Improving the Performance of the CMS ECAL Trigger Energy Reconstruction Algorithms for LHC Run 3

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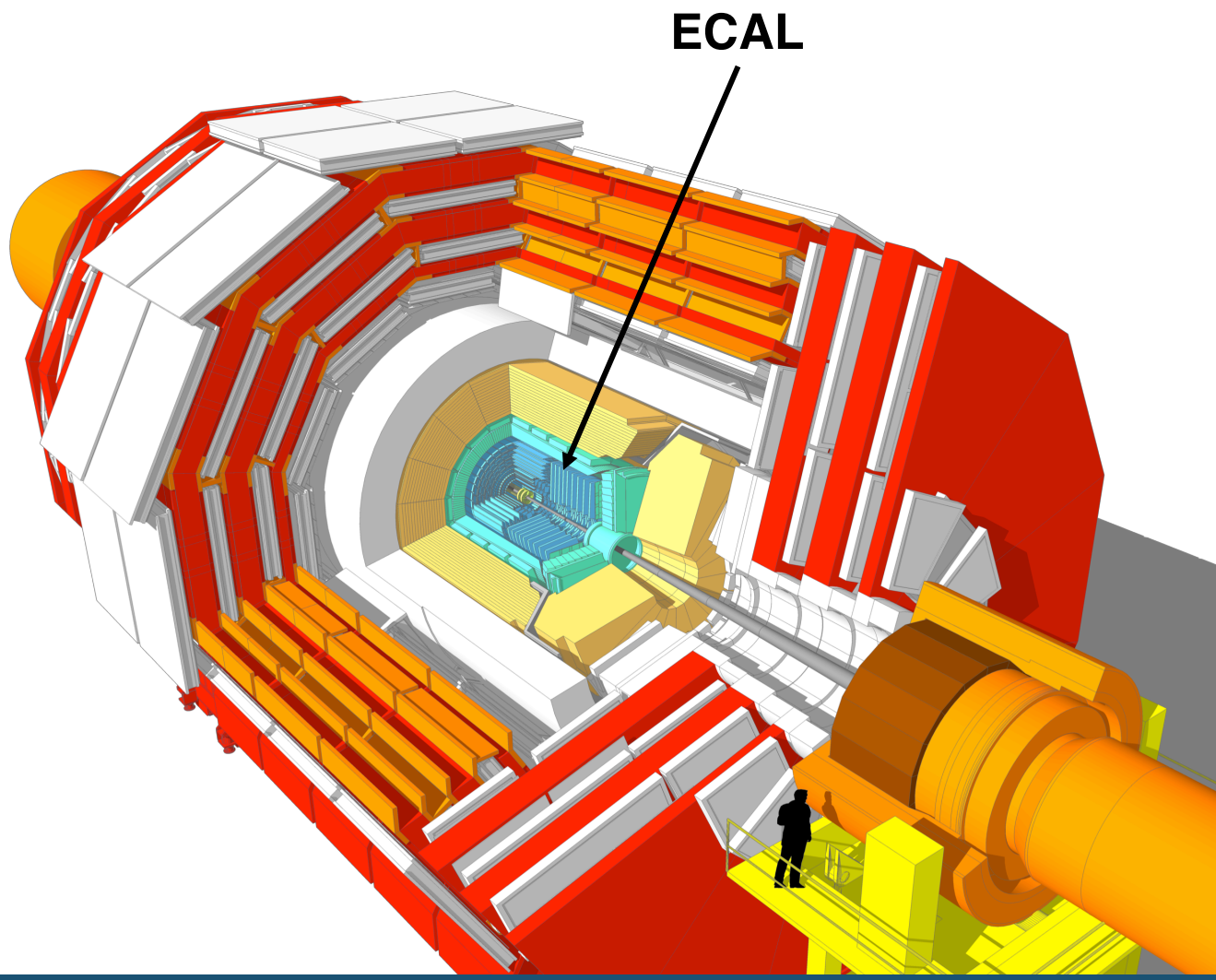
Introduction

- CMS is a general purpose detector at CERN
- The CMS Electromagnetic Calorimeter (ECAL) uses a **fast** energy reconstruction algorithm to perform energy measurements of e/ γ/ jets /missing energy
- These are used to identify potentially **interesting** physics events and trigger on them
- Despite challenging conditions, the **best** possible trigger performance must be maintained for LHC Run 3 (2021-23) to **maximise** physics
- **This project focuses on improving the ECAL energy reconstruction algorithms**

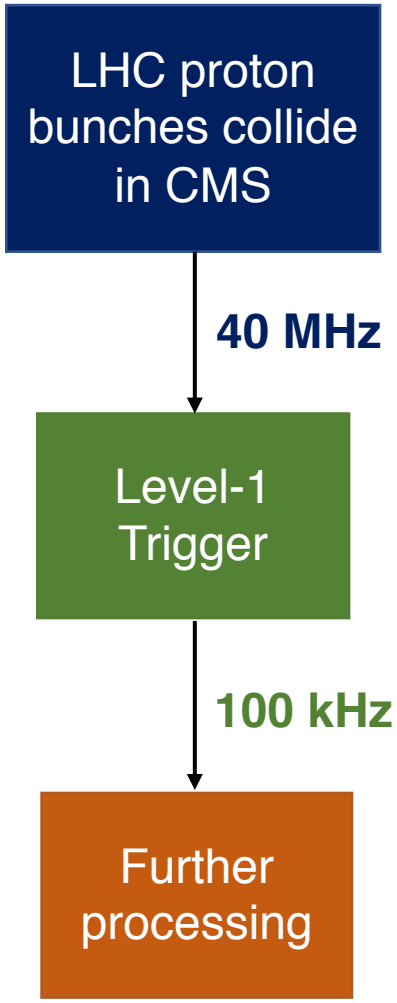
CMS

- Comprises four concentric subsystems that provide information about the LHC collisions
- 14,000 tons, 15m diameter and 28.7m long
- The LHC collides at 40 MHz and produces ~ 1 billion events per second
- CMS trigger selects only interesting physics events based on subsystem data



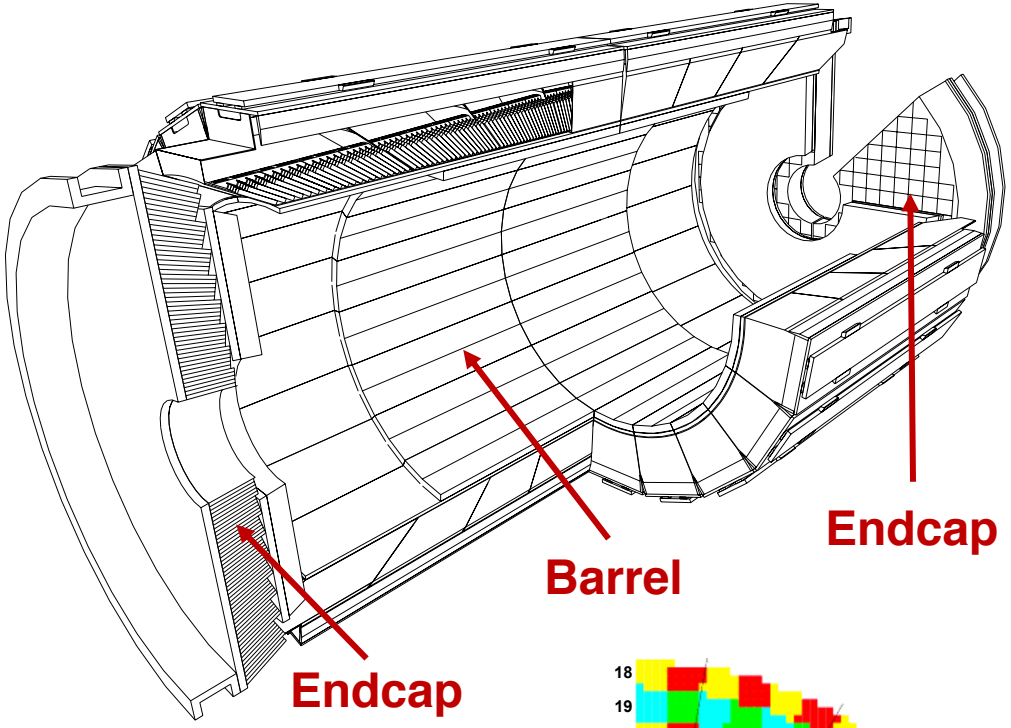
Level-1 Trigger

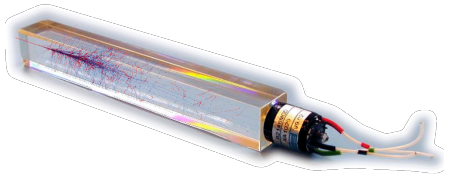
- The Level-1 trigger (L1T) takes place on-detector
- Identifies objects used in physics searches
- ECAL sends transverse energy sums to L1T to form e/γ candidates – called Trigger Primitives (TPs)
- If these TPs are inaccurate, events will be triggered on **unnecessarily** or **missed** entirely
- **Better trigger performance = more physics recorded**



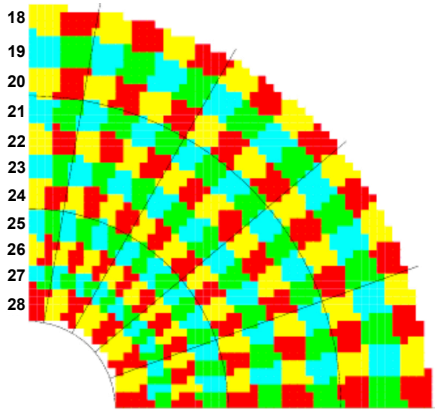
ECAL

- Scintillation calorimeter, comprising 75,848 $PbWO_4$ crystals (a)
- Endcaps (EE) are organised into 11 concentric rings of crystals (b)
- High energy resolution for e/γ, vital for 2012 Higgs discovery: $\mathrm{H} \rightarrow ZZ^* \rightarrow 4l$ and $\mathrm{H} \rightarrow \gamma\gamma$ decay channels
- Important for reconstruction of jets (QCD) and missing energy (SUSY and new particle searches)





a) ECAL $PbWO_4$ crystal



b) Endcap quadrant

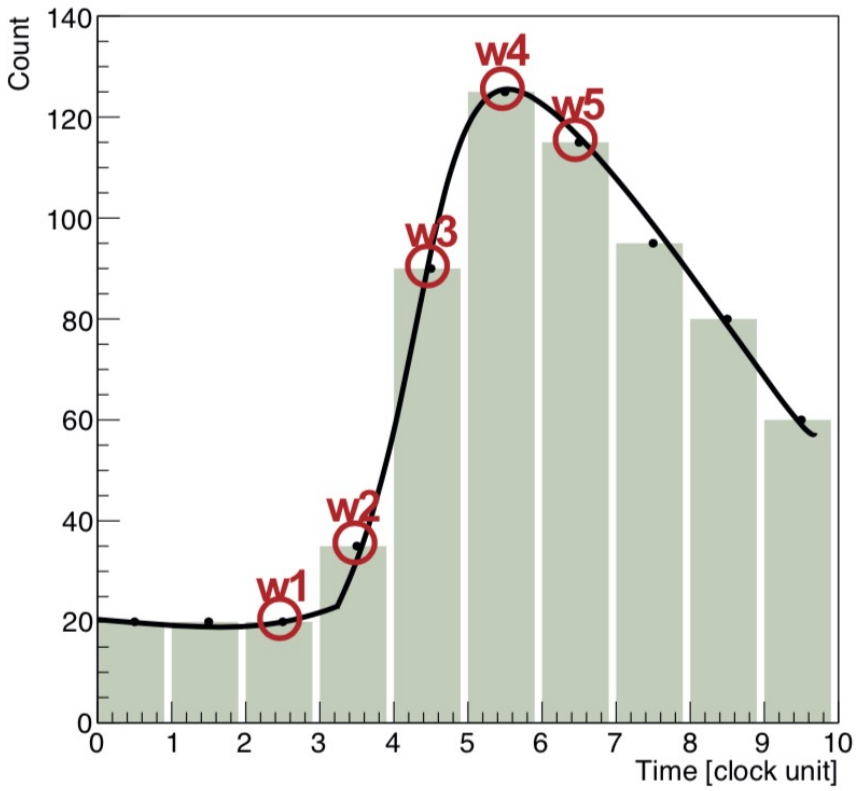
Trigger Primitive Generation

- Digitised signals from 5 crystals are summed into a ‘strip’ pulse
- Digital filter applied, with a weighted sum, to estimate the maximum signal amplitude:

$$\hat{A} = \sum_{i=1}^{n} S_i w_i \quad ,$$

where $\hat{A}$ is the signal amplitude estimator, S_i is the signal value at time sample i and w_i is the corresponding weight factor.

