Concepts for
A next generation LHC heavy-ion experiment

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EoI document signed by ~400 physicists (Dec 2018)

submitted to European Strategy for Particle Physics Preparatory Group

arXiv:1902.01211

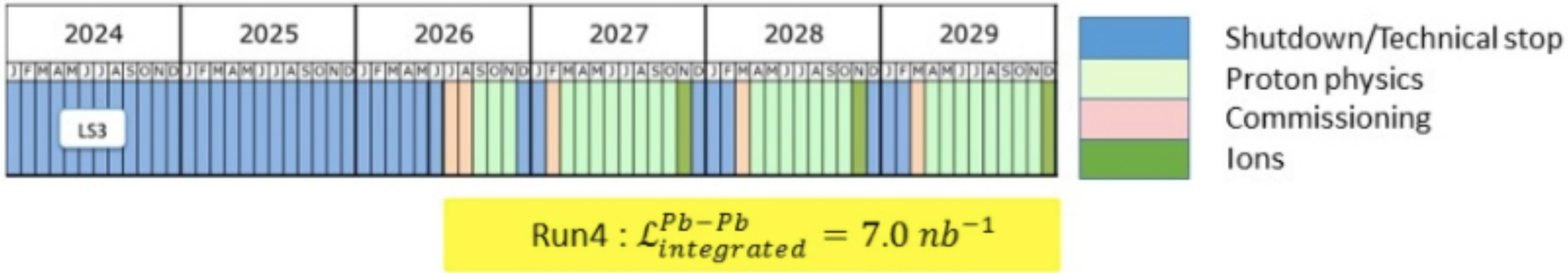
International Workshop on Forward Physics
and Forward Calorimeter Upgrade in ALICE
University of Tsukuba , March 7-9, 2019

Outline

- Motivations and physics potential
- Detector layout and main components
- Nearly 0-mass vertex detector
- High precision tracking
- Hadron, electron and photon ID

Approved ALICE programme

- Timeline



- LS2:
  - LHC injector upgrades, Pb-Pb rate → 50 kHz (now ~10 kHz)
  - ALICE upgrades
- Run 3 + Run 4:
  - experiments request > 10/nb (ALICE: 10/nb + 3/nb at 0.2 T)
  - in line with projections from machine group

LHC luminosity limitations with nuclear beams

max Pb-Pb lumi ~ a few 10^{27} cm^{-2} s^{-1}
→ max interaction rate ~ 50 kHz

main limitations:
- bound-free pair production
  σ_{BFPP} ~ Z^7 !
- collimation

⇨ larger lumi with lighter ions

estimates from Yellow Report (arXiv:1812.06772) →

	$^{16}O^{8+}$	$^{40}Ar^{18+}$	$^{40}Ca^{20+}$	$^{78}Kr^{36+}$	$^{129}Xe^{54+}$	$^{208}Pb^{82+}$
γ	3760.	3390.	3760.	3470.	3150.	2960.
$\sqrt{s_{NN}}$/TeV	7.	6.3	7.	6.46	5.86	5.52
σ_{had}/b	1.41	2.6	2.6	4.06	5.67	7.8
σ_{BFPP}/b	2.36×10^{-5}	0.00688	0.0144	0.88	15.	280.
σ_{EMD}/b	0.0738	1.24	1.57	12.2	51.8	220.
σ_{tot}/b	1.48	3.85	4.18	17.1	72.5	508.
N_b	1.58×10^{10}	3.39×10^{9}	2.77×10^{9}	9.08×10^{8}	4.2×10^{8}	1.9×10^{8}
$\epsilon_{xn}/\mu m$	2.	1.8	2.	1.85	1.67	1.58
f_{IBS}/(m Hz)	0.168	0.164	0.184	0.18	0.17	0.167
W_b/MJ	175.	84.3	76.6	45.2	31.4	21.5
$L_{AA0}/cm^{-2}s^{-1}$	9.43×10^{31}	4.33×10^{30}	2.9×10^{30}	3.11×10^{29}	6.66×10^{28}	1.36×10^{28}
$L_{NN0}/cm^{-2}s^{-1}$	2.41×10^{34}	6.93×10^{33}	4.64×10^{33}	1.89×10^{33}	1.11×10^{33}	5.88×10^{32}
P_{BFPP}/W	0.0199	0.601	0.935	11.	60.6	350.
P_{EMD1}/W	32.	55.6	52.2	78.3	107.	141.
τ_{L0}/h	6.45	11.6	13.1	9.74	4.96	1.57
T_{opt}/h	5.68	7.62	8.08	6.98	4.98	2.8
$\langle L_{AA}\rangle$ $cm^{-2}s^{-1}$	4.54×10^{31}	2.45×10^{30}	1.69×10^{30}	1.68×10^{29}	2.95×10^{28}	3.8×10^{27}
$\langle L_{NN}\rangle$ $cm^{-2}s^{-1}$	1.16×10^{34}	3.93×10^{33}	2.71×10^{33}	1.02×10^{33}	4.91×10^{32}	1.64×10^{32}
$\int_{month} L_{AA}$ dt/nb^{-1}	5.89×10^{4}	3180.	2190.	218.	38.2	4.92
$\int_{month} L_{NN}$ dt/pb^{-1}	1.51×10^{4}	5090.	3510.	1330.	636.	213.
R_{had}/kHz	1.33×10^{5}	1.12×10^{4}	7540.	1260.	378.	106.
μ	10.6	0.893	0.598	0.1	0.03	0.00842

A new HI dedicated experiment beyond LS4?

With the LS2 upgrade, ALICE will reach the maximal rate with a spectrometer based on a TPC

⇨ Maximum interaction rate limited by space-charge (ions) accumulated in drift volume (distortions ≈10cm) and track density (inner region signal occupancy ≈ 40%)

Running at higher rates seems excluded with a TPC

Running ALICE beyond RUN4? ⇨ Completely new detector without TPC

The use of CMOS technologies opens new opportunities

⇨ Vertex detectors, large area tracking detectors and digital calorimeters

- enhanced performance (very high spatial and time resolution)

an “all-MAPS” detector

Such a detector would play a central role in HI physics at the LHC in the 2030’s

A new HI dedicated experiment beyond LS4?

Design guidelines

- Increase rate capabilities (factor 20 to 50 wrt to ALICE RUN4): $\langle L_{NN} \rangle$ ~ up to 10^{34} $cm^{-2}s^{-1}$
- Improve vertexing
  - Ultra-thin wafer-scale sensors with truly cylindrical shape, inside beam pipe
  - spatial resolution ~ 1μm
  - material thickness < 0.05% X_0 /layer
- Improve tracking precision and efficiency
  - About 10 layers with a radial coverage of 1m
  - Spatial resolution of about 5μm up to 1m
  - whole tracker could be less than 6% X_0 in thickness (at mid-rapidity)
- Tracking over a wide momentum range (down to a few tens of MeV/c) and rapidity coverage ($|\eta| \leq 4$)

Magnetic fields of < 0.5T would be sufficient but 1T (or higher) is also considered

Physics Potential – some examples

- Heavy-flavor and quarkonia
  - Multiply Heavy Flavoured hadrons. e.g.: Ξ_{cc}, Ω_{cc}, Ω_{ccc}
  - $\chi_{c1,2}$ states
  - Ultimate precision on B mesons at low p_T
  - X, Y, Z charmonium-like states (e.g. X(3872))
- Low-mass dielectrons
  - Precision measurement of the thermal dilepton continuum, $0 < m < 3$GeV
- Real soft photons
  - down to 50MeV/c
- Real ultra-soft photons
  - Very low p_T photons: $1\text{MeV/c} < p_T^{\gamma} < 100\text{MeV/c}$
  - dedicated small forward spectrometer at $3.5 < |\eta| < 5$)

