Future Calorimetry R&D Directions

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January 11, 2022
Muon Collider Forum

Calorimeter R&D Future

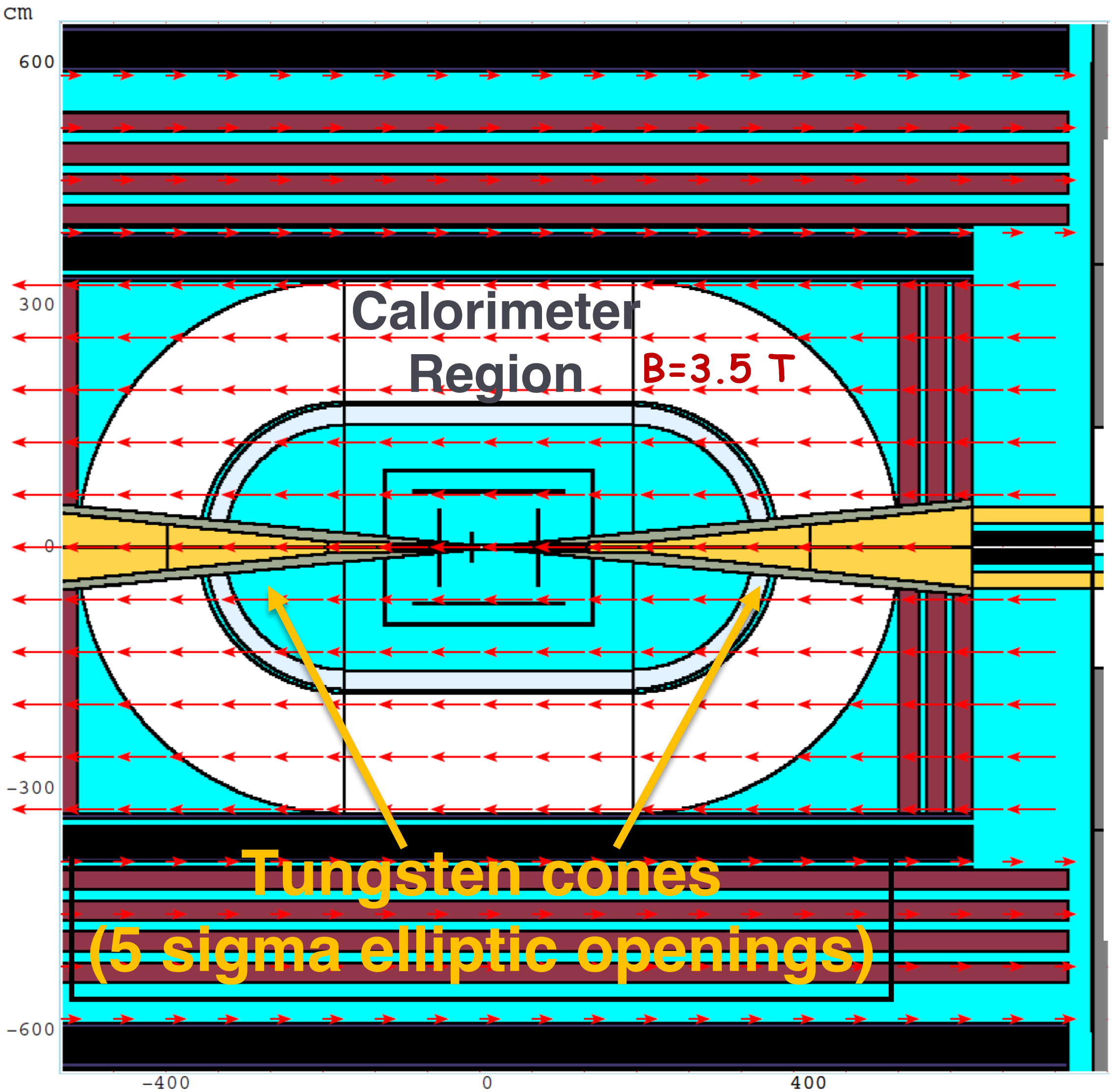
- **Maximize information content**
  - Measure and identify particles and event - and parameters needed to maintain calibration and remove backgrounds
  - Dig deep: high quality local data, but save frugally/intelligently
- **A strong guiding paradigm is Particle-Flow, but previous incarnations were hardly well-implemented**
  - In fact, PF is largely, at this time, based on a lot of assumptions
  - Energy “Flow”: assumes time is measured at different points along the trajectories – few examples of that
  - Assembly of particles out of the parts collected from vertex/tracking/calorimeter/muon – not fail safe
  - Calorimetry – often downgraded to minimum performance, driving many of the mistakes made in the algorithm

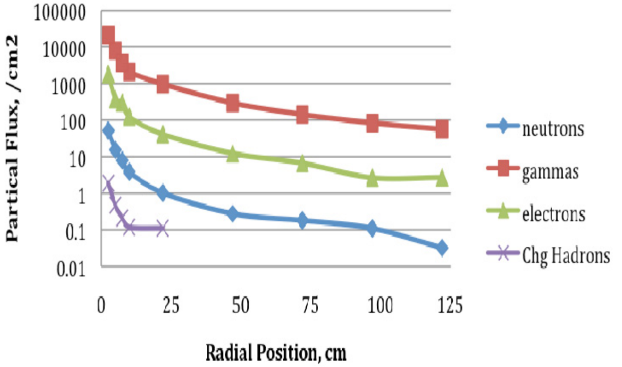
Muon Collider Calorimetry

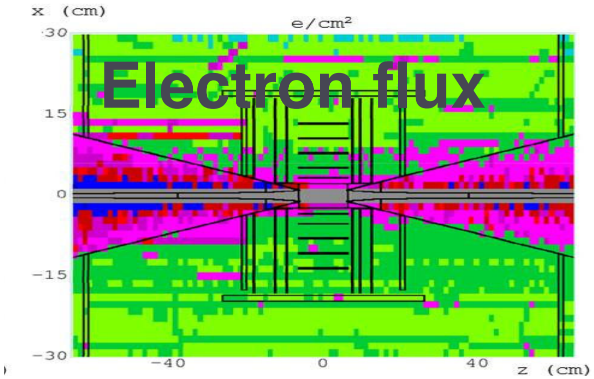
- **Need to drop some assumptions**
  - Measure hit times along trajectories
  - Track from IP outward and from Beam Collimators inward
- **Standard geometries are designed to be hermetic and uniform – tunnel vision on IP**
  - Locations of calorimeter surfaces influences the separation power on beam backgrounds
  - Prompt time of arrival distributions should not peak at background arrival times – and overlap should be suppressed by multiple times along trajectories leading up to calorimeter
  - Timing layers/walls should be arranged to efficiently catch beam backgrounds and maintain high event quality
  - Projective to the IP is for signal

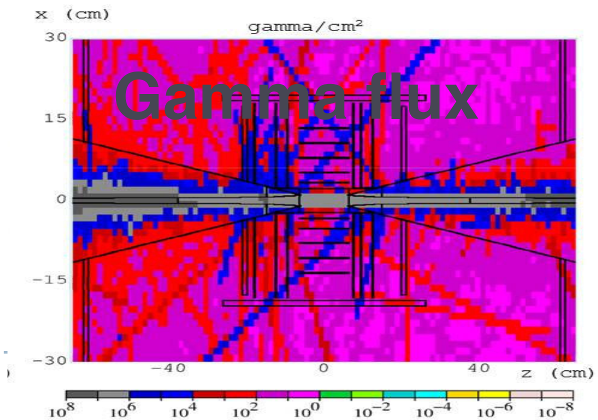
https://arxiv.org/abs/1204.5739
https://accelconf.web.cern.ch/ipac2012/papers/moppc037.pdf

Example Muon Collider Outline

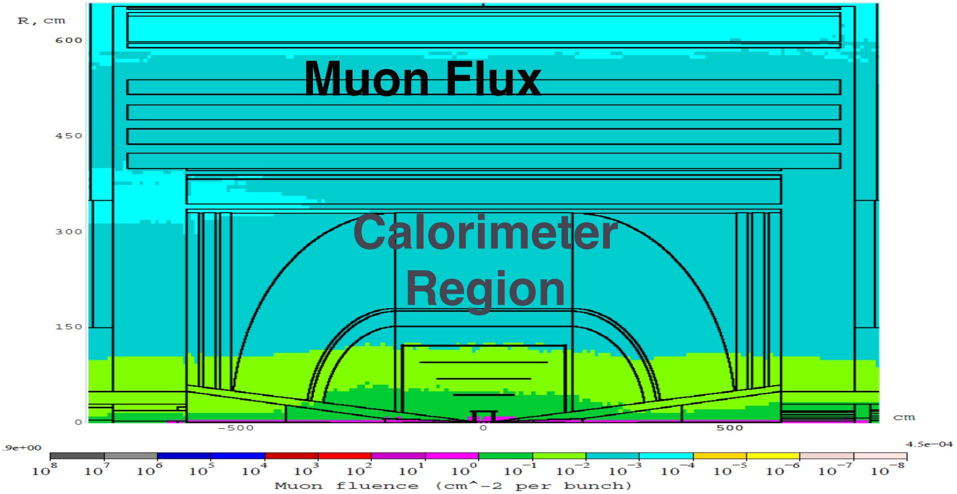


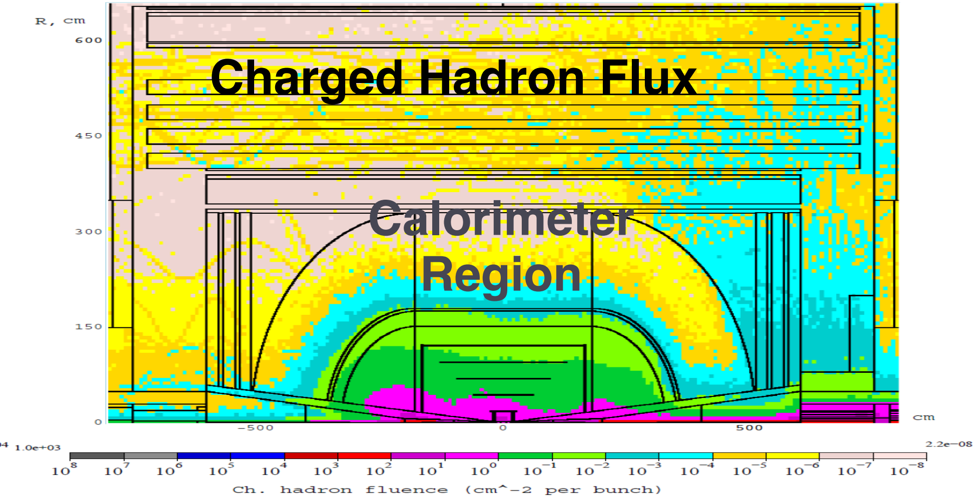


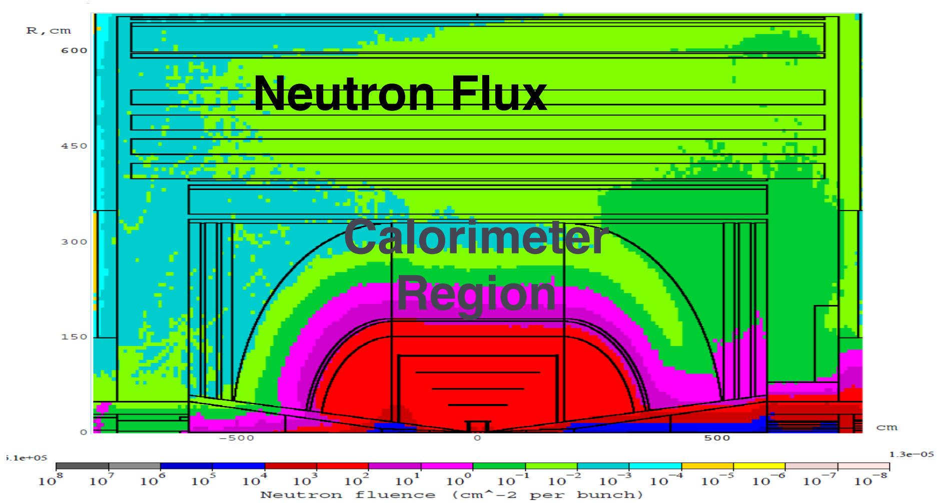


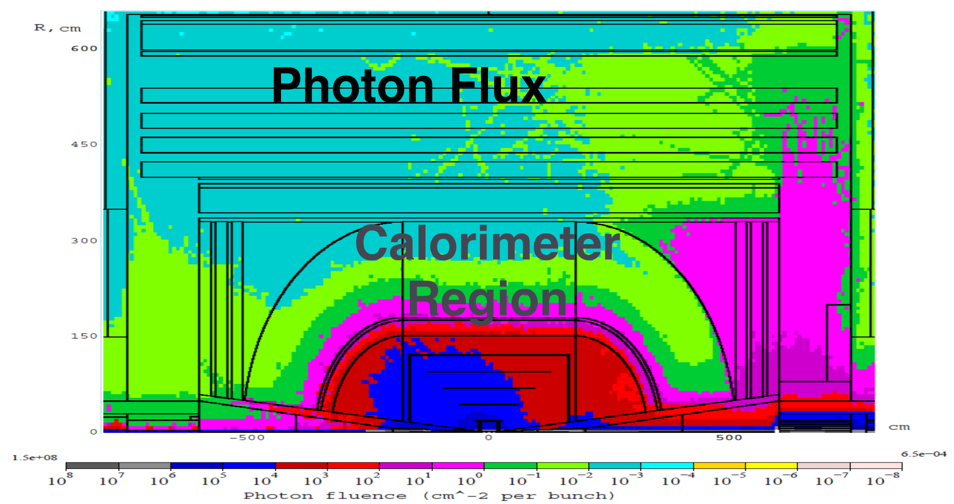


Expected Flux Through Calorimeters









Overview of Recent Calorimeter Work

- Highlight recent review of Calorimetry R&D (https://arxiv.org/abs/2109.00391)

Calorimetry at FCC-ee

Martin Aleksa[1], Franco Bedeschi[2], Roberto Ferrari[3], Felix Sefkow[4], and Christopher G. Tully[5]

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[4] Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany
[5] Princeton University, Department of Physics, Princeton, NJ, United States

- Specific Examples with Dual Readout PFA
- Experience with Precision Timing Layers
- Future R&D directions

Summary Table of Energy Resolutions

https://arxiv.org/abs/2109.00391

Detector technology (ECAL & HCAL)	E.m. energy res. stochastic term	E.m. energy res. constant term	ECAL & HCAL had. energy resolution (stoch. term for single had.)	ECAL & HCAL had. energy resolution (for 50 GeV jets)	Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets)
Highly granular Si/W based ECAL & Scintillator based HCAL	15 – 17 % [12,20]	1 % [12,20]	45 – 50 % [45,20]	≈ 6 % ?	4 % [20]
Highly granular Noble liquid based ECAL & Scintillator based HCAL	8 – 10 % [24,27,46]	< 1 % [24,27,47]	≈ 40 % [27,28]	≈ 6 % ?	3 – 4 % ?
Dual-readout Fibre calorimeter	11 % [48]	< 1 % [48]	≈ 30 % [48]	4 – 5 % [49]	3 – 4 % ?
Hybrid crystal and Dual-readout calorimeter	3 % [30]	< 1 % [30]	≈ 26 % [30]	5 – 6 % [30,50]	3 – 4 % [50]

If the focus is mainly jets, then high-granularity with PFA delivers 4% at 50 GeV – often called "PFA calorimetry"

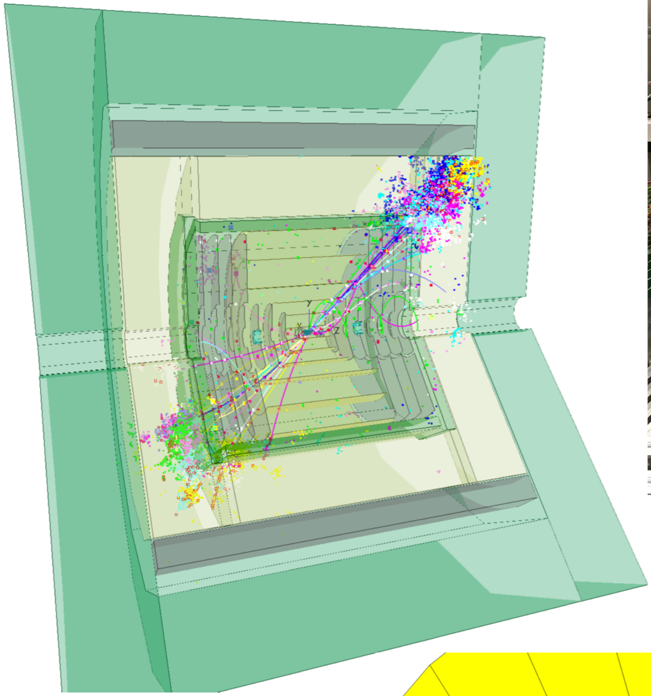
Noble Liquid is a better calorimeter across the board, but needs PFA studies

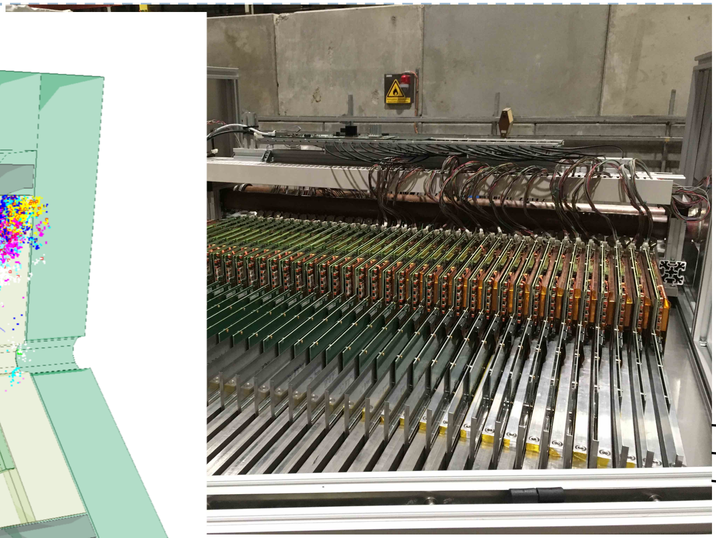
Higher EM performance with Noble Liquid or Fibers – Highest with Crystals

Best Intrinsic Hadron Performance with Dual-Readout Fibers

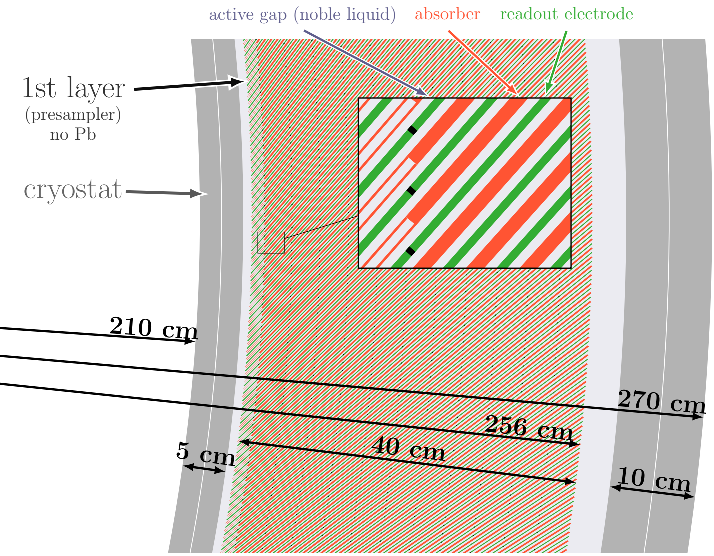
Hybrid Dual-Readout Crystals+Fibers attempts to maximize all performances

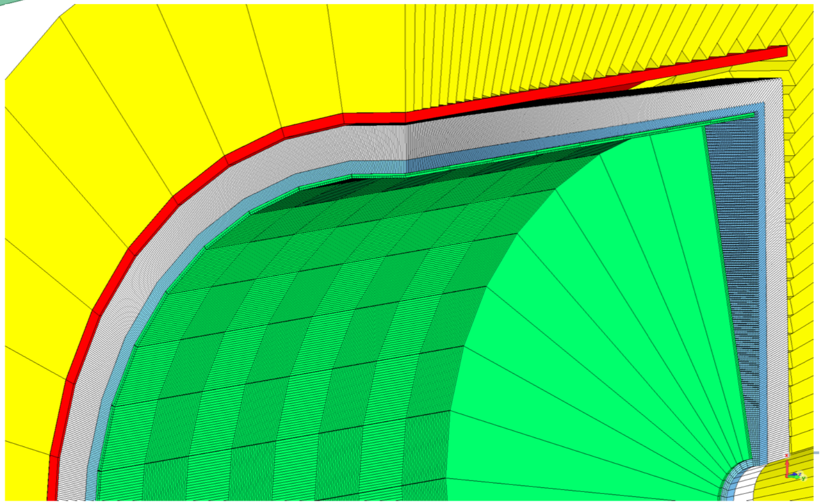
Optimize w/ Simulation and Test Beam

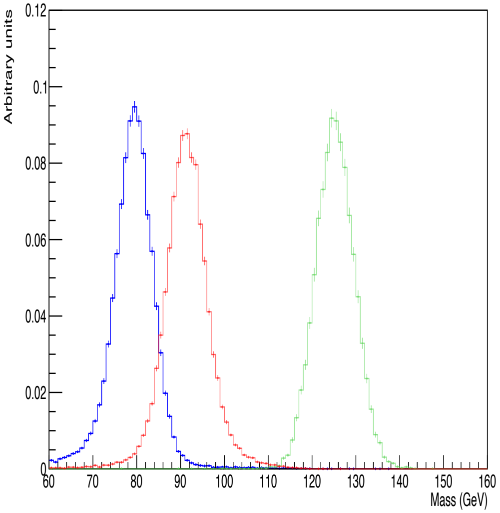




https://arxiv.org/abs/2109.00391

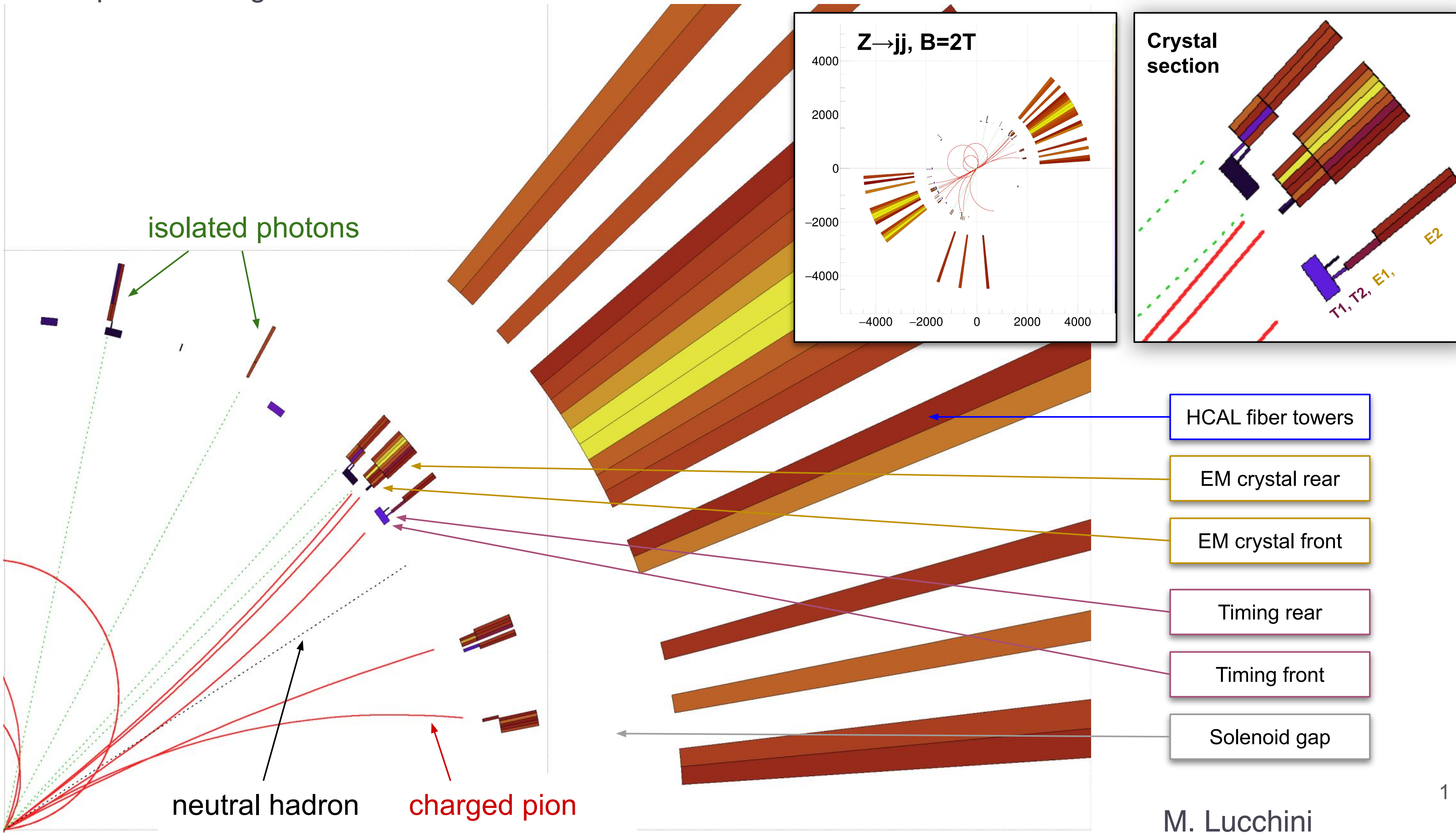






Hybrid Dual-Readout Crystals+Fibers

https://arxiv.org/abs/2008.00338



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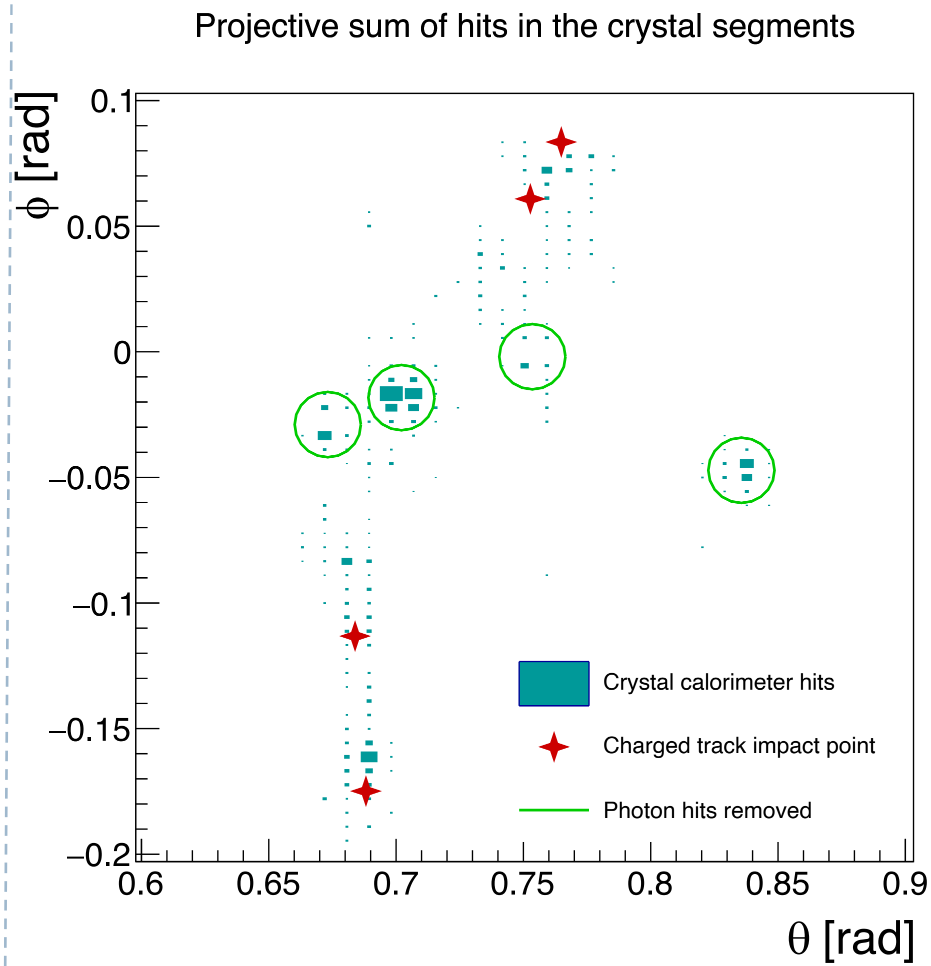
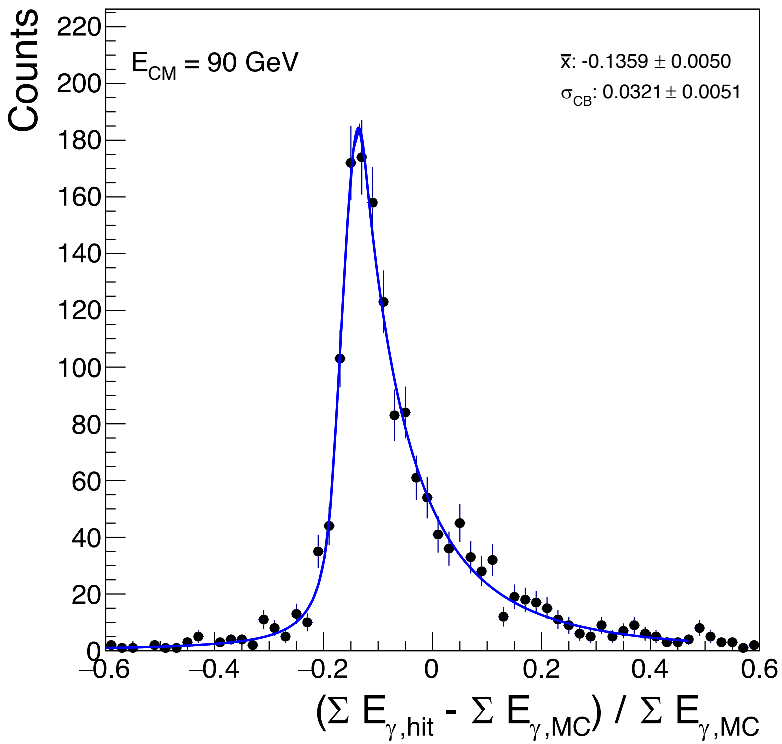
Photon Measurement and PFA removal





