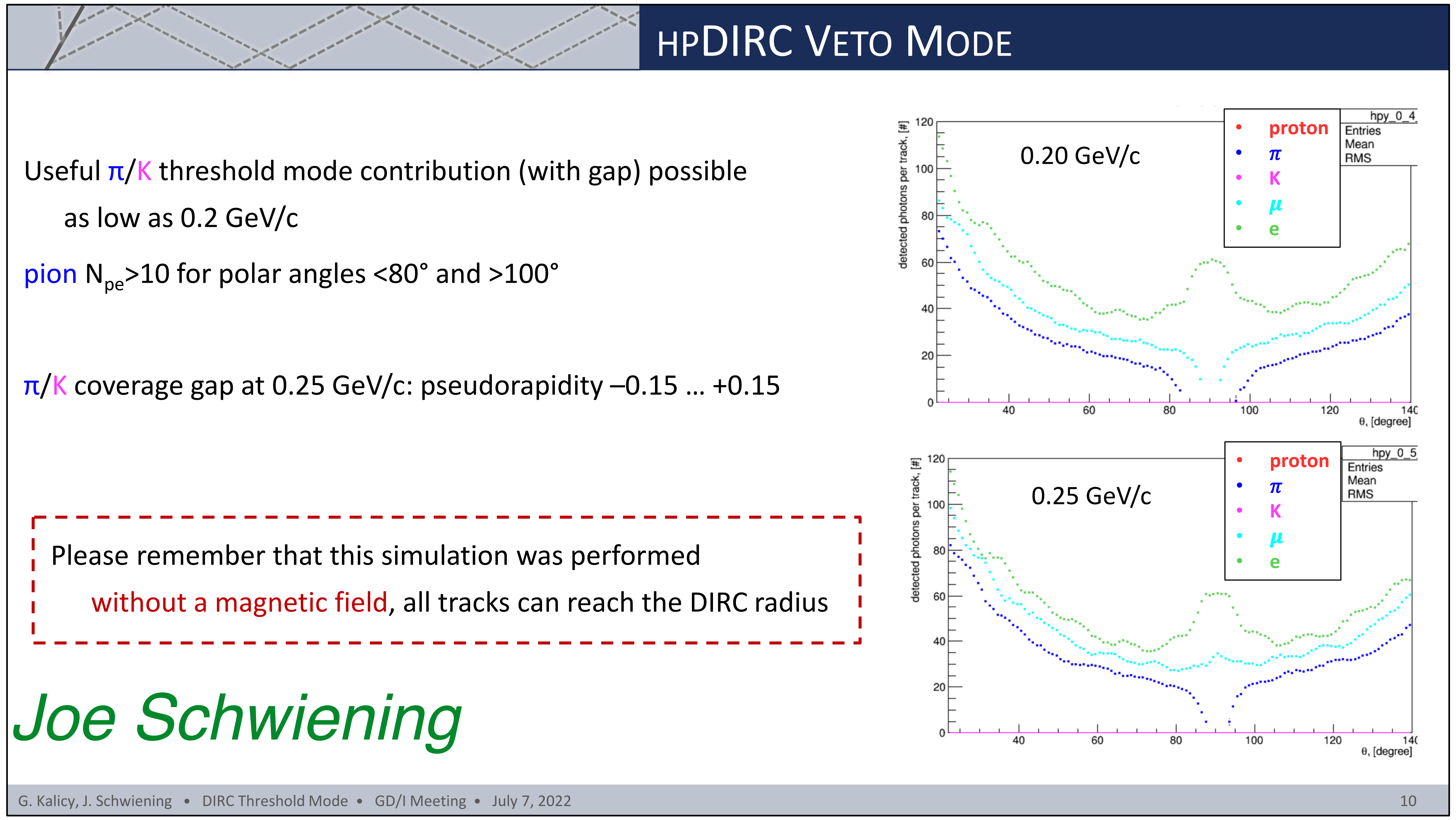
Evaluation of AC-LGAD based ToF in Backward Hemisphere

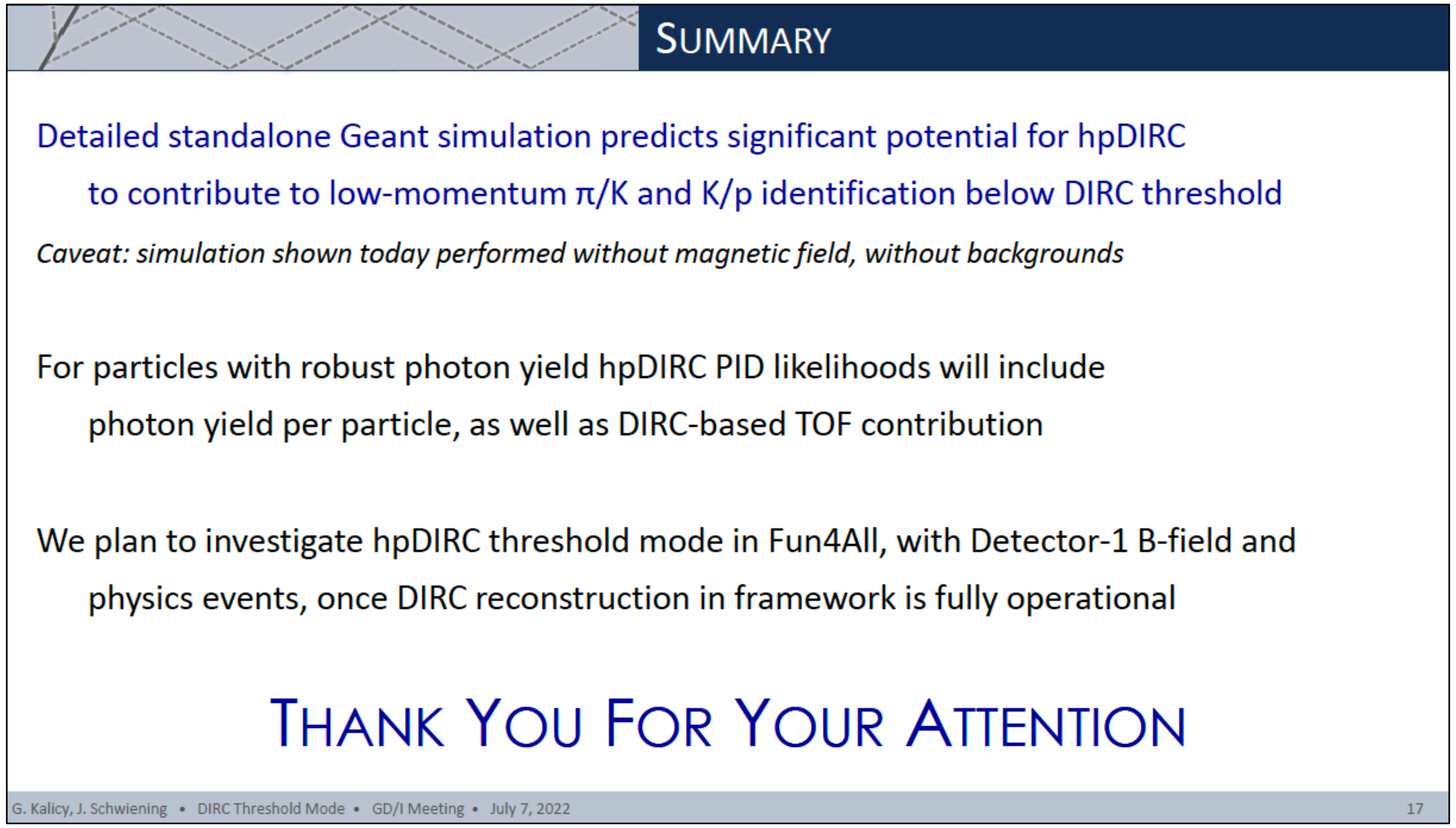
Thomas Ullrich on behalf of GD/I WG
ePIC Collaboration Meeting, JLab
Monday, January 9, 2023

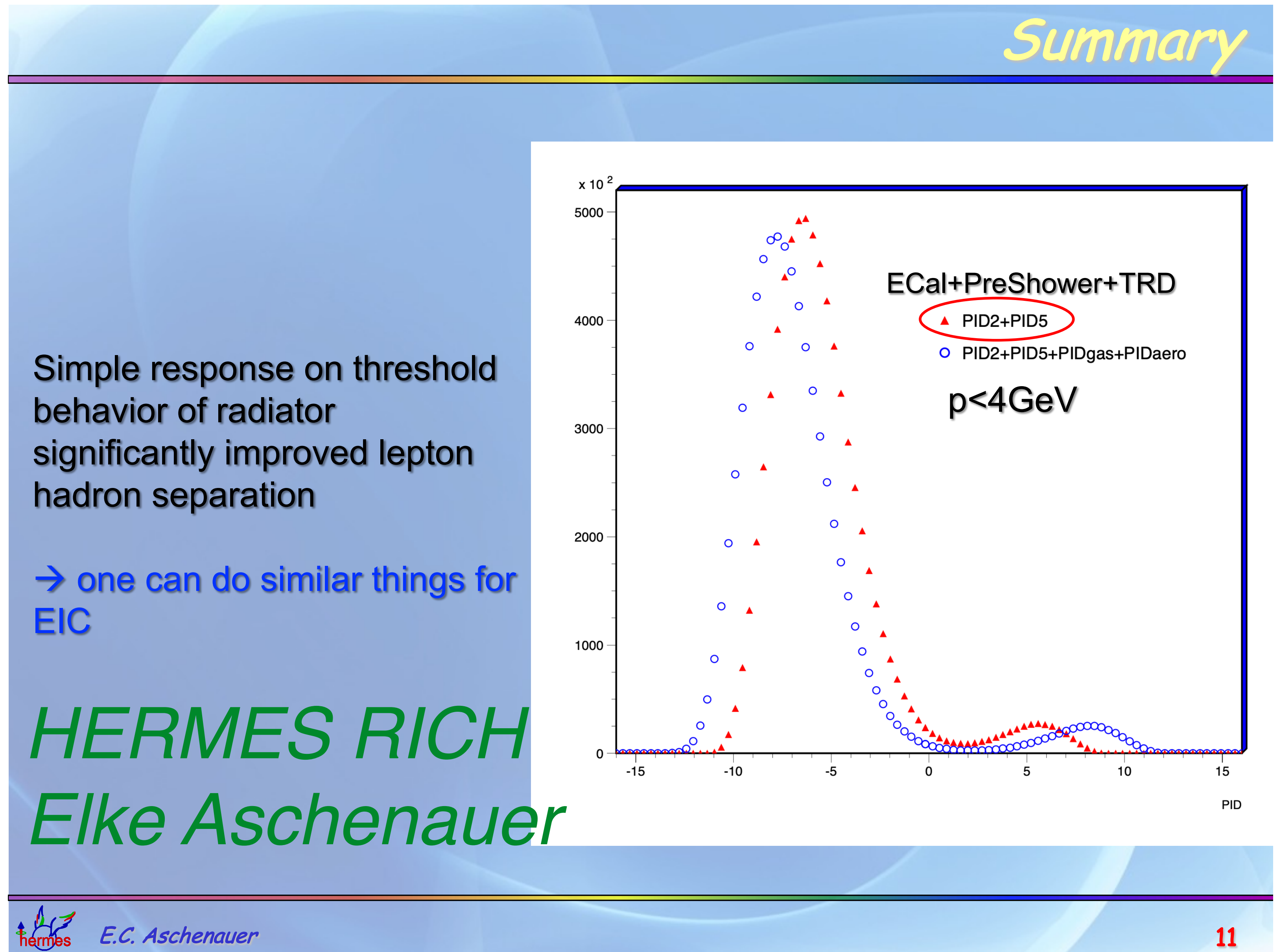
Early General ToF Evaluation (July 7, 2022 Meeting)

- ECCE baseline contained AC-LGAD in forward, barrel, and backward region for:
  - low-p PID
  - backward: provide t_0 for all ToF PID detectors ($|\eta| < 3.5$) from e'
- ATHENA baseline contained only barrel ToF (AC-LGAD)
- Reasons to have a second look
  - physics needs
  - material
  - heat/integration in tight region
- First step: What can ePIC do without dedicated low-p detectors?

