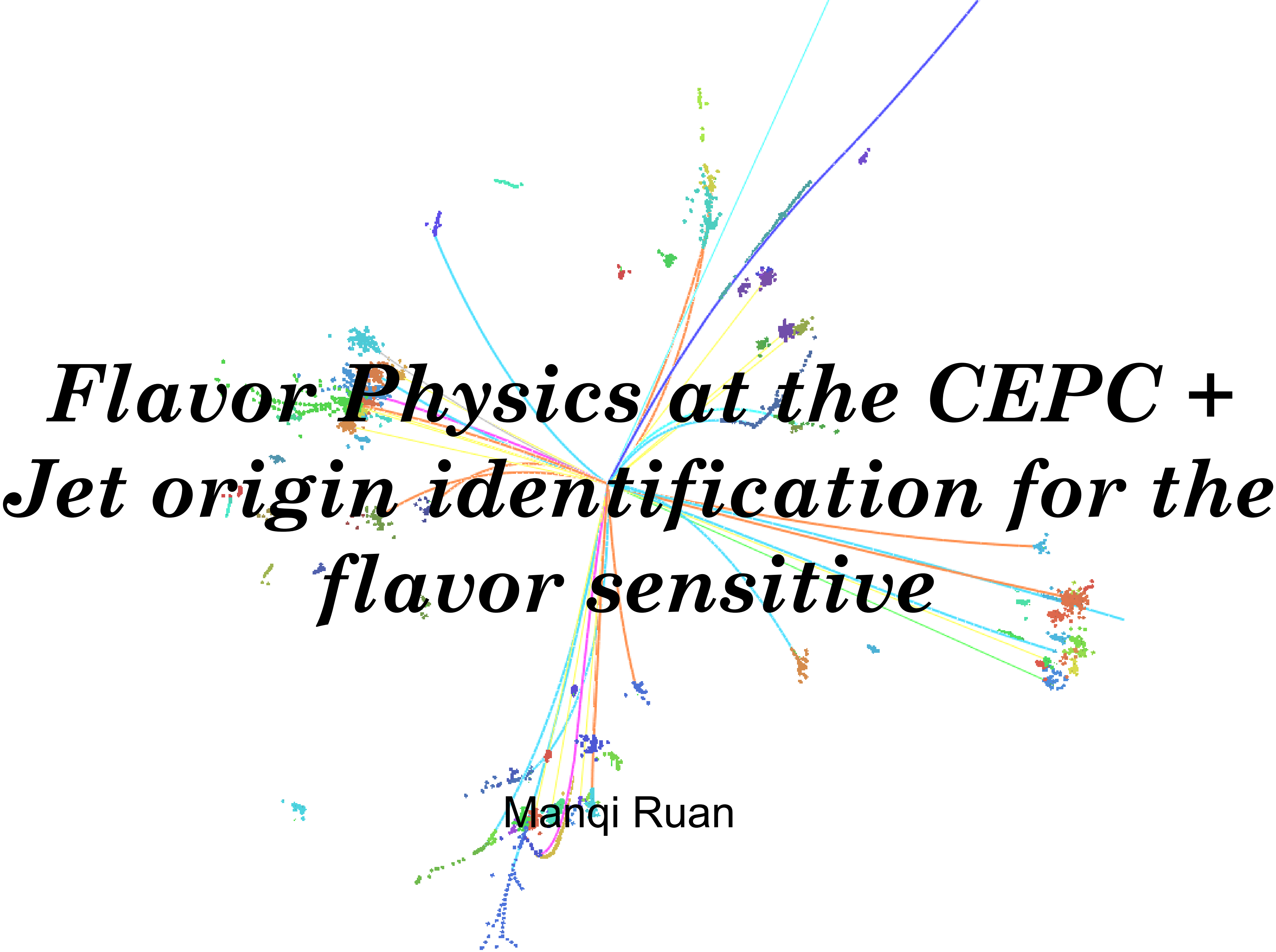
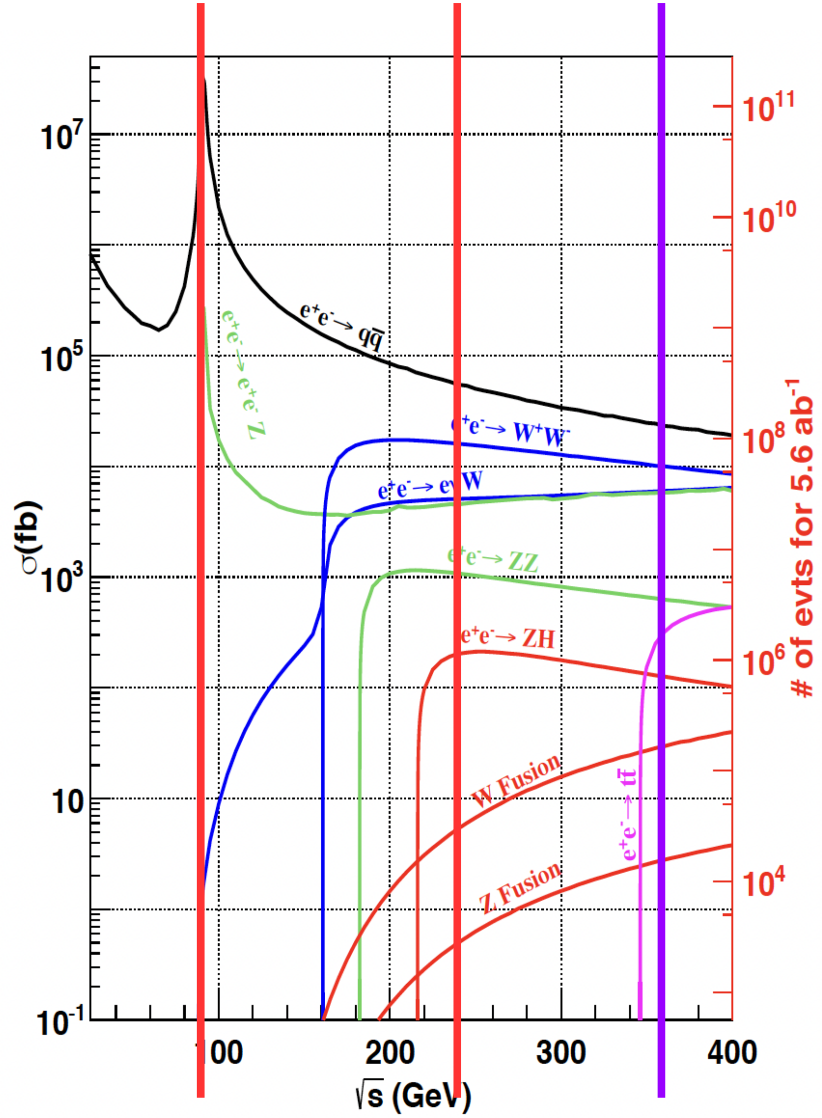
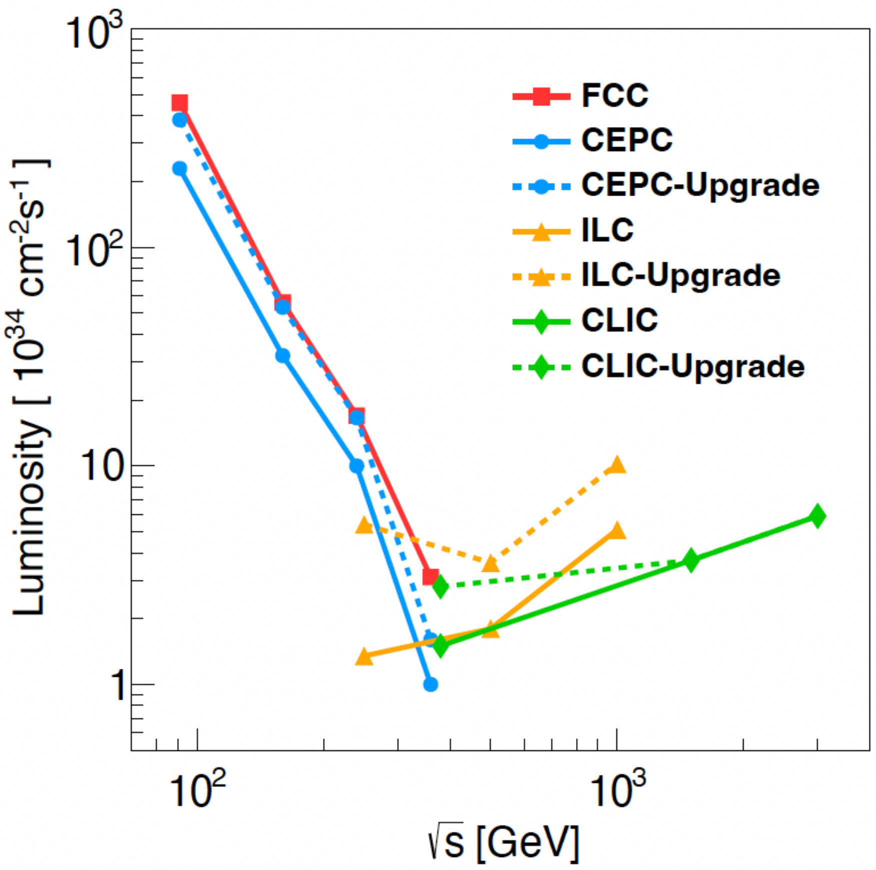


Flavor Physics at the CEPC + Jet origin identification for the flavor sensitive

Manqi Ruan

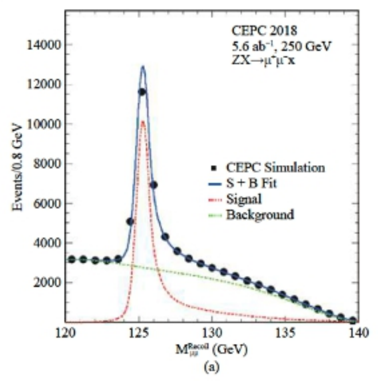
Yields ~ Xsec * Lumi * Time



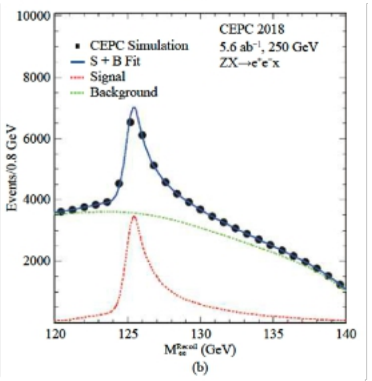


- 4 Million Higgs (10 years)
- ~ 1 Giga W (1 year) + 4 Tera Z (2 years)
- Upgradable: Top factory (500 k ttbar)

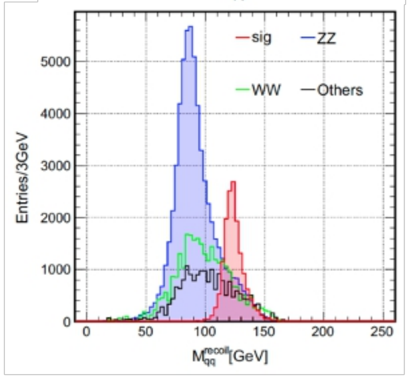
CEPC Physics study

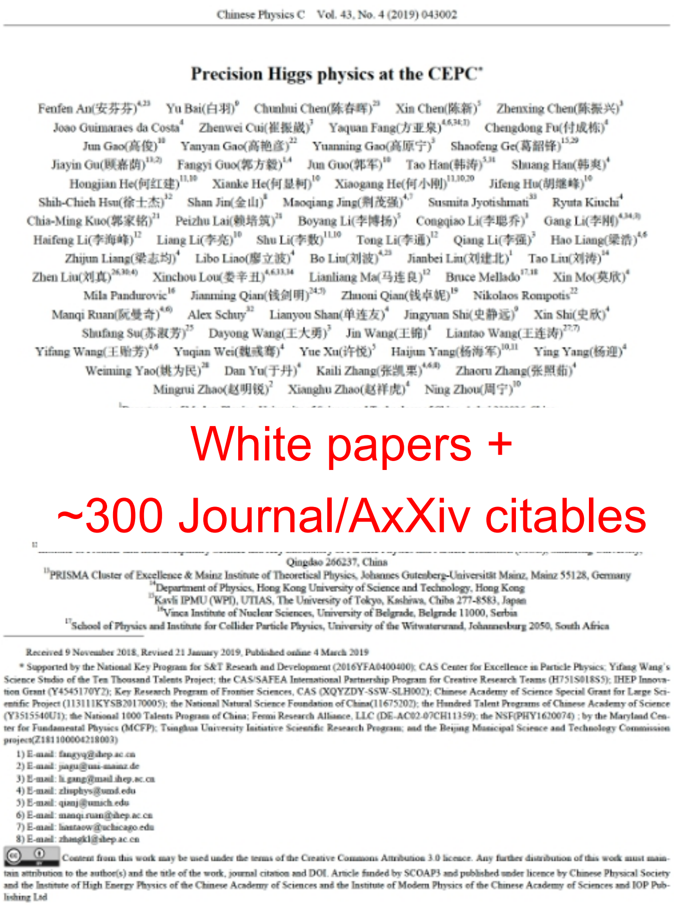


(a)



(b)




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

Precision Higgs physics at the CEPC*

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White papers +

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Received 9 November 2018, Revised 21 January 2019, Published online 4 March 2019

* Supported by the National Key Program for S&T Research and Development (2016YFA0400400); CAS Center for Excellence in Particle Physics; Yifang Wang's Science Studio of the Ten Thousand Talents Project; the CAS/SAFEA International Partnership Program for Creative Research Teams (H751S018S5); IHEP Innovation Grant (Y4545170Y2); Key Research Program of Frontier Sciences, CAS (XQYZDY-SSW-SLH002); Chinese Academy of Science Special Grant for Large Scientific Project (113111KYSB20170005); the National Natural Science Foundation of China(11675202); the Hundred Talent Programs of Chinese Academy of Science (Y3515540U1); the National 1000 Talents Program of China; Fermi Research Alliance, LLC (DE-AC02-07CH11359); the NSF(PHY1620074) ; by the Maryland Center for Fundamental Physics (MCFP); Tsinghua University Initiative Scientific Research Program; and the Beijing Municipal Science and Technology Commission project(Z181100004218003)

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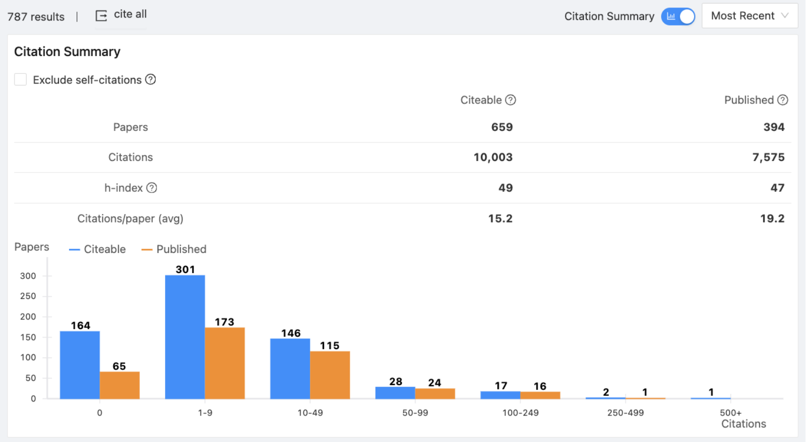


Citation Summary

☐ Exclude self-citations

	Citeable	Published
Papers	659	394
Citations	10,003	7,575
h-index	49	47
Citations/paper (avg)	15.2	19.2

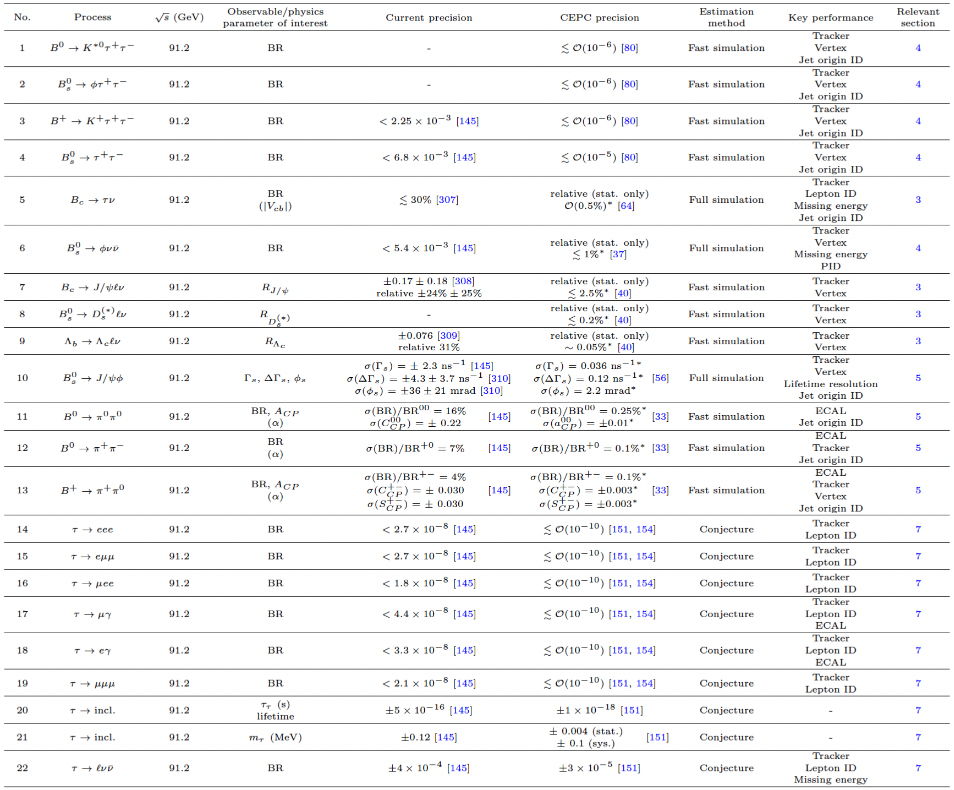
Table 2.1: Precision of the main parameters of interests and observables at the CEPC, from Ref. [1] and the references therein, where the results of Higgs are estimated with a data sample of 20 ab^{-1}. The HL-LHC projections of 3000 fb^{-1} data are used for comparison. [2]

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$(H \to \text{inv.})$	2.5%	0.07%	N_ν	2.5×10^{-3}	2×10^{-4}