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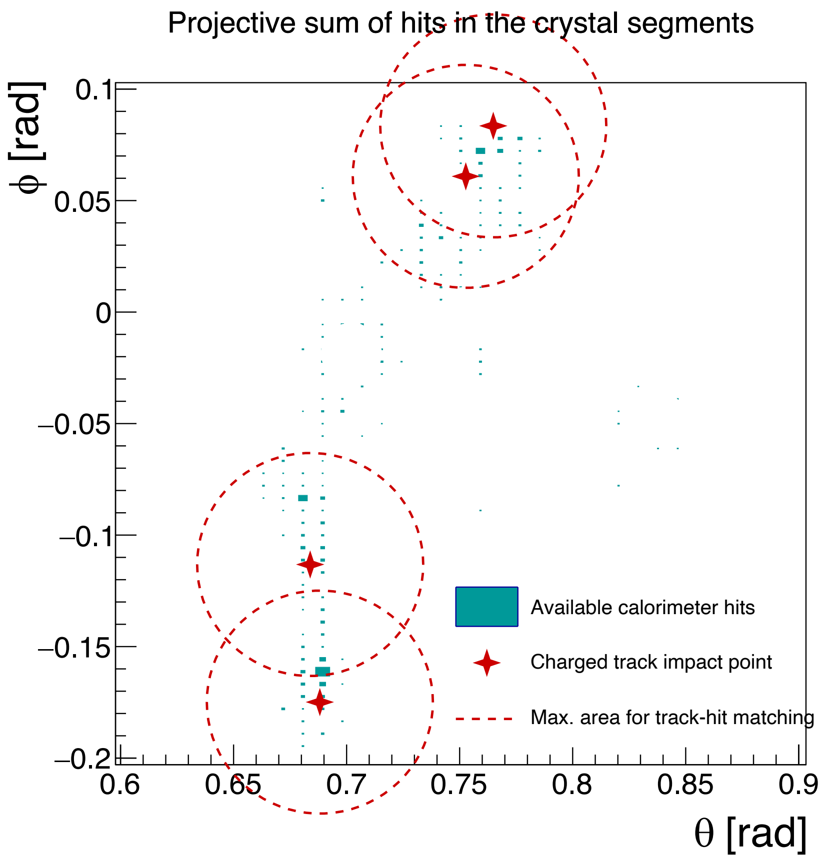
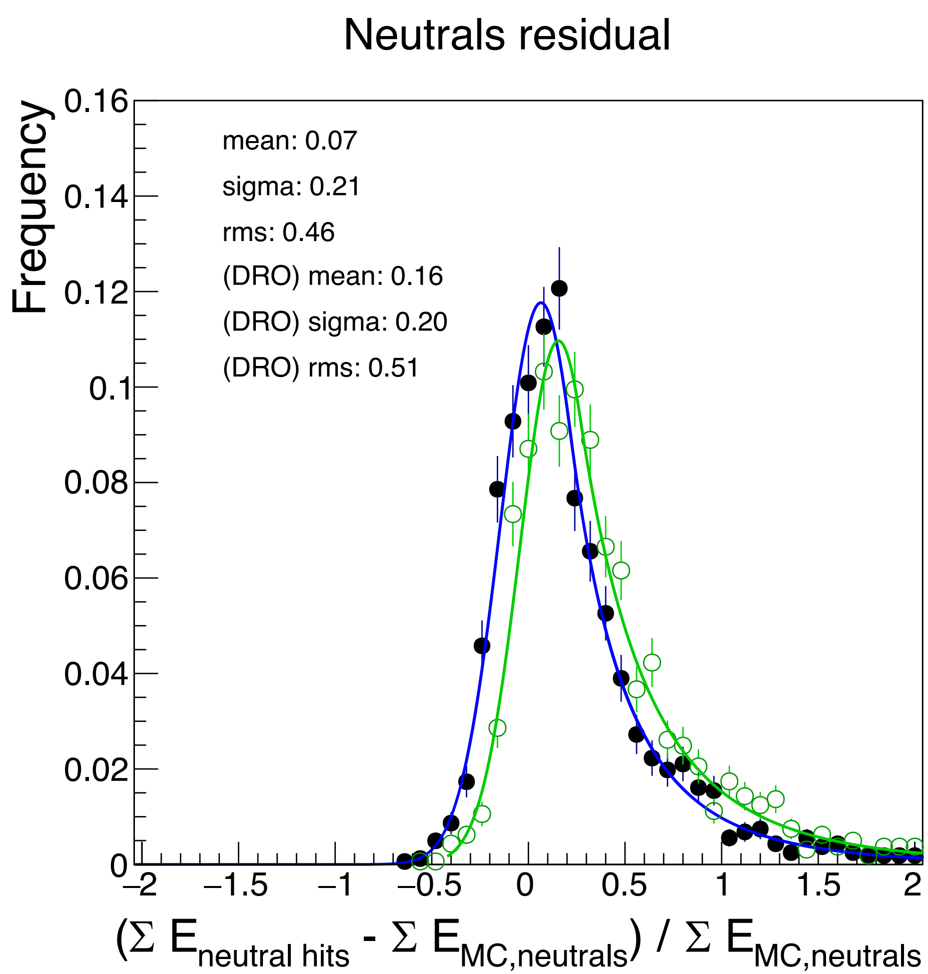
Neutral Hadronic Energy Residuals





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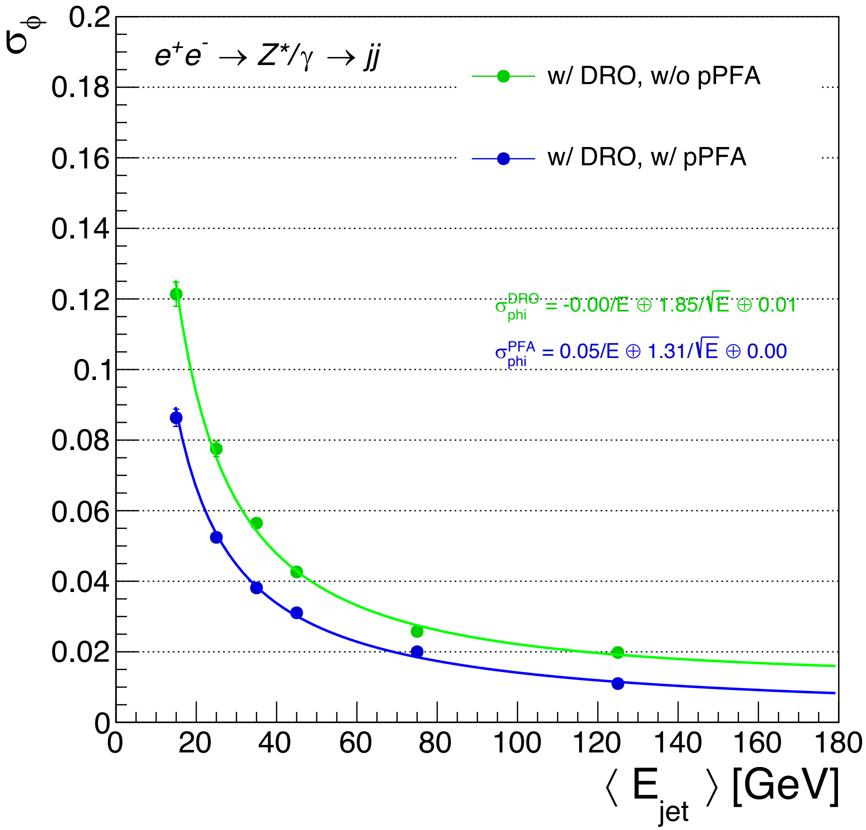
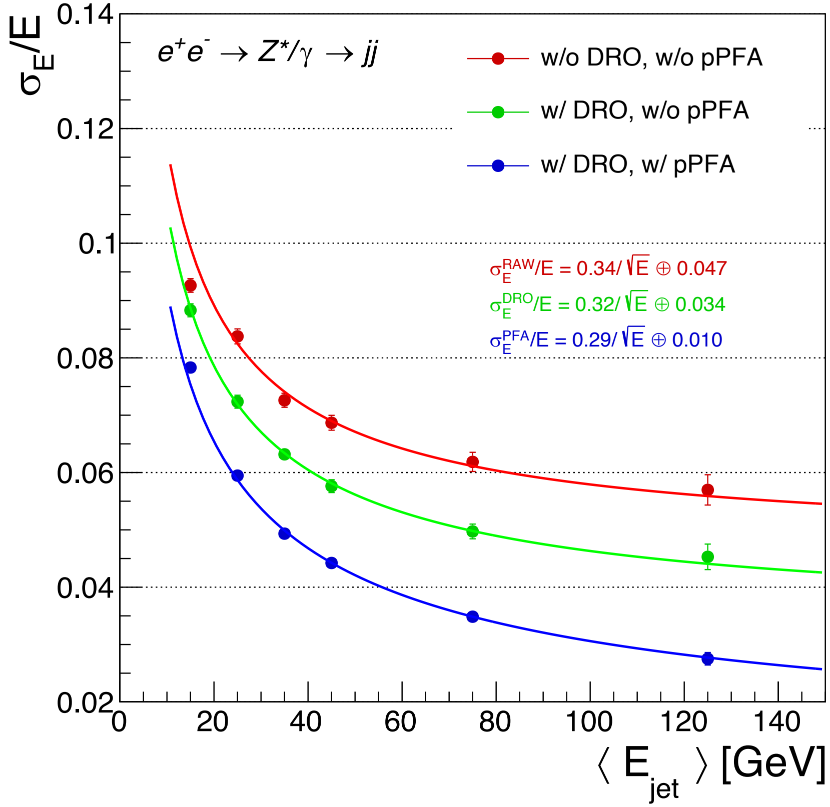
Dual-Readout PFA

Jet angular resolution (ϕ)



Jet energy resolution



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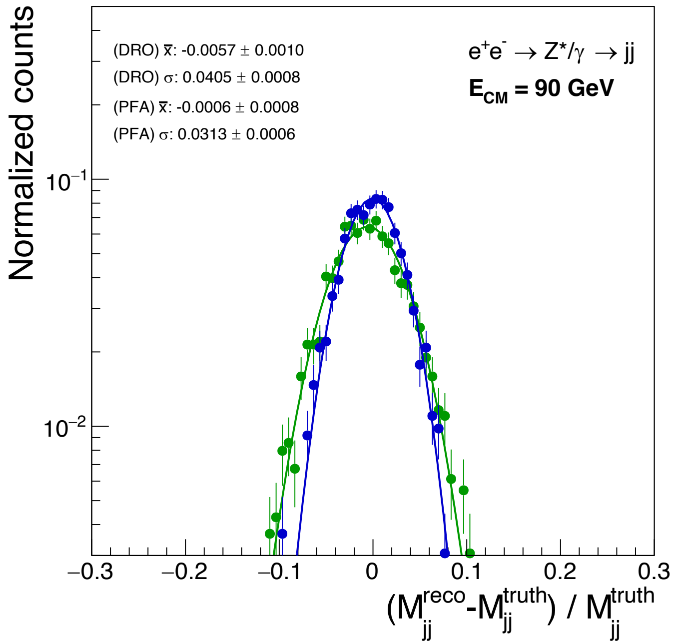
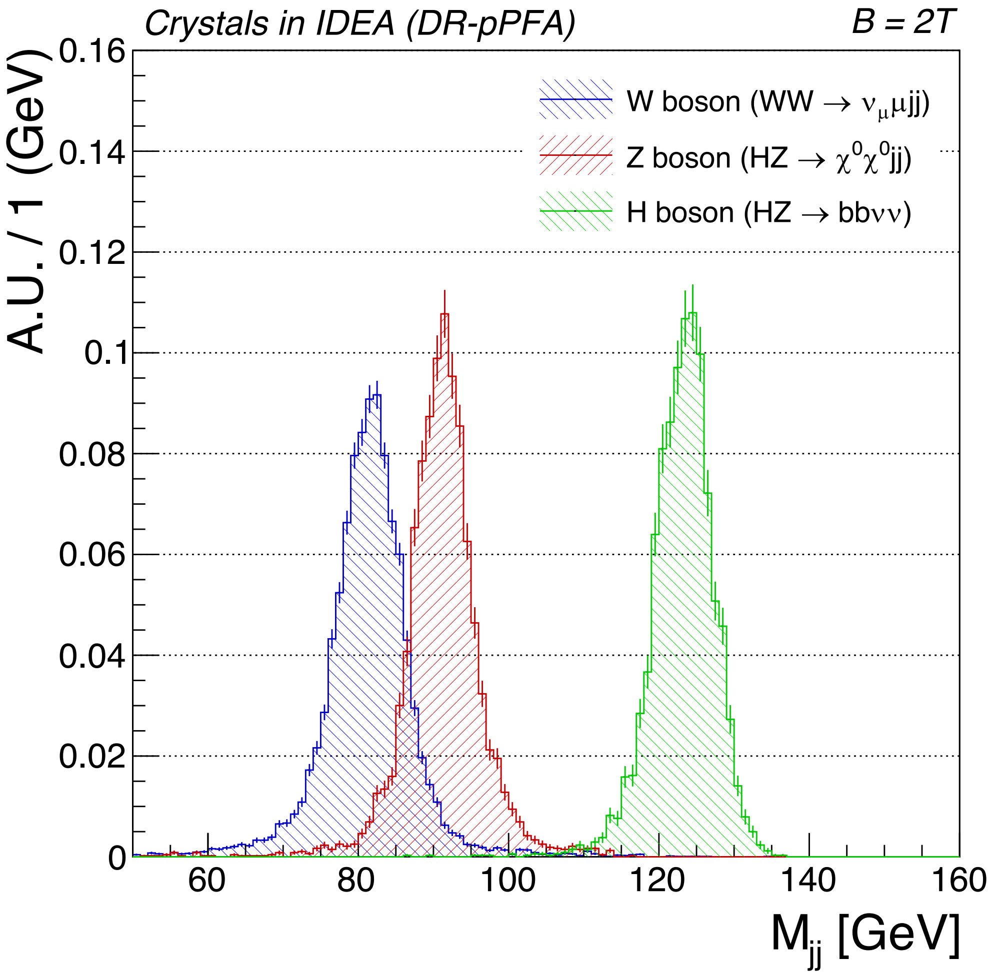
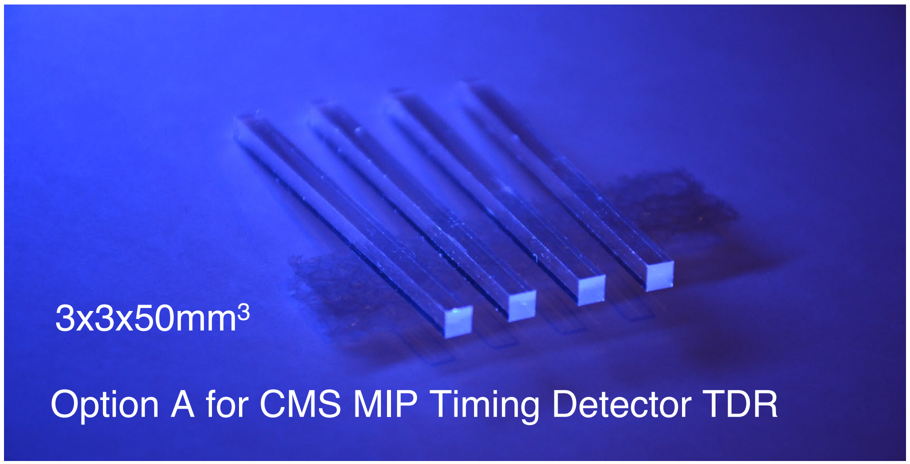
Dijet Resolutions



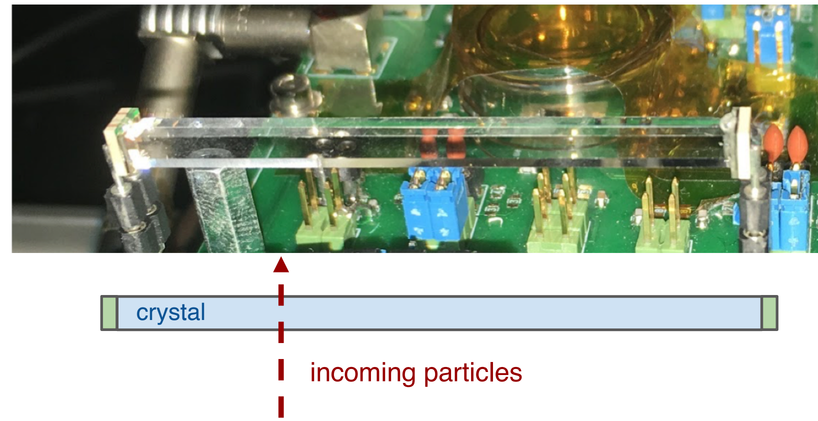


Importance of Timing Layers (in front of calorimeter)

- **New era of MIP timing**
  - ~25ps resolution per hit (1/c = 33ps/cm)

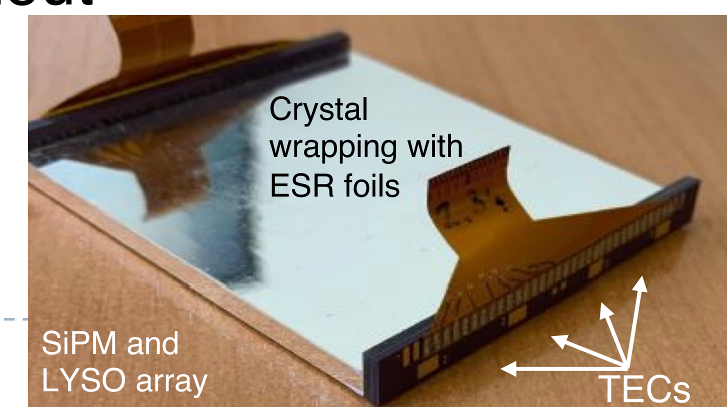


Non-wrapped crystal bar with 2 SiPMs attached at each end



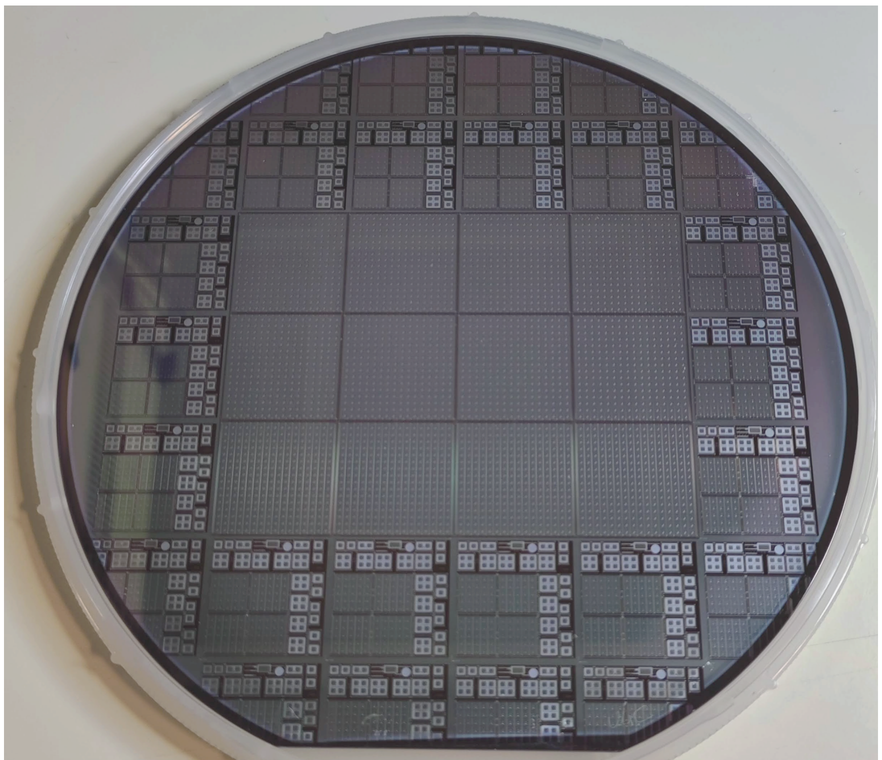
Low occupancy timing layer timing for ~0.3-1 X0

Transverse orientation w/ stereo readout

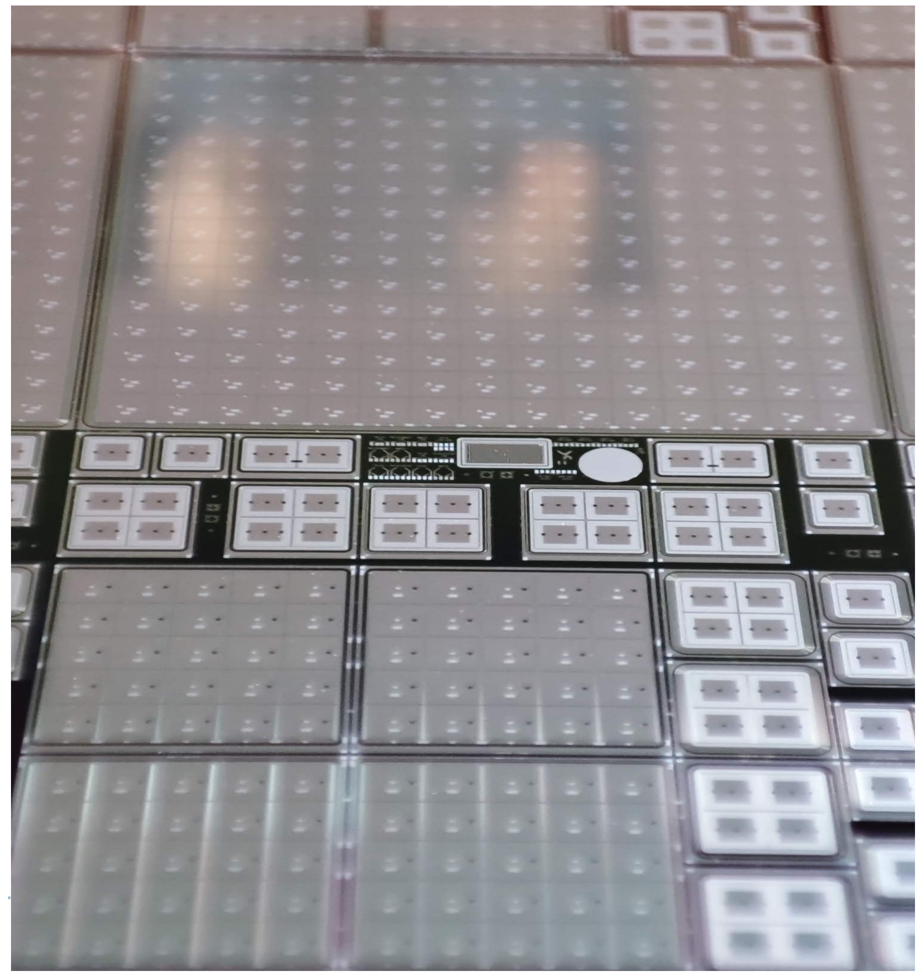


Importance of Timing Layers in tracker

- **New era of MIP timing**
  - ~40ps resolution per hit per layer



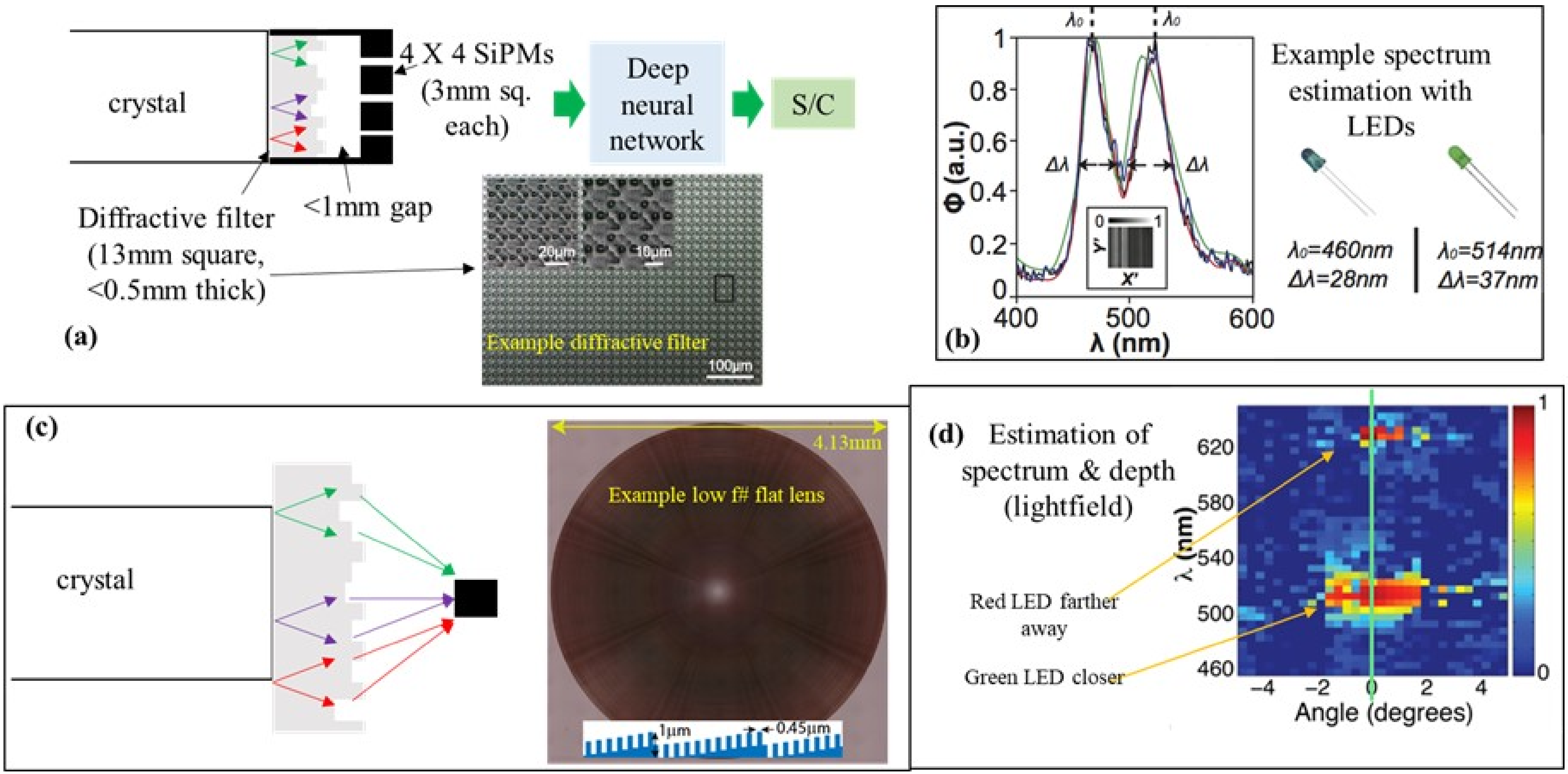
UFSD4 wafer - Courtesy of FBK



Sparks of New Ideas

Dual-Readout Blue Sky R&D

(CalVision Proposal, H. Newman)



