Alternative Calorimetry

September 17,2019
University of Chicago Workshop on Circular e^+e^- Colliders

Sarah Eno
University of Maryland

Question:

As we heard yesterday, even though there are well-studied detailed GEANT implementations of two specific detector proposals, these should be regarded as strawman. New ideas are encouraged and welcome?

Are there calorimetry options not presented in the TDR that may be worth exploring? If so, what are the possibilities? What work has been done so far in this area? What work remains to be done?

Slides taken from the following sources:

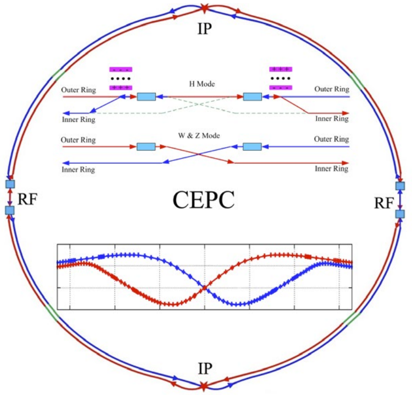
- https://indico.ihep.ac.cn/event/9195/other-view?view=standard
- https://indico.cern.ch/event/783429/overview
- https://agenda.infn.it/event/19047/
- https://indico.ihep.ac.cn/event/10439/
- http://iasprogram.ust.hk/hep/2019/
- https://arxiv.org/abs/1811.10545

Source of slide on bottom left of each slide

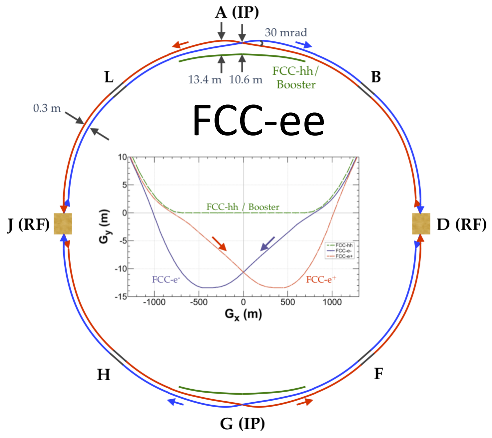
Timescales and number of detectors

ILC??

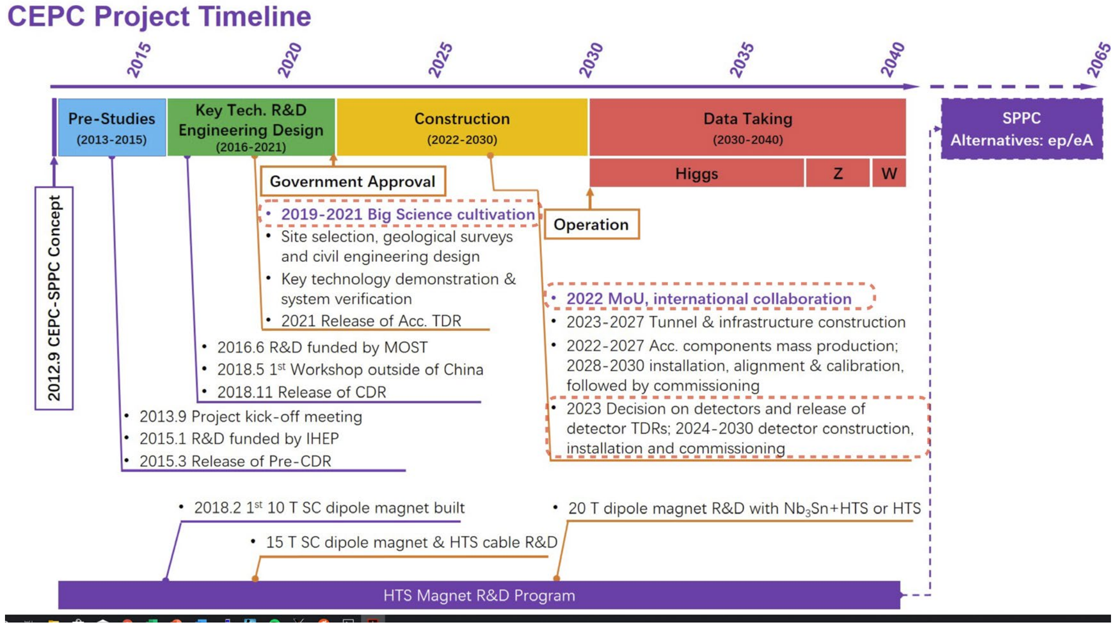
2018 LHC LS2 → 2023 LHC LS3 → 2026 HL-LHC → 2030 CEPC? → 2039 FCC-ee? → 2040 HE-LHC? → 2043 FCC-hh?



- The current design for both machines has two interaction regions. Conceivably 11 years until CEPC, 20 years until FCC-ee.
- First is tight to start considering alternative calorimetry schemes. Plenty of time for second?
- Is there a possibility of a 3rd detector?



2-3 years left for design and prototyping studies?

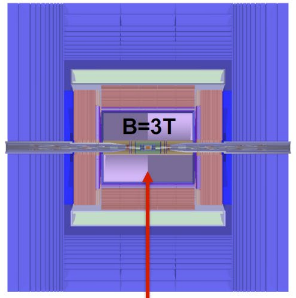


Joao Da Costa

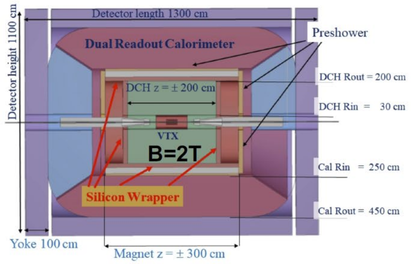
Two well developed detector concepts

CEPC Detector Concepts in CDR

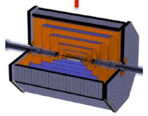
Baseline : PFA approach (derived from ILD)
Silicon + TPC
+ PFA-ECAL&HCAL + Muon



Alternative : IDEA
Silicon + Drift Chamber
+ Dual-readout calorimeter + Muon



Calorimeter outside the coil



Another tracking option with full-silicon

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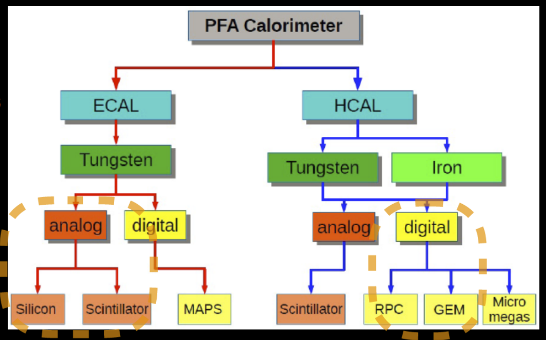
Calorimeter options

Chinese institutions have been focusing on Particle Flow calorimeters

R&D supported by MOST, NSFC and IHEP seed funding



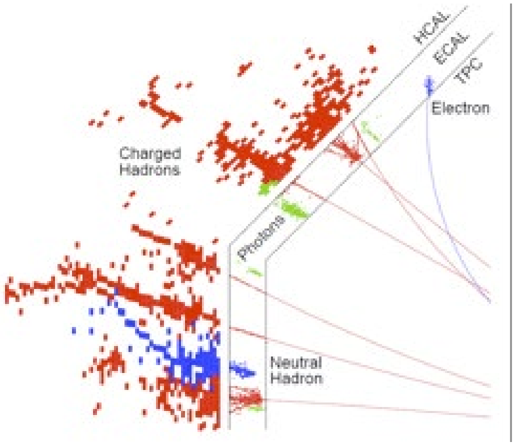
Electromagnetic	ECAL with Silicon and Tungsten (LLR, France) (*) ECAL with Scintillator+SiPM and Tungsten (IHEP + USTC)
Hadronic	(*) SDHCAL with RPC and Stainless Steel (SJTU + IPNL, France) SDHCAL with ThGEM/GEM and Stainless Steel (IHEP + UCAS + USTC) (*) HCAL with Scintillator+SiPM and Stainless Steel (IHEP + USTC + SJTU)
Non-PFA →	(*) Dual readout calorimeters (INFN, Italy + Iowa, USA) — RD52

CEPC CDR

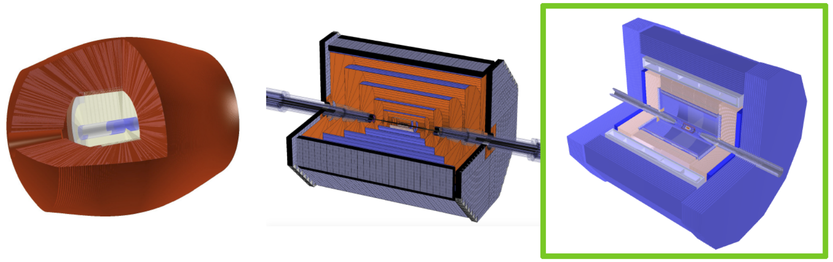
Chapter 5: Calorimetry
5.3: Particle flow oriented electromagnetic calorimeter
Jianbei Liu,[5] liujianb@ustc.edu.cn,
Tao Hu,[1] hut@ihep.ac.cn

5.4: Particle flow oriented hadronic calorimeter
Haijun Yang,[6,7] haijun.yang@sjtu.edu.cn

5.5: Dual-readout calorimeter
Franco Bedeschi,[16] bed@fnal.gov,
Roberto Ferrari,[15] roberto.ferrari@cern.ch



Status of simulation-performance study



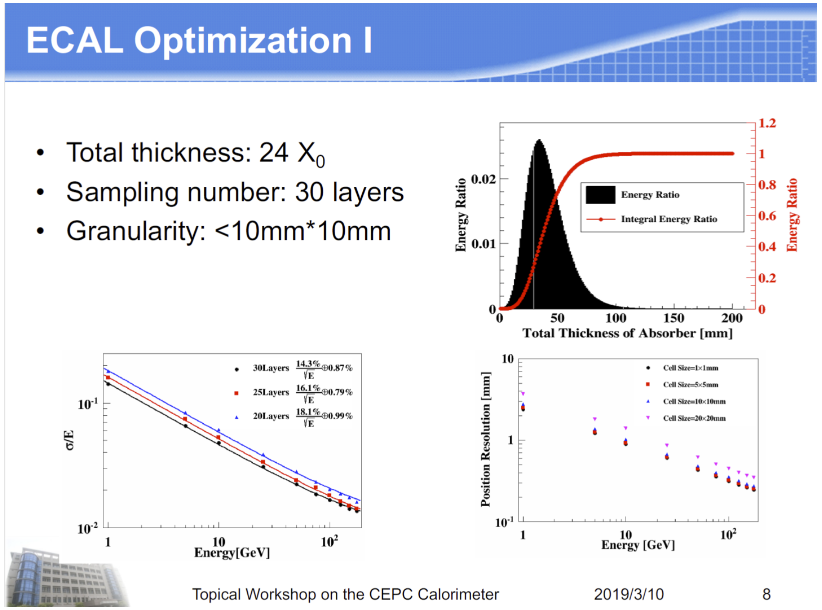
	Geant4-Simulation	Digitization	Reconstruction	Performance -Object	Performance -Benchmark
IDEA	■				
Full-Silicon	■	■	■	■	
APODIS	■	■	■	■	■

Last two are different tracking options for the CALICE-style calorimeter

11/03/19 Topical Calo WS@IHEP 9

Jianbei Liu, Manqi Ruan

A great deal of work has been done on their optimization

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iCal export More Asia/Shanghai English

EPC粒子流量能器专题讨论会暨CEPC重点研发计划量能器课题交流会

m Thursday, 8 August 2019 at **08:30** to Friday, 9 August 2019 at **18:00** (Asia/Shanghai)
近代物理系 (**210**)
省合肥市金寨路96号中国科学技术大学东校区

Description 环形正负电子对撞机（CEPC）粒子流量能器专题讨论会暨CEPC重点研发计划量能器课题交流会定于2019年8月8-9日在合肥举行。本次会议由核探测与核电子学国家重点实验室中国科学技术大学部主办。
CEPC质心系能量设计为240 GeV，用于产生大量希格斯粒子，从而精确测量希格斯粒子的属性，并在此基础上探索新物理现象。本次会议将针对CEPC探测谱仪中粒子流量能器的设计和技术研究进行深入讨论，议题包括：量能器关键物理参数的选择和优化，灵敏探测器方案和技术，读出电子学方案和技术、冷却设计等。会议还将讨论CEPC重点研发计划量能器课题研究进展和计划。

