Physics: analyses benchmarks, Global key performance & Key requirements

Manqi Ruan

Outline

- Physics benchmark analyses
- Total Detector Performance
  - BMR
  - Jet Origin ID
  - Particle id (optional)
- Sub-detector requirements

Ref. Det. TDR Table of Content

1、Science & Physics requirement-

2、Concept global –

Geometry description

Mechanics

3、MDI & Beam background

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Sub-system {VTX, Tracker, Pid, Calo…}

1、Performance requirement

2、Tech. Survey and review

3、Our Exploration & Choice on Tech –

4、Sub Detector Design – Electronics, Mechanics, Cooling

5、Conclusion: SubD Level Performance

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4+X、Electronics Global & T-DAQ

5+X、Software & Computing

6+X、Installation & Civil/Hall relevant part

7+X、Performance on Objects

8+X、Performance on Physics. Benchmarks

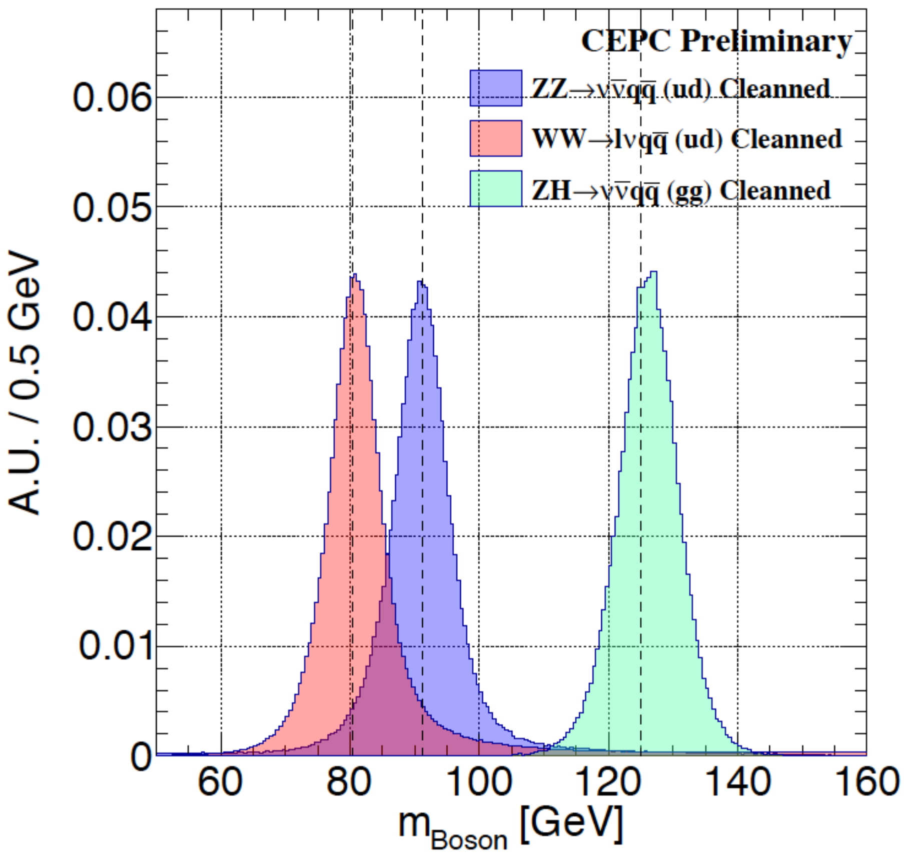
9+X、Overall Cost

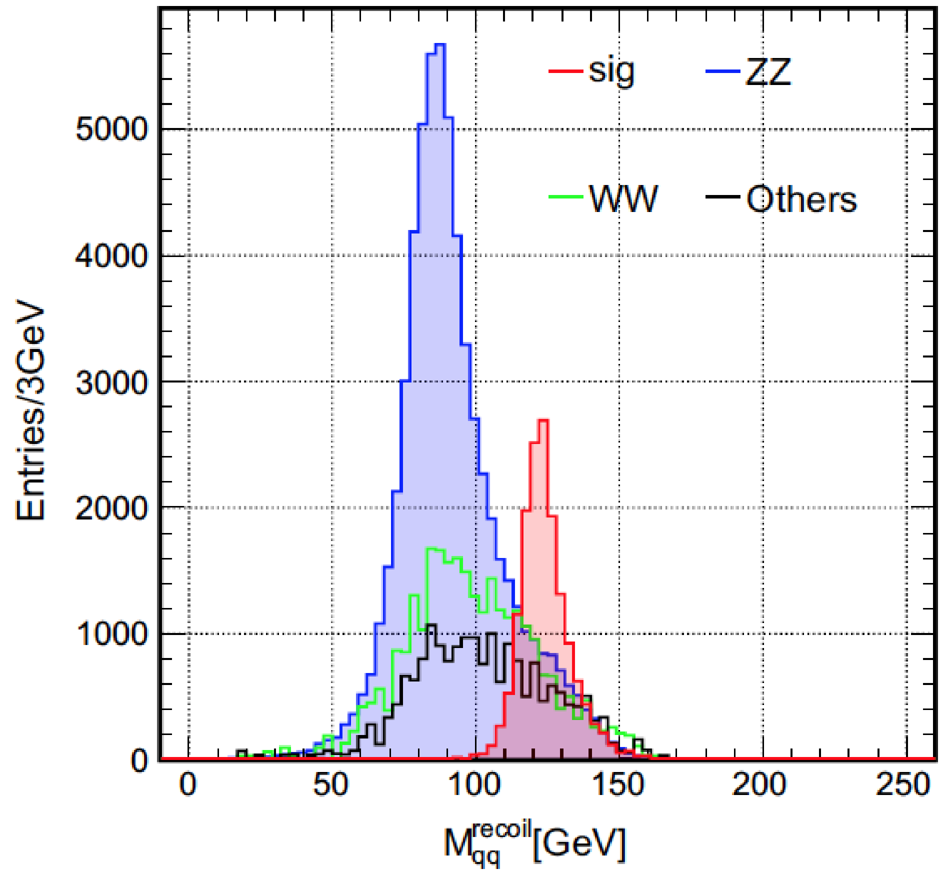
Appendix: Overall safety

Physics benchmarks

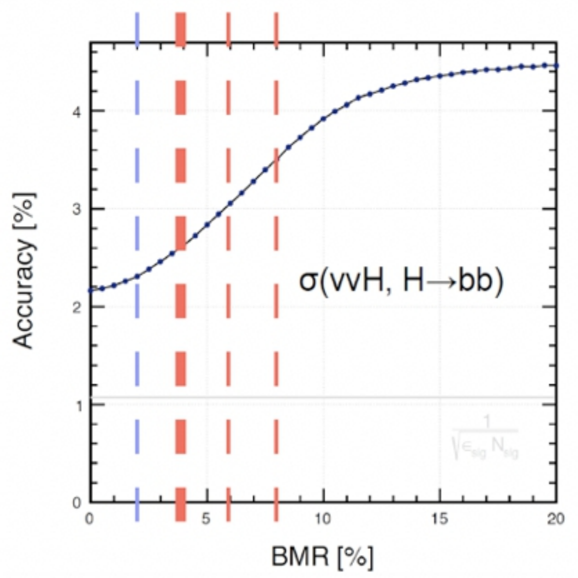
	Processes @ c.m.s.	Domain	Total Det. Performance	Sub-D
H->ss/cc/sb	vvH @ 240 GeV	Higgs	PFA + JOI (Jet origin id)	All sub-D, especially VTX
Vcb	WW@ 240/160 GeV	Flavor	JOI + Particle (lepton) id	All
W fusion Xsec	vvH @ 360 GeV	Higgs	PFA + JOI	All
α_S	Z->tautau @ 91.2 GeV	QCD	PFA: Tau & Tau final state id	ECAL + Tracker material
B->DK	91.2 GeV	Flavor	PFA + Particle (Kaon) id	All, especially Tracker & ToF
Weak mixing angle	Z	EW	JOI	All
Higgs recoil	llH	Higgs	Leptons id, track dP/P	Tracker, All
H->bb, cc, gg	vvH	Higgs	PFA + JOI	All
	qqH	Higgs	PFA + JOI + Color Singlet id	All
H->inv	qqH	Higgs/NP	PFA	All
H->di muon	qqH	Higgs	PFA, Leptons id	Calo, All
H->di photon	qqH	Higgs	PFA, Photons id	ECAL, All
W mass & Width	WW@160 GeV	EW	Beam energy	NAN
Top mass & Width	ttbar@360 GeV	EW	Beam energy	NAN
Bs->vvPhi	Z	Flavor	Object in jets; MET	All
Bc->tauv	Z	Flavor	-	All
B0->2 pi0	Z	Flavor	Particle/pi-0 in jets	ECAL

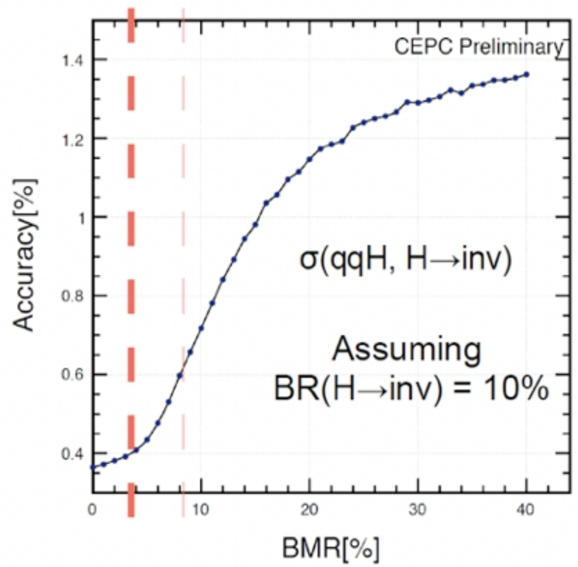
Boson Mass Resolution: Key Per. Para

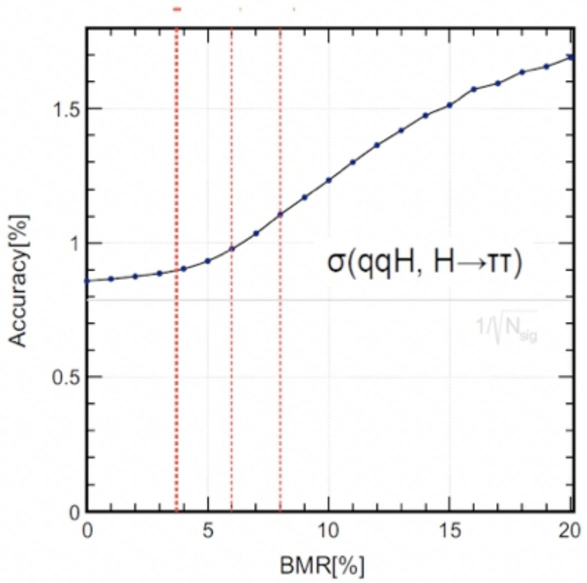


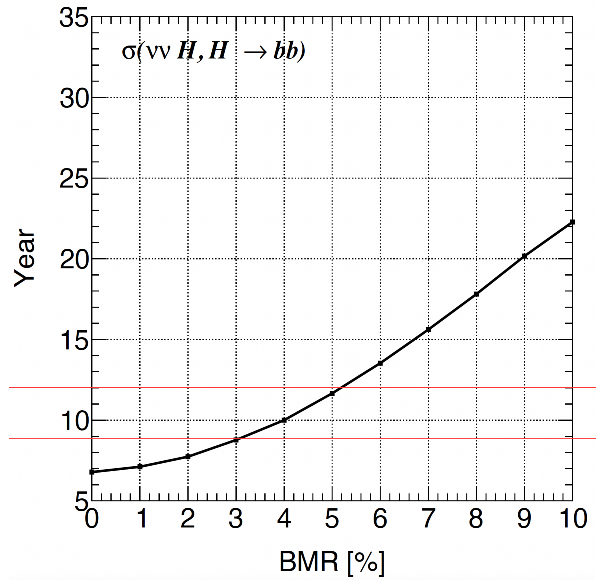


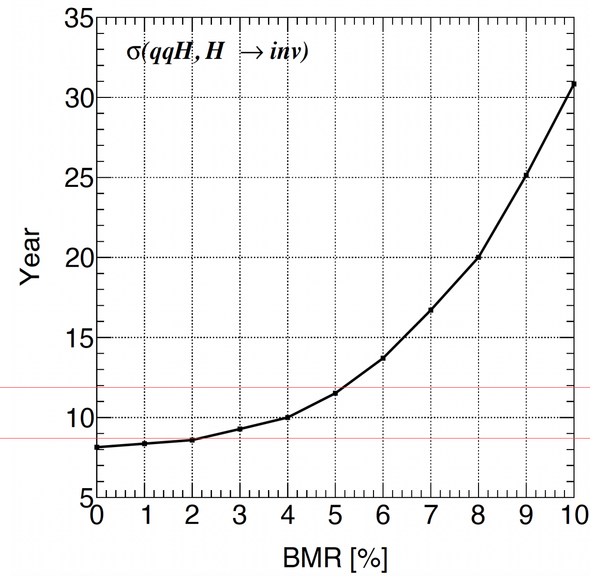
BMR: 4% is a must, should pursue 3%

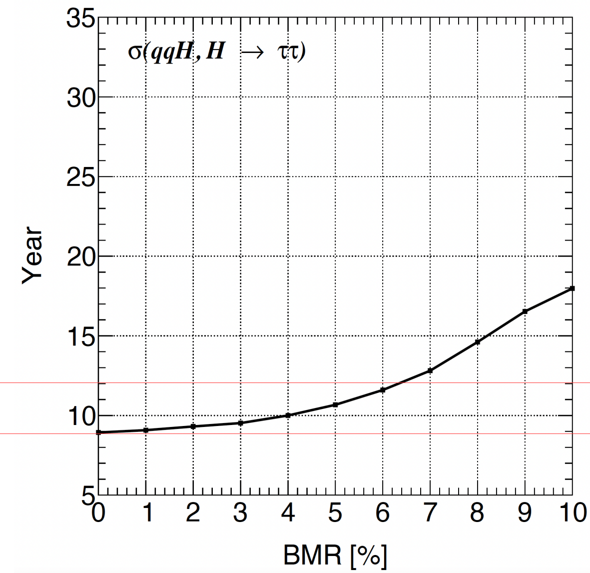




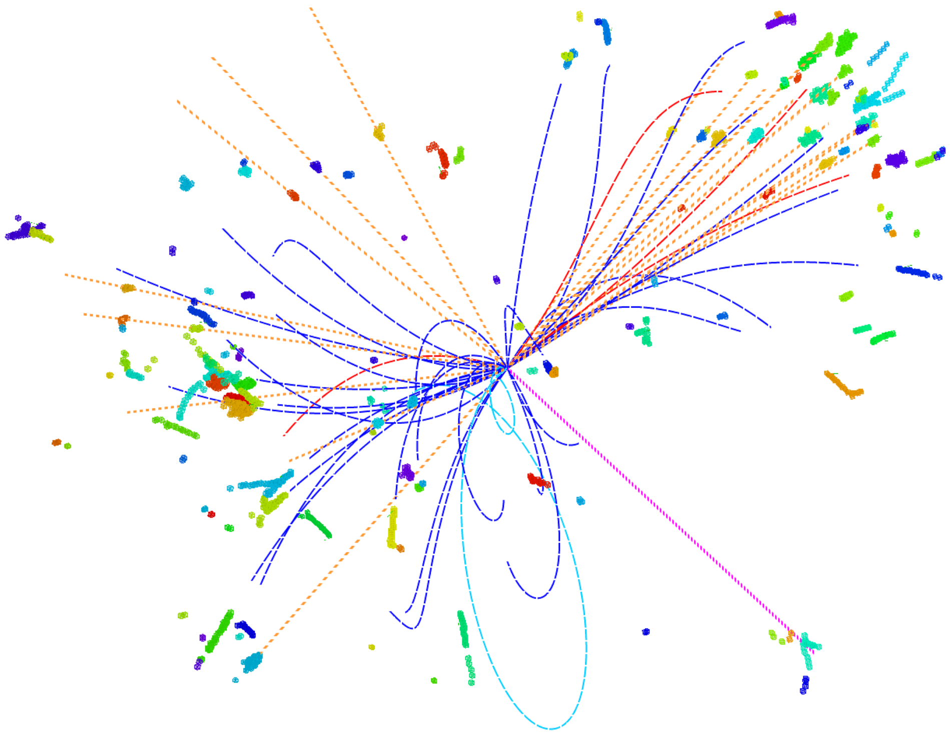


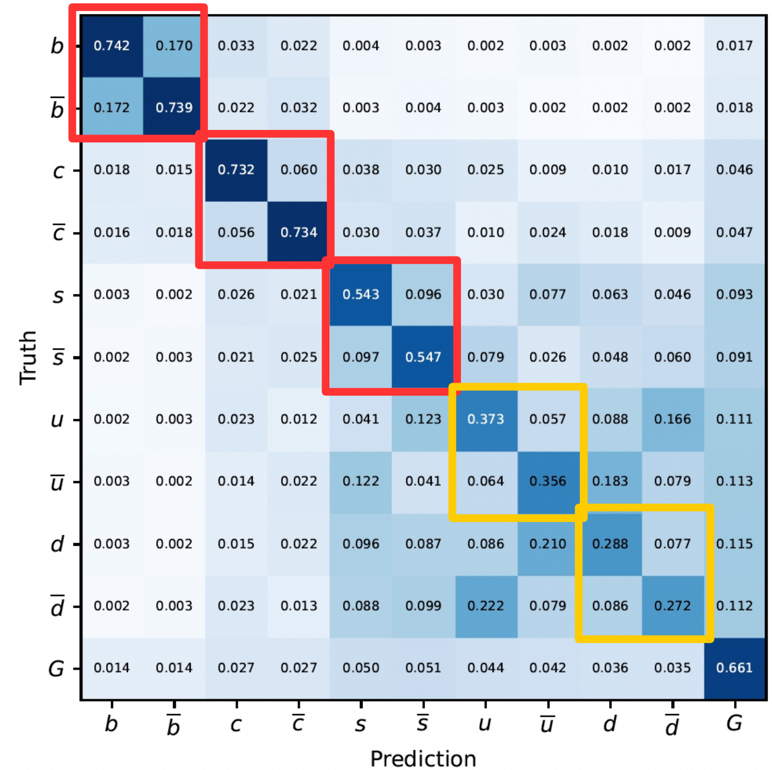






Jet Origin Identification





- **Jet origin identification: 11 categories (5 quarks + 5 anti quarks + gluon)**
  - Jet Flavor Tagging + Jet Charge measurements + s-tagging + gluon tagging...
- Full Simulated vvH, Higgs to two jets sample at CEPC baseline configuration: CEPC-v4 detector, reconstructed with **Arbor + ParticleNet (Deep Learning Tech.)**
- 1 Million samples each, 60/20/20% for training, validation & test

Benchmark analyses: Higgs rare/FCNC

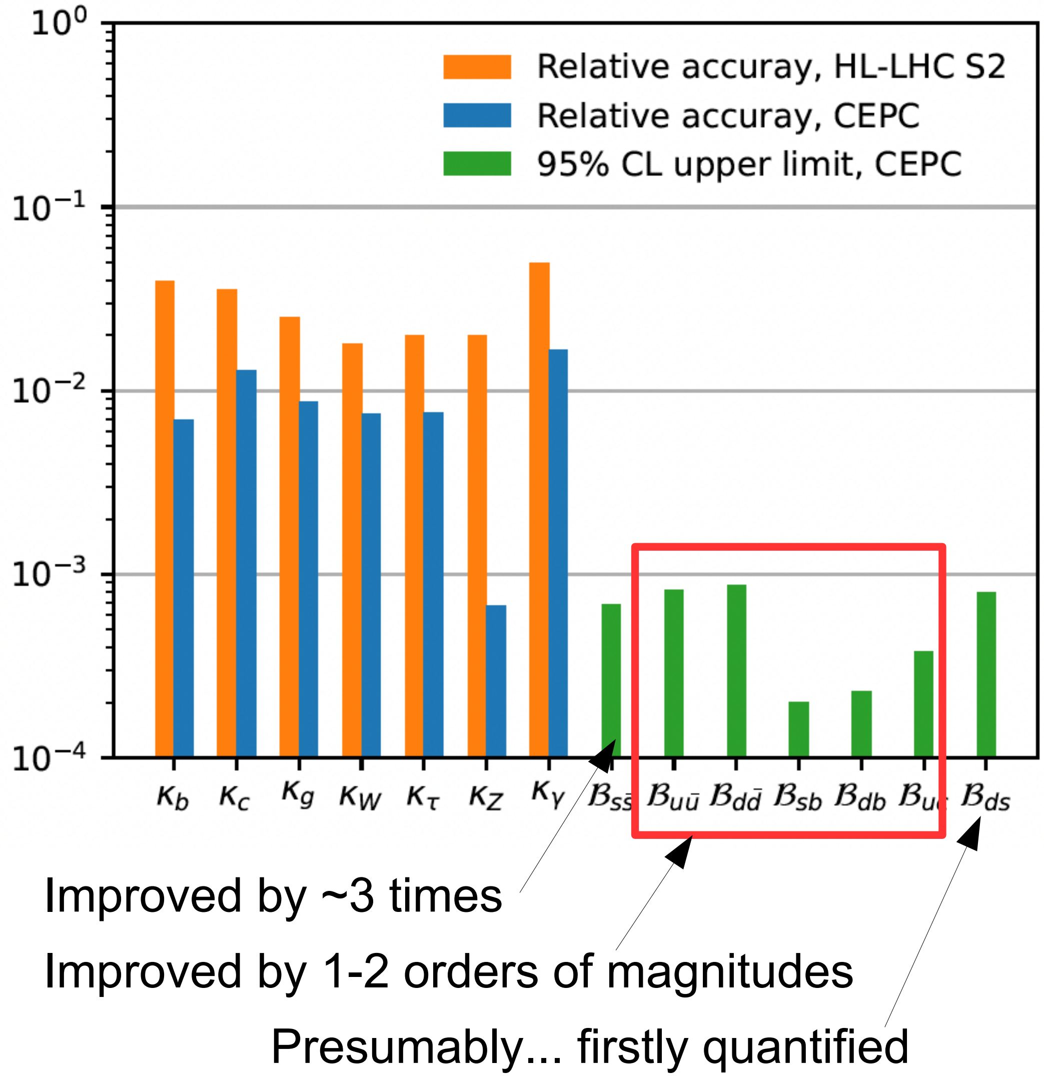


TABLE I: Summary of background events of $H \to b\bar{b}/c\bar{c}/gg$, Z, and W prior to flavor-based event selection, along with the expected upper limits on Higgs decay branching ratios at 95% CL. Expectations are derived based on the background-only hypothesis.

