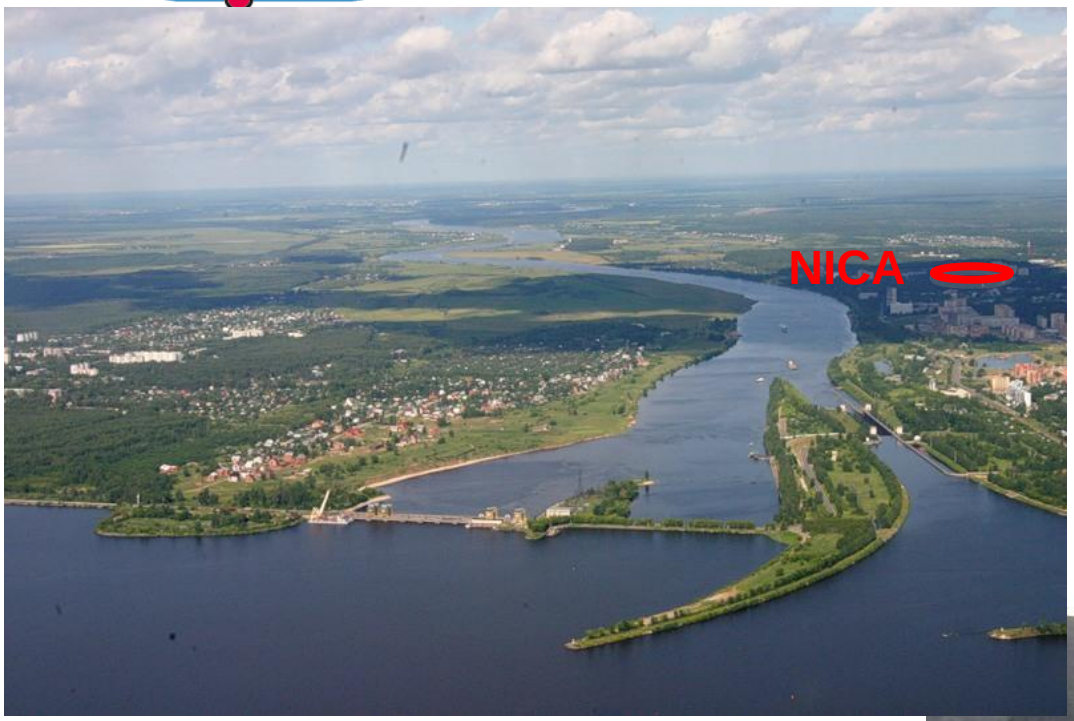
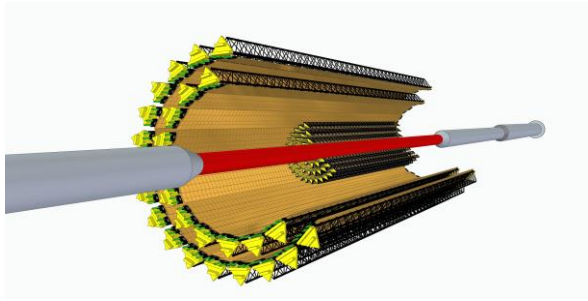
Novel Technologies for the MPD-ITS



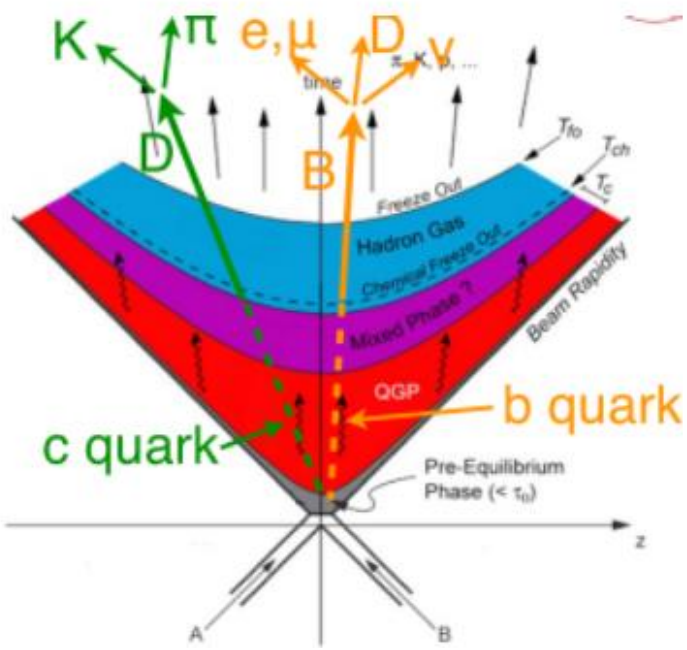


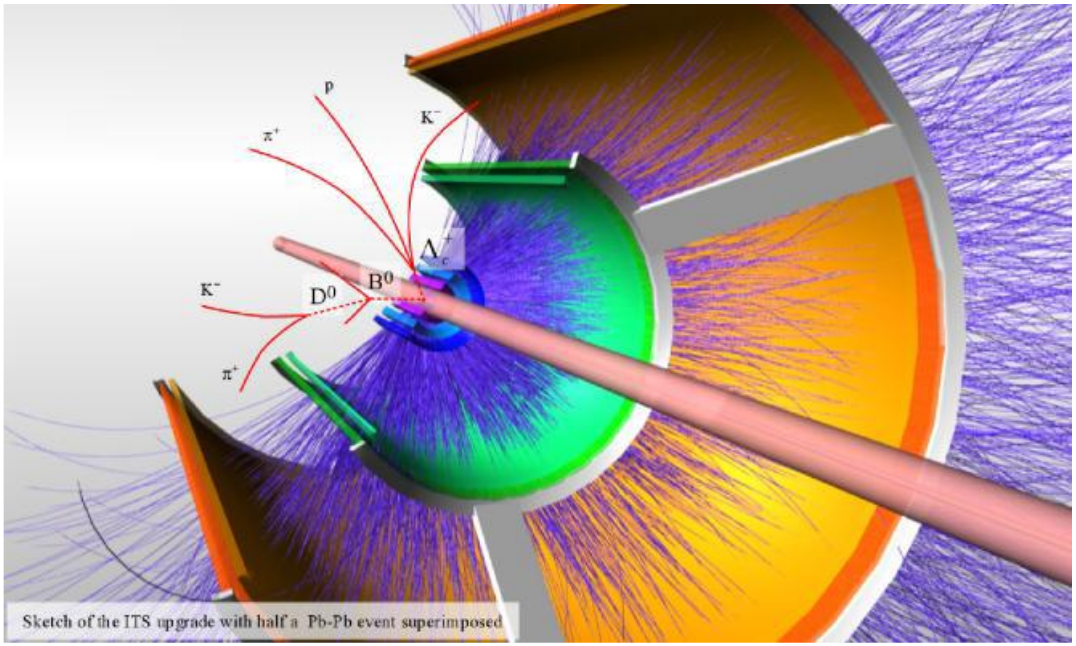
Yuri Murin, VBLHEP JINR
murin@jinr.ru

The outline:

- *The physics case – creation of deconfined matter in the lab and role of the rare probes (heavy hyperons and charmed mesons) in search of hints of critical point*
- *A story of silicon detectors in High Energy physics (after Luciano Musa, CERN, Bormio School , 2018)*
- *Transition from strips to pixels and MAPS "invasion"*
- *The new ALICE ITS experience*
- *Plans for it implementation for the NICA MPD ITS*

Look for a needle in a “hay” of tracks for rare events

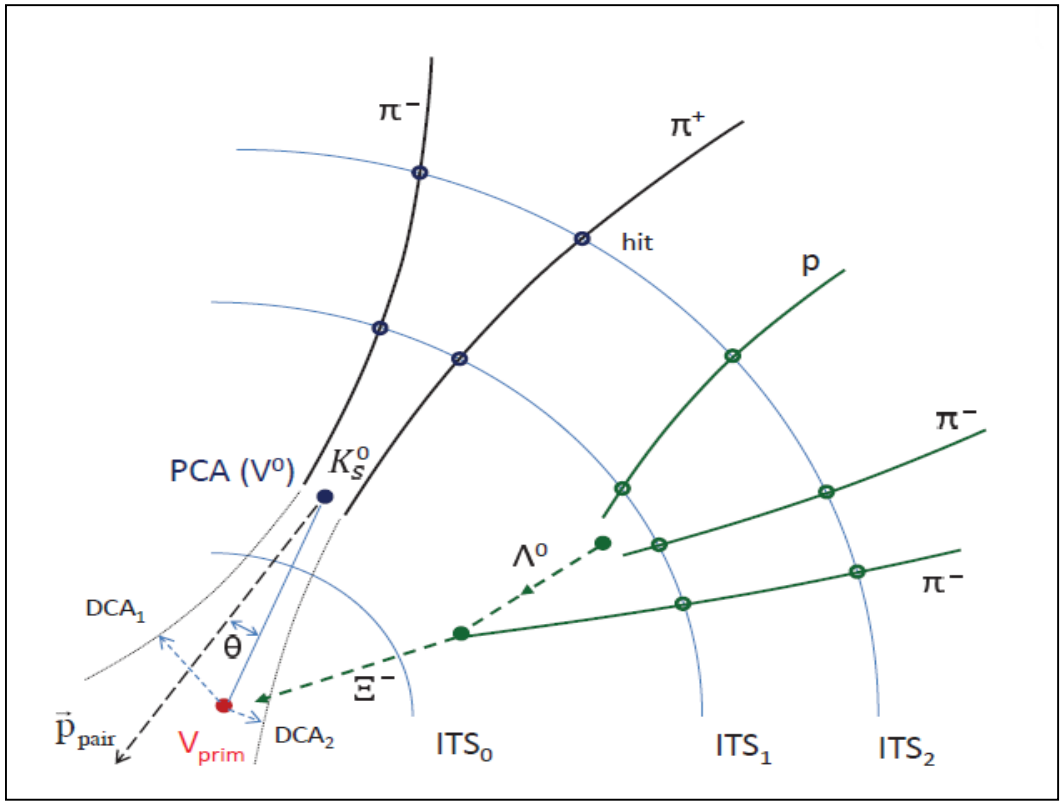




Sketch of the ITS upgrade with half a Pb-Pb event superimposed

The Inner Tracking System or *Vertex tracker is a* multilayer telescope which measures the position of particle hits positions to restore the track trajectory. It’s special task to be located as close as possible to the interaction point and to be as precise as possible to identify specific decays of particles carrying strangeness, charm or beauty i.e. S, C, or B - quarks

The basic task for the Inner Tracking System



$\Lambda \rightarrow p + \pi^-$

$\Xi^- \rightarrow \Lambda + \pi^-$
$\quad\quad\quad\quad \hookrightarrow p + \pi^-$

$\Omega^- \rightarrow \Lambda + K^-$
$\quad\quad\quad\quad \hookrightarrow p + \pi^-$

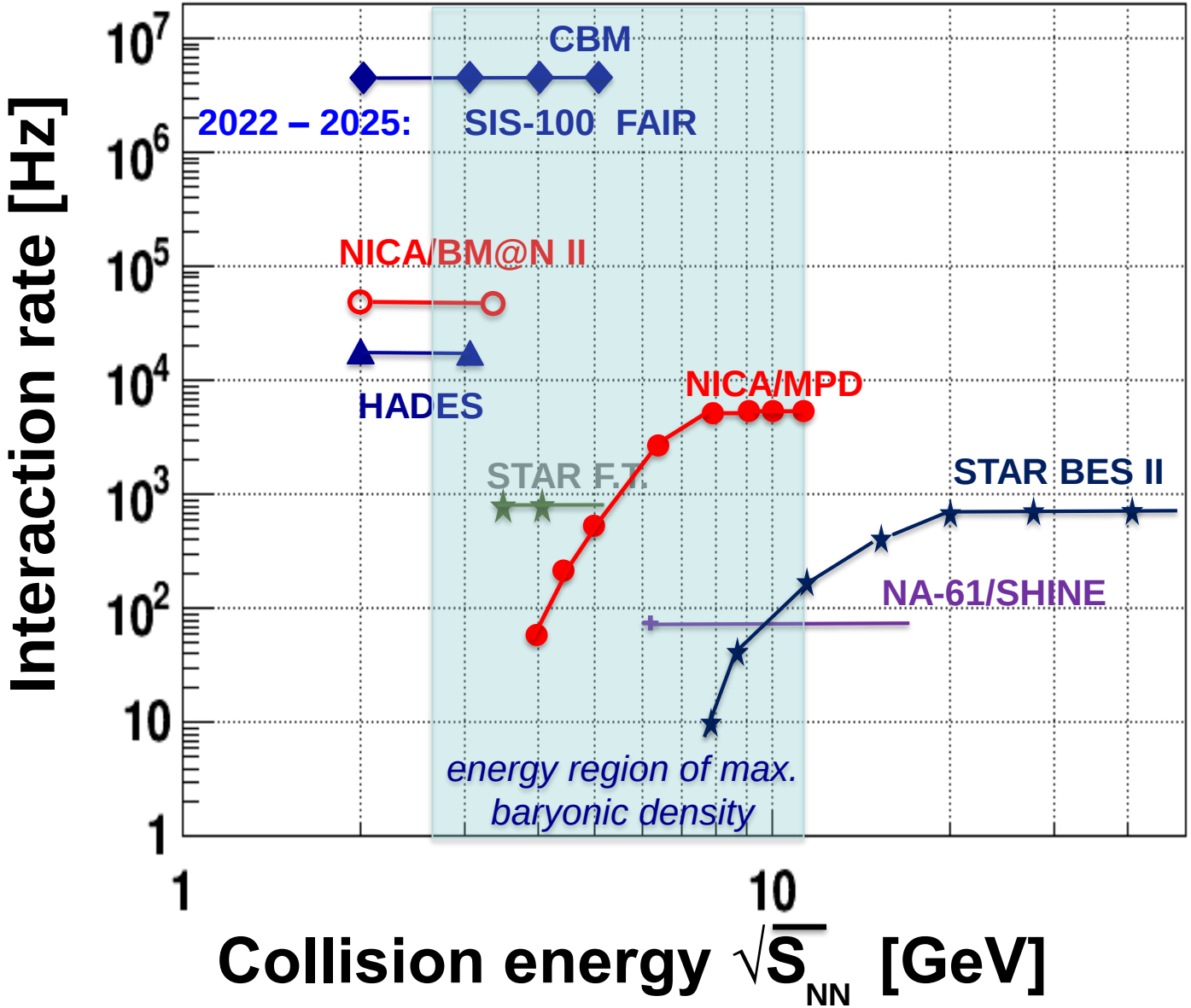
$D^+ \rightarrow K^- + \pi^+ + \pi^+$

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

$\Lambda_c \rightarrow p + K^- + \pi^+$

Identification of particles through inspection of Inverse Mass distributions $M^2 = sum(E_i)^2 - sum(P_i)^2 \quad (c=1)$

Current and future experiments on CBM



The rise of silicon detectors in HEP

Towards end of 1970's: intensive R&D on devices which could measure short-lived particles (10^{-12} - 10^{-13} s)

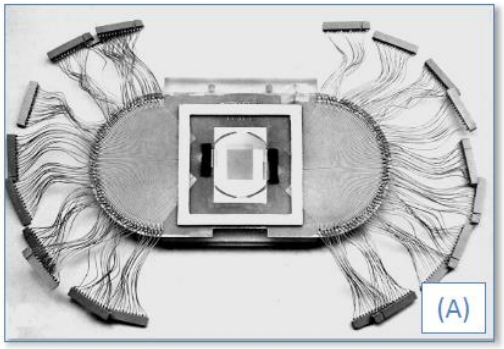
R&D at CERN[(A)] and Pisa[(B)] demonstrated that strip detectors (100-200μm pitch):

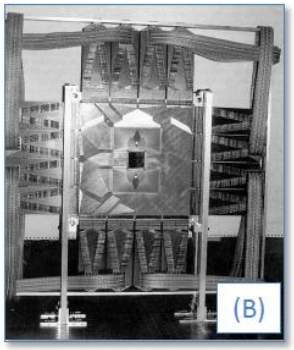
- high detection efficiency (>99%), good spatial resolution (~20μm) and good stability
- precise vertex reconstruction

However: fabrication of these devises was very tricky, thus limiting their availability

1980 – fabrication of silicon detectors using standard IC planar process (PIN diode ➔ μstrip detector)

J. Kemmer, et al., *"Development of 10-micrometer resolution silicon counters for charm signature observation with the ACCMOR spectrometer", Proceedings of Silicon Detectors for High Energy Physics, Nucl. Instr. and Meth. 169 (1980) 499.*





First use of silicon strips detectors by NA11(CERN SPS) and E706 (FNAL)

(A) NA11 (1981): 6 planes (24 x 36mm^2): resistivity 2-3 kΩcm, thickness 280μm, pitch 20μm

(B) E706 (1982): 4 planes (3x3 cm^2) + 2 planes (5x5cm^2)

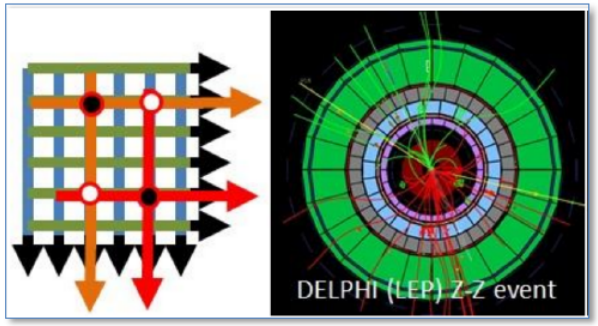
Erik Heine, Joseph Kemmer and Gherard Lutz: 2017 EPS prize for "Outstanding Contributions to HEP" (pioneering the development of silicon μstrip)

The rise of silicon detectors in HEP

The next step forward came with the advent of the VLSI technology that allowed coupling ASIC amplifier chips directly to the detectors

1990s - LEP, first silicon vertex detectors were installed in DELPHI and ALEPH experiments, then OPAL and L3

1989 - first DELPHI vertex detector, consisting of two layers of single-sided strip detectors



Projective geometry ➔ ambiguity at high multiplicities (high occupancy)

This started to become apparent already at DELPHI:

- High number of ambiguities ➔ reconstruction efficiency suffered a lot, especially in the forward direction

Not usable close to IP in hadron colliders (LHC) or HI experiments at SPS

Another problem at (very) high particle load ➔ degradation of the sensor by the high radiation dose

This implies starting with a very large signal-to-noise ratio, which can only be obtained with detector with small capacitance

The Inception of Silicon Pixel Detectors

"The silicon micropattern detector: a dream?"