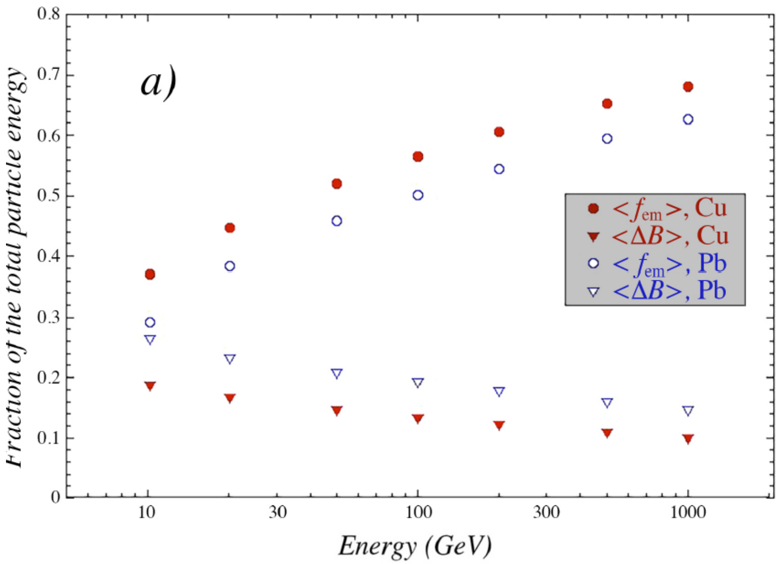
会议时间：
2019年8月8日- 8月9日（8月7日报到）

会议地点：
安徽省合肥市金寨路96号中国科学技术大学近代物理系210会议室

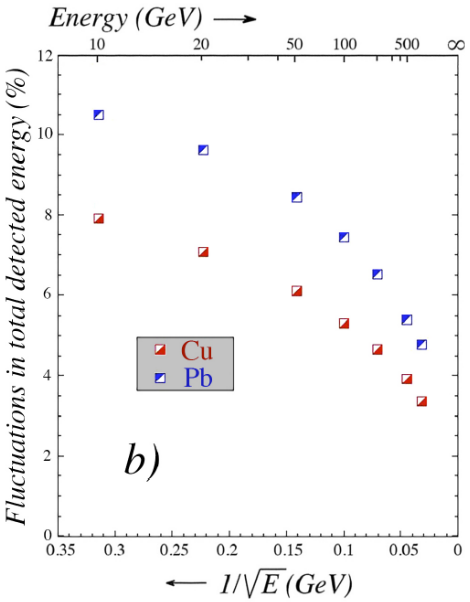
会议注册网址：点击直接进入注册页面

会议联系人：
王利敏 科研助理 邮箱：wlm215@ustc.edu.cn 手机：18119640629

<EM Shower fraction> and <Binding Energy Loss>



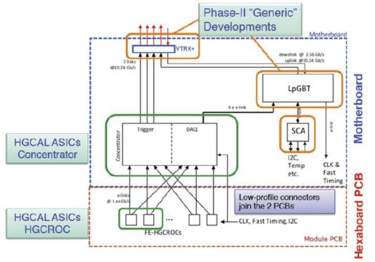
Limit on the hadronic energy resolution in the absence of DR or compensation



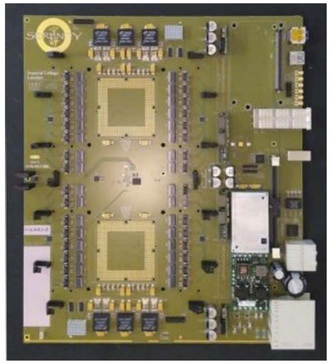
Yunlong Zhang
Sehwook Lee

Similar CMS calorimeter. Prototypes in the works

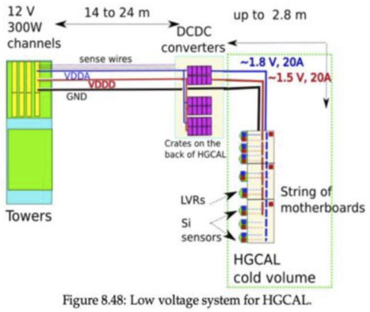
Building up on the HGC - R&D



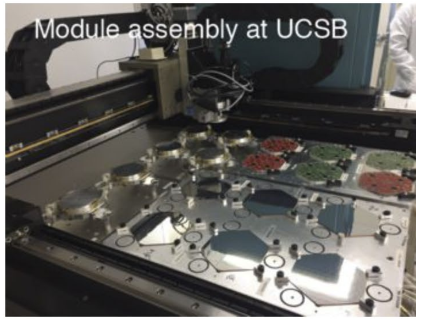
Front end electronics

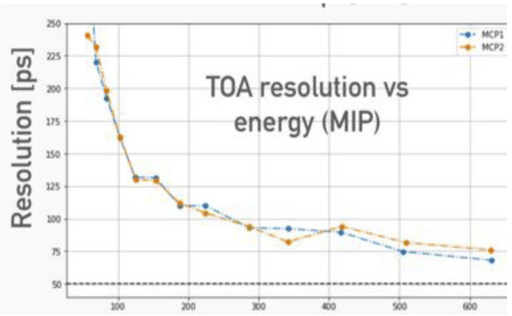


Back end electronics

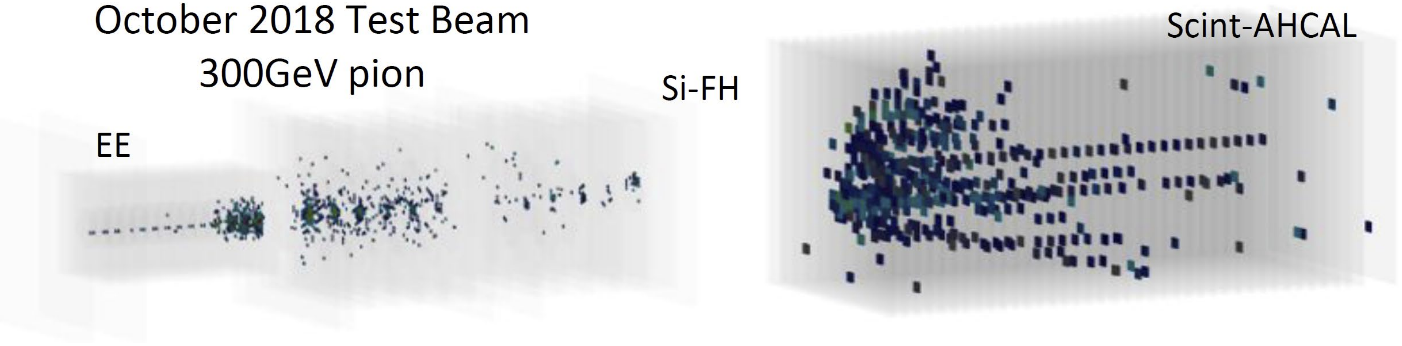


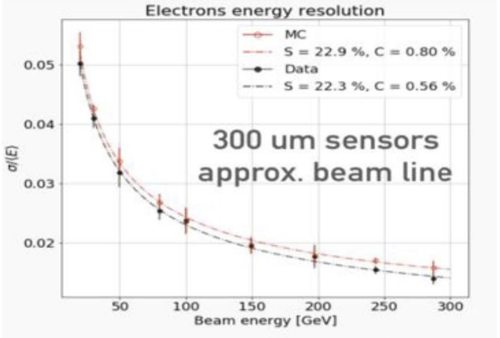
powering





October 2018 Test Beam
300GeV pion





8/29/19 M.D'Alfonso (MIT) 13

silicon-tungsten EM calorimeter and scintillator-brass hadron calorimeter. Is the tracking better in the Scint-AHCAL?

Yazhou Niu, Mariarosaria D'Alfonso

Performance

CALICE-style

- EM resolution: 15%/ √ E+0.7%, about 2% at 60 GeV
- Jet resolution: 25.7%/ √ E + 2.4% (3.5% at 100 GeV)

DREAM-style

- EM resolution: 10%/ √ E+0.3%, about 2% at 60 GeV
- Jet resolution: 34%/ √ E +0.6% (3.6% at 100 GeV)

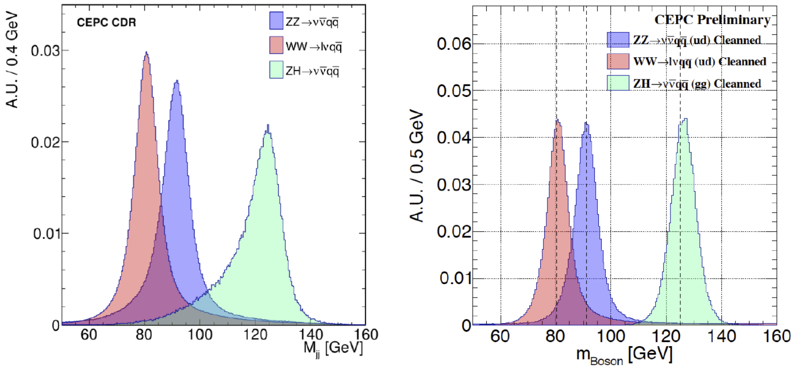
Canonical specs

CEPC Detector Performance Requirements

Primarily for the Higgs physics program at CEPC

Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E = 3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

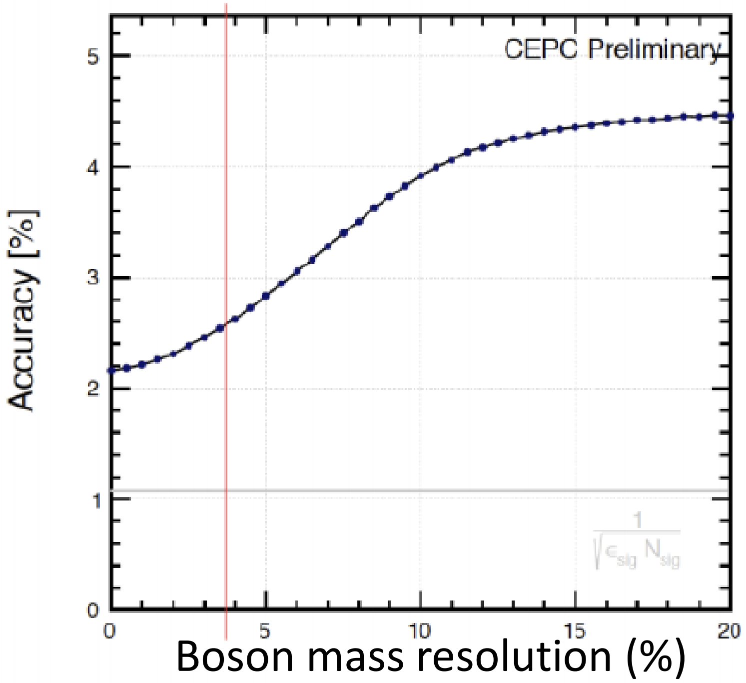
Massive Boson Separation



Peizhu Lai & CEPC CDR   *WW sample: using μνqq sample, Plot: the visible mass without the muon*   CEPC-RECO-2017-002 (DocDB id-164), CEPC-RECO-2018-002 (DocDB id-171),

11/03/19   Topical Calo WS@IHEP   *Eur. Phys. J. C (2018) 78: 426*   21

What are the physics drivers that require hadronic W/Z separation? According to Manqi Ruan, the analysis most sensitive to the hadronic resolution is the W width, using W boson fusion with Higgs to bb. The dominant background channel is Zh→ννbb. reconstruct the boson recoil mass reduce background.



For very precise measurements, stability and ability to monitor that stability may be crucial. Is there a good way to state this as a performance requirement?

Jianbei Liu
Manqi Ruan

What other possibilities exist?

Improve EM resolution for a machine where photon/electron resolutions can be a key to physics?