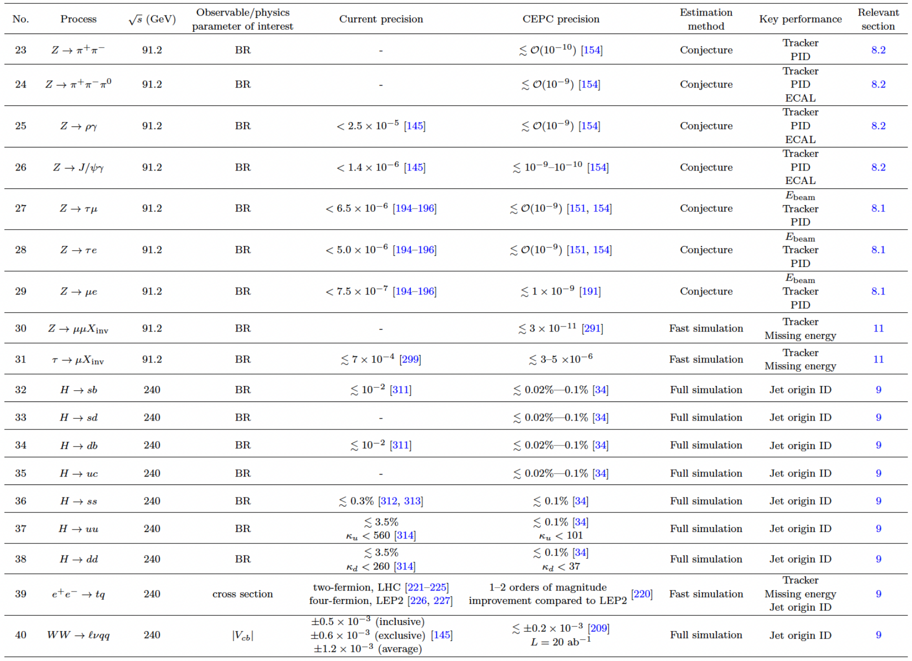
Scientific Significance quantified by **CEPC physics** studies, via full simulation/phenomenology studies:

- 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.
- …

~ 40 Flavor benchmarks @ Multiple sqrt(s)



No.	Process	$\sqrt{s}$ (GeV)	Observable/physics parameter of interest	Current precision	CEPC precision	Estimation method	Key performance	Relevant section
1	$B^0 \to K^{*0}\tau^+\tau^-$	91.2	BR	-	$\lesssim \mathcal{O}(10^{-6})$ [80]	Fast simulation	Tracker Vertex Jet origin ID	4
2	$B_s^0 \to \phi\tau^+\tau^-$	91.2	BR	-	$\lesssim \mathcal{O}(10^{-6})$ [80]	Fast simulation	Tracker Vertex Jet origin ID	4
3	$B^+ \to K^+\tau^+\tau^-$	91.2	BR	$< 2.25 \times 10^{-3}$ [145]	$\lesssim \mathcal{O}(10^{-6})$ [80]	Fast simulation	Tracker Vertex Jet origin ID	4
4	$B_s^0 \to \tau^+\tau^-$	91.2	BR	$< 6.8 \times 10^{-3}$ [145]	$\lesssim \mathcal{O}(10^{-5})$ [80]	Fast simulation	Tracker Vertex Jet origin ID	4
5	$B_c \to \tau\nu$	91.2	BR ($\lvert V_{cb}\rvert$)	$\lesssim 30\%$ [307]	relative (stat. only) $\mathcal{O}(0.5\%)^*$ [64]	Full simulation	Tracker Lepton ID Missing energy Jet origin ID	3
6	$B_s^0 \to \phi\nu\bar{\nu}$	91.2	BR	$< 5.4 \times 10^{-3}$ [145]	relative (stat. only) $\lesssim 1\%^*$ [37]	Full simulation	Tracker Vertex Missing energy PID	4
7	$B_c \to J/\psi\ell\nu$	91.2	$R_{J/\psi}$	$\pm 0.17 \pm 0.18$ [308] relative $\pm 24\% \pm 25\%$	relative (stat. only) $\lesssim 2.5\%^*$ [40]	Fast simulation	Tracker Vertex	3
8	$B_s^0 \to D_s^{(*)}\ell\nu$	91.2	$R_{D_s^{(*)}}$	-	relative (stat. only) $\lesssim 0.2\%^*$ [40]	Fast simulation	Tracker Vertex	3
9	$\Lambda_b \to \Lambda_c\ell\nu$	91.2	R_{Λ_c}	± 0.076 [309] relative 31%	relative (stat. only) $\sim 0.05\%^*$ [40]	Fast simulation	Tracker Vertex	3
10	$B_s^0 \to J/\psi\phi$	91.2	Γ_s, $\Delta\Gamma_s$, ϕ_s	$\sigma(\Gamma_s) = \pm\ 2.3\ \mathrm{ns}^{-1}$ [145] $\sigma(\Delta\Gamma_s) = \pm 4.3 \pm 3.7\ \mathrm{ns}^{-1}$ [310] $\sigma(\phi_s) = \pm 36 \pm 21$ mrad [310]	$\sigma(\Gamma_s) = 0.036\ \mathrm{ns}^{-1*}$ $\sigma(\Delta\Gamma_s) = 0.12\ \mathrm{ns}^{-1*}$ [56] $\sigma(\phi_s) = 2.2$ mrad*	Full simulation	Tracker Vertex Lifetime resolution Jet origin ID	5
11	$B^0 \to \pi^0\pi^0$	91.2	BR, A_{CP} (α)	$\sigma(\mathrm{BR})/\mathrm{BR}^{00} = 16\%$ $\sigma(C_{CP}^{00}) = \pm\ 0.22$ [145]	$\sigma(\mathrm{BR})/\mathrm{BR}^{00} = 0.25\%^*$ $\sigma(a_{CP}^{00}) = \pm 0.01^*$ [33]	Fast simulation	ECAL Jet origin ID	5
12	$B^0 \to \pi^+\pi^-$	91.2	BR (α)	$\sigma(\mathrm{BR})/\mathrm{BR}^{+0} = 7\%$ [145]	$\sigma(\mathrm{BR})/\mathrm{BR}^{+0} = 0.1\%^*$ [33]	Fast simulation	ECAL Tracker Jet origin ID	5
13	$B^+ \to \pi^+\pi^0$	91.2	BR, A_{CP} (α)	$\sigma(\mathrm{BR})/\mathrm{BR}^{+-} = 4\%$ $\sigma(C_{CP}^{+-}) = \pm\ 0.030$ [145] $\sigma(S_{CP}^{+-}) = \pm\ 0.030$	$\sigma(\mathrm{BR})/\mathrm{BR}^{+-} = 0.1\%^*$ $\sigma(C_{CP}^{+-}) = \pm 0.003^*$ [33] $\sigma(S_{CP}^{+-}) = \pm 0.003^*$	Fast simulation	ECAL Tracker Vertex Jet origin ID	5
14	$\tau \to eee$	91.2	BR	$< 2.7 \times 10^{-8}$ [145]	$\lesssim \mathcal{O}(10^{-10})$ [151, 154]	Conjecture	Tracker Lepton ID	7
15	$\tau \to e\mu\mu$	91.2	BR	$< 2.7 \times 10^{-8}$ [145]	$\lesssim \mathcal{O}(10^{-10})$ [151, 154]	Conjecture	Tracker Lepton ID	7
16	$\tau \to \mu ee$	91.2	BR	$< 1.8 \times 10^{-8}$ [145]	$\lesssim \mathcal{O}(10^{-10})$ [151, 154]	Conjecture	Tracker Lepton ID	7
17	$\tau \to \mu\gamma$	91.2	BR	$< 4.4 \times 10^{-8}$ [145]	$\lesssim \mathcal{O}(10^{-10})$ [151, 154]	Conjecture	Tracker Lepton ID ECAL	7
18	$\tau \to e\gamma$	91.2	BR	$< 3.3 \times 10^{-8}$ [145]	$\lesssim \mathcal{O}(10^{-10})$ [151, 154]	Conjecture	Tracker Lepton ID ECAL	7
19	$\tau \to \mu\mu\mu$	91.2	BR	$< 2.1 \times 10^{-8}$ [145]	$\lesssim \mathcal{O}(10^{-10})$ [151, 154]	Conjecture	Tracker Lepton ID	7
20	$\tau \to$ incl.	91.2	τ_τ (s) lifetime	$\pm 5 \times 10^{-16}$ [145]	$\pm 1 \times 10^{-18}$ [151]	Conjecture	-	7
21	$\tau \to$ incl.	91.2	m_τ (MeV)	± 0.12 [145]	$\pm$ 0.004 (stat.) $\pm$ 0.1 (sys.) [151]	Conjecture	-	7
22	$\tau \to \ell\nu\bar{\nu}$	91.2	BR	$\pm 4 \times 10^{-4}$ [145]	$\pm 3 \times 10^{-5}$ [151]	Conjecture	Tracker Lepton ID Missing energy	7



No.	Process	$\sqrt{s}$ (GeV)	Observable/physics parameter of interest	Current precision	CEPC precision	Estimation method	Key performance	Relevant section
23	$Z \to \pi^+\pi^-$	91.2	BR	-	$\lesssim \mathcal{O}(10^{-10})$ [154]	Conjecture	Tracker PID	8.2
24	$Z \to \pi^+\pi^-\pi^0$	91.2	BR	-	$\lesssim \mathcal{O}(10^{-9})$ [154]	Conjecture	Tracker PID ECAL	8.2
25	$Z \to \rho\gamma$	91.2	BR	$< 2.5 \times 10^{-5}$ [145]	$\lesssim \mathcal{O}(10^{-9})$ [154]	Conjecture	Tracker PID ECAL	8.2
26	$Z \to J/\psi\gamma$	91.2	BR	$< 1.4 \times 10^{-6}$ [145]	$\lesssim 10^{-9}$–10^{-10} [154]	Conjecture	Tracker PID ECAL	8.2
27	$Z \to \tau\mu$	91.2	BR	$< 6.5 \times 10^{-6}$ [194–196]	$\lesssim \mathcal{O}(10^{-9})$ [151, 154]	Conjecture	E_{beam} Tracker PID	8.1
28	$Z \to \tau e$	91.2	BR	$< 5.0 \times 10^{-6}$ [194–196]	$\lesssim \mathcal{O}(10^{-9})$ [151, 154]	Conjecture	E_{beam} Tracker PID	8.1
29	$Z \to \mu e$	91.2	BR	$< 7.5 \times 10^{-7}$ [194–196]	$\lesssim 1 \times 10^{-9}$ [191]	Conjecture	E_{beam} Tracker PID	8.1
30	$Z \to \mu\mu X_{\mathrm{inv}}$	91.2	BR	-	$\lesssim 3 \times 10^{-11}$ [291]	Fast simulation	Tracker Missing energy	11
31	$\tau \to \mu X_{\mathrm{inv}}$	91.2	BR	$\lesssim 7 \times 10^{-4}$ [299]	$\lesssim$ 3–5 $\times 10^{-6}$	Fast simulation	Tracker Missing energy	11
32	$H \to sb$	240	BR	$\lesssim 10^{-2}$ [311]	$\lesssim$ 0.02%—0.1% [34]	Full simulation	Jet origin ID	9
33	$H \to sd$	240	BR	-	$\lesssim$ 0.02%—0.1% [34]	Full simulation	Jet origin ID	9
34	$H \to db$	240	BR	$\lesssim 10^{-2}$ [311]	$\lesssim$ 0.02%—0.1% [34]	Full simulation	Jet origin ID	9
35	$H \to uc$	240	BR	-	$\lesssim$ 0.02%—0.1% [34]	Full simulation	Jet origin ID	9
36	$H \to ss$	240	BR	$\lesssim 0.3\%$ [312, 313]	$\lesssim 0.1\%$ [34]	Full simulation	Jet origin ID	9
37	$H \to uu$	240	BR	$\lesssim 3.5\%$ $\kappa_u < 560$ [314]	$\lesssim 0.1\%$ [34] $\kappa_u < 101$	Full simulation	Jet origin ID	9
38	$H \to dd$	240	BR	$\lesssim 3.5\%$ $\kappa_d < 260$ [314]	$\lesssim 0.1\%$ [34] $\kappa_d < 37$	Full simulation	Jet origin ID	9
39	$e^+e^- \to tq$	240	cross section	two-fermion, LHC [221–225] four-fermion, LEP2 [226, 227]	1–2 orders of magnitude improvement compared to LEP2 [220]	Fast simulation	Tracker Missing energy Jet origin ID	9
40	$WW \to \ell\nu qq$	240	$\lvert V_{cb}\rvert$	$\pm 0.5 \times 10^{-3}$ (inclusive) $\pm 0.6 \times 10^{-3}$ (exclusive) [145] $\pm 1.2 \times 10^{-3}$ (average)	$\lesssim \pm 0.2 \times 10^{-3}$ [209] $L = 20\ \mathrm{ab}^{-1}$	Full simulation	Jet origin ID	9

Table 10: Summary of flavor physics benchmarks. The related physics parameters of interest for some benchmarks are listed in brackets, such as the CKM matrix element $\lvert V_{cb}\rvert$ and the CKM angle α. The symbol X in benchmarks No. 30–31 denotes the particle related to NP with subscripts "inv" representing the invisible particles. The CEPC precision of some benchmarks marked with stars (*) are extrapolated to the statistic of 4 Tera-Z, and the CEPC precision of Higgs rare and FCNC decays (benchmarks No. 32–38) is statistical only.

- Access to non-seen

- Orders of magnitudes improvements

- Non-inclusive + long wishlist -> to be addressed in phase II flavor WP study

Accesses to the Non-Seen

$b \to s\nu\nu$

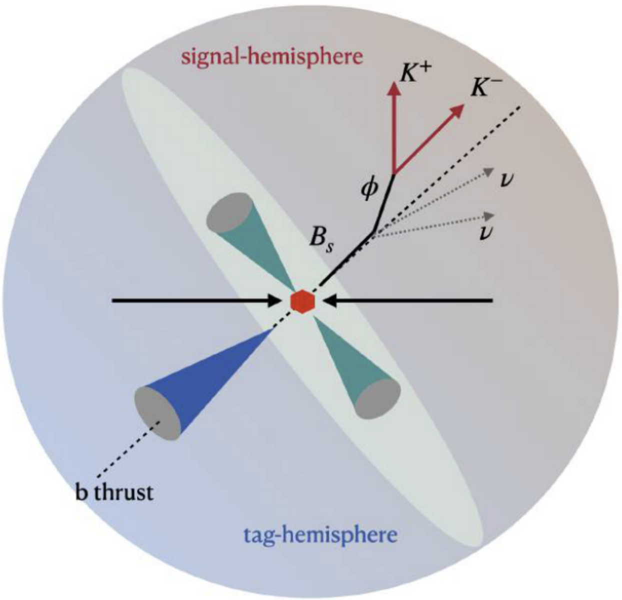
Li et al. '22

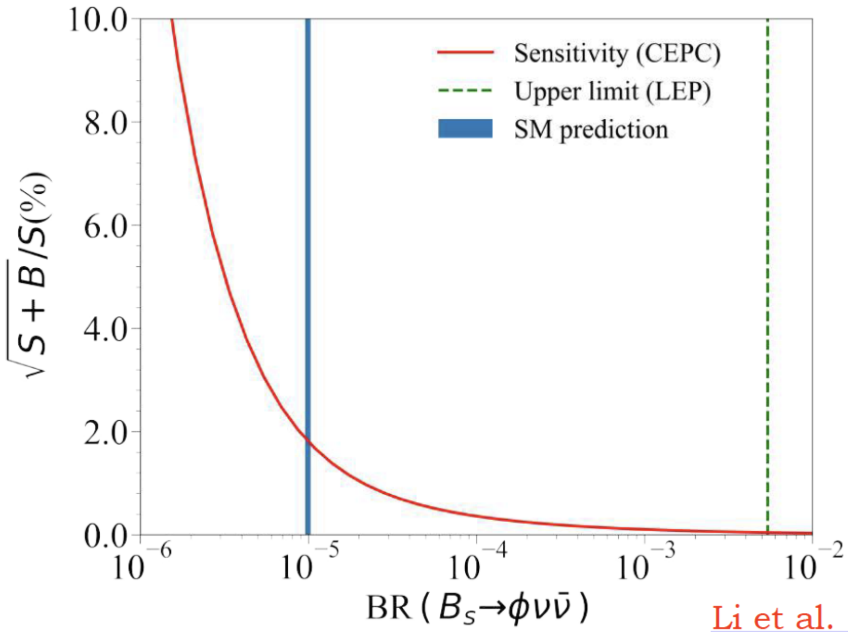
	Current Limit	Detector	SM Prediction
$\mathrm{BR}(B^0 \to K^0 \nu\bar{\nu})$	$< 2.6 \times 10^{-5}$ [3]	BELLE	$(3.69 \pm 0.44) \times 10^{-6}$ [1]
$\mathrm{BR}(B^0 \to K^{*0} \nu\bar{\nu})$	$< 1.8 \times 10^{-5}$ [3]	BELLE	$(9.19 \pm 0.99) \times 10^{-6}$ [1]
$\mathrm{BR}(B^\pm \to K^\pm \nu\bar{\nu})$	$< 1.6 \times 10^{-5}$ [4]	BABAR	$(3.98 \pm 0.47) \times 10^{-6}$ [1]
$\mathrm{BR}(B^\pm \to K^{*\pm} \nu\bar{\nu})$	$< 4.0 \times 10^{-5}$ [5]	BELLE	$(9.83 \pm 1.06) \times 10^{-6}$ [1]
$\mathrm{BR}(B_s \to \phi \nu\bar{\nu})$	$< 5.4 \times 10^{-3}$ [6]	DELPHI	$(9.93 \pm 0.72) \times 10^{-6}$

- Also these modes can be greatly enhanced by new physics responsible for the B anomalies

see e.g. LC Crivellin Ota '15

- A Tera Z can measure $B_s \to \phi\nu\nu$ with a percent level precision:





Li et al. '22

$B_c \to \tau\nu$

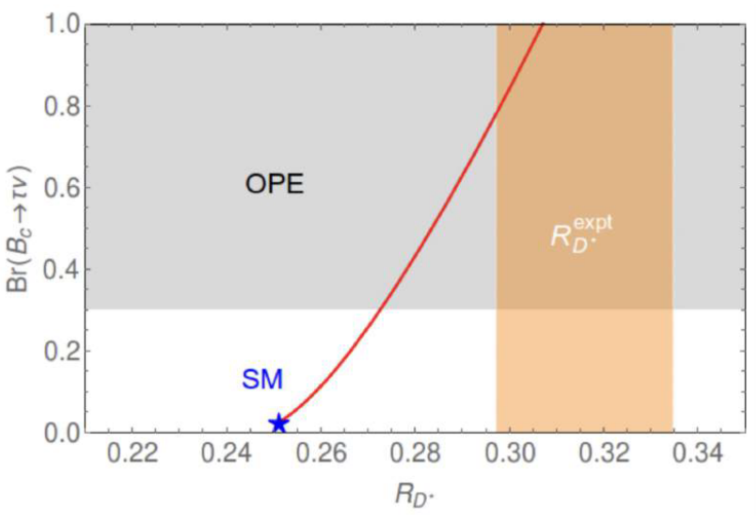
- Key observable to test the LFU anomalies in charged-current B decays

