Particle Identification for Full Silicon Detector Option

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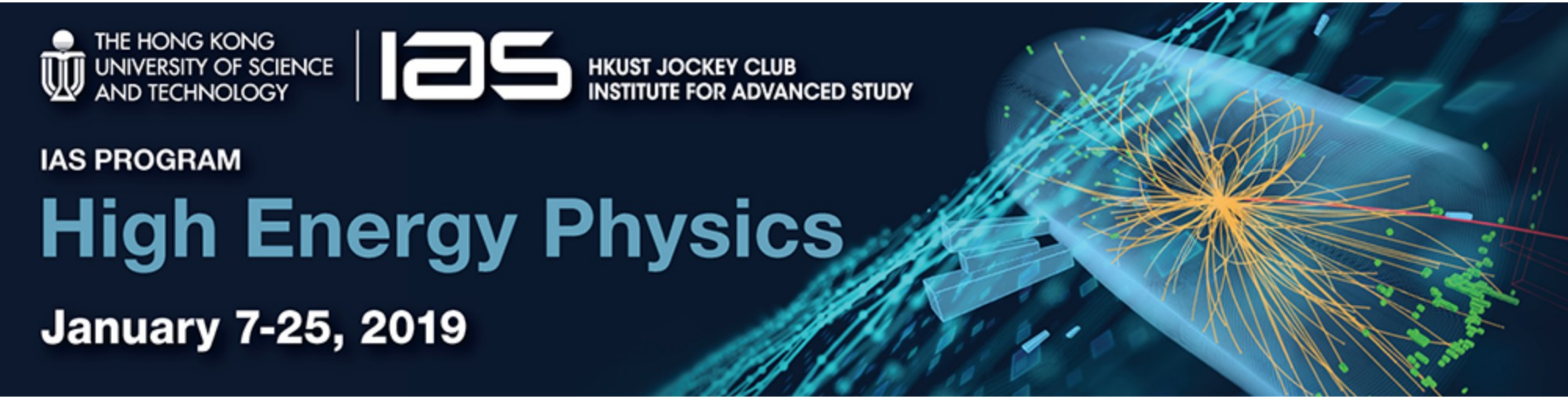


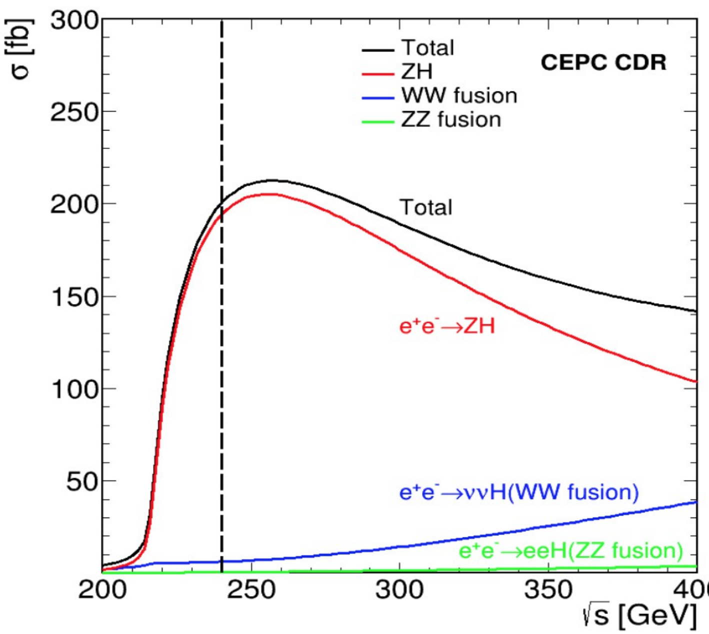
Outline

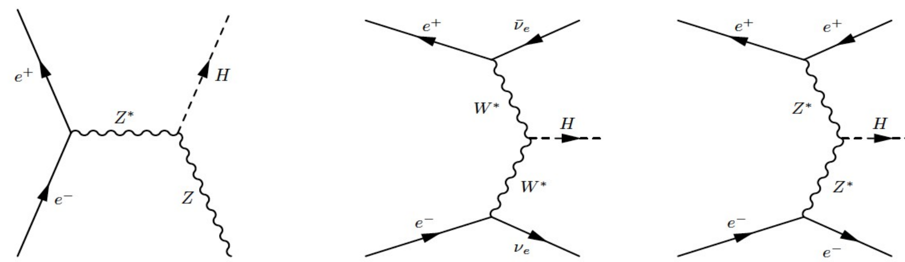
- Introduction
- Case studies for PID at future circular e+e- colliders
- PID options for FST
  - Super Granularity Timing Detector (SGTD)
  - RICH
- Conclusion

Future Circular Lepton Collider(CEPC)

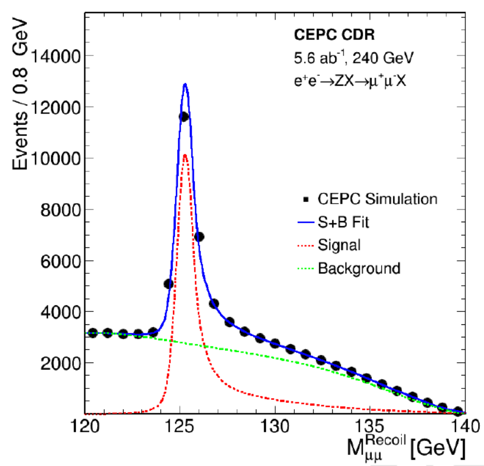
- CEPC will produce 1M ZH at Ecm=240 GeV and running at WW and Z-pole:

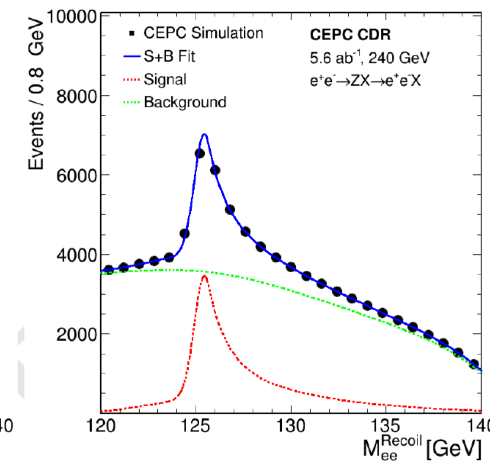
Operation mode	$\sqrt{s}$ (GeV)	L per IP (10^{34} cm^{-2}s^{-1})	Years	Total $\int L$ (ab^{-1}, 2 IPs)	Event yields
H	240	3	7	5.6	1×10^6
Z	91.2	32 (*)	2	16	7×10^{11}
W^+W^-	158–172	10	1	2.6	2×10^7 (†)





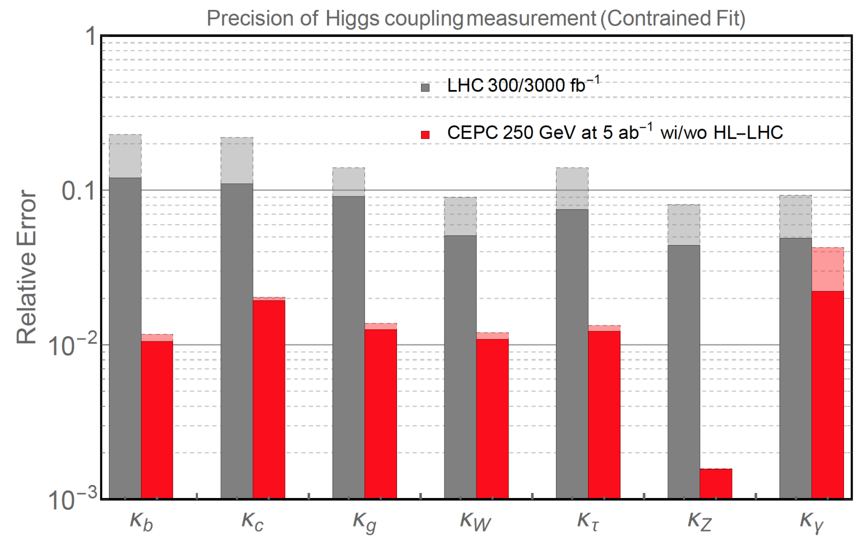
(a) (b) (c)