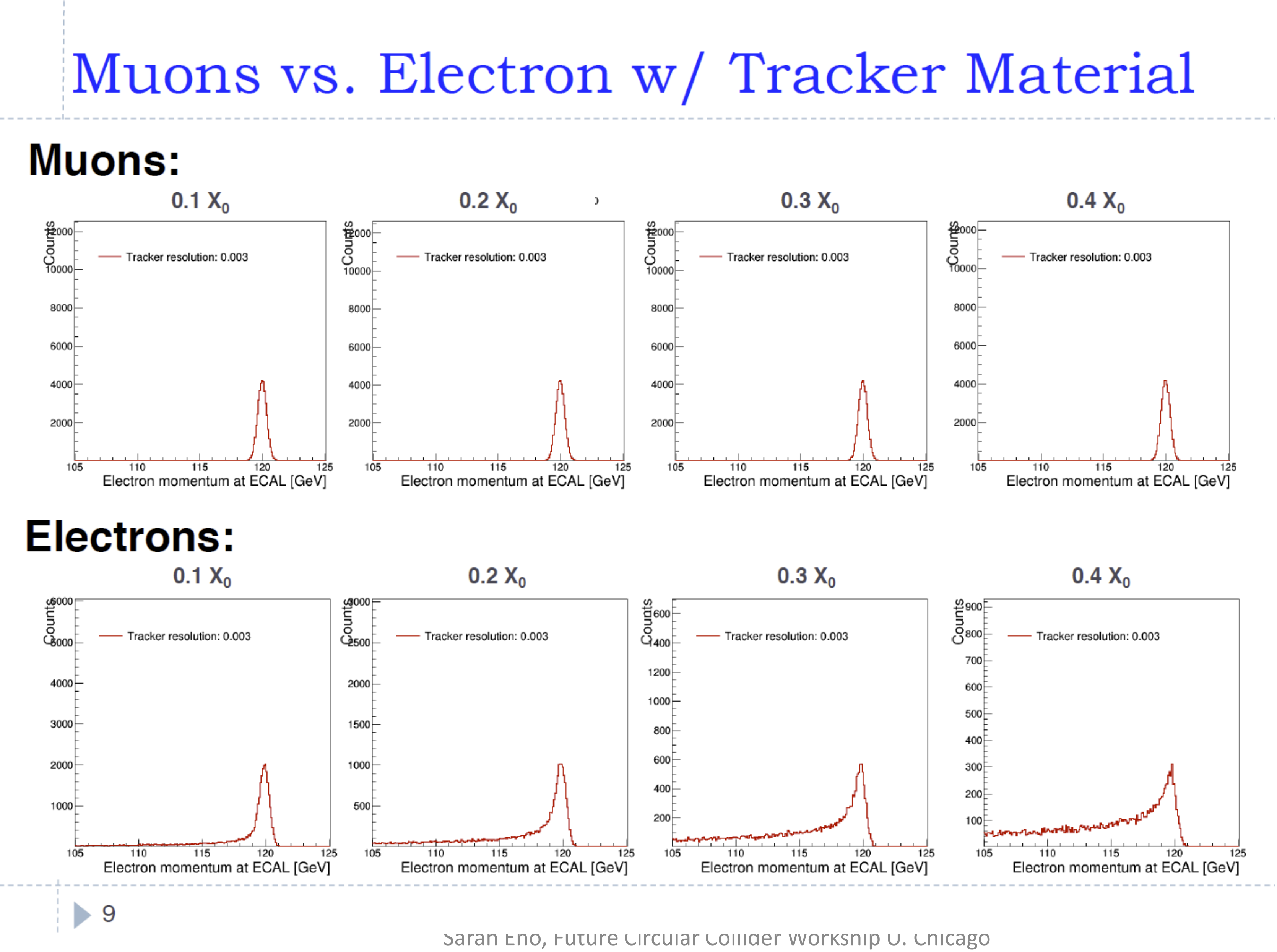
- Crystal calorimetry?

A better resolution EM sampling calorimeter for PF?

- ala KLOE?

What else?

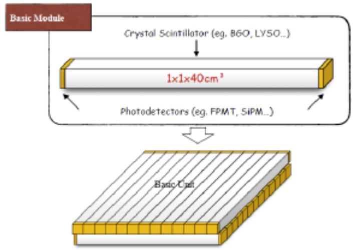
Motivation for precision EM calorimetry

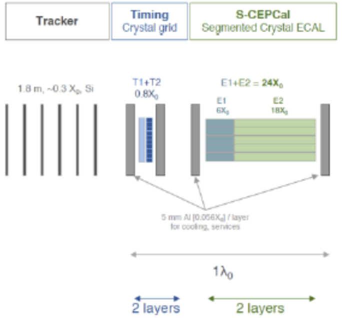


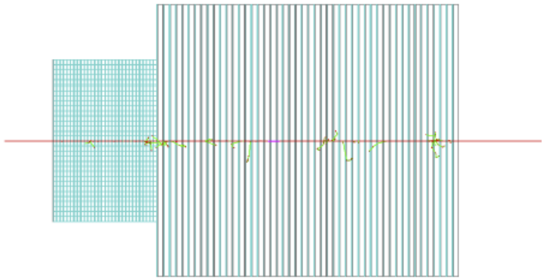
A crystal ECAL?

Overview: designs of crystal ECAL

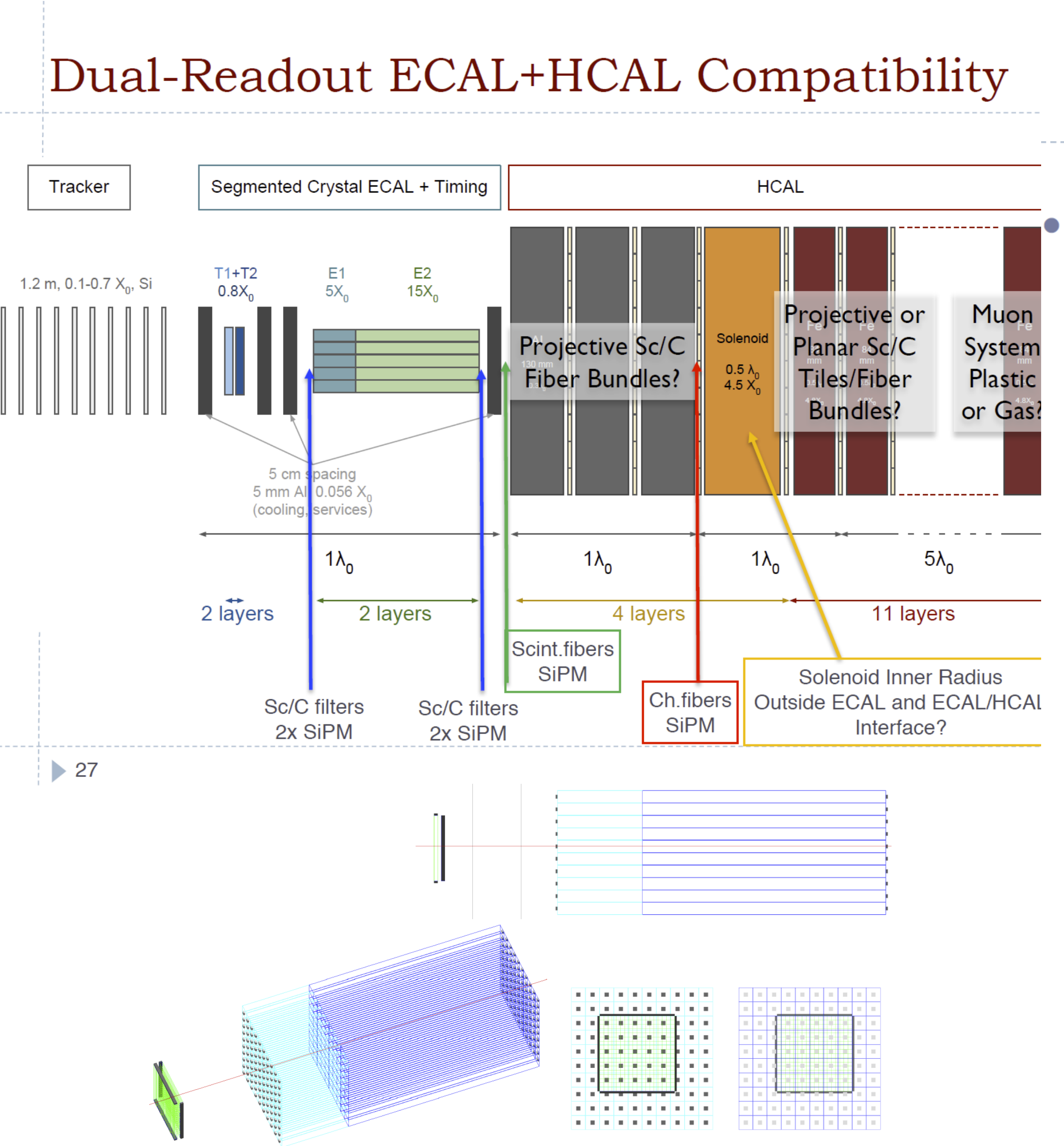
- 3 major designs being pursued
  - Long crystal bars with optical readout at both ends (Y. Wang, et al.)
    - Use timing information for hit positions; less #channels
  - Long crystal bars with optical readout at single ends (C. Tully, et al.)
    - Less segmentation in the longitudinal direction; space for cooling
  - 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







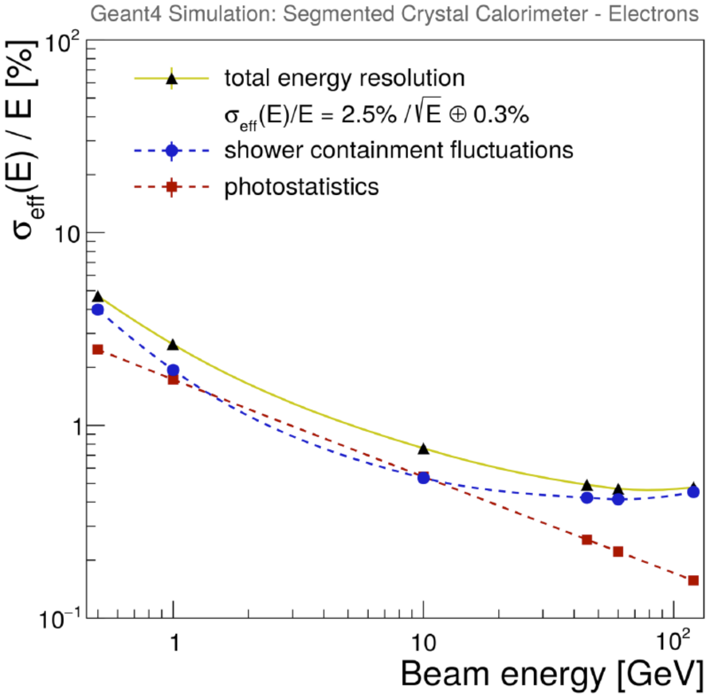
Example EM resolution



S-CEPCal Energy Resolution

Contributions :

- Shower containment fluctuations
  - Longitudinal leakage
  - Tracker material budget
  - Services for front layer readout
- Photostatistics
  - Tunable parameter depending on:
    - SiPM choice
    - Scintillator choice
    - Connected to dynamic range
- Noise
  - Negligible (low dark counts, high gain)

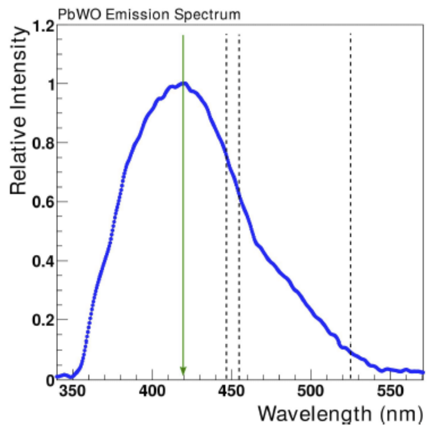


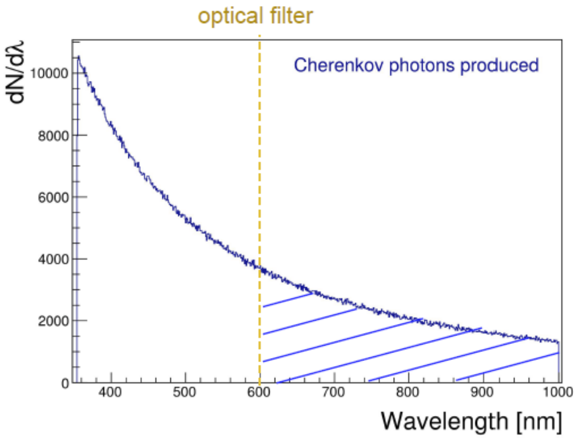
Chris Tully

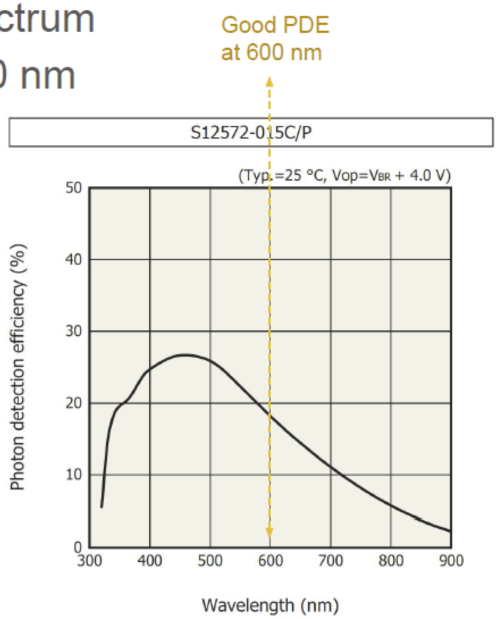
Dual-Readout Capability

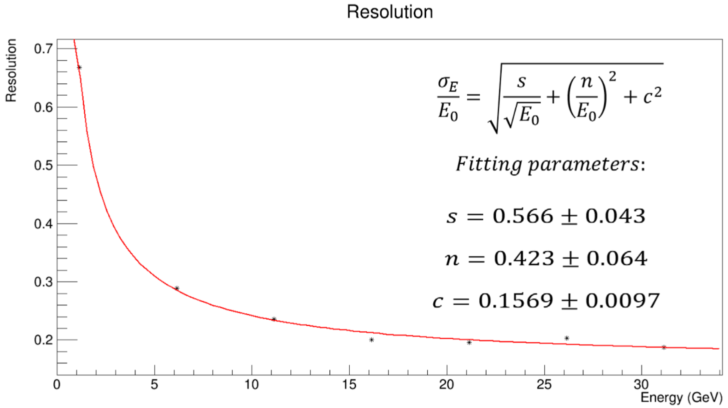
Resolution for pions studied without using this. Need to study improvement taking this into account.

