Measuring Electrons & Photons

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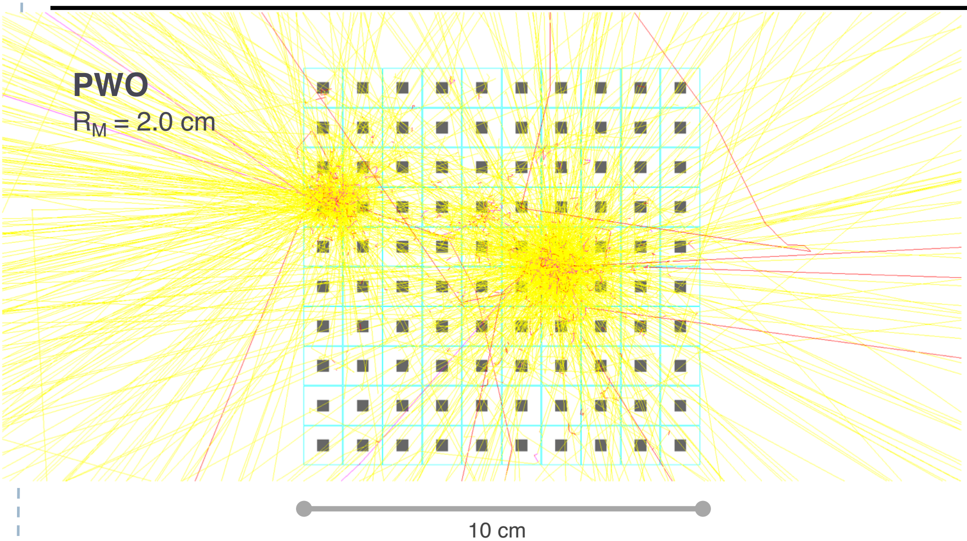
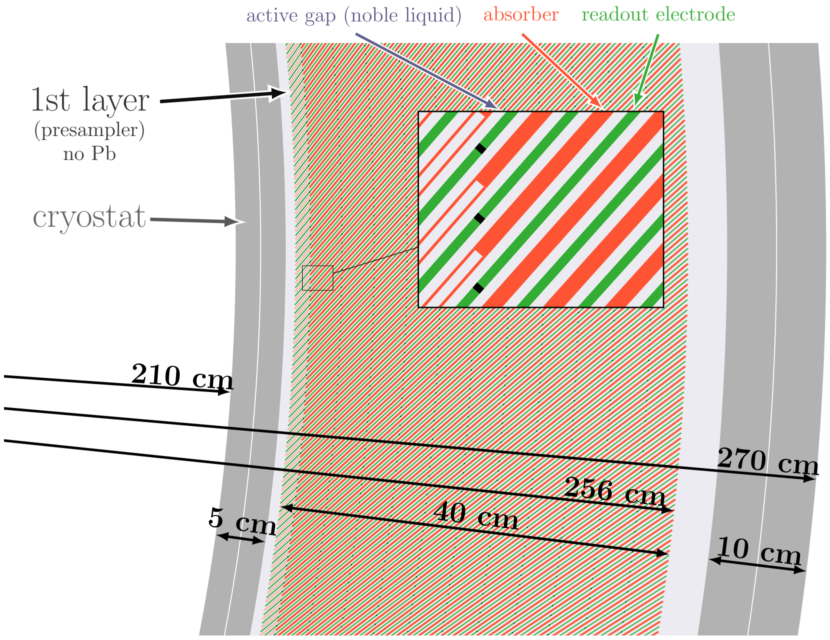
Key/Many Performance Parameters of ECAL

- **Energy** Resolution (Stochastic and Constant Terms)
- **Position** Resolution (x-y local on front face/COG)
- **Granularity** (Transverse, Longitudinal)
- **Angular** Resolution/Vector Direction (pointing)
- **Dual-Readout** Performance (S/C, ECAL+HCAL)
- **e/pi** (and gamma/$K0_L$) Separation (delayed EM showering ID)
- **Pizero Photon** Separation, **Brem-Recovery** Performance, …
- **Timing** Resolution (Stochastic and Constant Terms)
- **Noise** Floor and Pedestal Stability
- **Dead Material** Effects/Hermiticity
- Dynamic Range and **Containment**
- **Acceptance** Resolution (barrel/endcap and endcap/beamline)
- **Calibration** Performance, Response Stability, Monitoring, …
- **Alignment** Precision, Mechanic Support Photometry, …

Fundamentals of ECAL Technologies

Technology	EM energy resolution (stochastic term)	(constant term)
Highly granular Si/W based	15–17%	1%
Dual readout Fibre (ECAL+HCAL)	11%	<1%
Hybrid crystal (dual readout)	3%	<1%
Highly granular noble liquid based ECAL	8–10%	<1%





High-End of Performance Numbers

- **0.1-0.2mm** front-face position resolution
- **3%/sqrt(E)** stochastic energy term
- **<1%** on constant term
- **<1 mm** precision on IP z-vertex position
- **<1 mrad** angular pointing (photon 3-momentum)
- **<100ps** timing on all hits above 1 GeV
- e/pi **suppression >10^4**
- Upwards of **100 full sampling readings per EM shower** for **energy, position, angles, time, DR, PID**