→ Hadron formation from deconfined QGP

→ Chiral symmetry restoration ρ-a1 sector

→ QGP Radiation uncharted phase space region

→ Test of soft theorems

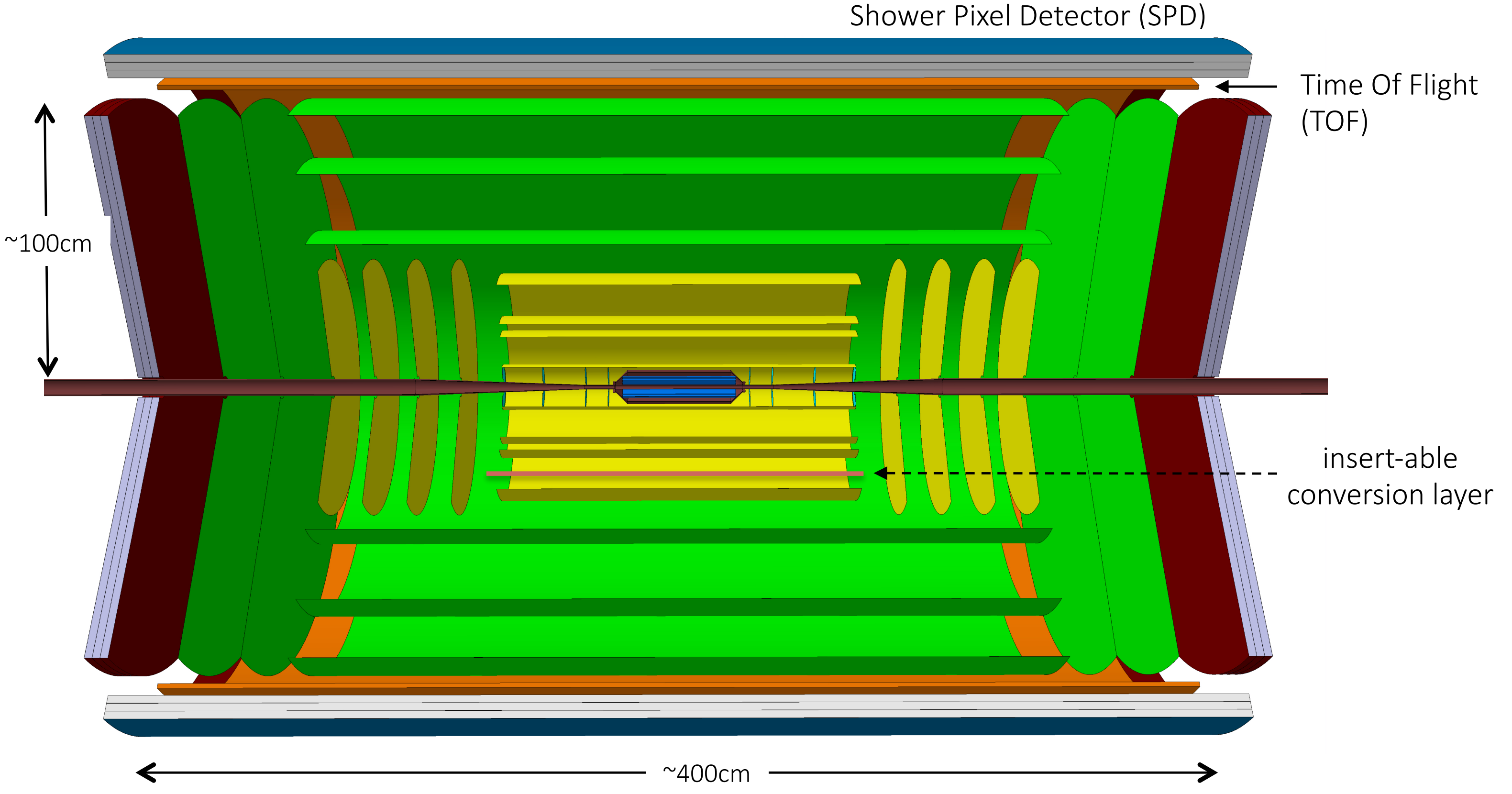
A new experiment based on a “all-silicon” detector

Tracker: ~10 tracking barrel layers (blue, yellow and green) based on CMOS sensors

Particle ID:

- TOF with outer silicon layers (orange)
- Shower Pixel Detector (outermost blue layer)

Extended rapidity coverage: **up to 8 rapidity units**
+ FoCal



Magnetic Field
- B = 0.5 or 1 T

Spatial resolution
- Innermost 3 layers: σ ~ 1μm
- Outer layers: σ ~ 5μm

Vertex material thickness
- X/X0 ~ 0.05% / layer

Time Measurement
Outermost layer integrates high precision time measurement (σ_t ~ 20ps)

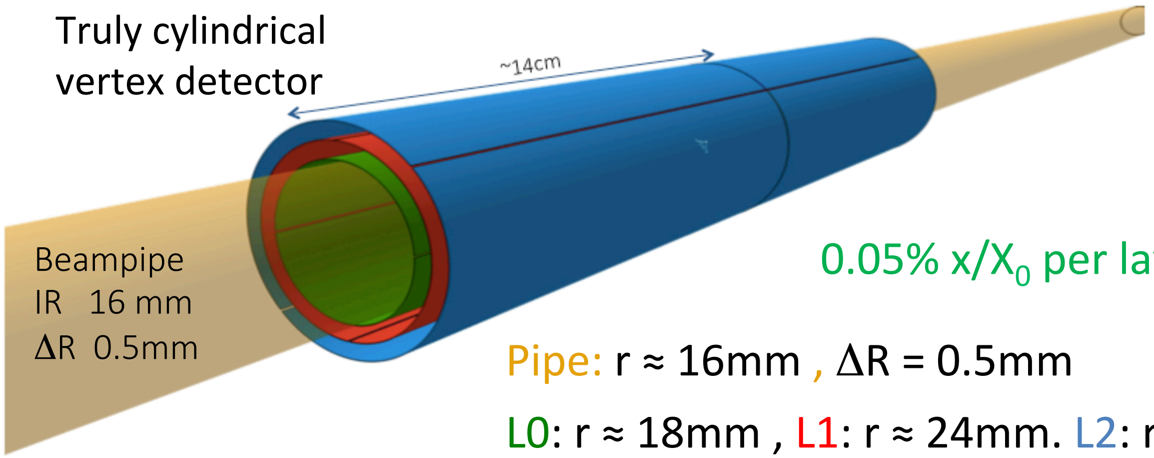
Vertex Detector (innermost 3 layers)

EoI for new ultra-light Inner Barrel in LS3 (CDS, ALICE-PUBLIC-2018-013)

Recent silicon technologies (ultra-thin wafer-scale sensors) allow

- Eliminate active cooling ➪ possible for power < 20mW/cm^2
- Eliminate electrical substrate ➪ Possible if sensor covers the full stave length
- Sensors arranged with a perfectly cylindrical shape ➪ sensors thinned to ~30mm can be curved to a radius 10-20mm

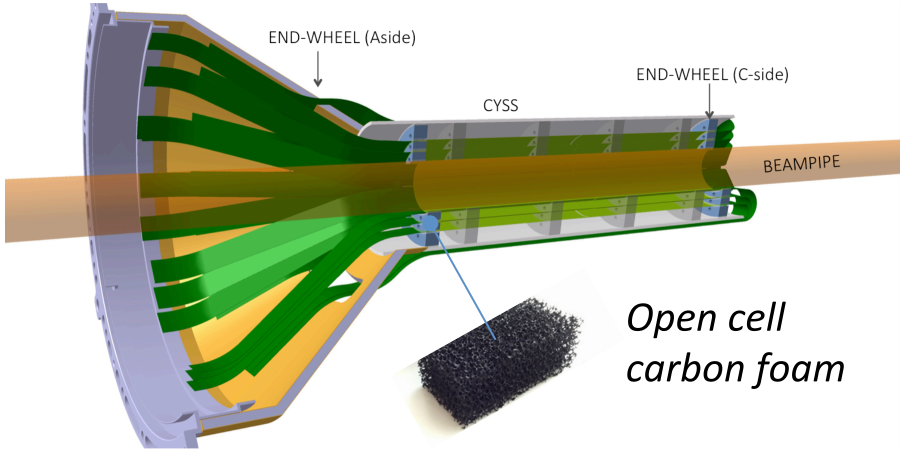
Truly cylindrical vertex detector



0.05% x/X_0 per layer

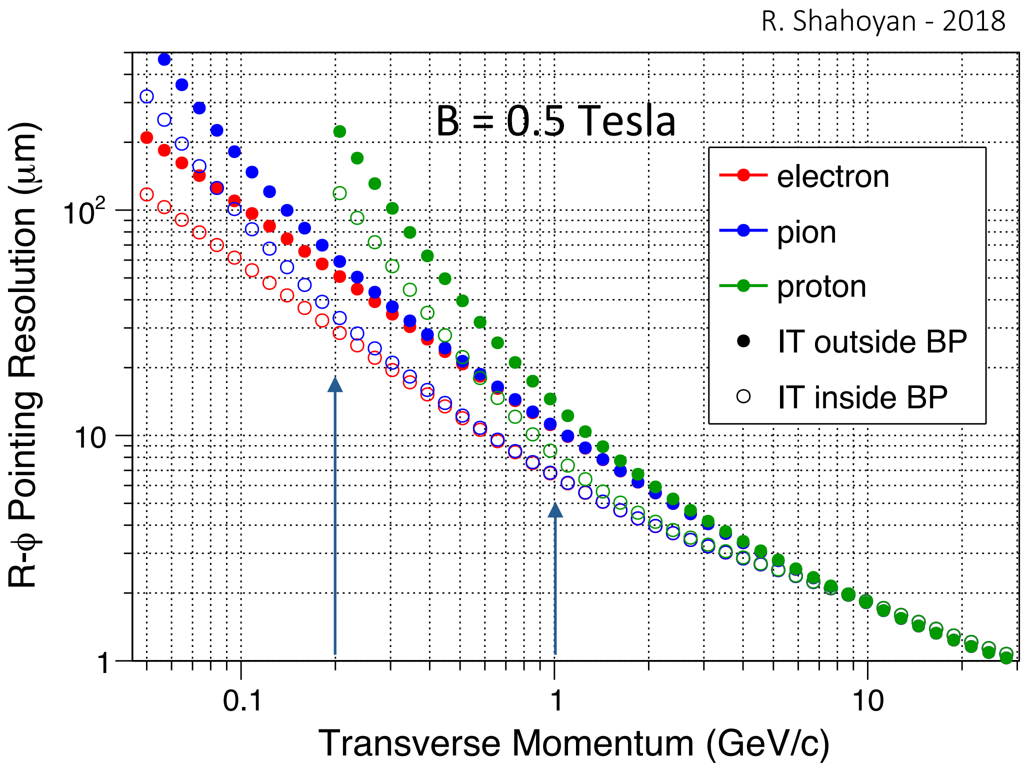
Pipe: r ≈ 16mm , ΔR = 0.5mm

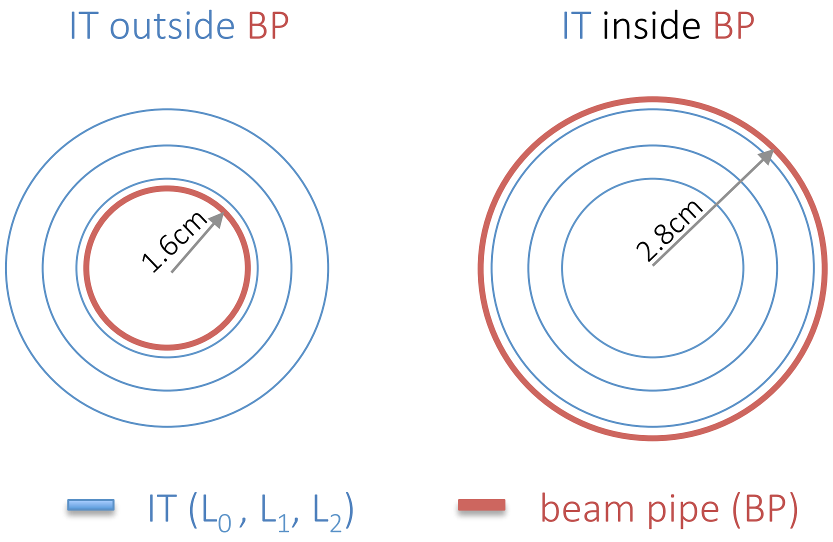
L0: r ≈ 18mm , L1: r ≈ 24mm. L2: r ≈ 30 mm

