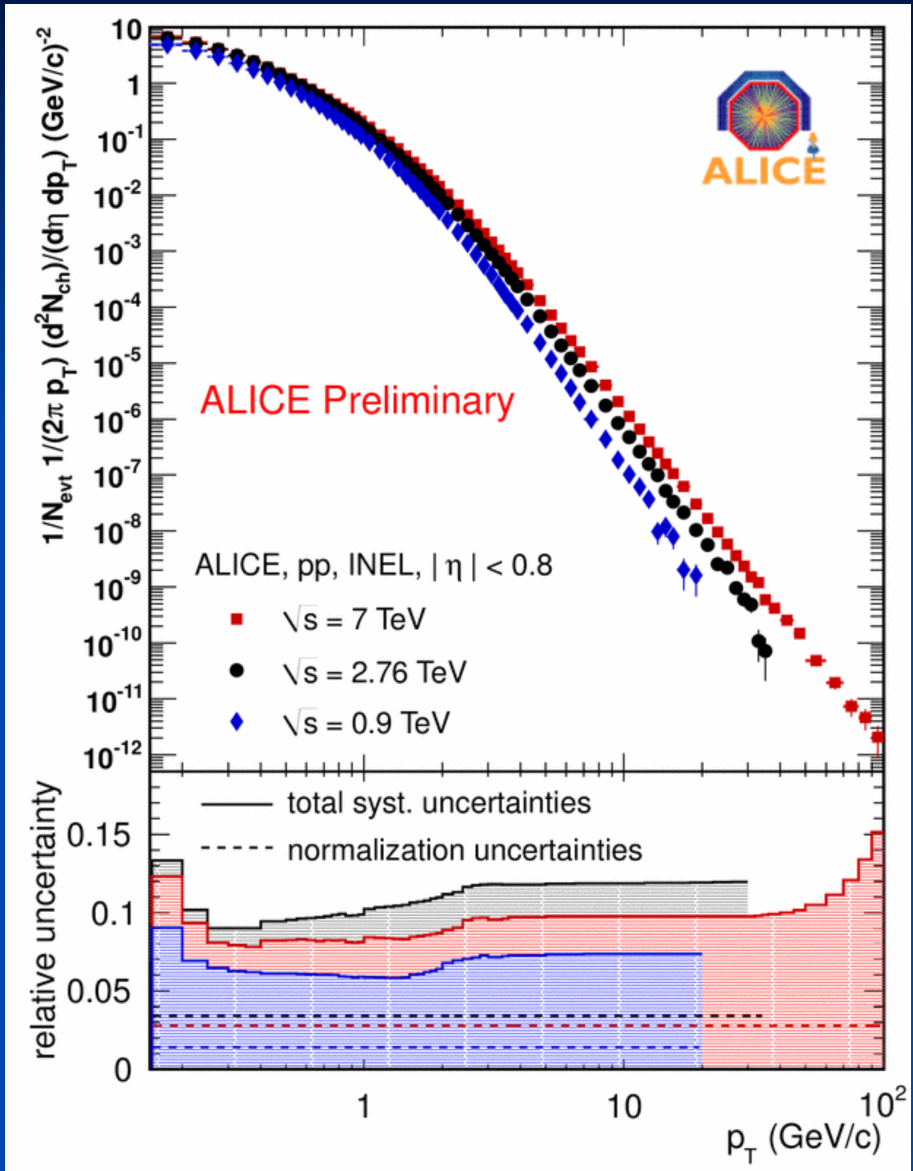
ALICE P.ID. Performance (Pb-Pb)