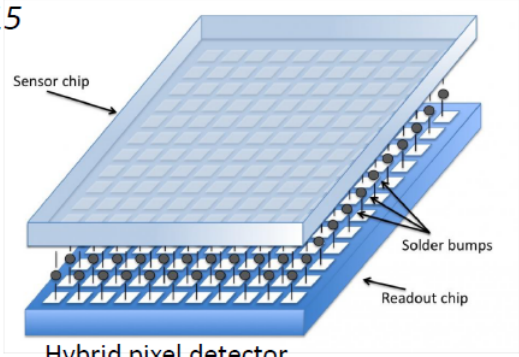
E.H.M Heijine, P. Jarron, A. Olsen and N. Redaelli , *Nucl. Instrum. Meth. A 273 (1988) 615*

"Development of silicon micropattern detectors"

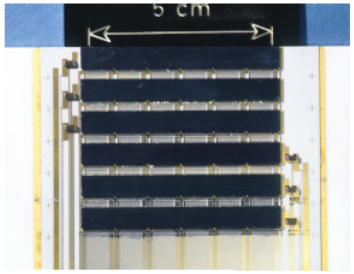
CERN RD19 collaboration, *Nucl. Instrum. Meth. A 348 (1994) 399*

1995 – First Hybrid Pixel detector installed in WA97 (CERN, Omega facility)

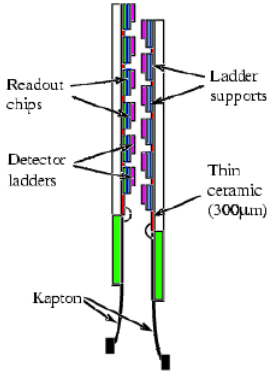
1996/97 – First Collider Hybrid Pixel Detector installed in DELPHI (CERN, LEP)



Hybrid pixel detector



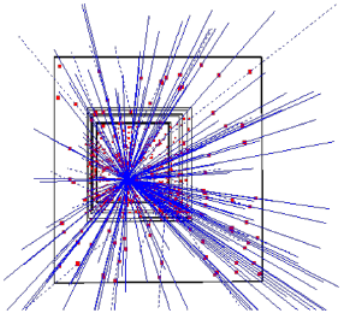
E. Heijne, E. Chesi



Work carried out by RD19 for WA97 and NA57/CERN

CERN – WA97 Experiment (1995)

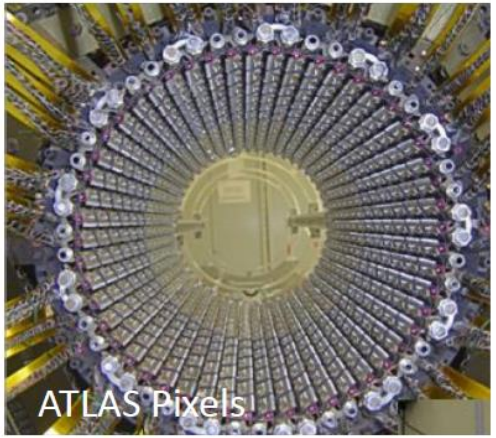
- 5 x 5 cm^2 area
- 7 detector planes
- ~0.5 M pixels
- Pixel size 75 x 500 μm^2
- 1 kHz trigger rate
- Omega2 chip

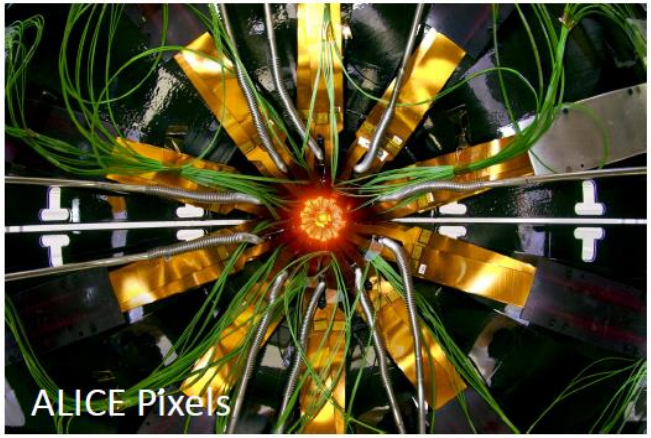


No-field, Pb-Pb, 153 reconstructed tracks

Pixel Detectors at the LHC

10 years after the first use in WA97… hybrid pixel detectors at the heart of the LHC experiments

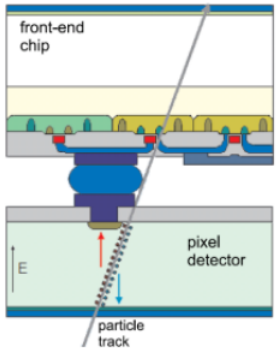




Parameters	ALICE	ATLAS	CMS
Nr. layers	2	3	3
Radial coverage [mm]	**39** - 76	**50** - 120	**44** – 102
Nr of pixels	9.8 M	80 M	66 M
Surface [m^2]	0.21	1.7	1
Cell size ($r\phi$ x z) [μm^2]	50 x 425	50 x 400	100 x 150
Silicon thickness (sens. + ASIC) - x/X_0 [%]	0.21 + 0.16	0.27 + 0.19	0.30 + 0.19

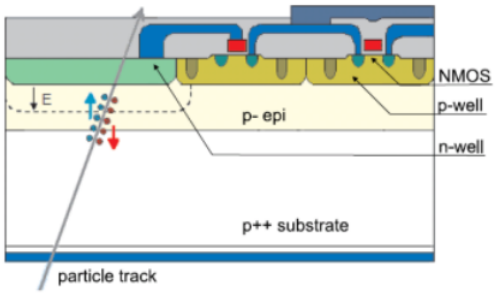
Beyond Hybrid Pixel Detectors …

Hybrid Pixel Detector



N. Wermes (Univ. of Bonn)

Monolithic Pixel Detector



N. Wermes (Univ. of Bonn)

Since the very beginning of pixel development (CERN RD 19):

dream to integrate sensor and readout electronics in one chip

Motivation to reduce: cost, power, material budget, assembly and integration complexity

Several major obstacles to overcome:

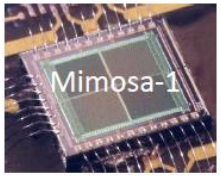
- CMOS generally not available on high resistivity silicon (needed as bulk material for the sensor)
- Full CMOS circuitry not possible within the pixel area (only one type of transistor ➔ slow readout)

MAPS exist in many different flavors: **CMOS**, HV CMOS, DEPFET, SOI

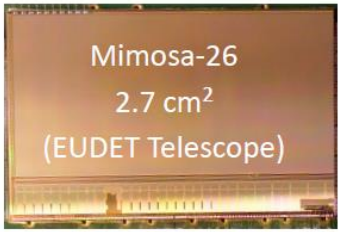
The following will cover only CMOS Active Pixel Sensors (CMOS MAPS) = **CMOS Active Pixel Sensors (CMOS APS)**

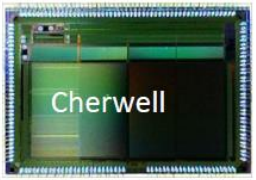
ALICE LS2 Upgrade

Owing to the industrial development of CMOS imaging sensors and the intensive R&D by HEP community

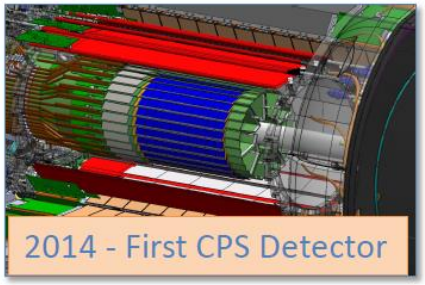


. . .

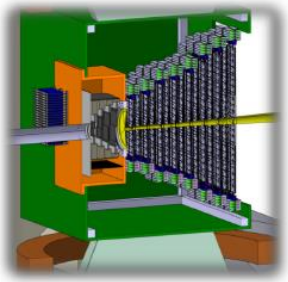




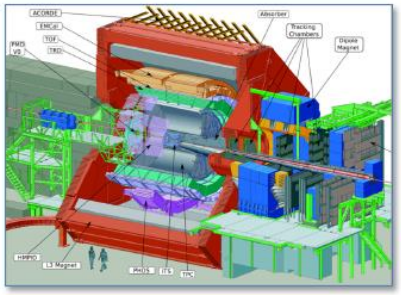
... several HI experiments have selected CMOS pixel sensors for their inner trackers and intensive R&D for ATLAS



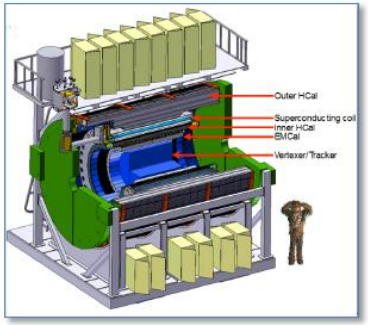
STAR HFT
0.16 m² – 356 M pixels



CBM MVD
0.08 m² – 146 M pixel



ALICE ITS Upgrade (and MFT)
10 m² – 12 G pixel



...

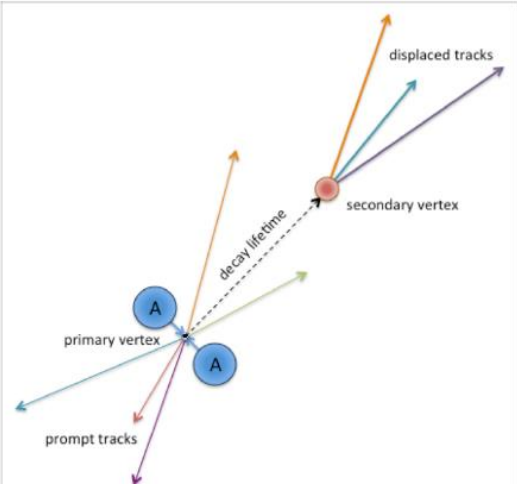
sPHENIX
0.2 m² – 251 M pixel

L. Musa (CERN) – International Winter Meeting on Nuclear Physics, Bormio, 8-11 Jan 2019 8

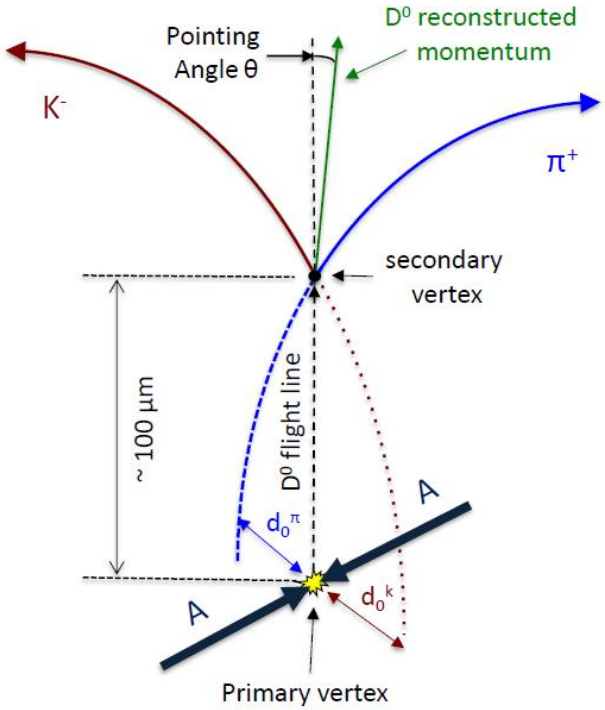
Secondary Vertex Determination

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

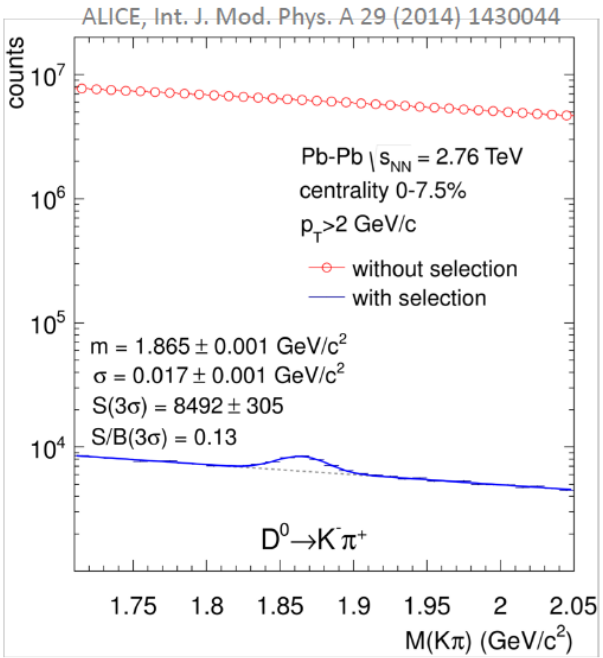


Example: D^0 meson



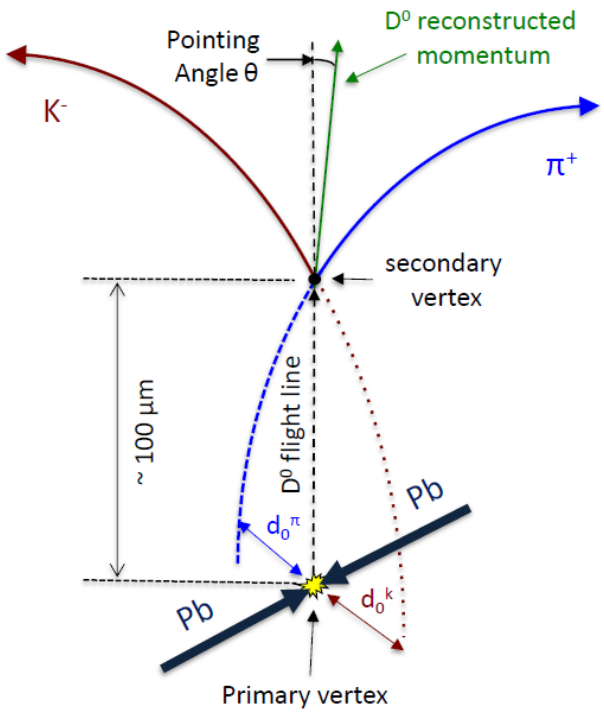
Analysis based on invariant mass, PID and decay topology

Secondary Vertex Determination



Invariant mass distribution of $K^-\pi^+$ pairs before and after applying selection criteria on the relation between the secondary (D^0 decay) and primary vertices

Example: D^0 meson



Analysis based on invariant mass, PID and decay topology

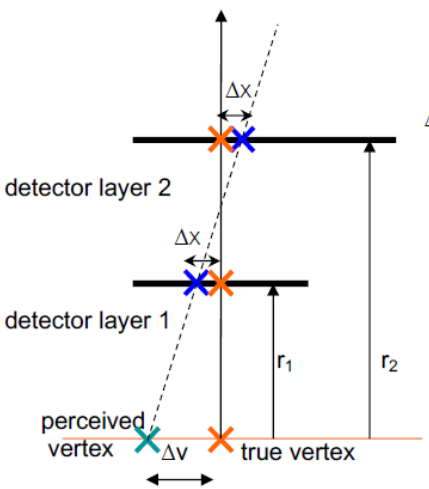
What determines the Impact parameter Resolution?

Vertex projection from two points: a simplified approach (telescope equation)

expectations for the ITS upgraded ➡ pointing resolution = (5 ⊕ 22GeV/p·c) μm

From detector position error

From Coulomb scattering



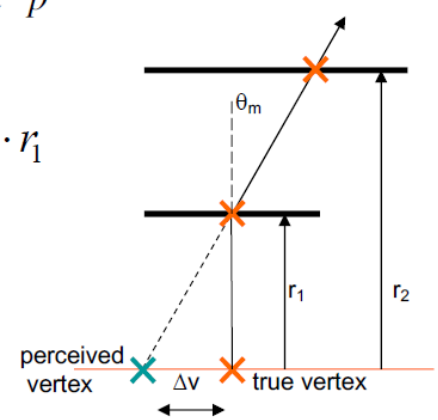
$$\Delta v = \Delta x \bullet \sqrt{\frac{r_2^2 + r_1^2}{(r_2 - r_1)^2}}$$

first pixel layer

$$X / X_0 = 0.3\%$$

$$\theta_m = \frac{13.6Mev}{\beta \cdot c \cdot p} \cdot \sqrt{X / X_0}$$

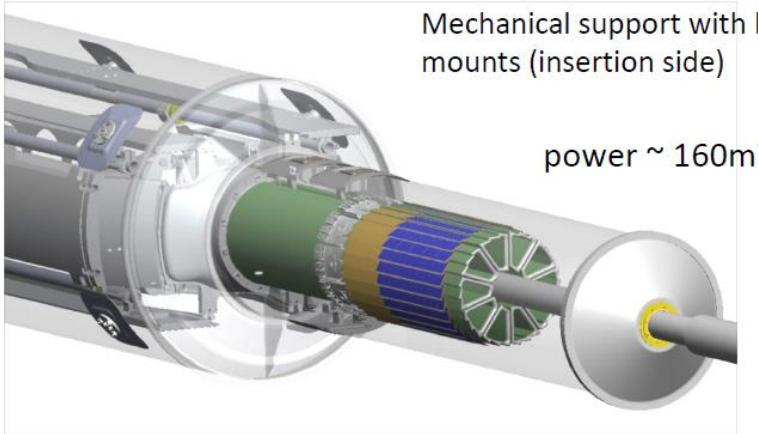
$$\Delta v = \theta_m \cdot r_1$$



Home task: to prove that spacious resolution of the strip or pixel sensor depends on size of the strip/pixel pitch D as

$$Sigma^2 = D^2/12$$

STAR Pixel Detector – First application of CMOS APS to HEP



- 2 layers
- 10 sectors total (in 2 halves)
- 4 ladders/sector

Rolling Shutter
~180μs integr. time

Ladder with 10 MAPS sensors (~ 2×2 cm² each)

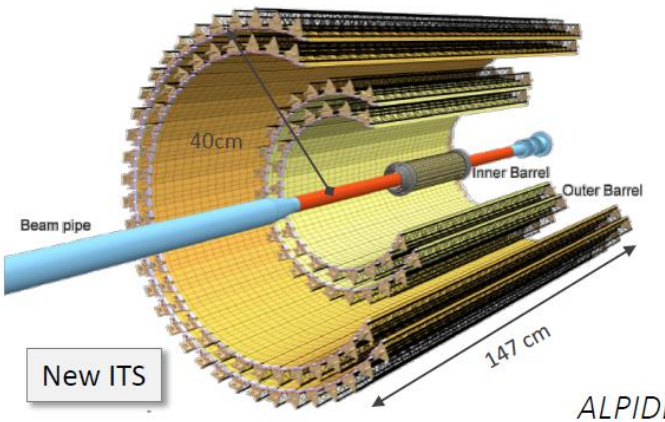
2-layer kapton flex cable with Al traces

