Luminosity Measurement and First Results from full LumiCal Simulation

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LAPP, Annecy

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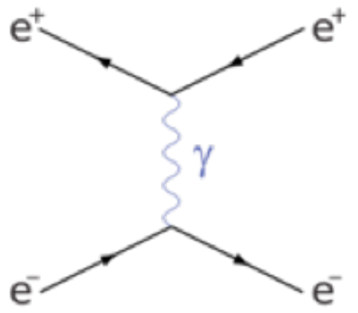
Disclaimer

- Today's talk will be mainly presenting results from first full simulation studies of the LumiCals
- Results are fresh and will be consolidated/extended over the coming months
  - Presented results and conclusions are clearly of a preliminary nature
- For a more general overview talk of the small angle Bhabha luminosity measurement see, e.g.
  - M. Dam, *FCC-ee Luminosity Measurement and LumiCal*, FCC-ee MDI and IR Mockup Workshop, Frascati, Nov. 2023

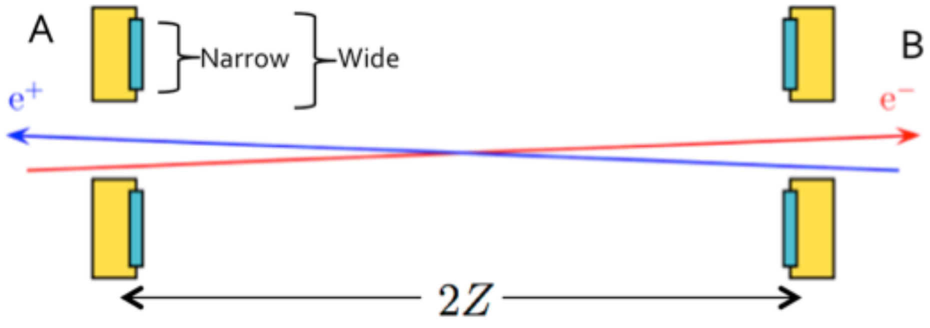
Luminosity Measurement with Small-angle Bhabha Scattering

- Bhabha scattering = Elastic scattering $e^+e^- \rightarrow e^+e^-$
  - Dominated by *t*-channel photon exchange
  - Very strongly forward peaked

$$\sigma^{\text{Bhabha}} = \frac{1040 \text{ nb GeV}^2}{s}\left(\frac{1}{\theta^2_{\text{min}}} - \frac{1}{\theta^2_{\text{max}}}\right)$$



- Measured with set of two calorimeters; one at each side of the IP
  - Crossing beams: *Center monitors around outgoing beam lines*



Two counting rates :
- SideA = NarrowA + WideB
- SideB = NarrowB + WideA

  - Minimize dependence on beam parameters and misalignment:
    - ***Restricted acceptance***: Average over two counting rates: **Rate = ½ × (SideA + SideB)**
- Important systematics from acceptance definition: *In particular minimum scattering angle*

$$\frac{\delta\sigma^{\text{acc}}}{\sigma^{\text{acc}}} \simeq \frac{2\delta\theta_{\text{min}}}{\theta_{\text{min}}} = 2\left(\frac{\delta R_{\text{min}}}{R_{\text{min}}} \oplus \frac{\delta z}{z}\right)$$

Normalisation to 10^{-4}

- The goal at FCC-ee is an **absolute normalization to 10^{-4}**
- After much effort, the precision on the absolute luminosity at LEP was eventually dominated by theory
  - Example **OPAL** - most precise measurement at LEP:

Theory: 5.4×10^{-4} **Experiment: 3.4×10^{-4}** arXiv:9910066

- Theory precision
  - Since LEP, theory precision has improved to **3.7×10^{-4}** arXiv:1912.02067
  - And a path is outlined to reach **10^{-4}** arXiv:1902.05912
- Instrumental precision – major effort to go to sub-permille level

OPAL is **the** reference

89 pages !

EAN ORGANIZATION FOR PARTICLE PHYSICS

CERN-EP/99-136
28 Sep 1999

arXiv:hep-ex/9910066v2 23 Nov 1999

Precision Luminosity for Z^0 Lineshape Measurements with a Silicon-Tungsten Calorimeter

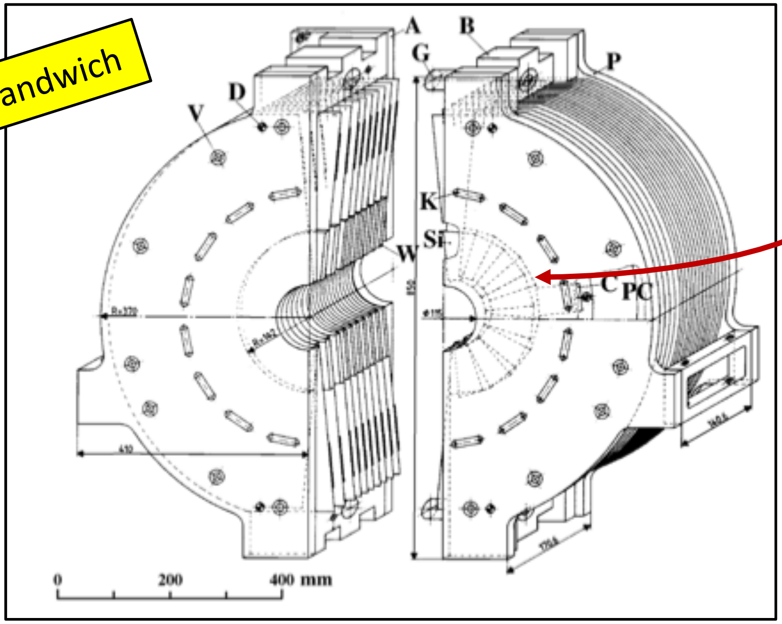
The OPAL Collaboration

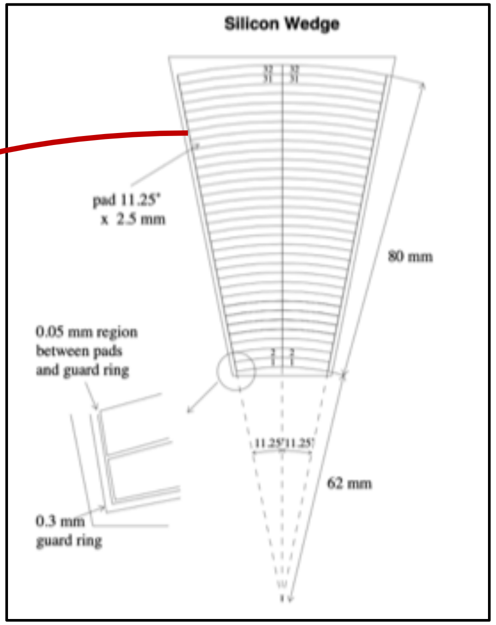
Abstract

The measurement of small-angle Bhabha scattering is used to determine the luminosity at the OPAL interaction point for the LEP I data recorded between 1993 and 1995. The measurement is based on the OPAL Silicon-Tungsten Luminometer which is composed of two calorimeters encircling the LEP beam pipe, on opposite sides of the interaction point. The luminometer detects electrons from small-angle Bhabha scattering at angles between 25 and 58 mrad. At LEP center-of-mass energies around the Z^0, about half of all Bhabha electrons entering the detector fall within a 79 nb fiducial acceptance region. The electromagnetic showers generated in the stack of 1 radiation length tungsten absorber plates are sampled by 608 silicon detectors with 38,912 radial pads of 2.5 mm width. The fine segmentation of the detector, combined with the precise knowledge of its physical dimensions, allows the trajectories of incoming 45 GeV electrons or photons to be determined with a total systematic error of less than 7 microns. We have quantified all significant sources of systematic experimental error in the luminosity determination by direct physical measurement. All measured properites of the luminosity event sample are found to be in agreement with current theoretical expectations. The total systematic measurement uncertainty is 3.4×10^{-4}, significantly below the theoretical error of 5.4×10^{-4} currently assigned to the QED calculation of the Bhabha acceptance, and contributes negligibly to the total uncertainty in the OPAL measurement of $\Gamma_{inv}/\Gamma_{\ell^+\ell^-}$, a quantity of basic physical interest which depends crucially on the luminosity measurement.

To be submitted to Eur. Phys. J. C

SiW sandwich





Via precise metrology, achieved 4.4 µm precision on inner acceptance border

OPAL Breakdown of Systematics

Table 24: This table summarizes the experimental systematic uncertainties on the absolute L_{RL} luminosity measurement for the nine data samples. The lines labeled correlated and uncorrelated refer to errors correlated and uncorrelated among the samples. All errors are in units of 10^{-4}.

"external"

"simulation"

Uncertainty	section	93 -2	93 pk	93 +2	94a	94b	94c	95 -2	95	95 +2
Radial Metrology	2.3									
uncorrelated		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
correlated		1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40
Radial Thermal	2.3.2									
uncorrelated		0.06	0.00	0.06	0.09	0.11	0.11	0.25	0.25	0.25
correlated		0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Inner Anchor	4.1.4									
uncorrelated		0.23	0.23	0.23	0.23	0.23	0.23	0.58	0.58	0.58
correlated		1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36
Outer Anchor	4.1.4									
uncorrelated		0.13	0.13	0.13	0.13	0.13	0.13	0.28	0.28	0.28
correlated		0.31	0.31	0.31	0.31	0.31	0.31	0.30	0.30	0.30
Z Metrology	2.4									
uncorrelated		0.00	0.00	0.00	0.00	0.00	0.00	0.37	0.37	0.37
correlated		0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
Background	5									
uncorrelated		0.76	0.76	0.76	0.75	0.75	0.75	0.76	0.76	0.76
correlated		0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Trigger	6									
uncorrelated		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
correlated		0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Wagon Tagger	6									
uncorrelated		0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.02
correlated		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total External ($\Delta\epsilon_{ext}$)										
uncorrelated		0.81	0.81	0.81	0.80	0.80	0.81	1.10	1.10	1.10
correlated		2.16	2.16	2.16	2.16	2.16	2.16	2.16	2.16	2.16
Energy	4.3									
uncorrelated		0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
correlated		1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
Beam parameters	7									
uncorrelated		0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57
correlated		0.57	0.57	0.57	0.57	0.57	0.57	0.76	0.76	0.76
Radial resolution	8									
uncorrelated		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
correlated		0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Acollinearity bias	8									
uncorrelated		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
correlated		0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
Azimuthal resolution	8									
uncorrelated		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
correlated		0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Clustering	8									
uncorrelated		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
correlated		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$\Delta R - \Delta\Theta$ cut difference	9.3									
uncorrelated		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
correlated		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
M.C. statistics	8									
uncorrelated		0.29	0.27	0.29	0.33	0.13	0.25	0.36	0.34	0.32
correlated		0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Total Simulation ($\Delta\epsilon_{sim}$)										
uncorrelated		0.65	0.64	0.65	0.67	0.59	0.63	0.68	0.67	0.66
correlated		2.32	2.32	2.32	2.32	2.32	2.32	2.37	2.37	2.37
Grand Total										
uncorrelated		1.04	1.03	1.04	1.04	1.00	1.03	1.29	1.28	1.28
correlated		3.17	3.17	3.17	3.17	3.17	3.17	3.21	3.21	3.21

