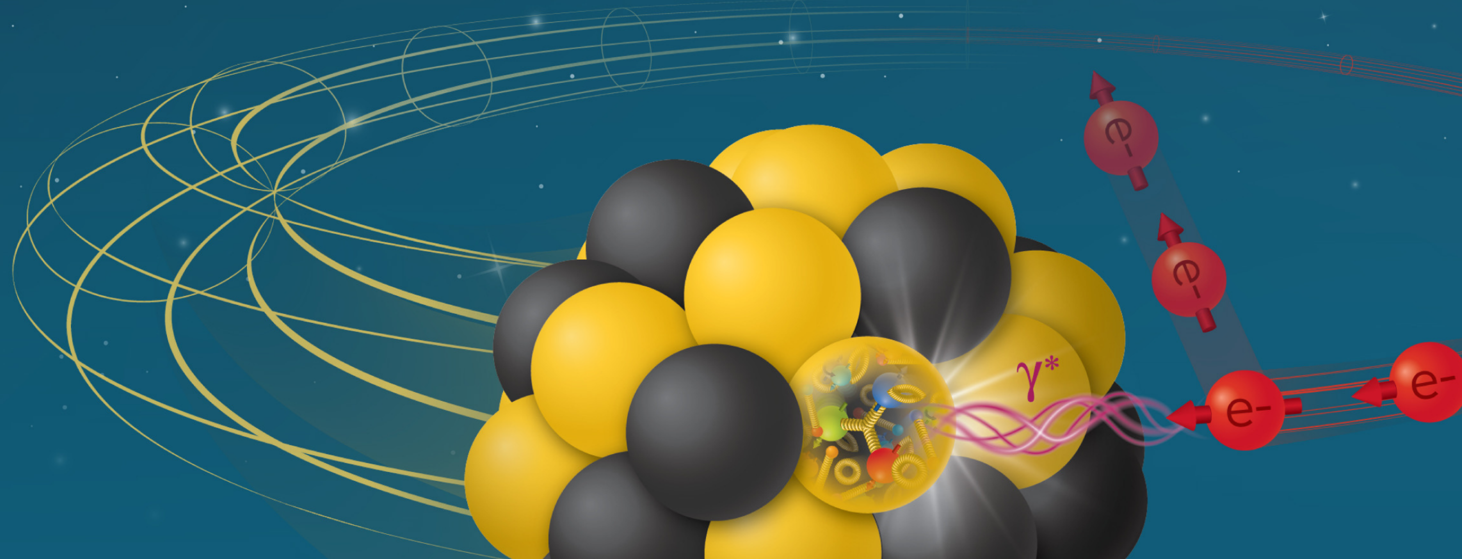
Far-Forward Detectors TDR Update

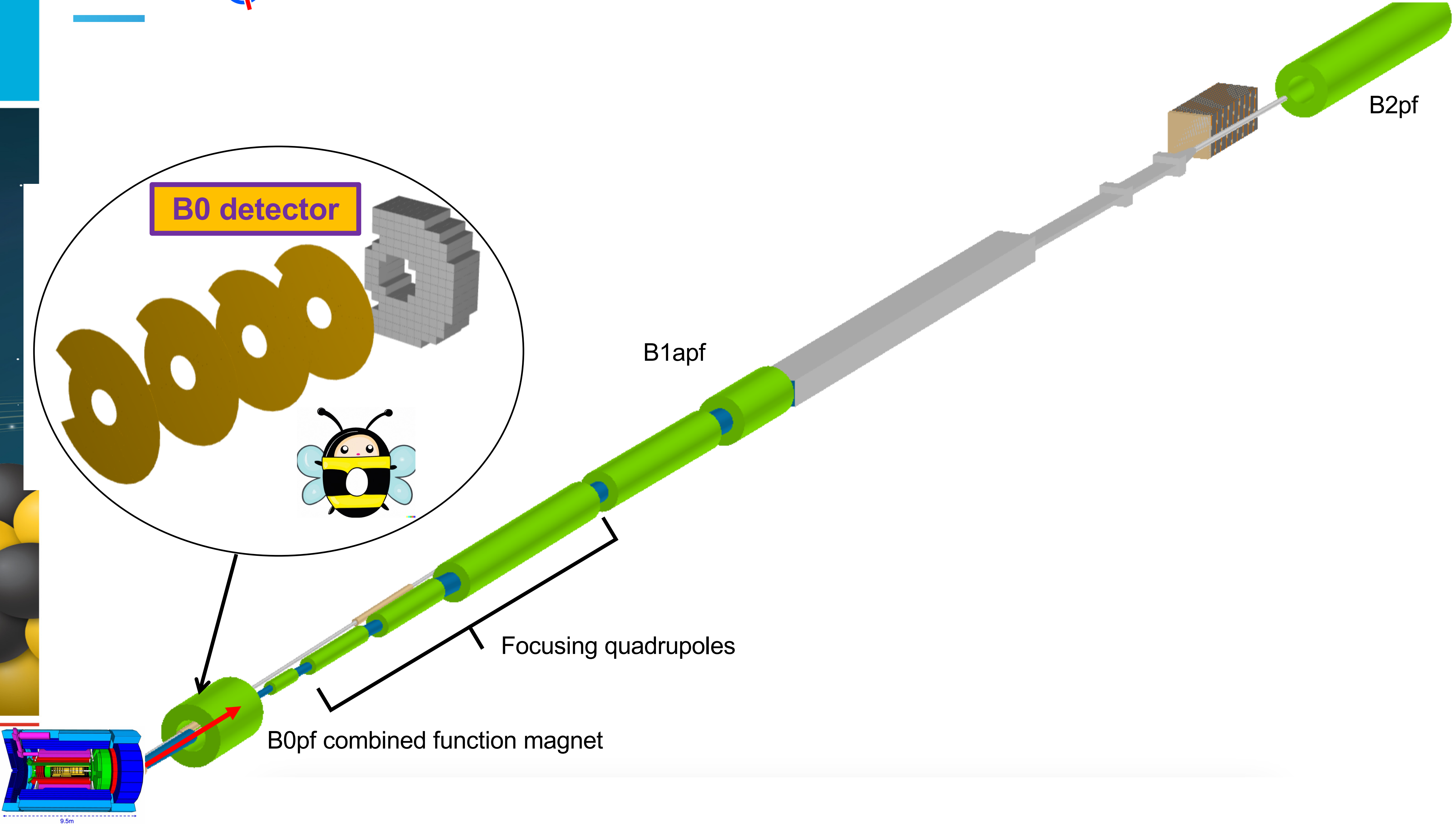
Alex Jentsch (BNL) ***on behalf of FF DWG***

ePIC TIC Meeting
June 24th, 2024

Electron-Ion Collider



The ePIC Far-Forward Detectors



Si Tracker Status

Slides: Zvi Citron

- AC-LGAD as detector means almost all R&D (eRD112 and eRD109) is shared with other detectors
- B0 tracker needs better spatial resolution than other AC-LGAD detectors → charge-sharing for reconstruction is *crucial*
  - Performance of charge-sharing in detector environment (i.e. radiation) still to be proven
  - Searching for *backup* technology as risk mitigation
- *Precise* positioning of detector layers still to be fixed
  - Detector shifted back 20cm compared to 'original' plan to optimize performance given non-uniform (in z) B field
  - Precise z position of each layer to be finalized – O(1 week)*
  - Precise transverse layout accounting for mechanical envelope, support structure, etc – O(< 1 month)

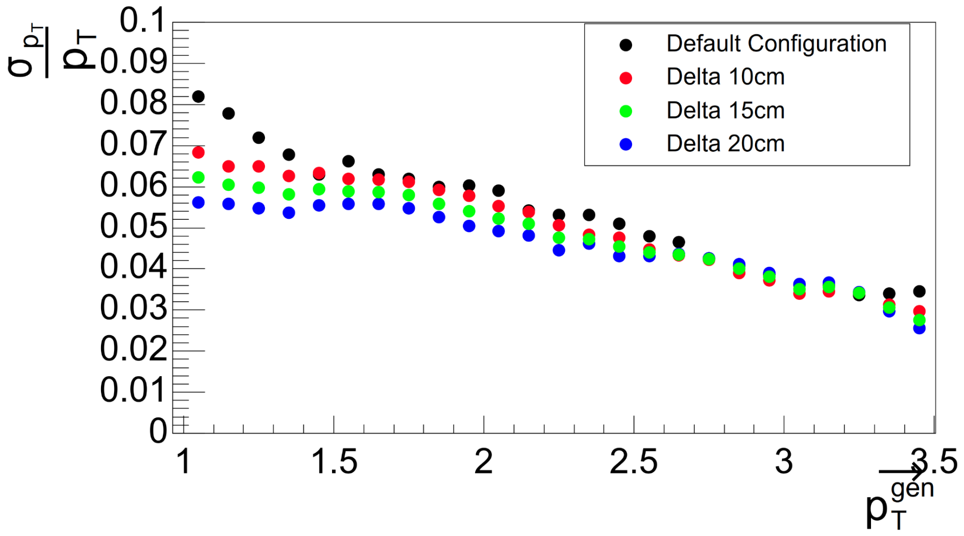
אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev

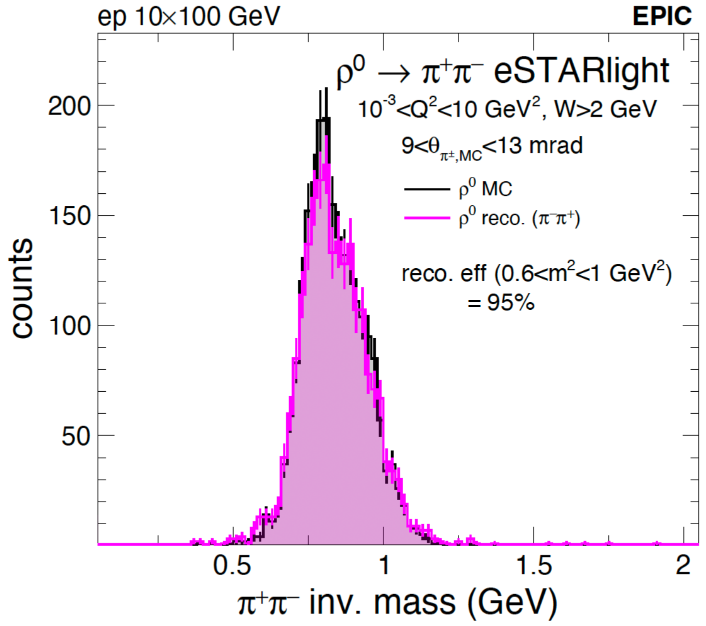
*problems with EICRecon *may* cause delay

Si Tracker Simulation Status/Issues

Slides: Zvi Citron

- Realistic B field implemented (h/t Alex)
- Proton momentum resolutions studies running (h/t Karthik)
  - But (just) now problems with EICRecon …
- Following updated detector geometry add rho benchmarks (h/t Zach)
- Digitization needs to be implemented, tbd w/ ToF
- [Physics sim needs to get/stay in synch with engineering CAD]





אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev

EM Calorimeter Status

Slides: Zvi Citron

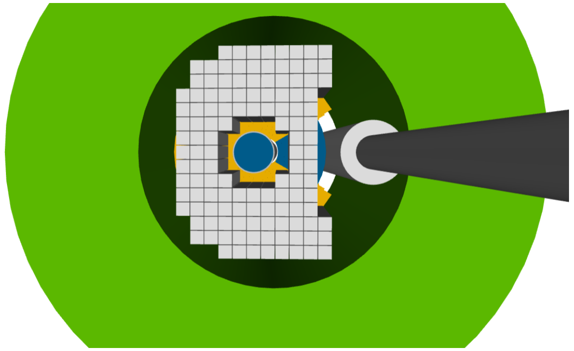
- Baseline plan was $PbWO_4$ crystals read out with SiPM, overlap with negative endcap
- Serious consideration of LYSO crystals for better light output in soft photon (~50 MeV) measurements
  - For soft photons performance of $PbWO_4$ worse but *meets requirements*
  - LYSO adds cost & complications
  - Bottom line: **$PbWO_4$ chosen**
- Serious consideration of APD readout rather than SiPM to accommodate large dynamic range
  - Worry about SiPM saturation/non-linear effects for large light yield of hard photons (~100 GeV) (pre-readout extra light attenuation would kill soft signal)
  - Detailed GEANT studies **suggest that SiPM will be acceptable**, still to be finalized – O(1 week)
  - In any case, dynamic range will require multiple readout channels/gains, still being worked out – O(month)

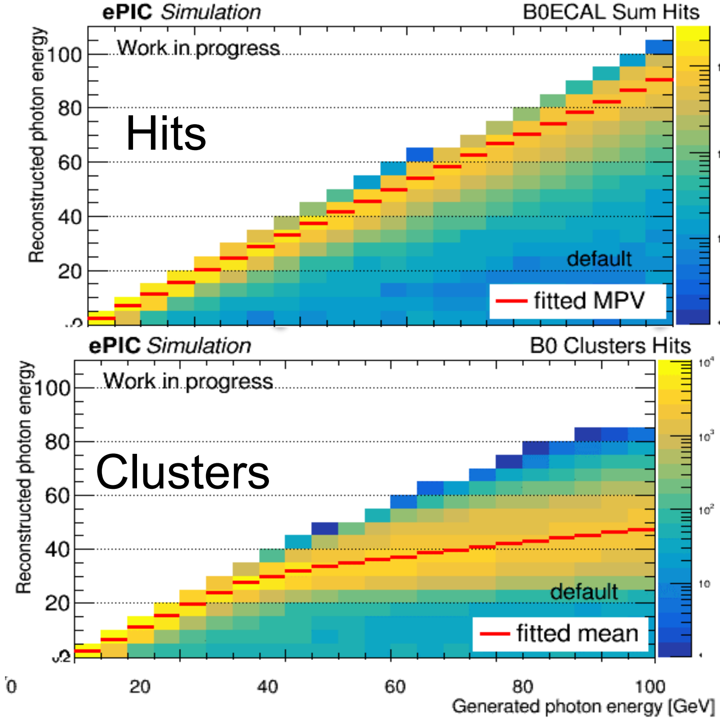
אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev

EM Calorimeter Simulation Status/Issues

Slides: Zvi Citron

- Individual crystals (position and length) implemented
- EICRecon has problems with photons >~ 40 GeV
- Light yield (not just energy deposited) has to be implemented for meaningful resolution studies, digitization etc.
- [Physics sim needs to get/stay in synch with engineering CAD]



