Optimizing the Hadronic Calorimeter

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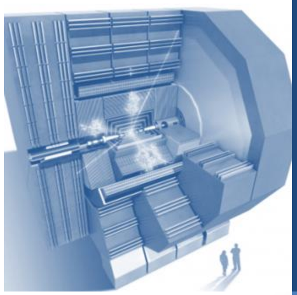


Introduction

- The topic is converging on the parameters for the HCal in the next simulation model

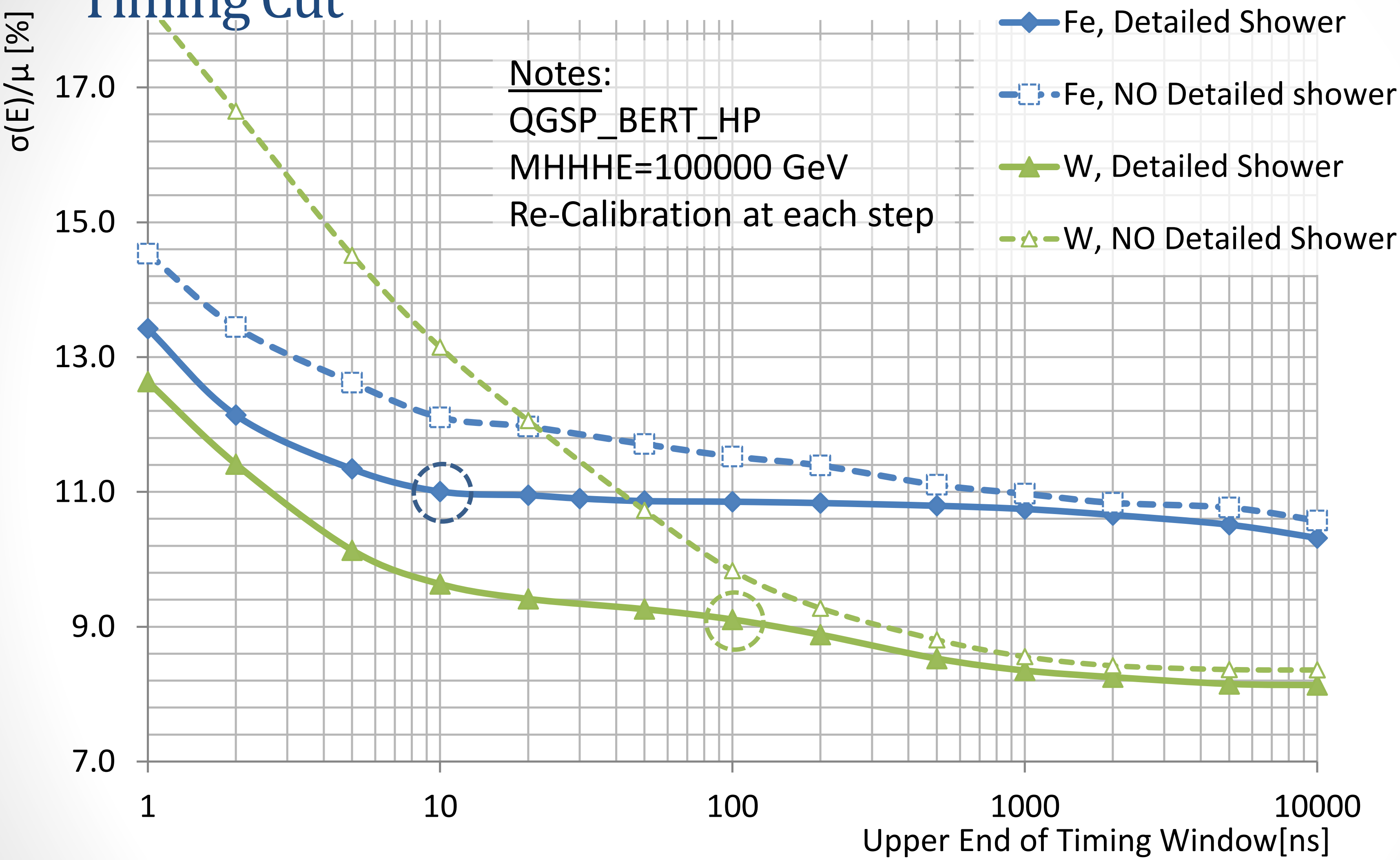
- In this talk we will cover mainly three general topics
  - HCal Barrel Optimization: Absorber selection
  - HCal Segmentation Optimization: #Layers, Cell size, …
  - HCal Endcap Optimization: Forward Coverage Extension

- Some notes:
  - Optimization often requires independently varying parameters that are correlated
  - **Modifying the geometry requires recalibrating the detector**
    - We used the updated calibration procedure from Cambridge
  - We are not applying Non Linearity Corrections (NLC)
  - At this stage we mostly see shallow dependences

HCal Barrel Absorber Material

- Essentially had to decide between Tungsten (W) and Steel (Fe)
- Investigated only two models (the two most realistic from earlier studies):
  - **10 mm W absorber, 70 layers, with steel cassette, 7.4 λ_I, $\Delta R \approx 1.2\ \mathrm{m}$**
  - **19 mm Fe absorber, 60 layers, with steel cassette, 7.55 λ_I, $\Delta R \approx 1.6\ \mathrm{m}$**
- Both models designed to present a depth close to ~7.5 λ_I, previously identified as optimal
- Both Implement a cassette and a realistic assembly:
  - 1 mm Steel in Cassette (0.5+0.5 mm)
  - 3 mm Scintillator, 2.7 mm air, 0.8 mm PCB
- An independent study was also performed at Cambridge
- **One needs to closely pay attention to calibration, SW optimization and options, Pandora Parameters and other "details":**
  - **For example: Maximum allowed Hadronic Energy in a single HCal Hit (MHHHE)**
  - **Timing window effects (next slide)**

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

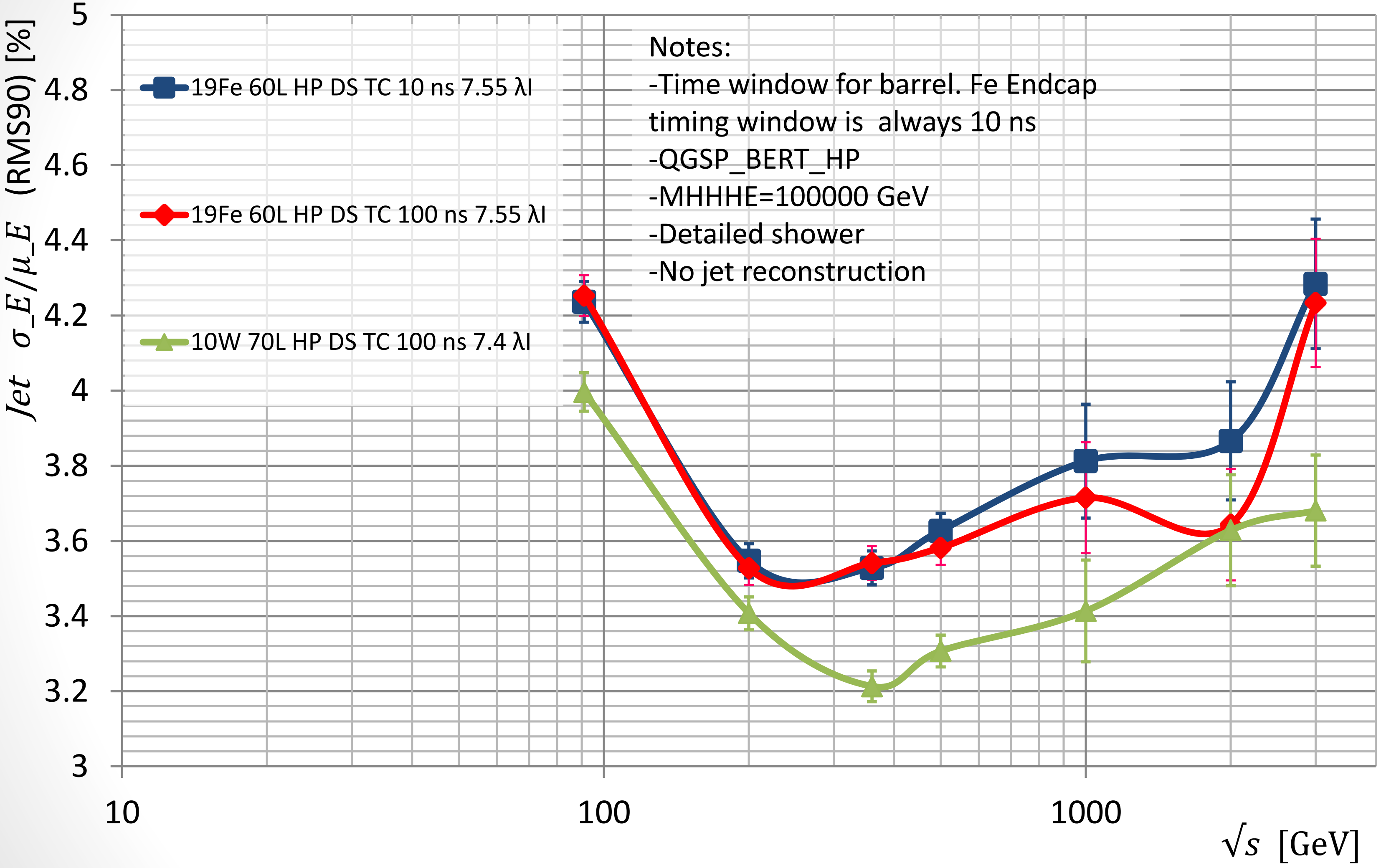


Notes:
QGSP_BERT_HP
MHHHE=100000 GeV
Re-Calibration at each step

- With the detailed shower option on Tungsten does much better than previously thought at narrower timing windows (Steel also improves at 10 ns)
- **Important to enable storing the Detailed Shower information**

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

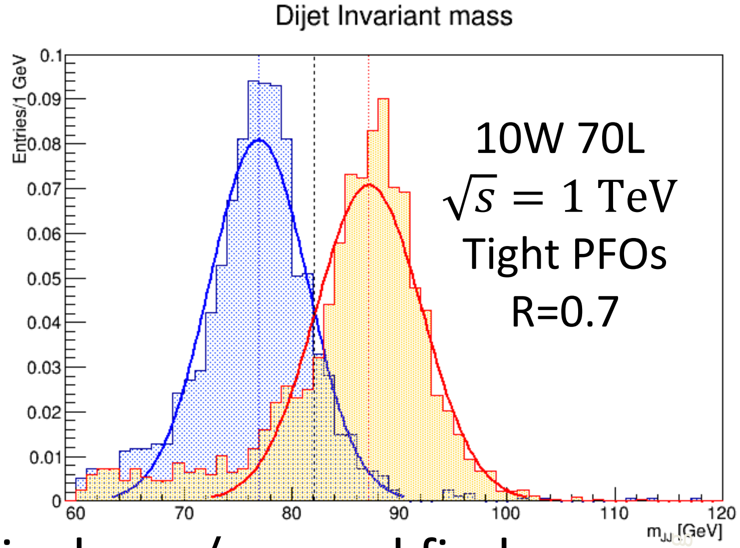
Results using `AnalysePerformance` in `PandoraAnalysis`



Notes:
-Time window for barrel. Fe Endcap timing window is always 10 ns
-QGSP_BERT_HP
-MHHHE=100000 GeV
-Detailed shower
-No jet reconstruction