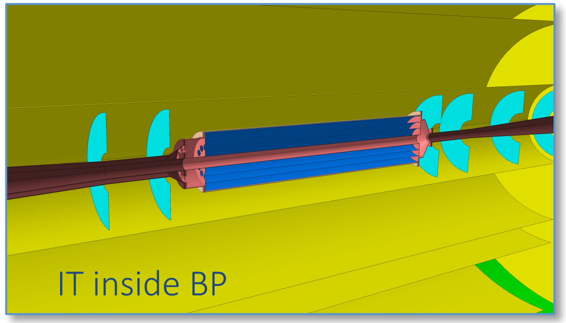


Open cell carbon foam

Pointing resolution







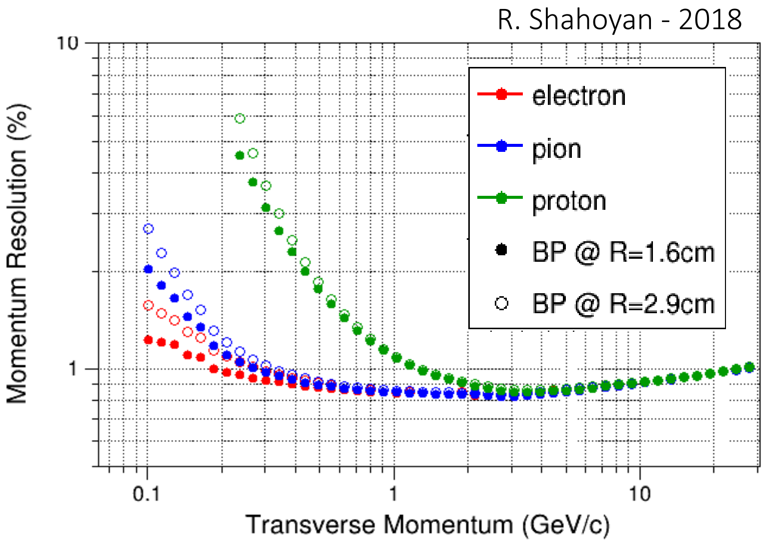
Pointing resolution (pions): ≈ 10 μm @ 1 GeV/*c*, <50μm @ 200 MeV/c

It does not depend on B field

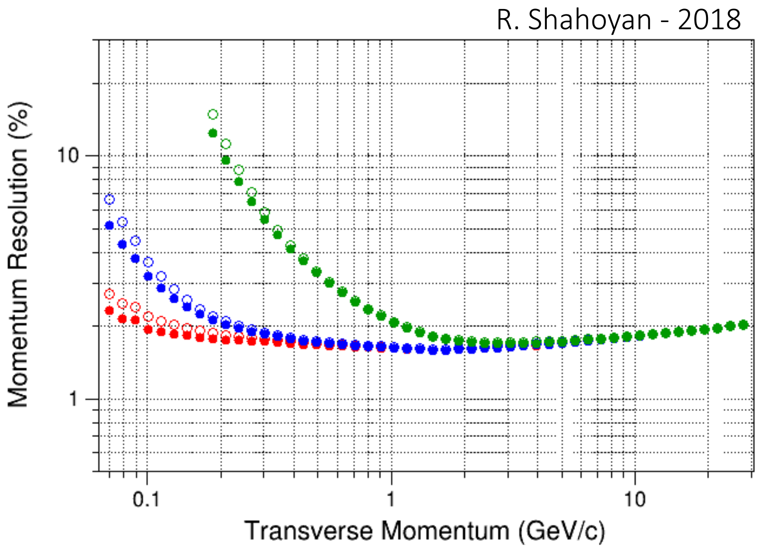
Operation at reduced B field for tracking low p_T particles

Compared to ALICE in Run3, same performance at high p_T, some improvement at very low p_T

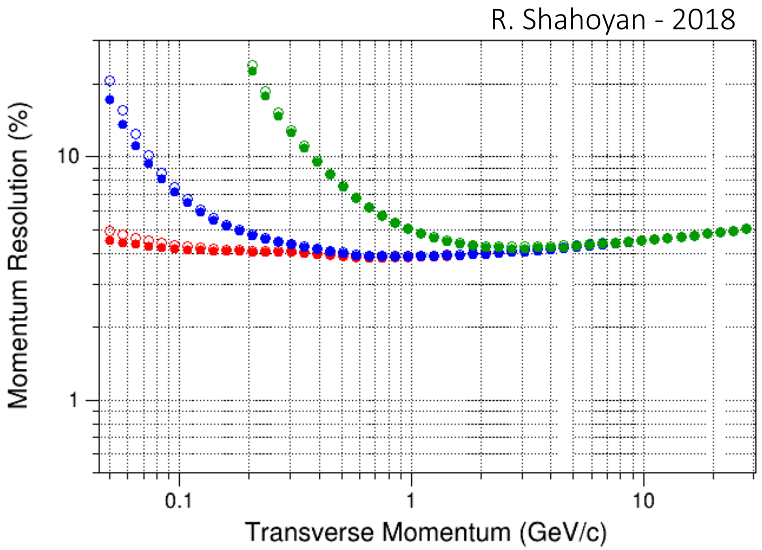
B = 1 T



B = 0.5 T



B = 0.2 T



momentum resolution for 1GeV/c pions: ≈ 0.8% (1 T), ≈1.6% (0.5 T), ≈ 4% (0.2 T)

$$\frac{\delta p}{p} = \frac{p}{0.3BL^2}\sigma\cdot\sqrt{C_N}$$

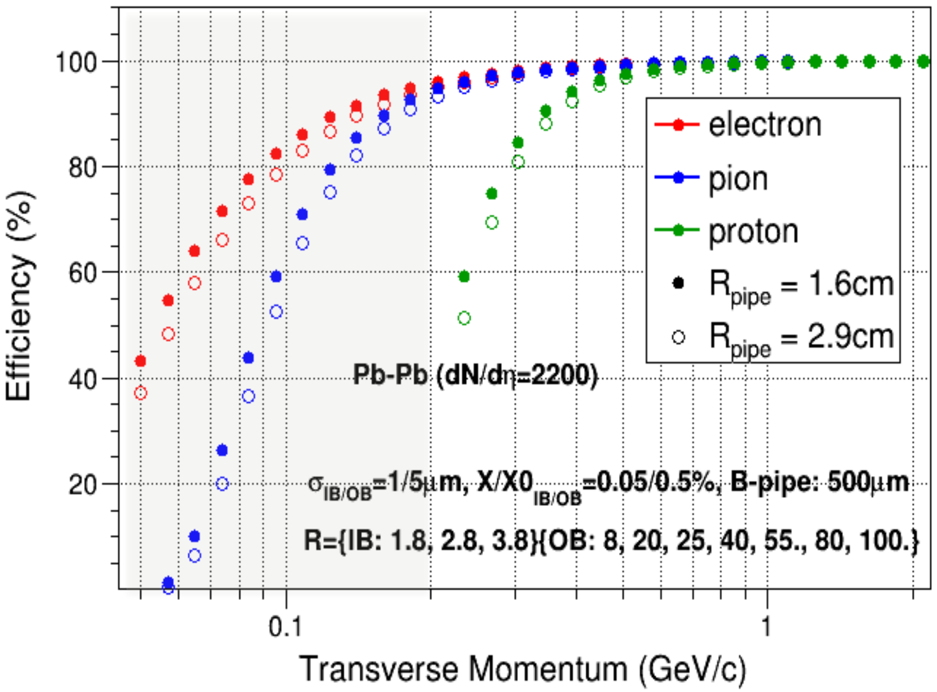
$$C_N = \frac{720N^3}{(N-1)(N+1)(N+2)(N+3)}$$

for layers equally spaced and neglecting multiple-scattering

Operation at reduced B field for tracking low p_T particles

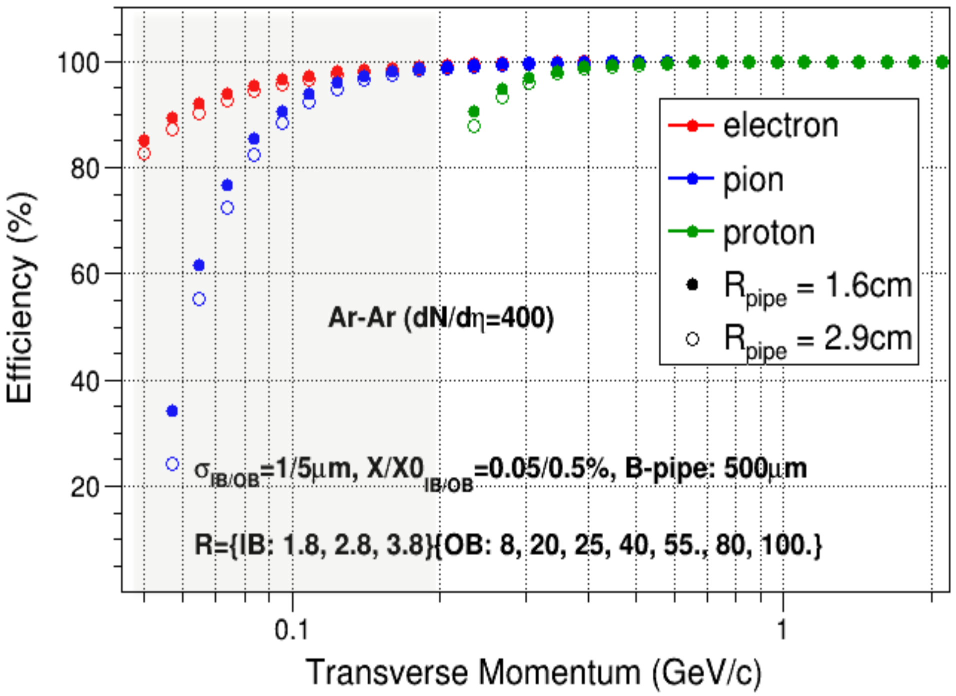
Pb-Pb (dN/dy = 2200), B = 0.2 Tesla

R. Shahoyan - 2018



dN/dy = 440, B = 0.2 Tesla

R. Shahoyan - 2018



Efficiency requiring that particles reach the outermost layer at 1m (10 layers)

