Optimizing the Hadronic Calorimeter for a detector at CLIC:
HCal Barrel absorber material

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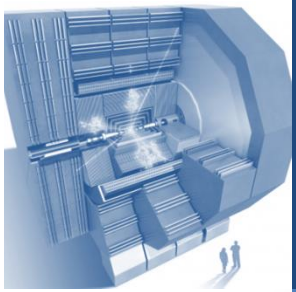
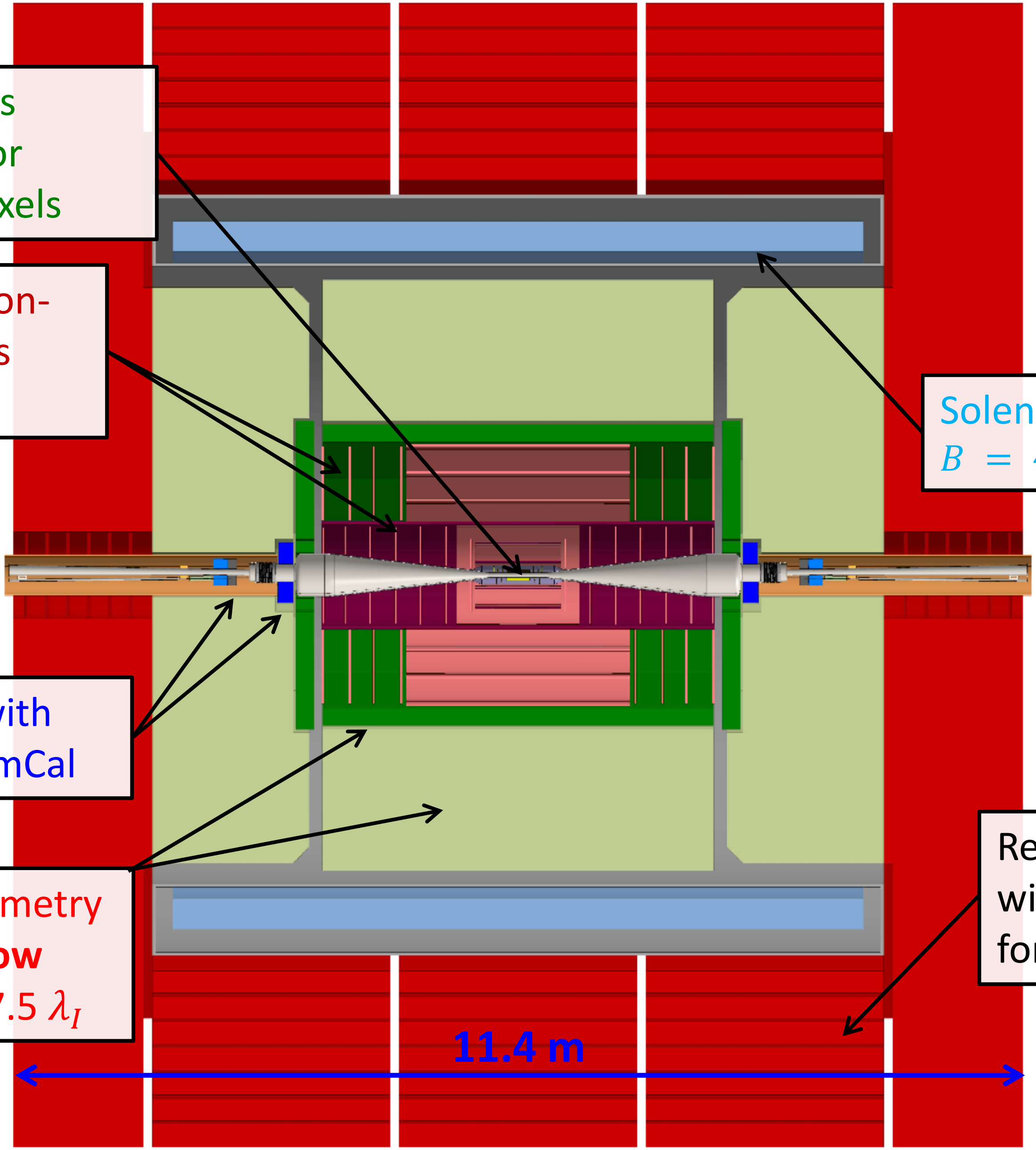


A detector for CLIC

Designed for excellent Jet Energy Resolution



Ultra low-mass vertex detector with 25 µm pixels

Main tracker, silicon-based (large pixels and/or strips)

Solenoid Magnet, $B = 4\ \mathrm{T}$, $R_{in} = 3.4\ \mathrm{m}$

Forward region with LumiCal and BeamCal

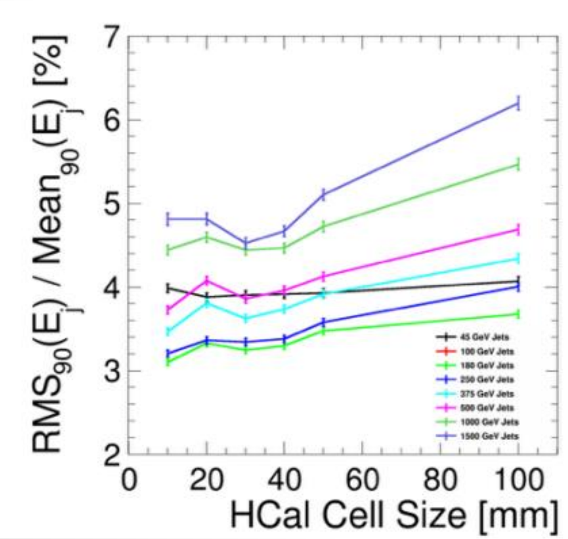
Fine grained calorimetry used in **Particle Flow (PFA)**, Depth: $1 + 7.5\ \lambda_I$

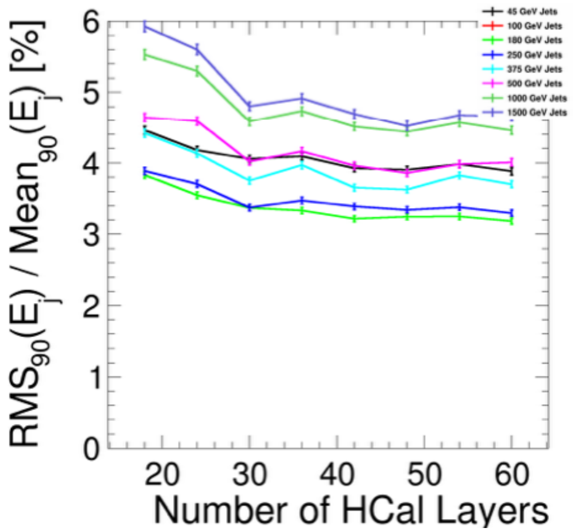
Return yoke (Fe) with detectors for muon ID

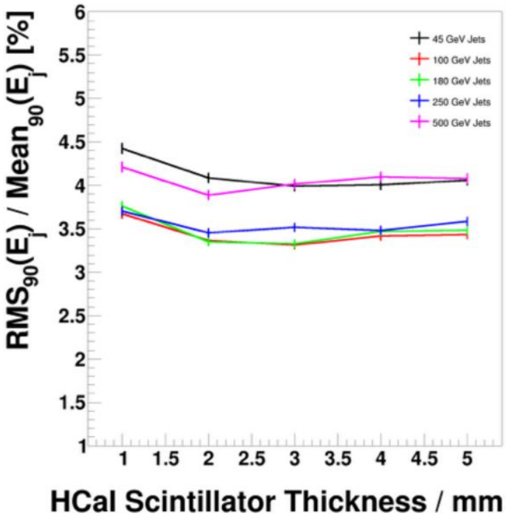
11.4 m

HCal Optimization

- **CLIC detector HCal in CDR**: **Tungsten** (W) in **Barrel**, **Steel** (Fe) in **Endcap**, scintillator active element
- Revisited optimization to determine if HCal size (and therefore coil radius) could be reduced or **W replaced with Fe (both cost drivers)**
- **Topics not covered in this talk (additional studies)**
  - **Cell size** optimization: 30x30 mm is a reasonable choice
  - **Number of layers**: 60 layers and above the performance is reasonable
  - **Scintillator thickness**: 3 mm is optimal







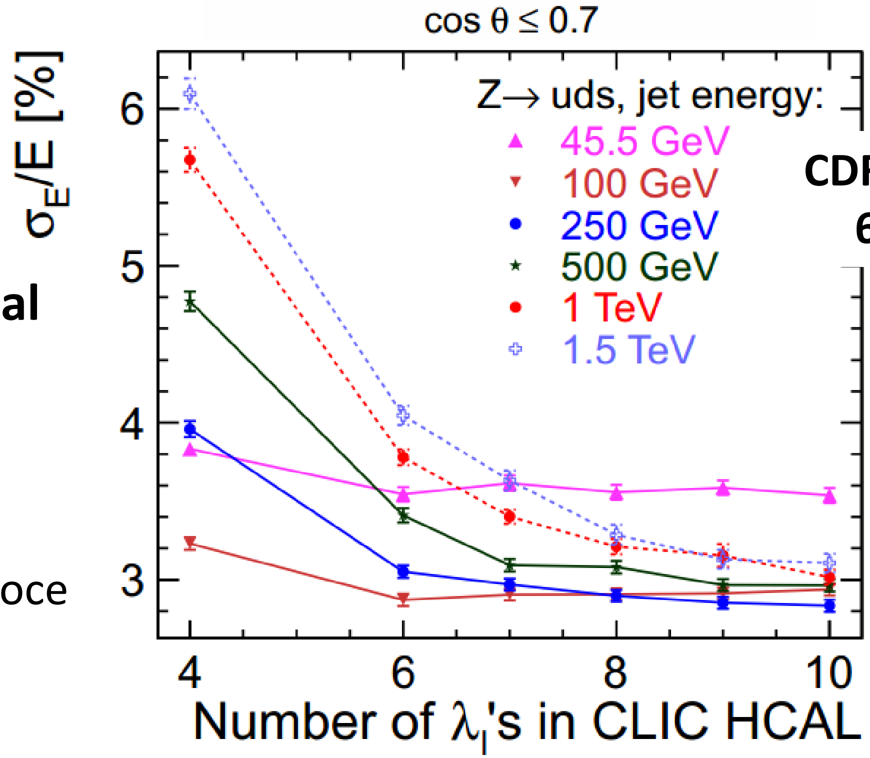
Some notes

- Most of the studies (especially the earlier ones) performed with **`Mokka`** (simulation tool previously used by ILD) in **full simulation** from detector drivers adapted from ILD
  - **`Geant4 9.5.p02`** (latest supported by **`Mokka`**)
  - **`QGSP_BERT_HP`** physics list (high precision neutron data important)
- Notice that the **new geometry, simulation and reconstruction framework based on DD4hep** is already now in use by the Linear Collider community
- Studied mainly **performance after `Pandora` Particle Flow reconstruction** but looked at single-particle performance as well
- Optimization often requires independently varying parameters that are correlated
- **Modifying the geometry requires recalibrating the digitization and particle flow reconstruction**

Previous Studies for the CLIC CDR

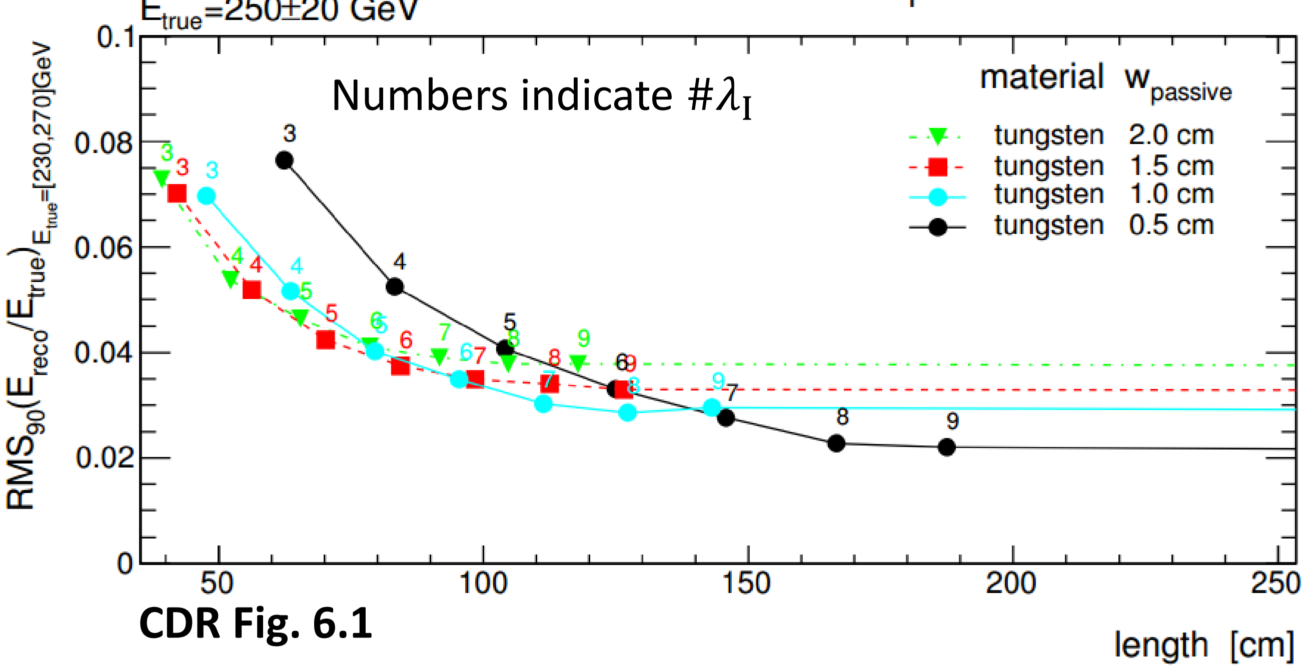
- **These studies drive the aim for an HCal depth of $\sim 7.5\ \lambda_I$ at $\theta \approx 90°$**
  - **Try now to constraint the Radial size of the HCal**

