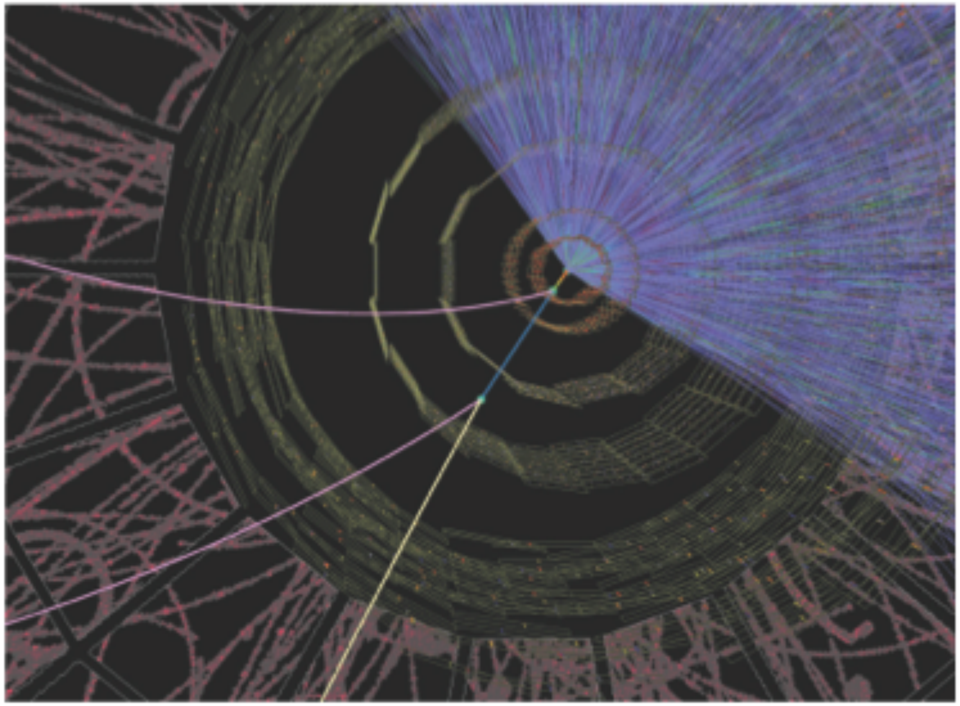
K^0_S & Λ Production in ALICE



Luke Hanratty

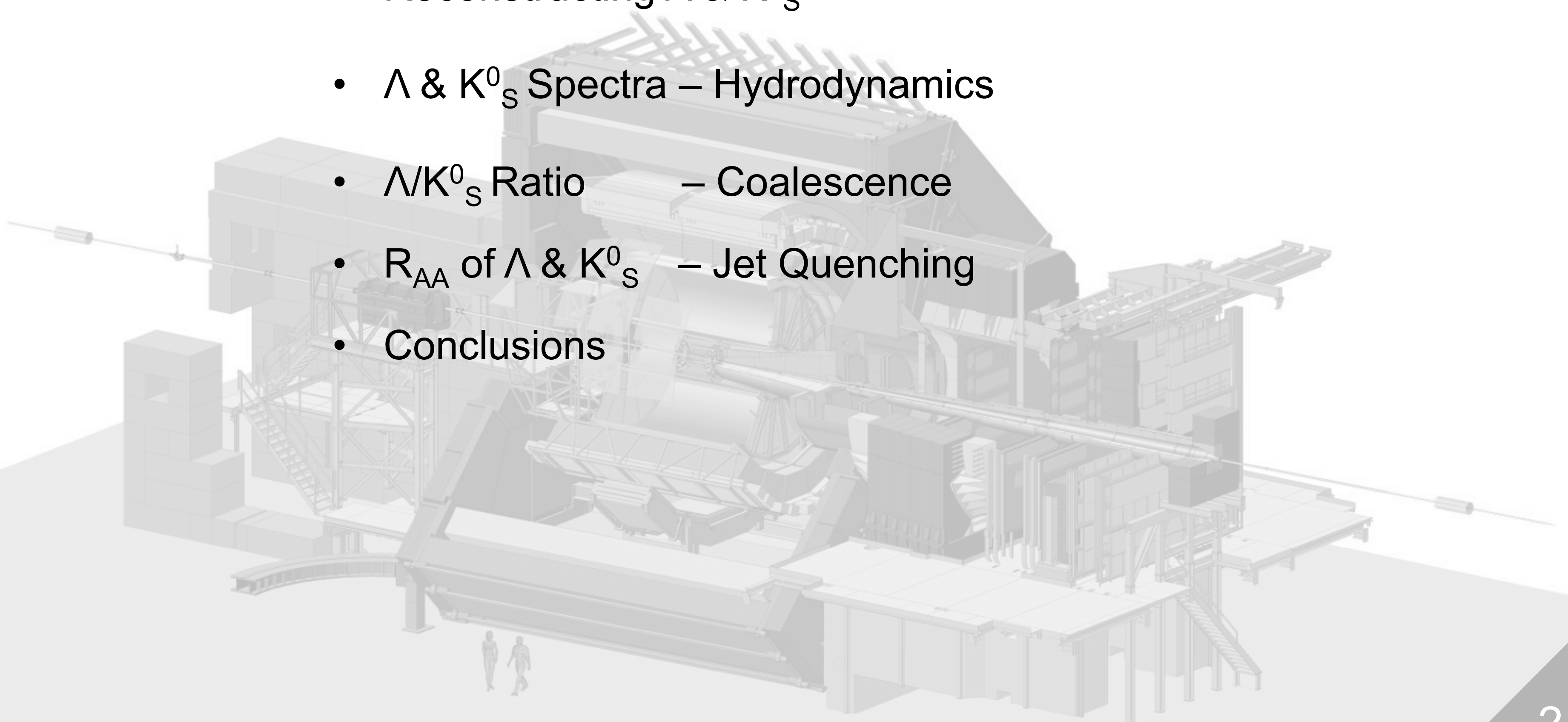
University of Birmingham

for the ALICE Collaboration

University of Birmingham Particle Physics Seminar *12 February 2014*

Outline

- The ALICE Experiment
- Quark-Gluon Plasma
- Reconstructing Λ & K^0_S
- Λ & K^0_S Spectra – Hydrodynamics
- Λ/K^0_S Ratio – Coalescence
- R_{AA} of Λ & K^0_S – Jet Quenching
- Conclusions



ALI-PERF-400

All unreferenced plots taken from my thesis, work in progress

ALICE

TPC:
(Time Projection Chamber)
tracking & PID

$|\eta| < 0.9$, $85 < r < 247$ cm

$\sigma_p/p \sim 0.7\%$ (1 GeV/c)
$\sigma_p/p \sim 6.5\%$ (10 GeV/c)
$\sigma_{dE/dx}/dE/dx \sim 6.5\%$

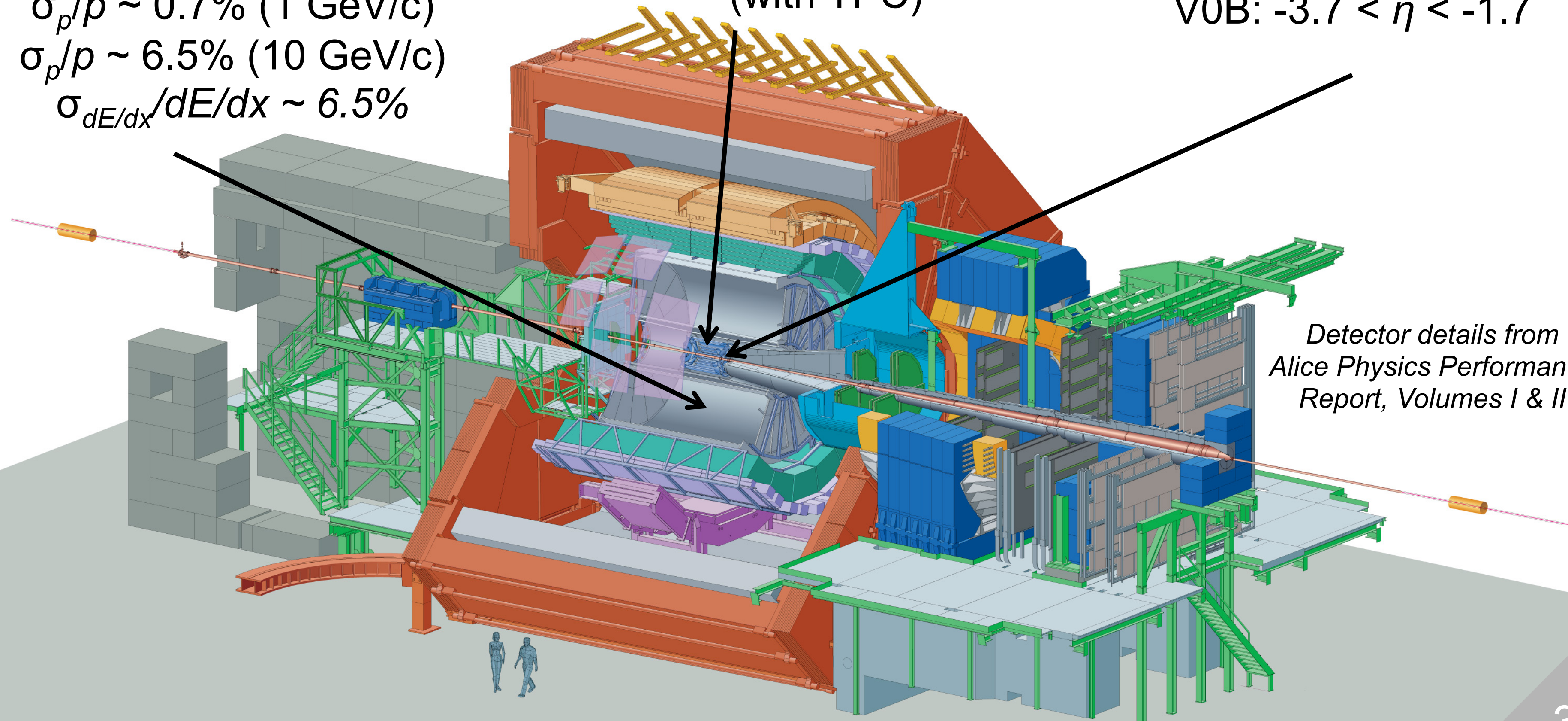
ITS:
(Silicon strips / pixels)
tracking & triggering

$|\eta| < 0.9$, $4 < r < 44$ cm

$\sigma_{vertex} \sim 100$ μm
$\sigma_p/p \sim 3.5\%$ (100 GeV/c)
(with TPC)

VZERO:
(Scintillator Arrays)
centrality selection &
triggering

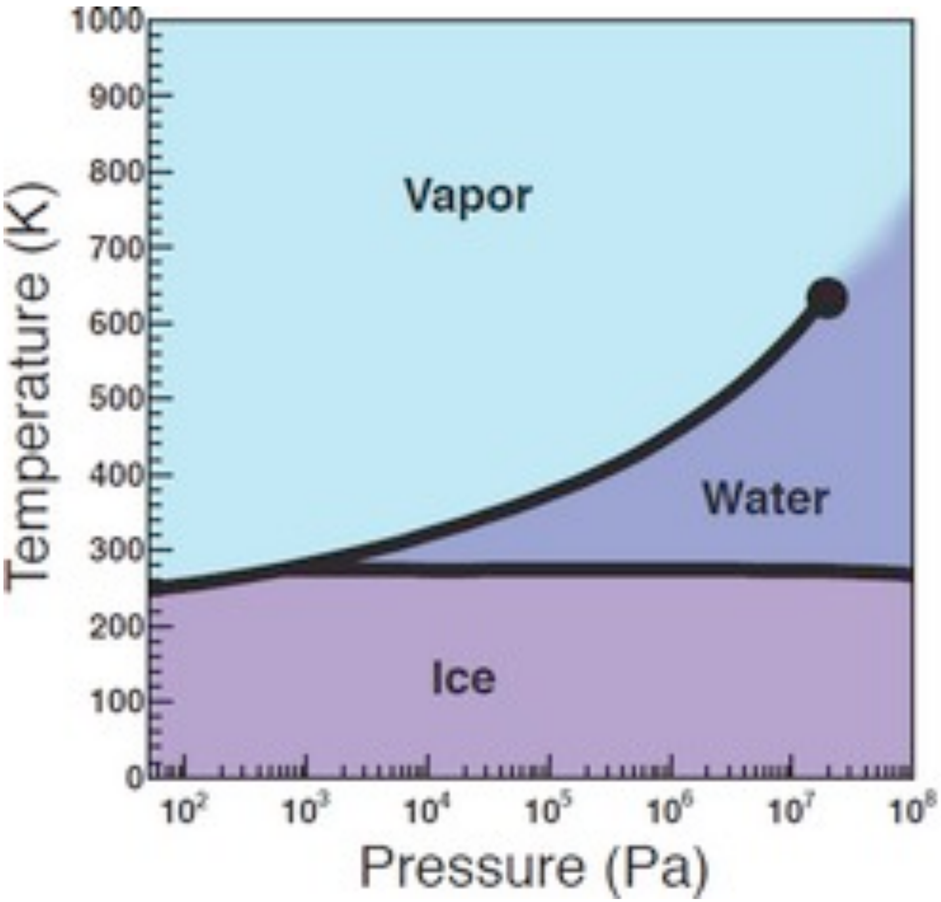
V0A: $2.8 < \eta < 5.1$
V0B: $-3.7 < \eta < -1.7$

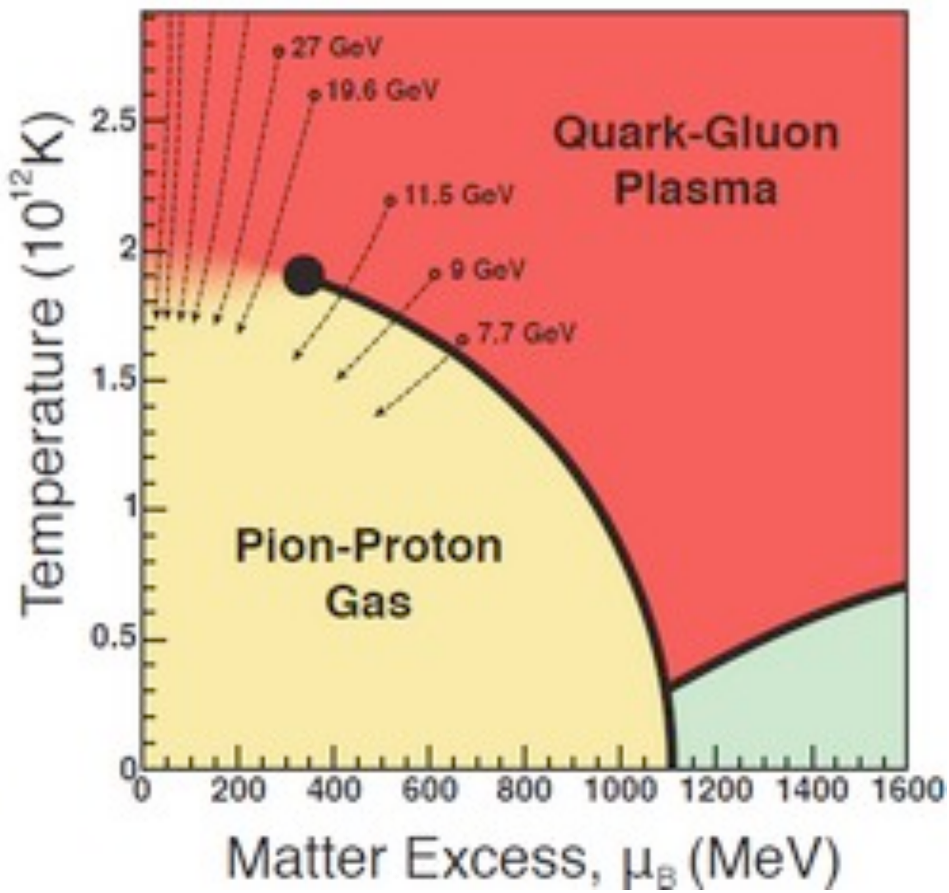


Detector details from Alice Physics Performance Report, Volumes I & II

ALI-PERF-400

QGP

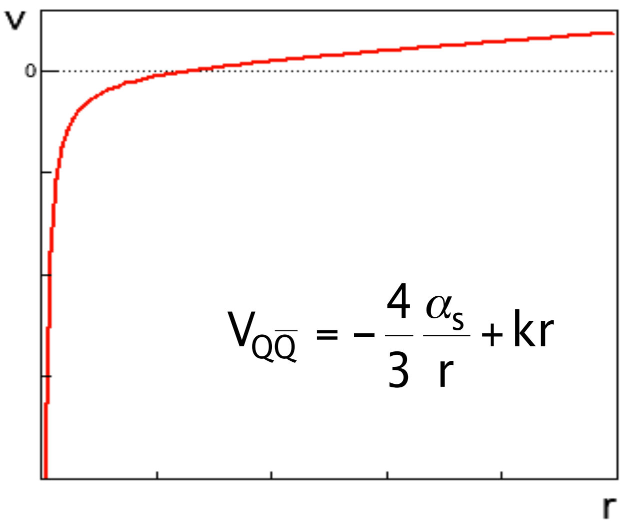


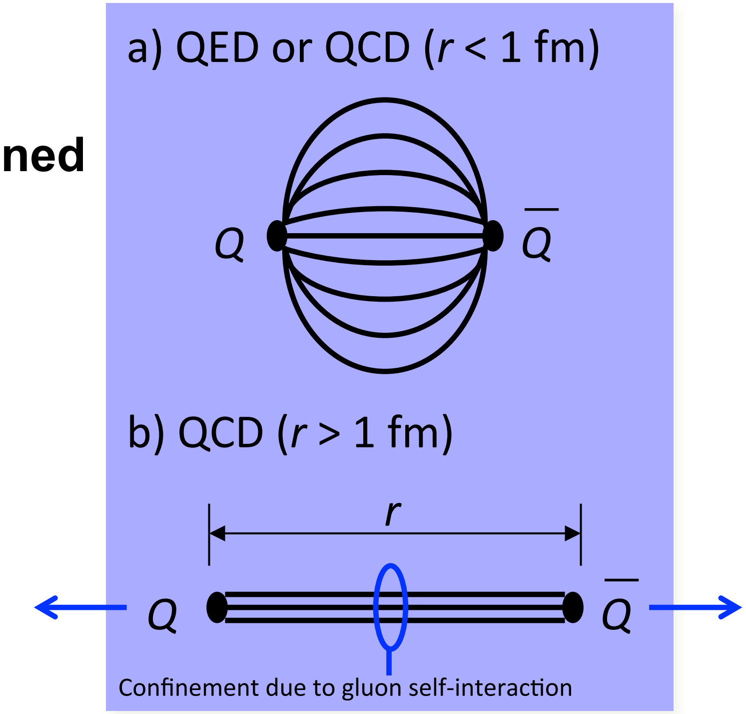


http://alicematters.web.cern.ch/?q=content/node/515

QGP

- Color charges are usually considered to be **confined**



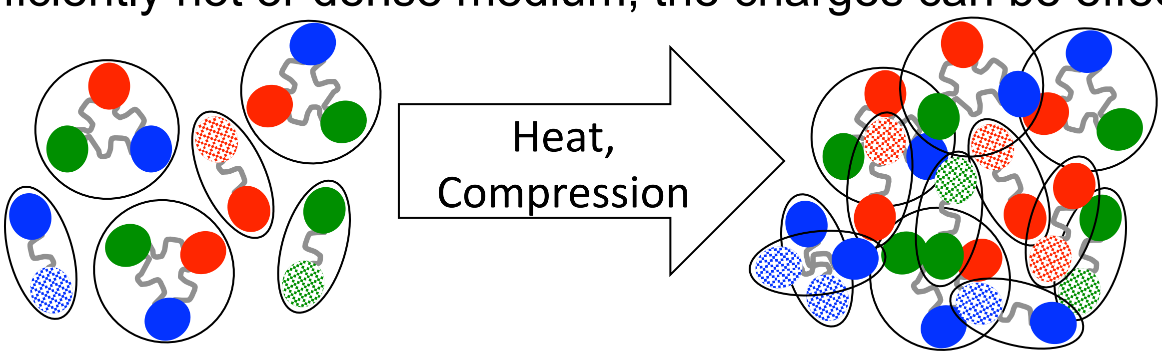


- But in a dense medium, the charge is screened (**Debye Screening**)

$$V_{Q\bar{Q}} \approx -\frac{4}{3}\frac{\alpha_s}{r}\exp\left(-\frac{r}{r_D}\right)$$

- So in a sufficiently hot or dense medium, the charges can be effectively free

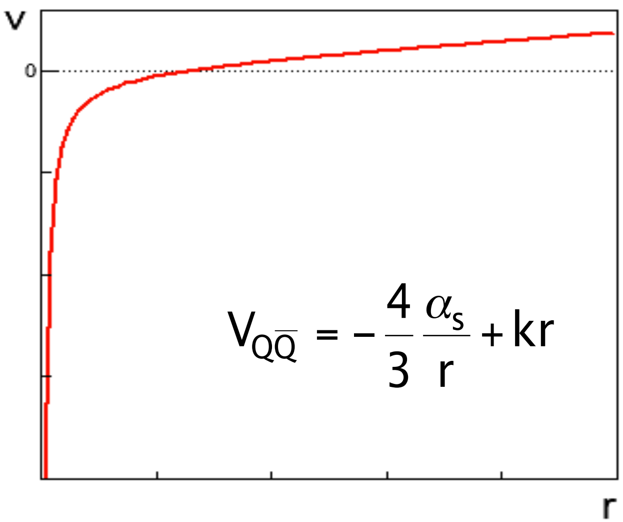
Hadron Gas



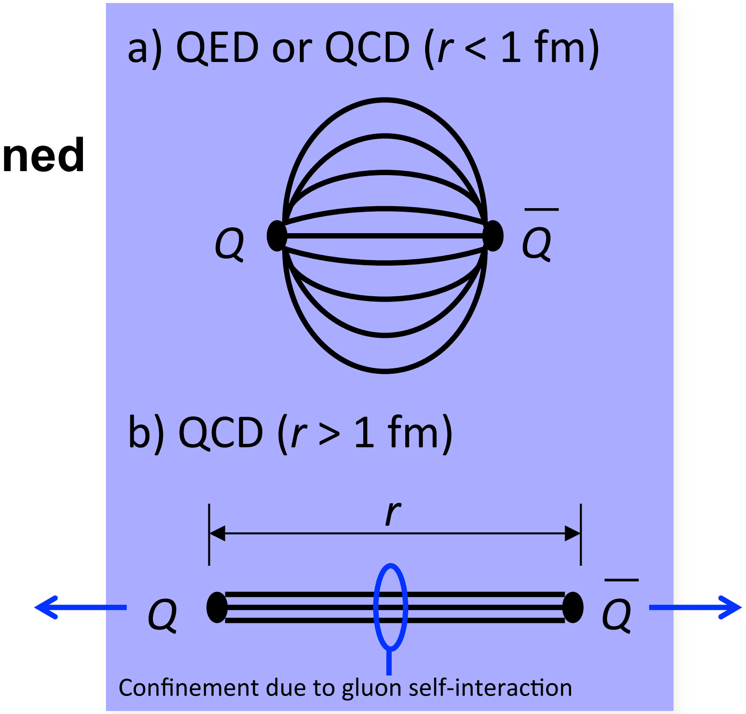
?

