Concepts for
A next generation heavy-ion experiment at the LHC

Luciano Musa (CERN)

EoI document, Dec 2018, submitted to European Strategy for Particle Physics Preparatory Group (arXiv: 1902.01211)

See also talk of J. Stachel on Saturday

Outline

CERN – EP Department

① Prelude

- ALICE detector upgrade in LS2

② Concepts for a future fast and lightweight heavy-ion detector

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

ALICE LS2 Upgrade

Strategy driven by these main physics topics

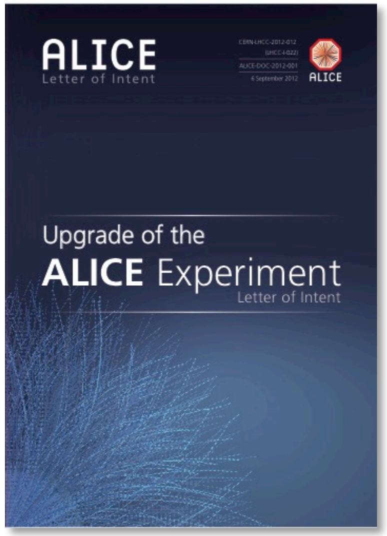
- Heavy flavour dynamics and hadronization at low p_T ⇨ heavy-quark interactions in QCD medium
- Charmonium down to zero p_T ⇨ quarkonium melting and regeneration in QGP
- Thermal dileptons, photons, vector mesons ⇨ QGP radiation and chiral symmetry restoration at $\mu_B = 0$
- High-precision measurement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

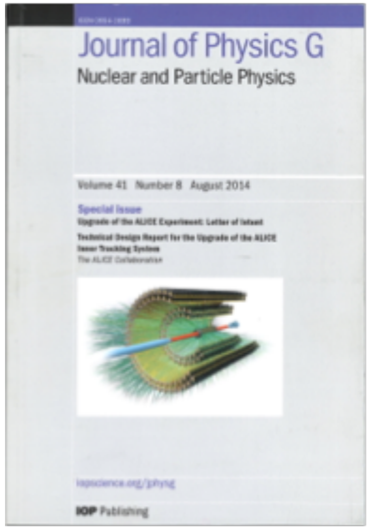
No Dedicated Trigger Possible !!

(RUN3+RUN4): 13/nb ⇨ x100 MB statistics (compared to RUN1+RUN2)

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 budget
- 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

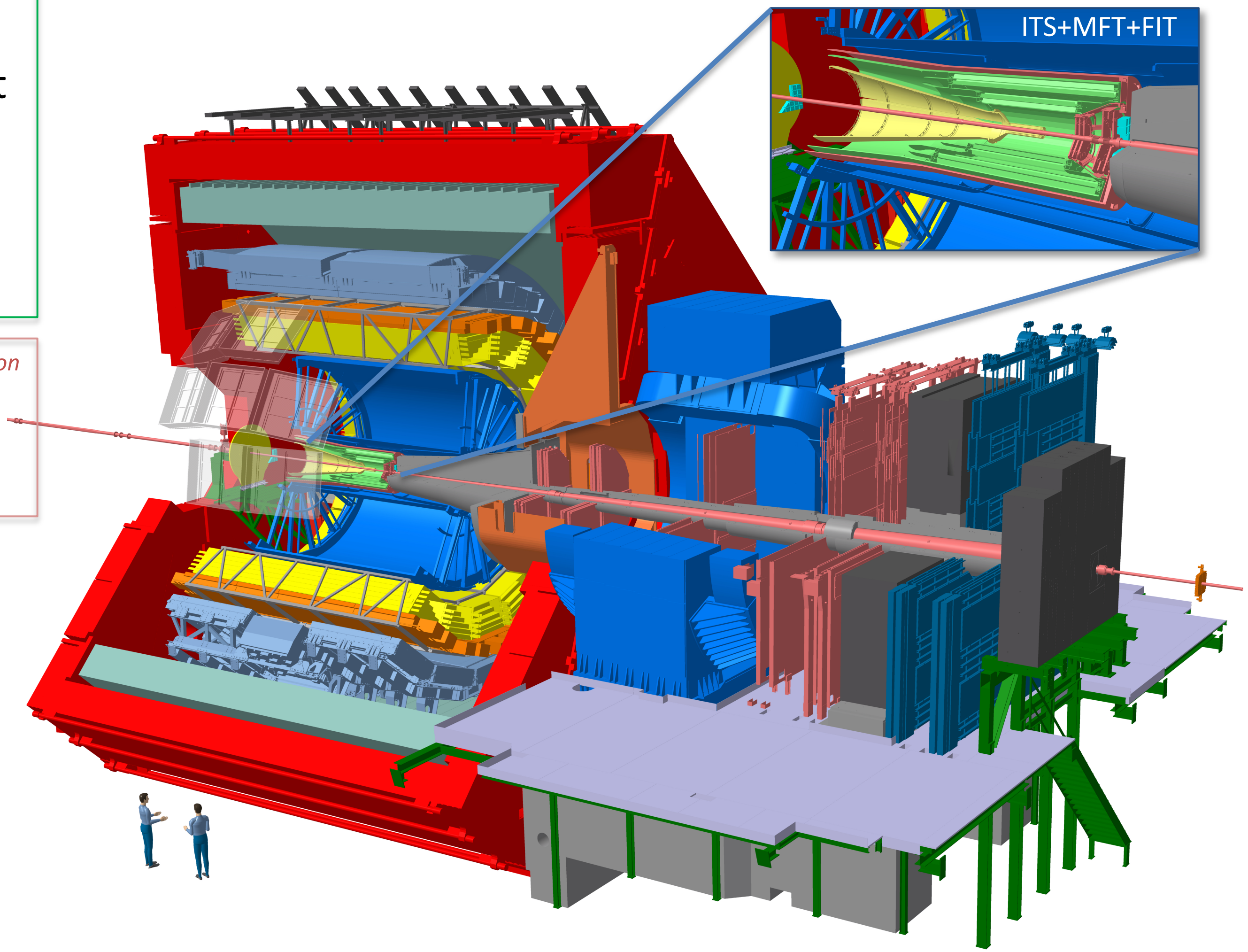
New TPC Readout Planes *Largest GEM application*
- 4-GEM detectors, new electronics

→ continuous readout

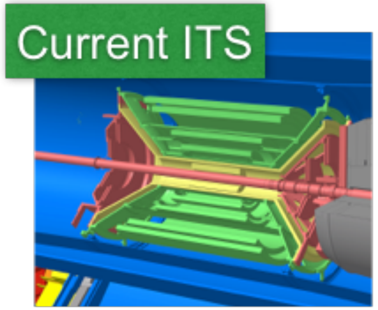
New trigger detectors (FIT, AD)
- Centrality, event plane

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

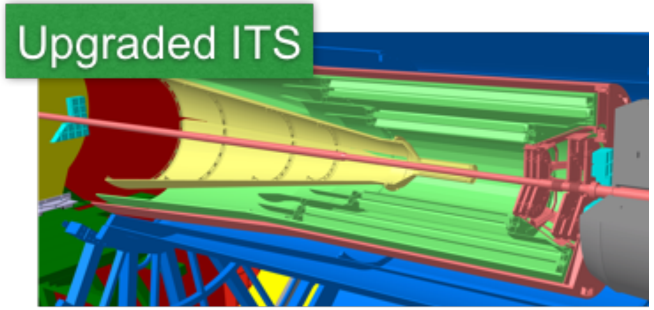
Integrated Online-Offline system (O^2)
- Record minimum-bias Pb-Pb data at > 50kHz (currently ~ 1 kHz)



ITS Upgrade in LS2 (ITS2)