- 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

Various Model Options for the HCAL Barrel

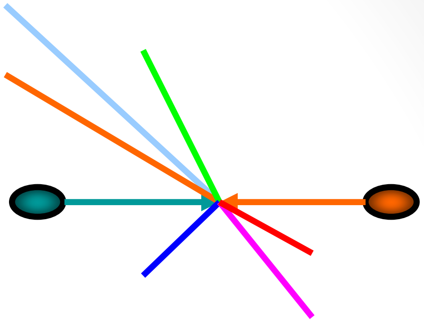
- Try variations **of absorber material, thickness and number of layers** resulting in depth around 7.5 λI (established from CDR studies)

- Modify `ILD_o1_v06` model in `Mokka`
  - Set $R_{in}^{HCal} = 1750$ mm, additional absorber plate at the end, 1 mm steel in **cassette (more realistic makeup of the layer)**
  - 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						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 . We will focus only on these two options

Methods to Gauge HCal Performance

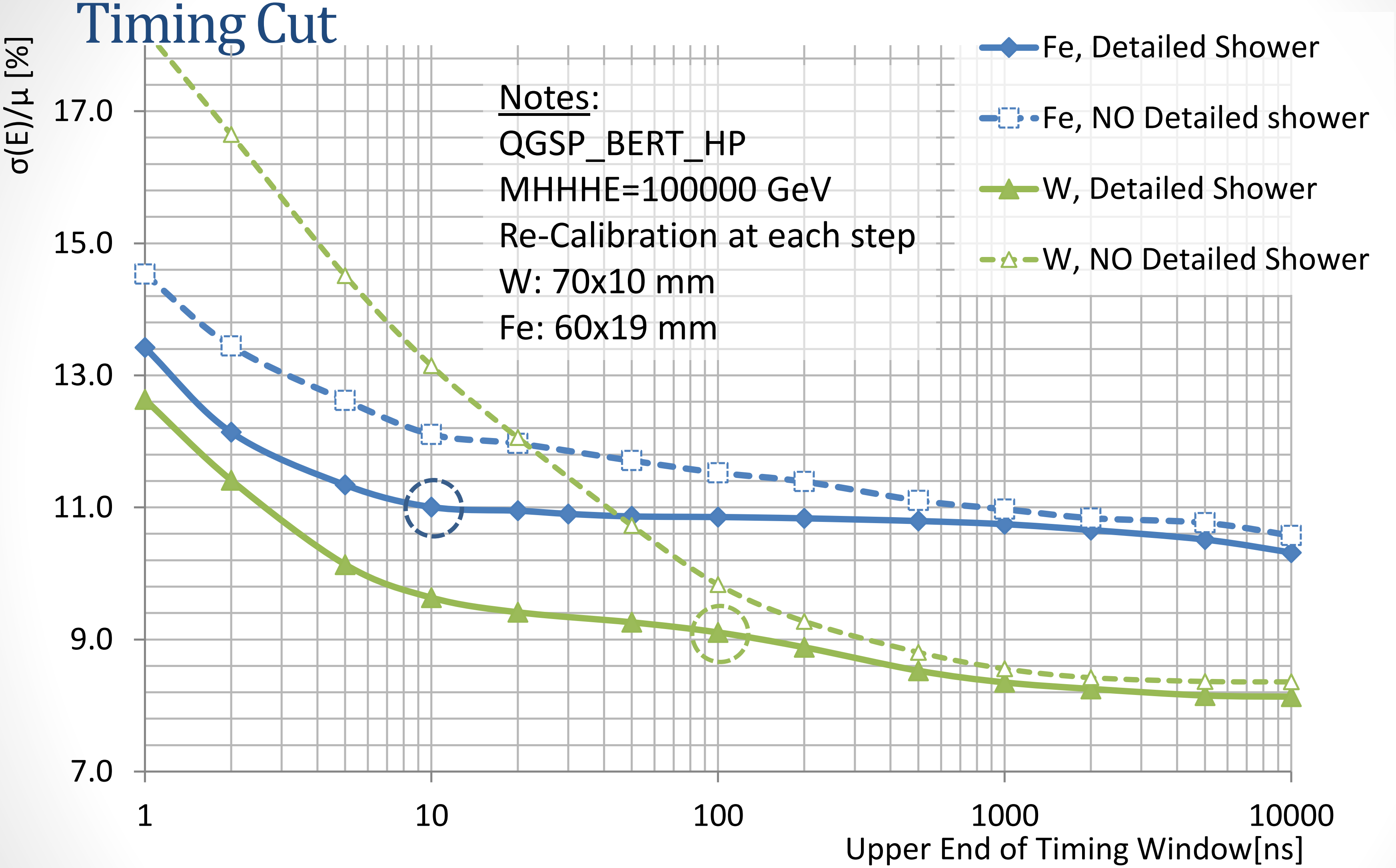


- Single Particle Response
  - E.g. single K_L^0 energy resolution
- Jet Energy Resolution (JER):
  - **From total Deposited Energy in $Z' \to q\bar{q}$ $(q = u, d, s)$**
    - Use **AnalysePerformance** (from **PandoraAnalysis**)
      - **Estimates single jet energy resolution from total reconstructed energy:** $\frac{RMS_{90}(E_j)}{mean_{90}(E_j)} = \frac{RMS_{90}(E_{jj})}{mean_{90}(E_{jj})}\sqrt{2}$
  - **From m_Z and m_W measurement from m_{jj} in $ZZ \to \nu\nu dd$ and $WW \to \nu\ell ud$ events, respectively**
    - **Use m_{JJ} overlap estimation as JER gauge**
  - **N.B.:** We simulate at **“several different $\sqrt{s}$ values”** as a technique to obtain jets of various energies

Calibration procedure

- Each model had to be individually **calibrated** before performing any study
- **Full simulation of single particles uniformly distributed in the detector:**
  - 10 GeV photons
  - 10 GeV muons
  - 50 GeV K_L^0
- **Perform iteratively:**
  1. Hit-level digitization calibration (ECal, HCal, mip-scale)
  2. Pandora PFA-level calibration (ECalToEM, HCalToEM, HCalToHad)
  3. Obtain single particle response
- Other *software* parameters to optimize/pay attention to:
  - **Time window** cuts (during digitization, PFO reconstruction)
  - **Cut on Maximum HCal Hit Hadronic Energy** (MHHHE)

W/Fe Response to 50 GeV Single K0L Vs HCal Barrel Timing Cut

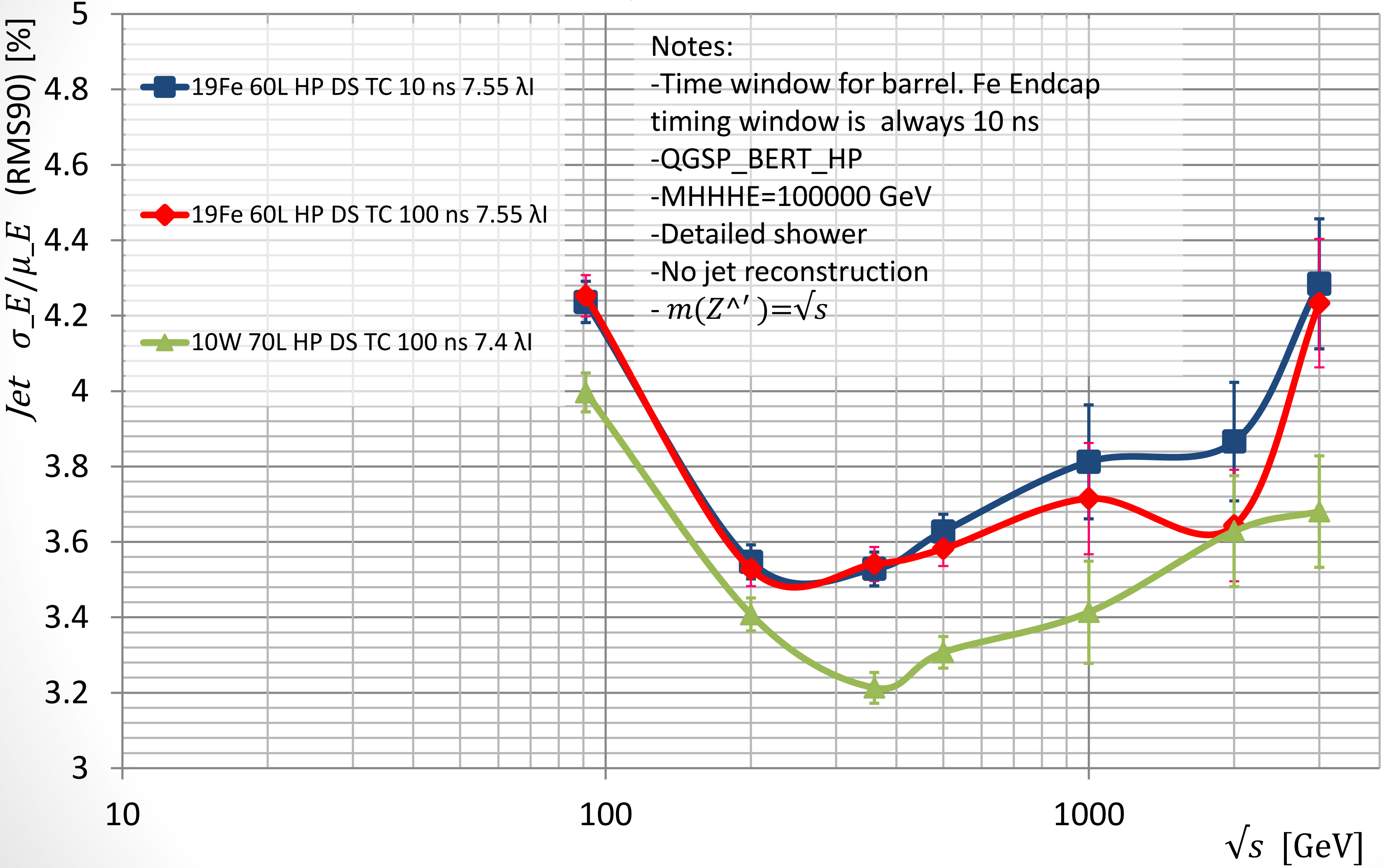


Notes:
QGSP_BERT_HP
MHHHE=100000 GeV
Re-Calibration at each step
W: 70x10 mm
Fe: 60x19 mm

- **Important to enable storing the Detailed Shower information (detailed list of contributions to cell energy and time from secondary particles)**

W Vs Fe JER without background overlay: $Z' \rightarrow uds$

Results using `AnalysePerformance` in `PandoraAnalysis`
(from sum of total PFO energy)

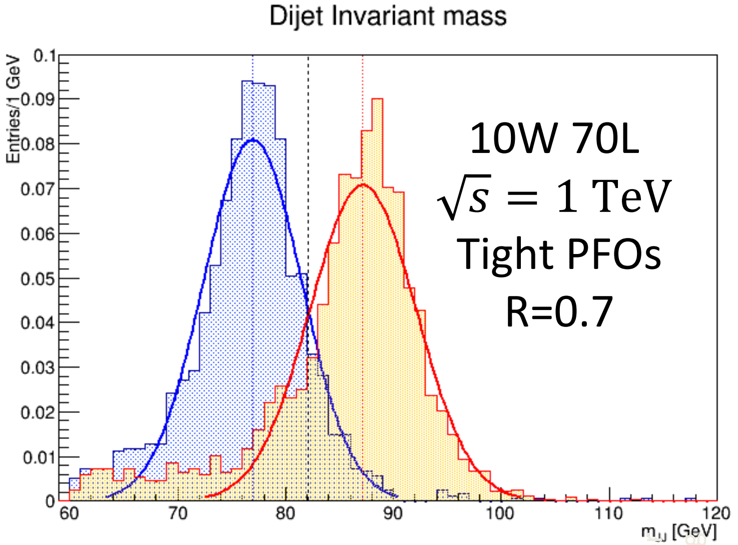


Notes:
-Time window for barrel. Fe Endcap timing window is always 10 ns
-QGSP_BERT_HP
-MHHHE=100000 GeV
-Detailed shower
-No jet reconstruction
- m(Z^′)=√s

- **W** appears to perform better than Fe (without using s/w comp) **but it should not drive solely our decision** (also, MHHHE is unrealistically large)