QGP

- Color charges are usually considered to be **confined**



$$V_{Q\bar{Q}} = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$



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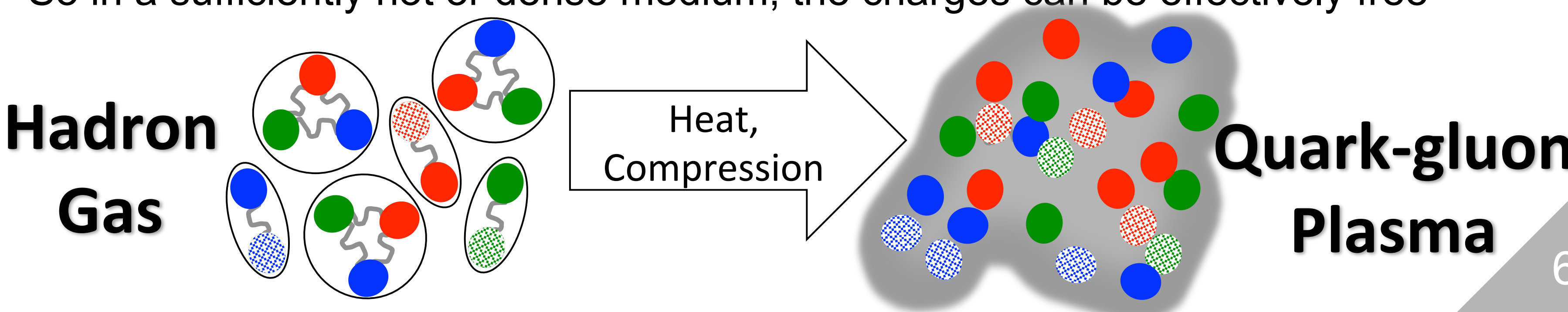
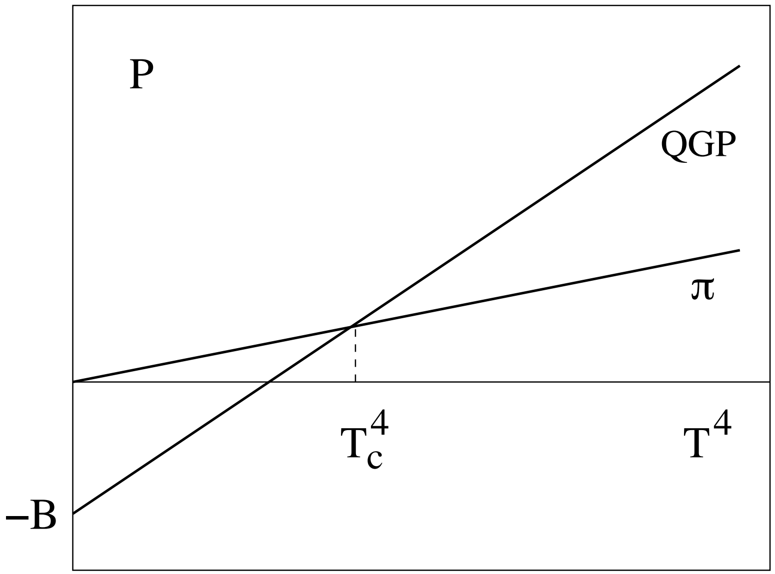
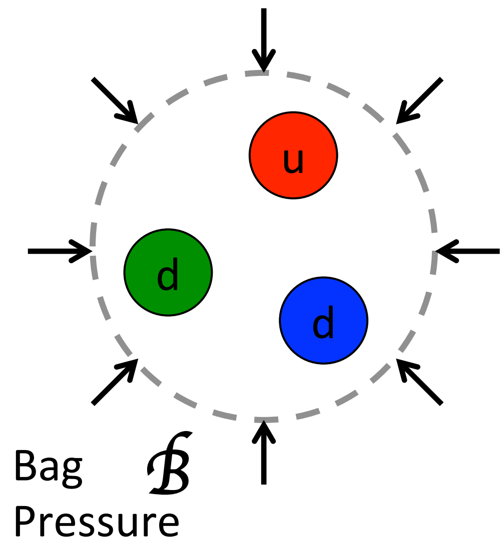


QGP

- Quark-gluon plasma is a **thermalised** system of **deconfined** quarks and gluons
- As a first approximation, we can treat Hadron Gas / QGP as an ideal gas:



Satz, Helmut arXiv:0903.2778



$$P = g\frac{\pi^2}{90}T^4$$

$g_{HadronGas} \sim 3$

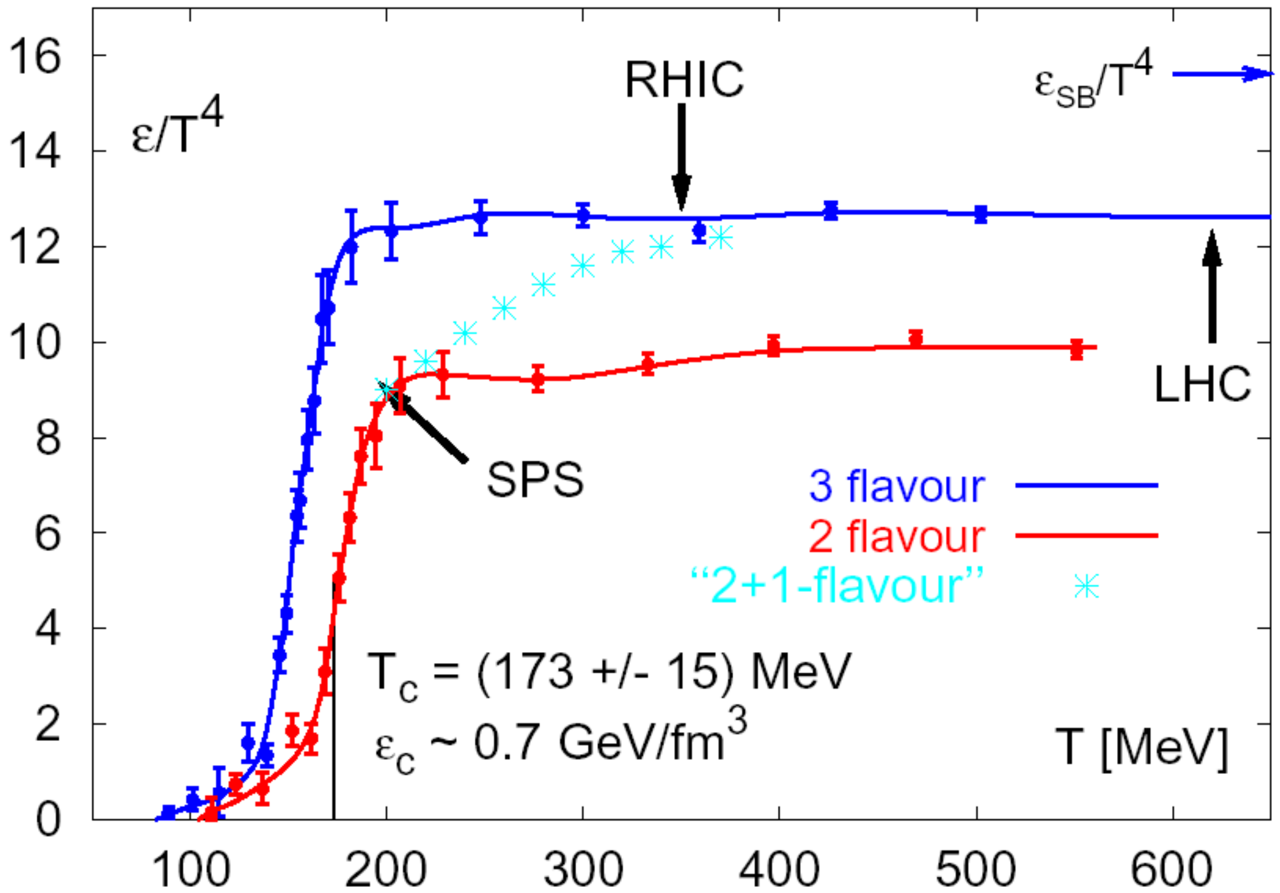
$g_{QGP} \sim 48$

A deconfined state can be attained if the QGP pressure is greater than the Bag pressure and the Hadron Gas pressure

➔ Transition temperature ~ 140MeV

QGP

- We can test this prediction using Lattice QCD



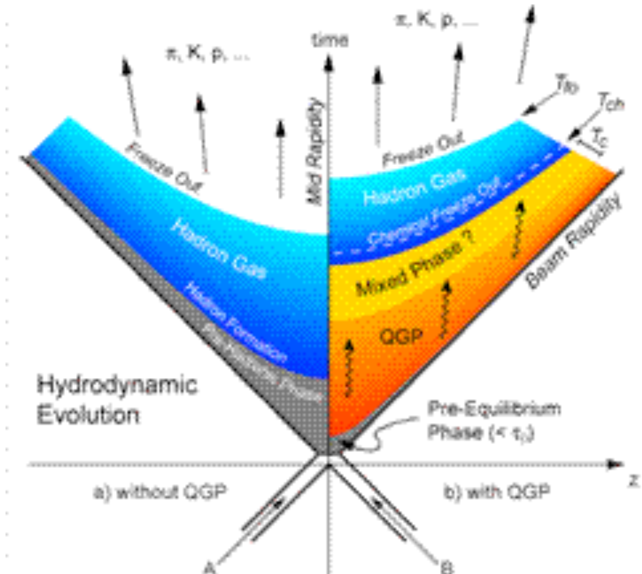
F Karsch: Quark Gluon Plasma 3 (World Scientific)

$$\frac{\varepsilon}{T^4} = g\frac{\pi^2}{30}$$

$g_{HadronGas} \sim 3$

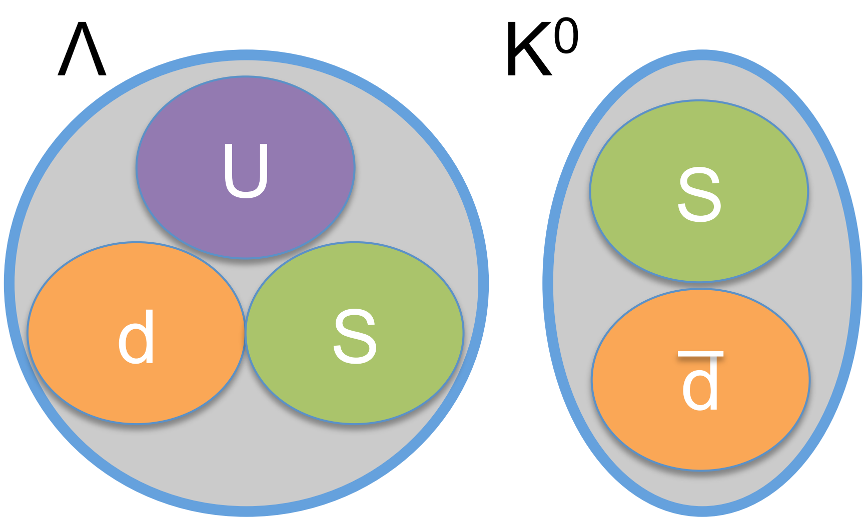
$g_{QGP} \sim 48$

Motivation



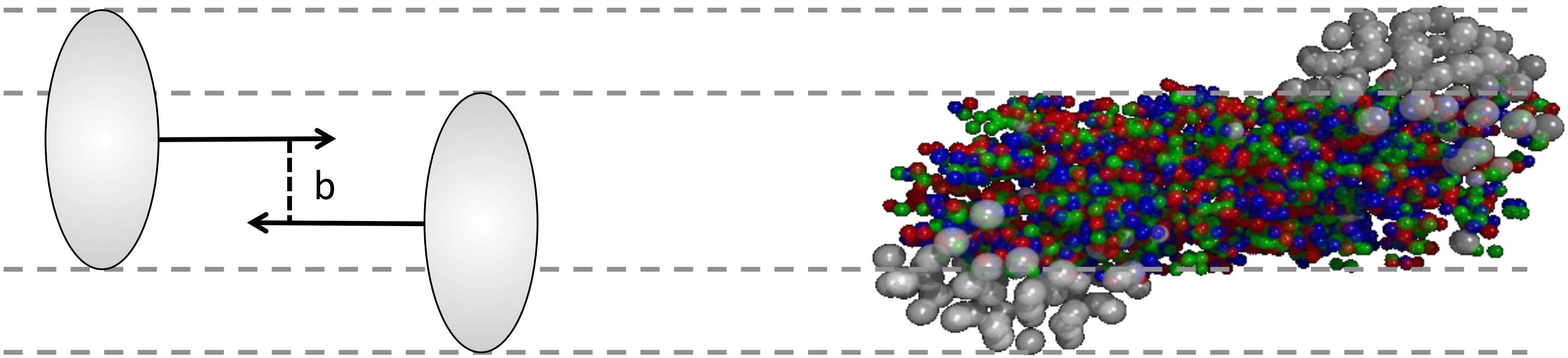
http://www-rnc.lbl.gov/~ssalur/www/Research3.html

- The QGP cools very rapidly in the lab
  ➔ τ ~ 11 fm/c ~ 10^{-23} s
- Most information in Hadron Spectra at freezeout
- Λ & K^0_S are the lightest strange baryon & meson
- Studying different hadrons allows understanding of mass & flavour dependence of Jet Quenching, Flow…

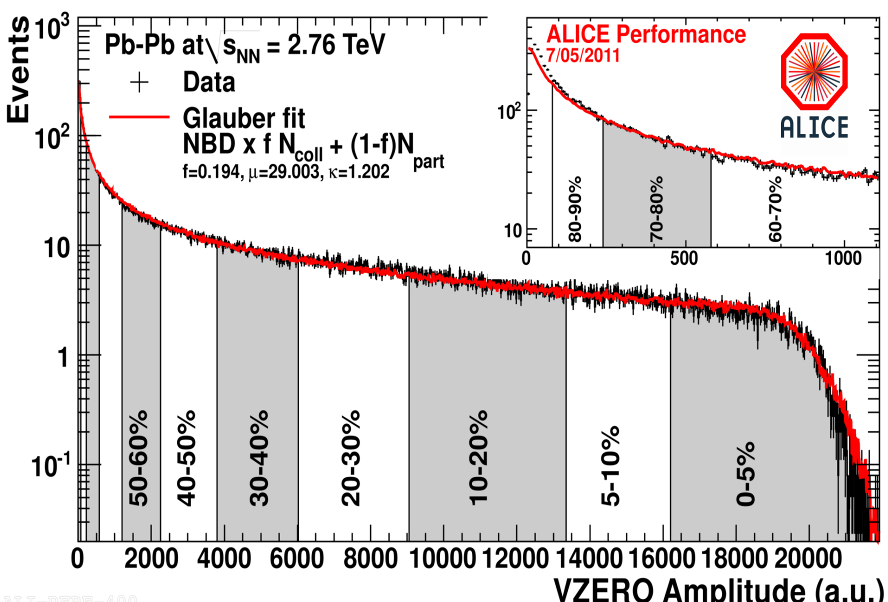


Phys.Lett.B 696 (4): 328-337, 2011
DOI:10.1016/j.physletb.2010.12.053

Centrality



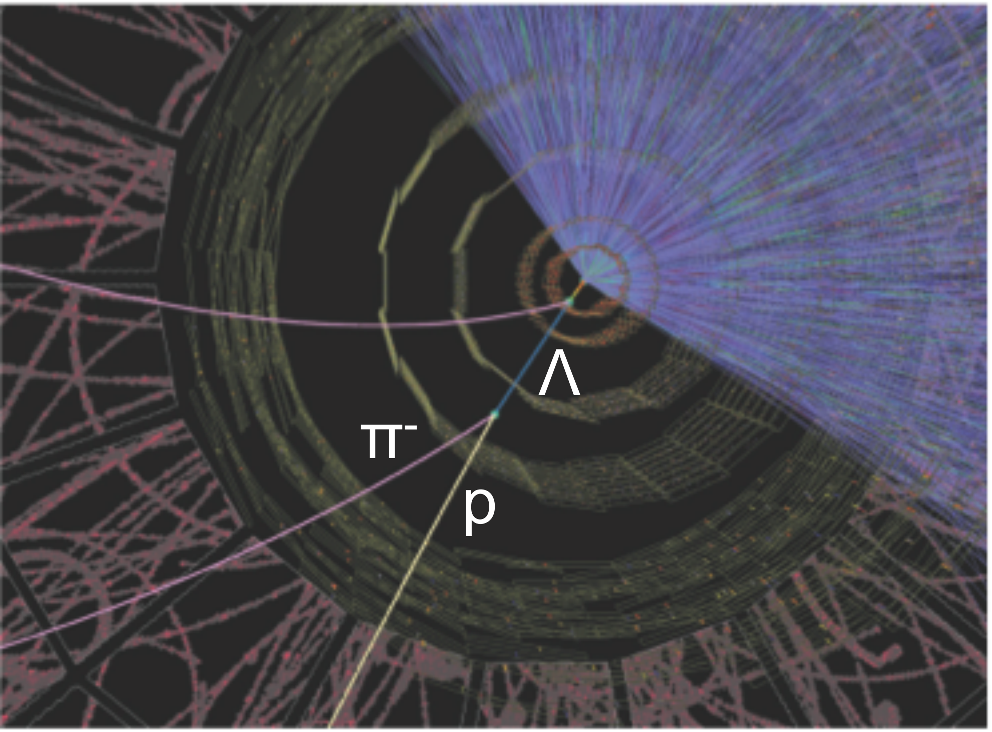
- Experimentally, we need to distinguish between head-on collisions, and glancing collisions.



B. Abelev et al. (ALICE Collaboration), PHYSICAL REVIEW C 88, 044909 (2013)

- Events are classified by their **centrality** – a % of the total nuclear interaction cross section
- The number of charged particles produced in a collision is dependent on both $N_{participants}$ and $N_{collisions}$
- The number of charged particles seen at the VZERO is fitted with a prediction from MC, and split into centrality regions

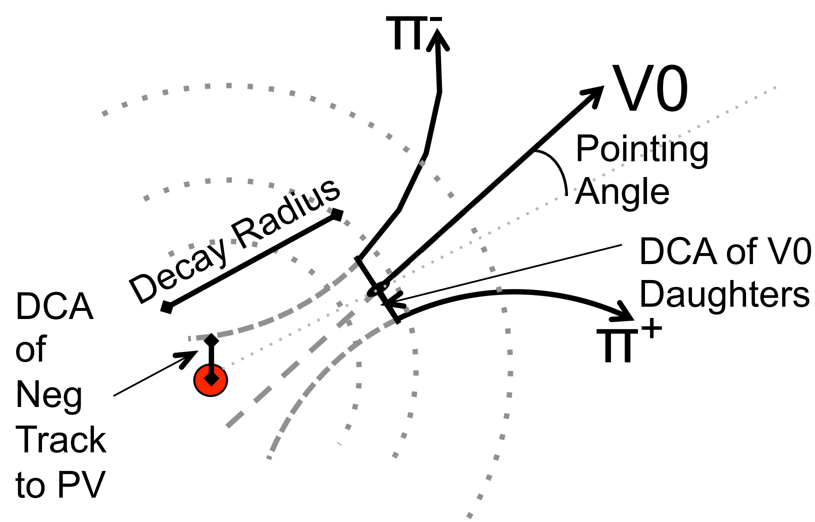
Reconstruction – V0s



Pb-Pb 5.5TeV Hijing MC Event, not all tracks shown
Alice Physics Performance Report, Volume II (Figure IV)

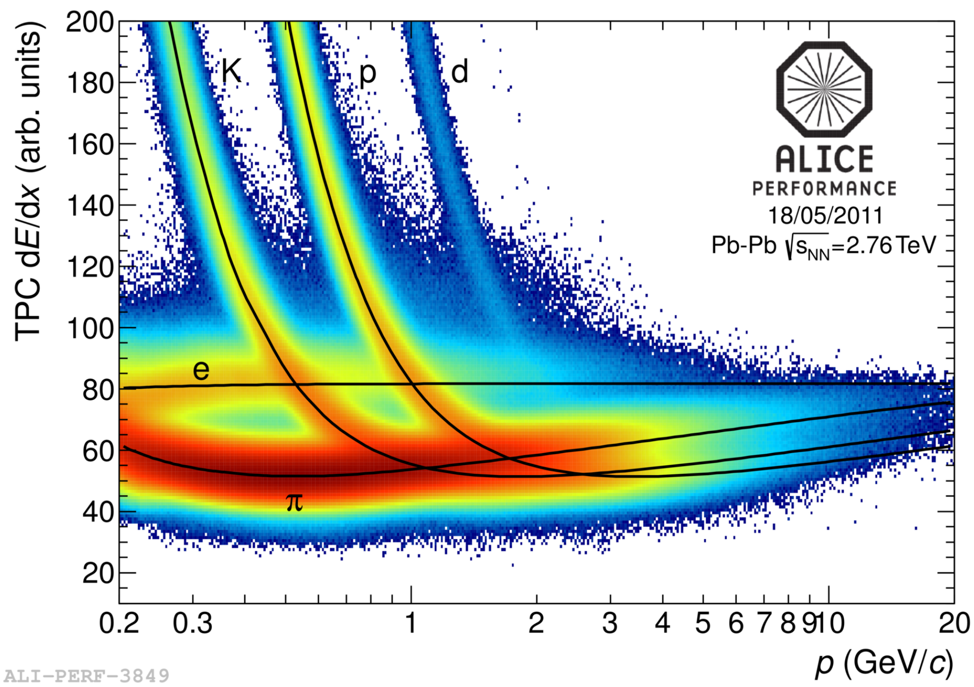
True 'V0's can be distinguished from combinatorial background by geometrical cuts on:

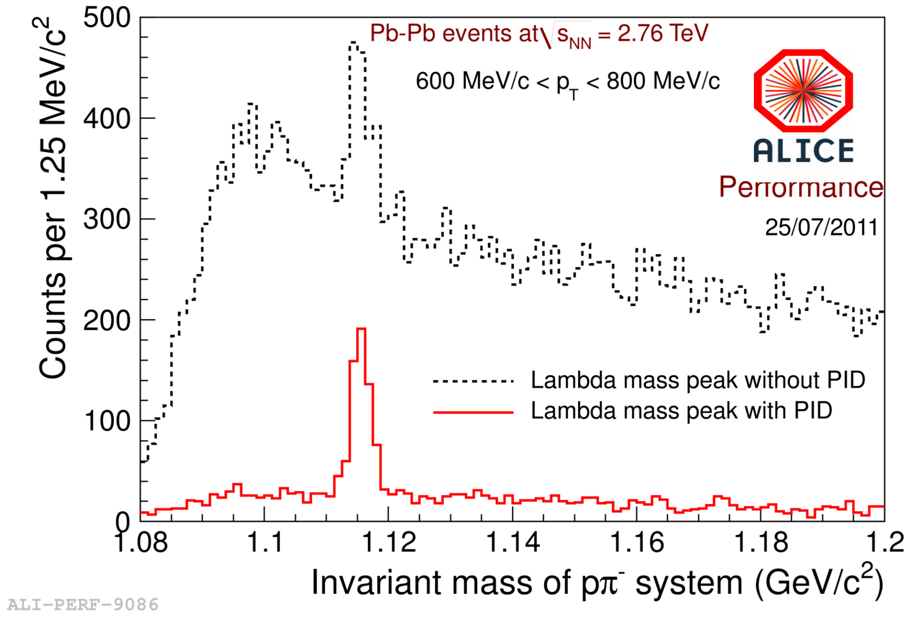
- DCA of daughters to each other
- DCA of daughters to primary vertex
- Cosine of pointing angle
- Decay radius



Decay	Branching Ratio
$K^0_S \Rightarrow \pi^+\pi^-$	69.2%
$\Lambda \Rightarrow p\pi^-$	63.9%

Reconstruction - PID

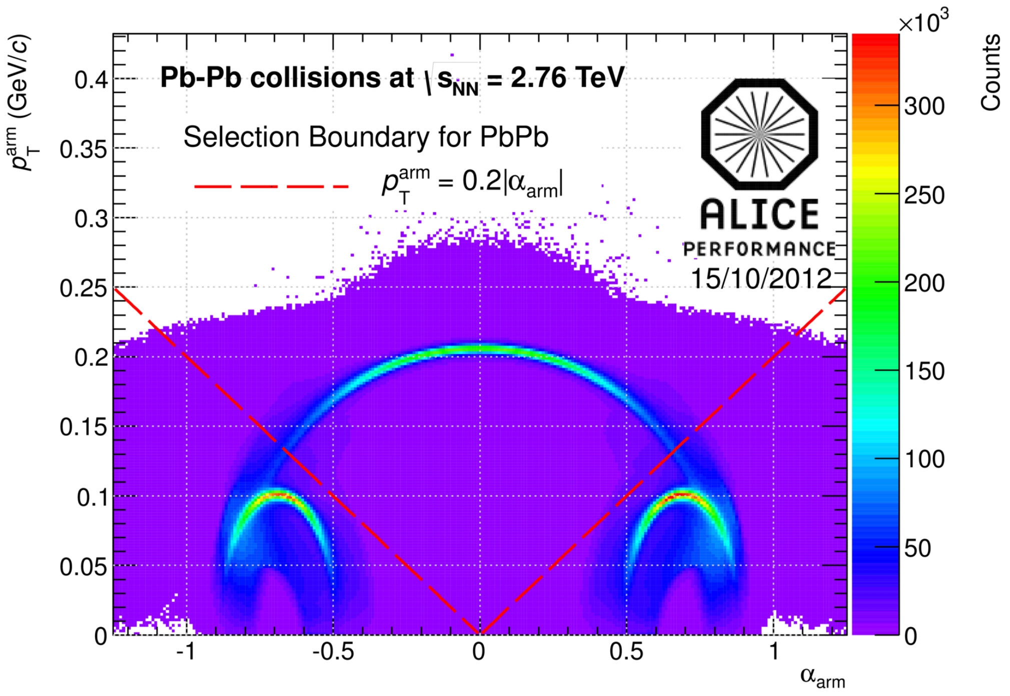




At low p_T, *dE/dx* information from the TPC allows separation of the signal from the pion dominated combinatorial background.

- 3σ cut on TPC dE/dx for proton daughters.

Reconstruction – Armenteros Plot



ALI-PERF-44262

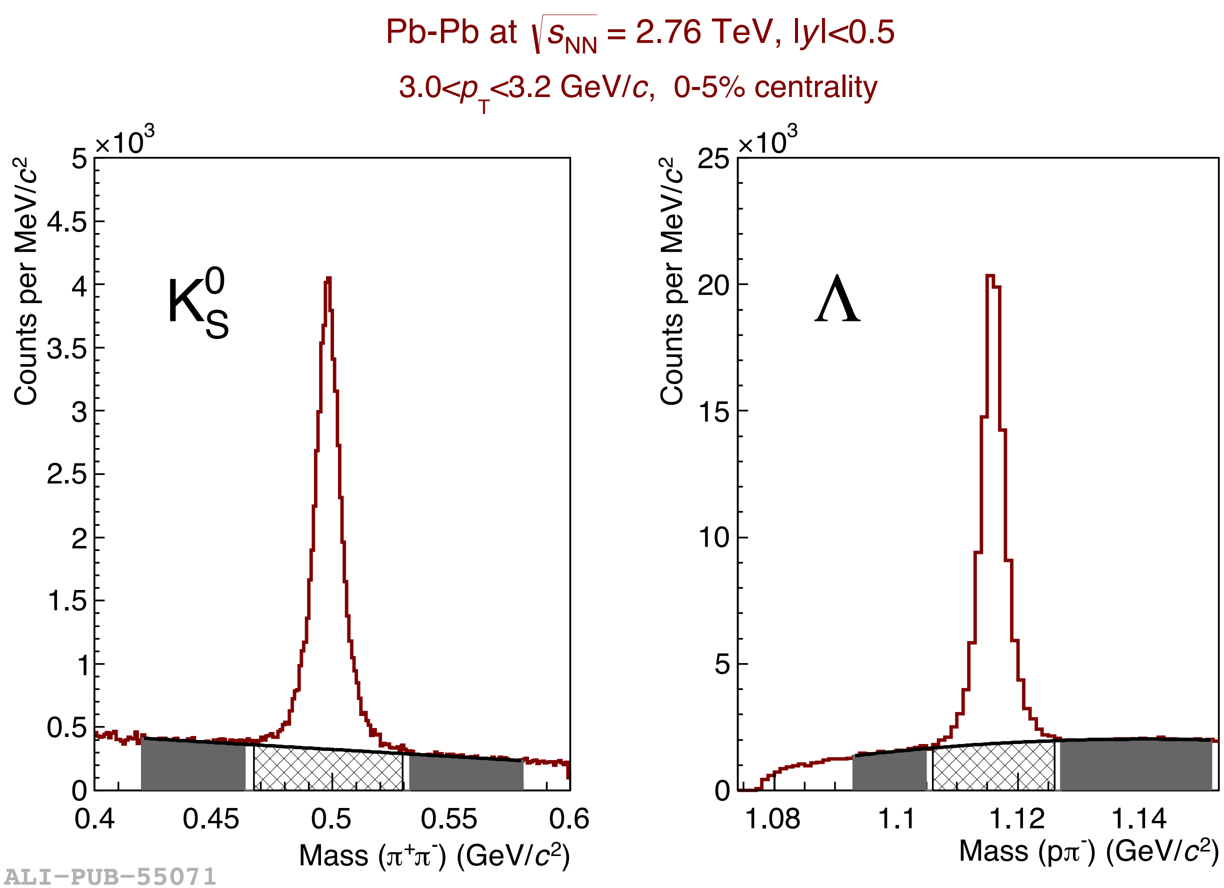
The Armenteros-Podolanski diagram is essentially another way of visualizing the invariant mass distribution of V0s

Momentum of the daughters relative to the mother are plotted, where:

$$\alpha = \frac{p_{\parallel}^{+} - p_{\parallel}^{-}}{p_{\parallel}^{+} + p_{\parallel}^{-}}$$

A cut on this diagram was used to remove Λ particles from the K^0_S background

Reconstruction – Mass Peaks



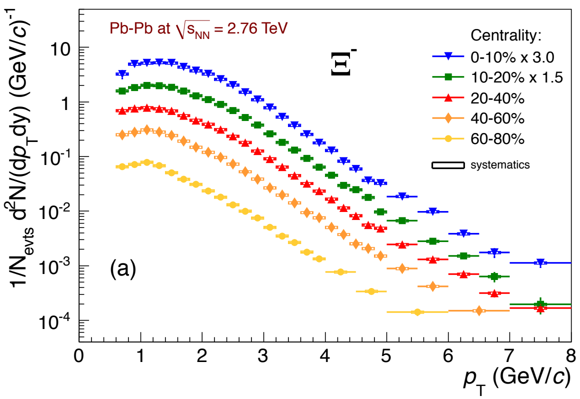
- Peak fitted with Gaussian + 2nd degree polynomial
- 'Sideband regions' fitted with 2nd degree polynomial
- Signal defined as the difference between the counts in the 'peak region' and the background fit

ALICE Collaboration, (2013), arXiv:nucl-ex/1307.5530

Reconstruction - Feeddown

Decay	Branching Ratio
$\Xi^- \Rightarrow \Lambda\pi^-$	99.887 ±0.035%
$\Xi^0 \Rightarrow \Lambda\pi^0$	99.525 ±0.012%

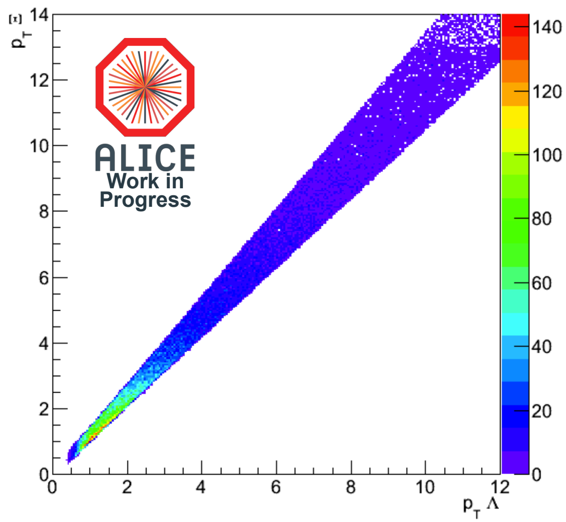
- Λ coming from weak decays of Ξ are removed



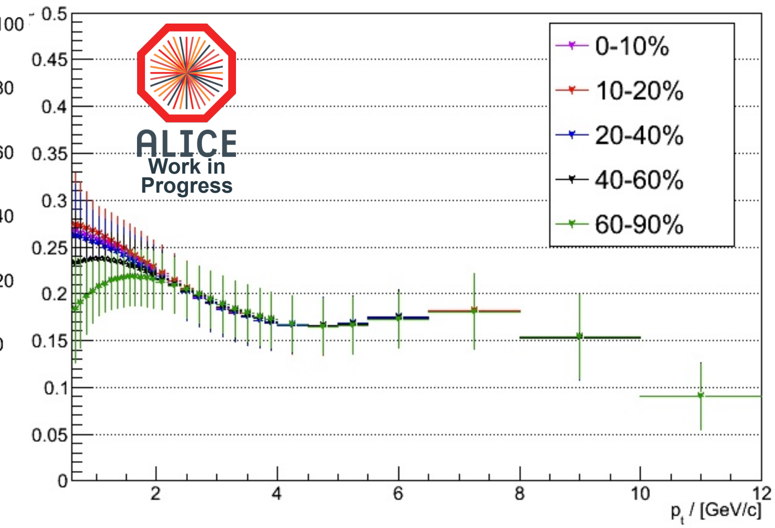
Measured Ξ Spectra

B. Abelev et al. (ALICE Collaboration), Physics Letters B 728 (2014) 216–227

MC Feeddown Matrix

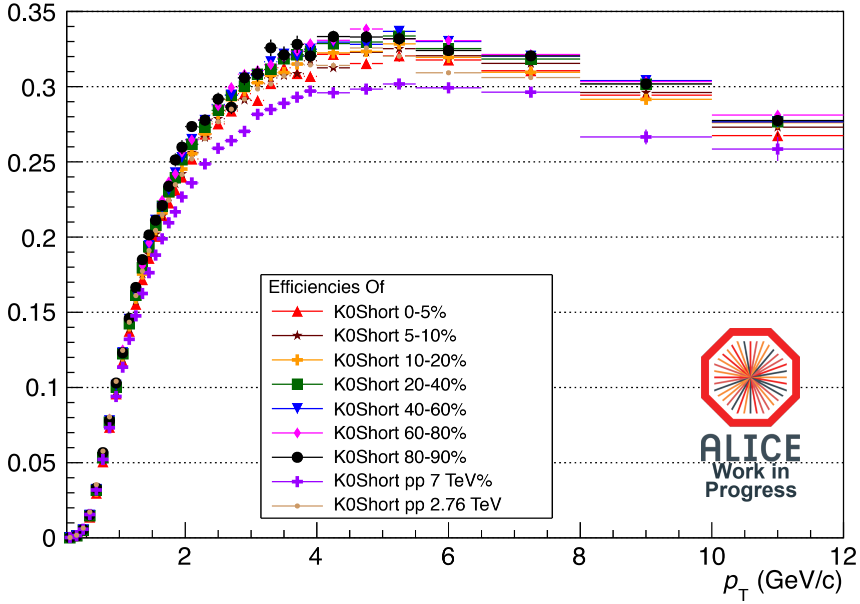


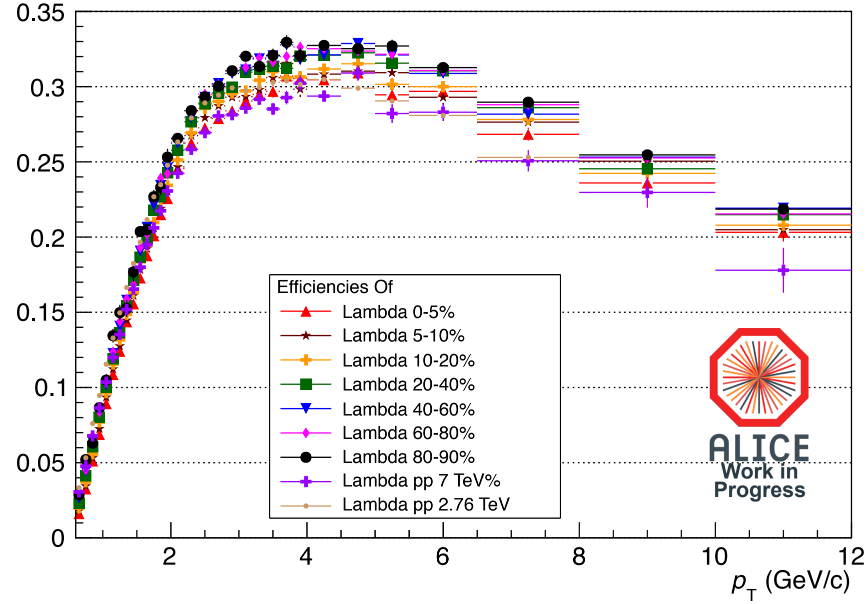
Feeddown Fraction



- Ω decay also considered, but found to be negligible

Efficiencies



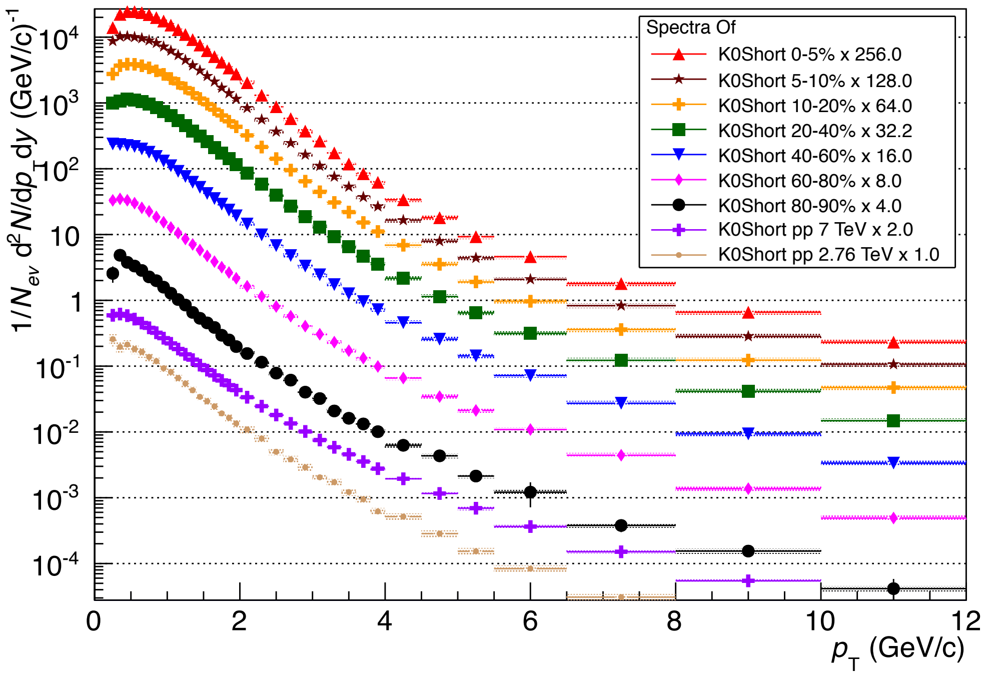


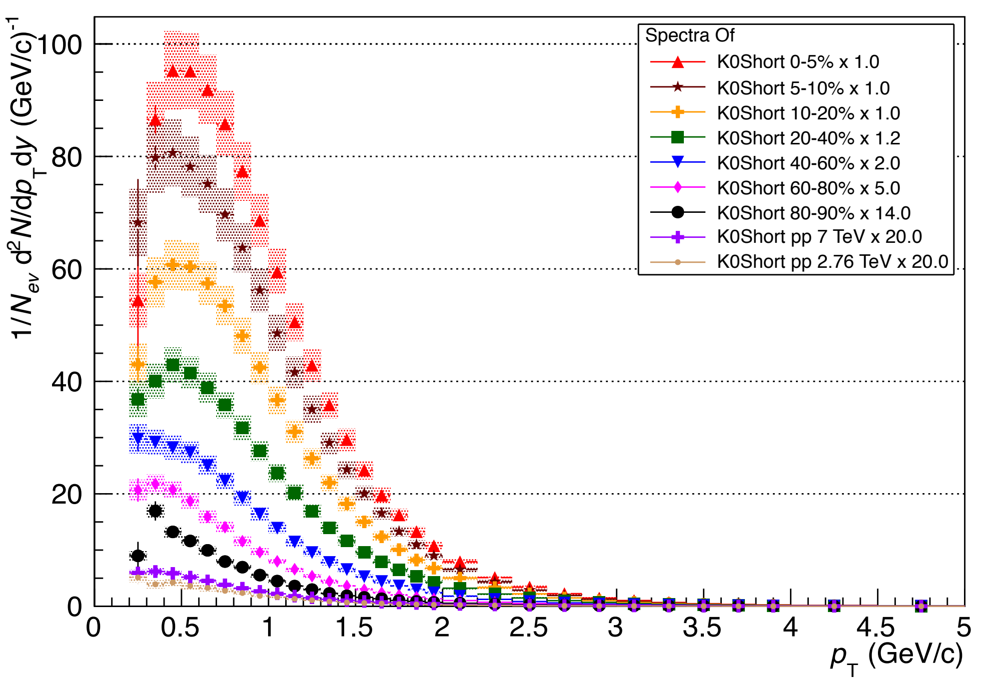
- Reconstruction efficiency ~20-30%
- Low p_T is more difficult ➔ low p_T cutoff; $\Lambda > 0.6$ GeV/c, $K^0_S > 0.4$ GeV/c
- Slight variations with centrality, $\sqrt{s}$, but largely consistent