6 layers (39mm < r < 440mm)
$-1 \leq \eta \leq 1$



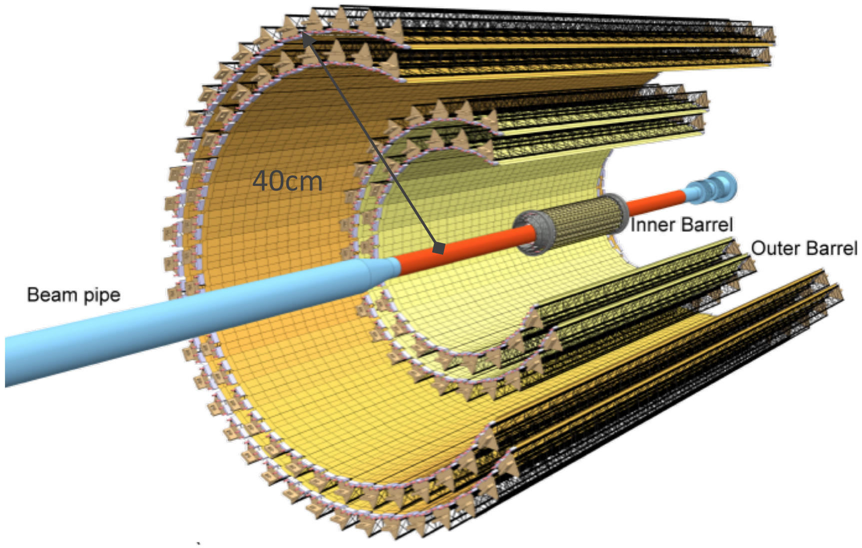
7 layers (22mm < r < 400mm)
$-1.3 \leq \eta \leq 1.3$

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 (w/o pile-up)
- Fake hit rate: < 1Hz/cm^2
- X/X_0 (first three layers): 0.35%

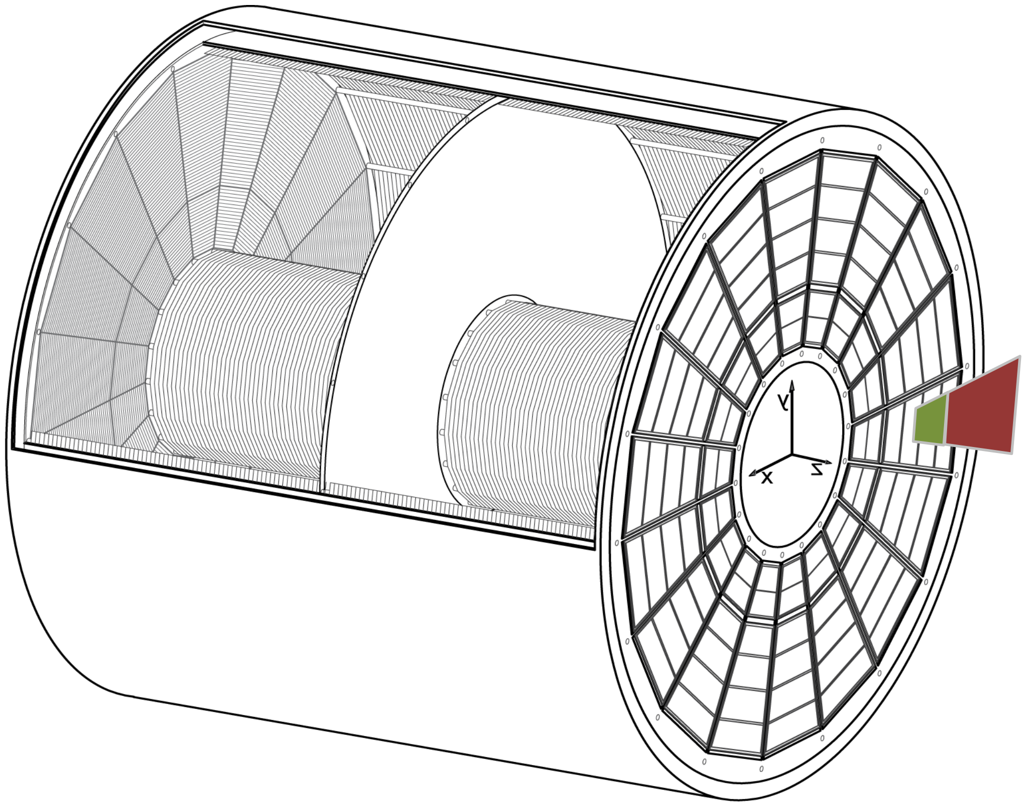


➩ further improvements exploiting technological innovations

TPC Continuous Readout with GEMs (Gas Electron Multiplier)

Gate-less TPC for continuous readout

Current MWPC: readout rate limited by ion backflow

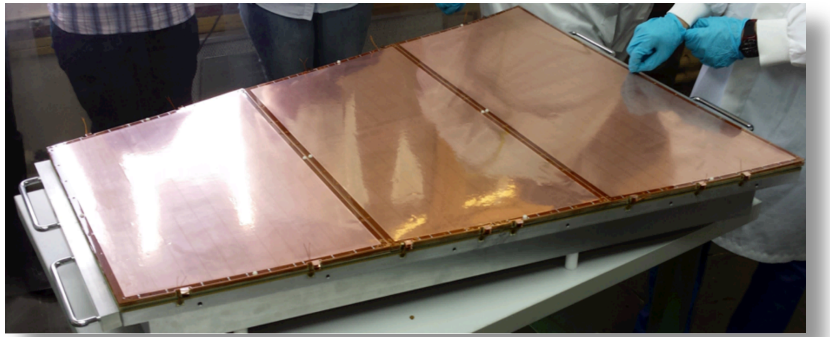


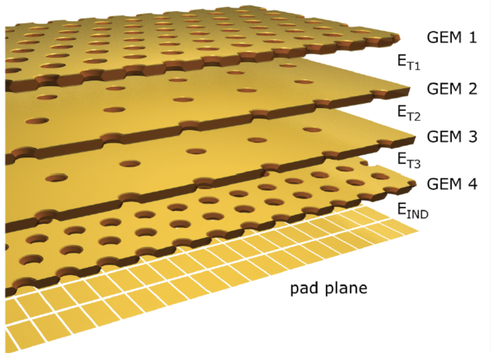
Operate TPC at 50 kHz ⇨ no gating grid

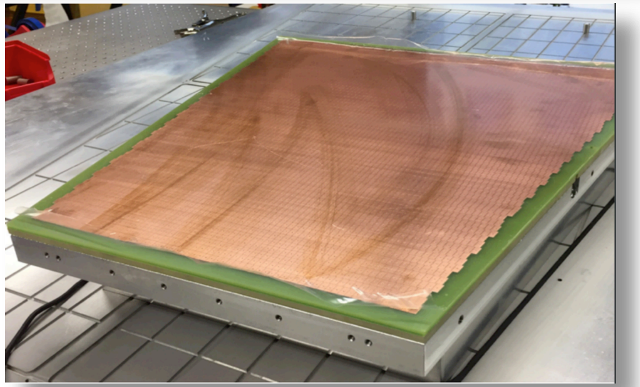
Need to minimize IBF ⇨ Replace MWPC with 4-GEMs

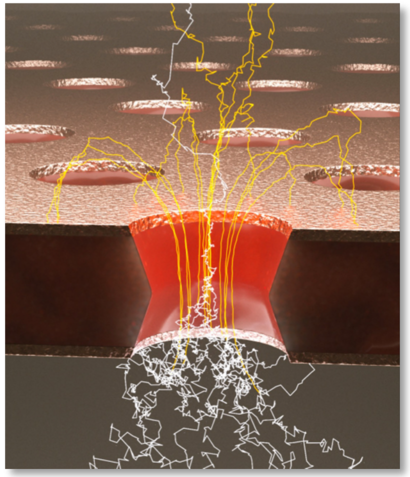
100 m^2 single-mask foils GEM production