Final Remarks

- **Simulation is absolutely central to optimizing the calorimeter in concert with PFA/PID performance**
  - Many options are open, but the software needs to be able to cycle through them and compare
- **Timing layers at ~20-40ps resolution are a new things, but will quickly be indispensable**
- **Calorimeter R&D should continue to be impressing, pushing on ASICs, PID, and novel detector signals**
  - Once even proposed a SQUID sampling array to estimate electron longitudinal polarization from statistical sampling of the EM shower

Additional slides

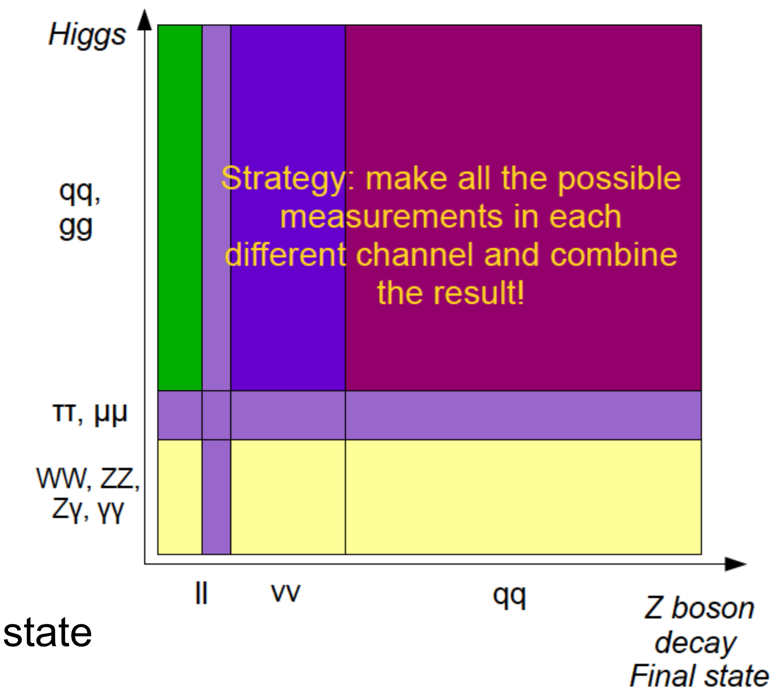
Final States of e+e- Higgs Physics @~246 GeV

- SM Higgs

Slide borrowed from Manqi Ruan (LCWS 2019, Sendai, Japan)

- ***0 jets: 3%:*** *Z→ll, νν (30%); H→0 jets (~10%, ττ, μμ, γγ, γZ/WW/ZZ→leptonic)*
- ***2 jets: 32%***
  - *Z→qq, H→0 jets. 70%*10% = 7%*
  - *Z→ll, νν; H→2 jets. 30%*70% = 21%*
  - *Z→ll, νν; H→WW/ZZ→semi-leptonic. 3.6%*
- ***4 jets: 55%***
  - *Z→qq, H→2 jets. 70%*70% = 49%*
  - *Z→ll, νν; H→WW/ZZ→4 jets. 30%*15% = 4.5%*
- ***6 jets: 11%***
  - *Z→qq, H→WW/ZZ→4 jets. 70%*15% = 11%*

2/3 { (4 jets and 6 jets)

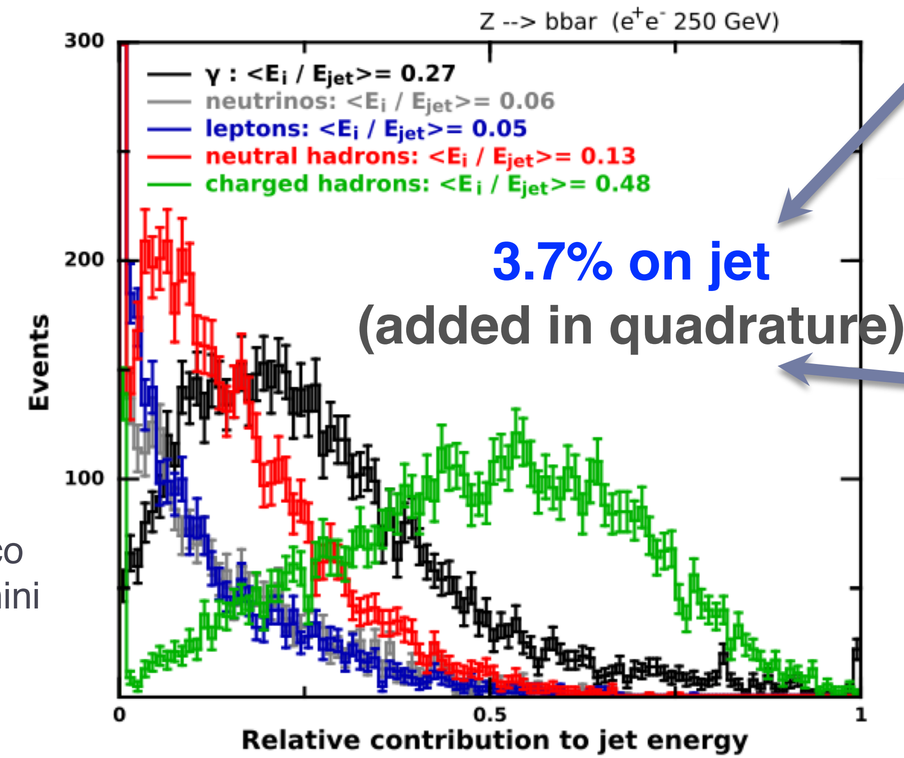


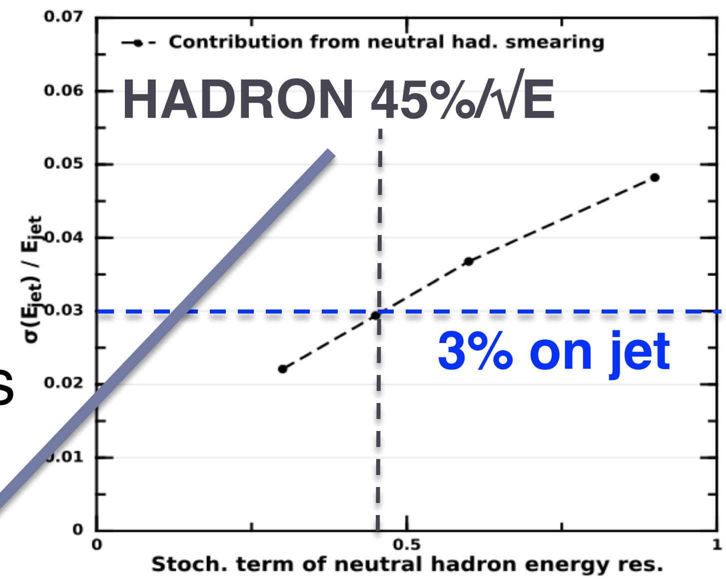
- **97%** of the SM Higgsstrahlung Signal has Jets in the final state
- **1/3** has only 2 jets: include all the SM Higgs decay modes
- **2/3** need color-singlet identification: grouping the hadronic final state particles into color-singlets
- Jet is important for EW measurements & jet clustering is essential for **differential** measurements

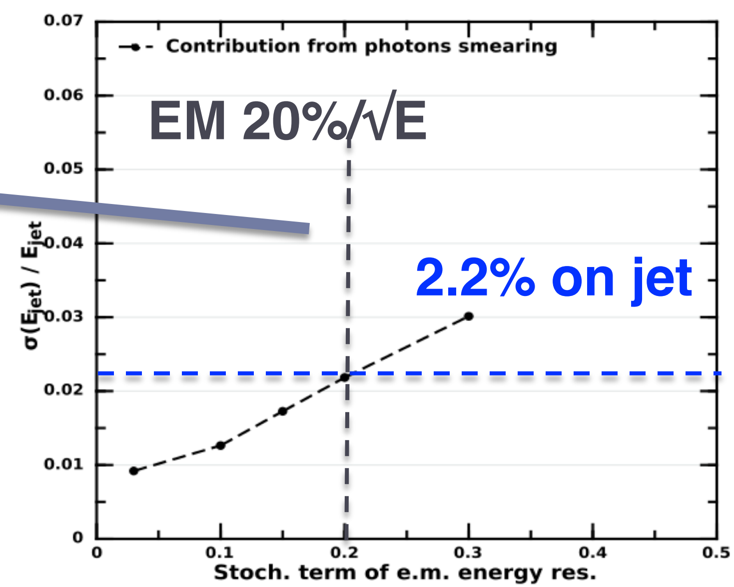
→ Include here the unexpected rare decays – <u>be prepared</u>

Some Quick Comments on PFA

- **Review of Principles of Jet Performance:**
  - Baseline performance depends on particle composition and the relevant sub-detector resolutions







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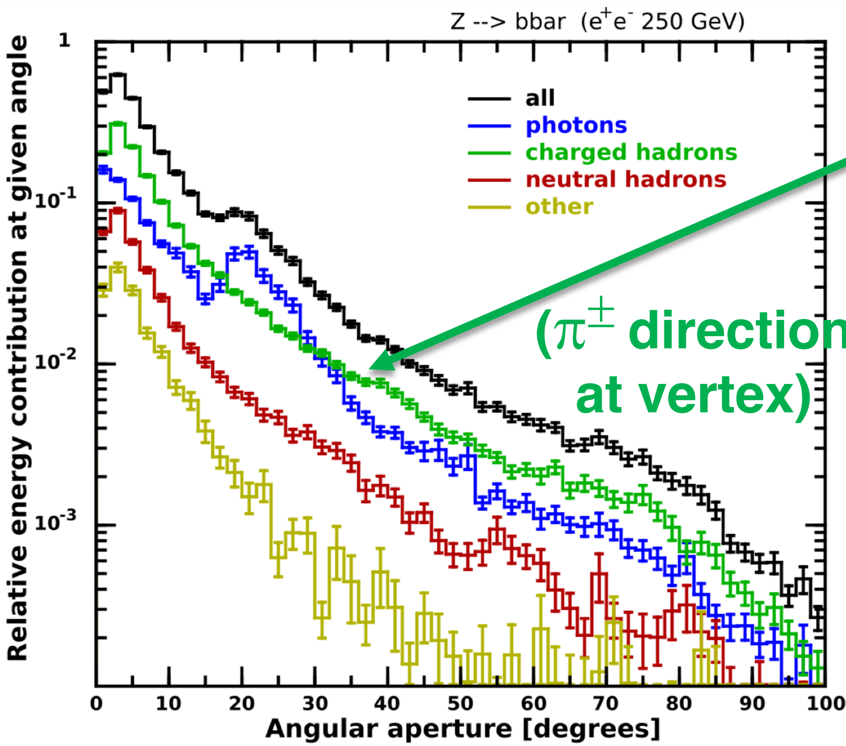
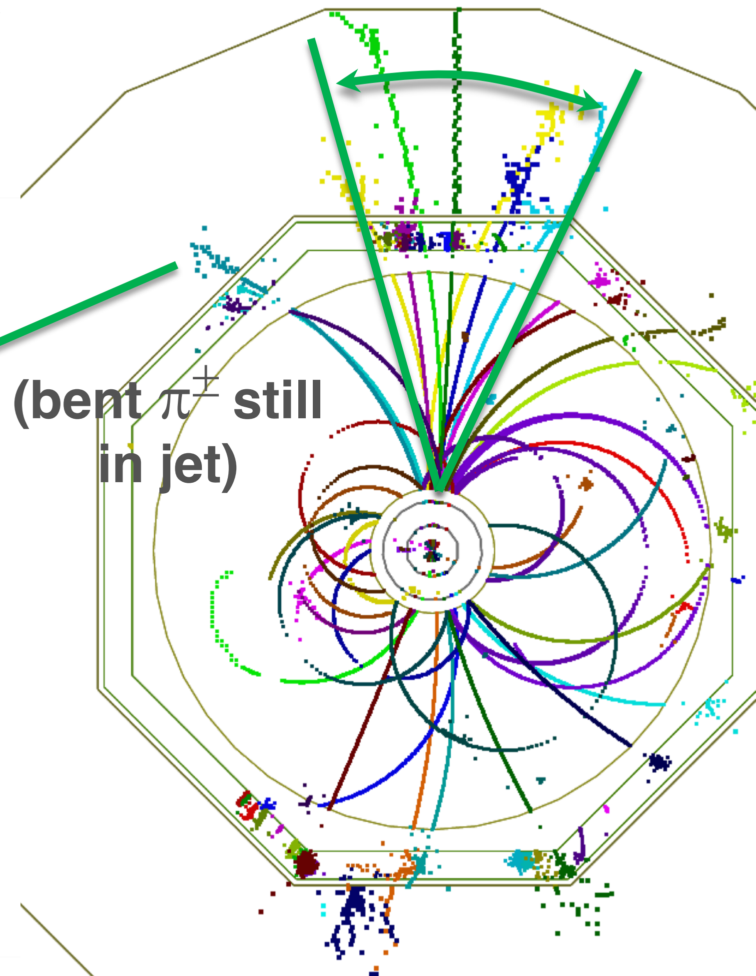
Some Quick Comments on PFA

- **Review of Principles of Jet Performance:**
  - Swaps out hadronic res. for track AND corrects momentum direction at the vertex

Slide borrowed from Marcel Vos





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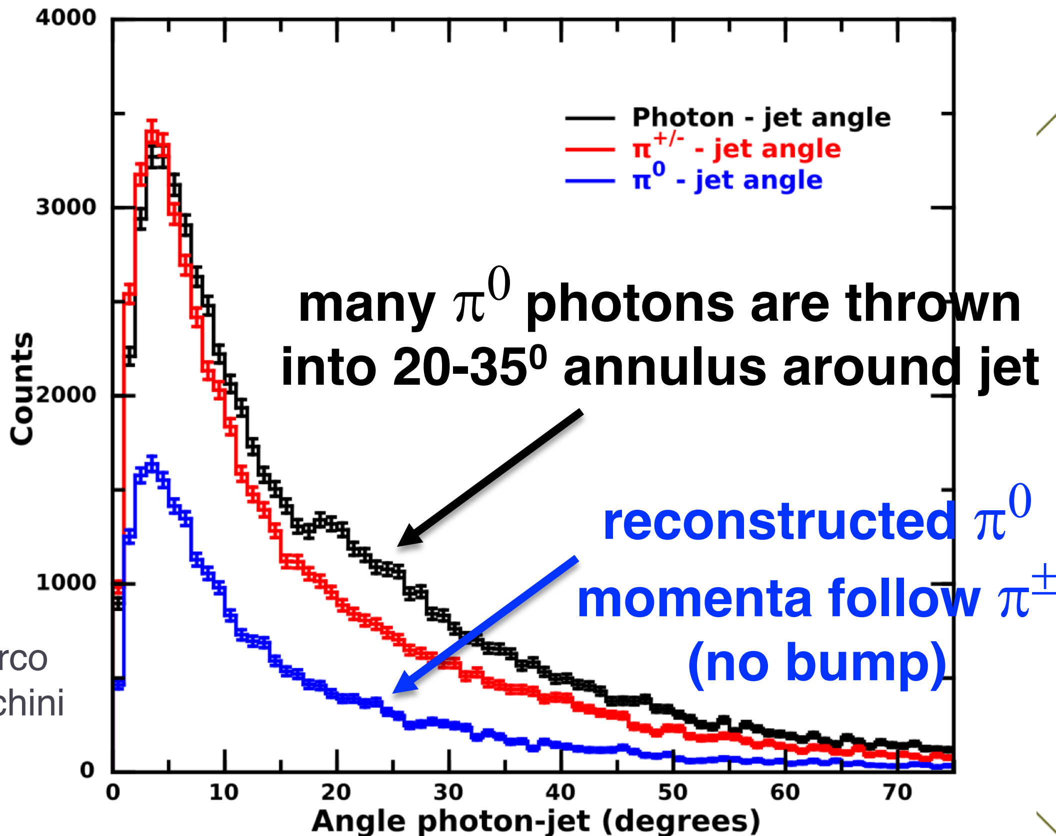
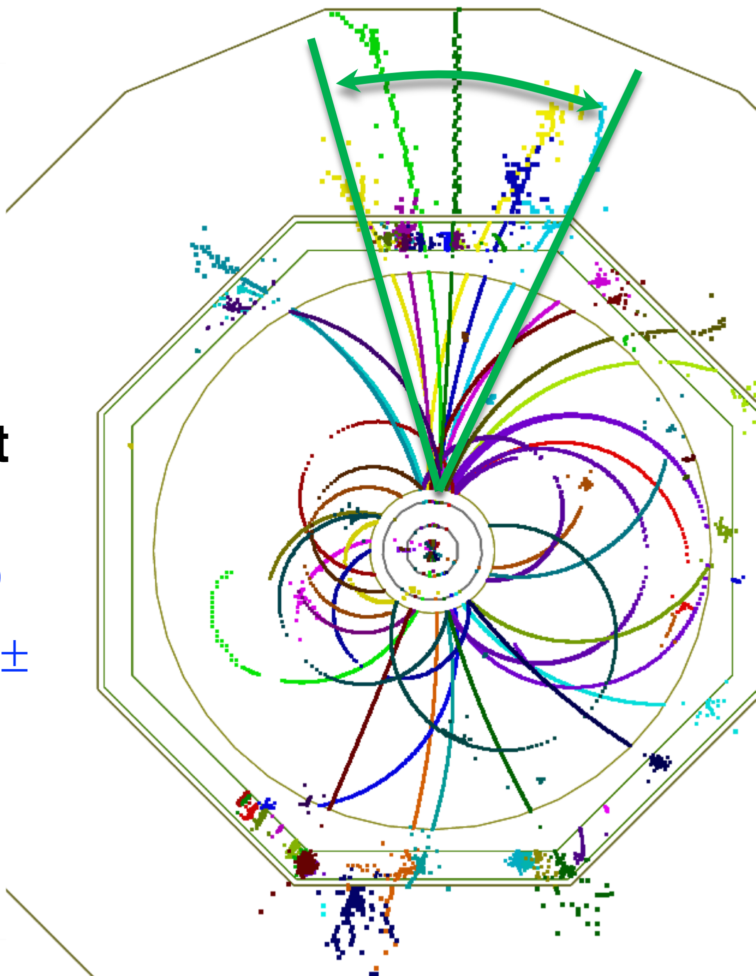
Some Quick Comments on PFA

- **Review of Principles of Jet Performance:**
  - How about photons?

Slide borrowed from Marcel Vos





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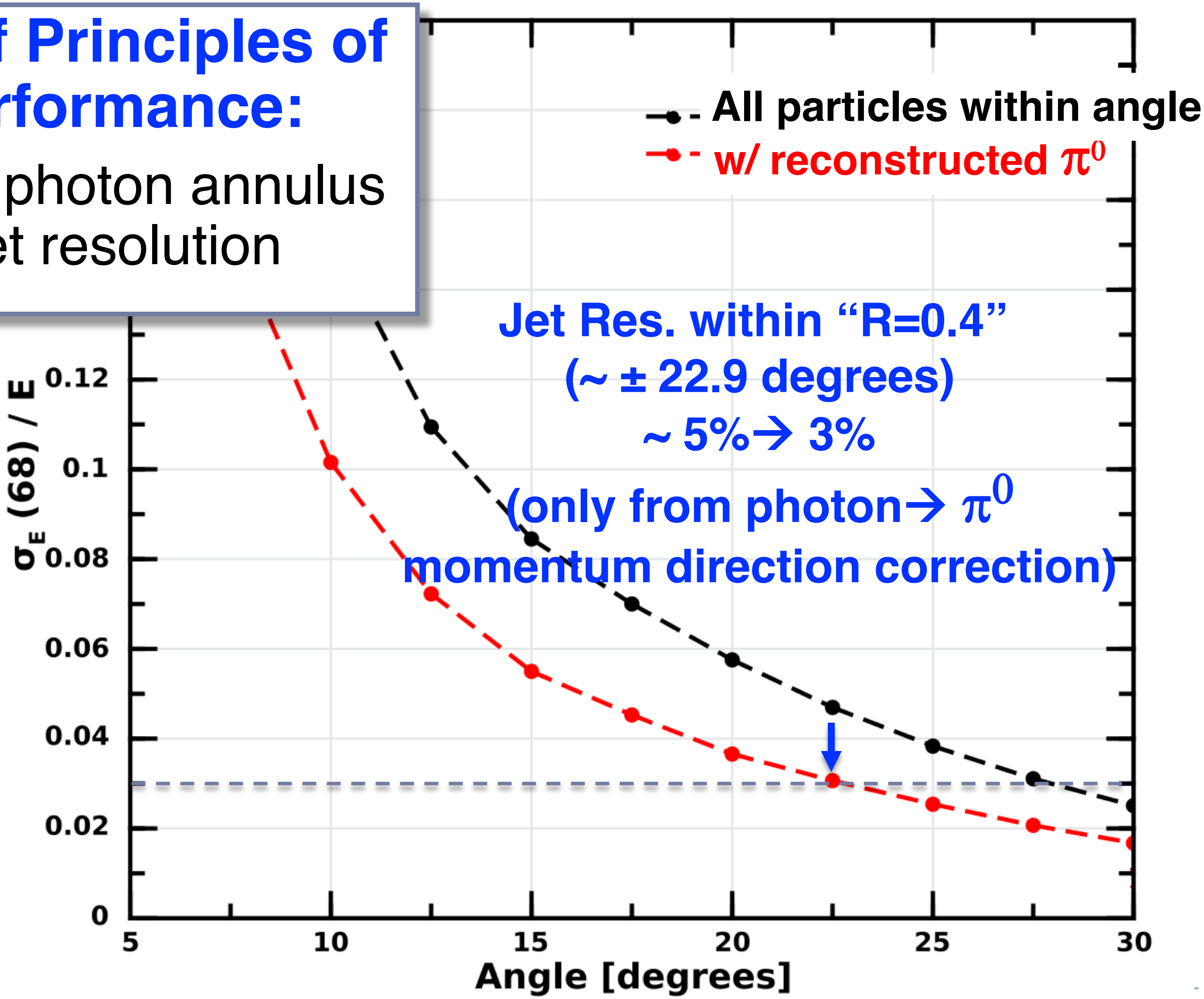
Some Quick Comments on PFA

- **Review of Principles of Jet Performance:**
  - Effect of photon annulus on jet resolution

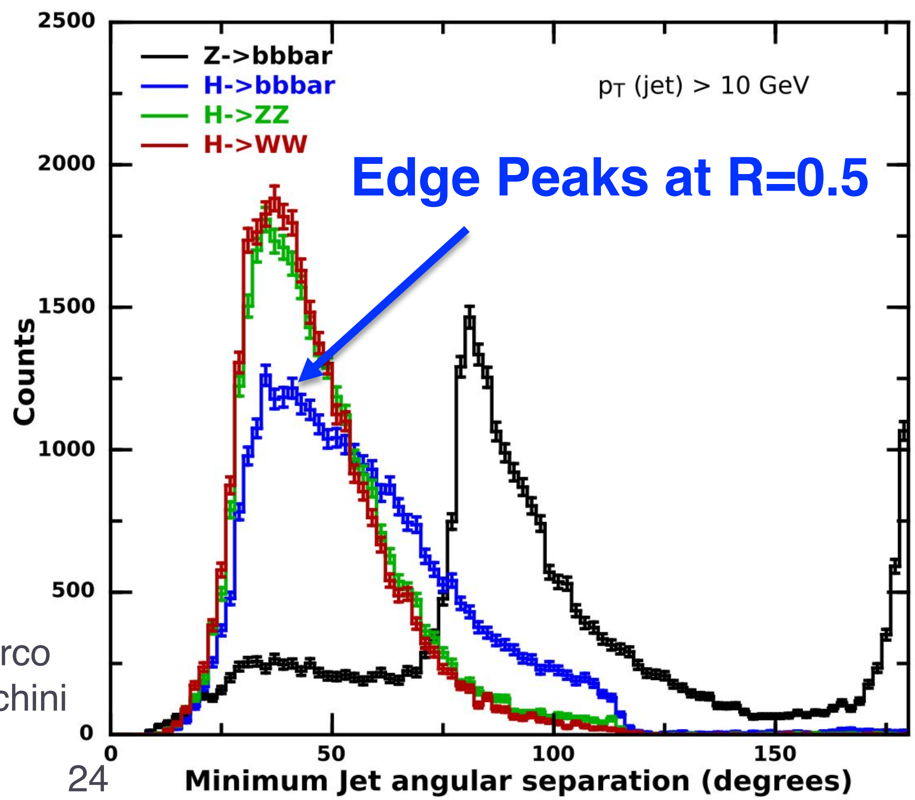
Jet Resolution based on limited integral of particles (out to specified angle) (photon annulus integrated out)

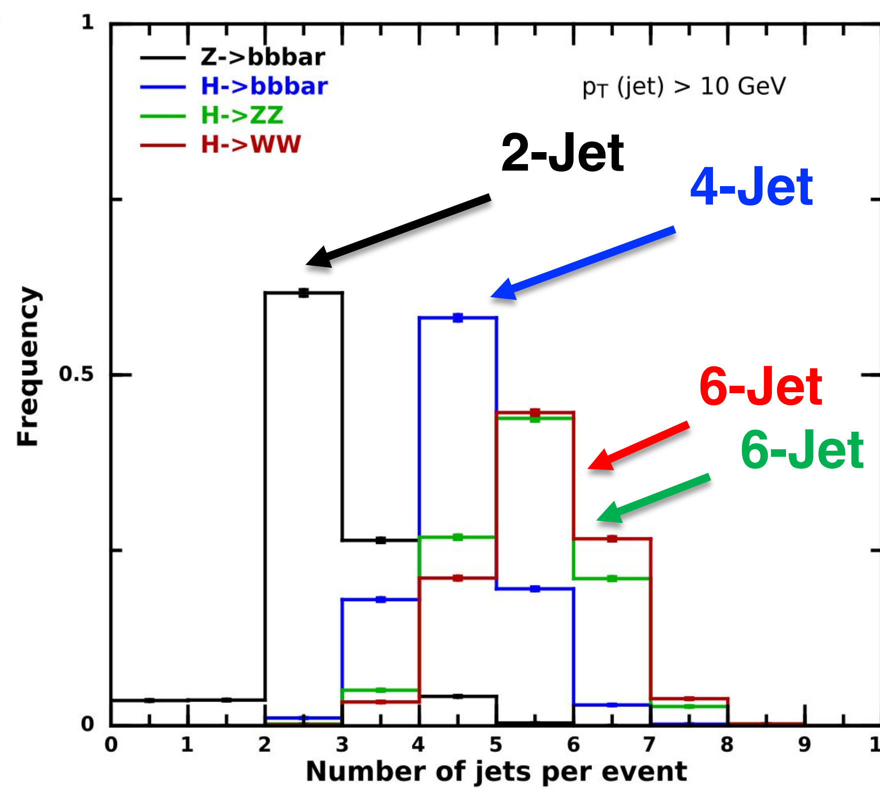


Some Quick Comments on PFA

- **Review of Principles of Jet Performance:**
  - Min Jet Angle Peaks at edge of Jet R parameter

Jet Algo:
anti-KT, E-mode, R=0.5,
min pT=10 GeV





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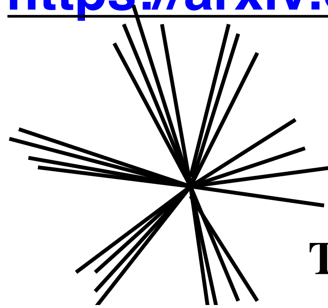
From 20 Years Ago… min $\theta_{\text{N-Jet}}$ matters!

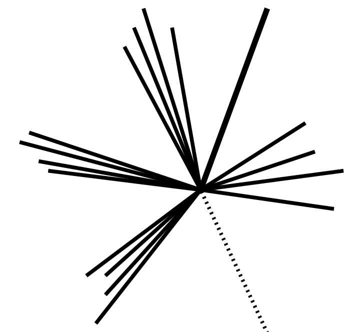
- **J. Mans, "Search for a Higgs Boson Decaying to Massive Vector Boson Pairs at LEP." https://arxiv.org/pdf/hep-ex/0204029.pdf**

The qqqqqq Channel

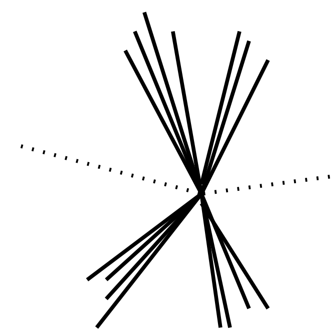


Variable	*Description*	*Trend*
E^{max}_{jet6}	Energy of the most energetic jet from the 6 jet fit.	Signal events should have six reasonably equal jets, while many backgrounds have several high energy jets and several very low energy gluon jets.
E^{min}_{jet6}	Energy of the least energetic jet from the 6 jet fit.	
n^{min}_{jet6}	Minimum number of charge tracks in any of the jets from the 6 jet fit.	Gluon jets and other "reconstruction" jets will have fewer charge tracks than signal jets.
θ^{min}_{jet6}	Minimum angle between any two of the six jets.	Gluon-radiation jets will tend to have a relatively small angle with respect to other jets.
$\log Y_{45}$	Durham Y value where the fit changes from four jets to five jets.	True six jet events should have larger values of the Durham cut values.
$\log Y_{56}$	Durham Y value where the fit changes from five jets to six jets.	