Spectra

K^0_S

- Plots scaled to separate centralities; ordering unchanged

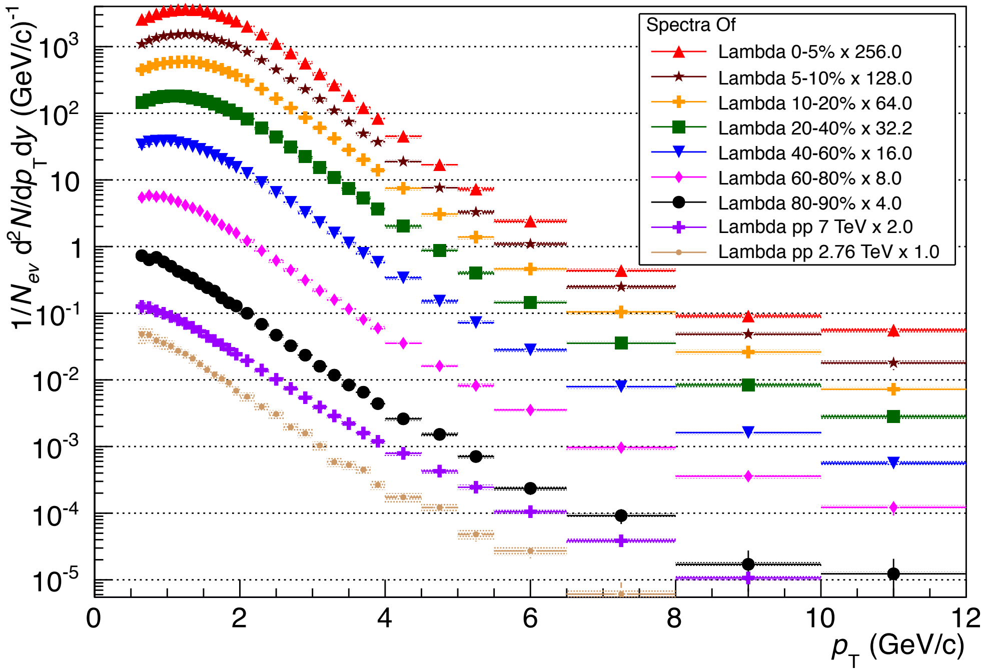


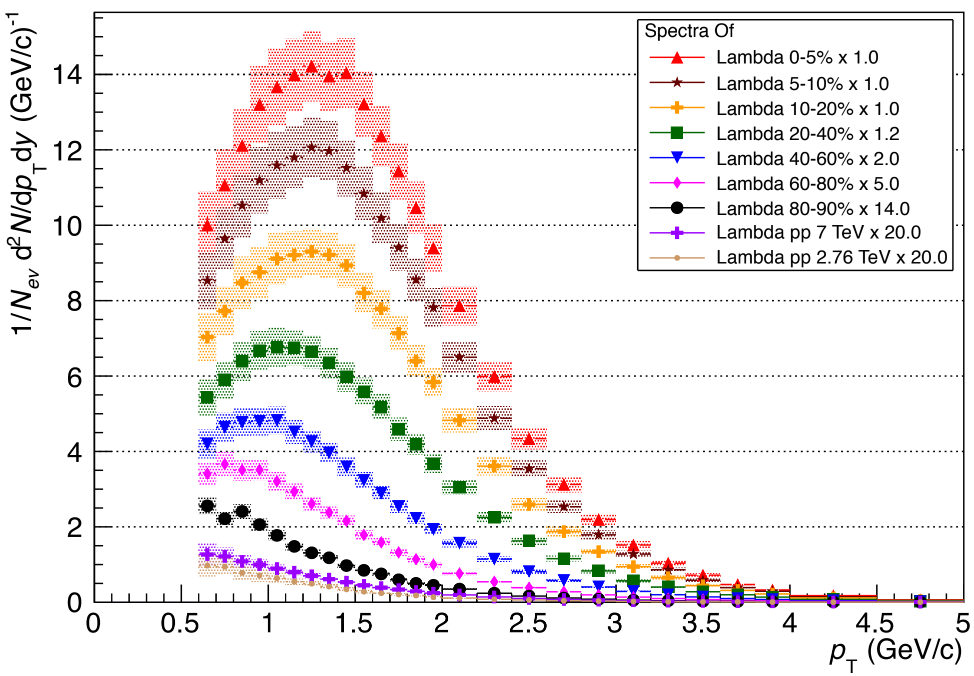


Spectra

Λ

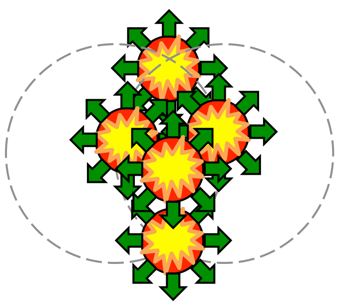
- Plots scaled to separate centralities; ordering unchanged

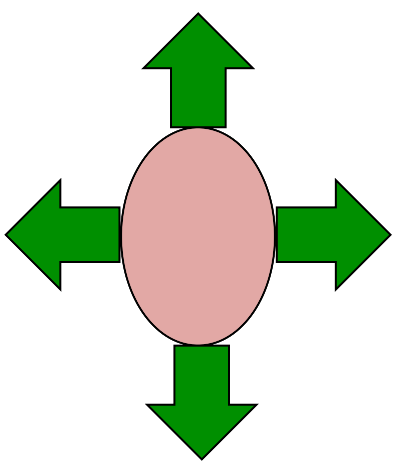




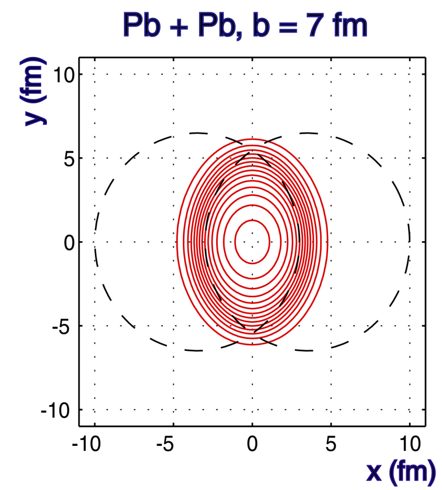
Hydrodynamics

Superposition of independent p-p

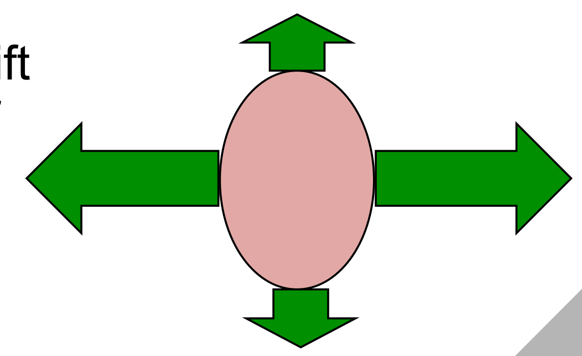




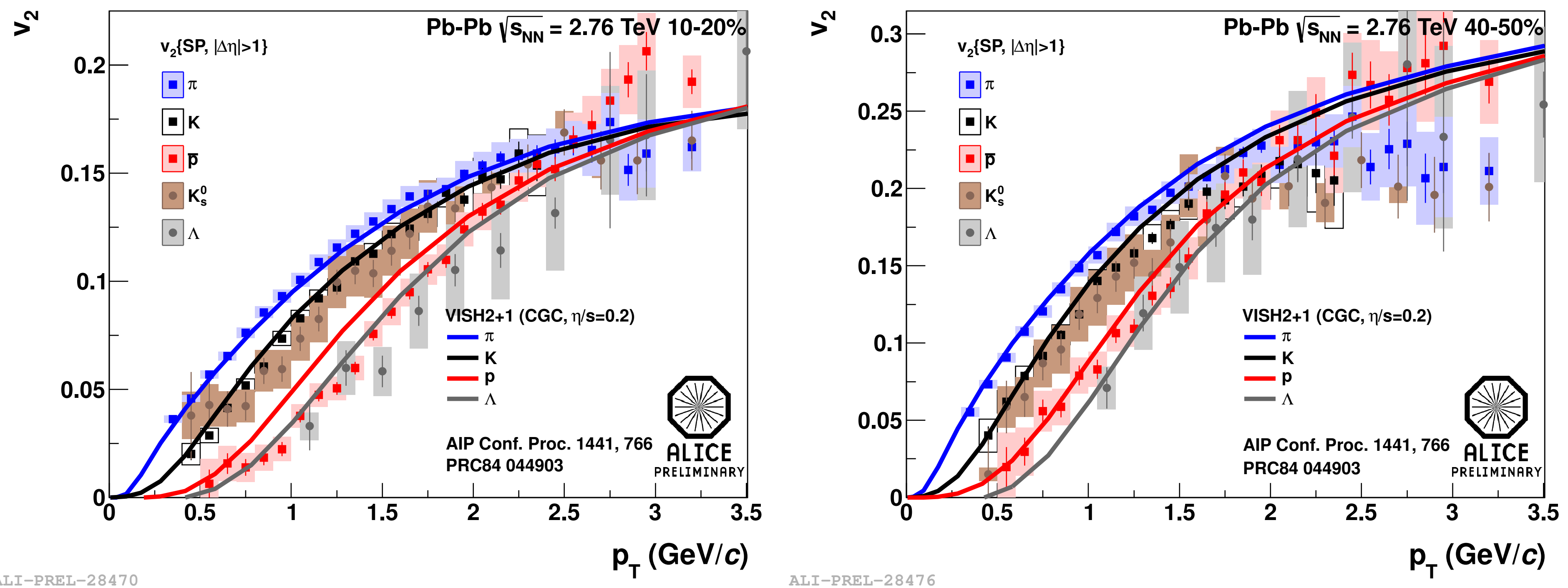
Collective Behaviour - flow



- If a thermalised medium is formed, one can have collective flow
- Initial spatial anisotropy leads final momentum anisotropy
- Typically studied by breaking down into Fourier components
  ➔ radial, elliptical…
- Radial flow causes a Doppler-shift of the momentum distributions of particles – larger for heavier particles



Hydrodynamics



- v_2 is a measure of the elliptical flow of the system
- Viscous hydrodynamics predicts its behaviour well

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos\left[n\left(\phi-\Psi_r\right)\right]\right)$$

$$v_2 = \left\langle \cos\left[2\left(\phi-\Psi_r\right)\right]\right\rangle$$

Blastwave

- Doppler-shifted Boltzmann distribution, characterised by:
  - Collective Velocity β
  - Temperature T

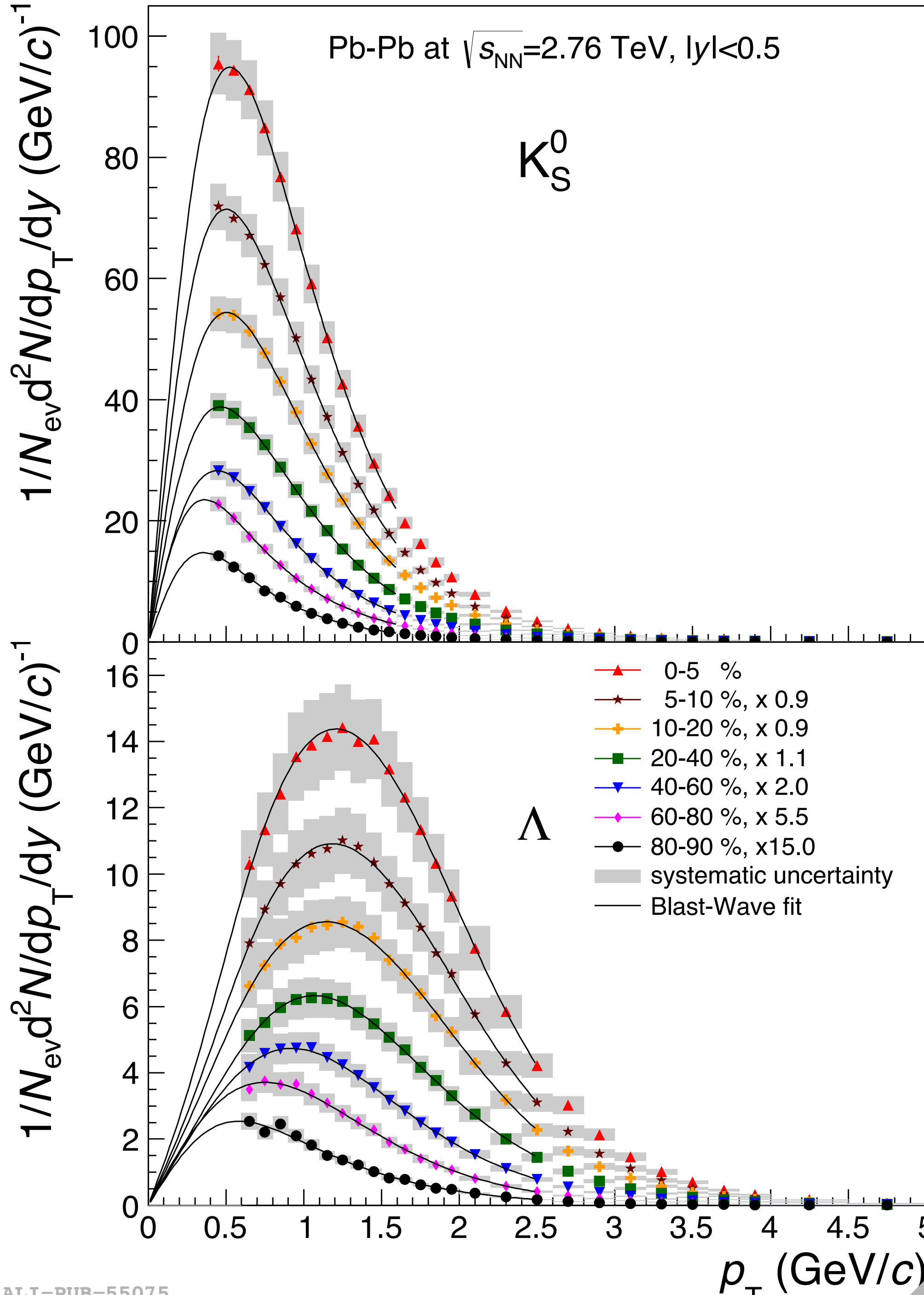
- Allows extrapolation down to p_T=0

$$\frac{dN}{dp_T} \propto p_T \int_0^1 x m_T K_1\left(\frac{m_T \cosh(\eta)}{T}\right) I_0\left(\frac{p_T \sinh(\eta)}{T}\right) dx$$

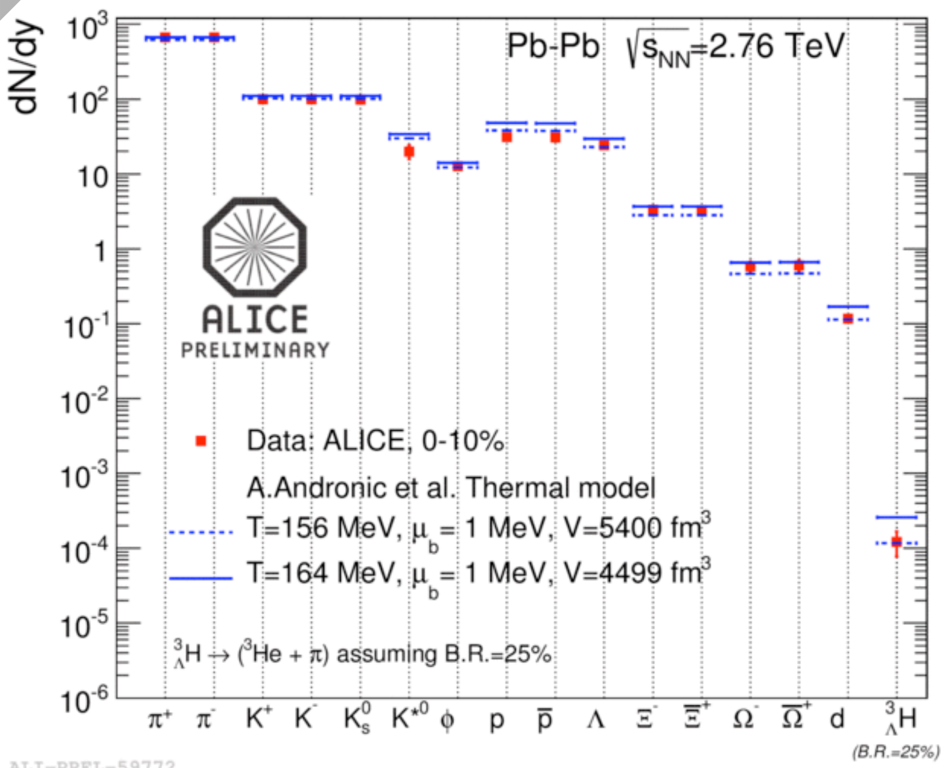
$$\eta = \tanh^{-1}(\beta),$$

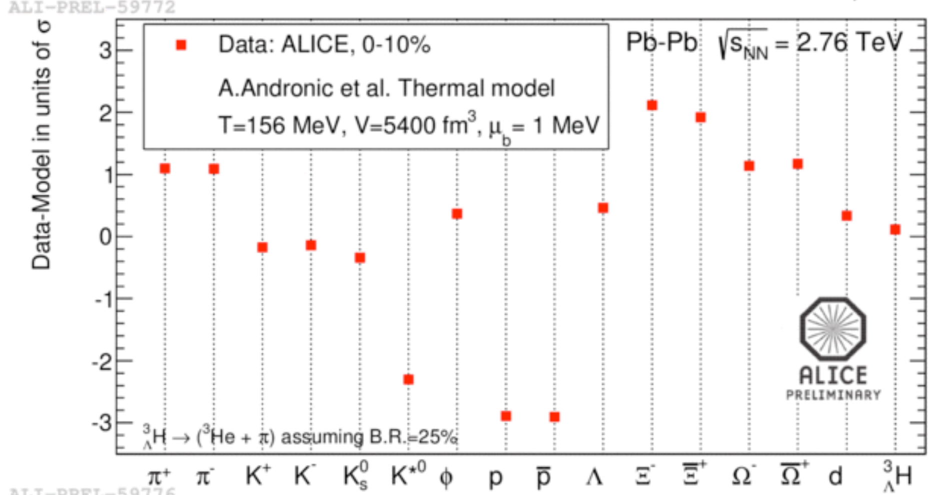
$$m_T = \sqrt{p_T^2 + m^2}$$

B. Abelev et al. (*ALICE Collaboration),*
PRL 111, 222301 (2013)

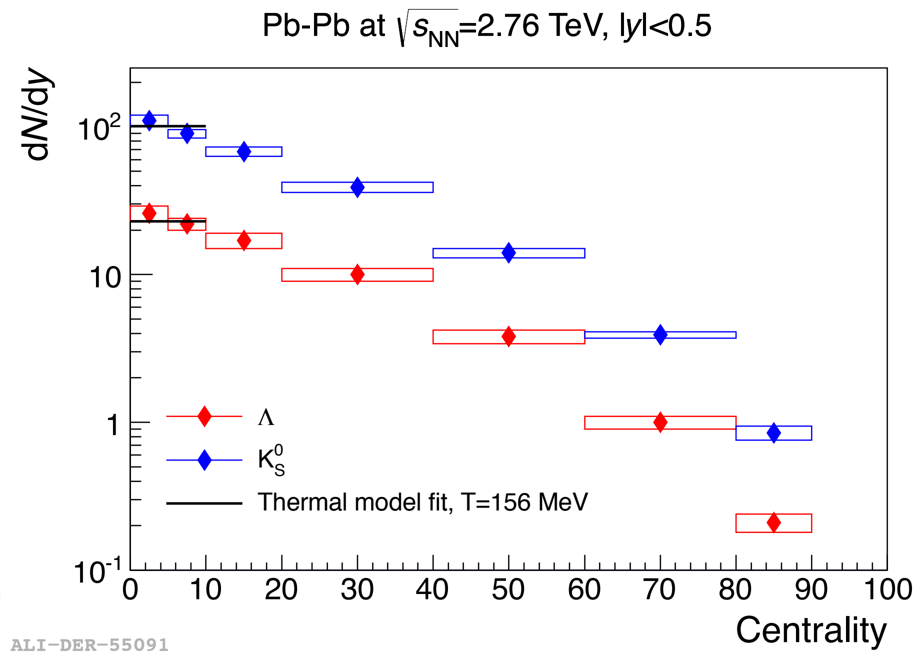


Thermal Yields





Plot created from values in:
ALICE Collaboration, (2013), arXiv:nucl-ex/1307.5530



Simultaneous thermal fit to all particles agrees well with Λ & K^0_S yields in central collisions

Theory Models used

Hydro – “Vish2+1”

- Viscous hydrodynamic model
- Sharp transition from fluid to hadrons at freeze-out temperature

H. Song and U. W. Heinz, Phys. Lett. B658, 279 (2008), arXiv:nucl-th/0709.0742 .
H. Song and U. W. Heinz, Phys. Rev. C77, 064901 (2008), arXiv:nucl-th/0712.3715 .
H. Song and U. W. Heinz, Phys. Rev. C78, 024902 (2008), arXiv:nucl-th/0805.1756 .