Read Out Chamber







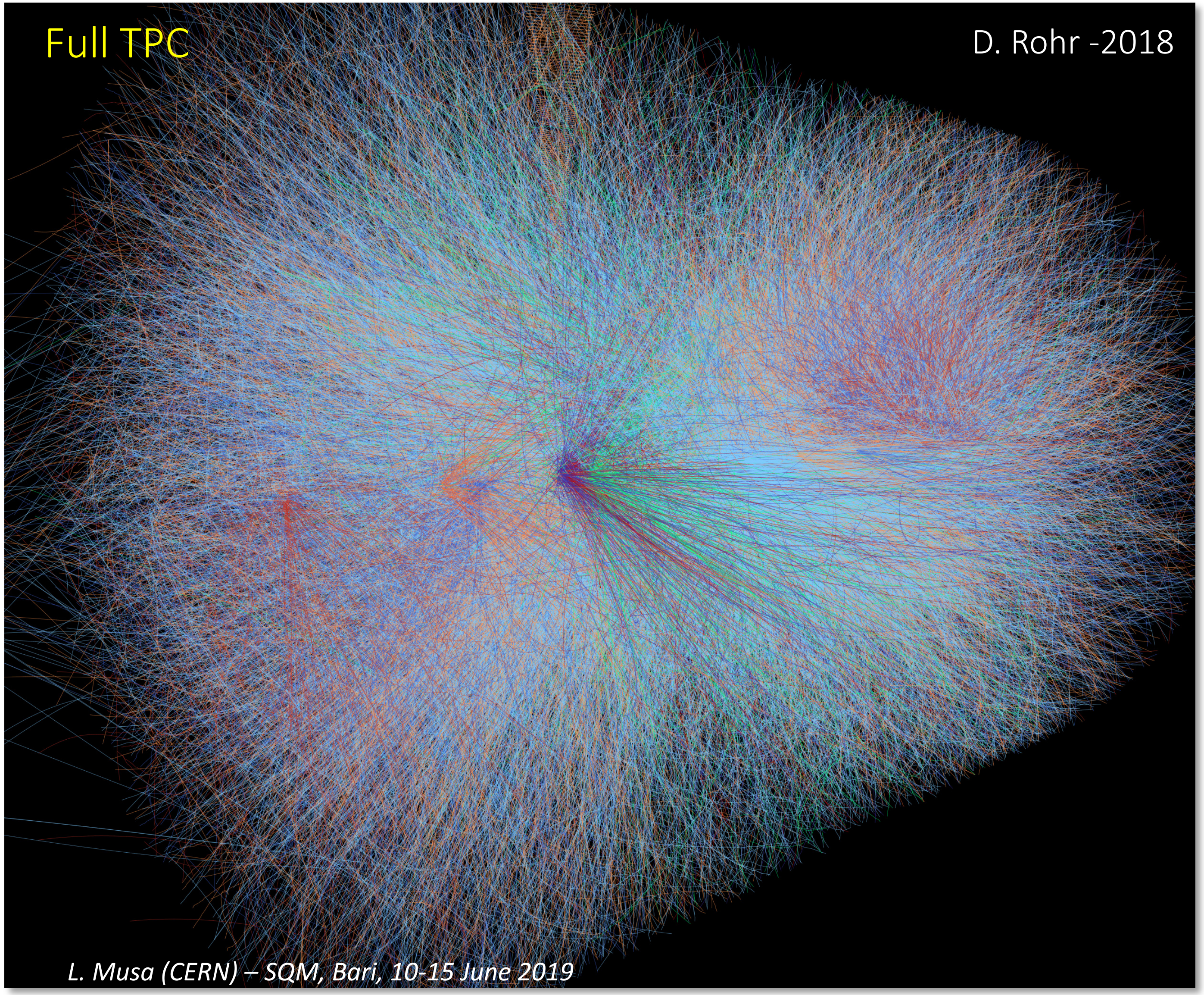


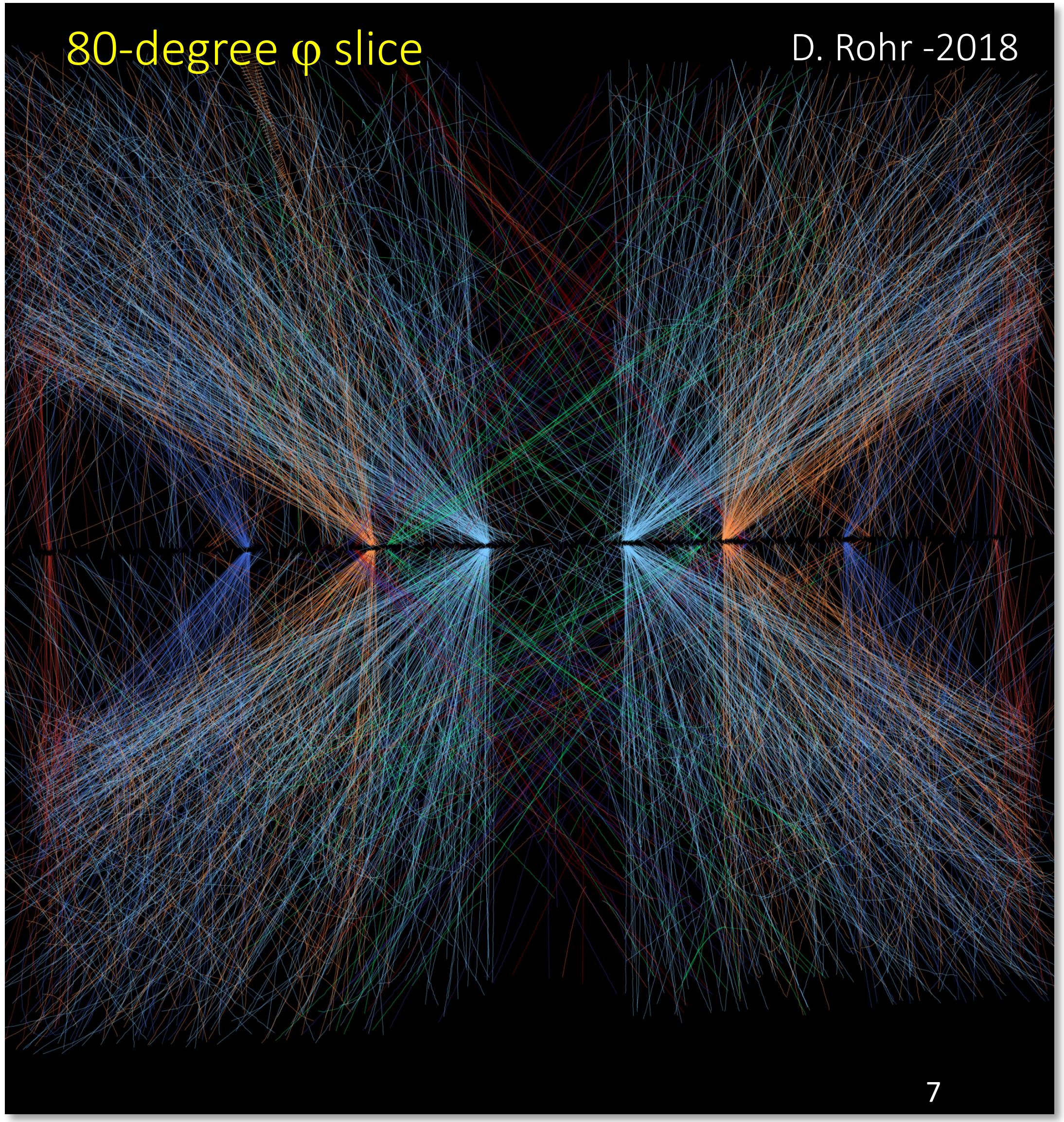
⇨ GEM provides ion backflow suppression to **< 1%**

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

ALICE Run3 – Event Display

Pb-Pb Collisions @ 50kHz





A new HI dedicated experiment beyond LS4?

With the LS2 upgrade, ALICE will reach the maximum 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 could 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 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 beampipe
  - spatial resolution < 3μm
  - 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 is also considered

