Upgrade of the ALICE Inner Tracking System

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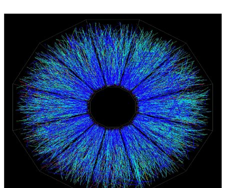
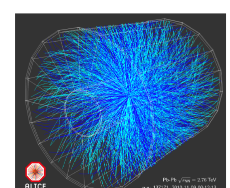


Workshop on QCD Thermodynamics
in High-Energy Collisions
July 27 - 31, 2015
College of Physical Science and Technology
Central China Normal University (CCNU), Wuhan, China

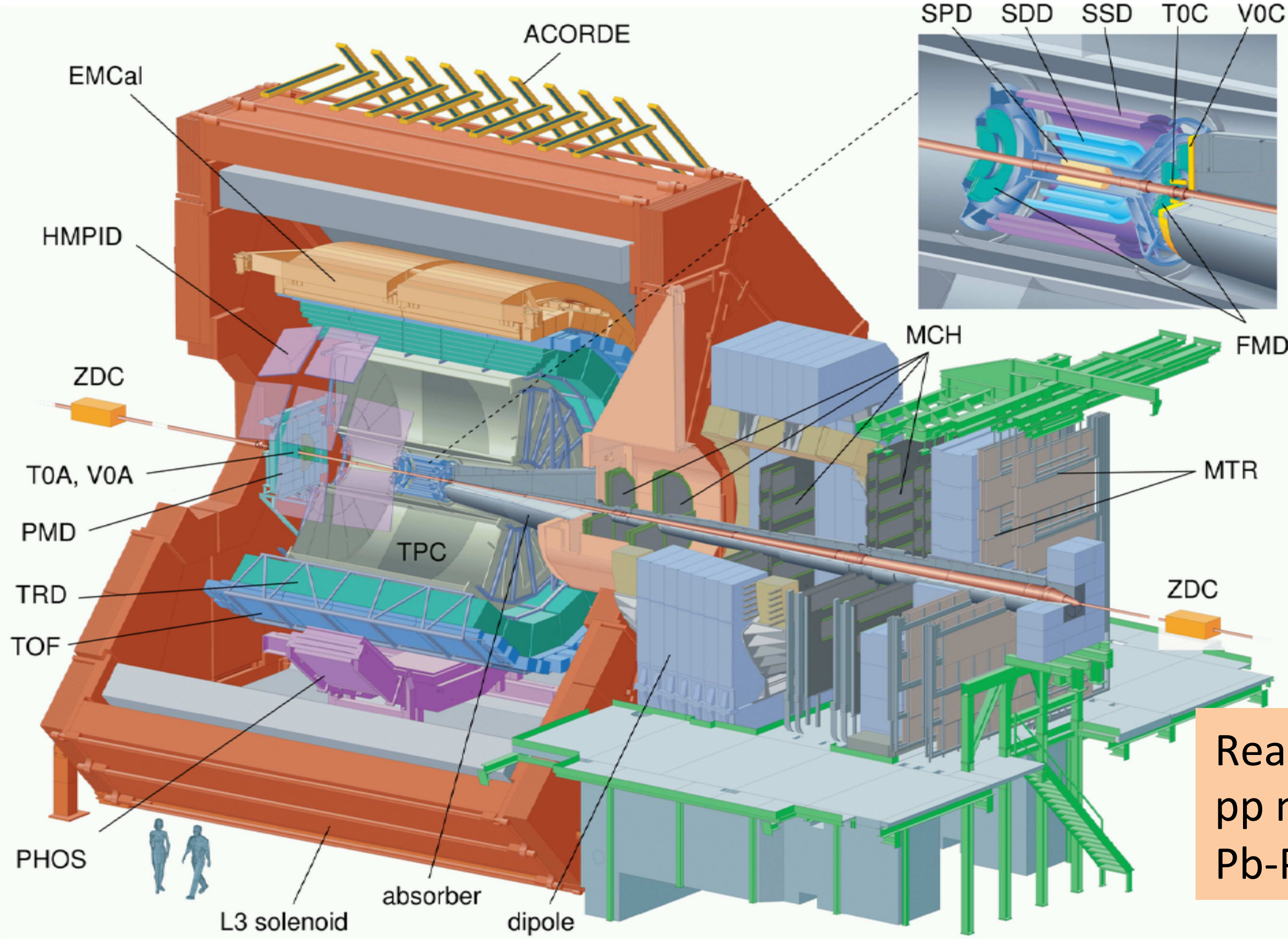


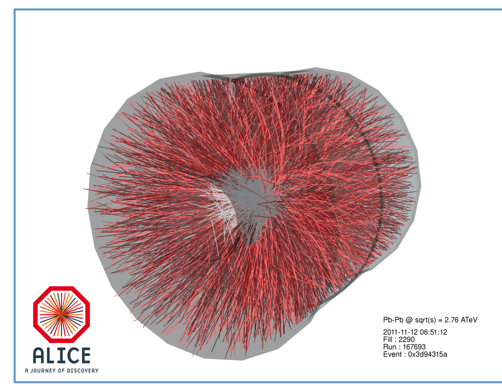
Outline

- ALICE current set-up and Inner Tracking System (ITS)
- ALICE upgrade motivation and objectives
- ITS upgrade layout and main components
- Detector simulated performance (examples)
- CCNU Plan on the ALICE ITS Upgrade

The Current ALICE Detectors

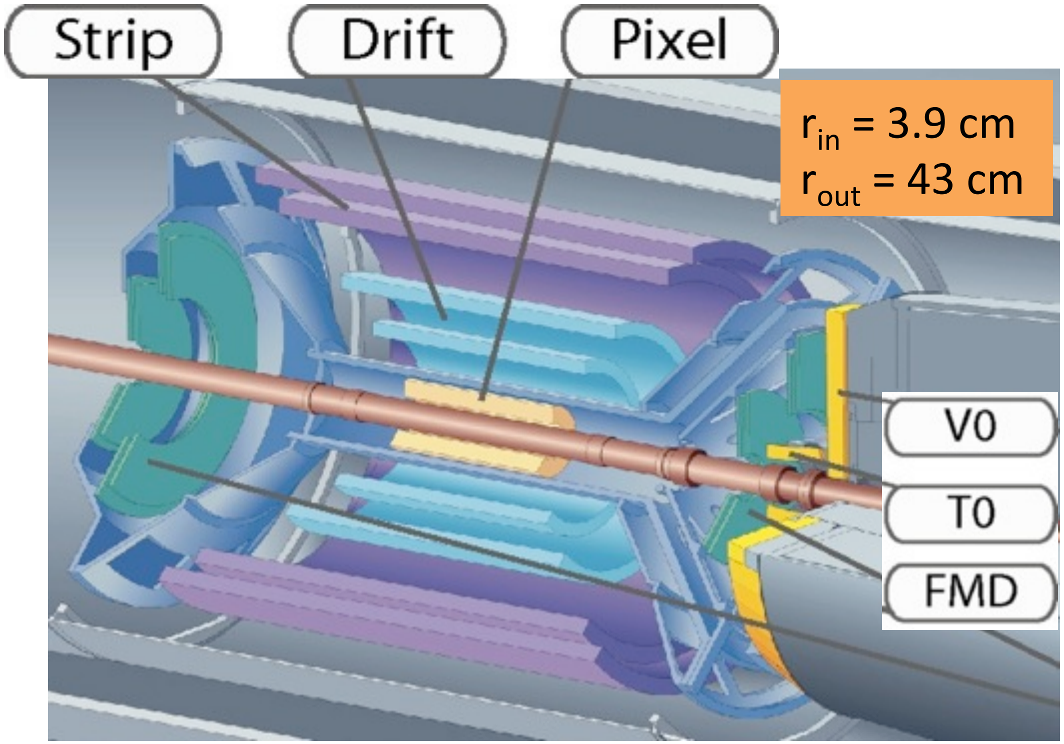
ALICE (A Large Ion Collider Experiment) is designed to study the physics of strongly interacting matter, and in particular the properties of the Quark-Gluon Plasma (QGP), using proton-proton, proton-nucleus and nucleus-nucleus collisions at the CERN LHC.

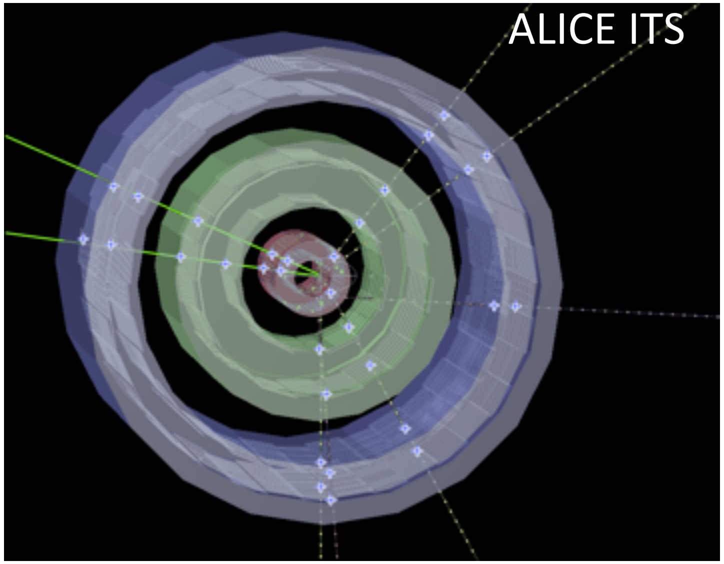


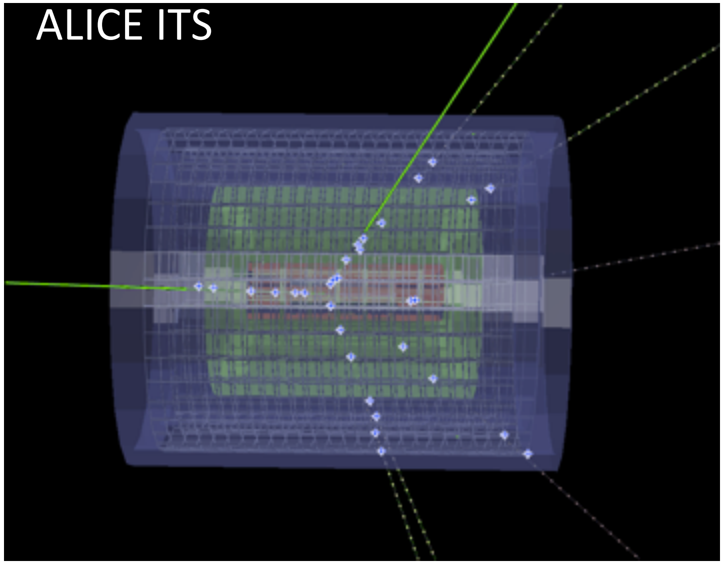


Readout rate:
pp minimum bias: ~ 1k Hz
Pb-Pb minimum bias: ~ 500 Hz

The Current ALICE Inner Tracking System







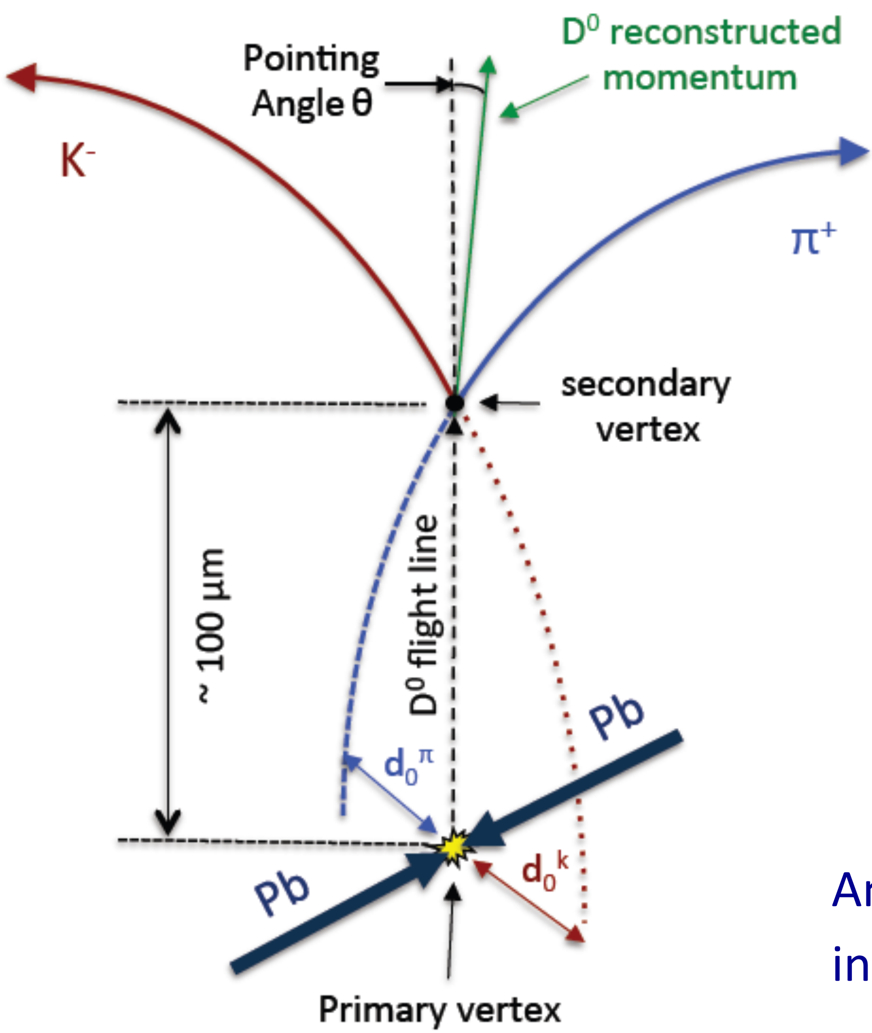
The Current ITS:

