A New proposal for the EIC Detector R&D Program

Precision Timing Silicon Detectors for a Combined PID and Tracking System at EIC

Frank Geurts, **Wei Li**, Shuai Yang (Rice University)

Constantin Loizides (ORNL)

Christophe Royon (The University of Kansas)

BNL EIC Detector R&D Meeting
July 27, 2020

Who are we – Heavy ion physics at RHIC and the LHC

RICE: Frank Geurts, Wei Li, Shuai Yang

- CMS Mip timing detector (MTD), STAR MRPC-TOF

KU: Christophe Royon

- CMS Mip timing detector (MTD), NASA-ANGILE (LGADs)

ORNL: Constantin Loizides

- ALICE BTU

Close collaboration with eRD24 team and CMS MTD collaborators

(A. Apresyan, N. Cartiglia, T. Liu etc.)

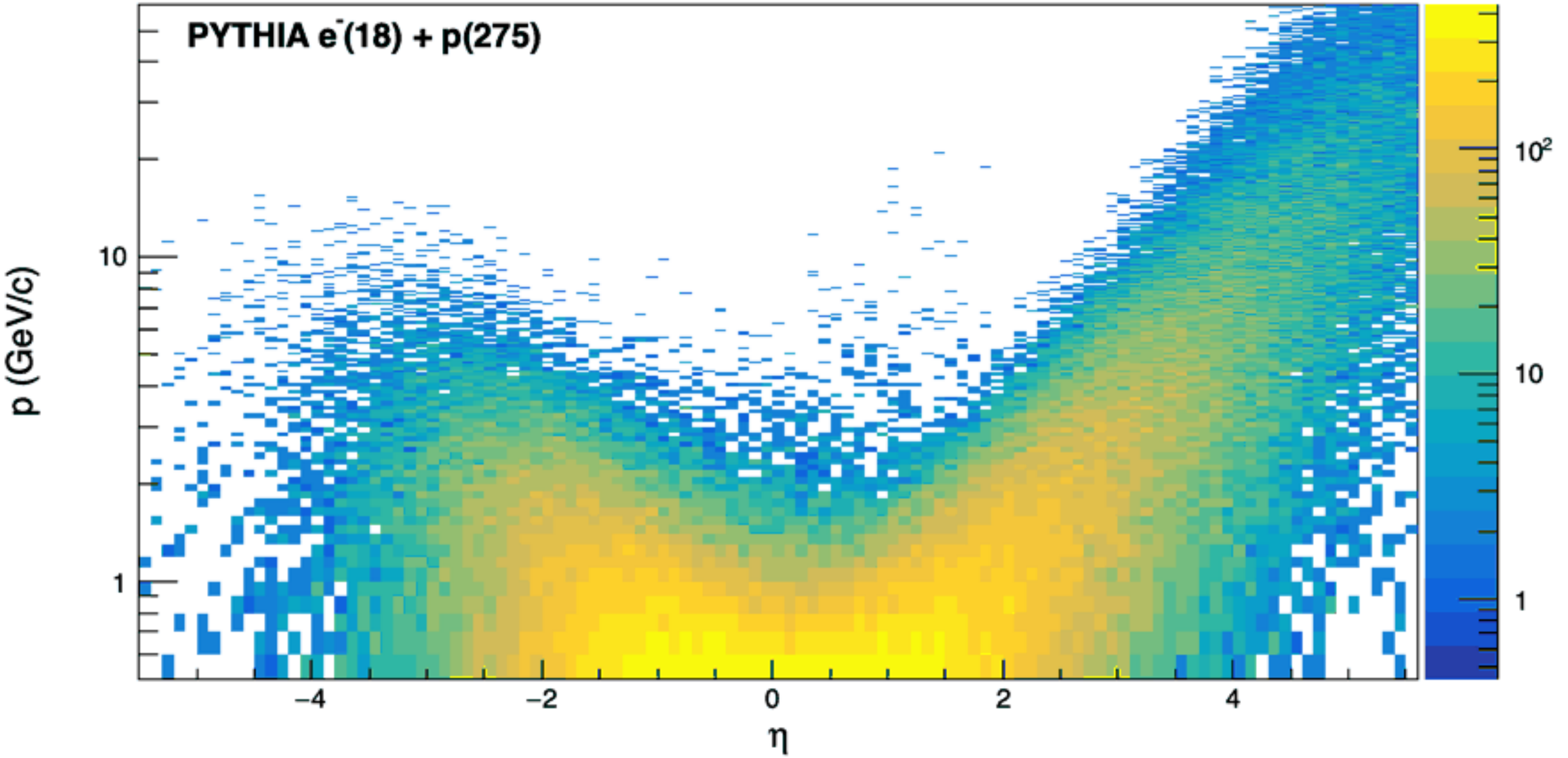
Outline:

- Overview of PID techniques at EIC and their complementarity
- LGADs and application at the CMS endcap timing layer
- Limitations of present LGADs
- R&D paths and proposed work
- Proposed budget

Particle identification (PID) at EIC

Physics:

- SIDIS
- Heavy flavor
- **Collectivity**
- …



EIC Handbook; PID YR WG; R&Ds at eRD6 and 14

	Backward (-4<η<-1.5)	Central (|η|<1.5)	Forward (1.5<η<4)
Low *p* (<3 GeV)	TOF	TOF, TPC, DIRC	TOF
Intermediate *p* (3-8 GeV)	TOF, RICH	TOF, DIRC	TOF, RICH
High *p* (8-50 GeV)			RICH

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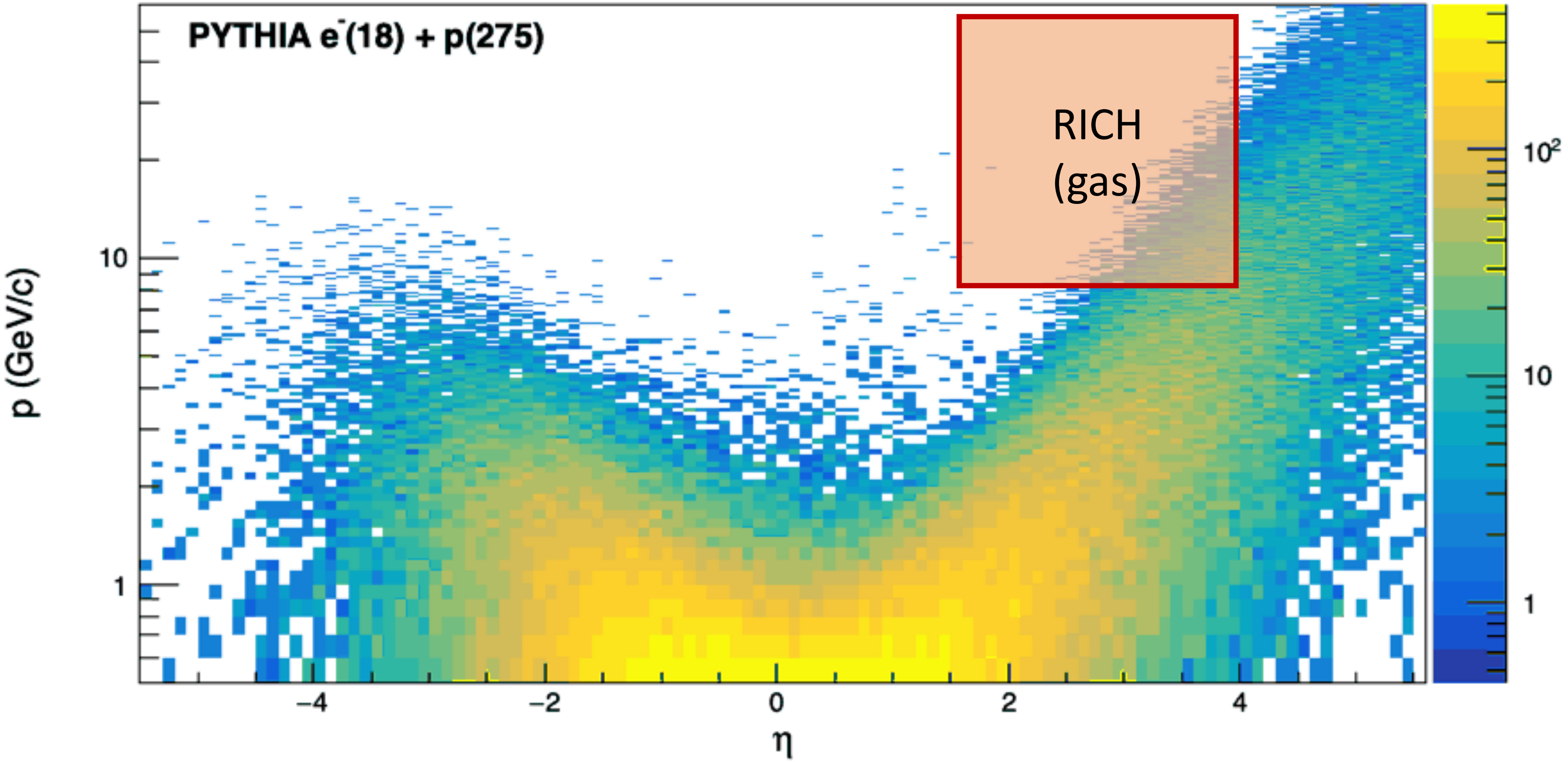