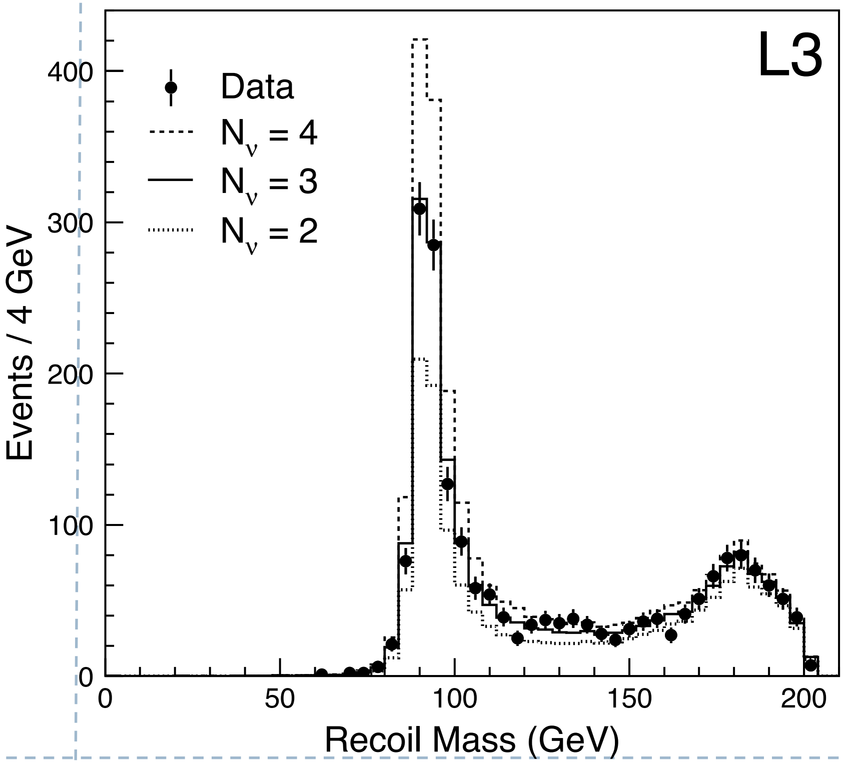
Do we need all that?
And what kinds of trade-offs are available?

