Present and future investigations of hadron formation mechanisms in heavy-ion collisions at LHC with the ALICE experiment

Current results on the transverse momentum dependence of the Λ/K^0_s ratios at LHC and RHIC

Parton coalescence and fragmentation processes

Prospects for baryon over meson ratios in the charm and beauty sectors (Λ_c/D, Λ_b/B)

Upgrade of the ALICE Inner Tracking System (ITS) Performance objectives and technological ingredients

ALICE

Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

Christian KUHN (IPHC-Strasbourg) for the ALICE collaboration

International Conference on new Frontiers in Physics (ICFP), Kolymbari, Creta, June 2012

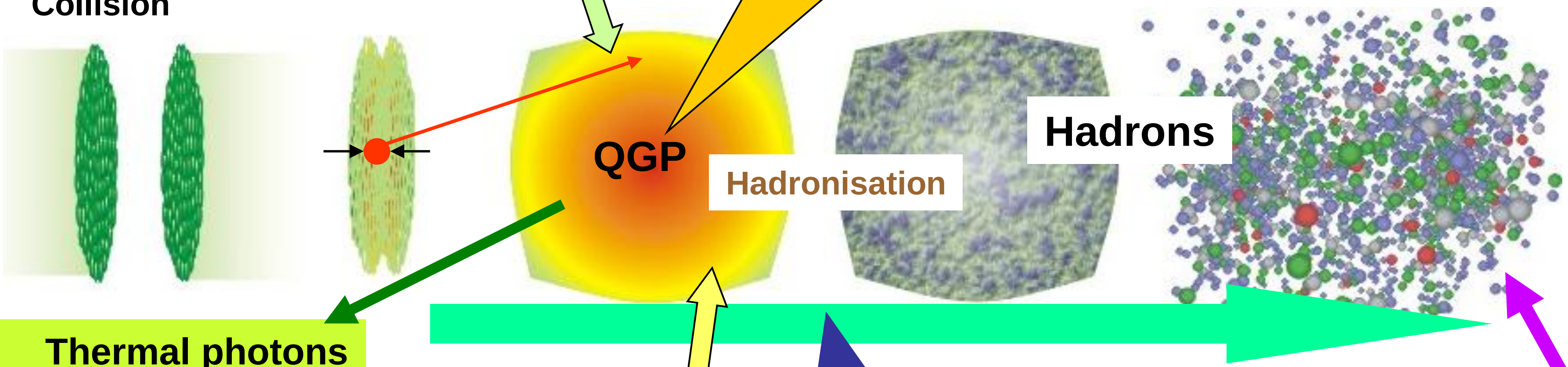
How to produce and how to observe a QGP ?

The 3 key aspects of the QGP:
- Thermally equilibrated state **(1)**
- Partonic degrees of freedom **(2)**
- Color dense opaque medium **(3)**

- High p_T suppression (Jet quenching)
- Quarkonia suppression (2) + (3)

Heavy Ion Collision

Chemical & kinetic freeze-out



Thermal photons
(1) + (2)

Elliptic & radial flow
(1) + (2)

- Chemical composition
- Strangeness enhancement
- Low mass resonances
(1) + (2)

And many other signatures and probes ...

At RHIC: Evidence for a strongly interacting and thermalized dense partonic medium: the QGP

At LHC: Systematic study of the QGP properties

p_T dependence of baryon/meson ratios (1) + (2)

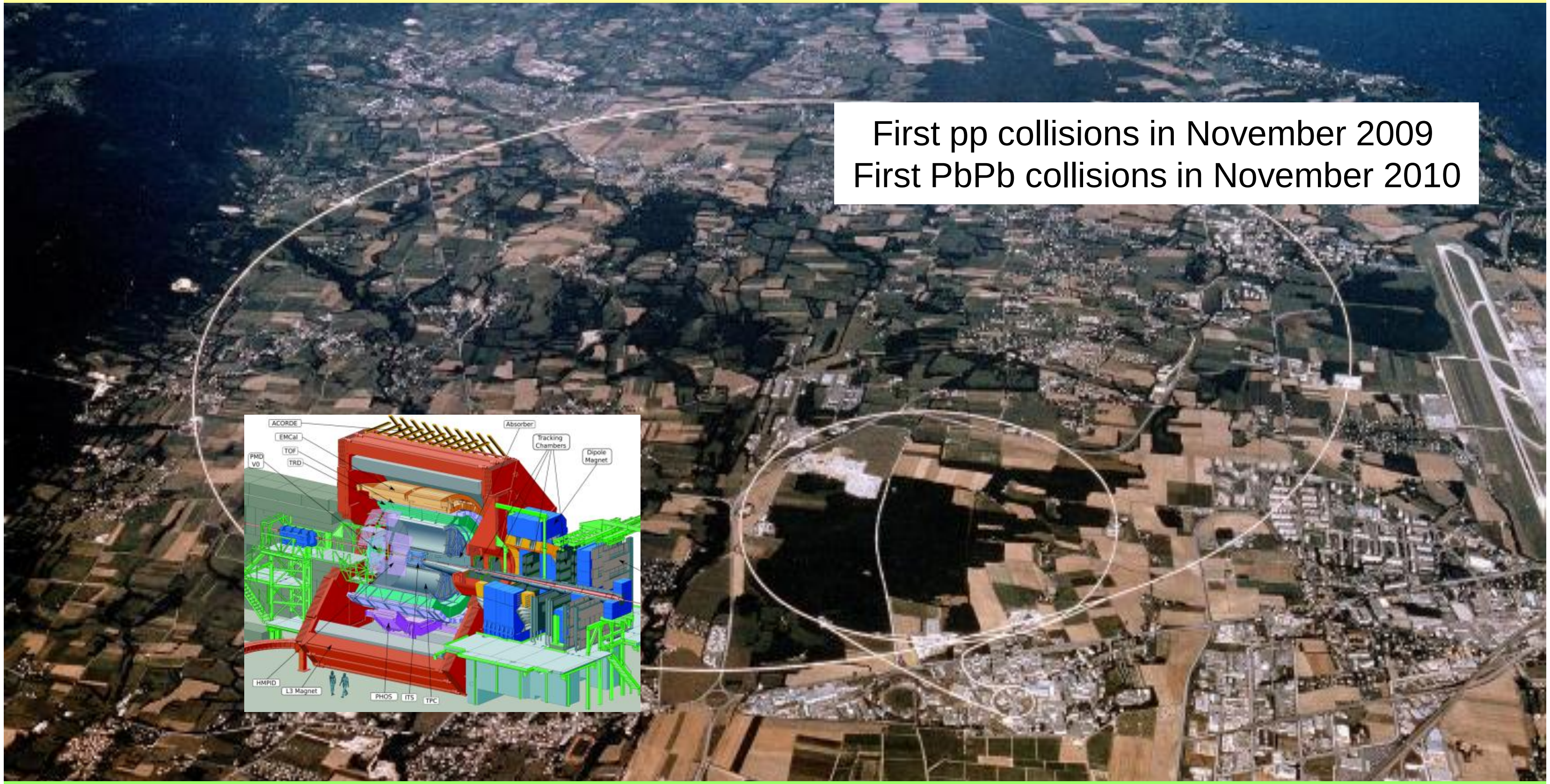
→ Hadron formation mechanisms (parton coalescence vs fragmentation)

ALICE@LHC

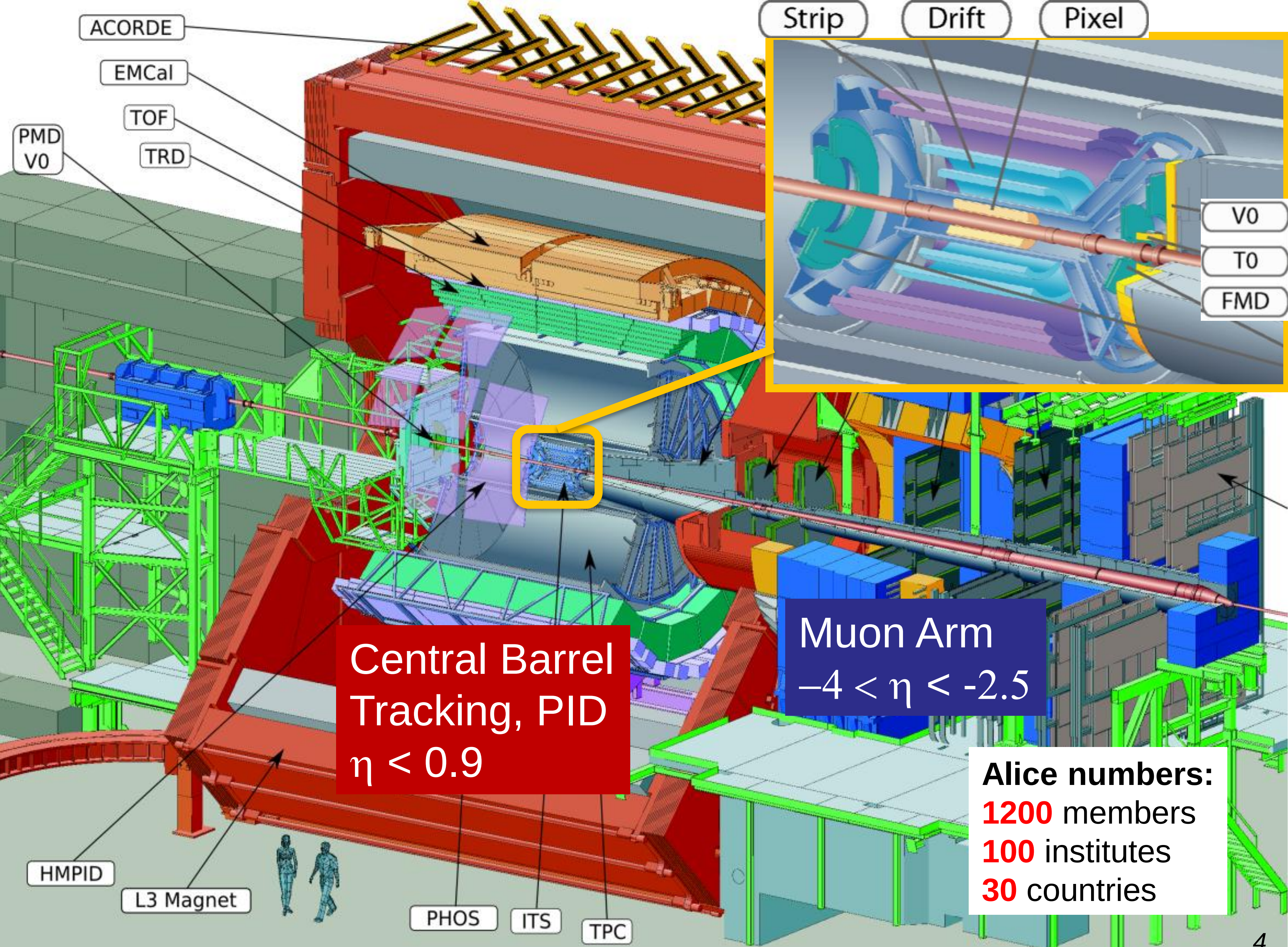
Many open and new questions !

➡ Excitation functions on the largest possible energy range
➡ Transition between hard and soft processes
At LHC: “old” (different / better conditions) + novel observables

First pp collisions in November 2009
First PbPb collisions in November 2010

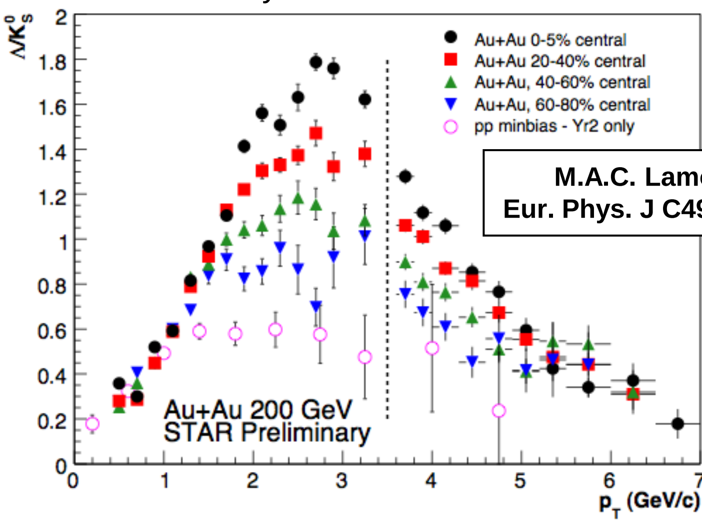


Designed to cover essentially all observables of interest in the soft and hard regimes (hadron, lepton and photon sectors)
➡ **Tracking & particle identification in a large acceptance and p_T domain**


ACORDE
EMCal
TOF
TRD
PMD
V0
Strip
Drift
Pixel
V0
T0
FMD
Central Barrel
Tracking, PID
η < 0.9
Muon Arm
–4 < η < -2.5
HMPID
L3 Magnet
PHOS
ITS
TPC
Alice numbers:
1200 members
100 institutes
30 countries

The surprise !

First seen by STAR and PHENIX in 2003



M.A.C. Lamont et al,
Eur. Phys. J C49 39–55 (2007)

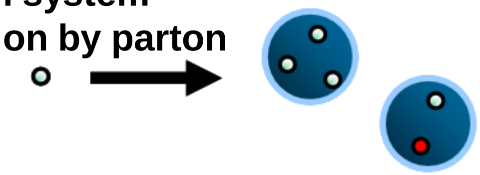
An anomalously high baryon over meson ratio at intermediate p_T in Au+Au collisions with respect to pp collisions at RHIC.