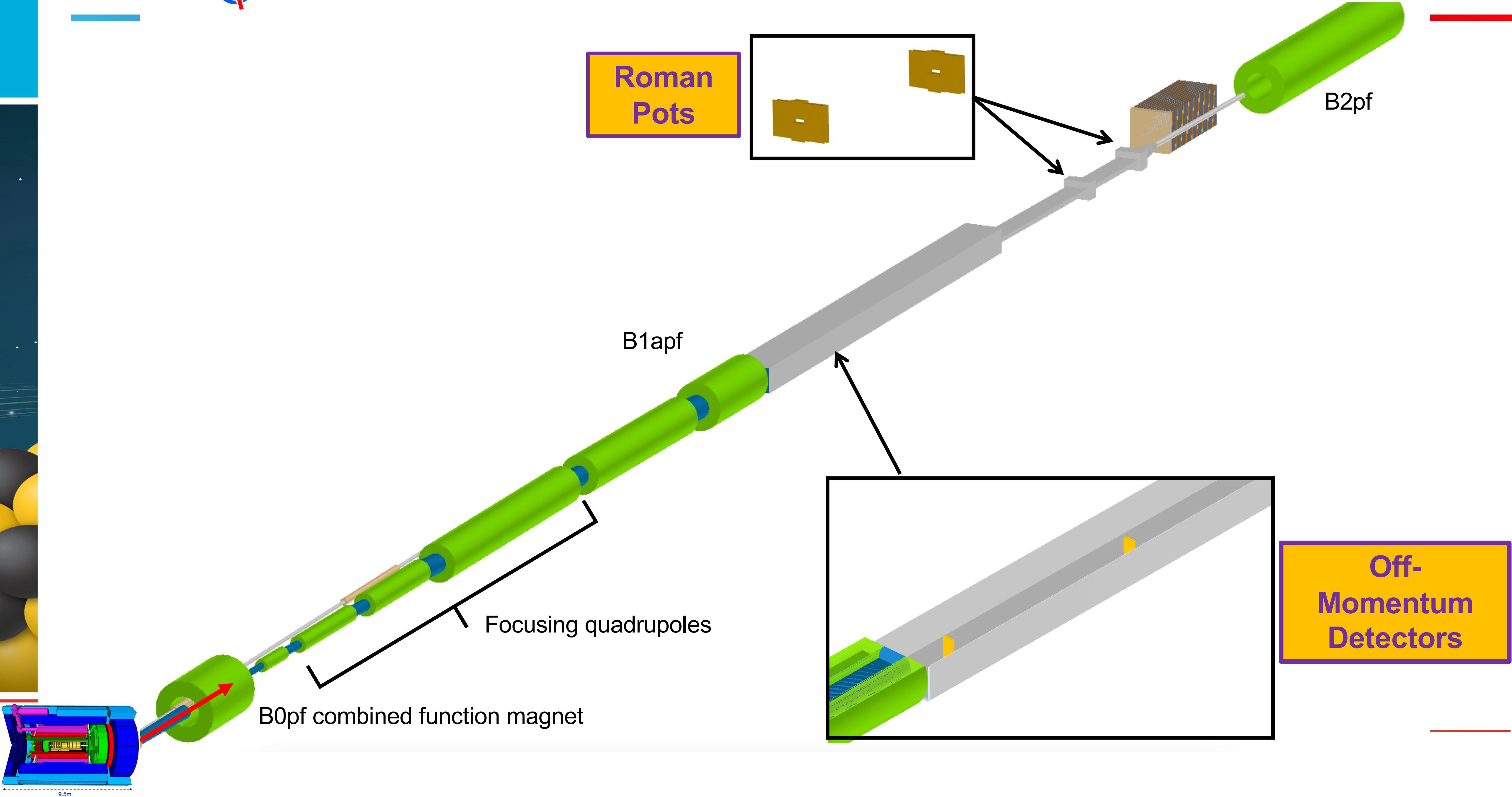


אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev

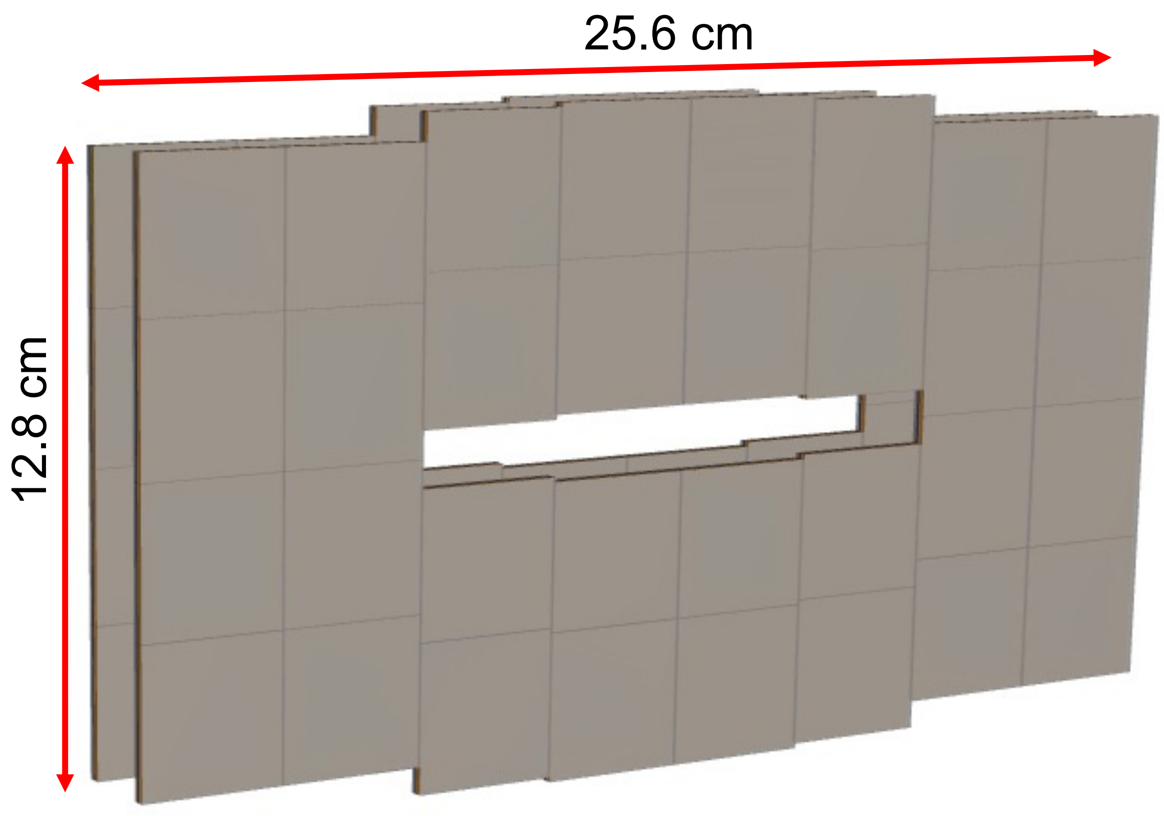
Integration

- ‘Final’ detector locations to be realized in O(1 week)
- → Implementation in CAD, check for problems etc
  - Fine tuning (e.g. small changes in acceptance) due to engineering issues fed back to physics sim, impact evaluated
- Then focus on solidifying installation/support plan, services etc

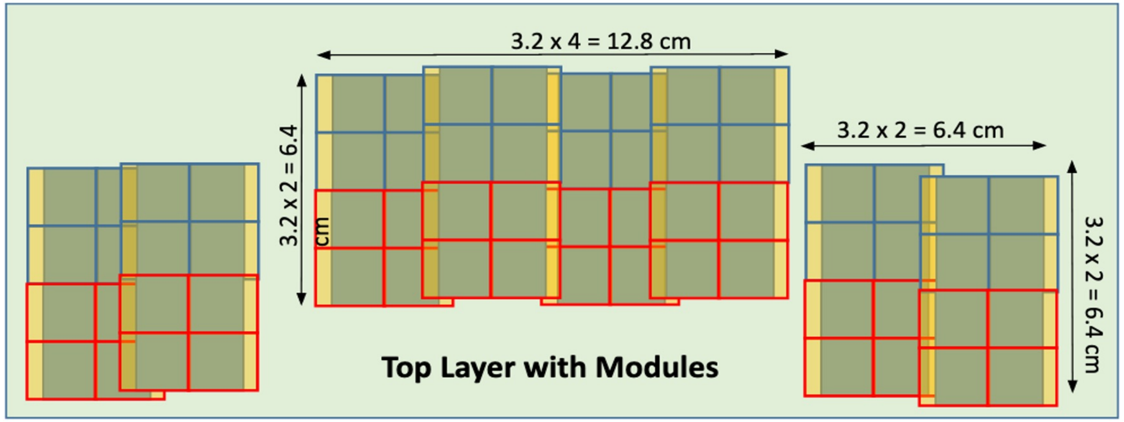
The ePIC Far-Forward Detectors



Technology: AC-LGAD

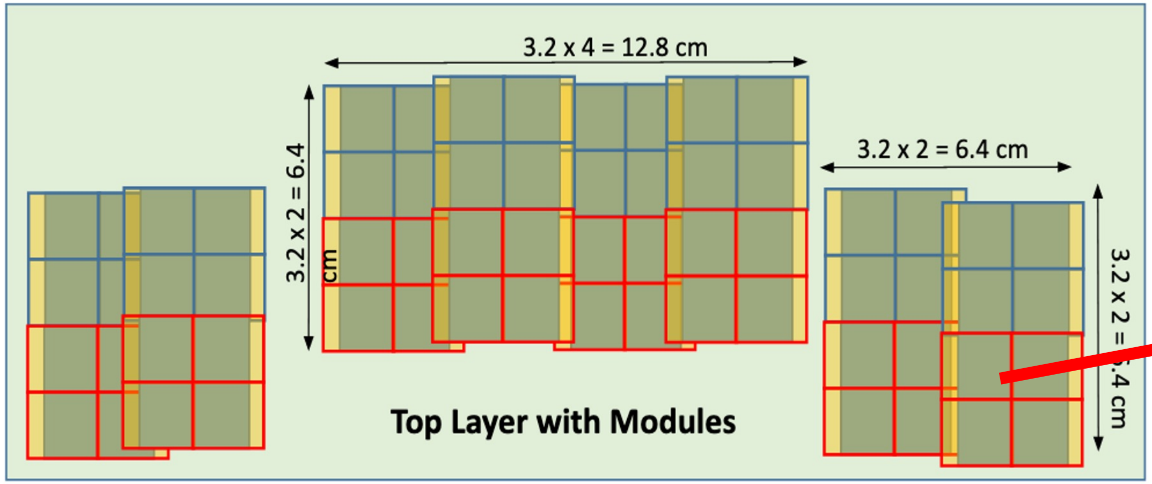


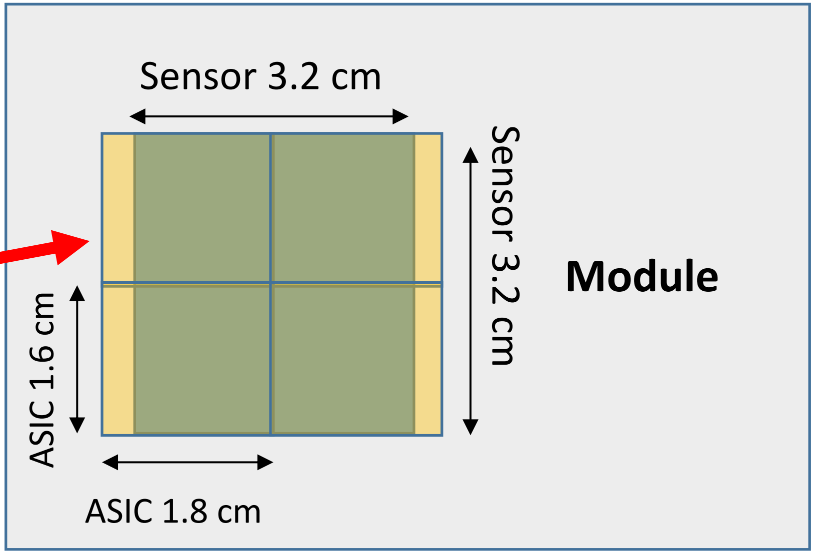
DD4HEP Simulation



- AC-LGAD sensor provides both **fine pixilation** (500um square pixels), and **fast timing** (~30ps).
  - Based on extensive work from EIC generic R&D (eRD24) to establish needs for the Far-Forward detectors and evaluate usage of AC-LGADs.

Sensor and ASIC layout



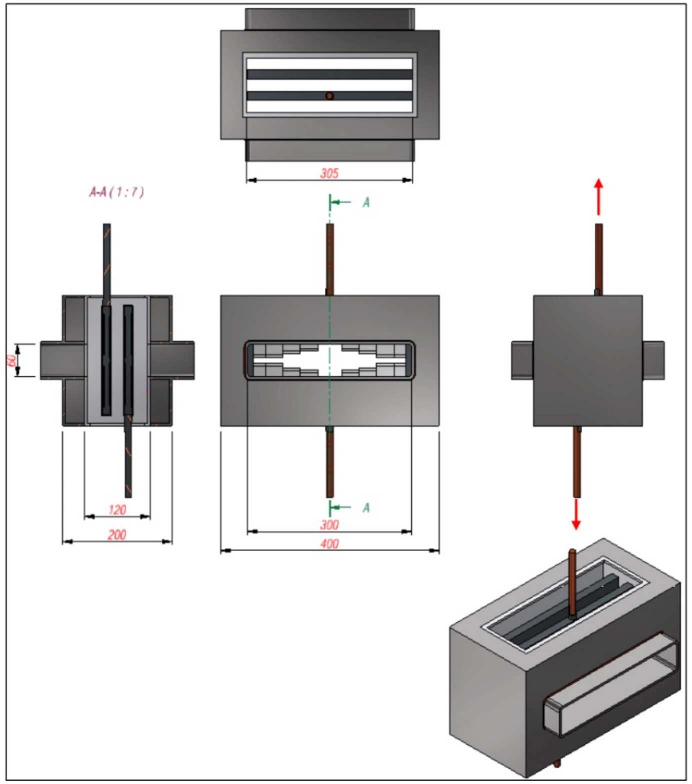


- Approach based on bump-bonding four custom ASICs to a single AC-LGAD sensor to make a “module”.
  - This is being re-evaluated now → smaller sensor (1 sensor to 1 ASIC) means same sensors can be used for all FF systems + FTOF.
  - Smaller sensors could provide more difficulty in limiting dead areas between sensor – careful design of carrier board to ensure overlaps required.

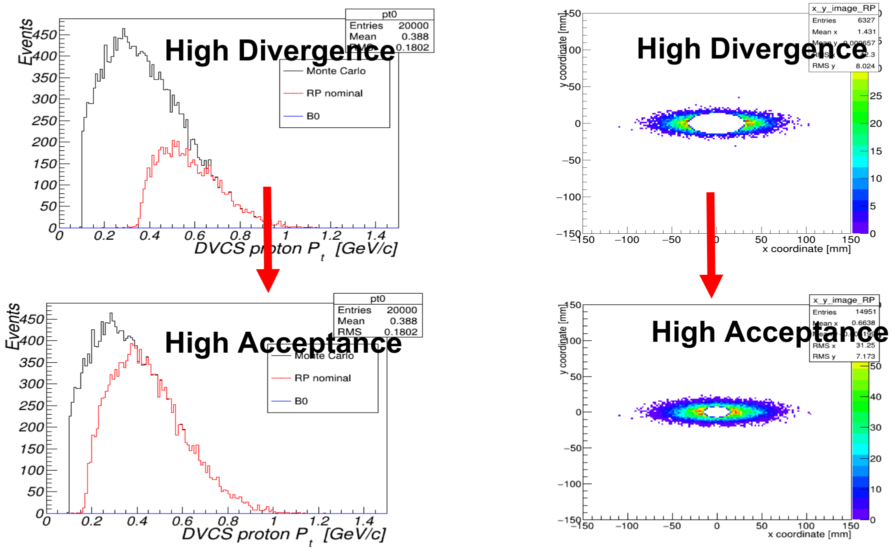
Cooling and structural support

- **Cooling**
  - Only heat sink methods can be used in-vacuum.
  - Plan is to use external chiller connected to cooling plates/strips on boards to bring heat off of detector.
  - **Current assumption is 1-2 mW/ch. heat dissipation. This leads to ~ 100 Watts per layer.**
  - This is only an estimate – we do not have a full system to make temperature measurements.
  - Detector heat will not necessarily be evenly distributed – most of the occupancy in the inner 30% of the active area.

New Concept



- **Mechanical Support**
  - Sensor plane layout needs to be re-visited with newer scattering chamber design.
  - Smaller sensors could help maximize acceptance near the beam.