	Bkg. (10^3)			Upper limit (10^{-3})						
	H	Z	W	$s\bar{s}$	$u\bar{u}$	$d\bar{d}$	sb	db	uc	ds
$\nu\bar{\nu}H$	151	20	2.1	0.81	0.95	0.99	0.26	0.27	0.46	0.93
$\mu^+\mu^-H$	50	25	0	2.6	3.0	3.2	0.5	0.6	1.0	3.0
e^+e^-H	26	16	0	4.1	4.6	4.8	0.7	0.9	1.6	4.3
Comb.	-	-	-	0.75	0.91	0.95	0.22	0.23	0.39	0.86

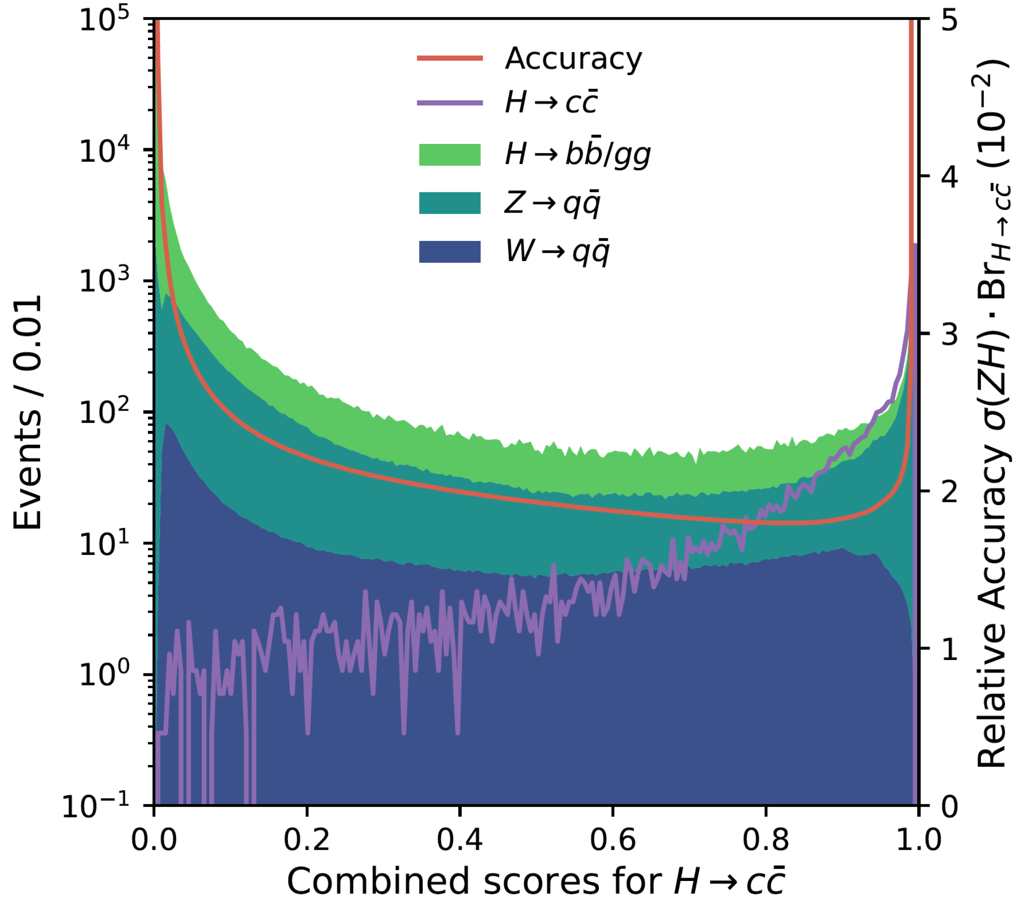
[28] J. Duarte-Campderros, G. Perez, M. Schlaffer, and A. Soffer. Probing the Higgs–strange-quark coupling at e^+e^- colliders using light-jet flavor tagging. *Phys. Rev. D*, 101(11):115005, 2020.

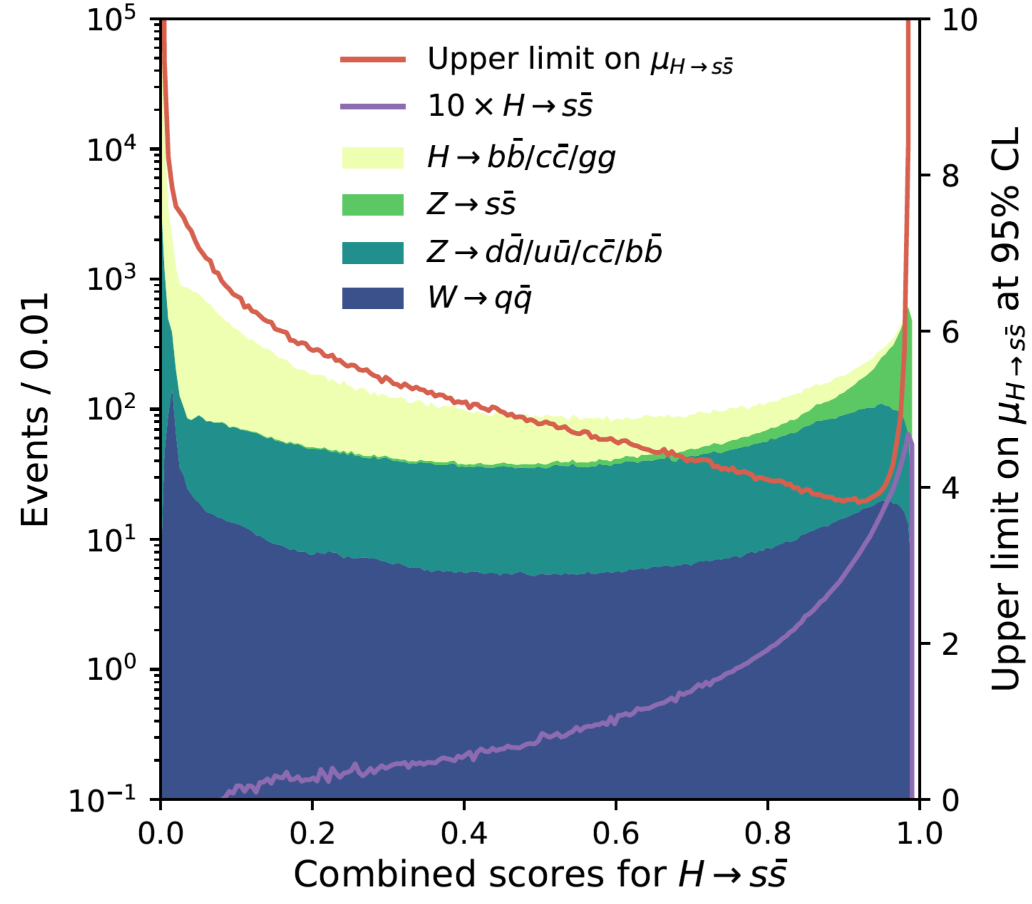
[50] Alexander Albert et al. Strange quark as a probe for new physics in the Higgs sector. In *Snowmass 2021*, 3 2022.

[59] J. de Blas et al. Higgs Boson Studies at Future Particle Colliders. *JHEP*, 01:139, 2020.

[60] Jorge De Blas, Gauthier Durieux, Christophe Grojean, Jiayin Gu, and Ayan Paul. On the future of Higgs, electroweak and diboson measurements at lepton colliders. *JHEP*, 12:117, 2019.

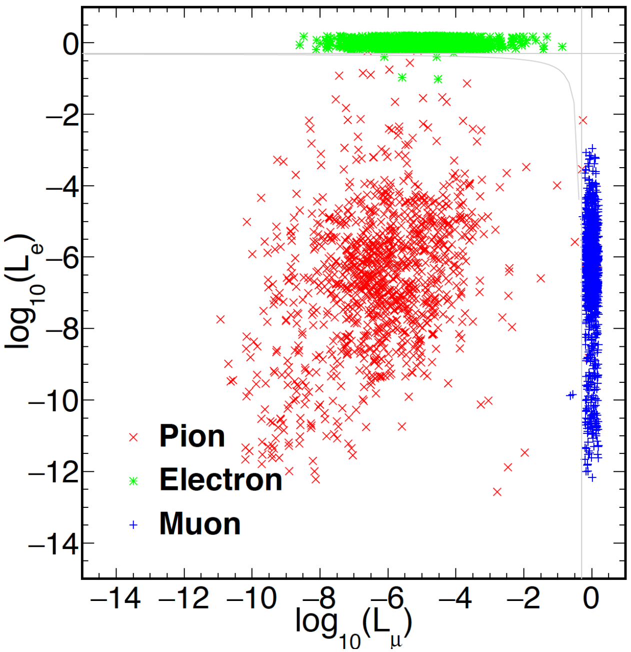
20 iab @ CDR baseline

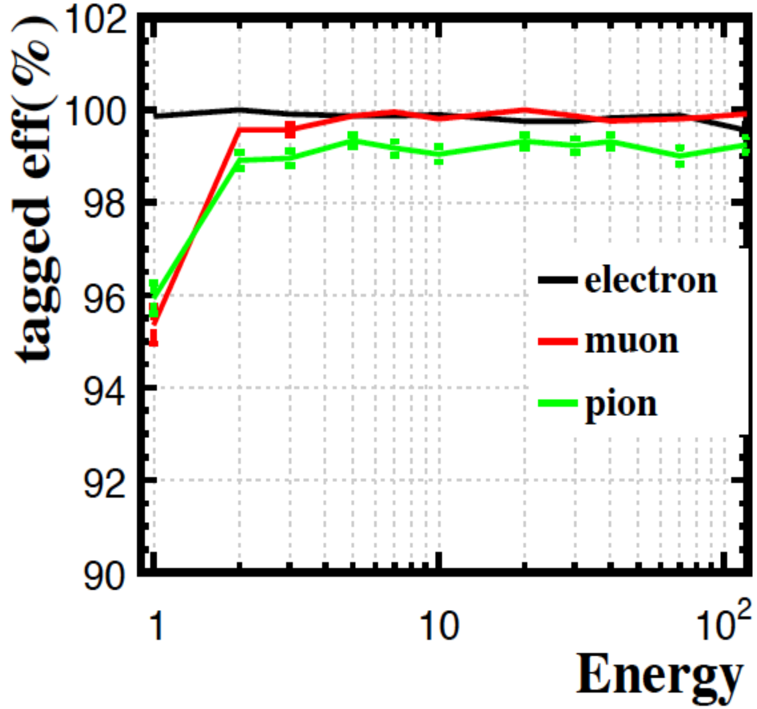


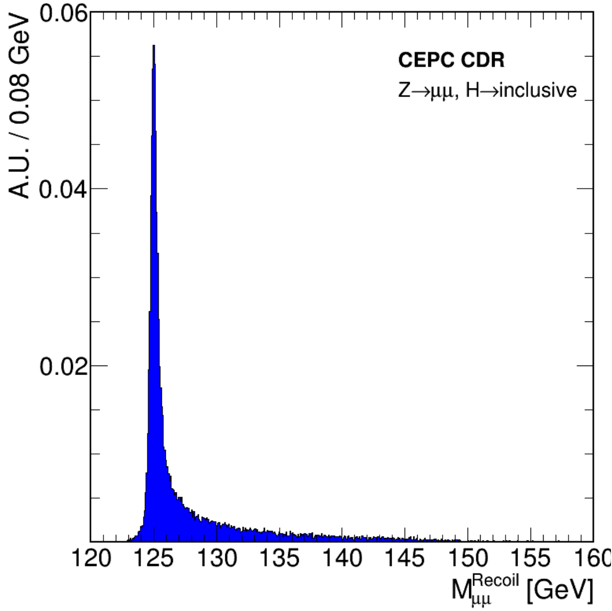


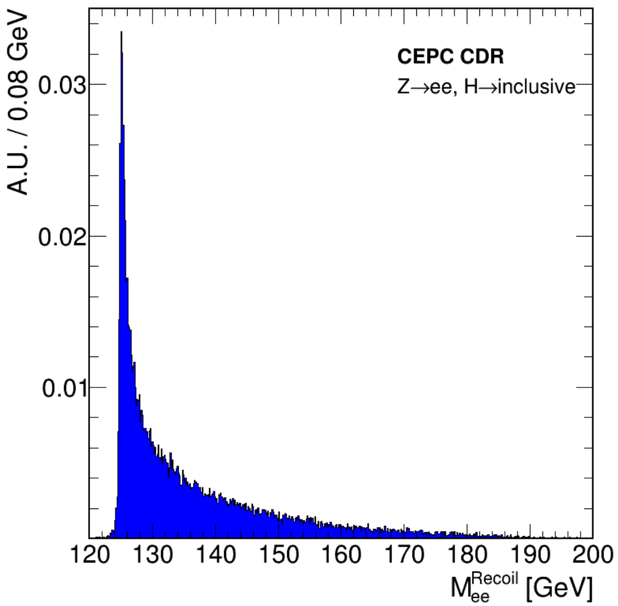
For vvH, H→ss, cc, gg: 3 time, ~80% (3% → 1.7%), ~20% (1% → 0.8%) improvement compared to CDR...

Particle id: Leptons







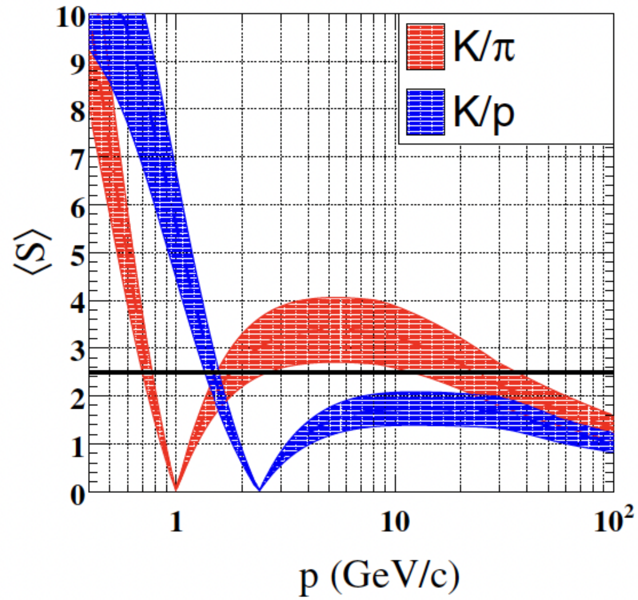


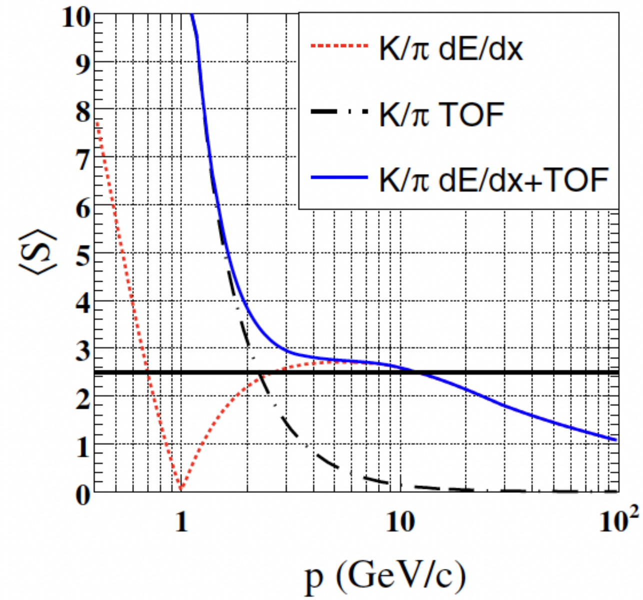
BDT method using 4 classes of 24 input discrimination variables.

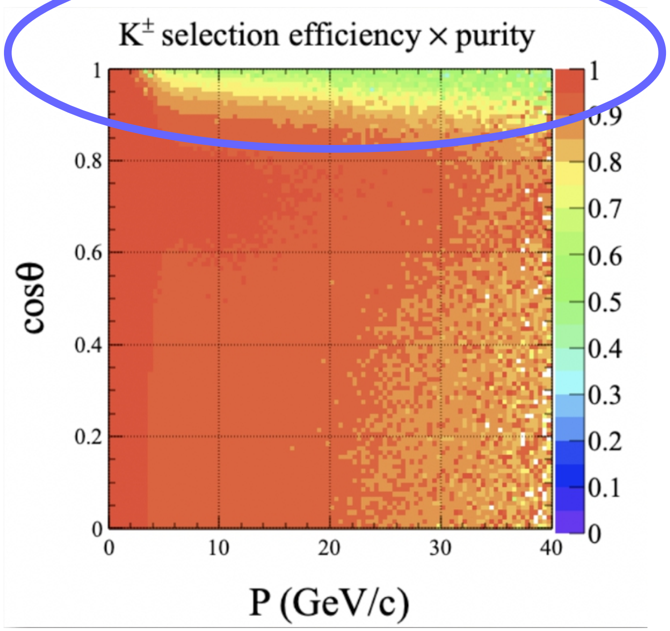
Test performance at: Electron = E_likeness > 0.5 ;
Muon = Mu_likeness > 0.5
Single charged reconstructed particle, for E > 2 GeV:
lepton efficiency > 99.5% && Pion mis id rate ~ 1%

Eur. Phys. J. C (2017) 77: 591

Particle id: charged hadron







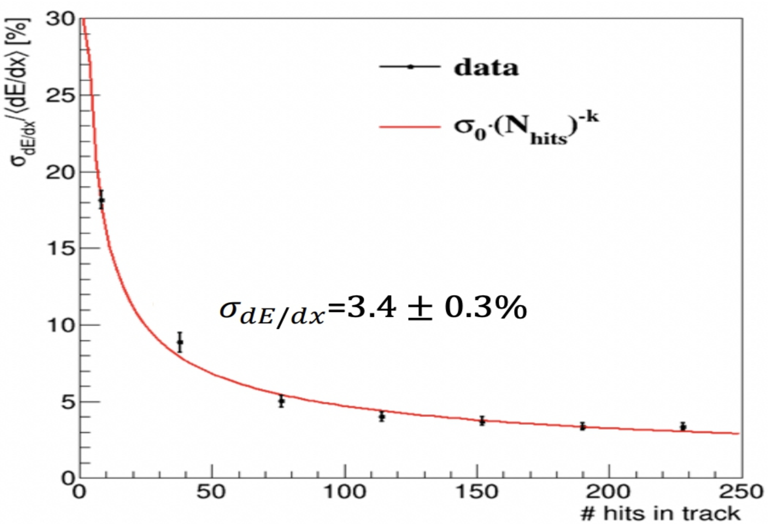
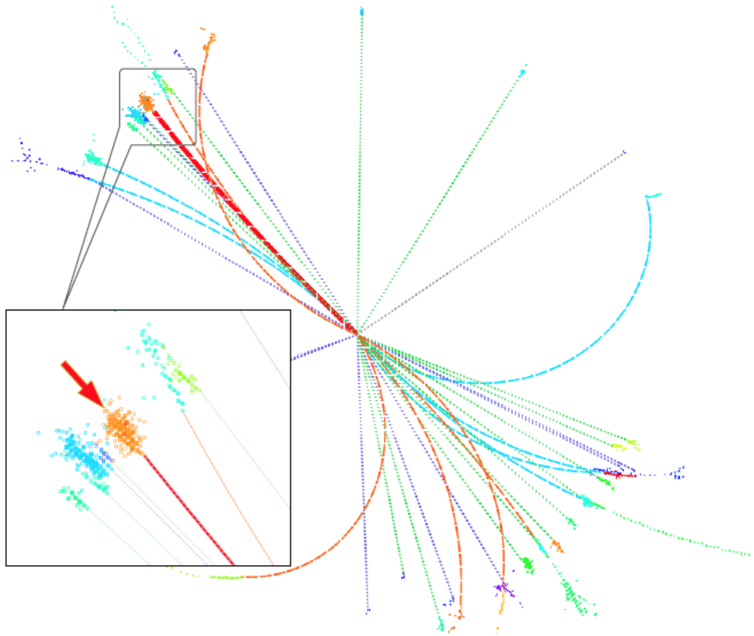


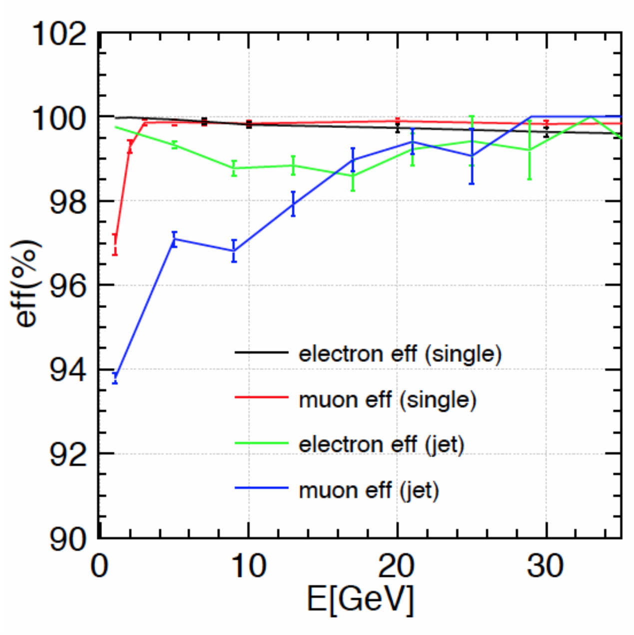
Table 3
The $K^{\pm}$ identification performance with different factors, $\sigma_{actual} = factor \cdot \sigma_{intrinsic}$, with/without combination of TOF information at the Z-pole.