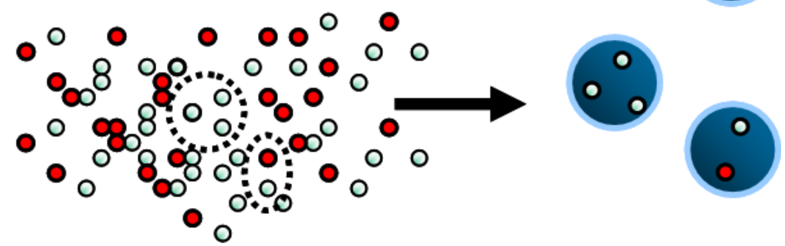
Strong increase of the effect with collision centrality

The first ideas ☺

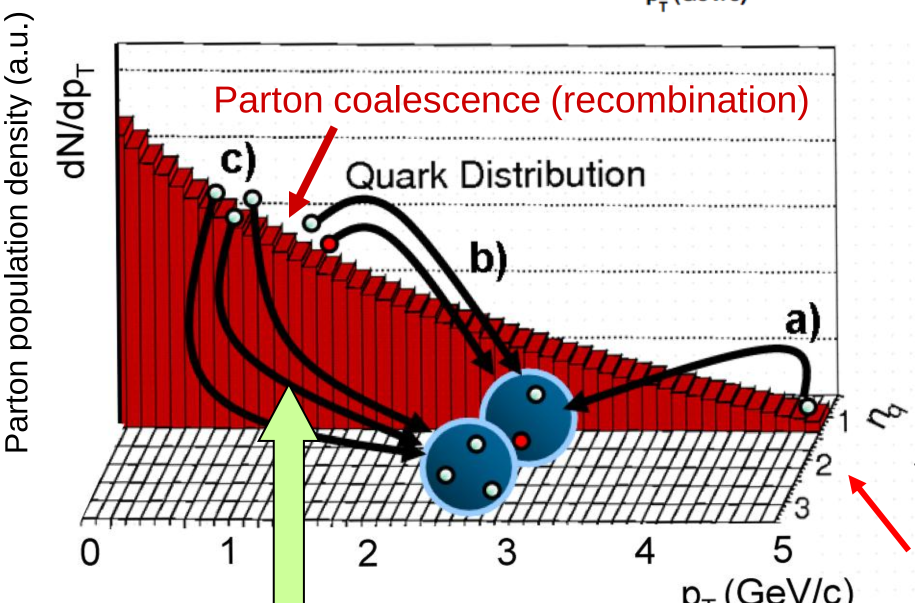
A strong hint of partonic degrees of freedom
→ QGP footprint

In pp: dilute parton system
hadron production by parton fragmentation





In Au-Au: dense (highly populated) parton medium
Partons close in coordinate space and momentum space in the low and intermediate p_T region
→ it is more effective (economic) to form hadrons by parton coalescence (b,c) than by fragmentation (a)



Why more baryons than mesons at intermediate p_T ?

Example: the 1 GeV region is more populated than the 1.5 GeV region
→ 3 GeV baryons (3 x 1 GeV quarks) are favored wrt 3 GeV mesons (2 x 1.5 GeV quarks)

From ideas to models

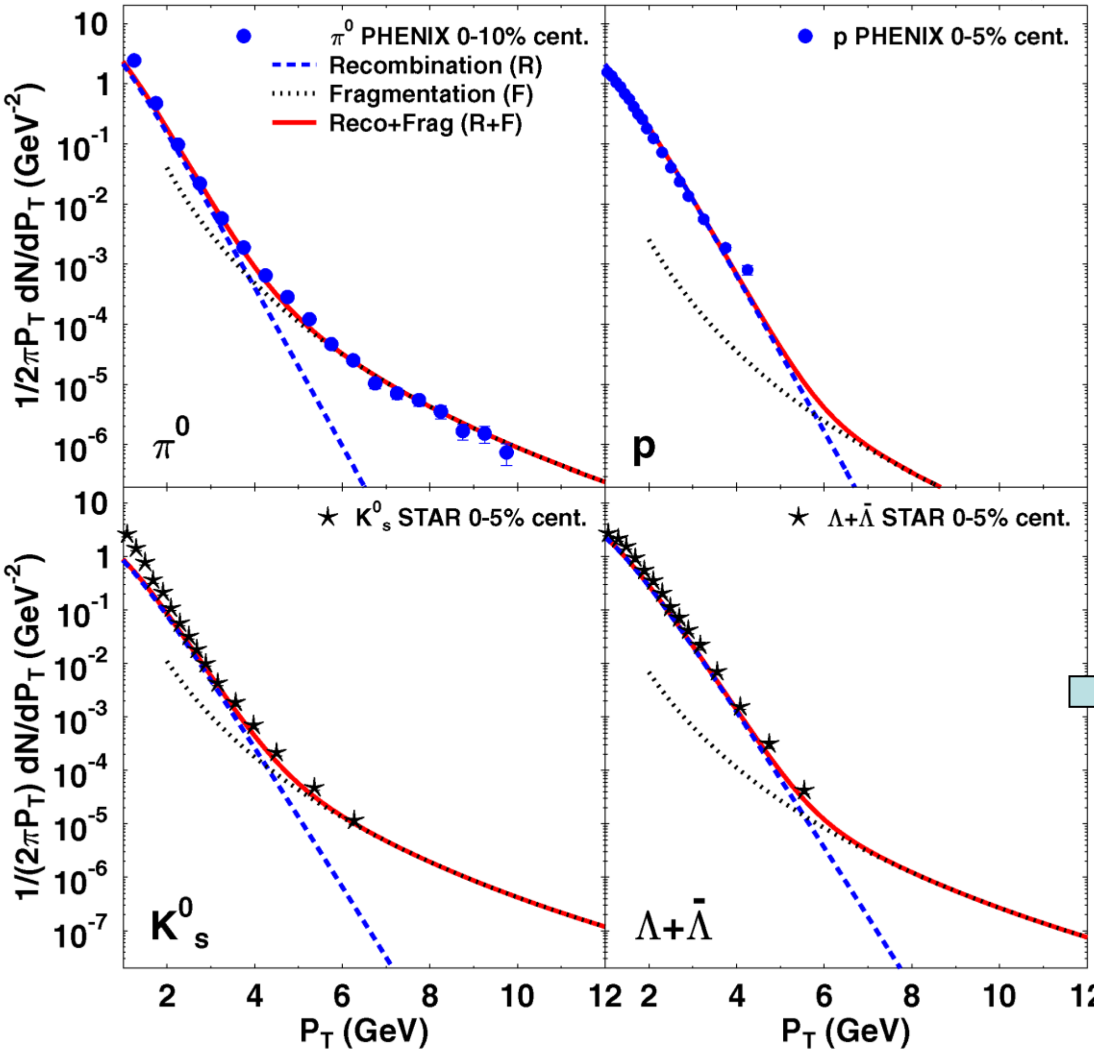
Parton Recombination + Parton Fragmentation (perturbative QCD) + Jet Quenching Effects

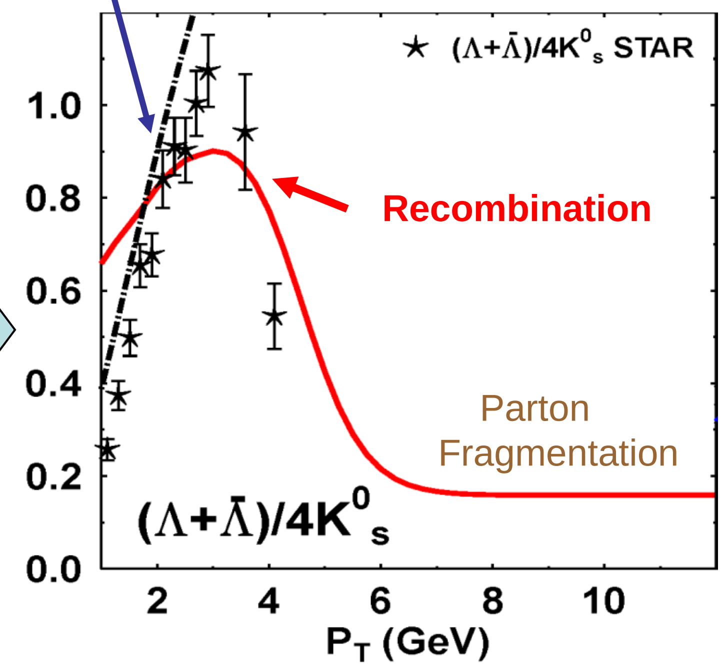
R. J. Fries, B. Müller, C. Nonaka and S. A. Bass
Phys. Rev. C **68**, 044902 (2003)

+ Radial Flow

1) Pushes baryons to higher p_T than mesons

2) Favors recombination of partons (collective motion → partons close in space are also closer in momentum space)



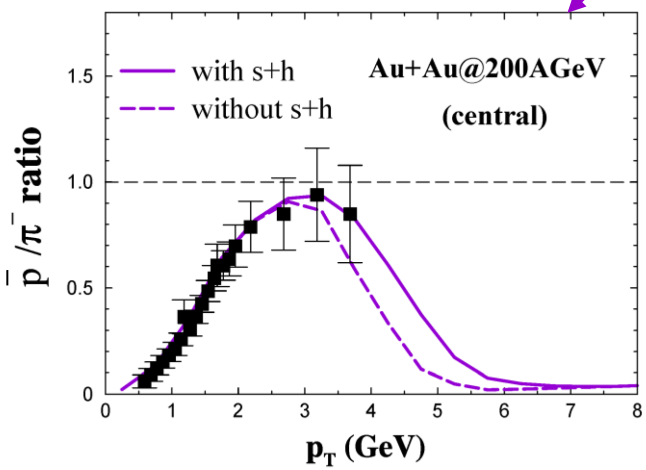


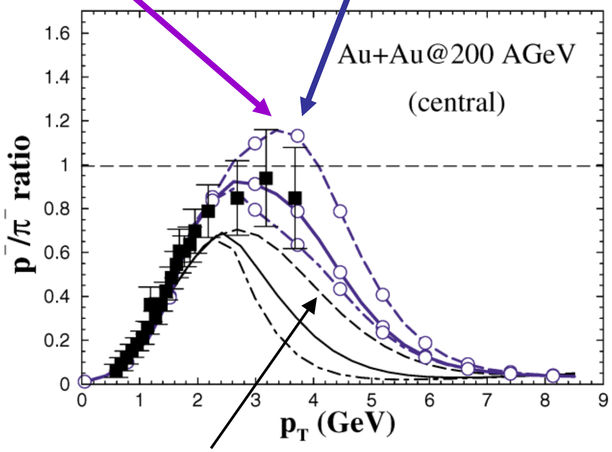
Parton coalescence models

Enabling coalesence of partons from minijets **(h)** with partons from the QGP bulk **(s)** has a substantial effect

Variation of flow effects: (240, 300, 340 MeV for the inverse slope parameter)

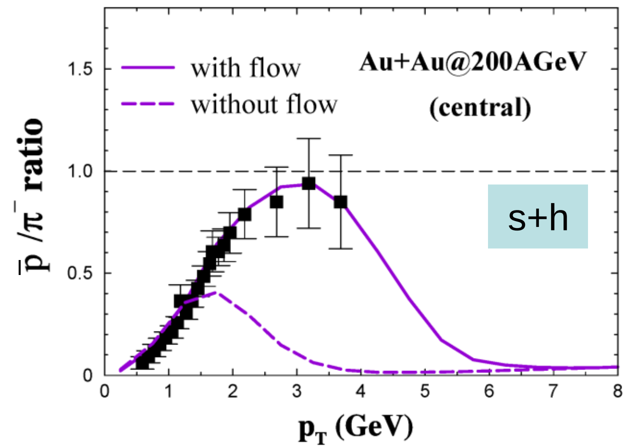
V. Greco, C. M. Ko and P. Lévai, Phys. Rev. C 68, 034904 (2003)





w.o s+h

Greco V, Ko C M and Lévai P 2003 *Phys. Rev. Lett.* 90 202302



Alternative idea and explanation: baryons junctions

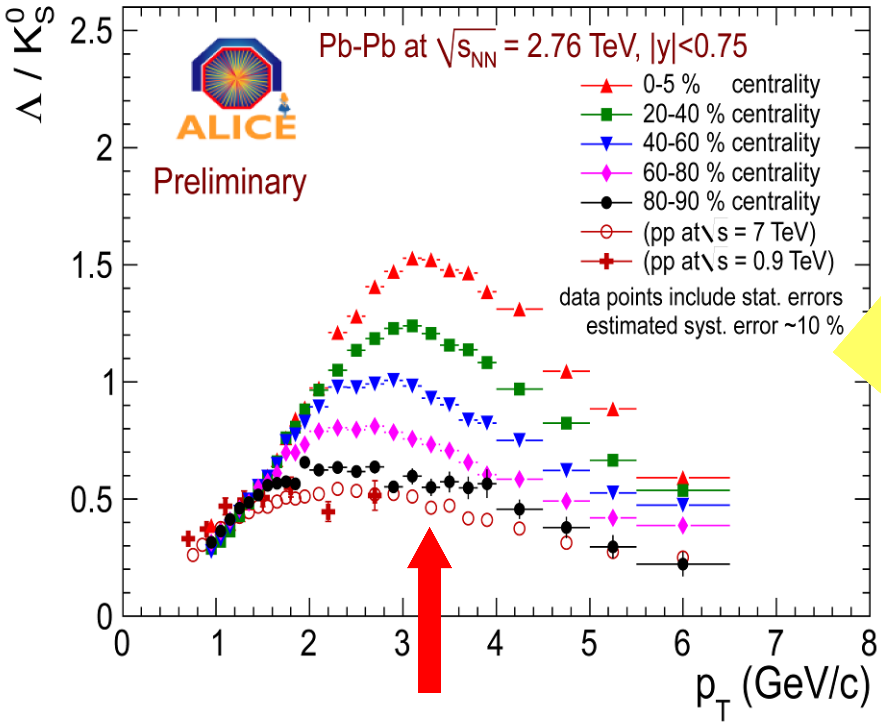
Existence of topological gluon field configurations ~ baryon junctions → predict long-range baryon number transport in rapidity as well as hyperon enhancement and considerable p_T enhancement relative to conventional diquark-quark string fragmentation (I. Vitev and M. Gyulassy, Phys Rev. C 65 (2002) 041902R

To discrimate between these scenarios, differential studies are needed:

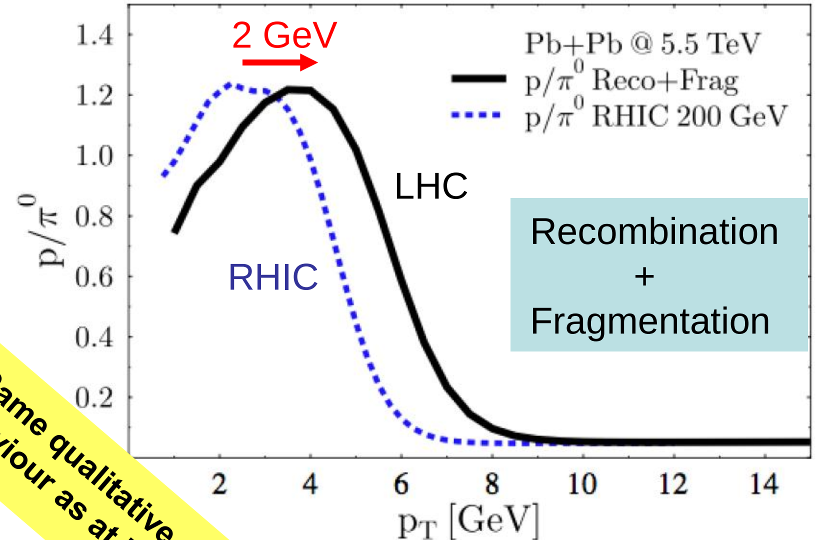
- **correlation between baryon/meson ratios and jets**
- **flavour dependence of baryon/meson ratios**

