Segmented Crystal Calorimetry and the Next Level of Precision Particle Flow

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3rd FCC Workshop, CERN

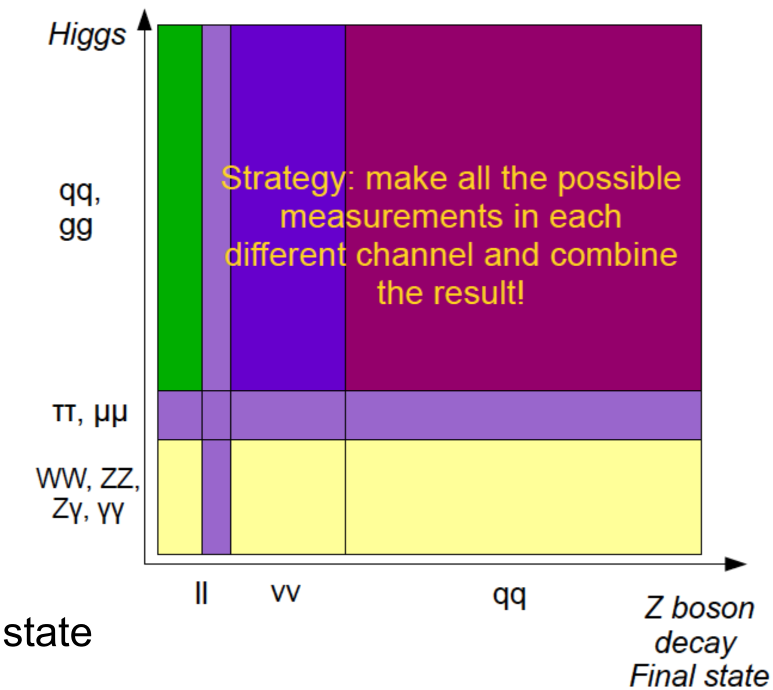
Final States of e+e- Higgs Physics @~246 GeV

- 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

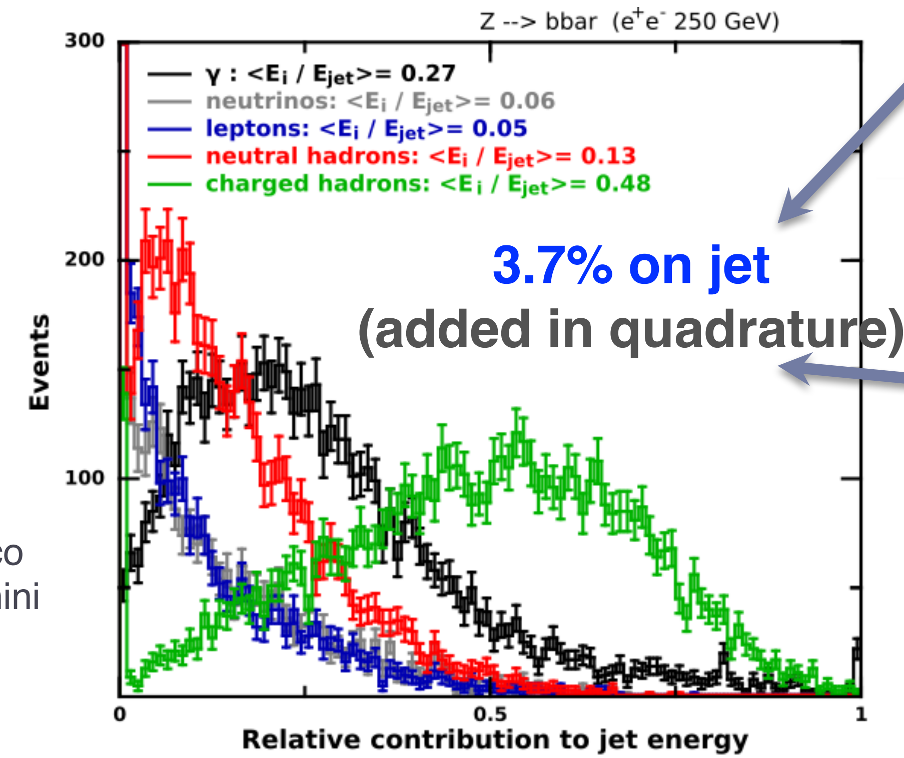


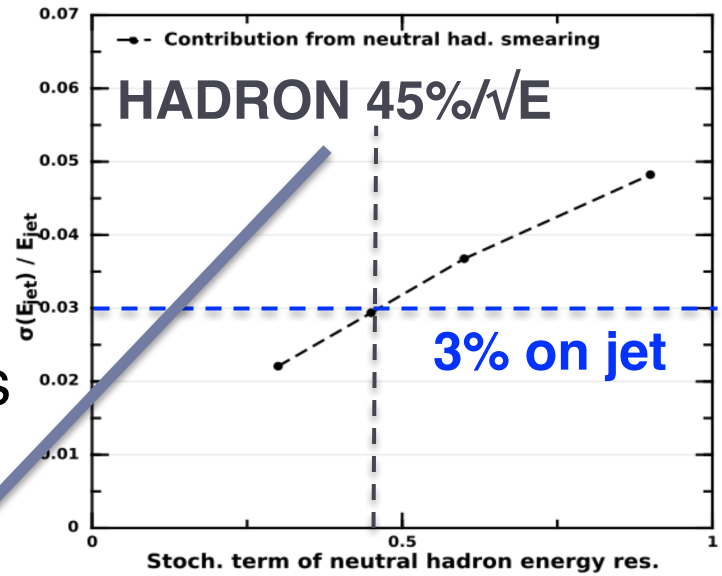
- **97%** of the SM Higgsstrahlung Signal has Jets in the final state
- **1/3** has only 2 jets: include all the SM Higgs decay modes
- **2/3** need color-singlet identification: grouping the hadronic final state particles into color-singlets
- Jet is important for EW measurements & jet clustering is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

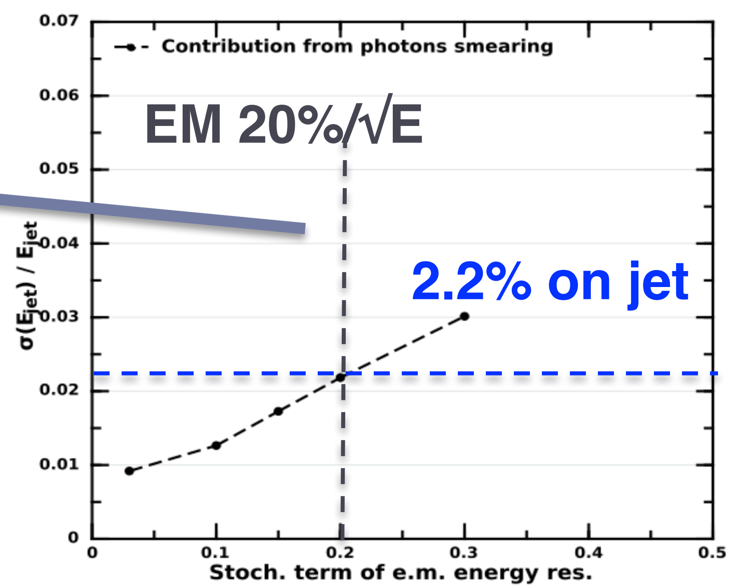
→ Include here the unexpected rare decays – be prepared

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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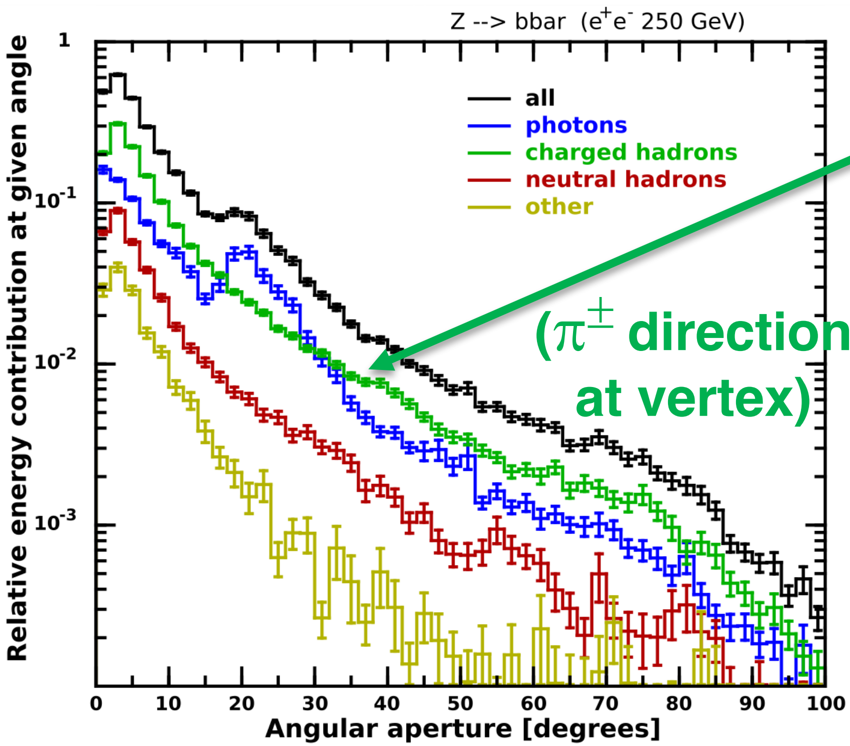
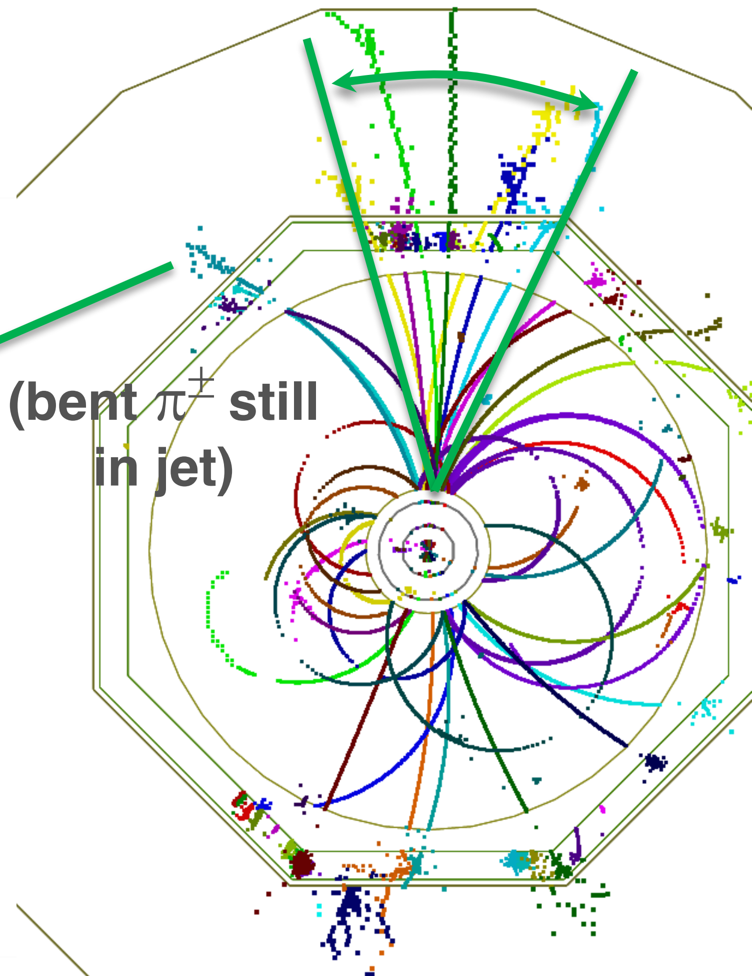
Some Quick Comments on PFA

- **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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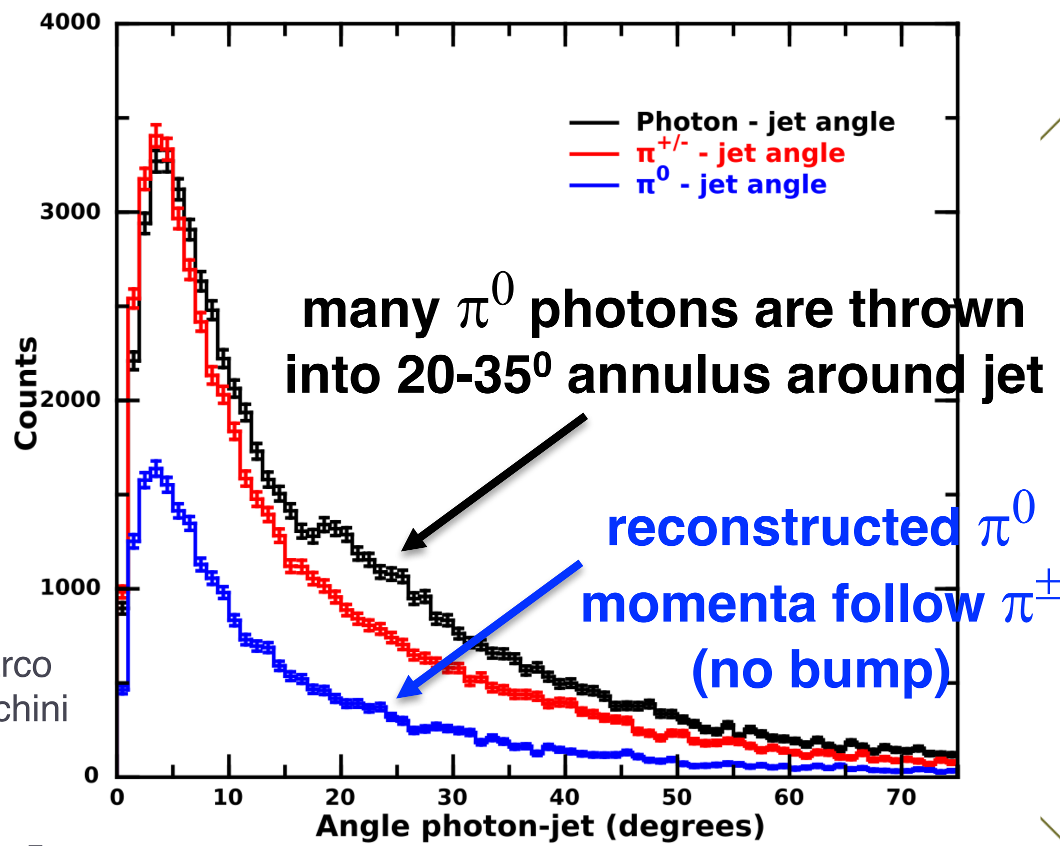
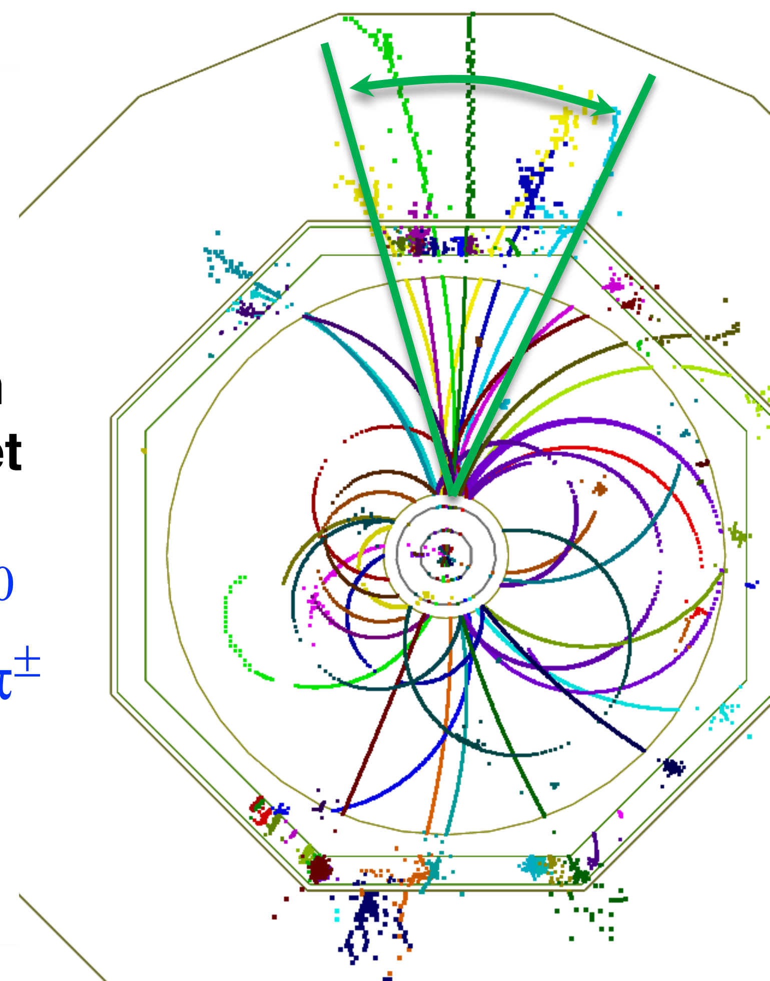
Some Quick Comments on PFA

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

Slide borrowed from Marcel Vos





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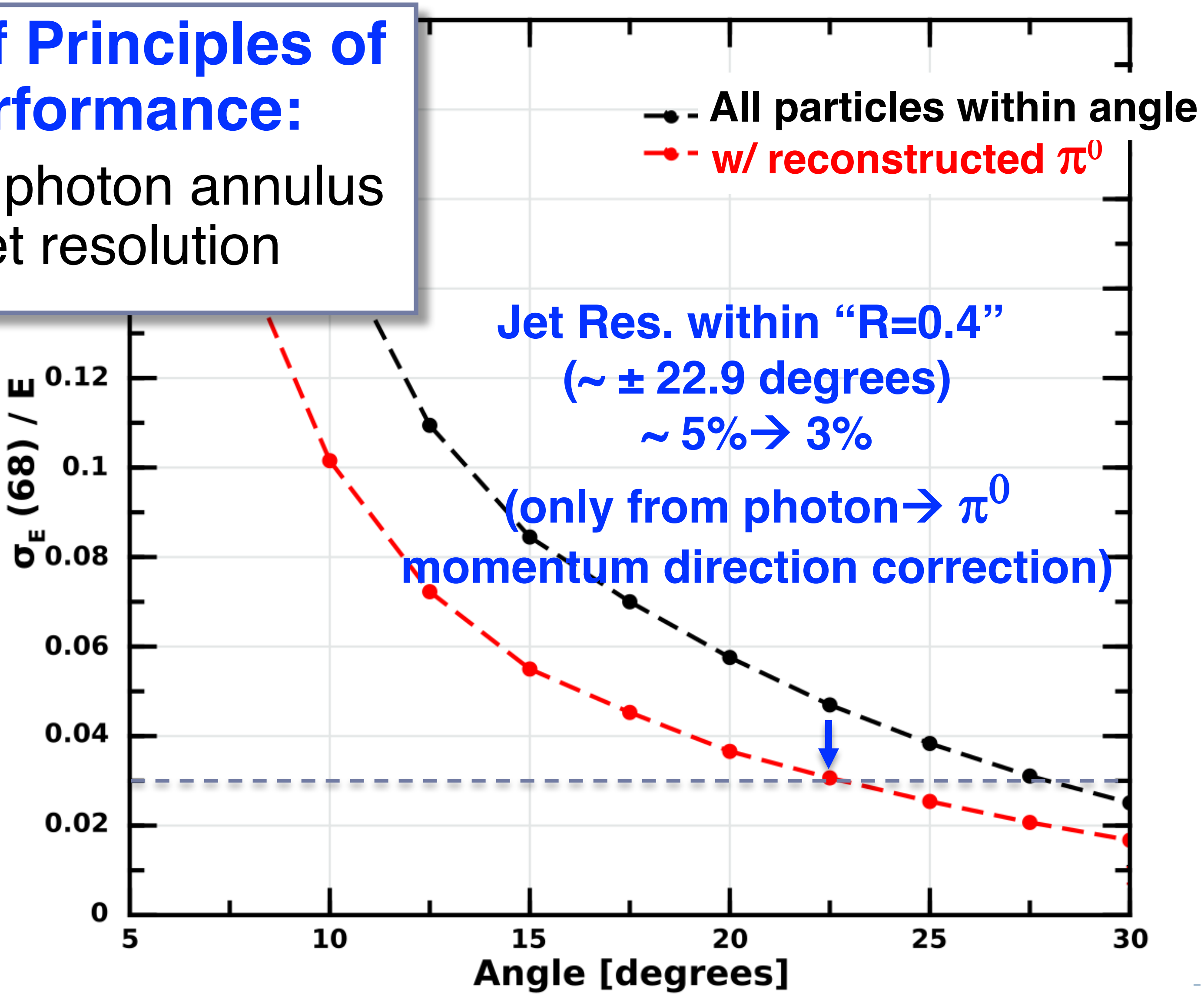
Some Quick Comments on PFA

