Detector optimization for Z running

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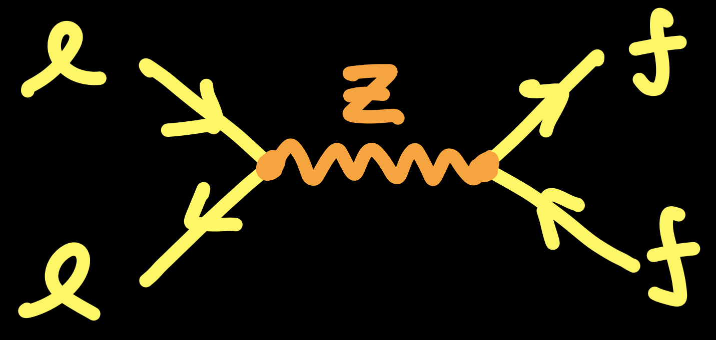
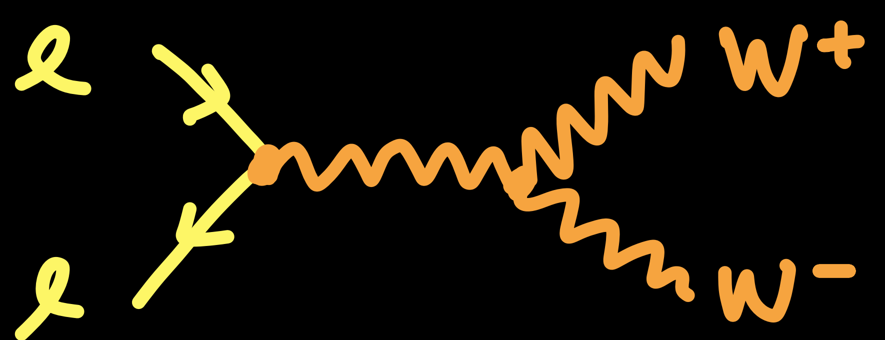
Updated CEPC collider parameters since CDR

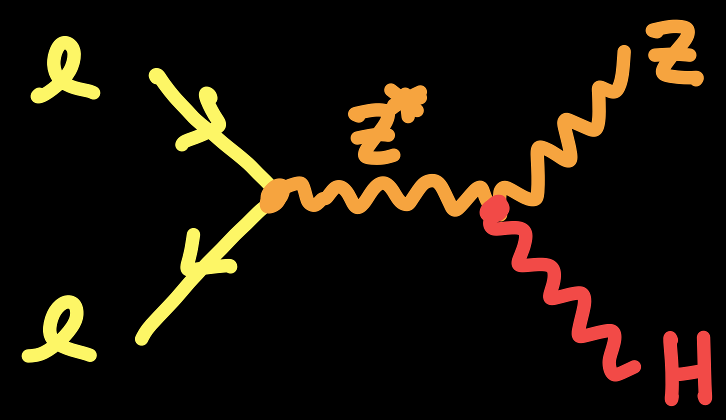
	Higgs		Z (2T)	
	CDR	Updated	CDR	Updated
Beam energy (GeV)	120	-	45.5	-
Synchrotron radiation loss/turn (GeV)	1.73	1.68	0.036	-
Piwinski angle	2.58	3.78	23.8	33
Number of particles/bunch N_e (10^{10})	15.0	17	8.0	15
Bunch number (bunch spacing)	242 (0.68μs)	218 (0.68μs)	12000	15000
Beam current (mA)	17.4	17.8	461.0	1081.4
Synchrotron radiation power /beam (MW)	30	-	16.5	38.6
Cell number/cavity	2	-	2	1
β function at IP β_x^* / β_y^* (m)	0.36/0.0015	0.33/0.001	0.2/0.001	-
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0031	0.89/0.0018	0.18/0.0016	-
Beam size at IP σ_x/σ_y (μm)	20.9/0.068	17.1/0.042	6.0/0.04	-
Bunch length σ_z (mm)	3.26	3.93	8.5	11.8
Lifetime (hour)	0.67	0.22	2.1	1.8
Luminosity/IP L (10^{34} $cm^{-2}s^{-1}$)	2.93	5.2	32.1	101.6

Luminosity increase factor: × 1.8 × 3.2

The CEPC Program

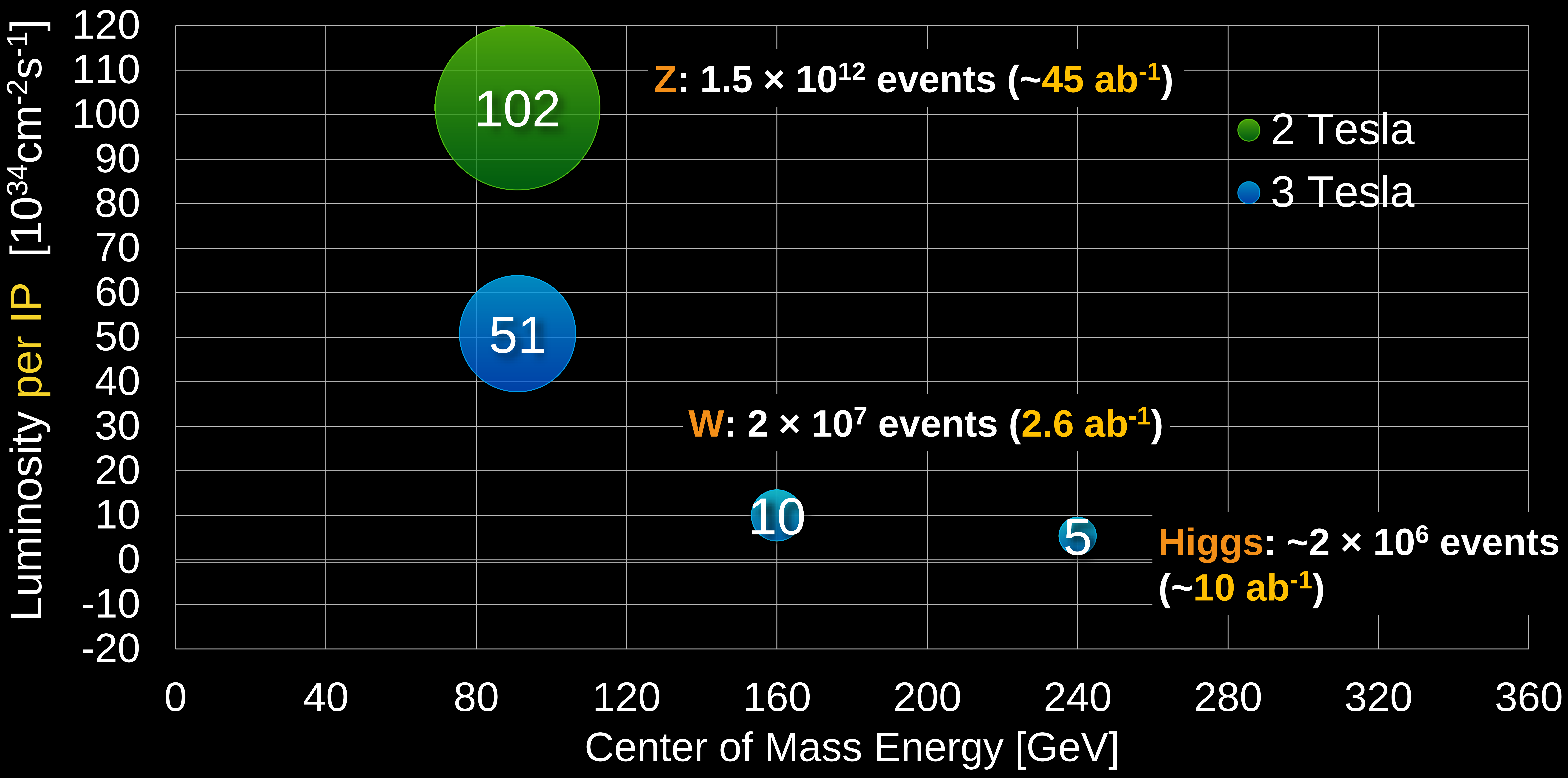






100 km e^+e^- collider

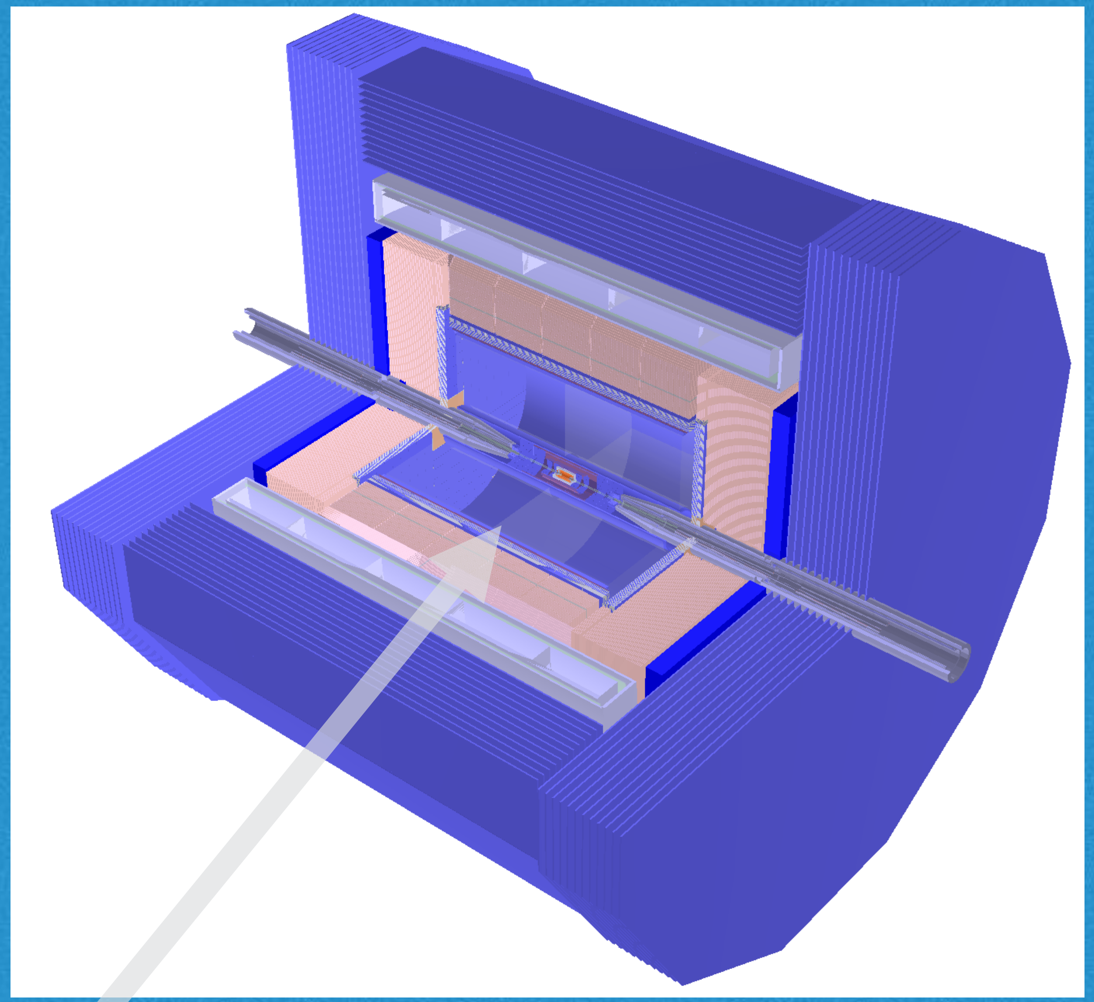
2 IPs

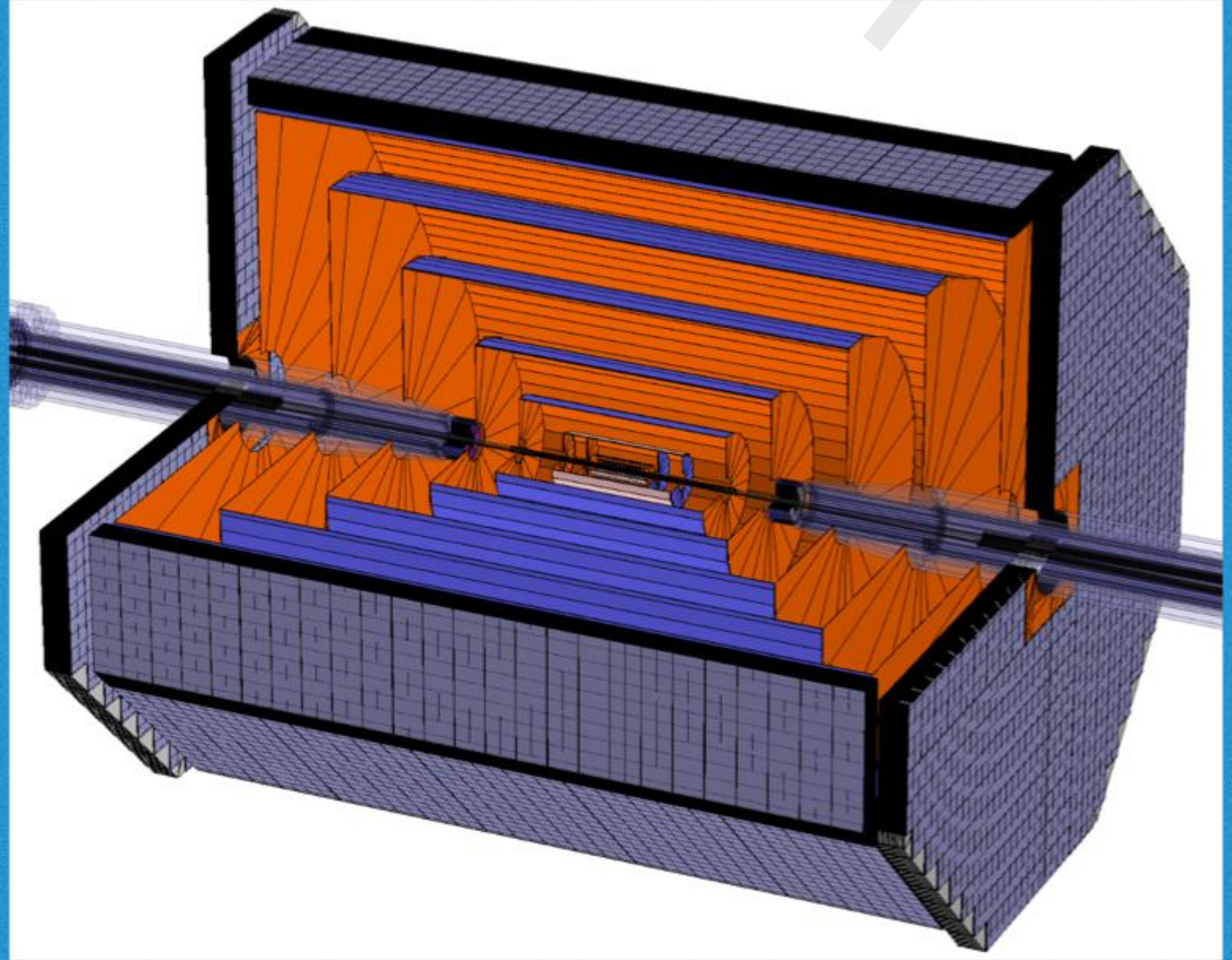


CEPC: 2.5 Detector Concepts

Particle Flow Approach

Baseline detector ILD-like (3 Tesla)

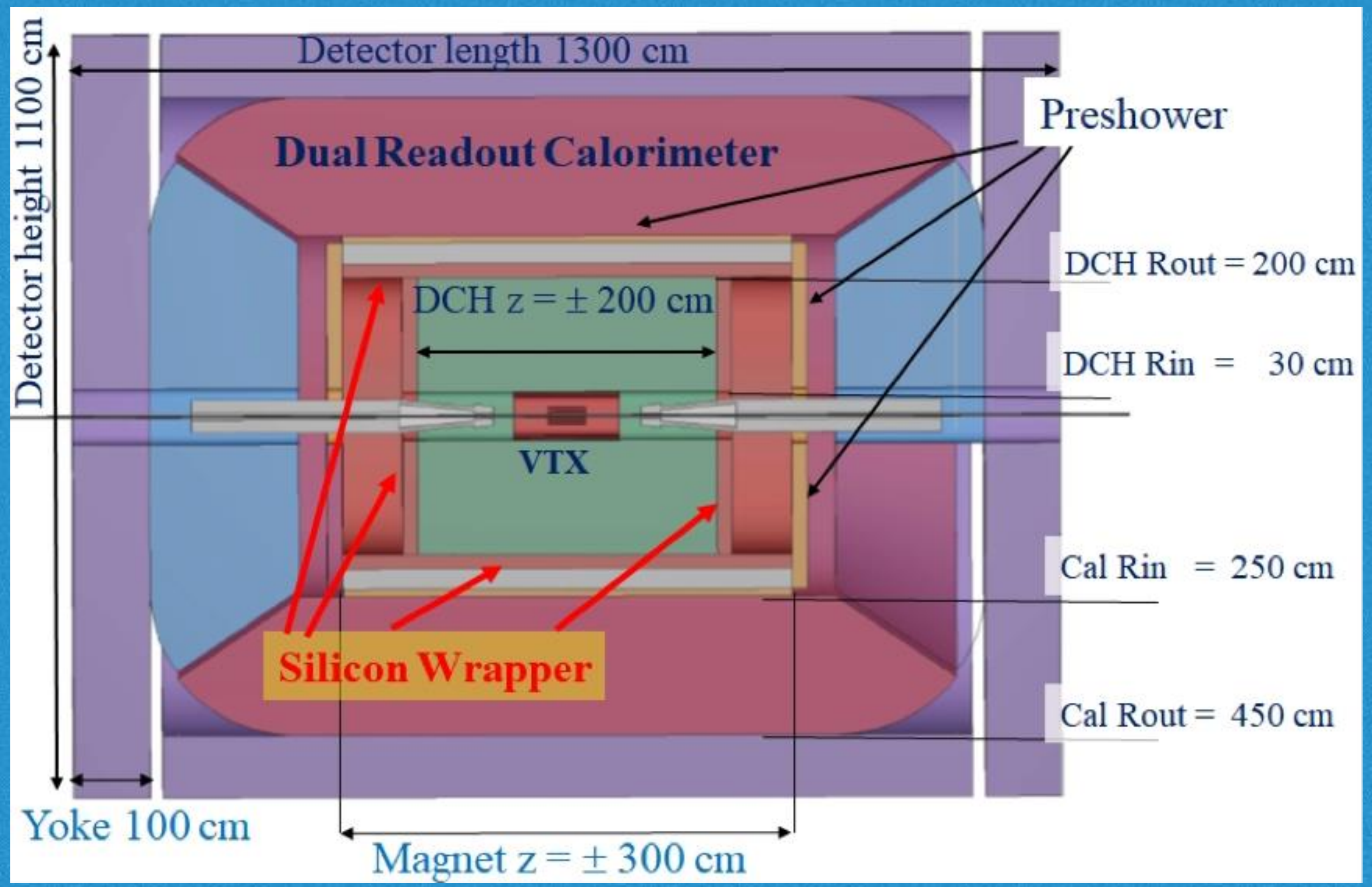




Full silicon tracker concept

CEPC plans for 2 interaction points

Low magnetic field concept (2 Tesla)