Λ / K^0_s in PbPb collisions at LHC

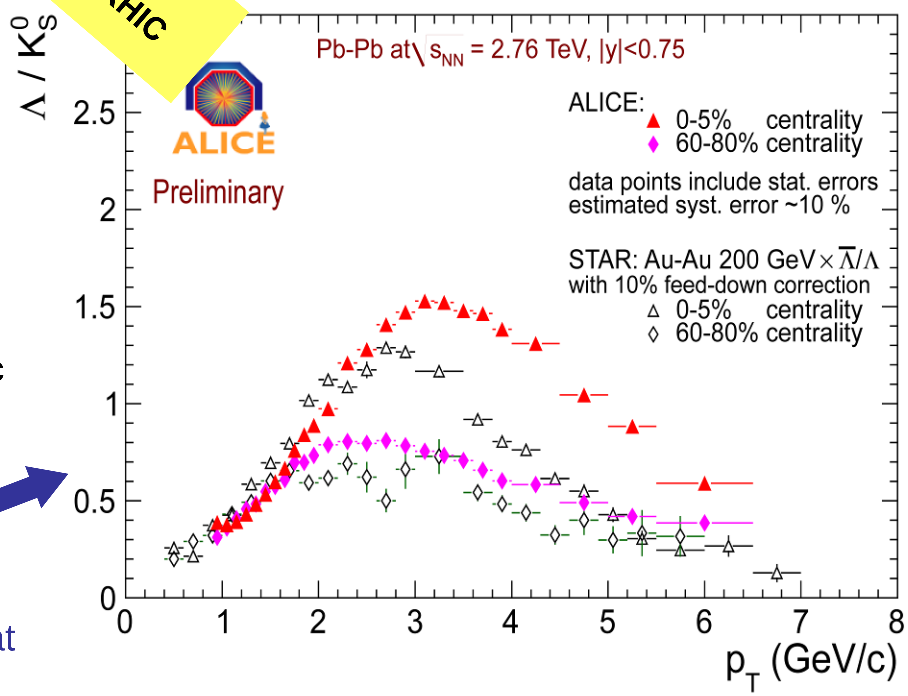
I. Belikov for the ALICE Collaboration, Quark Matter 2011,
J. Phys. G : Nucl. Part. Phys. 38 (2011) 124078



R.J.Fries and B.Müller, Eur. Phys. J C34, s279–s285 (2004)



Same qualitative behaviour as at RHIC

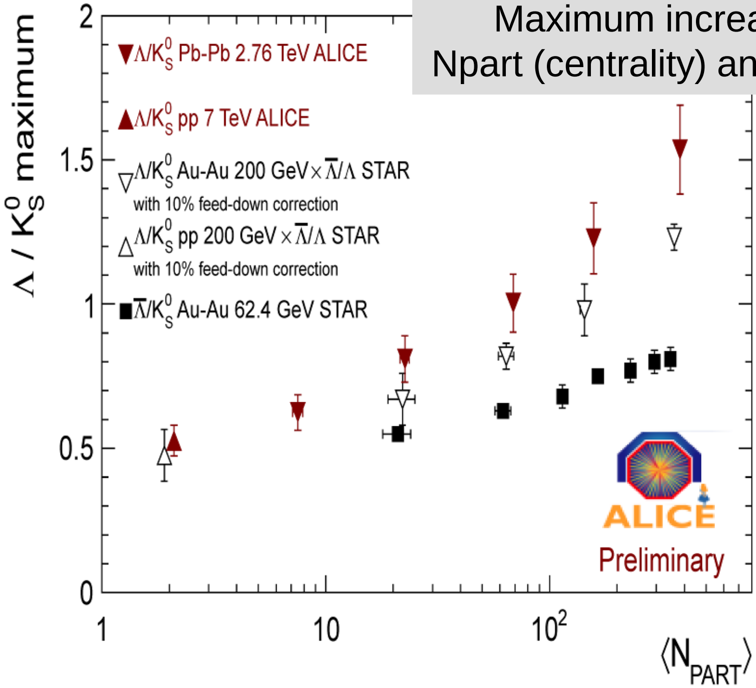


Maximum value of Λ/K^0_s: **1.5** for the 0-5 % most central events at p_T slightly larger than **3 GeV/c**

80-90 % centrality class: maximum ↘ **0.6** at **2.5 GeV/c** coming close to the behaviour observed in pp collisions

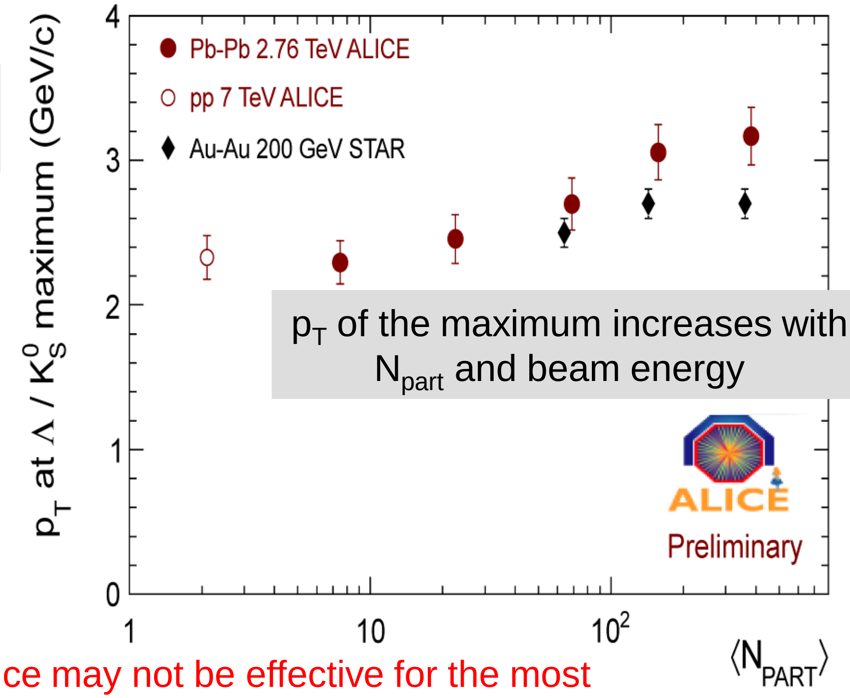
When going from RHIC to LHC:
- Increase of the maximum value of **~15 %** for all centrality classes
- Shift in p_T of the maximum **(+ 0.6 GeV/c)**: less than what is predicted by Recombination + Fragmentation models

Λ / K^0_s in PbPb collisions at LHC



Maximum increases with Npart (centrality) and beam energy

I. Belikov
QM 2011



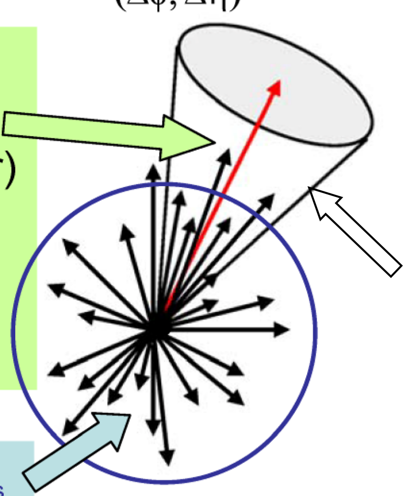
p_T of the maximum increases with N_{part} and beam energy

- Coalescence may not be effective for the most peripheral collisions ↔ phase space not populated enough
- In semi central collisions, the p_T of the maximum is less than in central collisions ↔ less radial flow

Λ/K^0_s around the jet axis or the high p_t leading particle (trigger) direction

$\Delta\phi = \phi_{trigger} - \phi_{\Lambda, K^0_s}$

$\Delta\eta = \eta_{trigger} - \eta_{\Lambda, K^0_s}$



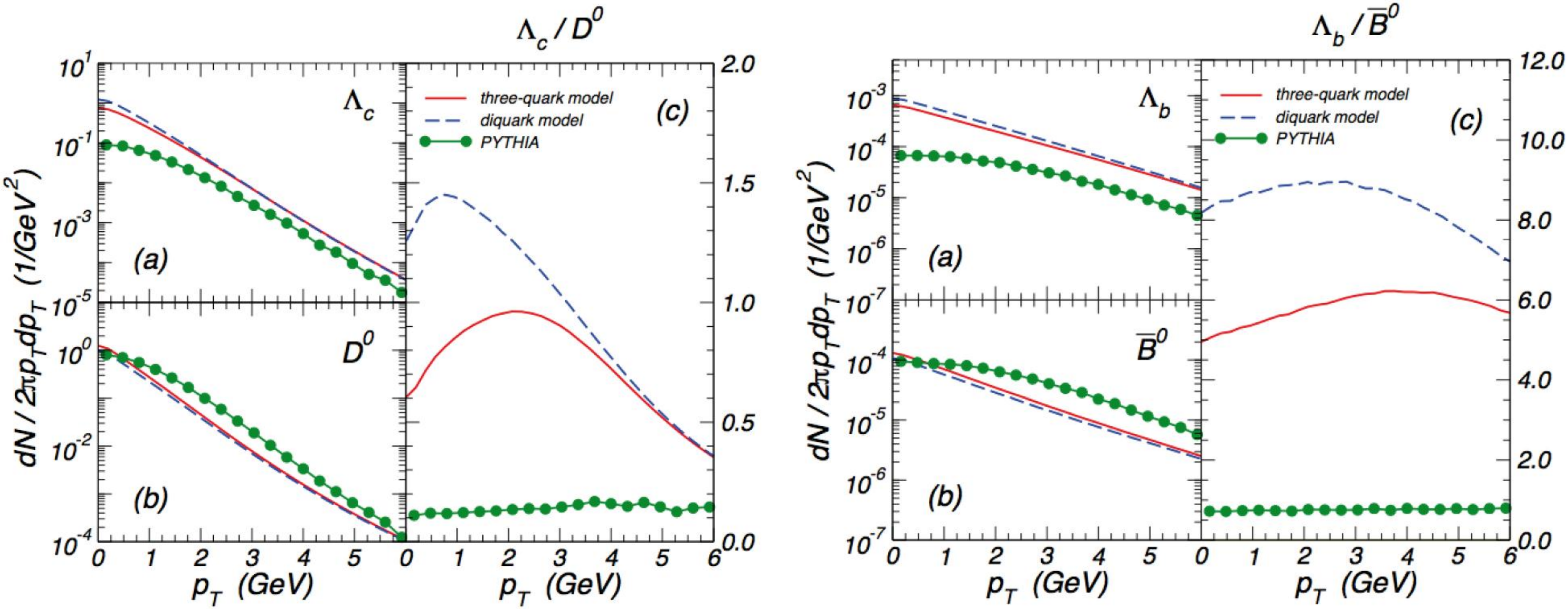
Global Λ/K^0_s

To validate/ quantify coalescence wrt fragmentation and other effects (influence of baryon junctions, …)

→ Correlations between baryon/meson ratios and jets in PbPb

If it comes close to the one in pp collisions, then the global baryon/meson enhancement effect can hardly be due to a modification of the fragmentation processes in the medium but is more likely related to coalescence mechanisms

Prospects for heavy flavor baryon/meson ratios



Coalescence model predictions for Λ_c/D and Λ_b/B at RHIC

Yongseok Oh, Che Ming Ko, Su Houng Lee and Shigehiro Yasui, Phys.Rev. C79, 044905 (2009)

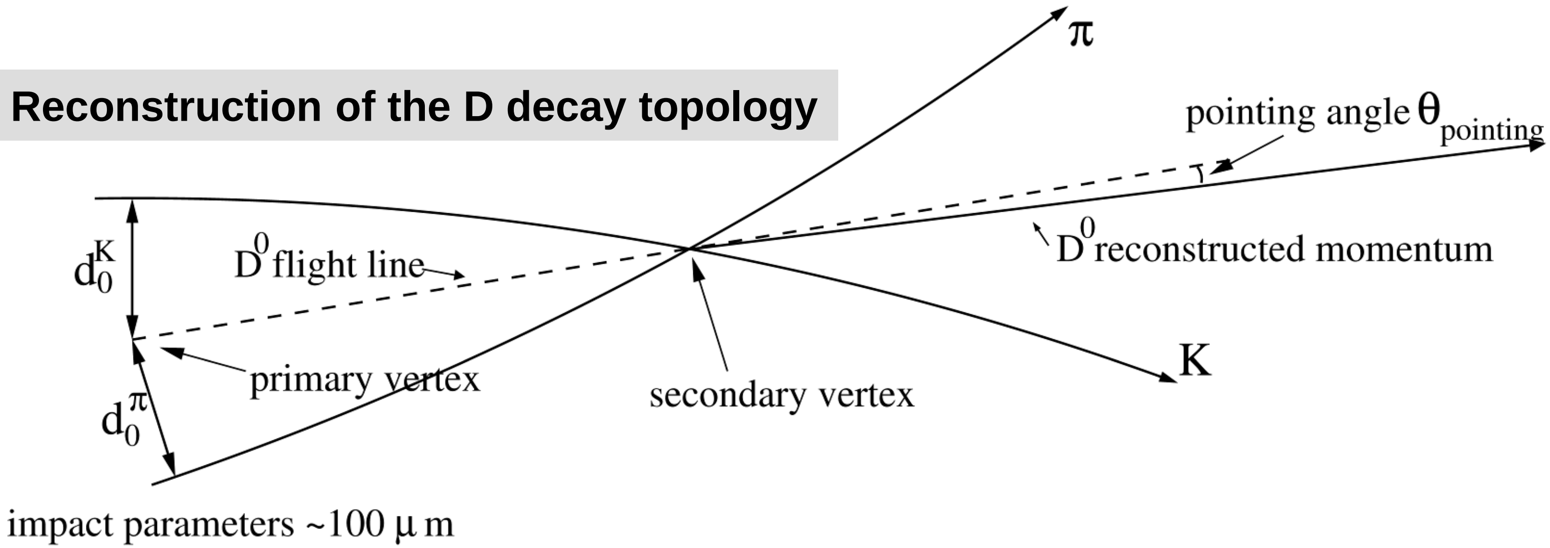
- Partons produced in hard scatterings can combine with quarks and anti-quarks in the QGP
- Possibility of recombination of a heavy quark with di-quarks present in the QGP (diquark model)

⇒ additional enhancement of the Λ_c and Λ_b

At low p_T, this could also lead to a rather significant enhancement of the Λ_c with respect to thermal models where the relative abundance of particles depends only on their masses

Current situation of charm and beauty measurements in PbPb collisions at LHC with ALICE

Reconstruction of the D decay topology



D mesons successfully measured today in their hadronic decay channels but not down to low p_T : $D^0 \rightarrow K\pi$ (p_T > 2 GeV/c), $D^+ \rightarrow K\pi\pi$ (> 5 GeV/c)