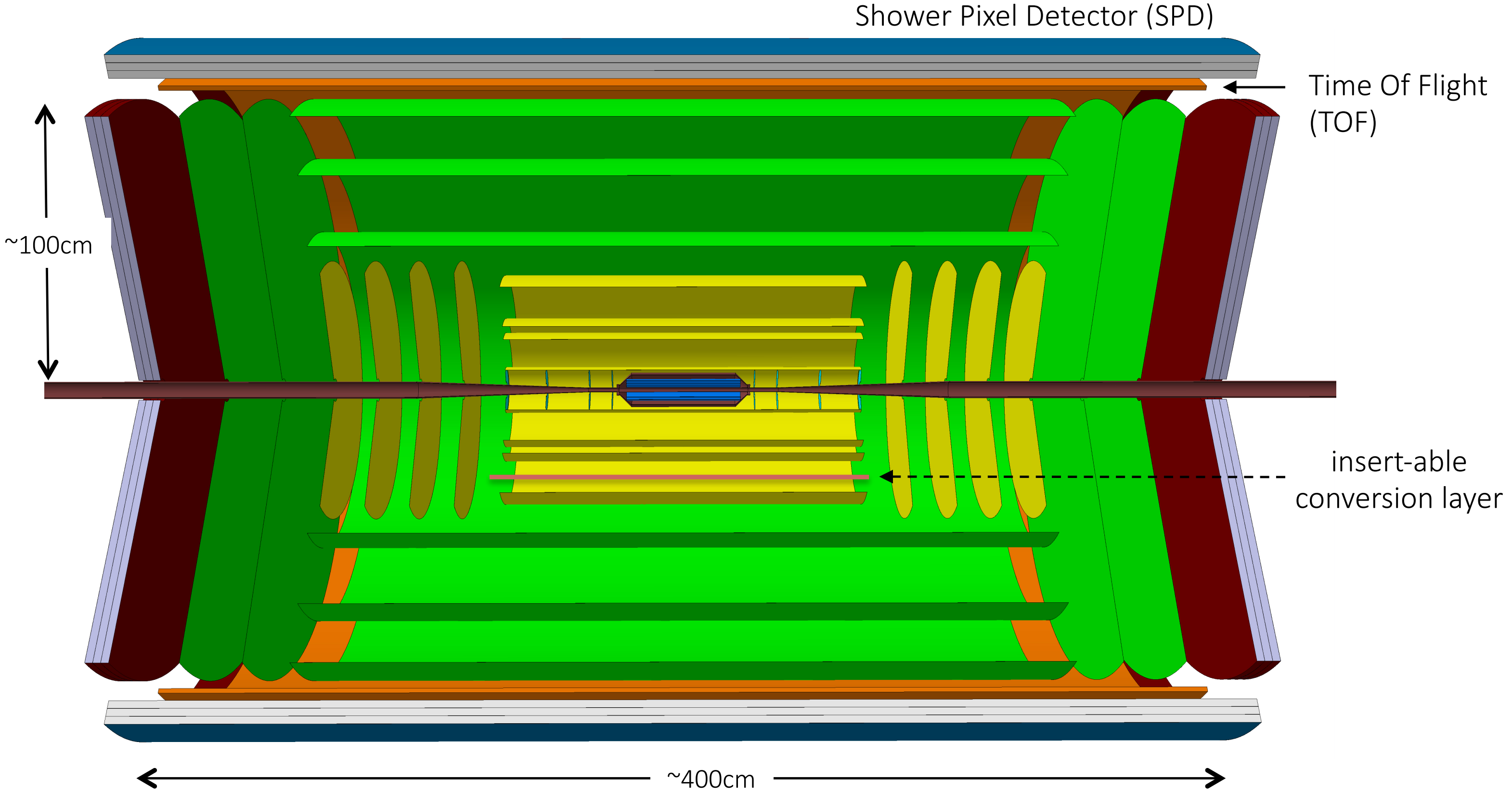
A new experiment based on a “all-silicon” detector

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**



Magnetic Field

- B = 0.5 or 1 T

Spatial resolution

- Innermost 3 layers: $\sigma < 3\mu m$
- Outer layers: $\sigma \sim 5\mu m$

Vertex material thickness

- X/X0 ~ 0.05% / layer

Time Measurement

Outermost layer integrates high precision time measurement ($\sigma_t \sim 20ps$)

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))

→ Hadron formation from deconfined QGP

- Low-mass dielectrons
  - Precision measurement of the thermal dilepton continuum, $0 < m < 3GeV$

→ Chiral symmetry restoration ρ-a1 sector

- Real soft photons
  - down to 50MeV/c

→ QGP Radiation unchartered phase space region

- Real ultra-soft photons
  - Very low p_T photons: $1MeV/c < p_T^{\gamma} < 100MeV/c$
  - dedicated small forward spectrometer at $3.5 < |\eta| < 5$)

→ Test of soft theorems

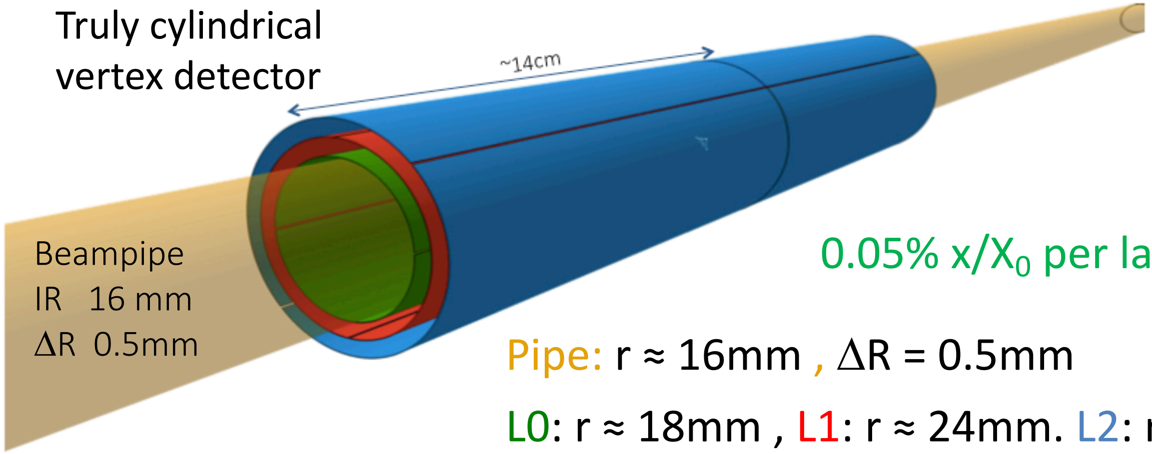
Vertex Detector (innermost 3 layers)

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 ~30μm can be curved to a radius of 10-20mm