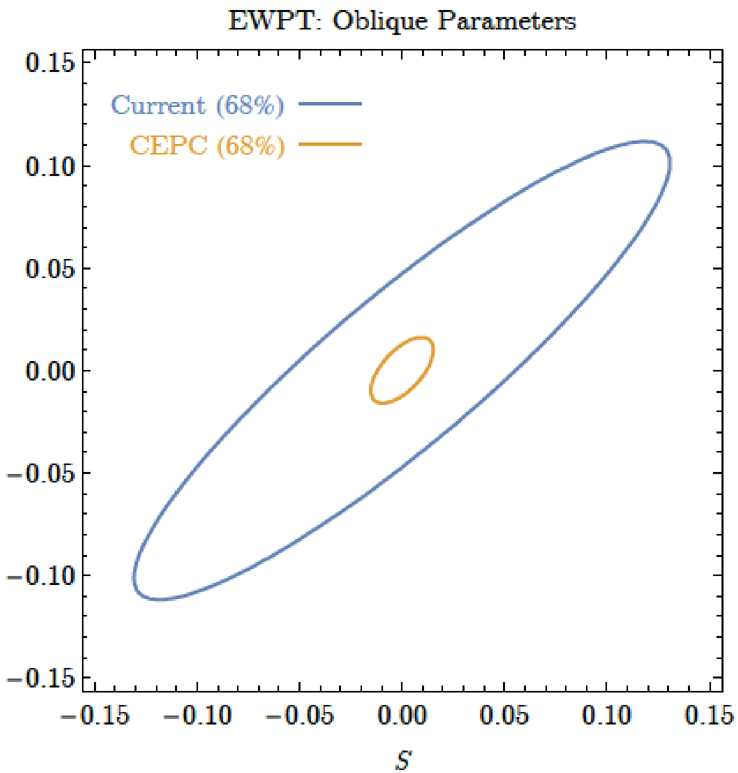




Physics Case

- Measuring Higgs coupling expected at or below 1% level via HZ.
- Discover and constrain BSM via precision EW data and heavy flavor physics.

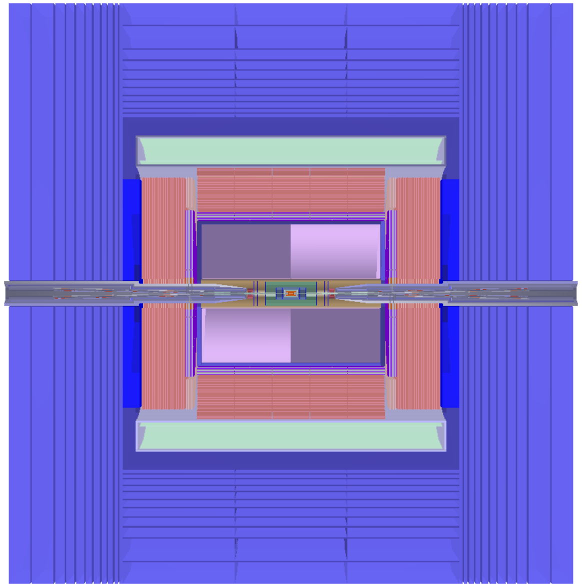


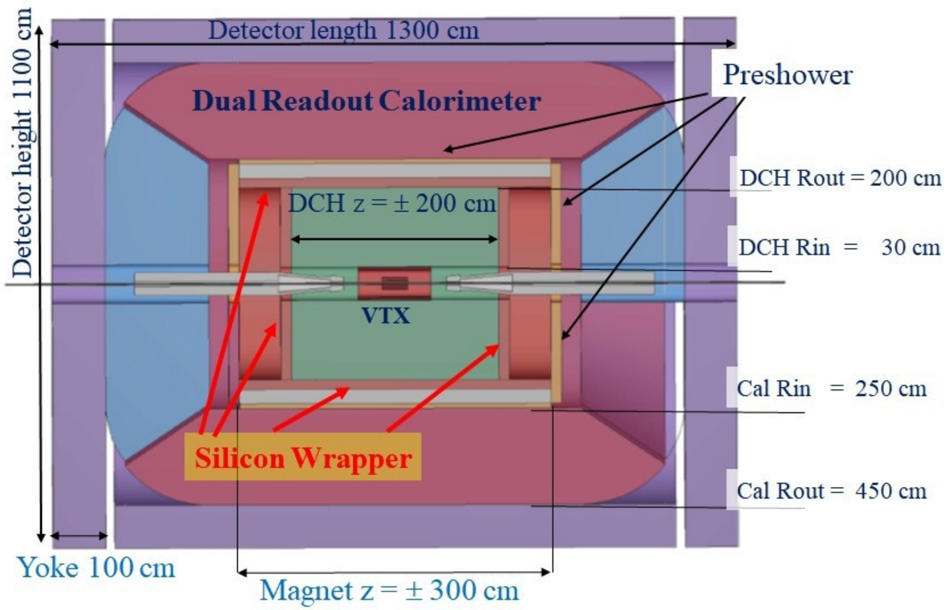


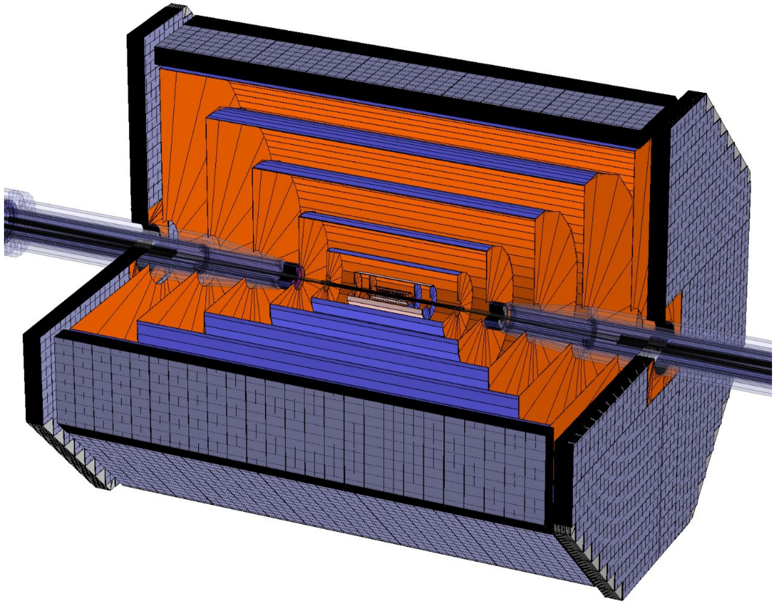
Observable	Current sensitivity	Future sensitivity	Tera-Z sensitivity
$\mathrm{BR}(B_s \to ee)$	2.8×10^{-7} (CDF) [438]	$\sim 7 \times 10^{-10}$ (LHCb) [435]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \mu\mu)$	0.7×10^{-9} (LHCb) [437]	$\sim 1.6 \times 10^{-10}$ (LHCb) [435]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \tau\tau)$	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]	~few% (LHCb/Belle II) [435, 442]	~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)	$\sim 10^{-8} - 10^{-10}$

Three Detector Concepts (CDR)

- Baseline: Silicon + TPC
- FST: all-silicon tracker
- IDEA: Silicon+Drift chamber(DCH)







Detector requirements

- Detector concepts are mainly driven by Higgs physics.
- Requirements at WW and Z-pole are not fully explored yet:
  - Particle identification and jet-charge using Kaon-tagger.