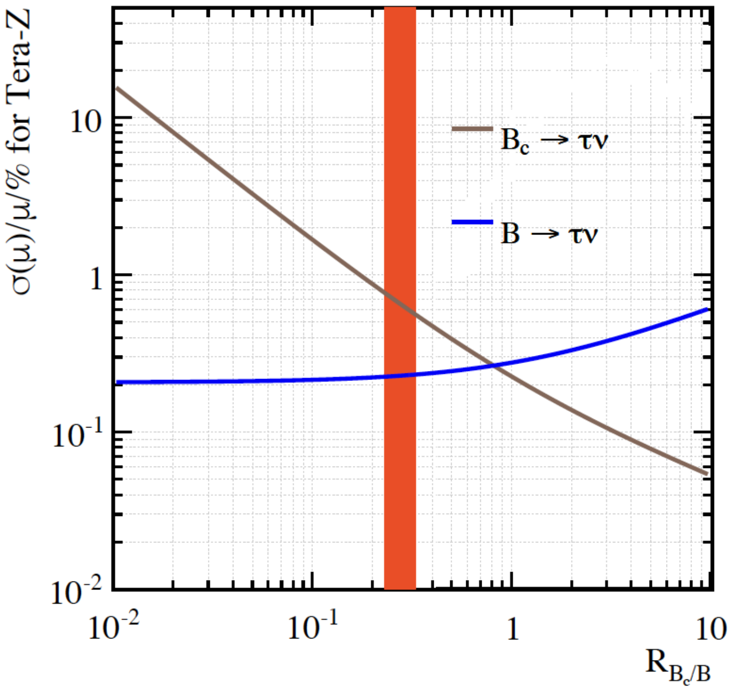
Alonso et al. '16

- SM prediction for the BR ~ 2%, beyond the reach of LHCb

- Tera Z could measure with percent level accuracy (thus providing also a percent level accurate measurement of V_{cb})

Zheng et al. '20





Summary of rare B decays

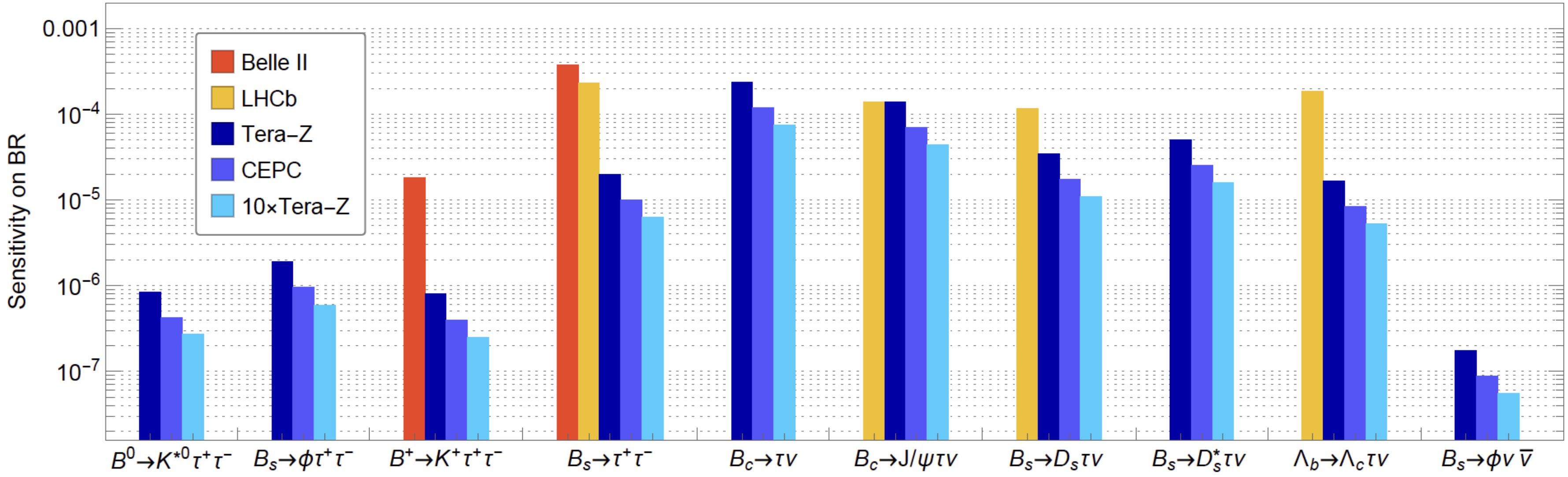


Figure 17: Projected sensitivities of measuring the $b \to s\tau\tau$ [71], $b \to s\nu\bar{\nu}$ [35] and $b \to c\tau\nu$ [37, 63] transitions at the Z pole. The sensitivities at Belle II @ 50 ab^{-1} [6] and LHCb Upgrade II [17, 72] have also been provided as a reference. Note, the LHCb sensitivities are generated by combining the analyses of $\tau^+ \to \pi^+\pi^-\pi^-(\pi^0)\nu$ and $\tau \to \mu\nu\bar{\nu}$. This plot is adapted from [37].

Ho et al. '22
CEPC flavour WP, in preparation

Orders of magnitude improvements

Summary of the tau and Z prospects

Measurement	Current [126]	FCC [115]	Tera-Z Prelim. [127]	Comments
Lifetime [sec]	$\pm 5 \times 10^{-16}$	$\pm 1 \times 10^{-18}$		from 3-prong decays, stat. limited
$\mathrm{BR}(\tau \to \ell \nu \bar{\nu})$	$\pm 4 \times 10^{-4}$	$\pm 3 \times 10^{-5}$		0.1× the ALEPH systematics
$\mathrm{m}(\tau)$ [MeV]	± 0.12	$\pm 0.004 \pm 0.1$		$\sigma(p_{\mathrm{track}})$ limited
$\mathrm{BR}(\tau \to 3\mu)$	$< 2.1 \times 10^{-8}$	$\mathcal{O}(10^{-10})$	same	bkg free
$\mathrm{BR}(\tau \to 3e)$	$< 2.7 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
$\mathrm{BR}(\tau^{\pm} \to e\mu\mu)$	$< 2.7 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
$\mathrm{BR}(\tau^{\pm} \to \mu ee)$	$< 1.8 \times 10^{-8}$	$\mathcal{O}(10^{-10})$		bkg free
$\mathrm{BR}(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$	$\sim 2 \times 10^{-9}$	$\mathcal{O}(10^{-10})$	$Z \to \tau\tau\gamma$ bkg , $\sigma(p_{\gamma})$ limited
$\mathrm{BR}(\tau \to e\gamma)$	$< 3.3 \times 10^{-8}$	$\sim 2 \times 10^{-9}$		$Z \to \tau\tau\gamma$ bkg, $\sigma(p_{\gamma})$ limited
$\mathrm{BR}(Z \to \tau\mu)$	$< 1.2 \times 10^{-5}$	$\mathcal{O}(10^{-9})$	same	$\tau\tau$ bkg, $\sigma(p_{\mathrm{track}})$ & $\sigma(E_{\mathrm{beam}})$ limited
$\mathrm{BR}(Z \to \tau e)$	$< 9.8 \times 10^{-6}$	$\mathcal{O}(10^{-9})$		$\tau\tau$ bkg, $\sigma(p_{\mathrm{track}})$ & $\sigma(E_{\mathrm{beam}})$ limited
$\mathrm{BR}(Z \to \mu e)$	$< 7.5 \times 10^{-7}$	$10^{-8} - 10^{-10}$	$\mathcal{O}(10^{-9})$	PID limited
$\mathrm{BR}(Z \to \pi^{+}\pi^{-})$			$\mathcal{O}(10^{-10})$	$\sigma(\vec{p}_{\mathrm{track}})$ limited, good PID
$\mathrm{BR}(Z \to \pi^{+}\pi^{-}\pi^{0})$			$\mathcal{O}(10^{-9})$	$\tau\tau$ bkg
$\mathrm{BR}(Z \to J/\psi\gamma)$	$< 1.4 \times 10^{-6}$		$10^{-9} - 10^{-10}$	$\ell\ell\gamma$+$\tau\tau\gamma$ bkg
$\mathrm{BR}(Z \to \rho\gamma)$	$< 2.5 \times 10^{-5}$		$\mathcal{O}(10^{-9})$	$\tau\tau\gamma$ bkg, $\sigma(p_{\mathrm{track}})$ limited

From the Snowmass report: The Physics potential of the CEPC

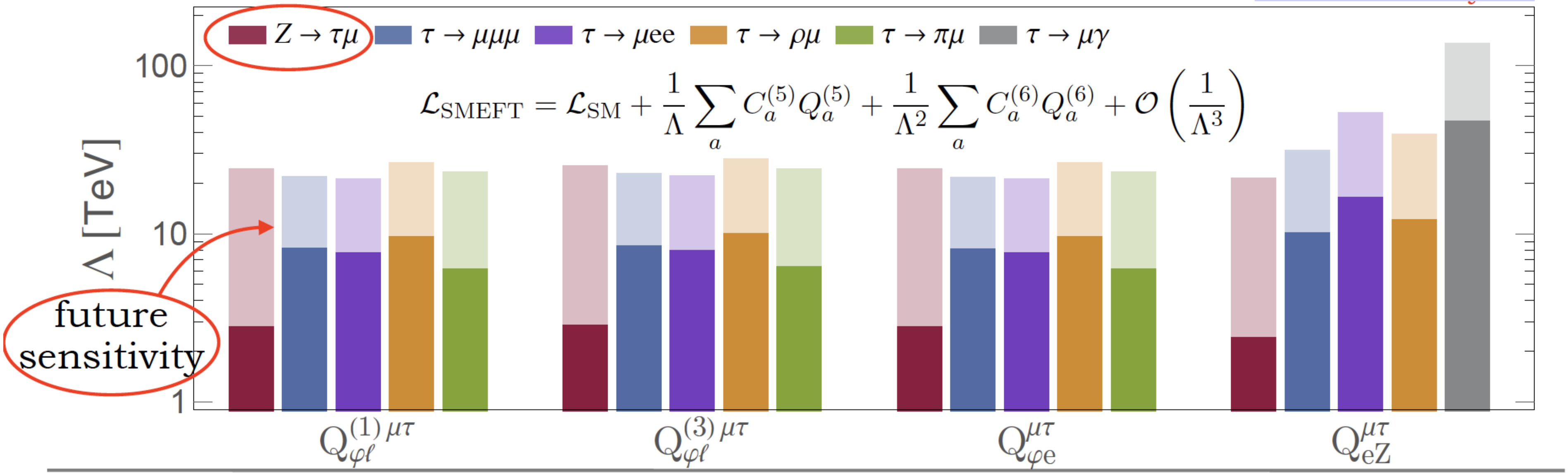
Lepton Flavour Violation in Z decays

Mode	LEP bound (95% CL)	LHC bound (95% CL)	CEPC/FCC-ee exp.
$\mathrm{BR}(Z \to \mu e)$	1.7×10^{-6} [2]	7.5×10^{-7} [3]	$10^{-8} - 10^{-10}$
$\mathrm{BR}(Z \to \tau e)$	9.8×10^{-6} [2]	5.0×10^{-6} [4, 5]	10^{-9}
$\mathrm{BR}(Z \to \tau \mu)$	1.2×10^{-5} [6]	6.5×10^{-6} [4, 5]	10^{-9}

M. Dam '18

- LHC searches limited by backgrounds (in particular $Z \to \tau\tau$): max ~10 improvement can be expected at HL-LHC (3000/fb)
- A Tera Z can test LFV new physics searching for $Z \to \tau\,\ell$ at the level of what Belle II (50/ab) will do through LFV tau decays (or better)

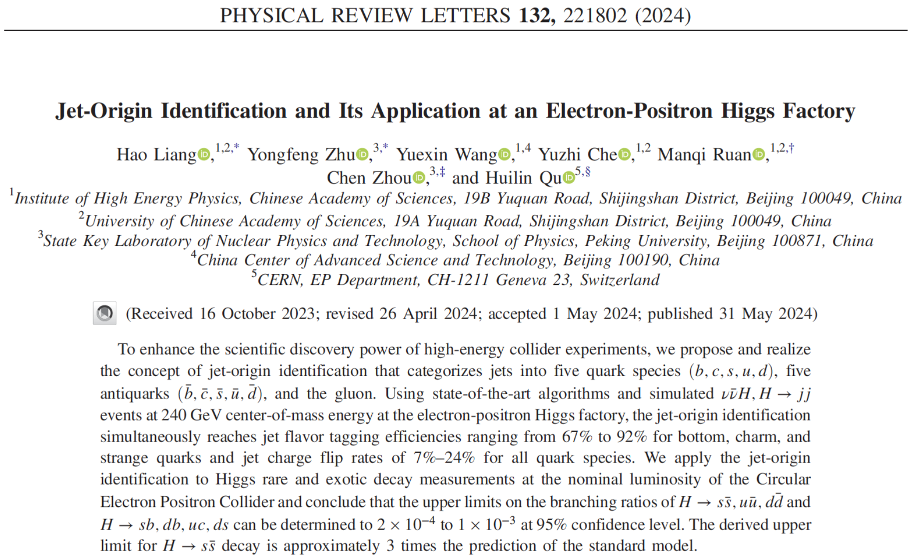
LC Marcano Roy '21



$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

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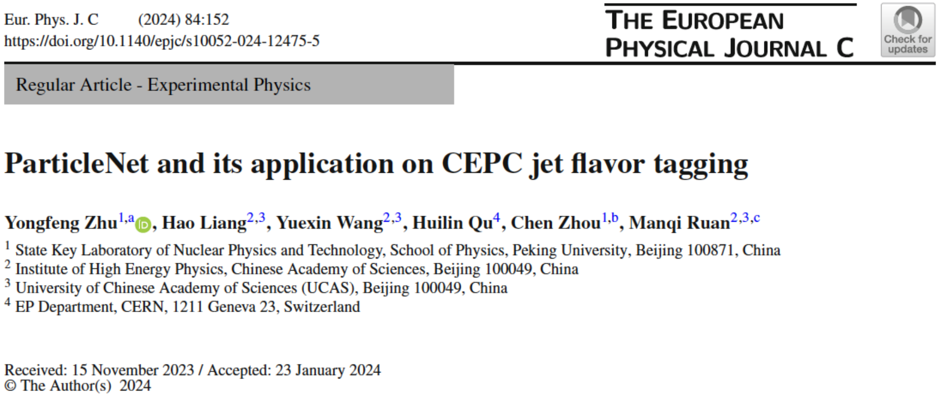
(Received 16 October 2023; revised 26 April 2024; accepted 1 May 2024; published 31 May 2024)

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

Regular Article - Experimental Physics

ParticleNet and its application on CEPC jet flavor tagging

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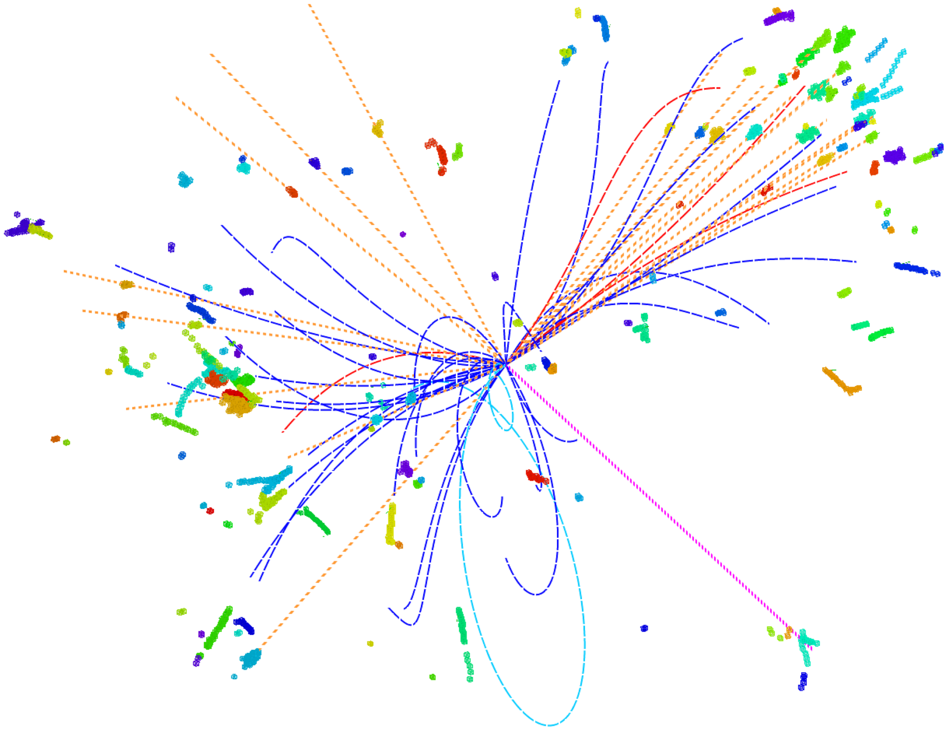
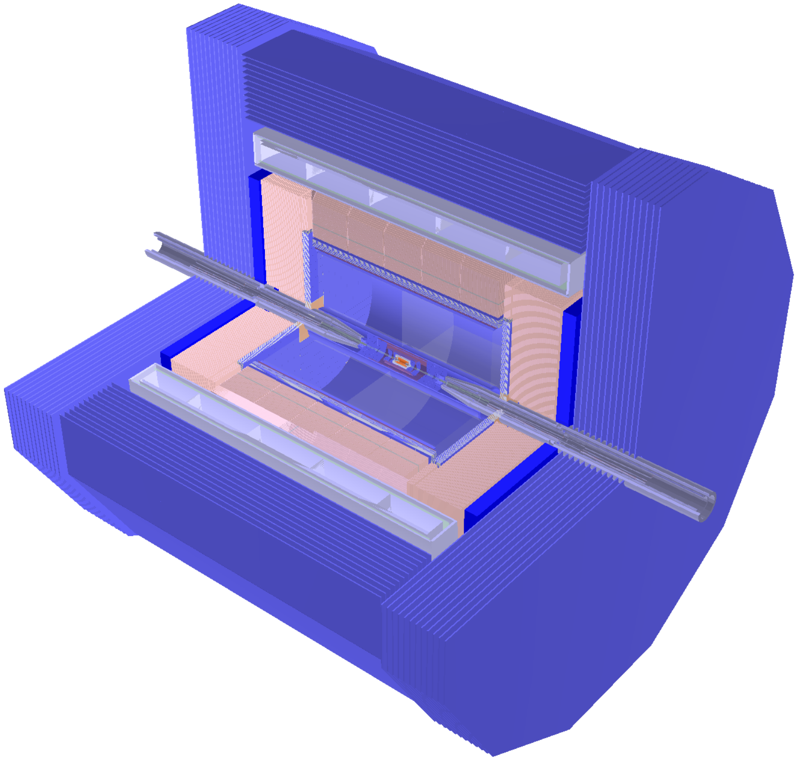
Received: 15 November 2023 / Accepted: 23 January 2024