RICH and hpDIRC in Threshold Mode







There seems to be good reasons to assume that threshold mode operation can extend our PID capabilities to lower p than anticipated, especially for K, π.

- experience from HERMES
- no studies of threshold/veto mode from BaBar, Belle II, GlueX, or PANDA

No Input on Low-p Requirements from YR

η	Nomenclature			Tracking				Electrons and Photons			π/K/p PID		HCAL		Muons
				Min p_T	Resolution	Allowed X/X_0	Si-Vertex	Min E	Resolution σ_E/E	PID	p-Range (GeV/c)	Separation	Min E	Resolution σ_E/E	
-6.9 — -5.8	↓ p/A	Auxiliary Detectors	low-Q² tagger		$\delta\theta/\theta < 1.5\%$; $10^{-6} < Q^2 < 10^{-2}$ GeV²										
…															
-4.5 — -4.0			Instrumentation to separate charged particles from γ						2%/√E+(1-3)%						
-4.0 — -3.5				100 MeV π 135 MeV K				50 MeV						~50%/√E+6%	
-3.5 — -3.0		Central Detector	Backwards Detectors		σ_p/p ~ 0.1%×p+2.0%	~5% or less	σ_{xy}~30µm/p_T+40µm			π suppression up to 1:10^4	≤ 7 GeV/c	≥ 3σ	500 MeV	~45%/√E+6%	Useful for bkg, improve resolution
-3.0 — -2.5															
-2.5 — -2.0					σ_p/p ~ 0.05%×p+1.0%		σ_{xy}~30µm/p_T+20µm								
-2.0 — -1.5									7%/√E+(1-3)%						
-1.5 — -1.0															
-1.0 — -0.5			Barrel		σ_p/p ~ 0.05%×p+0.5%		σ_{xyz} ~ 20 µm, $d_0(z)$ ~ $d_0(r\varphi)$ ~ 20/p_T GeV µm + 5 µm		(10-12)%/√E+(1-3)%		≤ 10 GeV/c			~85%/√E+7%	
-0.5 — 0.0															
0.0 — 0.5															
0.5 — 1.0											≤ 15 GeV/c				
1.0 — 1.5			Forward Detectors		σ_p/p ~ 0.05%×p+1.0%		σ_{xy}~30µm/p_T+20µm			3σ e/π	≤ 30 GeV/c			~35%/√E	
1.5 — 2.0											≤ 50 GeV/c				
2.0 — 2.5															
2.5 — 3.0					σ_p/p ~ 0.1%×p+2.0%		σ_{xy}~30µm/p_T+40µm				≤ 30 GeV/c				
3.0 — 3.5							σ_{xy}~30µm/p_T+60µm				≤ 45 GeV/c				
3.5 — 4.0	↑e	Auxiliary Detectors	Instrumentation to separate charged particles from γ												
4.0 — 4.5															
…															
> 6.2			Proton Spectrometer		$\sigma_{intrinsic}(\lvert t\rvert)/\lvert t\rvert$ < 1%; Acceptance: 0.2< p_T <1.2 GeV/c										

Much related to this evaluation has to do with the lack of a low-p PID requirements in the Yellow Report.

YR baseline detector as well as CDR detector feature no detectors for low-p PID

No Input on Low-p Requirements from YR

η	Nomenclatu			Tracking	Electrons and Photon	π/K/p PID	HCAL
-6.9 — -5.8	↓ p/A	Auxiliary Detectors	low				
...							
-4.5 — -4.0			Instru sepa par				
-4.0 — -3.5							
-3.5 — -3.0		Central Detector	Ba D				
-3.0 — -2.5							
-2.5 — -2.0							
-2.0 — -1.5							
-1.5 — -1.0							
-1.0 — -0.5							
-0.5 — 0.0							
0.0 — 0.5							
0.5 — 1.0							
1.0 — 1.5			F D				
1.5 — 2.0							
2.0 — 2.5							
2.5 — 3.0							
3.0 — 3.5							
3.5 — 4.0	↑e	Auxiliary Detectors	Instru sepa par				
4.0 — 4.5							
...							
> 6.2			Spe				

Solution: Ask the Physics Working Groups (July 11, 2022)

```
Dear Physics Working Group Convener,

We would like to remind you (and provide a bit more information) on the
_urgent_ need to investigate the requirements for low-momentum PID coverage.

As you know, the Yellow Report specifies the needed K/pi, pi/p
separation but does not discuss in detail the lower edge of the momentum
range.

We would like you to focus on the barrel and the forward region. In
terms of the barrel, we would like you to look at he slides from Joe
from the July 7 GD/I meeting:

https://indico.bnl.gov/event/16314/contributions/65336/attachments/42008/70364/20220707-hpDIRC-
threshold-mode-schwiening.pdf

This shows that the DIRC potentially can provide PID through
threshold/veto down to ~250 MeV/c. This is now being further studied by
the hpDIRC group. The question now is: *do we need to have PID below 250
MeV/c in the barrel?* How strong a physics case is there and what would
we lose if we do not cover the region?

The situation is a bit different in the fwd region. Here it is mainly
the dRICH aerogel threshold that sets the limit at low-p.
3 < p < 60 (K/pi)
0.85 < p < 15 (e/pi)
In threshold mode the K/pi lower limit can probably be pushed down to ~1
GeV according to studies.

So again: *what would we lose if we do not have PID below 1~ GeV in the
fwd region?*

Some of these studies will not need full simulations. Much can be done
already on the generator level with simple cuts on PID. We kindly ask
you to focus on this issue in the next few weeks. A better understanding
of the low-p PID requirements is of enormous relevance for the detector
design.

We also would like to emphasize that key physics measurements (featured
in WP/NAS) have priority here as we have to ensure their feasibility. We
understand that there is always a corner of physics that people find
interesting and that stretches the requirements but we need to focus on
our main topics.

We plan to have a GD/I meeting on your findings sometimes in August. We
hope that provides sufficient time to conduct the necessary studies.

Best regards
GD/I conveners
```

ated to this
n has to do
ack of a
)
ents in the
eport.

ine
as well as
ector
o detectors
PID

Backward AC-LGAD ToF Comes Into Focus

GD/I WG: Physics Requirements

Monday Sep 19, 2022, 9:00 AM → 11:00 AM US/Eastern

Description Zoom connection: https://bnl.zoomgov.com/j/1612787551?pwd=VzBZYVpsMGM3TnpMRHl2K1puOFd5Zz09

Meeting ID: 161 278 7551
Passcode: 707179
One tap mobile
+16692545252,,1612787551#,,,,*707179# US (San Jose)
+16468287666,,1612787551#,,,,*707179# US (New York)

Recording from ZOOM

https://bnl.zoomgov.com/rec/share/7tMJRxRmdZqWCf6ztWjYfOGJq2MrcWDkuLmhB8tbtjHK1taGA1vqAw3aOUZIlbxo.ZdD_4Sec6XveWbev
Passcode: Q^jSWv0k

There are minutes attached to this event. Show them.

9:25 AM → 9:45 AM **Backward end-cap integration** 20m
Speakers: E. C. Aschenauer (BNL), Rolf Ent (Jefferson Lab)
GDI_ePIC.09.19.20...

9:45 AM → 10:05 AM **Electron detection requirement from inclusive WG** 20m
Speaker: Barak Schmookler (UC Riverside)
EPIC_091922.pdf | Report

10:05 AM → 10:45 AM **Low pT hadron ID (pi/K, K/Proton)** 40m
First discussion | VM study

low pT impact on HF reconstruction 20m
Speakers: Wenqing Fan (Lawrence Berkeley National Laboratory), Wenqing Fan (Lawrence Berkeley National Laboratory)
ePIC_GDI_PID_wenqin...

SIDIS WG studies 20m
Speakers: Anselm Vossen (member@duke.edu;faculty@duke.edu), Anselm Vossen (Duke University)
SIDIS_GDI_lowPtPerfor...