Truly cylindrical vertex detector

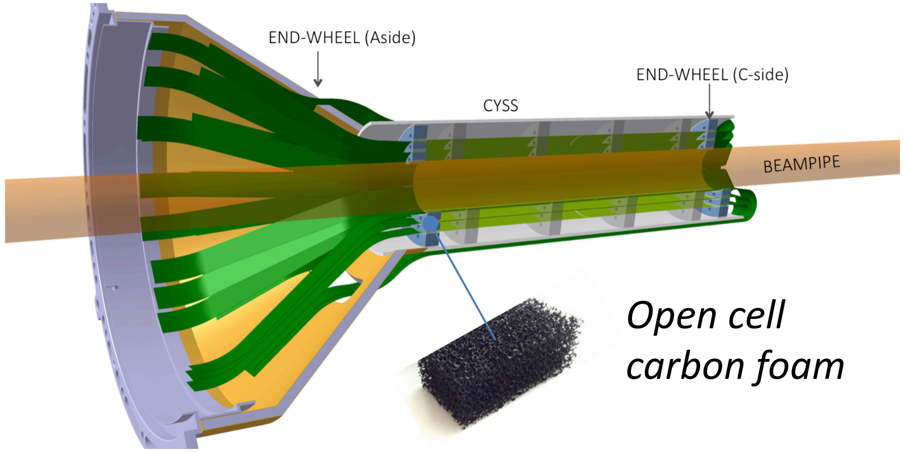


Beampipe
IR 16 mm
ΔR 0.5mm

0.05% x/X_0 per layer

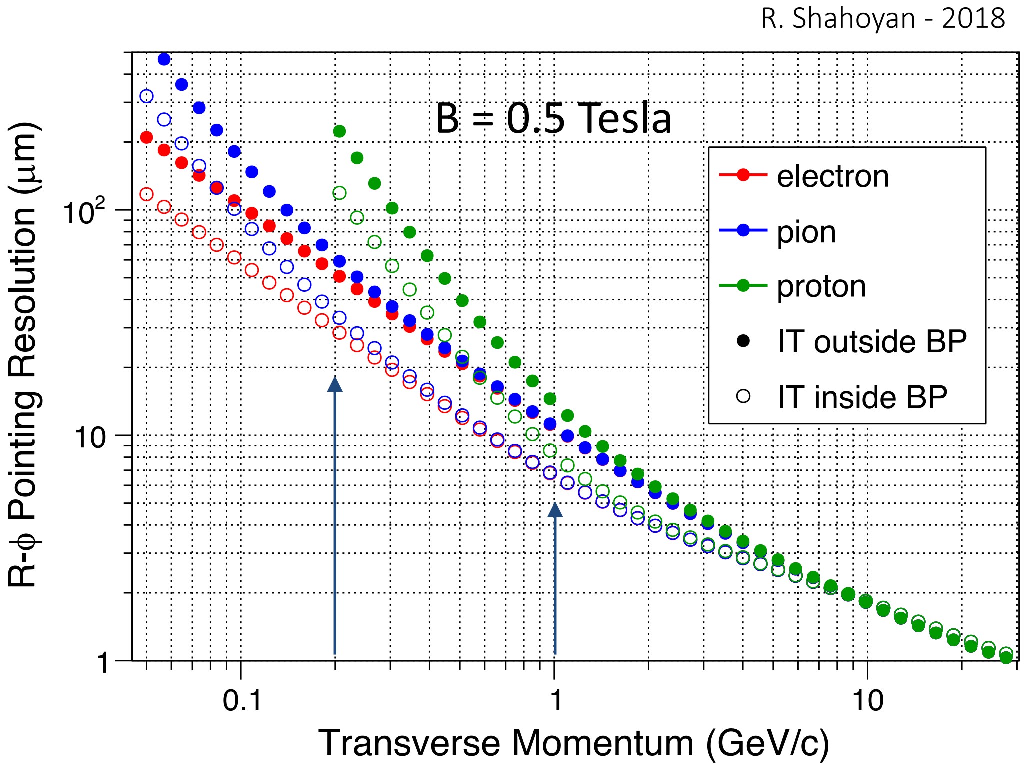
Pipe: r ≈ 16mm , ΔR = 0.5mm

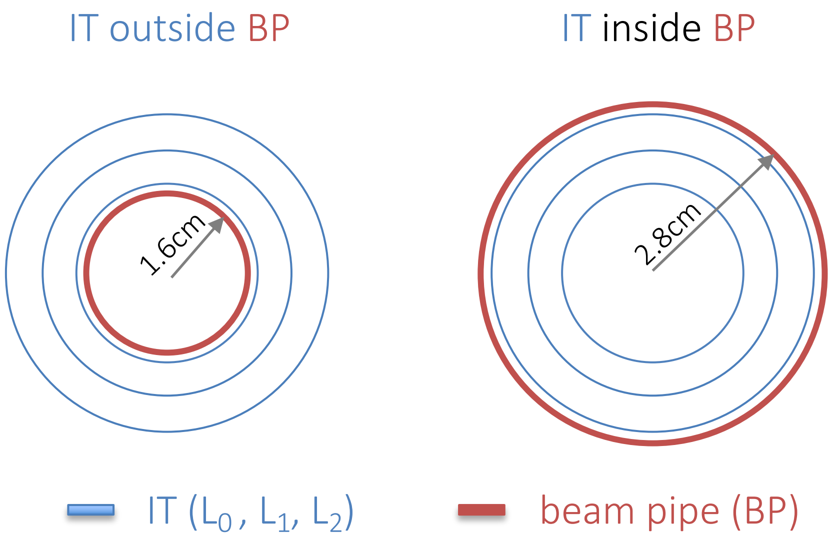
L0: r ≈ 18mm , L1: r ≈ 24mm. L2: r ≈ 30 mm

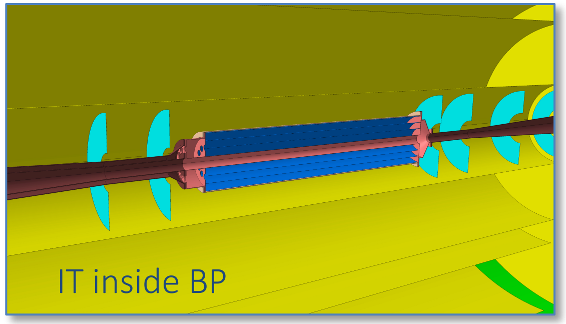


Open cell carbon foam

Pointing resolution







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

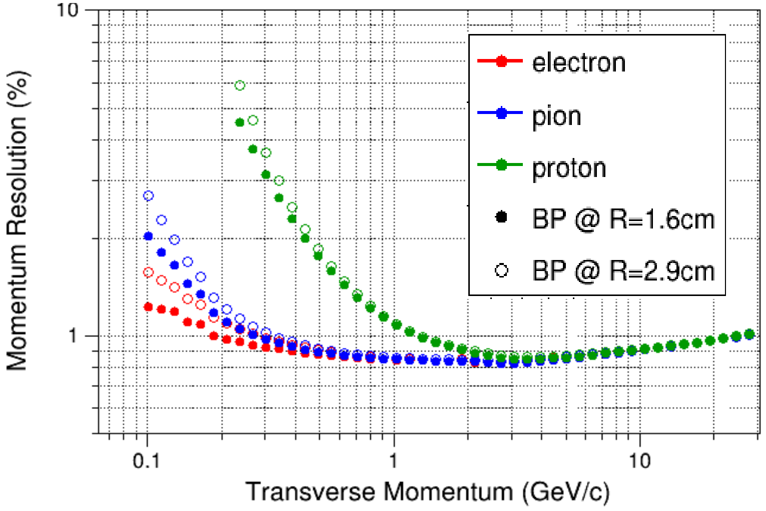
It does not depend on B field

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

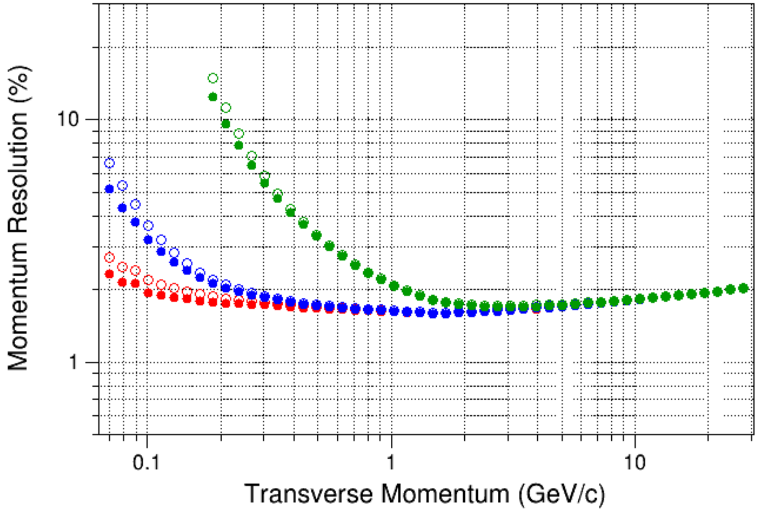
B = 1 T

R. Shahoyan - 2018



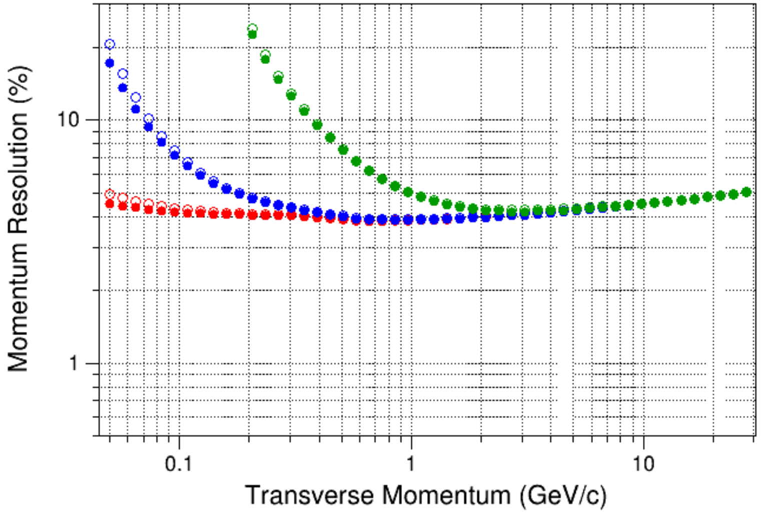
B = 0.5 T

R. Shahoyan - 2018



B = 0.2 T

R. Shahoyan - 2018

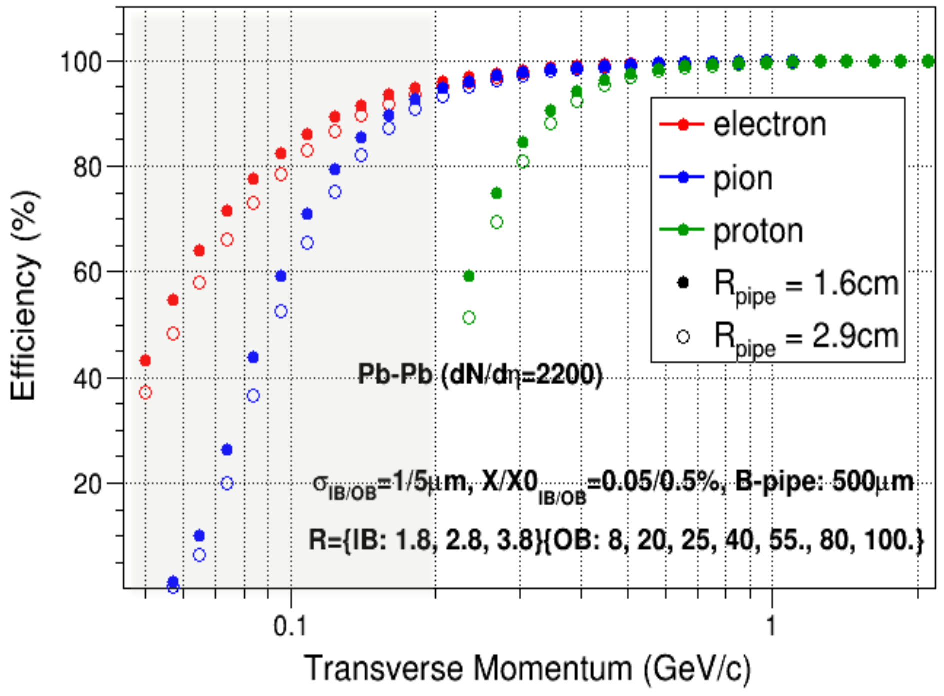


momentum resolution for 1GeV/c pions: ≈ 0.8% (1 T), ≈1.6% (0.5 T), ≈ 4% (0.2 T)

