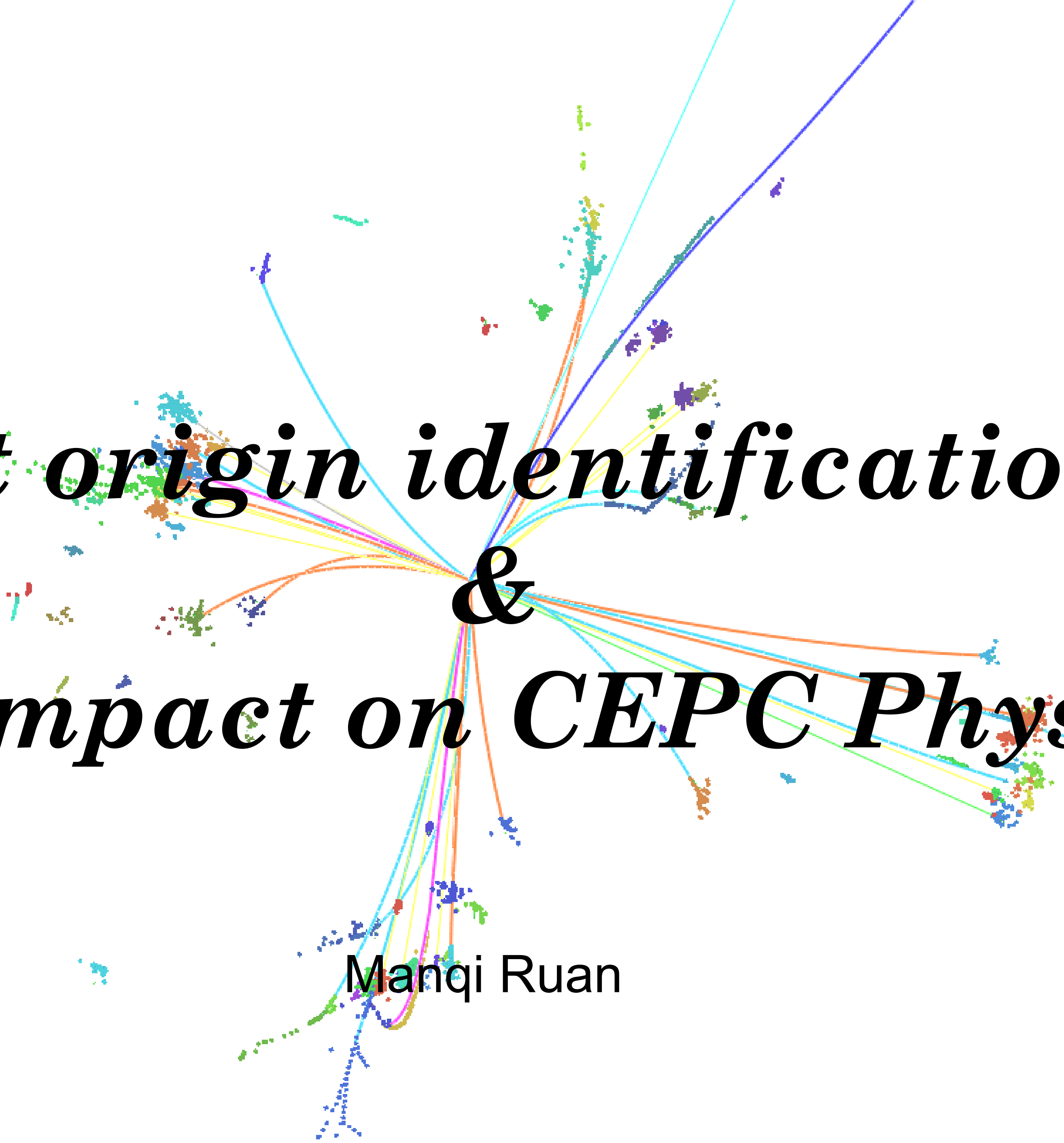
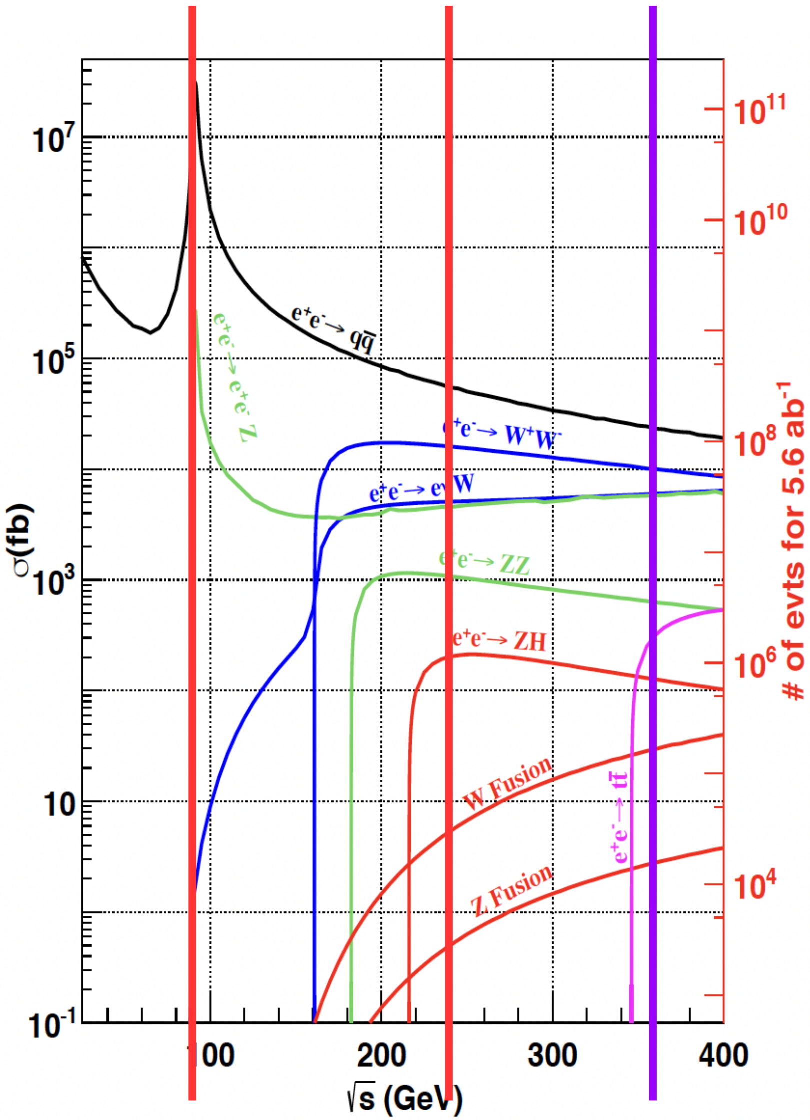
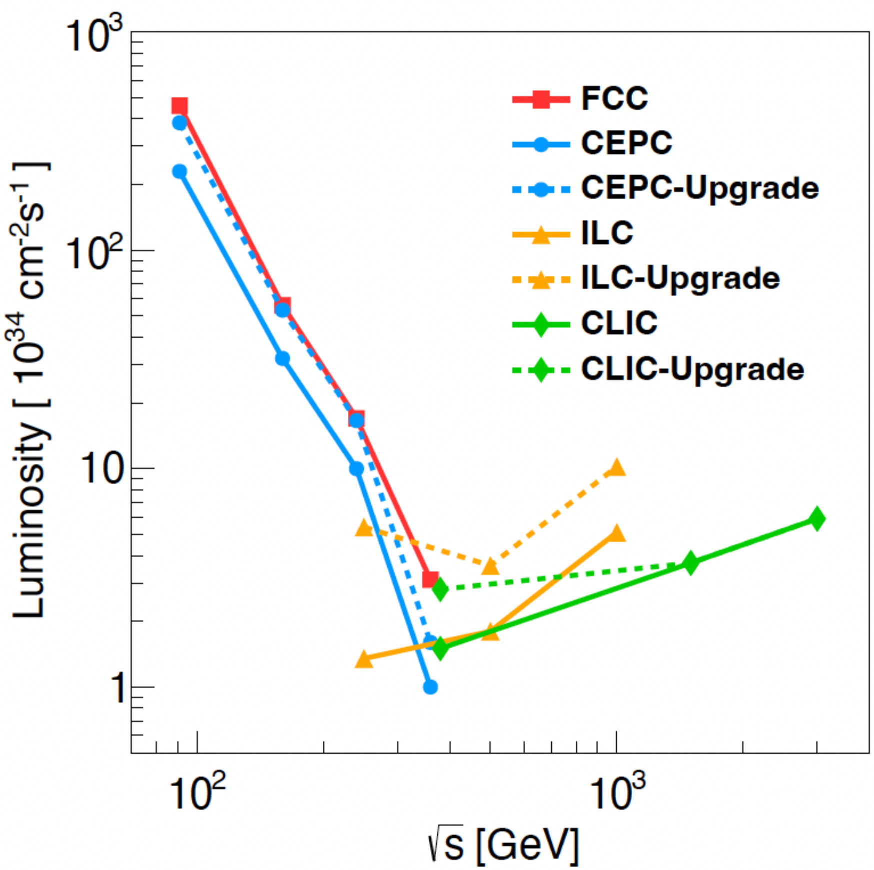
Jet origin identification
&
Its Impact on CEPC Physics



Manqi Ruan

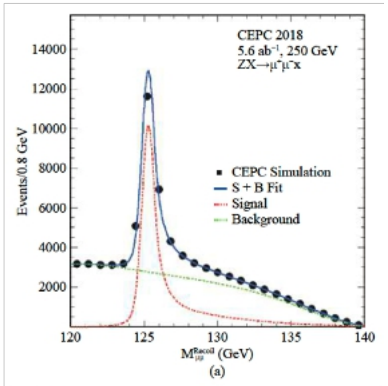
Yields ~ Xsec * Lumi * Time

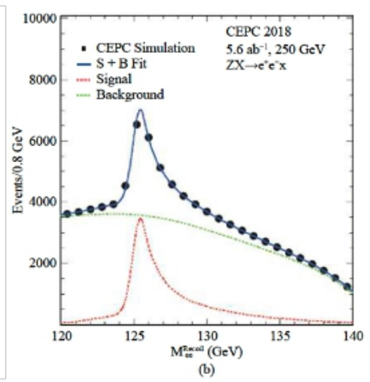


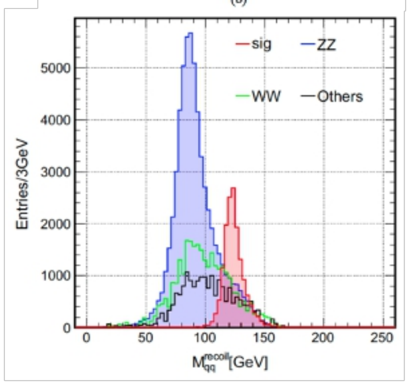


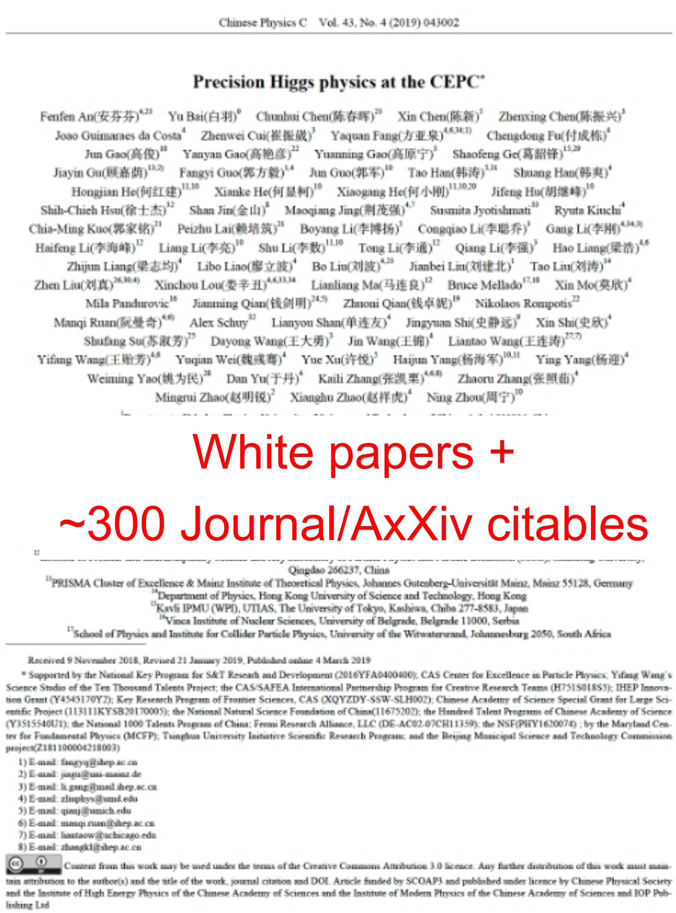
- 4 Million Higgs (10 years)
- ~ 1 Giga W (1 year) + 4 Tera Z (2 years)
- Upgradable: Top factory (500 k ttbar)

Physics study: 2023









White papers +

~300 Journal/AxXiv citables

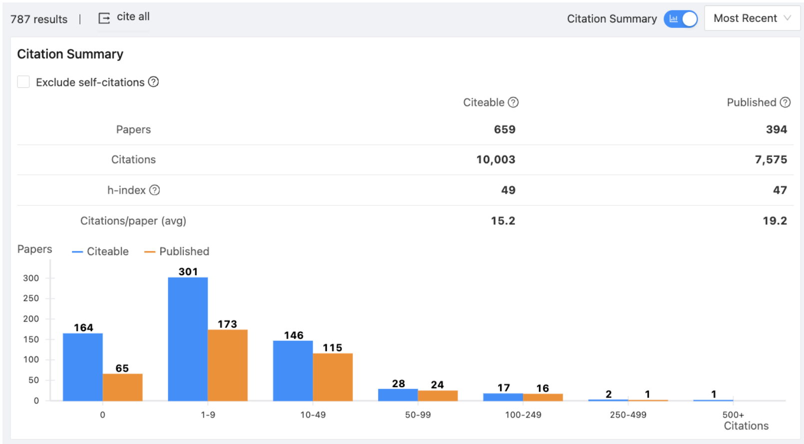


Table 2.1: Precision of the main parameters of interests and observables at the CEPC, from Ref. [1] and the references therein, where the results of Higgs are estimated with a data sample of 20 ab^{-1}. The HL-LHC projections of 3000 fb^{-1} data are used for comparison. [2]

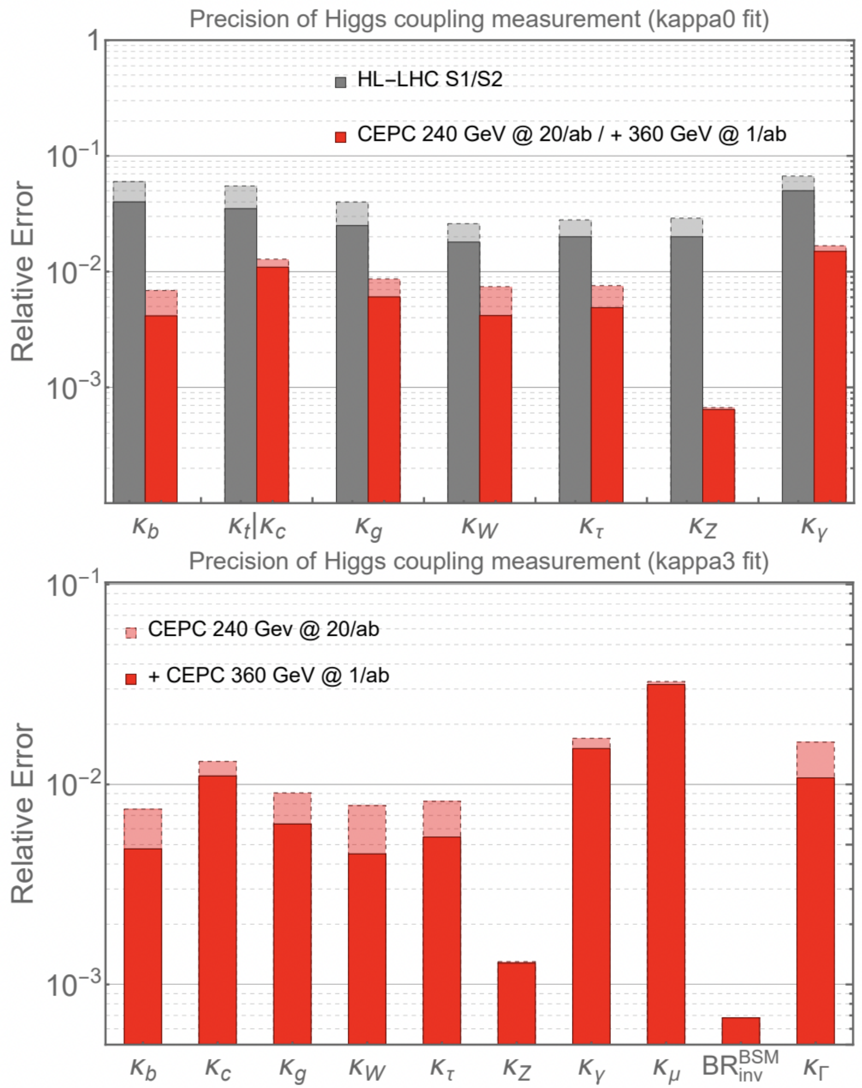
Higgs			W, Z and top		
Observable	HL-LHC projections	CEPC precision	Observable	Current precision	CEPC precision
M_H	20 MeV	3 MeV	M_W	9 MeV	0.5 MeV
Γ_H	20%	1.7%	Γ_W	49 MeV	2 MeV
$\sigma(ZH)$	4.2%	0.26%	M_{top}	760 MeV	$\mathcal{O}(10)$ MeV
$B(H \to bb)$	4.4%	0.14%	M_Z	2.1 MeV	0.1 MeV
$B(H \to cc)$	-	2.0%	Γ_Z	2.3 MeV	0.025 MeV
$B(H \to gg)$	-	0.81%	R_b	3×10^{-3}	2×10^{-4}
$B(H \to WW^*)$	2.8%	0.53%	R_c	1.7×10^{-2}	1×10^{-3}
$B(H \to ZZ^*)$	2.9%	4.2%	R_μ	2×10^{-3}	1×10^{-4}
$B(H \to \tau^+\tau^-)$	2.9%	0.42%	R_τ	1.7×10^{-2}	1×10^{-4}
$B(H \to \gamma\gamma)$	2.6%	3.0%	A_μ	1.5×10^{-2}	3.5×10^{-5}
$B(H \to \mu^+\mu^-)$	8.2%	6.4%	A_τ	4.3×10^{-3}	7×10^{-5}
$B(H \to Z\gamma)$	20%	8.5%	A_b	2×10^{-2}	2×10^{-4}
$Bupper(H \to inv.)$	2.5%	0.07%	N_ν	2.5×10^{-3}	2×10^{-4}

Scientific Significance quantified by **CEPC physics** studies, via full simulation/phenomenology studies:

- Higgs: Precisions exceed HL-LHC ~ 1 order of magnitude.
- EW: Precision improved from current limit by 1-2 orders.
- Flavor Physics, sensitive to NP of 10 TeV or even higher.
- Sensitive to varies of NP signal.
- …

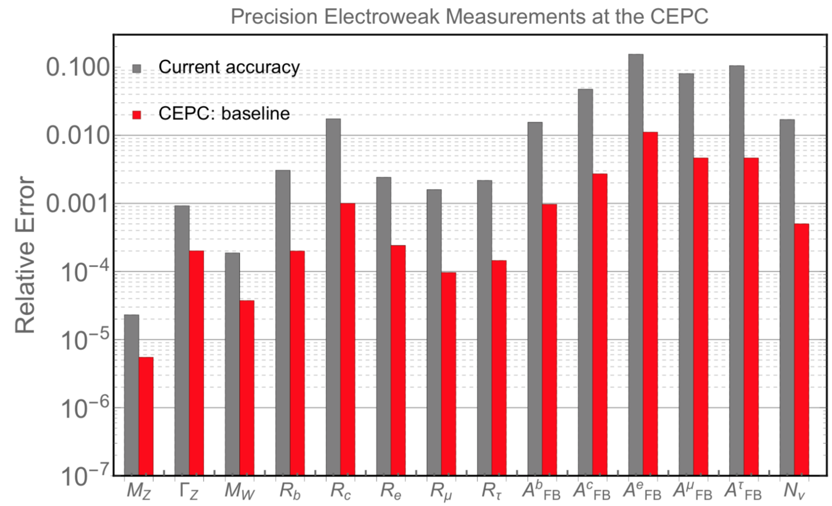
Physics reach via Higgs at CEPC

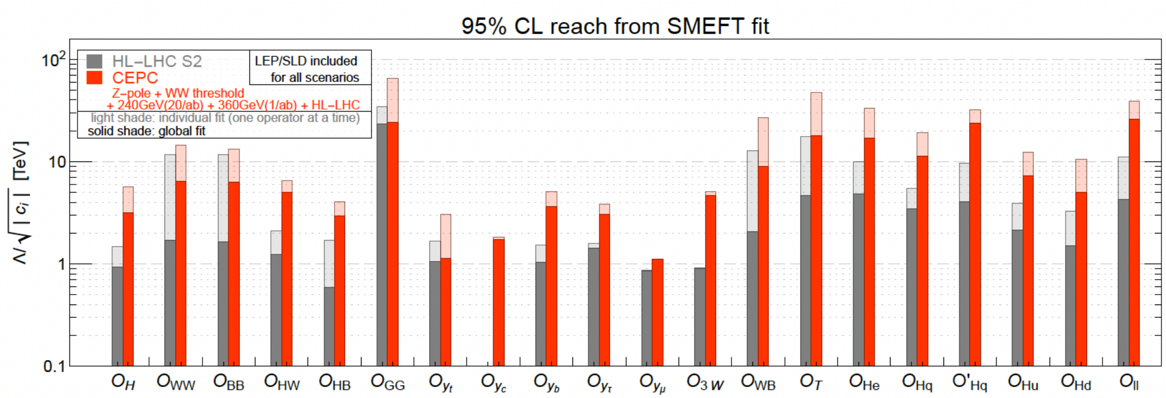
	240 GeV, 20 ab^{-1}		360 GeV, 1 ab^{-1}		
	ZH	**vvH**	ZH	**vvH**	**eeH**
inclusive	**0.26%**		**1.40%**	\	\
H→bb	**0.14%**	**1.59%**	**0.90%**	**1.10%**	**4.30%**
H→cc	**2.02%**		**8.80%**	**16%**	**20%**
H→gg	**0.81%**		**3.40%**	**4.50%**	**12%**
H→WW	**0.53%**		**2.80%**	**4.40%**	**6.50%**
H→ZZ	**4.17%**		**20%**	**21%**	
$H \to \tau\tau$	**0.42%**		**2.10%**	**4.20%**	**7.50%**
$H \to \gamma\gamma$	**3.02%**		**11%**	**16%**	
$H \to \mu\mu$	**6.36%**		**41%**	**57%**	
$H \to Z\gamma$	**8.50%**		**35%**		
$Br_{upper}(H \to inv.)$	**0.07%**				
Γ_H	**1.65%**		**1.10%**		

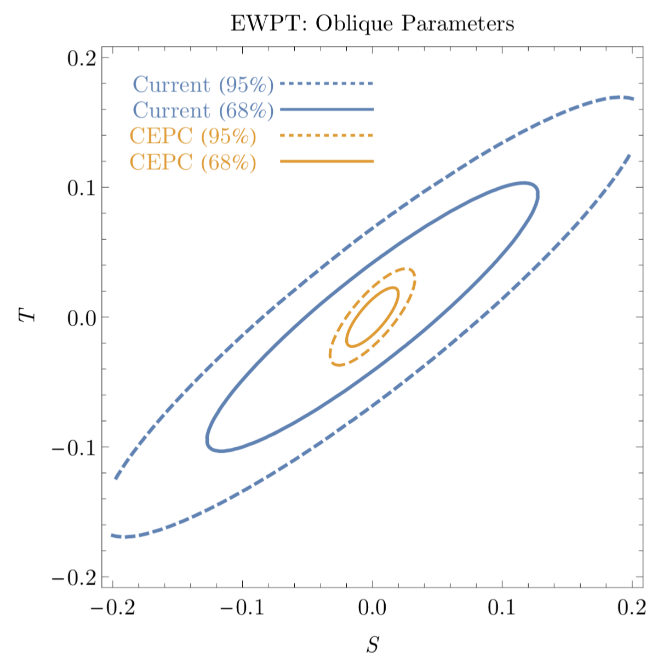


EW measurements & SMEFT

Observable	current precision	CEPC precision (Stat. Unc.)	CEPC runs	main systematic
Δm_Z	2.1 MeV [37–41]	0.1 MeV (0.005 MeV)	Z threshold	E_{beam}
$\Delta\Gamma_Z$	2.3 MeV [37–41]	0.025 MeV (0.005 MeV)	Z threshold	E_{beam}
Δm_W	9 MeV [42–46]	0.5 MeV (0.35 MeV)	WW threshold	E_{beam}
$\Delta\Gamma_W$	49 MeV [46–49]	2.0 MeV (1.8 MeV)	WW threshold	E_{beam}
Δm_t	0.76 GeV [50]	$\mathcal{O}(10)$ MeV[a]	$t\bar{t}$ threshold	
ΔA_e	4.9×10^{-3} [37, 51–55]	1.5×10^{-5} (1.5×10^{-5})	Z pole ($Z \to \tau\tau$)	Stat. Unc.
ΔA_μ	0.015 [37, 53]	3.5×10^{-5} (3.0×10^{-5})	Z pole ($Z \to \mu\mu$)	point-to-point Unc.
ΔA_τ	4.3×10^{-3} [37, 51–55]	7.0×10^{-5} (1.2×10^{-5})	Z pole ($Z \to \tau\tau$)	tau decay model
ΔA_b	0.02 [37, 56]	20×10^{-5} (3×10^{-5})	Z pole	QCD effects
ΔA_c	0.027 [37, 56]	30×10^{-5} (6×10^{-5})	Z pole	QCD effects
$\Delta\sigma_{had}$	37 pb [37–41]	2 pb (0.05 pb)	Z pole	lumiosity
δR_b^0	0.003 [37, 57–61]	0.0002 (5×10^{-6})	Z pole	gluon splitting
δR_c^0	0.017 [37, 57, 62–65]	0.001 (2×10^{-5})	Z pole	gluon splitting
δR_e^0	0.0012 [37–41]	2×10^{-4} (3×10^{-6})	Z pole	E_{beam} and t channel
δR_μ^0	0.002 [37–41]	1×10^{-4} (3×10^{-6})	Z pole	E_{beam}
δR_τ^0	0.017 [37–41]	1×10^{-4} (3×10^{-6})	Z pole	E_{beam}
δN_ν	0.0025 [37, 66]	2×10^{-4} (3×10^{-5})	ZH run ($\nu\nu\gamma$)	Calo energy scale







Flavor Physics

Flavor Physics at CEPC: a General Perspective

Contents

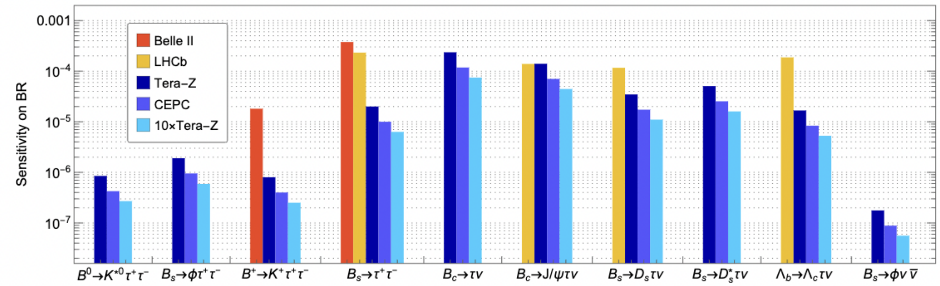


Figure 18: Projected sensitivities of measuring the $b\to s\tau\tau$ [70], $b\to s\nu\bar{\nu}$ [34] and $b\to c\tau\nu$ [35, 62] transitions at the Z pole. The sensitivities at Belle II @ 50 ab^{-1} [6] and LHCb Upgrade II [17, 71] have also been provided as a reference. Note, the LHCb sensitivities are generated by combining the analyses of $\tau^+\to\pi^+\pi^-\pi^-(\pi^0)\nu$ and $\tau\to\mu\nu\bar{\nu}$.

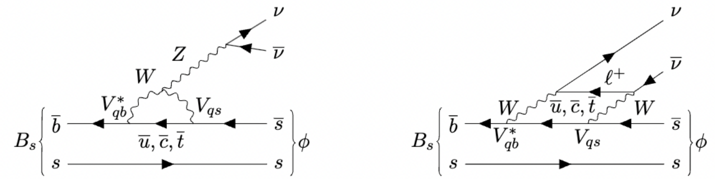


Figure 21: Illustrative Feynman diagrams for the $B_s\to\phi\nu\bar{\nu}$ transitions in the SM. **LEFT**: EW penguin diagram. **RIGHT**: EW box diagram.