September 19, 2022

- First reports from Physics Working Groups on low-p PID needs
- Integration Issues with backward AC-LGAD ToF reported
- Outcome caused GD/I to focus solely on backward region

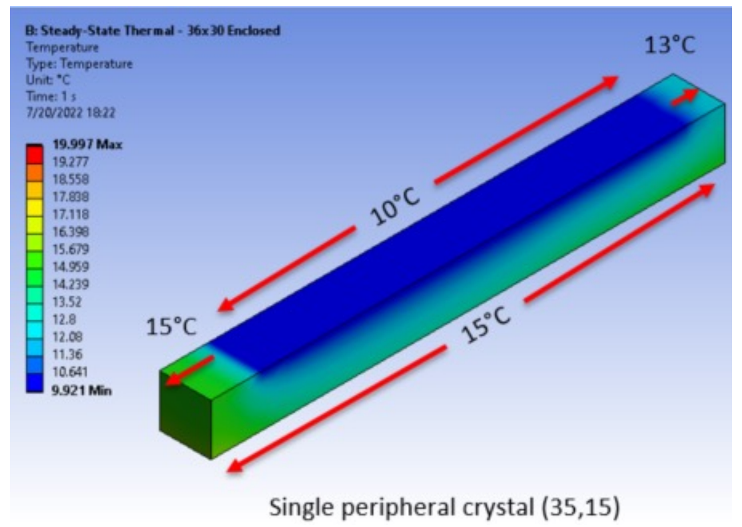
Slides from Elke/Rolf on Backward ToF Integration

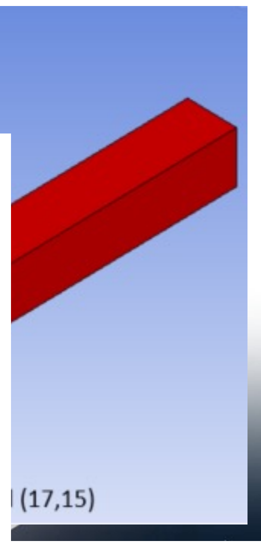
ETOF Power budget

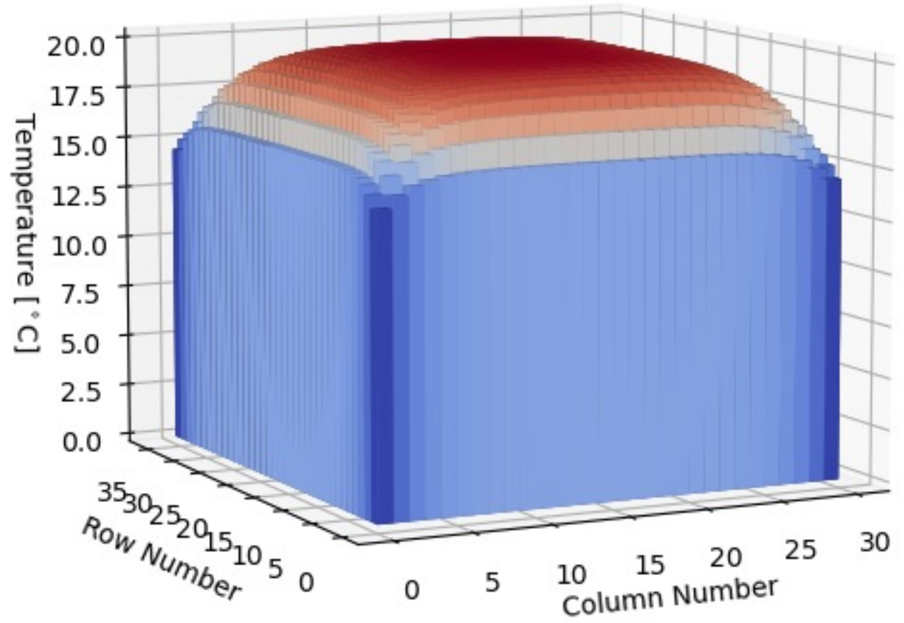
	Forward	Backward
Sensors	0.6kW	0.35kW
EPTROC	8.5kW (17kW)	4.8kW (9.6kW)
DC-DC	3.5kW	2kW
lpGBT, VTRx+, SCA	0.5kW	0.3kW
Power cables	0.5kW	0.3kW
Total	13.6kW (22.1kW)	7.75 (12.55kW)

The Issue with Heat Near the PbWO4 Calorimeter

In this ANSYS/FLUENT calculation the ambient room temperature is 20° C and we apply a temperature of 10°C on the outside periphery. Recall that the PbWO4 light yield has a temperature sensitivity of 2-2.5% per °C. The precision relies on a stable temperature. This is for the NPS in Hall C, that has 30 x 36 PbWO4 crystals.



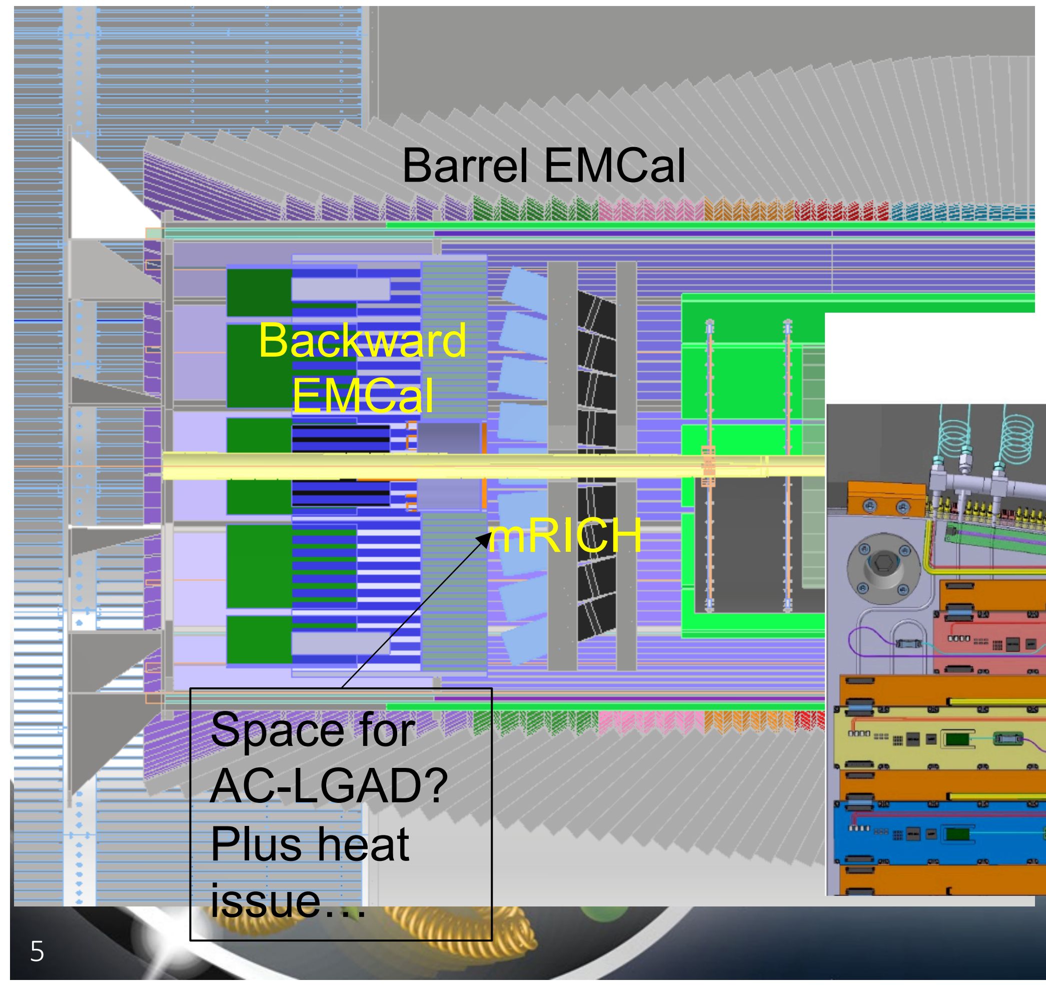


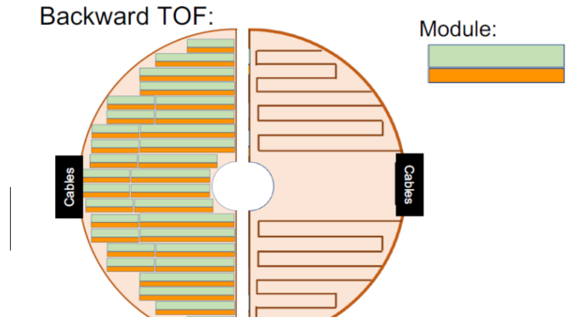


- Increasing worries that a heat source as the AC-LGAD ToF in front of backward EMCAL has potential to deteriorate the much needed energy resolution that is hard or impossible to correct for.

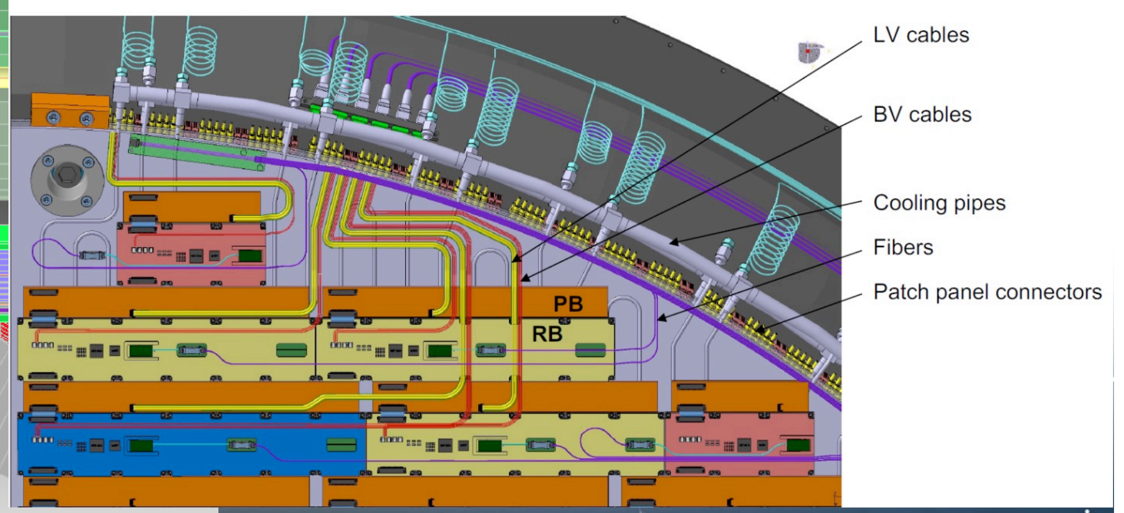
Integration Progress – Backward Detectors

- Backward EMCal is crucial for EIC, and we rely on it's high-precision performance.
- It has to be in a stable ambient temperature environment (< +/- 1° C)
- Even if material at the front face will not affect performance much, materials further away will and have to be minimized.
- AC-LGAD would provide both material and "a toaster" nearby…