- Weights calculated by variance minimisation of $\hat{A}$ when applied to a known template pulse [1]
- Maximum signal amplitude forms the TP



Example strip pulse with the weights applied

Current Weights

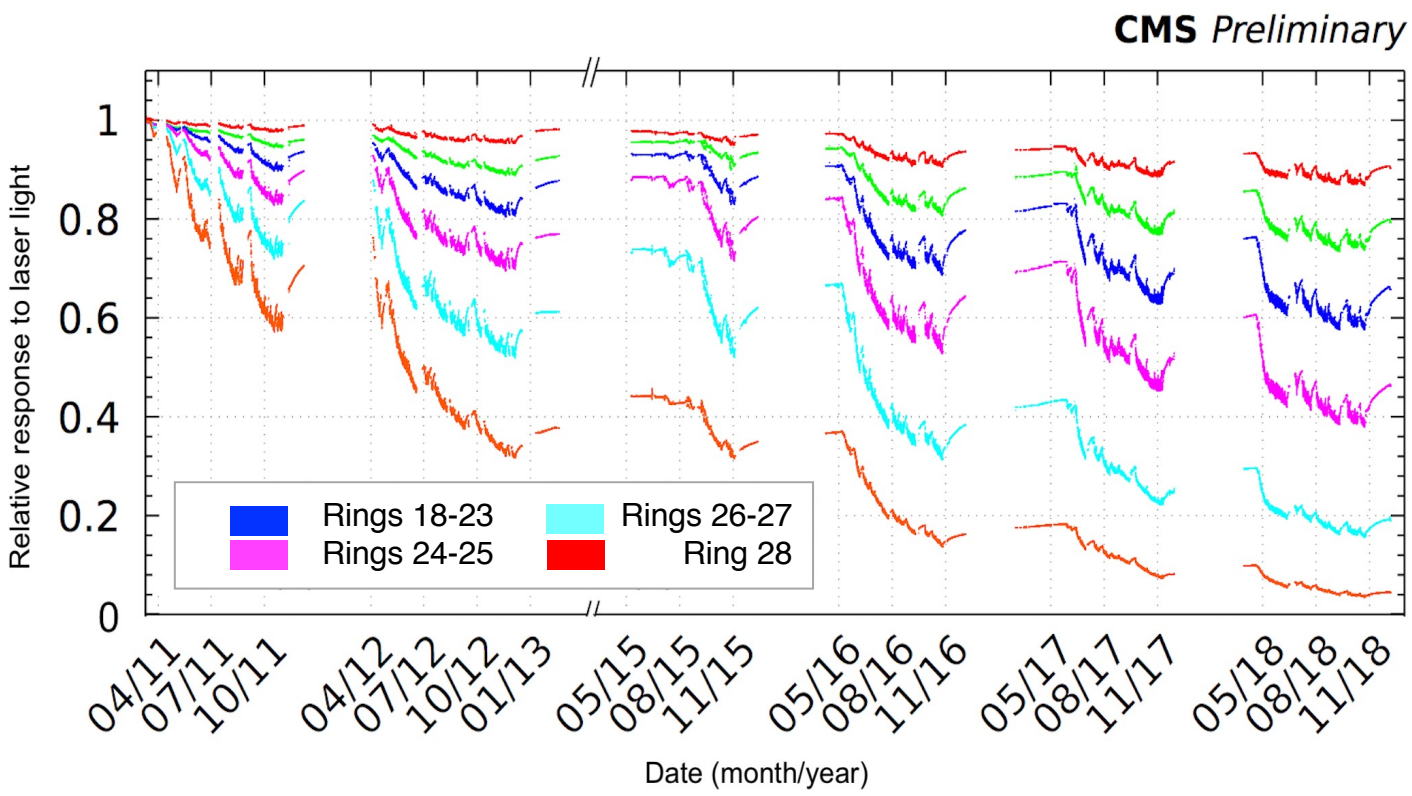
- Two sets of five weights: **one** each for EB and EE
- Weights calculated from 2003 electron test beam on new crystals
- Used **unchanged** in ECAL ever since

	w1	w2	w3	w4	w5
EE	-0.656250	-0.515625	0.250000	0.515625	0.406250
EB	-0.562500	-0.546875	0.250000	0.484375	0.375000

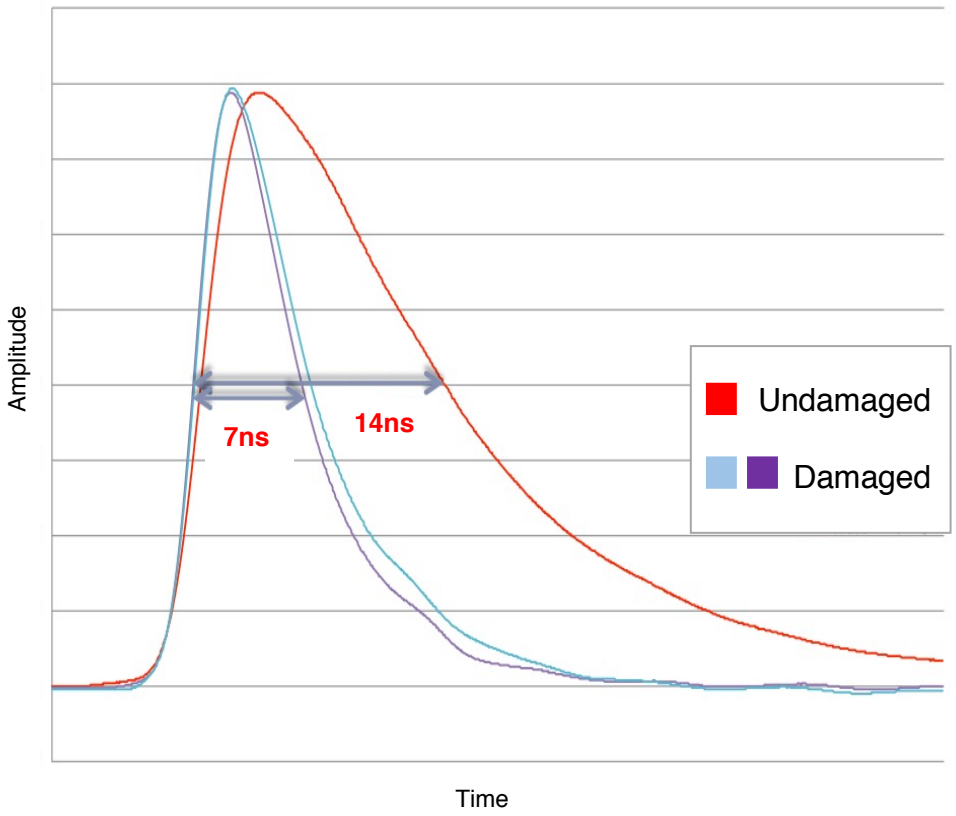
My Project

Project Rationale – Crystal Damage

- ECAL crystals **permanently damaged** by the LHC radiation



Crystal light response as a function of time [3]

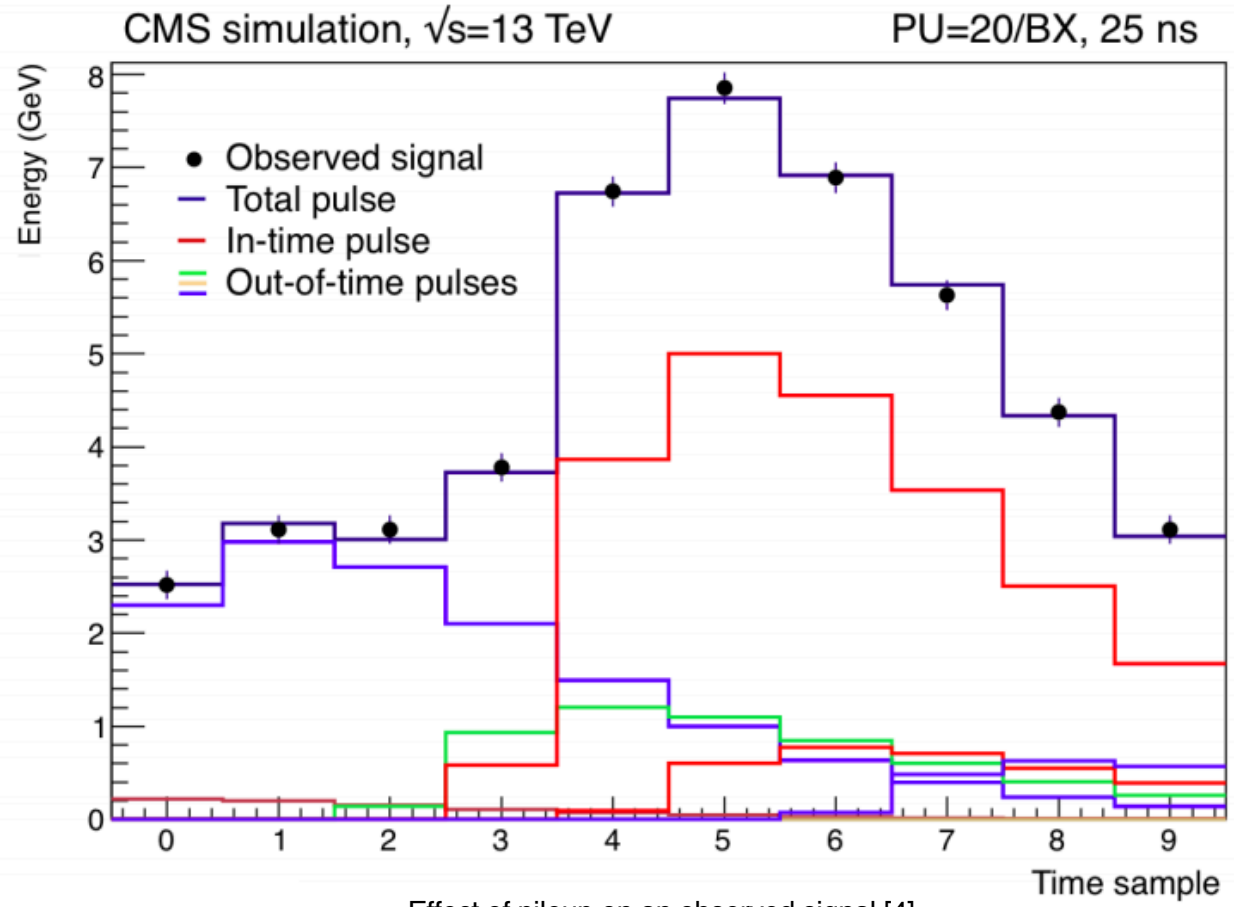


Pulse shape for 3 different crystals with an electron test beam [2]

- Changed pulse shapes will **reduce** the accuracy of the energy reconstruction

Project Rationale – Increased Pileup

- Pileup (PU) - number of proton-proton collisions occurring at each LHC bunch crossing
- Signals from different bunch crossings **constructively** interfere in the same crystal
- **Reduces** the energy measurement **accuracy** of physics objects
- **Increases** the trigger rate, resulting in an energy threshold increase and **fewer** recorded events



Effect of pileup on an observed signal [4]

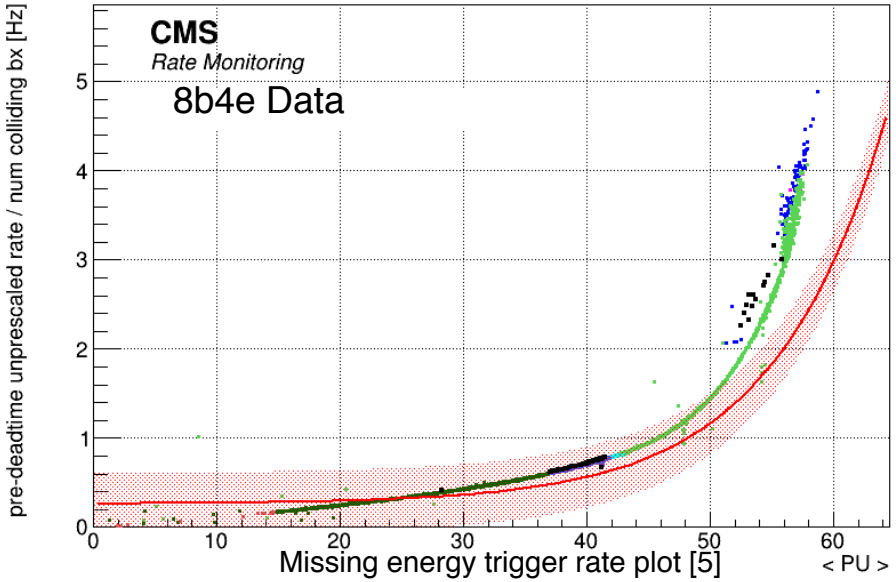
Project Rationale – LHC Filling Schemes

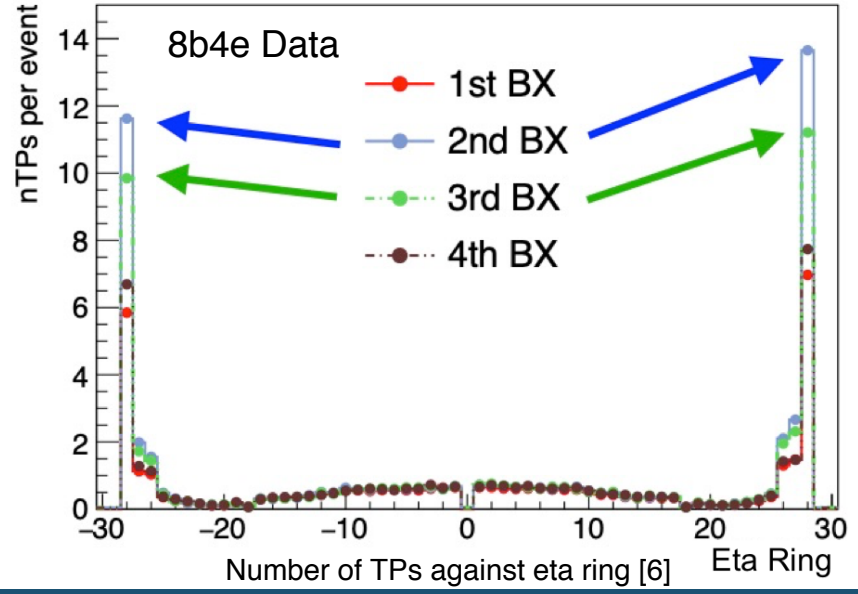
- The configuration of the LHC bunch train – filling scheme, effects detector performance

- 2017 8b4e = 
  - **Large** variation in out-of-time PU
  - **Increased** trigger rate
  - **Strong** bunch position dependence

- 2018 48b = 
  - More **stable** out-of-time PU contribution

- For LHC Run 3, the filling scheme is under debate





Project Questions

- **How well are the current weights reconstructing the energy of 2018 data?**

- **Could updated weights, suited for present-day detector conditions, improve the energy reconstruction?**

- **Could more granular weights or weights optimised for PU improve performance further?**

Project Method

1. Using 2018 crystal pulse shapes, weights were computed for each crystal and then averaged across the desired granularity