The qqqlν Channel



The ννqqqq Channel

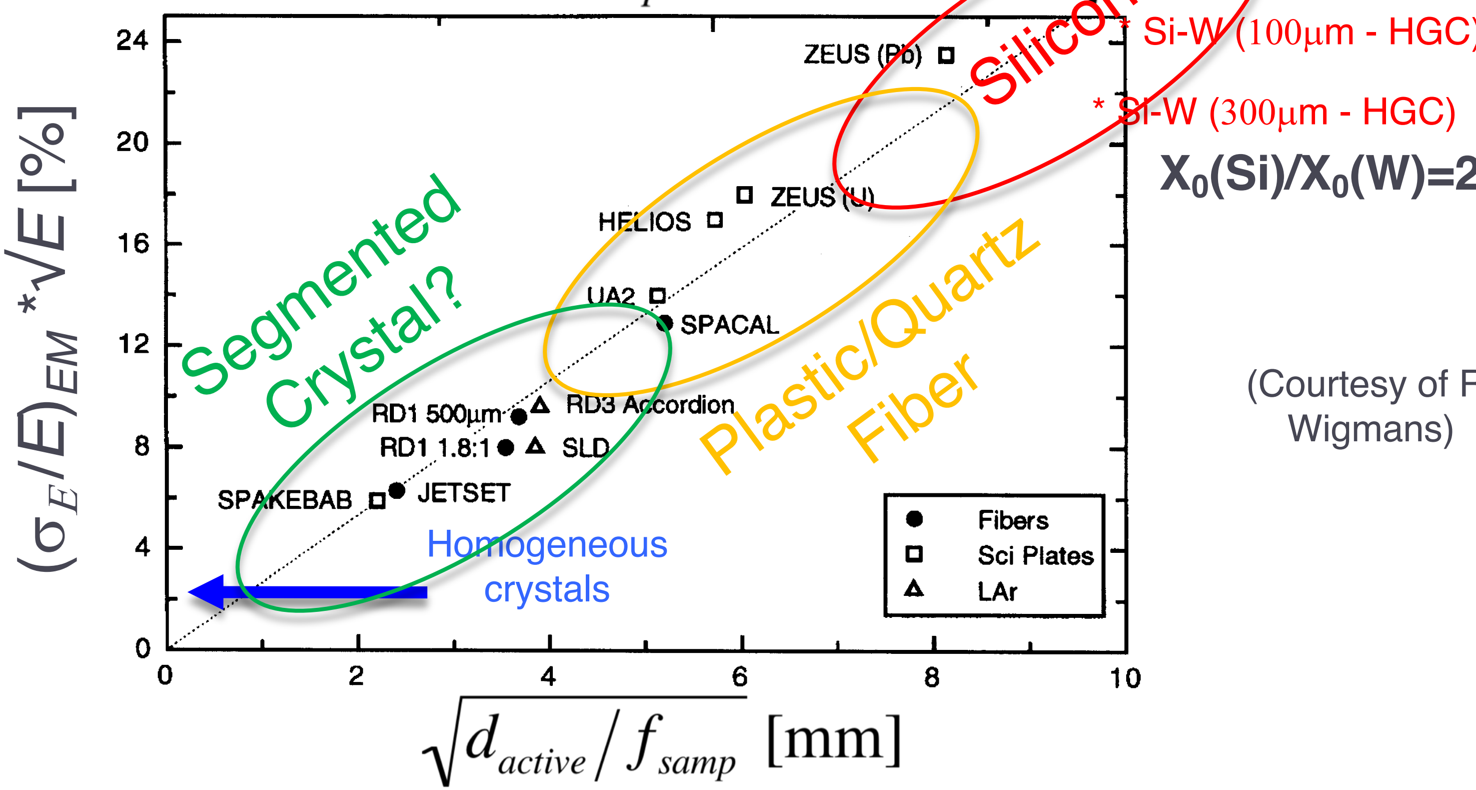


Variable	*Description*	*Trend*
E^{max}_{4j}	Energy of the most energetic jet from a fit to four jets.	Signal events tend to have two medium-energy and two low-energy jets, while backgrounds will tend to have higher E^{max} values and lower E^{min} values.
E^{min}_{4j}	Energy of the least energetic jet from a fit to four jets.	
θ^{min}_{4j}	Minimum angle between any two of the four jets.	Gluon jets tend to be emitted at small angles relative to the emitting quark jet.

Three Regimes of EM Resolution

- **For EM showers in a sampling calorimeter, the energy resolution is dominated by the sampling fluctuations:**

$$(\sigma_E/E)_{EM} \cdot \sqrt{E} \approx (\sigma_E/E)_{samp} \cdot \sqrt{E} = 2.7\% \sqrt{d_{active}/f_{samp}}$$

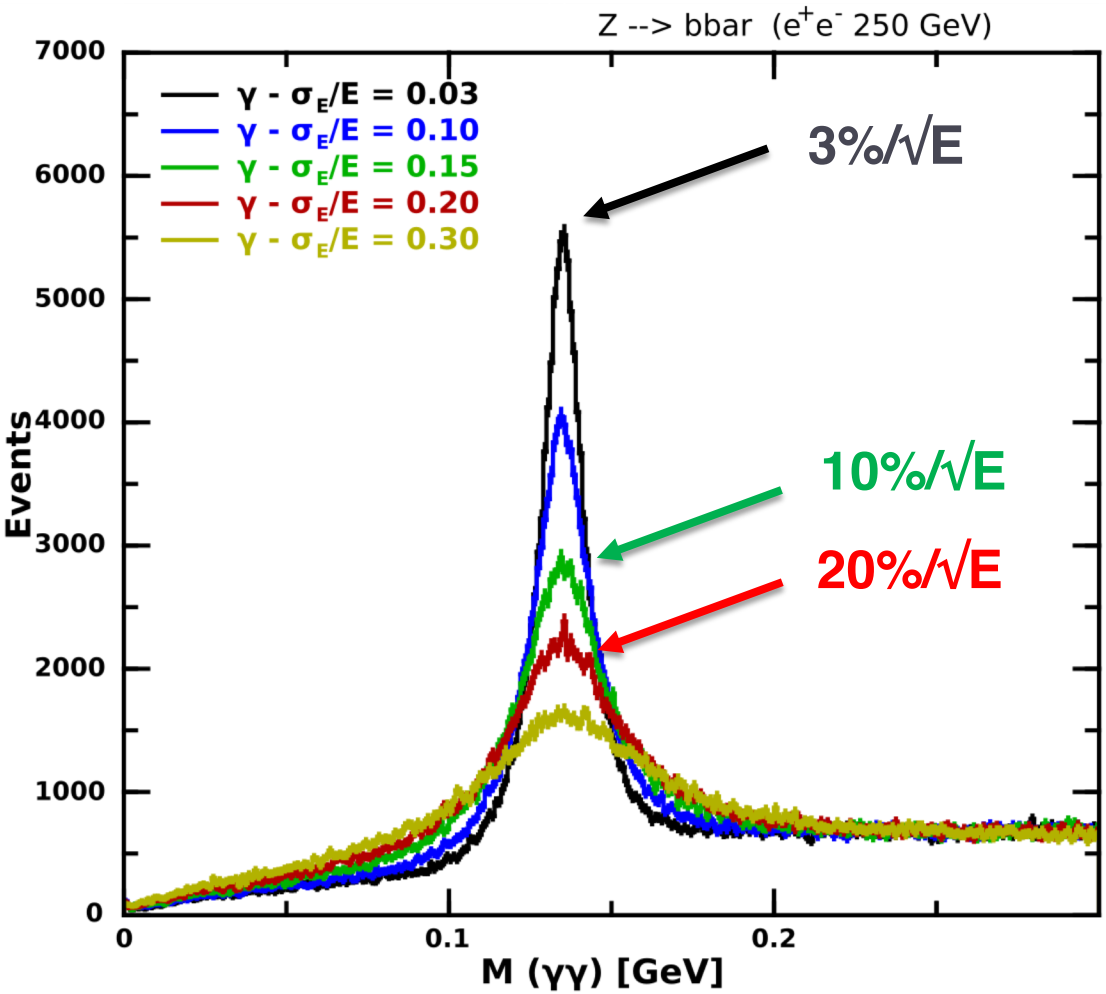


$X_0(Si)/X_0(W)=27$

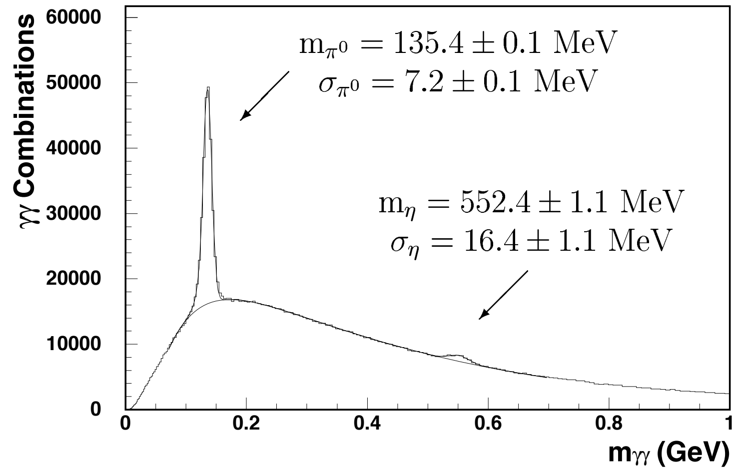
(Courtesy of R. Wigmans)

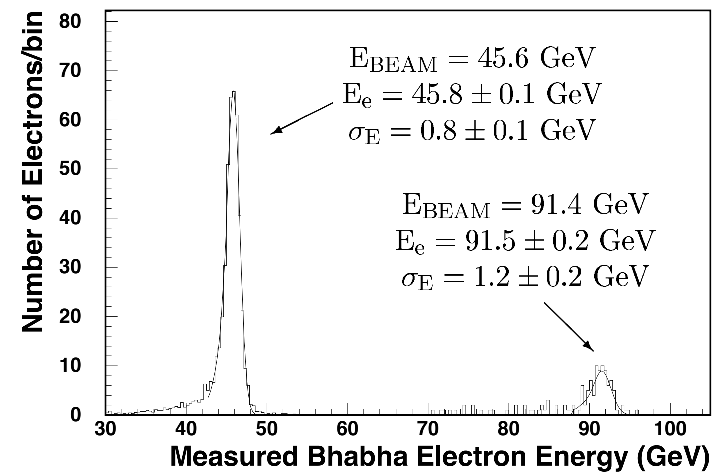
π^0 Resolution and Reconstruction Efficiency

- **Peak Height Matters!**



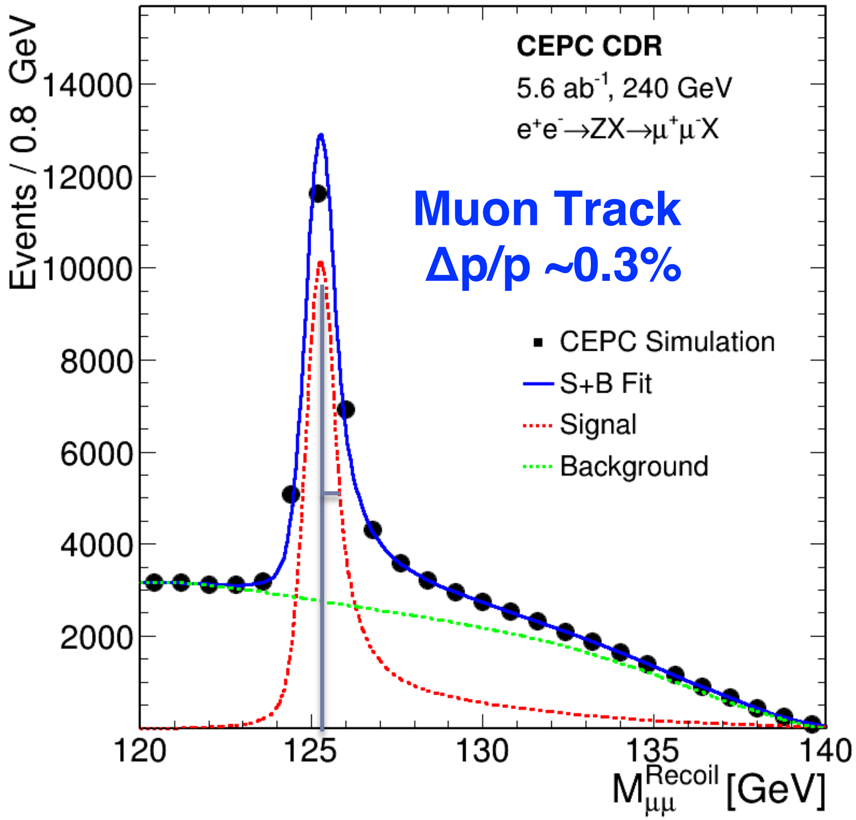
L3 Data (1997)



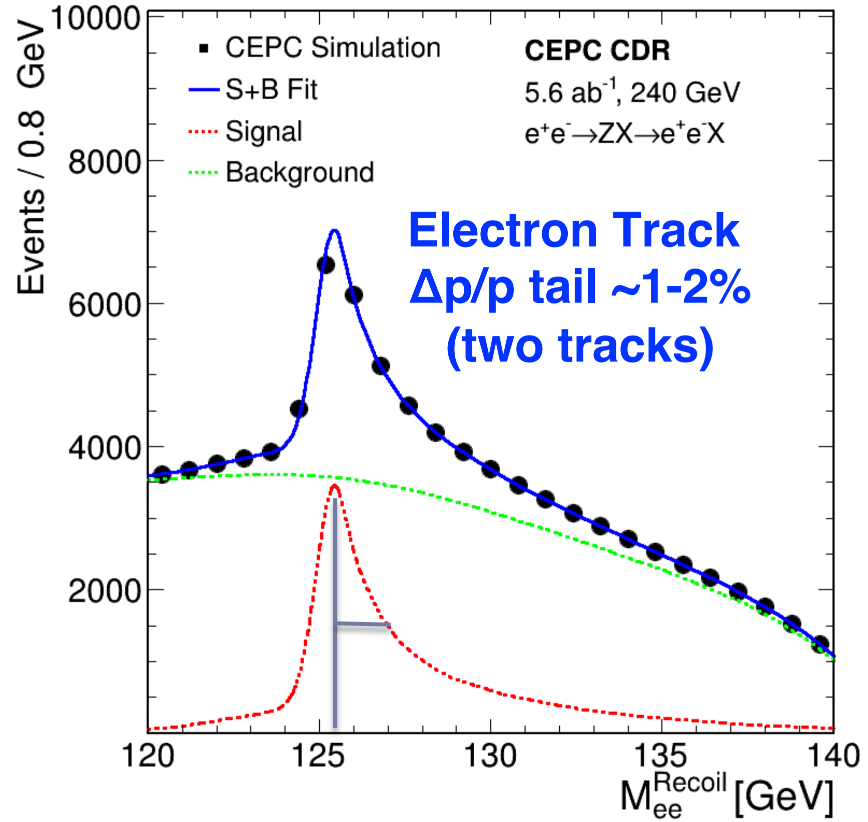


Recoil Analysis – Single Most Important Unbiased Sample of Higgs Boson Decays

- **Z→μ⁺μ⁻ Recoil**



- **Z→e⁺e⁻ Recoil**



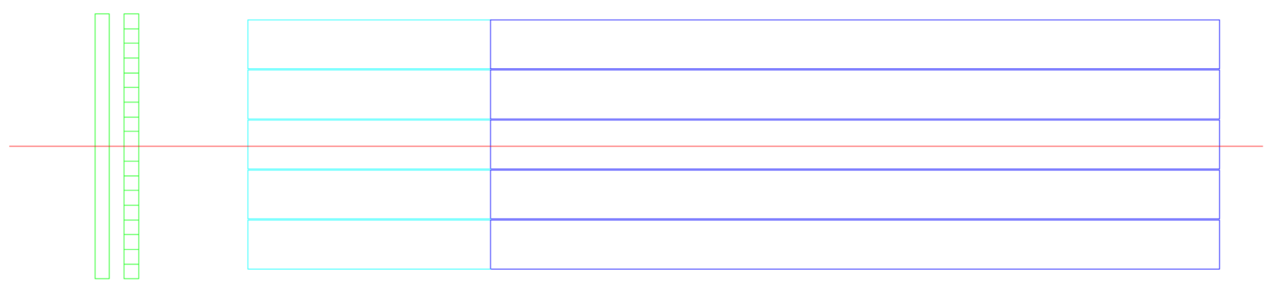
Example from CDR reference design
(electron tracks with no Brem. recovery)

→ ~80% of Resolution Recovery with 3%/√E

Segmented Crystal Calorimeter Module

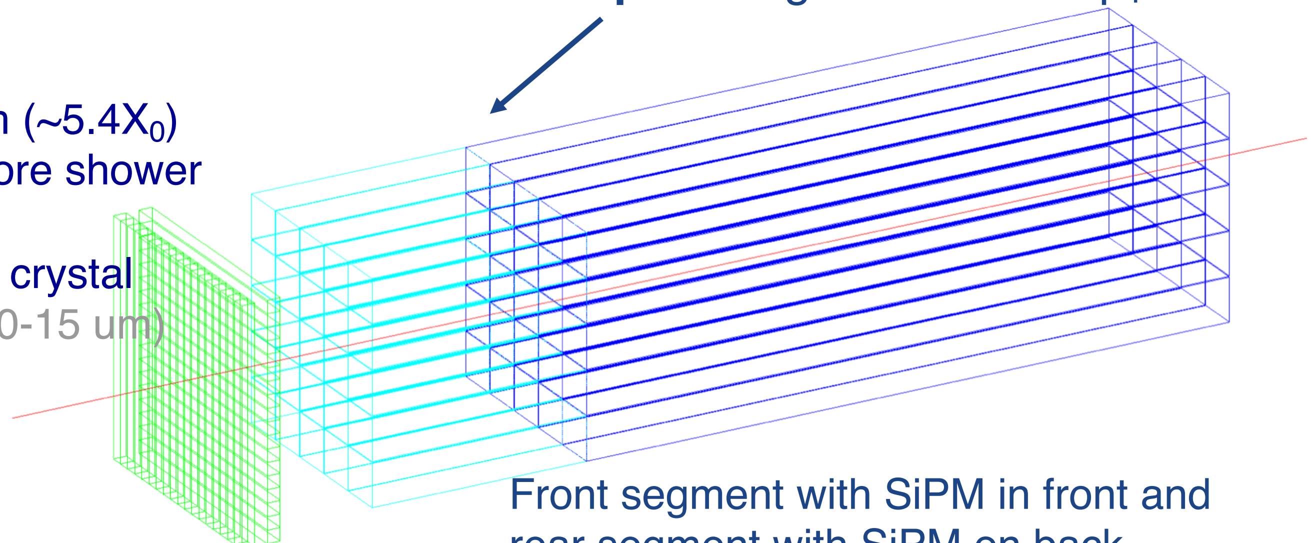
- **Timing layer:**
  - LYSO:Ce crystals
  - SiPMs
  - 3x3x54 mm³ active cell
  - 3x3 mm² SiPMs (15-25 um)

1 layer: **30 ps**
2 layers: **20 ps** + tracking



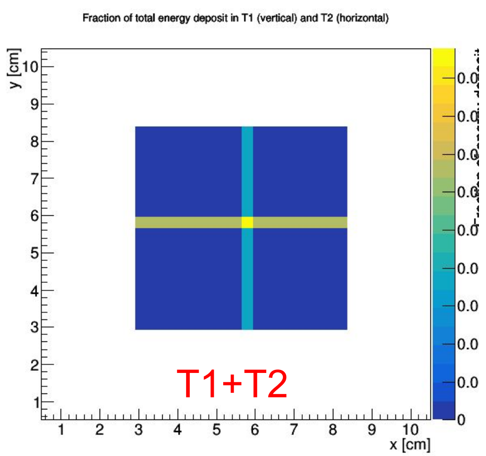
~3%/sqrt(E) (+) 1%
~30 ps timing achieved for p_T>40GeV

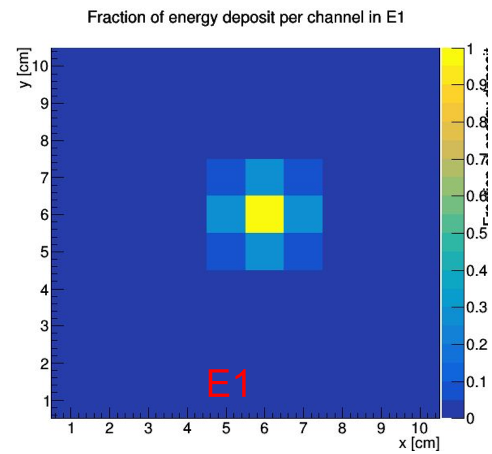
- **ECAL layer:**
  - PbWO crystals
  - front segment 5 cm (~5.4X_0)
  - rear segment for core shower
  - (15 cm ~16.3X_0)
  - 10x10x200 mm³ of crystal
  - 5x5 mm² SiPMs (10-15 um)

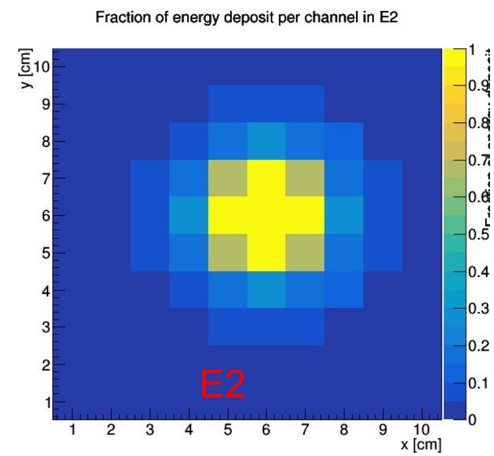


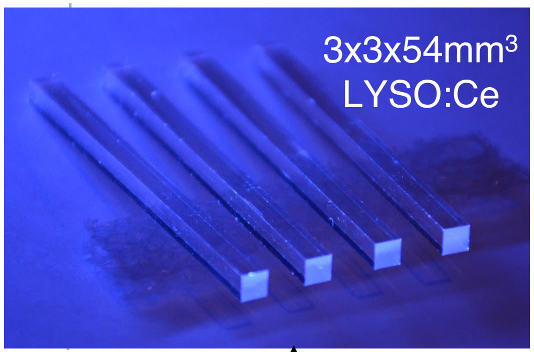
Front segment with SiPM in front and rear segment with SiPM on back
→ Avoids dead material at shower max

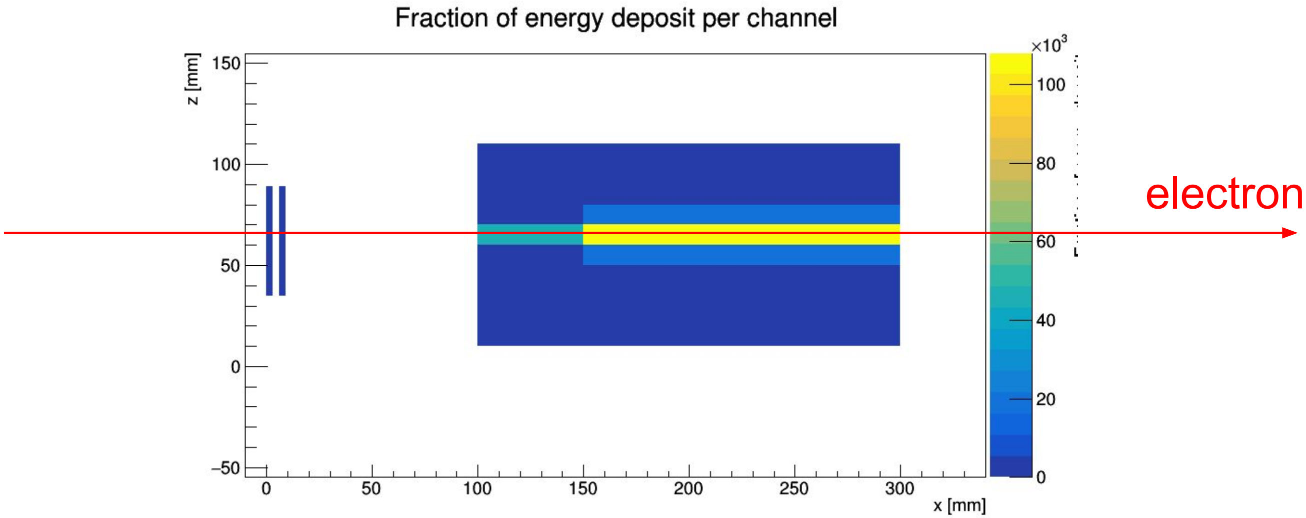
Single EM Shower (High Stat)









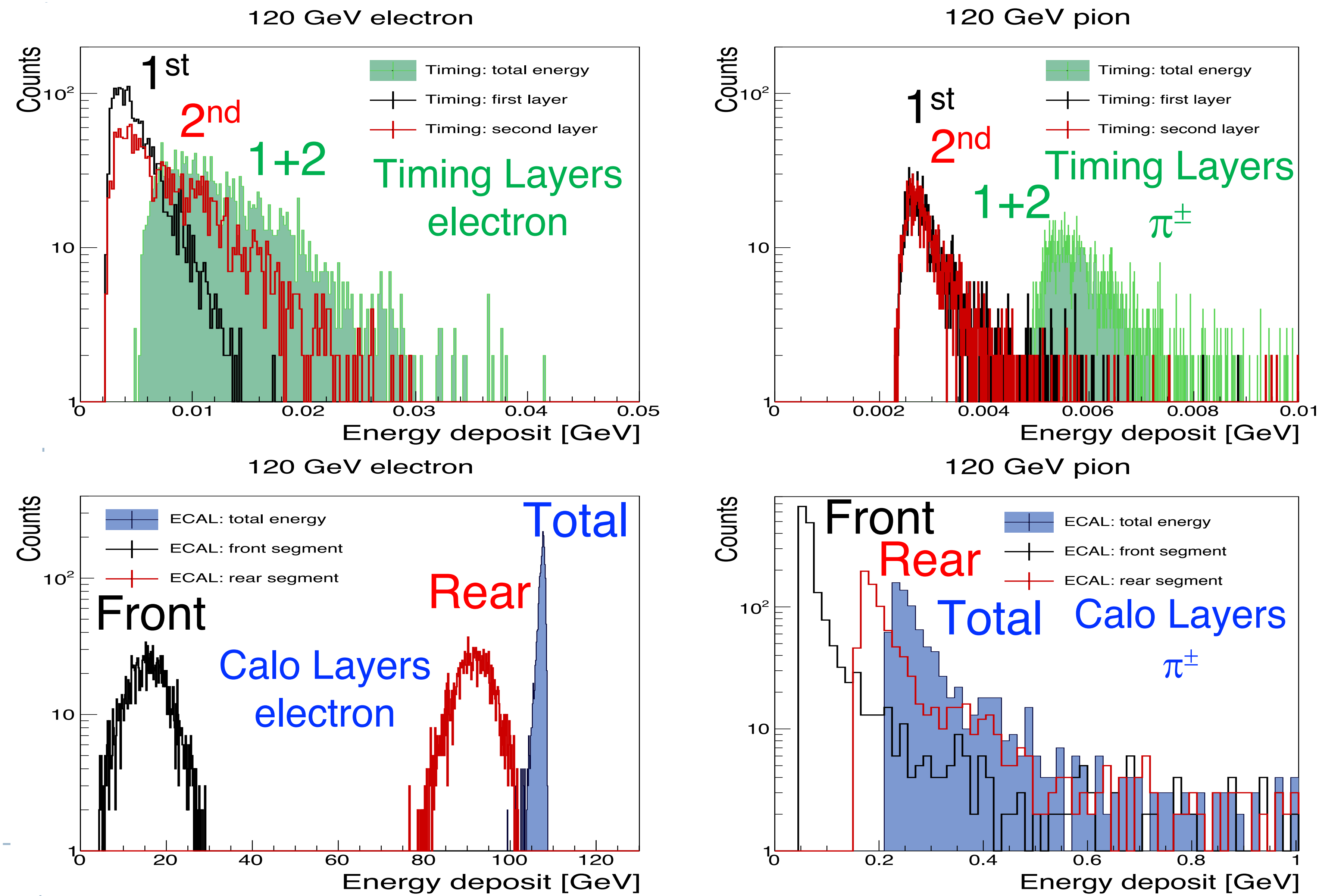


3mm (strip)