Service routing in CMS ETL



Summary

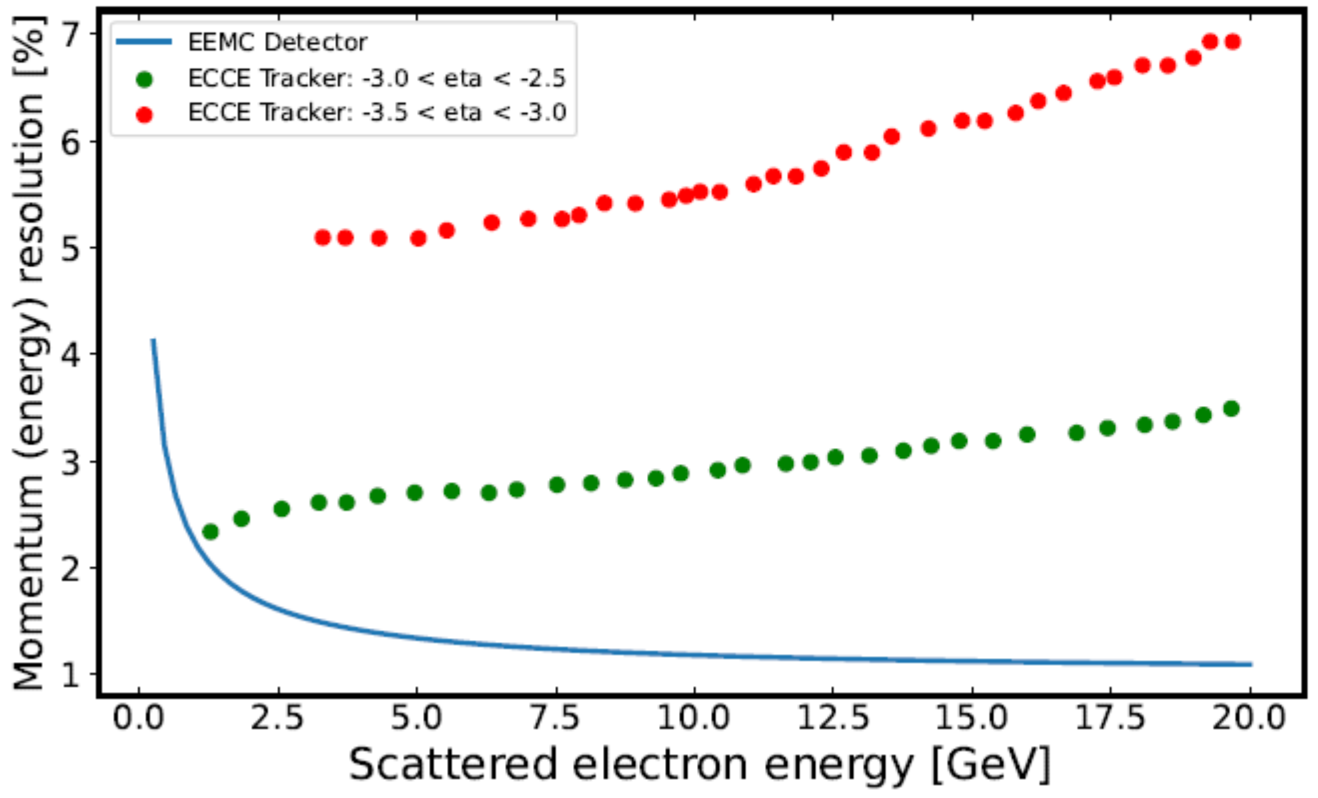
- It is crucial we do not optimize detector systems in isolation but directly look at the integration issues, including service needs (readout, cabling, cooling, …).
- The EIC science relies heavily on a high-resolution PbWO4-based electromagnetic calorimeter in the backward direction
  - This has implications for the material budget for the other backward-region detectors in front of it – one must obey the total integrated amount and localization of tolerable materials, which are additive (as % of formulated regions).
  - For example, if I need 10%X/X0 in the close-to-collision region, that's all. If I use Cu tubing for cooling with 2 mm wall thickness near the PbWO4, that may be all.
  - This has implications in that the backward EM calorimeter relies on a stable ambient temperature (+/- 1° C) to achieve high-precision performance, and thus prevents existence of large heat sources nearby.
- Folding in realistic readout space needs for any backward RICH detector invokes space budget issues.
- We suggest to consider study of a backward RICH detector based on LAPPD readout, even if there are also quantum efficiency issues to solve there, it may be the most practical solution compatible with EIC science needs and integration constraints.

Inclusive Physics PWG

Barak Schmookler

Momentum (energy) resolution

- The momentum (energy) resolution requirements for the scattered electron given in the yellow report are sufficient for all inclusive measurements.
- One important consideration is how best to perform the momentum (energy) reconstruction for the scattered electron in the electron endcap.
- If we consider again the case where we are interested in physics processes with $Q^2 > 1$ GeV^2, we see from the plot above that we only need to measure scattered electrons with energy greater than 5 GeV for $\eta < -3.0$.
- The higher Q^2 electron momentum reconstruction at these backwards angles will therefore rely on the EEMC detector, as can be seen in the right plot.



The tracking resolution curves shown above come from figure 2.7 in the ECCE proposal. The EEMC resolution is drawn assuming a 2% stochastic term and a 1% constant term.

9/19/2022 11

Electron purity

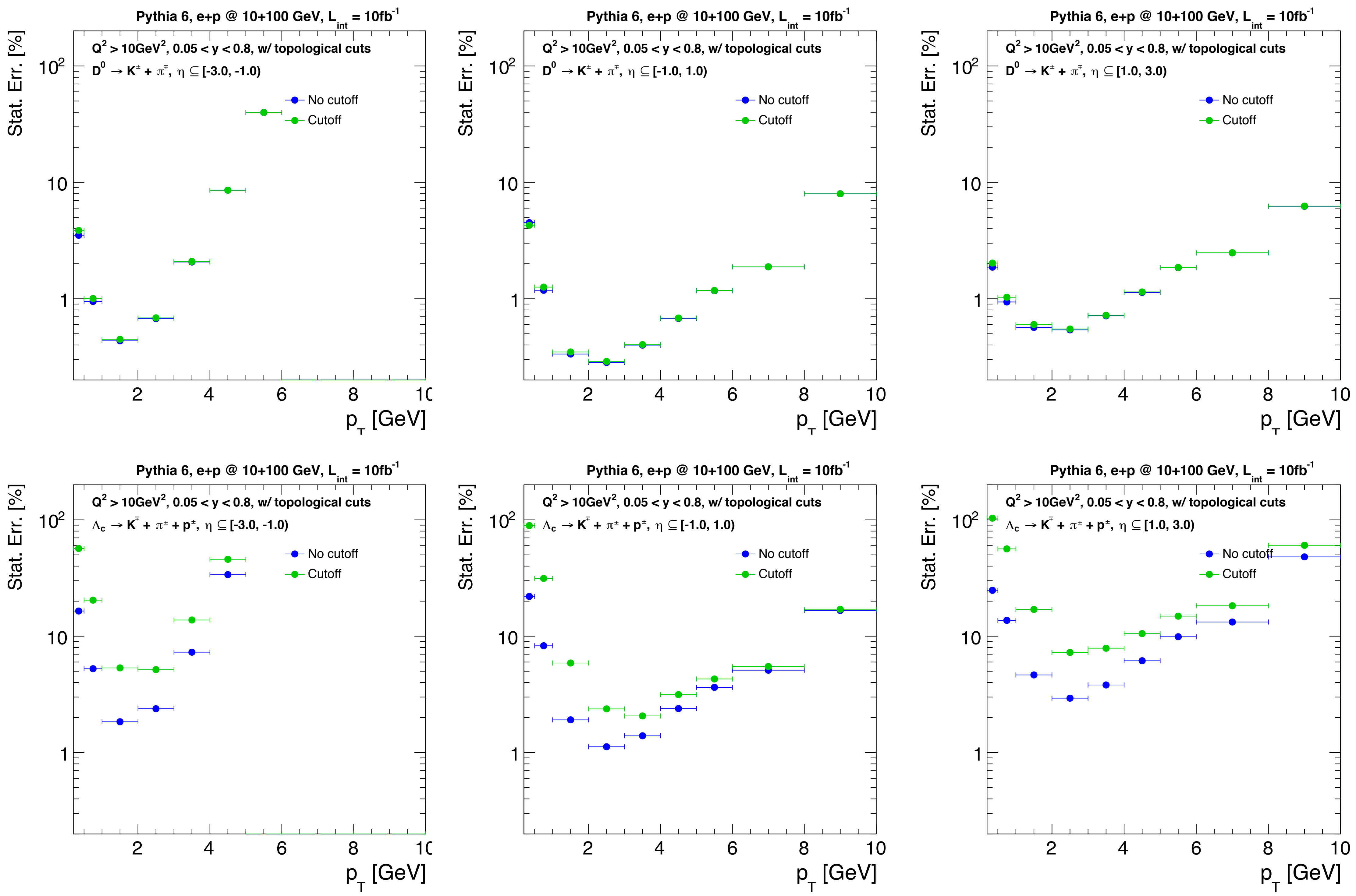
- Requirements on the scattered electron purity were determined by the inclusive working group during the yellow report. The requirement is given as 99% electron purity over the entire detector. This requirement is quite stringent and can be relaxed in certain regions of kinematic phase space, but there are a few good reasons to initially try to achieve this most stringent requirement:
  1. The most challenging place to meet the electron purity requirement is in the barrel region (see next slides). This has to do with the cross section dependence on Q^2, the momentum distribution of the negative pion background and the fact that, for $Q^2 > 1$ GeV^2 for example, lower momentum electrons only need to be reconstructed for more central pseudo-rapidities.
  2. As demonstrated in all the detector proposals – albeit using parameterized detector responses – the combination of tracking, EmCal, PID, and kinematic cuts can significantly remove the negative pion background. This suggests the more stringent requirement may be achievable. Once an adequate 'electron finder' algorithm is in place, electron purity will be a useful benchmark to compare detector configurations.
  3. During the yellow report, many of the physics studies done by groups other than the inclusive group assumed perfect electron purity and reconstruction efficiency. It is not obvious how sensitive these physics measurements are to the scattered electron identification, and so keeping a more stringent requirement would be wise for now.

- Program relies massively on the quality of the EMCs, especially backwards
- $Q^2 > 1$: p > 5 GeV^2
- No physics requirements in backward region for low-p PID

Heavy Flavor

Stat. Err. at different η and p_T

13/18



Physics impact

18/18

- Negligible impact on D^0 meson
  - Charm F_2, gluon helicity, gluon TMD measurements via D^0 will not be affected
- Larger impact on Λ_c baryon
  - Charm hadron double ratio R_{eA}: negligible impact on D^0 meson, about a factor of 2 stat. err. increase for Λ_c
  - Λ_c/D^0 ratio to study hadron chemistry: increasing impact at low p_T range and forward rapidity

Figure from ATHENA proposal (credit: Yuanjing Ji)