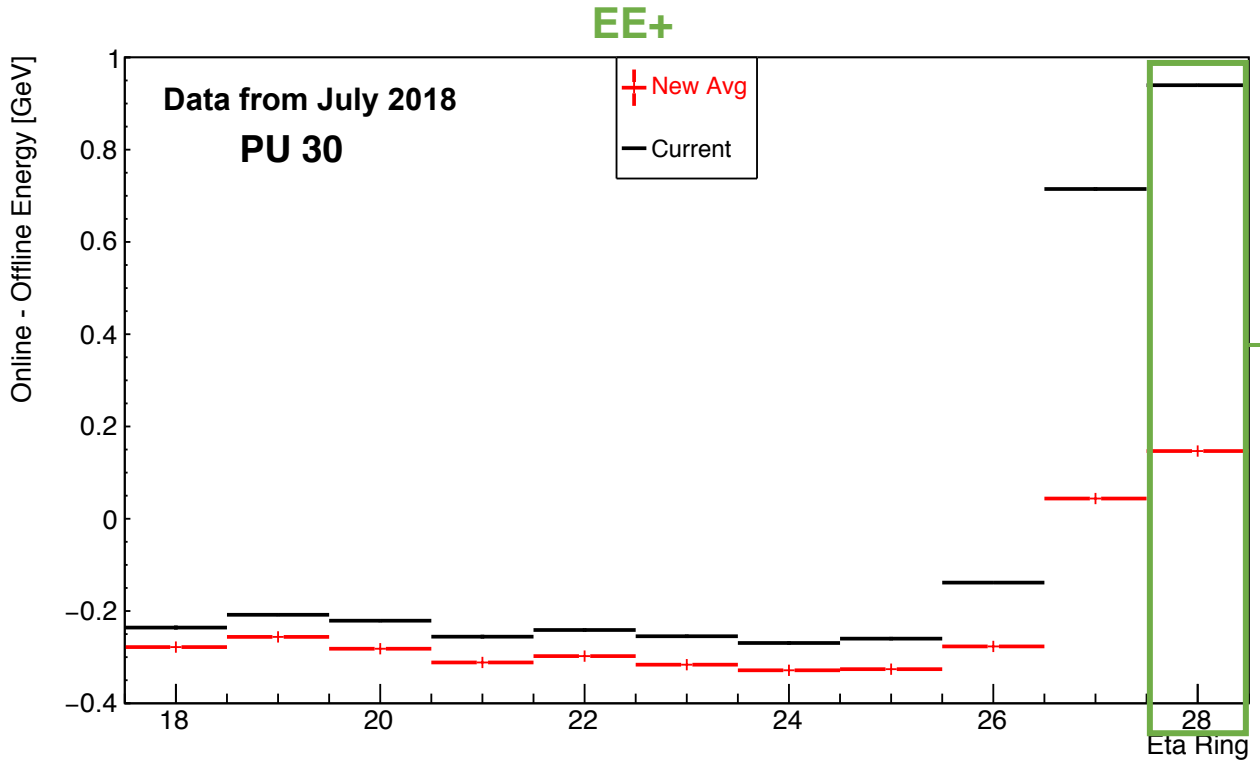
2. An emulator was used to produce **new** TPs with the **updated** weights

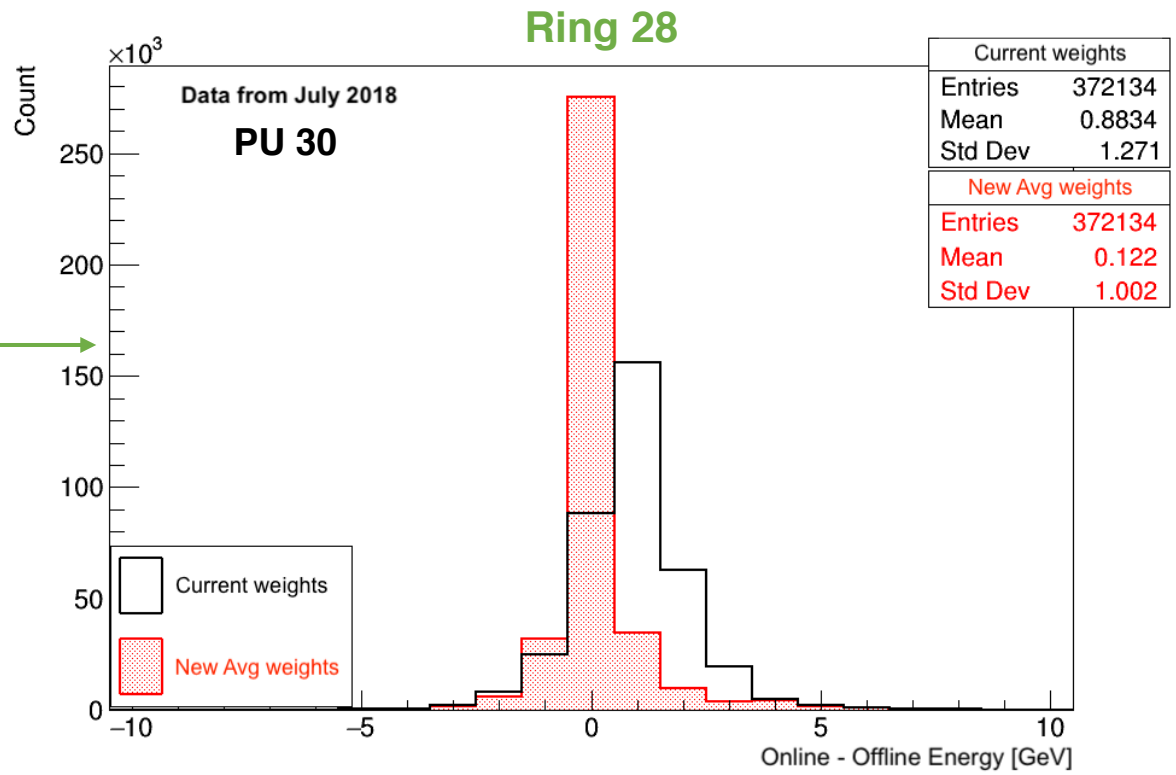
3. Online TP energy compared to the offline energy, which:
   - Is calculated off-detector with time consuming algorithms
   - Uses PU templates to subtract any PU contribution

4. Performance of the different weight configurations studied:
   - Online/offline energy differences
   - Bias in the absence of PU
   - Bias dependence on eta ring, bunch position and energy in the presence of PU
   - Bias = $\frac{\text{Online energy}}{\text{Offline energy}} - 1$

Results and Conclusions

Current and New Average Weights

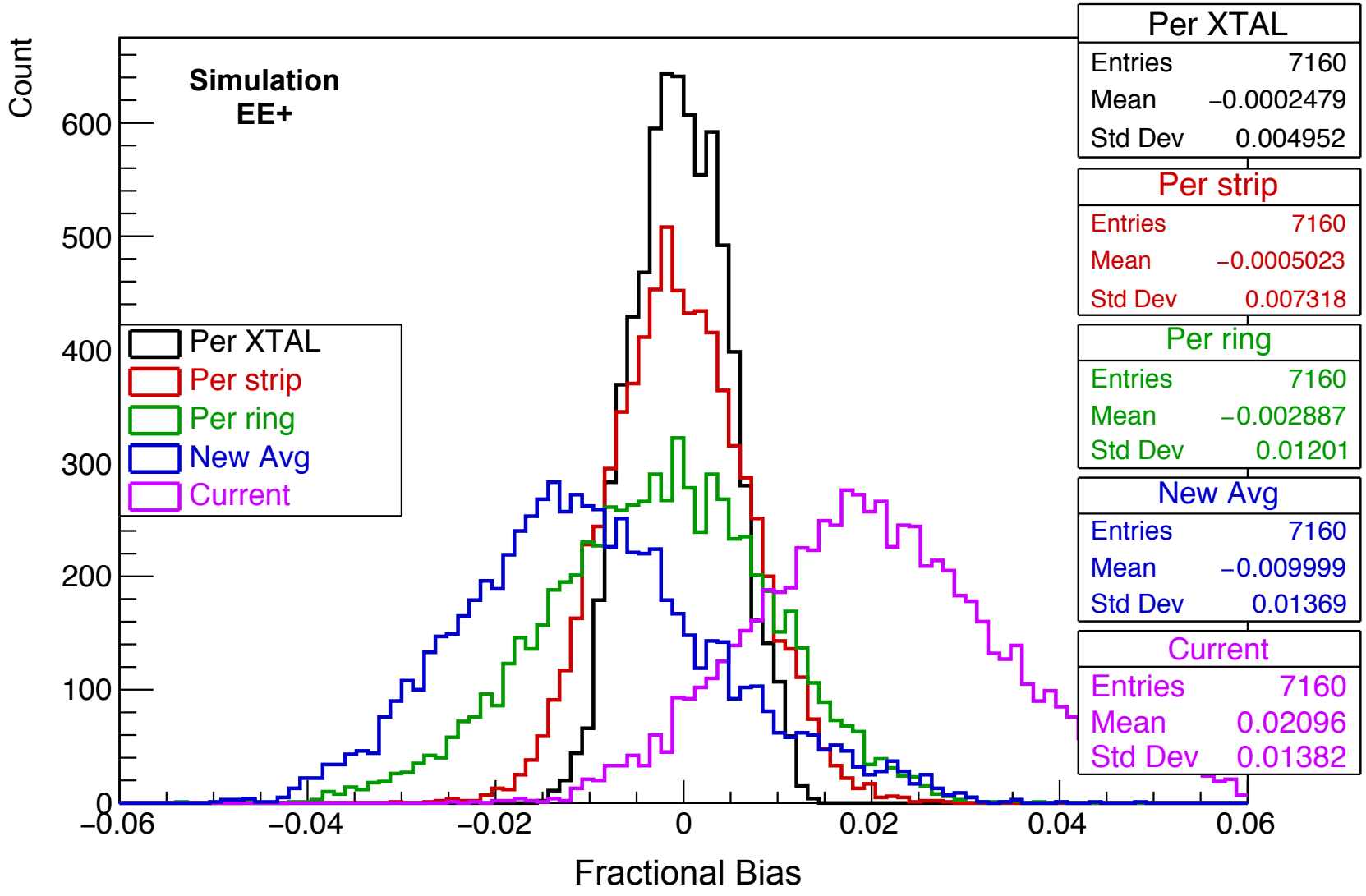




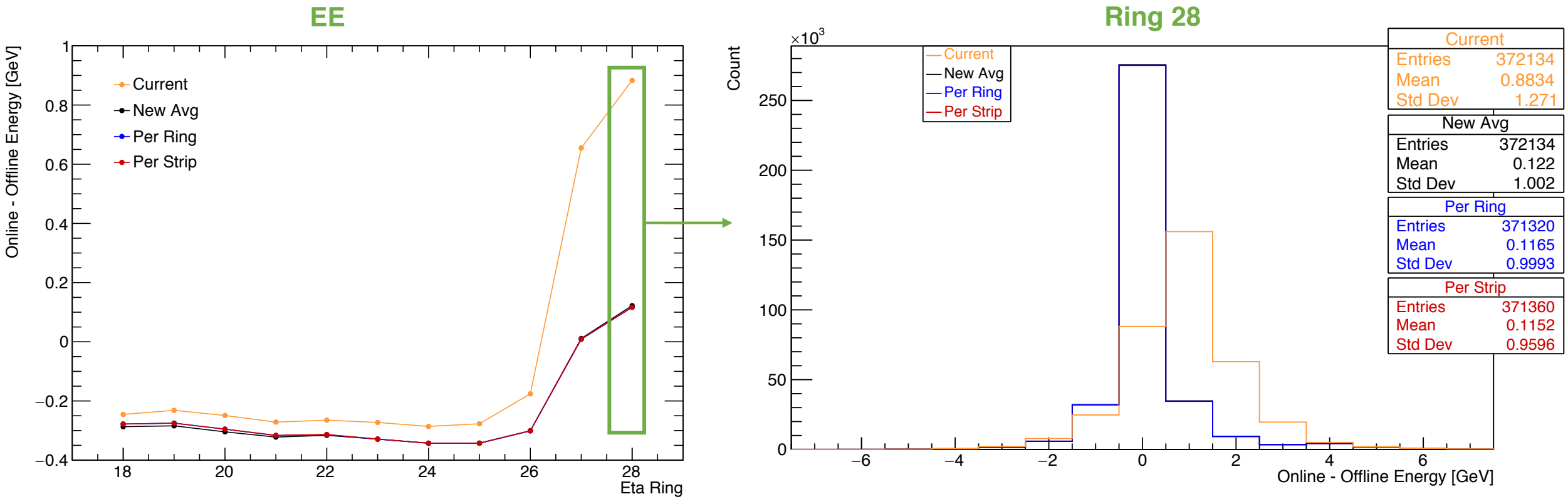
- Current weights **greatly** overestimating TP energies in rings 27 and 28
- **Large** spread with current weights, especially in ring 28
- Average EE bias and spread **reduced** with updated `New Avg' weights
- Limited by being an average for the whole EE - could more granular weights improve performance?

Increased Weight Granularity – **No PU**

- Weights used to reconstruct the maximum amplitude of known signal pulses
- Increased weight granularity **significantly reduces** the average bias and spread



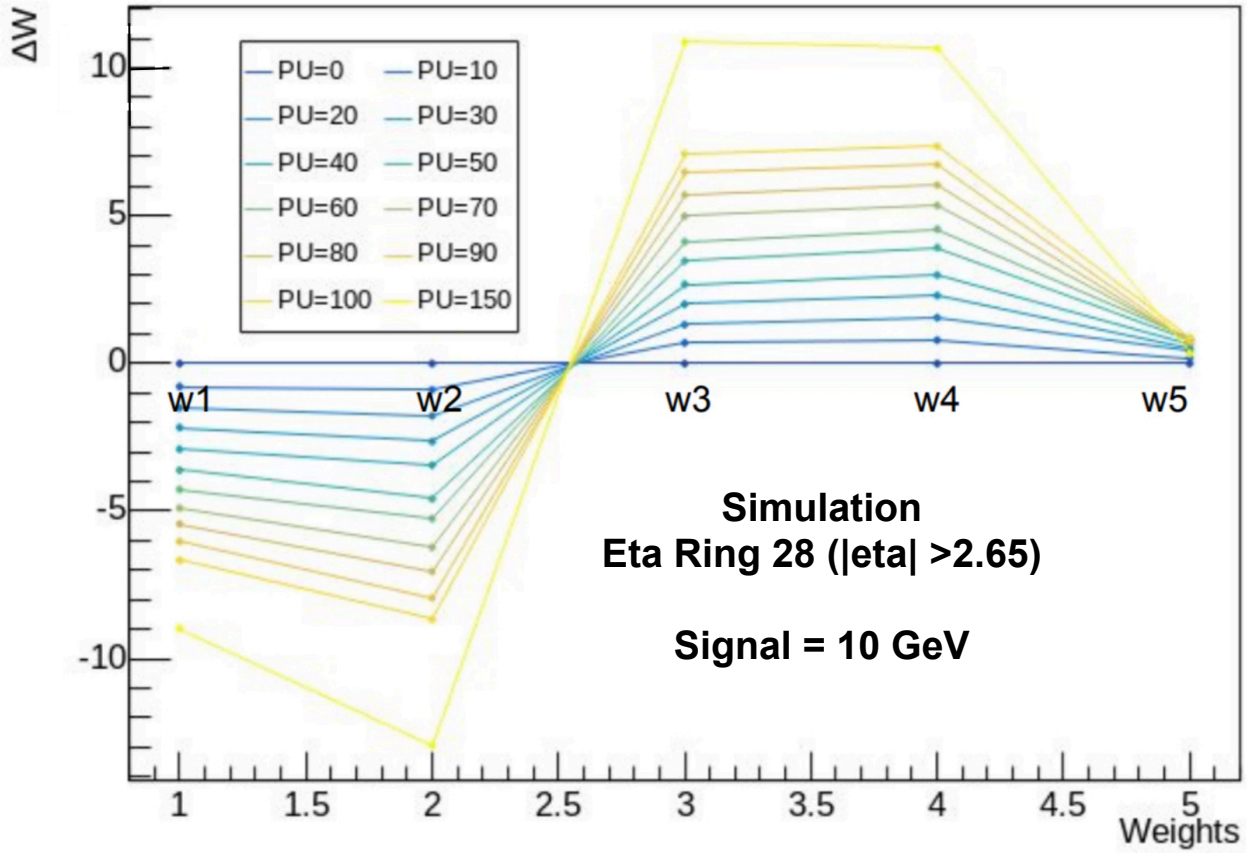
Increased Weight Granularity – **PU 30**



- **Big** improvement with updated weights, especially in rings 27 and 28
- Small improvement when increasing weight granularity
- PU has a **large** contribution and **limits** the improvements of increased granularity
- Could weights optimised for PU perform better?