EPOS *2.17v3*

- String-breaking model
- Low energy strings form a ‘medium’
- Strings breaking in medium take quarks from medium
- Models ‘Core-Corona’ effect

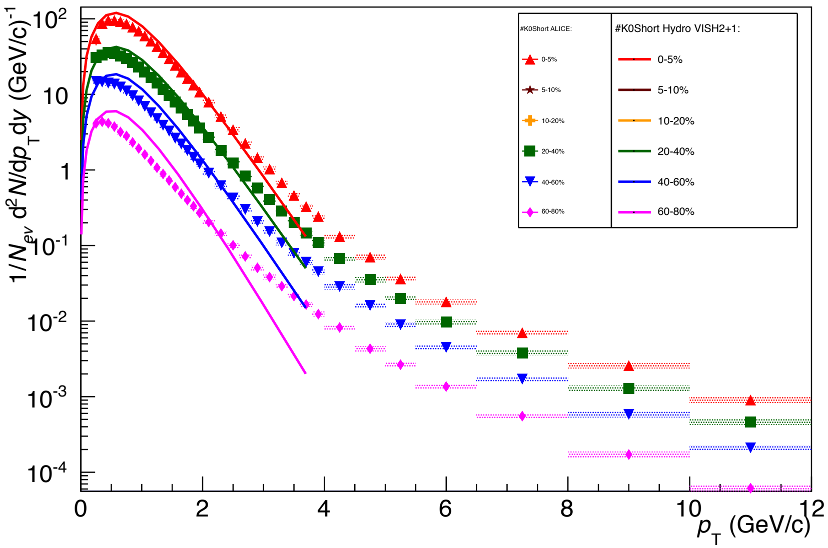
K. Werner, Phys. Rev. C 85, 064907 (2012) arXiv:1203.5704 .
K. Werner, Phys. Rev. Lett. 109, 102301 (2012) arXiv:1204.1394

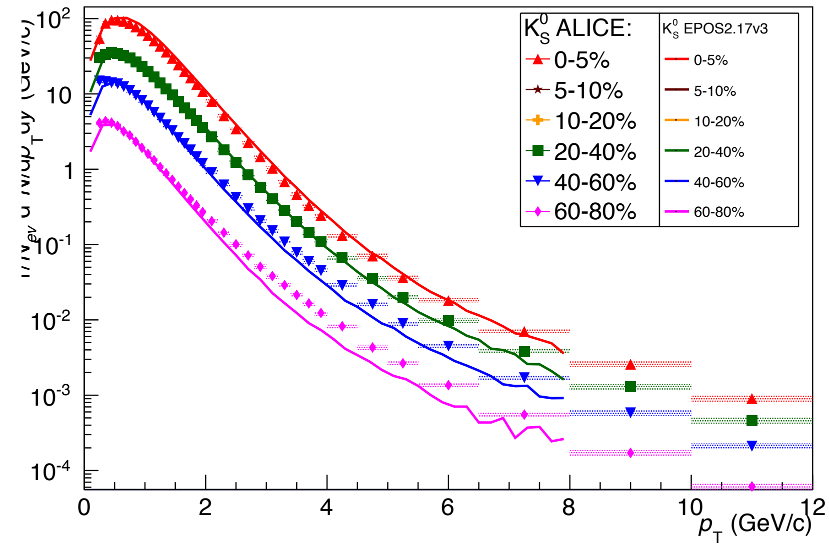
Spectra compared to models

Hydro

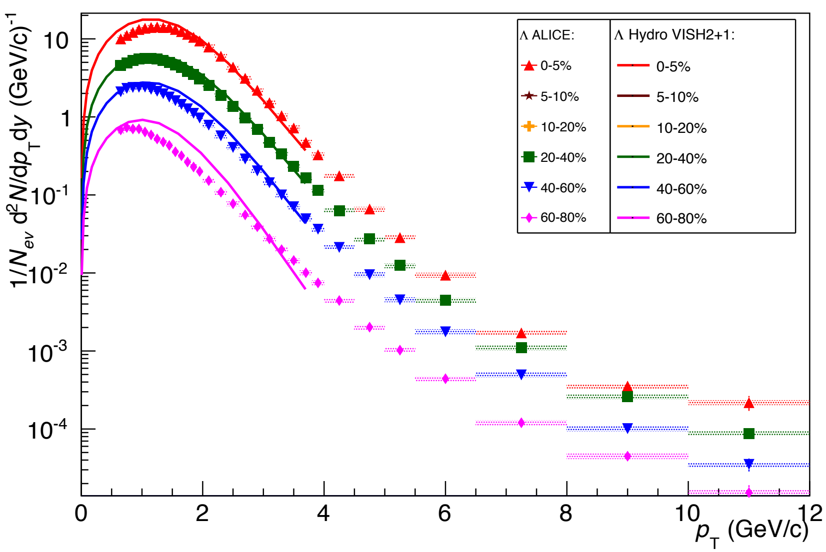
EPOS

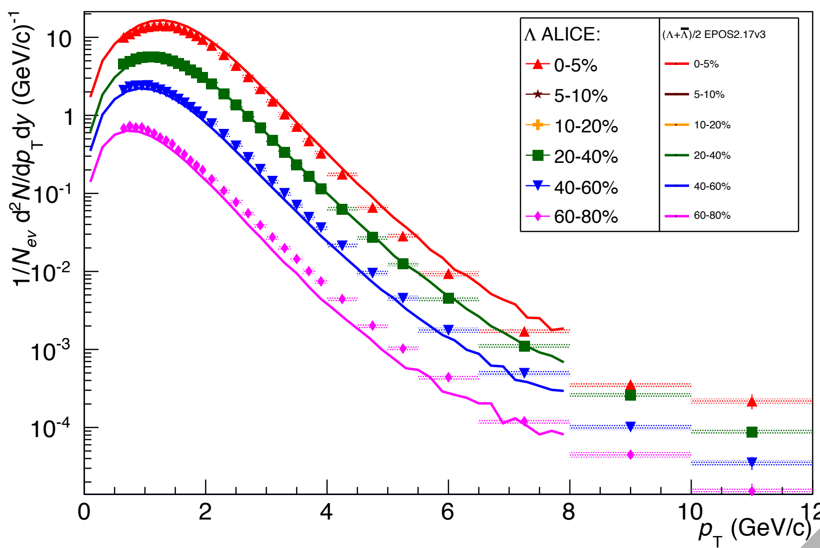
K^0_S



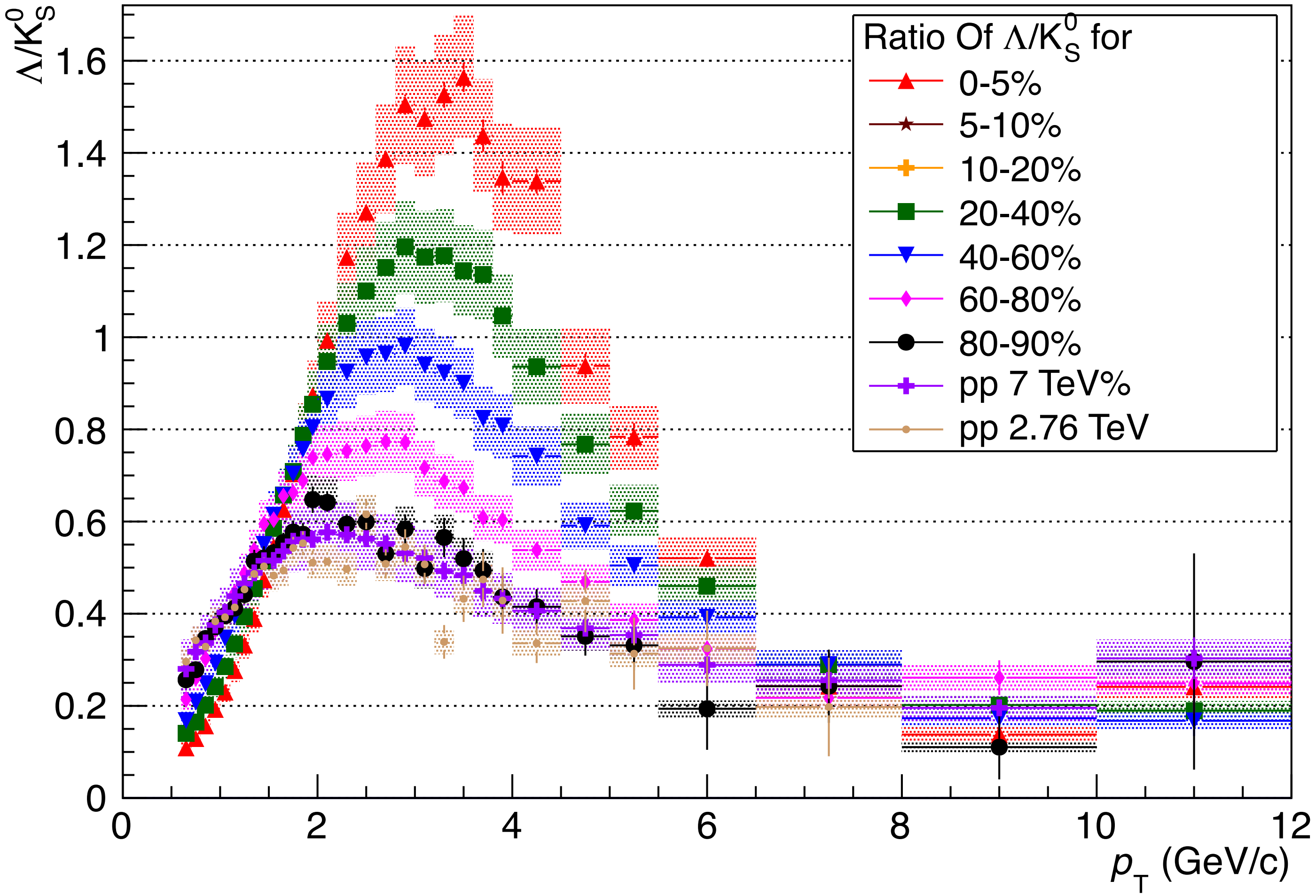


Λ



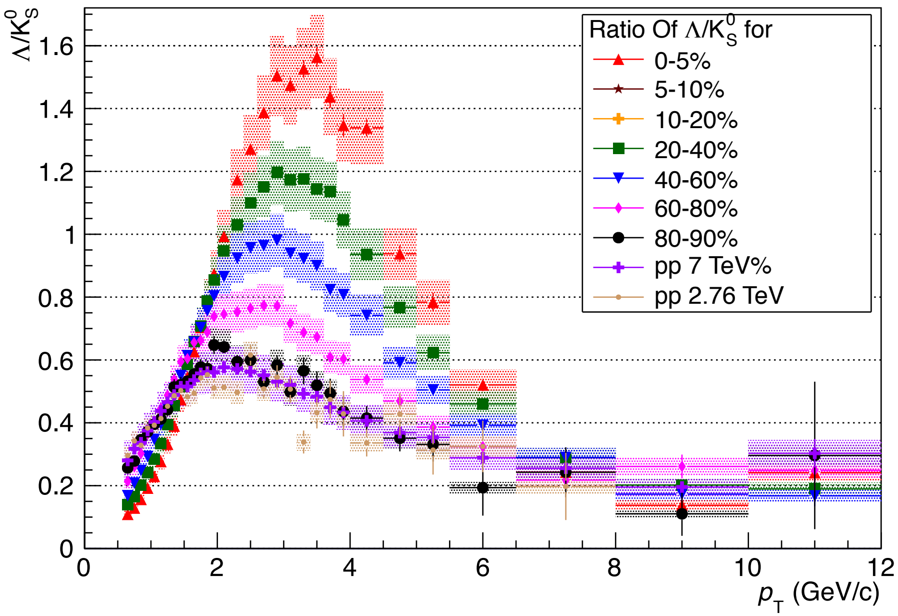


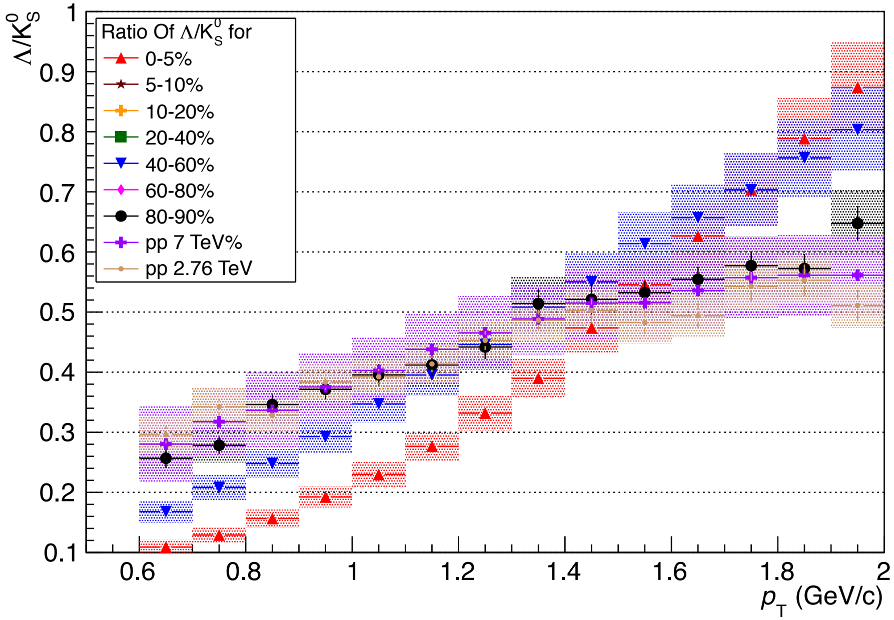
Λ/K^0_S Ratio



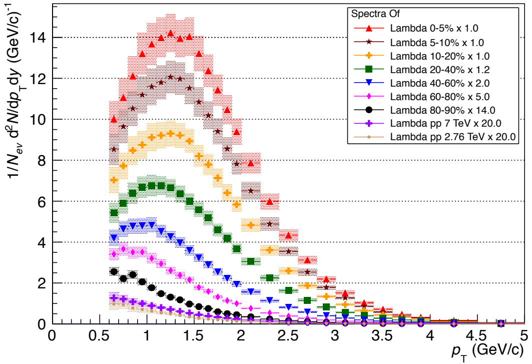
- Peripheral collisions, and p-p collisions at both energies agree well
- All centralities and systems consistent above p_T ~ 6.5 GeV/c
- Magnitude of enhancement increases with centrality

Λ/K^0_S Ratio – low pT

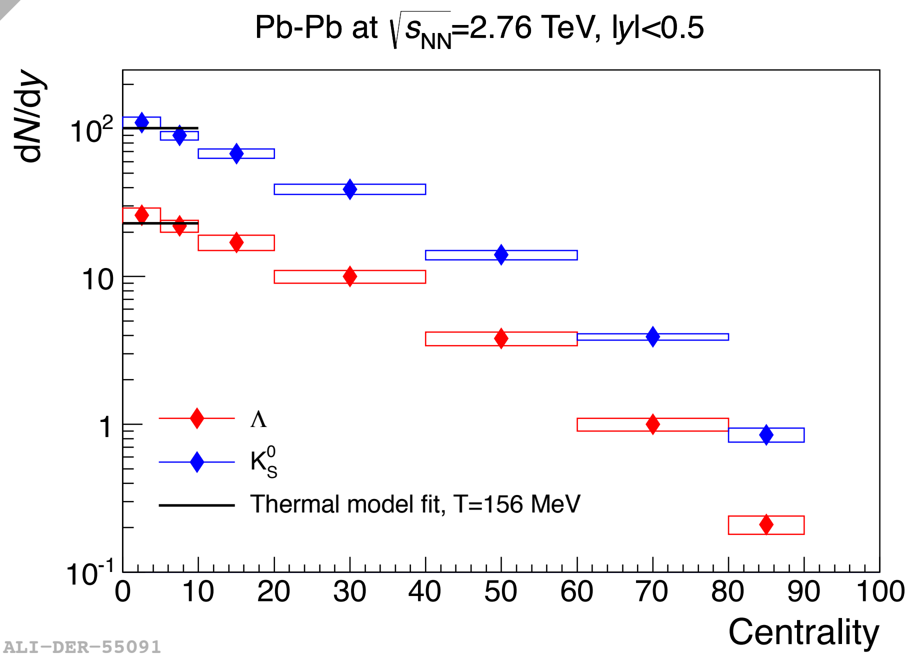


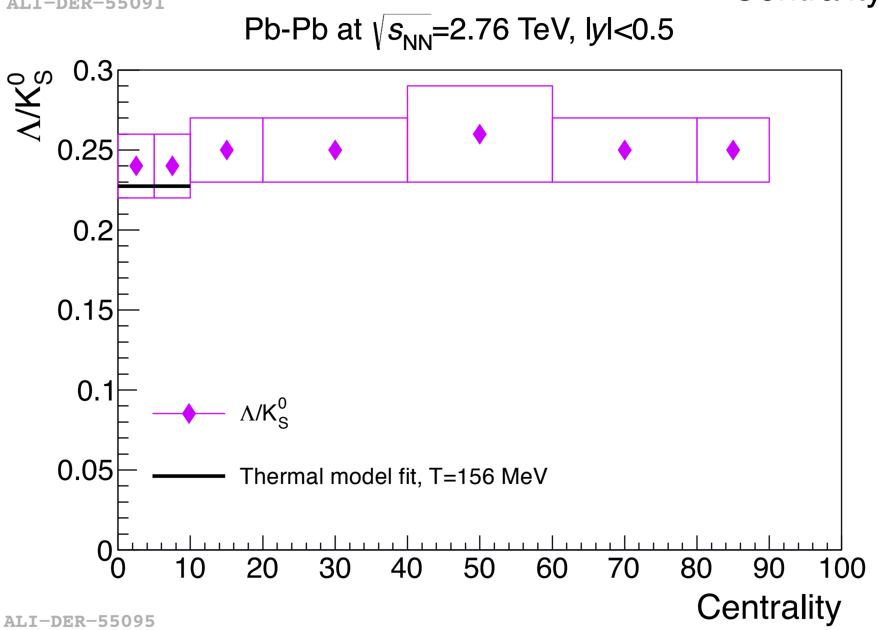


- At lowest momentum, more central collisions appear to show a suppression of the ratio
- This could hint towards a redistribution of particles from low to mid momentum



Λ/K^0_S ratio – integrated ratio



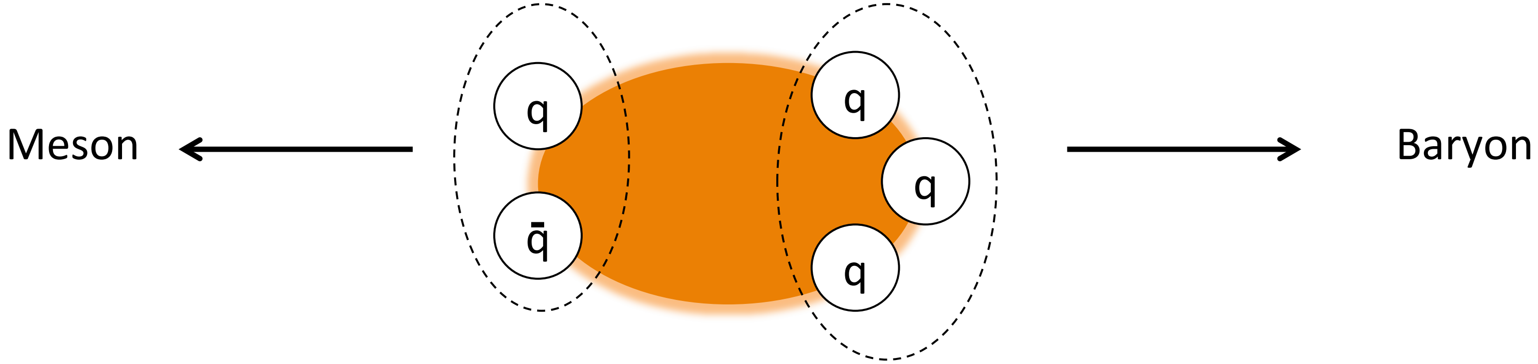


- Using a blastwave fit to extrapolate to low p_T, the yield of Λ & K^0_S can be integrated over p_T
- The Λ/K^0_S ratio of these integrated yields appears constant with centrality
- Further supports that baryons / mesons are redistributed in p_T rather than enhanced / suppressed

Plot created from values in: ALICE Collaboration, (2013), arXiv:nucl-ex/ 1307.5530

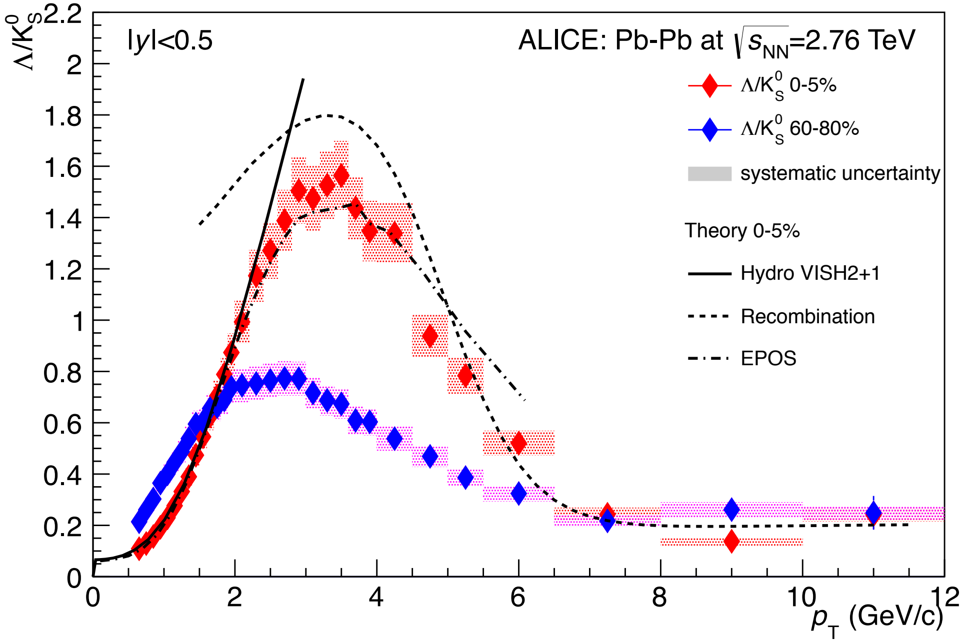
Coalescence

- As a QGP cools, it must pass back over the phase boundary and undergo hadronization
- The distribution of hadrons formed in this way need not be the same as for vacuum fragmentation
- In particular, it may allow for the formation of baryons/mesons by grouping 3/2 quarks close in phase space

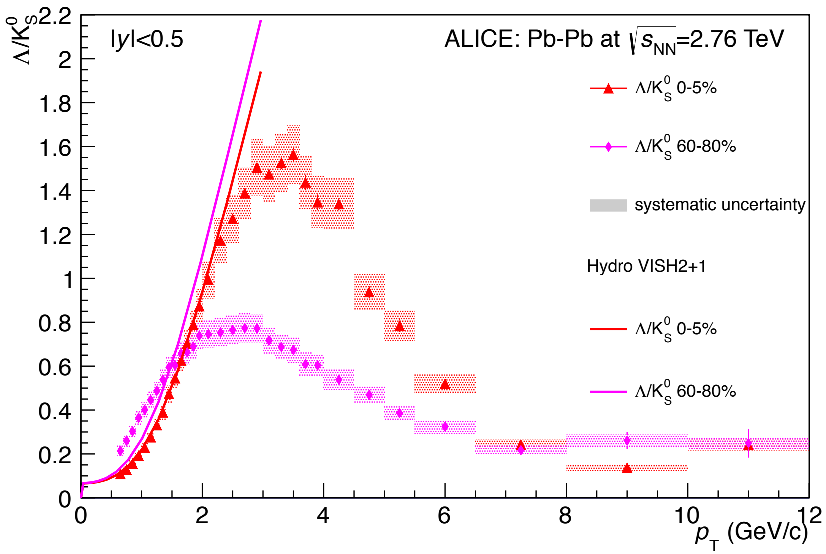


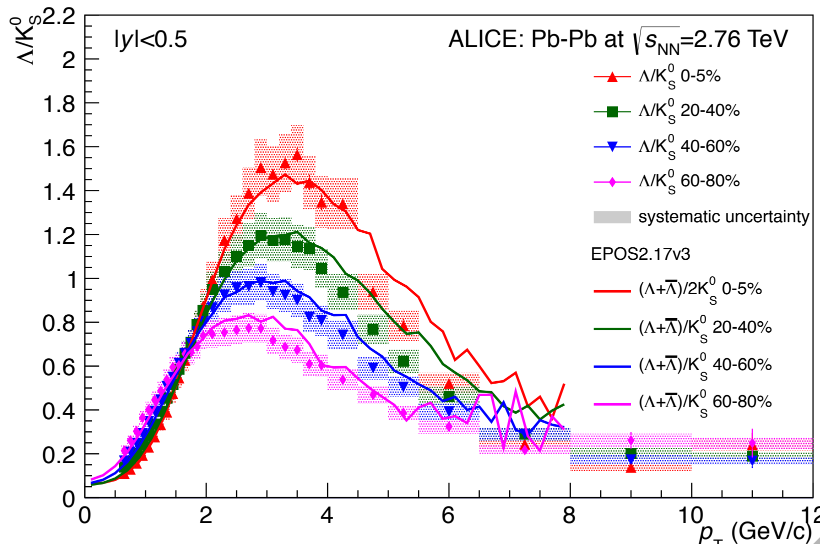
- From this process, one would expect the average momentum of the baryon to be ~3<p_q>, while the meson would have ~2<p_q>
- So, for hadrons formed from the medium, one could expect the baryons to be formed at higher momenta than the mesons