6 concentric barrels, 3 different technologies

- 2 layers of silicon pixel (SPD)
- 2 layers of silicon drift (SDD)
- 2 layers of silicon strips (SSD)

The Current ITS – Secondary Vertex Determination

Example: D^0 meson



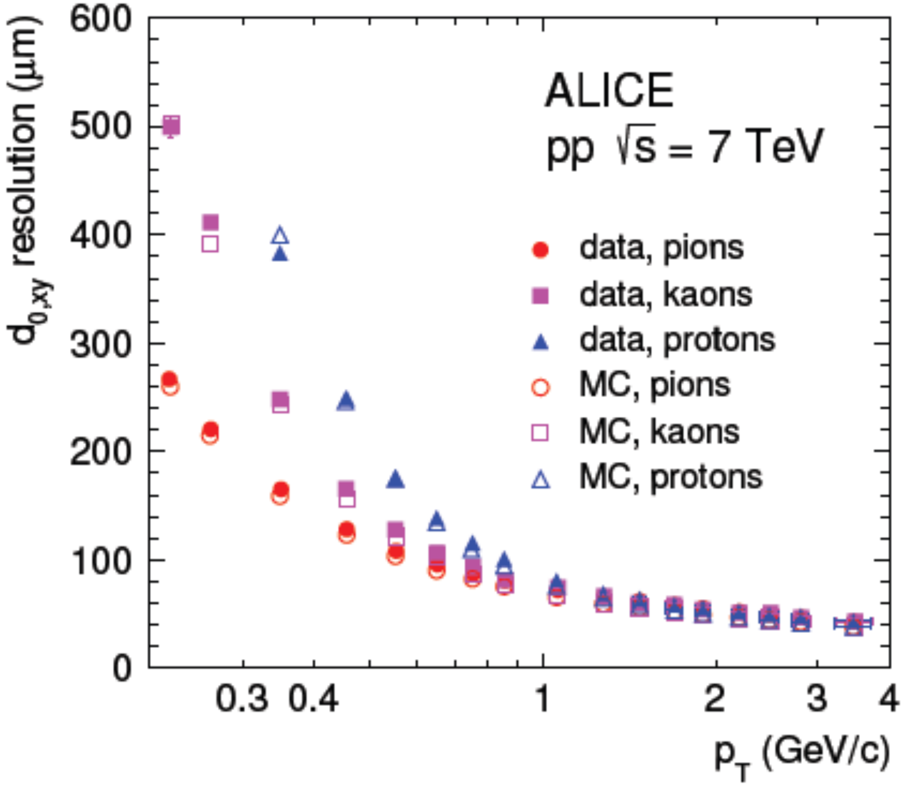
Open charm

Particle	Decay Channel	cτ (µm)
D^0	$K^- \pi^+$ (3.8%)	123
D^+	$K^- \pi^+ \pi^+$ (9.5%)	312
D_s^+	$K^+ K^- \pi^+$ (5.2%)	150
Λ_c^+	$p K^- \pi^+$ (5.0%)	60

Analysis based on decay topology and invariant mass technique

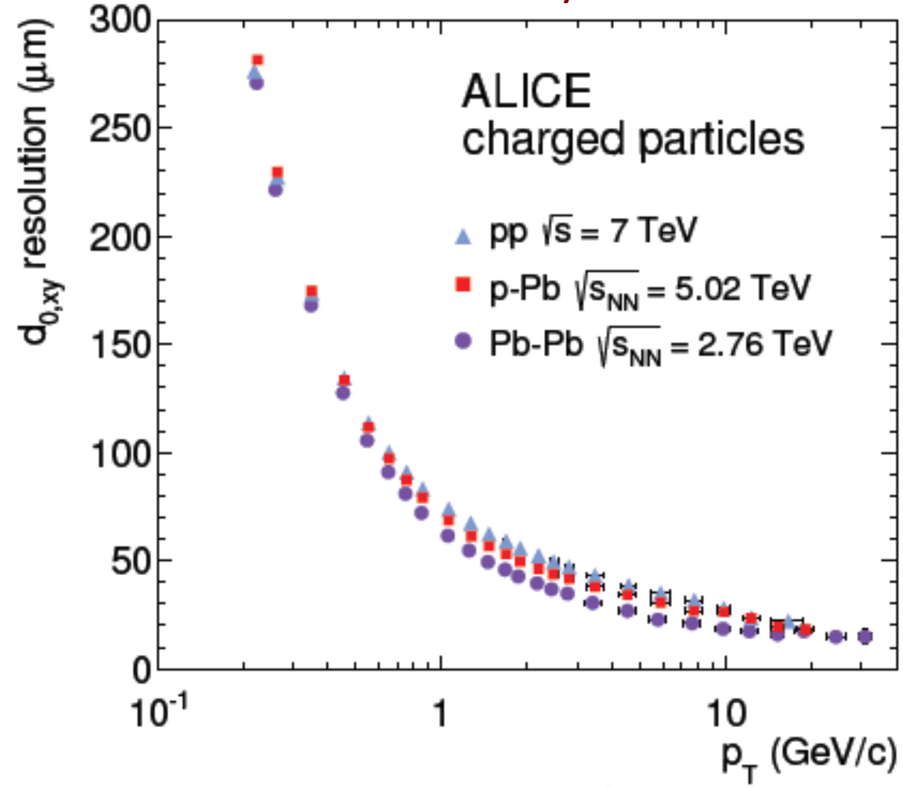
The Current ITS – Impact Parameter Resolution

Very good MC description



ALICE, Int. J. Mod. Phys. A29 (2014) 1430044

Very weak dependence on collision system



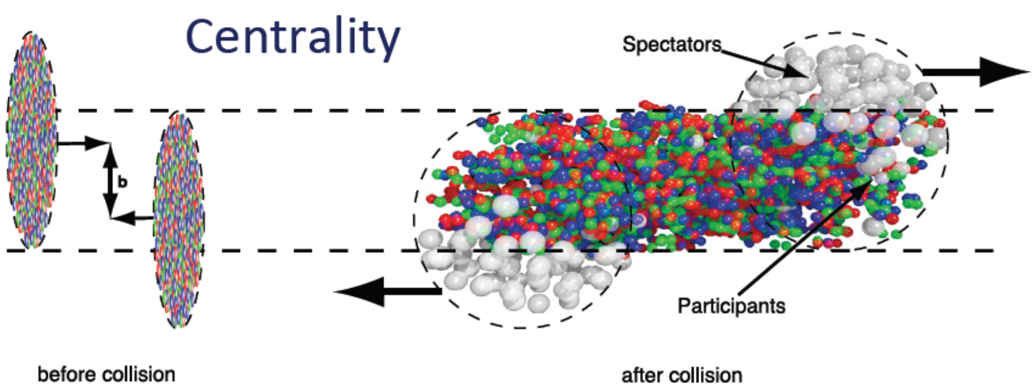
ALICE, Int. J. Mod. Phys. A29 (2014) 1430044

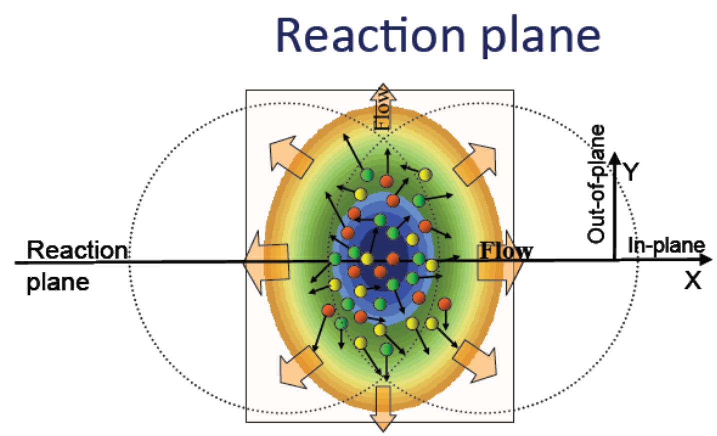
70 μm at p_T = 1 GeV/c

ALICE Upgrade Motivation

Characterize of QGP properties require:

- ✧ precision measurements of rare probes
- ✧ over a large kinematic range (from high to very low transverse momenta)
- ✧ as a function of multi-differential observables: centrality, reaction plane, …





Precision measurements of spectra, correlations and flow of heavy flavour hadrons and quarkonia at low transverse momenta (not possible to trigger!!)

ALICE Upgrade Strategy

These require statistics and precision measurements:

Target for upgrade programme (Run3 + Run4)

- Pb-Pb recorded luminosity $\geq 10\ nb^{-1} \rightarrow 8\times10^{10}$ events
- pp@5.5 TeV recorded luminosity $\geq 6\ pb^{-1} \rightarrow 1.4\times10^{11}$ events

1. Upgrade detectors, readout systems and online systems
   - Read out all Pb-Pb interactions at a maximum rate of 50 kHz (i.e. $L=6\times10^{27}\ cm^{-2}s^{-1}$), with a minimum bias trigger (at present 500 Hz)

   Gain a factor of 100 in statistics over originally approved programme (Run1 + Run2)

2. Significant improvement of vertexing and tracking capabilities at low p_T
   - New Inner tracking system (ITS, Muon Forward Tracker)

   It targets LHC 2nd Long shutdown (2018/19)

The ITS Upgrade Design Objectives

1. Improve impact parameter resolution by a factor of ~3

- Get closer to IP (position of first layer): 39mm ➡ 22mm
- Reduce x/X_0 /layer: ~1.14% ➡ ~ 0.3% (for inner layers)
- Reduce pixel size: currently 50μm x 425μm ➡ 28μm x 28μm

2. Improve tracking efficiency and p_T resolution at low p_T

- Increase granularity:
  - 6 layers ➡ 7 layers
  - silicon drift and strips ➡ pixels

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3. Fast readout

- readout Pb-Pb interactions at > 50 kHz and pp interactions at ~ 2 x 10^5 Hz (currently limited at 1kHz with full ITS and ~3kHz without silicon drift)

4. Fast insertion/removal for yearly maintenance

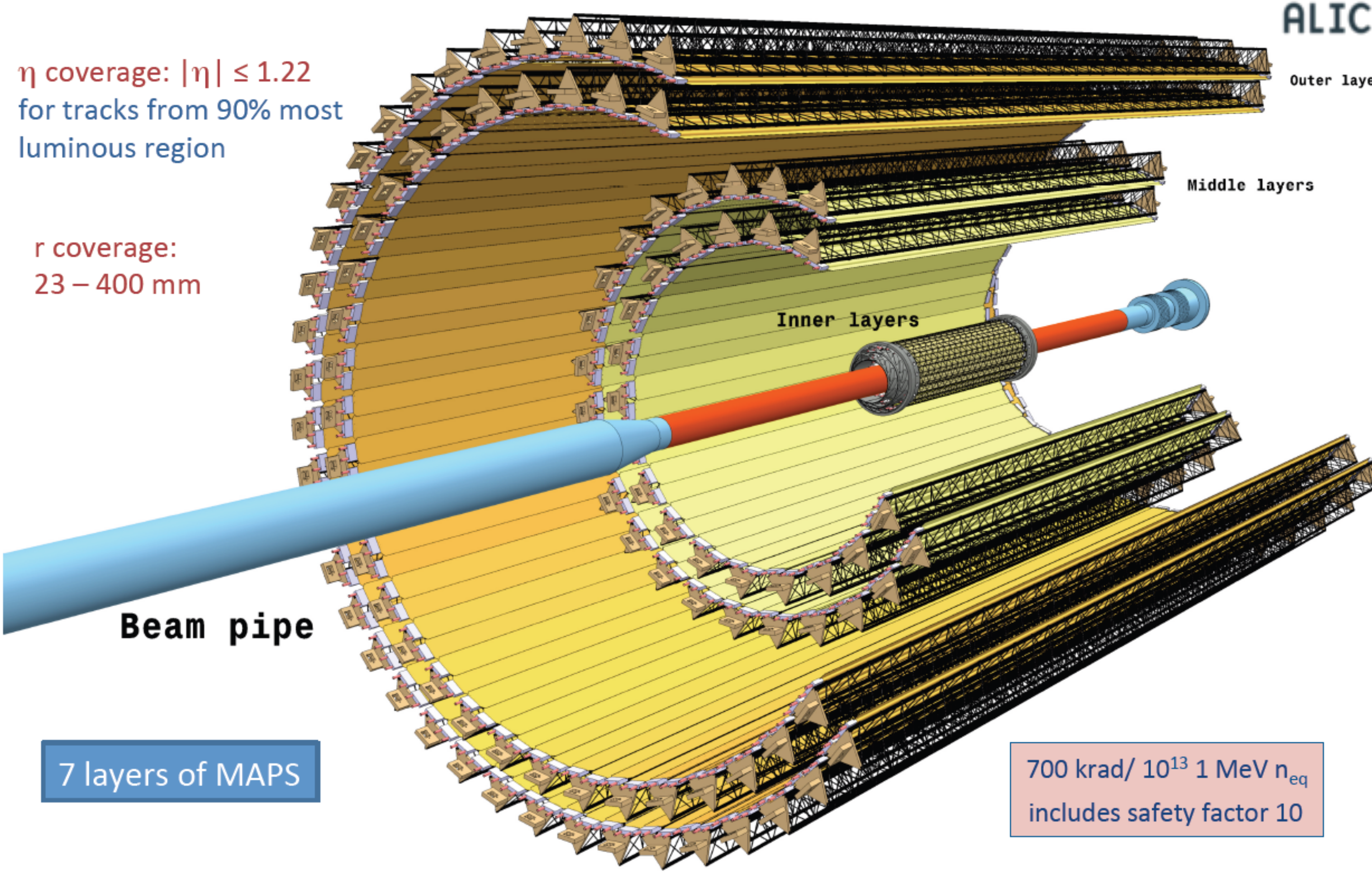
- possibility to replace non functioning detector modules during yearly shutdown

Install detector during LHCC LS2 (2018-19)