PU Optimised Weights

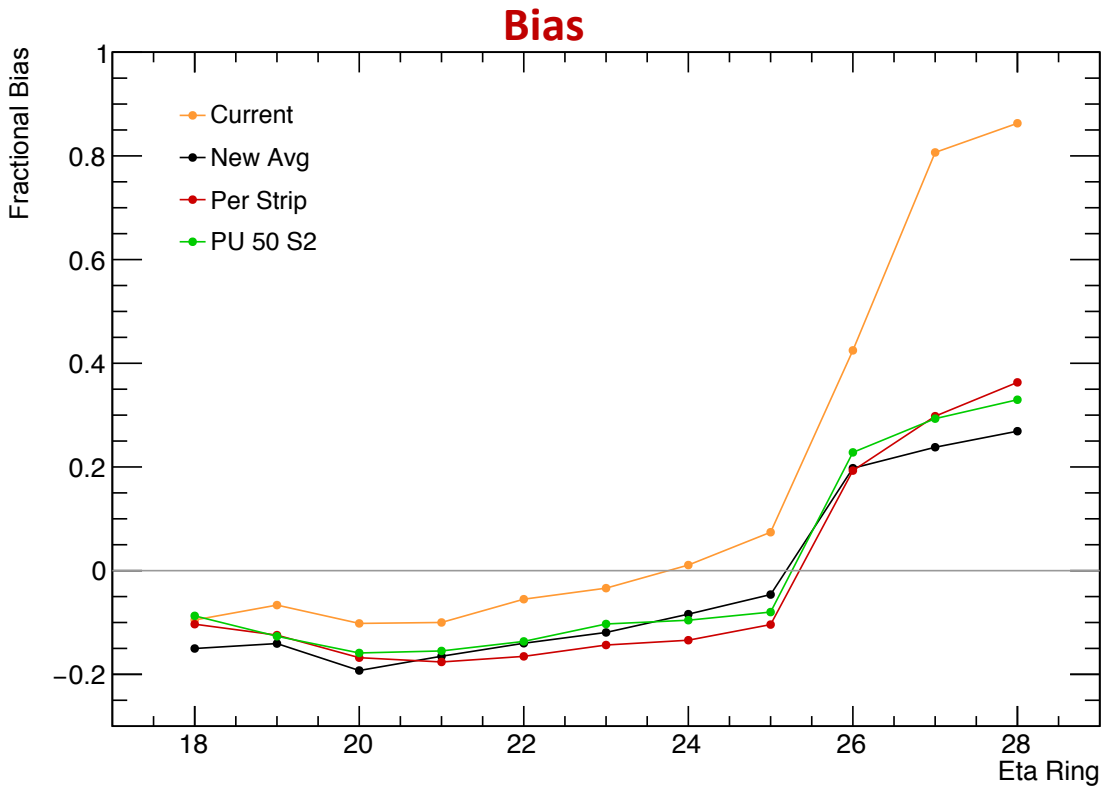
- Using a PU Monte Carlo Simulation [7], weights optimised for different levels of PU and signal were computed

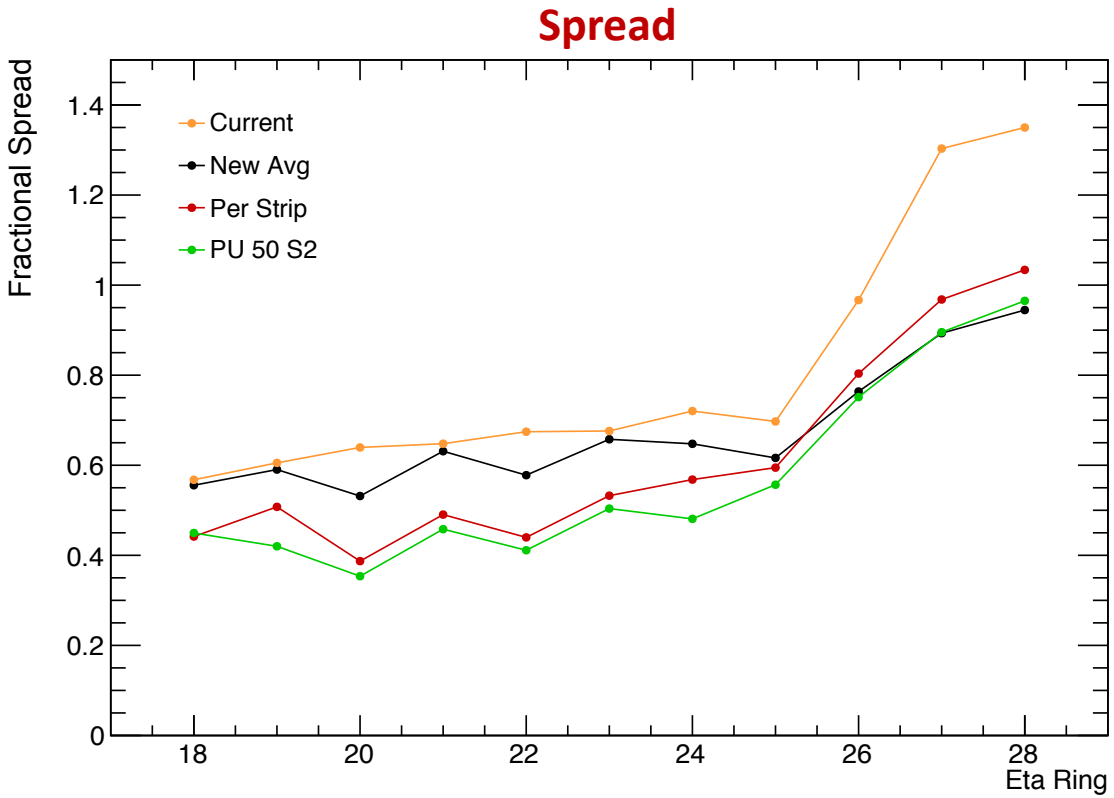


Weight change as a function of PU [8]

Endcap Ring Dependence

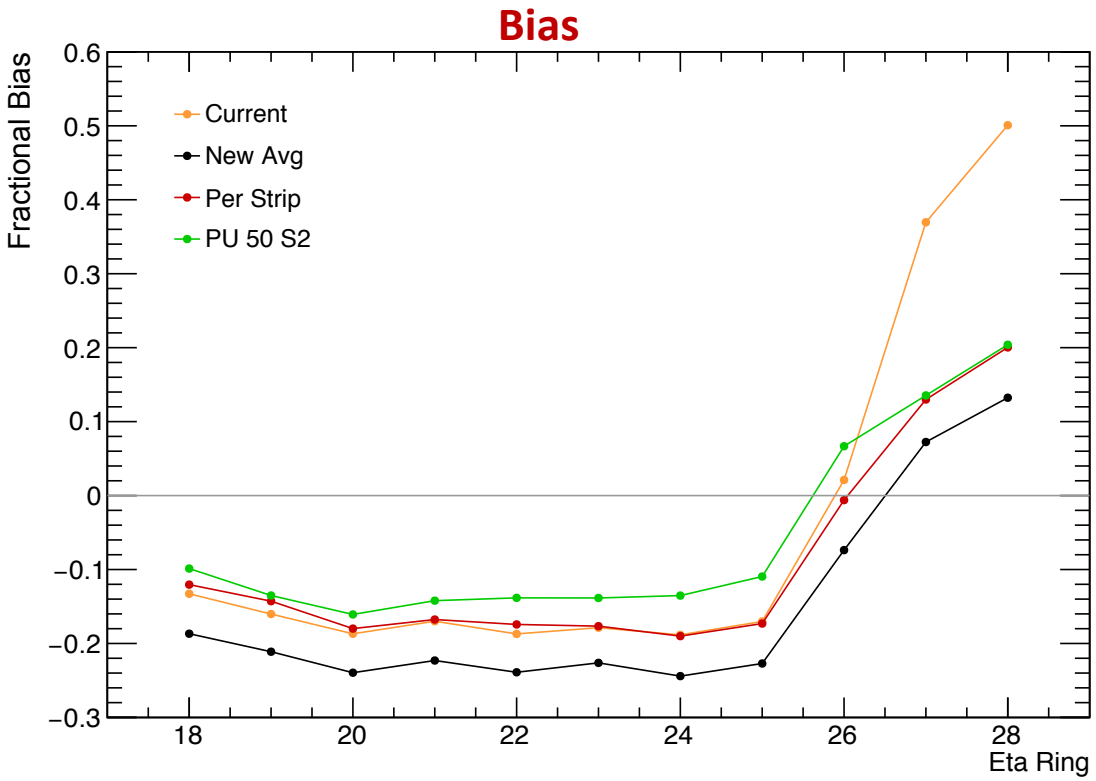
Eta Ring Dependence - **8b4e** PU 50

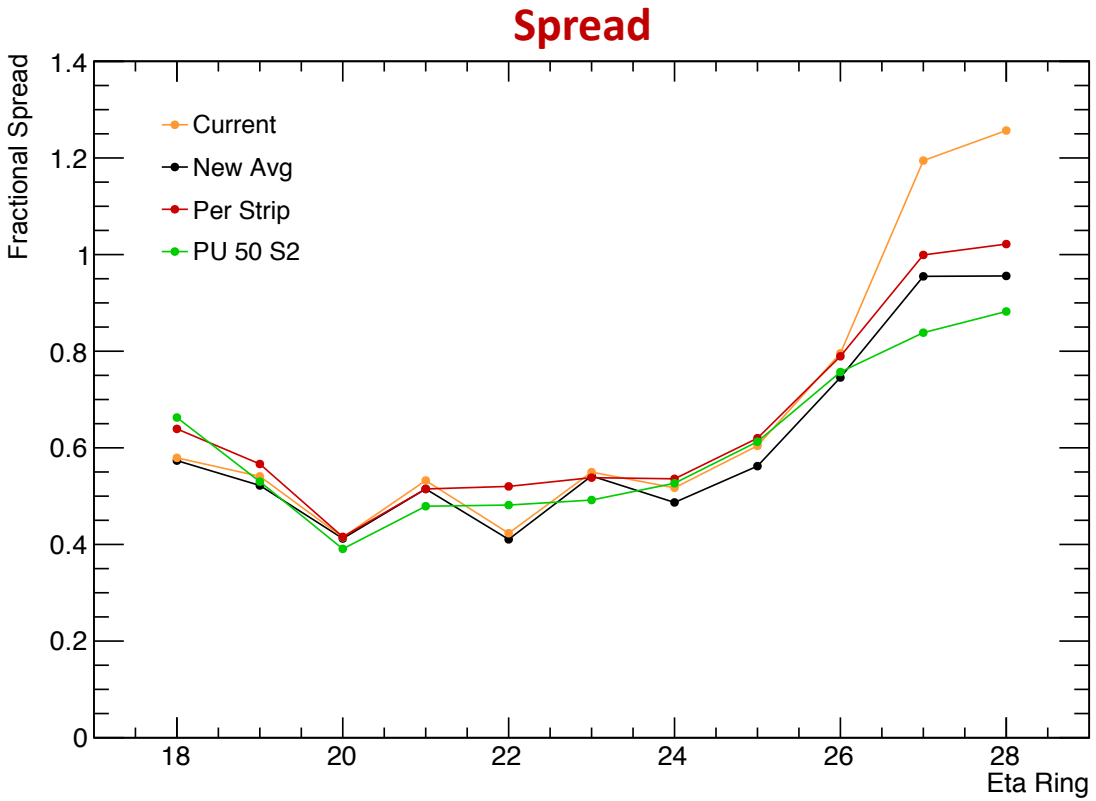




- **Large** biases/spreads with current weights in rings 27 and 28
- Increased granularity **reduces** spread
- Average bias/spread most **reduced** by PU optimised weights - 29%

Eta Ring Dependence - **48b** PU 50





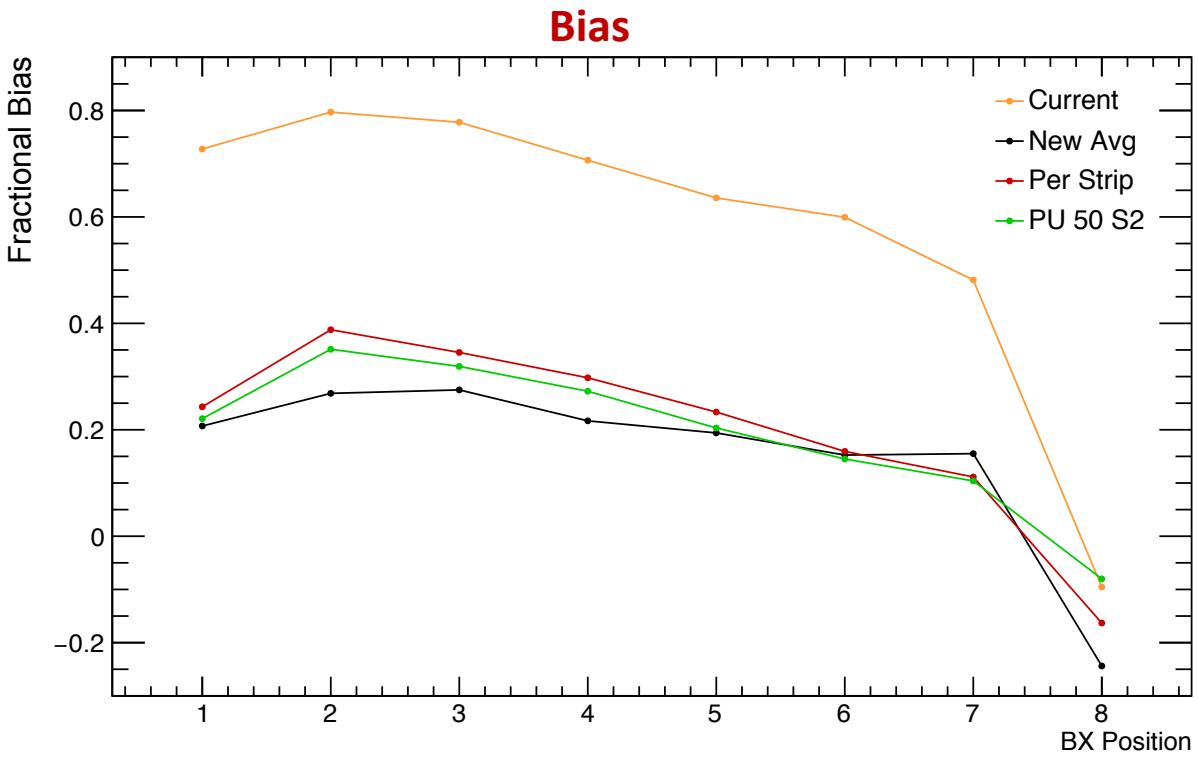
- Again, **large** biases/spreads with current weights in rings 27 and 28
- Spread most **reduced** by PU optimised weights