Λ/K^0_S Ratio - theory

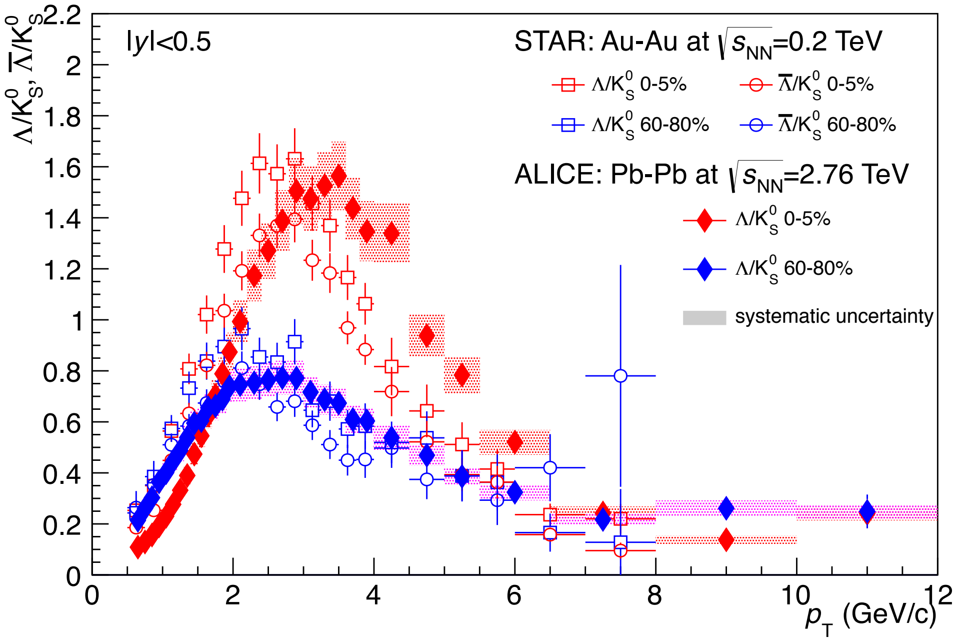


- Hydrodynamics describes low-p_T, central ratio very well
- Recombination describes general trend, but not normalisation
- Hydrodynamics less accurate for more peripheral collisions
- EPOS describes ratio well



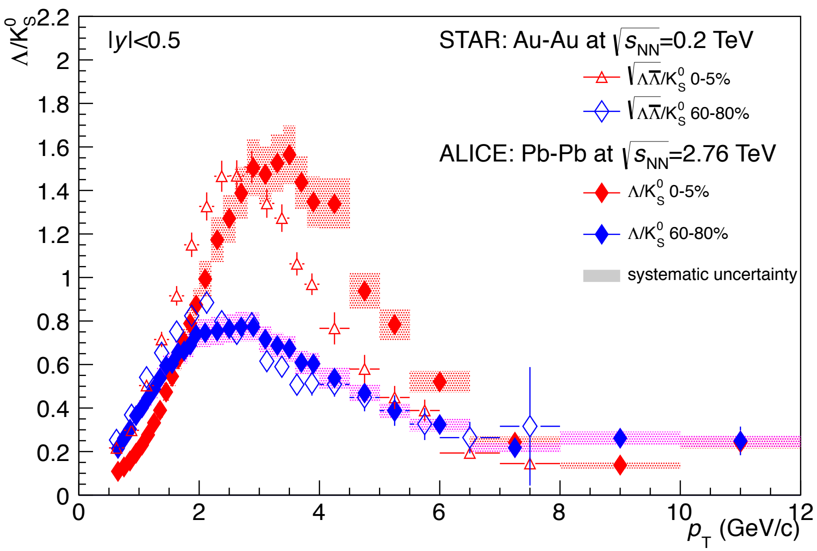


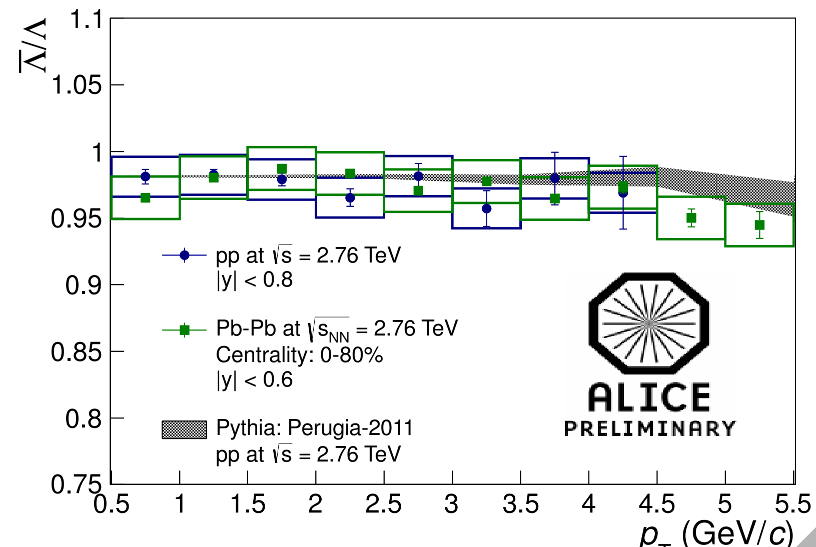
Λ/K^0_S Ratio - STAR



- Anti-Λ/Λ ratio:
  - at STAR ~ 0.8
  - at ALICE ~ 1
- Magnitude of enhancement unchanged
- Persists to slightly higher p_T at LHC energy

STAR points from G. Agakishiev et al. (STAR Collaboration), Phys. Rev. Lett. 108, 072301 (2012), arXiv:nucl-ex/ 1107.2955





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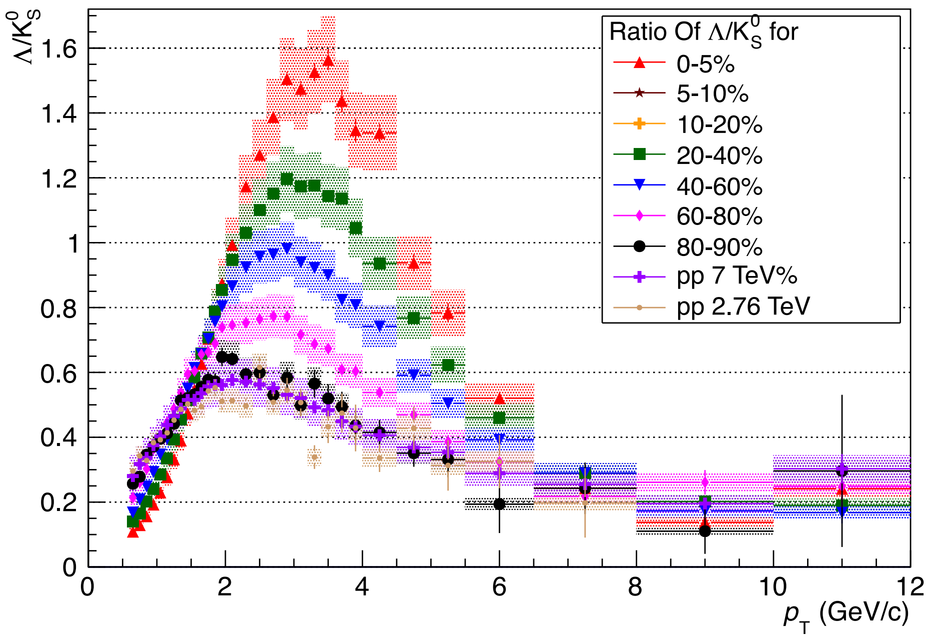
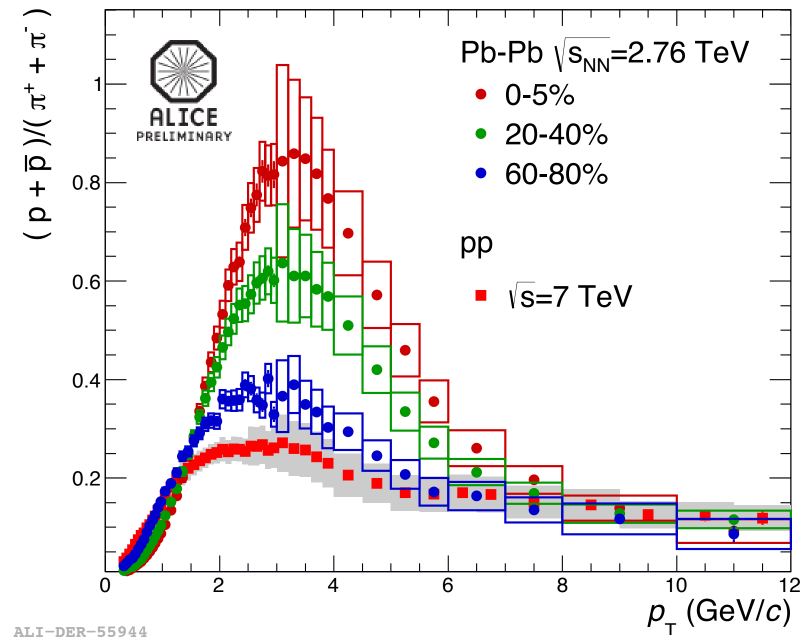
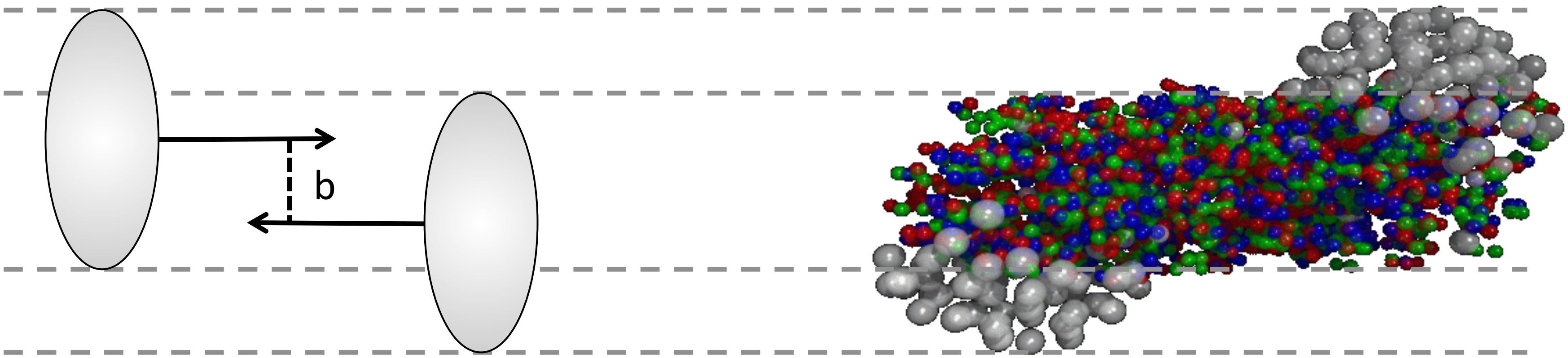
Λ/K^0_S Ratio – p/π





- Behaviour of the p/π ratio very similar to Λ/K^0_S
- Enhancement of ~x3 in range $1.5 < p_T < 6.5$ GeV/c
- p/π ratio consistently ~half of Λ/K^0_S

The Glauber Model



- The Glauber model is used to relate heavy ion collisions to p-p collisions

- Nucleons are considered to be distributed within the nucleus according to the Saxon-Woods nuclear density

$$\rho(r) = \rho_0 \frac{1 + \omega (r/R)^2}{1 + \exp(\frac{r-R}{a})}$$

- It is assumed that all collisions are binary with a constant cross section, and that there is no deflection of nucleons

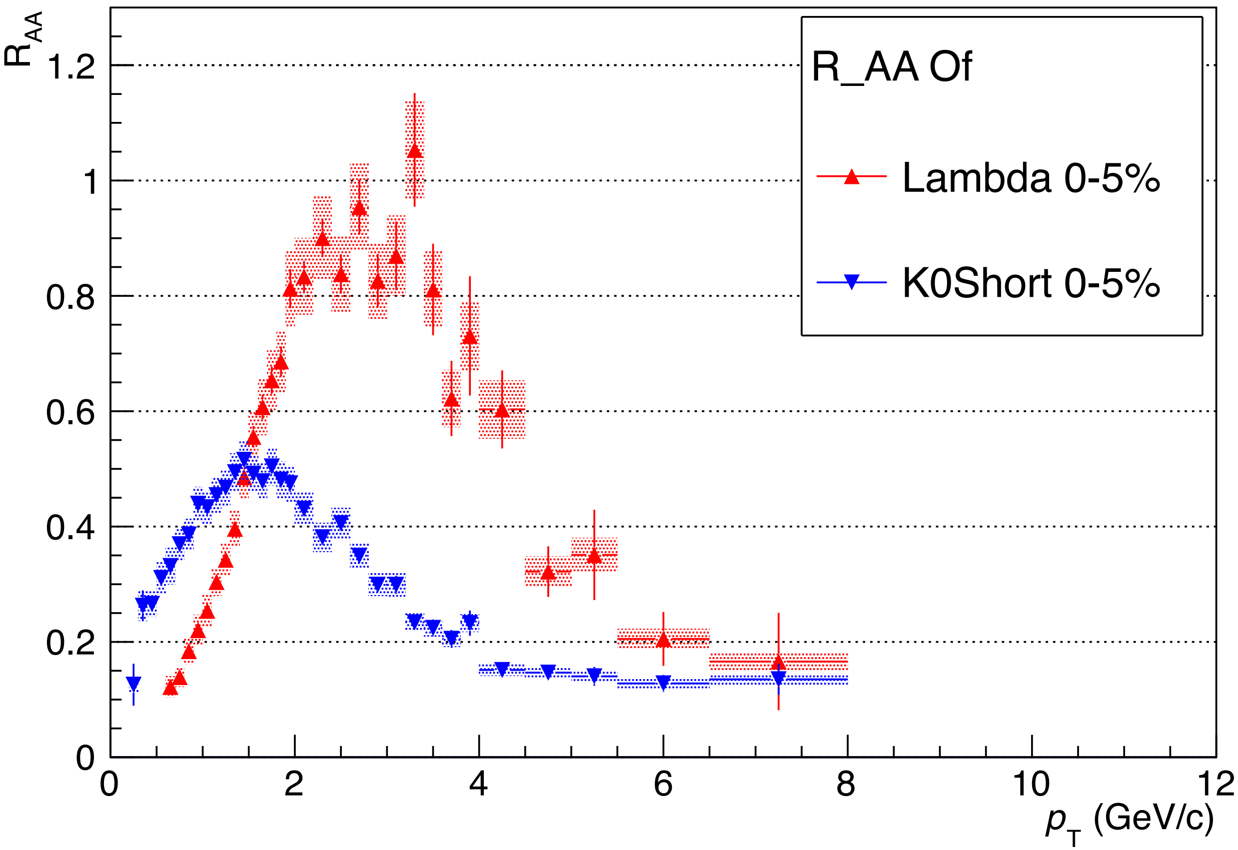
- This allows the calculation of the equivalent number of p-p collisions as the impact parameter, b, varies

B. Abelev et al. (ALICE Collaboration), PHYSICAL REVIEW C 88, 044909 (2013)

R_{AA} of Λ/K^0_S

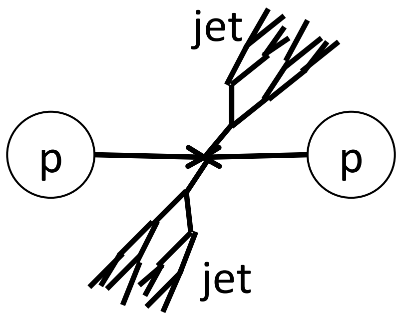
$$R_{AA}(b) = \frac{\frac{d^2N^{AA}}{dp_T dy}}{N_{coll}^{AA}(b)\frac{d^2N^{pp}}{dp_T dy}}$$

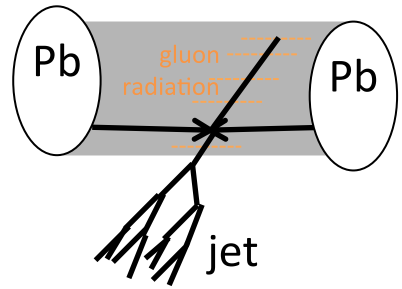
Centrality	<N$_{coll}$>
0-5%	1685
10-20%	921.2
40-60%	127.7
80-100%	4.441



Jet Quenching

- Jets are formed as a high energy parton from the initial collision fragments





- If a QGP is formed, the parton would be expected to lose energy to strong interactions within the plasma

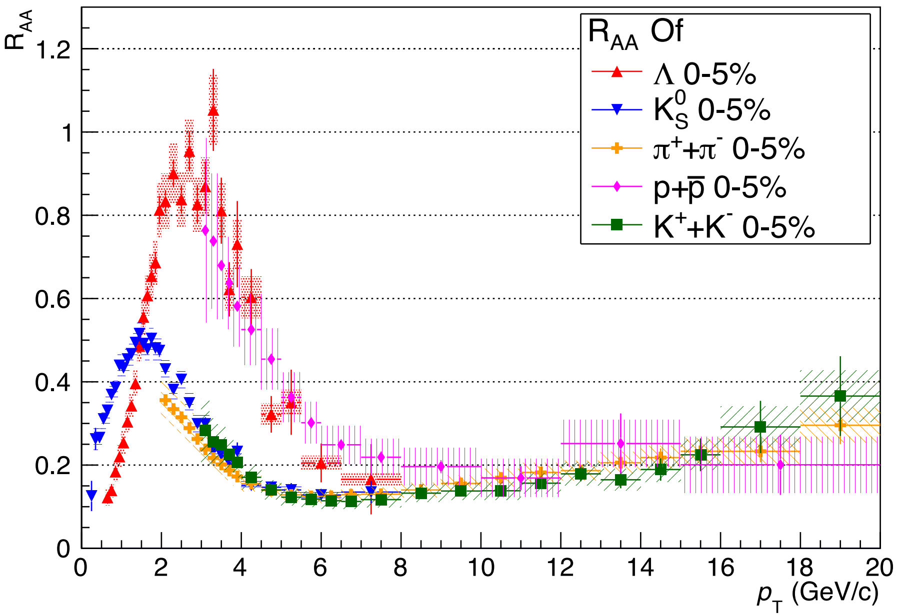
- This leads to jets being emitted at lower energy, or not escaping the medium at all

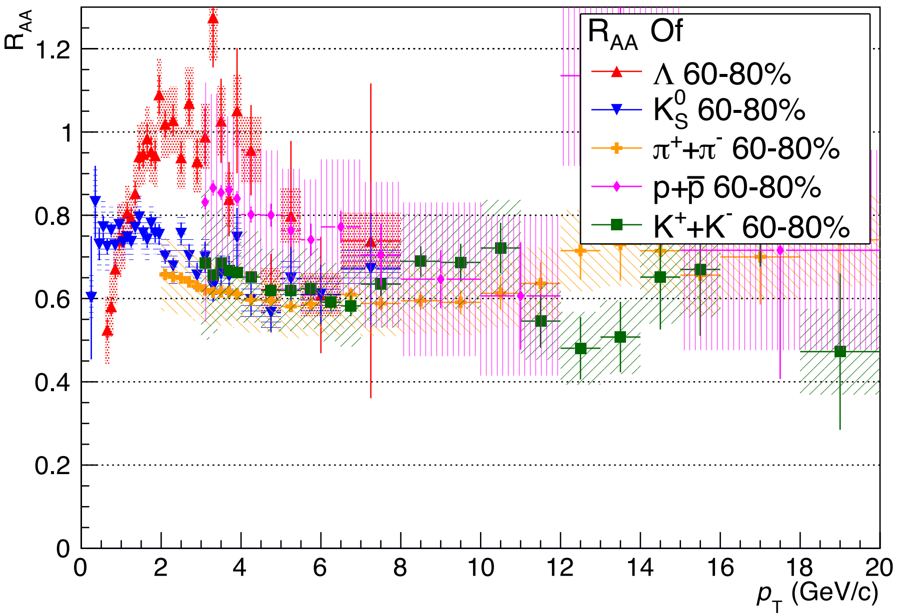
- Back-to-back jets may be asymmetric in energy, as one travels further through the medium than the other

- Some models suggest a variation in the suppression dependent on jet hadrochemistry

S. Sapeta and U. A. Wiedemann, Eur.Phys.J. C55, 293 (2008), arXiv:0707.3494 [hep-ph] .
P. Aurenche and B. Zakharov, Eur.Phys.J. C71, 1829 (2011), arXiv:1109.6819 [hep-ph] .
R. Bellwied and C. Markert, Phys.Lett. B691, 208 (2010), arXiv:1005.5416 [nucl-th] .

