Crystal Calorimetry

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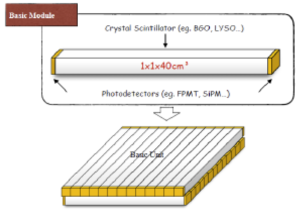
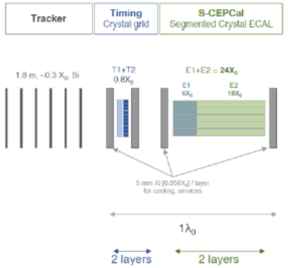
Crystal Calorimeters

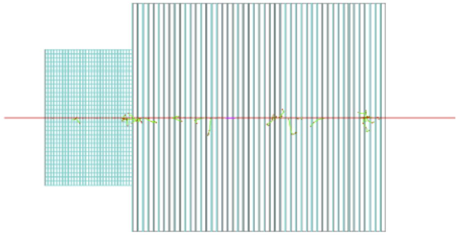
Three groups have started some work on ideas for a calorimeter for future e^+e^- colliders that use scintillating crystals for EM calorimetry

Overview: designs of crystal ECAL

- 3 major designs being pursued
  - Long crystal bars with optical readout at both ends (Y. Wang, et al.)
    - Use timing information for hit positions; less #channels
  - Long crystal bars with optical readout at single ends (C. Tully, et al.)
    - Less segmentation in the longitudinal direction; Simpler integration?
  - Thin crystal tiles with optical readout at single ends (Y. Liu, et al.)
    - Started with ultra-fine segmentation (both longitudinal and transverse)
    - Seeking trade-off between #channels and performance







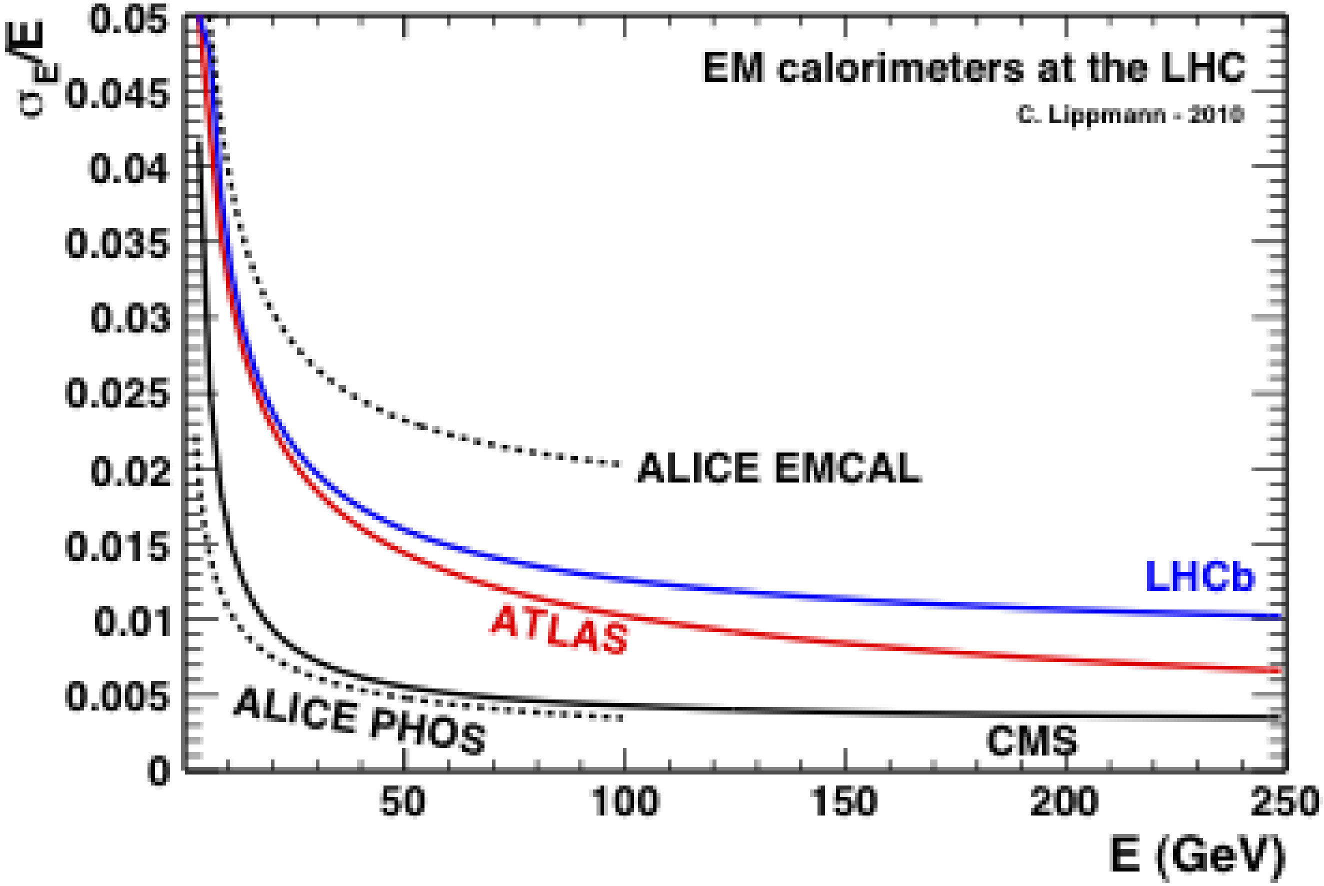
3/16/2019 Yong Liu (liuyong@ihep.ac.cn) CEPC Working Day 3

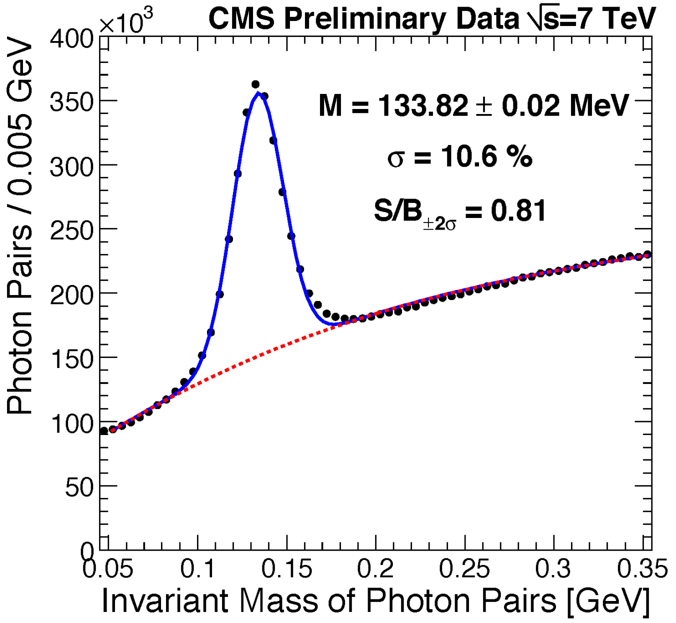
Advantages

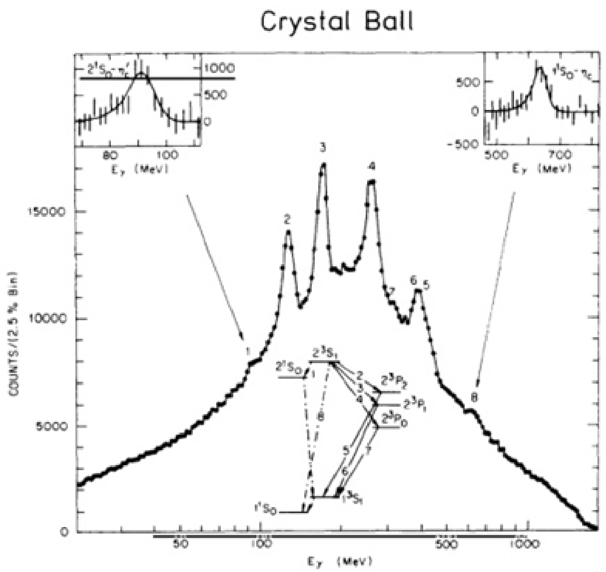
The advantages of crystal EM calorimetry are well known