https://arxiv.org/abs/2310.03440

https://arxiv.org/abs/2309.13231

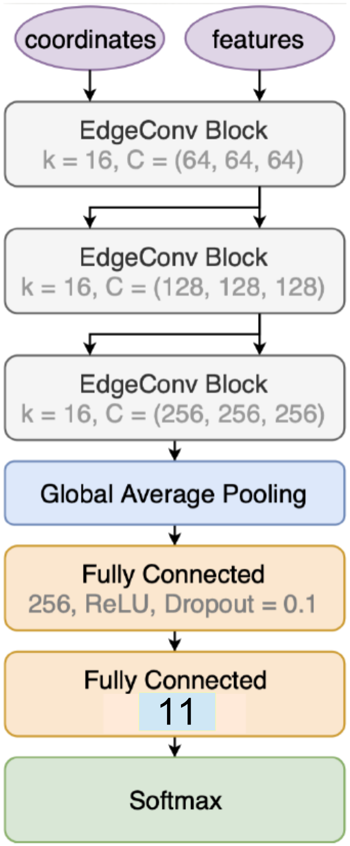
Geo. & Tools

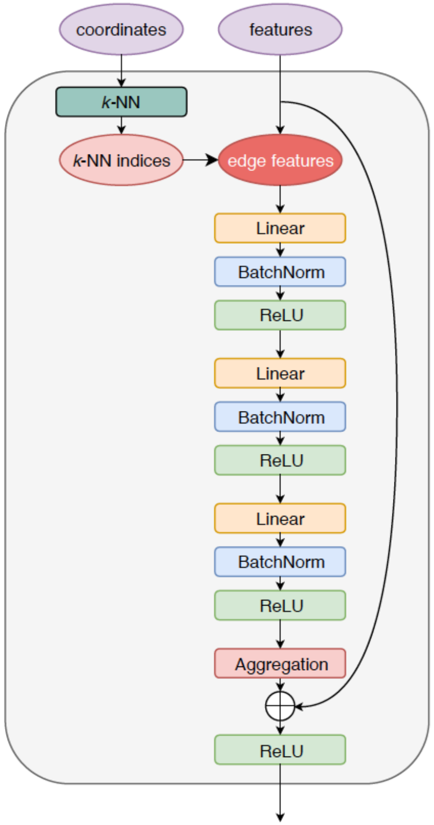


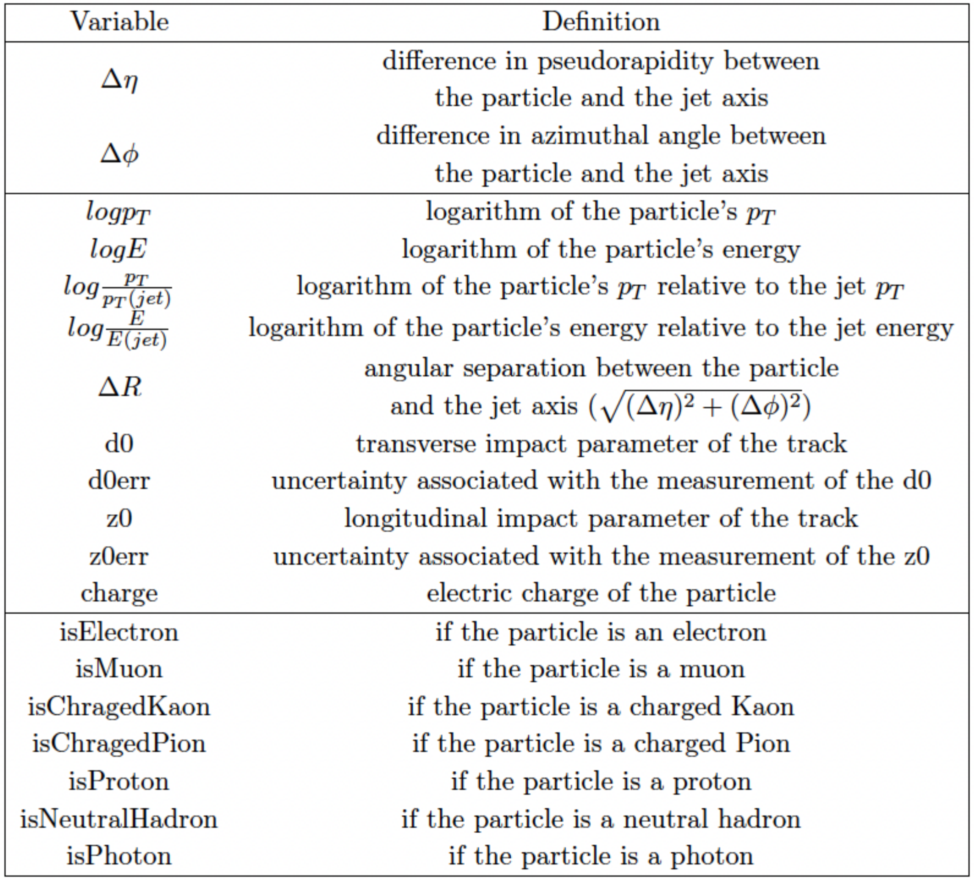


- **Jet origin identification: 11 categories (5 quarks + 5 anti quarks + gluon)**
  - Jet Flavor Tagging + Jet Charge measurements + s-tagging + gluon tagging...
- Full Simulated vvH, Higgs to two jets sample at CEPC baseline configuration: CEPC-v4 detector, reconstructed with **Arbor + ParticleNet (Deep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

Particle Net: IO







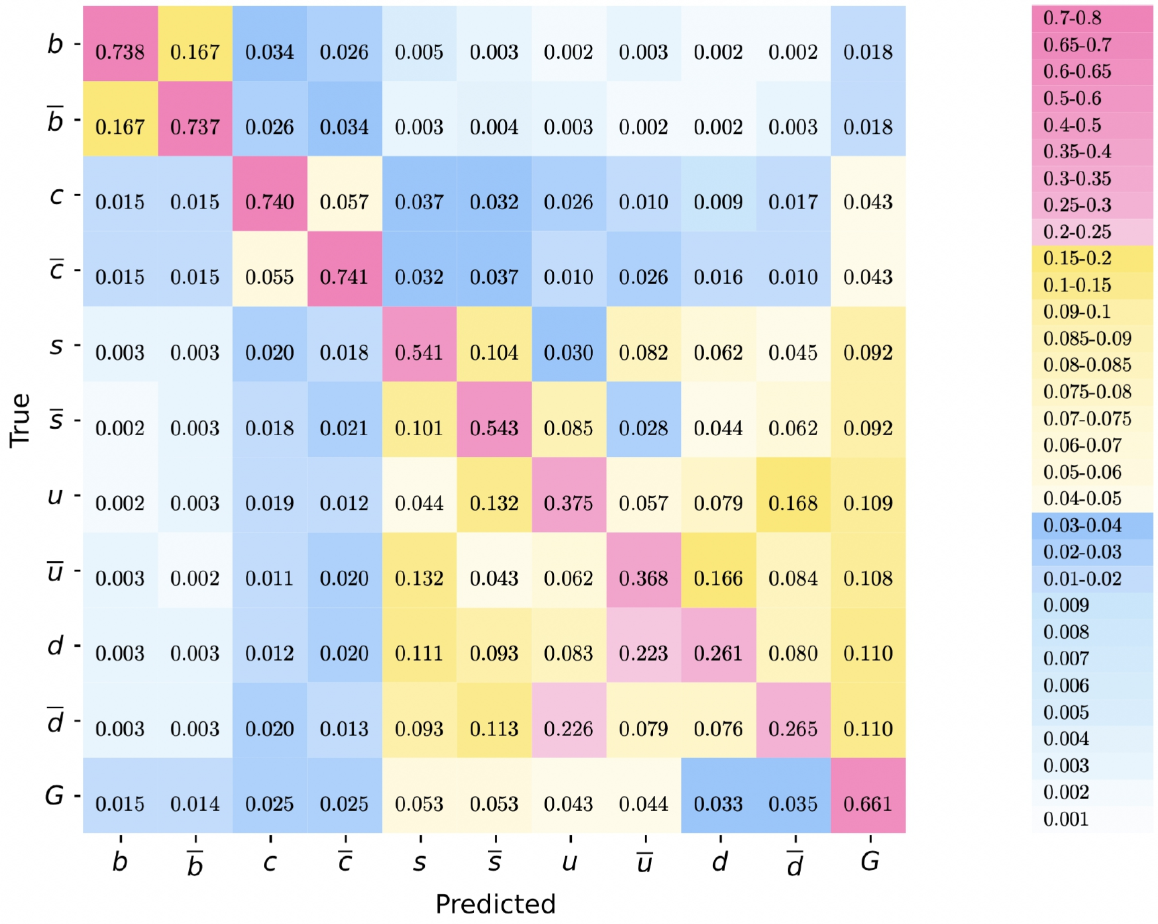
Variable	Definition
$\Delta\eta$	difference in pseudorapidity between the particle and the jet axis
$\Delta\phi$	difference in azimuthal angle between the particle and the jet axis
$log p_T$	logarithm of the particle's p_T
$log E$	logarithm of the particle's energy
$log \frac{p_T}{p_T(jet)}$	logarithm 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 information of all reconstructed jet particles
- Output: 10(11)-likelihoods to different categories

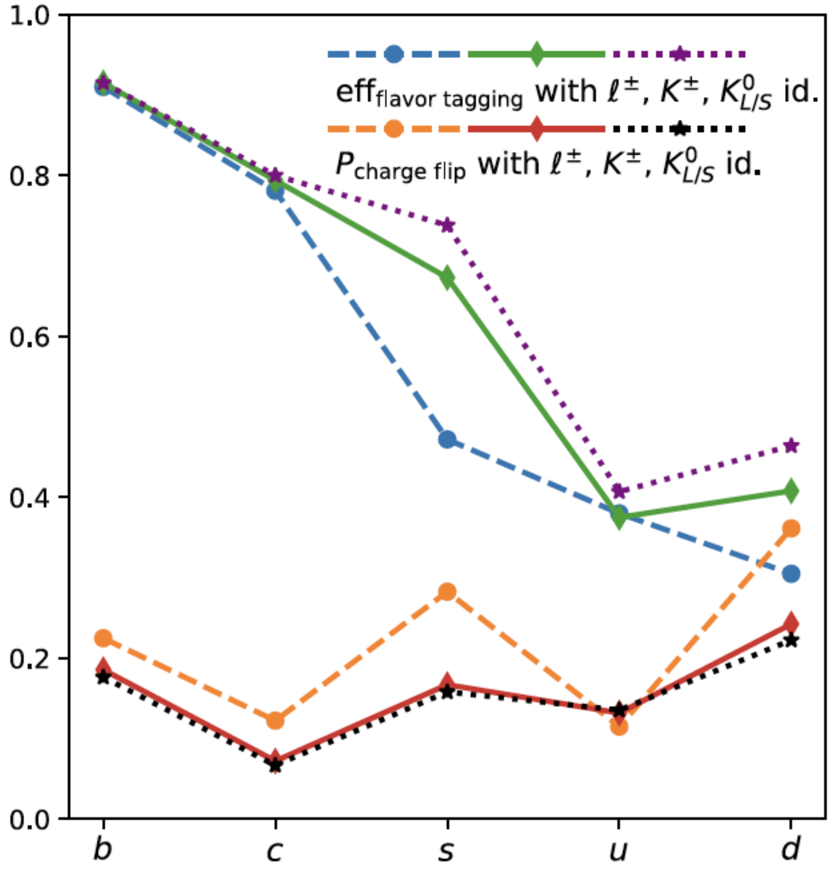
11-dim migration behavior

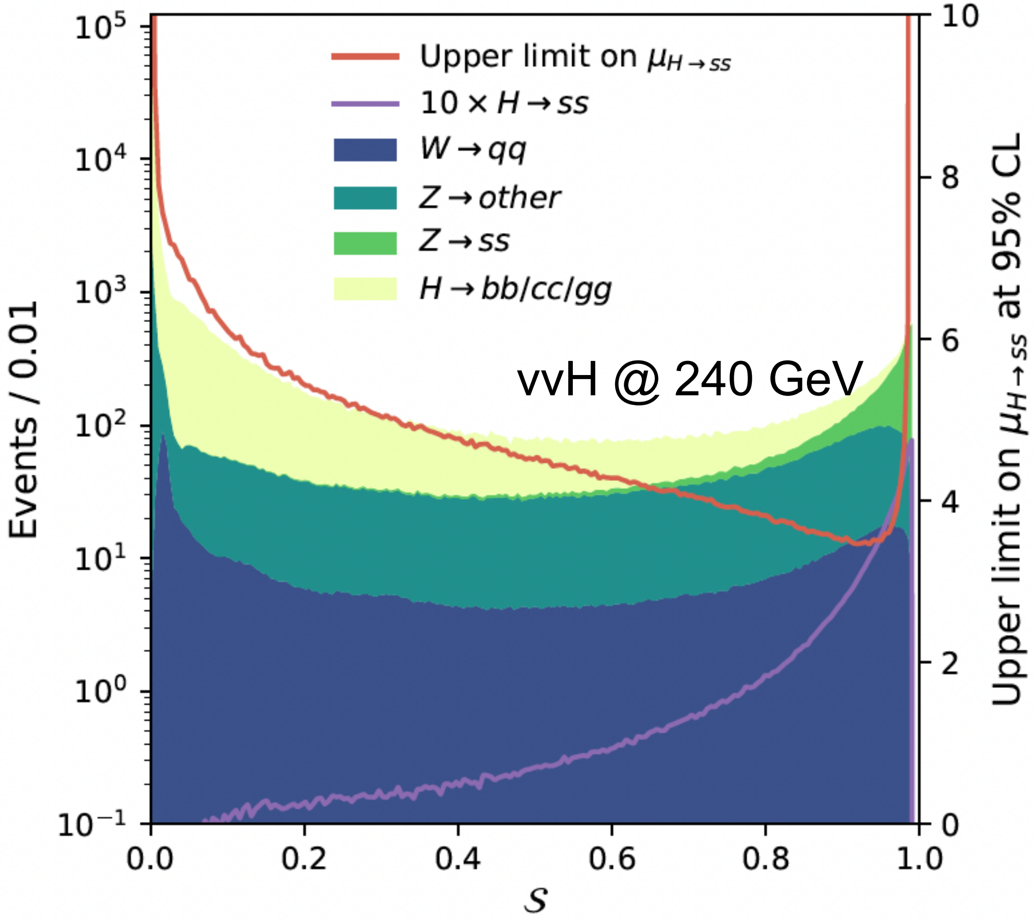
- Let the jet be identified as the category with highest likelihood:
- Pid: ideal Pid – three categories
  - Lepton identification
  - **Charged Kaon identification**
  - Neutral Kaon identification
- Patterns:
  - ~ Diagonal at quark sector...
  - P(g→q) < P(q→g)...
  - Light jet id...



