Converging towards an **HCal** option for the new CLICdp model

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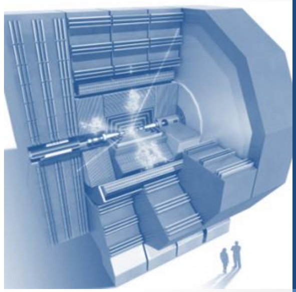


Introduction - Outline

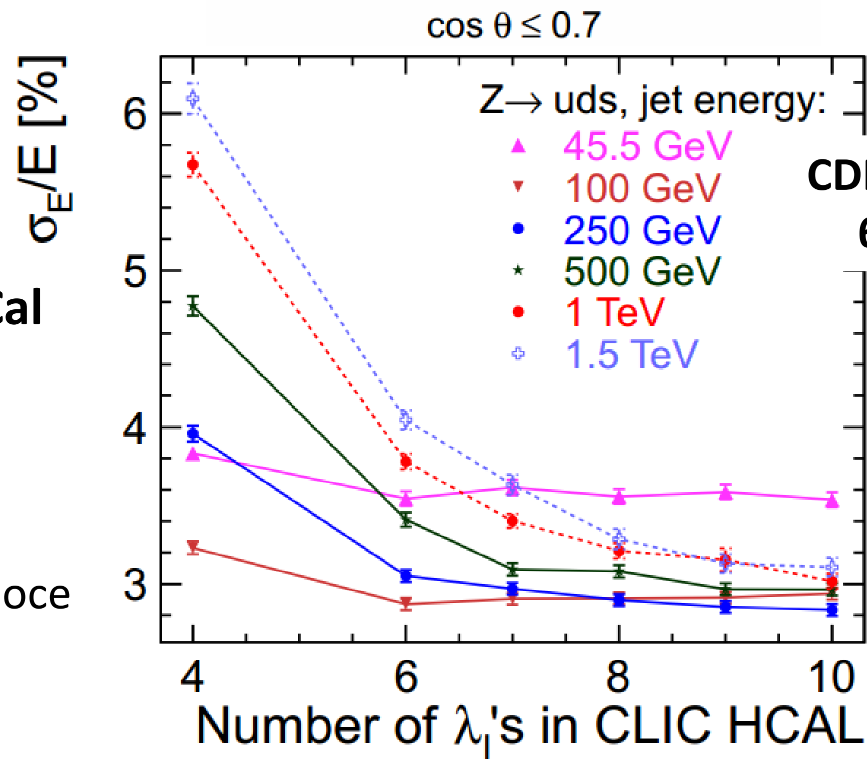
- Working towards an updated simulation model for the new CLIC detector
  - Include as much detail and up to date information from optimization/engineering studies as possible/available
  - **Feed back updated figures/requirements to engineering and feasibility studies**
- There have been already several iterations of detector optimization, including the HCal
- Two particularly interesting issues in the case of the HCal:
  - **HCal Barrel**: **Size (R)** ↔ **Abs. Material (W vs Fe)** ↔ **Assembly**
    - Implications **on coil size and requirements**, overall detector size
  - **HCal Endcap**: **Forward coverage and acceptance**
    - Implications on forward region instrumentation and engineering design

HCAL BARREL OPTIMIZATION

Previous Studies for the CDR

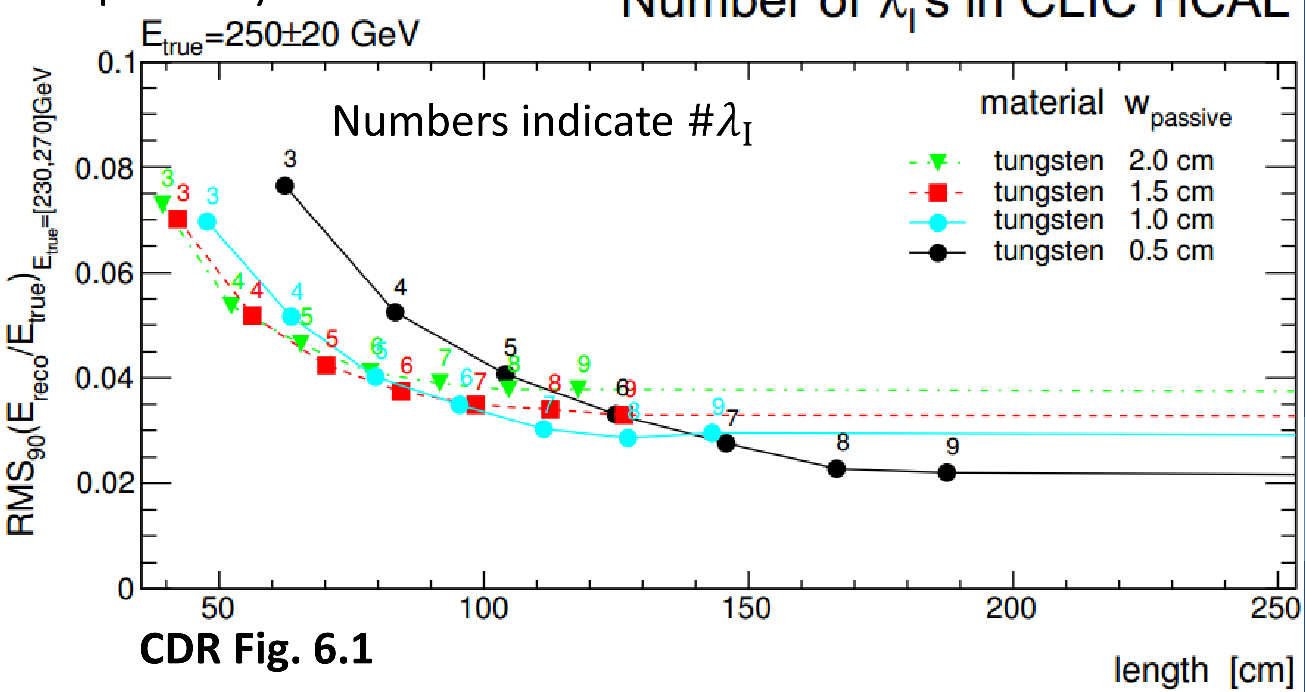
- **These studies drive the aim for an HCal depth of $\sim 7.5\ \lambda_I$ at $\theta \approx 90°$**
  - **Try now to constraint the Radial size of the HCal**

- Right: Pandora PFA study by A. Lucaci Timoce
- Bottom: Toy (testbeam stack) calorimeter study by C. Grefe and P. Speckmeyer



CDR Fig. 6.2

- Single π^+ (Slic)
- Hit based
- TMVA calibration
- Also compared performance of Tungsten and Steel Absorber

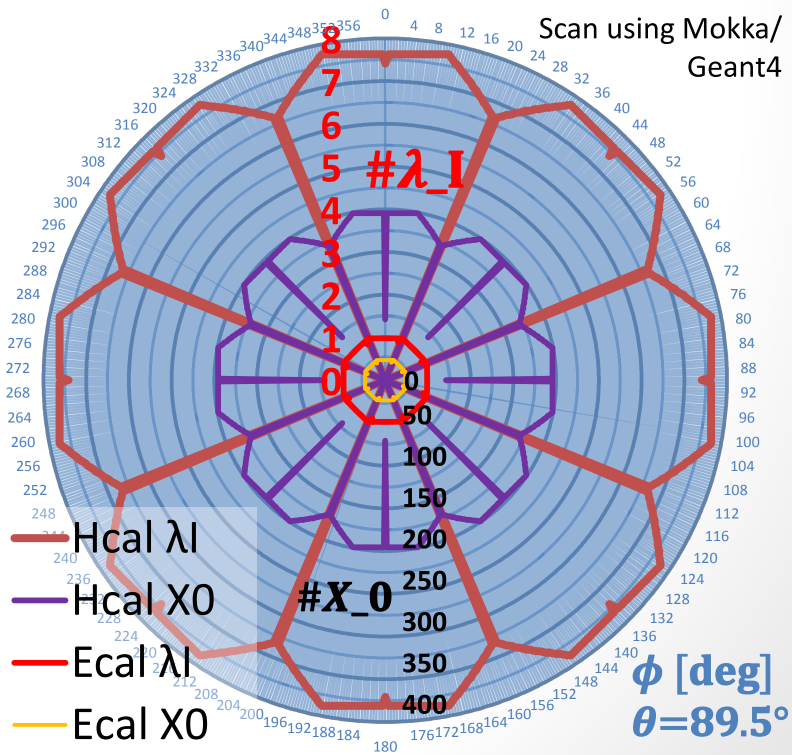


CDR Fig. 6.1

What was Previously There

- Verified that both previous simulation models (CLIC_SID, CLIC_ILD) and reconstruction chains included HCal Barrels with $\sim 7.5\ \lambda_I$ at $\theta = 90^o$
- Both models do not include support for the radiator or any sort of cassette for the active elements/electronics
  - **Looked into more realistic scenarios**
  - Studies performed using a modified version of ILD_o1_V06 model and the ILD software chain

HCAL BARREL	CLIC_ILD (SHcalSc02)	CLIC_SID
Number Of Layers	75	75
Number Of Sides	(8) 16	12
Inner Radius	2058 mm	1419 mm
Outer Radius *	**3296 mm**	2656.5 mm
Z Length	4700 mm	3530 mm
Section Phi	0.52 radians	0.52 radians
Cell Size	30.0 mm x 30.0 mm	30.0 mm x 30.0 mm
Layers 0 - 74		
10 mm	Tungsten	Tungsten
5 mm (sensor)	Polystyrene	Polystyrene
1.5 mm	Air	Air