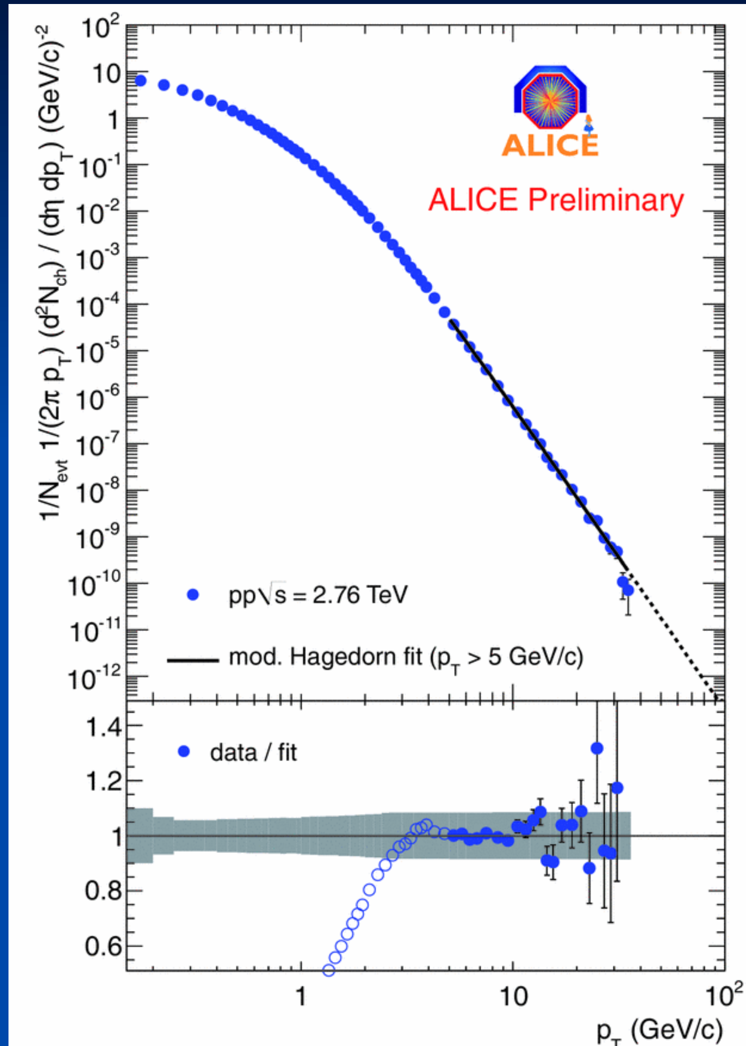






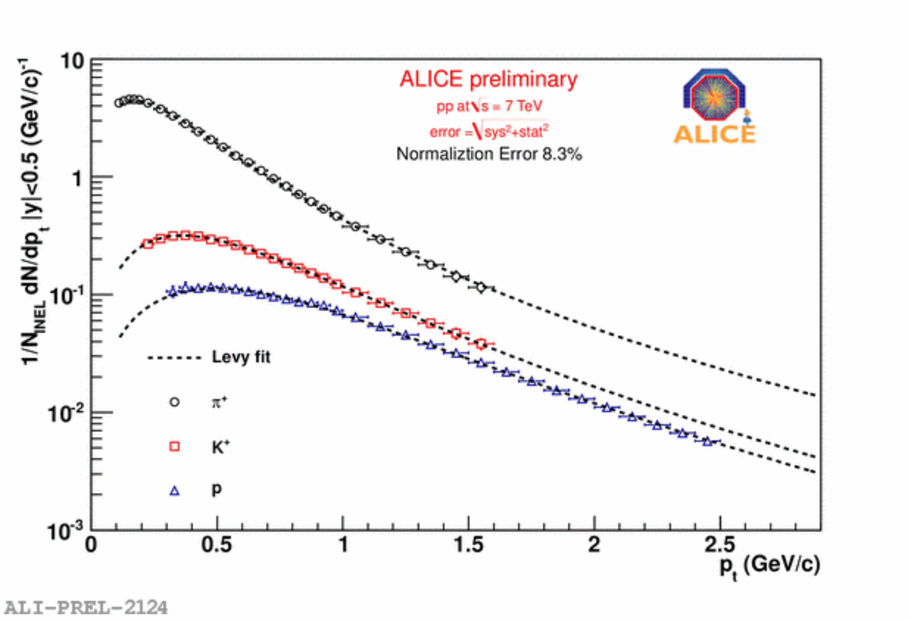
Charged particles: p_T spectra in pp





ALICE charged particle pt spectra in pp at 900 GeV: Phys. Lett. B 693 (2010) 53-68

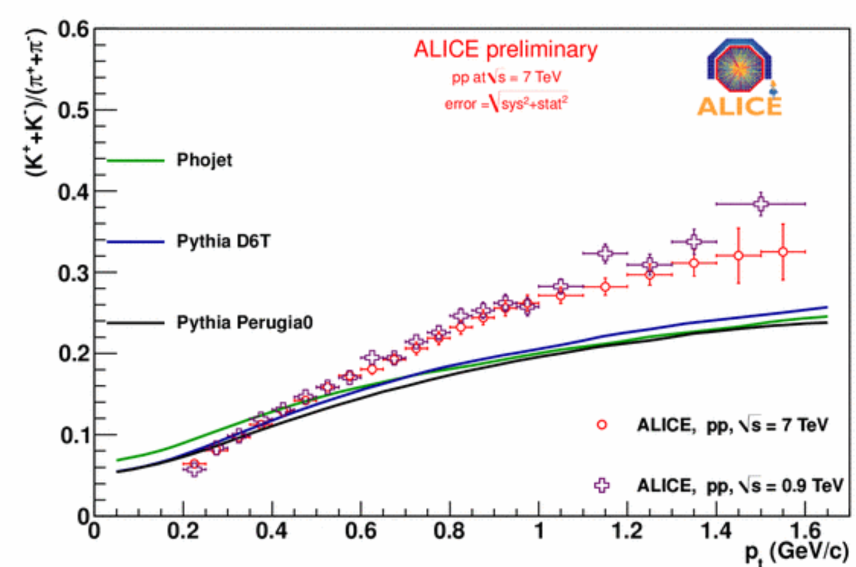
π, K, p spectra in pp (I)