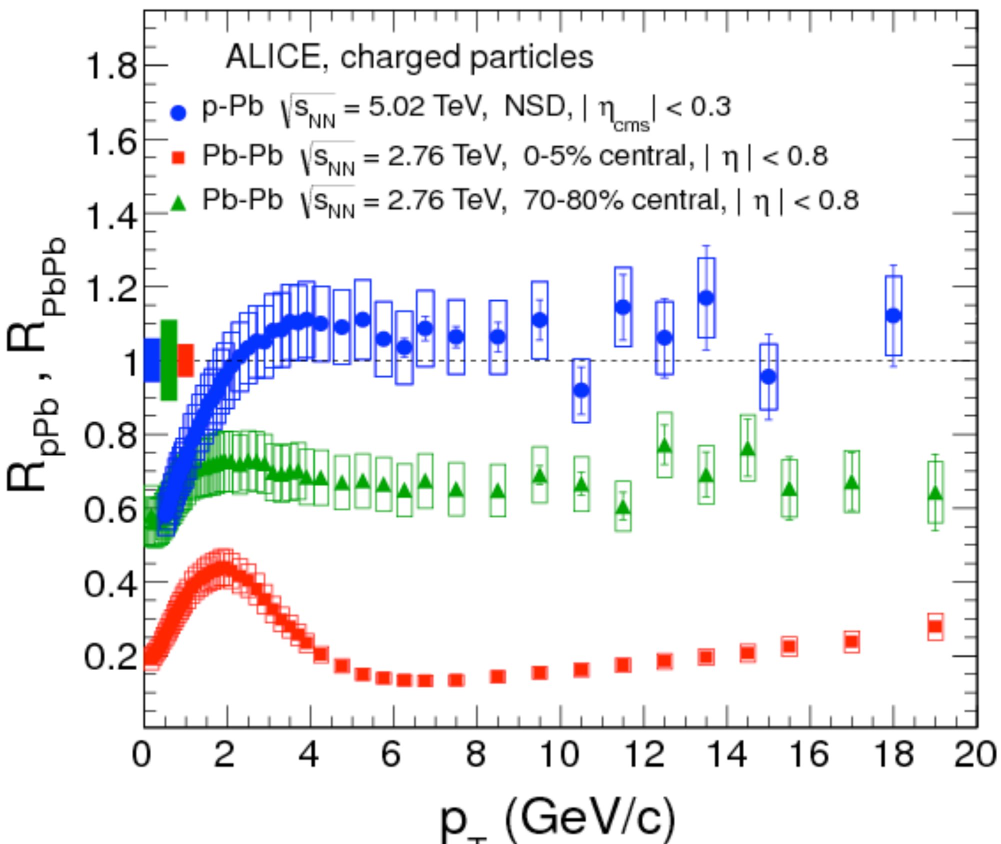
R_{AA} with other particles



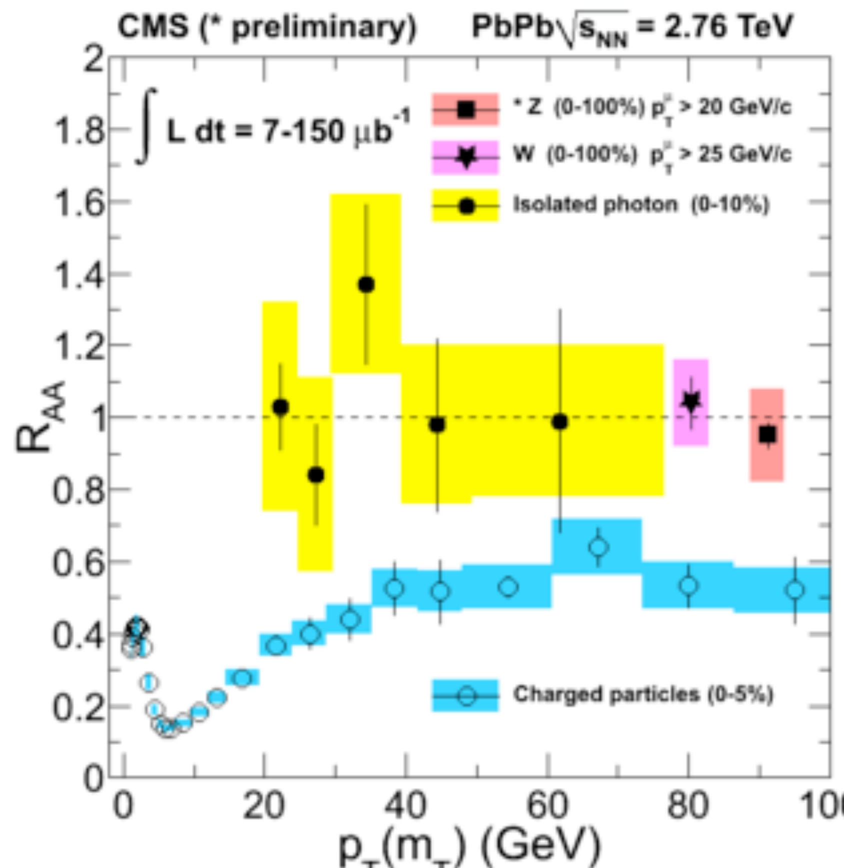


- Separation of baryons and mesons at lower p_T, as expected from Λ/K^0_S ratio behaviour
- Above 6 GeV/c, all hadrons are consistent
- No sign of hadrochemistry dependent jet suppression

R_{AA} for p-Pb & Electroweak probes



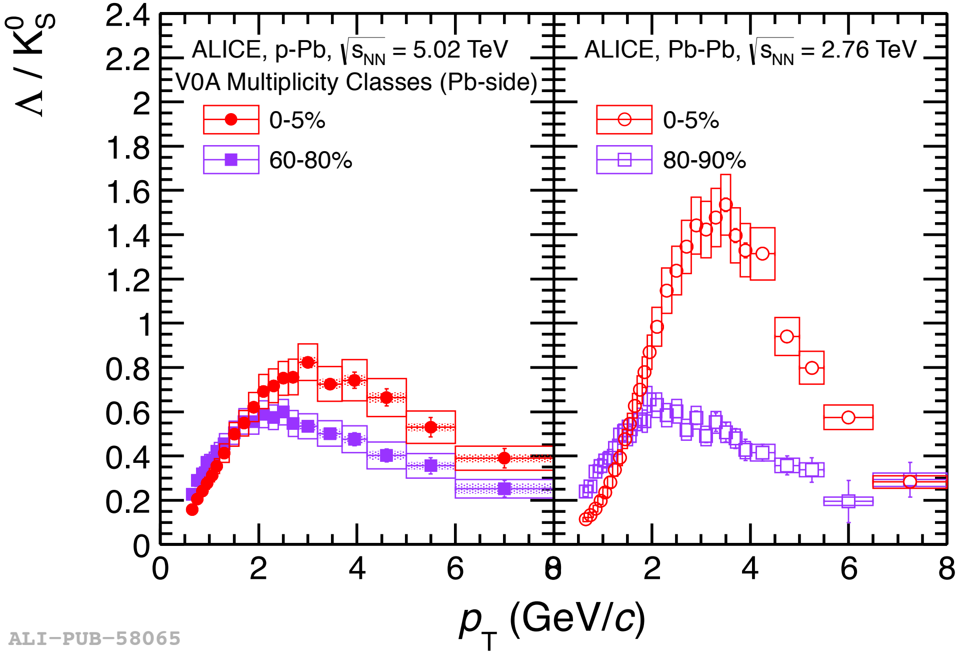
B. Abelev et al. (ALICE Collaboration), Phys.Rev.Lett. 110 (2013) 082302

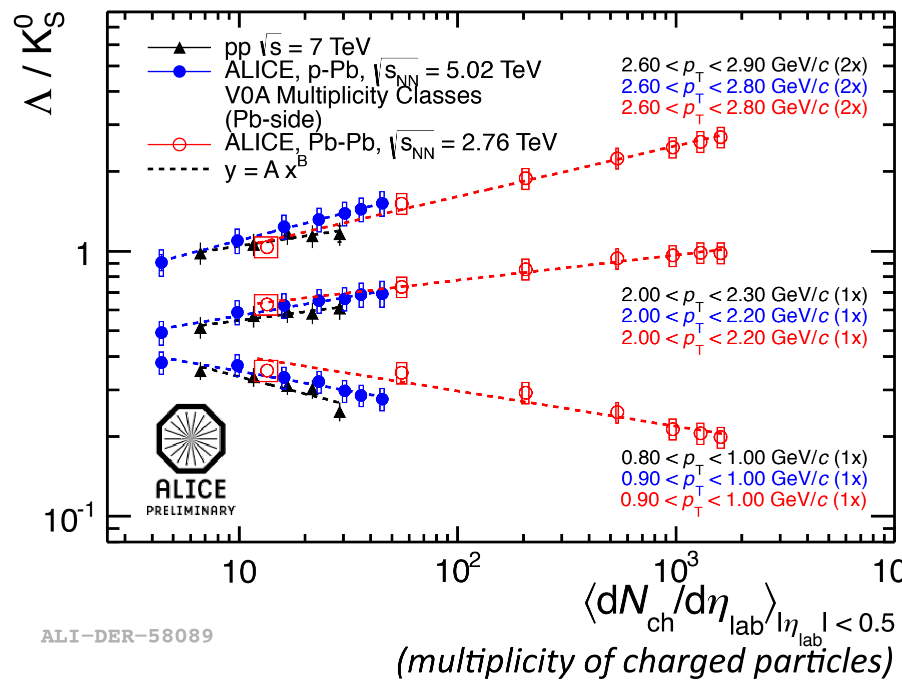


S. Chatrchyan. et al., (CMS Collaboration), Eur. Phys. J. C72, 1945 (2012).

- R_{AA} is not consistent with 1 even for more peripheral events or p_T ~ 100 GeV/c
- R_{pPb} is consistent with 1 above p_T ~ 2 GeV/c
- R_{AA} of electroweak probes is consistent with 1

Λ/K^0_S Ratio – p-Pb





- In p-Pb collisions, an enhancement of the Λ/K^0_S ratio with multiplicity can be seen
- The enhancement is less pronounced when compared with Pb-Pb collisions
- The value of the Λ/K^0_S ratio appears to be a function of the multiplicity.
- Further work is needed to understand the origin of this behaviour

Conclusions

- Λ & K^0_S spectra measured for transverse momentum range 0.4-12 GeV/c in Pb-Pb and pp collisions
- Λ/K^0_S ratio shows significant enhancement in central PbPb collisions when compared to pp collisions
- EPOS reproduces behaviour well, while pure Hydrodynamic and Recombination models are less successful
- Studies of the R_{AA} of identified particles shows no hadrochemical dependence at high p_T.
- Behaviour of the Λ/K^0_S ratio in p-Pb collisions is similar to that in PbPb

Backup

QGP

- Quark-gluon plasma is a **thermalised** system of **deconfined** quarks and gluons

- As a first approximation, we can treat Hadron Gas / QGP as an ideal gas:

$$p = \frac{\varepsilon}{3} = g\frac{\pi^2}{90}T^4$$

$$\frac{\varepsilon}{T^4} = g\frac{\pi^2}{30}$$

- For Hadron Gas, pions dominate so g ~ 3
- For QGP $g = g_{gluons} + g_{quarks} = 2_{spin} * 8_{color} + 7/8 * 3_{flavor} * 2_{q/anti\text{-}q} * 2_{spin} * 3_{color} \sim 48$

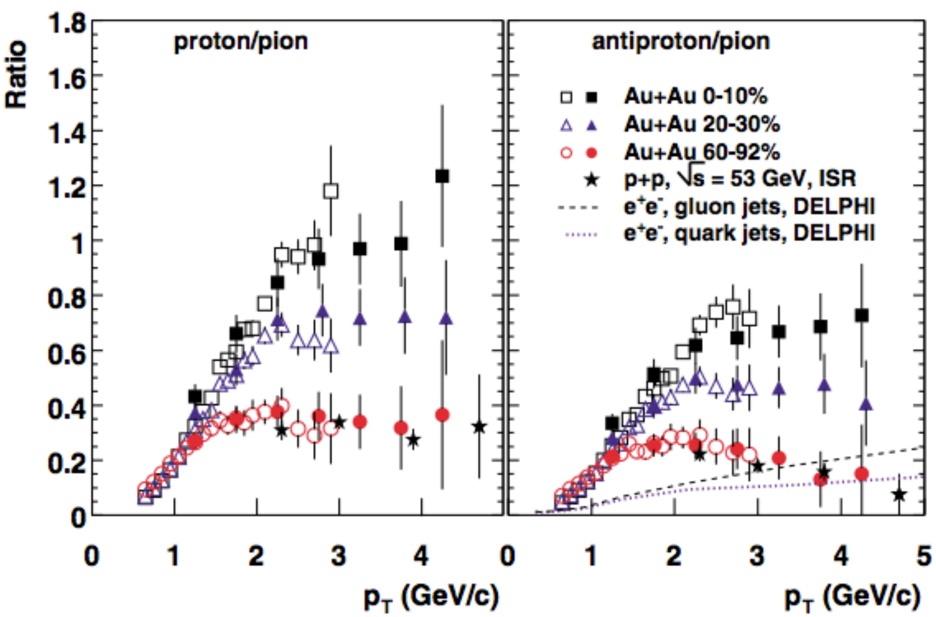
- By modelling hadrons as a ‘bag’, one can estimate the pressure holding them together

- A deconfined state can be attained if the QGP pressure is greater than the Bag pressure

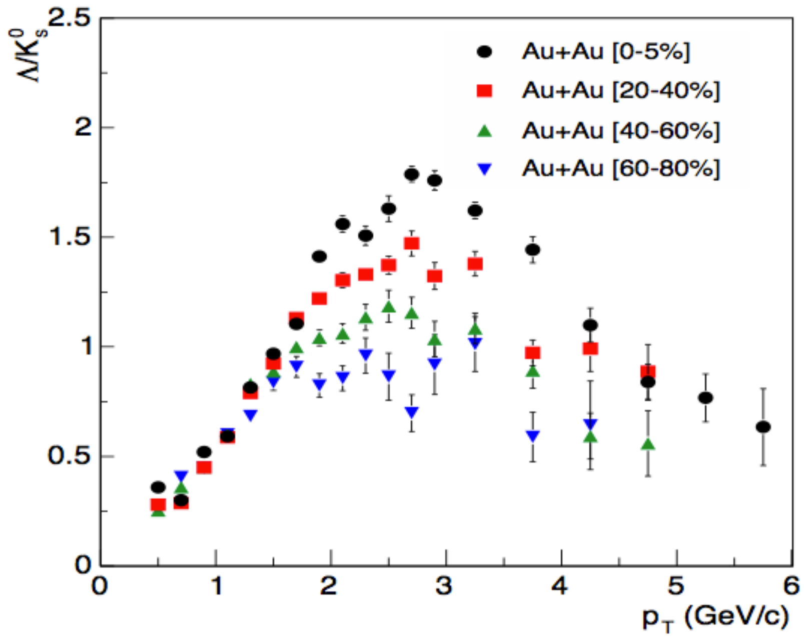
  ➔ Transition temperature ~ 140MeV

Motivation

- Observed at SPS & RHIC that p/π & Λ/K^0_S ratios are enhanced at intermediate momentum in heavy ion collisions, when compared to pp.
- Examining how this effect evolves with increased energy gives insight into the interplay between fragmentation and potential baryon-enhancing effects.
- Λ & K^0_S can be identified with a single technique over a wide momentum range

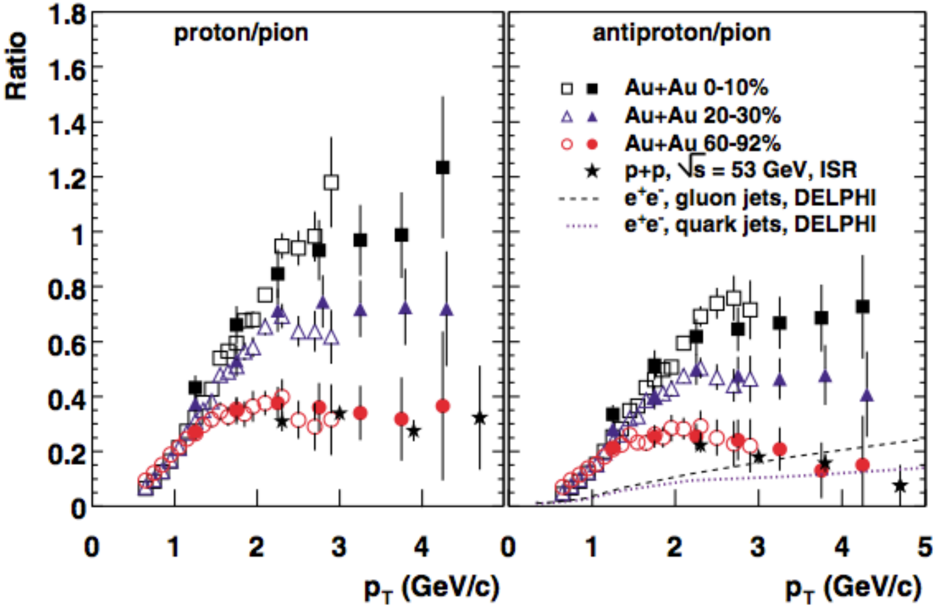


S. S. Adler et al. (PHENIX Collaboration), Phys. Rev. Lett. 91, 172301 (2003)



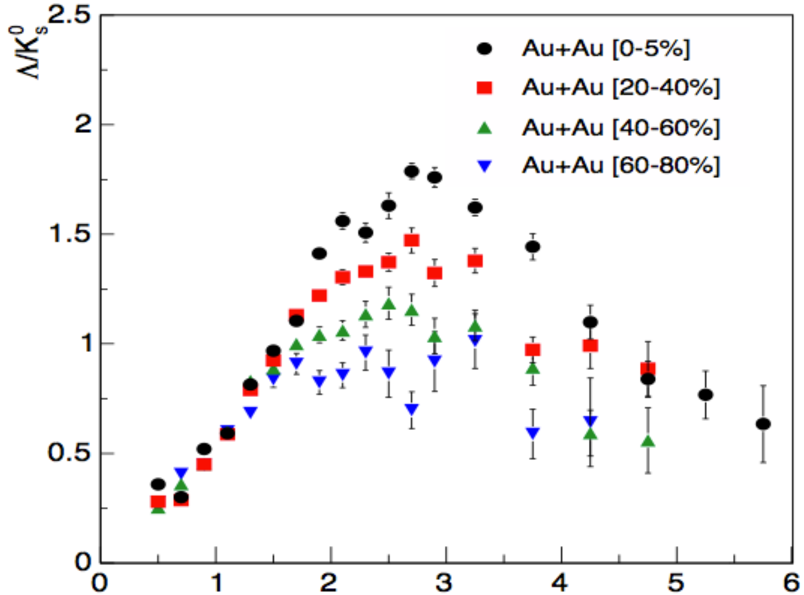
J. Adams et al. (STAR Collaboration), (2006),

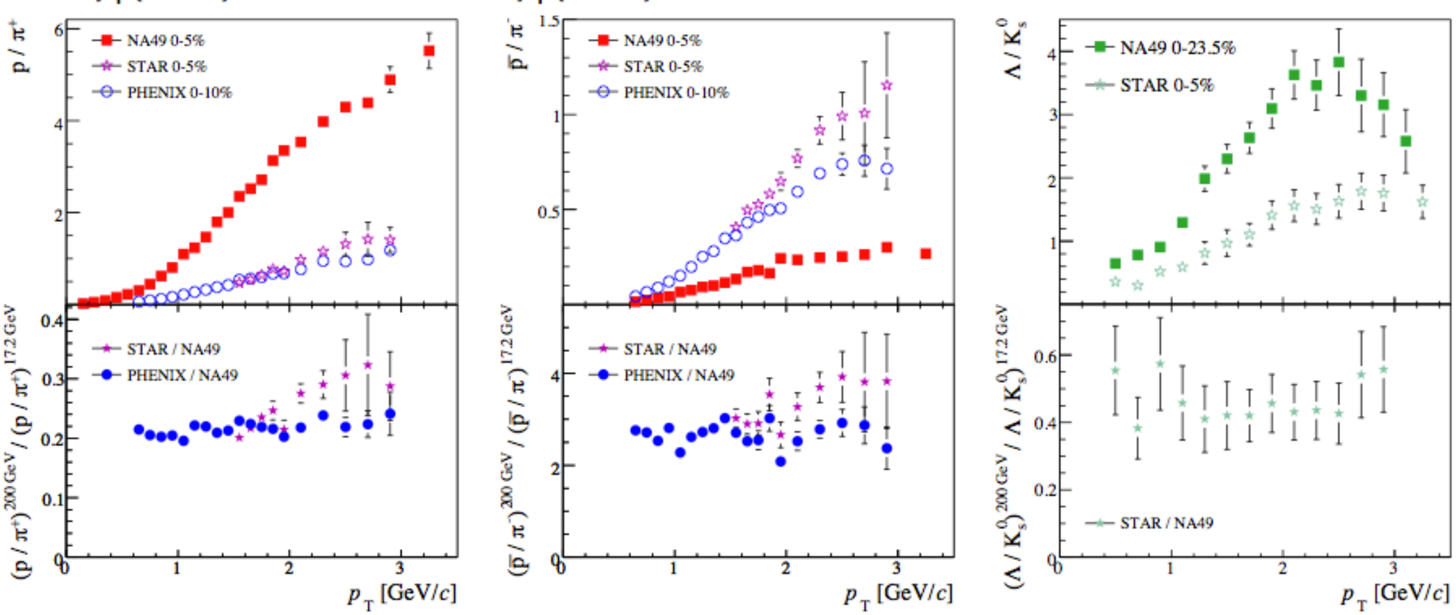
Motivation



S. S. Adler et al. (PHENIX Collaboration), Phys. Rev. Lett. 91, 172301 (2003)

J. Adams et al. (STAR Collaboration), (2006),





T. Schuster and A. Laszlo (for the NA49 Collaboration). J.Phys. G32 (2006) S479-S482.

Theory Models used

VISH2+1 - a viscous hydro code in (2+1) dimensions assuming longitudinal boost invariance. Sharp transition from fluid to non-interacting particles at freeze-out temperature.

H. Song and U. W. Heinz, Phys. Lett. B658, 279 (2008), arXiv:nucl-th/0709.0742 .
H. Song and U. W. Heinz, Phys. Rev. C77, 064901 (2008), arXiv:nucl-th/0712.3715 .
H. Song and U. W. Heinz, Phys. Rev. C78, 024902 (2008), arXiv:nucl-th/0805.1756 .

EPOS 2.17v3 – String breaking model of particle creation, where low p_T particles are allowed to reinteract, simulating hydrodynamic behaviour. Strings breaking in-medium take their quarks from the fluid, rather than Schwinger Mechanism. Also uses Core-Corona model to determine fluid region.

K. Werner, Phys. Rev. C 85, 064907 (2012) arXiv:1203.5704 .
K. Werner, Phys. Rev. Lett. 109, 102301 (2012) arXiv:1204.1394

Recombination – a model allowing quarks from the medium to coalesce into hadrons. Radial flow and jet quenching have been set to match that observed at the LHC.