Separate signal from background

Separate closely spaced states



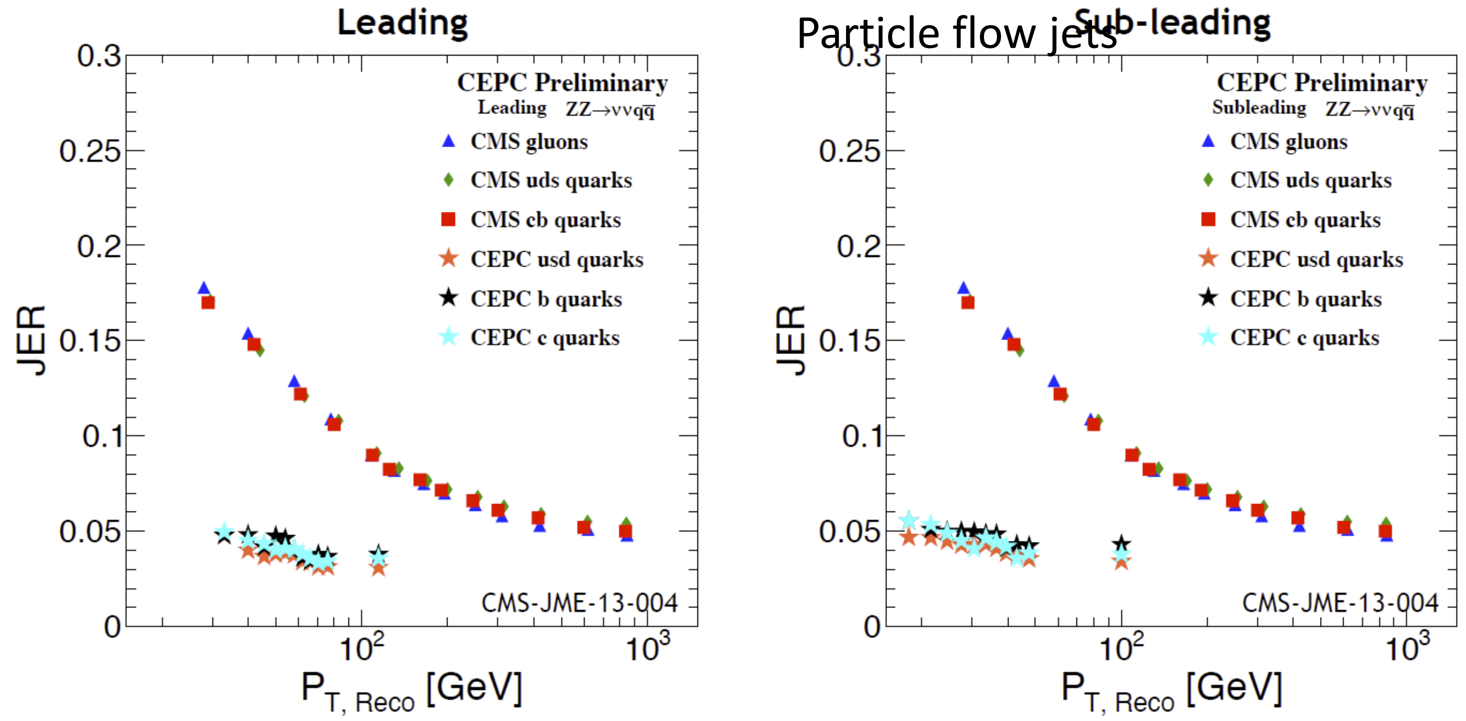


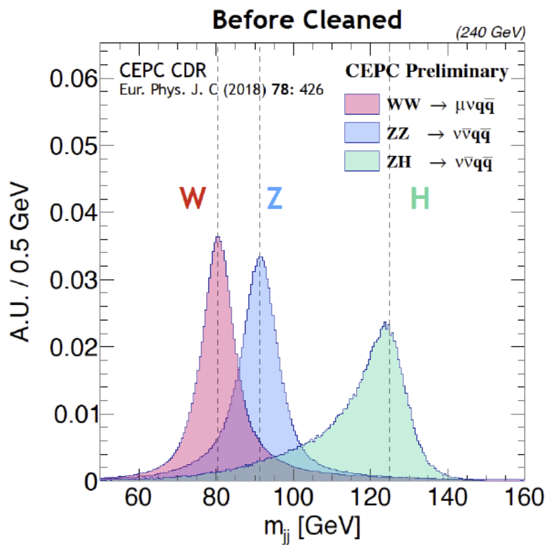


So are the disadvantages

Compare to CMS at LHC

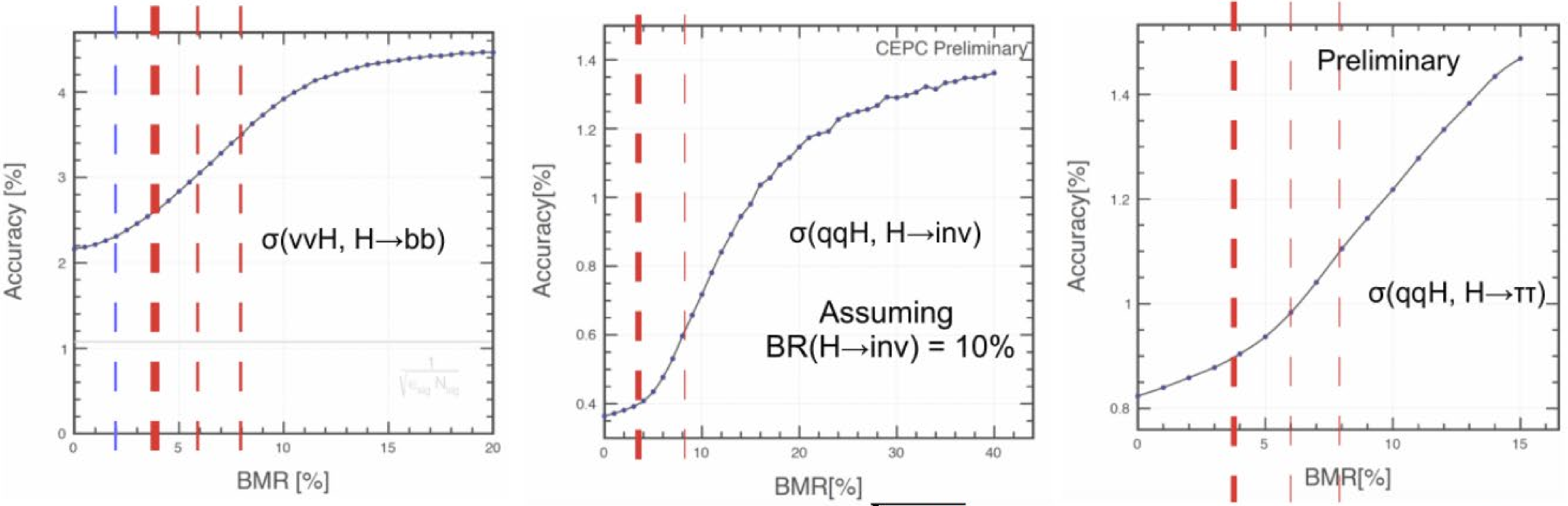
Particle flow jets





- JER at CEPC is better than CMS as it should be; 2-4 times better in the same energy region.

Jet resolution needs



$$\text{Accuracy} = \frac{\sqrt{S+B}}{S}$$

For details, see Manqi Ruan's talk at Sendai:
https://agenda.linearcollider.org/event/8217/contributions/44771/attachments/34967/54047/Jet_Requirement-LCWS.pdf

EM resolution needs

From Michael Peskin:

- Monophoton + dark matter search: This has actually be studied by Jenny List at DESY. She claims that the analysis has only a weak dependence on photon energy resolution. Much more important is angular coverage down to small angles.
- Study of tau+tau- in Z and Higgs decays: Here photon performance is needed to discriminate tau -> pi, rho , a1. However, Jean-Claude Brientl claimed that the crucial need is for good pattern recognition and photon ID down to small energies, while the actual photon energy resolution is less important
- Efficiency for h-> gamma gamma: This is a real need; the photon-photon efficiency here is somewhat pathetic, even worse than CMS. However, the statistics is not high in any event, and HL-LHC will give us an excellent value of BR(h->gamma gamma)/BR(h->ZZ*).
- Graham Wilson suggested that improved EM resolution might be important in W studies. A method for measuring the W mass is to use the endpoint in W-> e nu. This wins strongly with better EM resolution.
- Similarly, finding the exotic mode h -> tau e under the background of h-> tau tau depends on good performance at the endpoint.

Flavor physics

From Manqi Ruan

- On top of what you summarized, I would like to add a small comment that the rich flavor program - might appreciate a better EM energy resolution. However, to identify a representative benchmark with clear physics impact is not trivial.

CEPC Flavor Physics

70 OVERVIEW OF THE PHYSICS CASE FOR CEPC

Particle	Tera-Z	Belle II	LHCb
b hadrons			
B^+	6×10^{10}	3×10^{10} ($50\,\text{ab}^{-1}$ on $\Upsilon(4S)$)	3×10^{13}
B^0	6×10^{10}	3×10^{10} ($50\,\text{ab}^{-1}$ on $\Upsilon(4S)$)	3×10^{13}
B_s	2×10^{10}	3×10^{8} ($5\,\text{ab}^{-1}$ on $\Upsilon(5S)$)	8×10^{12}
b baryons	1×10^{10}		1×10^{13}
Λ_b	1×10^{10}		1×10^{13}
c hadrons			
D^0	2×10^{11}		
D^+	6×10^{10}		
D_s^+	3×10^{10}		
Λ_c^+	2×10^{10}		
τ^+	3×10^{10}	5×10^{10} ($50\,\text{ab}^{-1}$ on $\Upsilon(4S)$)	

Table 2.4: Collection of expected number of particles produced at a tera-Z factory from 10^{12} Z-boson decays. We have used the hadronization fractions (neglecting p_T dependencies) from Refs. [431, 432] (see also Ref. [433]). For the decays relevant to this study we also show the corresponding number of particles produced by the full $50\,\text{ab}^{-1}$ on $\Upsilon(4S)$ and $5\,\text{ab}^{-1}$ on $\Upsilon(5S)$ runs at Belle II [430], as well as the numbers of b hadrons at LHCb with $50\,\text{fb}^{-1}$ (using the number of $b\bar{b}$ pairs within the LHCb detector acceptance from [435] and the hadronization fractions from [431]).