IDEA Concept
also proposed for FCC-ee

Final two detectors likely to be a mix and match of different options

The status of electroweak global fit

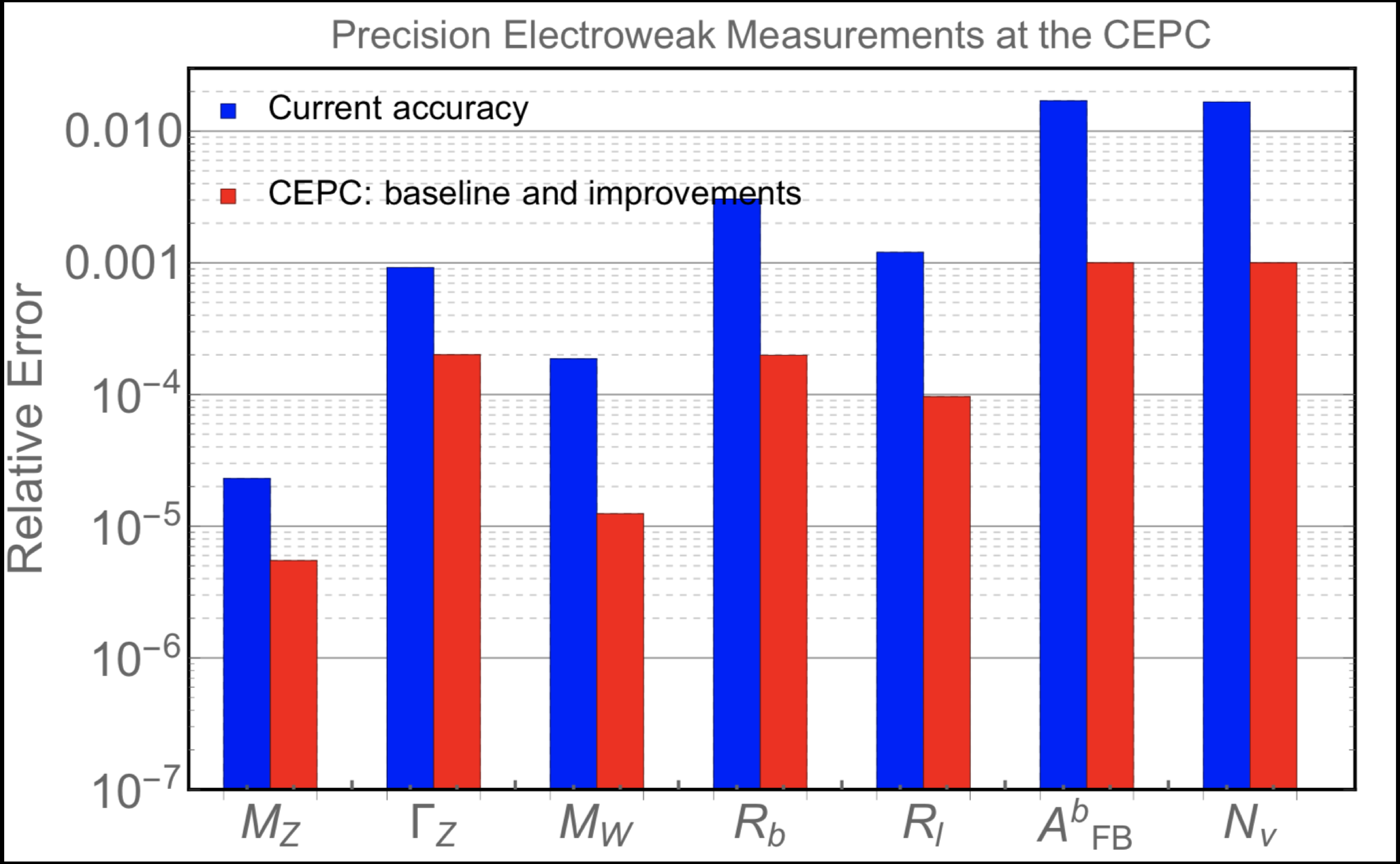
Fundamental constant	$\delta x/x$	measurements
$\alpha = 1/137.035999139\,(31)$	1×10^{-10}	$e^{\pm}\ g_2$
$G_F = 1.1663787\,(6)\times10^{-5}\ \mathrm{GeV}^{-2}$	1×10^{-6}	$\mu^{\pm}$ lifetime
$M_Z = 91.1876\pm0.0021\ \mathrm{GeV}$	1×10^{-5}	LEP
$M_W = 80.379\pm0.012\ \mathrm{GeV}$	1×10^{-4}	LEP/Tevatron/LHC
$\sin^2\theta_W = 0.23152\pm0.00014$	6×10^{-4}	LEP/SLD
$m_{top} = 172.74\pm0.46\ \mathrm{GeV}$	3×10^{-3}	Tevatron/LHC
$M_H = 125.14\pm0.15\ \mathrm{GeV}$	1×10^{-3}	LHC

Can be improved with Z pole data

From PDG

Prospect of CEPC EWK physics

Expect to have 1~2 order of magnitude better than current precision



flavor physics motivation at CEPC Z pole

- CP violation in quark and lepton sectors

  CPV in b-baryon and c-baryon decays, in tau production and decay

- FCNC processes: rare b-decays , rare charm, in tau decays, in Z decays

Observable	Current sensitivity	Future sensitivity	Tera-Z sensitivity
$\mathrm{BR}(B_s \to ee)$	2.8×10^{-7} (CDF) [438]	$\sim 7 \times 10^{-10}$ (LHCb) [435]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \mu\mu)$	0.7×10^{-9} (LHCb) [437]	$\sim 1.6 \times 10^{-10}$ (LHCb) [435]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \tau\tau)$	5.2×10^{-3} (LHCb) [441]	$\sim 5 \times 10^{-4}$ (LHCb) [435]	$\sim 10^{-5}$
R_K, R_{K^*}	$\sim 10\%$ (LHCb) [443, 444]	$\sim$few% (LHCb/Belle II) [435, 442]	$\sim$few %
$\mathrm{BR}(B \to K^*\tau\tau)$	–	$\sim 10^{-5}$ (Belle II) [442]	$\sim 10^{-8}$
$\mathrm{BR}(B \to K^*\nu\nu)$	4.0×10^{-5} (Belle) [449]	$\sim 10^{-6}$ (Belle II) [442]	$\sim 10^{-6}$
$\mathrm{BR}(B_s \to \phi\nu\bar{\nu})$	1.0×10^{-3} (LEP) [452]	–	$\sim 10^{-6}$
$\mathrm{BR}(\Lambda_b \to \Lambda\nu\bar{\nu})$	–	–	$\sim 10^{-6}$
$\mathrm{BR}(\tau \to \mu\gamma)$	4.4×10^{-8} (BaBar) [475]	$\sim 10^{-9}$ (Belle II) [442]	$\sim 10^{-9}$
$\mathrm{BR}(\tau \to 3\mu)$	2.1×10^{-8} (Belle) [476]	$\sim$ few $\times 10^{-10}$ (Belle II) [442]	$\sim$ few $\times 10^{-10}$
$\frac{\mathrm{BR}(\tau \to \mu\nu\bar{\nu})}{\mathrm{BR}(\tau \to e\nu\bar{\nu})}$	3.9×10^{-3} (BaBar) [464]	$\sim 10^{-3}$ (Belle II) [442]	$\sim 10^{-4}$
$\mathrm{BR}(Z \to \mu e)$	7.5×10^{-7} (ATLAS) [471]	$\sim 10^{-8}$ (ATLAS/CMS)	$\sim 10^{-9} - 10^{-11}$
$\mathrm{BR}(Z \to \tau e)$	9.8×10^{-6} (LEP) [469]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-11}$
$\mathrm{BR}(Z \to \tau\mu)$	1.2×10^{-5} (LEP) [470]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-10}$

Detector requirement at Z pole

- Most of detector requirement is based on Higgs physics at ZH run
- New requirement for Z pole
  - Particle identification requested by flavor physics (k/π separation , π0/γ separation)
  - Detector timing (Z pole @40MHz collision)

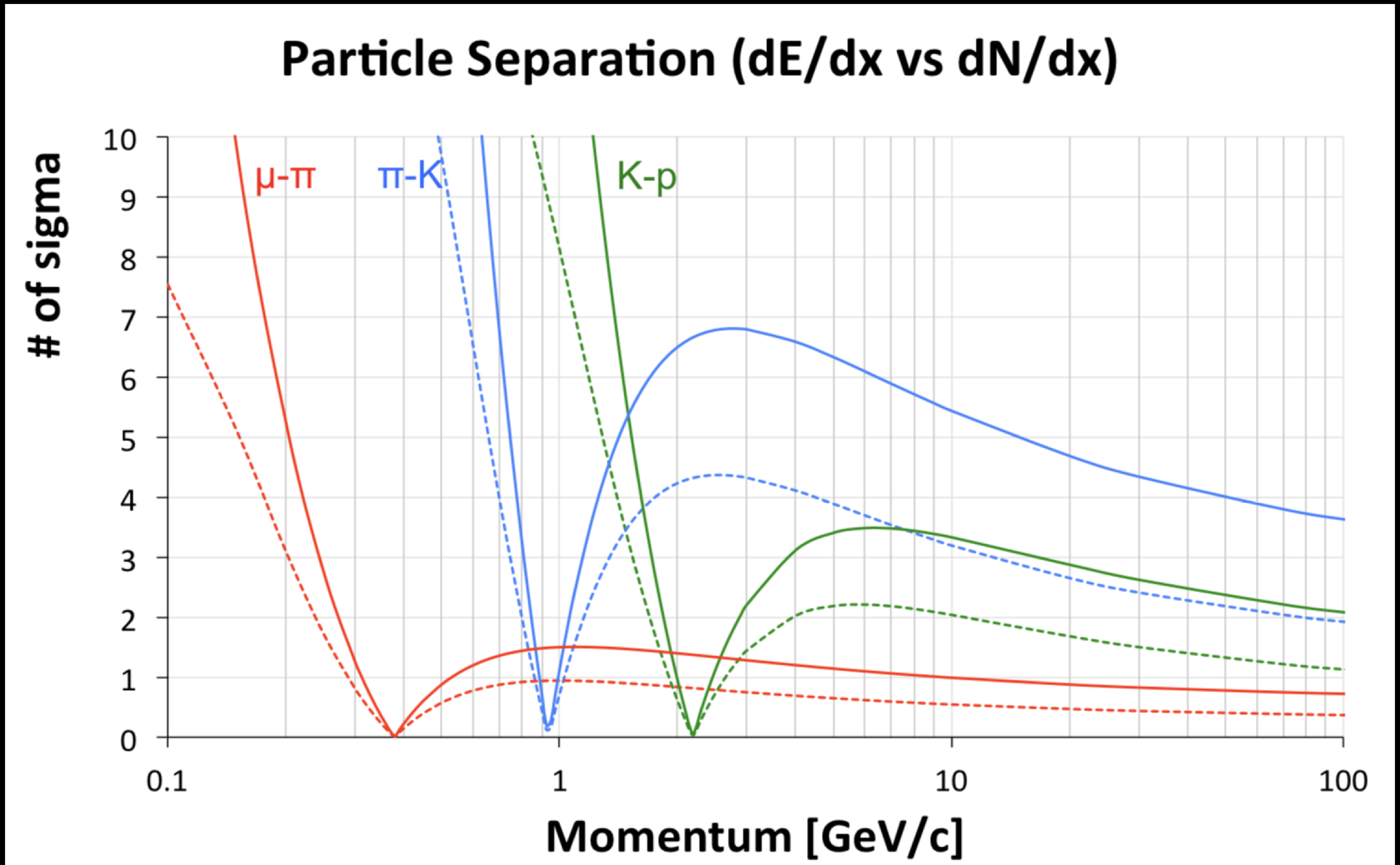
From CDR

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	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$	Too tight?
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$	Not enough?
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E = 3 \sim 4\%$ at 100 GeV	Too tight?
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$	Not enough?

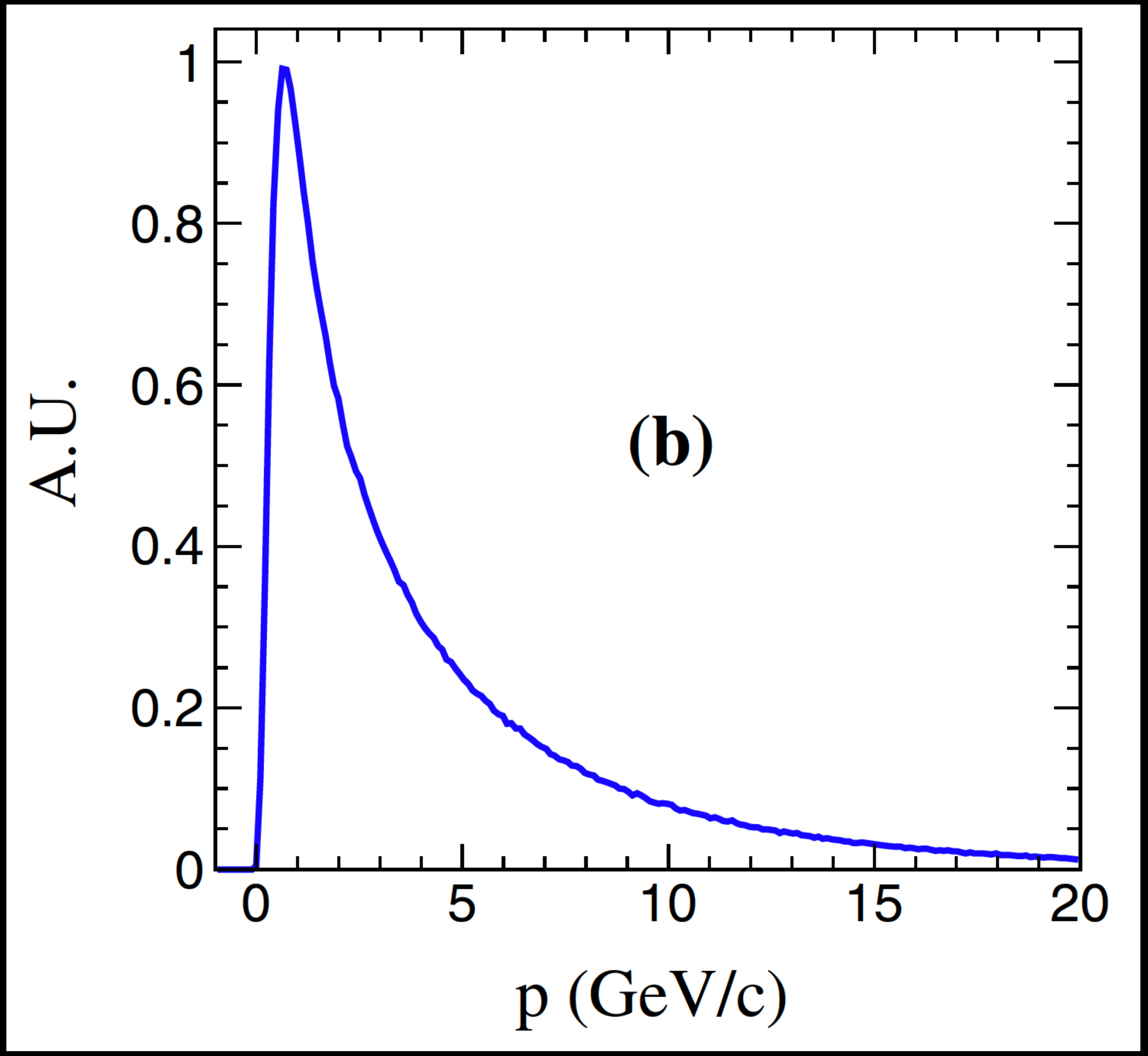
Particle identification (PID)

- CEPC flavor physics benchmark : CPV measurement in B->K*νν-> k πνν
- k/ π separation in momentum below 20GeV should be needed
- PID detector: TPC detector in baseline concept, drift chamber in IDEAL concept

Particle identification performance in drift chamber in IDEAL concept



Kaon momentum distribution at Z pole



Particle identification Challenge: Time projection Chamber(TPC)

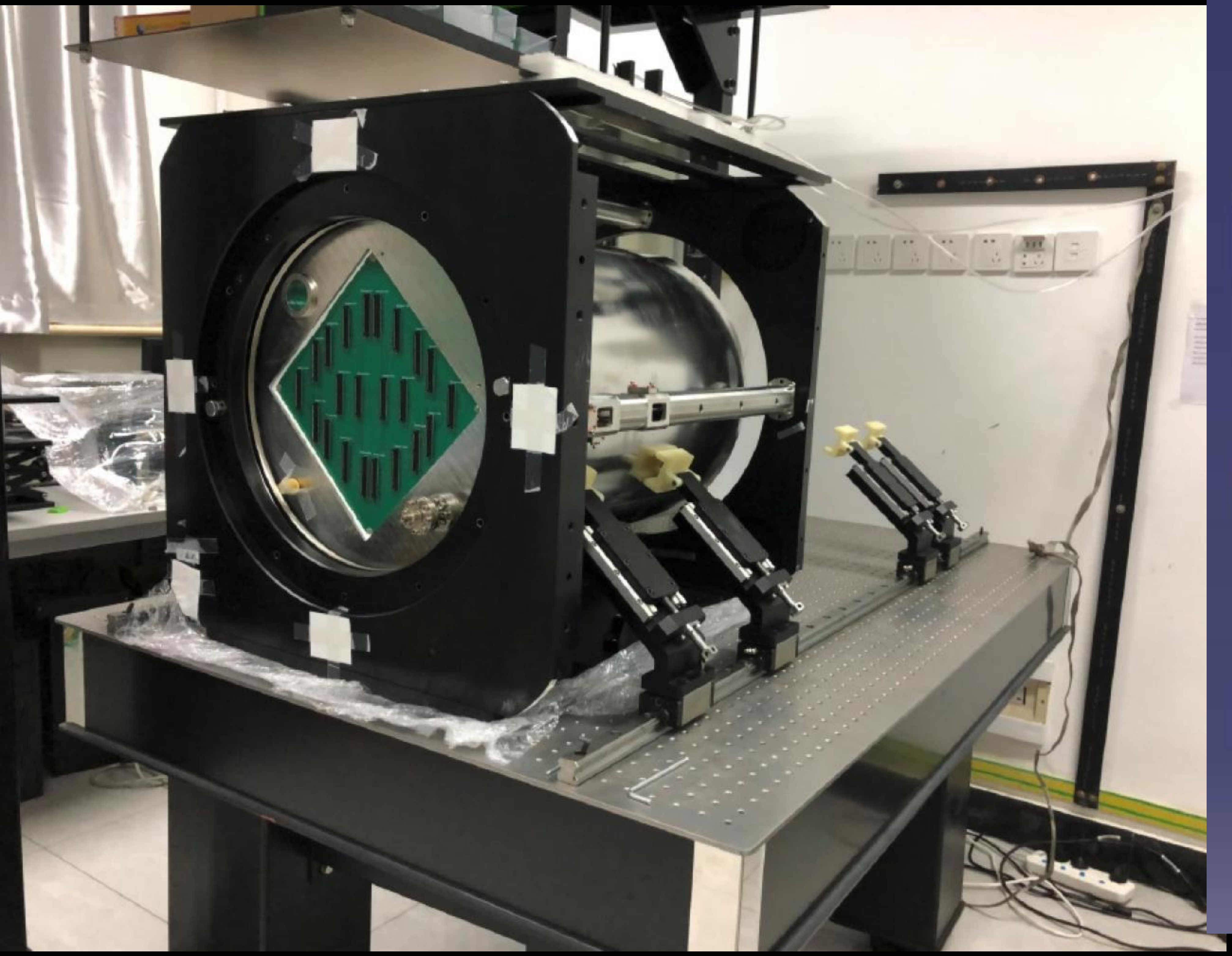
- At $10^{35}cm^{-2}s^{-1}$, Ion backflow and space charge effect can be calibrated by laser system
- However, In CEPC new Z pole luminosity $10^{36}cm^{-2}s^{-1}$
- ➢ Study the pixel TPC to replace pad TPC