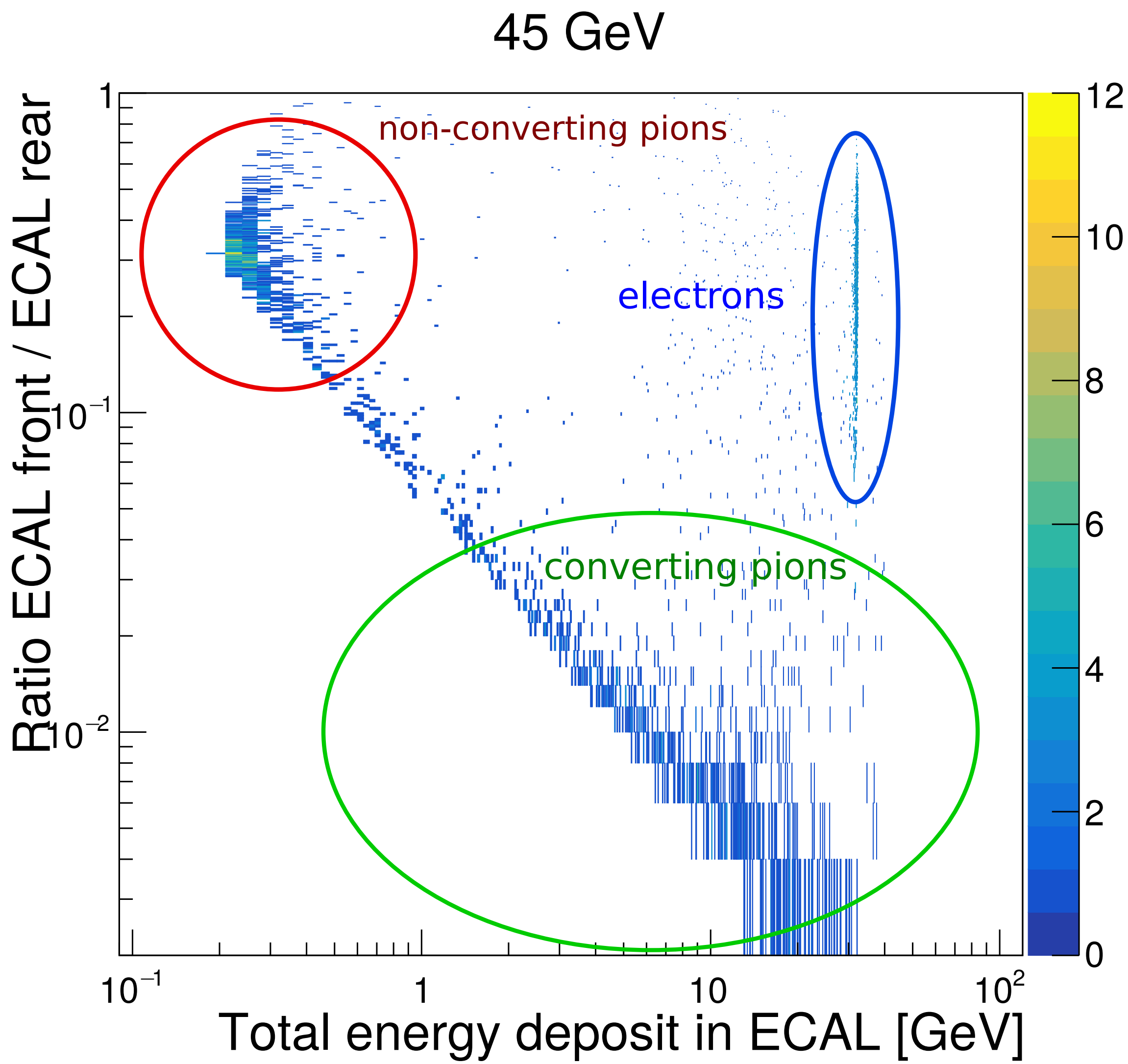
High Granularity

1x1 cm²

Electron/$\pi^{\pm}$ Discrimination



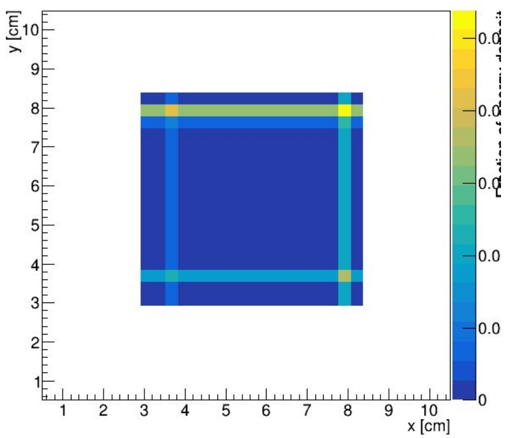
Electron/$\pi^{\pm}$ Discrimination

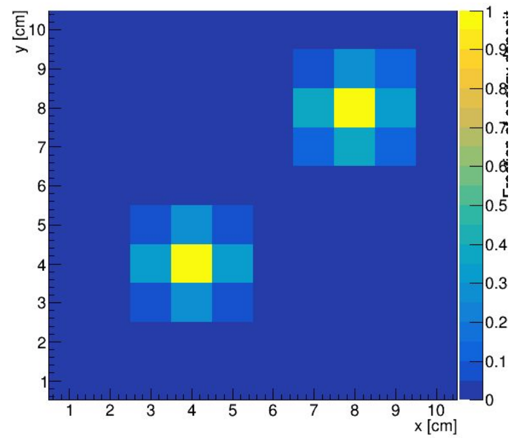


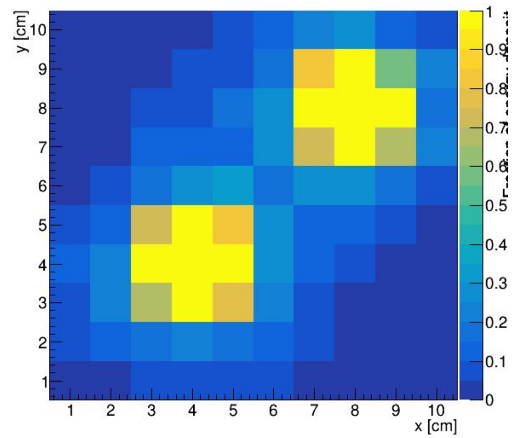
Marco Lucchini

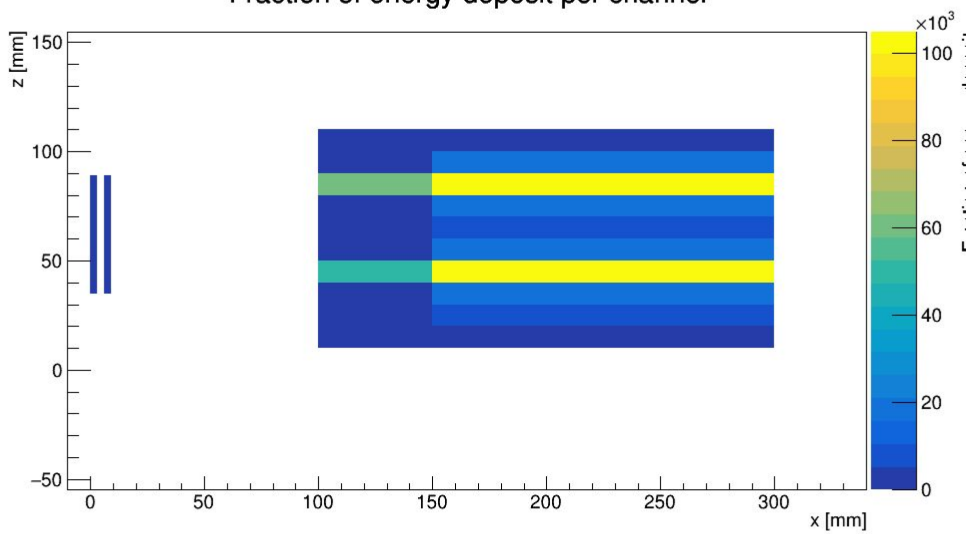
Pair of EM Showers (High Stat)

Linear-Scale



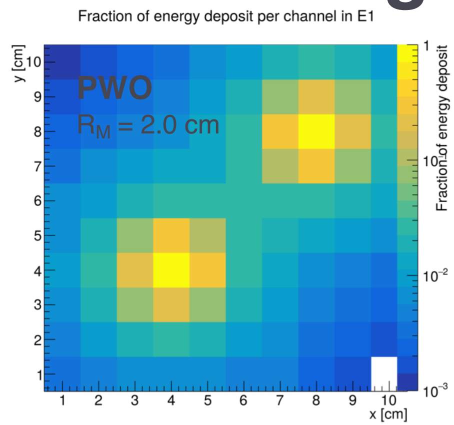




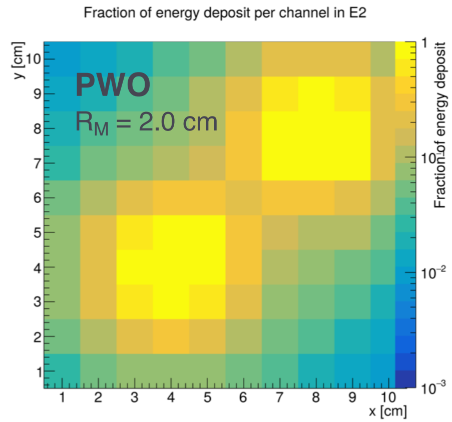


Electron Shower Profiles and Brem. Losses

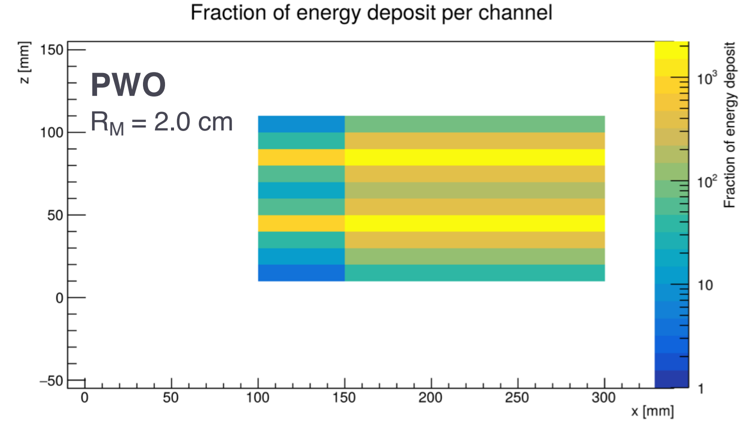
Log-Scale



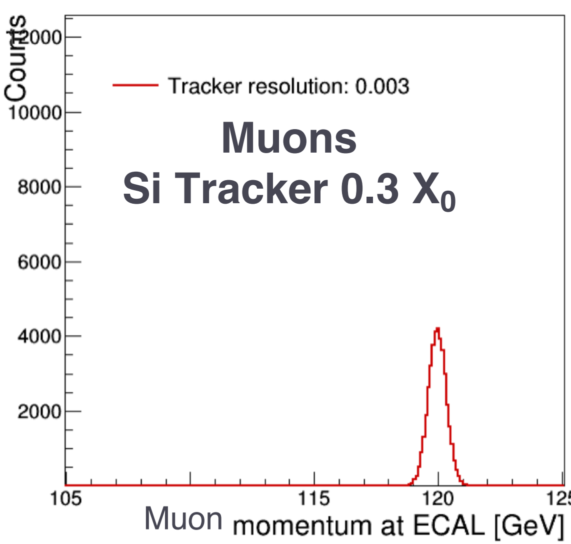
Cell Size: 1 cm^2
Front Xtals

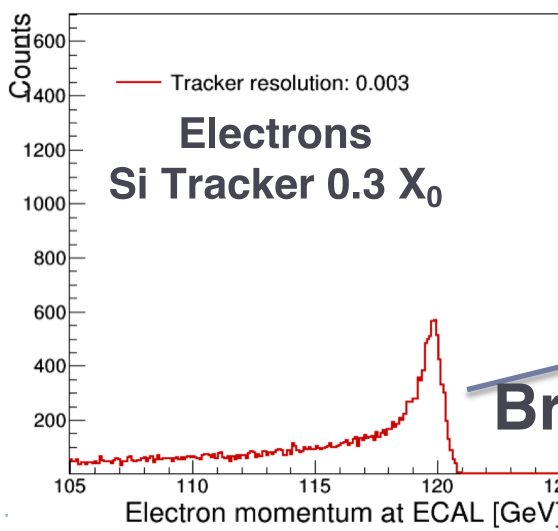


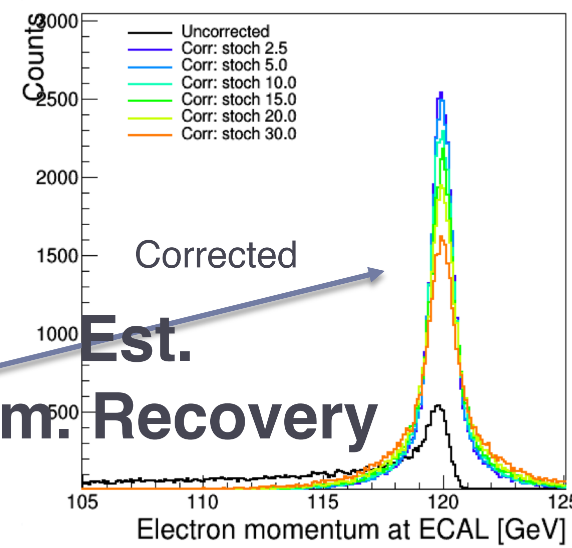
Cell Size: 1 cm^2
Rear Xtals



Size View

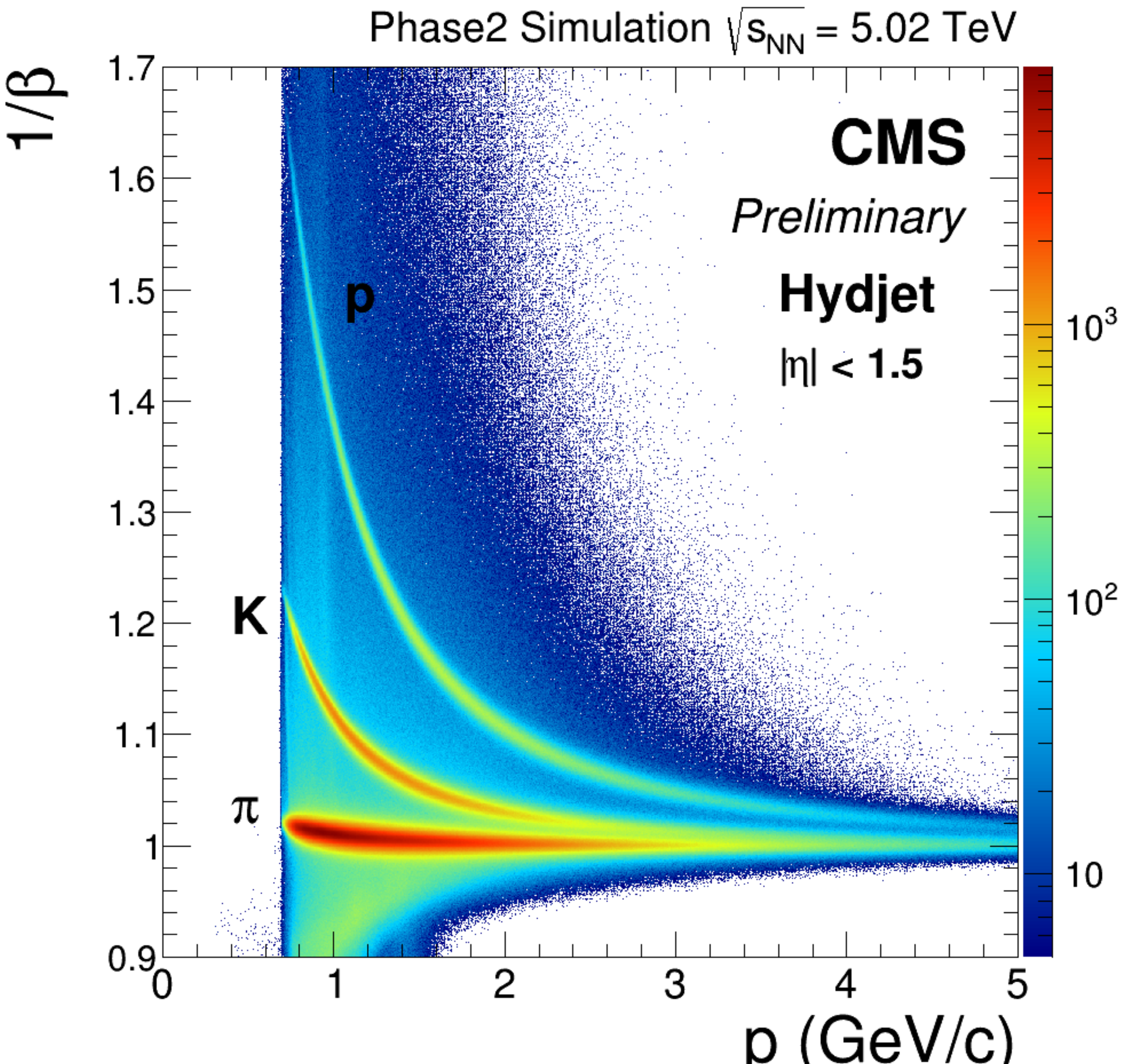






Est. Brem. Recovery

Time-of-Flight Particle ID (R=1.2m)

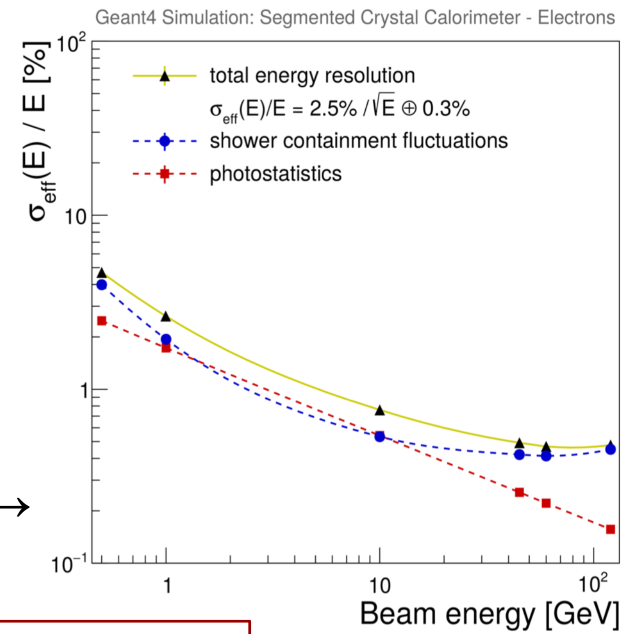


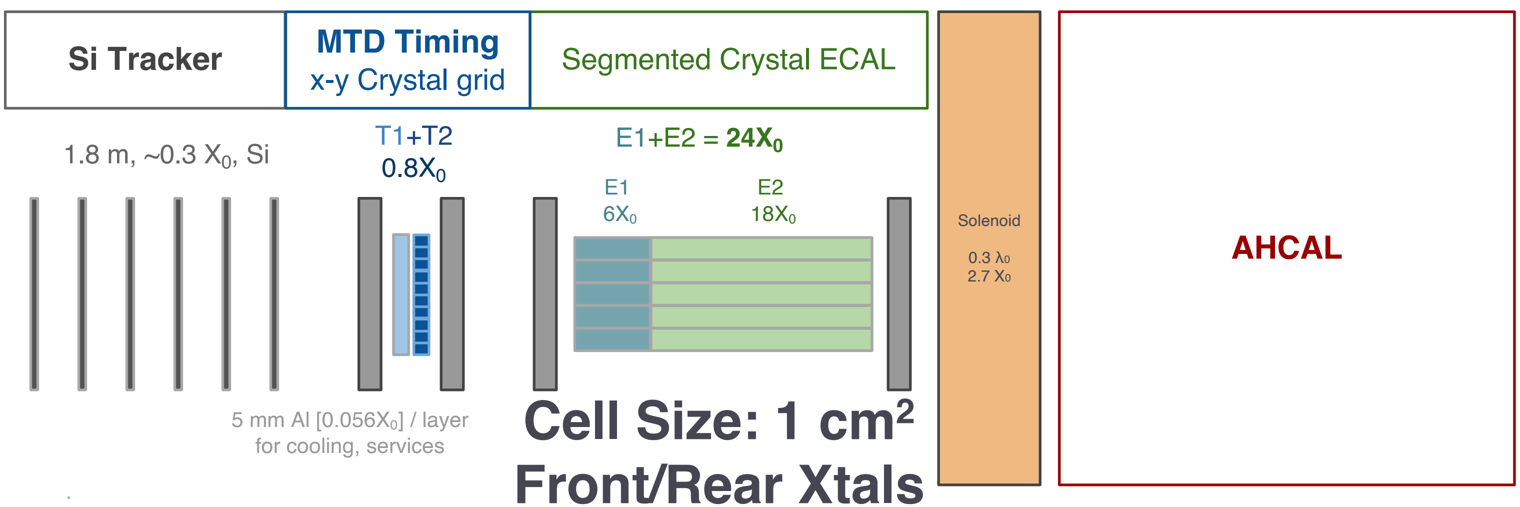
Single Layer (30 ps)

Improves by 1/√2 w/Dble Layer

High. Res. Segmented ECAL

- **EM Calo w/ ~3%/√E Stochastic Term:**
  - Shower fluctuations <2%
    - Material budget in front of ECAL < $0.3X_0$
  - Photostatistic fluctuations < 2%
    - Signal in photoelectrons >3500 phe/GeV
    - Assuming 30% PDE → LY*LCE > 12 ph/MeV
      - PWO: LY=100 ph/MeV → LCE>12% → SiPM area per crystal > 36 mm²

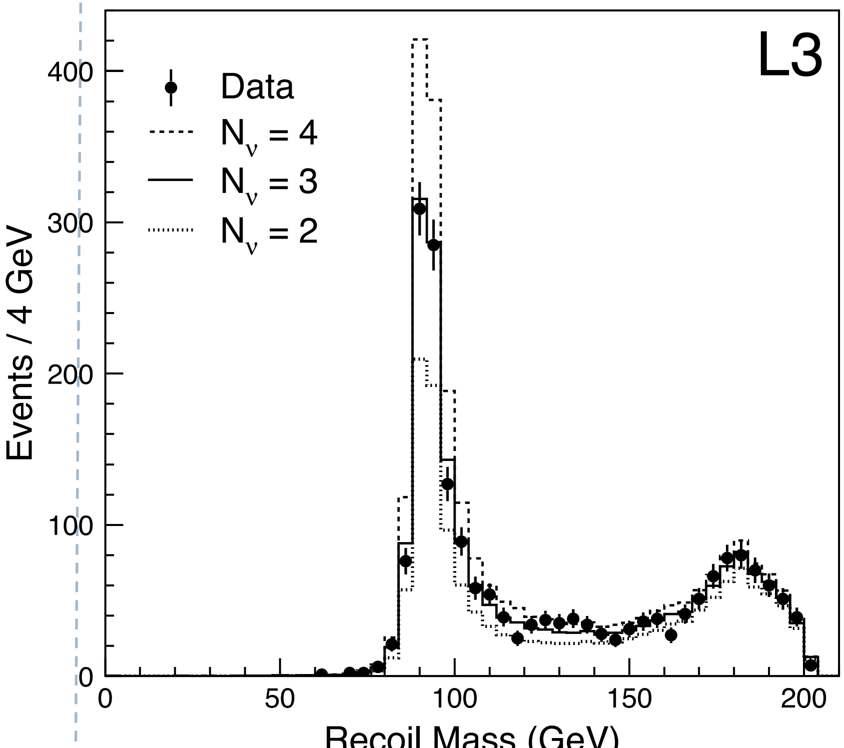


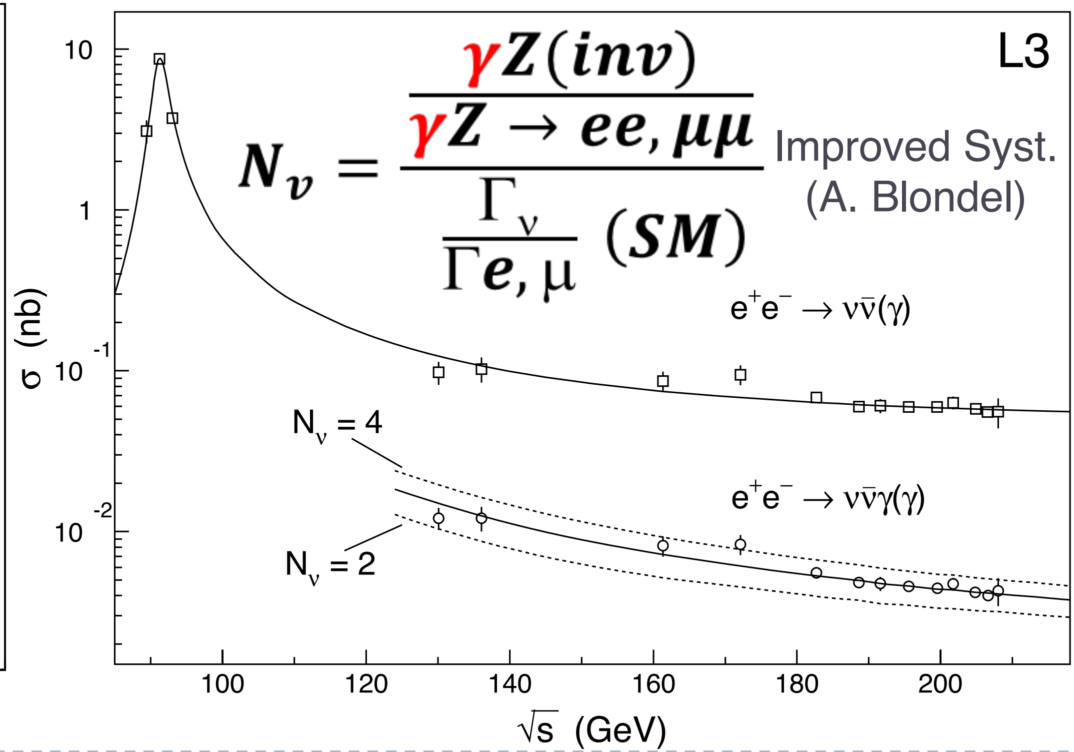


Next Goal: HADRON ~30%/√E

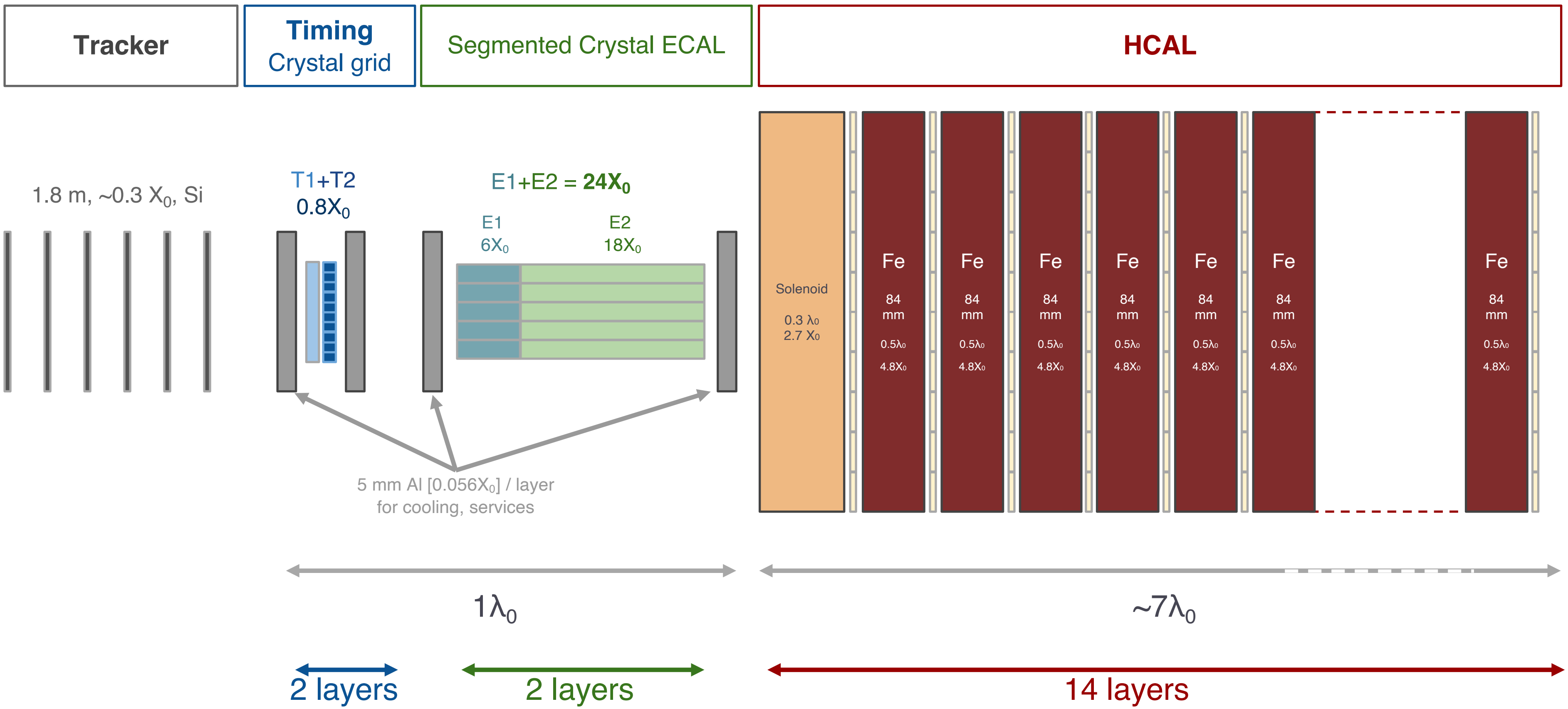
EM Resolution and Photon Counting

- **EM Resolution also improves angular measurements and resolves Nγ counting**
- **Recoil photons (~8% of full √s collision rate)**
  - New Physics Searches and Neutrino Counting