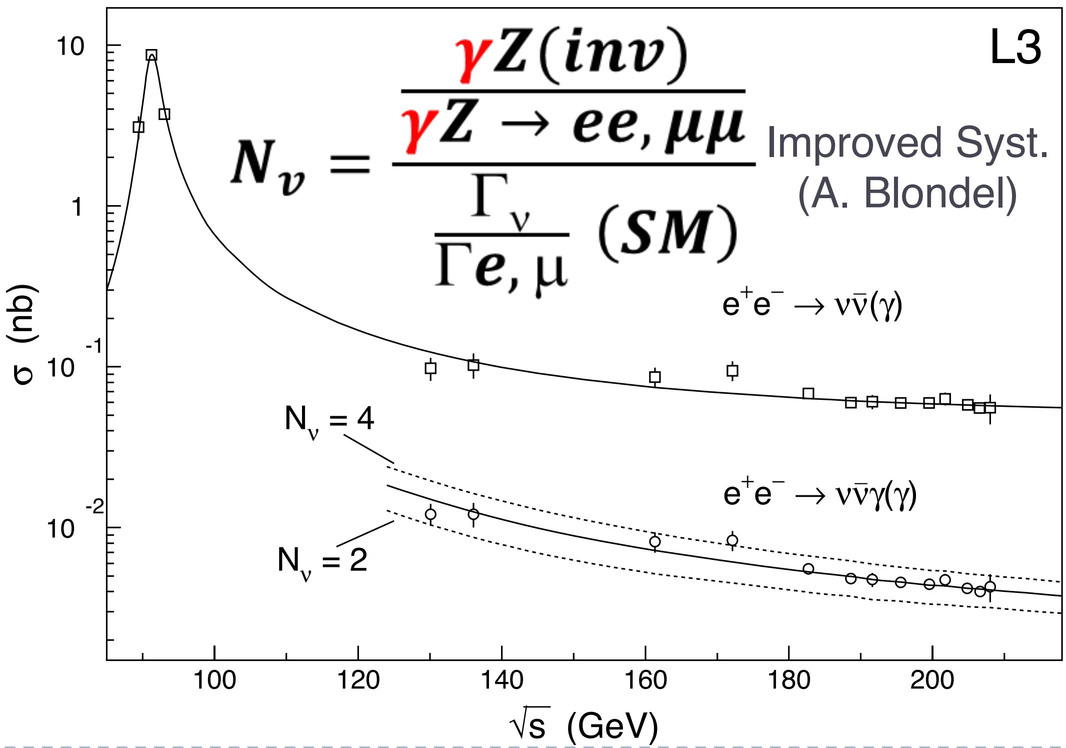
Leading Physics Drivers and Studies

- **Single photon spectra**
  - Precision Z to ν_e coupling (~1%), now at 18%
    - Stochastic term ~3% best, >5% big impact
    - Non-collision EM backgrounds (Cosmics, Beam Halo)
  - Precision LFV, $Z \rightarrow e\mu$, $Z \rightarrow \mu\mu \rightarrow \mu$"e"(hard Brem in ECAL)
    - Hard Brem rejection/angular resolution/vector direction
  - Recoil Mass/Radiative Return and $\tau \rightarrow \mu\gamma$
    - Event Missing Energy/Total Momentum ~0
- **Decay/Radiative Photons**
  - Pizeros from Jets, heavy flavor, tau-lepton decay
    - Graph theory π^0 preclustering, τ polarization
  - P_{tot}/E_{miss} balancing with multi-photons ($e^+e^- \rightarrow \gamma\gamma(\gamma)$)

EM Resolution and Photon Counting

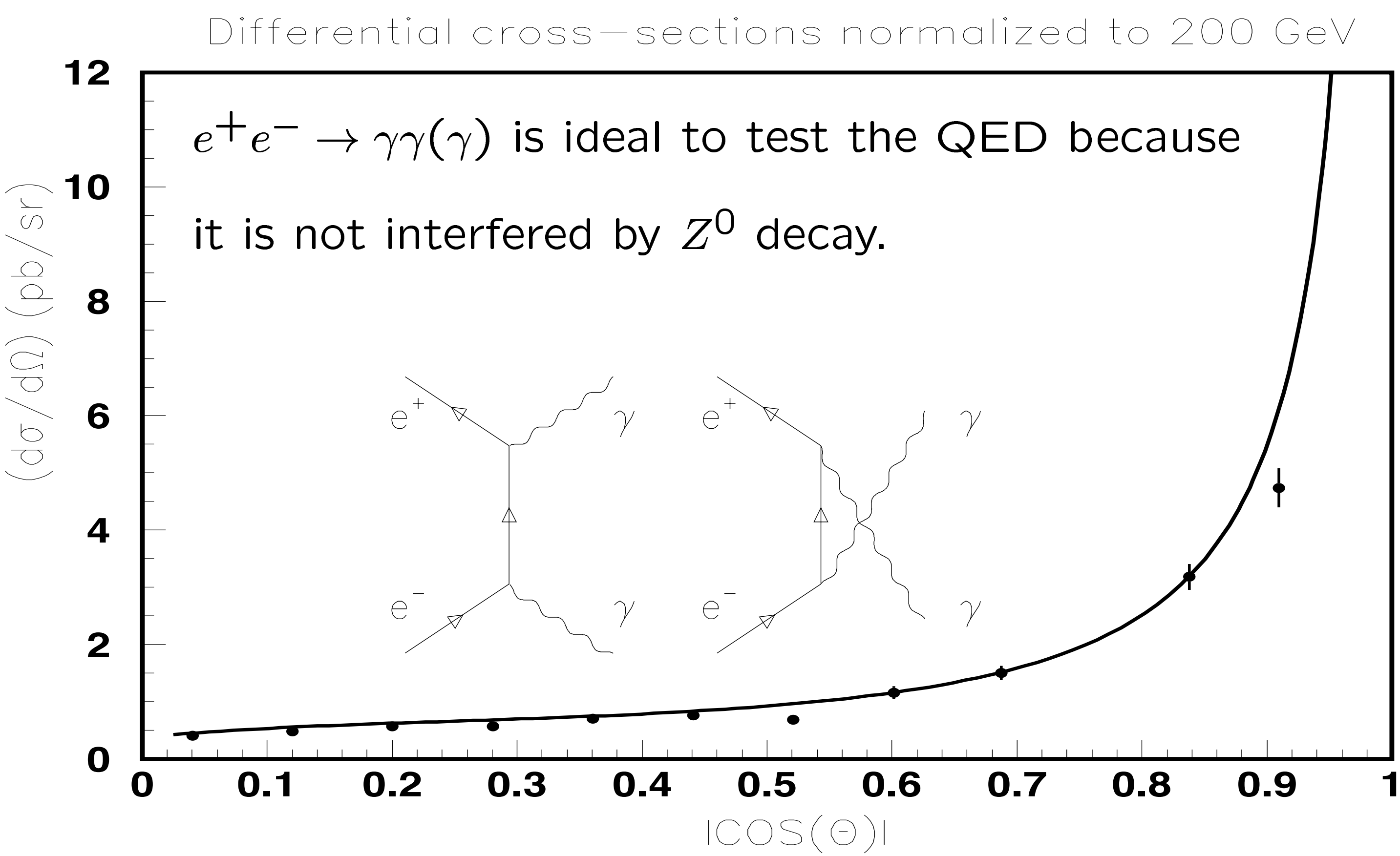
- **Improved angular measurements and Nγ counting**
  - Recoil photons (~8% of full √s collision rate)
    - New Physics Searches and Neutrino Counting





Precision QED/Lumi $e^+e^- \rightarrow \gamma\gamma(\gamma)$, $e^+e^- \rightarrow e^+e^-(\gamma)$

