Franco Bedeschi, INFN
Giornate sulla ESPP
Roma, September 21st, 2020

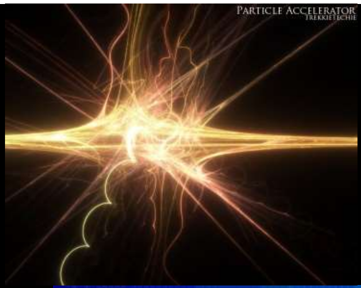
Detector R&D for a circular e+e- collider

OUTLINE

- Physics/accelerator drivers
- The IDEA detector
- Design guidelines
- Ongoing R&D
- Concluding comments

Setting the stage

- ESU approved from CERN council in June 2020
  - «**An electron-positron Higgs factory is the highest-priority next collider**……… a feasibility study of the colliders and related infrastructure should be …. completed on the timescale of the next Strategy update.»



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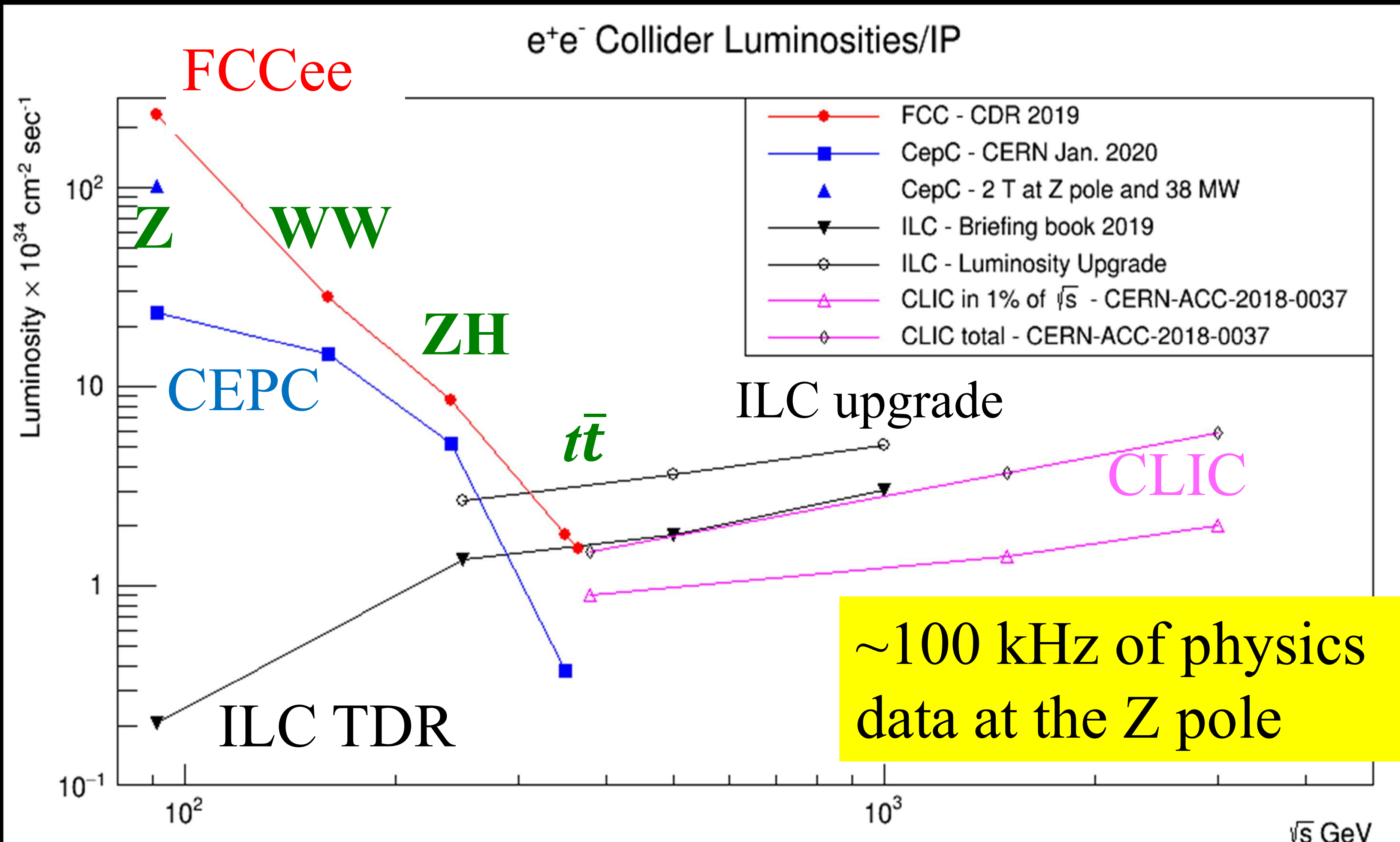
Implications on time scales:

- Proto-collaborations by end of 2023
- Experiment LoI (~TDR) by EU strategy 2025/26
  - R&D and detector design largely completed

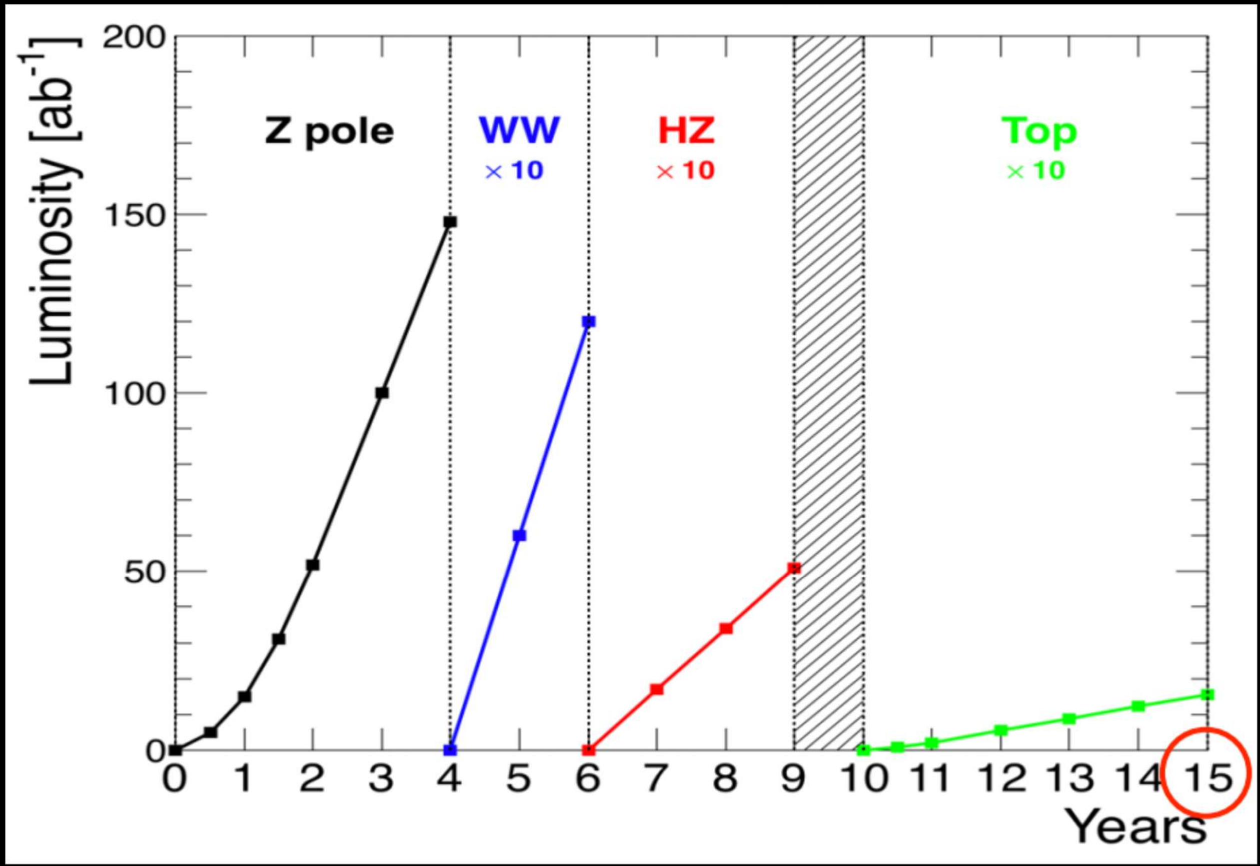
Luminosity is the key



~100 kHz of physics data at the Z pole

Physics at FCC-ee

- Higgs factory
  - 10^6 e+e- → HZ



Physics plan still under discussion – Order may change

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  - 3×10^{12} e+e- → Z
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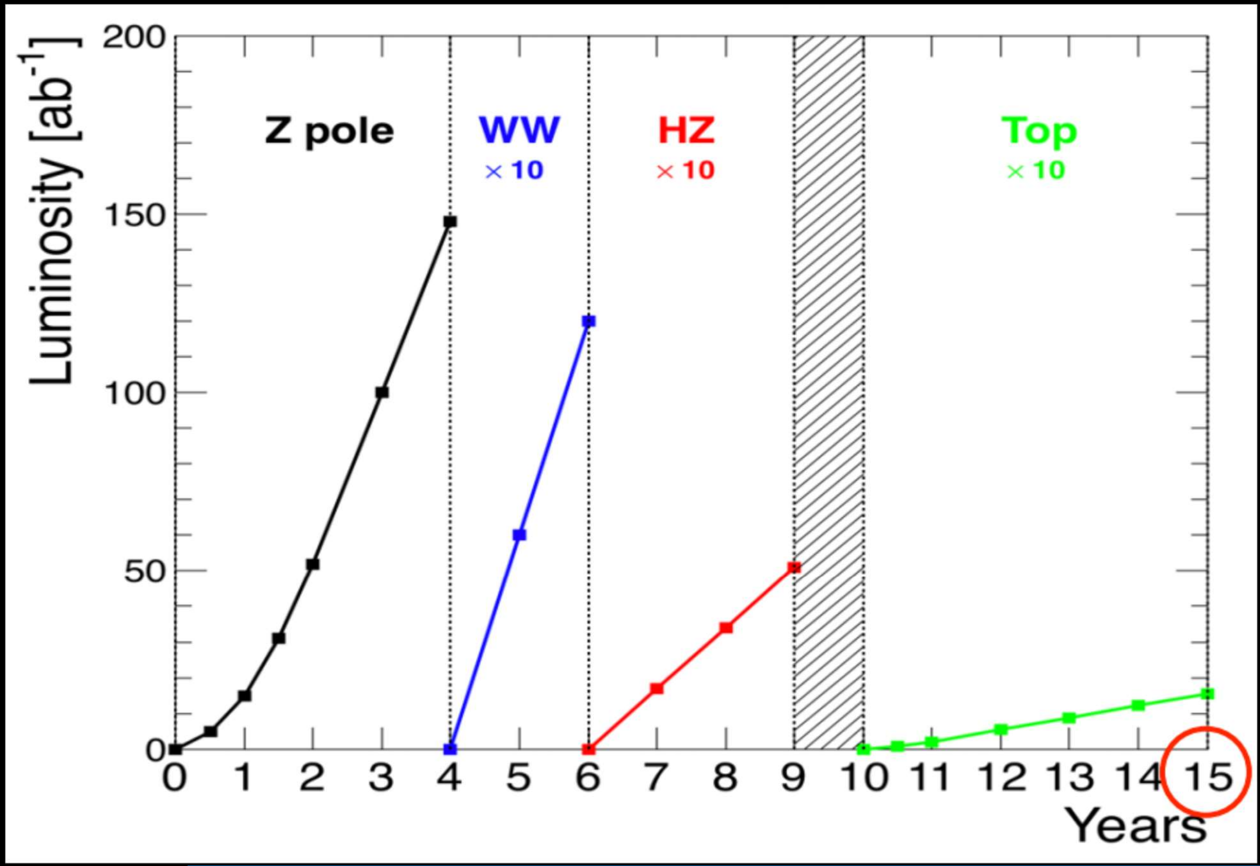

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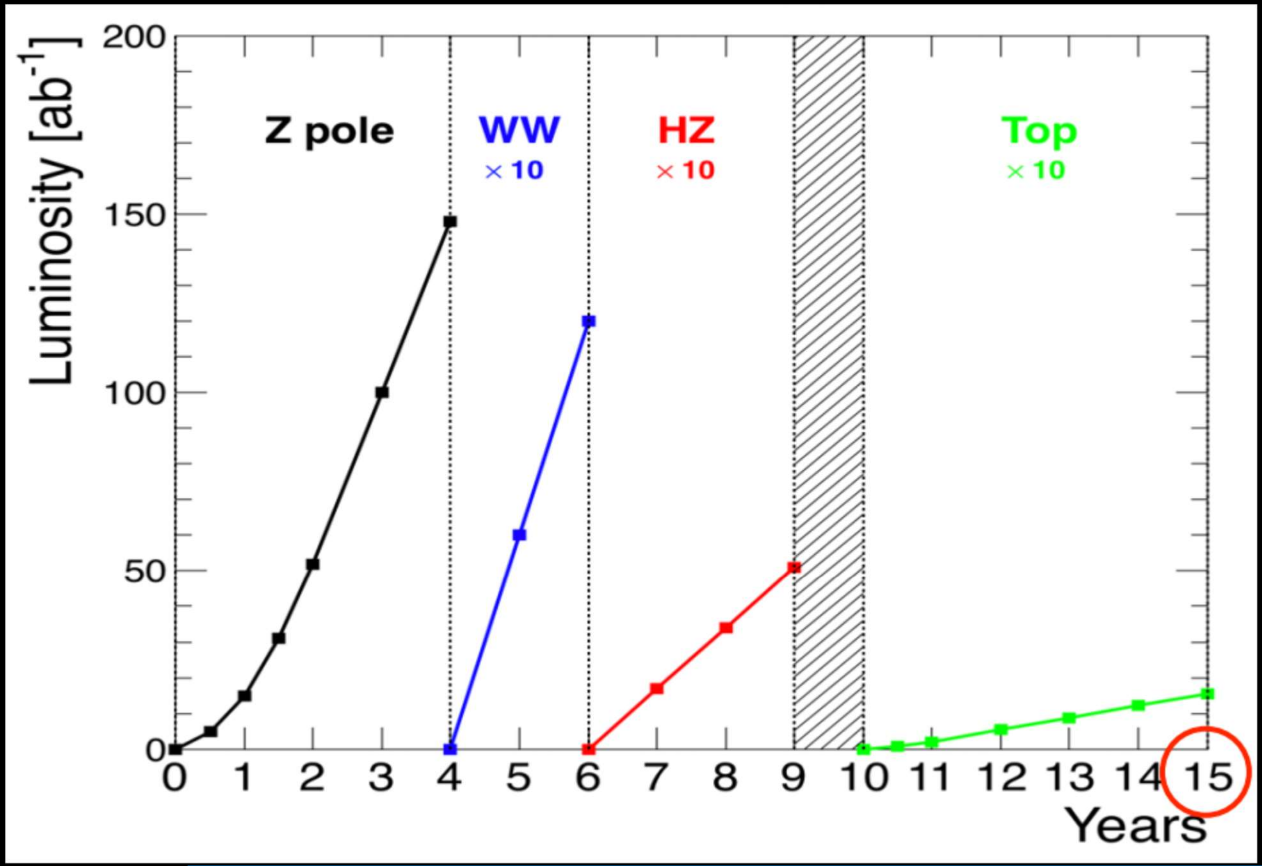
- Flavor factory
  - $5x10^{12}$ e+e- → bb, cc
  - 10^{11} e+e- → **τ+τ-**



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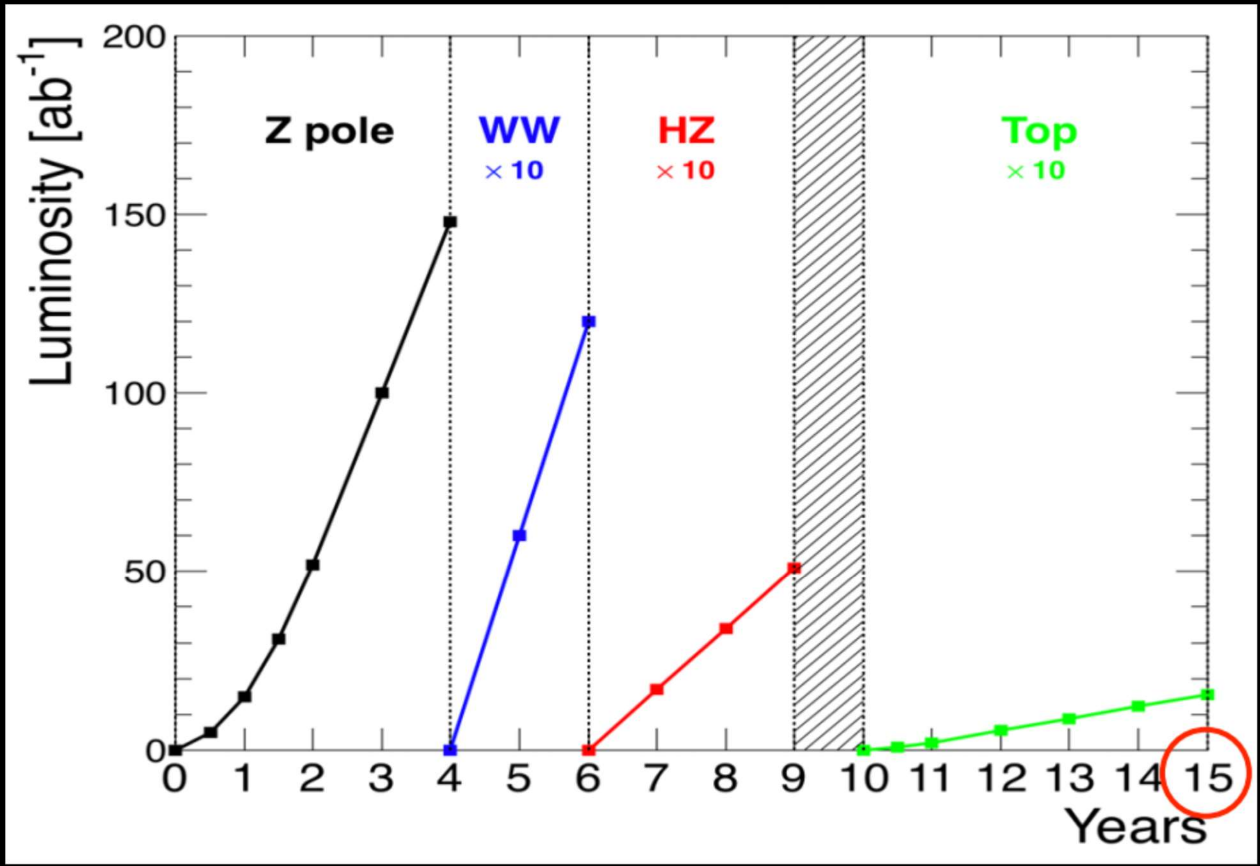
- Potential discovery of NP
  - ALPs, RH ν's, …



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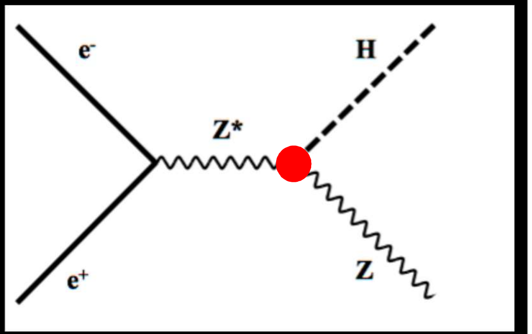
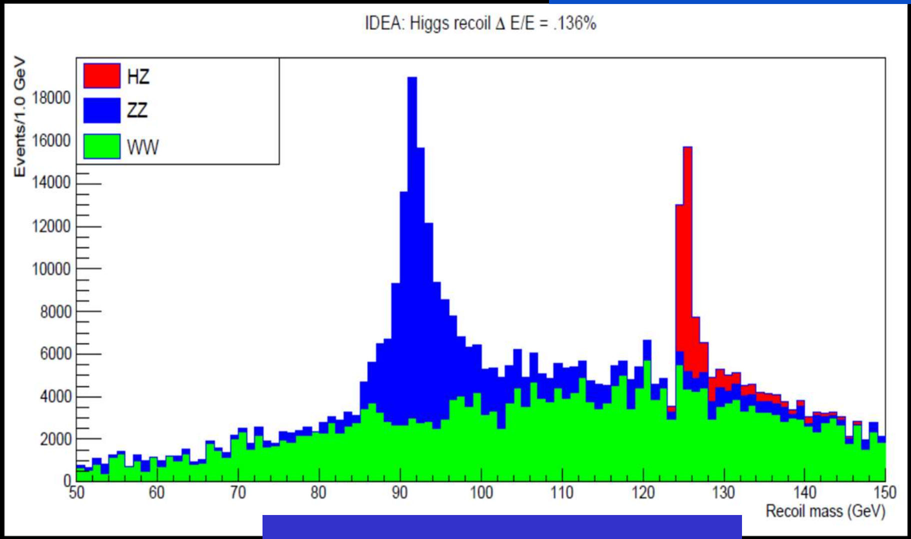
Higgs total width

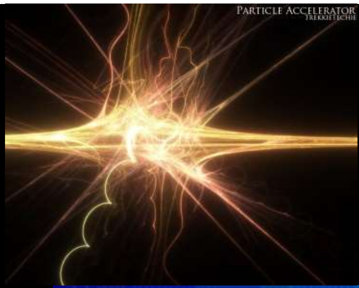
- Higgs recoil provides model independent measurement of coupling to Z
  - $\sigma(HZ) \propto g^2_{HZ}$

L = 5 ab^{-1}





Z→μμ recoil



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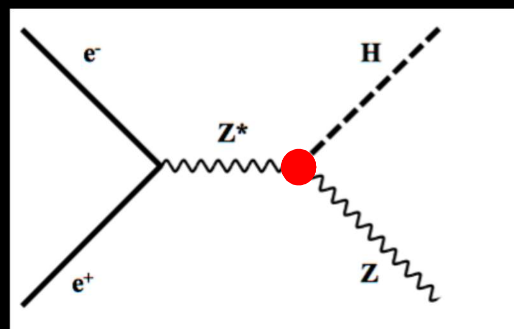
    - Beam energy spread: SR+BS
    - Tracking/jet resolution



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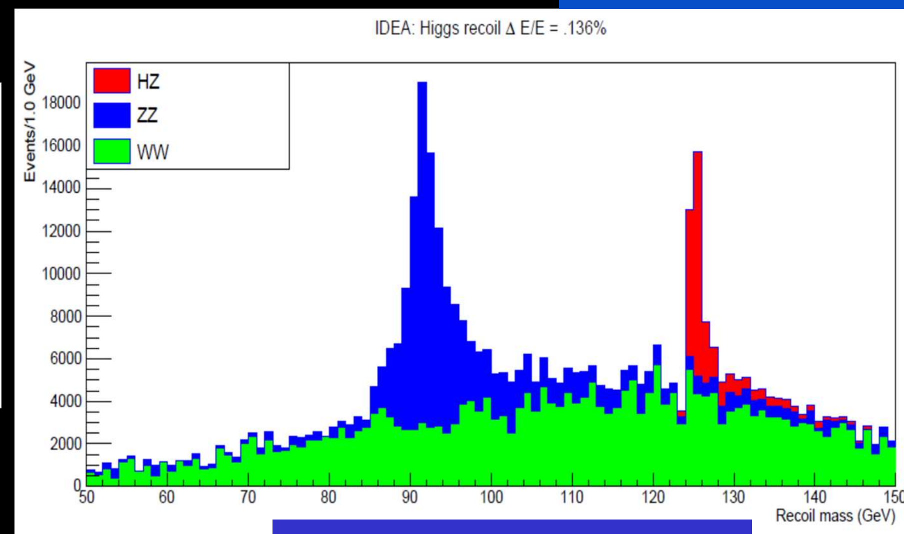