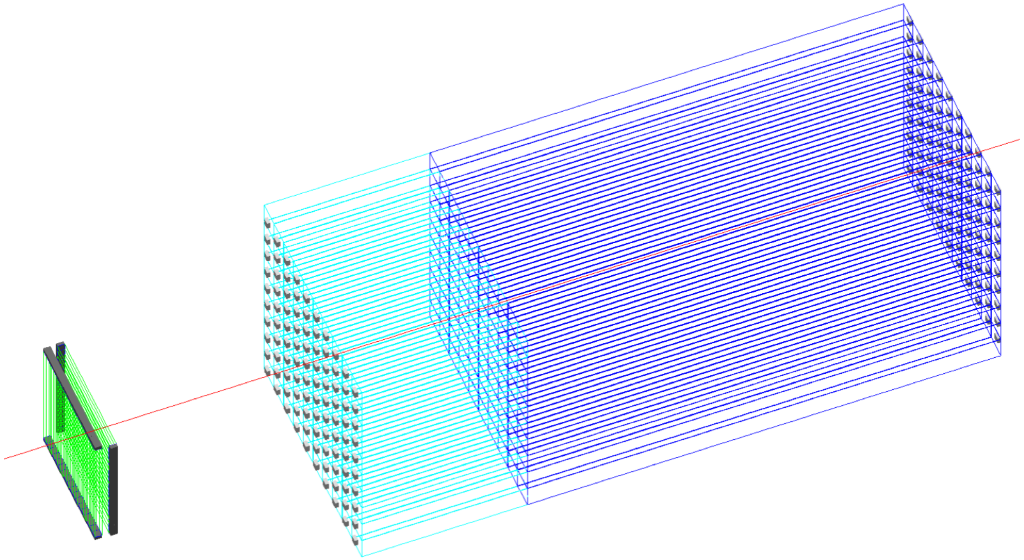


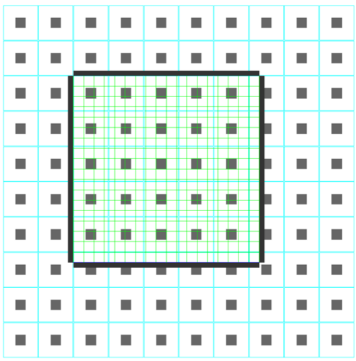


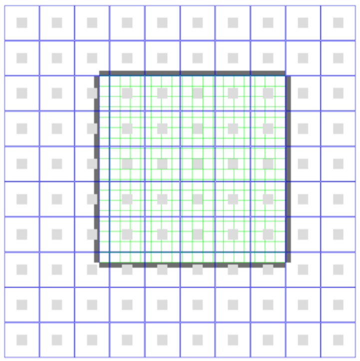
Simulated Detector Geometry



GEANT4 Views

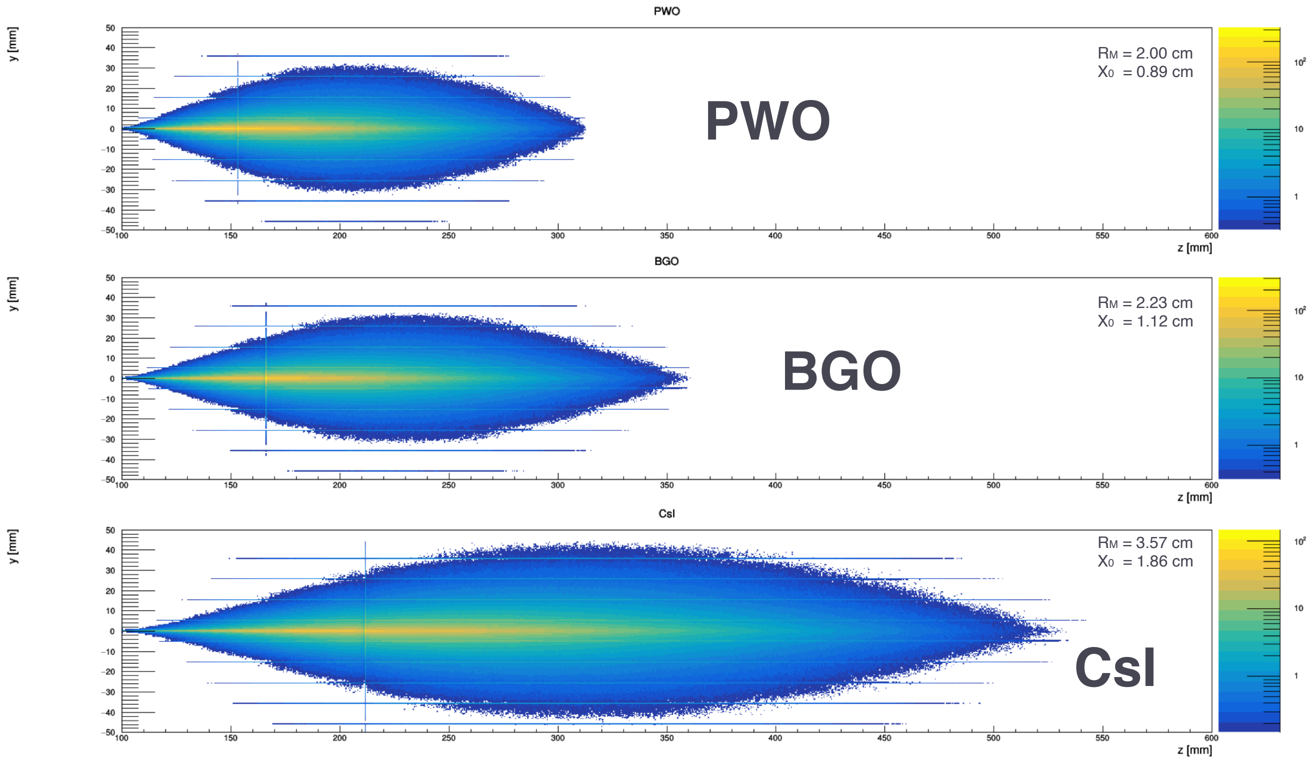






Optimization of Crystal Segmentation

Smaller Moliere radius in front segment → better shower separation



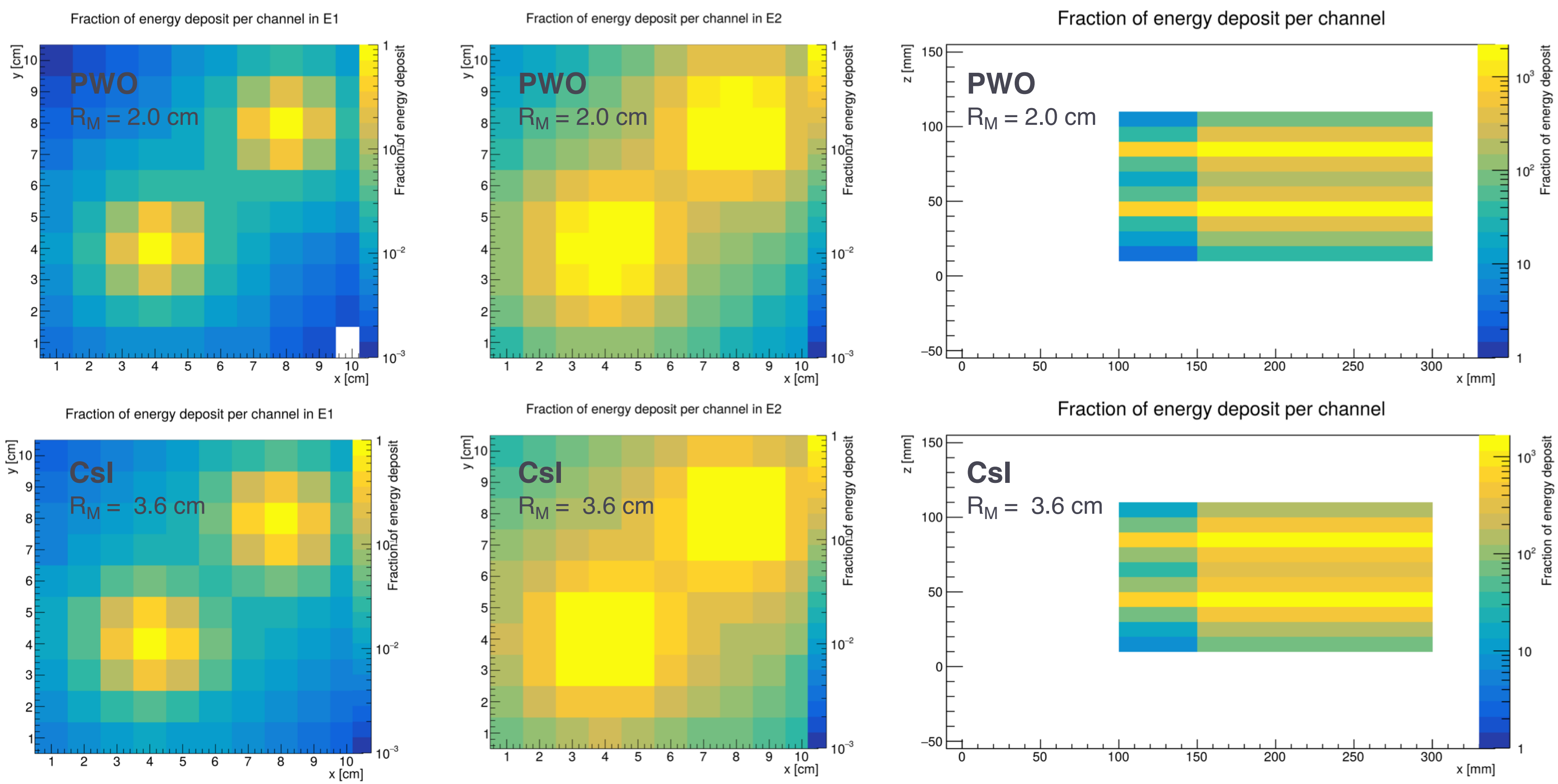
45 GeV electrons

X_0^{TRK} = 0.3

ECAL length: 24 X_0

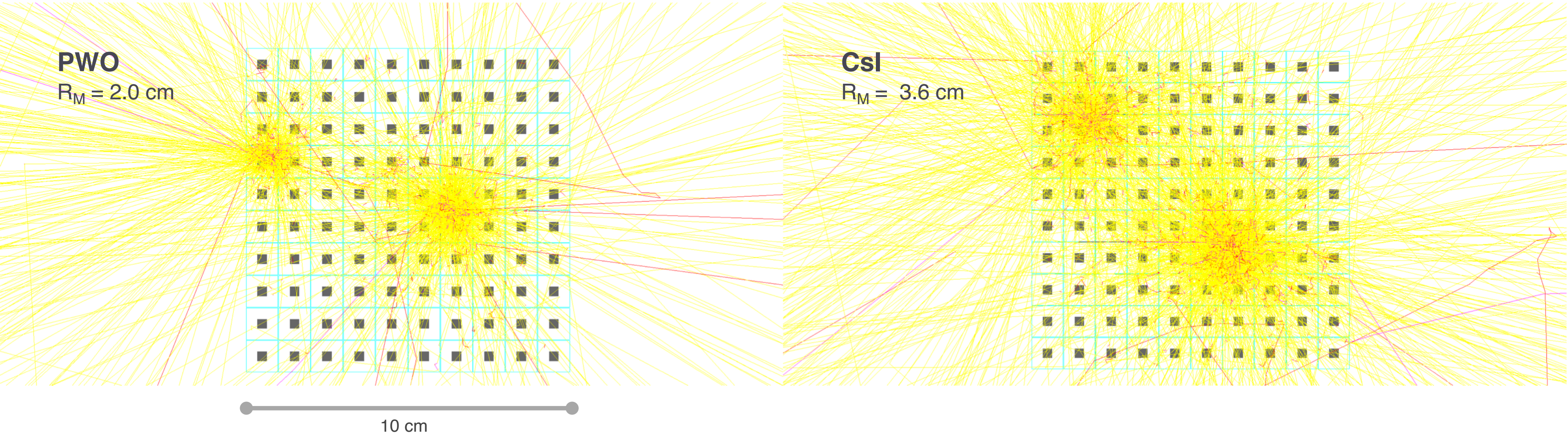
Module width: 10 cm

Pair of 45 GeV Electron Showers



10 GeV π^0 Photon Separation

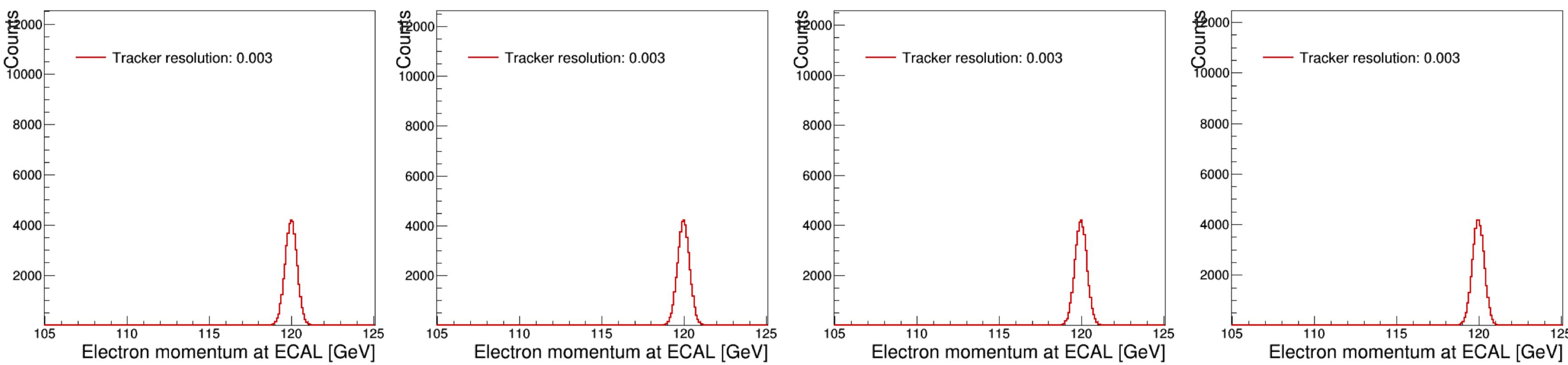
More practical example (front & rear compartments):



Muons vs. Electron w/ Tracker Material

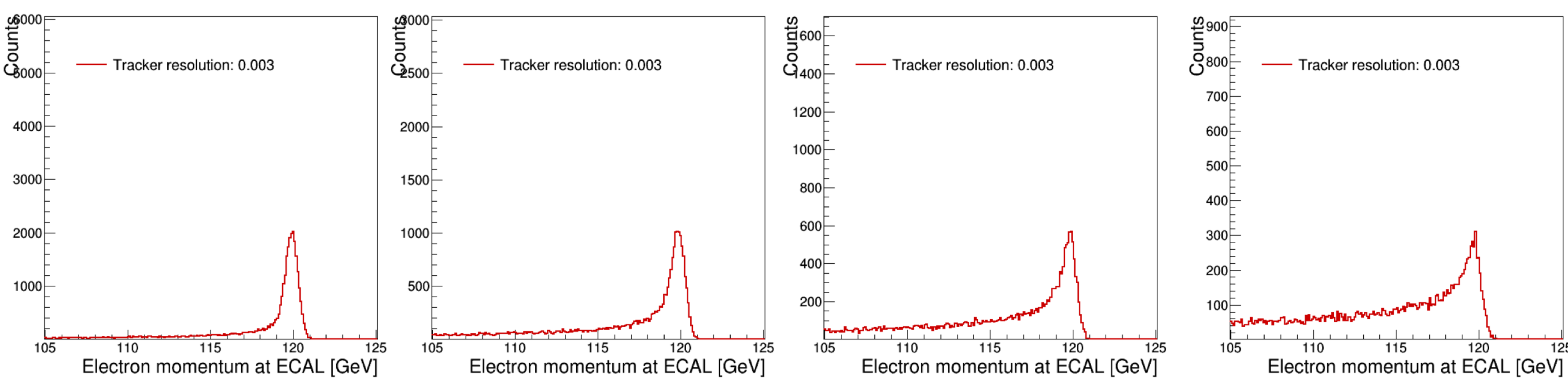
Muons:

0.1 X_0 | 0.2 X_0 | 0.3 X_0 | 0.4 X_0



Electrons:

0.1 X_0 | 0.2 X_0 | 0.3 X_0 | 0.4 X_0

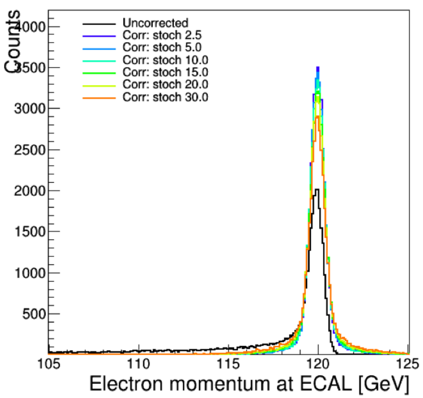


Z→e$^+$e$^-$ Sensitivity Recovery

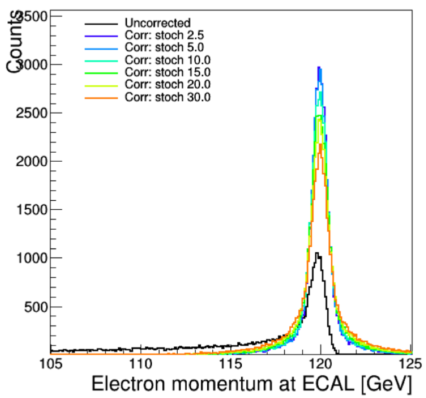
Highest Recovery for ~3%/√E ECAL Energy Resolution

→ Improvement largest for ~0.3-0.4 X_0

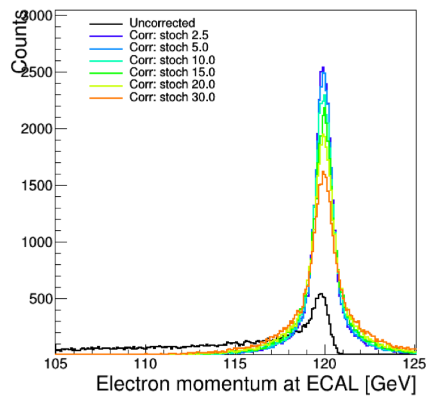
0.1 X_0



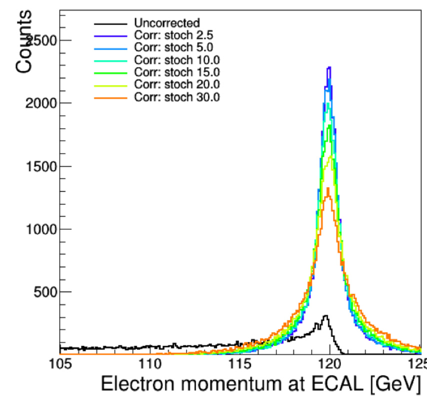
0.2 X_0



0.3 X_0



0.4 X_0

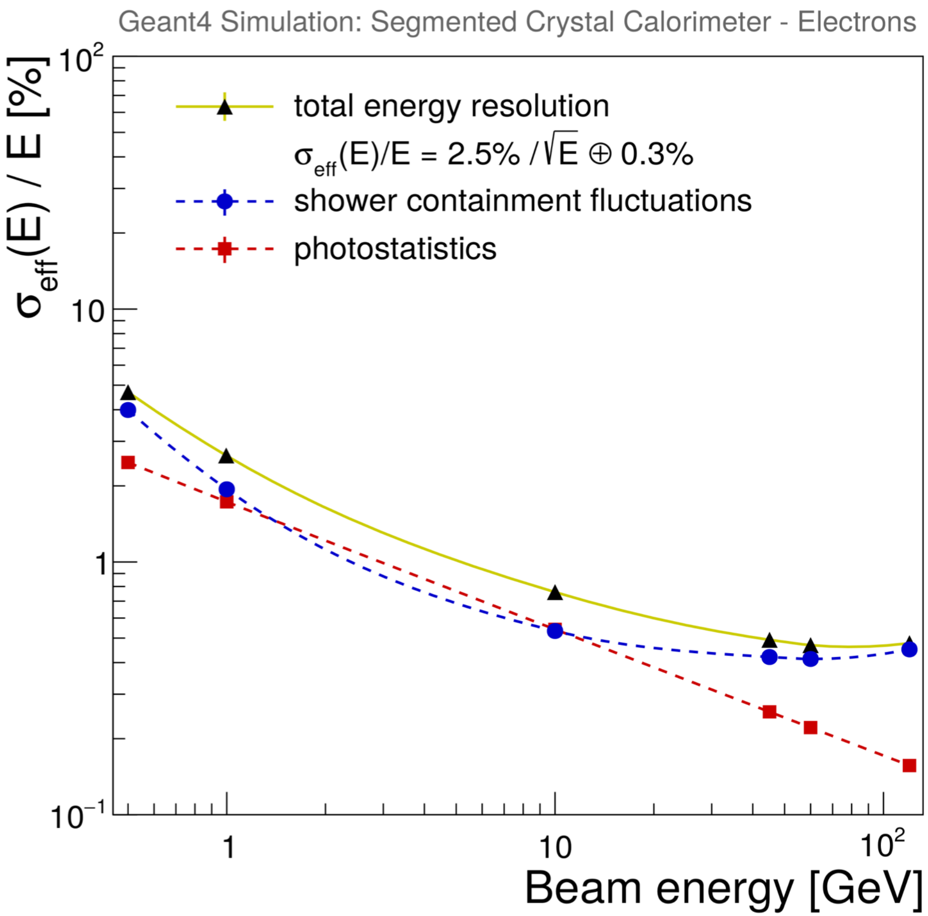


Energy Resolution Target: <3%/√E Stochastic Term

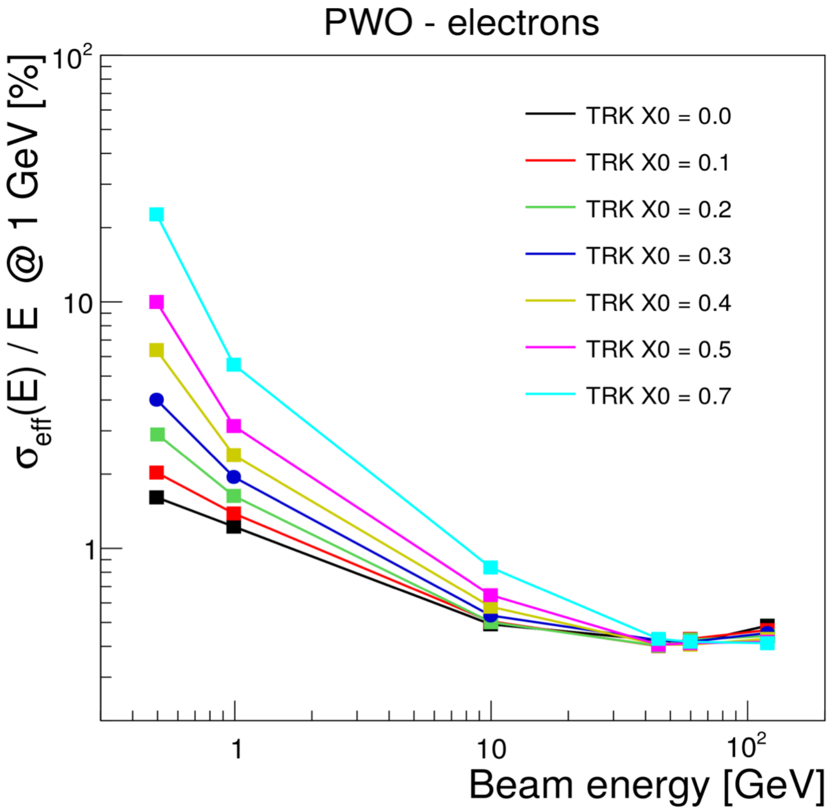
- **Requires:**
  - Shower fluctuations <2%
    - Material budget in front of ECAL < $0.3X_0$
  - Photostatistic fluctuations < 2%
    - Signal in photoelectrons >3500 phe/GeV
    - Assuming 20% PDE for 10 um cell SiPMs → LY*LCE > 18 ph/MeV
      - 5 um cells with high PDE in development
    - Need to tune SiPM active area accordingly to crystal LY
      - PWO: LY=100 ph/MeV → LCE>18% → SiPM area > 64 mm²
        - SiPM number of cells: 360k
      - BGO: LY=7000 ph/MeV → LCE>0.3% → SiPM area > 1 mm²
        - SiPM number of cells: 10k → dynamic range effectively x30-40 larger due to the fast time response of the pixel compared to the BGO decay time

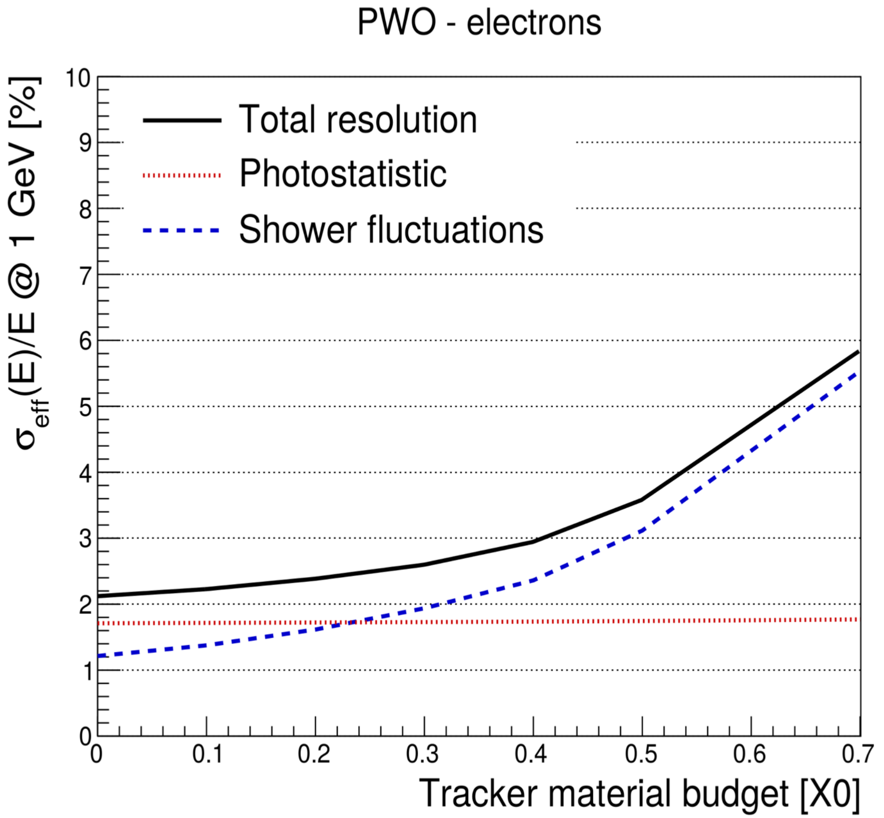
Energy Resolution

- **Contributions :**
  - Shower containment fluctuations
    - Longitudinal leakage
    - Tracker material budget
    - Services for front layer readout
  - Photostatistics
    - Tunable parameter depending on:
      - SiPM choice
      - Scintillator choice
      - Connected to dynamic range
  - Noise
    - Negligible (low dark counts, high gain)