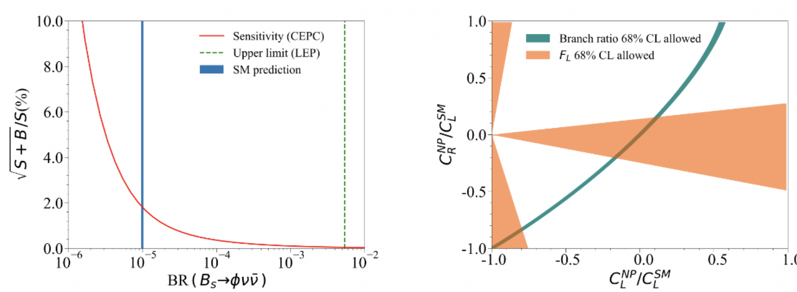
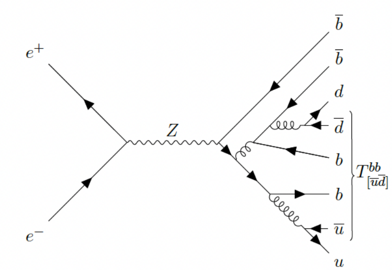


Figure 22: **LEFT**: Relative precision for measuring the signal strength of $B_s\to\phi\nu\bar{\nu}$ at Tera-Z, as a function of its BR. **RIGHT**: Constraints on the LEFT coefficients $C_L^{\rm NP}\equiv C_L-C_L^{\rm SM}$ and C_R with the measurements of the overall $B_s\to\phi\nu\bar{\nu}$ decay rate (green band) and the ϕ polarization F_L (orange regions). These plots are taken from [34].



$$\mathrm{BR}(Z\to X+T^{cc}_{[\bar{q}\bar{q}']})\sim\mathcal{O}(10^{-6})$$

$$\mathrm{BR}(Z\to X+\Xi_{cc})\sim 1\times10^{-5}$$

$$\mathrm{BR}(Z\to X+\Omega_{cc})\sim 5\times10^{-5}$$

~ 40+ benchmarks + ... Access to NP at 10 TeV or higher

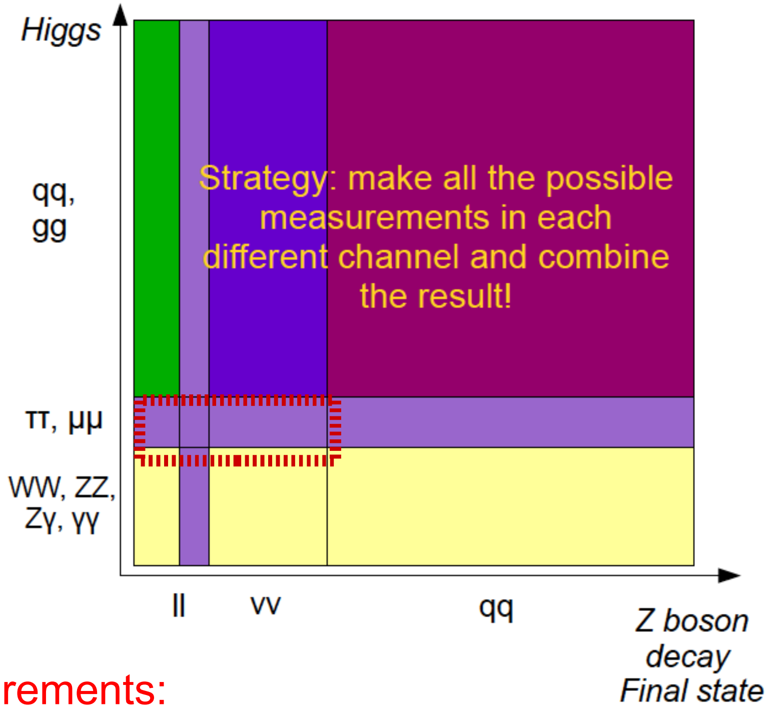
New Physics White paper

ABSTRACT (TO BE UPDATED)

The Circular Electron Positron Collider (CEPC) is a large-scale collider facility that can serve as a factory of the Higgs, Z, and W bosons and is upgradable to run at the $t\bar{t}$ threshold. This document describes the latest CEPC nominal operation scenario and particle yields and updates the corresponding physics potential. A new detector concept is also briefly described. This submission is for consideration by the Snowmass process.

CONTENTS

Performance requirements



- To reconstruct all kinds of Physics Object
  - Identification & Measurements
  - Objects:
    - Lepton, Photons, Kaon,
    - pi-0, Tau, Lambda, Kshort,
    - Heavy flavor hadrons,
    - Jets
    - Missing energy/momentum
    - Exotics...
- Massive Four in Standard Model:
  - Z & W: ~ 70% goes to a pair of jets
  - Higgs: ~90% final state with jets (ZH events)
  - Top: $t \to W + b$

- Requirements:
  - Excellent pattern. Reco. & Object id
  - Larger acceptance...
  - Excellent intrinsic resolutions
  - Extremely stable...
- Be addressed by state-of-art detector design, technology, and reconstruction algorithm!

Jet origin id

Hao Liang, Yongfeng Zhu, Yuzhi Che, Yuexin Wang, Huiling Qu, Cen Zhou, etc

PHYSICAL REVIEW LETTERS **132,** 221802 (2024)

Jet-Origin Identification and Its Application at an Electron-Positron Higgs Factory

Hao Liang,[1,2,*] Yongfeng Zhu,[3,*] Yuexin Wang,[1,4] Yuzhi Che,[1,2] Manqi Ruan,[1,2,†]
Chen Zhou,[3,‡] and Huilin Qu[5,§]

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(Received 16 October 2023; revised 26 April 2024; accepted 1 May 2024; published 31 May 2024)

To enhance the scientific discovery power of high-energy collider experiments, we propose and realize the concept of jet-origin identification that categorizes jets into five quark species (b, c, s, u, d), five antiquarks $(\bar{b}, \bar{c}, \bar{s}, \bar{u}, \bar{d})$, and the gluon. Using state-of-the-art algorithms and simulated $\nu\bar{\nu}H, H \to jj$ events at 240 GeV center-of-mass energy at the electron-positron Higgs factory, the jet-origin identification simultaneously reaches jet flavor tagging efficiencies ranging from 67% to 92% for bottom, charm, and strange quarks and jet charge flip rates of 7%–24% for all quark species. We apply the jet-origin identification to Higgs rare and exotic decay measurements at the nominal luminosity of the Circular Electron Positron Collider and conclude that the upper limits on the branching ratios of $H \to s\bar{s}, u\bar{u}, d\bar{d}$ and $H \to sb, db, uc, ds$ can be determined to 2×10^{-4} to 1×10^{-3} at 95% confidence level. The derived upper limit for $H \to s\bar{s}$ decay is approximately 3 times the prediction of the standard model.

Eur. Phys. J. C (2024) 84:152
https://doi.org/10.1140/epjc/s10052-024-12475-5

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

ParticleNet and its application on CEPC jet flavor tagging

Yongfeng Zhu[1,a], Hao Liang[2,3], Yuexin Wang[2,3], Huilin Qu[4], Chen Zhou[1,b], Manqi Ruan[2,3,c]

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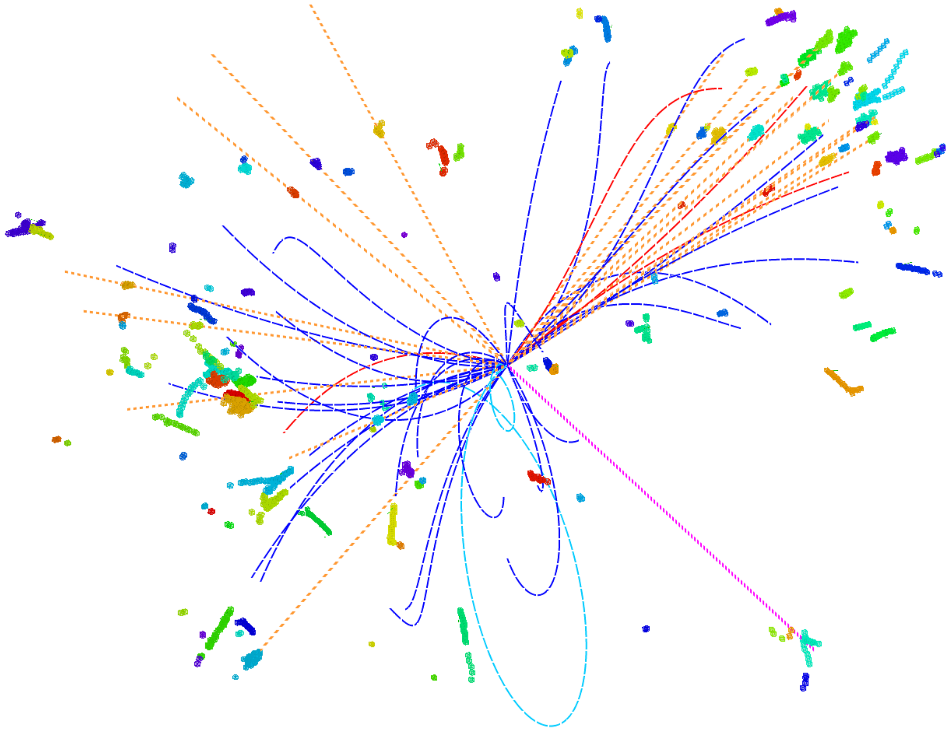
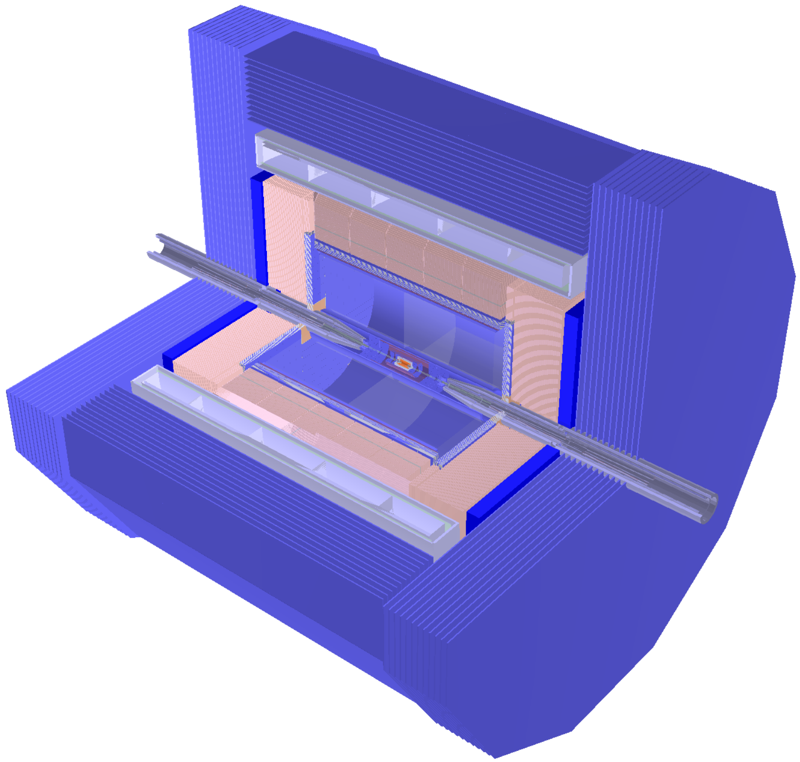
Received: 15 November 2023 / Accepted: 23 January 2024

https://arxiv.org/abs/2310.03440

https://arxiv.org/abs/2309.13231

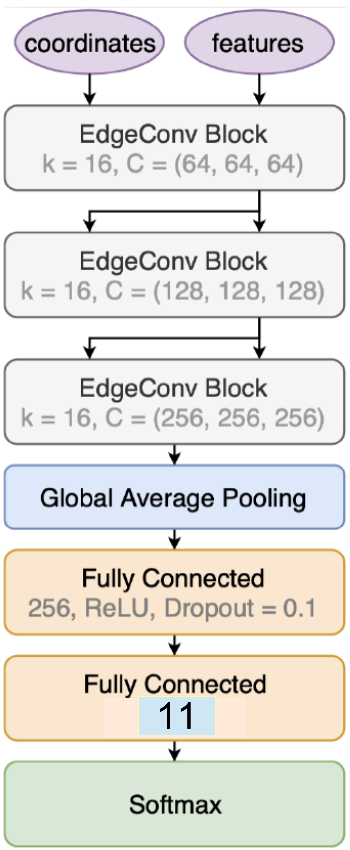
Detector & Sample

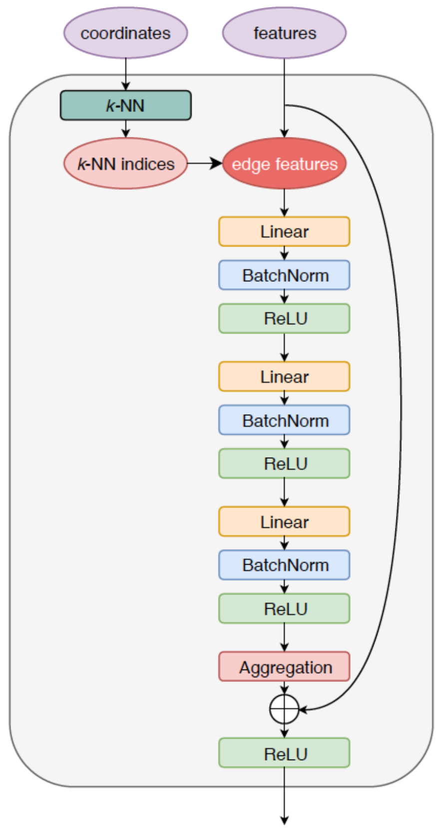




- **Jet origin identification: 11 categories (5 quarks + 5 anti quarks + gluon)**
  - Jet Flavor Tagging + Jet Charge measurements + s-tagging + gluon tagging...
- Full Simulated vvH, Higgs to two jets sample at CEPC baseline configuration: CEPC-v4 detector, reconstructed with **Arbor + ParticleNet (Deep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

Particle Net: IO





Variable	Definition
$\Delta\eta$	difference in pseudorapidity between the particle and the jet axis
$\Delta\phi$	difference in azimuthal angle between the particle and the jet axis
$log p_T$	logarithm of the particle's p_T
$log E$	logarithm of the particle's energy
$log \frac{p_T}{p_T(jet)}$	logarithm of the particle's p_T relative to the jet p_T
$log \frac{E}{E(jet)}$	logarithm of the particle's energy relative to the jet energy
ΔR	angular separation between the particle and the jet axis ($\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$)
d0	transverse impact parameter of the track
d0err	uncertainty associated with the measurement of the d0
z0	longitudinal impact parameter of the track
z0err	uncertainty associated with the measurement of the z0
charge	electric charge of the particle
isElectron	if the particle is an electron
isMuon	if the particle is a muon
isChragedKaon	if the particle is a charged Kaon
isChragedPion	if the particle is a charged Pion
isProton	if the particle is a proton
isNeutralHadron	if the particle is a neutral hadron
isPhoton	if the particle is a photon

Table 3. The input variables used in ParticleNet for jet flavor tagging at the CEPC.

- Input: measurable of all reconstructed jet particles ~ 500 input numbers
- Output: 10(11)-likelihoods to different categories

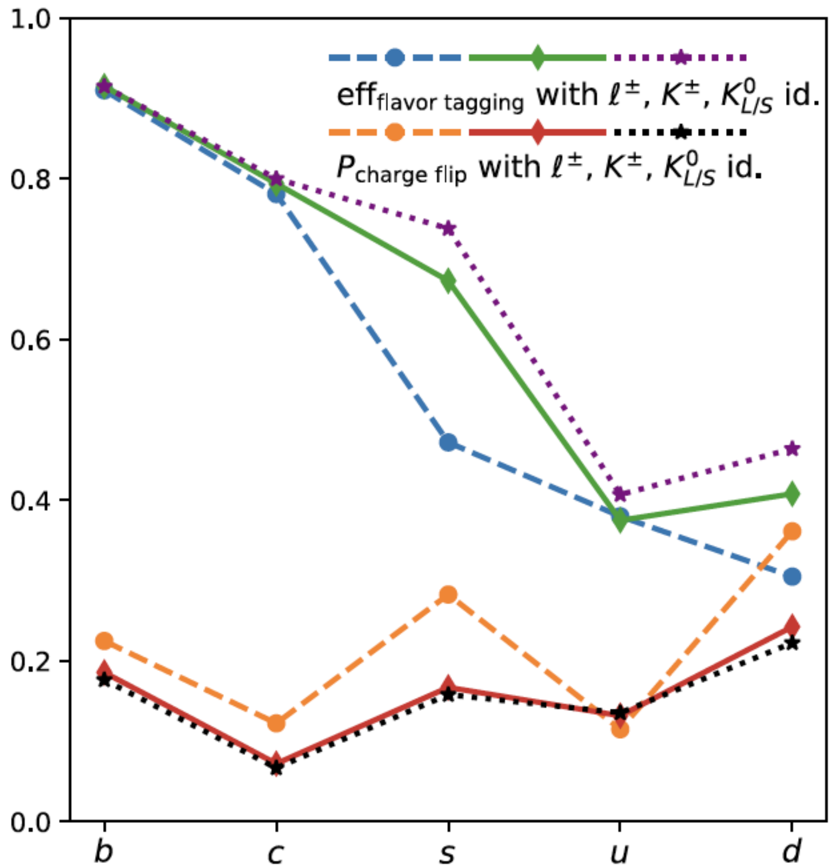
11-dim migration behavior

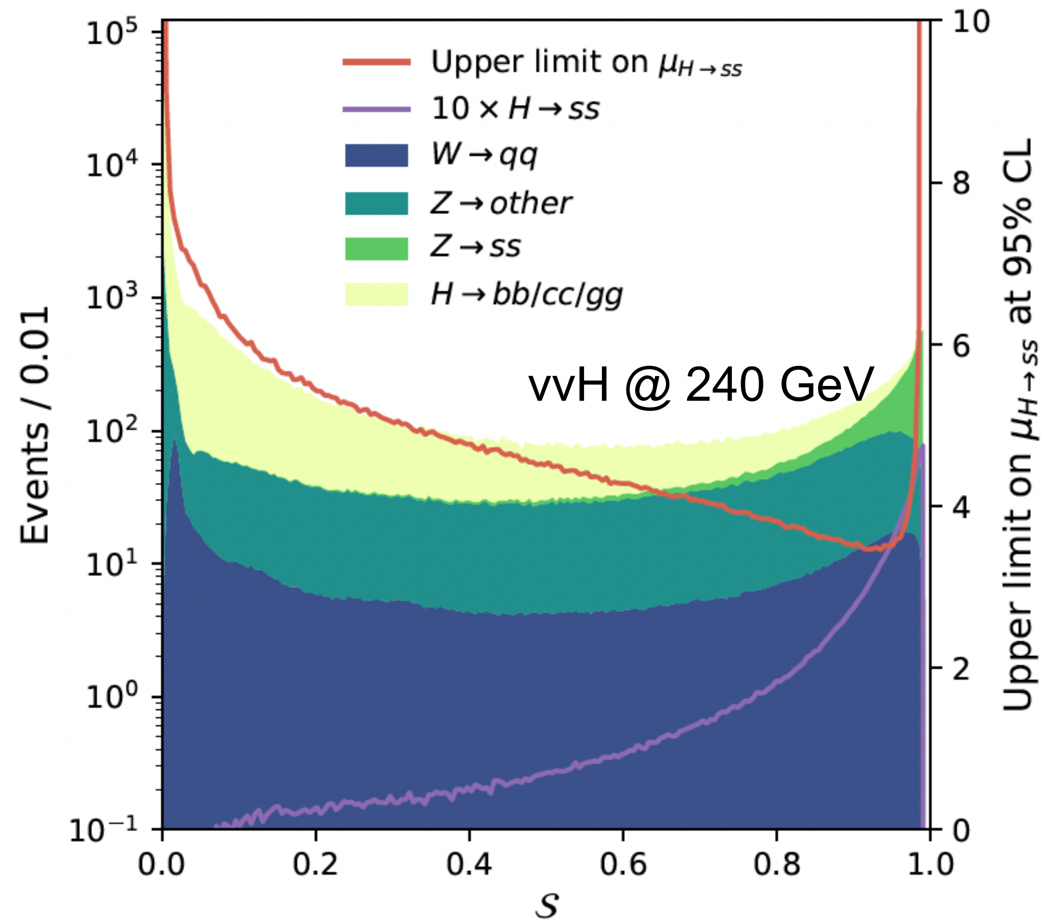
- Let the jet be identified as the category with highest likelihood:
- Pid: ideal Pid – three categories
  - Lepton identification
  - **Charged Kaon identification**
  - Neutral Kaon identification
- Patterns:
  - ~ Diagonal at quark sector...
  - P(g→q) < P(q→g)...
  - Light jet id...

True \ Predicted	b	$\bar{b}$	c	$\bar{c}$	s	$\bar{s}$	u	$\bar{u}$	d	$\bar{d}$	G
b	0.738	0.167	0.034	0.026	0.005	0.003	0.002	0.003	0.002	0.002	0.018
$\bar{b}$	0.167	0.737	0.026	0.034	0.003	0.004	0.003	0.002	0.002	0.003	0.018
c	0.015	0.015	0.740	0.057	0.037	0.032	0.026	0.010	0.009	0.017	0.043
$\bar{c}$	0.015	0.015	0.055	0.741	0.032	0.037	0.010	0.026	0.016	0.010	0.043
s	0.003	0.003	0.020	0.018	0.541	0.104	0.030	0.082	0.062	0.045	0.092
$\bar{s}$	0.002	0.003	0.018	0.021	0.101	0.543	0.085	0.028	0.044	0.062	0.092
u	0.002	0.003	0.019	0.012	0.044	0.132	0.375	0.057	0.079	0.168	0.109
$\bar{u}$	0.003	0.002	0.011	0.020	0.132	0.043	0.062	0.368	0.166	0.084	0.108
d	0.003	0.003	0.012	0.020	0.111	0.093	0.083	0.223	0.261	0.080	0.110
$\bar{d}$	0.003	0.003	0.020	0.013	0.093	0.113	0.226	0.079	0.076	0.265	0.110
G	0.015	0.014	0.025	0.025	0.053	0.053	0.043	0.044	0.033	0.035	0.661

0.7-0.8
0.65-0.7
0.6-0.65
0.5-0.6
0.4-0.5
0.35-0.4
0.3-0.35
0.25-0.3
0.2-0.25
0.15-0.2
0.1-0.15
0.09-0.1
0.085-0.09
0.08-0.085
0.075-0.08
0.07-0.075
0.06-0.07
0.05-0.06
0.04-0.05
0.03-0.04
0.02-0.03
0.01-0.02
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001

Performance with different PID scenarios & H→ss measurements



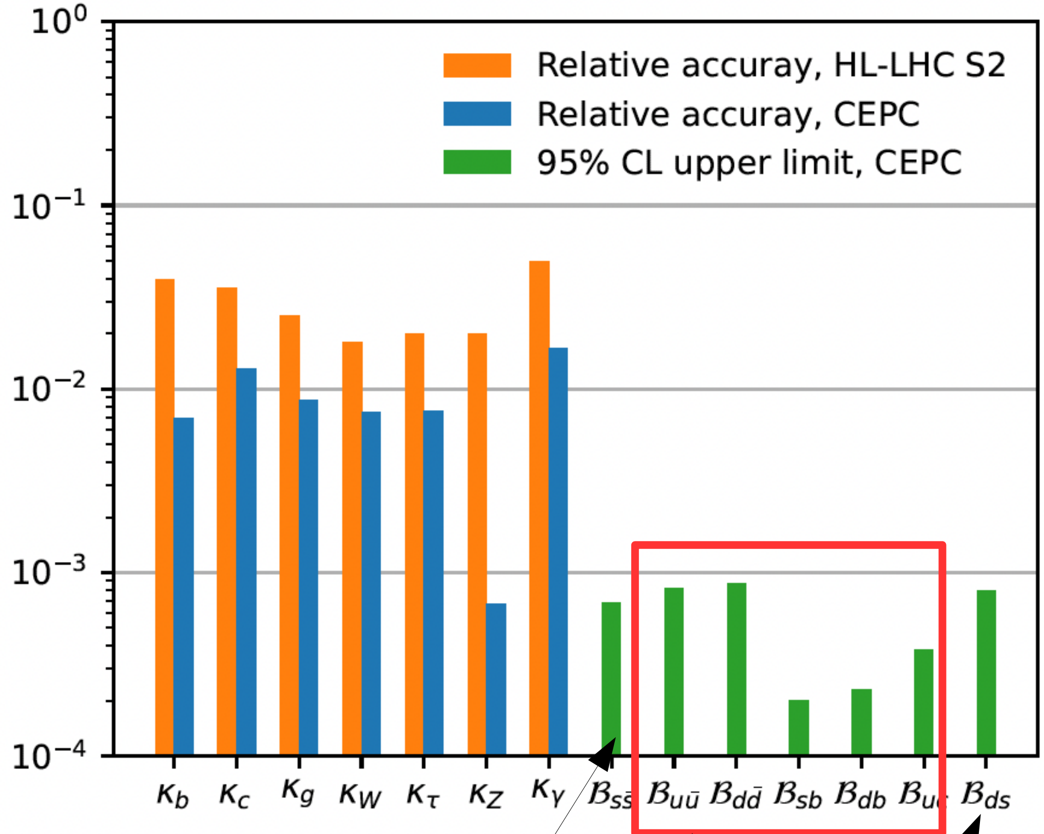


Flavor tagging: type that maximize {L_q + L_q_bar, L_g}

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

Remark: current jet flavor tagging efficiency & jet charge flip rates are projections of the 11-dim arrays produced by Jet origin id

Benchmark analyses: Higgs rare/FCNC



Improved by ~3 times

Improved by 1-2 orders of magnitudes

Presumably... firstly quantified

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

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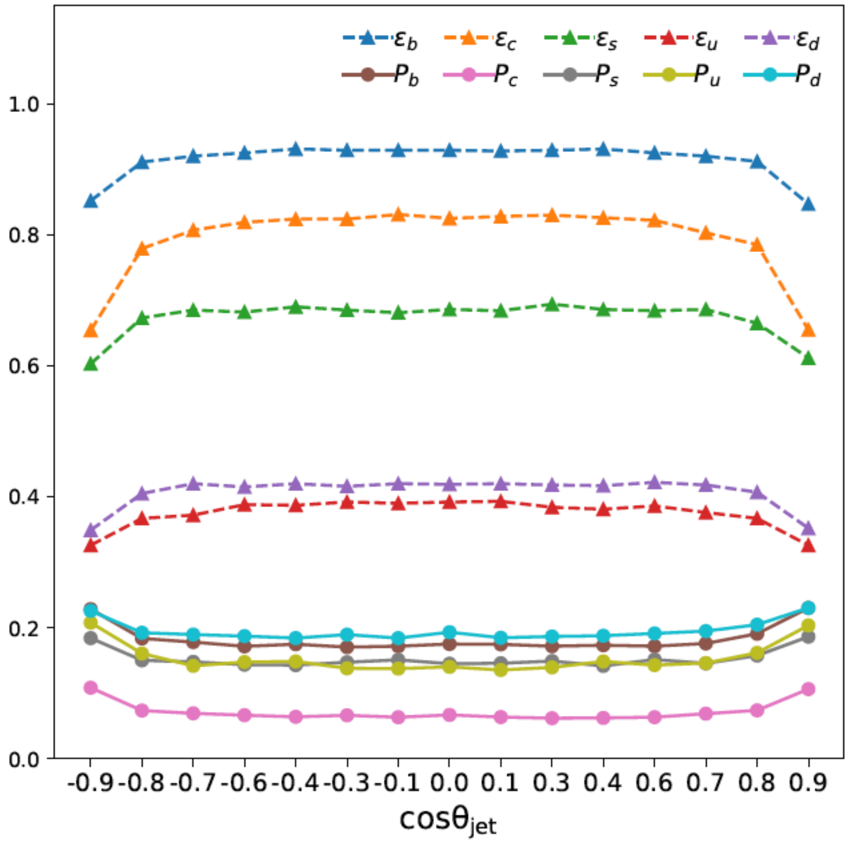
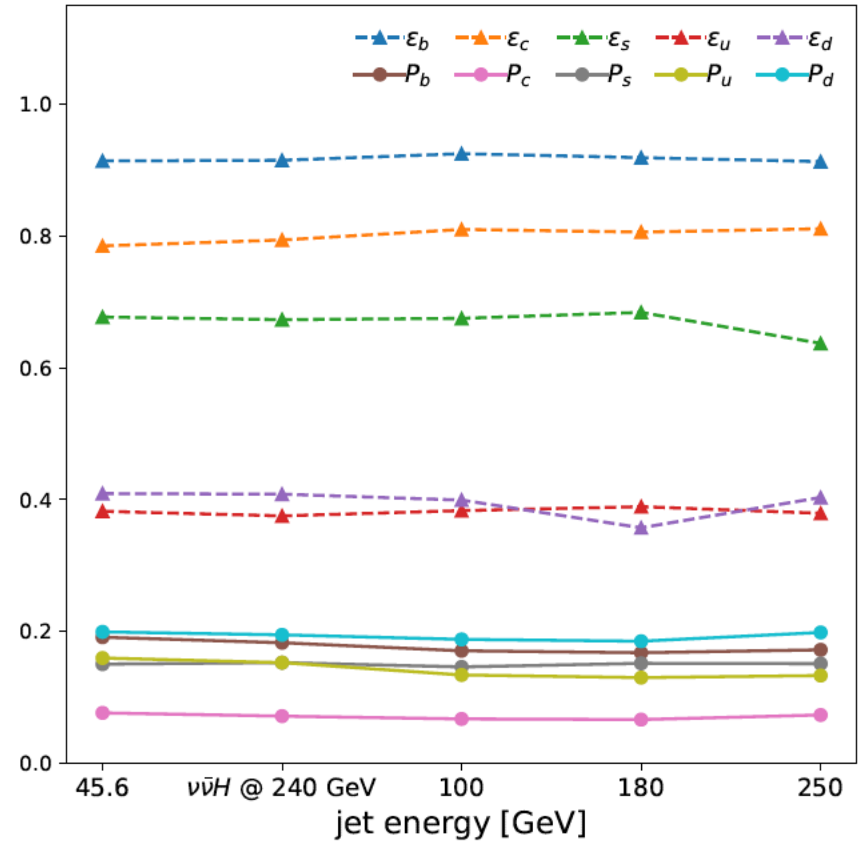
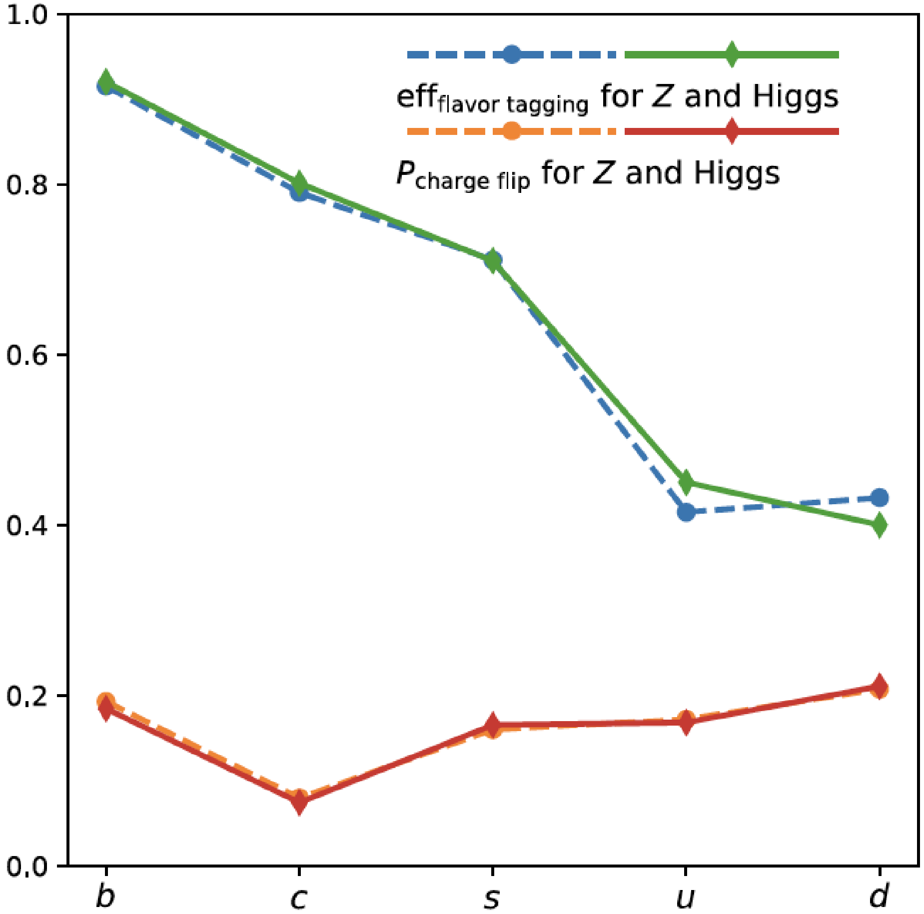
[60] Jorge De Blas, Gauthier Durieux, Christophe Grojean, Jiayin Gu, and Ayan Paul. On the future of Higgs, electroweak and diboson measurements at lepton colliders. *JHEP*, 12:117, 2019.