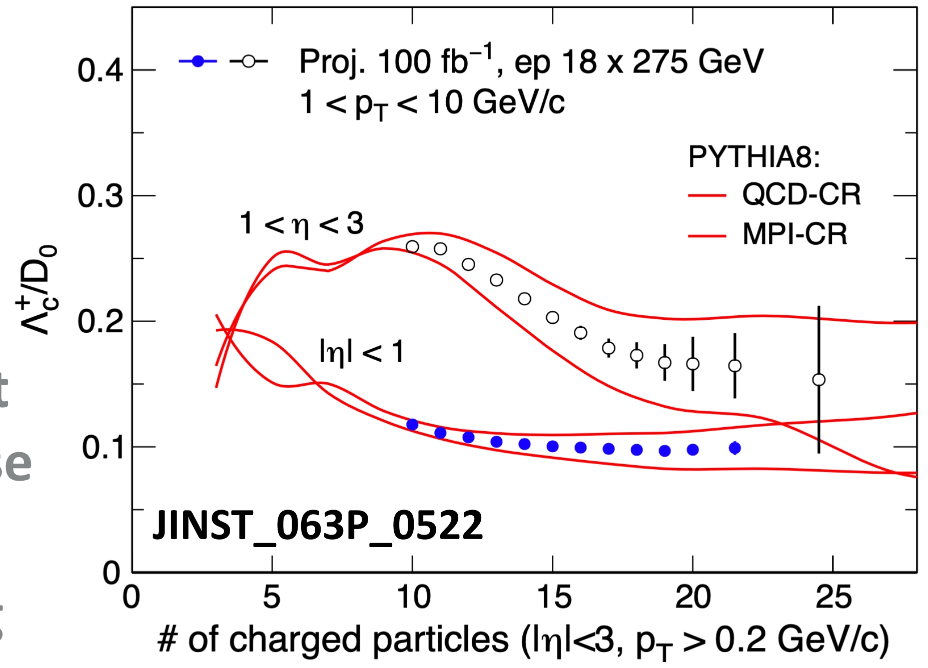
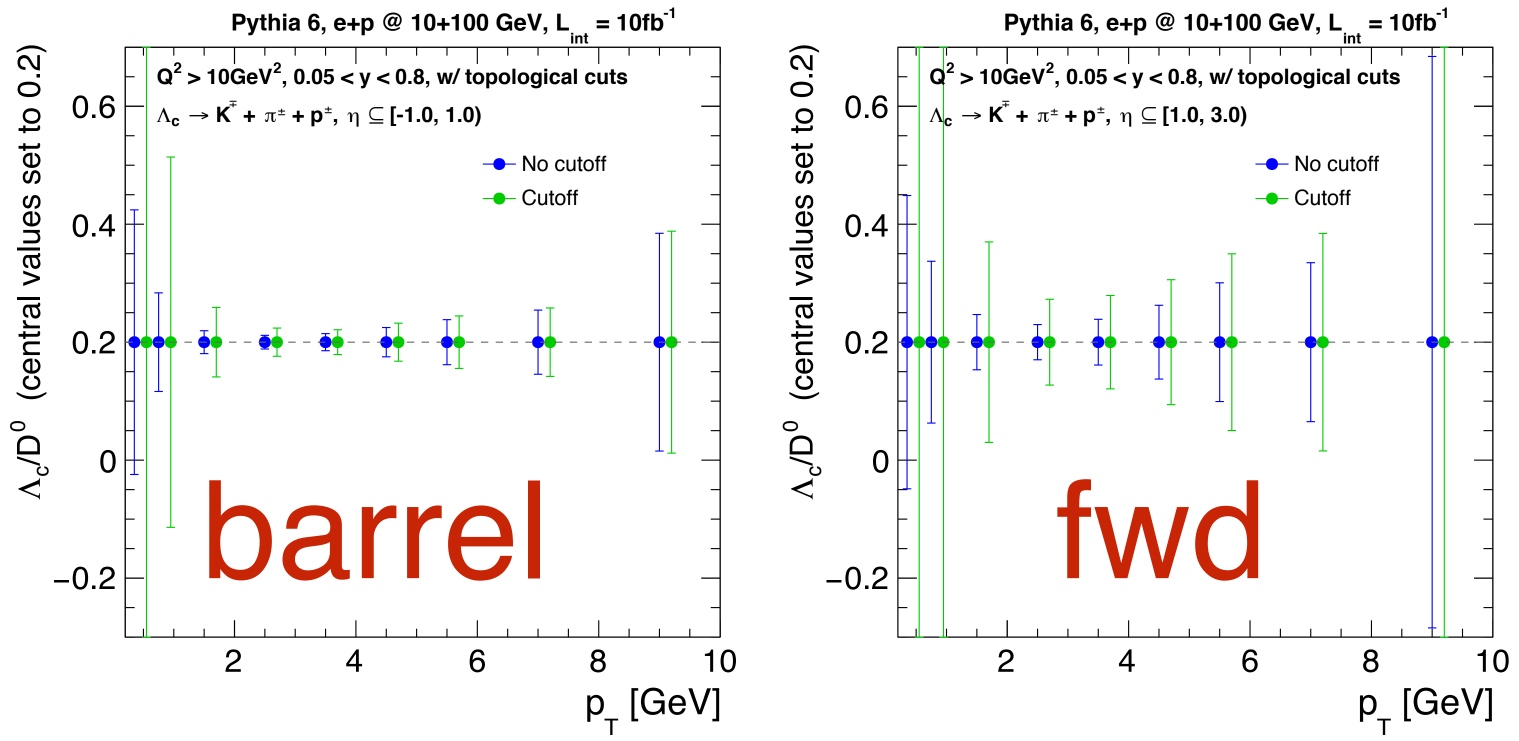


Figure 3.28: Projections for ATHENA measurements of the heavy-quark Λ_c^+ to D^0 baryon-to-meson ratio as a function of the charged track multiplicity (FastSim).



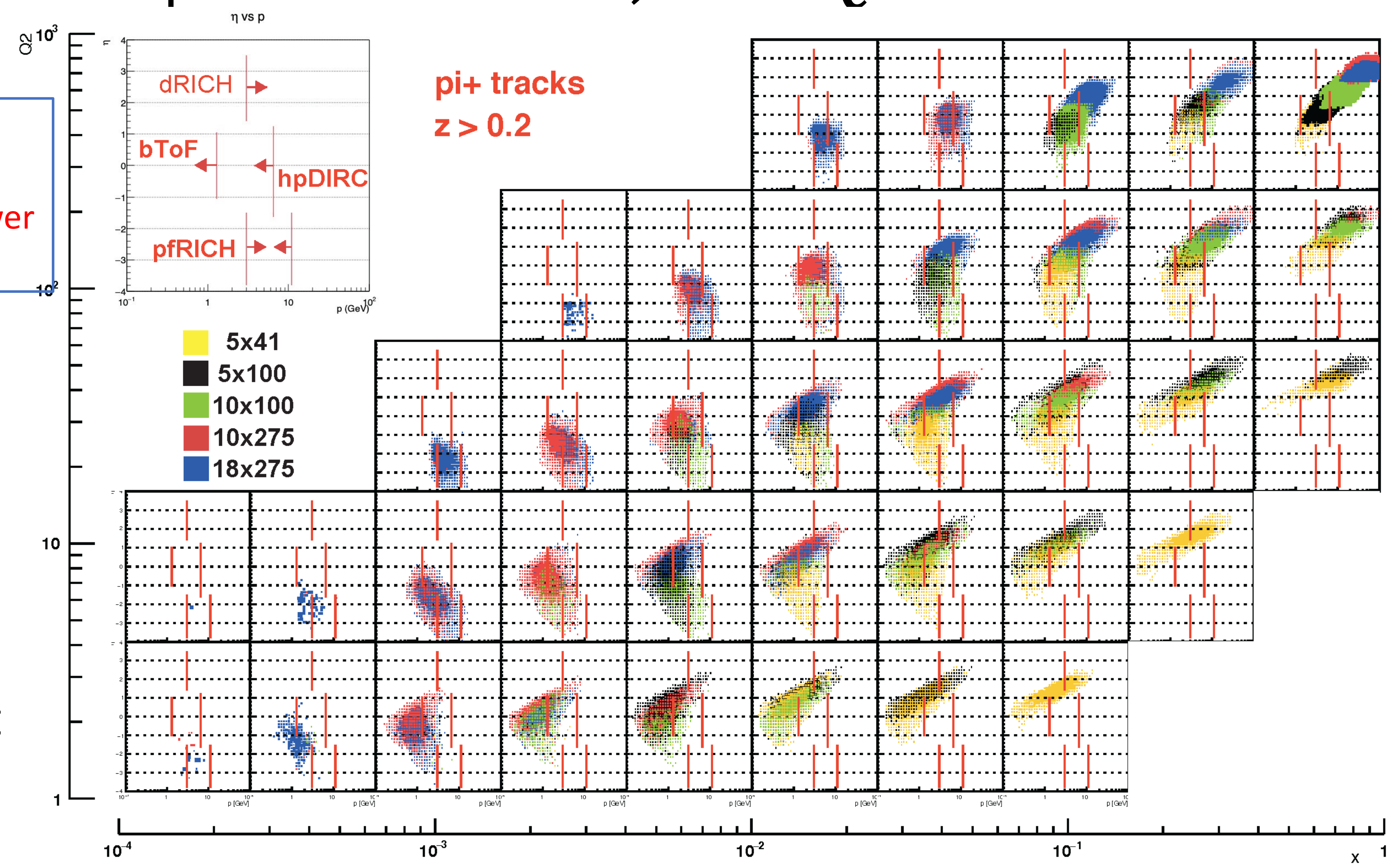
Wenqin Fan

- No impact on D_0 reconstruction if no low-p PID
- Different for Λ_C. Factor 2 increase of errors. What helps is fwd and barrel low-p PID
- No strong physics arguments in backward region for low-p PID

SIDIS PWG

General picture: very few events at low p
→some impact at low x, low Q^2

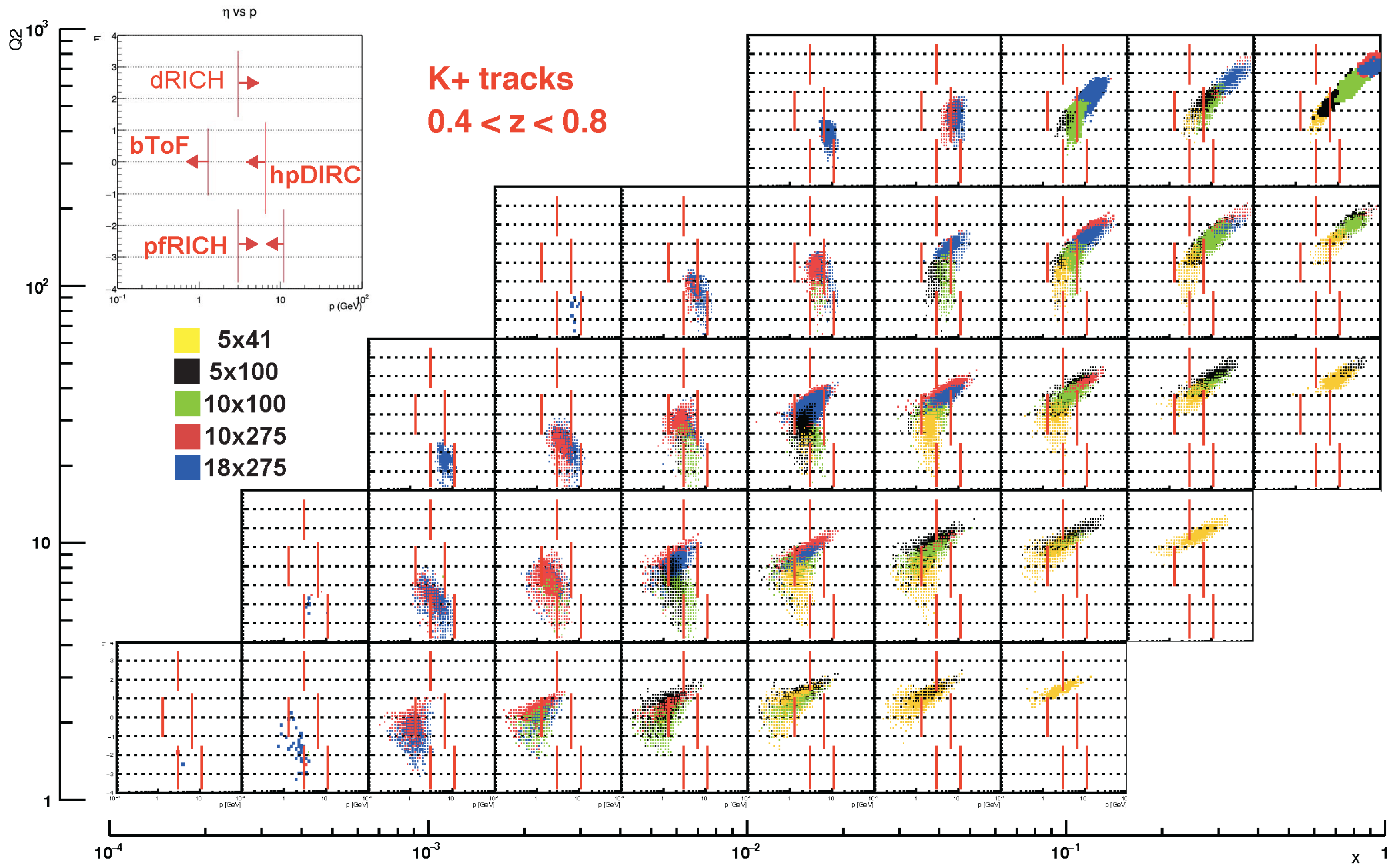
Note that a z cut is applied here
→low z will go to lower p_T