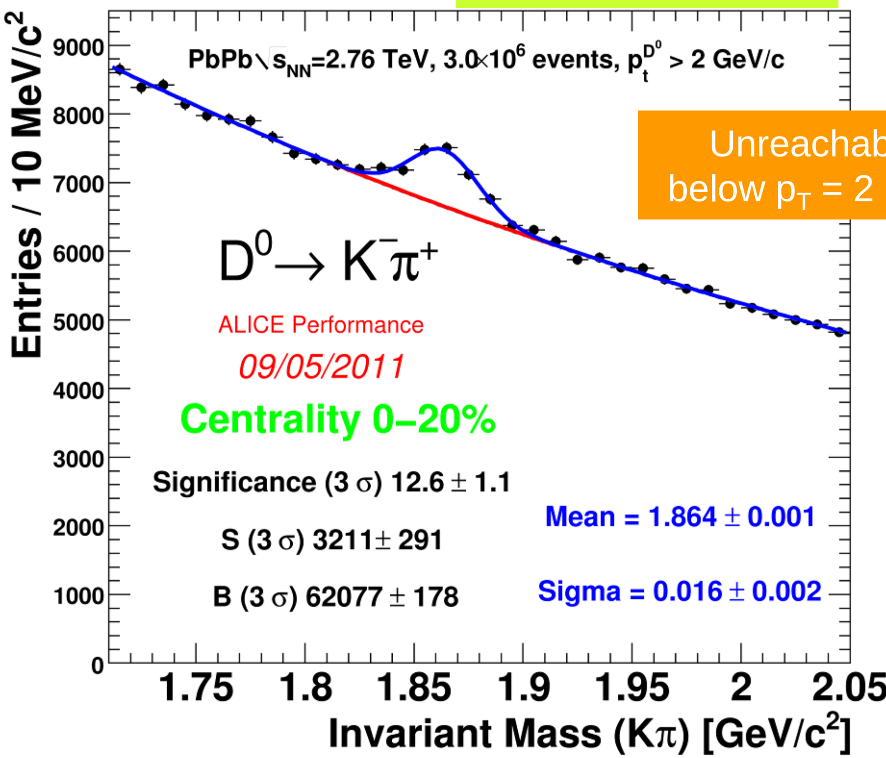
B mesons measured only in their semi-leptonic decay channels
Hadronic decay $B \rightarrow D (\rightarrow K\pi)$ not accessible

$\Lambda_c \rightarrow p K \pi$ (and $\Lambda_b \rightarrow \Lambda_c + X$) measurements beyond the present ALICE setup capabilities

The cτ of the Λ_c (60 μm) is a factor of 2 smaller than that of the D^0.
⇒ needs a more precise tracking and track impact parameter resolution (the decay tracks typically have displacements of a few tens of microns ~cτ from the primary interaction vertex)
+ trigger possibilities based on a topological selection of 3 tracks associated to a secondary vertex

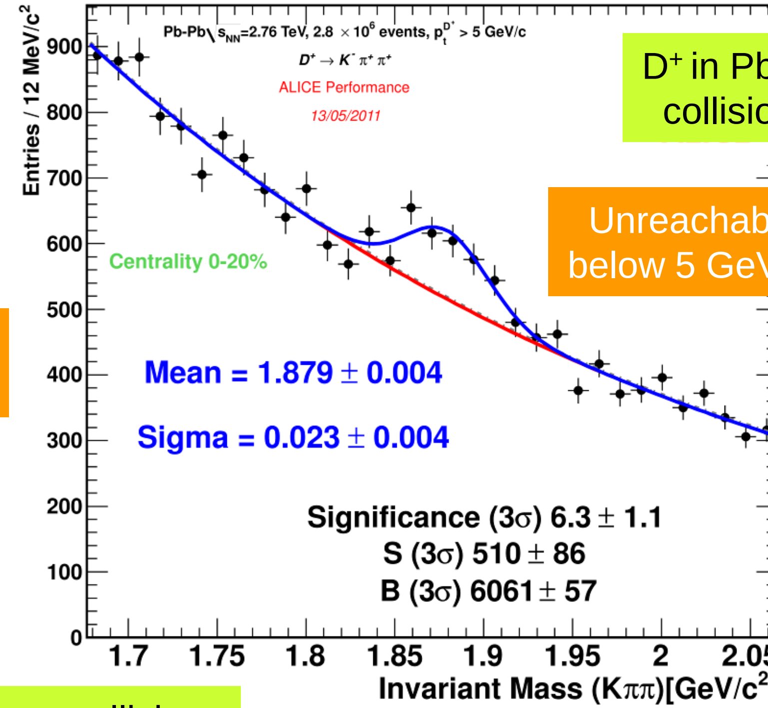
Current ALICE performance for D meson and Λ_c baryon measurements

D^0 in PbPb collisions



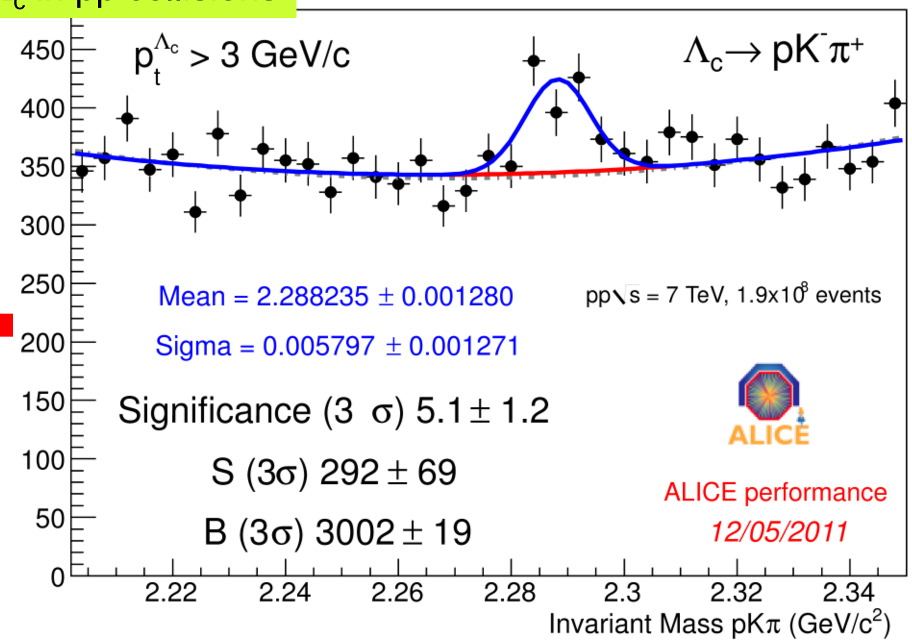
Unreachable below p_T = 2 GeV/c

D^+ in PbPb collisions



Unreachable below 5 GeV/c

Λ_c in pp collisions

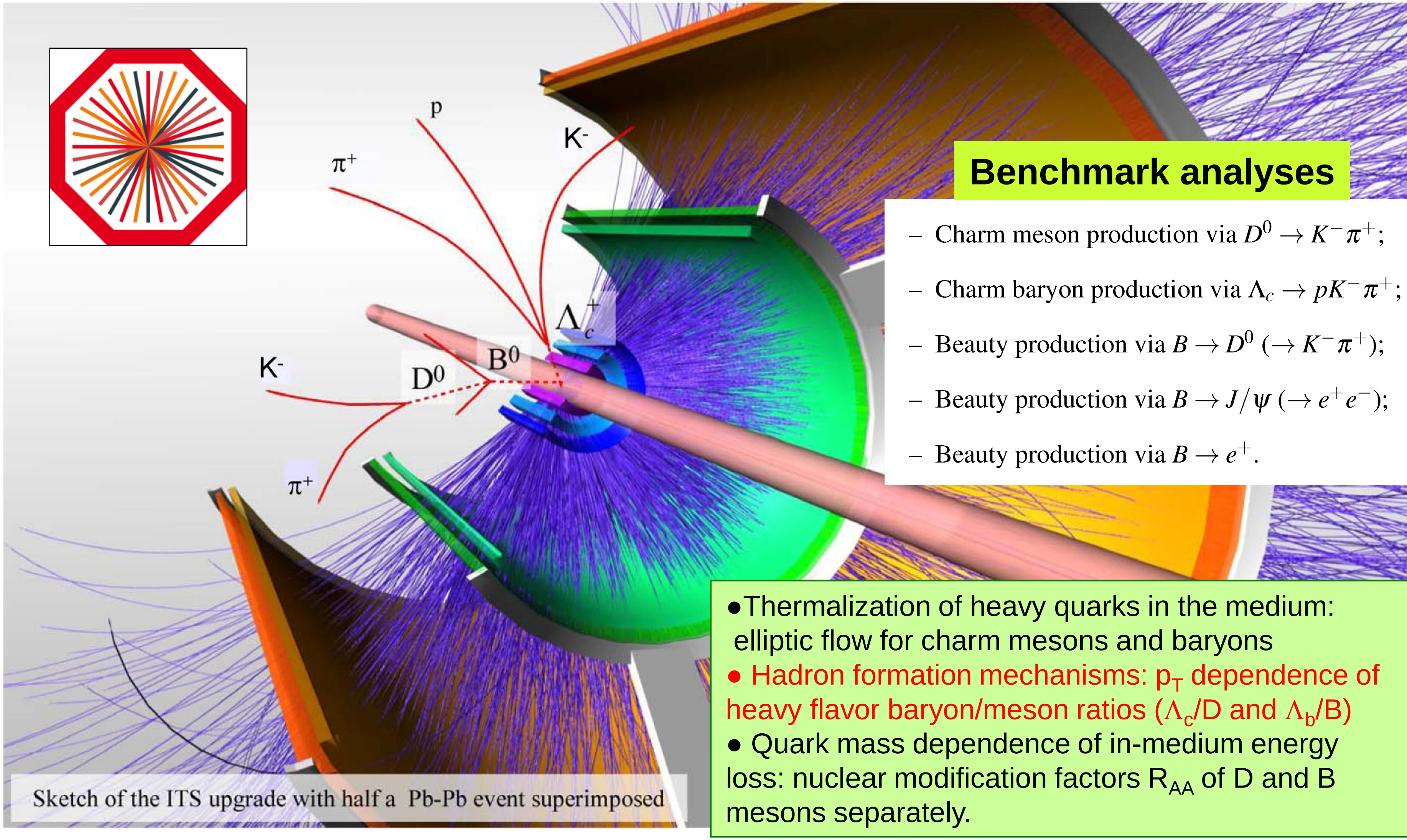


Unreachable in PbPb
Beyond the present setup capabilities

- Higher precision tracking
- Improvement of the track impact parameter resolution by a factor 2-3

→ **ALICE ITS upgrade**

Upgrade of the ALICE Inner Tracking System (ITS)



Sketch of the ITS upgrade with half a Pb-Pb event superimposed

Benchmark analyses

- Charm meson production via $D^0 \to K^-\pi^+$;
- Charm baryon production via $\Lambda_c \to pK^-\pi^+$;
- Beauty production via $B \to D^0\ (\to K^-\pi^+)$;
- Beauty production via $B \to J/\psi\ (\to e^+e^-)$;
- Beauty production via $B \to e^+$.

- Thermalization of heavy quarks in the medium: elliptic flow for charm mesons and baryons
- Hadron formation mechanisms: p_T dependence of heavy flavor baryon/meson ratios (Λ_c/D and Λ_b/B)
- Quark mass dependence of in-medium energy loss: nuclear modification factors R_{AA} of D and B mesons separately.

In the perspective of high luminosity PbPb (2018) and the frame of the global reforging of ALICE

Performance objectives and layout of the new ITS

Layout and technology optimisation to get:

- Track position resolution at the primary vertex (pointing resolution) improved by **a factor ~ 3**.
- Standalone tracking efficiency comparable to what is presently achieved by combining ITS & TPC.
- Momentum resolution of about **2% up to 2 GeV/c** and remaining **below 3% up to 20 GeV/c.**
- Particle identification (PID) capabilities at least equivalent to the present ones.

- Extension of the trigger capabilities for enhancing the statistics of rare heavy flavour signals.
- Capability to read the data related to each individual interaction up to a rate of **50 kHz for PbPb** collisions and **2 MHz for pp** collisions.
- Radiation tolerance / year: **> 700 kRad** (ionizing radiations) and **> 10^{13} n_{eq} /cm²** (non-ionizing)

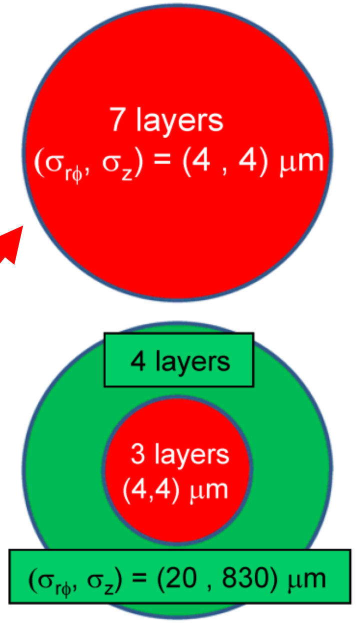
1. **First detection layer closer to the beam line.** A new beampipe with an outer radius of 19.8 mm is foreseen. First detection layer: 39 mm (current radius) → ~ 22 mm

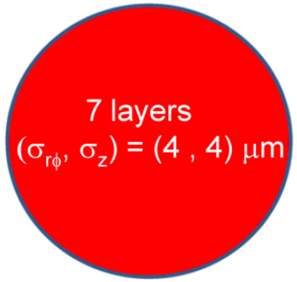
2. **Reduction of material budget.** Challenge: **0.3 - 0.4% of X0** per detection layer.