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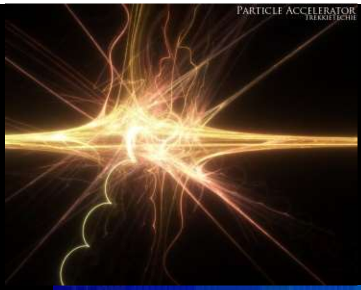

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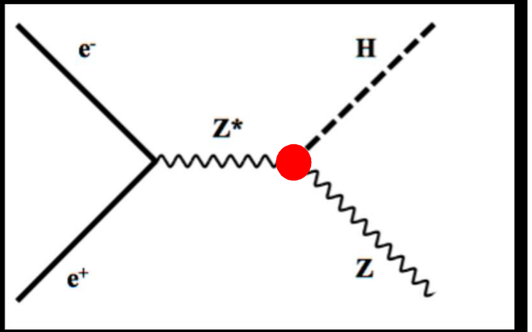

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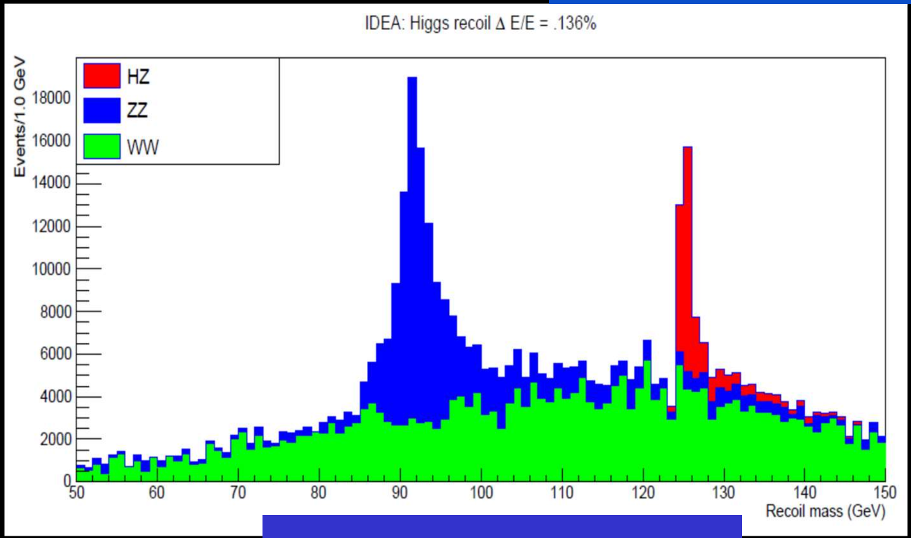
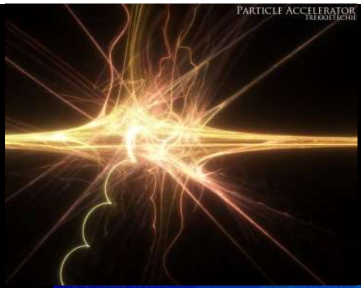


$Z \rightarrow \mu\mu$ recoil

- Total width combining with decays in specific channels

$$\sigma(ee \rightarrow ZH) \cdot BR(H \rightarrow ZZ) \propto \frac{g^4_{HZ}}{\Gamma}$$



Higgs coupling fits

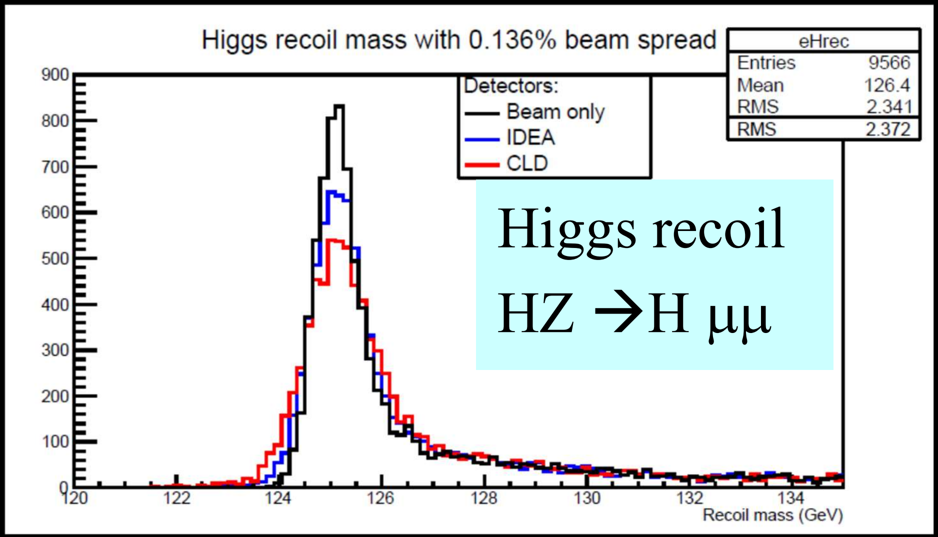
- Results limited only by statistics

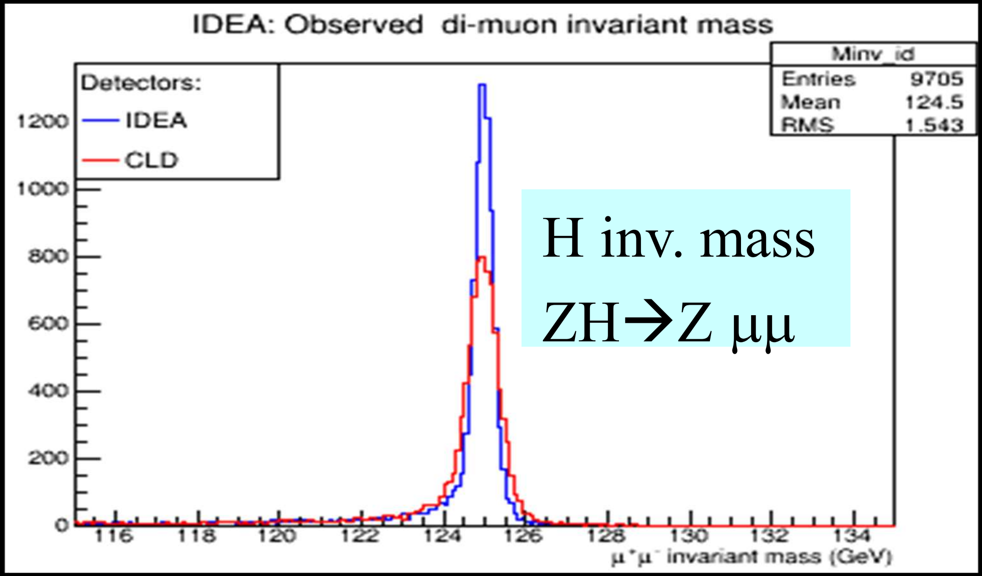
κ EFT

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$CEPC_{240}$	$FCC\text{-}ee_{240\to365}$
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5
Years		11.5 [5]	8	7	3 + 1 + 4
g_{HZZ} (%)	1.5 / 3.6	0.29 / 0.47	0.44 / 0.66	0.18 / 0.52	**0.17 / 0.26**
g_{HWW} (%)	1.7 / 3.2	1.1 / 0.48	0.75 / 0.65	0.95 / 0.51	**0.41 / 0.27**
g_{Hbb} (%)	3.7 / 5.1	1.2 / 0.83	1.2 / 1.0	0.92 / 0.67	**0.64 / 0.56**
g_{Hcc} (%)	SM / SM	2.0 / 1.8	4.1 / 4.0	2.0 / 1.9	**1.3 / 1.3**
g_{Hgg} (%)	2.5 / 2.2	1.4 / 1.1	1.5 / 1.3	1.1 / 0.79	**0.89 / 0.82**
$g_{H\tau\tau}$ (%)	1.9 / 3.5	1.1 / 0.85	1.4 / 1.3	1.0 / 0.70	**0.66 / 0.57**
$g_{H\mu\mu}$ (%)	4.3 / 5.5	4.2 / 4.1	4.4 / 4.3	3.9 / 3.8	**3.9 / 3.8**
$g_{H\gamma\gamma}$ (%)	1.8 / 3.7	1.3 / 1.3	1.5 / 1.4	1.2 / 1.2	**1.2 / 1.2**
$g_{HZ\gamma}$ (%)	11. / 11.	11. / 10.	11. / 9.8	6.3 / 6.3	**10. / 9.4**
g_{Htt} (%)	3.4 / 2.9	2.7 / 2.6	2.7 / 2.7	2.6 / 2.6	**2.6 / 2.6**
g_{HHH} (%)	50. / 52.	28. / 49.	45. / 50.	17. / 49.	**19. / 34.**
Γ_H (%)	SM	2.4	2.6	1.9	**1.2**
BR_{inv} (%)	1.9	0.26	0.63	0.27	**0.19**
BR_{EXO} (%)	SM (0.0)	1.8	2.7	1.1	**1.0**

Requirements for Higgs physics

- Tracking:
  - Momentum resolution for Z recoil (and H→μμ)
  - Vertex resolution to separate g, c, b, τ final states





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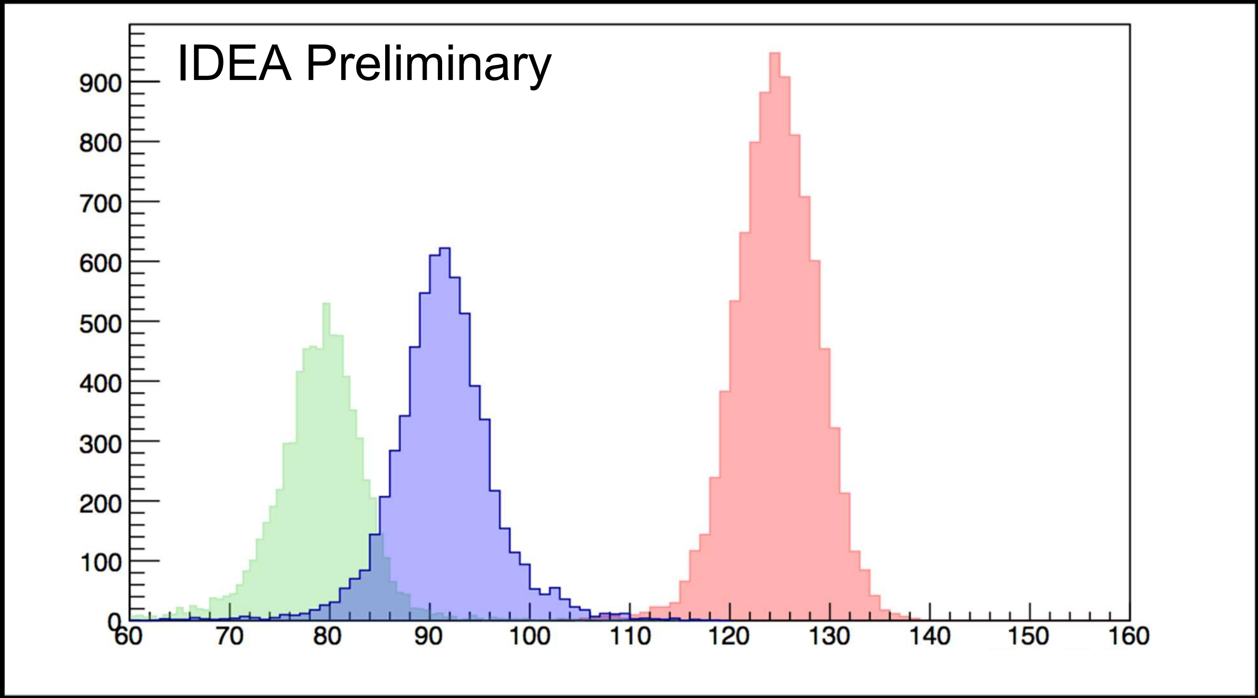
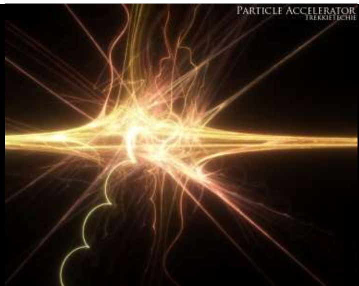
- Calorimetry:
  - Jet-jet invariant mass resolution to separate W, Z, H in 2 jets
  - Good π^0 ID for τ and HF tagging





EWK

- Outstanding program of precision EWK measurements
  - O(10-100) better than LEP precision
  - Substantially reduce parametric uncertainties in theory

Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	$91{,}186{,}700 \pm 2200$	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	$2{,}495{,}200 \pm 2300$	8	100	From Z line shape scan Beam energy calibration
R_ℓ^Z ($\times 10^3$)	$20{,}767 \pm 25$	0.06	0.2–1.0	Ratio of hadrons to leptons acceptance for leptons
α_s (m_Z) ($\times 10^4$)	1196 ± 30	0.1	0.4–1.6	From R_ℓ^Z above [43]
R_b ($\times 10^6$)	$216{,}290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [44]
σ^0_{had} ($\times 10^3$) (nb)	$41{,}541 \pm 37$	0.1	4	Peak hadronic cross-section luminosity measurement
N_ν ($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	$231{,}480 \pm 160$	3	2–5	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}$ (m_Z) ($\times 10^3$)	$128{,}952 \pm 14$	4	Small	From $A_{FB}^{\mu\mu}$ off peak [34]
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1–3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	0.15	< 2	τ Polarisation and charge asymmetry τ decay physics
m_W (MeV)	$80{,}350 \pm 15$	0.5	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
α_s (m_W) ($\times 10^4$)	1170 ± 420	3	Small	From R_ℓ^W [45]
N_ν ($\times 10^3$)	2920 ± 50	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	$172{,}740 \pm 500$	17	Small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410 ± 190	45	Small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.1	Small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	$\pm 30\%$	0.5–1.5%	Small	From $E_{CM} = 365$ GeV run

Z pole (rows m_Z through $A_{FB}^{pol,\tau}$)

WW (rows m_W through N_ν)

tt (rows m_{top} through ttZ couplings)

Requirements for EWK/HF physics

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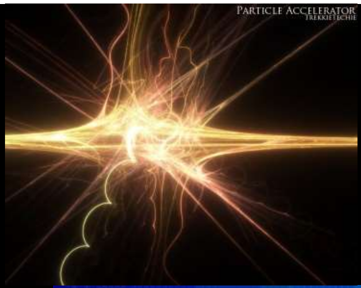
  - PID to accurately classify final states and flavor tagging



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HF:

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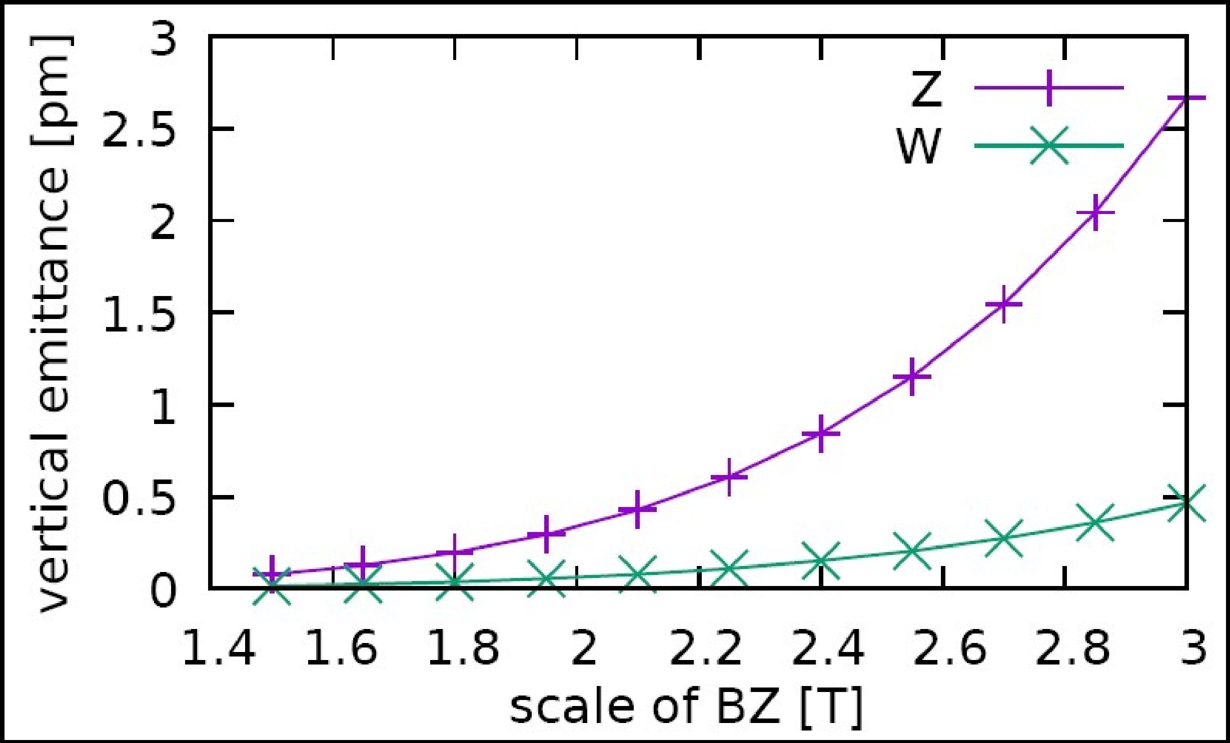
Other requirements highly overlap with Higgs req.

Circular vs. Linear

- Low field detector solenoid to maximize luminosity
  - Optimized at 2 T
  - Large tracking volume → calorimeter outside → very thin coil



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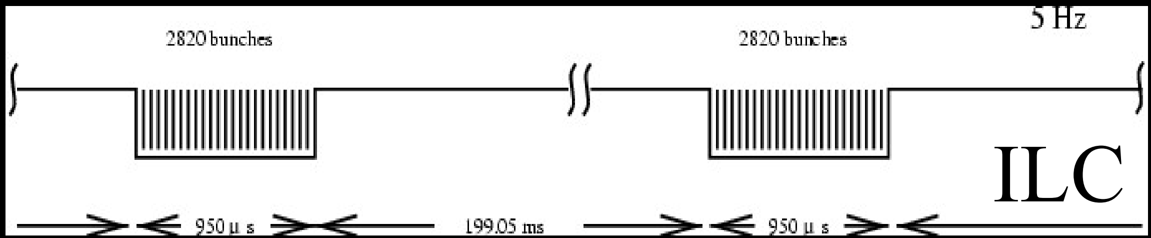
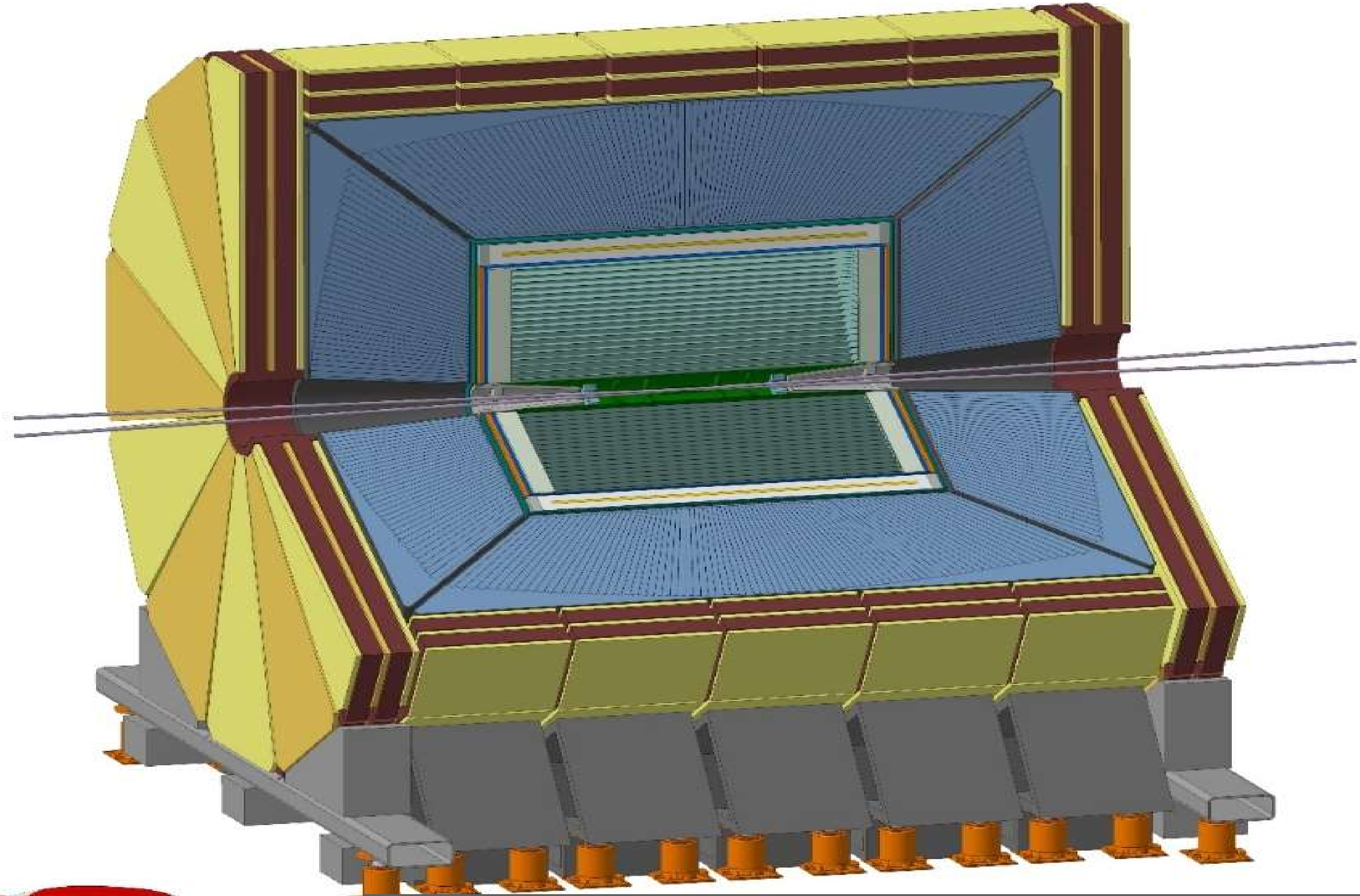


Beam time structure:

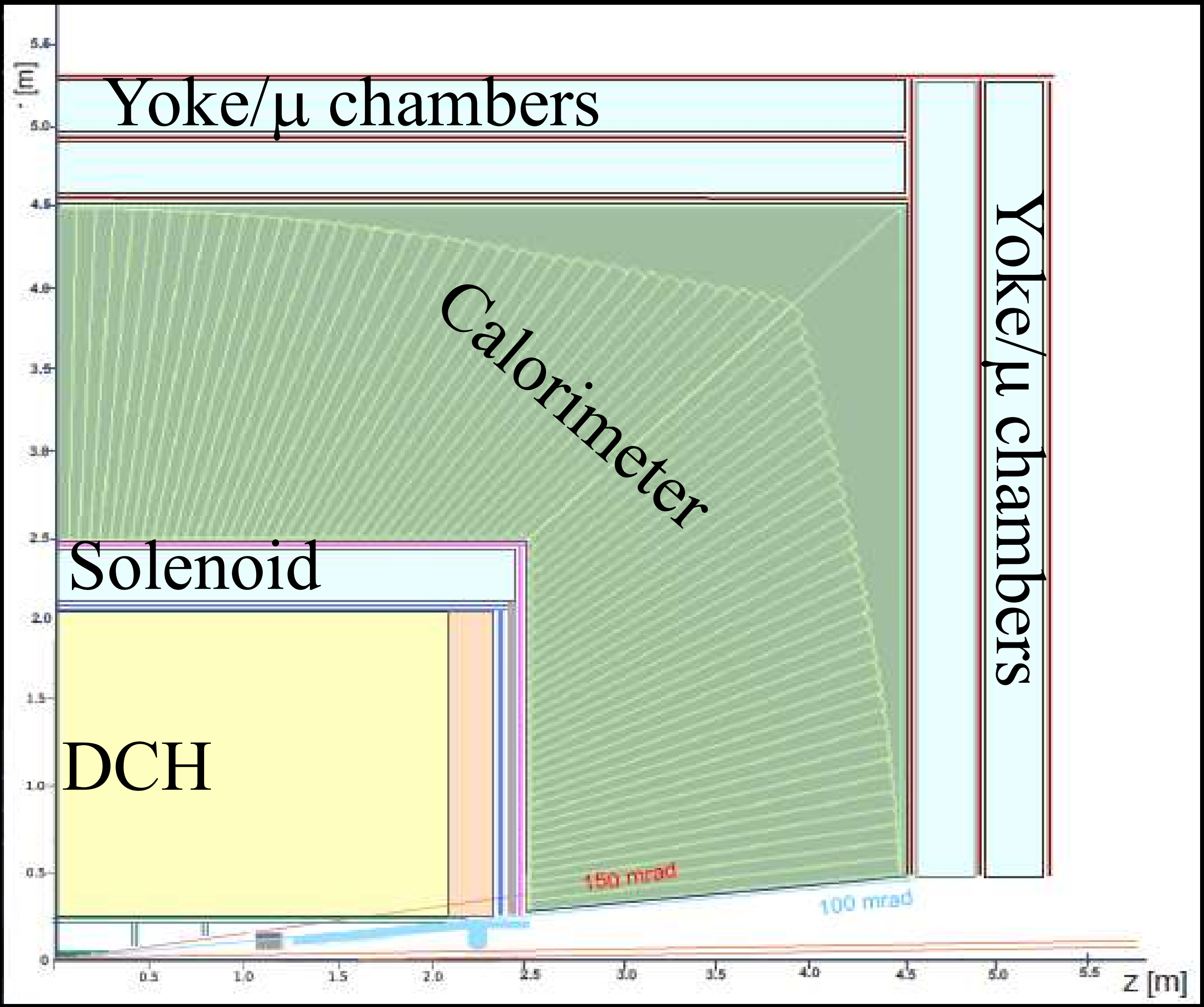
- Short bunch spacing (~ 20-30 ns Z, ~ 1 μs H)
- No large time gap
  - Cooling issues for PF calorimeter and vertex detector
  - TPC ion backflow



IDEA concept

Innovative Detector for E+e- Accelerator

IDEA details



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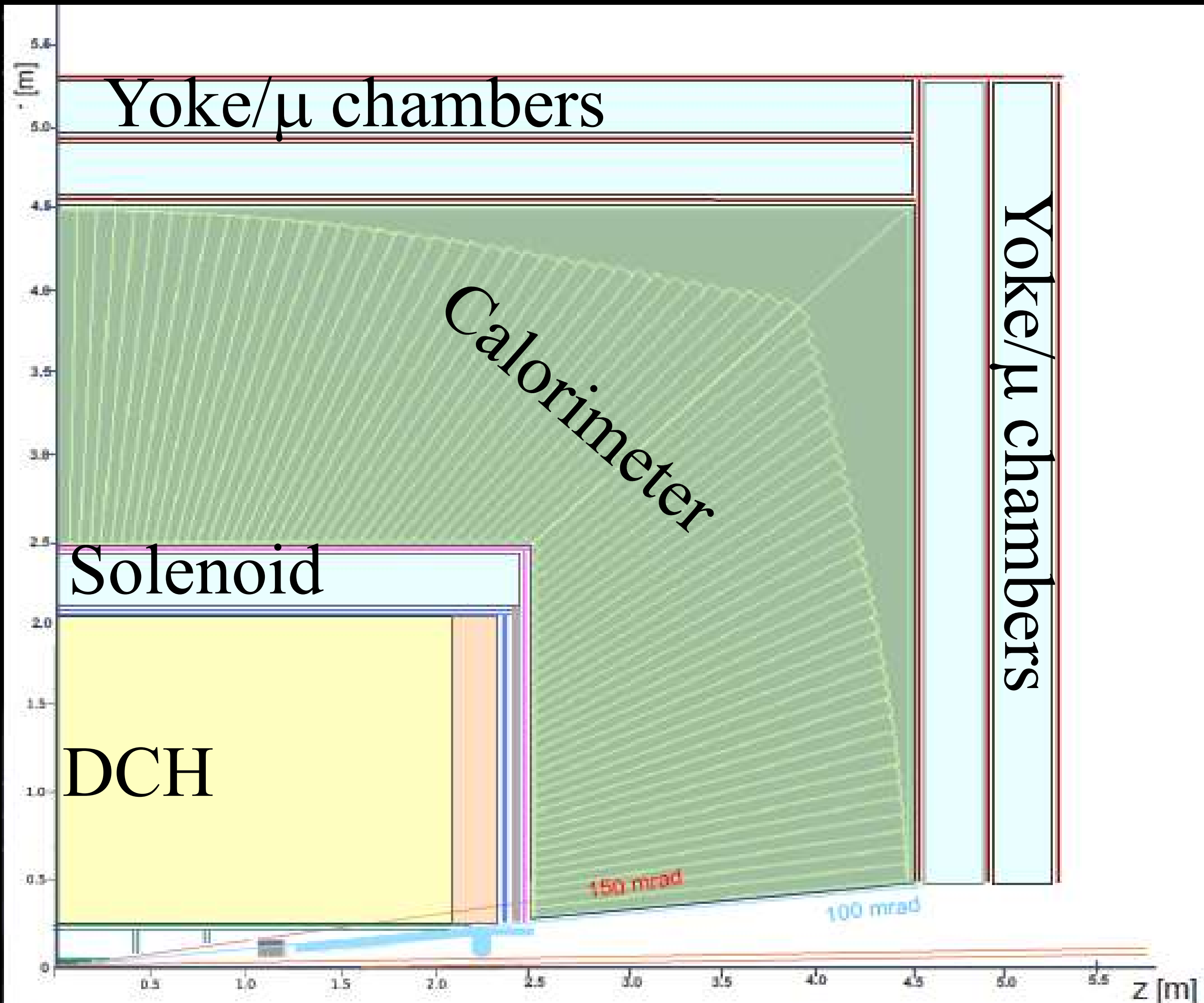

Small magnet

Small yoke

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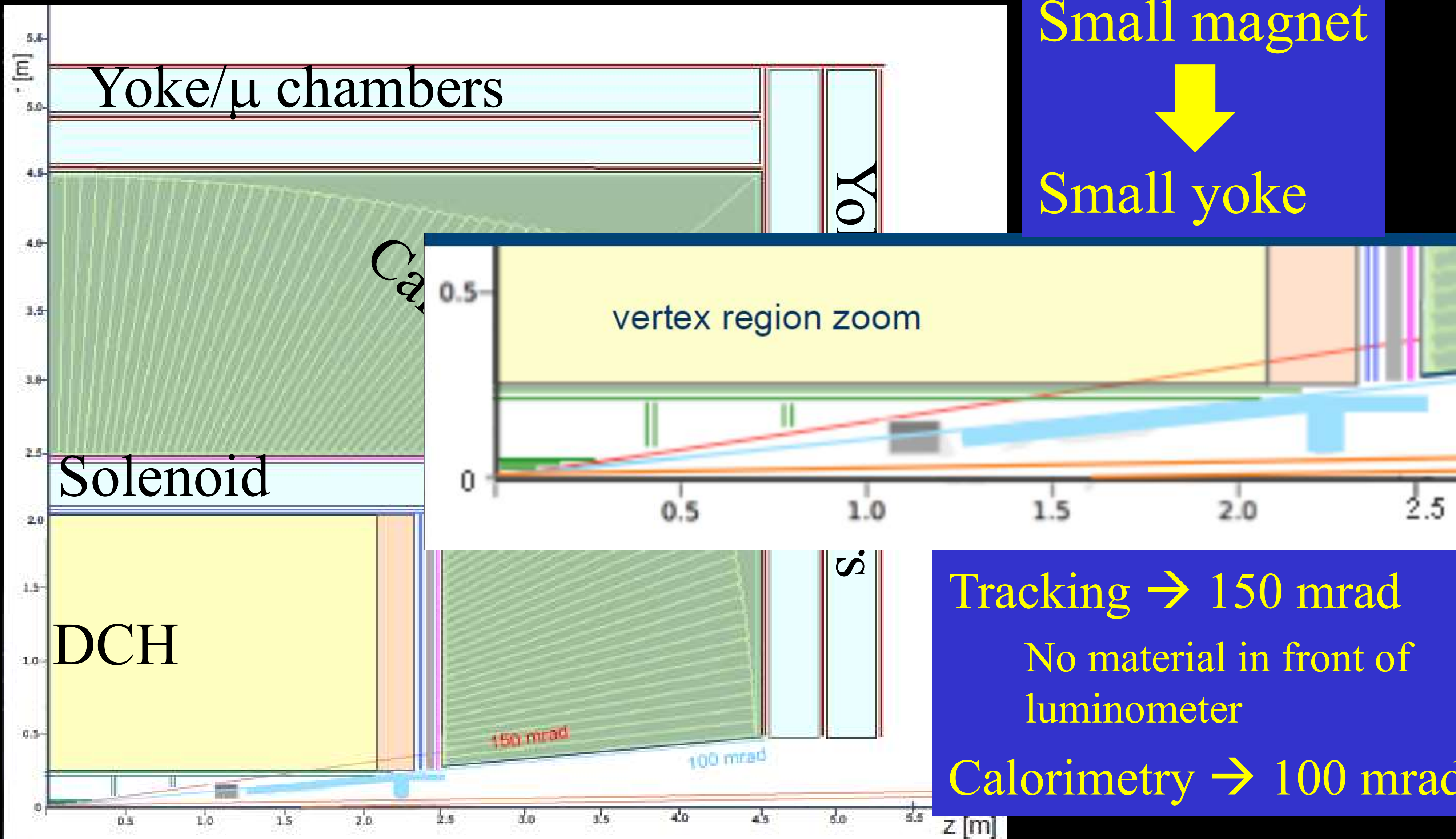


Small magnet

Small yoke

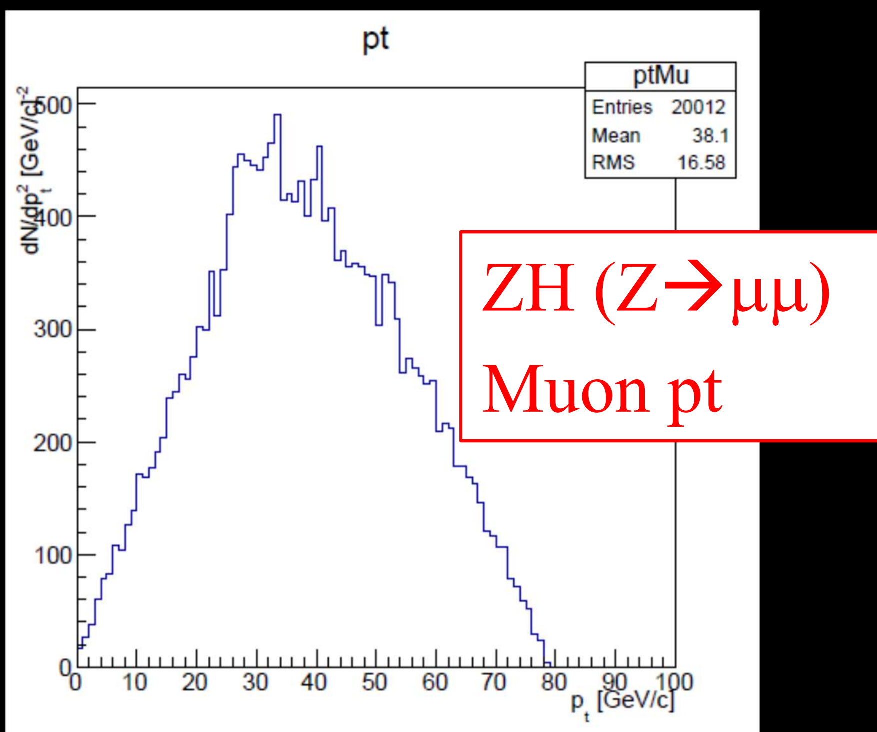
Tracking → 150 mrad

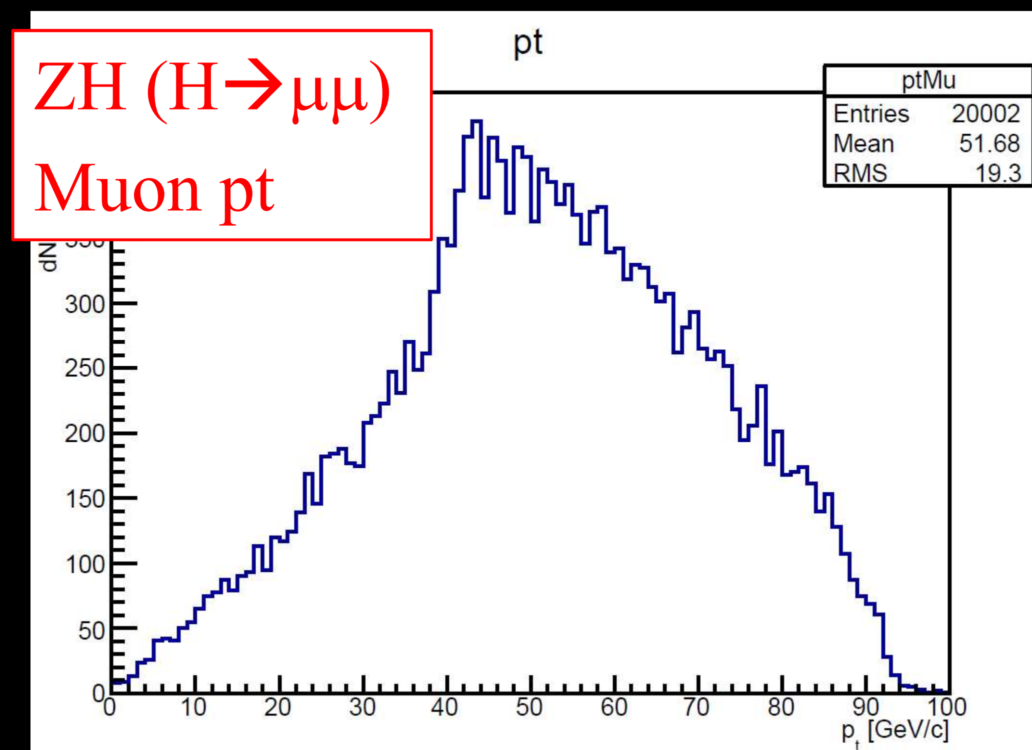
No material in front of luminometer

Calorimetry → 100 mrad

Design guidelines: Momentum resolution

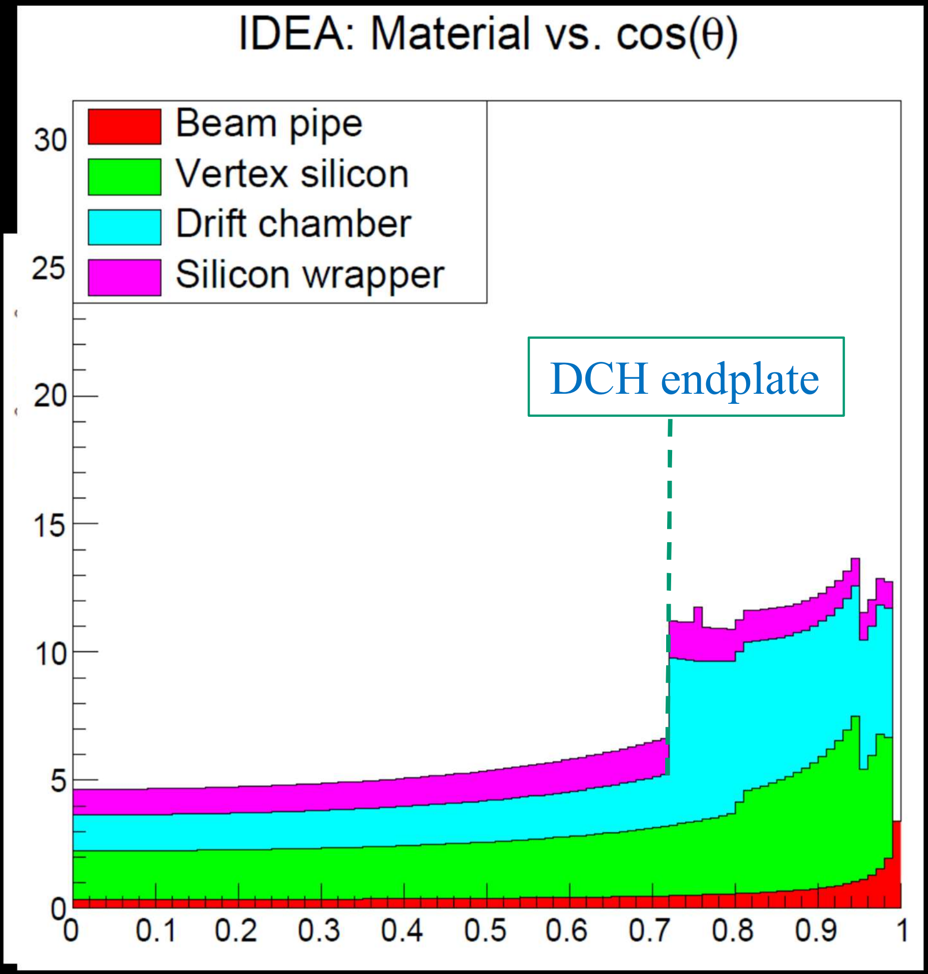
❖ Z or H decay muons in ZH events have rather small p_t

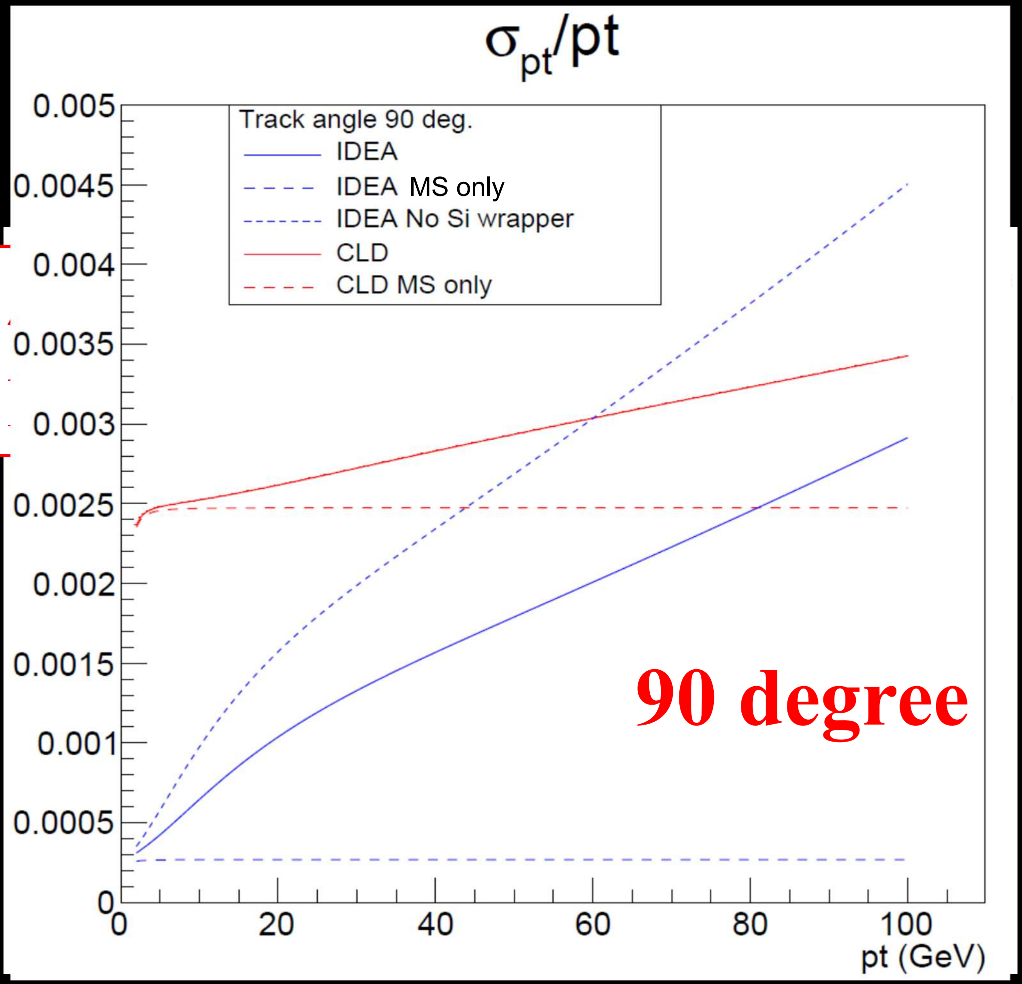




Design guidelines: Momentum resolution

- Z or H decay muons in ZH events have rather small p_t
  - Transparency more relevant than asymptotic resolution