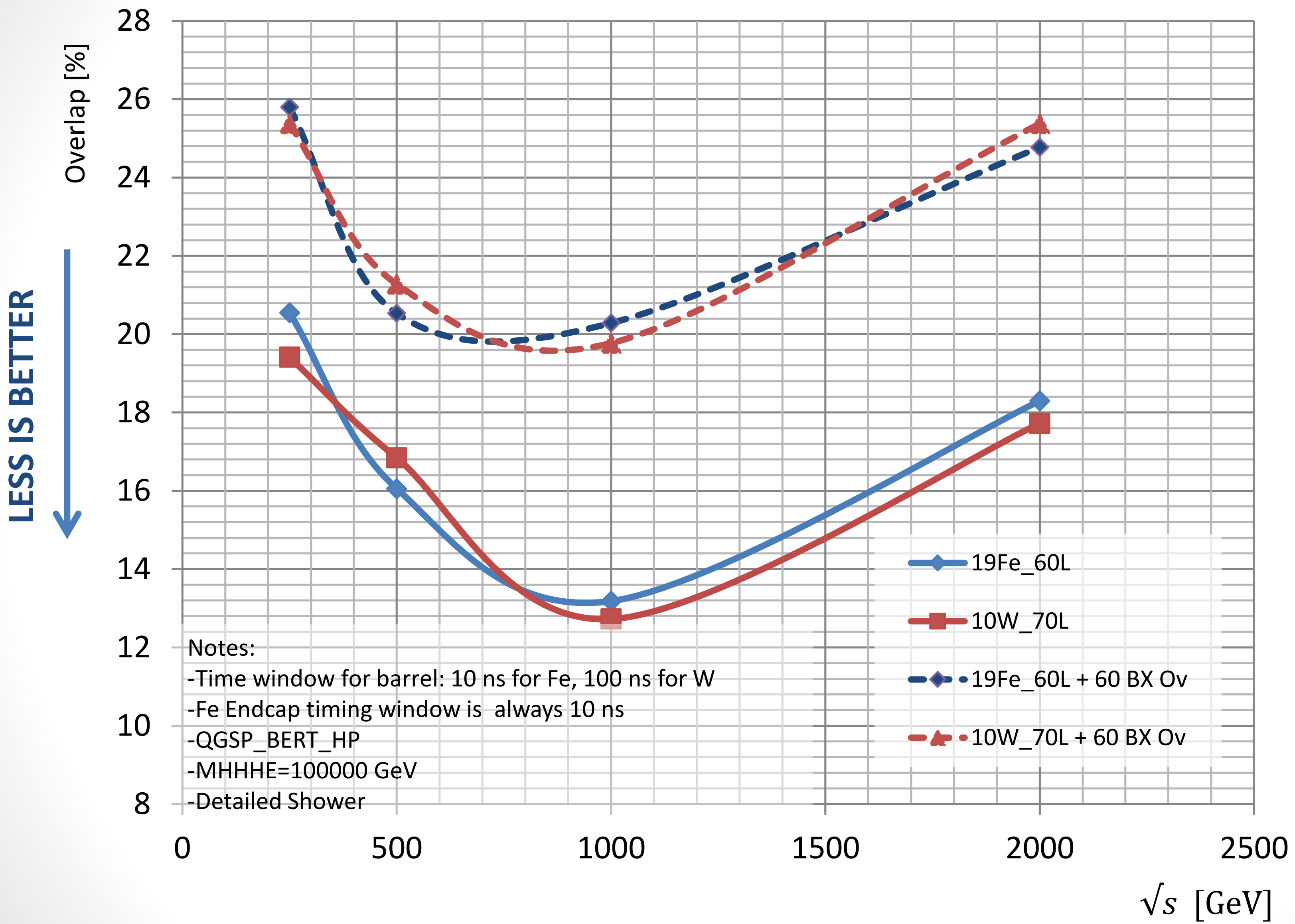
- **W** appears to perform better than Fe (without using s/w comp) **but it should not drive solely our decision**

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 (60 BX @ 3 TeV)
- 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 Non-Linearity Corrections (NLC) applied
  - MHHHE=100000 GeV (not optimized, not modified)

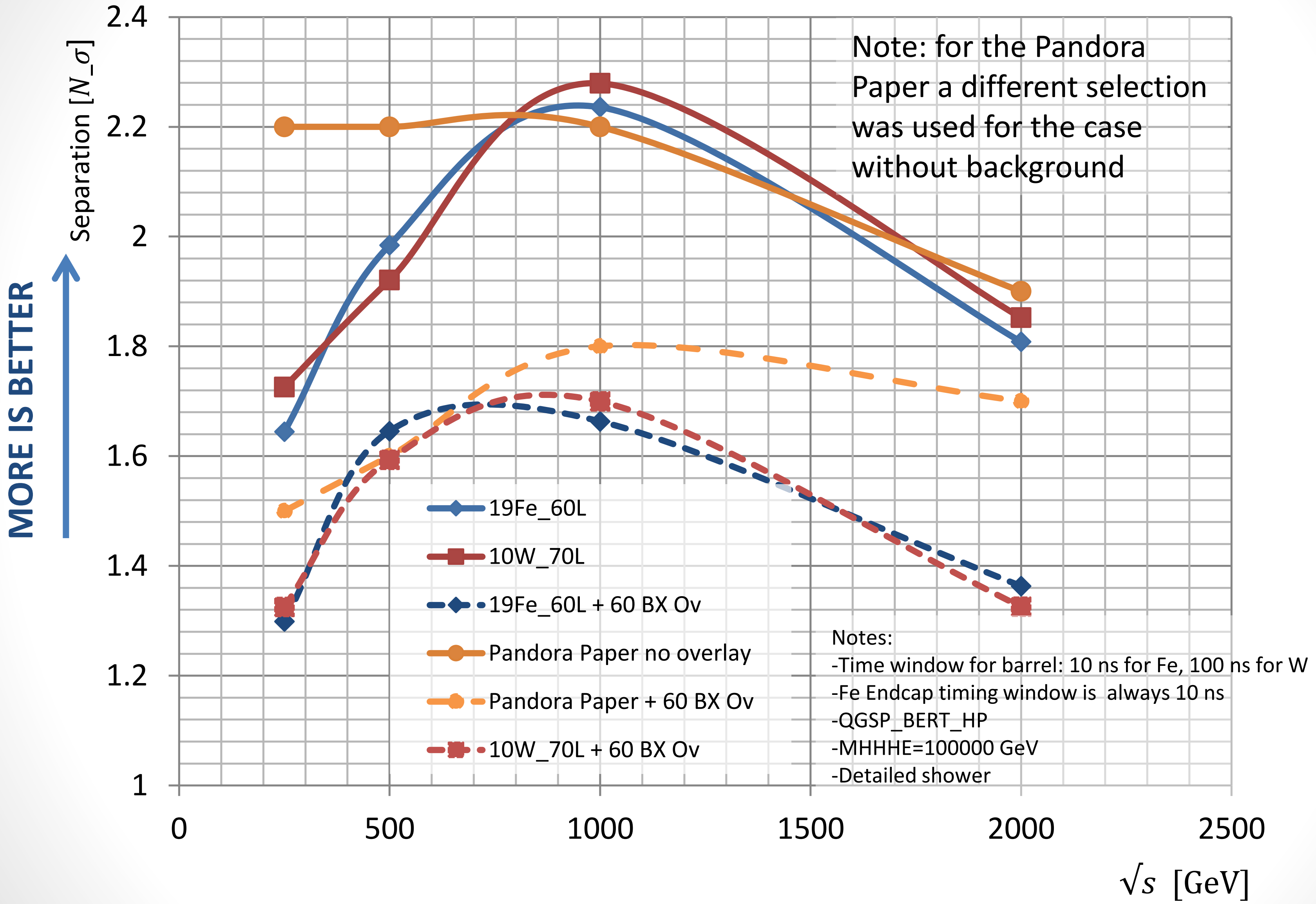
W Vs Fe JER: m_W and m_Z Overlap



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



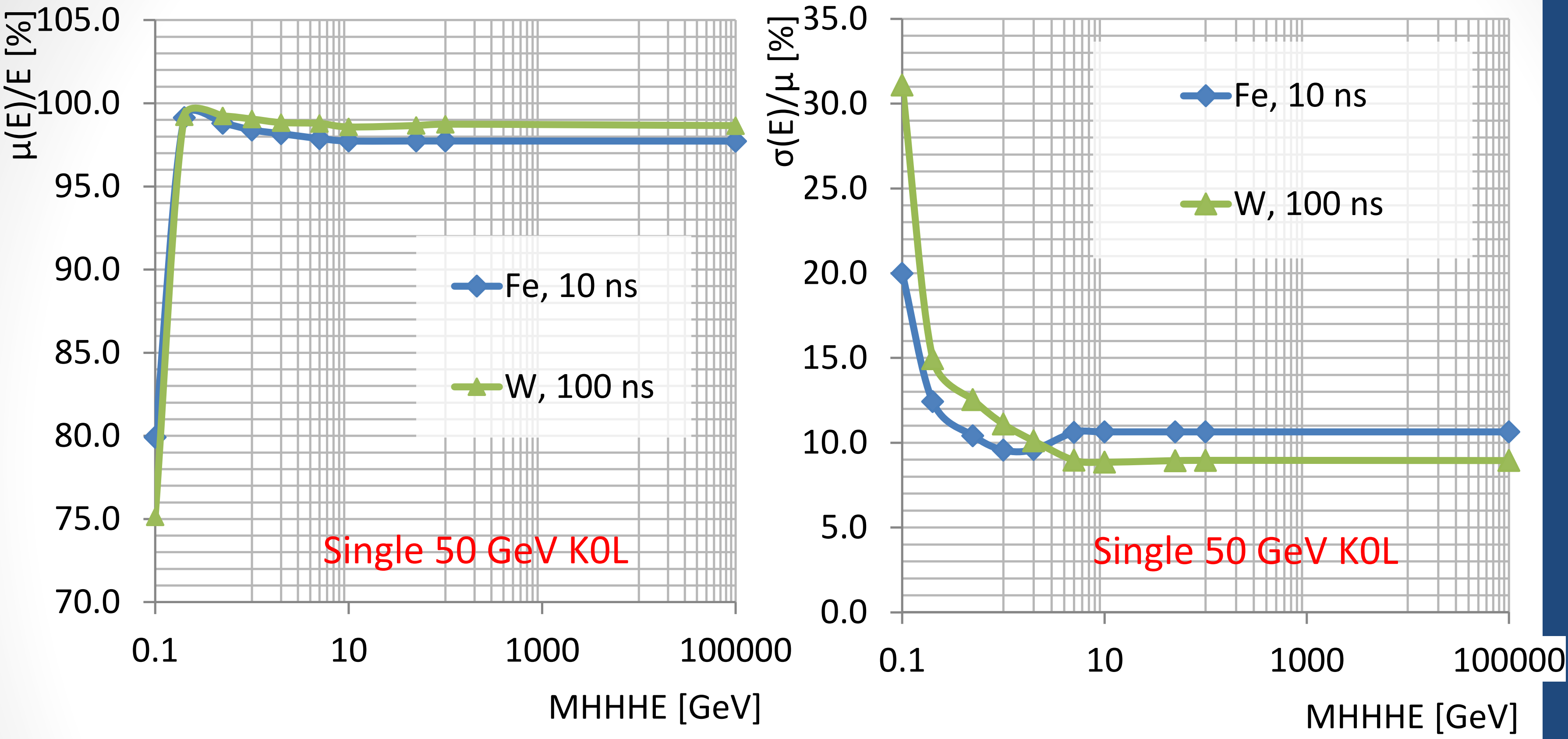
Note: for the Pandora Paper a different selection was used for the case without background

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 ….

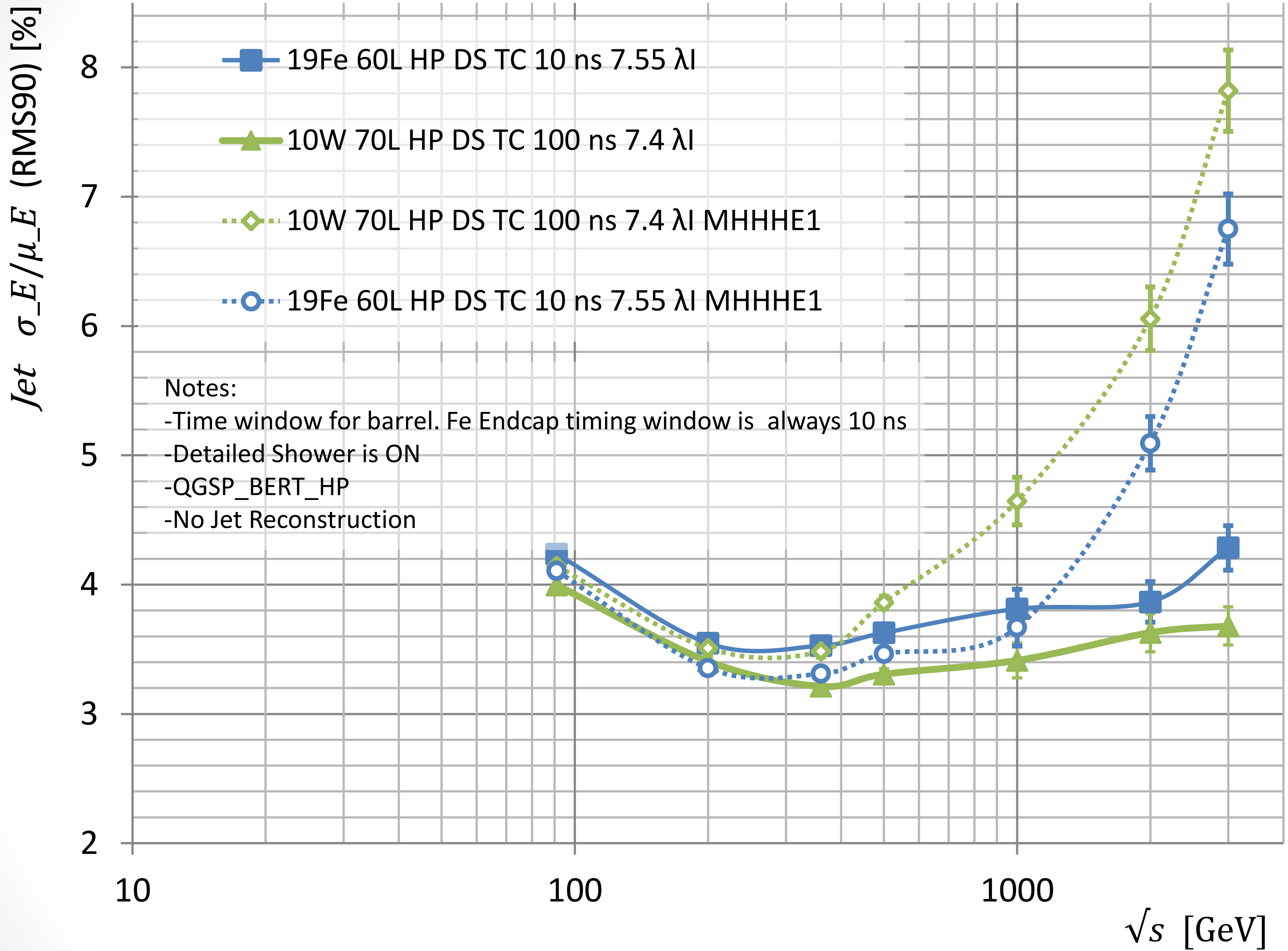
Effect of MHHHE Cut for Single 50 GeV K0L