The New ITS Layout

η coverage: $|\eta| \leq 1.22$
for tracks from 90% most luminous region

r coverage:
23 – 400 mm

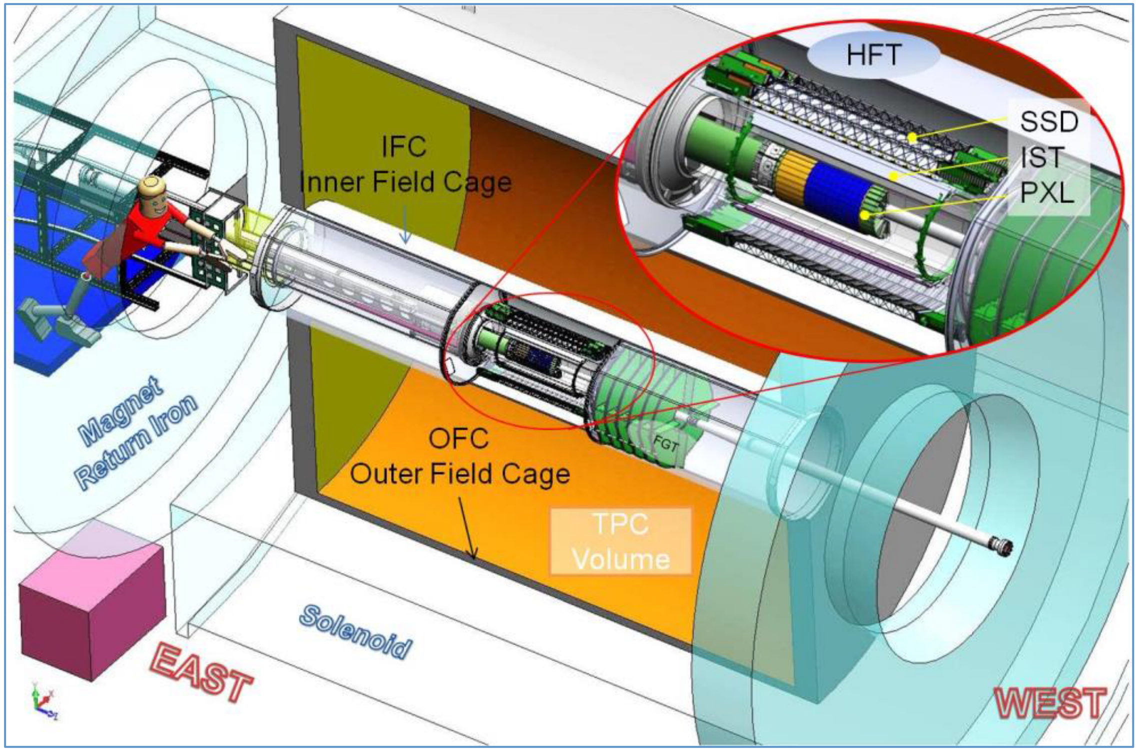


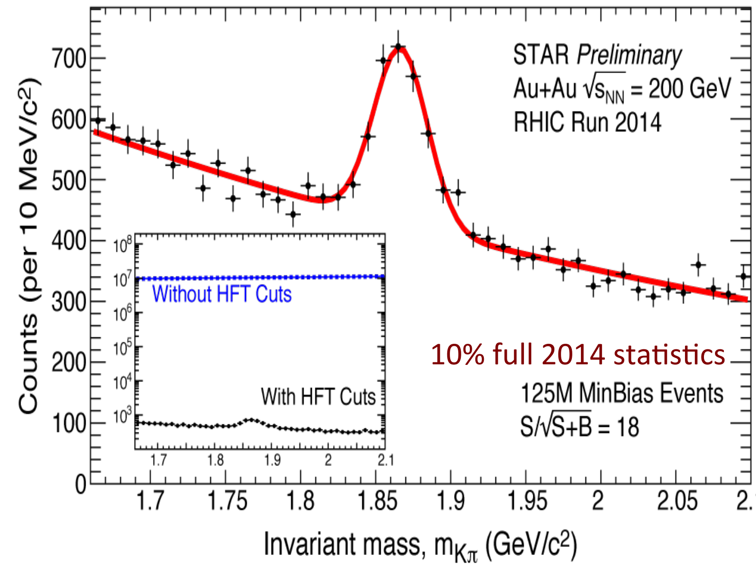
7 layers of MAPS

700 krad/ 10^{13} 1 MeV n_{eq}
includes safety factor 10

*MAPS: Monolithic Active Pixel Sensor

The MAPS Technology Application in STAR





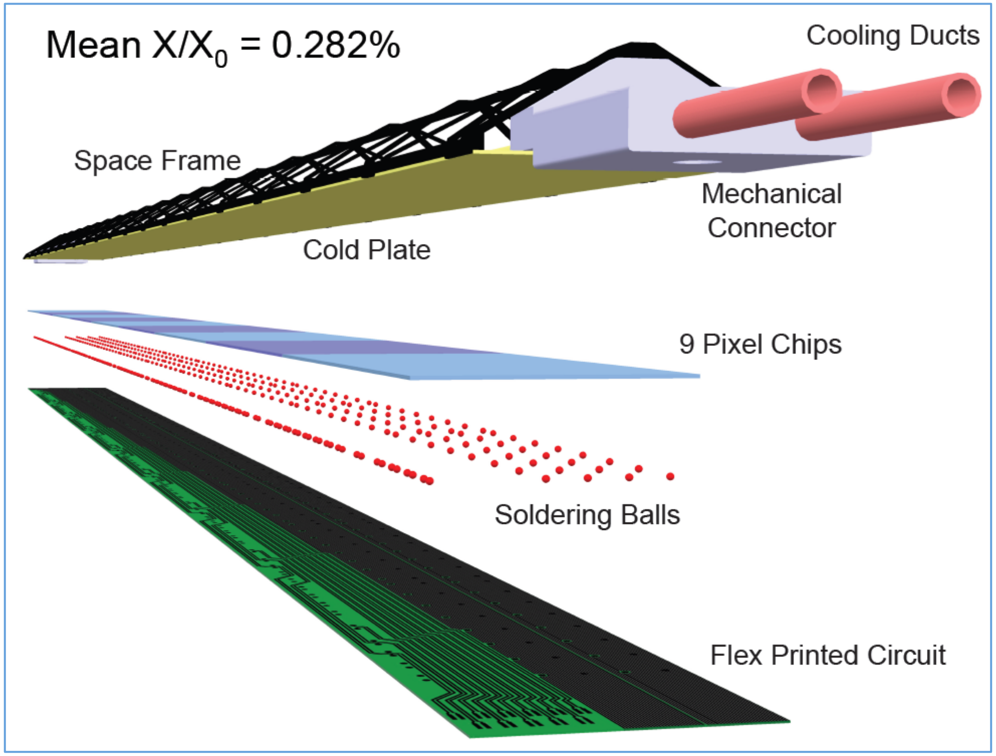
PIXEL

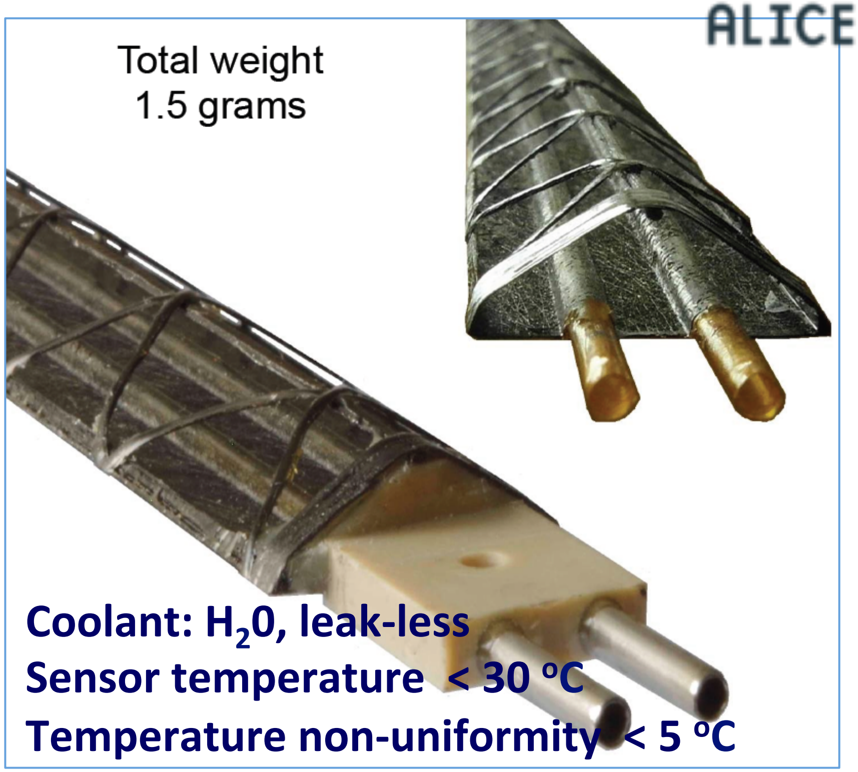
- 2 layers of thin MAPS, 18.4x18.4 μm pixel pitch
- Integration time ~ 180 μs
- Provide ultimate pointing resolution that allows for direct topological identification of charm

Track inward from TPC with graded resolution:

TPC → (~1 mm) → SSD → (~300 μm) → IST → (~250 μm) → PXL → (< 30 μm) → Vertex

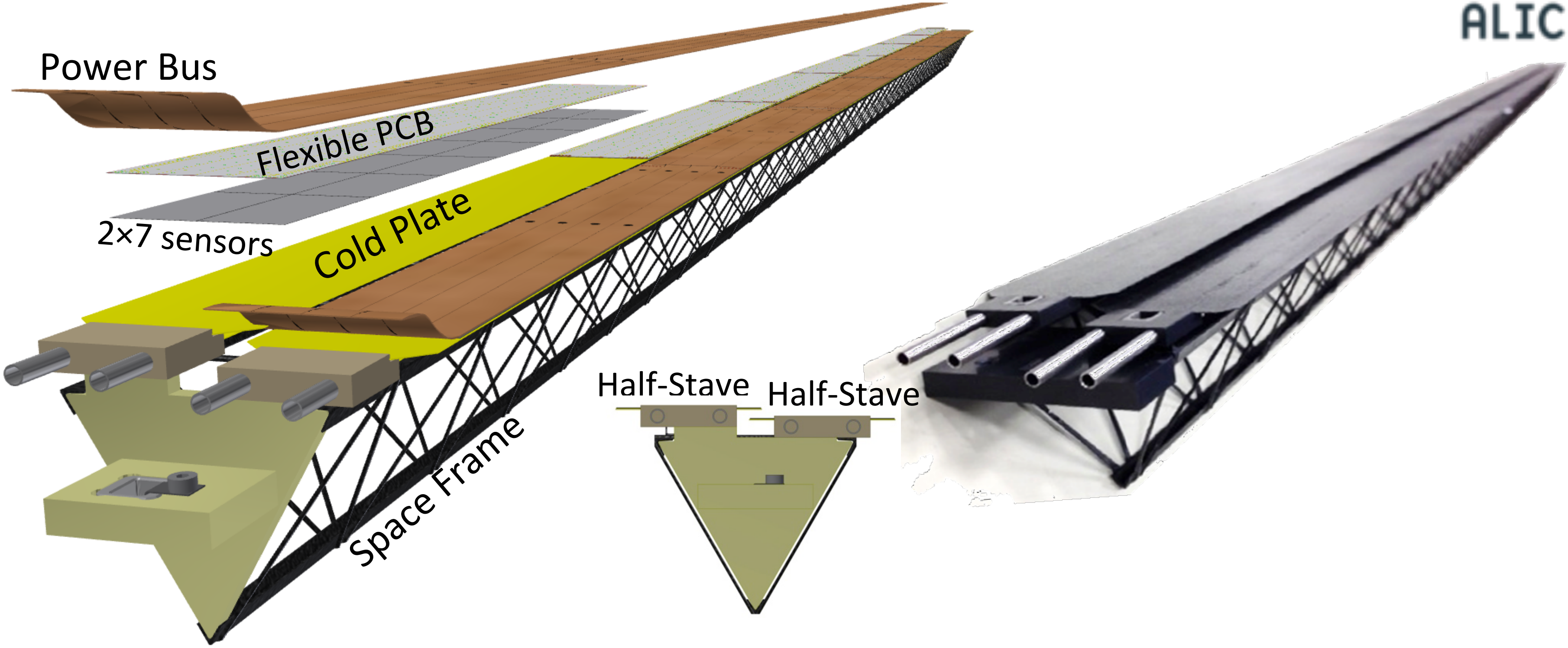
The New ITS Layout – Inner Barrel





<Radius> (mm): 23, 31, 39	Length in z (mm): 270
Nr. Of staves: 12, 16, 20	Nr. Of chips/stave: 9
Nr. Of chips/layer: 108, 144, 180	Material thickness: ~0.3% X_0
Power density: < 100 mW/cm^2	Throughput (@100kHz): < 80 $Mb/s \times cm^{-2}$

The New ITS Layout – Outer Barrel



<Radius> (mm): 194, 247, 353, 405

Nr. Of staves: 24, 30, 42, 48

Nr. Of chips/layer: 6048 (ML), 17740 (OL)

Power density: < 100 mW/cm^2

Length in z (mm): 900 (ML), 1500 (OL)

Nr. Of modules/stave: 4 (ML), 7(OL)