B. Muller, J. Schukraft, B. Wyslouch, arXiv:1202.3233 .

Reconstruction - Feeddown

Decay	Branching Ratio
$\Xi^- \Rightarrow \Lambda\pi^-$	99.887 ±0.035%
$\Xi^0 \Rightarrow \Lambda\pi^0$	99.525 ±0.012%

- Λ coming from weak decays of Ξ are removed
- Ω decay also considered, but found to be negligible

- With MC, we create a Feed-down matrix relating the p_T distribution of Λ to that of Ξ
- This can then be scaled to the measured Ξ p_T spectrum
- The raw yield of primary Λ is then obtained as:

$$\Lambda_{primary}^{raw} = \Lambda_{measured}^{raw} - \sum_j F_{ij} \int_{p_T(bin)} \frac{dN}{dp_T}(\Xi^-)$$

$$F_{ij} = \frac{N_{recon}(\Lambda)_{from\,\Xi\,bin\,j}^{in\,bin\,i}}{N_{generated}(\Xi)_{in\,bin\,j}}$$

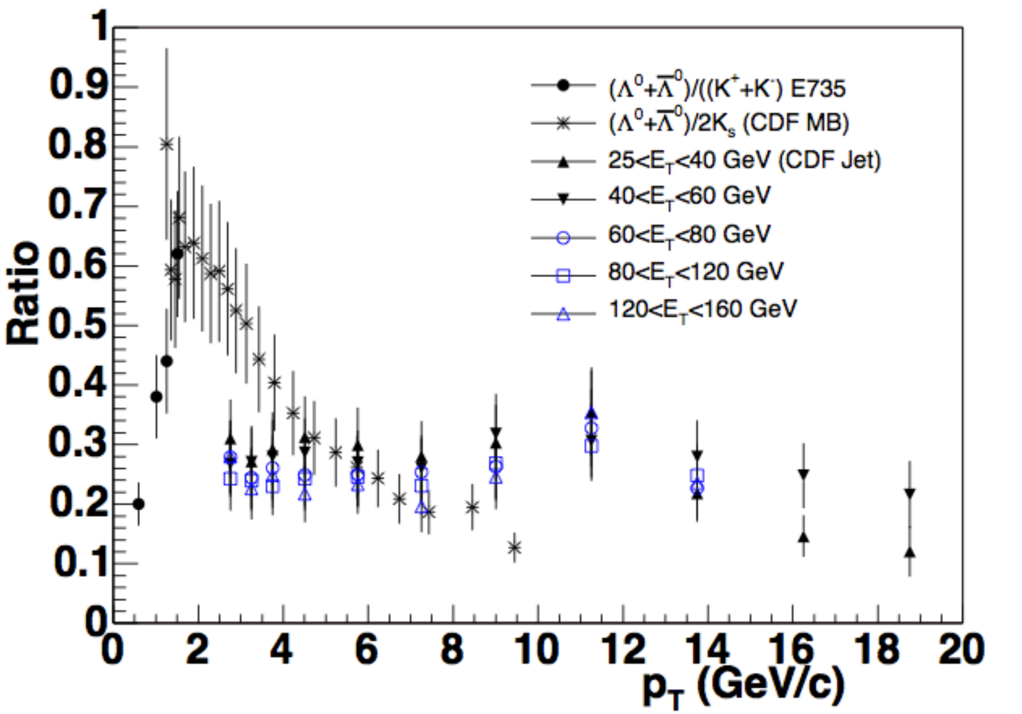
- Feed-down varies from ~25% at low p_T to neglible levels at high p_T

Backup

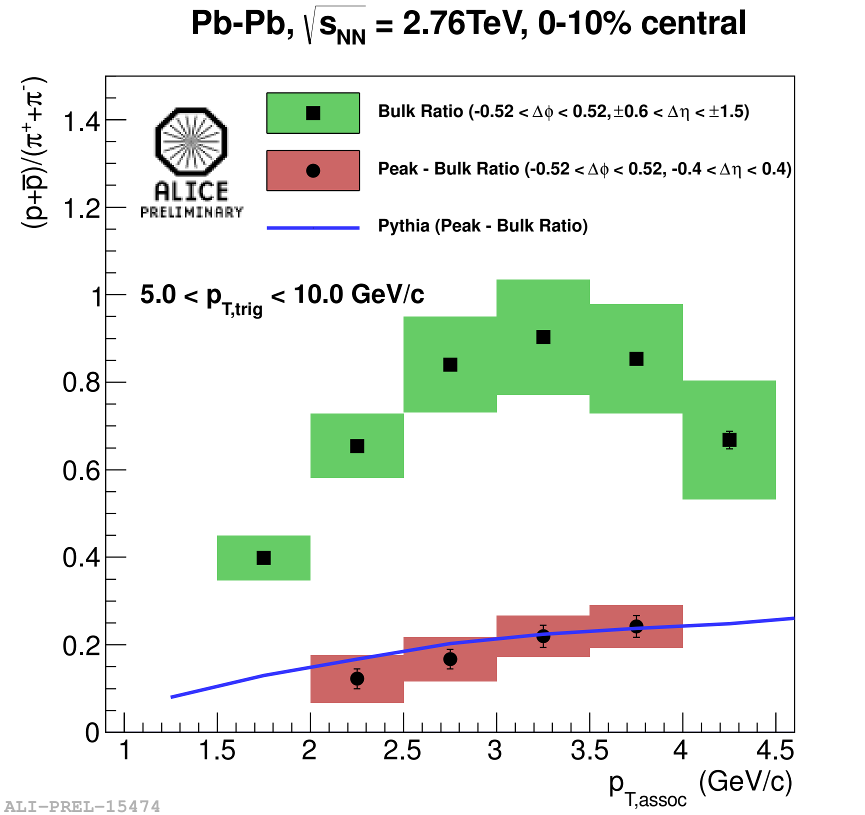
Centrality	dN/dy		
	Λ	K^0_S	Λ/K^0_S
0-5%	26+3	110+10	0.24+0.02
5-10%	22+2	90+6	0.24+0.02
10-20%	17+2	68+5	0.25+0.02
20-40%	10+1	39+3	0.25+0.02
40-60%	3.8+0.4	14+1	0.26+0.03
60-80%	1.0+0.1	3.9+0.2	0.25+0.02
80-90%	0.21+0.03	0.85+0.09	0.25+0.02

- Integrated ratio is constant within errors
- Suggests that baryons / mesons are redistributed in p_T rather than enhanced / suppressed

L/K Ratio – Jets & Bulk



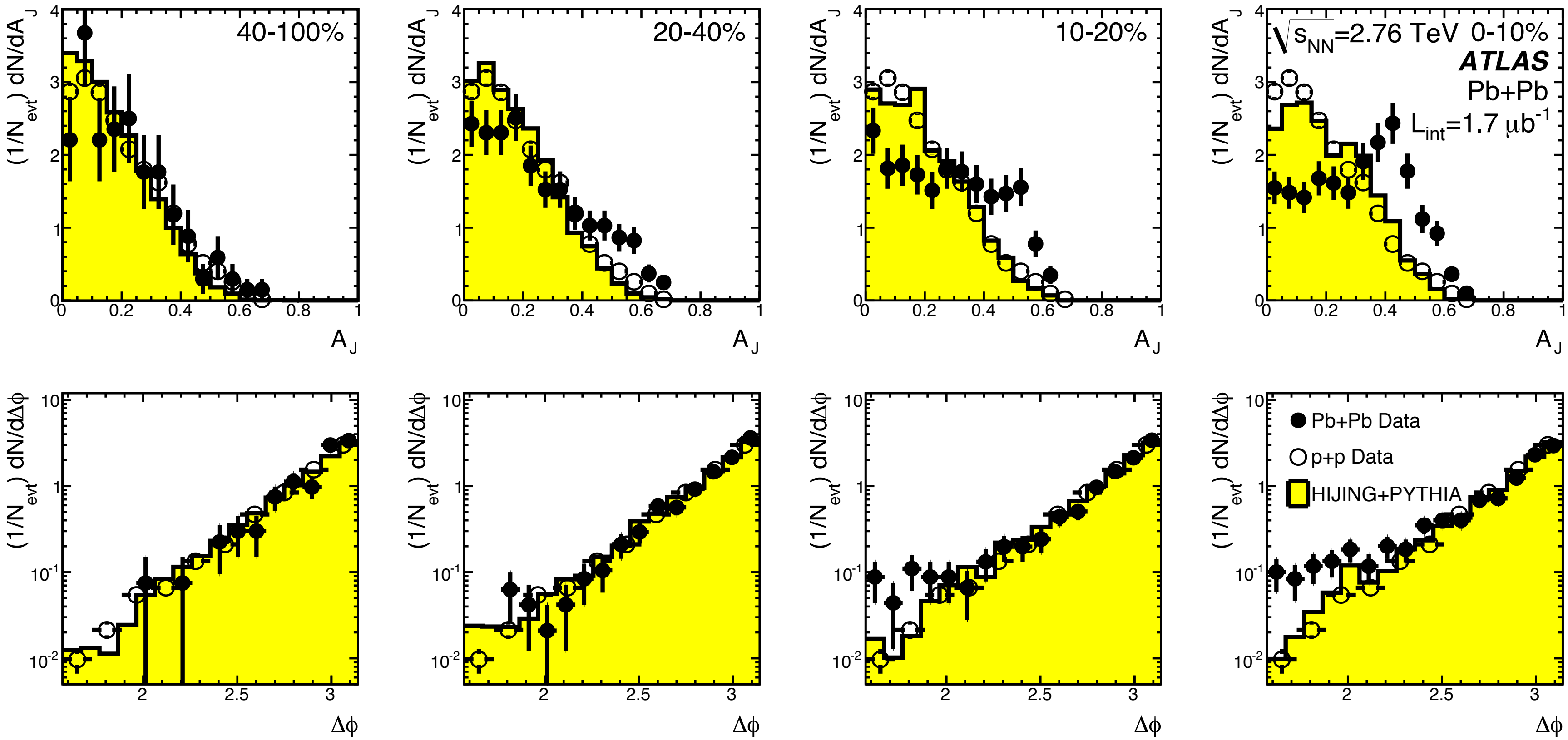
T. Aaltonen et al. (CDF Collaboration), Phys. Rev. D 88, 092005 (2013)



Misha Veldhoen for the ALICE collaboration, arXiv:1207.7195

- In $p\bar{p}$ collisions at Fermilab the Ratio of Λ/K is supressed in jets, when compared to inclusive studies
- This behaviour can be seen in Pb-Pb collisions at the LHC, where the p/π ratio in jets is supressed relative to that in the underlying event

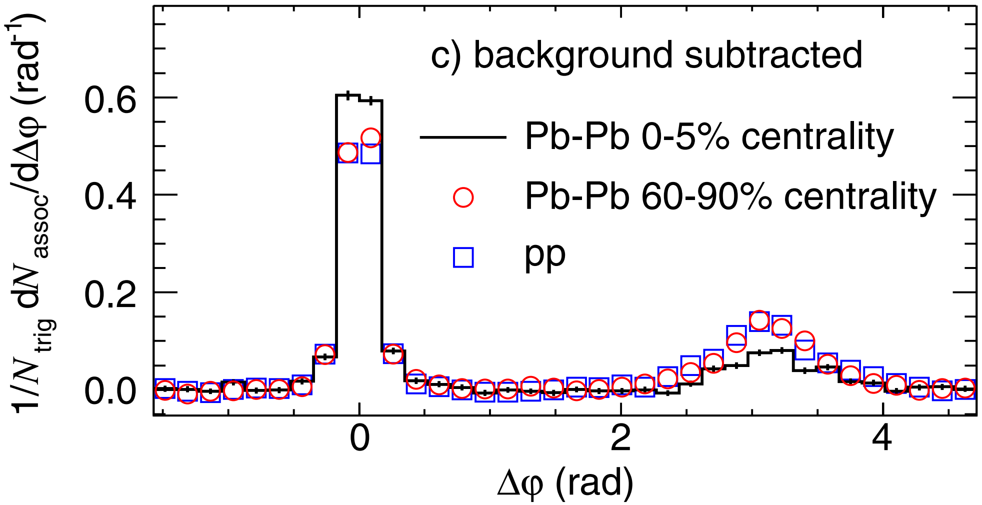
Jet Quenching



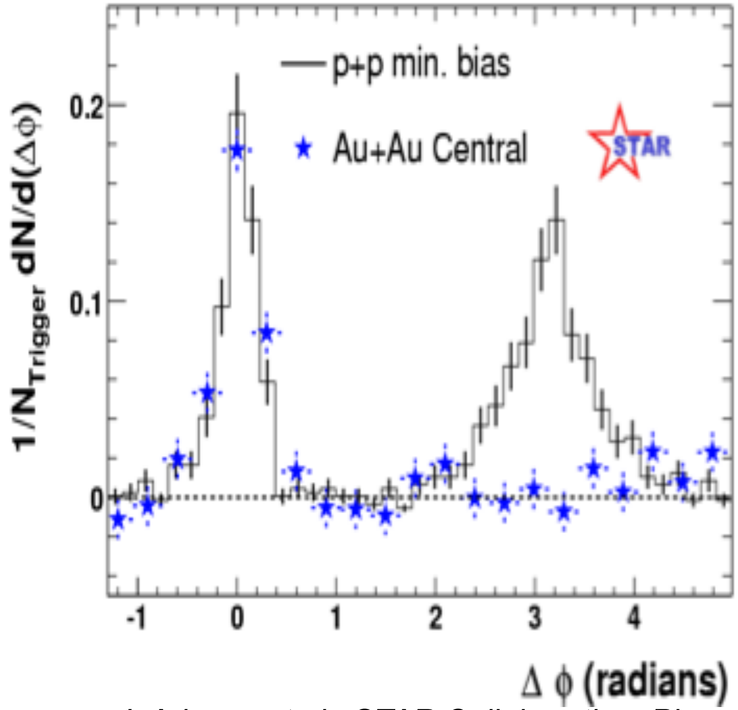
G. Aad et al (ATLAS Collaboration) PRL 105, 252303 (2010)

$$A_j = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

Jet Quenching

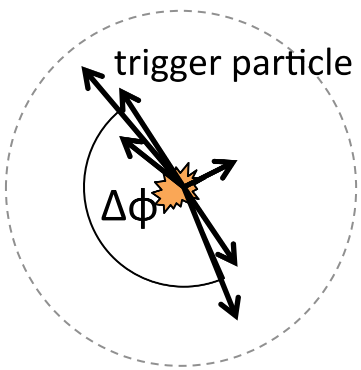


K. Aamodt et al., ALICE Collaboration, PRL 108, 092301 (2012)

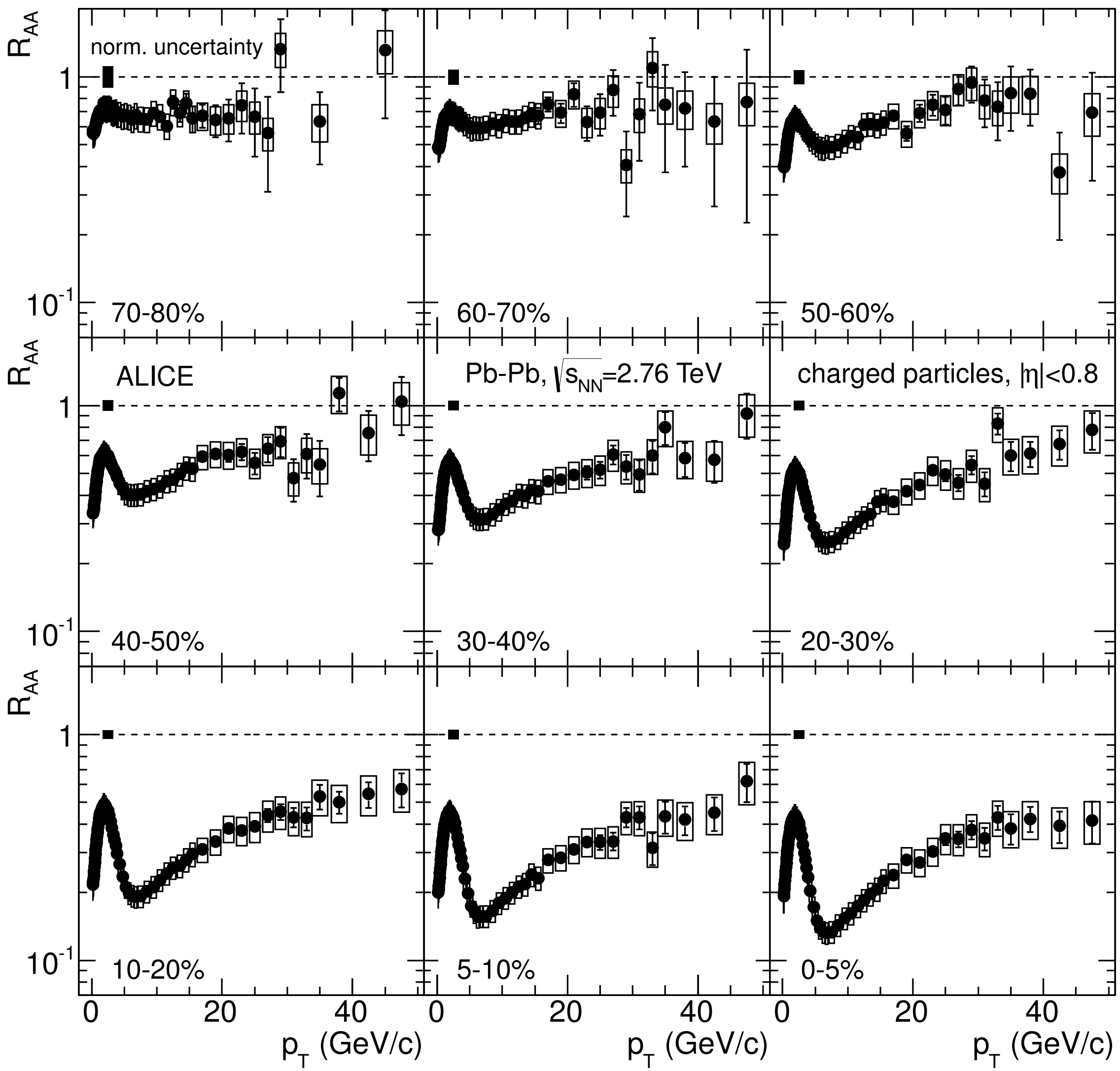


J. Adams, et al., STAR Collaboration, Phys. Rev. Lett. 91 (2003) 072304.

- Plots show distributions of particles relative to a triggered leading particle
- Underlying event subtracted to leave dijet structure

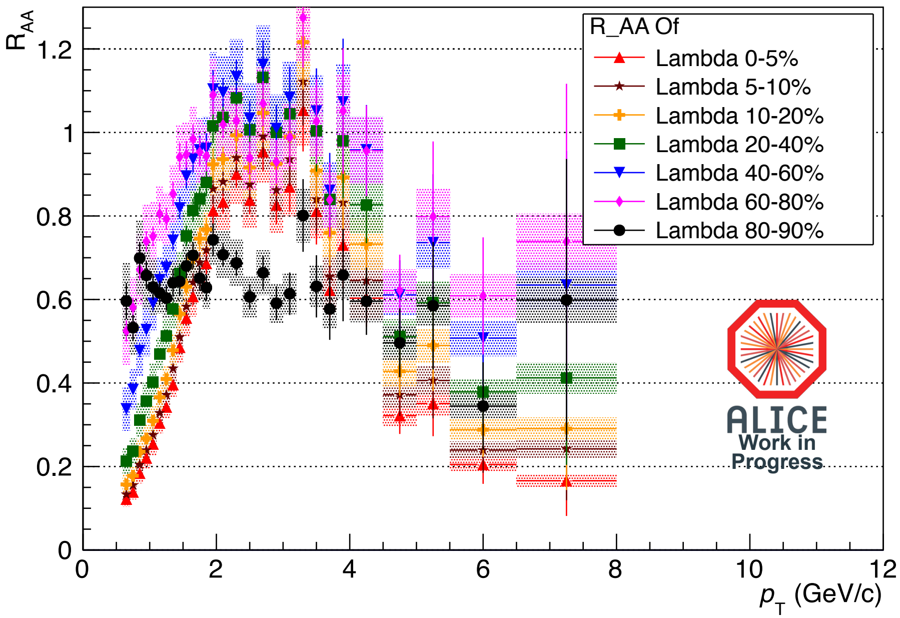


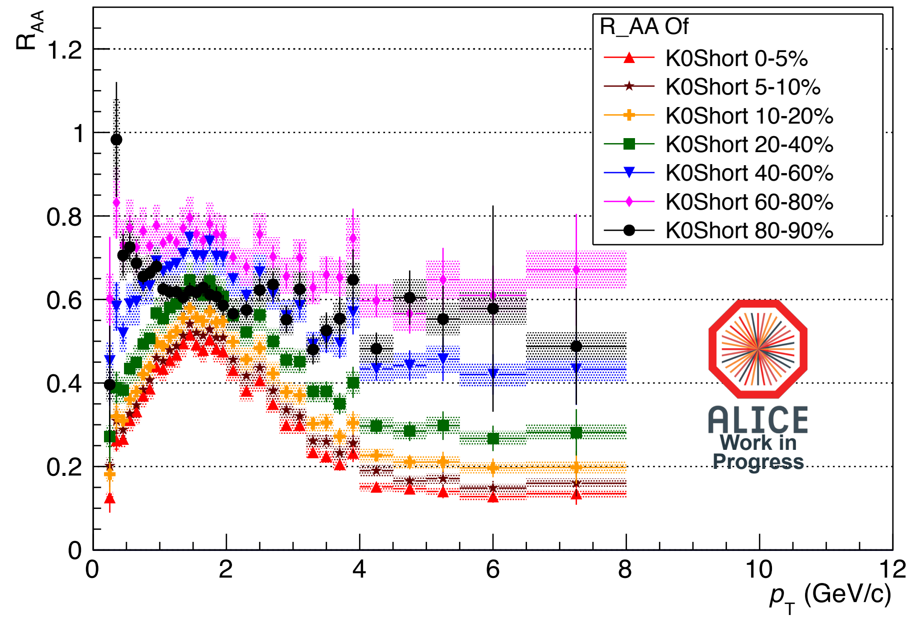
R_{AA} of Charged Particles



B. Abelev et al. (ALICE Collaboration), Physics Letters B 720 (2013), pp. 52-62

R_AA with centrality





- Ratio flattens out as we approach more peripheral events
- Ratio is not consistent with 1 even for most peripheral collisions