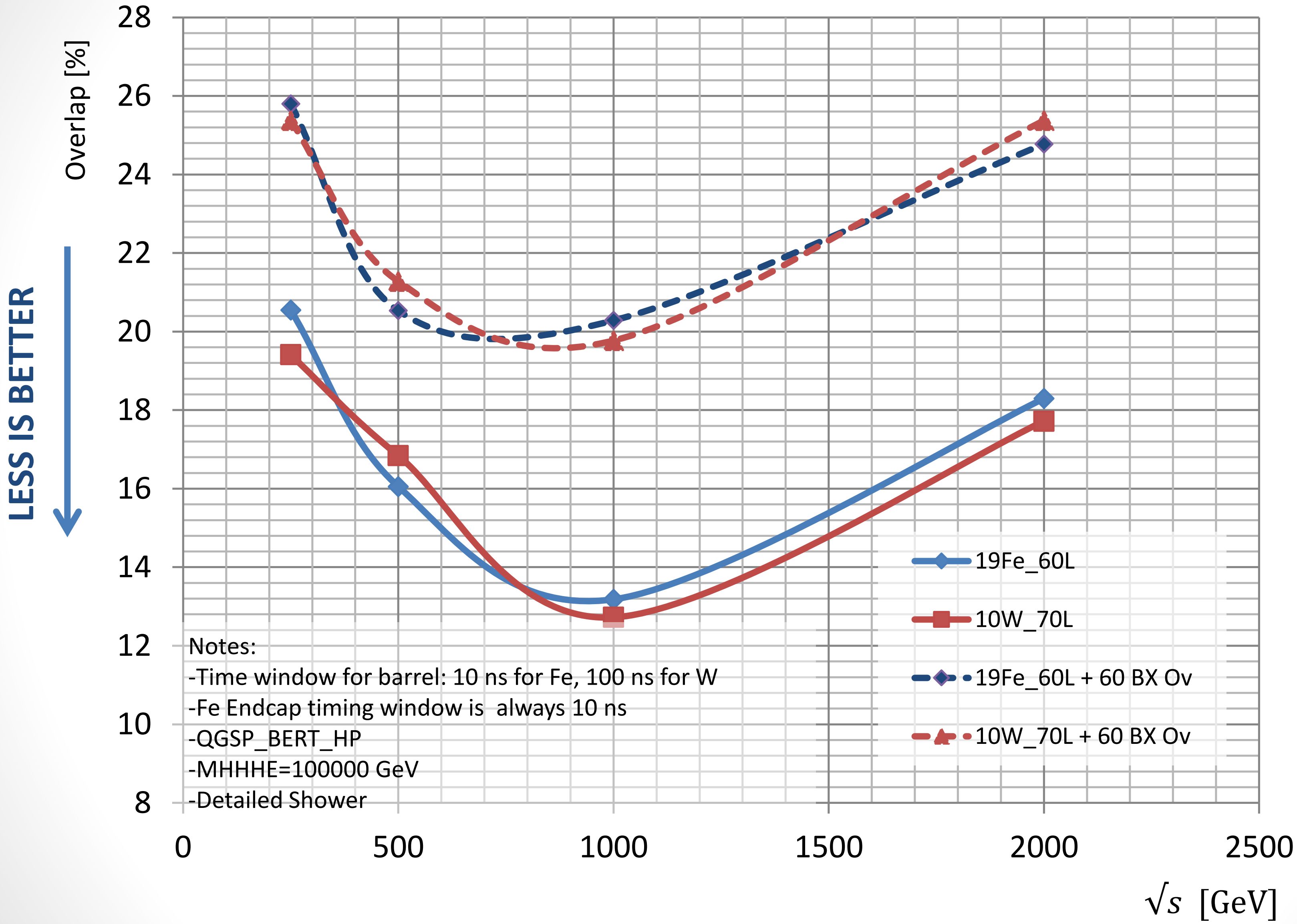
Performance in the presence of $\gamma\gamma \rightarrow had$

- Comparing the performance of the two models in the presence of $\gamma\gamma \rightarrow had$ background
- **PFO selection criteria using timing information is typically used to suppress the background in physics analyses**
- We use WW and ZZ events where one of the bosons decays to two jets



- **Reconstruct the m_{JJ} in these two sets of events for various $\sqrt{s}$**
- Fit gaussians to each peak, shift them to nominal m_W/m_Z and find intersection to define Overlap [%] and separation (in equivalent σ)
- Plot Overlap and Separation as a function of $\sqrt{s}$ (i.e. divide by a factor of 4 to get typical jet energies)
- Some very small details:
  - Tight PFOs, R=0.7 jets (did not try to optimize)
  - No Corrections for Non-Linearity applied
  - MHHHE=100000 GeV (not optimized, not modified)

W Vs Fe JER: m_W and m_Z Overlap

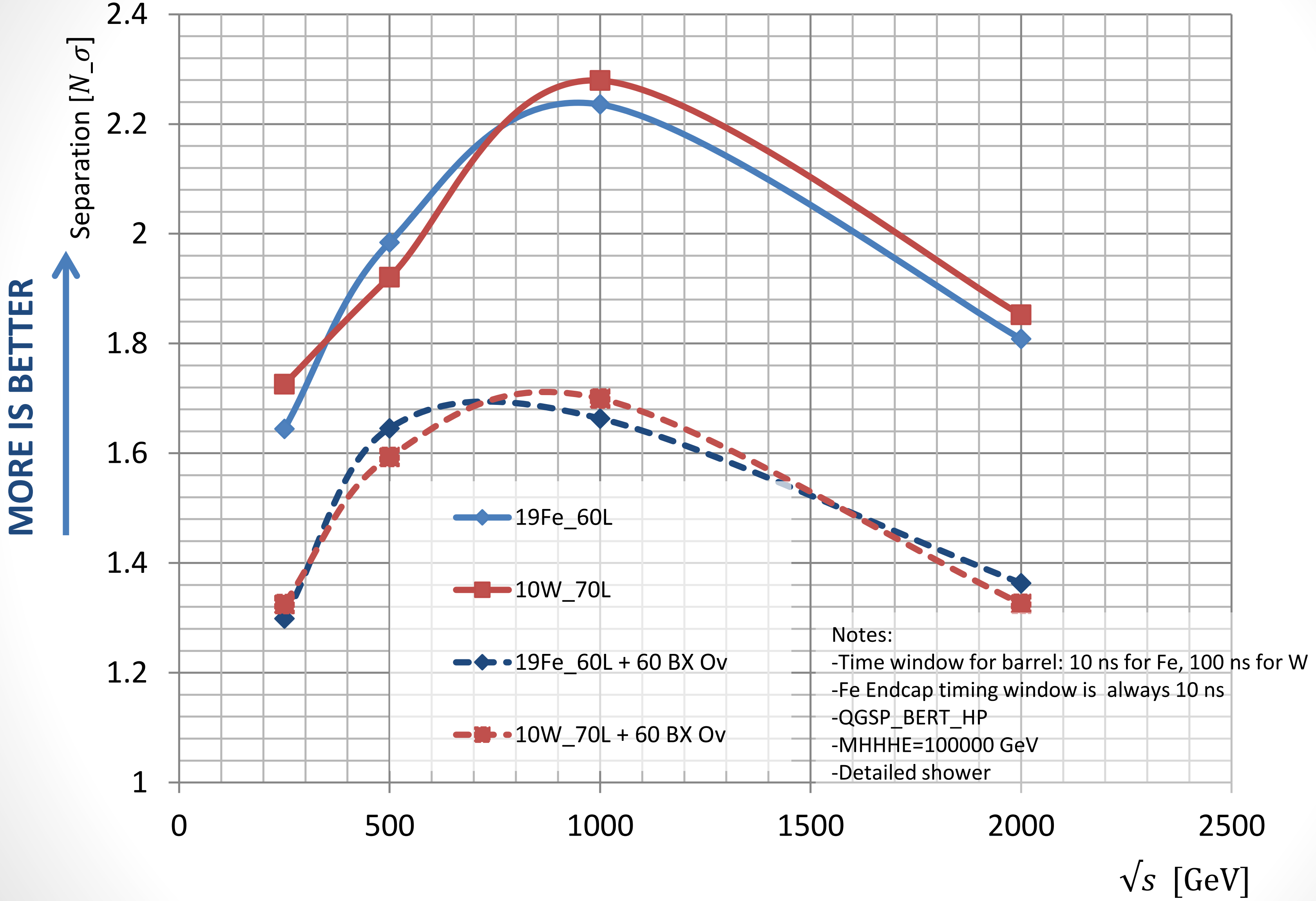


LESS IS BETTER

Notes:
-Time window for barrel: 10 ns for Fe, 100 ns for W
-Fe Endcap timing window is always 10 ns
-QGSP_BERT_HP
-MHHHE=100000 GeV
-Detailed Shower

The performance of the two models is very similar
See next slide for equivalent plot using Separation

W Vs Fe JER: m_W and m_Z Separation

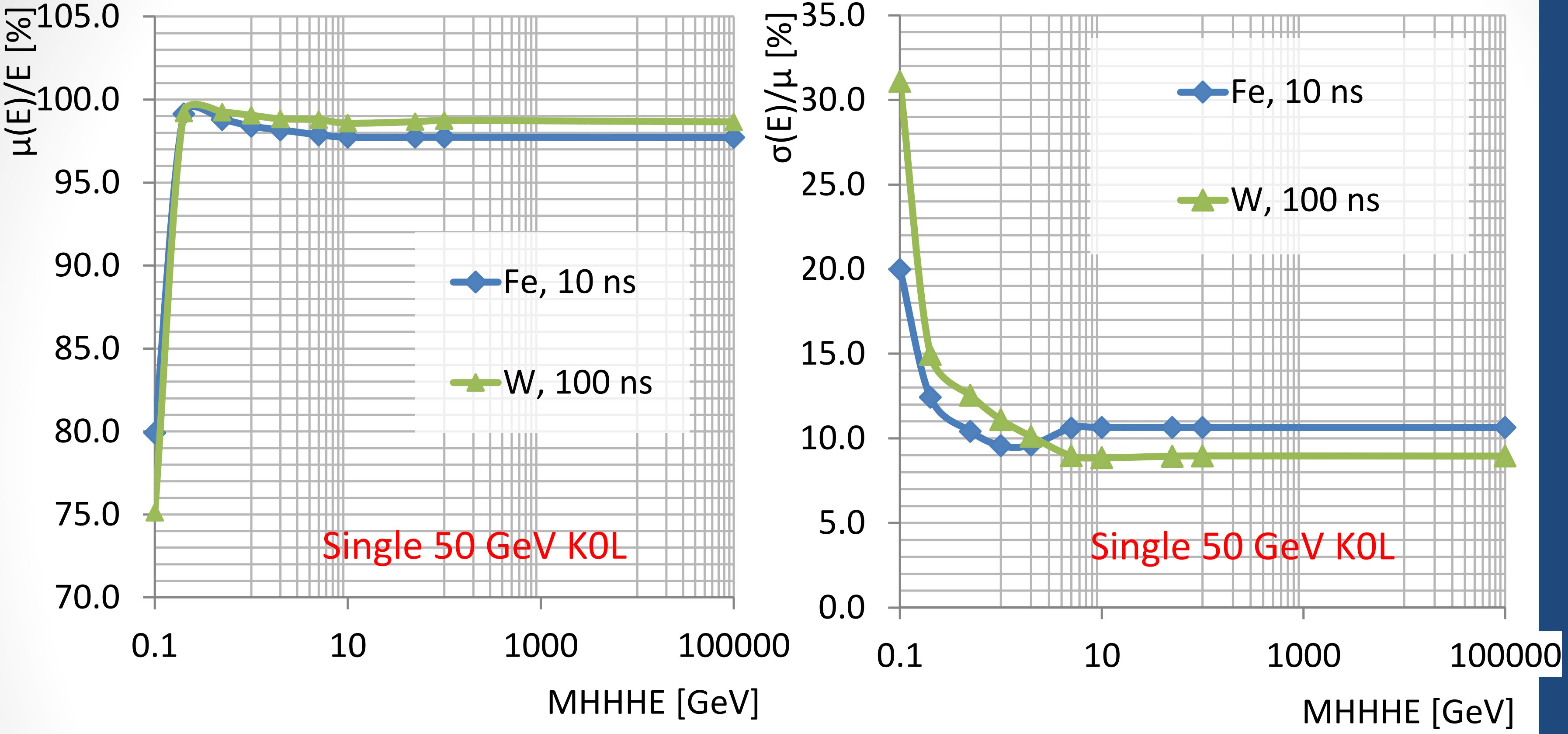


Notes:
-Time window for barrel: 10 ns for Fe, 100 ns for W
-Fe Endcap timing window is always 10 ns
-QGSP_BERT_HP
-MHHHE=100000 GeV
-Detailed shower

But what if we need to have a realistic MHHHE? Next slide ….