⇨ optimization possible (e.g. using only layers up to 40cm)

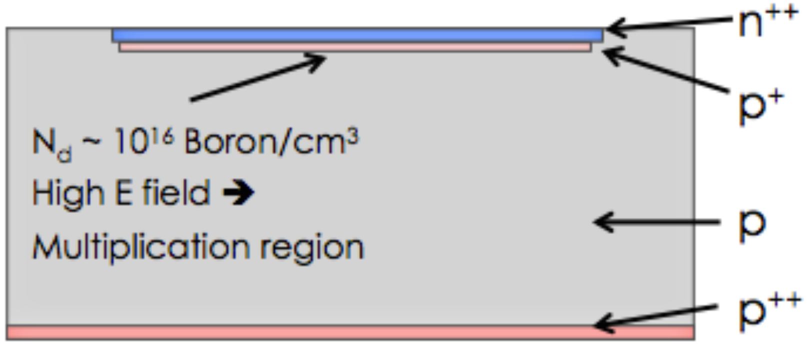
⇨ dramatic improvement for lower dN/dy

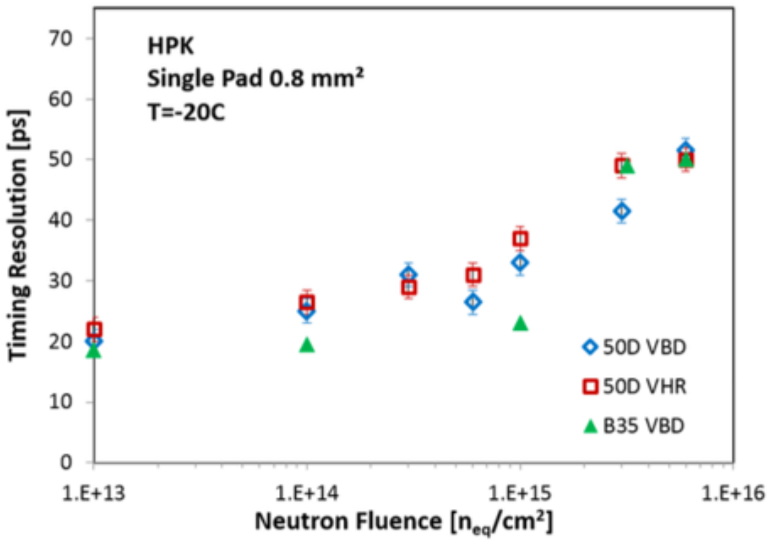
Further layout optimization possible!

Electron and hadron ID with TOF

LGAD (Low Gain Avalanche Diode)

- Technology proposed for ATLAS and CMS LS3 upgrades (timing layer)
- Developed for high radiation environment (10^{14} – 10^{15} 1MeV n_{eq}/cm^2)
- Currently low granularity O(1 mm^2)
- Add a thin layer of doping to produce low controlled multiplication
- Several vendors: Hamamatsu, FBK, CNN





Time resolution vs. neutron fluence of LGAD produced by HPK with a thickness of 50μm (50D) and 35μm (35D)

Resolution of 20-30ps demonstrated

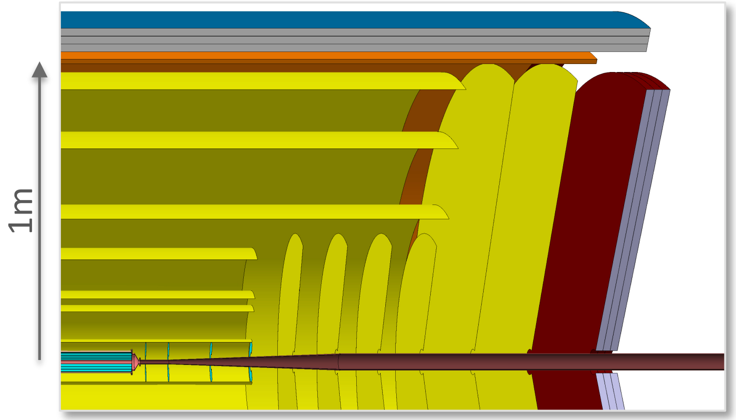
Cost (CMS estimate) ~ 50 CHF/cm^2

Can such a gain layer be implemented in CMOS?

➪ Single Photon Avalanche Diodes (SPADs)

Electron and hadron ID with TOF

TOF PID – few barrel layers instrumented with LGAD or high-granularity SPAD sensors



SPAD Sensors (Single Photon Avalanche Diode) $\stackrel{\text{def}}{=}$ arrays of avalanche photodiodes reverse-biased above their breakdown voltage

SPAD detectors of recent generation feature a time jitter of tens of picoseconds

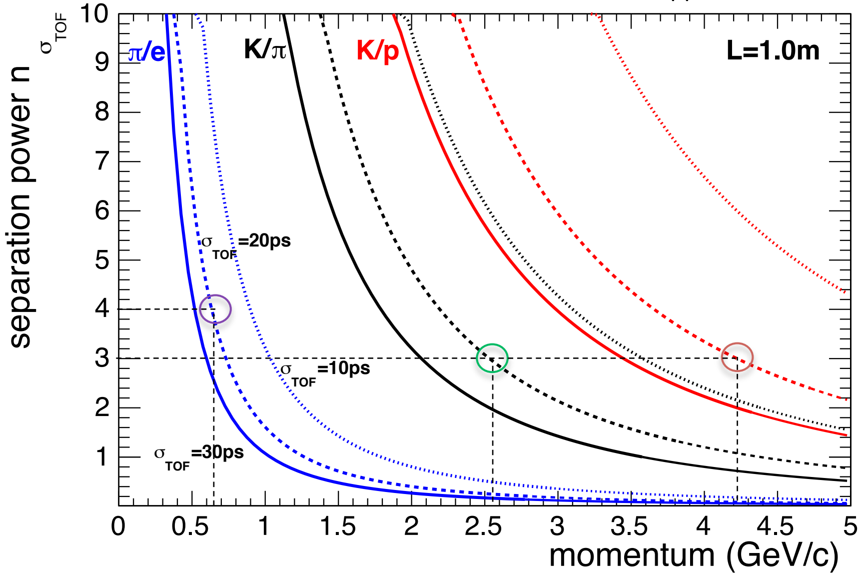
Number of layers will depend on time resolution and spatial fill factor achieved in the single layer

Ideal track length and p measurement

3 system time resolutions: 10ps, 20ps , 30ps. For σ_{TOF} = 20ps

- e/π (4σ) separation ≲ 650 MeV/c
- π /K (3σ) separation ≲ 2.6 GeV/c
- K/p (3σ) separation ≲ 4.2 GeV/c

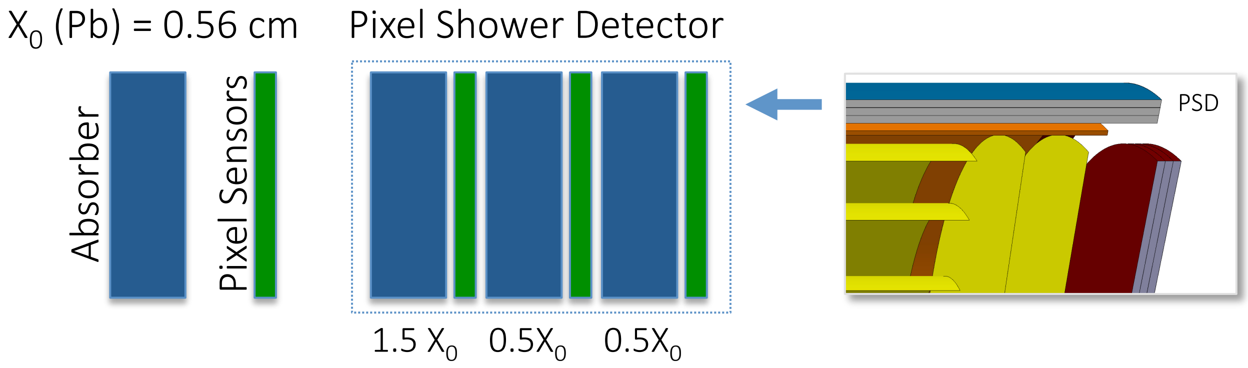
C. Lippmann - 2018



Electron ID with Pixel Shower Detector

Shower Detector (3 X_0) based on high-granularity digital calorimetry (CMOS pixel sensors)

➪ great potential to identify electrons down to few hundred MeV by detailed imaging of the initial shower (particle counting, geometry)