Radial Metrology : 1.4

"Inner Anchor" : 1.4

Z Metrology : 0.4

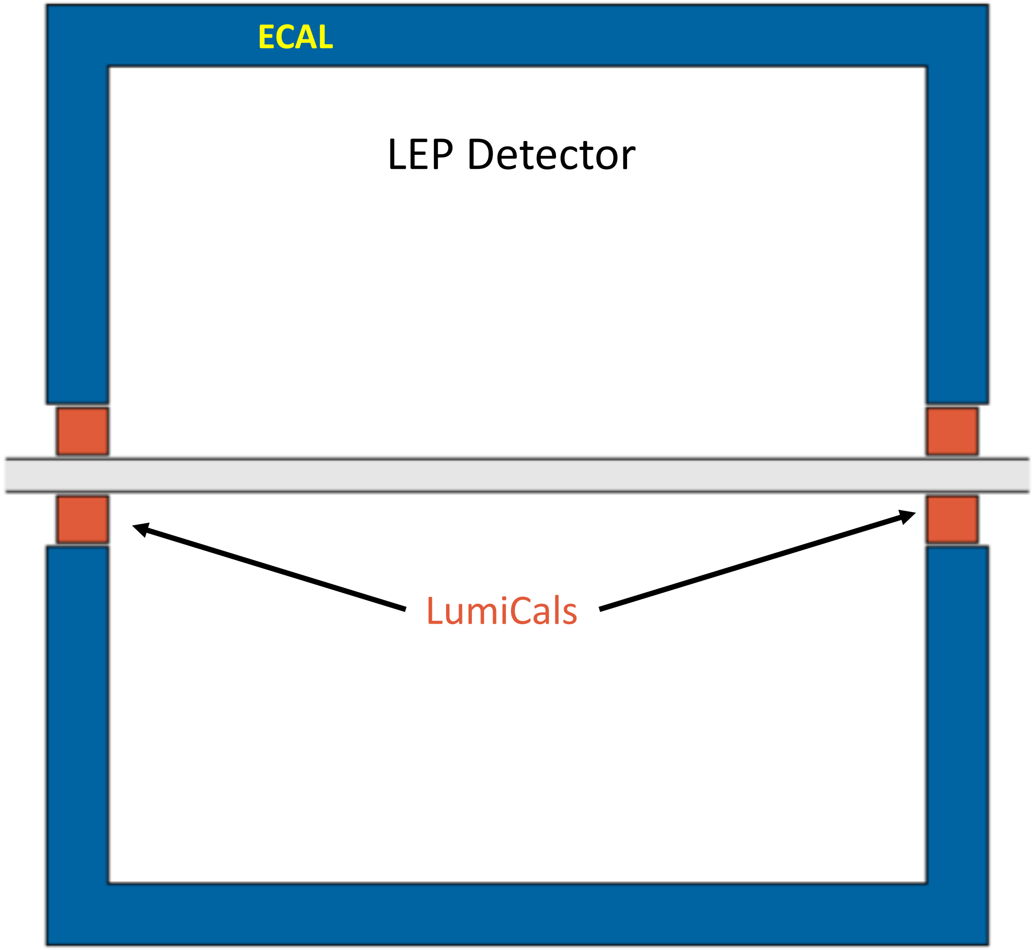
Energy Measurement : 1.8

Beam Parametrers : 0.6

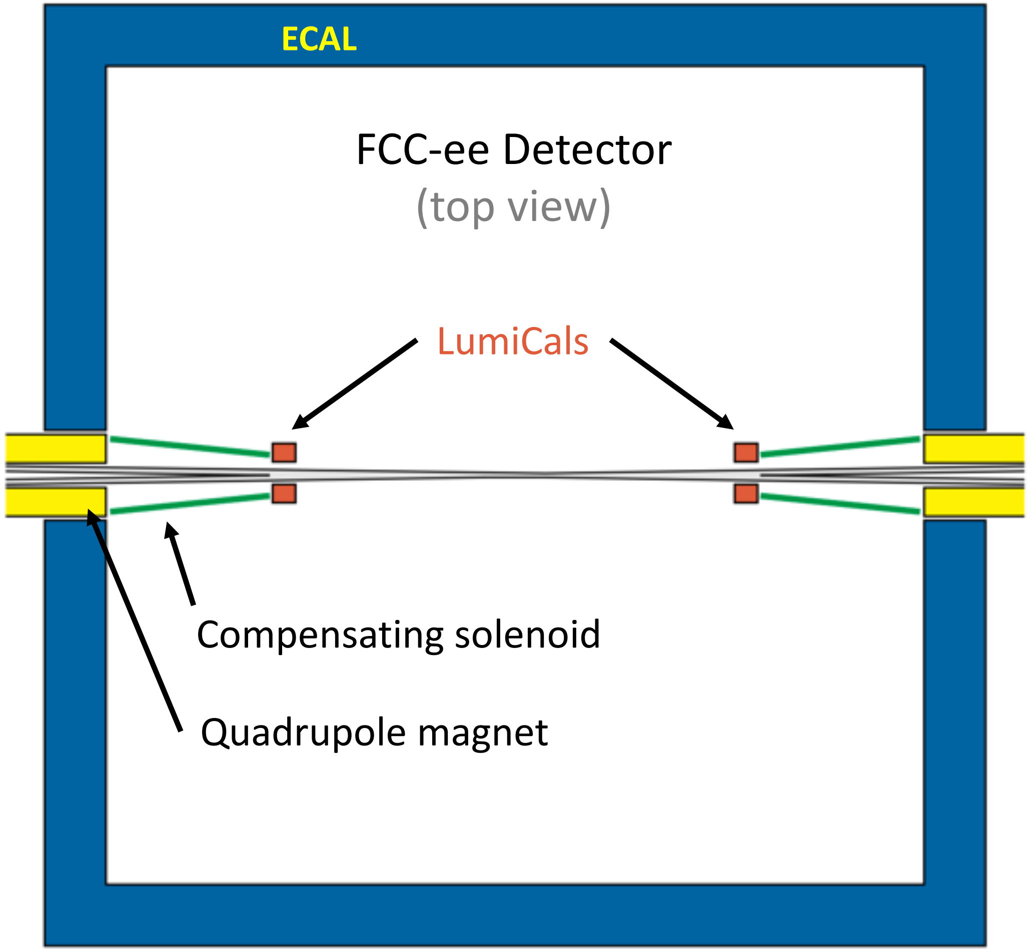
Clustering : 1.0

$\times 10^{-4}$

LumiCals at LEP and at FCC-ee

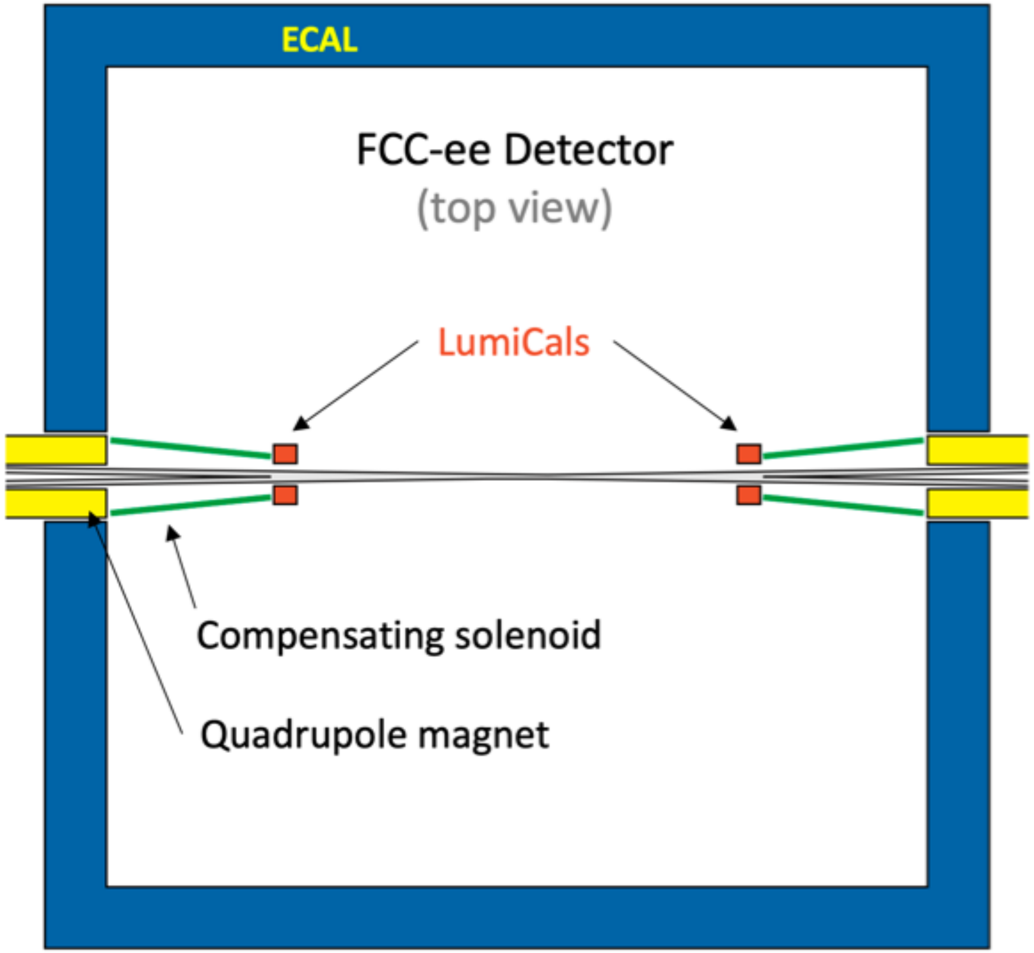


- LumiCals in same plane as forward ECAL at ~ 2.5 m



- Last quadrupole at ~ 2.1 m
- Compensating solenoid down to 1.2 m (compensate for influence of detector B-field on crossing beam)
- LumiCals situated deep inside detector volume
- LumiCals centred around outgoing beam pipe

LumiCal Challenges



- Geometrical constraints:
  - Stay away from beampipe
  - Stay away from tracker acceptance
  - Continuity of calorimetry below forward ECAL acceptance
- Precision constraints for 10^{-4} measurement:
  - Radial dimension of monitors to be controlled to $\mathcal{O}$(1 μm)
  - Distance between two monitors to be controlled to 100 μm
  - System of two monitors to be centred about collision point to precision of
    - few mm in z
    - few tenths on mm in xy plane
  - Well understood energy respons allowing good control of efficiency and background
    - Dominant single uncertianty contribution for OPAL (1.8×10^{-4})
- Pile up considerations (new wrt LEP):
  - Non-negligible probability to have two overlapping events (signal + signal/background) in the same bunch crossing

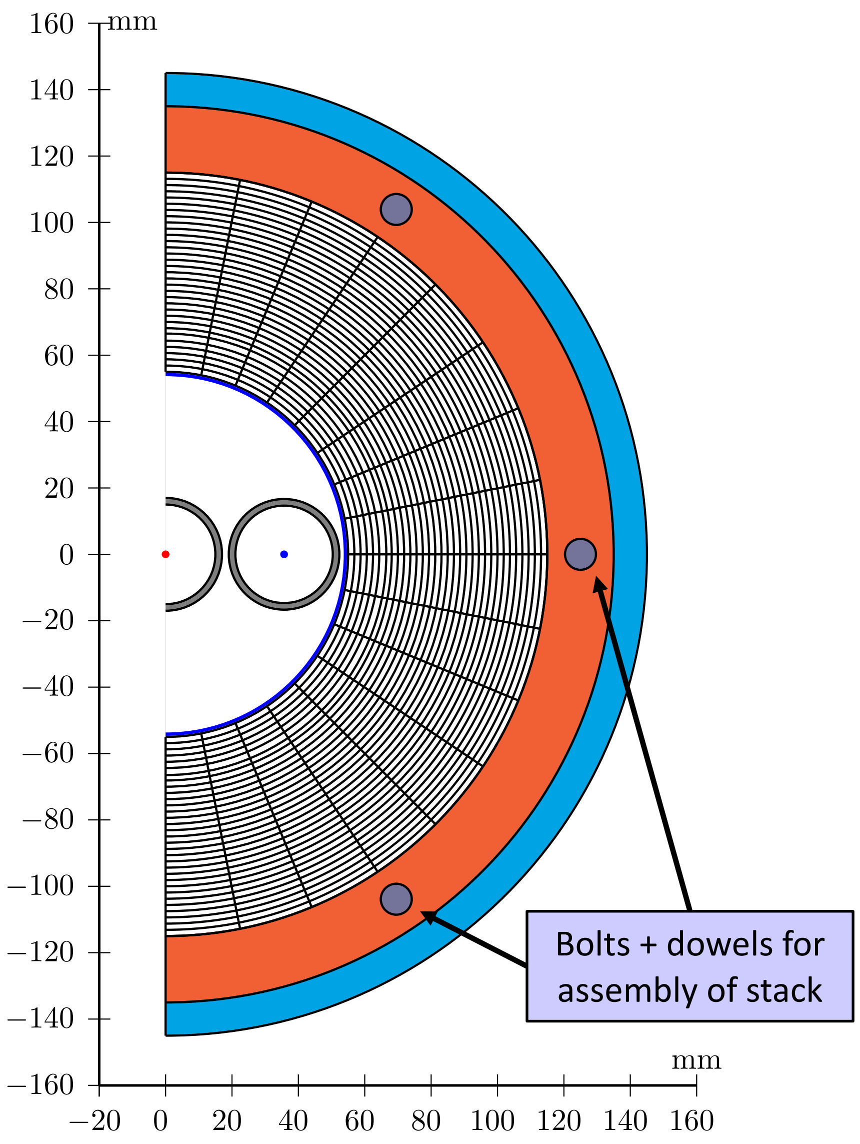
CDR LumiCal Design

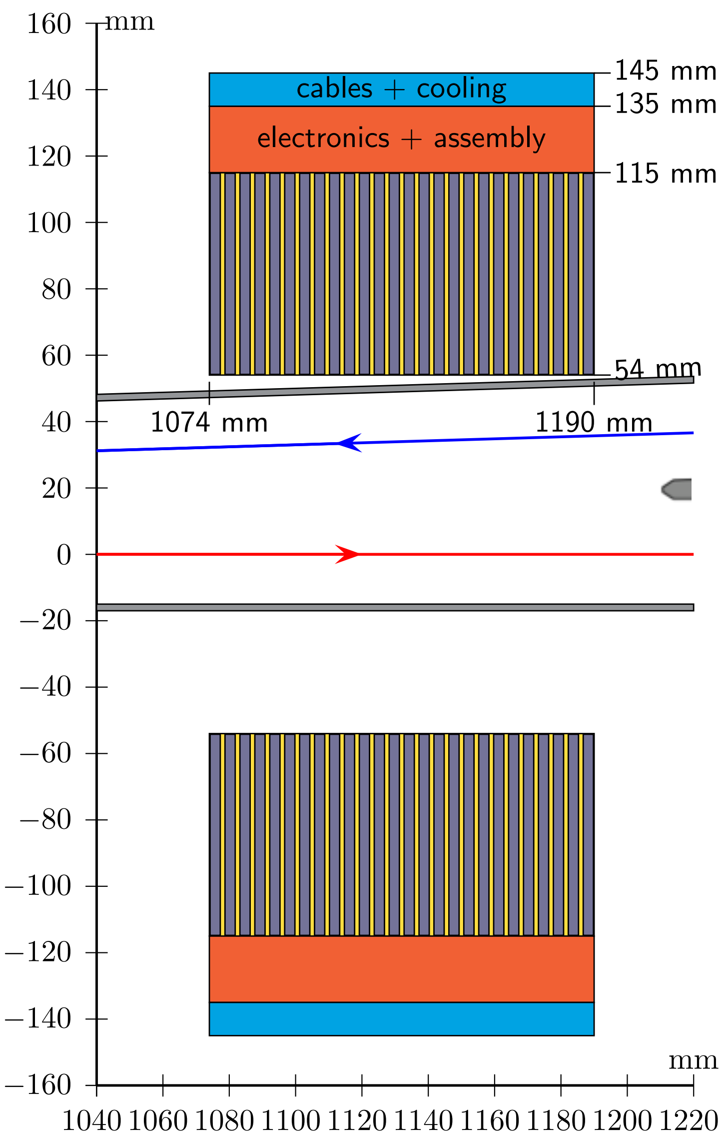
Design considerations:

- Need to control geometry to precision of $\mathcal{O}$(1 µm)
  - Keep **geometry as simple as at all possible**

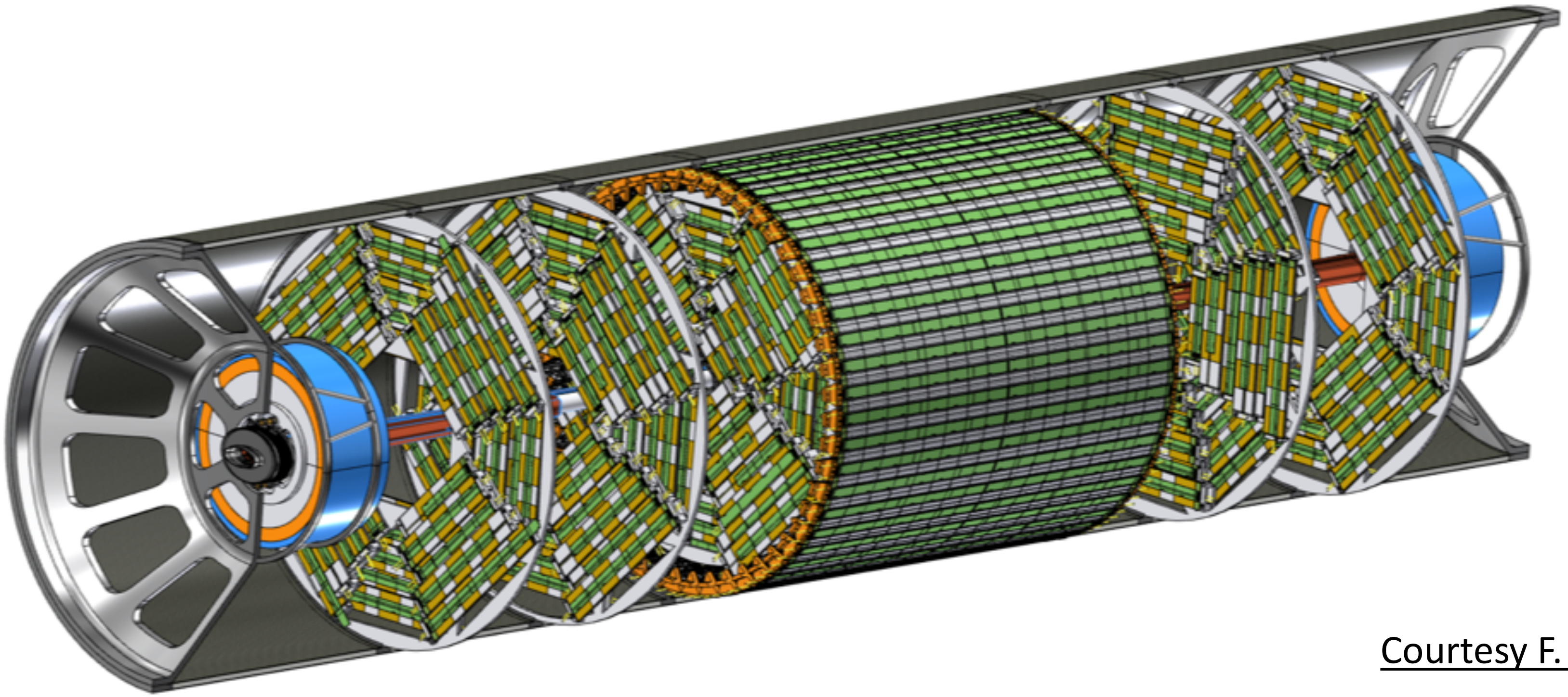
Multilayer barrels with all layers having identical circular geometry