(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)**

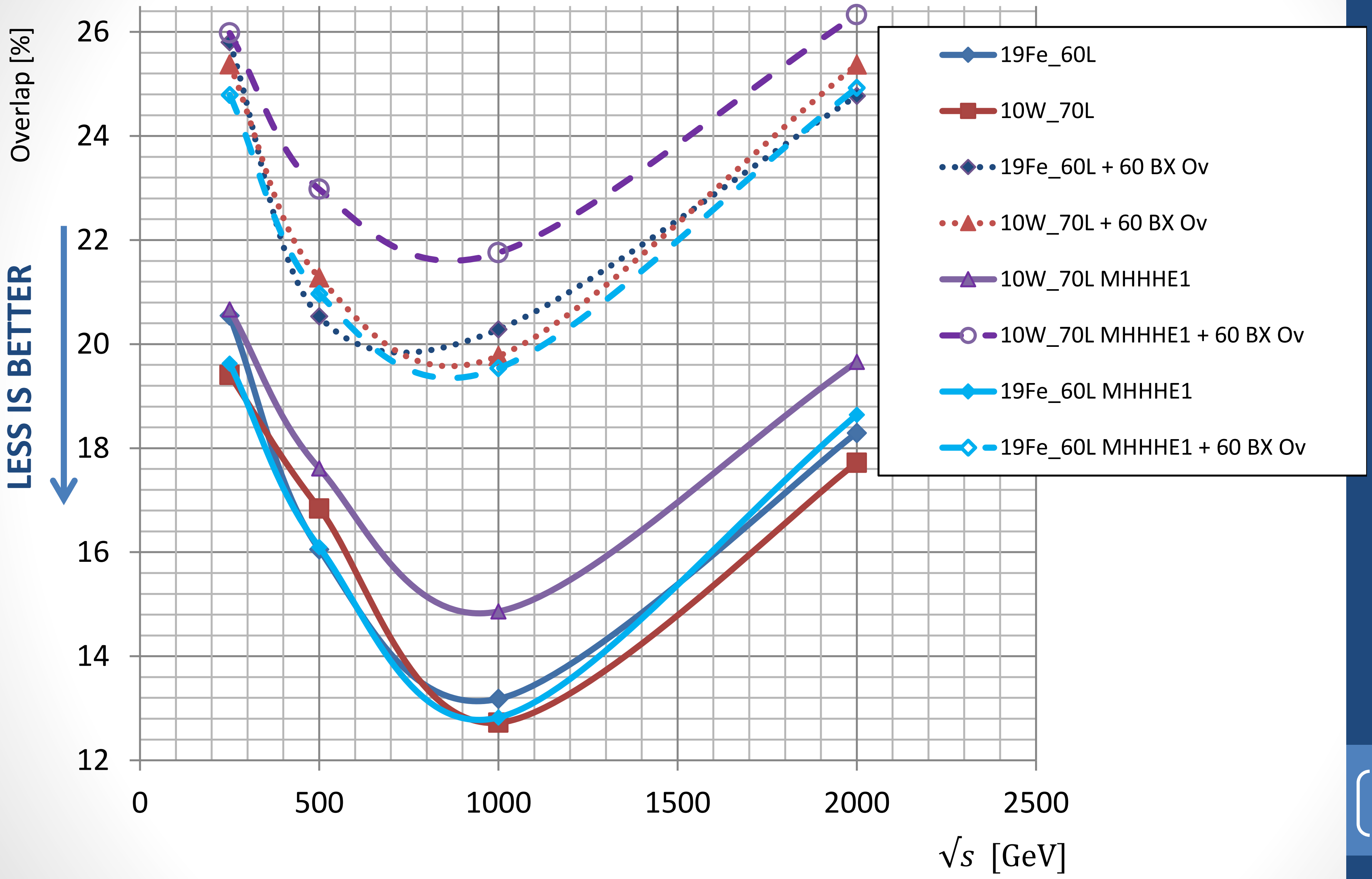
W Vs Fe JER without Overlay: $Z \to uds$



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 $\gamma\gamma \rightarrow had$)



Similar conclusion: for low MHHHE cuts, Fe performs better

HCal Parameter Optimization

- Next we present a series of results out of several studies to optimize the various parameters of the HCal
  - Include new results with higher energy jets ($E_J \sim 1$ and 1.5 TeV)

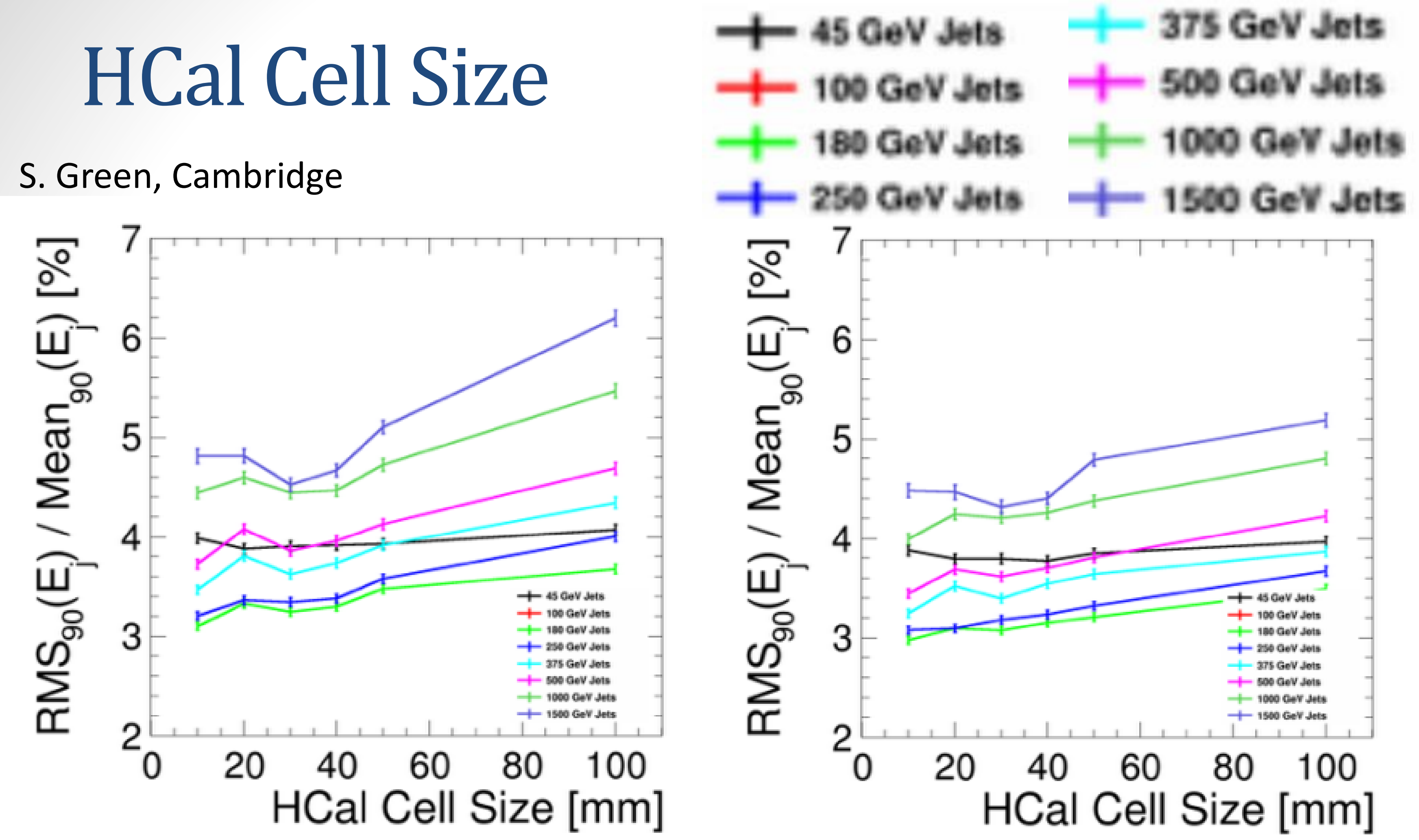
- Aim to converge towards the parameters for the next detector simulation model

- **The performance as a function of the varied parameter is studied in jets of various energies obtained in $Z \rightarrow uds$ events**
  - **`AnalysePerformance`** in **`PandoraAnalysis`**

- **Wanted to avoid introducing dependence on timing window**
  - Will show pairs of plots: Studies performed with a 10 ns timing window (left) and 10000 ns (right)