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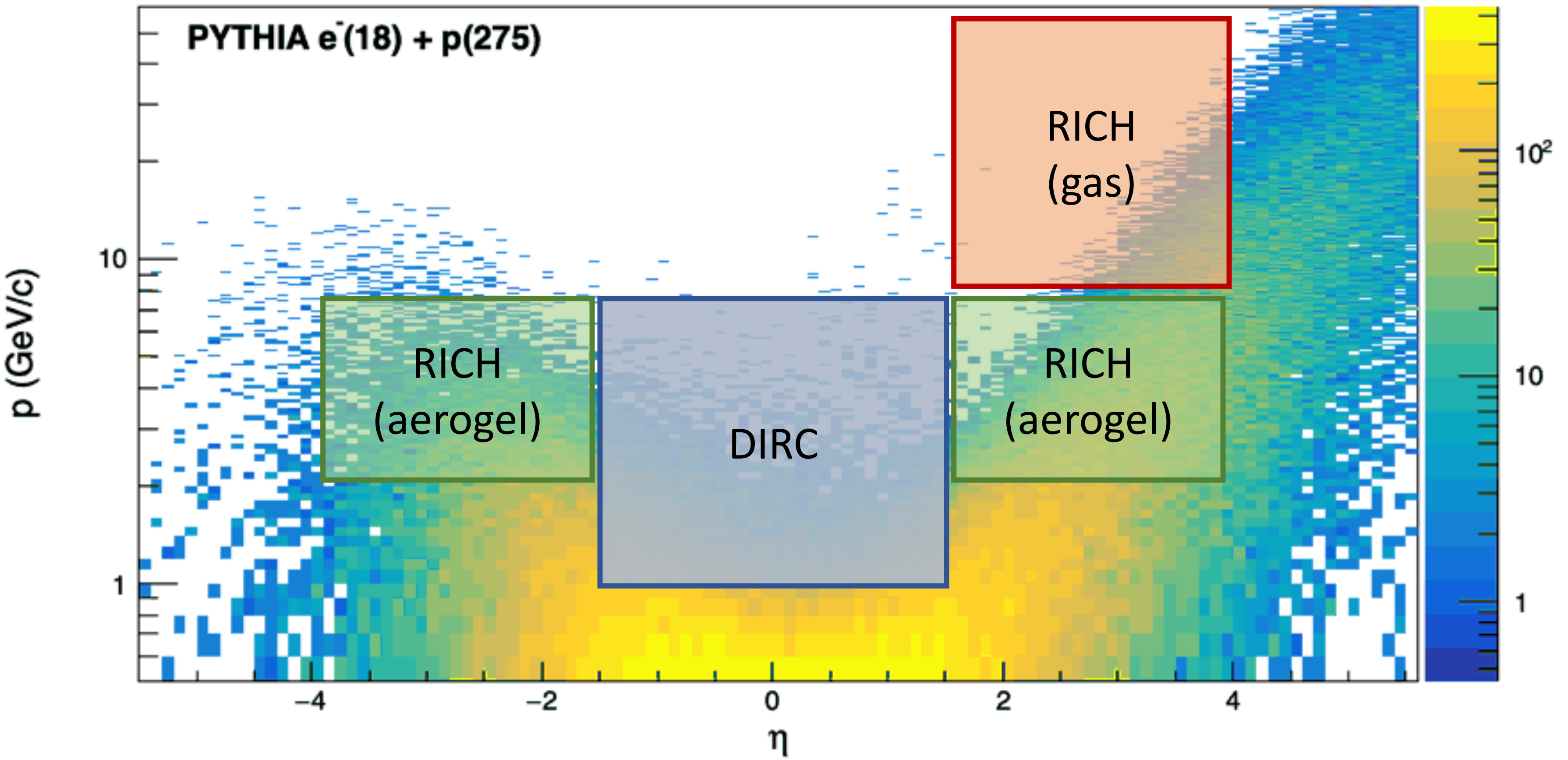

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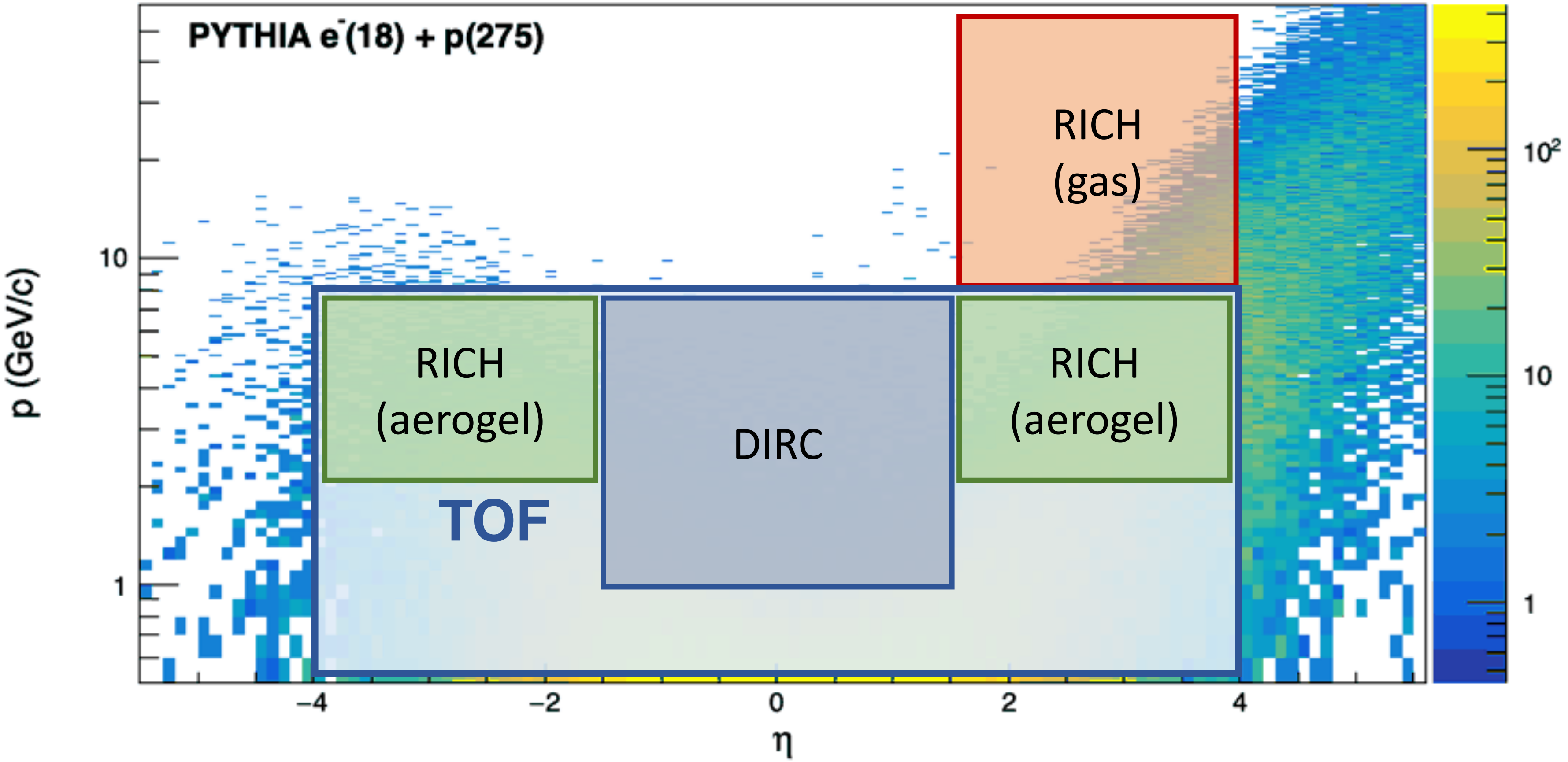

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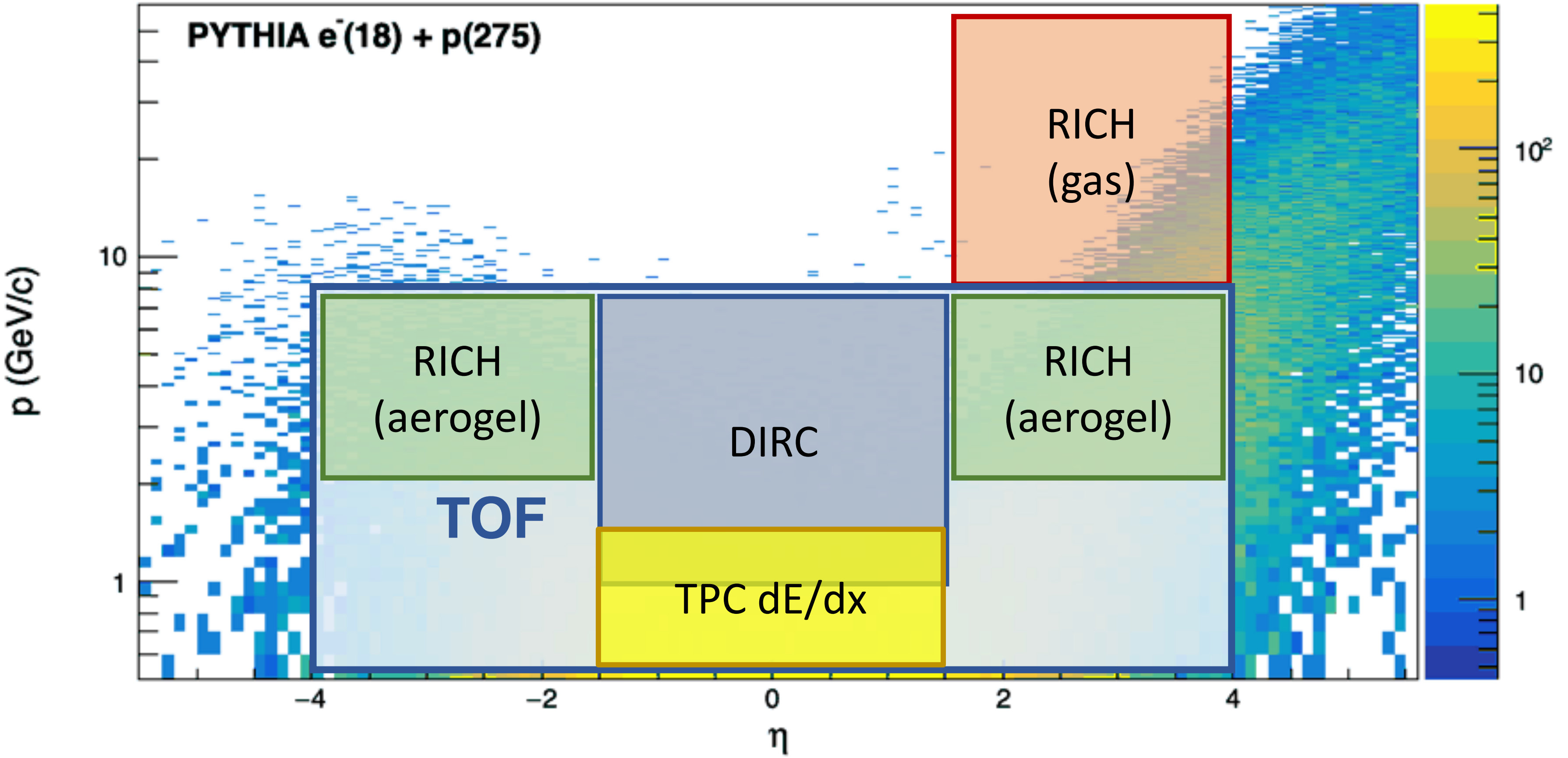

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Particle identification (PID) at EIC – TOF

(b) Complementarity of different TOF technologies

	LGADs	MRPC	LAPPD
Time resolution	20ps	20 ps	5ps
Spatial resolution	a few to hundreds μm	a few mm to 1 cm	1 mm
Overall thickness	2cm	10cm	2cm
High B field tolerant	Yes	Yes	No
Cost	High	Low	High