Key dates

- 3-sector prototype May 2013
- **Full detector Jan 2014**

Physics Runs in 2015-2016

A new ITS: closer to IP, thinner, higher position resolution



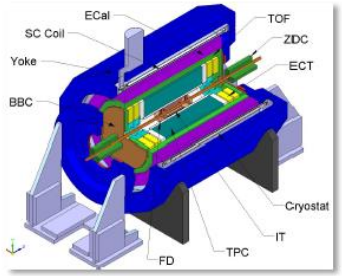
$1.5 \le \eta \le 1.5$

Closer to IP:	39mm ➡ 22mm
Thinner:	~1.14% ➡ ~ 0.3% (for inner layers)
Smaller pixels:	50μm x 425μm ➡ 27μm x 29μm
Increase granularity:	20 chan/cm^3 ➡ 2k pixel/cm^3
Faster readout:	x 10^2 Pb-Pb, x 10^3 pp

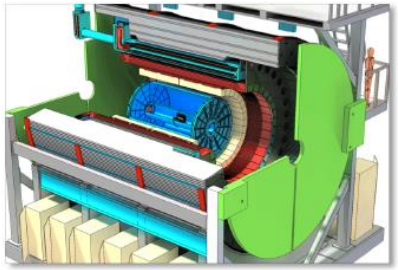
10 m^2 active silicon area: 12.5 G-pixels, $\sigma \approx 5\mu m$

ALPIDE (ALICE Pixel Detector) - Developed for the ALICE upgrade (ITS and MFT) will be used (or it is proposed) for several other HEP detectors and non HEP applications

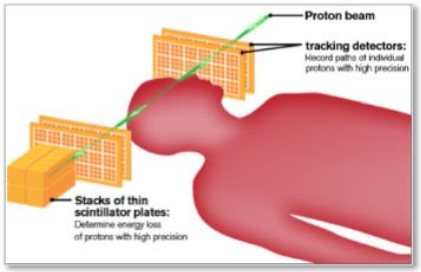
NICA MPD (@JINR)



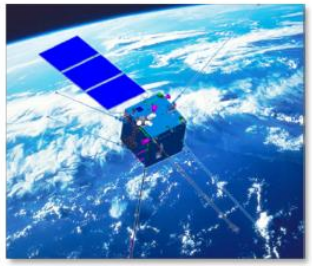
sPHENIX (BNL)



proton CT (tracking)



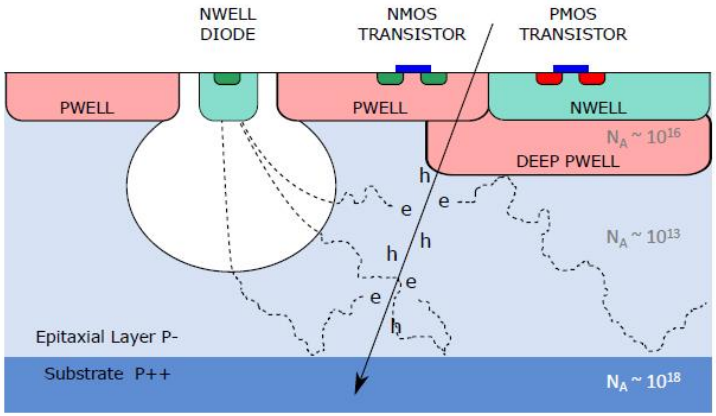
CSES – HEPD2



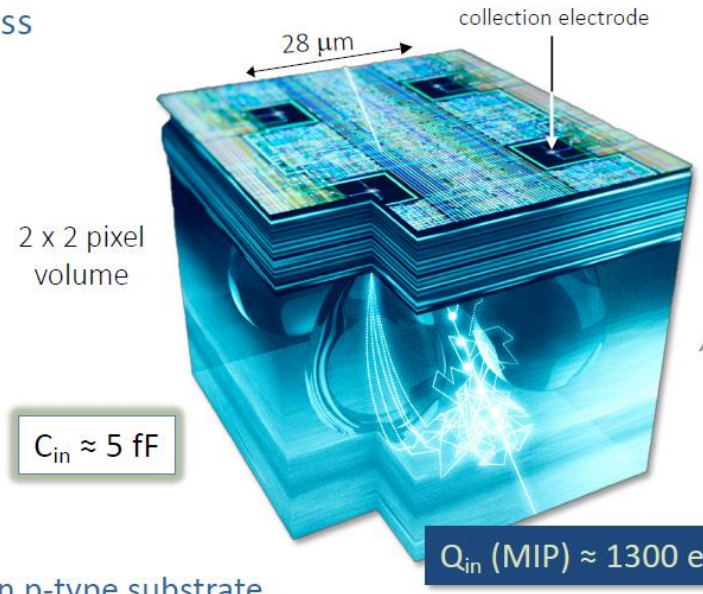
...

ALICE CMOS Pixel Sensor

CMOS Pixel Sensor using 0.18µm CMOS Imaging Process



pixel capacitance ≈5 fF (@ V_{bb} = -3 V)



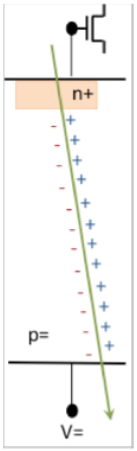
Artistic view of a SEM picture of ALPIDE cross section

- High-resistivity (> 1kΩ cm) p-type epitaxial layer (25µm) on p-type substrate
- Small n-well diode (2 µm diameter), ~100 times smaller than pixel => low capacitance (~fF)
- Reverse bias voltage (-6V < V_{BB} < 0V) to substrate (contact from the top) to increase depletion zone around NWELL collection diode
- Deep PWELL shields NWELL of PMOS transistors

➔ full CMOS circuitry within active area

ALICE CMOS Pixel Sensor

Low capacitance ➔ large S/N at low power



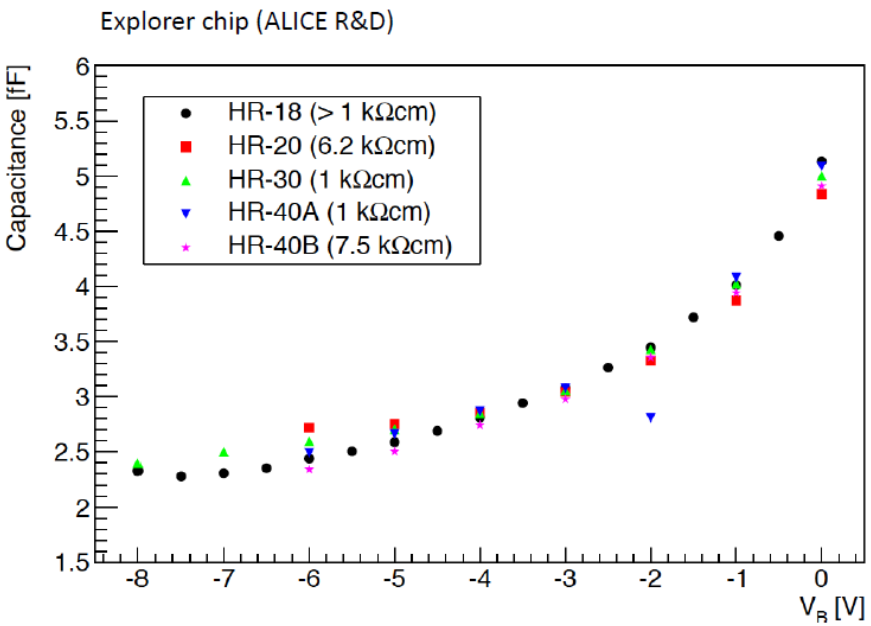
NWELL DIODE output signal = Q /C

- Minimize spread of charge over many pixels
- minimize capacitance:
  - ➡ small diode surface
  - ➡ large depletion volume

☞ Silicon strip capacitance: > 10 pF (~1.5 pF / cm)

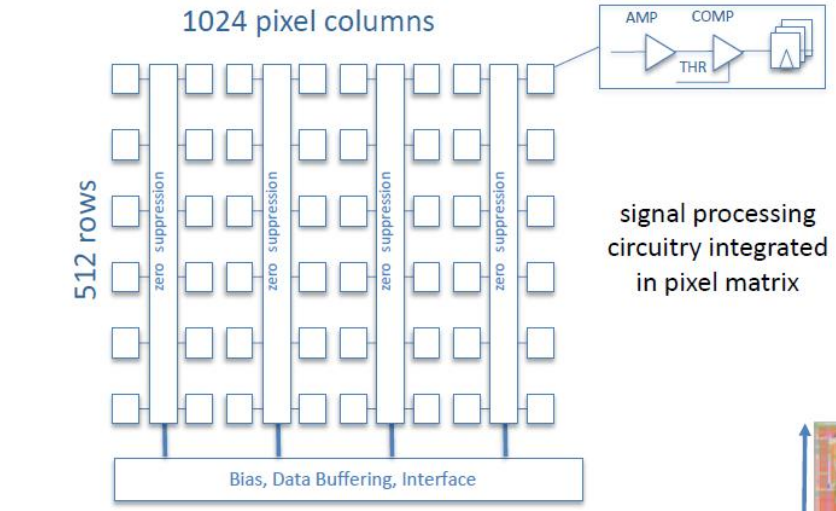
☞ Hybrid pixel capacitance: ~300 fF

☞ MAPS "small electrode" pixel capacitance: < 5 fF



C_d = 1fF: 1300 e^- ➔ 200mV (almost a digital signal)

ALICE PIxel DEtector (ALPIDE)



signal processing circuitry integrated in pixel matrix

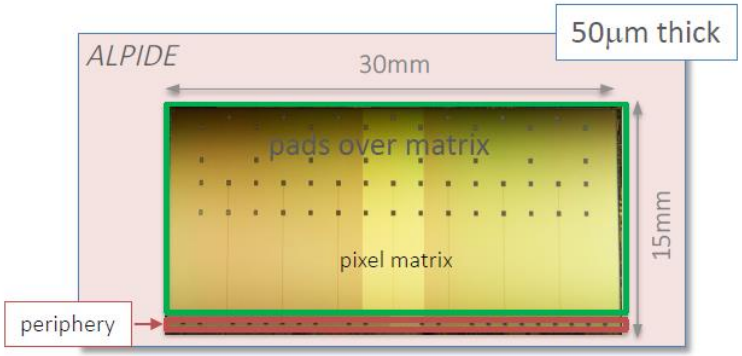
130,000 pixels / cm^2 27x29x25 μm^3

charge collection time <30ns (V_{bb} = -3V)

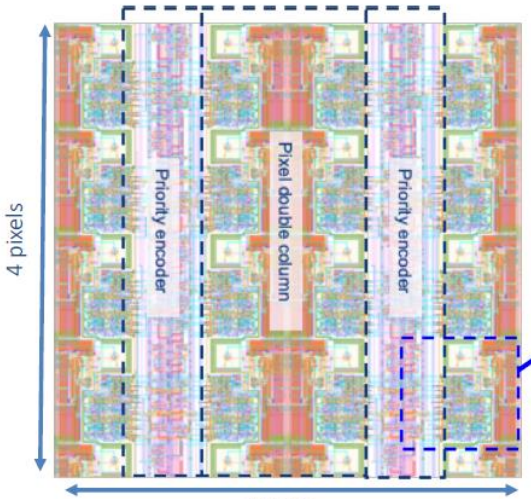
Max particle rate: 100 MHz/cm^2

fake-hit rate: < 1 Hz/ cm^2

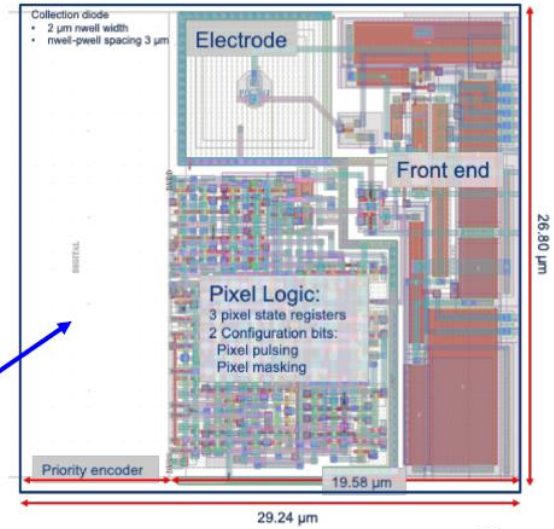
power : ≈300 nW /pixel (<40mW/cm^2)



Matrix Layout

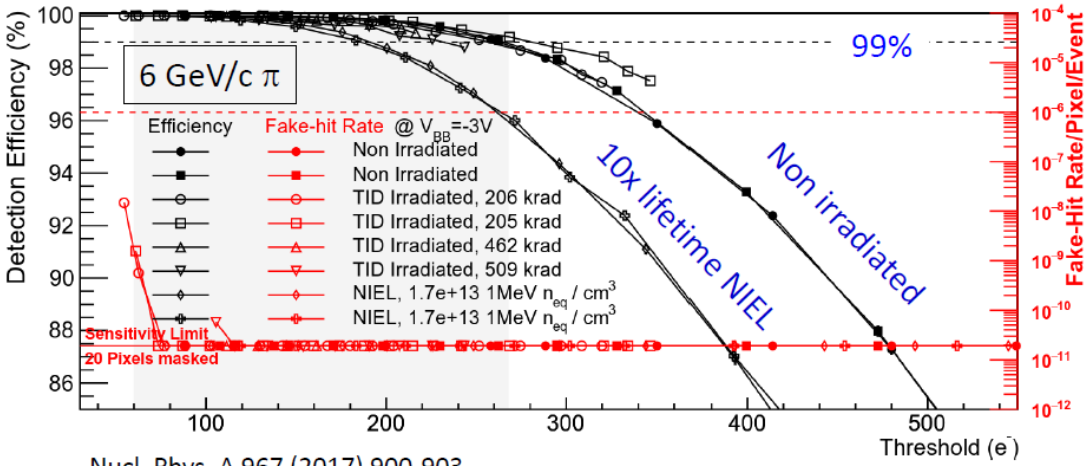


Pixel Layout



L. Musa (CERN) – International Winter Meeting on Nuclear Physics, Bormio, 8-11 Jan 2019 22

ALICE PIxel DEtector (ALPIDE)

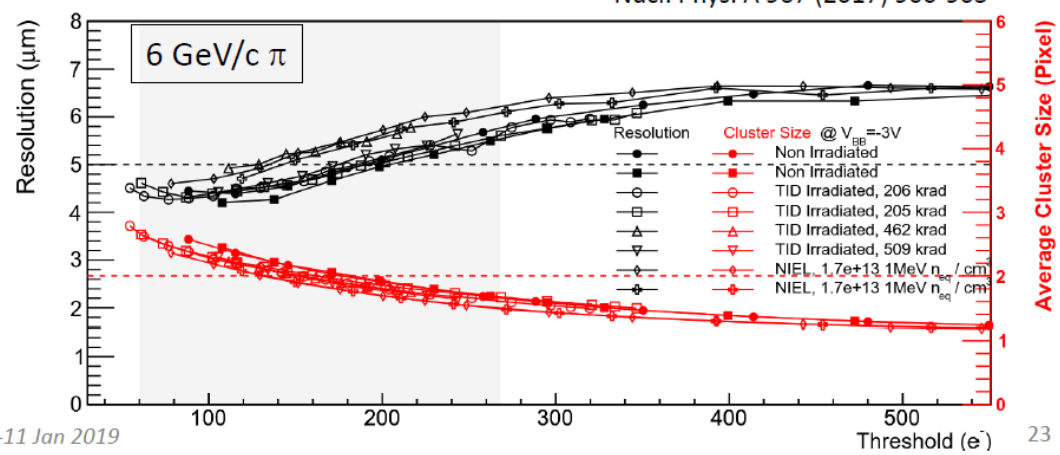


Nucl. Phys. A 967 (2017) 900-903

Large operational margin with only 10 masked pixels (0.002%), fake-hit rate < 2 x 10^{-11} pixel/event

Non irradiated and TID/NIEL chips similar performance

Nucl. Phys. A 967 (2017) 900-903

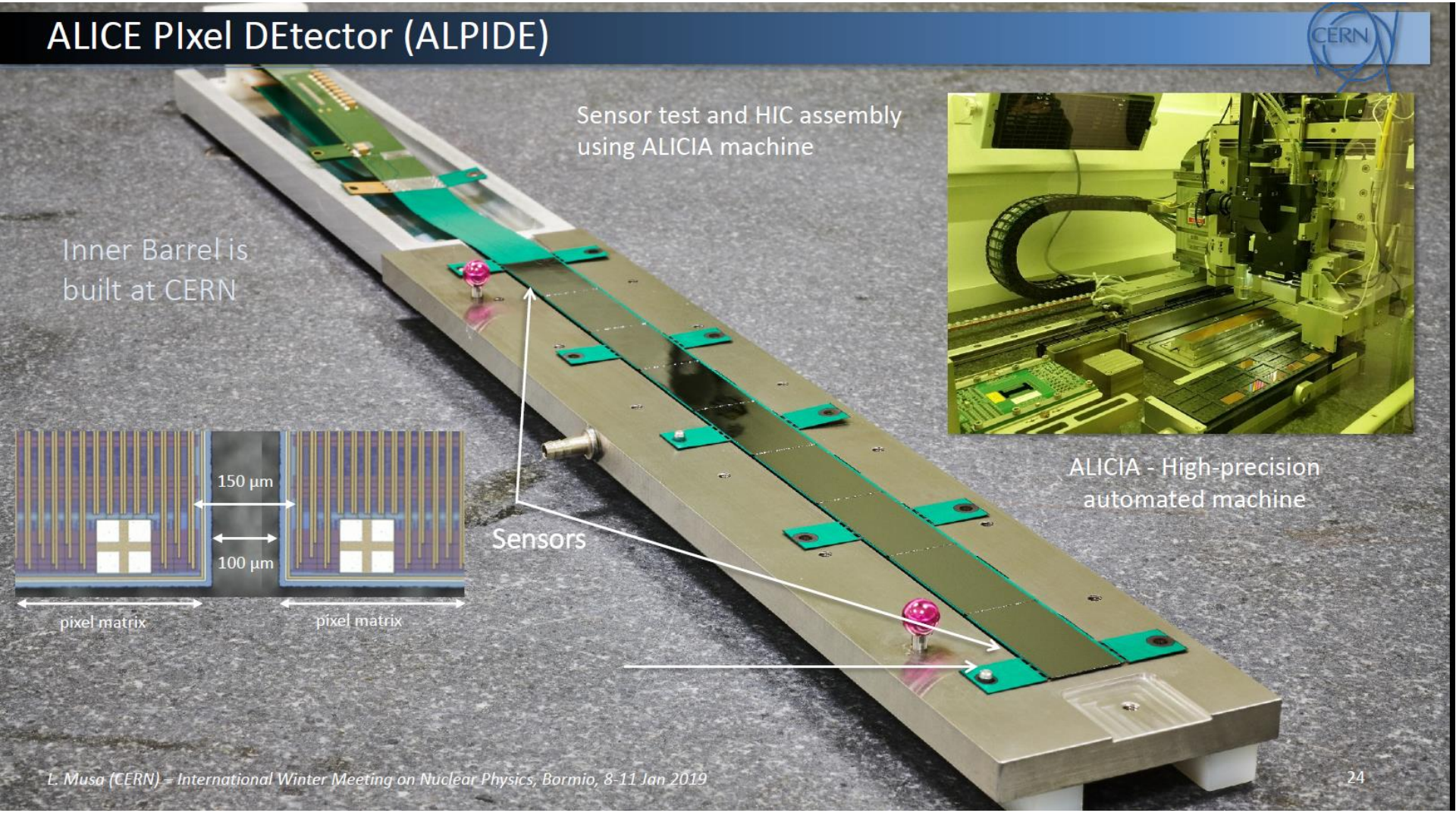


5 μm resolution @ 200 e$^-$ threshold

Chip-to-chip negligible fluctuations

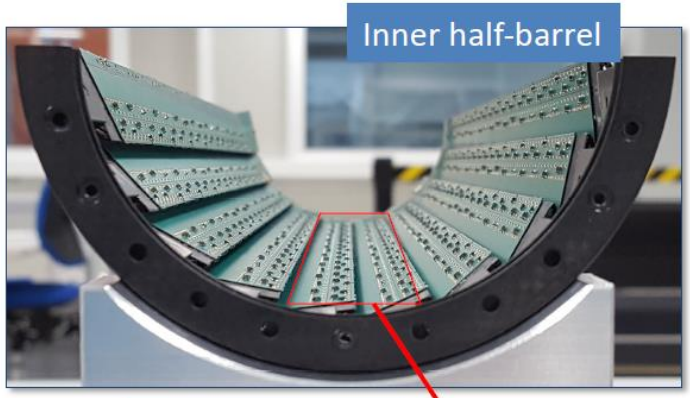
L. Musa (CERN) – International Winter Meeting on Nuclear Physics, Bormio, 8-11 Jan 2019