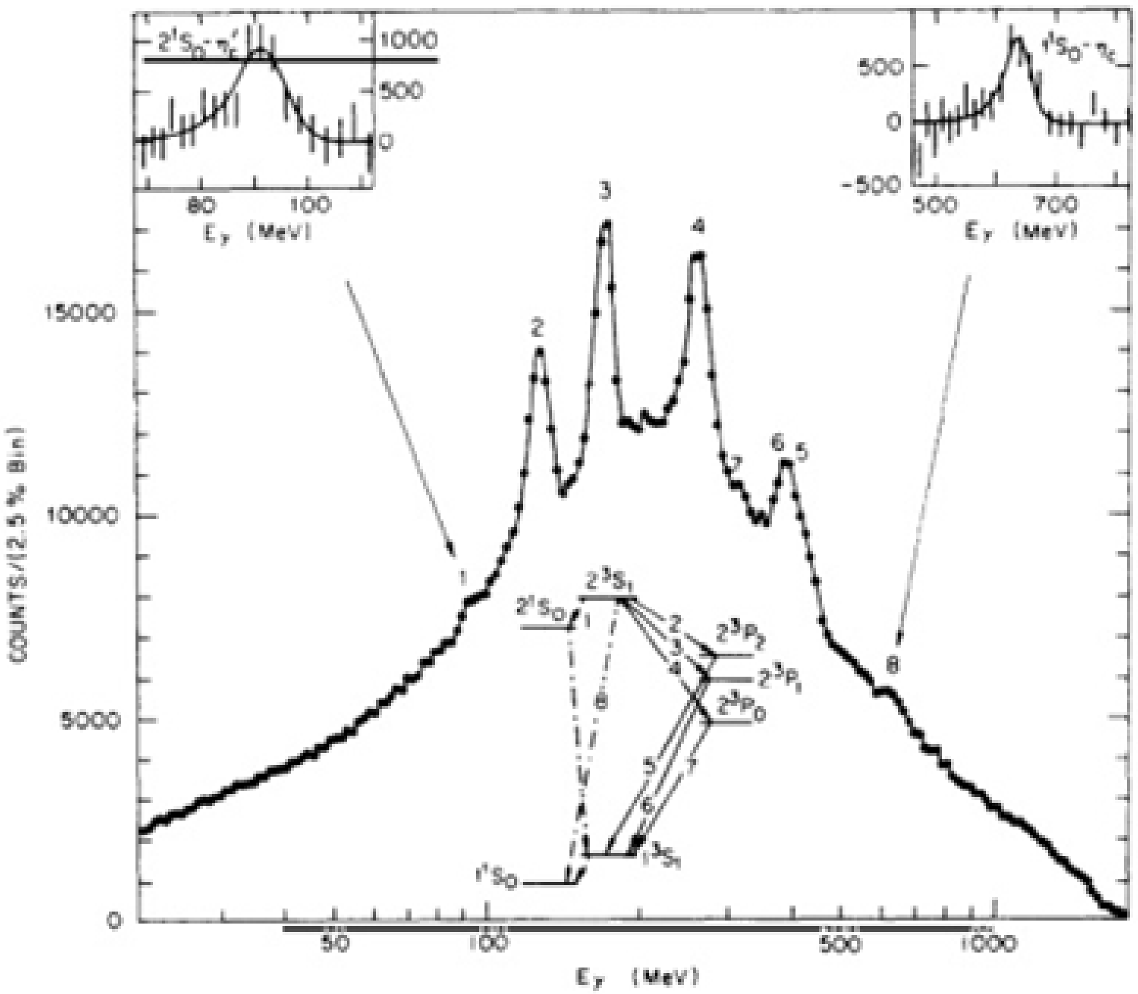
Comparative advantages

vs LHCb:
- Reconstruction of neutral particles
- Reconstruction of jet charge
- ...

vs Belle II:
- Higher Boost
- Large phase space

Challenges:
- Finding the decay products in Jets! (similar to LHCb)...

Crystal Ball



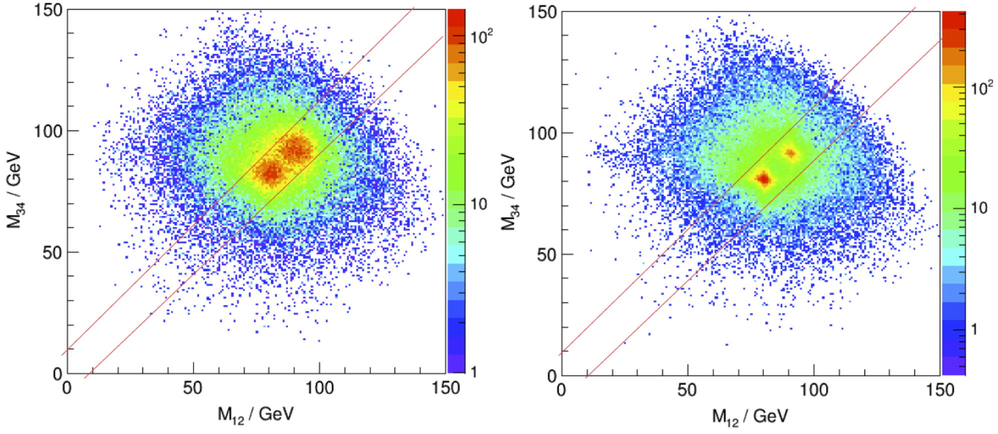
EM resolution needs

From Chris Tully

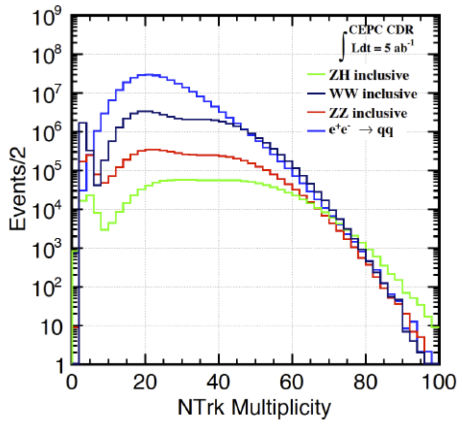
Correct assignment of hadrons to jets, even in events with 4 jets such as WW and ZZ, is said to be an important benchmark

- Perhaps we can reduce the need to remove half the stats with better EM resolution?
- And what is the size of the systematic error, even with this cut? Is it tractable unless we really can find all the pizeros?
- And what about ZH with Z to qq and H to anything?
- Are we really asking the question precisely enough to focus our goal?

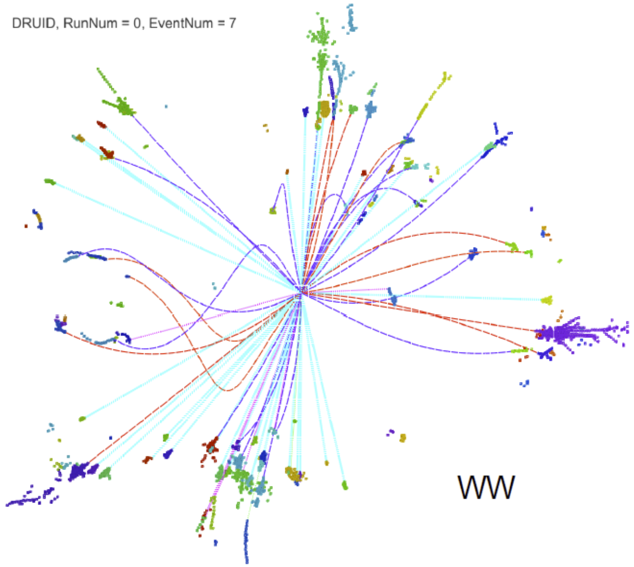
Reconstructed mass of the two di-jet system



How do we relate this to something not measurable at HL-LHC?



- Low energy jets! (20 – 120 GeV)
- Typical multiplicity ~ o(100)
- WW-ZZ Separation: determined by
  - Intrinsic boson mass/width
  - Jet confusion from color single reconstruction – jet clustering & pairing
  - Detector response



From Manqi Ruan's talk

Very useful in understanding affect of noise in resolution, scale

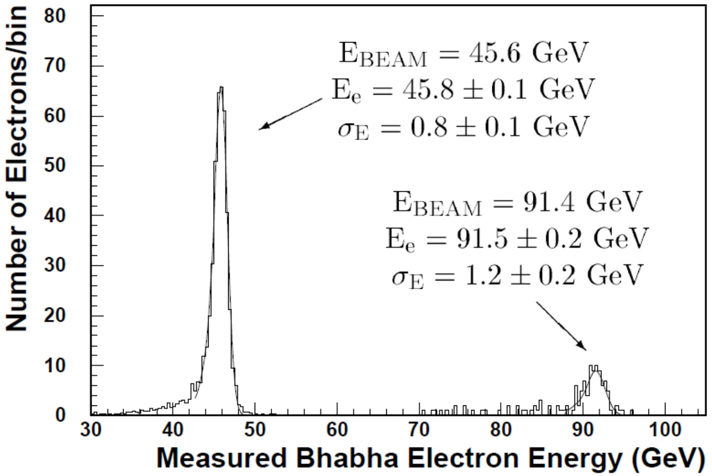


Fig. 5.14: **BGO Energy Linearity Measured with Bhabha Scattering.** The BGO energy calibration is adjusted every data-taking period to agree with the 45.6 GeV Bhabha peak. No further adjustment was needed to obtain less than 0.3% energy non-linearity for the 91.4 GeV high-energy Bhabhas. The width of the Bhabha peak is a measurement of the calibration errors.

$$\sigma_E^{\text{Full}}(E)^2 = \sigma_E^{\text{Full}}(E)^2 + N_9 \cdot \sigma_{\text{intrinsic}}^2 + (N_9 \cdot \sigma_{\text{correlated}})^2 + (\sigma_{\text{calibration}} \cdot E)^2 \quad (5.5)$$

From “Baryon production in Z decay”, thesis, Christopher Tully, 1998

Right now, the "most interesting" measurements seem to emphasize hadronic resolution. Since 3-4% hadronic resolution at 100 GeV is hard, and there doesn't seem to be a clear driver (yet) for anything more than average EM resolution, seems to be a killer for crystal calorimetry?????