HCal Cell Size

S. Green, Cambridge



$Z \rightarrow uds$

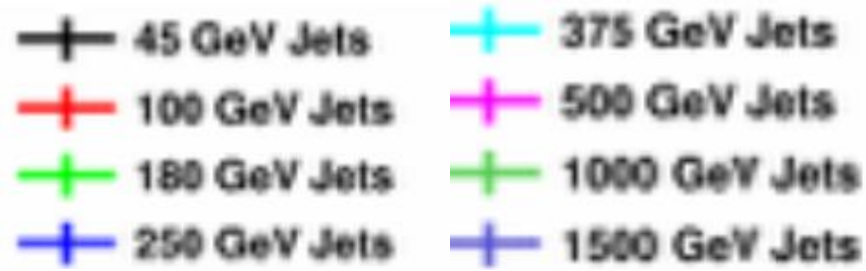
10 ns HCal Timing Cut

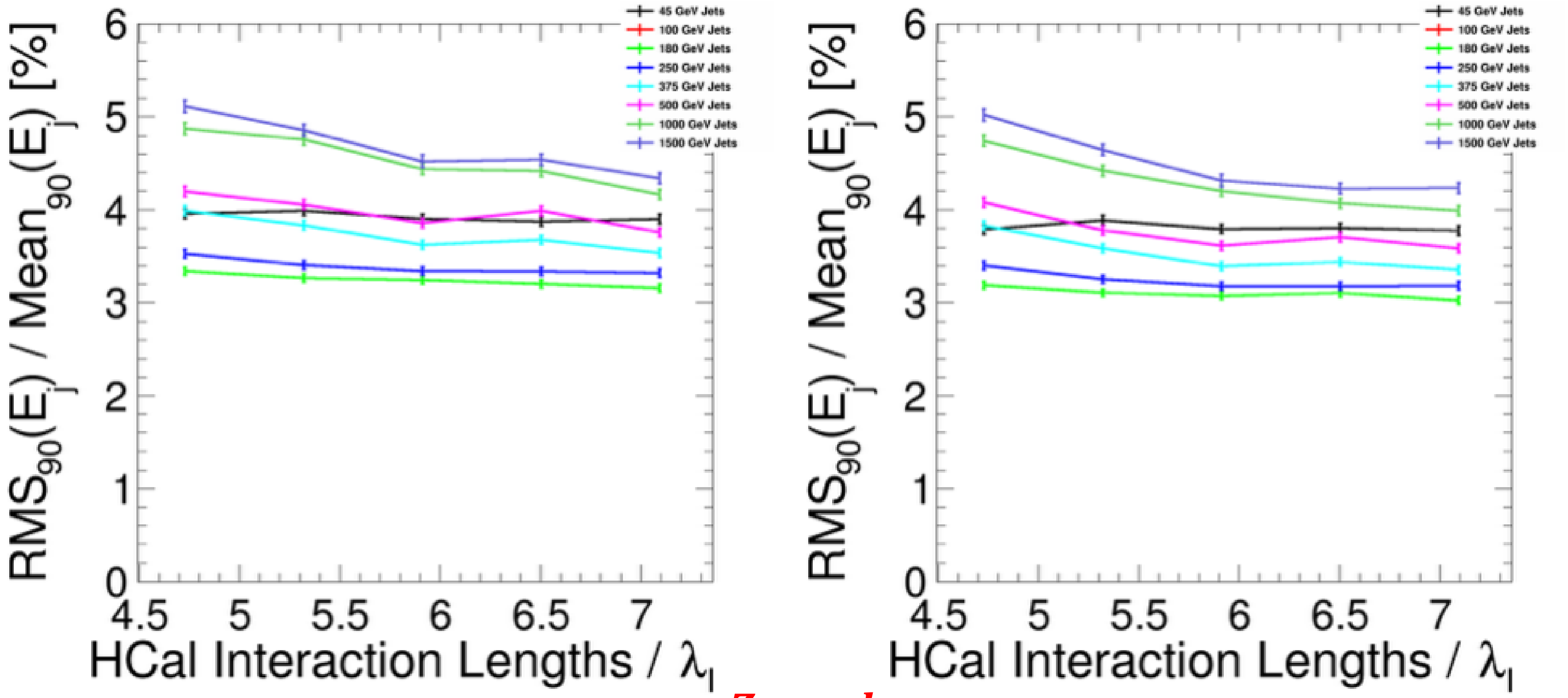
10^6 ns HCal Timing Cut

- 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





$Z \rightarrow uds$

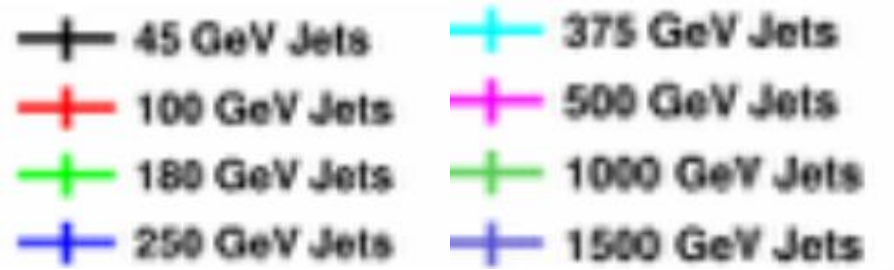
10 ns HCal Timing Cut

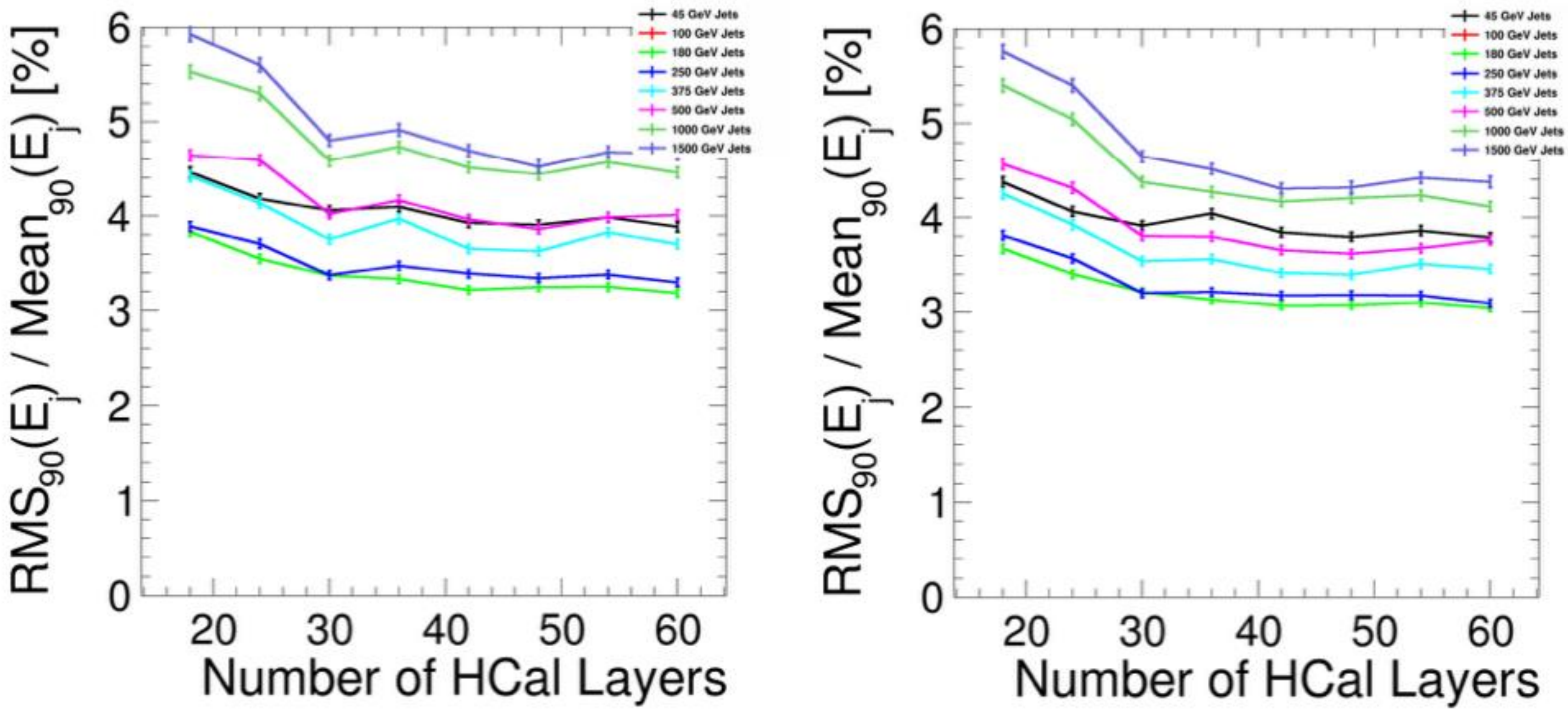
10^6 ns HCal Timing Cut

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

HCal #Layers

S. Green, Cambridge





$Z \rightarrow uds$

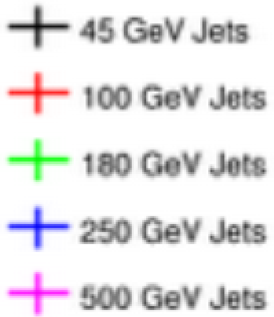
10 ns HCal Timing Cut

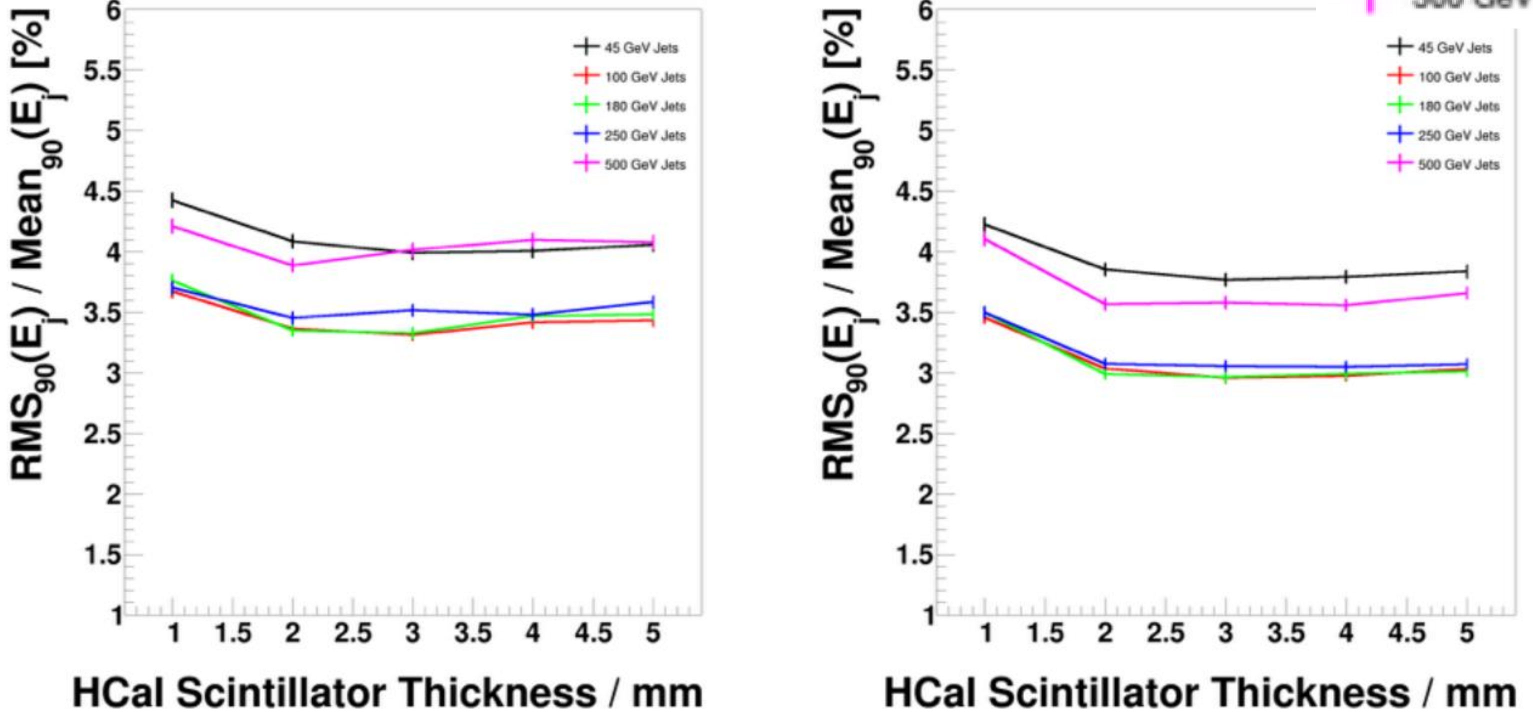
10^6 ns HCal Timing Cut

- 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**

HCal Forward Coverage Extension

- Study effects of increasing coverage of HCal by extending it down to beampipe
  - Modified ILD_o1_v06 driver, removed LHCal, masks,…
  - Verified that resulting performance is consistent with Nominal ILD models

	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**

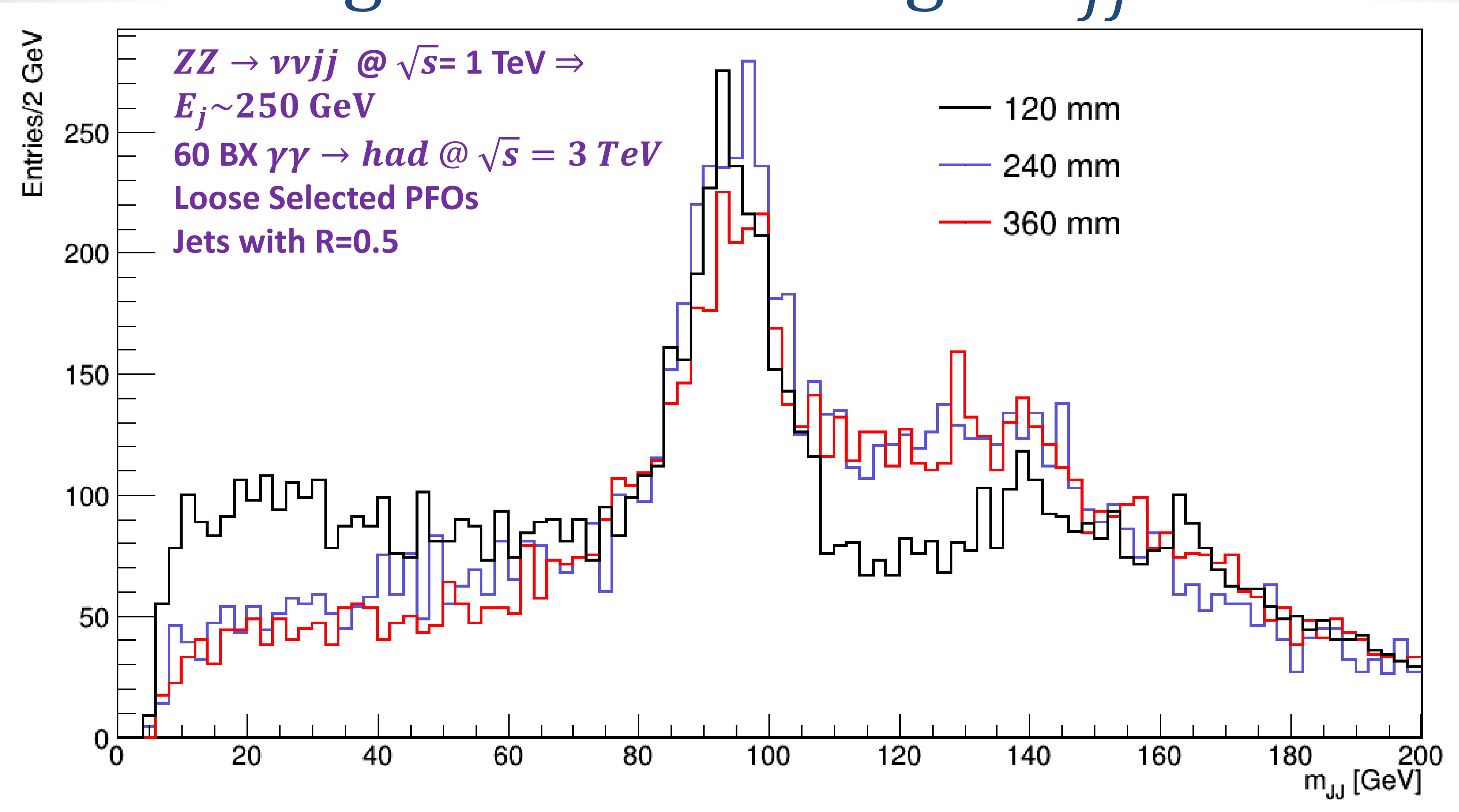
R Values for L=2.65 m

*If we ignore LHCal coverage

- Especially interested in the case where $(\gamma\gamma \rightarrow had)$ background is included