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

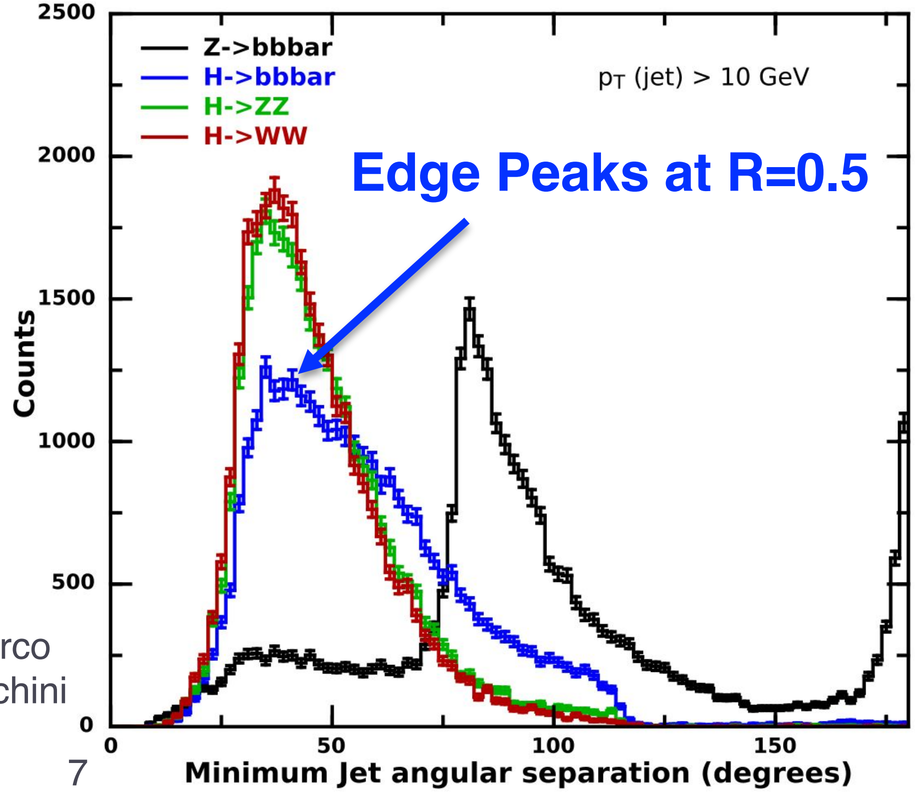


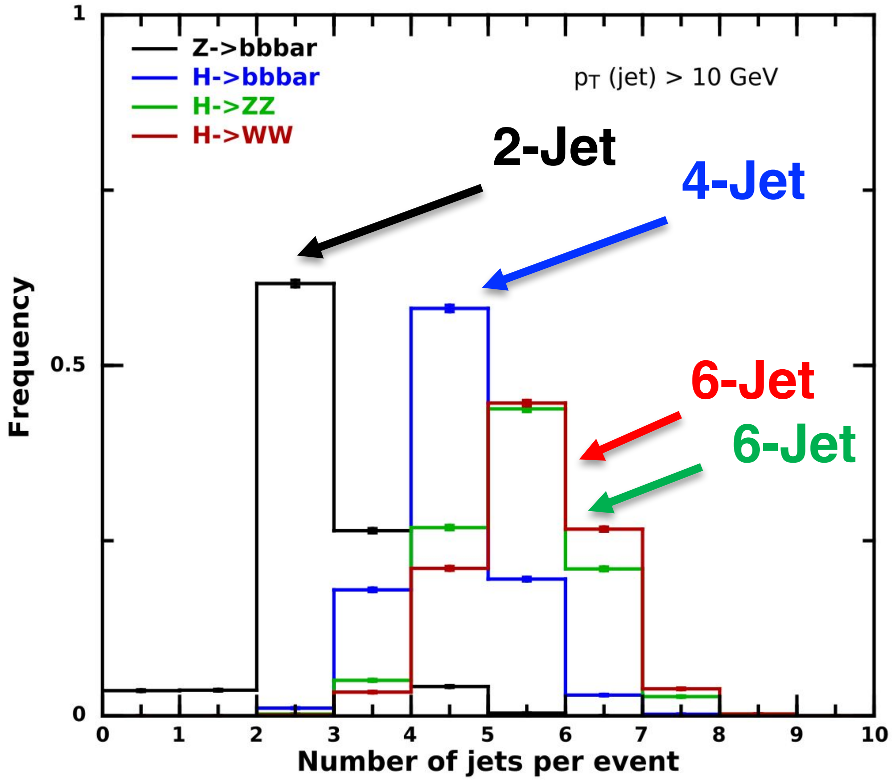
Jet Resolution based on limited integral of particles (out to specified angle) (photon annulus integrated out)

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

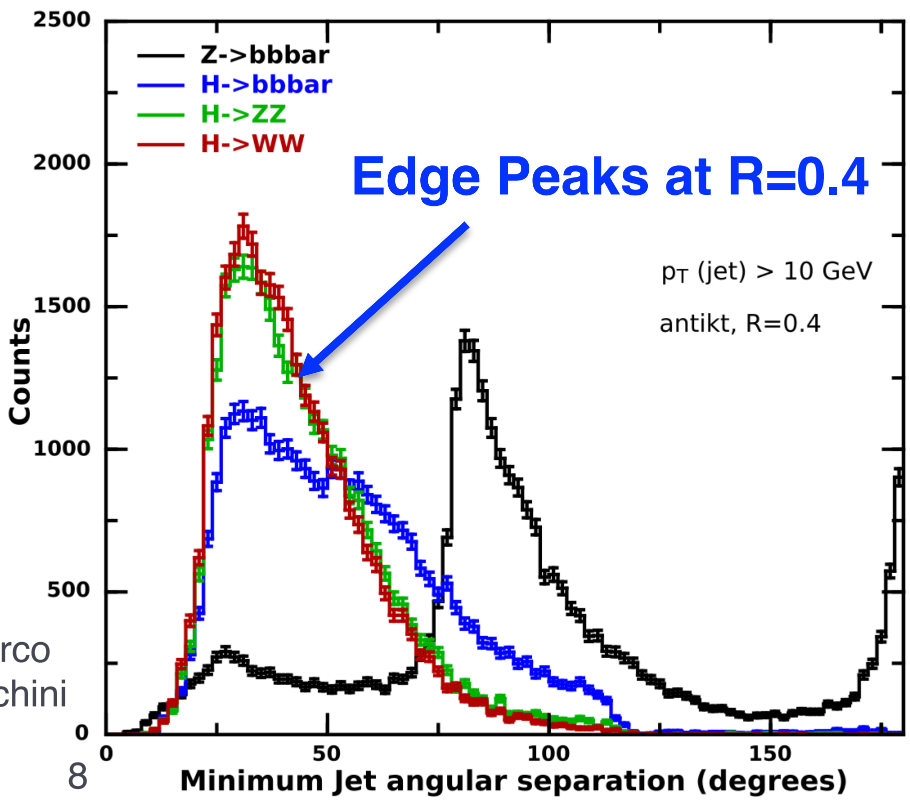


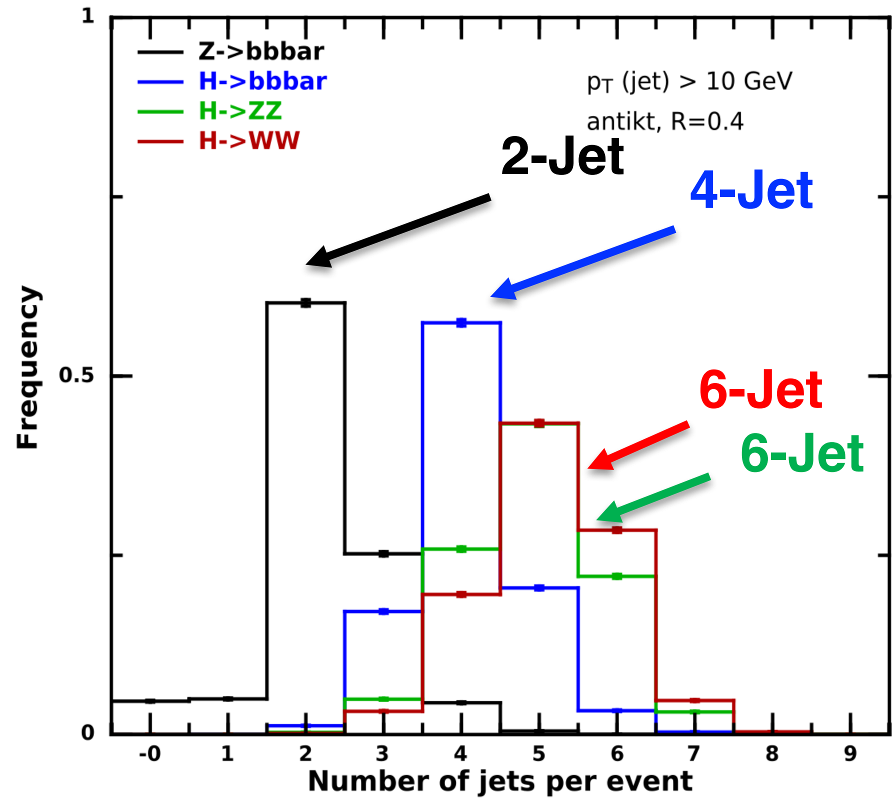


Some Quick Comments on PFA

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

Jet Algo: anti-KT, E-mode, R=0.4, min pT=10 GeV



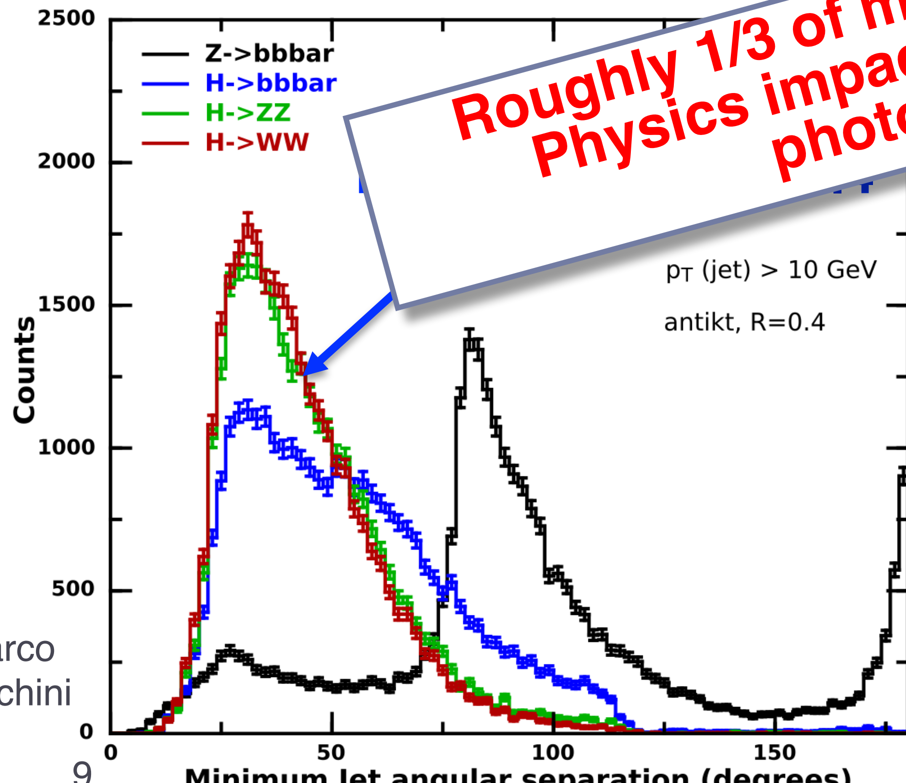


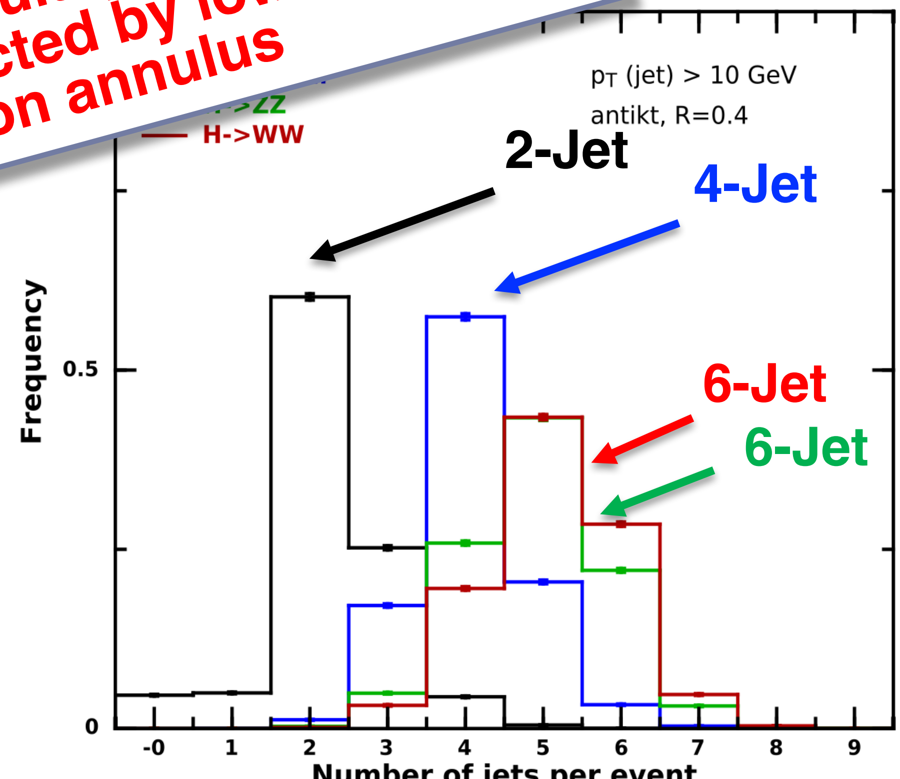
Some Quick Comments on PFA

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

Jet Algo:
anti-KT, E-mode, R=0.4,
min pT ... eV

Roughly 1/3 of multi-jet (2/3 of) Higgs Physics impacted by low energy photon annulus

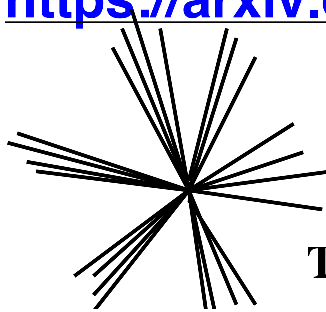




From 20 Years Ago… min $\theta_{\text{N-Jet}}$ matters!

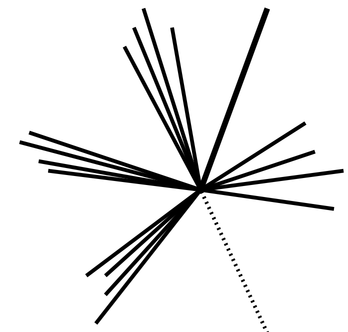
- **J. Mans, “Search for a Higgs Boson Decaying to Massive Vector Boson Pairs at LEP.” https://arxiv.org/pdf/hep-ex/0204029.pdf**

The qqqqqq Channel

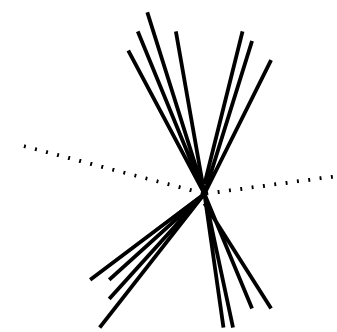


Variable	*Description*	*Trend*
E^{max}_{jet6}	Energy of the most energetic jet from the 6 jet fit.	Signal events should have six reasonably equal jets, while many backgrounds have several high energy jets and several very low energy gluon jets.
E^{min}_{jet6}	Energy of the least energetic jet from the 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

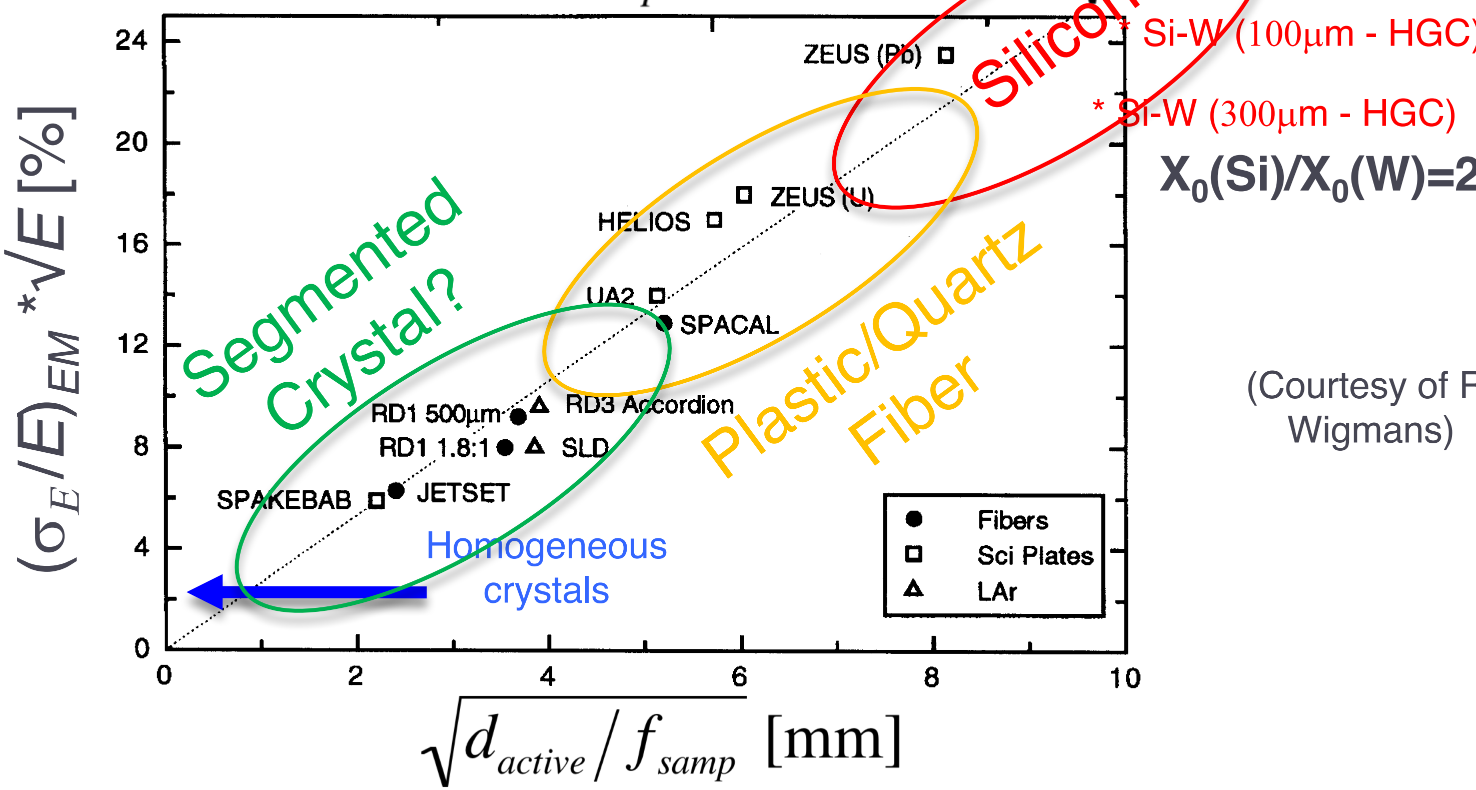


Variable	*Description*	*Trend*
E^{max}_{4j}	Energy of the most energetic jet from a fit to four jets.	Signal events tend to have two medium-energy and two low-energy jets, while backgrounds will tend to have higher E^{max} values and lower E^{min} values.
E^{min}_{4j}	Energy of the least energetic jet 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:**

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

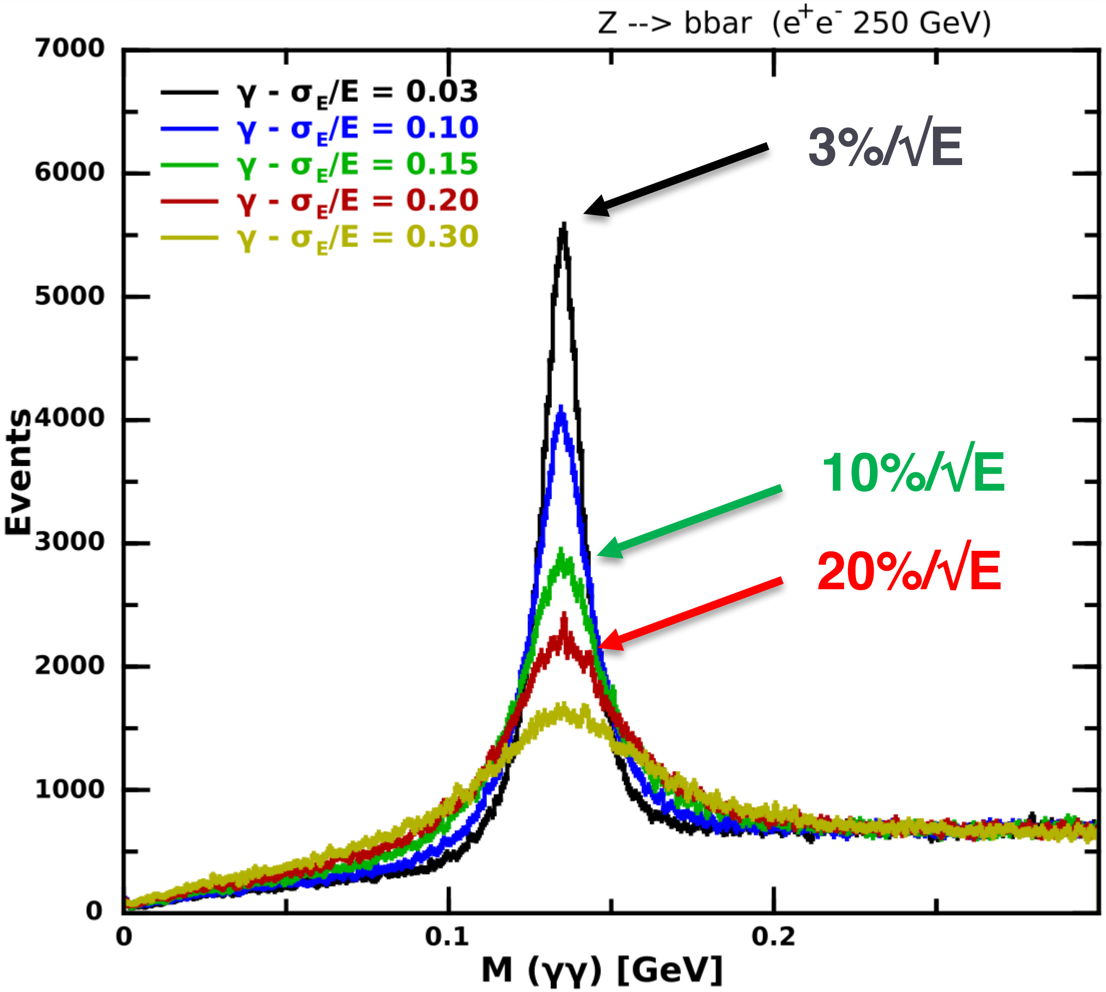


$X_0(Si)/X_0(W)=27$

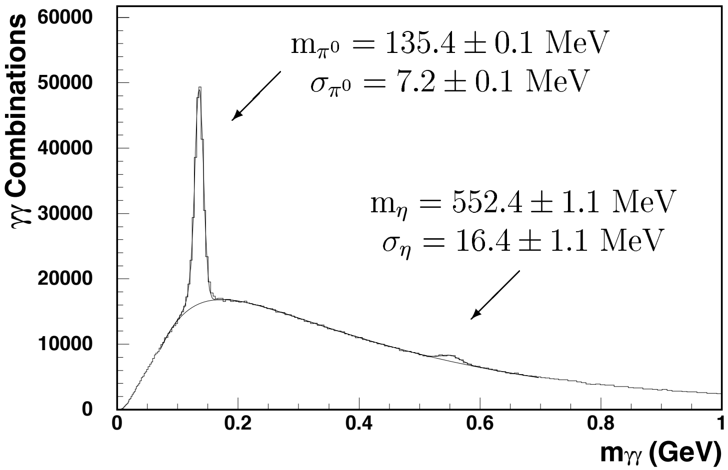
(Courtesy of R. Wigmans)