- Some impact of lower threshold in forward direction

→important not to have gaps!!

Acceptance vs p, η from Athena, see https://wiki.bnl.gov/athena/index.php/SIDIS_Supplemental_Material



Anselm Vossen

Summary

- Low momentum tracking and PID have impact on some SIDIS measurements
- Ideally $p > 100$ MeV, but $p > 250$ MeV seems still acceptable in the central region
- Similarly, forward going down to $1\ GeV$ would be ideal
- Note of caution: In particular for di-hadrons, a good separation ($3\ \sigma$) is also needed. Just positive π id might not be enough for kaon measurements (needs to be studied in more detail)

- Systematic study
- Point out advantages for low-p PID in barrel and fwd
- No strong arguments for low-p PID in backward region

Charge from SC (October 12, 2022)

Dear GD/I Conveners,

We are writing to you with regards to the backward endcap AC-LGAD TOF system. Following the TOF-PID group presentation at the GD/I meeting, and the subsequent discussions and presentations by the project, we feel it is important to make progress towards a decision about the feasibility of having an AC-LGAD TOF system in the backward endcap. This decision will inform the need to quantify the performance of alternative detection systems, namely via the use of the RICH photo-sensors and interaction-vertex measurements to secure the necessary TOF and/or t0 measurements.

As a first step in this direction, we are asking for your professional assessment of the present situation, based on the information that was presented to you thus far. Specifically, we would appreciate your input on the following questions, along with any other information you would like to convey to us on this matter.

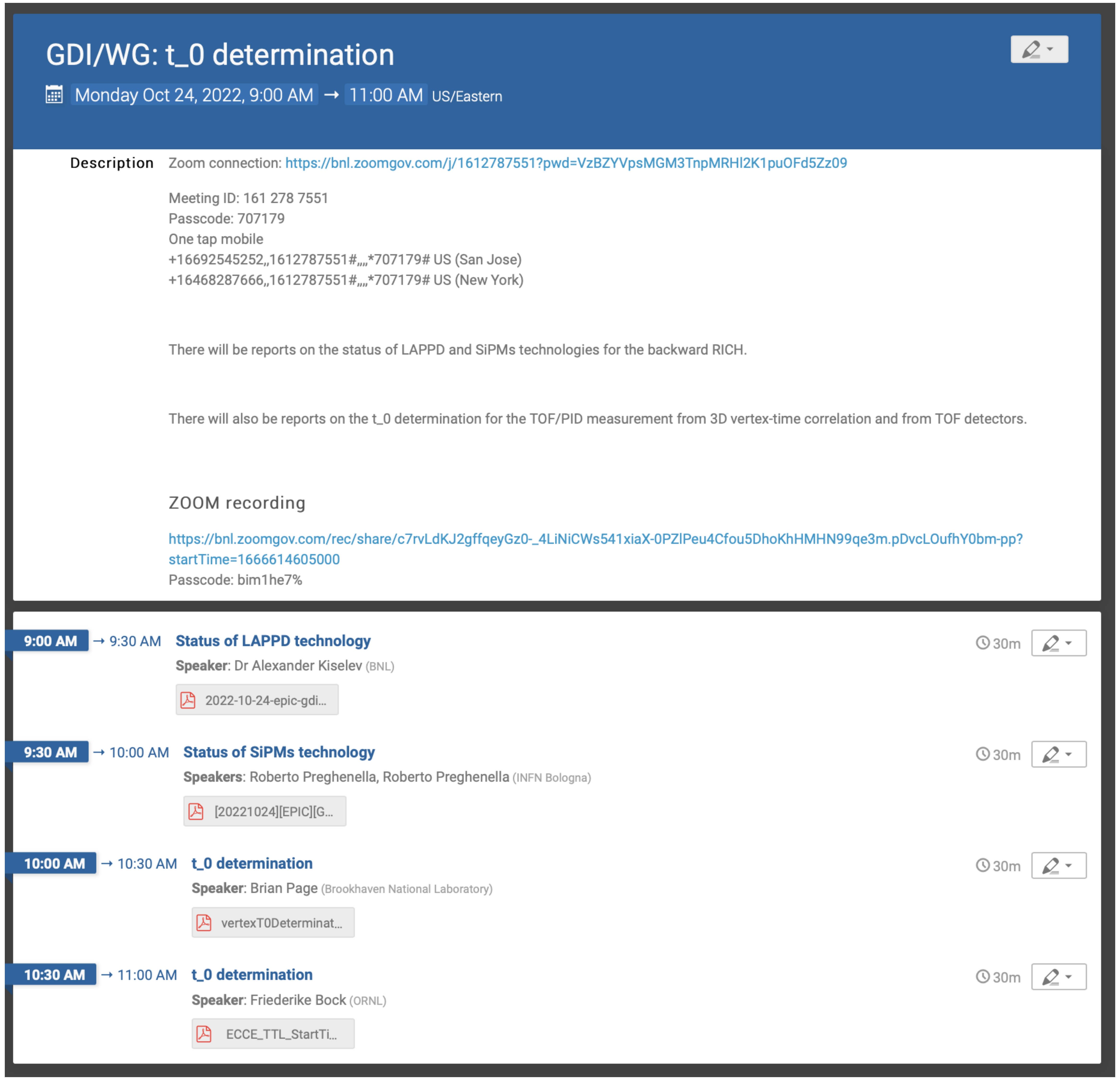
1. In your professional opinion, are the challenges of incorporating an AC-LGAD TOF layer in the backward endcap severe enough to justify replacing it with an alternative solution? Alternatively, should the collaboration invest more resources trying to find a way to make it fit without damaging the performance of other detectors, such as the backward EMCal?

2. Do you see any fundamental issues in using the RICH photo-sensors and interaction vertex measurements for TOF and/or t0 measurements? We realize the complete assessment of these solutions requires a serious study that was not done yet. Therefore, one cannot quantify the degree (e.g. coverage and resolution) to which these solutions can work. Instead we are asking for your technical assessment based on the information available at present to understand if you see anything we might have missed in discussing these solutions so far (and before we charge the relevant working groups with performing a detailed study).

Following your advice the SC will also consult with the project and convey a decision on this matter to the TOF-PID working group and the entire collaboration.

Thanks,
Or, for the SC

It Comes Down to t_0


GDI/WG: t_0 determination

Monday Oct 24, 2022, 9:00 AM → 11:00 AM US/Eastern

Description Zoom connection: https://bnl.zoomgov.com/j/1612787551?pwd=VzBZYVpsMGM3TnpMRHl2K1puOFd5Zz09

Meeting ID: 161 278 7551
Passcode: 707179
One tap mobile
+16692545252,,1612787551#,,,,*707179# US (San Jose)
+16468287666,,1612787551#,,,,*707179# US (New York)

There will be reports on the status of LAPPD and SiPMs technologies for the backward RICH.

There will also be reports on the t_0 determination for the TOF/PID measurement from 3D vertex-time correlation and from TOF detectors.

ZOOM recording

https://bnl.zoomgov.com/rec/share/c7rvLdKJ2gffqeyGz0-_4LiNiCWs541xiaX-0PZlPeu4Cfou5DhoKhHMHN99qe3m.pDvcLOufhY0bm-pp?startTime=1666614605000
Passcode: bim1he7%

9:00 AM → 9:30 AM **Status of LAPPD technology** 30m
Speaker: Dr Alexander Kiselev (BNL)
2022-10-24-epic-gdi...

9:30 AM → 10:00 AM **Status of SiPMs technology** 30m
Speakers: Roberto Preghenella, Roberto Preghenella (INFN Bologna)
[20221024][EPIC][G...

10:00 AM → 10:30 AM **t_0 determination** 30m
Speaker: Brian Page (Brookhaven National Laboratory)
vertexT0Determinat...

