FUTURE
CIRCULAR
COLLIDER

FCC WEEK 2021
28TH JUNE – 2ND JULY

From vertex to wrapper: the IDEA tracking system for FCC-ee

Online event, 1st July 2021

Attilio Andreazza

Università di Milano and INFN

For the IDEA community

(plus some stolen slides from other presentations...)

INFN MILANO

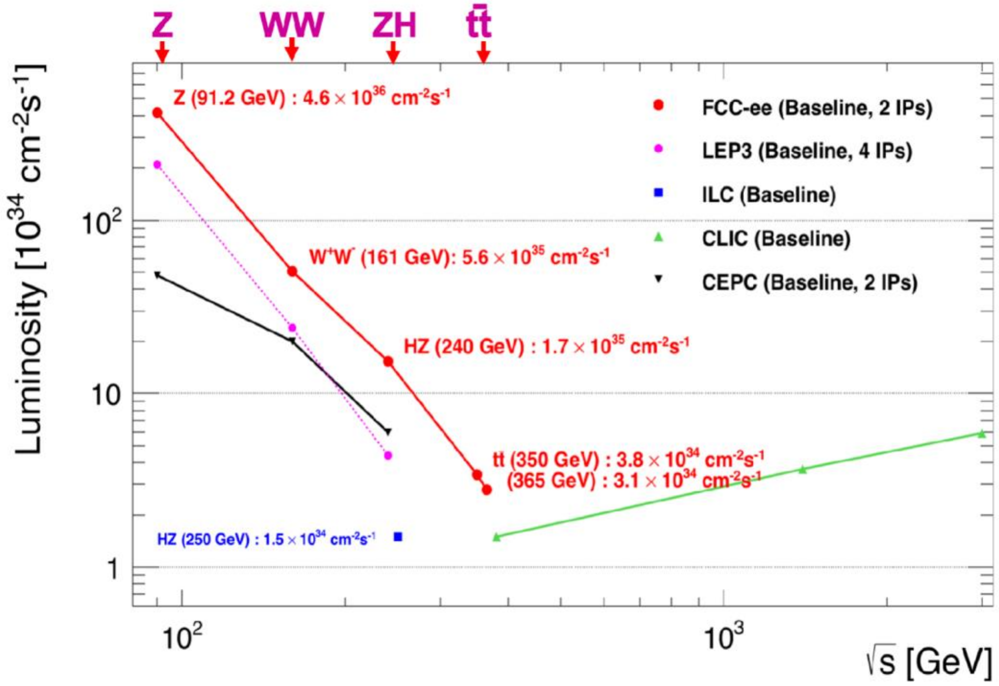
UNIVERSITÀ DEGLI STUDI DI MILANO
DIPARTIMENTO DI FISICA

Introduction

International **D**etector for **E**lectron-positron **A**ccelerators

- Detector concept for e^+e^- circular machine
- Documented in the FCCee CDR

- Focus of today presentations:
  - some considerations for the most challenging environment: **Z pole running**
  - updates on the R&D for the tracker



FCC-ee parameters		Z	W^+W^-	ZH	ttbar
√s	GeV	91.2	160	240	350-365
Luminosity / IP	10^{34} cm^{-2} s^{-1}	230	28	8.5	1.7
Bunch spacing	ns	19.6	163	994	3000
"Physics" cross section	pb	35,000	10	0.2	0.5
Total cross section (Z)	pb	40,000	30	10	8
Event rate	Hz	92,000	8.4	1	0.1
"Pile up" parameter [μ]	10^{-6}	1,800	1	1	1

See P. Giacomelli's talk on Monday

Physics requirements

- Impact parameter resolution

$$\sigma_d = a \oplus \frac{b}{p\sin^{\frac{3}{2}}\theta}$$

$$a \sim 5\ \mu\text{m}, \qquad b \sim 15\ \mu\text{m}\cdot\text{GeV}$$

- Particle identification capability (p/K/π)

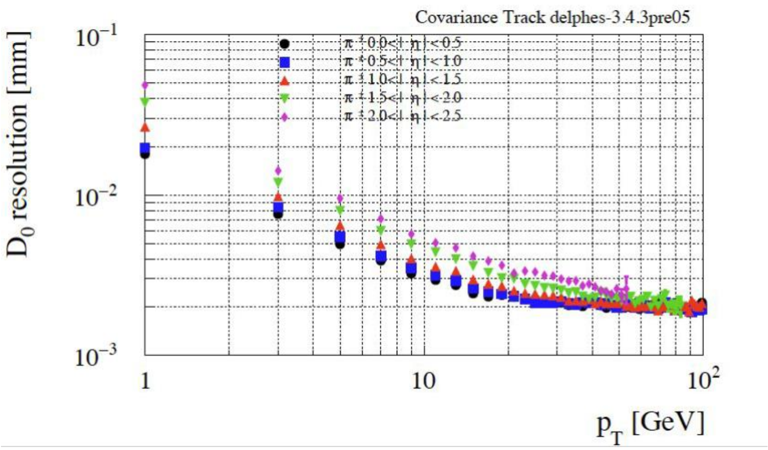
- Momentum resolution

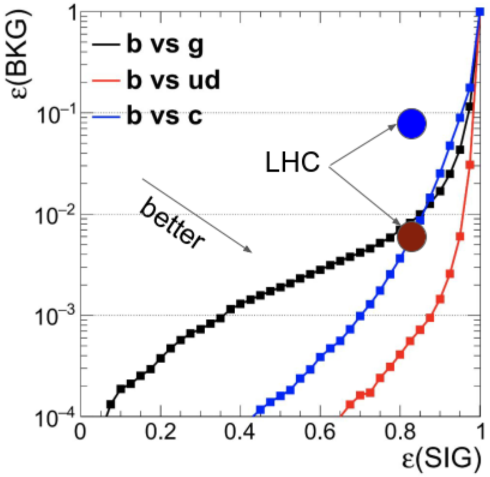
$$\frac{\sigma_p}{p} = p\cdot a + \frac{b}{\sin\theta}$$

$$a < 2\cdot 10^{-5}\text{GeV}^{-1}$$

- $b/c/g/\tau$ tagging
- Flavour physics

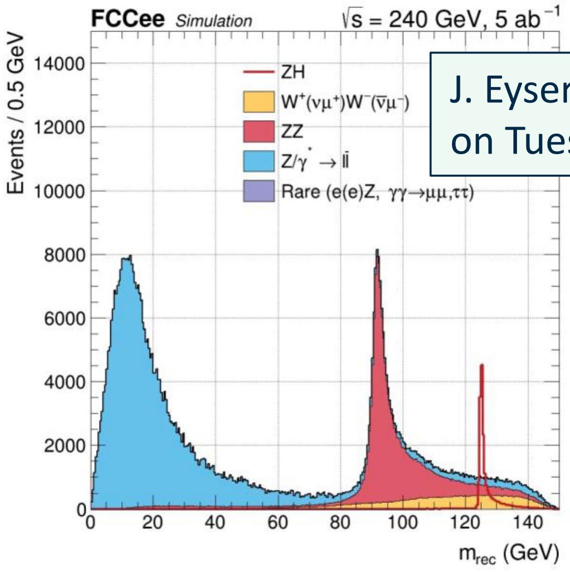
M. Selvaggi on Tuesday





- Recoil mass determination

J. Eysermans on Tuesday



Example: $H \to \begin{matrix} b\bar{b} \\ c\bar{c} \\ gg \end{matrix}$

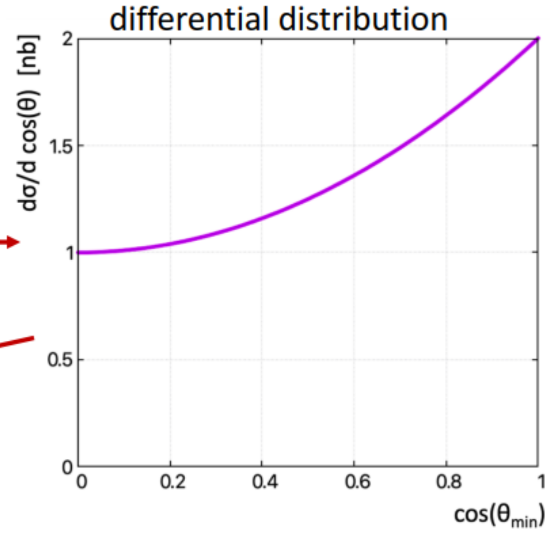
High precision measurements (1)

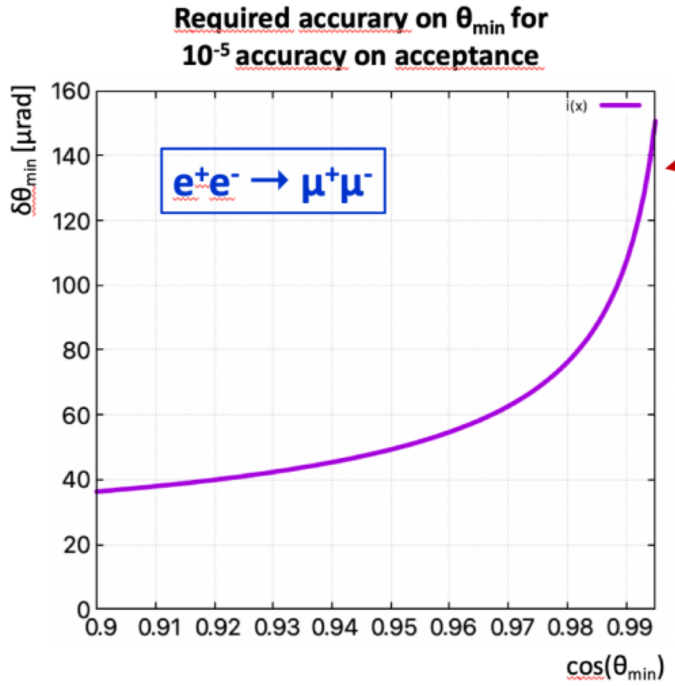
Strong requirements on detector design come from the systematics in high precision measurements

Example:

$$R_\ell = \frac{\Gamma(Z \to \text{hadrons})}{\Gamma(Z \to \ell^+\ell^-)}$$

- Goal is to measure R_ℓ to 10^{-5}
- Say, there would be no uncertainty on the number of multihadronic events
- Then, have to measure $\Gamma(Z \to \ell^+\ell^-)$ to 10^{-5}
  - ❑ In practice, probably primarily considering the muon channel, $Z \to \mu^+\mu^-$
- $Z \to \ell^+\ell^-$ at Z pole has (approximately) the angular dependence $1+\cos^2\theta$





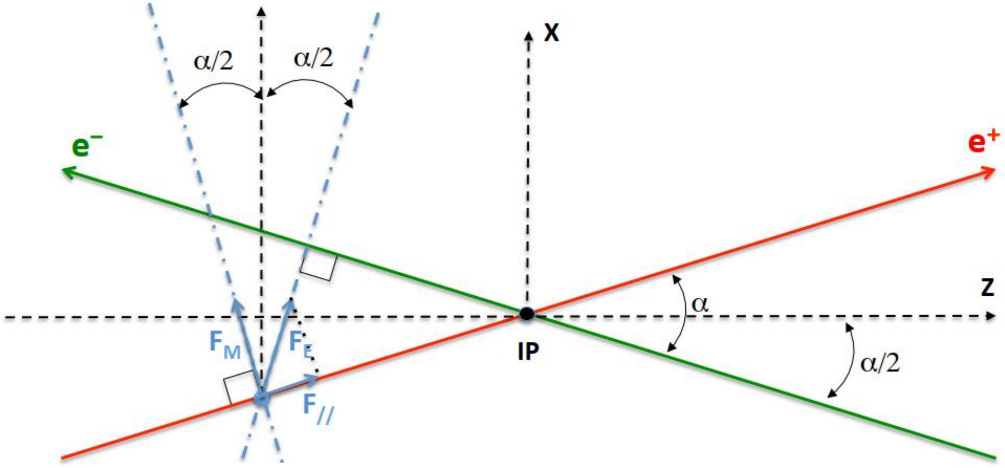
To reach 10^{-5}, have to control θ_{min} to $\mathcal{O}$(50 μrad)

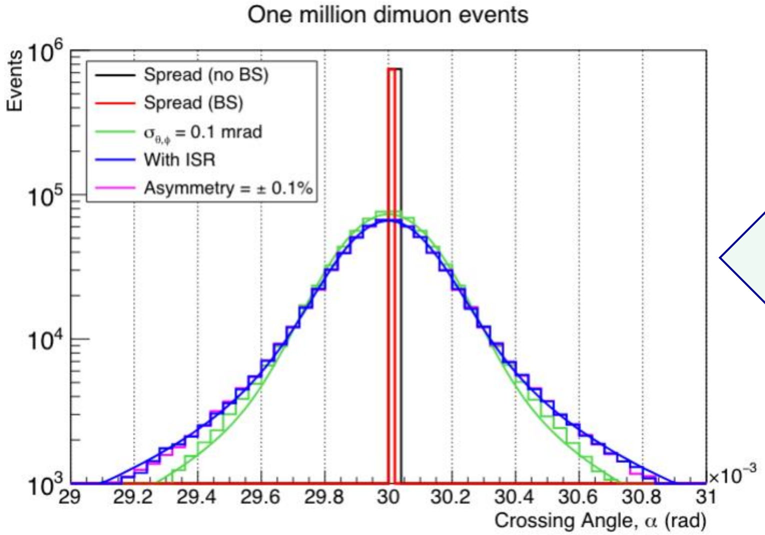
From M. Dam's talk at FCC Workshop November 2020