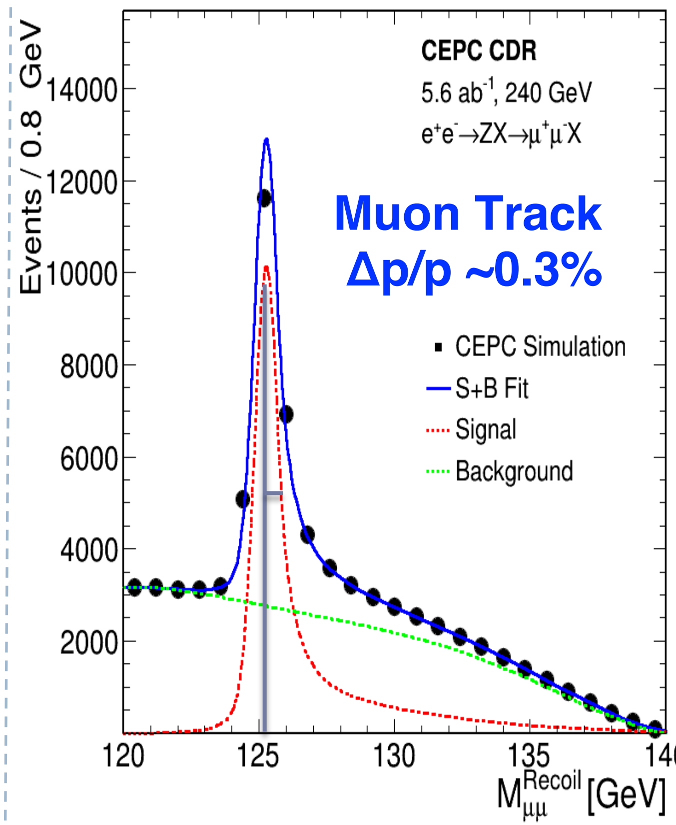
- **Total Momentum Zero Resolution**
  - Forward coverage/alignment

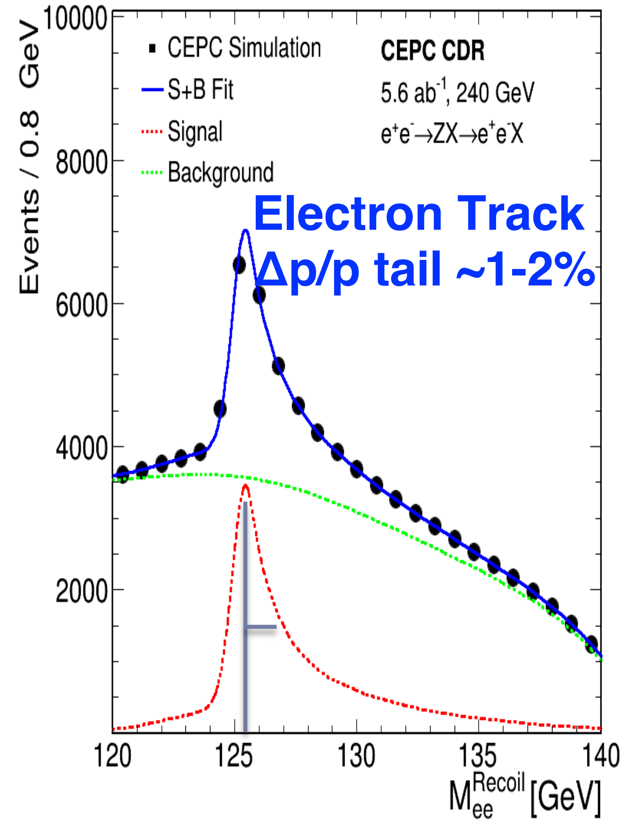


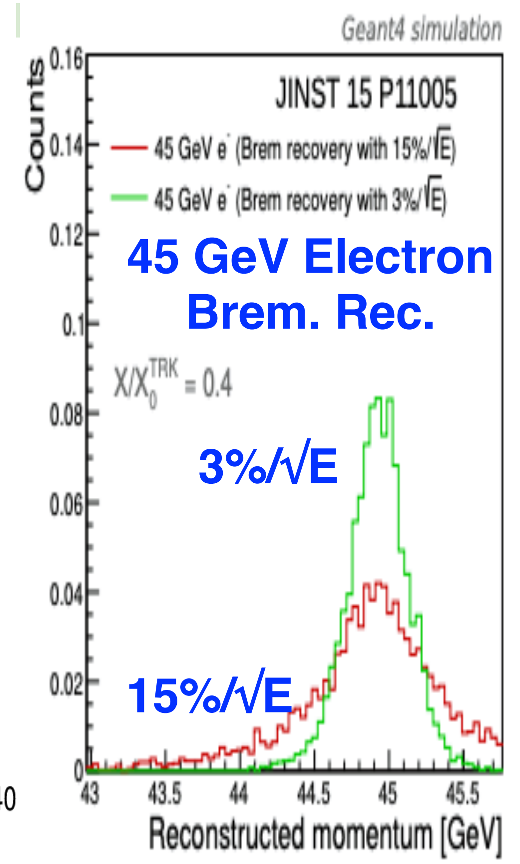
"tracking" calo **(Si-W)** known for precision **acceptance** near beamline **~10μm**