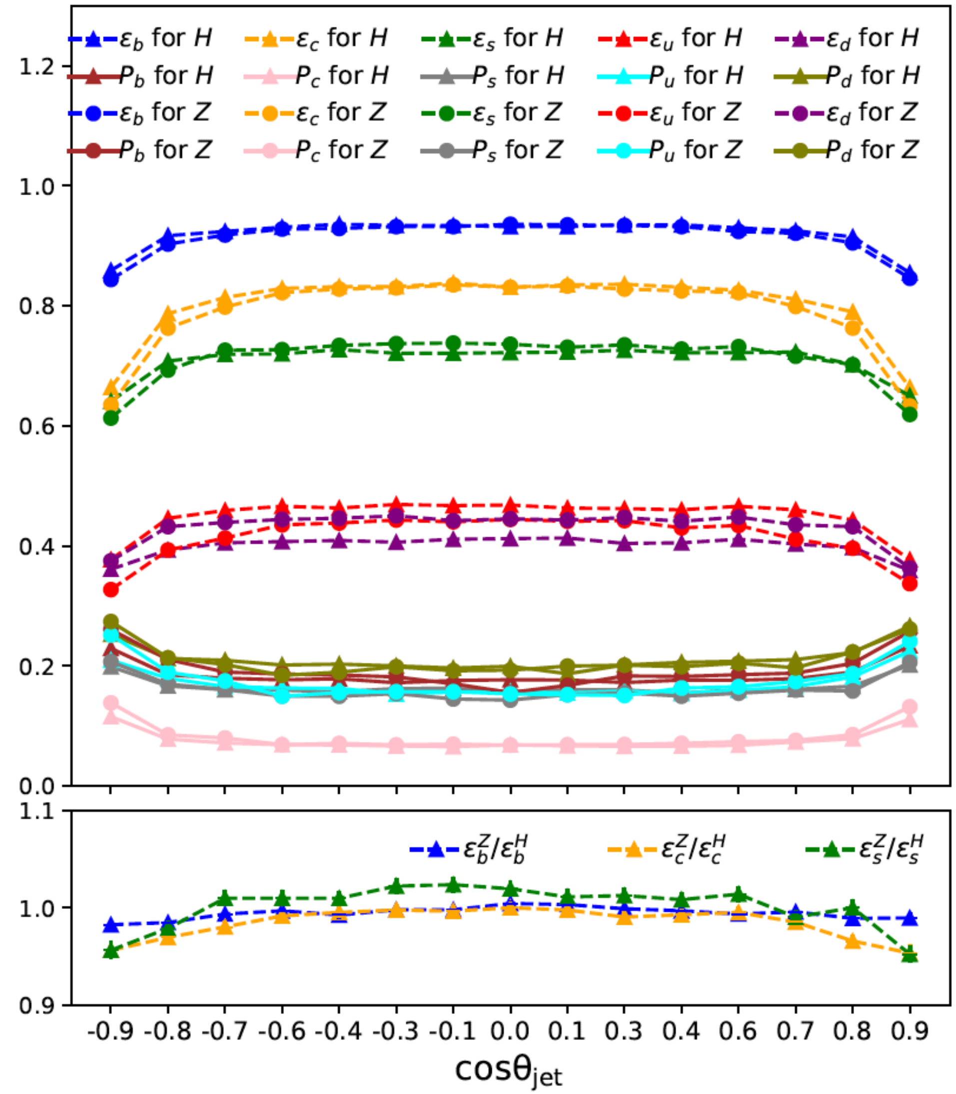
Performance V.S. Jet Kinematics





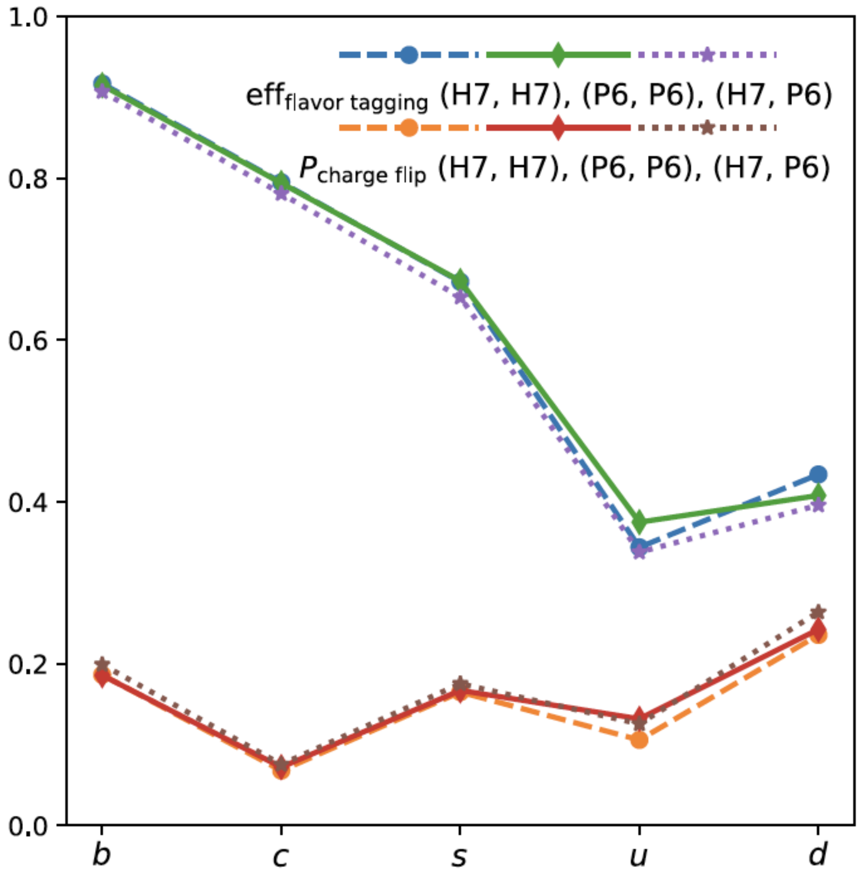
Performance @ Z and Higgs

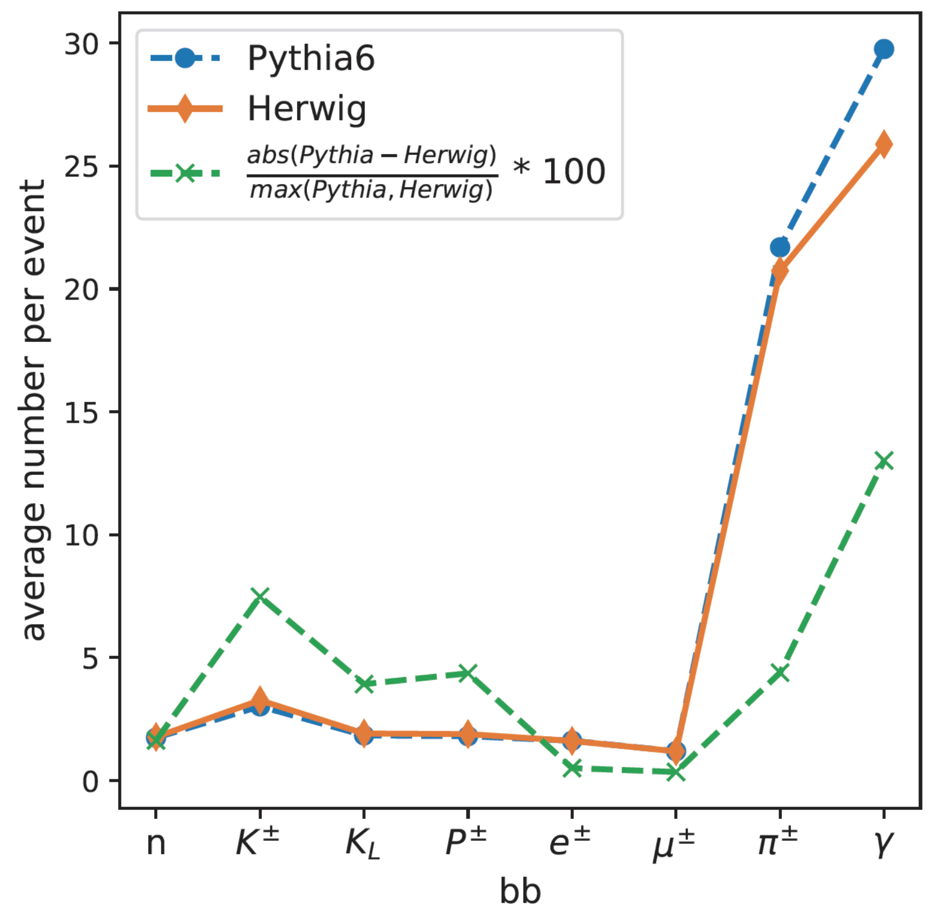




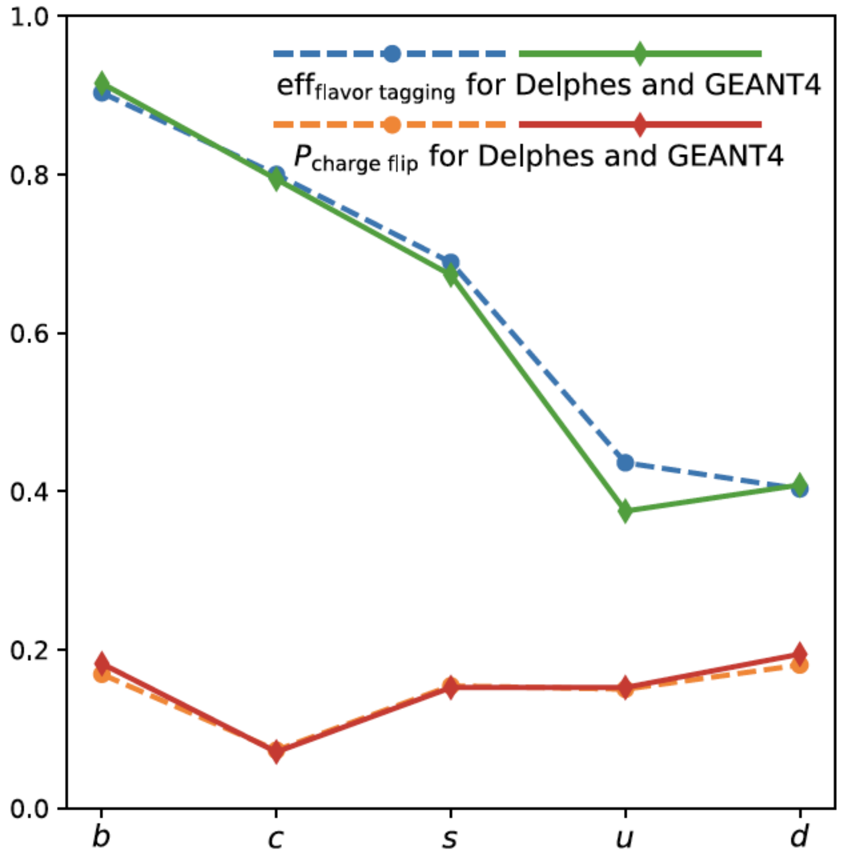
- *M10 instead of M11*

V.S. Hadronization models

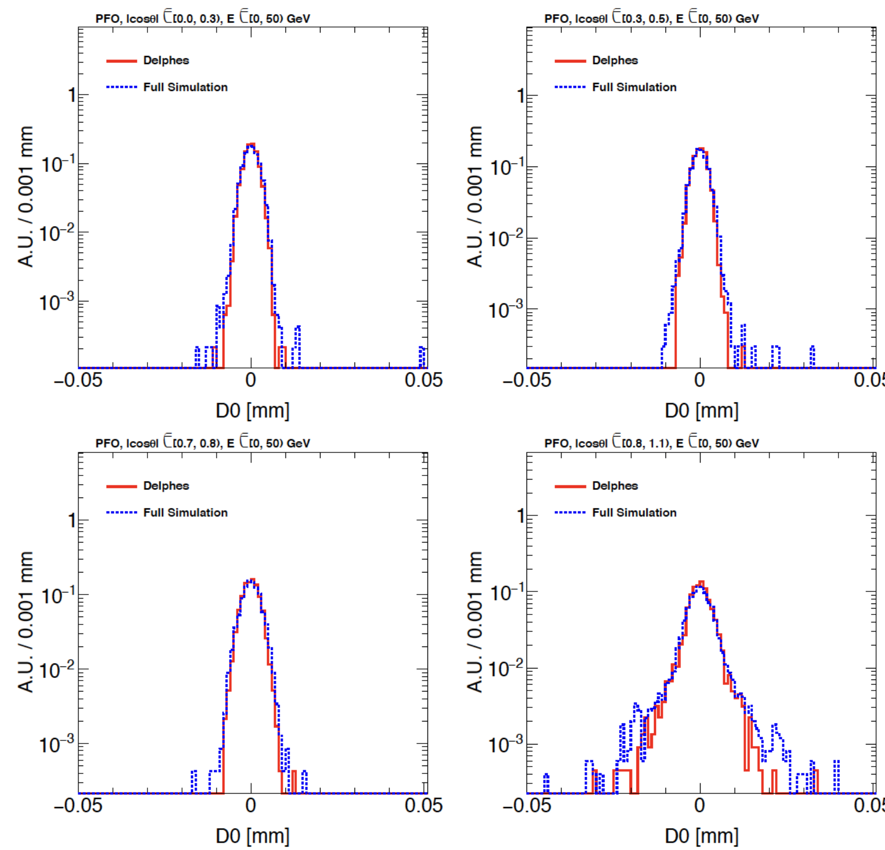




Fast/Full Simulation

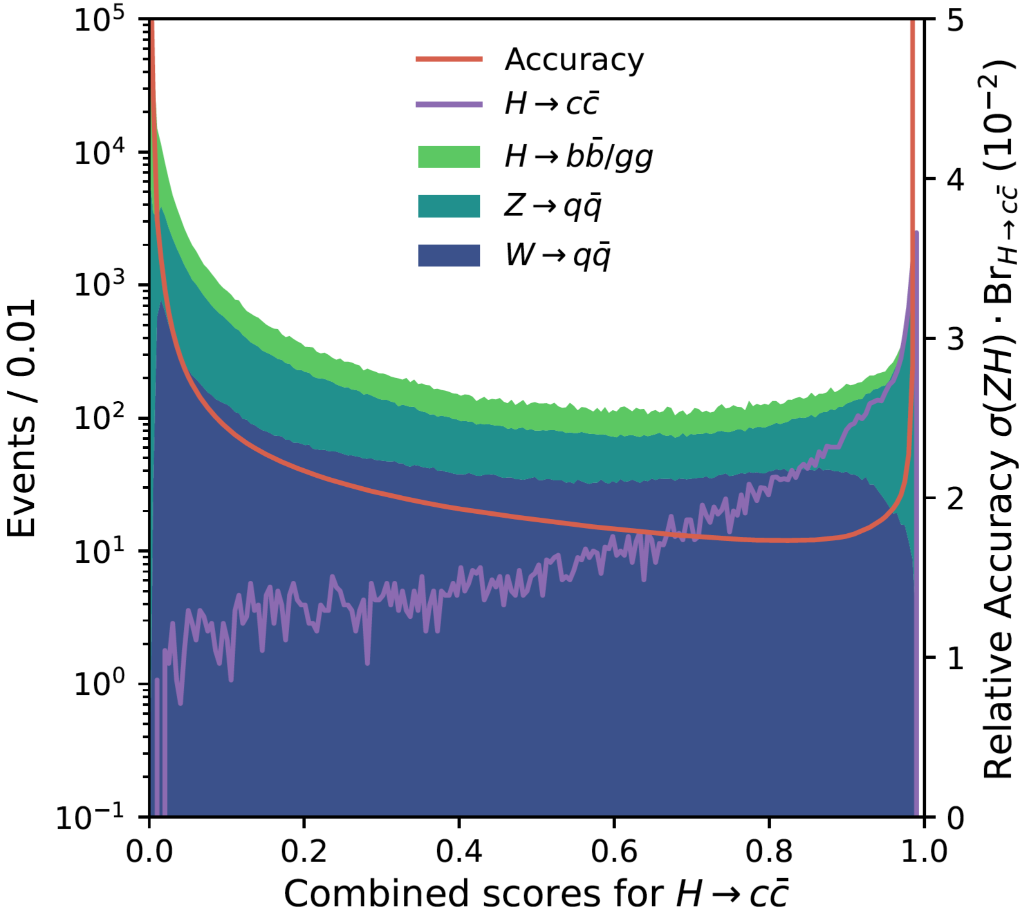


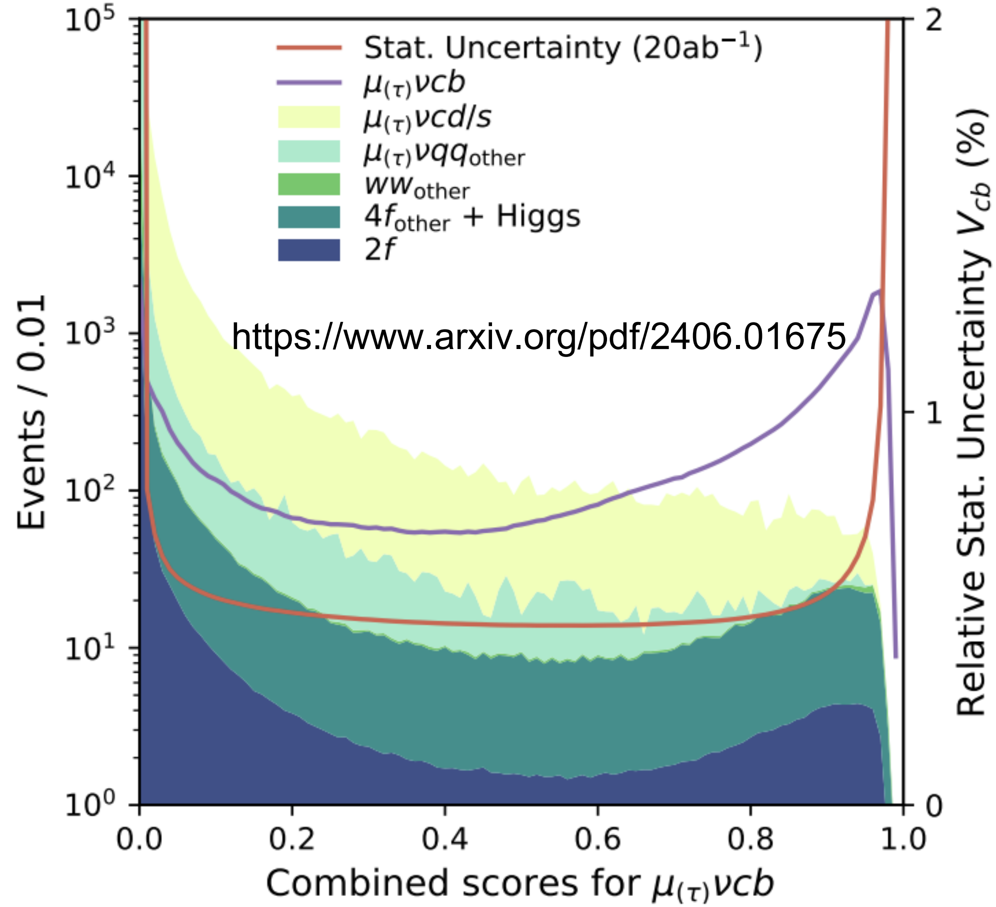
Z->μμ (91.2 GeV)



- Delphes ~ Perfect PFA (1 – 1 correspondence..)

Recent update at more benchmarks





- From Jet Flavor Tagging to Jet Origin ID:
  - vvH, H→cc: 3% → 1.7% (**Preliminary**)
  - Vcb: 0.75% → 0.45% (muvqq channel. evqq: 0.6%, combined 0.4%)

Updated result on $\sin^2\theta^l_{eff}$ measurement

Table 2. Sensitivity S of different final state particles.

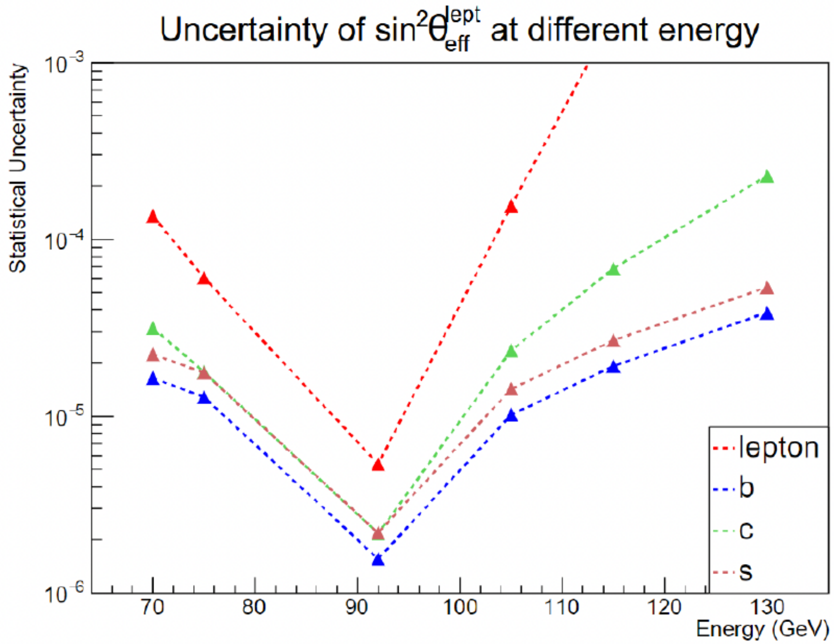
$\sqrt{s}$/GeV	S of $A^{e/\mu}_{FB}$	S of A^{d}_{FB}	S of A^{u}_{FB}	S of A^{s}_{FB}	S of A^{c}_{FB}	S of A^{b}_{FB}
70	0.224	4.396	1.435	4.403	1.445	4.352
75	0.530	5.264	2.598	5.269	2.616	5.237
92	1.644	5.553	4.200	5.553	4.201	5.549
105	0.269	4.597	1.993	4.598	1.994	4.586
115	0.035	3.956	1.091	3.958	1.087	3.942
130	0.027	3.279	0.531	3.280	0.520	3.261

Table 3. Cross section of process $e^+e^- \to f\bar{f}$ calculated using the ZFITTER package. Values of the fundamental parameters are set as $m_Z = 91.1875$ GeV, $m_t = 173.2$ GeV, $m_H = 125$ GeV, $\alpha_s = 0.118$ and $m_W = 80.38$ GeV.

$\sqrt{s}$/GeV	σ_μ/mb	σ_d/mb	σ_u/mb	σ_s/mb	σ_c/mb	σ_b/mb
70	0.039	0.032	0.066	0.031	0.058	0.028
75	0.039	0.047	0.073	0.046	0.065	0.043
92	1.196	5.366	4.228	5.366	4.222	5.268
105	0.075	0.271	0.231	0.271	0.227	0.265
115	0.042	0.135	0.122	0.135	0.118	0.132
130	0.026	0.071	0.068	0.071	0.066	0.069

Verify the RG behavior... using ~1 month of data taking

Expected statistical uncertainties on $\sin^2\theta^l_{eff}$ measurement.
(Using one-month data collection, ~ *4e12/24 Z events* at Z pole)

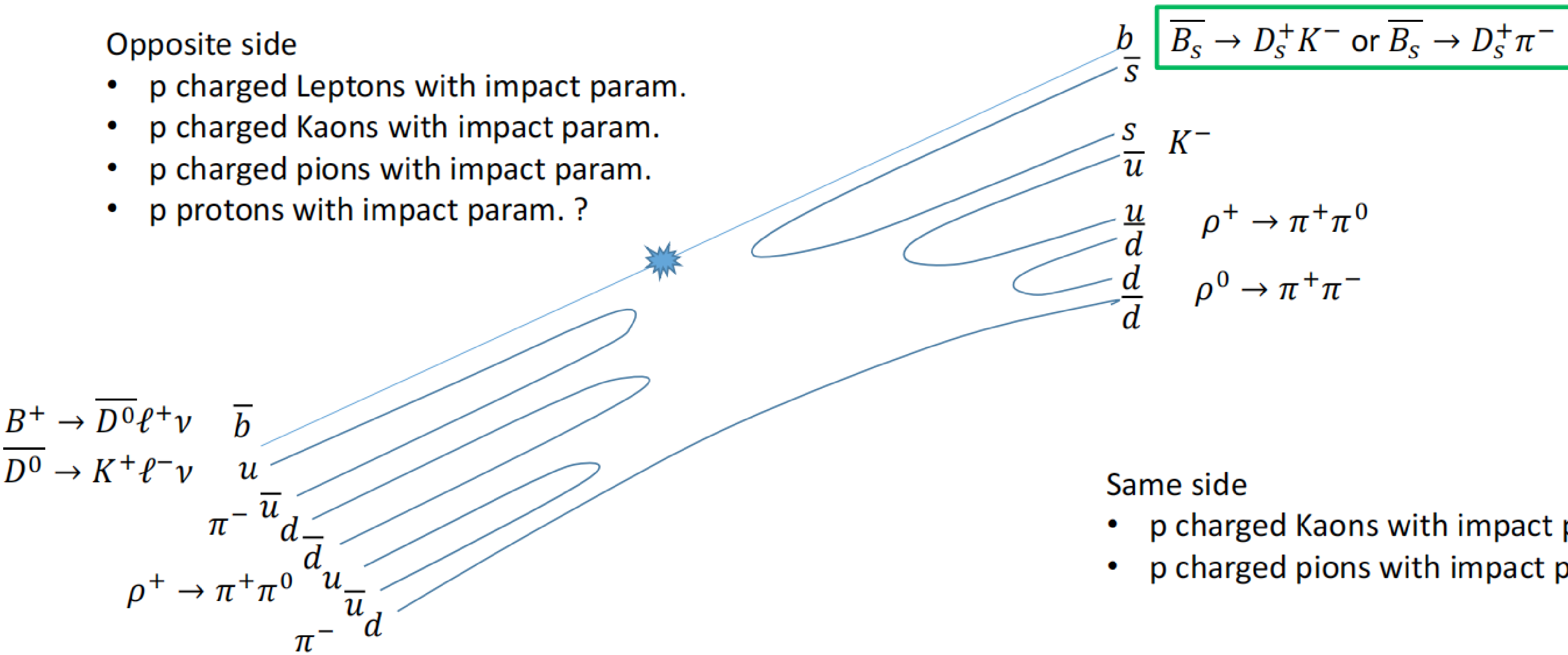


$\sqrt{s}$	b	c	s
70	1.6×10^{-5}	3.2×10^{-5}	2.2×10^{-5}
75	1.3×10^{-5}	1.8×10^{-5}	1.8×10^{-5}
92	1.6×10^{-6}	2.2×10^{-6}	2.2×10^{-6}
105	1.0×10^{-5}	2.4×10^{-5}	1.4×10^{-5}
115	1.9×10^{-5}	6.8×10^{-5}	2.7×10^{-5}
130	3.9×10^{-5}	2.3×10^{-4}	5.4×10^{-5}

B-charge flip rate: Bs oscillations

Opposite side

- p charged Leptons with impact param.
- p charged Kaons with impact param.
- p charged pions with impact param.
- p protons with impact param. ?

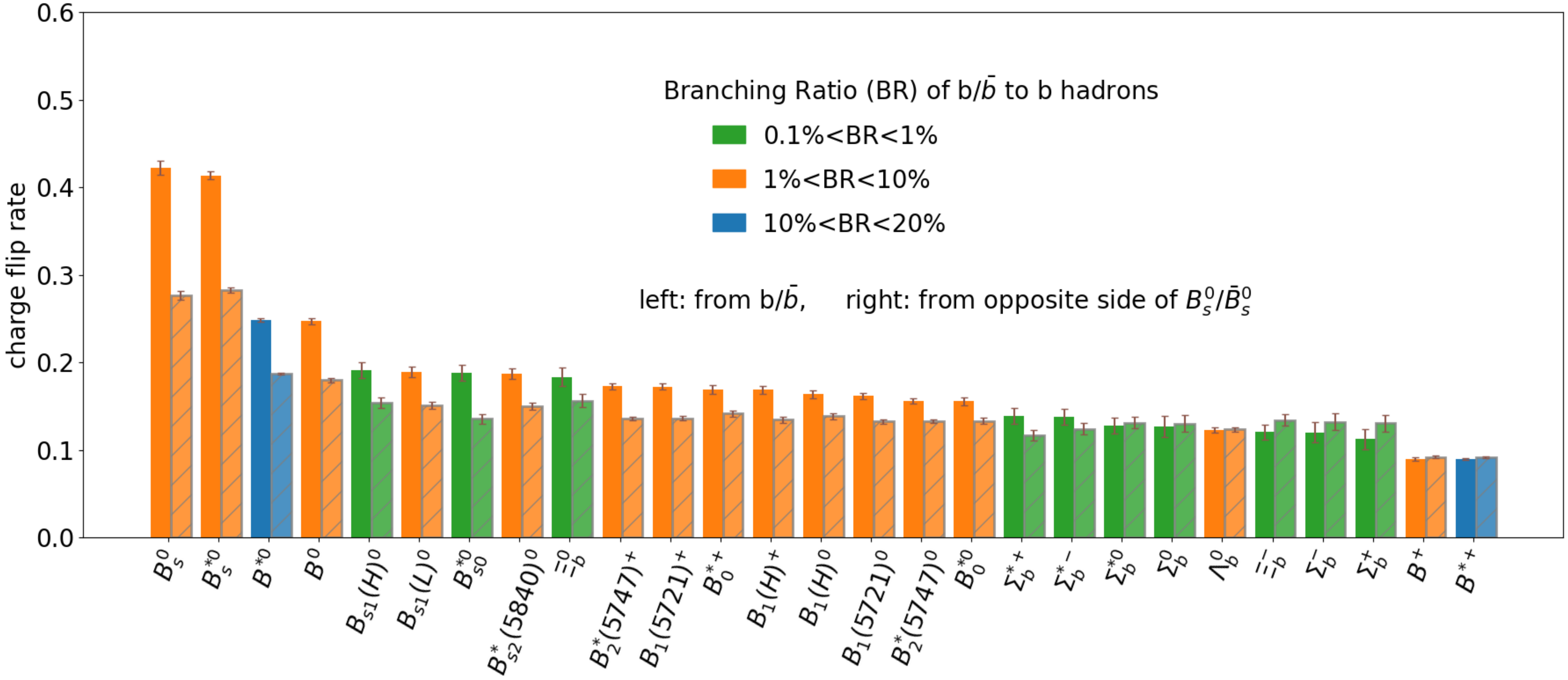


Same side

- p charged Kaons with impact param.
- p charged pions with impact param.