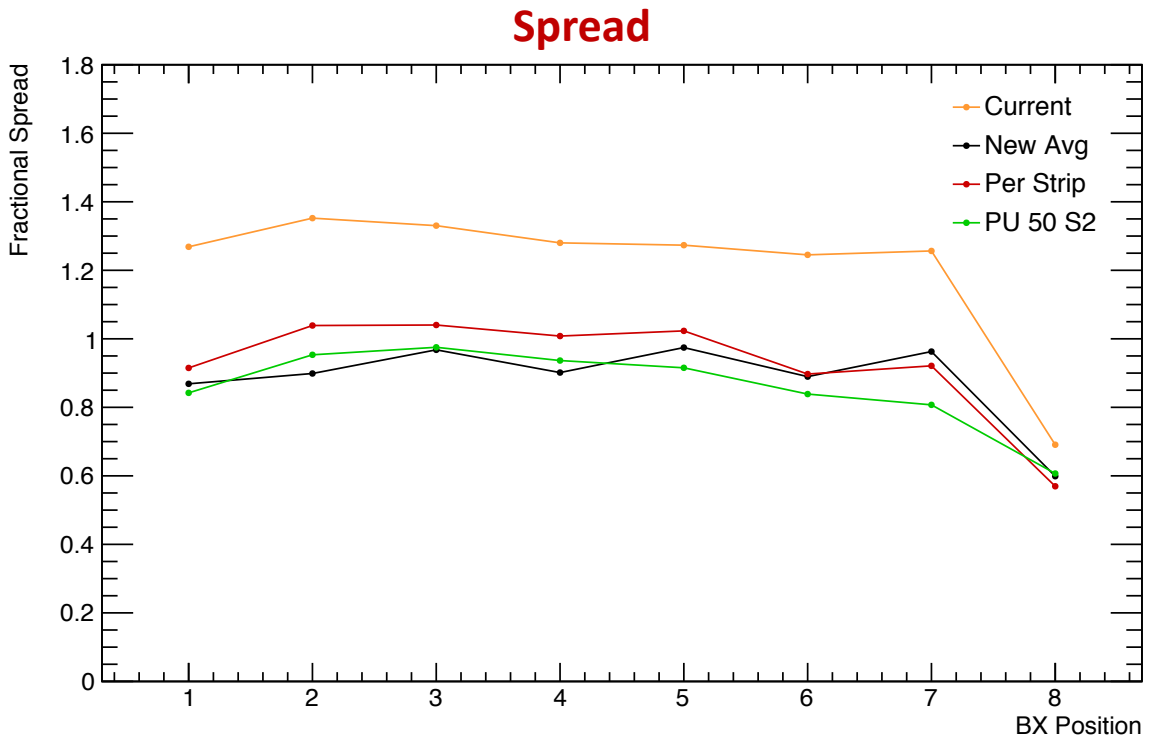
Interim Conclusions

- Across both filling schemes and PU levels, bias of current weights **heavily dependent** on eta ring
- Updating to any updated weights configuration **reduces** this dependence
- The biases in 48b are **significantly smaller** than in 8b4e - current weights bias in eta ring 28 for 48b is 57% that of 8b4e.
- For every weight configuration, the average spread **increases** at higher PU
- PU optimised weights **reduce** the spread more at higher PU than lower PU
- PU optimised weights perform the **best** at reducing the average spread - resolution improvement for physics objects

Bunch Position Dependence

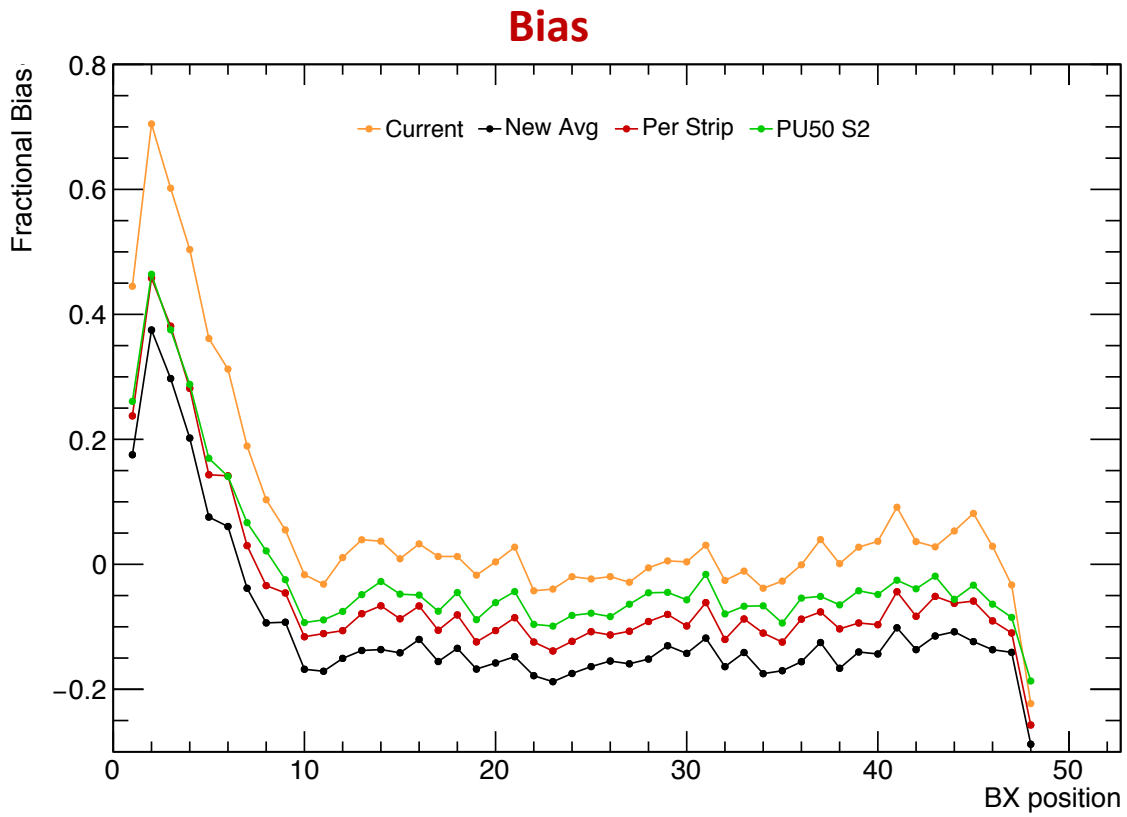
Bunch Position Dependence – **8b4e** PU 50

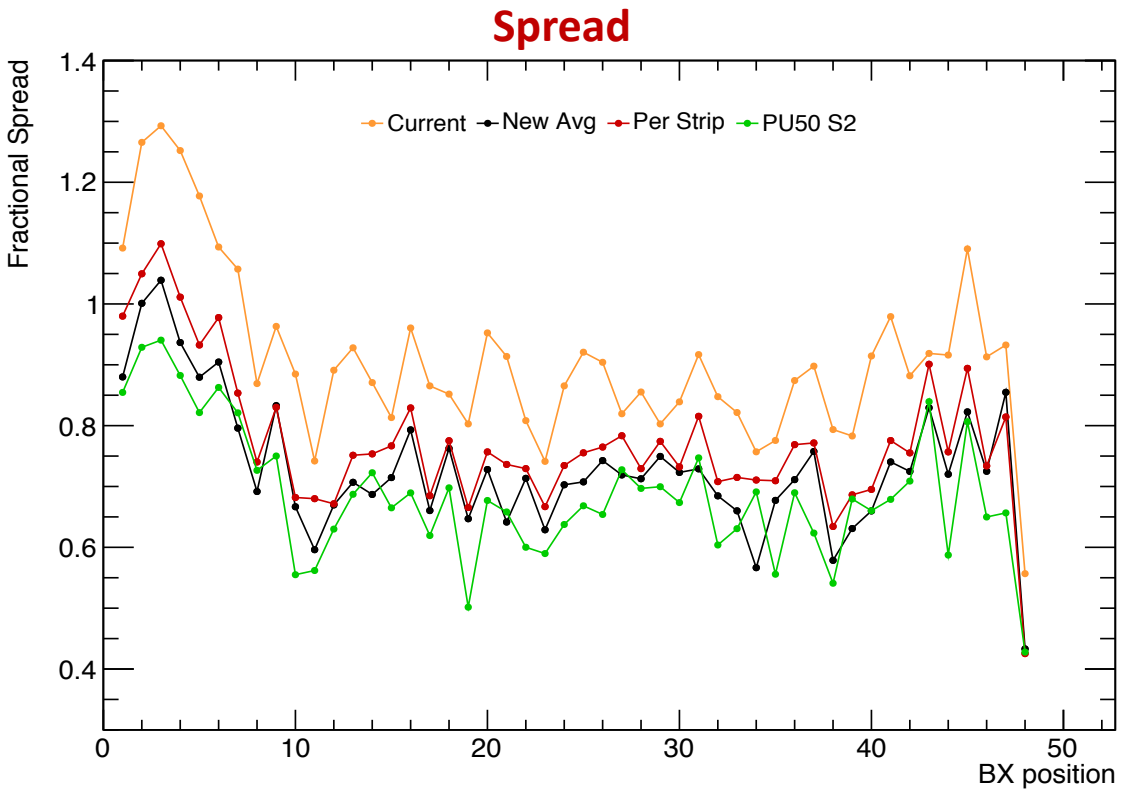




- **Large** bunch position dependence - **Largest** bias with current weights in position 2 – 80%
- Updating to any new weights configuration **reduces** bias and position dependence
- `New Avg' give **lowest** average bias. **Lowest** spread and flattest response with PU optimised weights

Bunch Position Dependence – **48b** PU 50





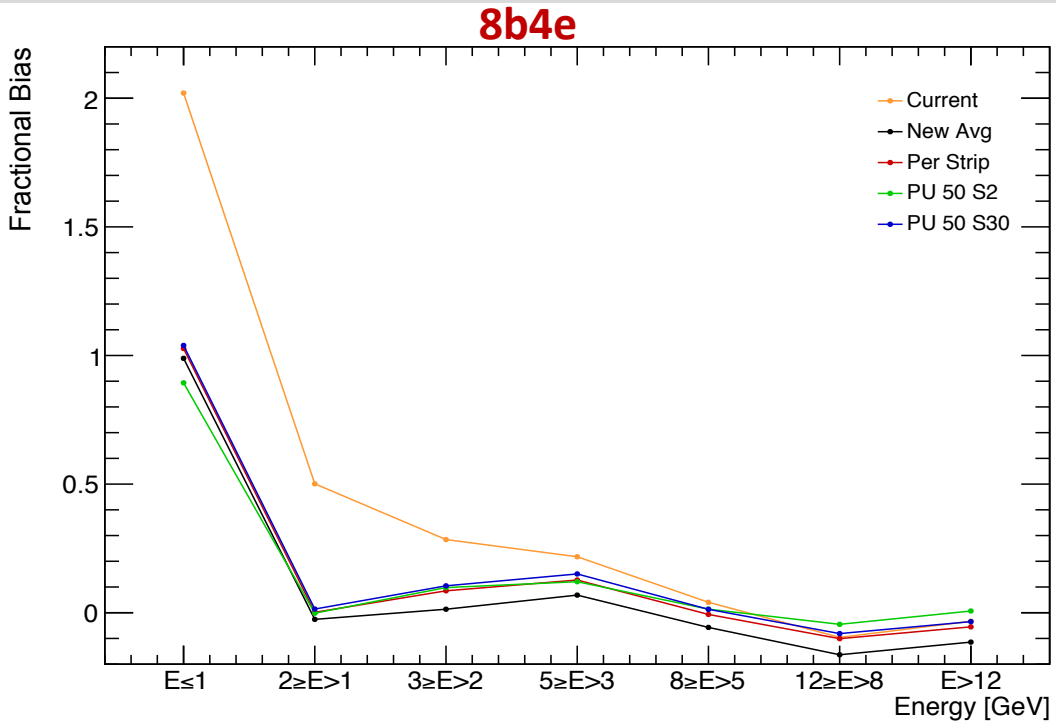
- **Large** biases at the start of the train, region of stability in the center
- Increased granularity **improves** performance
- **Flattest** response, **lowest** average bias and spread with PU optimised weights