Design guidelines: Vertex detector

- Transparency:
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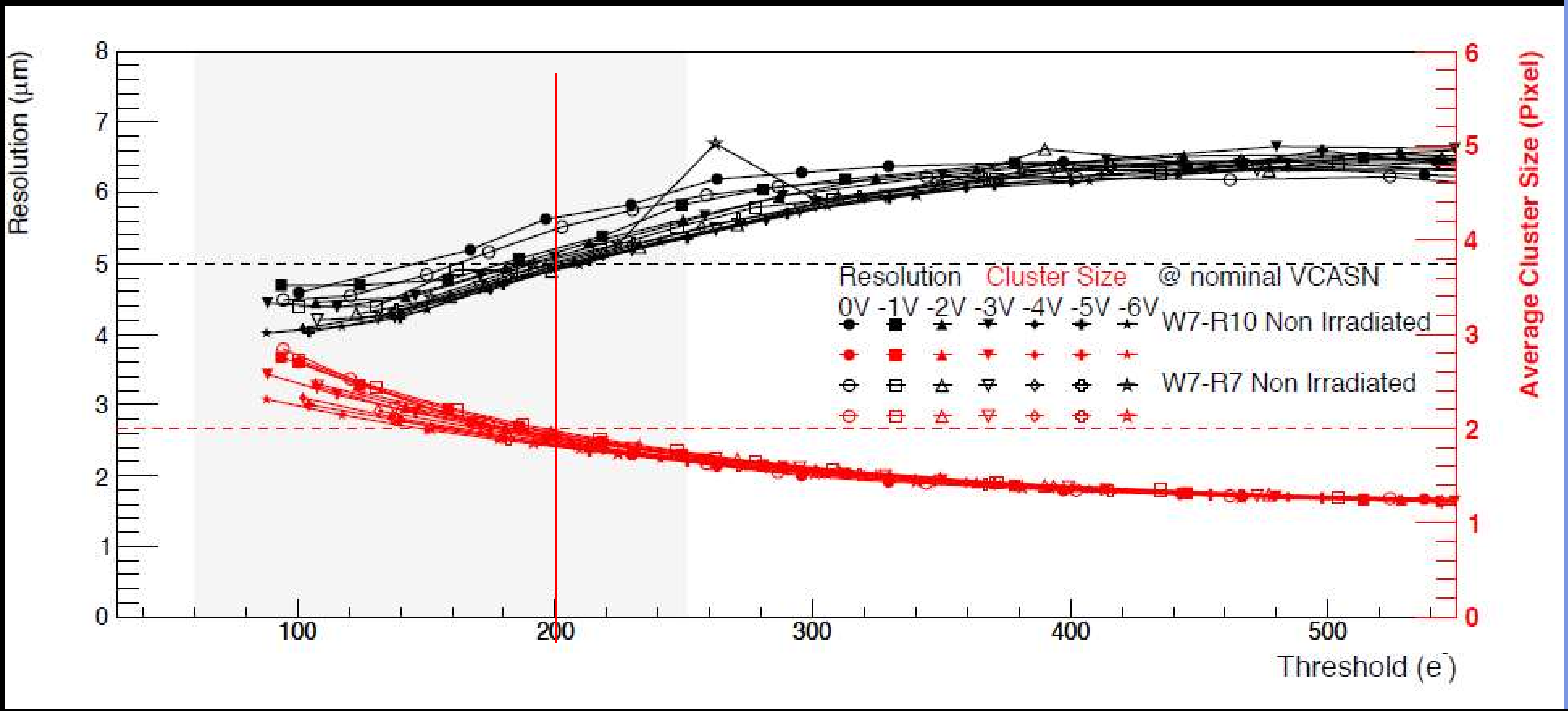
- Resolution:

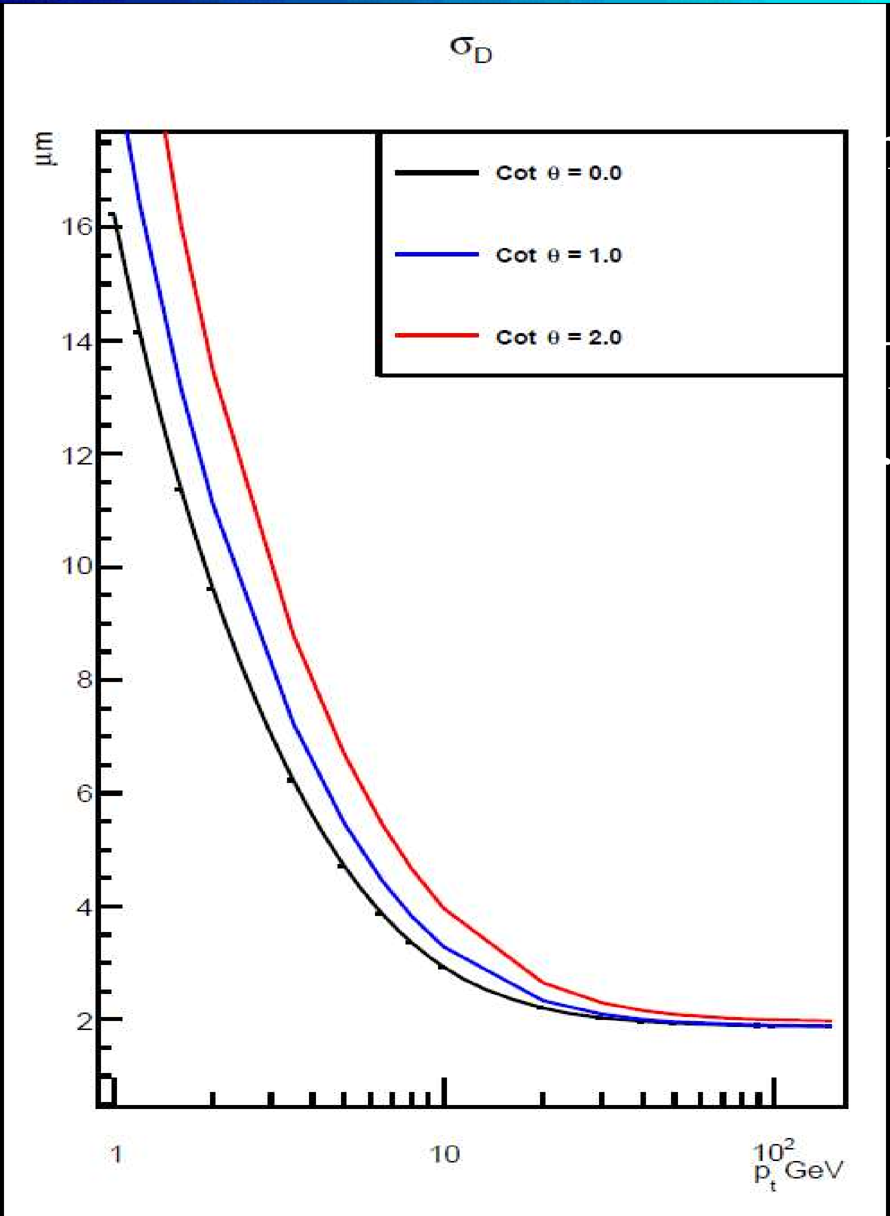
  5 μm shown by ALICE ITS (30 μm pixels)

  Aim at ~20 μm pixels for ~ 3 μm point resolution



Courtesy of ALICE J.W. van Hoorne

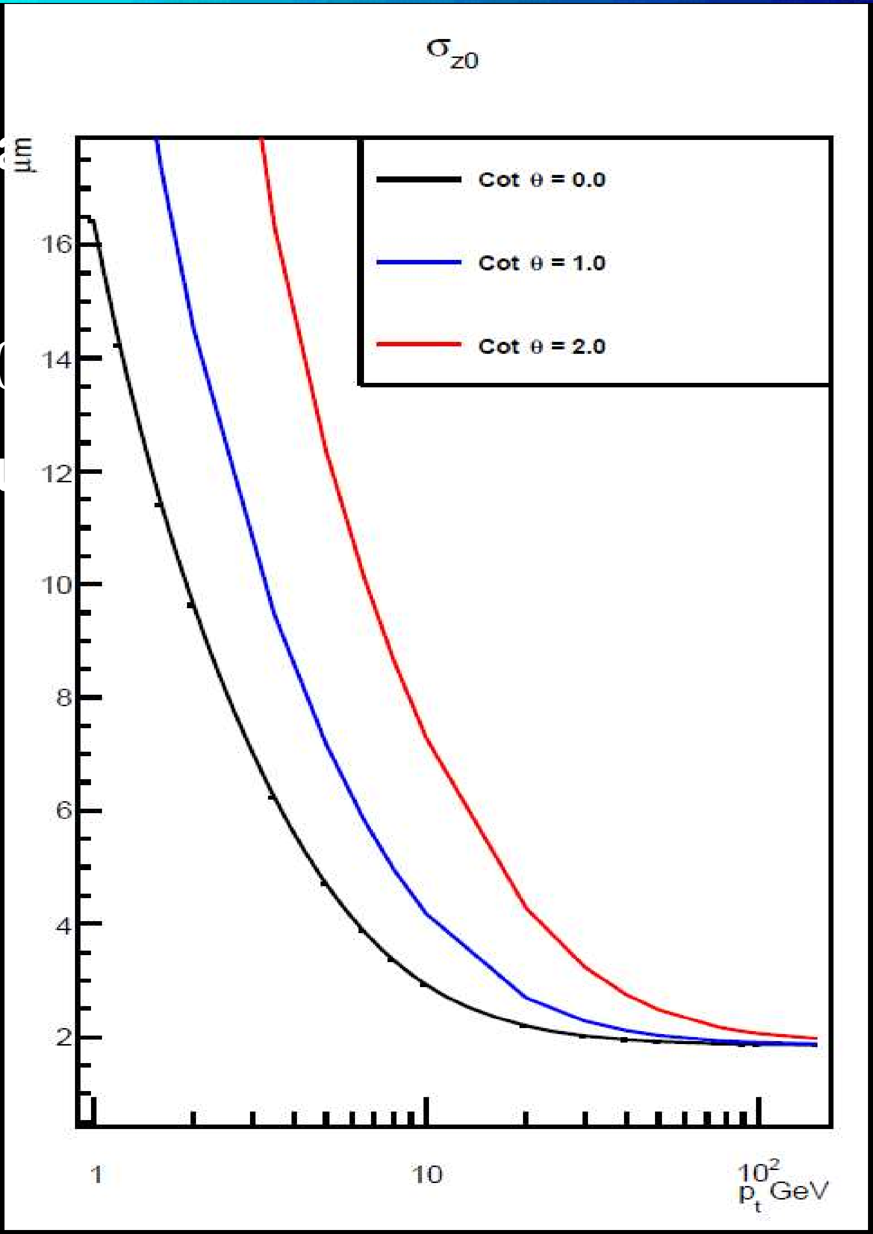
Design guidelines: Vertex detector



n²) to a

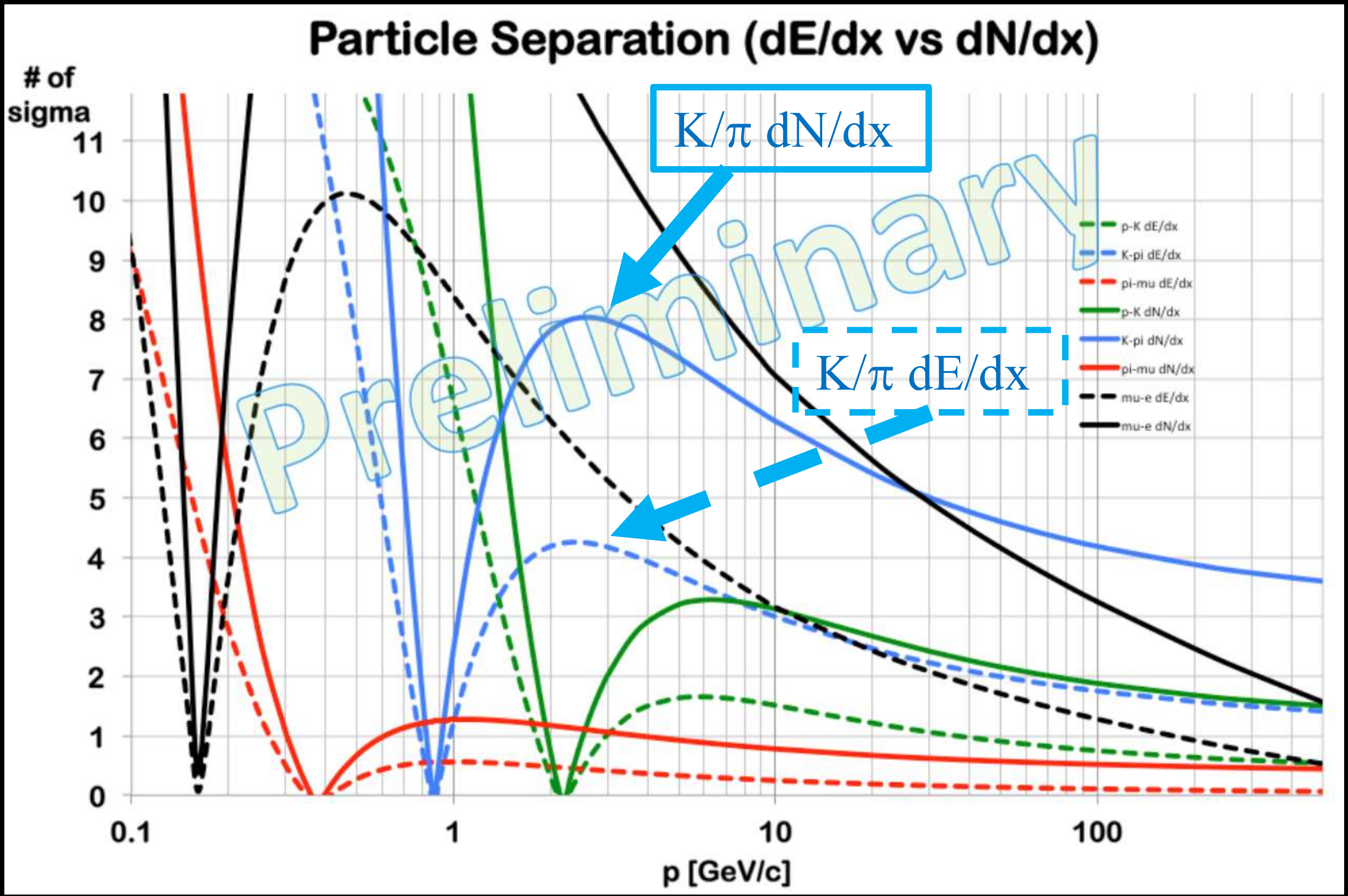
TS (30

~ 3 μ



Design guidelines: PID

- Cluster counting in DCH for good PID resolution
  - Excellent K/π separation except 0.75<p<1.05 GeV (blue lines)



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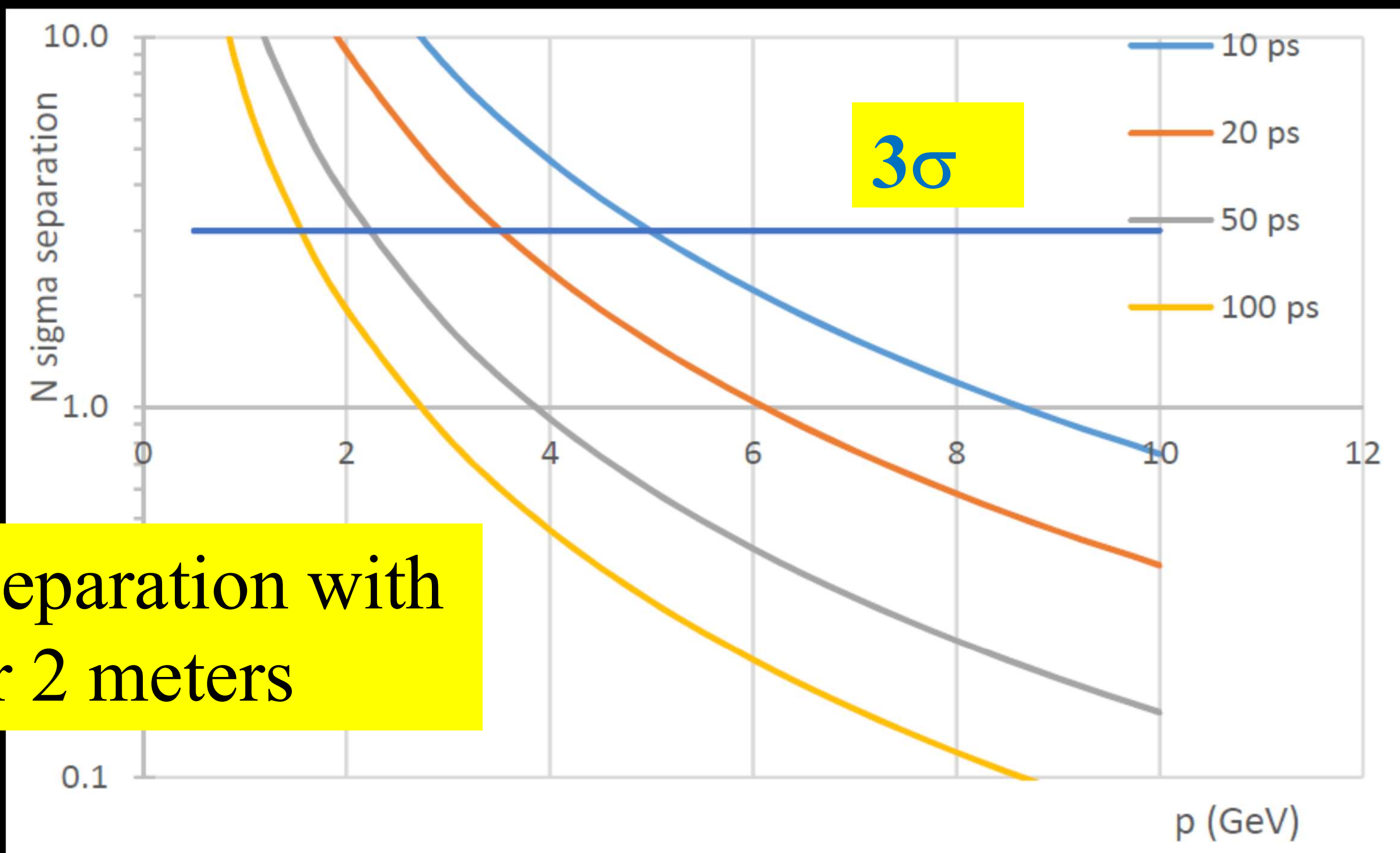

Nσ K/π separation with TOF over 2 meters

Design guidelines: calorimeter

- Good, but not extreme EM resolution
  - $\sim 10\%/\sqrt{E}$ sufficient for Higgs physics
- Jet resolution $\sim$ 30-40%/$\sqrt{E}$
  - Clearly identify W, Z, H in 2 jet decays
- Transverse granularity < 1 cm for τ physics
- All electronics in the back to simplify cooling and services

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- Transverse granularity < 1 cm for τ physics
- All electronics in the back to simplify cooling and services
- Dual Readout calorimeter satisfies all these requirements

  EM & Hadronic calorimeter in a single package

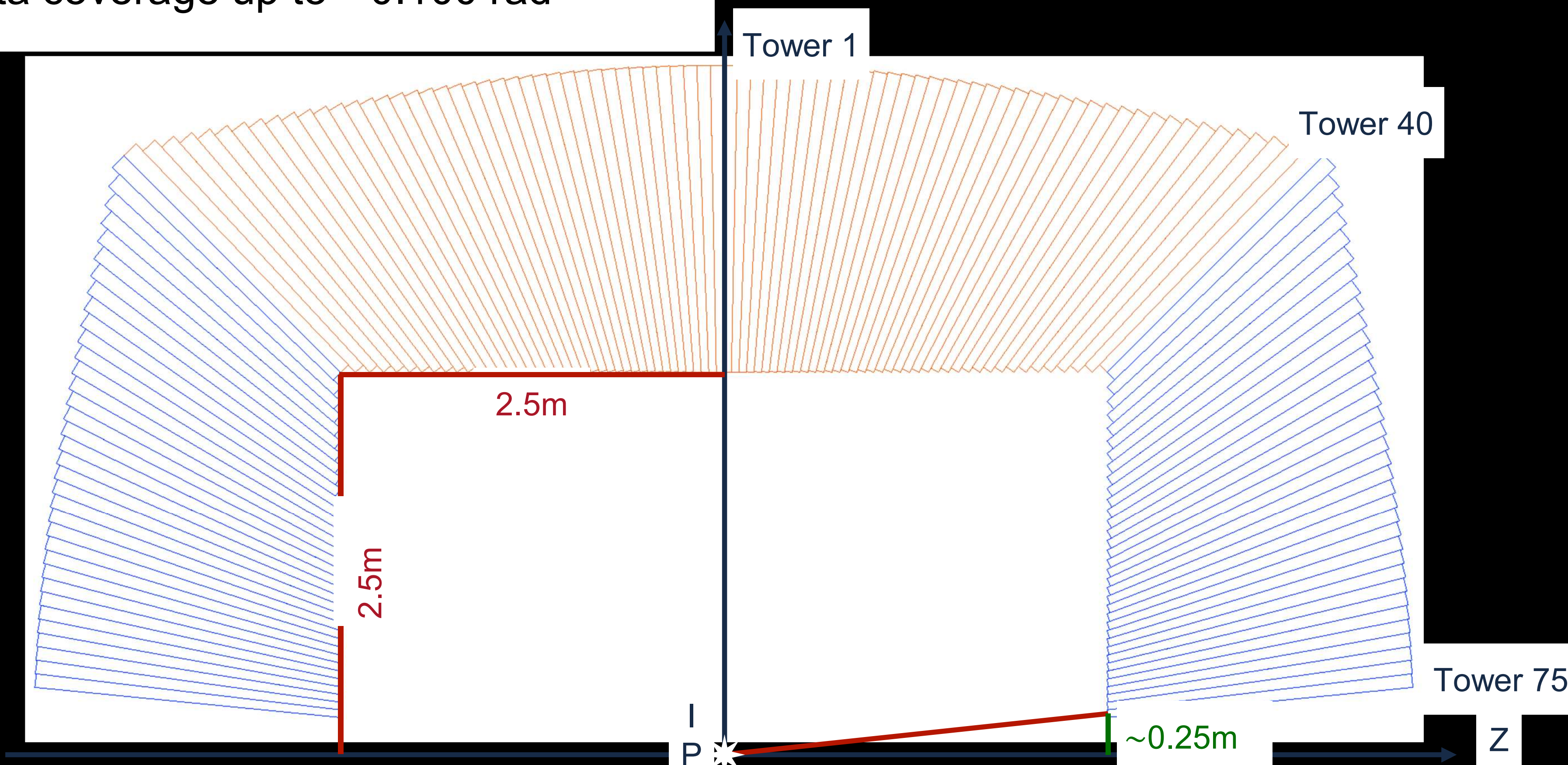
See for instance:

- "Dual-readout calorimetry", Sehwook Lee, Michele Livan, and Richard Wigmans Rev. Mod. Phys. 90, 025002 – Published 26 April 2018
- L. Pezzotti, CHEF2019, Nov. 2019, Fukuoka, Japan

Calorimeter simulation

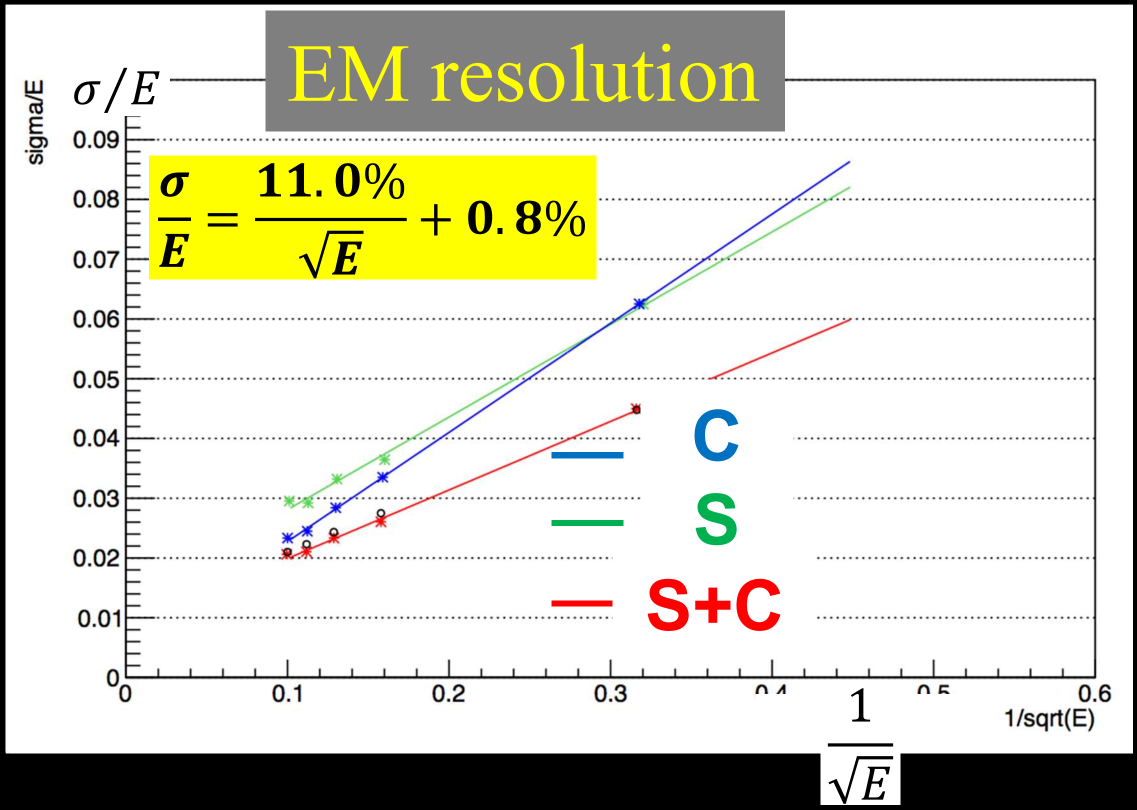
❖ 4π detector in GEANT4 tuned to RD52/DREAM test beam