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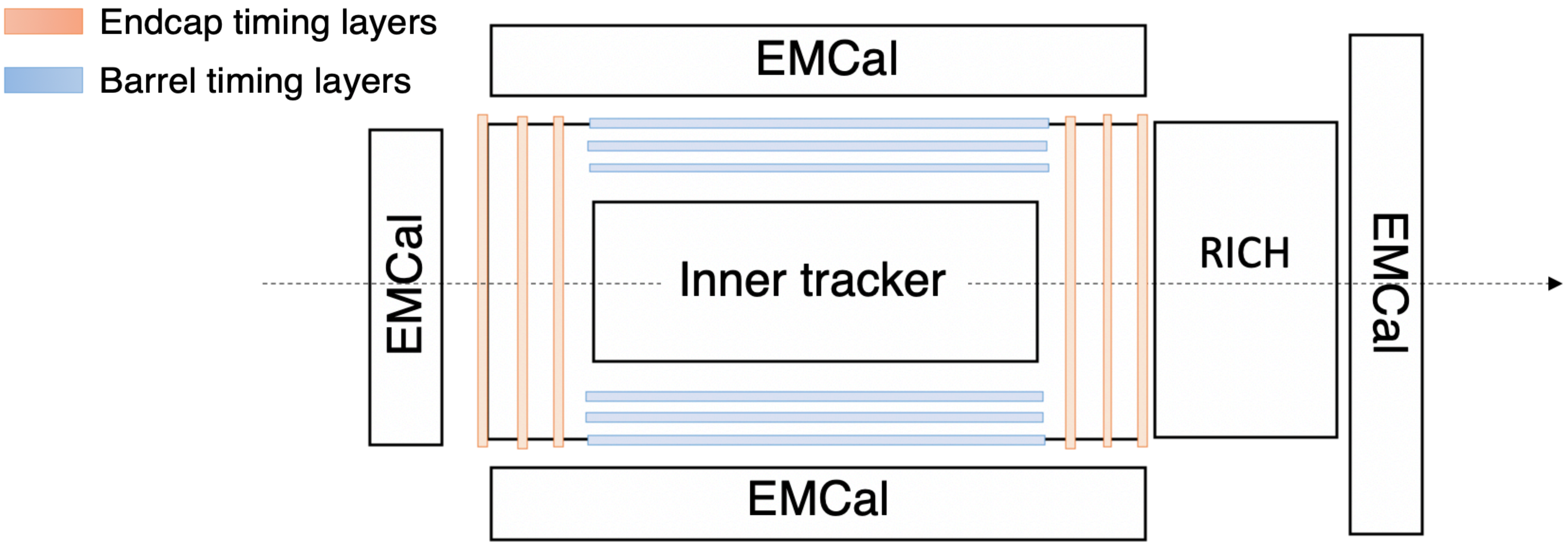
LGADs silicon sensor: low gain avalanche diodes

- Potential to combine TOF and (partially) tracker in one system
- Lots of R&Ds at the HL-LHC to synergize

TOF-tracker PID with LGADs at EIC

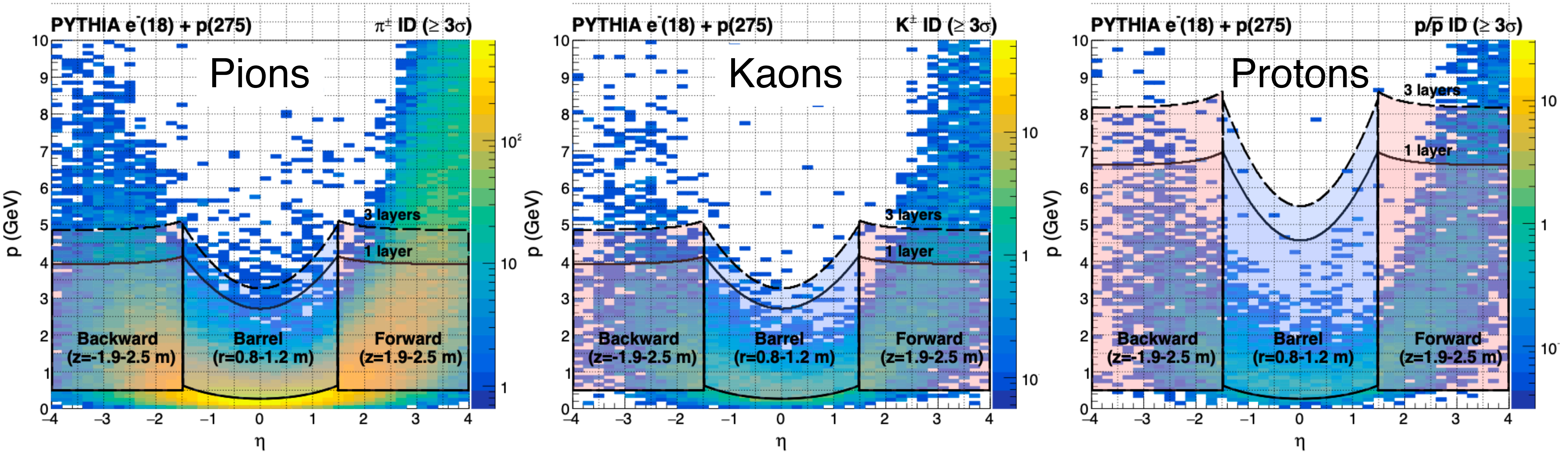


Timing layers outside inner tracker as both TOF and outer tracker

- presently not considering timing layers for the inner tracker due to too short flight distance and the requirement of low material budgets

TOF-tracker PID with LGADs at EIC

- Time resolution: $\sigma_T = 20$ ps / layer
- Flight distance: $L_{half} \sim 2$ m, r ~ 1m



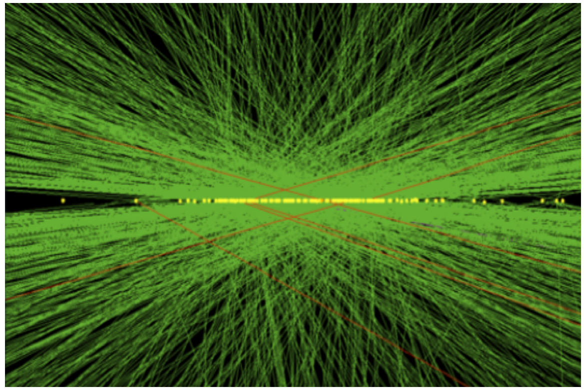
Cover a wide phase space of PID required at the EIC

A Hermetic TOF for CMS at the HL-LHC (2028)

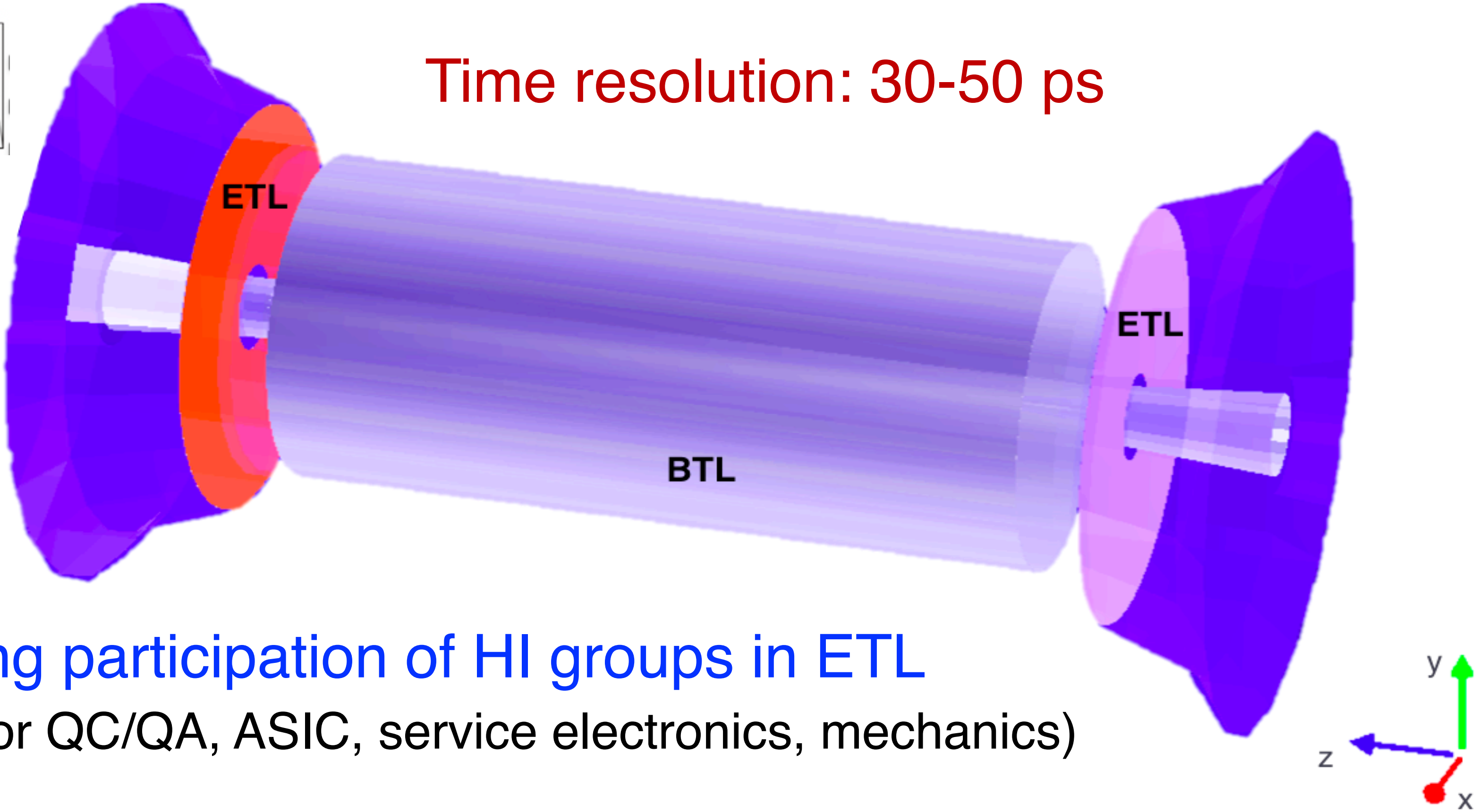
Barrel Timing Layer (BTL): |η|<1.5
- **LYSO bars + SiPM readout**
- Thickness ~ 40 mm
- Surface: ~38 m^2; Channels: 332k
- Radiation: $2 \times 10^{14}\ n_{eq}/cm^2$