23

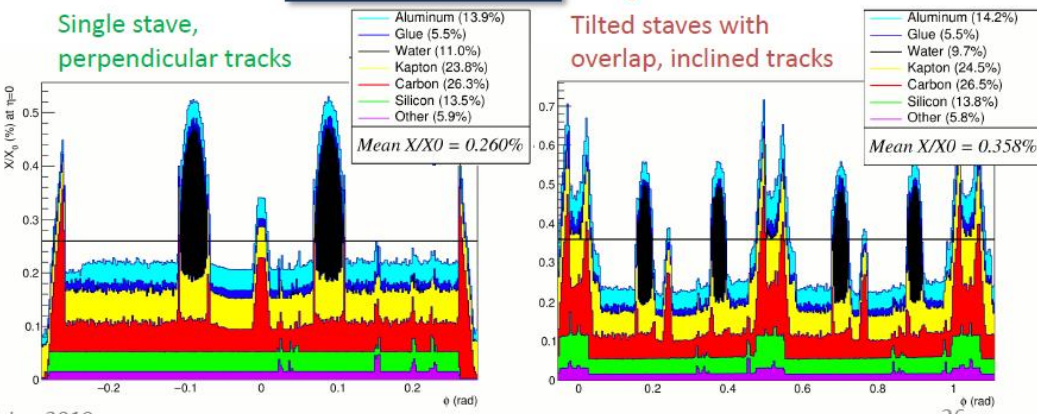

ALICE PIxel DEtector (ALPIDE)
CERN
Sensor test and HIC assembly using ALICIA machine
Inner Barrel is built at CERN
ALICIA - High-precision automated machine
Sensors
150 µm
100 µm
pixel matrix
pixel matrix
L. Musa (CERN) – International Winter Meeting on Nuclear Physics, Bormio, 8-11 Jan 2019
24

ALICE PIxel DEtector (ALPIDE)

Inner Barrel Production completed and all layers assembled



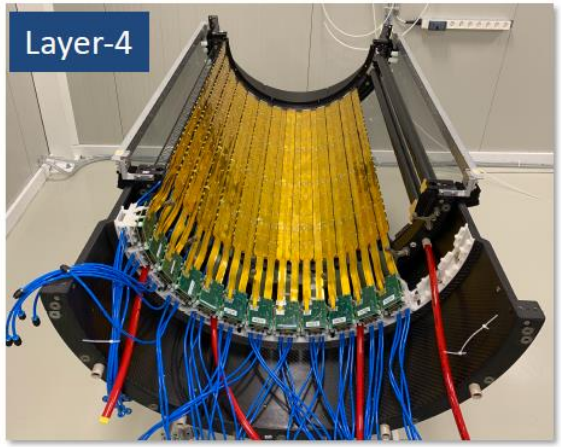
Material budget

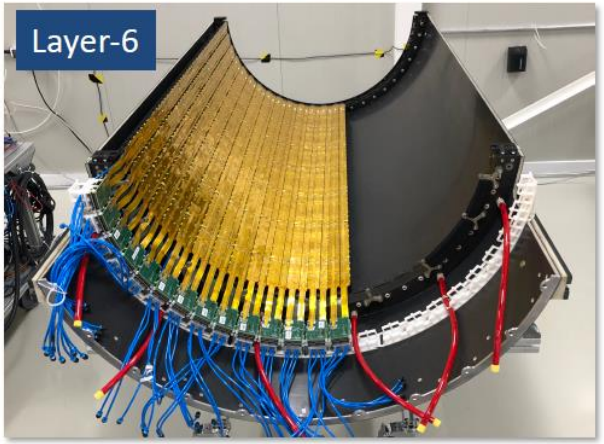


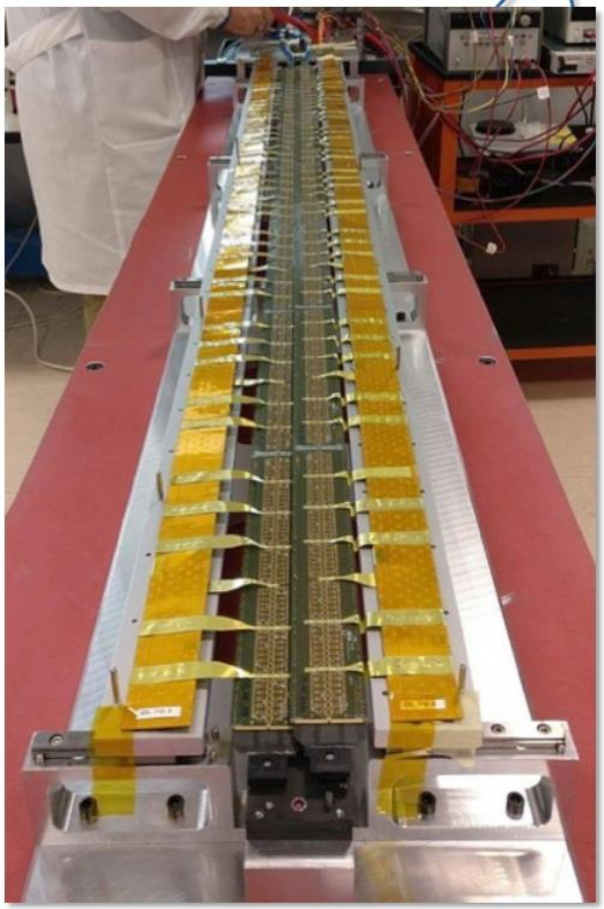
L. Musa (CERN) – International Winter Meeting on Nuclear Physics, Bormio, 8-11 Jan 2019

26

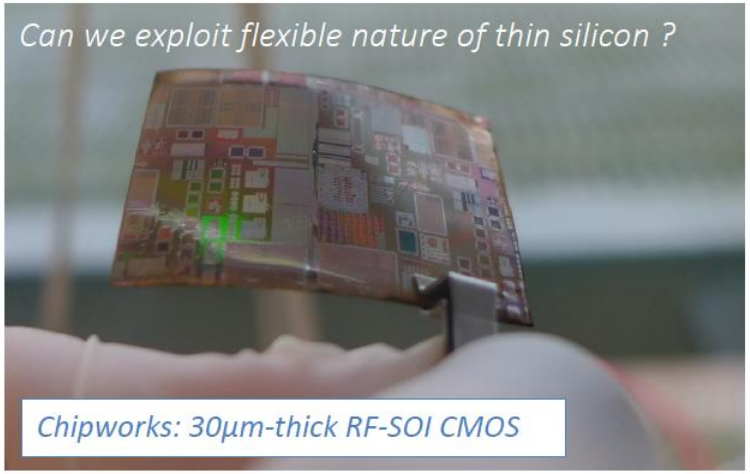
ALICE PIxel DEtector (ALPIDE)







Ultra-thin curved silicon chips



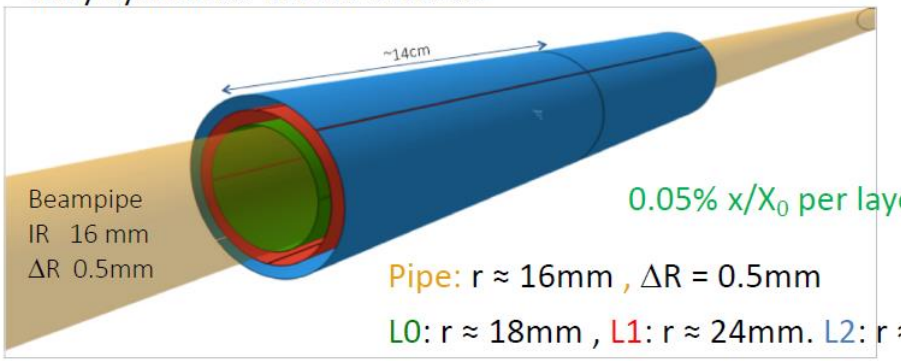
Ultra-thin chip (<50 um): flexible with good stability

Die type	Front/back side	Ground/polished/plasma	Bumps	Die thickness (µm)	CDS (MPa)	Weibull modulus	MDS (MPa)	r_{min} (mm)
Blank	Front	Ground	No	15–20	1263	7.42	691	2.46
Blank	Back	Ground	No	15–20	575	5.48	221	7.72
IZM28	Front	Ground	Yes	15–20	1032	9.44	636	2.70
IZM28	Back	Ground	Yes	15–20	494	2.04	52	32.7
Blank	Back	Polished	No	25–35	1044	4.17	334	7.72
IZM28	Back	Polished	Yes	25–35	482	2.98	107	24.3
Blank	Back	Plasma	Yes	18–22	2340	12.6	679	2.50
IZM28	Front	Plasma	Yes	18–22	1207	2.64	833	2.05
IZM28	Back	Plasma	Yes	18–22	2139	3.74	362	4.72

van den Ende DA et al. *Mechanical and electrical properties of ultra-thin chips and flexible electronics assemblies during bending.* Mircoelectron reliab (2014), http://dx.doi.org/10.1016/j.microrel.2014.07.125

Vertex Detector (innermost 3 layers)

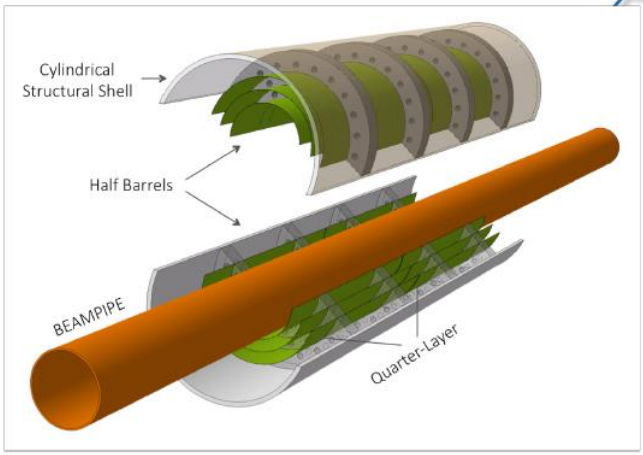
Truly cylindrical vertex detector



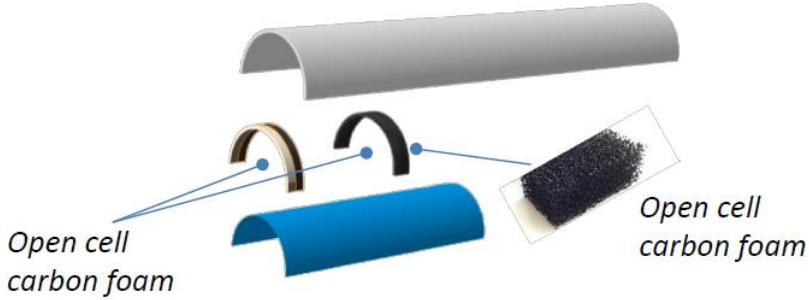
0.05% x/X_0 per layer

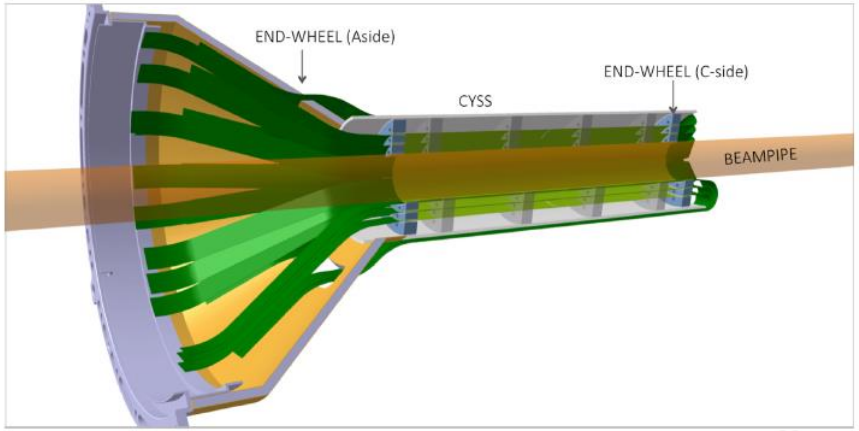
Pipe: r ≈ 16mm , ΔR = 0.5mm

L0: r ≈ 18mm , L1: r ≈ 24mm. L2: r ≈ 30 mm



Layers supported by high-thermal conductive carbon foam





L. Musa (CERN) – International Winter Meeting on Nuclear Physics, Bormio, 8-11 Jan 2019

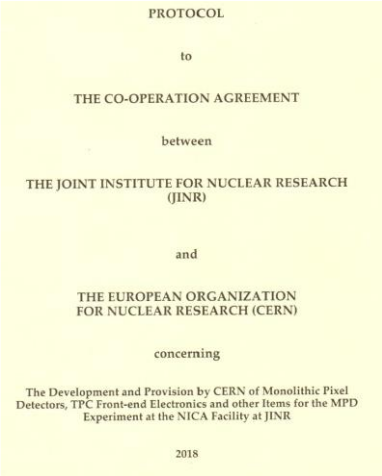
33

MPD-ITS (OB) is now recognized at Stage I

Stage I: TPC, TOF, ECAL, ZDC, FFD + ITS(OB)

Stage II : ITS(IB) + EndCap (CPC, Straw, TOF, ECAL)

Transfer of High Tech Instrumentation Know-How from CERN to NICA-MPD



PROTOCOL

to

THE CO-OPERATION AGREEMENT

between

THE JOINT INSTITUTE FOR NUCLEAR RESEARCH (JINR)

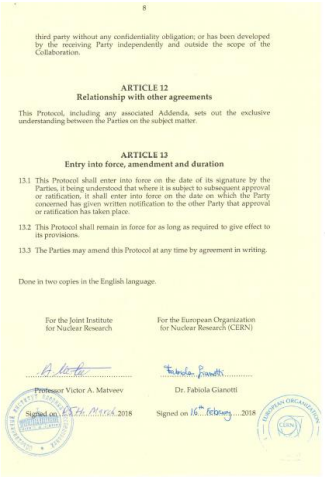
and

THE EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

concerning

The Development and Provision by CERN of Monolithic Pixel Detectors, TPC Front-end Electronics and other Items for the MPD Experiment at the NICA Facility at JINR

2018



8

third party without any confidentiality obligation; or has been developed by the receiving Party independently and outside the scope of the Collaboration.

ARTICLE 12
Relationship with other agreements

This Protocol, including any associated Addenda, sets out the exclusive understanding between the Parties on the subject matter.

ARTICLE 13
Entry into force, amendment and duration

13.1 This Protocol shall enter into force on the date of its signature by the Parties, it being understood that where it is subject to subsequent approval or ratification, it shall enter into force on the date on which the Party concerned has given written notification to the other Party that approval or ratification has taken place.

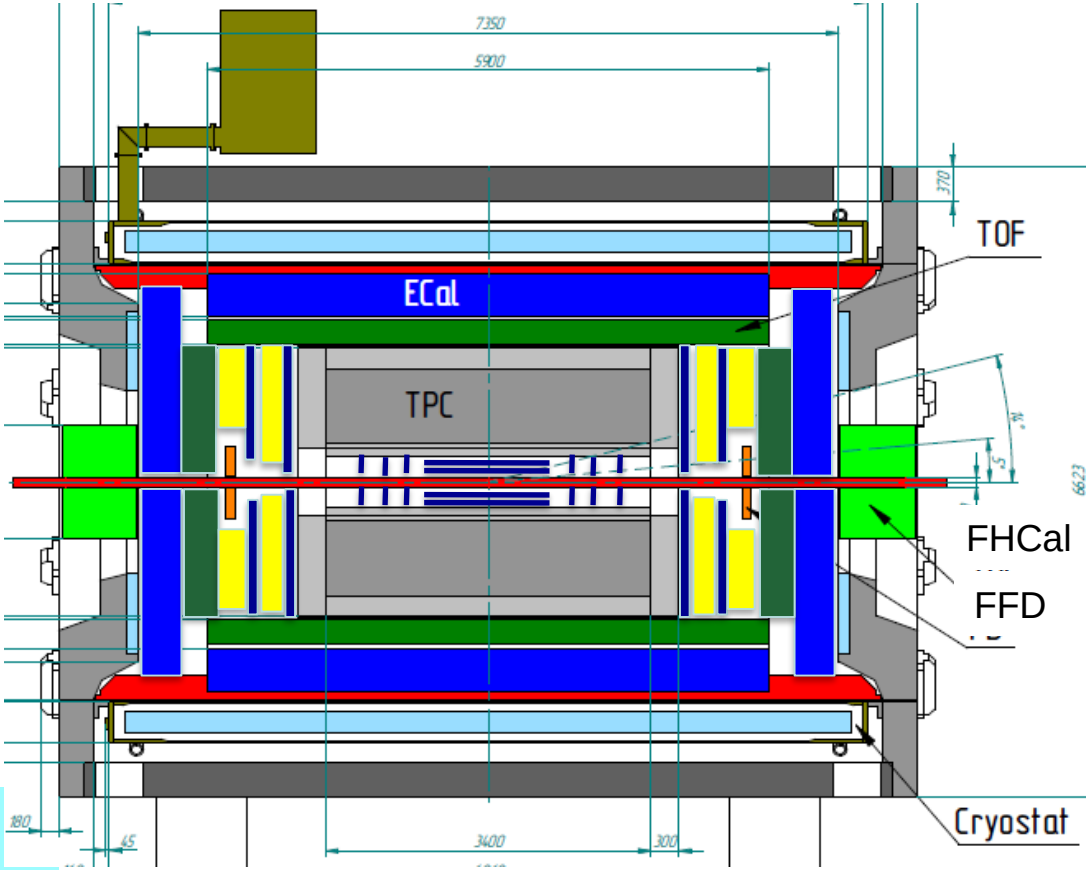
13.2 This Protocol shall remain in force for as long as required to give effect to its provisions.