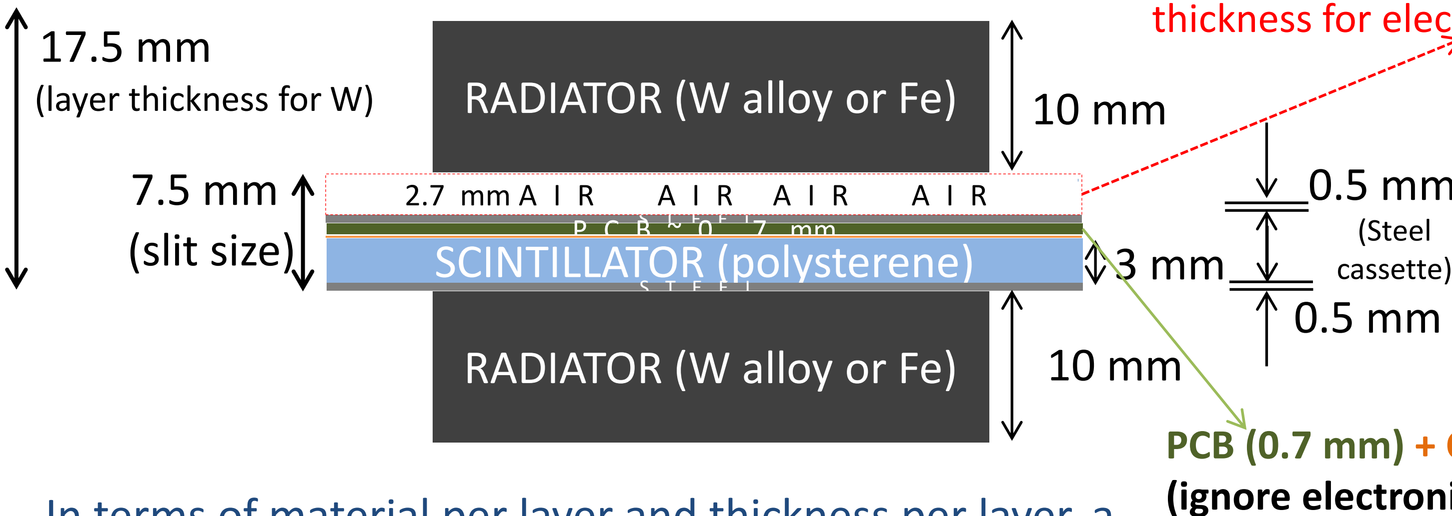


Modified ILD Assembly (17.5 mm per layer)

Kept ILD_o1_v06 thicknesses, added cassette, removed 1 mm from Steel absorber thickness

- Gain 2 mm

- Generous 2.7 mm air gap
(called “Fiber gap” in Mokka ILD driver)
- Stack on top for simplicity
- Could also accommodate some thickness for electronics



- In terms of material per layer and thickness per layer, a 19 mm steel absorber thickness model will basically be the same as the ILD_o1_v06 model with this assembly
- **For a 10 mm Tungsten HCal, it follows that we will have extra material**
  - Updated calculations on next slide
- Still does not address support and assembly
  - Would more naturally fold into absorber structure in the case of Fe

Active Element Cassette	
Material	Thickness mm
Steel	1
PCB	0.7
Cu (etching)	0.1
Electronics	0
Scintillator	3
Sum (per layer)	4.8
#λI (per layer)	0.01

Various Model Options for the HCAL Barrel

- Try variations **of absorber material, thickness and number of layers** resulting in depth around 7.5 λI (established from CDR studies)
- Modify ILD_o1_v06 model in Mokka
  - Set $R_{in}^{HCal} = 1750$ mm, additional absorber plate at the end, 1 mm steel in **cassette**
  - 4.5 T field (constant for all variations, rest same as ILD)

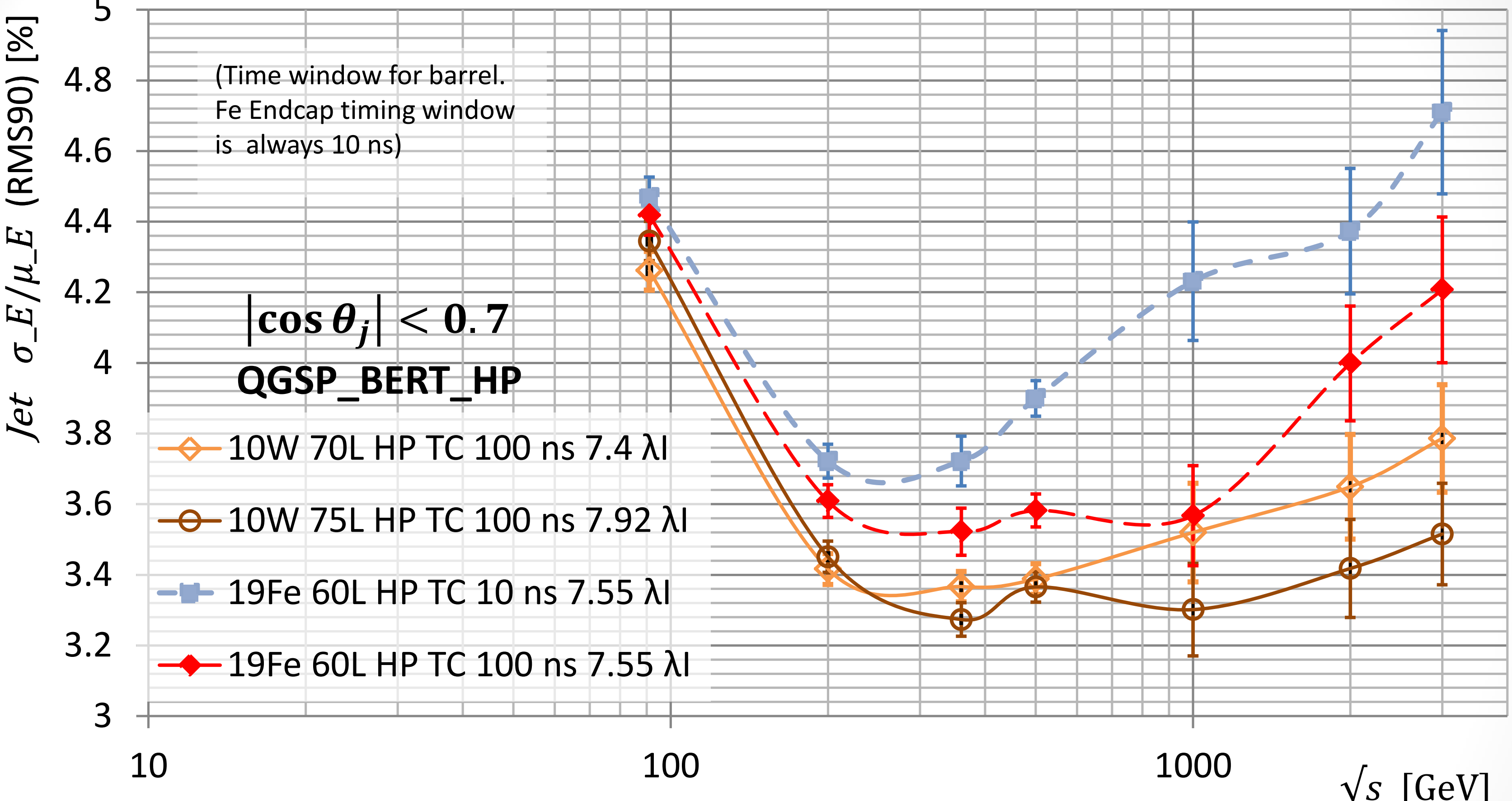
Detector	# Layers	Abs Thick	Cass. Thick	Air	Total Depth	Total Thickness	Inner R	Outer Face Position	Outer Radius
		mm	mm	mm	#λI	mm	mm	mm	mm
CLIC_ILD_CDR	75	10	5* (*Scint)	1.5	7.42	1237.5	2058	3295.5	3341.2
CLIC_SID_CDR	75	10	5* (*Scint)	1.5	7.42	1237.5	1447	2684.5	2721.7
W + cassette	75	10	4.8	2.7	7.92	1322.5	1750	3072.5	3115.1
W + cassette	**70**	**10**	**4.8**	**2.7**	**7.40**	**1235**	**1750**	**2985**	**3026.4**
Fe + cassette	**60**	**19**	**4.8**	**2.7**	**7.55**	**1609**	**1750**	**3359**	**3405.6**
Fe + cassette	70	16	4.8	2.7	7.93	1661	1750	3411	3458.3

Notice two most promising options (bold black) result in outer radii differing by ~40 cm

Methods to Gauge HCal Performance

- Tried to gauge performance of various models:
  - Single Particle Response
  - Jet Energy Resolution (JER):
    - **From total Deposited Energy in $Z' \to uds$**
      - Use AnalysePerformance (from PandoraAnalysis-v00-06)
    - **From Z/W measurement $ZZ \to \nu\nu dd$** and **$WW \to \nu\ell ud$**
      - **Use m_{JJ} overlap estimation**
- Each model had to be individually **calibrated** before performing any study, **including corrections for Non-linearity**
  1. Hit-level digitization calibration
  2. Pandora PFA-level calibration (modified procedure from Cambridge)
  3. Obtain single particle response
- Other Pandora PFA parameters not optimized
  - E.g. **No Cut** on Maximum HCal Hit Hadronic Energy (MHHHE)
- Recalibrate when changing **Readout Window Timing Cut**

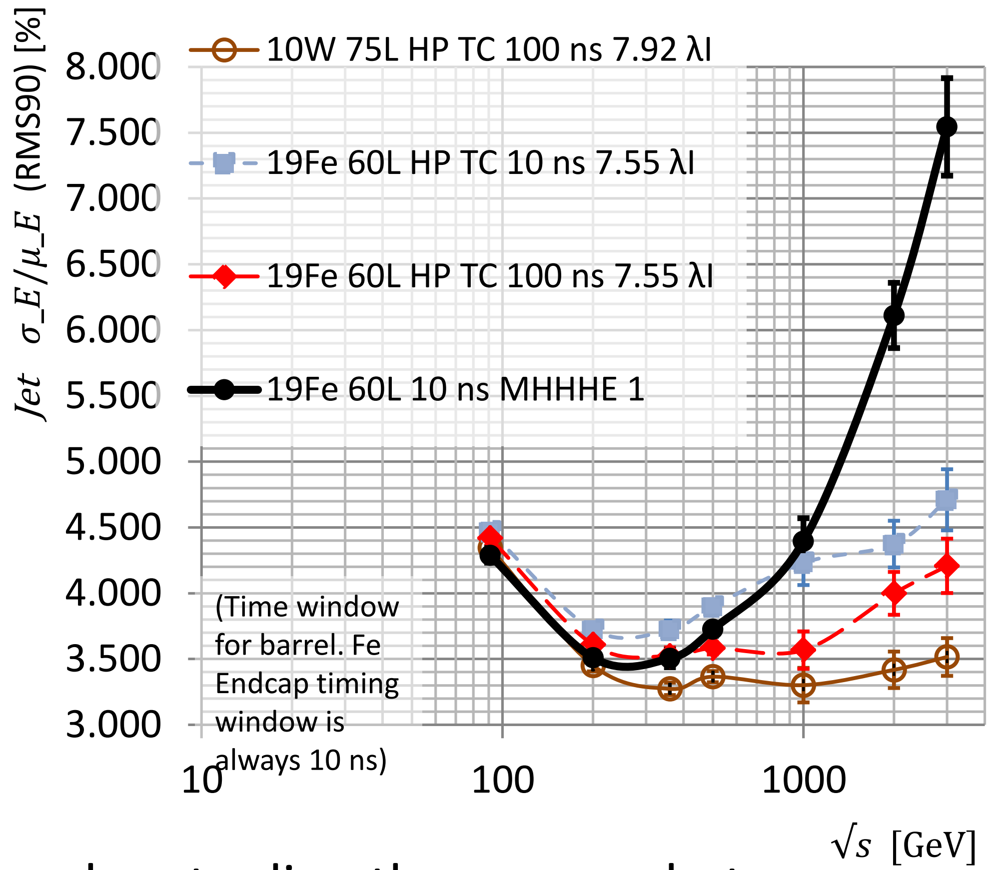
$Z' \rightarrow uds$ JER Results For the Most Promising HCal Model Options