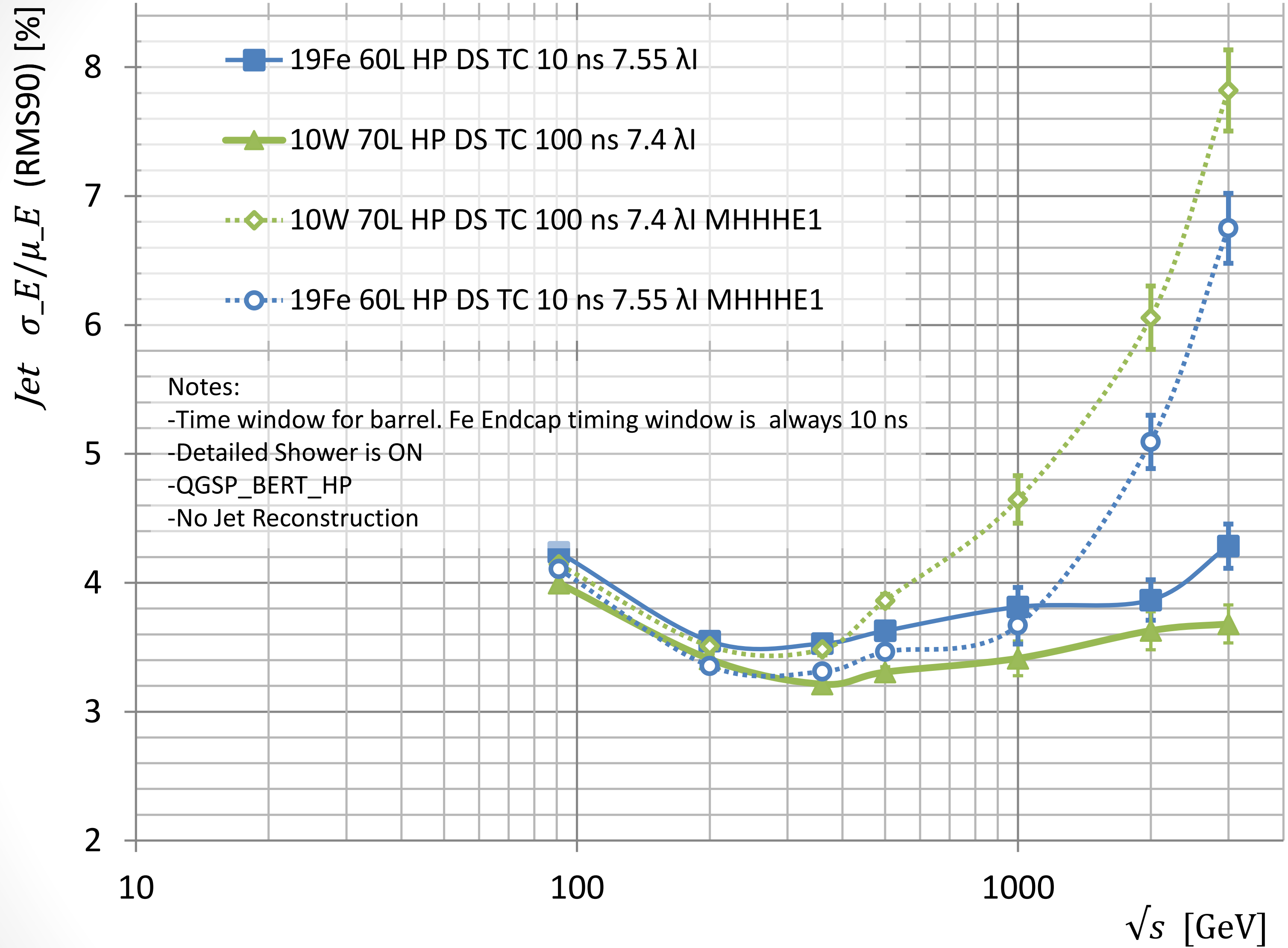
Effect of MHHHE Cut for Single 50 GeV K0L

(i.e. cut on the max hadronic energy on a single hcal hit)



- **As one naively expects, when you go to very tight (low energy) cuts, the performance degrades significantly**
- **Optimum for 10 ns Fe at ∼1-2 GeV**
- **100 ns W appears to level after 5 GeV**
- **Repeated the study with MHHHE=1 GeV (next two slides)**

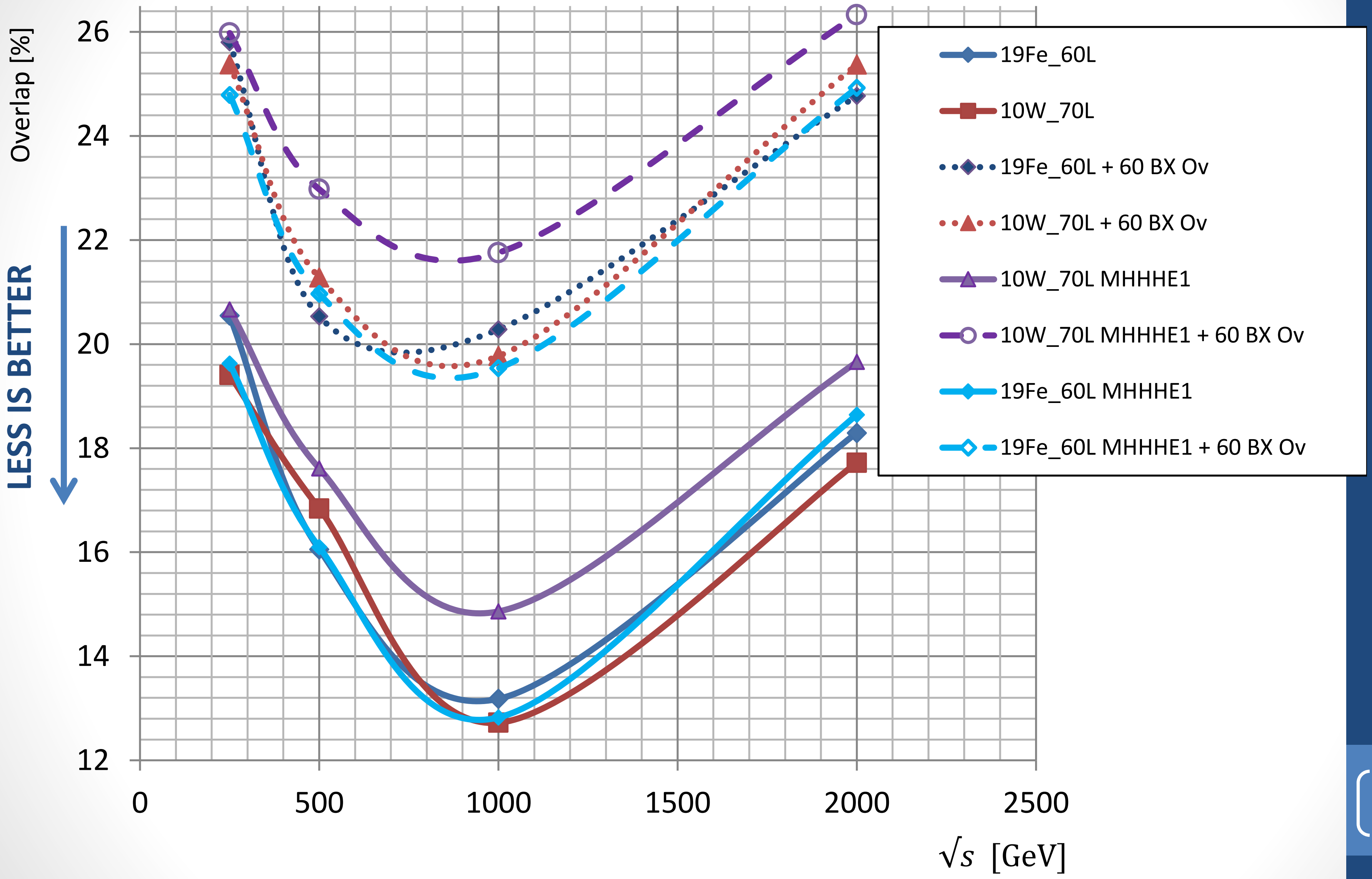
W Vs Fe JER without Overlay: $Z \to uds$



Notes:
-Time window for barrel. Fe Endcap timing window is always 10 ns
-Detailed Shower is ON
-QGSP_BERT_HP
-No Jet Reconstruction

With a 1 GeV MHHHE cut the performance in high energies is degraded for both, but **Fe wins ("poor man's SW compensation") -> What about a more "realistic" event topology? (next slide)**

W/Z Separation (and effect of $\gamma\gamma \to had$)



Similar conclusion: for low MHHHE cuts, Fe performs better

Conclusions

- **Tungsten does not perform better than steel especially with realistic reconstruction parameters and in the presence of beam induced background**
- **Tungsten is more expensive and much harder to machine compared to steel**
- **With a Steel HCal a solenoid with $R_{in} \approx 3.4$ m and field up to 4.5 T should be technically feasible**

- **Converged to the following parameters for the HCal (inside a 4 T solenoid) in the new CLIC detector model:**
  - **20 mm Steel** Absorber in both Barrel and Endcap
    - 1 mm in steel cassette
  - 60 Layers in both Barrel and Endcap with a target depth of ∼7.5λ
  - 3 mm Scintillator
  - 30 mm x 30 mm cell sizes

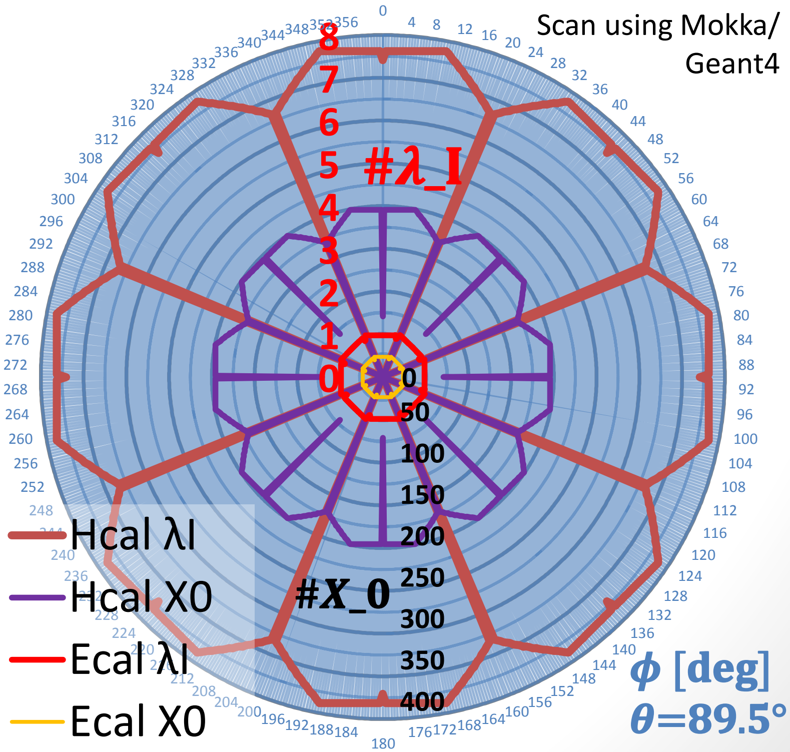
- New model already implemented in DD4hep
  - More detailed timing studies (and all future studies) performed with DD4hep and new simulation/reconstruction framework

BACKUP SLIDES

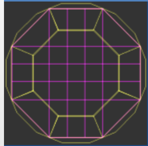
What was Previously There

- 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



Scan using Mokka/ Geant4

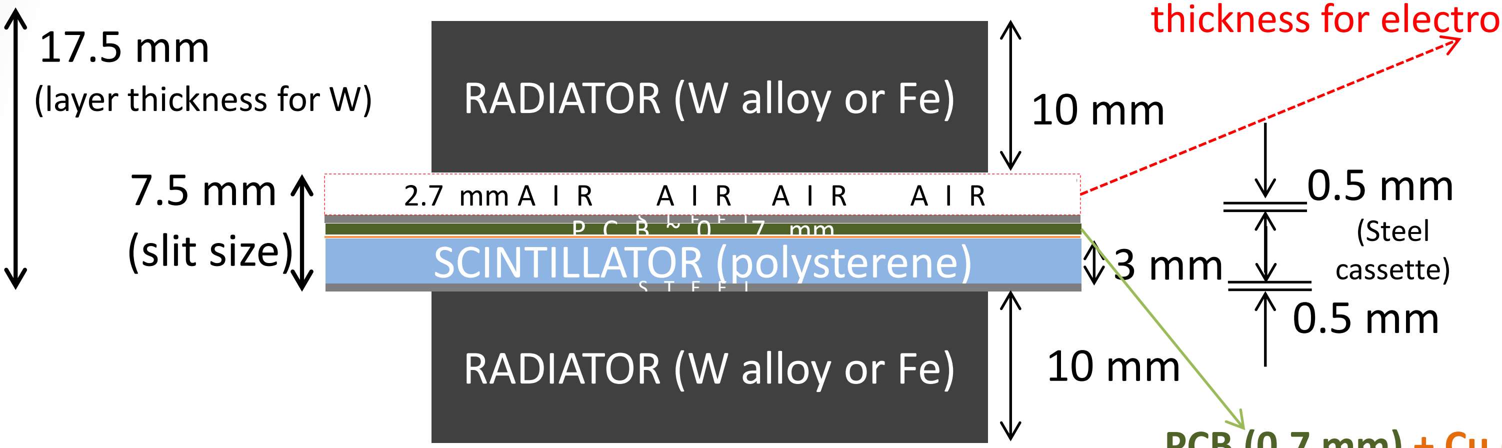


Modified ILD Assembly (17.5 mm per layer)