TPC challenges

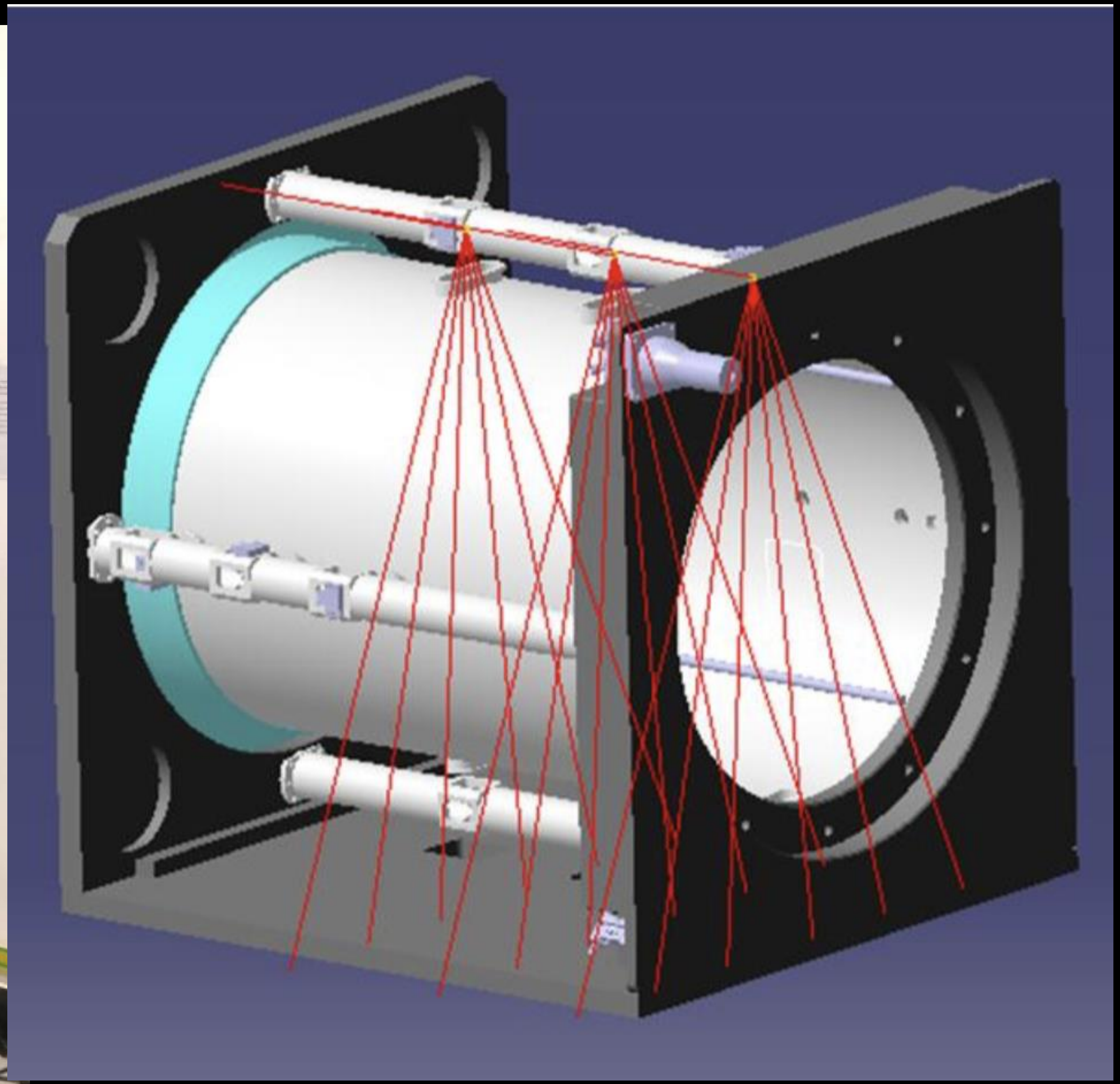
Ion backflow → affects resolution

Solution: Gating concepts and new readout modules under study

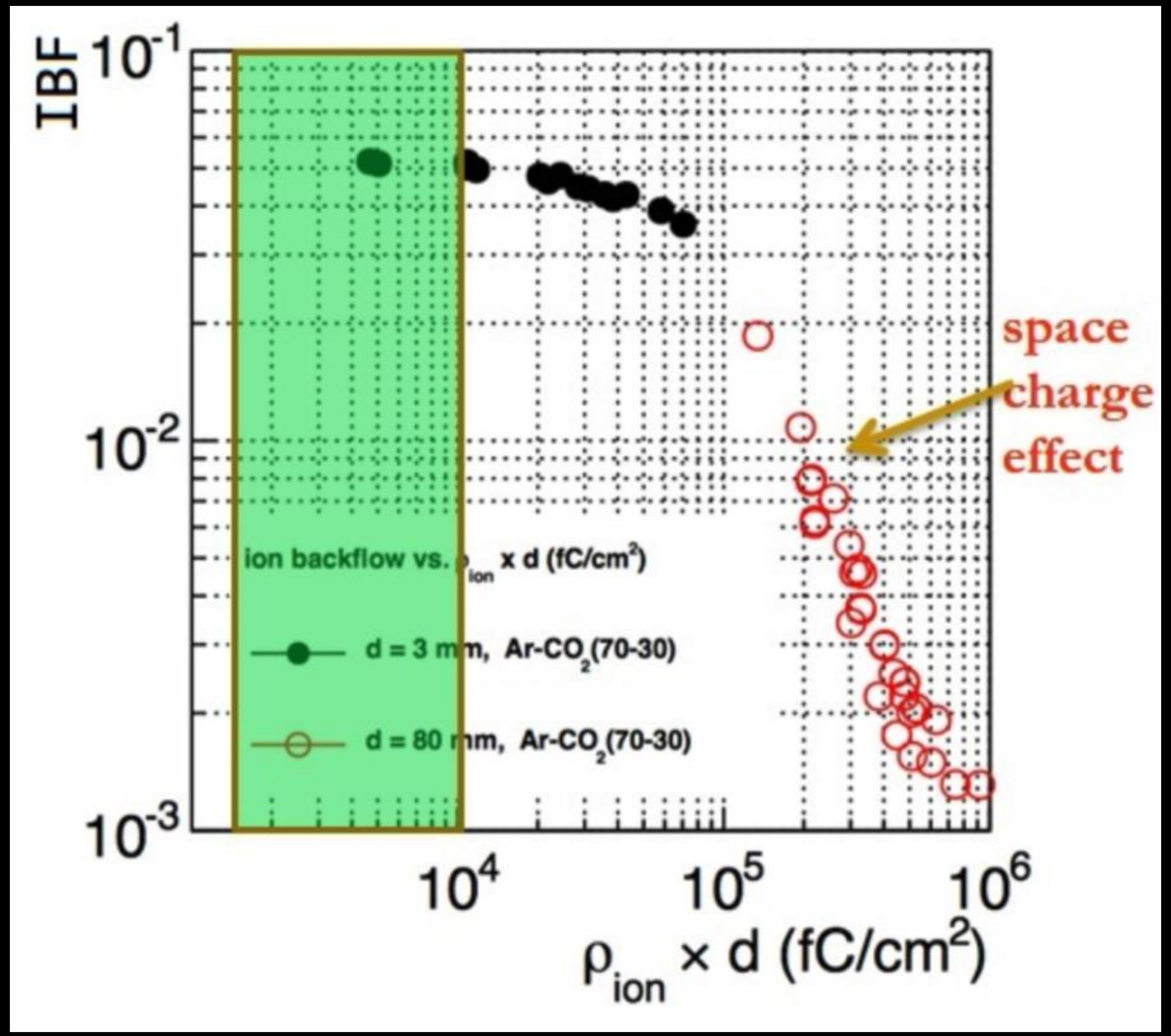
Photo of TPC prototype



Laser calibration for space charge effect



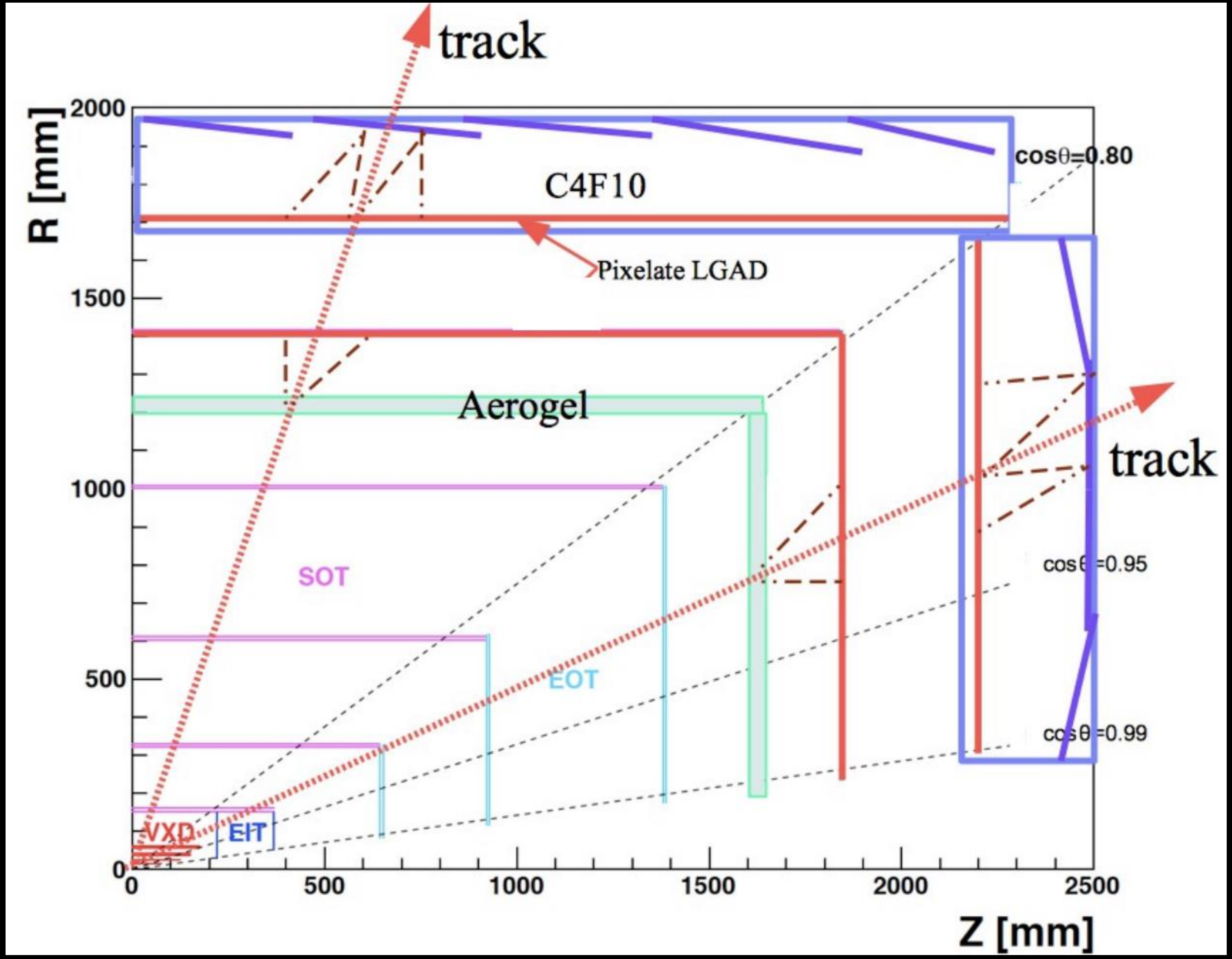
Ion backflow and space Charge effect



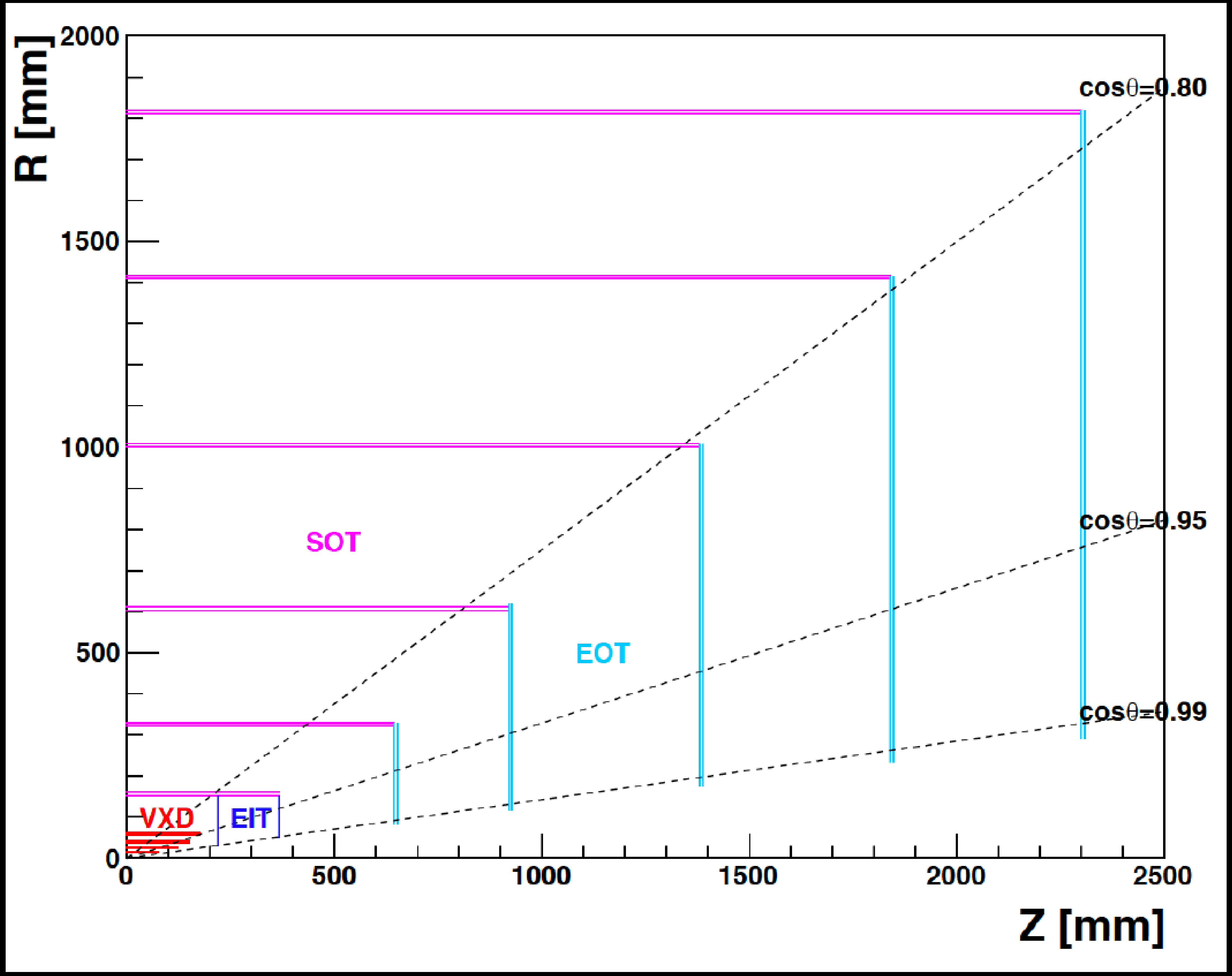
Particle identification in full silicon concept

- RICH detector in outer layer in full silicon concept (Aerogel and C4F10 gas)
- Pprovide PID up to 30 GeV
- Need collaboration for dedicated design and study