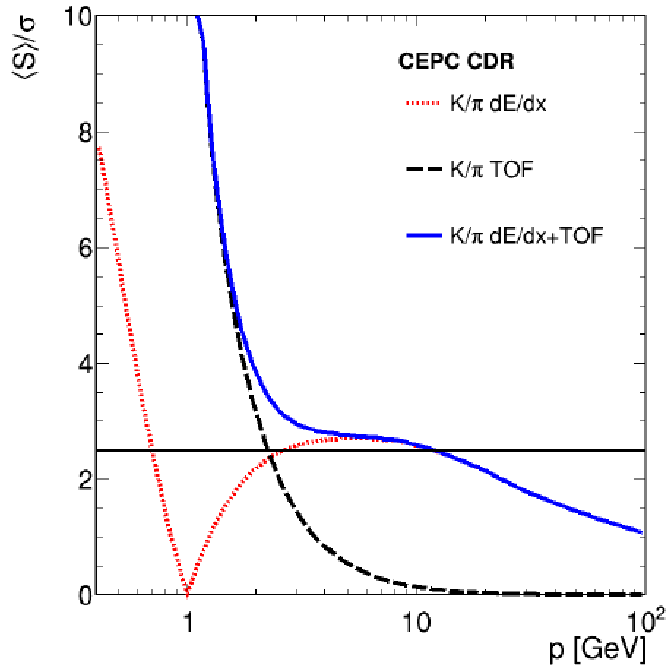
Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) =$ $2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	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	$\Delta E/E =$ $\frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

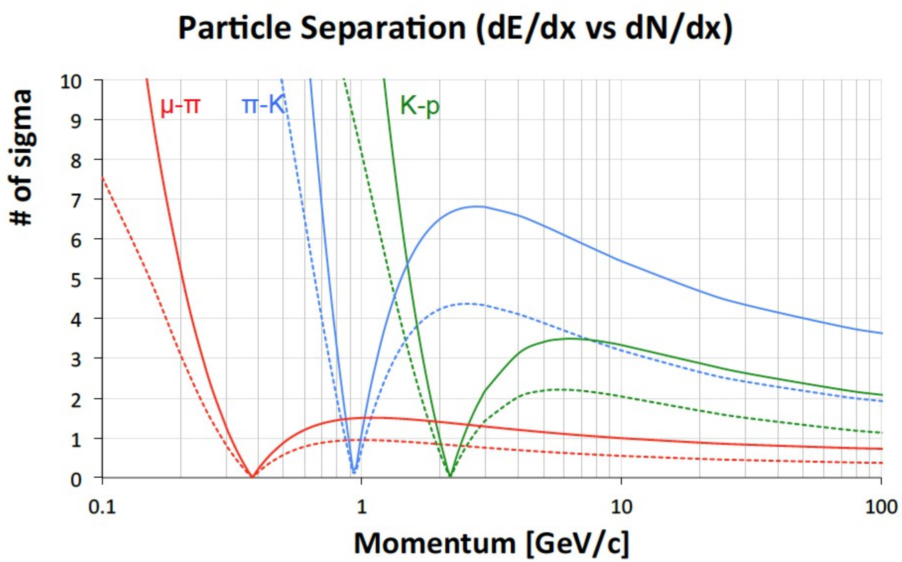
Particle Identification (PID)

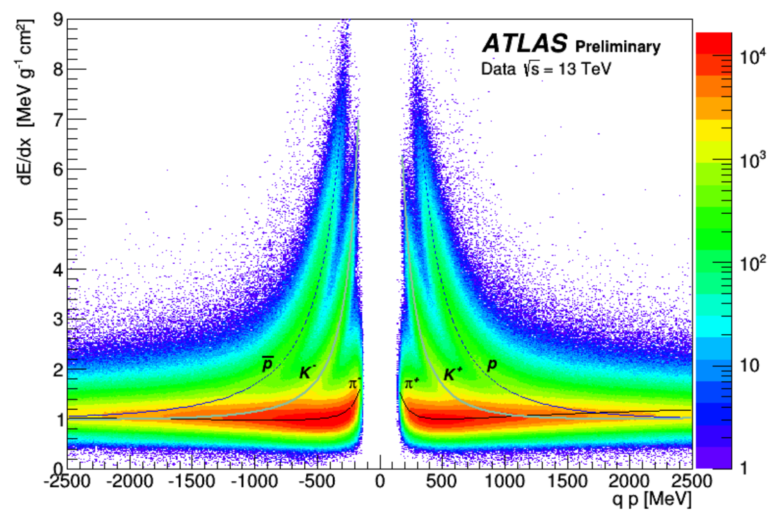
- Particle identification plays a key role in Heavy Flavour physics, but its impact on the Higgs physics is not fully explored yet.
- Detectors must work at three different energies to minimize downtime:
  - at Z-pole (91 GeV)
  - at WW (160 GeV)
  - at Higgs factory (240 GeV)
- FST with limited dE/dx seems a concern for running at Z-pole, which can be mitigated by including fast timing LGAD silicon and RICH detectors:
  - Pros: improving jet-charge and charm tagging.
  - Cons: extra material budget and detector R&D.
- Build a better and robust detector will ensure the success of CEPC program.

Particle ID Capabilities

- TPC, DCH both have:
  - dE/dx ~4% + Ecal timing
  - K/π 3σ up to 10 GeV
- Full silicon tracker(FST):
  - Limited dE/dx + Ecal timing
  - K/π 3 σ up to 3 GeV.