High precision measurements (2)

Strong requirements on detector design come from the systematics in high precision measurements

Example:
center of mass energy correction from beam-beam interactions





Beam-beam interactions change the energy and direction of the beams:

- changes are correlated such that center of mass energy is constant:

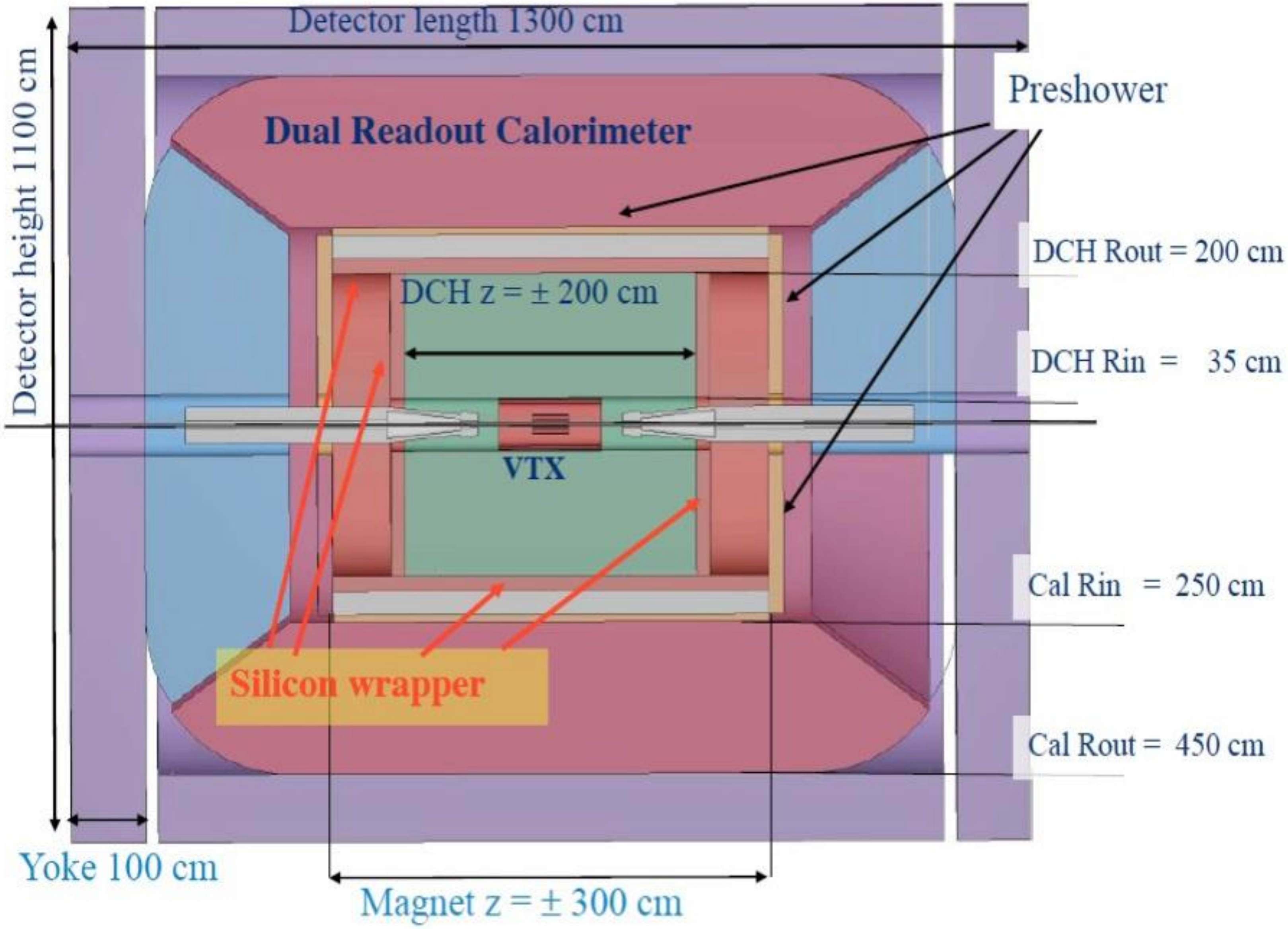
$$\sqrt{s} = \sqrt{E_0^+ E_0^-}\cos\frac{\alpha_0}{2} = \sqrt{E^+ E^-}\cos\frac{\alpha}{2}$$

- but α_0 is only measured with 0.1 mrad accuracy by the BPM
- It can be derived by monitoring the measured value of α as a function of the beam intensity
- With statistical uncertainties $\sigma_{\theta,\varphi}$ of 0.1 mrad, can get a 0.3 μrad uncertainty on α in ~5 minutes

See P. Janot's talk at FCC Week 2019

But what about systematics?

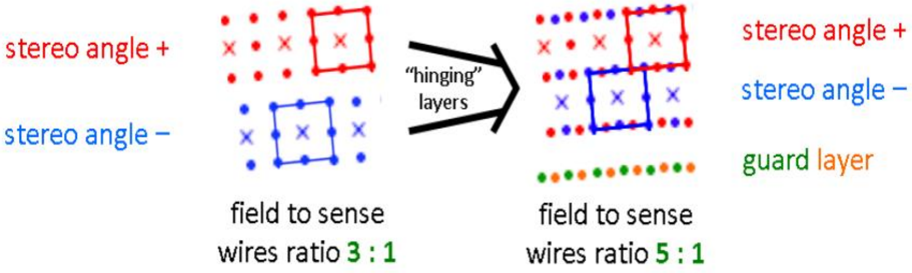
The IDEA concept



- Central tracking device:
  - light Drift CHamber
- Silicon detectors for precision measurements
  - vertex region
  - silicon wrapper
- Thin solenoid with 2T field (according to MDI limits)
- Dual readout calorimeter
  - supplemented by a pre-shower detector
- Muon chambers in the solenoid return yoke

The IDEA Drift CHamber

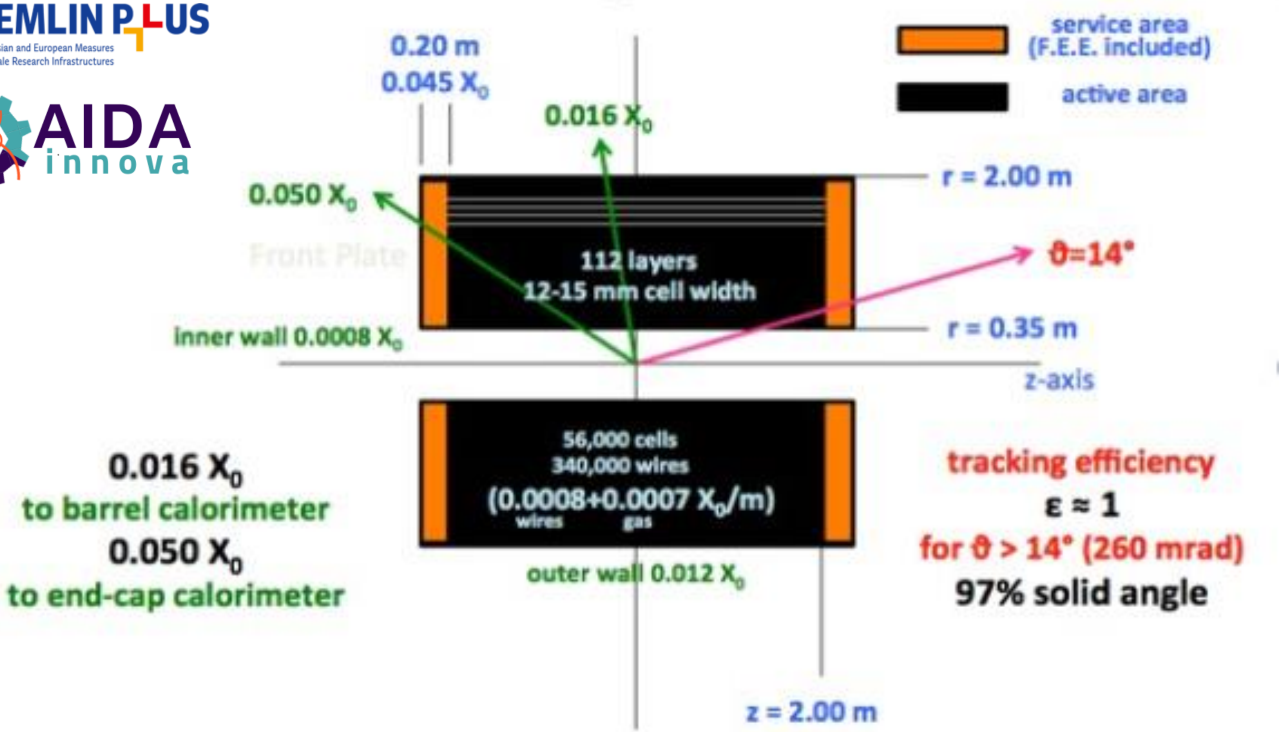
- Extremely light and fast drift chamber
- Gas mixture: 90% He + 10% iC4H10
- 12-15 mm wide wire cells



  - The wire net created by the combination of + and orientation generates a more uniform equipotent surface
  - 400 ns max drift time
- 14 co-axial super-layers, 8 layers each (112 layers in total) with alternating sign stereo angles ranging from 50 to 250 mrad.

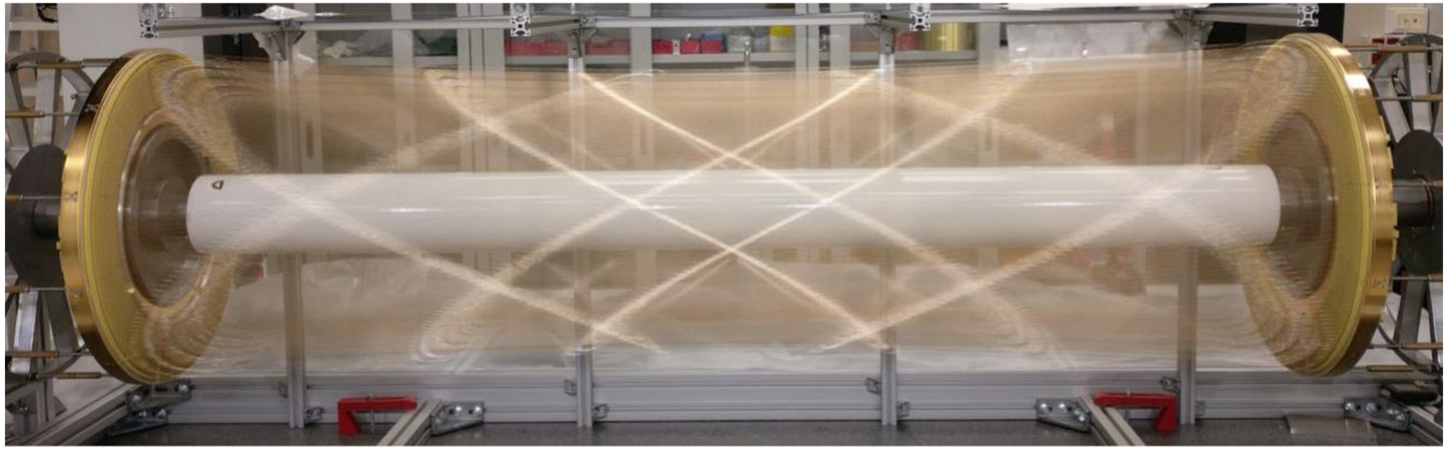
CREMLIN PLUS
Connecting Russian and European Measures for Large-scale Research Infrastructures

AIDA innova



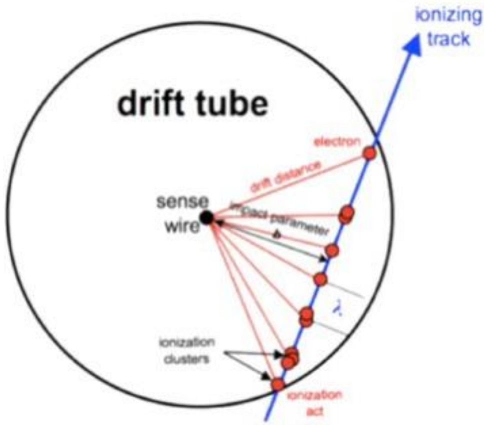
0.016 X_0 to barrel calorimeter
0.050 X_0 to end-cap calorimeter