Work in progress – A first look

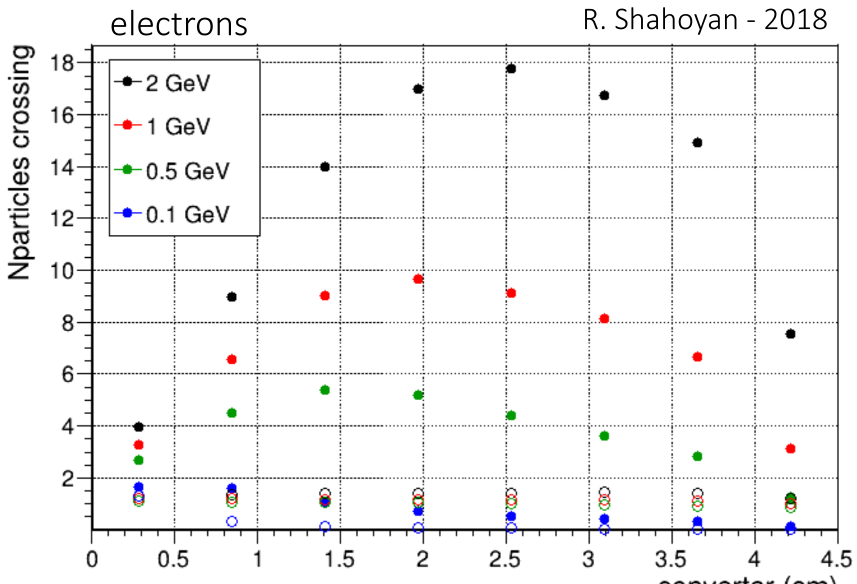


Figure 1

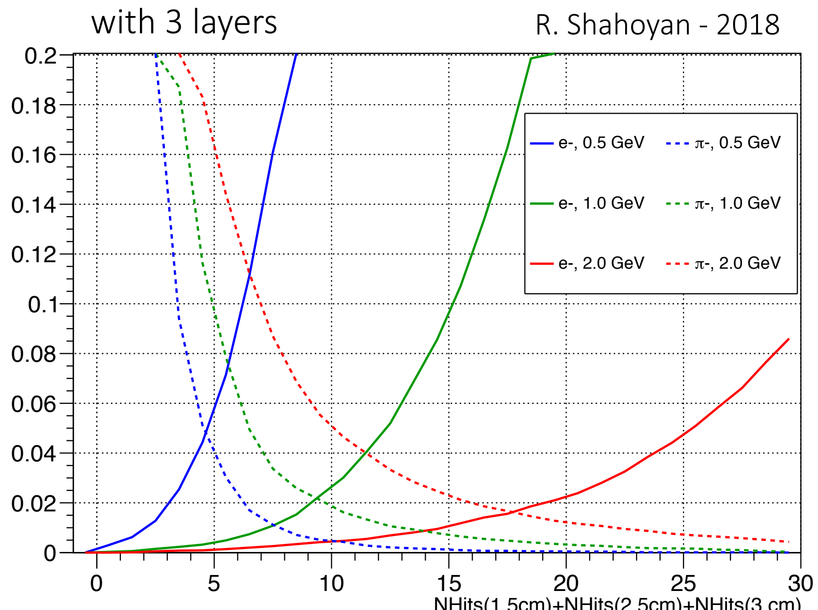


Figure 2

——— e – fraction below N (e-loss) - - - - - - - π – fraction above N (contam.)

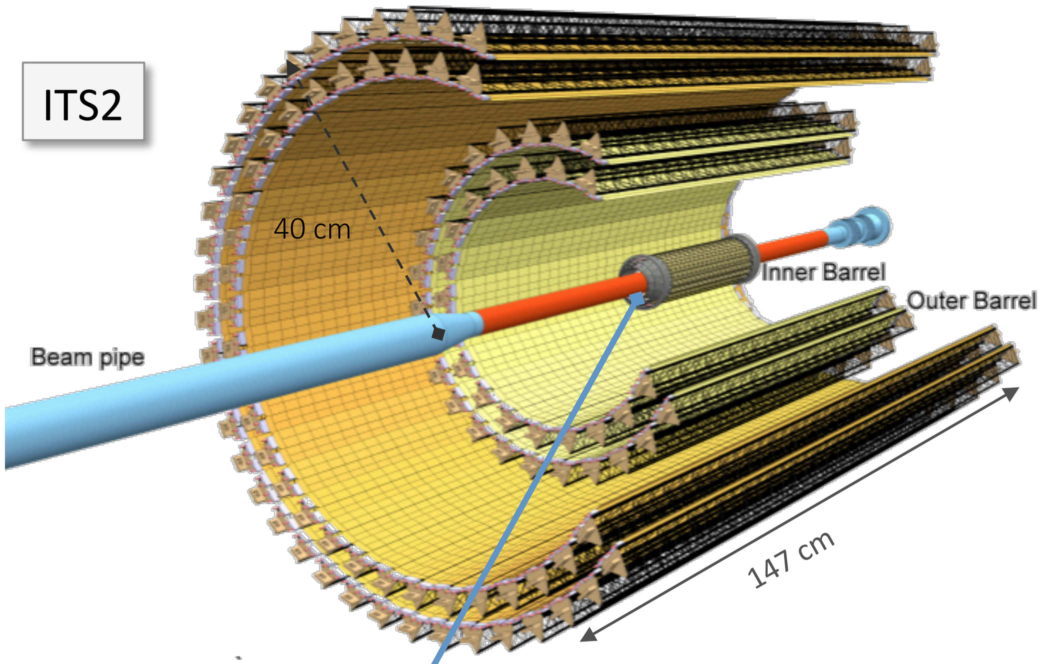
Summary

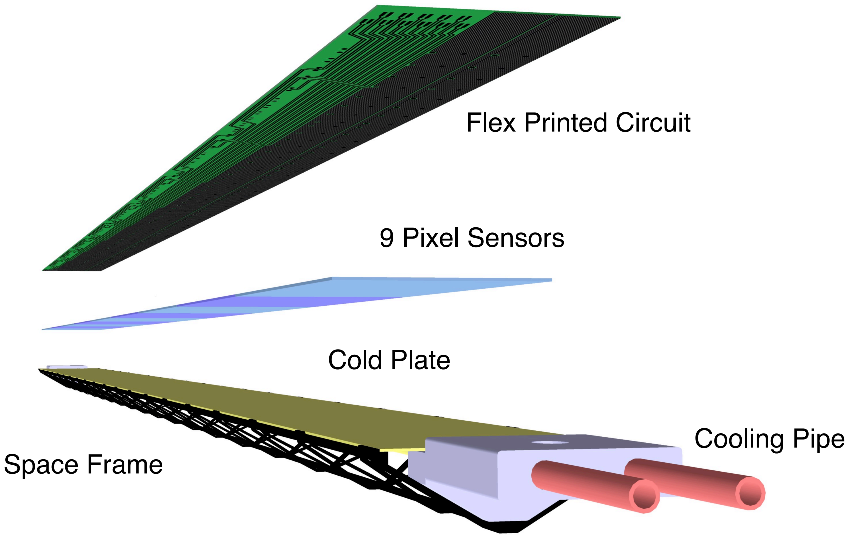
Concepts for a next generation LHC heavy-ion experiment

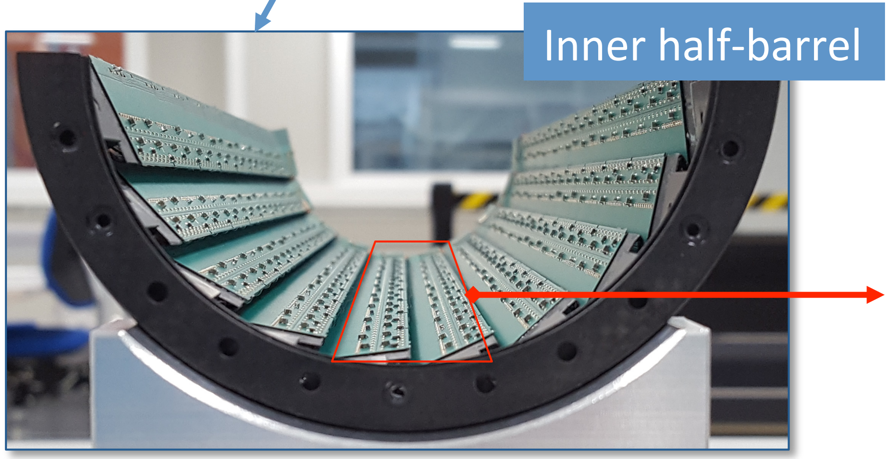
- a detector conceived for studies of pp, pA and AA collisions at luminosities a factor of 20 to 50 times higher than possible with the upgraded ALICE detector
- three truly cylindrical layers based on curved wafer-scale ultra-thin CMOS Active Pixel sensors (⇨ $x/X_0 \approx 0.05\%$ per layer)
- unprecedented low material budget for the inner layers of 0.05% X_0, with the innermost layers possibly positioned inside the beam pipe
- superior tracking and vertexing capabilities over a wide momentum range down to a few tens of MeV/c
- particle ID via time-of-flight determination with about 20ps resolution. Electron and photon ID identification will be performed in a separate pixel shower detector.
- enables rich physics program: from measurements with electromagnetic probes at ultra-low transverse momenta to precision physics in the charm and beauty sector.