- 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









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Chris Tully, SE

CALICE-style

- EM resolution: 15%/√E+0.7%, about 2% at 60 GeV
- Jet resolution: 25.7%/√E + 2.4% (3.5% at 100 GeV)

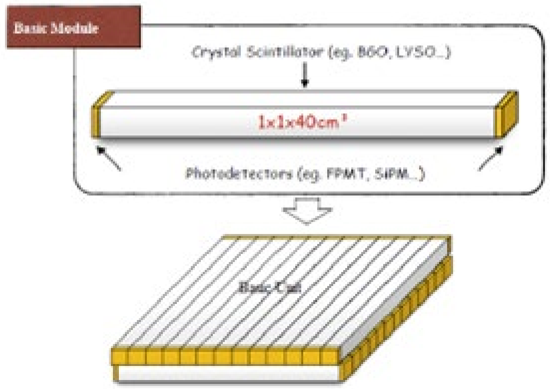
Dual Readout-style

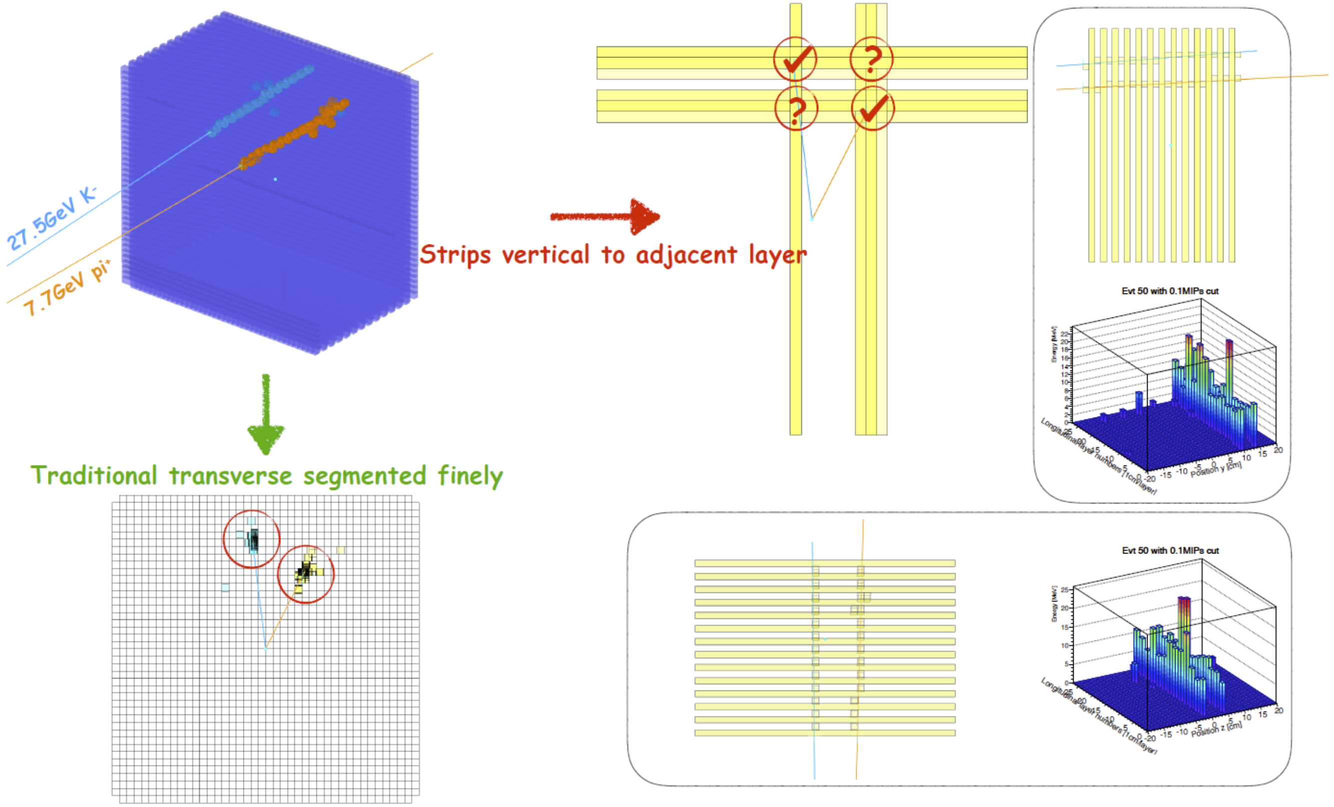
- EM resolution: 10%/ √ E+0.3%, about 2% at 60 GeV
- Jet resolution: 34%/ √ E +0.6% (6% at 100 GeV)

Long bar crystals

- EM resolution: 3%/√E+0.3% with achievable increase in light collection efficiency and deeper crystals.
- Jet resolution? Need detector in official software and perhaps PF algorithm tuned to evaluate

Key issue: separation of multi-particle shower





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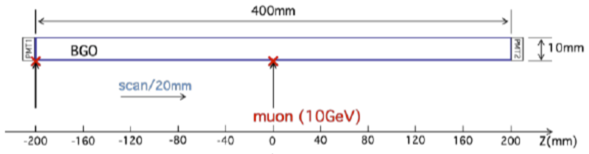
Yuexin Wang

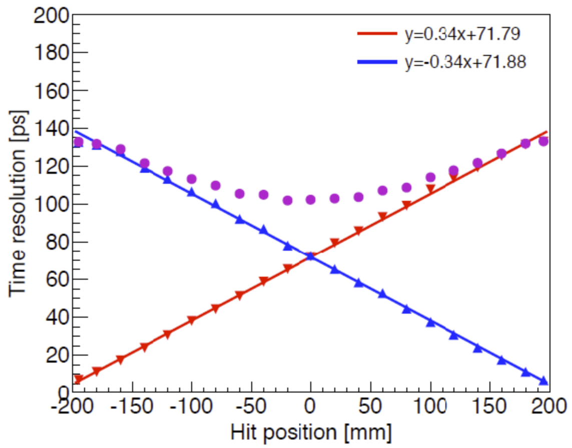
ECAL with crystal bars

Yuexin Wang (IHEP)

- Geant4 full simulation with a single long bar
  - Implemented realistic optical properties: detailed simulation of optical photons
  - Time stamps and #photons at both 2 PMTs for muons
  - Extract timing resolutions at different hitting positions



Parameter	Value
发光光谱峰位能量 Photon Energy	2.59eV (480nm)
发光光谱半峰宽 Photon Energy Width	0.6987eV (420-550nm)
快成分时间常数 FastTime Constant	60ns
慢成分时间常数 SlowTime Constant	300ns
光衰减长度 Absorption Length	7-15m
光产额 Scintillation Yeild	9000-10000/MeV
折射率 Refractive Index	2.15



Another possible geometry

New ideas: in a nutshell

- Si-W ECAL: as a starting point
- Idea 1: replace the W-plates with scintillating crystals (homogeneous ECAL)
  - Maximize the sampling fraction, while still keeping high-granularity with silicon pads
  - Optimal intrinsic energy resolution: MC simulation in Geant4
  - Estimate of major constraints
- Idea 2: introduce Si-Sc-W super-layers (hybrid-1)
  - Still higher sampling fraction than Si-W
  - Possibility of compactness: tune the ratio of Sc-W thickness
  - Uniform sampling fraction of each super-layer
- Idea 3: inhomogeneous sampling fraction (hybrid-2)
  - Put crystals in first layers to cover most shower maxima
  - Use Si-W layers in rear layers to constrain the "shower tails"

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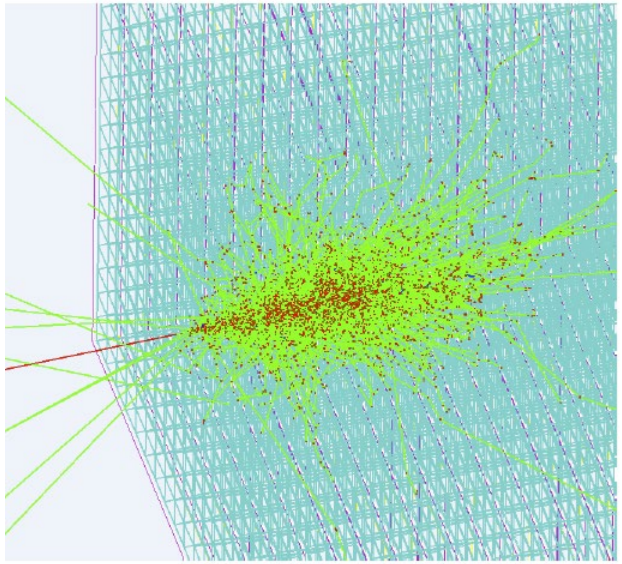
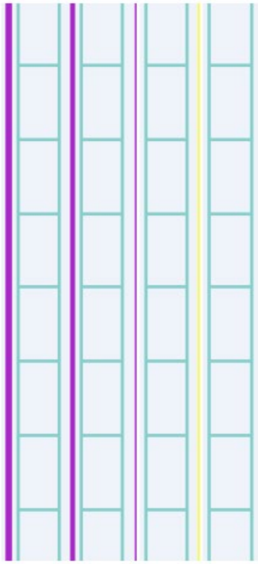
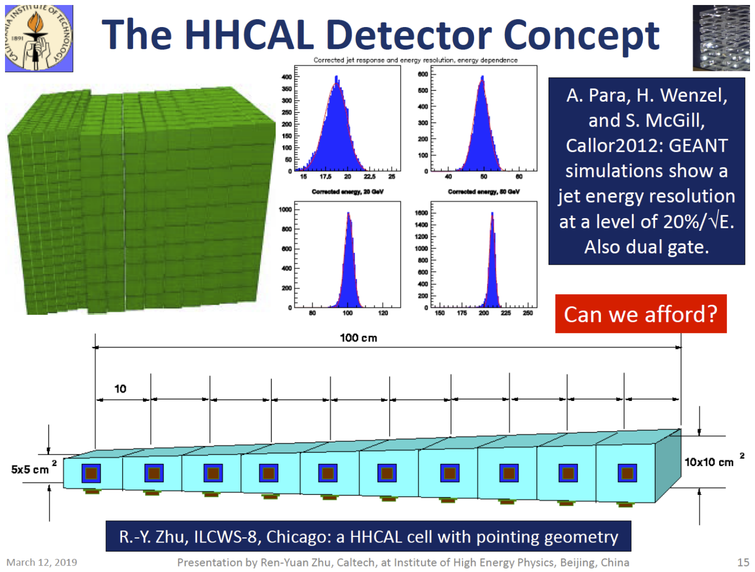
Showers of a 10GeV electron



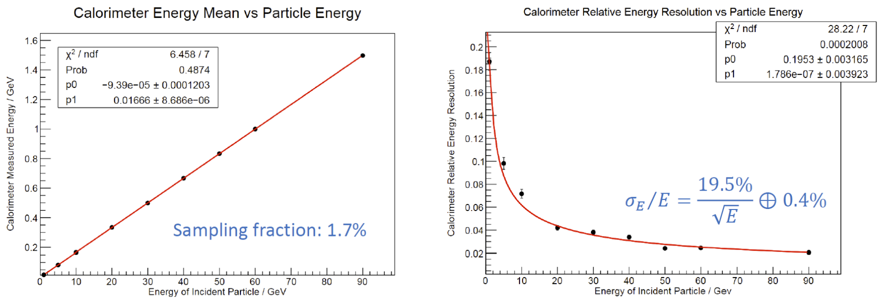


Si-Sc-W layers (side view)



Yong Liu, Ren-Yuan Zhu

Si-W: baseline option



- W-plate: tungsten alloy, X0=3.9 mm
- PCB: 2.1mm/layer, also implemented in the new designs
  - Based on CALICE SiW-ECAL 14-layer PCB

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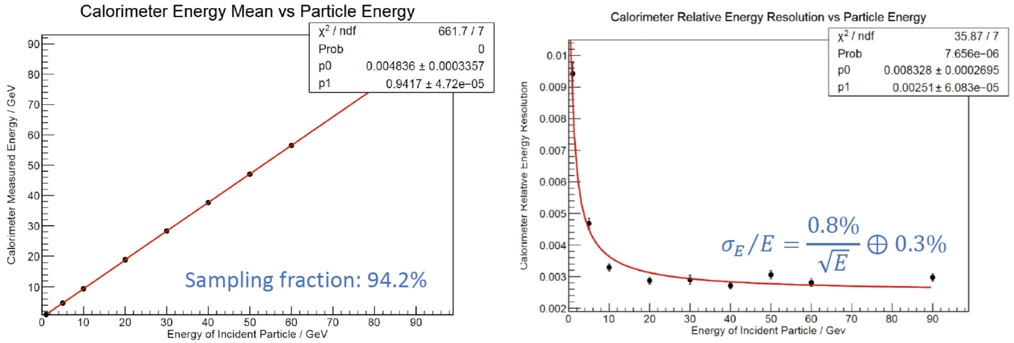
	EM resolution
Si-W	19%/√E+0.4%
Si-Sc	0.8%/√E+0.3%
Si-SC-W	6.9%/√E+0.4%

Si-Sc ECAL: homogenous



- 24 layers: silicon(0.5mm) + BGO(1X0 thick)
- Simple simulation: only use energy hits
  - Not including photons in crystal, photosensor statistics, digitizer, etc.