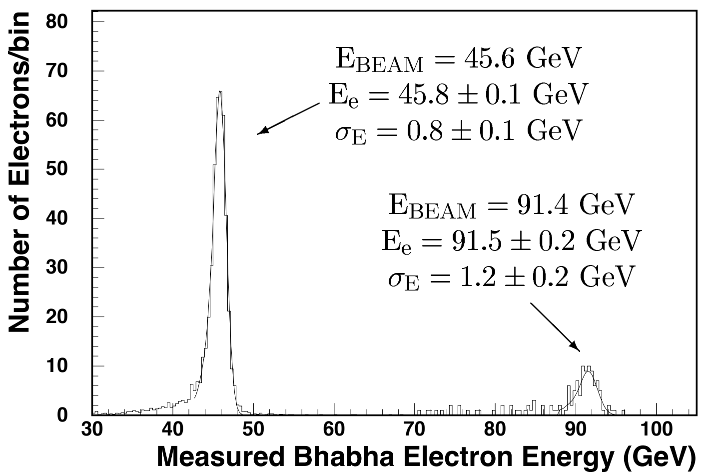
π^0 Resolution and Reconstruction Efficiency

- **Peak Height Matters!**



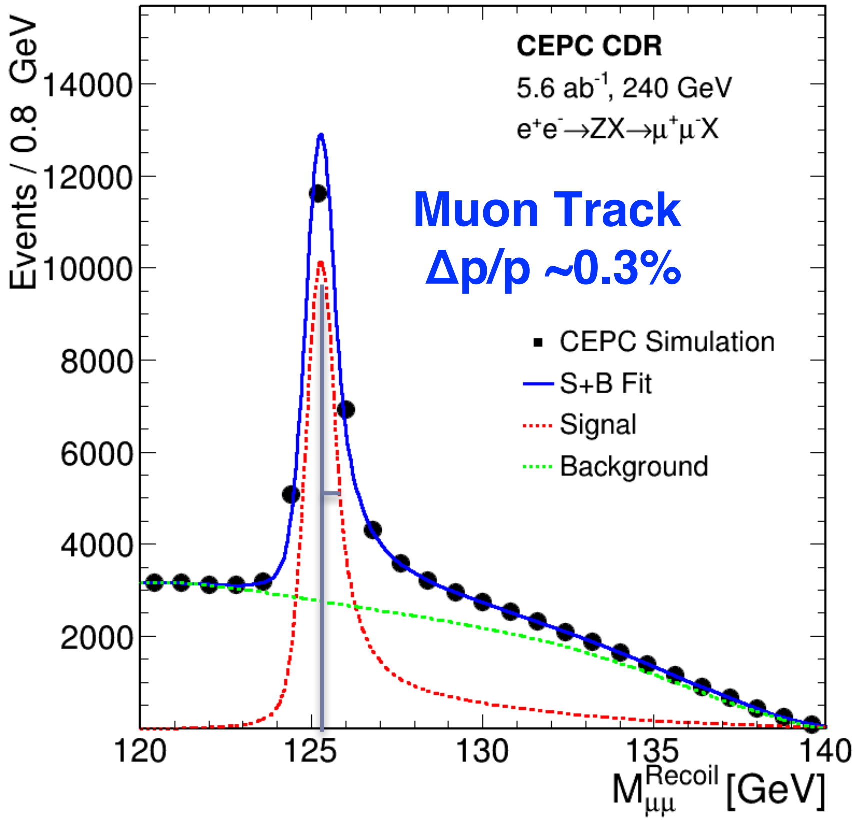
L3 Data (1997)



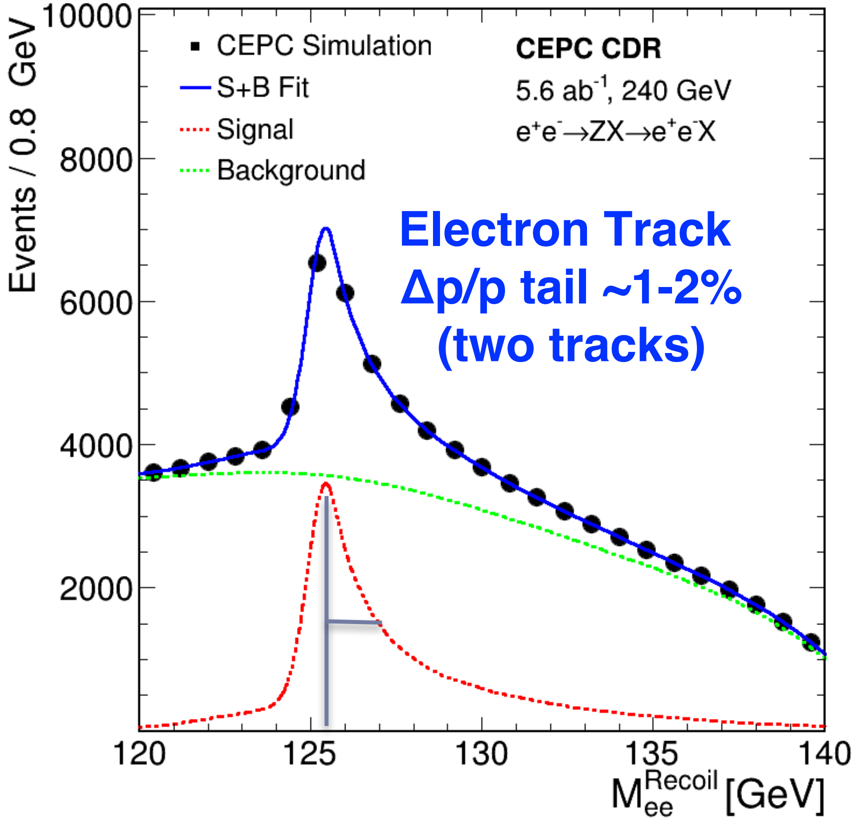


Recoil Analysis – Single Most Important Unbiased Sample of Higgs Boson Decays

- **$Z \rightarrow \mu^+\mu^-$ Recoil**



- **$Z \rightarrow e^+e^-$ Recoil**



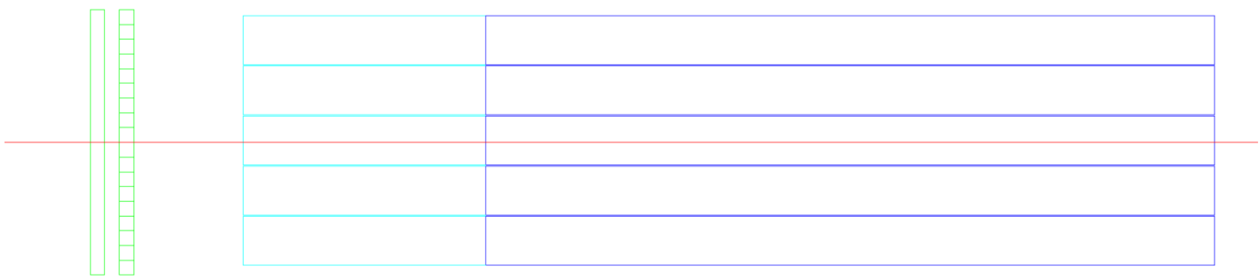
Example from CDR reference design
(electron tracks with no Brem. recovery)

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

Segmented Crystal Calorimeter Module

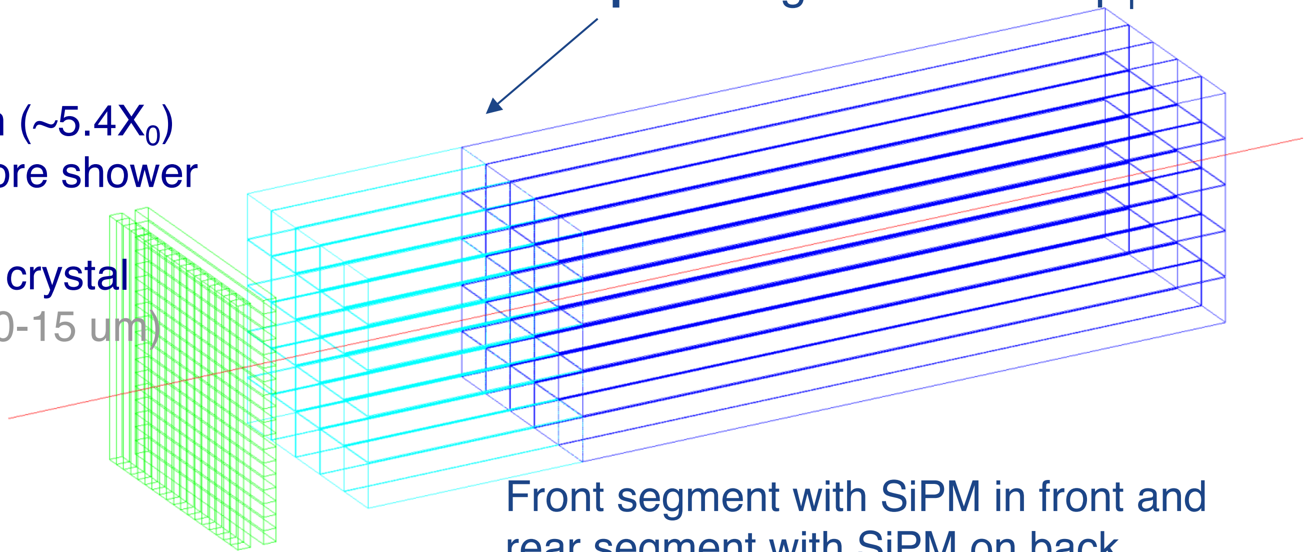
- **Timing layer:**
  - LYSO:Ce crystals
  - SiPMs
  - 3x3x54 mm³ active cell
  - 3x3 mm² SiPMs (15-25 um)

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



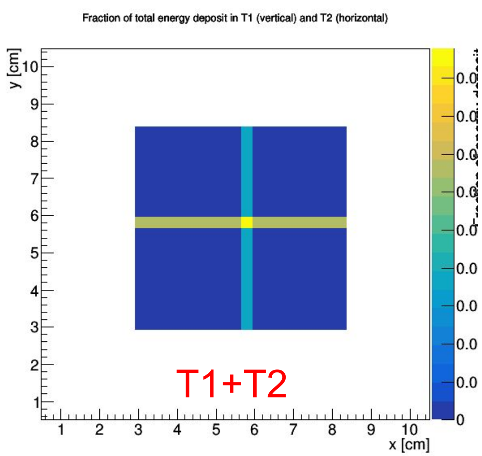
~3%/sqrt(E) (+) 1%
~30 ps timing achieved for p_T>40GeV

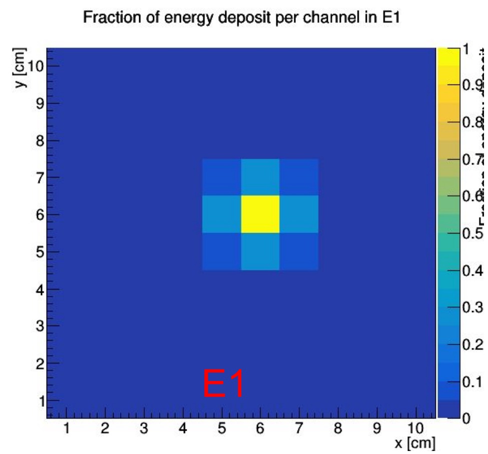
- **ECAL layer:**
  - PbWO crystals
  - front segment 5 cm (~5.4X_0)
  - rear segment for core shower
  - (15 cm ~16.3X_0)
  - 10x10x200 mm³ of crystal
  - 5x5 mm² SiPMs (10-15 um)

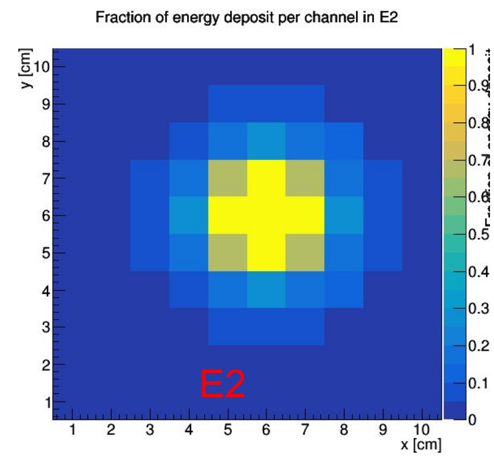


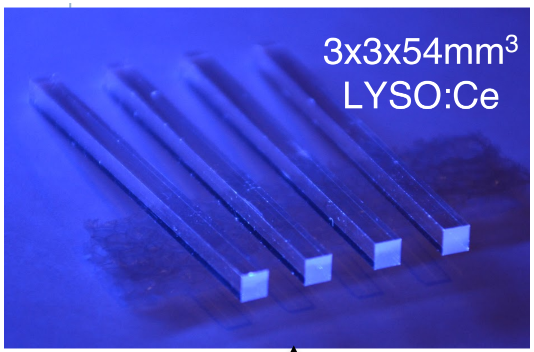
Front segment with SiPM in front and
rear segment with SiPM on back
→ Avoids dead material at shower max

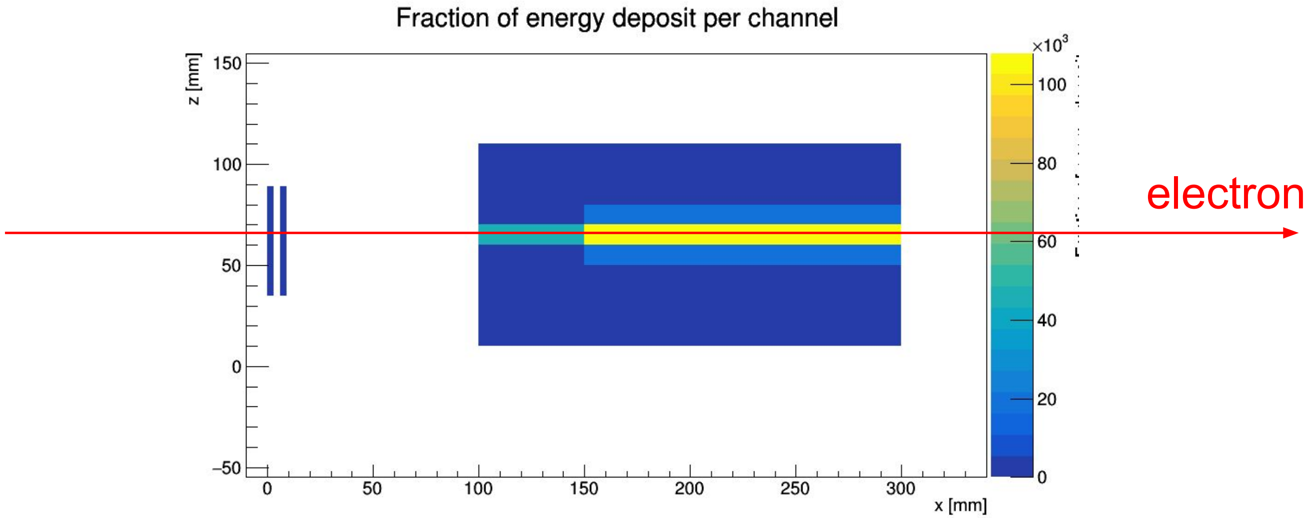
Single EM Shower (High Stat)









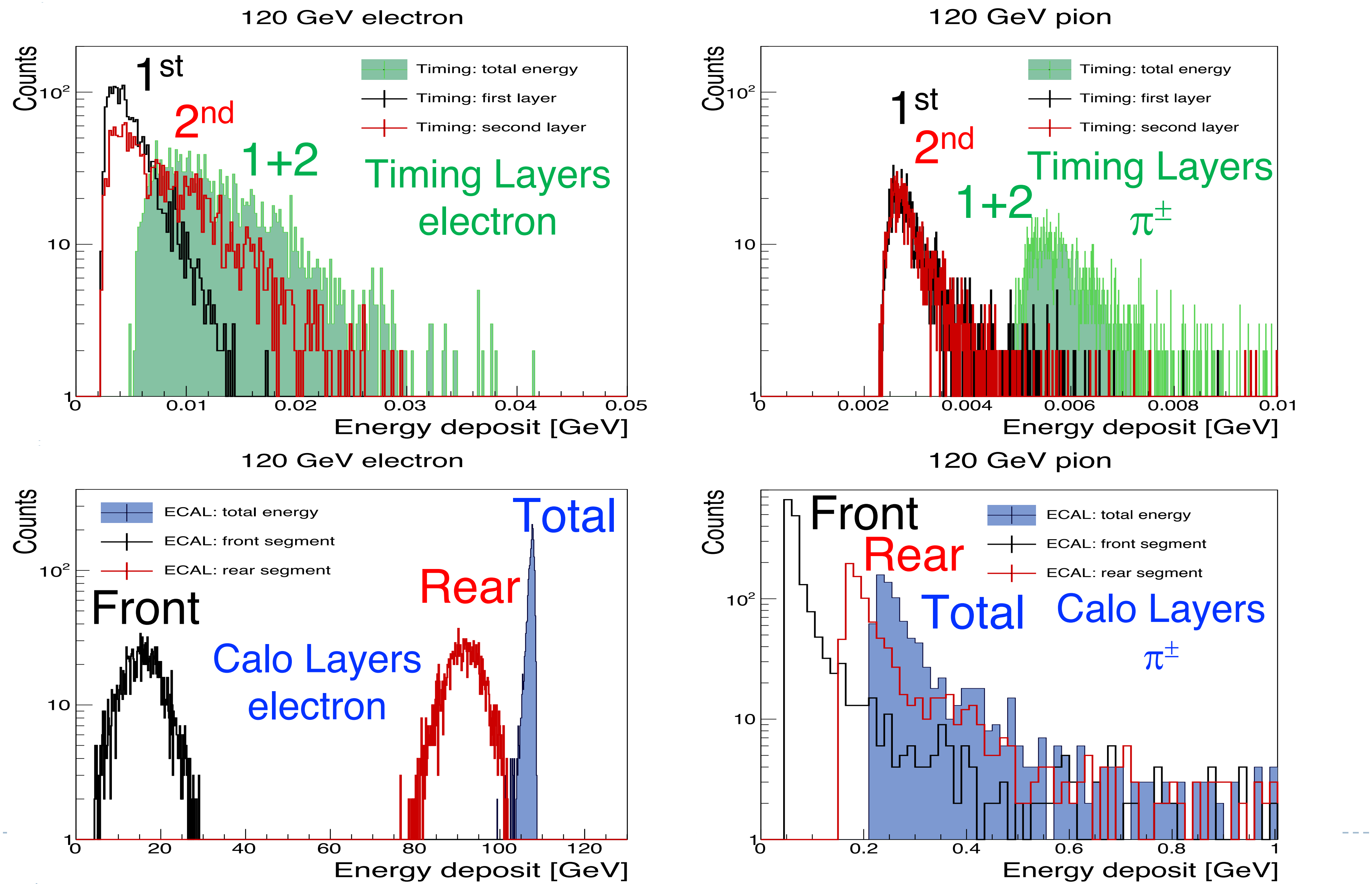


3mm (strip)