CNPEM

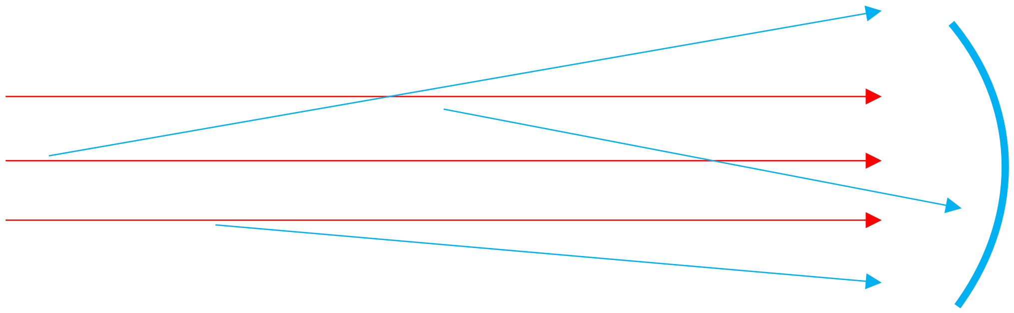
MINISTRY OF SCIENCE TECHNOLOGY AND INNOVATION

BRAZILIAN GOVERNMENT BRASIL UNITING AND REBUILDING

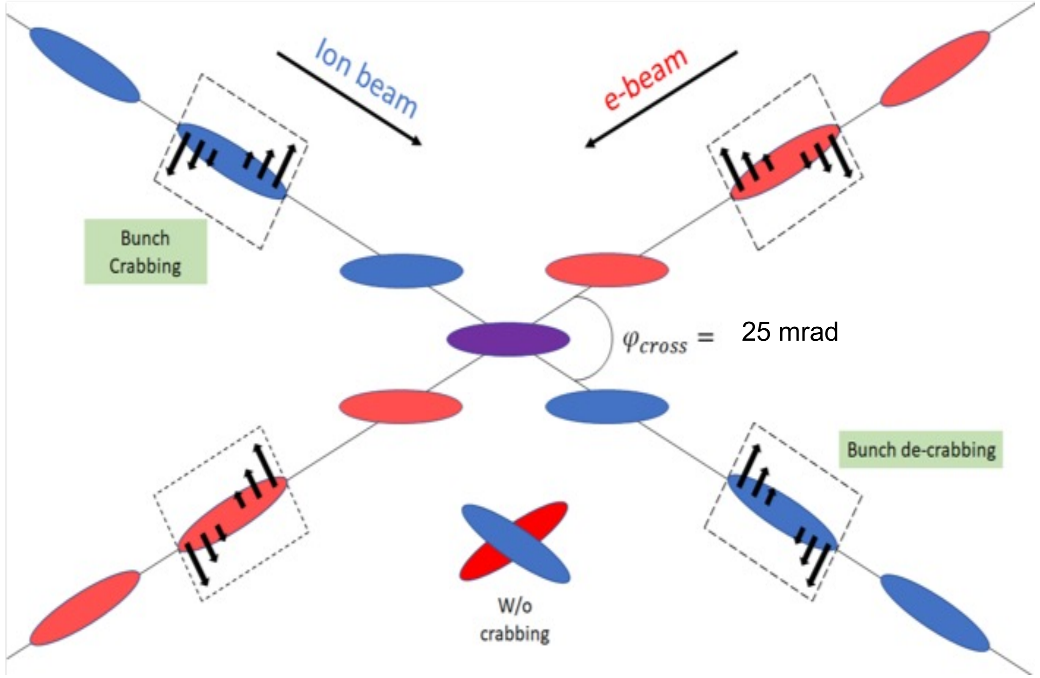
Vacuum system design → in-kind contribution from Brazil.

Soapbox: Quick Reminder on Beam Effects

- Angular divergence
  - Angular “spread” of the beam away from the central trajectory.
    - Transverse momentum kick to the beam particles.

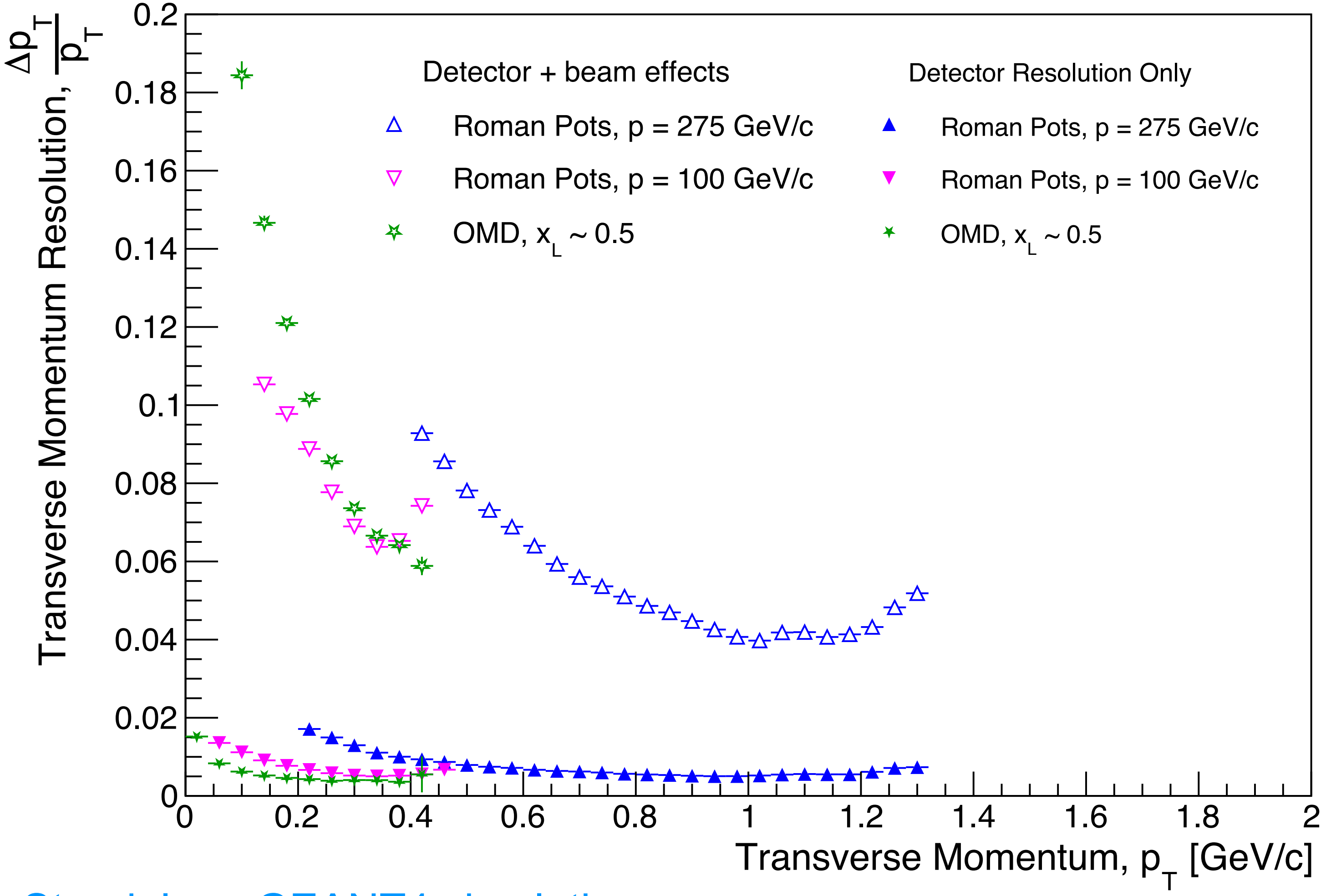


- Crab cavity rotation
  - Rotates beam bunches in 2D.
  - Used to account for the luminosity drop due to the crossing angle – allows for head-on collisions to still take place.
  - **Induces effective vertex smearing.**



These effects introduce smearing in our transverse momentum reconstruction.

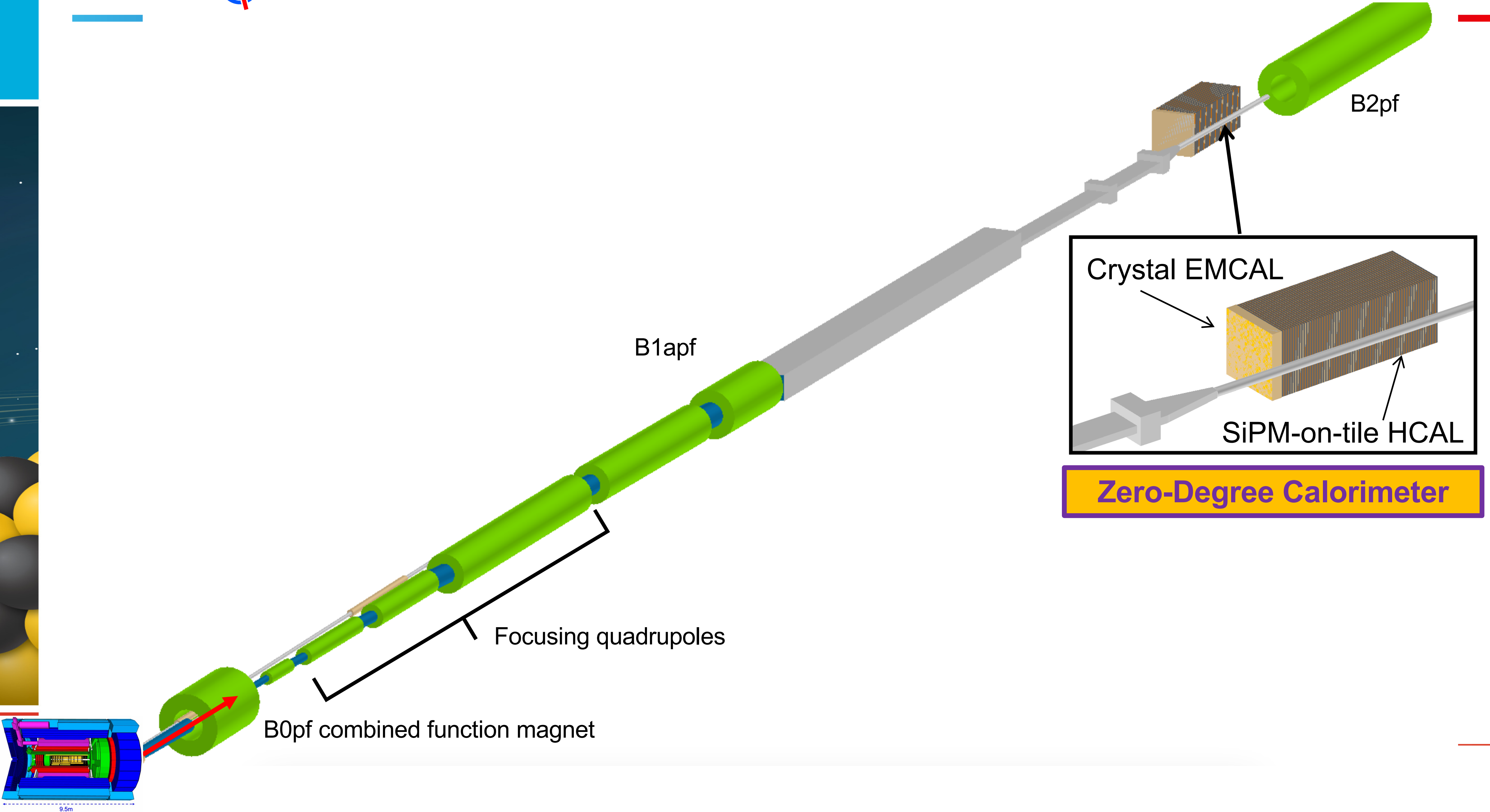
Summary of Detector Performance



Standalone GEANT4 simulations

- Work being done now to ensure we can evaluate this in DD4HEP.
  - https://github.com/eic/EICrecon/pull/1492
  - "post-burner" ready to go to handle removal of afterburner (beam effects, crossing angle) effects needed for simulation.
  - This step has to be done to separate the components and see if previous assumptions are still valid.

The ePIC Far-Forward Detectors



ZDC crystal calorimeter

- Detector design
  - LYSO or PWO crystal selection
    - Preferring short (e.g. 6 X0) LYSO
    - Comparison of performance, cost, temperature dependence
  - ELPH positron test beam
    - Comparison of LYSO & PWO
    - Test module under construction in Taiwan (NCU & Academia Sinica)
- Performance
  - Physics performance simulation studies
    - Low-E photon & high-E pi0
    - Combination with hadron calorimeter
- Status in DD4HEP
  - Geometry implemented
  - Clustering code development underway

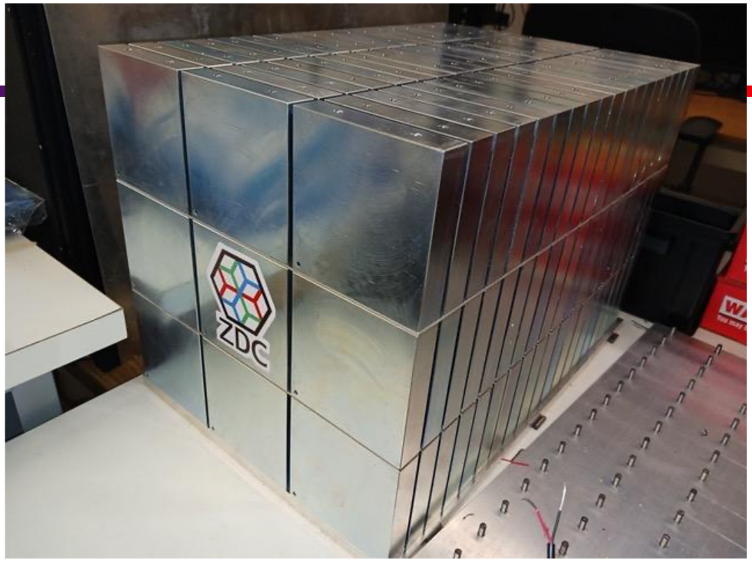
ZDC crystal calorimeter

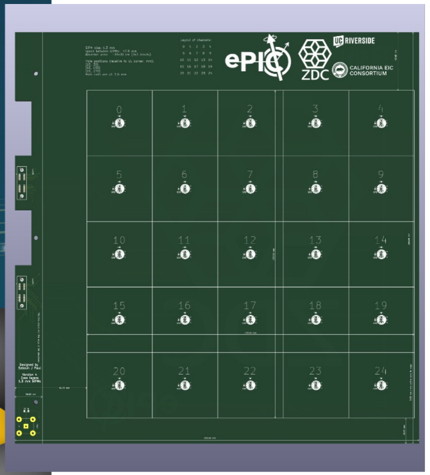
- Photosensors/Readout
  - Electric engineer: Chih-Hsun Lin (Academia Sinica)
  - SiPM / APD / PIN photodiode
    - SiPM for PWO (low light yield)
    - APD or PIN photodiode for LYSO (high light yield)
  - ASIC selection
    - Necessary dynamic range (ADC bits)?
    - Synergetic study with the backward calorimeter and B0 calorimeter
- Assembly
  - In our current test module, glueing modules together
    - Building 4x4 crystals, then four modules to put 64 crystals together
- Cooling, monitoring system, beamline integration
  - TBD, lots to do

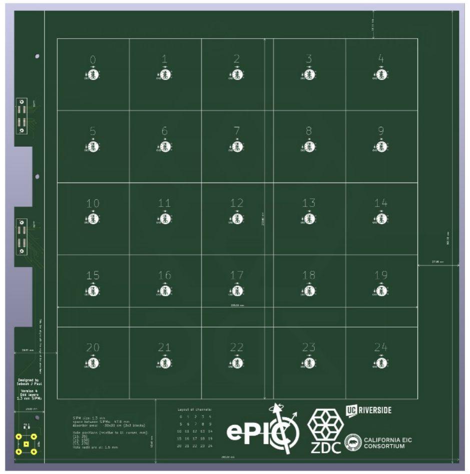
SiPM-on-tile HCAL

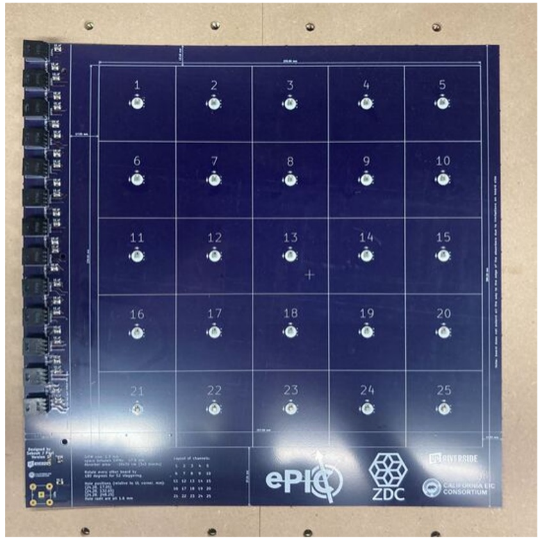
Simulation: Full-simulation completed, including 3D clustering and software-compensation with AI. Neutron reconstruction performance TDR ready.