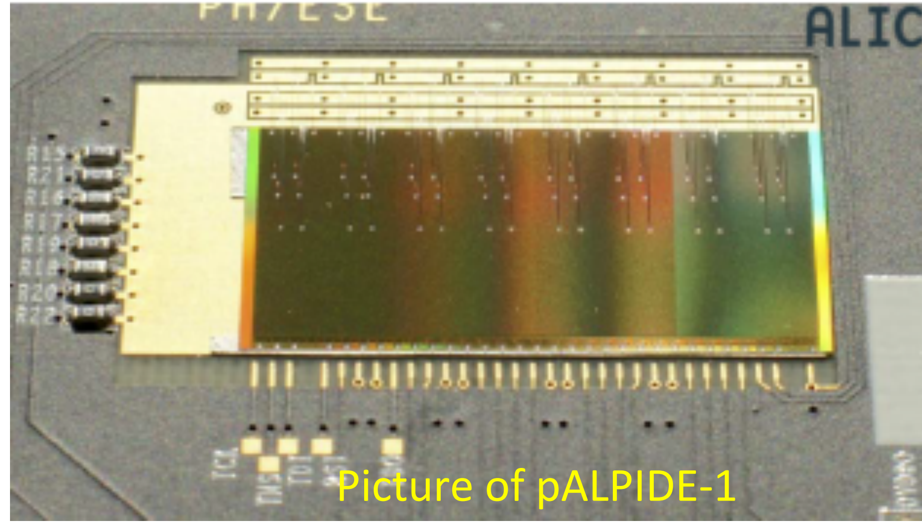
Material thickness: ~1% X_0

Throughput (@100kHz): < 3 Mb/s × cm^{-2}

The New ITS CMOS Pixel Sensor

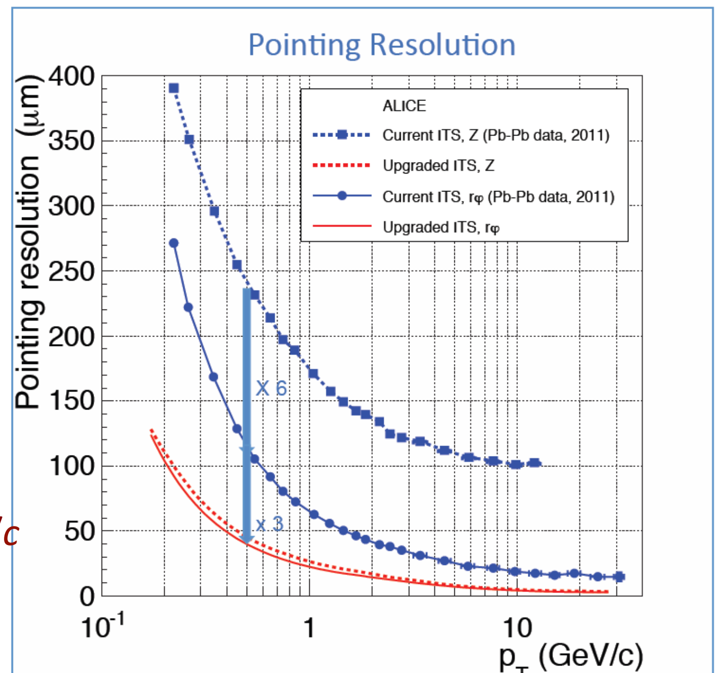
ALPIDE Full Scale prototype (MAPS):

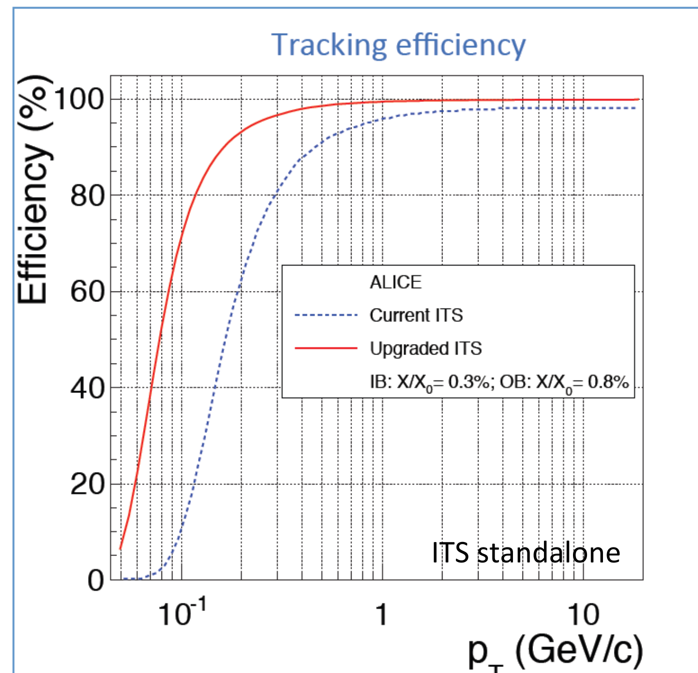
- Dimensions: 15 mm × 30 mm
- About 0.5M pixels: 28 µm × 28 µm
- 40 nW front-end (4.7 mW/cm^2)
- ~40 mW/cm^2 total
- Integration time: ~4 µs
- Peaking time (defines time res.): <2µs



MC simulations:

Pointing resolution: ~ 40 µm at p_T = 0.5 GeV/c





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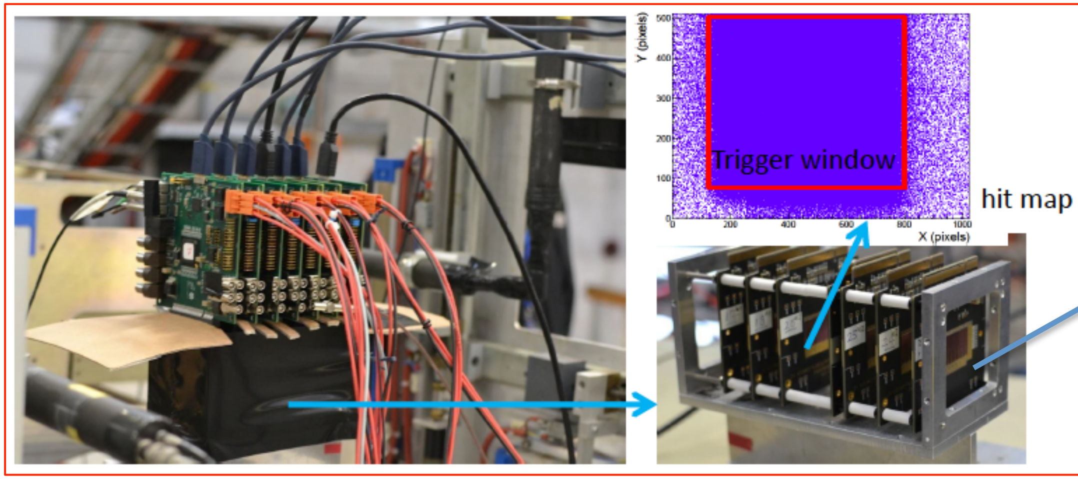
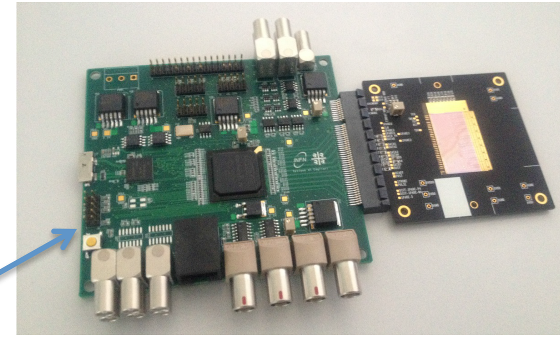
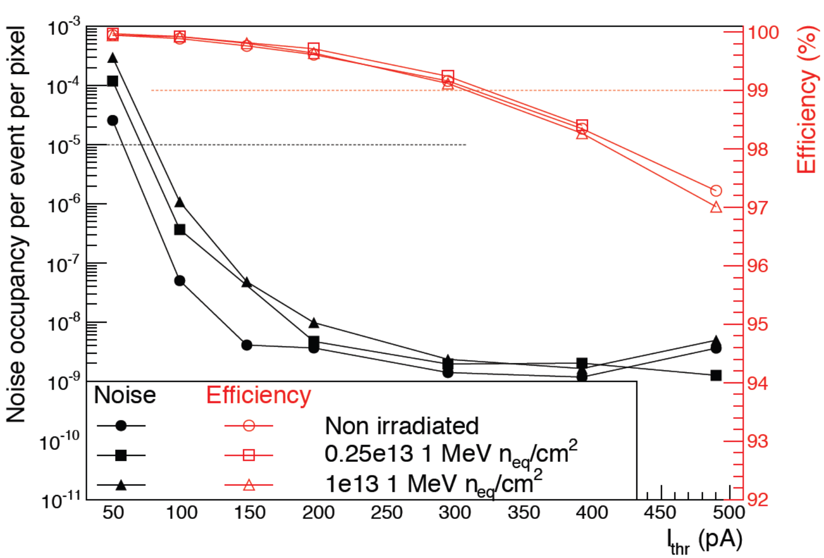
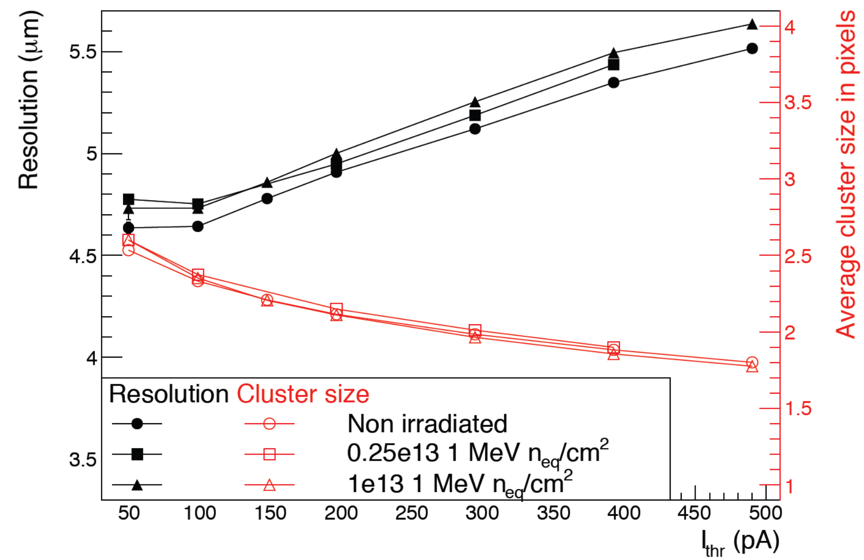
The New ITS CMOS Pixel Sensor





7-plane telescope based on pALPIDE-1 chip





$\lambda_{fake} << 10^{-5}$/event/pixel @ $\varepsilon_{det} > 99\%$

$\sigma_{det} < 5$ μm is achieved

★ Measurements at PS: 5-7 GeV π^- (refer to 50 μm thick chips, 10× load expected in 6 years)

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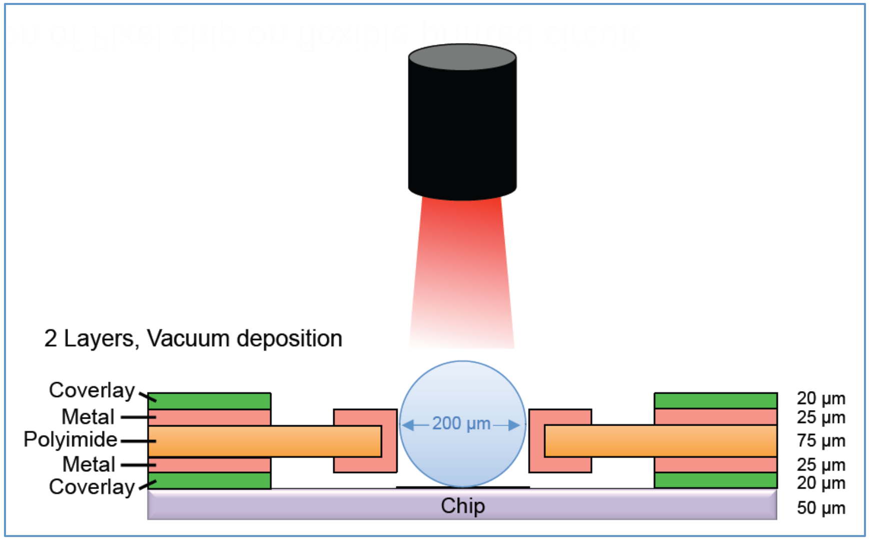
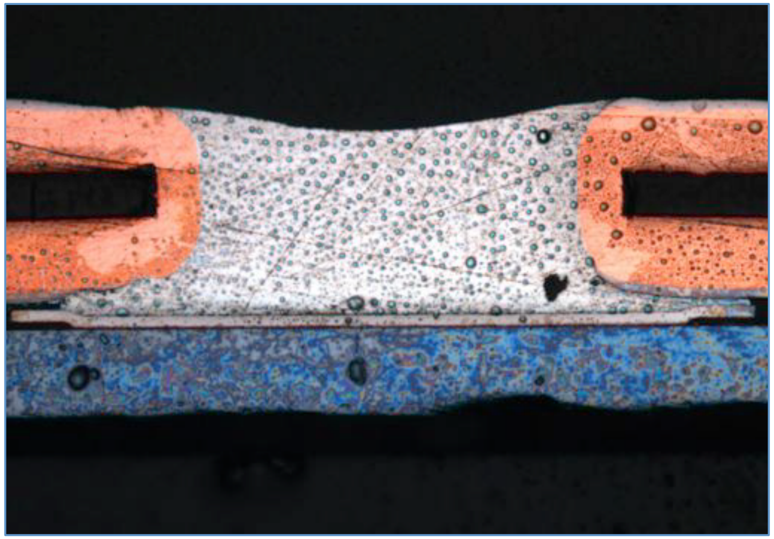
Interconnection of pixel chip to flex PCB

Interconnection of pixel chip on flexible printed circuit:

- Some redundancy in the quantity of modules to be produced is required, specifically 120% for the IB, 20% for the OB, resulting in a total 2136 modules; more specifically:
  - IB: n. 106 "*9-chips*" modules (954 chips to be soldered)
  - OB: n. 2030 "*14-chips*" modules (28420 chips to be soldered)
- Considering ~ 80 solder pads/chip → ~ 2.4 M interconnections
- A chip placement accuracy of ±5 μm is required.