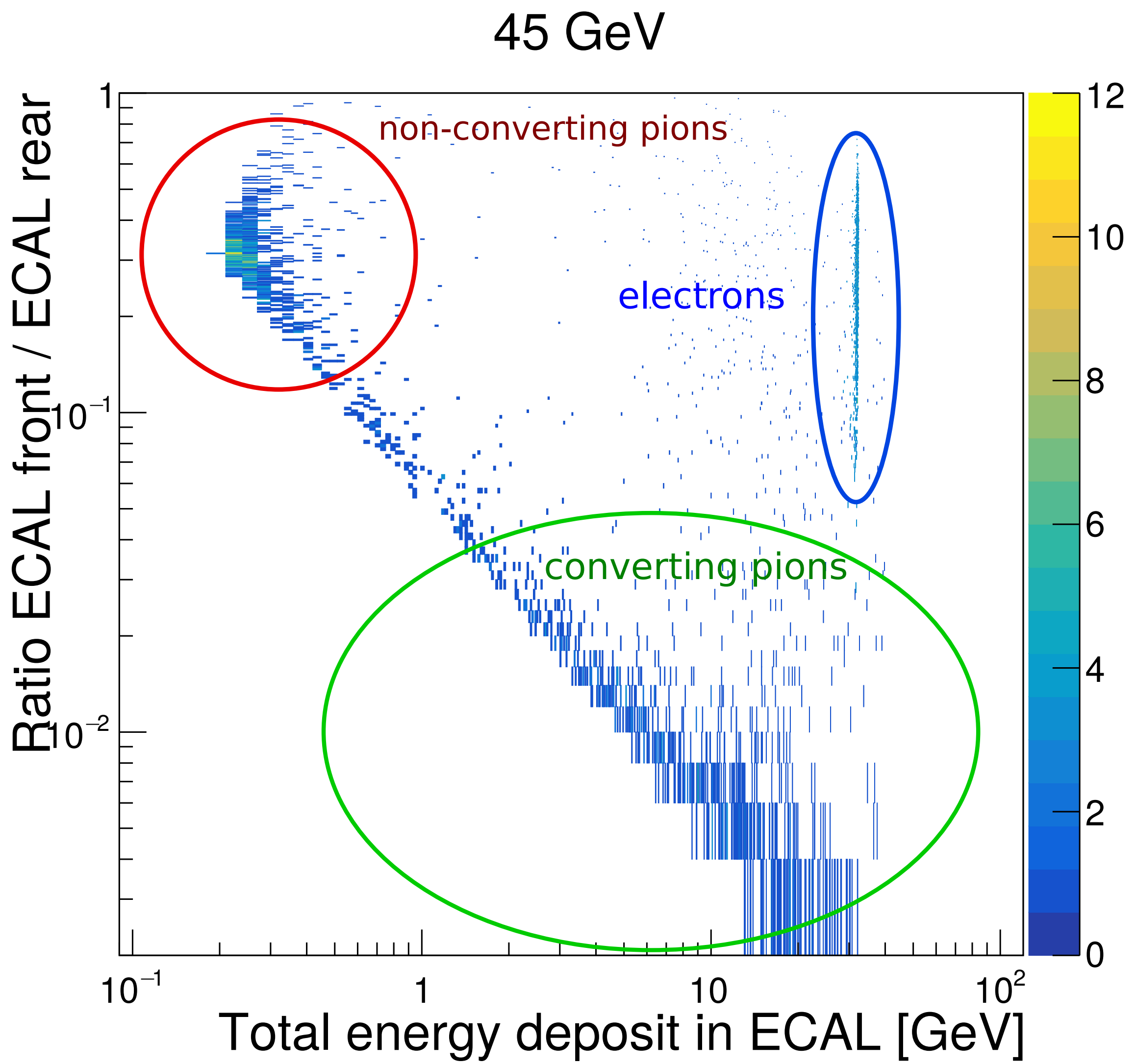
High Granularity

1x1 cm^2

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



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



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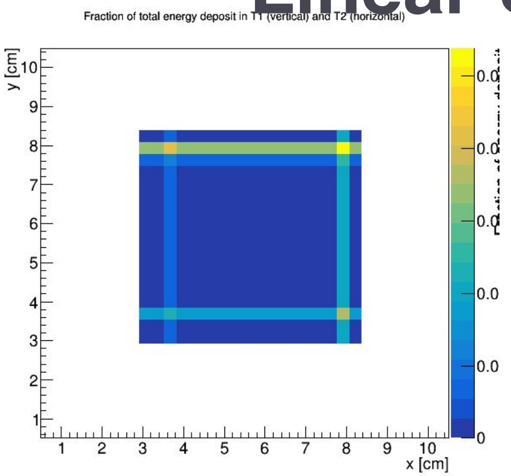
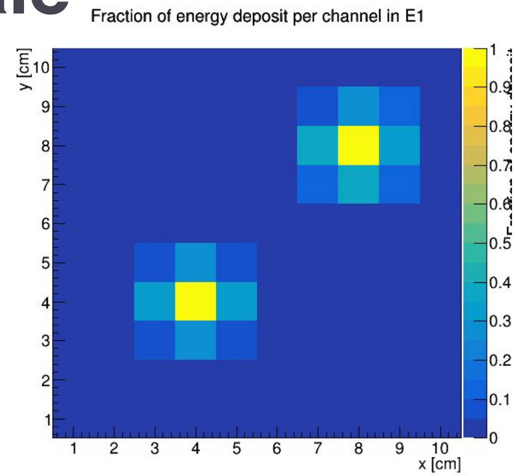
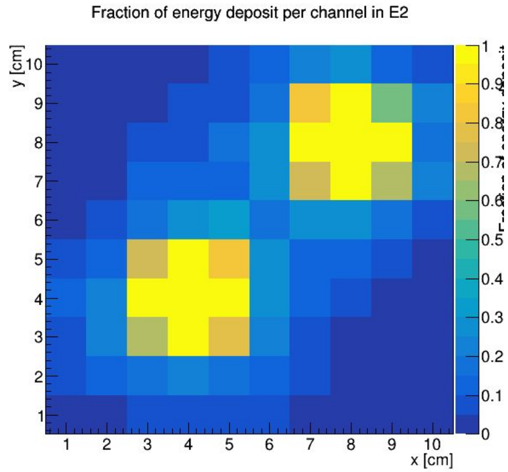
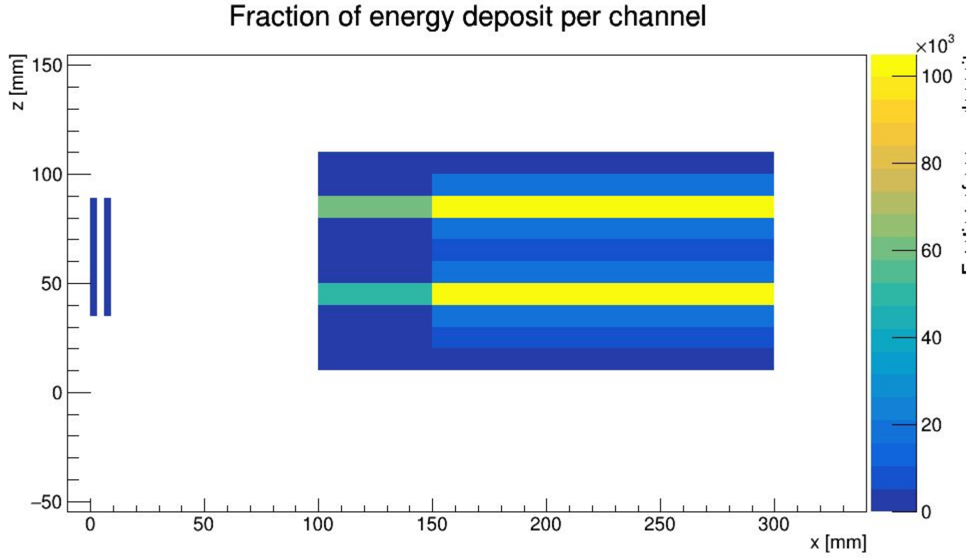
Pair of EM Showers (High Stat)

Linear-Scale



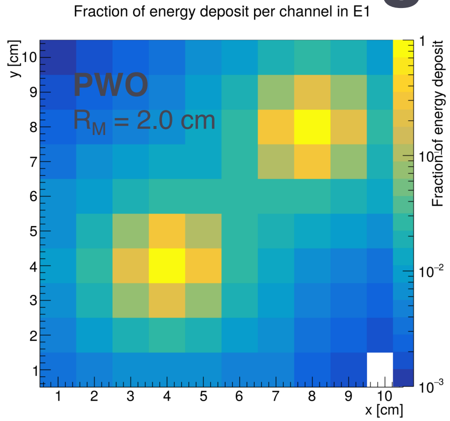




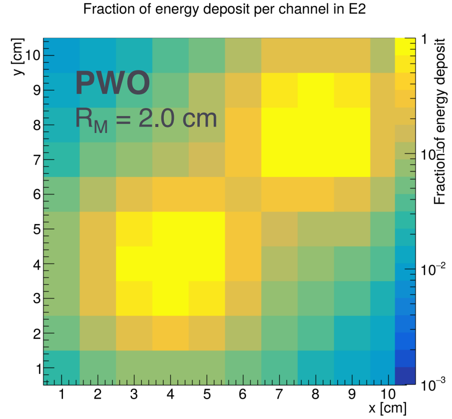


Electron Shower Profiles and Brem. Losses

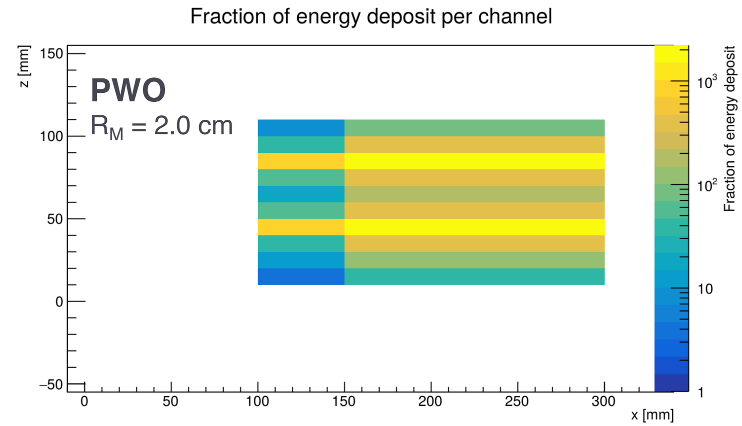
Log-Scale



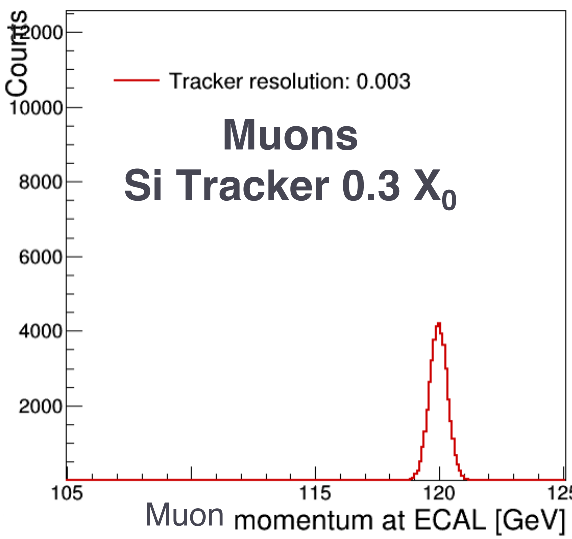
Cell Size: 1 cm²
Front Xtals

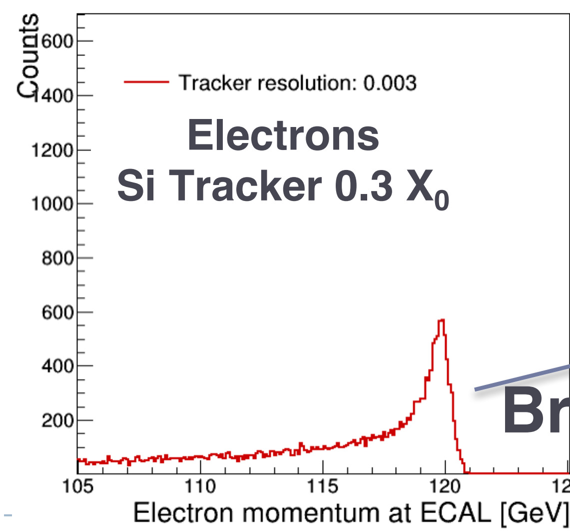


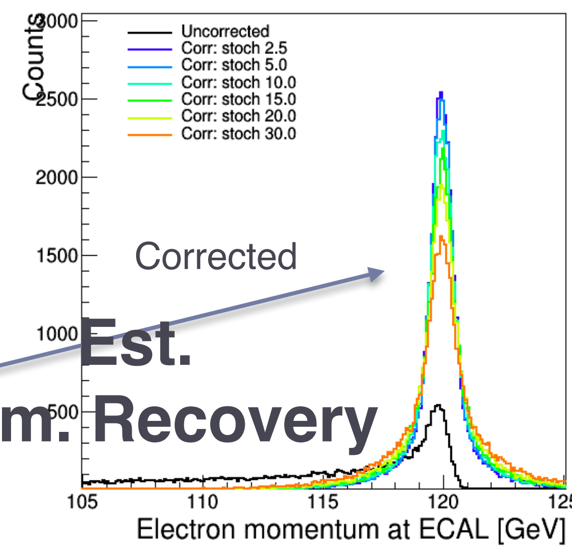
Cell Size: 1 cm²
Rear Xtals



Size View

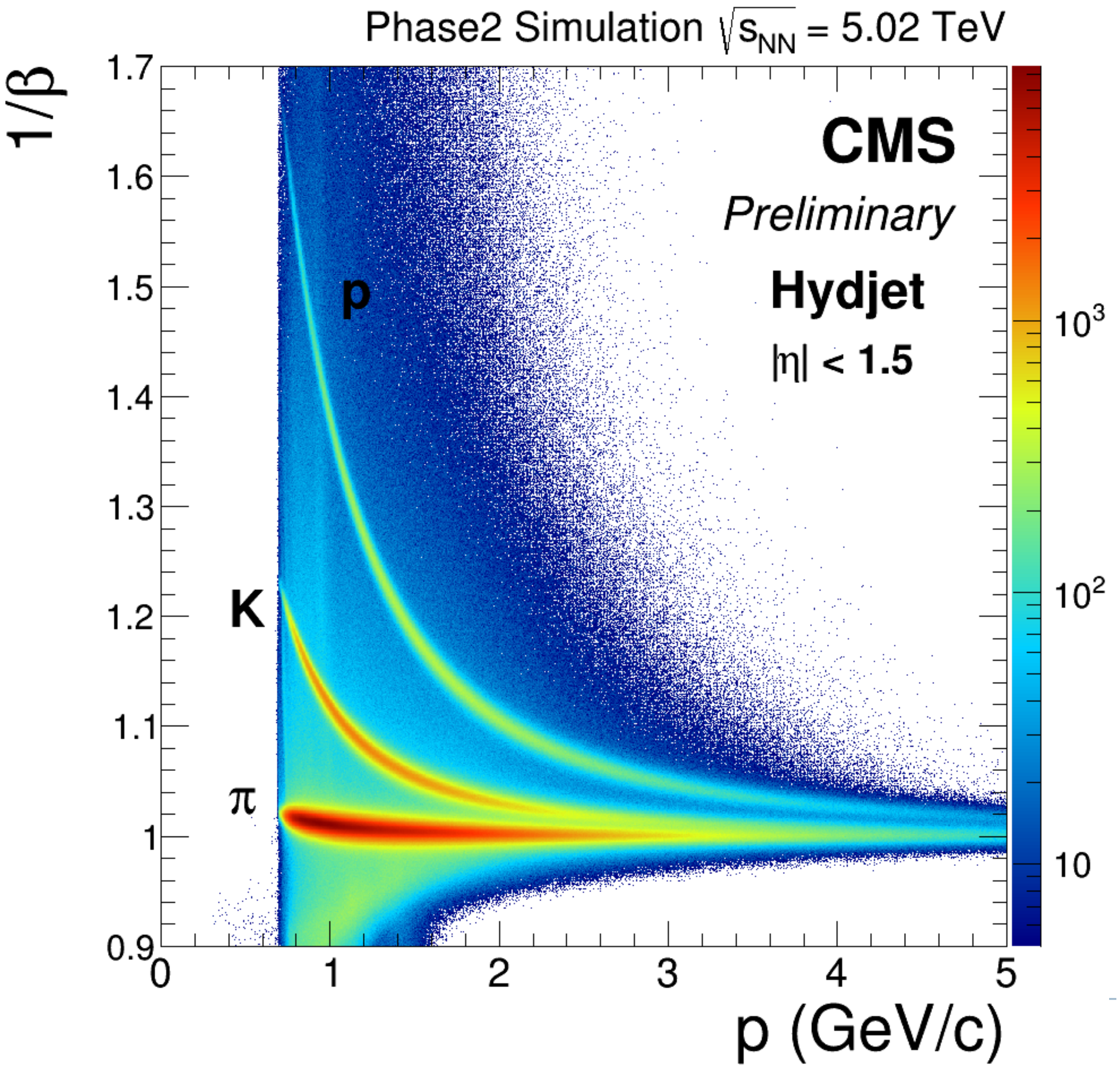






Est. Brem. Recovery

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

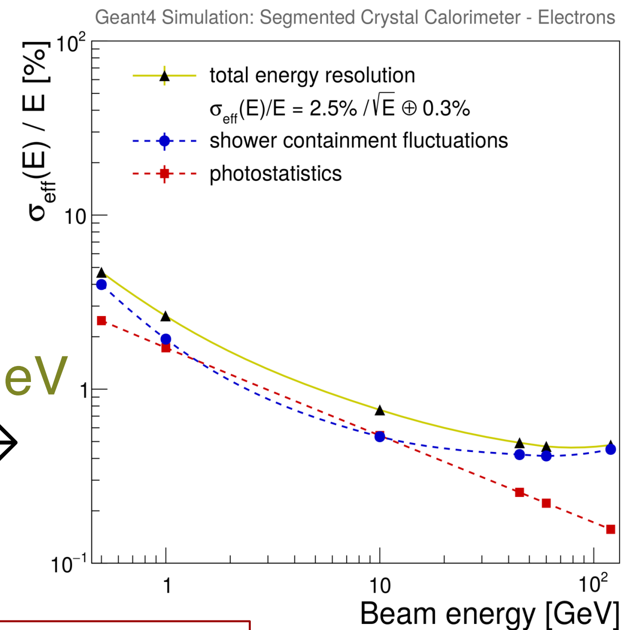


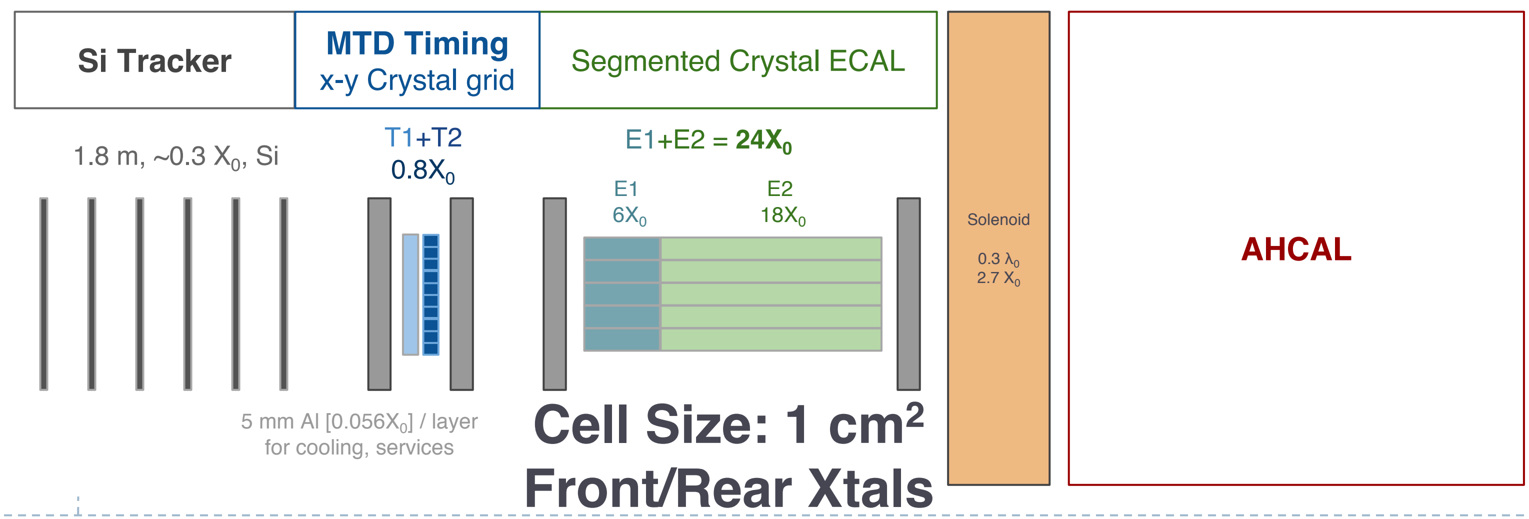
Single Layer (30 ps)

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

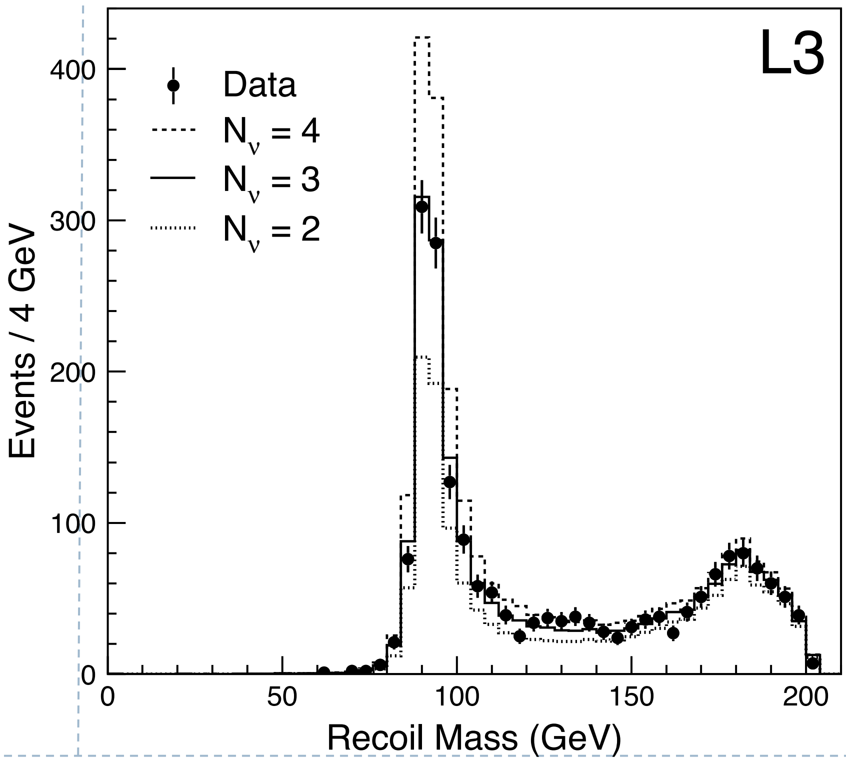
Summary

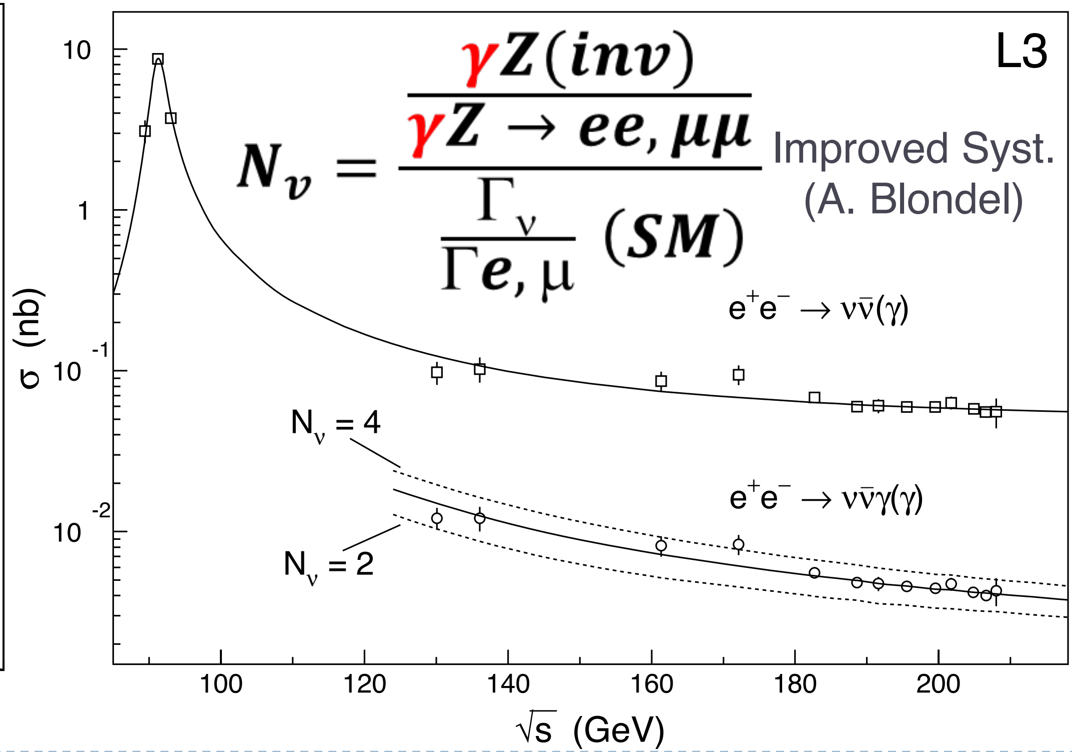
- **Roughly 1/3 of multi-jet (2/3 of) Higgs Physics impacted by low energy photon annulus around jets**
- **Great time to apply new approaches to benchmarking calorimeter performance**
  - Single particle test beam resolutions don't capture the complexity of the calorimeter function
  - Di-jet (hemispherical) resolutions are a good measurement of performance, but we rarely study isolated di-jet events
  - Deeper, more quantitative assessment of PFA is welcome
    - What fraction of particle per particle type ($\pi^{\pm}$ at vertex, reco π^{0}) and per momentum range are correctly identified per event
    - What are the operating points for physics and how can we rank/order different detector concepts by PFA and measures directly applicable to precision EW and Higgs Physics.
- **Segmented Crystal Detectors are impressive**
  - Incorporating a high res. crystal EM w/ strong PFA performance would be **IDEA**L