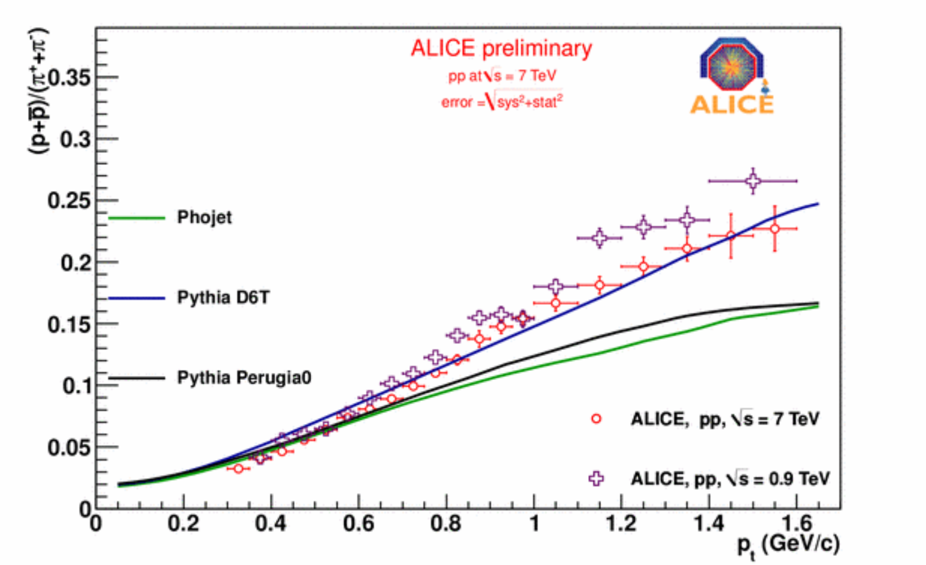


7 TeV: ALICE Preliminary
900 GeV: Charged → EPJ C 71 (2011) 1655
Strange particles → EPJ C 71 (2011) 1594

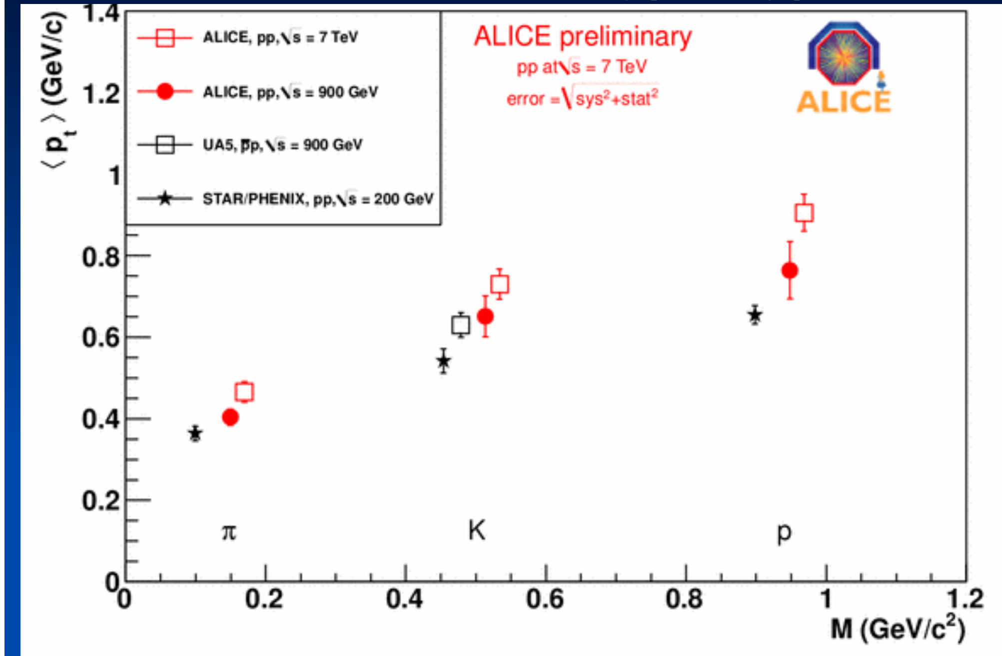
Different techniques used
Minimum p_T = 0.1 / 0.2 / 0.3 GeV/c for π/K/p
(small extrapolation for yields and <p_T> calculation)

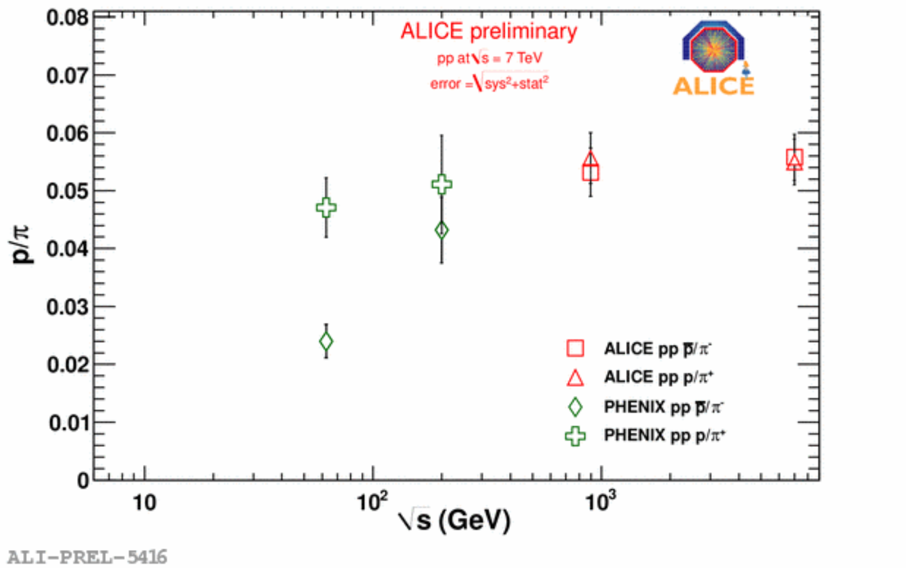
MC models: poor description of data

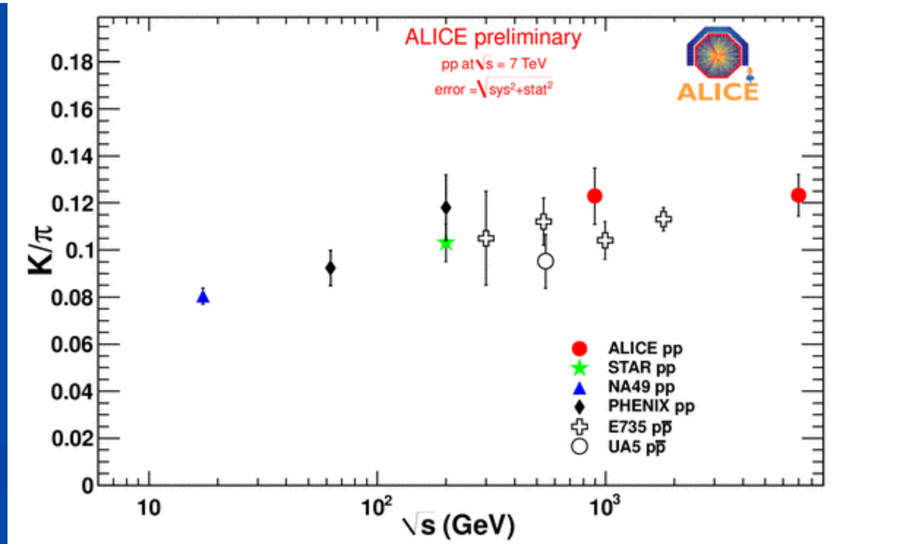




π, K, p spectra in pp (II)