13.3 The Parties may amend this Protocol at any time by agreement in writing.

Done in two copies in the English language.

For the Joint Institute for Nuclear Research — Professor Victor A. Matveev — Signed on 15th March 2018

For the European Organization for Nuclear Research (CERN) — Dr. Fabiola Gianotti — Signed on 16th February 2018



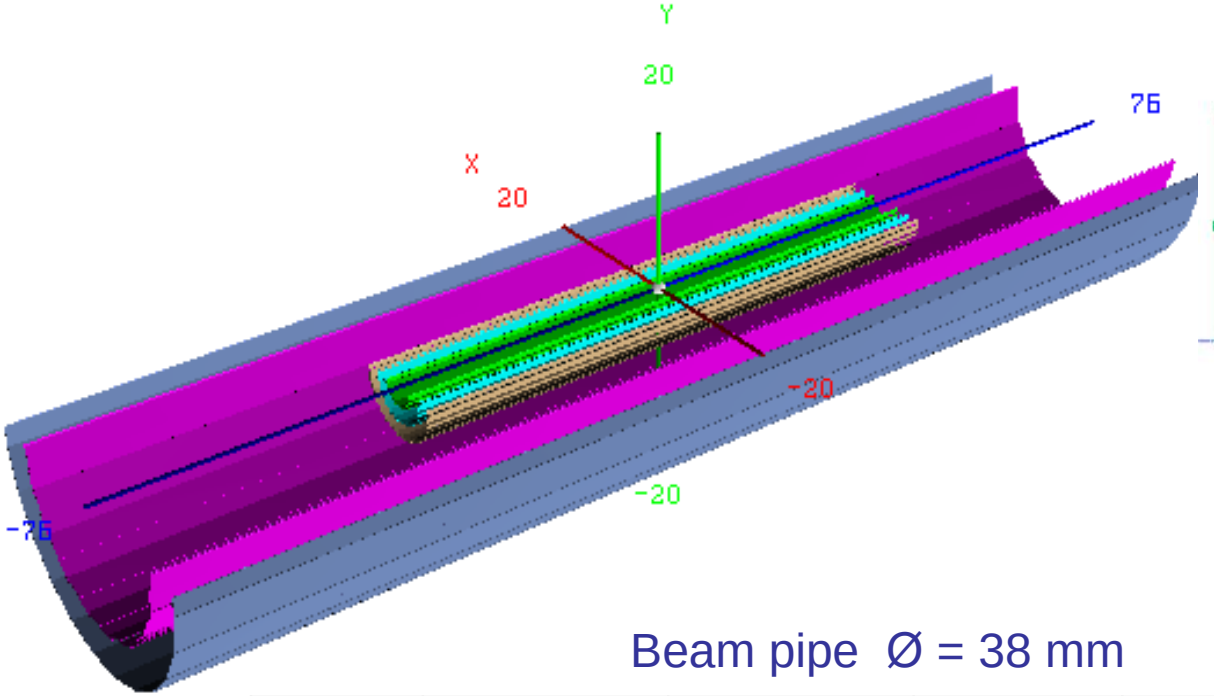
Stage I: *overall commissioning starts in* ***2022 (t.b.c.)***

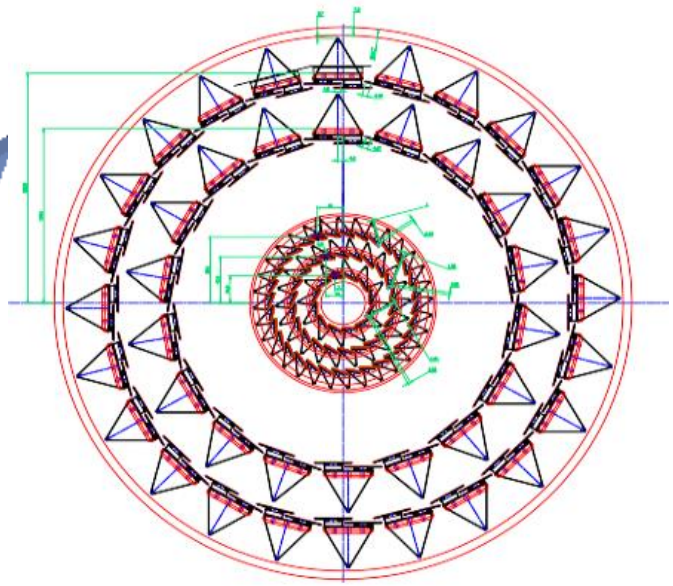
Items to be shipped from CERN formulated in Addendums to the Protocol

CERN will procure, test and deliver to NICA

- 19'000 ALPIDE Monolithic Active Pixel Sensors for the MPD ITS
- 4'500 SAMPA electronic circuits for the TPC readout
- 5'000 FEAST DC/DC converters for the ECAL MPD
- Jigs and fixtures for module and supermodule assembly for the MPD ITS
- Training of personal for assembly and QA certification modules and supermodules of the MPD ITS
- Provision of complete technical and commercial information on parts of the new ALICE Inner Tracking System, including drawings, internal technical reports, quotes, etc.

MPD ITS based on the ALPIDE MAPS CERN technology

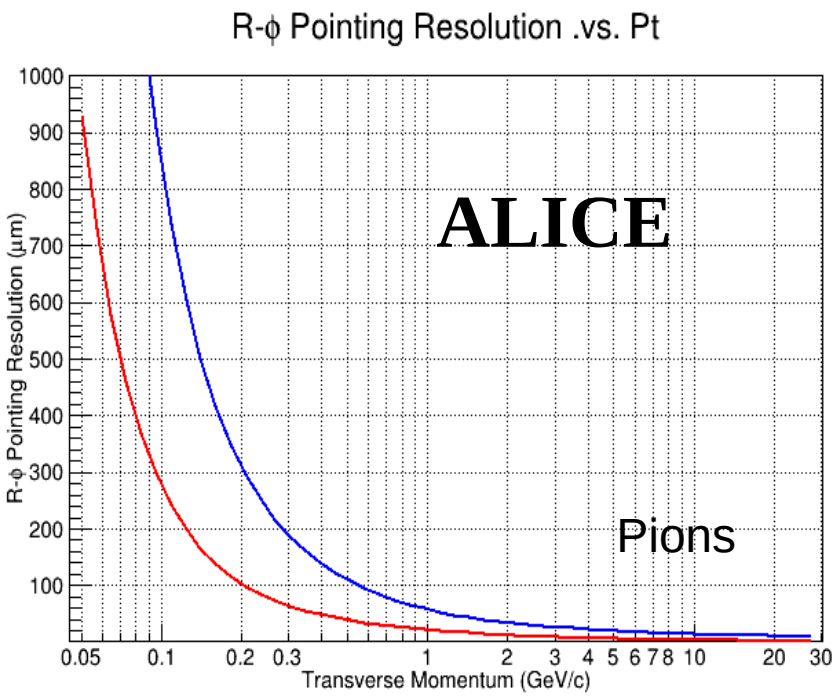


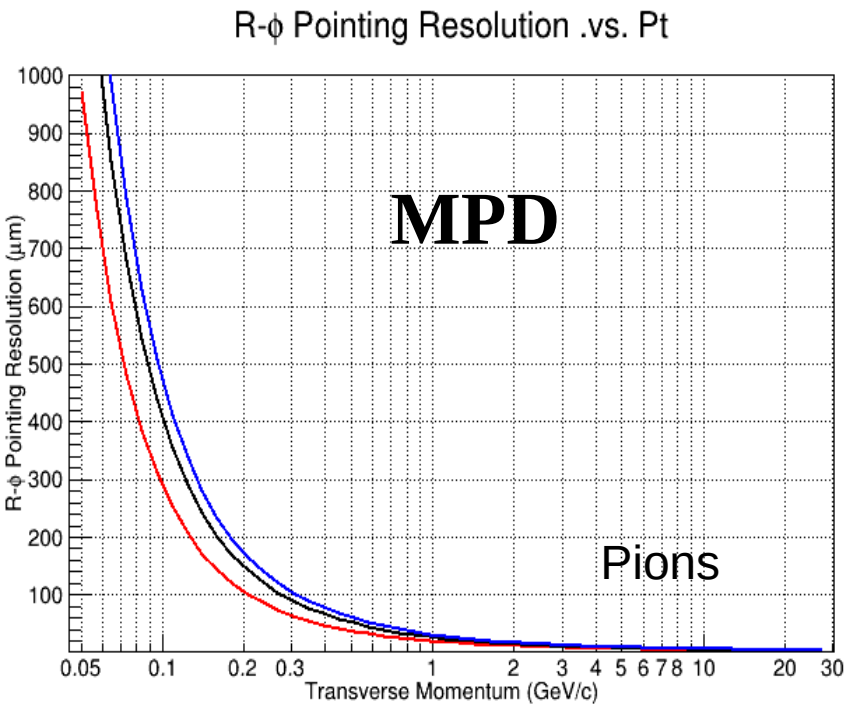


Beam pipe Ø = 38 mm

Layer	Number of staves	Number of ALPIDEs per a stave	R_{min}, mm	R_{max}, mm	Ladder active length, mm
1	12	12	22.4	26.7	360
2	22	23	40.7	45.9	608
3	32	37	59.8	65.1	708
4	18	196	144.5	147.9	1190
5	24	196	194.4	197.6	1468

ITS pointing resolution within STAR-ALICE toy model





New ITS

Old ITS

Ø = 40 mm

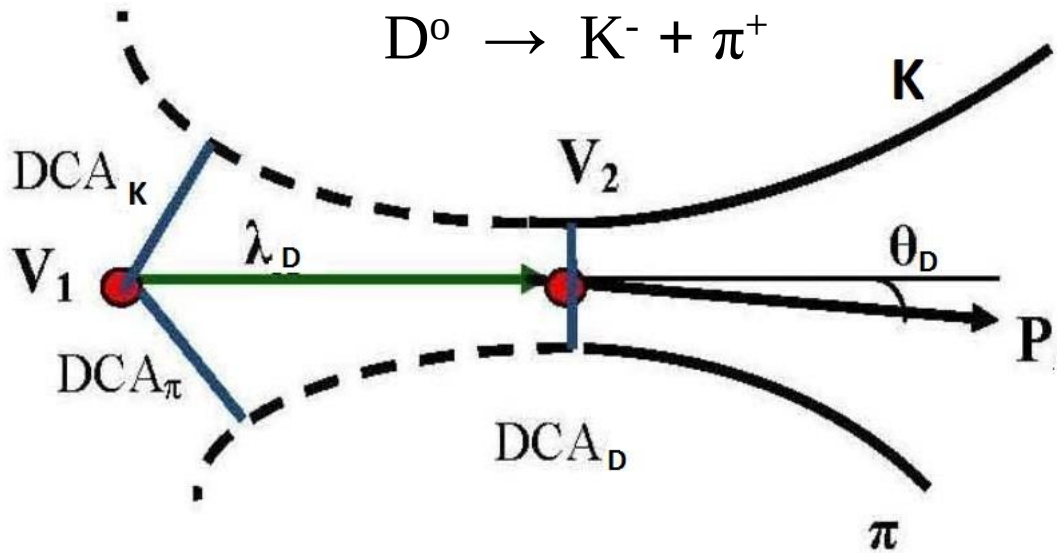
Ø = 50 mm

Ø = 60 mm

Selection criteria

D^0 selection parameters:

- distances of closest approach to the collision vertex $DCA_{\pi,K}$,
- two-track separation DCA_D ,
- decay path λ_D,
- pointing angle θ_D.



Selection criteria:

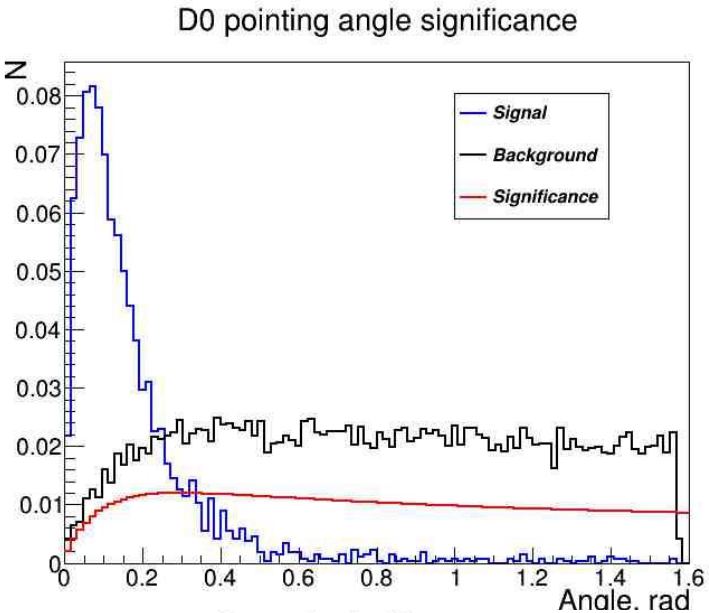
$DCA_\pi > C_1$ && $DCA_K > C_2$ && $DCA_D < C_3$ && $\lambda_D > C_4$ && $\theta_D < C_5$

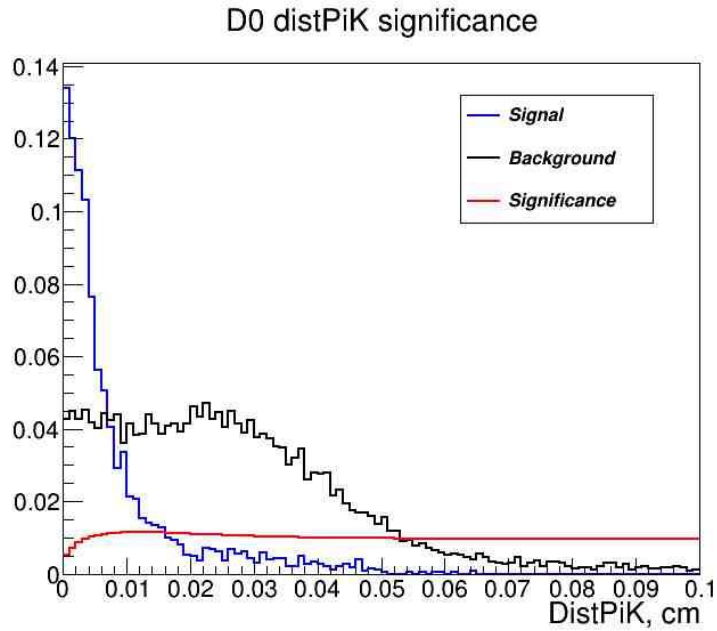
The parameters of the corresponding selections are optimized by maximizing the signal significance :

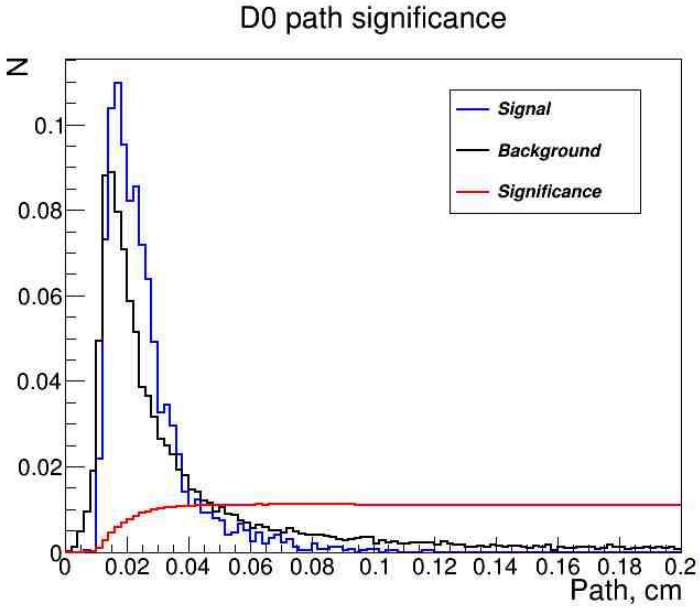
$$Sg(a) = \int_0^a \frac{S}{\sqrt{S+B}} da$$

where S and B are the estimated numbers of the signal and background events.