- Probably the performance for Tungsten shown here is close to its optimal
  - Tungsten has been observed to be compensating
- **Steel** on the contrary, may benefit from software compensation -> expect some improvement in JER
- Fe and W performance ***comparable***

Effects of Tweaking

- Results depend of course on Pandor Parameters
- **E.g. MHHHE cut. Clearly the 1 GeV cut is not optimal for high jet energies**
- **However this demonstrates that a lot can be accomplished by optimizing /configuring the software**

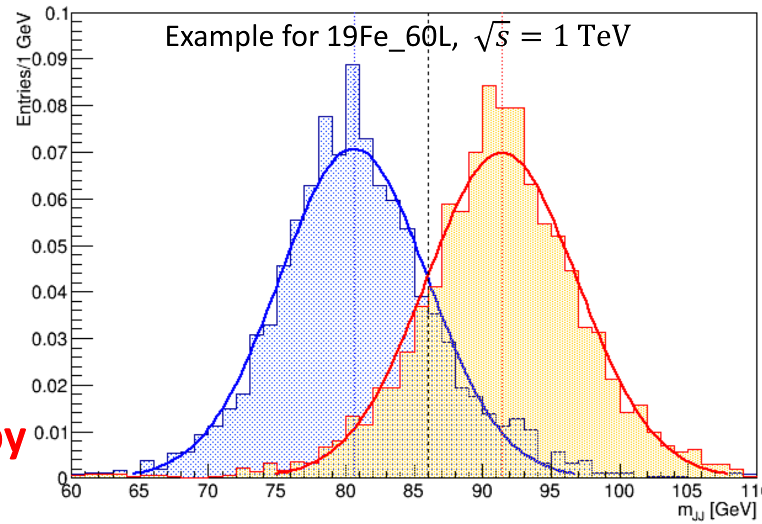


- It also shows that it is not easy or clear to directly compare between independent studies if the configuration is not the same

- Perhaps more importantly, it shows that the performance of individual models under investigation should not be considered in absolute terms

W/Z Separation Study

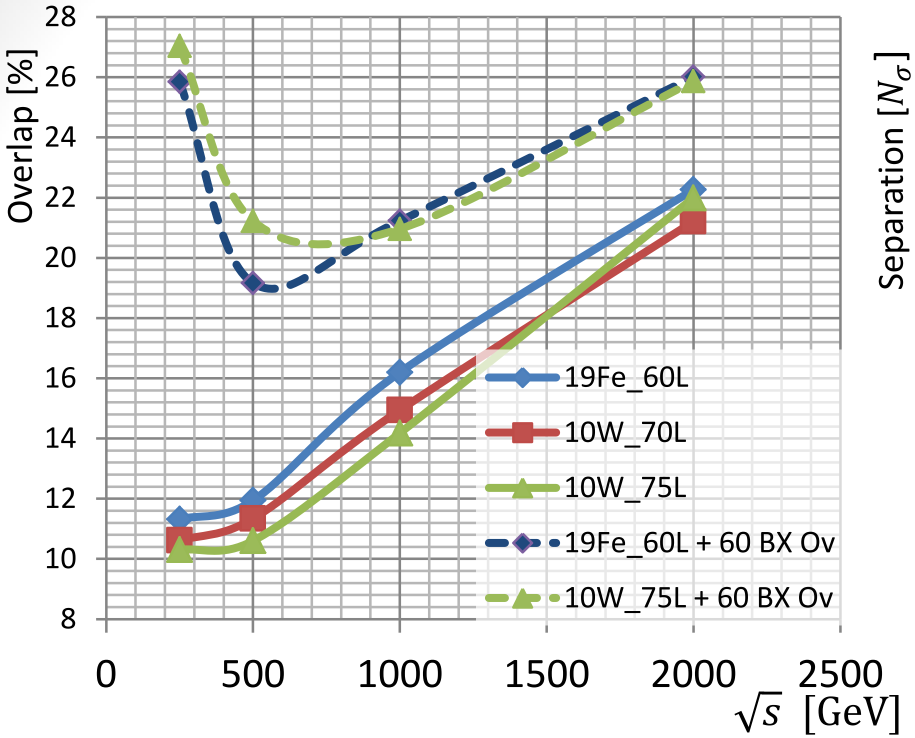
- *How do the models perform in the presence of background?*
- $ZZ \rightarrow \nu\nu\boldsymbol{dd}$ and $WW \rightarrow \nu\ell\boldsymbol{ud}$: **2 jets in an event topology similar to interesting physics events**
- **Method similar to PFA perf. Studies**
  - **See arXiv:1209.4039 and LCD-Note-2011-028**
  - $\sqrt{s} = 250, 500, 1000, 2000$ GeV
- Half of energy shared between the two jets, dijet invariant mass $\sim m_W \mid m_Z$
  - **Gauge performance of different HCal models by looking at its W/Z separation power**

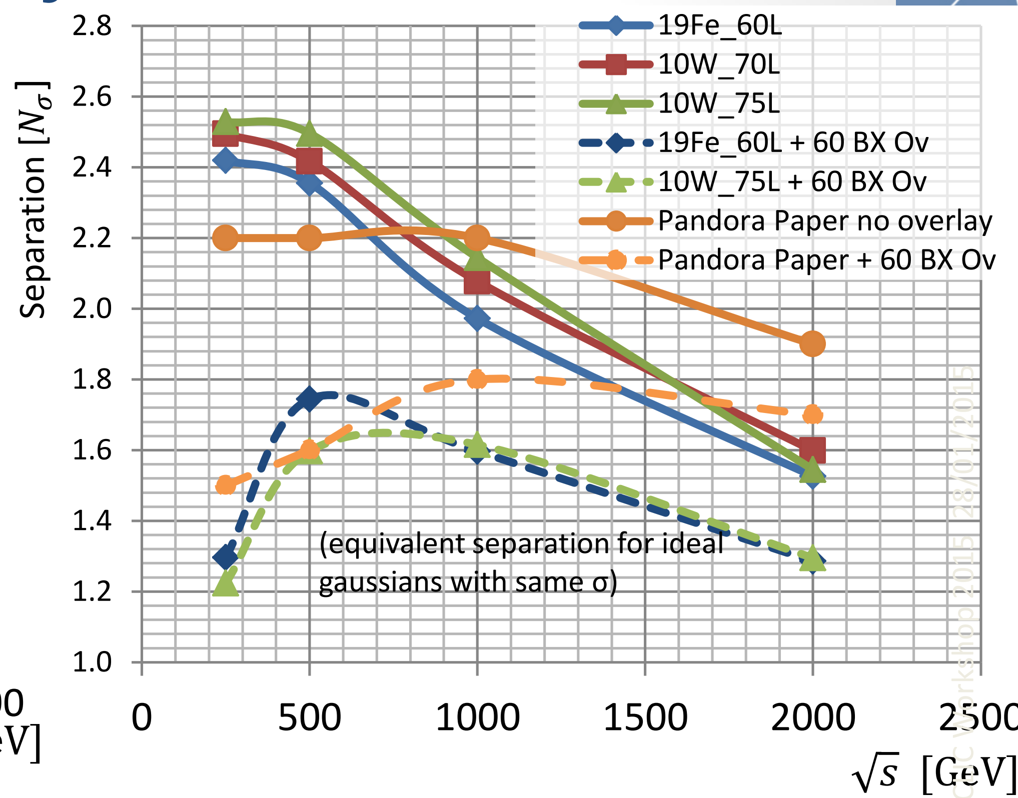


- Use *FastJet* to exclusively find and reconstruct 2 jets
- Simulate and reconstruct events for each energy and model ***(19Fe_60L, 10W_70L and 10W_75L)***
- Plot m_{JJ} for $|\cos(\theta_{W,Z,J_0,J_1})| < 0.7$ and $60 < m_{JJ}$<110 GeV
- **The overlap of the two peaks is an estimate of the separation**
- **Study with and without background overlay**
  - **60 BX $\gamma\gamma \rightarrow had$ generated at 3 TeV**

W/Z Separation Study Results

W models: 100 ns Barrel
Fe: model: 10 ns Barrel
Both: 10 ns Endcap





- **Analysis including beam background ($\gamma\gamma \rightarrow had$) (dashed lines)**
  - Included Pandora PFA Perf. paper results (arXiv:1209.4039 table 3)
    - Similar degradation with inclusion of background – method seems **OK**
  - **No change in conclusion; W and Fe HCal performance similar**
    - **Any difference appears to evaporate with the inclusion of background (and use of required background rejection criteria)**

Conclusions on HCal Barrel

- **JER:** "For the HCAL Barrel models investigated, Fe does not appear to perform better than W, **assuming the same timing window of 100 ns or larger**"
  - At the very least, one can say that at 100 ns, Fe can perhaps have a comparable (within ~5-10%) JER performance with W
  - **Indications that Fe can benefit from software compensation** (conversely, W is already compensating)
- The **single particle** response results **as well as the W/Z separation study** appear to agree with JER conclusions
- **With the inclusion of background** the performance is even more similar
- **JER Performance similar** => Other criteria have a more increased significance (cost, engineering, machinability, …)

Proceed with using Steel as absorber for the next CLIC detector simulation model

Ongoing work:

HCAL ENDCAP COVERAGE OPTIMIZATION

HCal Coverage Extension - Introduction

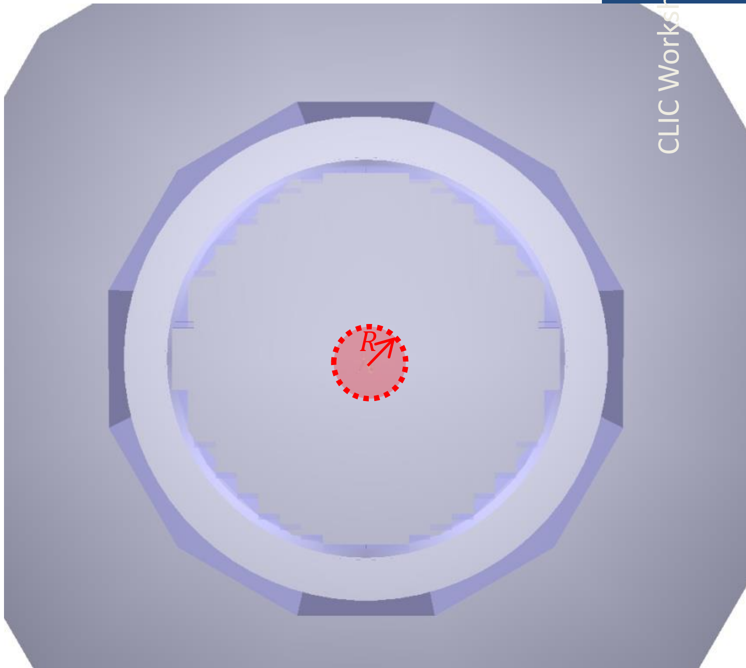
	cosθ	θ [rad]	θ [deg]	tanθ	R [mm]
	0.95	0.32	18	0.33	756
CLIC_ILD	0.989	0.15	8.6	0.15	400
ILD	0.991	0.13	7.5	0.13	350
	0.998	**0.06**	**3.2**	**0.06**	**150**
(Values for L=2.65 m)					

- Basically two (?) options:
  - Extend main HCal endcap
  - Introduce additional detector behind forward detectors
- Put as close to beampipe as possible; minimize beampipe radius
- Engineering, supports and beam instrumentation in the way
- Region engineering design is already highly optimized given present requirements (i.e. position of QD0)
- Before embarking on another engineering design adventure, revisit gains in physics performance with increased coverage in the presence of background
  - Study performance of physics processes as a function of R_{in}^{HCal}

Original Strategy

- Work with **ILD_o1_v06** (adapted to CLICdp Radius, Nlayers, etc)
- **Remove** BeamCal08, LumiCalV, LHcal01 and maskX03
- Need to extend coverage without messing up driver too much
  - Fully extend the calorimeter down to $R_{in} = 0$
  - Simulate once, reconstruct many: Mask (remove) HCal hits within given $\boldsymbol{R}$ before creating PFOs
  - Ignoring secondary interactions (probably won't work)

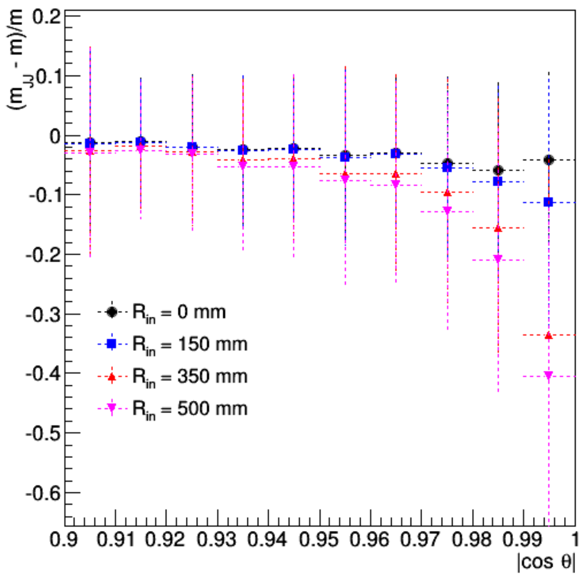
- <u>First attempt</u>: Study W/Z overlap in WW and ZZ events (same as Barrel study)
  - Peak forward direction at higher $\sqrt{s}$
- Proven to be too convoluted
- Fallback: Study m_Z resolution in ZZ events
  - More straightforward method, more appropriate for a first study
  - First results (without background) on next slide

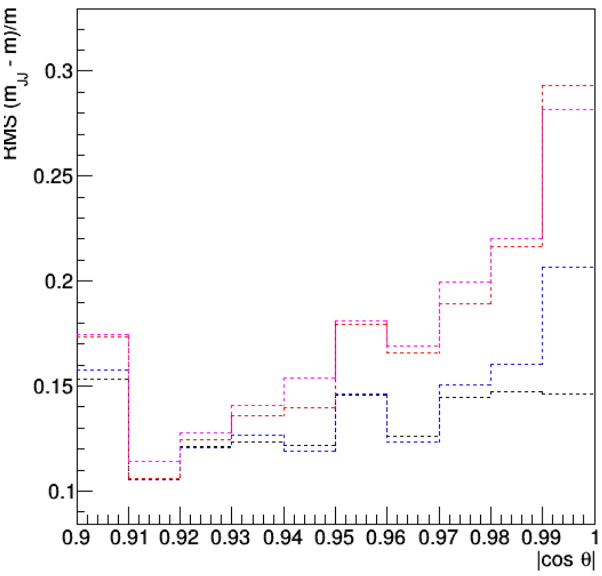


Preliminary Results and Problems

- Profile of m_{JJ} and its RMS as a function of $\cos(\theta_Z)$ for various R_{in}
- Without background overlay for now

=> Not much information





- With the inclusion of background (60 BX $\gamma\gamma \rightarrow had$) there was a problem reconstructing m_{JJ} properly, even with the Tight cuts
  - Looking into FastJet configuration and other parameters
- Could very well be that one cannot ignore the secondary interactions outside the masking radius -> It was suggested to actually remove the particles from the event (and simulate for each model)
  - No easy way to do so with Mokka/stdhep; first attempts failed or corrupted the event
  - Will either try again or write a new HCal driver with variable R_{in}

Summary and Next Steps

- **HCal barrel** optimization studies were performed varying the material and number of layers. Complementary to other ongoing studies
- For the new CLIC detector simulation model:
  - A realistic active layer cassette layout was proposed
  - It was decided to move with a steel HCal barrel
- A CLICdp note is in preparation

- For the HCal Endcap coverage extension, studies are ongoing to gauge gains in physics performance, weighted against increased acceptance of background
- Encountered several issues during first attempts
- Confident that it will eventually yield results so we can propose new requirements for an updated engineering design

BONUS MATERIAL – OLDER PLOTS

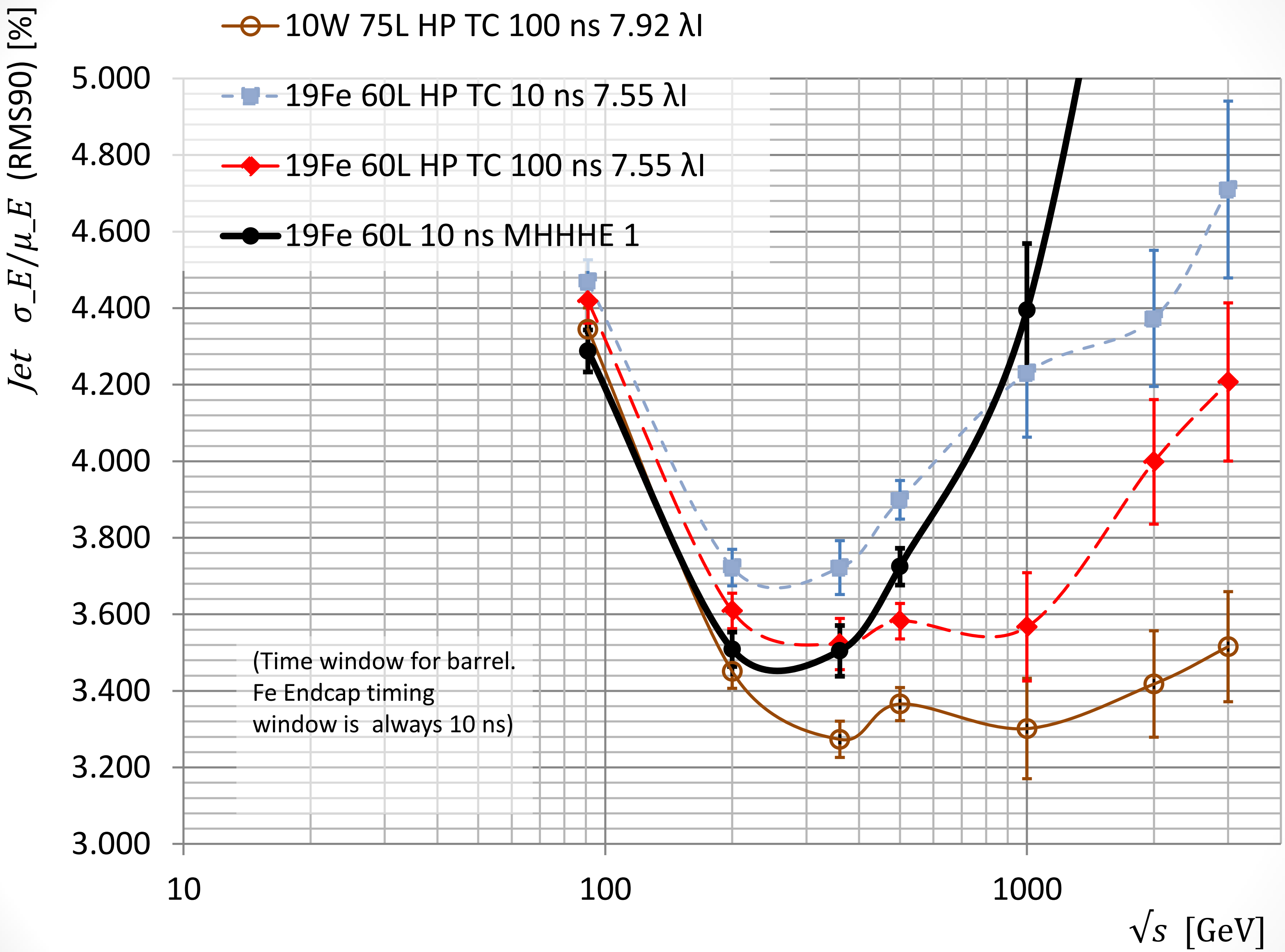
Outline of Calibration Procedure and JER study