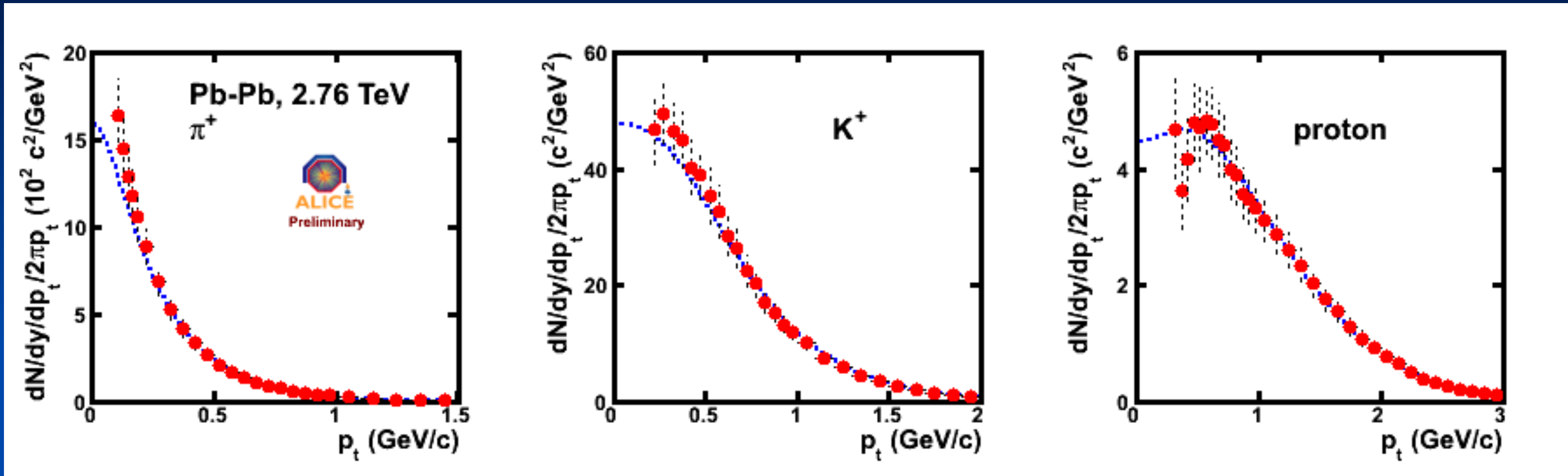




Modest increase of $<p_T>$ with √s
➔ harder spectra

Integrated (and p_T differential) particle ratios ~ independent of energy between 0.9 and 7 TeV

Blast-wave fits



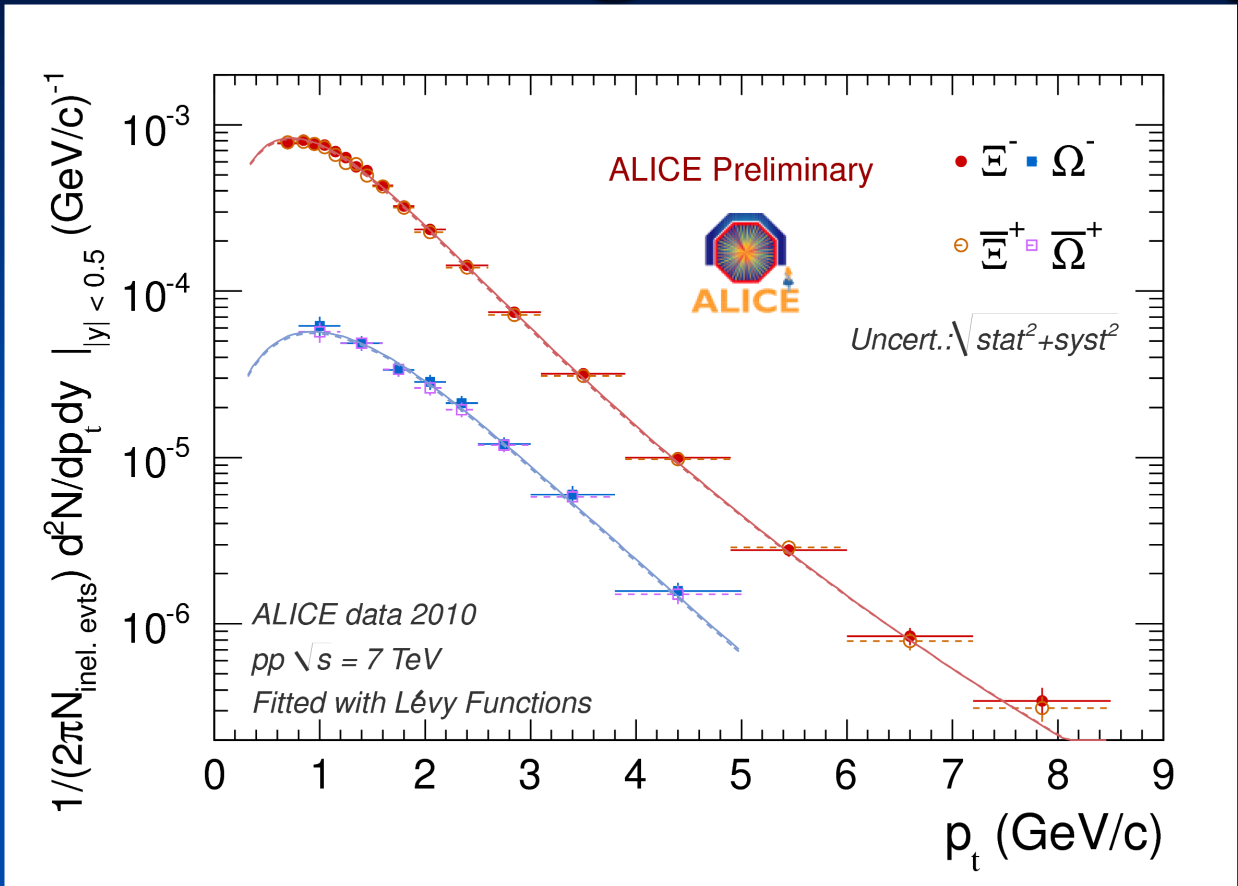
$$E\frac{d^3N}{dp^3} \propto \int_\sigma e^{-(u^\mu p_\mu)/T_{fo}} p d\sigma_\mu \Rightarrow$$