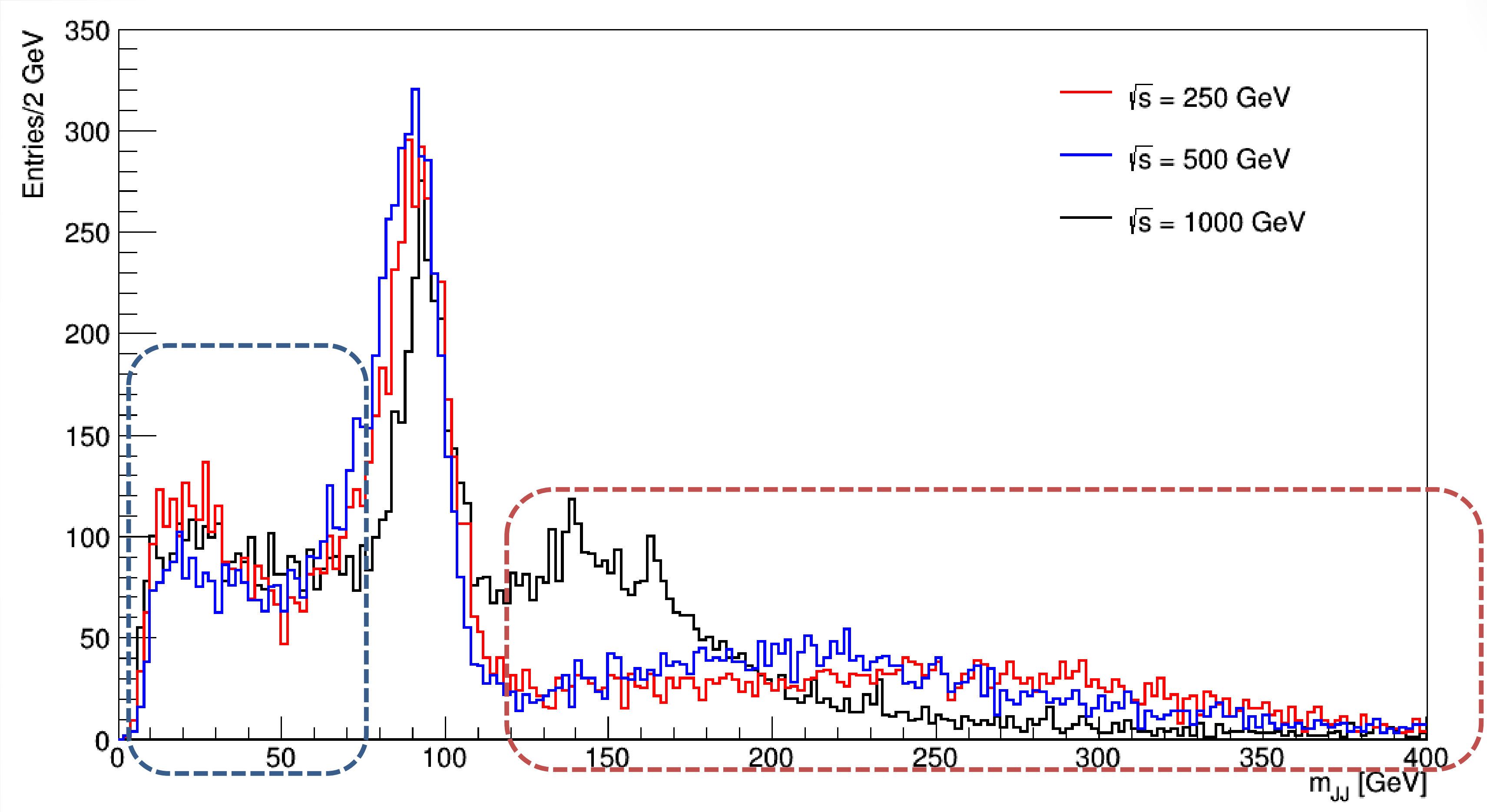
- Study performance of physics processes as a function of R_{in}^{HCal}
  - Study $\boldsymbol{ZZ \rightarrow q\bar{q}\nu\bar{\nu}}$, study m_{JJ} reconstruction (efficiency, resolution,…)
    - Implemented “cheating” to find side of detector where $Z \rightarrow q\bar{q}$ decays to split PFO collections to two (and feed to FastJet)
    - Request **exclusive** reconstruction of **two (2) Jets**
    - Tried to optimize selection (very rudimentary)
      - Jets with $R{\sim}0.5$ work better, Looser PFOs work better

Extending the HCal coverage: m_{JJ}



- The peak is resolved better with smaller HCal inner radius
- $R_{in} \sim 120$ mm **performs well even in the presence of background**
- However, the increased background probably starts to spoil the efficiency
- **An HCal with $R_{in} \sim 240$ mm is an attractive and feasible option**

m_{JJ} for different $\sqrt{s}$ at fixed $R_{in} = 120$ mm



- **Dependence on $\sqrt{s}$ in the production of the ZZ system hints at inability to resolve the two jets**
- Investigated origin of tails (next slide)

CLICdp Collaboration Meeting 02/06/2015

Anatomy of a Mass Measurement

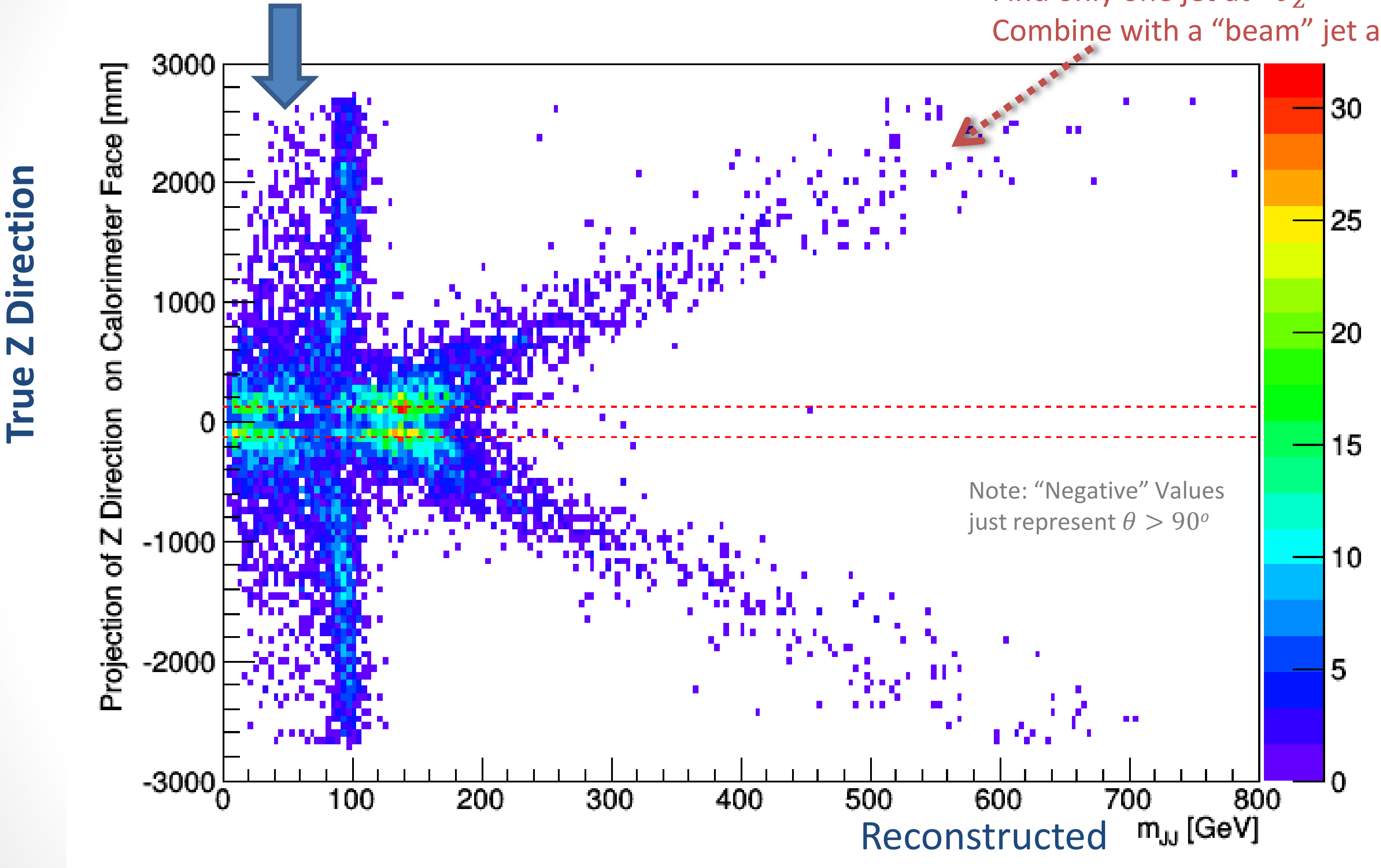
ZZ @ $\sqrt{s}$= 1 TeV -> E_j~250 GeV, 120 mm, Loose, R=0.5 Jets

$m_{JJ}^2 \sim (1 - cos\theta)$

Find only one jet at ~θ_Z

Combine with a “beam” jet at $\theta \sim 0$

$E_{J0} + E_{J1} < 200\ GeV$



Note: “Negative” Values just represent $\theta > 90^o$

Perhaps a re-optimized PFO selection and/or smarter use of Fastjet could improve the efficiency

- **An HCal with $R_{in} \sim 120$ mm is not as sensitive to $\gamma\gamma \rightarrow had$ as previously thought**

Conclusions

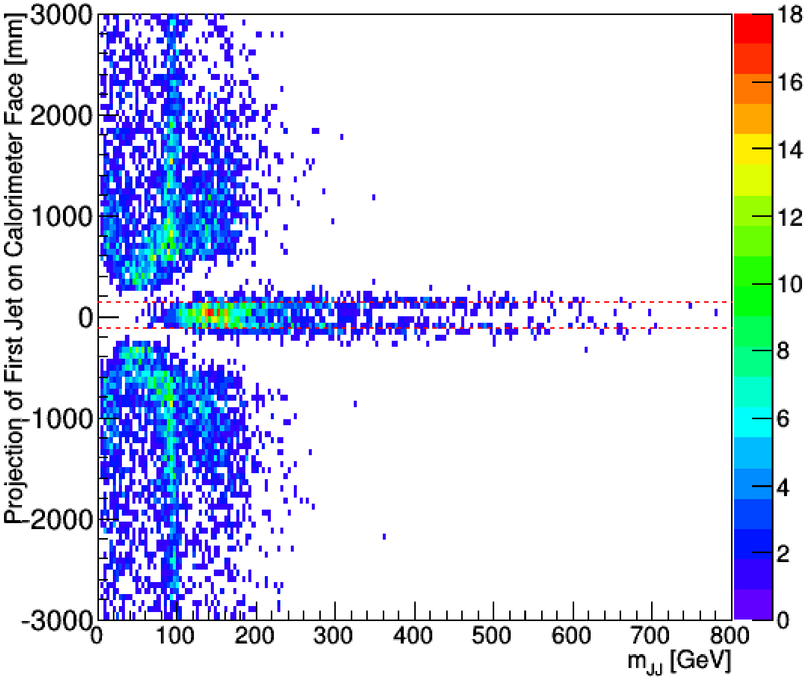
- $R_{in}\sim 240\ \mathrm{mm}$ **appears feasible from engineering side**
  - **Probably extremely difficult to go below that**
  - **A good option, behaving well under $\gamma\gamma \rightarrow \boldsymbol{had}$**

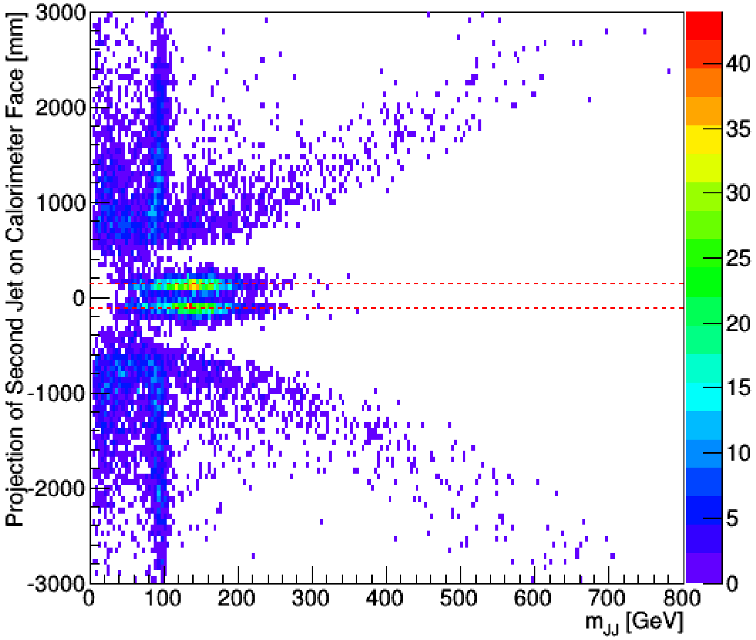
- **Converging towards the following other HCal parameters for next simulation model:**
  - **20 mm Steel** Absorber in both Barrel and Endcap
    - 1 mm in steel cassette
  - ≲60 Layers in both Barrel and Endcap with a target depth of ∼7.5λ
  - 3 mm Scintillator
  - 30 mm x 30 mm cell sizes