- Modify ILD_o1_v06 model in Mokka
  - $R_{ECal}^{in} = 1500$ mm, 4.5 T field (constant for all variations, rest same as ILD)
  - Vary absorber material and thickness in HCal Barrel
- Simulate events in Mokka/G4 (**QGSB_BERT_HP**):
  - γ (10 GeV), μ (10 GeV), K0L(1,2,5,10,20,50,100,200,500 GeV) [G4 GPS]
  - Also generate $Z \rightarrow uds$ events ($\sqrt{s} = 91{,}200{,}360{,}500$ GeV and 1,2,3 TeV) [stdhep files]
- Hit-level, digitization calibration:
  - Dump root ntuples from LCIO files with sum of energies per layer
  - Use γ events to set CalibrEcal (do once, assume same then)
  - Use 50 GeV K0L to set CalibrHCalBarrel (do for every variation of HCal). Do once for CalibrHCalEndcap and keep the same (not varying endcap)
  - Use μ to set EcalToMip (verified that remains ~the same) and HcalToMip
  - Assume CalibrMuon, CalibrOther, same as ILD

Outline of Calibration Procedure - II

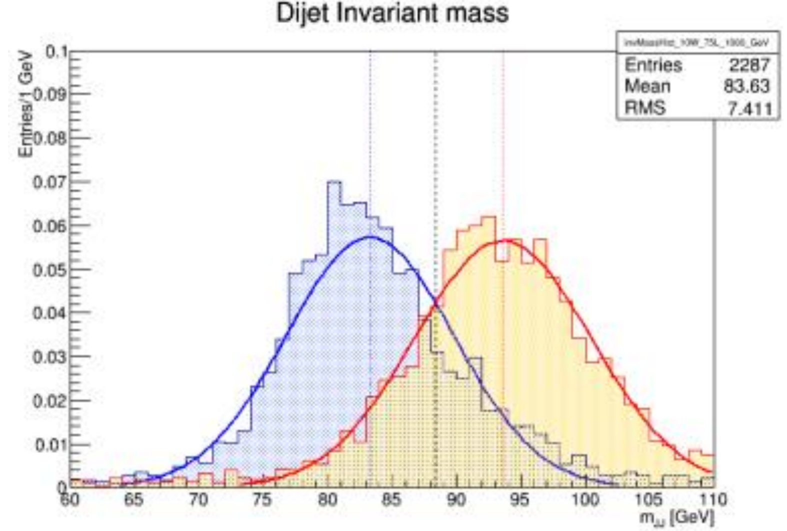
- PandoraPFA calibration:
  - Run PandoraPFA over the γ events to get ECALToEM , HCALToEM (actually set both to 1 for these studies)
  - Run Calibration procedure over the Kaon events to obtain ECALToHAD, HCALToHAD at 50 GeV
  - Obtain **Non-Linearity Corrections (NLC) [Note Difference from Steve's studies who does not use NLC]:**
    - Measure response for 1,2,5,10,20,50,100,200,500 GeV Kaons and calculate scaling factor (extrapolate in-between)
- Recalibrate when changing **Readout Window Timing Cut**
- Having these numbers, we can study the Jet Energy Resolution
- Use AnalysePerformance (from PandoraAnalysis-v00-06)
- Study the performance various models
  - Also look at different Timing Cuts

19Fe 60L 10 ns HCal with MHHHE=1 and 20 ns ECal



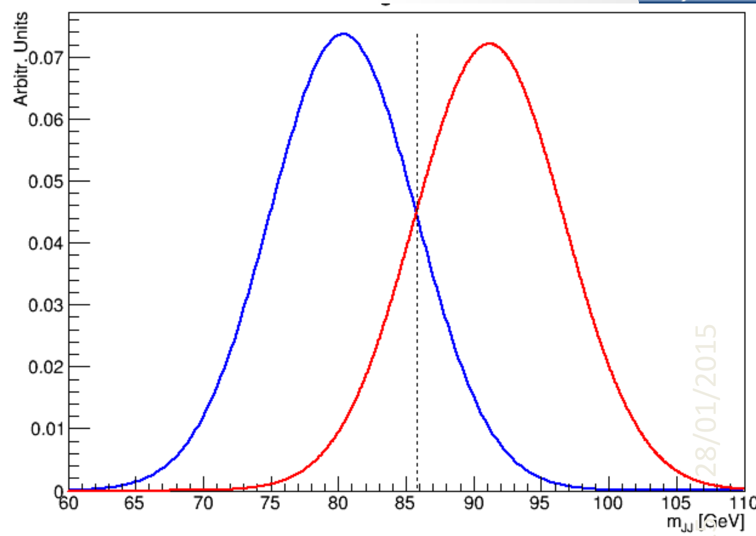
Performance of **10 ns Steel HCa**l is now comparable to the performance of **100 ns Steel** with previous calibration at low energies

W/Z Separation Study - Reminders



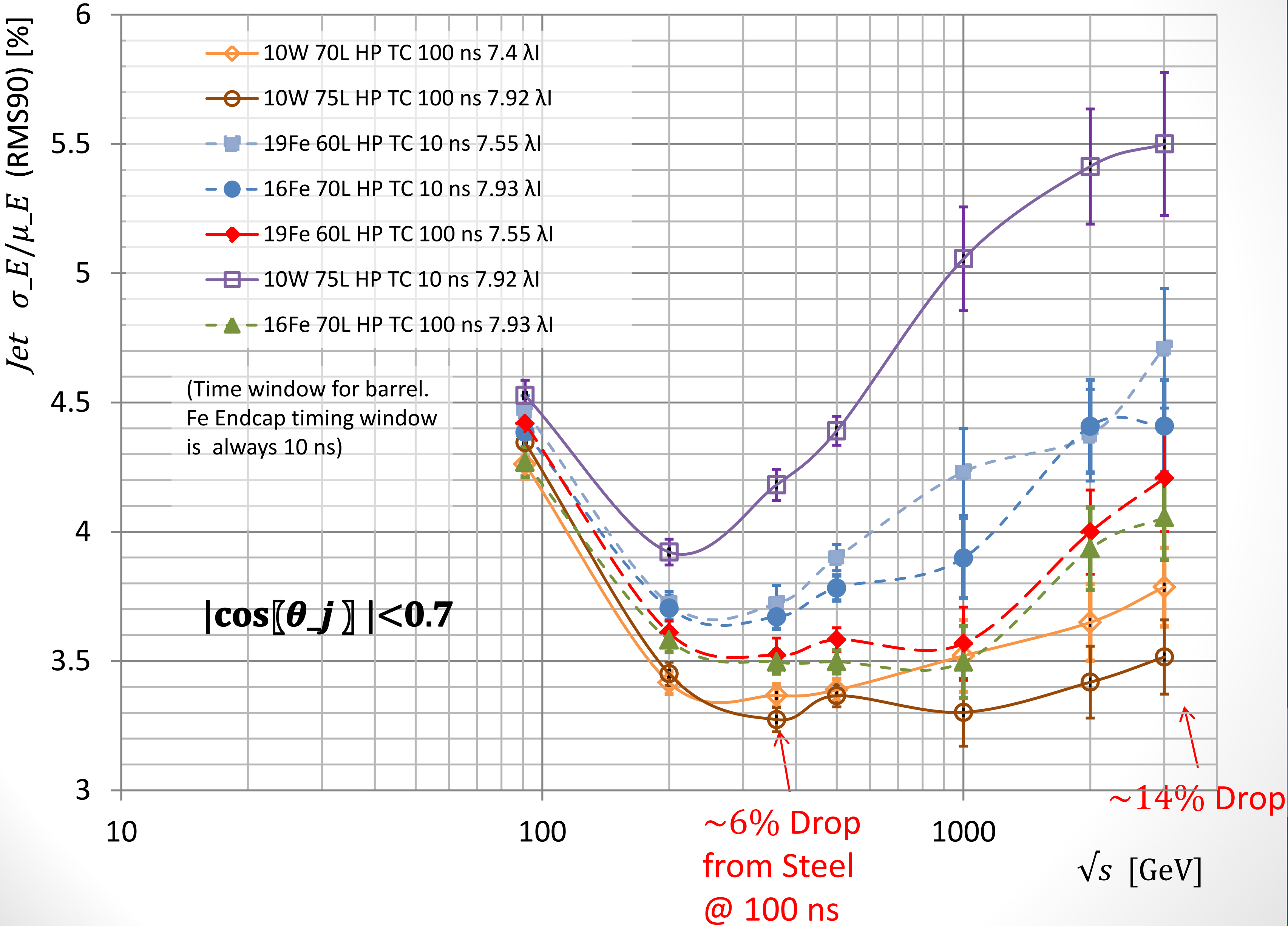
- Generating WW and ZZ events. At various center of mass energies $\sqrt{s}$
- One of the bosons in the pairs decays to 2 jets
- Obtain jets with energies $\sim\sqrt{s}/4$
- Reconstructing dijet invariant mass m_{JJ}
- Calculate overlap of W/Z mass peaks and estimate equivalent separation in terms of N_σ
- Perform with and without $\gamma\gamma \rightarrow had$ background overlay (60 BX)
- Added some more data since last time
- Today plot also includes studies from similar study previously performed in “Performance of Particle Flow Calorimetry at CLIC” (J. Marshall *et al.*)

W/Z Separation Study – cont'd



- Draw unit gaussians at nominal $m_W = 80.385$ GeV and $m_Z = 91.188$ GeV with fitted widths
- Find intersection analytically:
- $x_{int} = \frac{-\beta \pm \sqrt{\beta^2 - 4\alpha\gamma}}{2\alpha}$ with $$\alpha = \sigma_2^2 - \sigma_1^2$$ $$\beta = 2(\sigma_1^2\mu_2 - \sigma_2^2\mu_1)$$ $$\gamma = \sigma_2^2\mu_1^2 - \sigma_1^2\mu_2^2 - 2\sigma_1^2\sigma_2^2 \log\frac{\sigma_2}{\sigma_1}$$
- Define "Overlap fraction":
  - $A_O = \left(\int_{60}^{x_{int}} f_Z(x)dx + \int_{x_{int}}^{110} f_W(x)dx\right)/2$
- Equivalent ideal gaussian separation:
  - $N_{sep} = 2|ROOT :: Math :: normal\_quantile(A_0, 1)|$
  - **Basically the number of σ the means are apart** for two gaussians with the same σ and different means
- Unfortunately, calculating uncertainties is time consuming, so I neglected to do so