Additional slides

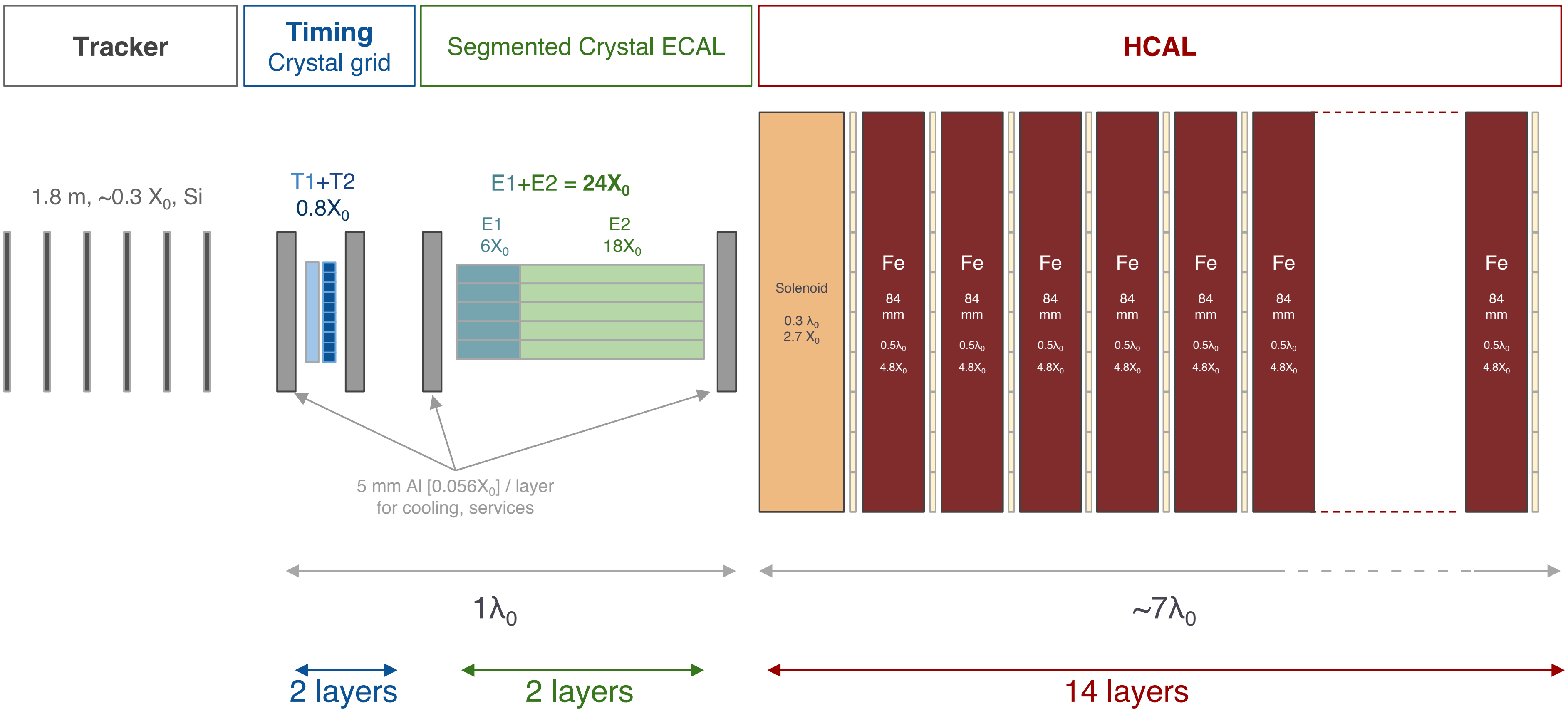
EM Resolution and Photon Counting

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

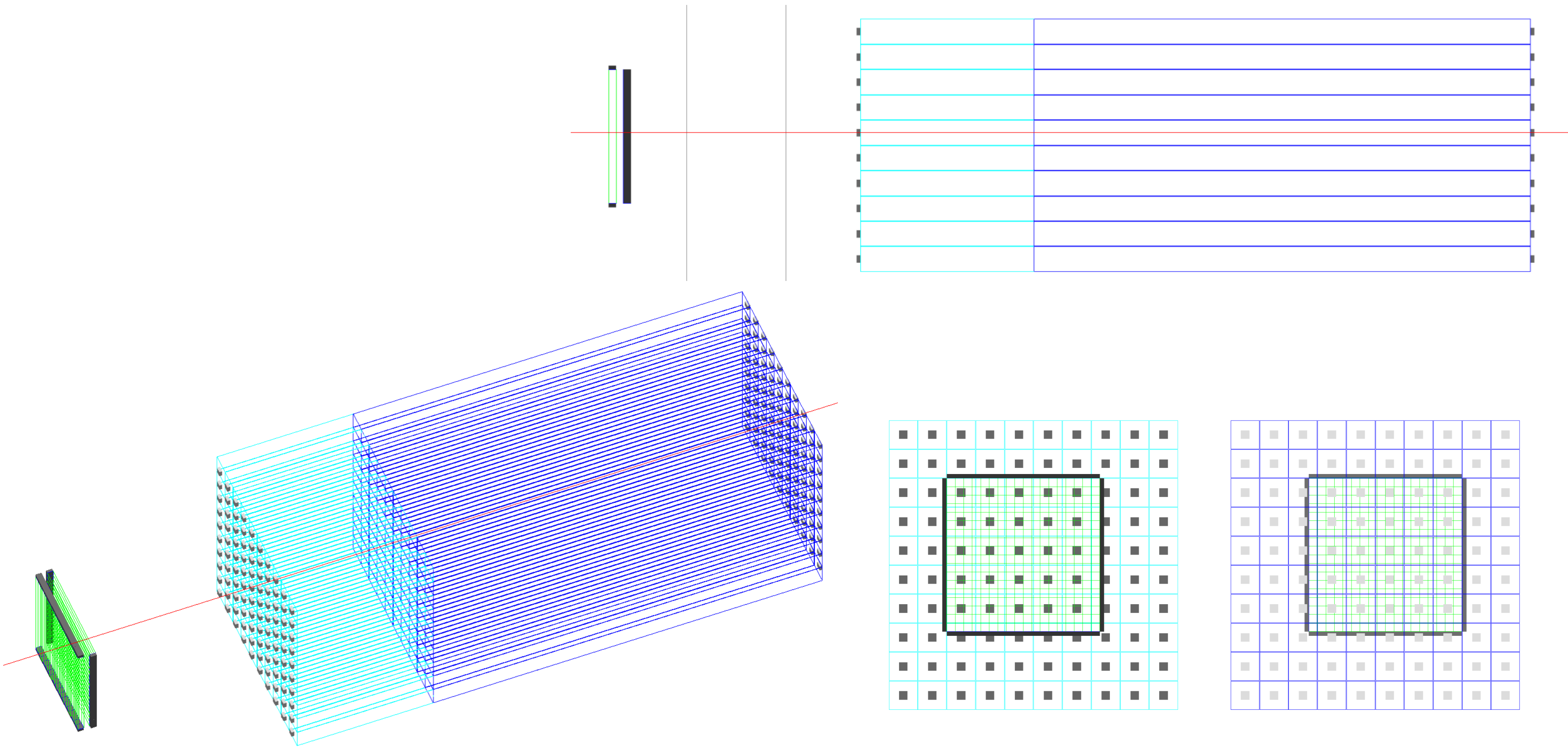




Simulated Detector Geometry

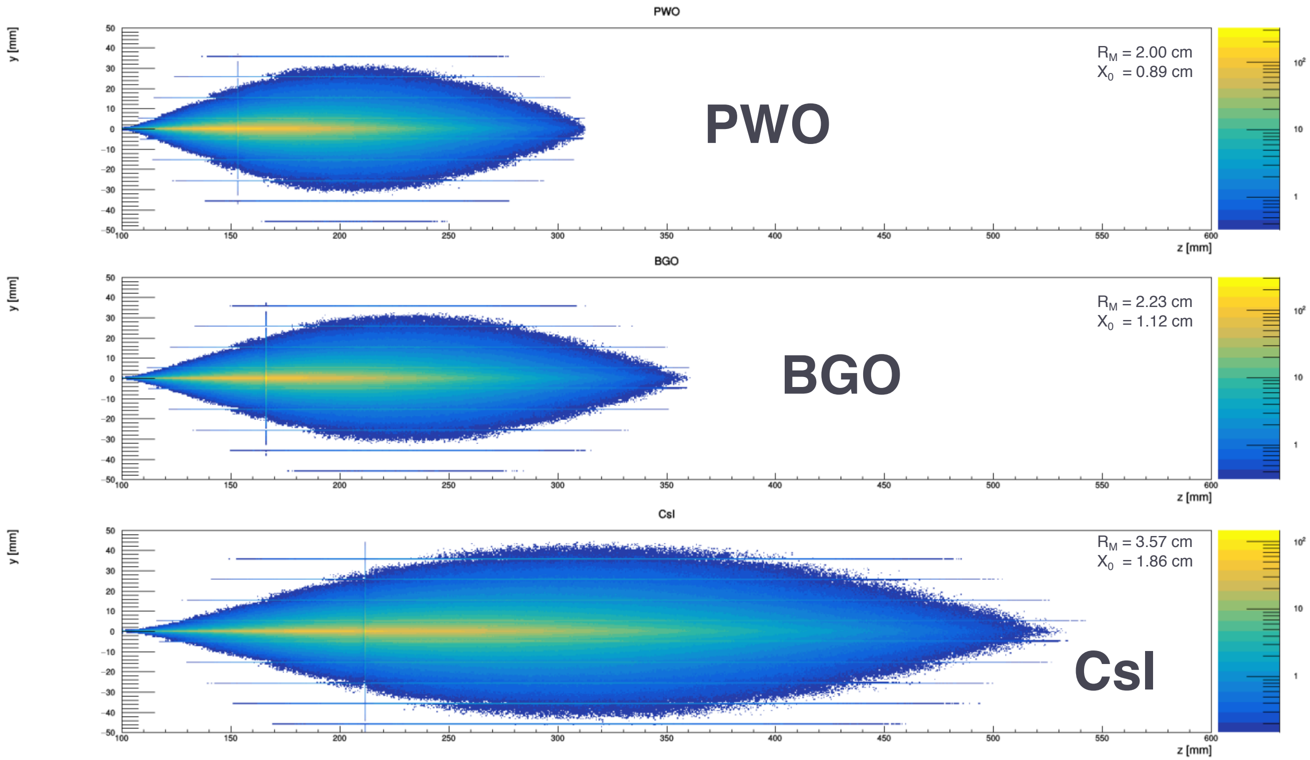


GEANT4 Views



Optimization of Crystal Segmentation

Smaller Moliere radius in front segment
→ better shower separation



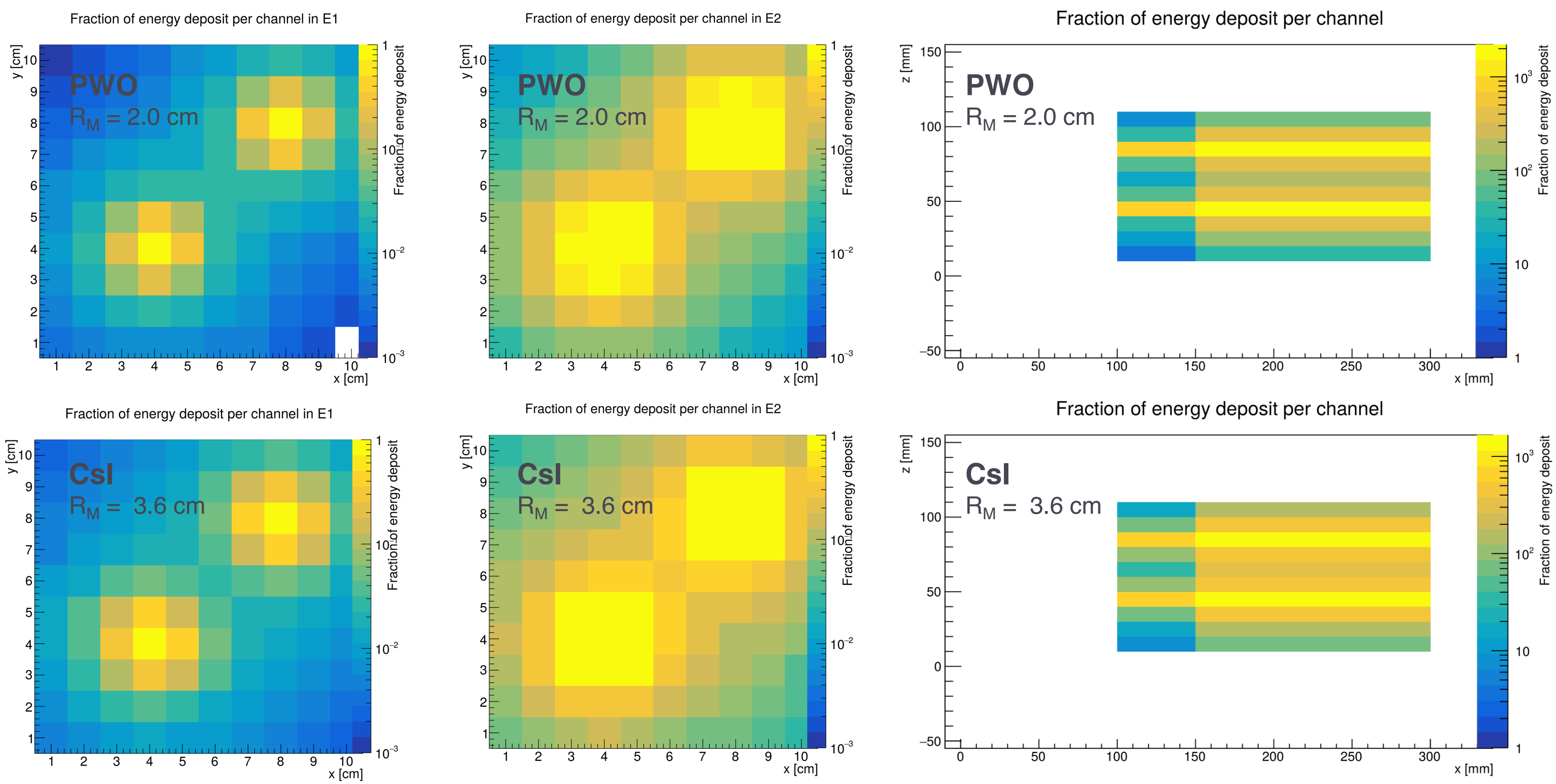
45 GeV electrons

$X_0^{TRK} = 0.3$

ECAL length: 24 X_0

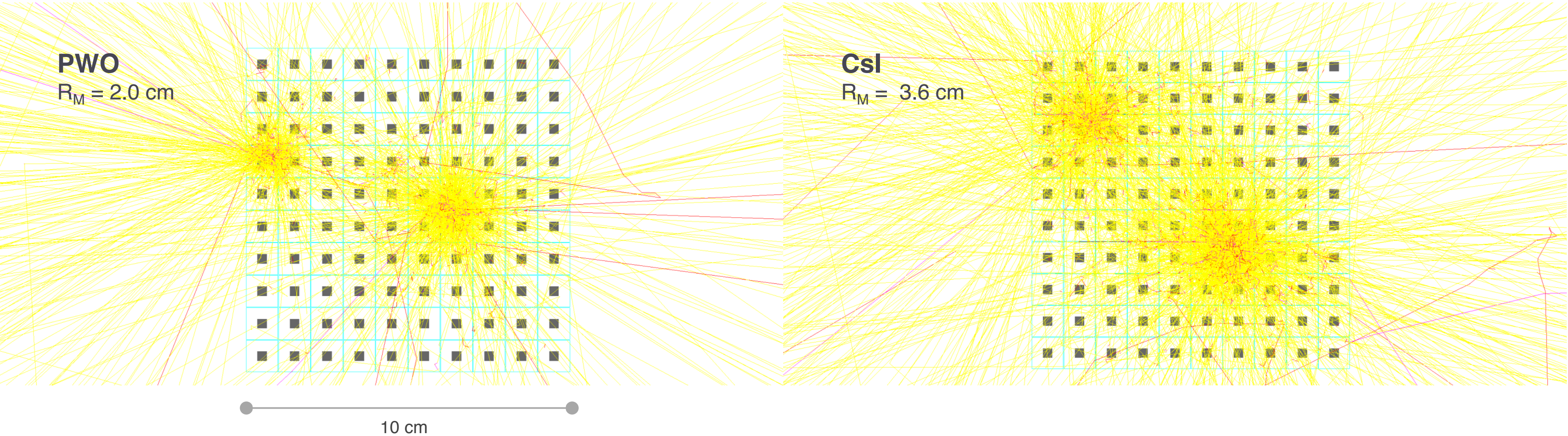
Module width: 10 cm

Pair of 45 GeV Electron Showers



10 GeV π^0 Photon Separation

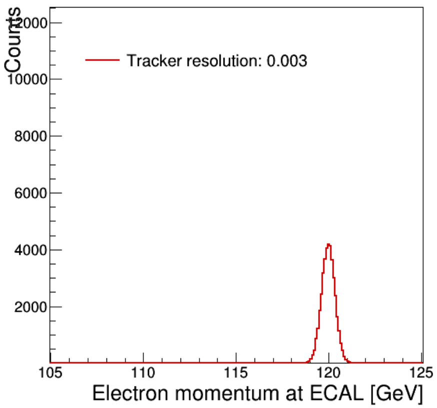
More practical example (front & rear compartments):



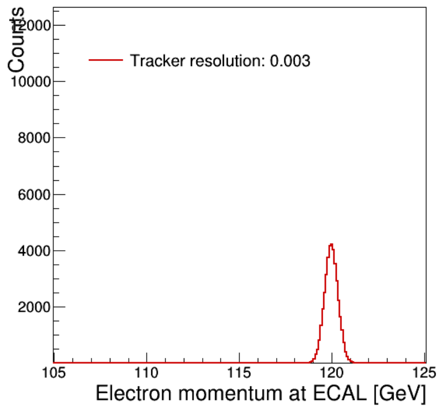
Muons vs. Electron w/ Tracker Material

Muons:

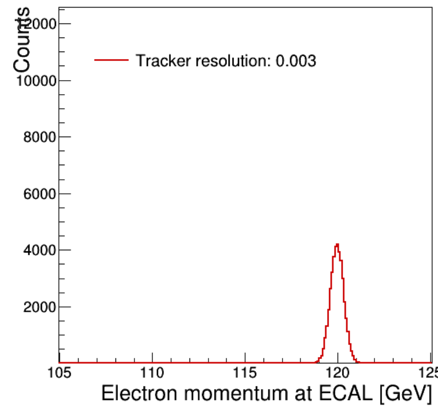
0.1 X_0



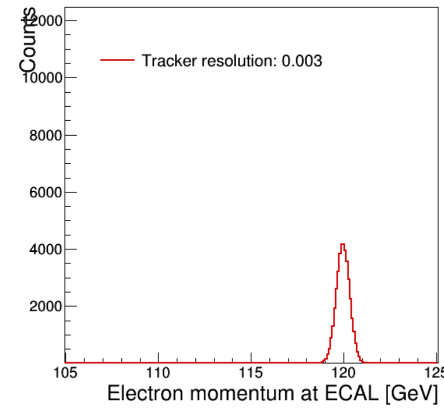
0.2 X_0



0.3 X_0

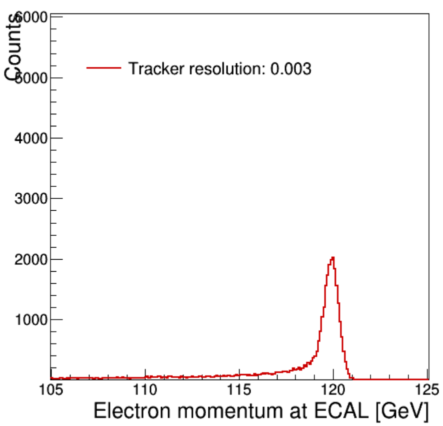


0.4 X_0

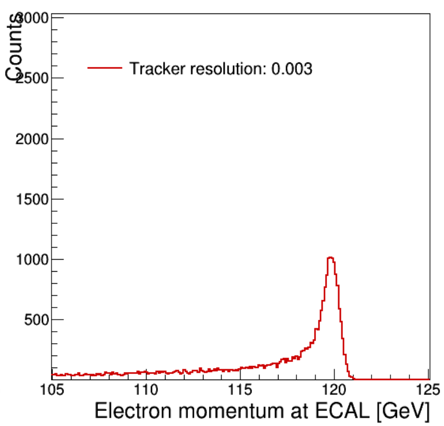


Electrons:

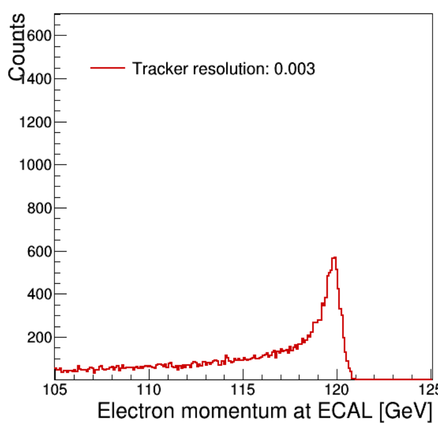
0.1 X_0



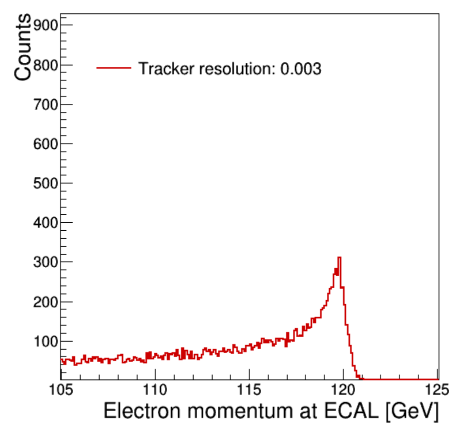
0.2 X_0



0.3 X_0



0.4 X_0

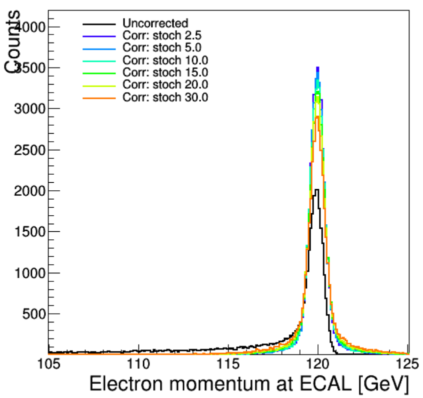


Z→e^{+}e^{-} Sensitivity Recovery

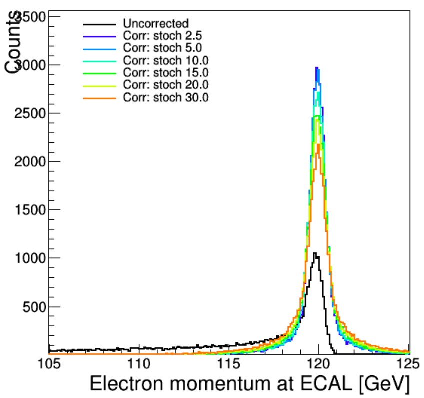
Highest Recovery for ~3%/√E ECAL Energy Resolution

→ Improvement largest for ~0.3-0.4 X_0

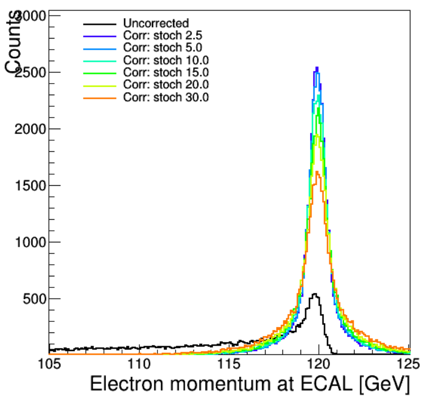
0.1 X_0



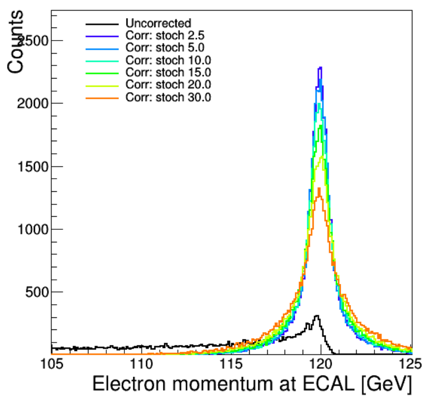
0.2 X_0



0.3 X_0



0.4 X_0

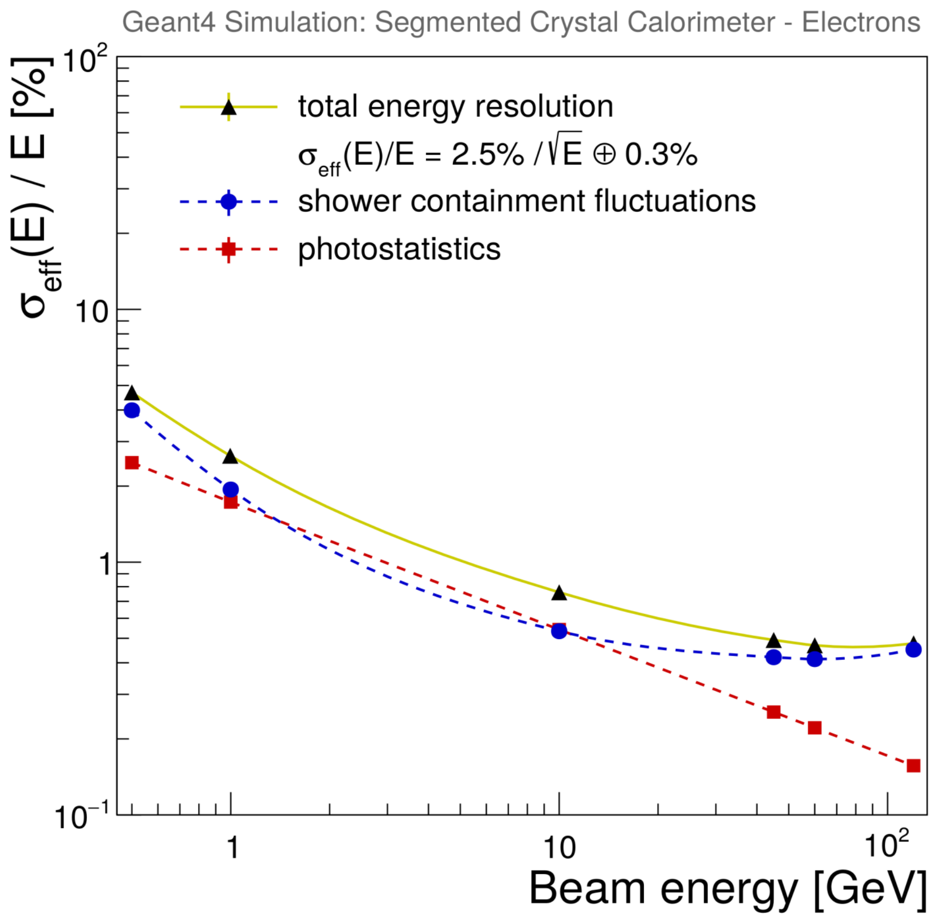


Energy Resolution Target: <3%/√E Stochastic Term

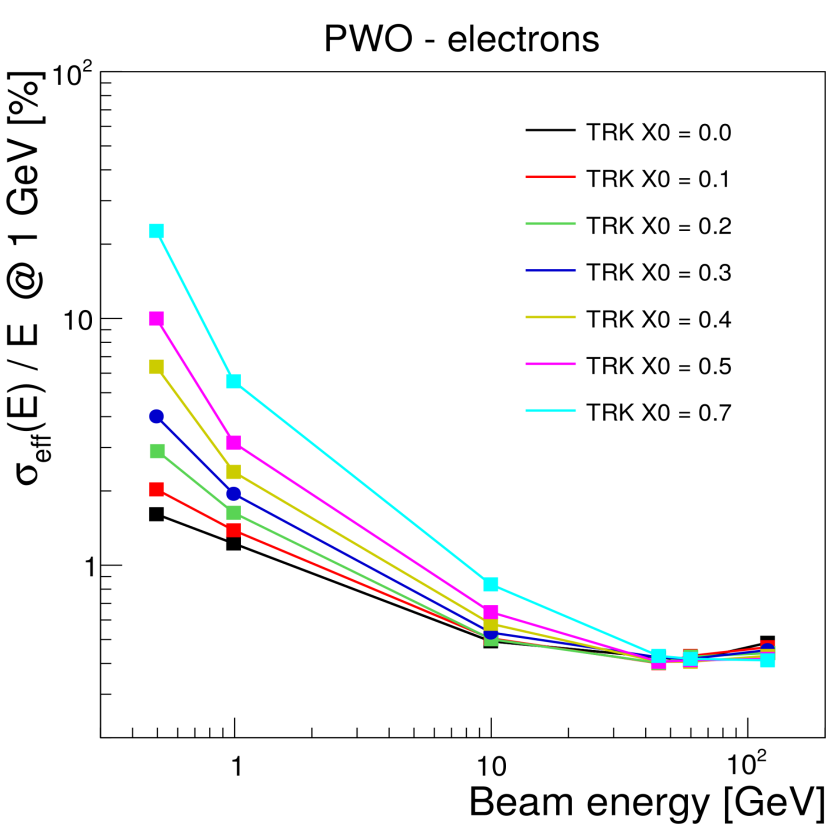
- **Requires:**
  - Shower fluctuations <2%
    - Material budget in front of ECAL < $0.3X_0$
  - Photostatistic fluctuations < 2%
    - Signal in photoelectrons >3500 phe/GeV
    - Assuming 20% PDE for 10 um cell SiPMs → LY*LCE > 18 ph/MeV
      - 5 um cells with high PDE in development
    - Need to 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

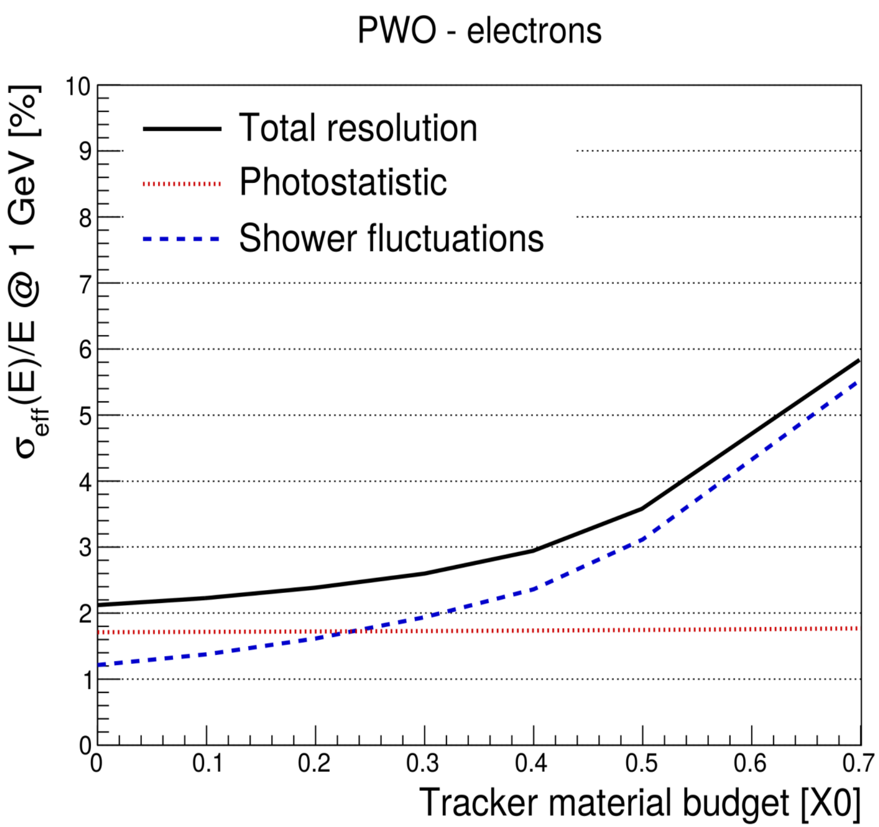
Energy Resolution

- **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

better for PFA

better stochastic term

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

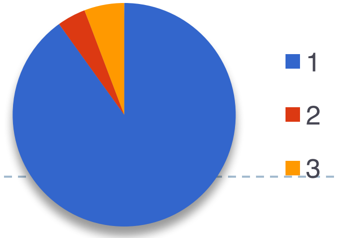
Barrel ECAL	
Total SiPM power (kW)	1.7172
Total electronics (kW)	23.1822
Total barrel ECAL power (kW)	24.8994
2 Endcaps ECAL	
Total SiPM power (kW)	0.696
Total electronics (kW)	9.396
Total endcap	10.092
Grand total ECAL (barrel+endcap) [kW]	35

(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
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

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 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

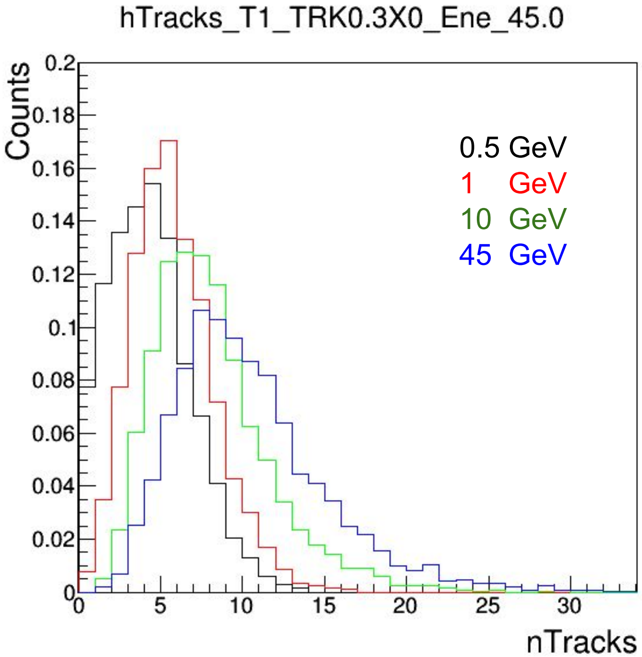
Total ECAL crystal volume [m³]	12
Grand total ECAL (barrel+endcap) [# channels]	1206600
Grand total ECAL (barrel+endcap) [k€]	101686

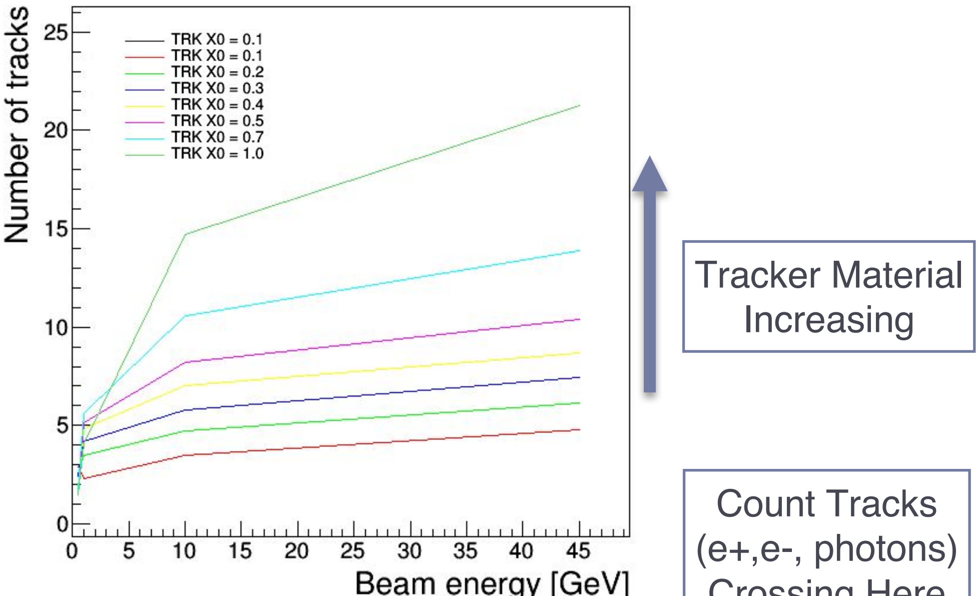


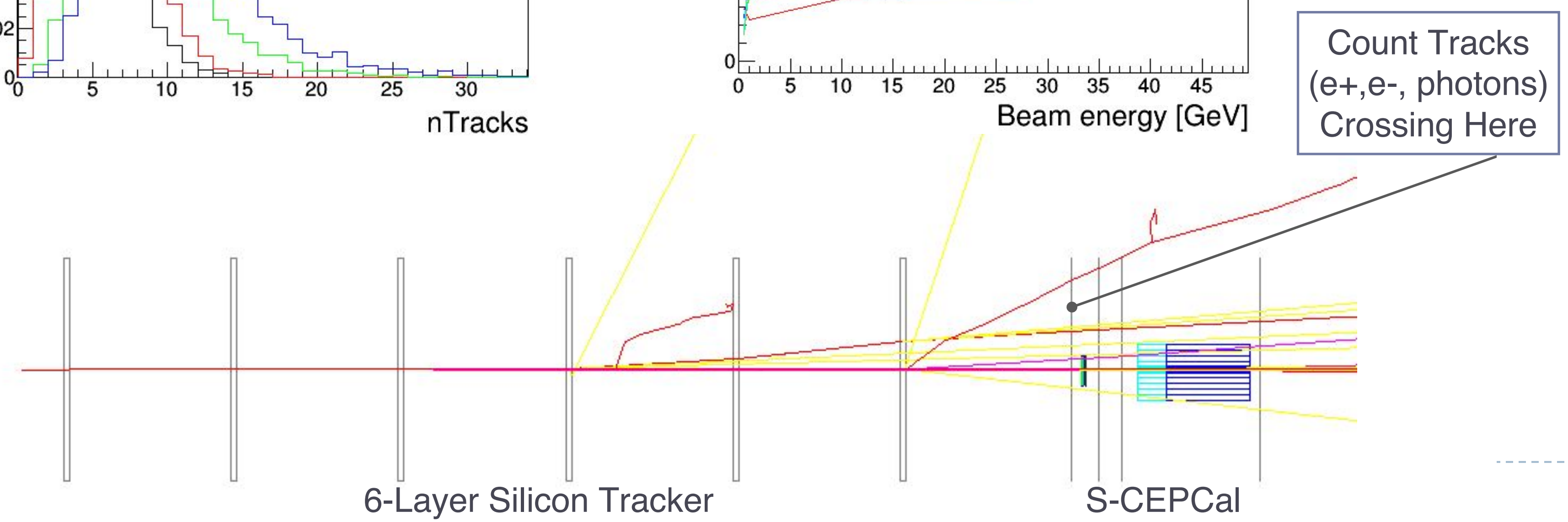
~100 Meuros

Electron Bremsstrahlung in Tracker

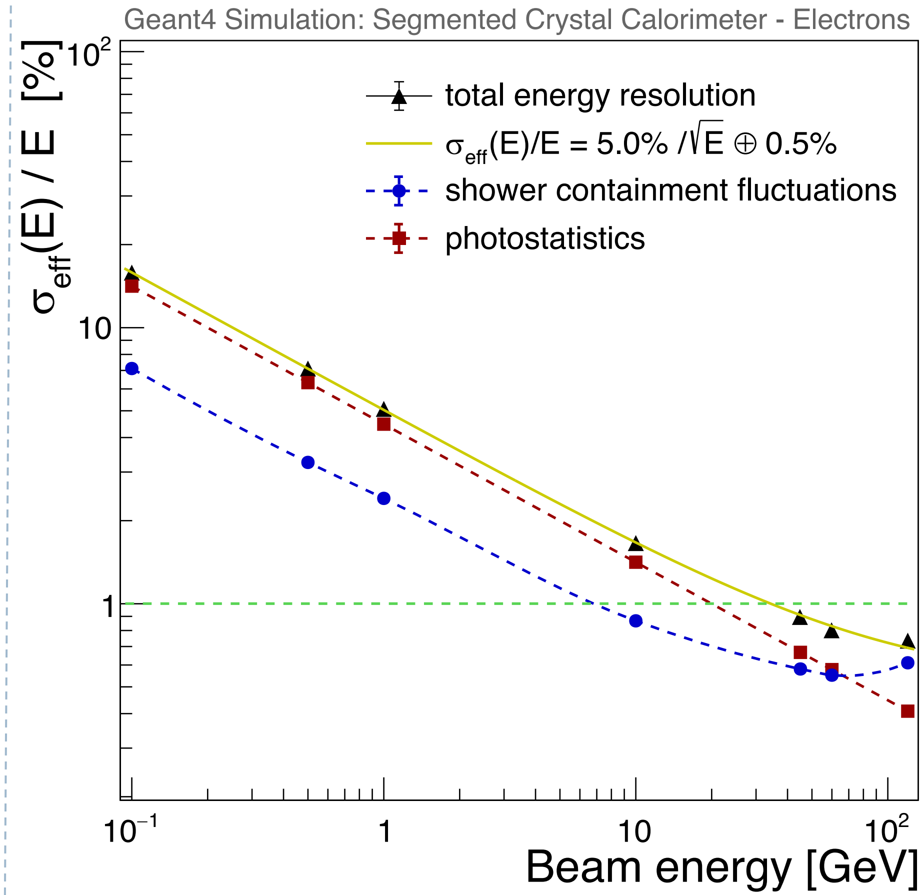
- counting number of tracks at the entrance of the timing layer (e+, e-, gamma)