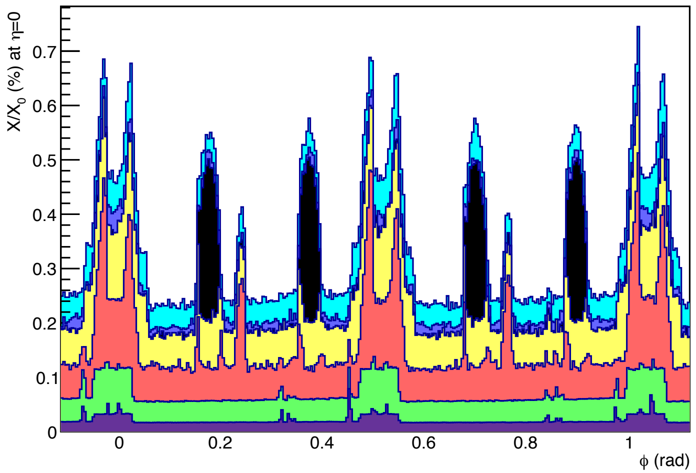
ありがとうございました！

ITS2 – Material Thickness

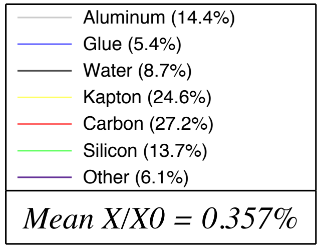








Silicon ⇨ only 15%



ALICE LS2 Upgrade

Strategy driven by these main physics topics

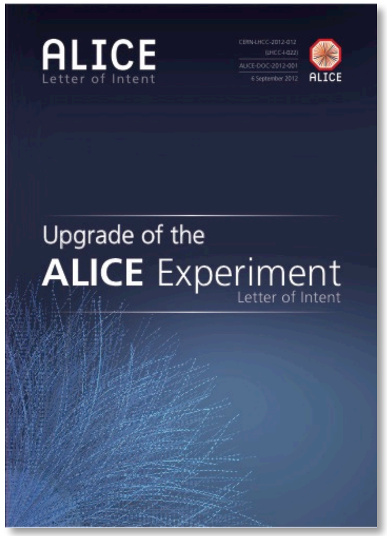
- Heavy flavour dynamics and hadronization at low p_T ➪ heavy-quark interactions in QCD medium
- Charmonium down to zero p_T ➪ quarkonium melting and regeneration in QGP
- Thermal dileptons, photons, vector mesons ➪ QGP radiation and chiral symmetry restoration at $\mu_B = 0$
- High-precision measurement of light and hyper-nuclei ➪ production mechanism in QGP and degree of collectivity

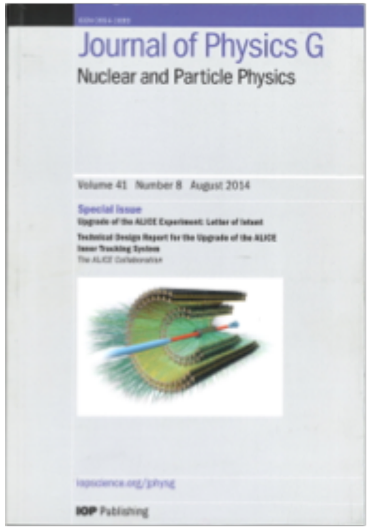
No Dedicated Trigger Possible !!

(RUN3+RUN4): 13/nb ➪ x100 MB statistics

Main requirements

- Un-triggered data sample
  - ☞ Increase readout rate, reduce data size (online data reduction)
- Improve tracking accuracy and efficiency at low p_T
  - ☞ Closer to IP, increase granularity, reduce material thickness
- Preserve particle id capabilities
  - ☞ Consolidate and “speed-up” PID detectors





ALICE Upgrades in LS2 (2019-2020) – Layout and key systems

New Inner Tracking System (ITS) *Novel MAPS technology*
- CMOS Active Pixel Sensors

→ improved resolution, less material, faster readout

New Muon Forward Tracker (MFT)
- CMOS Active Pixel Sensors

→ vertex tracker at forward rapidity

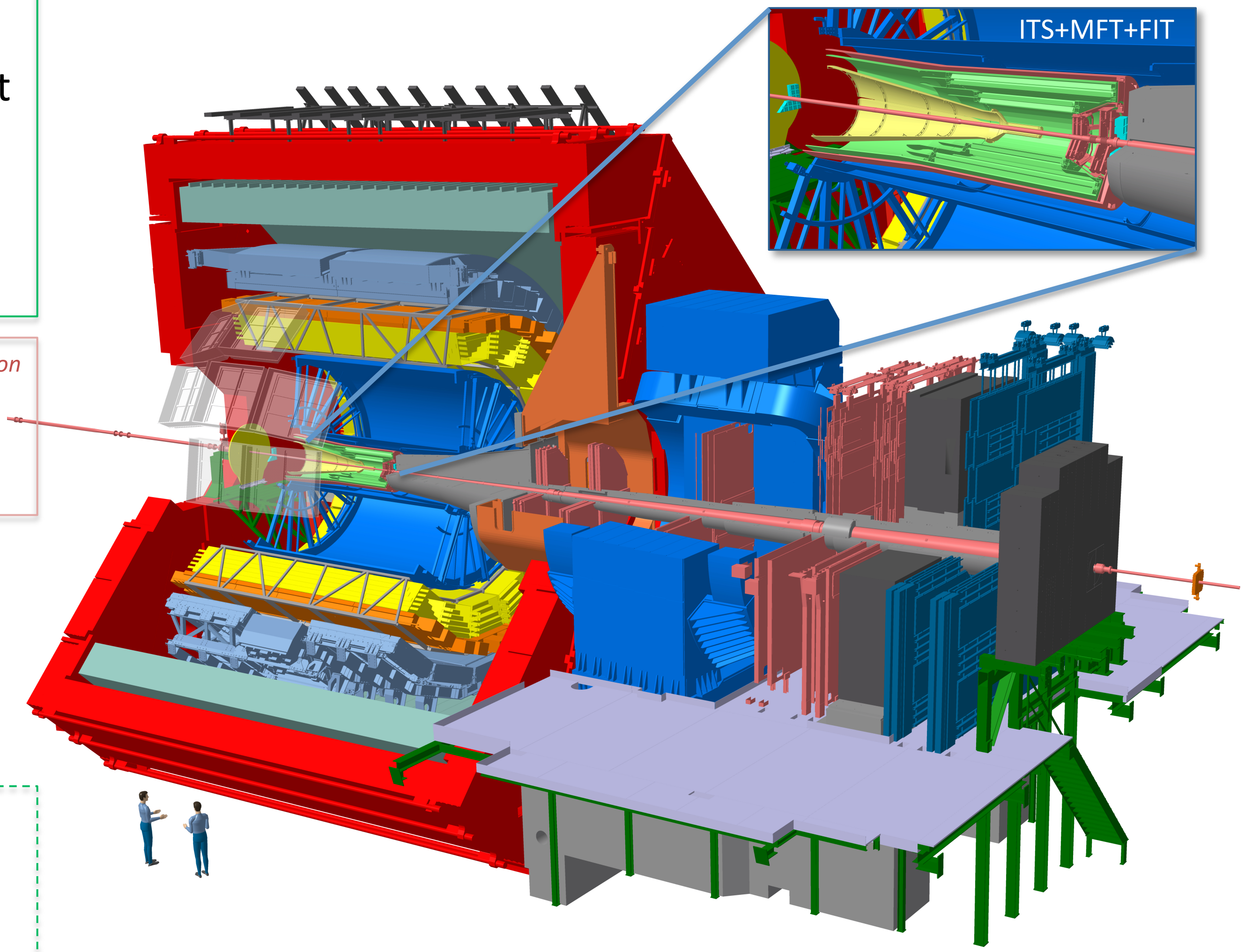
New TPC Readout Planes *Largest GEM application*
- 4-GEM detectors, new electronics

→ continuous readout

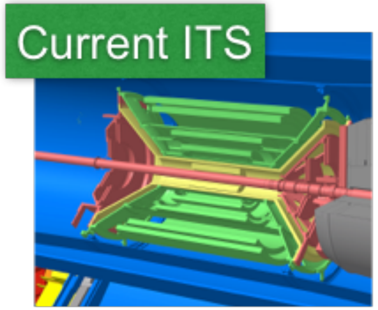
New trigger detectors (FIT, AD)
- Centrality, event plane

Upgrades readout for TOF, TRD, MUON, ZDC, Calor.

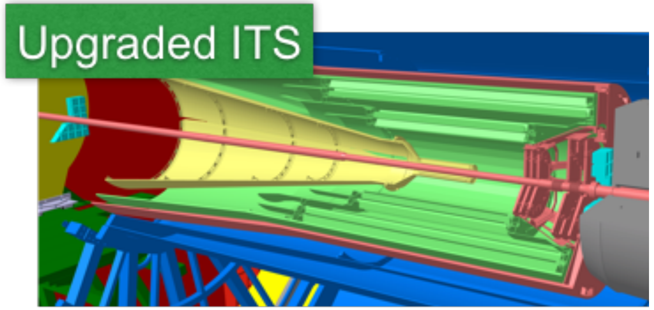
Integrated Online-Offline system (O^2)
- Record minimum-bias Pb-Pb data at > 50kHz (currently ~ 1 kHz)



ITS Upgrade in LS2 (ITS2)



6 layers (39mm < r < 440mm)
-1 ≤ η ≤ 1



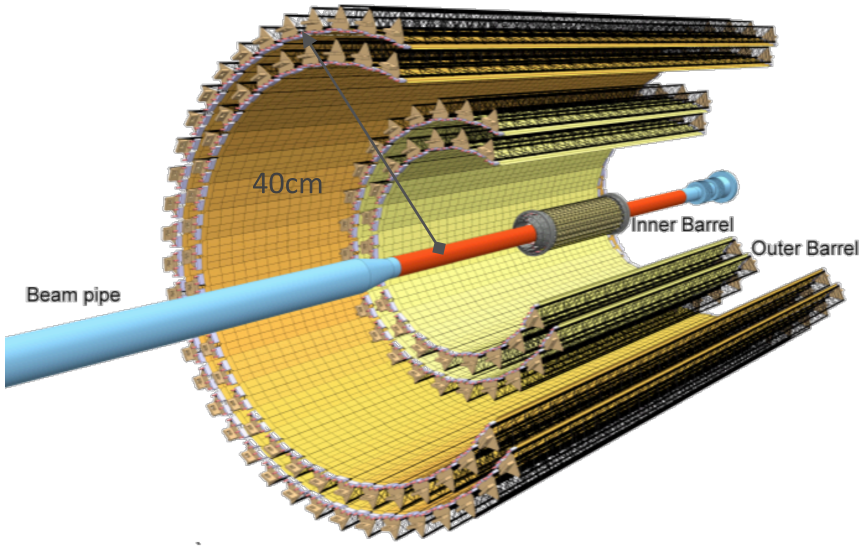
7 layers (22mm < r < 400mm)
-1.5 ≤ η ≤ 1.5