Less longitudinal granularity (possible with thicker crystals), determined by PFA

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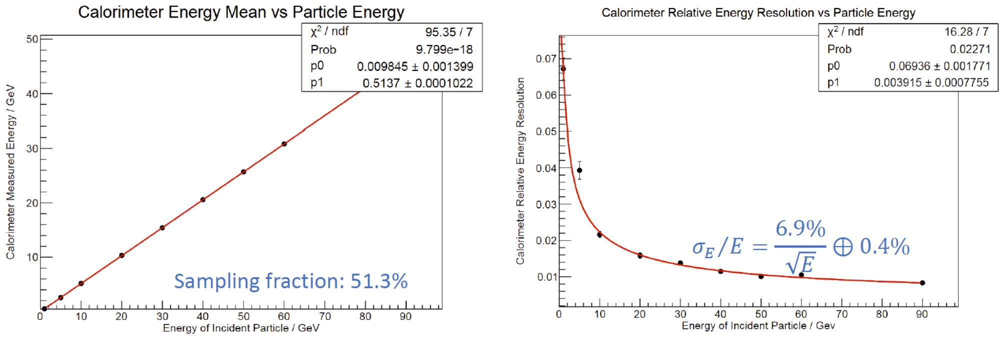

- 1 Si-Sc-W layer: ~2X0 in total, with BGO(1X0) + W-plate(1X0)

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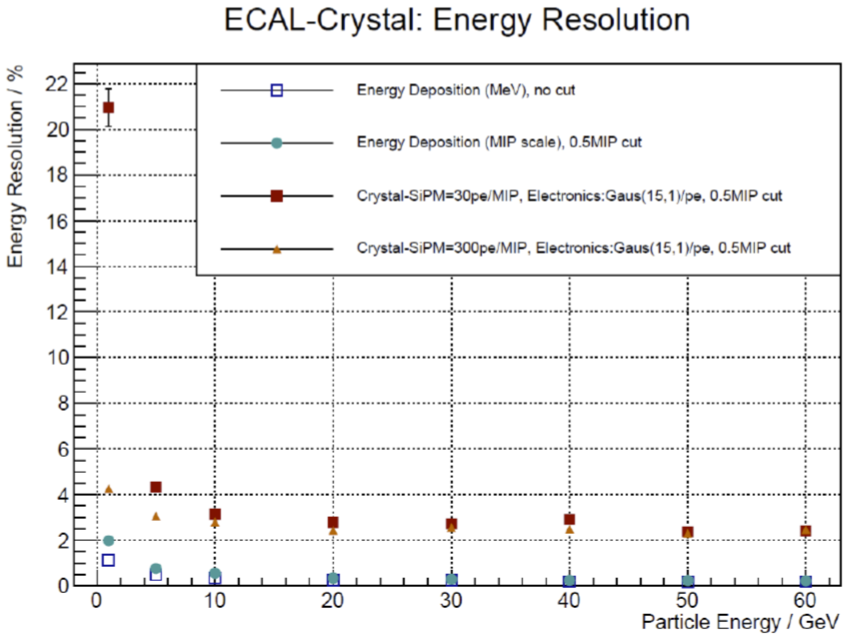
Digitization: impacts to energy resolution

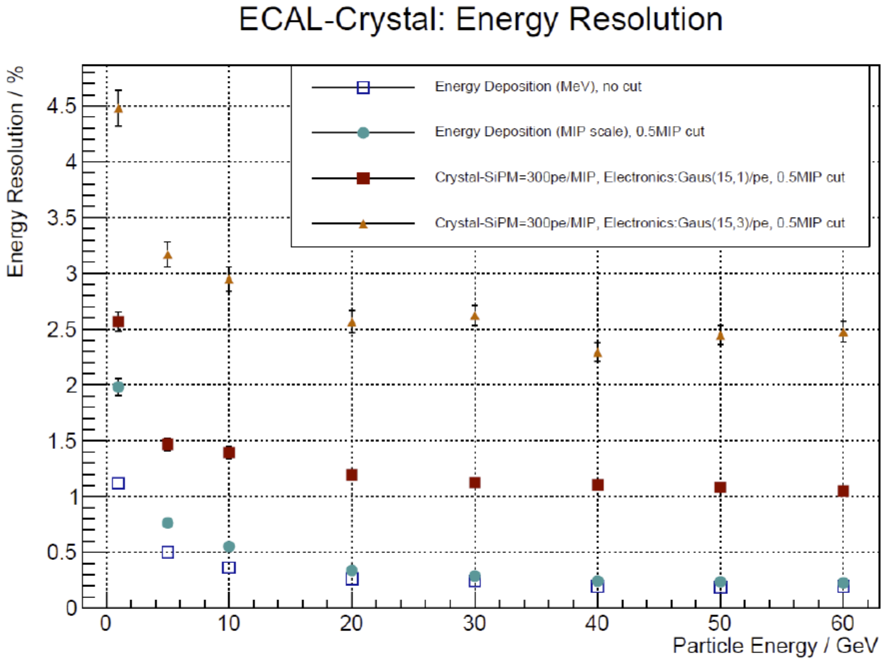
Geant4 version 10.5.0

MC samples: electrons

Control of light collection important at low energy



Impact from photon statistics:
30 p.e./MIP vs 300 p.e./MIP



Impact from electronics resolution for single photons:
Sigma of SiPM gain ~7%/p.e. vs 20%/p.e.

Control of electronice noise important at high energy

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CALICE-style

- EM resolution: $15\%/\sqrt{E}+0.7\%$, about 2% at 60 GeV
- Jet resolution: $25.7\%/\sqrt{E} + 2.4\%$ (3.5% at 100 GeV)

Dual Readout-style

- EM resolution: $10\%/\sqrt{E}+0.3\%$, about 2% at 60 GeV
- Jet resolution: $34\%/\sqrt{E} +0.6\%$ (6% at 100 GeV)

Long bar crystals

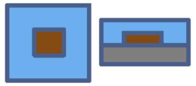
- EM resolution: $3\%/\sqrt{E}+0.3\%$ with achievable increase in light collection efficiency and deeper crystals.
- Jet resolution?

Tile options

- EM resolution sampling term runs from 0.8 to 6.9%
- Jet resolution?

Better sampling ECAL?

Option 1: Sampling ECAL

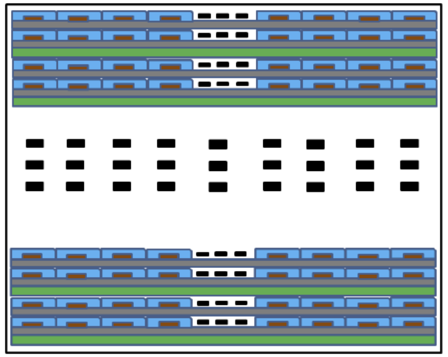


Sensitive Unite (SU)

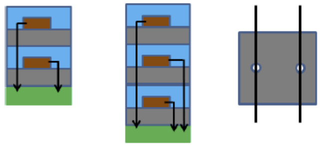
1.5mm/W+2mm/PS+SiPM , 60 layers

PS: 10mmx10mmx2mm

SiPM: 3mmx3m, 5μm pitch, PDE＞10%



Tot: 90mm/W + 120mm/PS + 90mm/Electronics



Two or three even six SU connected together to readout as one channel -**Read Unite (RU)**

dE/dX of MIPs in SU： 3.7MeV ~ 100pe
(~25pe/MeV)
The linear range of SiPM: 1.2 x10^5 pe
Dynamic range of SU is 1-1200 MIPs

2 SU -> 1 RU： 30 layer, 200pe/MIPs;
3 SU -> 1 RU： 20 layer, 300pe/MIPs;
6 SU -> 1 RU： 15 layer, 400pe/MIPs;

Sampling fraction and light output are much higher than the Sci-ECAL in CDR, necessary to get a good energy resolution.

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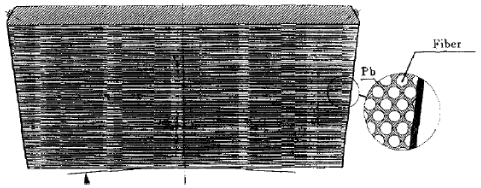
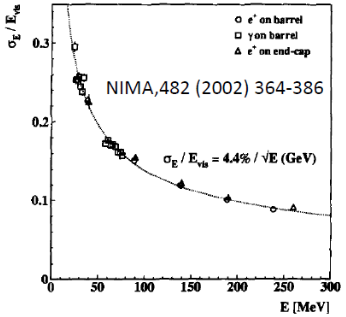
Performance and cost estimation

Reference : KLOE ECAL



A very fine sampling lead-scintillator fiber calorimeter, with PMT readout. 200 layers of 1mm fiber glued between 0.5mm thick lead foils.

The fraction of lead:fiber:glue is 42:48:10
L/fiber=4.3M, (~8pe/MeV)



Expected energy resolution
σE/E ≤ 6%/√E(GeV) ?
Need detailed MC study

Cost
SiPM, 3mm×3mm，15￥/piece. Electronics: 100 ￥/channel ?
30 RL ~20 M ch ~ 2 billion ￥,
20 RL ~13 M ch ~ 1.3 bilion￥,
10 RL ~6.7Mch ~ 0.67 bilion￥

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CALICE-style

- EM resolution: 15%/√E+0.7%, about 2% at 60 GeV
- Jet resolution: 25.7%/√E + 2.4% (3.5% at 100 GeV)

DREAM-style

- EM resolution: 10%/ √ E+0.3%, about 2% at 60 GeV
- Jet resolution: 34%/ √ E +0.6% (6% at 100 GeV)

Crystals

- EM resolution: 5.4%/√E + 0.3%, about 0.8% at 60 GeV

Tile options

- EM resolution sampling term runs from 0.8 to 6.9%
- Jet resolution?