	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

Performance with different PID scenarios & H→ss measurements



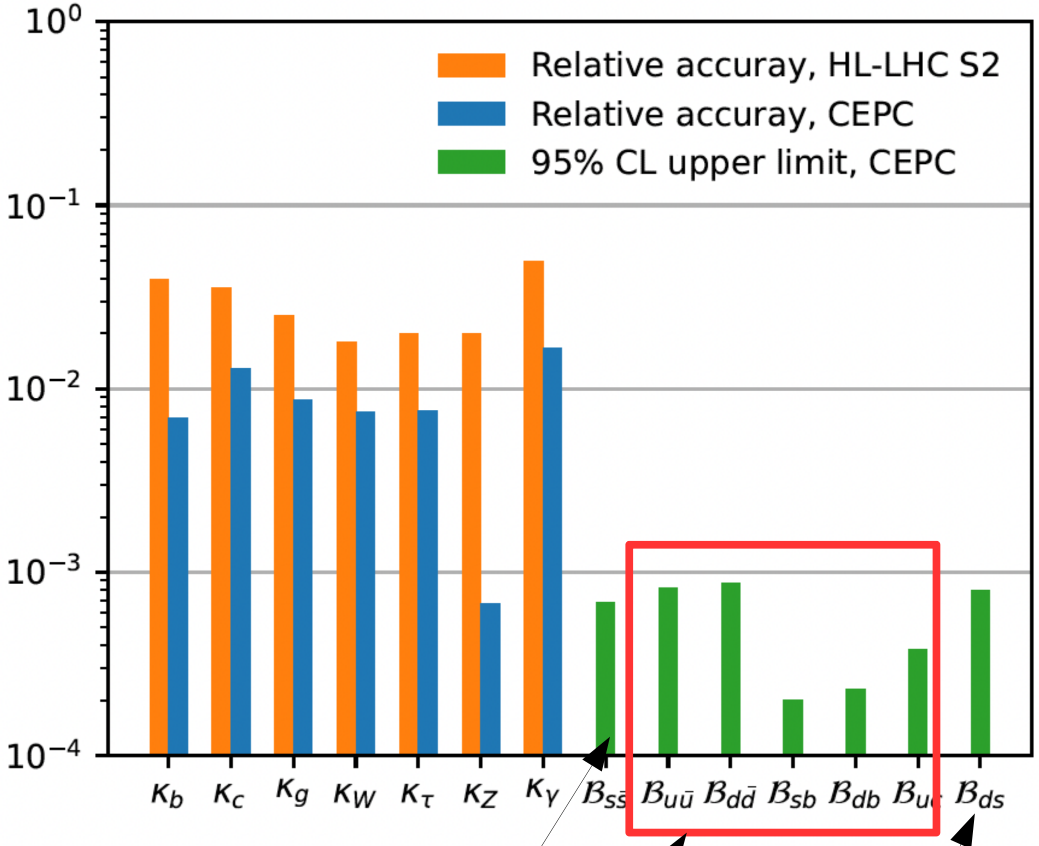


Flavor tagging: type that maximize {L_q + L_q_bar, L_g}

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

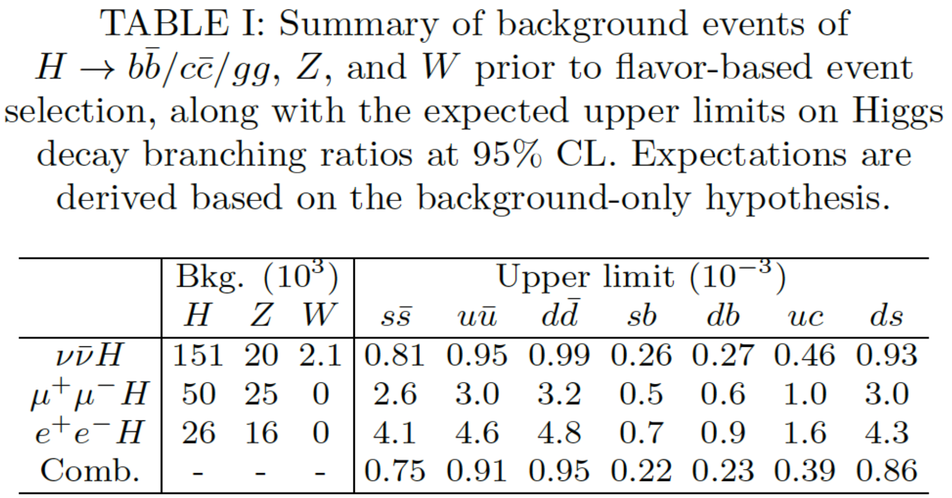
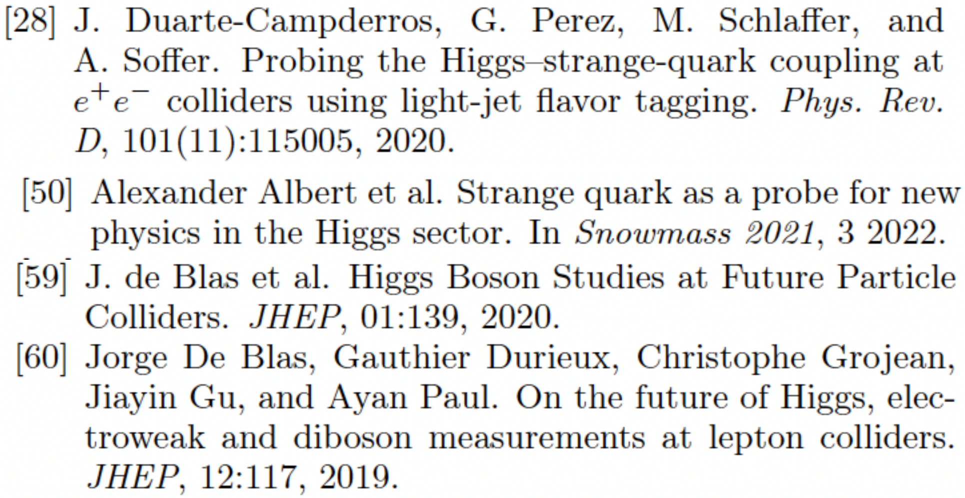


TABLE I: Summary of background events of $H \to b\bar{b}/c\bar{c}/gg$, Z, and W prior to flavor-based event selection, along with the expected upper limits on Higgs decay branching ratios at 95% CL. Expectations are derived based on the background-only hypothesis.

	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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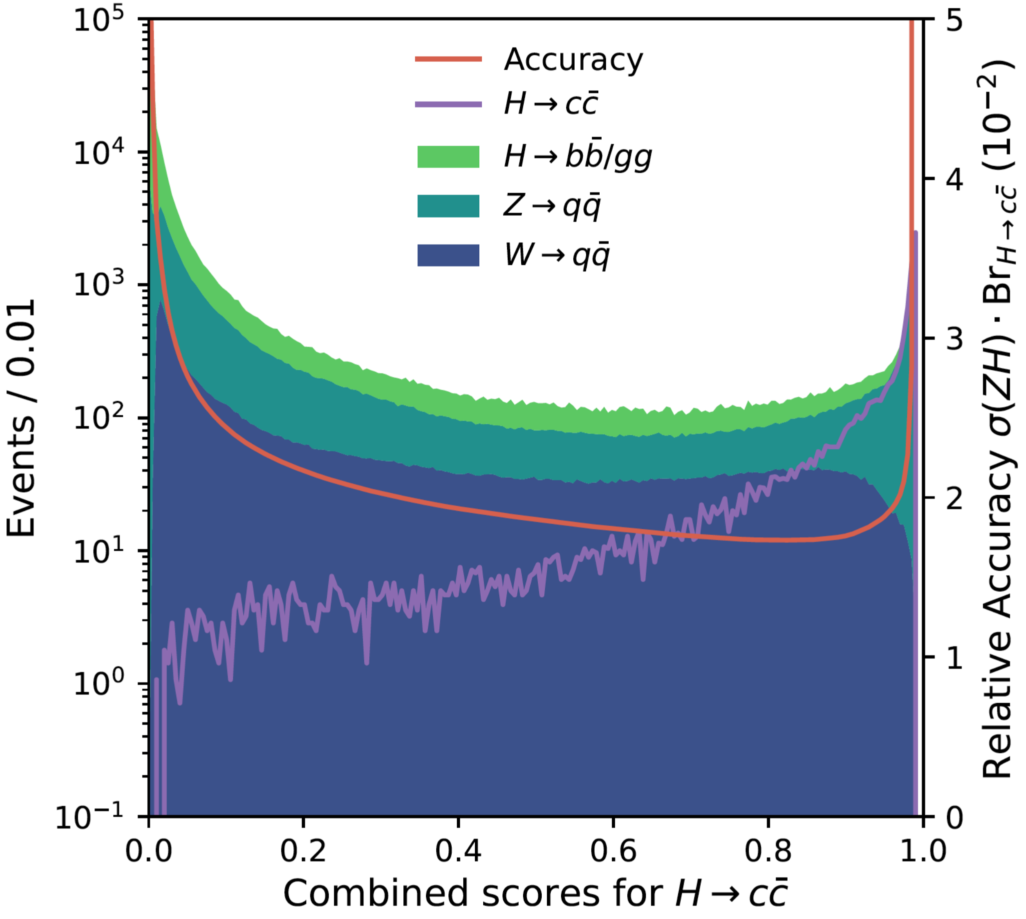
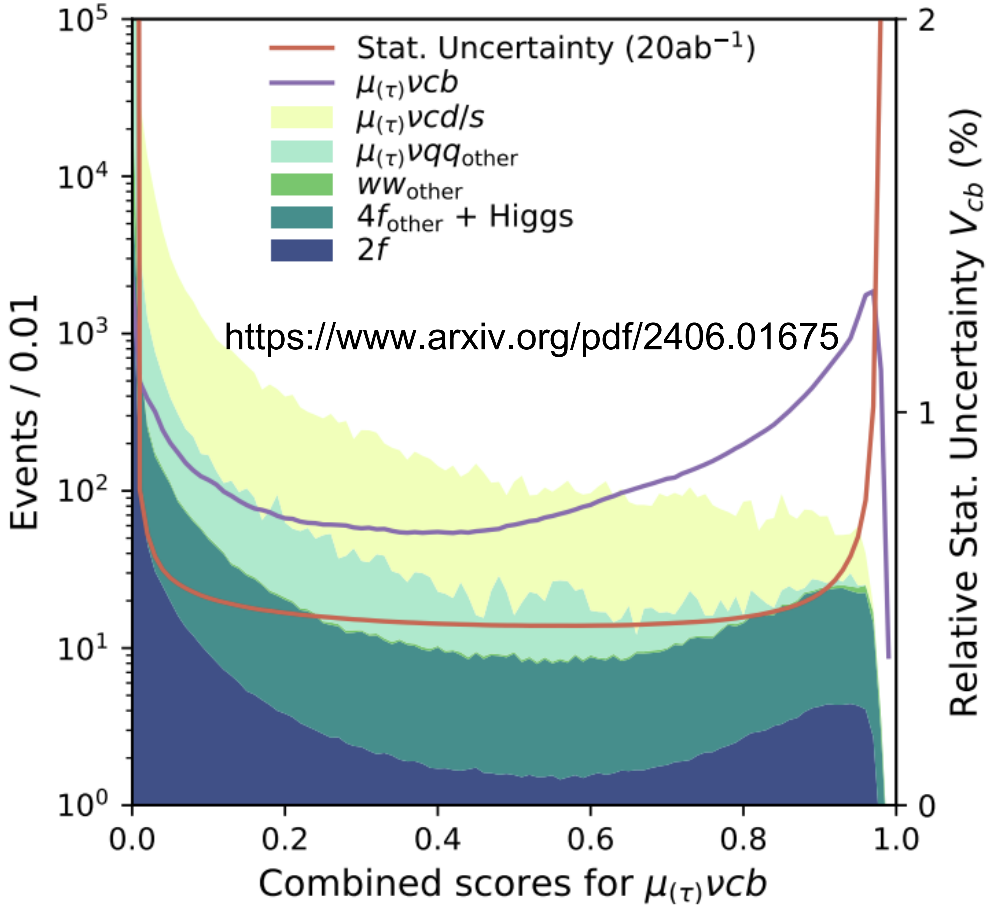
Recent update at more benchmarks





https://www.arxiv.org/pdf/2406.01675

- 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 $\sin^2\theta_{eff}^{l}$ measurement

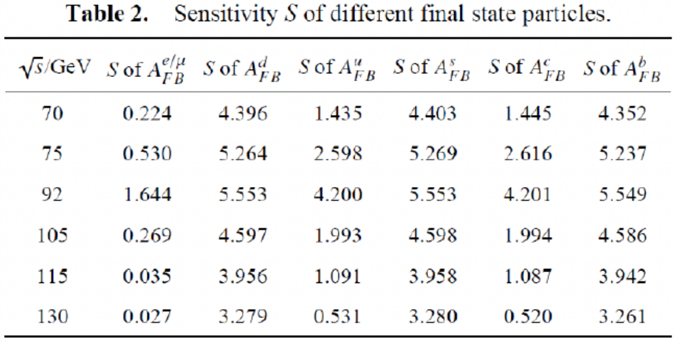


Table 2. Sensitivity S of different final state particles.

$\sqrt{s}$/GeV	S of $A_{FB}^{e/\mu}$	S of A_{FB}^{d}	S of A_{FB}^{u}	S of A_{FB}^{s}	S of A_{FB}^{c}	S of A_{FB}^{b}
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

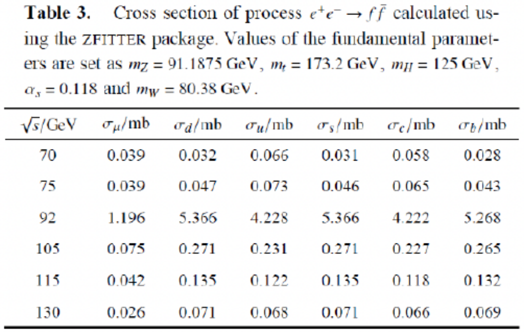


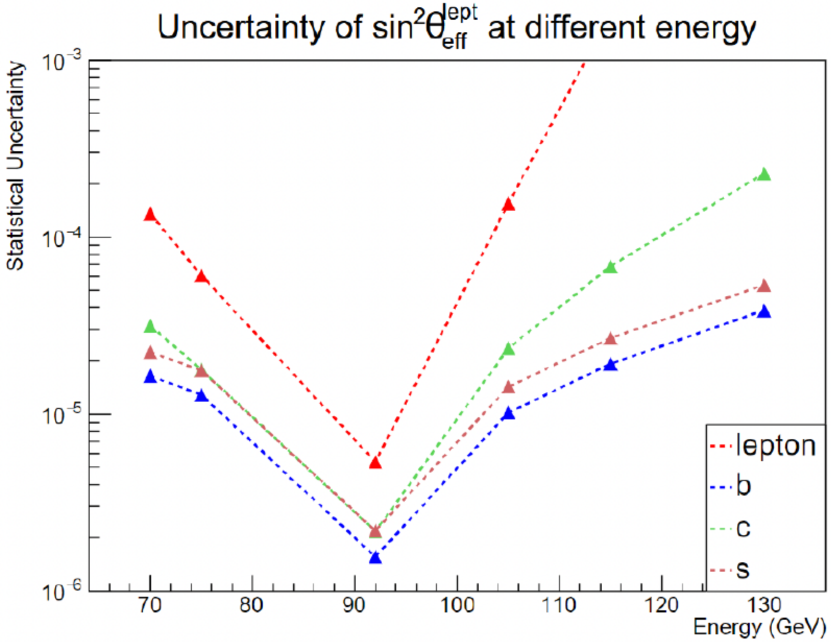
Table 3. Cross section of process $e^+e^- \rightarrow f\bar{f}$ calculated using the ZFITTER package. Values of the fundamental parameters are set as $m_Z = 91.1875$ GeV, $m_t = 173.2$ GeV, $m_H = 125$ GeV, $\alpha_s = 0.118$ and $m_W = 80.38$ GeV.

$\sqrt{s}$/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 $\sin^2\theta_{eff}^{l}$ measurement.

(Using one-month data collection, ~ *4e12/24 Z events* at Z pole)

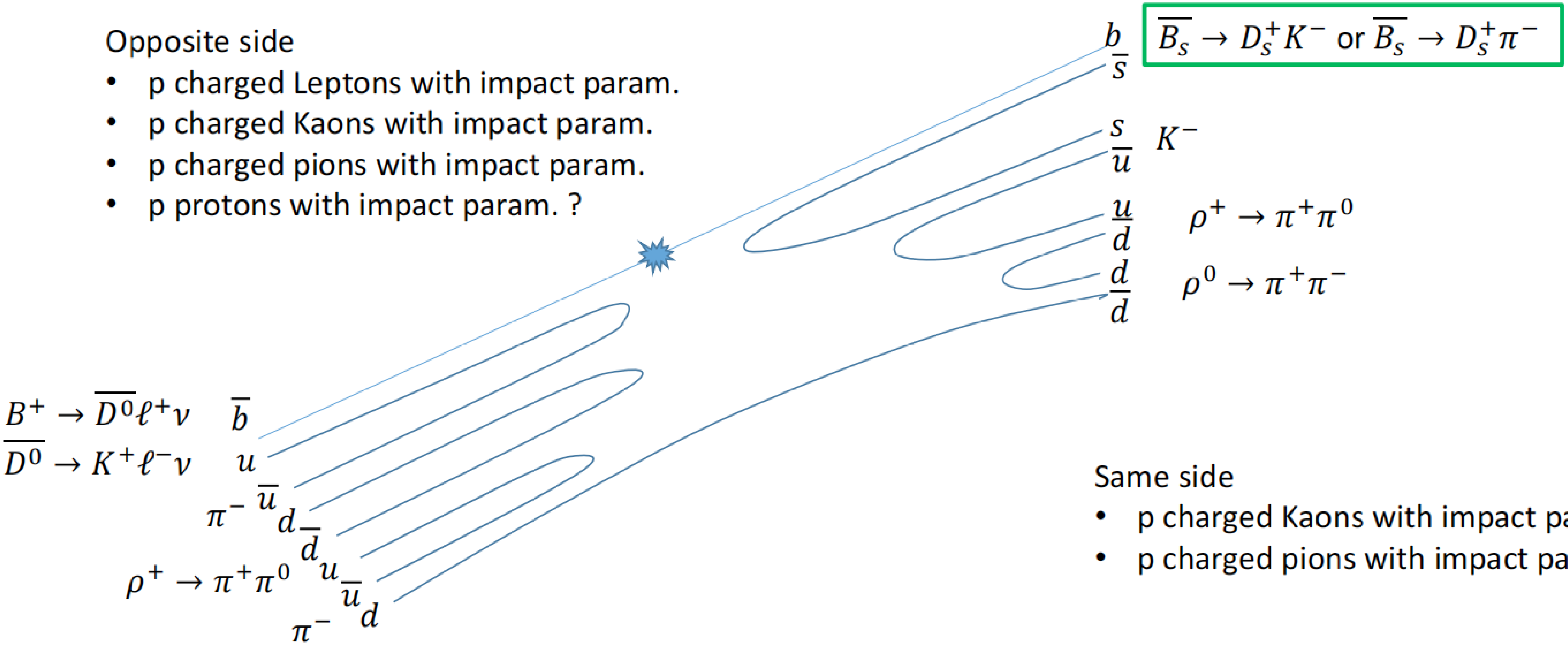


$\sqrt{s}$	b	c	s
70	1.6×10^{-5}	3.2×10^{-5}	2.2×10^{-5}
75	1.3×10^{-5}	1.8×10^{-5}	1.8×10^{-5}
92	1.6×10^{-6}	2.2×10^{-6}	2.2×10^{-6}
105	1.0×10^{-5}	2.4×10^{-5}	1.4×10^{-5}
115	1.9×10^{-5}	6.8×10^{-5}	2.7×10^{-5}
130	3.9×10^{-5}	2.3×10^{-4}	5.4×10^{-5}

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

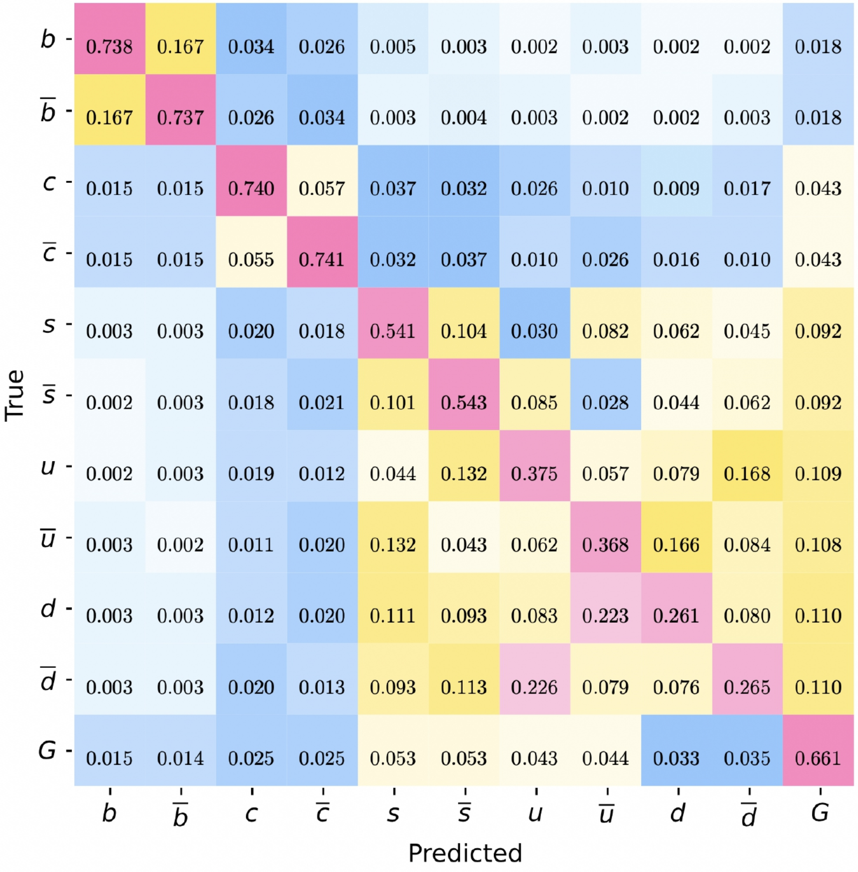
- p charged Kaons with impact param
- p charged pions with impact param.