Endcap Timing Layer (ETL): 1.6<|η|<3.0
- **Si with internal gain (LGAD)**
- Thickness ~ 45 mm for two layers
- Surface: ~15 m^2; Channels: 8.5 M
- Radiation: $2 \times 10^{15}\ n_{eq}/cm^2$

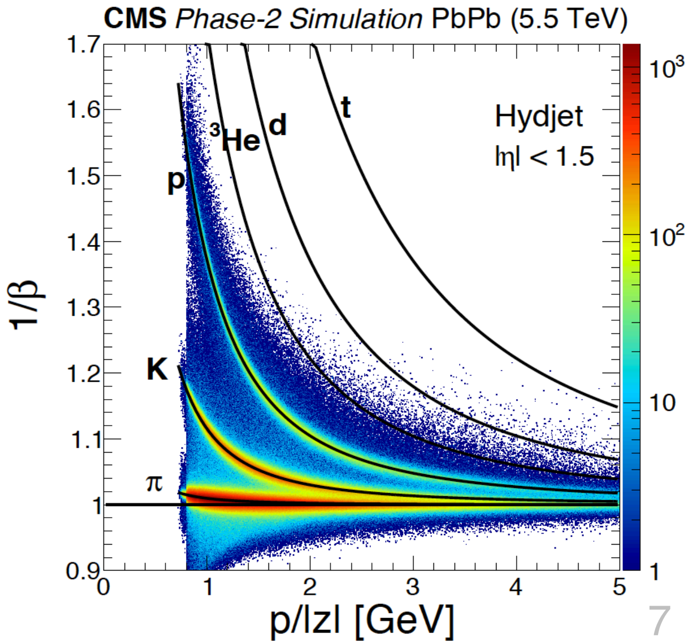
Pileup mitigation in pp



Time resolution: 30-50 ps



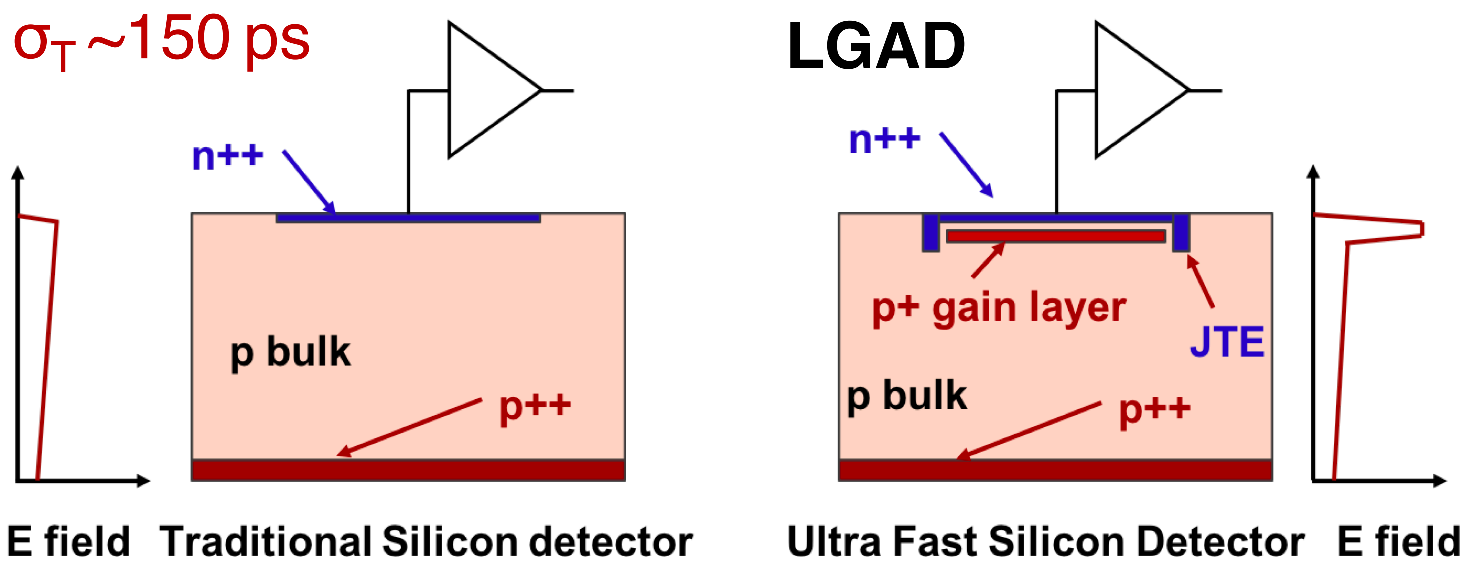
Particle ID in HI

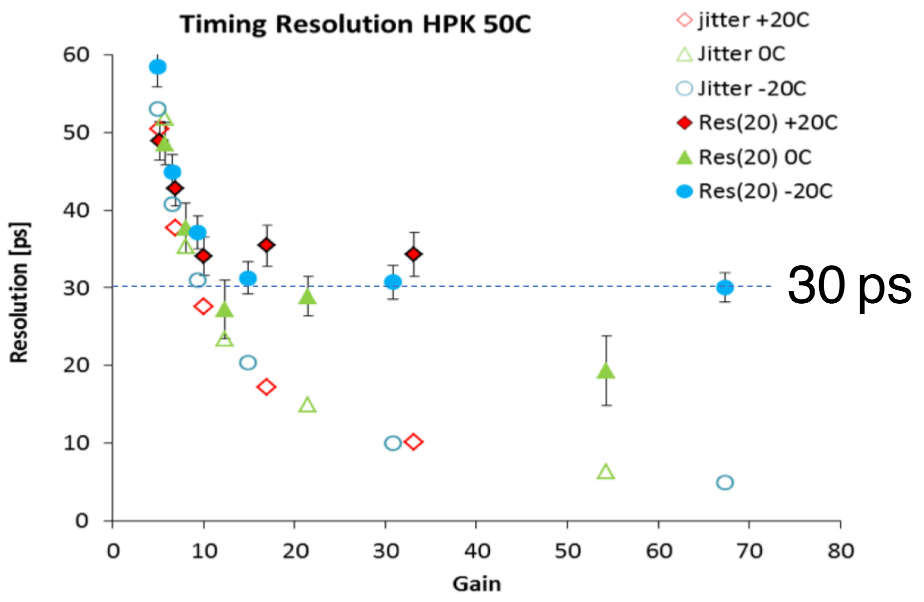


Strong participation of HI groups in ETL

(sensor QC/QA, ASIC, service electronics, mechanics)

CMS Endcap Timing Layer (ETL)



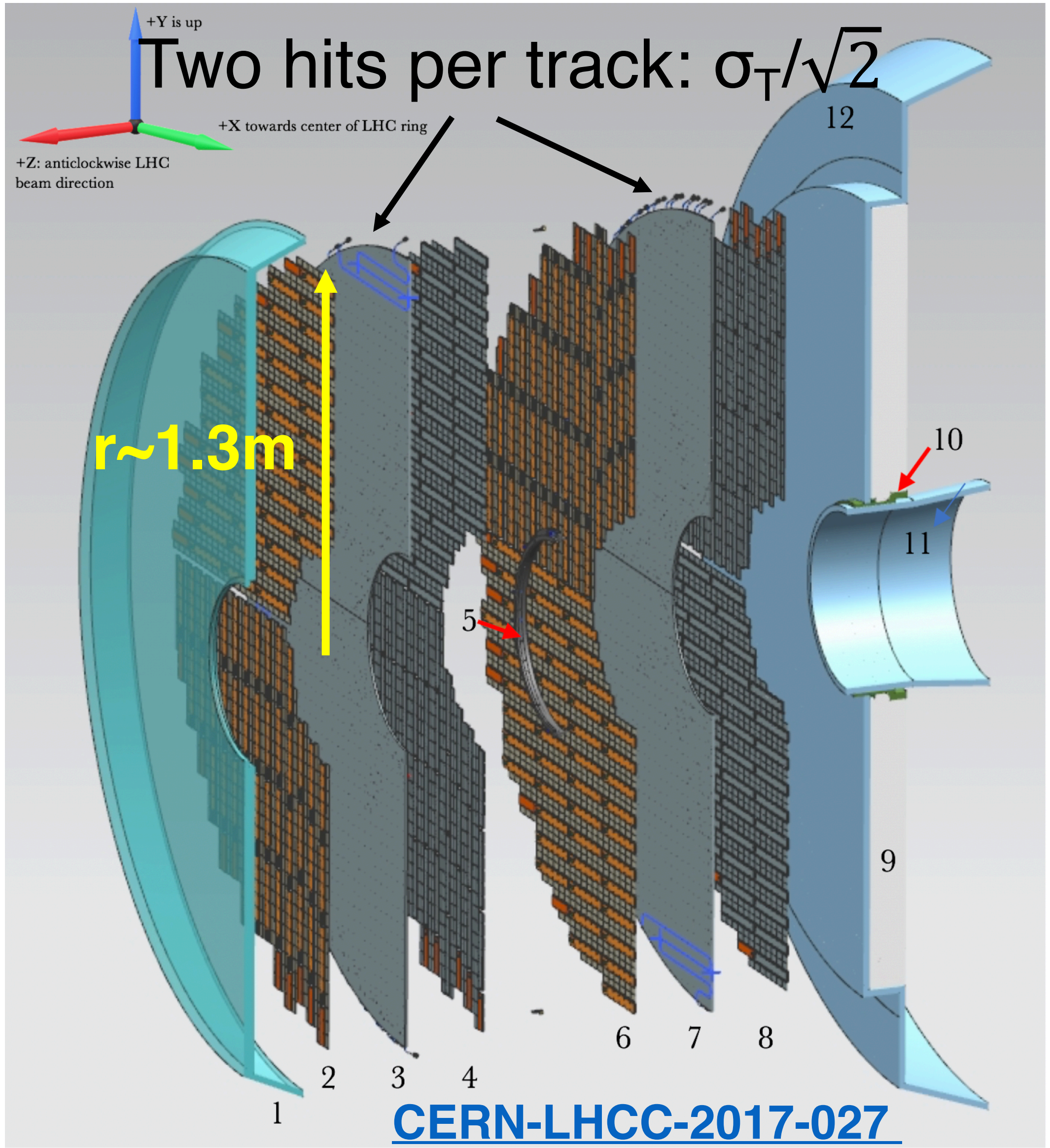


LGAD sensor for CMS ETL:

- Pixel size: 1.3 x 1.3 mm^2
- Thickness: 50 μm
- Time resolution: **σ_T ~ 30-50 ps** (over the lifetime of HL-LHC)

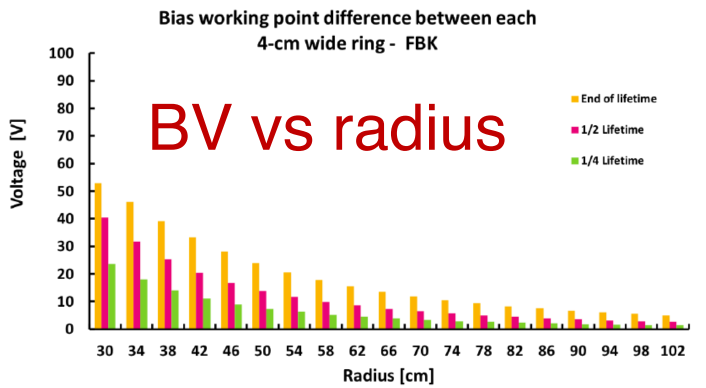
Vendors under consideration: HPK (Japan), FBK (Italy), CNM (Spain)

CMS Endcap Timing Layer (ETL)



Many challenges to overcome:

- ASIC chips: $\sigma_T \sim 30$ ps
- Clock distribution jitter: $\sigma_T \sim 10$ ps
- Radiation-hard: $\sim 2\text{x}10^{15}\ n_{eq}/cm^2$

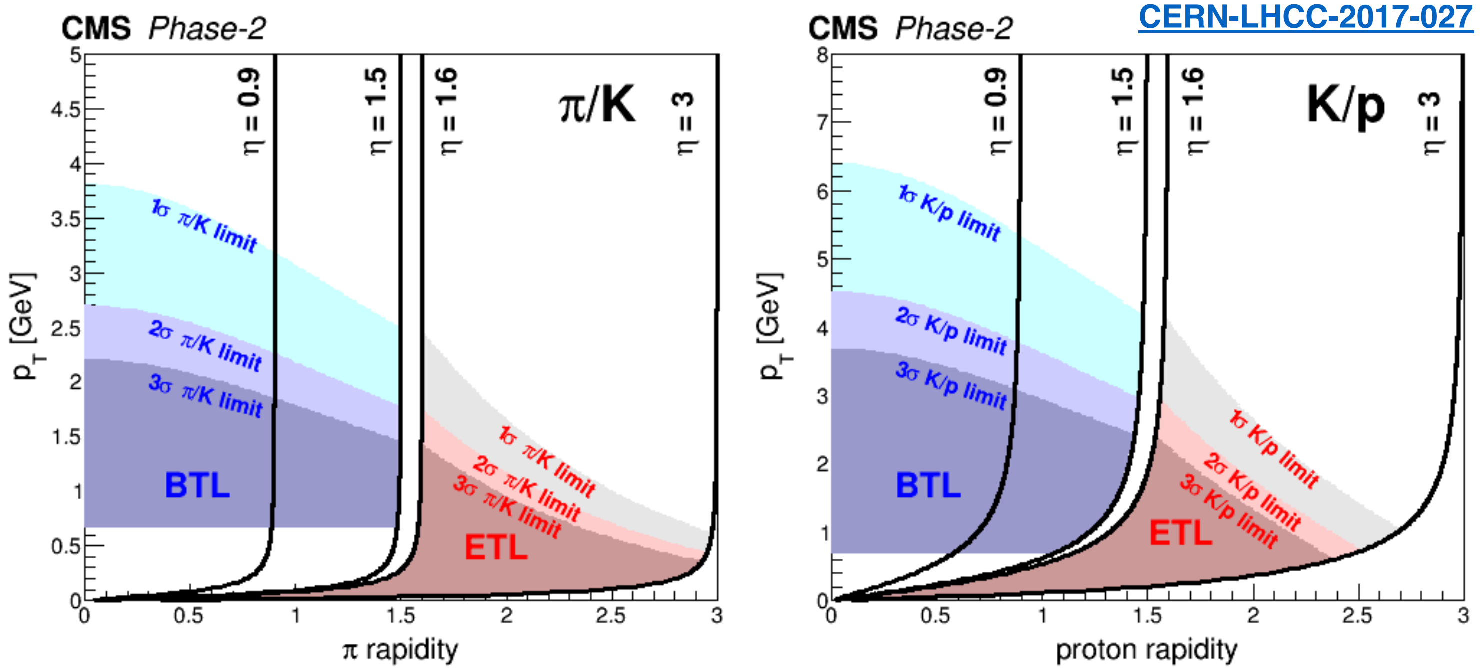


- Magnetic field tolerant: 4 T
- Mechanics and integration: 2.25cm / layer
- High DAQ rate: ~ MHz

Prototyping			Production		Assembly	
2020	2021	2022	2023	2024	2025	2026

Performance for PID with CMS-MTD

CERN-LHCC-2017-027



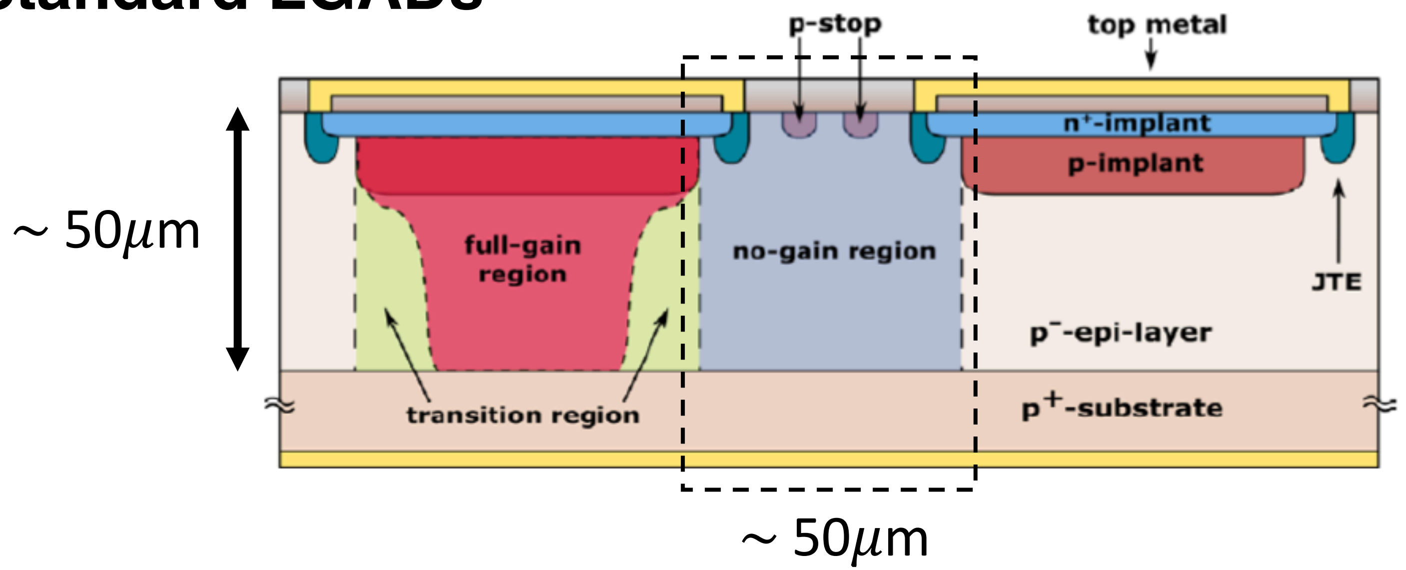
- p_T coverage comparable to STAR/ALICE
- **Unique wide η coverage**

A large coverage, LGAD-based TOF(-track) at EIC

- Significant synergies to leverage with the HL-LHC upgrade
- Advantage of no radiation constraints at the EIC

Limitations with CMS/ATLAS LGADs

Standard LGADs



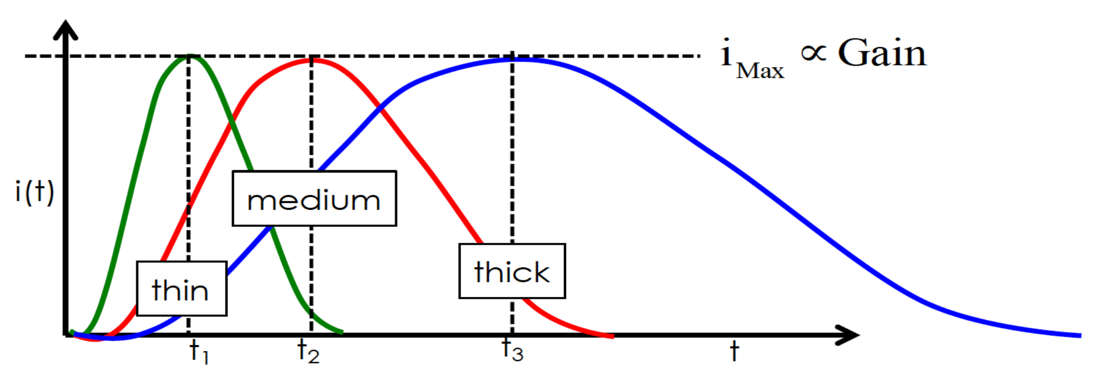
a) Time resolution ≥ 30 ps – *limited by thickness (rad. hard)*
b) Pitch size ≥ ~1 mm – *limited by no-gain region*

Not yet sufficient for TOF and/or tracker at the EIC

R&D paths toward the EIC detetor

(a) Time resolution

$$\sigma_t^2 = \boxed{\sigma_{jitter}^2 + \sigma_{Landau}^2} + \sigma_{distortion}^2 + \sigma_{TDC}^2$$



Go thinner to improve $\boldsymbol{\sigma_{jitter}}$ and $\boldsymbol{\sigma_{Landau}}$ (35, 30, 25, 20 μm)

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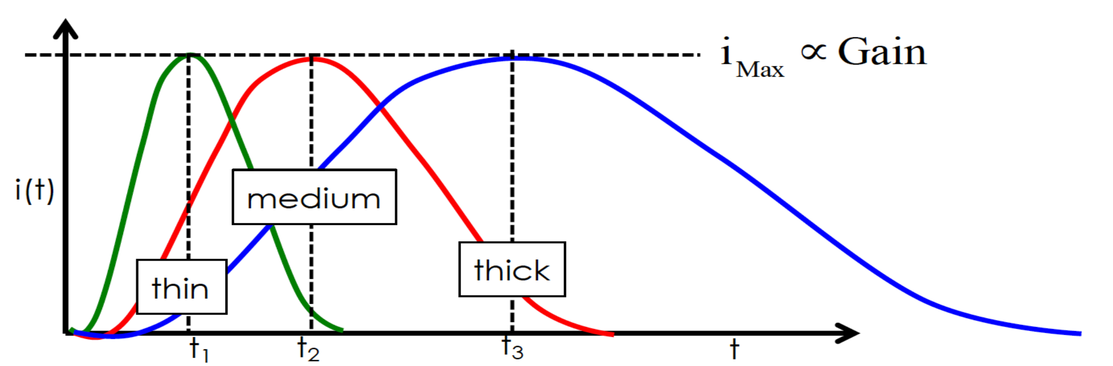