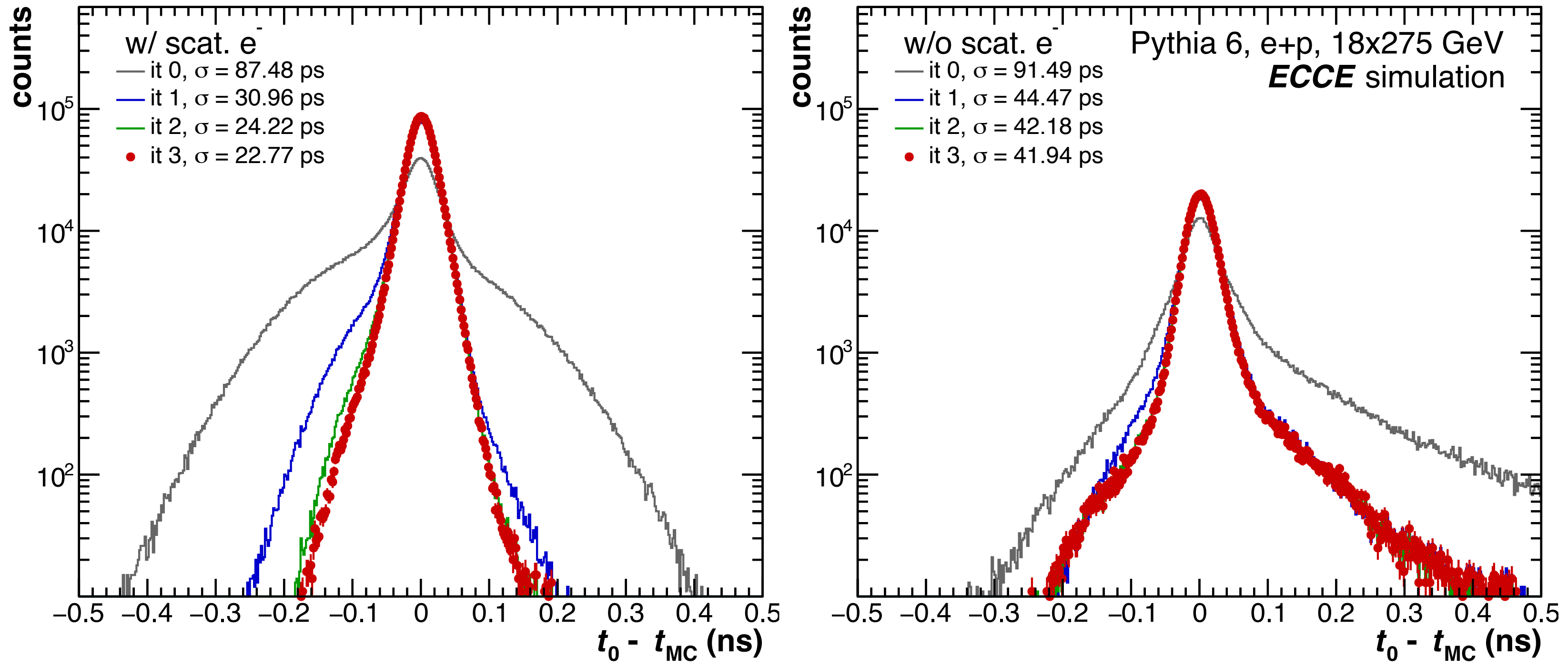
10:30 AM → 11:00 AM **t_0 determination** 30m
Speaker: Friederike Bock (ORNL)
ECCE_TTL_StartTi...

- We could not identify a solid physics case for low-p PID in backward region
- Remaining question is what could replace t_0 in lieu of AC-LGAD ToF?
  - LAPPDs
    - serve as single photon detector (RICH) **and** as timing device
      - $\delta t/t\,|_{\mathrm{LAPPD}} \leq \delta t/t\,|_{\mathrm{AC-LGAD}}$
    - cheaper than MCP-PMTs and w/o radiation issues SiPM have (cooling, annealing)
    - at that point (Oct ’23) not in baseline
    - needs R&D (eRD110)
  - Completely different method independent of dedicated detector?

Benefits of Using Scattered Electron for t_0

Friederike Bock

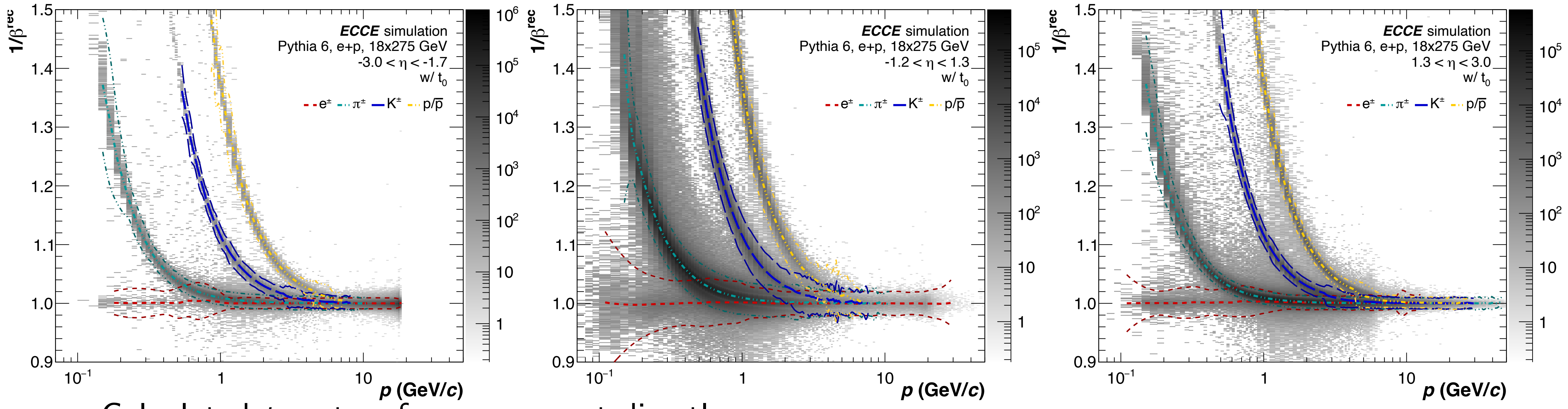
Iterative Improvements to t_0



- Common procedure after intial t_0 determination
- For all particles the velocity estimate is based on $t_{part,rec} - t_{0,it-1}$
- In iterations $1/\beta$ is calculated and compared to expectation value for π,K,p and e
  $\rightarrow$ assumed to be corresponding particle if within 1% of expectation value & $p < 6$ GeV/c
  $\rightarrow$ $p > 15$ GeV/c pion mass assumed, except for scattered electron candidates
- Latest after 4 iterations no significant change observed any more

F. Bock (ORNL) TTL May 16, 2022 3 / 4

PID performance of TTL

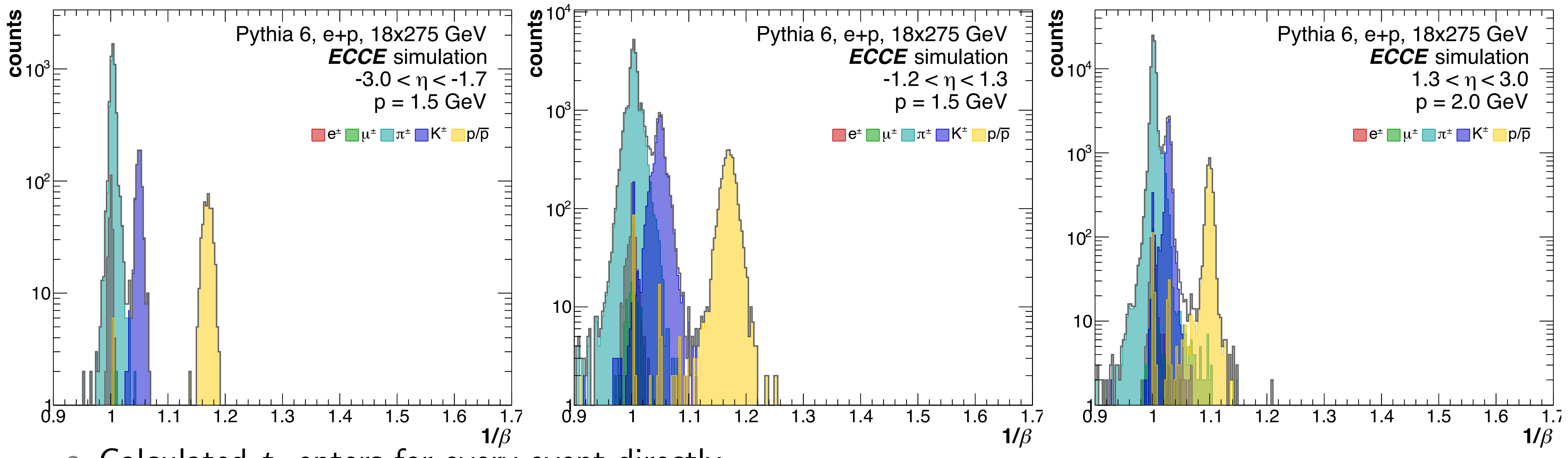


- Calculated t_0 enters for every event directly
- Optimized η coverage in particular towards electron end cap would improve scattered electron finding
  $\rightarrow$ PID discrimination in barrel & forward direction

N.B. TTL = Timing Tracking Layer

F. Bock (ORNL) TTL May 16, 2022 4 / 4

PID performance of TTL



- Calculated t_0 enters for every event directly
- Optimized η coverage in particular towards electron end cap would improve scattered electron finding
  $\rightarrow$ PID discrimination in barrel & forward direction

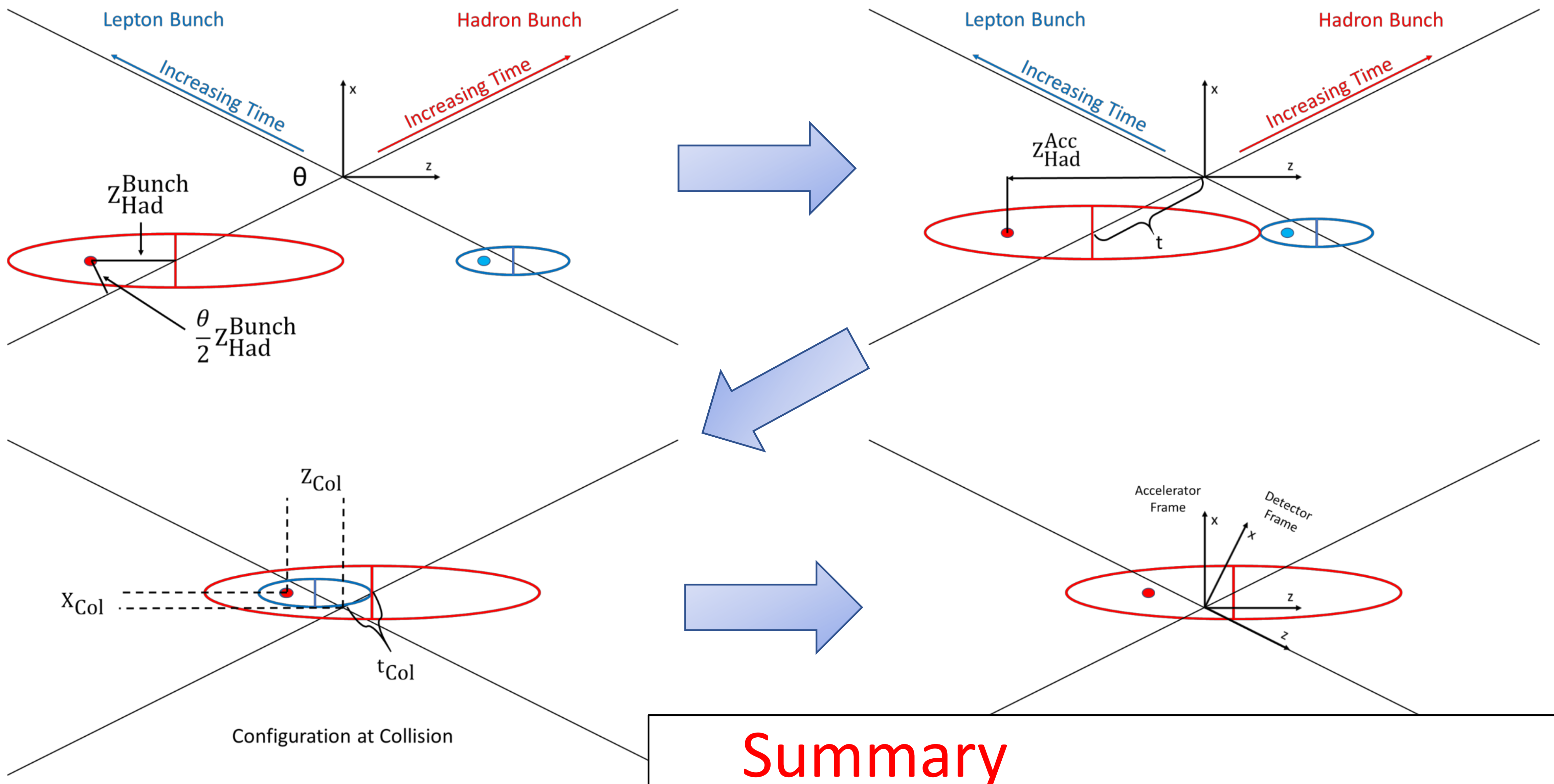
---

- Full coverage PID allows for iterative improvements of t_0
- In traditional ToF way much speaks for TTL in backward region
- Clear argument for LAPPDs