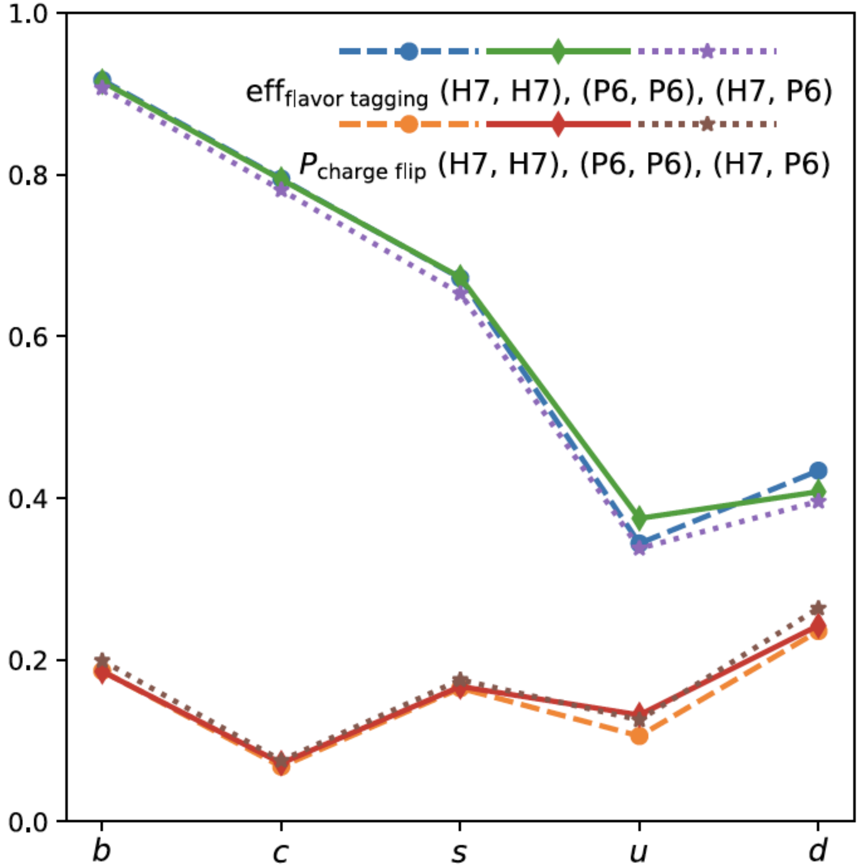
Roy. Aleksan, et. al @ CEA Saclay

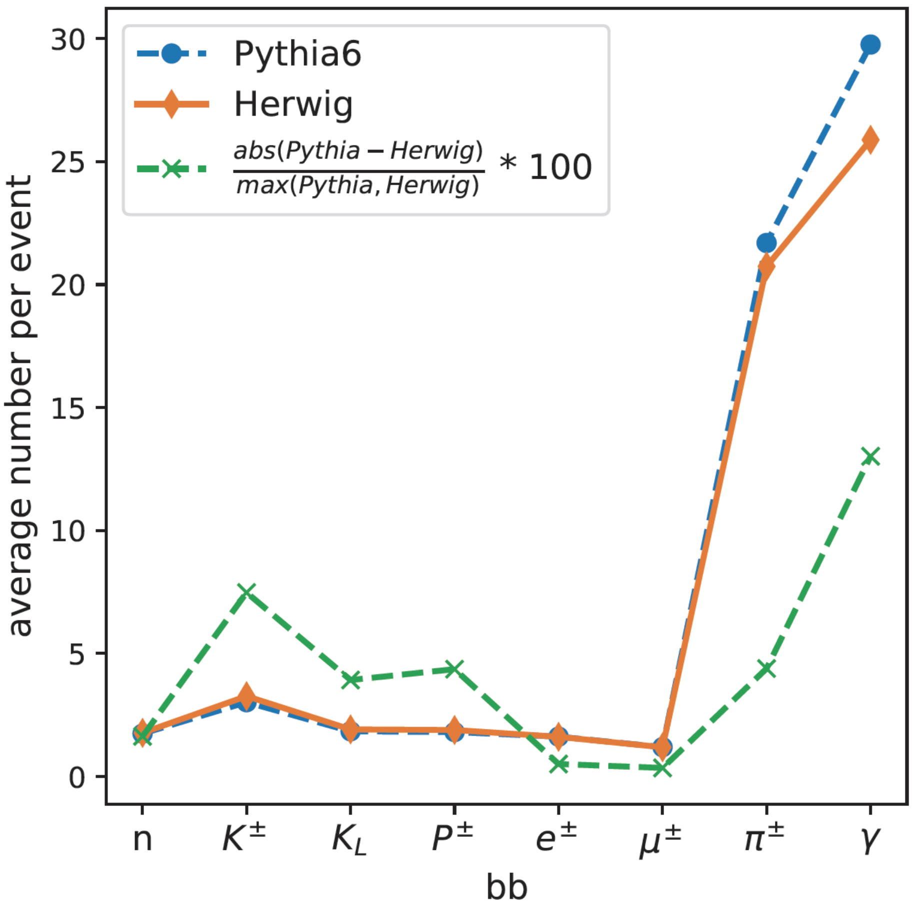
B-charge flip rate: Bs oscillations



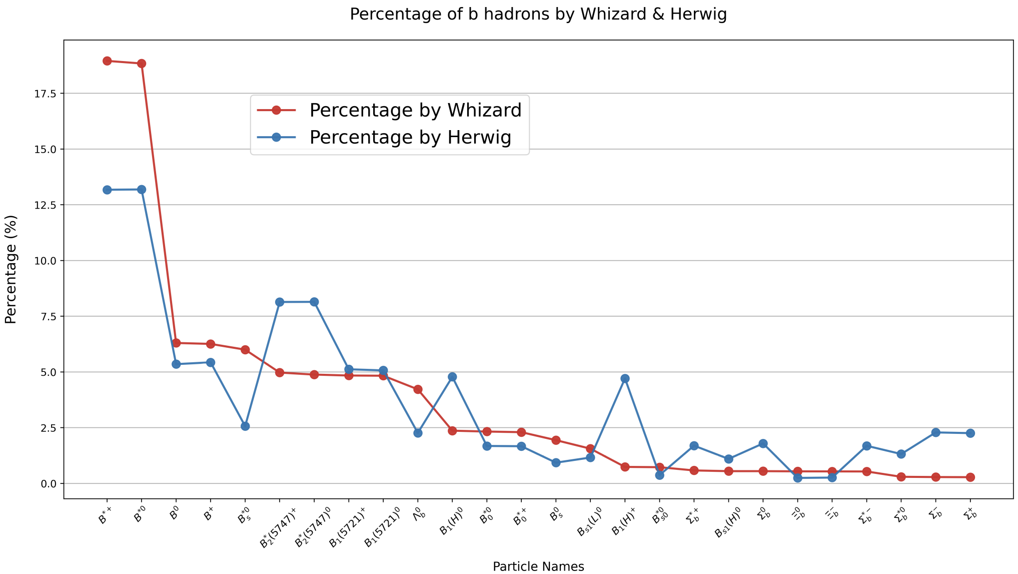
- Flip rate ~ 15%, Eff. Tagging power > 40%