- Parameters already implemented in DD4hep
  - Drivers being refined

BACKUP SLIDES

mJJ Vs Jet Directions



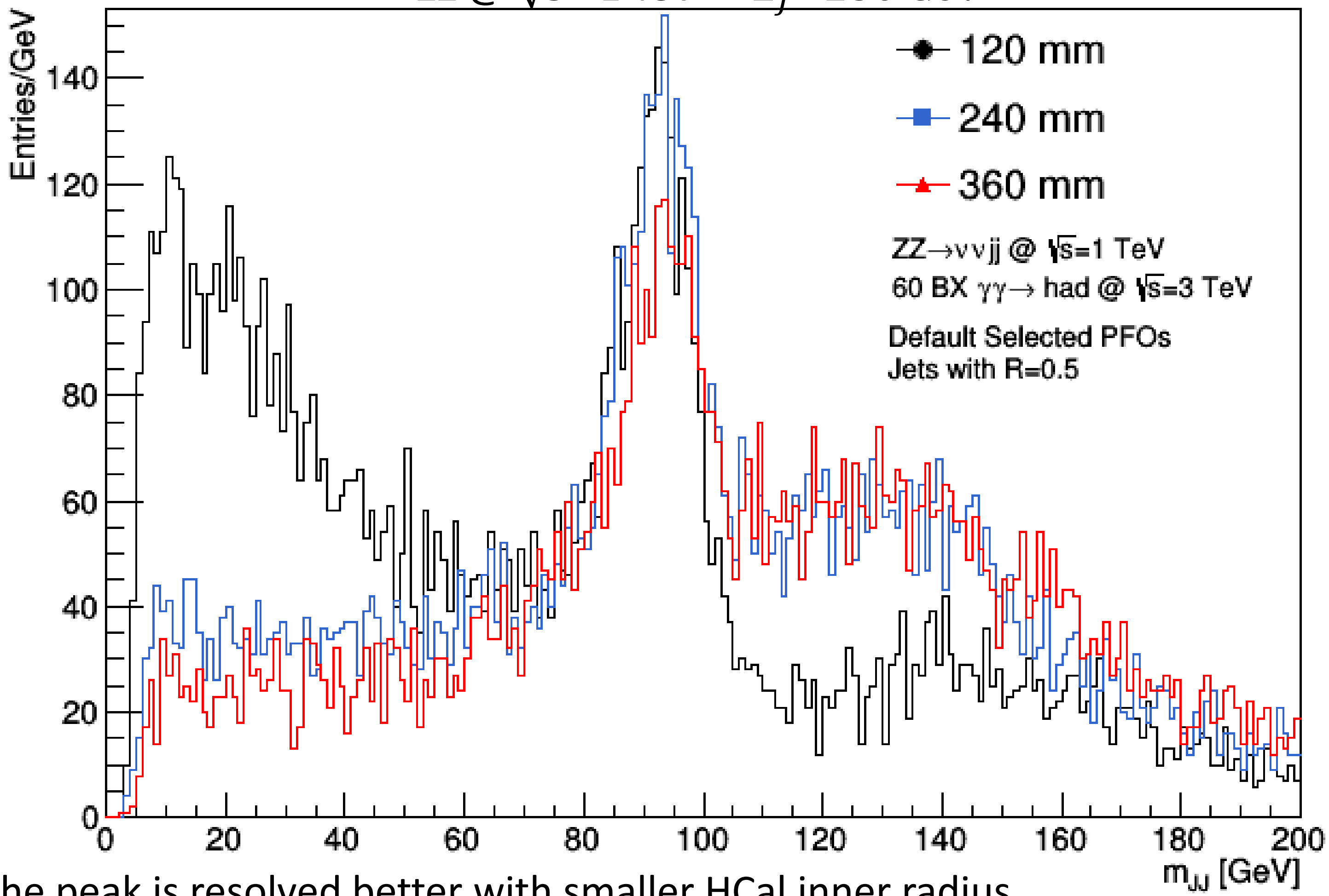


Note: “Negative” Values represent $\theta > 90^{o}$

ZZ @ $\sqrt{s}$= 1 TeV -> $E_j \sim 250$ GeV, 120 mm
Loose Selected PFOs
R=0.5 Jets

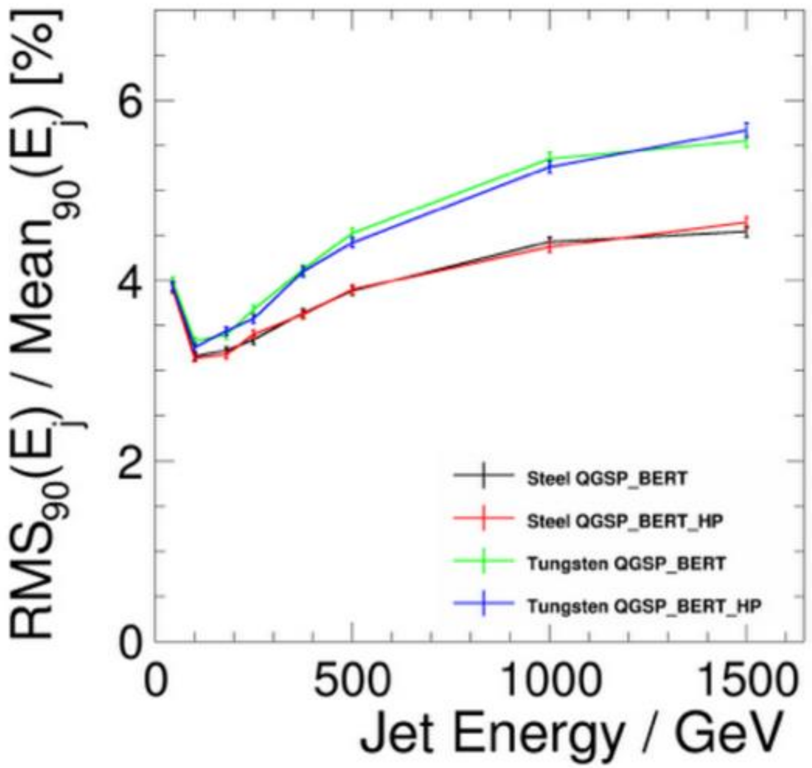
Extending the HCal coverage: m_{JJ}

ZZ @ $\sqrt{s}$= 1 TeV -> E_j~250 GeV

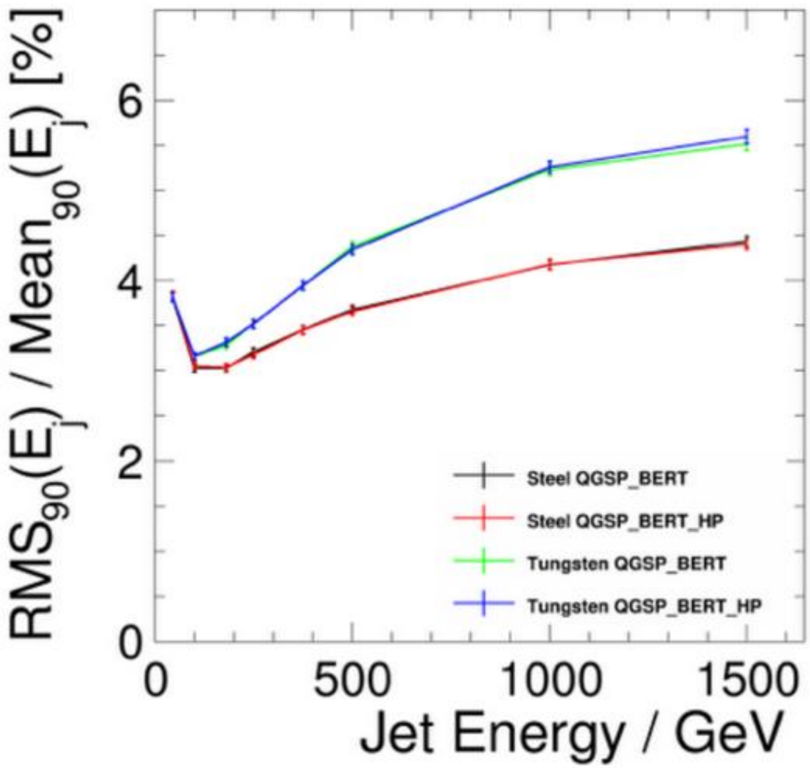


- The peak is resolved better with smaller HCal inner radius
- R_{in}~240 mm **performs well even in the presence of background**
- However, at 120 mm probably the increased background spoils the efficiency

Additional Study on HCal Absorber Material (S.Green, Cambridge)