An Independent Way of Determining t_0

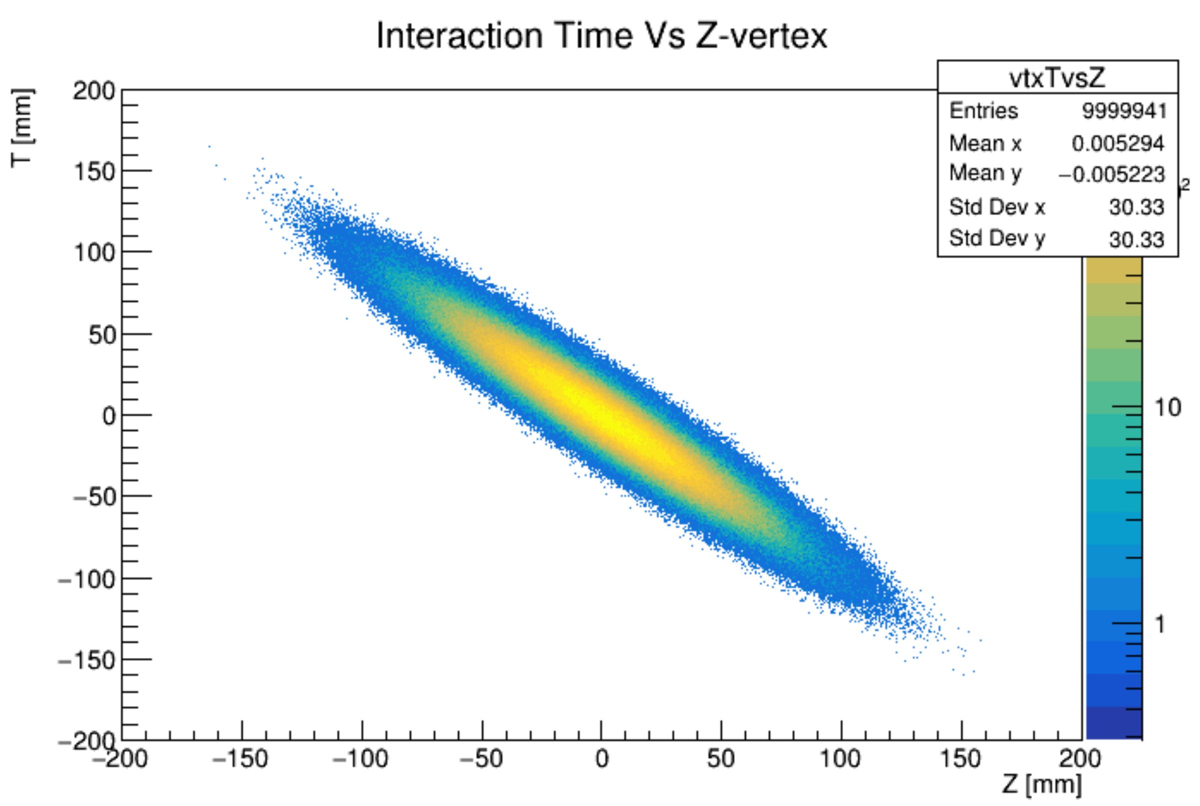
Brian Page

Vertex Model

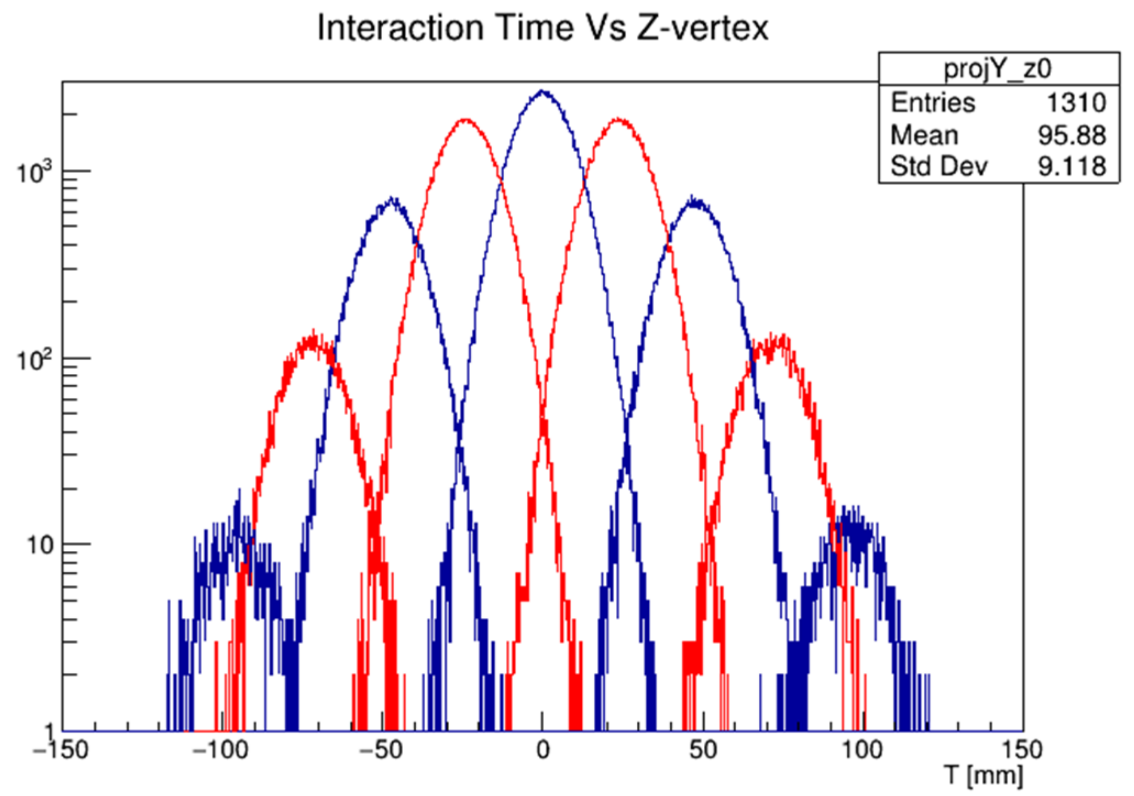


Description of model used to simulate vertex distributions and correlations between x,z vertex positions and collision times

Z-Vertex – T0 Correlations: 18x275



- ❑ Z-Vertex and T0 of the collision are tightly correlated due to the relative size differences of the hadron and electron bunches (6 vs 0.9 cm) – practically, determined by size of electron bunch



5

Summary

- ❑ Bunch sizes and beam crossing configuration provide opportunity to derive the time of the collision from the position of the primary vertex
- ❑ Based on the model used to simulate beam effects in MC, T0 resolutions on the order of 20 to 25 pico seconds should be achievable by measuring the X and Z positions of the primary vertex within reasonable tolerances
- ❑ Beam energy combinations of 18x275, 10x100, and 5x41 in hi-divergence mode were compared: T0 resolutions for 18x275 and 10x100 were comparable and somewhat better than for 5x41
- ❑ Possible next step – look into EIC machine simulations of the interacting beams to confirm model predictions
- ❑ Additional information in the technical note on Beam Effects: https://zenodo.org/record/6514605#.Y0VOrS-B1qs

- Elegant and precise solution for t_0
- Beam effects?

[…]

GDI assessment: the physics WGs have identified that the *sole* purpose of the backward TOF is to provide t0 tagging that matches the precision needed for the TOF measurement in the barrel and forward directions. No compelling physics requirements have been identified that would motivate low-p hadron PID in the backward region. In recent meetings, multiple challenges related to AC-LGAD as the backward TOF have been identified: (1) space available for the MAPS-tracking volume (2) power dissipation that can compromise the performance of the crystal ECAL (3) the amount of material in front of ECAL. Although we encourage design and engineering studies to resolve these concerns, we recommend not to include the backward AC-LGAD TOF as the baseline choice for the backward TOF. (with further recommendations see item 2.)

[…]

GDI assessment: We believe a fast RICH photo-sensor, specifically the LAPPD, provides a better-integrated detector solution for the backward t0 measurement. We believe this measurement can be realized and augmented using 3D_Vertex-time correlation (which, if used alone, may induce TOF PID uncertainties that stem from the non-Gaussian component of the beam bunch and beam conditions).

We recognize that not all information necessary for the backward TOF down selection is available at this time:

There are still risks in performance, endurance, B-field resistance, and production schedule for a potential large-scale LAPPD deployment in EPIC;

The holistic approach of extracting t0 information from vertex reconstruction needs to be revisited.

Nevertheless, given the fast approaching CD-2 review, we recommend the adoption of the fast RICH photo sensors as the baseline configuration […]

Take Away Message (Pun Intended)

- Impact of loss of low-p PID in the backward on the physics program is minimal
- Studies show value of low-p PID in barrel and fwd hemisphere
  - AC-LGAD ToF group will have all hands full even w/o backwards layer
- Reduction of material and elimination of heat source benefits backward EM calorimetry which is essential for the physics program
- t_0 info from backward region comes from LAPPDs timing capabilities that match those of AC-LGADs
- Added 10 cm space for e-arm integration, in particular for tracker & RICH
- New studies show that the correlation between 3D vertex positions and collision time could provide t_0 with high accuracy
  - beam effects could spoil the soup - play safe with good LAPPD timing
- The SC adopted the GD/I recommendation