- 25 layer SiW sandwich
  - 3.5 mm W (1 X_0) + 1.0 mm gap for Si sensors
- Physical dimensions
  - Sensitive region: *r* = 55-115 mm
  - Region for "services": 115-145 mm
  - Calorimeter front face at *z* = 1074 mm
- Proposed segmentation
  - 32x32 pads/layer (1.9 x 10-22 mm^2 pads)
  - 25,600 channels per LumiCal
- Weight
  - About 65 kg per LumiCal





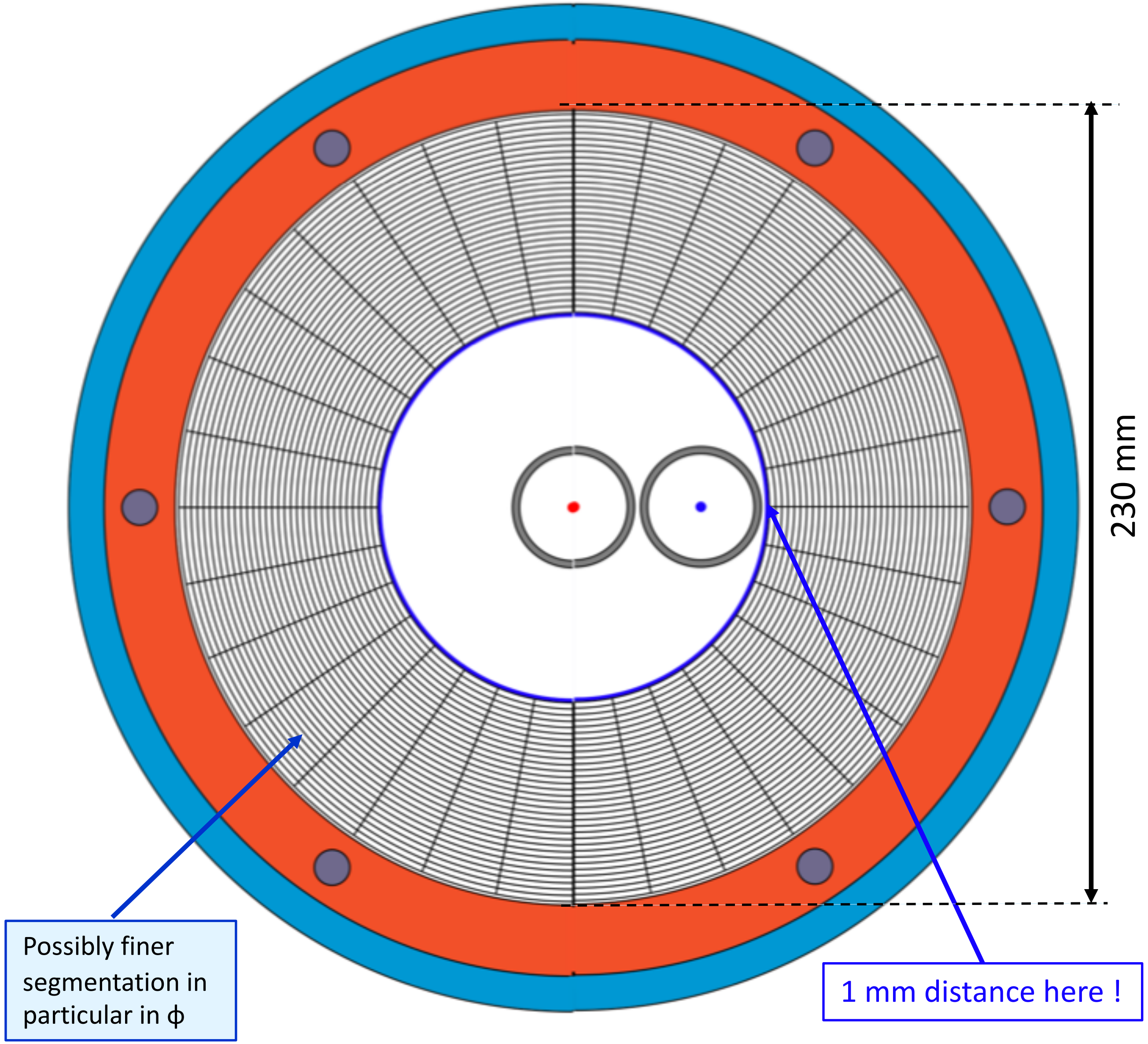
LumiCal Integration



Courtesy F. Palla

Condiderations and Concerns

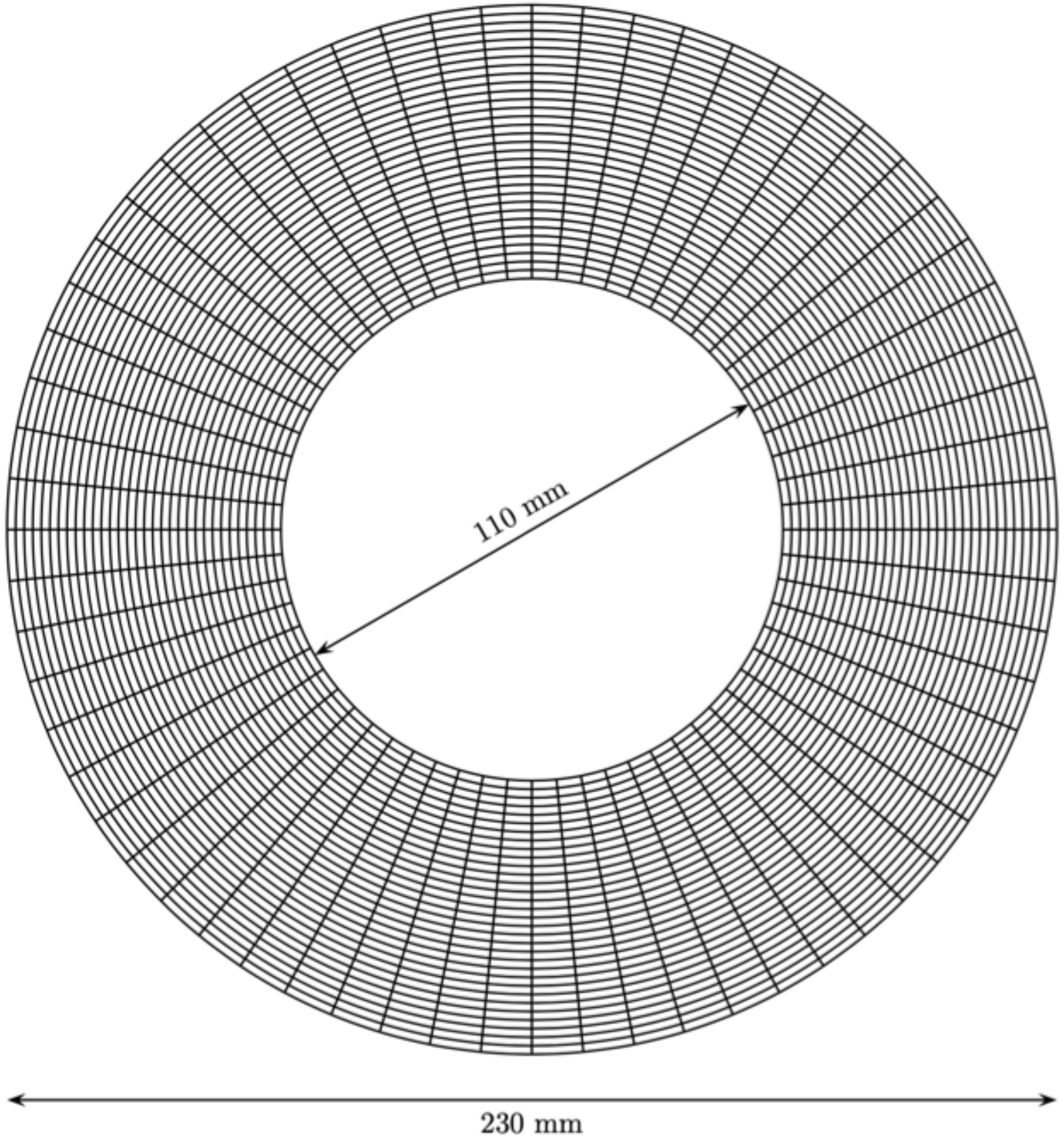
- Considerations for improved precision on radial coordinates:
  - Suggest to construct LumiCals as full barrels and not (as at LEP) as two half barrels
    - Avoid systematic from half-barrel separation
  - Fabricate each Si layer from one single Si crystal **??**
    - Uncertainty on inner (and outer) radius would then basically be controlled by ”Hamamatsu”
    - Can such Si sensors be produced?
    - What about thermal stability: cracks?
- Concerns:
  - By (ignorant?) design, LumiCal sits very close to incomming beam pipe
    - Only 1-2 mm clearance – is that sufficient ?
    - Beam pipe will be (how) hot ⇒ local warming of LumiCal?
  - For control of geometrical precison, temperature should be controlled to $\mathcal{O}$(1 degree);
    - gradients should be minimized



Full Simulation Studies - Geometry

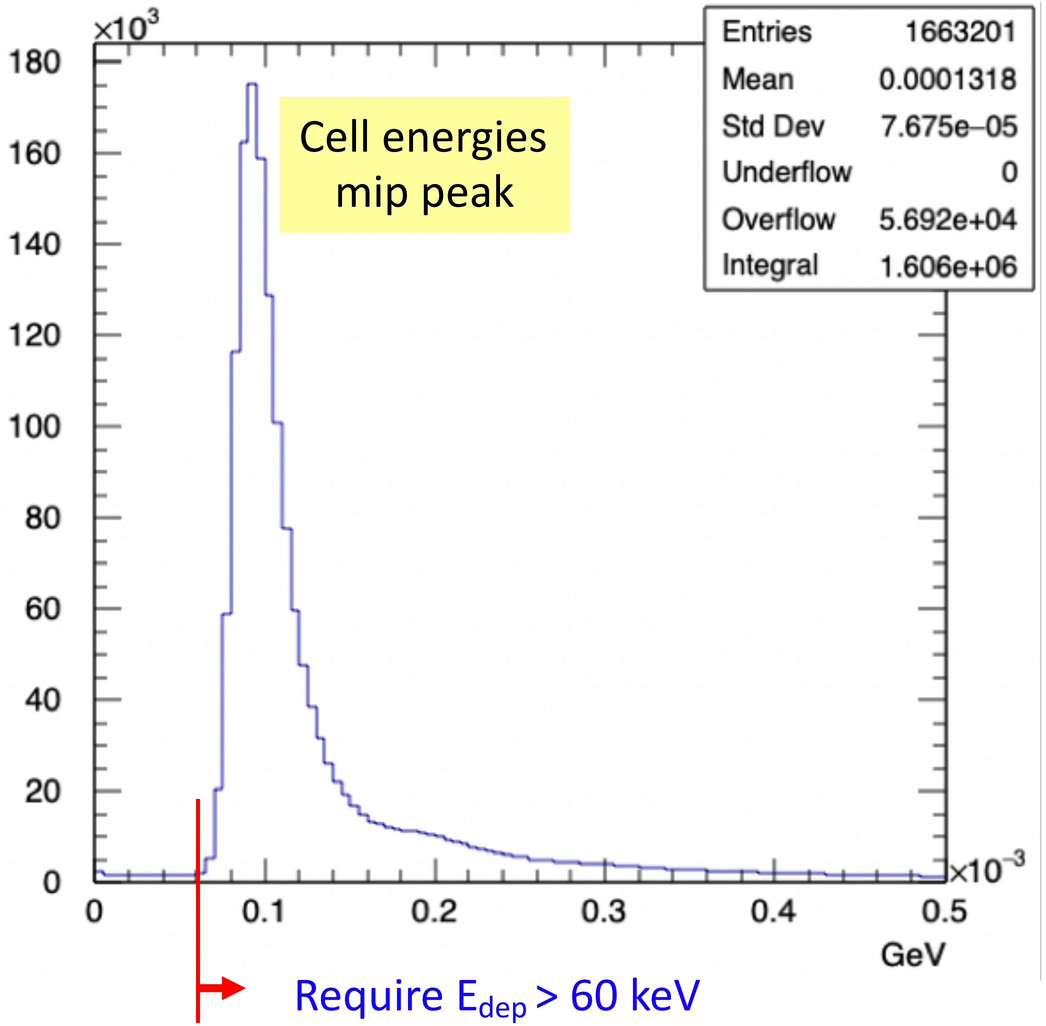
- Monitors centred along outgoing beam line
  - 25 sandwich layers of
    - 3.5 mm W (1 X_0)
    - 1.0 mm gaps with
      - 0.28 mm Kapton
      - 0.32 mm Si sensor
      - 0.40 mm Cu (?)
  - Additional 3.5 mm W layer at back
  - Extending along outgoing beam axis: 1074 -- 1186.5 mm
- Segmentation of Si sensors (increased ϕ segmentation by ×4 wrt CDR):
  - 32 pad rows along r (1.875 mm pads)
  - 128 pad rows along ϕ (CDR × 4)
  - 25 x 32 x 128 = 102400 channels per endcap

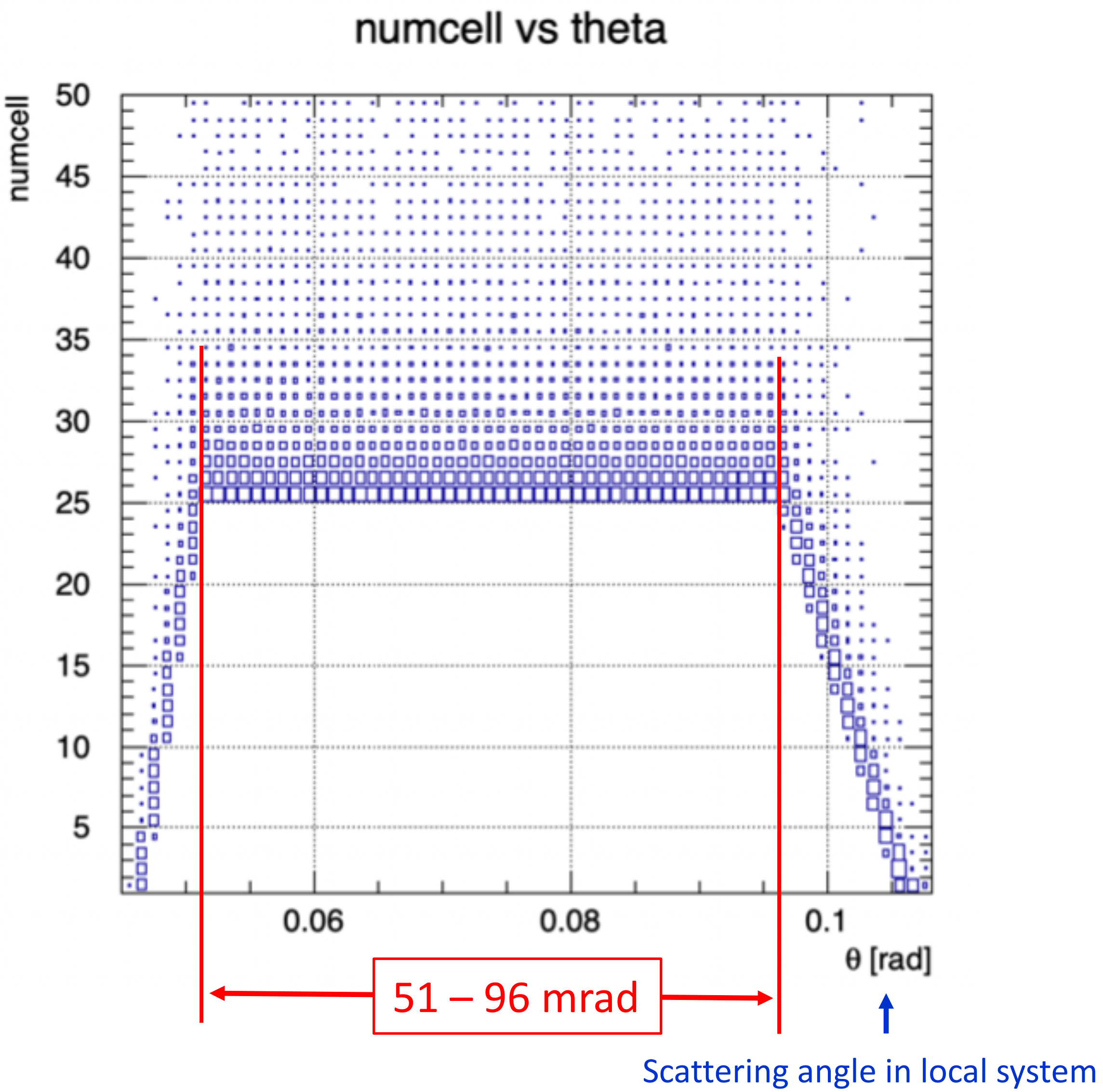
[Actually simulation saves SimHits.
Segmentation applied later in ”analysis stage”.]