Recoil Analysis – Single Most Important Unbiased Sample of Higgs Boson Decays

- **Z→$\mu^+\mu^-$ Recoil**
- **Z→e^+e^- Recoil**



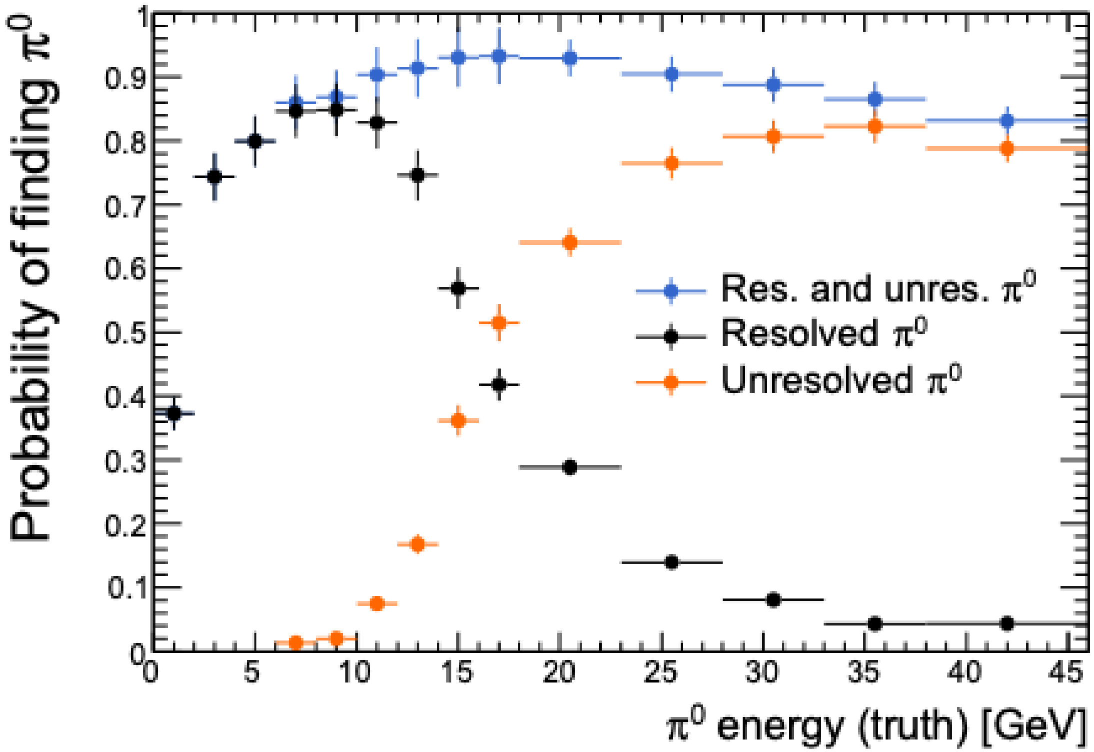


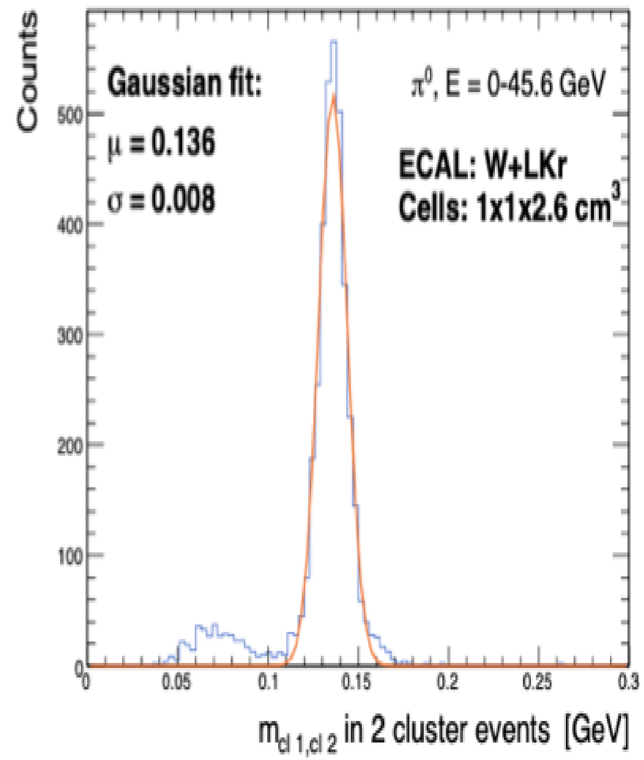


→ Up to ~80% of Electron Resolution Recovery with 3%/√E (Mid-Term) ~22% improvement on Higgs mass from ZH events where the uncert. on mass mean is comparable to H width