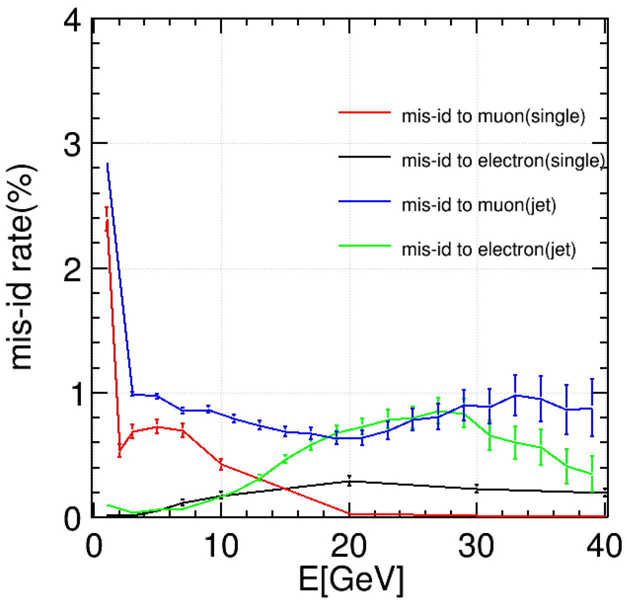
	Factor	1.	1.2	1.5	2.
dE/dx	ϵ_K (%)	95.97	94.09	91.19	87.09
	$purity_K$ (%)	81.56	78.17	71.85	61.28
dE/dx & TOF	ϵ_K (%)	98.43	97.41	95.52	92.3
	$purity_K$ (%)	97.89	96.31	93.25	87.33

- Pid via dEdx or dNdx: **< 3%**
- Current TPC studies using laser reaches 3.4%
- 50 ps Timing on Calo. Clusters

Lepton: inside jet







Compared the single particle sample, the jet lepton (at Z->bb sample at sqrt = 91.2 GeV) Performance will be slightly degraded – Due to the limited clustering performance (splitting & containimation).

At the same working point, the efficiency can be reduced by up to 3%; while mis-id rate increases up to 1%. Marginal Impact on Flavor Physics measurements as Bc->tauv.

Global Performance & Sub Detector correlations

- PFA: BMR < 4%, to pursues 3%
  - Tracker: intrinsic resolution + Material Budget
  - Calorimeter: resolution + Sep. Power + Pattern id capability

- Jet Origin ID: vvH, H→cc/ss be better than ~2%/4 times SM prediction (CDR baseline performance: ~ 1.7%/3.7 times)
  - Tracker + Calo (~ good PFA) + VTX

- Particle id (optional): efficiency ~ 99%, mis-id < 1% in fiducial region
  - Tracker, Calo, ToF.
  - Strongly depends on PFA, and strong impact to JOI

Vertex

Differential Efficiency.

Requirement: ~ 100%; dead channel number < o(0.1)%

Intrinsic spatial & time (optional) resolution.

Requirement: 5 micro-meter spatial resolution

Ref: CDR baseline design

Timing: shall be addressed from DAQ + Online system study

Differential Occupancy (with beam background + MDI studies).

Requirement: ~o(0.1)%, shall be addressed from DAQ + Online system study

Acceptance? -> Differential Jet origin Id performance

Material - Cooling?

Differential Performance = Performance as a function of relevant object(jet, track, ...)'s polar angle & energy

Tracker

Differential Efficiency.

Requirement: Pt threshold ~ o(100) MeV, |cos(theta)| < 0.99

Ref: CDR baseline design

Differential Material Budget.

Requirement: < 10%/50% X0 in Barrel/endcap

Ref: CDR baseline design + BMR & Material Dependence

Differential Resolution of 5 track parameters.

Requirement: In the barrel

δ(D0/Z0) ~ < 3 micro meter at 20 GeV

δ(Pt)/Pt ~ o(0.1%)

Ref: CDR baseline performance

Differential Pid Capability: eff*purity of Kaon id @ Z pole.

Requirement: eff*purity > 90% for all charged Kaon (@ Z pole)

~ relative resolution of dE/dx (or dN/dx) be better than 3%

ToF of 50 ps

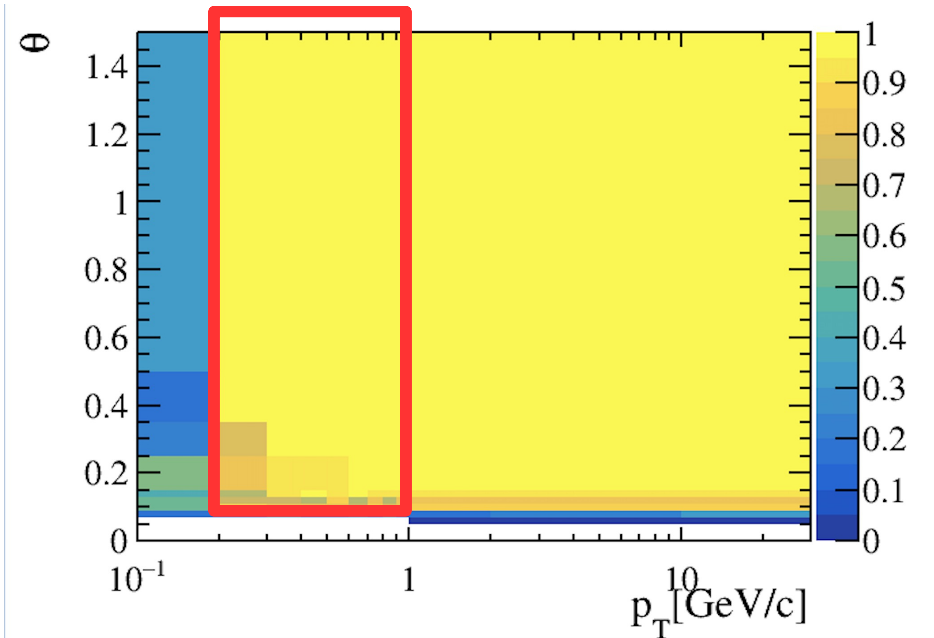
Ref: Nuclear Inst. and Methods in Physics Research, A 1047 (2023) 167835

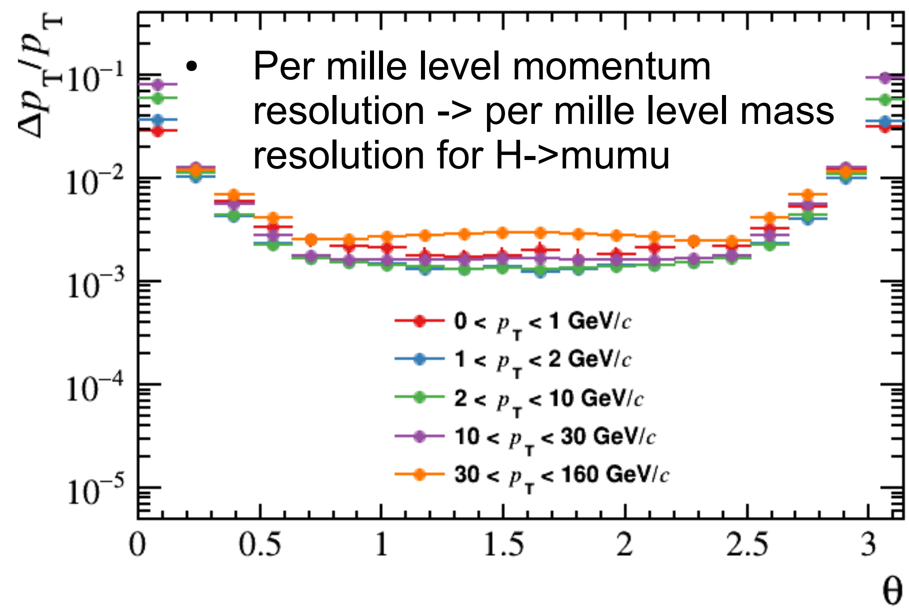
Sep. power: On 3 prong tau decay @ Z pole.

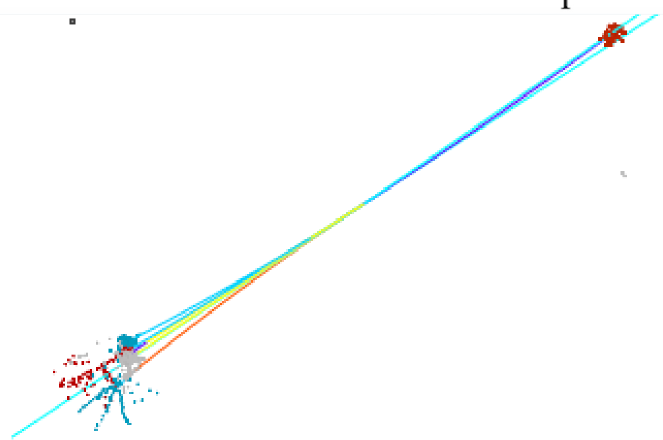
Requirement: efficiency > 99% at 3-prong tau