Response to Muons

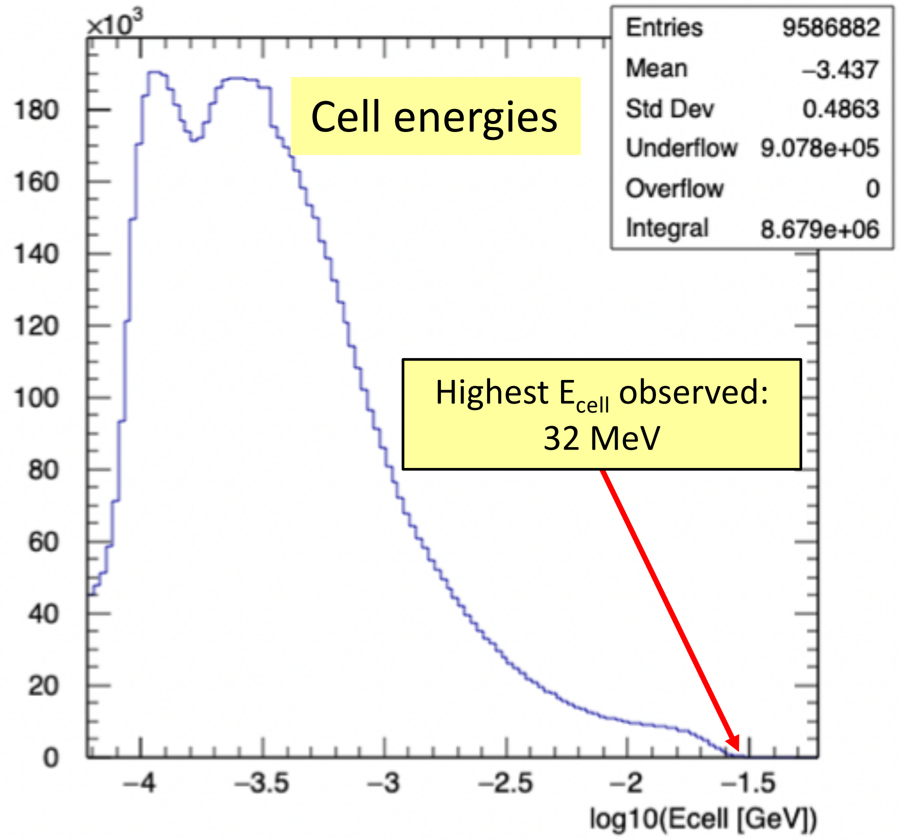
Single particle gun: 45.6 GeV muons

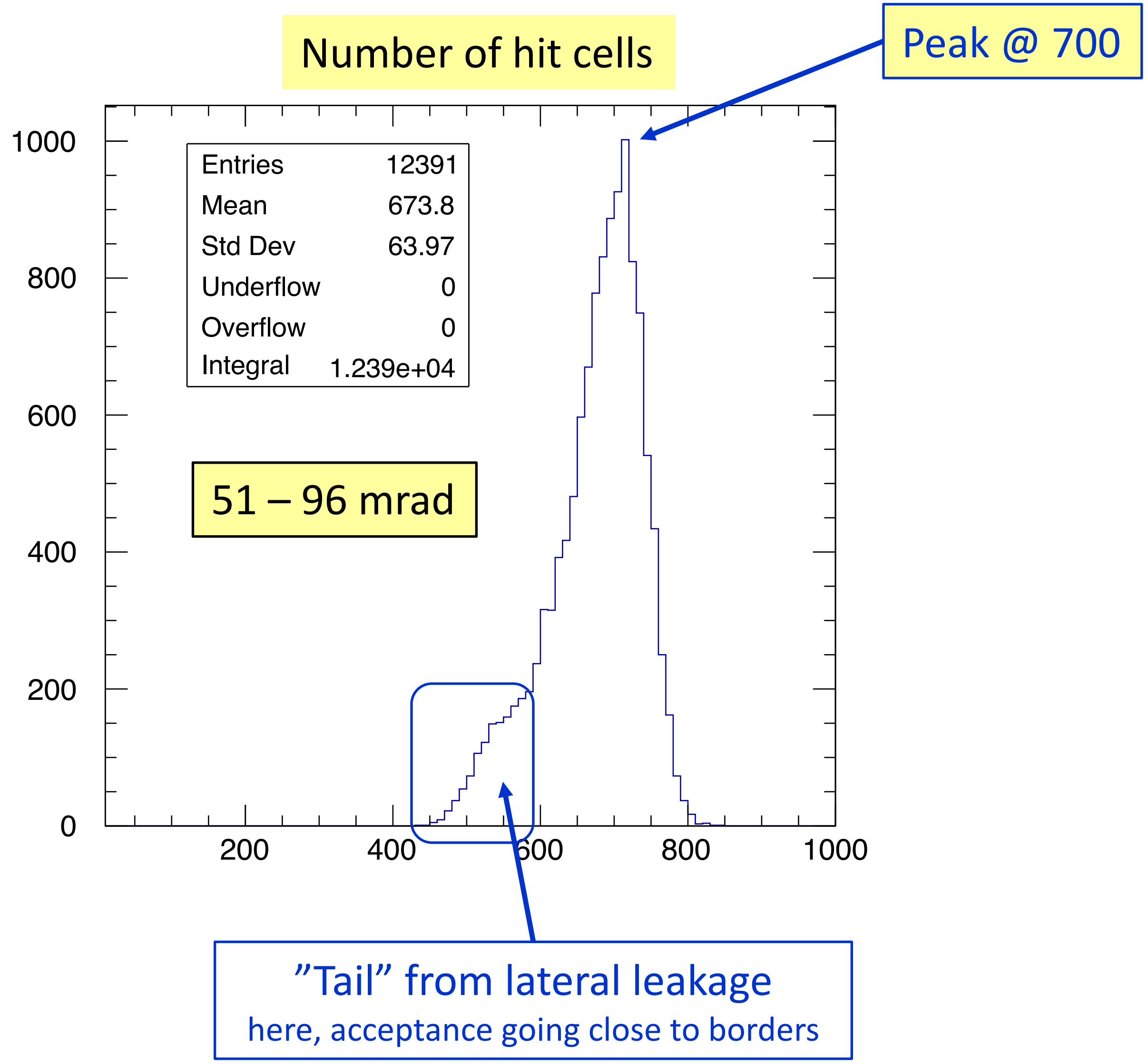




Response to electrons

Single particle gun: 45.6 GeV electrons



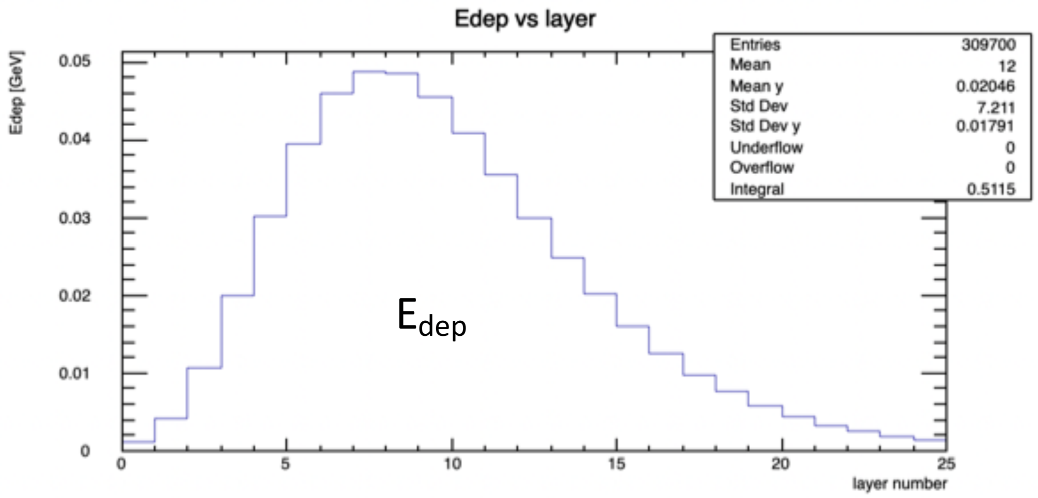


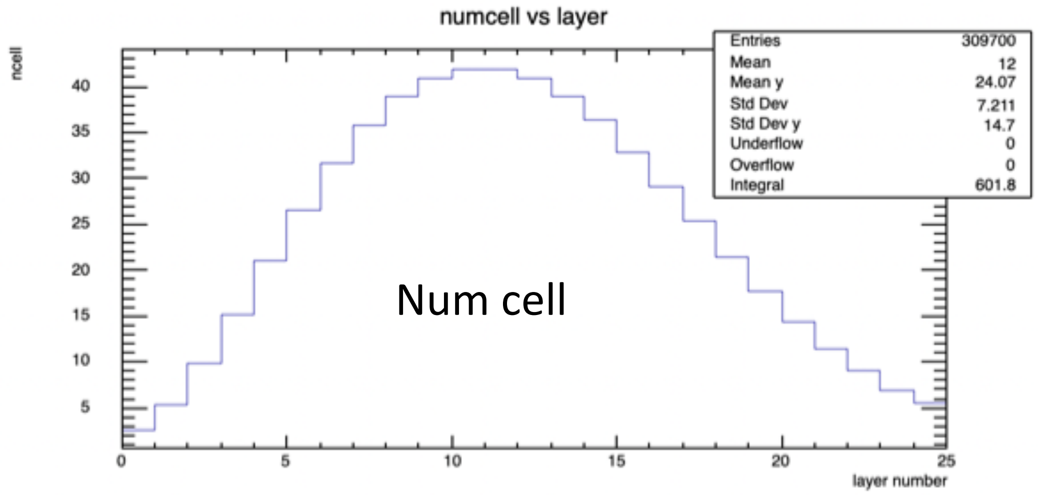
Dynamic range of factor 1000 needed

- mip: > 60 keV
- Electron_max: 32 MeV

Longitudinal Development and Energy Response

Longitudinal shower development

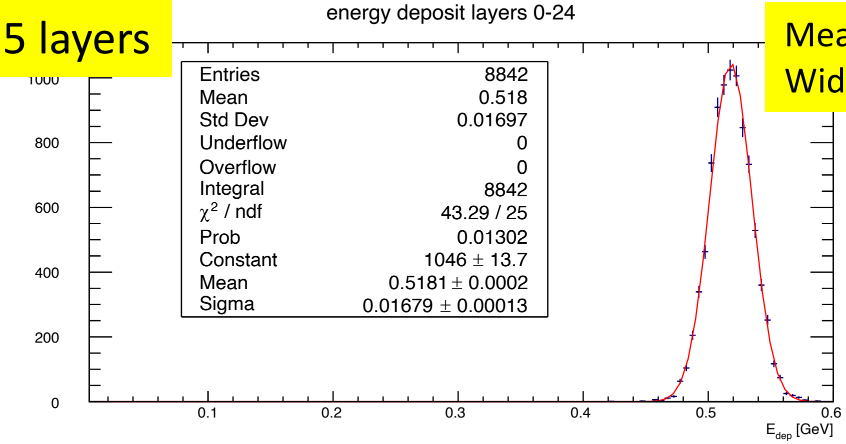




Layer number 0-24

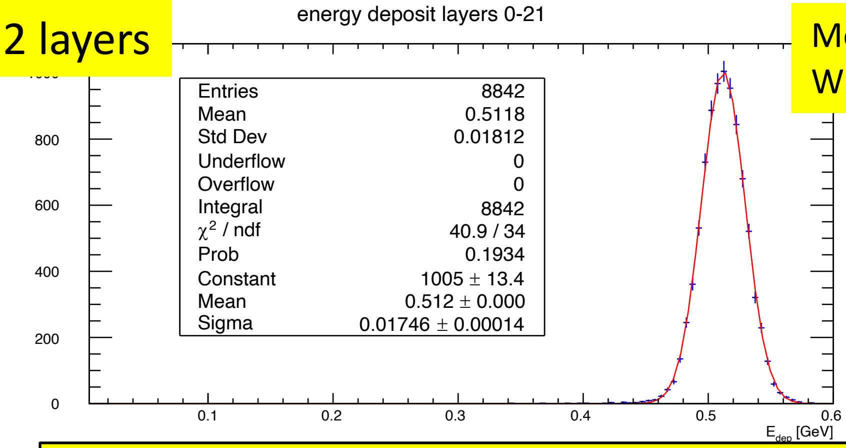
Total deposited energy all layers

25 layers



Mean: 0.518 GeV
Width: 3.2%

22 layers

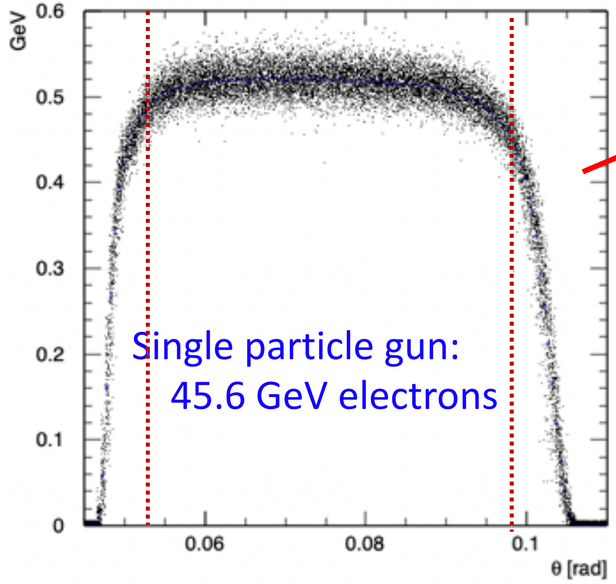


Mean: 0.512 GeV
Width: 3.4%

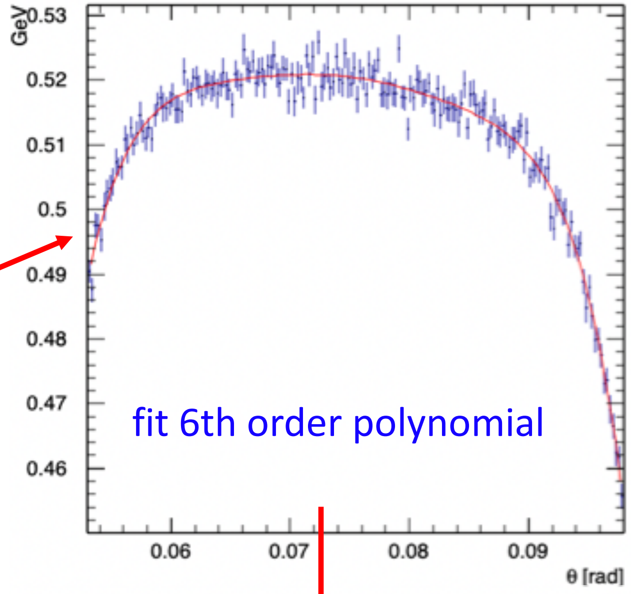
25 → 22 layers:
- Mean energy response falling by 1.2%
- Resolution increasing: 3.2 → 3.4%