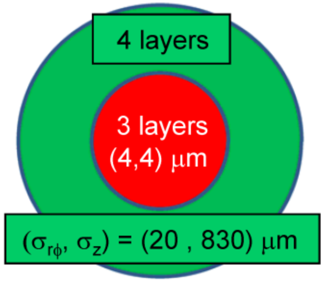
3. **Optimisation of the geometry and improvement of the granularity. Baseline scenario = completely new ITS with 2 options:**

   7 pixel (20 x 20 μm²) layers with intrinsic resolution **$(\sigma_{r\phi}, \sigma_z) = (4, 4)$ μm**

   3 pixel layers (the innermost ones) and 4 micro-strip layers (outermost) with **$(\sigma_{r\phi}, \sigma_z) = (20, 830)$ μm.**



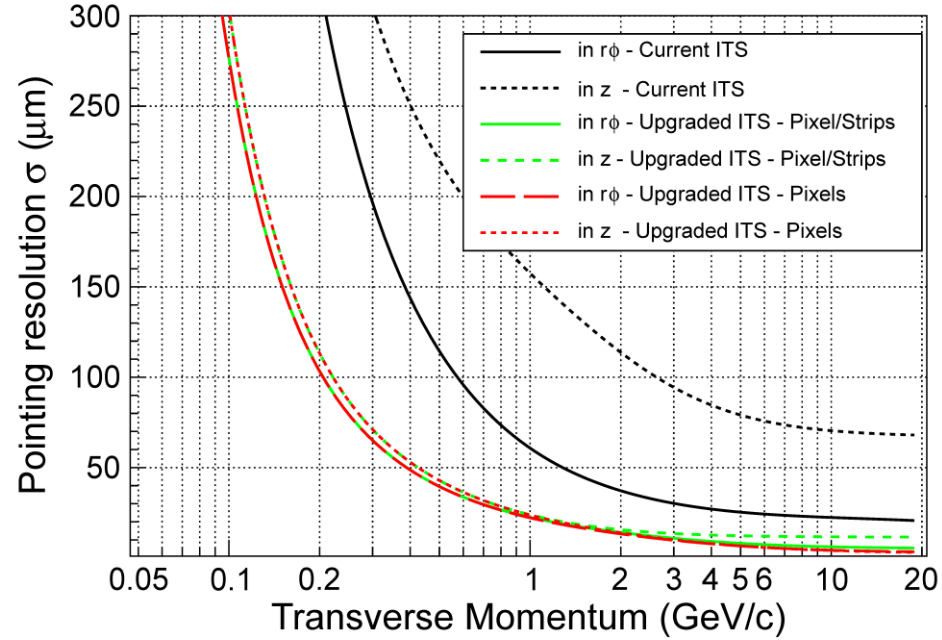




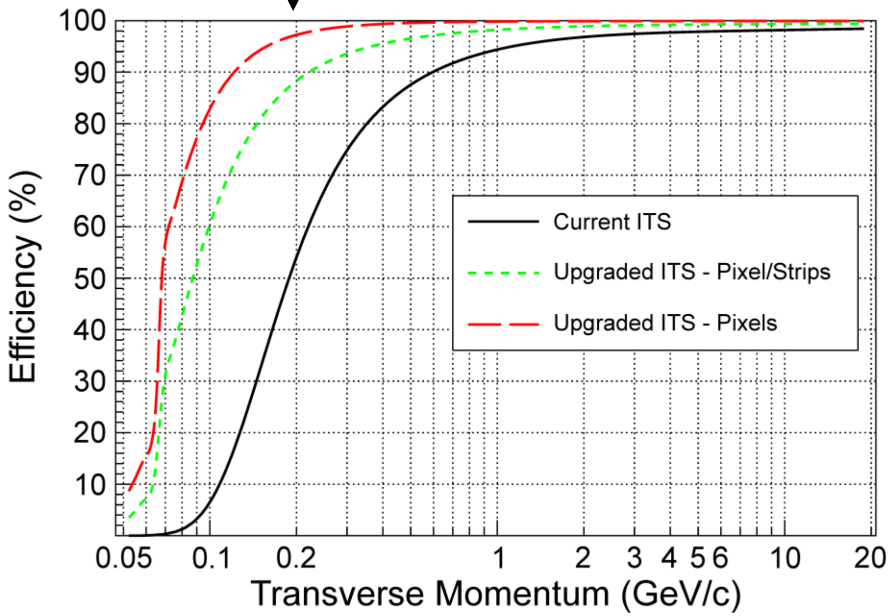
Performance simulations

Pointing resolution significantly improved:

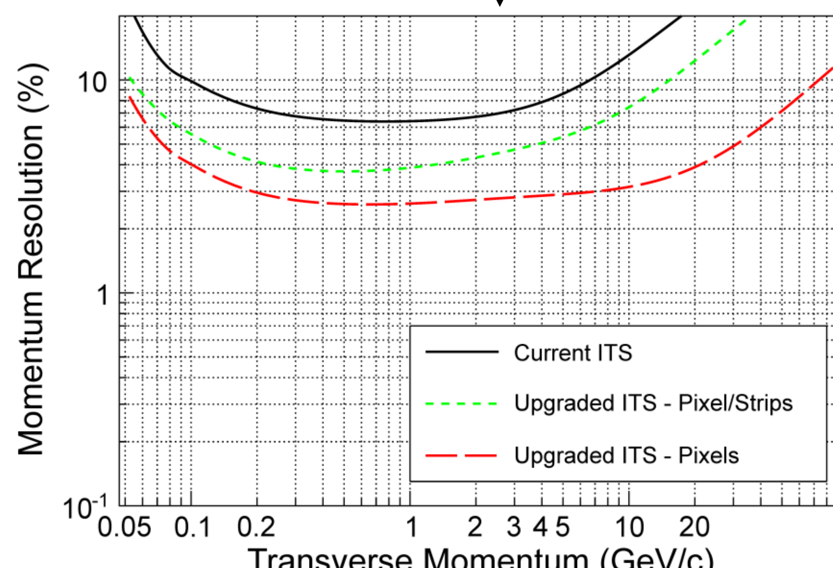
- Factor 3 in rφ-plane at 0.5 GeV/c: 120 μm → 40 μm
- Factor 5 along z axis at 0.5 GeV/c: 200 μm → 40 μm



Tracking efficiency significantly improved at low p_T: almost a factor 2 at 0.2 GeV/c



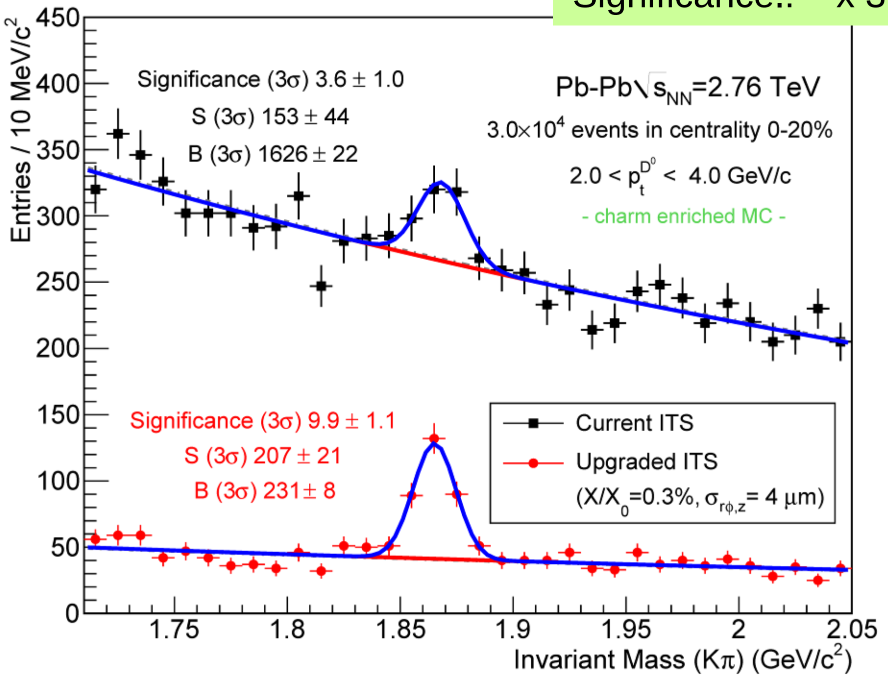
p_T resolution improved by at least a factor 2



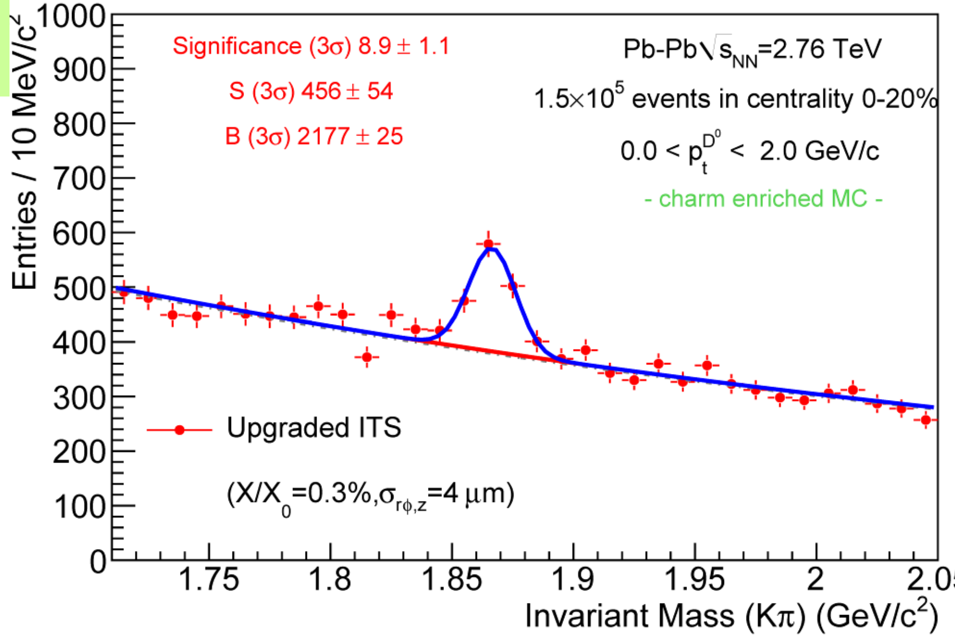
Charm and beauty meson measurement with the upgraded ITS

$D^0 \rightarrow K^- \pi^+$

2 < p_T< 4 GeV/c
S/B: ~ x 10
Significance.: ~ x 3

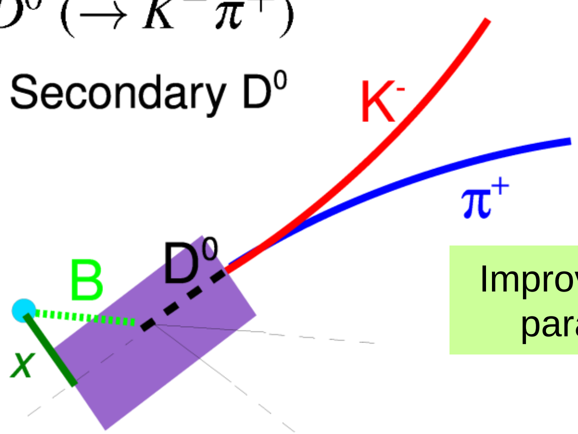


The range 0< p_T< 2 GeV/c becomes accessible

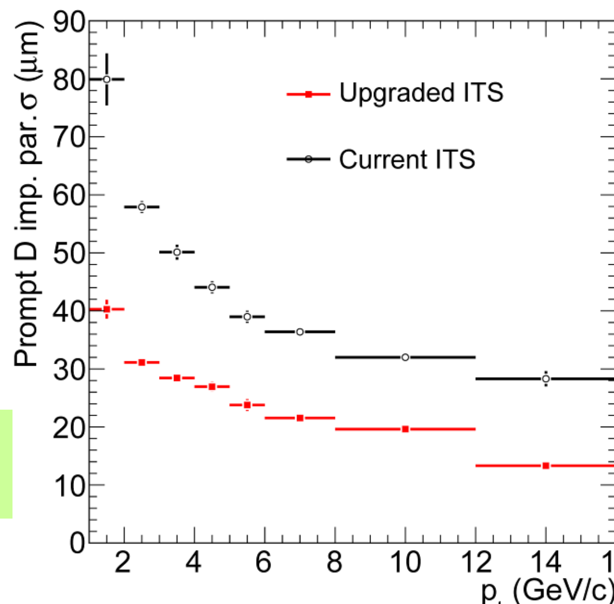


$B \rightarrow D^0\ (\rightarrow K^- \pi^+)$

Secondary D^0



Improvement of D impact parameter resolution

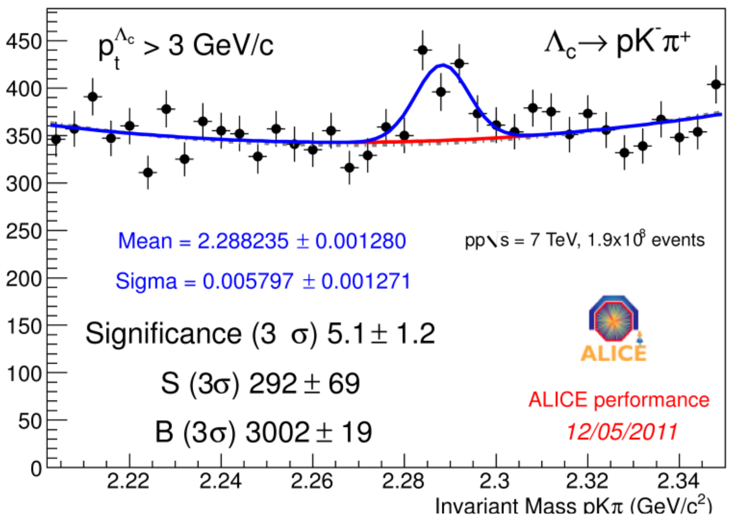


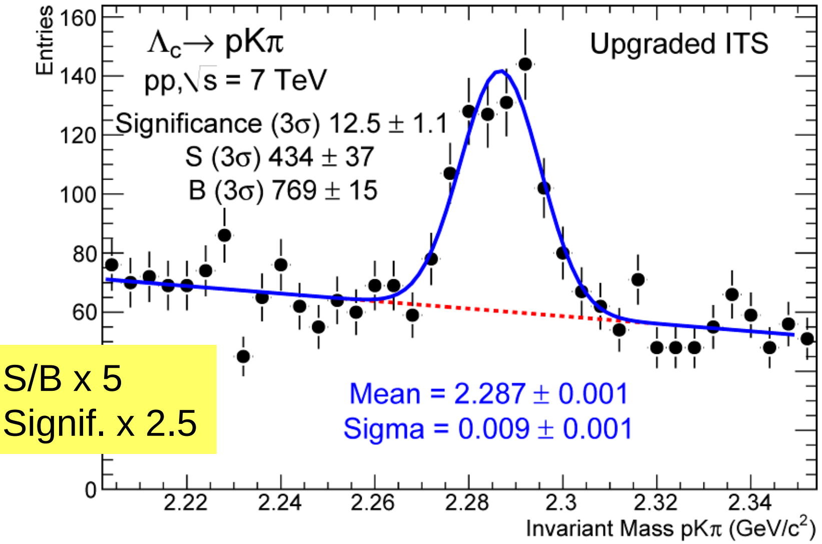
Charm and beauty baryon measurement with the upgraded ITS