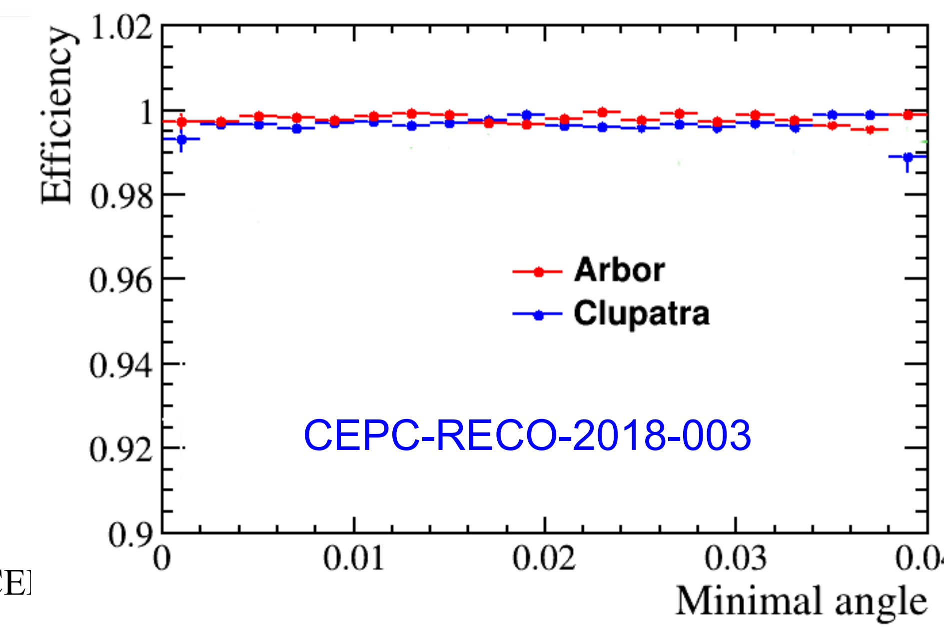
Ref: CDR baseline performance

Tracking



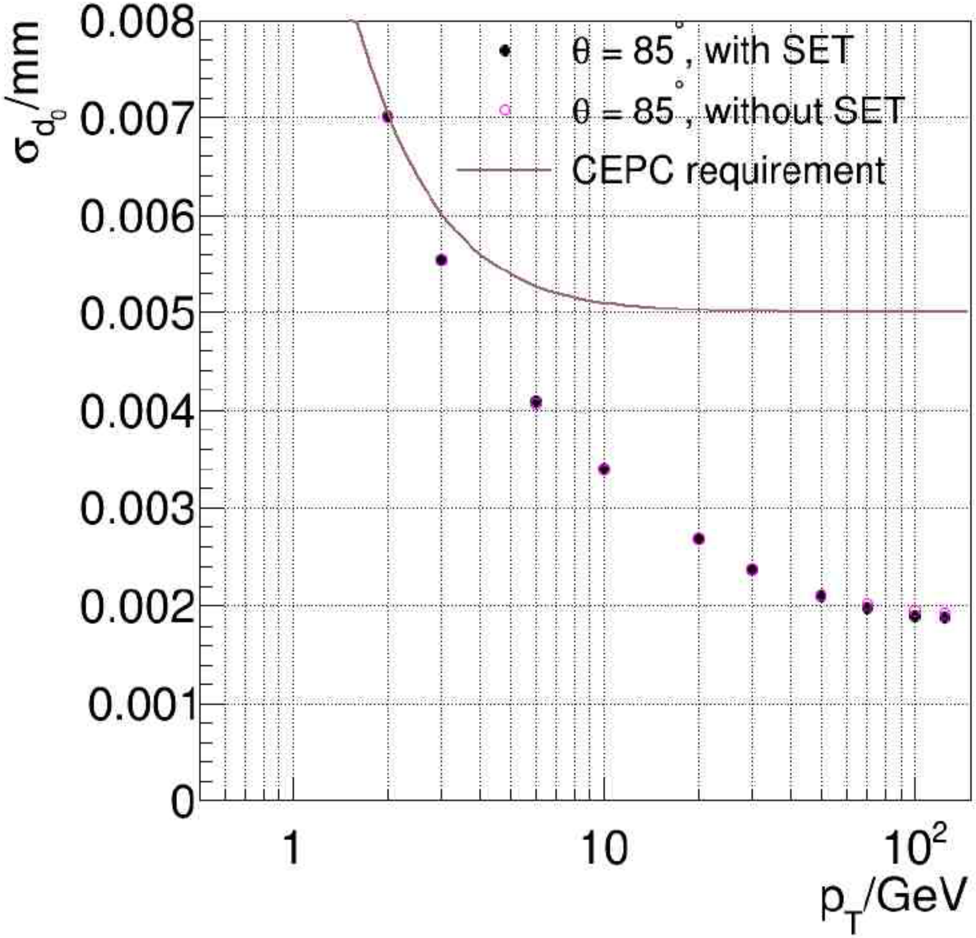




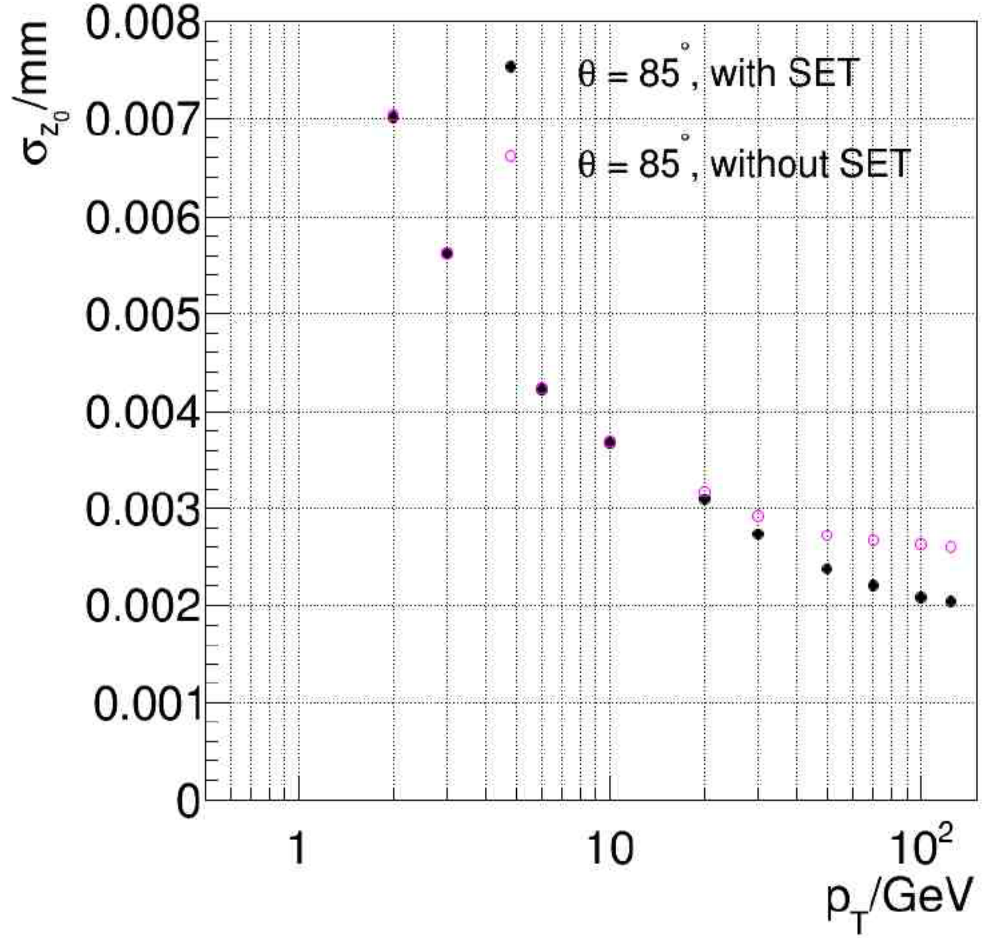


See Mingrui Zhao's talk

D0/Z0 at CDR baseline

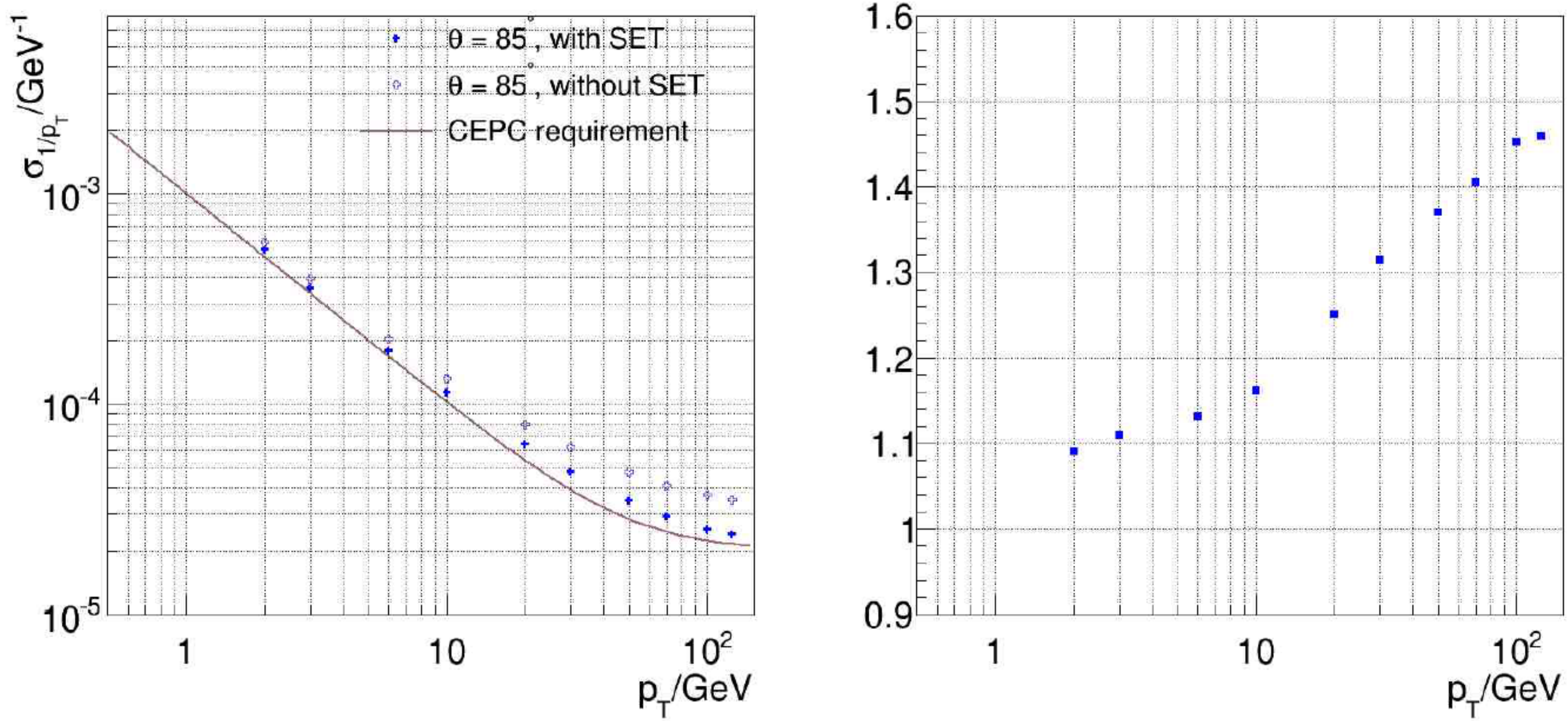


(a) σ_{d_0}



(a) σ_{z0}

SET impact on Pt: 85 deg



(a) Momentum resolution

(b) $\sigma_{\mathrm{withoutSET}}/\sigma_{\mathrm{withSET}}$

Figure 19: Comparison of transverse momentum resolution at $\theta = 85°$

SET impact

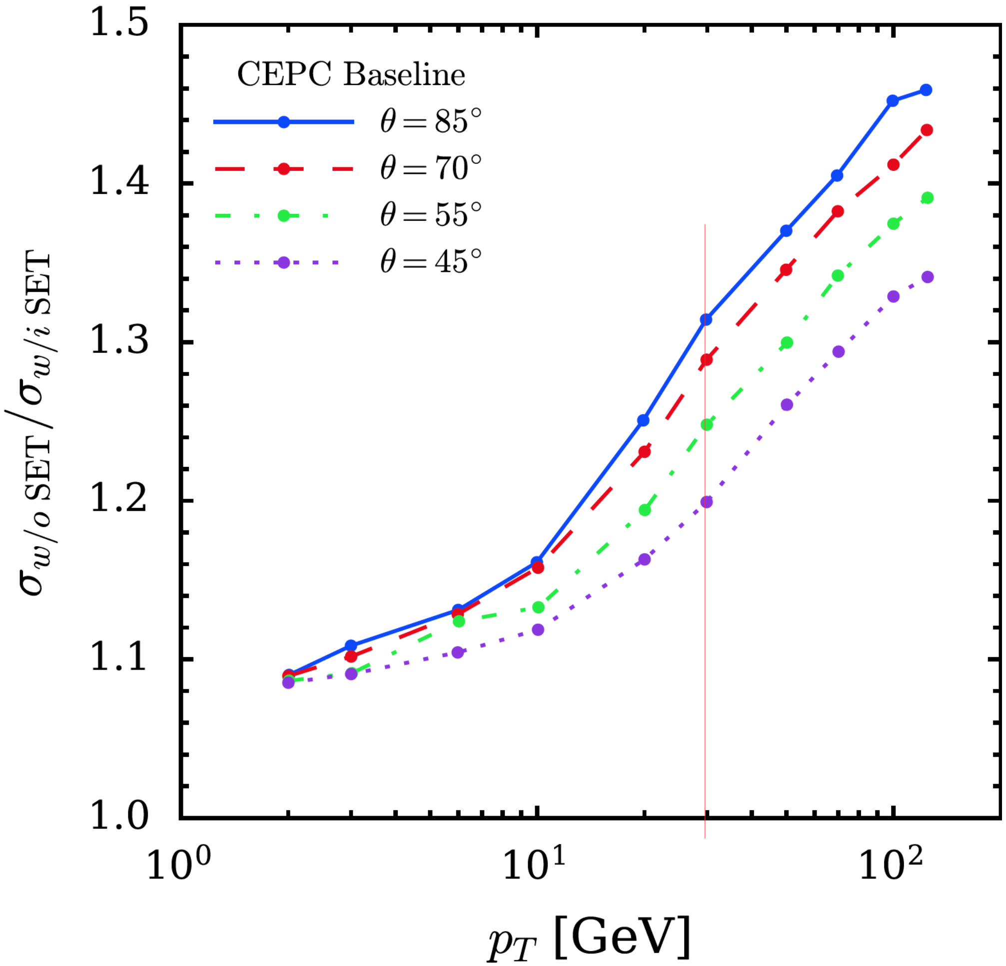


Table 1: Planned resolution of TPC and SET

Detector	Type	Resolution/μm
TPC	Gas tracker	σ_r=50, σ_z=400
SET	Double sided silicon microstrip	σ=7

Exercises @ 2018

A bit awkward at TDR set up...

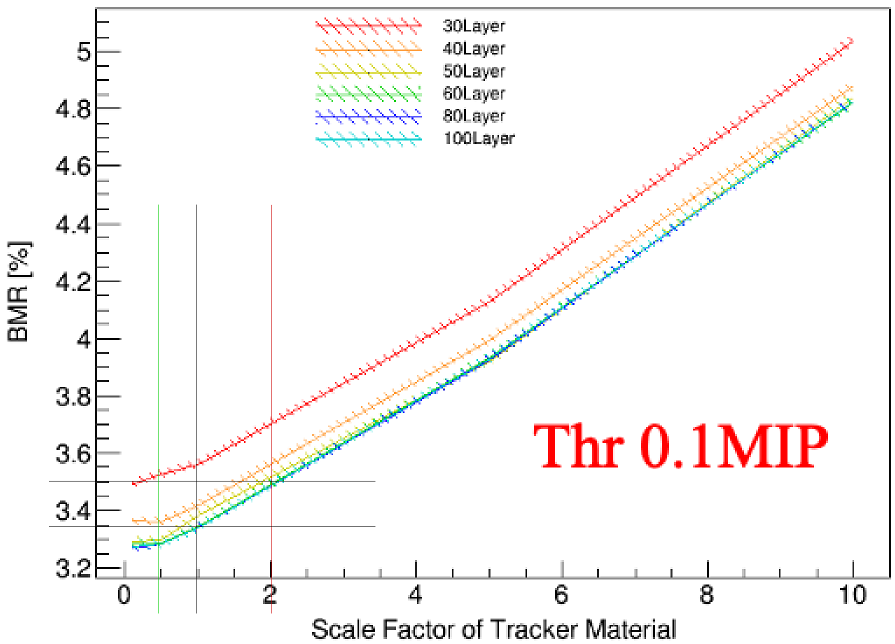
NOT a conclusion, but a indication for needed Exercise!

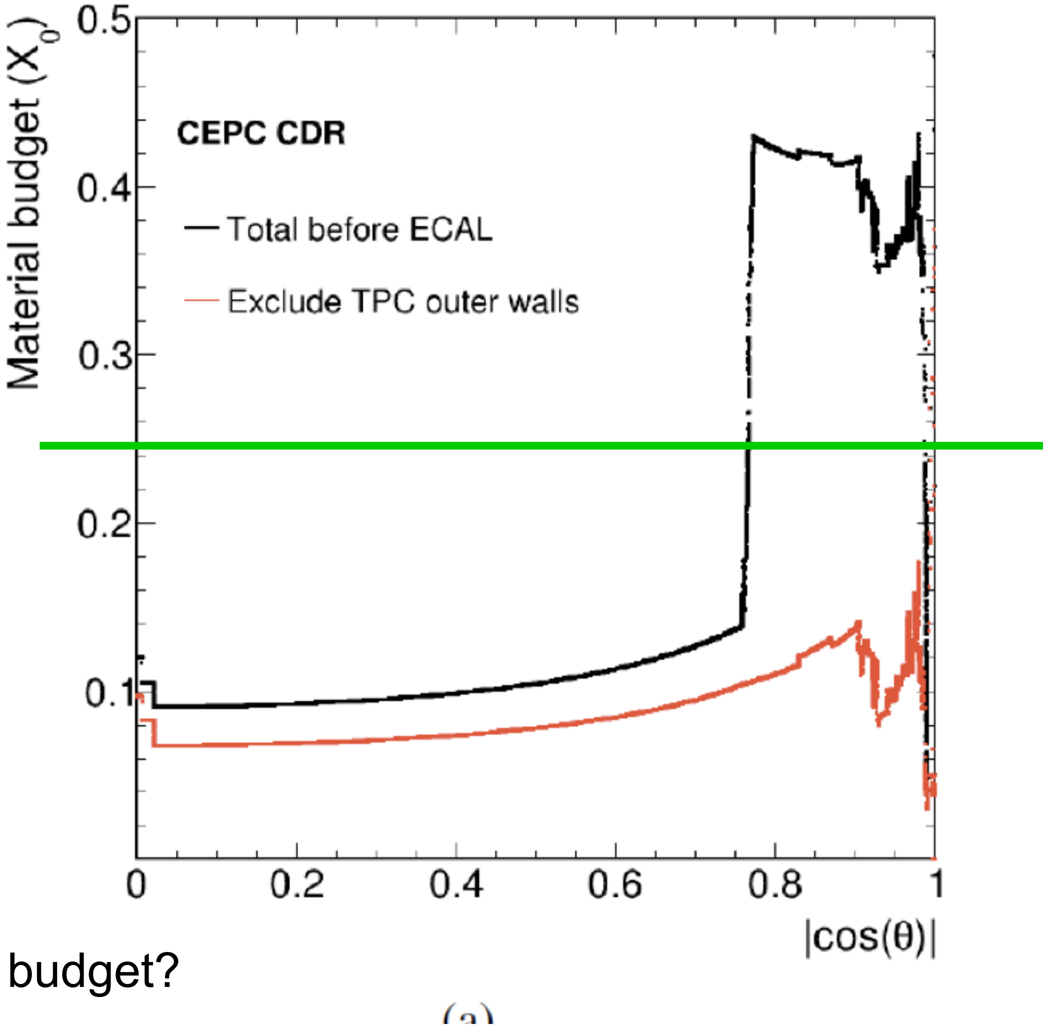
Is the simulation reliable?
- → First Principle calculation
- → To repeat & Xcheck @ different tools

Is the det. Modeling realistic?
- → To Xcheck with Tracker design

Impact strongly depends on tracker design & Performance of inner trackers
- → To cover a set of ref. Design, and Derive carefully the conclusion...

BMR V.S. Tracker Material





BMR appreciates small upstream material

Would it be possible... to even half the Material budget?

Each HCAL layer: 0.06 lambda Glass + 0.06 lambda Iron

Eur. Phys. J. C (2018) 78:464
https://doi.org/10.1140/epjc/s10052-018-5803-3

THE EUROPEAN PHYSICAL JOURNAL C

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Regular Article - Experimental Physics

Monte Carlo study of particle identification at the CEPC using TPC dE/dx information

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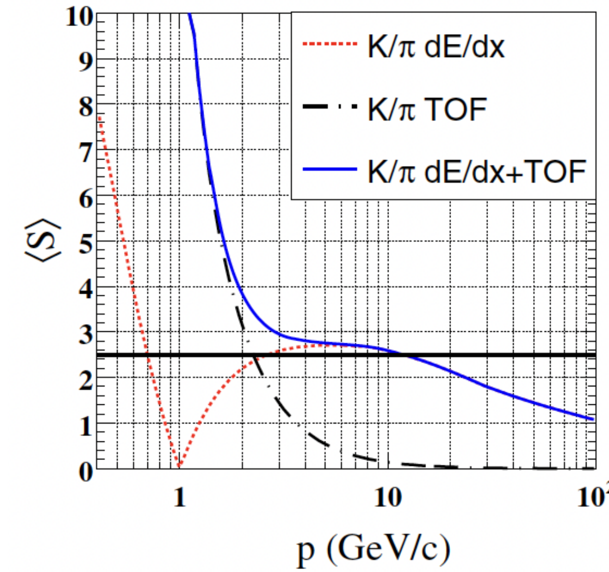
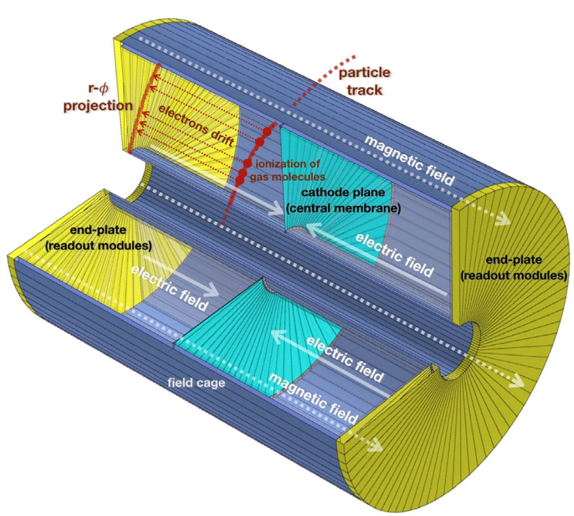
[3] Physics Department, University of Texas at Dallas, Richardson, TX, USA
[4] University of Chinese Academy of Science (UCAS), Beijing, China

Received: 14 March 2018 / Accepted: 12 April 2018





Nuclear Inst. and Methods in Physics Research, A 1047 (2023) 167835

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

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ELSEVIER

Requirement analysis for dE/dx measurement and PID performance at the CEPC baseline detector

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ARTICLE INFO

Keywords:
CEPC
TPC
PID

ABSTRACT

The Circular Electron–Positron Collider (CEPC) can be operated not only as a Higgs factory but also as a Z-boson factory, offering great opportunities for flavor physics studies where Particle Identification (PID) is critical. The baseline detector of the CEPC could record TOF and dE/dx information that can be used to distinguish particles of different species. We quantify the physics requirements and detector performance using physics benchmark analyses with full simulation. We conclude that at the benchmark TOF performance of 50 ps, the dE/dx resolution should be better than 3% for incident particles in the barrel region with a relevant momentum larger than 2 GeV/c. This performance leads to an efficiency/purity for $K^{\pm}$ identification of 97%/96%, for $D^0 \to \pi^+ K^-$ reconstruction of 68.19%/89.05%, and for $\phi \to K^+ K^-$ reconstruction of 82.26%/77.70%, providing solid support for relevant CEPC flavor physics measurements.

ToF: necessarily

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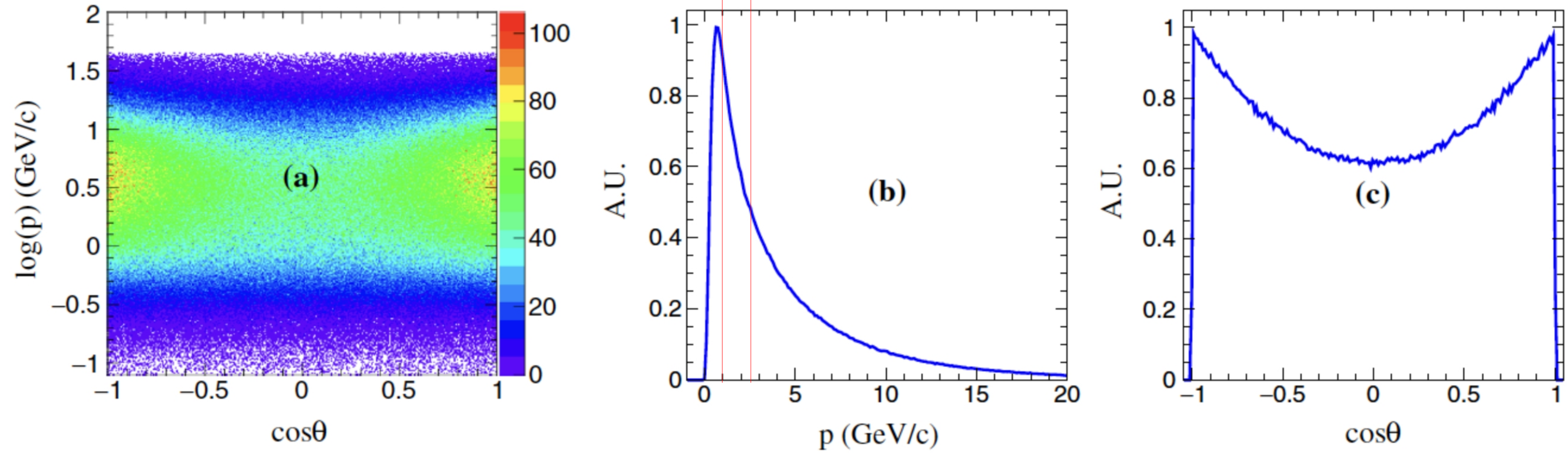
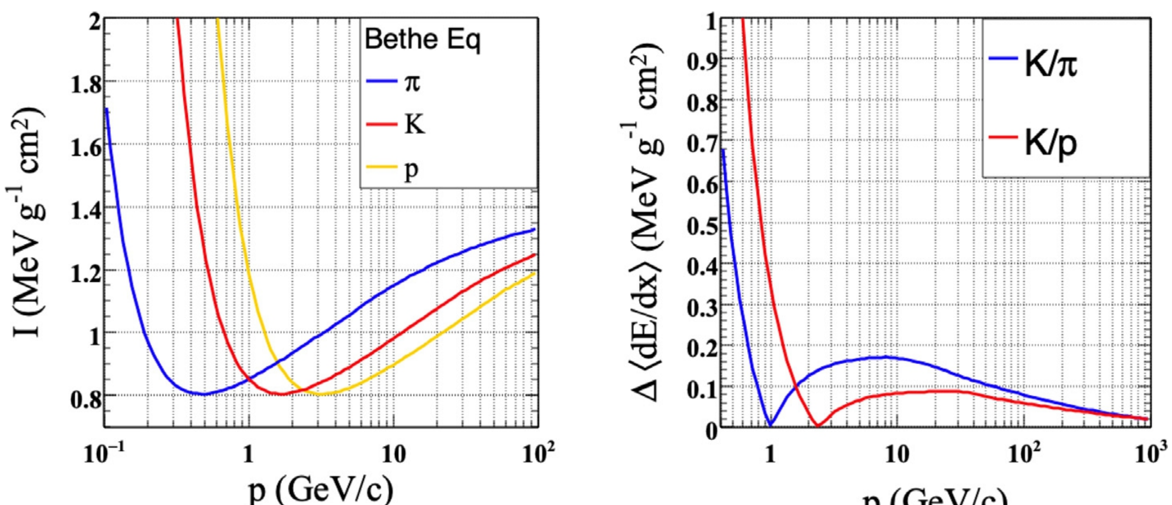
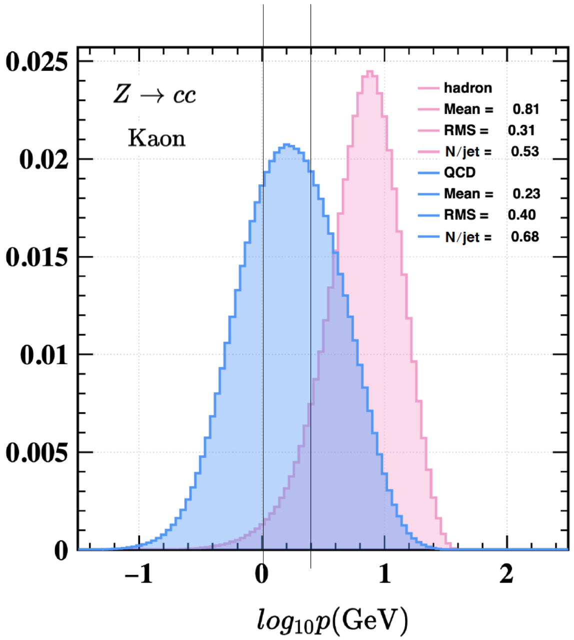


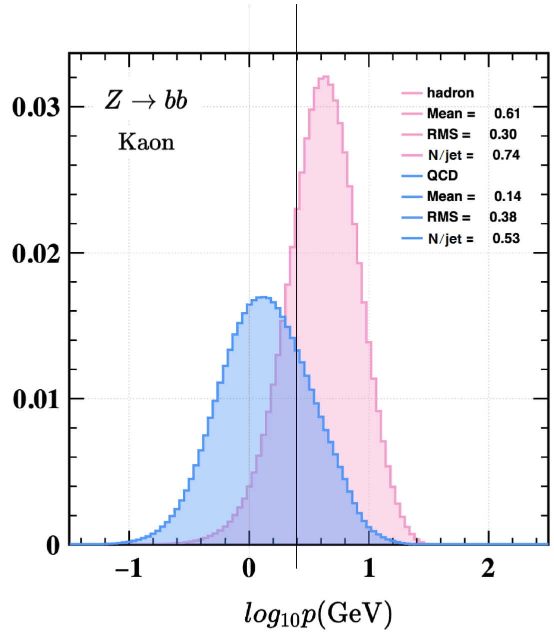
Fig. 3 Kinematic distribution of kaons in $e^+e^- \rightarrow Z \rightarrow q\bar{q}$ MC events as a function of $\log(p)$ and $\cos\theta$ (**a**), p (**b**), and $\cos\theta$ (**c**)

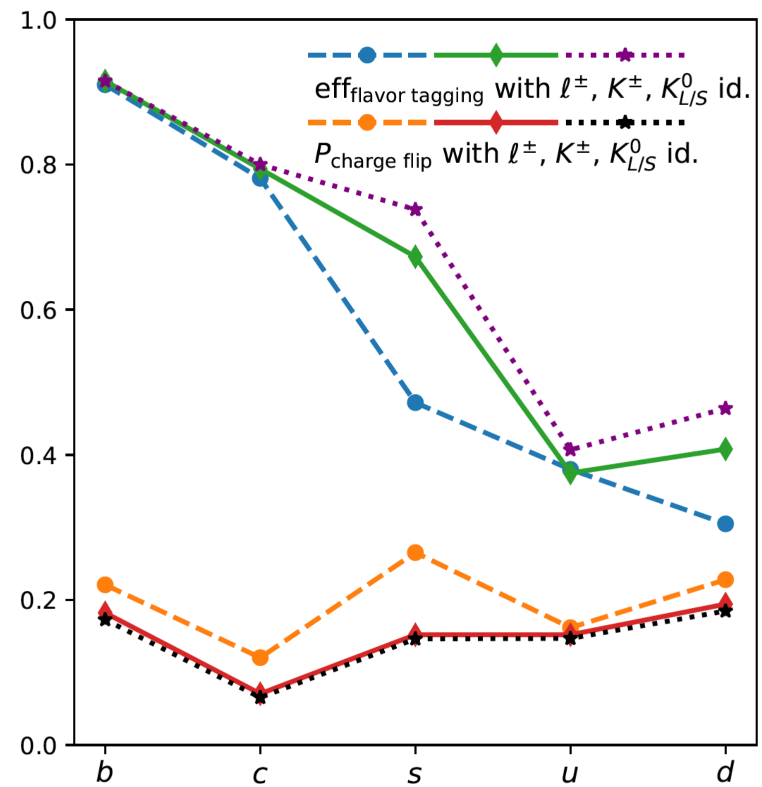


(a) (b)

Momentum spectrum of Kaon...