Summary

- Higgs factory: immense science...
  - Flavor Program: reaching to NP of 10 TeV energy scale
- 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→ss, uu, dd, sb, uc, sd, db by 3-100 times, and H→cc by 2 times
  - Flavor: Improve Vcb precision by ~50%, effective tagging power for b-jet > 40%...
  - EW: Weak mixing angle...
  - QCD: Fragmentation relevant - **Road Map wanted**: towards better hadronization models + experimental validation (from both current data + GigaZ + TeraZ) + applications
  - NP: ...
- Long term version: 'see' gluon + quarks, as we see photon + leptons

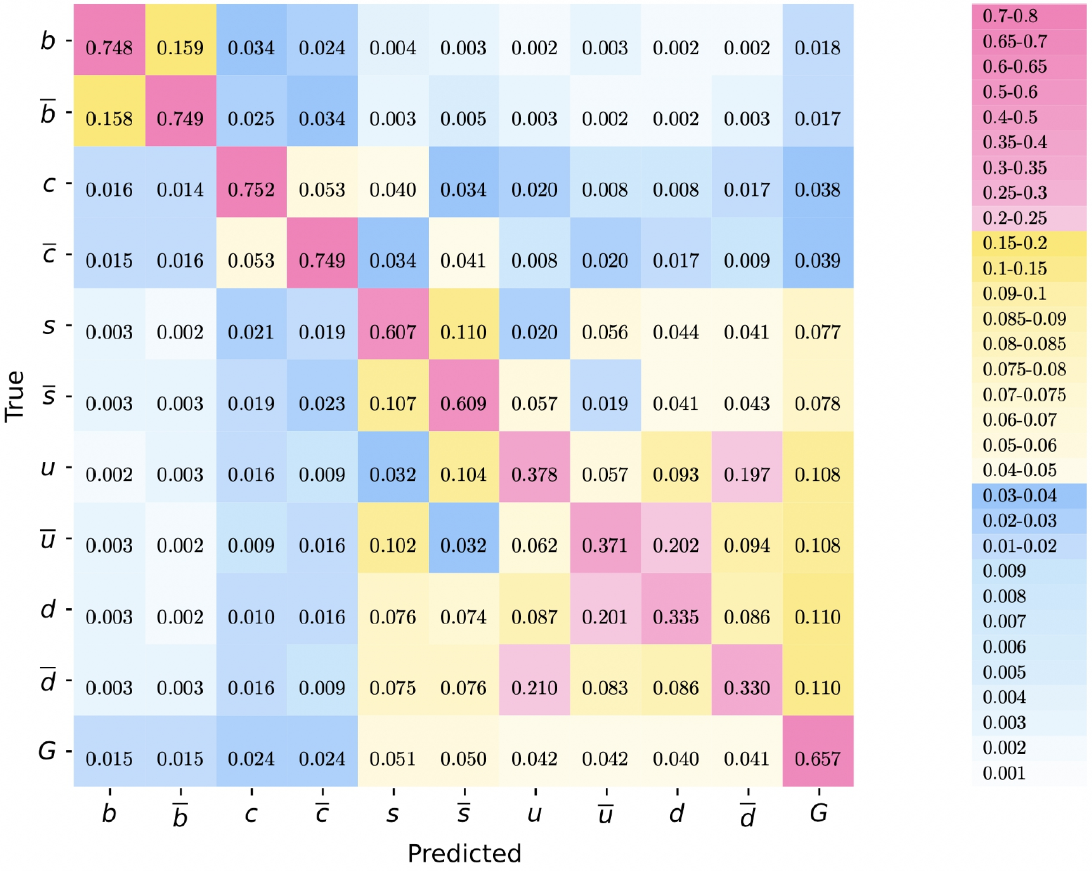
Back up

M11 2 with charged hadron

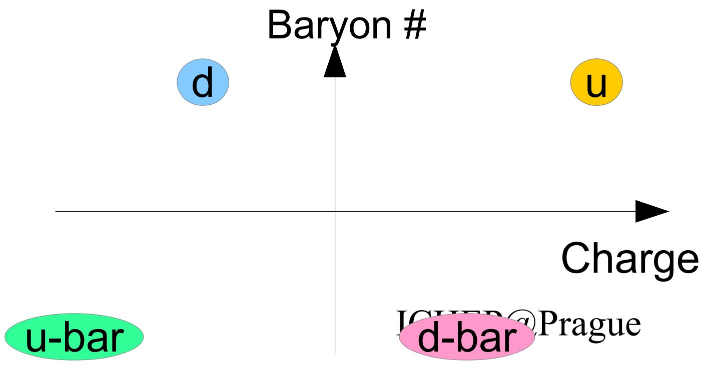


	b	$\bar{b}$	c	$\bar{c}$	s	$\bar{s}$	u	$\bar{u}$	d	$\bar{d}$	G
b	0.738	0.167	0.034	0.026	0.005	0.003	0.002	0.003	0.002	0.002	0.018
$\bar{b}$	0.167	0.737	0.026	0.034	0.003	0.004	0.003	0.002	0.002	0.003	0.018
c	0.015	0.015	0.740	0.057	0.037	0.032	0.026	0.010	0.009	0.017	0.043
$\bar{c}$	0.015	0.015	0.055	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

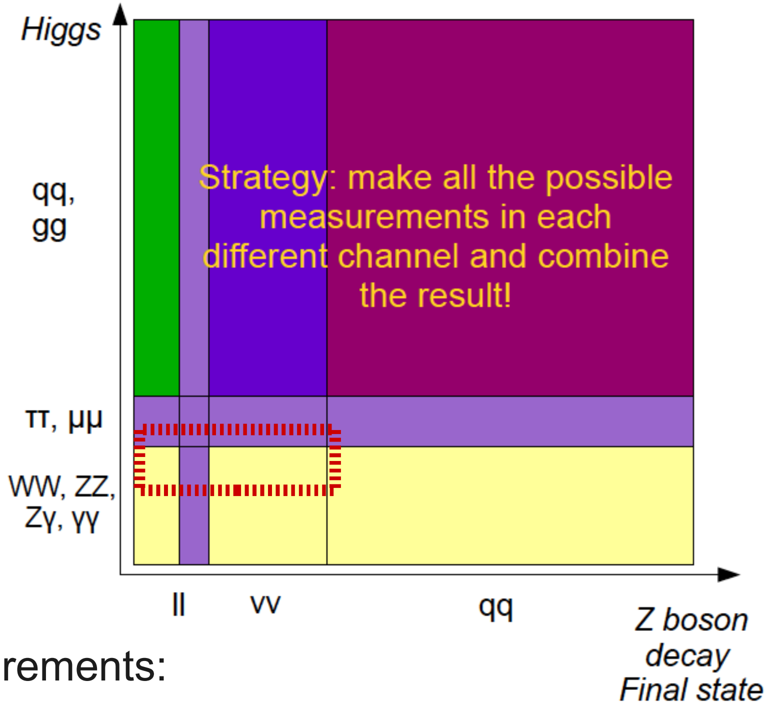


	b	$\bar{b}$	c	$\bar{c}$	s	$\bar{s}$	u	$\bar{u}$	d	$\bar{d}$	G
b	0.748	0.159	0.034	0.024	0.004	0.003	0.002	0.003	0.002	0.002	0.018
$\bar{b}$	0.158	0.749	0.025	0.034	0.003	0.005	0.003	0.002	0.002	0.003	0.017
c	0.016	0.014	0.752	0.053	0.040	0.034	0.020	0.008	0.008	0.017	0.038
$\bar{c}$	0.015	0.016	0.053	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



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 → W + b

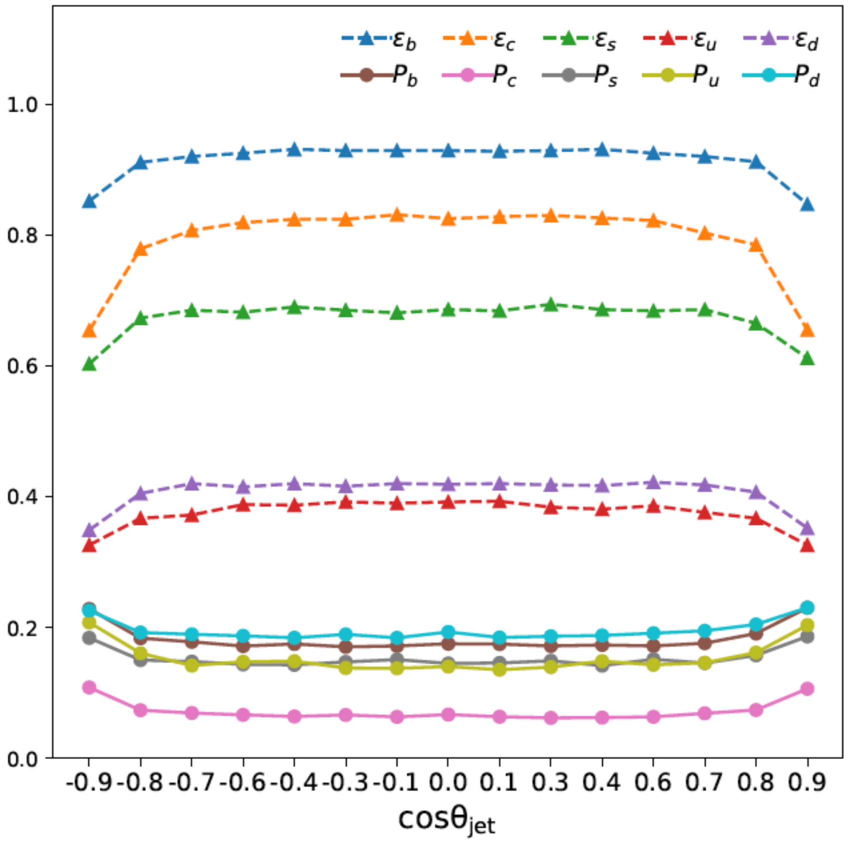


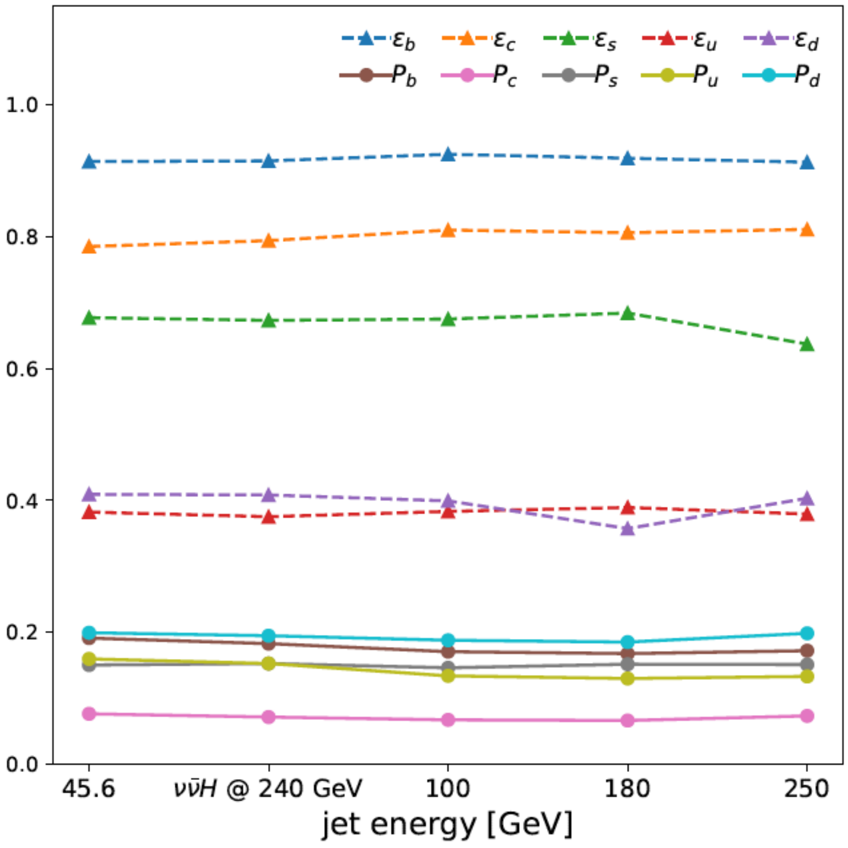
Strategy: make all the possible measurements in each different channel and combine the result!

- Requirements:
  - **1-1 correspondence**

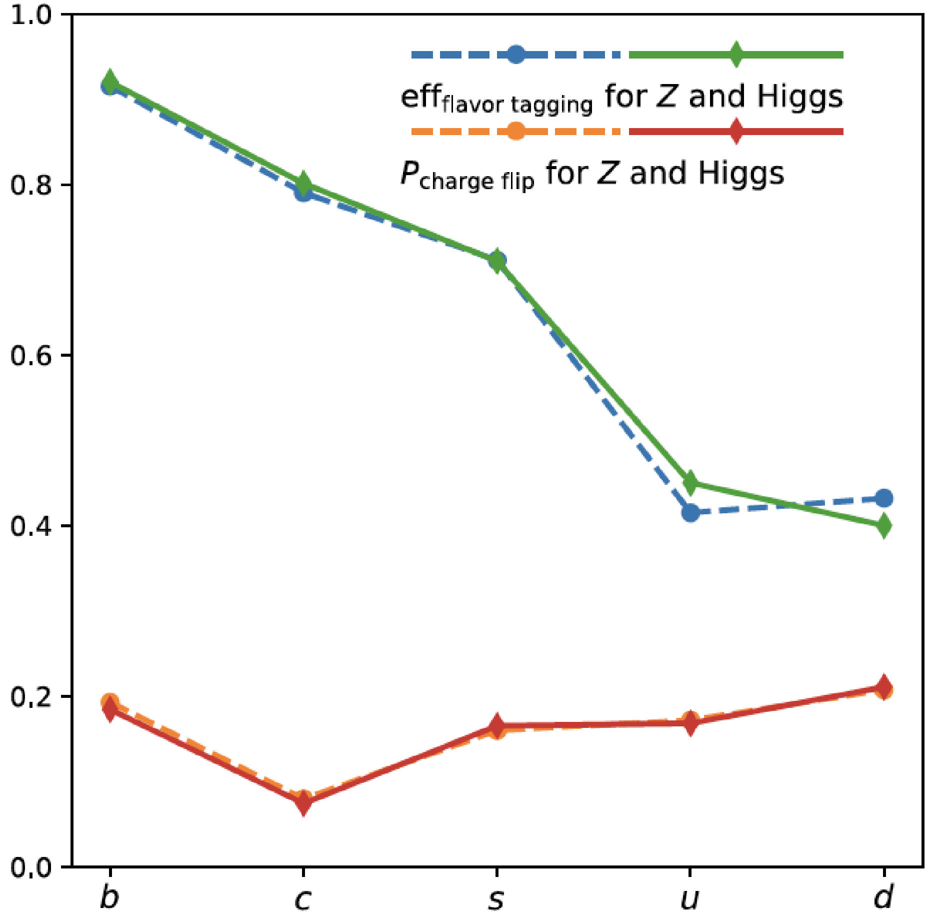
    Excellent pattern. Reco. & Object id
  - Larger acceptance, Excellent intrinsic resolutions, Extremely stable...
- Be addressed by detector design, technology, and reconstruction algorithm