D^0 reconstruction – cut selection

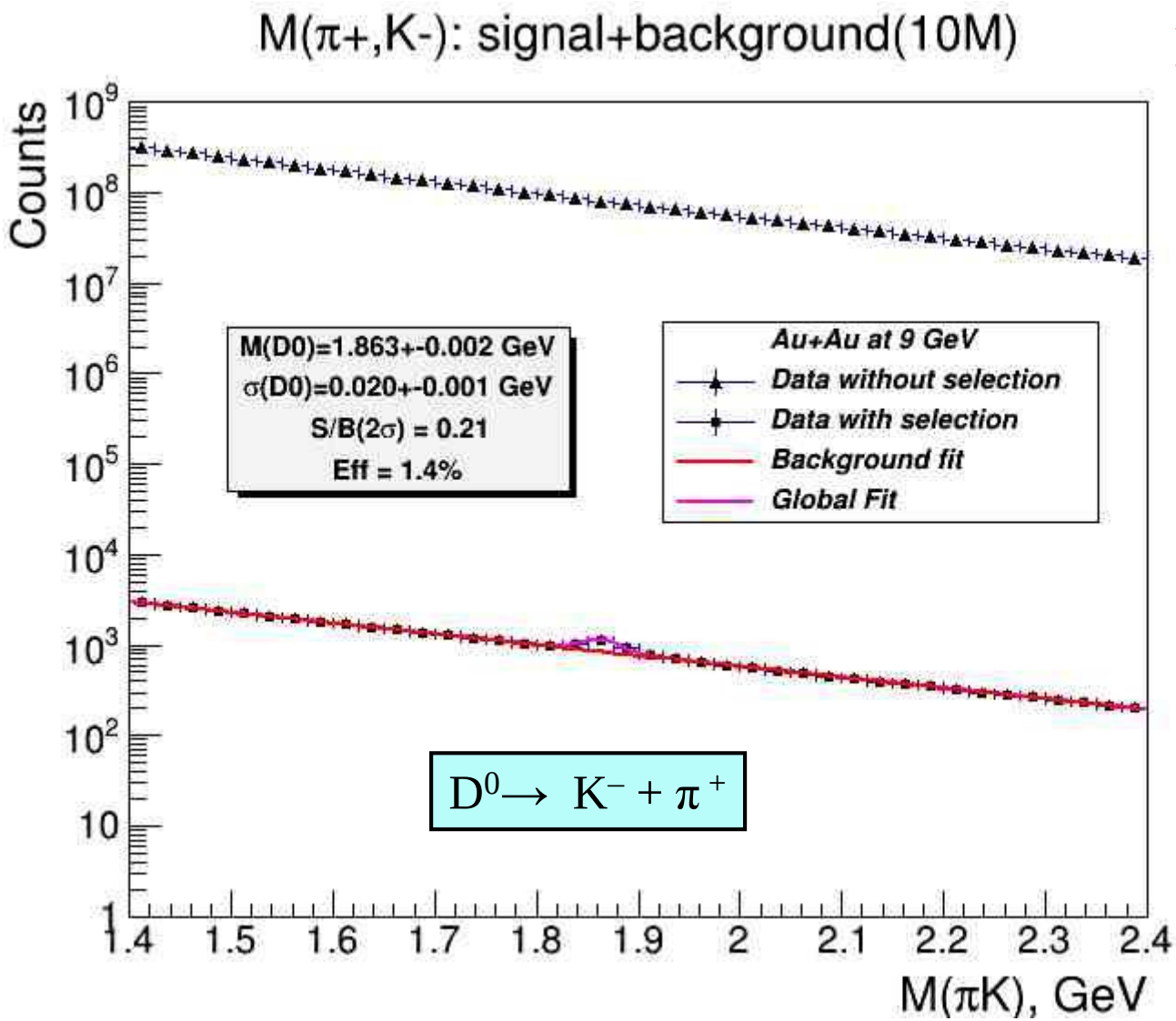






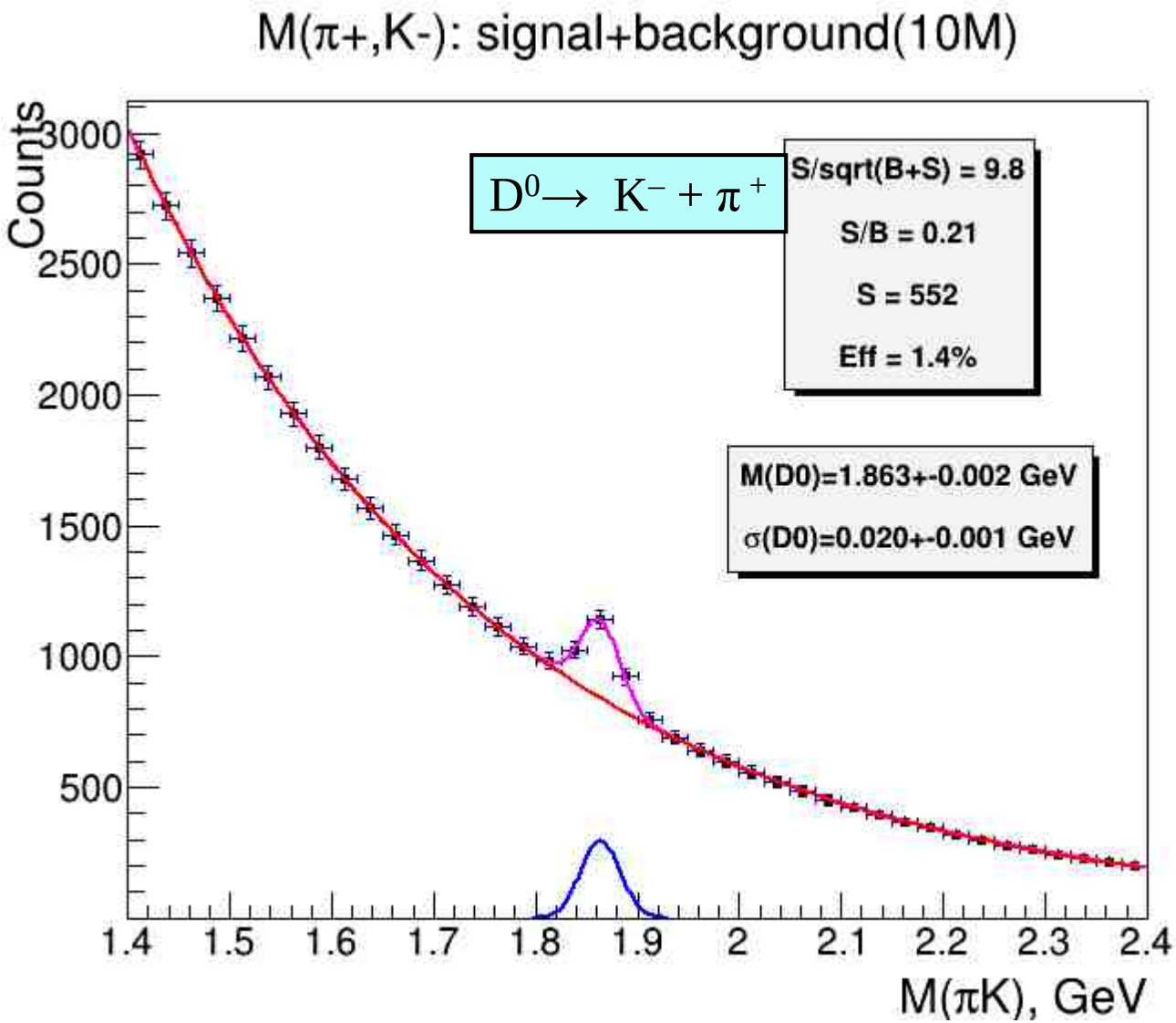
dcaK>0.01 cm &
dcaPi>0.01 cm &
distPiK < 0.02 cm &
path(D^0) > 0.025 cm &
angle(D^0) < 0.2 rad

D^0 reconstruction – invariant mass spectrum for ITS#1



ITS – option#1:
t1=t2=t3=50μ
t4=t5=700μ

D^0 reconstruction – invariant mass spectrum for ITS #1

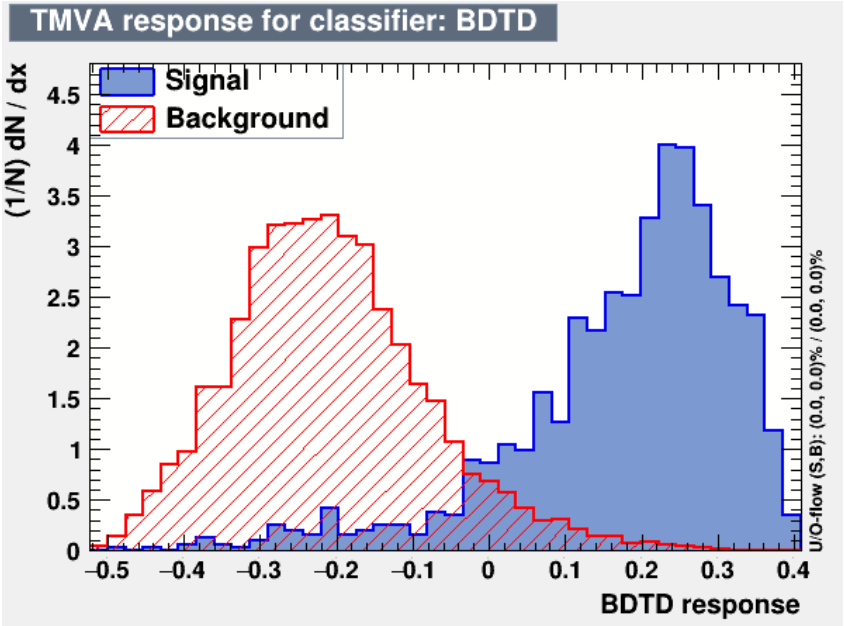


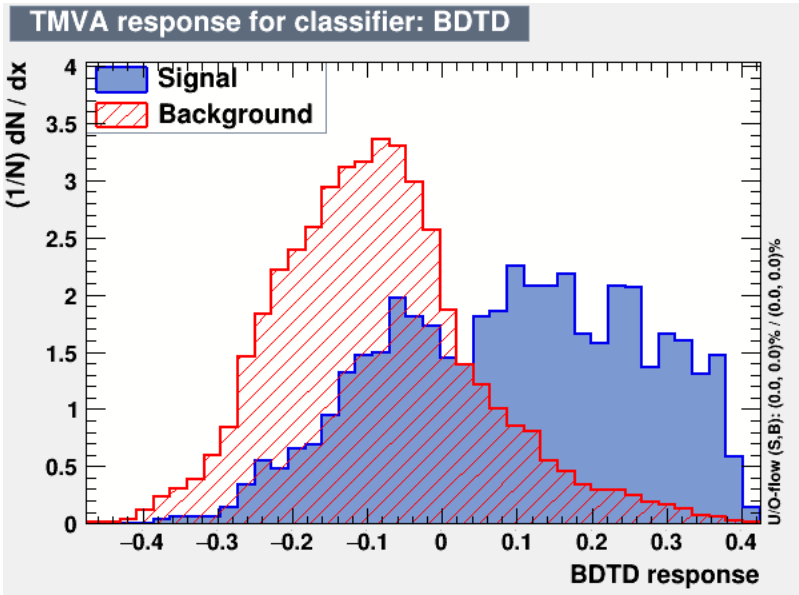
t1=t2=t3=50μ
t4=t5=700μ

D^0 reconstruction – TMVA selection

IT – option#1:
t1=t2=t3=50μ (IB ITS3)
t4=t5=700μ (OB ITS2)

IT – option#2:
t1=t2=t3=200μ (IB ITS2)
t4=t5=700μ (OB ITS2)



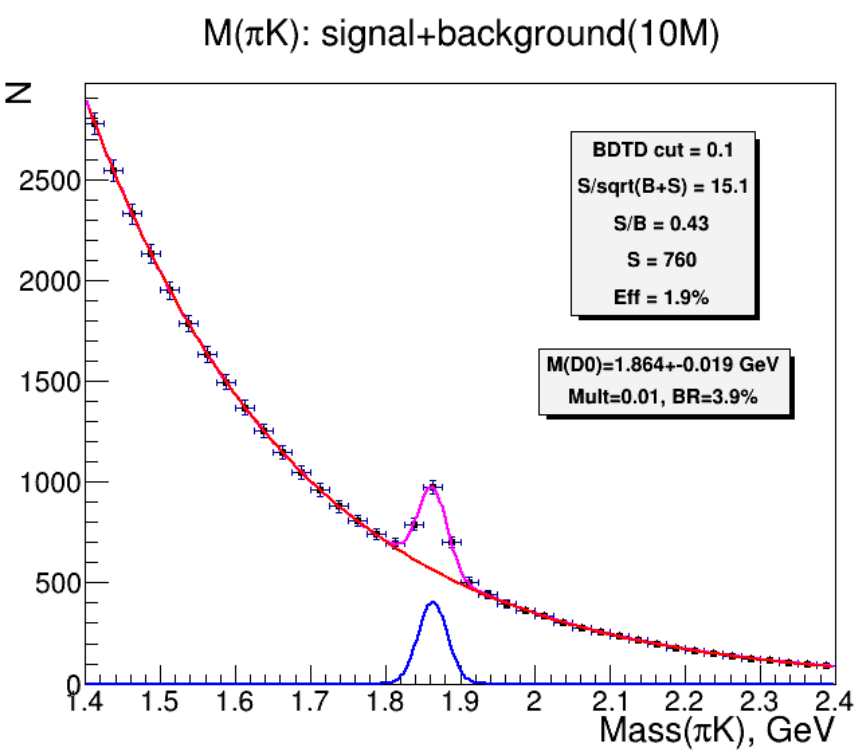


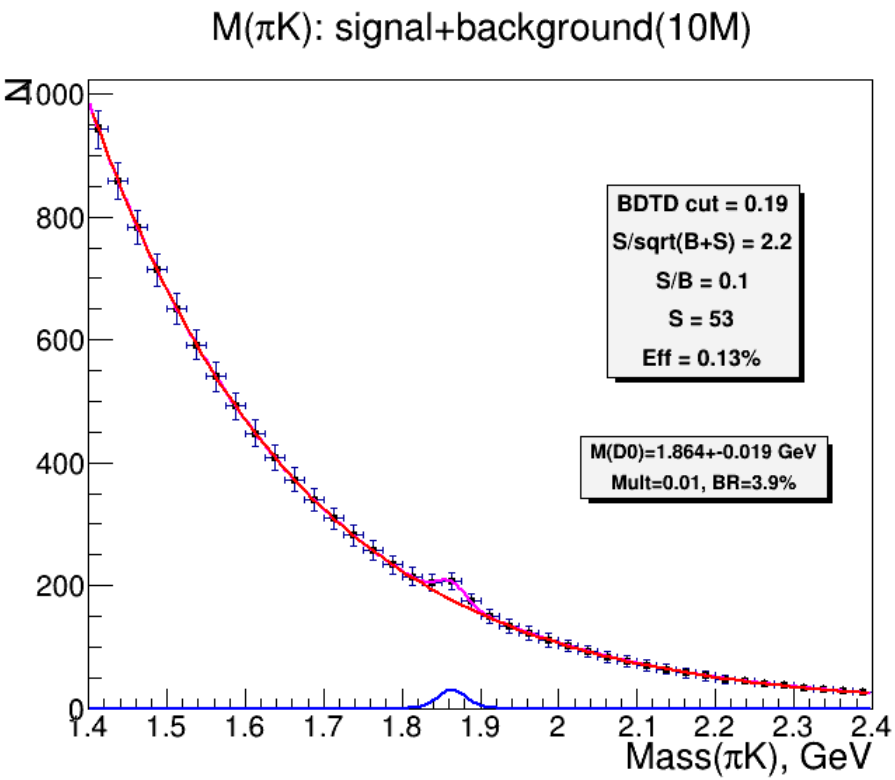
DCA(π, K,D^0), path(D^0),angle(D^0) cuts → BDTD cut

D^0 reconstruction – invariant mass spectrum

ITS – option#1:
t1=t2=t3=50μ (IB ITS3)
t4=t5=700μ (OB ITS2)

ITS – option#2:
t1=t2=t3=200μ (IB ITS2)
t4=t5=700μ (OB ITS2)





Preliminary results of TMVA-BDTD simulations of 10M 9 GeV central Au-Au central collisions (V. Kondratiev)

D^+ reconstruction – TMVA selection

ITS – option#1:

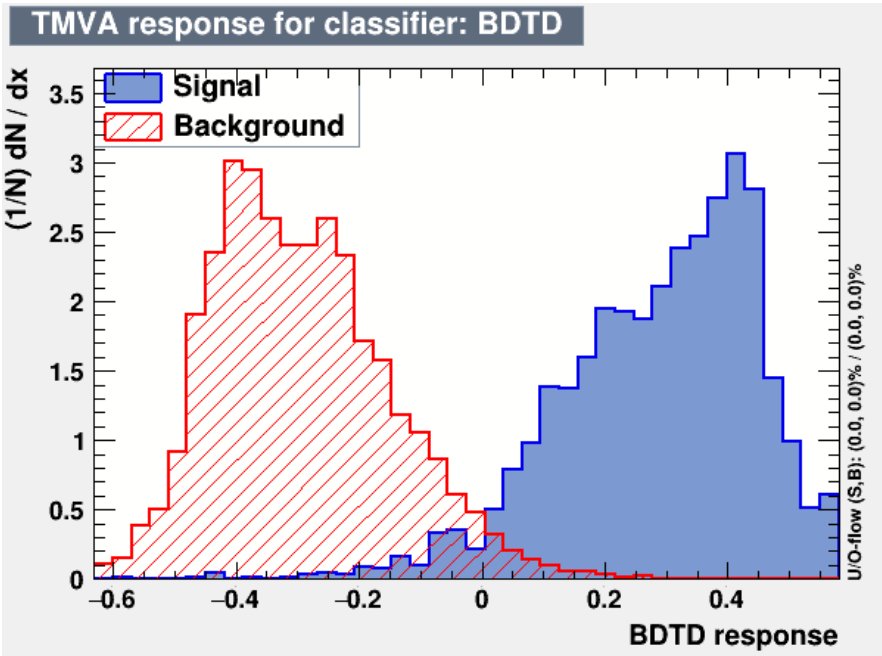
t1=t2=t3=50μ (IB ITS3)

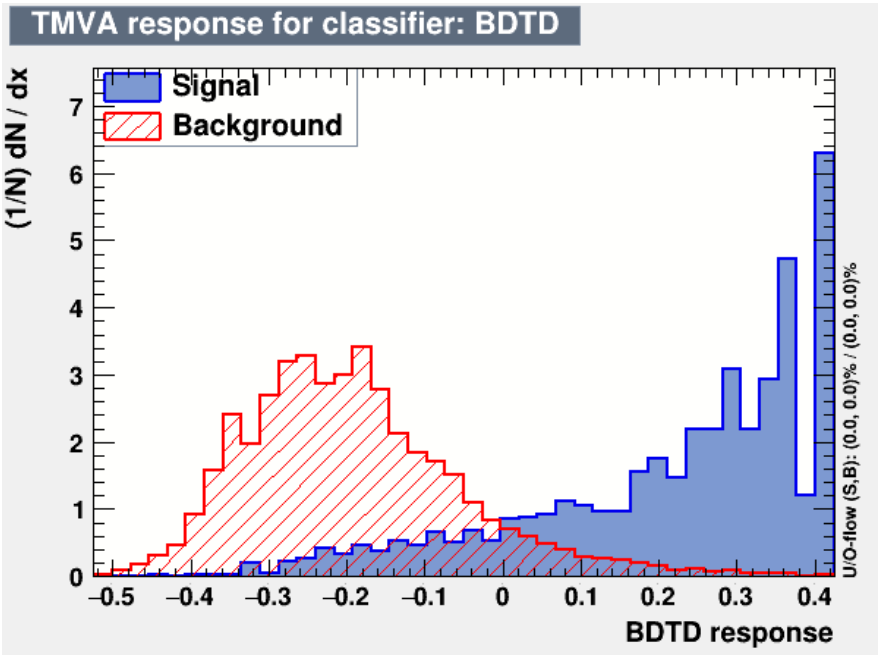
t4=t5=700μ (OB ITS2)

IT – option#2:

t1=t2=t3=200μ(IB ITS2)

t4=t5=700μ (OB ITS2)