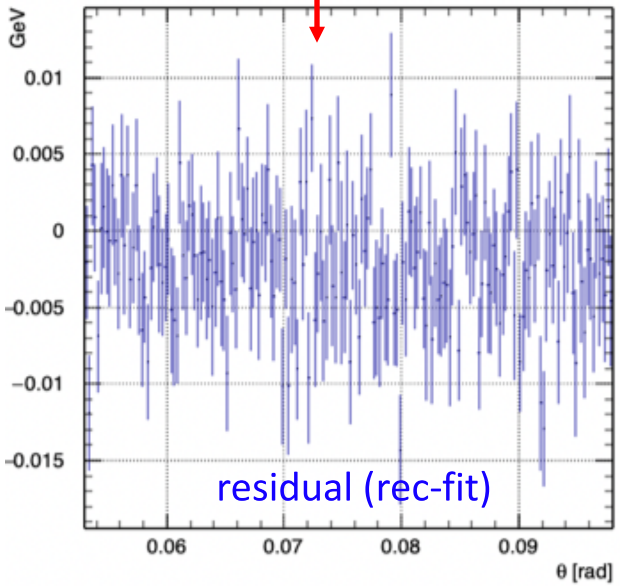
Energy Response and Acceptance

Total calorimeter energy response vs. generated polar angle

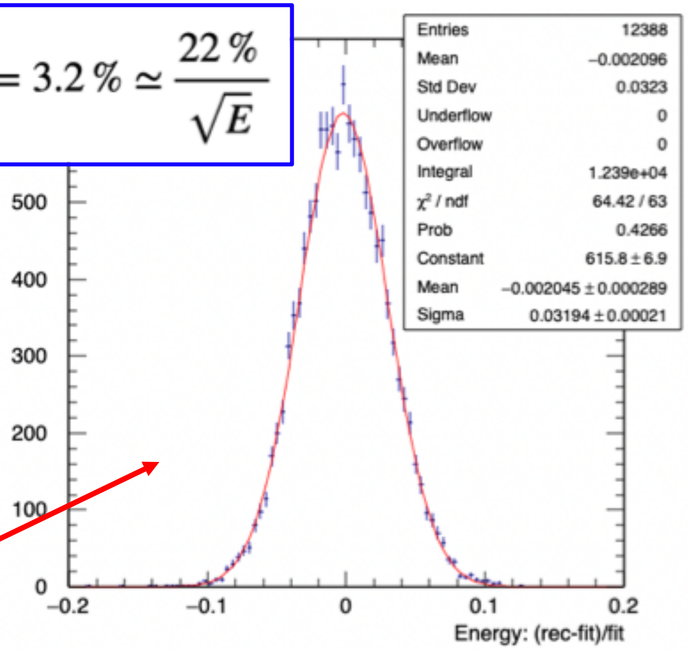


Inside range 53 – 98 mrad





$$\frac{\delta E}{E} = 3.2\,\% \simeq \frac{22\,\%}{\sqrt{E}}$$



Sampling fraction:

$$f_S = \frac{0.52\,\mathrm{GeV}}{45.6\,\mathrm{GeV}} = 1.1\,\%$$

- Angular acceptance
  - CDR (gut feeling based on 15 mm Moliere radius)
    - 62-88 mrad wide; 64-86 mrad narrow
      - σ_{Bhabha} = **14 nb** @ Z peak
  - As indicated here
    - 53-98 mrad wide; 55-96 mrad narrow
      - σ_{Bhabha} = **28 nb** @ Z peak

× 2

Beam Pipe and Cooling Manifold

FCC 31 Jan 2024, LAPP, Annecy 7th FCC Physics Workshop INFN FUTURE CIRCULAR COLLIDER 12

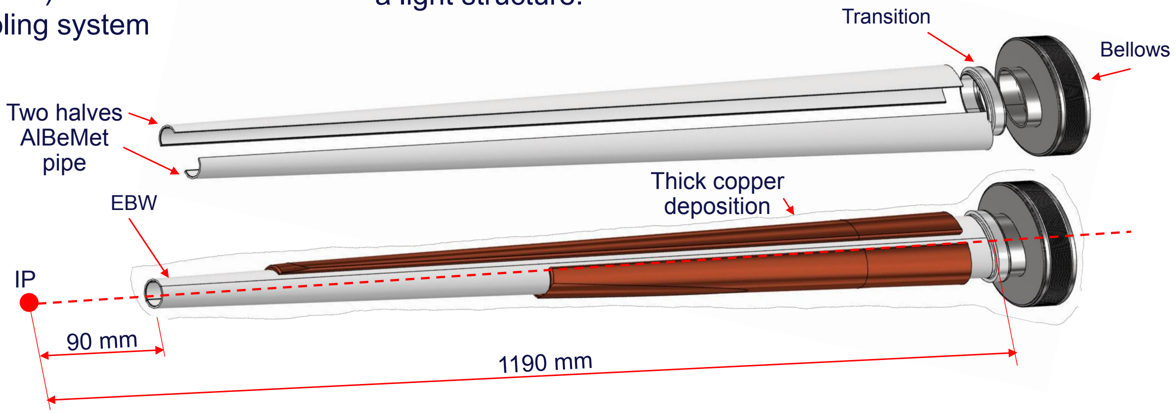
Conical chamber

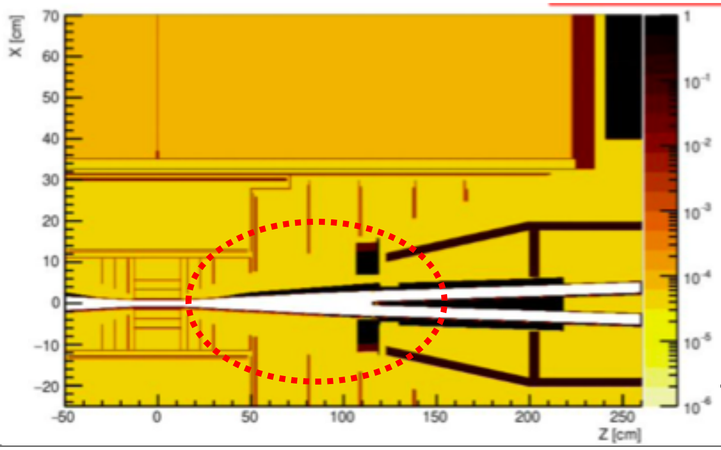
link

Main characteristics:

- Starting from 90 mm to 1190 mm from IP
- AlBeMet162 as main material
- Chamber in two halves and assembled using electron beam welding (EBW)
- Copper cooling system

- The cooling is based on an **asymmetric solution**, using the 50 mrad cone as the cutting profile, to assure the respect of the spatial constraint due to the **LumiCal requirement**.
- To reduce the cooling material, the design provides **five channels** for each side; in this way is possible to use the needed quantity of coolant and reduce the material, creating a light structure.

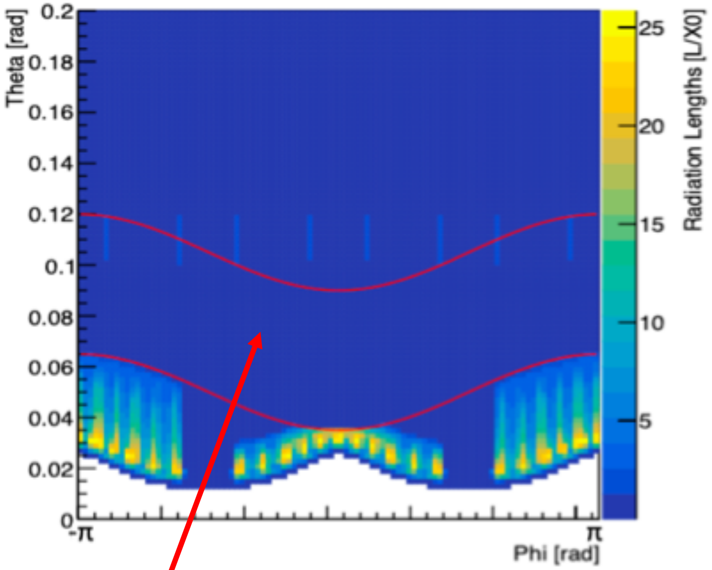




- FCCee MDI
- CLD inner tracker

Talk by Thomas Madlener this morning

Up to 20 X_0 just below LumiCal accepance



LumiCal acceptance

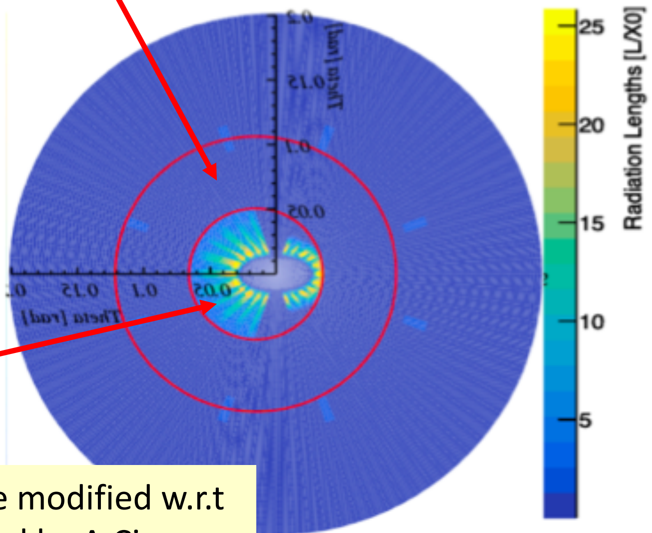
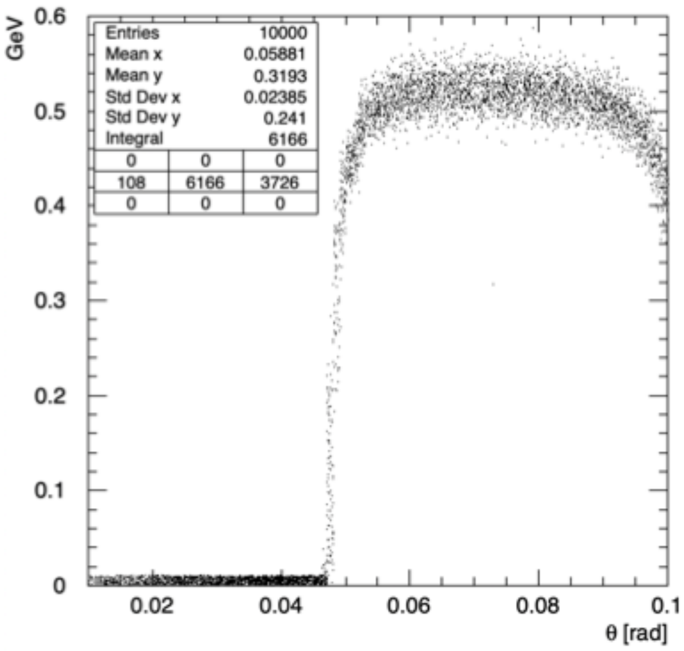


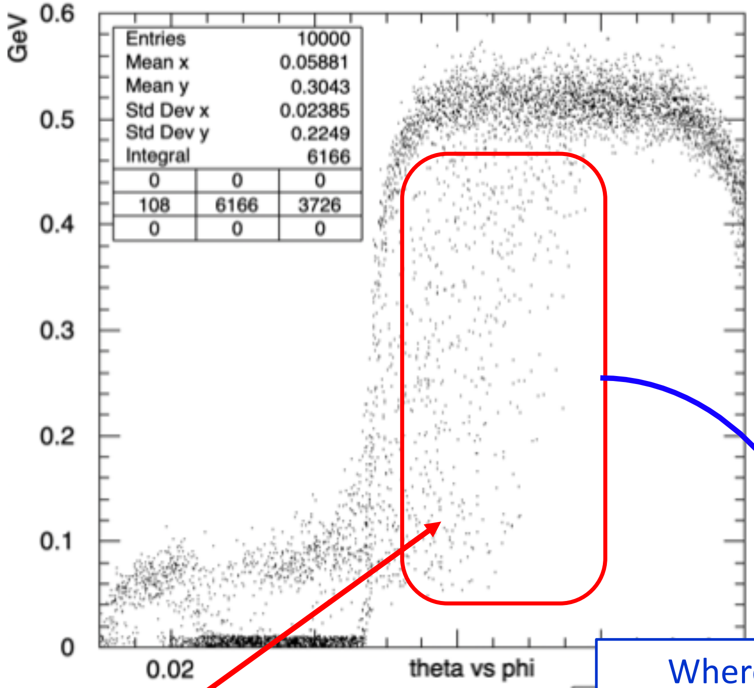
Figure modified w.r.t original by A.Ciarma

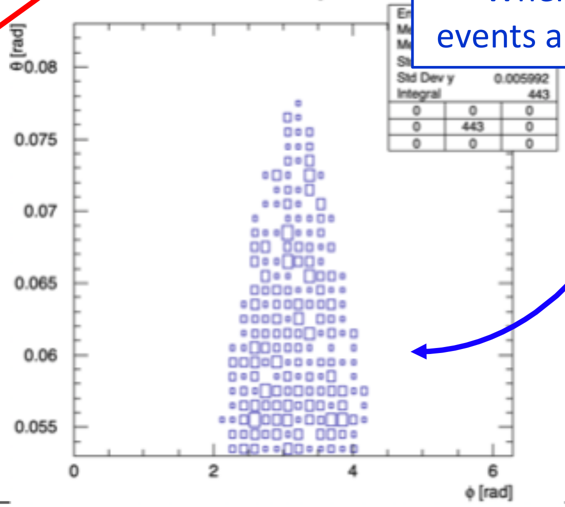
First (erroneous!) results of beam pipe simulation

No beam pipe



Beam pipe in FCCSW

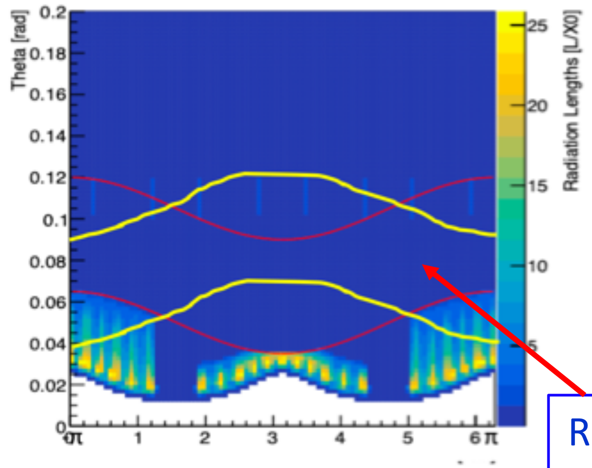




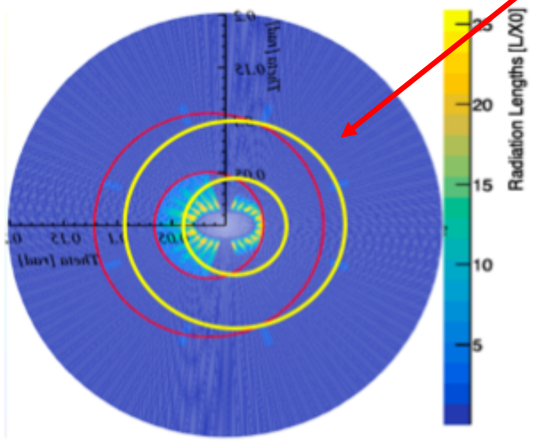
Where these events are situated

Catastrophic loss of energy inside LumiCal acceptance window!