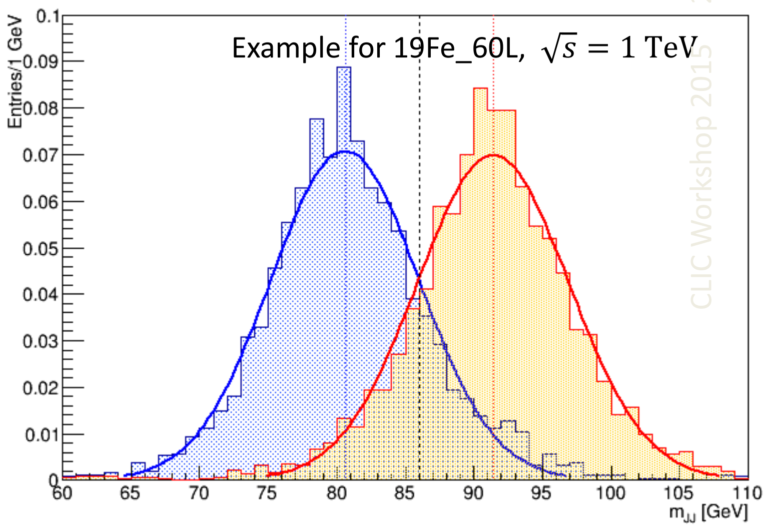
JER Results



6
5.5
5
4.5
4
3.5
3
10
100
1000
Jet σ_E/μ_E (RMS90) [%]
√s [GeV]
10W 70L HP TC 100 ns 7.4 λI
10W 75L HP TC 100 ns 7.92 λI
19Fe 60L HP TC 10 ns 7.55 λI
16Fe 70L HP TC 10 ns 7.93 λI
19Fe 60L HP TC 100 ns 7.55 λI
10W 75L HP TC 10 ns 7.92 λI
16Fe 70L HP TC 100 ns 7.93 λI
(Time window for barrel.
Fe Endcap timing window
is always 10 ns)
|cos⁡(θ_j)|<0.7
~6% Drop
from Steel
@ 100 ns
~14% Drop

W/Z Separation Study

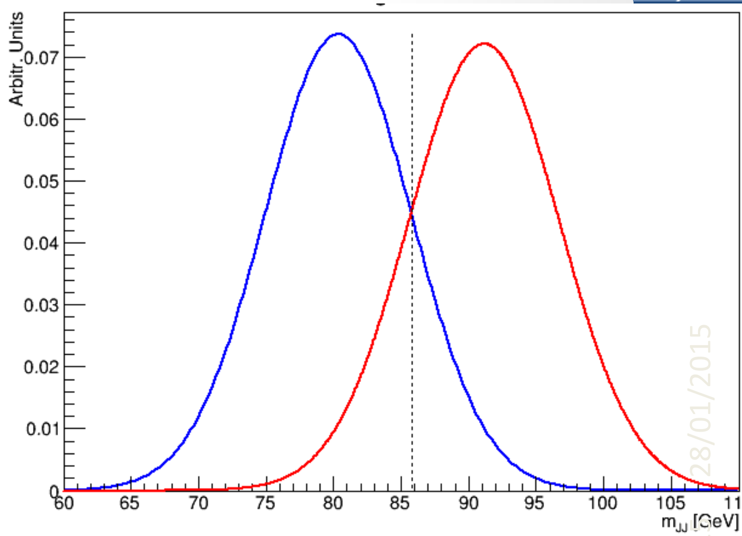
- $ZZ \rightarrow \nu\nu\boldsymbol{dd}$ and $WW \rightarrow \nu\ell\boldsymbol{ud}$: **2 jets in an event topology similar to interesting physics events.**
- **Method similar to PFA perf. Studies (stdhep files should be the same)**
  - **See arXiv:1209.4039 and LCD-Note-2011-028**
  - $\sqrt{s} = 250, 500, 1000, 2000$ GeV
- Half of energy shared between the two jets, dijet invariant mass $\sim m_W \mid m_Z$
  - **Gauge performance of different HCal models by looking at its W/Z separation power**
- Use *FastJet* Marlin Processor to exclusively find and reconstruct 2 jets
  - For WW: First remove lepton from PFOParticles (matching to MC within cone with $|\cos(\theta)| < 0.9998$)
  - No truth linking info due to bug with Mokka/G4 9.6
- Simulate and reconstruct events for each energy and model ***(19Fe_60L, 10W_70L and 10W_75L)***
- Plot m_{JJ} for $|\cos(\theta_{W,Z,J_0,J_1})| < 0.7$ and $60 < m_{JJ} < 110$ GeV



- **The overlap of the two peaks is an estimate of the separation**
- Still some tails, so fit around m_W, m_Z iteratively within 3σ and use fits for overlap calculation
- **Note: No beam induced background assumed for now**

W/Z Separation Study – cont'd

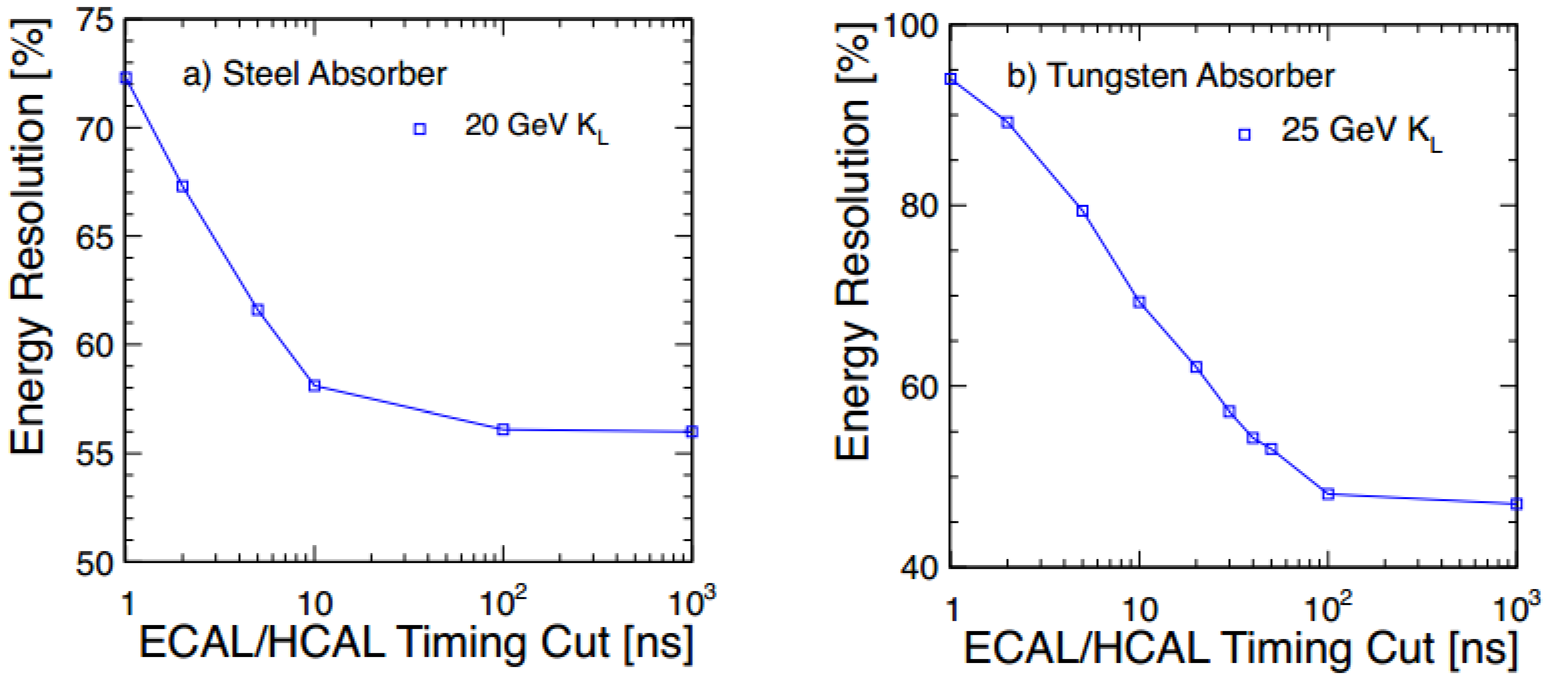
- Draw unit gaussians at nominal $m_W = 80.385$ GeV and $m_Z = 91.188$ GeV with fitted widths
- Find intersection analytically:
- $x_{int} = \frac{-\beta \pm \sqrt{\beta^2 - 4\alpha\gamma}}{2\alpha}$ with $\alpha = \sigma_2^2 - \sigma_1^2$, $\beta = 2(\sigma_1^2\mu_2 - \sigma_2^2\mu_1)$, $\gamma = \sigma_2^2\mu_1^2 - \sigma_1^2\mu_2^2 - 2\sigma_1^2\sigma_2^2 \log\frac{\sigma_2}{\sigma_1}$
- Define "Overlap fraction":
  - $A_O = \left(\int_{60}^{x_{int}} f_Z(x)dx + \int_{x_{int}}^{110} f_W(x)dx\right)/2$
- Equivalent ideal gaussian separation:
  - $N_{sep} = 2|ROOT :: Math :: normal\_quantile(A_0, 1)|$
  - **Basically the number of σ the means are apart** for two gaussians with the same σ and different means
- Unfortunately, calculating uncertainties is time consuming, so I neglected to do so



Energy	19Fe_60L		10W_70L		10W_75L	
[GeV]	Overlap [%]	Nsep [σ]	Overlap [%]	Nsep [σ]	Overlap [%]	Nsep [σ]
250	11.3	**2.4**	10.6	**2.5**	10.3	**2.5**
500	11.9	**2.4**	11.3	**2.4**	10.6	**2.5**
1000	16.2	**2.0**	14.9	**2.1**	14.2	**2.1**
2000	22.3	**1.5**	21.2	**1.6**	22.0	**1.5**

Reminder: Readout Windows

- See talks by M. Thompson:
  - http://indico.cern.ch/event/115459/contribution/14/material/slides/0.pdf (slides 3,4)
  - https://agenda.linearcollider.org/getFile.py/access?contribId=13&sessionId=1&resId=0&materialId=slides&confId=5134 (slides 16,17…)



Steel (Endcap): ~10 ns

Tungsten (Endcap): ~100 ns

Further timing cuts (mainly for background/pileup suppression) are applied at the PFO level. NOT CONSIDERED IN THE STUDY PRESENTED TODAY