Tower segmentation: Δϑ = 1.125°, Δϕ = 10.0°
Number of towers in barrel: 40 x 2 x 36 = 2880
Number of towers per endcap: 35 x 36 = 1260
Theta coverage up to ~0.100 rad



Calorimeter simulation

- 4π detector in GEANT4 tuned to RD52/DREAM test beam data
- Good EM resolution averaged over η and ϕ



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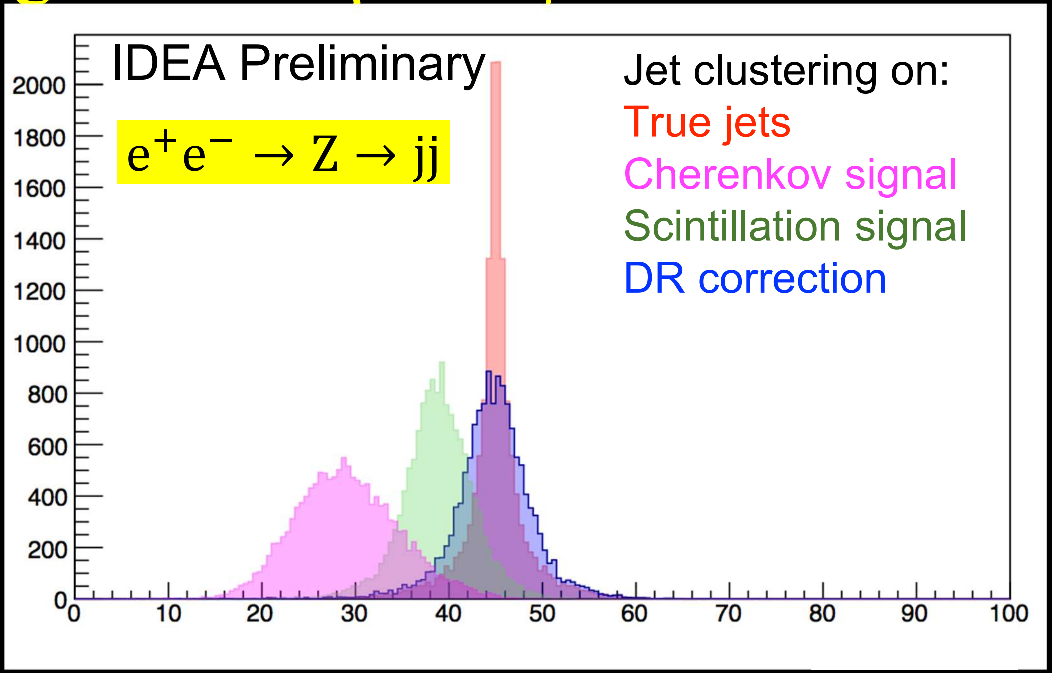


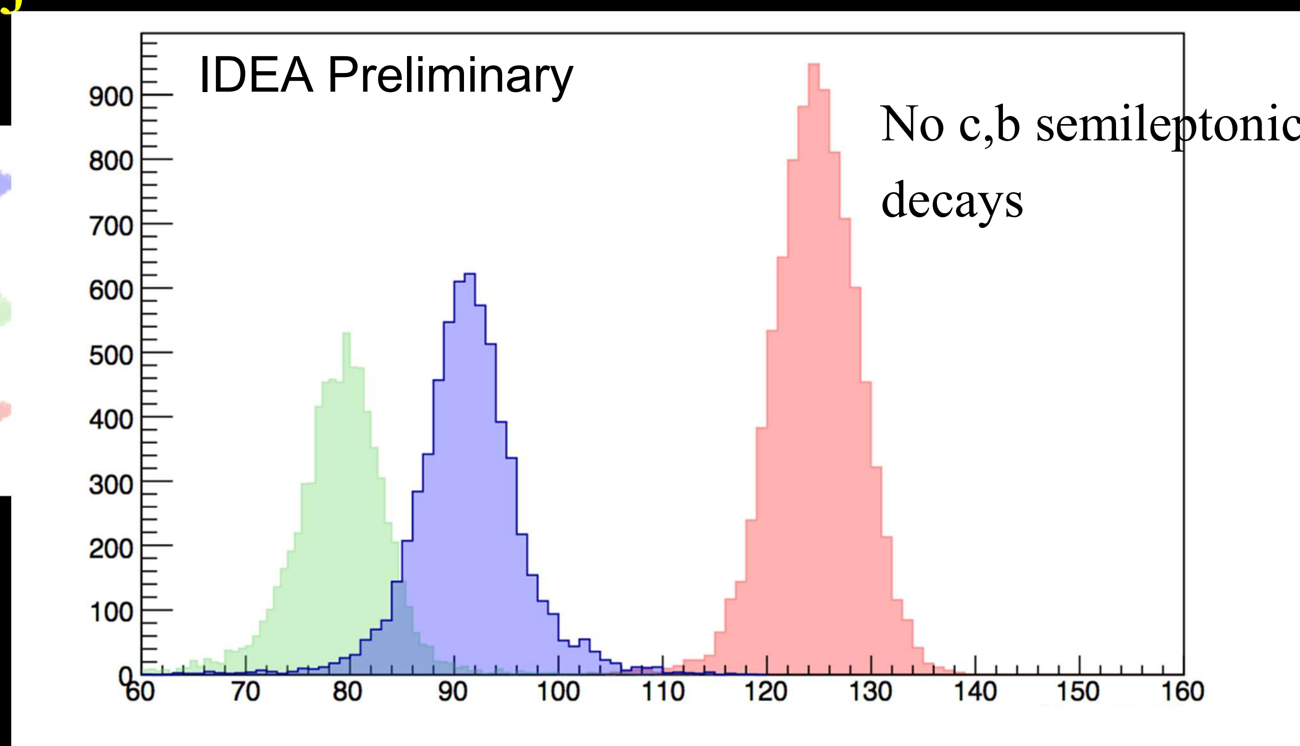
Calorimeter simulation

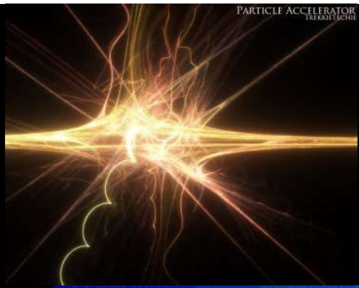
- 4π detector in GEANT4 tuned to RD52/DREAM test beam data
- Good EM resolution averaged over η and ϕ
- DR works well with jets
- Adequate separation

$e^+e^- \to HZ \to \tilde{\chi}^0\tilde{\chi}^0 jj$

$e^+e^- \to WW \to \nu_\mu \mu jj$

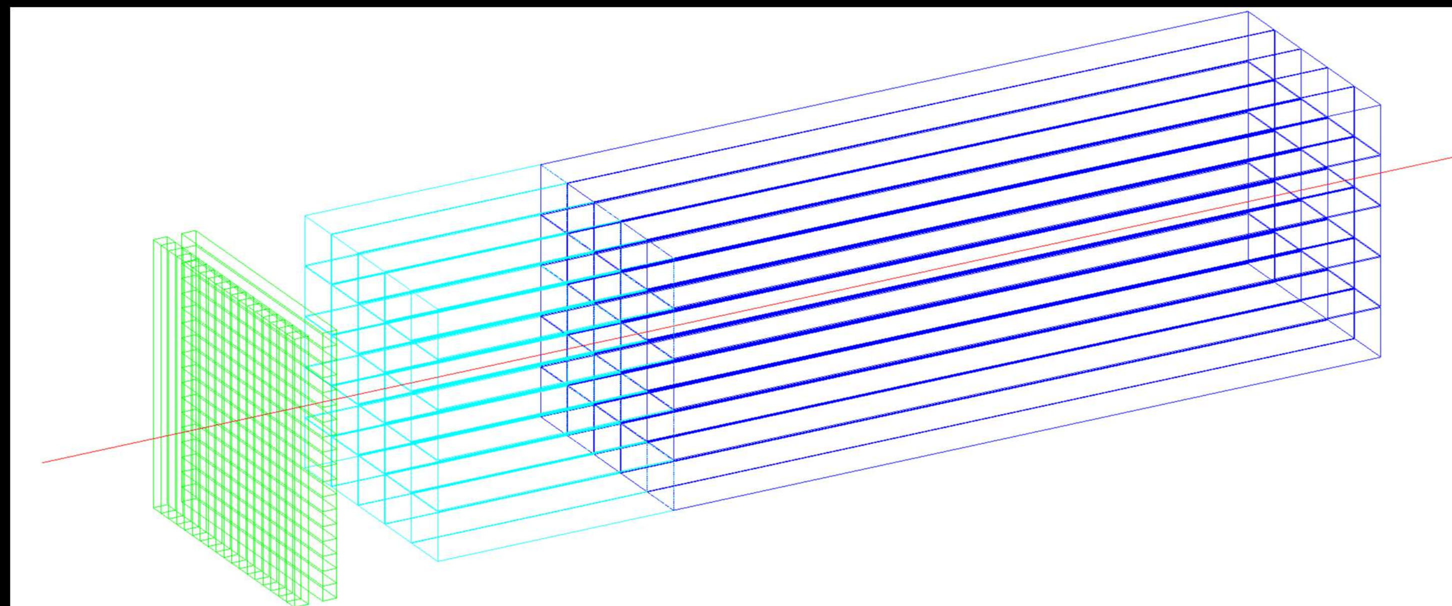
$e^+e^- \to HZ \to bb\nu\nu$



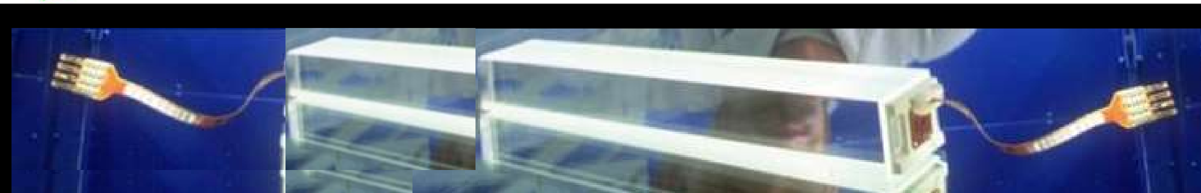


Crystal option

- ~20 cm $PbWO_4$
- $3\%/\sqrt{E}$
- DR w. filters
- Timing layer
  - Lyso 20-30 ps

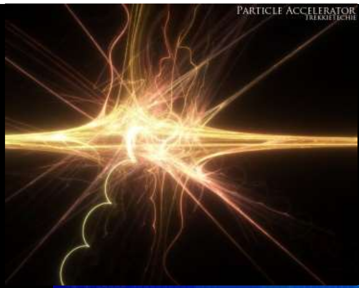


- **ECAL layer:**
  - PbWO crystals
  - front segment 5 cm (~$5.4X_0$)
  - rear segment for core shower
  - (15 cm ~$16.3X_0$)
  - $10x10x200\ mm^3$ of crystal
  - $5x5\ mm^2$ SiPMs (10-15 um)



$1x1x5cm^3$ PbWO

$1x1x15cm^3$ PbWO



Current R&D

- Silicon systems:
  - VTX: Low power, high speed MAPS – CMOS to limit costs
    - Time stamping ~ 10 ns, Stitching
  - Outer Si: CMOS passive strips, long pixels, evolution from R&D at HL-LHC

Requirements	ARCADIA
Pixel pitch (um)	20 - 25
Thickness (um)	50 - 100
Scalability (cm)	Up to ~ 4 x 4
Hit rate (MHz/cm^2)	10 → 100
Cluster size (pixels)	2-4
Timing res. (ns)	10
Power (mW/cm^2)	< 20
Rad. Hard (Mrad)	1
Tiling	Side-buttable
Trigger	Triggerless

First Implementation

- Target hit rate: $100MHz/cm^2$
- Target efficiency: 99.9% (in every regard)
- Pixel size: 20μm × 20 μm
- Double column arrangement
- Support for 2048 pixels in column (4cm)

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  - VTX: Low power, high speed MAPS – CMOS to limit costs
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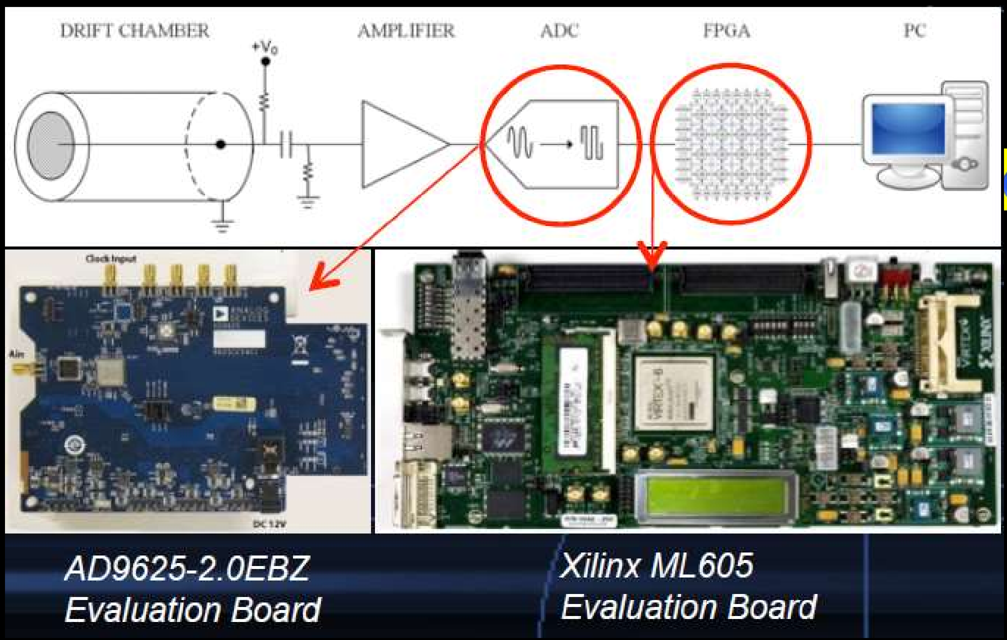
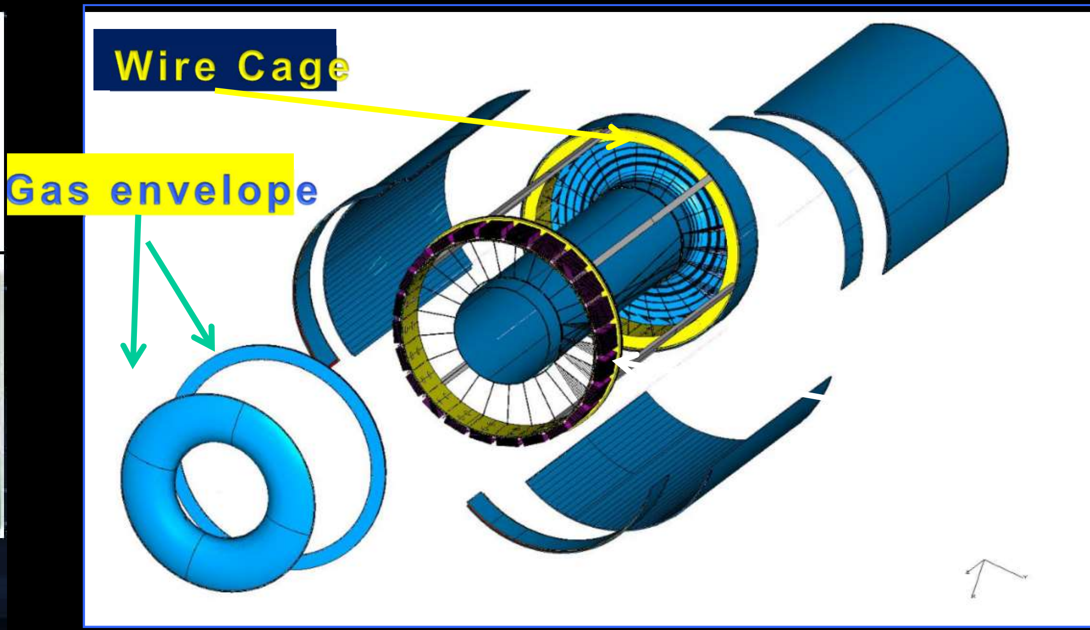
- Drift chamber:
  - Light mechanics and new wire technology (e.g. C-fiber)

    Cluster counting electronics



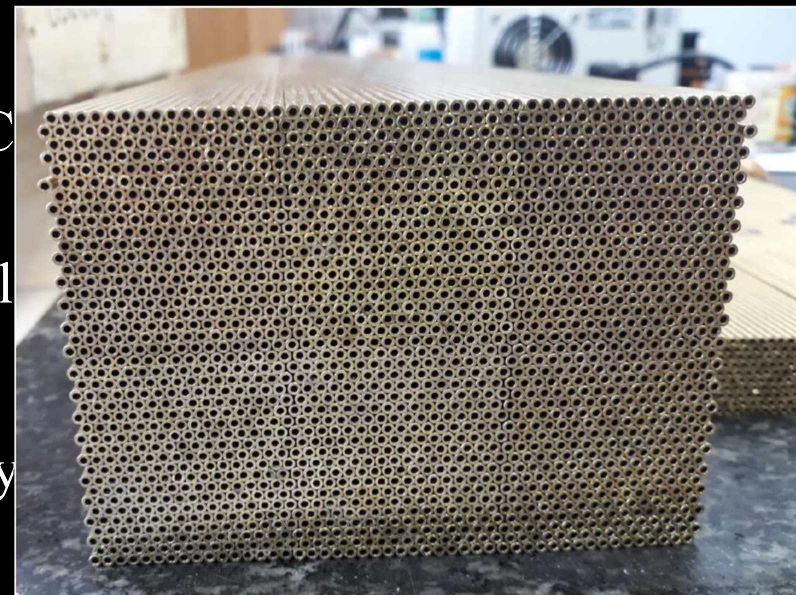


Current R&D

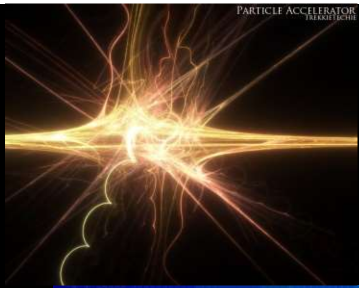
MAPS – C

long pixel C

echnology



- Calorimeter:
  - Scalable mechanical options



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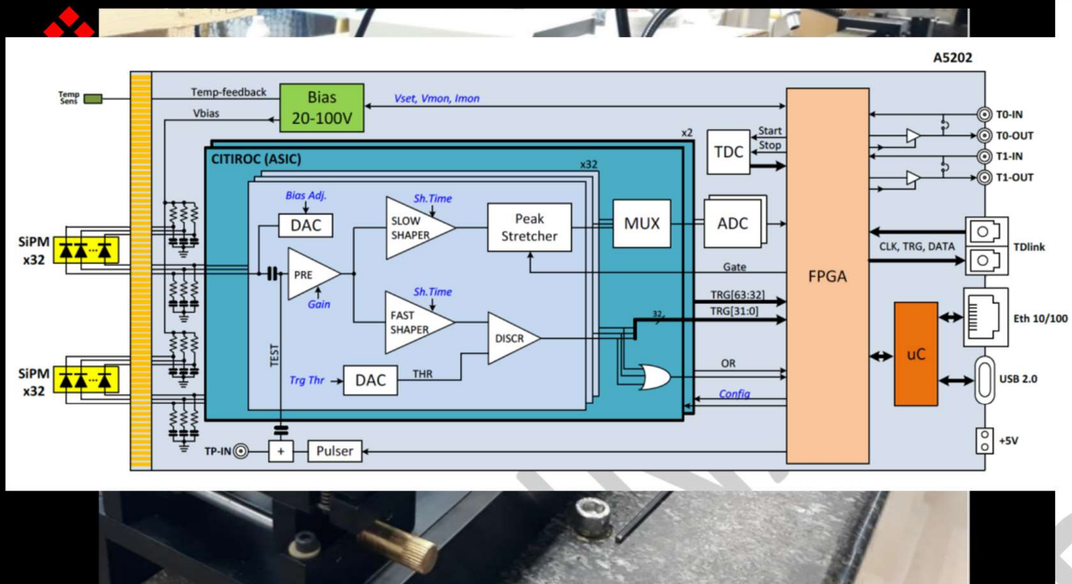
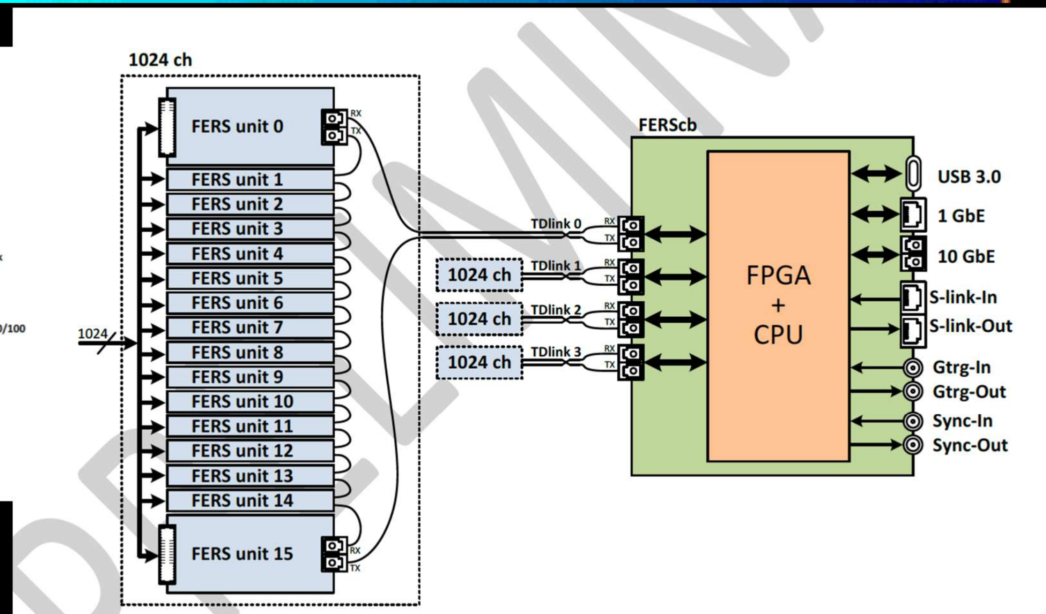
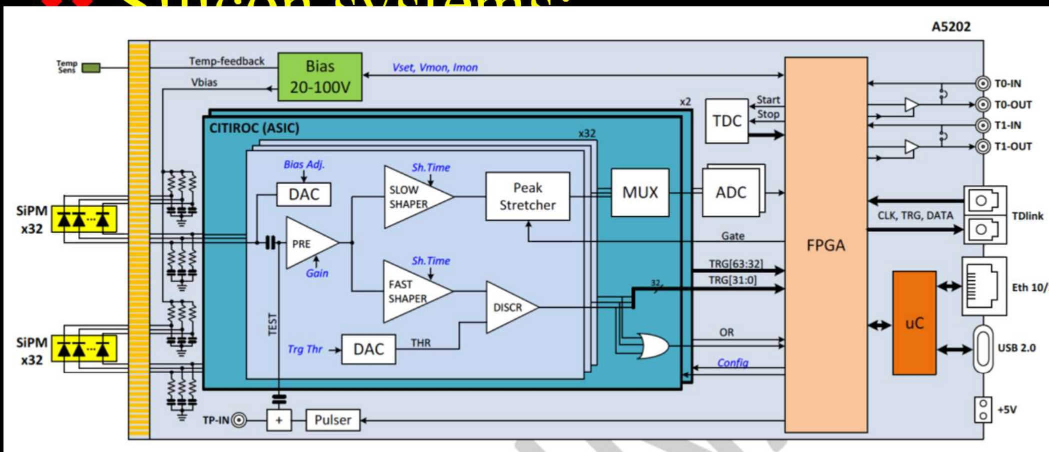