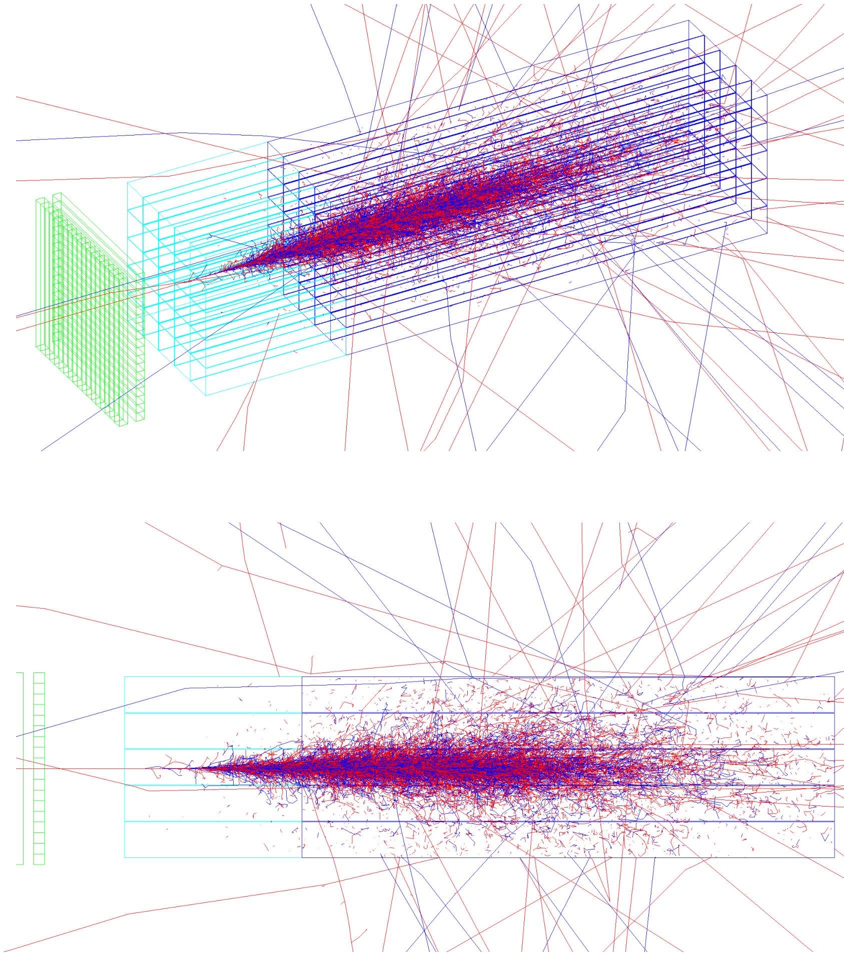






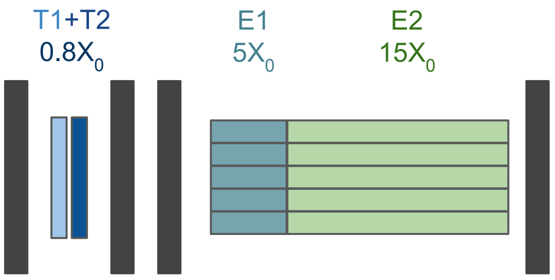
Electron Energy Resolution (no Dead Material)

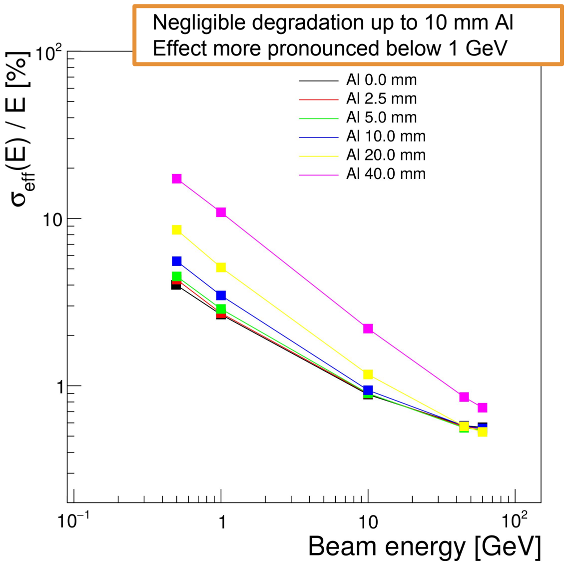




Dead Material between Layers

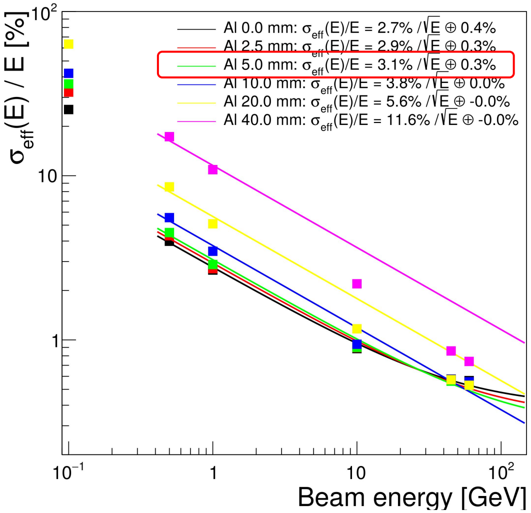
- Services required:
  - FE/ASIC for read-out → PCB material
  - Cooling plate
  - Cables
- Space allocated:
  - 5 cm in front of crystal timing layer T1 (for T1 read-out)
  - 10 cm in front of crystal ECAL E1
    - 5 cm for T2 and 5 cm for E1 → **cooling plate may be shared**
  - 5 cm in rear of crystal 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



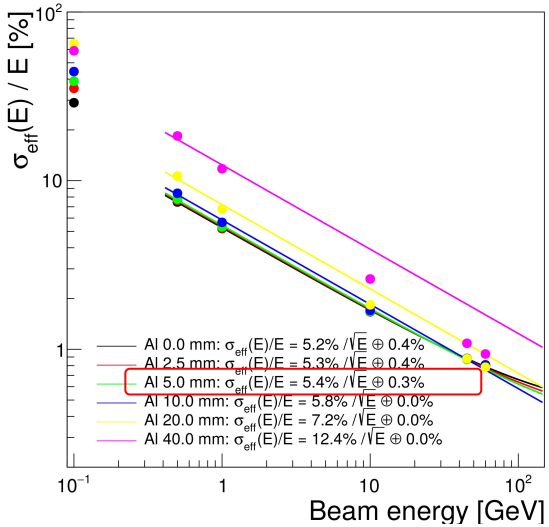


Impact of Dead Material between Layers

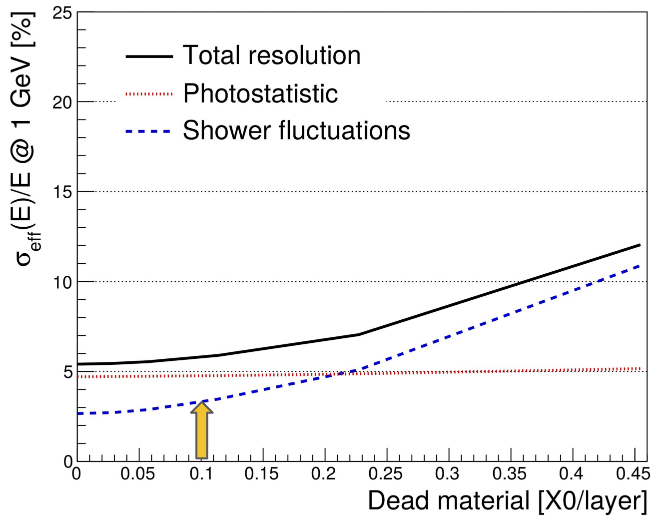
Shower fluctuations only



Total (including photostat.)

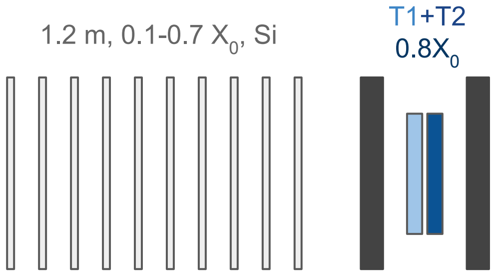


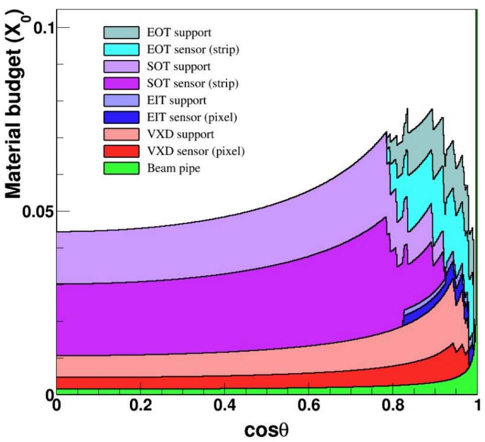
Stochastic term vs dead material

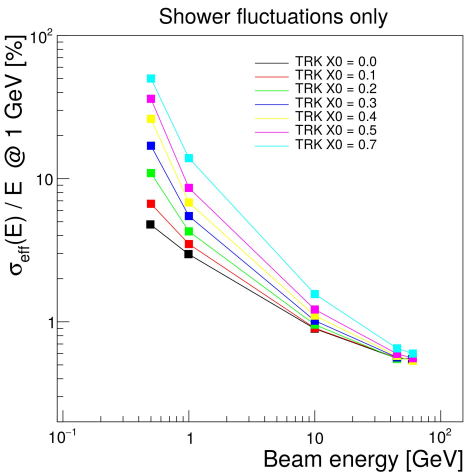


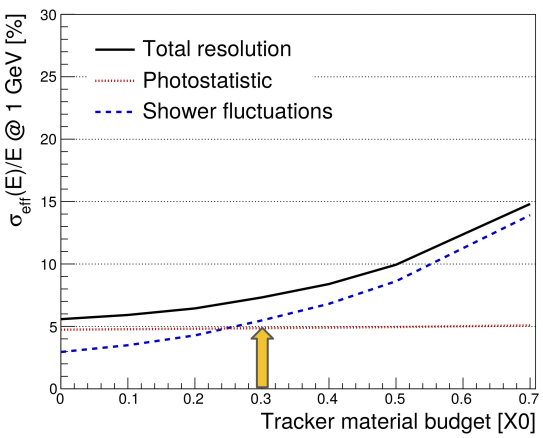
Impact of Tracker Material

- 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

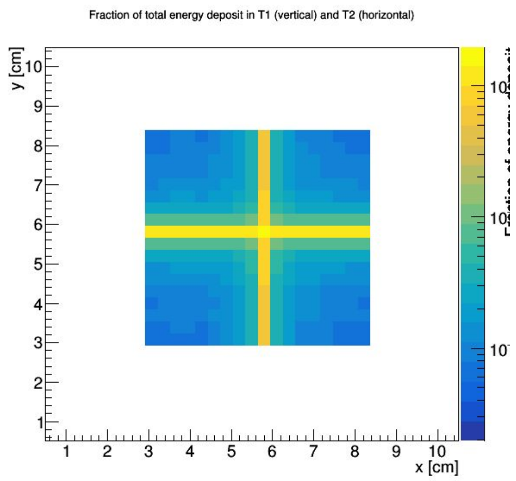


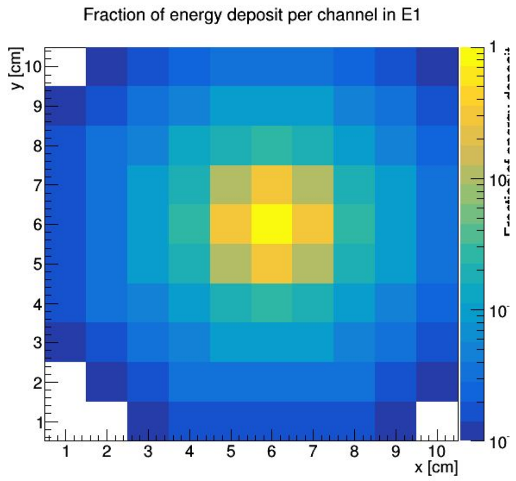


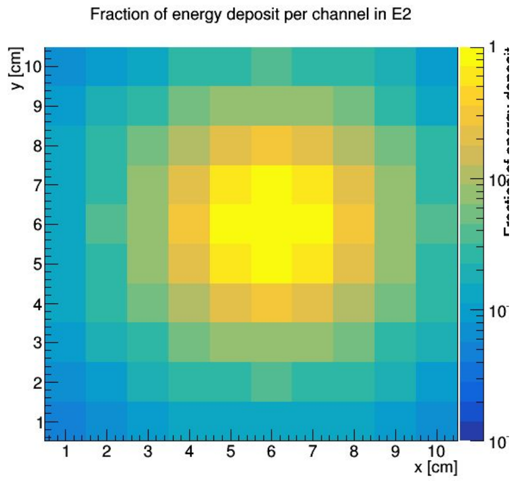


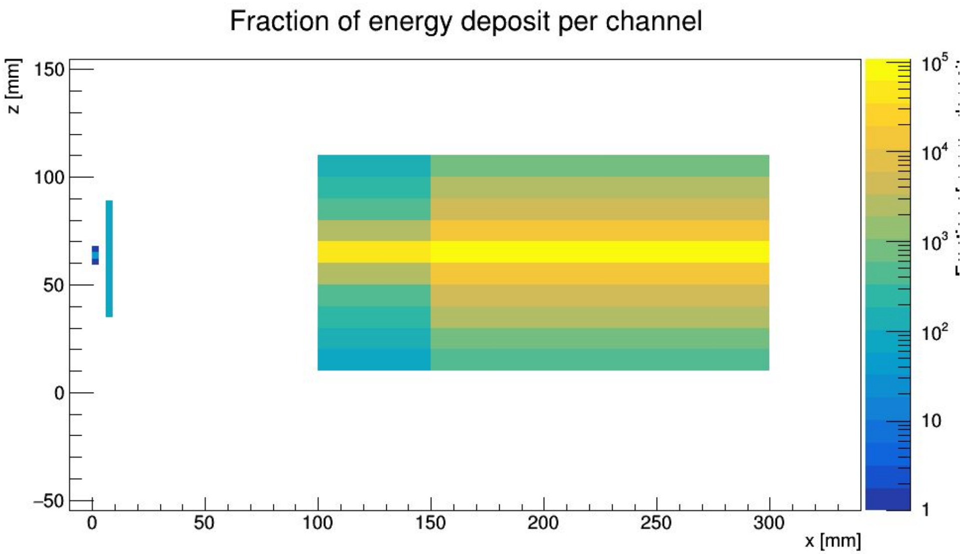


Single EM Shower (High Stat- Log)

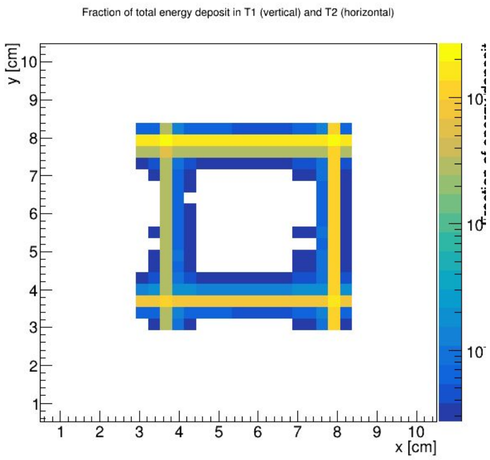


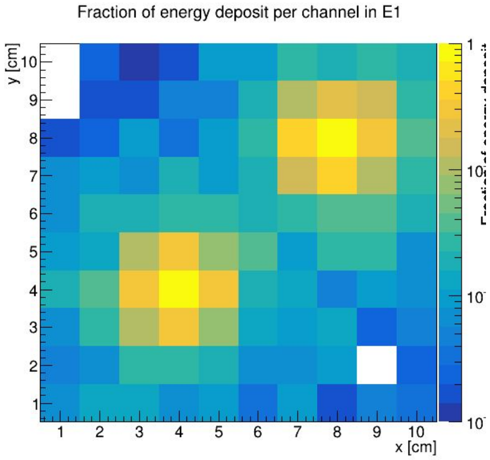


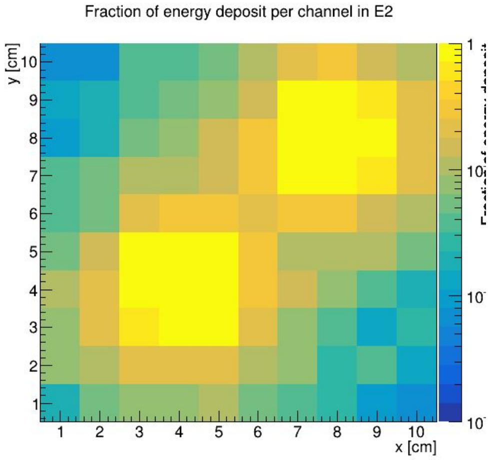


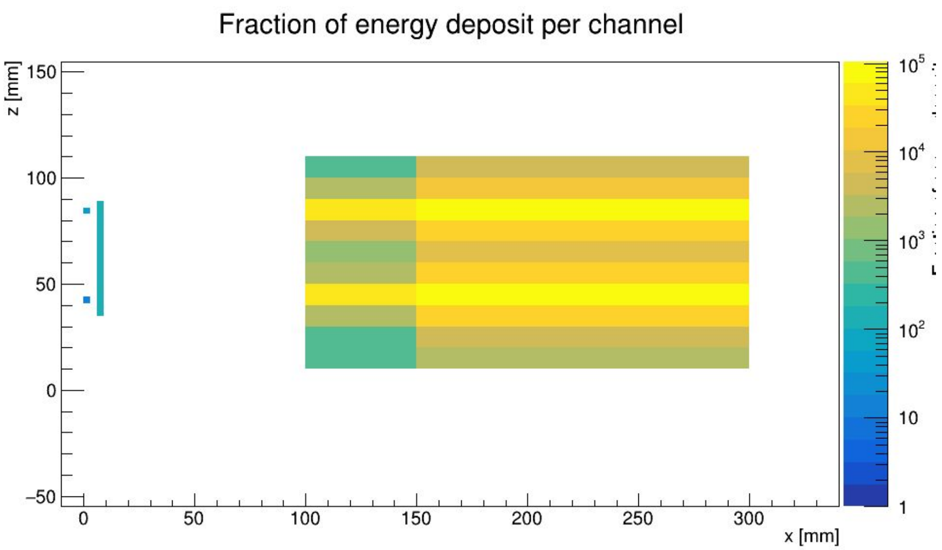


Pair of EM Showers (High Stat - Log)

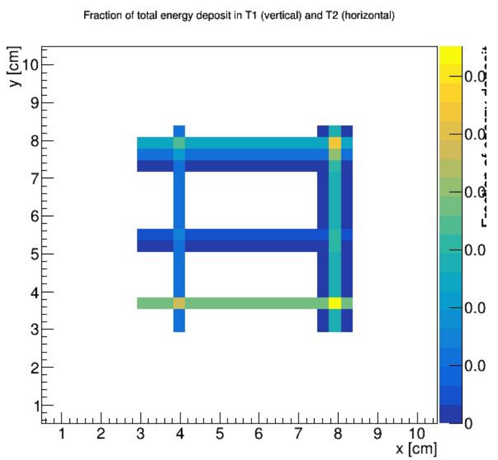


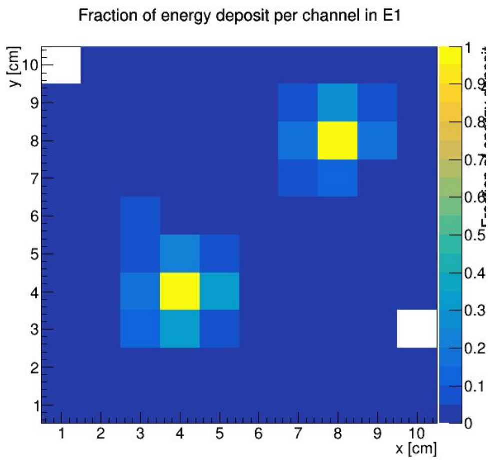


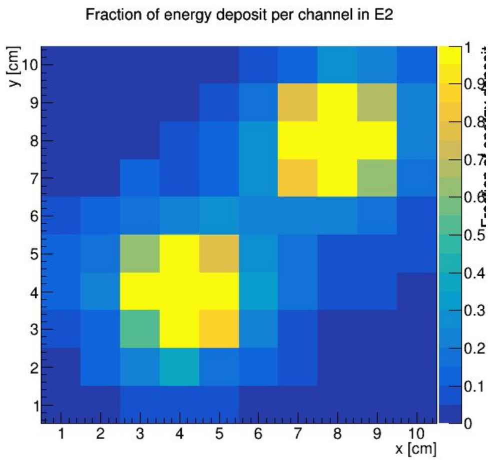


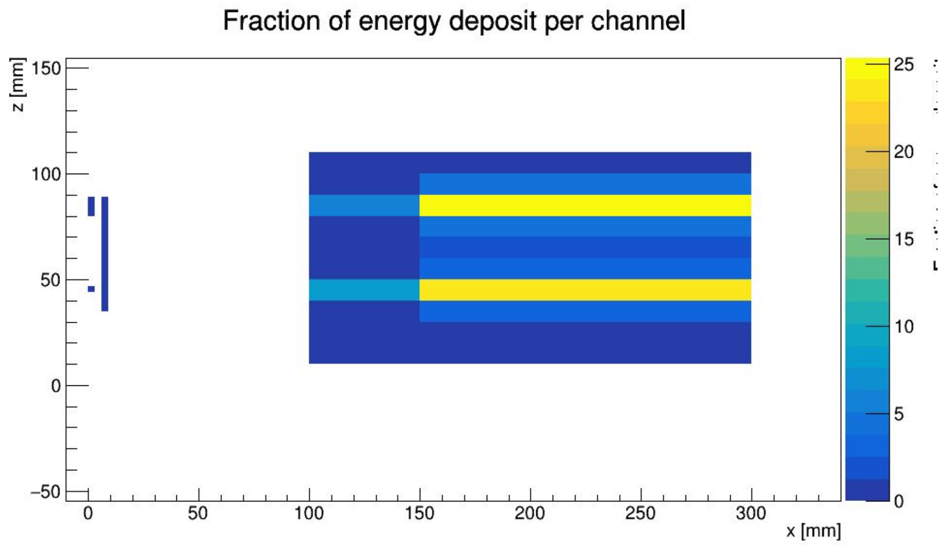


Pair of EM Showers (Single Event)