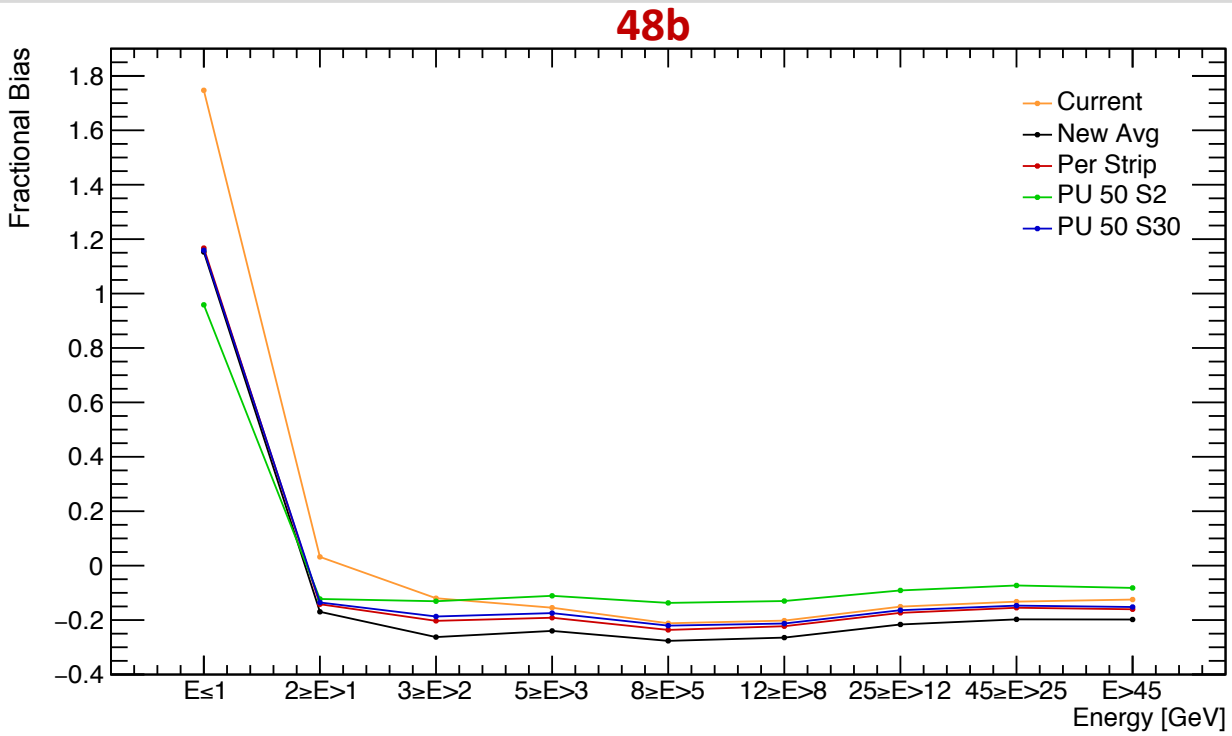
Interim Conclusions

- Across both filling schemes and PU levels, bias of current weights **heavily dependent** on bunch train position
- Updating to any updated weights configuration **reduces** this dependence
- Larger biases with 8b4e than with 48b
- PU optimised weights are more effective at higher PU
- PU optimised weights provide the **flattest** response and **lowest** average spread across both filling schemes and PU levels

Energy Dependence

Energy Dependence – PU 50





- For both filling schemes:
  - **Large** positive bias at low energy with the current weights
  - Which is **reduced** by updating to any of the updated weights configurations
  - Average EE behaviour is dominated by rings 26 – 28
  - Updated weights perform the best

Summary and Final Conclusions

Summary and Final Conclusions

- Different weight configurations have been computed and their energy reconstruction performance compared

- The current weights are no longer optimal for present-day conditions:
  - **Large** biases/spreads in eta rings 27 and 28, especially at low energy
  - This **reduces** the reconstruction accuracy of jets and missing energy
  - **Strong** dependence on bunch position for both 8b4e and 48b

- Updated weights and increased granularity:
  - **Reduce** eta ring, bunch position and energy scale dependence
  - Will result in **improved** trigger performance, with **more** physics being recorded and with **reduced bias**

- PU optimised weights matching the PU/S level:
  - Provide the **best** performance in the majority of cases
  - Will be **important** as the PU level increases – **fully** utilise the increased number of collisions

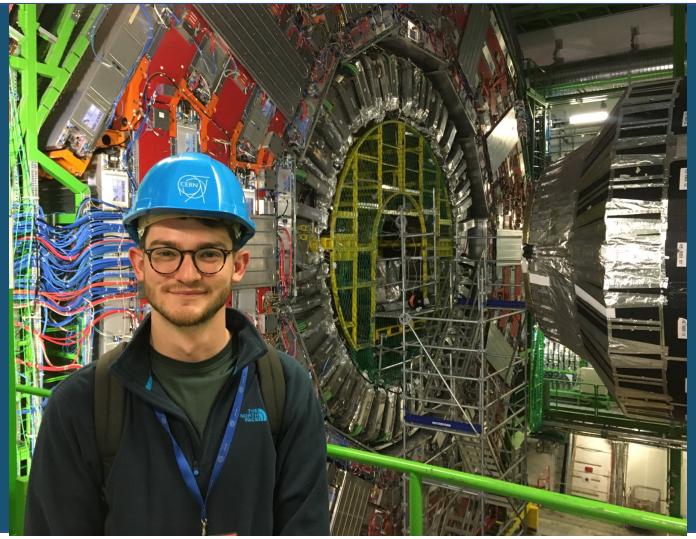
- **These new weights will be used in Run 3 and will result in <u>improved</u> trigger performance for physics**

Future Work

- L1 Trigger team - re-emulate L1 physics objects with updated weights
  - Check trigger rates/efficiencies

- Use the PU MC simulation to investigate advantages of a possible 6th additional weight and a second set of weights for each strip

- Using a test bed with ECAL front-end and off-detector boards:
  - Check functionality of a 6th weight and a 2nd set of weights in hardware
  - Check electronics configuration time of per strip weights



Thank you for listening

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- My supervisor, David Petyt
- Abe Tishelman-Charny, for his updated weights computations
- Davide Valsecchi, for his PU Monte Carlo simulation and PU optimised weights

References

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- [2] A.Singovsky. “ECAL Longevity”. (accessed: 14.5.2019). 2012. url: https://indico.cern.ch/event/187073/contributions/1459593/attachments/260648/364058/ECAL_UpgradePlenary_May2012.pdf.
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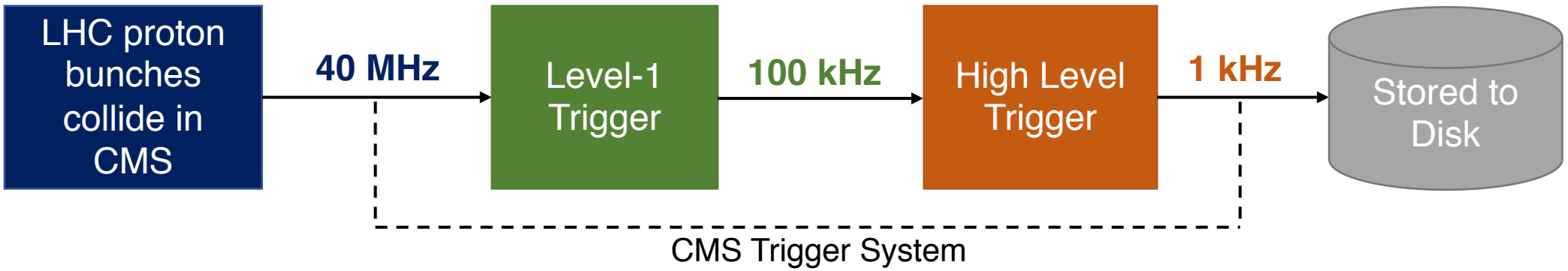
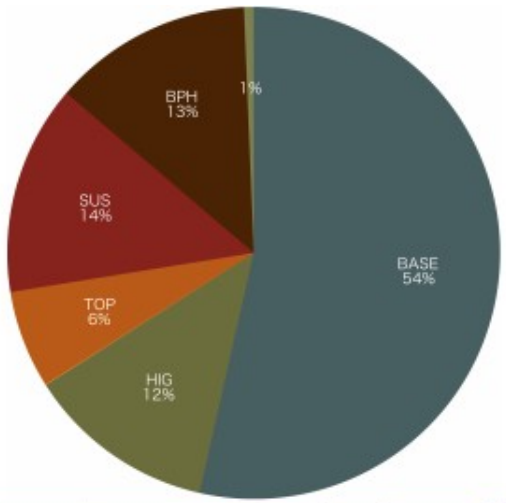
- [5] Figure from CMS Web Based Monitoring rate plots
- [6] A.Zabi and A.Brinkerhoff. “Effect of ECAL and HCAL conditions on L1T jets and MET”. (ac- cessed: 26.4.2019). 2017. url: https://indico.cern.ch/event/674023/contributions/2805549/attachments/1573395/2483478/2017_12_11_L1T_JetMET_ECAL_HCAL.pdf.
- [7] D.Valsecchi. “PU optimized weights for ECAL TP generation”. (accessed: 3.5.2019). 2019. url: https: / / indico . cern . ch / event / 817480 / contributions / 3412893 / attachments / 1837763 / 3011641 / ECAL_Trigger_meeting_2019_05_02_-_PU_optimized_weights_summary.pdf.
- [8] D.Valsecchi. “TPG weights optimization including the effect of the PU”. (accessed: 26.4.2019). 2019. url: https://indico.cern.ch/event/801425/contributions/3332627/attachments/1803201/2941765/DPG_27_02_2019_TPG_optimization_with_PU_Davide_Valsecchi.pdf.

Backup

CMS Trigger System



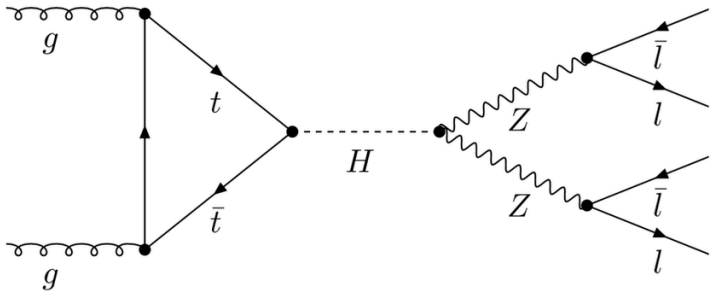
L1T Allocation

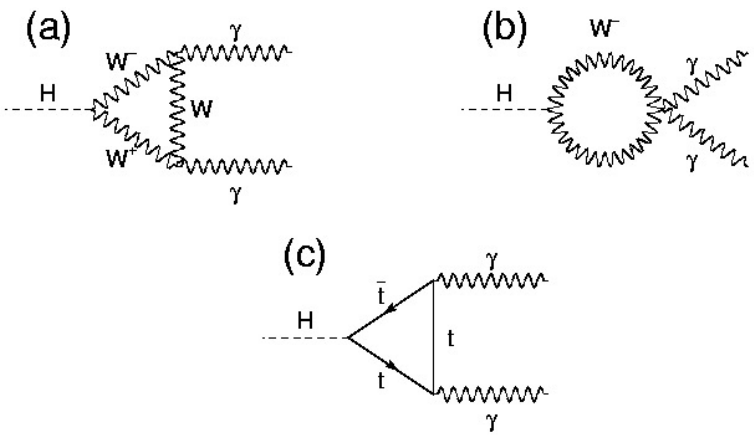


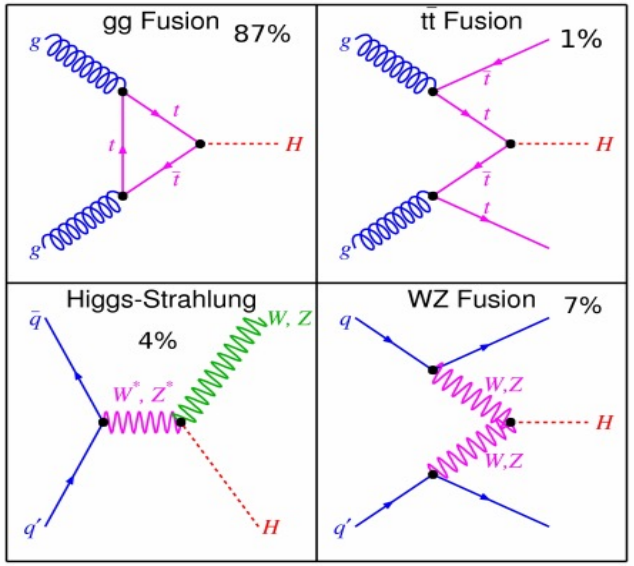
category	proportional rates [kHz]
base	37.0
higgs	8.6
exo	0.02 (w/o NotBptxOR seeds)
top	4.4
susy	9.5
b-phys	9.0
smp	<0.001
btv	0.4

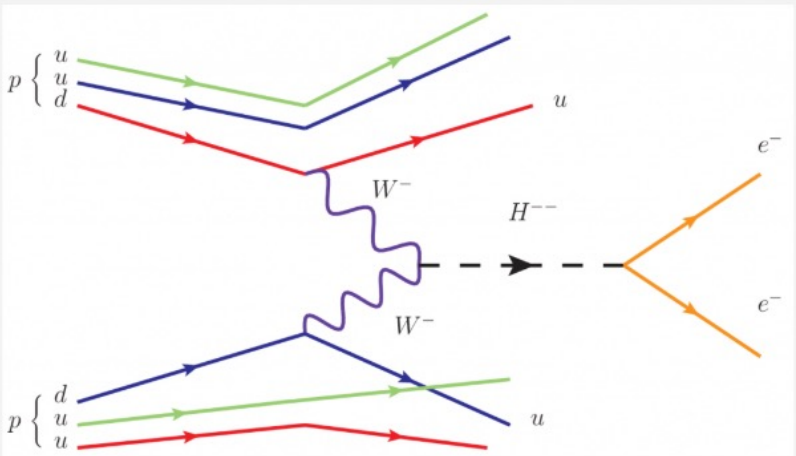
L1 Trigger bandwidth allocation for different physics analysis groups. ‘Base’ refers to general purpose triggers such as single electron, single muon, single tau or single jet, that are not specific to any one analysis. Data from 2017 Fill 6358.

Higgs Production/Decays





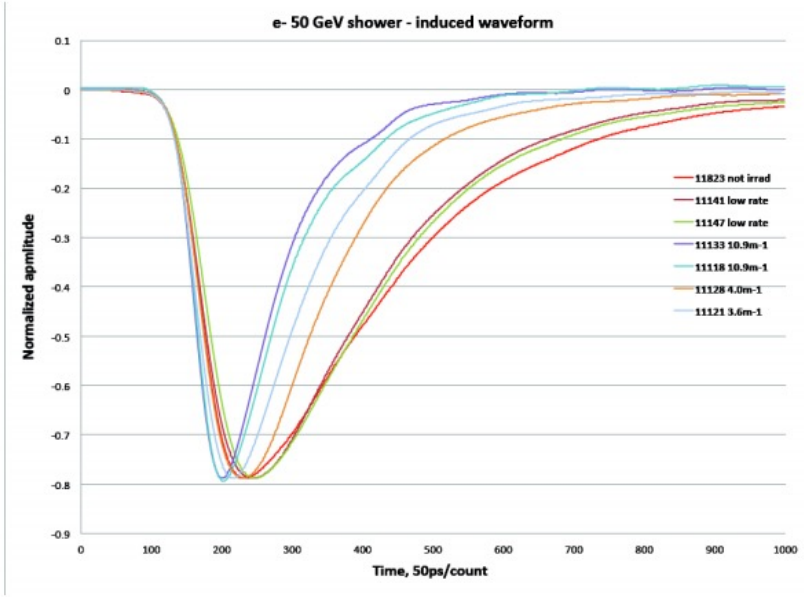




Same-sign W- pairs fusing into a doubly charged Higgs boson that decays into same-sign electrons.