Sampling ECAL

- EM resolution 6%/√E
- Jet resolution

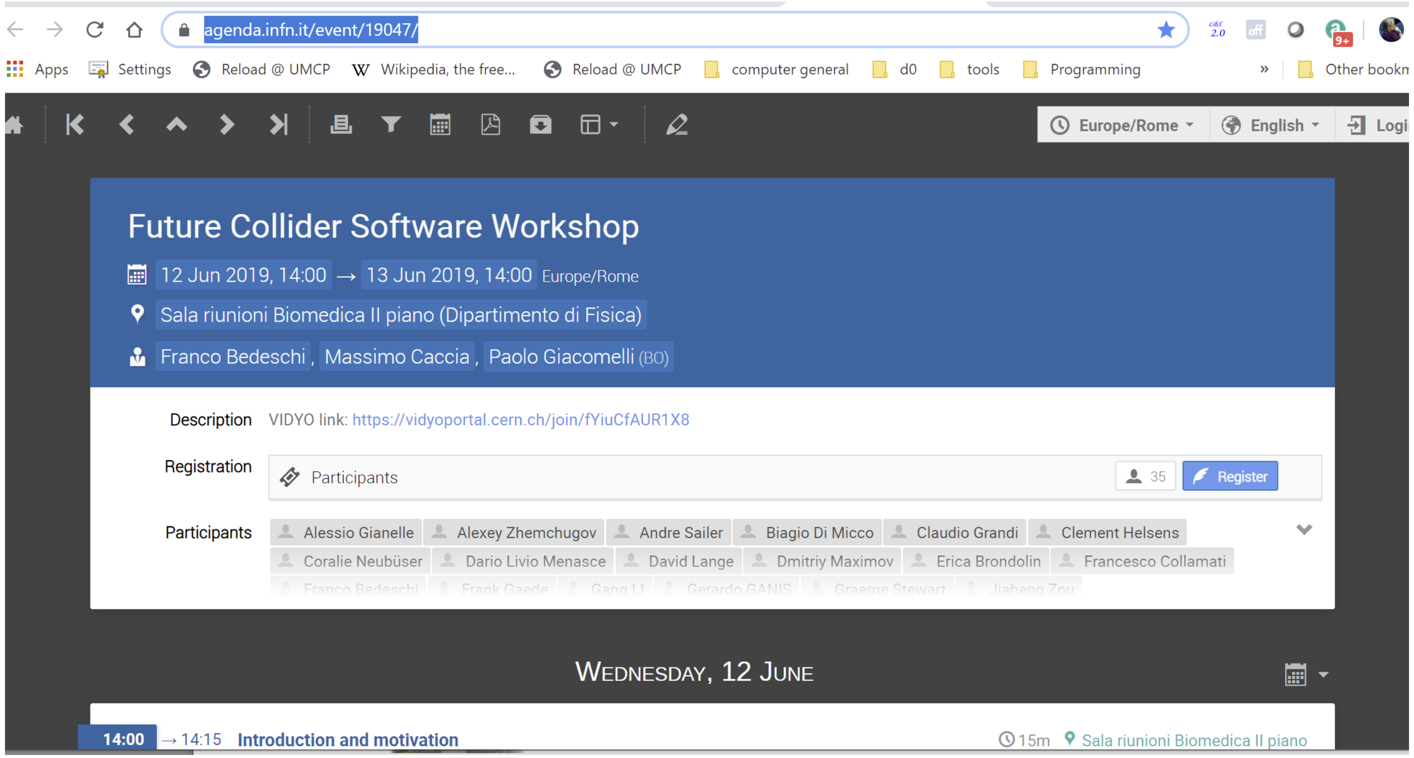
Person power

The default PFA calorimeter has a large cohesive team that works together to produce results quickly. Do any of the other efforts have this? How to collalesce to one precision EM calorimetry option? How to increase manpower working on hadron calorimetry with these options?

Understanding if the old idea that precision EM resolution is not a high priority at an e^+e^- collider would also need a team working on the physics case.

Questions:

How to make it easier to compare different options:



Will here more about this later during this workshop

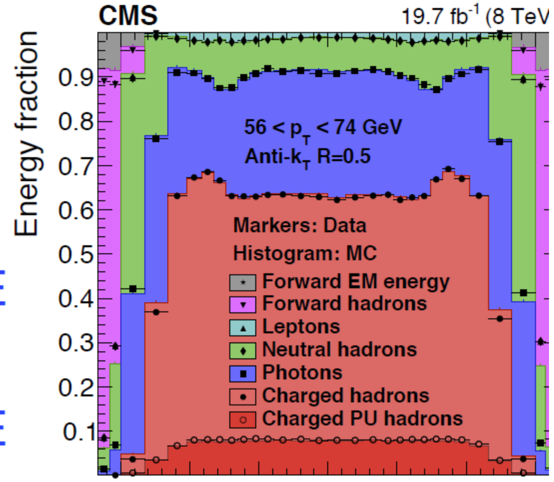
Conclusions

There are interesting options beyond those in current cTDRs. But a cohesive team is needed to bring any of them to reality.

Backup

Balancing Jets and EM particle resolutions

- **For HZ production, all Z recoils matter**
  - ~70% of Z decay are hadronic
- **Particle Flow Principle**
  - Optimal use of measurement information applied to each reconstructed particle
    - Charged hadrons (~65%)
      - Replaced by track (~0.1%)
    - Neutral hadron (~10%)
      - HCAL (~45%/√E) ~4.5%/√E
    - Photons/EM (~25%)
      - ECAL (~15%/√E) ~3.8%/√E



Z Jets ~ 3.5 - 5.5% (Limited by HCAL & EM)

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Chris Tully

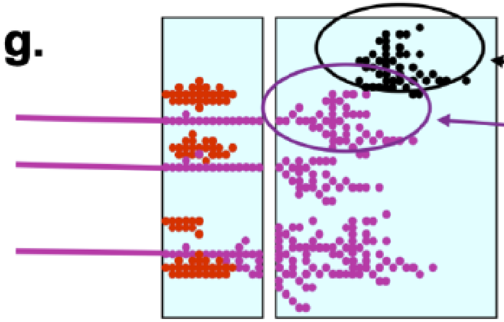
Why separation is a "must have":

26

Reconstruction of a Particle Flow Calorimeter:

- ★ **Avoid double counting of energy from same particle**
- ★ **Separate energy deposits from different particles**

e.g.

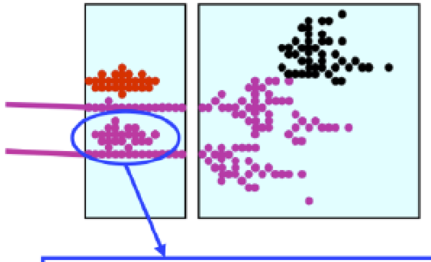


If these hits are clustered together with **these**, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

Level of mistakes, "confusion", determines jet energy resolution
not the intrinsic calorimetric performance of ECAL/HCAL

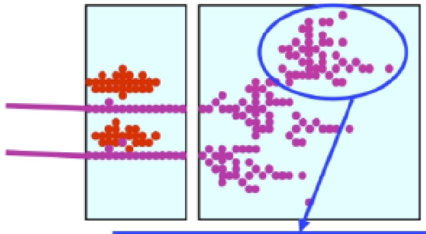
Three types of confusion:

i) Photons



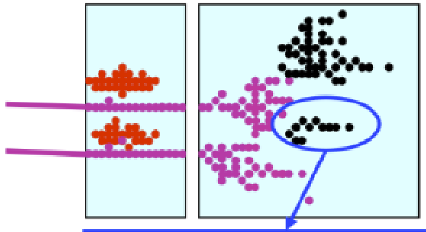
Failure to resolve photon

ii) Neutral Hadrons



Failure to resolve neutral hadron

iii) Fragments



Reconstruct fragment as separate neutral hadron

credits: Mark Thomson

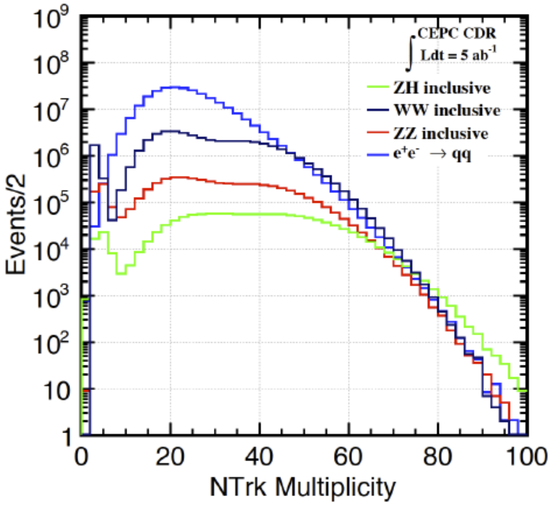
$$\frac{\sigma_E}{E} = \frac{21}{\sqrt{E}} \oplus 0.7 \oplus 0.004E \oplus 2.1\left(\frac{E}{100}\right)^{+0.3} \%$$

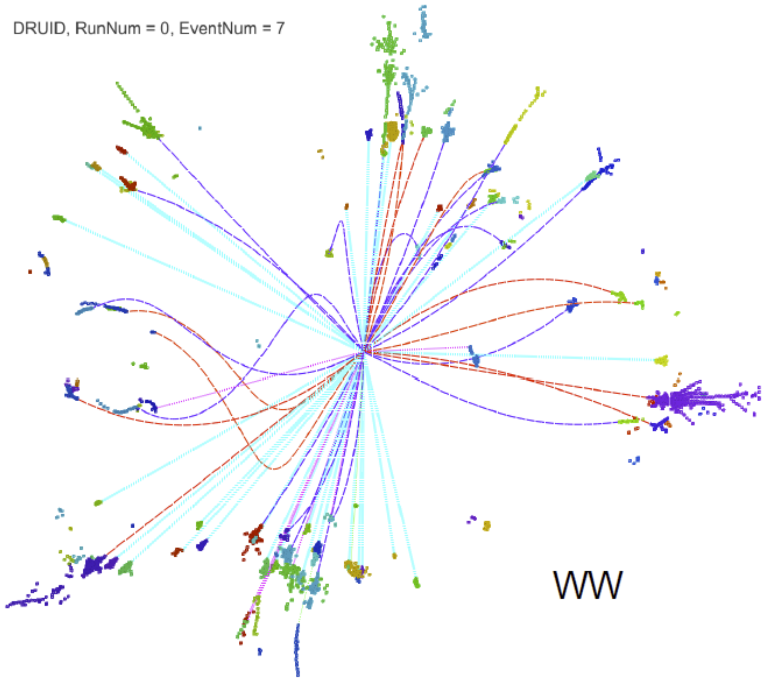
Resolution | Tracking | Leakage | Confusion

Total Resolution	3.1 %
Confusion	2.3 %
i) Photons	1.3 %
ii) Neutral hadrons	1.8 %
iii) Charged hadrons	0.2 %

Manqi Ruan

Separation of full hadronic WW-ZZ event





- 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

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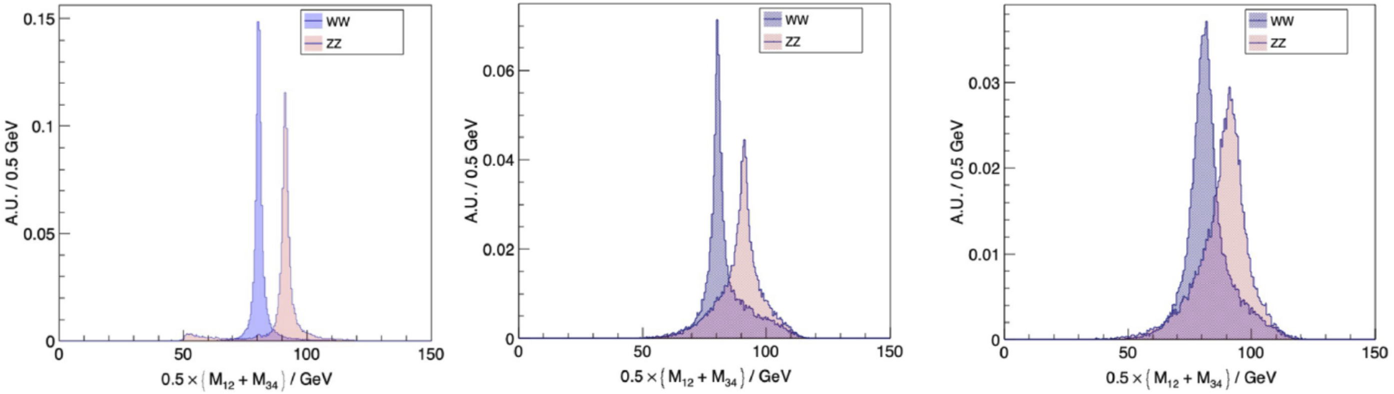
Manqi Ruan

Jet confusion: the leading term



- Separation be characterized by

$$overlapping\ ratio = \sum_{bins} min(a_i, b_i)$$

- Final state/MC particles are clustered into Reco/Genjet with ee-kt, and paired according to chi2

$$\chi^2 = \frac{(M_{12} - M_B)^2 + (M_{34} - M_B)^2}{\sigma_B^2}$$

- WW-ZZ Separation at the inclusive sample:
  - Intrinsic boson mass/width - lower limit: Overlapping ratio of 13%
  - + Jet confusion – Genjet: Overlapping ratio of **53%**
  - + Detector response – Recojet: Overlapping ratio of 58%