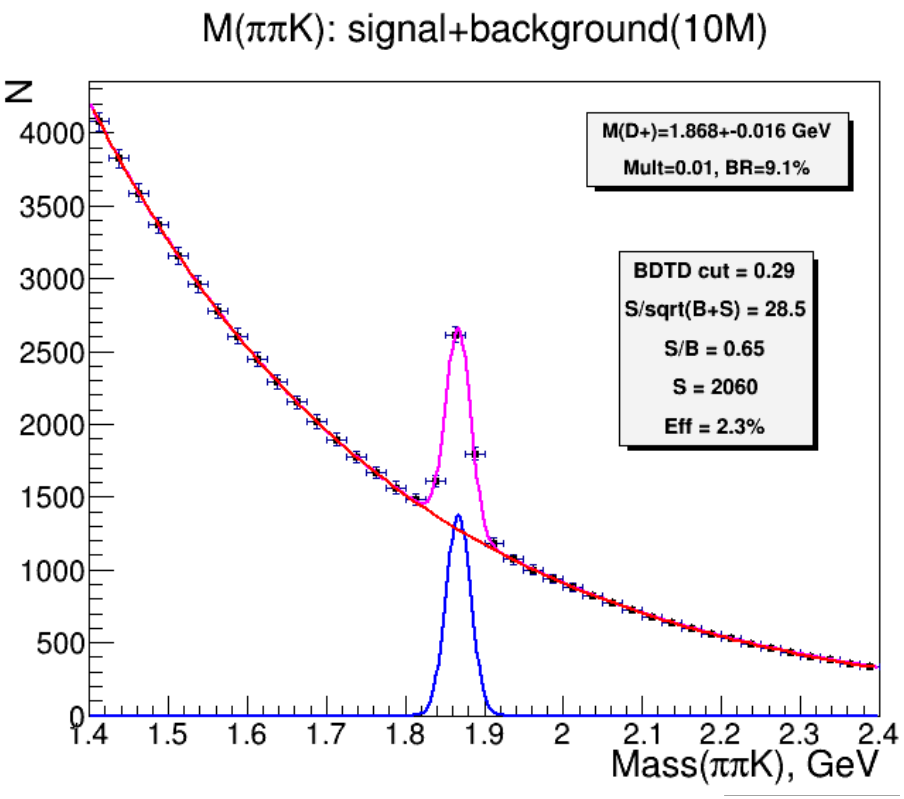


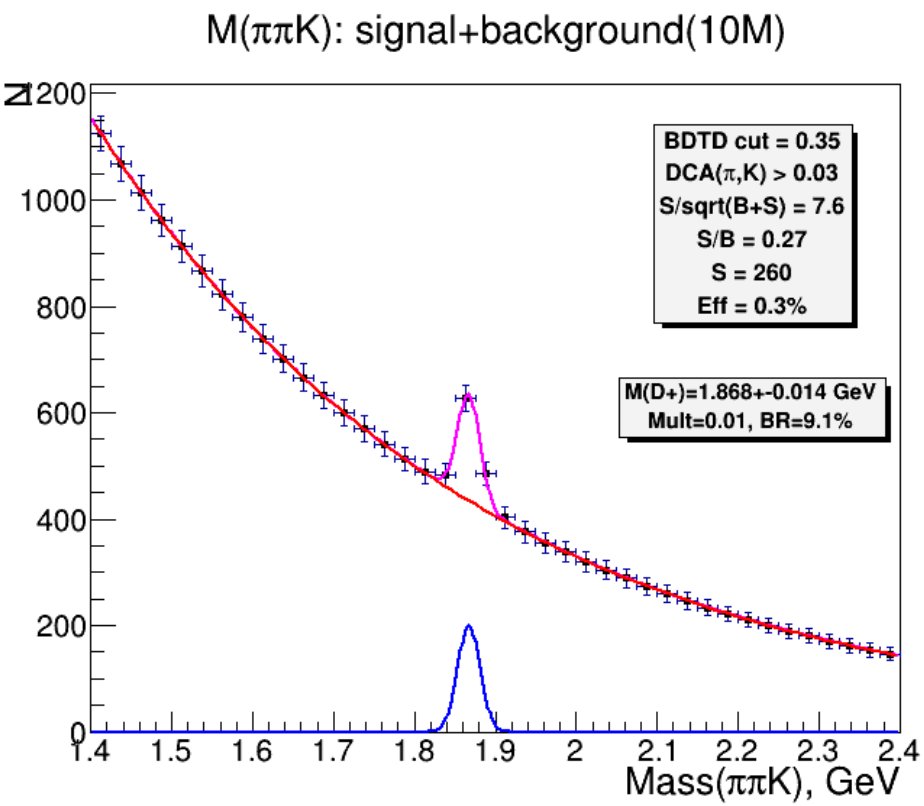
DCA(π, K,D^+), path(D^+),angle(D^+) cuts → BDTD cut

D^+ reconstruction – invariant mass spectrum

ITS – option#1:
t1=t2=t3=50μ (IB ITS3)
t4=t5=700μ (OB ITS2)

ITS – option#2:
t1=t2=t3=200μ (IB ITS2)
t4=t5=700μ (OB ITS2)



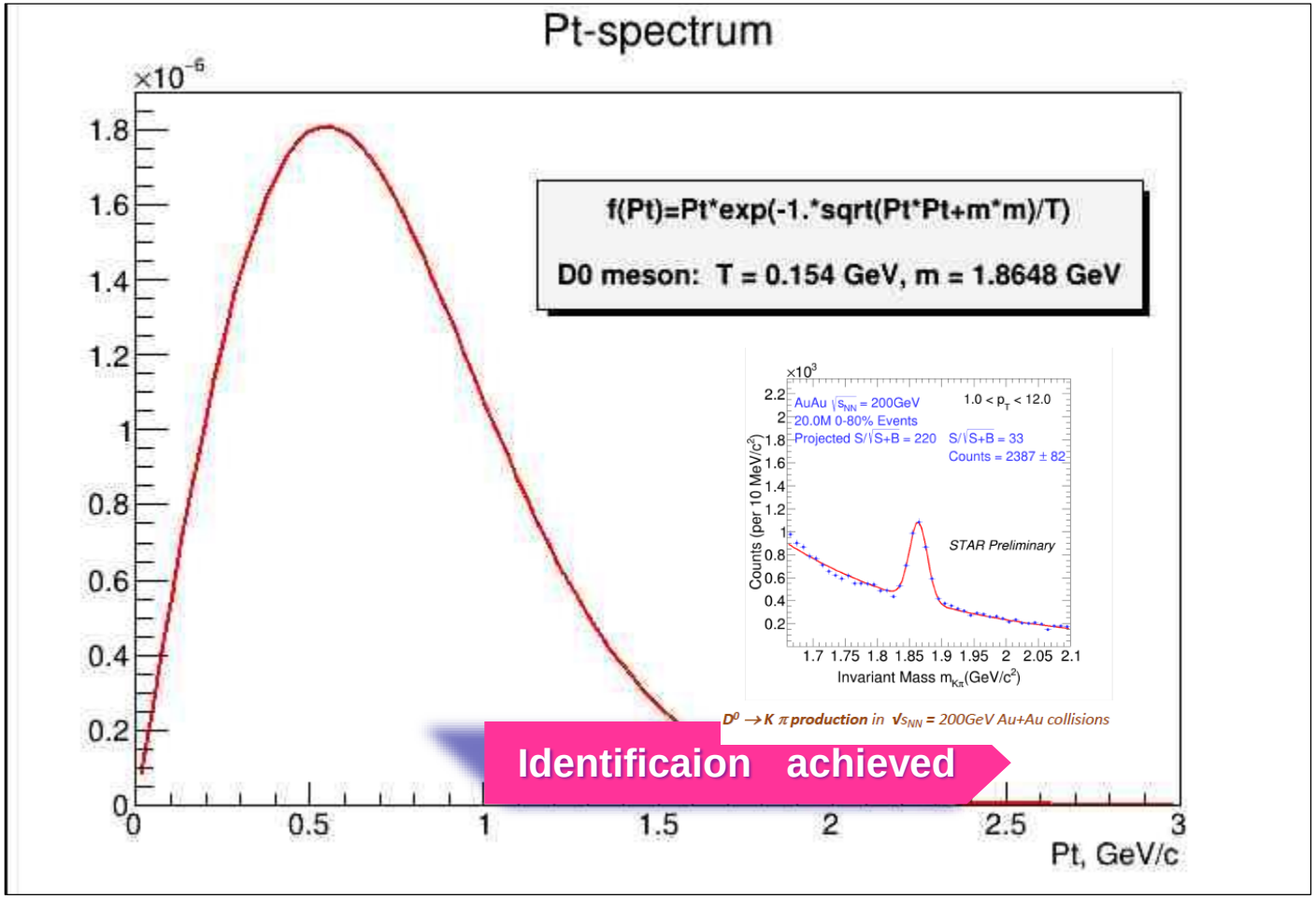


Preliminary results of TMVA-BDTD simulations of 10M 9 GeV central Au-Au central collisions (V. Kondratiev)

D-meson parameters in 100M central Au+Au collisions at $\sqrt{s_{NN}} = 9$ ГэВ

Particle	D^0		D^+	
Decay channel	$D^0 \rightarrow K^- + \pi^+$		$D^+ \rightarrow K^- + \pi^+ + \pi^+$	
Multiplicity (HSD	10^{-2}		10^{-2}	
BR,%	3.9		9.1	
IT option	#1	#2	#1	#2
S/B(2σ)	0.43	0.10	0.65	0.27
Significance	15.1	2.2	28.5	7.6
Efficiency,%	1.9	0.13	2.3	0.3

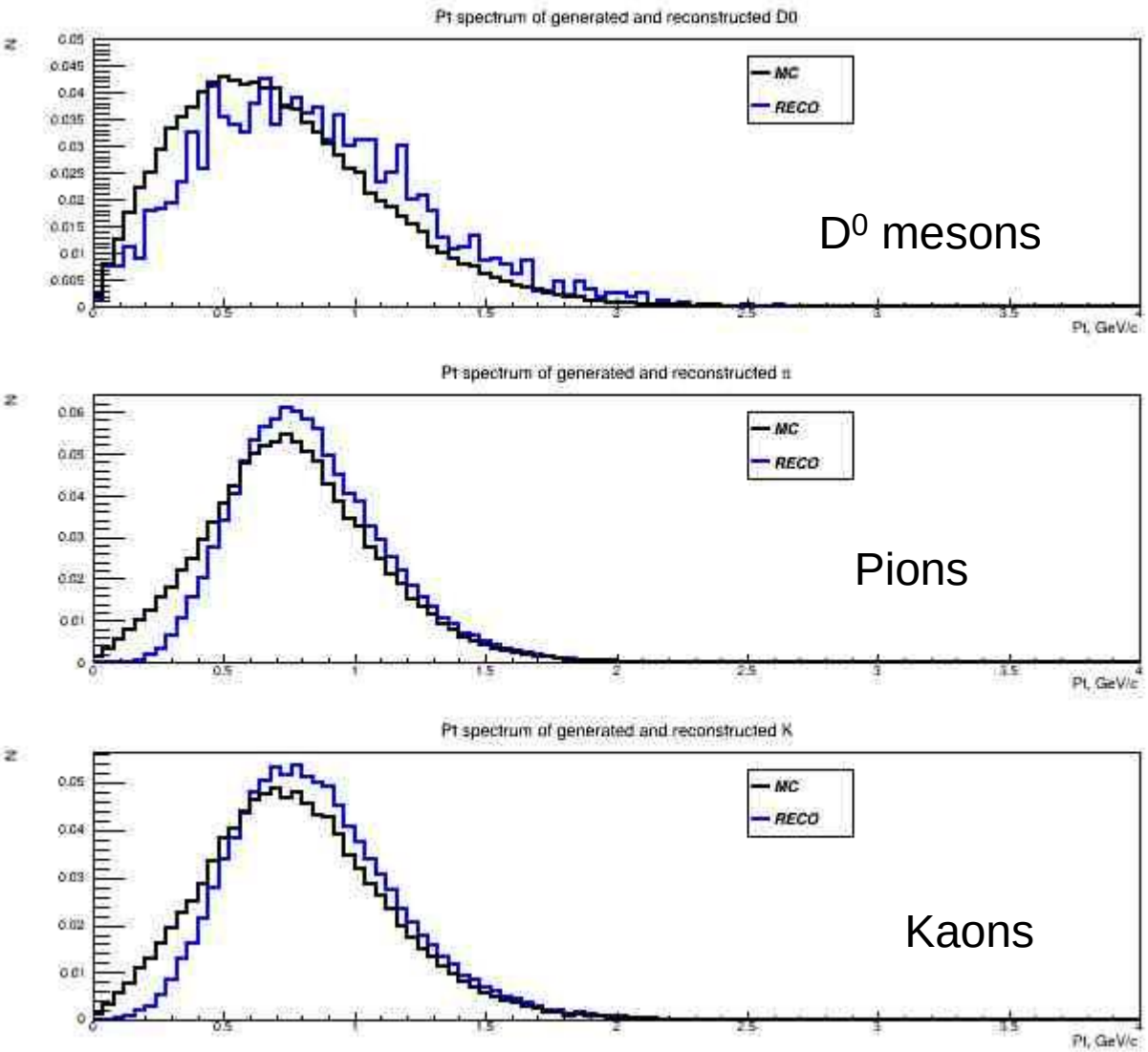
Current limitations of experimental data on D meson



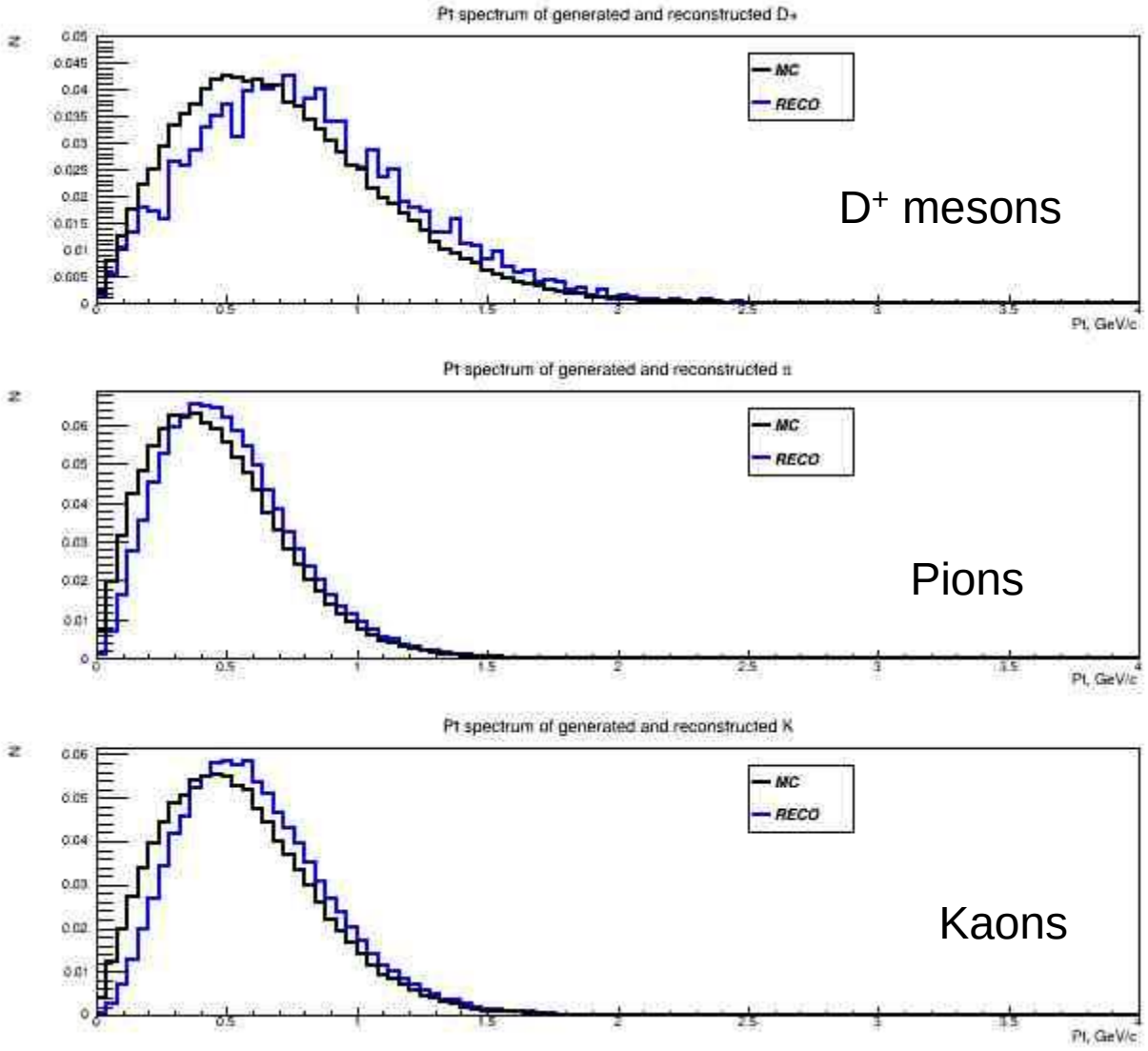
Thermal generator: D meson's p_t - spectrum

Abdel Nasser TAWFIK† and Ehab ABBAS
Thermal Description of Particle Production in Au-Au Collisions at STAR Energies
Physics of Particles and Nuclei Letters. November 2013

MC and reconstructed p_t-spectra of D^0-mesons and their decay products



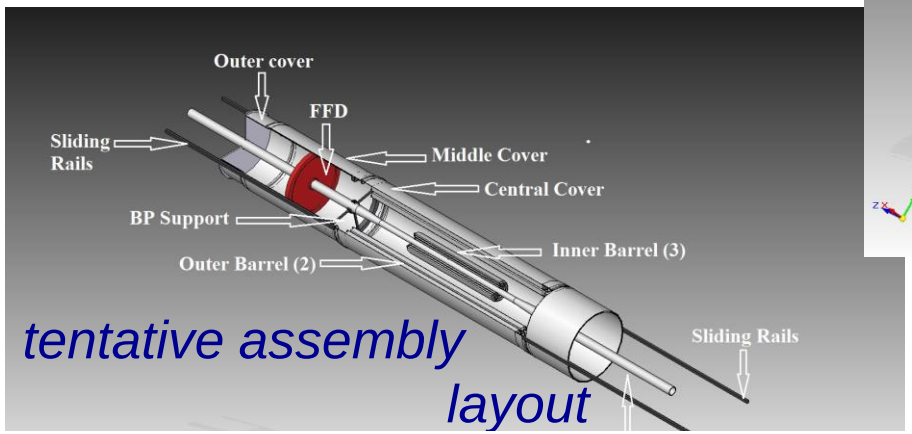
MC and reconstructed p_t-spectra of D^+-mesons and they decay products