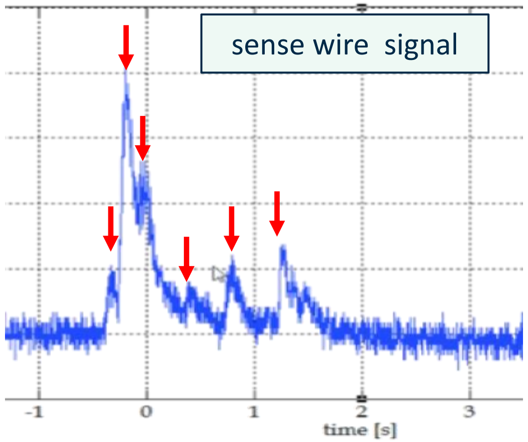
tracking efficiency
ε ≈ 1
for θ > 14° (260 mrad)
97% solid angle

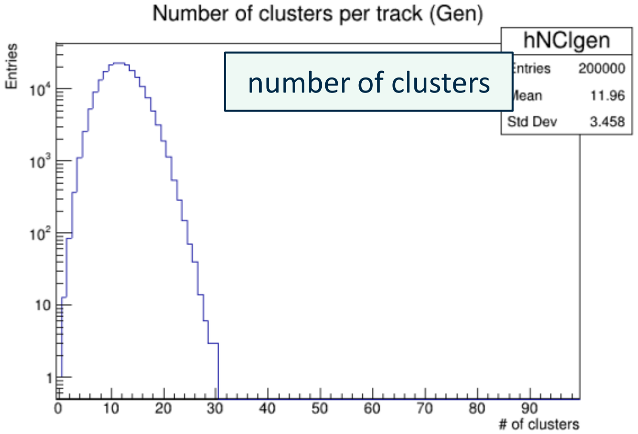


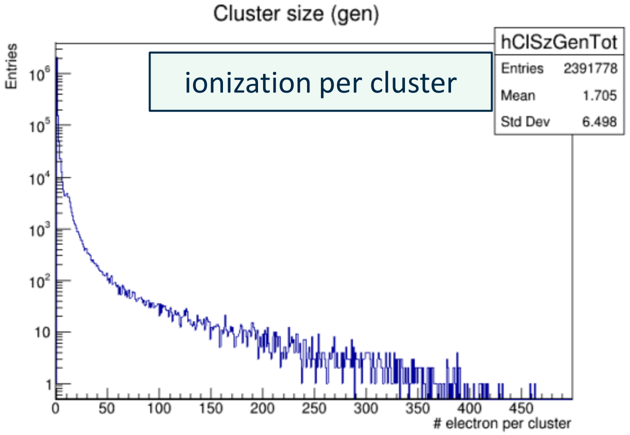
IDEA DCh: Cluster counting method

- In He based gas mixtures the signals from each ionization act can be spread in time to few ns.
- A fast read-out electronics could identify them efficiently.
- By counting the number of ionization acts per unit length ($\mathrm{d}N/\mathrm{d}x$), it is possible to identify the particles (PID) with a better resolution w.r.t the $\mathrm{d}E/\mathrm{d}x$ method:
  - **dE/dx**: analog information, affected by Landau fluctuation; truncated mean suppresses part od the information (112 samples ~4.3% resolution)
  - **dN/dx**: digital information, affected by only by Poisson fluctuation (~2% on a 2 m tracks)
  - Individual timing of ionization acts could also improve the **position resolution** (~20%)









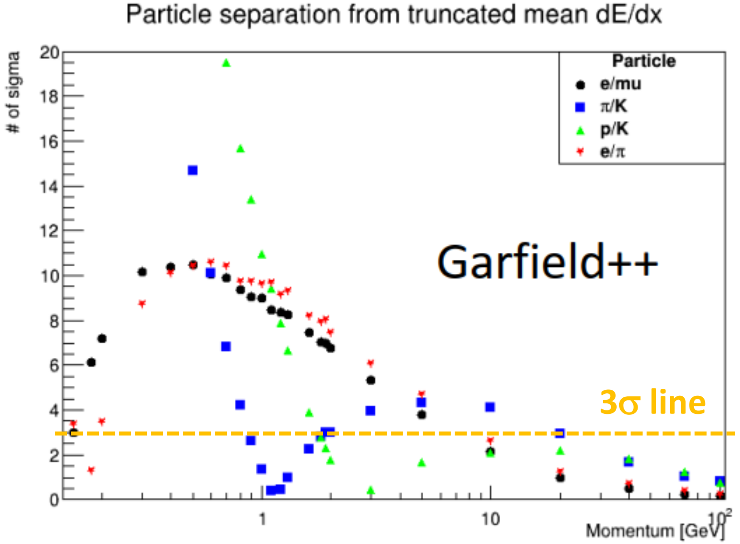
Particle identification performance

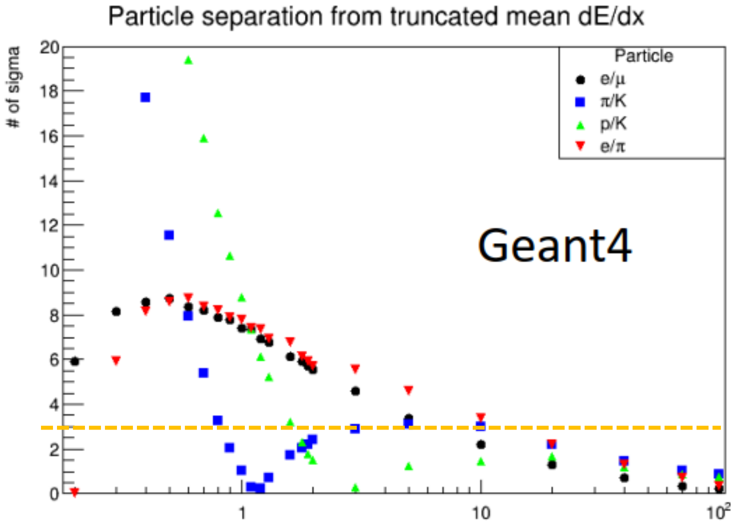
Garfield++

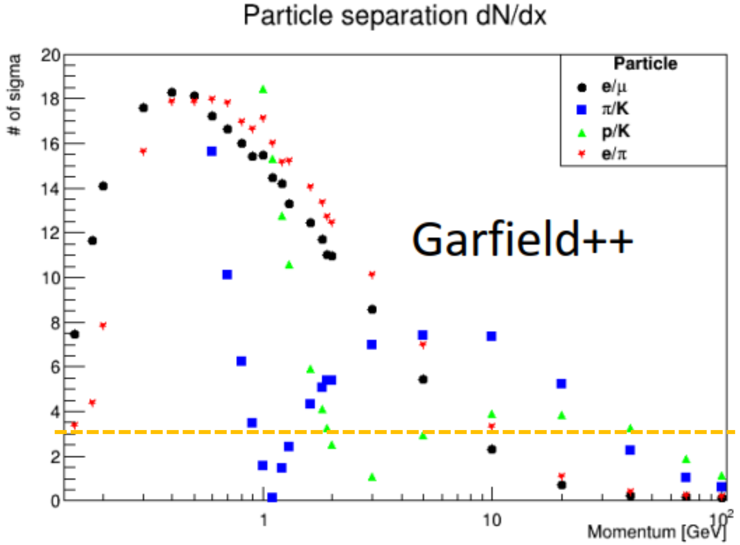
- Simulation of ionization process in gases
- Detailed gas properties
- Solves the single cell electrostatic planar configuration and simulates the free charges movements and collections on the electrodes

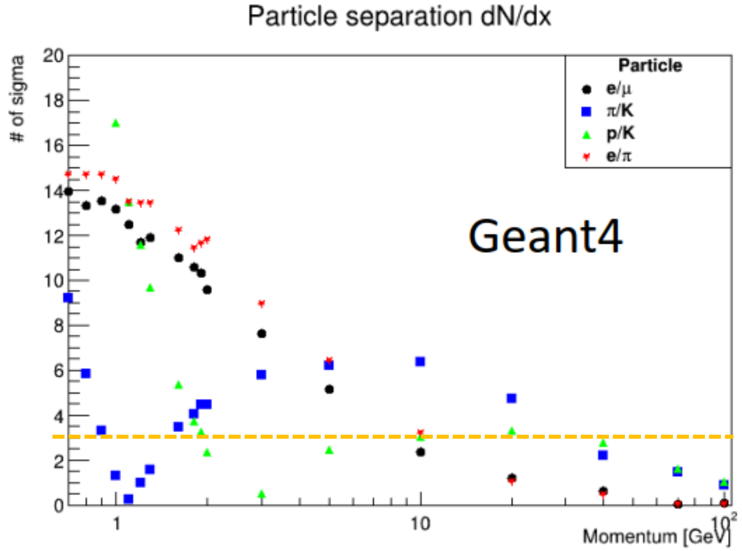
Ported to detector simulation software:

- **Geant4**
  - Implemented cell properties in the Geant4 IDEA simulation.
  - Clearly **improved particle separation** with cluster counting
- **DELPHES**
  - Fast simulation of cluster counting and also timing layer is available
  - Results shown in Selvaggi's talk on Tuesday


Particle separation from truncated mean dE/dx

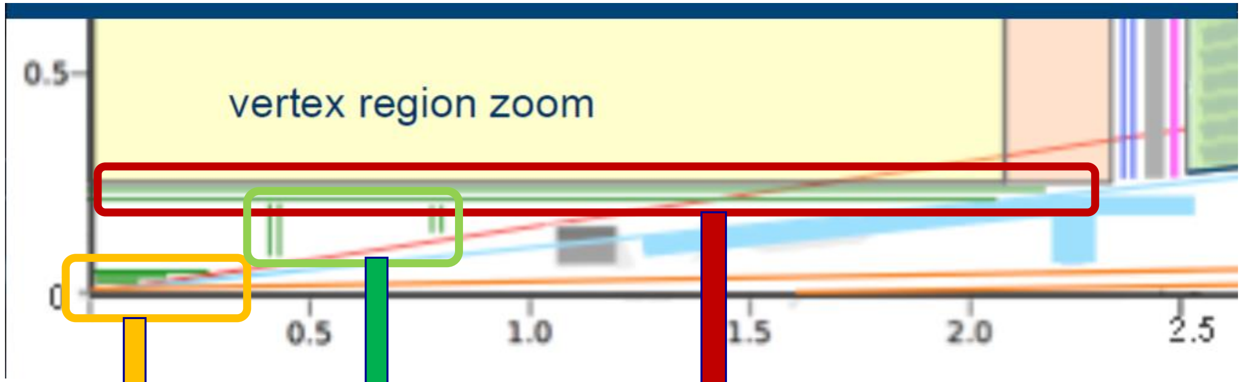

Particle separation from truncated mean dE/dx


Particle separation dN/dx


Particle separation dN/dx

IDEA: the vertex region

- High precision impact parameter reconstruction with low mass **vertex detector**
  - at least 20 μm granularity
  - thickness < 0.3% of radiation length
  - low power <20 mW/cm^2 to minimize services
- Supplemented by coarser/faster **silicon detectors** in front of the drift chamber
- **D**epleted **M**onolithic **A**ctive **P**ixels sensors
  - not necessarily the same technologies for both: different requirements
  - present technologies are very promising
  - R&D on different approaches (ARCADIA, ATLASPIX3)



Layer	R [mm]	L [mm]	Si eq. thick. [μm]	X_0 [%]	pixel size [mm^2]	area [cm^2]	# of channels
1	17	±110	300	0.3	0.02×0.02	235	60M
2	23	±150	300	0.3	0.02×0.02	434	110M
3	31	±200	300	0.3	0.02×0.02	780	200M
4	200	±2040	450	0.5	0.05×1.0	52K	105M
5	220	±2240	450	0.5	0.05×1.0	62K	124M

Disks	R_{in} [mm]	R_{out} [mm]	z [mm]	Si eq. thick. [μm]	X_0 [%]	pixel size [mm^2]	area [cm^2]	# of channels
1	42	190	±400	300	0.3	0.05×0.05	2.2K	87M
2	44	190	±420	300	0.3	0.05×0.05	2.2K	86M
3	78	190	±760	300	0.3	0.05×0.05	1.9K	76M
4	80	190	±780	300	0.3	0.05×0.05	1.9K	75M