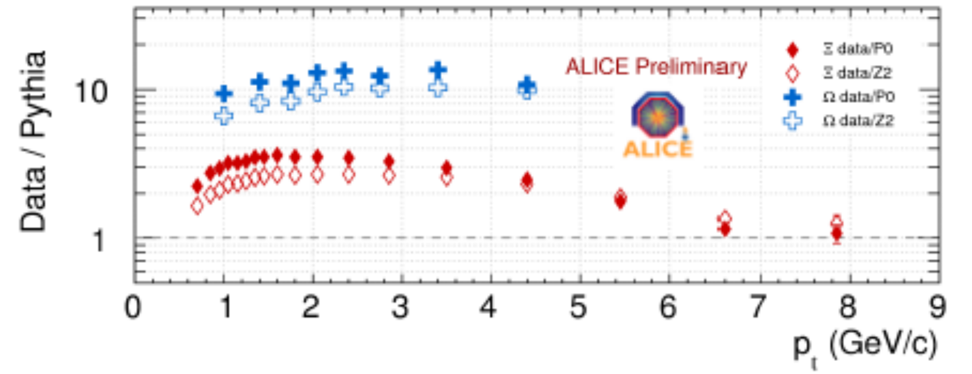
$$\frac{dN}{m_T dm_T} \propto \int_0^R r dr m_T K_1\left(\frac{m_T \cosh\rho}{T_{fo}}\right) I_0\left(\frac{p_T \sinh\rho}{T_{fo}}\right)$$

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

- E. Schnedermann, J. Sollfrank, and U. Heinz, Phys. Rev. C48, 2462 (1993)
- Free parameters: T_{fo}, β, α

Multi-strange hadrons in pp (I)

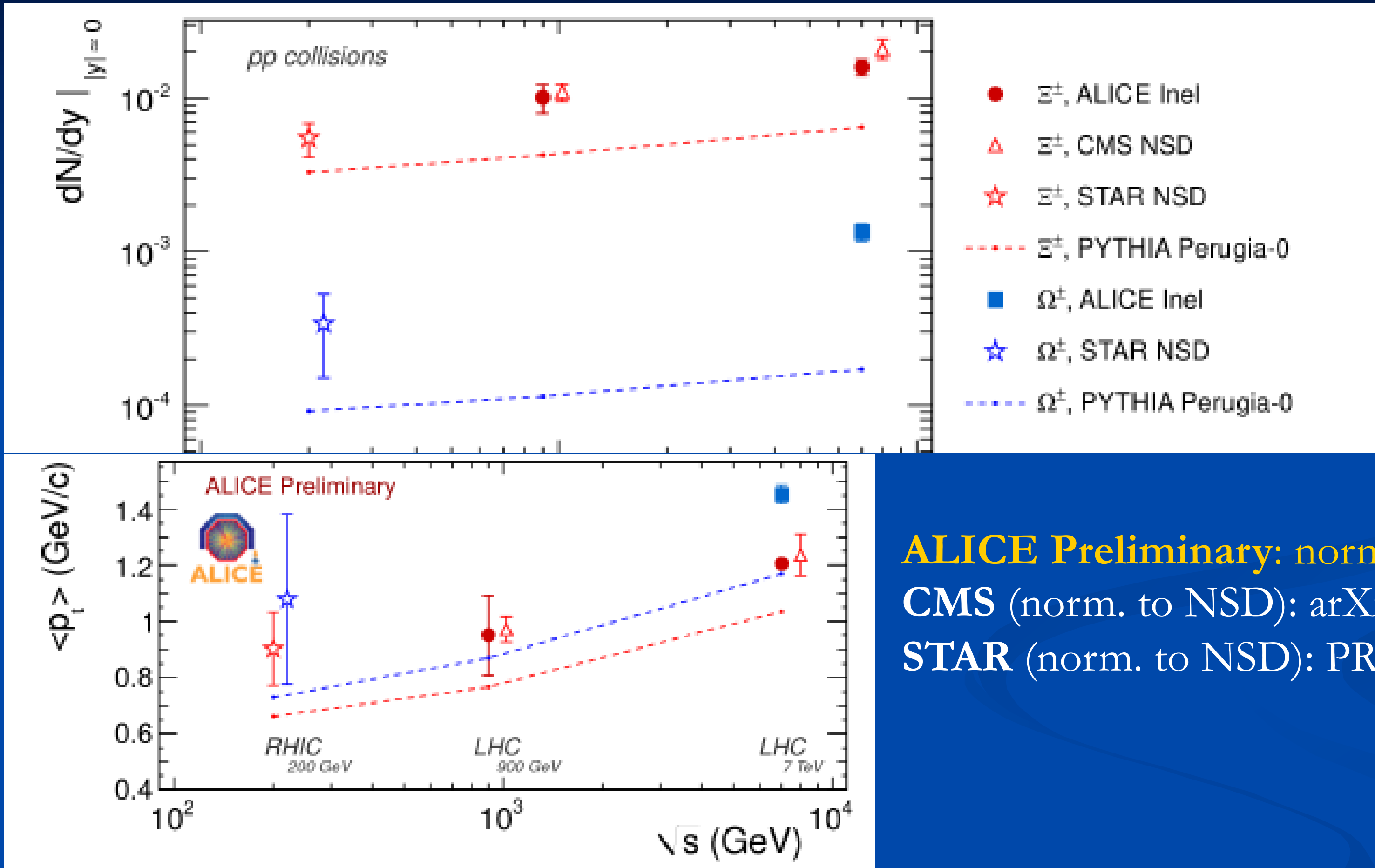




Antiparticle/particle ratios, measured in wide p_T range, are compatible with 1 (see also M. Broz)

MC's (PYTHIA tunes **Perugia-0** and **Z2**) underpredict yields, particularly for the Ω

Multi-strange hadrons in pp (II)



ALICE Preliminary: normalized to INEL
CMS (norm. to NSD): arXiv:1102.4282
STAR (norm. to NSD): PRC 75, 064901 (2007)

<p_T> and yield from ALICE agree with CMS (INEL vs. NSD);
PYTHIA underpredicts yields (particularly for Ω)
(new PYTHIA tunes like Z2 show only slight improvement)