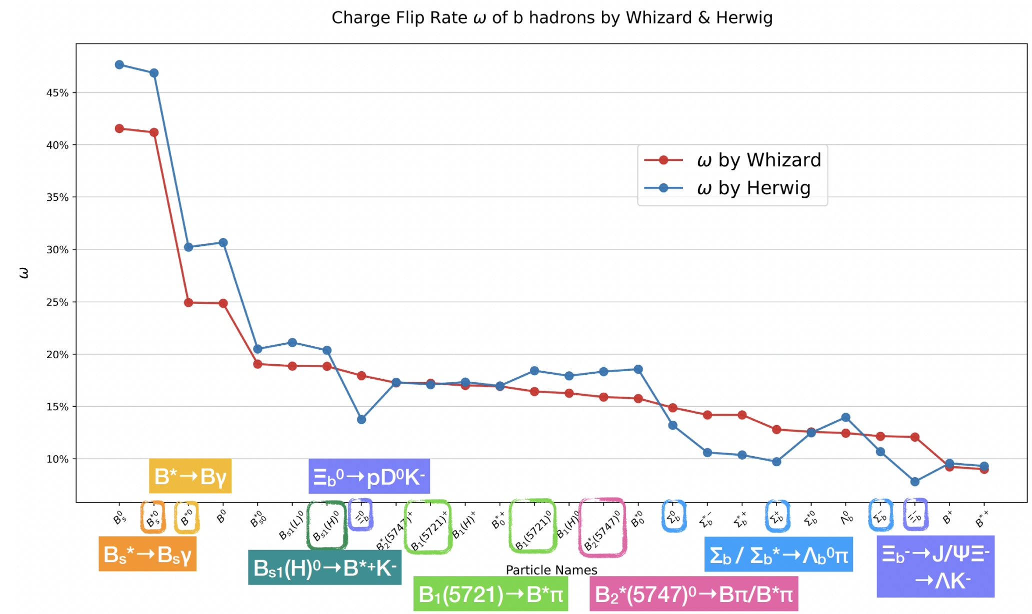
V.S. Hadronization models

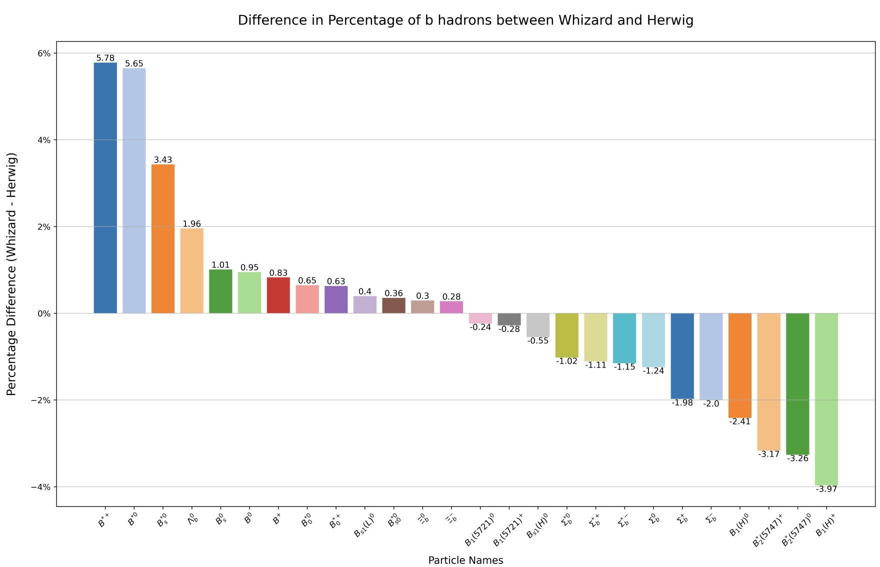


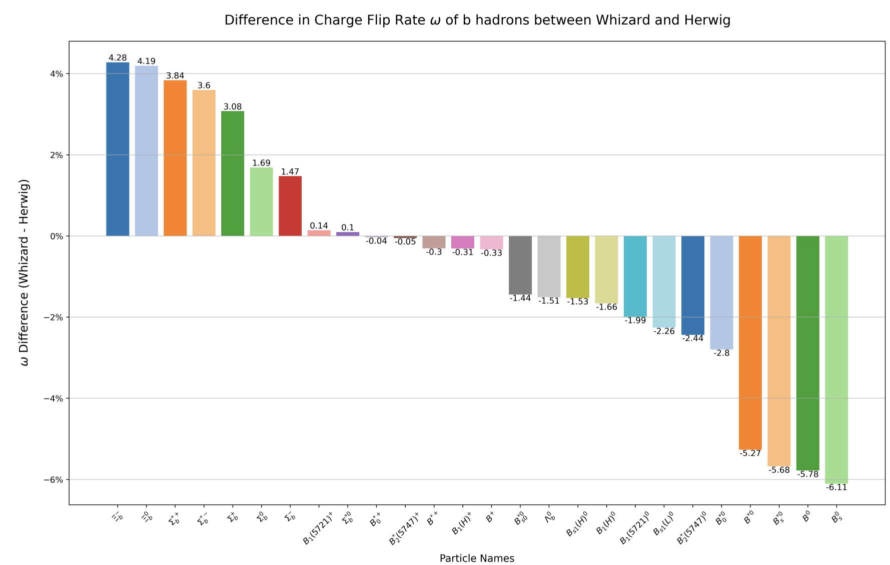


b-jet: leading b-hadrons & flip rates

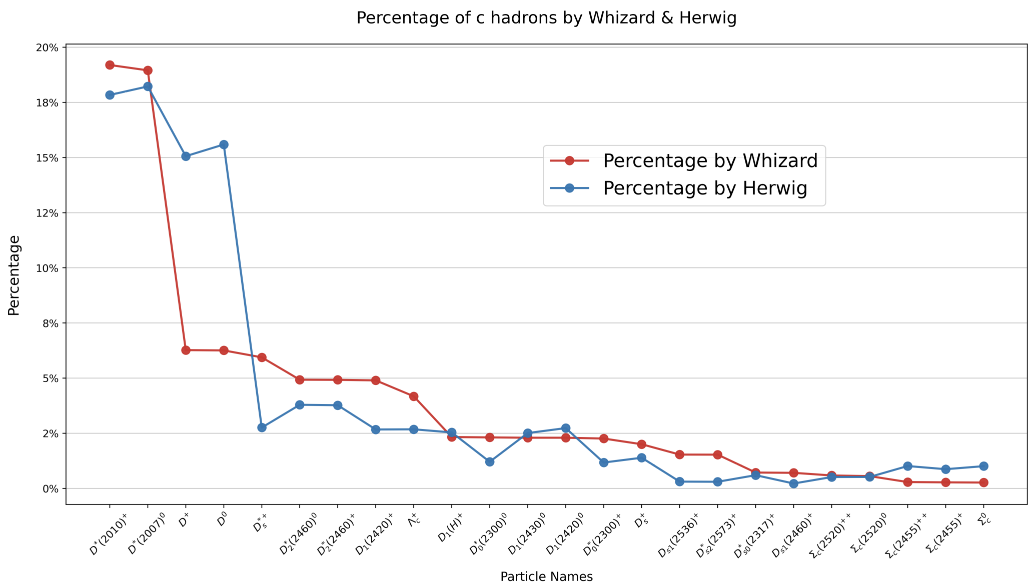


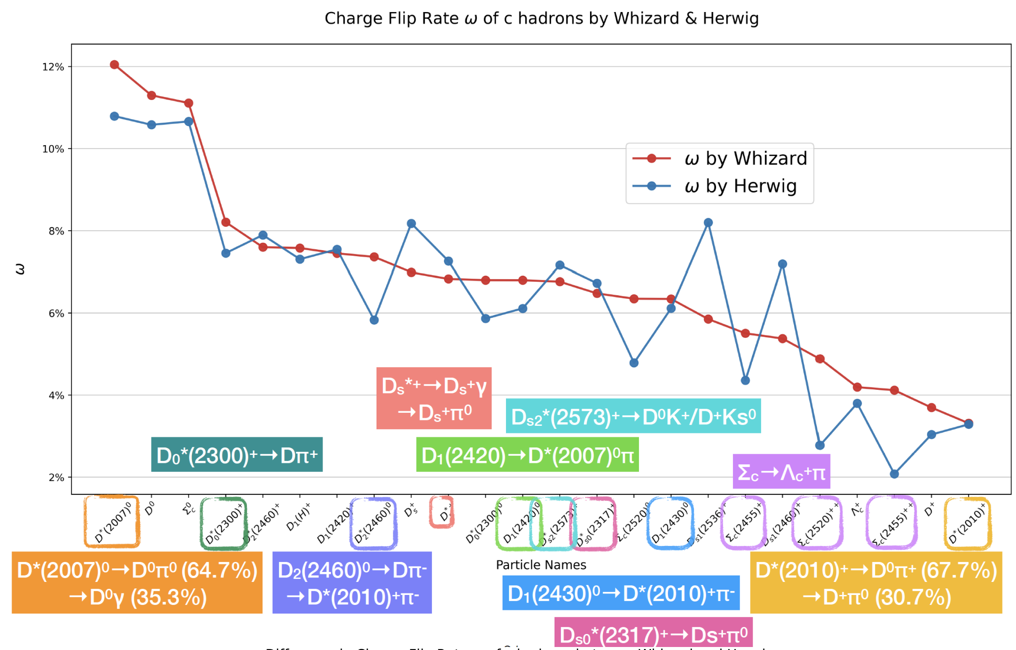


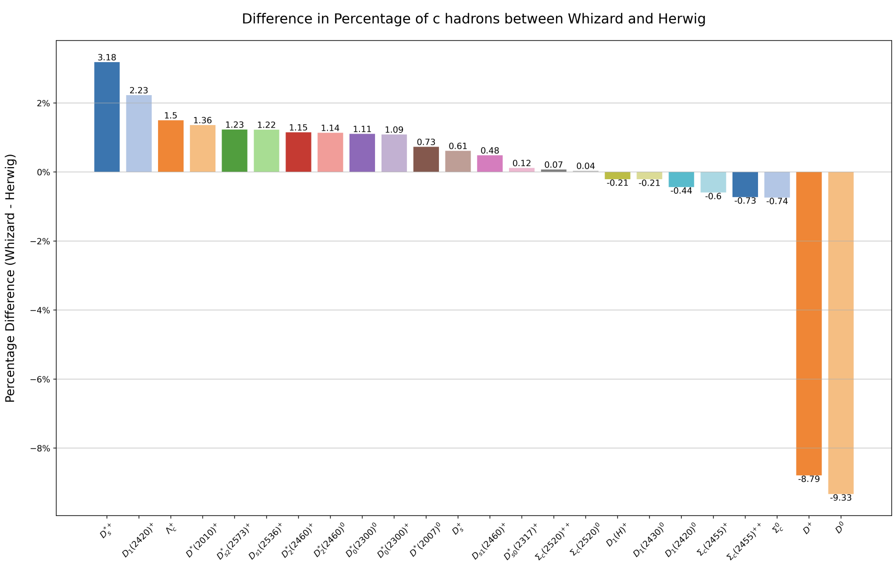


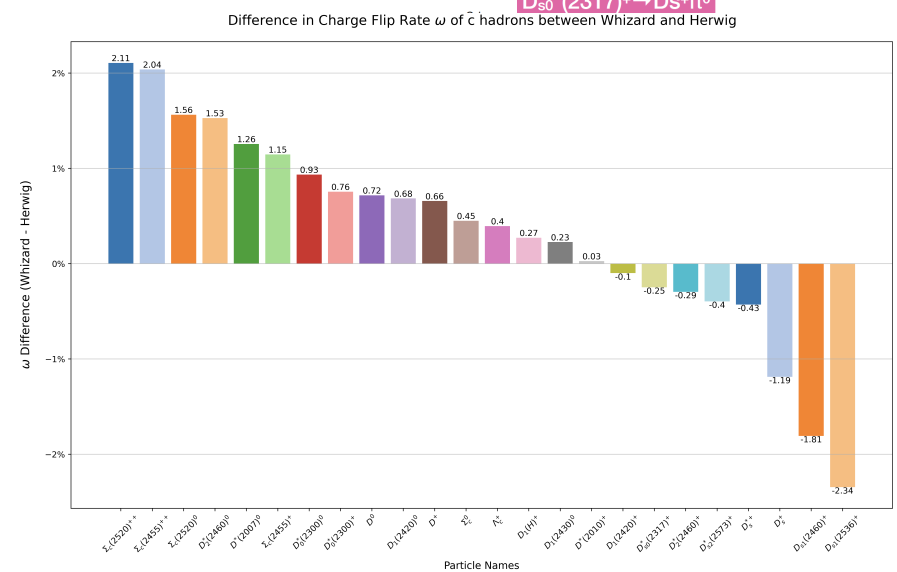


c-jet: leading c-hadrons & flip rates

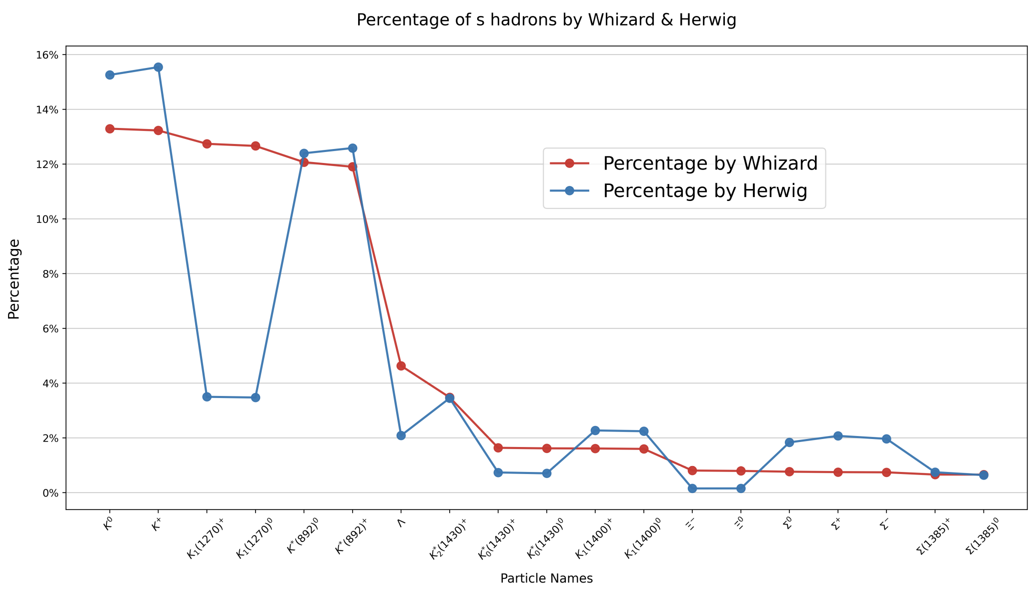


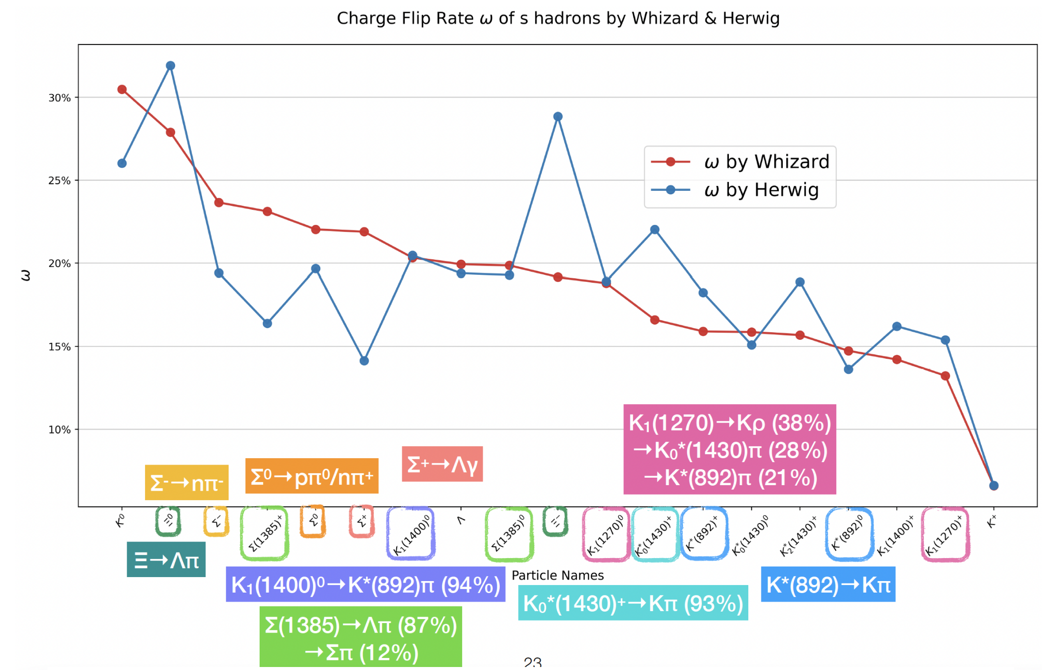


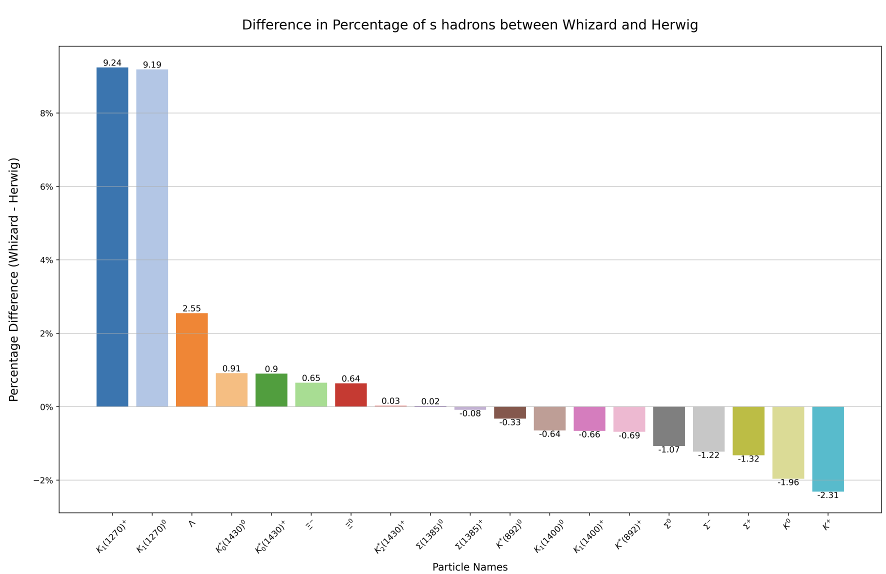


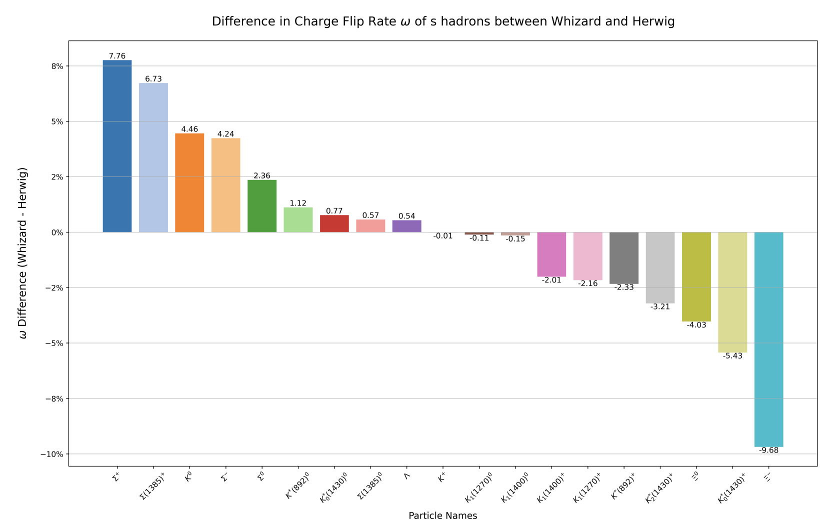


s-jet: leading s-hadrons & flip rates

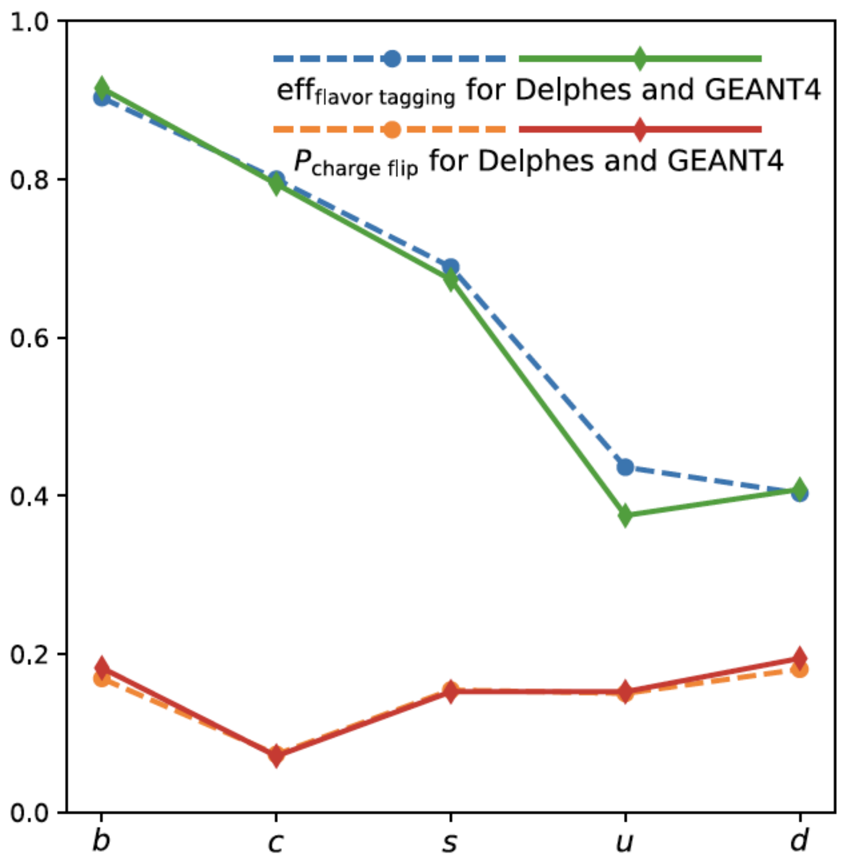




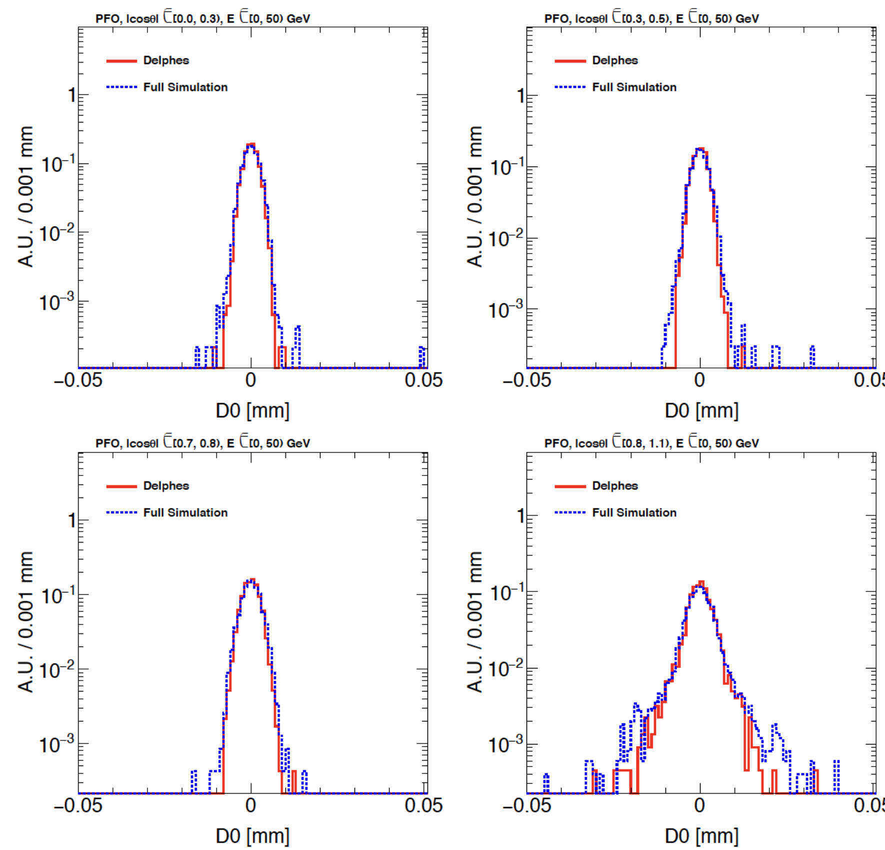




Fast/Full Simulation

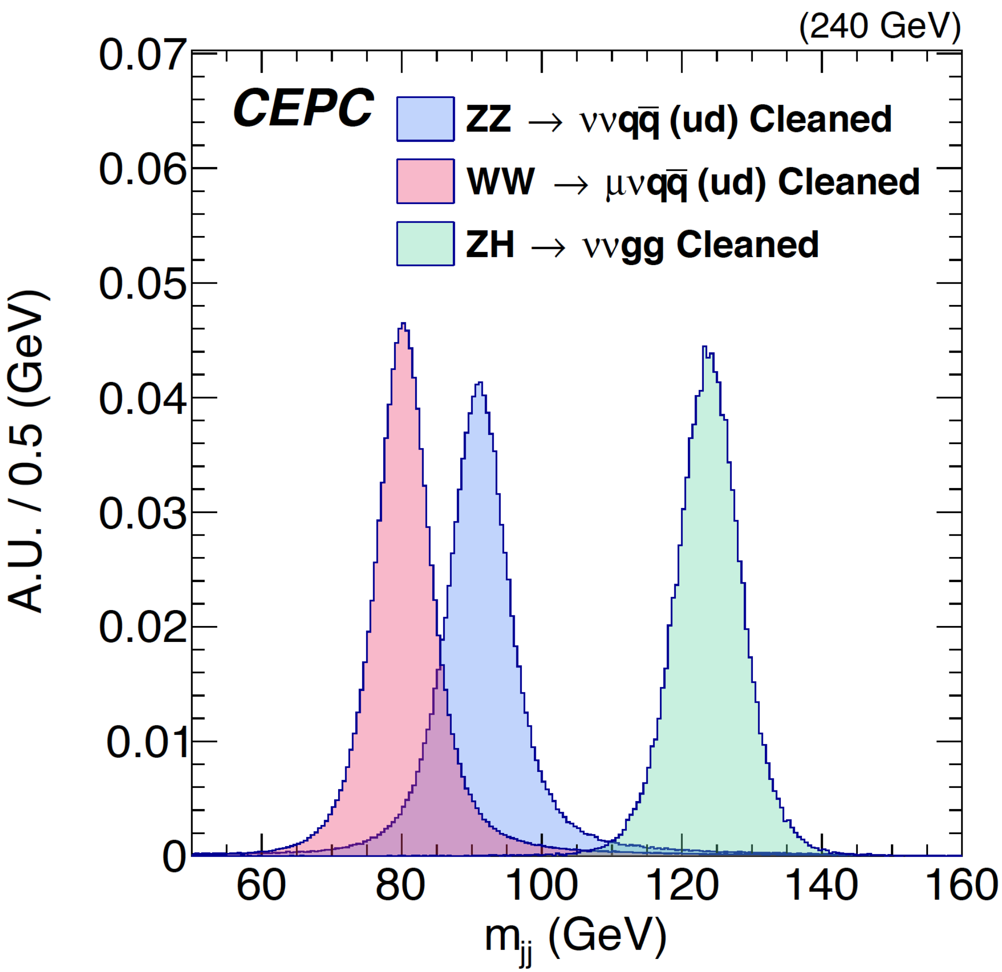


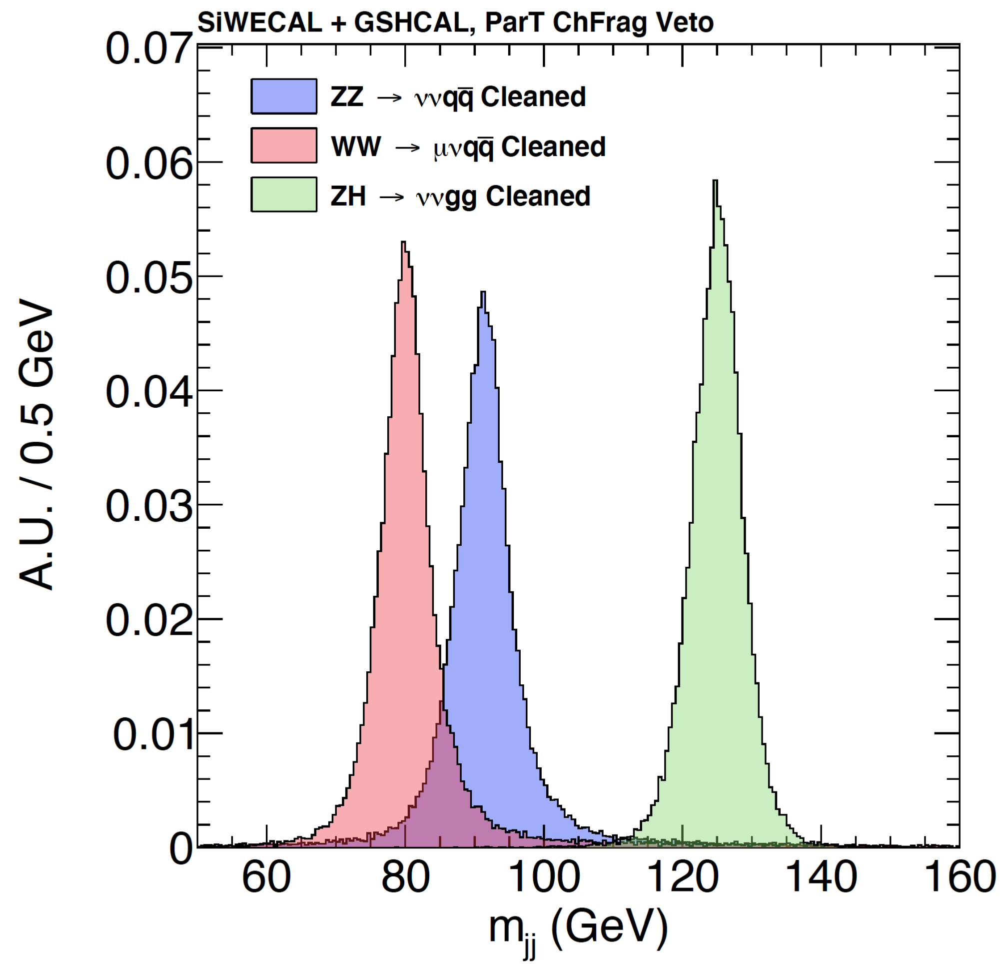
Z->μμ (91.2 GeV)



- Delphes ~ Perfect PFA (1 – 1 correspondence..)

... At Bosons Mass resolution...





Summary

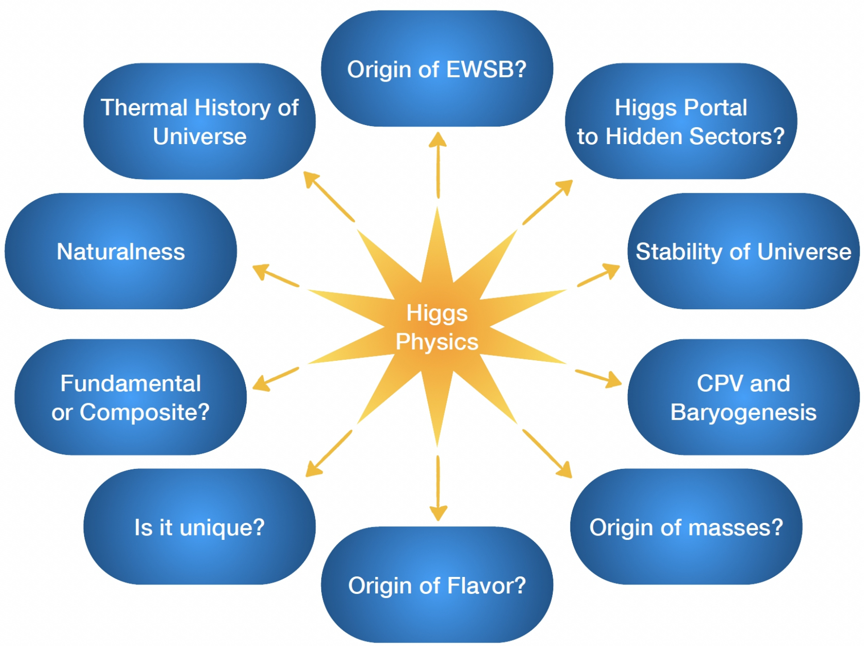
- CEPC: immense physics opportunities! Require excellent detector & reconstruction
- Jet origin id: efficiently separate different species of colored SM particle
  - A “game changer” and opens new horizon for precise flavor studies at all future experiments
- Significantly impact on physics
  - Higgs: improve $H\rightarrow ss$, uu, dd, sb, uc, sd, db by 3-100 times, and $H\rightarrow cc$ by 2 times
  - Flavor: Improve Vcb precision by ~50%, effective tagging power for b-jet > 40%...
  - EW: Weak mixing angle...
  - QCD: Fragmentation, etc...
  - NP: ...
- Jet Fragmentation : highly relevant,
  - **Road Map wanted**: towards better hadronization models + experimental validation (from both current data + GigaZ + TeraZ) + applications
- Long term version: 'see' gluon + quarks, as we see photon + leptons

Back up

Higgs white paper

Mystery Higgs sector

Snowmass 2021 US Community Study
on the Future of Particle Physics



Chinese Physics C Vol. 43, No. 4 (2019) 043002

Precision Higgs physics at the CEPC*

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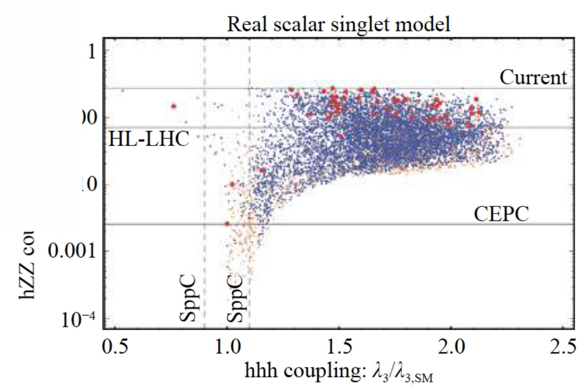

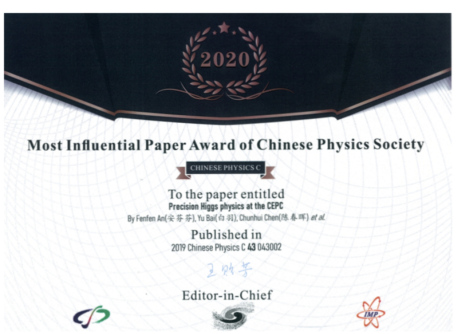

Snowmass White Paper

The Physics potential of the CEPC

Prepared for the US Snowmass Community Planning Exercise

(Snowmass 2021)

CEPC Physics Study Group

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ABSTRACT

The Circular Electron Positron Collider (CEPC) is a large-scale collider facility that can serve as a factory of the Higgs, Z, and W bosons and is upgradable to run at the $t\bar{t}$ threshold. This document describes the latest CEPC nominal operation scenario and particle yields and updates the corresponding physics potential. A new detector concept is also briefly described. This submission is for consideration by the Snowmass process.

CONTENTS

- Summarize ~ 20 citables for CEPC Snowmass studies

M11 2 with charged hadron

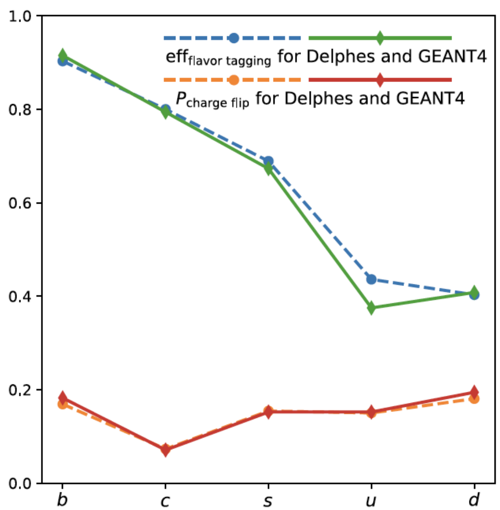
True \ Predicted	b	$\bar{b}$	c	$\bar{c}$	s	$\bar{s}$	u	$\bar{u}$	d	$\bar{d}$	G
b	0.738	0.167	0.034	0.026	0.005	0.003	0.002	0.003	0.002	0.002	0.018
$\bar{b}$	0.167	0.737	0.026	0.034	0.003	0.004	0.003	0.002	0.002	0.003	0.018
c	0.015	0.015	0.740	0.057	0.037	0.032	0.026	0.010	0.009	0.017	0.043
$\bar{c}$	0.015	0.015	0.055	0.741	0.032	0.037	0.010	0.026	0.016	0.010	0.043
s	0.003	0.003	0.020	0.018	0.541	0.104	0.030	0.082	0.062	0.045	0.092
$\bar{s}$	0.002	0.003	0.018	0.021	0.101	0.543	0.085	0.028	0.044	0.062	0.092
u	0.002	0.003	0.019	0.012	0.044	0.132	0.375	0.057	0.079	0.168	0.109
$\bar{u}$	0.003	0.002	0.011	0.020	0.132	0.043	0.062	0.368	0.166	0.084	0.108
d	0.003	0.003	0.012	0.020	0.111	0.093	0.083	0.223	0.261	0.080	0.110
$\bar{d}$	0.003	0.003	0.020	0.013	0.093	0.113	0.226	0.079	0.076	0.265	0.110
G	0.015	0.014	0.025	0.025	0.053	0.053	0.043	0.044	0.033	0.035	0.661

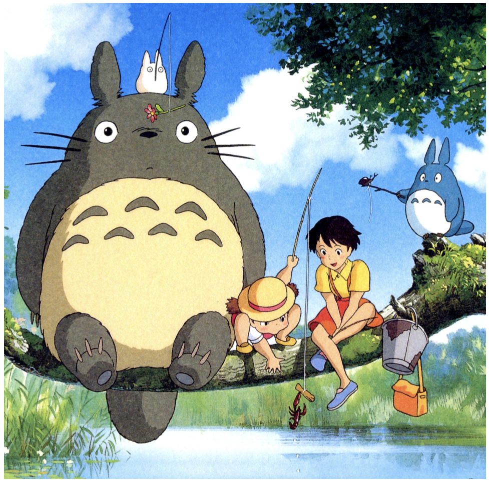
M11 3 with charged hadron and K_L K_S

True \ Predicted	b	$\bar{b}$	c	$\bar{c}$	s	$\bar{s}$	u	$\bar{u}$	d	$\bar{d}$	G
b	0.748	0.159	0.034	0.024	0.004	0.003	0.002	0.003	0.002	0.002	0.018
$\bar{b}$	0.158	0.749	0.025	0.034	0.003	0.005	0.003	0.002	0.002	0.003	0.017
c	0.016	0.014	0.752	0.053	0.040	0.034	0.020	0.008	0.008	0.017	0.038
$\bar{c}$	0.015	0.016	0.053	0.749	0.034	0.041	0.008	0.020	0.017	0.009	0.039
s	0.003	0.002	0.021	0.019	0.607	0.110	0.020	0.056	0.044	0.041	0.077
$\bar{s}$	0.003	0.003	0.019	0.023	0.107	0.609	0.057	0.019	0.041	0.043	0.078
u	0.002	0.003	0.016	0.009	0.032	0.104	0.378	0.057	0.093	0.197	0.108
$\bar{u}$	0.003	0.002	0.009	0.016	0.102	0.032	0.062	0.371	0.202	0.094	0.108
d	0.003	0.002	0.010	0.016	0.076	0.074	0.087	0.201	0.335	0.086	0.110
$\bar{d}$	0.003	0.003	0.016	0.009	0.075	0.076	0.210	0.083	0.086	0.330	0.110
G	0.015	0.015	0.024	0.024	0.051	0.050	0.042	0.042	0.040	0.041	0.657

0.7-0.8
0.65-0.7
0.6-0.65
0.5-0.6
0.4-0.5
0.35-0.4
0.3-0.35
0.25-0.3
0.2-0.25
0.15-0.2
0.1-0.15
0.09-0.1
0.085-0.09
0.08-0.085
0.075-0.08
0.07-0.075
0.06-0.07
0.05-0.06
0.04-0.05
0.03-0.04
0.02-0.03
0.01-0.02
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001

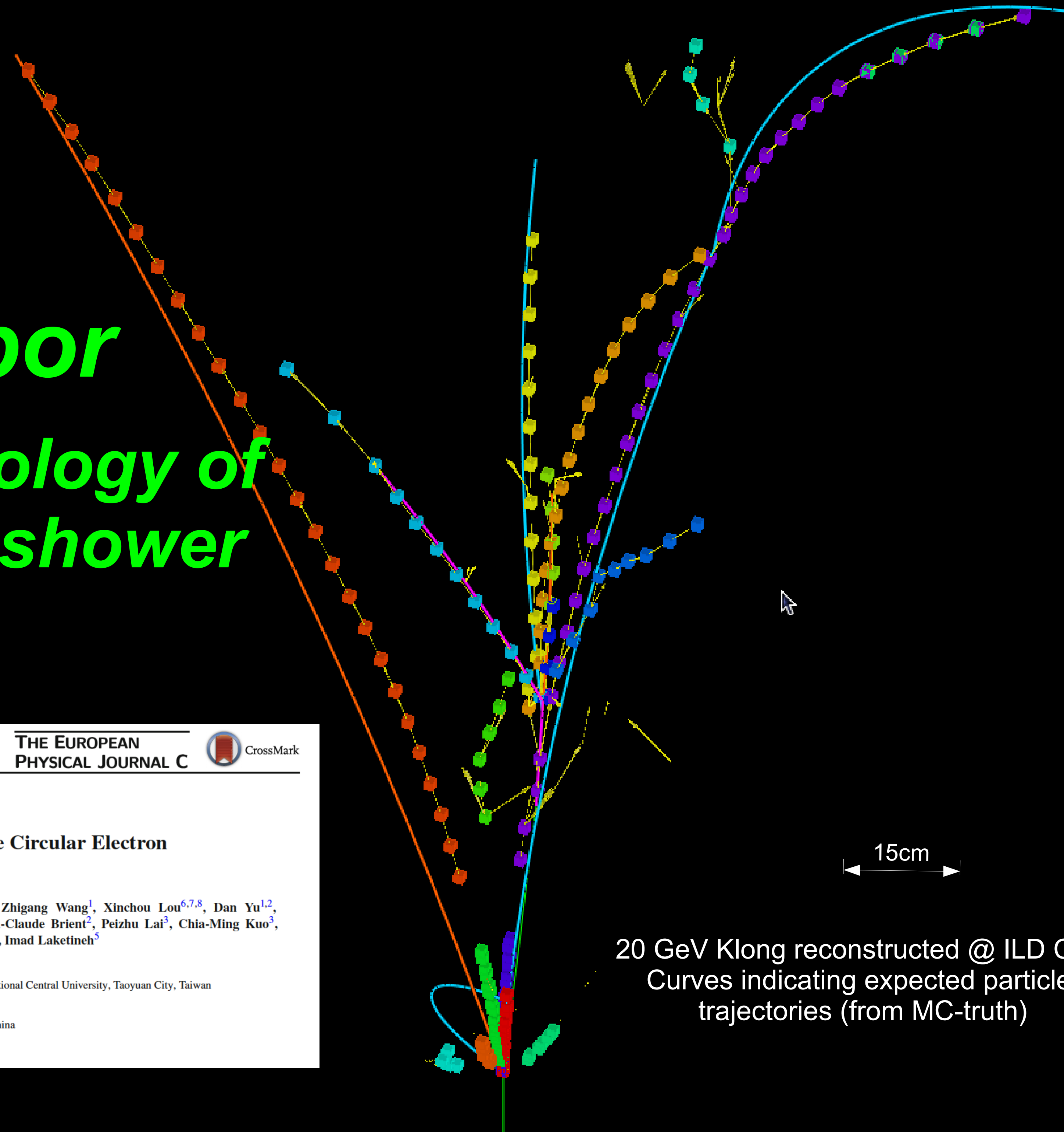
Arbor PFA: Towards one-to-one correspondence (Totoro)





Arbor

Tree topology of particle shower



20 GeV Klong reconstructed @ ILD Calo
Curves indicating expected particle trajectories (from MC-truth)

Eur. Phys. J. C (2018) 78:426
https://doi.org/10.1140/epjc/s10052-018-5876-z

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Special Article - Tools for Experiment and Theory

Reconstruction of physics objects at the Circular Electron Positron Collider with Arbor

Manqi Ruan[1,a], Hang Zhao[1], Gang Li[1], Chengdong Fu[1], Zhigang Wang[1], Xinchou Lou[6,7,8], Dan Yu[1,2], Vincent Boudry[2], Henri Videau[2], Vladislav Balagura[2], Jean-Claude Brient[2], Peizhu Lai[3], Chia-Ming Kuo[3], Bo Liu[1,4], Fenfen An[1,4], Chunhui Chen[4], Soeren Prell[4], Bo Li[5], Imad Laktineh[5]

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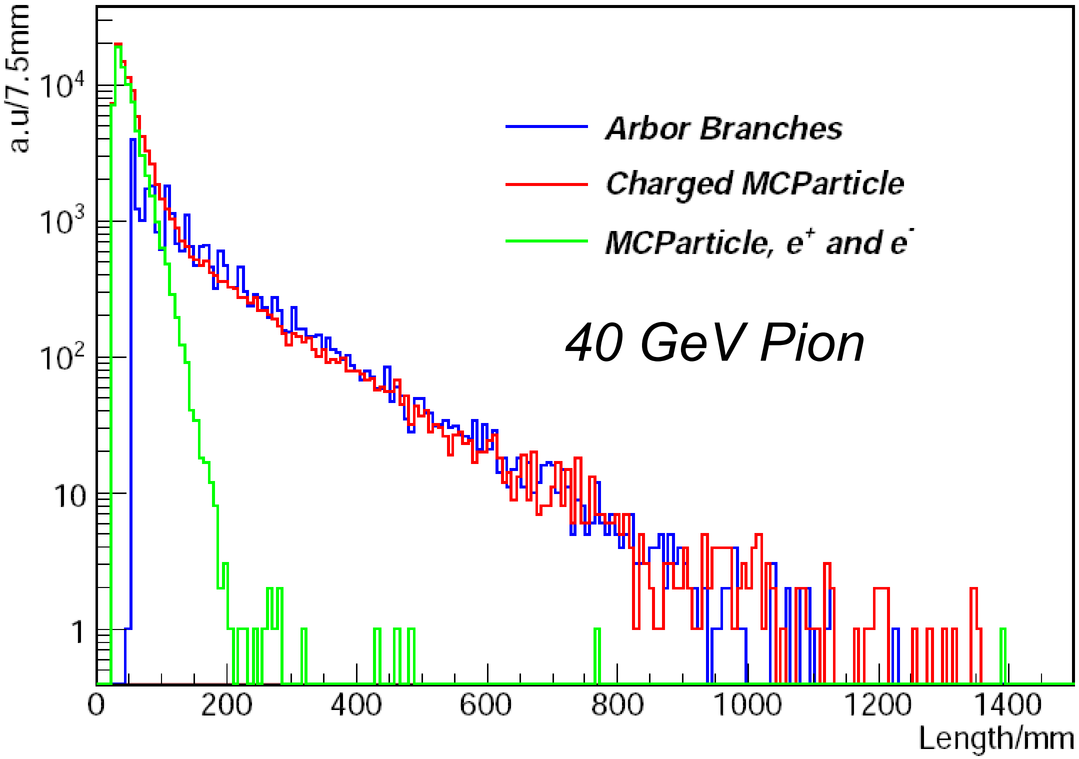
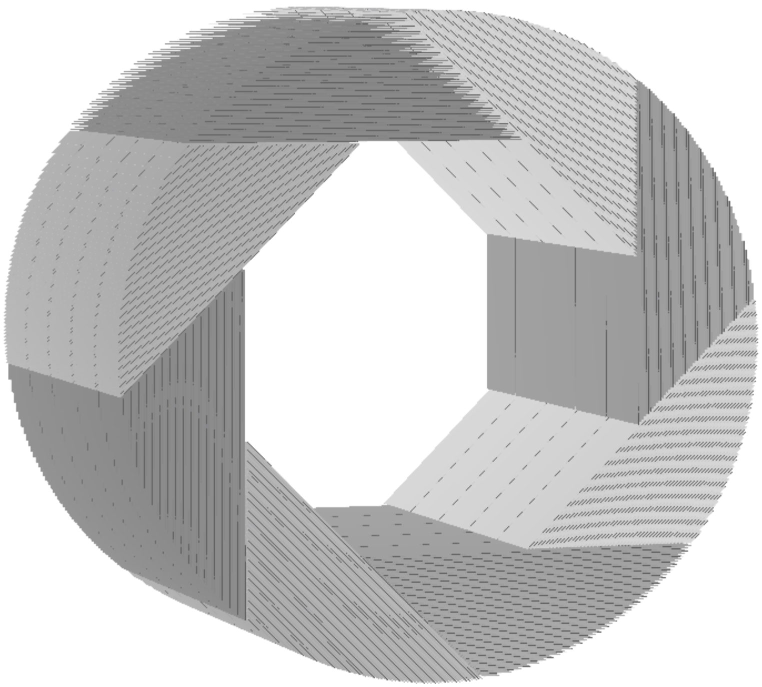
[3] Department of Physics and Center of high energy and high field physics, National Central University, Taoyuan City, Taiwan
[4] Iowa State University, Ames, USA
[5] Institute de Physique Nucleaire de Lyon, Lyon, France
[6] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
[7] Physics Department, University of Texas at Dallas, Richardson, TX, USA
[8] University of Chinese Academy of Sciences (UCAS), Beijing, China

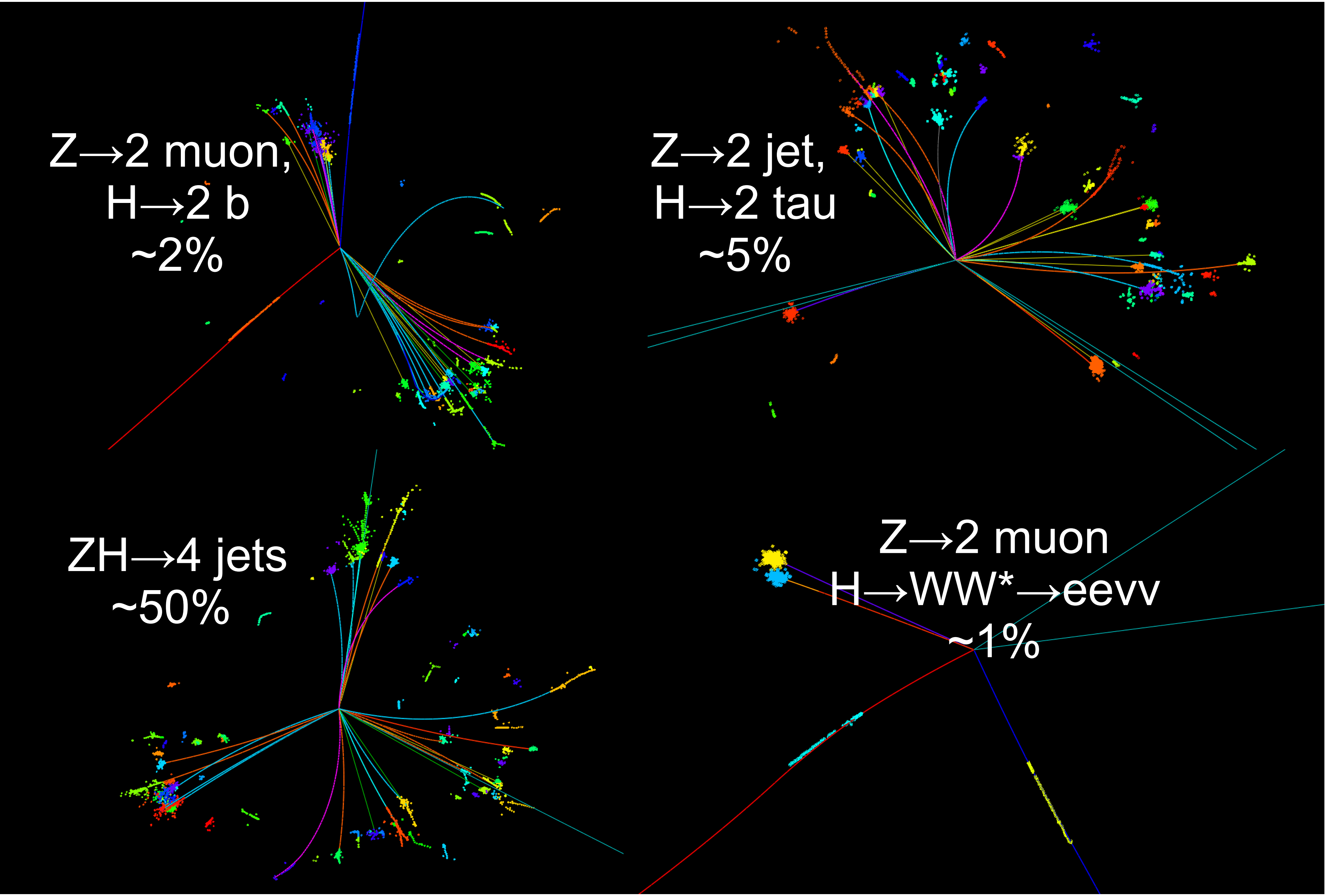
Validation: Arbor Branch Length Vs MC Truth