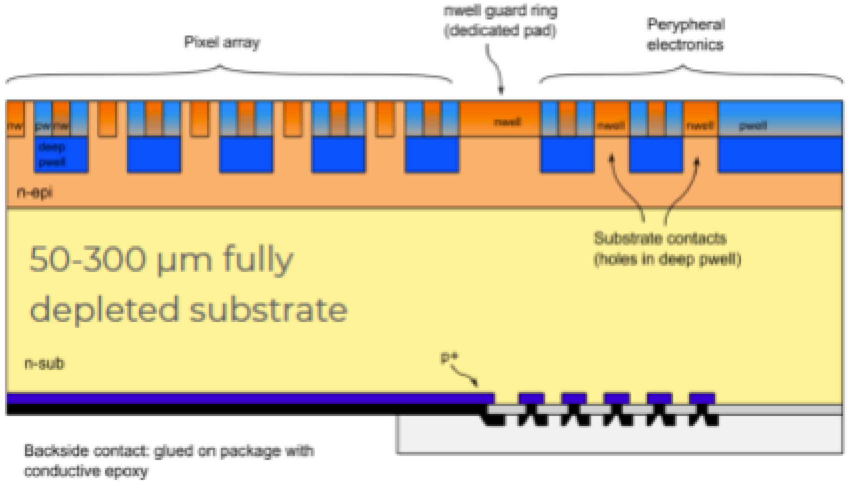
ARCADIA Project

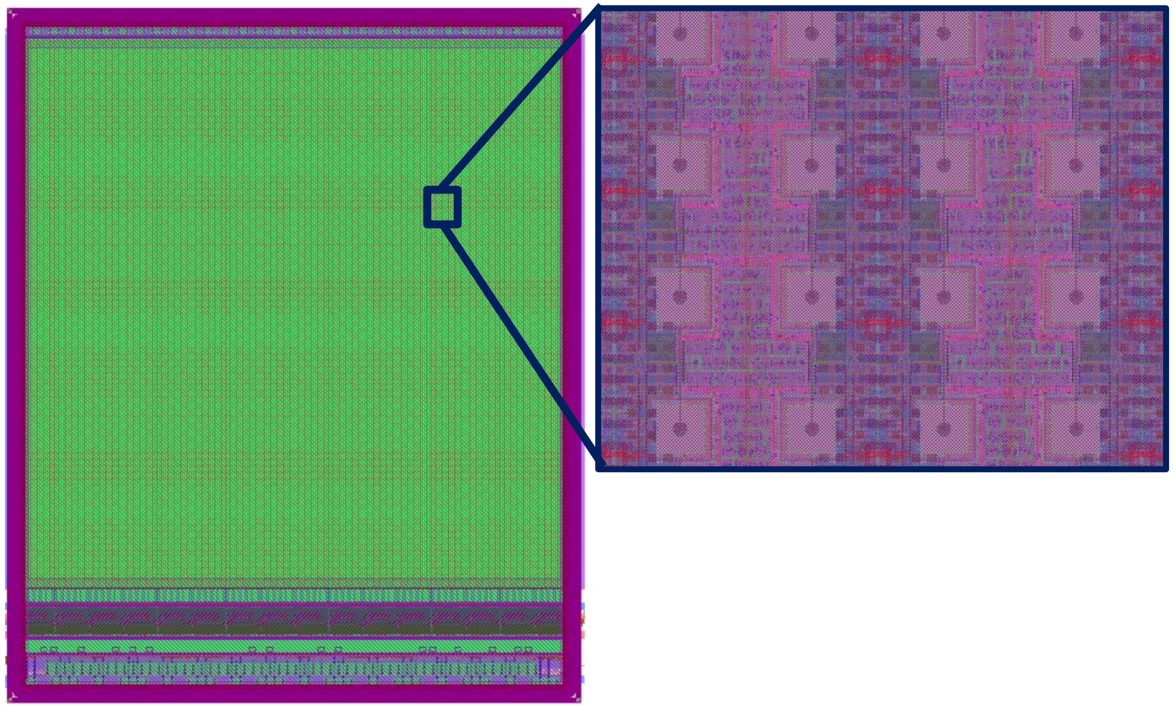
- CMOS DMAPs Platform
    - Started as INFN project, collaborations with Switzerland and China
    - Project within AIDAInnova WP5
- Fully depleted monolithic sensor
- LFoundry 110 nm CMOS process

- Pixels:
    - sensor and back-side processing already tested on silicon
    - 25 × 25 μm^2 size
    - Area 50% analog – 50% digital
    - small collection electrode (20% of pixel area)
    - versions with ALPIDE and BULKDRIVEN front-ends

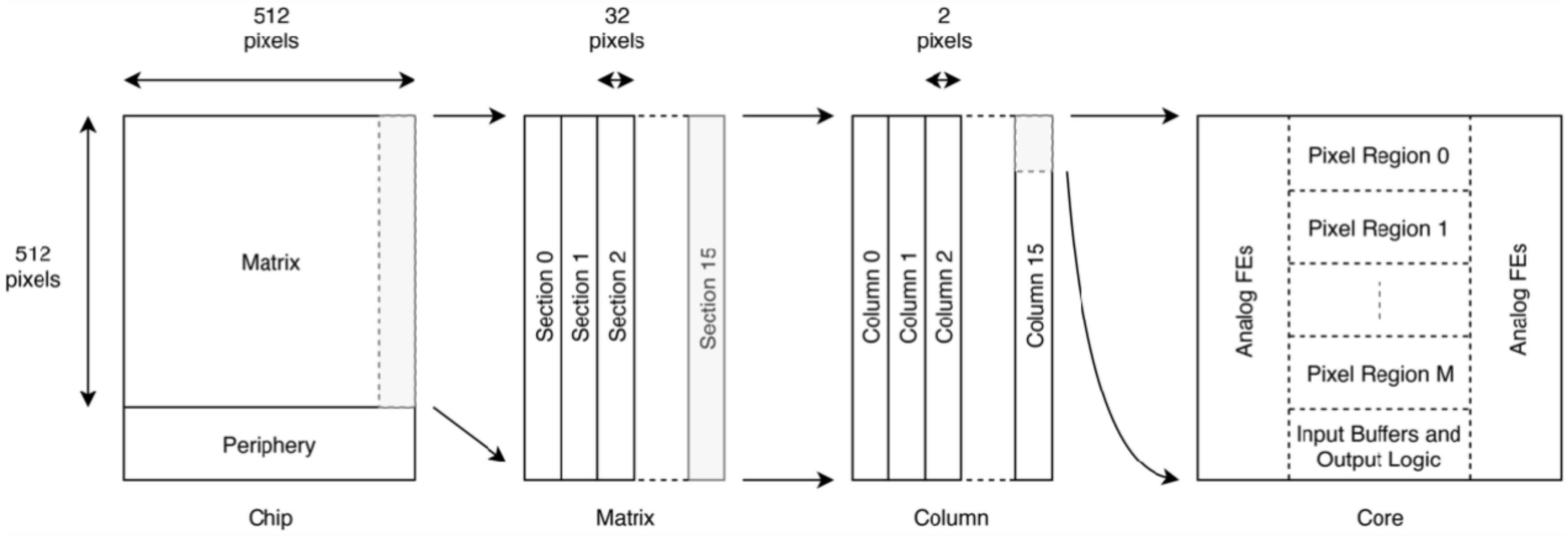
ARCADIA

AIDA innova



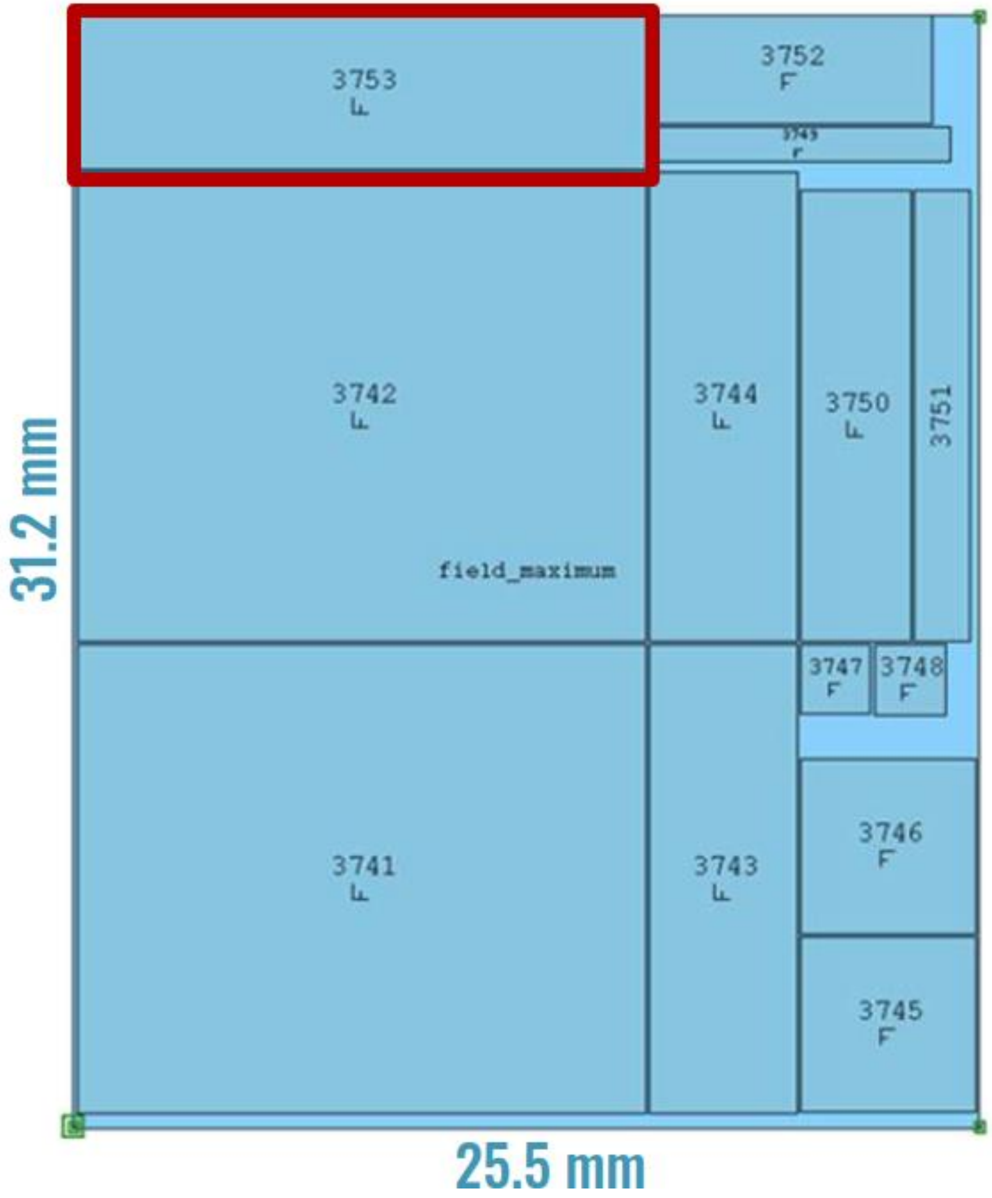


ARCADIA Main Demonstrator



- Matrix core 512 x 512, “side-abuttable” to accomodate a 1024 x 512 silicon active area (2.56 x 1.28 cm^2)
- Each 2x512 Column is composed of 2x32-pixel Cores
- Matrix and EoC architecture, data links and payload ID: scalable to 2048 x 2048
- Clock-less matrix integrated on a power-oriented flow
- Triggerless binary data readout, event rate up to 100 MHz/cm^2
- Submitted 11/2020, back from foundry on 04/2021, now under characterization. 2nd and 3rd run expected in 2021 and 2022.

ARCADIA Engineering Run

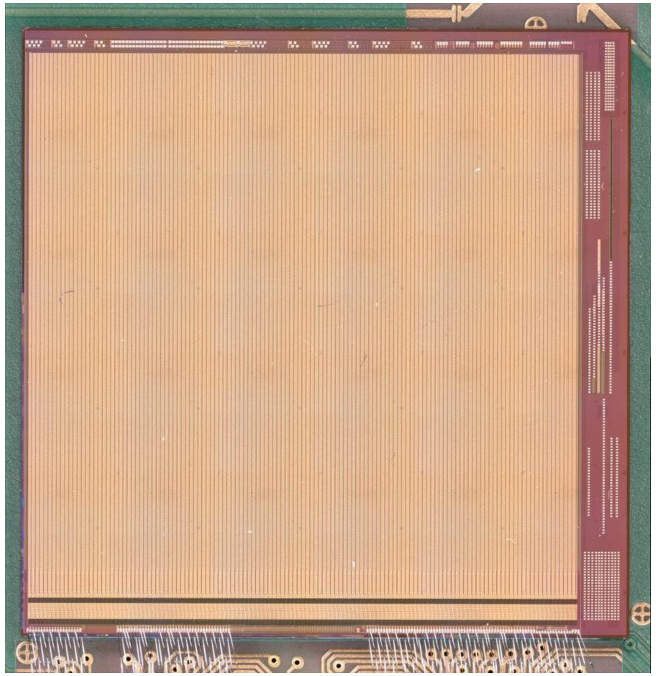


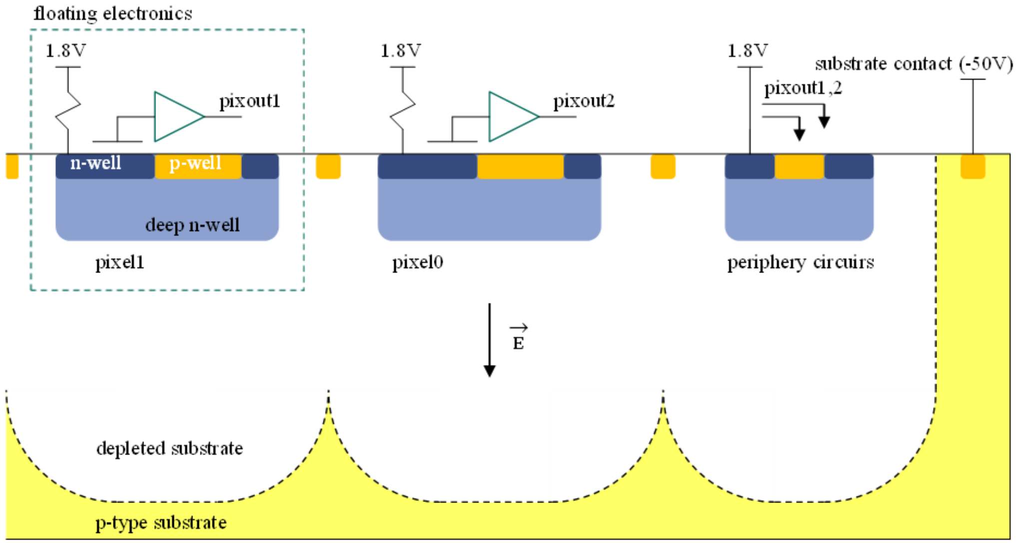
- BN3741/2: ARCADIA-MD1a/b
- BN3743: ARCADIA-miniD (debug)
- BN3744: TC_PMGMT (on-chip LDOs for large-scale yield management)
- BN3745/6: MAPS and test structures for PSI
- BN3747/8: MATISSE2020 and MATISSE Low Power (front-end for space instruments)
- BN3749/50/51: pixel and strip test structures
- BN3752: 64-channel mixed signal ASIC for Si-Strip readout
- BN3753: 32-channel **monolithic strip and embedded readout electronics**