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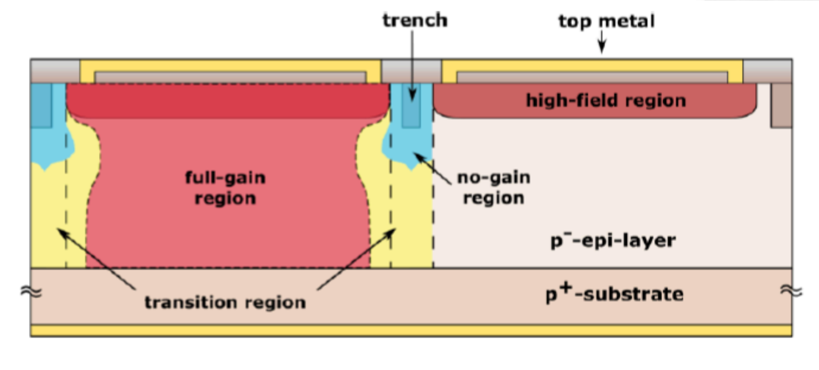
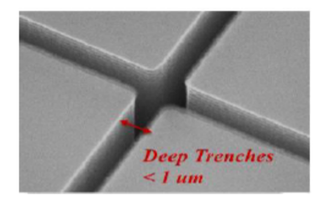
(b) Position resolution

- Trench-Isolated (TI) LGAD Eliminate no-gain zone





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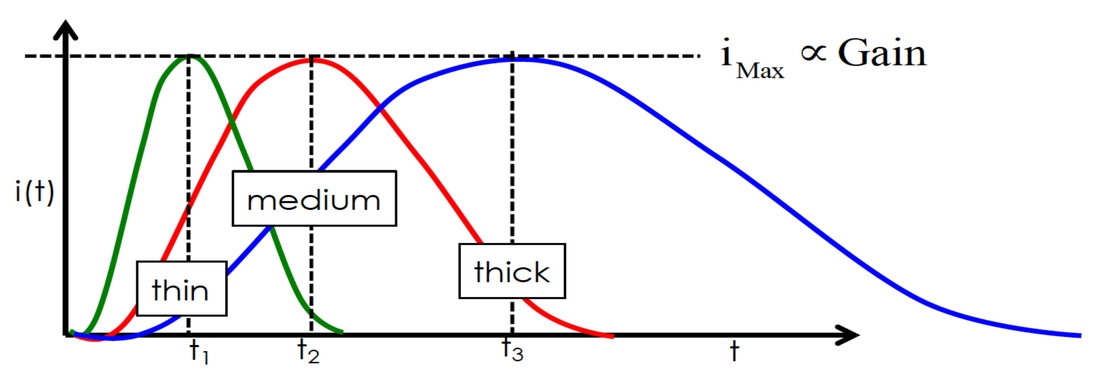

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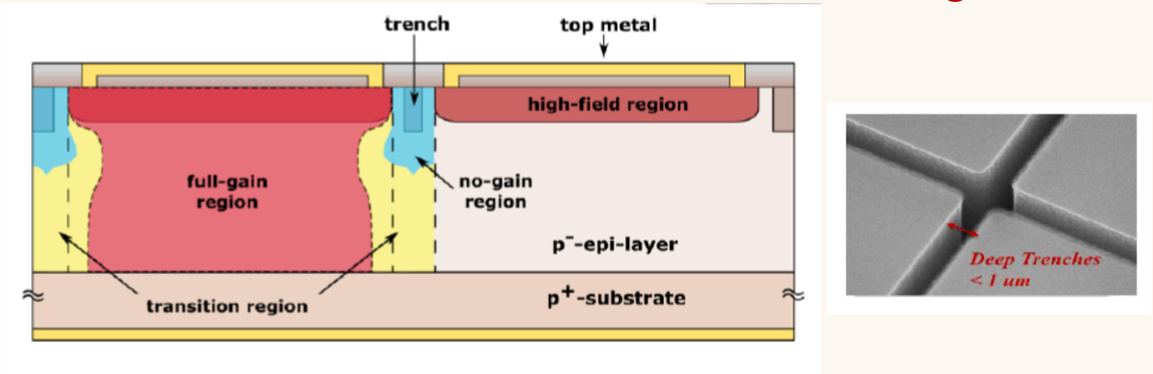
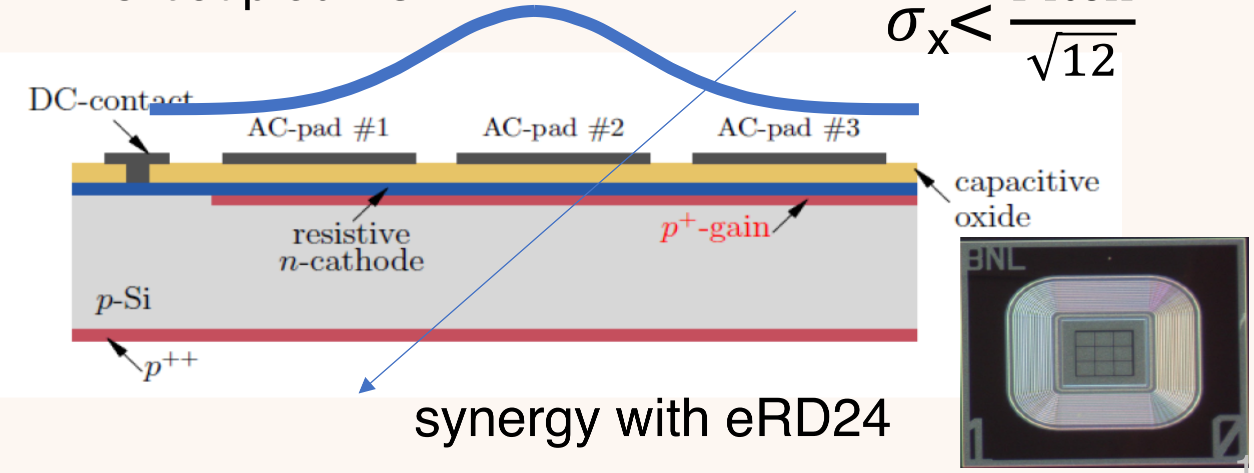


- AC-coupled LGAD

$$\sigma_x < \frac{\text{Pitch}}{\sqrt{12}}$$



synergy with eRD24

R&D paths toward the EIC detetor

(a) Time resolution

Our proposed activities

Deliverable 1 (10/2020–03/2021):
R&D of ultra-thin LGADs
– to achieve $\sigma_T \leq 20$ ps

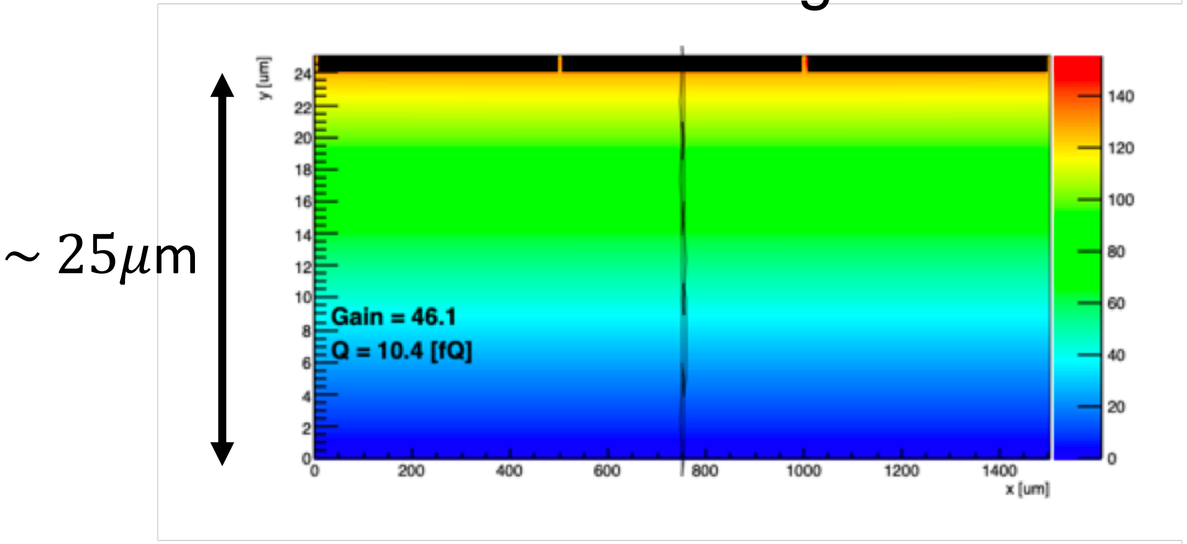
(b) Position resolution

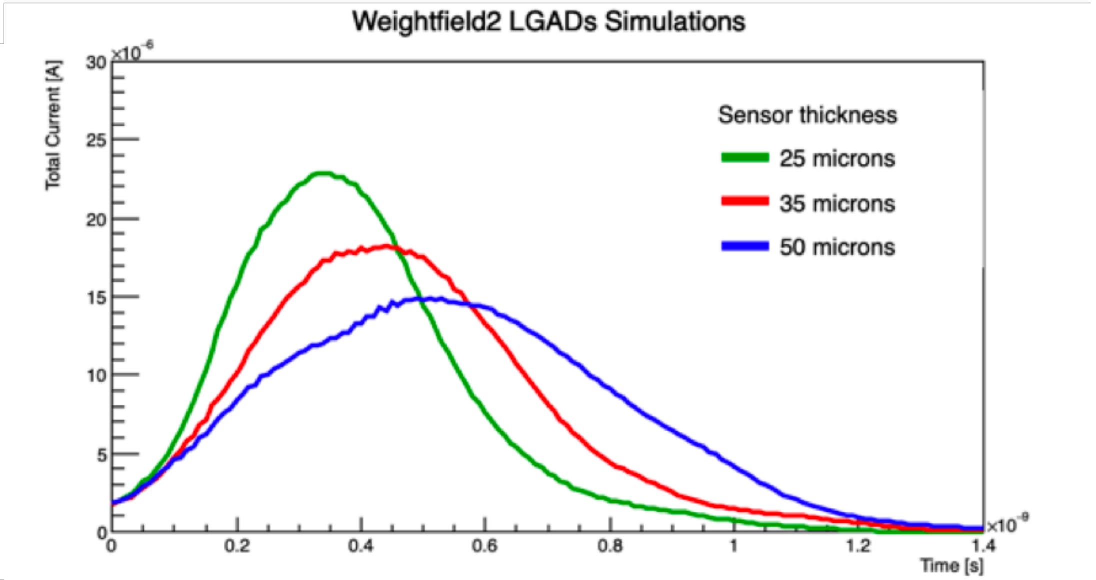
Deliverable 2 (10/2020–05/2021):
Simulations of a LGAD-based TOF-tracker
– to determine the pixel size