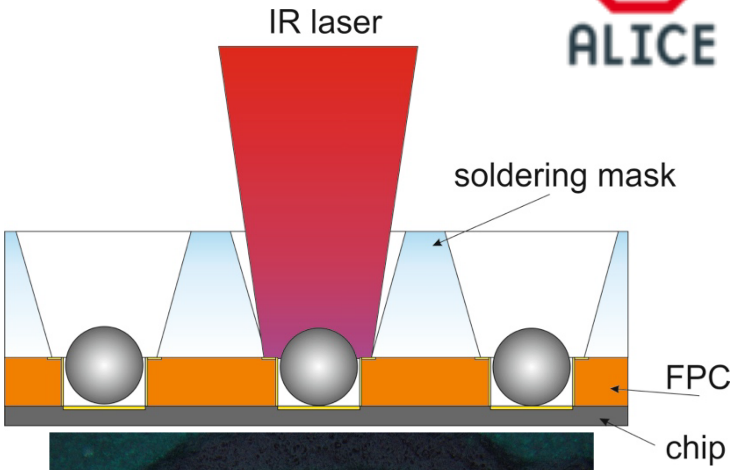


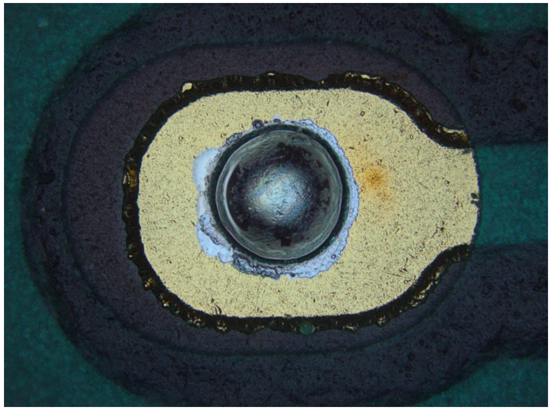


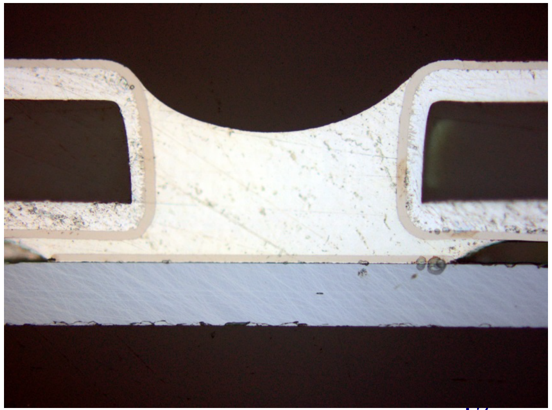
Interconnection of pixel chip to flex PCB

Laser Soldering:

- Flux-less soldering of 200 μm diameter Sn/Ag(96.5/3.5) balls (227 °C melting T) in vacuum (≤10^{-1} mbar)
- IR diode laser, 976 nm, 25 W, 50 mm focal length, 250 μm beam spot size
- Laser power modulated by pyrometer, programmable T profile ensures precise limitation of heating
- Soldering mask (in Macor® or Rubalit ®) used to press FPC on chip and guide soldering balls inside FPC vias
- Solder provides electrical and mechanical connection → no glue





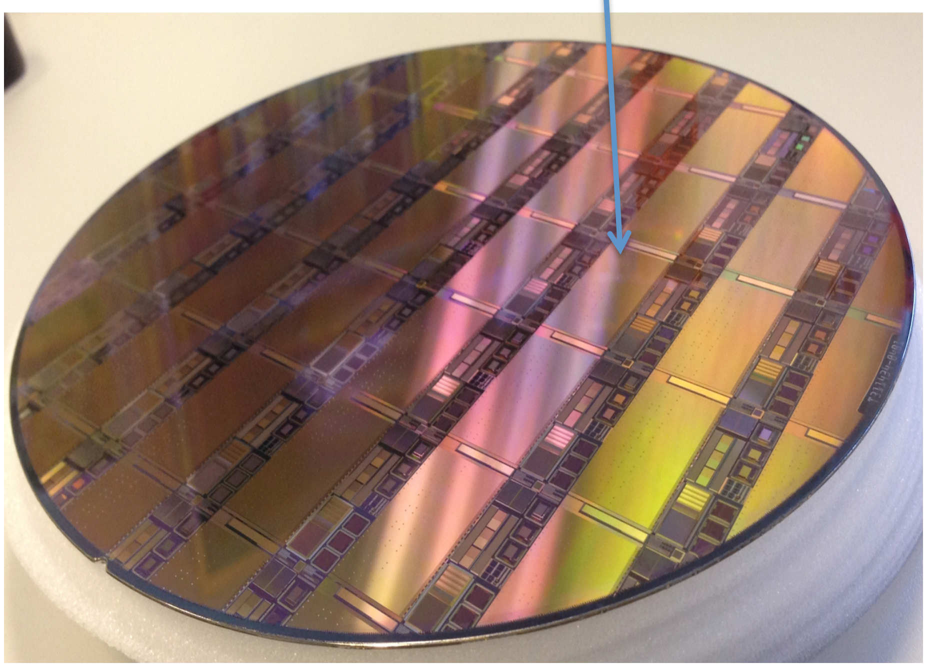


Interconnection of pixel chip to flex PCB

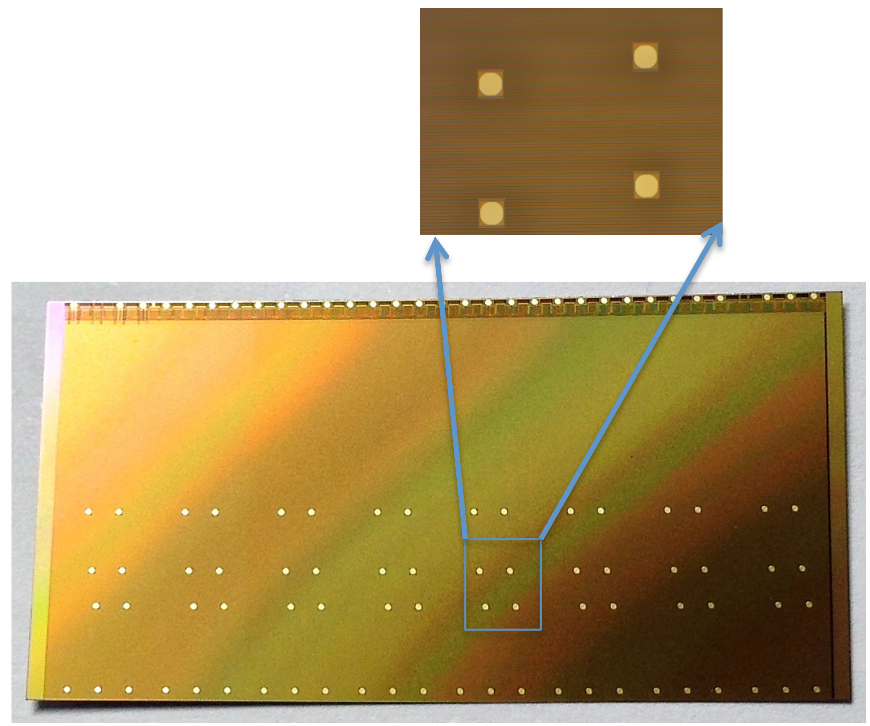
Laser Pads:

- In order to solder the chip on the flexible printed circuit (FPC), the chip Al pads need to be covered with Ni-Au (wet-able surface)
- Plating is done on wafers level using electroless Ni-Au plating, prior to thinning and dicing

ALPIDE-1 (~15×30 mm^2)

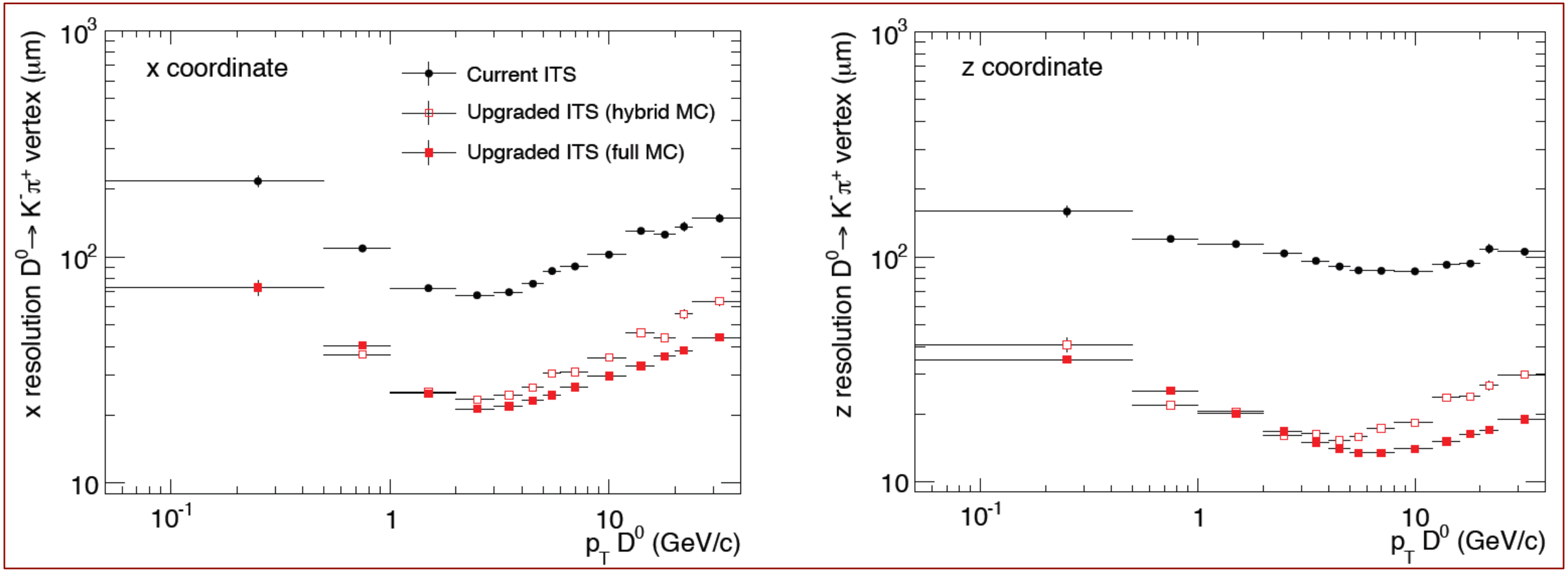


Ni-Au plated pads



Performance of the New ITS (MC simulation)

$D^0 \rightarrow k^-\pi^+$ secondary vertex position resolution:



- Pb+Pb events in the 0-10% centrality class at 5.5 TeV generated with HIJING, and enriched heavy flavor signals generated with PYTHIA 6.
- With the upgraded ITS, the resolution improves by a factor of about 3 for the x (and y) coordinates and about 6 for z.

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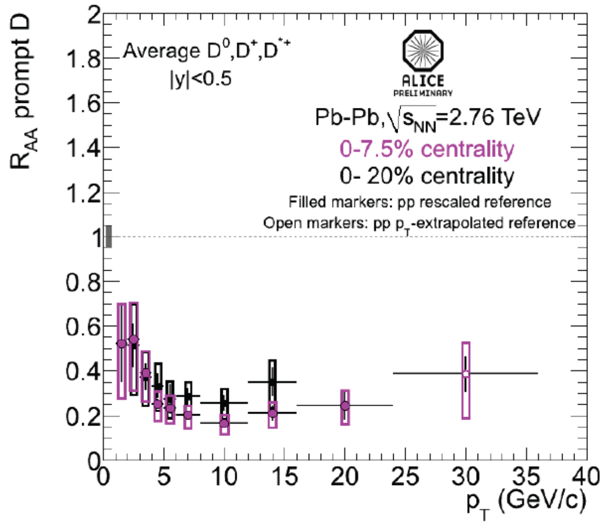
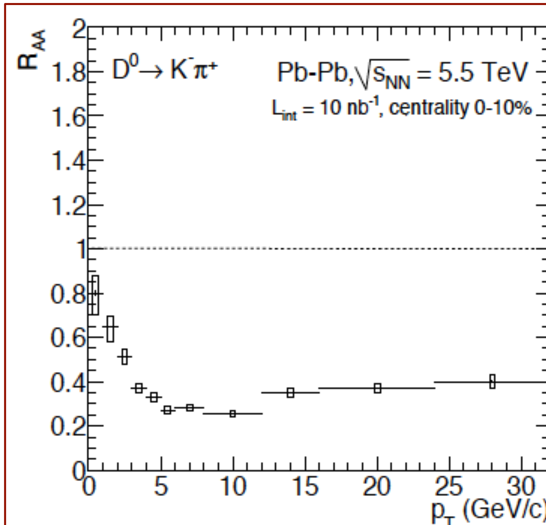
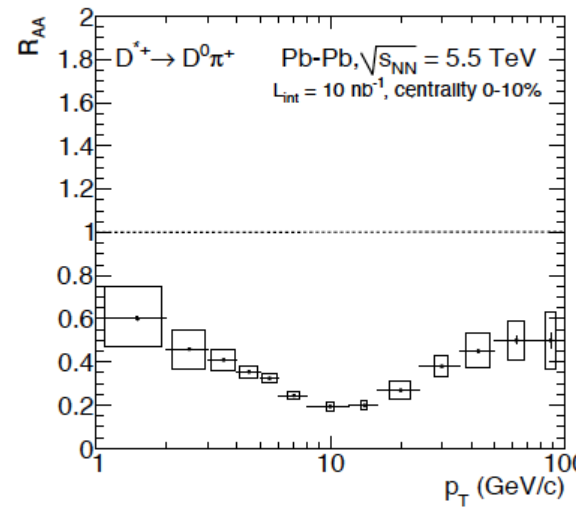
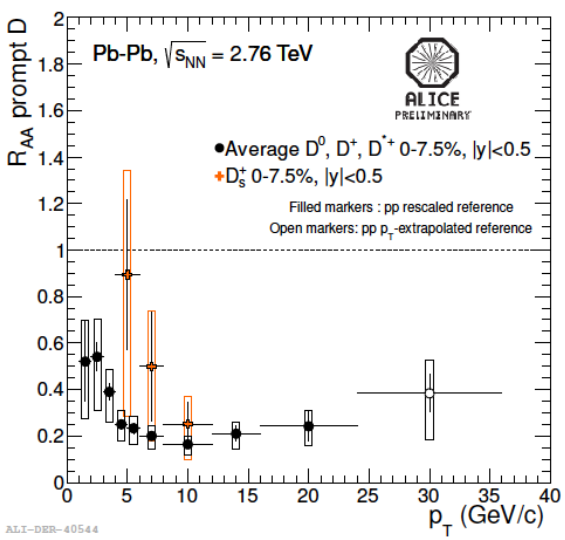
Performance of the New ITS (MC simulation)