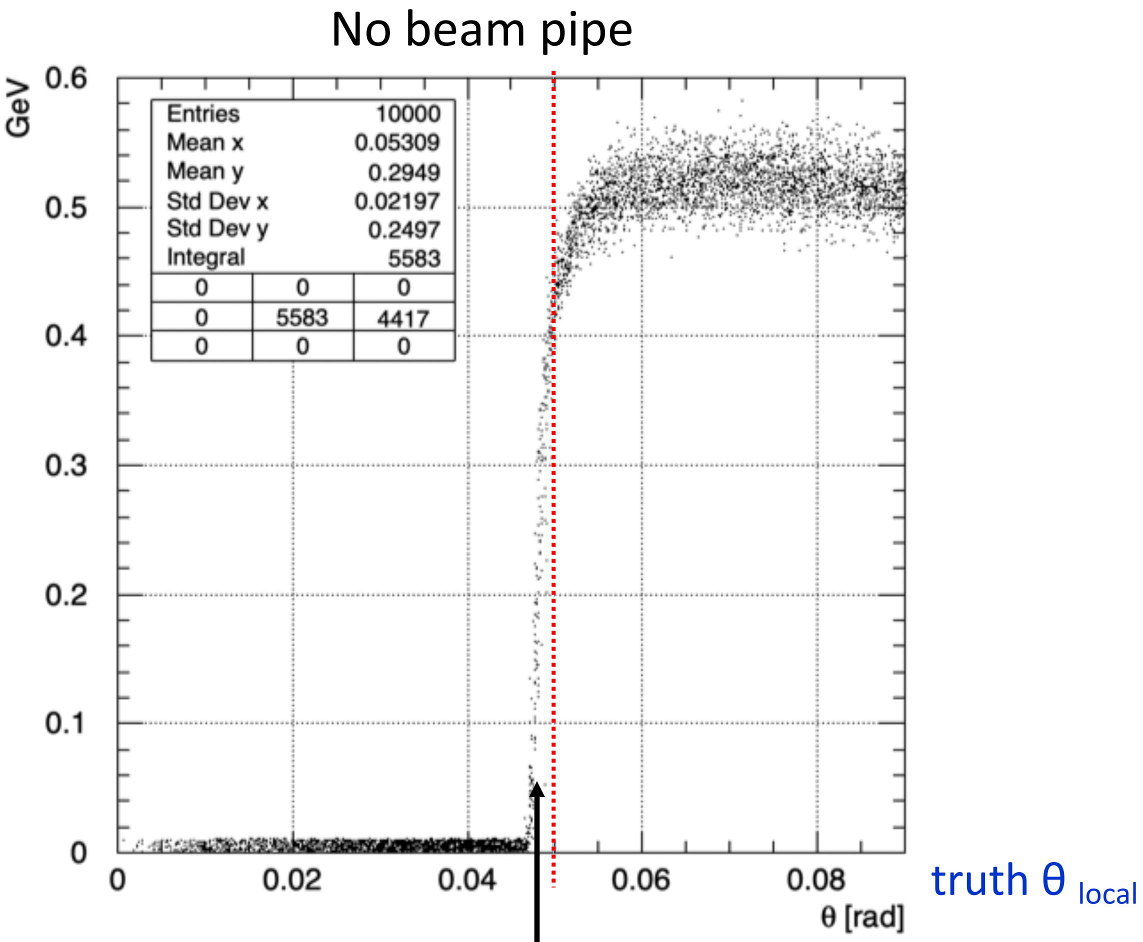
Turns out that in FCCSW, LumiCals were mistakenly centred around *incoming* (positive x) and not *outgoing* (negative x) beam lines!

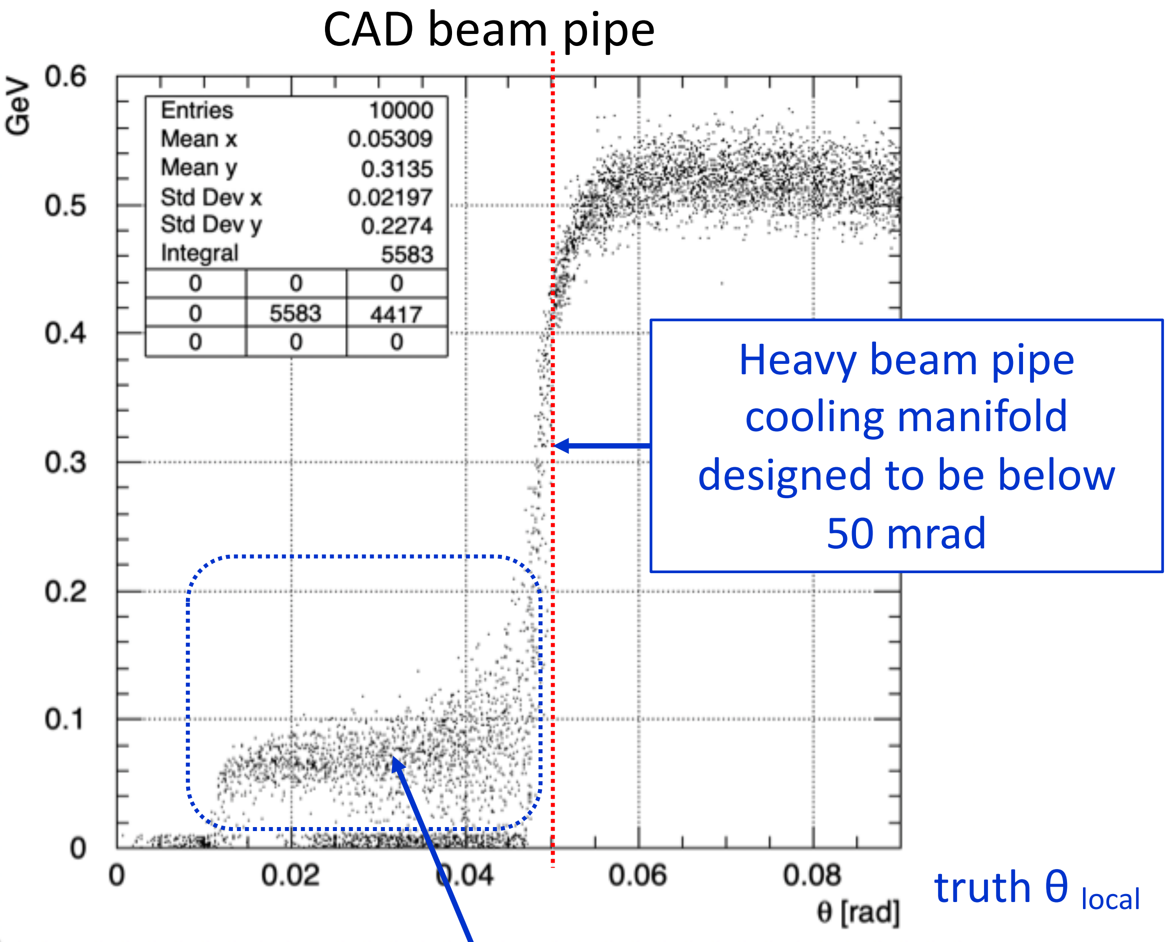


Red: correct
Yellow: wrong



Influence of Beam Pipe (Correct placement)

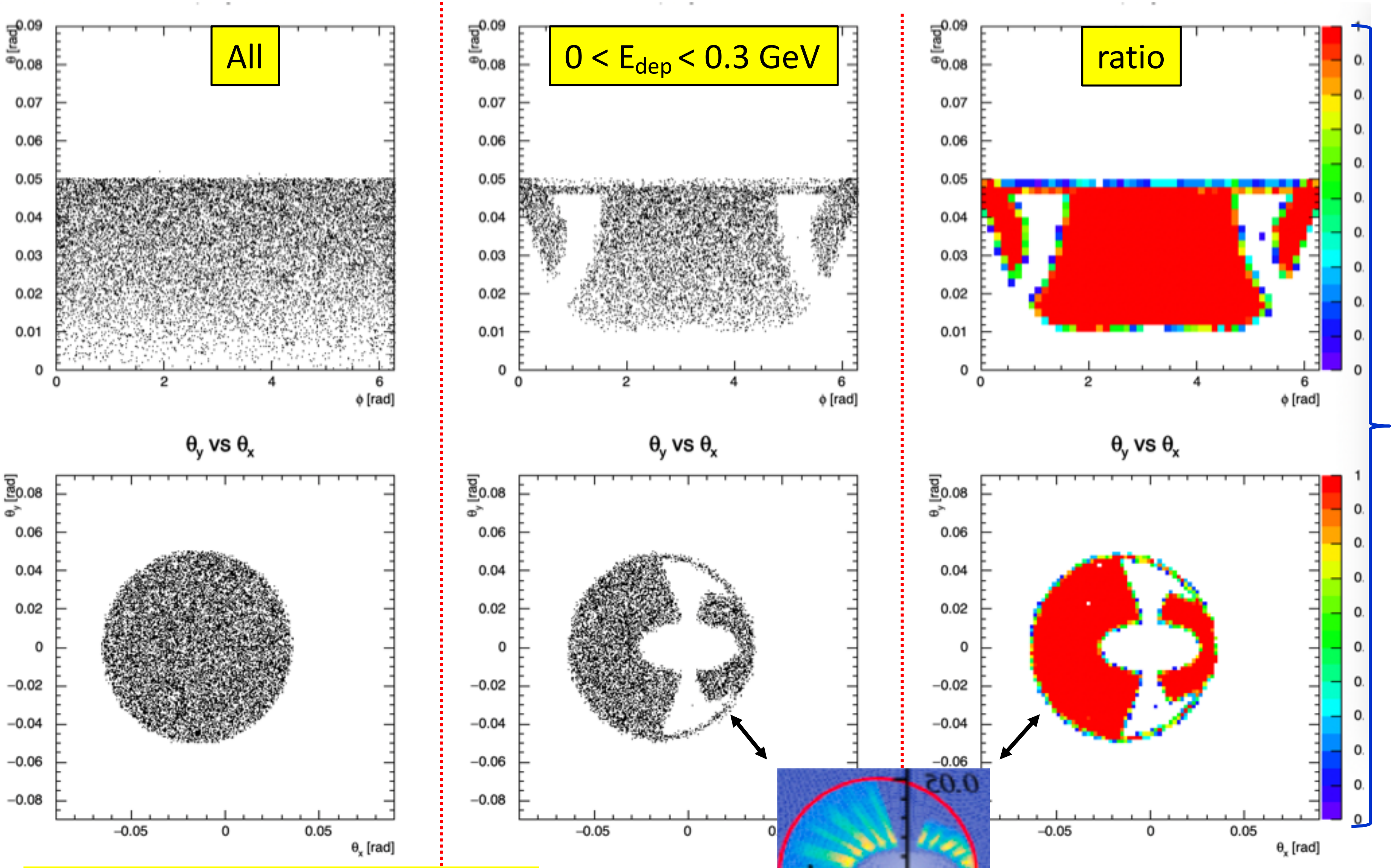


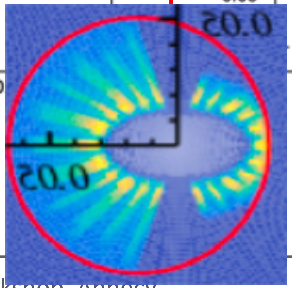


Sharp turn-on of energy response at LumiCal acceptance boundary

Energy deposit in the LumiCal from particles genereted below aceptance. Energies about 10-15% of Bhabhas.

Influence of heavy Cooling Manifold





Single 45.6 GeV electron sample generated flat inside $\theta_{local} < 50$ mrad

Conclusion

About 2/3 of 45.6 GeV electrons produced in the range θ = 12-50 mrad give sizeable energy deposit in LumiCal due to shower development in heavy cooling manifold

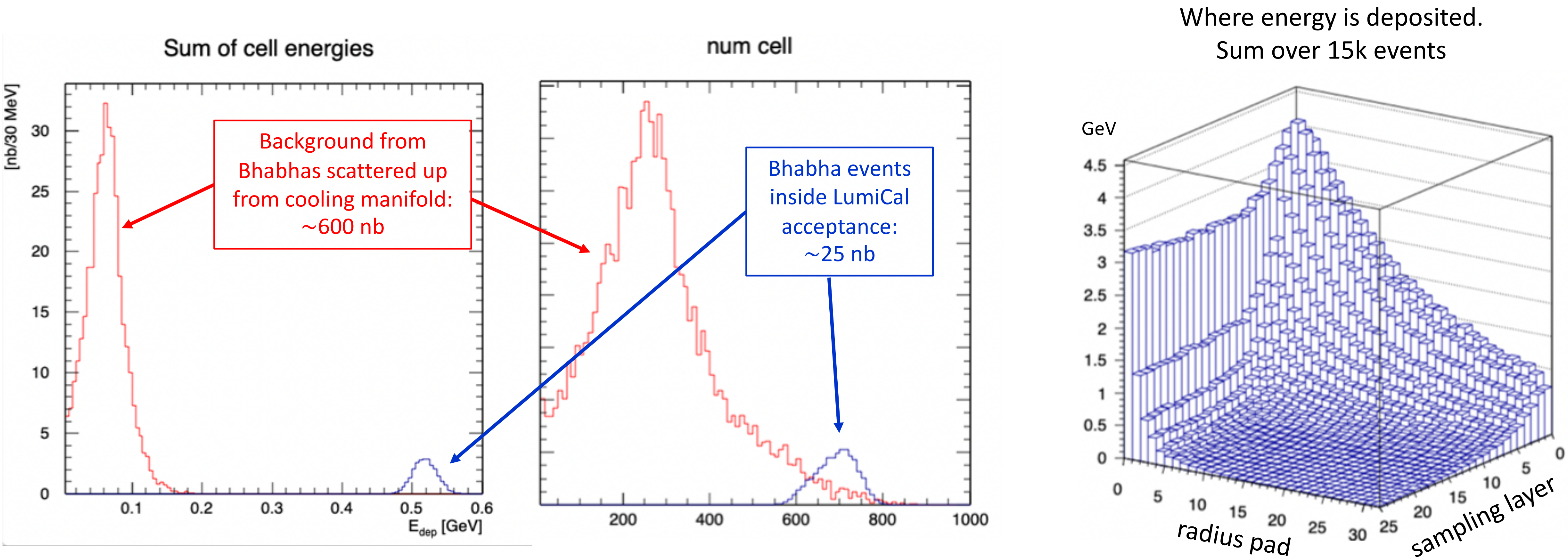
Rate estimate

- $\sigma_{BB}^{10\text{-}50\ \mathrm{mrad}} = 900$ nb
- $L = 1.8 \times 10^{36}$ cm^{-2} s^{-1}
- x 2/3