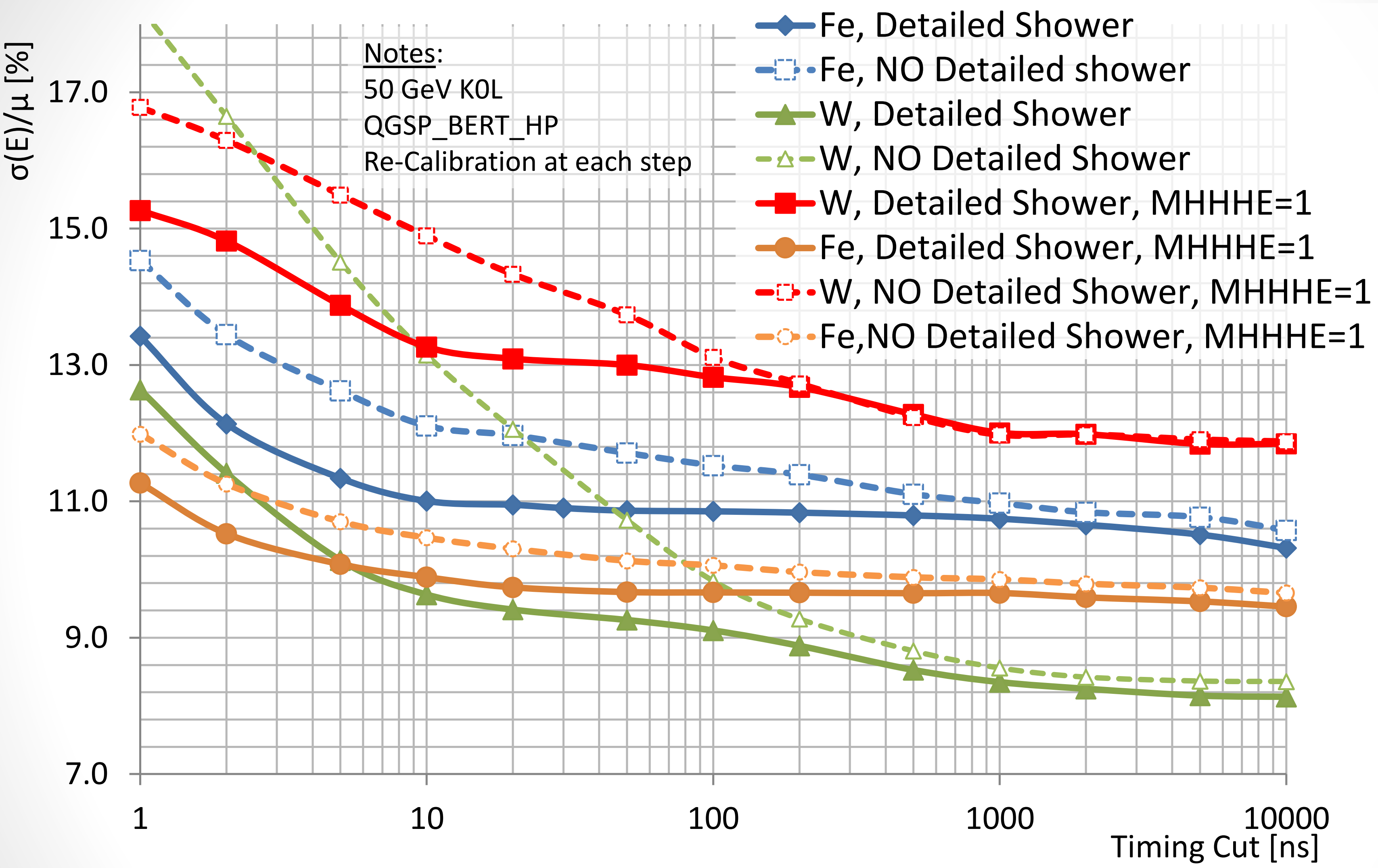


10 ns HCal Timing Cut



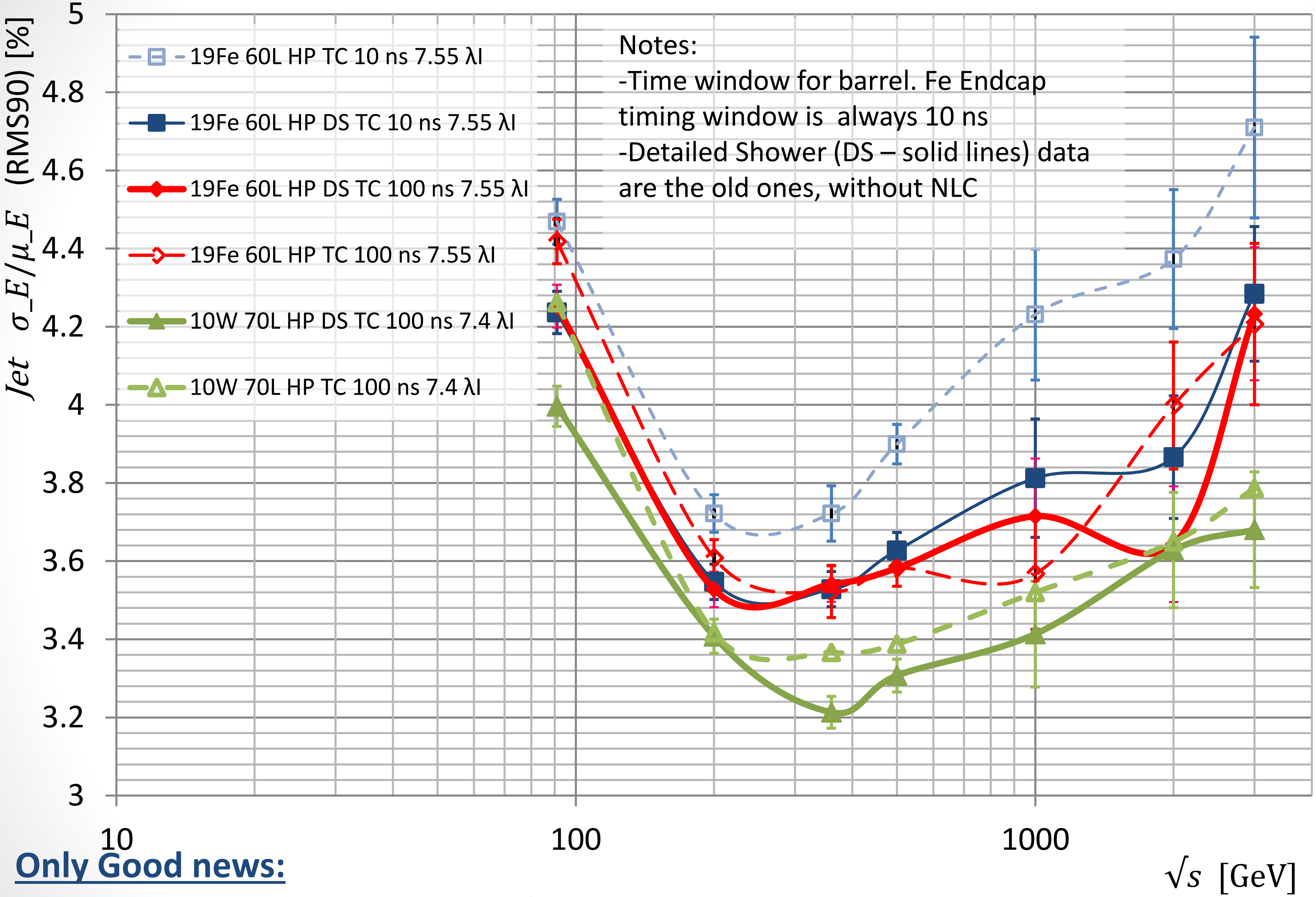
10^6 ns HCal Timing Cut

Effect of MaxHCalHitHadronicEnergy



- 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: $Z \to uds$



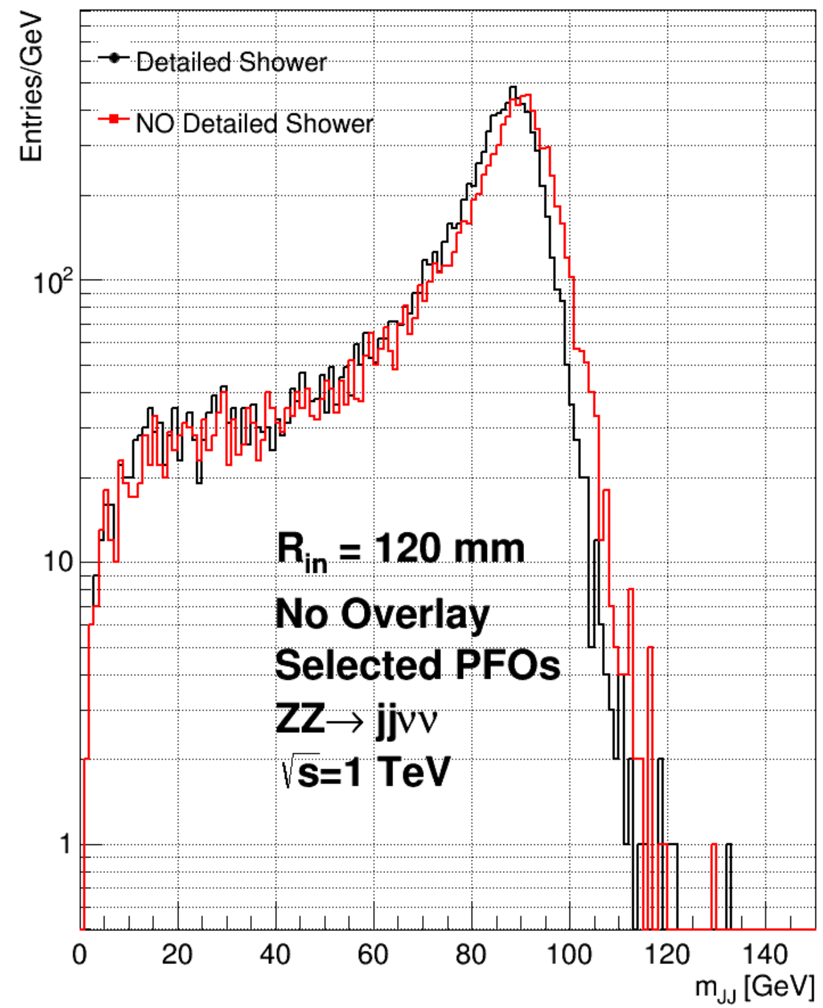
Notes:
-Time window for barrel. Fe Endcap timing window is always 10 ns
-Detailed Shower (DS – solid lines) data are the old ones, without NLC

Only Good news:

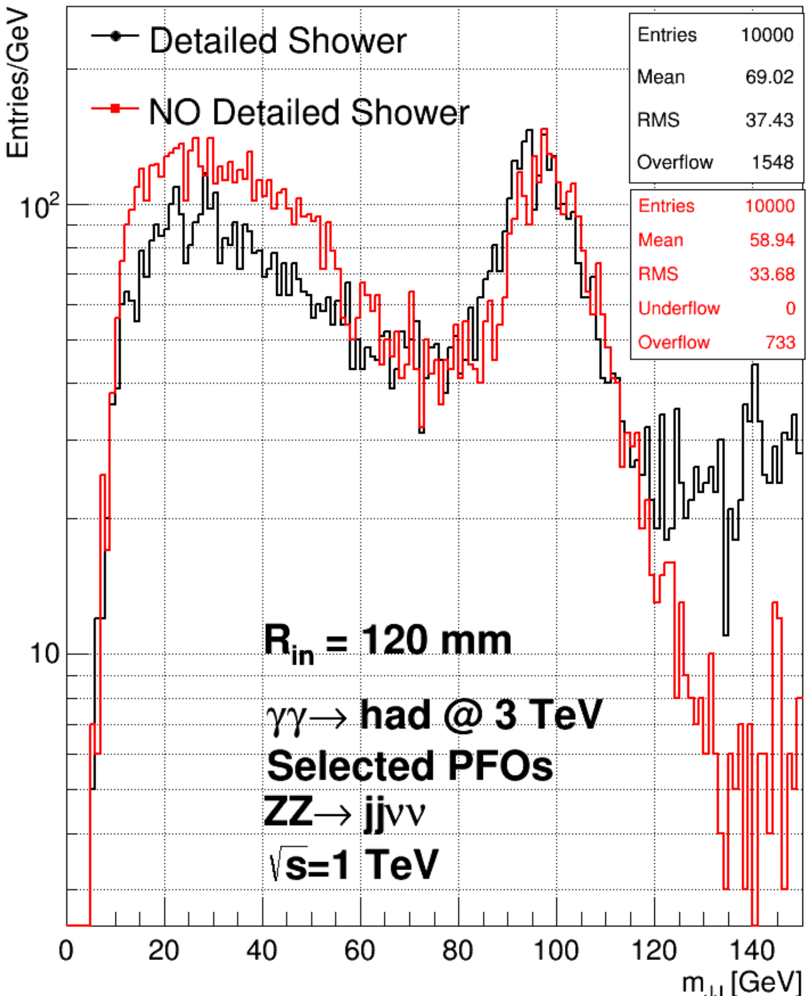
- **10 ns Fe JER is better than before**
- **The previous conclusions are still valid:** W is a bit better than Fe (without s/w comp) **but it should not drive solely our decision**

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)



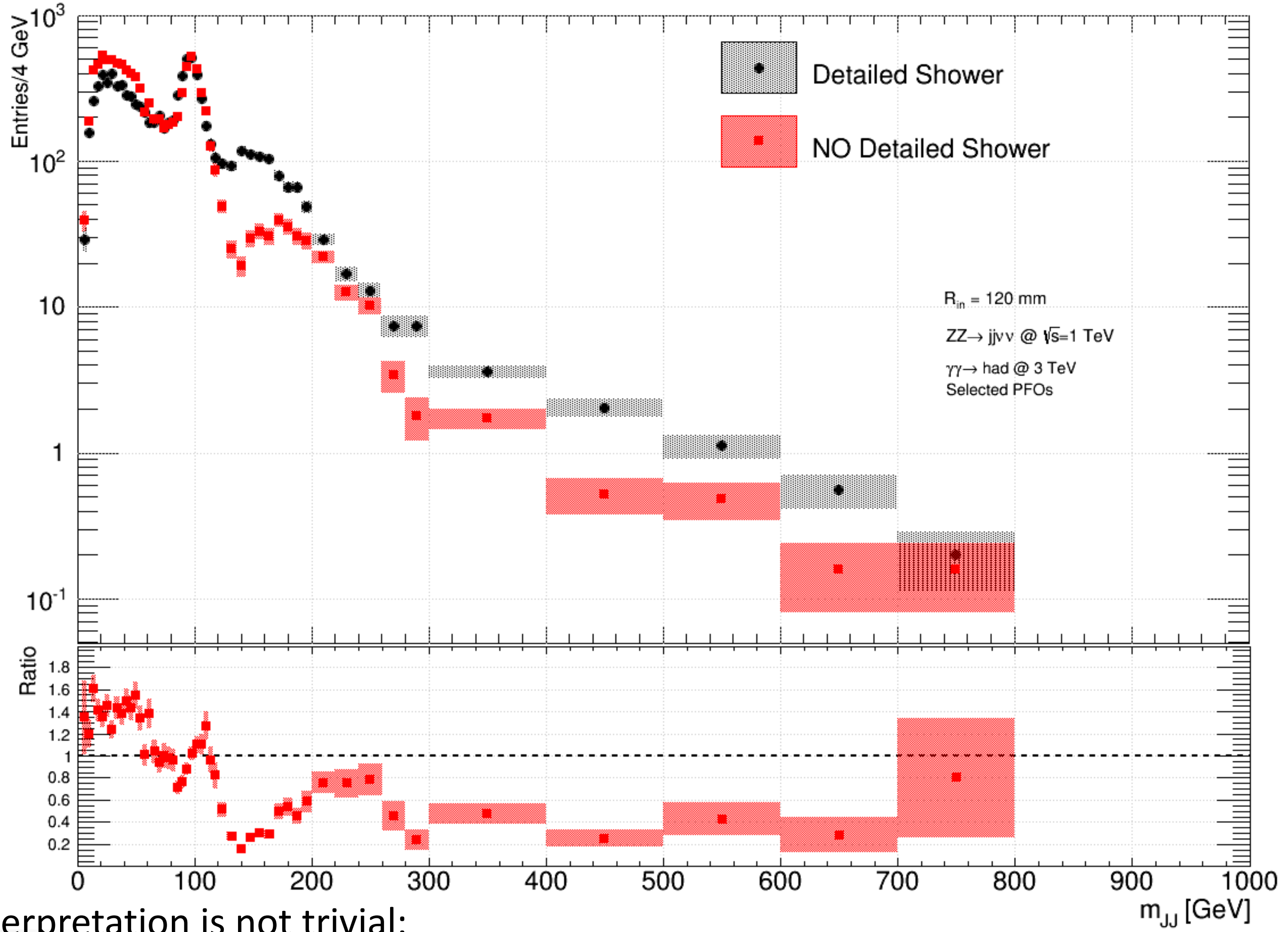
Without overlay, the effect appears to be small



