Detector (synergies)

Towards a Higgs Factory

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Simulations for detector optimizations
Physics studies to inform detector benchmarks
Emerging technology R&Ds

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

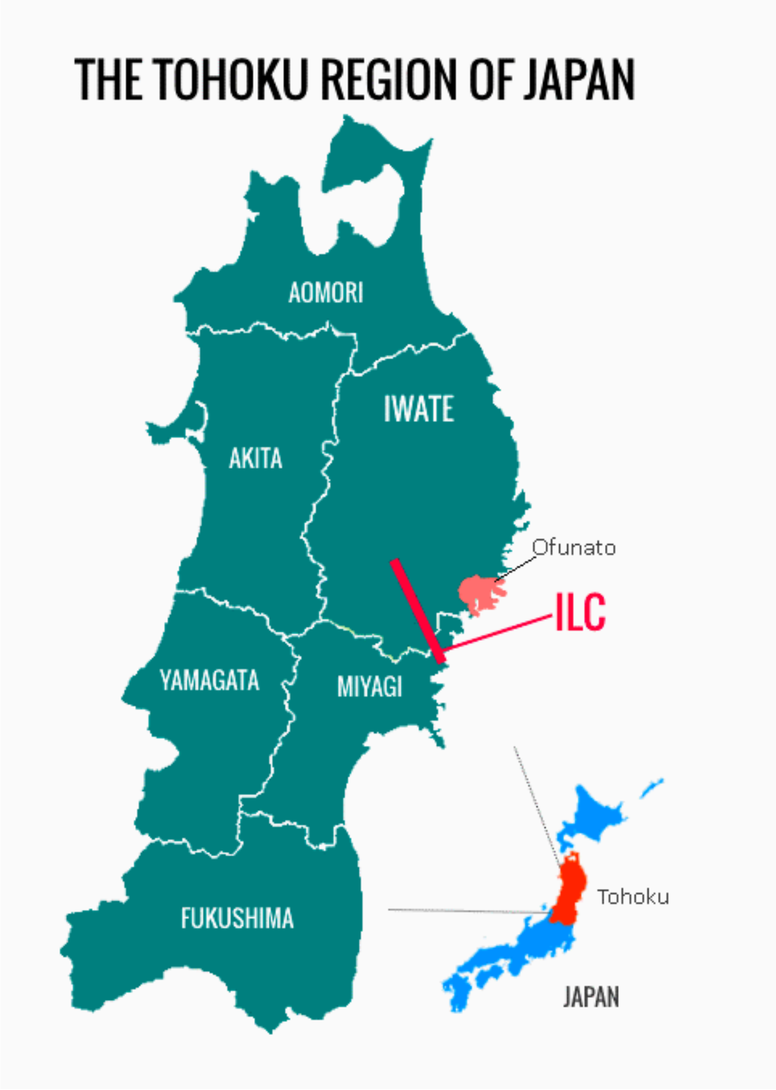
Reminder: P5 Priorities

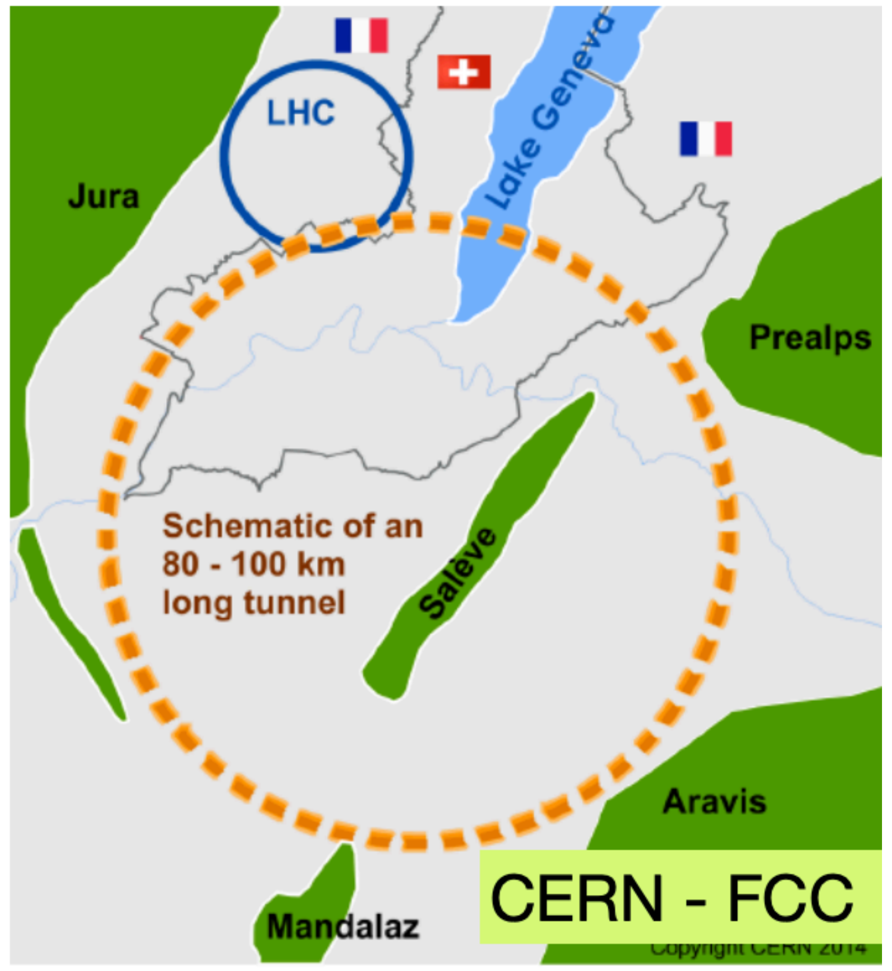
- **Offshore Higgs Factory R2c** *delayed under less favorable scenario*

  Recommendation 2c: Once a specific project is deemed feasible and well-defined the US should aim for a contribution at funding levels commensurate to that of the US involvement in the LHC and HL-LHC, while maintaining a healthy US on-shore program in particle physics

- Detector R&D **AR10:** ***To enable targeted R&D before specific collider projects are established in the US, an investment in collider detector R&D funding at the level of $20M (…) per year in 2023 dollars is warranted***

ILC
250/500 GeV

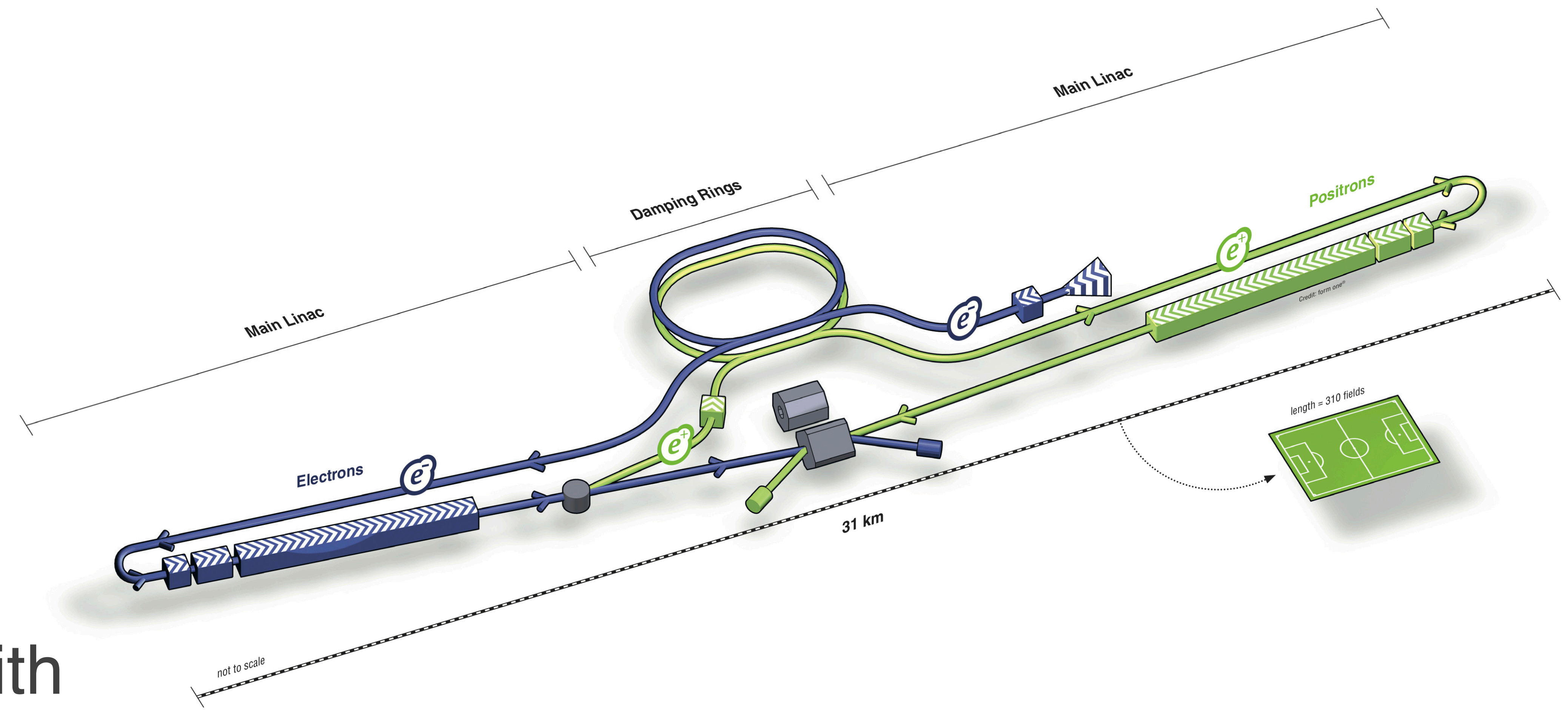


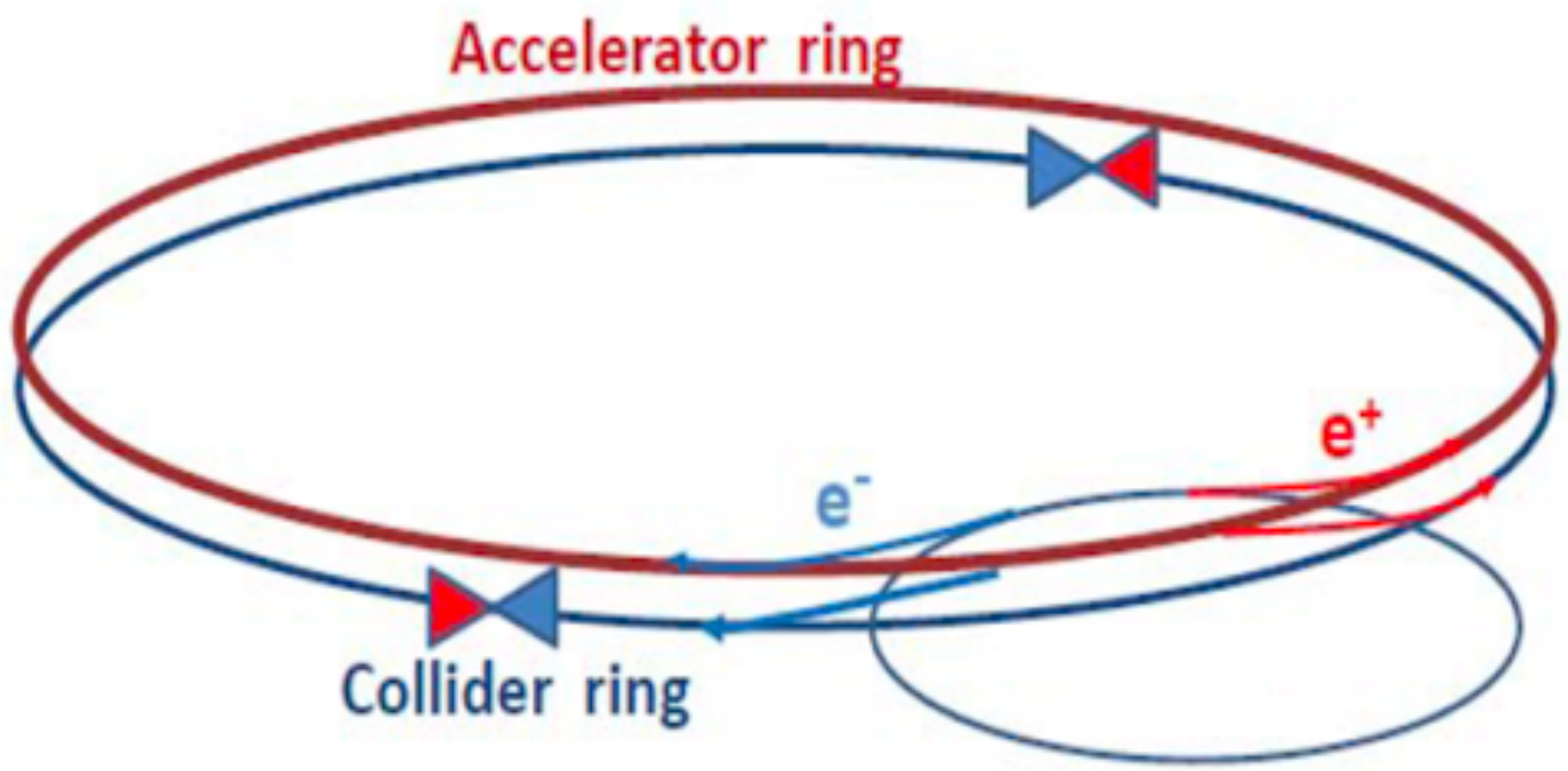


FCC-ee
90/240/365 GeV

Higgs Factory: Linear vs. Circular

- **Linear** e^+e^- colliders: **higher energies** (~ TeV)
  - Can use **polarized** beams
  - Collisions in bunch trains (~0.5% duty cycle)
    - Trigger-less readout
    - Power pulsing → Significant power (& material) saving for detectors
  - **One interaction point** with two detectors alternating with push-pull
- **Circular** e^+e^- colliders: **highest luminosity** at Z/WW/Zh
  - Limited by synchrotron radiation above 350/400 GeV
  - Beam continues to circulate after collision
    - Detectors need active cooling (more material)
  - **Multiple interaction points**





Lots of work in the past decades into ILC/CLIC detectors designs and more recently into first FCC detector concepts

Ingredients for Detector requirements

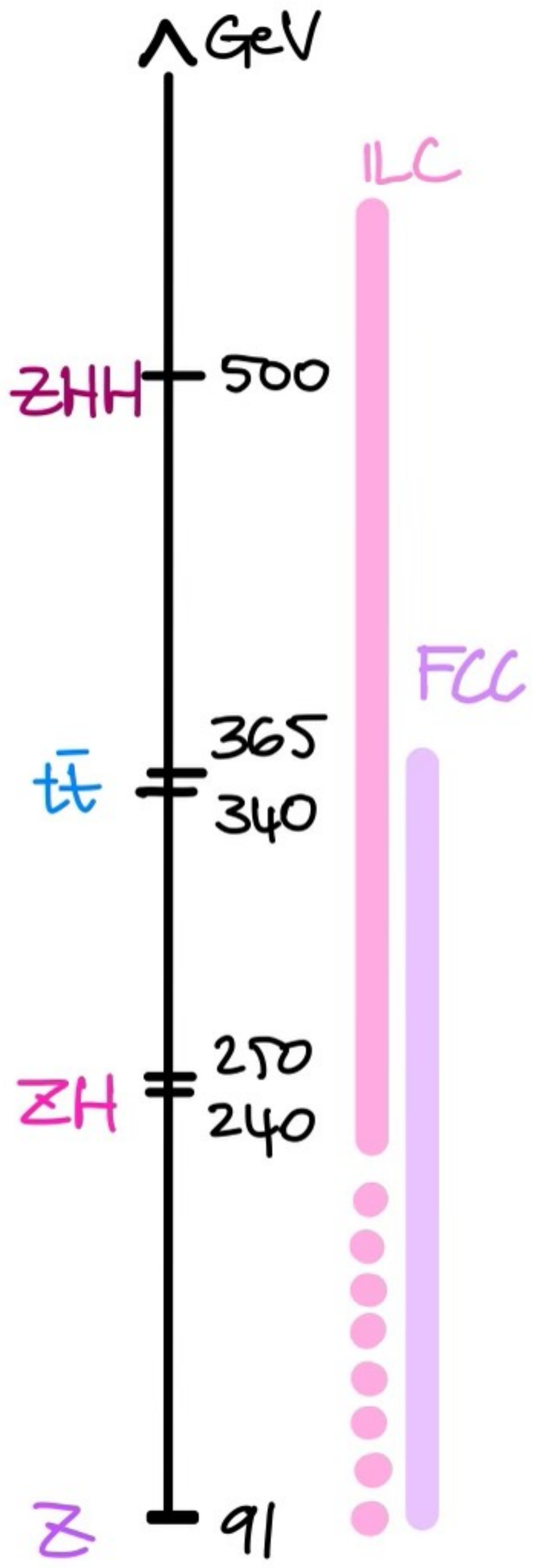
(Higgs) Physics drivers have informed preliminary detector designs

more to investigate

Beam structure and beam induced backgrounds add constraints

Physics benchmarks

ILC and FCC have different & complementary energy reach and goals



Higher Energies, O(500) GeV

- ZHH and ttH: multi-(b)jets final state
  - Set needs to resolve large secondary vertex decay lengths and collimated decays

tt, top mass

Higgs boson physics at 240-250 GeV

- Measurement of the total ZH cross section with <1% uncertainty
- Measure Higgs boson mass to 0.01% accuracy and branching ratio to invisible particles using Z recoil, with 0.1% or better uncertainty.
  - Requirements on: charged track momentum and impact parameters, jet resolutions.

Z pole run, TeraZ program, WW threshold

- Precision measurement of electroweak parameters ($\sin^2\theta_W$, Z and W masses and widths, …
- Limits B field to 2 T
- *Z width extraction* - Requires excellent control of acceptance
  - Constraints on Tracking, LumiCal and forward Calorimeters
  - Requirements for muon tracks from Z decays: angular resolution of 100 mrad to control the beam energy spread; Stability of the track momentum scale (40 KeV/91 GeV ≈) 10^{-7} to control measurement of COM energy.

(Higgs) physics requirements for detectors

arXiv:2003.01116

Precision challenges detector design

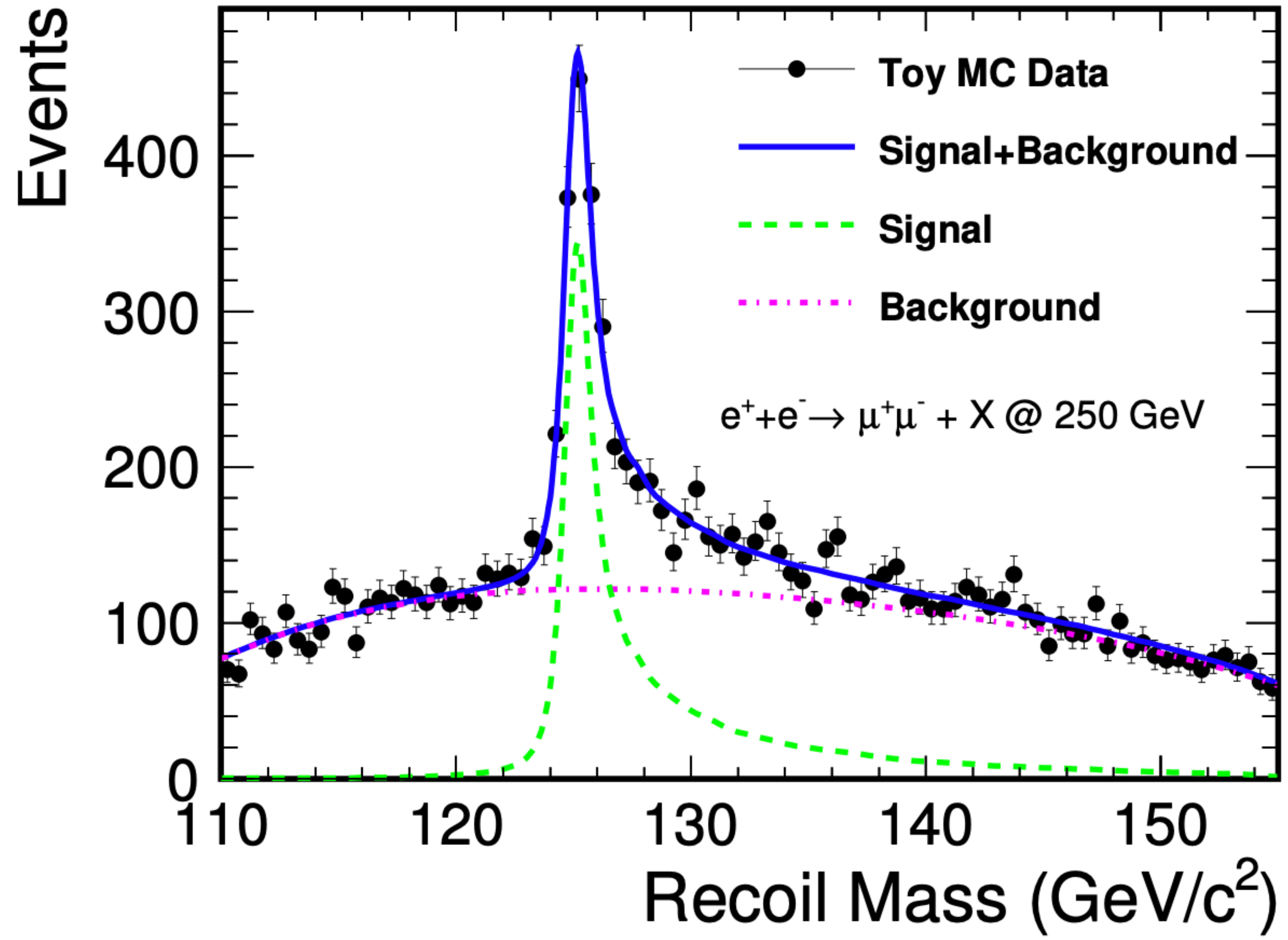
ZH process: Higgs recoil reconstructed from Z decays

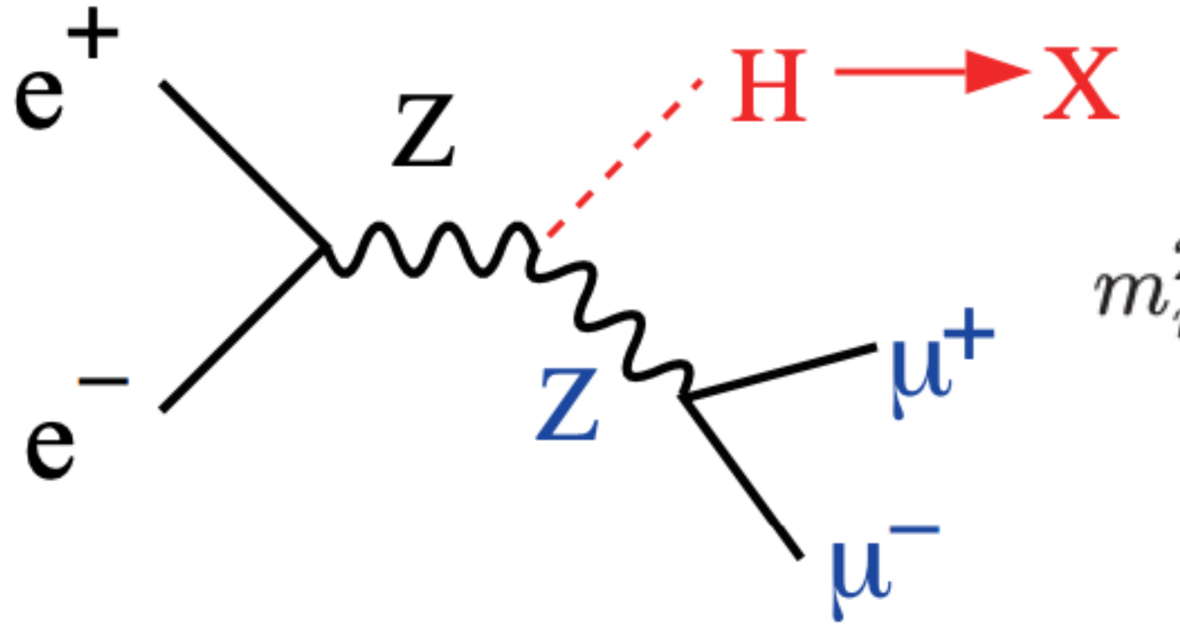
- Drives requirement on charged track momentum and jet resolutions
- Drives need for high field magnets and high precision / low mass trackers

Higgs → bb/cc decays: Flavor tagging tagging at unprecedented level

- Drives requirement on charged track impact parameter resolution → low mass trackers near IP

  <0.3% X0 per layer (ideally 0.1% X_0)





$$m^2_{recoil} = s + m^2_Z - 2 \cdot E_Z \cdot \sqrt{s}$$

Current benchmarks and next steps

The goal of measuring Higgs properties with sub-% precision translates into ambitious requirements for detectors at e+e-

Initial state	Physics goal	Detector	Requirement
e^+e^-	hZZ sub-%	Tracker	σ_{p_T}/p_T=0.2% for $p_T < 100$ GeV
			$\sigma_{p_T}/p_T^2 = 2 \cdot 10^{-5}/$ GeV for $p_T > 100$ GeV
		Calorimeter	4% particle flow jet resolution
			EM cells 0.5×0.5 cm^2, HAD cells 1×1 cm^2
			EM $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$
			shower timing resolution 10 ps
	$hb\bar{b}/hc\bar{c}$	Tracker	$\sigma_{r\phi} = 5 \oplus 15(p \sin\theta^{\frac{3}{2}})^{-1} \mu$m
			5μm single hit resolution

Arxiv:2209.14111 Arxiv:2211.11084 DOE Basic Research Needs Study on Instrumentation

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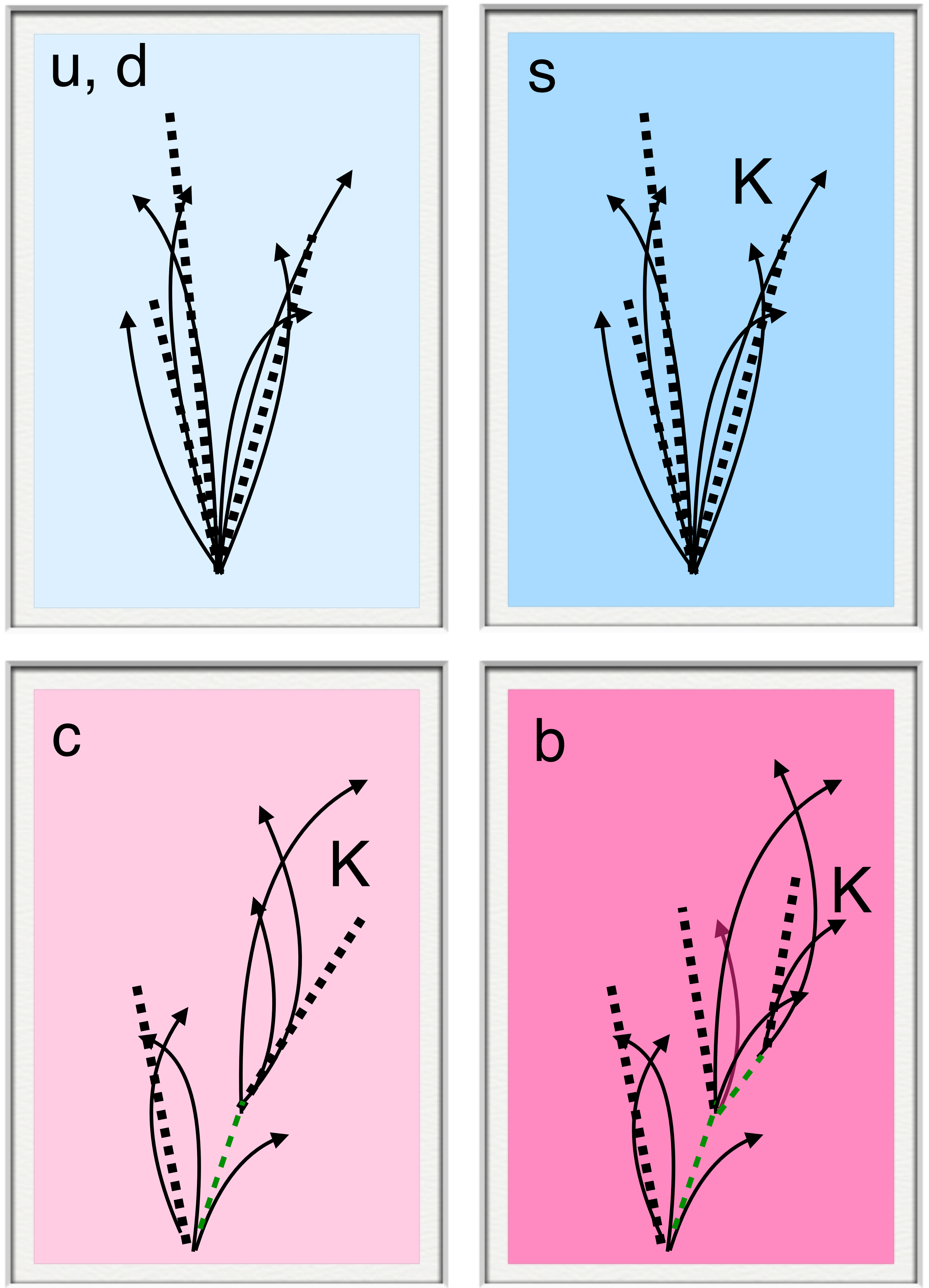
- Requirements mostly driven by (Higgs) specific benchmarks
- Technological advances can open new opportunities and additional physics benchmarks (i.e. H→ss) can add more stringent requirements

Focus topics for the ECFA study on Higgs / Top / EW factories *should* provide further detector design guidelines (2401.07564) by Spring 2025

PRL 85 (2000), 5059
SLAC-R-520
arXiv:2101.04119
arXiv:2203.07535

s-tagging, a new benchmark?

Tagging strange is a challenging but not impossible task for future detectors at e^+e^-, as demonstrated by SLD and DELPHI



- As b,c, and s jets contain at least one strange hadron
- Strange quarks mostly hadronize to prompt kaons which carry a large fraction of the jet momentum
  - H →ss requires strange tagging capability for $p_T > 10$ GeV
- Strange hadron reconstruction:
  - $K^\pm$ PID
  - K^0_L PF (neutral)
  - $K^0_S \rightarrow \pi^+\pi^-$ (~70%) / $\pi^0\pi^0$ (~30%)
  - $\Lambda^0 \rightarrow p\pi^-$ (~65%)

Distinctive two-prong vertices topology

Jet flavour	Number of secondary vertices (excluding V^0s)	Number of strange hadrons (e.g., $K^\pm$, $K^0_{L/S}$, and Λ^0)
Bottom	2	≥1
Charm	1	≥1
Strange	0	≥1
Light	0	0

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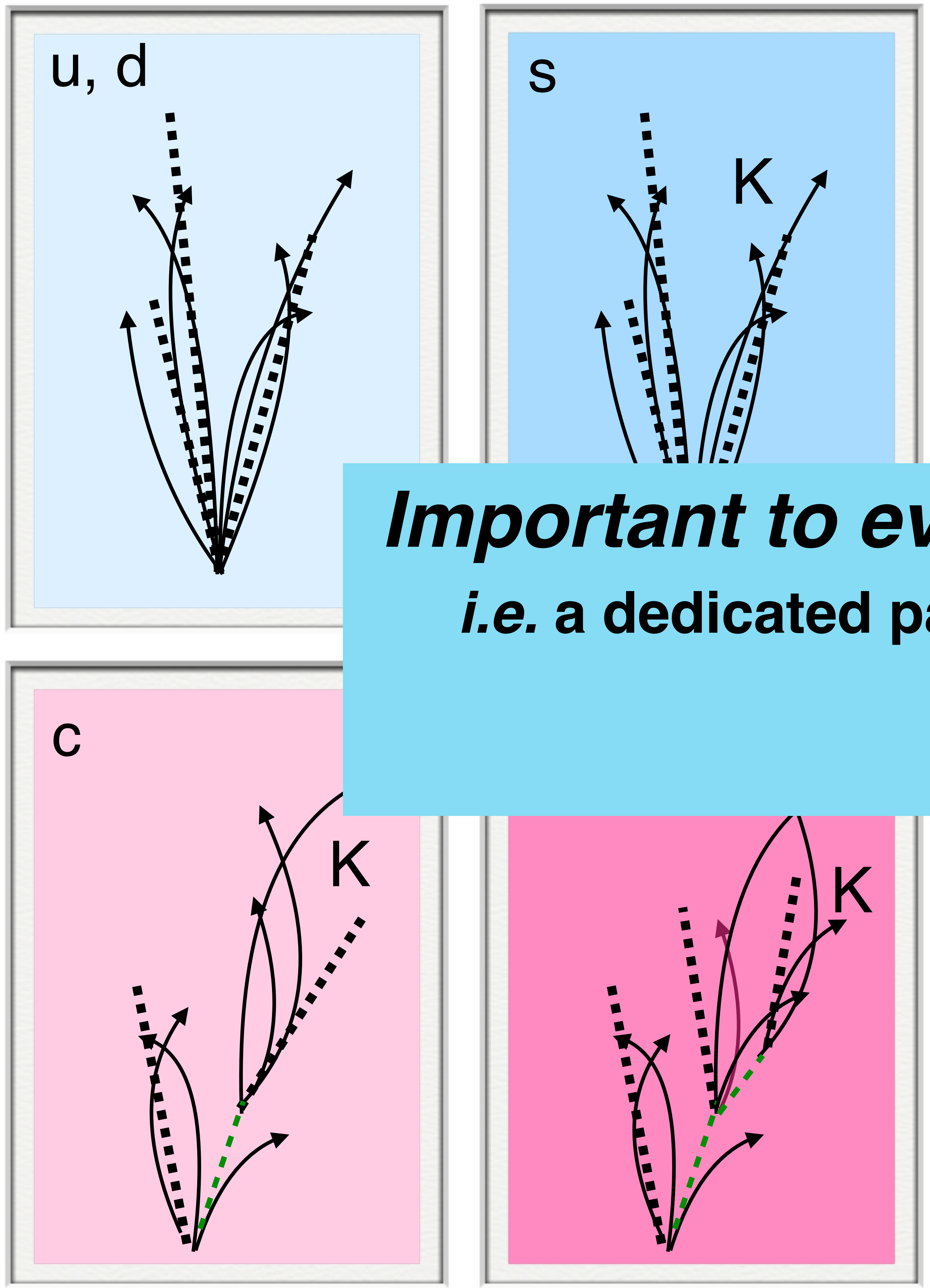

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/o-prong
oology

Important to evaluate simultaneously other Higgs benchmarks

i.e. **a dedicated particle ID device in front of the calorimeter could compromise other physics measurements**