⇒ **Rate ≈ 1.1 MHz** ⇐

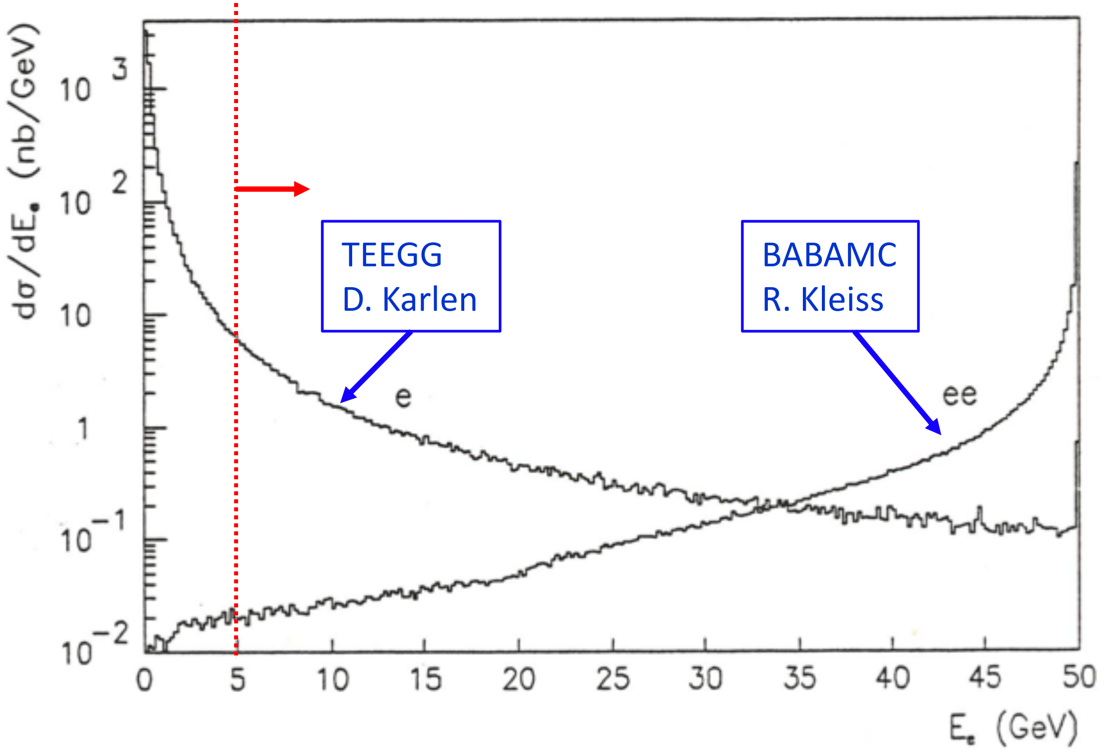
- 25 times Bhabha rate
- One out of 45 BX

Bhabha background scattered from Cooling Manifold



- Background ×25 higher rate than Bhabha signal
- Background energy 5-15% of Bhabha
- Background event enerdy can be spread over a sizeable number of cells
- Energy deposited primarily at low radius and/or early in calorimeter (first half)

Bhabha and "Single Bhabha" rates



Rule of thumb:

- For an energy cut, $E_{DEP} > 0.1 * E_{BEAM}$, single Bhabha rate ≈ Bhabha rate

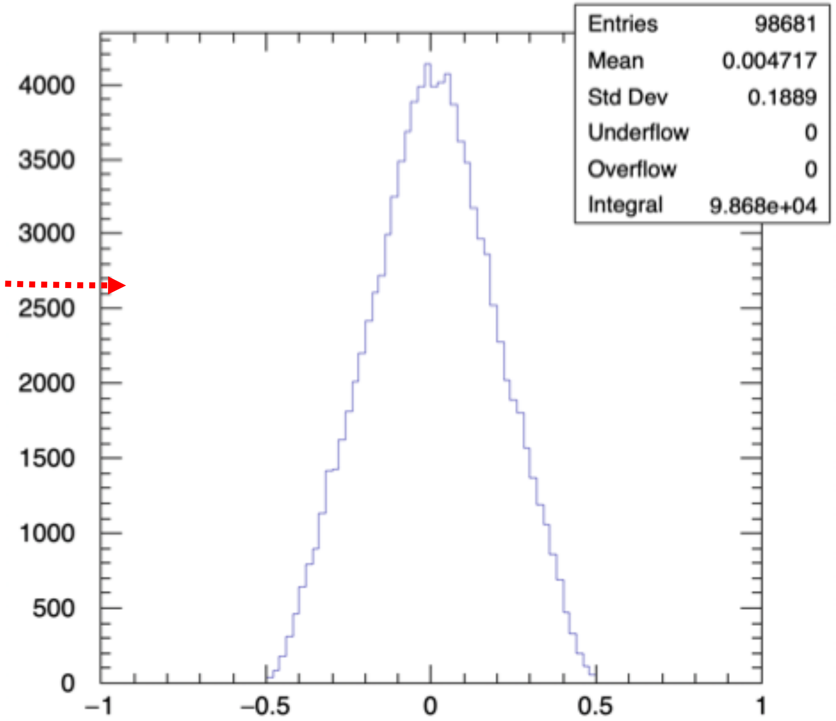
LumiCal Spatial Resolution

- Concentrate at this time only on the radial coordinate
- Quote everywhere resolution at a z reference plane corresponding to the 7th Si layer (Layer 6)
  - z = 1104.91 mm

- General philosophy:
  a. Simply use the centre-coordinate of the Si pad with maximum deposited energy as estimator in a given plane
  b. Optionally correct this r-estimator, r_i for radial pad i, with the correction function

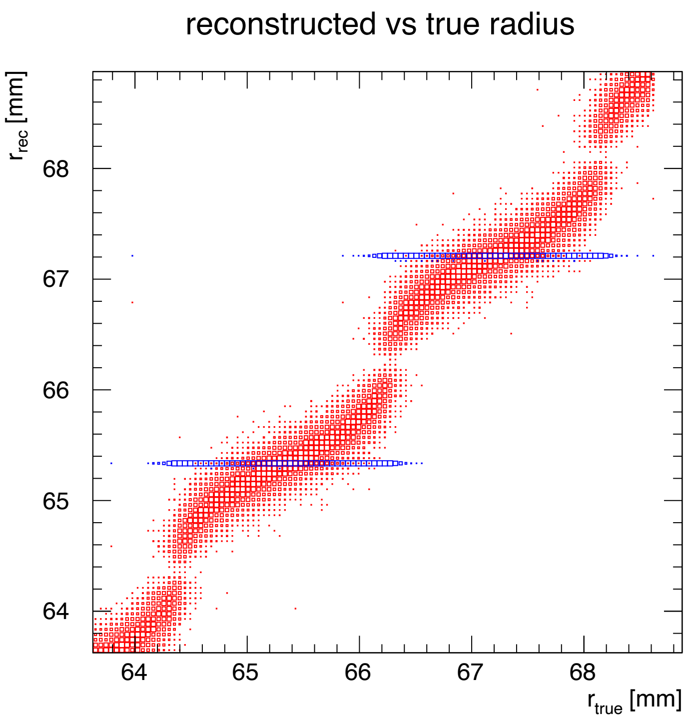
$$\delta r_i = \frac{E_{i+1} - E_{i-1}}{E_{i+1} + E_i + E_{i-1}} \times w,$$

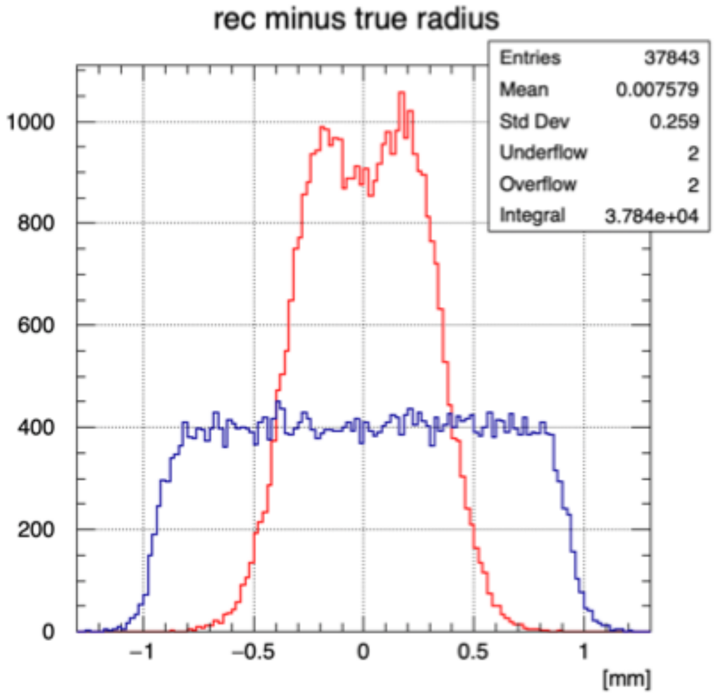
where w is the pad width

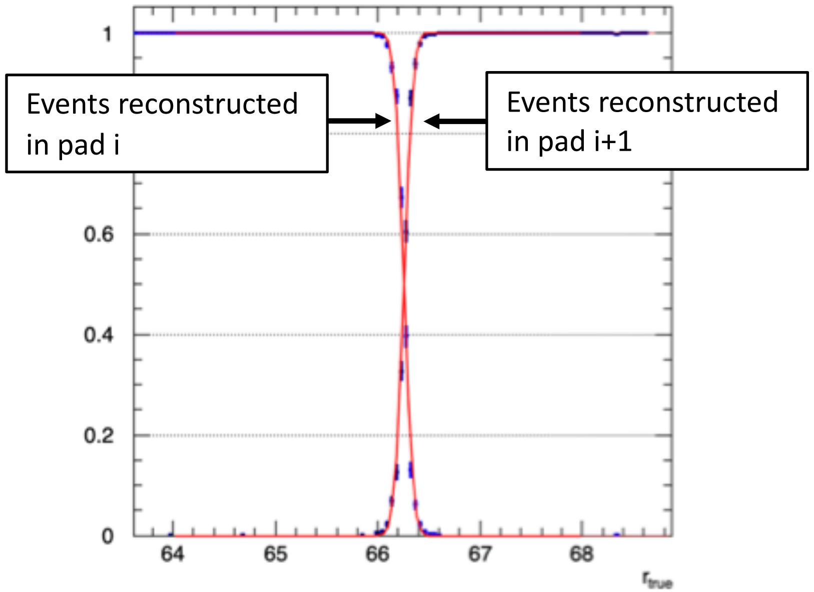


- This moves the r-estimator inside the pad boundary of the max energy cell but never it outside the cell

Spatial Resolution – Use Layer 6 only







Width of overlap region gives **resolution at boundary**.
From fit of function:

$$\frac{1}{2}\left(1 + \mathrm{Erf}\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right)$$

σ = 73 µm

Blue: Use pad center
Red: Use correction function

$$\delta r_i = \frac{E_{i+1} - E_{i-1}}{E_{i+1} + E_i + E_{i-1}} \times w,$$

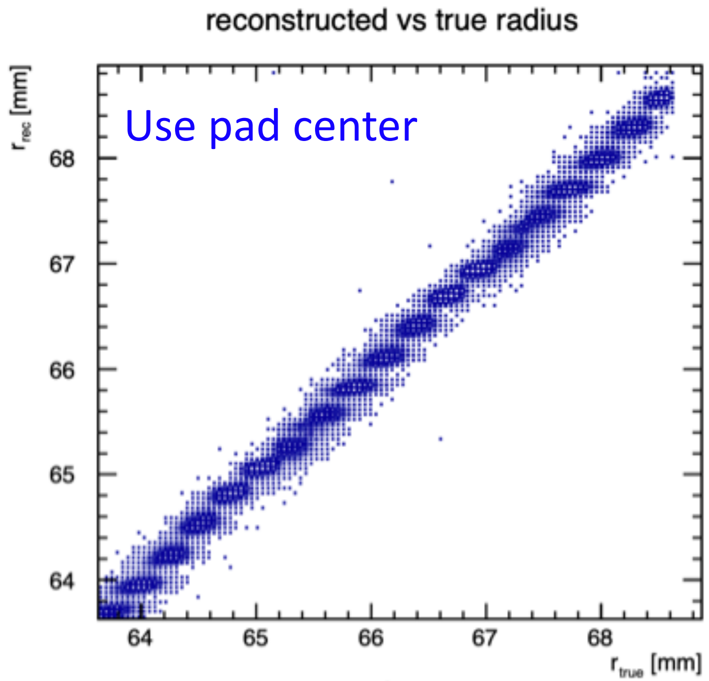
Average resolution:
- 546 µm
- 259 µm

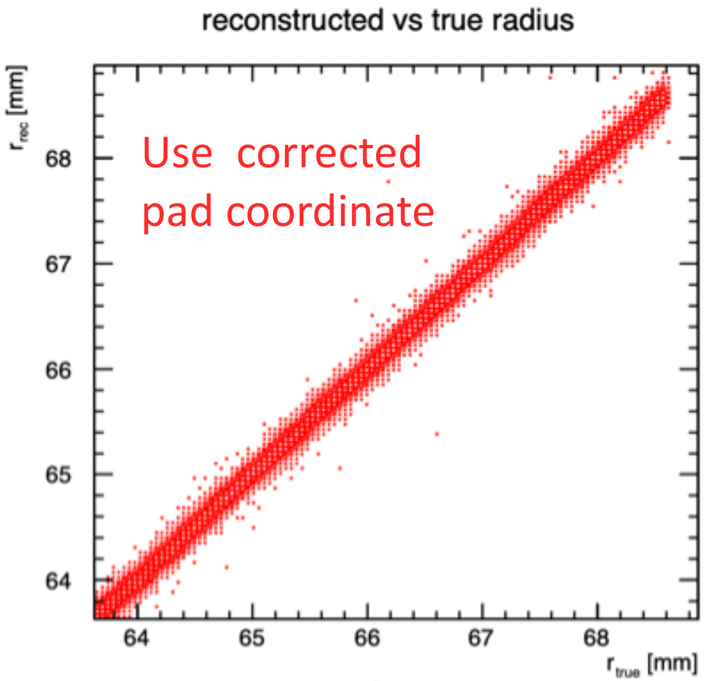
Note: 1875 µm / √12 = 541 µm

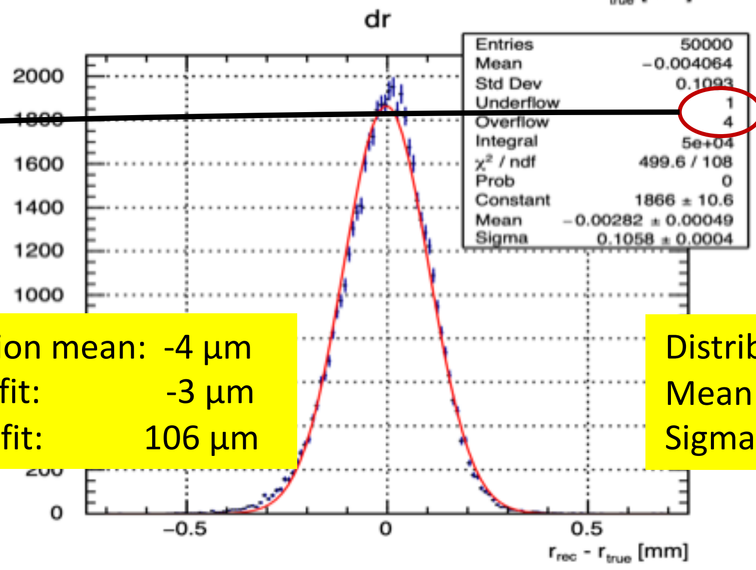
Spatial Resolution – Use Layers 2-9

Each of 8 layers provide an estimator of the r-coordinate at the reference z. Use the energy averaged of these 8 estimators as the overall estimator.