CEPC full silicon concept+ Rich detector



CEPC full silicon concept

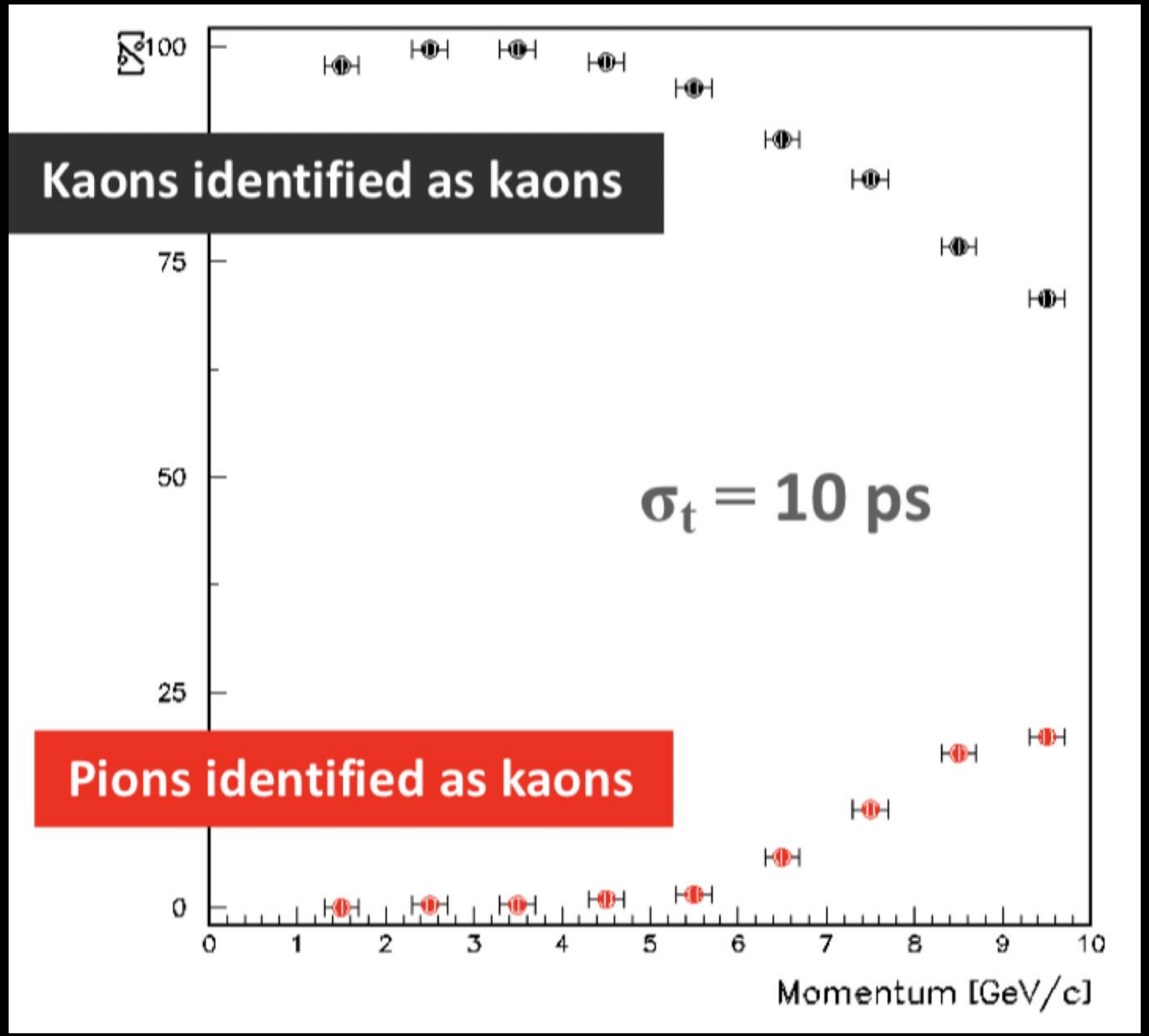


Wei-Ming Yao (LBNL) talk in 2019 Oxford CEPC workshop

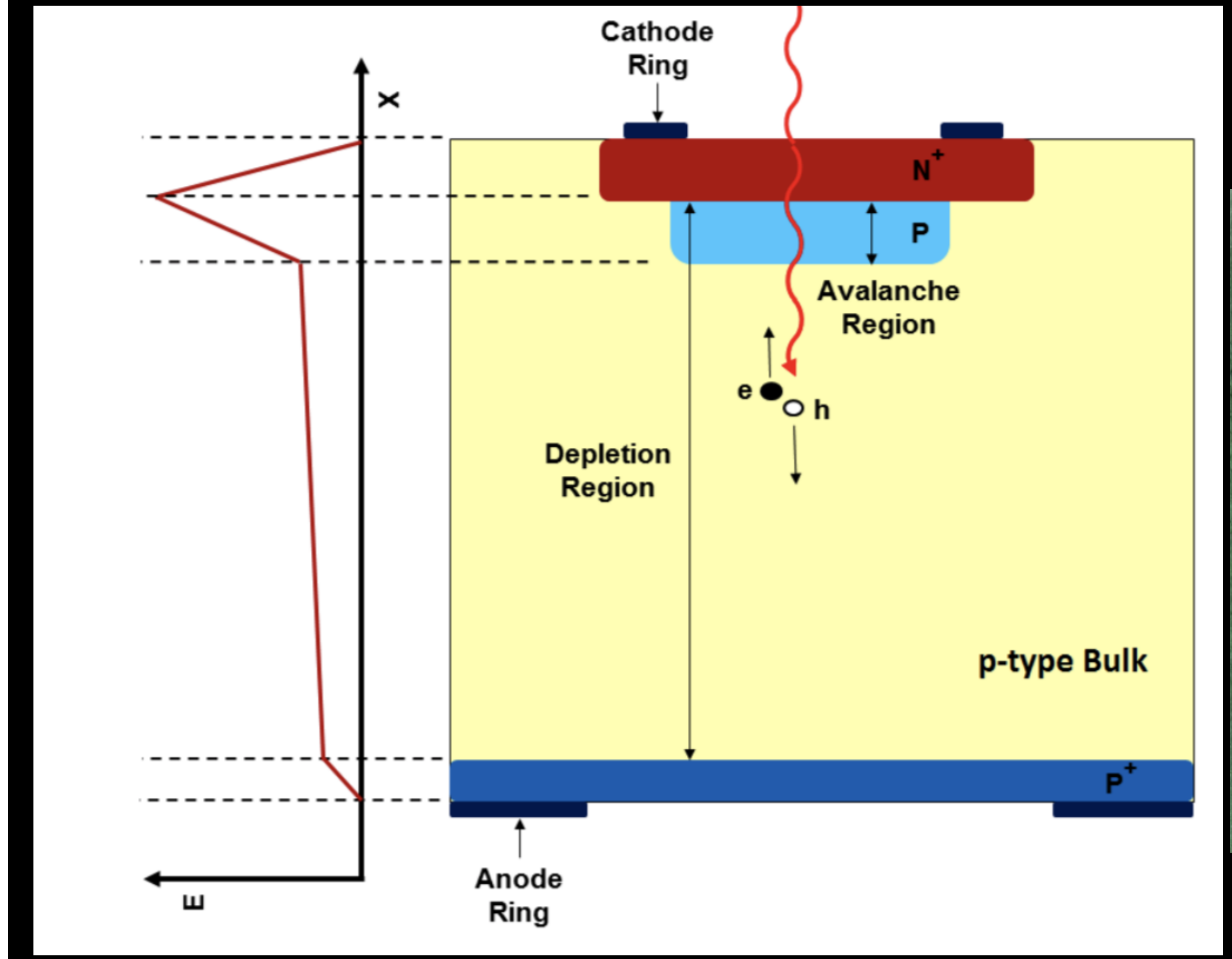
Particle identification in full silicon concept：TOF detector

- Replace outer layer of silicon tracker with fast timing layer
- Timing resolution 10ps, provide PID to 10GeV
- Timing layer with Low-Gain-Avalanche-detector (LGAD) technology
  - Timing resolution can reach 20-30ps today (ATLAS and CMS timing detector)
  - LGAD sensor developed by IHEP and Novel device lab

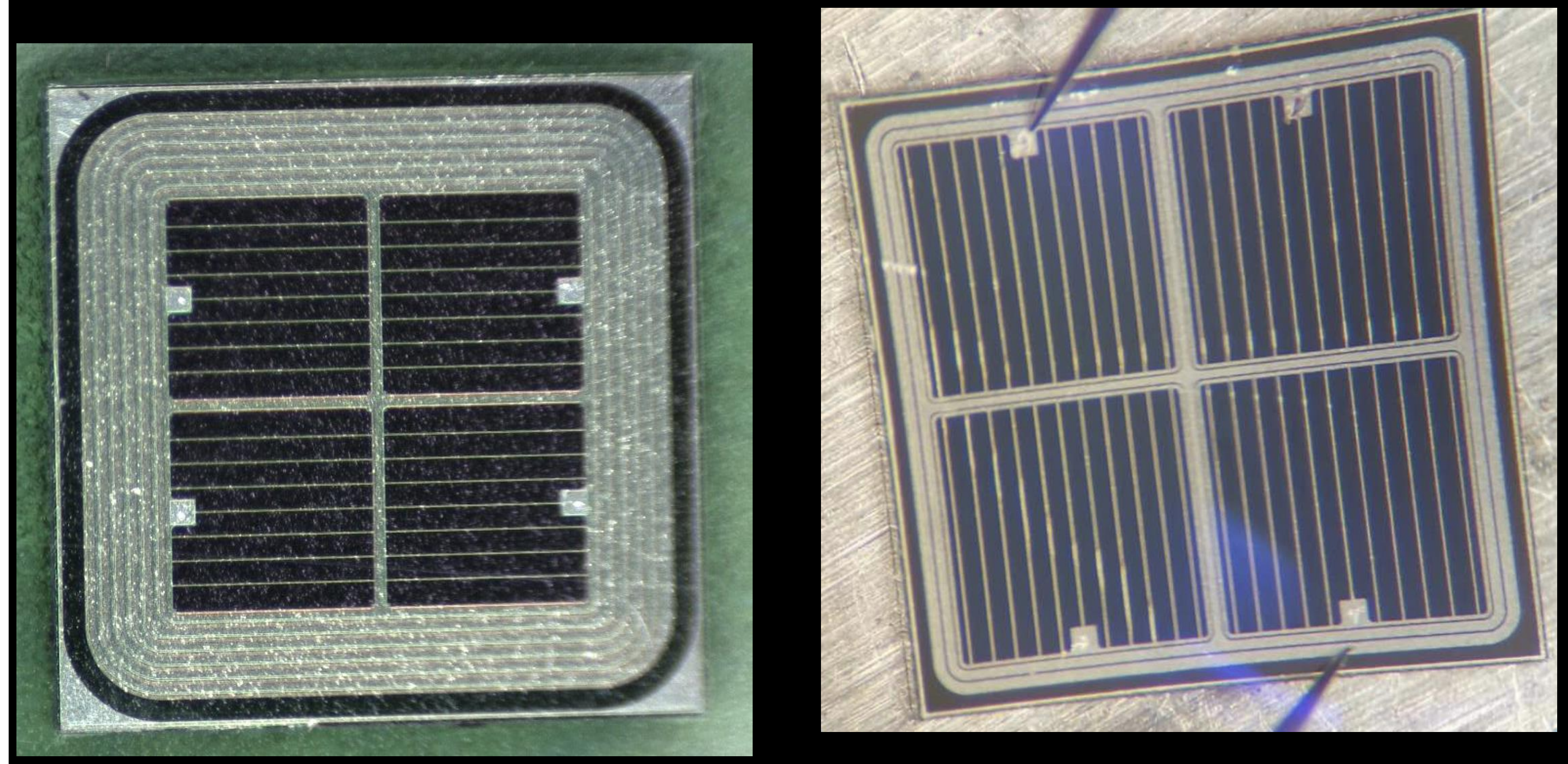
PID performance by Topside



LGAD sensor

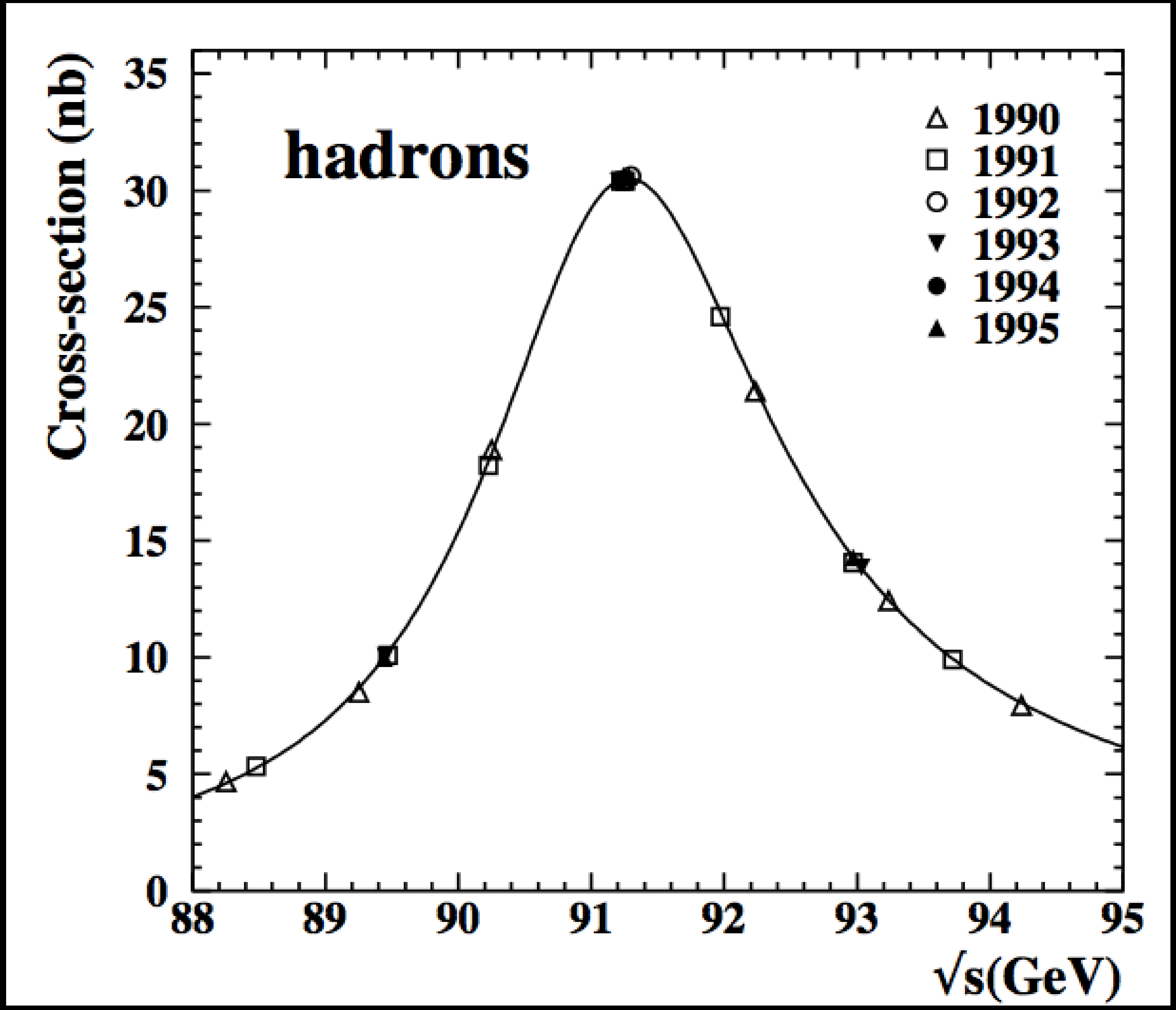


LGAD sensor by IHEP and NDL
Time resolution can reach 25ps



Z mass measurement : luminosity systematics

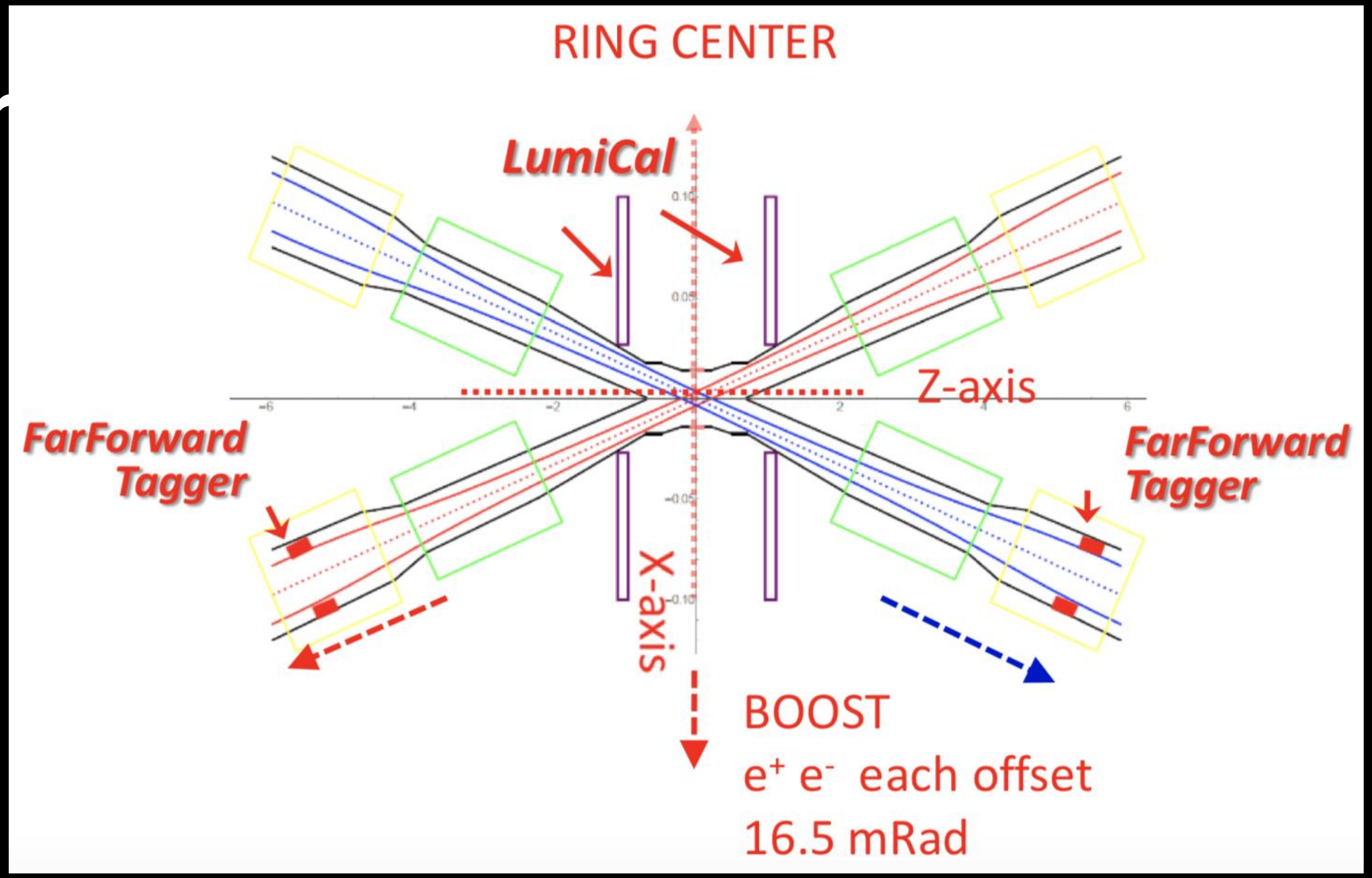
- LEP precision ： 2MeV ， 91.1876±0.0021 GeV
- CEPC goal : 0.5 MeV (CDR) → 0.1MeV (toward TDR)
- ➢ Beam energy uncertainty is major systematics (~0.1MeV)
- ➢ Luminosity measurement (**$\delta L/L = 10^{-4}$**)