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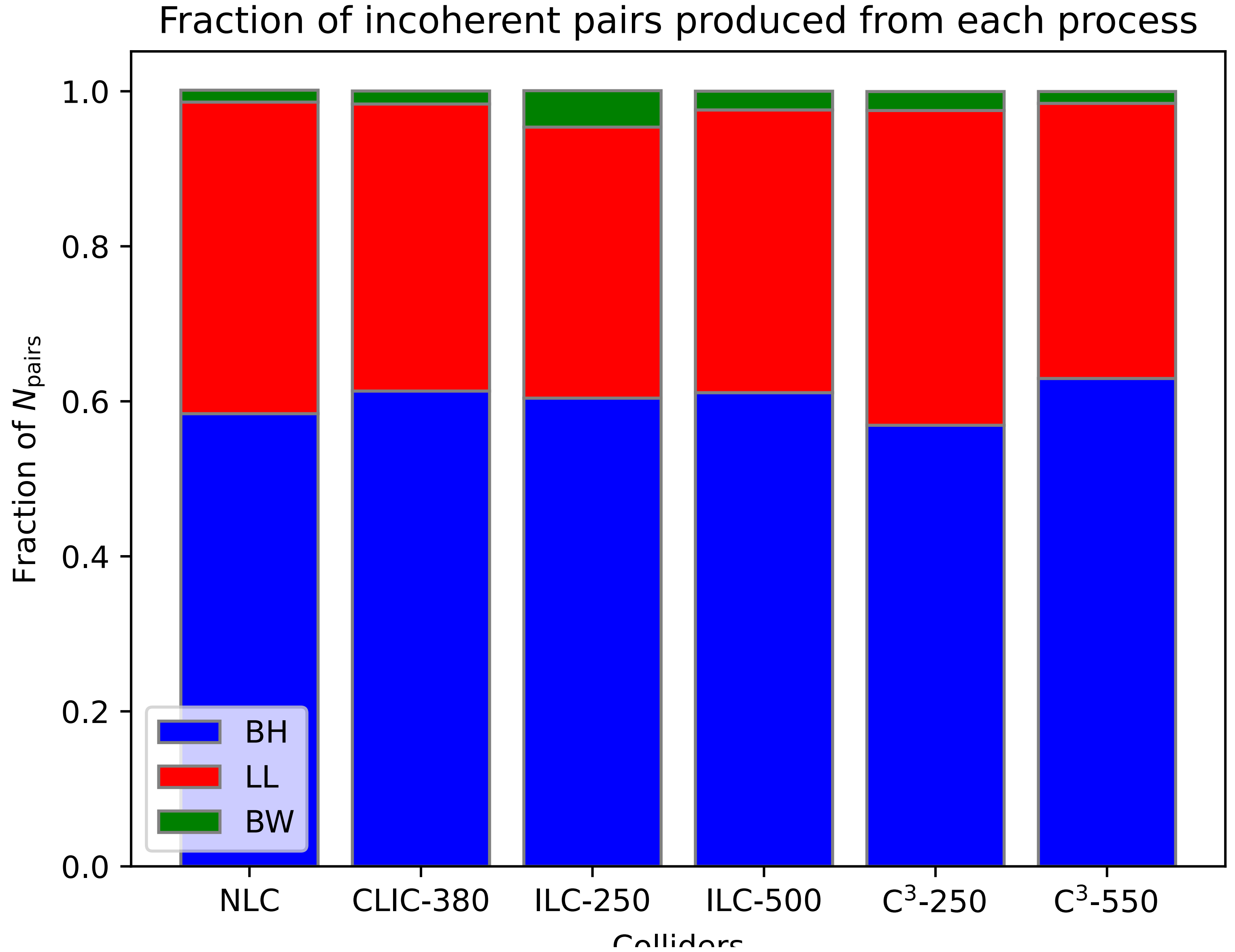
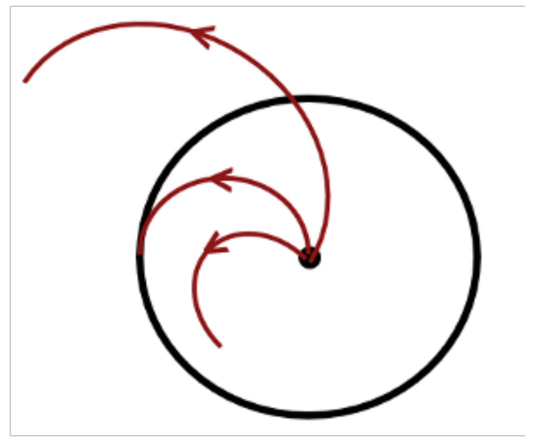
Joint simulation/detector optimization effort
ILC WG3 March 21
arXiv:2403.07093

Importance of beam-beam background

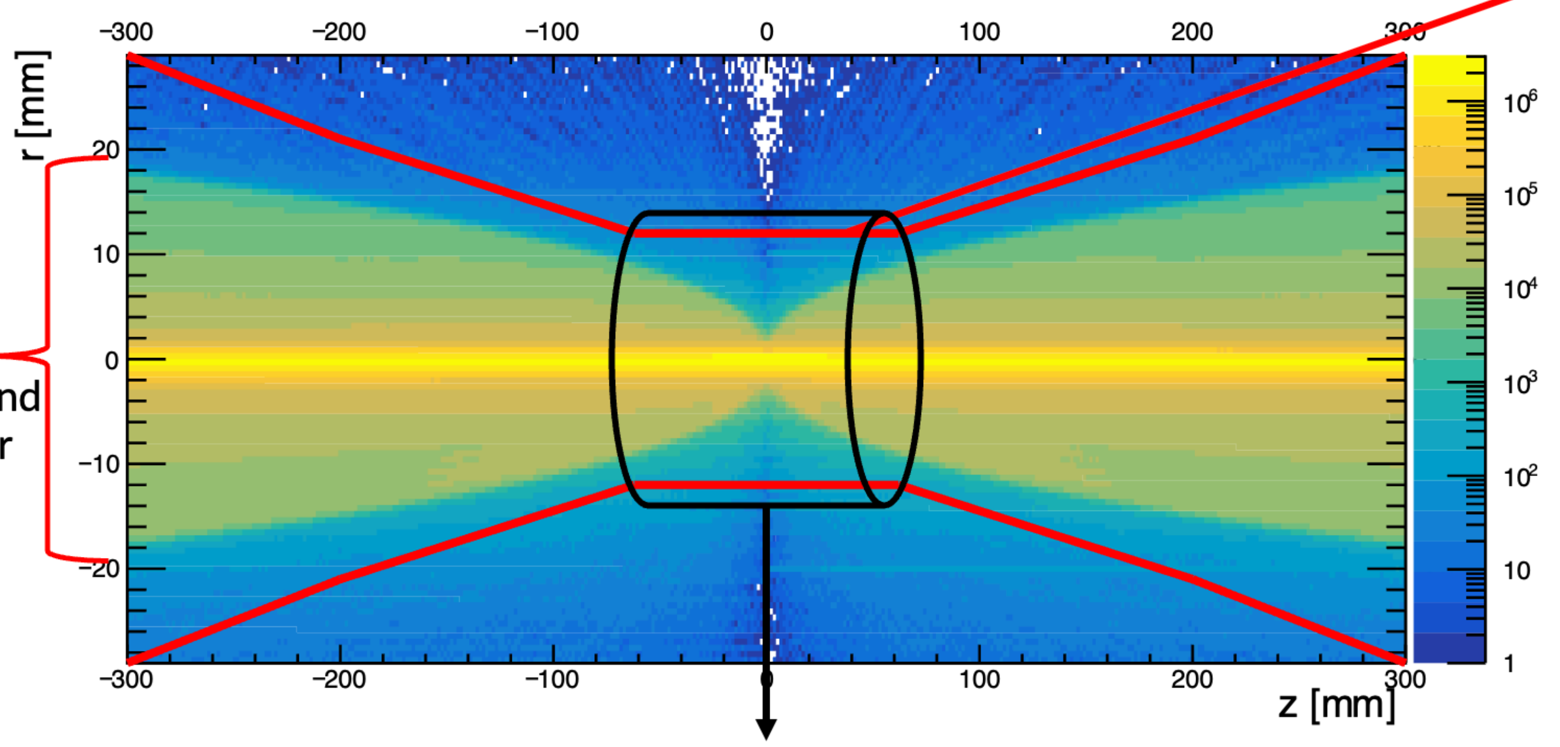
The effects of beam-beam interactions have to be careful simulated for physics and detector performance

- Beamstrahlung photons are radiated at the IP and can produce:
  - Incoherent pair production
  - Muon and Hadron photo-production
- Beamstrahlung widens the luminosity spectrum
  - Enables collisions at lower $\sqrt{s}$ and softens initial state constraints → important for physics observables (ZH)
  - Photoproduced jets affect clustering performance, JER, JES
  - High flux in vertex barrel and forward sub detectors
    - Increase in detector occupancy → Impacts detector design
    - At low momentum incoherent pairs deflected by B field





$$p_T^{(\min)}[\text{MeV}] = 0.3 \cdot B[\text{T}] \cdot \frac{\rho}{2}[\text{mm}] \simeq 10\ \text{MeV}$$



D. Ntounis (2023)
G. Marchiori (2023)
TDAQ@Annecy2024

Current status of beam-background studies

Same tools and methodology between ILC & FCC within Key4HEP

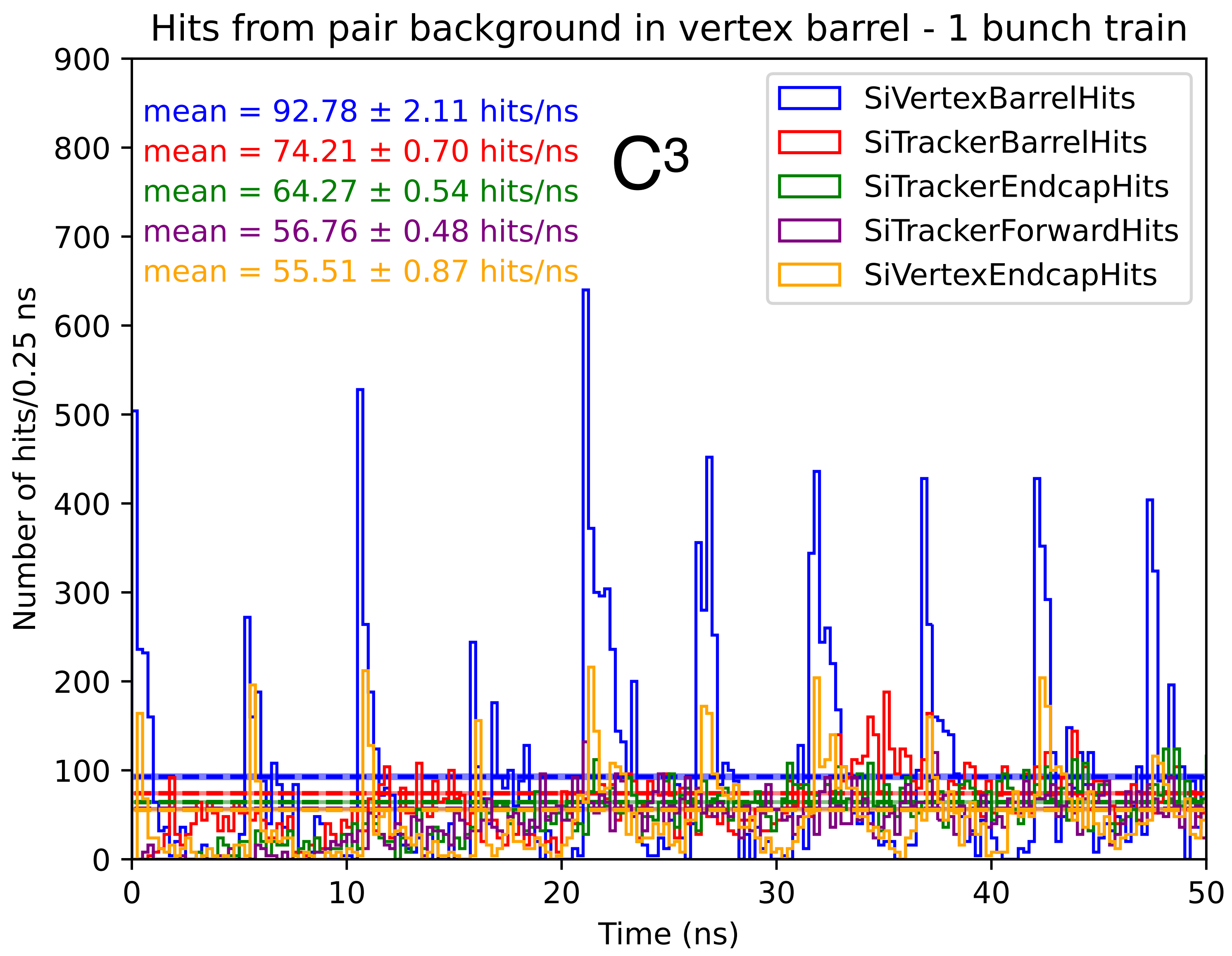
- ILC physics studies are based on full simulation data and some have been recently repeated for C[3]
  - Time distribution of hits per unit time and area on 1st layer ~ $4.4 \cdot 10^{-3}$ hits/(ns·mm²) ≃ 0.03 hits/mm² /BX
- CLD detailed studies @FCC show an overall occupancy of 2-3% in the vertex detector at the Z pole
  - assuming 10μs integration time

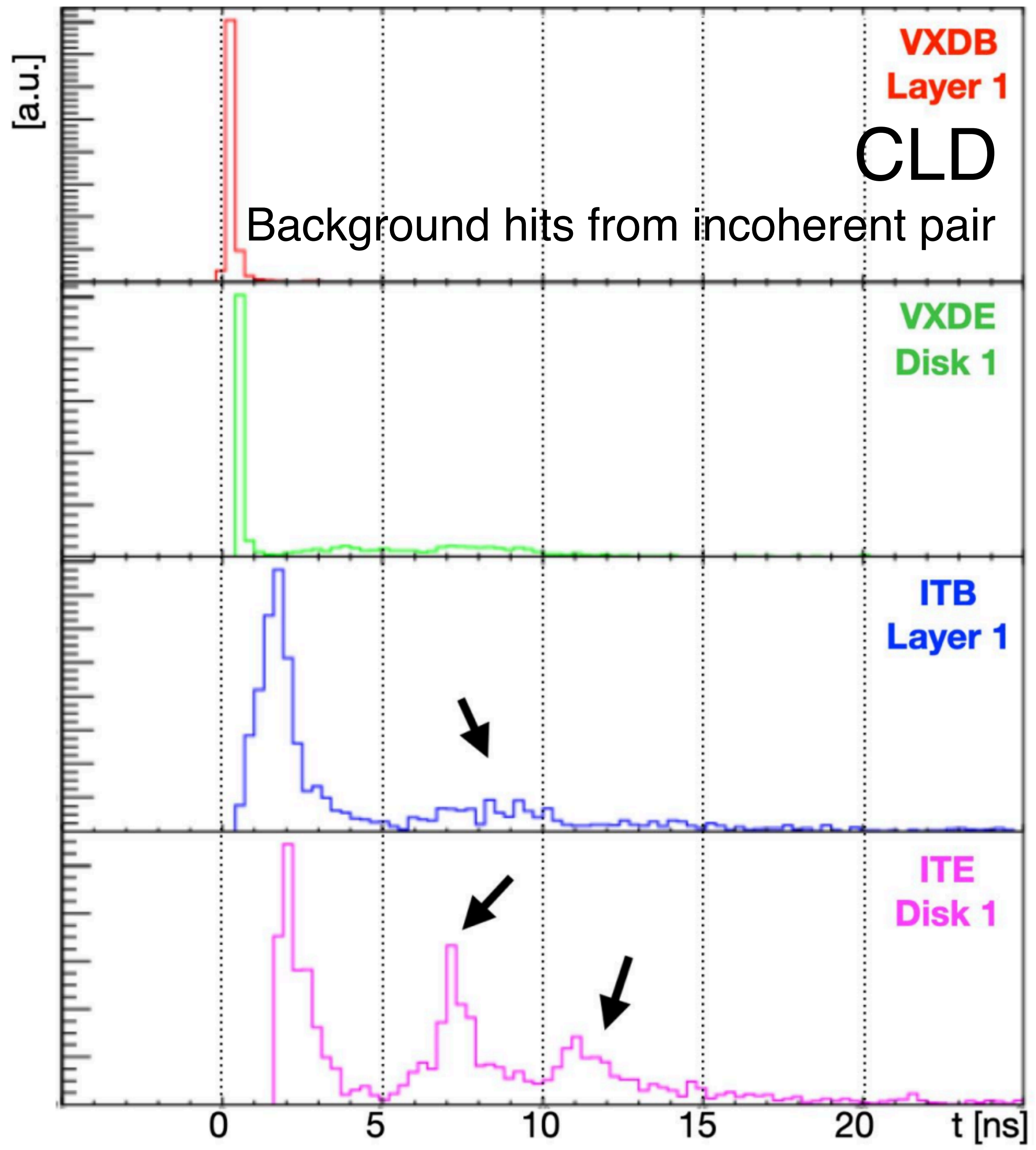
$$occupancy = hits/mm^2/BX \cdot size_{sensor} \cdot size_{cluster} \cdot safety$$

$$size_{sensor} = \begin{matrix} 25\mu m \times 25\mu m\ (pixel) \\ 1mm \times 0.05mm\ (strip) \end{matrix} \qquad size_{cluster} = \begin{matrix} 5\ (pixel) \\ 2.5\ (strip) \end{matrix} \qquad safety = 3$$

	Z	WW	ZH	Top
Bunch spacing [ns]	30	345	1225	7598
Max VXD occ. 1us	2.33e-3	0.81e-3	0.047e-3	0.18e-3
Max VXD occ.10us	23.3e-3	8.12e-3	3.34e-3	1.51e-3
Max TRK occ. 1us	3.66e-3	0.43e-3	0.12e-3	0.13e-3
Max TRK occ.10us	36.6e-3	4.35e-3	1.88e-3	0.38e-6

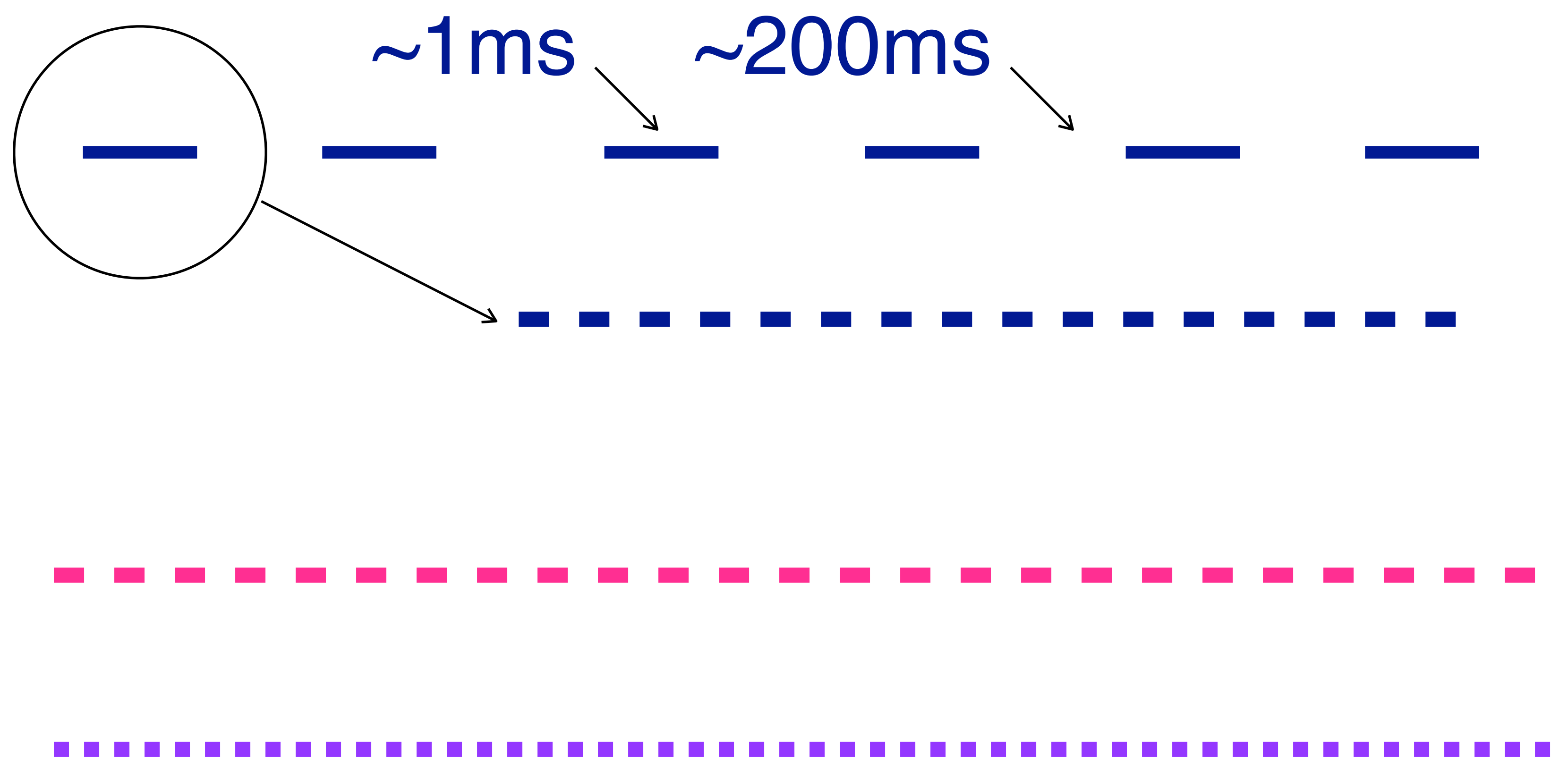
Occupancy in readout window (10μs)





Beam Format and Detector Design Requirements

arXiv:2003.01116
FCC Mid Term Report



ILC Trains at 5Hz, 1 train 1312 bunches
Bunches are 369 ns apart

FCC@ZH Bunches 1 μs apart

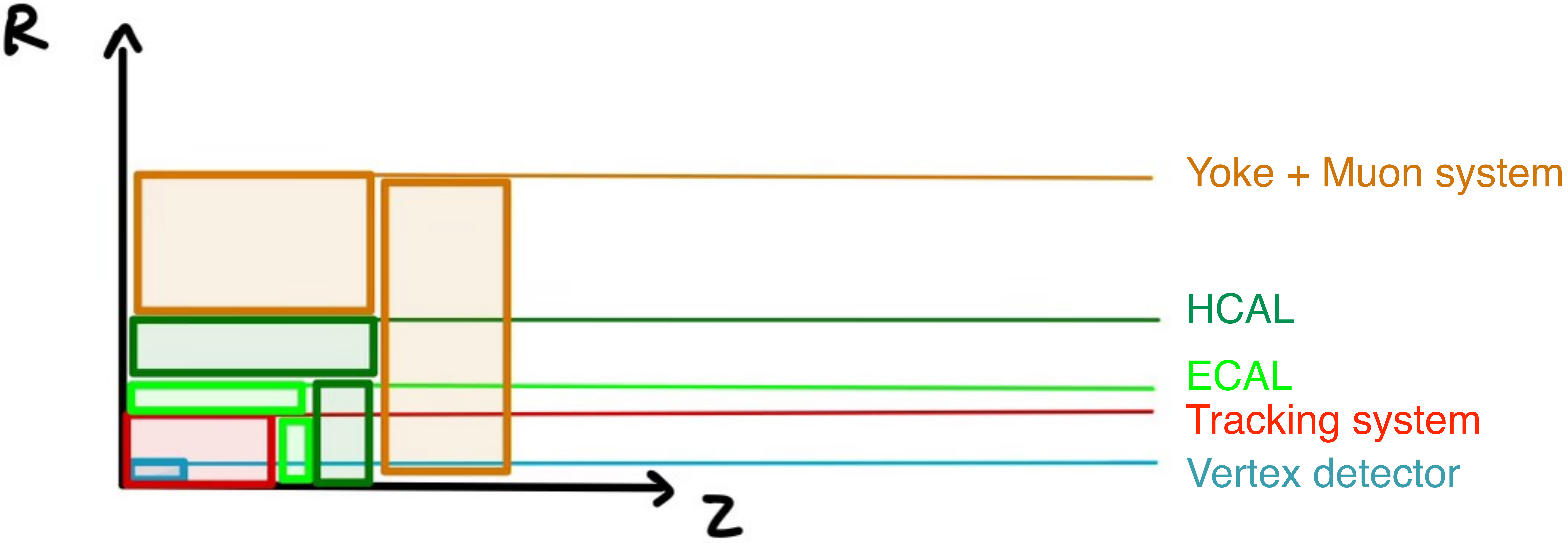
FCC@Z Bunches 20 ns apart

- Very low duty cycle at LC (0.5% ILC, 0.03% C^3) allows for trigger-less readout and power pulsing
  - Factor of 100 power saving for front-end analog power
  - **O(1-100) ns bunch identification capabilities**
- Impact of beam-induced background to be mitigated through MDI and detector design
  - Timing resolution of O(ns) can further suppress beam-backgrounds and keep occupancy low
  - **O(1-10) ns for beam background rejection and/or trigger decision before reading out the detector**
  - Tracking detectors need to achieve good resolution while mitigating power consumption

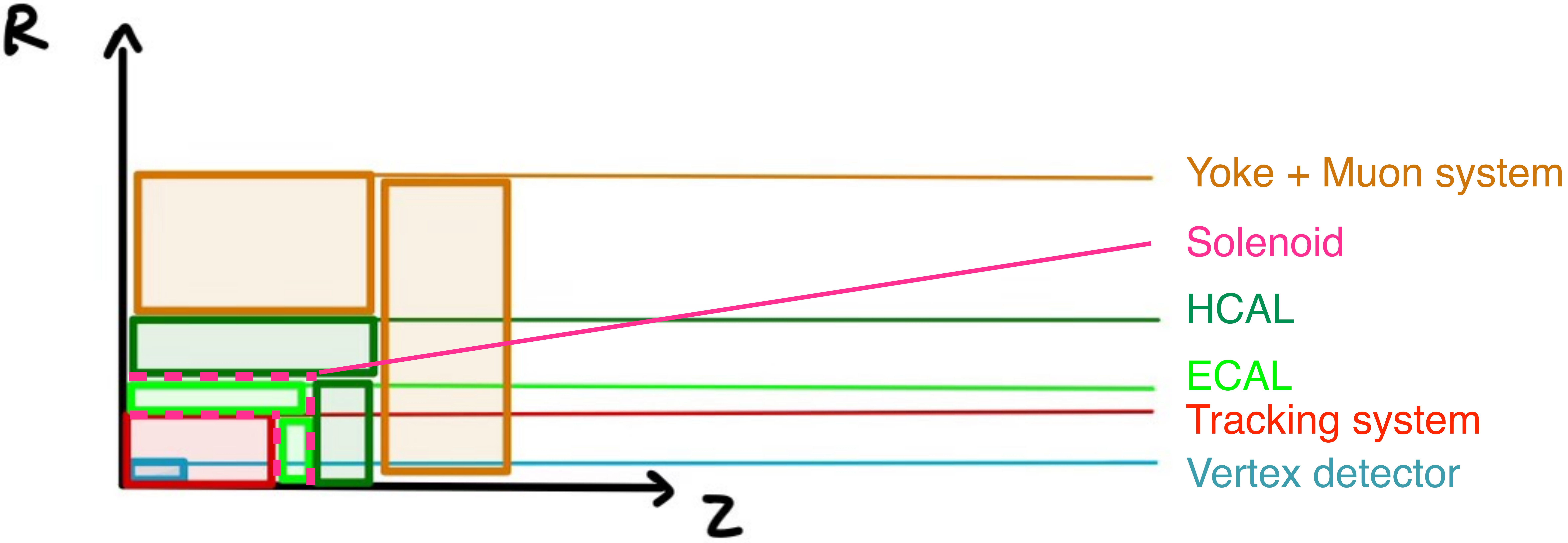
Detector concepts

Different approaches to achieve *same* physics goals
Many synergistic R&D directions

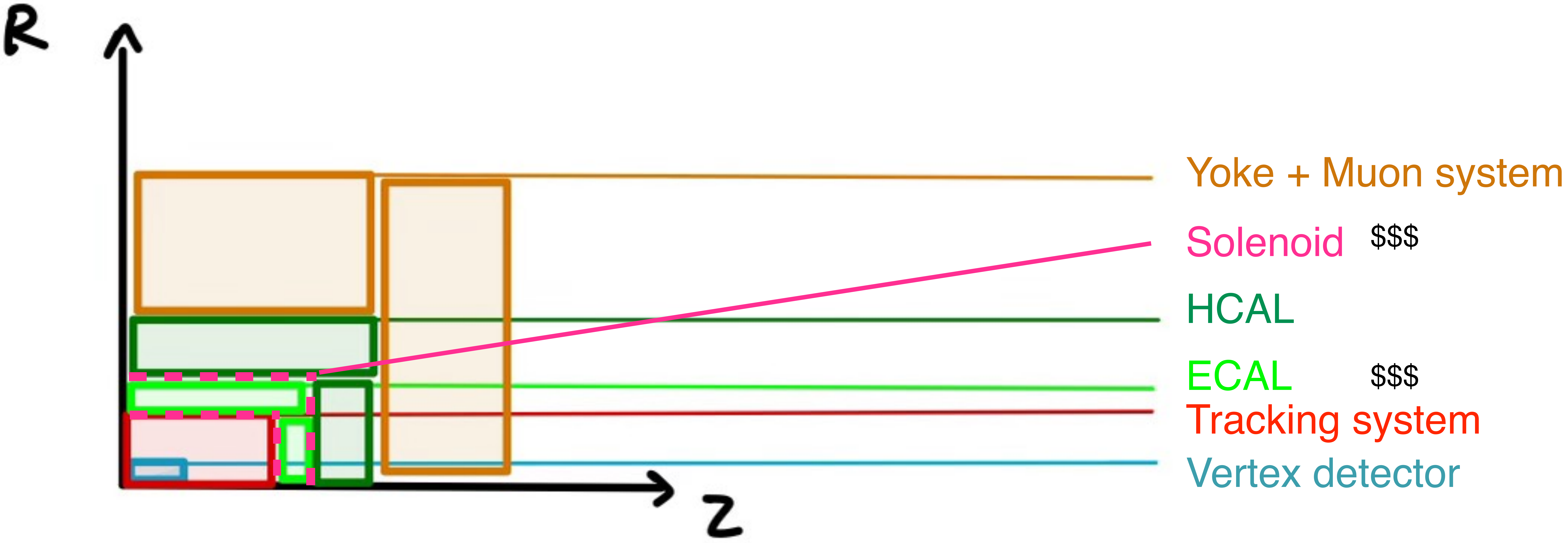
Detector concepts



Detector concepts

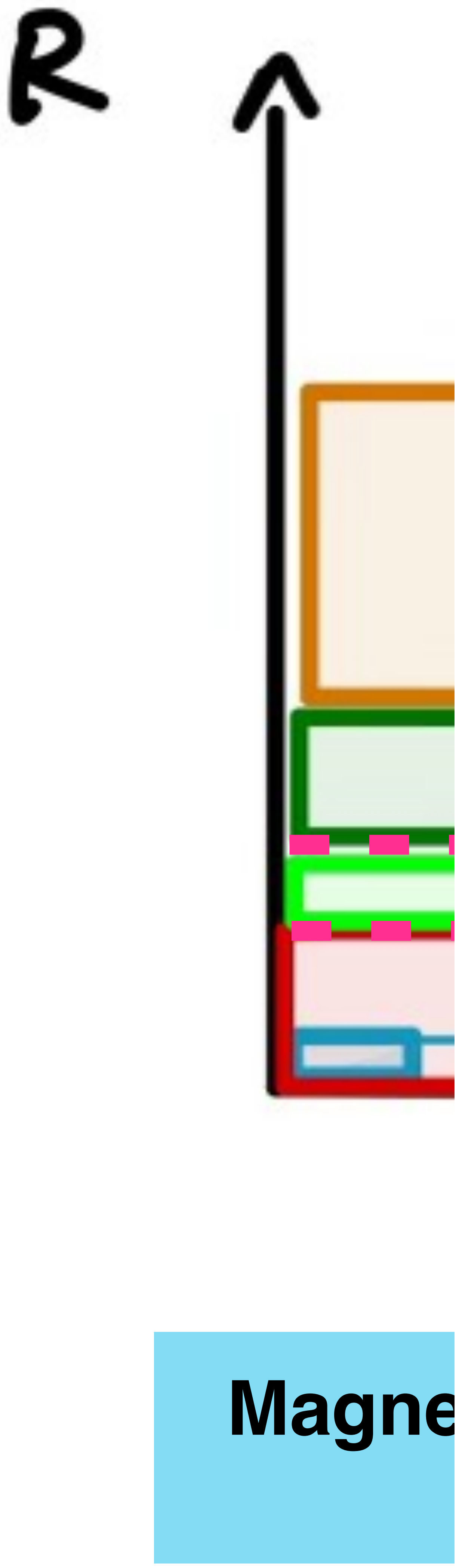


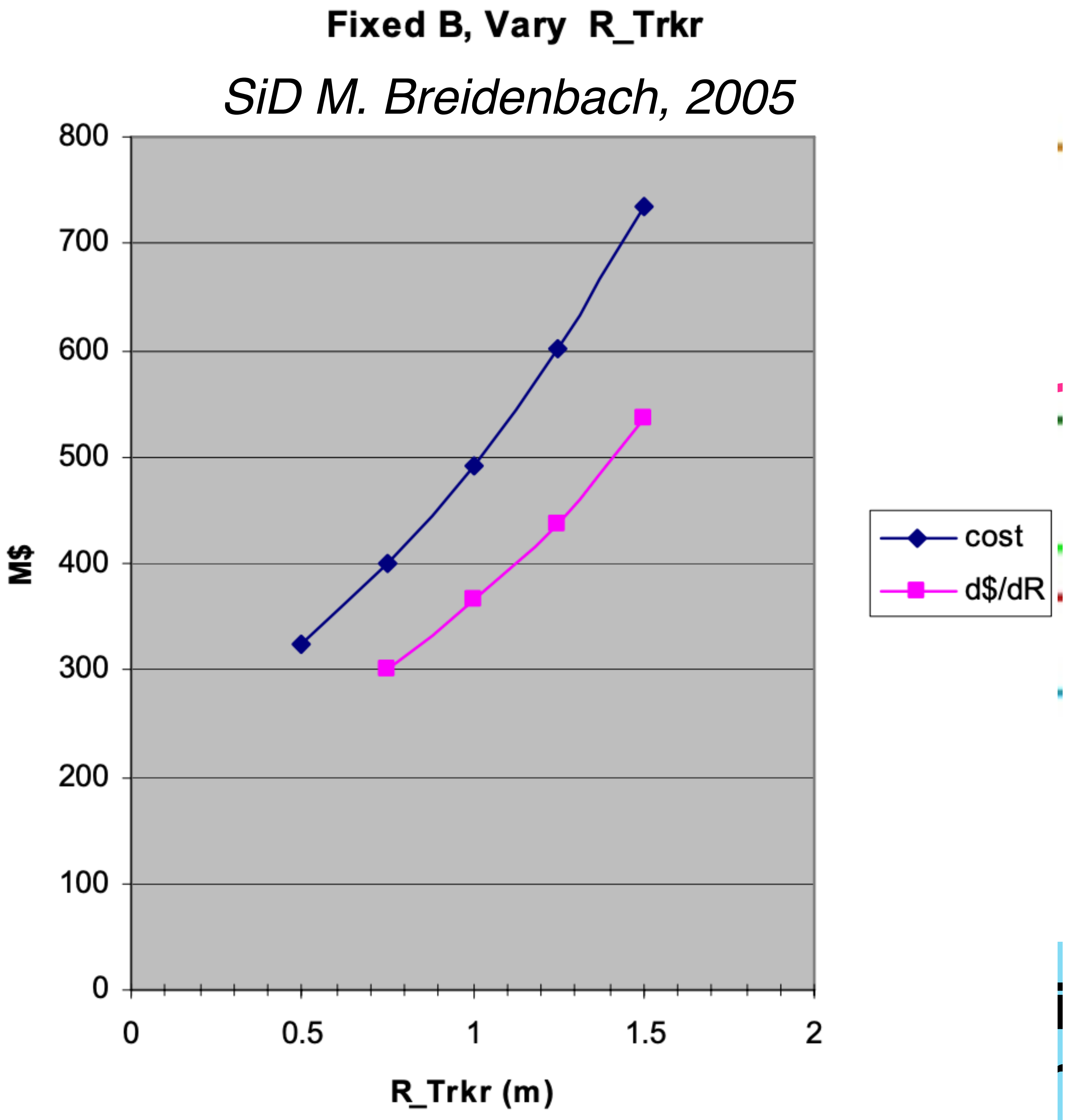
Detector concepts

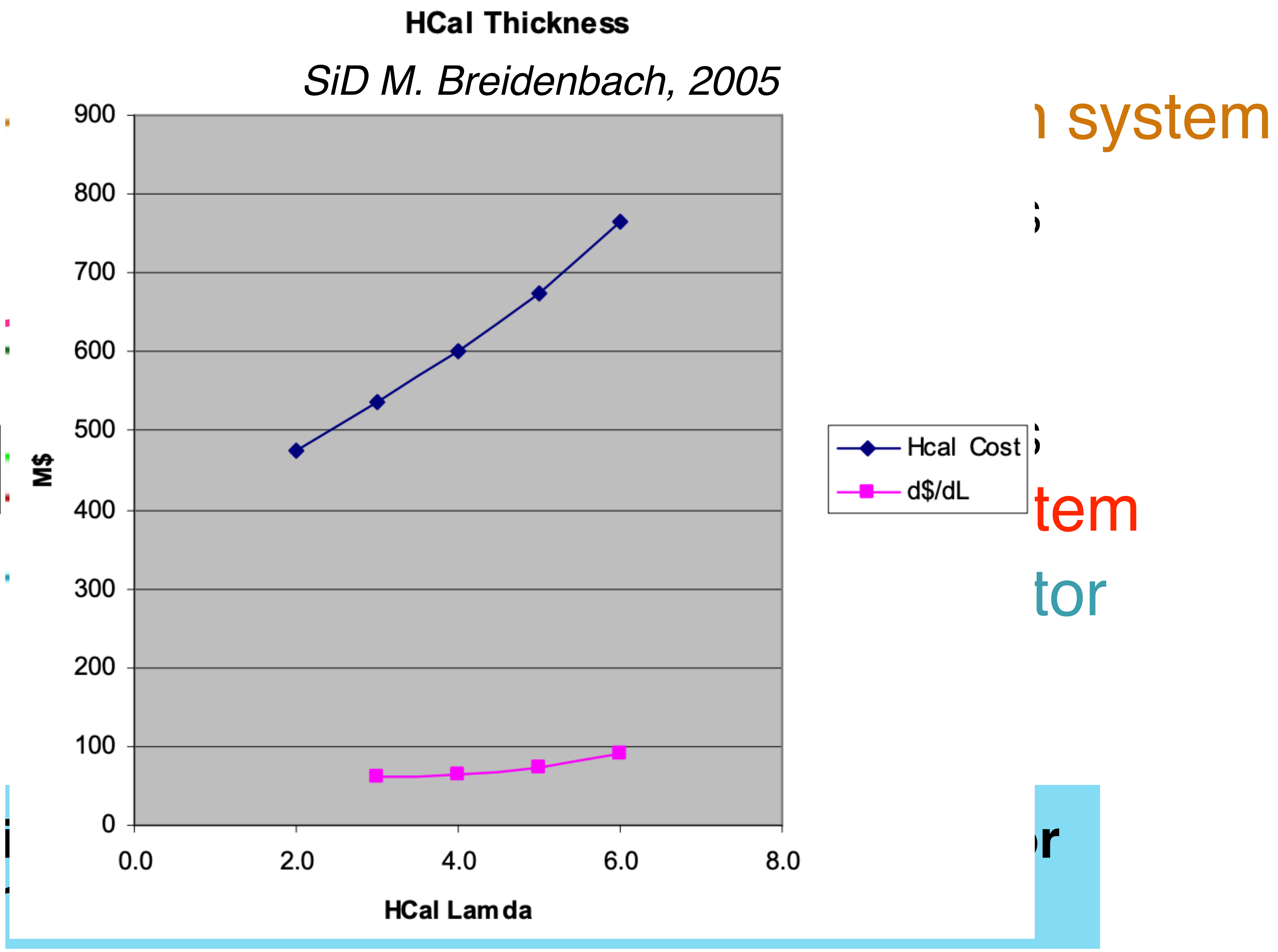


Magnet and Calorimeters are generally driving the cost (>30% each) of the detector
Optimizations and cost reduction are possible with targeted R&D