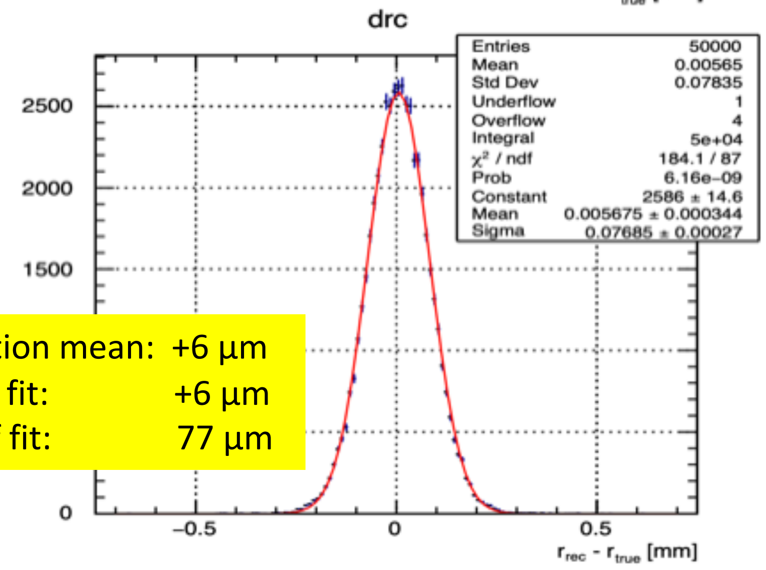
Since the geometry is non-pointing there are now 8 times as many pad boundaries to cross
⇒ Much better *average* resolution over surface







Distribution mean: -4 µm
Mean of fit: -3 µm
Sigma of fit: 106 µm



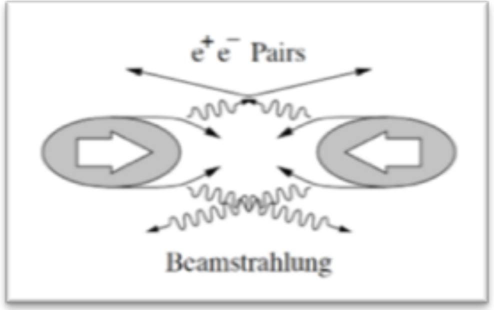
Distribution mean: +6 µm
Mean of fit: +6 µm
Sigma of fit: 77 µm

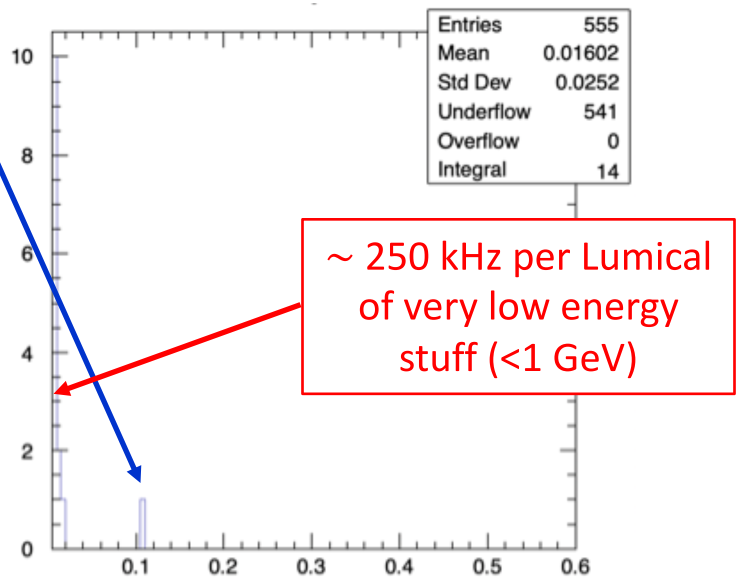
Beware:
Over-/underflow
at the 10^{-4} level

Summary of LumiCal Rates

Source	Cross section / rate	Energy
$\mu^+\mu^-$ (possibly valuable for alignment)	10 Hz	Deposit: 0.25 GeV equivalent
Bhabha	40 nb / 70 kHz	45.6 GeV
Single arm Bhabha ($E>0.1 \times E_{BEAM}$)	40 nb / 70 kHz (single arm)	5 - 45.6 GeV (peaking low)
Beam-beam interaction e^+e^- pairs	100 kHz (single arm)	~ 5 GeV
Bhabha scattered from Manifold	1100 kHz (mainly double arm)	0-7 GeV

Extremely uncertain estimate:
One event from the GunieaPig simulation of 555 bunch crossings

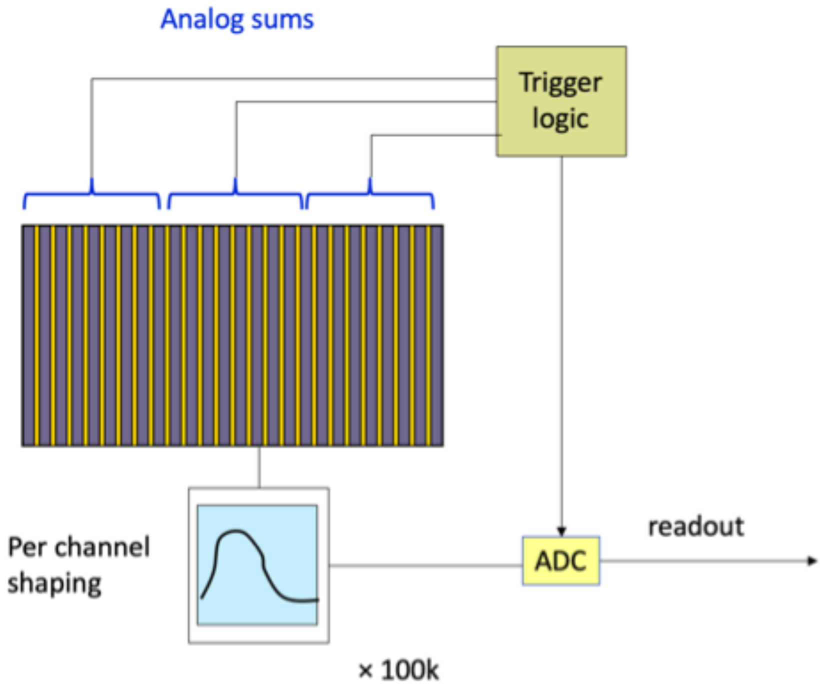




- Probability to have a second event ("pile-up") on top of a Bhabha event in same BX:
  - 70 kHz : 0.14 %
  - 1100 kHz : 2.2 %
- Would we have to integrate over several BX(?), numbers increase corresponsingly
- Important to minimize pile-up in order to undersand energy repsponse
  - "Keep it clean"

First thoughts on local read-out

- For alignment purposes, we may wish to save muons
- Seems we cannot push out all active channels, i.e. all channels above mip threshold (60 keV deposited) in all bunch crossings
- Probably need some kind of local trigger, e.g.
  - Analog sum in depth of e.g. 3 x 8-9 layers with some ϕ segmention
  - From fast shaped analog sum signals, take local decision per LumiCal on readout
    - Energy threshold for Bhabha
    - Depth requirement for muons
- Slower (more precise/less power hungry) shaping of the full set of channels
  - On local trigger accept, digitize and read out all channels (w. zero suppression)



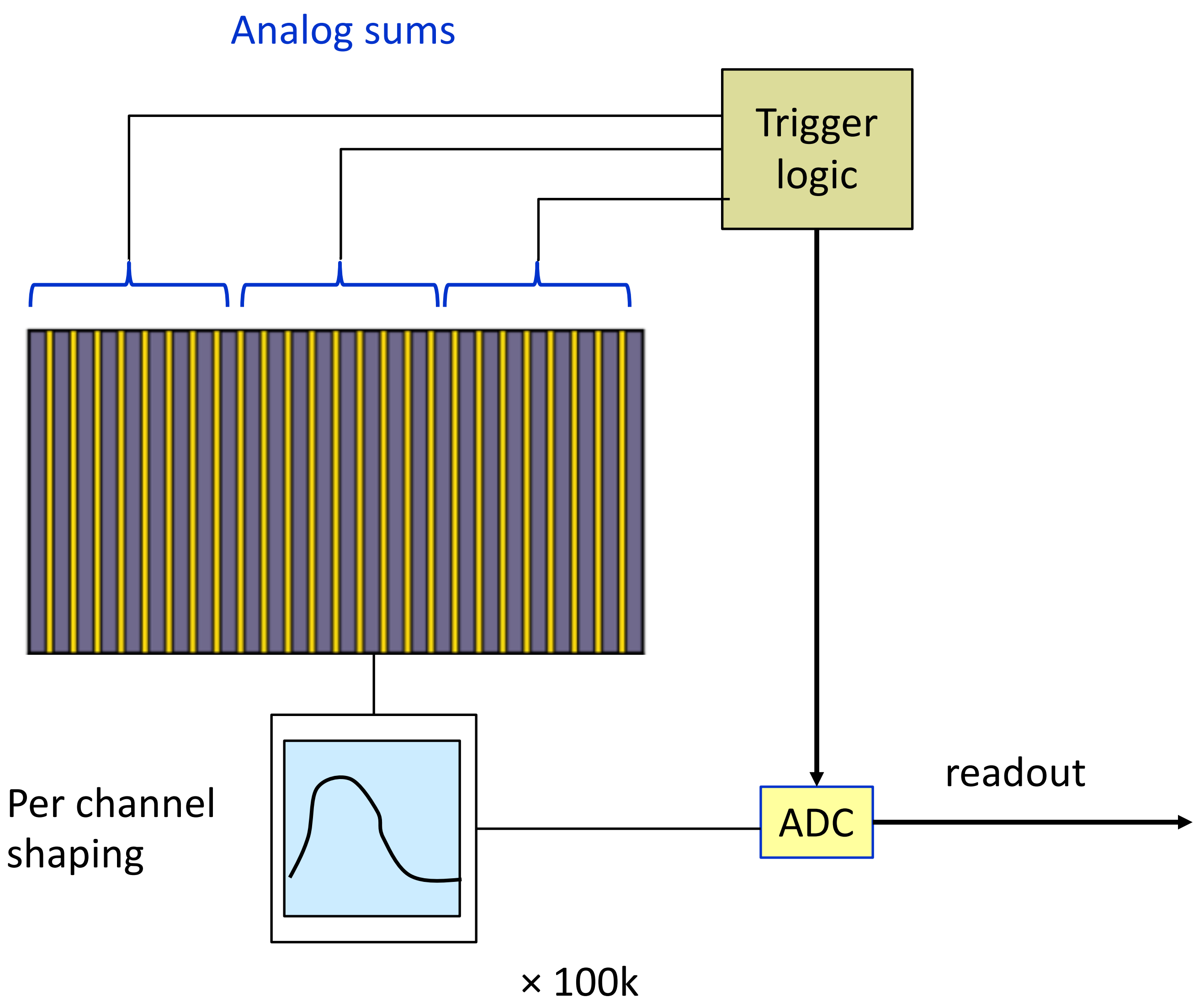
Summary & Conclusions

- Ambitious FCC-ee absolute normalisation goal of 10^{-4}
  - More than a factor 3 better than at LEP in less favourable conditions
- First results from full simulation of LumiCals
  - Maximum pad energy deposit from core of e.m. shower corresponds to ~500 × mip signal
    - EM shower spreads over ~700 cells (out of 100k)
  - Energy resolution of 3.2% at 45.6 GeV for 25 sampling layers of 1 X_0 each
  - By correcting for lateral energy leakage, LumiCal acceptance can be 55-96 mrad corresponding to 28 nb for Bhabha scattering without comprimising energy resolution
    - × 2 larger cross section that CDR estimate
  - Heavy Cu beam-pipe cooling manifold causes large rate of leaked em showers from Bhabhas into LumiCal acceptance
    - 25 x Bhabha rate ⇒ 2.2% pile-up rate inside same BX
  - Spatial resolution of ~75 μm on radius coordinate at border between two Si pads
    - By exploiting signals from several longitudunal samplings, resolution of same order over full calorimeter surface

Thank you for your attention!

And a special thanks to Brieuc Francois for his untireable helpfulness with the software

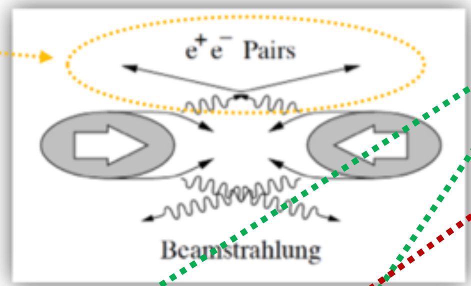
Extra material


Analog sums
Trigger logic
readout
ADC
Per channel shaping
× 100k

Beam-background: e^+e^- pairs

<u>Study presented at 2018 FCC Week, Amsterdam</u>

- e^+e^- pairs created in beam-beam interactions
  - Dominant process at FCC-ee: Incoherent pair production
  - Events studied/generated by GuineaPig program
- Example: **Z-pole energy**
  - 800 $e^\pm$ particles per BX (with E > 5 MeV)
  - 500 GeV radiated in total per BX

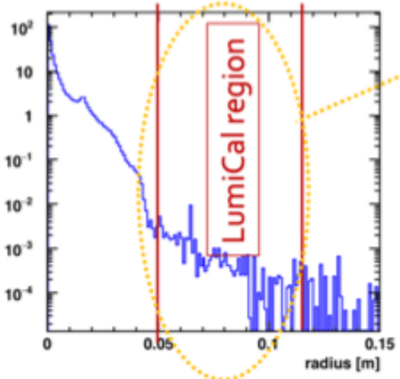


Basis for study:
- events generated by **GuineaPig** program
- helix extrapolation to LumiCal face

- Number of radiated particles and their total energy evolve strongly as function of √s
  - Also energy per radiated particle increases ⇨ Focussing becomes realtively weaker
  - At Z-pole energy, very low energy into LumiCal region
  - At top-energy, energy into LumiCal region at the GeV level – study ongoing

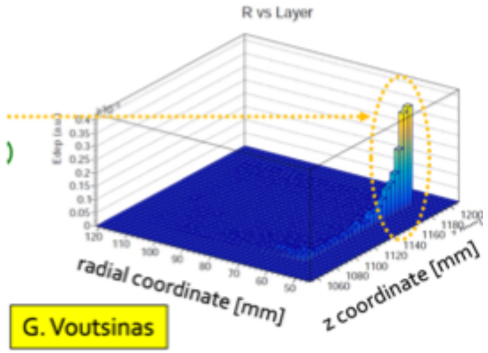
Energy	# e± total	# e± LumiCal	Energy total	Energy LumiCal
91.2 GeV	400	0.3	250 GeV	0.06 GeV
365 GeV	3100	15	4500 GeV	3.2 GeV

[N.B. Numbers given here are per LumiCal]



Conclusion:
- Very high per BX number of generated e^+e^- pairs and radiated energy
- Generally very low particle energies ⇒ strong focusing in detector B-field ⇒ rather low per BX energy hitting LumiCal :
  60 MeV @ 91.2 GeV

At the time, full simulation showed 300 MeV impact on LumiCal @ 91.2 GeV. This was based on the wrong positioning of the LumiCals around the incoming beam axis



Now, full simulation reanalysis of original GuineaPig sample confirm 60 MeV number.

Conclusion: New study, reconfirms that beam-beam background is not an issue for LumiCals at FCC-ee