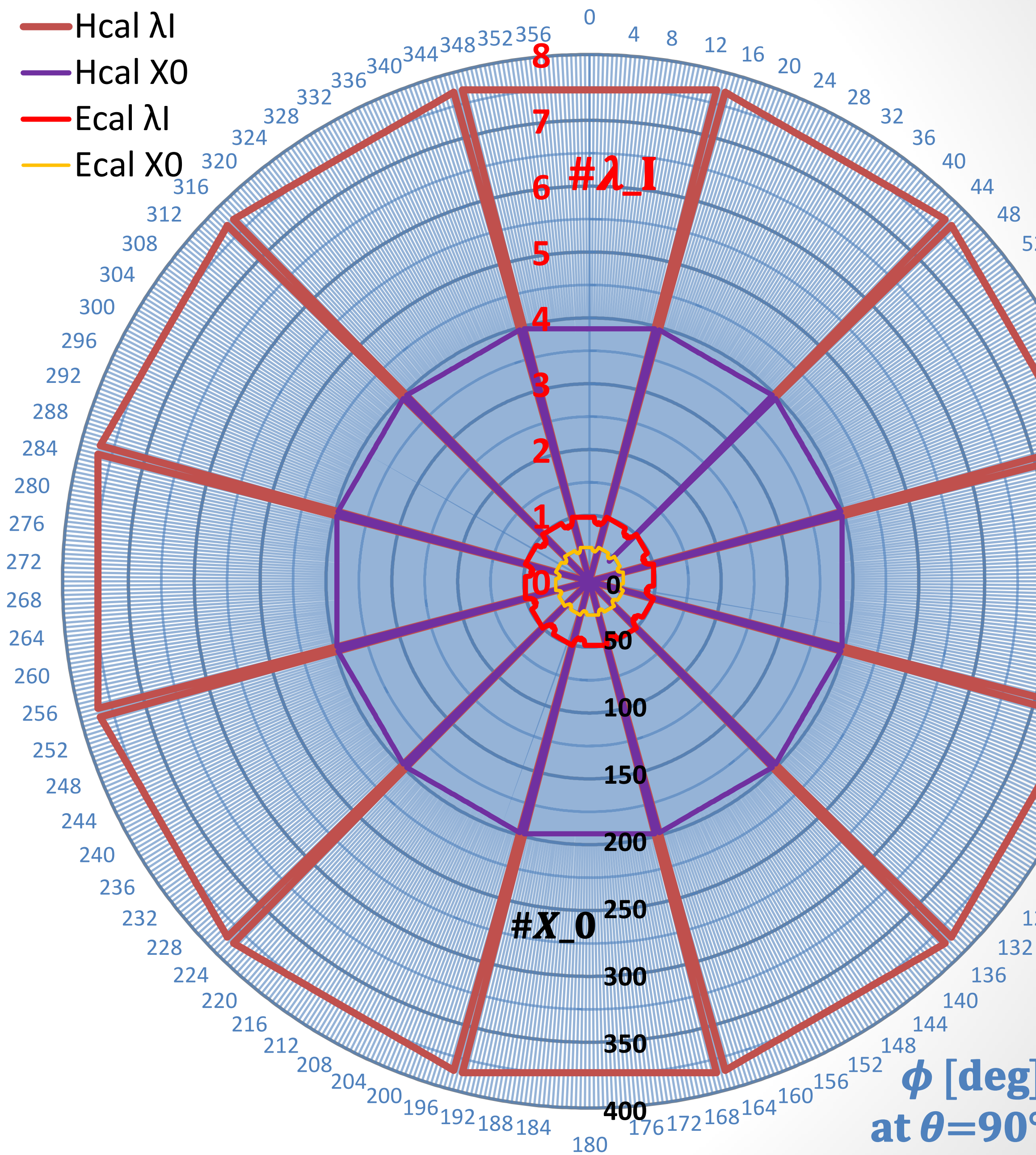
- **We will apply cuts at the digitization level**

Material Scan of W-HCAL (CLIC_SID_CDR)

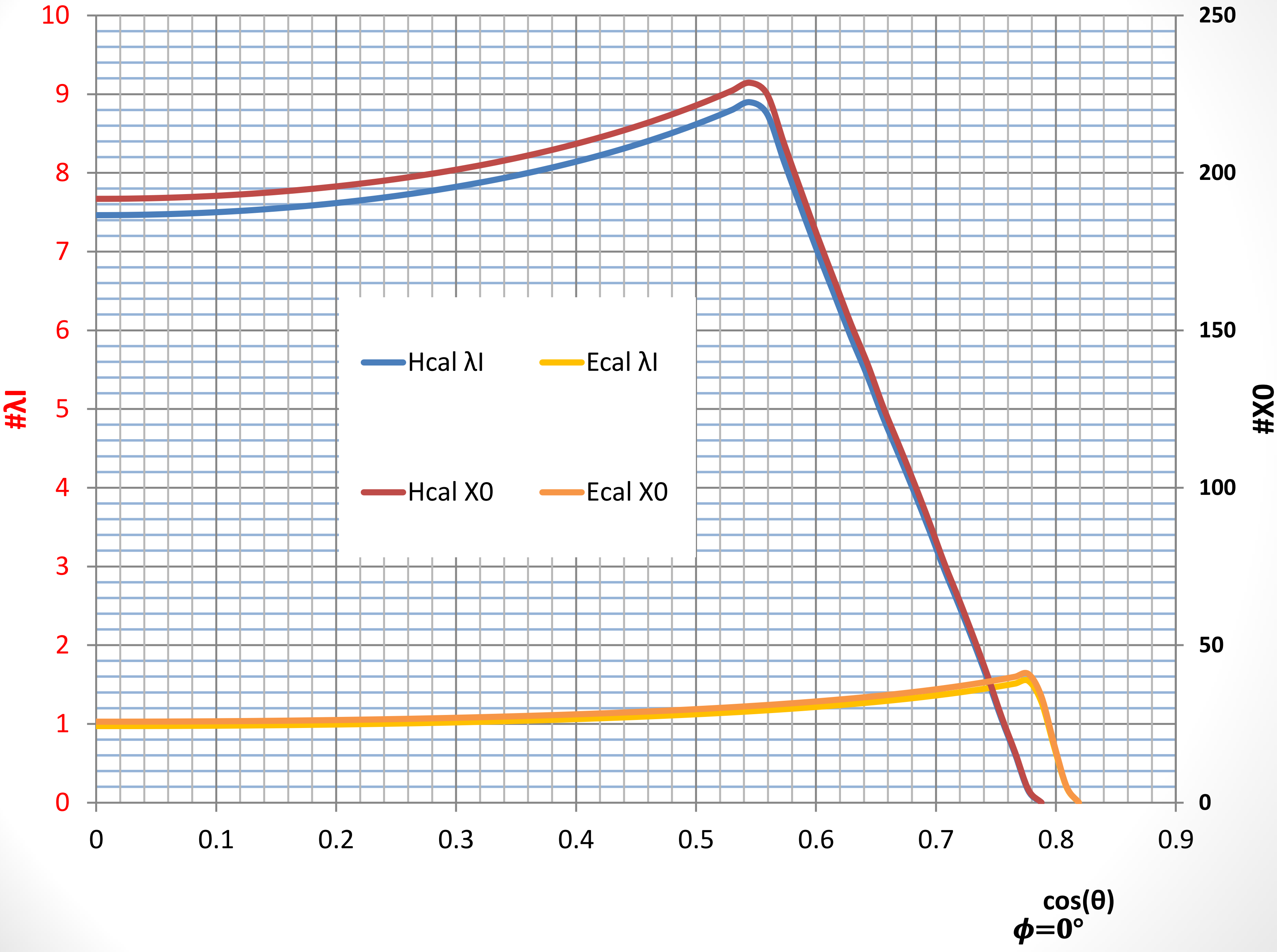
- Try to verify material budget in current detector geometry implementations
- See whether we can squeeze some more the HCal outer radius
- Scan using Slic/Geant4 (see backup)
- Geometry Parameters:

(www.lcsim.org/detectors/clic_sid_cdr.html)

HCAL BARREL	
Number Of Layers	75
Number Of Sides	12
Inner Radius	1419 mm
Outer Radius	2656.5 mm
Z Length	3530 mm
Section Phi	0.52 radians
Cell Size U	30.0 mm
Cell Size V	30.0 mm
Layers 0 - 74	
10 mm	Tungsten
5 mm (sensor)	Polystyrene
1.5 mm	Air



CLIC_SID_CDR Material Scan in θ

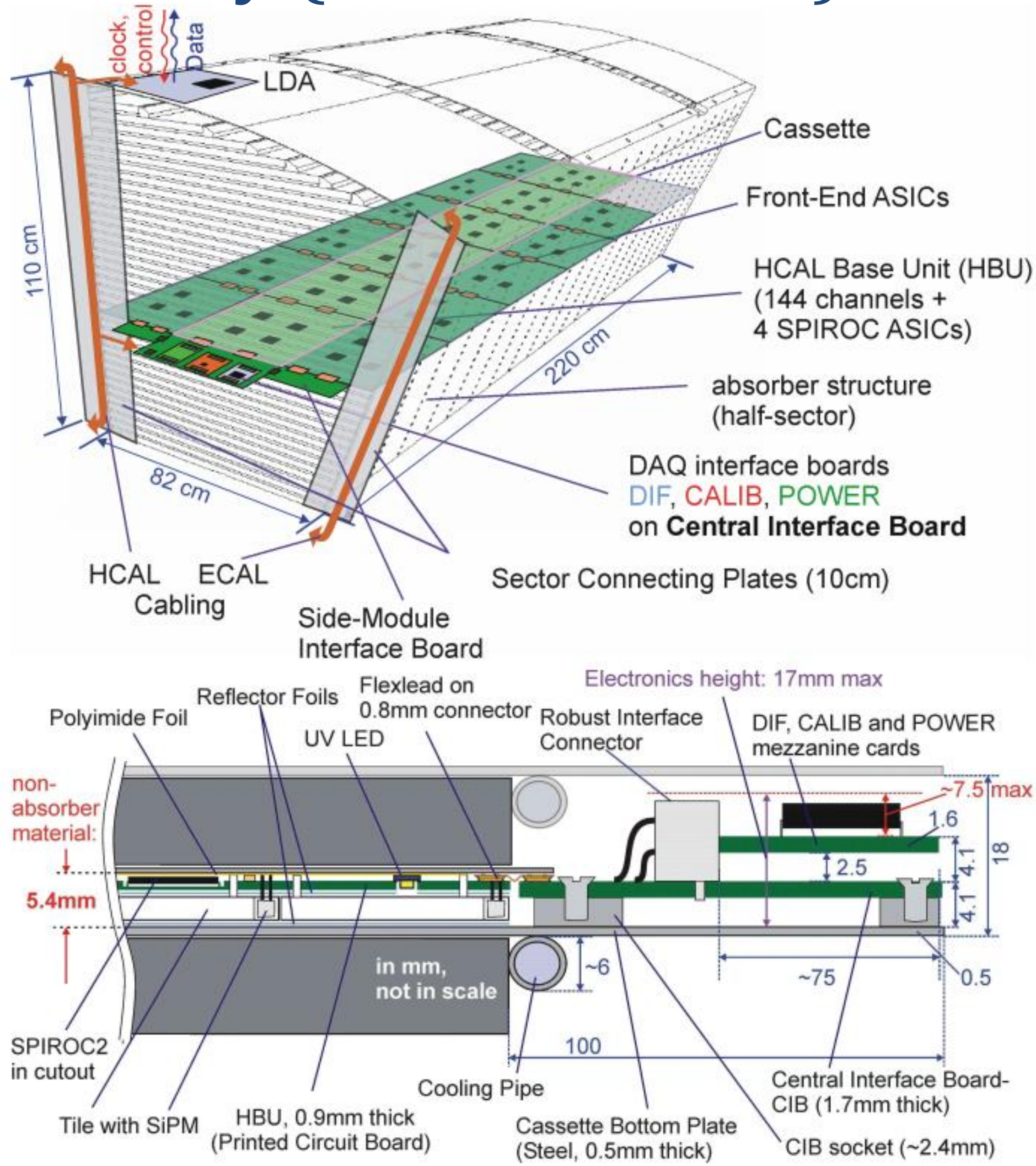


ILD AHCAL Assembly (from ILD TDR)