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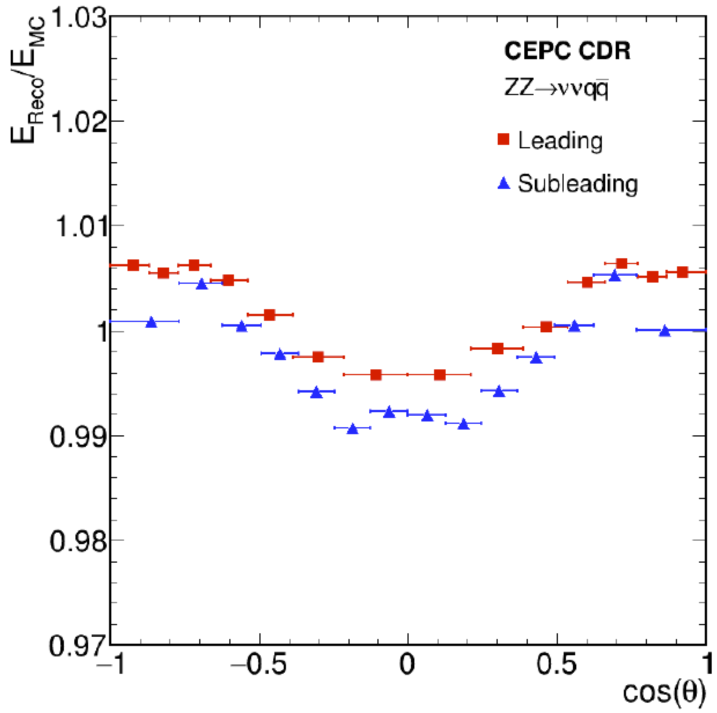
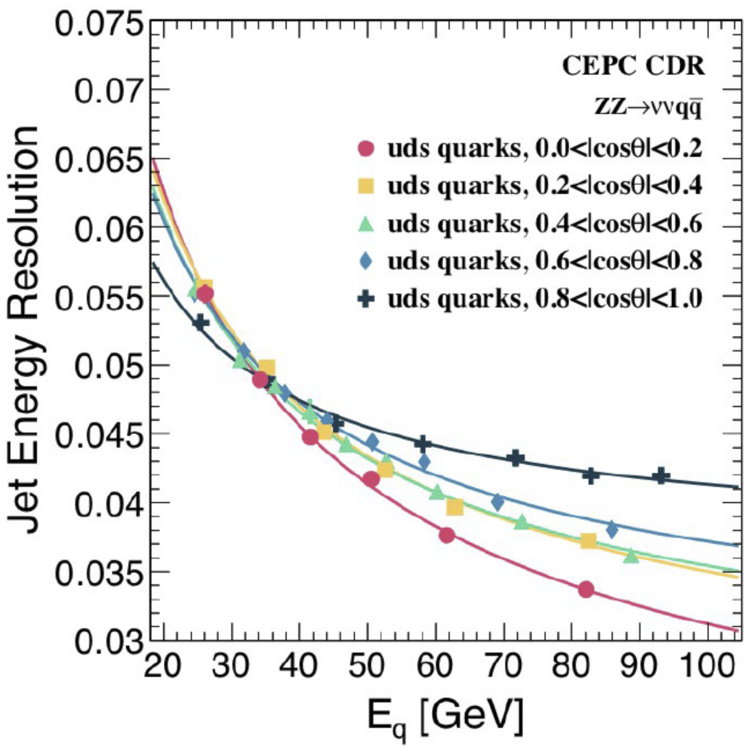
Jet Energy Scale & Resolution





- JES ~ with 1% of the unity (without correction)
- JER ~ 3.5% - 5.5% for E ~ 20 – 100 GeV Jets
- **Both Superior to LHC experiments by 3-4 times**

Peizhu LAI

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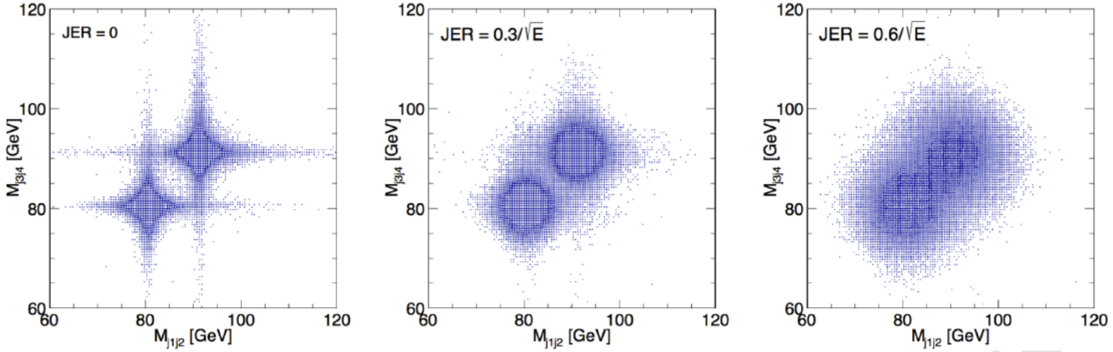
Manqi Ruan

Jet measurement at CEPC

- Separation of W/Z bosons in their hadronic decays translates into a jet energy resolution requirement of ~ 30% /√E (or 3-4% in the energy range of interest).
- The chief factor driving the design of the CEPC calorimetry system.



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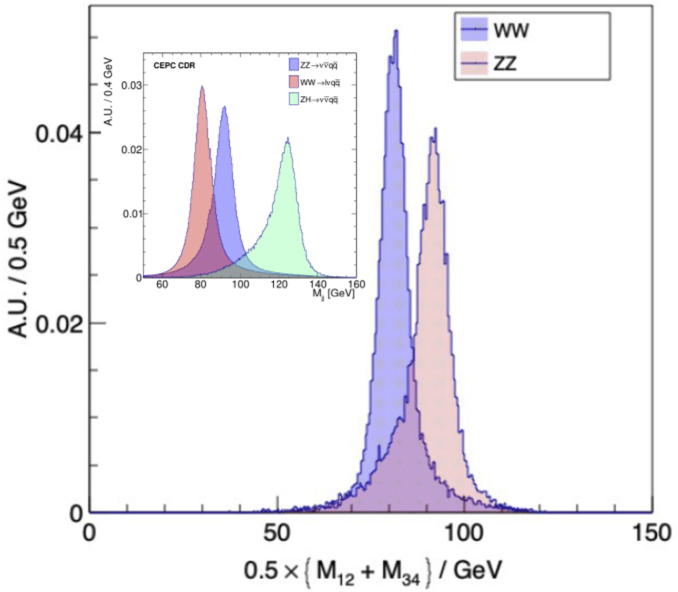
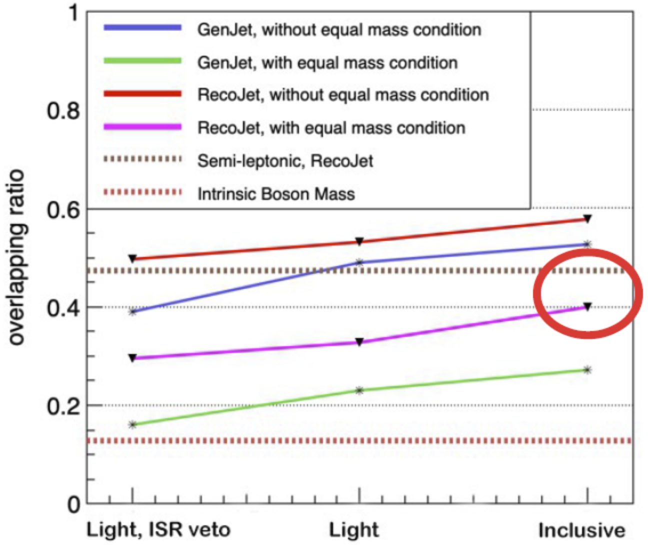
Separation of full hadronic WW-ZZ event





The CEPC Baseline could separate efficiently the WW-ZZ with full hadronic final state.

Critical to develop color singlet reconstruction: improve from the naive Jet clustering & pairing.

Quantified by differential overlapping ratio.

Control of ISR photon/neutrinos from heavy flavor jet is important.

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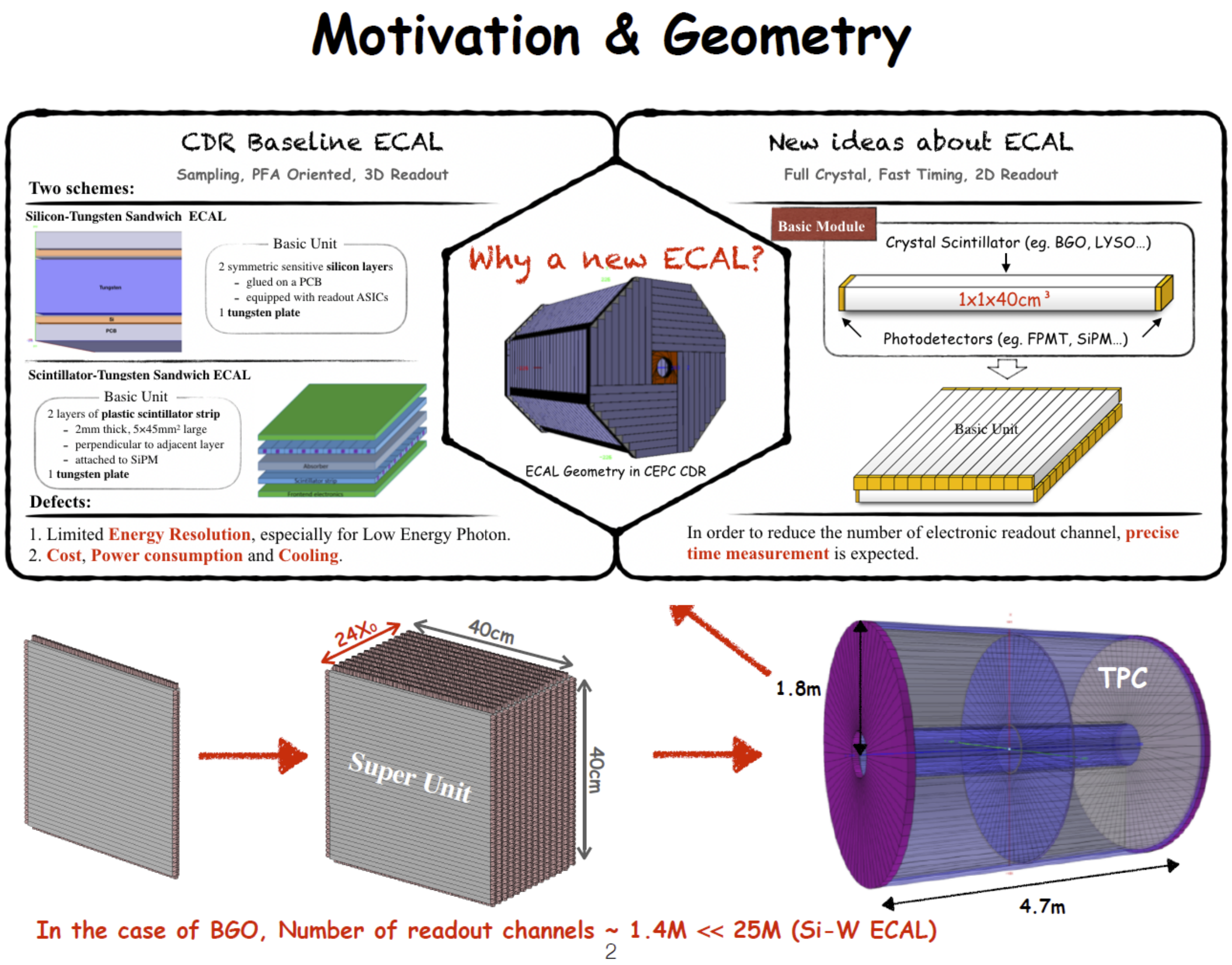
Yuexin Wang

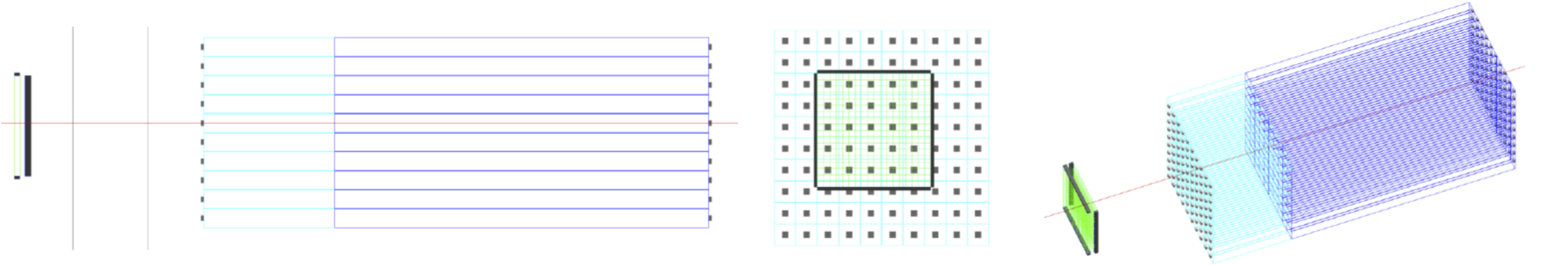


Motivation & Geometry
CDR Baseline ECAL
Sampling, PFA Oriented, 3D Readout
Two schemes:
Silicon-Tungsten Sandwich ECAL
Basic Unit
2 symmetric sensitive silicon layers
- glued on a PCB
- equipped with readout ASICs
1 tungsten plate
Scintillator-Tungsten Sandwich ECAL
Basic Unit
2 layers of plastic scintillator strip
- 2mm thick, 5×45mm² large
- perpendicular to adjacent layer
- attached to SiPM
1 tungsten plate
Defects:
1. Limited Energy Resolution, especially for Low Energy Photon.
2. Cost, Power consumption and Cooling.
Why a new ECAL?
ECAL Geometry in CEPC CDR
New ideas about ECAL
Full Crystal, Fast Timing, 2D Readout
Basic Module
Crystal Scintillator (eg. BGO, LYSO...)
1x1x40cm³
Photodetectors (eg. FPMT, SiPM...)
Basic Unit
In order to reduce the number of electronic readout channel, precise time measurement is expected.
24X₀
40cm
Super Unit
40cm
1.8m
TPC
4.7m
In the case of BGO, Number of readout channels ~ 1.4M << 25M (Si-W ECAL)
2