Detector concepts

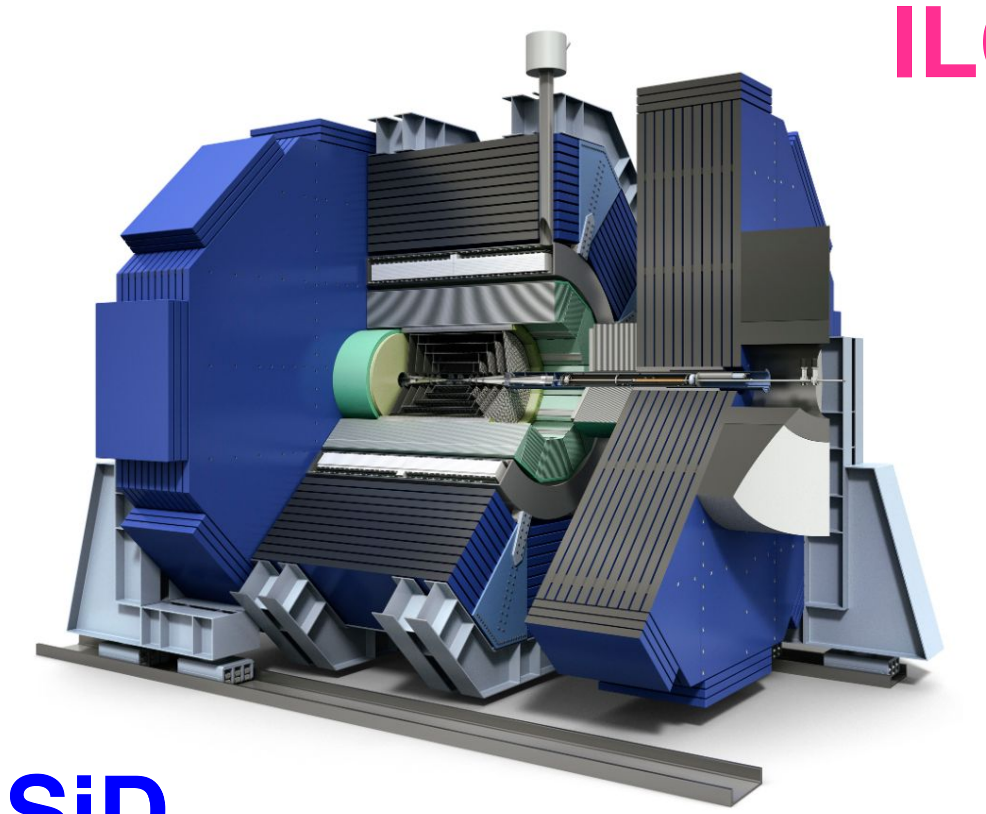






Detector Designs, a quick overview

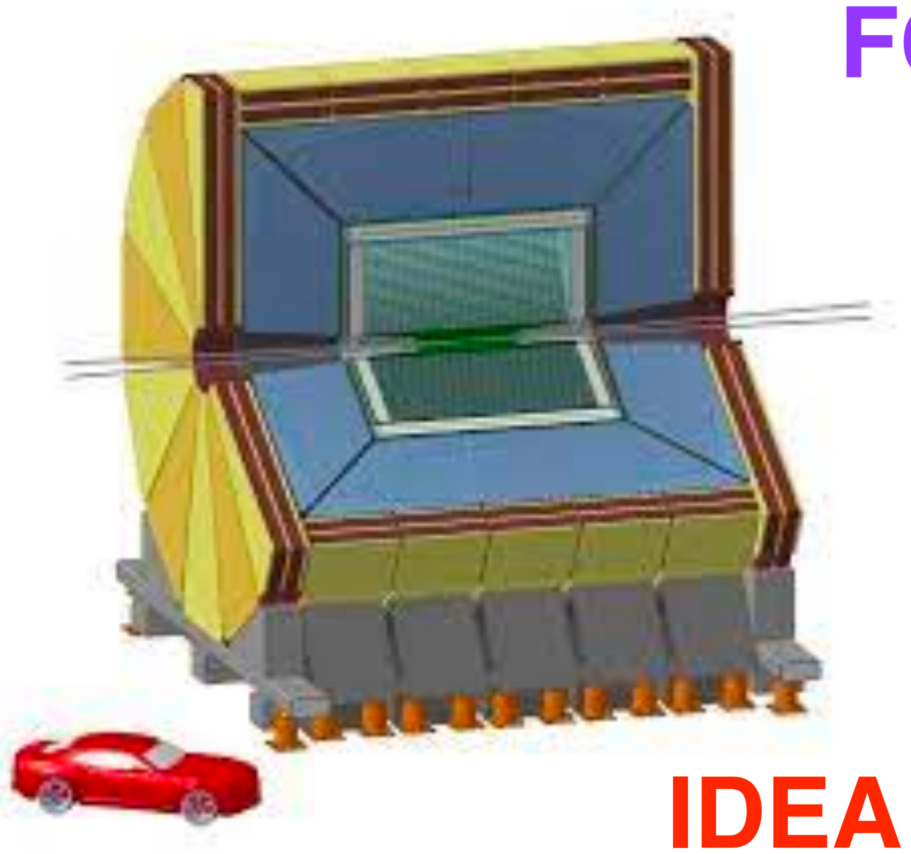
ILC



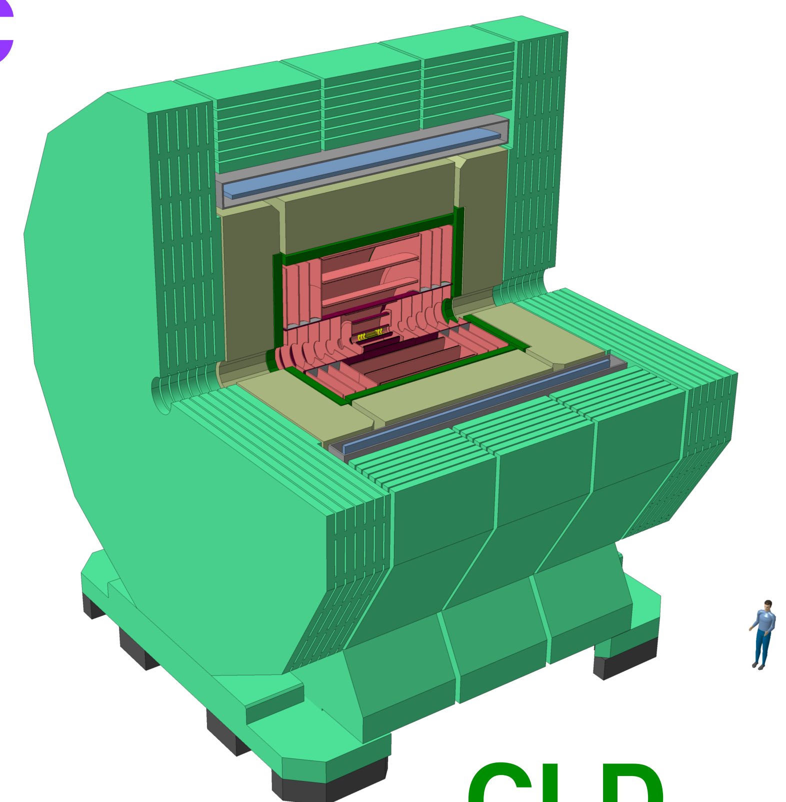
SiD

ILD

FCC



IDEA



CLD

ALLEGRO

- Detector designs at all colliders features very similar strategies, main difference is in the B field
    - FCC@Z limits B field to 2 T to avoid a blow up of the vertical beam emittance
- SiD/CLD - Compact all silicon tracking systems with highly segmented calorimeters optimized for PFA
    - CLD compensates the lower B field (2 T) with a larger tracking radius
- ILD - Larger detector with TPC tracker with PFA calorimeter
- IDEA - Drift chamber with PID and dual readout calorimeter
- Allegro - Drift chamber and silicon wrapper with timing information and noble gas calorimeter

Detector Designs, a quick overview

A tail of synergies and complementarity

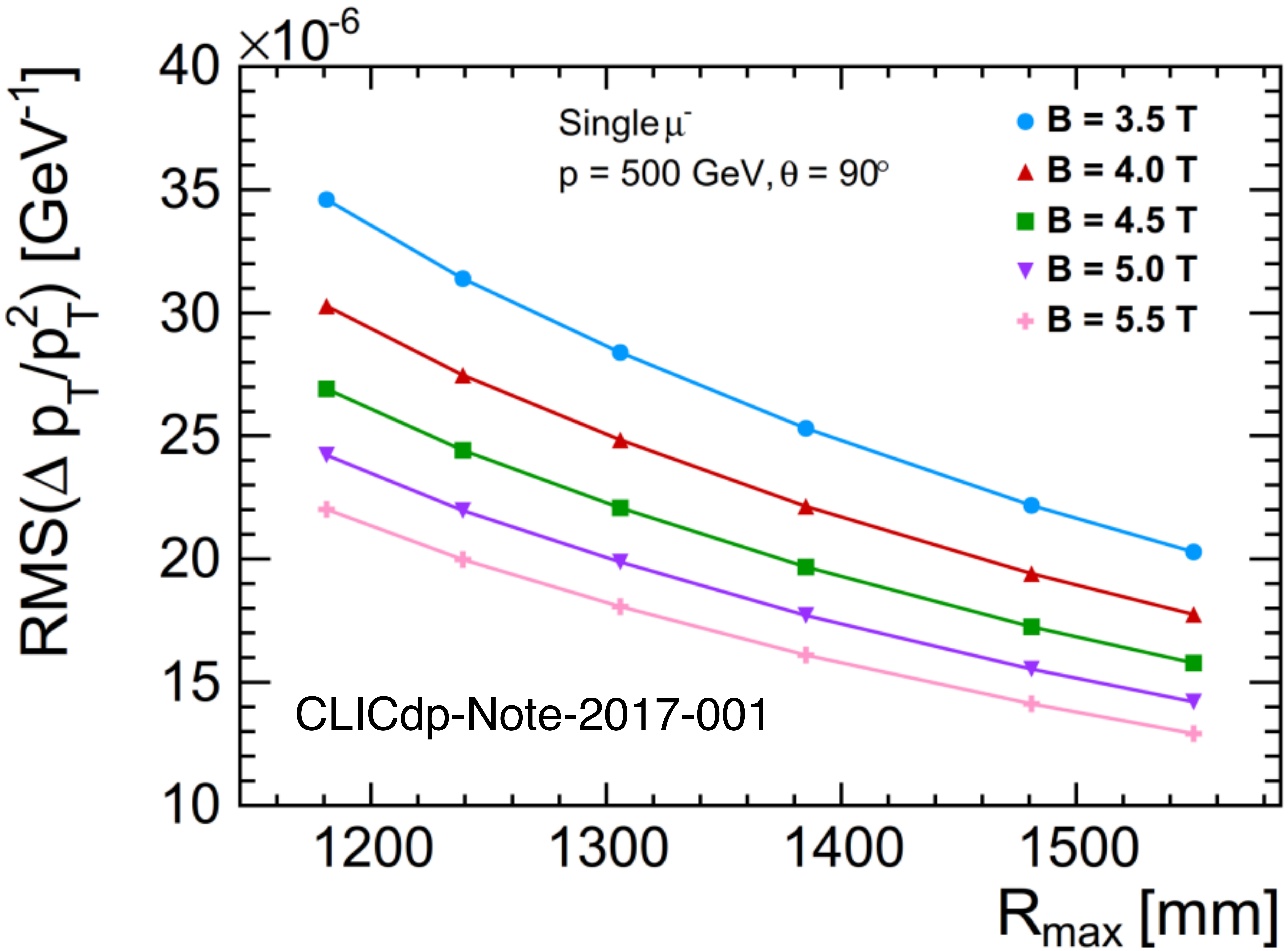
	ILD	SID	IDEA	CLD	ALLEGRO
Vertex Inner Radius (cm)	1.6	1.4	1.2	1.2	1.2
Tracker technology	TPC+Silicon	Silicon	Si+Drift Chamber	Si	Si+Drift Chamber
Outer Tracker Radius (m)	1.77	1.22	2	3.3	2
ECal thickness	24 X_0	26 X_0	Dual RO	22 X_0	22 X_0
HCal thickness	5.9 λ_0	4.5 λ_0	7 λ_0	6.5 λ_0	9.5 λ_0
HCal Outer Radius (m)	3.3	2.5	4.5	3.5	4.5
Solenoid field (T)	3.5	5	2	2	2
Solenoid length (m)	7.9	6.1	6	7.4	6
Solenoid Radius (m)	3.4	2.6	2.1	4	2.7

Timing? Ongoing R&D to exploit O(10ps) capabilities
BUT nowadays there are several technologies to achieve O(10) ps resolution

Detector Designs, a quick overview

A tail of synergi

	ALLEGRO
Vertex Inner Ra	1.2
Tracker tech	Si+Drift Chamber
Outer Tracker F	2
ECal thick	22 X_0
HCal thick	9.5 λ_0
HCal Outer Ra	4.5
Solenoid fie	2
Solenoid len	6
Solenoid Rad	2.7



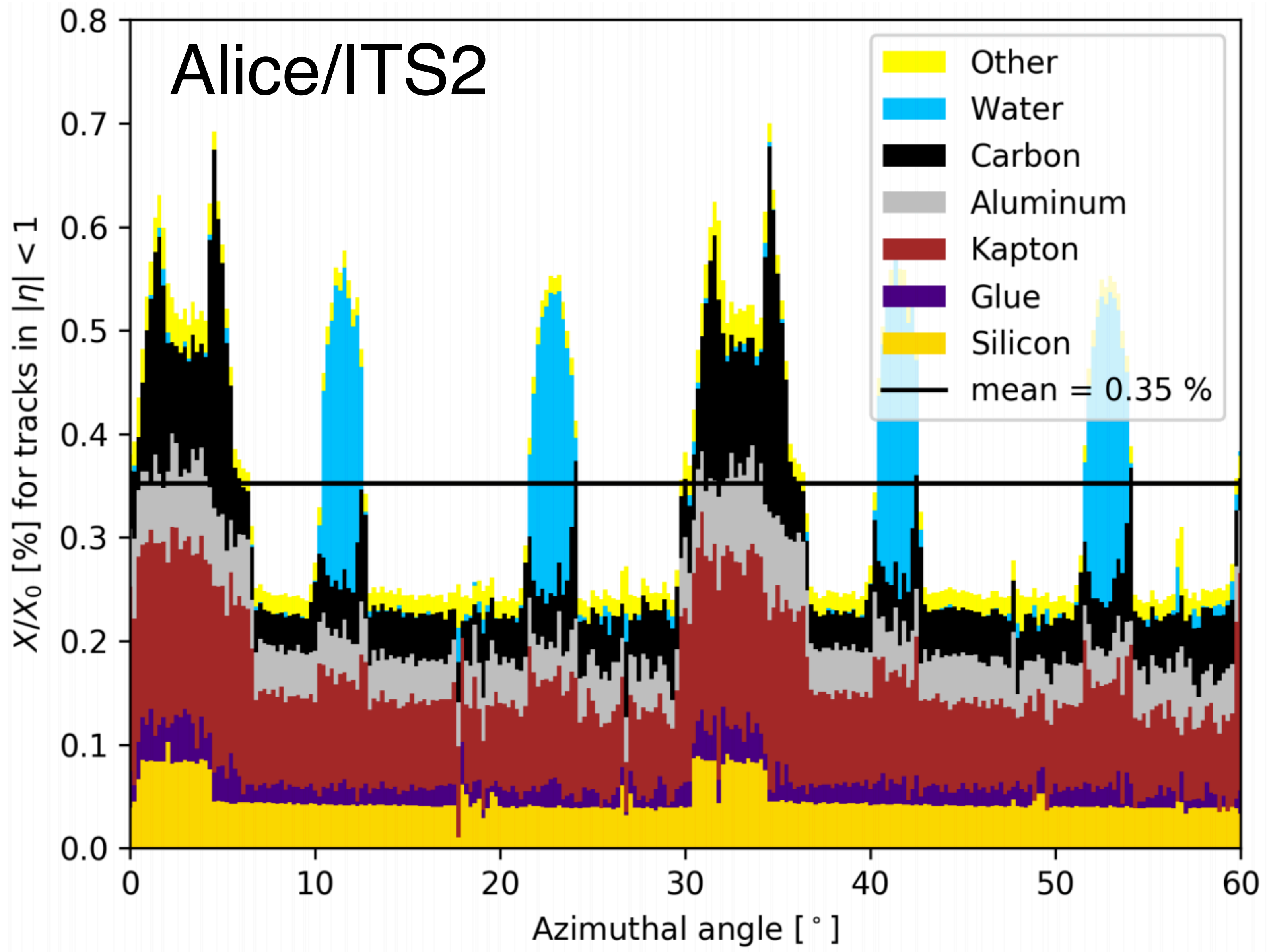
B-field and tracker radius optimization driven by:
PFA performance, vertex detector occupancy, technical considerations

Sensors technology requirements for Vertex Detector

Several technologies are being studied to meet the physics performance

- Sensor's contribution to the total material budget is 15-30%
  - Services cables + cooling + support make up most of the detector mass
- Sensors will have to be less than 75 μm thick with at least 3-5 μm hit resolution (17-25 μm pitch) and low power consumption
- Beam-background suppression
  - ILC/C^3 - evolve time stamping towards O(1-100) ns (bunch-tagging)
  - FCC, continuous r/o integrated over ~10μs with O(1) ns timing resolution for beam background suppression

CERN-LHCC-2019-018



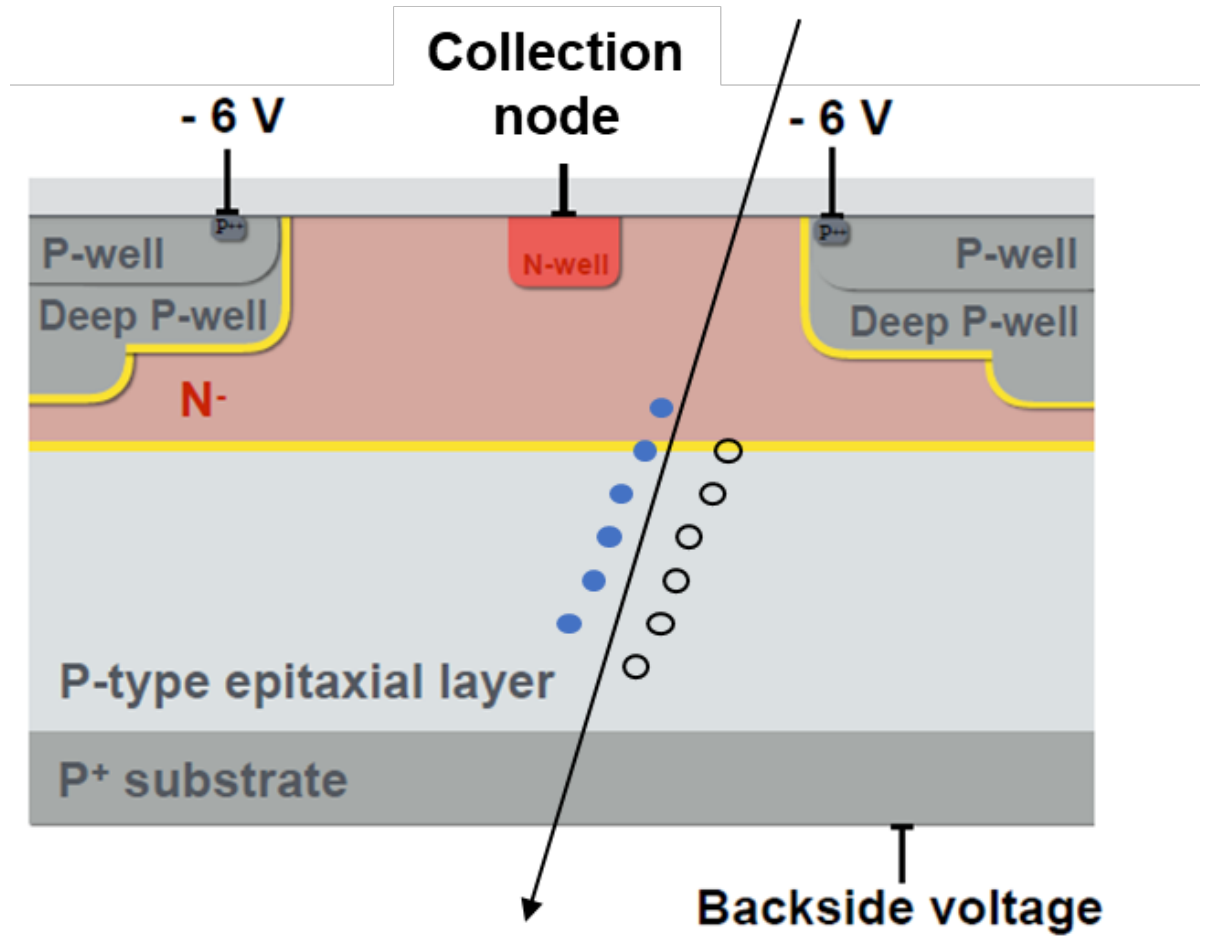
Physics driven requirements — **Running constraints** — **Sensor specifications**

- σ ($< 3\ \mu m$) → Small Pixel: *~15μm*
- Material budget ($0.1\% X_0$/layer) → Thinning to: *50 μm*
- Material budget → Cooling → Low Power: *20-50 mW/cm²*
- r of the Inner most layer (12-14 mm) → Beam-background → Fast Readout: *~1-10 μs*
- r of the Inner most layer → Radiation damage → Radiation Tolerance: *10 MRad, $10^{14}\ n_{eq}$ / /cm²*

Monolithic Active Pixel Sensors - MAPS

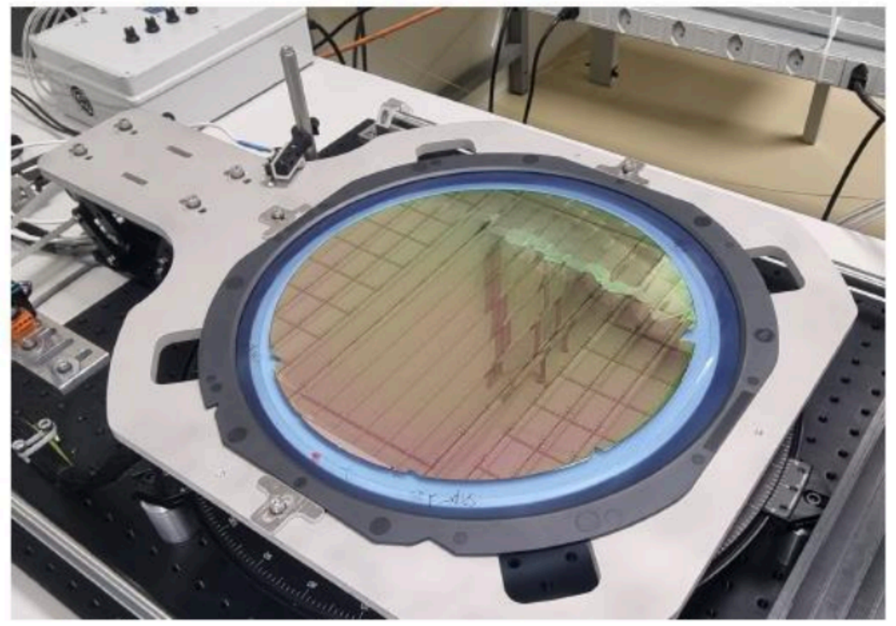
A suitable technology for high precision tracker and high granularity calorimetry

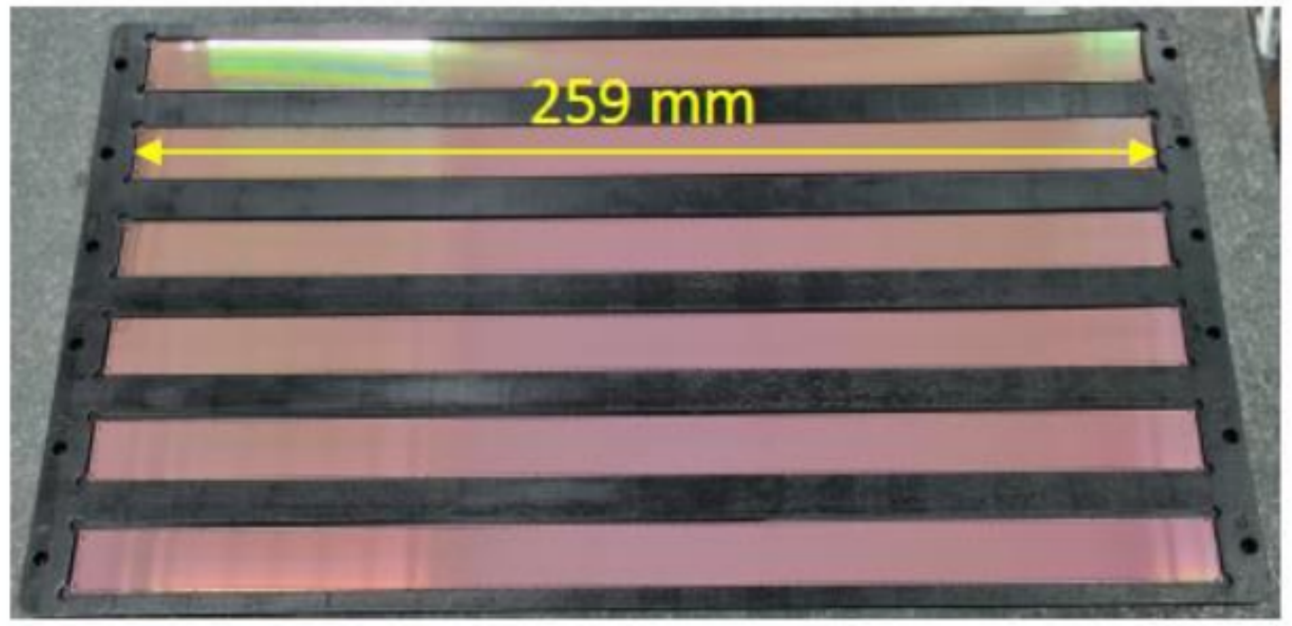
- Monolithic technologies can yield to higher granularity, thinner, intelligent detectors at lower overall cost
- Significantly lower material budget: sensors and readout electronics are integrated on the same chip
  - Eliminate the need for bump bonding : thinned to less to 50μm
  - Smaller pixel size, not limited by bump bonding (<25μm)
  - Lower costs : implemented in standard commercial CMOS processes technologies with small feature size (65-110 nm)
    - Either reduce power consumption or add more features
- Target big sensors (up to wafer size) through use of “stitching” (step-and-repeat of reticles) to reduce further the overall material budget



Current sensor optimization in TJ180/TJ65 nm process
Effort to identify US foundry on going

M. Winter, 2024





Snowmass White Paper 2203.07626
Common US R&D initiative for future Higgs Factories 2306.13567

Time resolution vs. power

O(ns) time resolution for beam-background suppression requires dedicated optimizations

Current designs that can achieve ns or sub-ns time resolutions compensate with higher power consumption

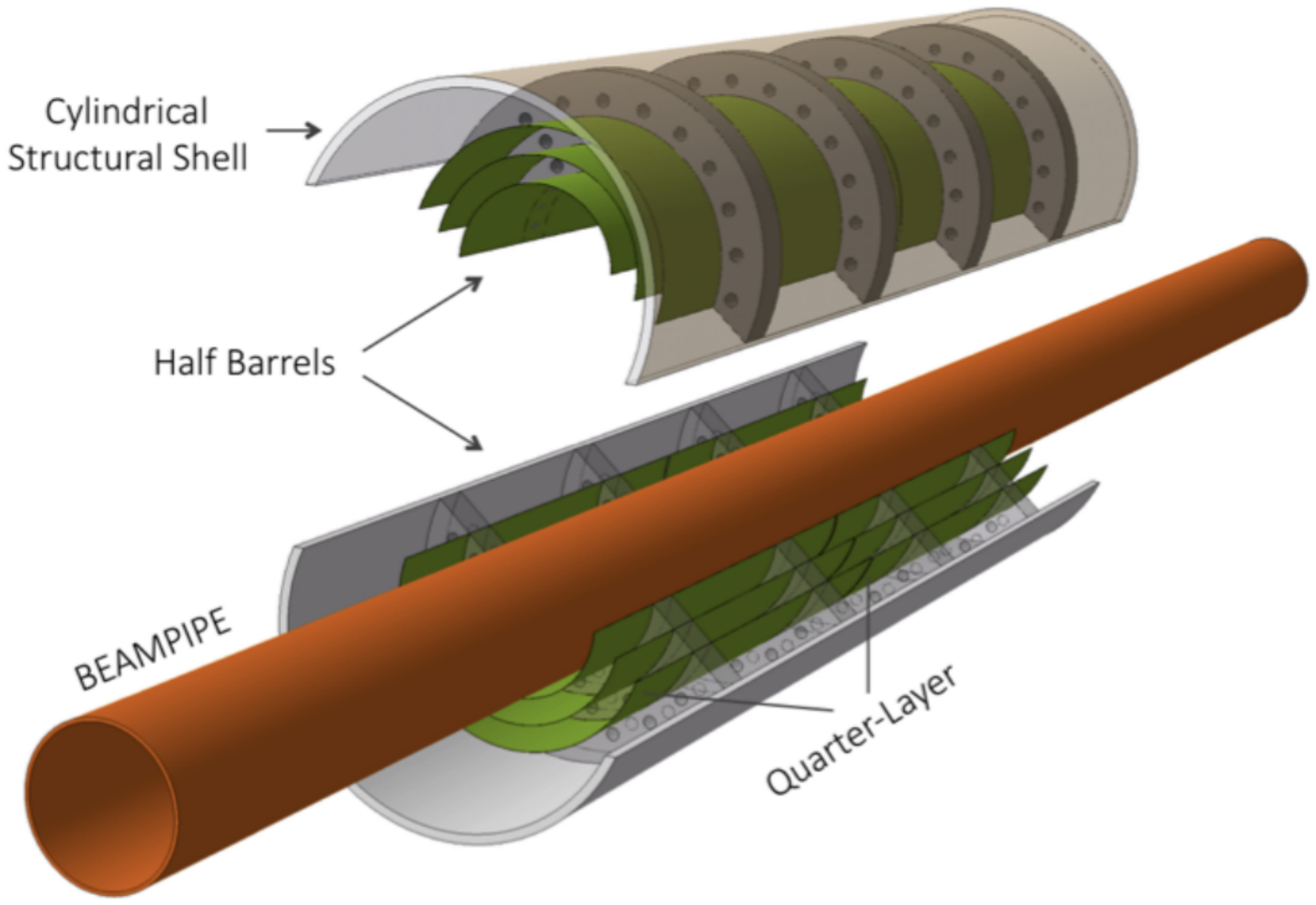
- Target power consumption is less than 20 mW/cm^2