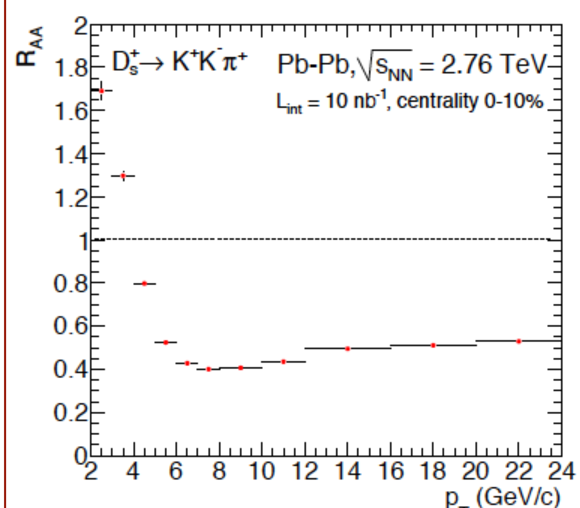
Charm nuclear modification factors:

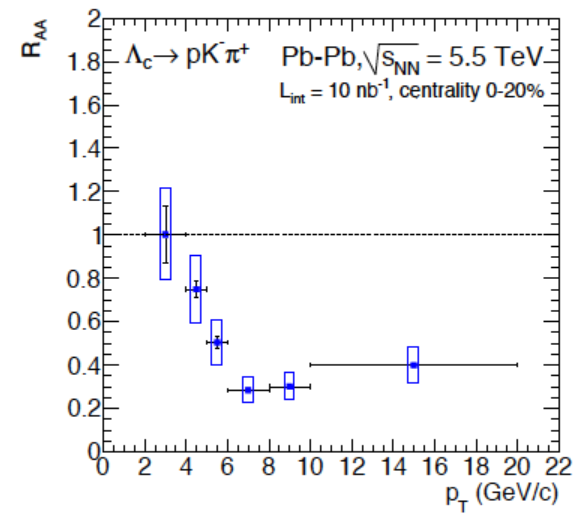












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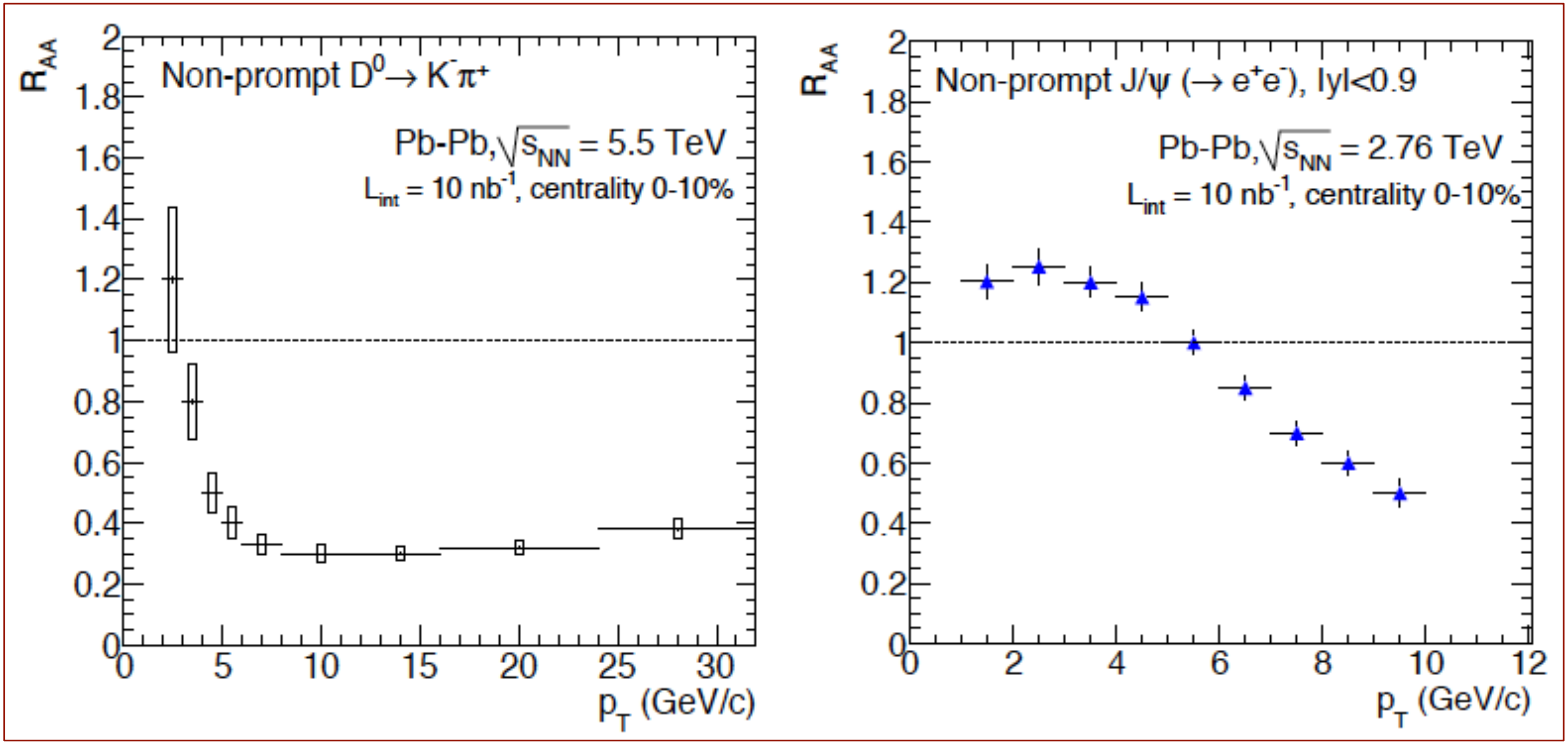
Performance of the New ITS (MC simulation)

Beauty nuclear modification factors:



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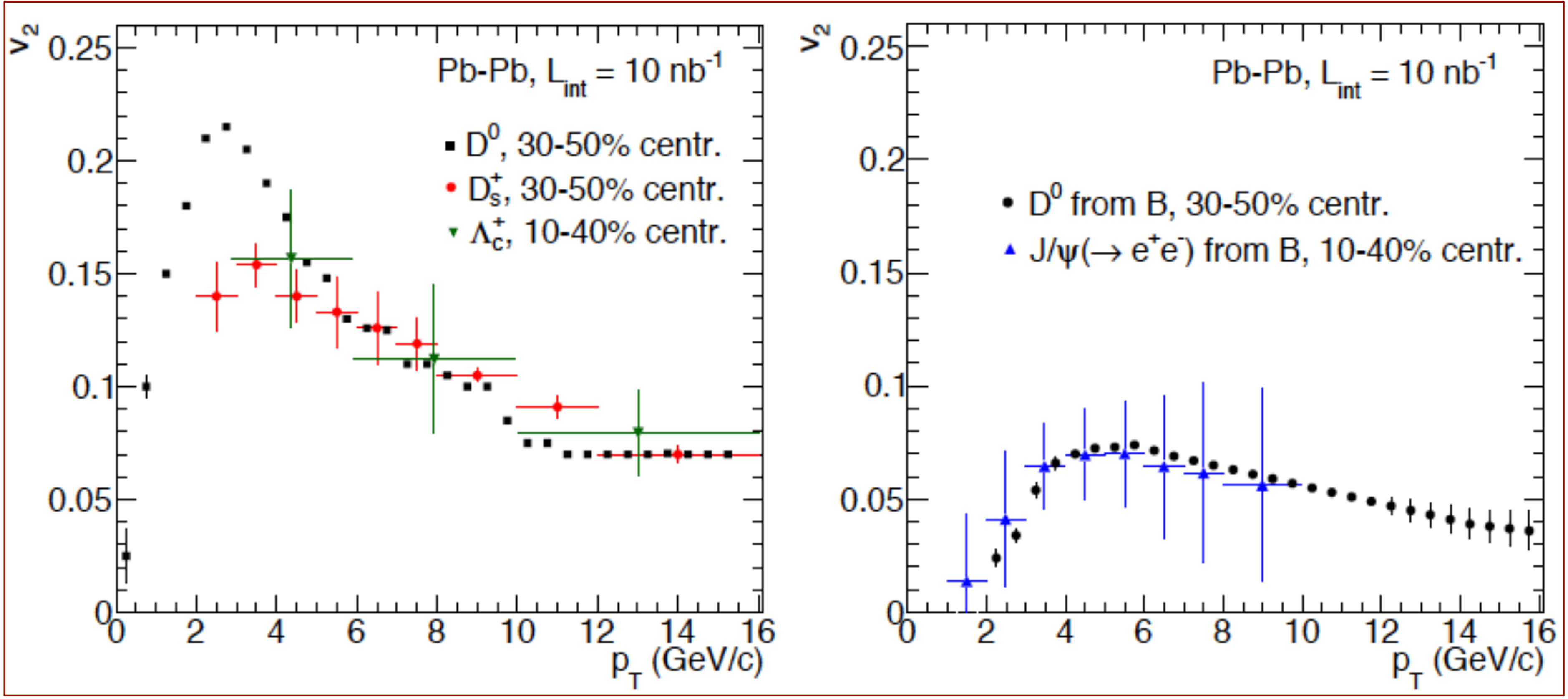
Performance of the New ITS (MC simulation)

Charm and beauty v_2:



- The v_2 result at RHIC points to a partonic degree of freedom in the initial state.

- The expected precision of measurement of v_2 with the upgraded ITS. The systematic uncertainties can be expected to be rather small.

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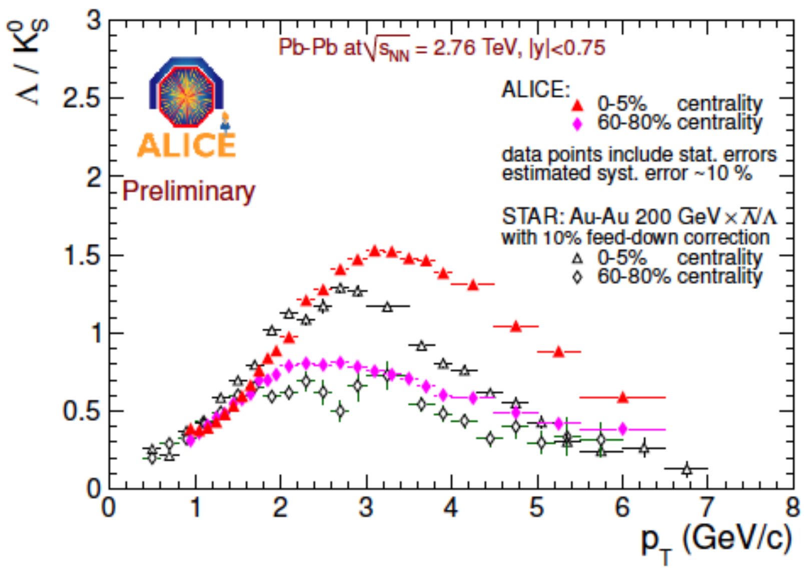
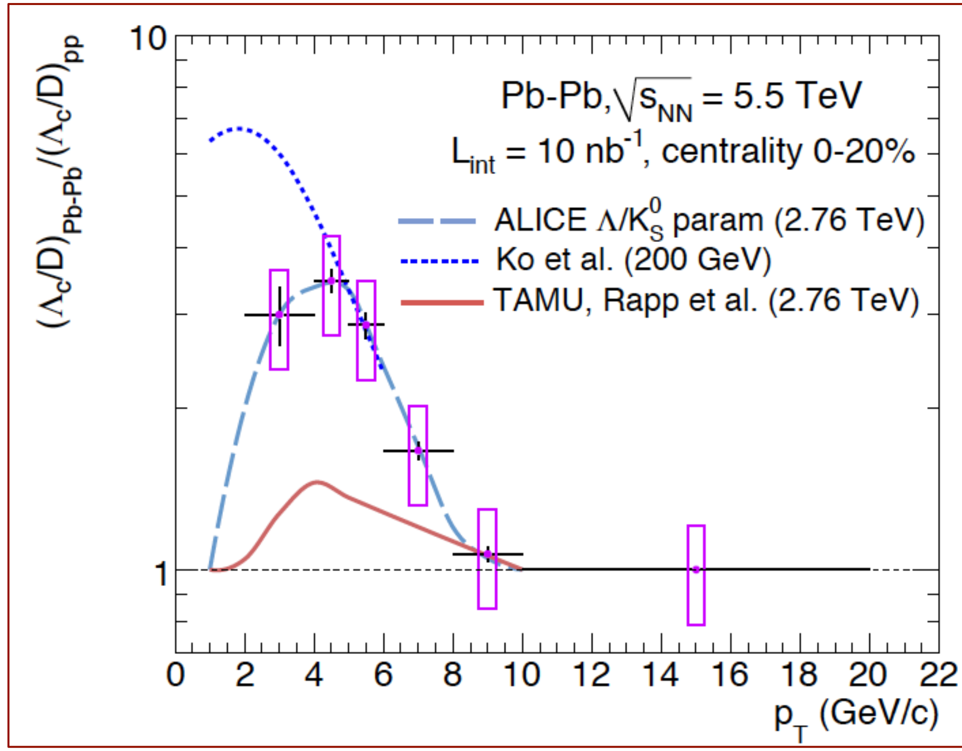
Performance of the New ITS (MC simulation)

Enhancement of Λ_c/D^0 ratio:





- The production of charm and beauty baryons has also a particular interest to assess the thermalization and the mechanisms of hadronization of heavy flavors in the medium.
- For light flavor and strange baryons, an enhancement was observed at intermediate p_T at RHIC and LHC.