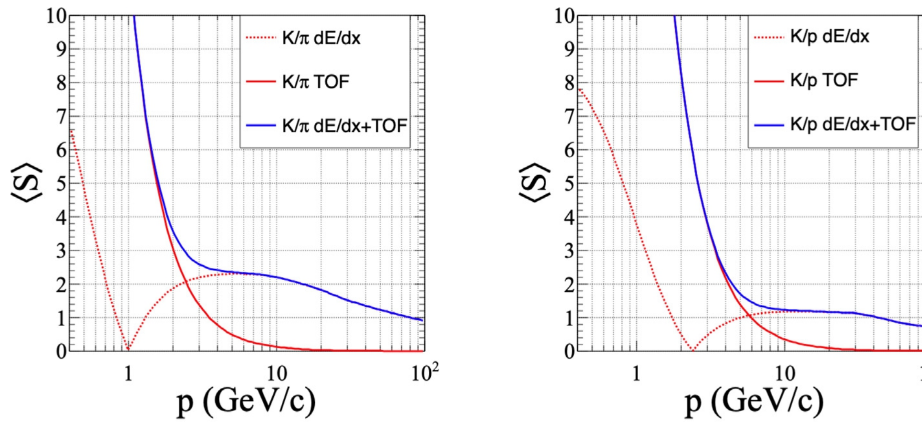


Charged Kaons from B/D hadrons → Flavor Physics

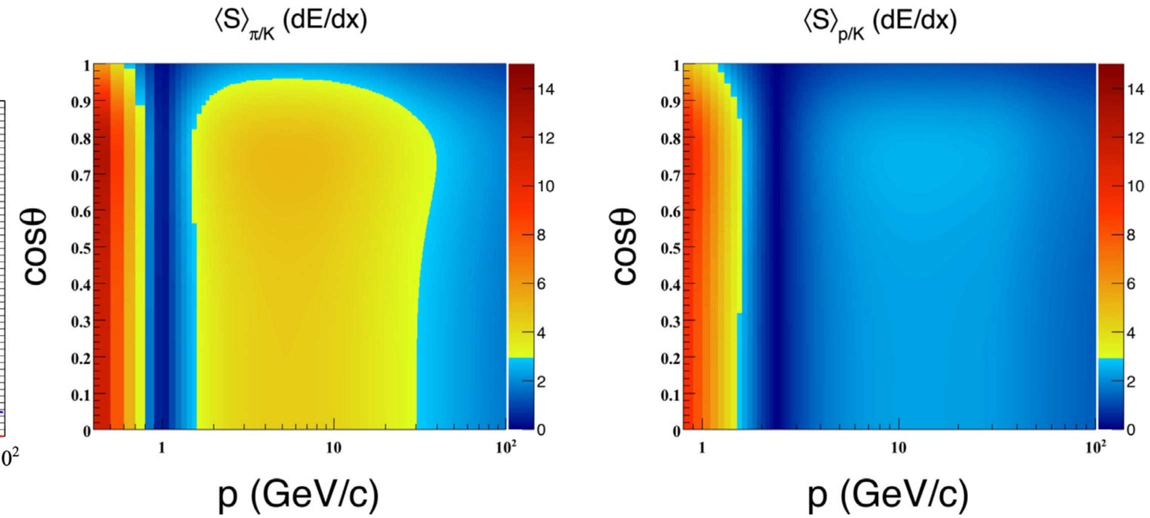
Charged Kaon from QCD → QCD

Both Contributed significantly to Jet Origin ID

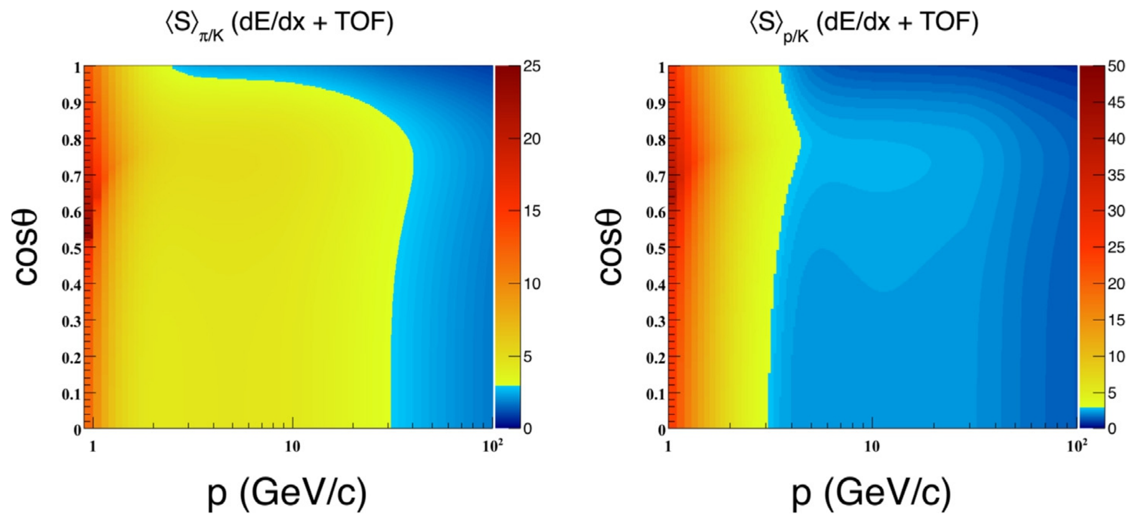
Sep. power



(a) (b)



(a) (b)

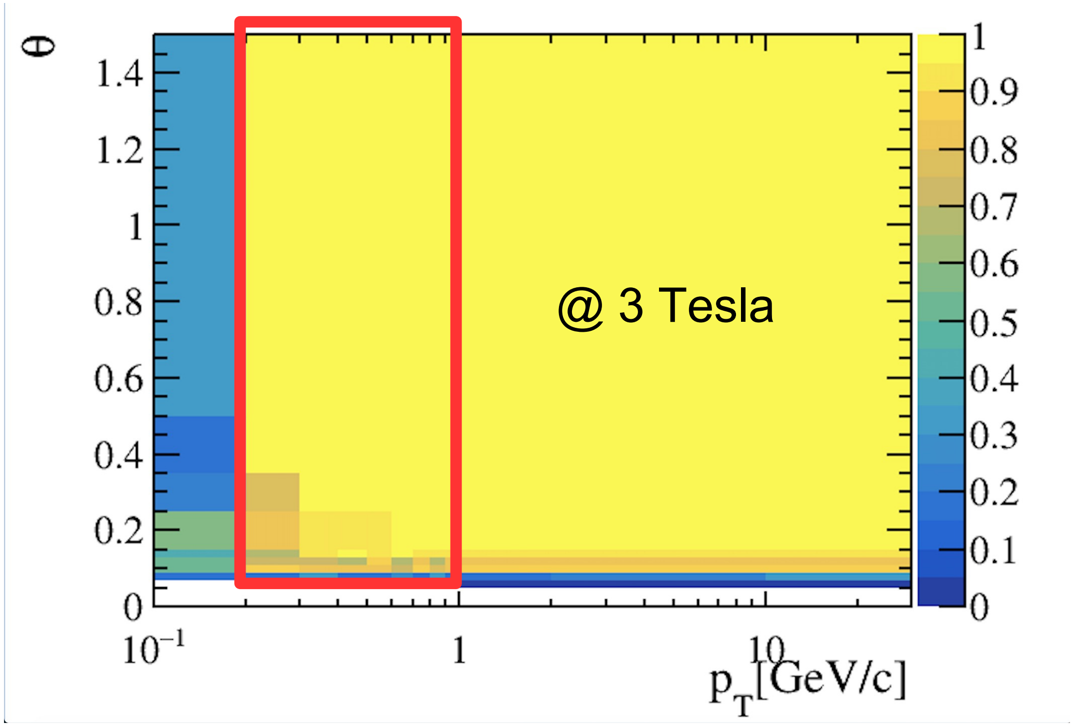


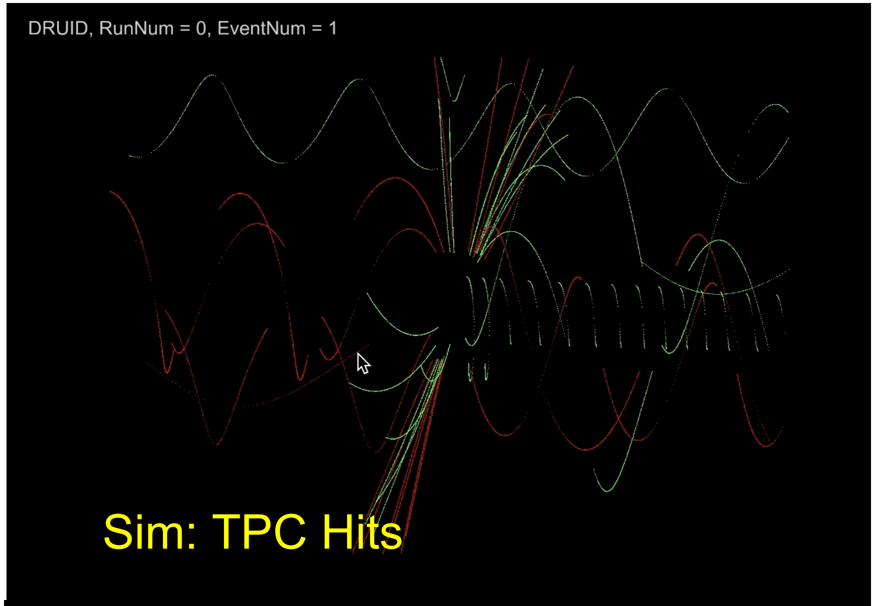
(a) (b)

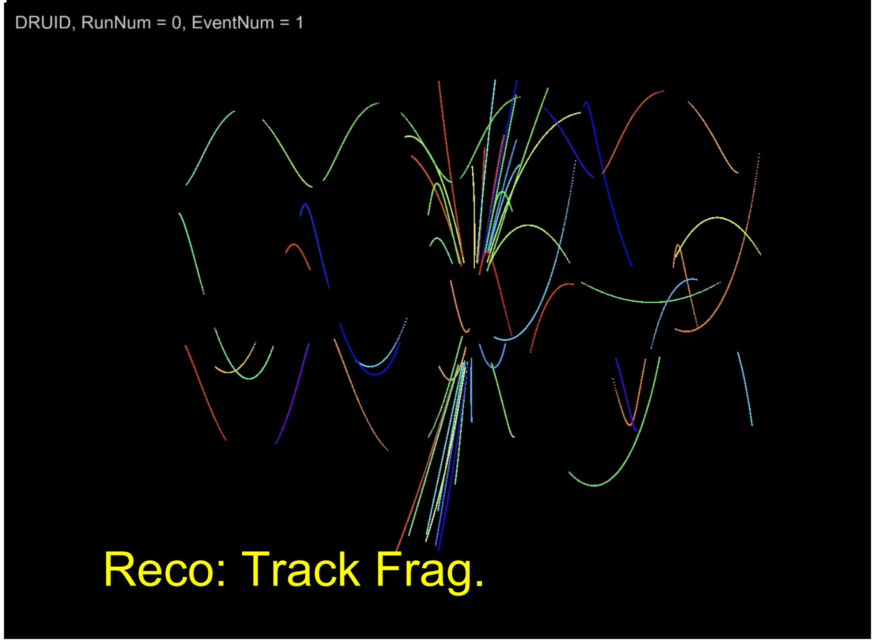
Table 3
The $K^{\pm}$ identification performance with different factors, $\sigma_{actual} = factor \cdot \sigma_{intrinsic}$, with/without combination of TOF information at the Z-pole.

	Factor	1.	1.2	1.5	2.
dE/dx	ε_K (%)	95.97	94.09	91.19	87.09
	$purity_K$ (%)	81.56	78.17	71.85	61.28
dE/dx & TOF	ε_K (%)	98.43	97.41	95.52	92.3
	$purity_K$ (%)	97.89	96.31	93.25	87.33

ToF: at R = 1.8, or 0.6 meter







ToF at 0.6 meter is discussed to have better efficiency for low Pt.

The efficiency of track at relevant Pt range (200 – 1GeV @ 3 Tesla + 1.8 m) is slightly degraded, I recommend ToF at 1.8 m:

Independent, or combined with ECAL

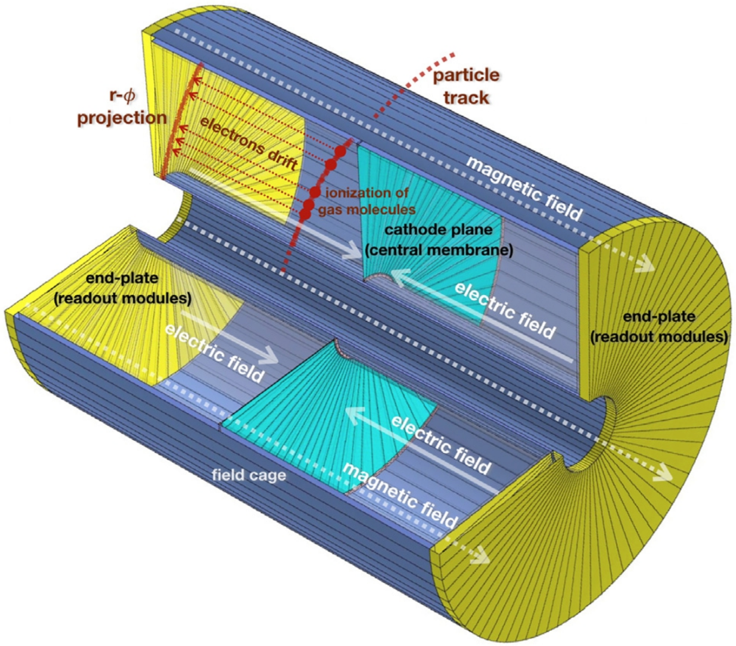
Summary

- Performance & Physics benchmarks: defined
  - Physics analysis benchmark (5-6): analysis results at CDR baseline is partly ready
  - Global Det. Performance: PFA, JOI, and Pid (optional)
  - Sub-D: requirement partly quantified

- Requirements:
  - PFA is essential:
    - BMR < 4% & pursue 3%
    - Highly relevant – and even as the pre-request for excellent JOI & Pid (in jets)
  - ToF is needed
  - ToF shall be located at the Tracker-Exit/Calo entrance, or combined with Calo

Back up

dE/dx at TPC



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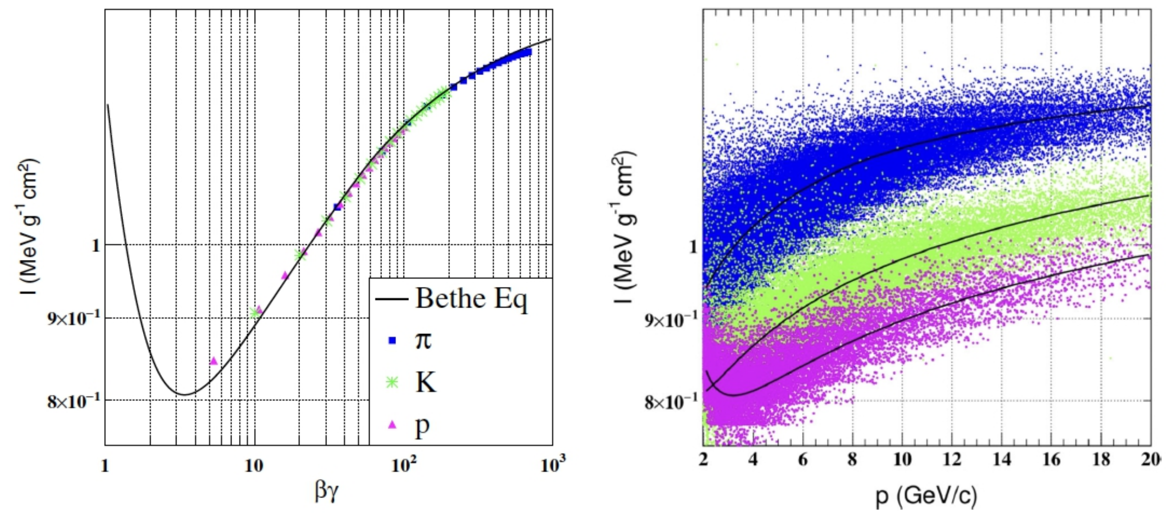

Fig. 1 The dependence of the truncated mean I of the track dE/dx, as a function of $\beta\gamma$ (left) and p (right) for charged particles traversing the TPC of the CEPC detector. In the left plot the dots represent the MC result of single-particle events with the theoretical prediction by the Bethe equation [16] overlaid. In the right plot the dots are from simulation of $e^+e^- \to Z \to q\bar{q}$ events

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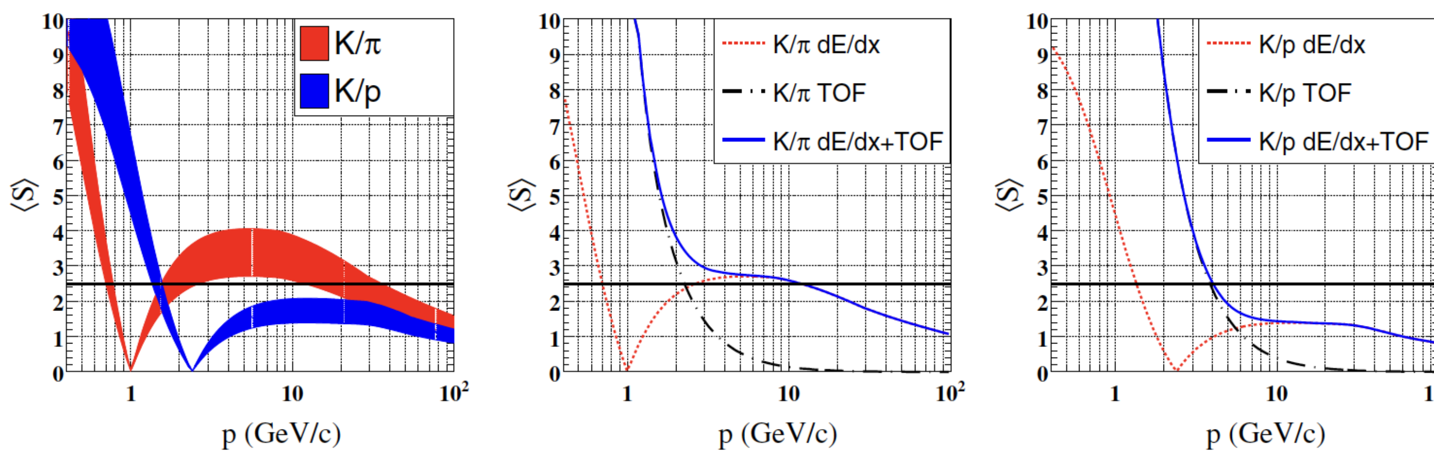
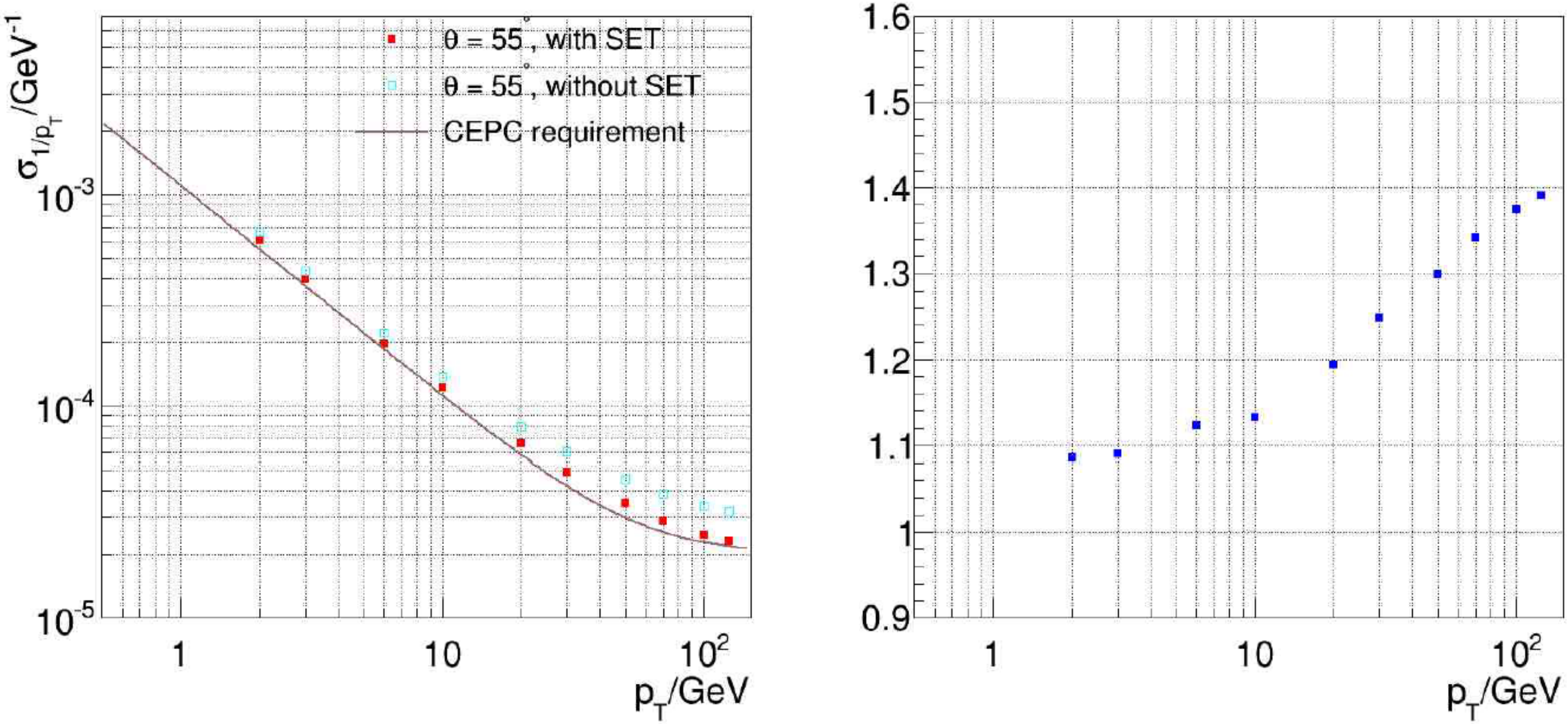