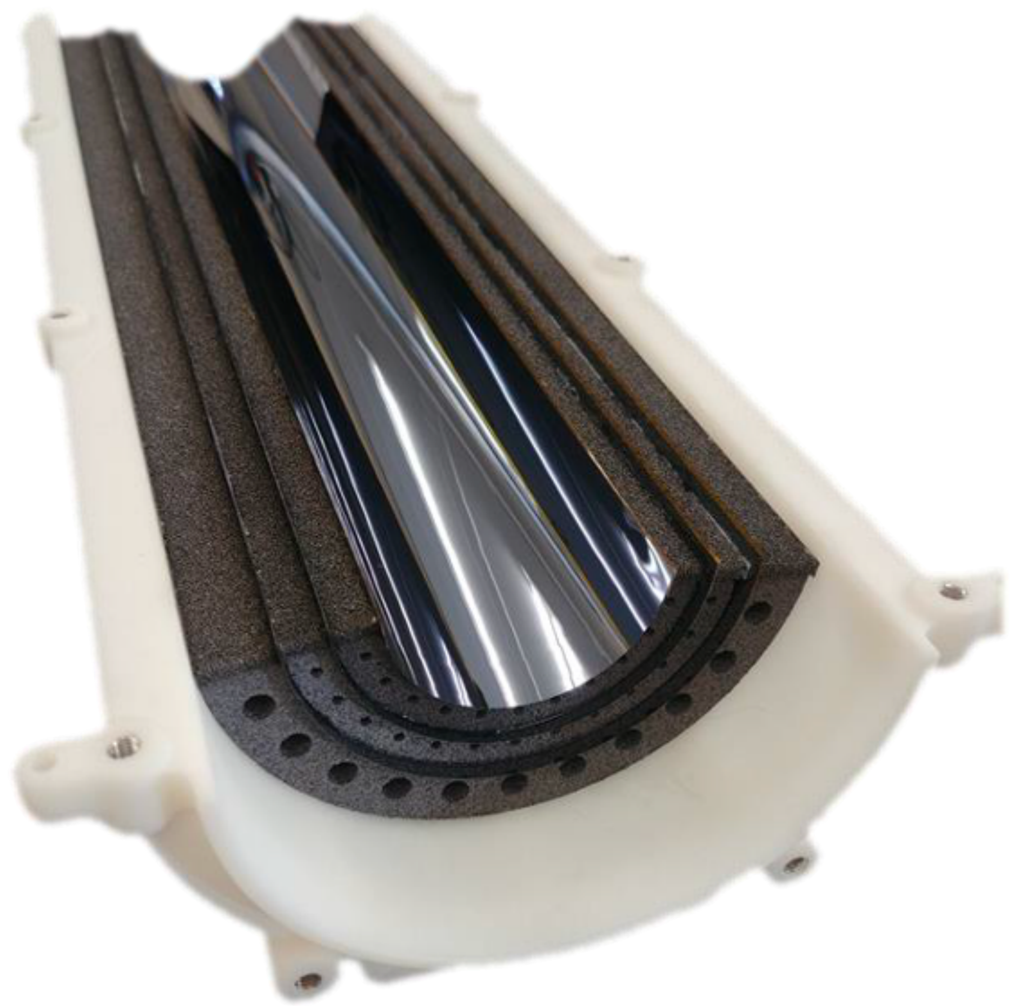
Chip name	Experiment	Subsystem	Technology	Pixel pitch [μm]	Time resolution [ns]	Power Density [mW/cm^2]
ALPIDE	ALICE-ITS2	Vtx, Trk	Tower 180 nm	28	< 2000	5
Mosaic	ALICE-ITS3	Vtx	Tower 65 nm	25x100	100-2000	<40
FastPix	HL-LHC		Tower 180 nm	10 - 20	0.122 – 0.135	>1500
DPTS	ALICE-ITS3		Tower 65 nm	15	6.3	112
NAPA	SiD	Trk, Calo	Tower 65 nm	25x100	<1	< 20
Cactus	FCC/EIC	Timing	LF 150 nm	1000	0.1-0.5	145
MiniCactus	FCC/EIC	Timing	LF 150 nm	1000	0.088	300
Monolith	FCC/Idea	Trk	IHP SiGe 130 nm	100	0.077 – 0.02	40 - 2700
Malta	LHC, ..	Trk	Tower 180 nm	36x40	25	> 100
Arcadia	FCC/Idea	Trk	LF 110 nm	25	-	30

Dedicated ongoing effort to target O(ns) resolution with MAPS (slides)
First prototype (Napa-p1) produced in TJ 65 nm process 5x5 mm^2, 25 µm pitch

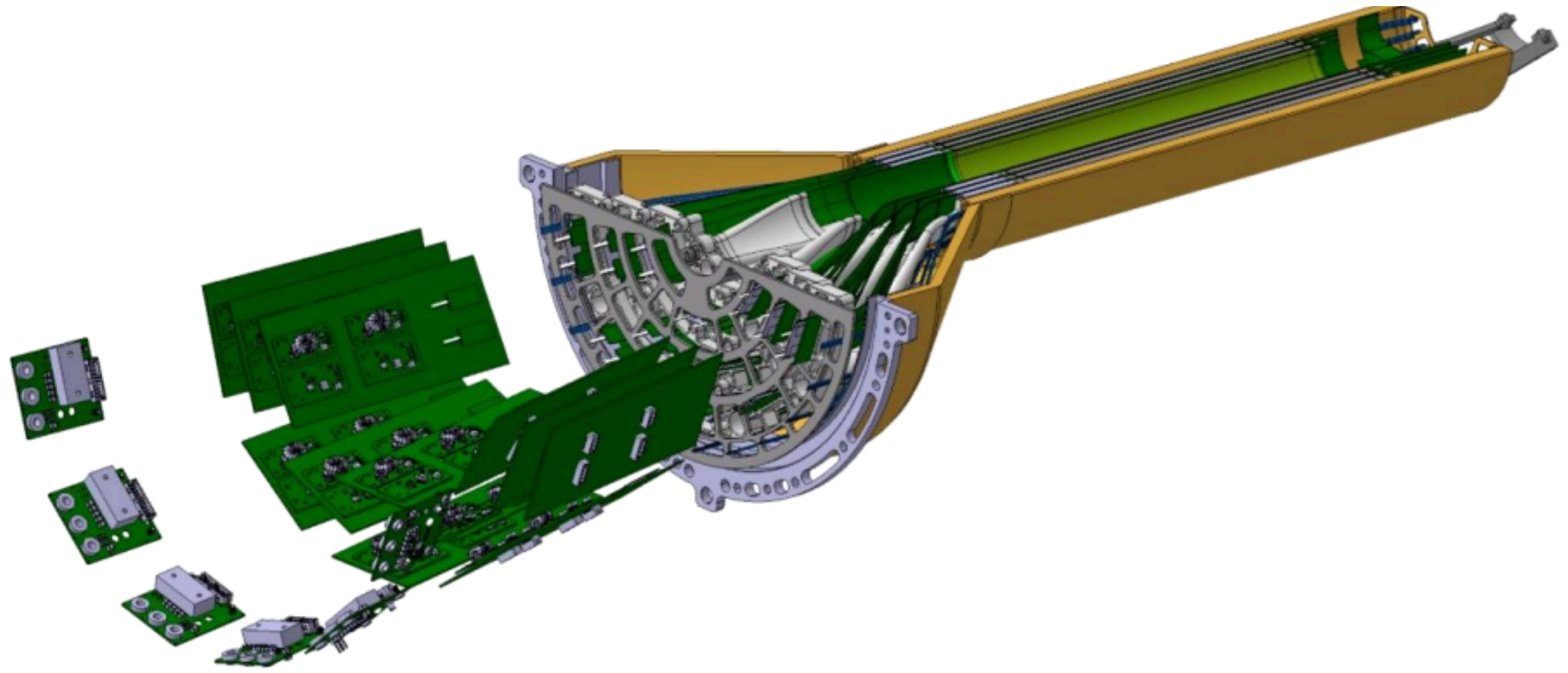
ALICE: Bent MAPS for Run 4

CERN-LHCC-2019-018





Forced air flow at 8 m/s



Bending Si wafers + circuits is possible

Recent ultra-thin wafer-scale silicon technologies allow:

Sensor thickness of 20-40 µm - 0.02-0.04% X_0

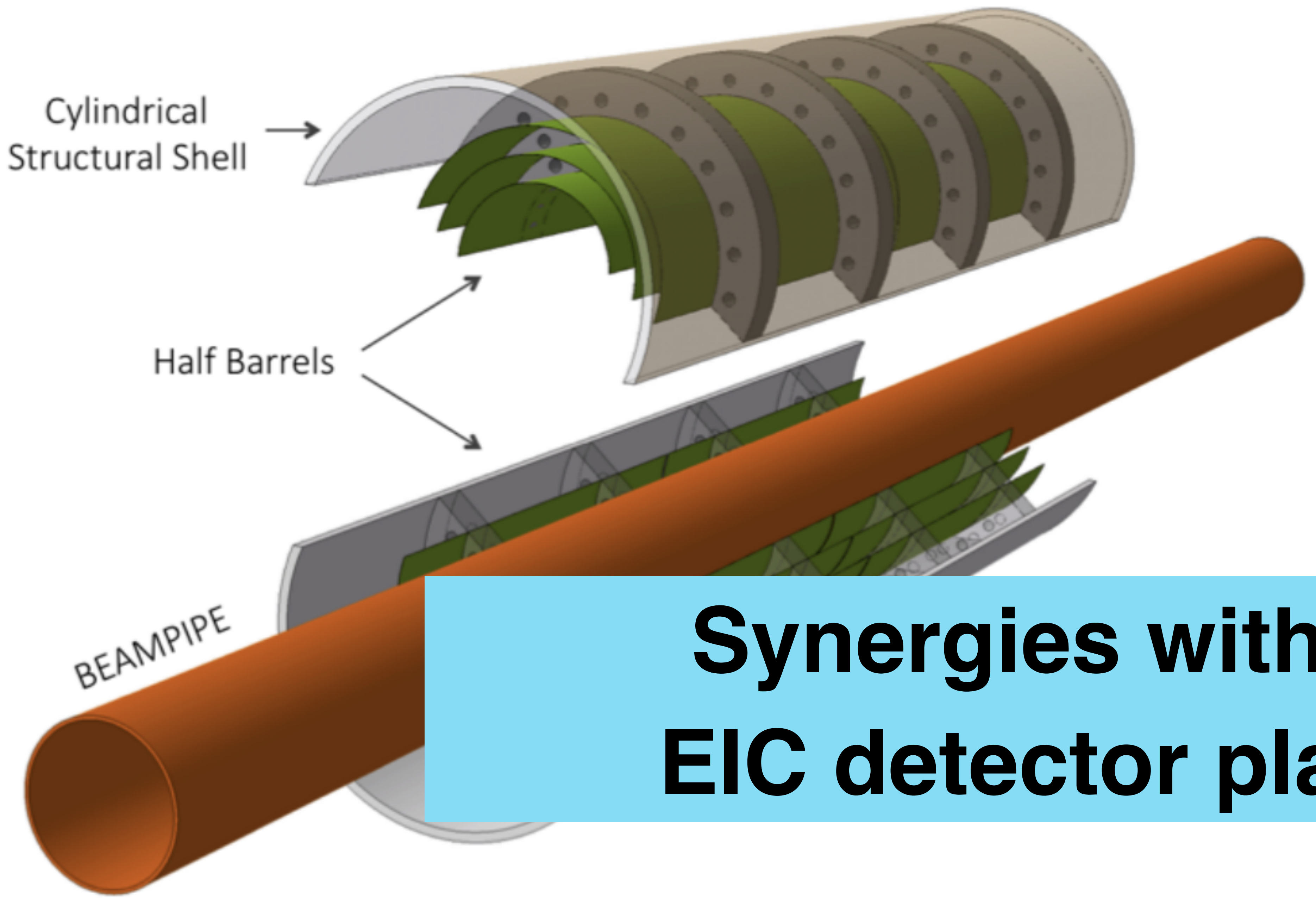
Sensors arranged with a perfectly cylindrical shape

a sensors thinned to ~30μm can be curved to a radius of 10-20mm (ALICE-PUBLIC-2018-013)

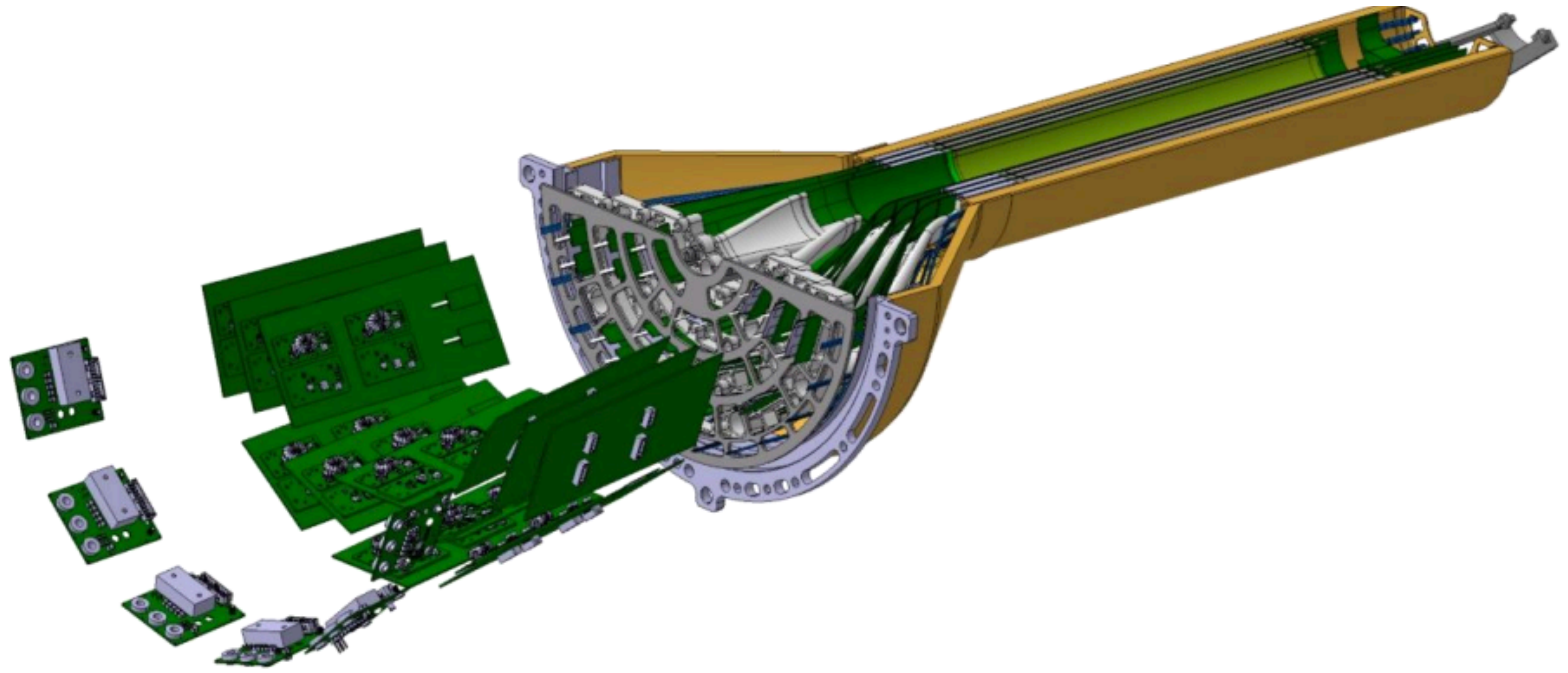
Industrial stitching & curved CPS along goals of ALICE-ITS3, possibly with TJ 65 nm process

ALICE: Bent MAPS for Run 4

CERN-LHCC-2019-018



Forced air flow at 8 m/s



Synergies with every detector concepts at e^+e^-
EIC detector plans to use ITS3 detector concept

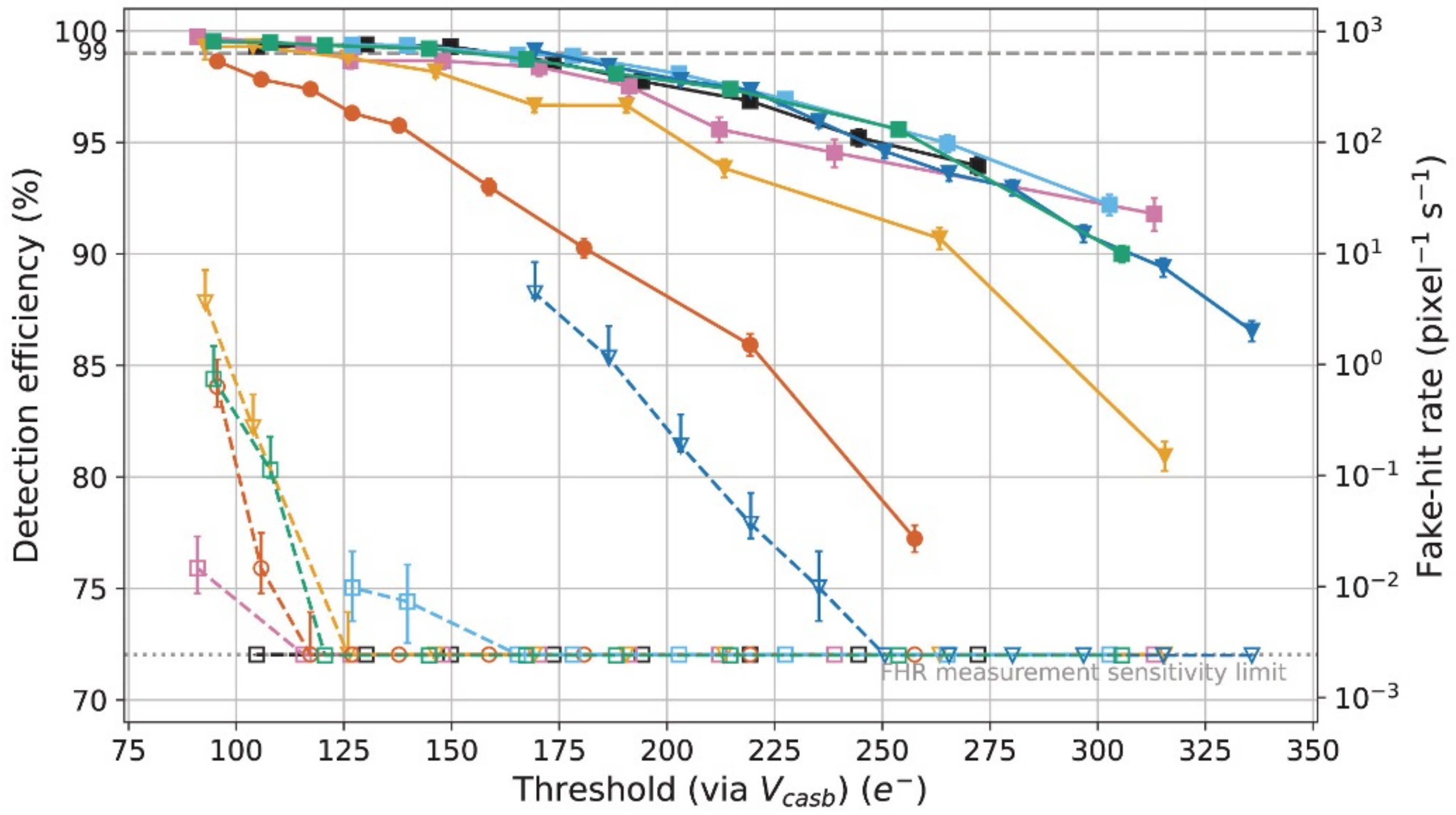
Recent ultra-thin wafer-scale silicon technologies allow:

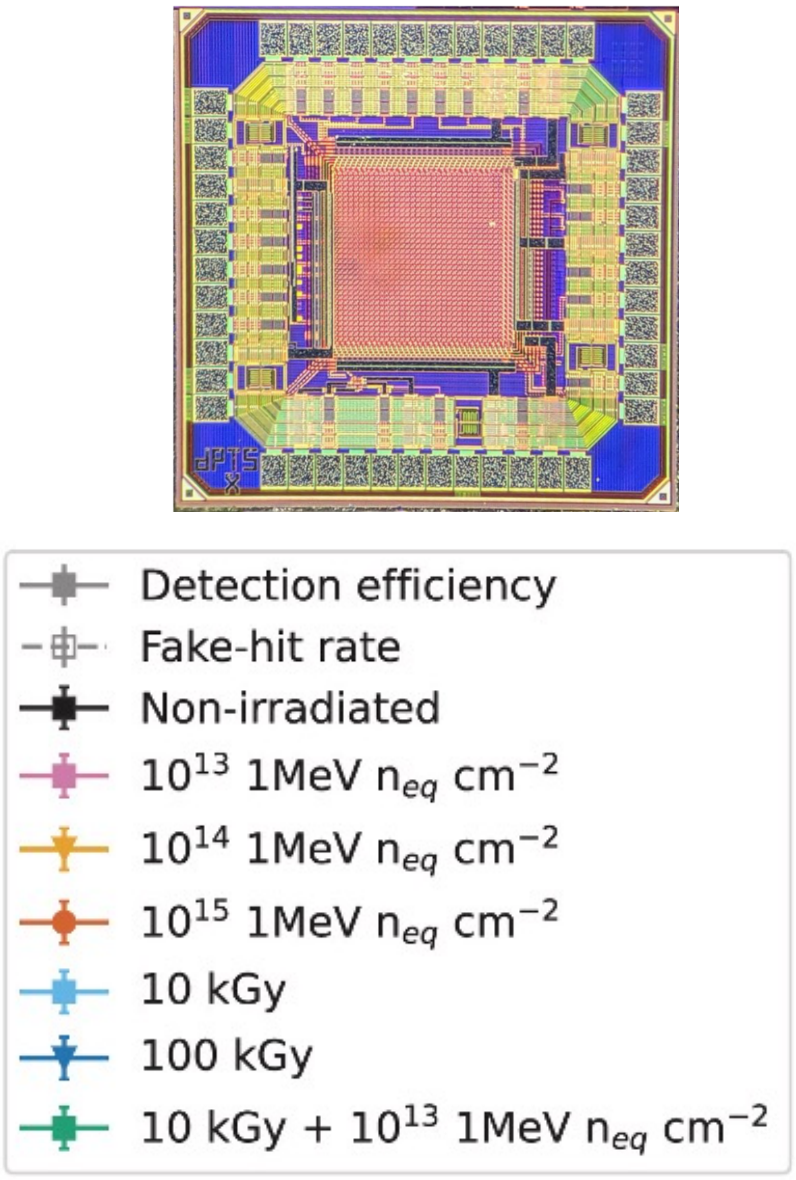
- Sensor thickness of 20-40 μm - 0.02-0.04% X_0
- Sensors arranged with a perfectly cylindrical shape
  - a sensors thinned to ~30μm can be curved to a radius of 10-20mm (ALICE-PUBLIC-2018-013)
- Industrial stitching & curved CPS along goals of ALICE-ITS3, possibly with TJ 65 nm process

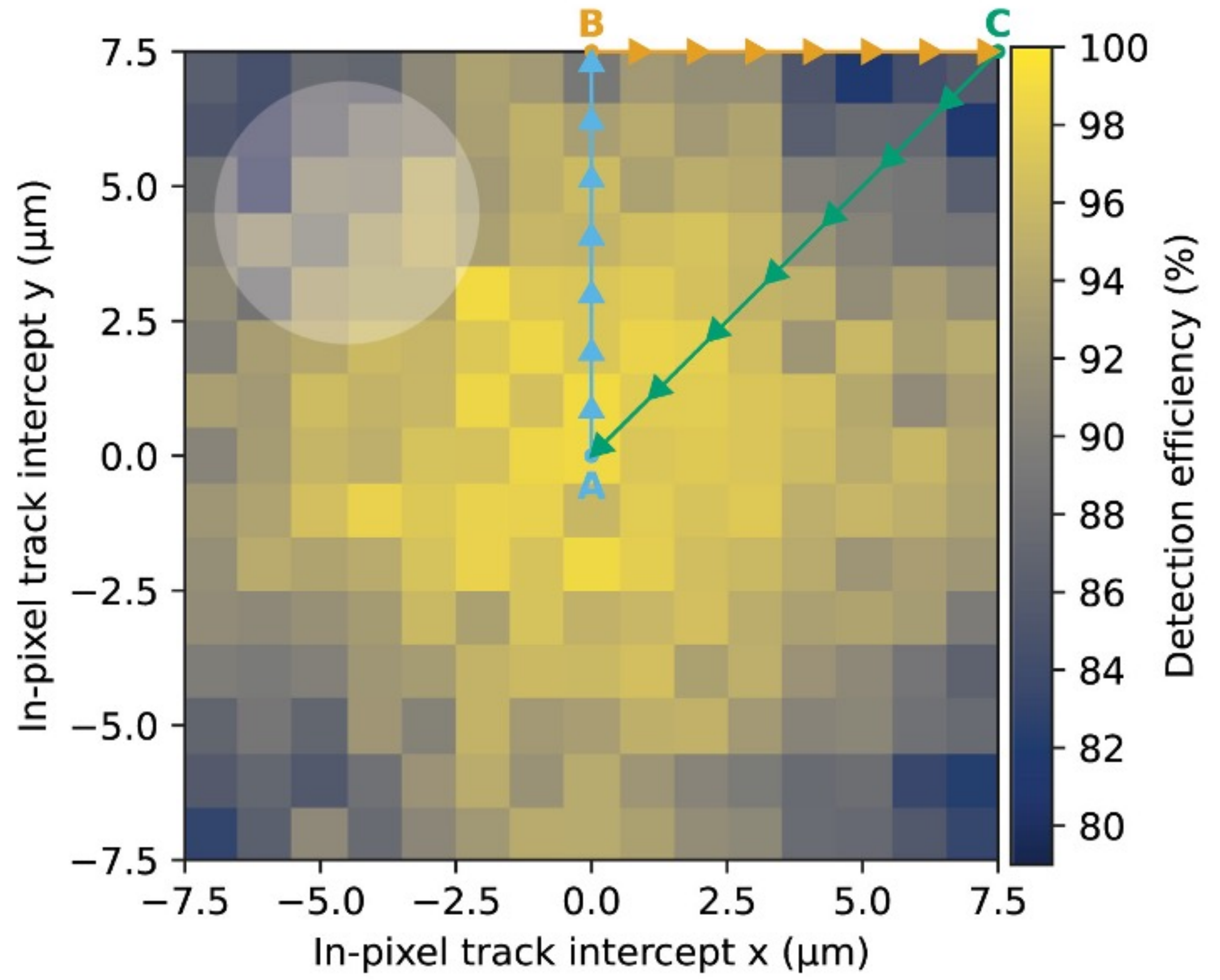
Recent results with Digital Pixel Test Structures

Synergies with DPTS characterization at CERN test beam facility within ALICE Collaboration

Characterization done up to 10^{15} 1 MeV n_{eq} cm^{-2}





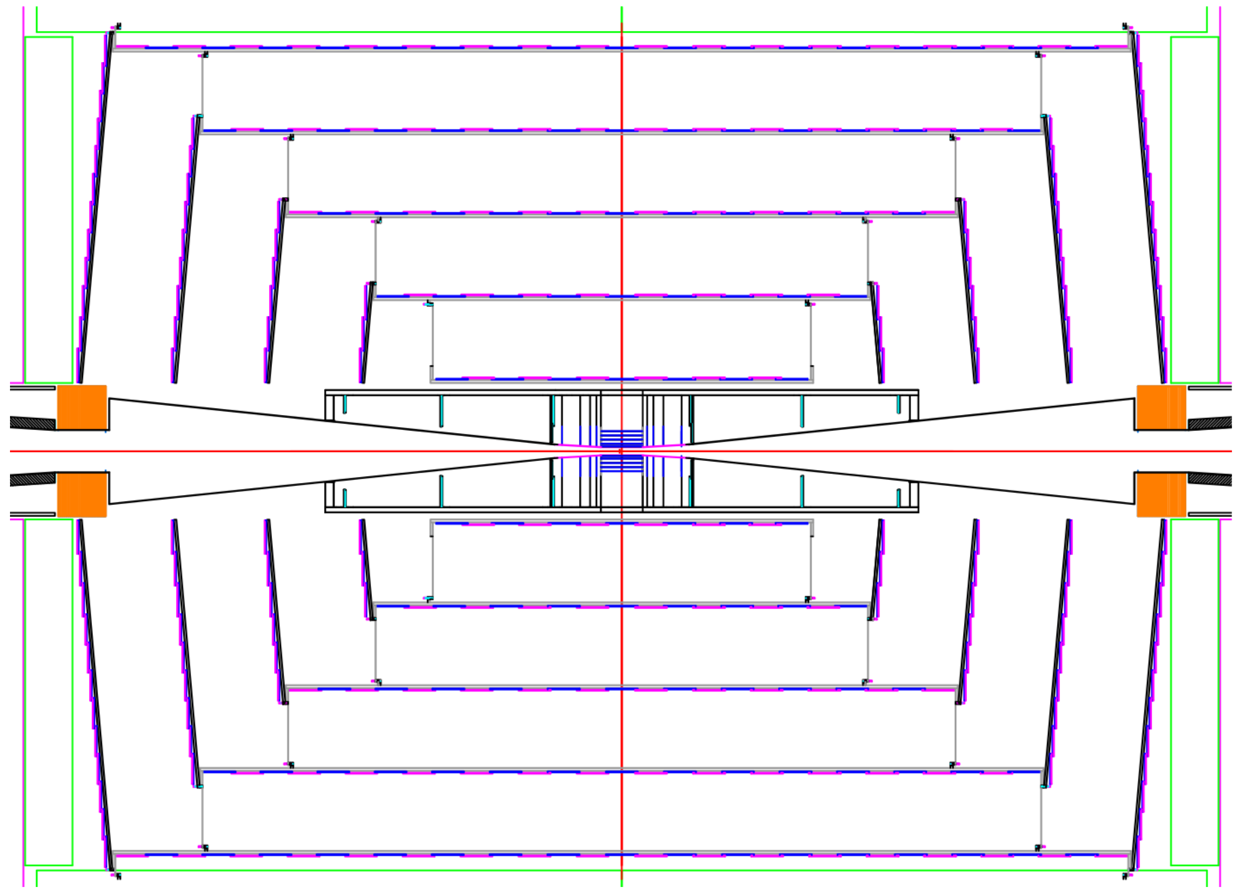


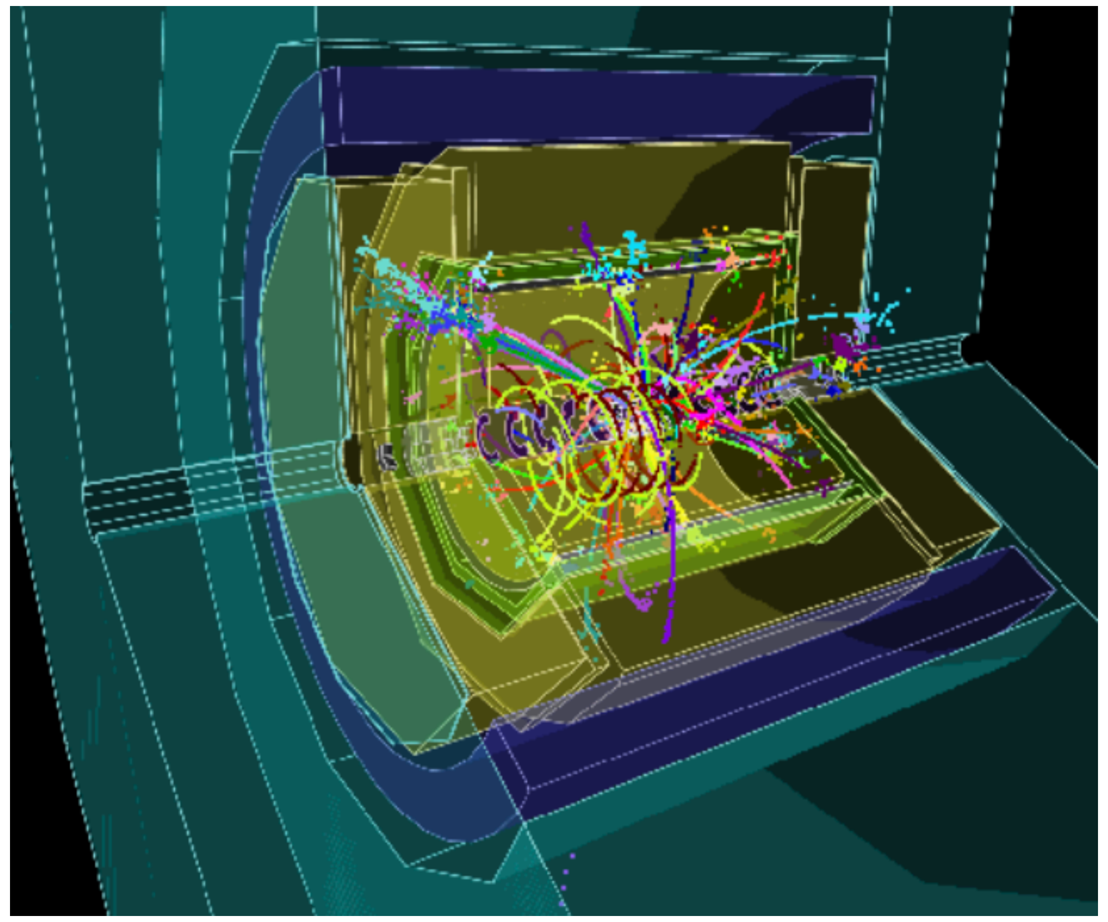
Digital pixel test structures implemented in a 65 nm CMOS process
A Compact Front-End Circuit for a Monolithic Sensor in a 65-nm CMOS Imaging Technology