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

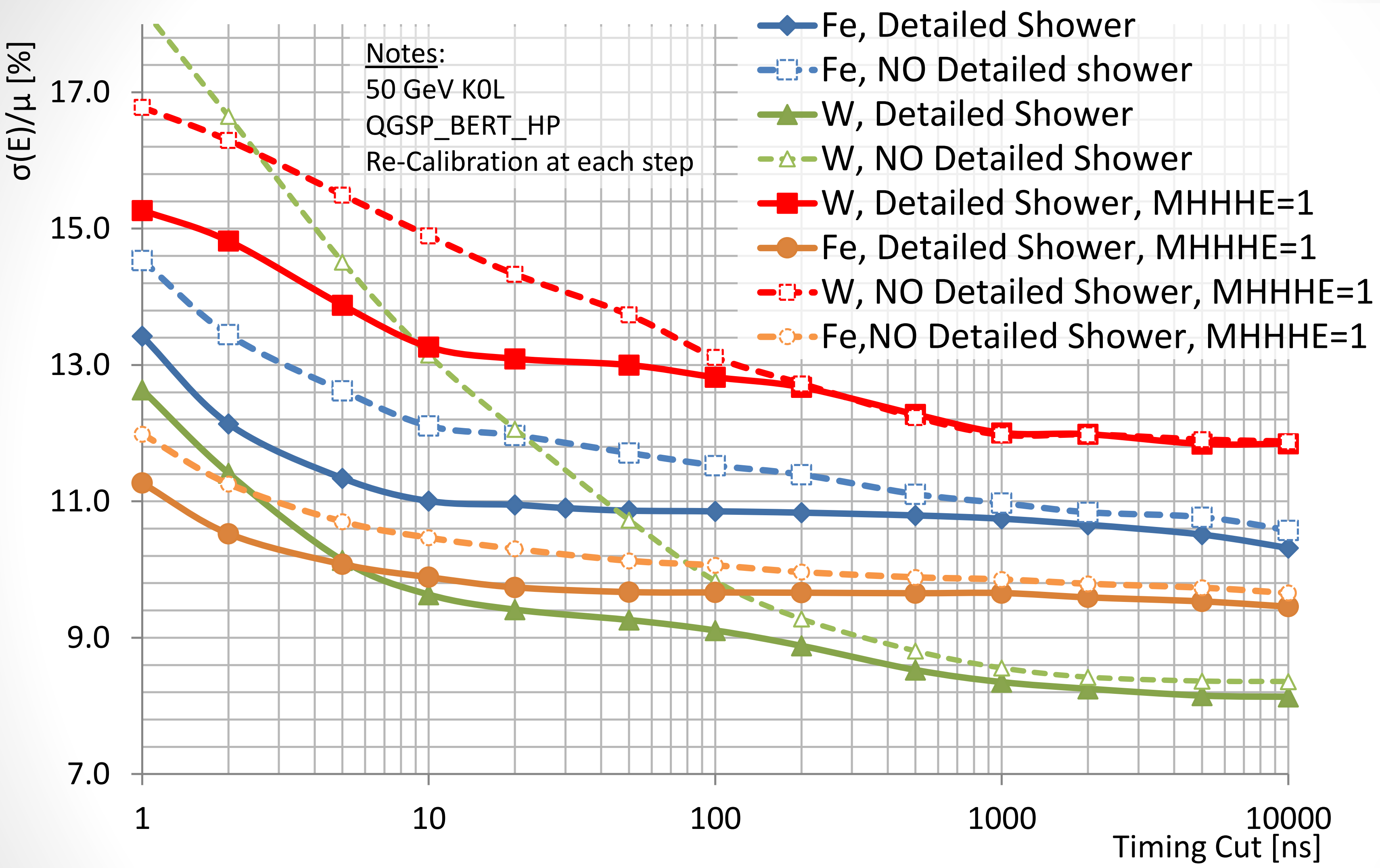


PCB (0.7 mm) + Cu (0.1 mm)
(ignore electronics)

- 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**
- Still does not address support and assembly
    - Would more naturally fold into absorber structure in the case of Fe

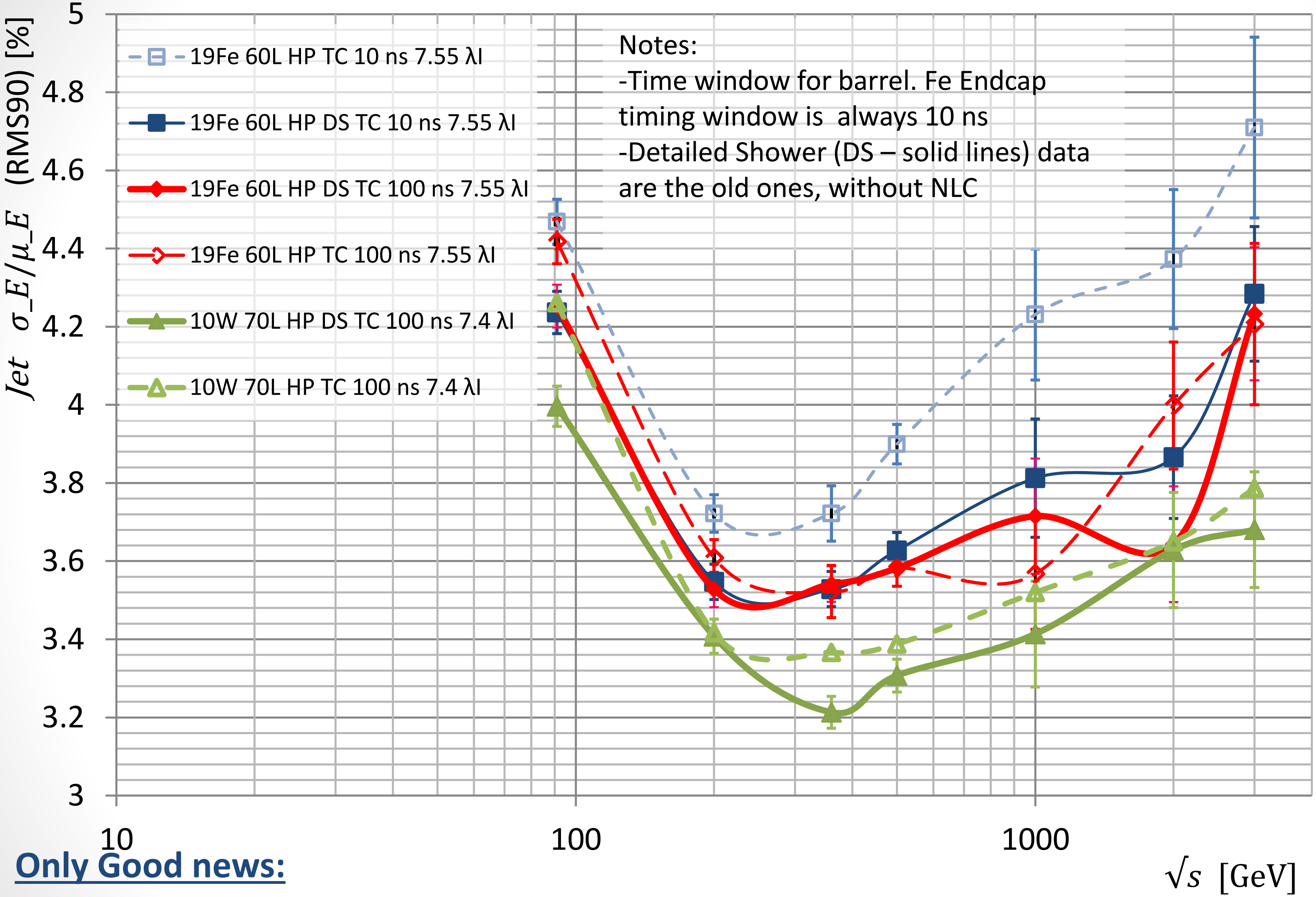
Active Element Cassette	
Material	Thickness mm
Steel	1
PCB	0.7
Cu (etching)	0.1
Electronics	0
Scintillator	3
Sum (per layer)	4.8
#λI (per layer)	0.01

Effect of **M**ax**HC**al**H**it**H**adronic**E**nergy



- Steel performance can be improved by optimizing MHHHE (~ sw comp)
- With this in mind, its unlikely that the conclusions will change for the HCal Barrel
- What about more "realistic" events (jets, backgrounds)? Next slides …

W Vs Fe JER without Overlay: $Z \rightarrow uds$



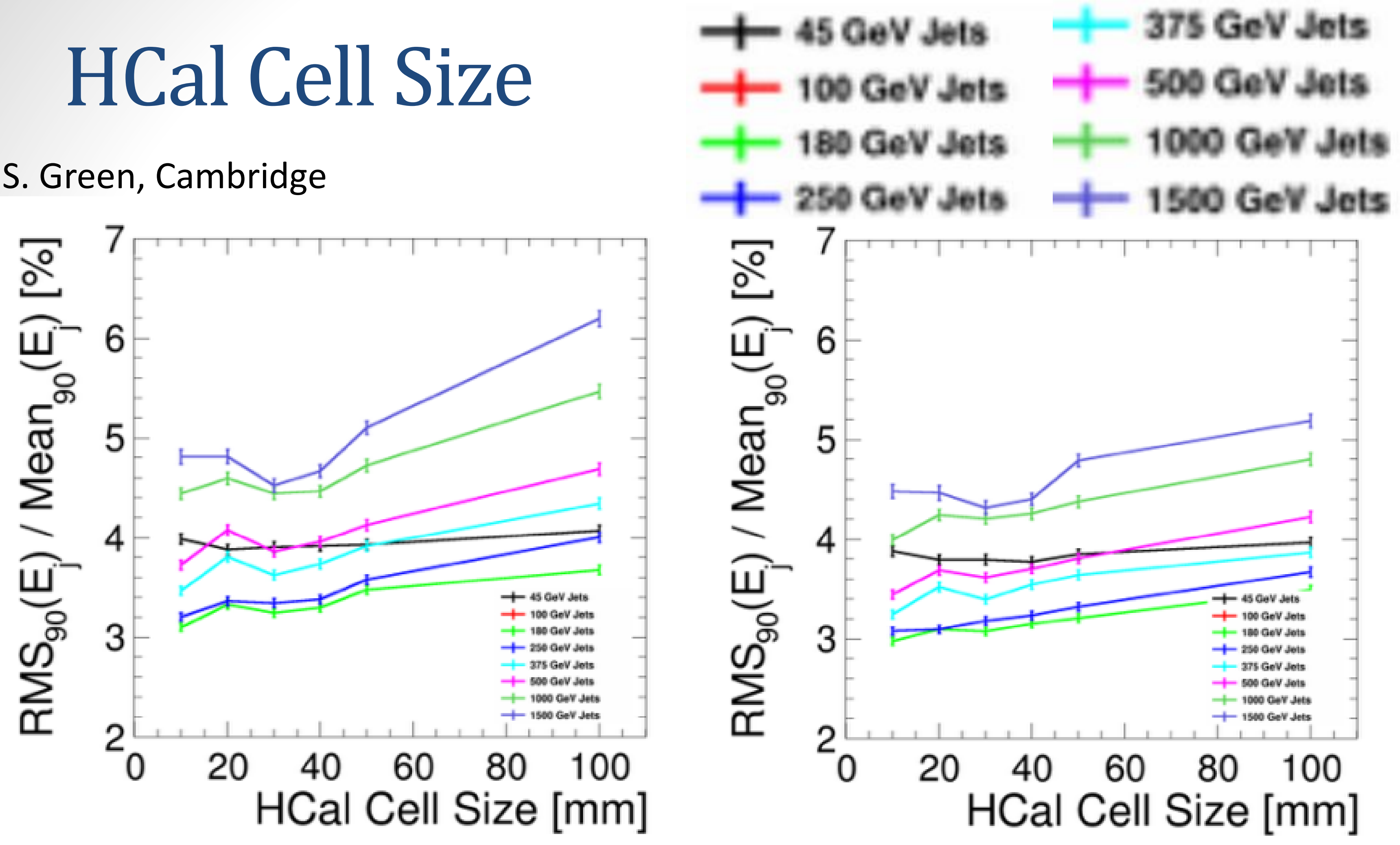
Notes:
-Time window for barrel. Fe Endcap timing window is always 10 ns
-Detailed Shower (DS – solid lines) data are the old ones, without NLC

Only Good news:

- **10 ns Fe JER is better than before**
- **The previous conclusions are still valid:** W is a bit better than Fe (without s/w comp) **but it should not drive solely our decision**