Fig. 5 Average separation power $\langle S \rangle$ versus momentum between different particle types in hadronic decays at the Z pole. Left: only dE/dx is used. The bands delimit the area between the ideal simulation and the conservative scenario for the CEPC TPC. The optimistic scenario is shown as dash-dotted lines. Middle and right: dE/dx (in the conservative scenario) and/or TOF are used for K/π and K/p separation. The black solid line corresponds to 2.5 σ separation

SET impact on Pt: 55 deg

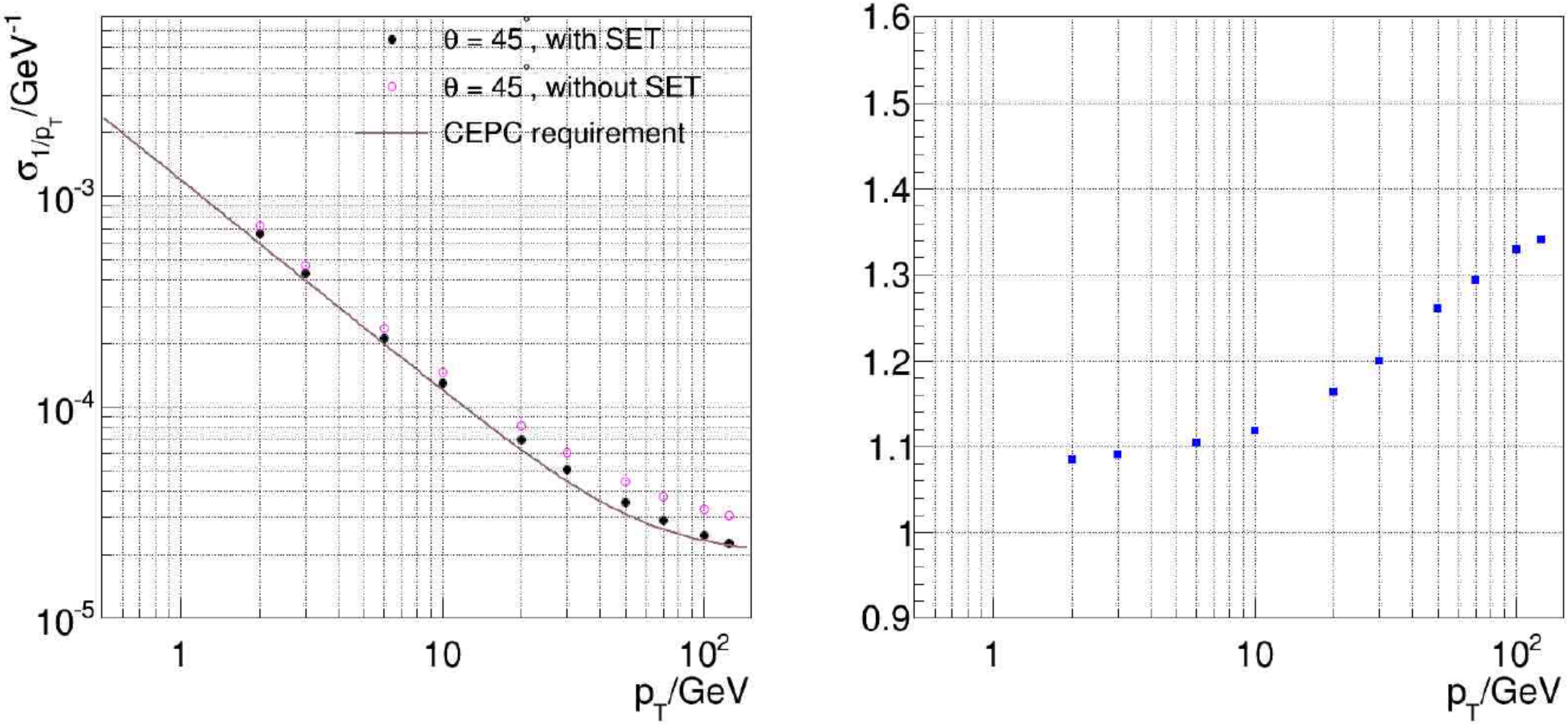


(a) Momentum resolution

(b) $\sigma_{\text{withoutSET}}/\sigma_{\text{withSET}}$

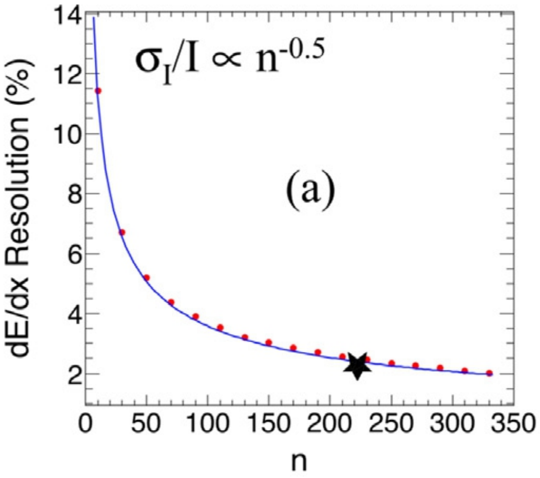
Figure 17: Comparison of transverse momentum resolution at $\theta = 55°$

SET impact on Pt: 45 deg



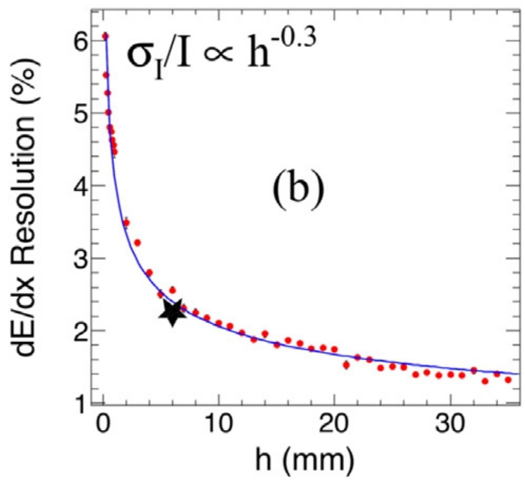
(a) Momentum resolution (b) $\sigma_{\text{withoutSET}}/\sigma_{\text{withSET}}$

Figure 16: Comparison of transverse momentum resolution at θ = 45°



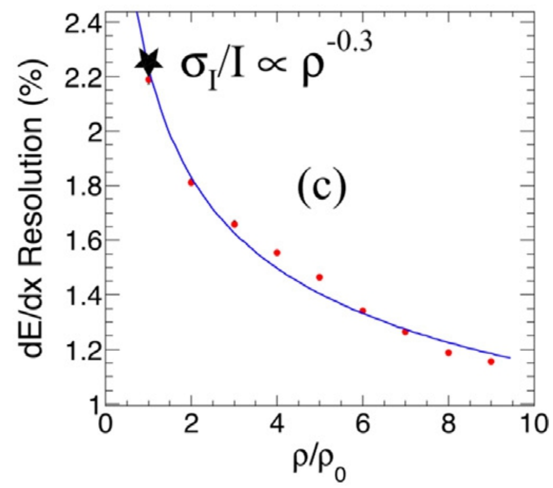
σI/I ∝ n^-0.5
(a)
dE/dx Resolution (%)
n

(a)



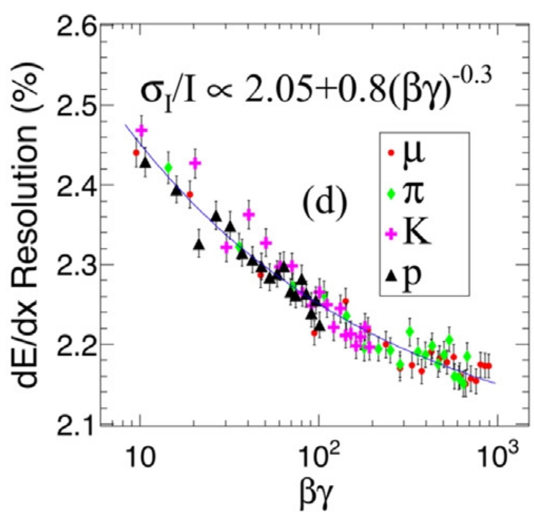
σI/I ∝ h^-0.3
(b)
dE/dx Resolution (%)
h (mm)

(b)



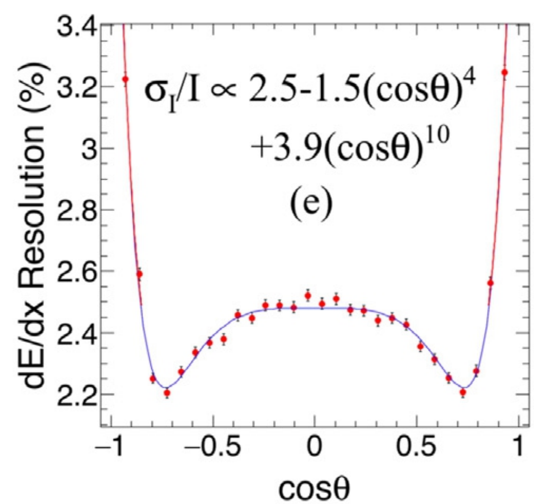
σI/I ∝ ρ^-0.3
(c)
dE/dx Resolution (%)
ρ/ρ0

(c)



σI/I ∝ 2.05+0.8(βγ)^-0.3
(d)
μ
π
K
p
dE/dx Resolution (%)
βγ

(d)



σI/I ∝ 2.5-1.5(cosθ)^4
+3.9(cosθ)^10
(e)
dE/dx Resolution (%)
cosθ

(e)

Hit collection efficiency V.S. Energy resolution

- Hit leakage in energy, ..., and time...
- Energy threshold...

Requirement on dE/dx & dN/dx

Y. Zhu, S. Chen, H. Cui et al. *Nuclear Inst. and Methods in Physics Research, A 1047 (2023) 167835*

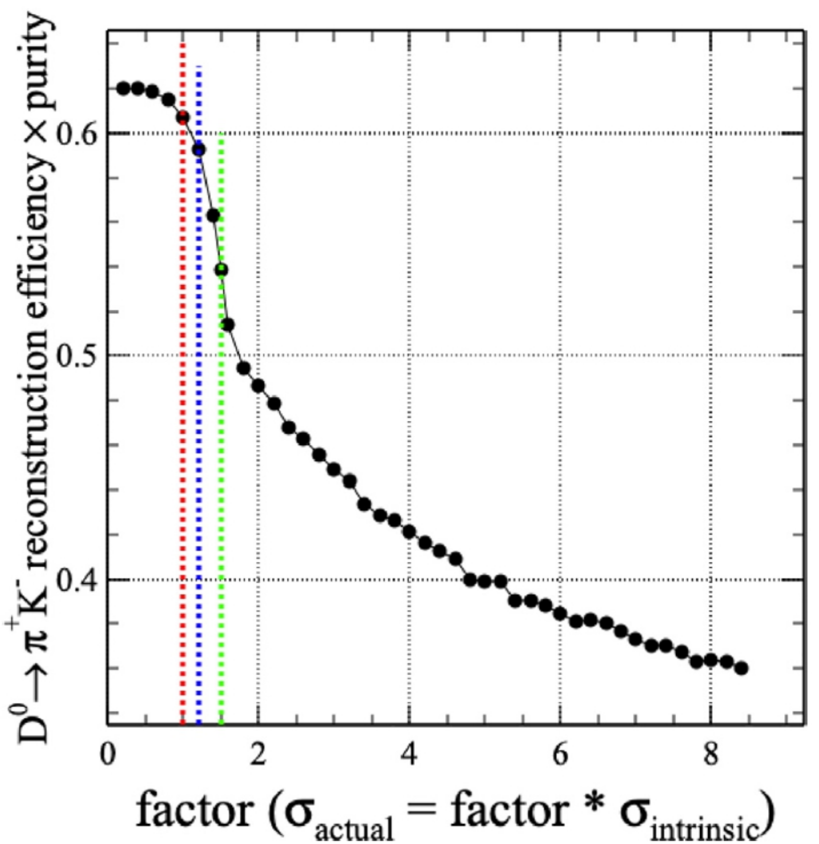


Fig. 12. The distribution of $D^0 \to \pi^+K^-$ reconstruction performance as a function of the factor defined in $\sigma_{actual} = factor \cdot \sigma_{intrinsic}$. The red/blue/green line corresponds to the 0%/20%/50% degradation of dE/dx resolution.

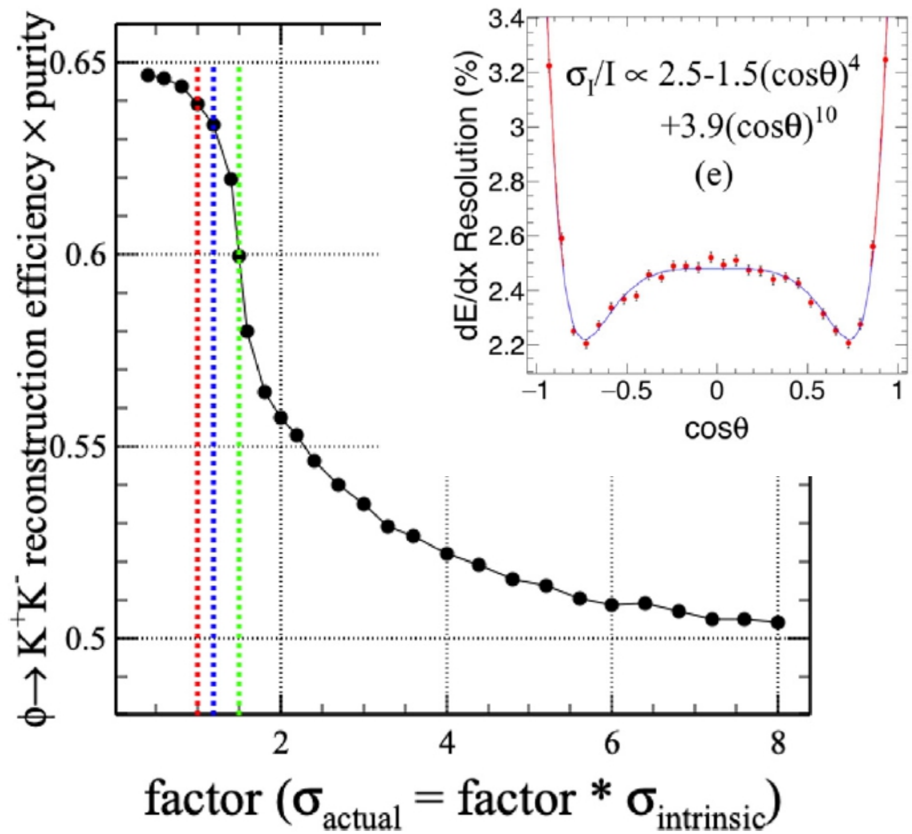


Fig. 13. The distribution of $\phi \to K^+K^-$ reconstruction as a function of the factor defined in $\sigma_{actual} = factor \cdot \sigma_{intrinsic}$. The red/blue/green line corresponds to the 0%/20%/50% degradation of the dE/dx resolution.

→ 3% dE/dx resolution in the barrel for E > 2 GeV tracks

Calorimeter

Intrinsic energy resolution: wi/wo Clustering – Hit/Energy collection efficiency.

Requirement:

EM resolution: ~ 3%/sqrt(E) \conv 0.5%

Ref: JHEP12(2022)135

Had resolution: ~ 50%/sqrt(E) \conv 2%

Ref: CDR baseline performance

Di-particle separation power.

Di photon; requirement: ~ 1.5 cm. eff. ~ 50%

Pion + Photon; requirement: ~ 1.5 cm. eff. ~ 50%

Pion + Neutral Hadron; ~ ? cm (TBD studied)

Ref: 2018 JINST 13 P03010

Ref: CDR baseline performance

Shower Profile -> Pid potential (e, mu, hadron). Shower Profile Patterns

Requirement:

eff ~ 99% & mis-id ~ 1% for isolated charged particle with E > 2 GeV

Ref: Eur. Phys. J. C (2017) 77:591

Ref: 2021 JINST 16 P06013

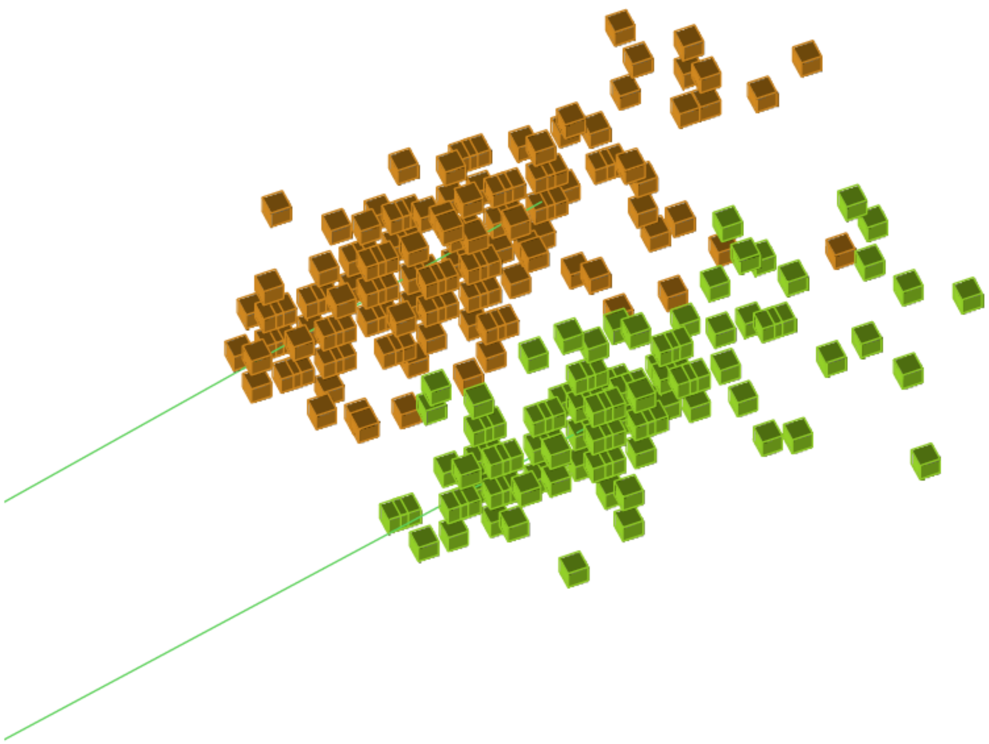
Ref: CALICE TB data analyses

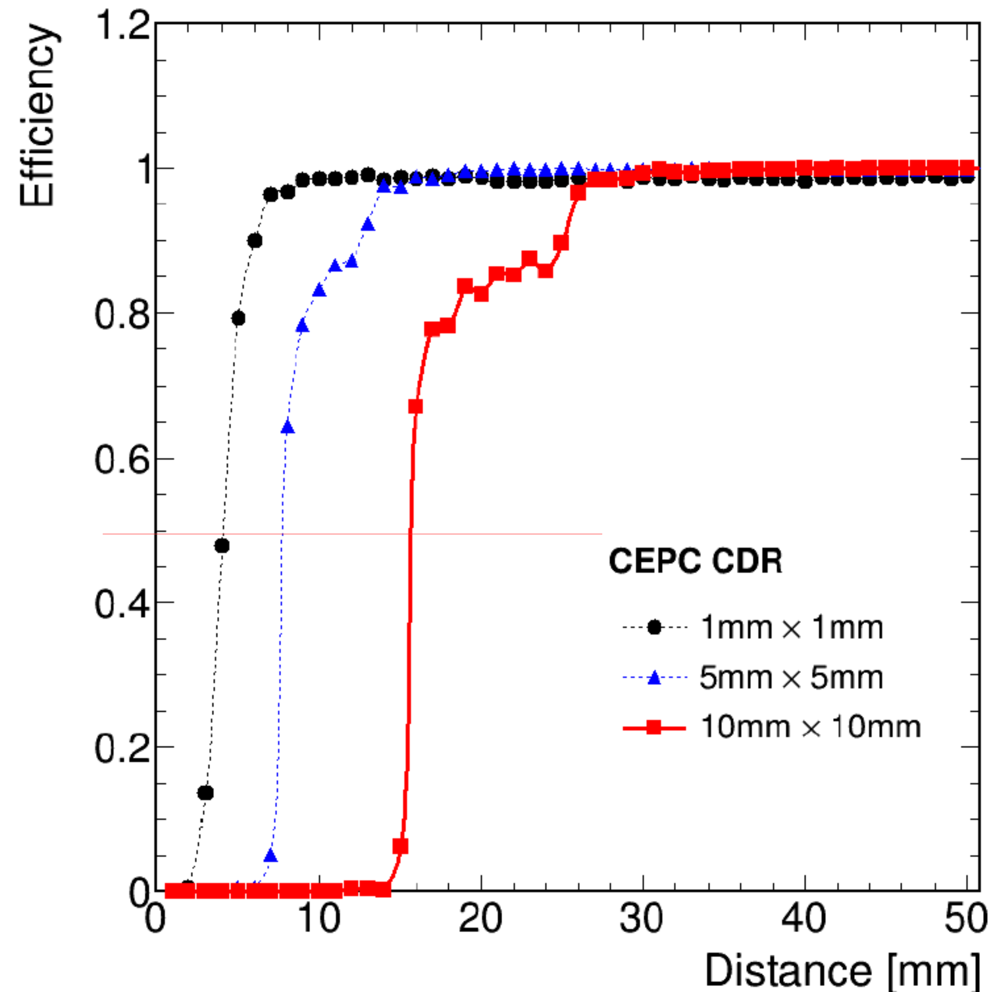
Differential Eff (long-term).