W-LKr π^0 Photon Separation

- **High granularity 3D cells (1cm x 1cm x 2.6 cm)**
  - ~5%/sqrt(E) from LKr

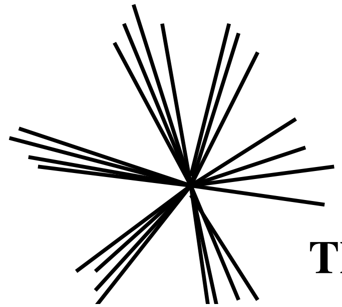




Resolving Jets and Photon-Jet mis-assignment

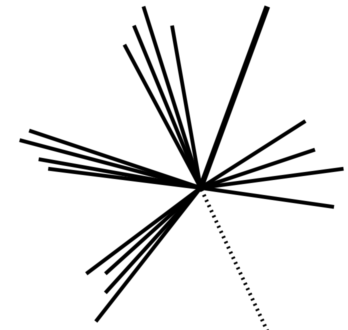
- Improved with Graph theory π^0 pre-clustering

The qqqqqq Channel

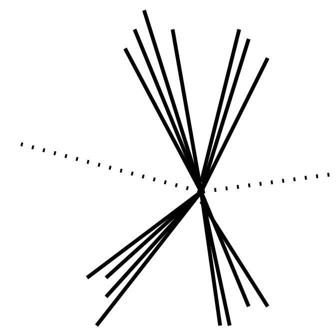


Variable	*Description*	*Trend*
E^{max}_{jet6}	Energy of the most energetic jet from the 6 jet fit.	Signal events should have six reasonably equal jets, while many backgrounds have several high energy jets and several very low energy gluon jets.
E^{min}_{jet6}	Energy of the least energetic jet from the 6 jet fit.	
n^{min}_{jet6}	Minimum number of charge tracks in any of the jets from the 6 jet fit.	Gluon jets and other "reconstruction" jets will have fewer charge tracks than signal jets.
θ^{min}_{jet6}	Minimum angle between any two of the six jets.	Gluon-radiation jets will tend to have a relatively small angle with respect to other jets.
$\log Y_{45}$	Durham Y value where the fit changes from four jets to five jets.	True six jet events should have larger values of the Durham cut values.
$\log Y_{56}$	Durham Y value where the fit changes from five jets to six jets.	