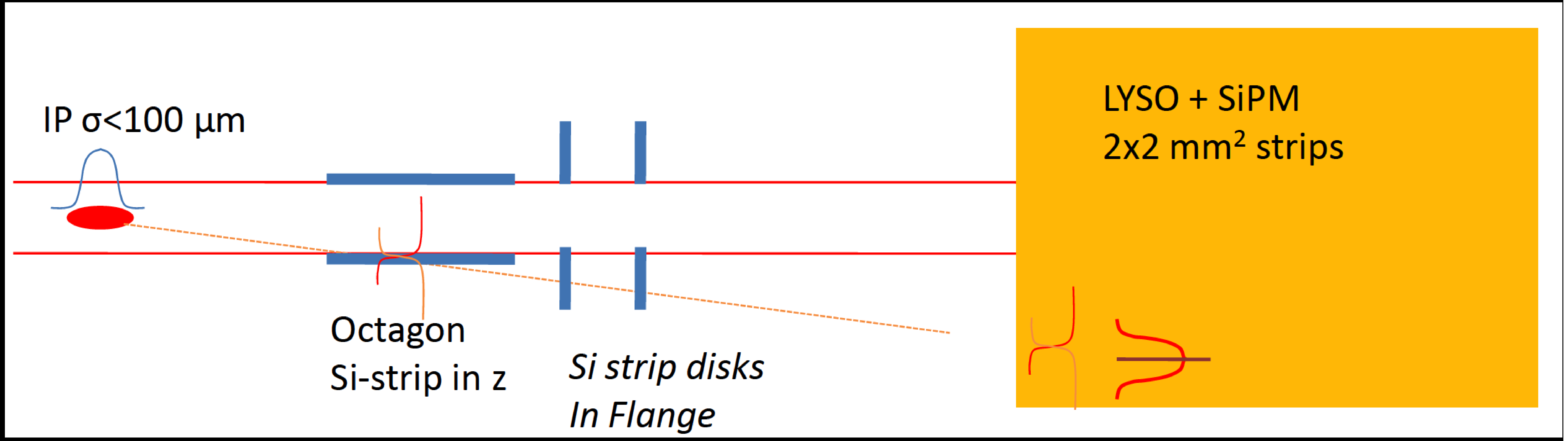


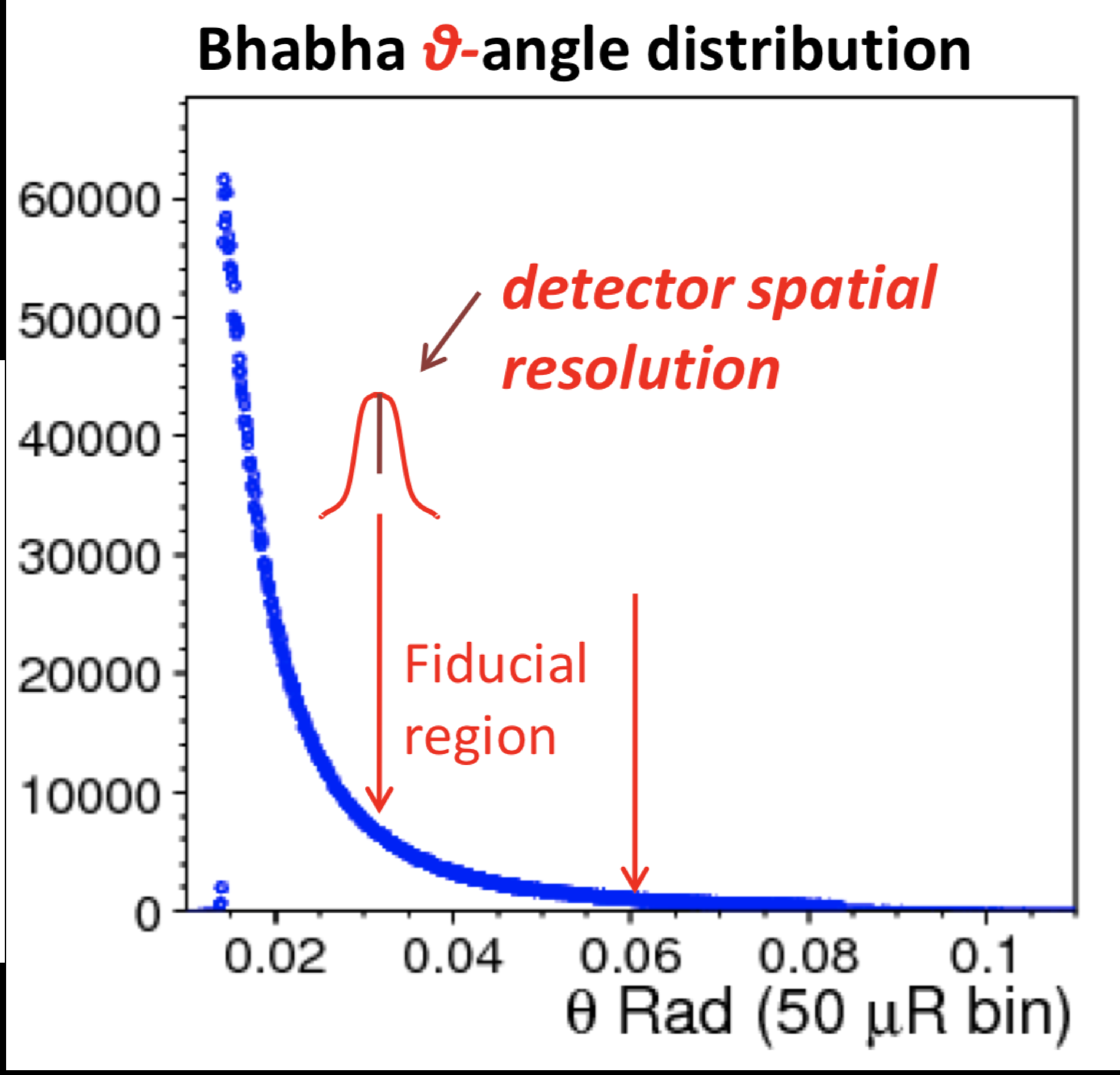
Z threshold scan @ LEP

Luminosity measurement: Lumical detector

- **For luminosity δL/L = 10^{-4}**
- 30 <θ <100 mRad
- Lumical : silicon strip disks + LYSO+SiPM calorimeter
- **strip Resolution dr = .75 μm**
- **Strip detector resolution dz = 25 μm**





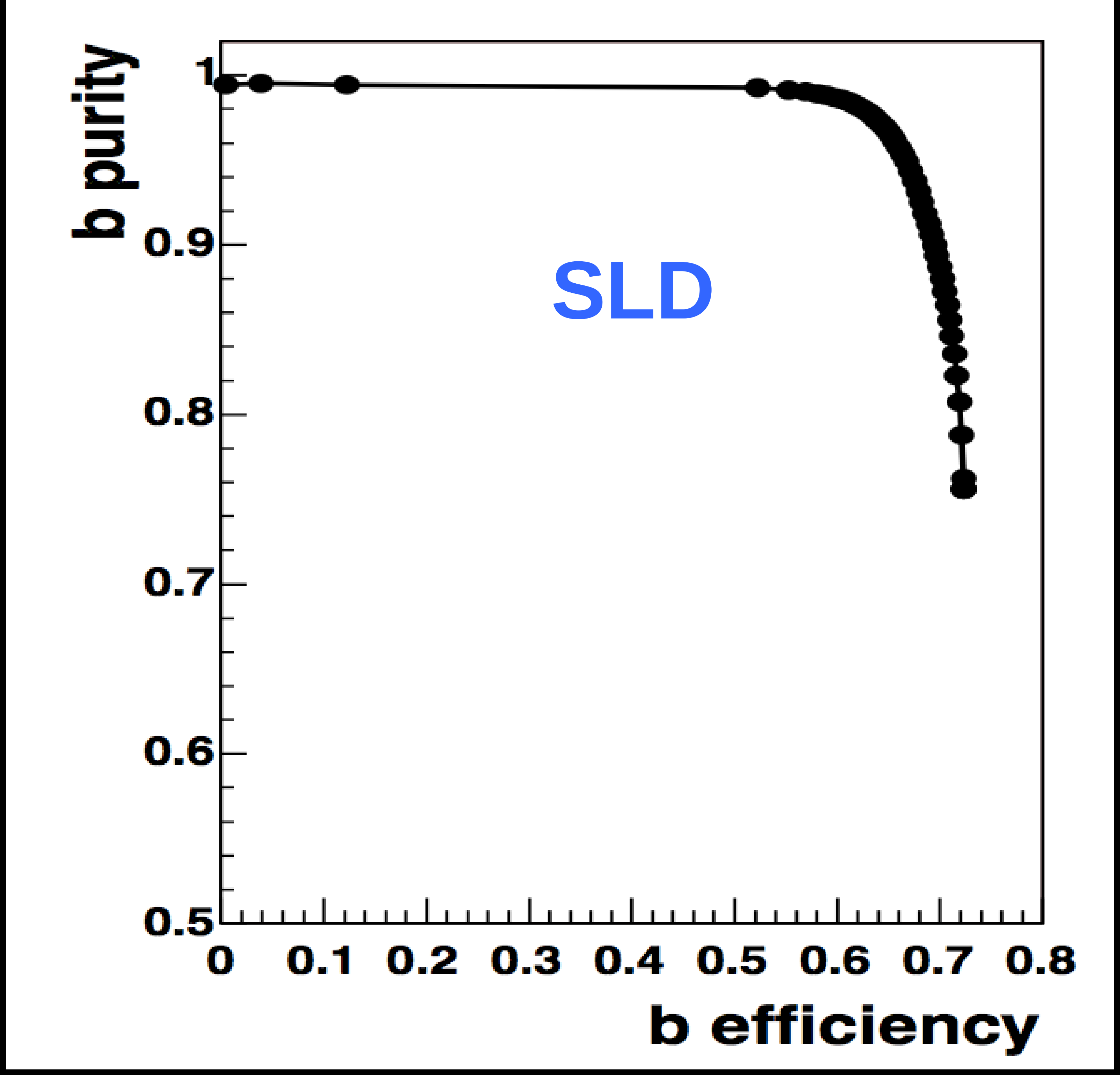


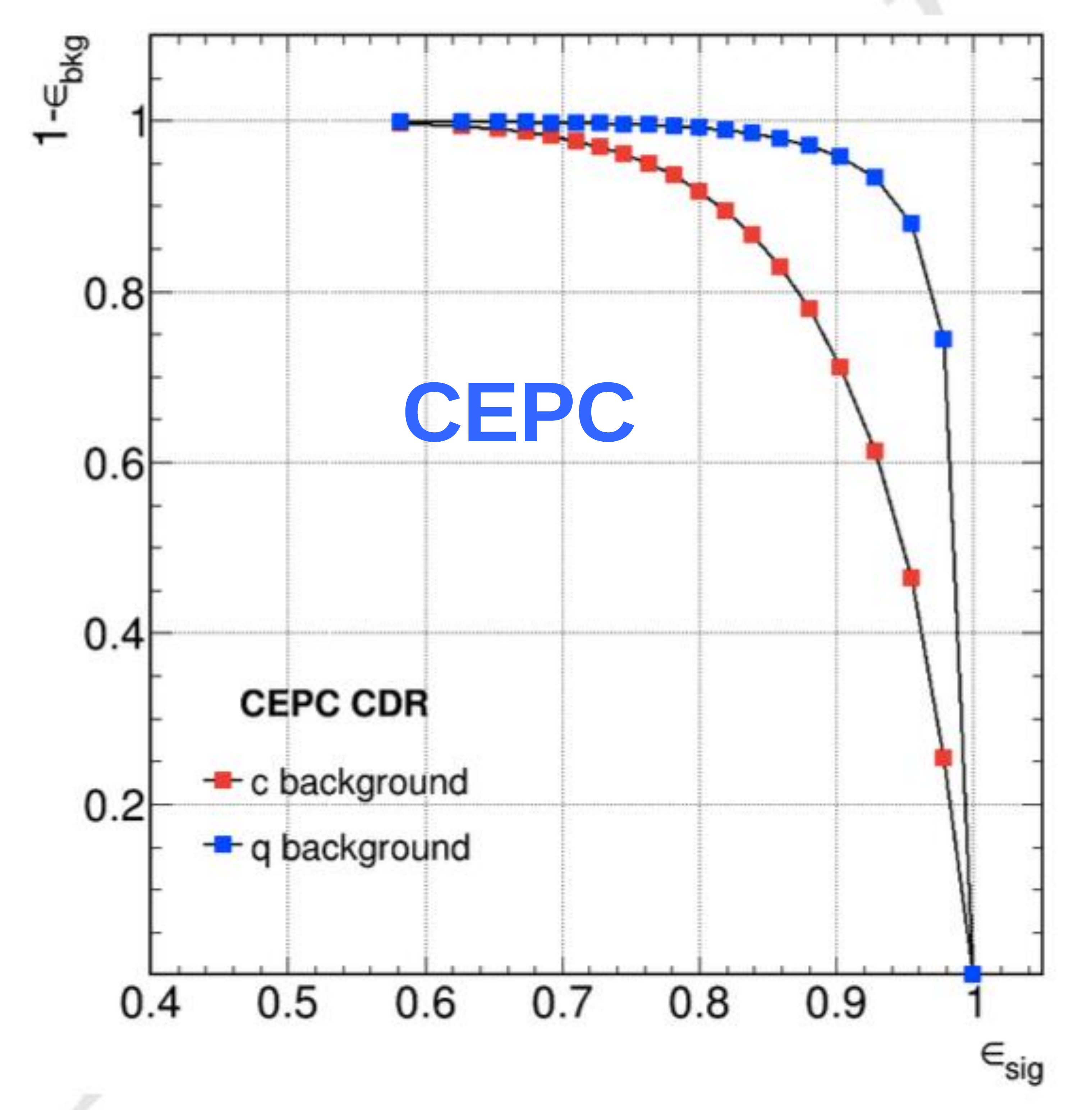
By Suen, Academia Sinica

Branching ratio (R^b) and vertex detector

$$\frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{had})}$$

- LEP measurement Syst error : ~0.2% (0.21594 ±0.00066)
- CEPC Expected Syst error (0.02%)
  - hemisphere tag correlations depends on b tagging efficiency
  - Expect 20~30% higher B tagging efficiency than SLD
  - Need pixel hit resolution: 5μm
  - Need more understanding B tagging algorithm

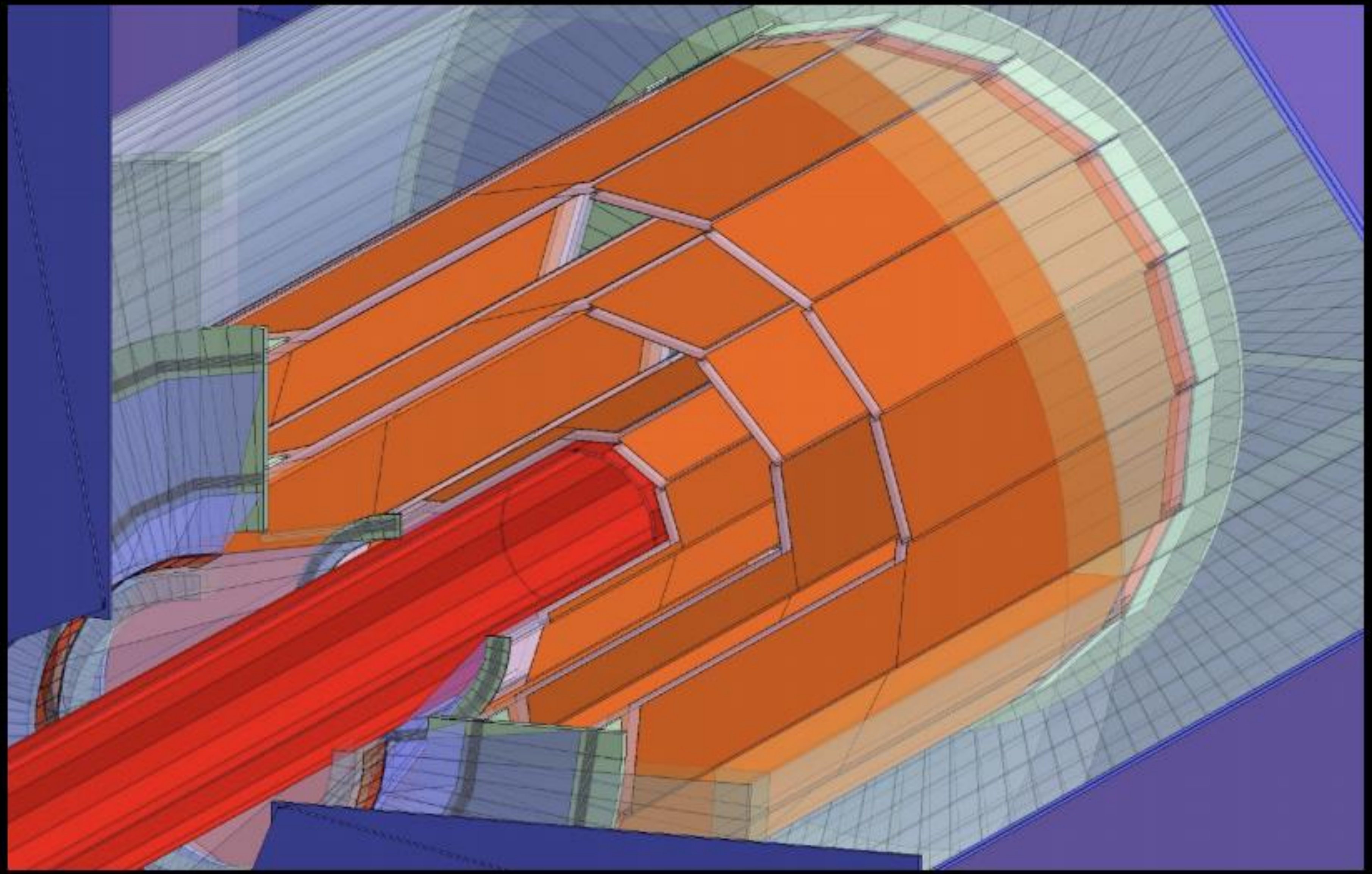




Challenges in vertex detectors

Vertex detector design driven by needs of flavor tagging

- Extremely accurate/precise
- Extremely light



Large surfaces: ~ 1 m^2

Single point resolution $\sigma < 3 - 5\ \mu m$ → **Pixel pitch** ~ 16 – 25 μm

Low material budget < 0.1 — 0.3% X_0 per layer
→ Thin sensors and ASICs; Light-weight support
→ Power pulsing (LC); Air cooling → **Low power dissipation** ≤ 50 mW/cm^2

Time stamping
~10 ns (CLIC)
~300 ns — μs (ILC/CC)