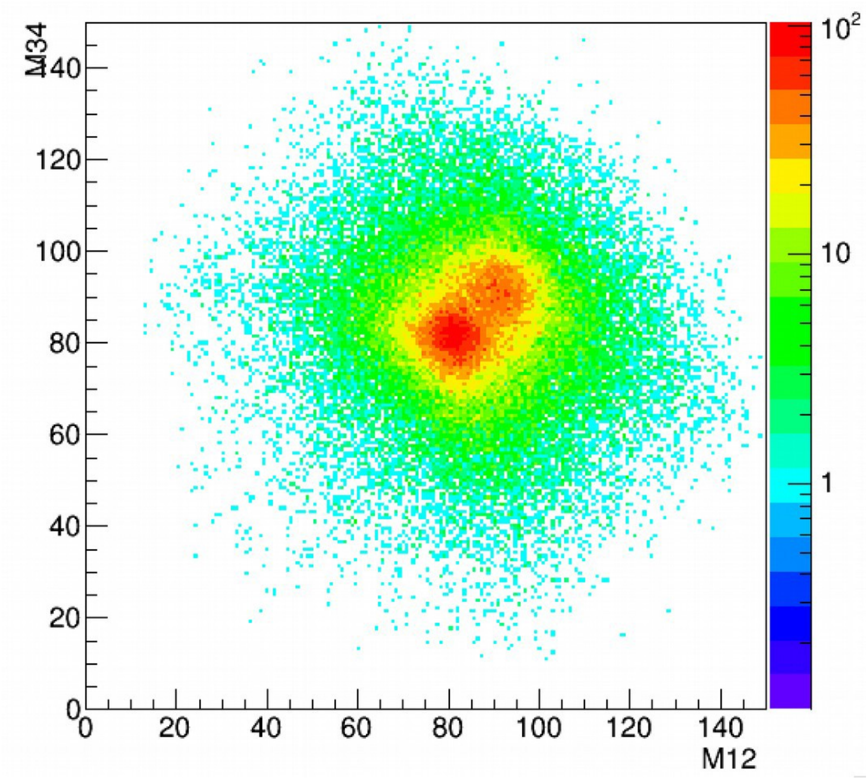


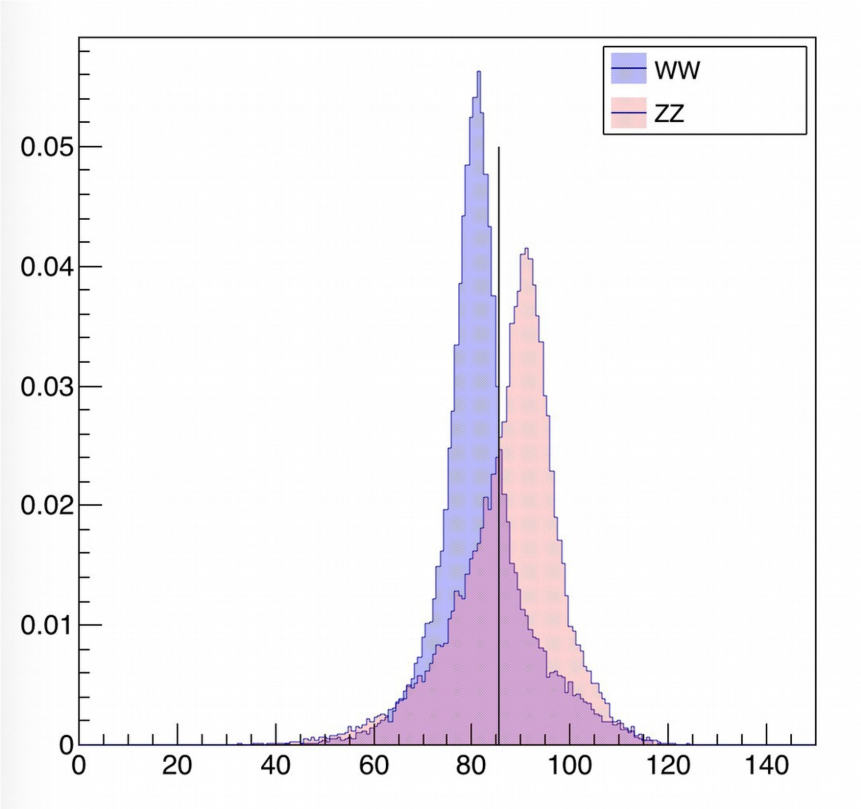




Separating H→WW from H→ZZ in hadronic decays

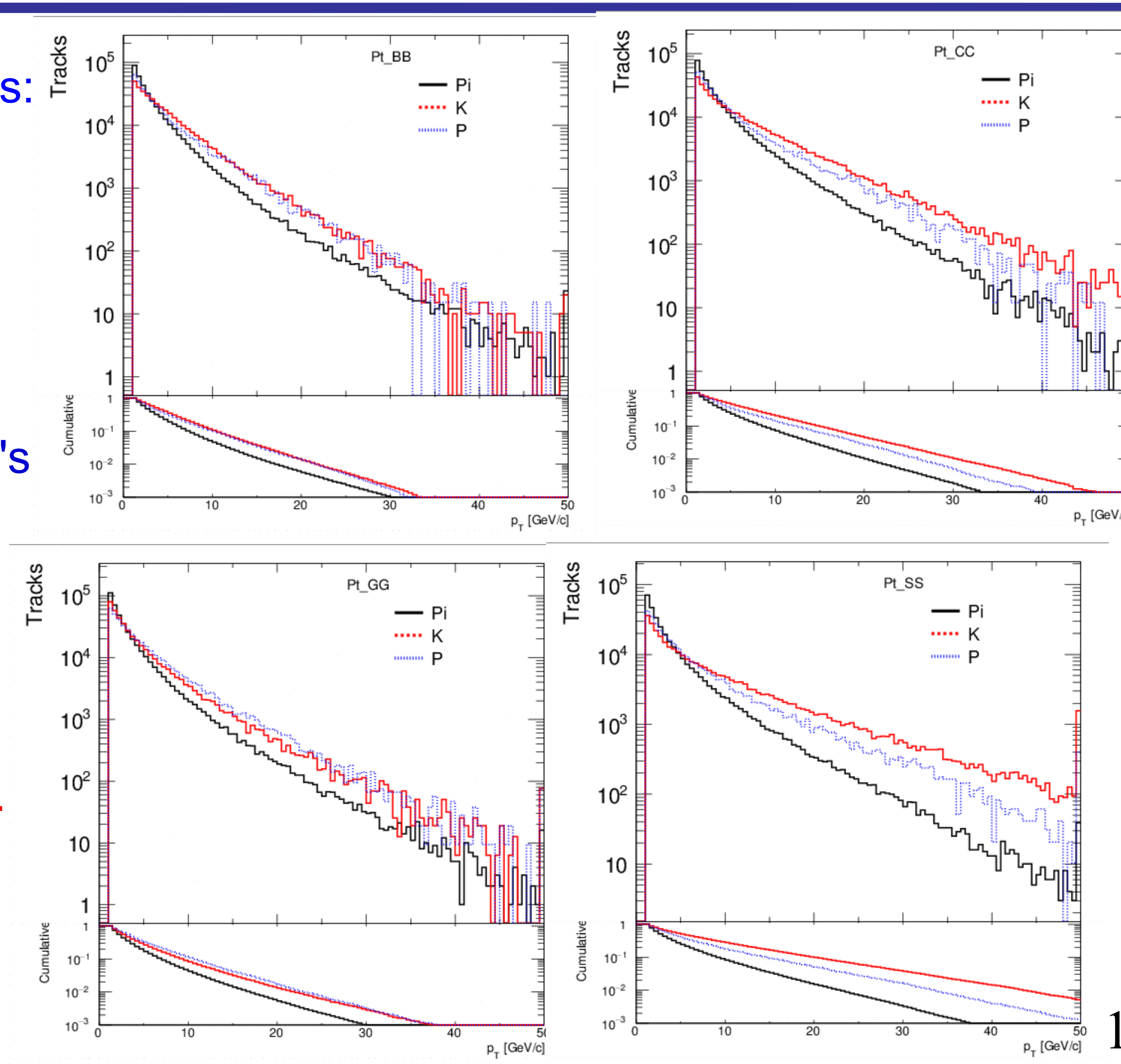
- Selecting 4 jets and find best match pair of W and Z.
- Separating W/Z is difficult due to extra jet radiation and jet resolution.
- Jet-charge could help to improve jet-pairing.