Operation at reduced B field for tracking low p_T particles

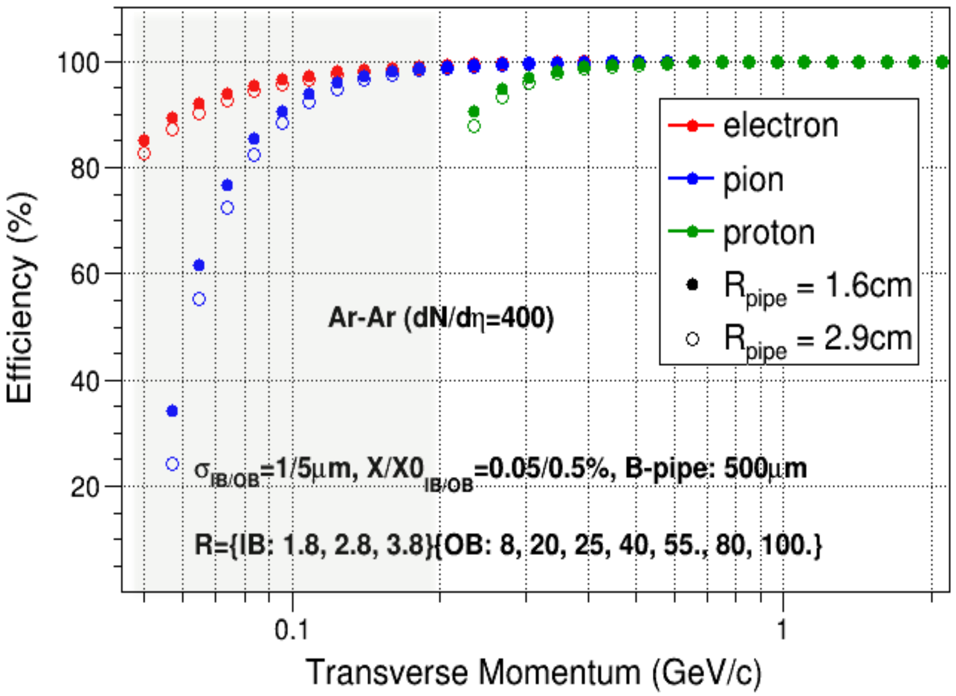
Pb-Pb (dN/dη = 2200), B = 0.2 Tesla

R. Shahoyan - 2018



dN/dη = 440, B = 0.2 Tesla

R. Shahoyan - 2018



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

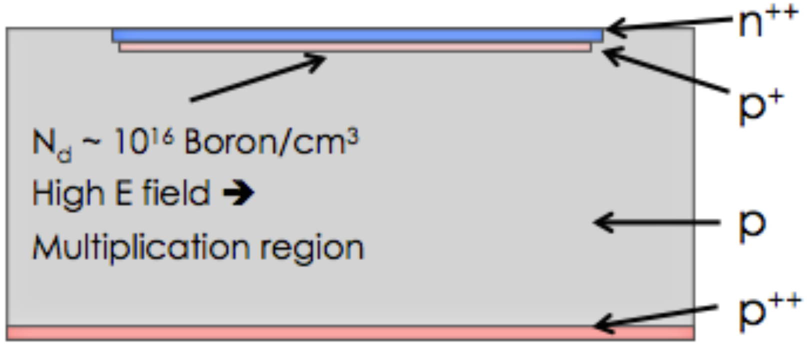
⇨ optimization possible (e.g. using only layers up to 40cm)

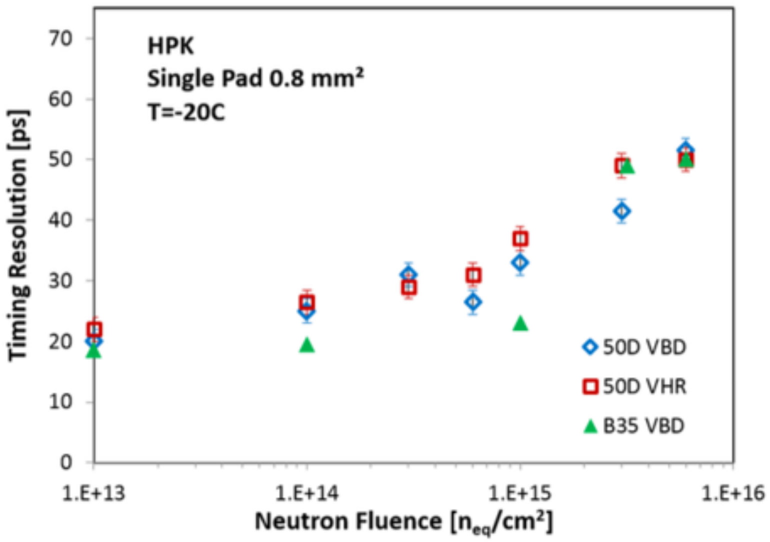
⇨ improvement for lower dN/dη

Further layout optimization possible!

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: Hammamatsu, FBK, CNN





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

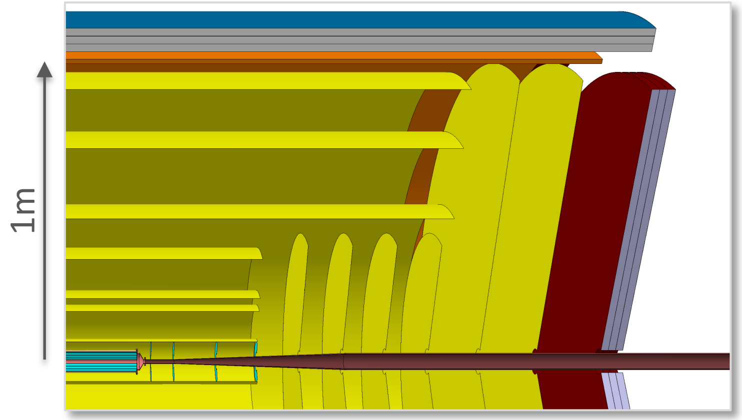
Resolution of 20-30ps demonstrated

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

Can such a gain layer be implemented using CMOS? ⇨ large cost saving

⇨ Single Photon Avalanche Diodes (SPADs)

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

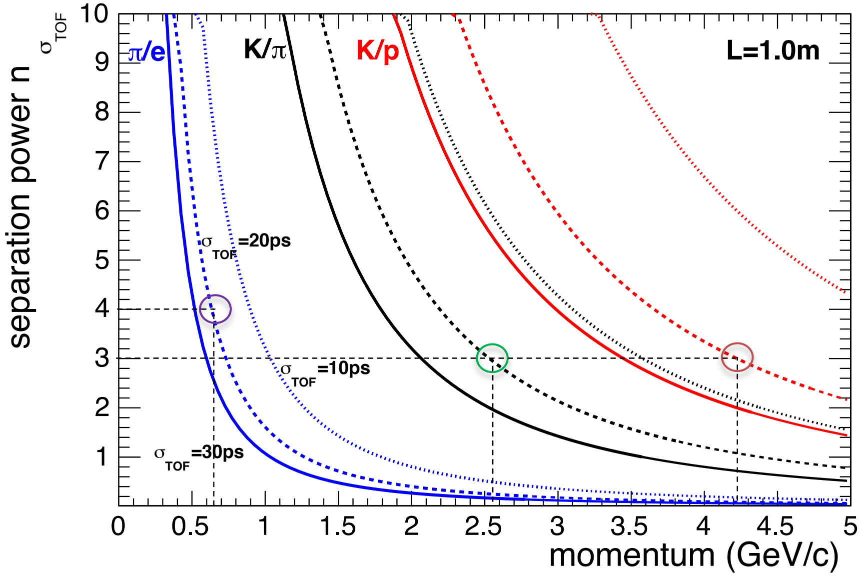
Number of layers will depend on time resolution and spatial fill factor achieved in the single layer