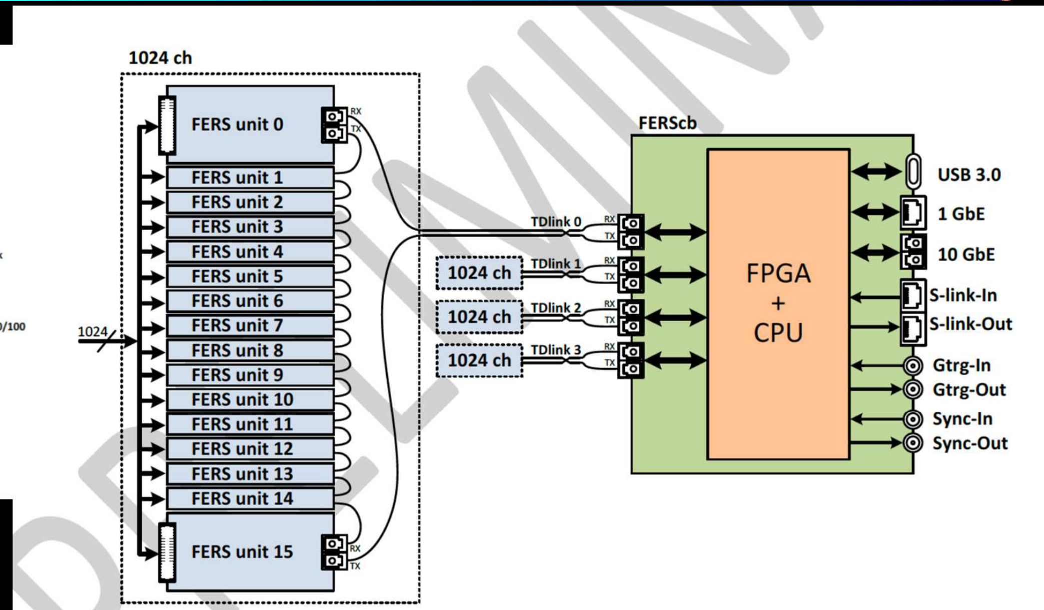


- Calorimeter:
  - Scalable mechanical options
  - SiPM readout architectures/chips – Digital SiPM

Current R&D

- ❖ Silicon systems:





  - ➢ Cluster counting electronics

- ❖ Calorimeter:
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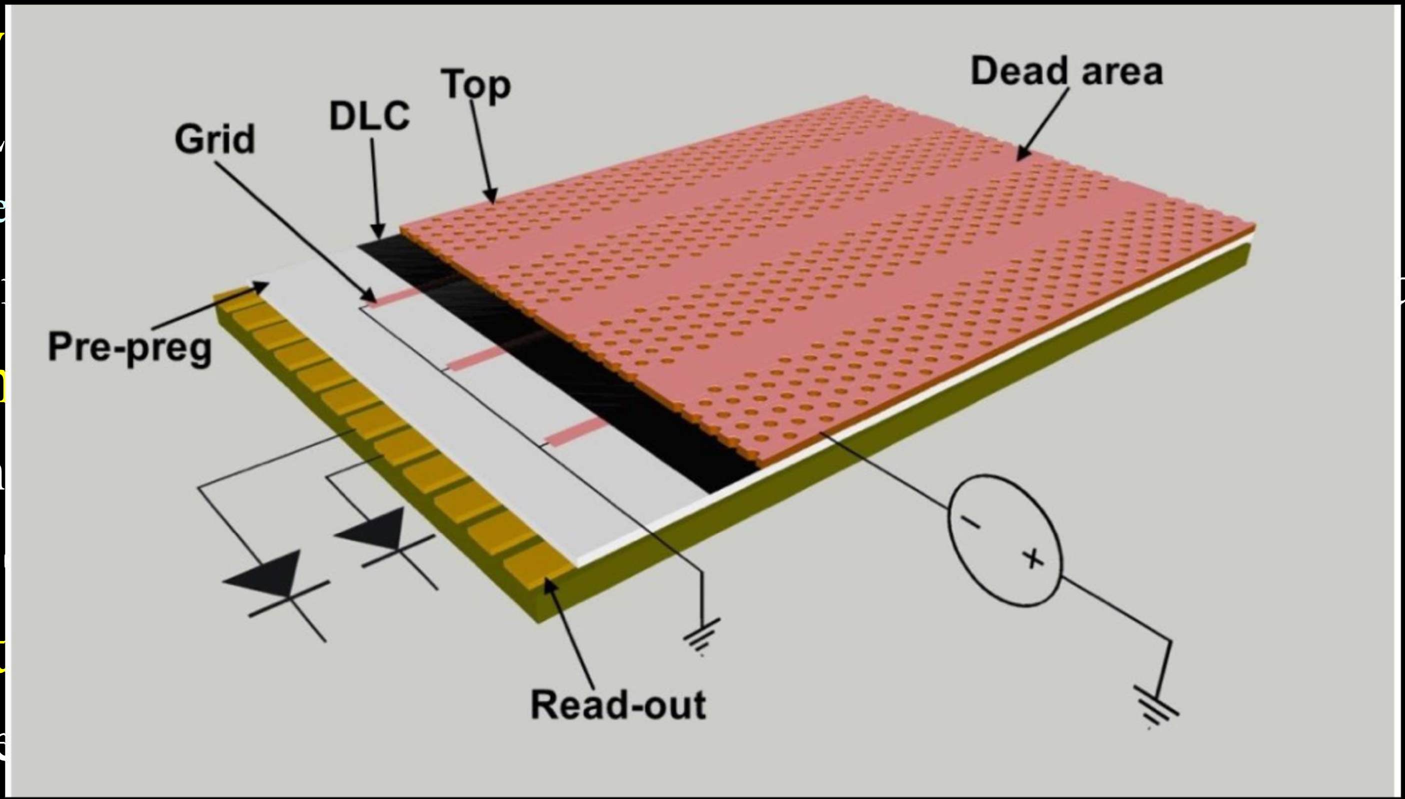
  - ➢ Crystals

Current R&D

- Silicon sy
  - VTX: L
    - Time
  - Outer S… HL-LHC
- Drift chan
  - Light m
  - Cluster
- Calorimet
  - Scalable
  - SiPM readout architectures/chips – Digital SiPM
  - Crystals
- Muon chambers:
  - µRwell industrialization
  - DLC sputtering



Software and DAQ

- Significant SW R&D and studies in progress
  - Worldwide development of Key4HEP guided by CERN
    - DD4HEP, EDM4HEP, ….. for the serious SW developer
  - FCCee physics groups restructured to tackle several "case studies"
    - Physics Performance Coordinators: P. Azzi, E. Perez
  - Lot of infrastructure still under development for IDEA:
    - Porting to DD4HEP of calorimetry and tracking
    - Put all detectors in GEANT4 simultaneously
      - With digitization
    - Tune reconstruction algorithms/ Machine learning techniques
    - Tune DELPHES to GEANT simulation
- Trigger/DAQ/On-detector/On-line computing

Final comments

- Summary of main features:
  - High precision vertex detector
  - High transparency and momentum resolution
    - Good integrated PID with cluster counting → even better with timing layer
  - Excellent calorimetry → FANTASTIC with crystals
  - Light solenoid and minimal yoke
  - Tracking muon system
  - Excellent performance at all energies: Z, WW, ZH, tt

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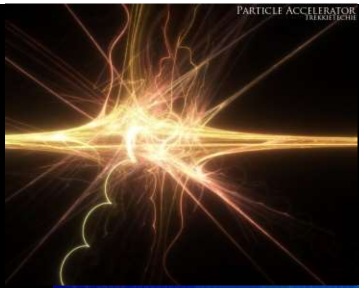

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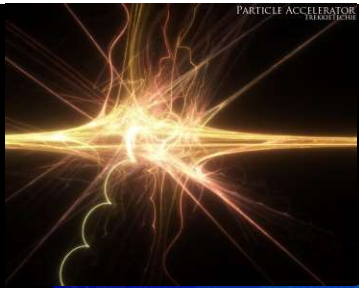

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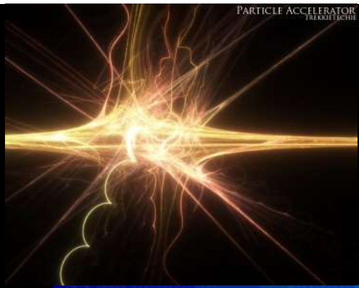

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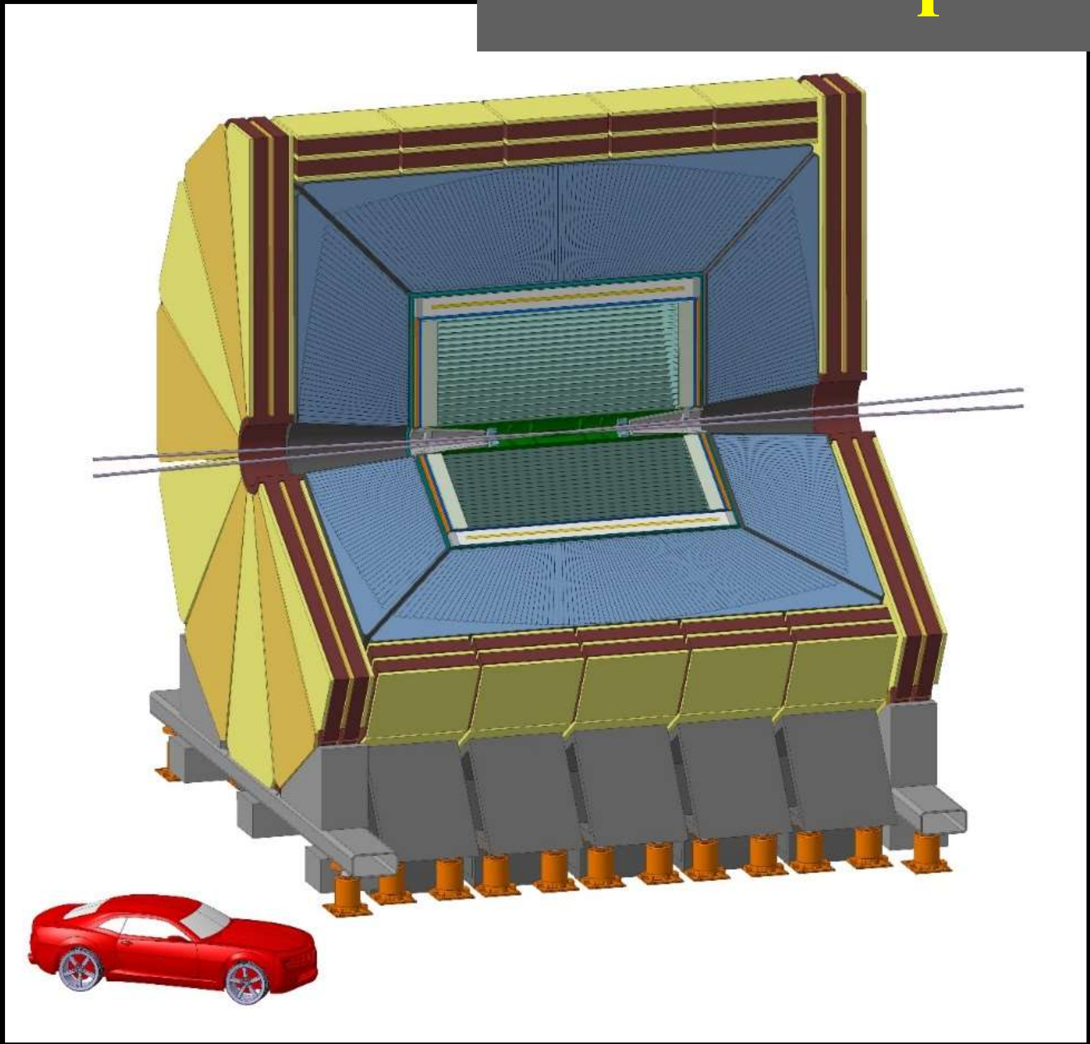
- Must strengthen Italian collaboration!

Backup

BACKUP

Detector concept IDEA

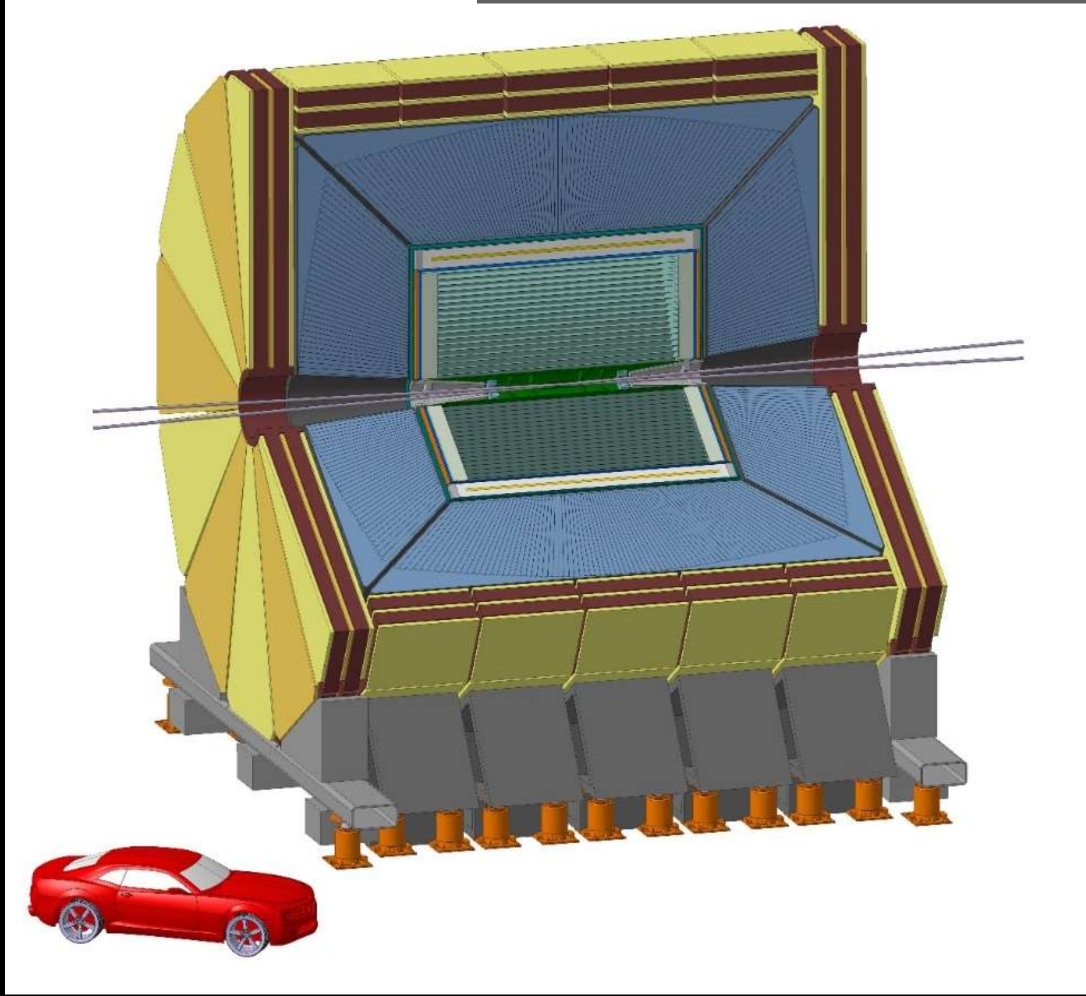
IDEA concept



Detector concept IDEA

- Si pixel vertex detector
  - 5 MAPS layers
    - R = 1.7 – 34 cm

IDEA concept



Detector concept IDEA

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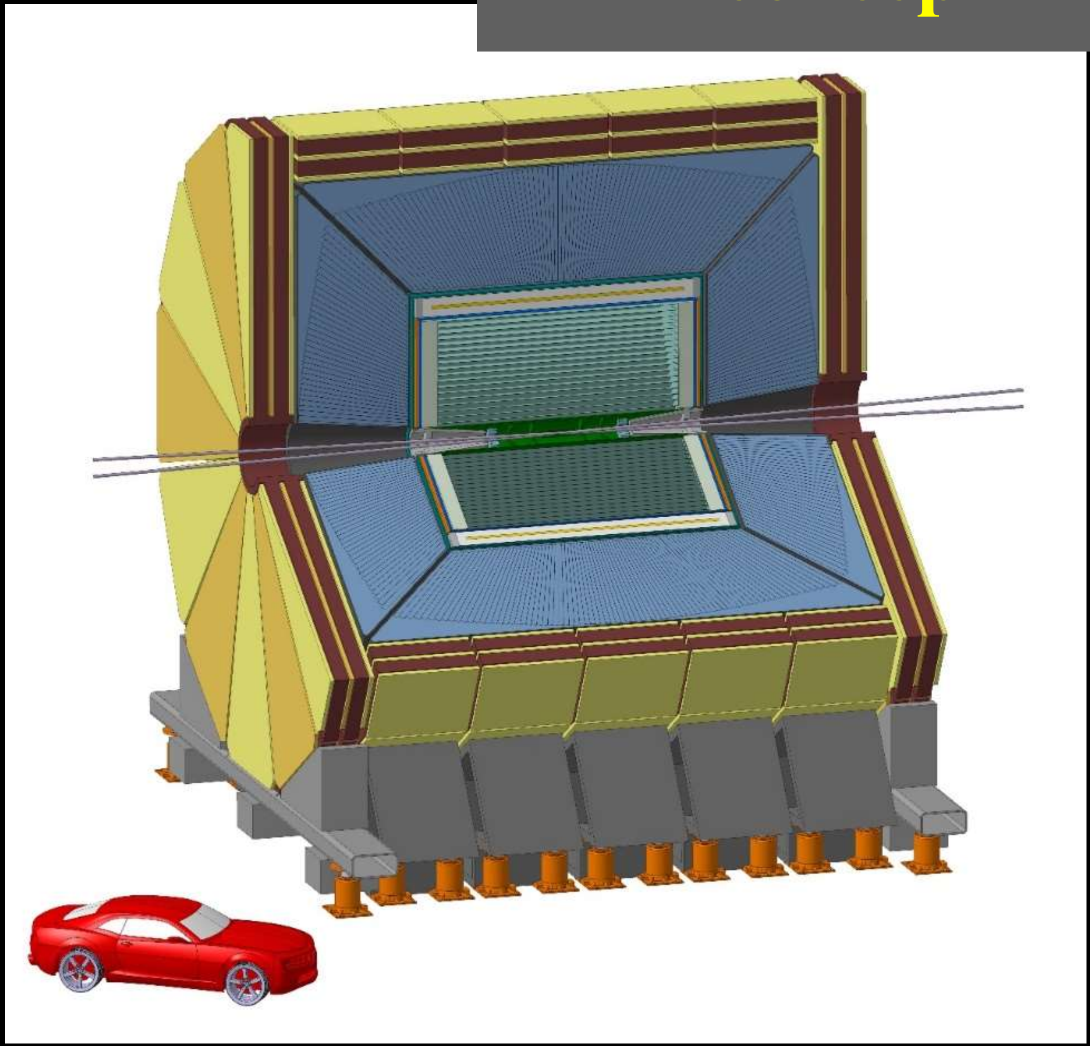
- Drift chamber (112 layers)

  4m long, r = 35 – 200 cm

IDEA concept



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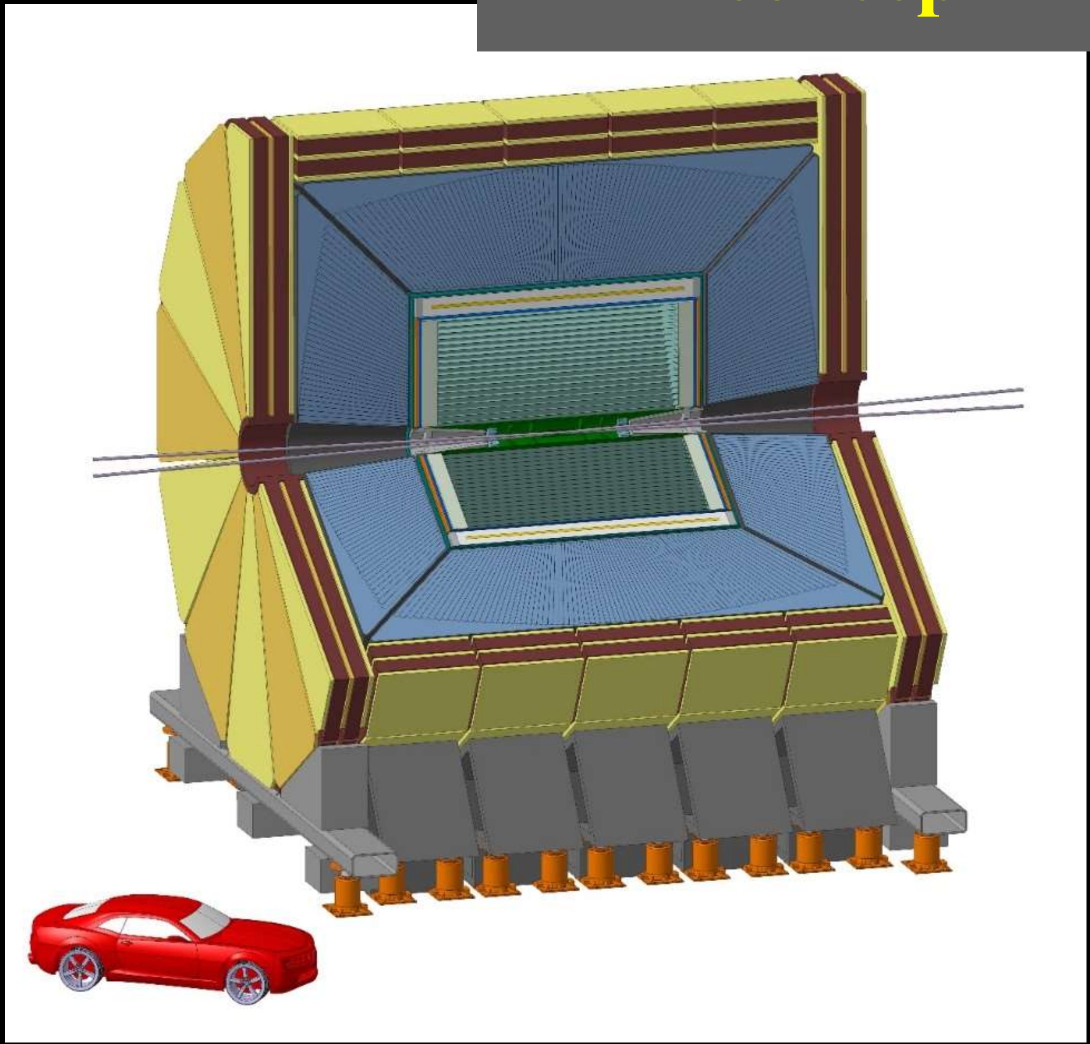
IDEA concept