$\Lambda_c \rightarrow pK^- \pi^+$

DATA Current ITS ~ 2 x 10^8 pp collisions SIMULATION Upgraded ITS

in pp

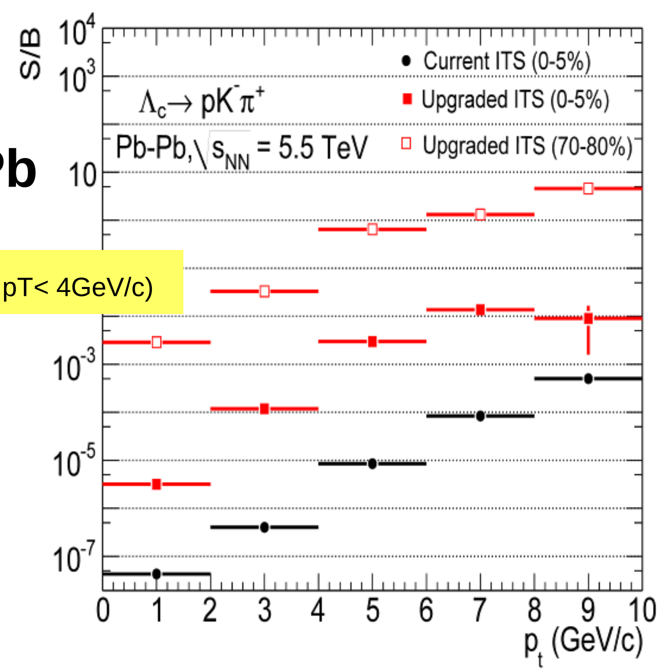




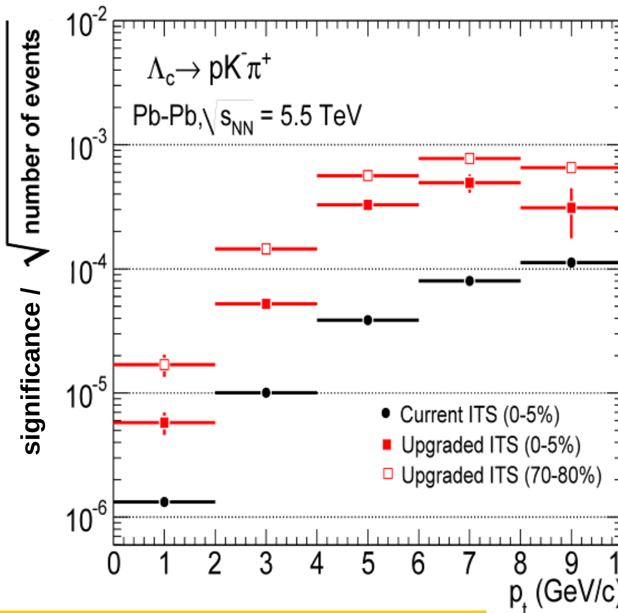
S/B x 5
Signif. x 2.5

in PbPb

x 400 (2< pT< 4GeV/c)

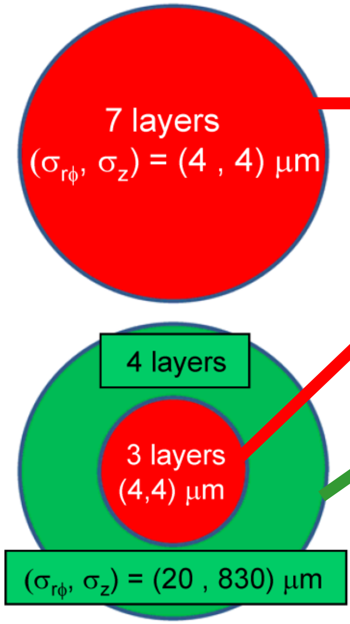


x 5-10



+ the very challenging: $\Lambda_b \rightarrow \Lambda_c$ ($\rightarrow pK\pi$)

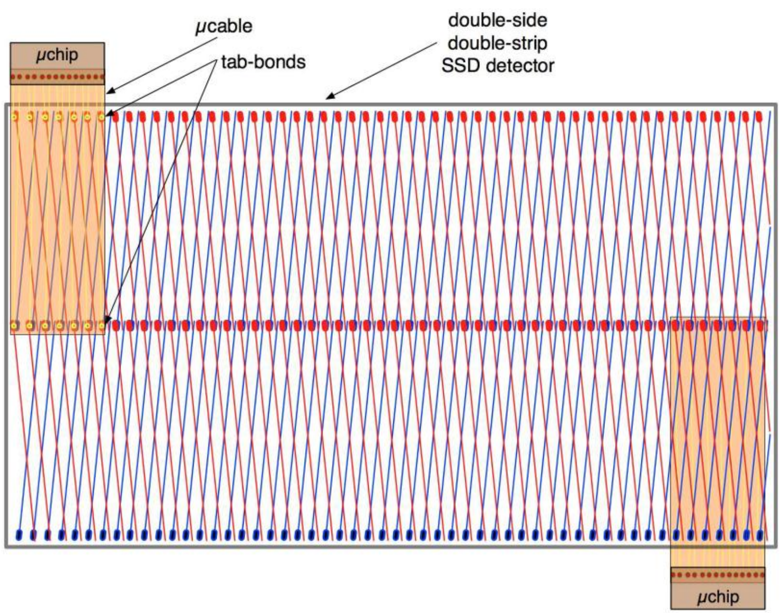
The various Silicon detector technologies

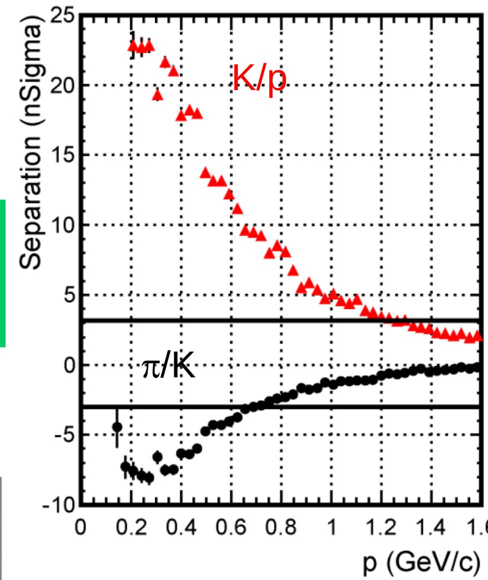


Hybrid and monolithic pixel detectors

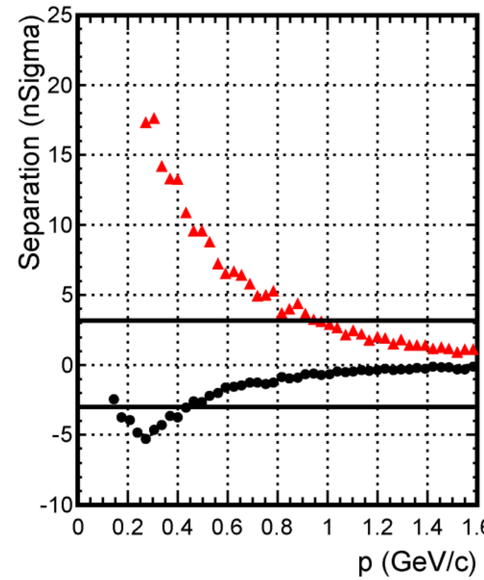
Double sided micro-strip detectors

Improved PID capabilities





3 pixel layers + 4 strip layers (300 μm of Si per layer)

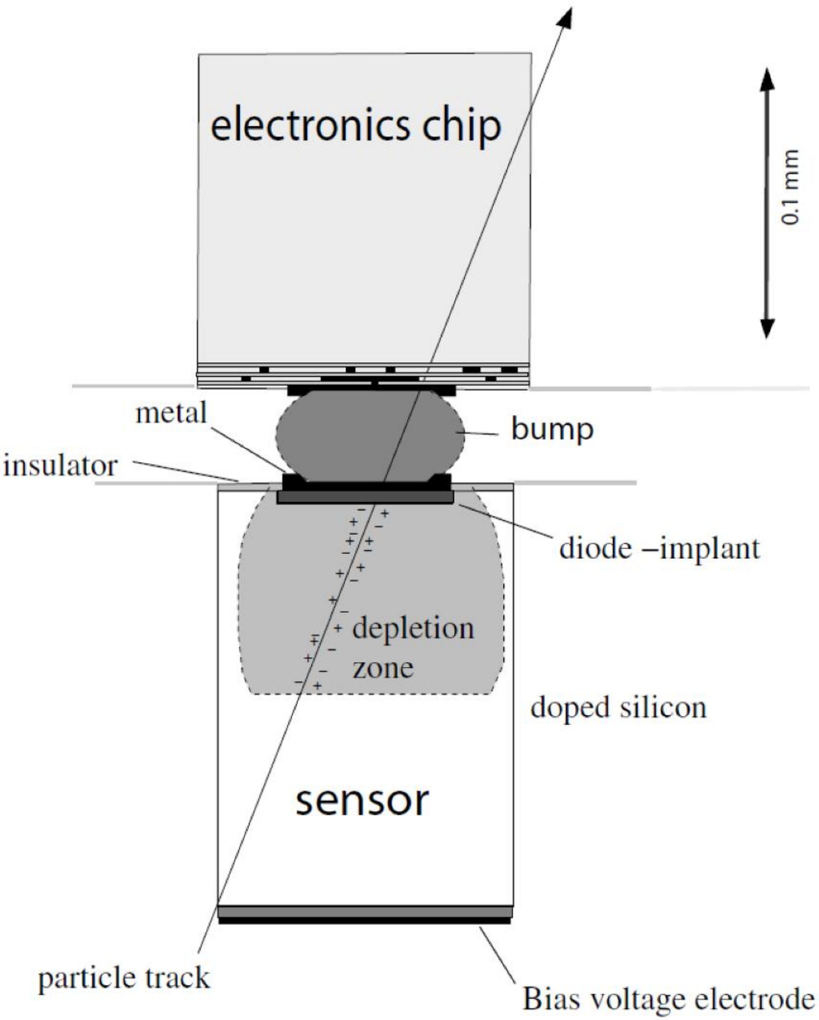


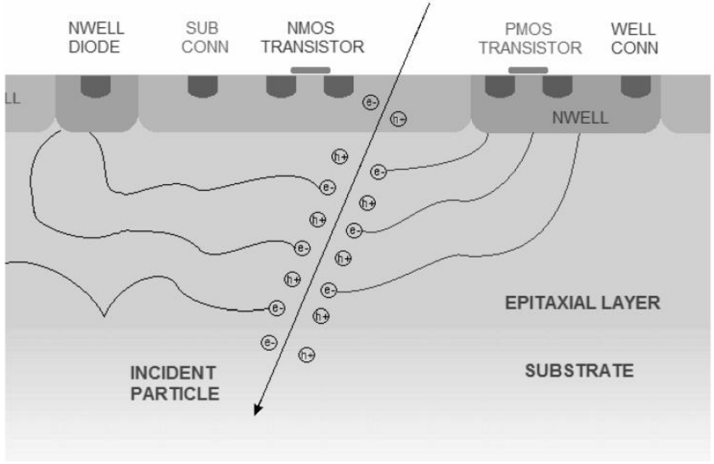
7 Layers of MAPS (active Si thickness per layer: 15 μm)

Well known technology
Sensor based on the existing design
Granularity is adequate for the external layers only

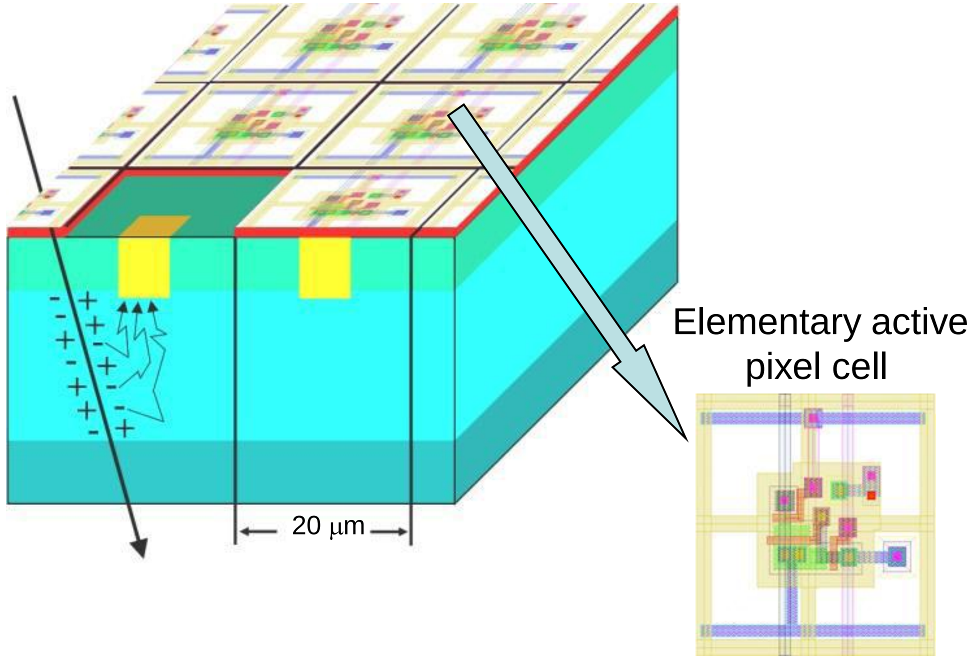
The pixel technologies

Hybrid Pixels





Monolithic Pixels



The pixel technologies

Some key parameters	Hybrid pixels	Monolithic pixels
Granularity	Pixel size limited due to the bump bonding R&D ongoing: bump bonding with 30 μm pitch.	Small pixel size (~ 20 x 20 μm^2)
Material budget	Two Si-chips limit the minimal material budget. R&D ongoing: thinning of the sensor → 50 μm and of the readout chip → 100 μm)	Thin sensor: 50 μm (0.05% X0)
Radiation tolerance	Proven radiation hardness	Ionizing: a few hundred kRad Non ionizing: $3 \times 10^{12}\ n_{eq}/cm^2$ To be improved by a factor 4 R&D ongoing: new technology (TOWER/JAZZ CMOS 0.18 μm)
Readout time	Fast enough (L1 trigger)	To be improved R&D ongoing (target : < 7 μs)
Cost	High due to to bump bonding	Low

Conclusion

It is possible to build a new silicon tracker with greatly improved features in terms of:
- determination of the distance of closest approach (dca) to the primary vertex
- standalone tracking efficiency at low p_T
- momentum resolution
- readout rate capabilities

+ opportunity to perform online event selection on the basis of topological criteria

→ Consequence of the spectacular progress made in the field of imaging sensors over the last ten years as well as the possibility to install a smaller radius beampipe

The new ITS will enable:
- Measurement of charm and beauty production in Pb-Pb collisions with sufficient statistical accuracy down to very low transverse momentum
- Measurement of charm baryons
- Exclusive measurements of beauty production