- Assumed the statistical uncertainties for the D^0 measurements and for the Λ_c measurements in pp are negligible with respect to those for the Λ_c measurements in Pb+Pb.

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Physics Reach of the New ITS

Observable	Current, $0.1\,\mathrm{nb}^{-1}$		Upgrade, $10\,\mathrm{nb}^{-1}$	
	$p_{\mathrm{T}}^{\mathrm{min}}$ (GeV/c)	statistical uncertainty	$p_{\mathrm{T}}^{\mathrm{min}}$ (GeV/c)	statistical uncertainty
Heavy Flavour				
D meson R_{AA}	1	10 %	0	0.3 %
$\mathrm{D_s}$ meson R_{AA}	4	15 %	< 2	3 %
D meson from B R_{AA}	3	30 %	2	1 %
J/ψ from B R_{AA}	1.5	15 % (p_{T}-int.)	1	5 %
$\mathrm{B^+}$ yield	not accessible		2	10 %
Λ_{c} R_{AA}	not accessible		2	15 %
$\Lambda_{\mathrm{c}}/\mathrm{D^0}$ ratio	not accessible		2	15 %
Λ_{b} yield	not accessible		7	20 %
D meson v_2 ($v_2 = 0.2$)	1	10 %	0	0.2 %
$\mathrm{D_s}$ meson v_2 ($v_2 = 0.2$)	not accessible		< 2	8 %
D from B v_2 ($v_2 = 0.05$)	not accessible		2	8 %
J/ψ from B v_2 ($v_2 = 0.05$)	not accessible		1	60 %
Λ_{c} v_2 ($v_2 = 0.15$)	not accessible		3	20 %
Dielectrons				
Temperature (intermediate mass)	not accessible			10 %
Elliptic flow ($v_2 = 0.1$) [4]	not accessible			10 %
Low-mass spectral function [4]	not accessible		0.3	20 %
Hypernuclei				
${}^{3}_{\Lambda}\mathrm{H}$ yield	2	18 %	2	1.7 %

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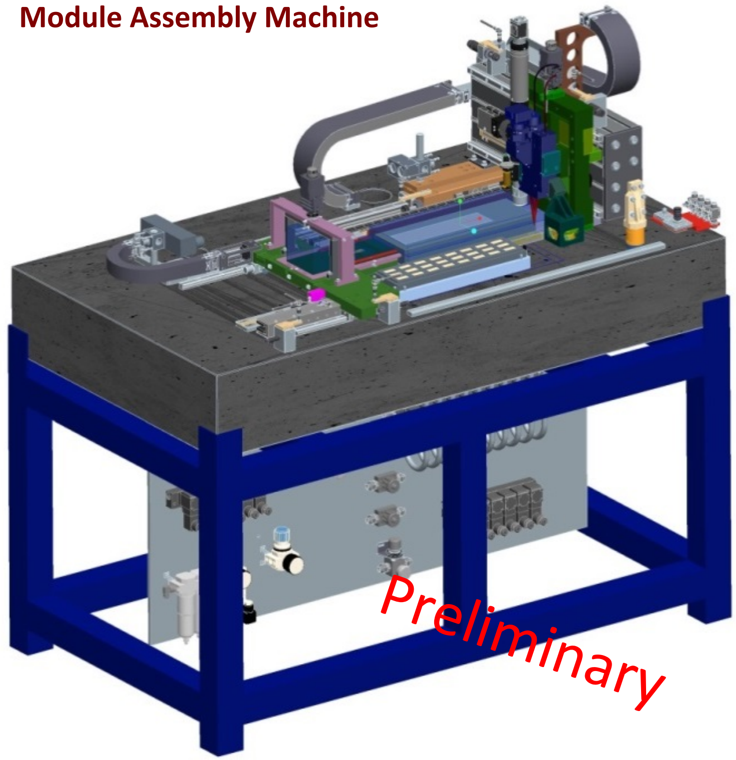
Wuhan Plan on the ALICE ITS Upgrade

- The amount of modules and the time available require a distributed production over 6 sites (Bari/Italy, CERN, Liverpool/UK, Pusan/Korea, Strasbourg/France, Wuhan/China).
- Usage of same procedure and system is necessary to ensure homogenous production.

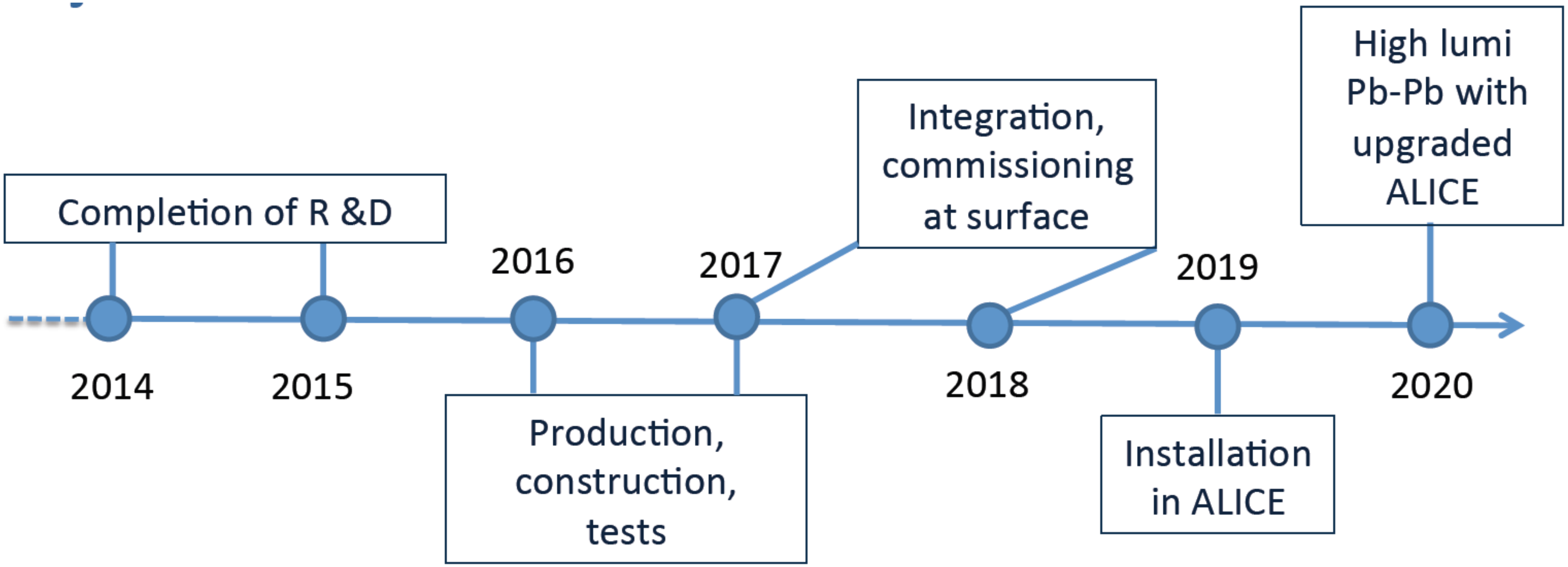
Wuhan efforts on ITS upgrade:

- CCNU plans to import a module assembly machine, and involves one outer layer module assembly (~ 400 modules production at Wuhan).
- Efforts on vision control software development for the module assembly machine.
- Efforts on the Pixel chip ALPIDE design:
  - ☑ Pixel analog front end revision and optimization in ALPIDE chip design
  - ☑ New matrix readout architecture in ALPIDE chip design

Module Assembly Machine



Project Timeline and Collaboration



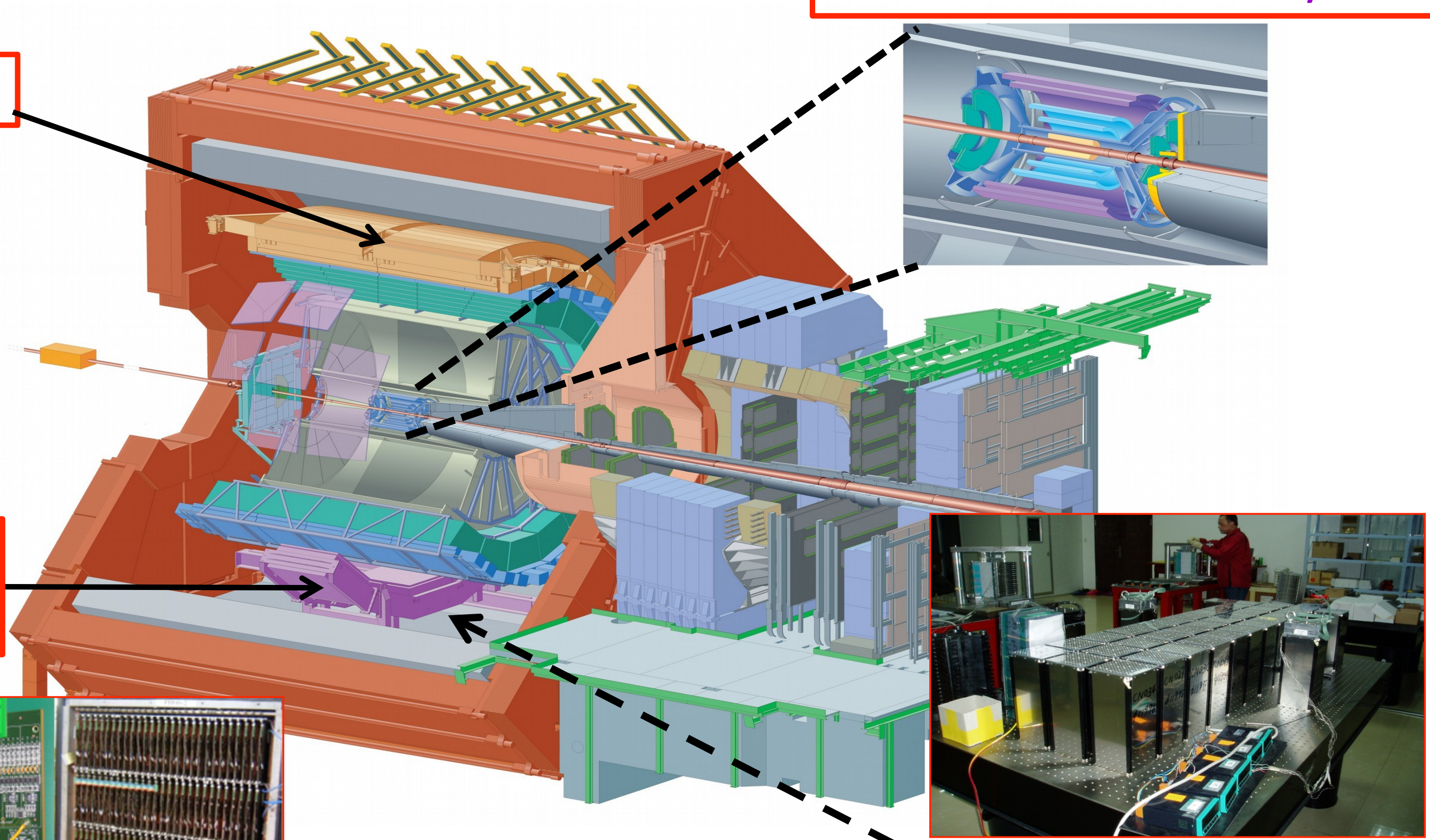
ALICE ITS Collaboration:

CERN, China (Wuhan), Check Republic (Prague), France (Grenoble, Strasbourg), Italy (Aless., Bari, Cagliari, Catania, Frascati, Padova, Roma, Trieste, Torino), Indonesia (LIPI), Korea (Pusan, Inha, Yonsei), Netherlands (Nikhef, Utrecht), Pakistan (CIIT-Islamabad), Russia (St. Petersburg), Slovakia (Kosice), Thailand (Suranaree, SLRI, TMEC), UK (Daresbury, Liverpool, RAL), Ukraine (Kharkov), USA (Austin, Berkeley)

Chinese team in ALICE

ITS upgrade: pixel design, module assembly

EMCAL: SRU



PHOS:
FEE + SRU

DCAL: one supermodule + SRU

Physics analysis: high p_T physics (photon, correlation, jet, heavy flavor) and flow (HF-muon, multi-strangeness and pi0) **HF Physics!**

Spares

The New ITS CMOS Pixel Sensor

Pixel chip general requirements:

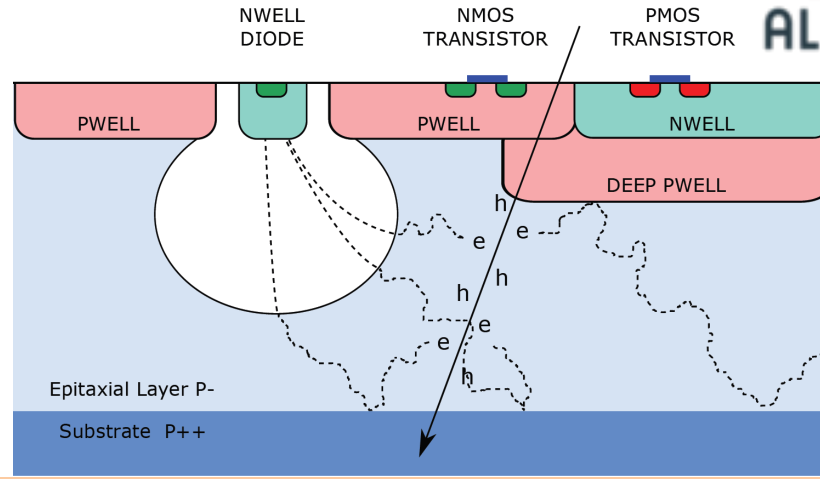
Parameter	Inner Barrel	Outer Barrel
Silicon thickness	50 μm	
Spatial resolution	5 μm	10 μm
chip dimensions	15 mm x 30 mm	
Power density	< 300 mW/cm^2	< 100 mW/cm^2
Event time resolution	< 30 μs	
Detection efficiency	> 99%	
Fake hit rate	< 10^{-5} per readout frame	
TID radiation hardness (*)	2700 krad	100 krad
NIEL radiation hardness (*)	1.7×10^{13} 1MeV n_{eq} /cm^2	10^{12} 1MeV n_{eq} / cm^2

* 10x radiation load integrated over approved programme (~ 6 years of operation)

The New ITS CMOS Pixel Sensor

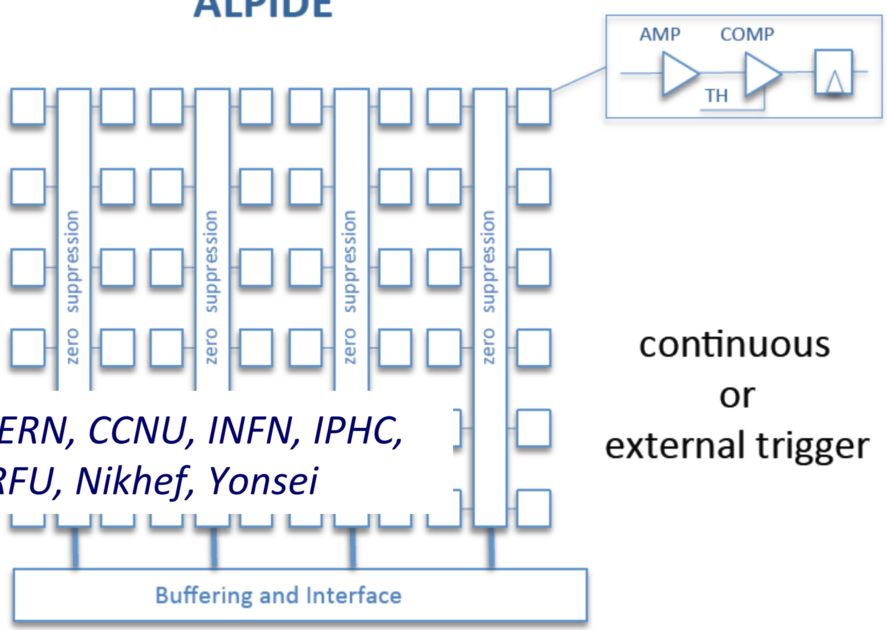
Monolithic pixel chip using TowerJazz
0.18 µm CMOS imaging process:

- ✧ Chip size: 15 mm × 30 mm
- ✧ Pixel pitch: ~ 30 µm
- ✧ Spatial resolution: ~ 5 µm
- ✧ Power density: < 100 mW/cm^2
- ✧ Architectures: MISTRAL, ALPIDE



Deep p-well allows truly CMOS circuit inside pixel

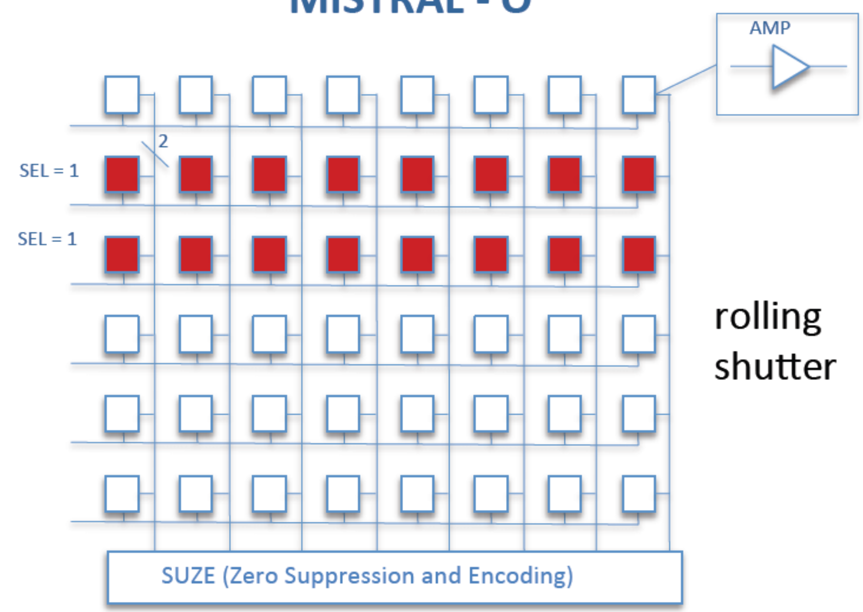
ALPIDE



continuous
or
external trigger

CERN, CCNU, INFN, IPHC, IRFU, Nikhef, Yonsei

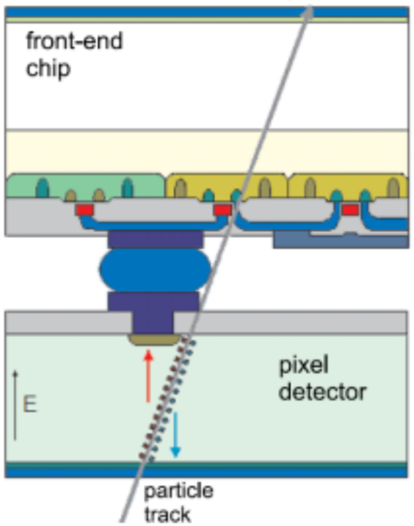
MISTRAL - O



rolling
shutter

The New ITS CMOS Pixel Sensor

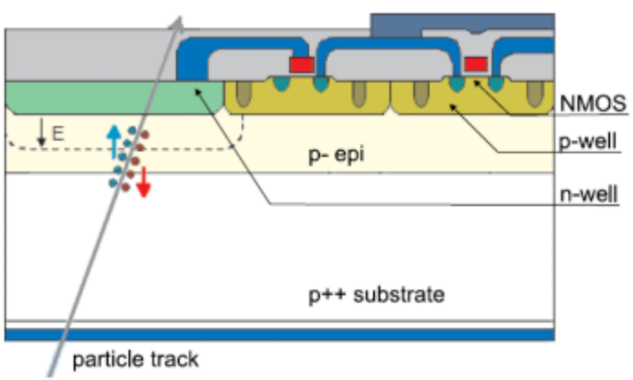
Hybrid Pixel Detector



N. Wermes (Univ. of Bonn)

- Sensor based on silicon junction detectors produced in a planar process
- High resistivity wafers (few kWcm) with diameters of 4” – 6”
- Specialized producers (~10 world wide)
- Readout Chip: ASIC - CMOS sub-micron technology
- Interconnect technology based on flip-chip bonding

Monolithic Pixel Detector



N. Wermes (Univ. of Bonn)

- Charge generation volume integrated into the ASIC
- Exist in many different flavours: CCDs, CMOS MAPS, HV/HR CMOS, DEPFET, SOI, …
- This talk will cover only CMOS Monolithic Active Pixel Sensors (CMOS MAPS) = CMOS Pixel Sensors (CPS)

ALICE Upgrade Strategy

- The upgrade plans entails building
  - New, high-resolution, high-rate ITS
  - Upgrade of TPC with replacement of MWPCs with GEMs and new pipelined readout electronics
  - Upgrade of readout electronics of: TRD, TOF, PHOS and Muon Spectrometer
  - Upgrade of the forward trigger detectors and ZDC
  - Upgrade of the online systems (DAQ & HLT)
  - Upgrade of the offline reconstruction framework

  O2

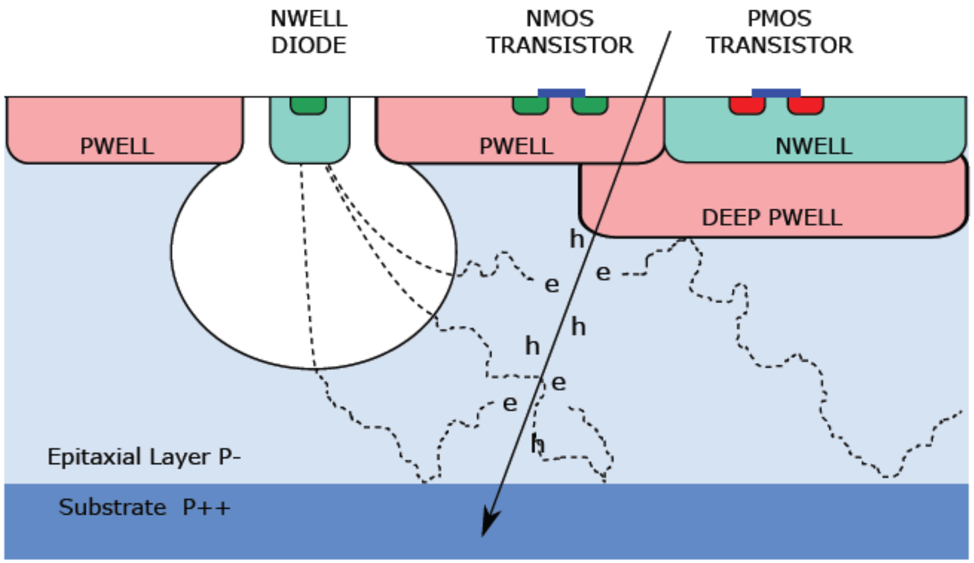
  - New 5-plane silicon telescope in front of the hadron absorber covering the acceptance of the muon Spectrometer
- It targets 2018/19 (LHC 2nd Long Shutdown)

LoI
Sep 2012

Add. LoI
Sep 2013

ITS Pixel Chip – technology choice

CMOS Pixel Sensor using TowerJazz 0.18μm CMOS Imaging Process



Tower Jazz 0.18 μm CMOS

- feature size 180 nm
- metal layers 6

➔ Suited for high-density, low-power

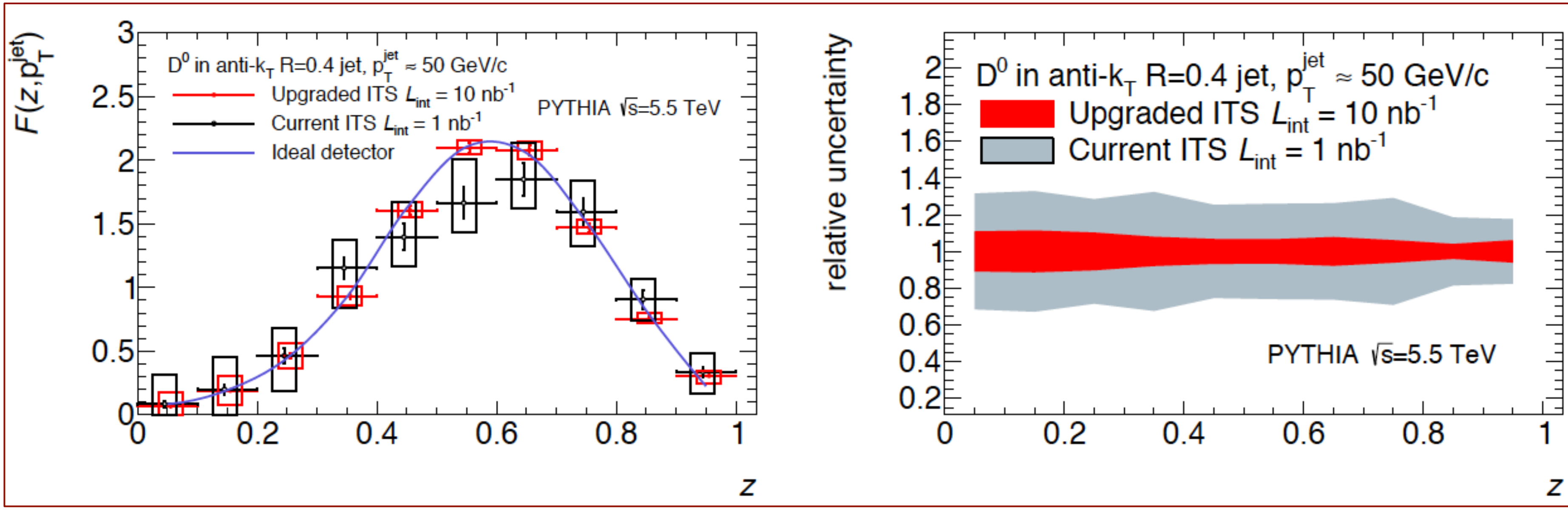
- Gate oxide 3nm

➔ Circuit rad-tolerant

- High-resistivity (> 1kΩ cm) p-type epitaxial layer (20μm - 40μm thick) on p-type substrate
- Small n-well diode (2-3 μm diameter), ~100 times smaller than pixel => low capacitance
- Application of (moderate) reverse bias voltage to substrate can be used to increase depletion zone around NWELL collection diode
- Quadruple well process: deep PWELL shields NWELL of PMOS transistors, allowing for full CMOS circuitry within active area

Performance of the New ITS (MC simulation)

D meson fragmentation function in jets:



- Projection for the measurement of the fragmentation function of D^0 mesons within charm quark induced jets in central Pb+Pb collisions (0-10% centrality class).
- Provide insight into the energy loss of high-momentum leading charm quarks.
- Improved reconstruction of various heavy flavor decay channels will largely enhance the performance for tagging jets that contain heavy flavors.

* J. Phys. G(41) 087002