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Solenoid: 2 T - 5 m, r = 2.1-2.4

- $0.74\ X_0$, $0.16\ \lambda$ @ 90º

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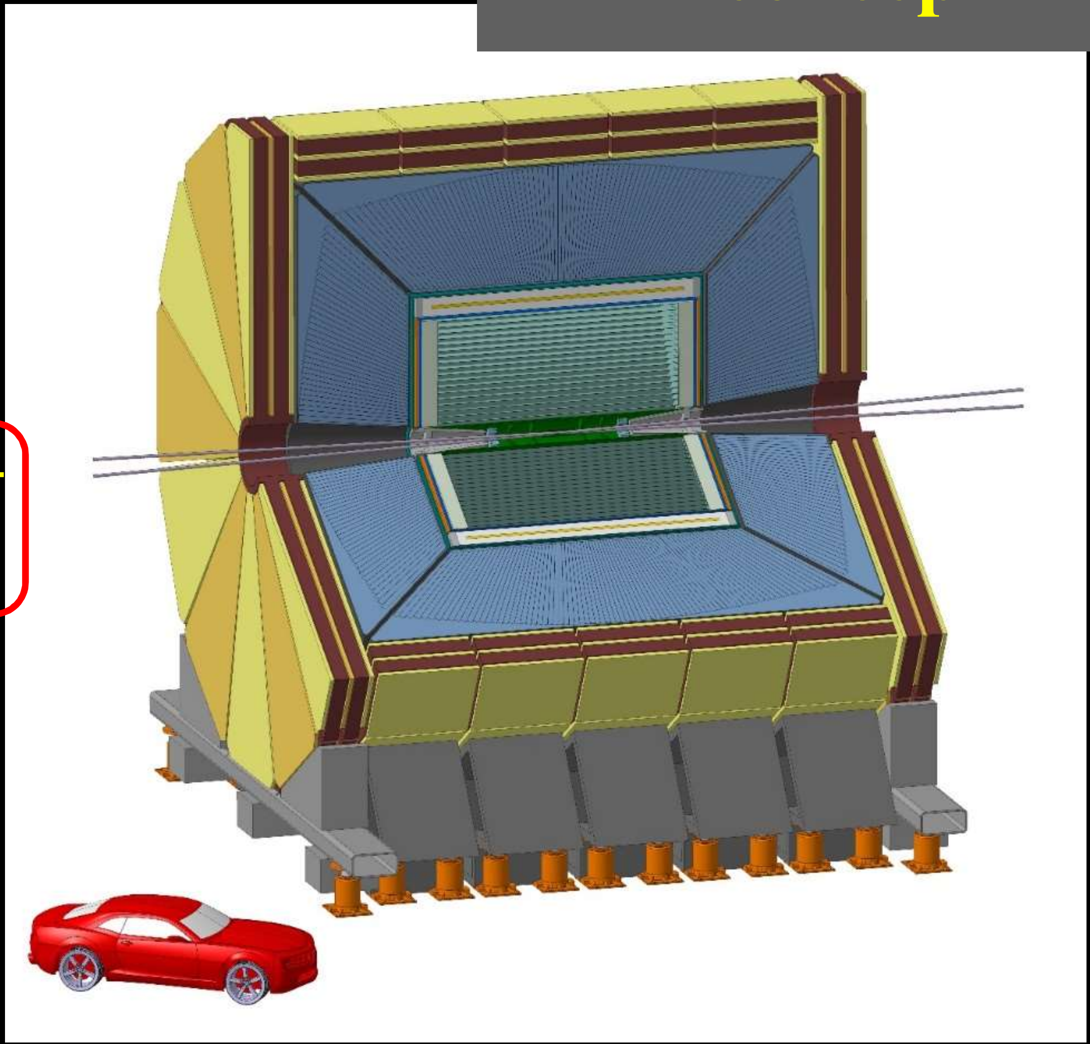

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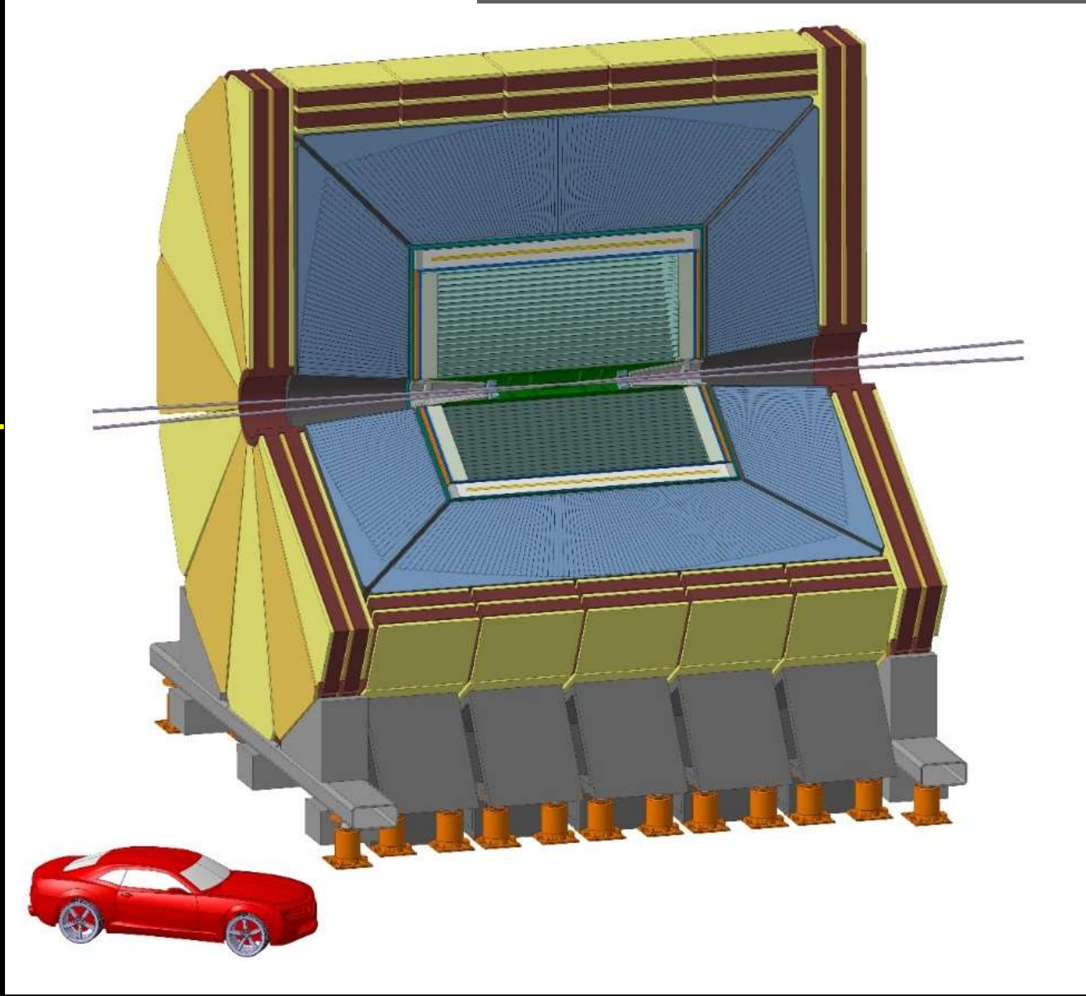

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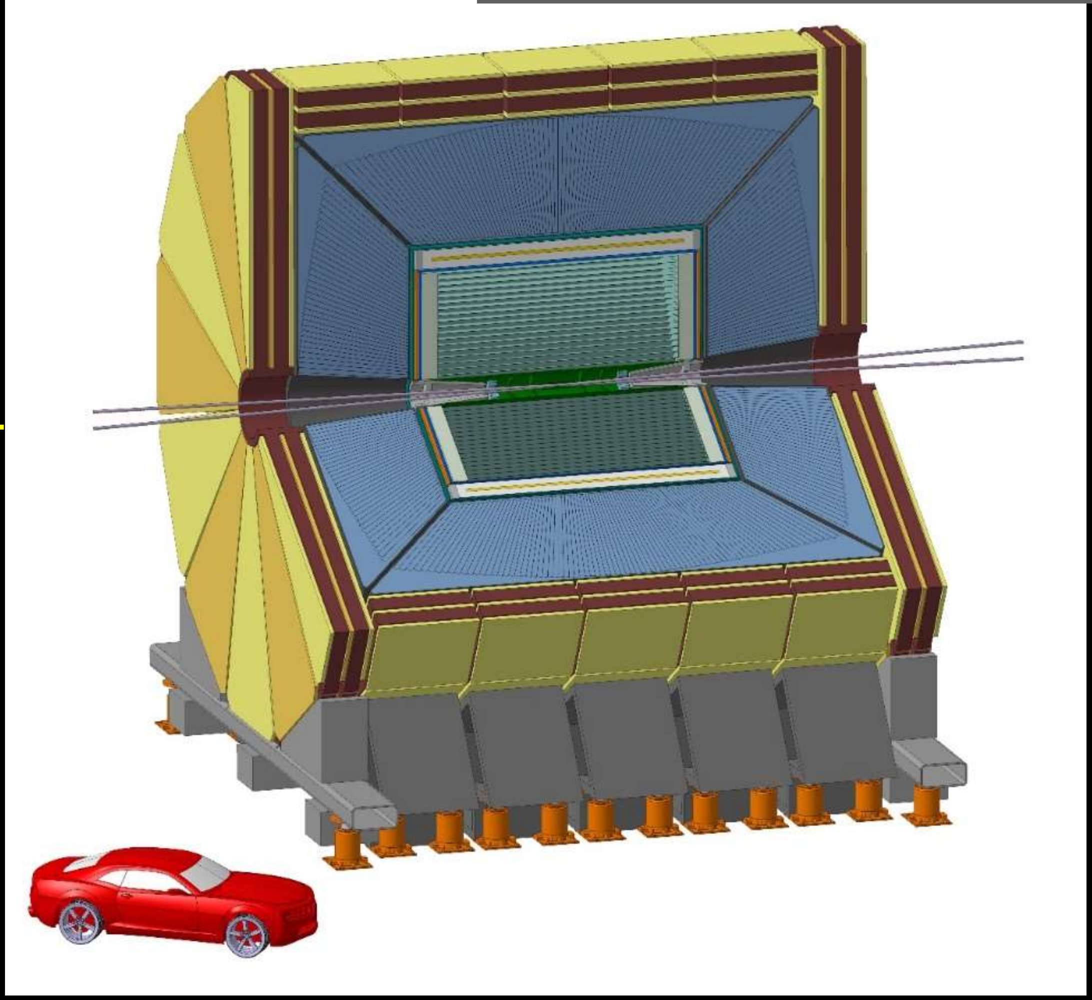
Dual Readout calorimetry
- 2m deep/8 λ

IDEA concept



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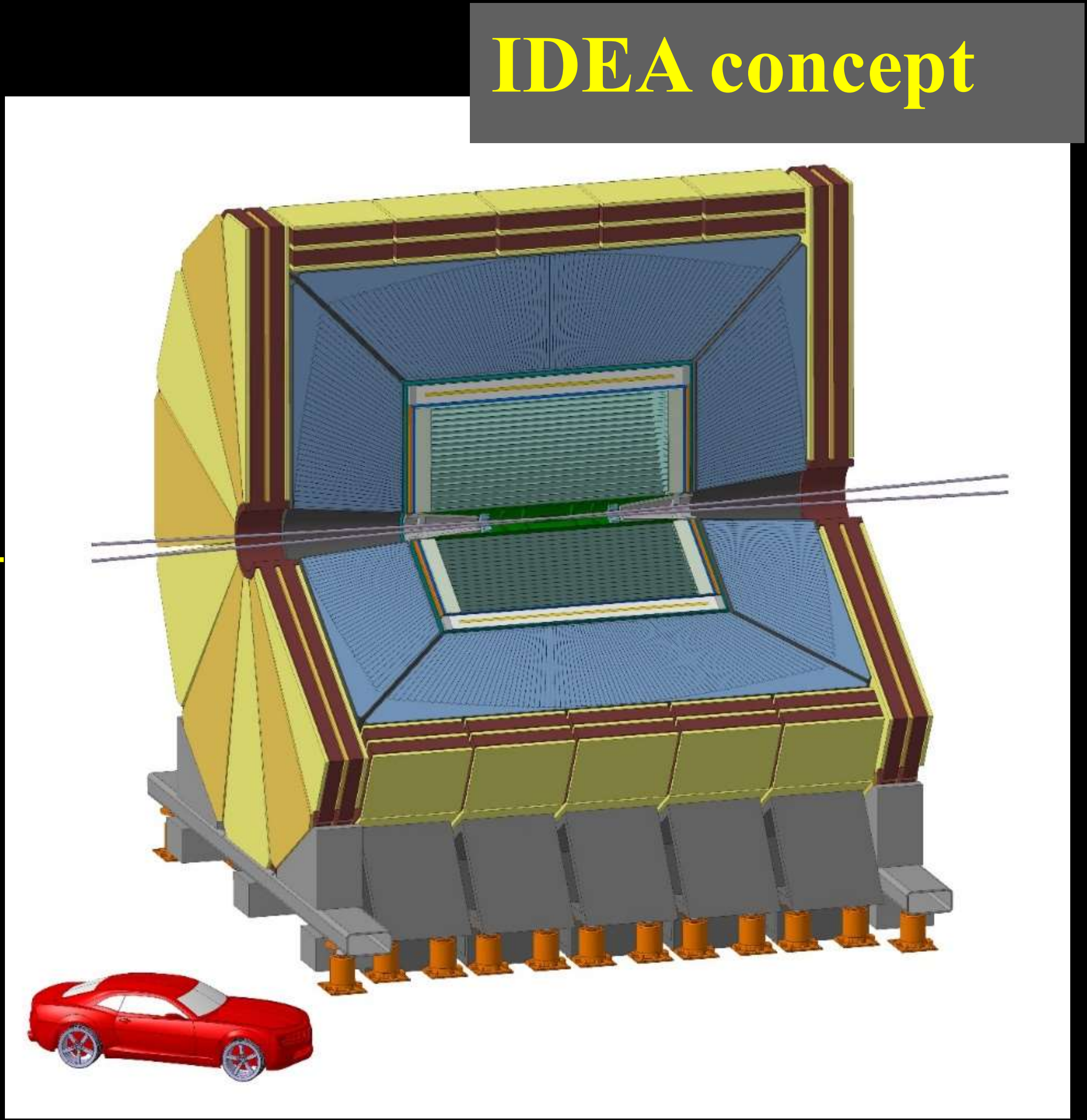
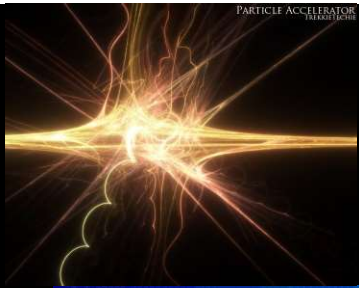
- Muon chambers
  - μRwell





Detector requirements

- Requirements:
  - Constraints from physics (similar to LC …. more or less)

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	$\Delta(1/p_T) =$ $2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
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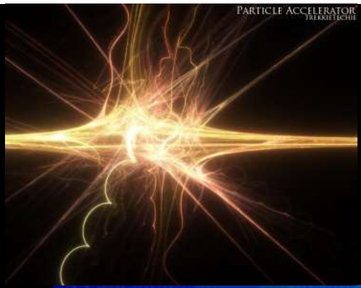
From CDR



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Too tight?

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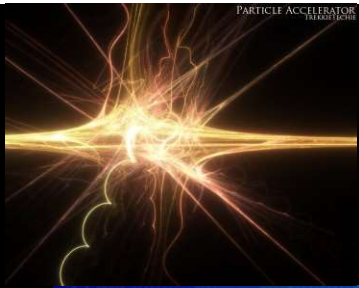

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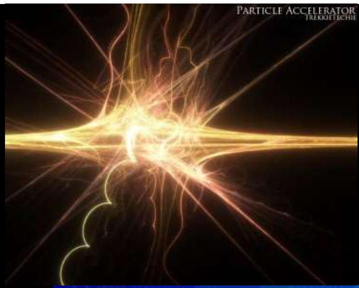

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From CDR

Too tight? (Tracker)

Not enough? (Vertex)

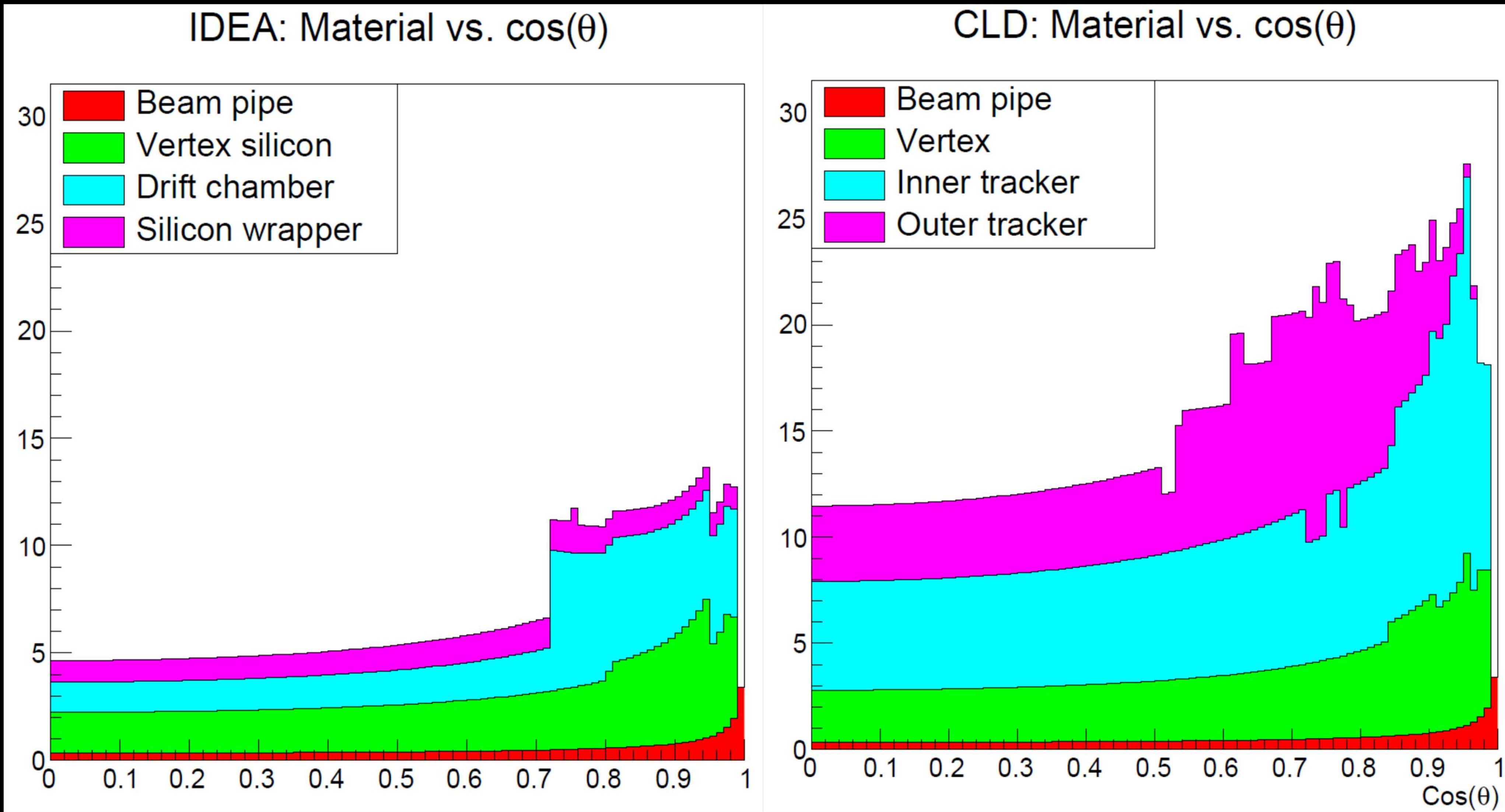
Too tight? (ECAL/HCAL)

Not enough? (ECAL)

- Additional constraints
  - Excellent acceptance and luminosity control
  - PID & π^0 ID for HF/τ physics
  - Low B field to avoid emittance blow up
  - Power pulsing not allowed