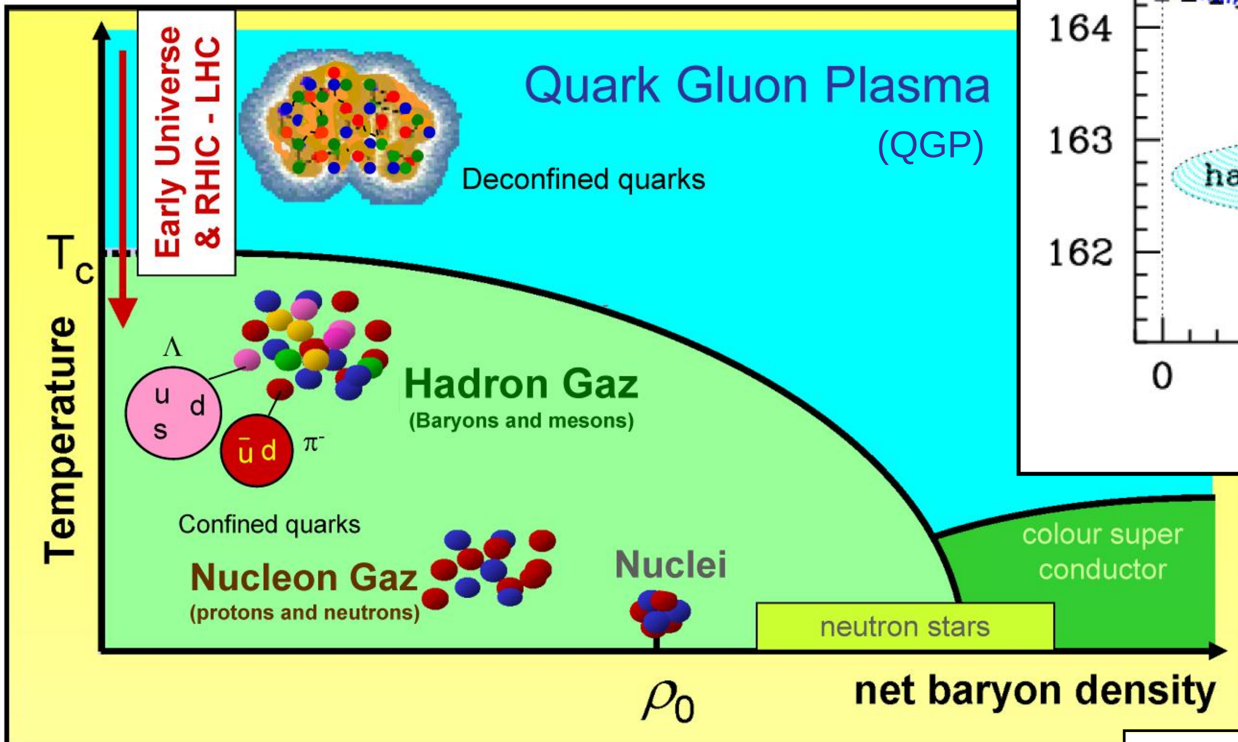
➡ Understanding of the energy loss mechanism, the hadronisation processes and the thermalization of heavy quarks.
Essential for the longterm goal of the ALICE experiment that is to provide a precise determination of the Quark Gluon Plasma properties

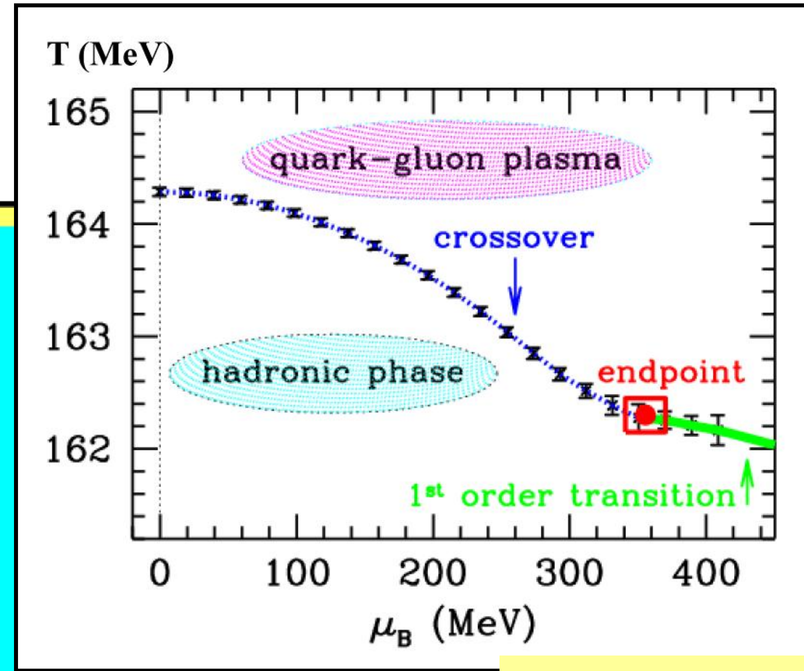
BUSY YEARS AHEAD !

2012 - 2014 : R&D activities and prototyping
2014 - 2016 : Component fabrication, module construction and characterization
2016 - 2017 : Detector integration and pre-commissioning on surface in laboratory
2017 - 2018 : Installation, commissioning and operation

Backup

The Quark Gluon Plasma over the 25 years

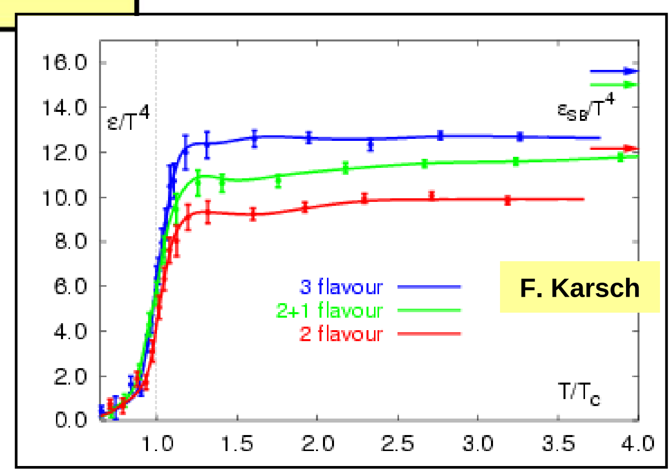




Z. Fodor and S.D. Katz

QCD Phase Transition

Tc ~ 160 - 180 MeV



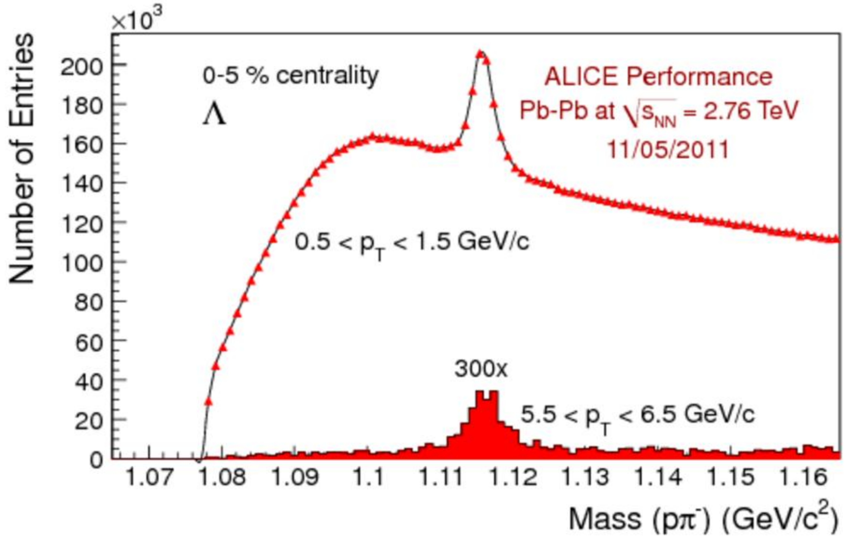
F. Karsch

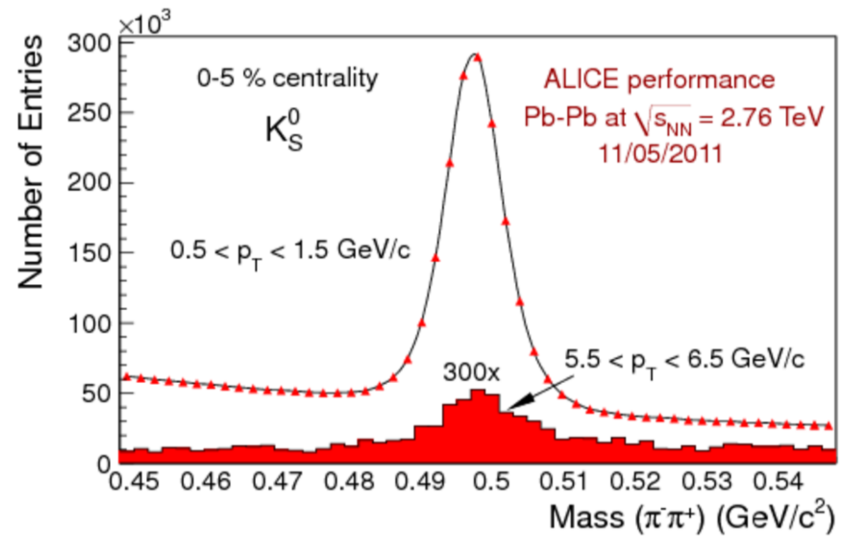
Which definition for the QGP nowadays ?

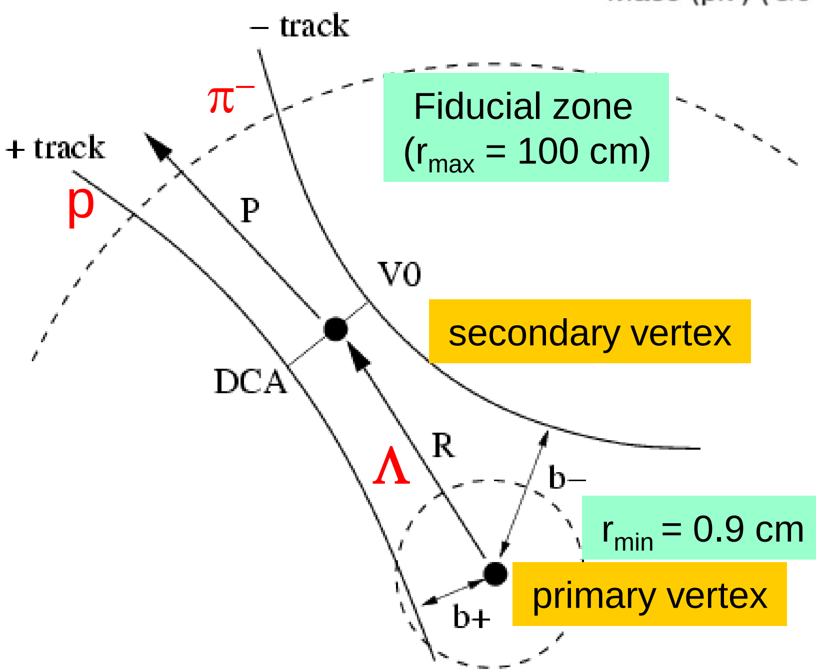
From the RHIC era:

“A (locally) thermally equilibrated state of matter in which quarks and gluons are deconfined from hadrons, so that color degrees of freedom become manifest over nuclear, rather than merely nucleonic, volumes”

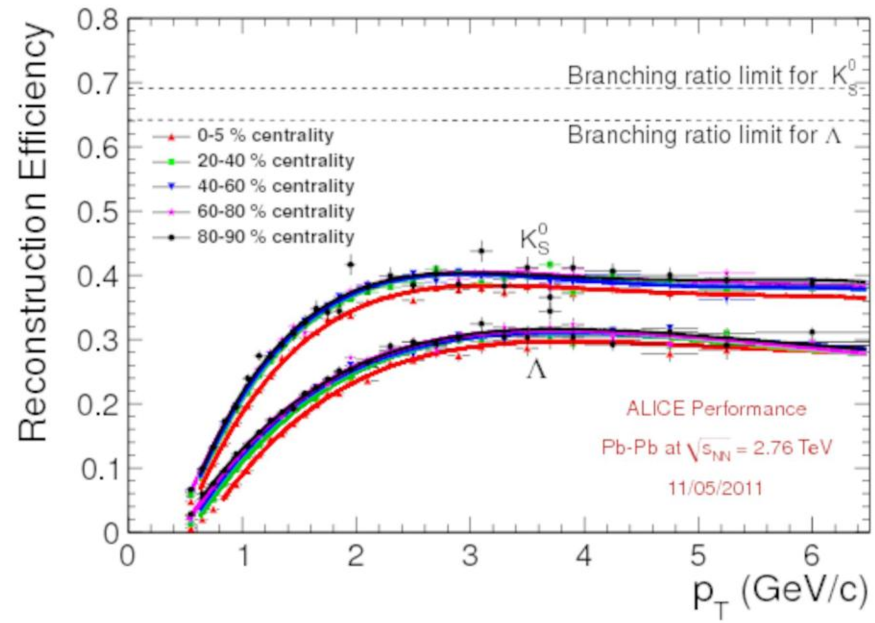
Weak decaying strange particles play a key role for the baryon over meson ratio measurements since they can be measured in a wide p_T range thanks to the topological recontruction of their decay chain