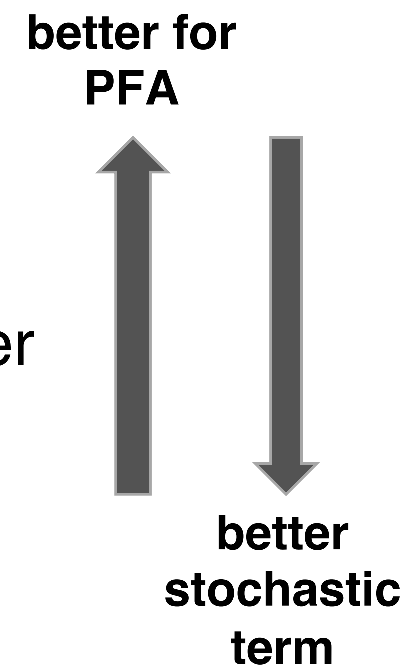
Impact of Tracker Material Budget





Crystal Options

- **PWO:**
  - the most compact, the fastest, the cheapest
- **BGO:**
  - close to PWO in compactness, slower, brighter
- **CsI:**
  - the least compact, the slowest, the brightest



Crystal	Density g/cm³	λ_I cm	X_0 cm	R_M cm	Relative LY @ RT	Decay time ns	Photon density (LY / τ_D) ph/ns	dLY/dT (% / °C)	Cost (10 m³) $/cm³	Cost*X_0 $/cm²
PWO	8.3	20.9	0.89	2.00	1	10	0.10	-2.5	8	**7.1**
BGO	7.1	22.7	1.12	2.23	70	300	0.23	-0.9	7	**7.8**
CsI	4.5	39.3	1.86	3.57	550	1220	0.45	+0.4	4.3	**8.0**

Values from: Journal of Physics: Conference Series **293** (2011) 012004

Cost Estimate (and Power)

ECAL INPUTs	
Number of crystals per m² (front E1)	8100
Number of crystals per m² (rear E2)	8100
Number of SiPM per crystal (front E1)	1
Number of SiPM per crystal (rear E2)	1
Cost/crystal (front+rear) (1x1x20 cm³) - SIC	152.0832
Cost per SiPM (€)	3
Electronics cost per channel (€)	2
Power cost per channel (€)	1
Calibration-monitoring cost / channel (€)	0.5

Barrel ECAL	
Total SiPM power (kW)	1.7172
Total electronics (kW)	23.1822
Total barrel ECAL power (kW)	24.8994
2 Endcaps ECAL	
Total SiPM power (kW)	0.696
Total electronics (kW)	9.396
Total endcap	10.092
Grand total ECAL (barrel+endcap) [kW]	35

(35kW)

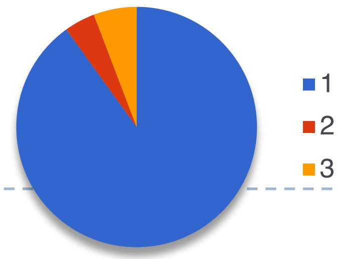
Barrel ECAL	
Radius	1.8
Length	4.7
Area (m²)	53
Number of crystals (front E1)	429300
Number of crystals (rear E2)	429300
Number of SiPMs (front E1)	429300
Number of SiPMs (rear E2)	429300

Endcaps ECAL	
Inner radius	0.35
Outer radius	1.7
Area (m²) for two endcaps	17.4
Number of crystals (front E1)	174000
Number of crystals (rear E2)	174000
Number of SiPMs (front E1)	174000
Number of SiPMs (rear E2)	174000

Total barrel crystal cost (k€)	65289
Total barrel SiPM cost (k€)	3005
Total electronics cost (k€)	1717
Power system	859
Services (CO2 cooling)	1318
Mechanics and assembly	300
Total barrel ECAL cost (k€)	72488

Total endcap crystal cost (k€)	26462
Total endcap SiPM cost (k€)	1218
Total electronics cost (k€)	696
Power system	348
Services (CO2 cooling)	174
Mechanics and assembly	300
Total endcap ECAL cost (k€)	29198

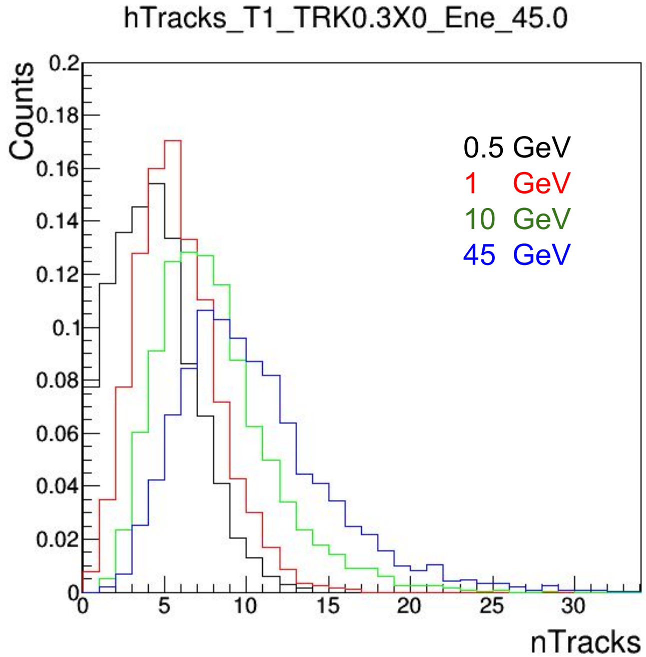
Total ECAL crystal volume [m³]	12
Grand total ECAL (barrel+endcap) [# channels]	1206600
Grand total ECAL (barrel+endcap) [k€]	101686

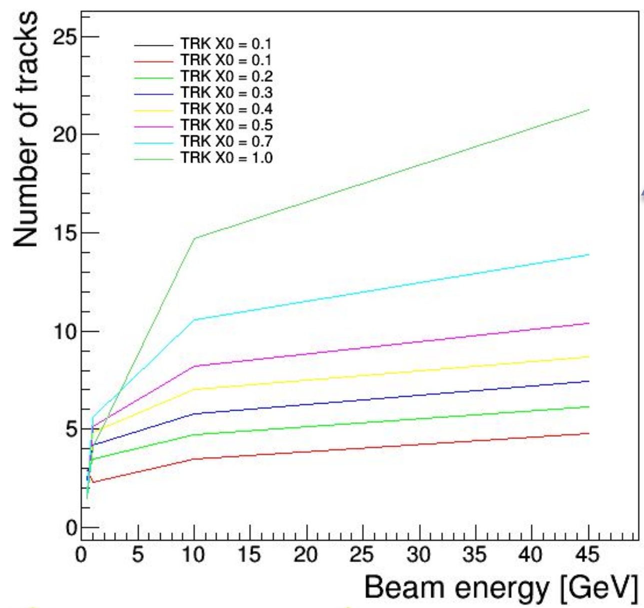


~100 Meuros

Electron Bremsstrahlung in Tracker

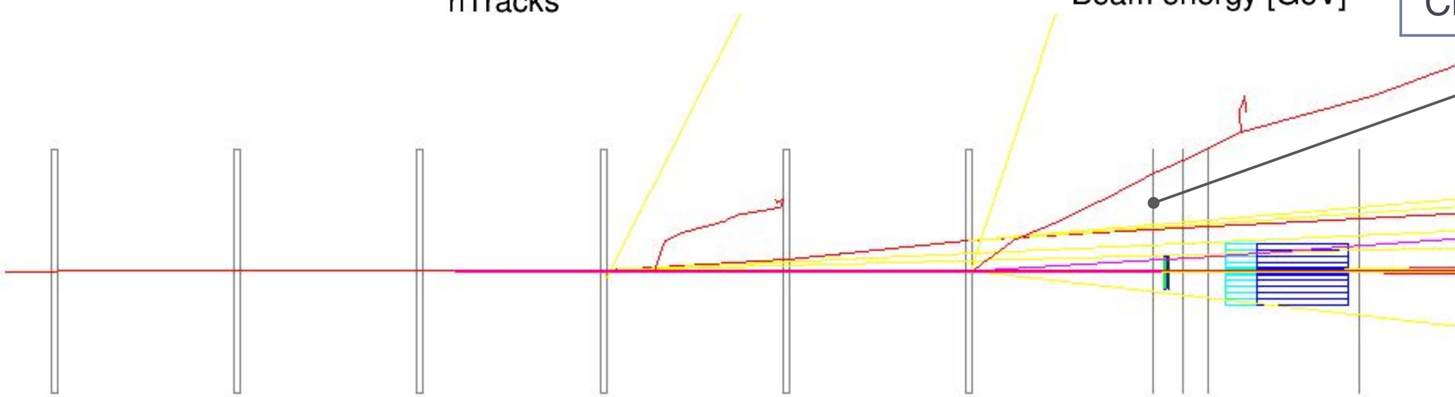
- counting number of tracks at the entrance of the timing layer (e+, e-, gamma)





Tracker Material Increasing

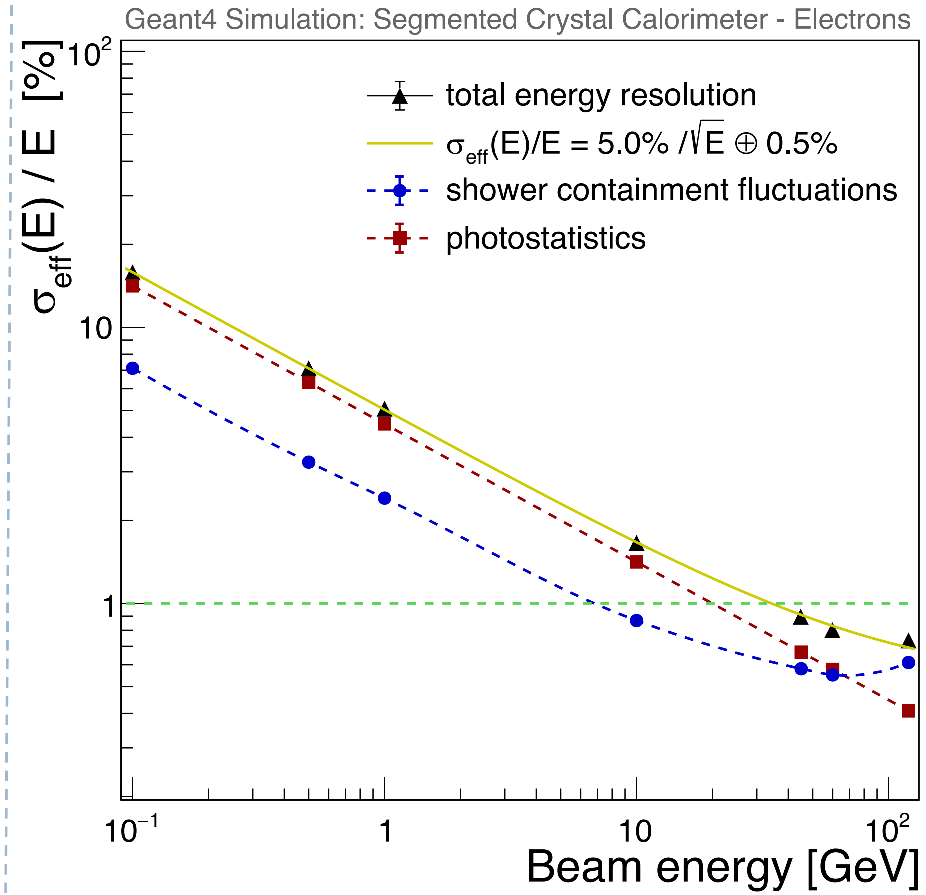
Count Tracks (e+,e-, photons) Crossing Here

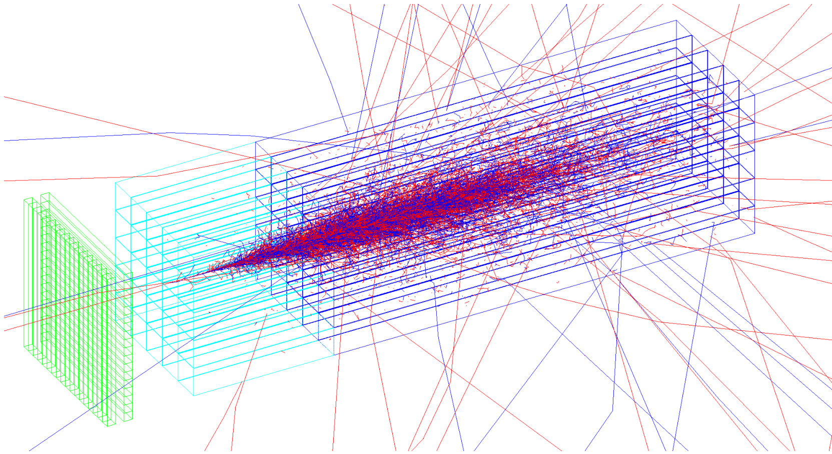


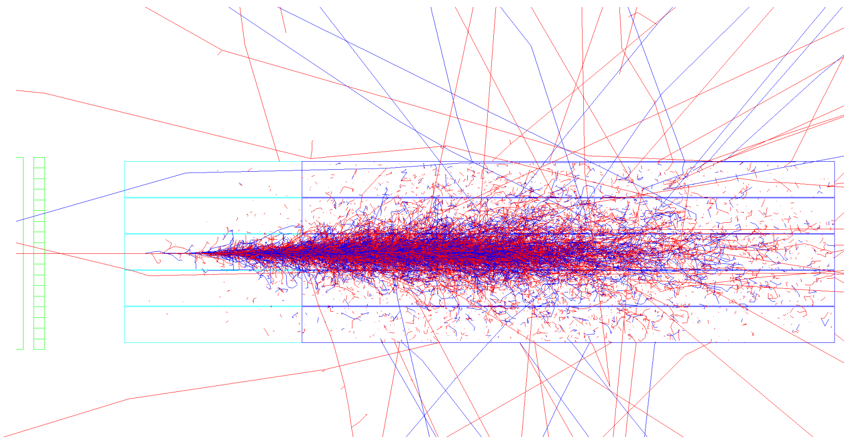
6-Layer Silicon Tracker

S-CEPCal

Electron Energy Resolution (no Dead Material)

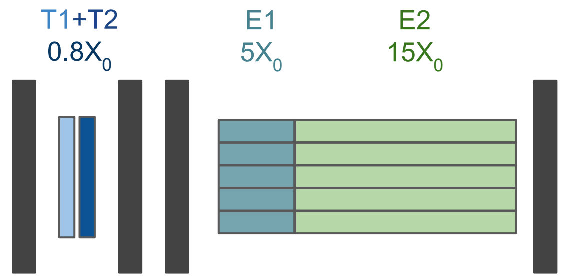


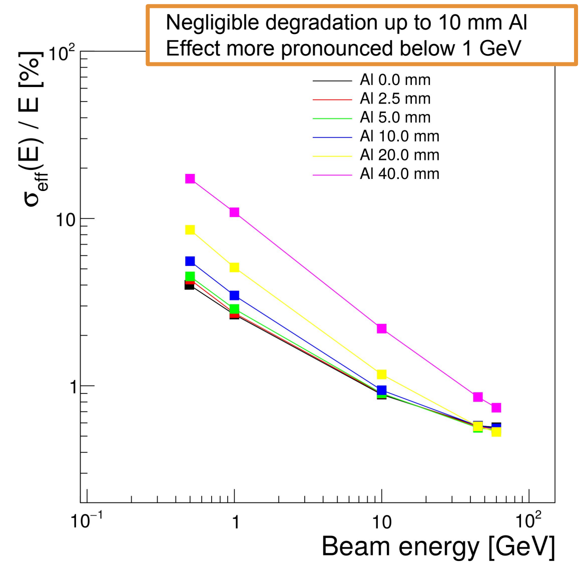




Dead Material between Layers

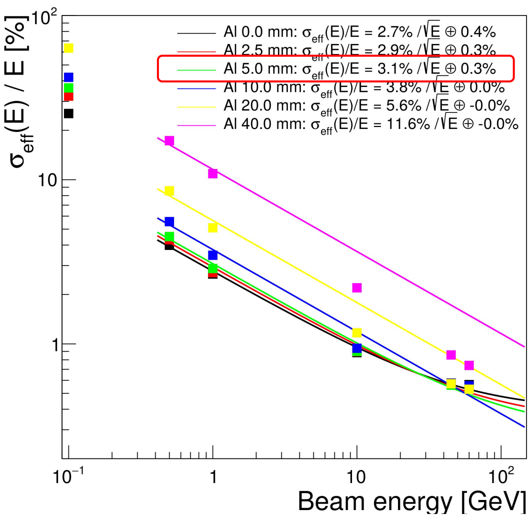
- Services required:
  - FE/ASIC for read-out → PCB material
  - Cooling plate
  - Cables
- Space allocated:
  - 5 cm in front of crystal timing layer T1 (for T1 read-out)
  - 10 cm in front of crystal ECAL E1
    - 5 cm for T2 and 5 cm for E1 → **cooling plate may be shared**
  - 5 cm in rear of crystal ECAL E2 (for E2 read-out)
- Material budget:
  - Realistic cooling plate ~ 3 mm Al → 0.035 X_0
  - PCB ~ 2 mm, + cables, etc
  - **total: 0.056 X_0** (5 mm Al equivalent) for each layer
  - Scan up to 0.5X_0 / layer



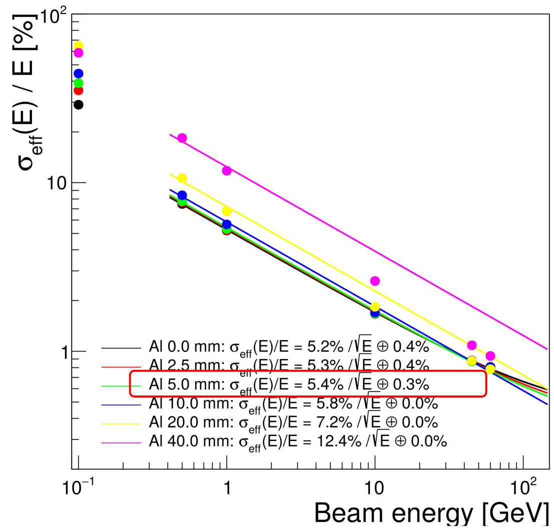


Impact of Dead Material between Layers

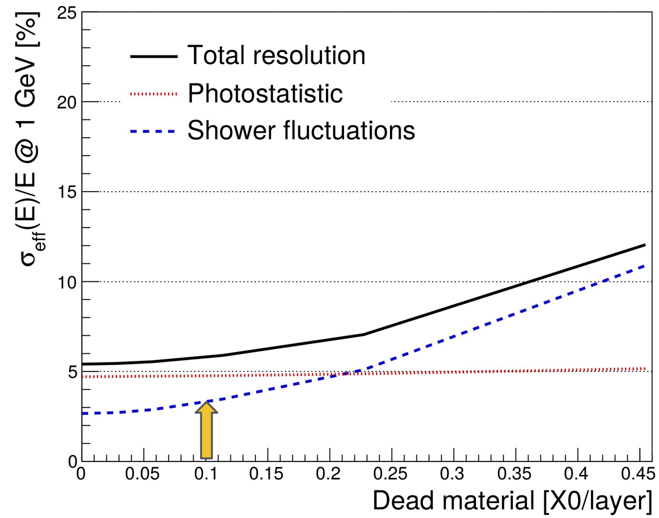
Shower fluctuations only



Total (including photostat.)

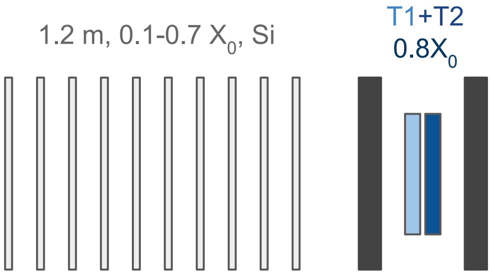


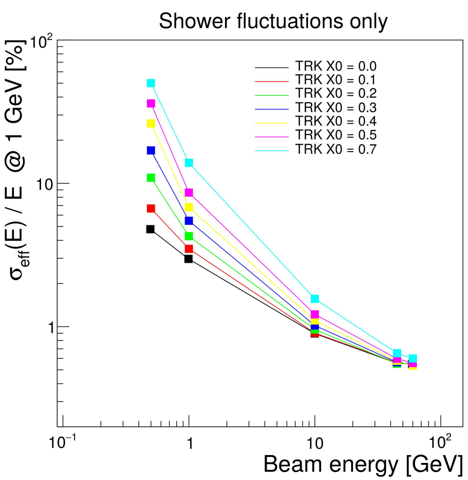
Stochastic term vs dead material

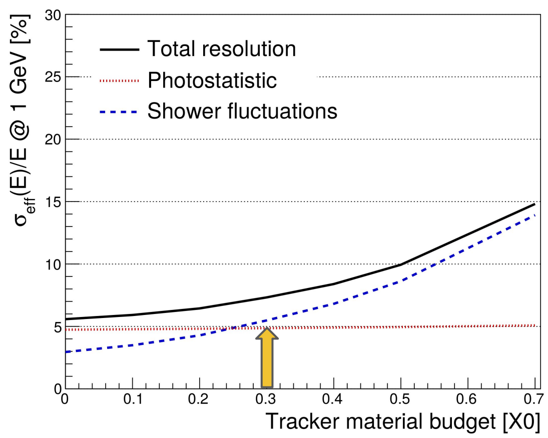


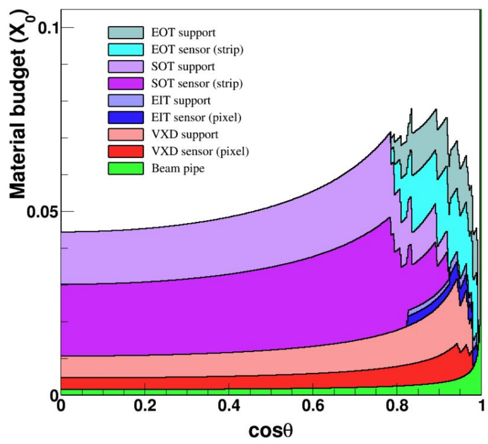
Impact of Tracker Material

- Study impact of tracker material budget in front of SC-E(P)CAL
- Material budget:
  - Realistic material budget ~$0.3X_0$ **?**
  - Scan up to **$0.7X_0$**
- Negligible impact on energy resolution

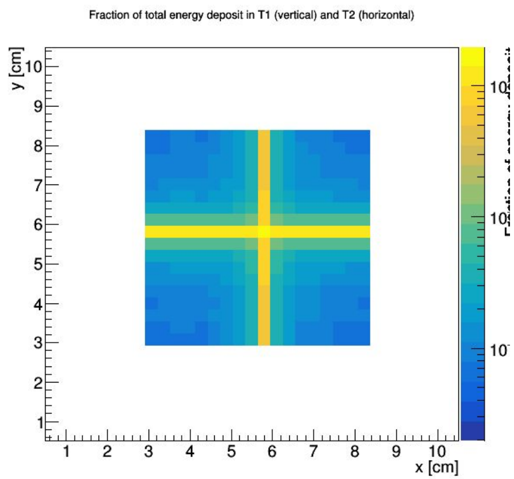


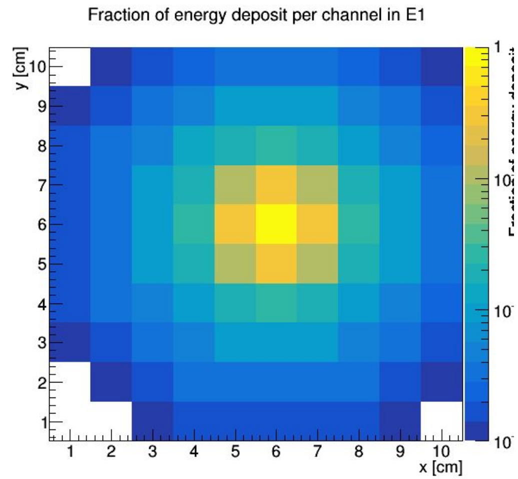


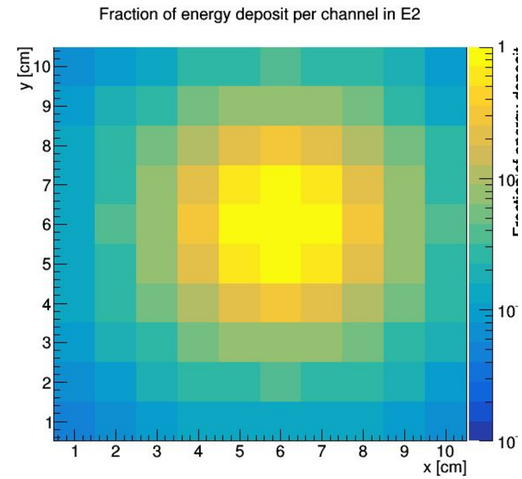


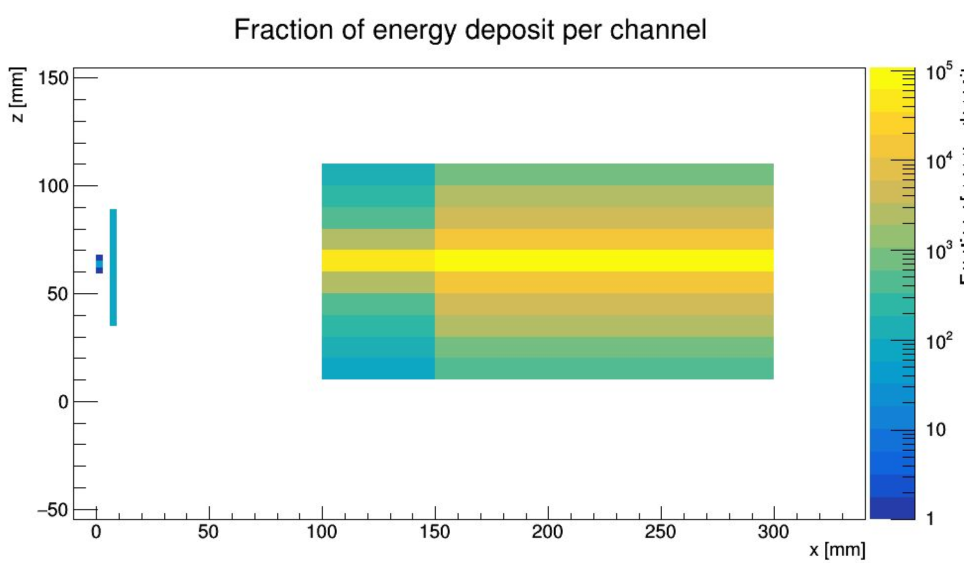


Single EM Shower (High Stat- Log)