Requirement: Energy threshold ~ o(50) MeV, |cos(theta)| < 0.995

Ref: CDR baseline performance

Separation



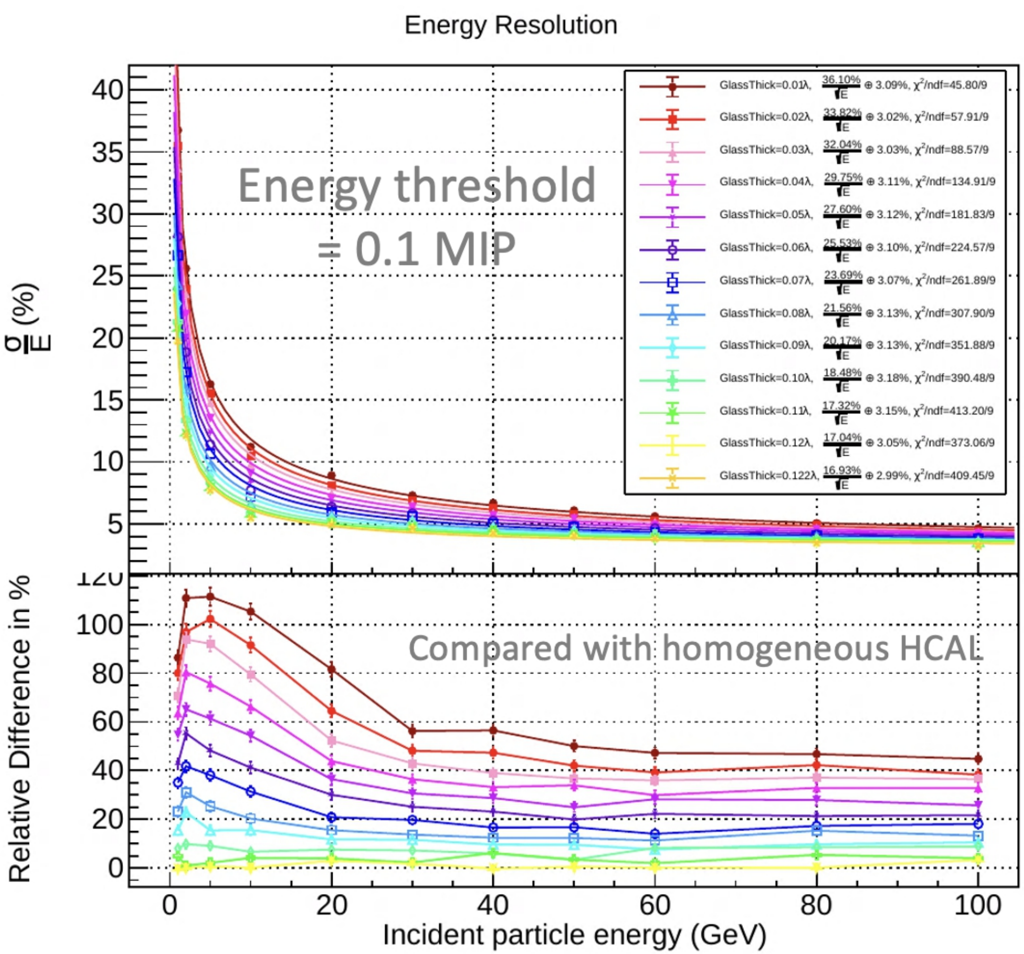


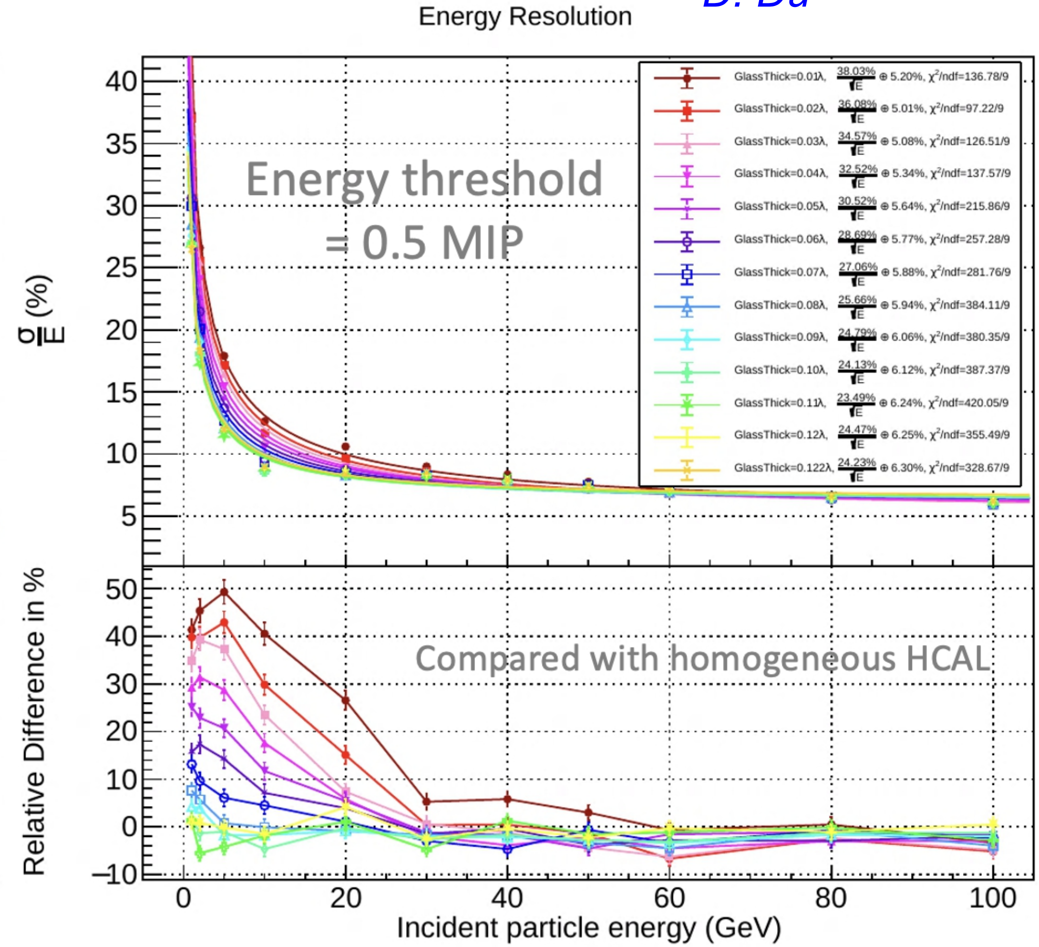
Critical energy to separate an evenly decay π_0: 30 GeV

See Hang Zhao's talk

HCAL

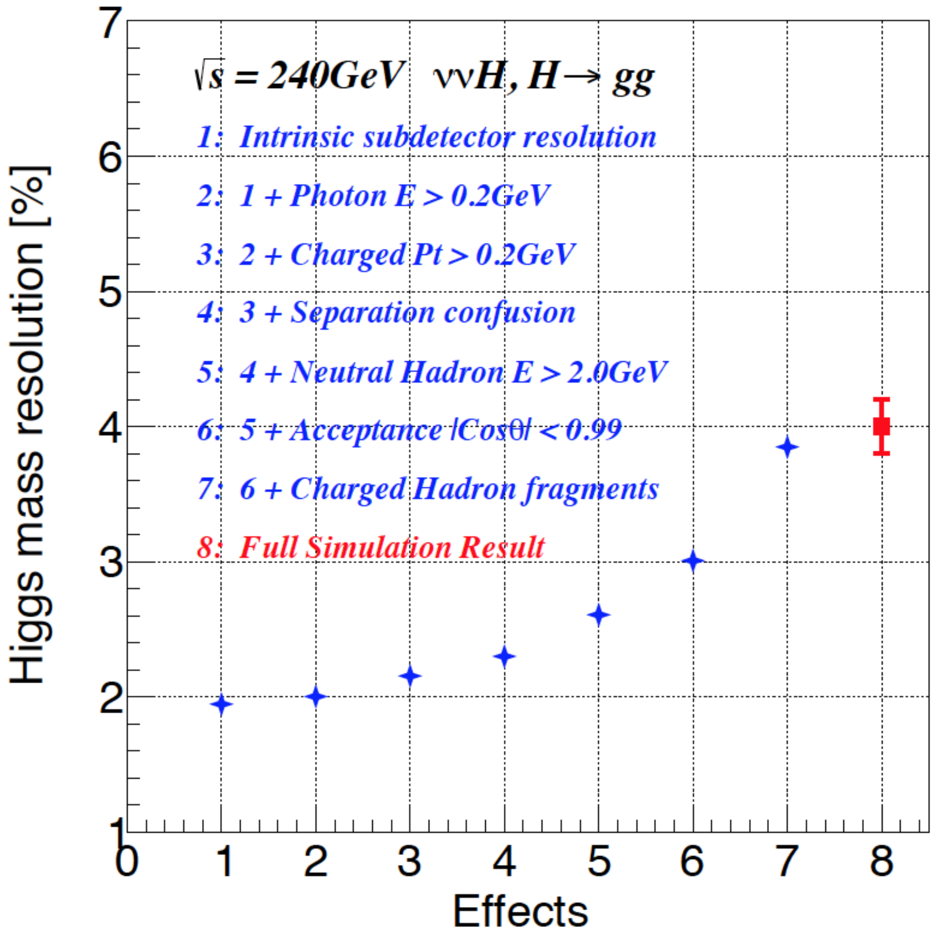
D. Du

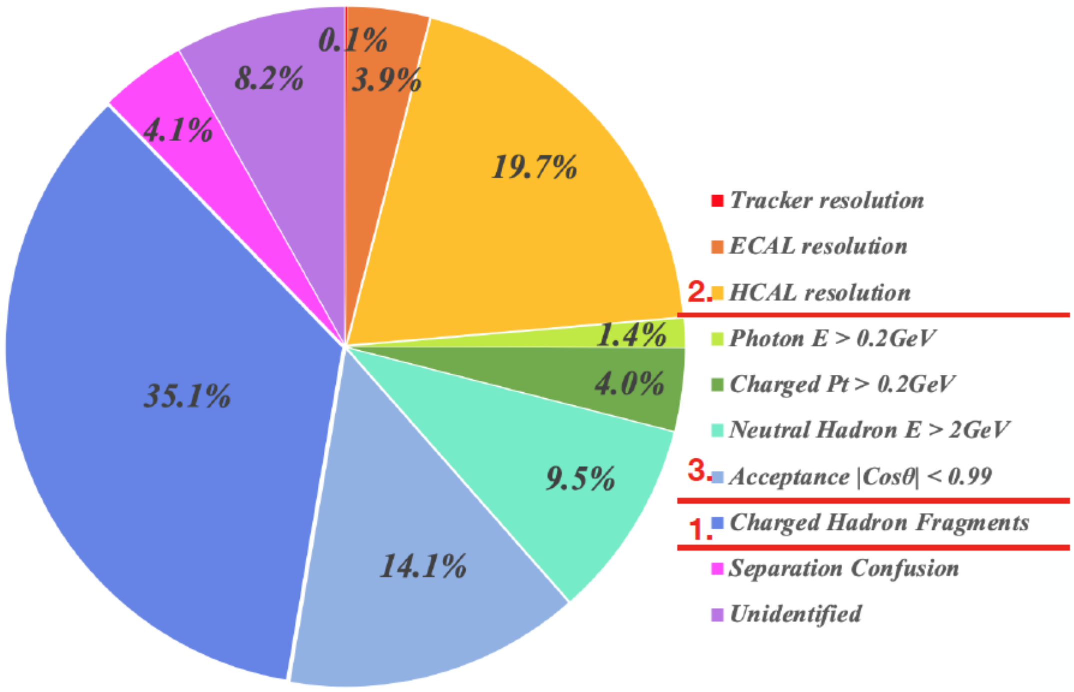




- In an ideal case - ideal Geometry ~ semi infinite...
- HCAL resolution significantly w.r.t. Baseline, at single particle level

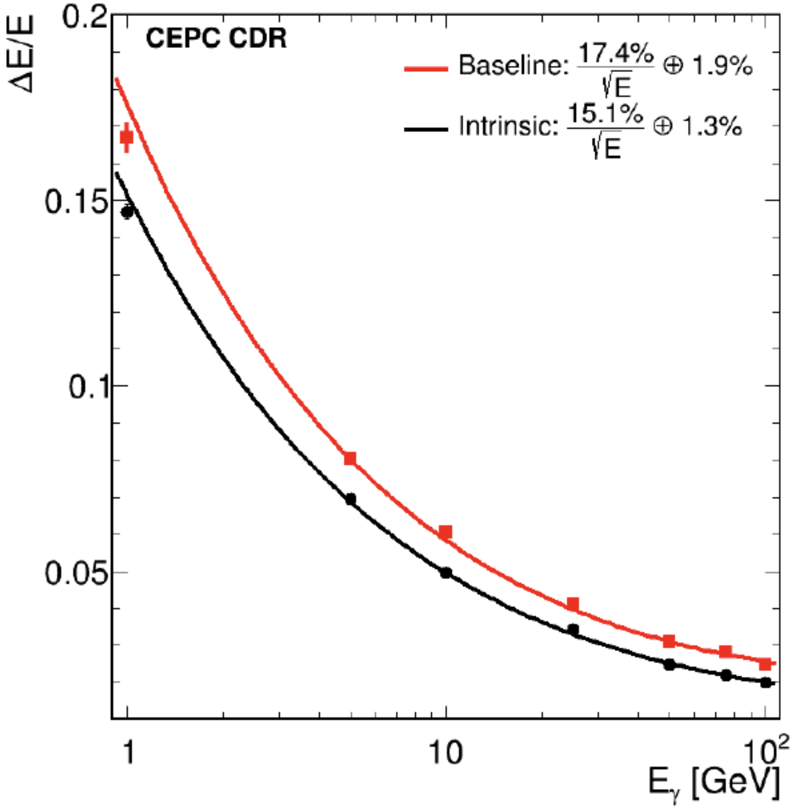
PFA Fast simulation (Preliminary)





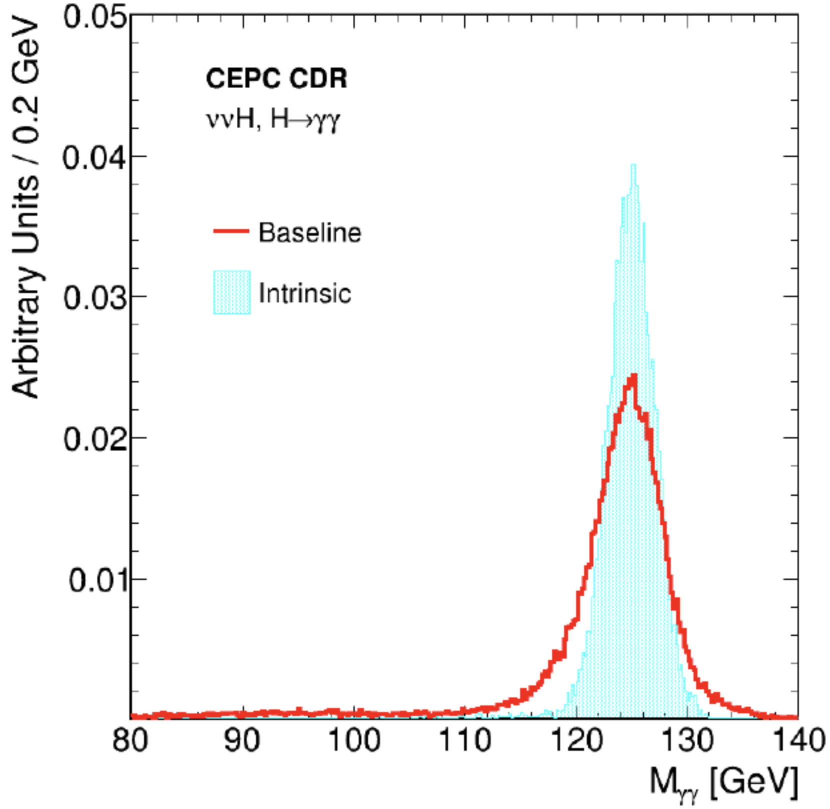
YX. Wang

Fast simulation reproduces the full simulation results, factorize/quantifies different impacts
Same cleaning condition as in the Full simulation applied
Early phase of modeling/tuning



CEPC CDR
Baseline: $\frac{17.4\%}{\sqrt{E}} \oplus 1.9\%$
Intrinsic: $\frac{15.1\%}{\sqrt{E}} \oplus 1.3\%$
ΔE/E
0.2
0.15
0.1
0.05
1
10
10^2
E_γ [GeV]

(a)



CEPC CDR
ννH, H→γγ
Baseline
Intrinsic
Arbitrary Units / 0.2 GeV
0.05
0.04
0.03
0.02
0.01
80
90
100
110
120
130
140
$M_{\gamma\gamma}$ [GeV]

(b)

Sub-D key info.

- Intrinsic performance
  - Tracker + VTX
    - Differential efficiencies
    - 5 resolution
    - Separation
  - Calorimeter
    - Intrinsic resolution
    - Separation Power
    - Hit Coll. Efficiency. (Cluster Splitting Chance...)
  - Digitization development, Validation from TB/Prototype experience
- Integration oriented -> input to Electronic + TDAQ, and to Mechanics
  - Mass, dimension,
  - Material budget & Distribution for Tracker & VTX
  - Power-cooling,
  - Noise rate: Intrinsic Noise, MIP Noise, Gamma-Bath relevant Noise
  - Noise dependency (temp. Radiation) -> MDI & Machine Protection
- Cost: Current, extrapolate ~ 1 decades, corr. with R&D.