Other structures of interest for FCCee detectors

ATLASPIX3

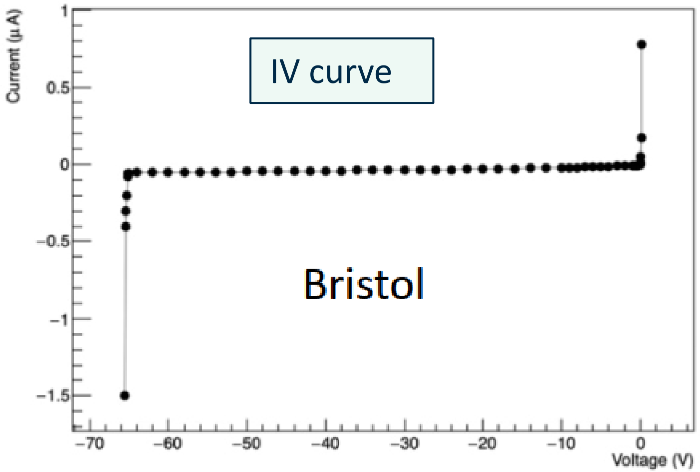
- **Monolithic CMOS**
  - widespread process allows to produce **large areas**, **fast** and **cheap**
  - **no hybridization** (bump-bonding) needed
  - **single detection layer**, can be **thinned** keeping high signal efficiency and low noise rate
- **ATLASPIX3 features**
  - pixel size $50 \times 150\ \mu\text{m}^2$ ($25 \times 165\ \mu\text{m}^2$ feasible)
  - up to 1.28 Gbps downlink
  - reticle size $20 \times 21\ \text{mm}^2$
  - TSI 180 nm process on 200 Ωcm substrate
  - 132 columns of 372 pixels
  - digital part of the matrix located on periphery
  - both **triggerless** and **triggered** readout possible:
    - two End of Column buffers
    - 372 hit buffers for triggerless readout
    - 80 trigger buffers for triggered readout





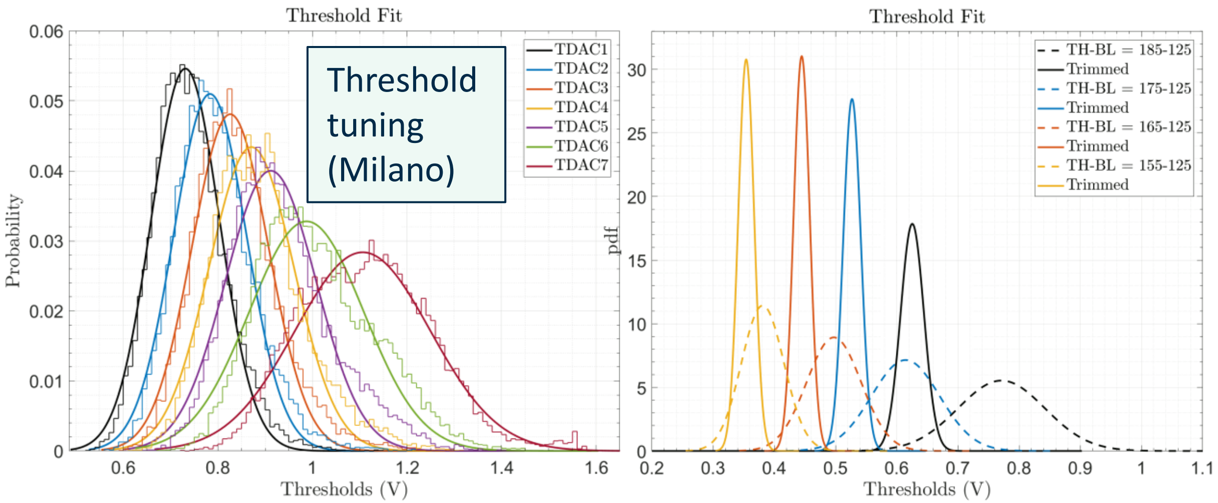
ATLASPIX3

- ATLASPIX3 performance tested in participating laboratories
- **KIT + China + UK + INFN collaboration**

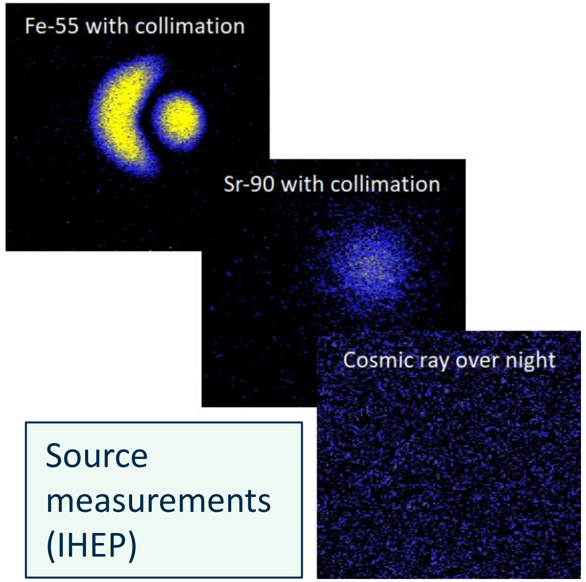


IV curve

Bristol

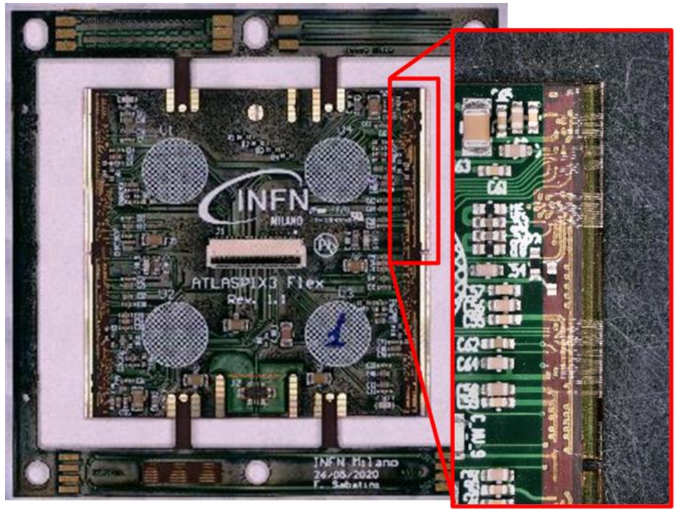


Threshold tuning (Milano)



Source measurements (IHEP)

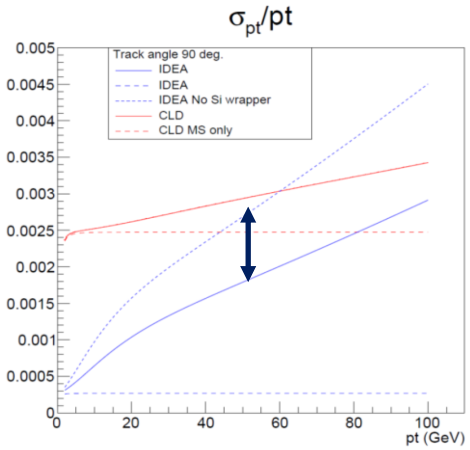
- Multi-chip module assembly
  - quad module, inspired by ATLAS hybrid pixels
  - implemented interface to laboratory readout system
  - future version with **ATLASPIX3.1**:
    - full usage of on-chip internal regulators
    - compatible with serial powering



Si Wrapper

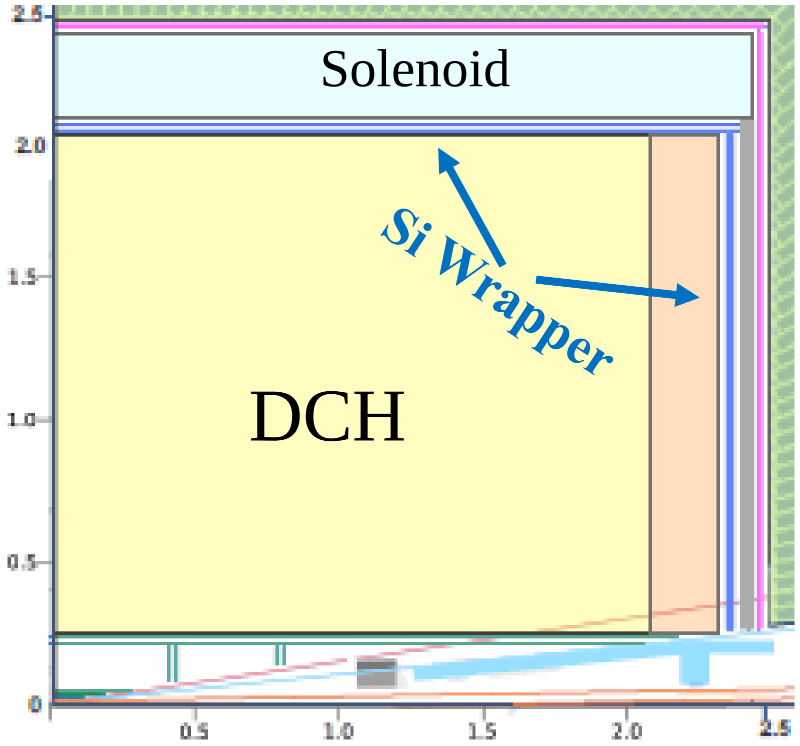
Precision silicon layer around the central tracker

- Functionalities:
  - momentum resolution



  - extend tracking coverage in the forward/backward region by providing an additional point to particle with few measurements in the drift chamber
  - precise and stable ruler for acceptance definition
- Covered area ~90 m^2
- Suitable technologies:
  - microstrips (2 layers)
  - double sided microstrip
  - **DMAPS** → single layer, high resolution on both coordinates, maybe simpler integration

Layer	R [mm]	L [mm]	Si eq. thick. [μm]	X_0 [%]	pixel size [mm^2]	area [cm^2]	# of channels
1	2100	±2400	450	0.5	0.05×100	634K	12.7M
2	2120	±2400	450	0.5	0.05×100	640K	12.8M

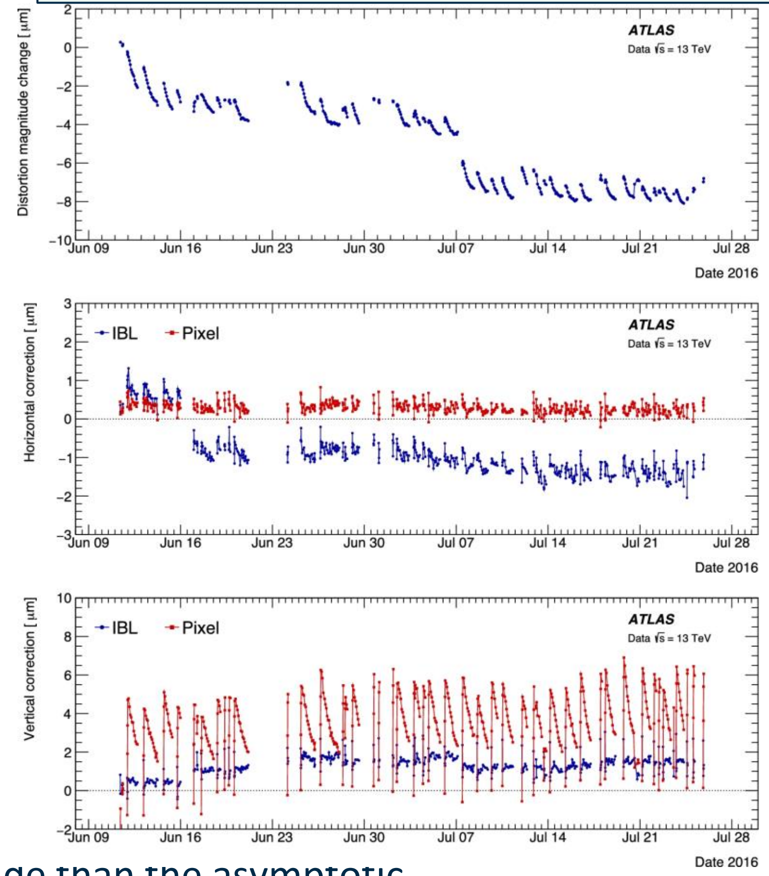


Disks	R_{in} [mm]	R_{out} [mm]	z [mm]	Si eq. thick. [μm]	X_0 [%]	pixel size [mm^2]	area [cm^2]	# of channels
1	240	2080	±2380	450	0.5	0.05×100	268K	5.4M
2	242	2080	±2400	450	0.5	0.05×100	268K	5.4M

Si Wrapper: why pixels?