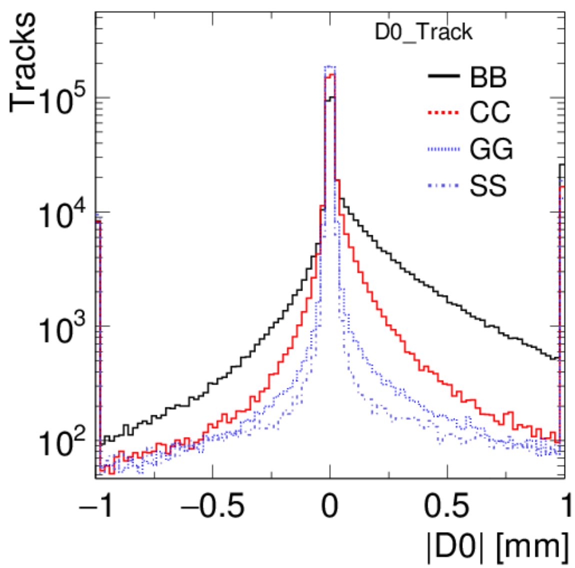
Improving H→bb, cc decays with PID

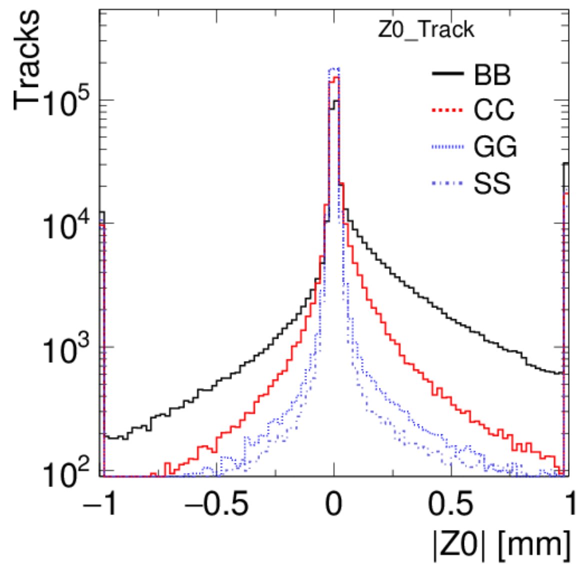
- Used CEPCV4 samples:
  - ZH→μμbb
  - ZH→μμcc
  - ZH→μμgg
  - ZH→μμss
- Reclustered with Gang's classifier.
- Selecting π/K/P based on MC truth.
- Most kaon: Pt<30 GeV.

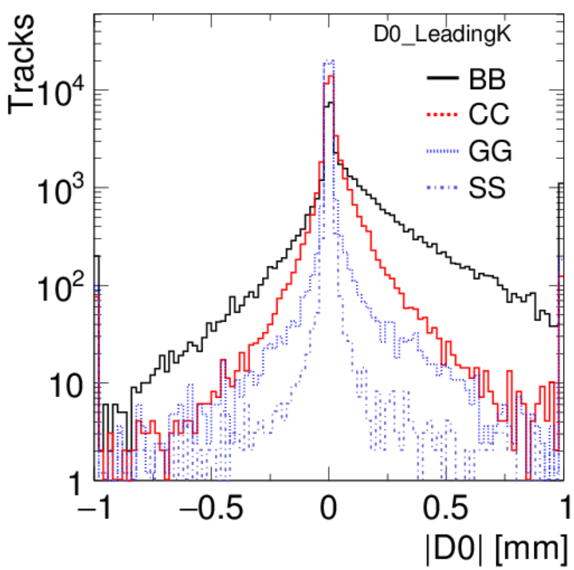


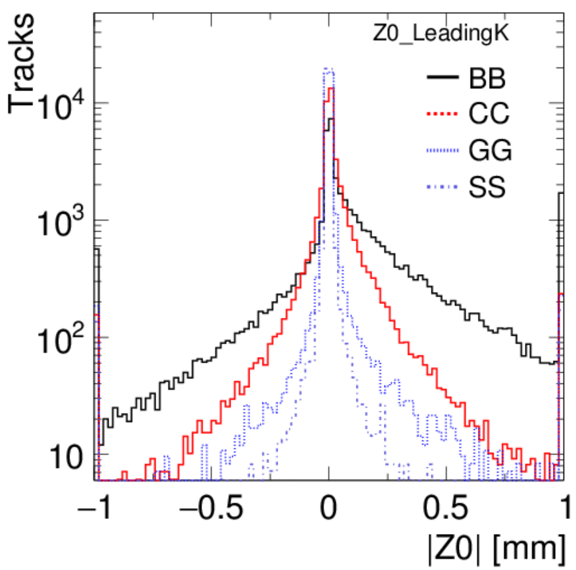
Signed D0, Z0 for Higgs decays

- D0, Z0 for Higgs decays:
  - H→BB/CC/GG/SS
  - B-tracks have long lifetime as expected.
  - Gluon-, Strange-tracks have no-lifetime.
  - C-tracks have short lietime.