HCal Cell Size

S. Green, Cambridge



$Z \rightarrow uds$

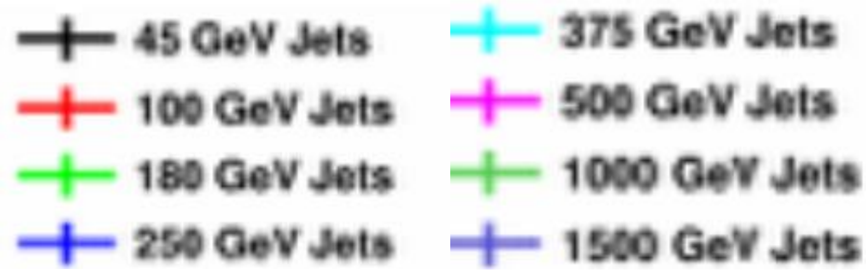
10 ns HCal Timing Cut

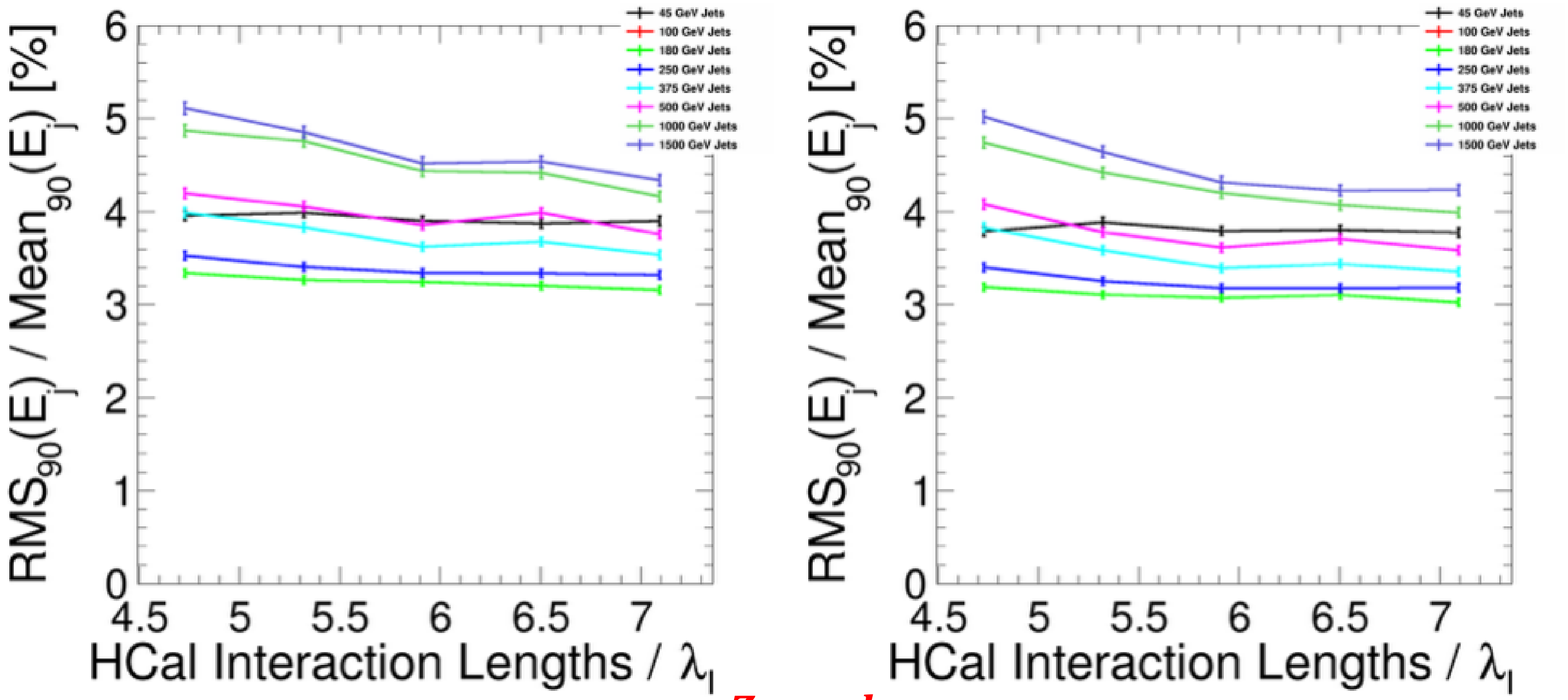
10^6 ns HCal Timing Cut

- Using a 7.5 λ HCal model
- 30 mm x 30 mm (Currently used) is a reasonable option for the simulation model
- Note: suspicions for bias towards 30 mm case under investigation

HCal Depth

S. Green, Cambridge





$Z \rightarrow uds$

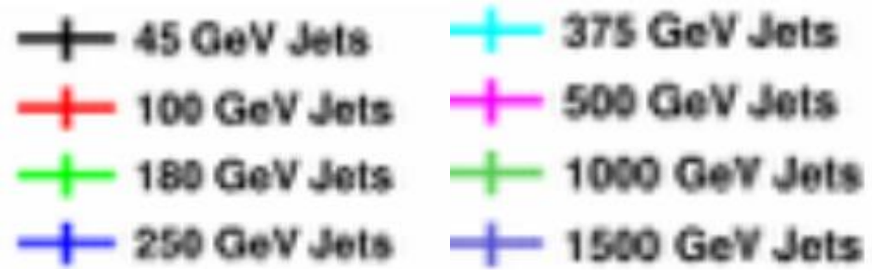
10 ns HCal Timing Cut

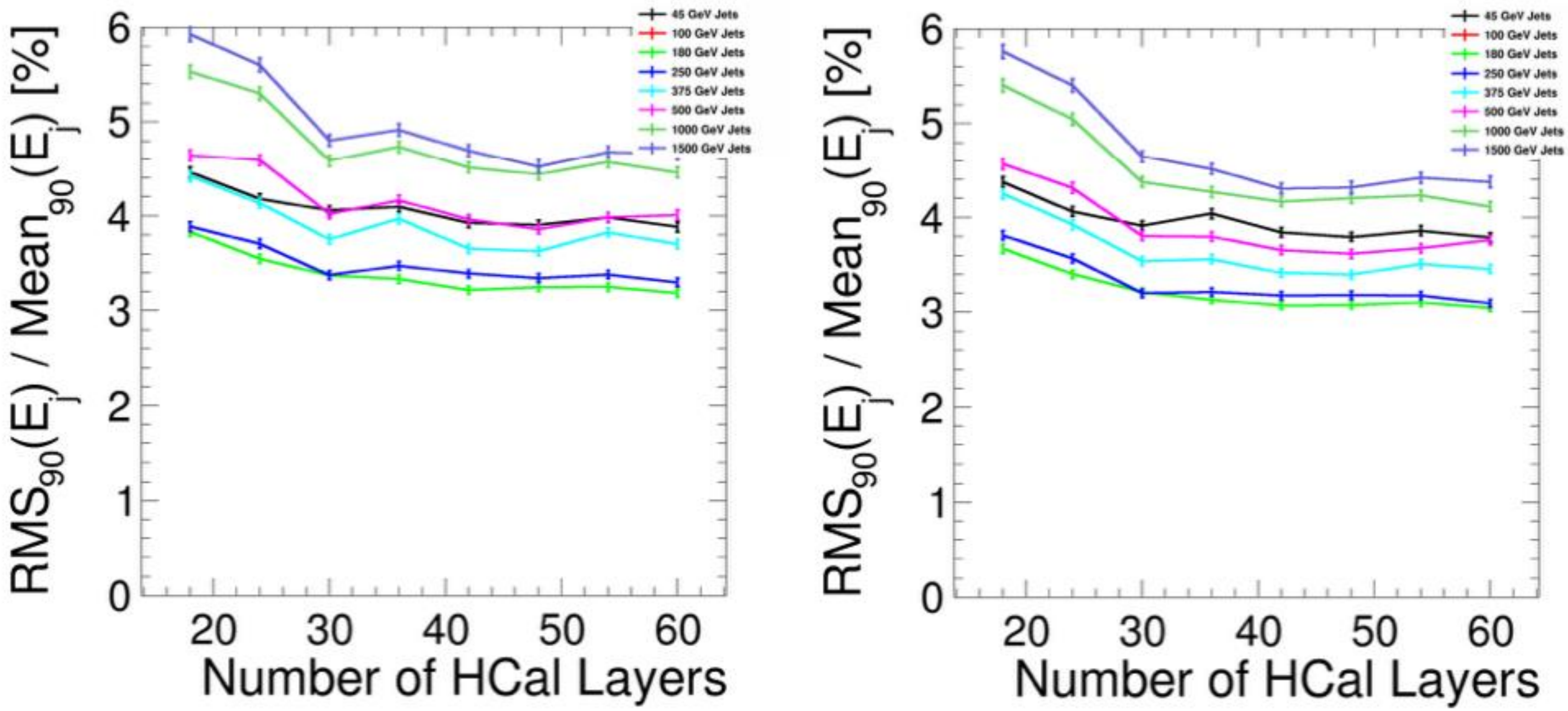
10^6 ns HCal Timing Cut

- **Results in line with previous studies: ~7.5λ in the HCal is optimal**

HCal #Layers

S. Green, Cambridge





$Z \rightarrow uds$

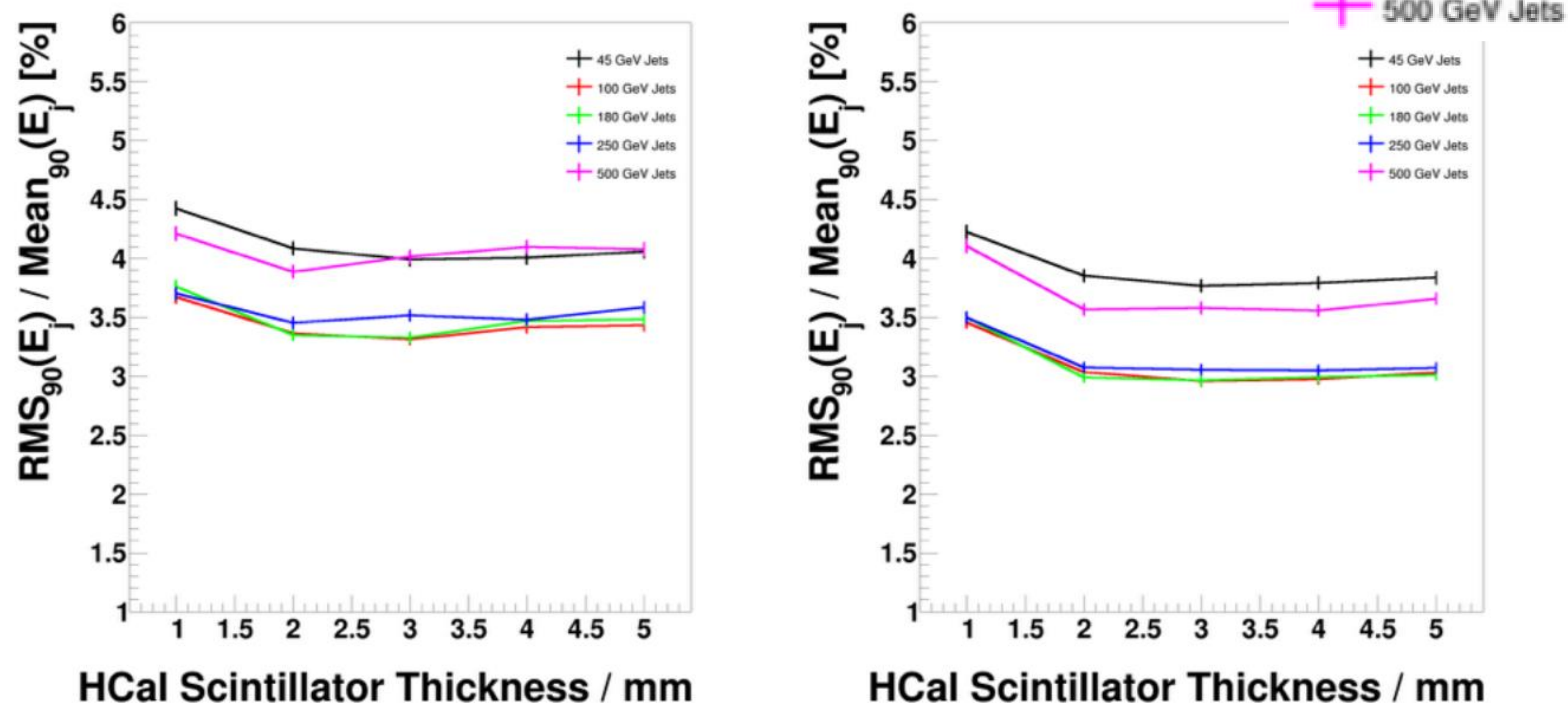
10 ns HCal Timing Cut

10^6 ns HCal Timing Cut

- HCal Depth (7.5 λ) and sampling fraction kept constant
- **Currently using 60 Layers in HCal**