The qqqqlν Channel



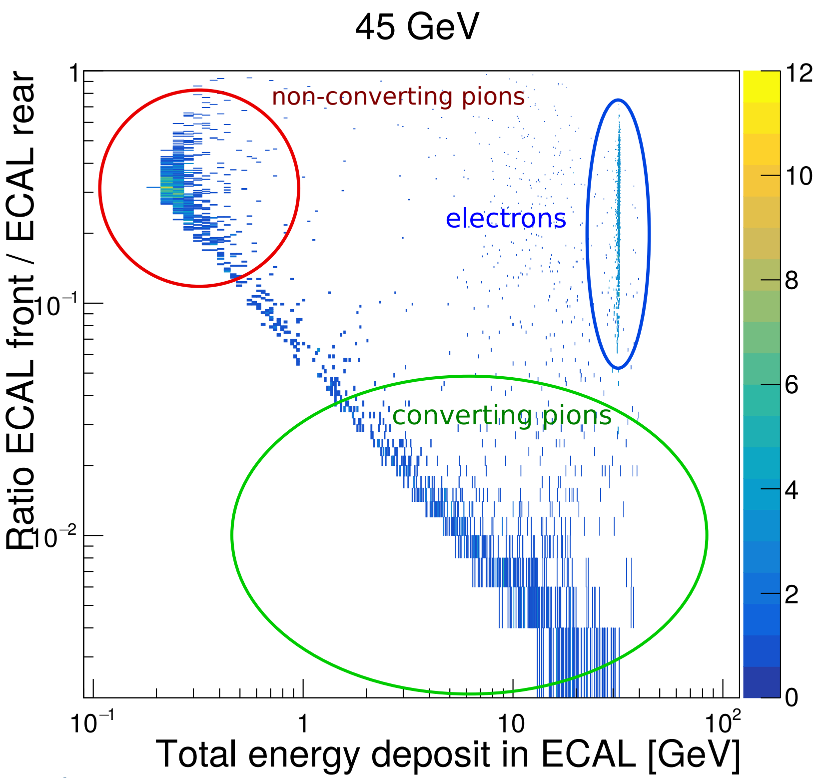
The ννqqqq Channel



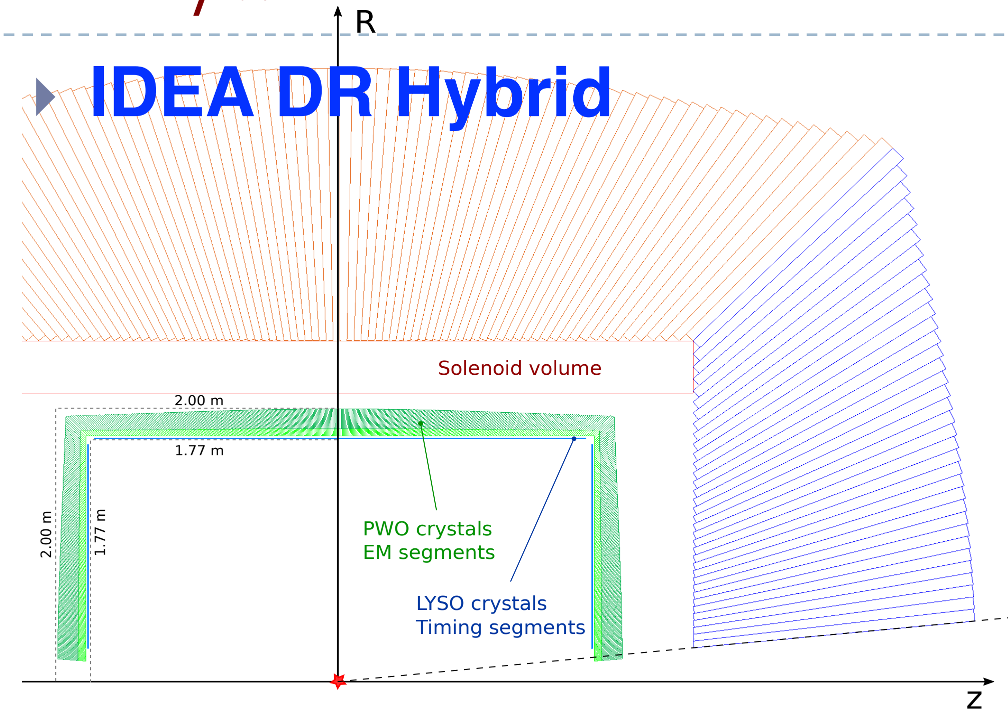
Variable	*Description*	*Trend*
E^{max}_{4j}	Energy of the most energetic jet from a fit to four jets.	Signal events tend to have two medium-energy and two low-energy jets, while backgrounds will tend to have higher E^{max} values and lower E^{min} values.
E^{min}_{4j}	Energy of the least energetic jet from a fit to four jets.	
θ^{min}_{4j}	Minimum angle between any two of the four jets.	Gluon jets tend to be emitted at small angles relative to the emitting quark jet.

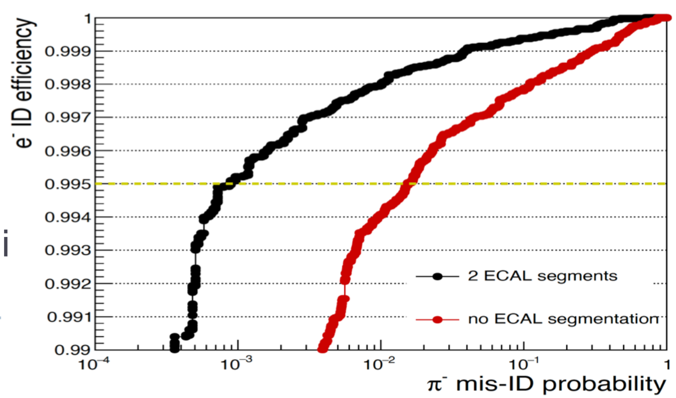
https://arxiv.org/pdf/hep-ex/0204029.pdf