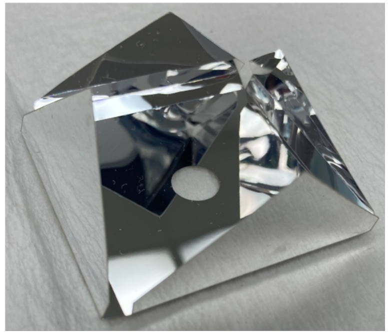
Prototyping: 500 chanel prototype under construction, to be tested at JLab in Fall 2024



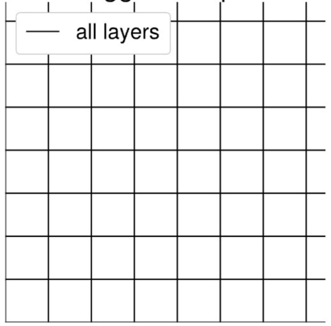




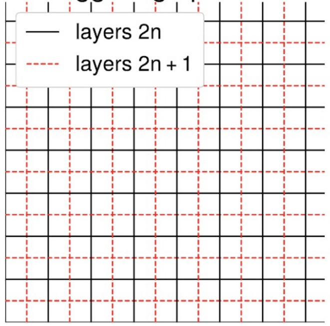




unstaggered squares

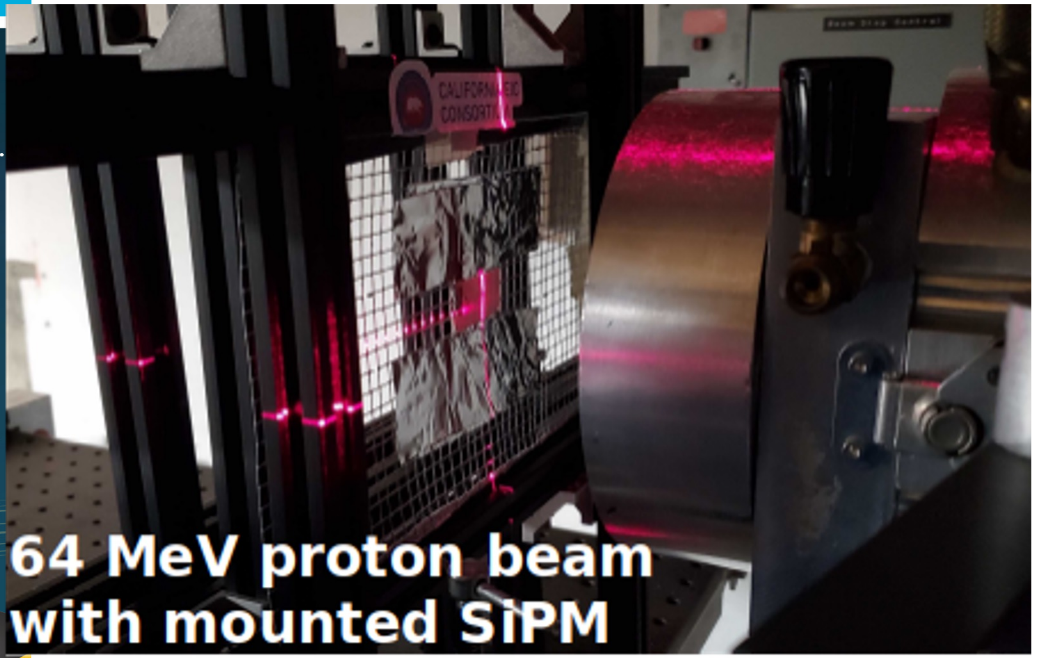


staggering option S2



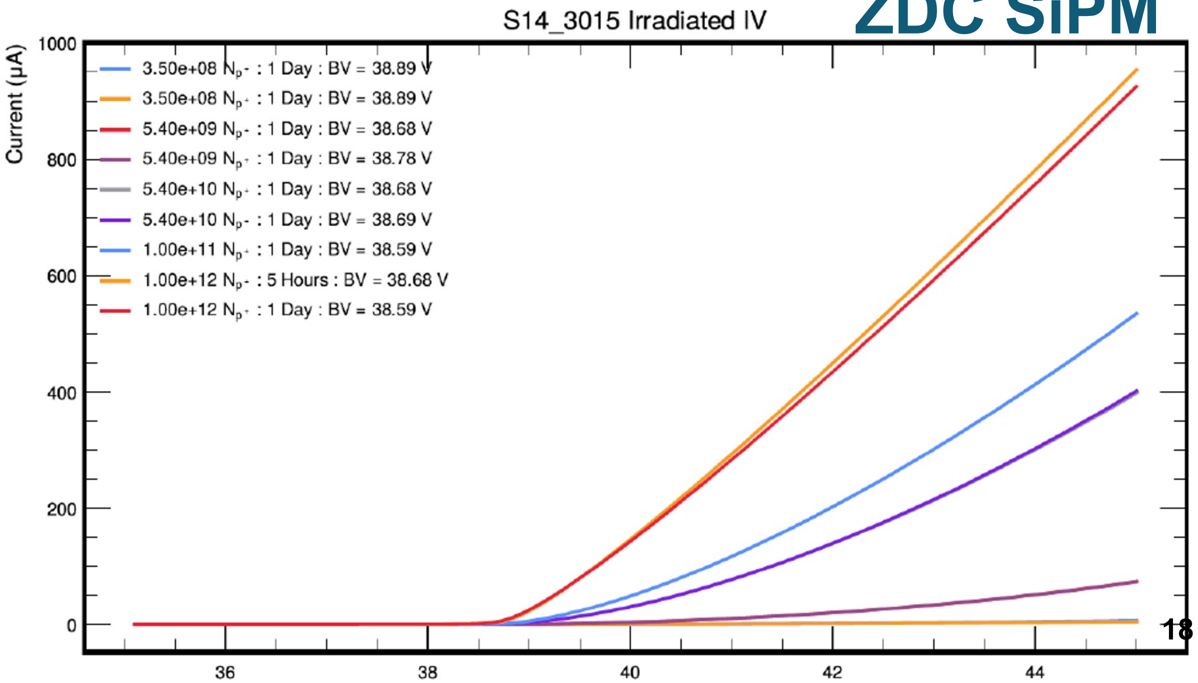
30x30 cm2 staggered-layer design prototype with 25 cm2 square cells

SiPM proton irradiation test at UC Davis Cylotron – May 14th – 15th



- All SiPM models to be used in all ePIC Calorimeters tested for all fluence range relevant for EIC
- Dark current vs. proton fluence for set overvoltage values, and other measurements done
- High-temperature annealing studies relevant for ZDC are ongoing
- With hard data at hand, simulation of noise will ensue

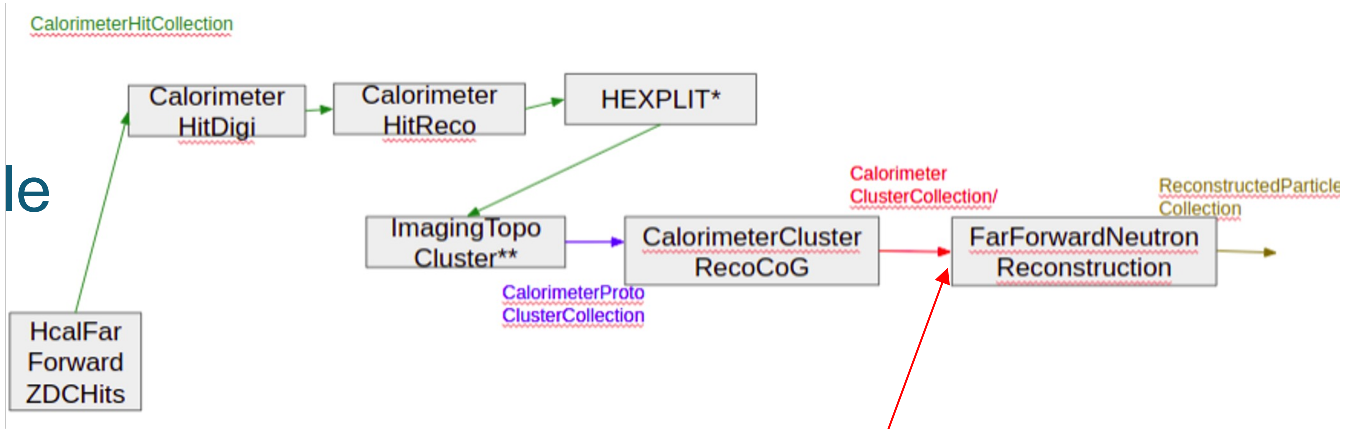
ZDC SiPM



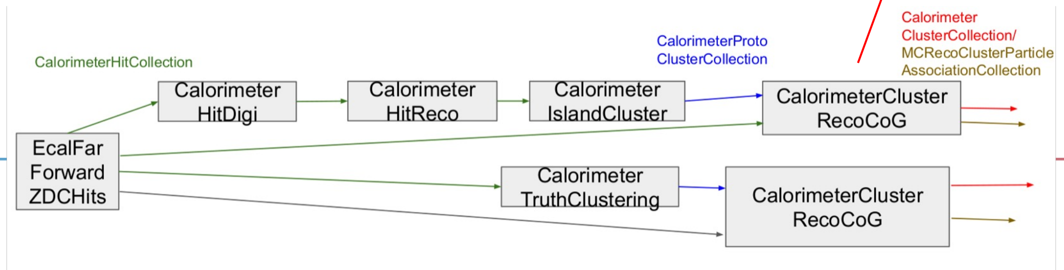
Status of Simulation

- Full reconstruction chain of both SiPM-on-tile and of Crystal parts are **finished** and in EICRECON (including digitization, staggering & HEXPLITfor SiPM-on-tile, clustering in 3D and 2D respectively). Overall ZDC effort lead by Sebouh Paul.
- Benchmark using DEMP pi+ (i.e.a neutron in ZDC) is finished, lead by Barak et al.
- Benchmark using DEMP K+ (i.e. a Lambda in ZDC) is in progress, with preliminary results already suggesting satisfactory results , lead by Sebouh et al.
- Benchmark for soft-photons using “semi-coherent” events is in the planning phase.
- Using benchmark and different configurations, i.e. Craterlake vs other TBD, various options can be studied automatically, i.e. LYSO vs PbW04 vs none, and various sizes.