Ideal track length and p measurement for 3 scenarios (10ps, 20ps , 30ps) are show in figure

For σ_{TOF} = 20ps

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

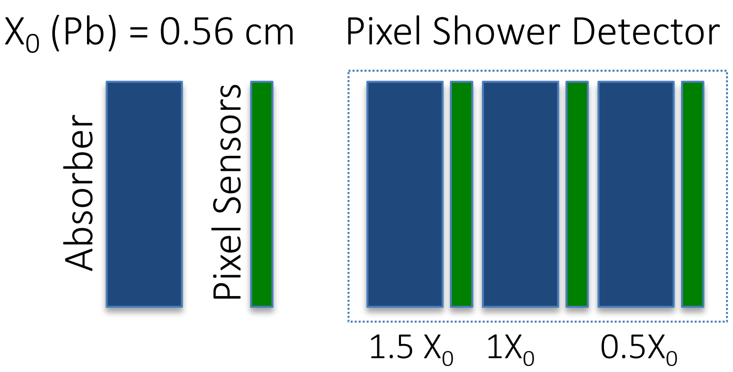
C. Lippmann - 2018

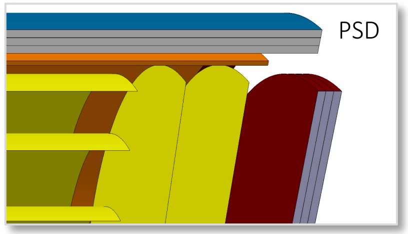


Electron ID with Pixel Shower Detector

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

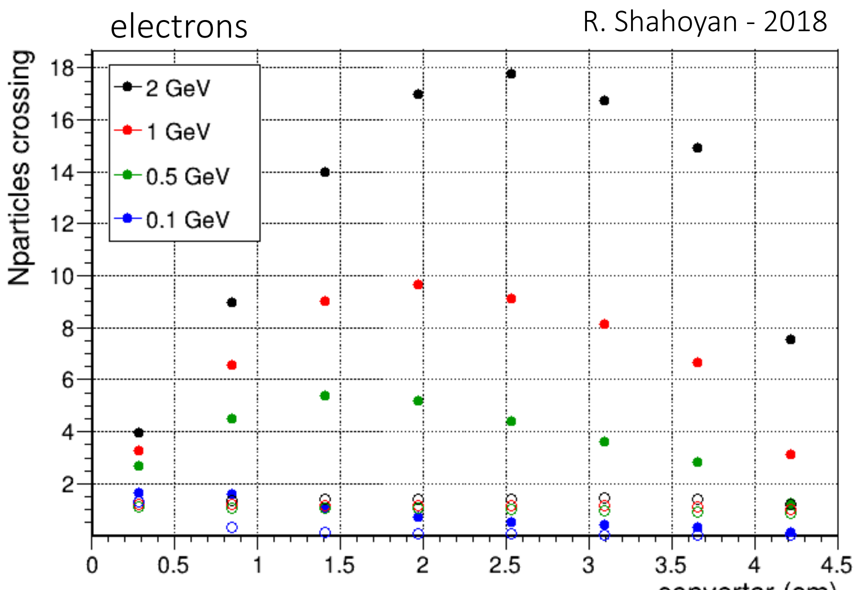


Figure 1

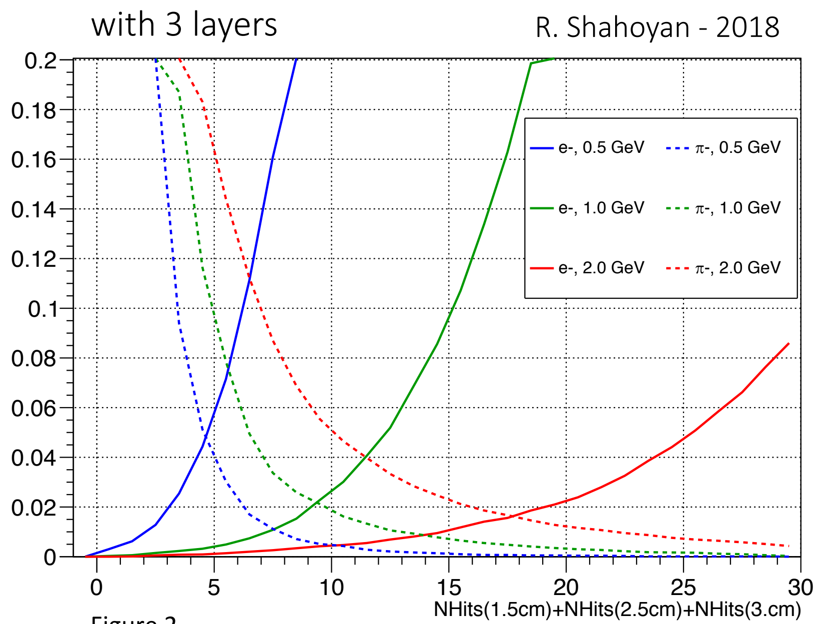


Figure 2

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

Summary

Concepts for a next generation LHC heavy-ion experiment

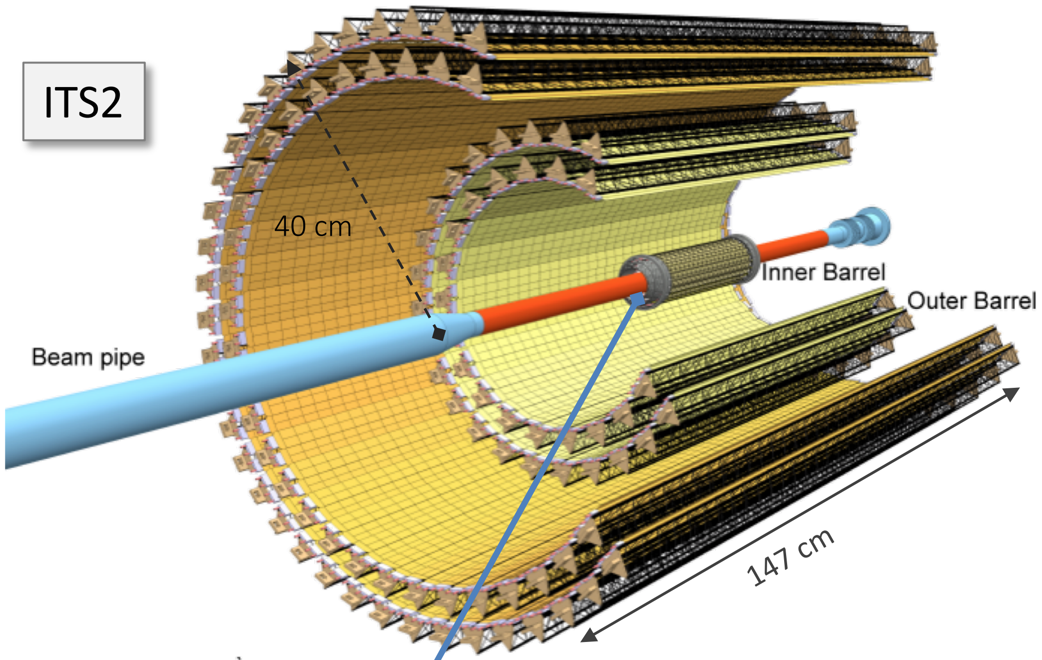
- A detector conceived for studies of pp, pA and AA collisions at luminosities 50 times higher than possible with the upgraded ALICE detector
- enables rich physics program: from measurements with electromagnetic probes at ultra-low transverse momenta to precision physics in the charm and beauty sector.