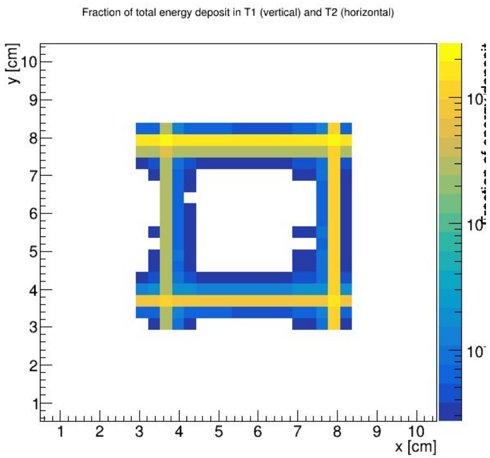


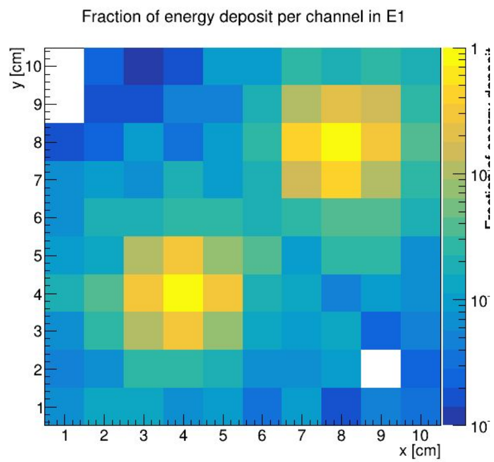


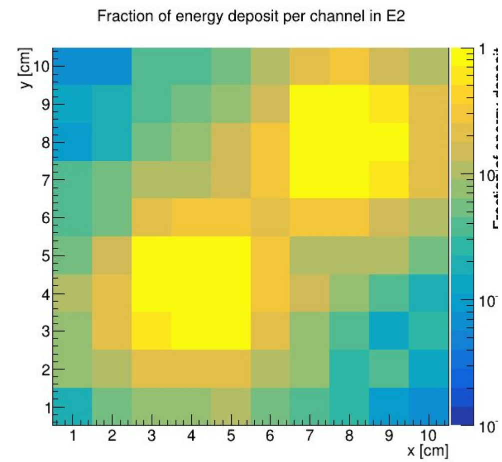


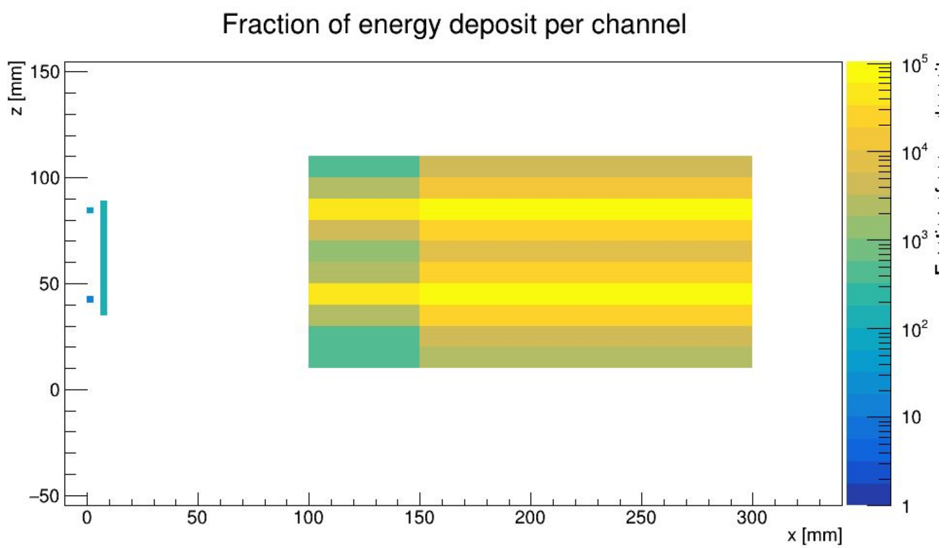


Pair of EM Showers (High Stat - Log)

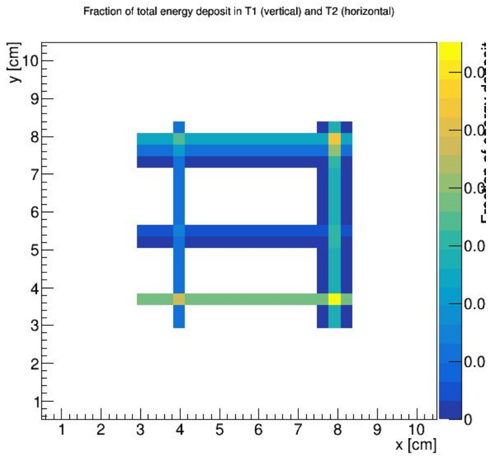


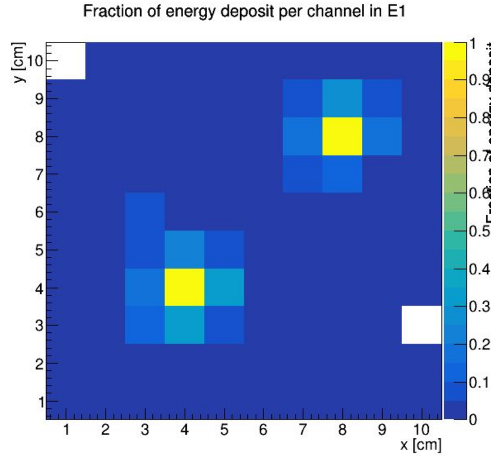


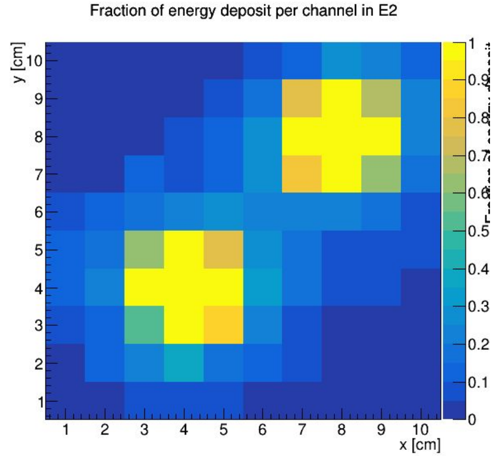


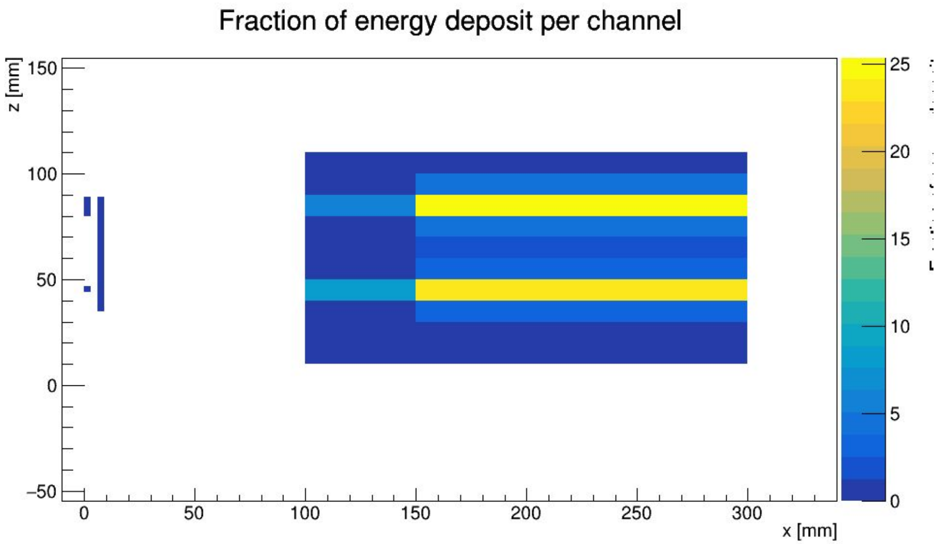


Pair of EM Showers (Single Event)



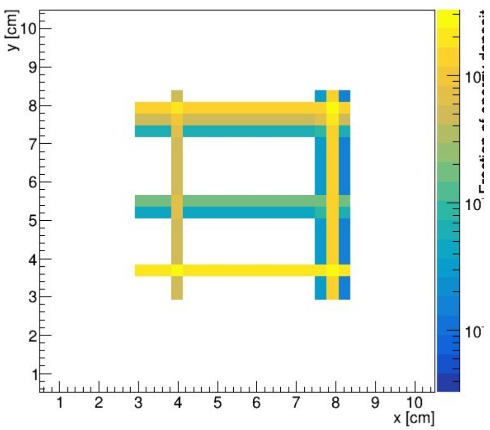




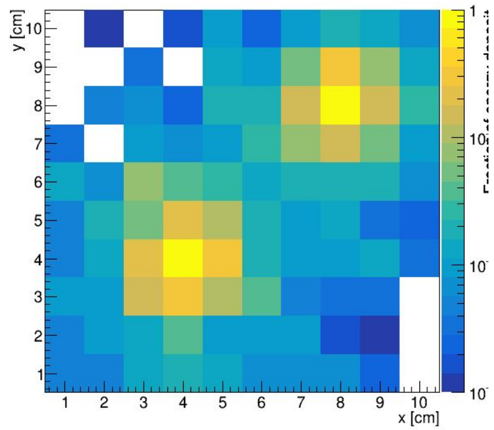


Pair of EM Showers (Single Event - Log)

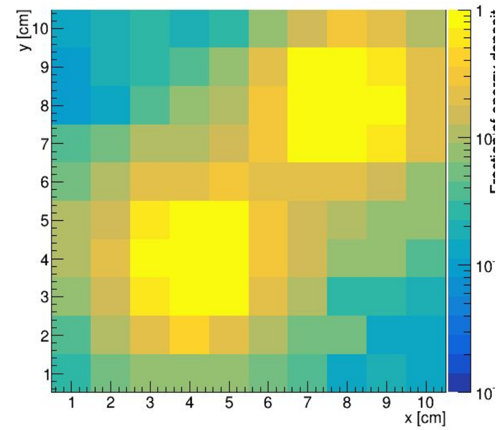
Fraction of total energy deposit in T1 (vertical) and T2 (horizontal)



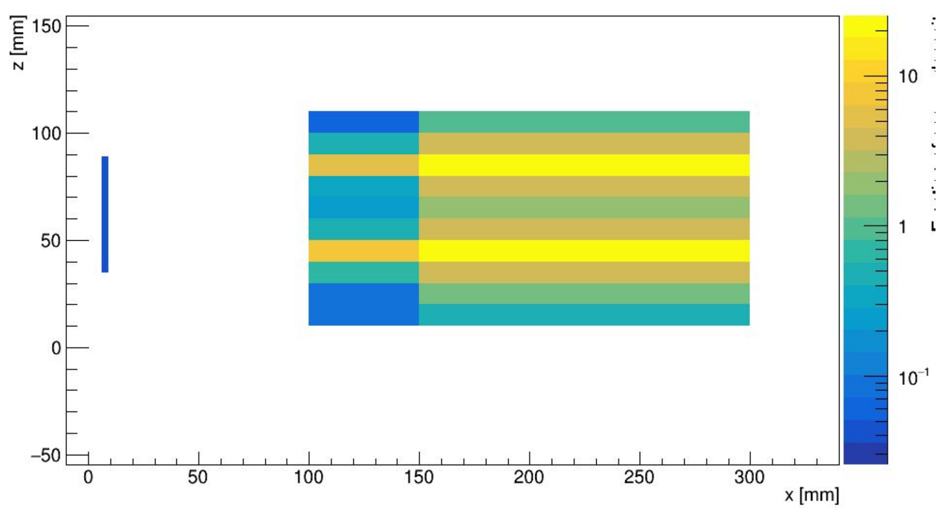
Fraction of energy deposit per channel in E1



Fraction of energy deposit per channel in E2



Fraction of energy deposit per channel

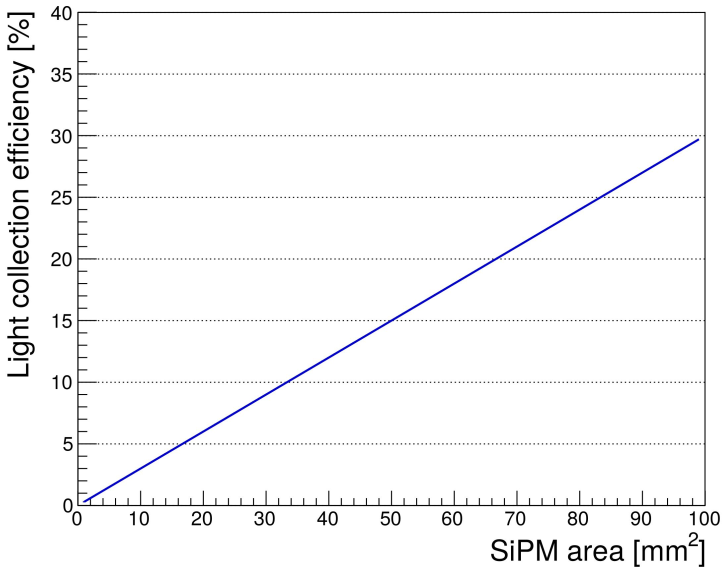


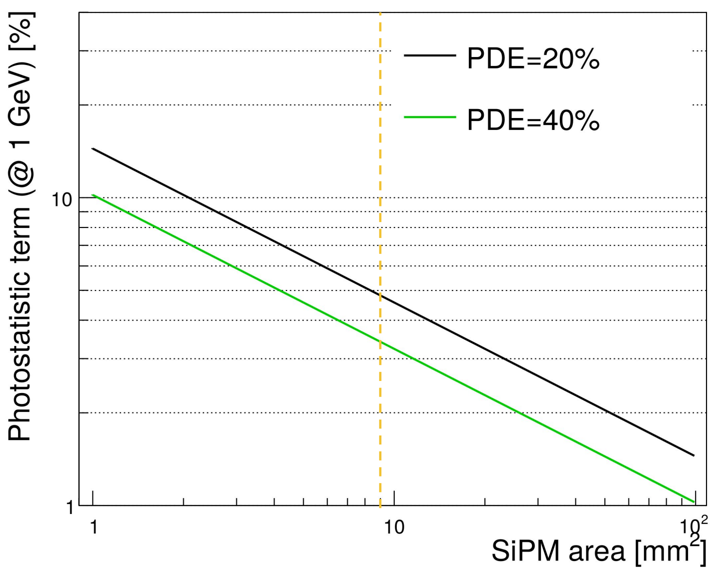
Energy Resolution and Dynamic Range

- **5%/sqrt(E) → LO>400 phe/GeV → LO>0.4 phe/MeV**
  - at LCE~2.5%, PDE ~ 20% → LY>80 ph/MeV
  - Ok for PWO (~100 ph/MeV)
- **Maximum energy deposit in single crystal for 120 GeV e.m. shower ~60%**
  - ~ 35000-70000 phe for ~72 GeV (at PDE~20-40% resp.)
- **SiPM 5x5 mm^2 on a 10x10 mm^2 crystal is sufficient**
  - LCE~2.5%
  - if cell size: 15 um → cells / SiPM ~110,000 and PDE up to 40%
  - if cell size: 10 um → cells / SiPM ~250,000 and PDE up to 25%
- **Sensitivity for 0.1 GeV particles**
  - 40 phe signal
  - Noise from SiPM within 30 ns integration gate negligible (DCR<10MHz → noise<1 phe)

Photostatistics

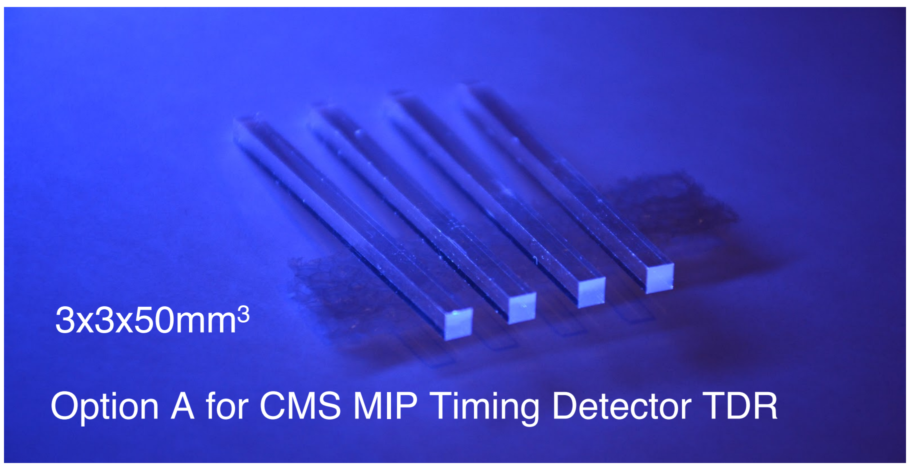
- 5%/sqrt(E) → LO>0.4 phe/MeV
  - for LCE~2.5% (9 mm² SiPM), PDE ~ 20% → The crystal must have a LY>80 ph/MeV
- SiPM 3x3 mm² on a 10x10 mm² crystal is sufficient
  - with SiPM area = crystal end face → LCE~30%



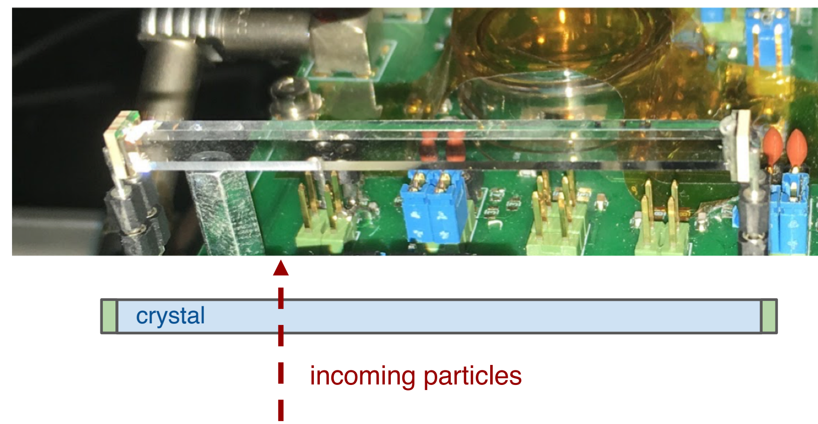


Small Crystal Geometries for Timing Detectors

- **Tiles and Bars (few mm thick w/ area of ~1cm^2)**
  - CMS MTD: Single layer ~330,000 channels
  - Stereo readout for bars (L/R) ~25ps timing resolution



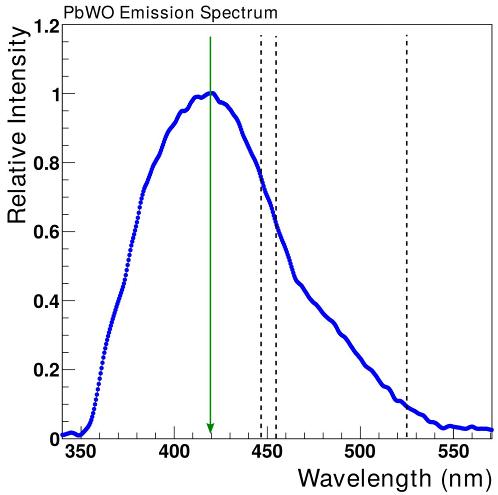
Non-wrapped crystal bar with 2 SiPMs attached at each end

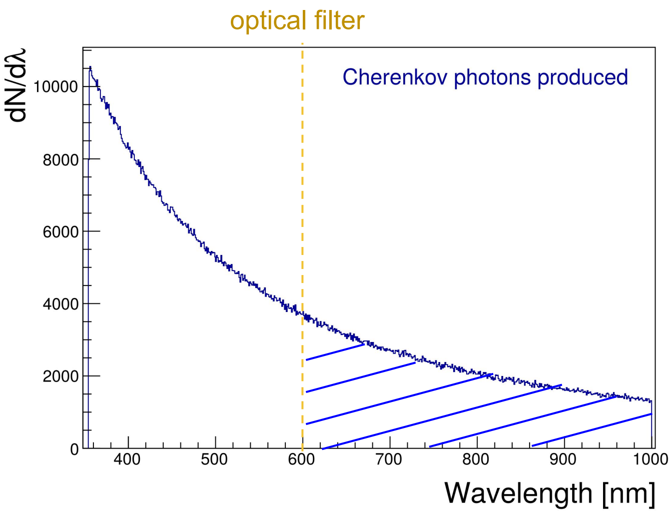


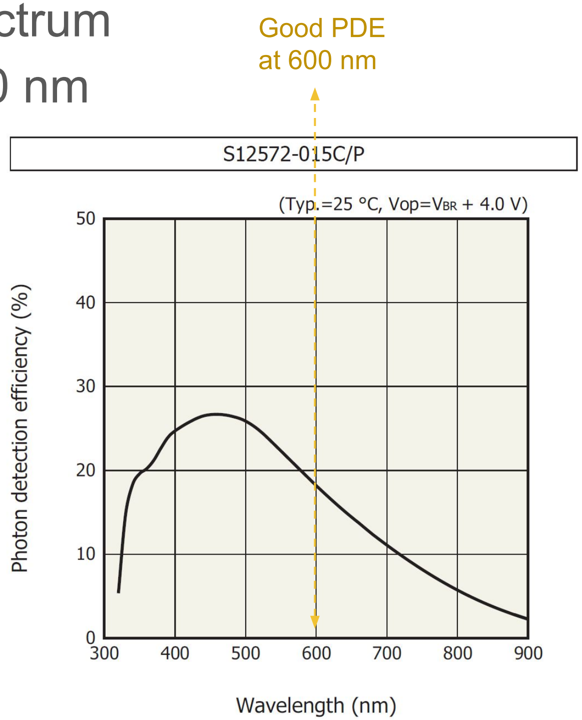
Low occupancy timing layer timing for ~1 X0
Transverse orientation w/ stereo readout

Dual-Readout Capability

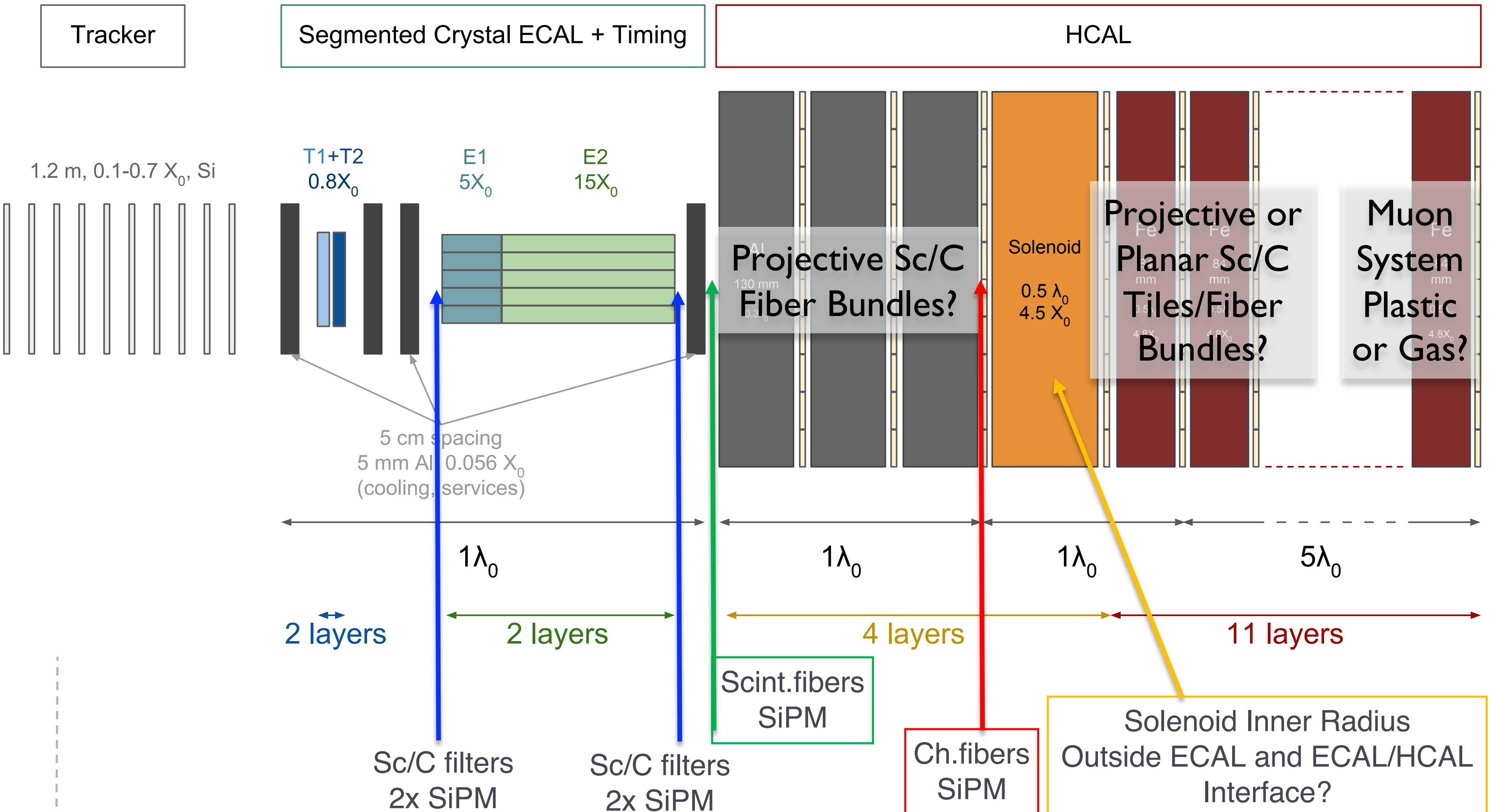
- PWO - excellent Cherenkov radiator (transparency cut off at 350 nm)
- Exploit Cherenkov photons **above** PWO emission spectrum
- 2 SiPMs, one with optical filter > 600 nm, another <600 nm







Dual-Readout ECAL+HCAL Compatibility



Comparisons with CMS and PANDA ECALs

- **LY (PWO) ~ 100 ph/MeV**
- **CMS EE:**
  - QE_{VPT} ~22%,
  - LCE ~ 9% (1 VPT: size~ 11 mm radius - area: 380 mm²)
  - PbWO, crystal end face size: ~30x30 mm²
- **CMS EB:**
  - QE_{APD}~75%,
  - LCE~9% (2xAPDs, size: 5x5 mm²)
  - PbWO crystal size: ~22x22 mm²
- **Resolution measured in test beam: ~3-6% stochastic + 0.3-0.6% constant**

http://iopscience.iop.org/article/10.1088/1748-0221/2/04/P04004/pdf
https://arxiv.org/pdf/1306.2016.pdf

PANDA ECAL
PWO-II development:
→ factor 4 higher LO at -25°C wrt to +25°C
→ ~20 phe/MeV @PDE=20%
→ <2% stochastic term

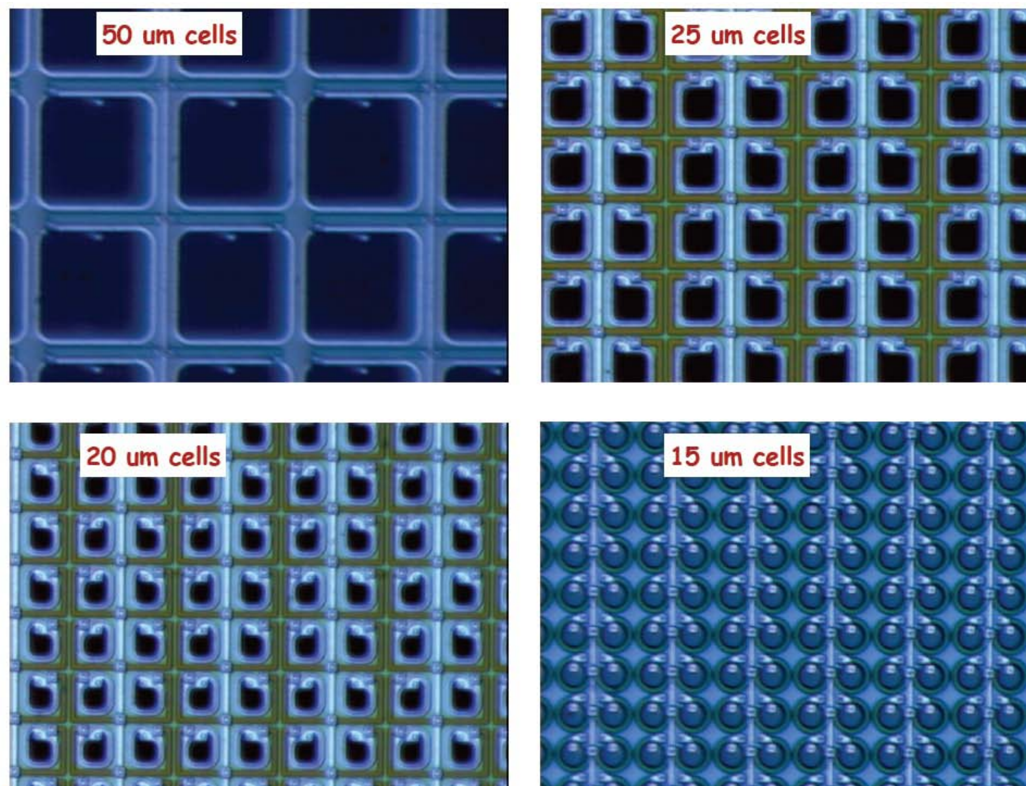
https://arxiv.org/pdf/0810.1216.pdf

Silicon Photomultiplier (SiPM) Cells

- **Typical dynamic range customization for SiPM**
  - More (small) SPADS to count more photons (50→15µm)
  - Bright crystal (LYSO, GAGG) and high photodetection efficiency (PDE) and light collection efficiency (LCE)

Currently:
Large device ~6x6mm^2
CMS MTD ~4.5 m^2 of SiPMs
(of 3x3mm^2)

Segmented Crystal ECAL:
~200 m^2 of crystal surface
(3-4 layers)
Which SiPM device?



Further Possibilities for SiPMs with High Dynamic Range and Packing Density

- **Large pixel count w/ large gain leads to current output limitations for large area devices**
  - Multiple analog outputs per device
    - Regional lumped analog sums - split output currents per region and sum (1/128, 1/32,1/8,1/2)
    - Multi-gain SPADs (5, 15, 50μm) for different cell sizes and fill factors – dynamic range built into SPAD layout
  - On-chip ADC with regional serializers
  - Commercial market for LIDAR advances is growing rapidly – many new developments expected