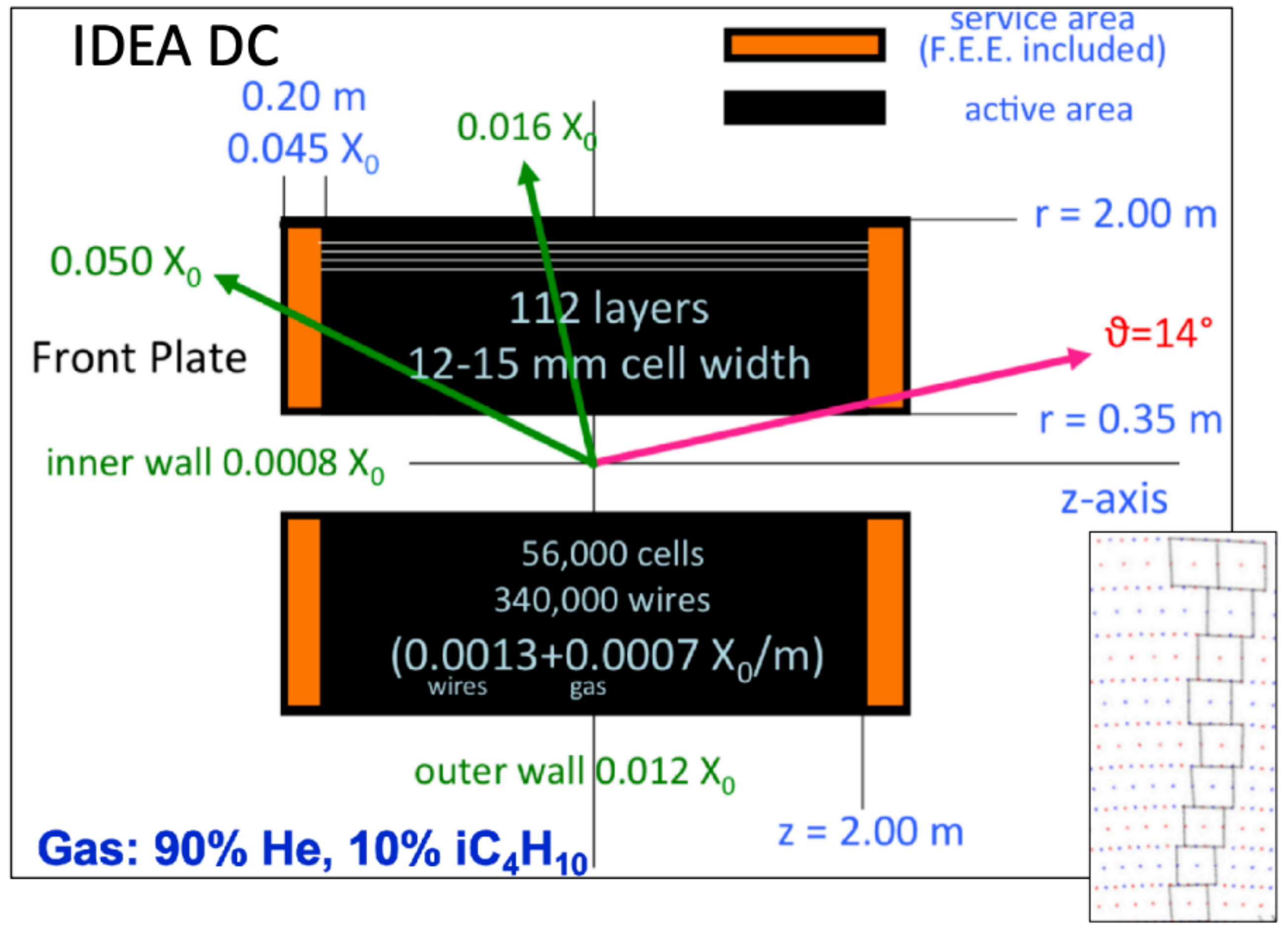
arXiv:1306.6329
arXiv:1912.04601
e2019-900045-4

Tracking detectors

A diverse set of options targeting unprecedented precision





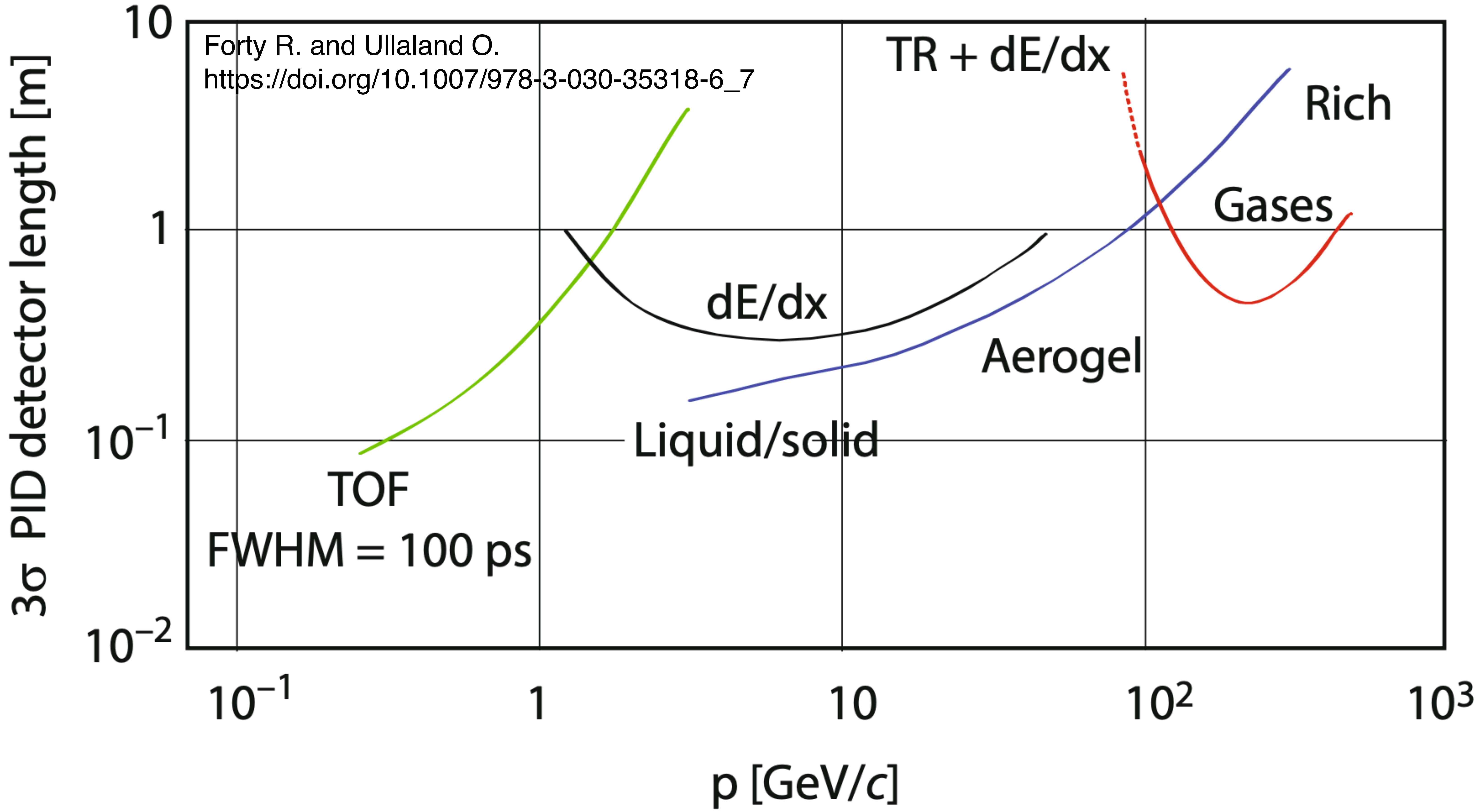


- Full **silicon detectors** (SiD, CLID) aiming at 0.1-0.15% X_0 in the central region
  - MAPS (TJ 65 nm) being investigated but also AtlasPix3 - TSI 180 nm process, 50μm pitch, 175 mW/cm^2 (target 100 mW/cm^2)
- ILD features a **TPC**, which provides 3D track reconstruction exploiting timing of drift with low material budget
  - Pad (GEM or Micromegas) or pixelated (Gridpix) readout both achieve desired resolution
- IDEA/Allegro, **Drift Chambers**: gas detectors with many dense sampling layers yield to similar track momentum resolution, but much smaller material budget than CLD, thus better overall resolution at low p_T
  - Tungsten wires dominant contribution to material budget

Particle ID

arXiv:2202.03285
arXiv:1912.04601
e2019-900045-4
NIMA 1059 (2024)

Combining different strategies for optimal PID performance across a wide p_T range

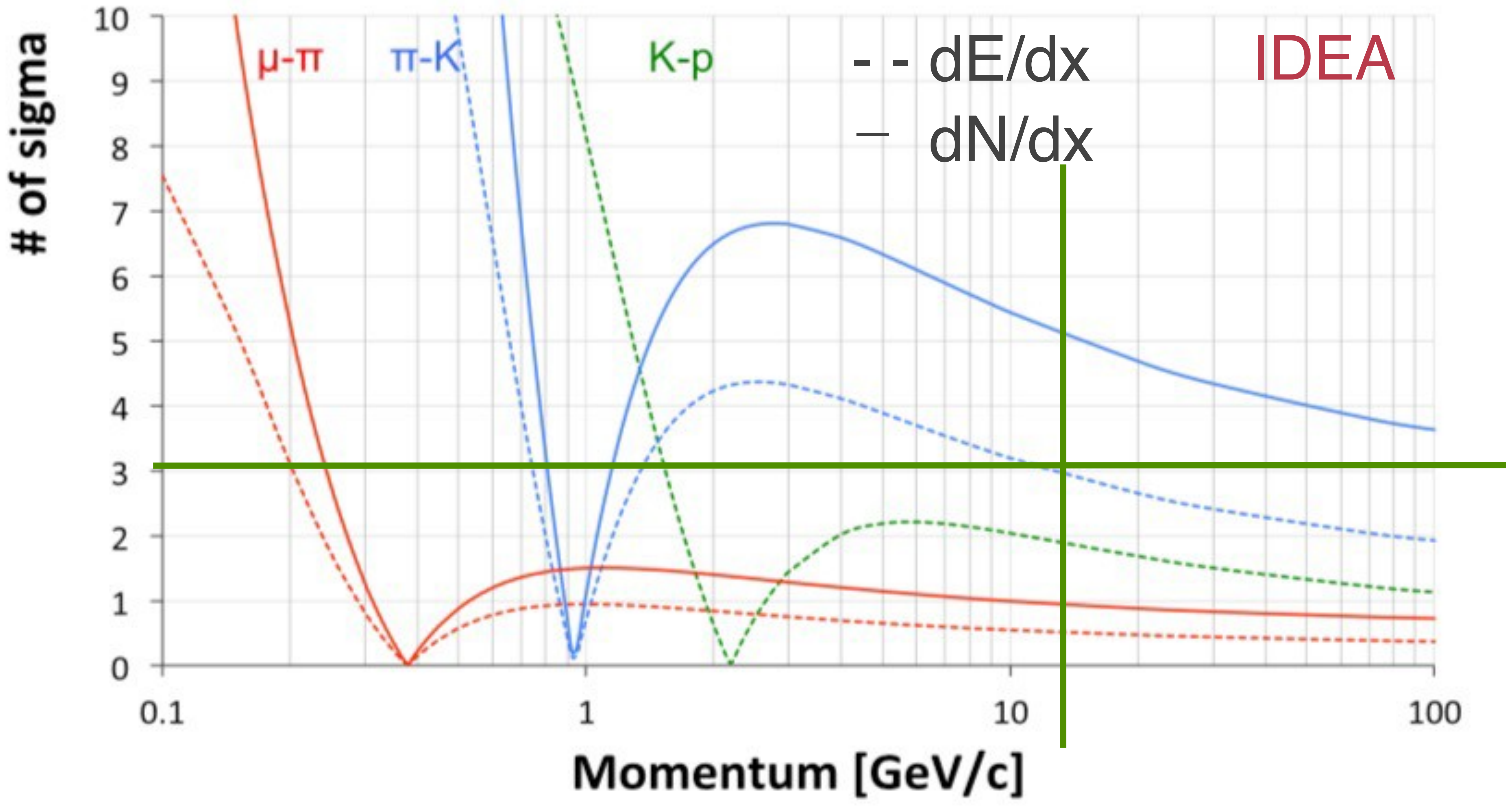


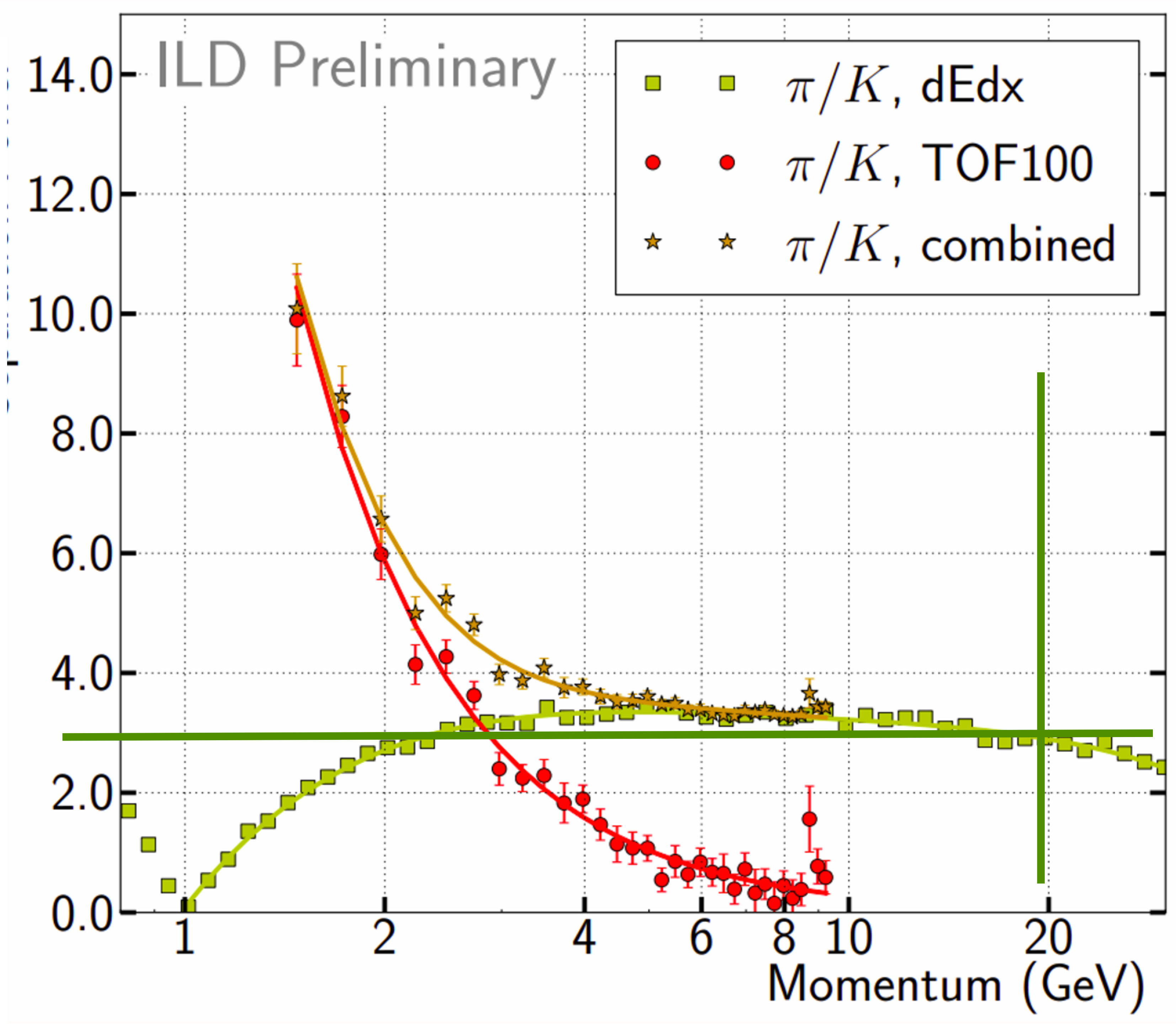
arXiv:2202.03285
arXiv:1912.04601
e2019-900045-4
NIMA 1059 (2024)

Particle ID

Combining different strategies for optimal PID performance across a wide p_T range

- Timing (e.g. ECAL, HCAL or timing layer) for time-of-flight for momentum < 5 GeV
- dE/dx from silicon (< 5 GeV) and large gaseous tracking detectors (< 30 GeV)
  - PID for momentum larger than few GeVs via ionisation loss measurement (dE/dx or dN/dx)
- Use H → ss to inform detector design, while monitoring other benchmarks' performance
  - RICH could improve reconstruction of $K^{+/-}$ at high momentum (10-30 GeV)



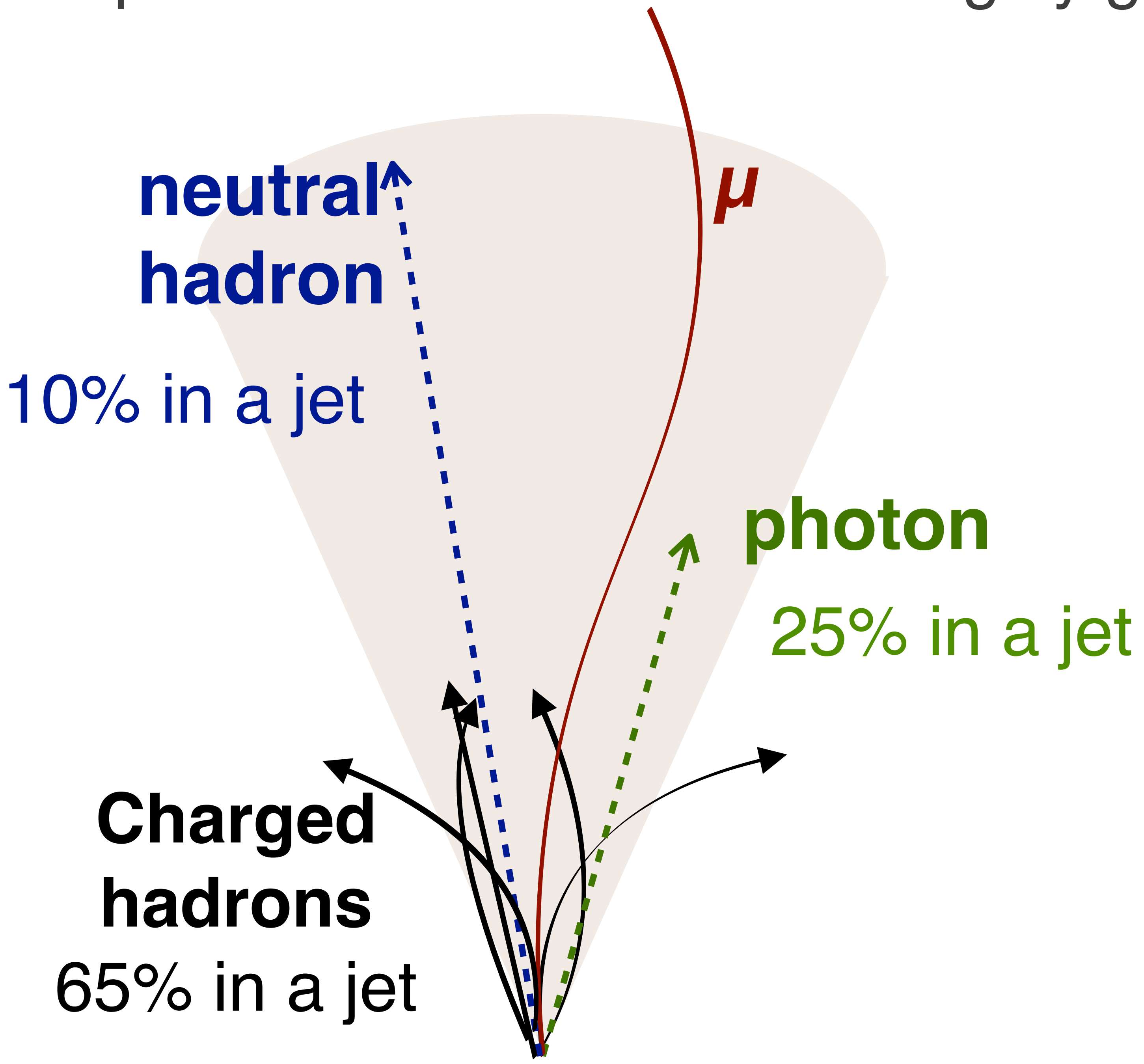


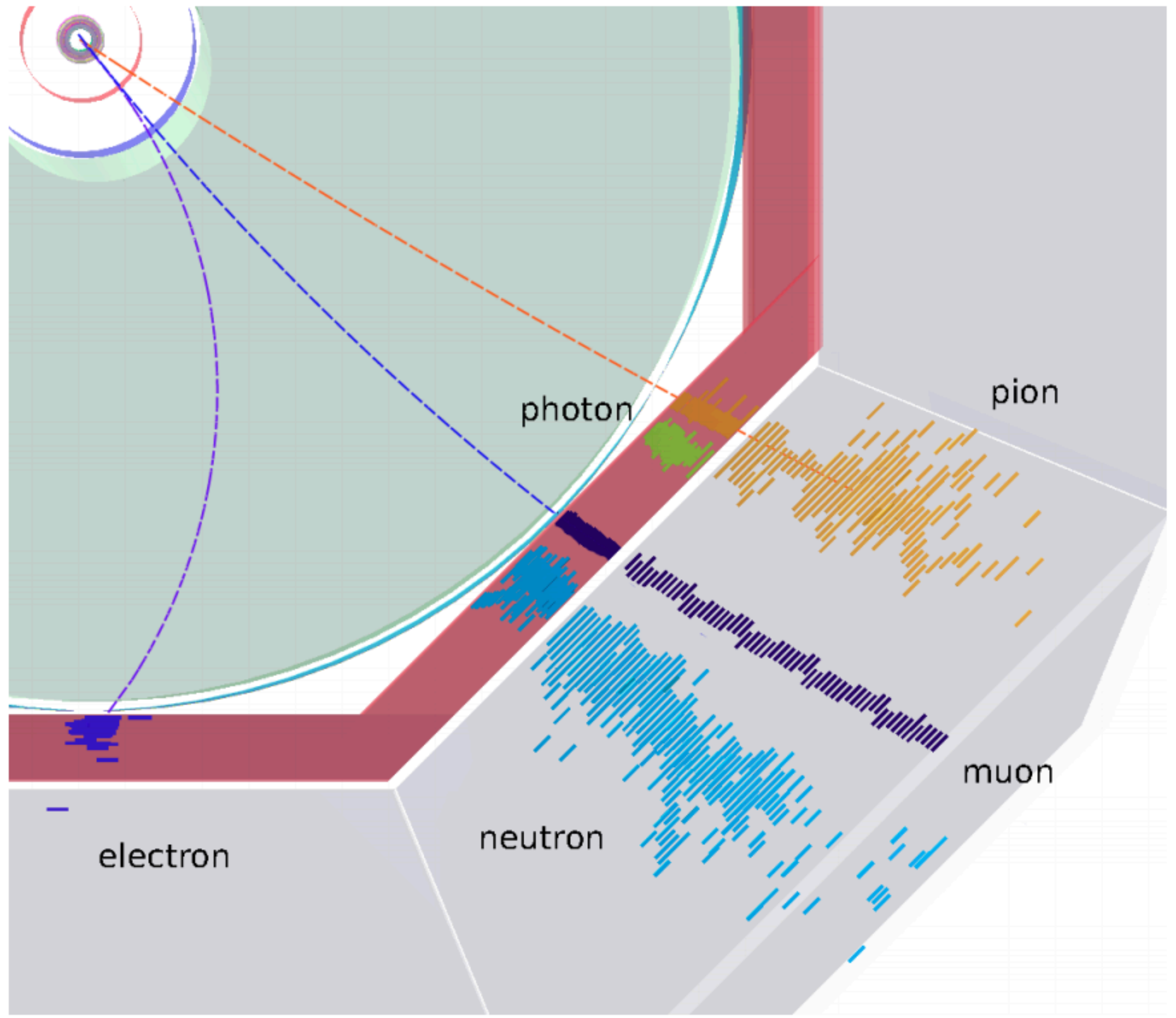
Particle Flow Calorimeters

CALICE

Build on studies by CALICE: development and study of finely segmented and imaging calorimeters

- Particle-flow algorithm (PFA) leverages excellent momentum resolution from tracker to measure charged hadron contribution to allow a precise reconstruction of each particle within the jet
- **CALICE R&D** inspired CMS high granularity solution HGCAL - Common test beams with the AHCAL prototype
  - homogeneous crystal ECAL + scintillating glass HCAL
    - Integrated engineering prototypes already tested to address system level issue
- **R&D line**: MAPS (see Alice FoCAL) and (ns-ps) timing information (ex: LGADs)
- ALLEGRO concept for FCC-ee built around highly granular noble-liquid (Ar, Kr) ECAL with Pb or W absorbers





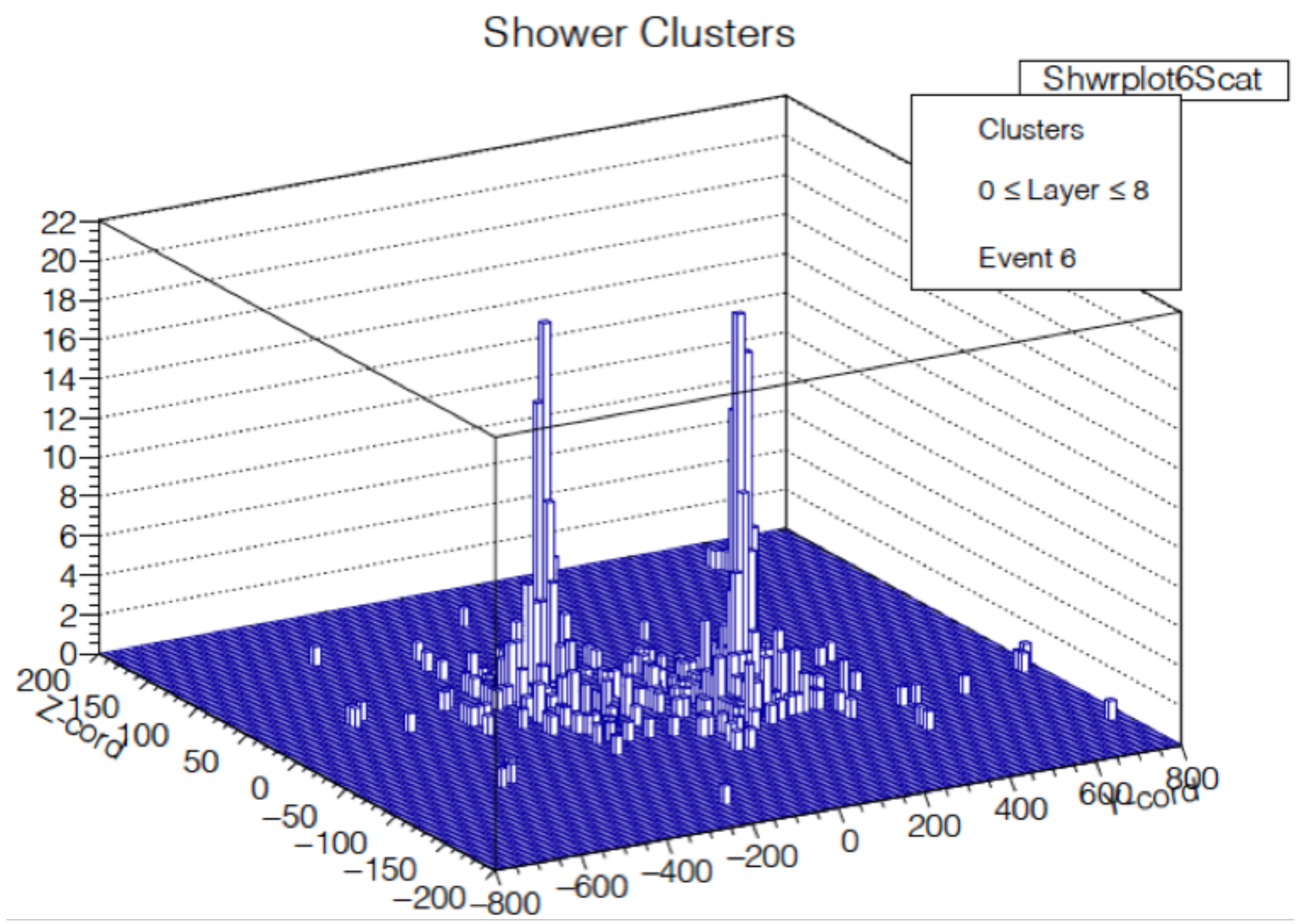
ECAL 3%/√E
HCAL 30%/√E

MAPS for ECal, SiD example

arXiv:2110.09965

Fine granularity allows for identification of two showers down to the mm scale of separation

- SiD detector configuration with 25x100 μm^2 pixel in the calorimeter at ILC
  - Changing analog to binary digital has no energy resolution degradation
- ***The design of the digital MAPS applied to the ECal exceeds the physics performance as specified in the ILC TDR***
- The 5T magnetic field degrades the resolution by a few per cent due to the impact on the lower energy electrons and positrons in a shower
- Future planned studies include the reconstruction of showers and π^0 within jets, and their impact on jet energy resolution



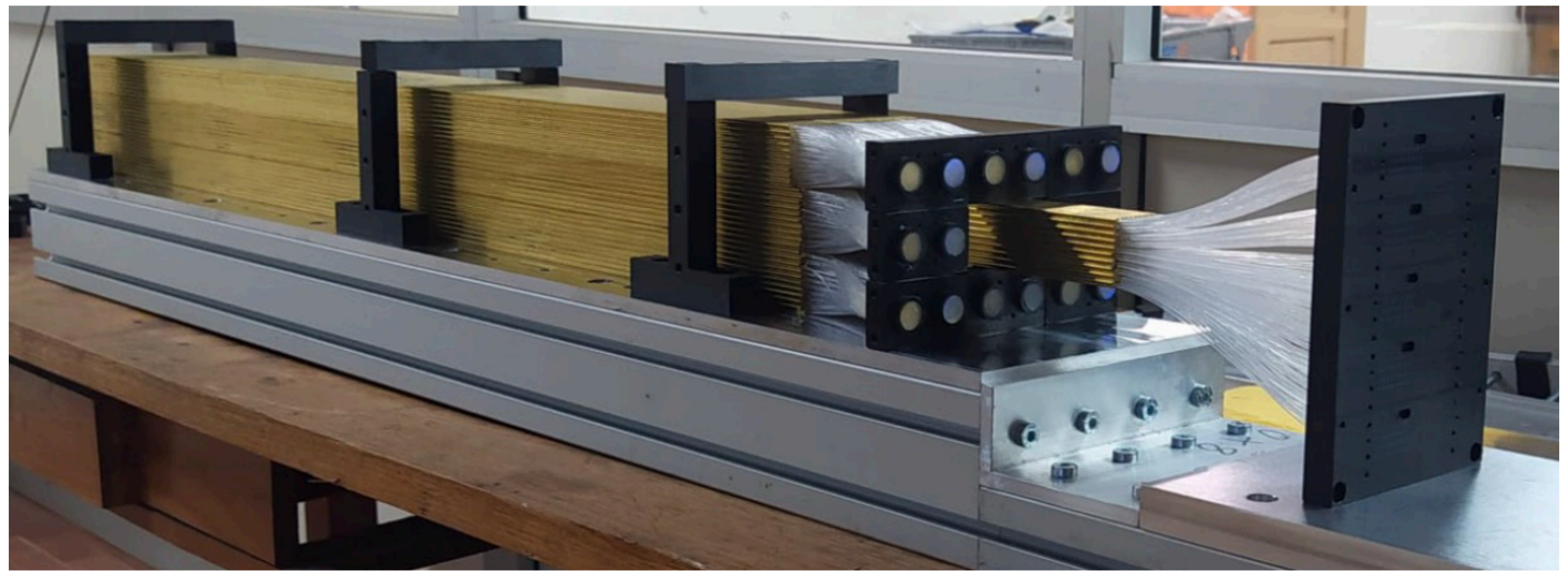
GEANT4 simulations of Transverse distribution of two 10 GeV showers separated by one cm

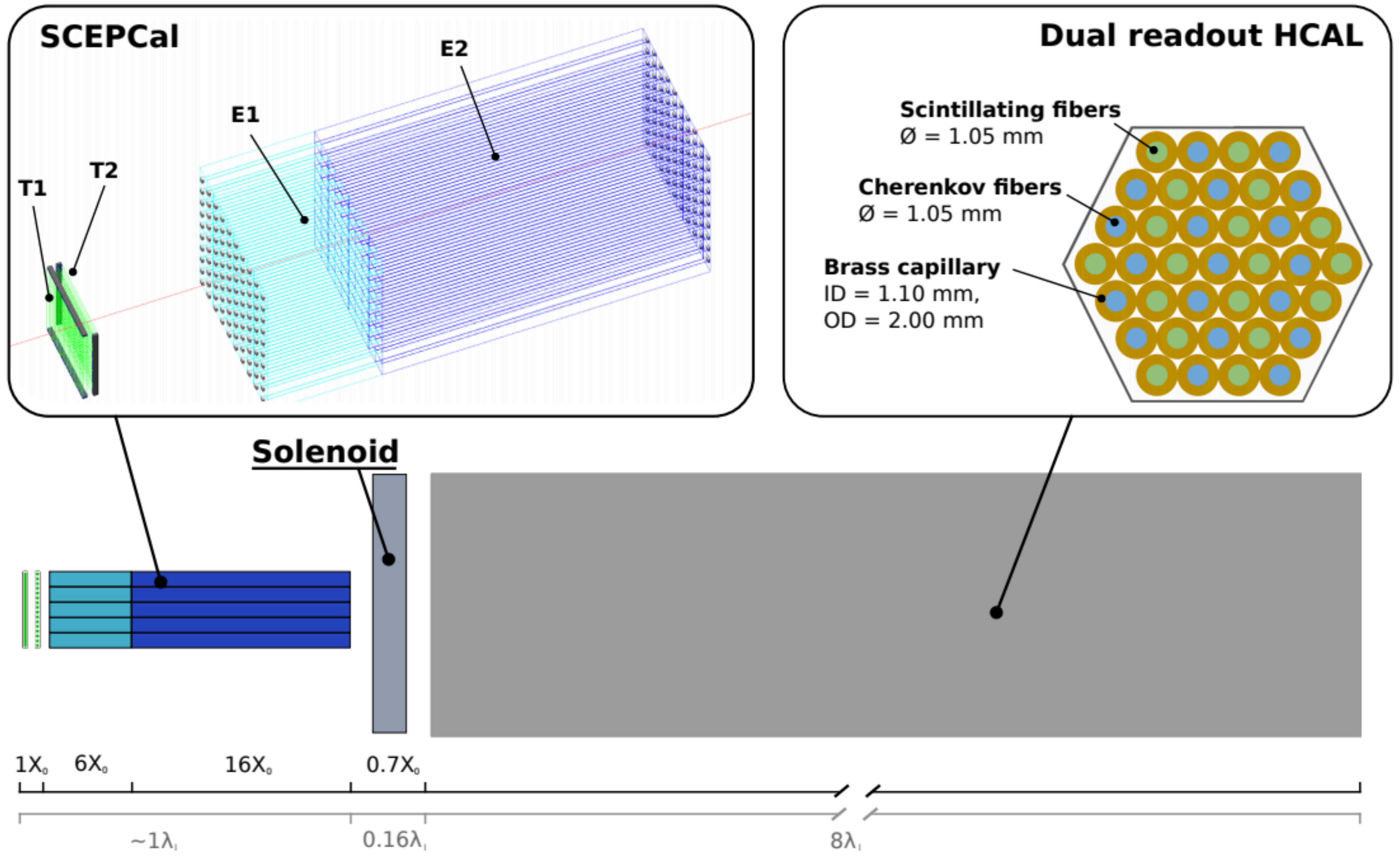
arXiv:2008.00338
JINST 15 (2020) P11005
G. Polesello (2023)

Dual Readout calorimetry

Correct HCAL event-by-event through measurement of EM fraction with dual readout calorimeter

- **Dual readout Calorimetry**, e.g. DREAM (FCC-ee) improvement of the energy resolution of hadronic calorimeters for single hadrons:
  - Cherenkov light for relativistic (EM) component
  - Scintillation light for non-relativistic (hadronic)
  - EM prototype built and tested on beams (DESY/CERN) to understand construction issues + integration with SiPMs
  - Hadronic-size module funded and under construction
- **IDEA**: DR crystals inside solenoid + DR fibers outside
  - ECAL ~3%/√E, HCAL ~29%/√E
  - Sensible improvement in jet resolution using dual-readout information combined with a particle flow approach → 3-4% for jet energies above 50 GeV