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

- See next slide for wider range

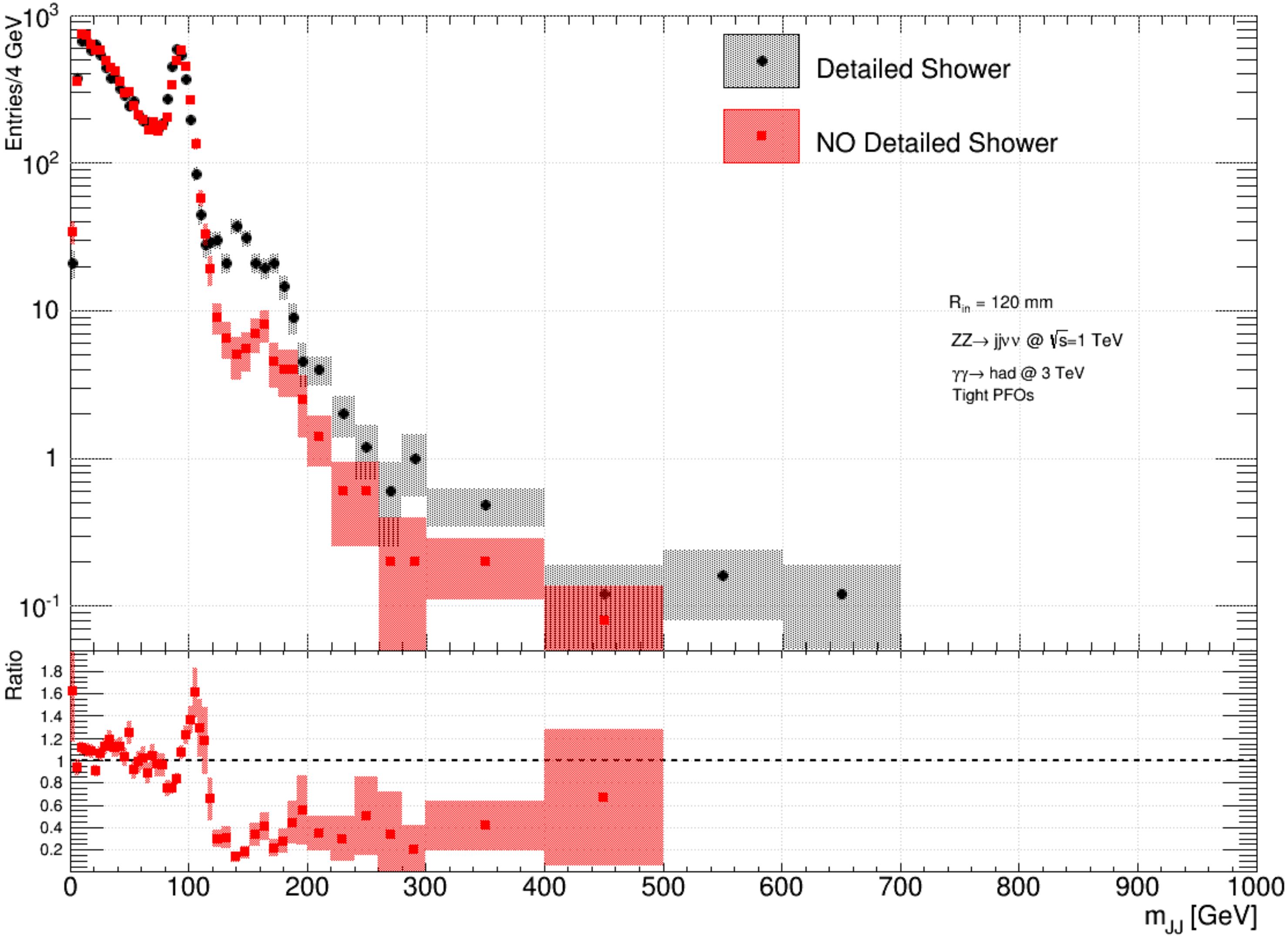
Comparison of m_{JJ} for Jets Reconstructed with Selected PFOs



Interpretation is not trivial:

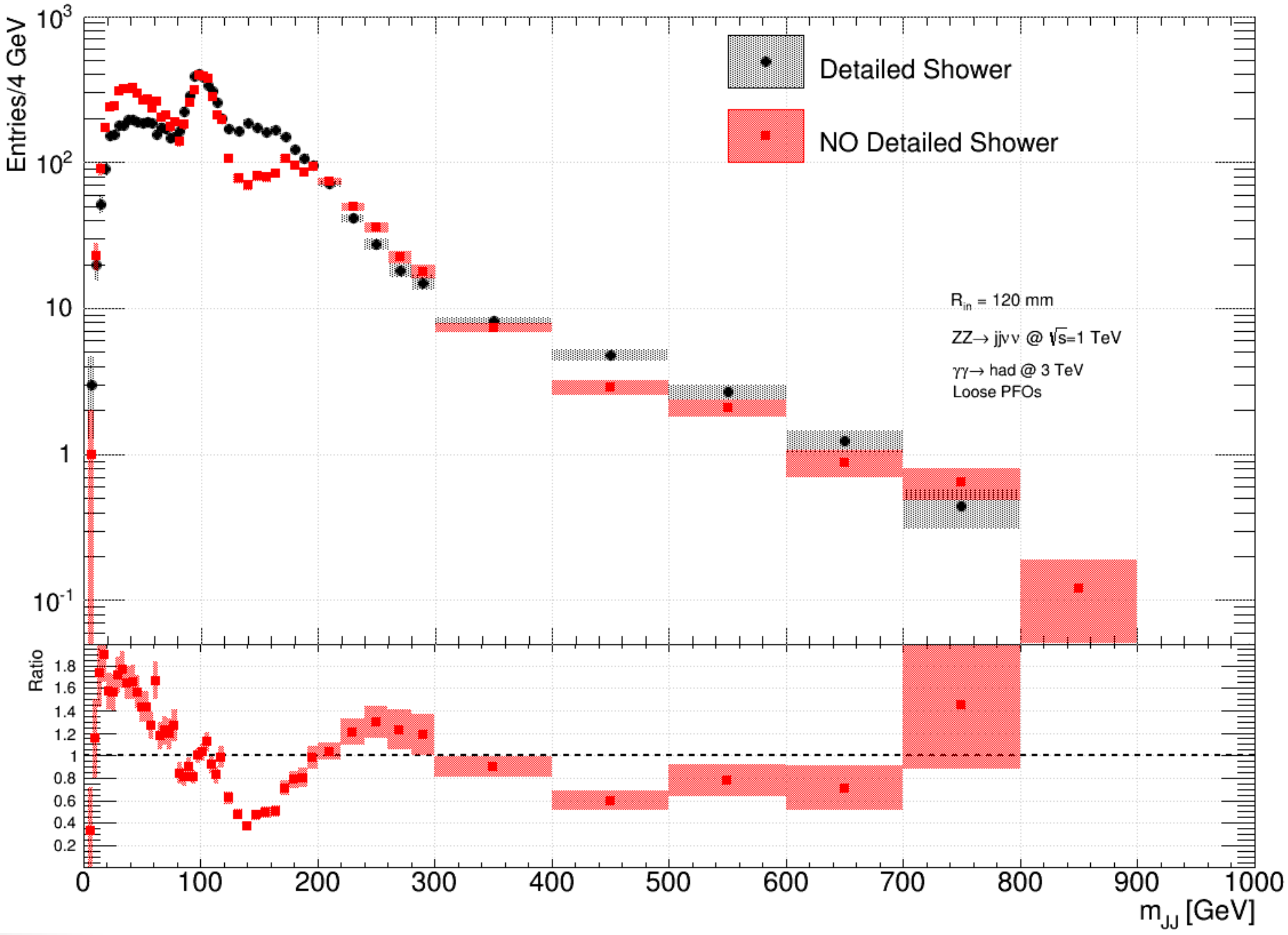
- On one hand, trying to understand differences in tails
- On other hand, comparing a steeply falling distribution (Z peak) with a ratio plot…

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

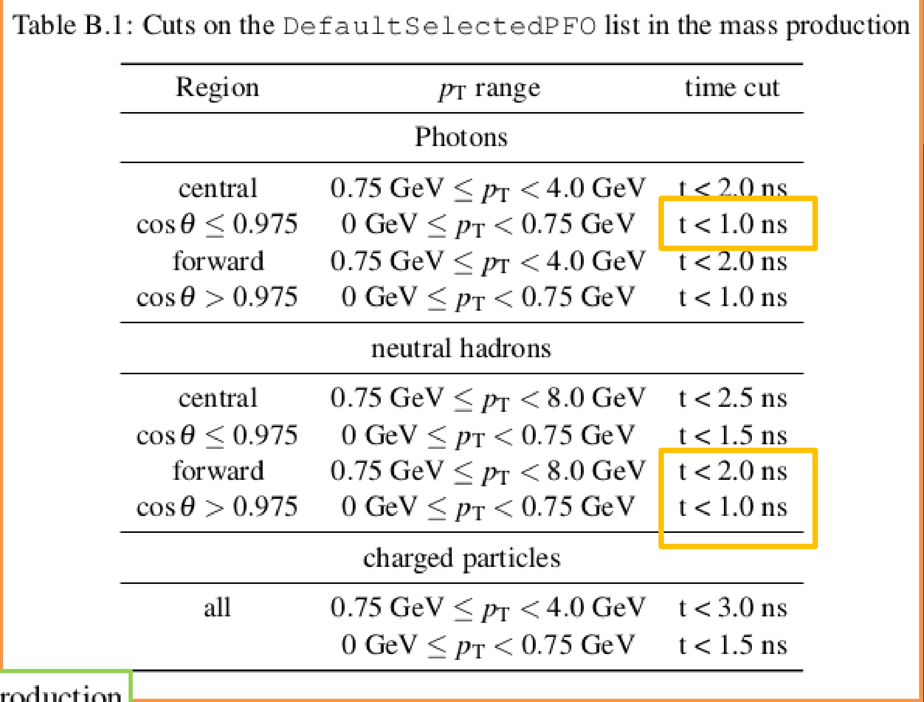


Table B.1: Cuts on the `DefaultSelectedPFO` list in the mass production

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

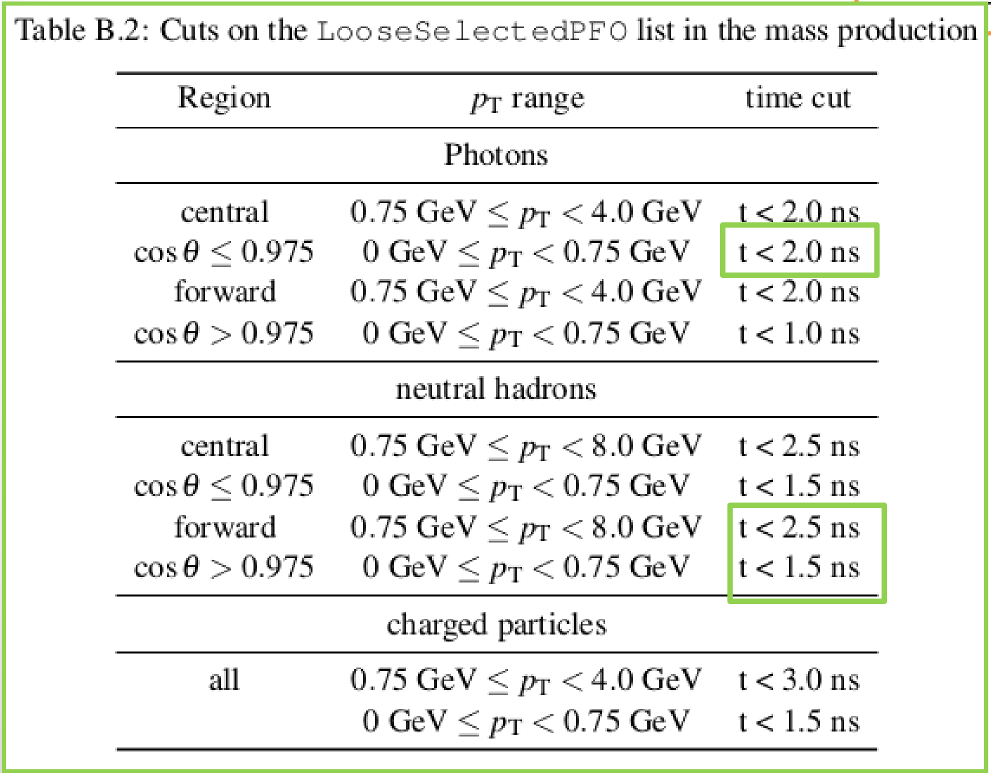


Table B.2: Cuts on the `LooseSelectedPFO` list in the mass production

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

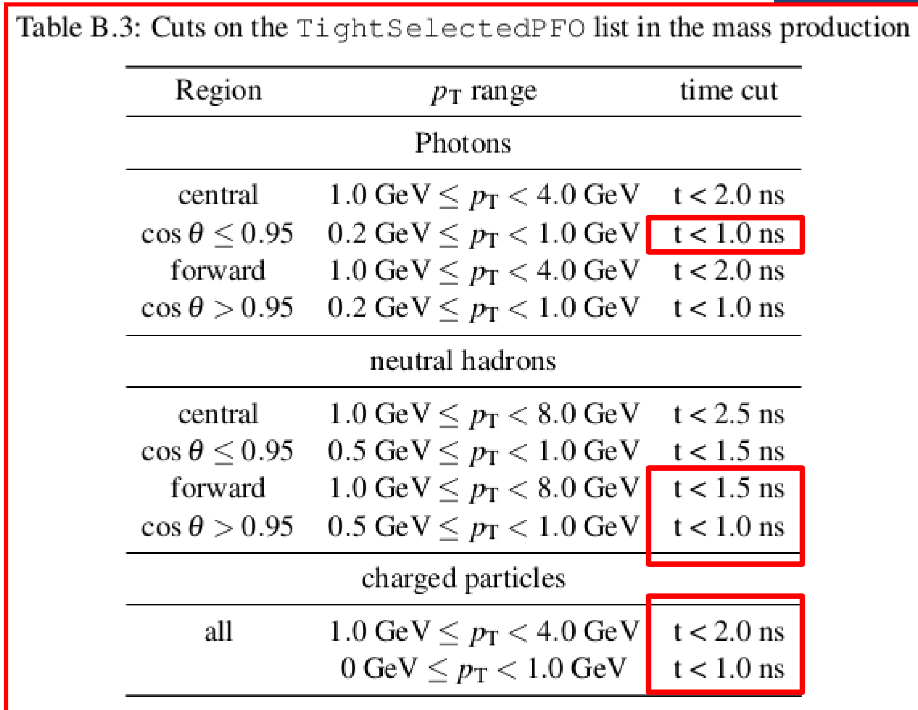


Table B.3: Cuts on the `TightSelectedPFO` list in the mass production

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