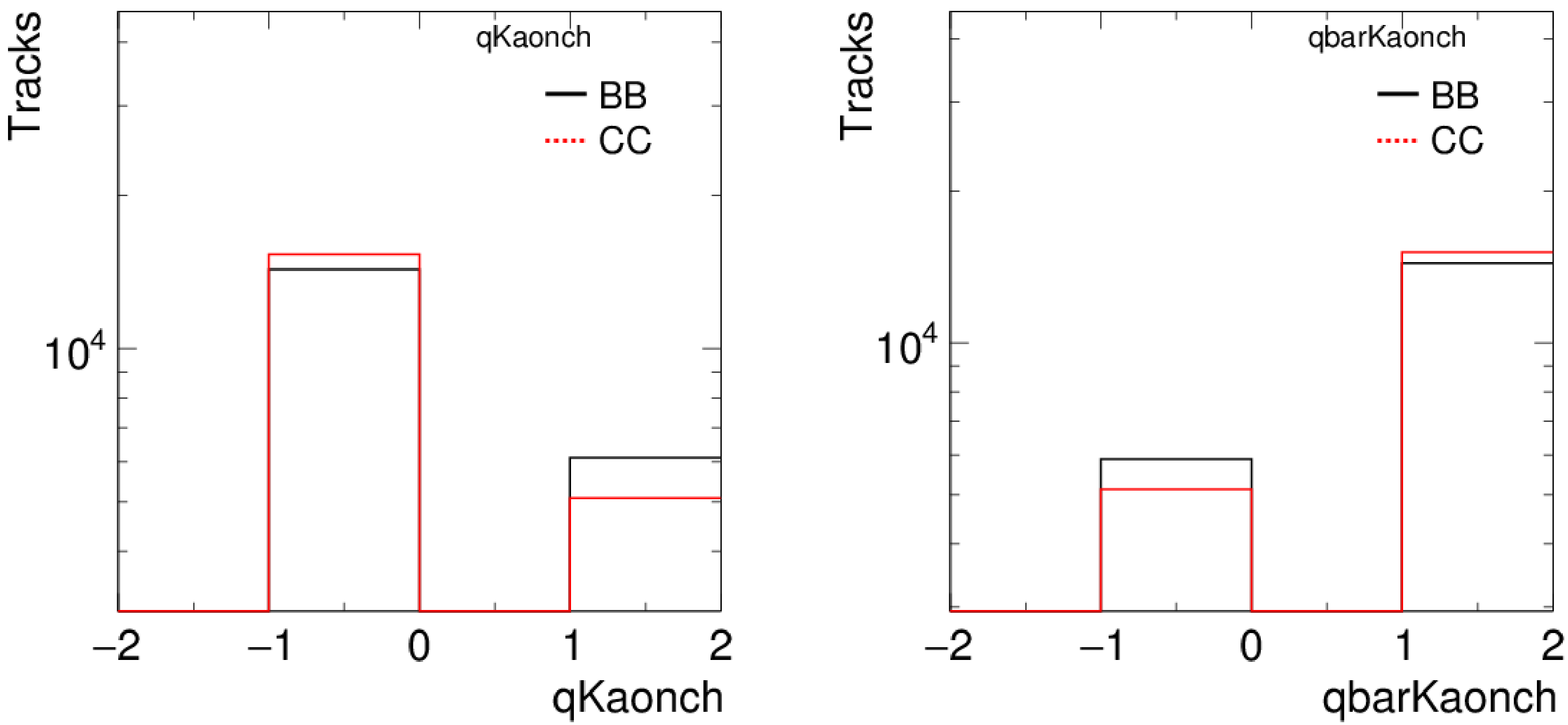






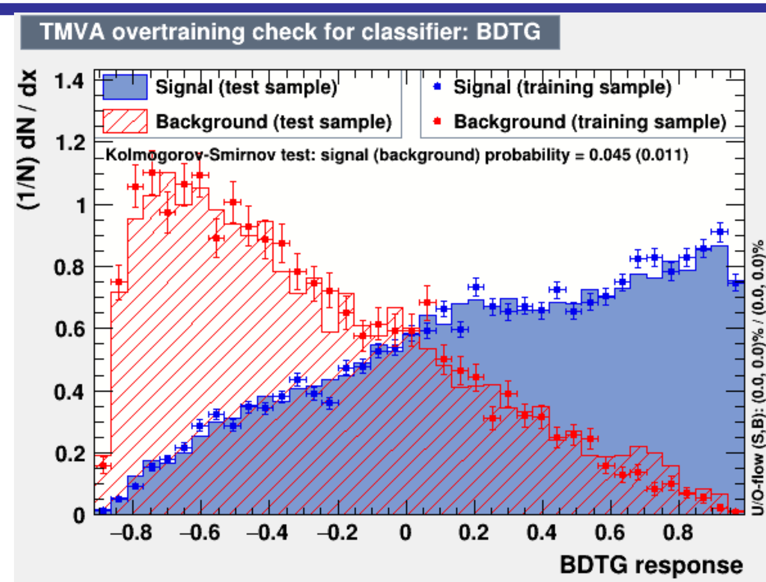
Jet-Kaon Charge Correlation

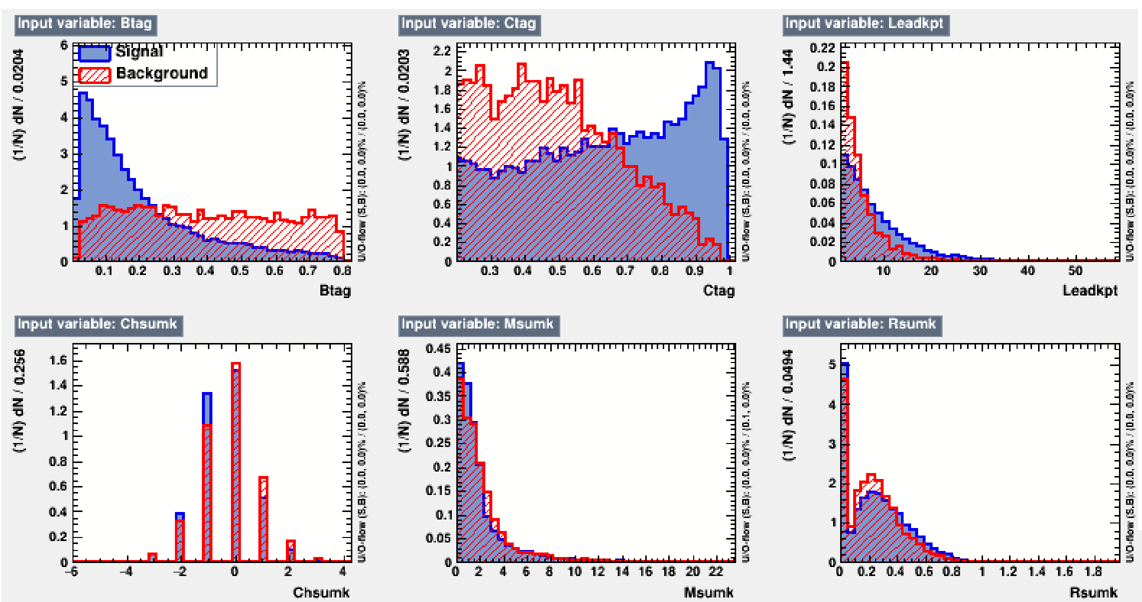
- Leading kaon provides a tag for the charge of b and c quark:
  - $b \to c \to s \to K^-$
  - $bbar \to cbar \to sbar \to K^+$
- Kaon-tagger help to identify jet-charge and reducing jet combinatorics.

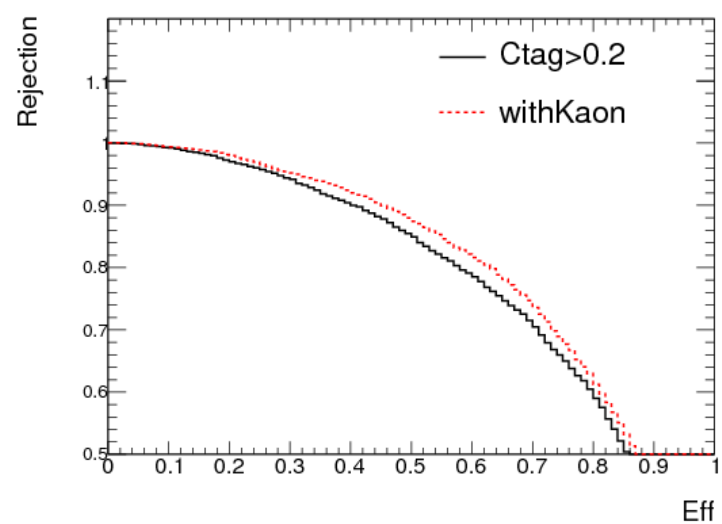


Improving b/c separation

- Standard b-tag based on vertexing.
- Retrained BDT to separate c- from b-jets with additional kaon tracks:
  - Preliminary: Btag, Ctag, LeadKpt, charge, mass, and track pt of displaced tracks.
  - Future: seeding with kaon for b-, c- vertex and including lepton-kaon correlations...