- **For cross section measurements need to keep systematics on the angular acceptance at the level of 50 μrad at $\theta = 10°$.**
- in principle, silicon is a very good ruler:
  - Inner Silicon Tracker disks: at 40 cm, δR_{sys}<20 μm
    - alignment in principle is better than that, but stability need to be followed accordingly
    - for example: in ATLAS seen few μm systematics movements, but the tracker support will be much lighter in IDEA
  - SiWrapper: at 2 m, δR_{sys}<100 μm
    - benefits from pixel structure (order of pixel size)
    - if anchored to the calorimeter provides an independent frame, giving some redundancy

https://doi.org/10.1140/epjc/s10052-020-08700-6



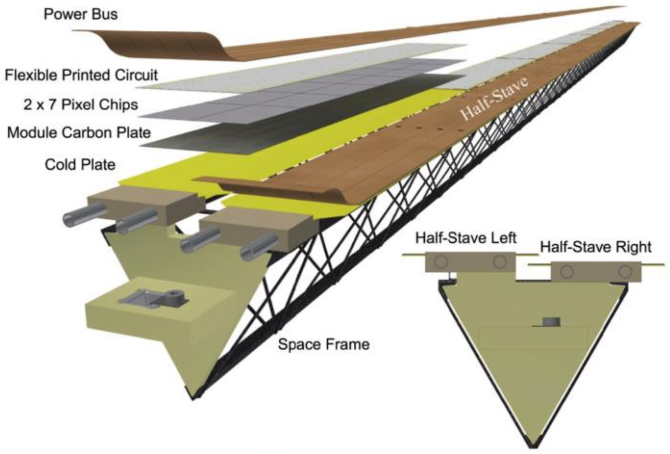
- With 50 μm pitch pixels and digital readout, $\sigma_z = 14\ \mu\mathrm{m}$, expect a θ resolution below 10 μrad
  - with the caveat that multiple scattering effects can be of a similar order of magnitude than the asymptotic resolution even for $Z \rightarrow \mu\mu$ events: 1% X_0 is 30 μrad for p=45 GeV at 90°
  - instabilities at the μm level may have an impact in the accuracy of the acollinearity measurement for beam angle crossing determination
  - having an independent detector with 2 m lever arm and same resolution as the inner tracker will allow the monitoring and correction of instabilities in both coordinates

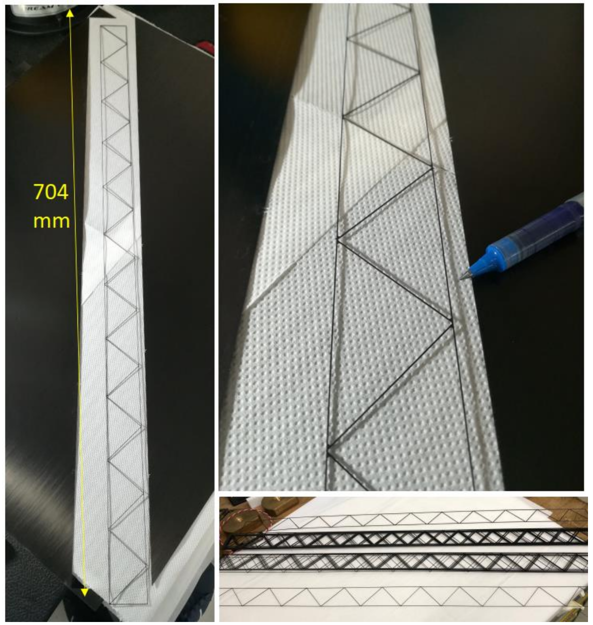
Si tracker - Mechanics

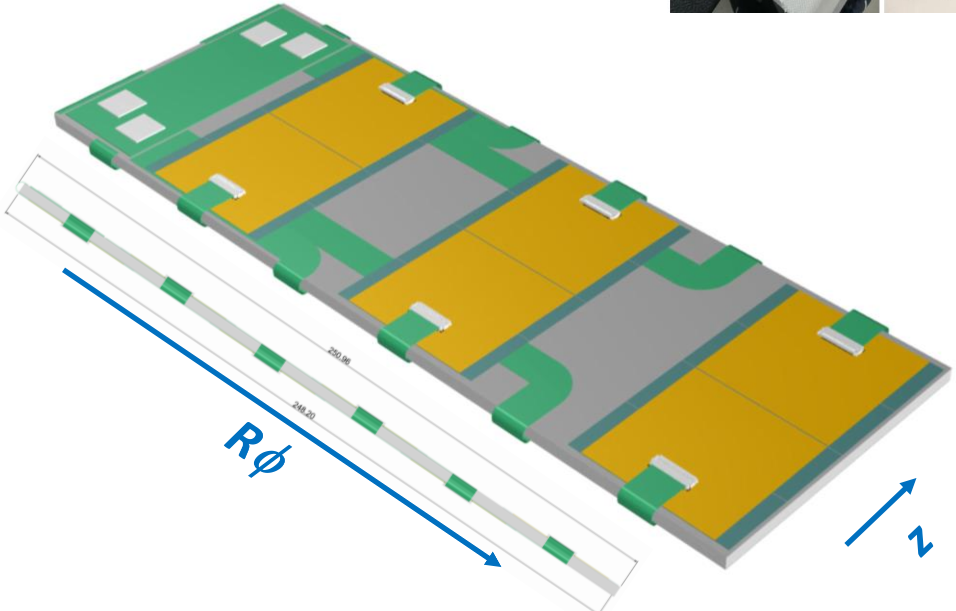
- Local supports needs original solutions for the internal tracker (lightweight) and the wrapper (long-term stability)

- Just a couple of examples:
  - ALICE like staves, but built with subtractive technology
  - Stavelets with ATLASPIX3 modules as option for the Si Wrapper

- Different cooling options available
  - pipes materiale: Titanium, steel, carbon, microchannel
  - CO_2 or water cooling
  - alternative cooling of edge supports for the vertex (à la Belle II)







Si tracker: system considerations

- **Complete system consists of 900'000 cm^2 area / 4 cm^2 chip = 225k chips (56k quad-modules)**
  - aggregation of several modules for data and services distribution is essential
  - inner tracker will be 5--10% of this
- **Data rate** constrained by the inner tracker
  - average rate 10^{-4} - 10^{-3} particles cm^{-2} $event^{-1}$ at Z peak
  - assuming 2 hits/particle, 96 bits/hit for ATLASPIX3
  - **640 Mbps link/module** (assuming local module aggregation) provides ample operational margin
  - 16 modules can be arranged into **10 Gbps fast links**: **3.5k links**
    - can also assume 100 Gbps links will be available: 350 links
- **DAQ architecture**
  - **triggerless readout** will fit the data transmission budget but requires off-chip re-ordering of data
  - **triggered readout** will be **simpler** and would also reduce the bandwidth occupancy
- **Power consumption**
  - ATLASPIX3 power consumption **150 mW/cm^2**
  - 600 mW/chip → 2.4 W/module → **total FE power 130 kW**
  - additional power for on detector aggregation and de-randomizations **~2W/link**

Conclusions

- The IDEA detector concept is evolving since the FCCee FDR
- Besides pure detector resolution, it is important to consider the handle on systematics uncertainties
- The tracking system implements
  - Drift Chamber for tracking and particle identification
  - high precision vertex detector
  - Si-wrapper to improve momentum resolution and monitor systematics
- R&D is on-going on all three components
  - developing new technologies
    - building demonstrators with available devices
  - making the transition from a concept to a design
    - following the path to the FCCee feasibility study
    - building collaborations along common lines of developments

BACKUP

ATLASPIX3 groups involvement

KIT + China + UK + INFN collaboration

Institute of High Energy Physics
Chinese Academy of Sciences

清華大學 Tsinghua University

山东大学 SHANDONG UNIVERSITY

李政道研究所 Tsung-Dao Lee Institute

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

西北工業大學 NORTHWESTERN POLYTECHNICAL UNIVERSITY

南華大學 UNIVERSITY OF SOUTH CHINA

哈爾濱工業大學（威海） HARBIN INSTITUTE OF TECHNOLOGY

中国科学技术大学 University of Science and Technology of China

Queen Mary University of London

KIT Karlsruhe Institute of Technology

INFN Istituto Nazionale di Fisica Nucleare MILANO PISA TORINO

UKRI Science and Technology Facilities Council

University of BRISTOL

The University Of Sheffield.