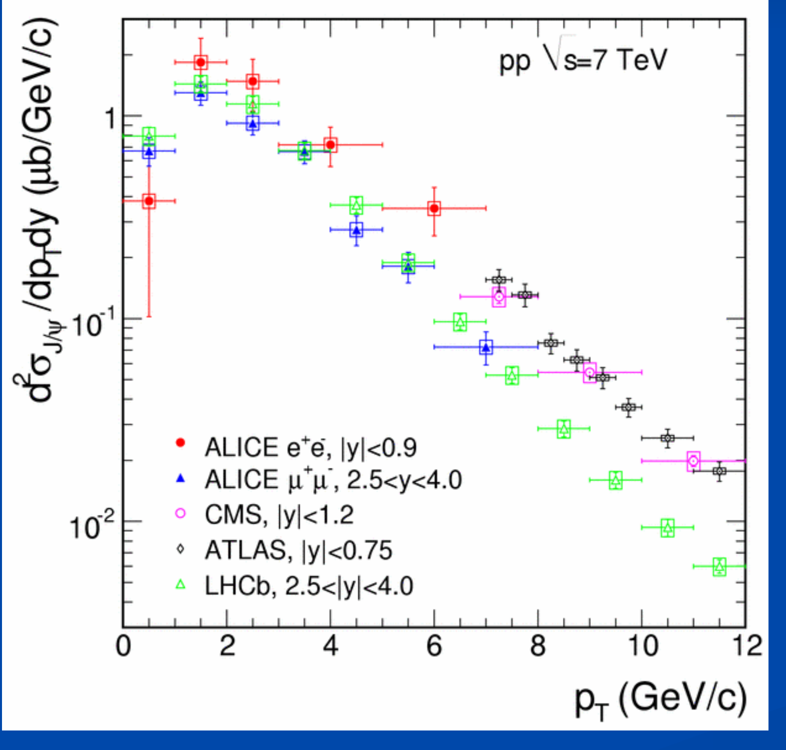
J/ψ production (pp 7 TeV)

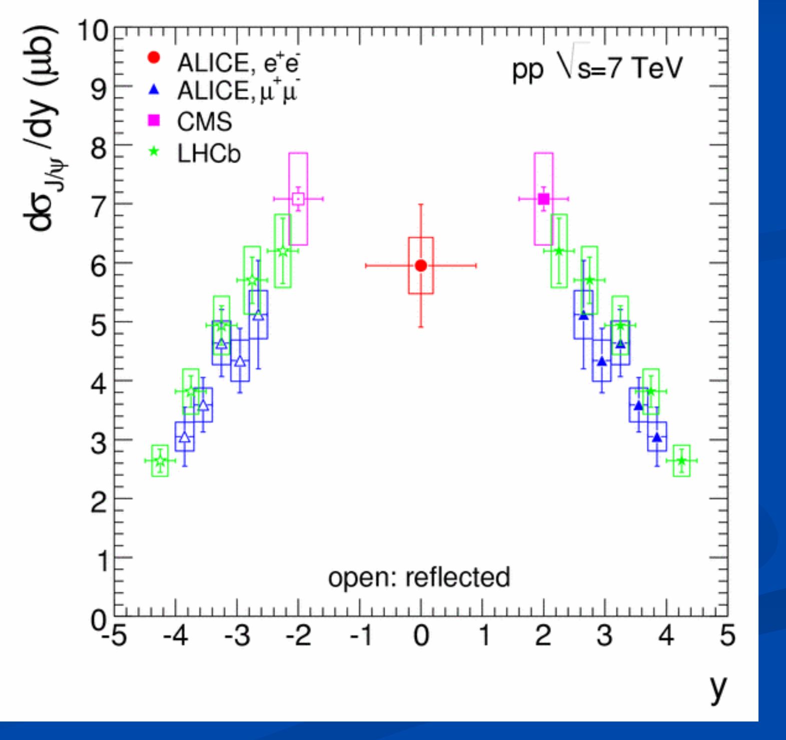
Inclusive J/ψ (direct + feed-down) production cross sections at 7 TeV:

$\sigma_{J/\psi}$ (2.5<y<4)= 6.31±0.25(stat)±0.80(syst)+0.95(λ_{CS}=1)-1.96(λ_{CS}=-1) μb

$\sigma_{J/\psi}$ (|y|<0.9)= 10.7±1.2(stat)±1.7(syst)+1.6(λ_{HE}=1)-2.3(λ_{HE}=-1) μb