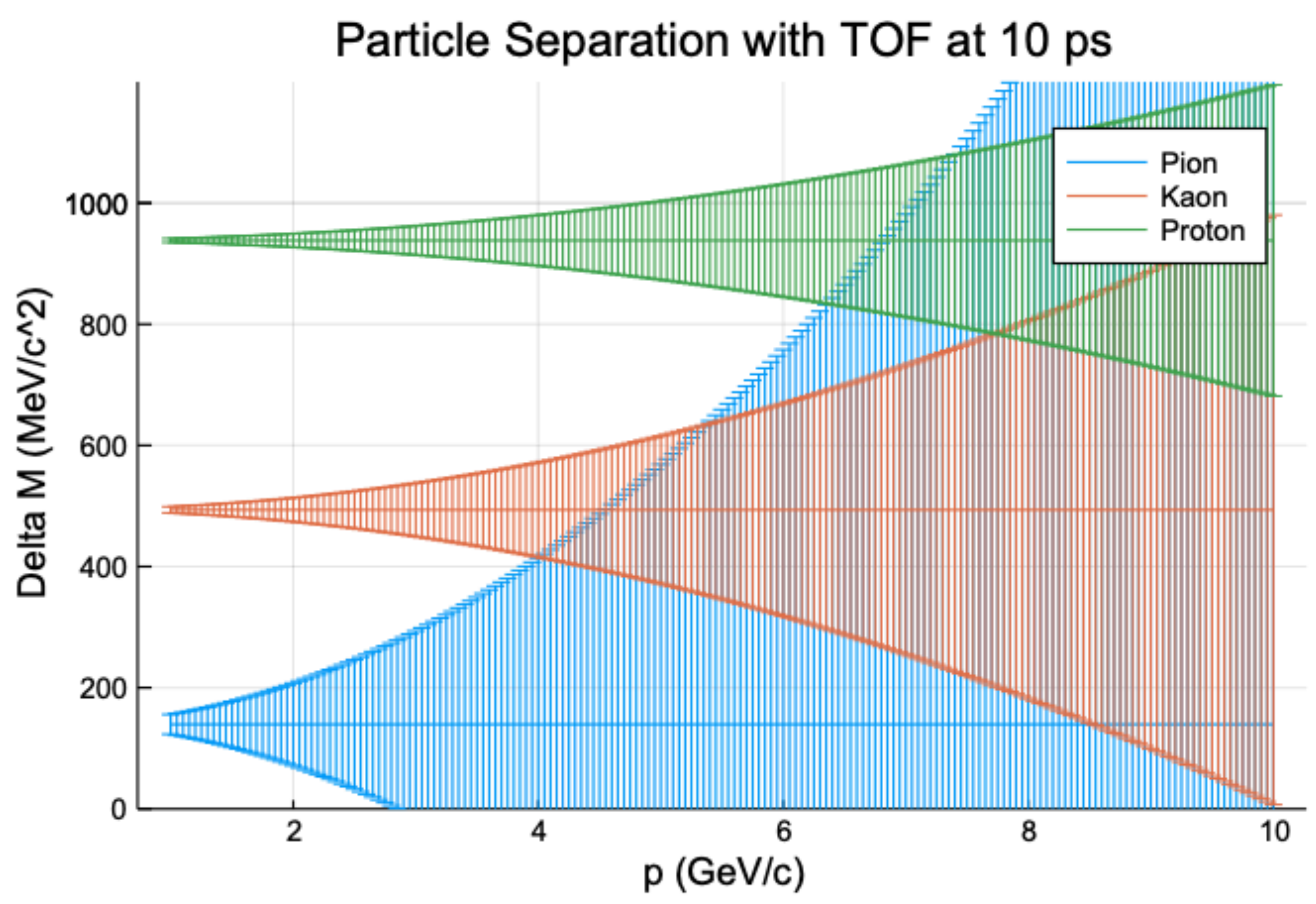


Timing layer(s)

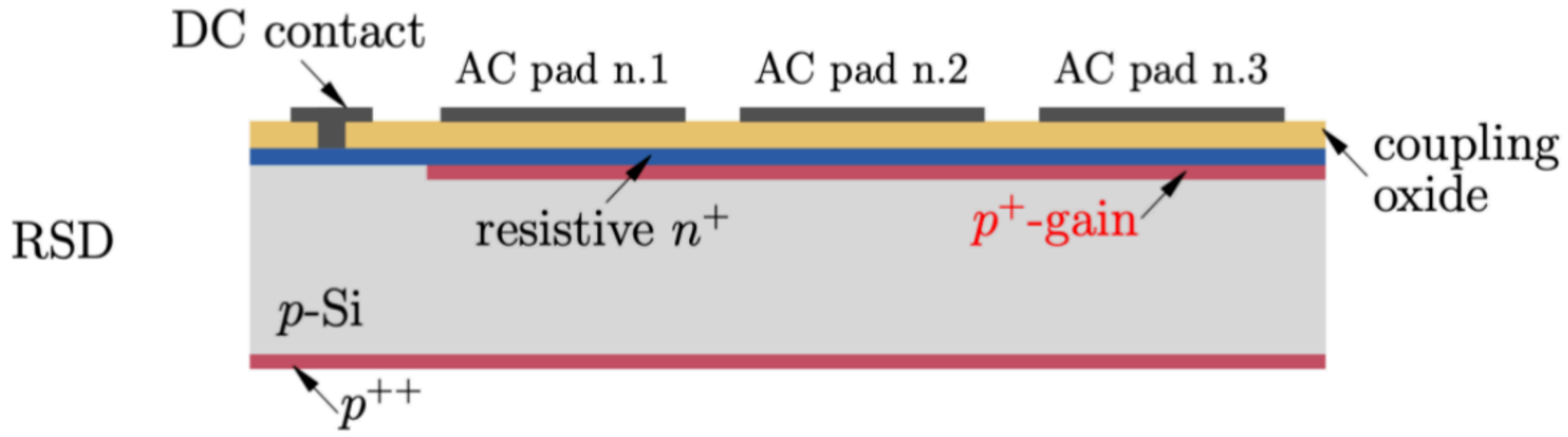
arXiv:2110.09965

Timing is being explored as additional information from the calorimeter and a dedicated layer

- A timing layer with O(ns) resolution into the HCAL could allow beneficial identification of slow shower components from prompt components
- A timing layer as part of the tracking system or between tracker and ECAL could serve as a powerful Time-of-Flight (TOF) system
  - physics reach needs to be further studied
- Very attractive option for timing in Si wrapper region of IDEA/Allegro
  - O(10) ps needed for PID with TOF
  - Some "fast" devices prototyped by Arcadia & US groups based on resistive LGAD technology
    - 35 ps time resolution so far



Mass resolution for a TOF system with a performance of 10 ps in SiD

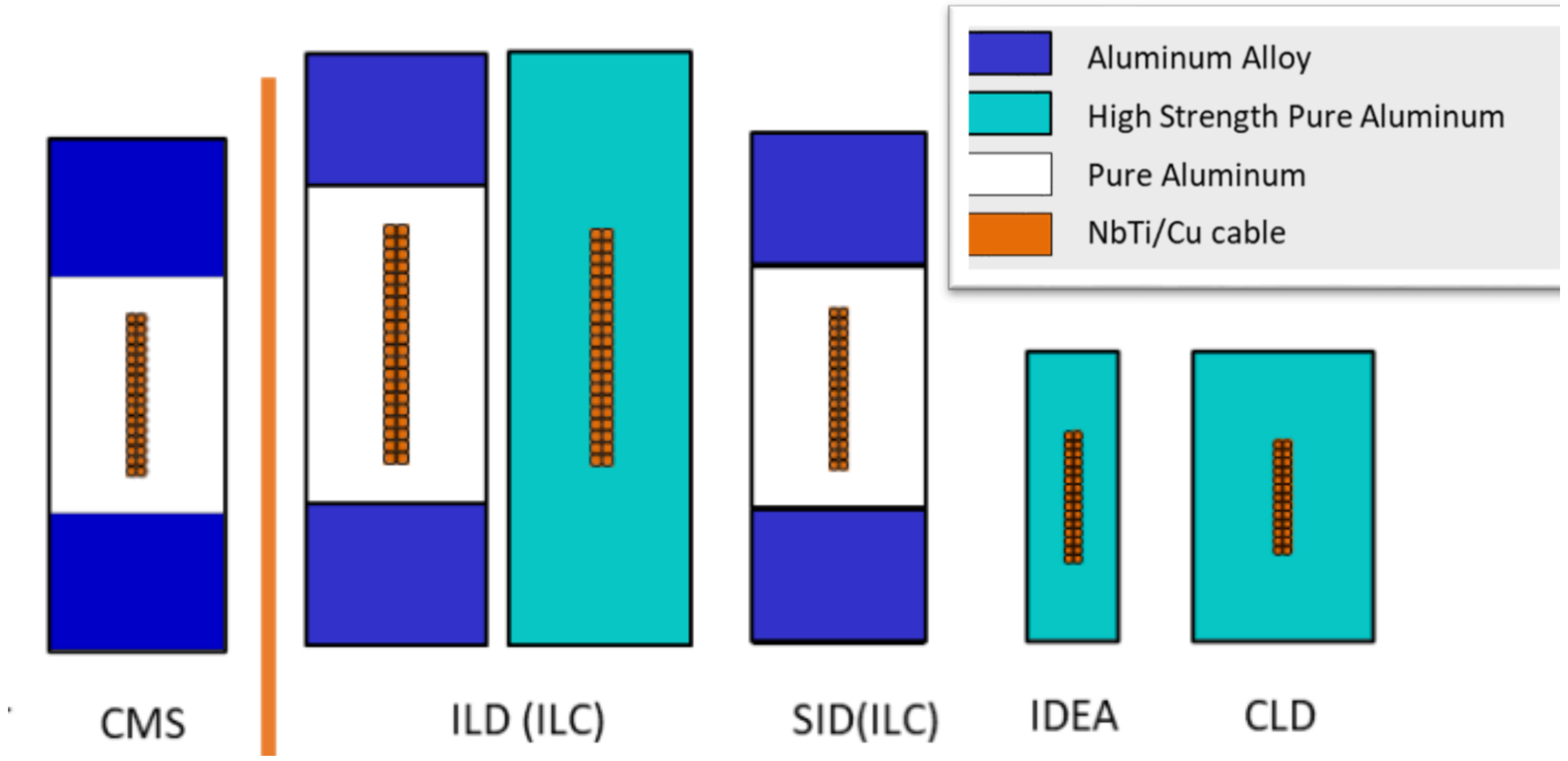


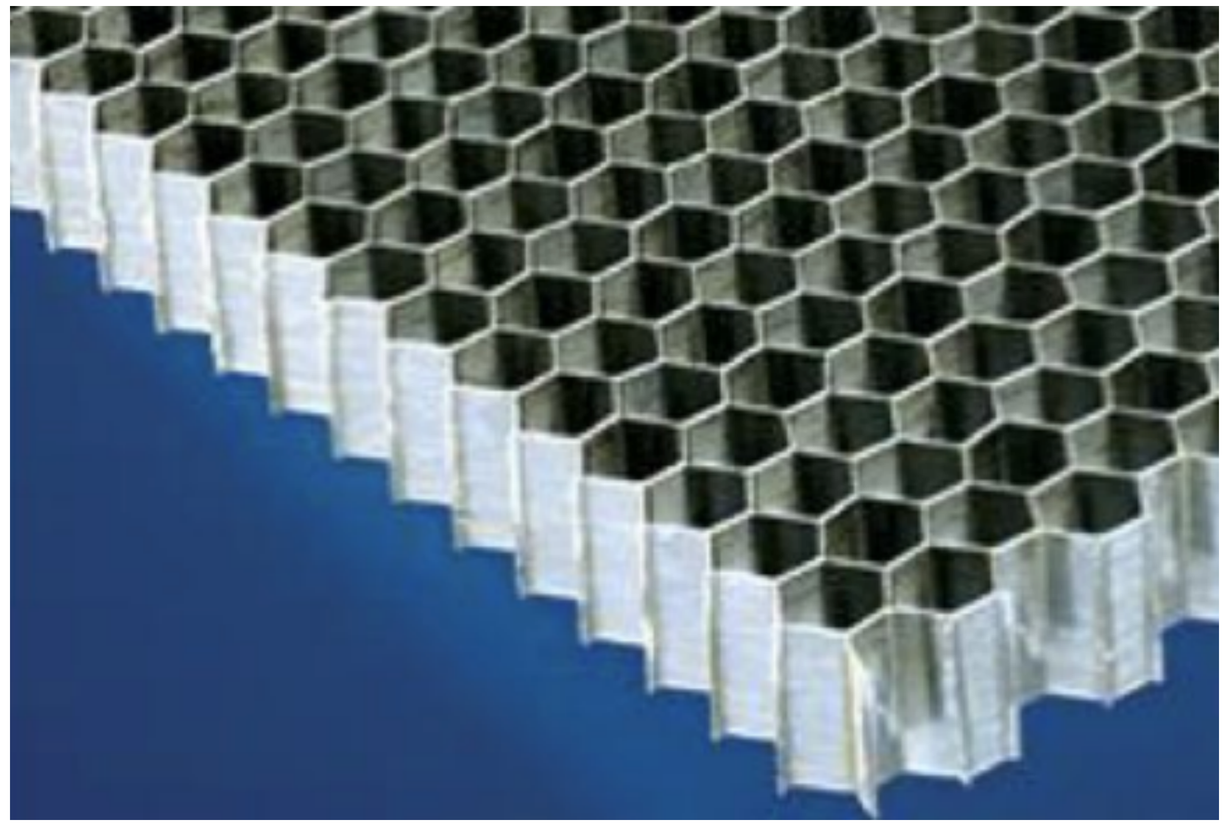
More physics/detector simulation studies needed to refine the case for timing layers

Solenoid

A big, reliable, stable - and very thin - solenoid magnet to provide the field for charged track p_T measurement

- SiD/ILD - High field – 5/4 T for BR^2 - 5/4 layers of "CMS" conductor + more structural aluminum
  - Stored energy ~1.5 (2.3) GJ SiD (ILD)
- IDEA, ultra light 2 T solenoid with a vacuum vessel (25 mm Al) with honeycomb structure X0 = 0.04 to reduce material
- **Critical R&D area** – Al-stabilized technology needs to be resumed
  - No industrial production available, as of today
- Backup solutions:
  - CICC (Cable-in-conduit conductor) approach may also be a solution - requires different magnet system design
  - HTS: New types of conductor being investigated to allow higher temperature operations > 10K (lower cost)





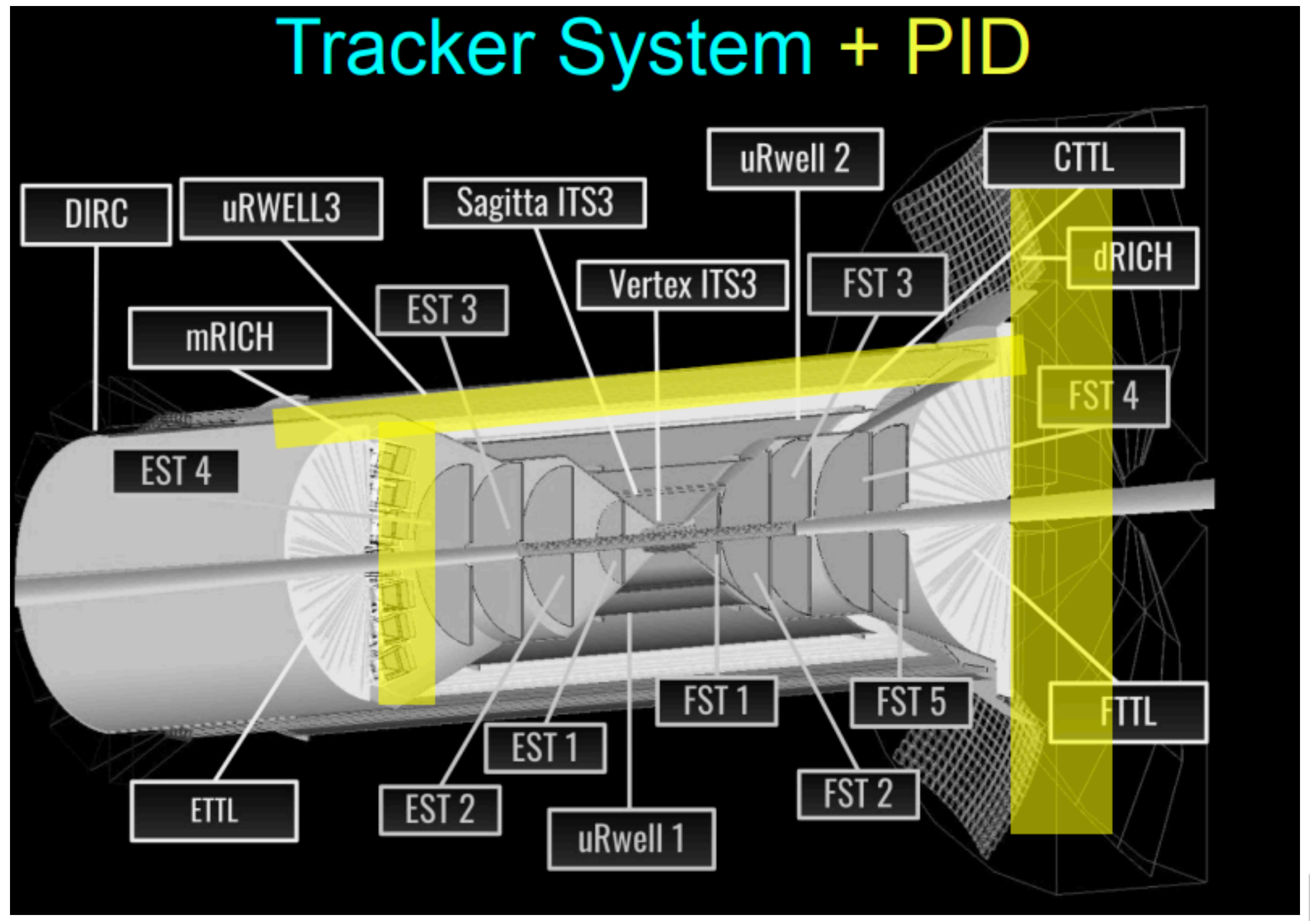
KEK-CERN leading R&D. But need to push for R&D in labs together with industry to keep the timelines of future projects!

C. Fanelli EPIC (2023) arXiv:2205.09185
NeurIPS 33, 14650-14662 (2020)
arXiv:2308.16680

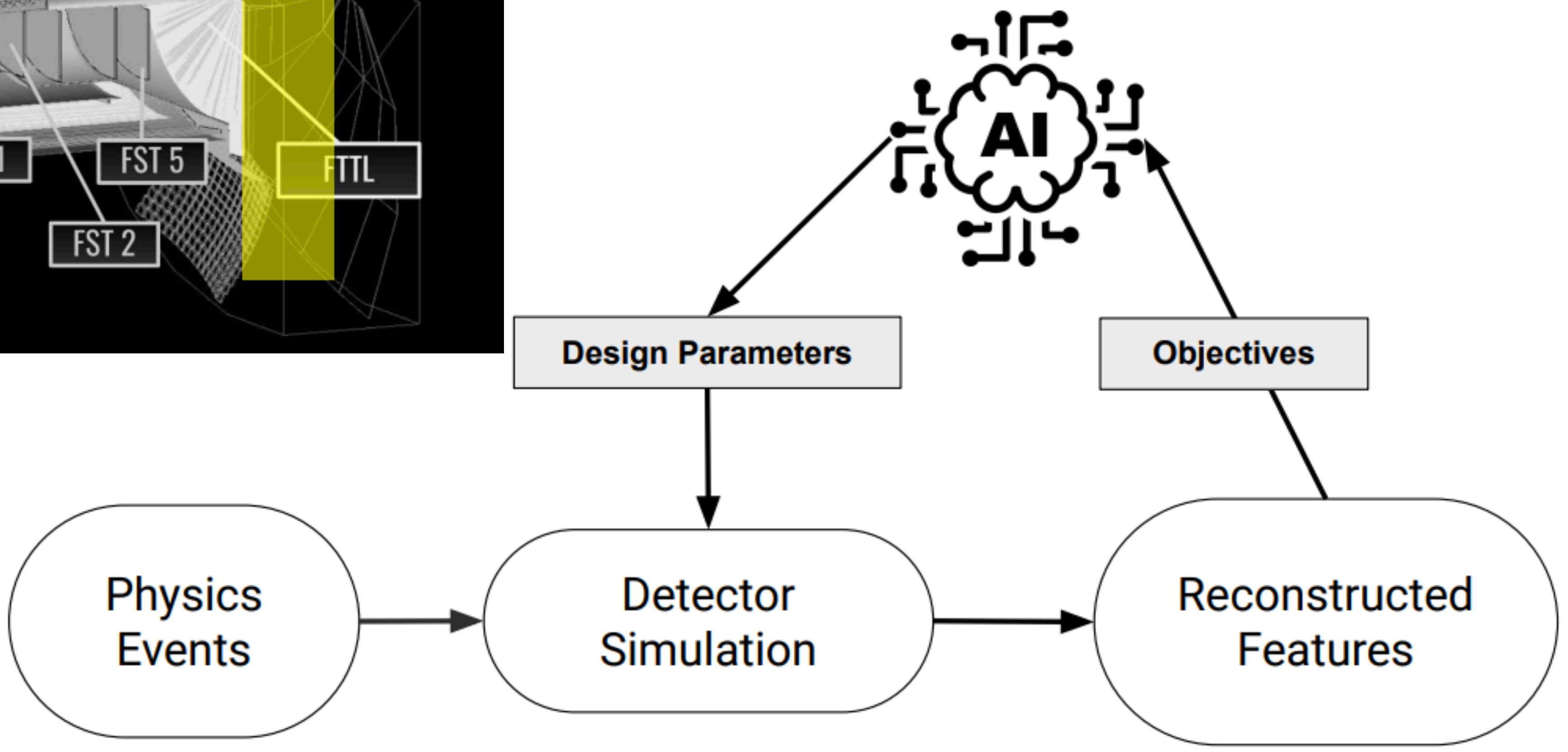
AI for detector optimization

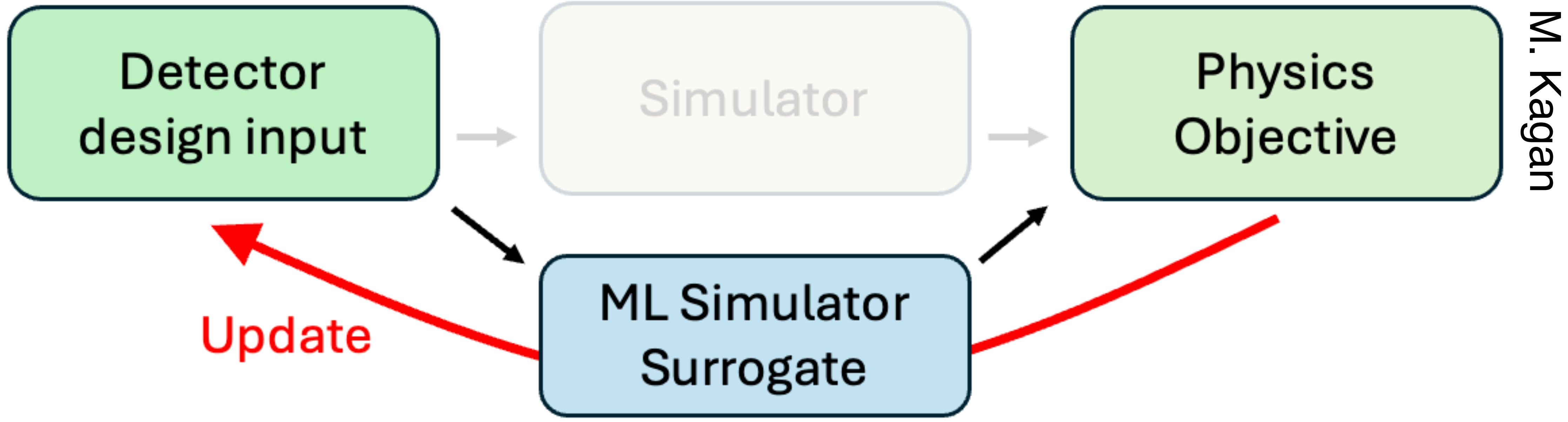
EIC is employing AI to assist detector design

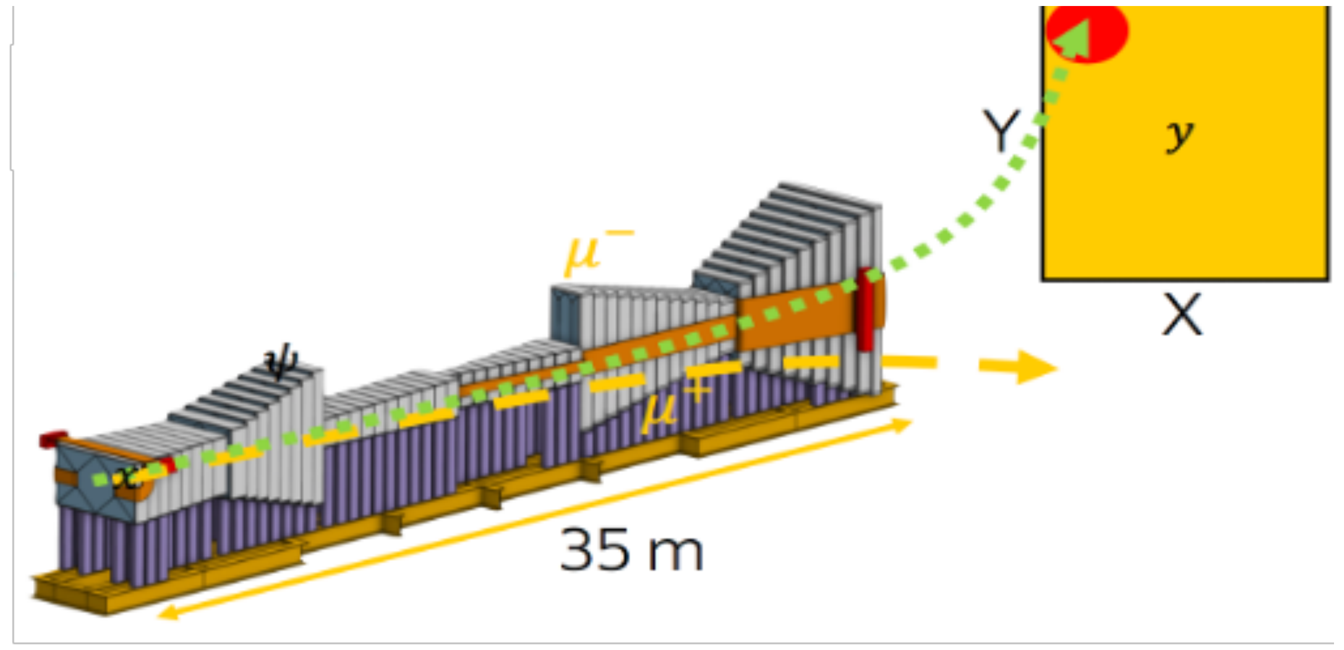
- Detector optimization is a multi-dimensional design optimization problem
  - Multiple objectives that encode the detector performance and several mechanical constraints
  - The AI-assisted design is agnostic to the simulation framework and can be extended to any sub-detectors
- Train generative model as surrogate simulator to automatize detector design optimization
  - Recent work to integrate and optimize simulators directly into ML frameworks to optimize simulator directly



EIC







Outlook

Many opportunities for creativity in the design of Higgs factory detectors

- ILC has developed two detector designs that have been studied in full simulation – ILD and SiD — but the bulk of this work is more than 10 years old
  - There are new emerging technologies and it is likely we can do better today and inform designs for detectors at FCC-ee
- Several big questions to be further evaluated, ***some examples***:
  - Silicon vs. gaseous (TPC) tracking
  - Particle Flow vs. Dual Readout calorimetry, which can make better use of ML to achieve higher quality results
  - Does the Higgs factory detector need a dedicated device for strange quark identification, and is it worth it to compromise other systems for this?
- **Revisit physics goals:** different emphasis on various detector requirements together with new technology possibilities to sharpen up the requirements and optimize overall detector design.
- The linear collider community has built many tools that should be shared in this interest of building a common US Higgs factory community.
  - *Important to take advantage of what it has been built and what it has been learned already*

Thanks to Jim Brau, Loukas Gouskos, Lindsey Gray, Giovanni Marchiori, Michael Peskin, Ariel Schwartzman, Su Dong, Andy White for the feedback on this talk

Getting involved

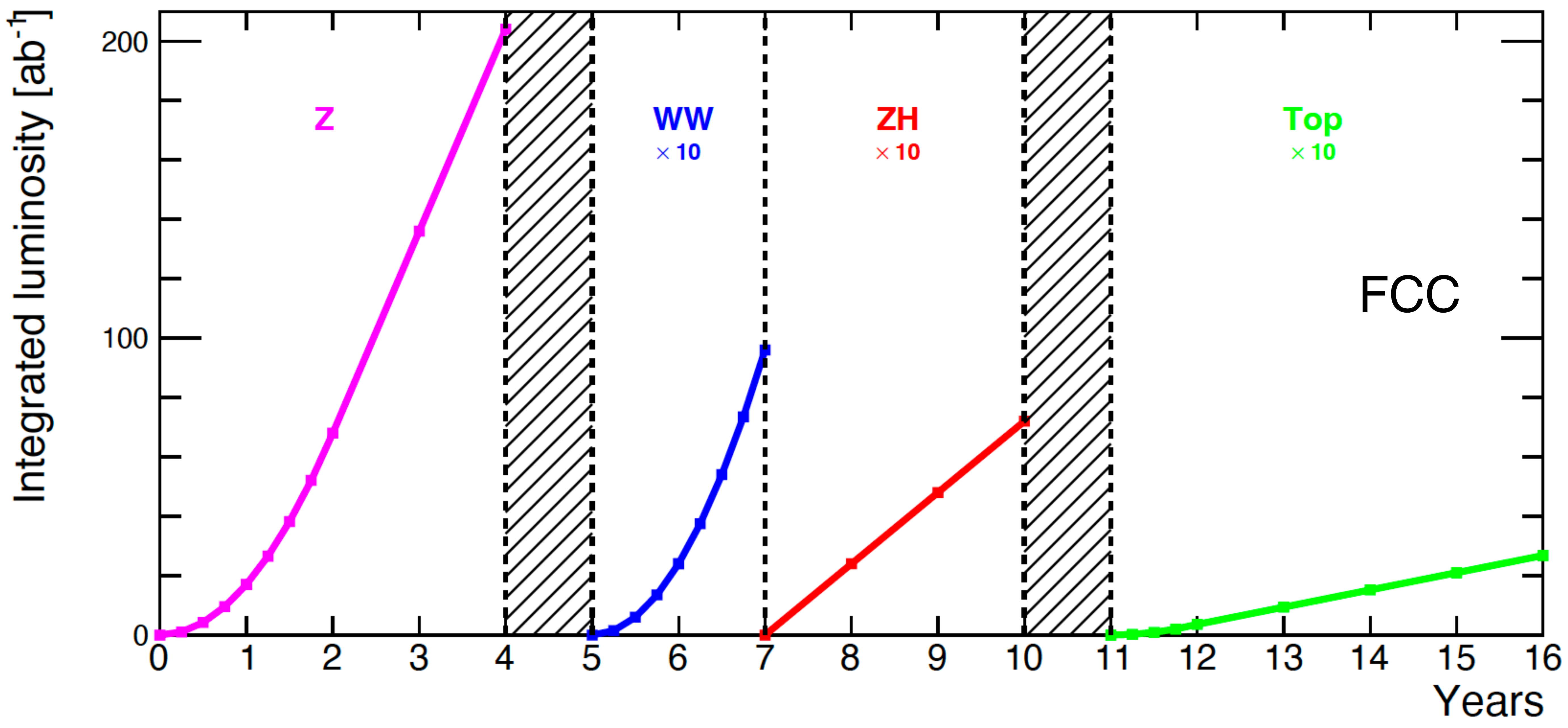
Link to DRD	egroups: us-fcc*	link email list
ECFA DRD	**US Higgs Factory Detector R&D**	**CPAD RD**
Gaseous Detectors	Solid State Devices (*A. Apreysan, C. Haber, C. Vernieri*)	Noble Element Detectors
Liquid Detectors	Calorimeter (*H. Chen, C. Tully, A. White*)	Photodetectors
Solid State Detectors	Gaseous detectors (*G. Iakovidis, M. Hohlmann, B. Zhou*)	Solid State Tracking
Photon Detectors and PID	Particle ID (*M. Artuso, G. Wilson, Z.Ye*)	Readout and Asics
Quantum and Emerging Technologies	ASICs/Electronics (*J. Gonski, J. Hirschauer*)	Trigger/DAQ
Calorimetry	Trigger/DAQ (*Z. Demiragli, J. Zhang*)	Gaseous Detectors
Electronics and On-detector Processing	Quantum Devices (*M. Demarteau, Si Xie, C. Pena*)	Low-Background Detectors
Integration	Software/Computing (*J. Strube*)	Quantum/Superconducting Sensors
Training		Calorimetry
		Detector Mechanics
		Fast Timing

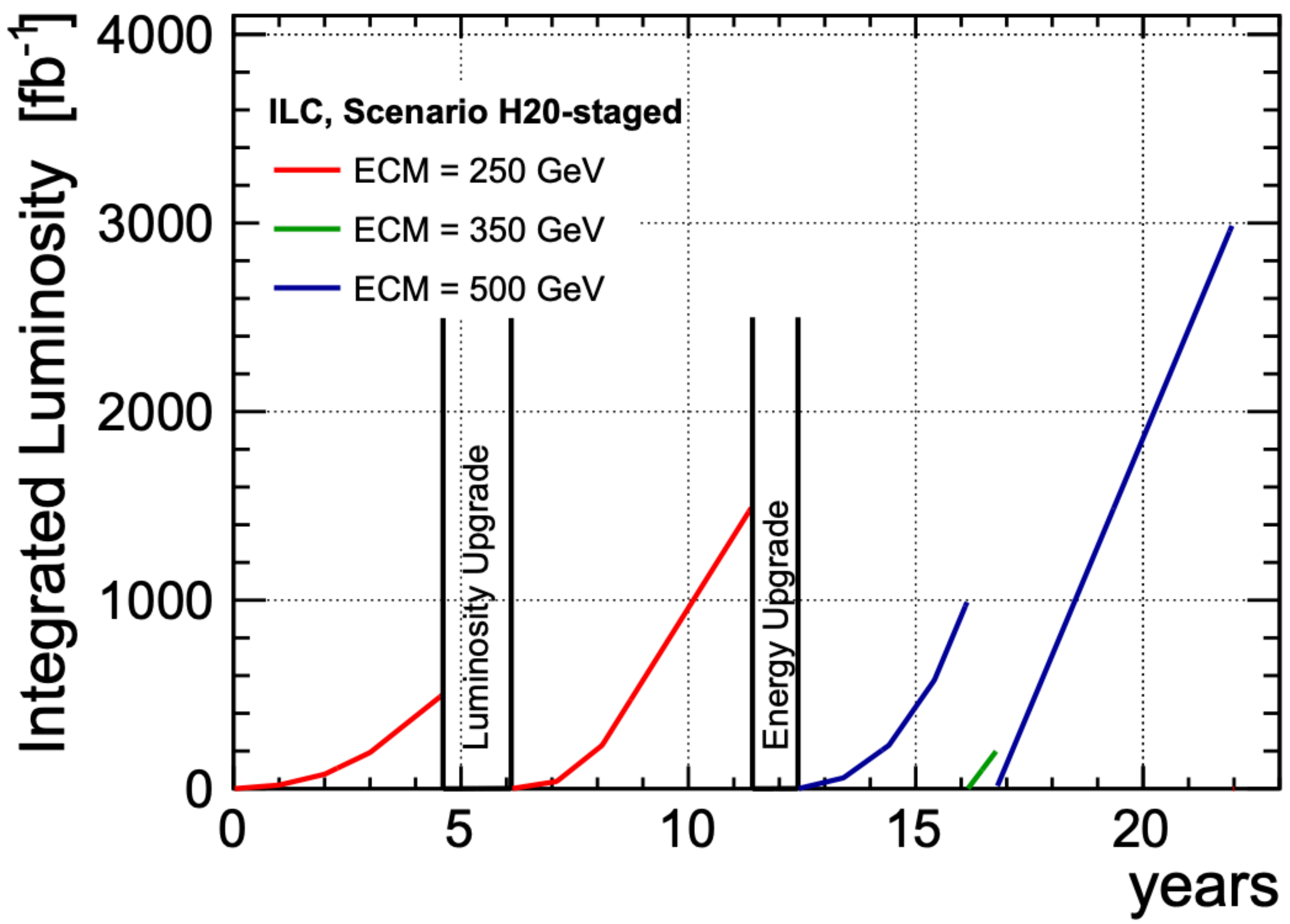
Thank you!