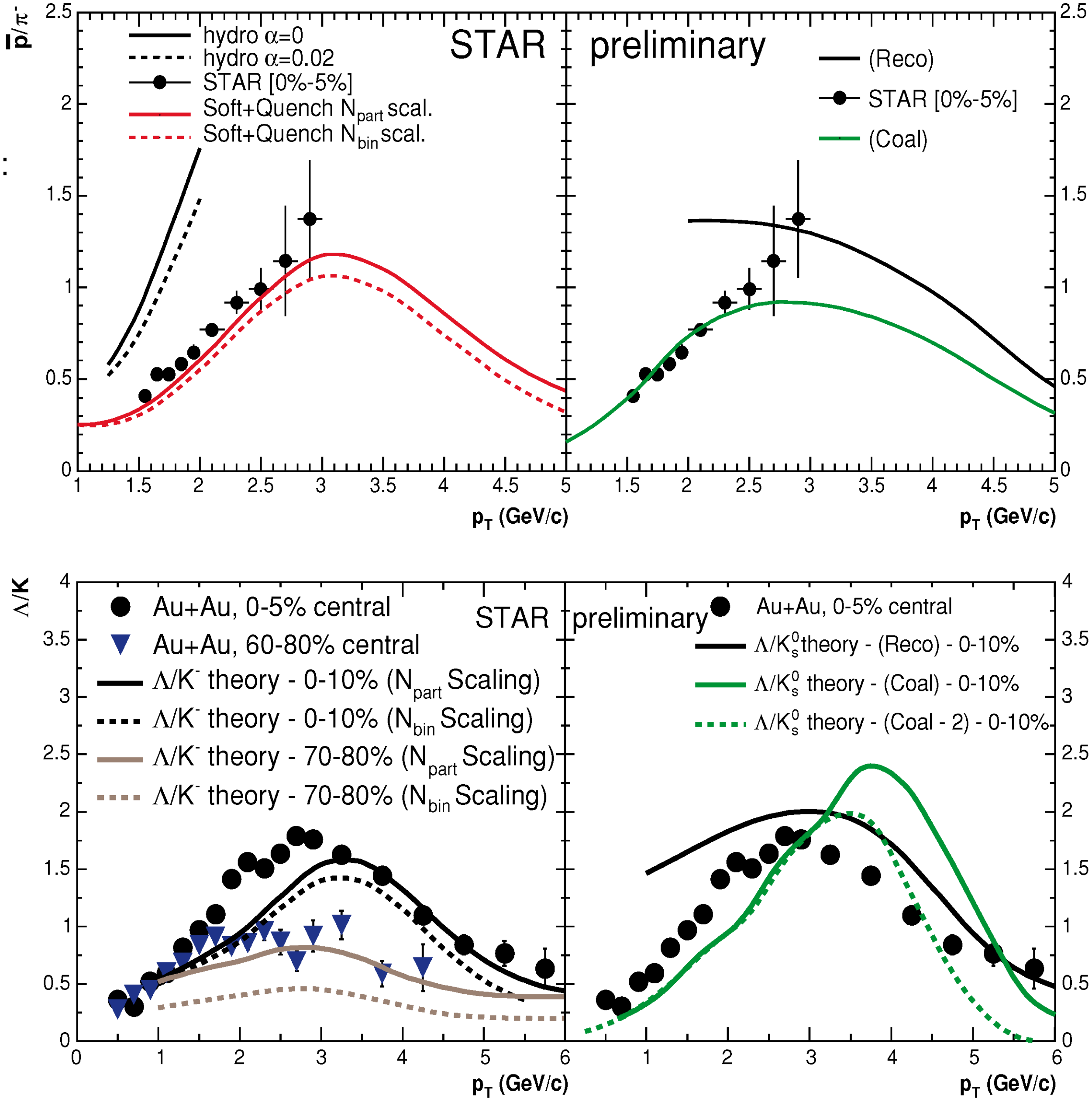


Topological recontruction of the Λ decay

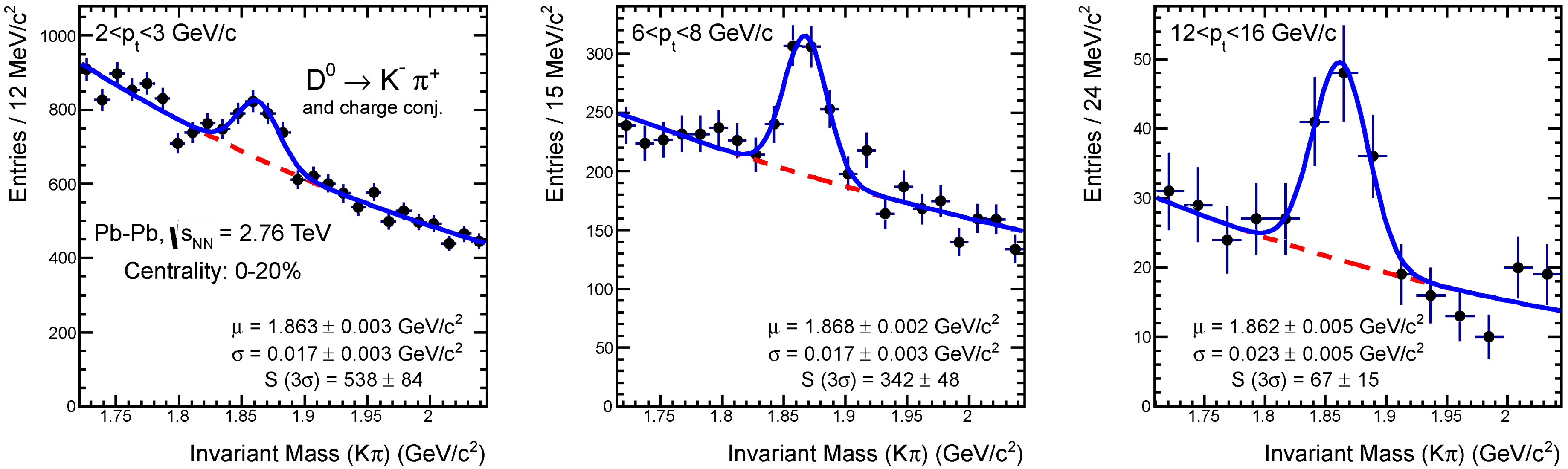


Recombination versus coalescence versus baryon junctions

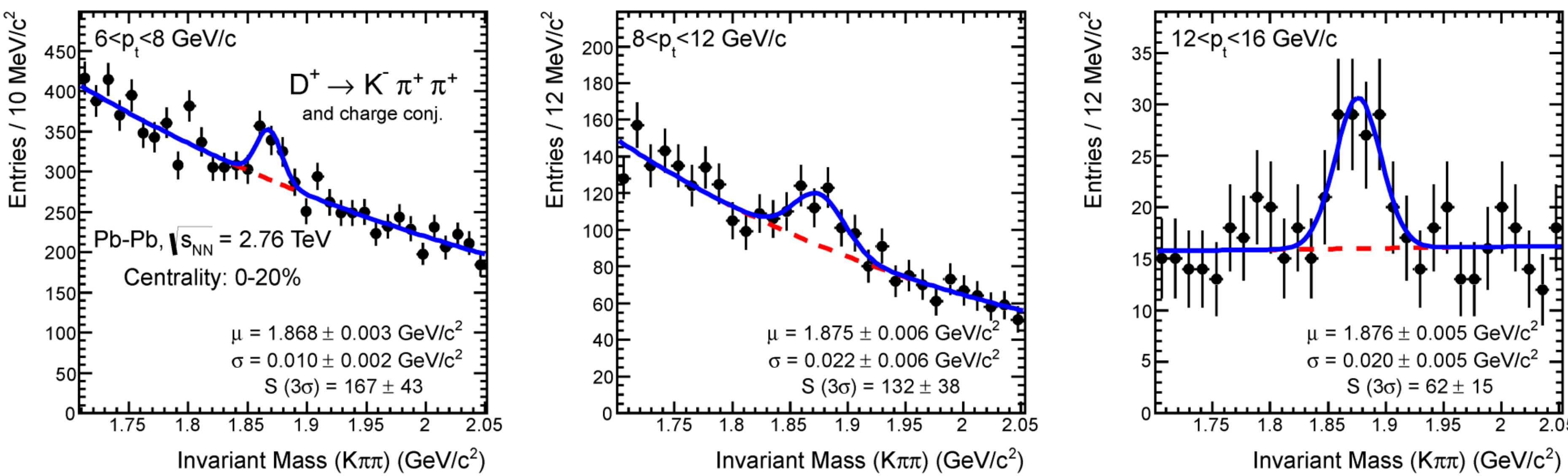
Baryon junctions:
Soft + Quench



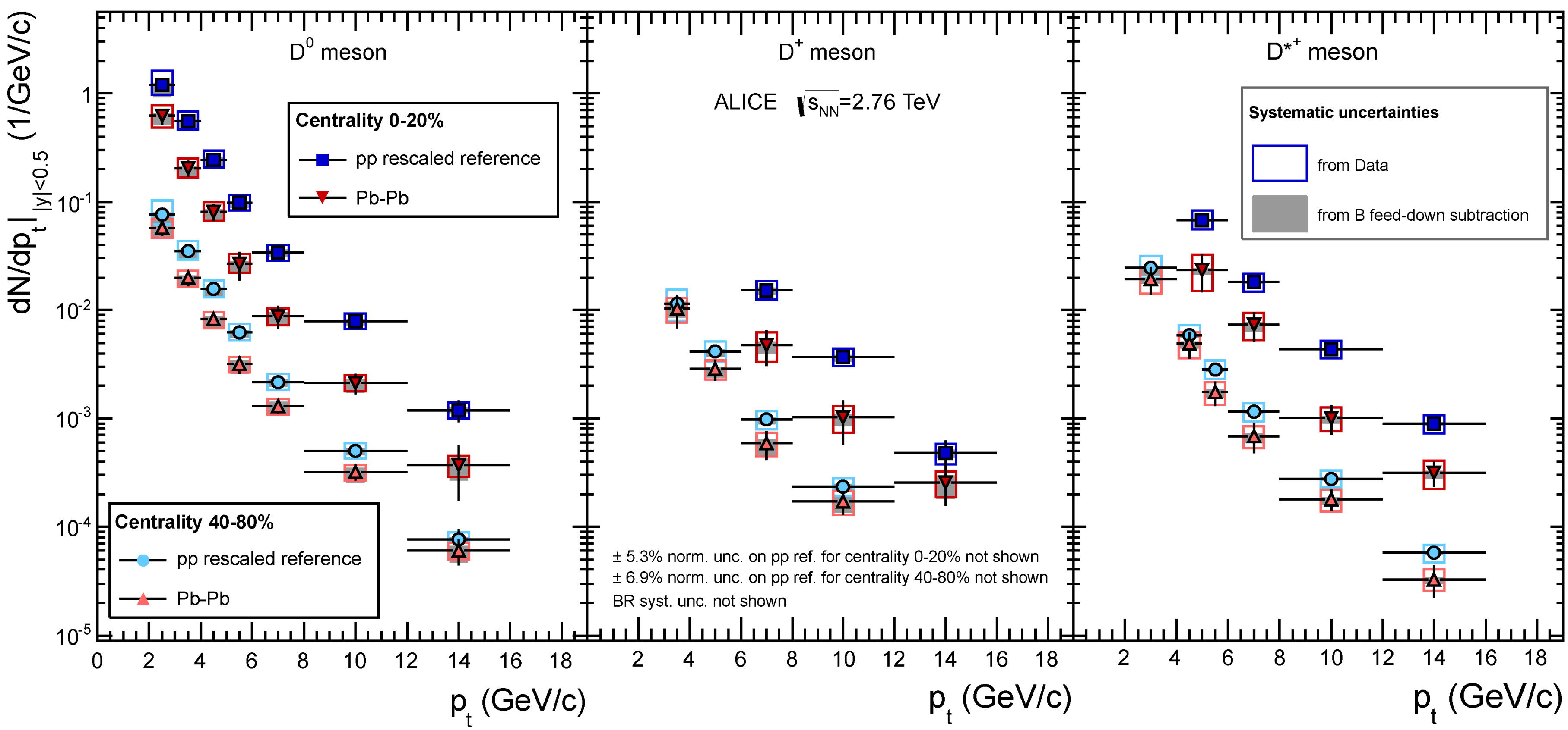
P_T dependence of D^0 and D^+ invariant mass distributions in PbPb at 2.76 TeV



ALICE Collaboration: arXiv:1203.2160v1 [nucl-ex]



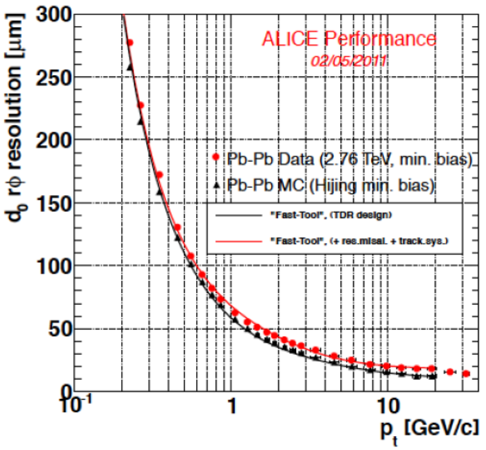
Transverse momentum spectra of D^0, D^*, D^{*+} in PbPb collisions at 2.76 TeV



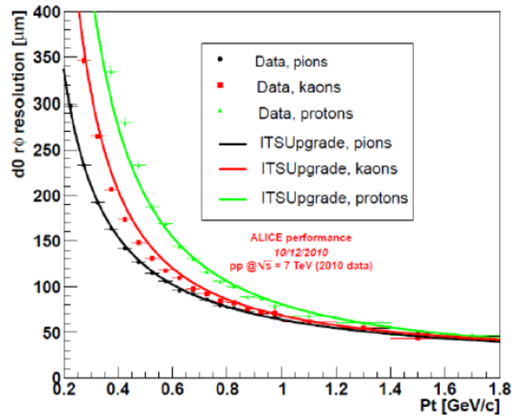
ALICE Collaboration: arXiv:1203.2160v1 [nucl-ex]

Simulation validation

Fast Estimation Tool

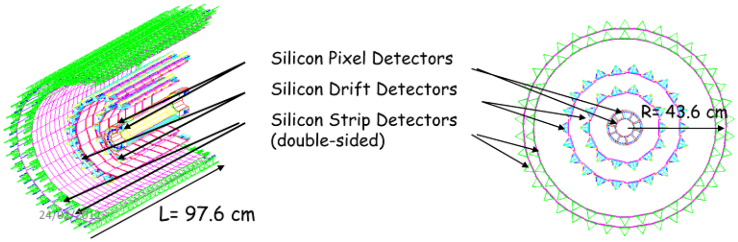


Full Monte Carlo simulation



Present Inner Tracking System (ITS)

Layer	Technology	R (cm)	±z (cm)	Spatial resolution (µm) rϕ	Spatial resolution (µm) z	Material budget X/X_0 (%)	
1	Pixel	4.0	14.1	12	100	1.14	Provide Level 0 trigger (latency < 800 ns)
2	Pixel	7.2	14.1	12	100	1.14	
3	Drift	15.0	22.2	38	28	1.13	
4	Drift	23.9	29.7	38	28	1.26	Provide dE/dx for the particle identification
5	Strip	38.5	43.2	20	830	0.83	
6	Strip	43.6	48.9	20	830	0.83	



Simulation tools

- **Fast Estimation Tool** (FET): "Toy-Model" originally developed by the STAR HFT collaboration which allows to build a simple detector model.
- **Fast MC Tool** : Extension of the FET -> allows to disentangle the performance of the layout from the efficiency of the specific track finding algorithm
- **Full Monte Carlo** : Transport code (geant3) designed to be flexible : the detector segmentation, the number of layers, their radii and material budgets can be set as external parameters of the simulation.

Two basic ITS upgrade scenarios

Layer / Type	R [cm]	±z [cm]	Intrinsic resolution [µm] rϕ	Intrinsic resolution [µm] z	Material budget X/X_0 [%]
Beam pipe	2.0	-	-	-	0.22
1 / pixel	2.2	11.2	4	4	0.3
2 / pixel	2.8	12.1	4	4	0.3
3 / pixel	3.6	13.4	4	4	0.3
4 / pixel (strips)	20.0	39.0	4 (20)	4 (830)	0.3 (0.83)
5 / pixel (strips)	22.0	41.8	4 (20)	4 (830)	0.3 (0.83)
6 / pixel (strips)	41.0	71.2	4 (20)	4 (830)	0.3 (0.83)
7 / pixel (strips)	43.0	74.3	4 (20)	4 (830)	0.3 (0.83)