THE UNIVERSITY OF EDINBURGH

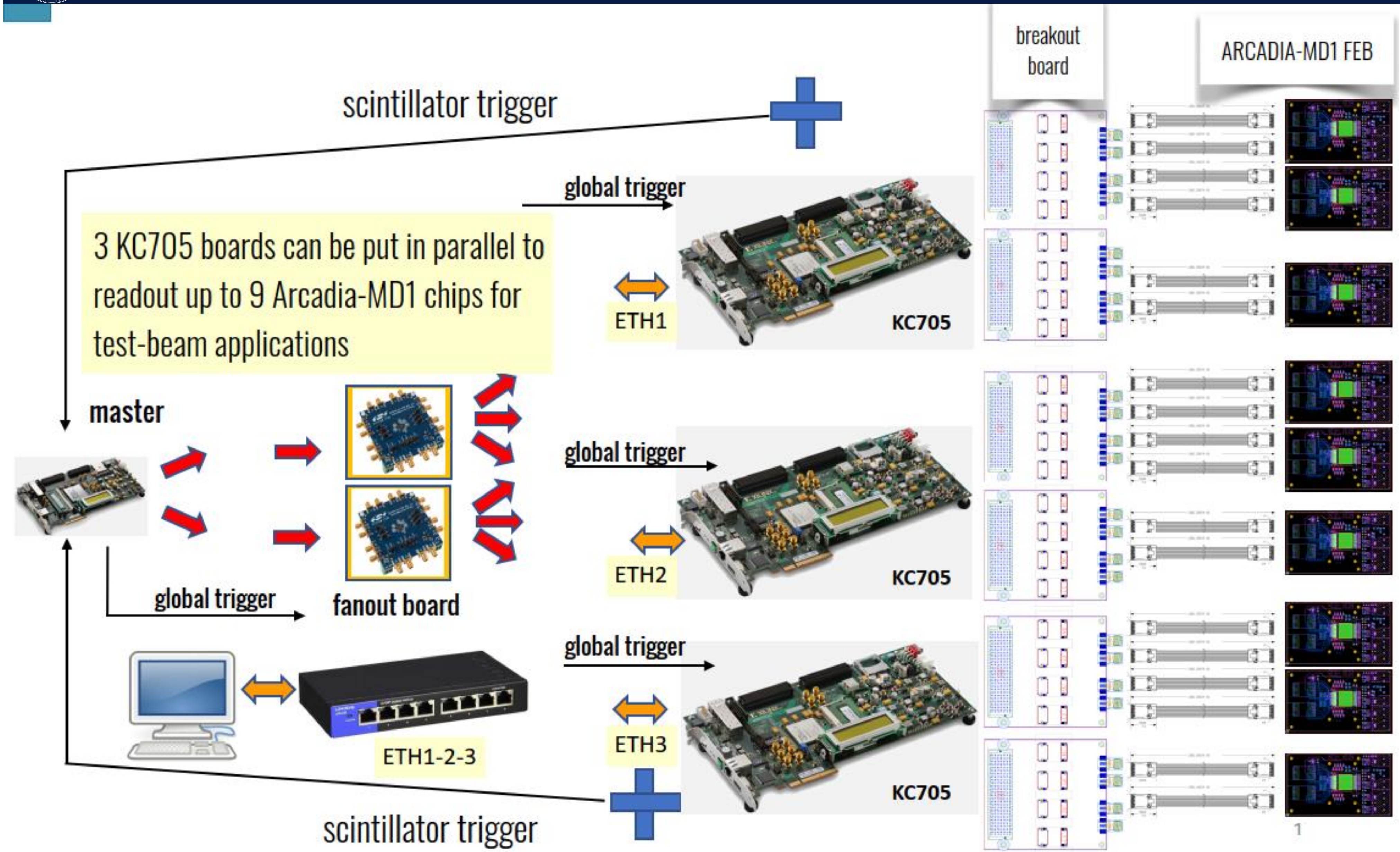
UNIVERSITY OF LIVERPOOL

WARWICK THE UNIVERSITY OF WARWICK

Physics Lancaster University

UNIVERSITY OF OXFORD

ARCADIA MD1 test beam setup

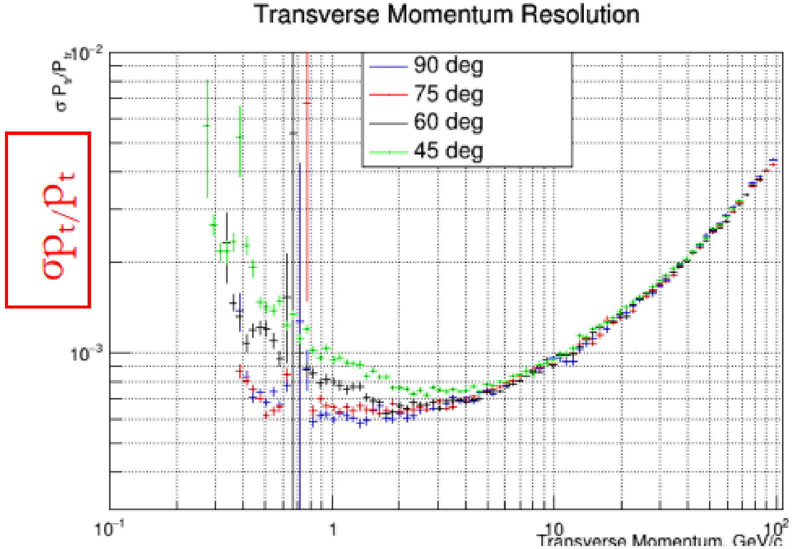


3 KC705 boards can be put in parallel to readout up to 9 Arcadia-MD1 chips for test-beam applications

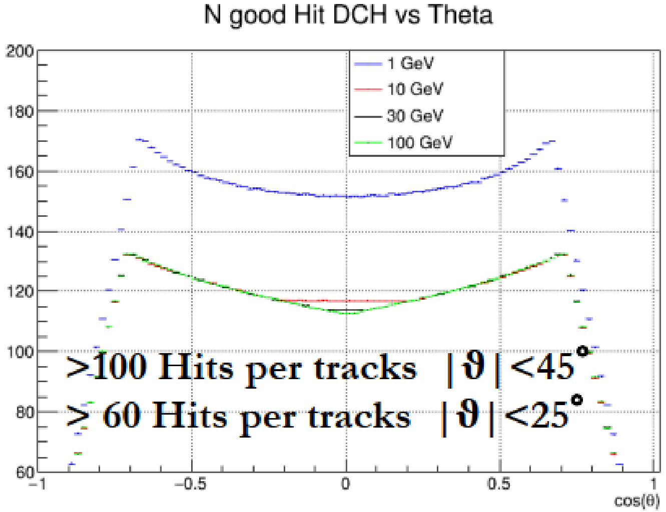
IDEA Drift Chamber Performance

Drift Chamber simulation - Review geometry and reconstruction status

assumed: $\sigma_d = 100\ \mu m$ and (conservative for Si) $\sigma_{Si} = \text{pitch}/\sqrt{12}\ \mu m$

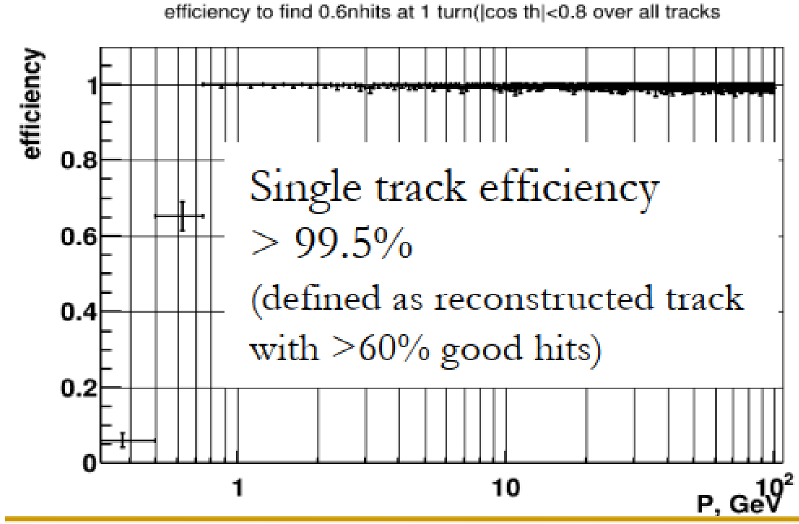


$\sigma P_t/P_t$

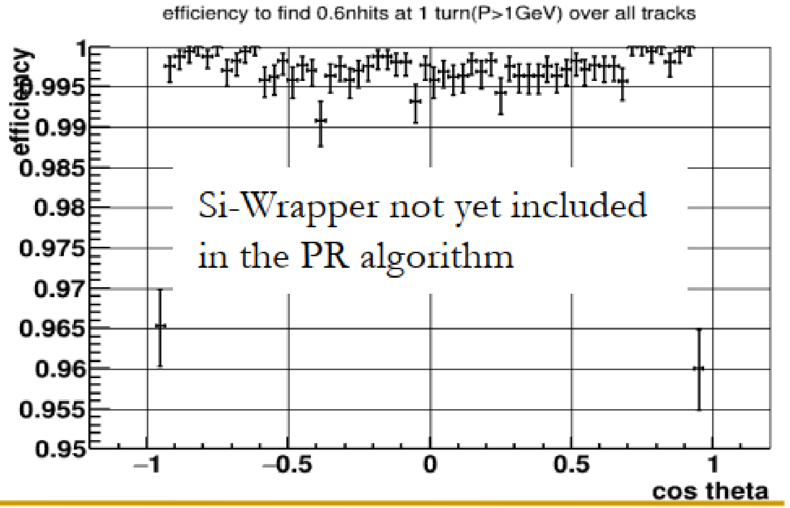


>100 Hits per tracks |ϑ|<45°

> 60 Hits per tracks |ϑ|<25°

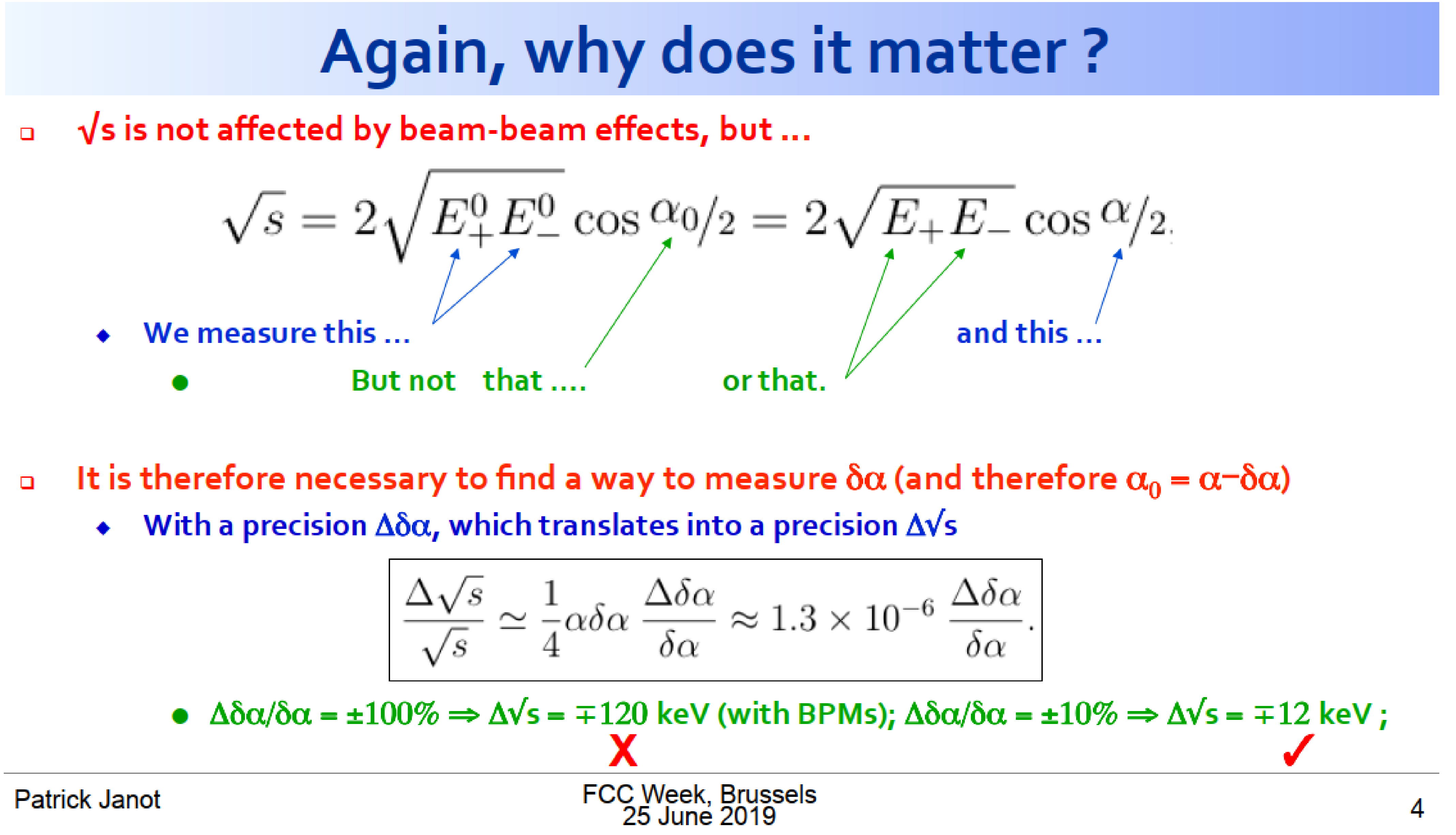


Single track efficiency
> 99.5%
(defined as reconstructed track with >60% good hits)



Si-Wrapper not yet included in the PR algorithm

Beam-beam effects



Again, why does it matter ?

- √s is not affected by beam-beam effects, but …

$$\sqrt{s} = 2\sqrt{E_+^0 E_-^0}\,\cos{}^{\alpha_0}\!/_2 = 2\sqrt{E_+ E_-}\,\cos{}^{\alpha}\!/_2$$

  - We measure this … and this …
    - But not that …. or that.

- It is therefore necessary to find a way to measure δα (and therefore $\alpha_0 = \alpha - \delta\alpha$)
  - With a precision Δδα, which translates into a precision Δ√s

$$\boxed{\frac{\Delta\sqrt{s}}{\sqrt{s}} \simeq \frac{1}{4}\alpha\delta\alpha\,\frac{\Delta\delta\alpha}{\delta\alpha} \approx 1.3\times 10^{-6}\,\frac{\Delta\delta\alpha}{\delta\alpha}.}$$

    - Δδα/δα = ±100% ⇒ Δ√s = ∓120 keV (with BPMs); Δδα/δα = ±10% ⇒ Δ√s = ∓12 keV ;

X ✓

Patrick Janot

FCC Week, Brussels
25 June 2019

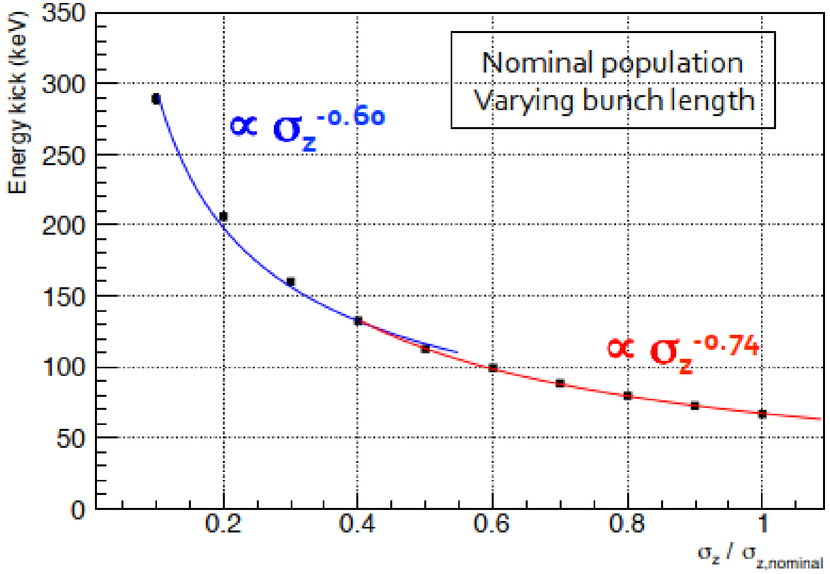
4

Extrapolation to $N^{\pm} = 0$

- Energy kicks $\delta E^{\pm}$ directly proportional to opposite bunch population $N^{\mp}$
  - Also increases when opposite bunch length decreases (charge density increases)
    - From independent numerical integration
      - (Code from E. Perez)
    - Fit to a power law in σ_z (or in σ_δ, equivalently)

$$\delta E^{\pm} \propto \frac{N^{\mp}_{\mathrm{part}}}{\sigma_{\delta}^{\mp 2/3}}.$$

Bunch length/energy spread



- Uncertainty of ±0.05 on the exponent

Treated as systematic uncertainty in the following

Patrick Janot
FCC Week, Brussels
25 June 2019
6

Measurement of $\delta\alpha$

- For equal e^+ and e^- bunch populations, $\delta\alpha$ is proportional to the common δE:

$$\boxed{\delta\alpha = \frac{1}{\tan {}^{\alpha}\!/_{2}}\left(\frac{\delta E_+}{E_+} + \frac{\delta E_-}{E_-}\right)}$$

  - Therefore, $\delta\alpha$ follows the same power law as δE: $\delta\alpha \propto \frac{N_{\rm part}}{\sigma_{\sqrt{s}}^{2/3}}$. with $\sigma_{\sqrt{s}} = \sigma_\delta^+ \oplus \sigma_\delta^-$

  - The bunch population $N_{\rm part}$ is in turn related to the luminosity: $\mathcal{L} \propto \frac{N_{\rm part}^2}{\sigma_z} \Leftrightarrow \mathcal{L} \propto \frac{N_{\rm part}^2}{\sigma_{\sqrt{s}}}$.