Pulse Shape Change

Both simulations and TB data predict a variation of the pulse shape as a function of the radiation damage of crystals.
(from 14.5 ns for low μ_{ind} to 6.5 ns for $\mu_{ind} \approx 10m^{-1}$)



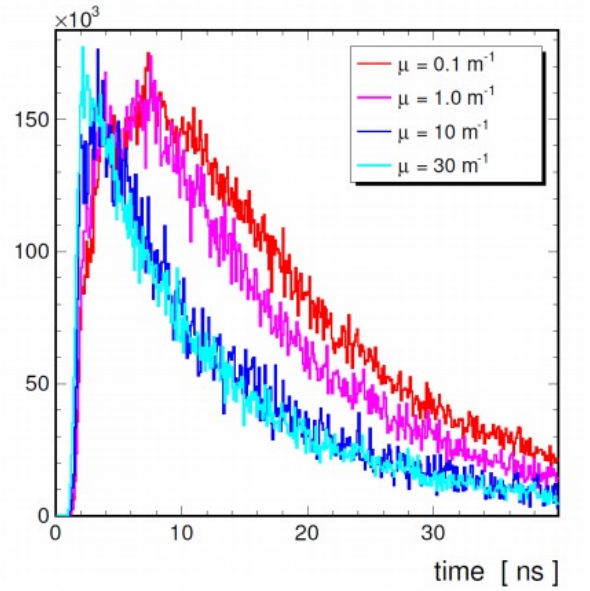
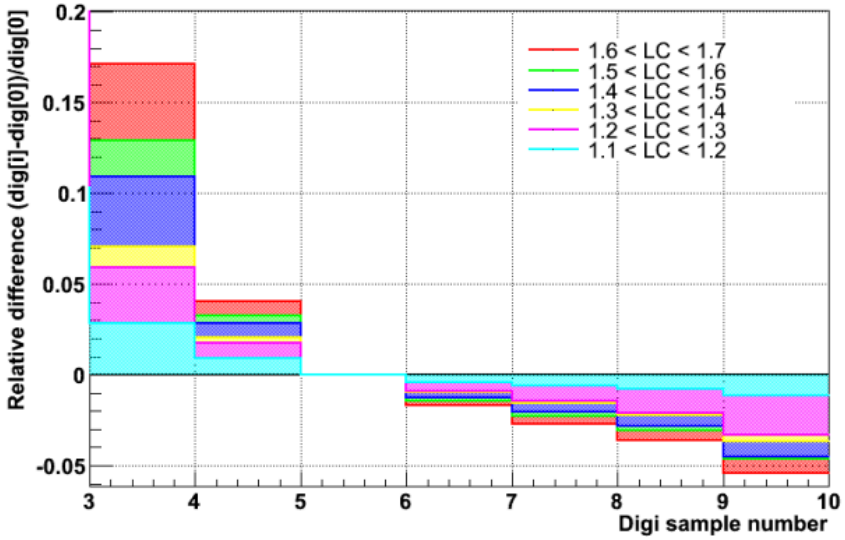


Figure: TB results presented by A.Singovski during CMS Upgrade Workshop in May 22, 2012 and simulations with Geant4+Slitrani by A.Ledovskoy during Forward Calorimetry Task Force Meeting in June 7, 2012.



Pulse shape change as a function of laser correction [2]

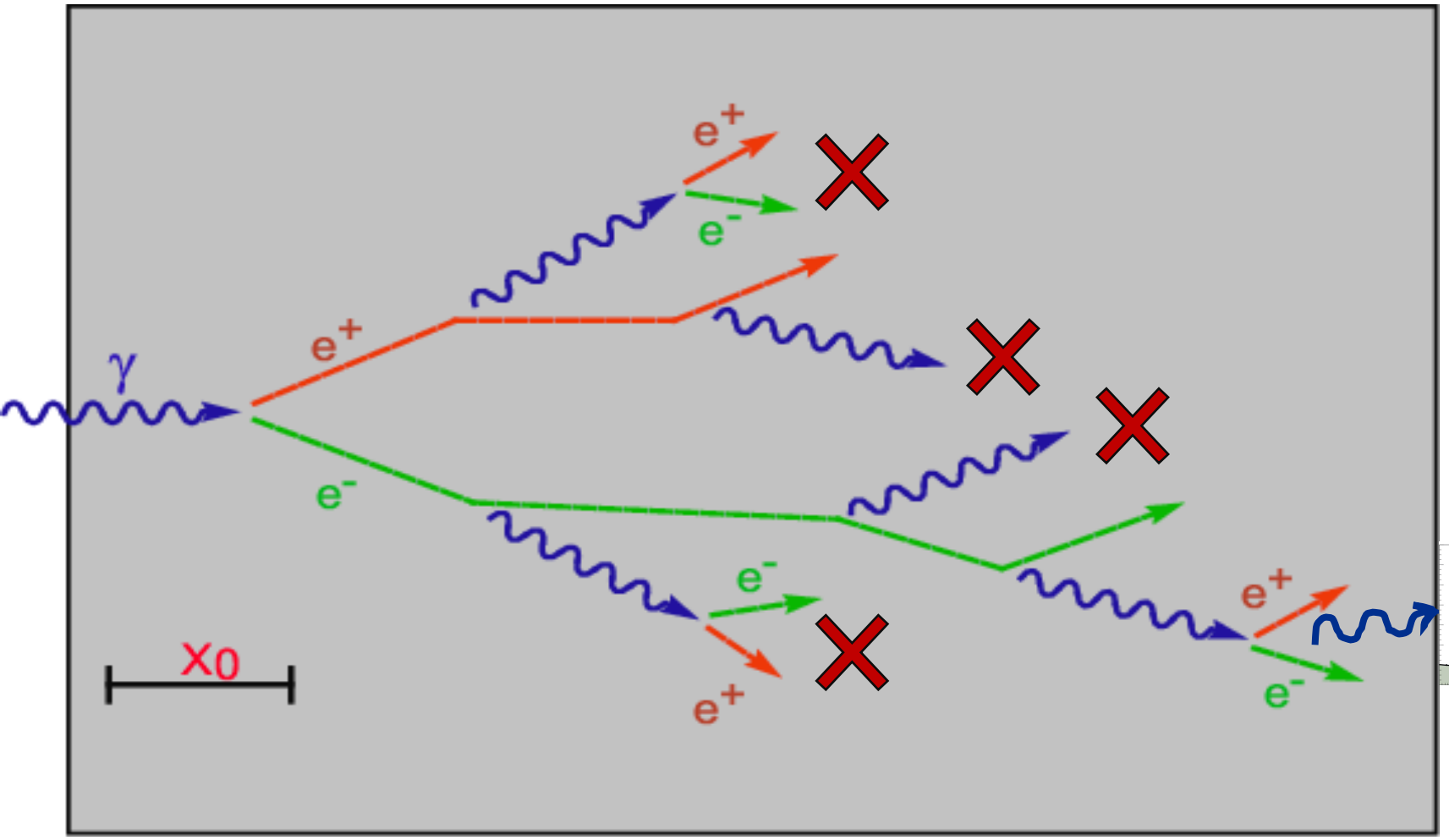
Crystal Damage 1

- Two main mechanisms contribute to this darkening and crystal transparency loss:

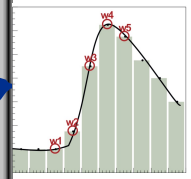
1. The formation of colour centres, caused by the ionising radiation displacing anions within the crystal lattice, which then get filled with unpaired electrons and absorb light.

2. The direct collision of high energy hadrons with the nuclei in the crystal lattice. The nuclei split into charged fragments and propagate through the crystal, ionising other nuclei within the crystal and creating permanent colour centres.

Crystal Damage 2



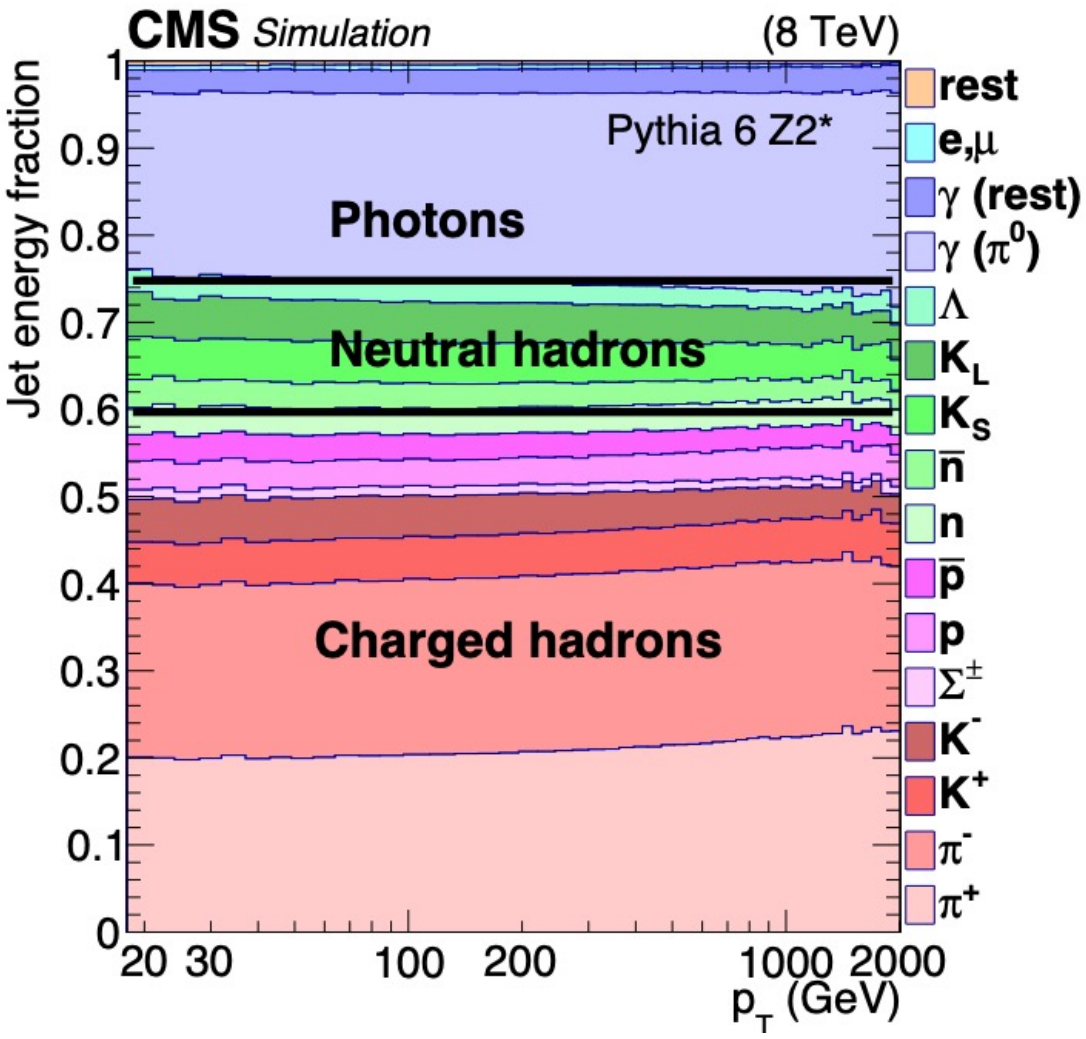
- e/γ create EM showers in the crystals
- Light from EM shower is produced along the crystal
- Colour centres/defects are present
- Light from far end is less likely to reach the photodetector
- Only light from nearest region will not be absorbed
- The apparent arrival time of the pulse is therefore earlier



Jets in ECAL

- Jets are composed of 25% photons 15% neutral hadrons 60% charged hadrons
- Jets deposit 50% of their energy in ECAL in the endcaps 25% directly from photons (π->γγ)
- 25% from hadrons (50% of hadrons EH hadrons, depositing 2/3 of energy to ECAL)

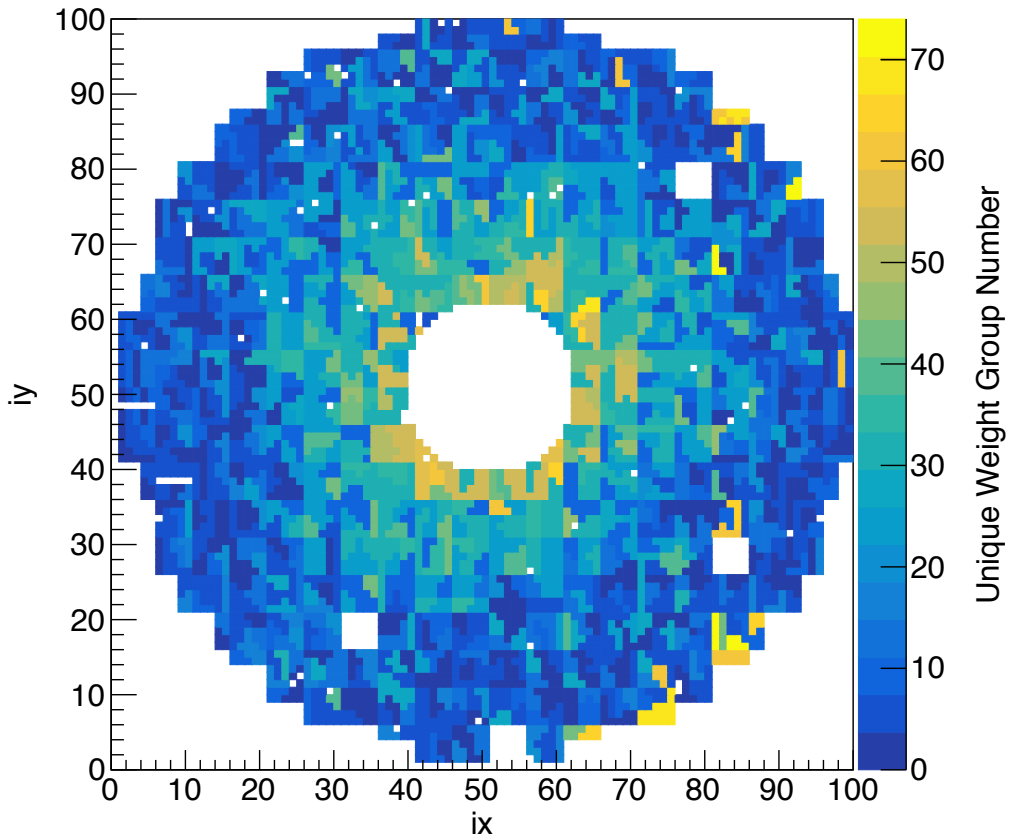
- QCD (jet) interactions are more probable at low transverse energy, therefore inner EE
- No tracker above eta >2.5, therefore rings 27 and 28 are important for jet reconstruction



M.Voutilainen

Increased Weight Granularity

- Finest granularity possible on-detector is **per strip**
- 2018 pulse shapes were used to compute weights per strip and per ring
- These weights were then encoded for use on-detector
- Involves rounding to nearest 1/64 multiple and places a **limit** on the number of different weights possible
- For example, 1468 unique decimal weights per strip in EE+ becomes 74 unique encoded weights (right)
- These studies focus on EE, as the radiation damage and therefore number of encoded weights is greatest



Unique sets of per strip weights in EE+, once encoded

Changing OOT PU Problem

- $\hat{A} = \sum S \cdot w$ with $S = S_t + p$ where p is a fixed pedestal
- $\hat{A} = \sum (S_t + p) \cdot w = \sum S_t \cdot w + \sum p \cdot w = \sum S_t \cdot w + p \sum w$
- But, $\sum w = 0$ by design
- Therefore, $\hat{A} = \sum S_t \cdot w + 0$

- A constant pedestal, from noise or non-changing OOT PU has no impact on the amplitude reconstruction
- However, a changing OOT PU contribution (i.e. p(t)) ***will*** have an impact

Bias vs Eta Ring Data

Data for bias against eta ring. Numbers in bold show the best performing weights for that metric.