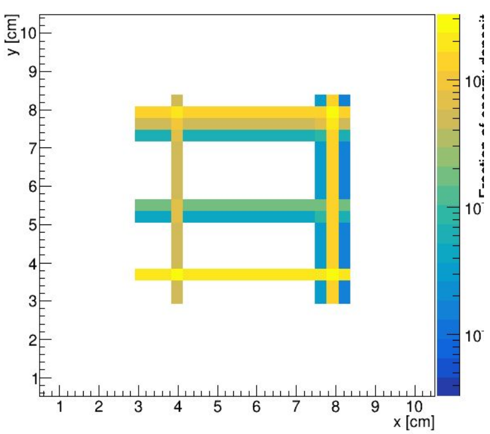


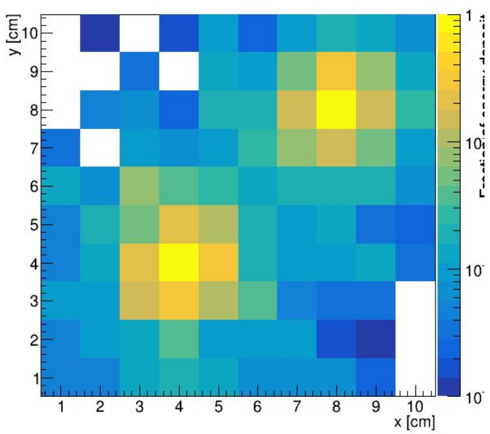


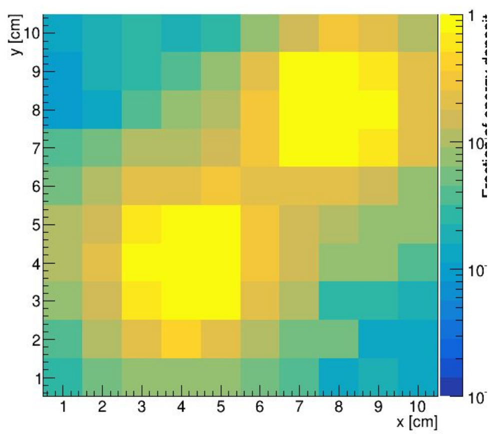


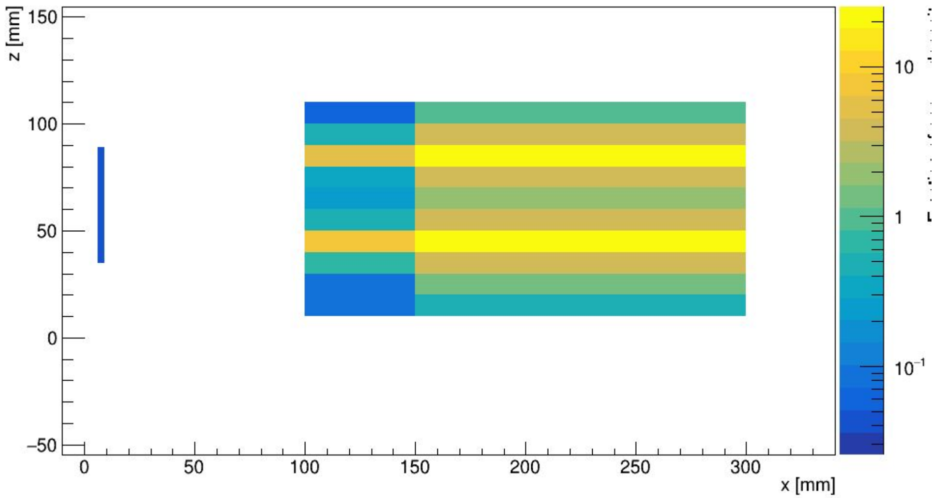


Pair of EM Showers (Single Event - Log)







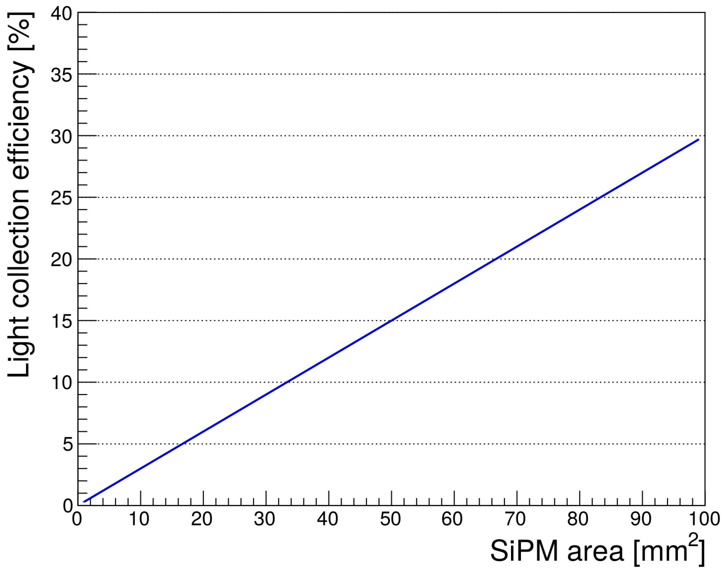


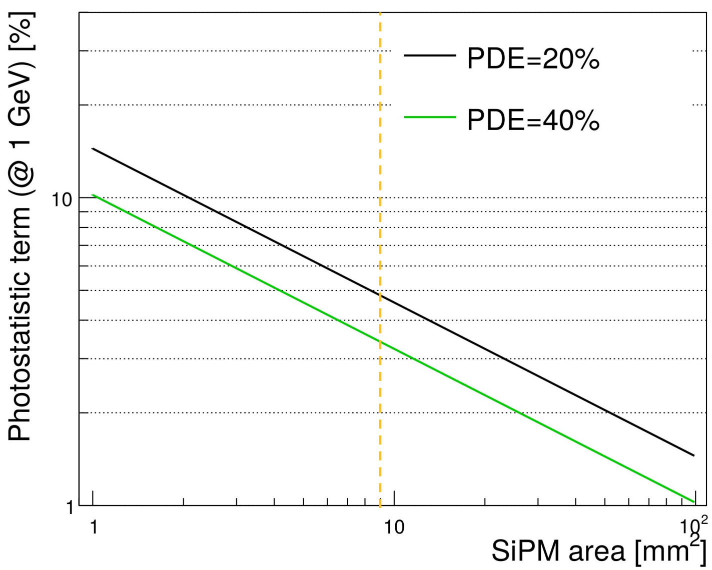
Energy Resolution and Dynamic Range

- **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

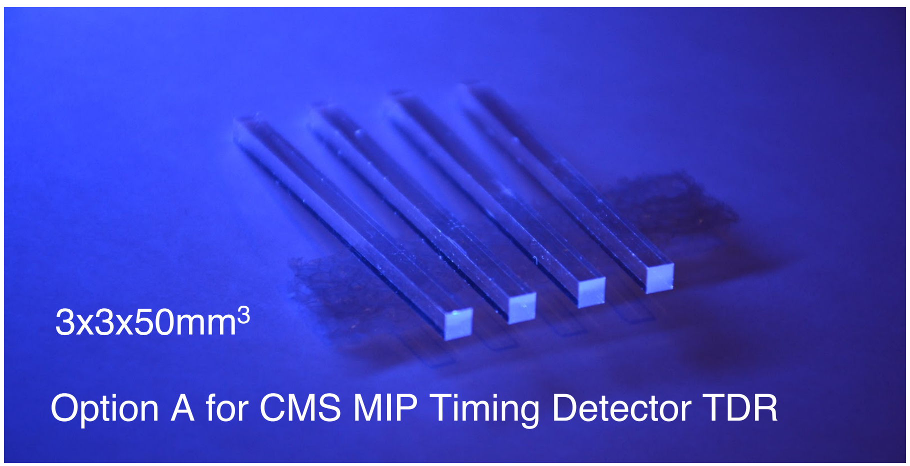
- 5%/sqrt(E) → LO>0.4 phe/MeV
  - for LCE~2.5% (9 mm² SiPM), PDE ~ 20% → The crystal must have a LY>80 ph/MeV
- SiPM 3x3 mm² on a 10x10 mm² crystal is sufficient
  - with SiPM area = crystal end face → LCE~30%



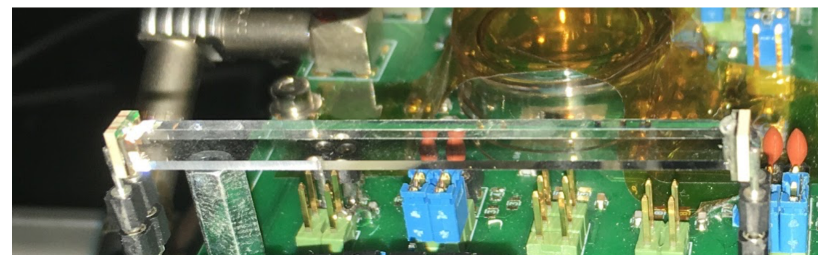


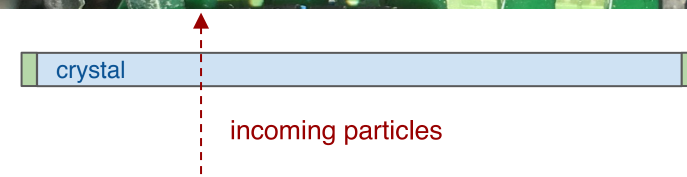
Small Crystal Geometries for Timing Detectors

- **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



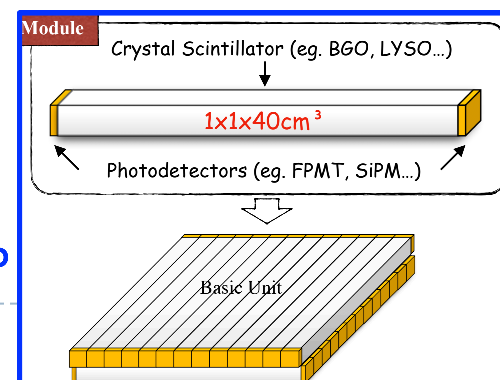
Non-wrapped crystal bar with 2 SiPMs attached at each end





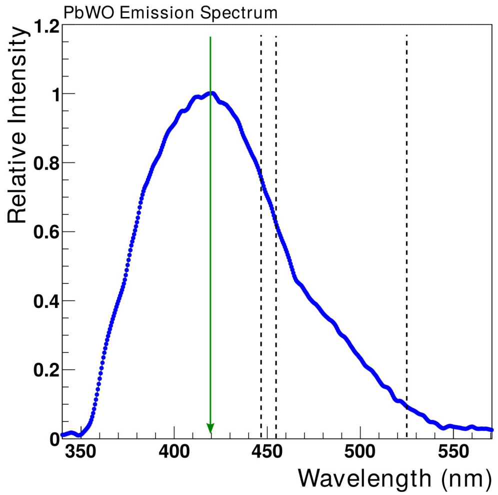
Low occupancy timing layer timing for ~1 X0
Transverse orientation w/ stereo readout

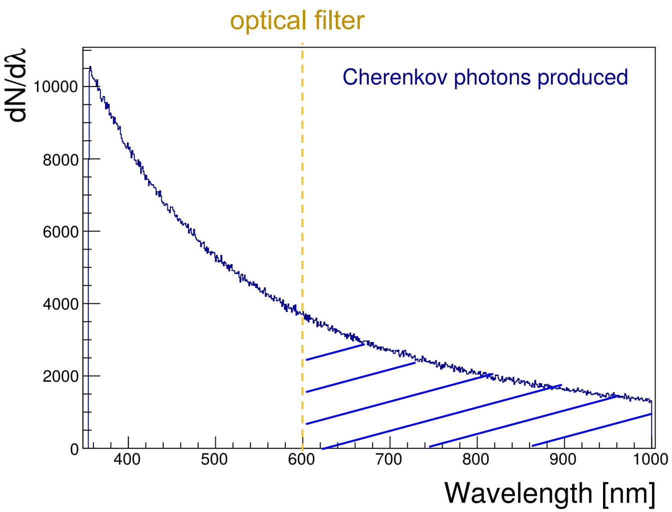
Similar study at IHEP
by Yuexin Wang

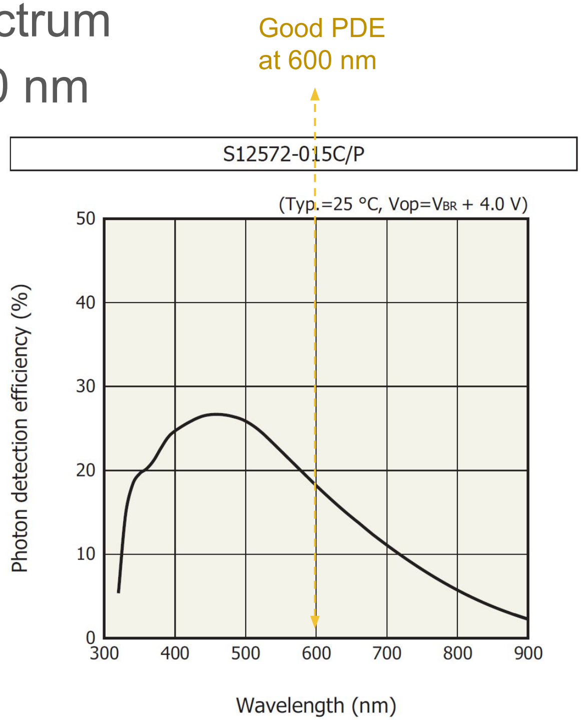


Dual-Readout Capability

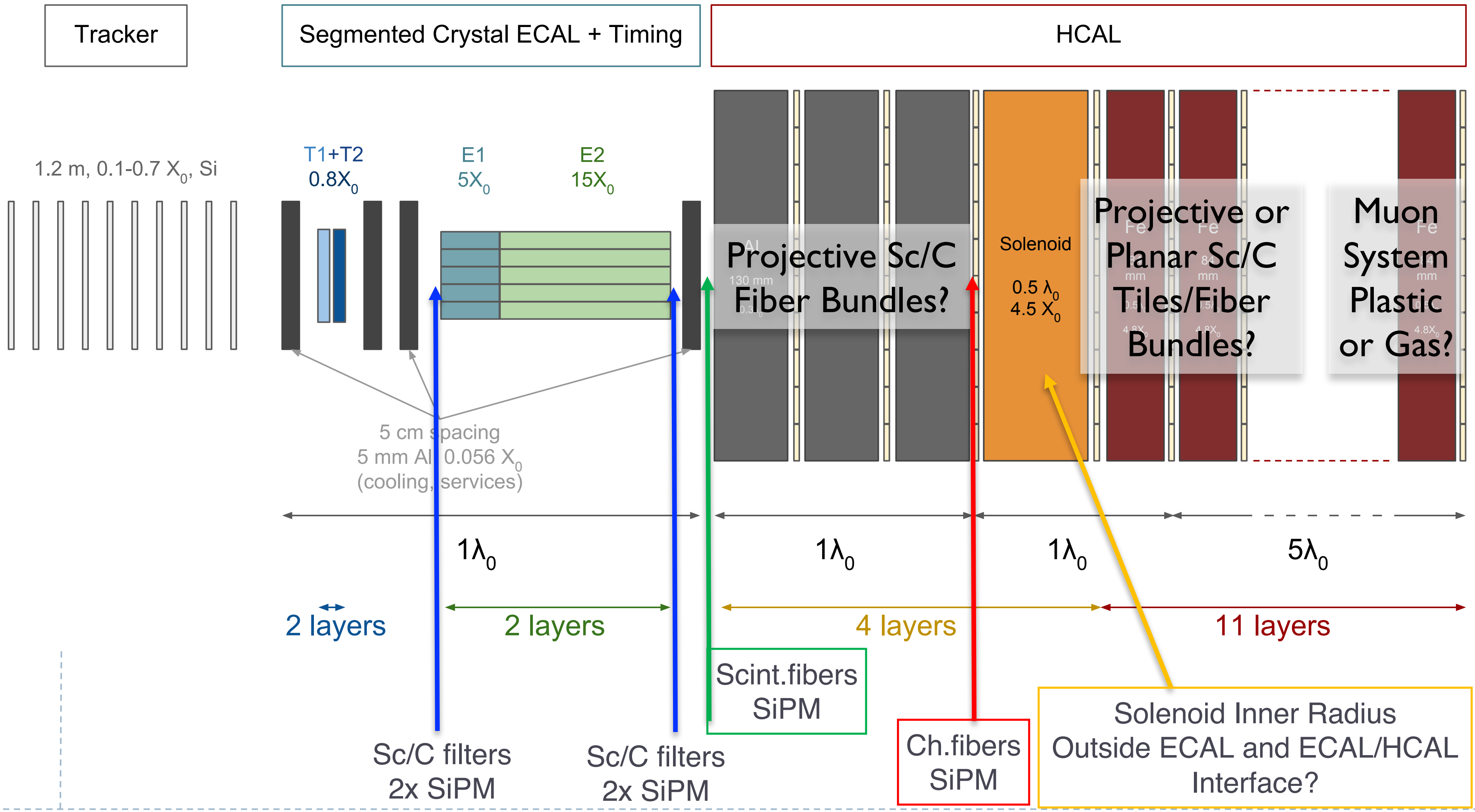
- PWO - excellent Cherenkov radiator (transparency cut off at 350 nm)
- Exploit Cherenkov photons **above** PWO emission spectrum
- 2 SiPMs, one with optical filter > 600 nm, another <600 nm







Dual-Readout ECAL+HCAL Compatibility



Conclusions

- **Physics case at e^+e^- colliders calls for high resolution ECAL**
  - $Z \rightarrow e^+e^-$ recoil resolution w/ Brem. recovery methods
  - Highly resolved PFA clustering from high sampling fraction
  - 20ps Resolution Time-of-Flight Particle ID for π/K/p
  - Photon counting with high fidelity/angular resolution
- **Homogenous and segmented crystal calorimeters can provide outstanding energy resolution in the energy range 0.1-120 GeV**
- **Calorimeter design can capitalize on the expertise from previous HEP crystal calorimeters**
- **Recent progress in the fields of crystals and SiPMs enables a flexible, compact and lower cost solution for a high resolution ECAL**
- **A highly segmented calorimeter in transverse and longitudinal direction combined with 20 ps timing capabilities extends the physics program for particle ID, long-lived particles and improves out-of-time background rejection**

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

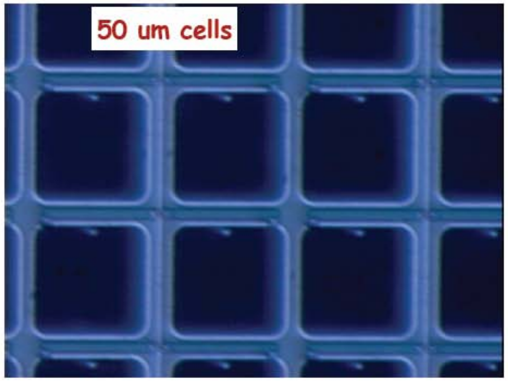
https://arxiv.org/pdf/0810.1216.pdf

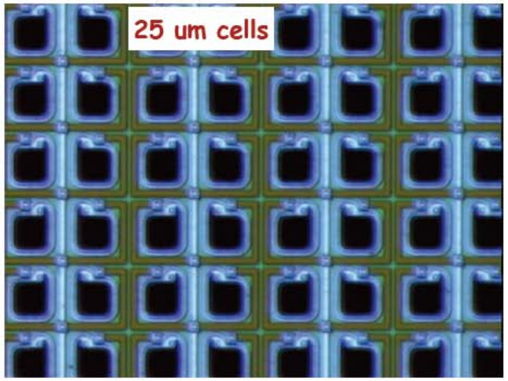
Silicon Photomultiplier (SiPM) Cells

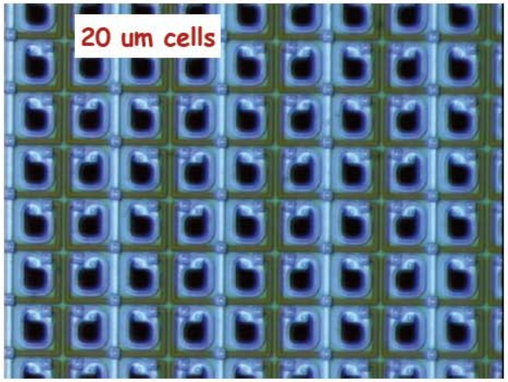
- **Typical dynamic range customization for SiPM**
  - More (small) SPADS to count more photons (50→15µm)
  - Bright crystal (LYSO, GAGG) and high photodetection efficiency (PDE) and light collection efficiency (LCE)

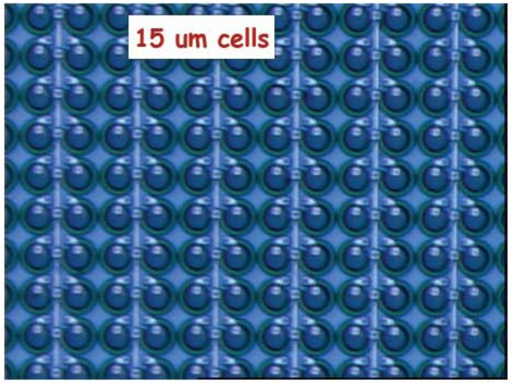
Currently:
Large device ~6x6mm^2
CMS MTD ~4.5 m^2 of SiPMs (of 3x3mm^2)

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