Deliverable 3 (03/2021–09/2021):
R&D of TI- and AC-LGADs
– to realize the pixel size needed

Deliverable 1: R&D of ultra-thin LGADs

Simulations with Weightfield2





Similar total charges $\geq$ 10 fC

Better time resolution of thinner LGADs predicted by simulations but optimal thickness and doping concentration with reasonable gains to be studied in detail and verified experimentally

Deliverable 1: R&D of ultra-thin LGADs

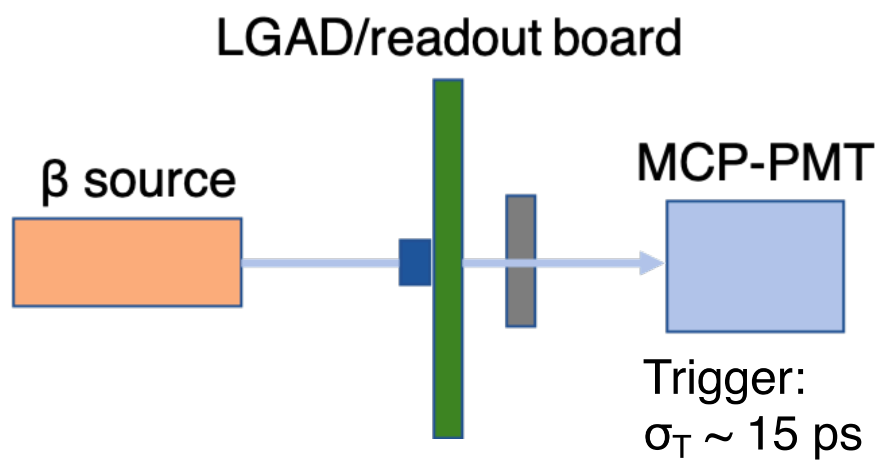
Proposed work:

1) Characterization of standard LGADs for various sensor thicknesses with lasers and sources.

- N. Cartiglia (Torino) will help obtain samples with 55, 45, 35 and 25 µm from FBK

2) Fabrication of thin LGADs at BNL in collaboration with the eRD24 team.

- the only LGADs producer in US and possibly a domestic vendor in longer term



Standard lab teststand of LGADs (available at KU, RICE, FNAL, BNL)

Beam tests for CMS ETL at FNAL foreseen next year

Deliverable 2: simulations of a LGADs TOF-tracker

Proposed work:

1) Realistic TOF-PID performance, including effects of start-time (T_0) determination, based on sensor time resolution achievable from work in Part I.

2) Determination of LGADs pitch sizes needed to achieve the required track momentum and back-pointing resolutions at EIC.

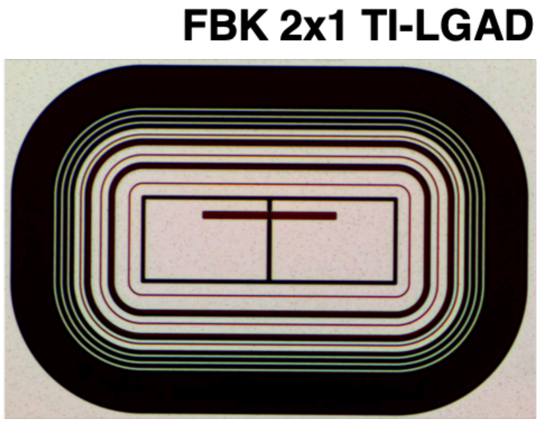
3) Studies of benefits from combined position and timing information to tracking.

Will perform in EIC common software framework
(eic-smear library, Fun4All)

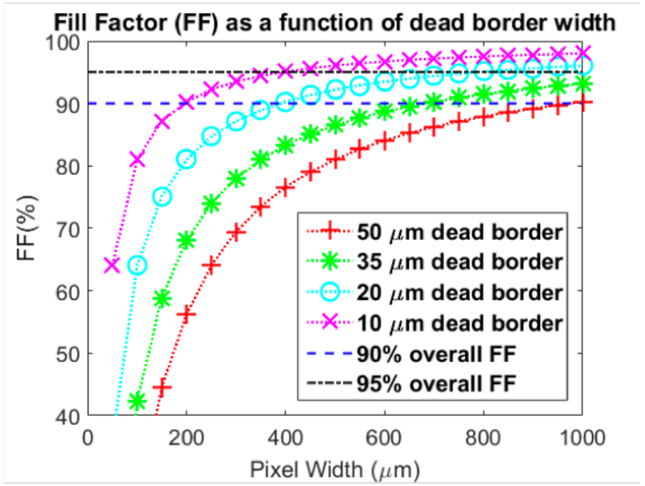
Deliverable 3: R&D of TI- and AC-LGADs

Proposed work:

1) Performance Studies of the TI-LGADs (FBK) and direct comparisons to standard LGAD at the same thickness (50 µm)



Pixel size: 0.375x0.25 mm²



G. Borghi, 34th RD50 Workshop

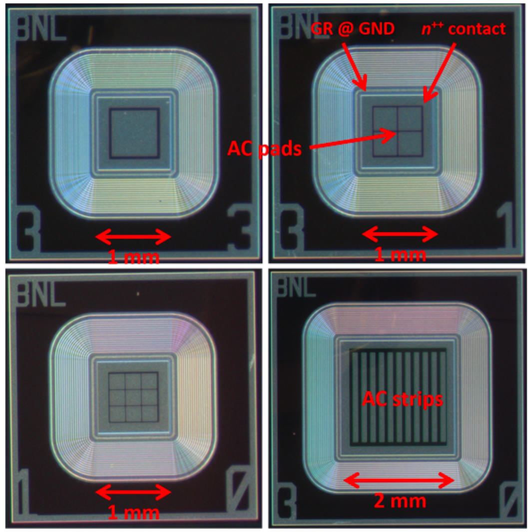
(a) (b)

If timing performance comparable (as expected), seek for production of TI-LGADs with desired thickness and pixel sizes determined in Part I & II (if possible and time allows)

Deliverable 3: R&D of TI- and AC-LGADs

2) Fabrication of AC-coupled LGADs with desired thickness and pixel sizes at BNL in collaboration with eRD24

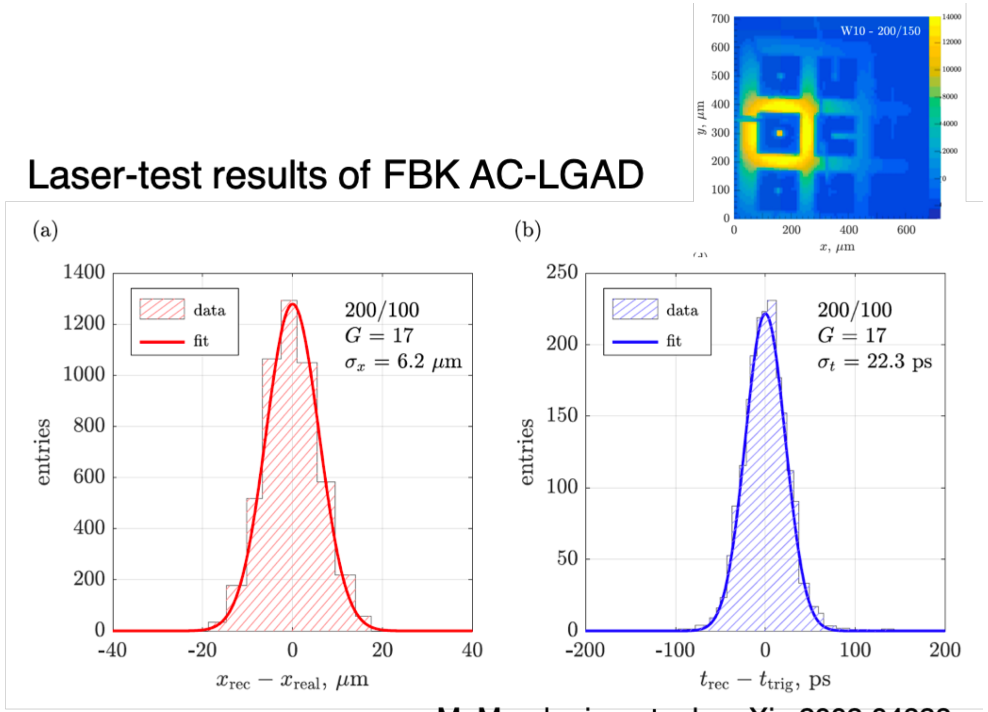
BNL AC-LGAD



G. Giacomini et. al., JINST 14 (2019) 09, P09004

(a)

Laser-test results of FBK AC-LGAD



M. Mandurrino et. al., arXiv:2003.04838

(b)

$\sigma_x \sim 6$ μm with a pitch size of 200 μm

Prospective on readout ASIC chips

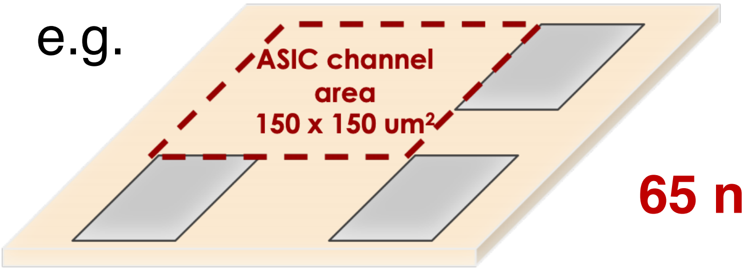
– outside the scope of this proposal but for the future

A common challenge to address in collaboration with eRD24

- Up to a pixel size of 500x500 μm², use ETROC/ALTIROC architecture (eRD24 focus in FY21)

- For even smaller pixels, major redesigns are necessary

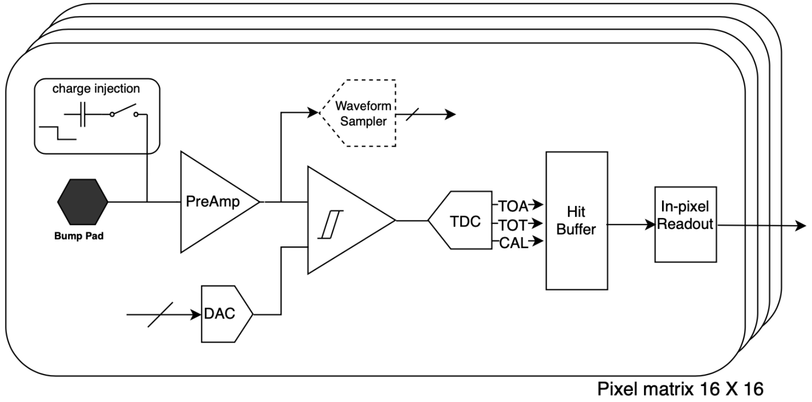
e.g.