Or is it?

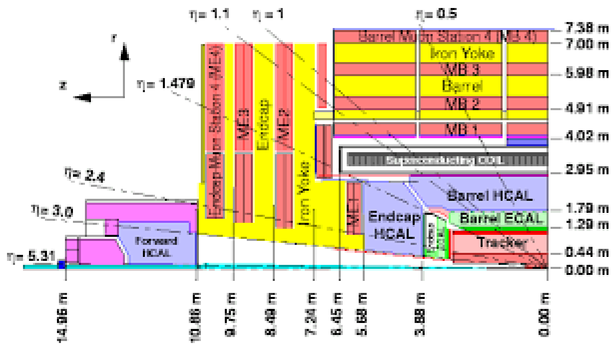
CMS calorimeter

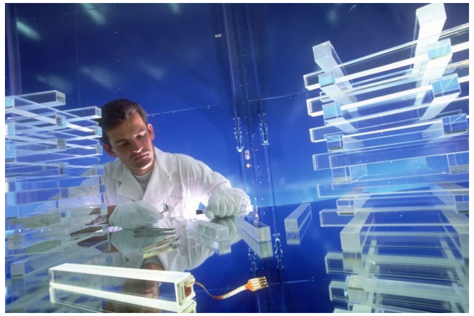
The CMS calorimeter does not represent the ultimate in hadronic resolution when using crystal EM calorimeters for two reasons:

- Transverse and longitudinal segmentation
- Crystals and bronze/scintillator sampling calorimeters have very different e/h

Segmentation

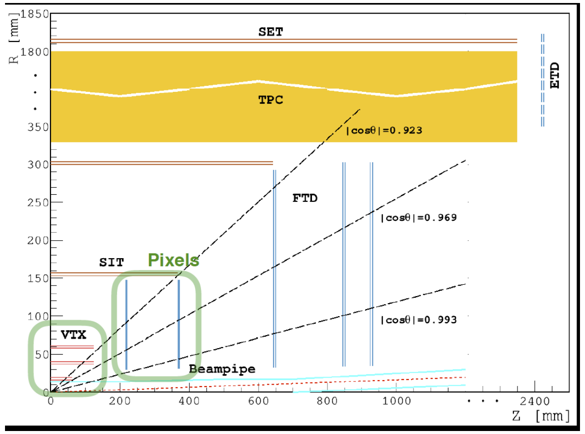
CMS crystal calorimeter

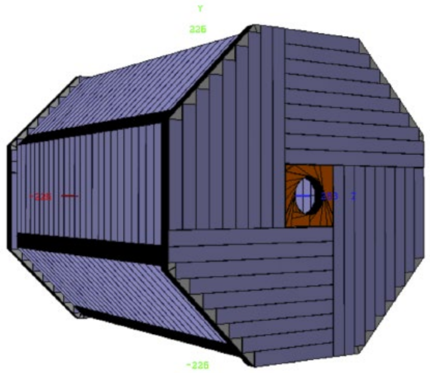




- Front face of 2.2x2.2 cm^2
- radius of 1.29m (subtended angle 0.0003 steradian)
- Only 1 longitudinal depth

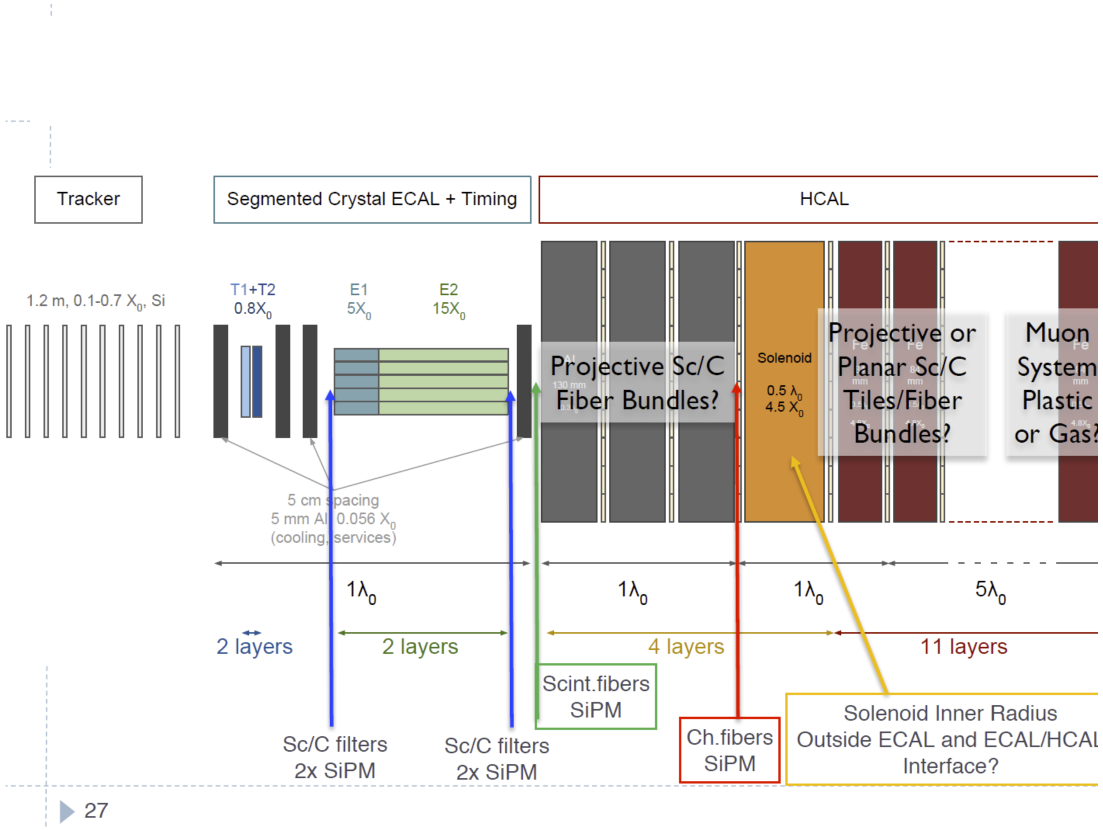
CEPC Baseline Wi-W





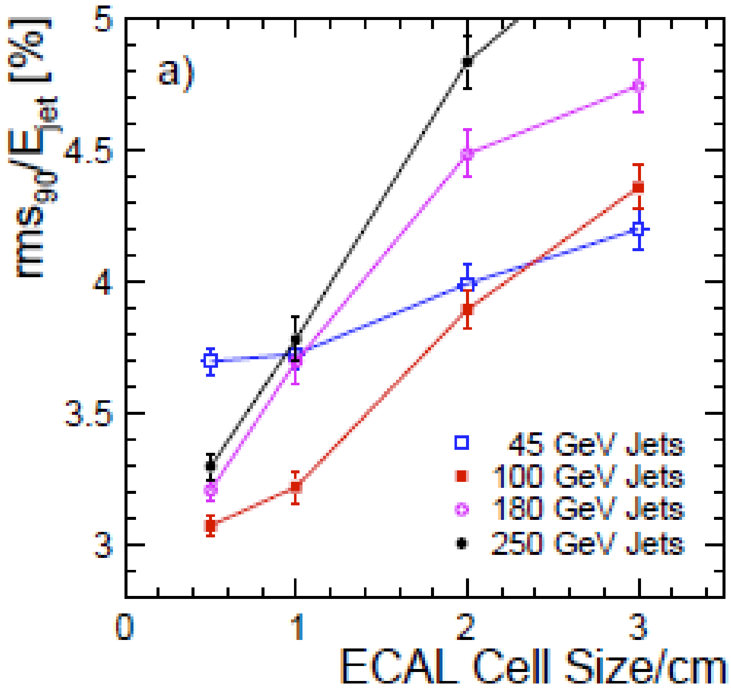
- Segmentation of 1x1 cm^2
- At a radius of 2 m (subtended angle 0.0001 steradian)
- 30 depth segments, but may be gained into 4 depth segments to save on electronics? (more later)