Run Plans

1710.07621
FCC Mid Term Report

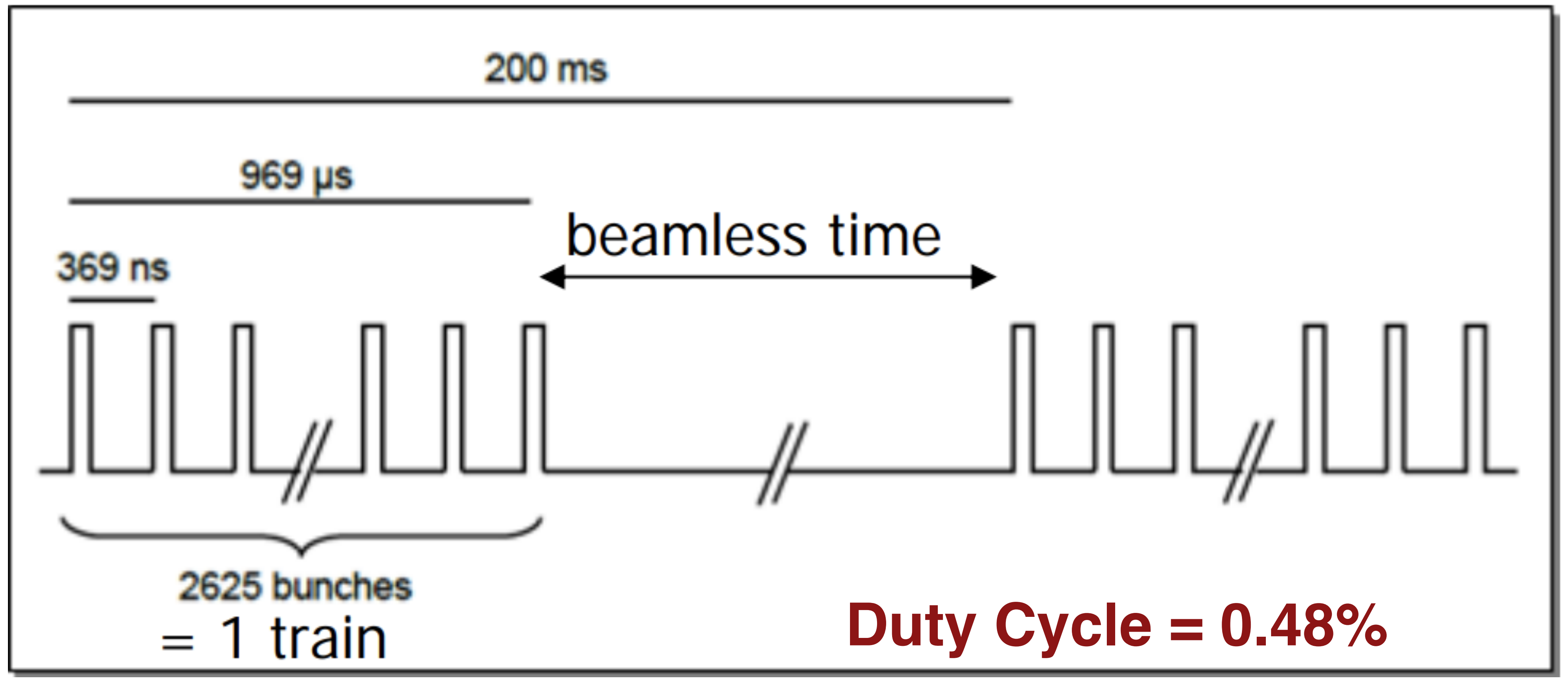
ILC and FCC





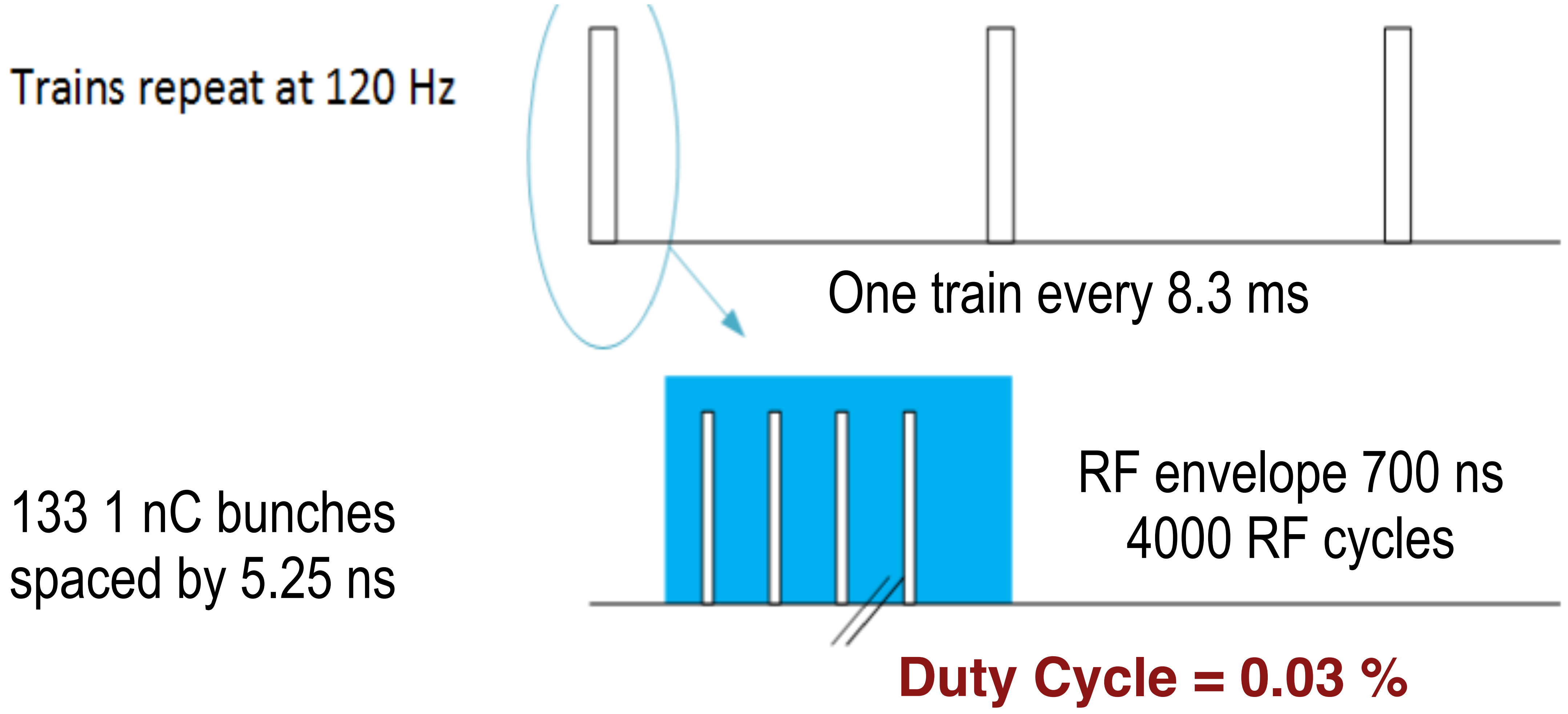
Beam Format and Detector Design Requirements

ILC timing structure



1 ms long bunch trains at 5 Hz
308ns spacing

C^3 timing structure



- Linear e+e- colliders are characterized by a very low duty cycle
- Power Pulsing can be an additional handle to reduce power consumption and cooling constraint
  - Factor of 100 power saving for FE analog power
- Tracking detectors don't need active cooling
  - Significantly reduction for the material budget

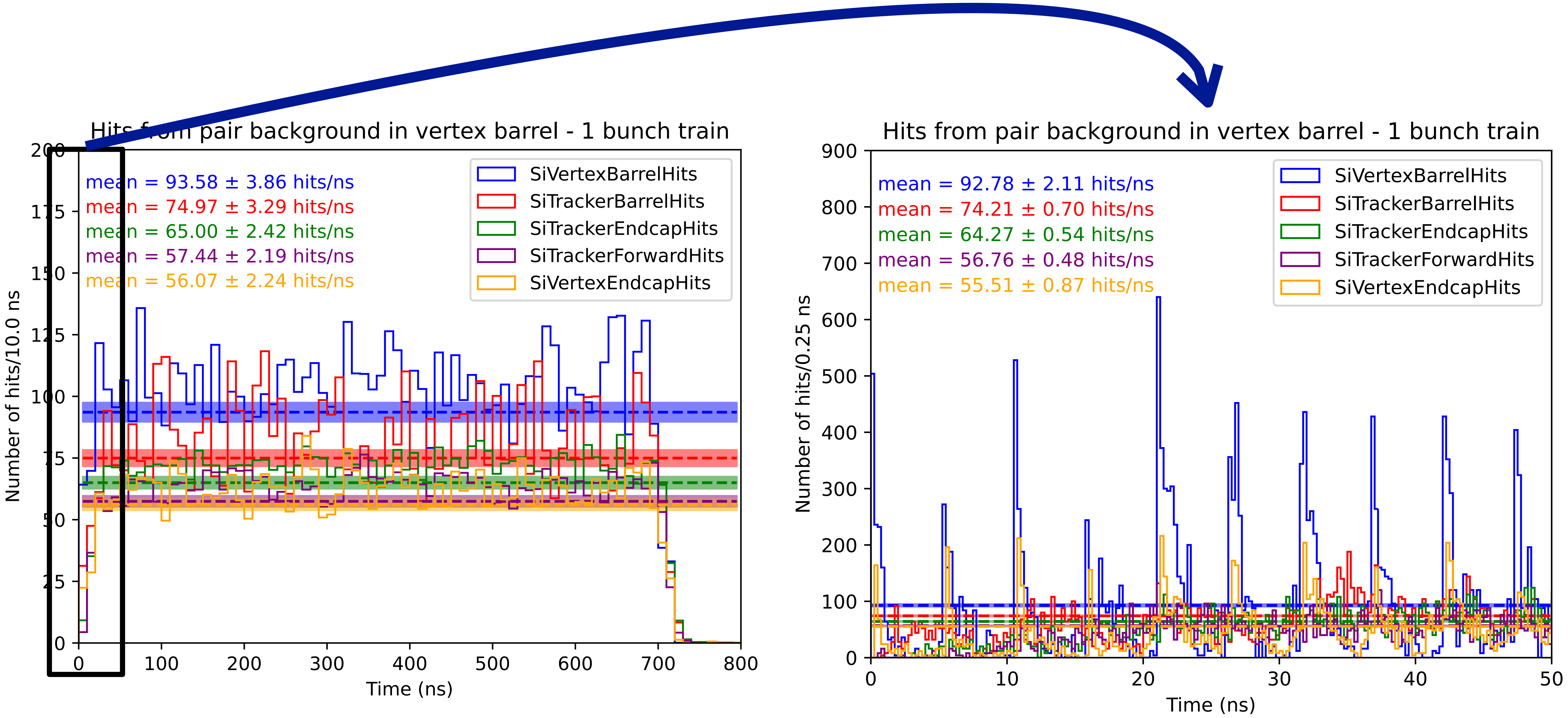
Joint simulation/detector optimization effort with ILC groups
Common US R&D initiative for future Higgs Factories 2306.13567

C^3 time structure is compatible with ILC-like detector overall design and ongoing optimizations.

Tracking performance

O(ns) timing capabilities as an additional handle to suppress beam induced backgrounds

Time distribution of hits per unit time and area: ~ $4.4 \cdot 10^{-3}$ hits/(ns·mm²) ≃ 0.03 hits/mm² /BX
in the 1st layer of the vertex barrel SiD-like detector for ILC/C³



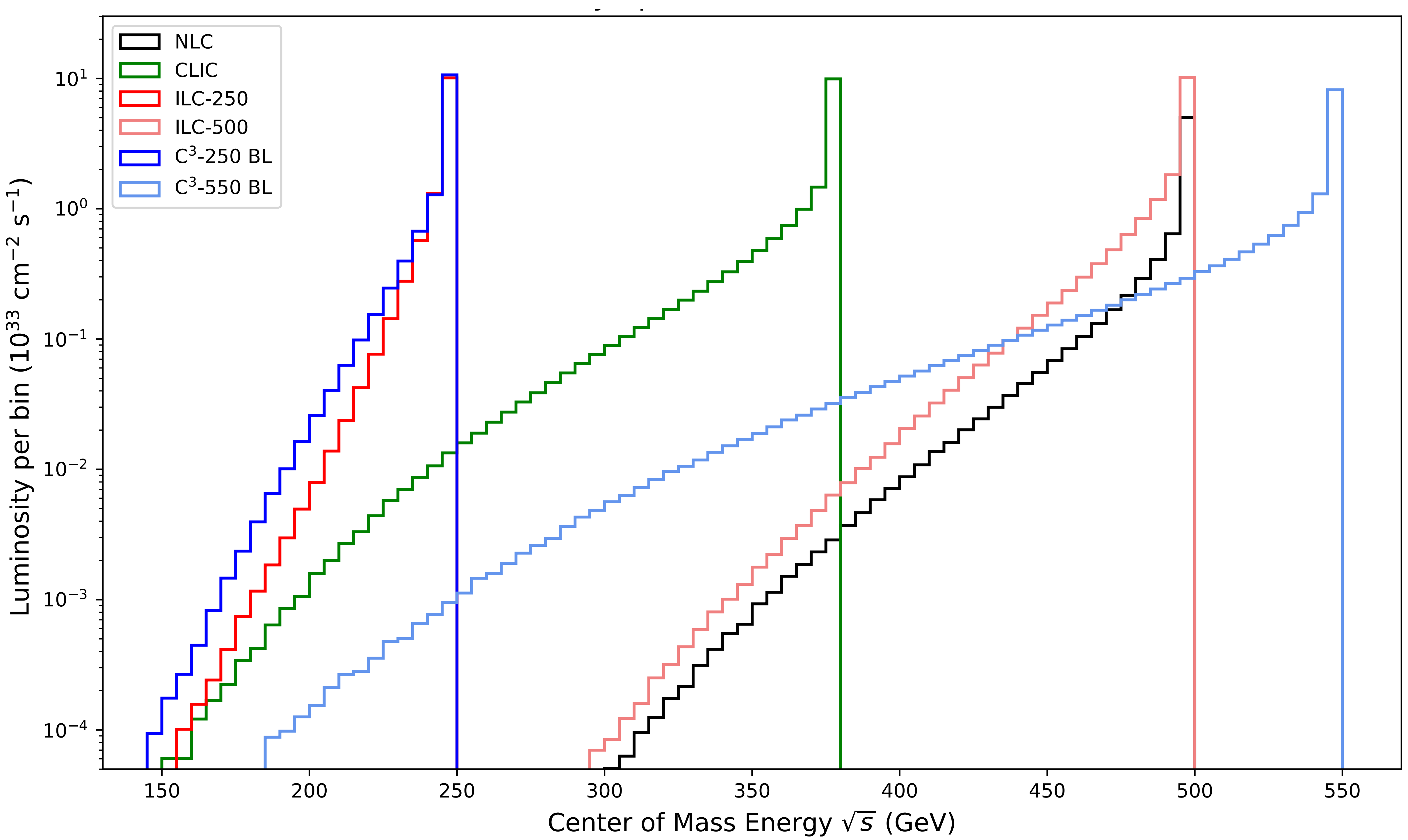
Parameter	Value
Time resolution	1 ns-rms
Spatial Resolution	7 μm
Expected charge from a MIP	500 – 800 e/h
Minimum Threshold	200 e-
Noise	< 30 e-rms
Power density	< 20 mW/cm²
Maximum particle rate	1000 hits/cm²

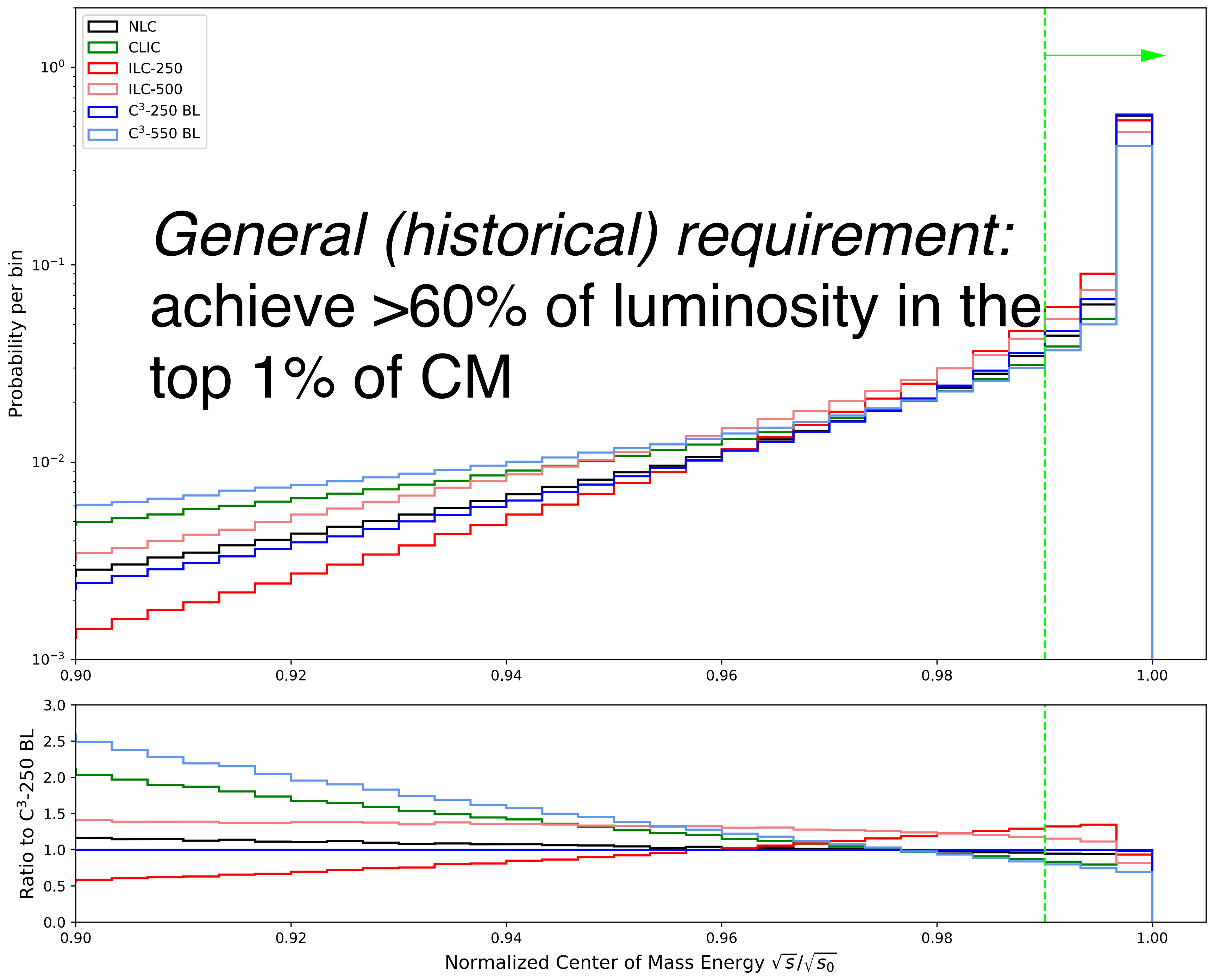
D. Ntounis talk on beam background simulations at ECFA 2023

Luminosity Spectra

arXiv:2403.07093

The emission of Beamstrahlung photons reduces the energy of the colliding beam particles such that a luminosity spectrum is created, with contribution to the luminosity from various $\sqrt{s}$ energies.





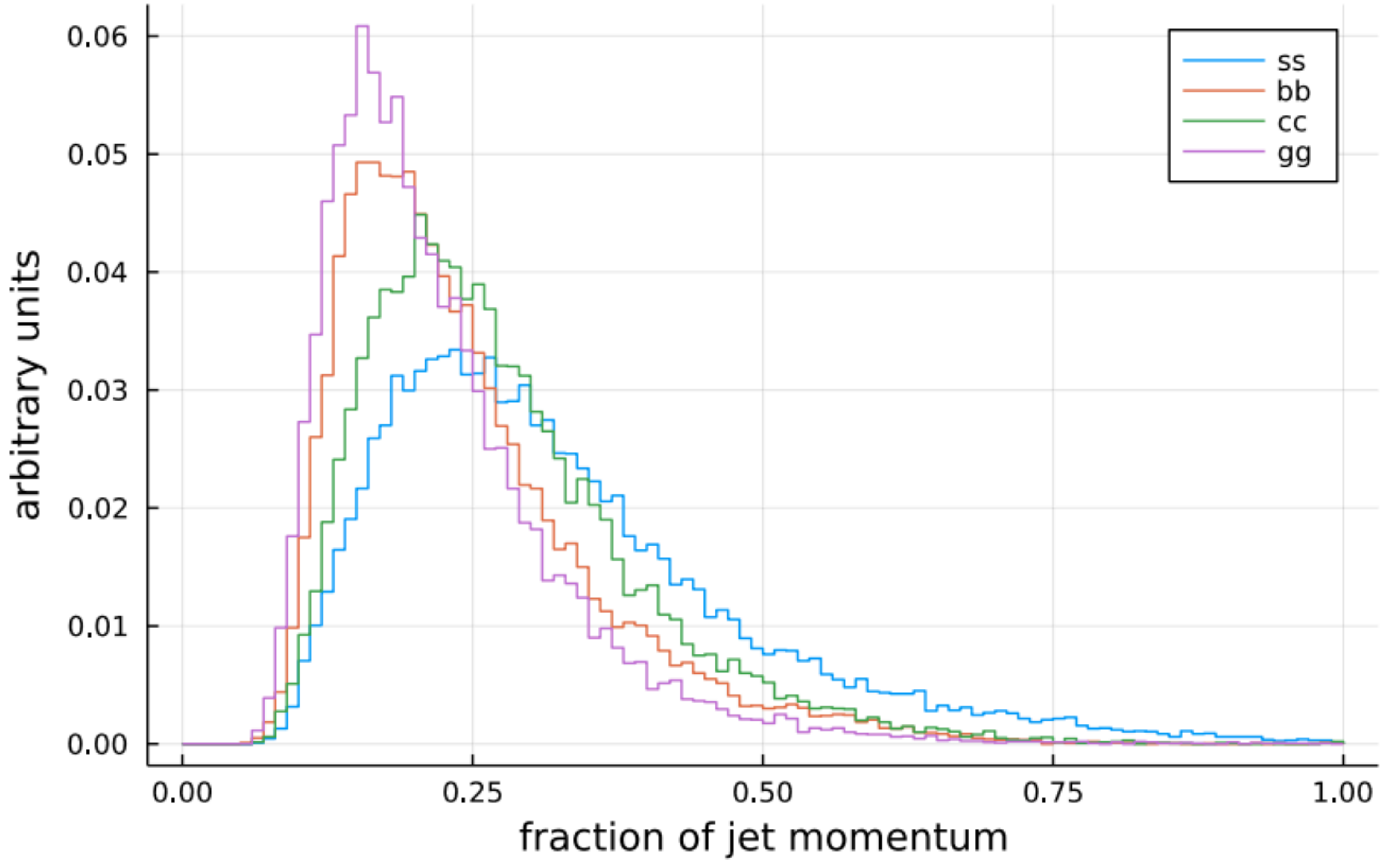
Understanding the impact of the various beam parameters on the instantaneous luminosity and the beam-induced background is relevant for any future collider, linear or circular.

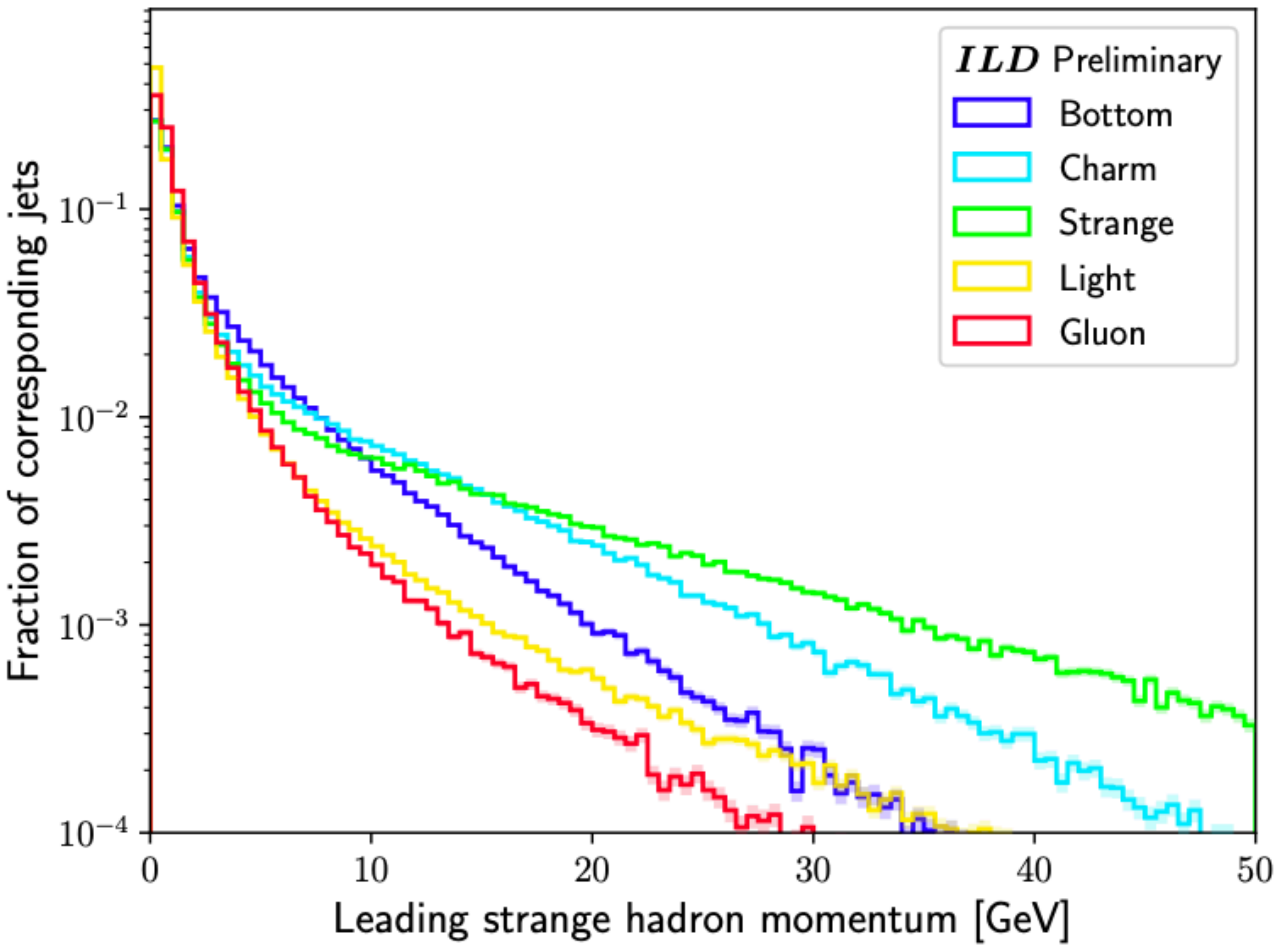
Write up on the methodology in preparation

Strange tagging

2203.07535

Momentum spectrum



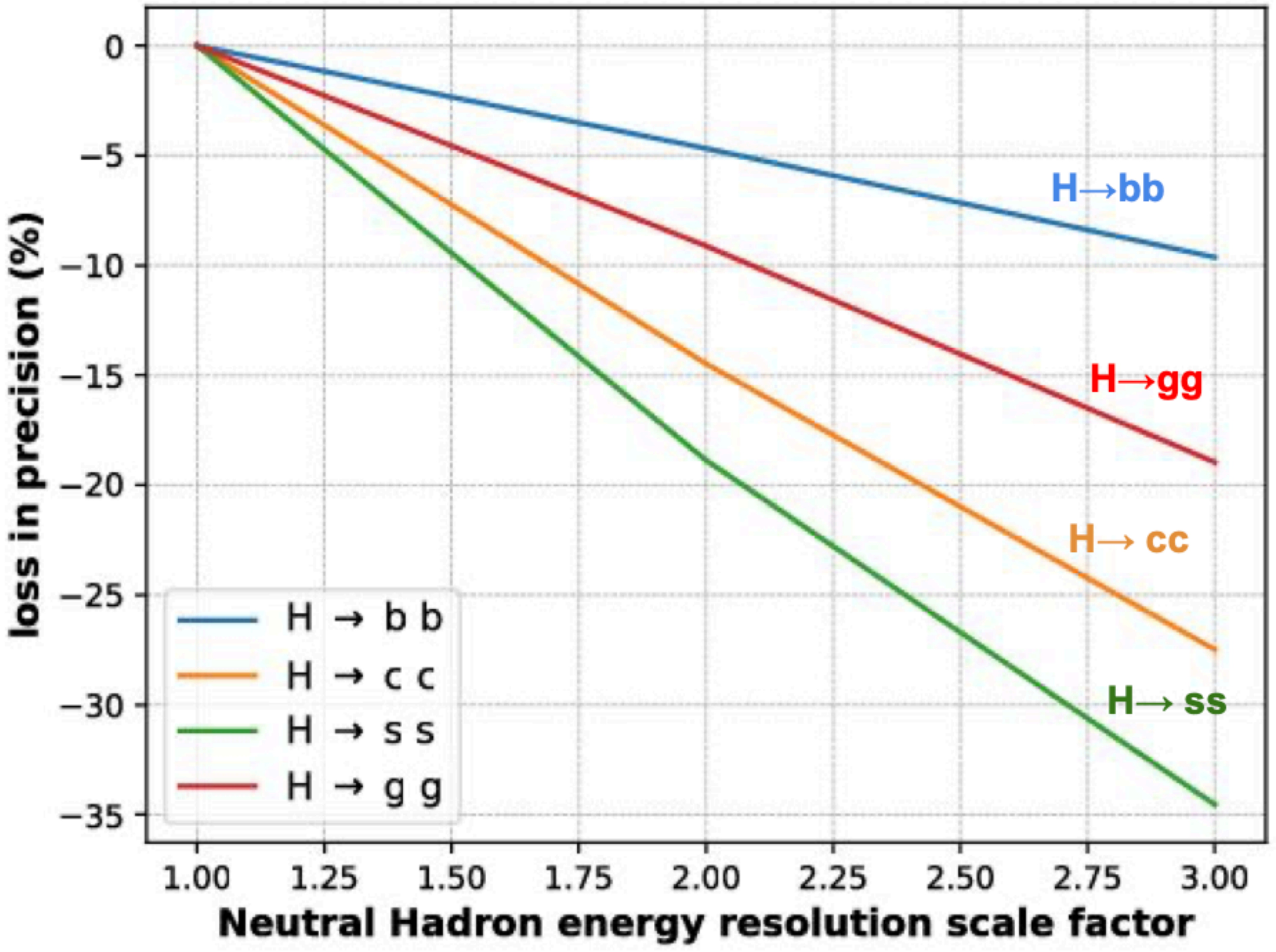


arXiv:2203.07535
L. Gouskos @FCC week

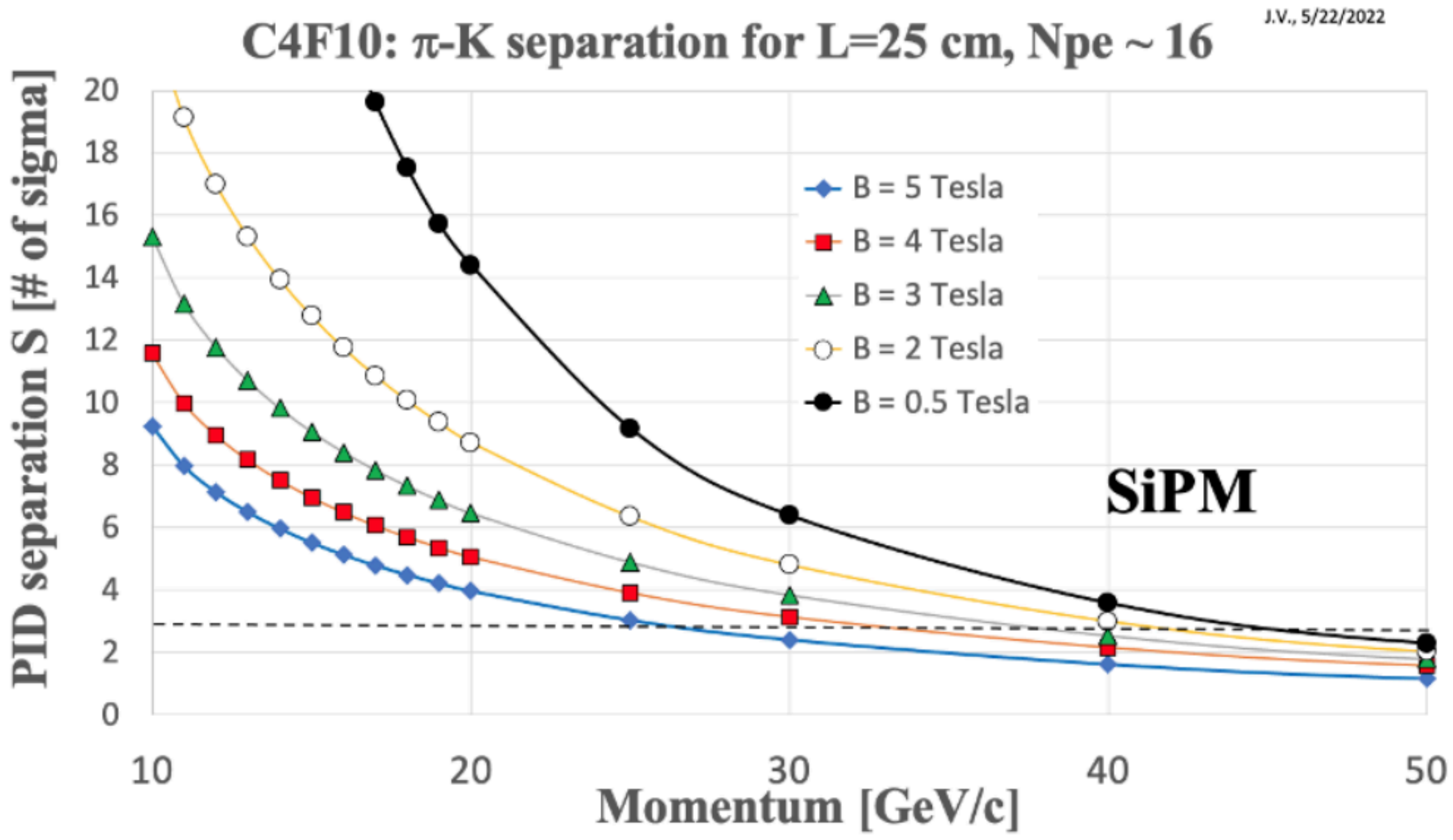
Application: s-tagging

Use H → ss to inform detector design, while monitoring other benchmarks' performance