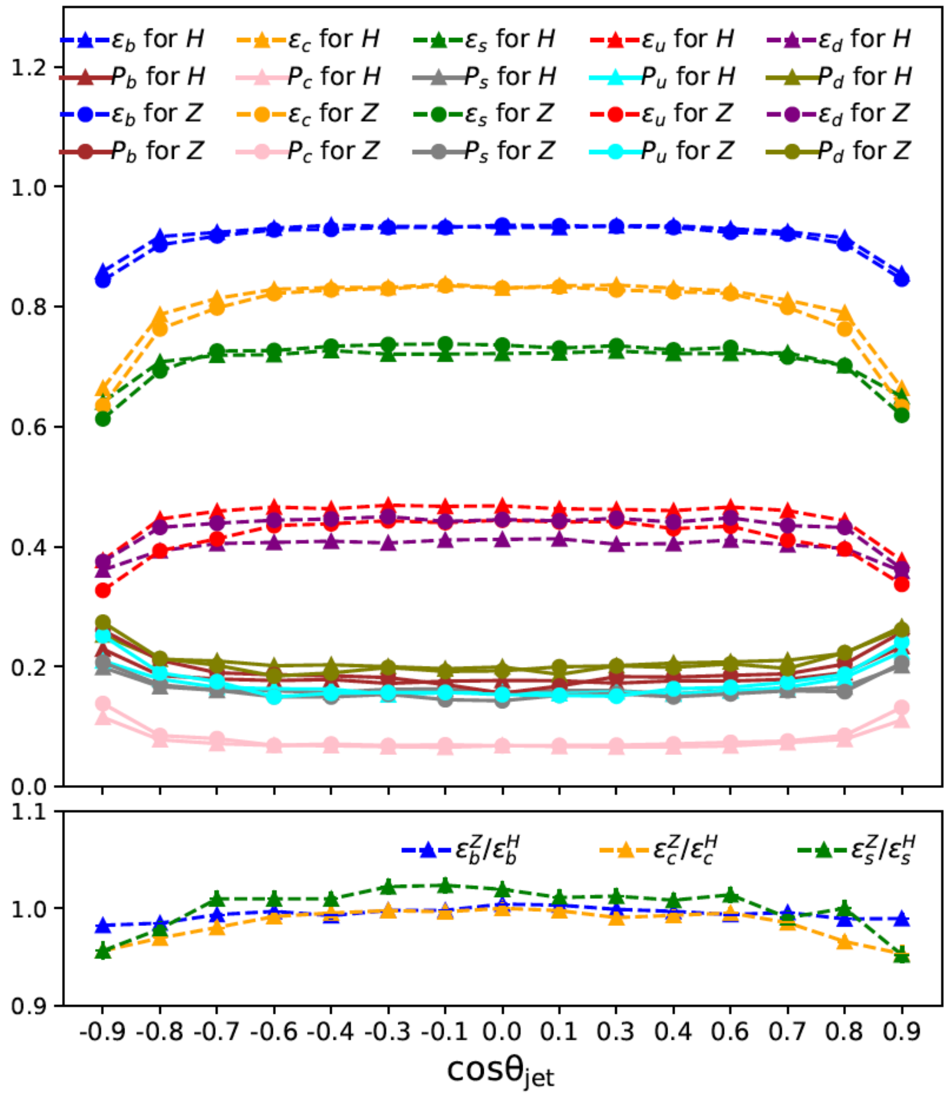
Performance V.S. Jet Kinematics





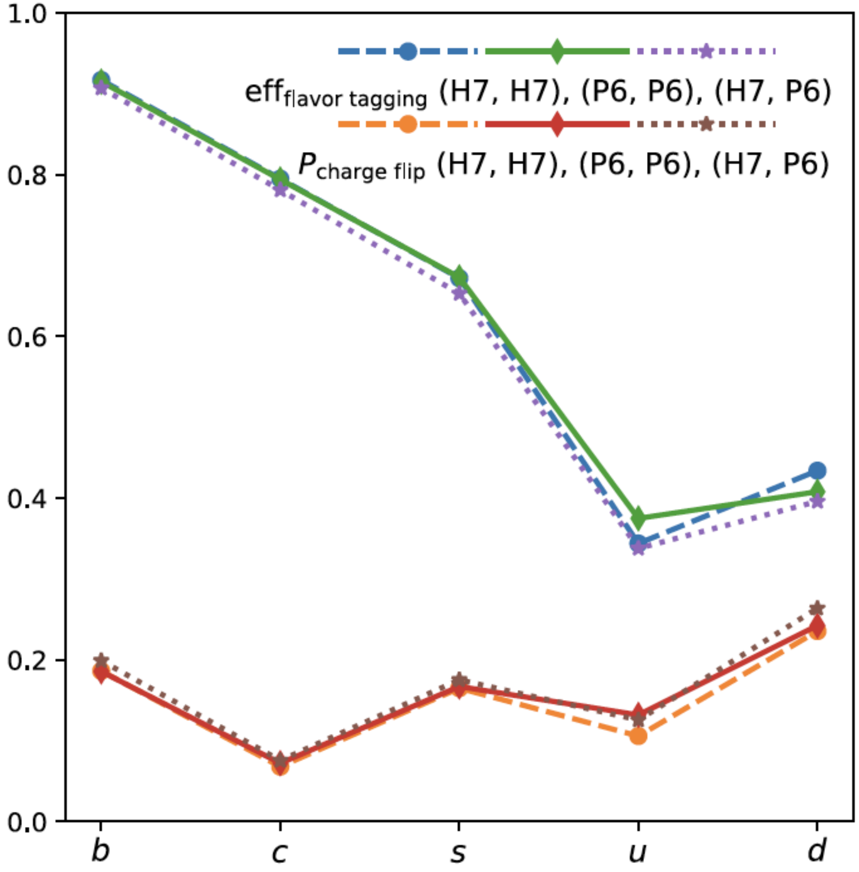
Performance @ Z and Higgs

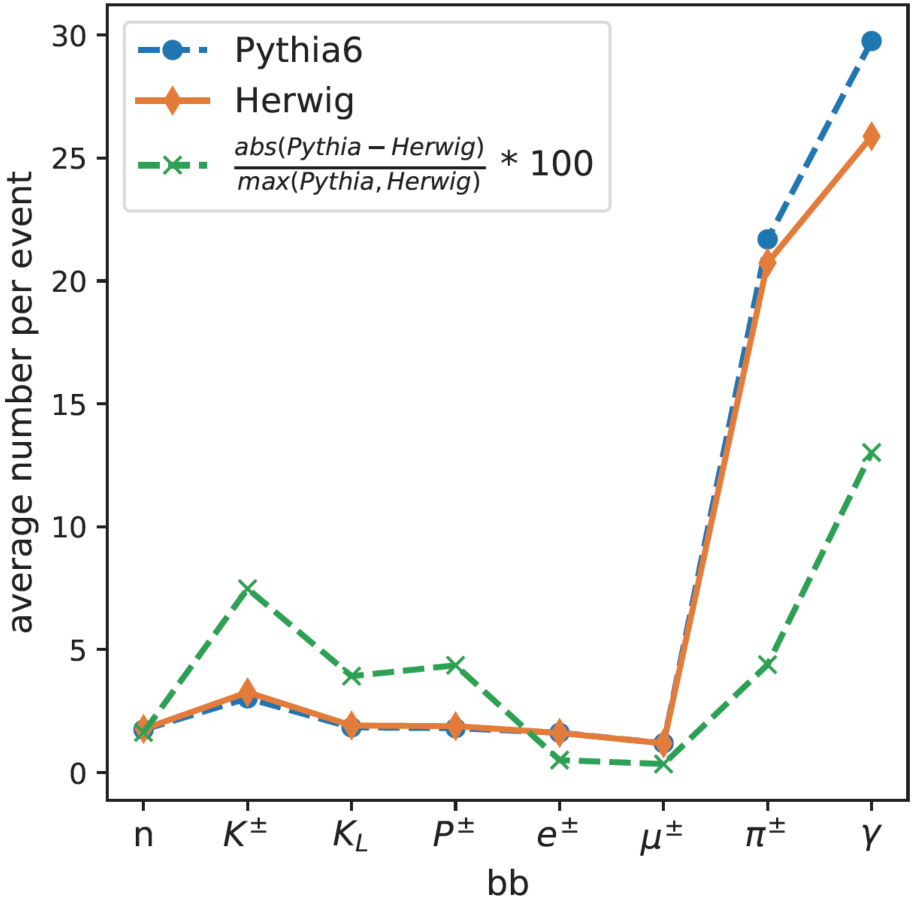




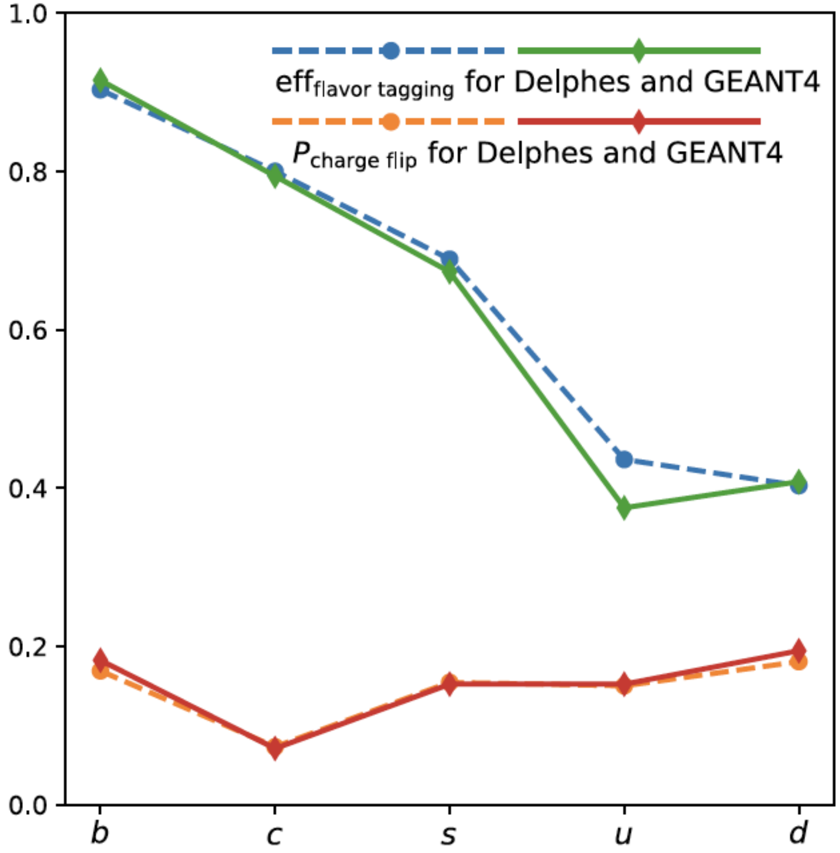
- *M10 instead of M11*

V.S. Hadronization models

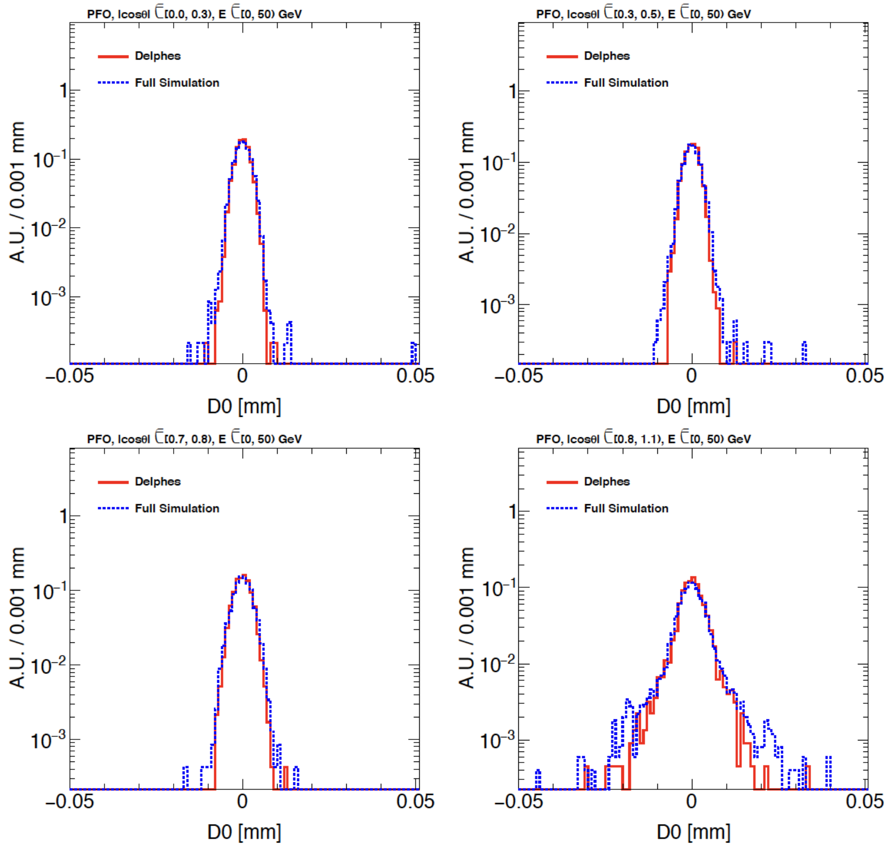




Fast/Full Simulation

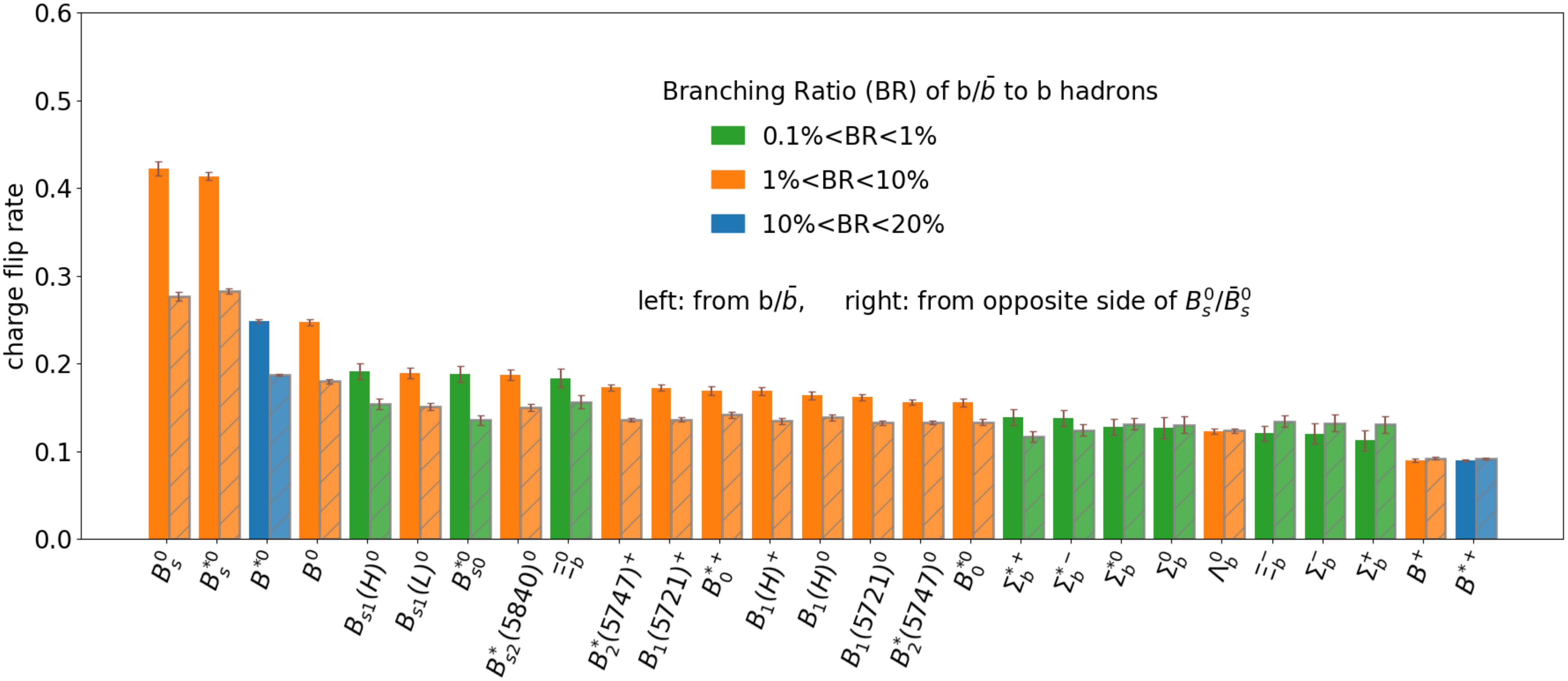


Z->μμ (91.2 GeV)



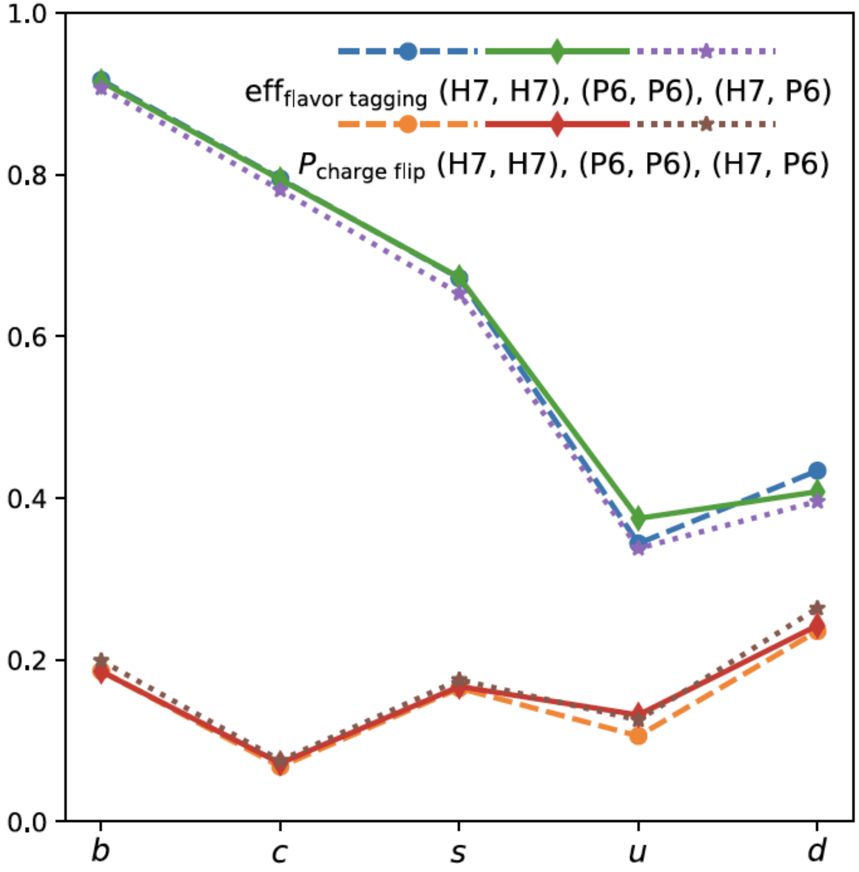
- Delphes ~ Perfect PFA (1 – 1 correspondence..)