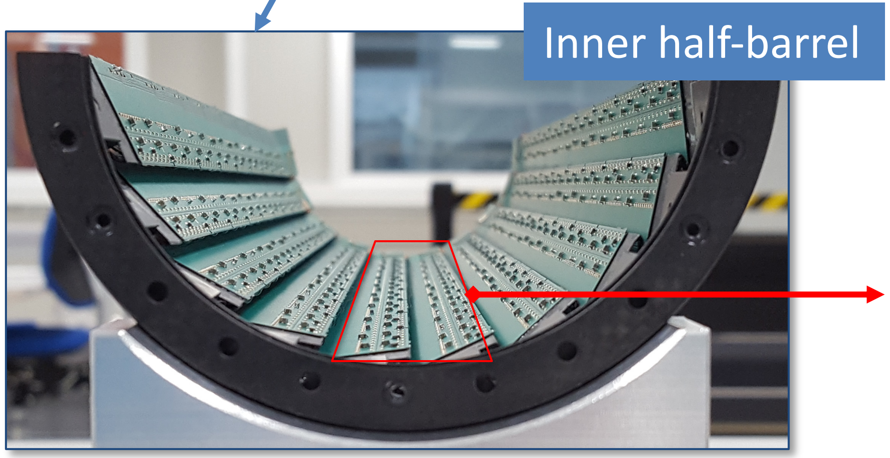
- Three truly cylindrical layers based on curved wafer-scale ultra-thin CMOS Active Pixel sensors
- Unprecedented low material budget for the inner layers of 0.05% X_0, with the innermost layers possibly positioned inside the beam pipe
- Tracking and vertexing capabilities over a wide momentum range 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.

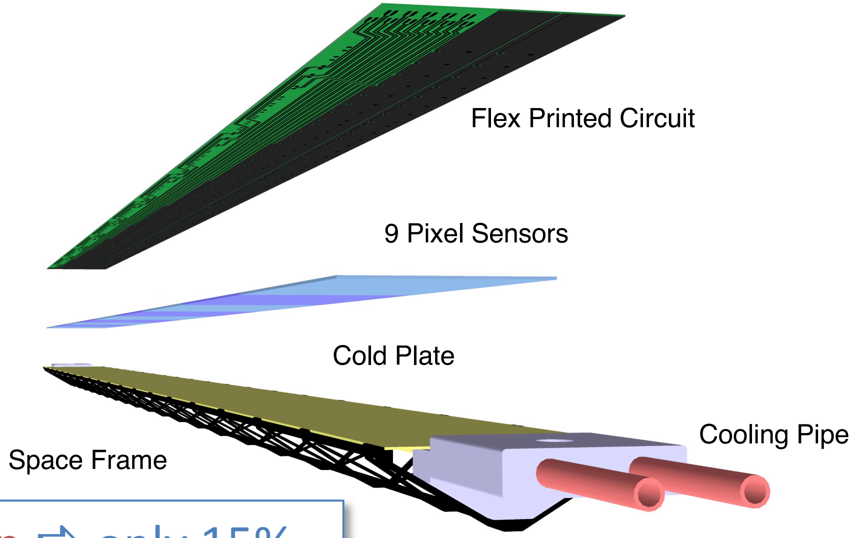
Thank You

ITS2 – Material Thickness

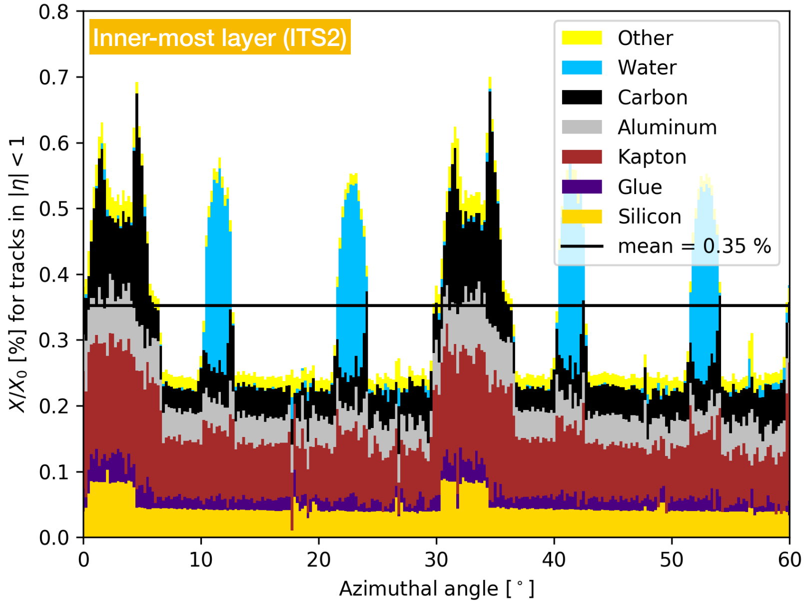
ITS2







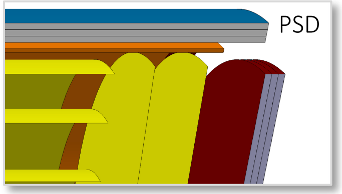
Silicon ⇨ only 15%



Electron ID with Pixel Shower Detector

Electron and photon ID using Pixel Shower Detector

$e/\pi \sim 10^{-2}$



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

R. Shahoyan - 2018

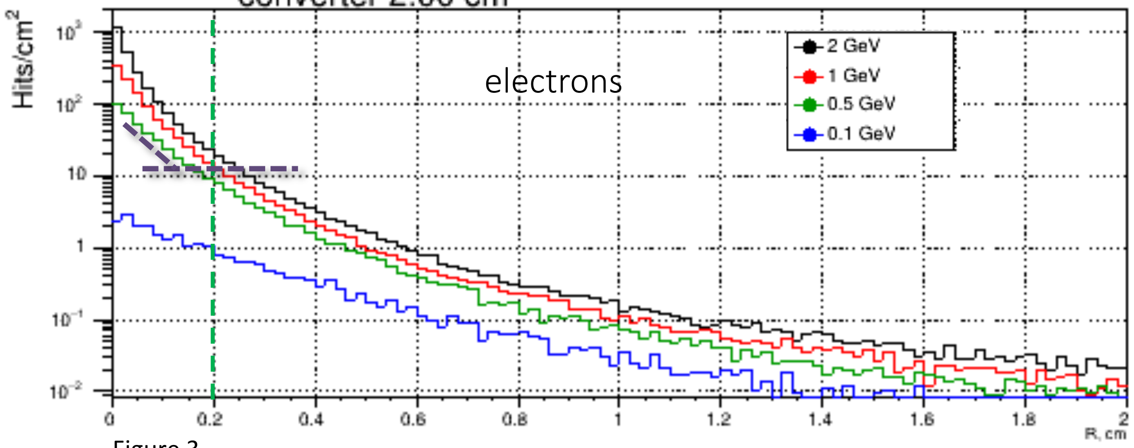


Figure 3

R. Shahoyan - 2018

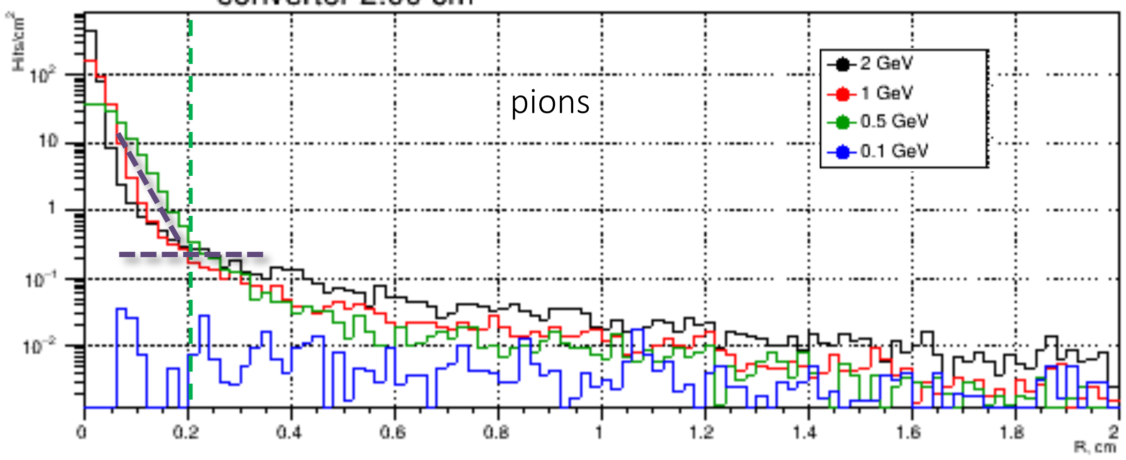


Figure 4

Work in progress – very preliminary!

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