PF resolution and segmentation



Proposed segmentation for modern crystal calorimeters 1x1 cm^2 at 2 m

Thomson: https://arxiv.org/abs/0907.3577

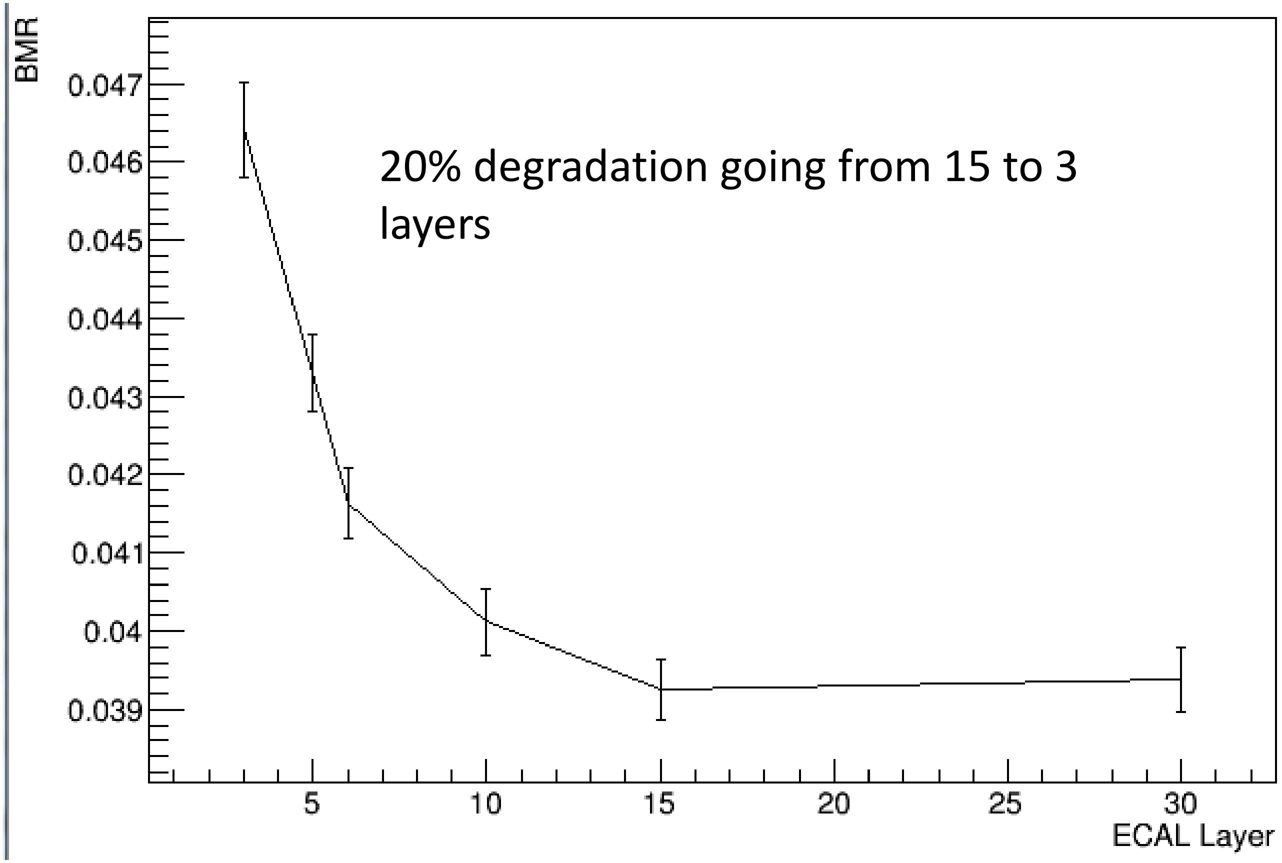


- For CEPC, mostly interested in the 45 and 100 GeV curve?
- However, Moliere radius for W is 0.93 cm and for $PbWO_4$ is 1.96 cm, so not trivial to use this graph for different material

Longitudinal segmentation

from Manqi Ruan:

This preliminary plot shows the BMR (Higgs mass resolution with full hadronic final state + standard cleaning) at 240 GeV, with different ECAL Longitudinal segmentation. To disentangle the intrinsic resolution from the clustering-matching, we start from the baseline and Merges the longitudinal cells into large cells. This treatment gives exactly the same total energy response for single particle, and provides a critical test for the PFA pattern recognition. So, no significant effect observed once reducing the ECAL layer from 30 to 15 or 10. Become significant once the #layer is reduced to 6 or less, and leads to a degrading of 20% with only 3 layers.

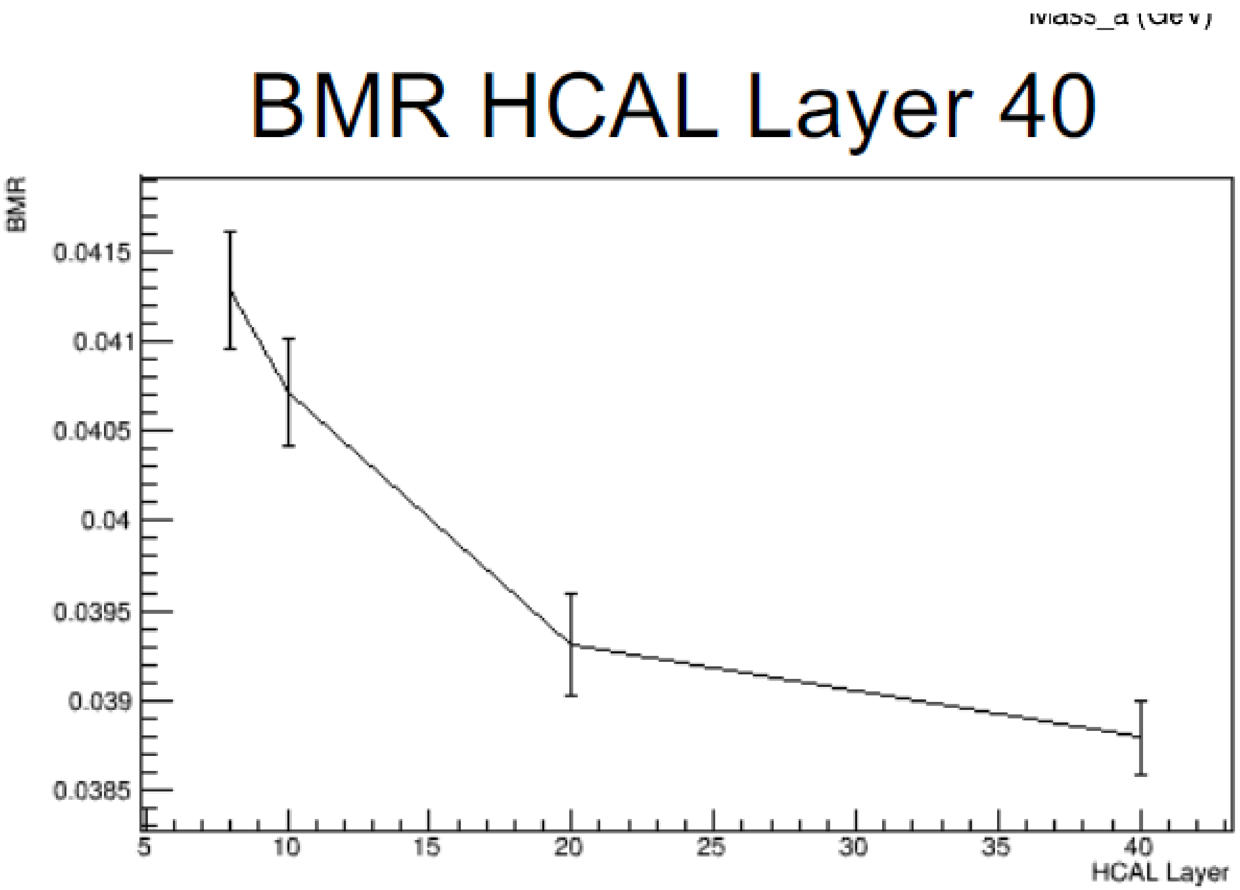


20% degradation going from 15 to 3 layers

Crystals can be segmented longitudinally, at the expense of some dead material. Trade off between EM resolution and JER. Certainly 3 segments can be imagined?