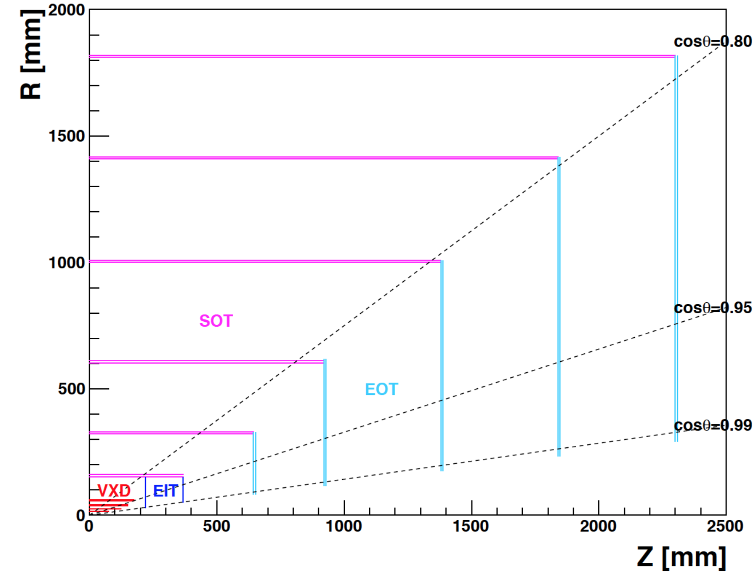


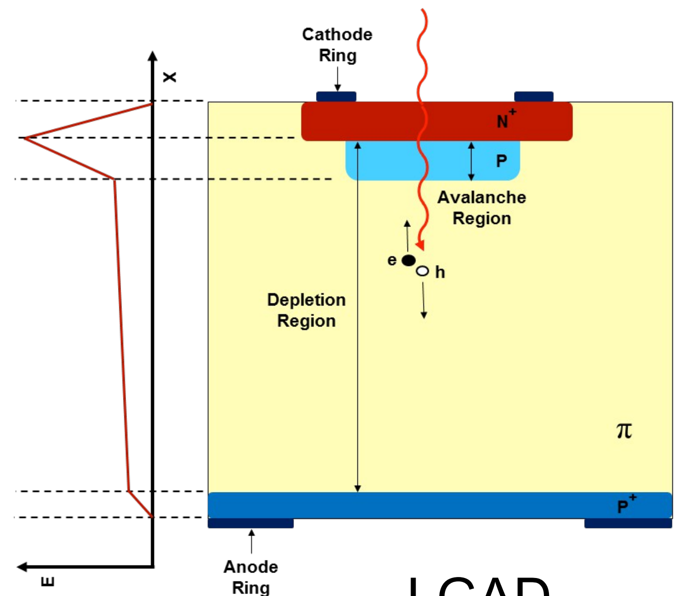




PID detector options for FST

- FST in CDR has few concerns:
  - Limited dE/dx
  - Double sided strip layers with higher material budget
- TOF from fast timing LGAD silicon(20 ps):
  - Replacing outer strip layers with super granularity timing detector (SGTD) with 50 μm pitch.
  - Providing timing for PID up to 5 GeV.
- RICH provide PID up to 30 GeV:
  - Minimizing material budget
  - Cherenkov light detection:
    - MWPC, SiPM, HPDs...
    - SGTD detecting:charged tracks and cherenkov photons.

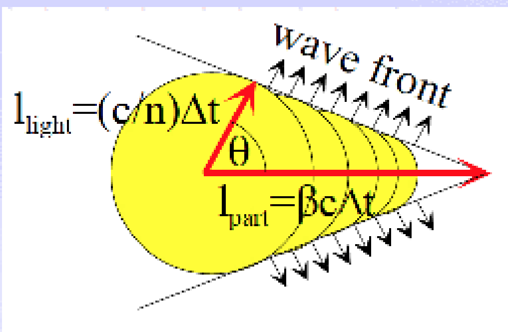




LGAD

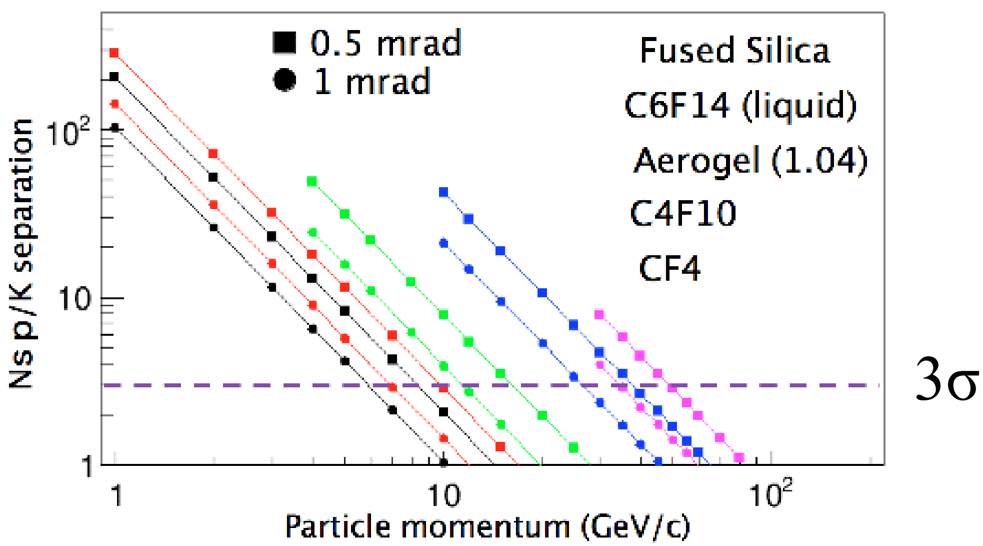
RICH detector for PID

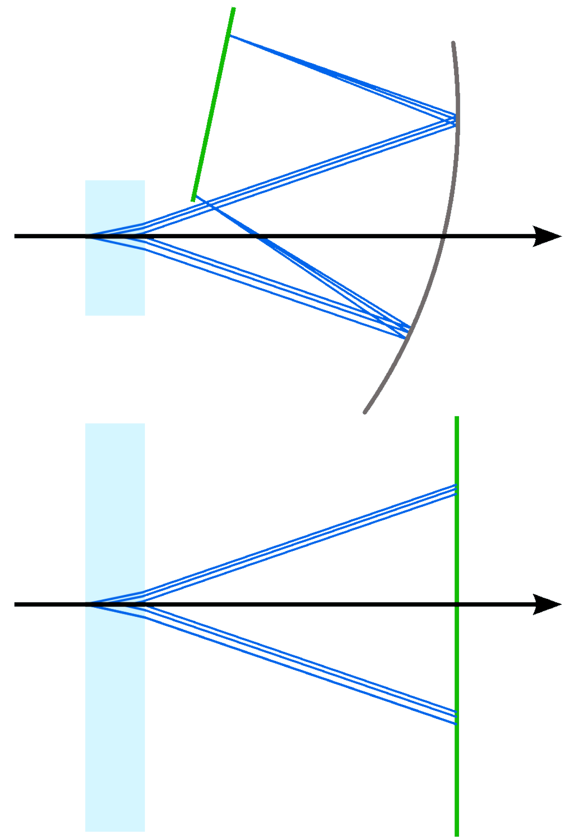
- Ring Image CHerenkov (RICH) can provide PID for high momenta particle.
- Multiple RICH detectors required to cover full momentum ranges.