  - Leading to the remarkable power law: $\boxed{\delta\alpha \propto \frac{\mathcal{L}^{1/2}}{\sigma_{\sqrt{s}}^{1/6}}.}$

    - It turns out that the beam crossing angle, the luminosity, and the centre-of mass energy spread can be measured altogether with $\mu^+\mu^-(\gamma)$ events **[see slide 10]**

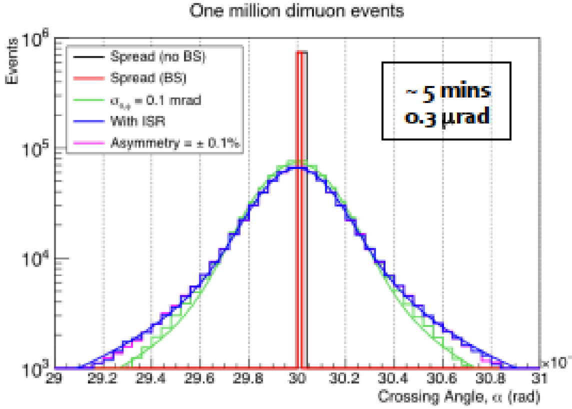
      - ➨ Linear fit of a vs $L^{1/2}/\sigma_{\sqrt{s}}^{1/6}$ will give in turn the values of $\delta\alpha$ and α_0

Measurement with $\mu^+\mu^-(\gamma)$ events

- **From total energy-momentum conservation**
  - In the transverse plane [p_x, p_y, E] : see slide 3

$$\alpha = 2\arcsin\left[\frac{\sin(\varphi^- - \varphi^+)\sin\theta^+\sin\theta^-}{\sin\varphi^-\sin\theta^- - \sin\varphi^+\sin\theta^+}\right]$$

$$\Delta\alpha = \frac{0.3\,\mathrm{mrad}}{\sqrt{N_{\mu\mu}}}.$$


One million dimuon events

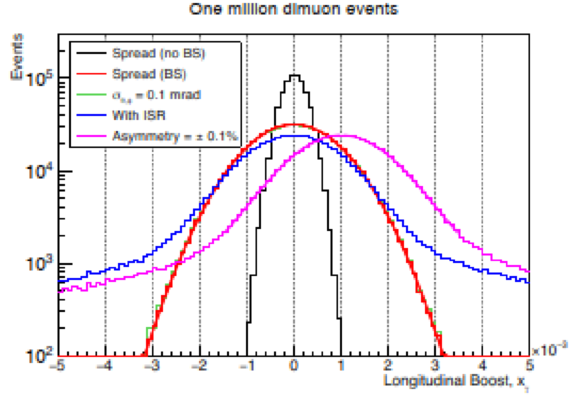
~ 5 mins
0.3 µrad

  - In the longitudinal direction [p_z, E] : see my presentation in Amsterdam and the Energy Calibration paper
    - Longitudinal boost distribution ~ √s spread due to σ_δ

$$x_\gamma = -\frac{x_+\cos\theta^+ + x_-\cos\theta^-}{\cos(\alpha/2) + |x_+\cos\theta^+ + x_-\cos\theta^-|},$$

$$\text{with}\quad x_\pm = \frac{\mp\sin\theta^\mp\sin\varphi^\mp}{\sin\theta^+\sin\varphi^+ - \sin\theta^-\sin\varphi^-}.$$

$$\frac{\Delta\sigma_{\sqrt{s}}}{\sigma_{\sqrt{s}}} = \frac{1}{\sqrt{N_{\mu\mu}}}$$


One million dimuon events

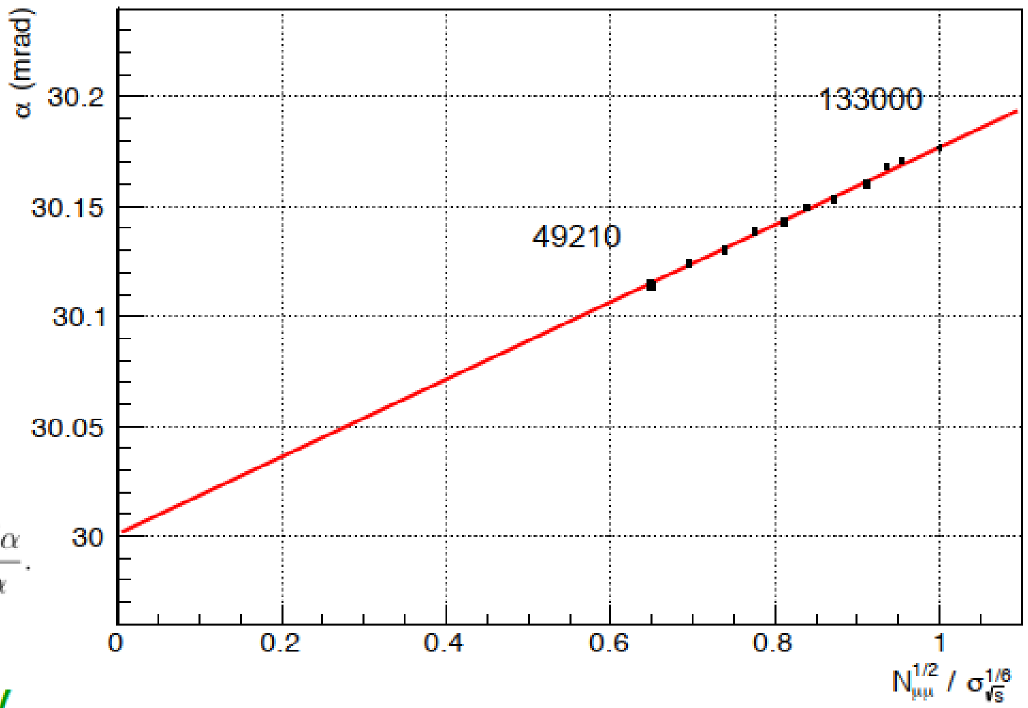
  - Luminosity directly proportional to $N_{\mu\mu}$

$$\frac{\Delta\mathcal{L}}{\mathcal{L}} = \frac{1}{\sqrt{N_{\mu\mu}}}$$

Measurements during the filling period (Z pole)

- **Measure α, $\sigma_{\sqrt{s}}$ and $N_{\mu\mu}$ for 11 steps of 40 seconds at the Z pole**
  - Plot a versus $\sqrt{N_{\mu\mu}} / \sigma_{\sqrt{s}}^{1/6}$
    - And fit a straight line to the data

$$\begin{aligned} \alpha_0 &= 30.0008 \pm 0.0016(\text{stat.}) \pm 0.0031(\text{syst.})\ \text{mrad}, \\ \delta\alpha &= 0.1761 \pm 0.0016(\text{stat.}) \pm 0.0032(\text{syst.})\ \text{mrad}, \end{aligned}$$

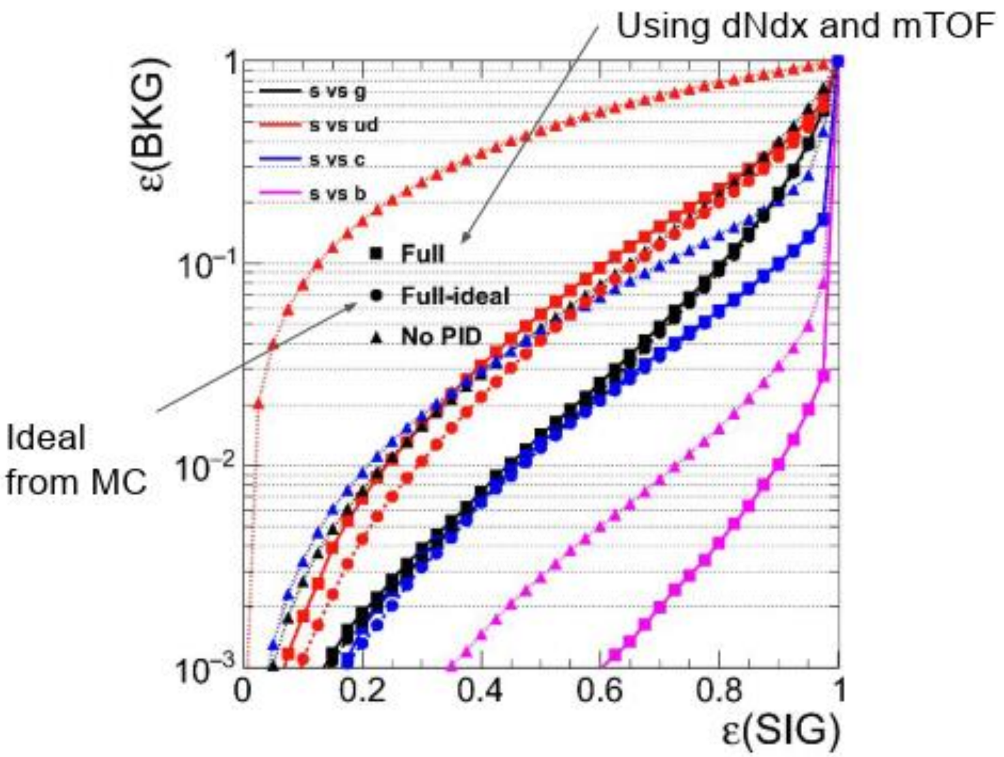


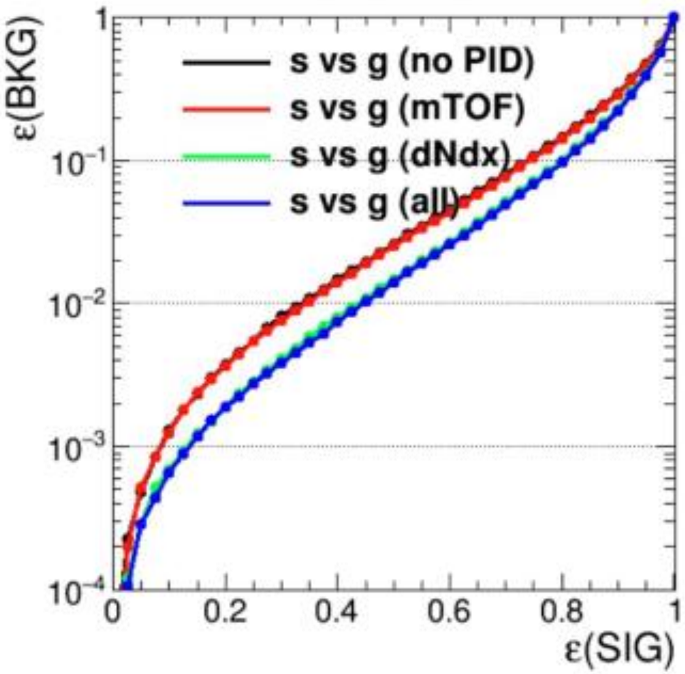
  - Feed α_0 back to the centre-of-mass energy

$$\sqrt{s} = 2\sqrt{E_+^0 E_-^0}\cos\alpha_0/2 \quad \text{and} \quad \frac{\Delta\sqrt{s}}{\sqrt{s}} \simeq \frac{1}{4}\alpha\delta\alpha\,\frac{\Delta\delta\alpha}{\delta\alpha} \approx 1.3\times10^{-6}\,\frac{\Delta\delta\alpha}{\delta\alpha}.$$

    - Uncertainty of √s of the order of 2.5 keV
      - ➨ Well within the requirements, negligible w.r.t. to the beam energy uncertainty (50 keV)

Strange tagging





- Small room for improvement on the PID, in particular for strange tagging
  - TOF does not contribute as much as dNdx (30 ps resolution enough?)
    - low pT tracks are not discriminating ?
    - Can be further improved using timing resolution for neutral K_L vs n ?

REQUIRES FURTHER INVESTIGATION