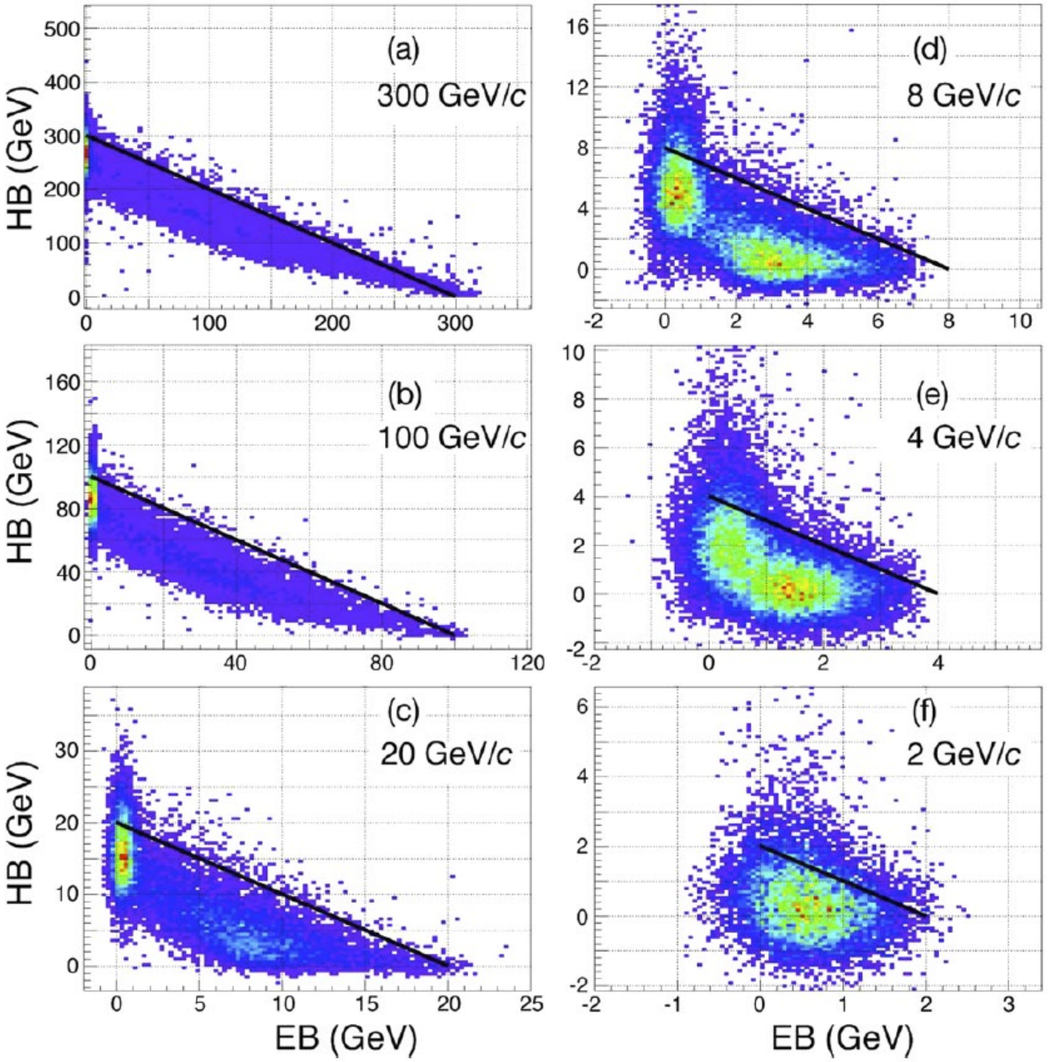
Oddly enough, the conclusion is different for the HCAL

Yukun Shi



e/h in CMS Ecal/Hcal

The hadronic energy resolution of the CMS calorimeter is degraded by the very different e/h of its ECAL and HCAL



Eur. Phys. J. C (2009) 60: 359-373

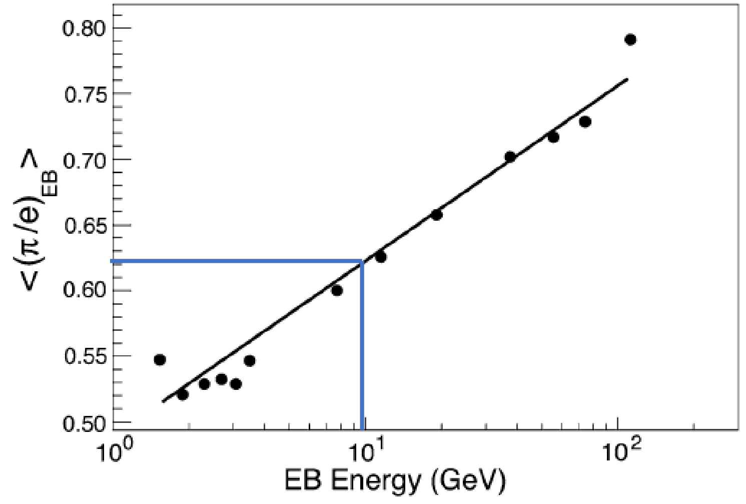


Fig. 5.3 Measured $(\pi/e)_{EB}$ *vs* E_{EB} after correcting the energies of pions that interacted in the EB (see text for details)

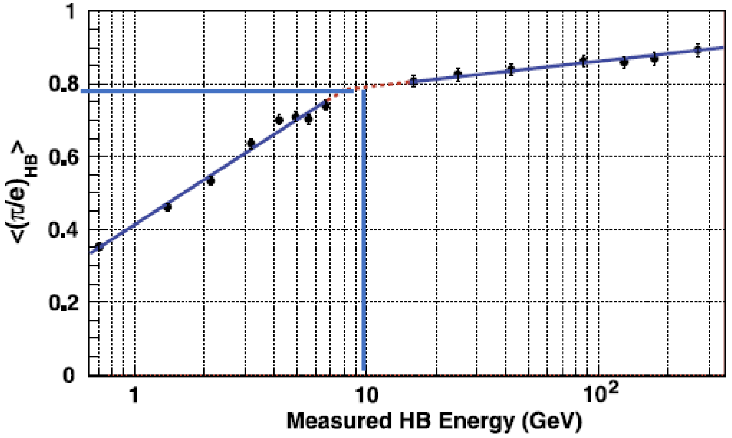
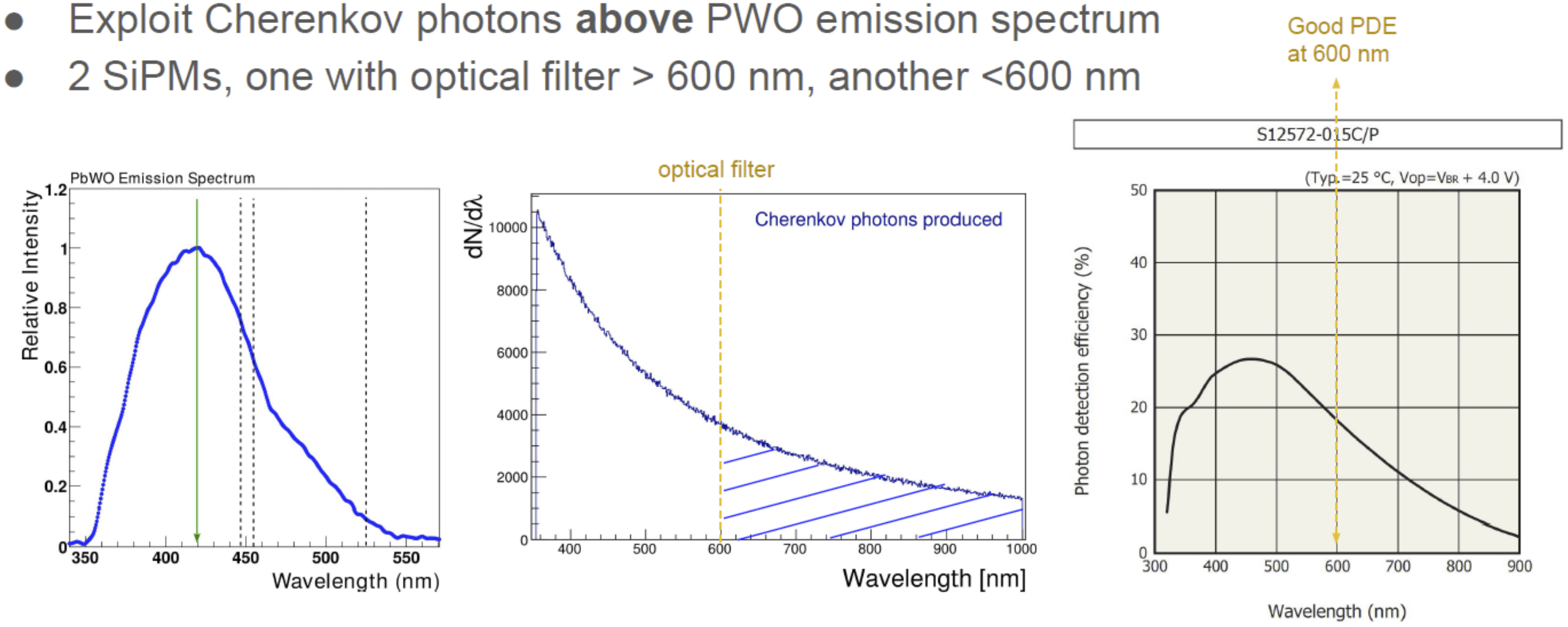


Fig. 5.2 π/e *vs* E_{HB} for events interacting in the HB. The data are fit to two separate log functions with a break at about 8 GeV

But now this might be mitigated?