Yong Liu

Crystal ECAL status at US

Christopher Tully (Princeton)



Design and simulation studies at CEPC Oxford Workshop (Apr. 2019)

- Crystal ECAL: new ideas
  - Exploring ways of dual readout in the ECAL (i.e. in the first nuclear interaction length)
    - Proposal sent to DR colleagues
  - Maintain a large fraction of active crystal volume to provide 3%/sqrt(E) for electrons/photons
  - Also provide projective Cherenkov sampling (C)
  - Compare the EM fraction (C) with the total from the crystals (S)

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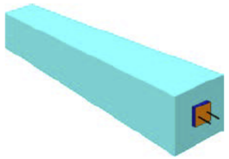
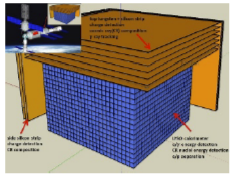
Ren-Yuan Zhu

Existing Crystal Calorimeters in HEP

Date	75-85	80-00	80-00	80-00	90-10	94-10	94-10	95-30
Experiment	C. Ball	L3	CLEO II	C. Barrel	KTeV	*BaBar*	BELLE	CMS
Accelerator	SPEAR	LEP	CESR	LEAR	FNAL	SLAC	KEK	CERN
Crystal Type	NaI(Tl)	BGO	CsI(Tl)	CsI(Tl)	CsI	CsI(Tl)	CsI(Tl)	$PbWO_4$
B-Field (T)	-	0.5	1.5	1.5	-	1.5	1.0	4.0
r_{inner} (m)	0.254	0.55	1.0	0.27	-	1.0	1.25	1.29
Number of Crystals	672	11,400	7,800	1,400	3,300	6,580	8,800	76,000
Crystal Depth (X_0)	16	22	16	16	27	16 to 17.5	16.2	25
Crystal Volume (m^3)	1	1.5	7	1	2	5.9	9.5	11
Light Output (p.e./MeV)	350	1,400	5,000	2,000	40	5,000	5,000	2
Photosensor	PMT	Si PD	Si PD	WS^a+Si PD	PMT	Si PD	Si PD	APD^a
Gain of Photosensor	Large	1	1	1	4,000	1	1	50
σ_N/Channel (MeV)	0.05	0.8	0.5	0.2	small	0.15	0.2	40
Dynamic Range	10^4	10^5	10^4	10^4	10^4	10^4	10^4	10^5



Future crystal calorimeters in HEP:
LSO/LYSO for COMET, HERD, and HL-LHC (Sampling)
CsI and BaF_2:Y for Mu2e, PWO for PANDA
BGO, BSO or scintillating glasses for HHCAL



March 12, 2019 Presentation by Ren-Yuan Zhu, Caltech, at Institute of High Energy Physics, Beijing, China 4

Crystal Options

- **PWO:**
  - the most compact, the fastest, the cheapest
- **BGO:**
  - close to PWO in compactness, slower, brighter
- **CsI:**
  - the least compact, the slowest, the brightest

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**

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

Yuexin Wang

Yong Liu

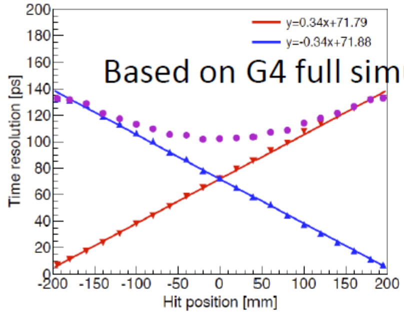
Separation power: di-photons showers

Yuexin Wang (IHEP)

Simplified Digitization

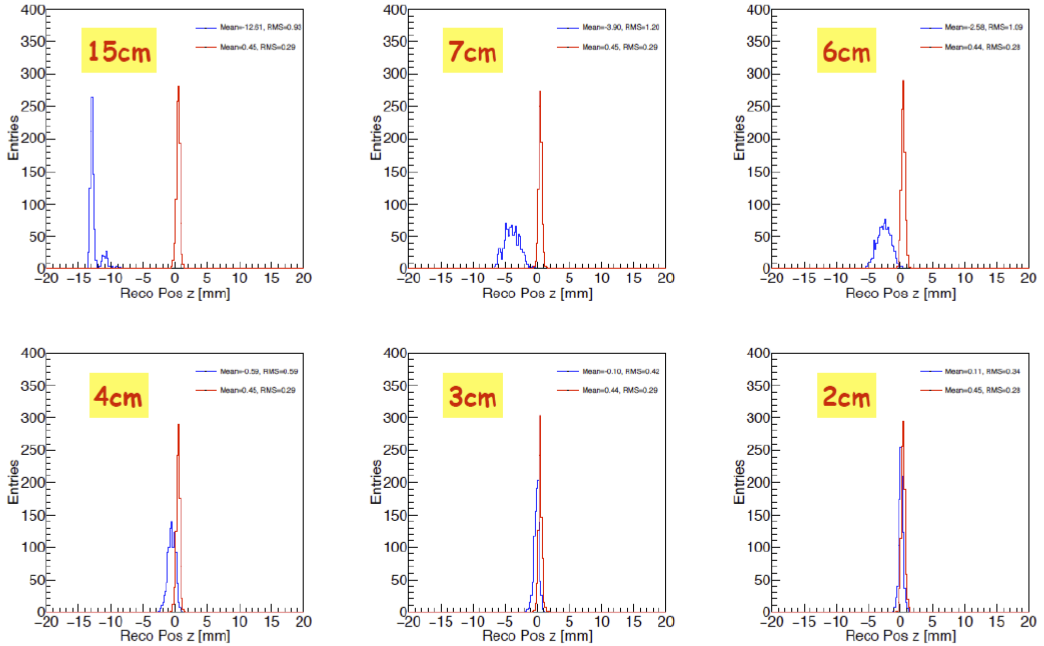
$\sigma_t = \sigma_{intrinsic} \oplus \sigma_{PMT} \oplus \sigma_{electronics} \oplus \sigma_{time\text{-}walk}$

30ps 20ps 0ps



5GeV diphoton

145ps



- Can separate 5GeV di-photon showers when distance >= 4cm with ~145 ps resolution

~145 ps as the conservative estimate for the intrinsic timing resolution

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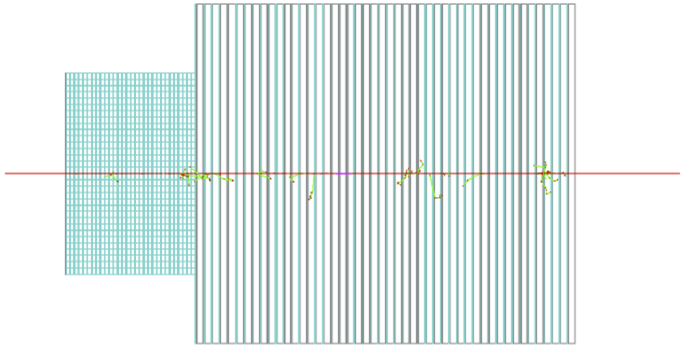
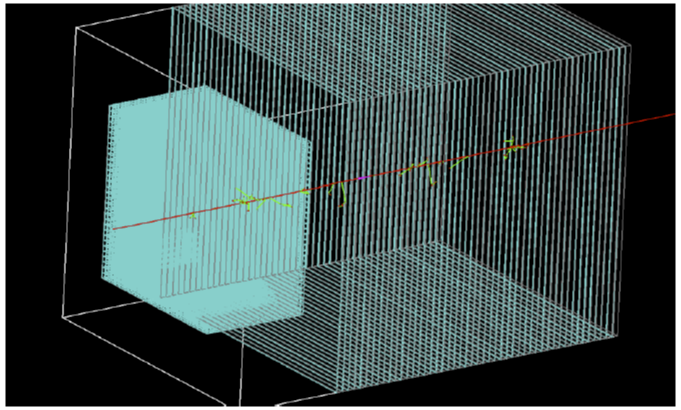
Simulation for ECAL+HCAL

Geant4 version 10.5.0

- Combined setup ECAL+HCAL
  - Established stand-alone Geant4 simulation (no optical photons at this large scale)
  - Crystal ECAL: 30 layers (30X0)
    - BGO/PbWO crystal tiles, 1X0 thick
    - Transverse granularity: 20mm (~Moliere radius)
  - HCAL: scintillator + steel plates
    - 48 layers in total
    - Plastic scintillator: 3mm thick, 30x30mm²
    - Steel: 20 mm
- Digitization in simulation: crucial
  - For scintillator: crystal (ECAL), plastic (HCAL)
  - Energy depositions (hits) → scintillation photons → SiPM pixels → ADC signals in electronics



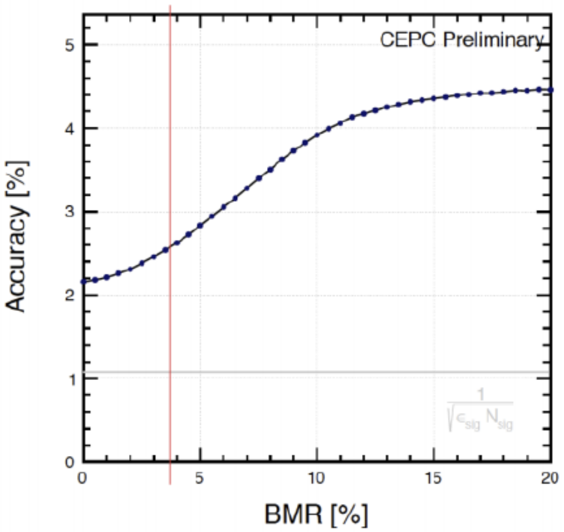
Calibration runs: 120 GeV mu-



Benchmark 3: W boson fusion, $H \to bb$

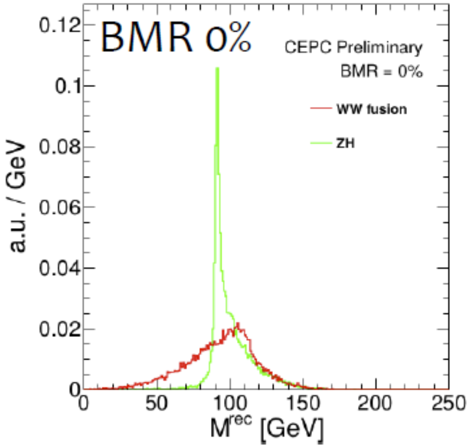
Backgrounds

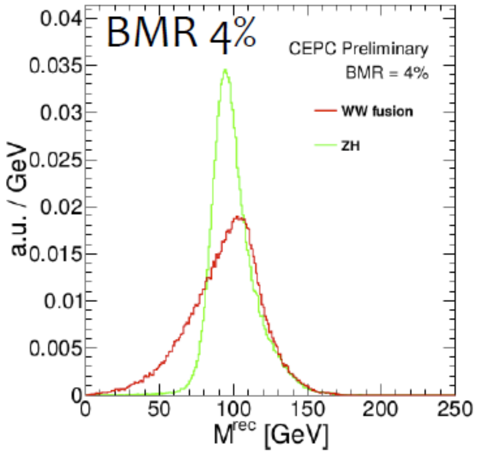
- ✓ $vvH(ZH), H \to bb$
- ✓ Other backgrounds from full simulation added w/o smearing (not shown in the figure)
- ✓ Eff. statistics etc. set according to full simulation

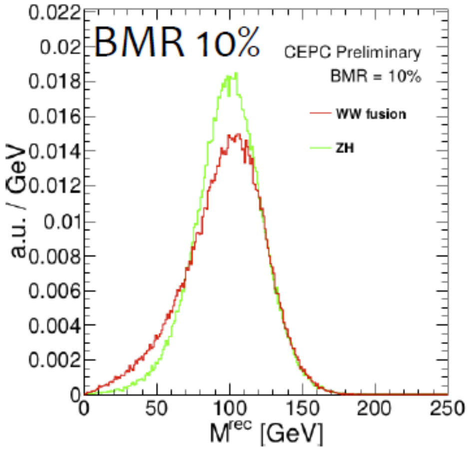


The recoil mass distribution change with BMR

(Note: $ZH, Z \to vv$ is about 7 times larger than The W boson fusion)







2019/7/17 ILD Analysis/Software Meeting 10