Data	Weights	Average Bias	Flatness	Average Spread
8b4e PU 30	Current	0.1884	0.4411	0.8021
	New Avg	-0.0092	**0.2372**	0.6681
	Per Strip	-0.0154	0.2460	0.5857
	PU 30 S2	**0.0003**	0.2465	**0.5650**
8b4e PU 50	Current	0.1570	0.3501	0.8044
	New Avg	-0.0303	**0.1672**	0.6736
	Per Strip	-0.0240	0.1939	0.6152
	PU 50 S2	**-0.0083**	0.1818	**0.5678**
48b PU 30	Current	**-0.0670**	0.2420	0.5714
	New Avg	-0.1356	0.1418	0.5203
	Per Strip	-0.1334	**0.1346**	0.5182
	PU 30 S2	-0.1006	0.1464	**0.5083**
48b PU 50	Current	**-0.0439**	0.2346	0.6735
	New Avg	-0.1515	0.1286	0.6073
	Per Strip	-0.0910	0.1311	0.6510
	PU 50 S2	-0.0593	**0.1237**	**0.6048**

Bias vs Bunch Position Data

Data for bias against BX position. Numbers in bold show the best performing weights for that metric.

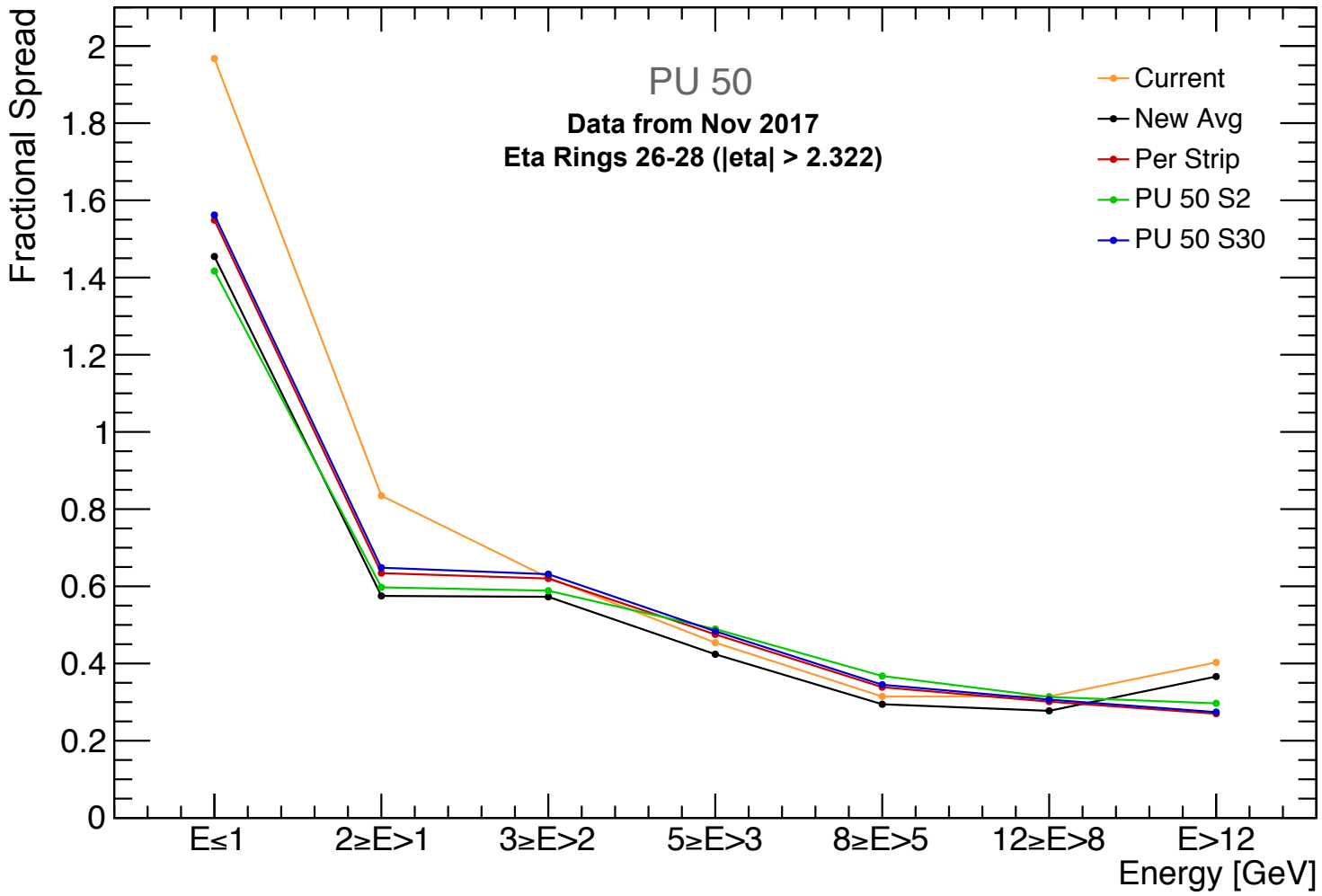
Data	Weights	Average Bias	Flatness	Average Spread
8b4e PU 30	Current	0.7899	0.2722	1.3924
	New Avg	**0.2845**	0.1564	1.0096
	Per Strip	0.3131	0.1452	1.0518
	PU 30 S2	0.3224	**0.1368**	**1.0151**
8b4e PU 50	Current	0.5788	0.2723	1.2121
	New Avg	**0.1531**	0.1559	0.8828
	Per Strip	0.2012	0.1621	0.9266
	PU 50 S2	0.1920	**0.1289**	**0.8595**
48b PU 30	Current	0.06812	0.1250	0.9029
	New Avg	-0.0582	0.0911	0.7395
	Per Strip	-0.0631	0.0889	0.7307
	PU 30 S2	**-0.0176**	**0.0888**	**0.7080**
48b PU 50	Current	0.0692	0.1738	0.9097
	New Avg	-0.1025	0.1247	0.7320
	Per Strip	-0.0468	0.1333	0.7743
	PU 50 S2	**-0.0151**	**0.1244**	**0.6870**

Bias vs Energy Data

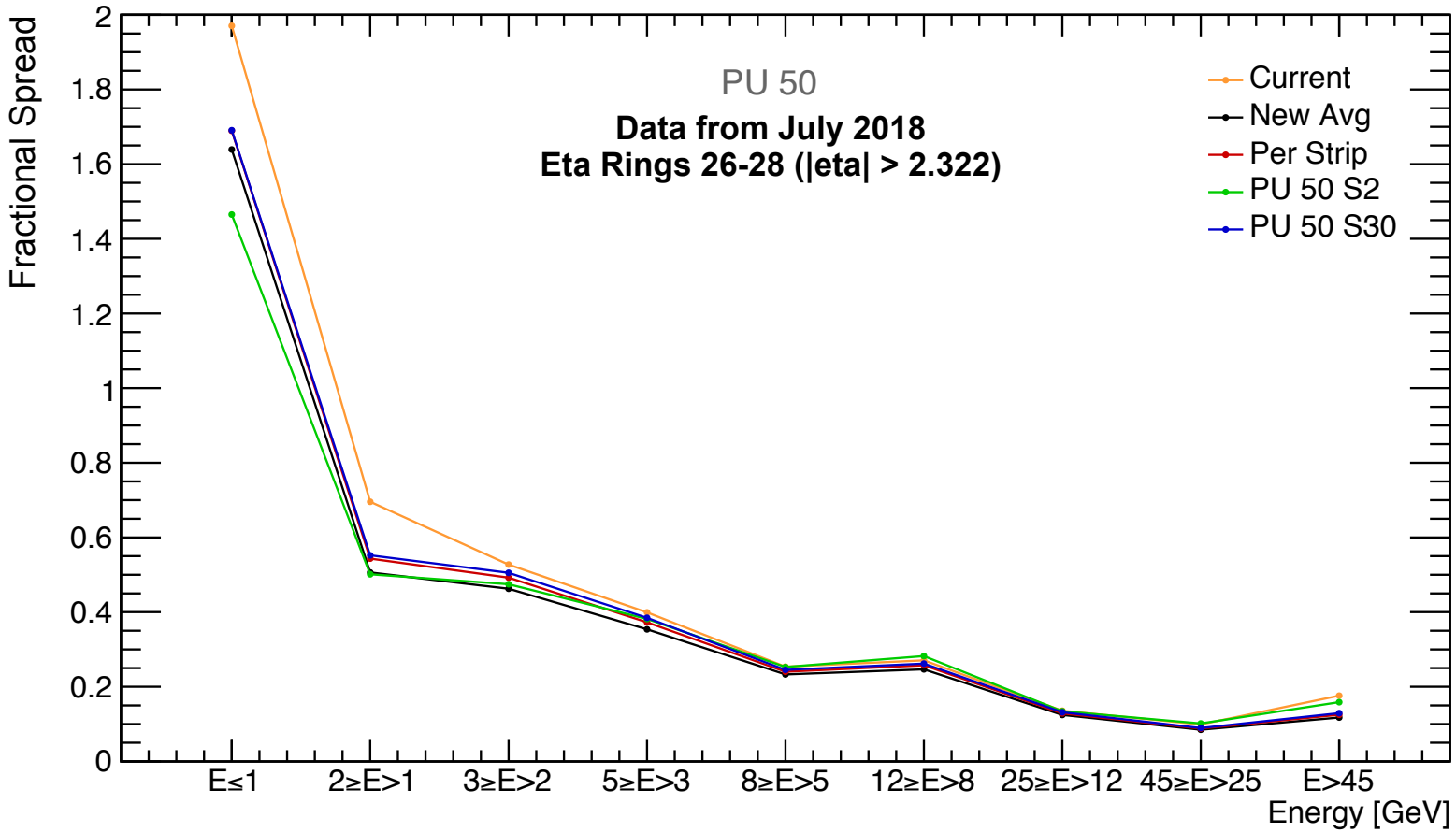
Data for bias against energy. Numbers in bold show the best performing weights for that metric.

Data	Weights	Average Bias	Flatness	Average Spread
8b4e PU 50 Whole EE	Current	0.4193	0.6806	0.6943
	New Avg	**0.1015**	0.3693	**0.5530**
	Per Strip	0.1541	0.3634	0.5804
	PU 50 S2	0.1551	**0.3063**	0.5601
	PU 50 S30	0.1723	0.3613	0.5894
8b4e PU 50 Rings 18 - 21	Current	-0.1729	0.0825	0.1173
	New Avg	-0.2388	0.1122	0.1117
	Per Strip	-0.1568	0.0814	0.1181
	PU 50 S2	**-0.0940**	0.0859	**0.0847**
	PU 50 S30	-0.1564	**0.0809**	0.1179
8b4e PU 50 Rings 22 - 25	Current	-0.0764	0.3977	0.2770
	New Avg	-0.1730	0.3815	0.2407
	Per Strip	-0.1111	0.3090	0.2499
	PU 50 S2	**-0.0672**	**0.2498**	**0.2311**
	PU 50 S30	-0.1054	0.3085	0.2450
8b4e PU 50 Rings 26 - 28	Current	0.4740	0.7171	0.7015
	New Avg	**0.1253**	0.3691	**0.5663**
	Per Strip	0.1834	0.3714	0.5983
	PU 50 S2	0.1850	**0.3159**	0.5814
	PU 50 S30	0.2030	0.3689	0.6072
48b PU 50 Whole EE	Current	0.0759	0.5945	0.4557
	New Avg	-0.0747	0.4353	0.3782
	Per Strip	-0.0352	0.4261	0.3930
	PU 50 S2	**0.0090**	**0.3364**	**0.3706**
	PU 50 S30	-0.0260	0.4198	0.3965
48b PU 50 Rings 18 - 21	Current	-0.0094	0.4352	0.3309
	New Avg	-0.0763	0.4383	0.3140
	Per Strip	-0.0527	0.3451	0.2992
	PU 50 S2	**-0.0370**	**0.3047**	**0.2867**
	PU 50 S30	-0.0536	0.3238	0.2921
48b PU 50 Rings 22 - 25	Current	-0.0890	0.4001	0.2772
	New Avg	-0.1530	0.3895	0.2563
	Per Strip	-0.1187	0.3895	0.2563
	PU 50 S2	**-0.0769**	**0.3083**	**0.2492**
	PU 50 S30	-0.1150	0.3629	0.2606
48b PU 50 Rings 26 - 28	Current	0.1313	0.6428	0.5031
	New Avg	-0.0531	0.4436	0.4187
	Per Strip	-0.0124	0.4479	0.4375
	PU 50 S2	0.0536	**0.3423**	**0.4168**
	PU 50 S30	**0.0008**	0.4427	0.4434

Spread vs Energy – 8b4e rings 26-28



Spread vs Energy – 48b rings 26-28



Per Strip Weights in EB

- 17 sets of unique encoded weights in EB from 12240 decimal per strip weights