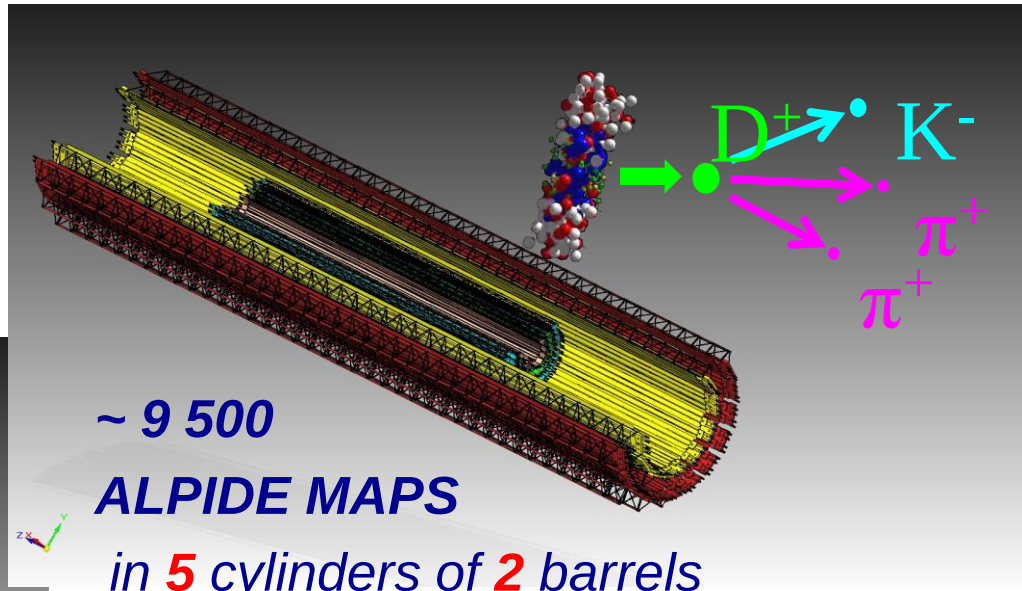
ITS realization in two Steps (OB first) due to BP sequence

Stage I: Installation of OB (2022-23)

Stage II: OB+IB (2022+25) ?



tentative assembly layout



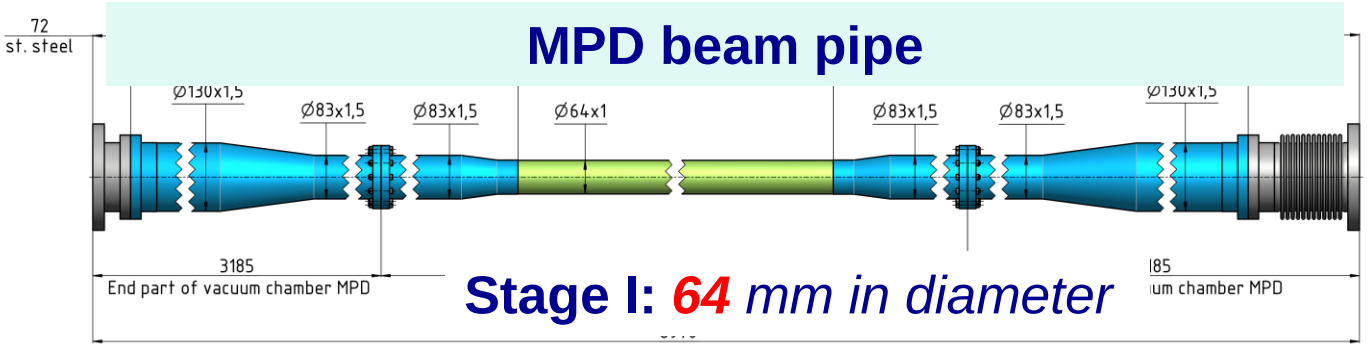
~ 9 500

ALPIDE MAPS

*in **5** cylinders of **2** barrels*

4,9 ·10⁹ *pixels, active area* ***3,9 m²****.*

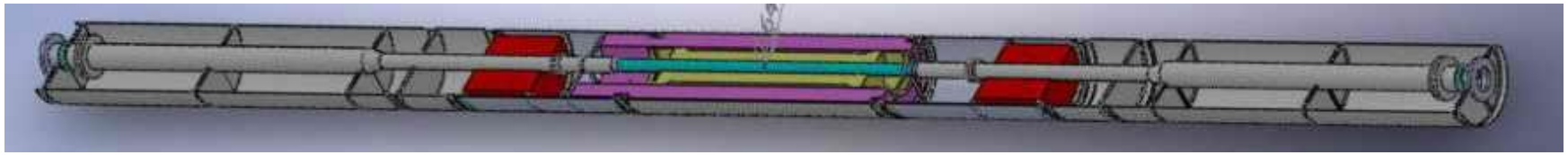
MPD beam pipe

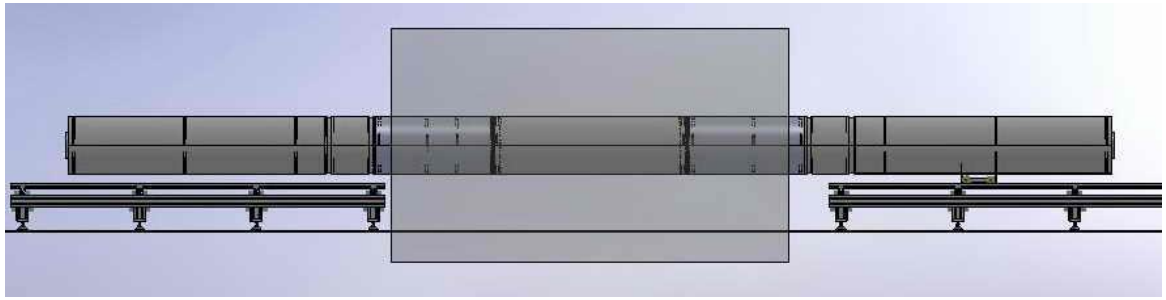


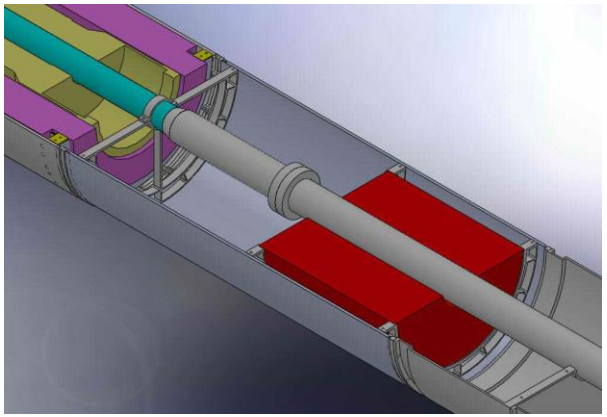
Stage I: ***64*** *mm in diameter*

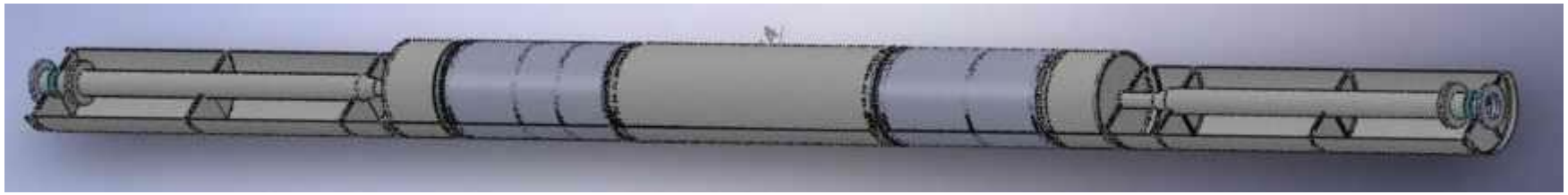
Stage II:
38 *mm in diameter*

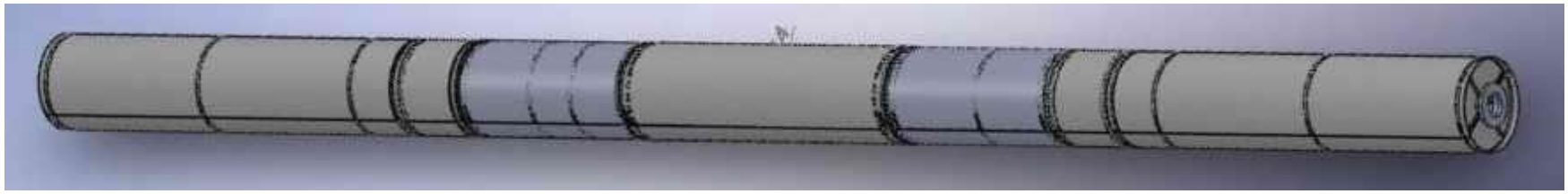
Task 1. Mechanics for integration with the TPC - JINR



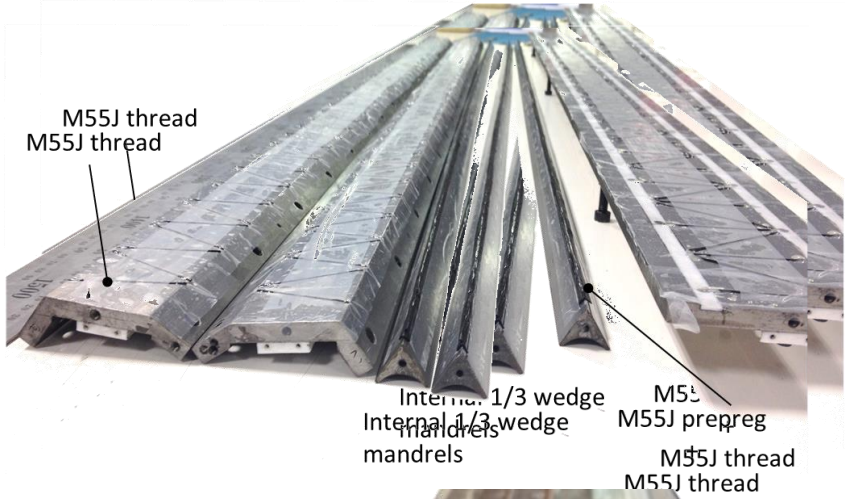


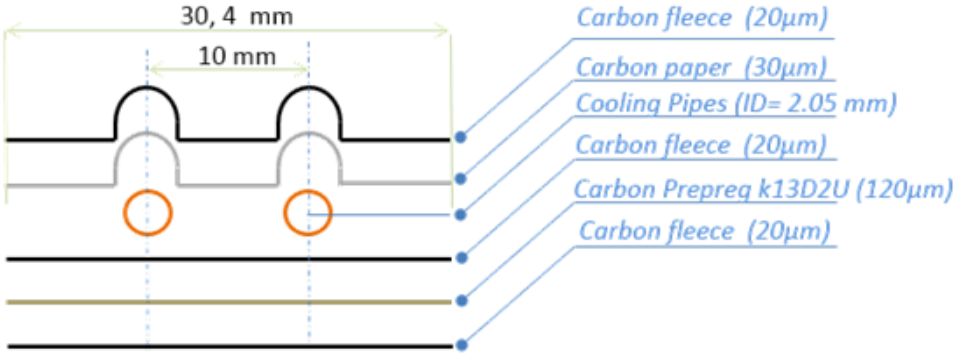




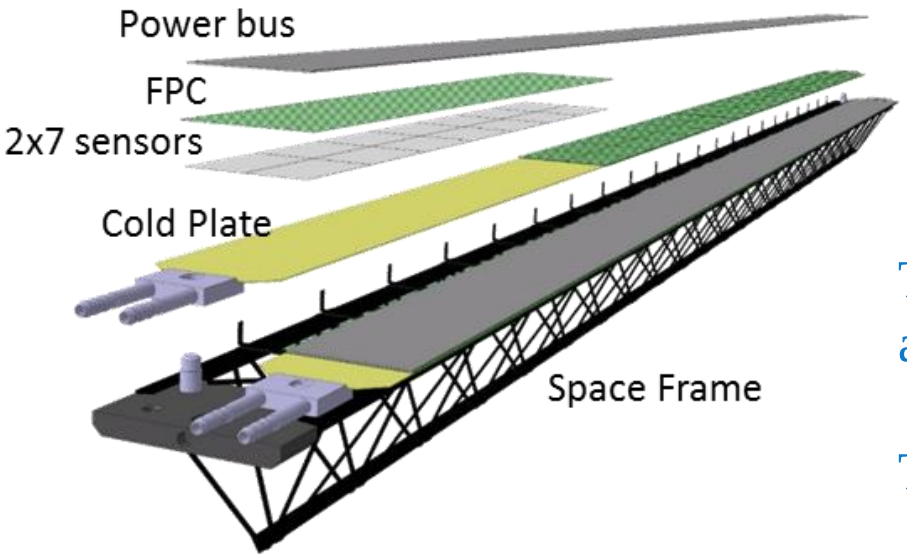


Task 2 . FC trusses (60), cooling plates (120)
JINR &SPbSU





Task 3: Assembly of HICs and OB Staves (60 pcs incl.)
JINR & CCNU

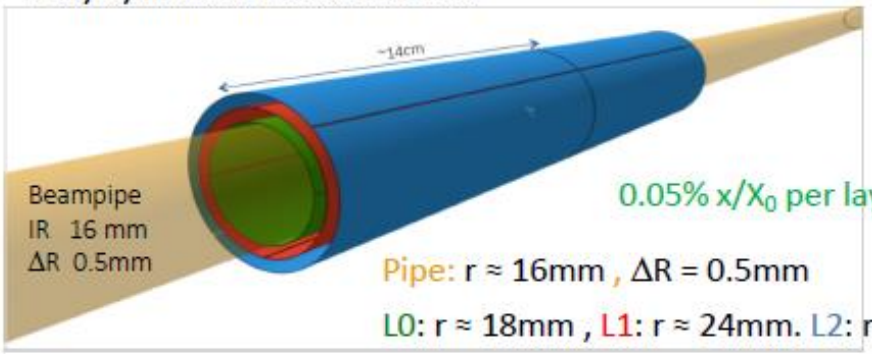


Truss length is 1540 mm. Modules (HICs) are are located on two cooling plates .
OB stave carriers 196 sensors.
The MPD ITS need is 42 OB staves.

Task 4. R@D for the IB as part ALICE ITS3 upgrade plan (*under supervision of CERN*)

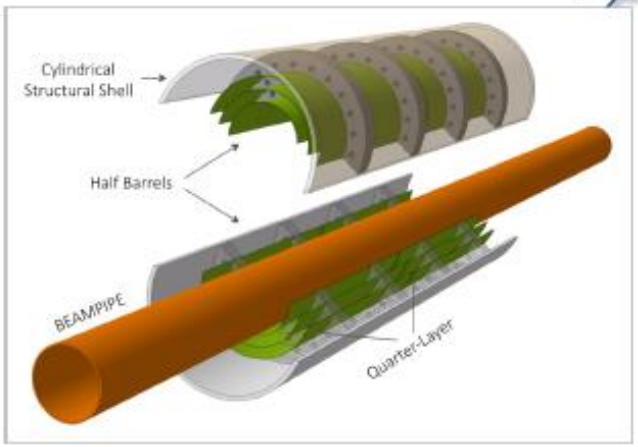
Vertex Detector (innermost 3 layers)

Truly cylindrical vertex detector

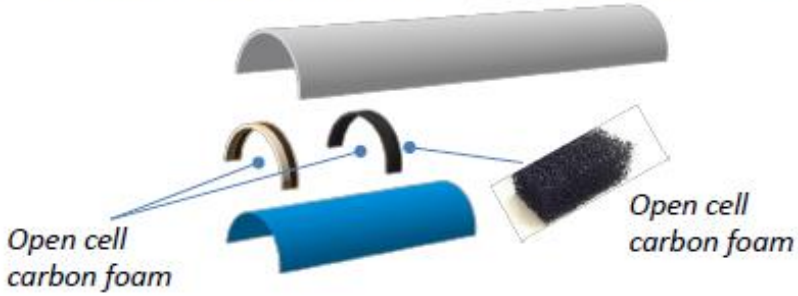


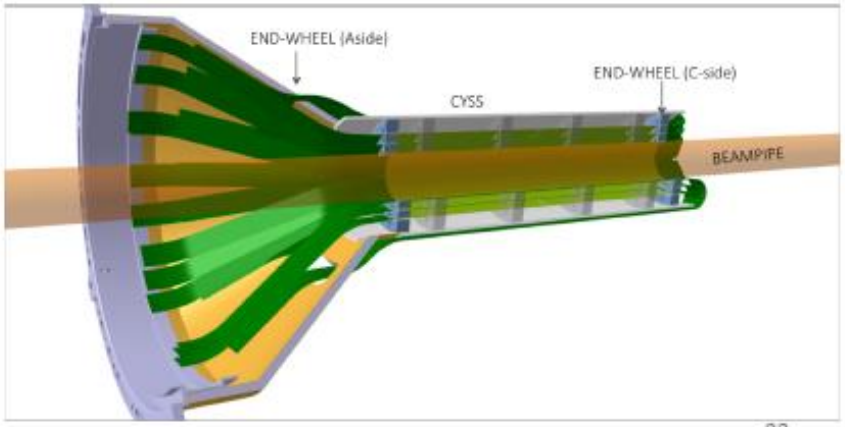
Pipe: r ≈ 16mm , ΔR = 0.5mm

L0: r ≈ 18mm , L1: r ≈ 24mm. L2: r ≈ 30 mm



Layers supported by high-thermal conductive carbon foam





L. Musa (CERN) – International Winter Meeting on Nuclear Physics, Bormio, 8-11 Jan 2019

33

Conclusions and summary

major milestones of the MPD ITS project (tentavily!)

- ***2018*** – *paper work and infrastructure*
- ***2018 –2019*** – *simulations and start of delivery of parts from CERN*
- ***2019*** – *organization of the Russian-Chinese Consortium*
- ***2019*** – *Writing TDR (Draft)*
- ***2019-2020*** – *Production of first HICs at VBLHEP and CCNU*
- ***2020 –2021*** – *Mechanics including parts for integration*
- ***2020 –2021*** – *updating the readout chain (with China and ?)*
- ***2020 –2023*** – *R@D effort on IB together with ALICE*
- ***2021 –2023*** – *Production HICs, assembly of OB staves (with China)*
- ***2023 (?)*** – ***ITS-OB*** *assembly, bench testing, commissioning*
- ***2025(?)*** – ***ITS-OB+IB*** *commissioning (**Stage II**)*

summary

- The MPD-ITS project is both scientific- and time-wise well justified
- The project has a solid reason to be accomplished in two stages
- The MPD-ITS(OB) (stage 1) one is now recognized and approved for financing at JINR
- The MPD-ITS(IB) (stage 2) contains R@D proposed to be performed under the supervision of ALICE Collaboration (ITS-3)
- The project effort due to its technical complexity cannot be undertaken by JINR alone and calls for organization of a Consortium of Institutes from Russia and China (and elsewhere!) functioning at least till 2025

Thank you !