SiPM-on-tile

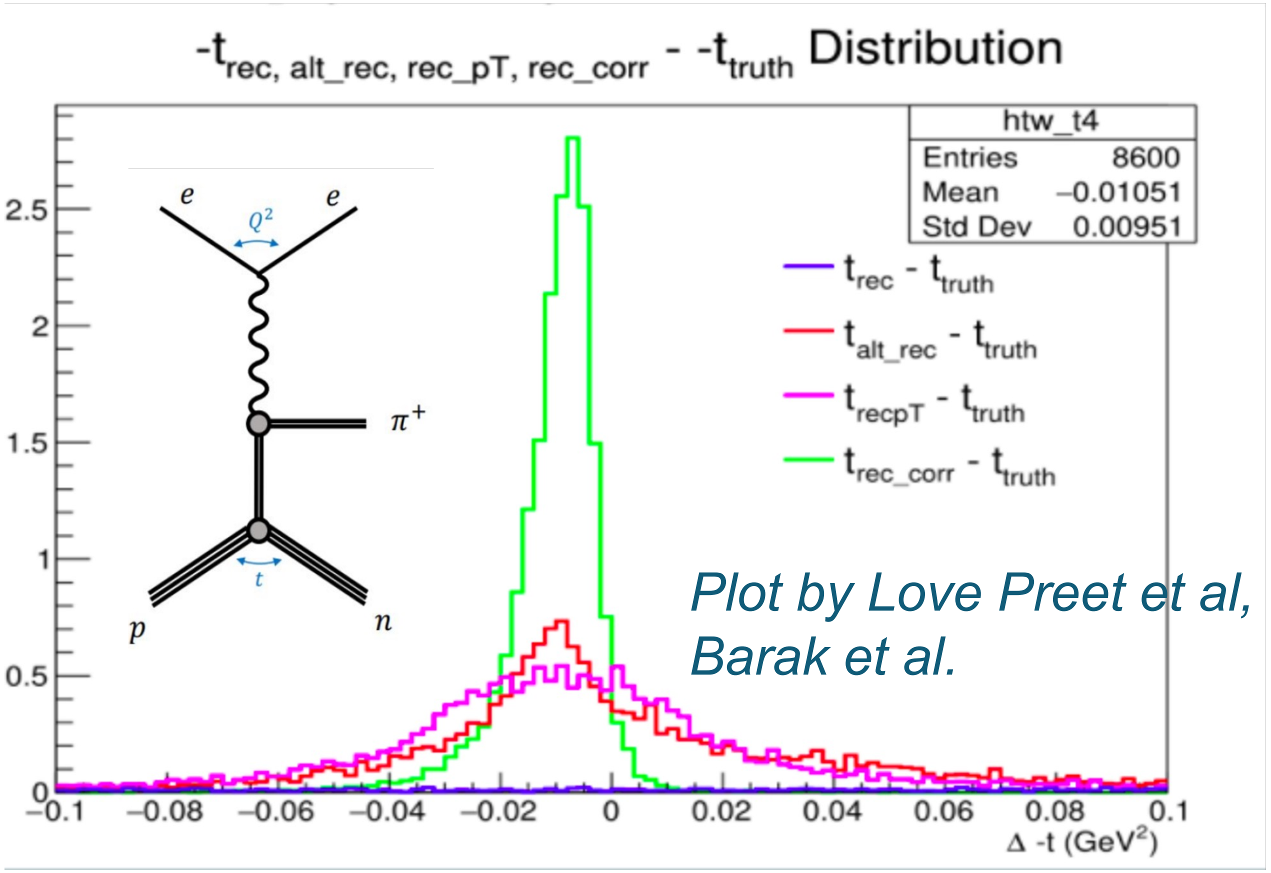


Crystal



Benchmarks and Performance

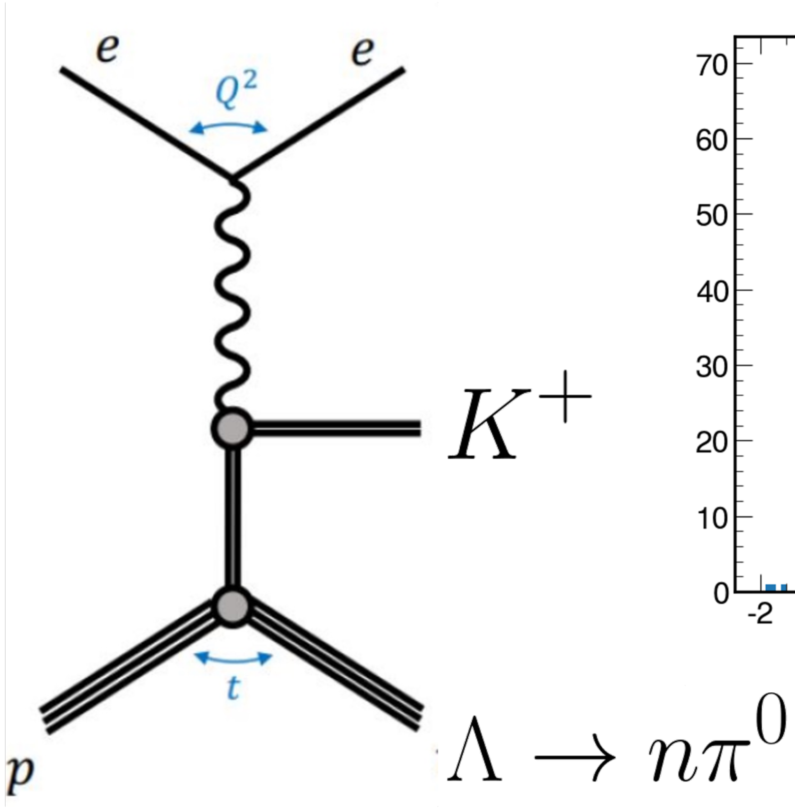
ZDC

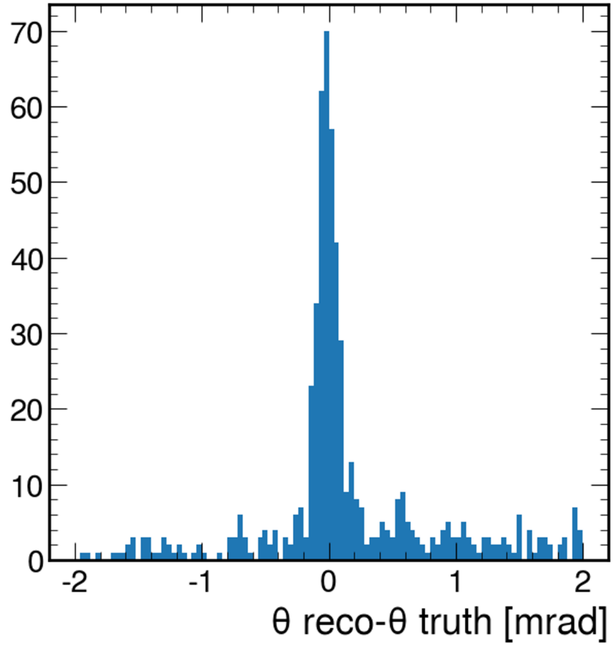


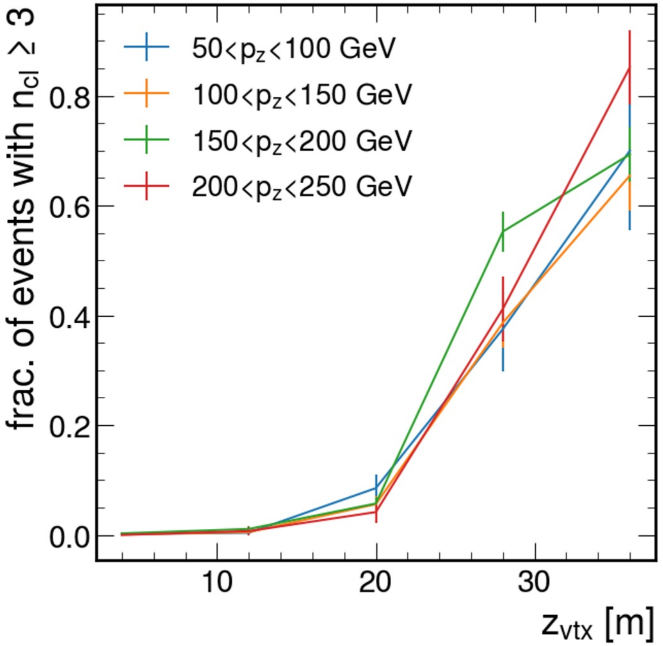
Plot by Love Preet et al, Barak et al.

- DEMP pi+ benchmark by Barak et al., Love Preet et al., was updated to use the latest EICRECON neutron reconstruction code from Sebouh Paul.
- Uses CraterLake configuration, which has LYSO + SiPM-on-tile ZDC.
- Push to main branch is imminent. TDR candidate plot.

Benchmarks and Performance







- DEMP K+ benchmark under construction
- So far, promising early results with SiPM-on-tile only configuration (i.e. no crystal simulated). Lambda theta peak width is ~0.08 mrad, comparable to single neutron at ~100 GeV.
- Benchmark will be ready by the Summer collaboration meeting

Summaries

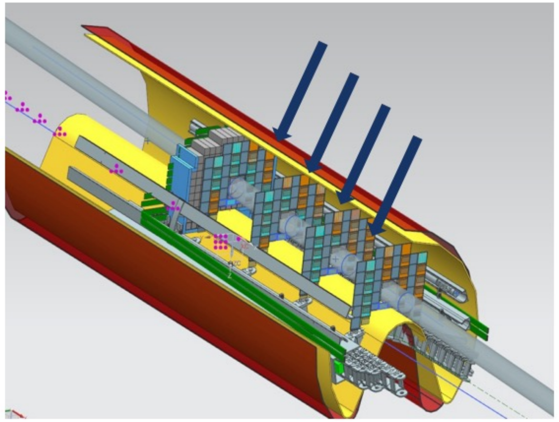
B0 Si Tracker
Zvi Citron

Detector Design
- Overview
- Detector requirements
- Radiation requirements
- Piggy back off of test beam results from other AC-LGAD groups

Performance
- Some benchmarks defined
- Full event reconstruction

Mechanics and Integration
- Structure
- Support structures

Status in dd4hep
- Baseline detector implemented
- More sophisticated implementation needed (e.g. digitization)
- Synchronization of dd4hep and CAD on the engineering side



Ready
Work in progress
Lots to do

Readout
- Piggybacking off of readout in use by other sub-systems

Cooling
- TBD

Monitoring System
- TBD

Beamline integration
- Basic installation plan exists, lots still to do

Summaries

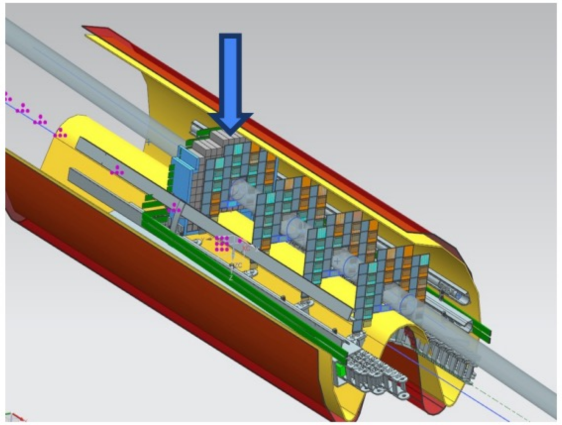
B0 EM Calorimeter
Zvi Citron

Detector Design
- Overview
- Detector requirements
- Radiation requirements
- Test beam: can we join other system (e.g. backwards EMCal) efforts?

Performance
- Full set of benchmarks defined
- Full event reconstruction

Mechanics and Integration
- Structure
- Support structures

Status in dd4hep
- Baseline detector implemented
- More sophisticated implementation needed (e.g. digitization), some problems in reco/clustering
- Synchronization of dd4hep and CAD on the engineering side



Ready
Work in progress
Lots to do

Readout
- Readout with APD with two different gains

Cooling
- TBD

Monitoring System
- TBD

Beamline integration
- Basic installation plan exists, lots still to do

Summaries

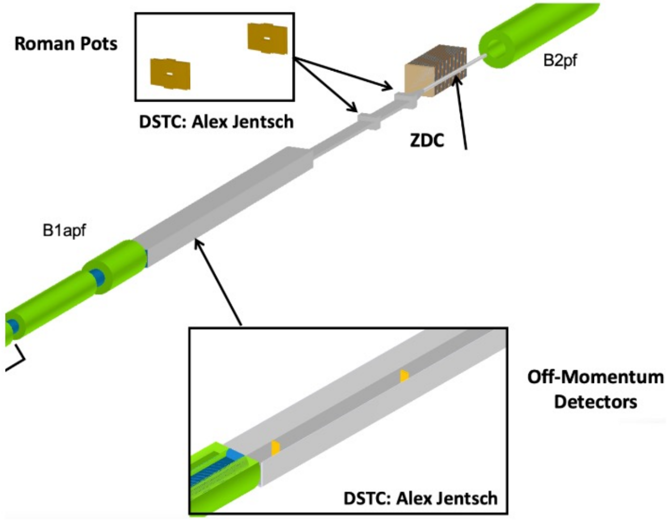
Roman Pots and Off-Momentum Detectors (DSTC: Alex Jentsch)

Detector Design
- Overview
- Detector requirements
- Radiation requirements
- Test beam results

Performance
- Studies required for the detector
- Full event reconstruction
  - ML reco + transfer matrix

Mechanics and Integration
- Structure
- Support structures

Status in dd4hep
- Basic Geometry and support
- Handling of all reco cases (e.g. various nuclei)
- Updates and refinements needed for material.



Readout
- AC-LGAD
- EICROC0
- Full ASIC
- DAQ/ASIC connection
- Carrier boards

Cooling
- Conductive cooling
- Actual requirements

Monitoring System
- Temperature and voltage monitoring

Beamline integration
- Basic designs
- Impedance impact
- Safety systems
- Alignment, BPMs, etc.

Ready
Work in progress
Lots to do

Summaries

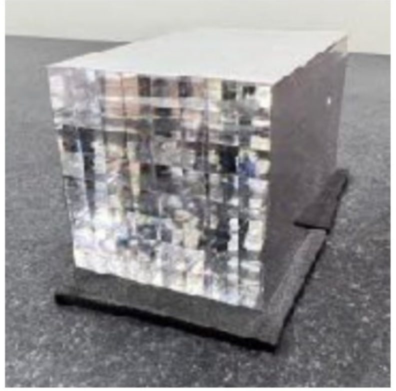
ZDC crystal calorimeter
DSTC: Yuji Goto

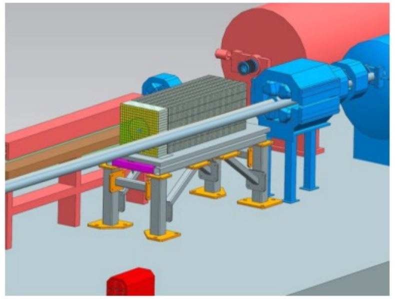
Detector Design
- Overview
- Detector requirements
- Radiation requirements
- PWO or LYSO crystal selection
- ELPH positron test beam

Performance
- Full event reconstruction
- Physics performance studies:
  - low-E photon & high-E pi0
  - combination with hadron calorimeter

Mechanics and Integration
- Structure
- Support structures

Status in dd4hep
- Geometry implemented
- Clustering code development





Ready
Work in progress
Lots to do

Readout
- Photosensor selection
- ASIC selection

Cooling
- TBD

Monitoring System
- TBD

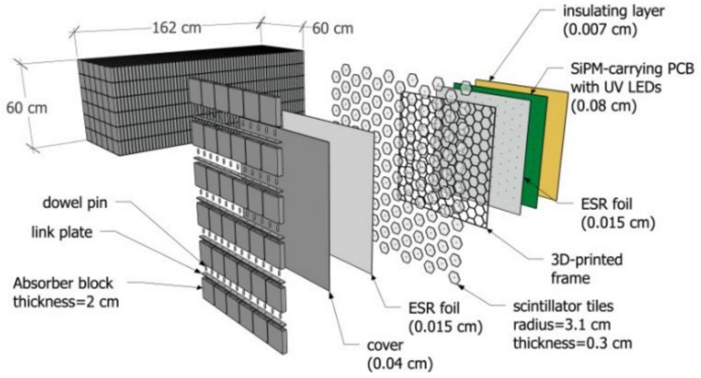
Beamline integration
- TBD

Summaries

ZDC SiPM-on-tile portion

Miguel Arratia

Detector Design
- Overview
- Detector requirements
- Radiation requirements
- Test beam results



Performance
- Full event reconstruction
- Physics performance studies:
  - Single neutron
  - Single photon, photon/pi0 separation
  - Multiple neutrons
  - Lambda

Mechanics and Integration
- Self-supporting Fe structure

Status in dd4hep
- Geometry fully implemented
- Clustering algorithms tested

Readout
- HGCROC2

Cooling
- No

Monitoring System
- TBD

Beamline integration
- TBD

Backup

Generic Performance Requirements

- Spatial resolution requirement → **140um or less**.
  - Angular divergence largest contributor, reduces impact of detector choice.
- Crab cavity rotation of the bunches → transverse “kick” to the particles, dependent on the location along the bunch.
  - Results in effective vertex smearing, disentangled with fast timing → **35ps to remove the full effect**.
- Timing also needed for background rejection.
- Technologies need to be radiation hard → expected radiation load on the RP and OMD ~ 100x less than at the LHC.
  - Radiation damage has impact on **timing resolution** and **spatial resolution (when charge sharing is used)**.
  - Radiation studies carried out for ePIC indicate that doses delivered to AC-LGADs for RP/OMD will not lead to reduction in performance during life of experiment.

Generic Performance Requirements

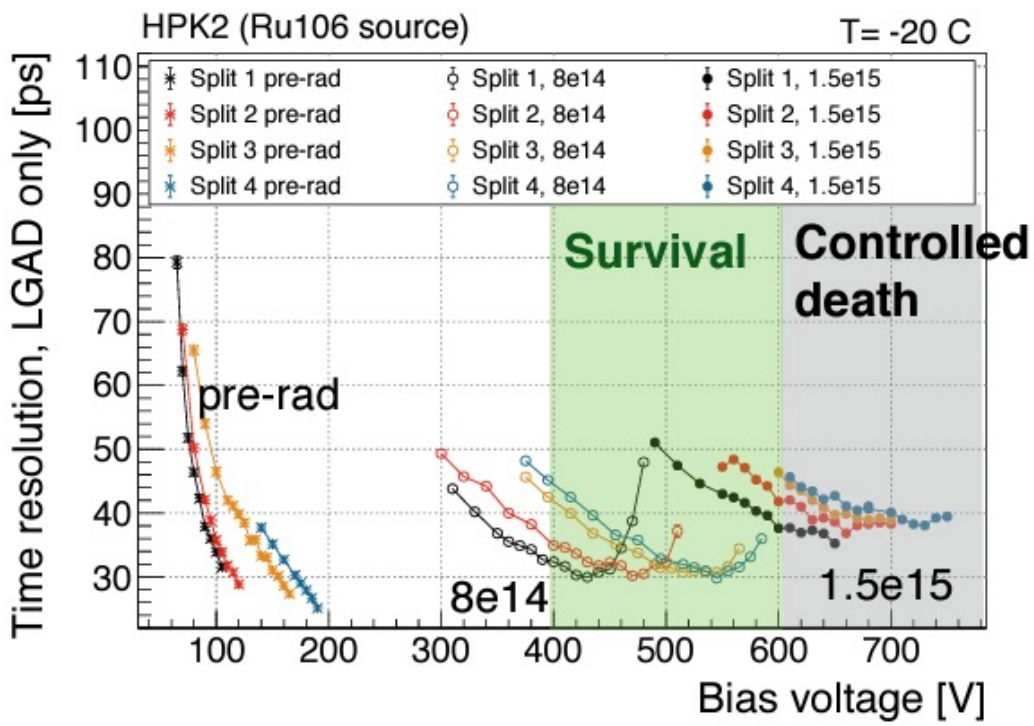
From:
https://indico.cern.ch/event/1029124/contributions/4411270/attachments/2269713/3854416/heller_LGAD_mortality_RD50.pdf

Plot shows time resolution as a function of bias voltage for various levels of irradiation of a batch HBK DC-LGADs used by ATLAS and CMS.