Dual-Readout Capability

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



Also works for BGO (used in TOF-PET applications) and other crystals

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Chris Tully

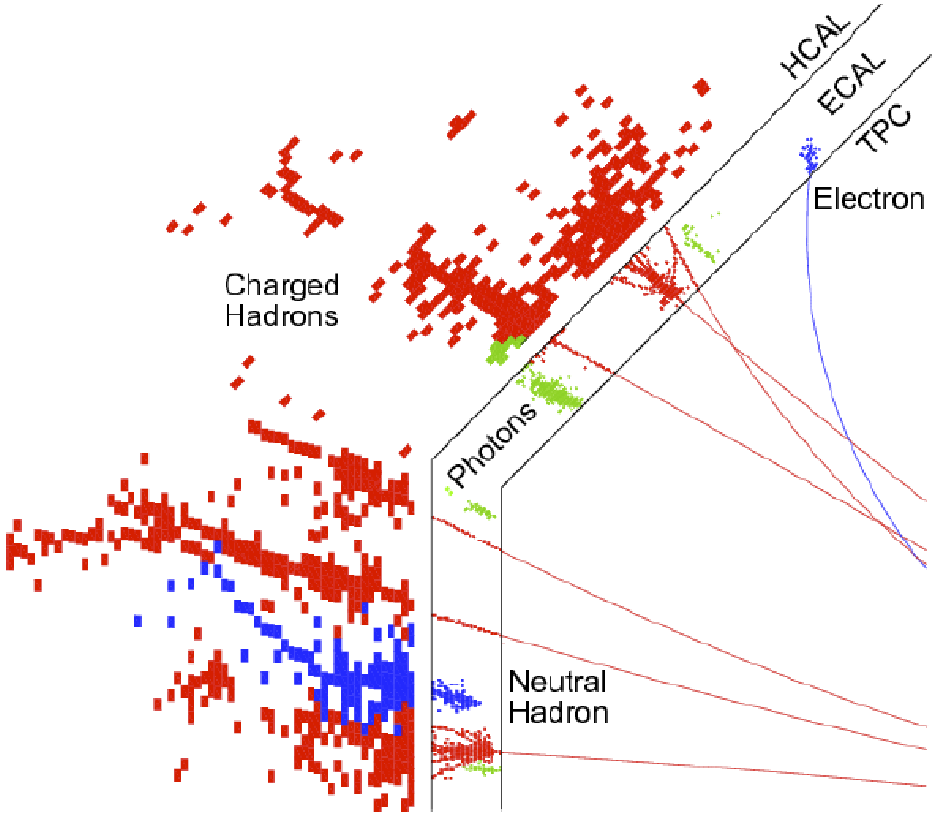
Hadron fragmentation

An interesting parameter is the ratio of the hadronic to electromagnetic interaction length.

Having deeper hadronic showers helps separation of gammas and neutral hadrons.

Material	Radiation length	Absorp. length	ratio
W	3.5 mm	99.5 mm	28
$PbWO_4$	8.9 mm	240 mm	27

W:Cu	100:0	85:15	75:25
X_0 (mm)	3.5	4.4	5.1

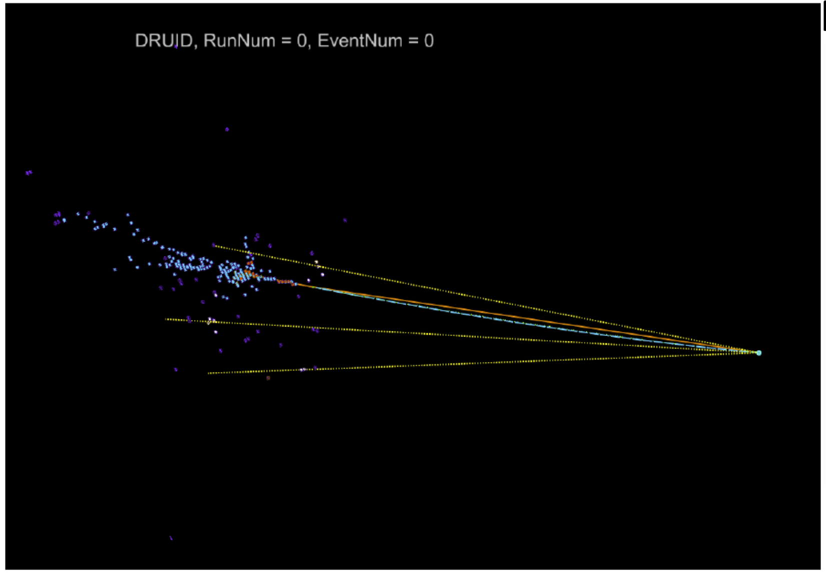


Similar for baseline CEPC and for potential crystal ECAL detectors.

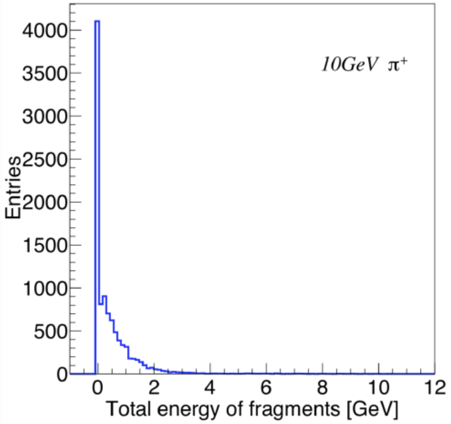
Related to hadronic splintering as well.
Can timing help mitigate this splitting?
Which would have better timing?

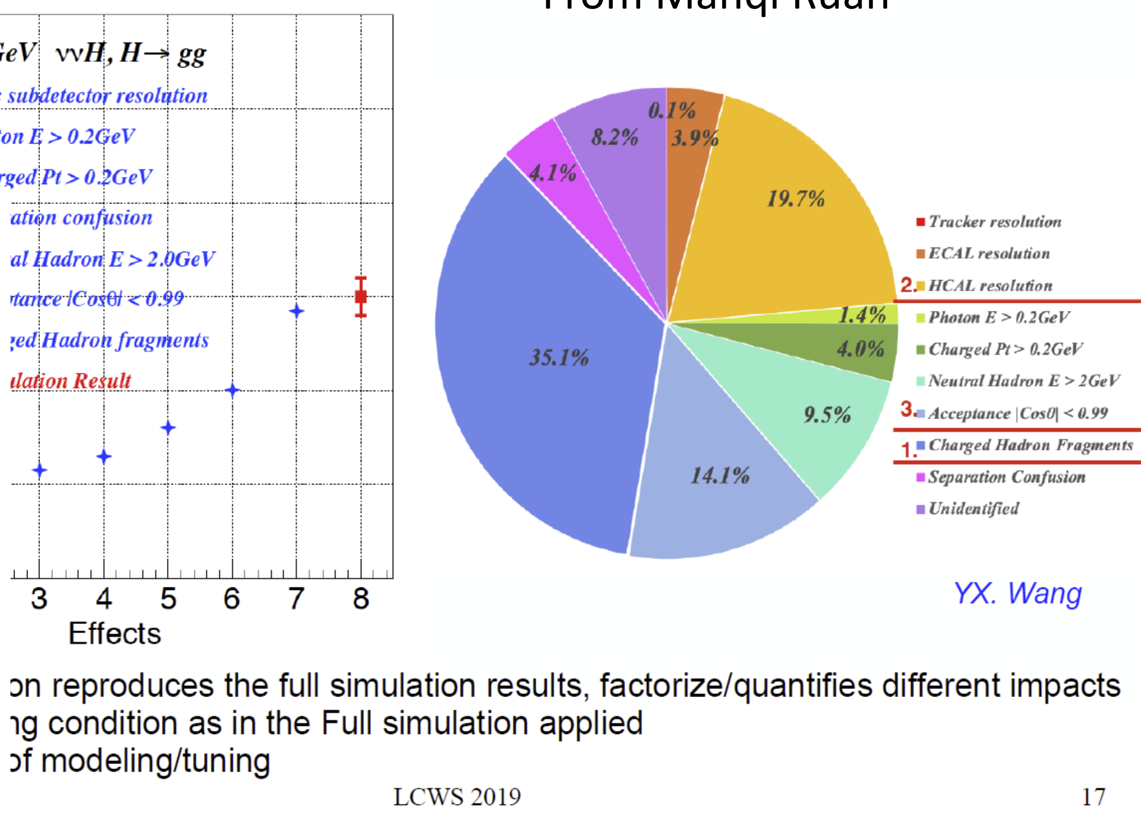
PFA Fast simulation (Preliminary)

From Manqi Ruan



From Manq Ruan's talk





Time/pattern recognition may help a lot, in identify the charged cluster fragmentations without arise the threshold for the neutral hadron significantly...

Other crystals possible

Small Moliere radius probably key

Crystal options

- PWO: the most compact, the fastest, the cheapest
- BGO: in between
- CsI: the less compact, the slowest, the brightest

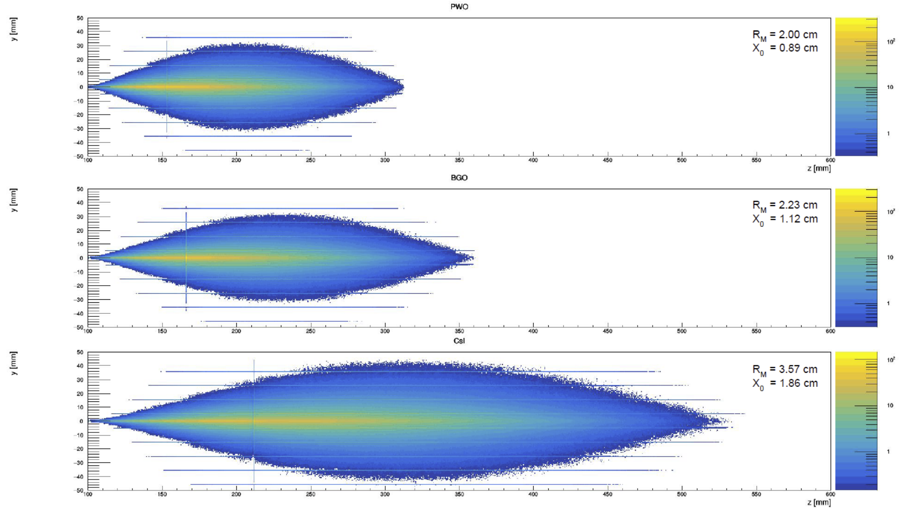
better for PFA

better stochastic term

Crystal	Density g/cm³	λ_I cm	X_0 cm	R_M cm	Relative LY @ RT	Decay time ns	Photon density (LY / τ_D) ph/ns	dLY/dT (% / °C)	Cost (10 m³) \$/cm³	Cost*X_0 \$/cm²
PWO	8.3	20.9	0.89	2.00	1	10	0.10	-2.5	8	7.1
BGO	7.1	22.7	1.12	2.23	70	300	0.23	-0.9	7	7.8
CsI	4.5	39.3	1.86	3.57	550	1220	0.45	+0.4	4.3	8.0

from: Journal of Physics: Conference Series **293** (2011) 012004

- Smaller Moliere radius in front segment (better shower separation)