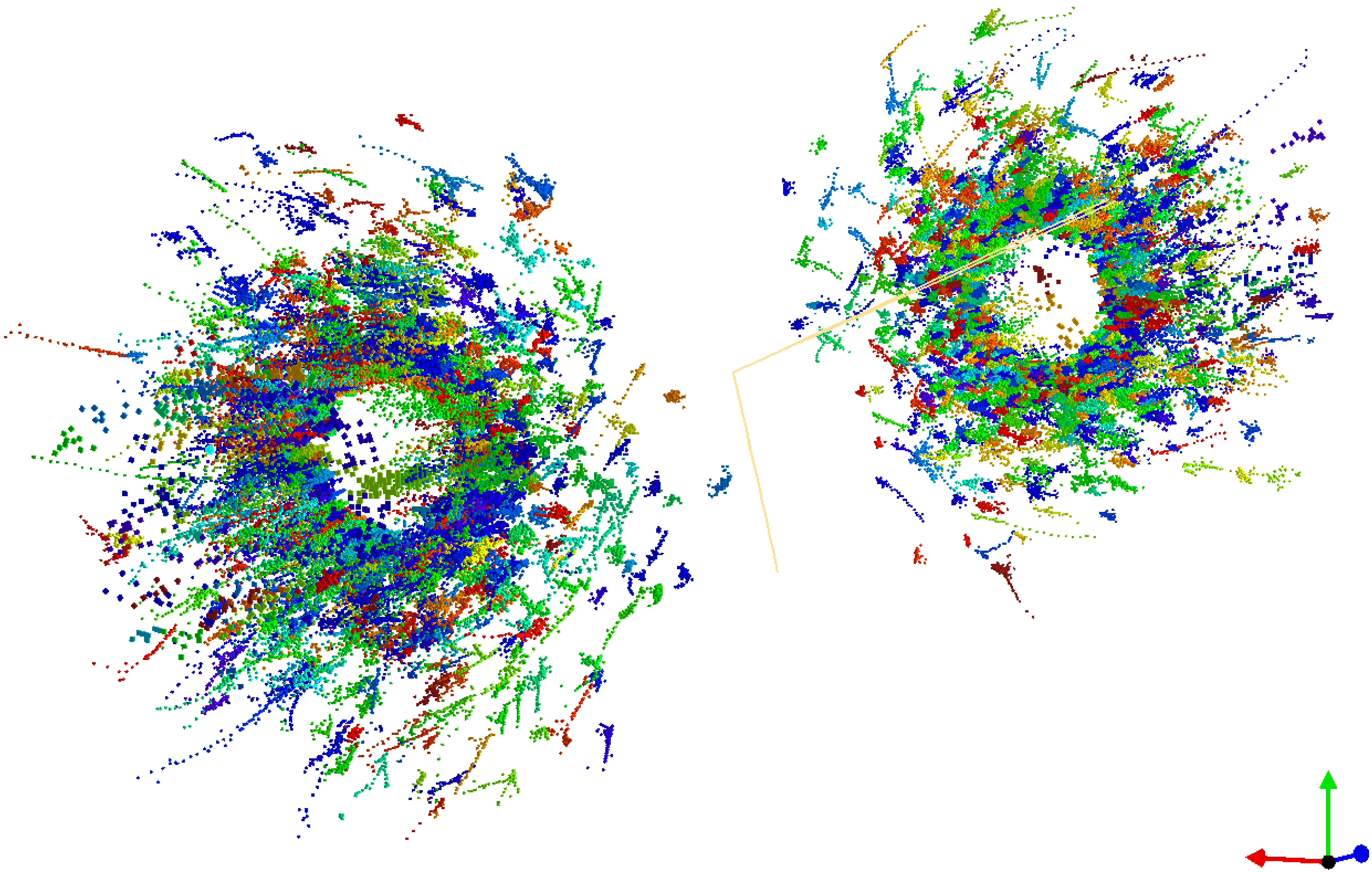


Arbor: successfully tag sub-shower structure

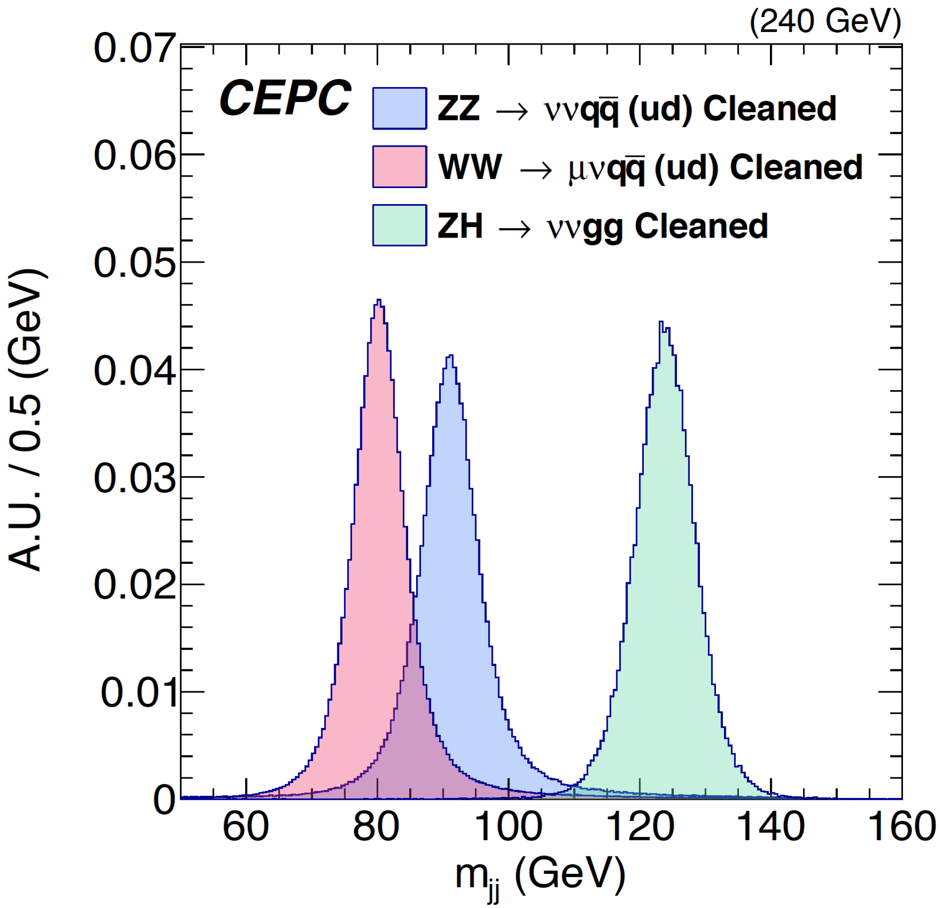
Samples: Particle gun event at ILD HCAL (readout granularity 1cm^2 & layer thickness 2.65cm)
Length:
Charged MCParticle: spatial distance between generation/end points
Arbor branch: sum of distance between neighboring cells

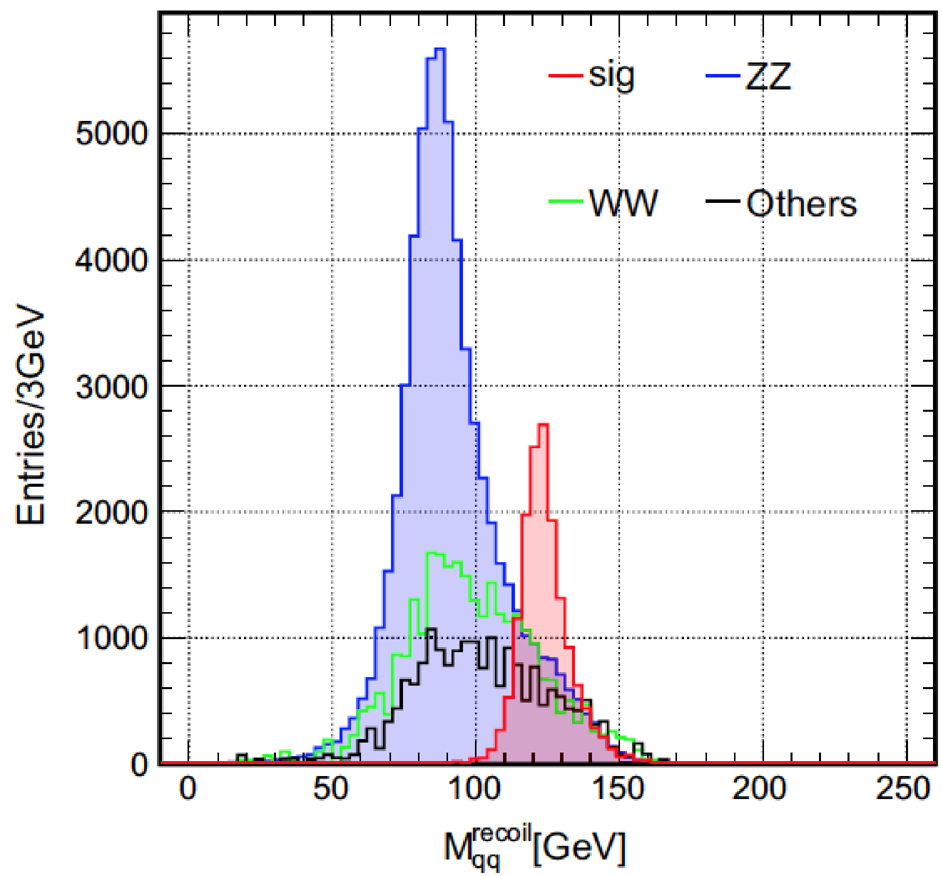

Z→2 muon,
H→2 b
~2%
Z→2 jet,
H→2 tau
~5%
ZH→4 jets
~50%
Z→2 muon
H→WW*→eevv
~1%

CMS Experiment at LHC, CERN
Data recorded: Thu Jan 1 01:00:00 1970 CEST
Run/Event: 1 / 1201
Lumi section: 13

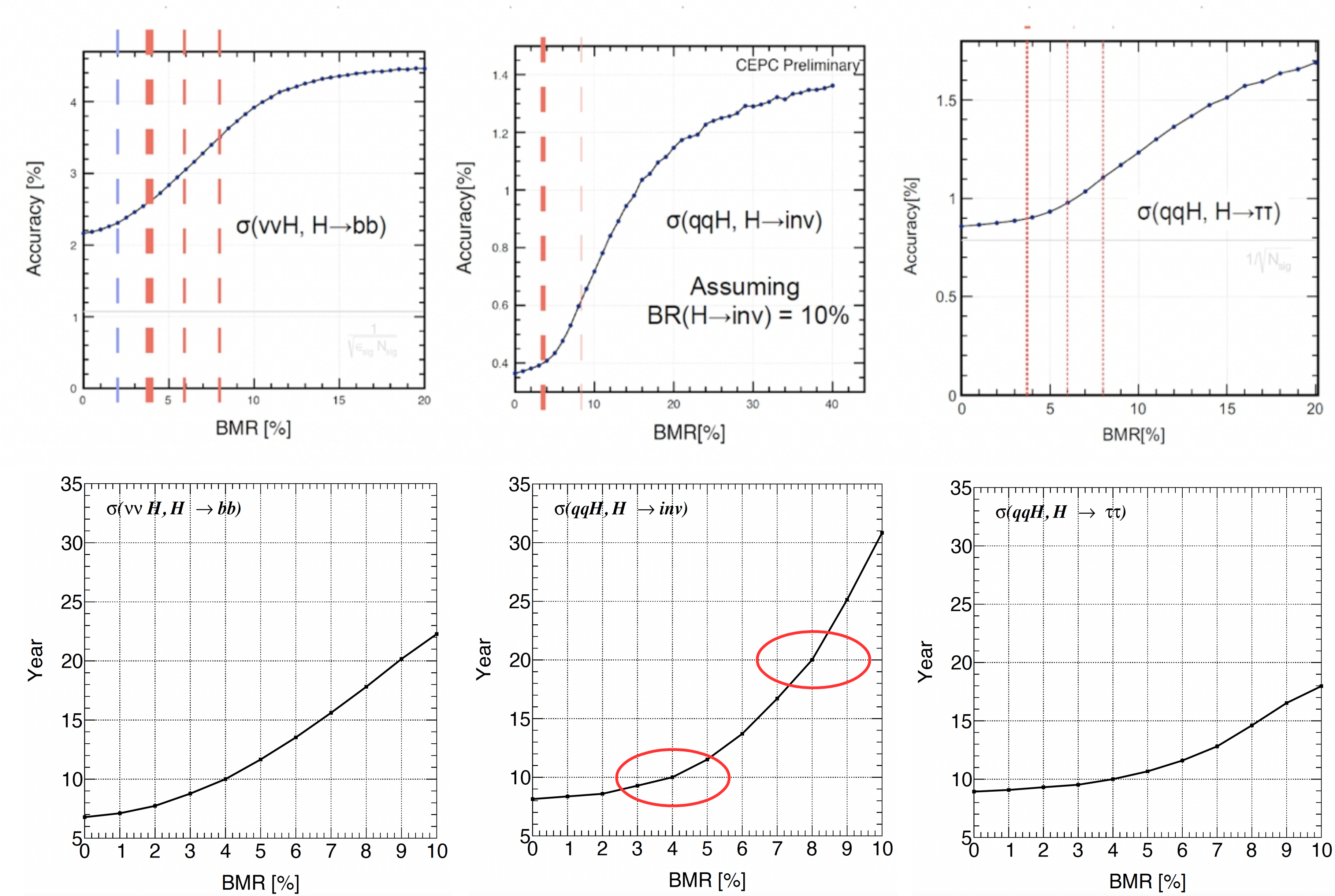


Boson Mass Resolution: Key Per. Para

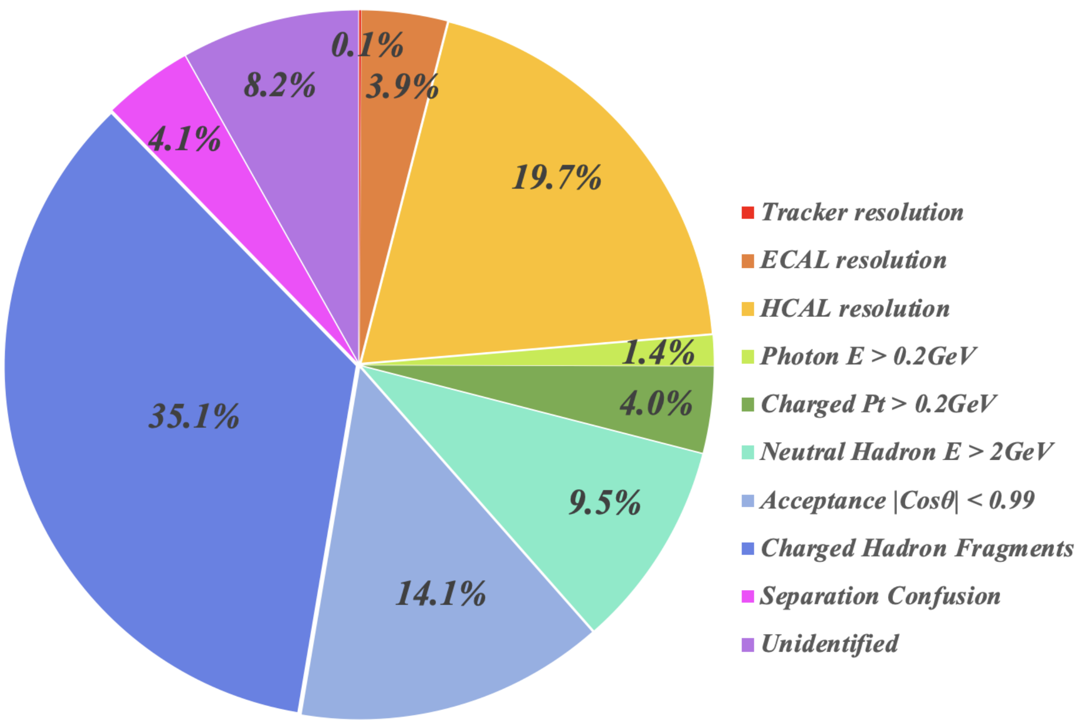




BMR: impact on critical measurements



BMR decomposition @ CDR baseline



- *1st, Ultimate Precision ~ 2.8 with CDR baseline3rd, HCAL*
- *2nd, HCAL resolution dominant the uncertainties from intrinsic detector resolution: need better HCAL*
- *3rd Leading contribution: Confusion from shower Fragments (fake particles), need better Pattern Reco.*

Improving HCAL:

RPC Digital HCAL → GSHCAL

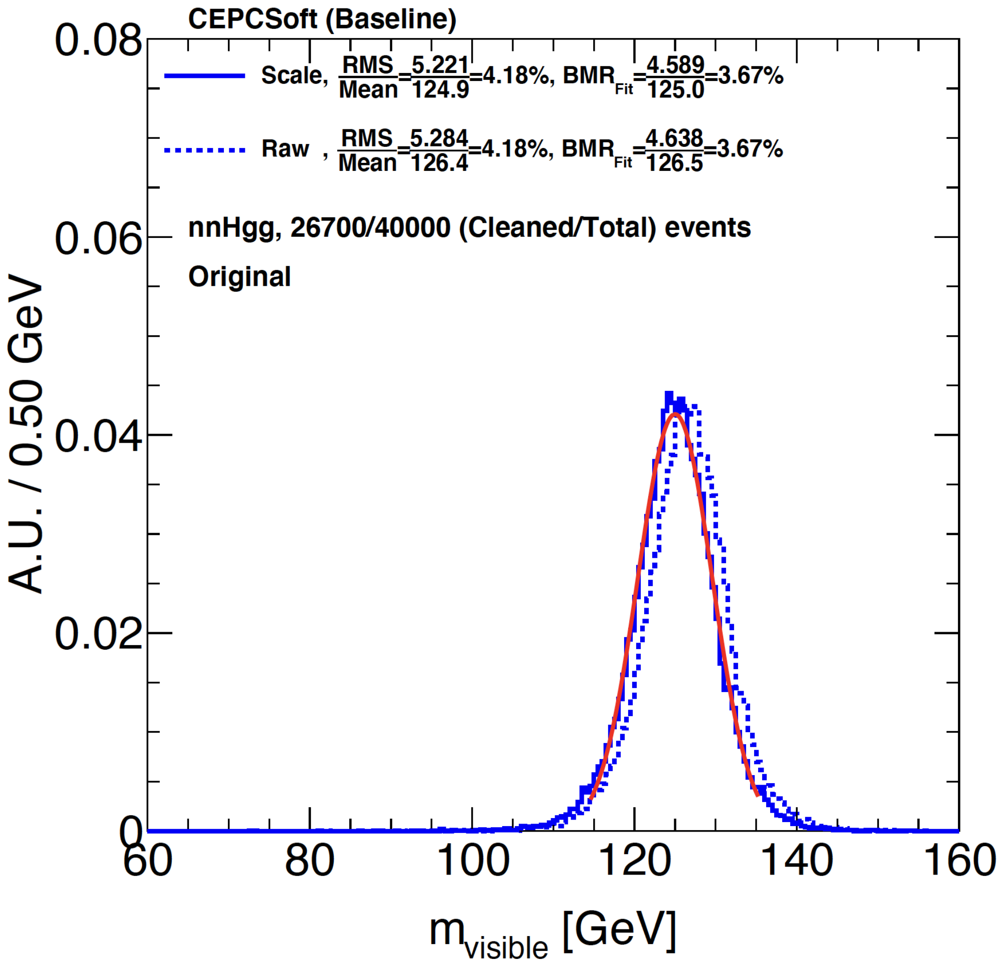
Remarks:

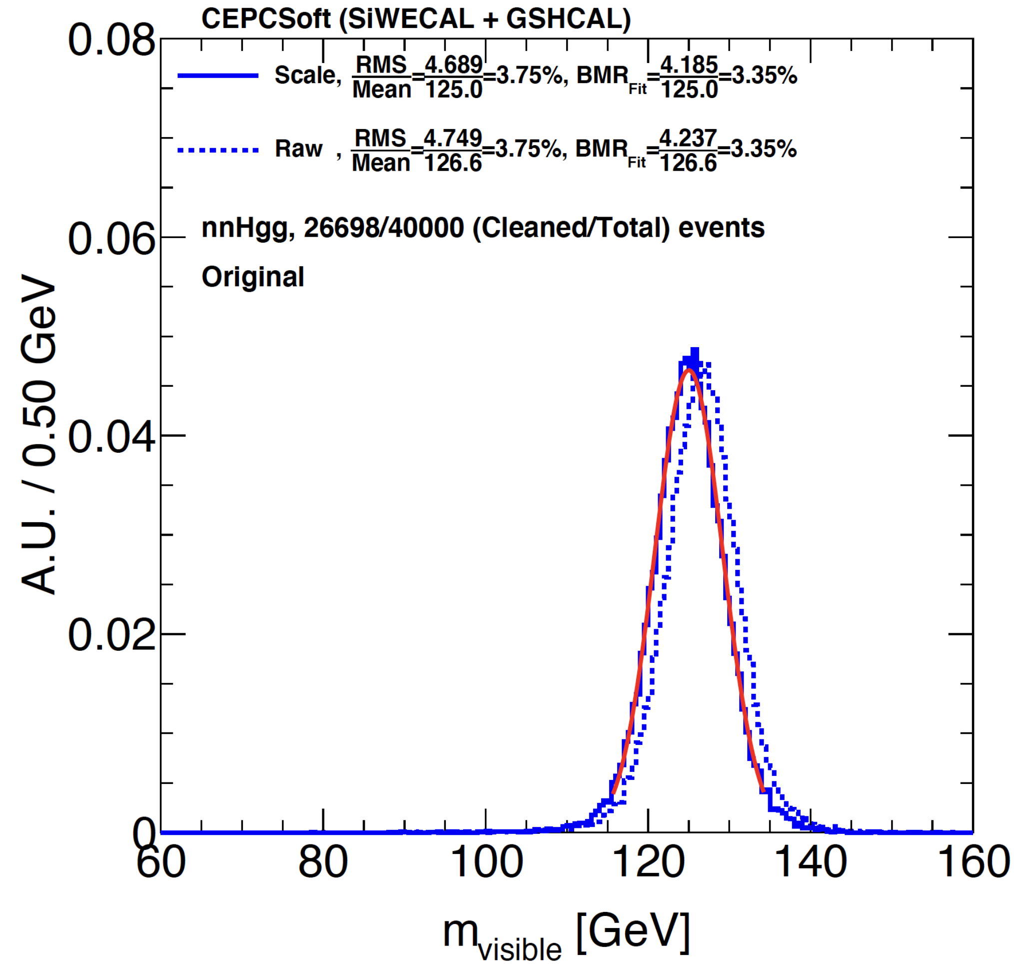
- *1st, what matters is not only intrinsic HCAL resolution... but hadron resolution at ECAL + HCAL: Dedicated development towards shower energy estimator is needed*
- *2nd, performance dependents on Energy threshold, timing cut, etc: digitization study need to be enhanced*

Three detector models

Parameters	SiWECAL + SDHCAL (Baseline)	SiWECAL + GSHCAL	CSECAL + GSHCAL
ECAL Material	Si + W	Si + W	BGO (Homogeneous)
ECAL Transverse cell size	1×1 cm^2	1×1 cm^2	1×1 cm^2
ECAL Number of layers	30	30	27
ECAL Total thickness	24 X_0	24 X_0	24 X_0
ECAL Thickness/layer	Si 0.5 mm (30 layers) W 2.1 mm (20 layers) W 4.2 mm (10 layers)	Si 0.5 mm (30 layers) W 2.1 mm (20 layers) W 4.2 mm (10 layers)	10 mm
HCAL Material	GRPC	Glass + Steel	Glass + Steel
HCAL Transverse cell size	1×1 cm^2	2×2 cm^2	2×2 cm^2
HCAL Number of layers	40	48	48
HCAL Total thickness	5 λ	6 λ	6 λ
HCAL Thickness/layer	0.125 λ 3 mm GRPC + 3 mm Electronics + 20 mm Steel	0.125 λ 10 mm Glass + 13.85 mm Steel	0.125 λ 10 mm Glass + 13.85 mm Steel
HCAL Glass density	-	6 g/cm^3	6 g/cm^3

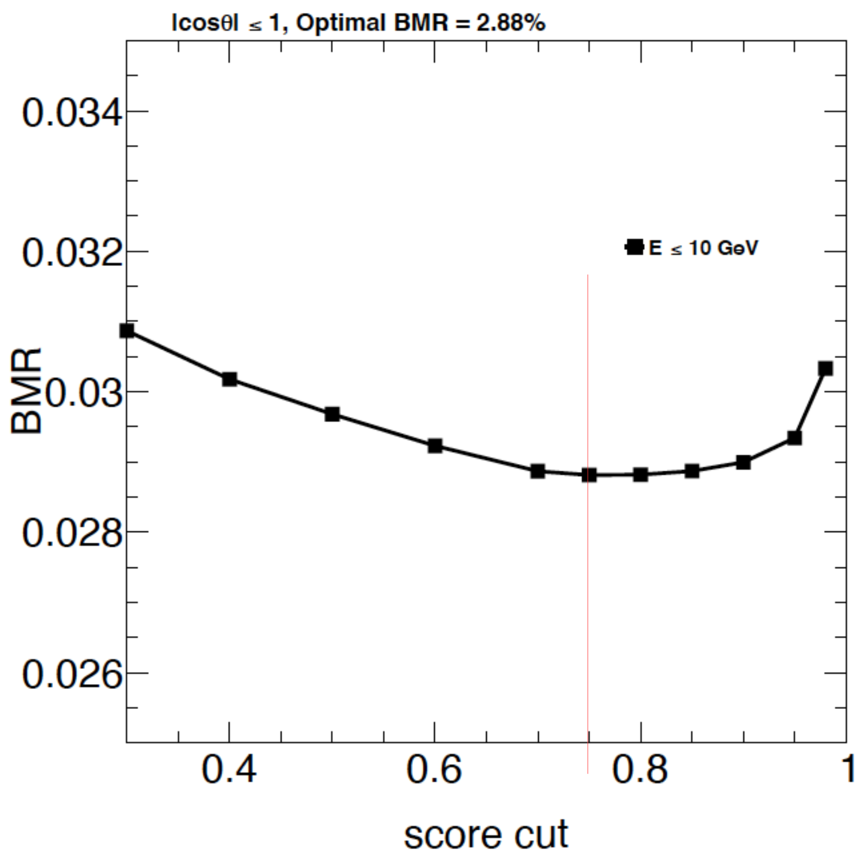
Baseline → M1: BMR 3.67% → 3.35%

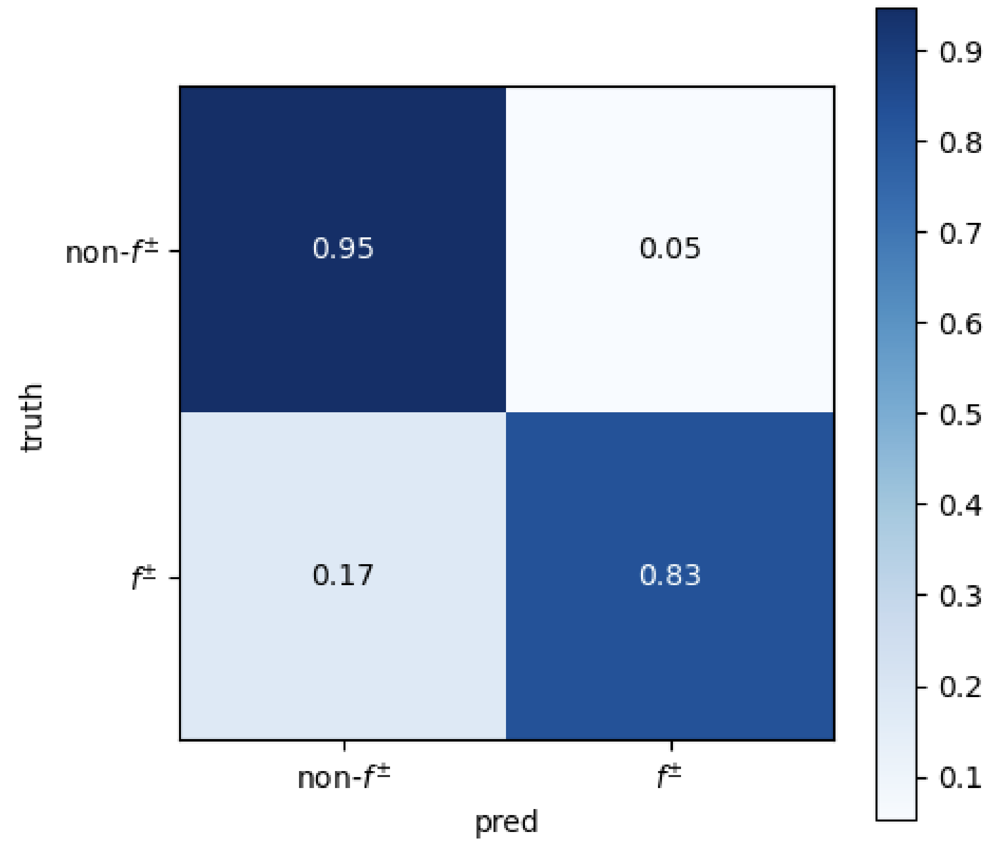




Reminder: Not only larger sampling (0.2)... but also thicker (0.1)!