Circular colliders: continuous operation → more cooling → more material

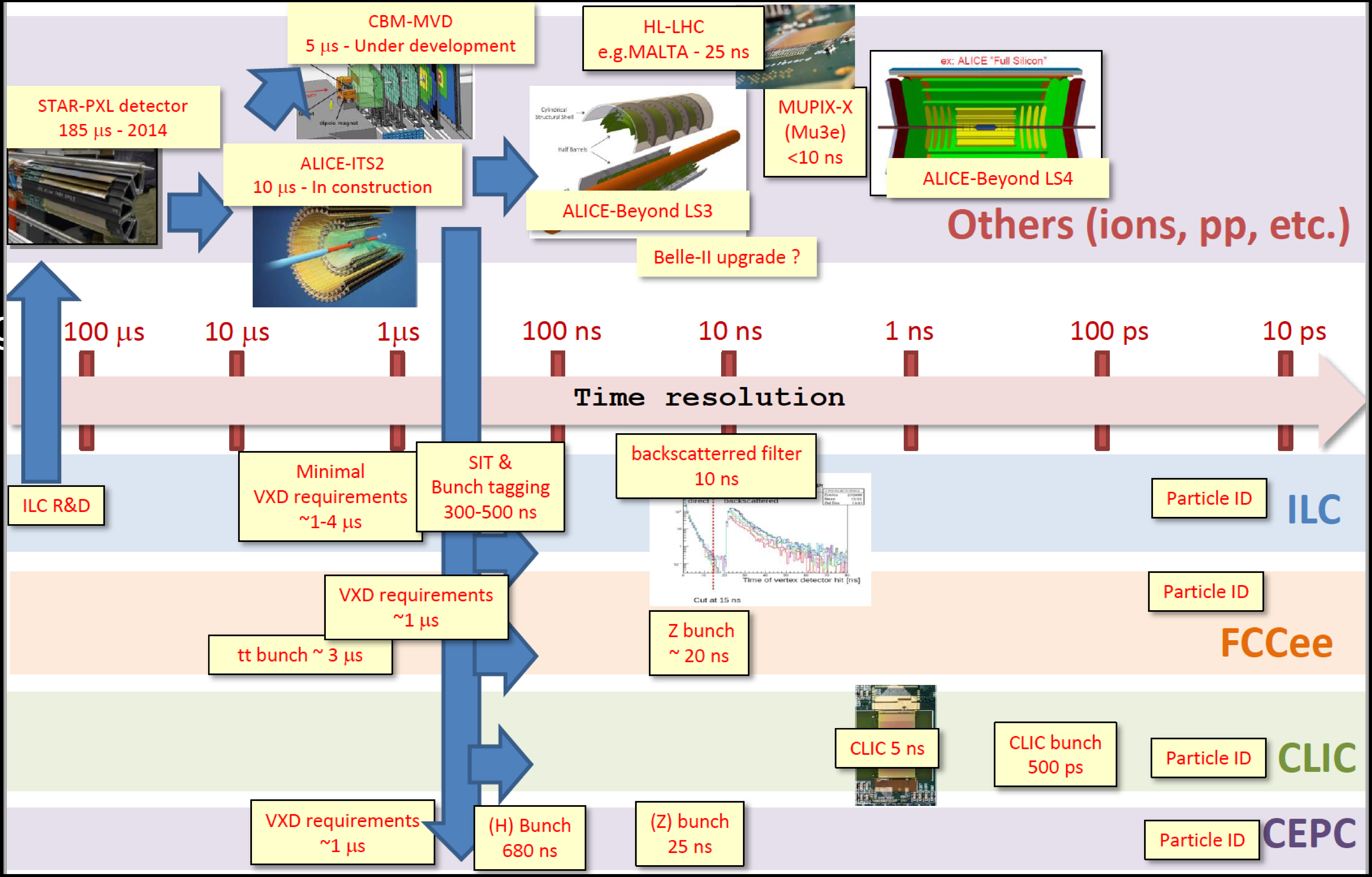
Timing of detector for Z pole running

CEPC Z (91GeV)

- 40MHz collision
- 25ns bunch spacing

CEPC ZH (240GeV)

- 680ns bunch spacing



From Auguste Besson's talk in Fcc workshop

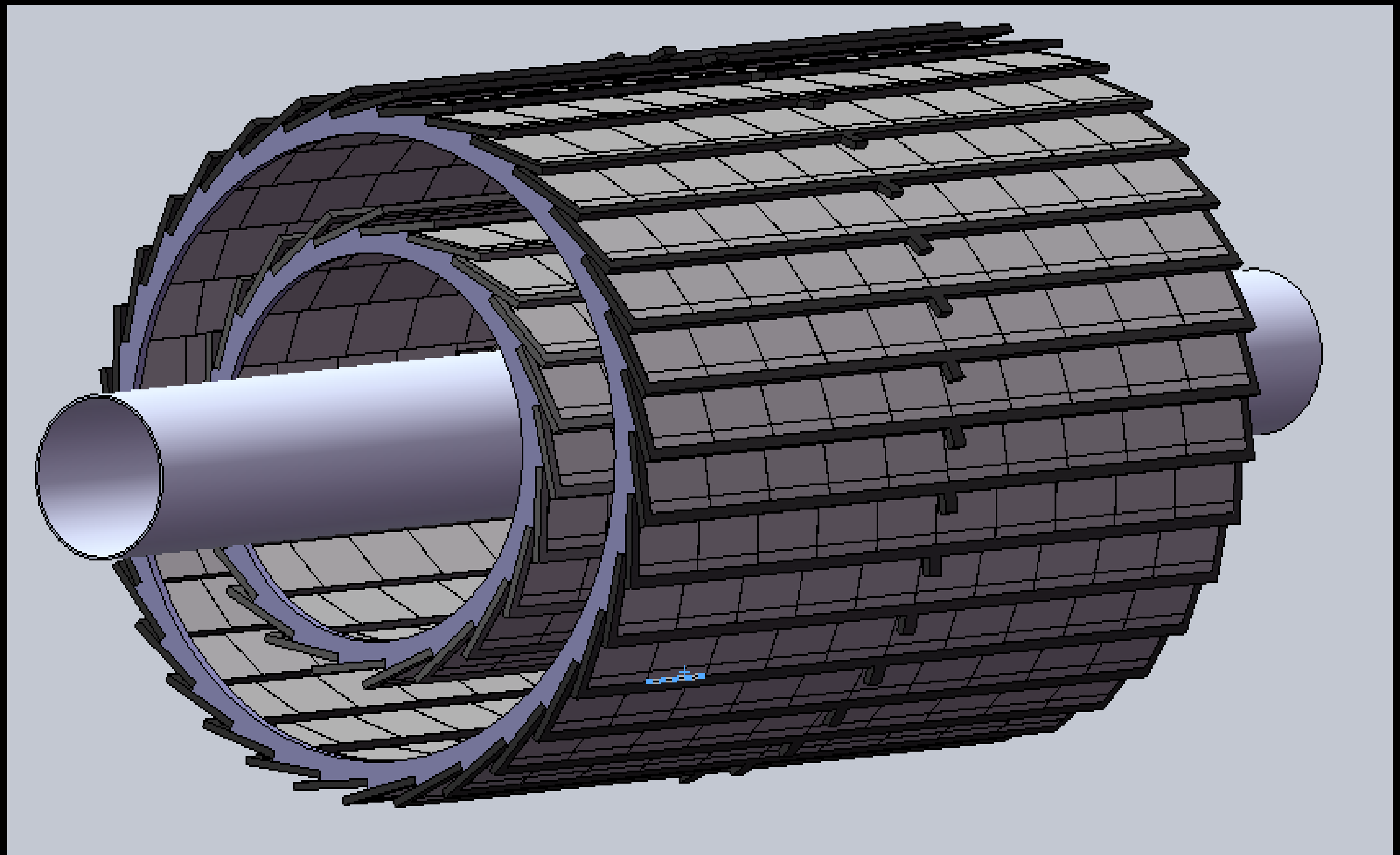
vertex prototype optimized for Z run

- **CEPC Vertex prototype R & D project, optimized for Z pole running (40MHz)**
- **Taichu sensor chip designed (based one standard CMOS MAPS tech.)**

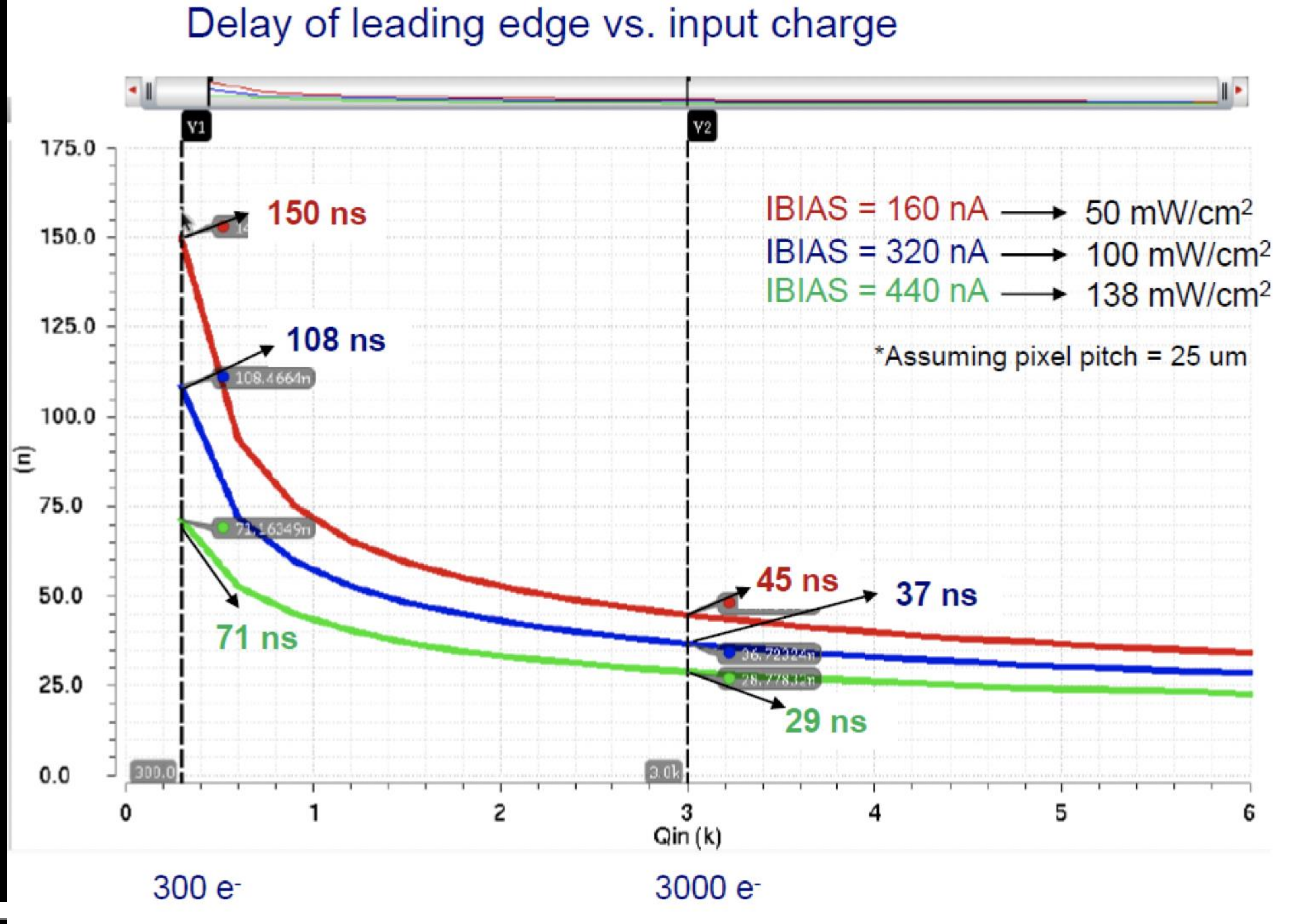
➢ **Resolution: 75ns~150ns**

Collaborating with:
- Barcelona, IFAE
- Liverpool
- Oxford
- RAL
- QMU
- UMass, US

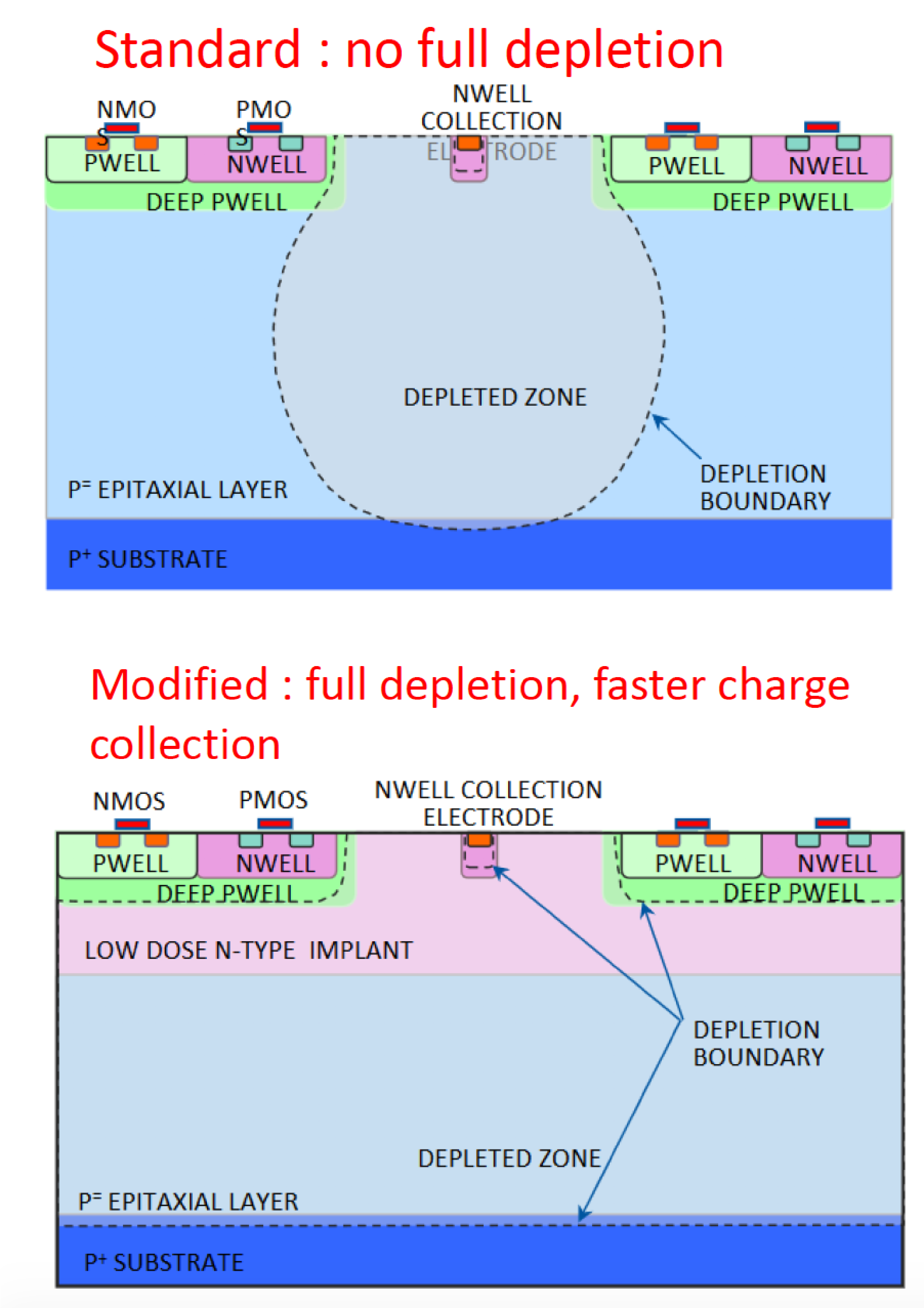
CEPC vertex detector prototype



Time resolution



CMOS MAPS sensor

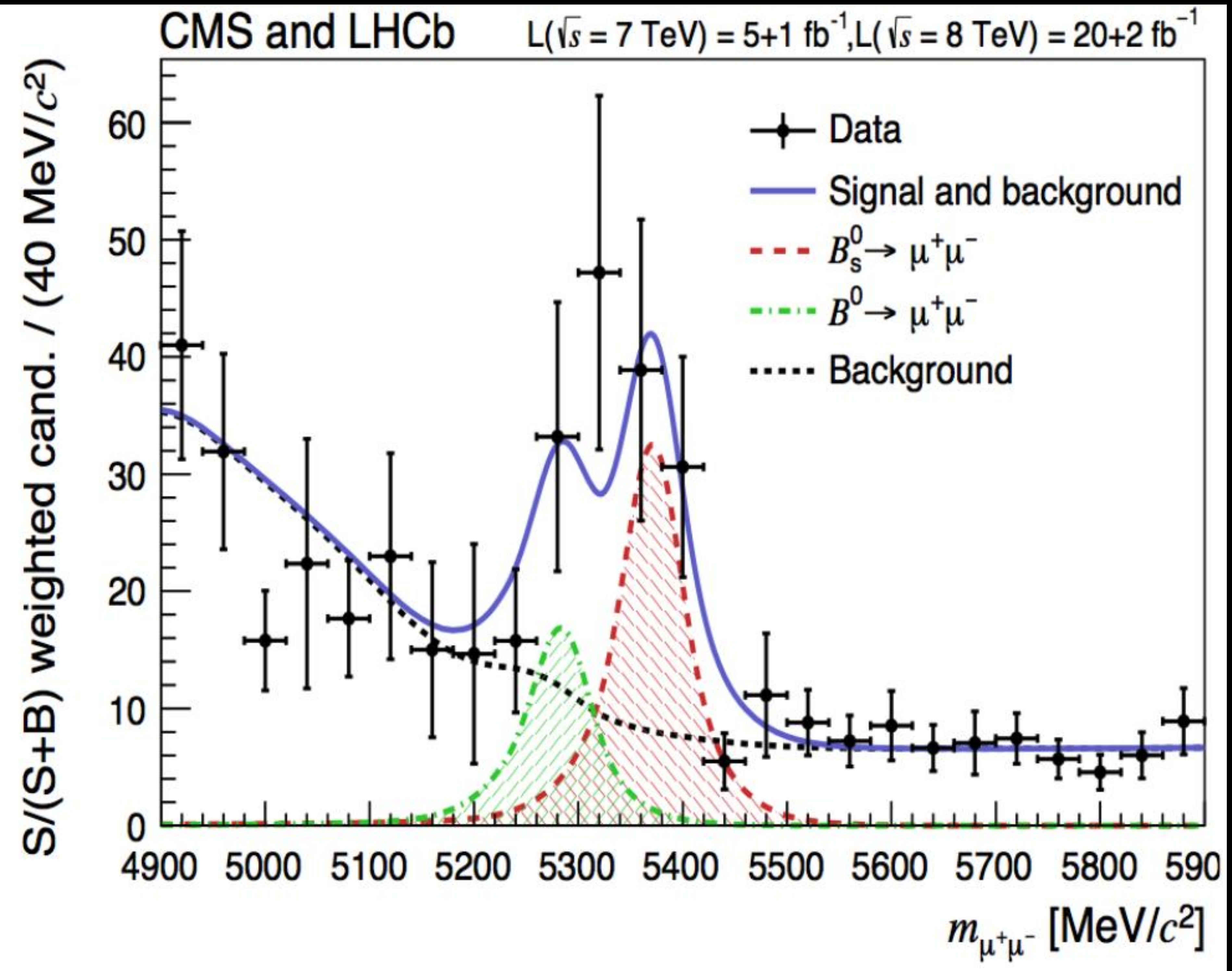


	Resolution	Readout Speed	TID	Power Consumption
Taichu-1 (TJ 180nm)	3~5μm	~50ns@40MHz Digital readout	Te be tested	100~200mW/cm2