Split 1 — Split 4 (lowest to highest operating voltage)

Radiation: n_{eq} = 8e14 and 1.5e15 n/cm^2

***Note: the fluences shown here are ~ 2-3 orders of magnitude higher than what is expected at ePIC.



- Technologies need to be radiation hard → expected radiation load on the RP and OMD ~ 100x less than at the LHC.
  - Radiation damage has impact on **timing resolution** and **spatial resolution (when charge sharing is used)**.
  - Radiation studies carried out for ePIC indicate that doses delivered to AC-LGADs for RP/OMD will not lead to reduction in performance during life of experiment.

Generic Performance Requirements

Study from eRD24 effort

- The various contributions add in quadrature (this was checked empirically, measuring each effect independently).

$$\Delta p_{t,total} = \sqrt{(\Delta p_{t,AD})^2 + (\Delta p_{t,CC})^2 + (\Delta p_{t,pxl})^2}$$

Angular divergence

Primary vertex smearing from crab cavity rotation.

Smearing from finite pixel size.

These studies based on the "ultimate" machine performance with strong hadron cooling.

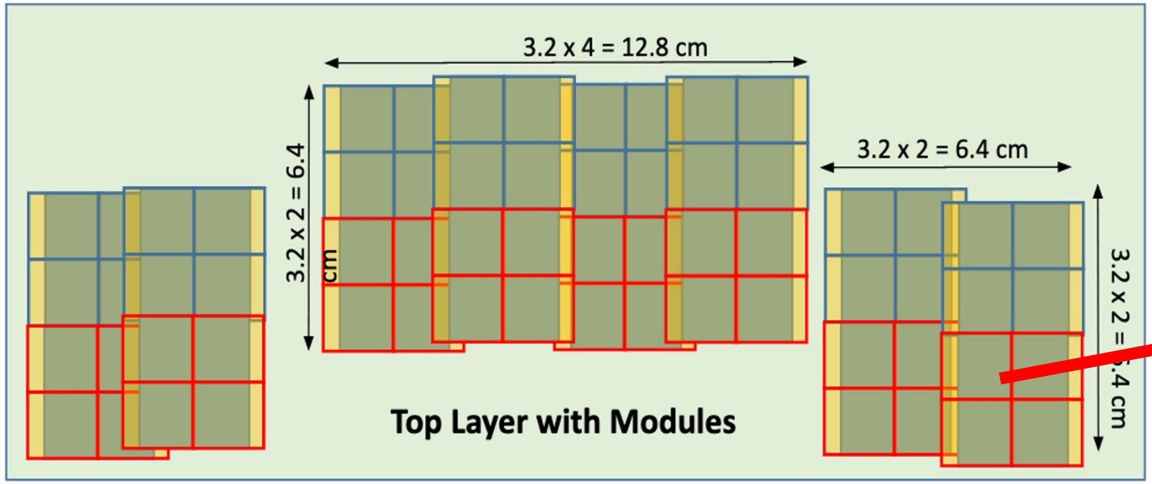
	Ang Div. (HD)	Ang Div. (HA)	Vtx Smear	250μm pxl	500μm pxl	1.3mm pxl
$\Delta p_{t,total}$ [MeV/c] - 275 GeV	40	28*	20	6	11	26
$\Delta p_{t,total}$ [MeV/c] - 100 GeV	22	11	9	9	11	16
$\Delta p_{t,total}$ [MeV/c] - 41 GeV	14	-	10	9	10	12

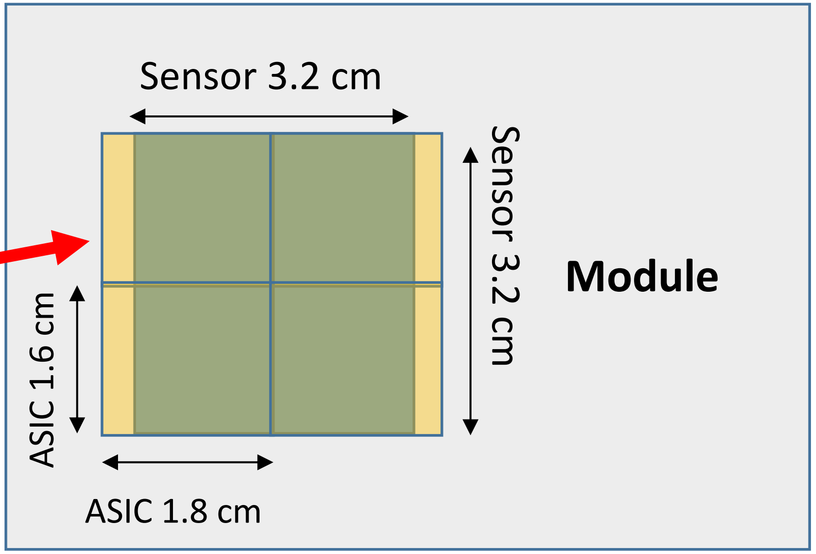
- **Beam angular divergence**
  - Beam property, can't correct for it – sets the lower bound of smearing.
- **Vertex smearing from crab rotation**
  - Correctable with precise timing (~35ps).
- **Finite pixel size on sensor**
  - 500μm seems like the best compromise between potential cost and smearing.

These requirements can be met by the new **AC-coupled LGAD sensor technology** (eRD24 was focused on applications of this technology to the far-forward detectors).

Technology: AC-LGAD

- Updated layout for the **Roman Pots** with current design for AC-LGAD sensor + ASIC.



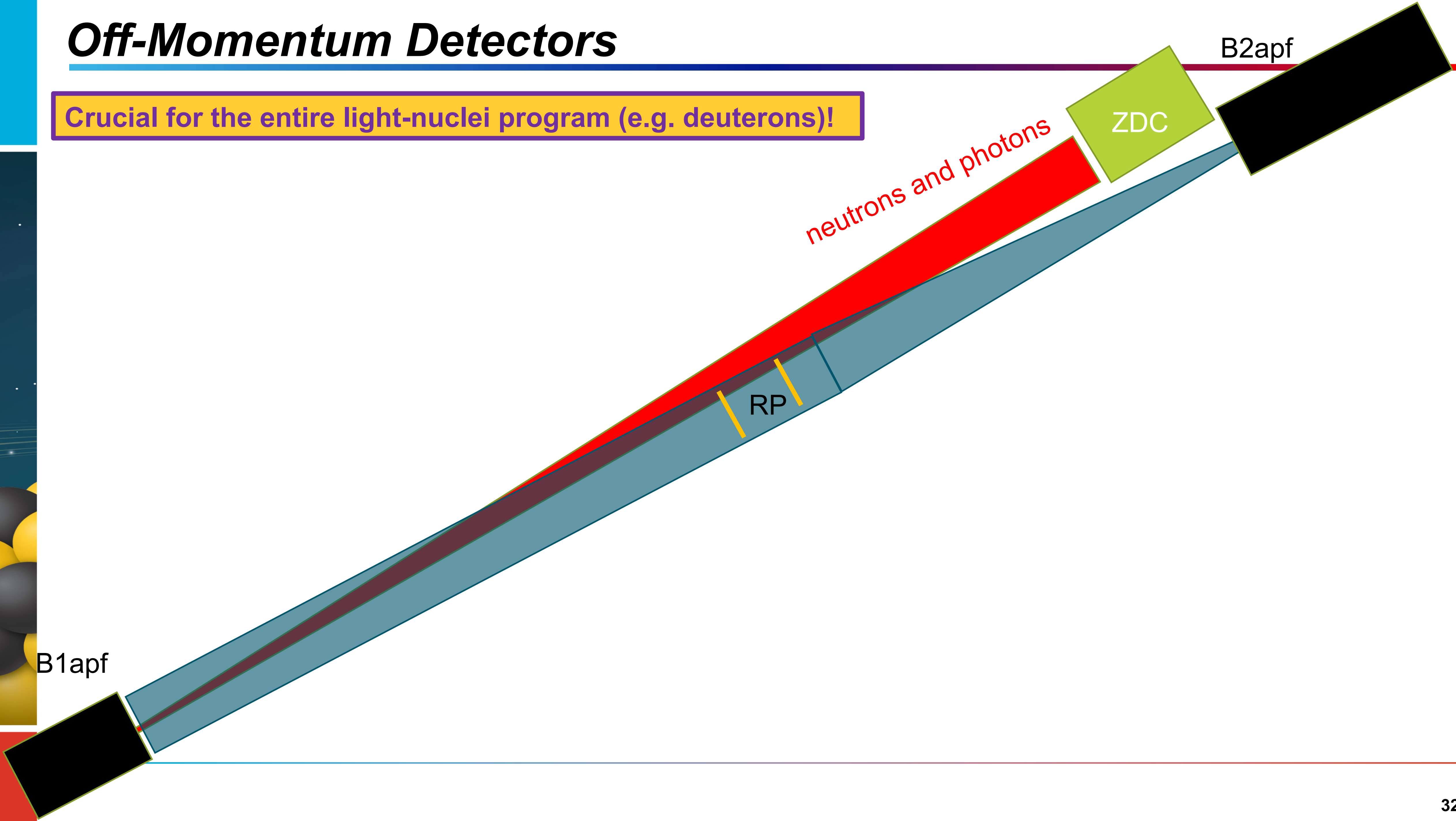


- Approach based on bump-bonding four custom ASICs to a single AC-LGAD sensor to make a “module”.
  - This is being re-evaluated now.

ASIC size	ASIC Pixel pitch	# Ch. per ASIC	# ASICs per module	Sensor area	# Mod. per layer	Total # ASICs	Total # Ch.	Total Si Area
1.6x1.8 cm^2	500 μm	32x32	4	3.2x3.2 cm^2	32	512	524,288	1,311 cm^2

Off-Momentum Detectors

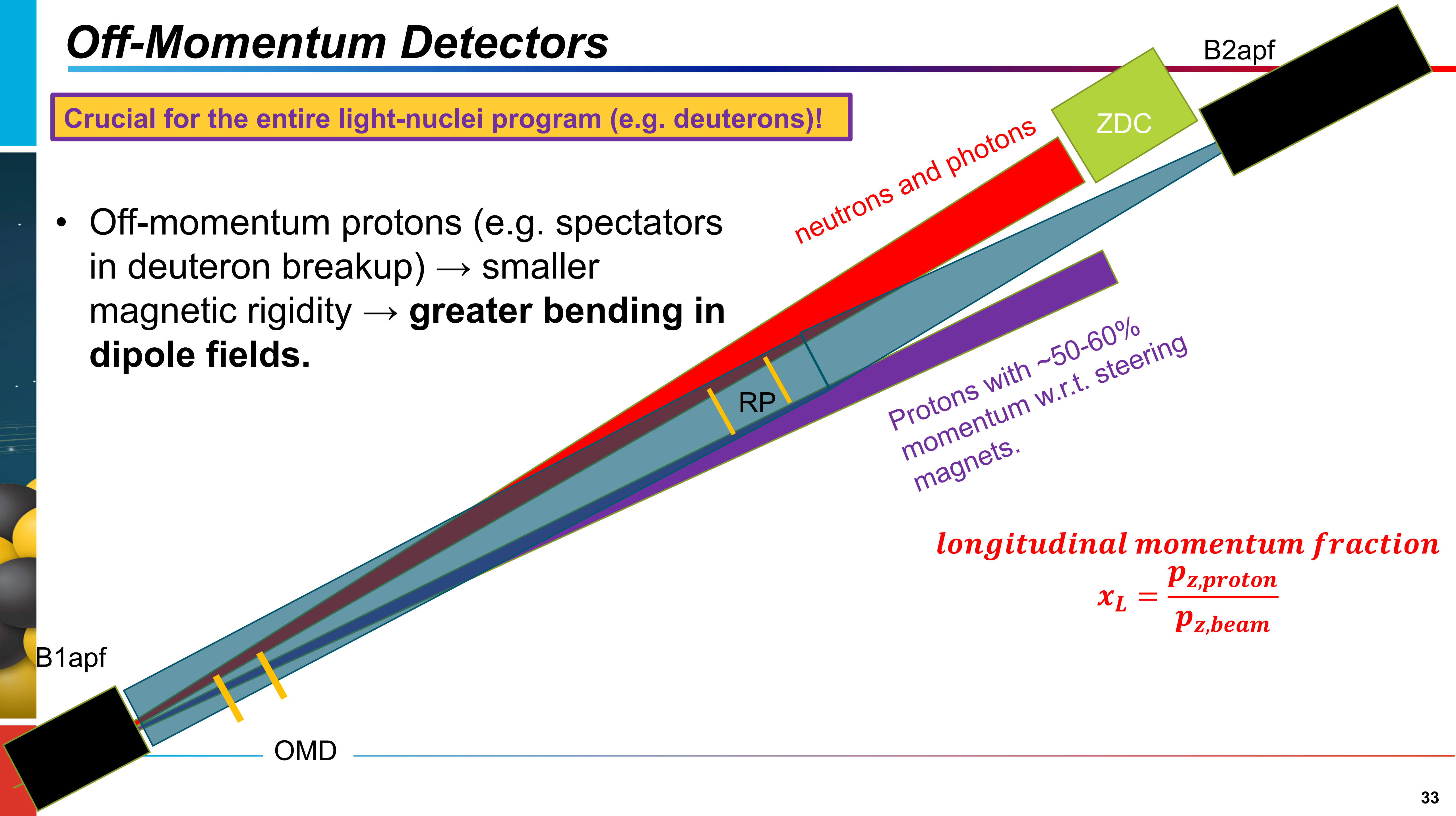
Crucial for the entire light-nuclei program (e.g. deuterons)!



Off-Momentum Detectors

Crucial for the entire light-nuclei program (e.g. deuterons)!