Preliminary: Identify & veto charged shower fragments using AI



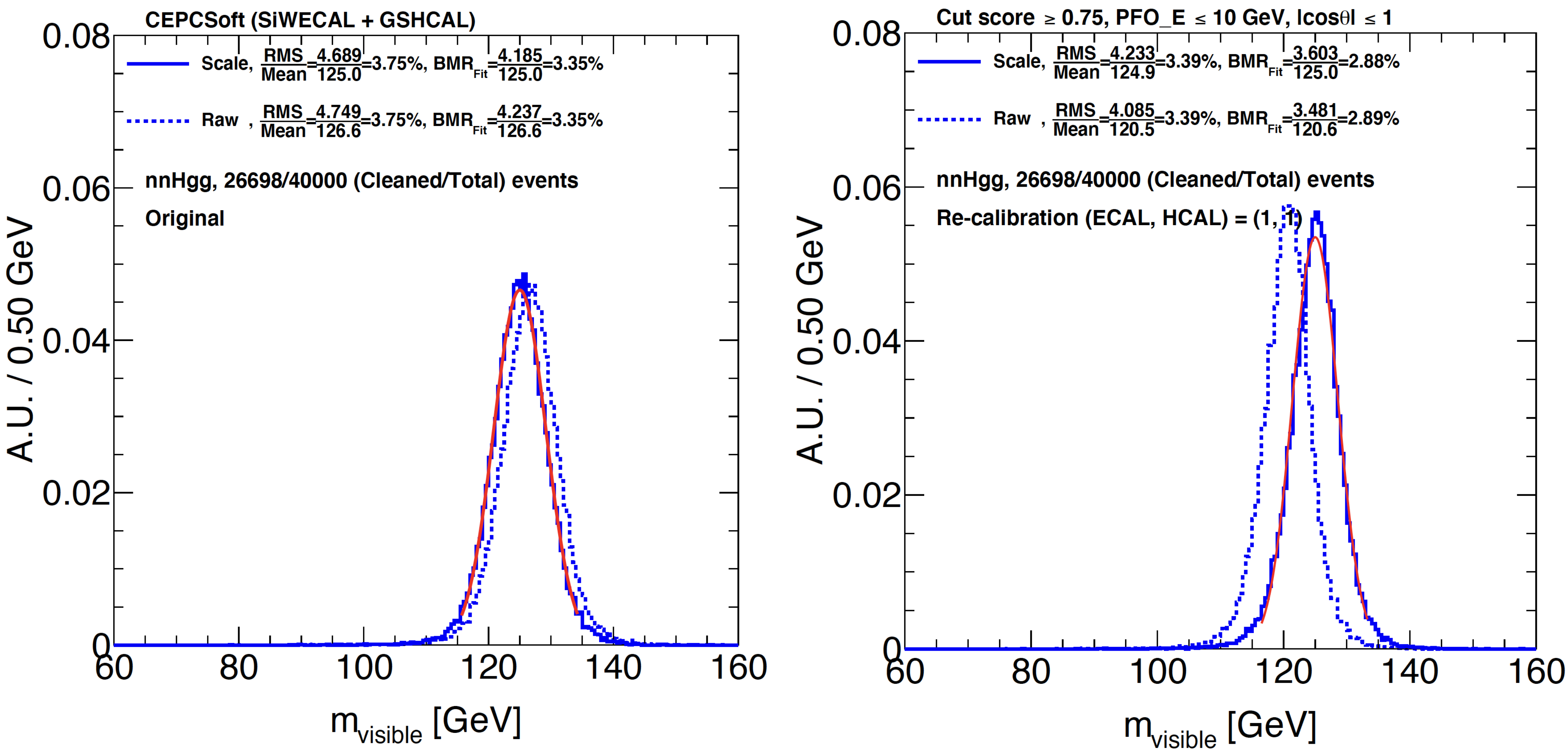


Trained at 12E4 events,

Test & Applied at 4E4 events

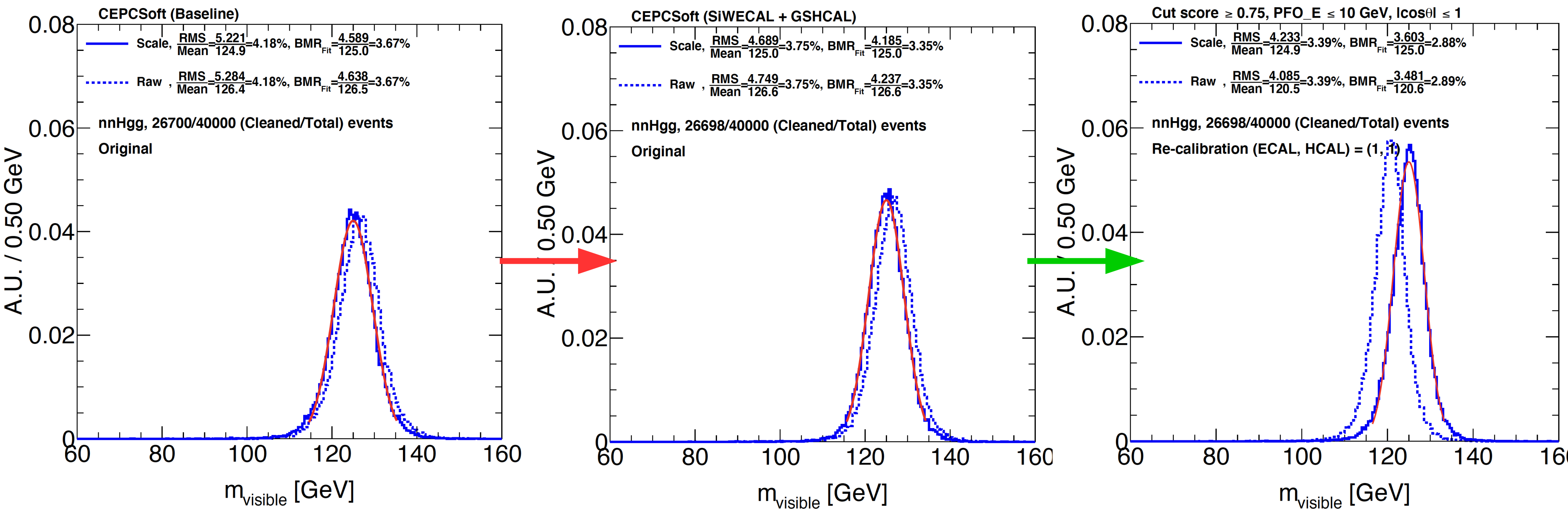
score > 0.75
efficiency ~83%
purity ~95%

M1(SiW + GS): BMR 3.35 → 2.89%



Truth level veto prediction: 3.32 -> 2.98%

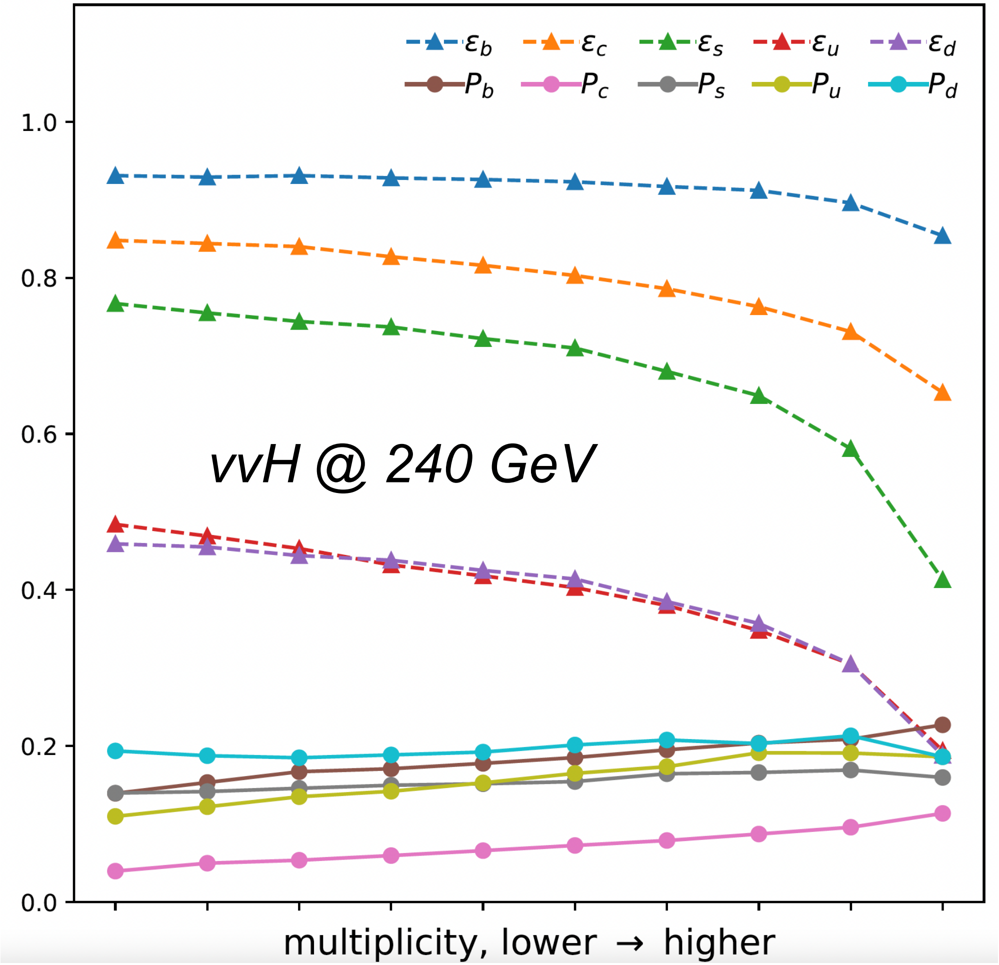
BMR Comparison

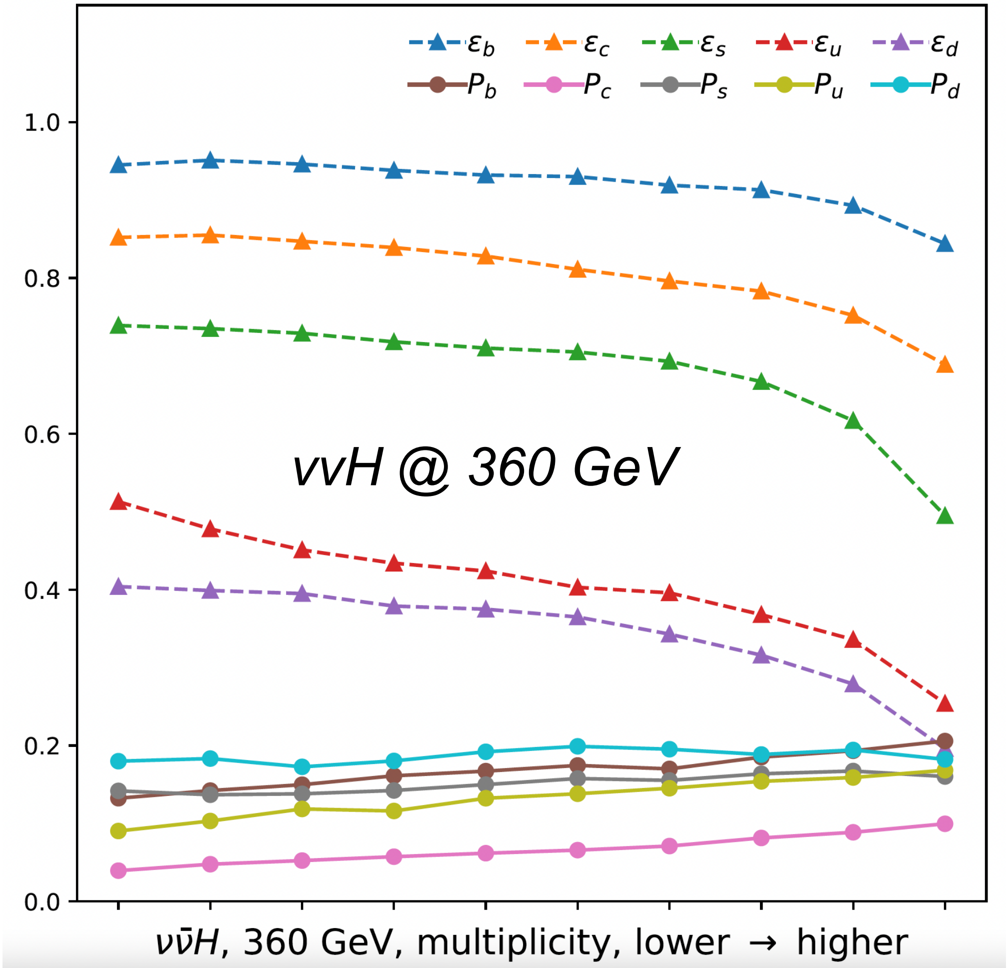


Detector	Arbor	A4: AI Assistant Arbor	Improvement
SiW ECAL + RPC DHCAL	3.67	3.31	0.4
SiW ECAL + GSHCAL	3.35	2.88	0.5
Xstal ECAL + GSHCAL	3.53	3.27	0.3

@ Xstal ECAL: ...to be optimized...

V.S. Multiplicity





- *...many patterns need further understanding & towards further optimization...*

Particle identification

JINST
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Lepton identification performance in jets at a future electron positron Higgs Z factory

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THE EUROPEAN PHYSICAL JOURNAL C
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Regular Article - Experimental Physics

Lepton identification at particle flow oriented detector for the future e^+e^- Higgs factories

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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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PRL **112,** 012001 (2014) PHYSICAL REVIEW LETTERS week ending 10 JANUARY 2014

Fractal Dimension of Particle Showers Measured in a Highly Granular Calorimeter

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(Received 24 May 2013; published 8 January 2014)

We explore the fractal nature of particle showers using Monte Carlo simulation. We define the fractal dimension of showers measured in a high granularity calorimeter designed for a future lepton collider. The shower fractal dimension reveals detailed information of the spatial configuration of the shower. It is found to be characteristic of the type of interaction and highly sensitive to the nature of the incident particle. Using the shower fractal dimension, we demonstrate a particle identification algorithm that can efficiently separate electromagnetic showers, hadronic showers, and nonshowering tracks. We also find a logarithmic dependence of the shower fractal dimension on the particle energy.

DOI: 10.1103/PhysRevLett.112.012001 PACS numbers: 13.85.-t, 07.20.Fw, 13.40.-f

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

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Eur. Phys. J. C (2023) 83:93
https://doi.org/10.1140/epjc/s10052-023-11221-7
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Experimental Physics

Cluster time measurement with CEPC calorimeter

Yuzhi Che[1], Vincent Boudry[2], Henri Videau[2], Muchen He[1], Manqi Ruan[1,a]
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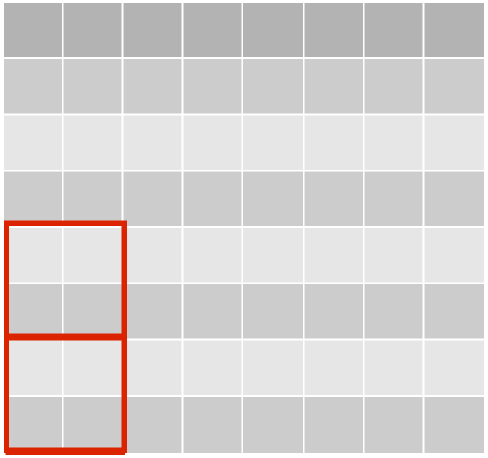
[2] LLR, Ecole Polytechnique, Palaiseau, France

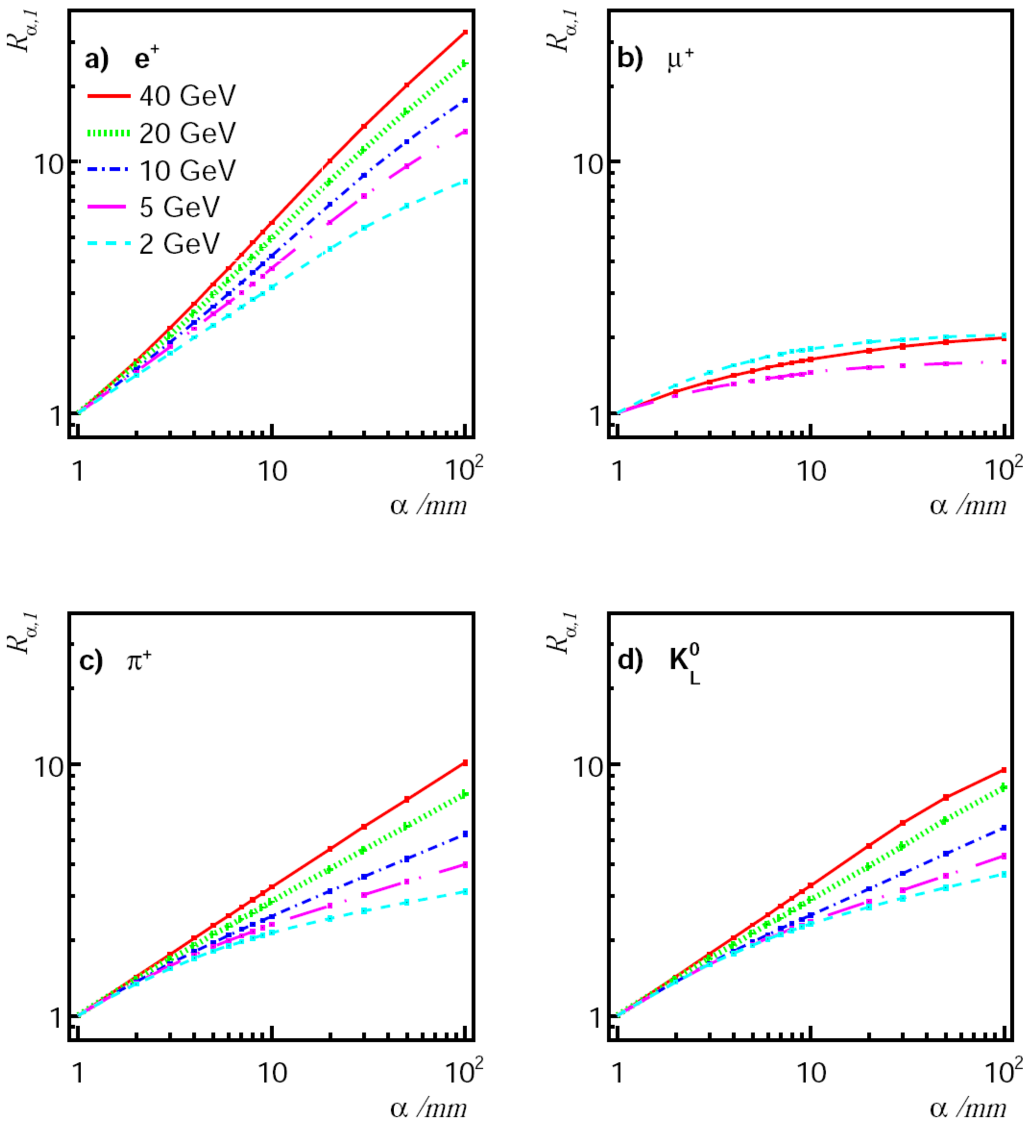
Received: 21 September 2022 / Accepted: 11 January 2023 / Published online: 30 January 2023

Fractal dimension of particle shower

$$FD_\beta = \left\langle \frac{\log(R_{\alpha,\beta})}{\log(\alpha)} \right\rangle + 1.$$

$$R_{\alpha,\beta} = N_\beta / N_\alpha.$$

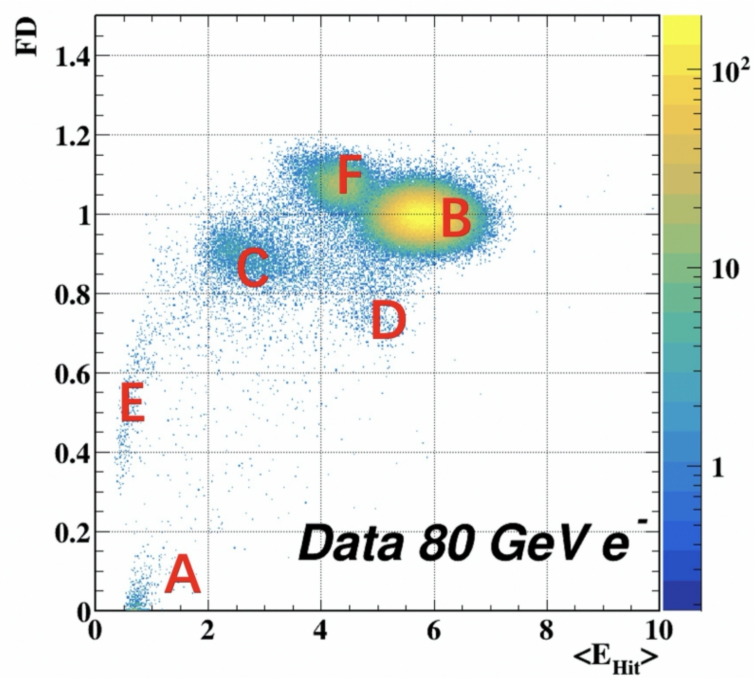


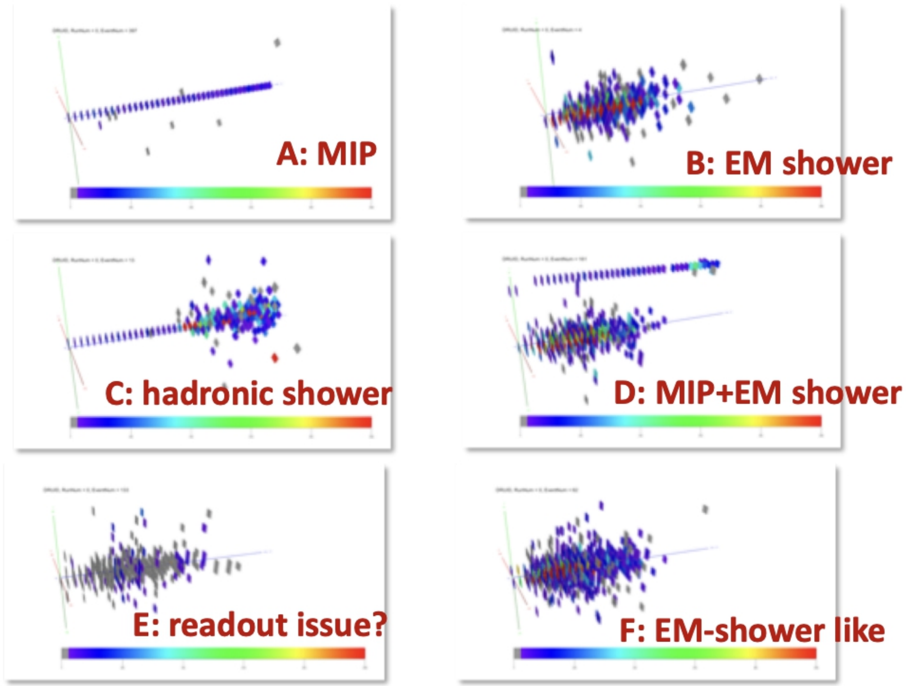


Ultimate cell size: 1mm
Resize cell: 2 – 10, 20, 30, 50, 60, 90, 120, 150 mm.
Sample: particle gun events at ILD SDHCAL

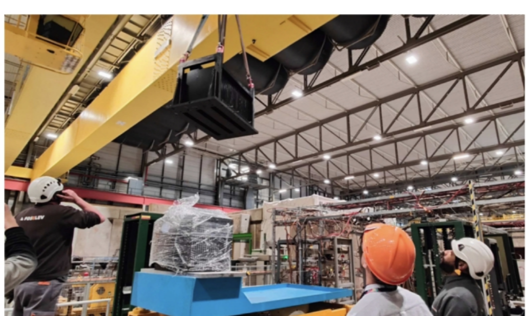
PID studies with beamtest data

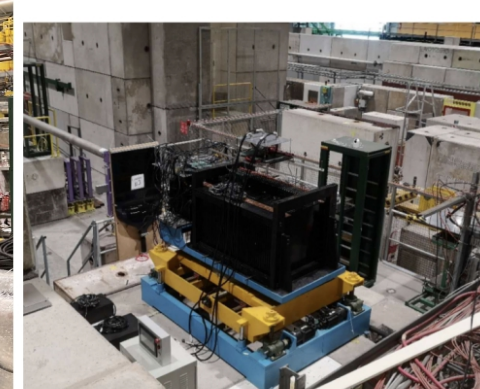
- FD characteristics of different beam particles
  - Imaging capability of high granularity calorimeter ()



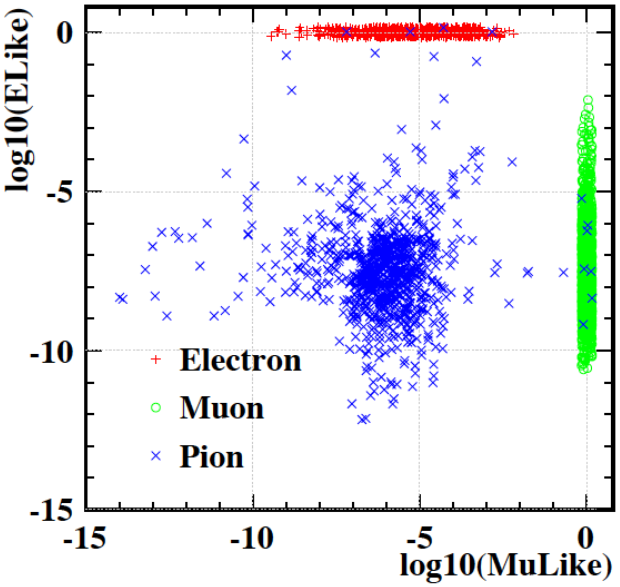


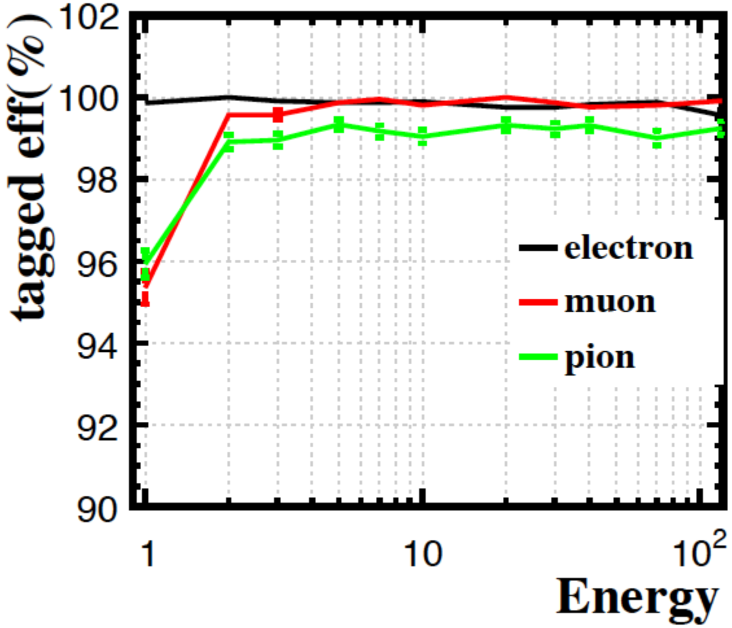
Oct 19 – Nov 2, 2022 — SPS H8 beamline
Apr 26 – May 10, 2023 — SPS H2 beamline
May 17 – 31, 2023 — PS T9 beamline

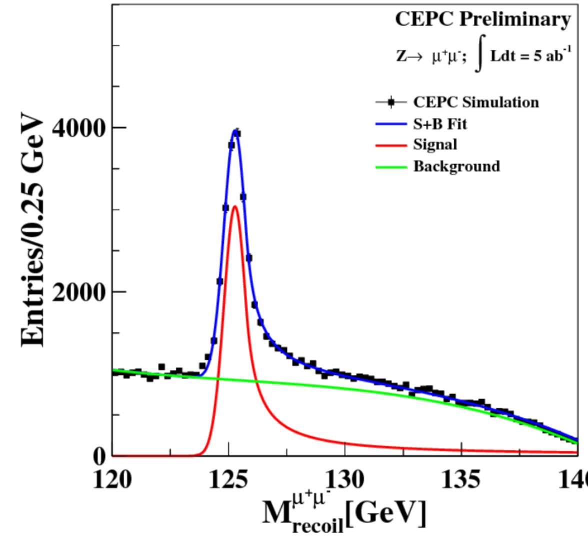


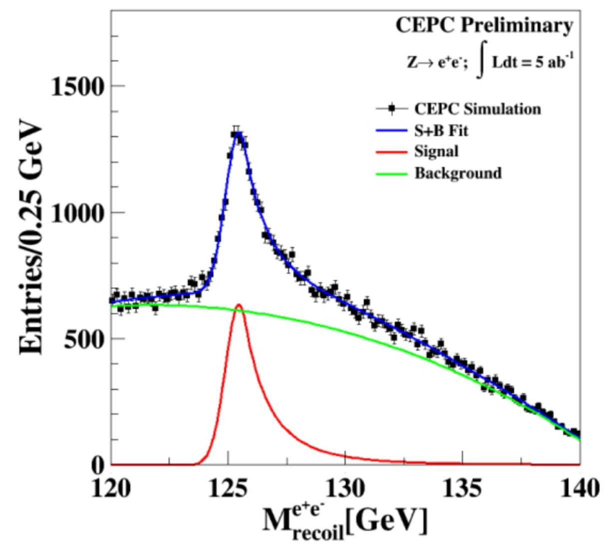


Lepton: isolated







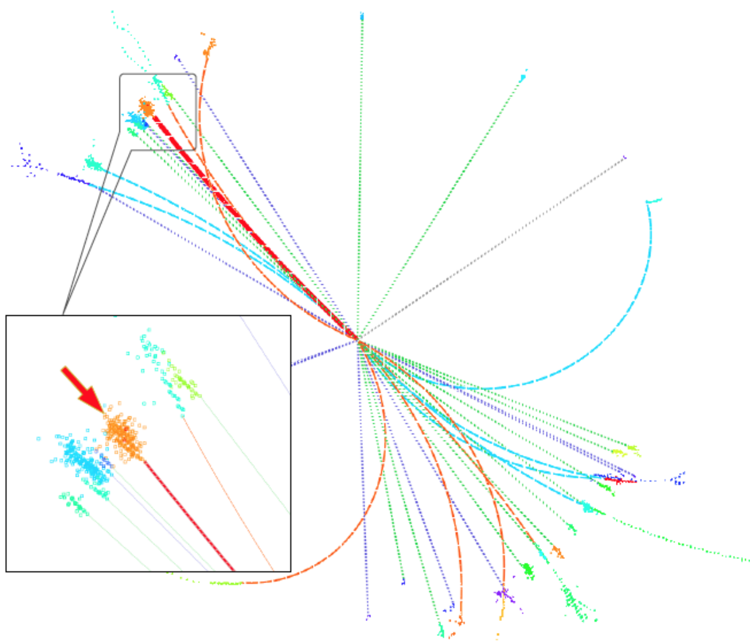


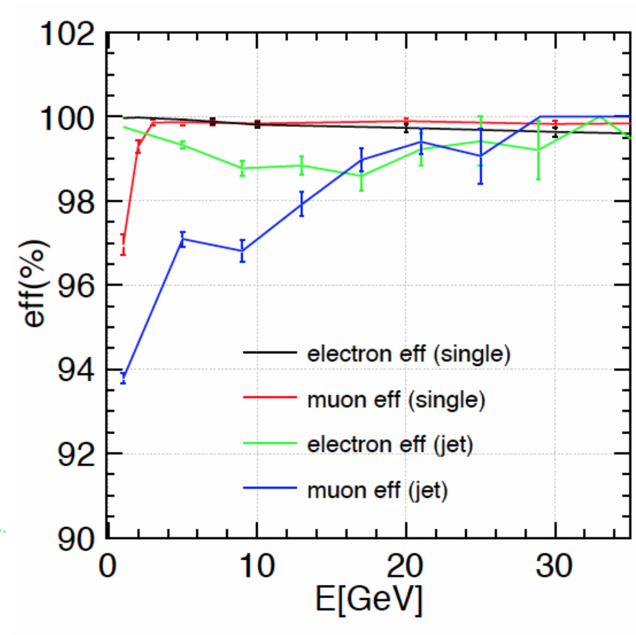
BDT method using 4 classes of 24 input discrimination variables.