Track momentum resolution @ Z pole

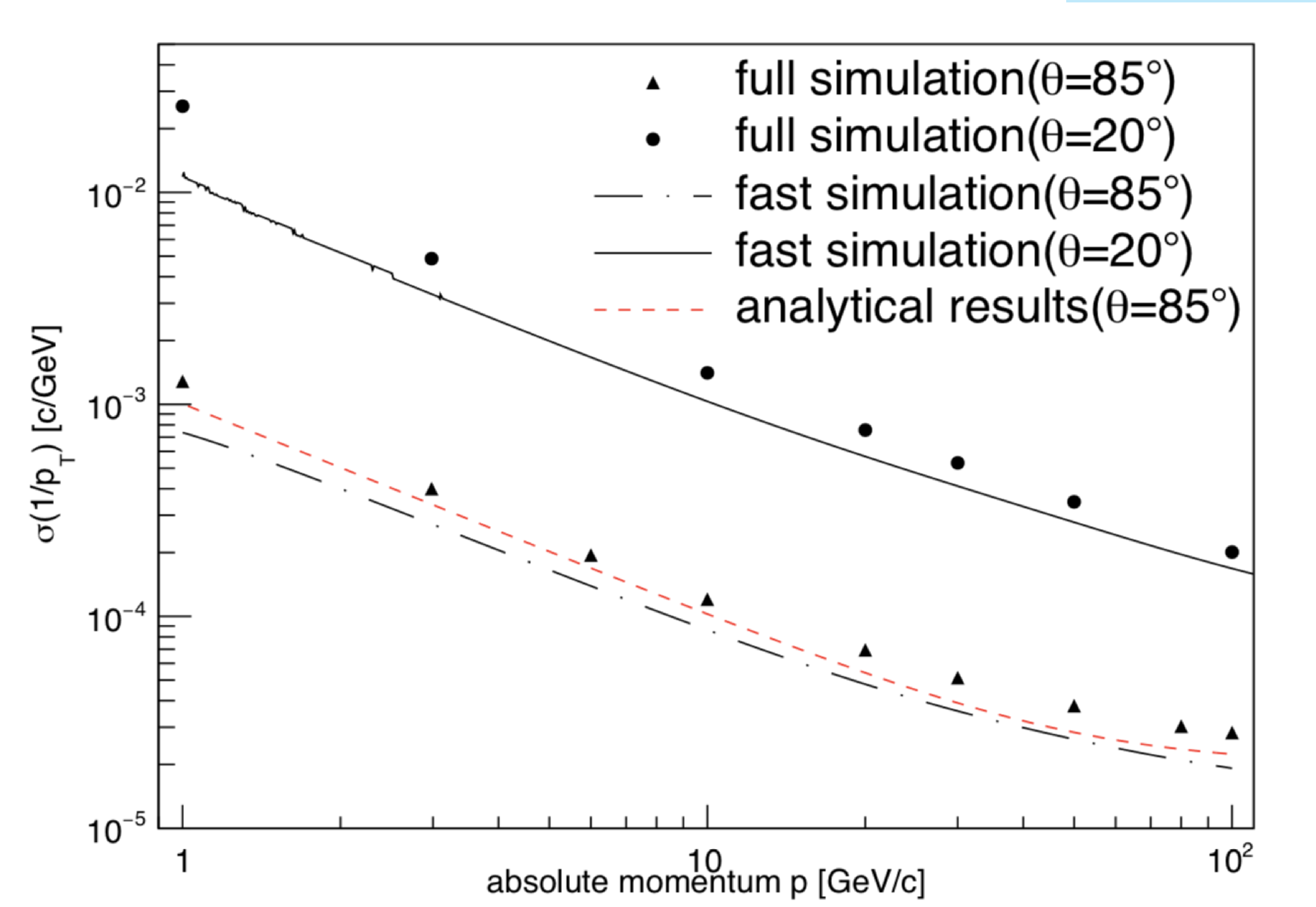
- Current optimization based on ZH runs @ 240GeV
- Most demanding case for low momentum track resolution is flavor physics
- Current design is good enough for EWK and flavor physics at Z pole

B_s /B^0-> μ μ by CMS and LHCb



Momentum resolution in CEPC

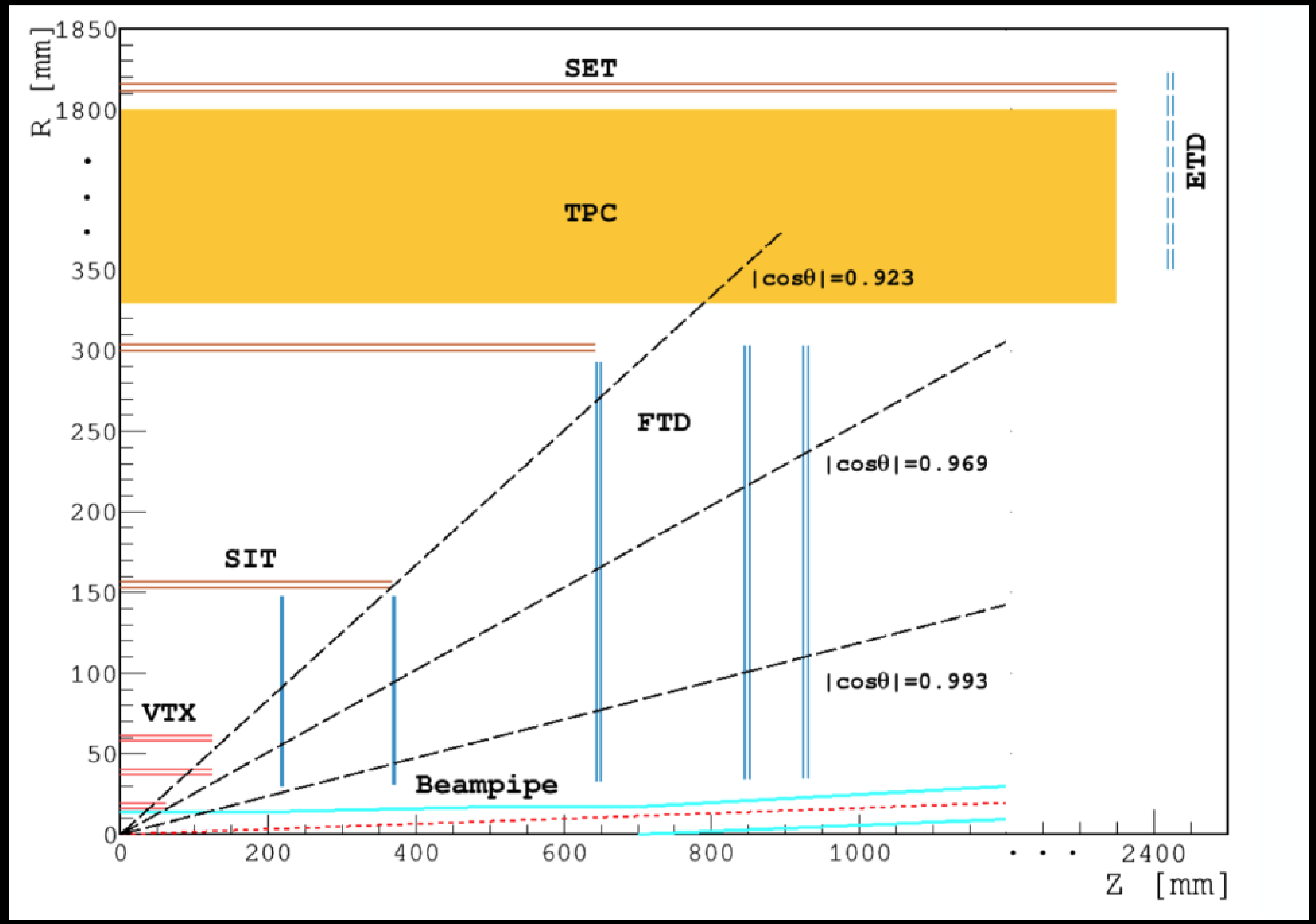
$$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$$



From CEPC CDR

CEPC silicon tracker project

- Outer track project:
- HV-CMOS technology: was developed for ATLAS
- Adapt Alice pixel support structure
- Full silicon concept still need more study



Silicon tracker challenges

Large surface area of O(100 m²)

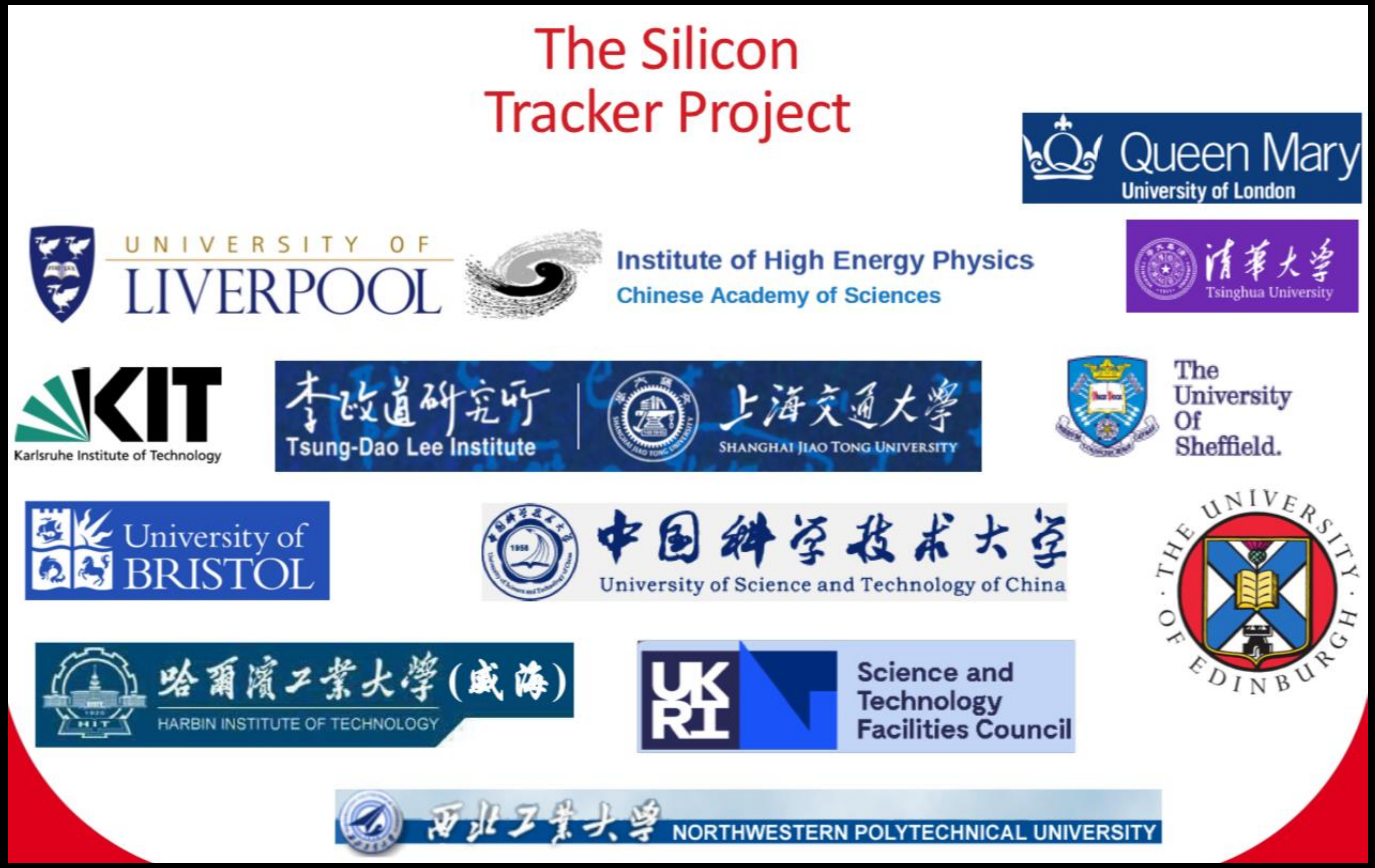
Solution: Integrated sensors with large pixels/strips (~ 30 μm × 1-10 mm)

Maintain efficiency and good timing

(despite large detector area)

Mechanical stiffness with low-mass materials

Light-weight cooling methods



Harald Fox’s talk in CEPC day

Calorimeter optimization at Z pole : photon energy resolution

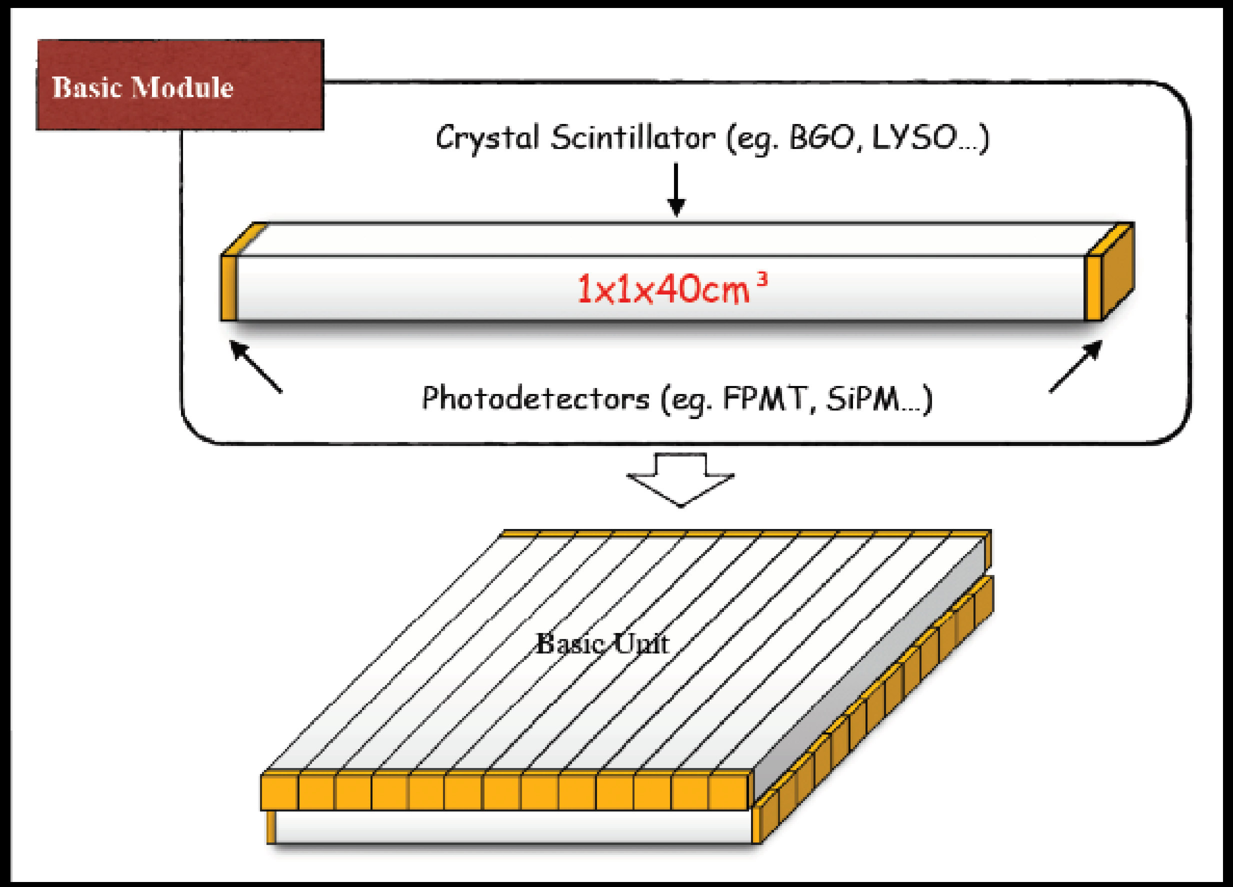
- Z->μμ measurement: systematics dominated by photon energy measurement Z->μμγ events
- Similar limitation from number of neutrino generation measurement by Z->μμγ events
- π0/γ separation for Z->ττ, weak mixing angle measurement
- Have room to improve jet and photon energy re
- New Crystal calorimeter R & D is likely to help

ECAL $\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

Not enough?

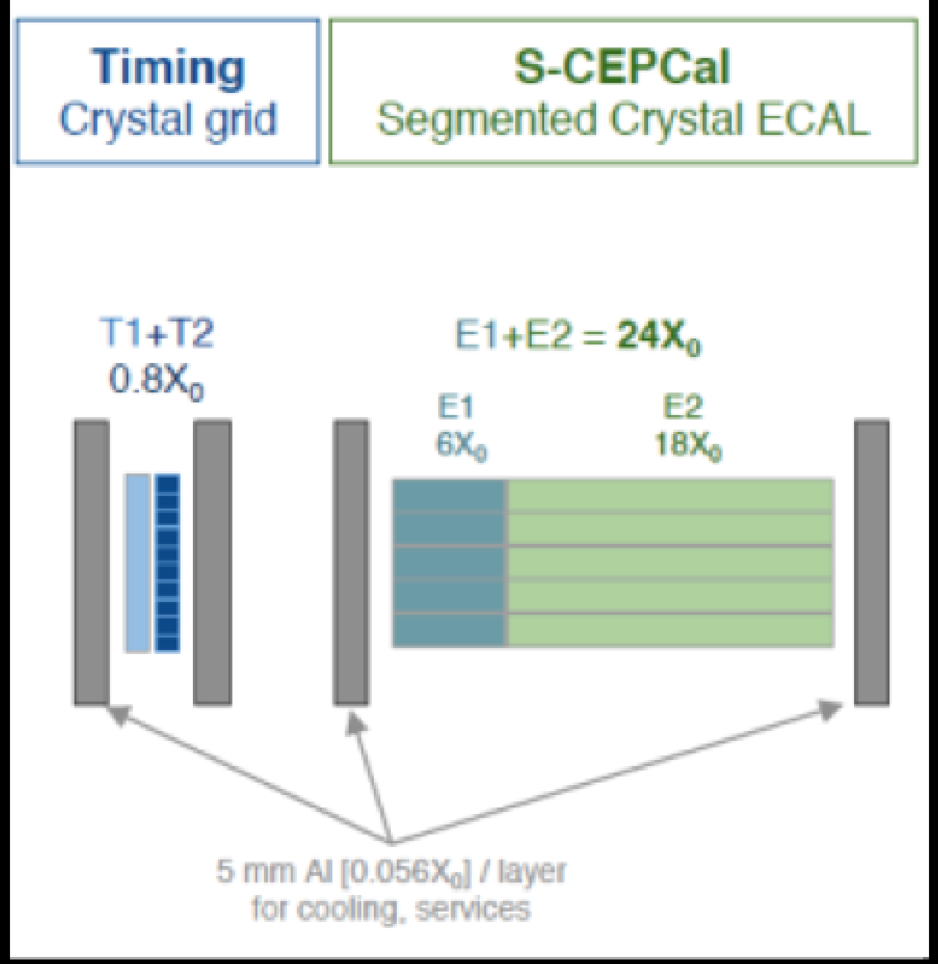
Long crystal bars with optical readout at both ends