- Off-momentum protons (e.g. spectators in deuteron breakup) → smaller magnetic rigidity → **greater bending in dipole fields.**



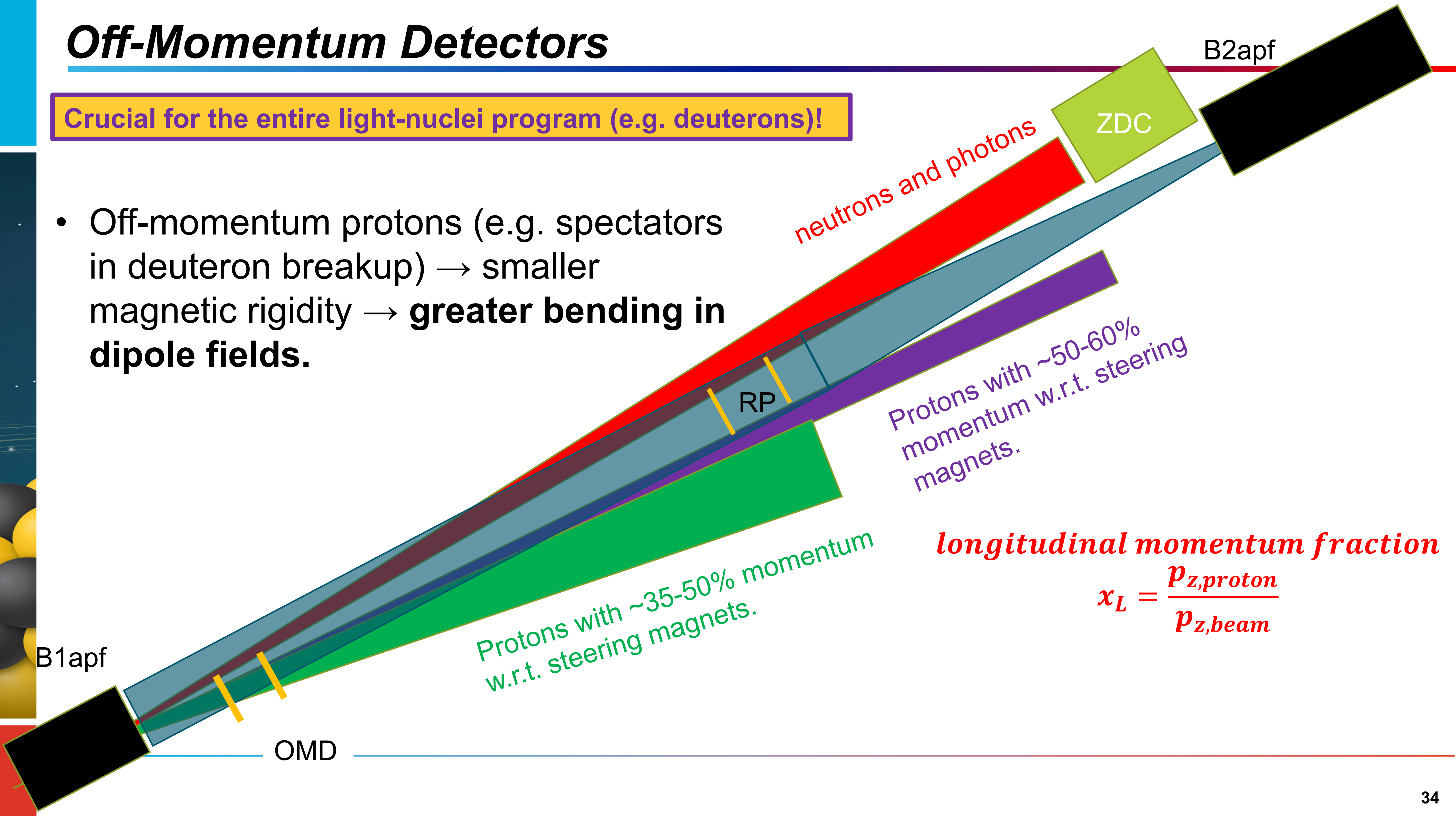
longitudinal momentum fraction

$$x_L = \frac{p_{z,proton}}{p_{z,beam}}$$

Off-Momentum Detectors

Crucial for the entire light-nuclei program (e.g. deuterons)!

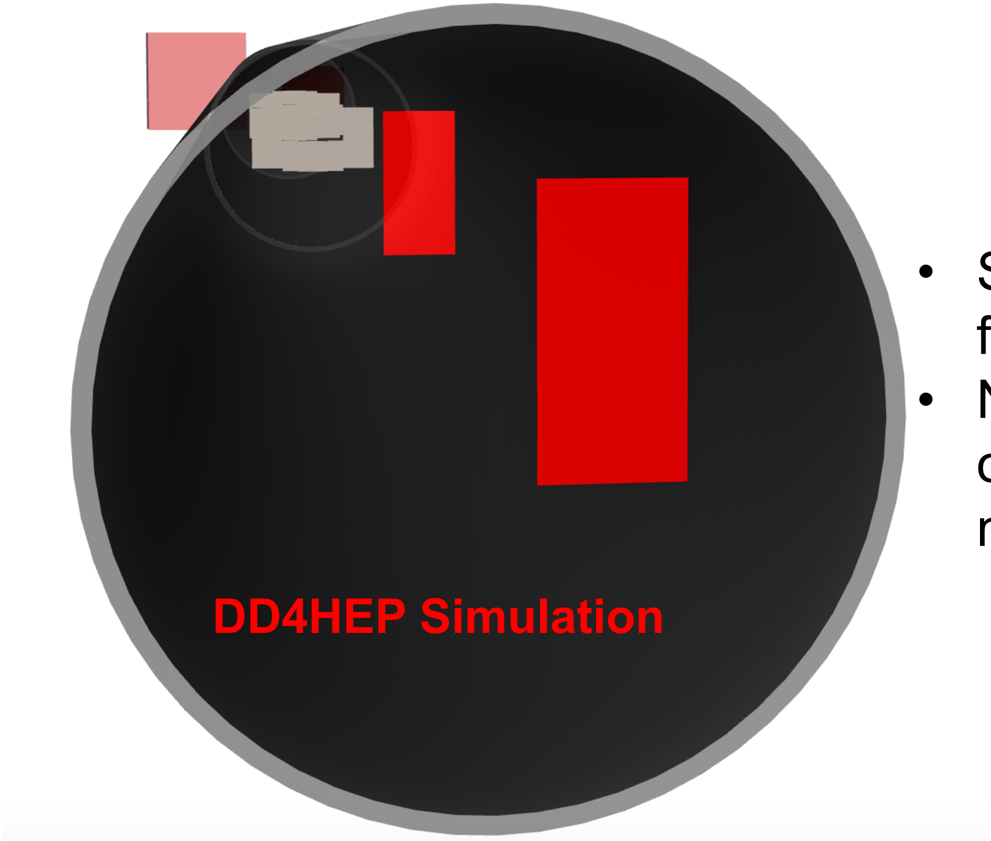
- Off-momentum protons (e.g. spectators in deuteron breakup) → smaller magnetic rigidity → **greater bending in dipole fields.**



$$\text{longitudinal momentum fraction}$$

$$x_L = \frac{p_{z,proton}}{p_{z,beam}}$$

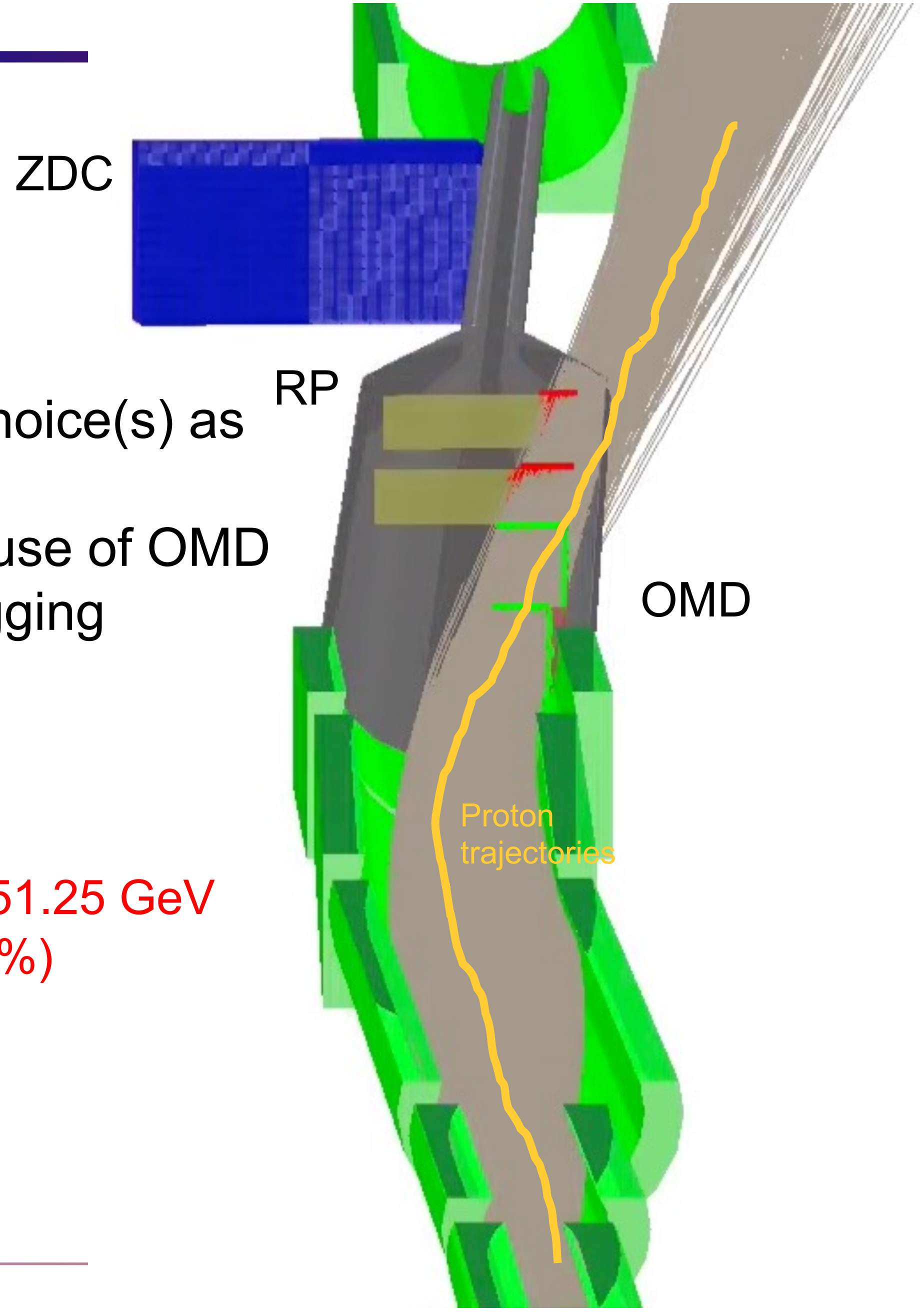
Off-Momentum Detectors



Off-momentum detectors implemented as horizontal ”Roman Pots” style sensors.

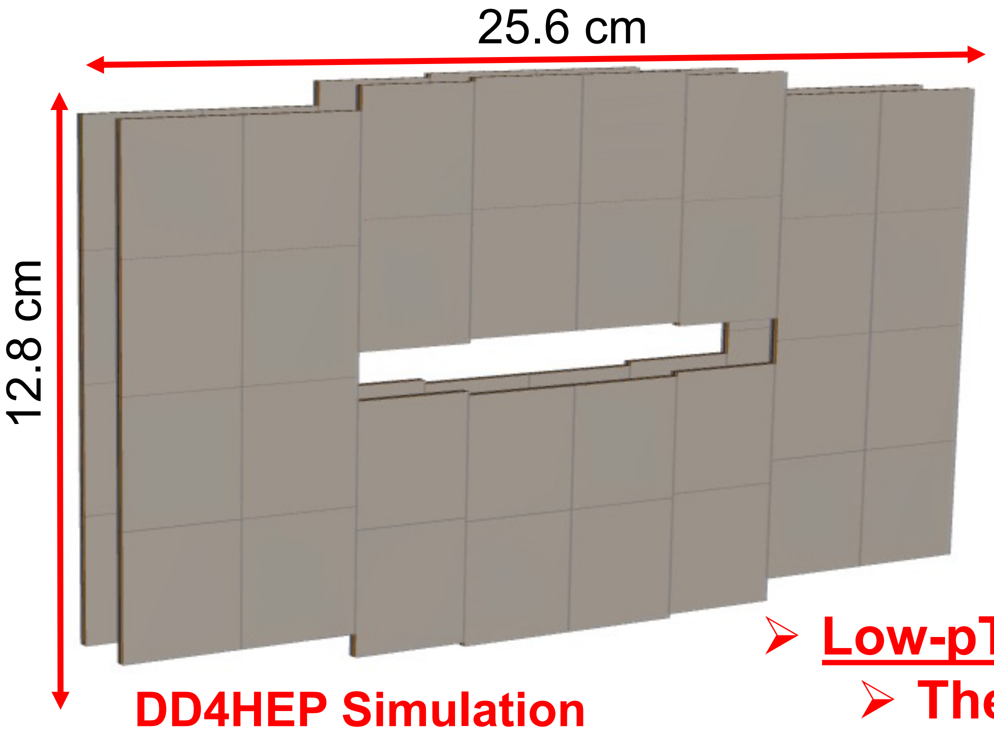
- Same technology choice(s) as for the Roman Pots.
- Need to also study use of OMD on other side for tagging negative pions.

Protons
123.75 < E < 151.25 GeV
(45% < xL < 55%)
0 < θ < 5 mrad



EICROOT GEANT4 simulation.

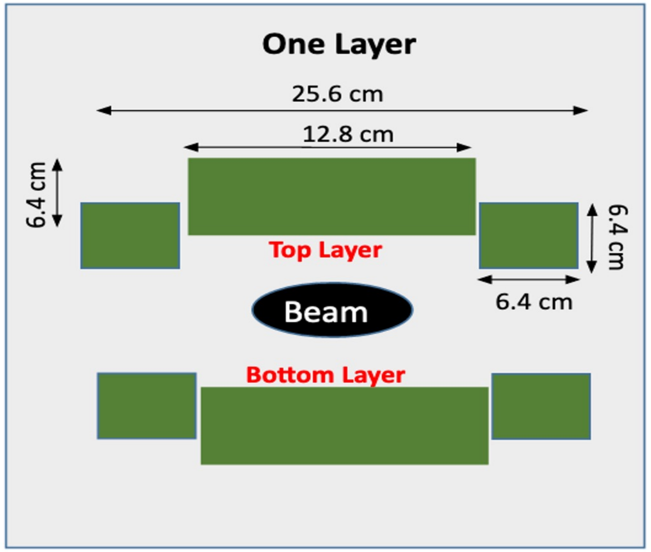
Roman Pots @ the EIC



DD4HEP Simulation

$\sigma(z)$ is the Gaussian width of the beam, $\beta(z)$ is the RMS transverse beam size. ε is the beam emittance.

$$\sigma(z) \sim \sqrt{\varepsilon \cdot \beta(z)}$$

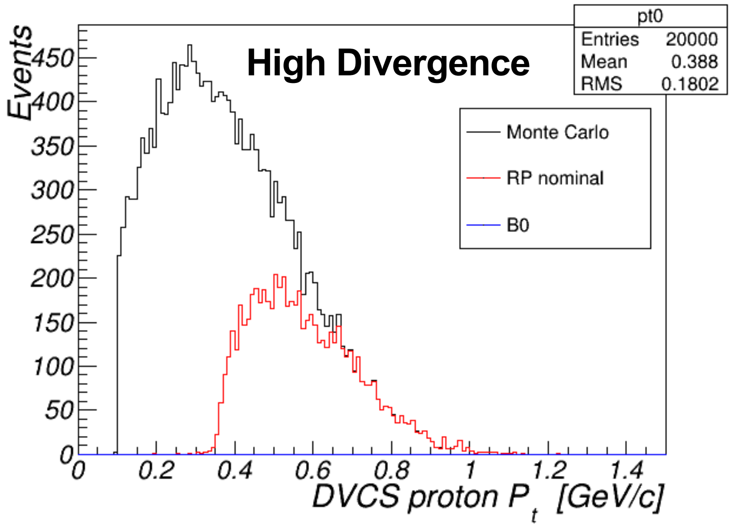


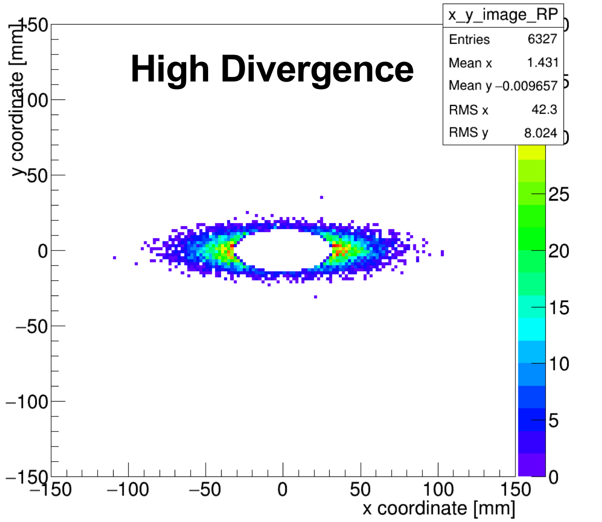
- **<u>Low-pT cutoff determined by beam optics.</u>**
  - **The safe distance is ~10σ from the beam center (1$\sigma \sim 1$mm).**
- **Optics change with energy**
  - **Can also be changed within a single energy to maximize *either acceptance at the RP, or the luminosity.***