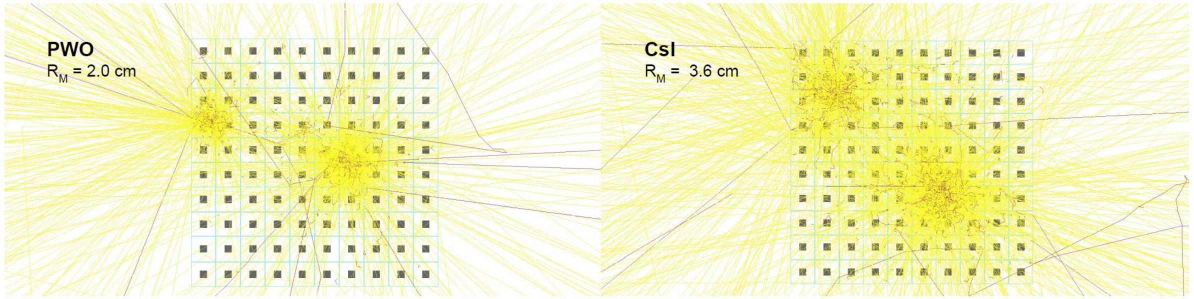


45 GeV electrons

X_0^{TRK} = 0.3

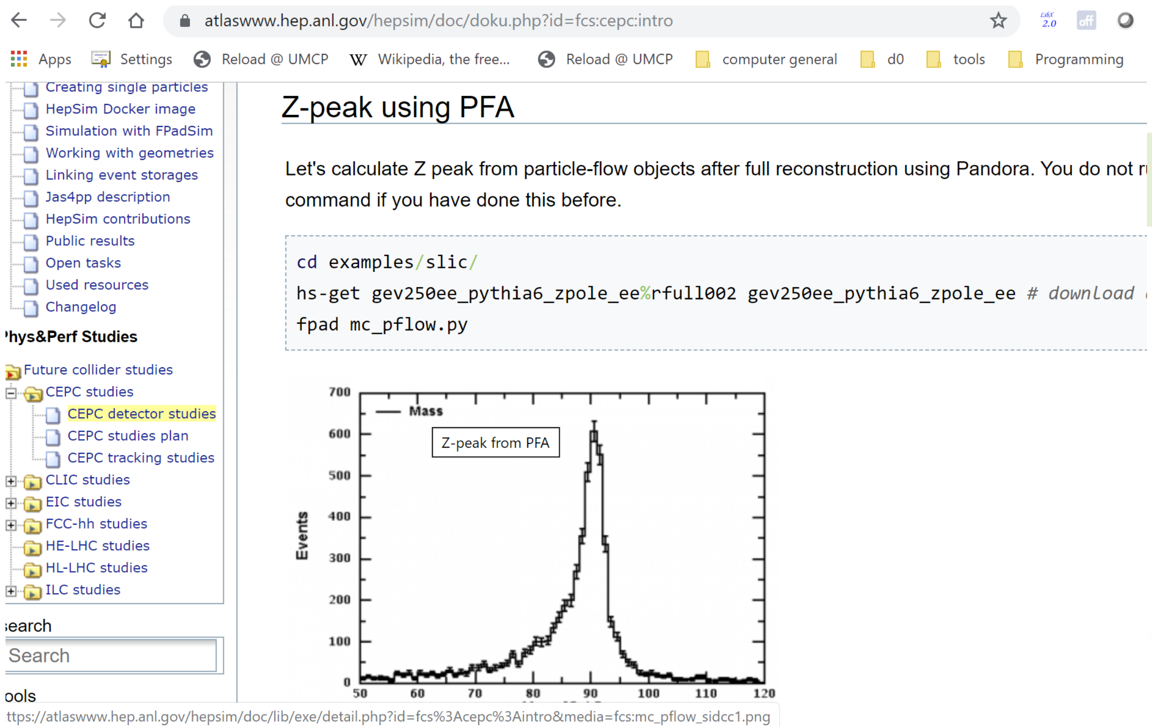
ECAL length: 24 X_0

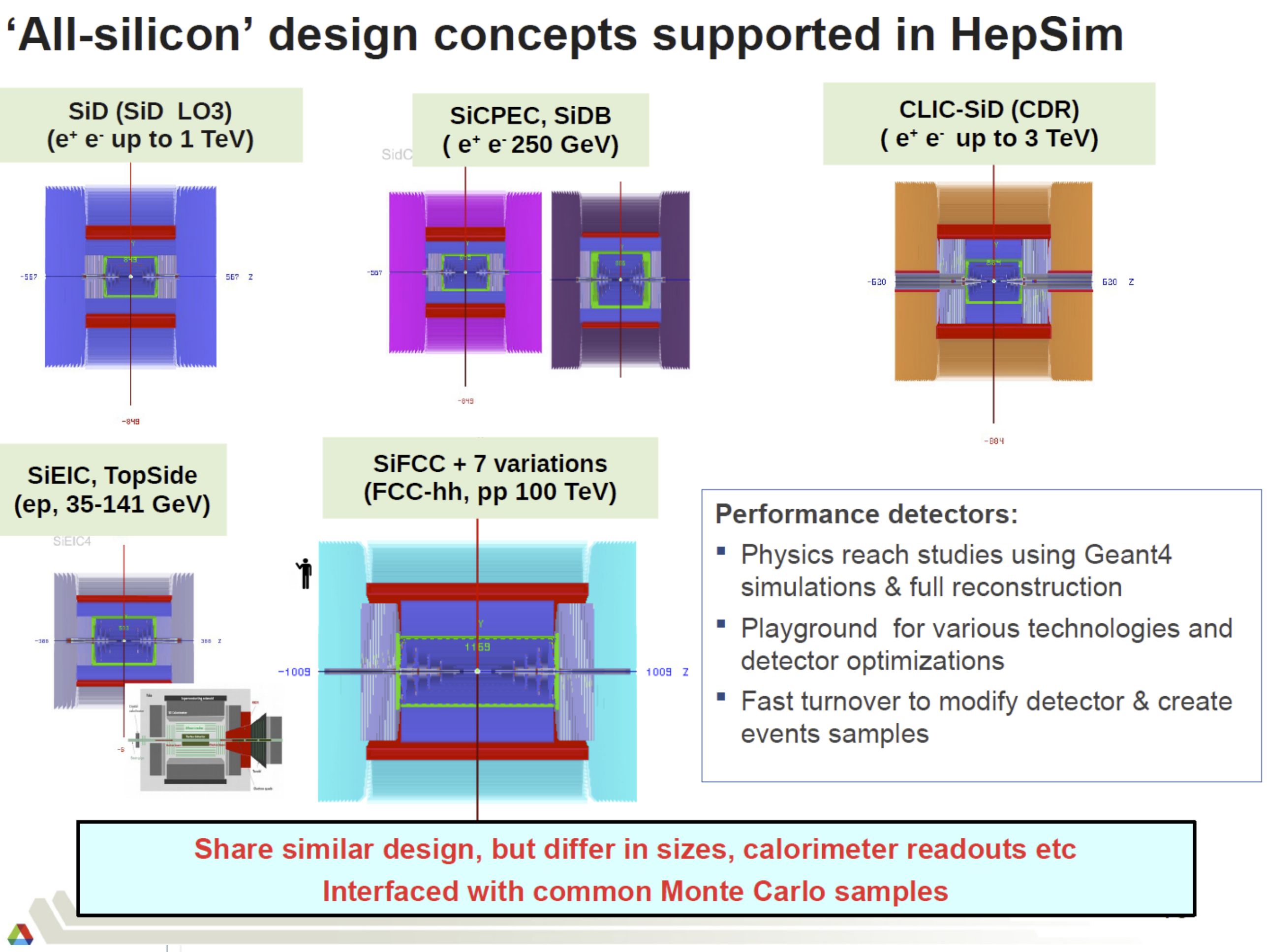
Module width: 10 cm



Next Steps

hepsim: https://atlaswww.hep.anl.gov/hepsim/#
Generic, which is politically useful. Use it to study crystal detector with full PF





Next steps

- Scan sampling fraction from 0.3% (in benchmark calorimeter) to 100% (possible with crystals) to see evolution of performance
- See what grouping into 3-4 readouts of 100% sampling gives best performance

Next steps

- Somehow get more people and money

Conclusions

- Jet energy resolution is crucial for future e+e- colliders
- However, it is not clear that the limits when using a precision EM calorimeter have been tested
- May be possible to have your cake and eat it too? Only detailed simulation can resolve this.

backup