ALICE unique features: wide y coverage, down to p_T=0 for y=0

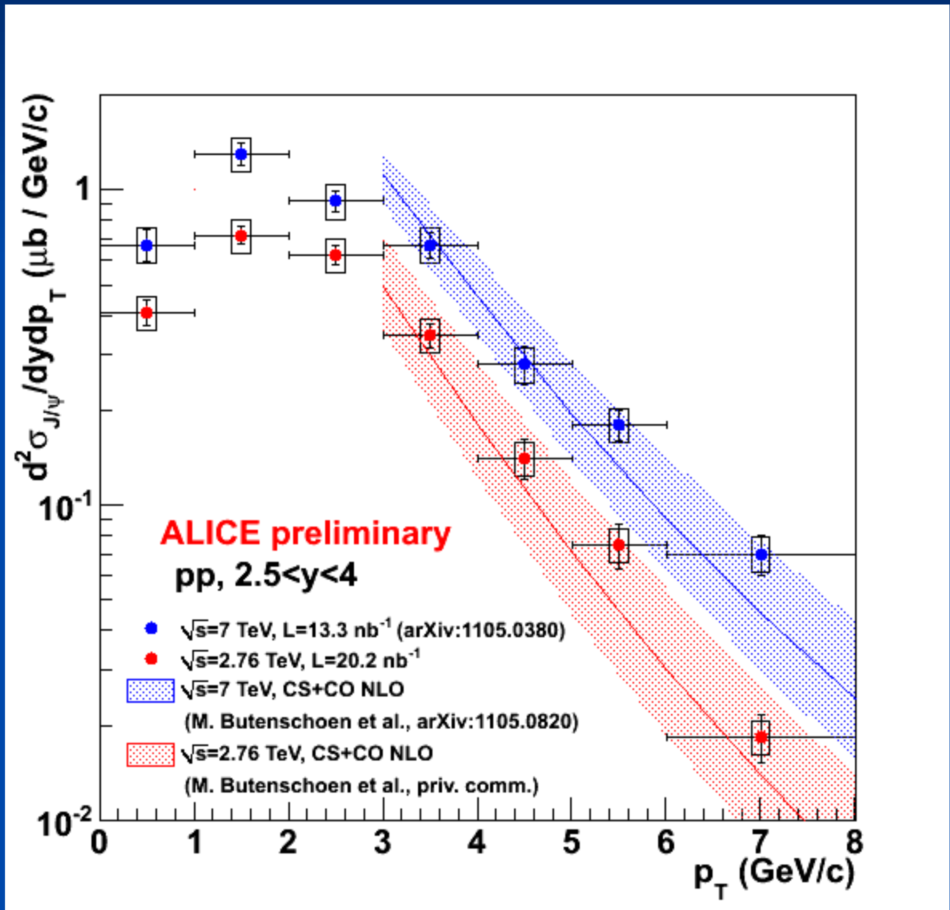


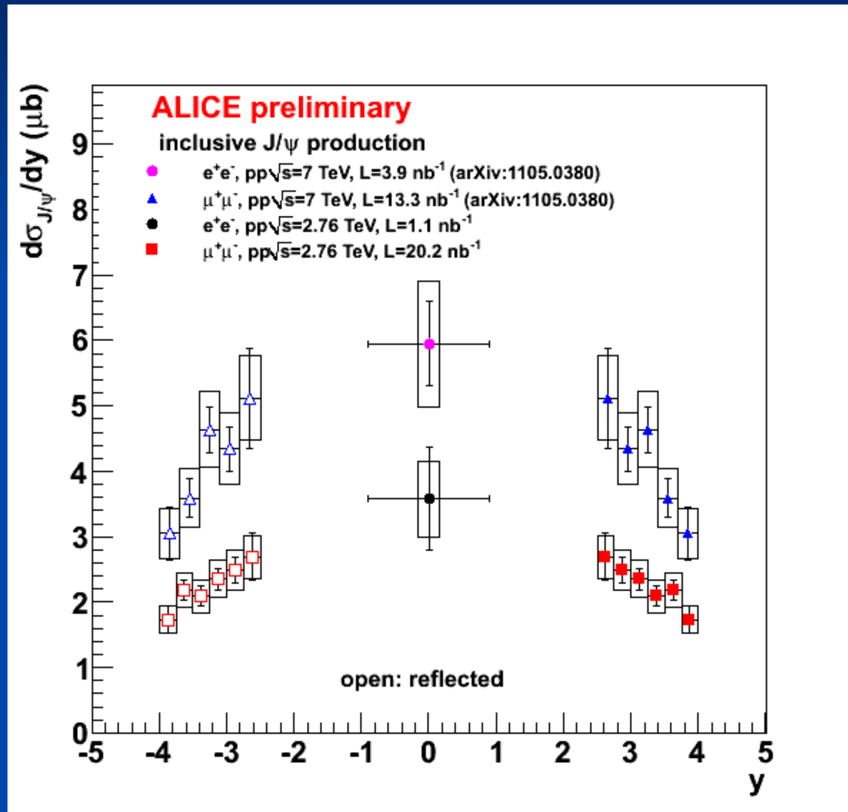


ALICE **J/ψ pp** results: Phys. Lett. B 704, 442 (2011) [arXiv:1105.0380]

J/ψ production (pp 2.76 & 7 TeV)

Preliminary results for pp at 2.76 TeV (needed for Pb-Pb):

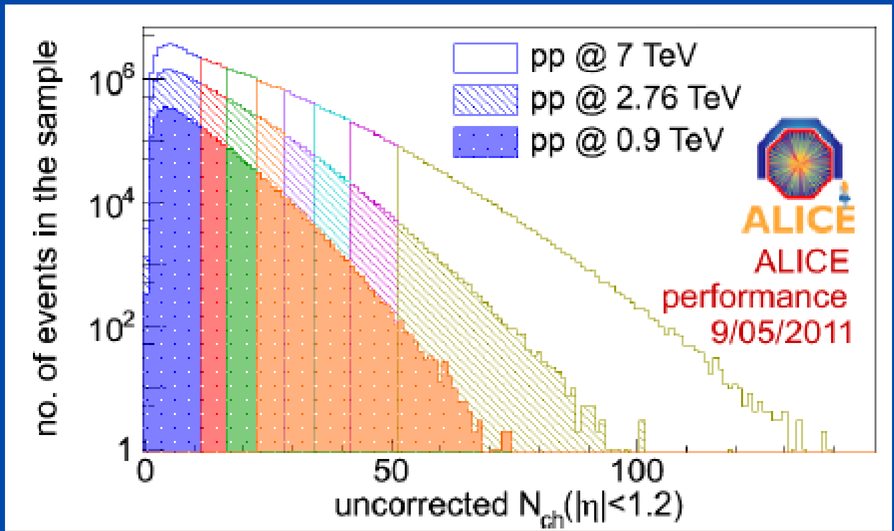


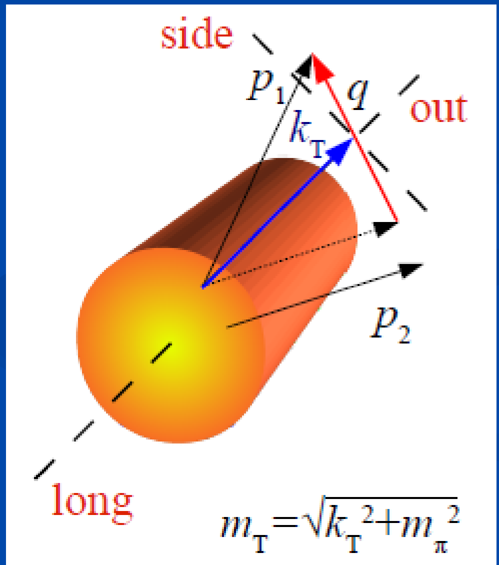


- J/ψ polarization: see arXiv:1111.1630
- prospect: separate B→J/ψ (mid-rapidity)