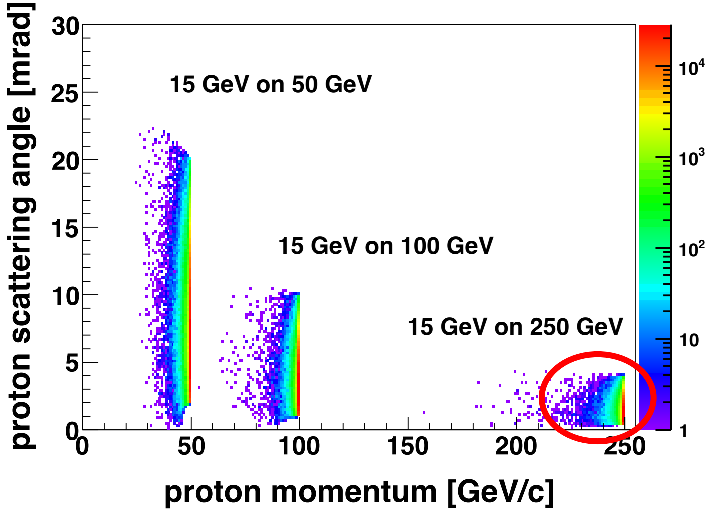
- **Detectors need to be able to move to different positions for different optics configurations.**

Digression: Machine Optics Impact

275 GeV DVCS Proton Acceptance



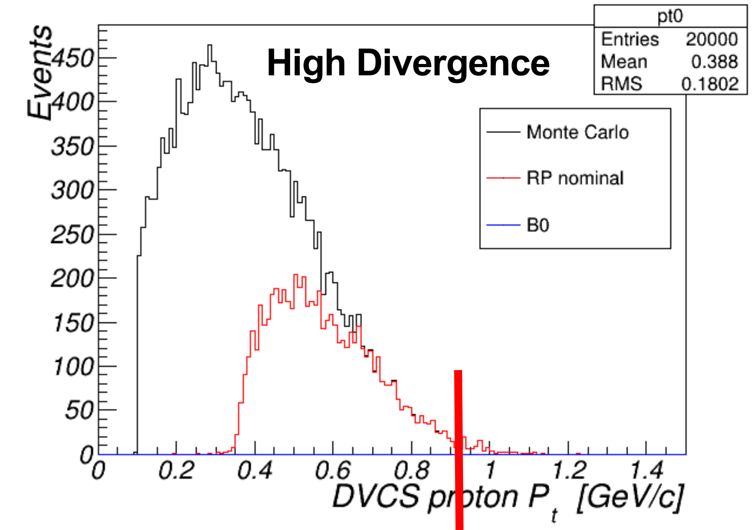


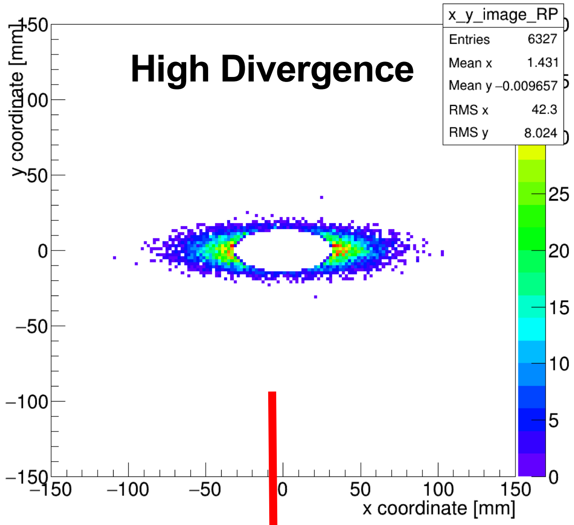


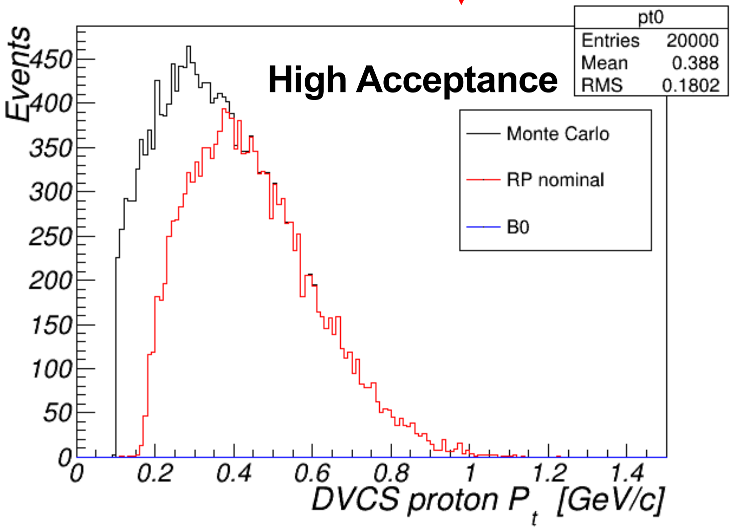
High Divergence: smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

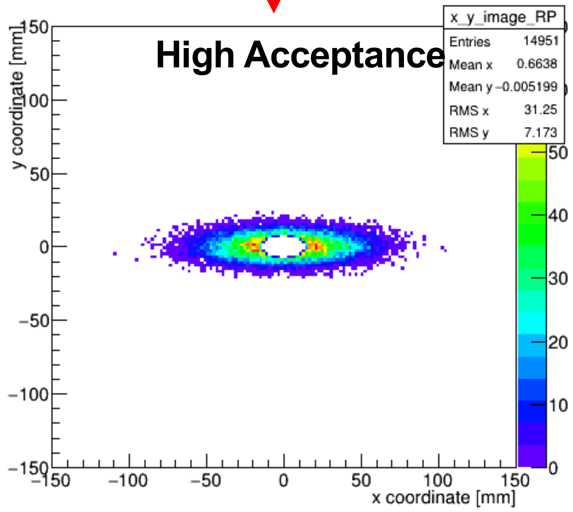
Digression: Machine Optics Impact

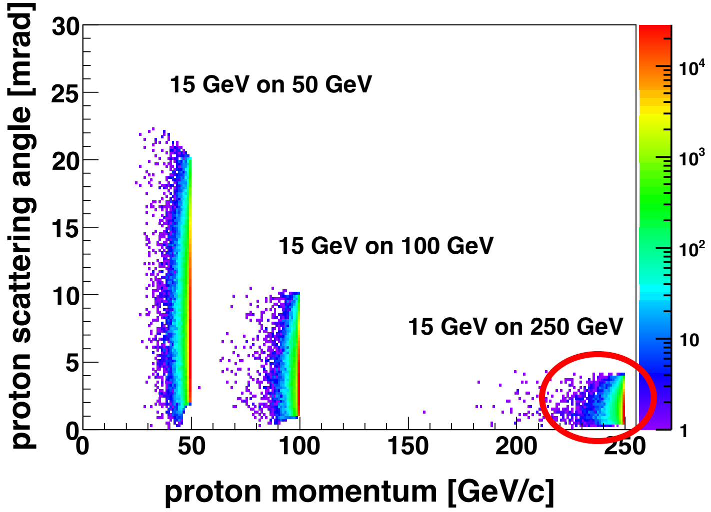
275 GeV DVCS Proton Acceptance









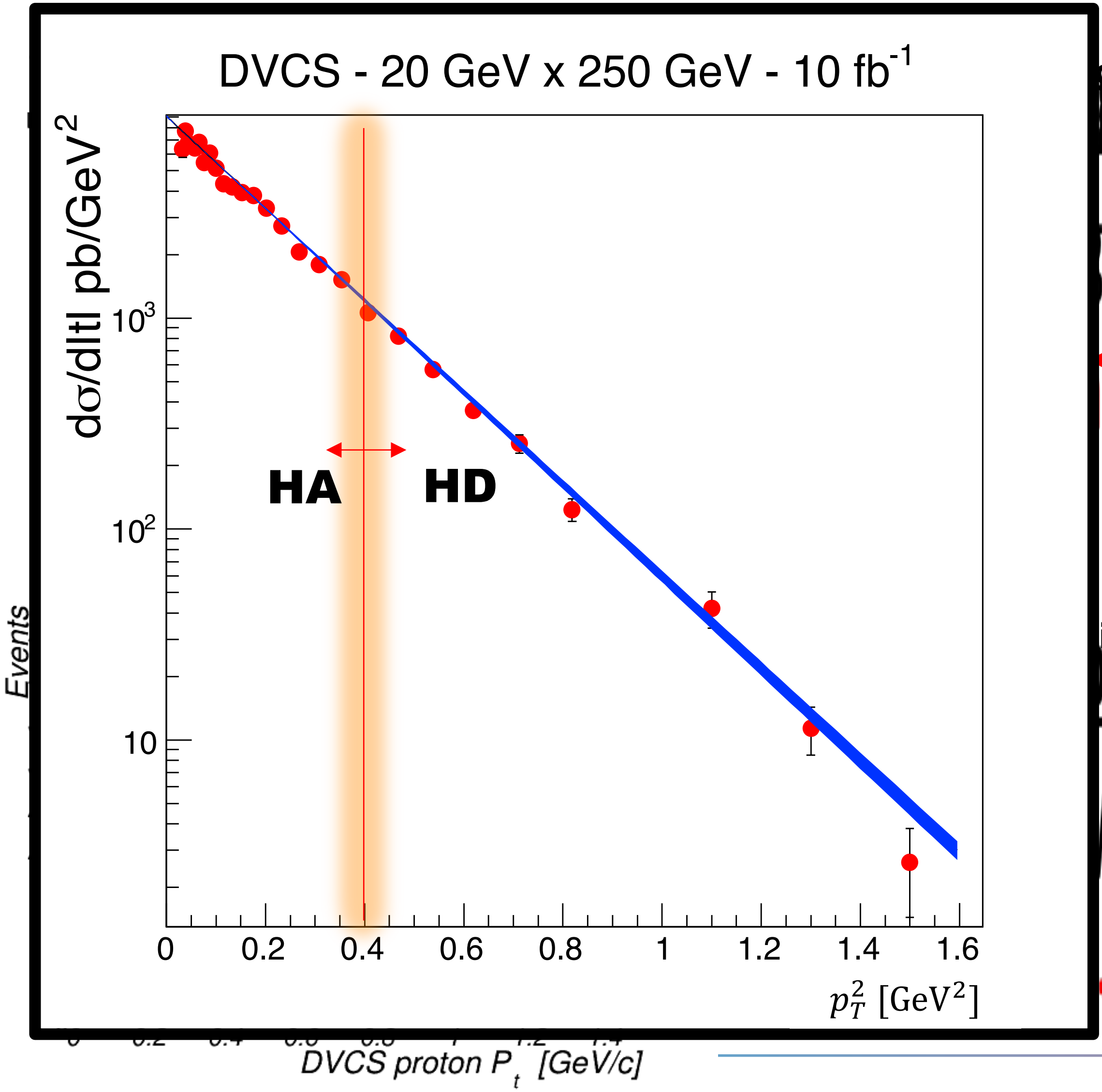


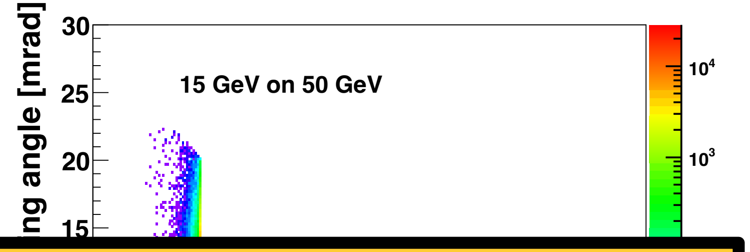
High Divergence: smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

High Acceptance: larger β^* at IP, smaller $\beta(z = 30m)$ -> lower lumi., smaller beam at RP

Digression: Machine Optics Impact

275 GeV DVCS Proton Acceptance





gh Divergence

gence: smaller β^* at

Using the two configurations, we are able to measure the low-p_T region (with better acceptance) and high-t tail (with higher luminosity).

Detectors need to be able to move to different positions for different optics configurations.

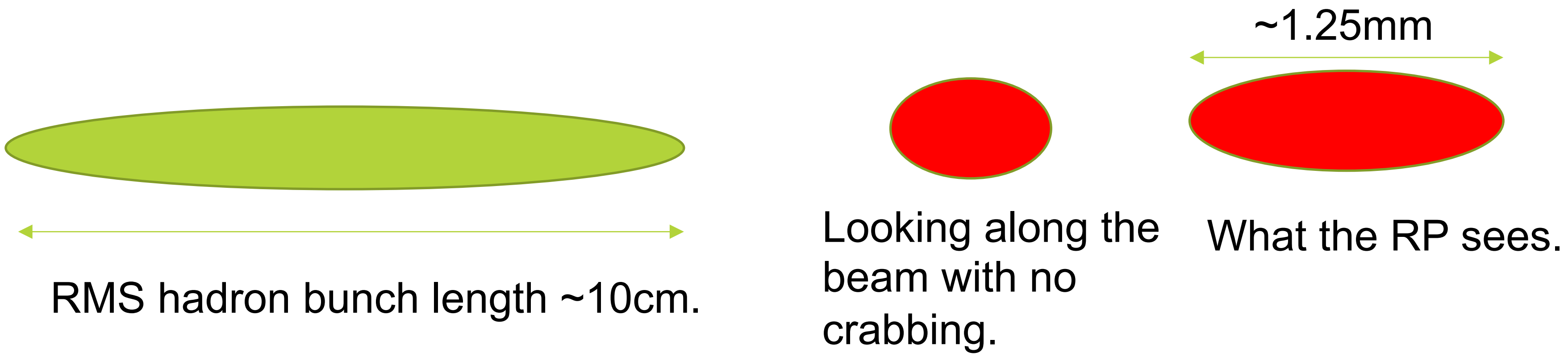
at IP, smaller $\beta(z = 30m)$ ->

lower lumi., smaller beam at RP

, smaller beam at RP

Momentum Resolution – Timing

For exclusive reactions measured with the Roman Pots we need good timing to resolve the position of the interaction within the proton bunch. But what should the timing be?



- Because of the rotation, the Roman Pots see the bunch crossing smeared in x.
- Vertex smearing = 12.5mrad (half the crossing angle) * 10cm = **1.25 mm**
- If the effective vertex smearing was **for a 1cm bunch**, we would have **.125mm** vertex smearing.
- The simulations were done with these two extrema and the results compared.

> - **From these comparisons, reducing the effective vertex smearing to that of the 1cm bunch length reduces the momentum smearing to negligible from this contribution.**
> - **This can be achieved with timing of ~ 35ps (1cm/speed of light).**