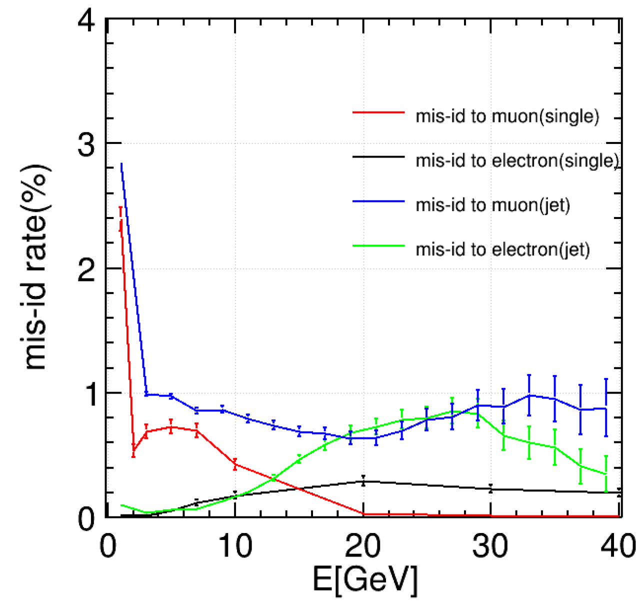
Test performance at: Electron = E_likeness > 0.5 ;
Muon = Mu_likeness > 0.5
Single charged reconstructed particle, for E > 2 GeV:
lepton efficiency > 99.5% && Pion mis id rate ~ 1%

https://link.springer.com/article/10.1140/epjc/s10052-017-5146-5
CEPC-DocDB-id:148, Eur. Phys. J. C (2017) 77: 591

Lepton: inside jet



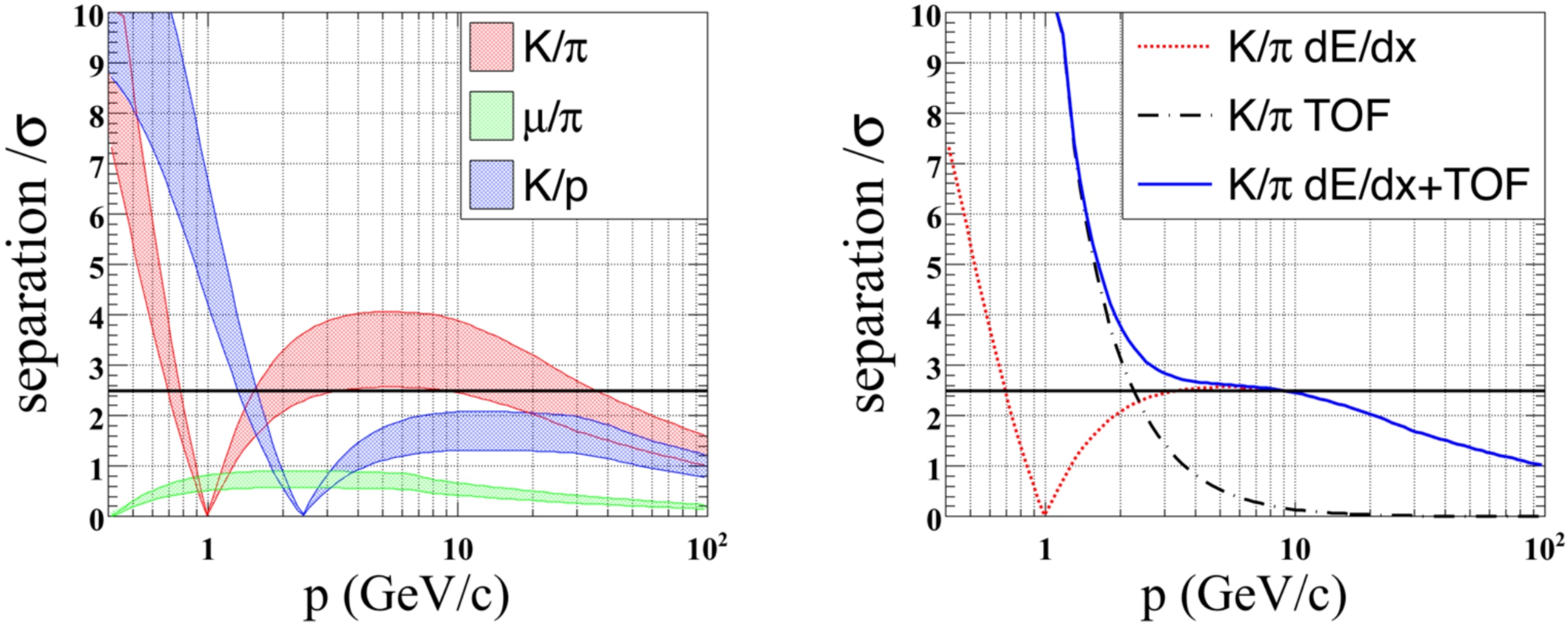




Compared the single particle sample, the jet lepton (at Z->bb sample at sqrt = 91.2 GeV) Performance will be slightly degraded – Due to the limited clustering performance (splitting & containimation).

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.

Kaon



Highly appreciated in flavor physics @ CEPC Z pole

TPC dEdx + ToF of 50 ps

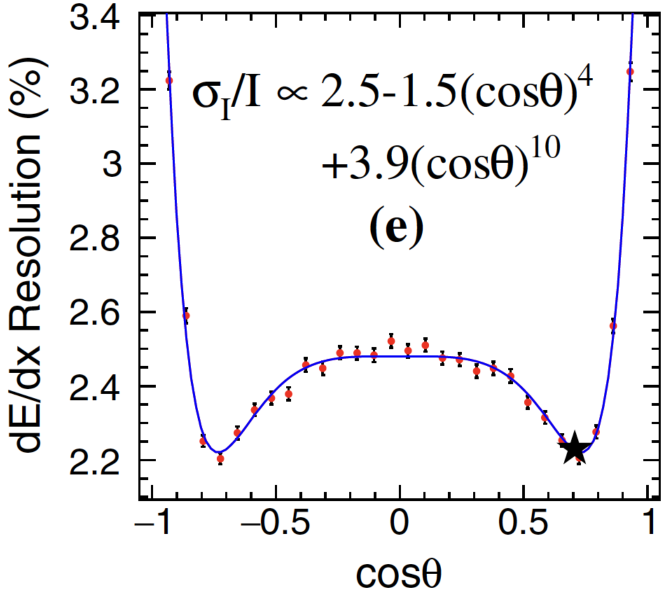
At inclusive Z pole sample:

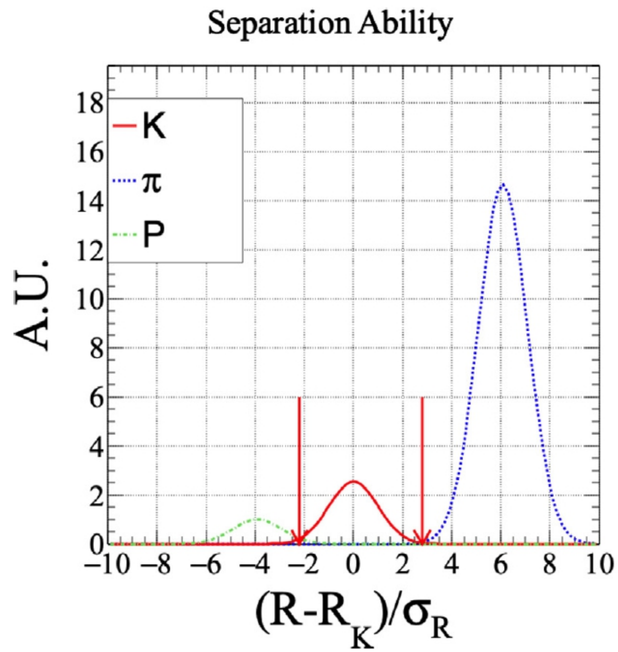
Conservative estimation gives efficiency/purity of 91%/94% (2-20 GeV, 50% degrading +50 ps ToF)

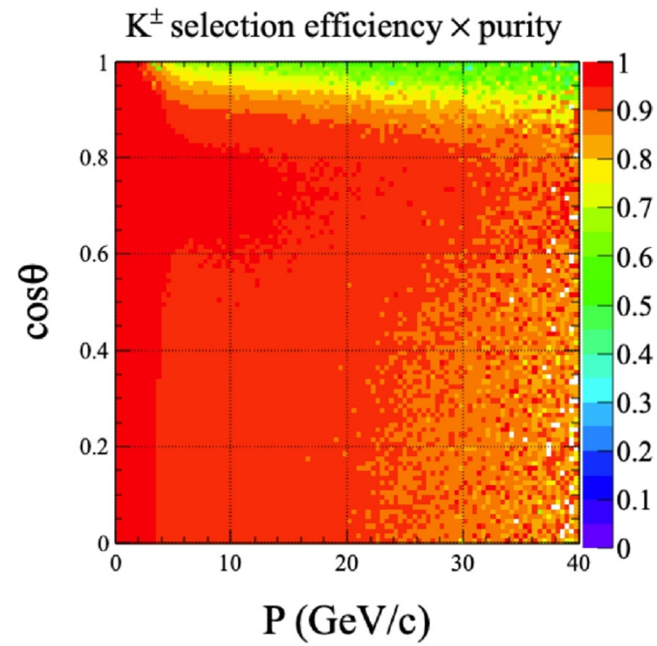
Could be improved to 96%/96% by better detector/DAQ performance (20% degrading + 50 ps ToF)

Eur. Phys. J. C (2018) 78:464

Pid performance





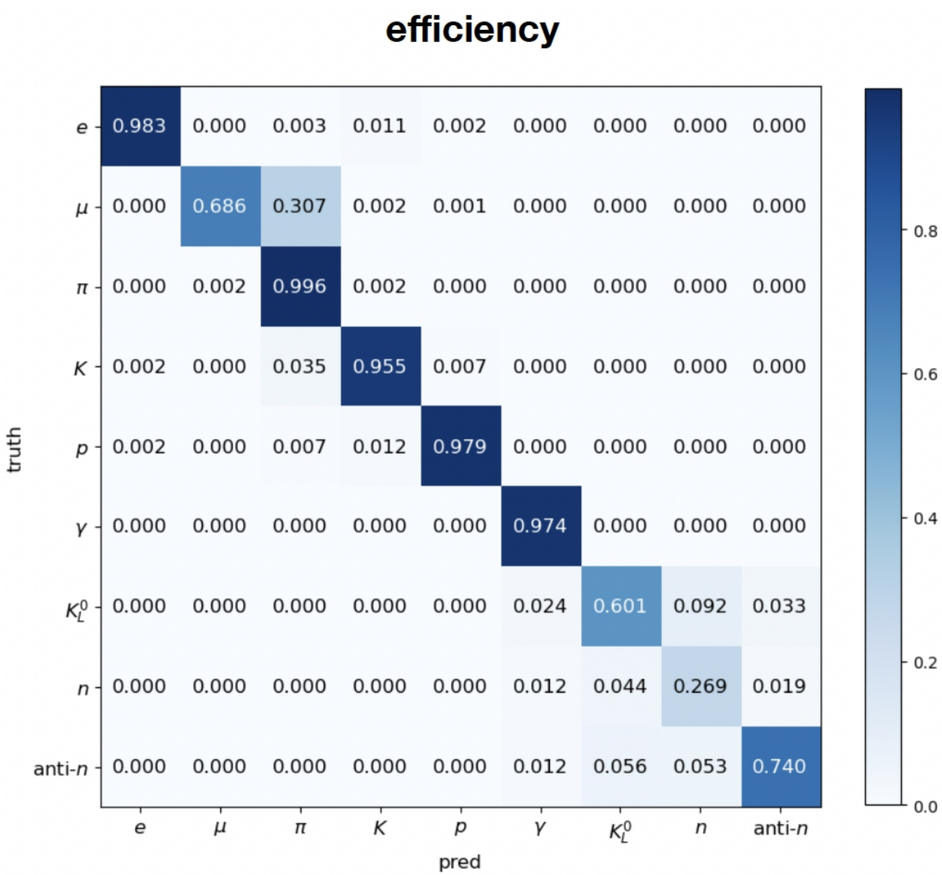


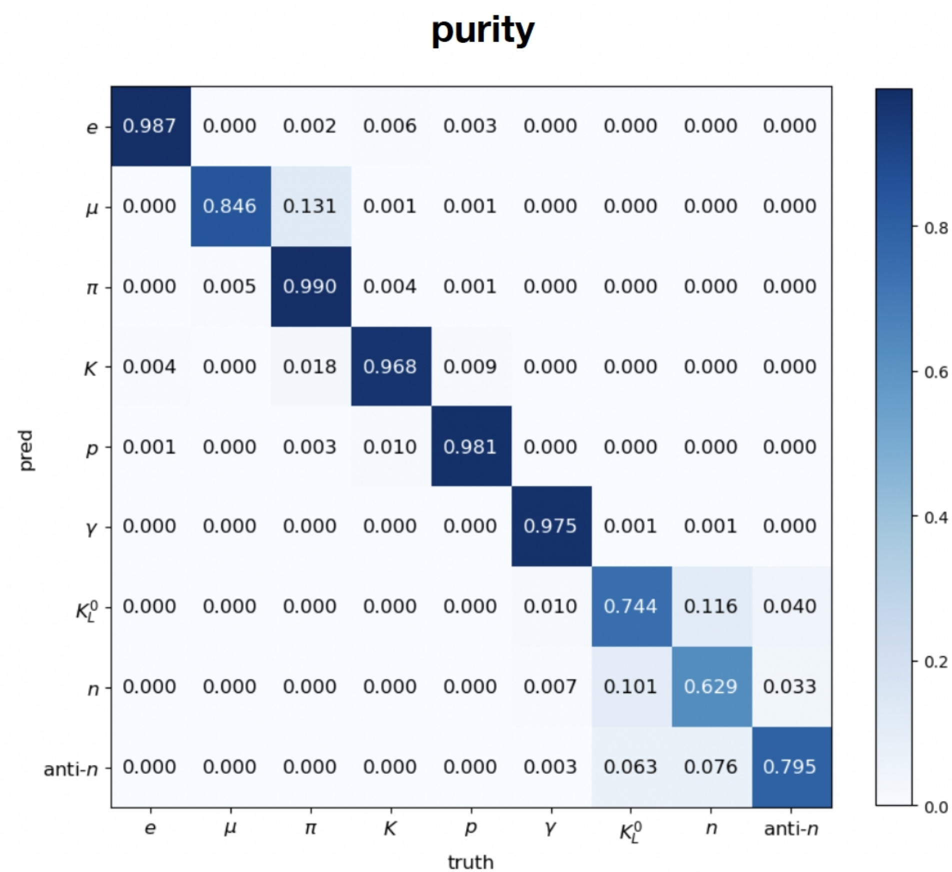
	factor	1.	1.2	1.5	2.
dE/dx	ε_K (%)	95.97	94.09	91.19	87.09
	$purity_K$ (%)	81.56	78.17	71.85	61.28
dE/dx & TOF	ε_K (%)	98.43	97.41	95.52	92.3
	$purity_K$ (%)	97.89	96.31	93.25	87.33

(b)

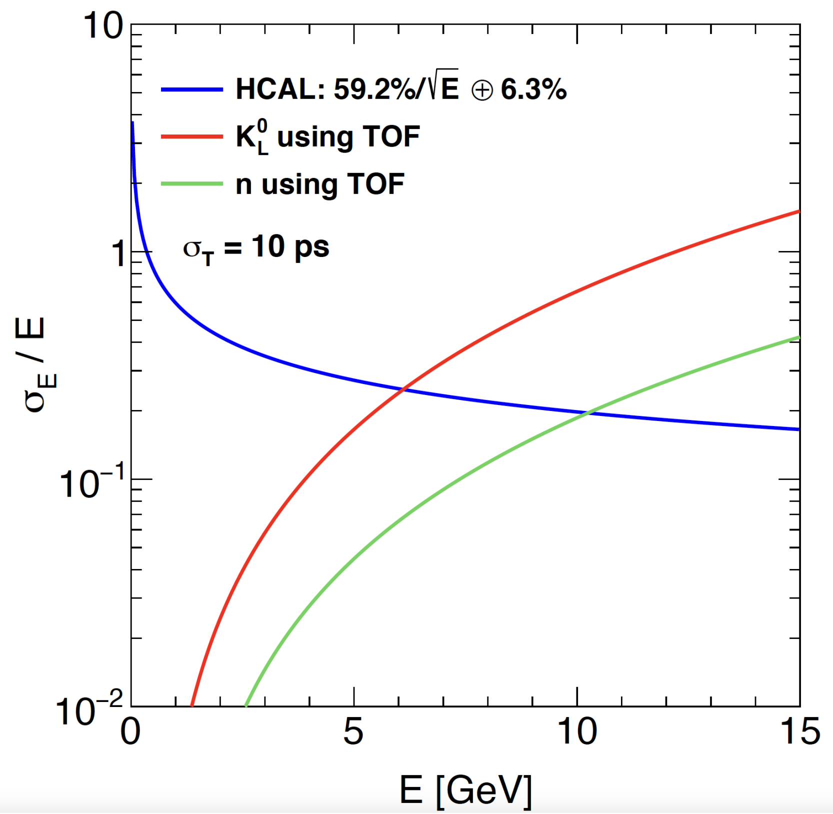
3% of dE/dx & dN/dx + 50 ps ToF: eff/purity of Kaon reco > 95%

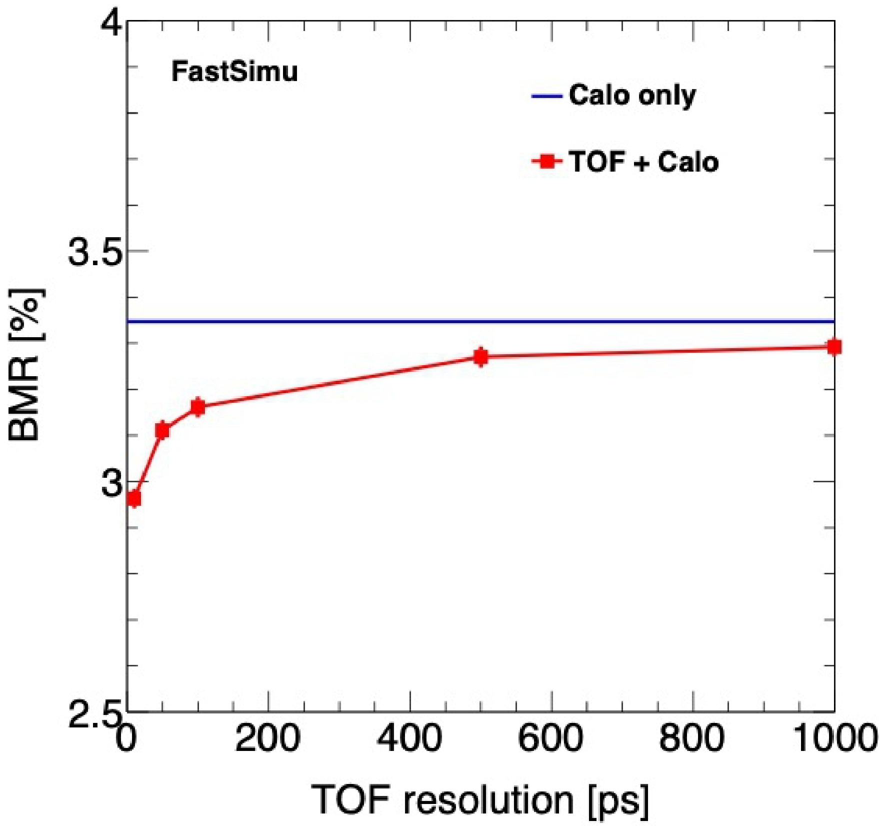
Inc. Reco. Particle id: Preliminary & in progress





Neutral Particle id: Very Preliminary

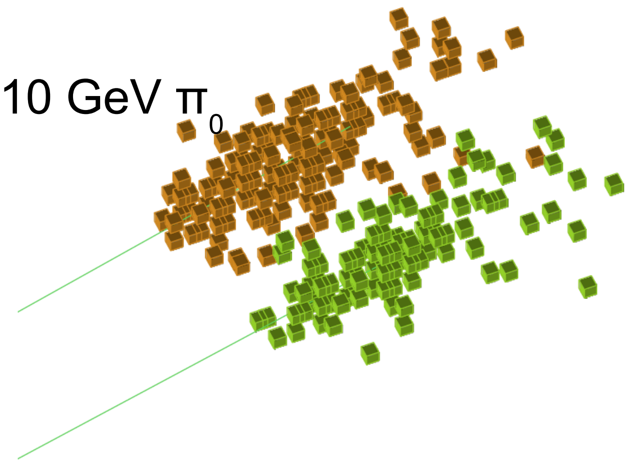


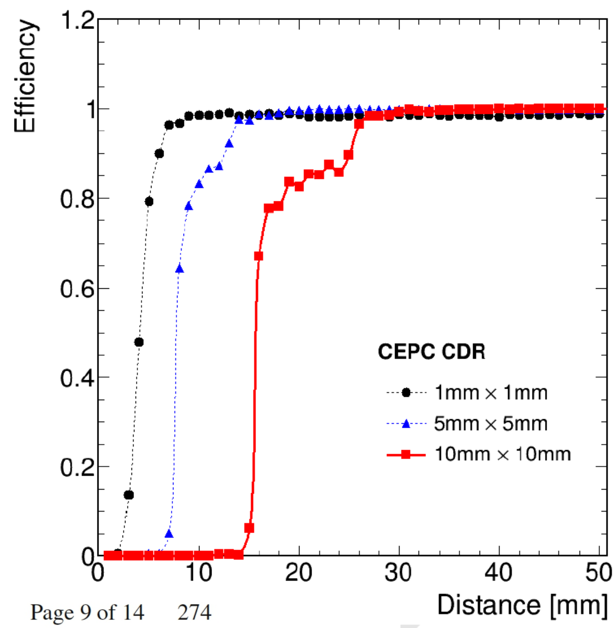


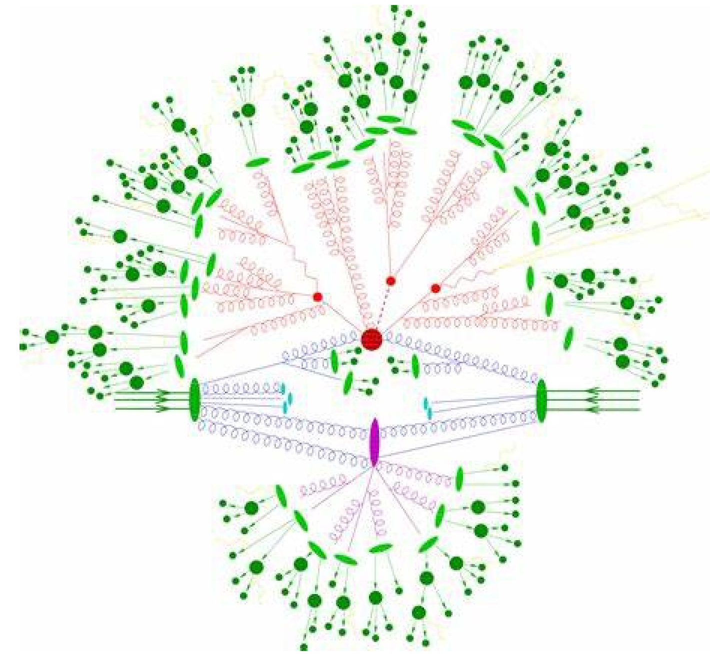
- Fast Sim Prediction: BMR: 2.9 → 2.6
  - Need excellent CALO + ToF ~ o(10 ps)
  - Need high efficiency neutral hadron reco (1-1 correspondence)

2-body decay particles and tau leptons

10 GeV π_0







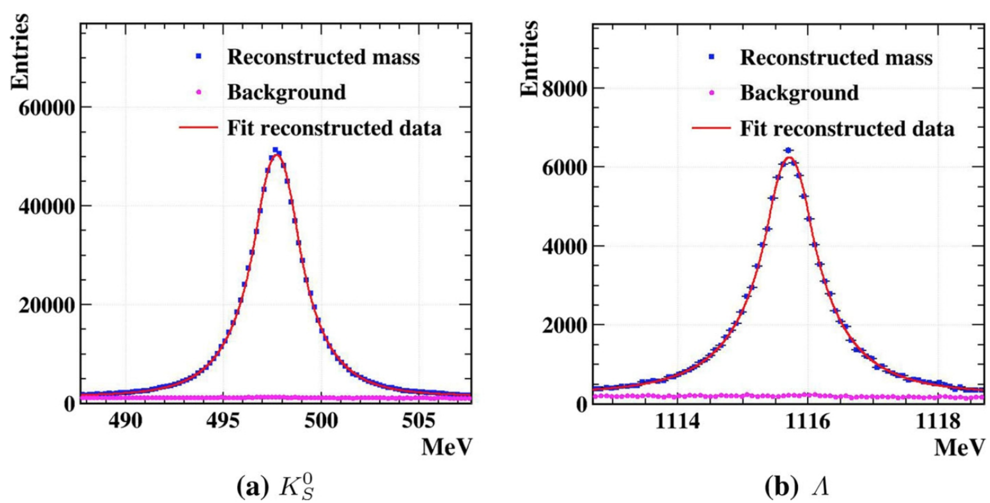
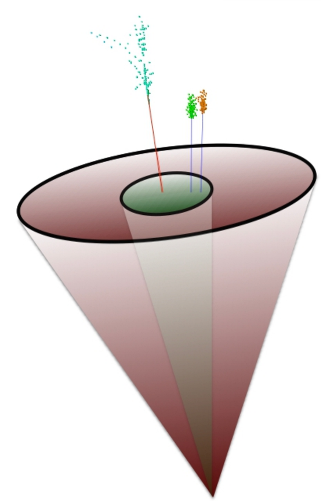


Fig. 7 All reconstructed mass distributions of K_S^0 and Λ. They are fitted with double-sided crystal ball functions



π_0: 60/30 GeV with 5/10 mm cell.

Kshort, Lambda, Phi, Tau, D meson...

Summary

- Jet origin id: efficiently separate different species of colored SM particle
  - Stable & Smooth...
  - World leading performance of the tagger with strongest expected constrains...
  - A “game changer” and opens new horizon for precise flavor studies at all future experiments
- Significantly impact on physics
  - Higgs: Boost the access to g(Hss) and Higgs exotic/FCNC with jet final state (3 – 100 times), and H→cc precision by 2 times
  - Flavor: Improve Vcb precision by ~50%, effective tagging power for b > 40%...
  - EW: Weak mixing angle
    - Reach 1E-6 level precision (at 92 GeV) using 1 month data taking with different flavors.
    - Verify RG behavior
  - QCD: Fragmentation, etc.
  - NP: ...
- Long term version: 'see' gluon + quarks, as we see photon + leptons

Summary

- Arbor + AI: Towards Toolkits of One To One correspondence RecOnstruction: TOTORO
- BMR of 2.9% reached:
  - Using A4 (AI Assistant Arbor Algorithm) + SiW ECAL + GS HCAL
  - Compared to 4% BMR, BMR ~ 3% saves ~ 10% machine time for key physics benchmarks... benefit all physics measurements
- A4 significantly eliminates the shower fragment confusions: Transformer provides unprecedented identification capability (same methodology as Jet Origin ID)
  - SiW ECAL + GS HCAL: BMR ~ 2.5% @ no confusion limit
  - Similar improvements observed at other geometry
- High Granularity Calorimeter with high precision timing: Further improvements anticipated

One to one correspondence reco. at Higgs factory

The should, and we could

Via state-of-art det. Design & technology + AI enhanced algorithms

Key figures of the CEPC-SPPC

- **Tunnel ~ 100 km**
- **CEPC (90 – 240 GeV)**
  - Higgs factory: **4M** Higgs boson
    - Absolute measurements of Higgs boson width and couplings
    - Searching for exotic Higgs decay modes (New Physics)
  - Z & W factory: **~ 4 Tera** Z boson
    - Precision test of the SM
    - Rare decay
    - Flavor factory: b, c, tau
    - QCD studies
- **Upgradable to ttbar threshold (360 GeV)**
- **SPPC (~ 100 TeV)**
  - Direct search for new physics
  - Complementary Higgs measurements to CEPC g(HHH), g(Htt)
  - ...
- **Heavy ion, e-p collision...**