Yuexin Wang (IHEP), et al



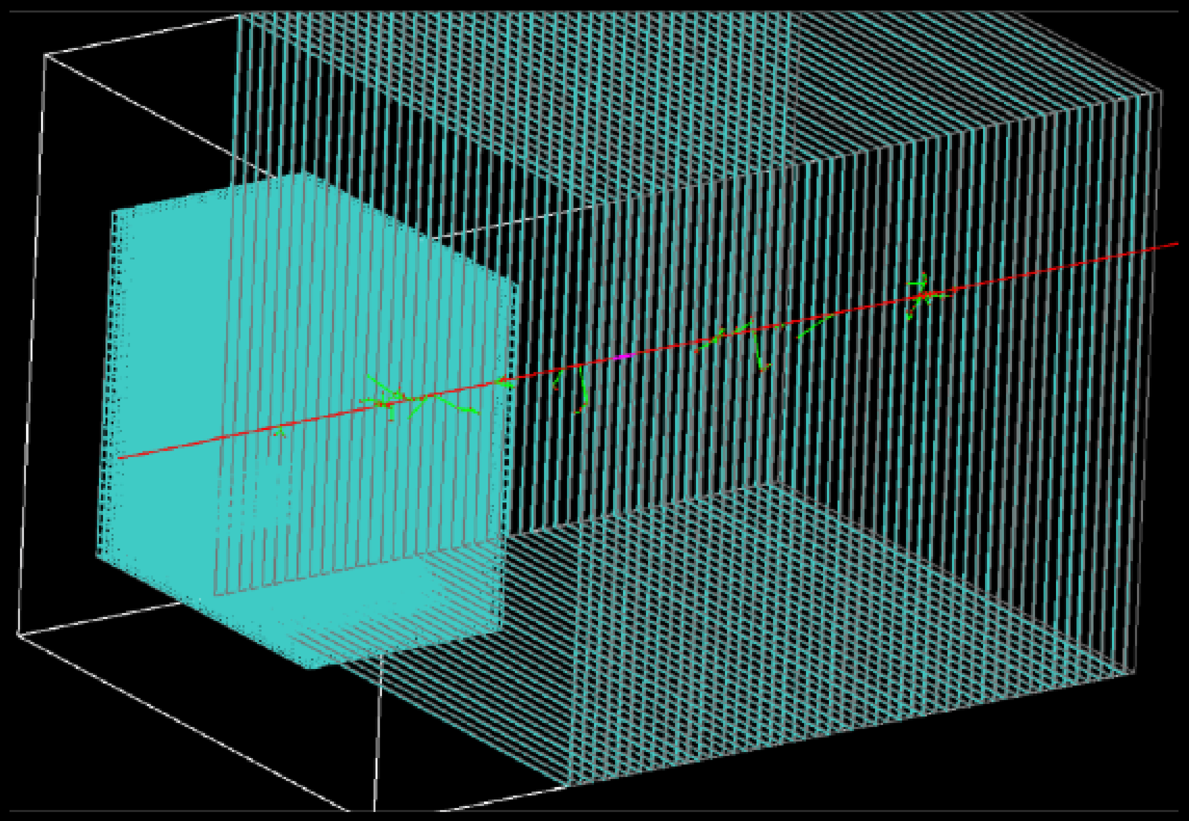
Long crystal bars with optical readout at single ends

Tully (Princeton), Eno (UMD), et al



Thin crystal tiles with optical readout at single ends

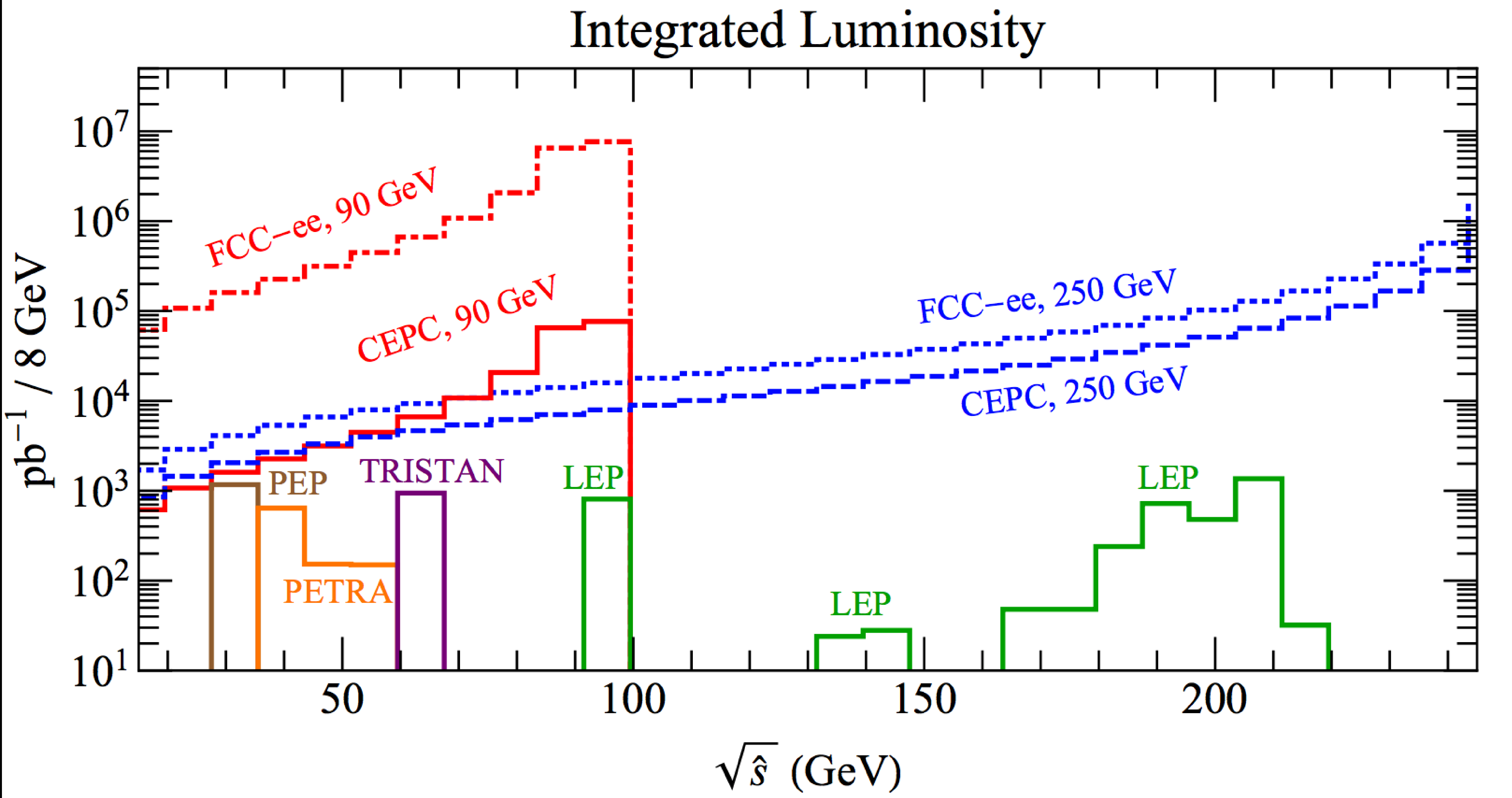
Yong Liu (IHEP), et al

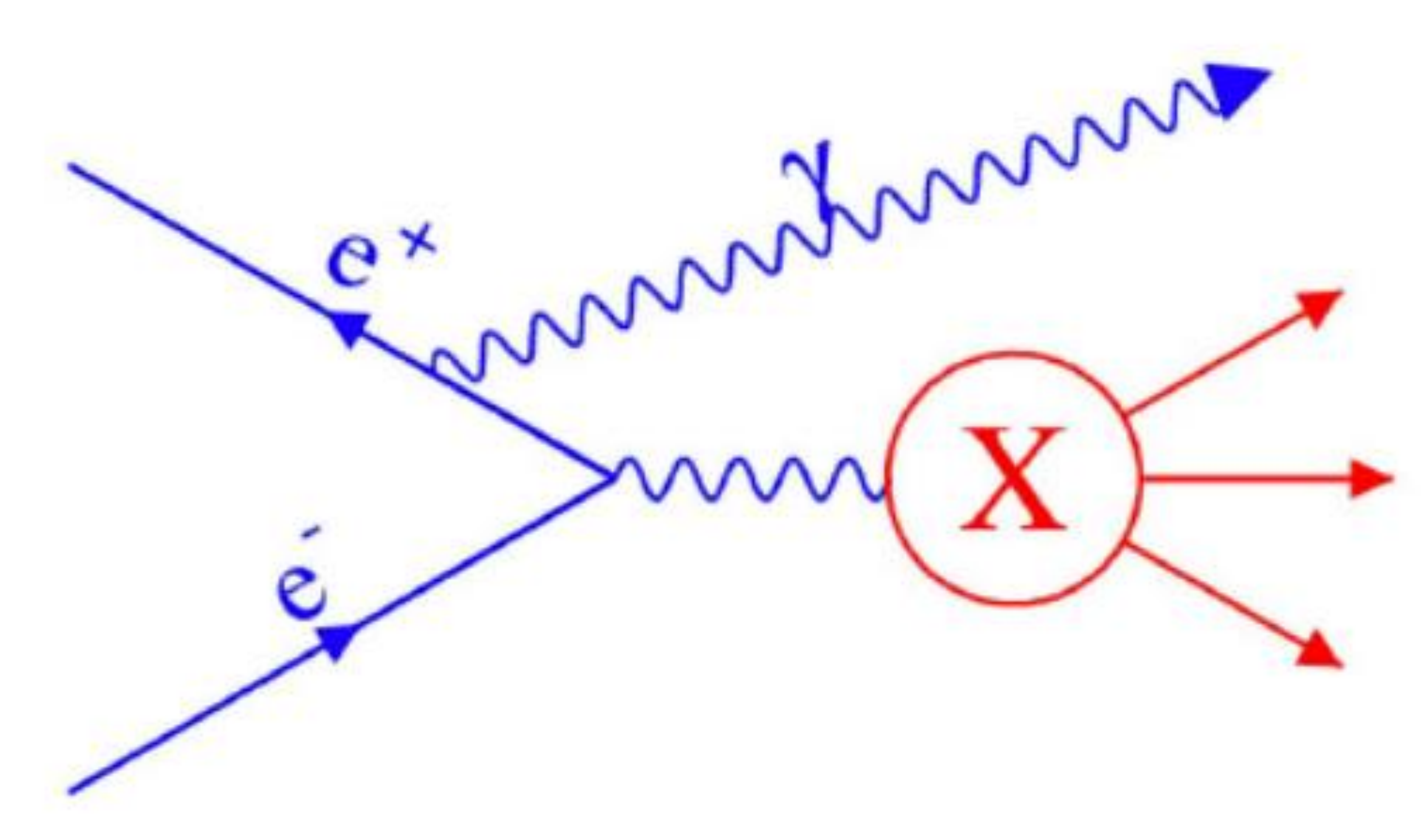


ECAL: 30 layers

Forward calorimeter for Radiation return events

- CEPC can access to B meson threshold study in Radiation return events
- Need forward (far forward) detector in (0.1 <θ<2.5 radians)
  - To detector forward photon from radiation return events
  - Not yet included in CDR, need collaboration for dedicated study



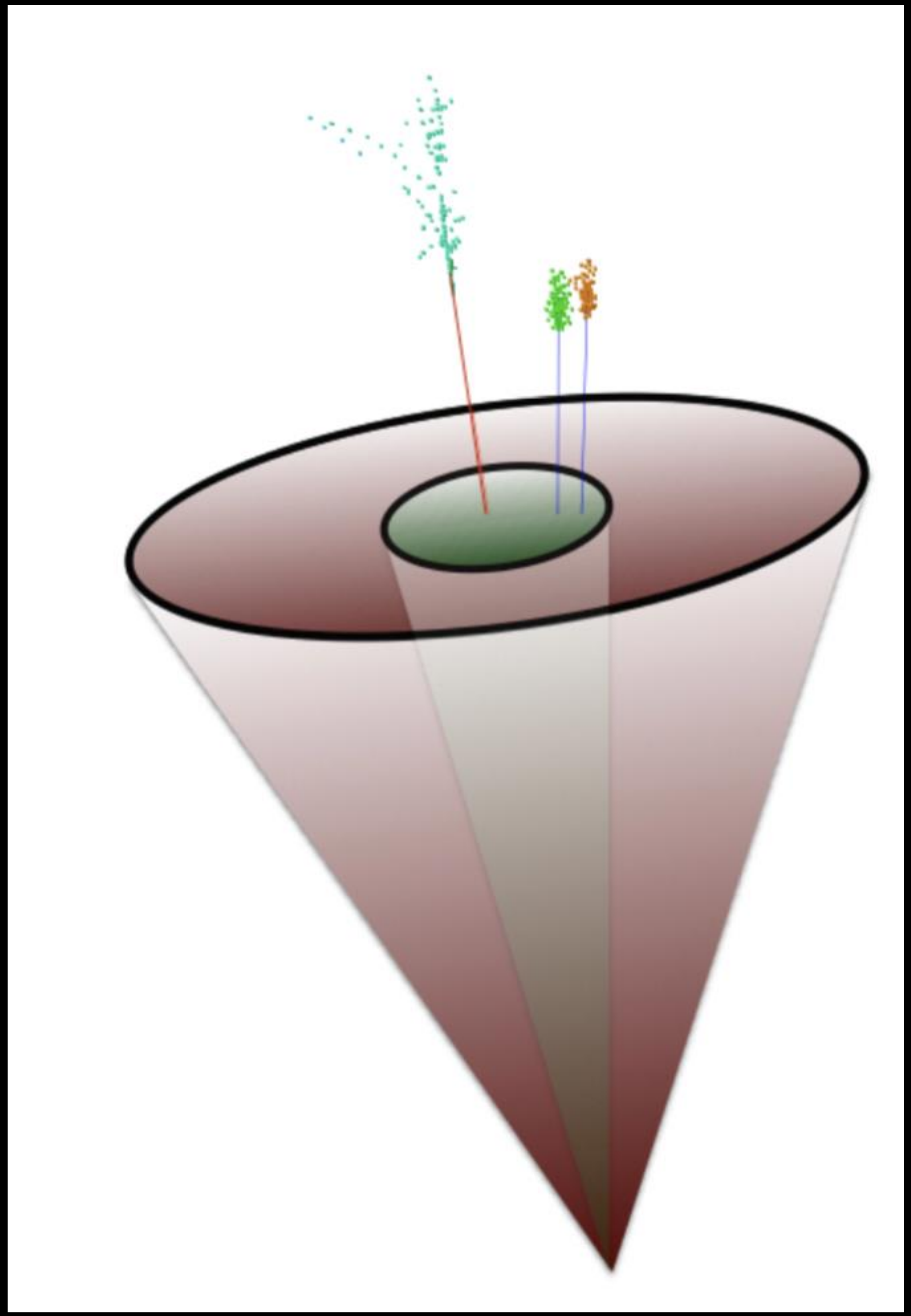


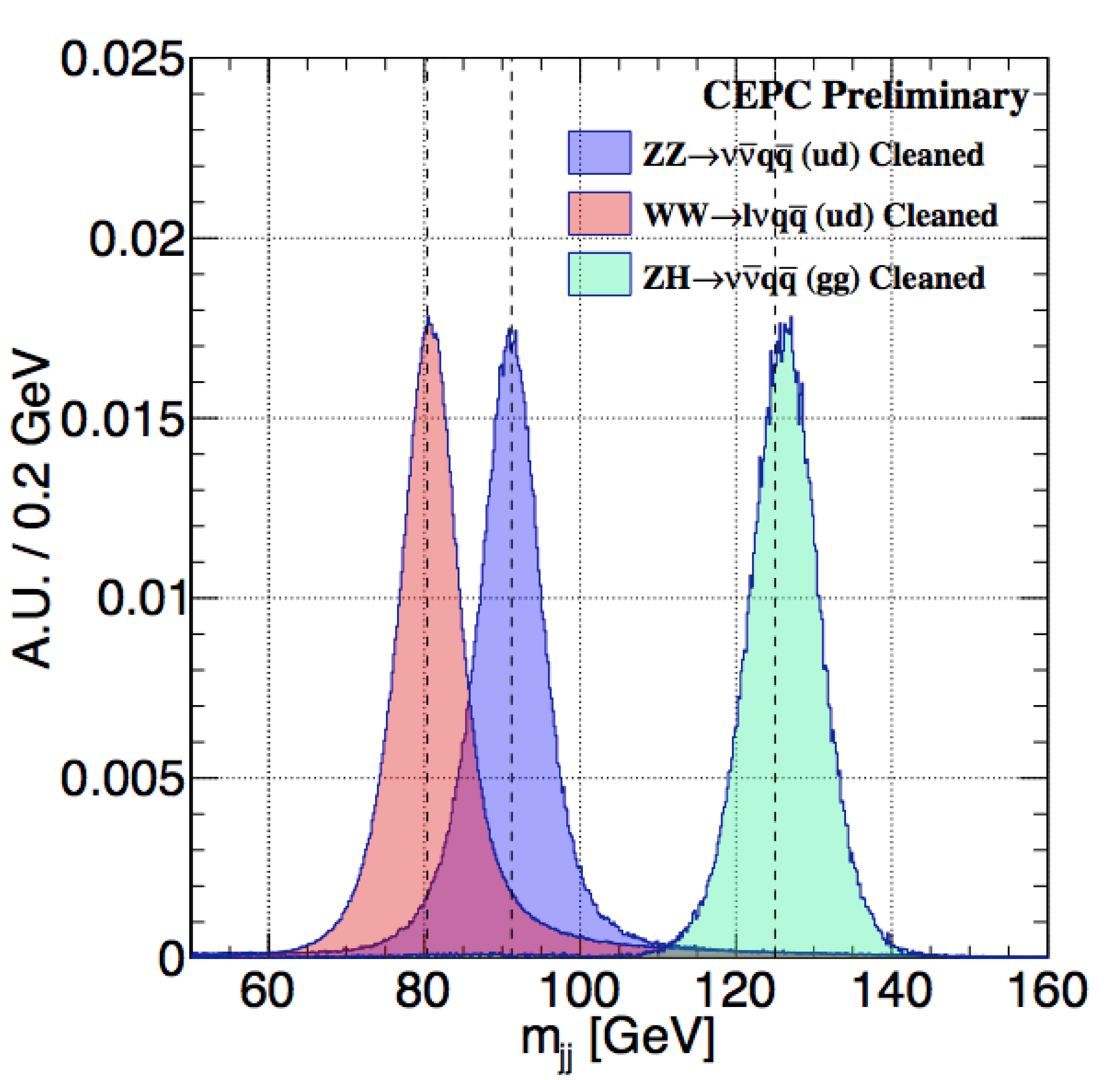
Phys. Rev. D 92, 035010 (2015) , Marek Karliner, Matthew Low, Jonathan L. Rosner, Lian-Tao Wang

Hadron calorimeter optimization at Z pole

- Physics case :τ physics and W mass measurement
  - lepton flavor violation in Z->ττ, weak mixing angle measurement in Z->ττ
  - W mass measurement with direct reconstruction WW->lvjj

$$\sigma_E^{\text{jet}}/E = 3 \sim 4\% \text{ at } 100 \text{ GeV}$$





Summary

- **Fantastic prospects to probe the EWK and flavor physics at CEPC Z run**

- **Need more dedicated optimization**
- **Particle Identification detector**
  - ✓ **New idea on Rich detector and TOF detector in full silicon concept**
  - ✓ **Z pole high rate study for TPC**
- **Vertex detector**
  - **Small pixel, fast readout time, low material**
- **Silicon tracker**
  - **Larger area, need dedicated design and full silicon concept**
- **ECAL**
  - **New idea about crystal calo, room to improve on energy resolution**
- **HCAL**
  - **Need more optimization for**