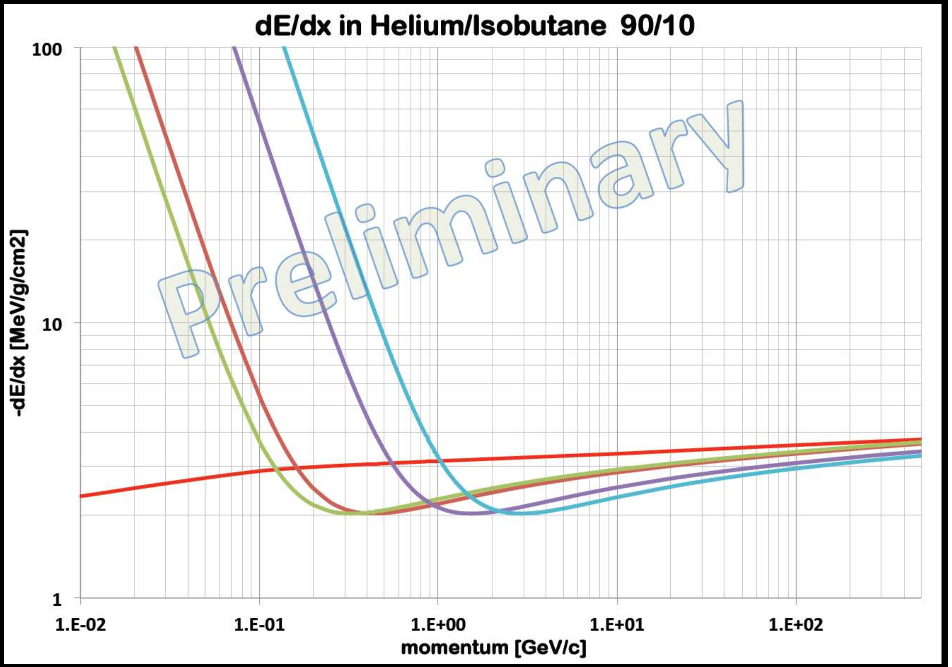
} Not present at LC

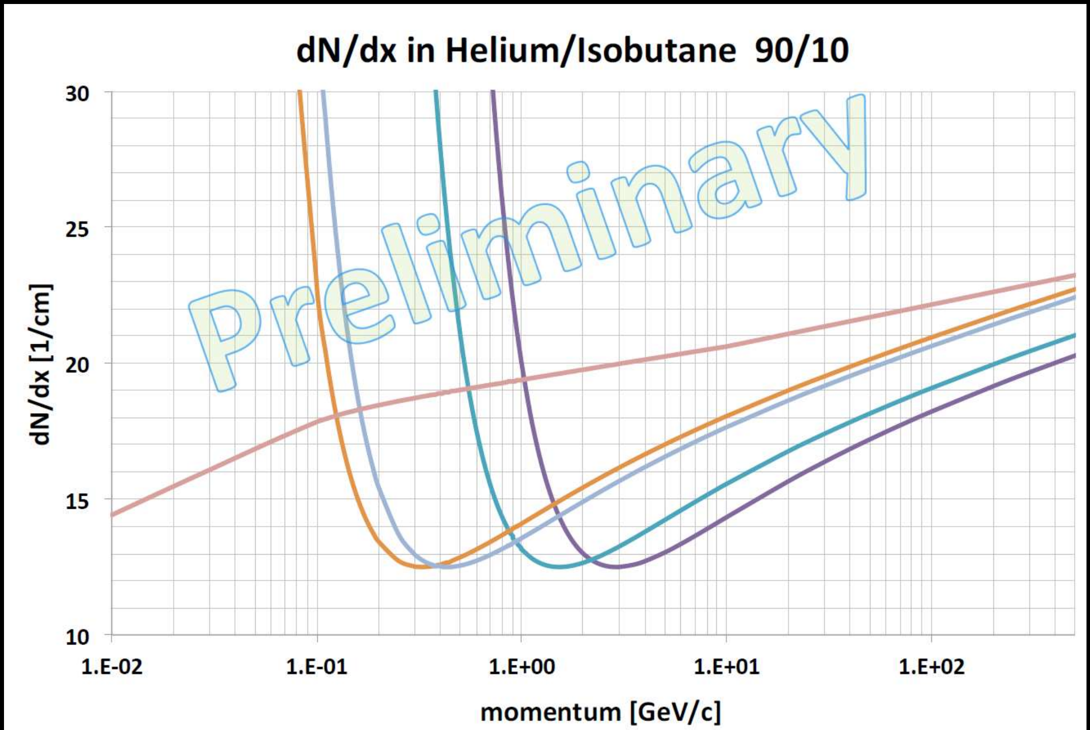
Transparency



dE/dx vs dN/dx

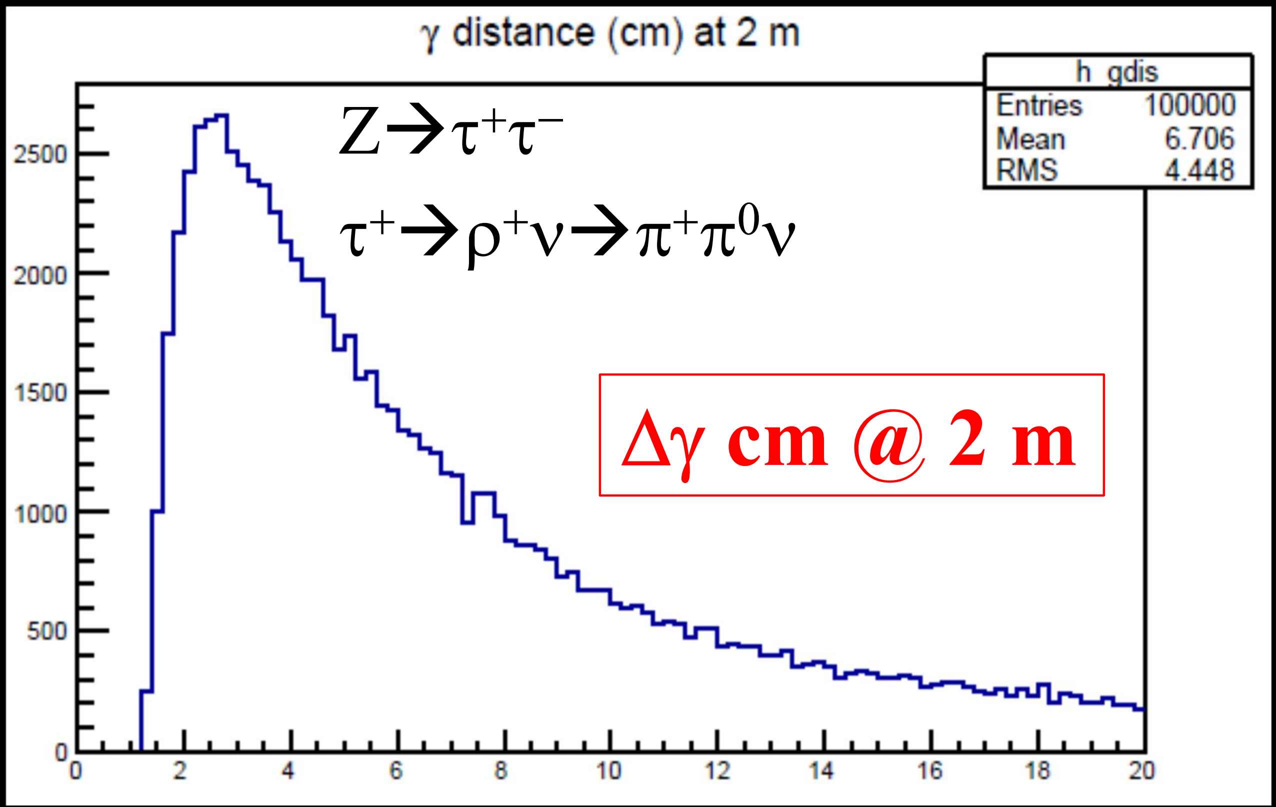
- Steeper high energy rise of #clusters than ionization E





Calorimeter separation (γ)

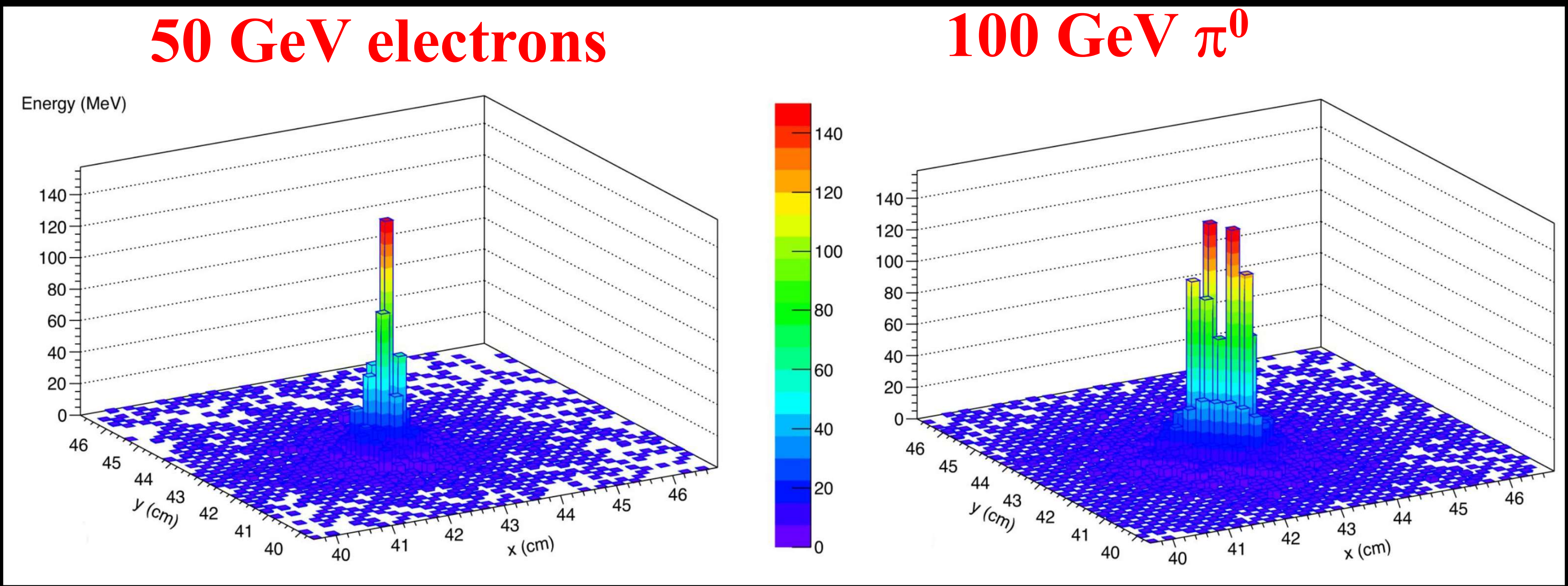
- Transverse granularity below 1 cm seems adequate

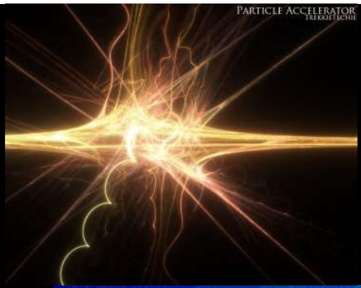


Calorimeter separation (γ)

- Transverse granularity below 1 cm seems adequate
  Extreme granularity (~2 mm) achievable with DR

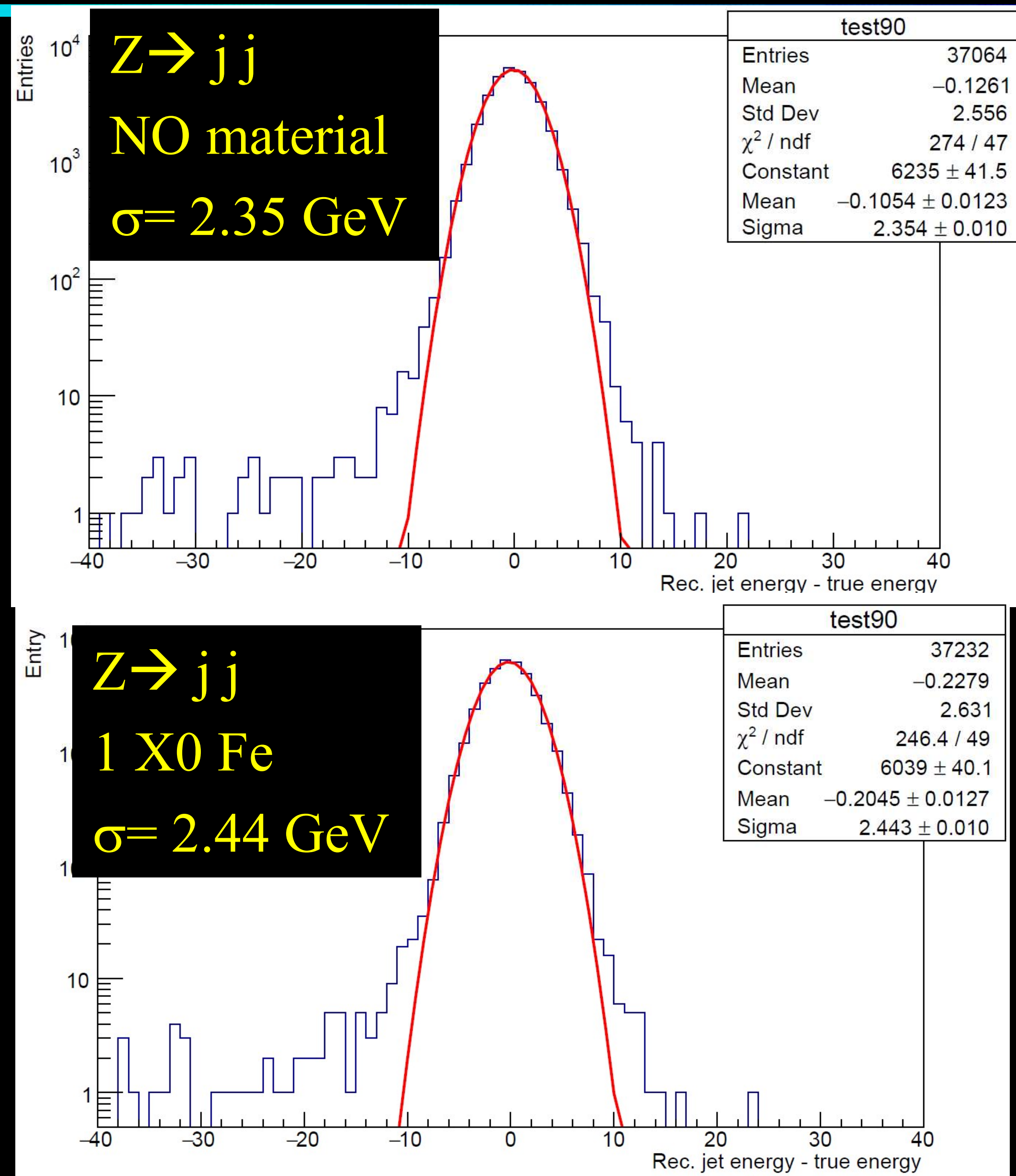
  At a cost ….

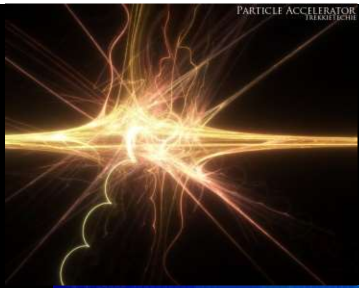




Effect of material

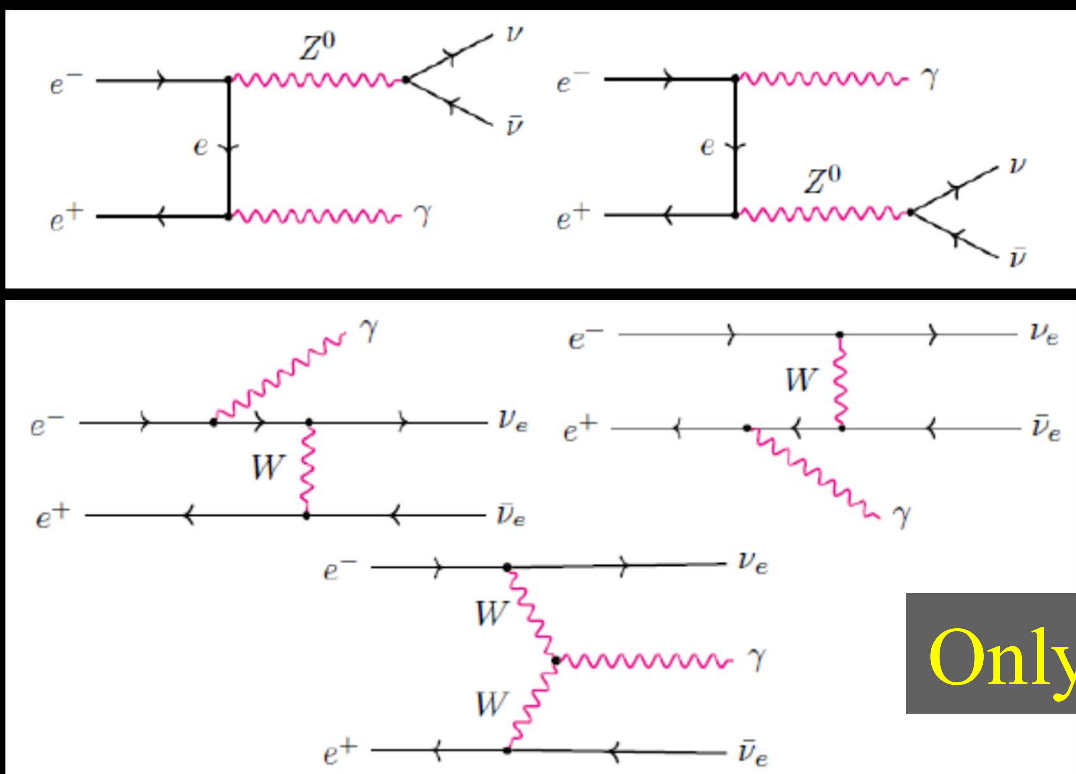
- Effect of 1 X0 Fe
- Distance from calor.
  - 30 cm barrel
  - 10 cm endcap





Calorimeter resolution (γ)

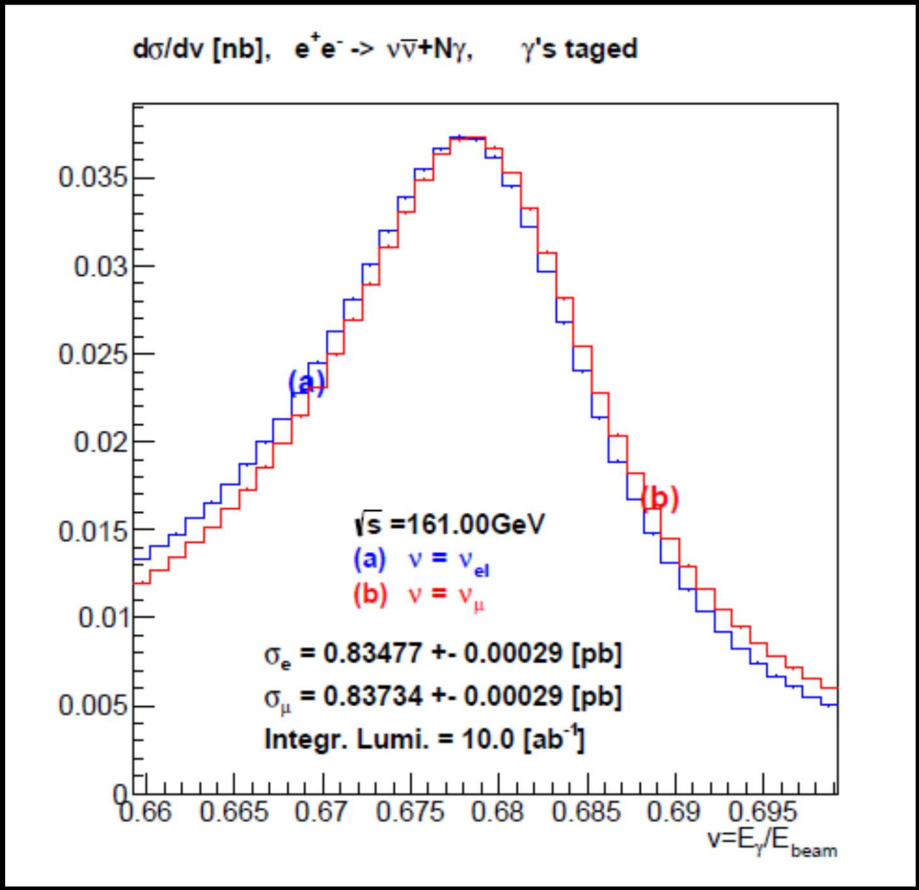
- Is 20%/sqrt(E) acceptable? Can we trigger on single γ?
- What about radiative return analysis?
  - Eg. Nν, and Z→ ν_e ν_e



Only ν_e interfere

Calorimeter resolution (γ)

- Is 20%/sqrt(E) acceptable? Can we trigger on single γ?
- What about radiative return analysis?
  - Eg. Nν, and Z→ $\nu_e\, \nu_e$



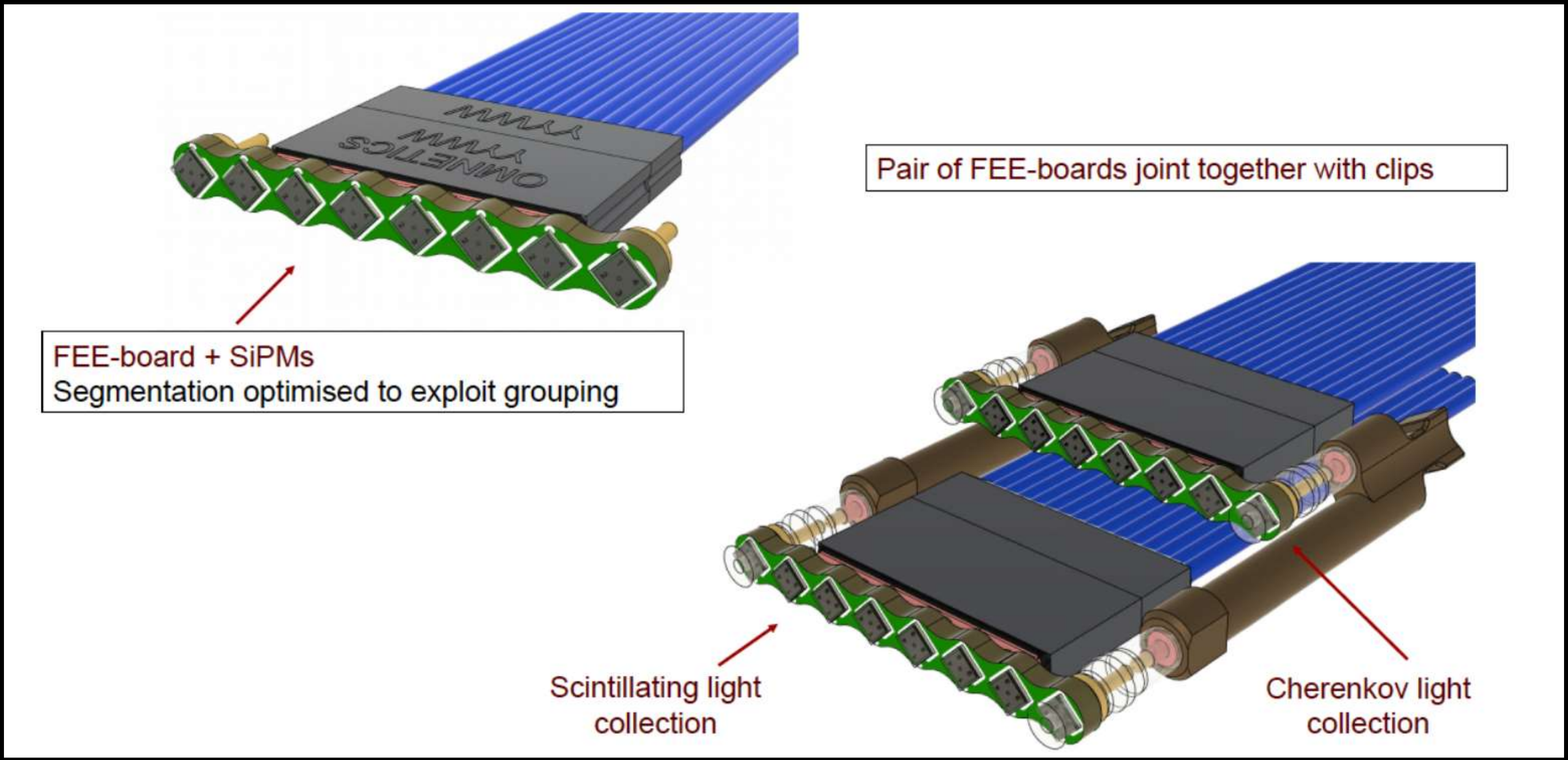
Need 5-10%/sqrt(E) for a good measurement

$\sigma(g_{\nu e})$: 18% →1.4-2.4%

- Worse resolution make separation difficult

Calorimeter R&D

❖ Direct coupling scheme



Calorimeter R&D

❖ Direct coupling scheme