Motivations and goals

- Improved vertex and tracking precision
  - ⇨ closer to IP, smaller pixels, less material
- Faster readout

Based on novel MAPS (ALPIDE)

- 10 m^2 active silicon area (12.5 G-pixels)
- Spatial resolution ~5μm
- Power density < 40mW / cm^2
- Max particle rate ~ 100MHz /cm^2 (pile-up)
- Fake hit rate: < 1Hz/cm^2
- X/X_0 (first three layers): 0.35%

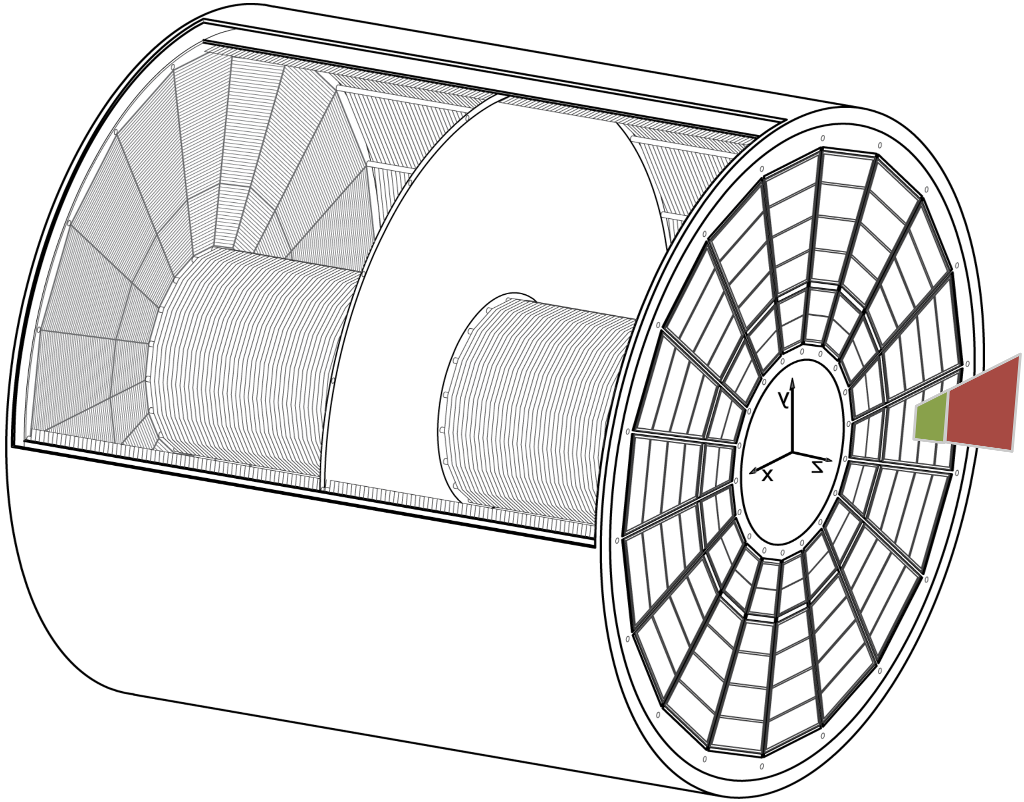


⇨ further improvements exploiting technological innovations

TPC Continuous Readout with GEMs (Gas Electron Multiplier)

Gate-less TPC for continuous readout

Current MWPC: readout rate limited by ion backflow

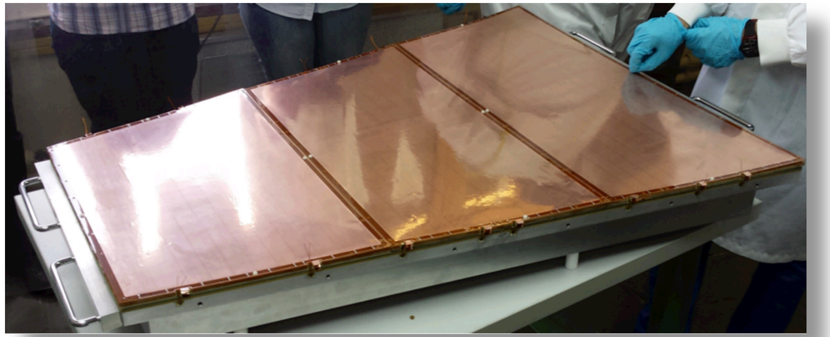


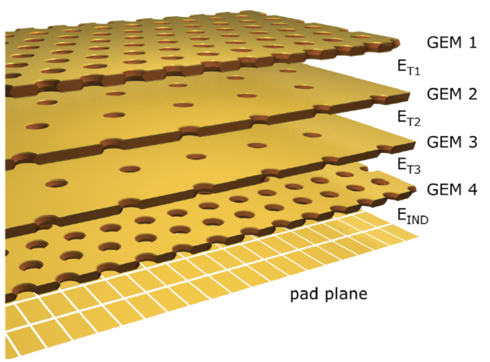
Operate TPC at 50 kHz ⇨ no gating grid

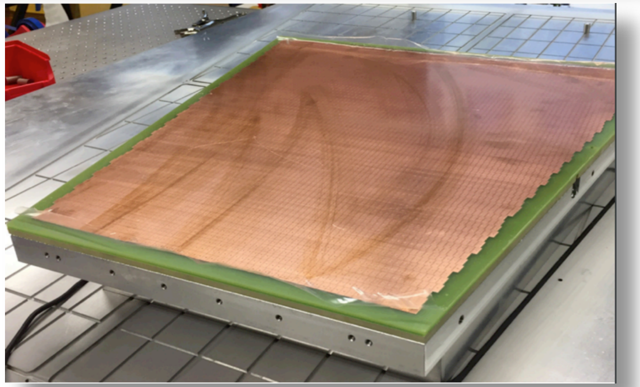
Need to minimize IBF ⇨ Replace MWPC with 4-GEMs

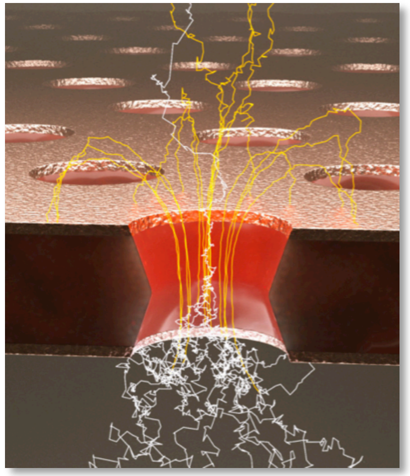
100 m^2 single-mask foils GEM production