HCal Scintillator Thickness

S. Green, Cambridge



$Z \rightarrow uds$

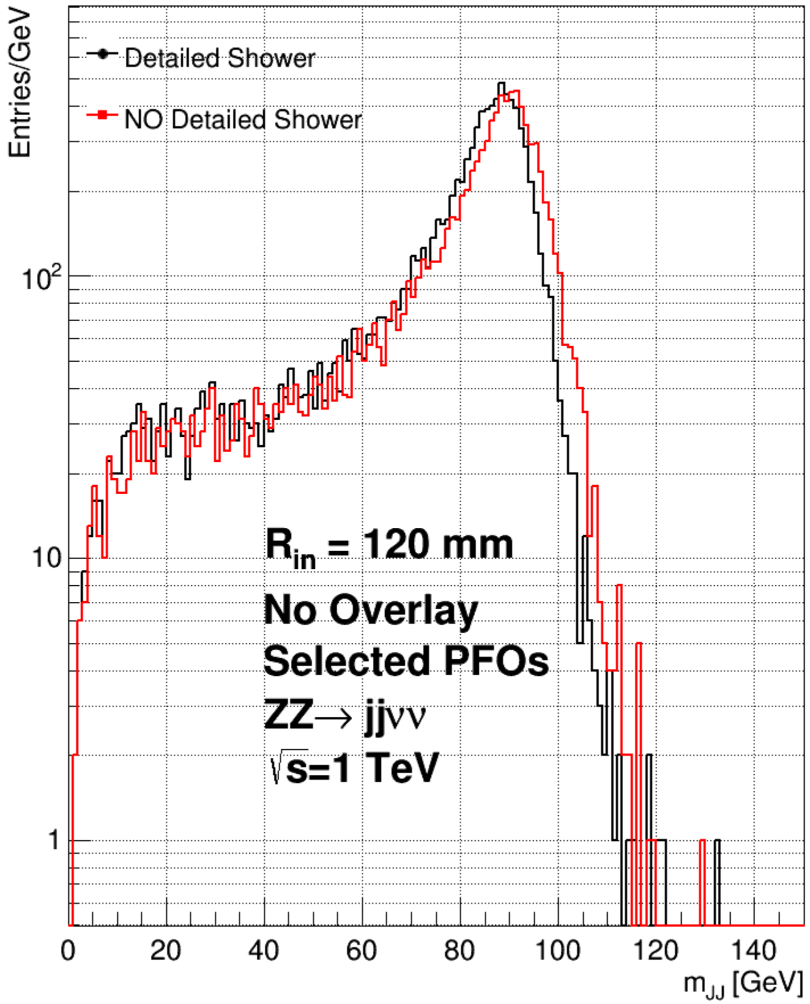
10 ns HCal Timing Cut

10^6 ns HCal Timing Cut

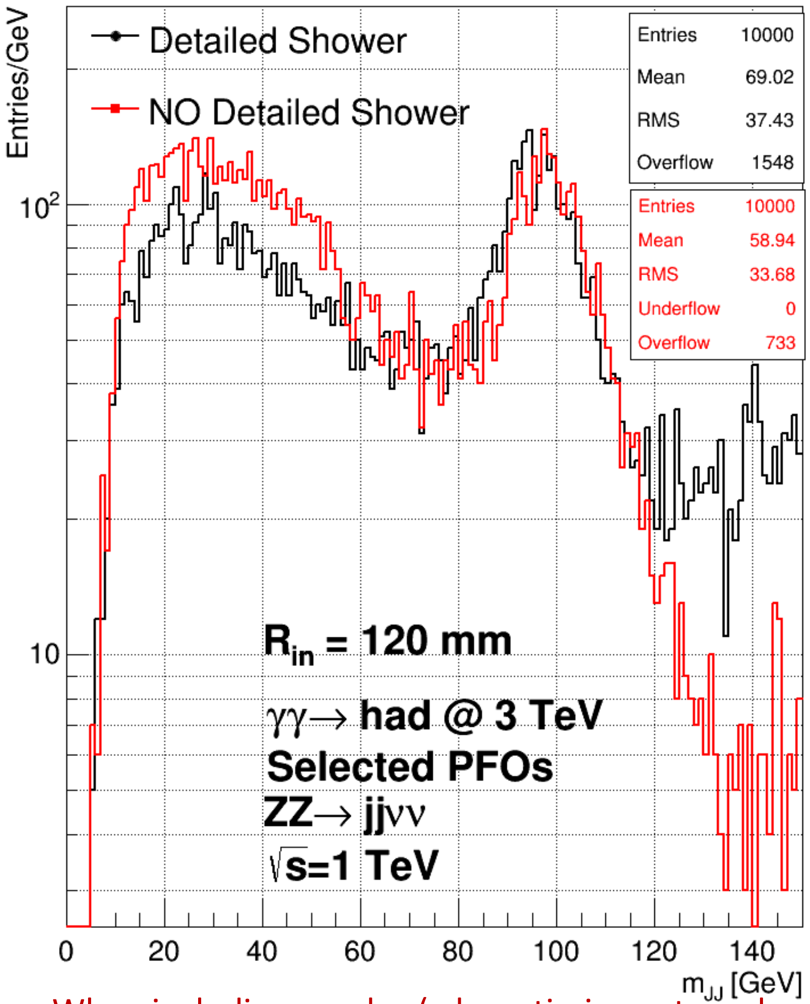
- 3 mm Scintillator thickness appears to be optimal
- **=> Plan to use 3 mm for the next Simulation model**

Effect on Jet Reconstruction

Look at Forward ZZ events and Extended HCal since we want to see the effects in the presence of background (also had them handy)



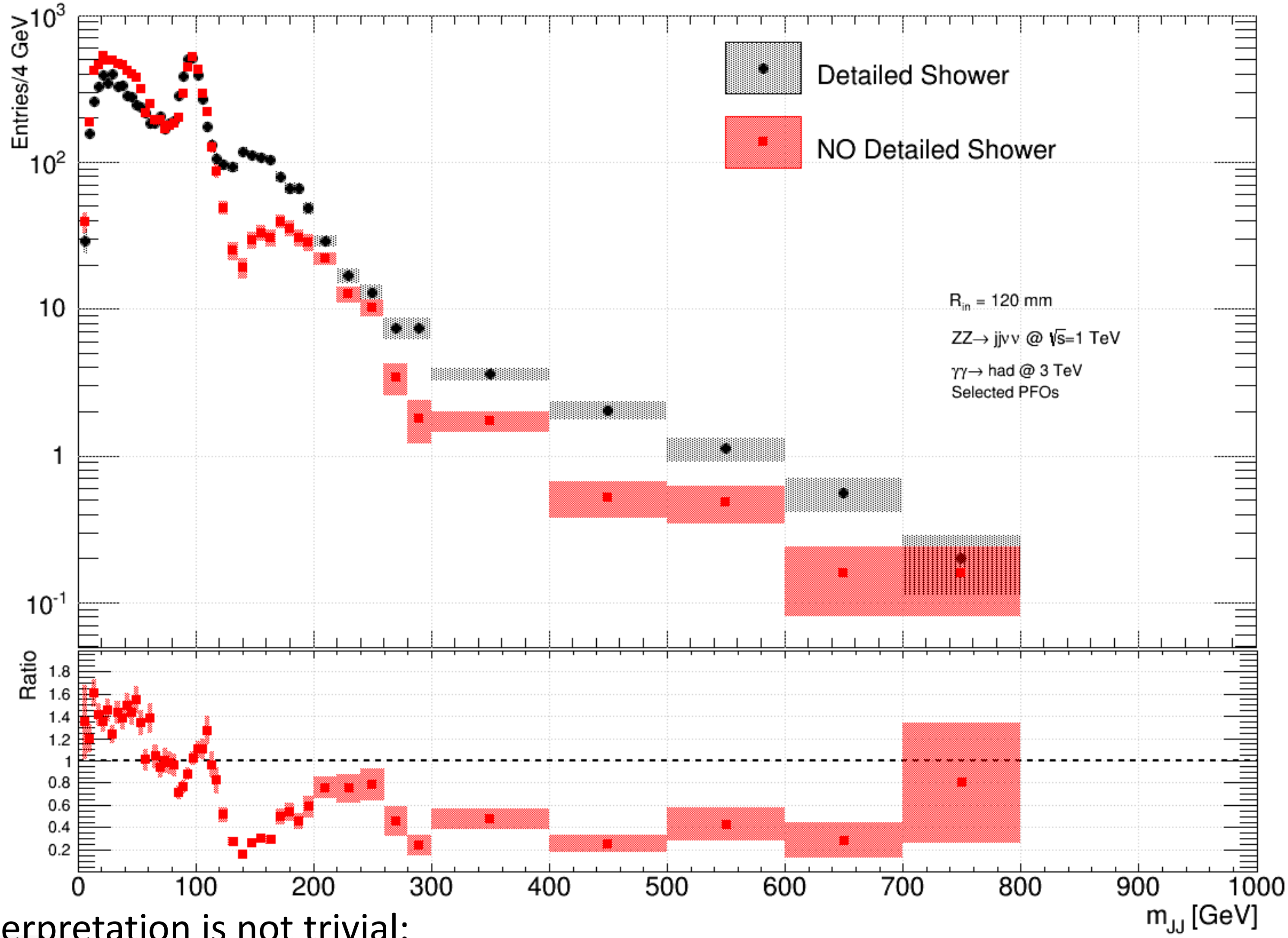
Without overlay, the effect appears to be small



When including overlay (where timing cuts make a difference) the structure of the tails is different

- See next slide for wider range

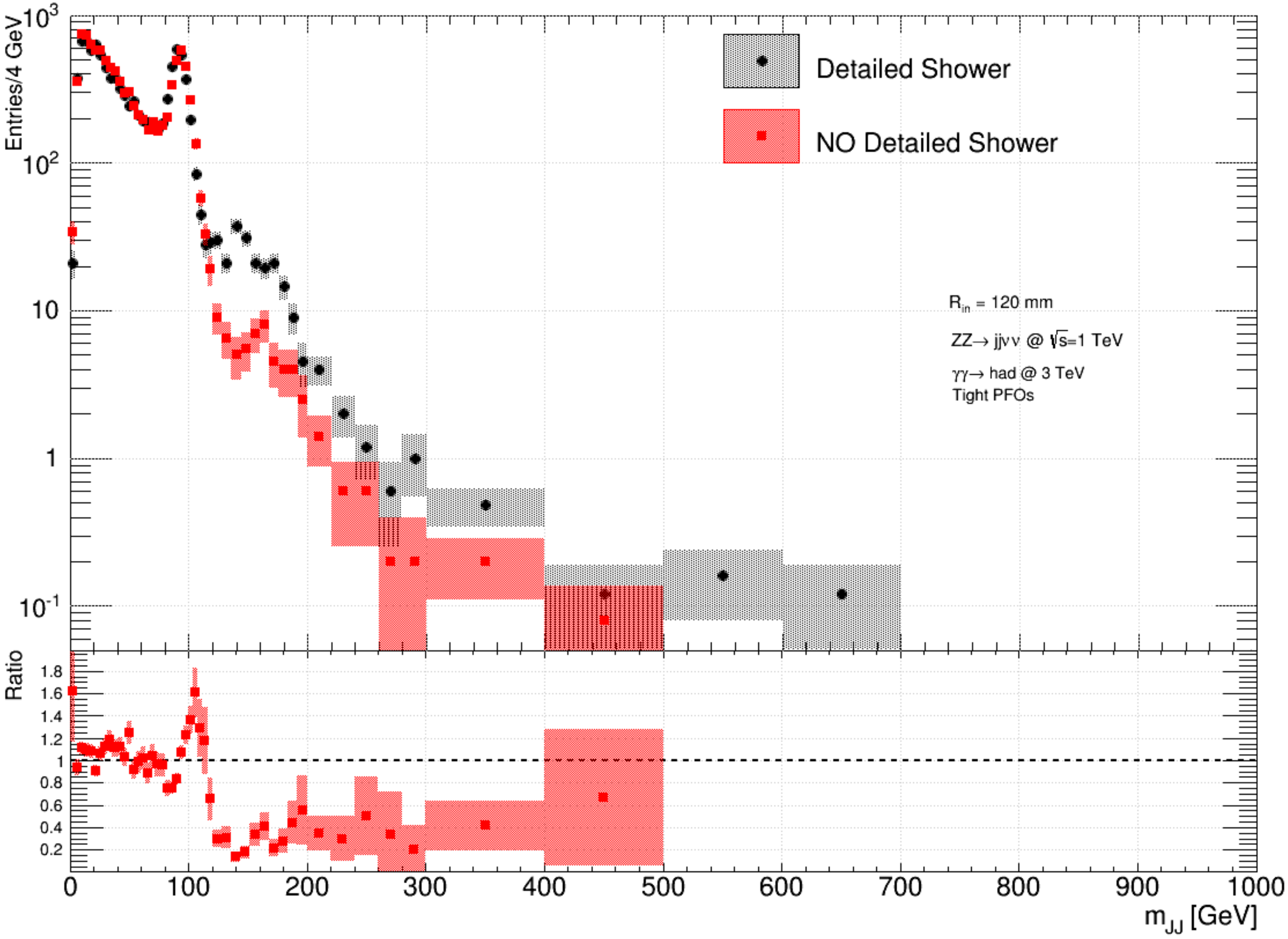
Comparison of m_{JJ} for Jets Reconstructed with Selected PFOs



Interpretation is not trivial:

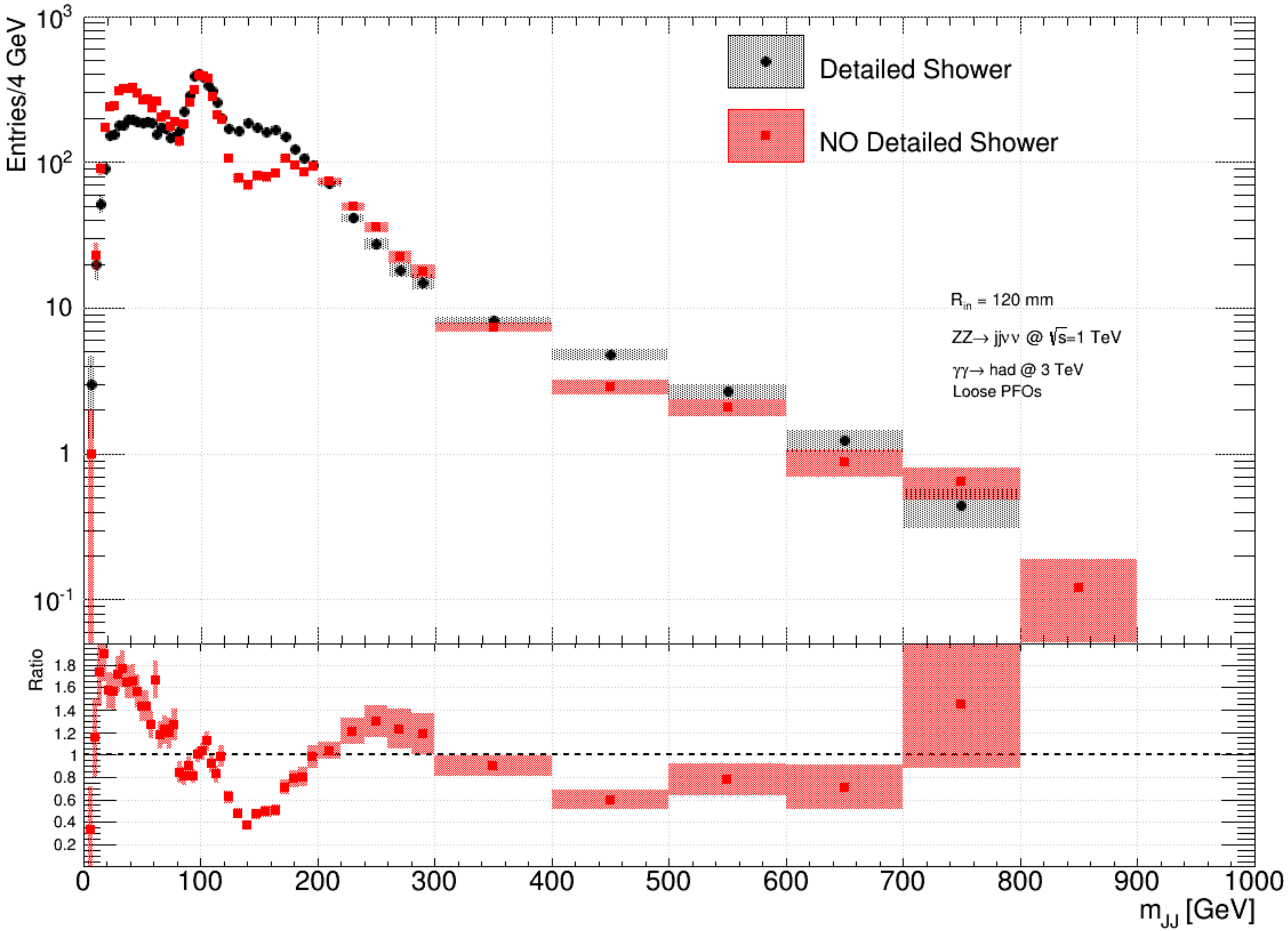
- On one hand, trying to understand differences in tails
- On other hand, comparing a steeply falling distribution (Z peak) with a ratio plot…

Comparison of m_{JJ} for Jets Reconstructed with Tight PFOs



Would have expected the discrepancies be more prominent with "Tight"

Comparison of m_{JJ} for Jets Reconstructed with Loose PFOs



Probably competing effects need to be disentangled (e.g. look in θ-bins)

PFO Selection Cut Definitions

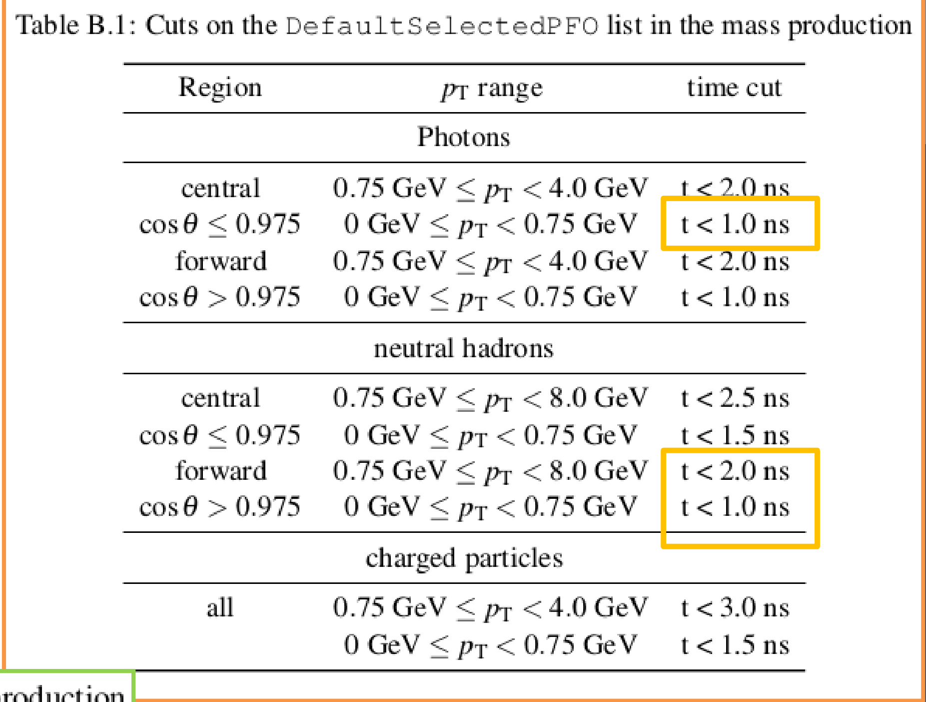


Table B.1: Cuts on the `DefaultSelectedPFO` list in the mass production

Region	p_T range	time cut
Photons		
central	0.75 GeV $\leq p_T <$ 4.0 GeV	t < 2.0 ns
$\cos\theta \leq 0.975$	0 GeV $\leq p_T <$ 0.75 GeV	t < 1.0 ns
forward	0.75 GeV $\leq p_T <$ 4.0 GeV	t < 2.0 ns
$\cos\theta > 0.975$	0 GeV $\leq p_T <$ 0.75 GeV	t < 1.0 ns
neutral hadrons		
central	0.75 GeV $\leq p_T <$ 8.0 GeV	t < 2.5 ns
$\cos\theta \leq 0.975$	0 GeV $\leq p_T <$ 0.75 GeV	t < 1.5 ns
forward	0.75 GeV $\leq p_T <$ 8.0 GeV	t < 2.0 ns
$\cos\theta > 0.975$	0 GeV $\leq p_T <$ 0.75 GeV	t < 1.0 ns
charged particles		
all	0.75 GeV $\leq p_T <$ 4.0 GeV	t < 3.0 ns
	0 GeV $\leq p_T <$ 0.75 GeV	t < 1.5 ns

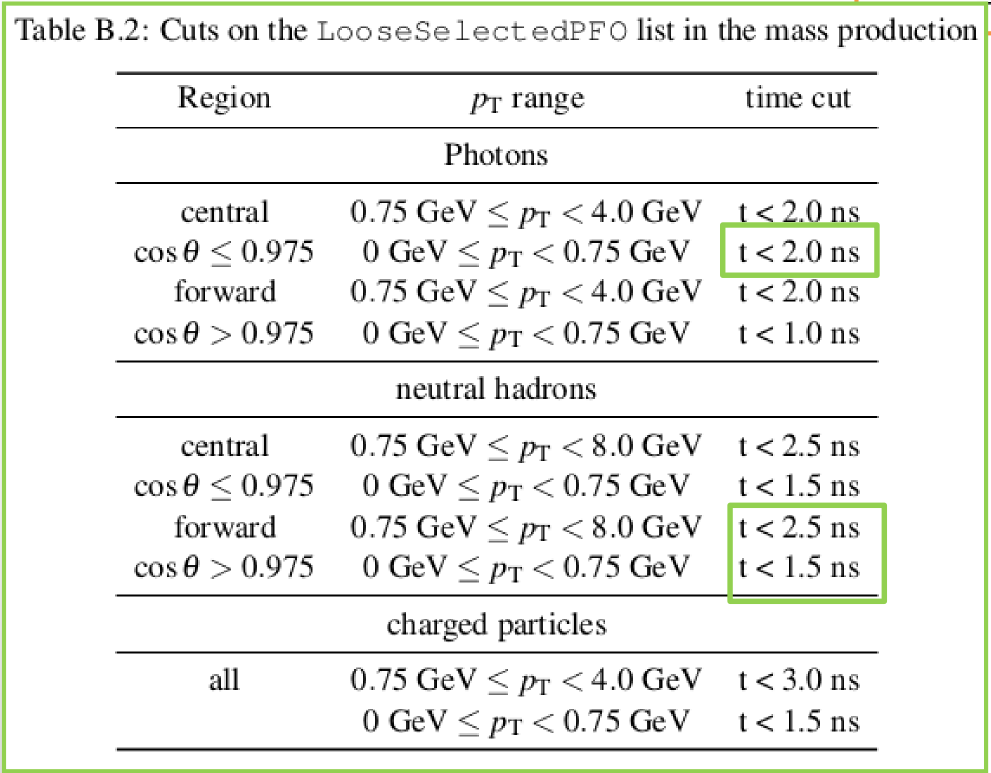


Table B.2: Cuts on the `LooseSelectedPFO` list in the mass production

Region	p_T range	time cut
Photons		
central	0.75 GeV $\leq p_T <$ 4.0 GeV	t < 2.0 ns
$\cos\theta \leq 0.975$	0 GeV $\leq p_T <$ 0.75 GeV	t < 2.0 ns
forward	0.75 GeV $\leq p_T <$ 4.0 GeV	t < 2.0 ns
$\cos\theta > 0.975$	0 GeV $\leq p_T <$ 0.75 GeV	t < 1.0 ns
neutral hadrons		
central	0.75 GeV $\leq p_T <$ 8.0 GeV	t < 2.5 ns
$\cos\theta \leq 0.975$	0 GeV $\leq p_T <$ 0.75 GeV	t < 1.5 ns
forward	0.75 GeV $\leq p_T <$ 8.0 GeV	t < 2.5 ns
$\cos\theta > 0.975$	0 GeV $\leq p_T <$ 0.75 GeV	t < 1.5 ns
charged particles		
all	0.75 GeV $\leq p_T <$ 4.0 GeV	t < 3.0 ns
	0 GeV $\leq p_T <$ 0.75 GeV	t < 1.5 ns

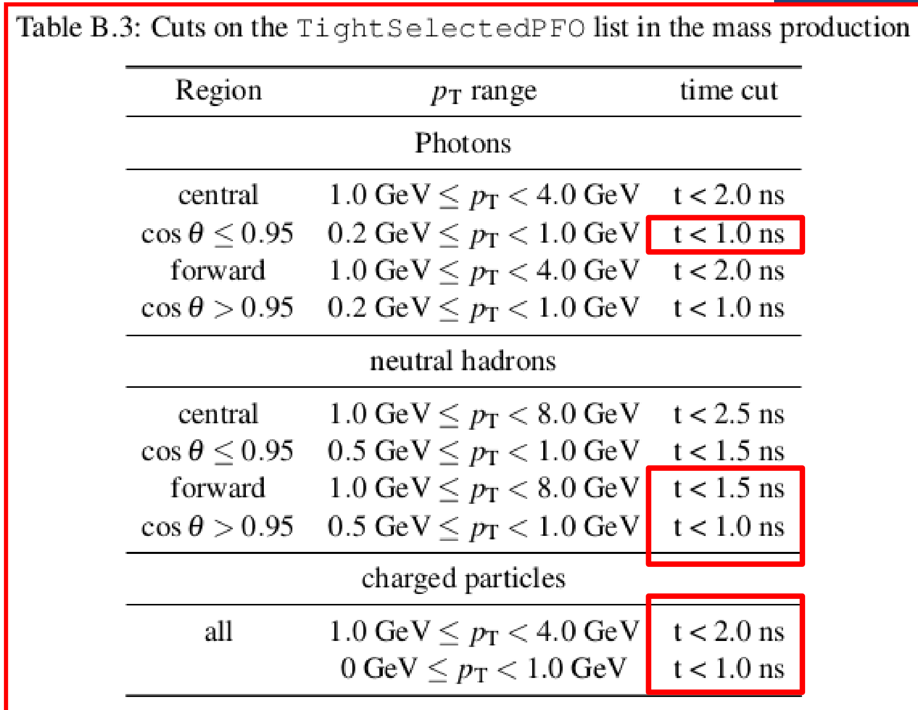


Table B.3: Cuts on the `TightSelectedPFO` list in the mass production

Region	p_T range	time cut
Photons		
central	1.0 GeV $\leq p_T <$ 4.0 GeV	t < 2.0 ns
$\cos\theta \leq 0.95$	0.2 GeV $\leq p_T <$ 1.0 GeV	t < 1.0 ns
forward	1.0 GeV $\leq p_T <$ 4.0 GeV	t < 2.0 ns
$\cos\theta > 0.95$	0.2 GeV $\leq p_T <$ 1.0 GeV	t < 1.0 ns
neutral hadrons		
central	1.0 GeV $\leq p_T <$ 8.0 GeV	t < 2.5 ns
$\cos\theta \leq 0.95$	0.5 GeV $\leq p_T <$ 1.0 GeV	t < 1.5 ns
forward	1.0 GeV $\leq p_T <$ 8.0 GeV	t < 1.5 ns
$\cos\theta > 0.95$	0.5 GeV $\leq p_T <$ 1.0 GeV	t < 1.0 ns
charged particles		
all	1.0 GeV $\leq p_T <$ 4.0 GeV	t < 2.0 ns
	0 GeV $\leq p_T <$ 1.0 GeV	t < 1.0 ns