- Neutral Hadron energy resolution
- dE/dx and dN/dx: evaluate PID performance for H-strange coupling
- Timing resolution to be further investigated but less critical for s-tagging
- RHIC for improved reconstruction of $K^{+/-}$ at high momentum (< 30 GeV)



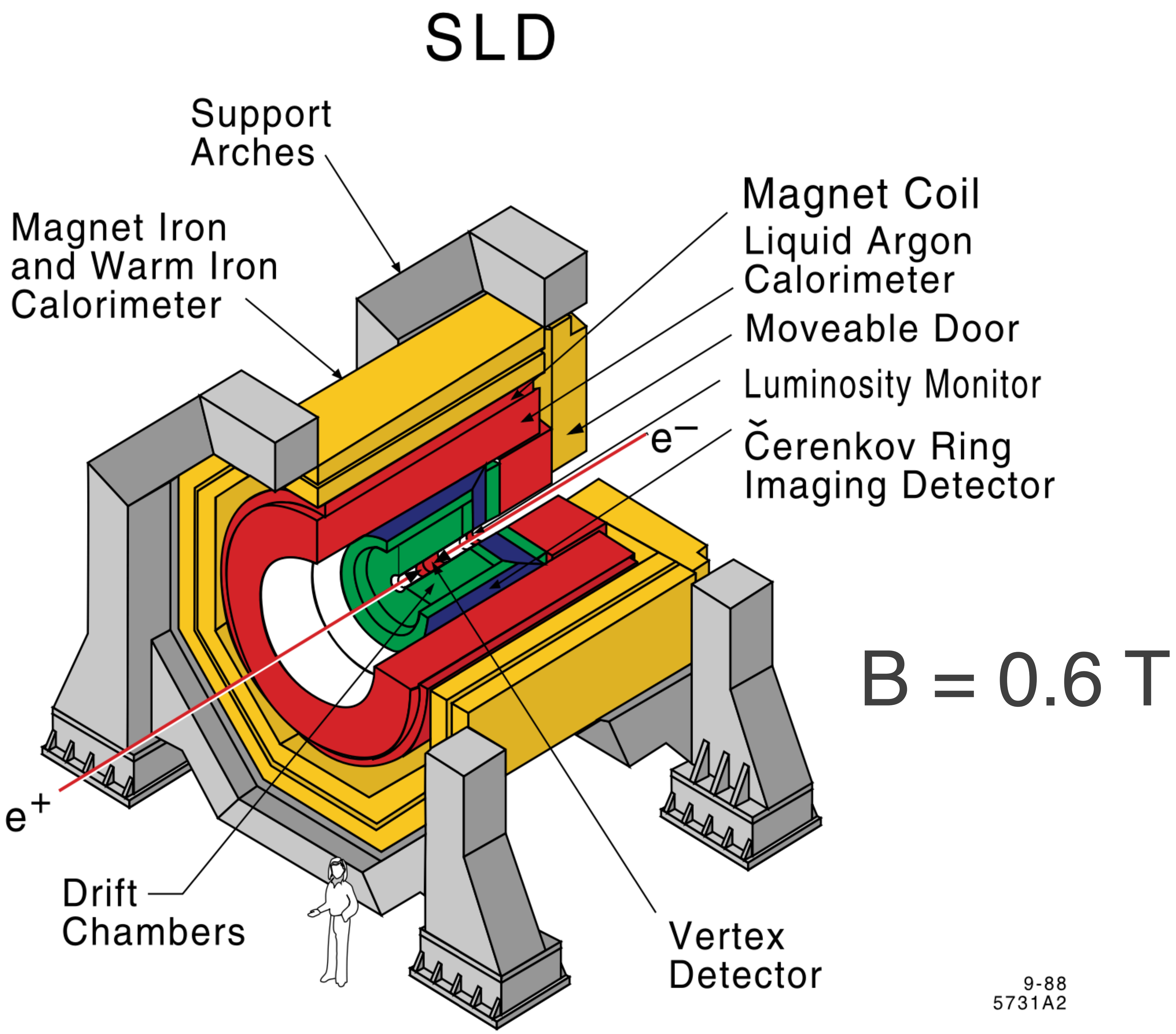
Compact RHIC



PRL 85 (2000), 5059
SLAC-R-520
PRD (1999) 59 52001

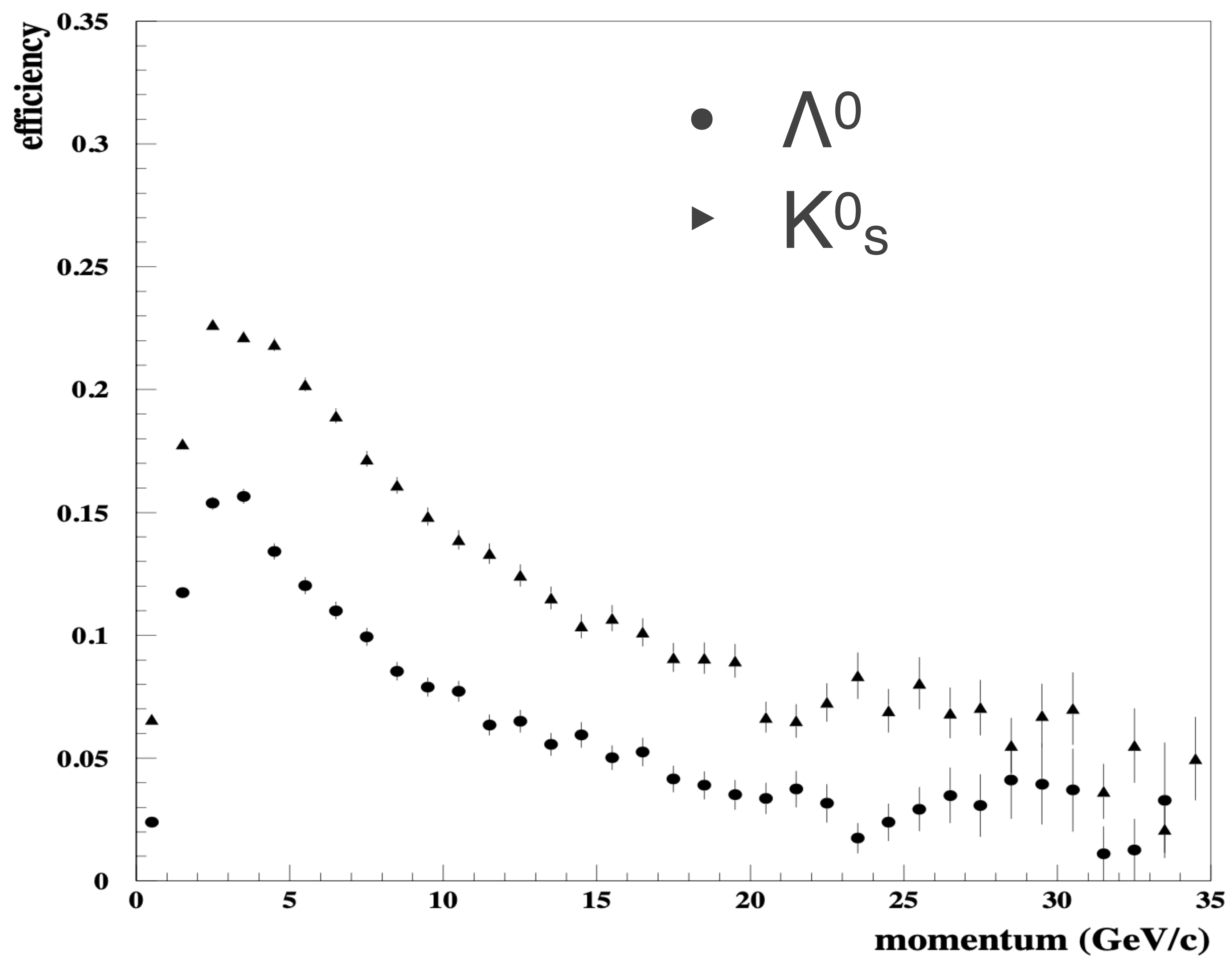
s-tagging in the past

SLD at SLC (e+e- at the Z) measured asymmetry in $Z \rightarrow s\bar{s}$



A Cherenkov Ring Imaging Detector combined with a drift chamber and vertex detector

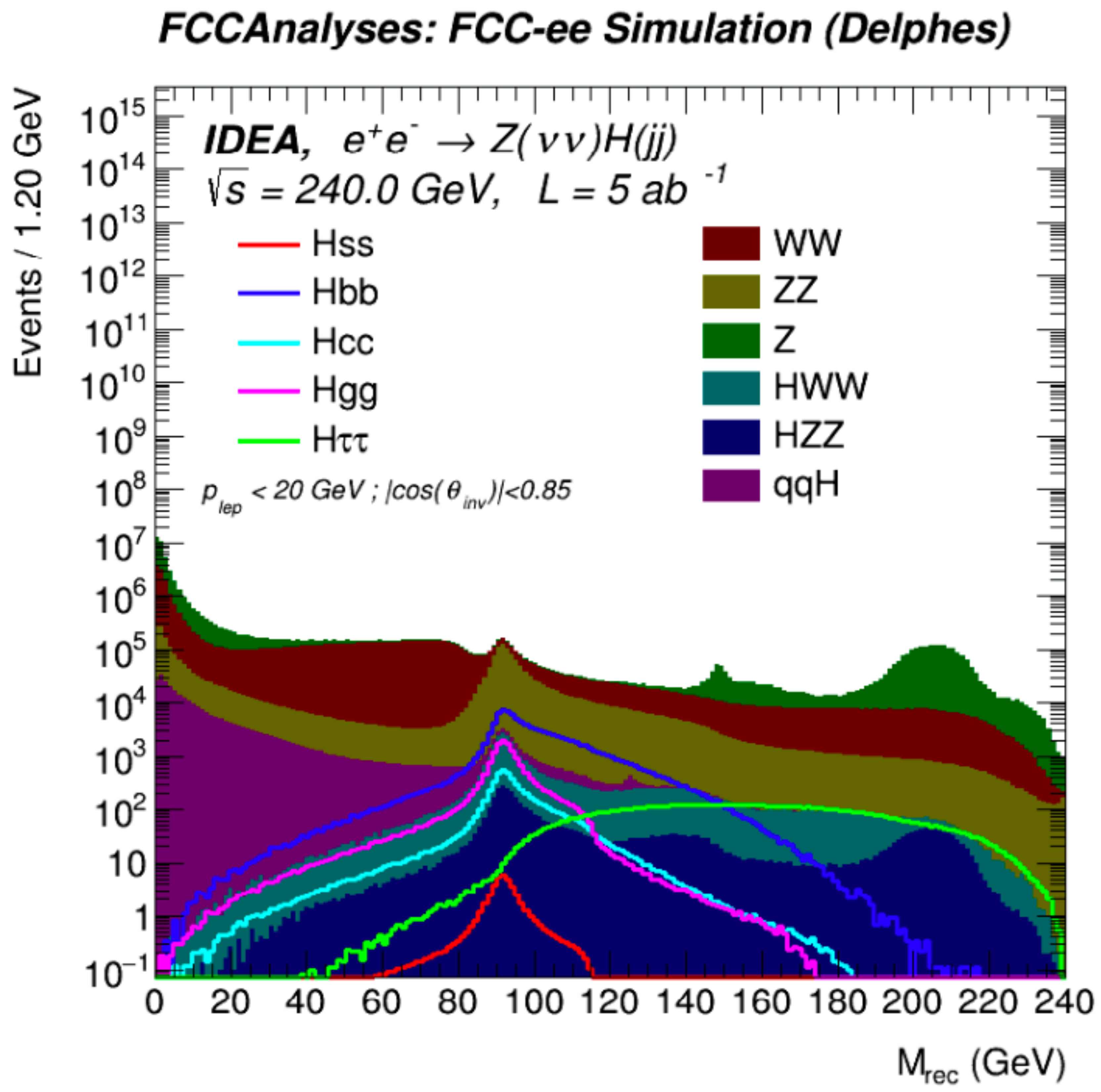
- CRID only available for $K^{\pm}$ with $p_T > 9$ GeV with a selection efficiency (purity) of 48% (91.5%)
- $K^0{}_S$ efficiency (purity) of 24% (90.7 %)

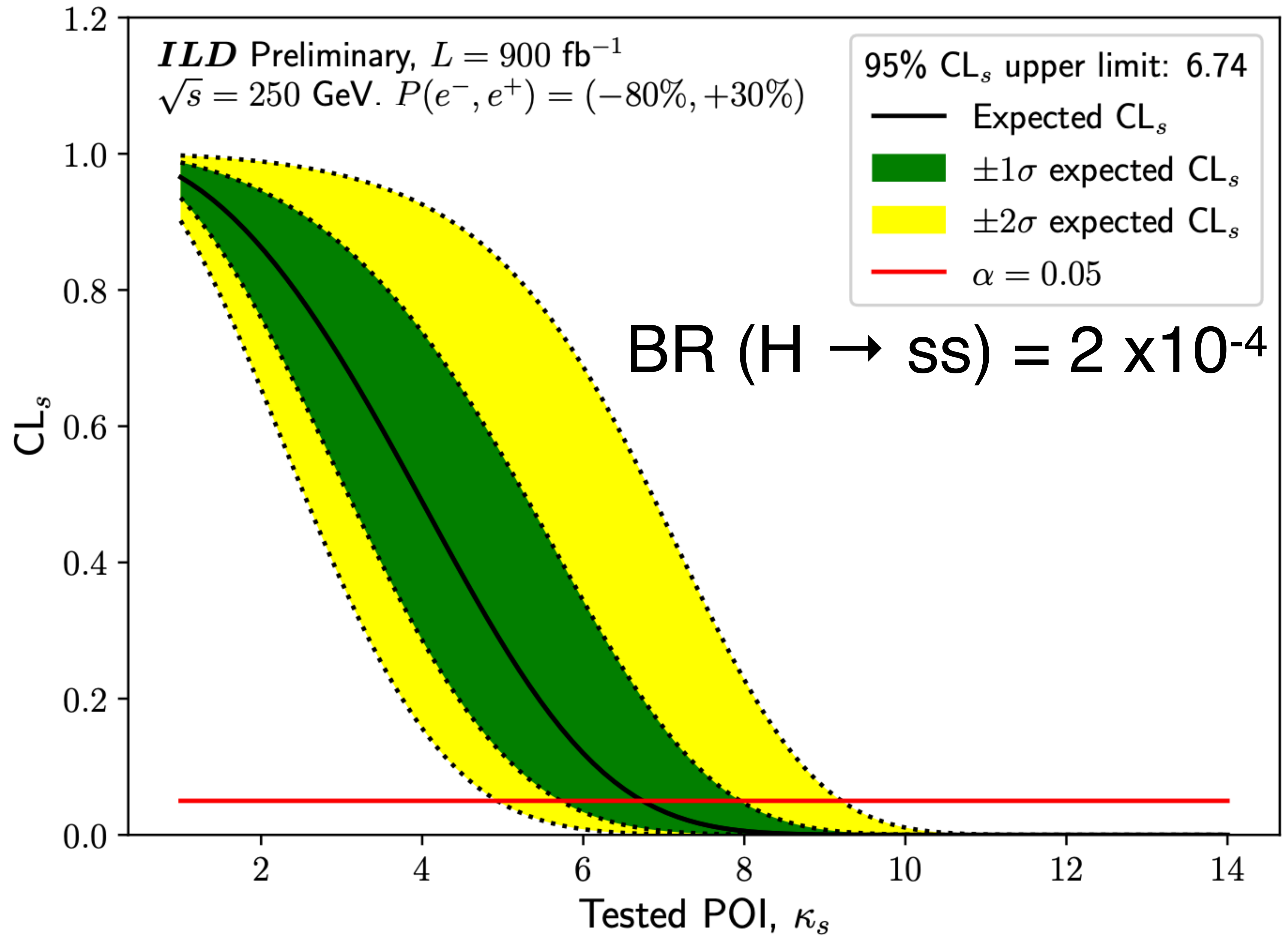


Constraints on s-coupling

Compatible results for both FCC and ILC like analyses

- ILD combined limit of $\kappa_s < 6.74$ at 95% CL with 900/fb at 250 GeV (i.e. half dataset)
  - No PID worsen the results by 8%
- FCC for Z(vv) only sets a limit of $\kappa_s < 1.3$ at 95% CL with 5/ab at 250 GeV and 2 IPs
  - No PID to PID with dN/dx → at fixed mistag, efficiency doubles





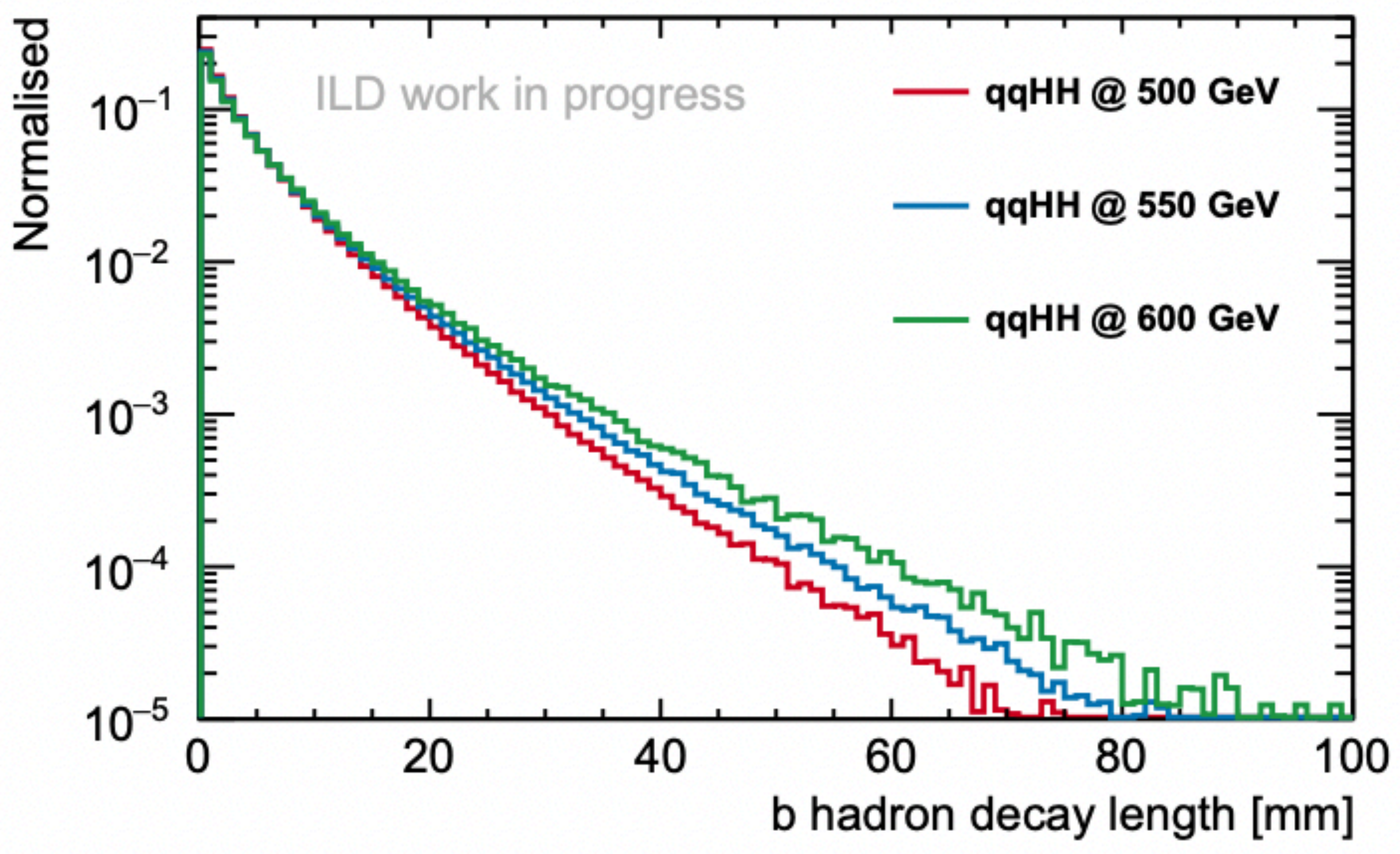
Goals of the HSelf focus studies

Talk at the ECFA workshop 2023
Ongoing work: 2311.16774

An example pertinent to detector optimization:

Double-Higgs observables at CM > 500 GeV:

- Evaluate how various algorithms can improve substantially di-Higgs cross section measurements
  - A 5% relative improvement in the b-tagging efficiency (at the same background rejection rate) could lead to an 11% relative improvement in the self-coupling precision
- Evaluate sensitivity as a function of center-of-mass energy
  - As a function of jet clustering, flavor tagging and kinematic reconstruction performance



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self-subscription CERN e-group

Goals of the H → ss focus study

s-tagging & PID would allow for a complete exploration of the 2nd generation Yukawa couplings

- ILD combined limit of $\kappa_s < 6.74$ at 95% CL with 900/fb at 250 GeV (i.e. half dataset)
  - No PID worsen the results by 8%
- FCC for Z(vv) only sets a limit of $\kappa_s < 1.3$ at 95% CL with 5/ab at 250 GeV and 2 IPs
  - No PID to PID with dN/dx → at fixed mistag, efficiency doubles
- study detector benchmarks:
  - the complementarity in momentum reach of charged hadron ID from dN/dx, dE/dx, ToF, RICH
  - reconstruction of in-flight decays, $K^0_S \to \pi^+\pi^-$
  - strangeness-tagging and s/sbar separation
- ***Important to evaluate simultaneously other Higgs benchmarks :*** **a dedicated particle ID device in front of the calorimeter can compromise other physics measurements; need to find a good strategy or compromise.**

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Goals of the ZH focus study

Study CP-odd interactions and extend the sensitivity to a global SMEFT analysis to probe the Higgs self-coupling

- Use angular information or an optimal observable to improve sensitivity to the CP structure of the hZZ vertex
  - Towards a joint constraint on the CP-even and CP-odd components of the hZZ vertex using pseudo-observables or the SMEFT, rather than just the CP-odd fraction
- An expanded interpretation framework **connecting the SMEFT to specific model scenarios** could be used to clarify the coverage of an e+e- collider to the CP-odd interaction strengths that can explain the baryon asymmetry in the universe.
  - Perform a complete NLO analysis of the ZH process within the context of a global SMEFT analysis, including constraints from other measurements
  - Determine whether angular or other observables can target the **sensitivity to the self-coupling**, possibly in conjunction with ***different centre-of-mass energies and beam polarizations***
  - Extend the global SMEFT analysis to dimension-8 operators and all terms at order $1/\Lambda^4$: both CP-odd and CP-even operators contribute to many observables at this order

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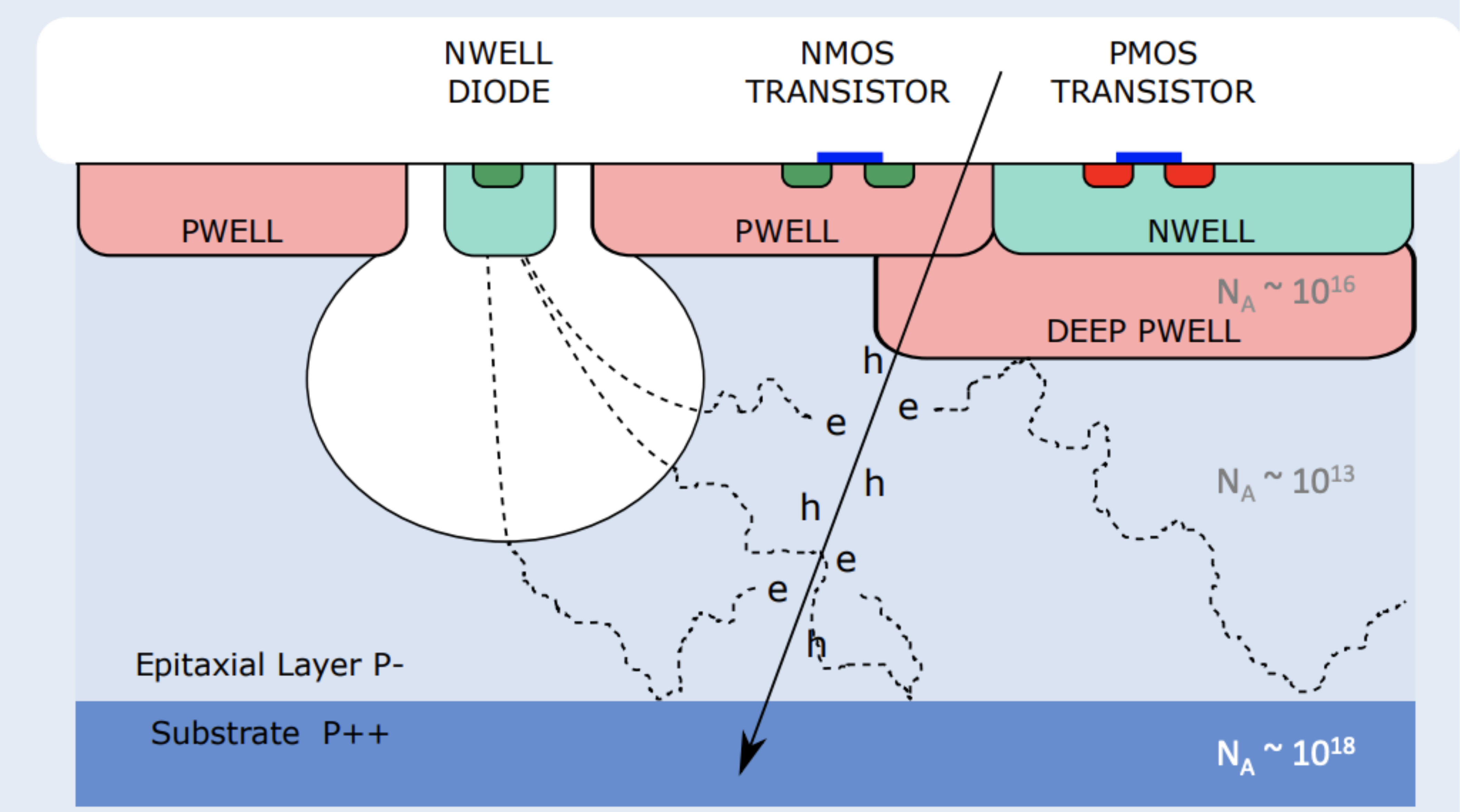
ALPIDE

- With the current tracker upgrade ALICE redefined the new state-of-the art in CMOS MAPS technology and its applications in HEP
- ALice PIxel DEtector (ALPIDE) uses CMOS Pixel sensor used in imaging process
- Full CMOS circuitry within active area
  - Sensor thickness = 20-40 µm (0.02-0.04% X_0)
  - 5μm spatial resolution
  - Radiation hard to 10^{13} 1 MeV neq



V. Manzari, 2019

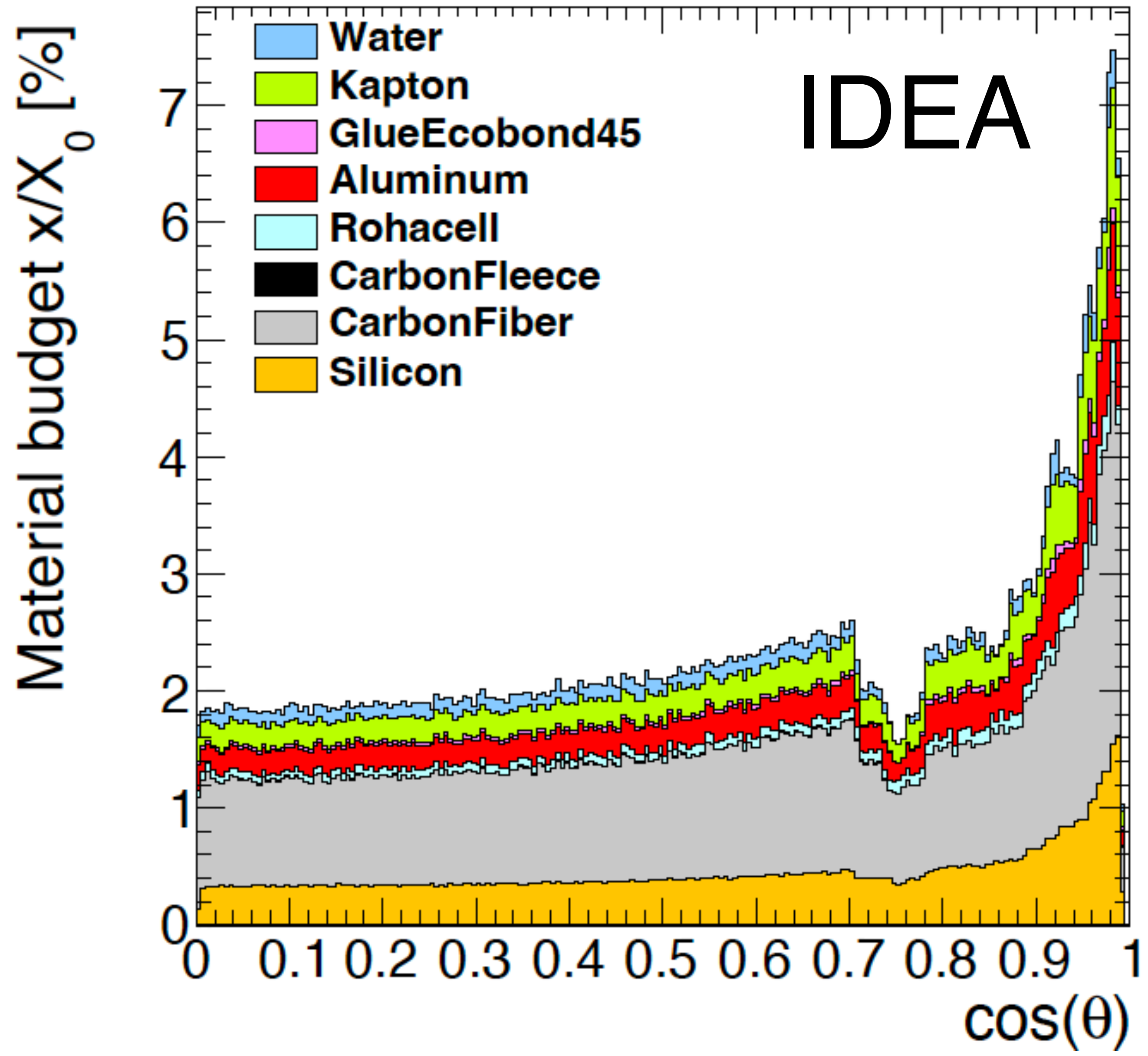
The used technology offers further opportunities: smaller feature size, **bending** that directly impact the key measurements that highly rely on precise vertexing and low material budget

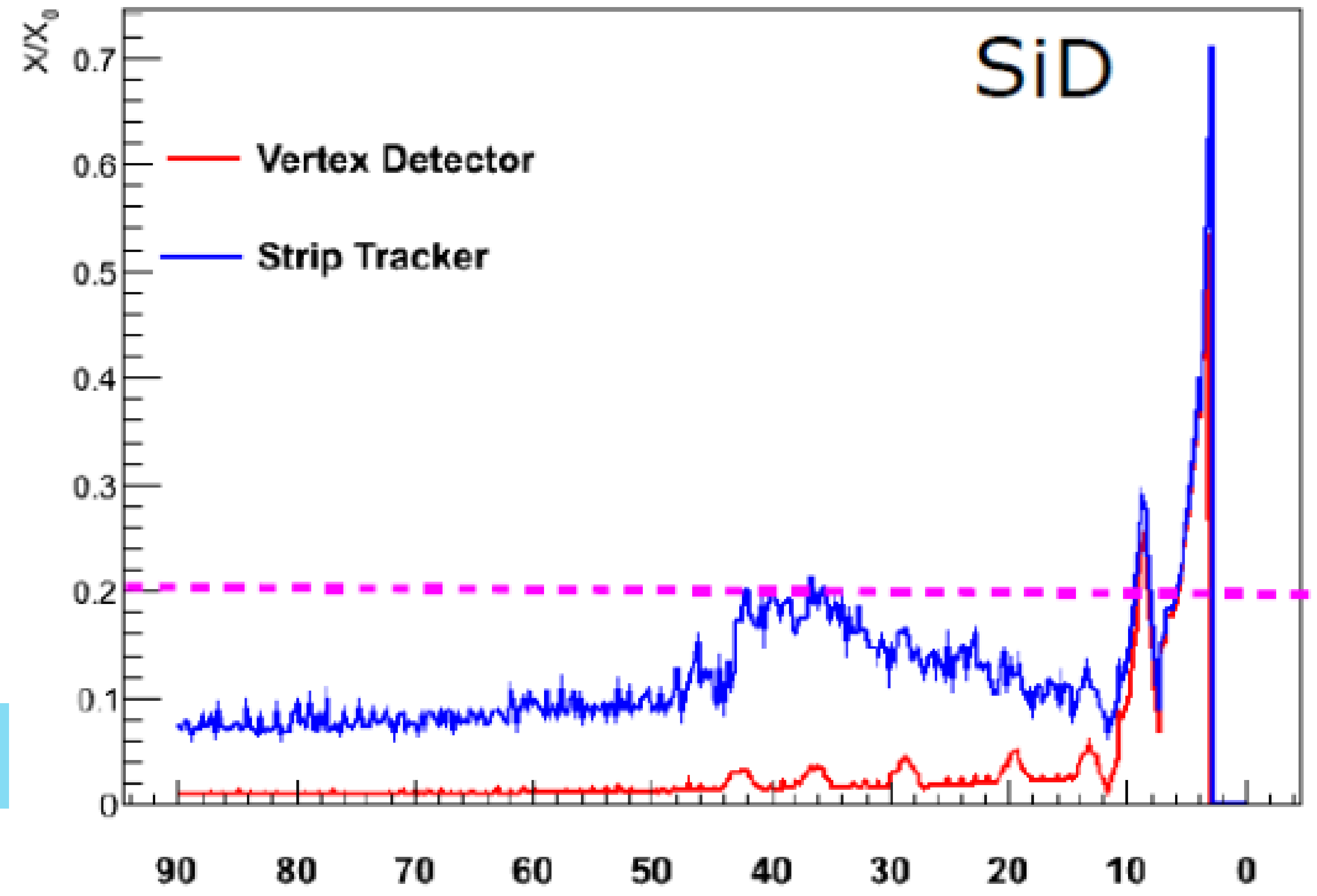
From physics to detector

arXiv:2003.01116
FCC Mid Term Report

Stringent detector requirements from ZH reconstruction & flavor tagging

- Strong **magnetic field** 2-5 T
- (Ultra) low material budget & high granularity **tracker** close to the interaction point for optimal b/c separation
  - <0.3% X0 per layer (ideally 0.1% X0) for vertex detector
  - <1% X0 per layer for Si-tracker
  - At least 5 μm hit resolution (17-25μm pitch)
- High granularity **calorimeter** with resolution of
  - 3-4% for E_{jet} 30-100 GeV for separation of $W/Z/H \to qq$ peaks





For reference, 0.4/0.6 X_0 at η ~0 for CMS/ATLAS Phase 2