BE correlations of identical pions

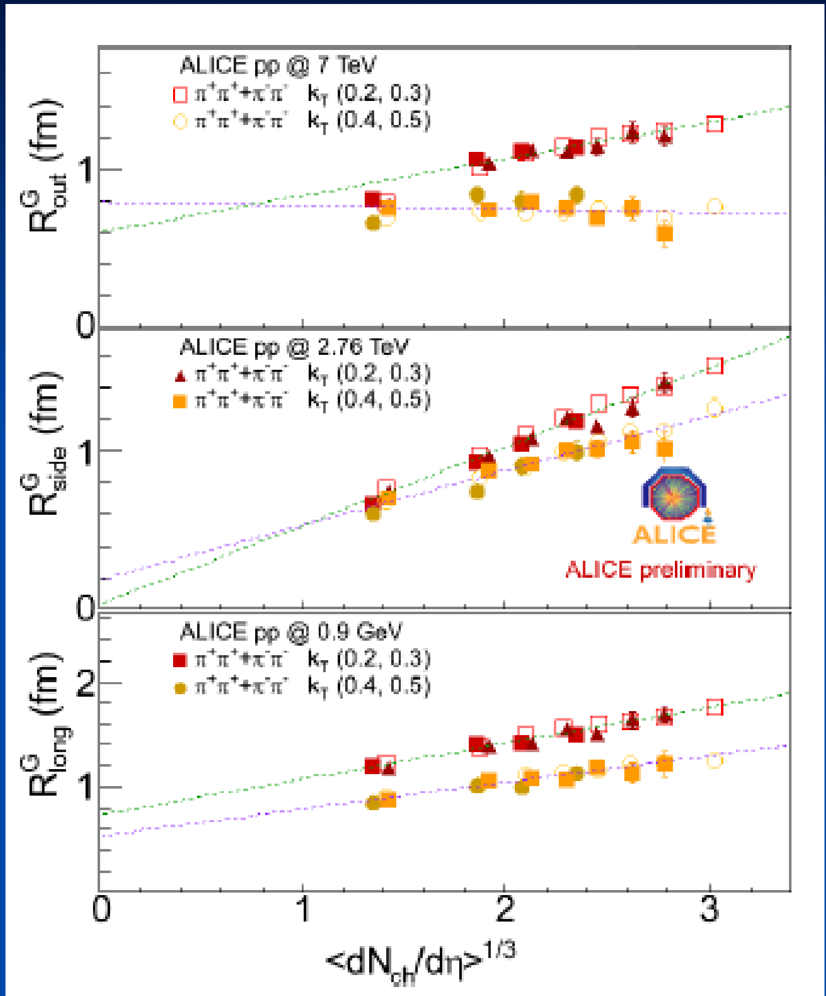
- Study space-time characteristics of particle production (homogeneity region) by measuring HBT radii (long, side, out):
  - vs. pair transverse momentum k_T
  - vs. event multiplicity N_{ch} (high multiplicity pp ≈ peripheral Pb-Pb)
  - vs. center-of-mass energy $\sqrt{s}$

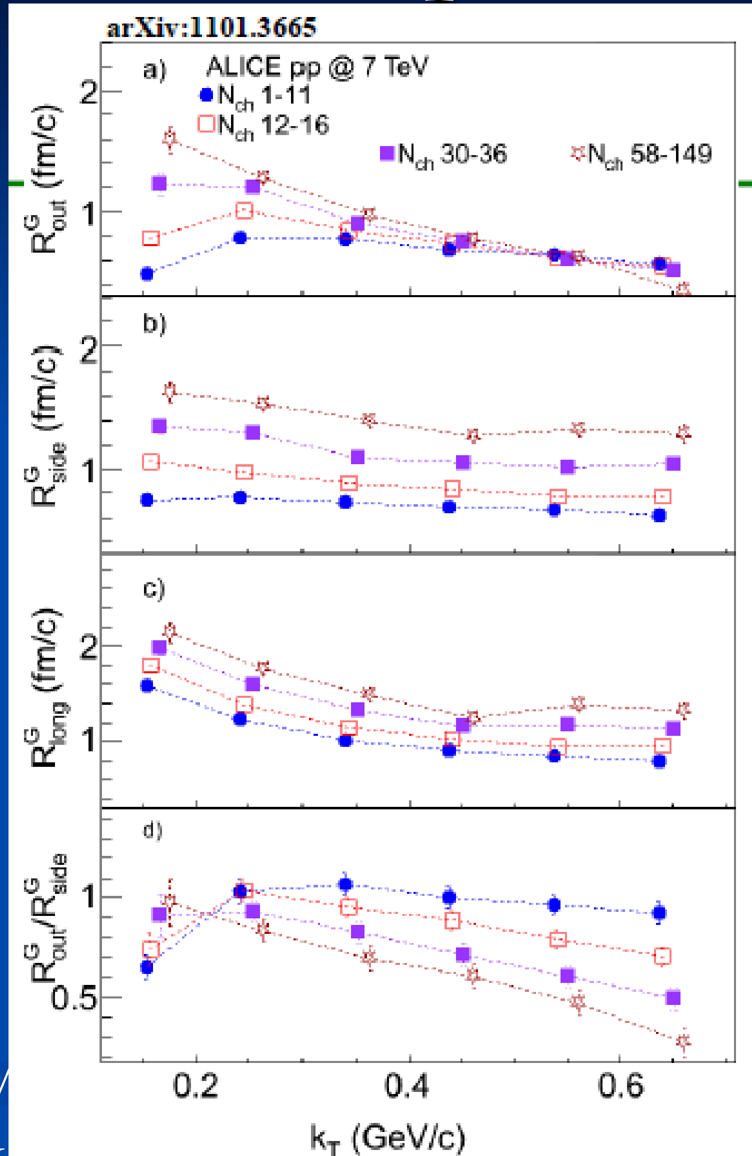




7 TeV: Phys. Rev. D 84 (2011) 112004, arXiv:1101.3665
2.76 TeV: Preliminary [900 GeV: Phys. Rev. D **82**, 052001 (2010)]

Radii obtained with identical pions





Radii at different √s scale with $dN_{ch}/d\eta$; R_{SIDE} & R_{LONG} grow with $dN_{ch}/d\eta$ at all k_T' s, R_{OUT} is flat/ decreasing at high k_T; at high mult., radii fall with k_T