Read Out Chamber







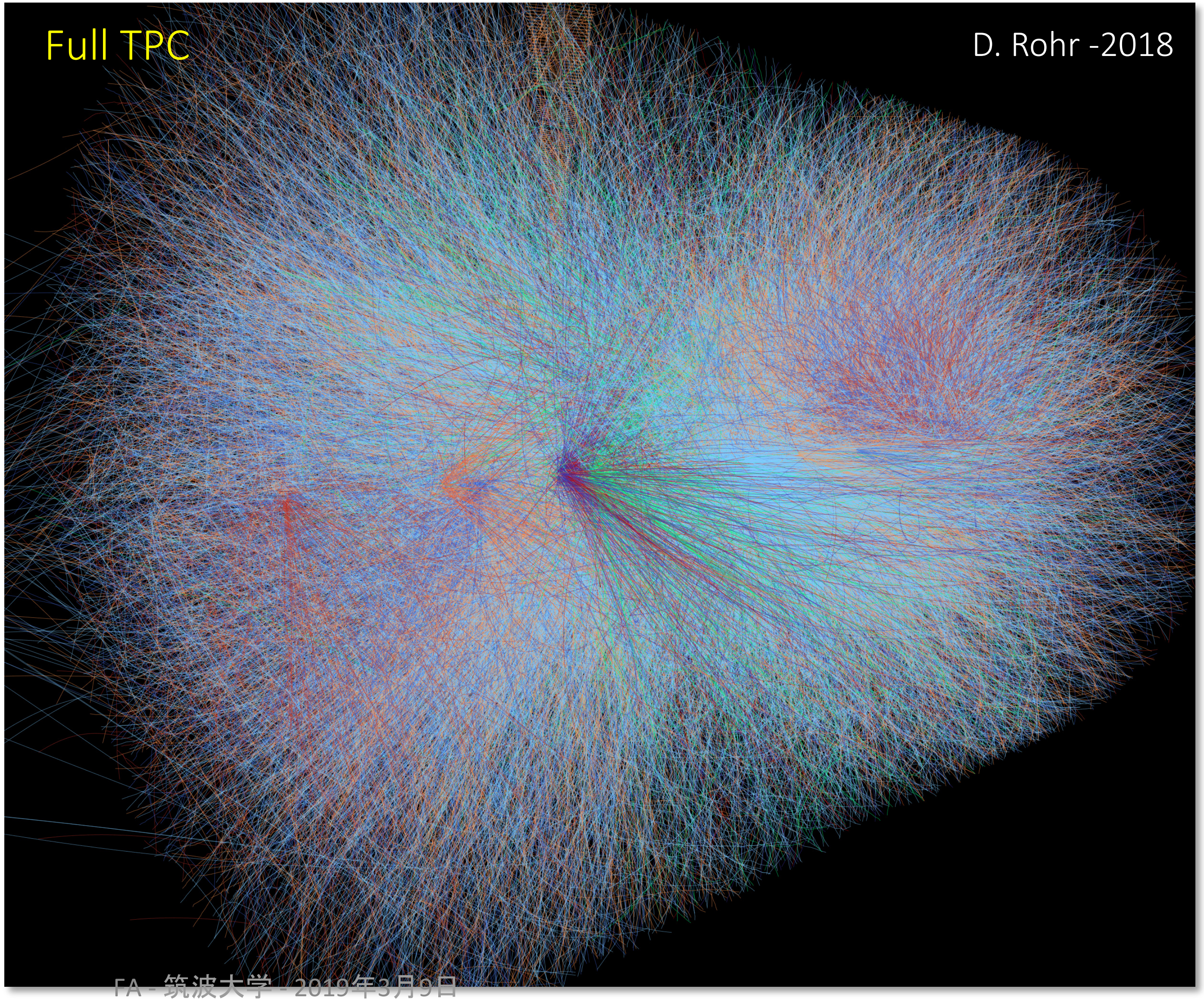


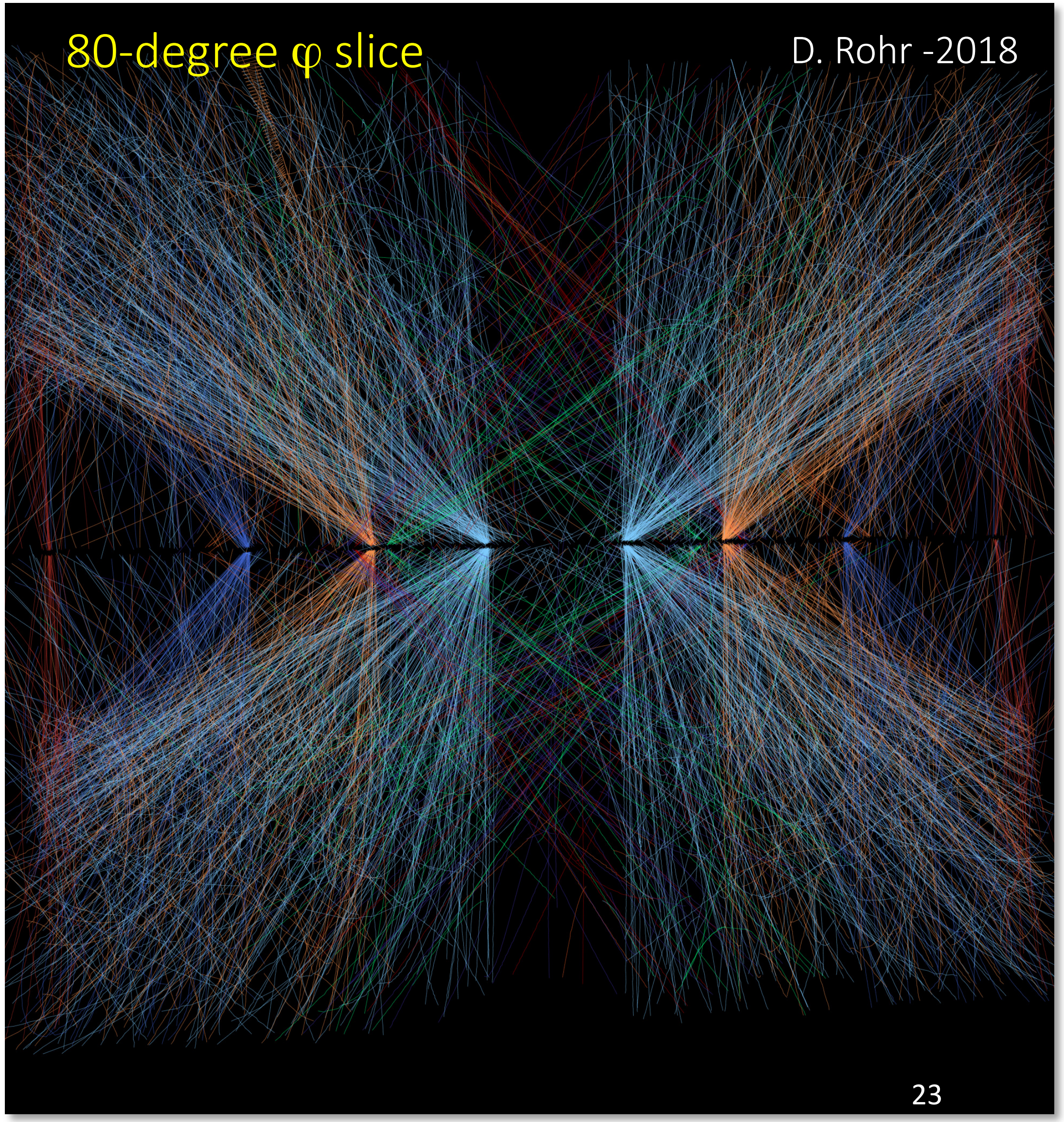
⇨ GEM provides ion backflow suppression to **< 1%**

⇨ 524 000 pads readout continuosly (10bit x 5MSPS) via 6552 links ⇨ **3.4 TByte/sec**

ALICE Run3 – Event Display

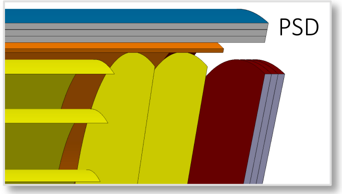
Pb-Pb Collisions @ 50kHz





Electron ID with Pixel Shower Detector

Electron and photon ID using Pixel Shower Detector   e/π ~ 10^{-2}



density vs radial distance from the impact axis for the particles crossing each Si layer

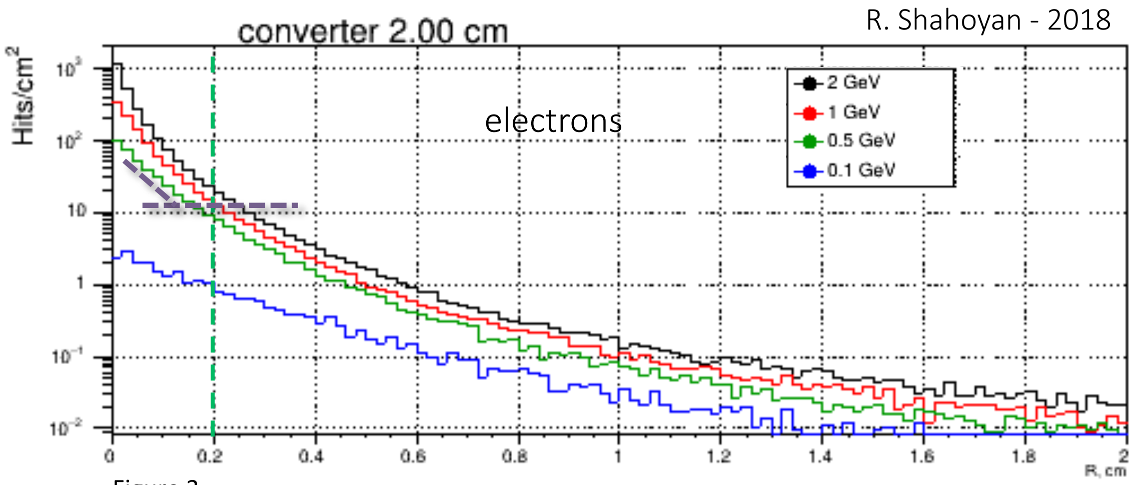


Figure 3

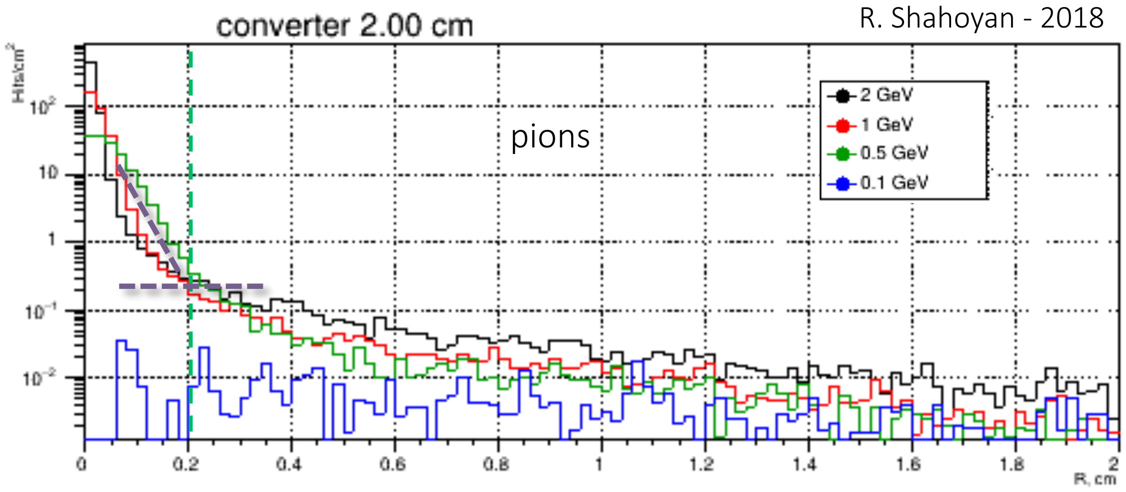


Figure 4

Work in progress – very preliminary!

➪ great potential to further reduce pion contamination by detailed shower imaging (geometry)