Multi-Signal ECAL and e/π$^{\pm}$ Discrimination



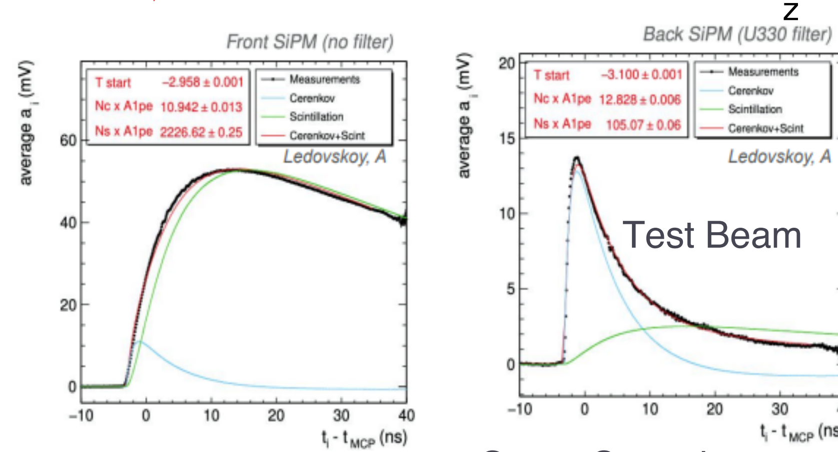
IDEA DR Hybrid





Marco Lucchini

Central MIP signals



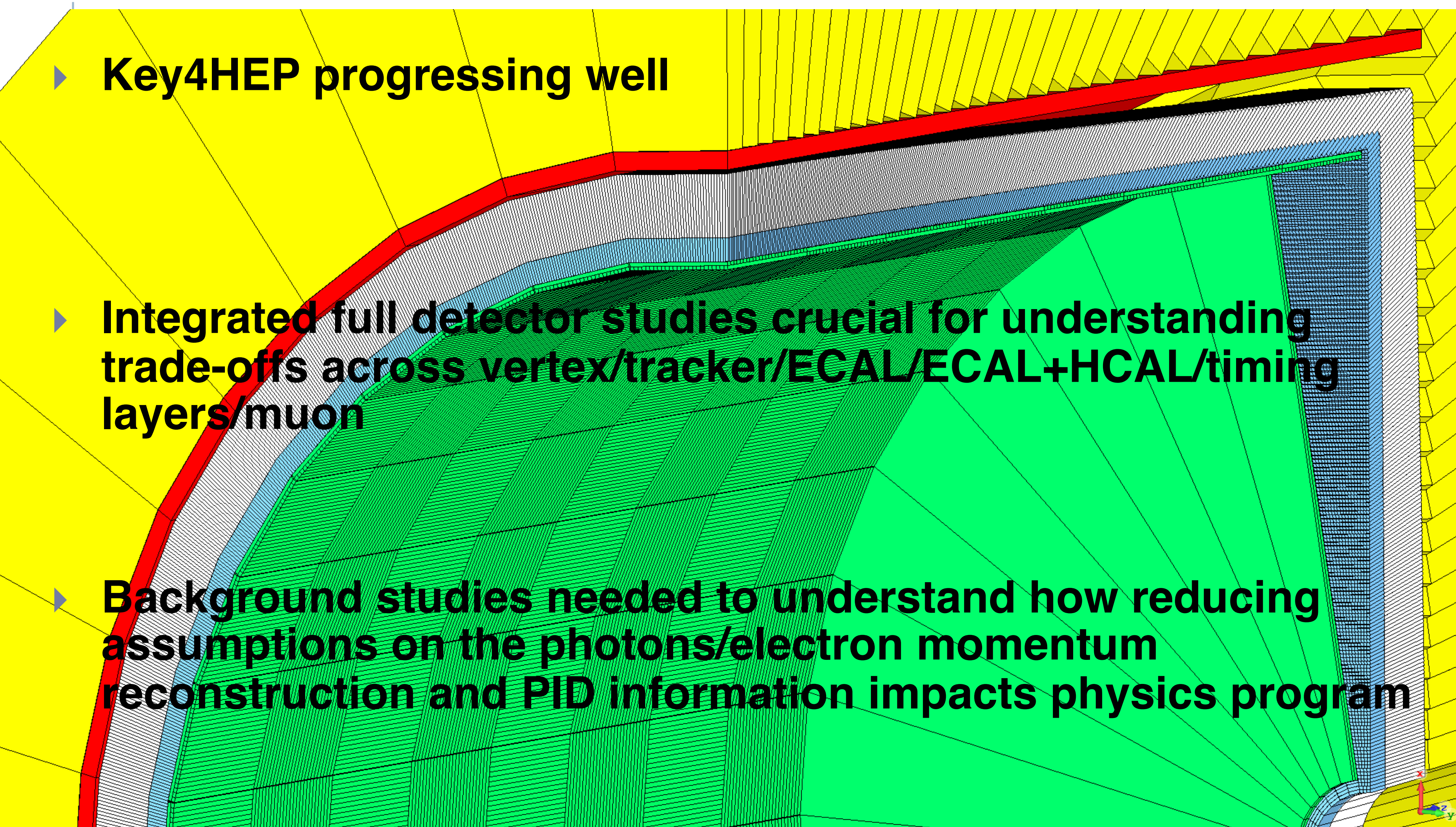
Grace Cummings

S/C adds a Single Crystal EM PID

More Physics Studies Needed

- **Full Simulation will help tie together trade-offs in tracking, timing layers, ECAL EM, and ECAL+HCAL Jets/taus**
    - Photon 3-momentum measurement with precise sub-mm vertexing and 20-30ps timing resolution will bring measurements from EM showers out of the dark – not requiring assumptions on IP and signal hypotheses to constrain total momentum
- **ALP-sstrahlung processes**
  - Boosted pseudo-scalars decaying to photons
    - Rare events need highly resolved event-by-event measurements
- **Backgrounds need to be studied for high statistics, systematics-limited searches**

More Emphasis on Full Simulation



- **Key4HEP progressing well**
- **Integrated full detector studies crucial for understanding trade-offs across vertex/tracker/ECAL/ECAL+HCAL/timing layers/muon**
- **Background studies needed to understand how reducing assumptions on the photons/electron momentum reconstruction and PID information impacts physics program**

Outlook

- **More Detector-Level Performance Evaluation (w/TB)**
  - Bootstrap full event sims with limited volume ECAL setups
    - Provide full set of detector readings from local EM shower
    - Non-collision EM backgrounds (Cosmics, Beam Halo)
  - Enable analyses to form new variables and test new PFA
    - LLP semi-neutral displaced vertex pointing
    - High efficiency tagging and separation of photons
- **Big Opportunities in EM Domain**
  - Photon 3-Momentum/Vector Direction w/Precision Timing
  - Dual-Readout/Multi-Signal ECAL
  - High Resolution P_{total} w/ Low Energy Single and Multi-Photon
  - More Precision Inputs to Improve PFA & PID Performances