$$\cos\theta_C = \frac{1}{n\beta}$$

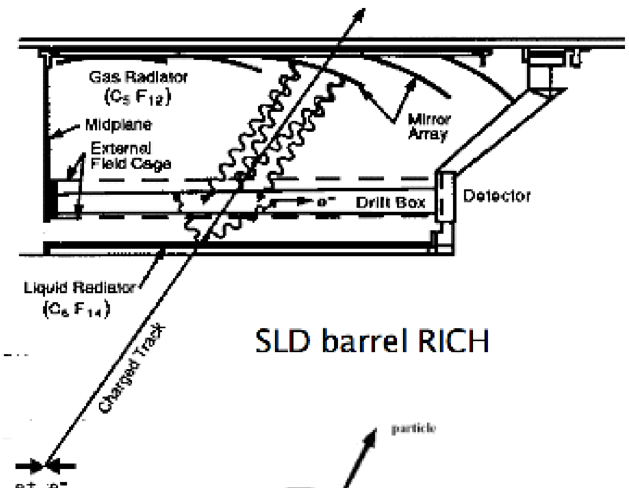
with $n = n(\lambda) \geq 1$

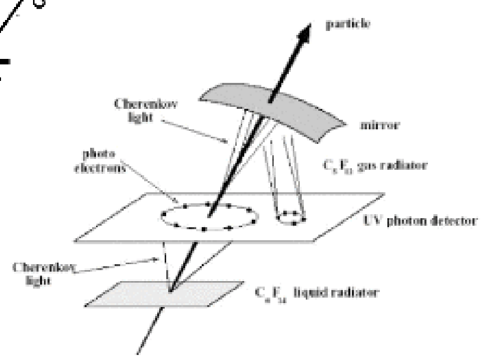


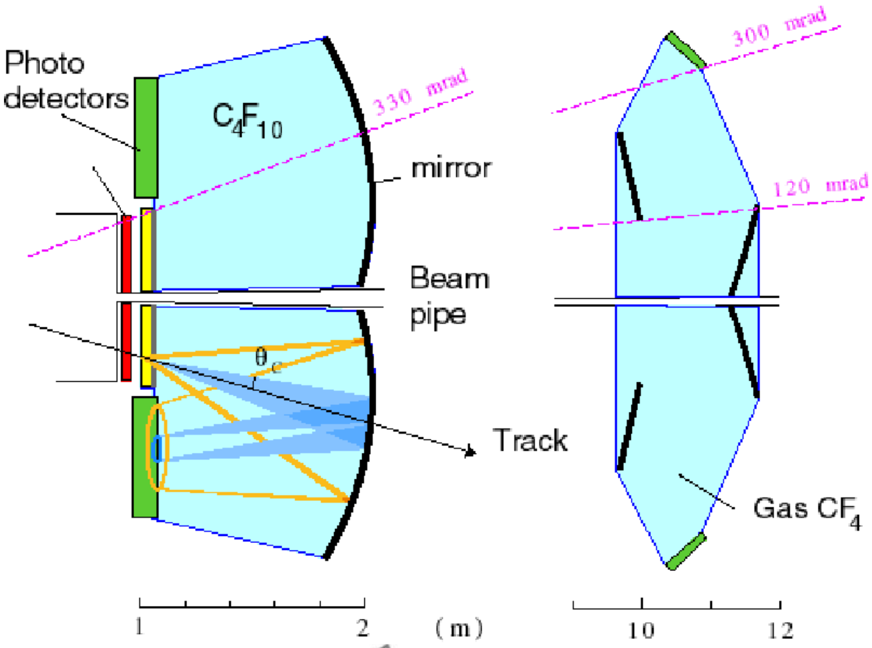


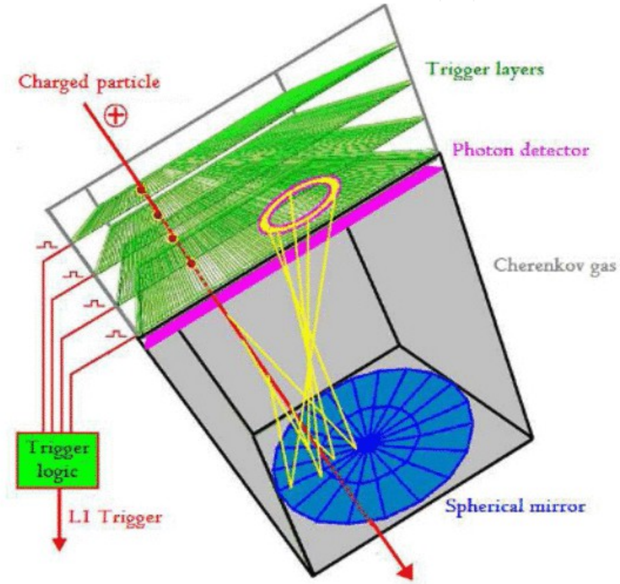
RICH detectors for collider experiments

- High momentum RICH detectors:
  - RICH(Delphi, SLD)
  - VHMPID (Alice)
  - RICH2 (LHCb)

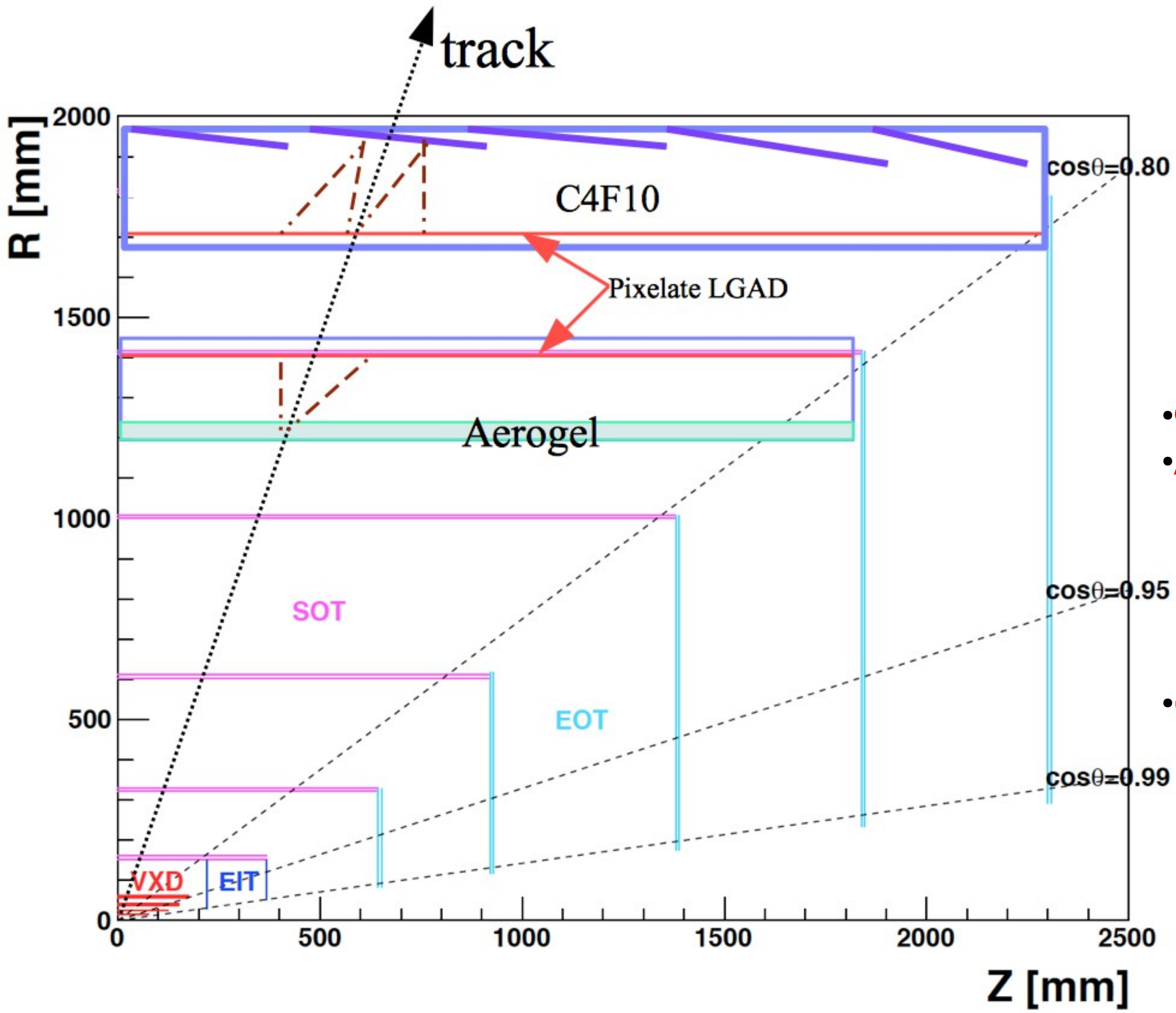








RICH detector option for FST



- $dN/dx = 2\pi\alpha(1-1/n^2)(1/\lambda_L - 1/\lambda_H)\varepsilon$
- Aerogel:
  - $n=1.025$
  - $\lambda=350\text{-}900$ nm
  - $\varepsilon=0.30$
  - L=2.0 cm(1.5%X0)
  - N=20
- C4F10:
  - $n=1.0014$
  - L=30 cm(1.7%X0)
  - N=20

Conclusion

- PID could improve both Heavy Flavor physics as well as the Higgs physics.
  - Improve the jet-charge to reduce jet combinatorics.
  - Improve the charm-tagger
- TOF+RICH will cover momenta up to 30 GeV for Full silicon detector option.
- R&D and physics case studies are needed for the final proposal.