Resources needed

- Well validated Samples (1 Billion ~ 1 M CPU*day)
  - 240 GeV ~ 1 Billion (Phy events ~ o(5) Billion)
  - Z pole ~ 1 Billion (Phy events ~ 4 Tera)
  - WW ~ o(10) M?
  - Top ~ o(10) M
  - 1 Billion ~ 1 M CPU*day ~ 10k CPU * 3 months.
  - // 1 CPU*day ~ 1k events

- Experienced Analysts: 2 months

Benchmark analysis timeline

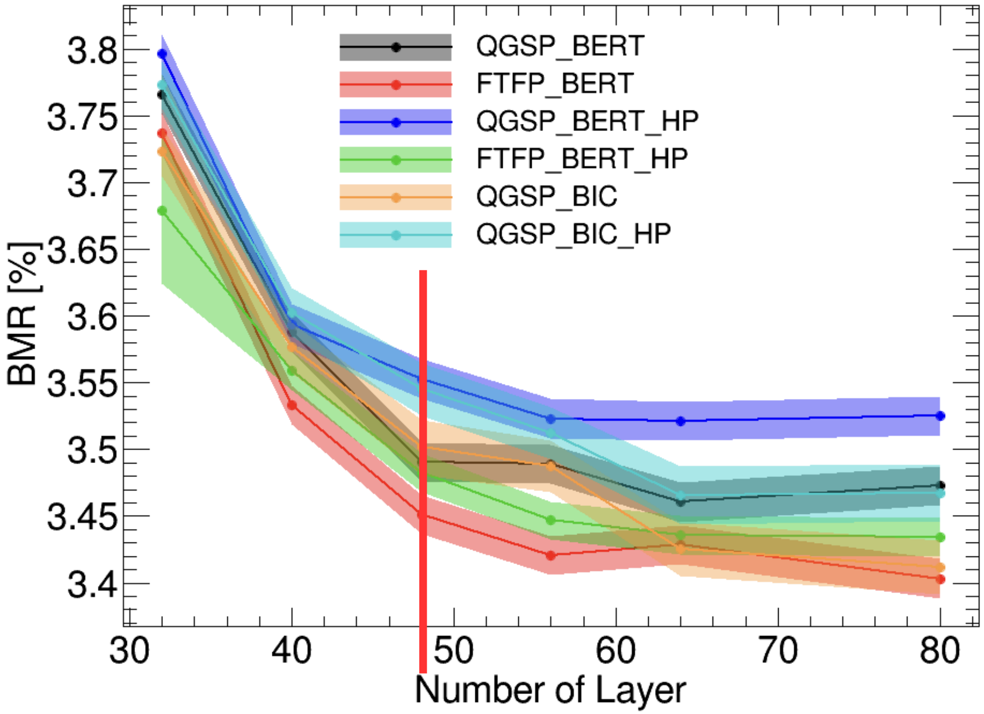
- 2024. now - May: Geo. Fix

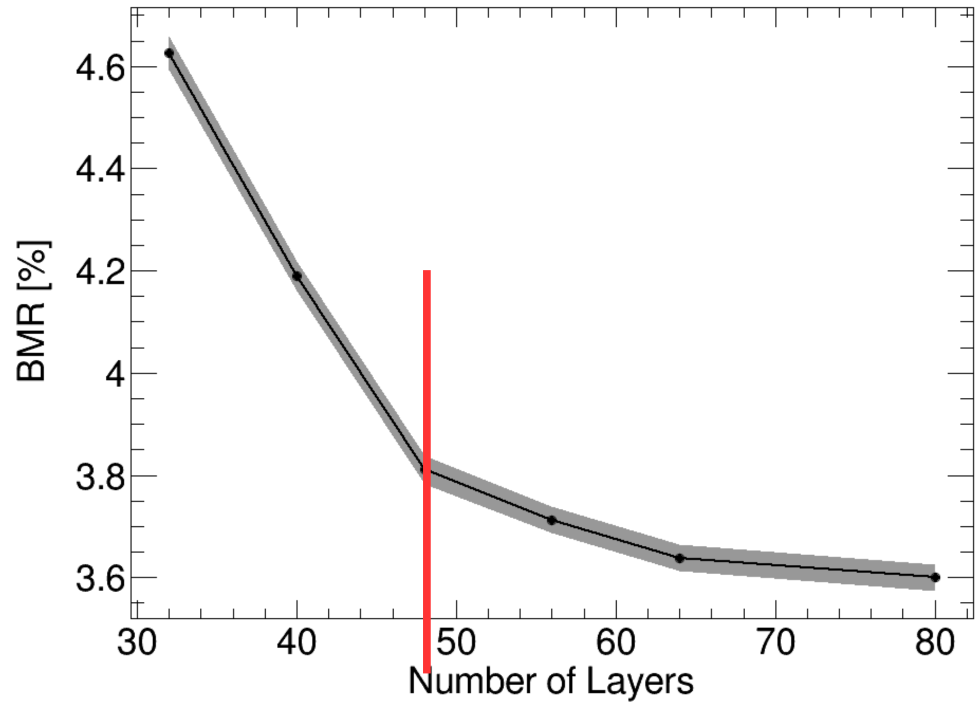
- 2024. May - Aug:
  - Reconstruction Fine tune & Optimization
  - Performance Validation: BMR + Jet Origin ID

- 2024. Aug – Nov: Sample massive Generation
  - Generator Level Validation & Analysis
    - Delphes: fast simulation level analyses and training.

- 2024. Nov – 2025. Jan: Benchmark analysis

HCAL Thickness

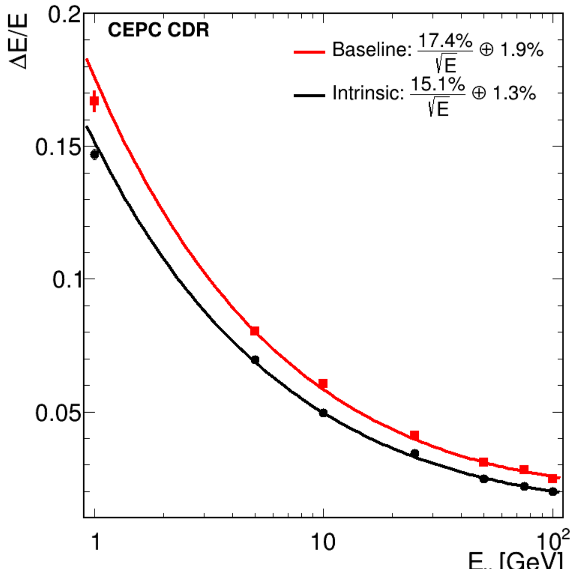


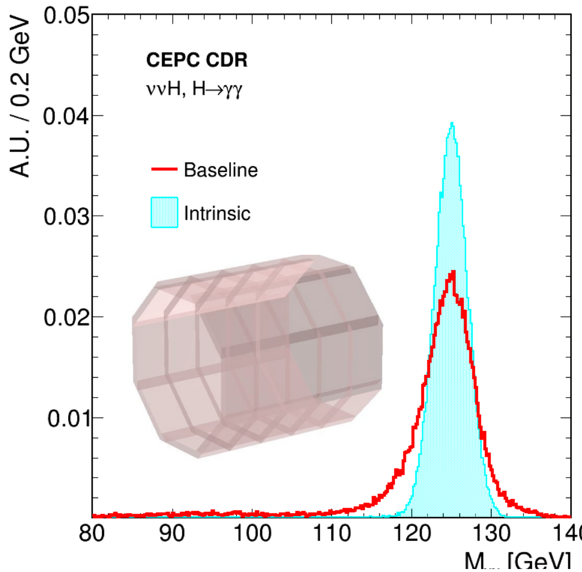


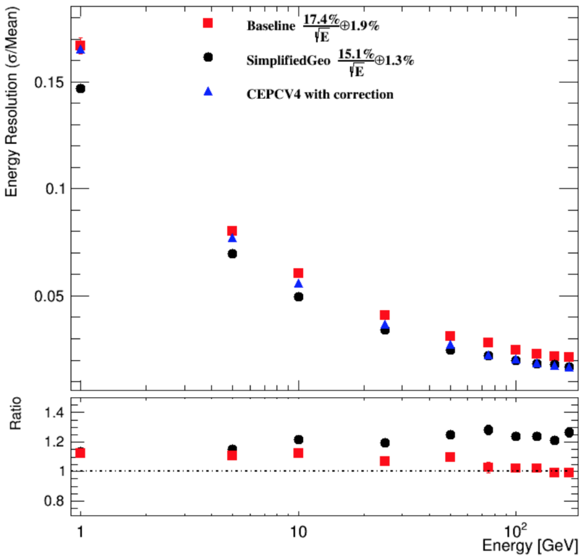
With ECAL ~ 1 lambda in the front.

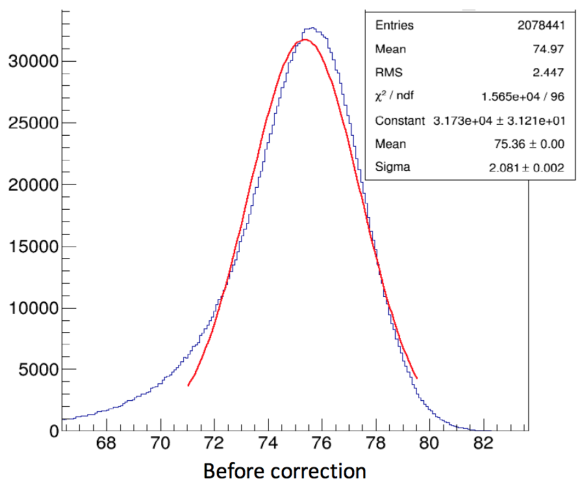
Thus the current optimal setup: ECAL (1 lambda) + HCAL (6 lambda)

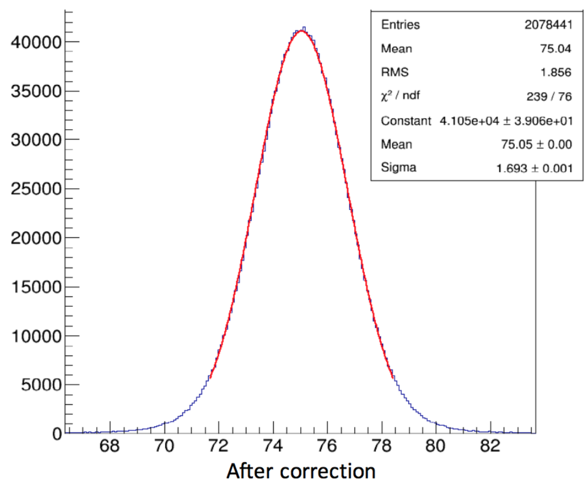
Photon: resolution







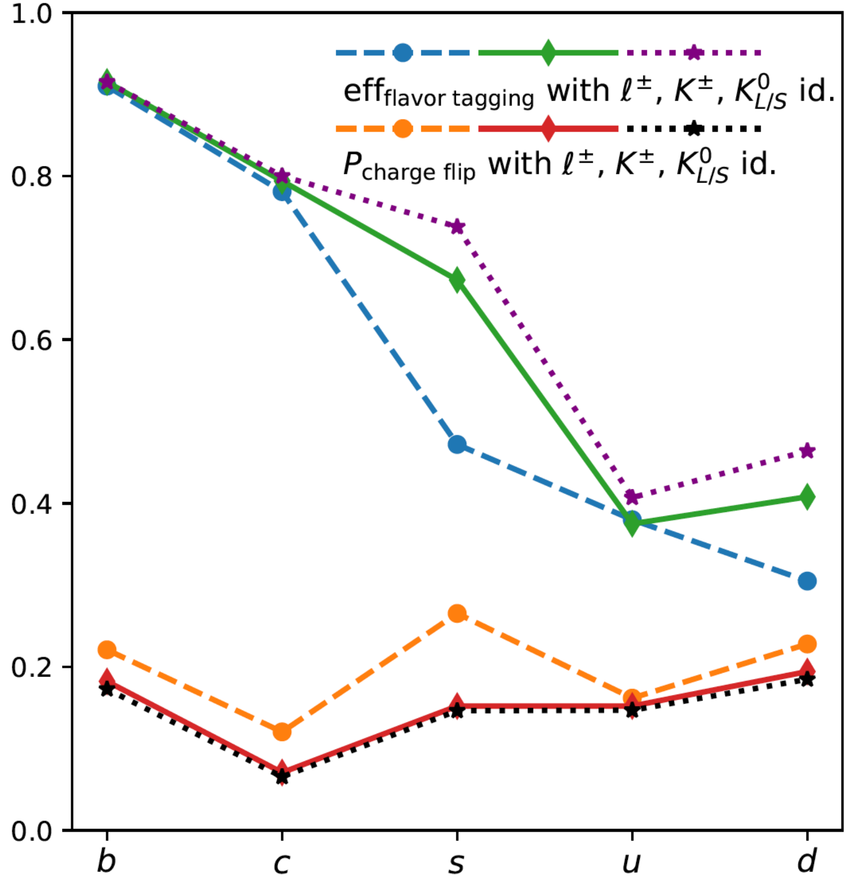


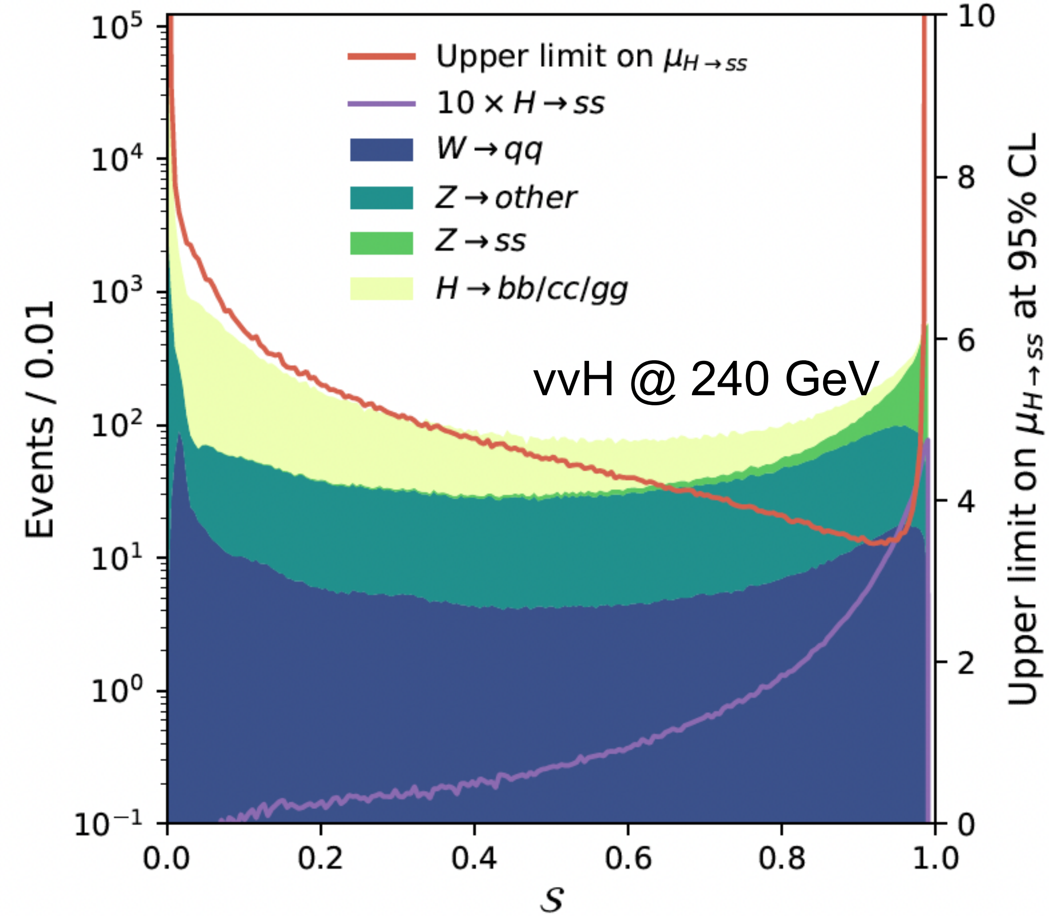


- A Higgs mass resolution of 1.7/2.5% is achieved in the Higgs to di-photon final states with simplified/baseline geometry
- The geometry defects correction could be efficiently corrected (Preliminary)

See Yuqiao Shen's talk

Performance with different PID scenarios & H→ss measurements





Flavor tagging: type that maximize {L_q + L_q_bar, L_g}

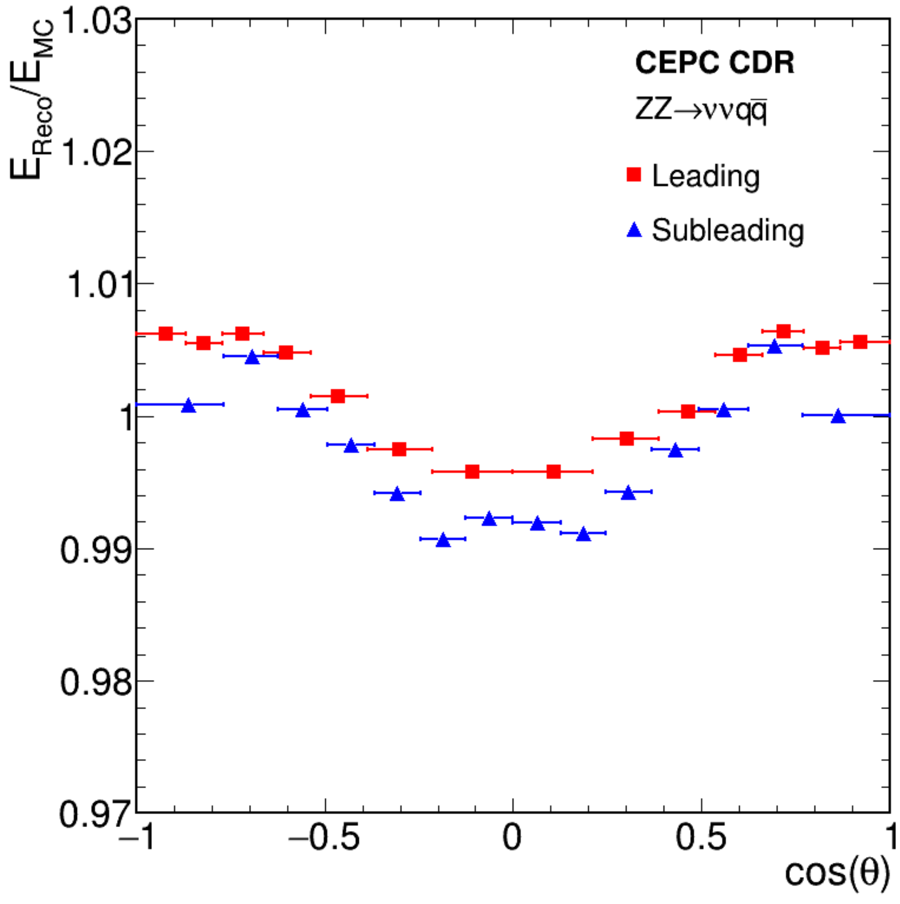
If quark jet: jet charge ~ compare {L_q, L_q_bar}

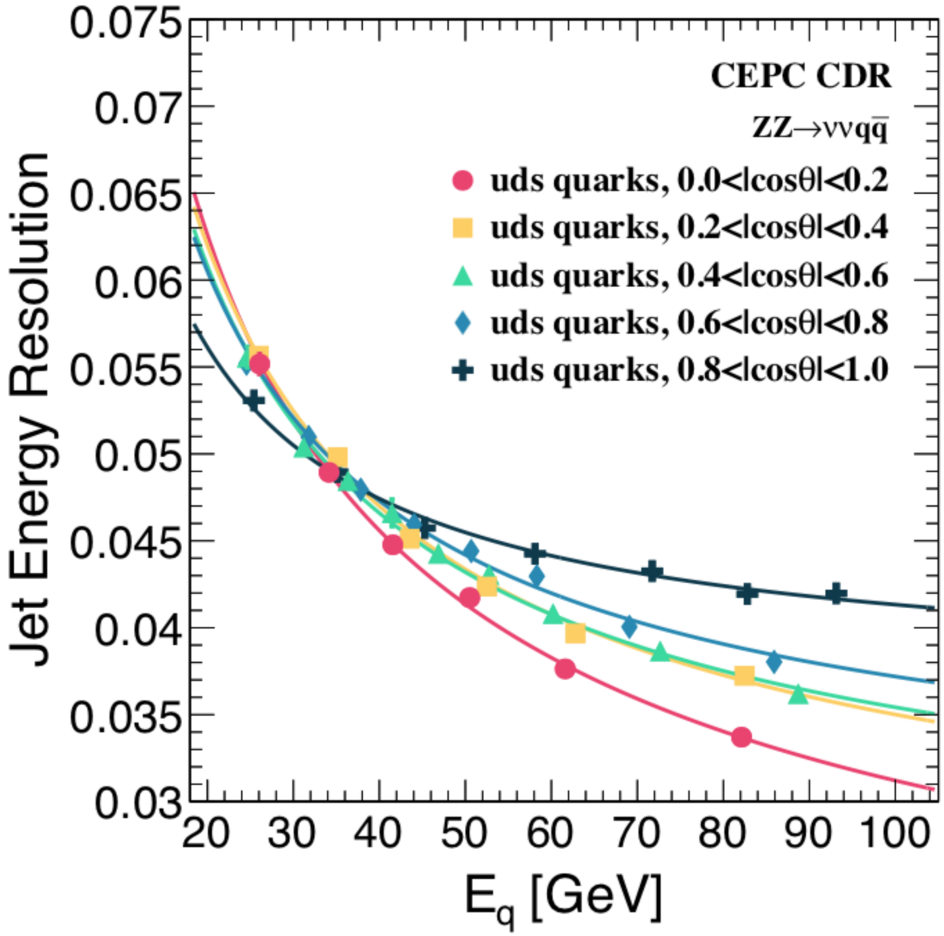
- How to address the manpower of reconstruction, especially PFA reco?

- Reconstruction =
  - Digitization (Need to validate on experimental data - SubD)
  - Tracking (Track finding + Fitting)
  - PFA (Calo. Clustering + Track Matching(1 FTE) + Pid(1 FTE))

- High level Reco.
  - Tau, Ks, Lambda, pi-0 finding, converted photon recon
  - Jet origin id (1 FTE), etc.

Jet Energy Scale & Resolution





- JES ~ with 1% of the unity (without correction)
- JER ~ 3.5% - 5.5% for E ~ 20 – 100 GeV Jets
- **Both Superior to LHC experiments by 3-4 times**

See Peizhu Lai's talk