Figure III-3.14
Arrangement of AH-CAL layers with electronic components (left), cross section of an active layer (right).

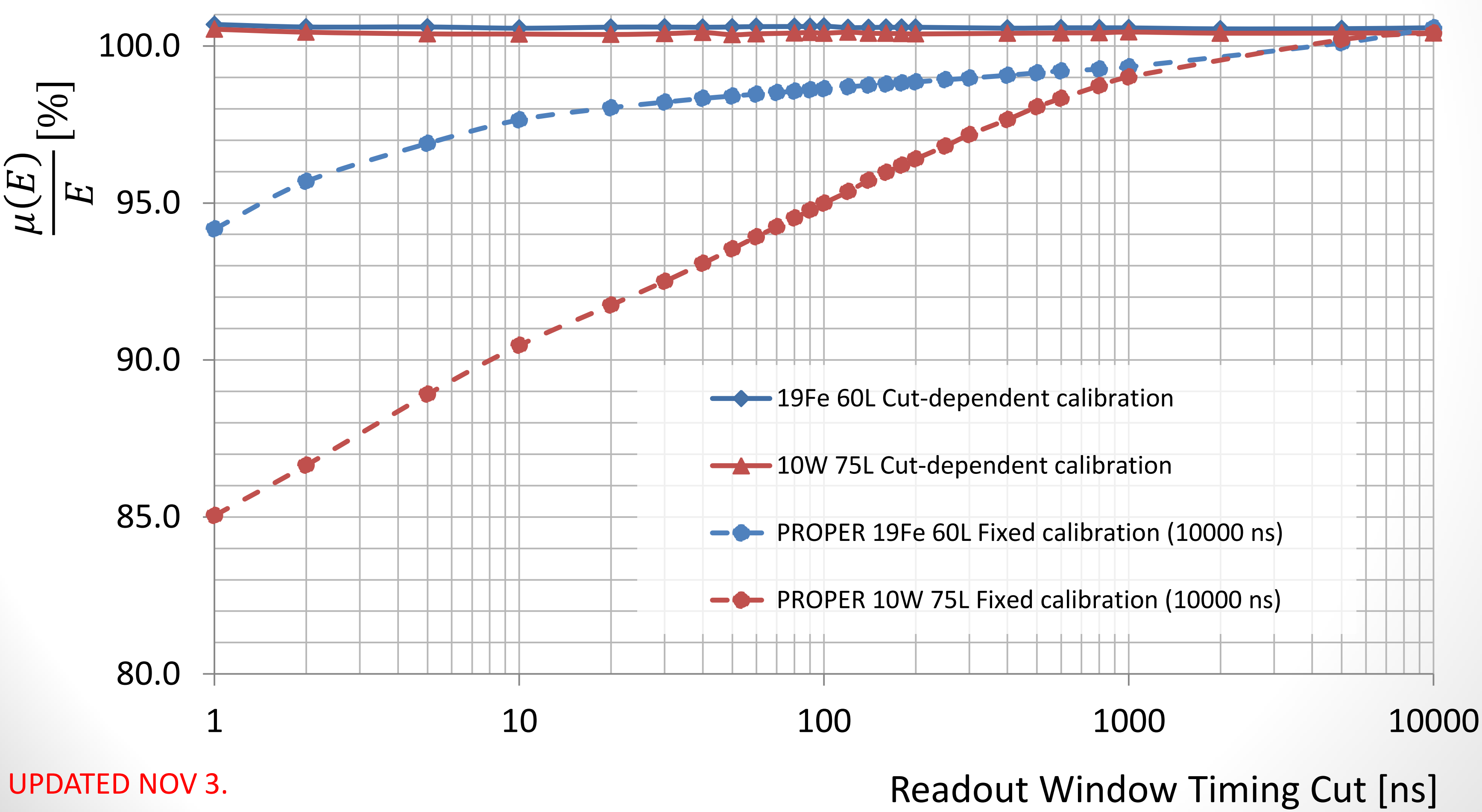
Active Element Cassette		ILD
Material	Thickness mm	Thickness mm
Steel	2	0.5
PCB	1.4	1
Cu (etching)	0.1	0
Electronics (30%)	1.5	1
Scintillator	5	3
Sum (per layer)	**10**	5.5
#λI (per layer)	**0.02**	0.01

- NB: ILD TDR also mentions "The active layers will contribute 4 mm of steel to each absorption layer"
- Not shown in diagram?
- 16 mm (absorber layer) + 4 mm = 20 mm steel
- +0.5 mm bottom plate?
- Not clear what is done in code (comment says ignored)



Tungsten and Steel Response to 50 GeV K0L for various Timing Cuts: Fraction of Reconstructed Energy

- Tighter timing cut = Smaller Fraction of reconstructed energy
  - Tungsten is more sensitive
  - Calibration procedure adapts to correct for the lost energy

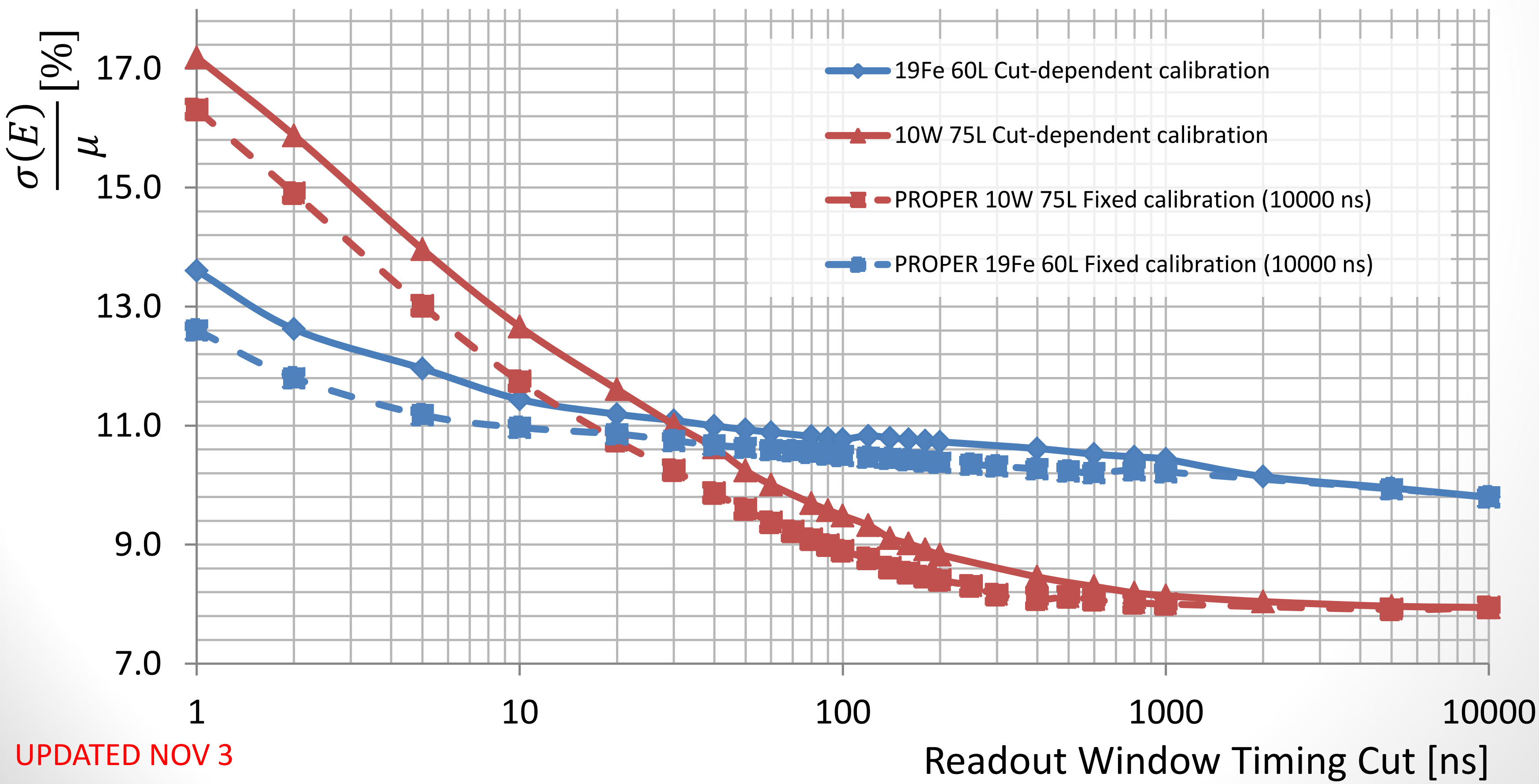


UPDATED NOV 3.

Tungsten and Steel Response to 50 GeV K0L for various Timing Cuts: Energy Resolution (normalized to fitted mean)

- First attempt to reproduce previous studies by M. Thomson and J. Marshall (see backup)
- **Similar conclusion to JER study:**

Tungsten@100 ns "outperforms" Steel at 10 ns and 100 ns



UPDATED NOV 3