65 nm → 28 nm (?)

EIC will drive the cutting-edge technology

CMS ETROC architecture



65nm process:

- Preamp.: 90 x 94 μm²
- Discriminator: 81 x 67 μm²
- TDC: 245 x 40 μm²

Budget

Costed Item	100%	80%	60%
Labor	$57k	$48k	$36k
M&S	$5k	$2k	$2k
Travel	$1k	$1k	0
Total	$63k	$51k	$38k

Labor: 0.6 FTE RICE postdoc + 1 FTE KU undergrad.
M&S: acquiring and fabricating LGAD sensors
Travel: minimal due to the COVID-19

Reduced scenarios:

- 80%: drop new sensor fabrication and focus on AC-LGADs only for Part III
- 60%: possibly only to pursue part I

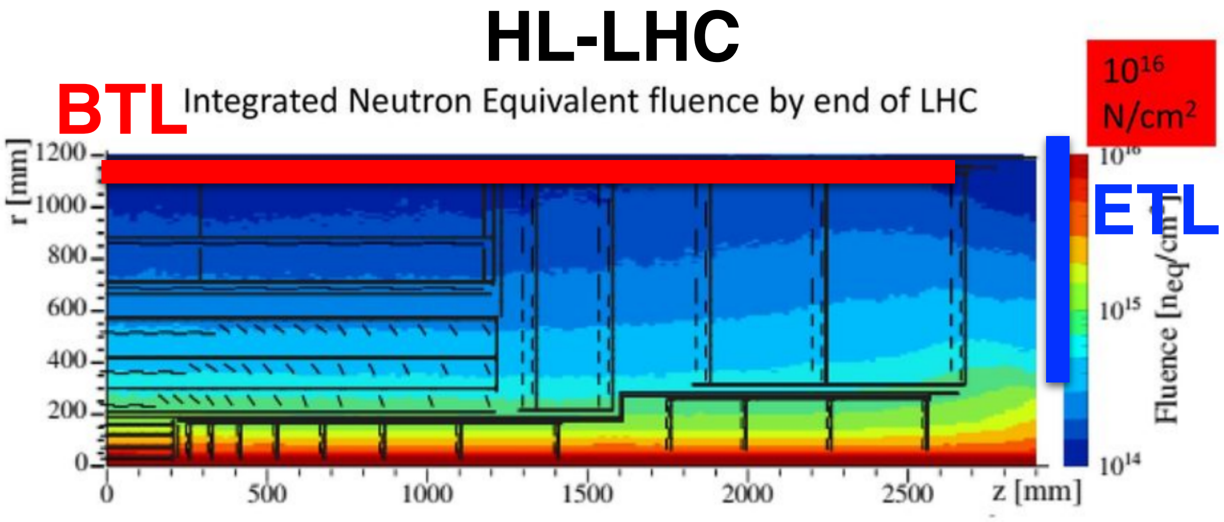
Contributed resources:

- 0.5 FTE RICE graduate + 0.5 FTE ORNL postdoc to lead the simulation work
- A. Novikov (post-doc), T. Isidori and F. Gautier (graduate) from KU on the NASA ANGILE project, will provide assistance to this project.
- All lab equipment and resources (leveraged from other projects).
- Additional travels if needed.

Backups

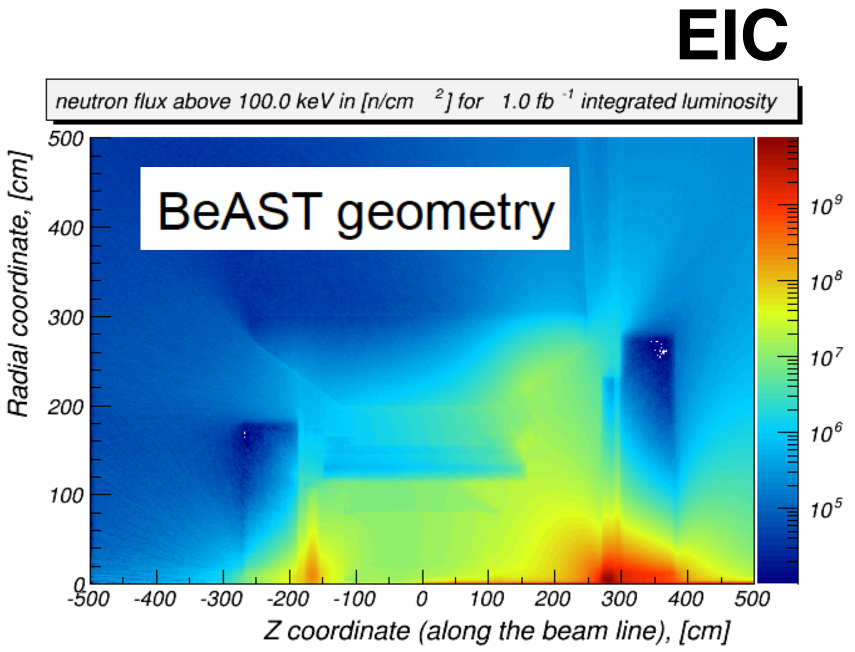
EIC: the next QCD frontier

Radiation fluence



~ $2x10^{14}$ n_{eq}/cm^2 for BTL

~ $2x10^{15}$ n_{eq}/cm^2 for inner radius of ETL



Up to 10^{11} n_{eq}/cm^2 over 10 yrs

Synergies between LHC and EIC but also different challenges:

- No radiation constraints for EIC – good for the entire lifetime
- Optimize for better time and position resolutions

EIC Detector Requirements

<table>
<tr><th rowspan="2">η</th><th colspan="3" rowspan="2">Nomenclature</th><th colspan="3">Tracking</th><th colspan="2">Electrons</th><th colspan="2">π/K/p PID</th><th>HCAL</th><th rowspan="2">Muons</th></tr>
<tr><th>Resolution</th><th>Allowed X/X_0</th><th>Si-Vertex</th><th>Resolution σ_E/E</th><th>PID</th><th>p-Range (GeV/c)</th><th>Separation</th><th>Resolution σ_E/E</th></tr>
<tr><td>-6.9 — -5.8</td><td rowspan="4">↓ p/A</td><td rowspan="4">Auxiliary Detectors</td><td>low-Q^2 tagger</td><td>$\delta\theta/\theta < 1.5\%$; $10^{-6} < Q^2 < 10^{-2}$ GeV^2</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>...</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>-4.5 — -4.0</td><td rowspan="2">Instrumentation to separate charged particles from photons</td><td></td><td></td><td></td><td rowspan="5">2%/√E</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>-4.0 — -3.5</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>-3.5 — -3.0</td><td rowspan="14"></td><td rowspan="14">Central Detector</td><td rowspan="5">Backwards Detectors</td><td rowspan="2">$\sigma_p/p \sim 0.1\% \times p + 2.0\%$</td><td rowspan="14">~5% or less</td><td rowspan="5">TBD</td><td rowspan="9">π suppression up to 1:10^4</td><td rowspan="5">≤ 7 GeV/c</td><td rowspan="14">≥ 3σ</td><td rowspan="5">~50%/√E</td><td></td></tr>
<tr><td>-3.0 — -2.5</td><td></td></tr>
<tr><td>-2.5 — -2.0</td><td rowspan="3">$\sigma_p/p \sim 0.05\% \times p + 1.0\%$</td><td></td></tr>
<tr><td>-2.0 — -1.5</td><td rowspan="2">7%/√E</td><td></td></tr>
<tr><td>-1.5 — -1.0</td><td></td></tr>
<tr><td>-1.0 — -0.5</td><td rowspan="4">Barrel</td><td rowspan="4">$\sigma_p/p \sim 0.05\% \times p + 0.5\%$</td><td rowspan="4">$\sigma_{xyz} \sim 20$ μm, $d_0(z) \sim d_0(r\phi) \sim 20/p_T$ GeV μm + 5 μm</td><td rowspan="11">(10-12)%/√E</td><td rowspan="4">≤ 5 GeV/c</td><td rowspan="4">TBD</td><td rowspan="4">TBD</td></tr>
<tr><td>-0.5 — 0.0</td></tr>
<tr><td>0.0 — 0.5</td></tr>
<tr><td>0.5 — 1.0</td></tr>
<tr><td>1.0 — 1.5</td><td rowspan="5">Forward Detectors</td><td rowspan="3">$\sigma_p/p \sim 0.05\% \times p + 1.0\%$</td><td rowspan="5">TBD</td><td></td><td rowspan="2">≤ 8 GeV/c</td><td rowspan="5">~50%/√E</td><td></td></tr>
<tr><td>1.5 — 2.0</td><td></td><td></td></tr>
<tr><td>2.0 — 2.5</td><td></td><td rowspan="2">≤ 20 GeV/c</td><td></td></tr>
<tr><td>2.5 — 3.0</td><td rowspan="2">$\sigma_p/p \sim 0.1\% \times p + 2.0\%$</td><td></td><td></td></tr>
<tr><td>3.0 — 3.5</td><td></td><td>≤ 45 GeV/c</td><td></td></tr>
<tr><td>3.5 — 4.0</td><td rowspan="4">↑e</td><td rowspan="4">Auxiliary Detectors</td><td rowspan="2">Instrumentation to separate charged particles from photons</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>4.0 — 4.5</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>...</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>> 6.2</td><td>Proton Spectrometer</td><td>$\sigma_{intrinsic}(|t|)/|t| < 1\%$; Acceptance: $0.2 < p_T < 1.2$ GeV/c</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Table 2: Physics requirements for a an EIC detector

[Electron-Ion Collider Detector Requirements and R&D Handbook]