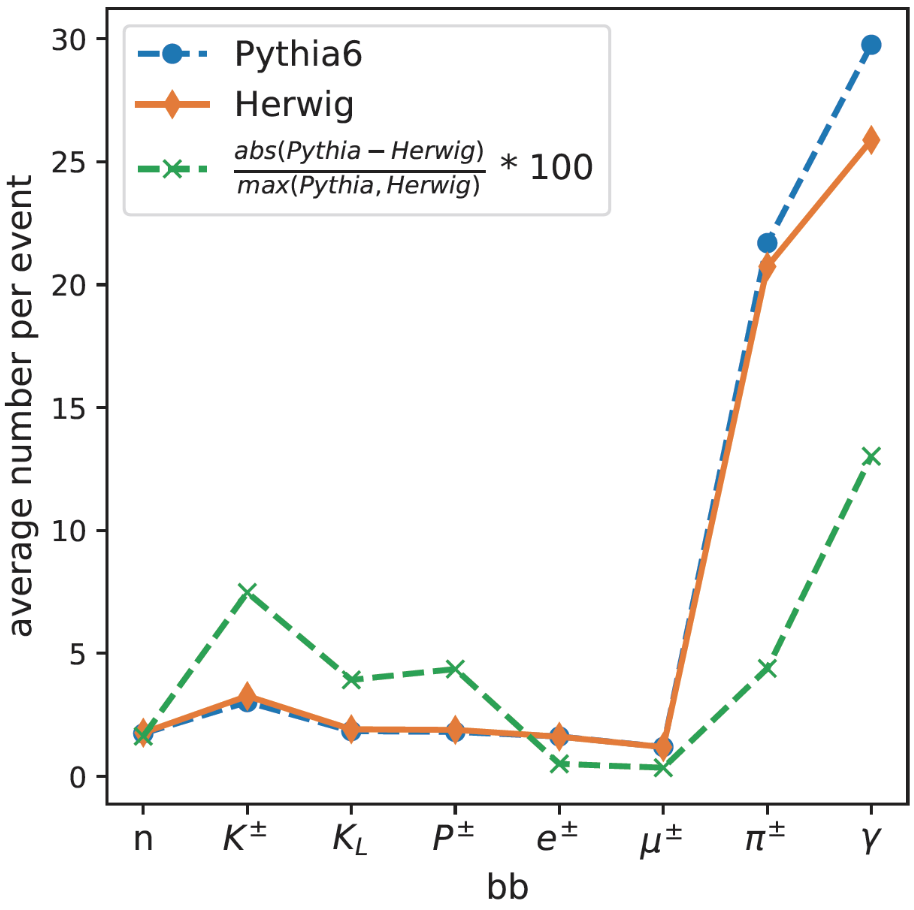
B-charge flip rate: Bs oscillations



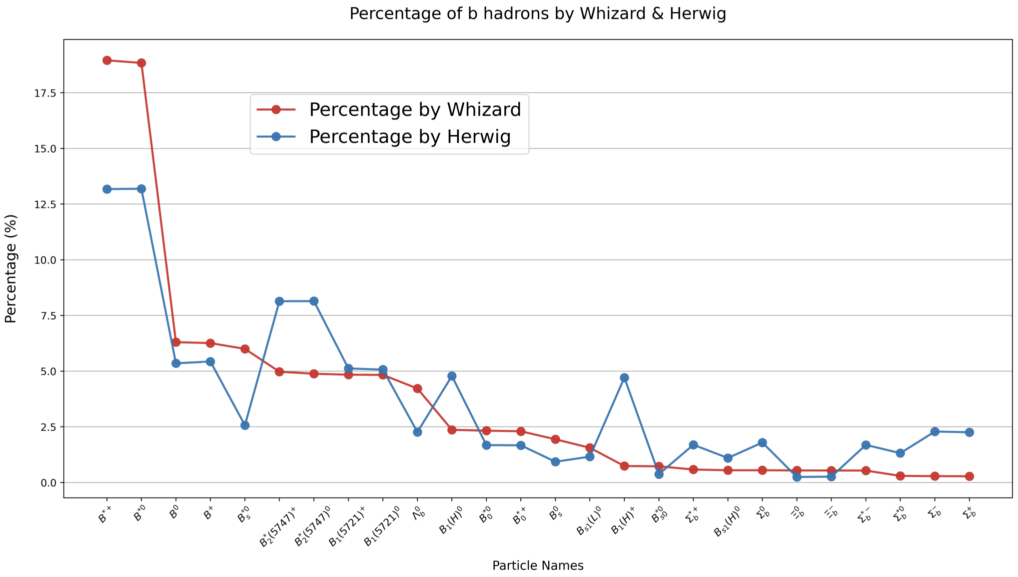
- Flip rate ~ 15%, Eff. Tagging power > 40%

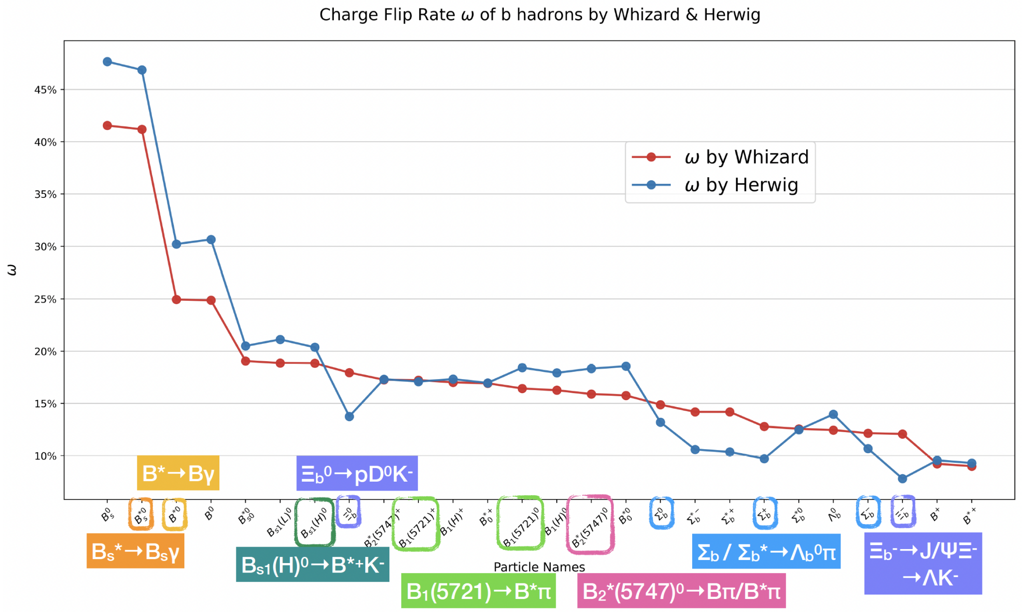
V.S. Hadronization models





b-jet: leading b-hadrons & flip rates





$B^* \to B\gamma$

$\Xi_b^0 \to pD^0K^-$

$B_s^* \to B_s\gamma$

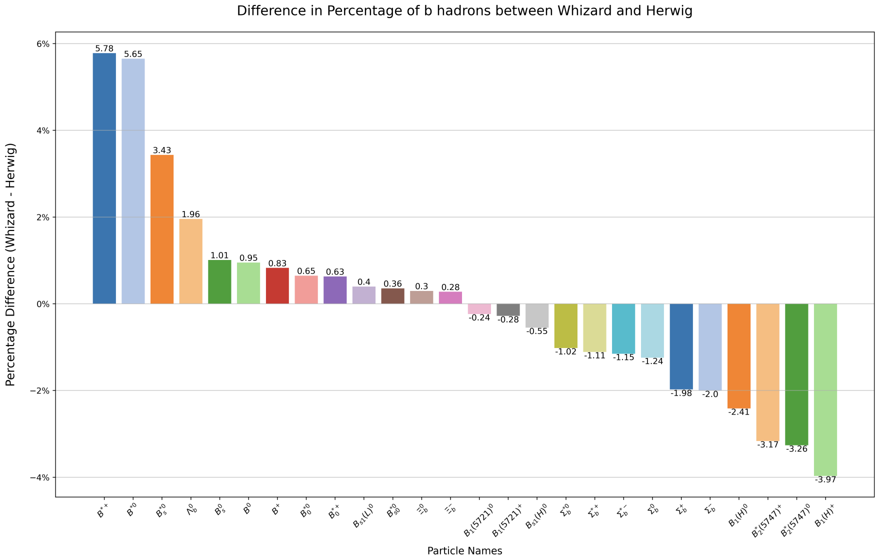
$B_{s1}(H)^0 \to B^{*+}K^-$

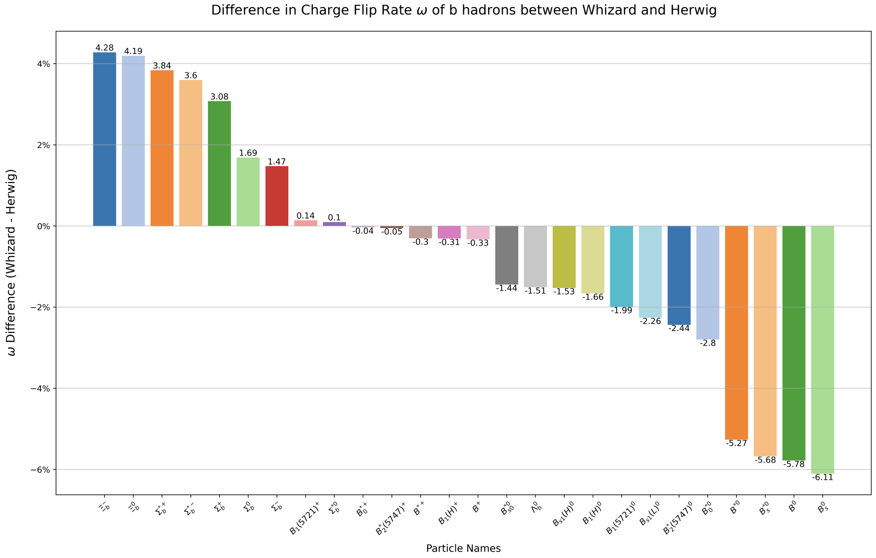
$B_1(5721) \to B^*\pi$

$B_2^*(5747)^0 \to B\pi/B^*\pi$

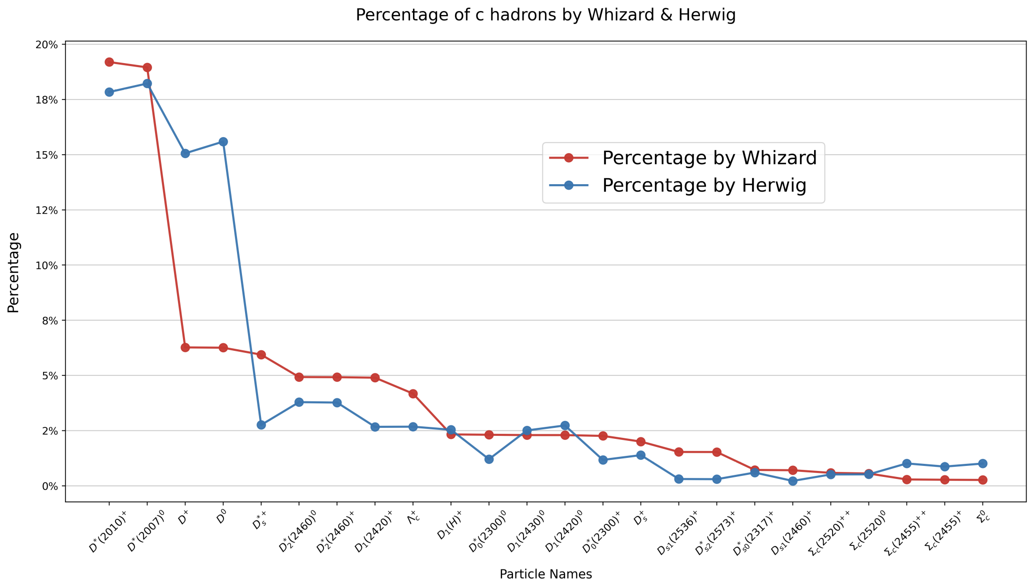
Σ_b / $\Sigma_b^* \to \Lambda_b^0\pi$

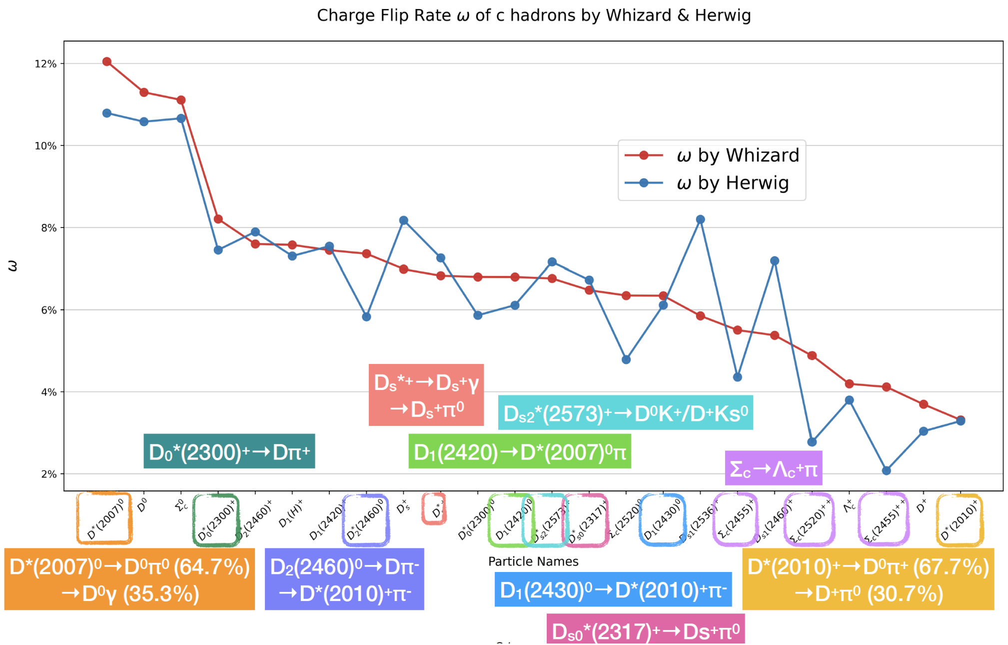
$\Xi_b^- \to J/\Psi\Xi^- \to \Lambda K^-$





c-jet: leading c-hadrons & flip rates


Percentage of c hadrons by Whizard & Herwig


Charge Flip Rate ω of c hadrons by Whizard & Herwig

$D_s^{*+} \to D_s^+\gamma$
$\to D_s^+\pi^0$

$D_{s2}^*(2573)^+ \to D^0K^+/D^+K_S^0$

$D_0^*(2300)^+ \to D\pi^+$

$D_1(2420) \to D^*(2007)^0\pi$

$\Sigma_c \to \Lambda_c^+\pi$

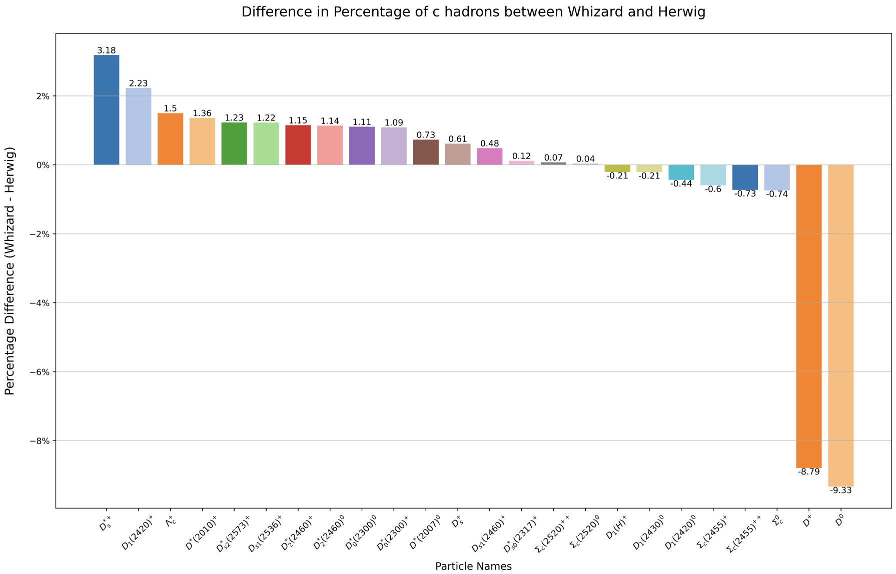
$D^*(2007)^0 \to D^0\pi^0$ (64.7%)
$\to D^0\gamma$ (35.3%)

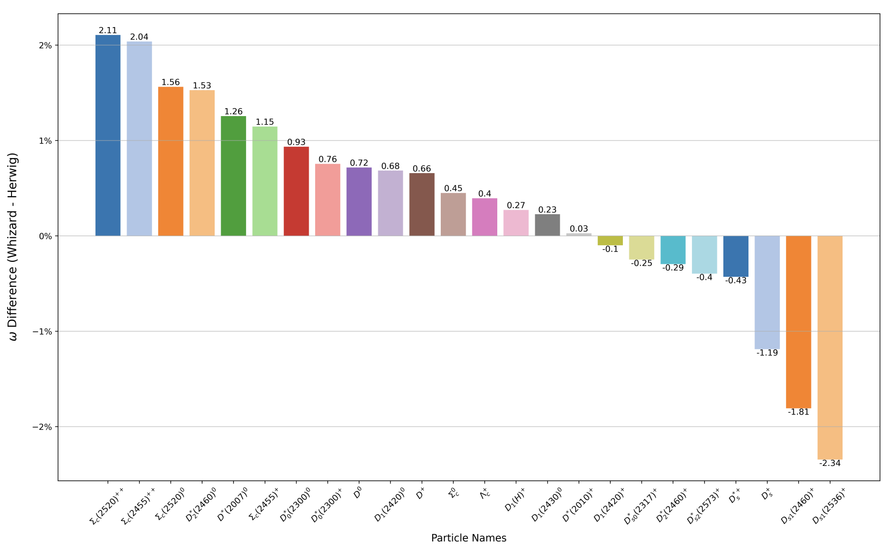
$D_2(2460)^0 \to D\pi^-$
$\to D^*(2010)^+\pi^-$

$D_1(2430)^0 \to D^*(2010)^+\pi^-$

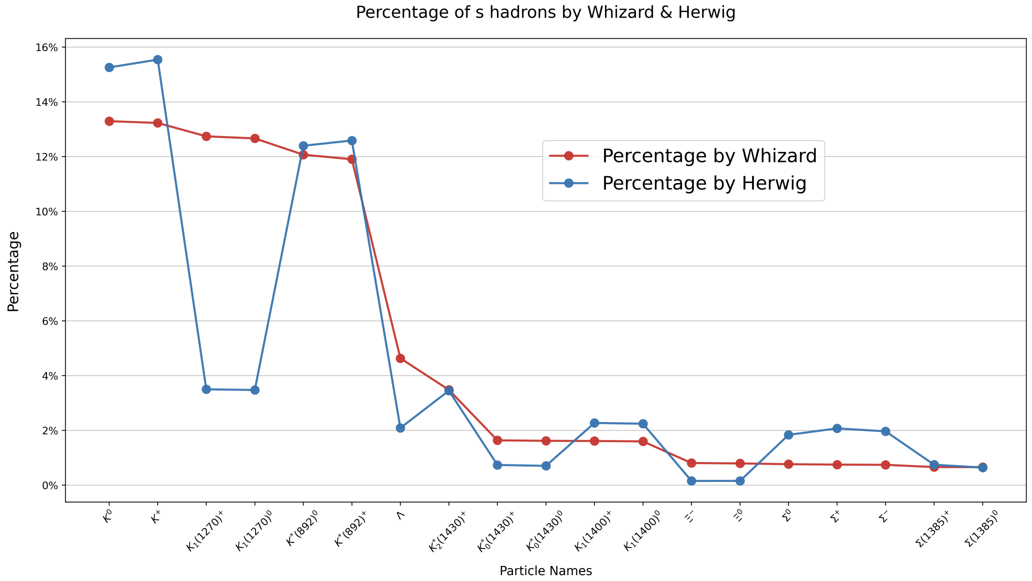
$D^*(2010)^+ \to D^0\pi^+$ (67.7%)
$\to D^+\pi^0$ (30.7%)

$D_{s0}^*(2317)^+ \to D_s^+\pi^0$

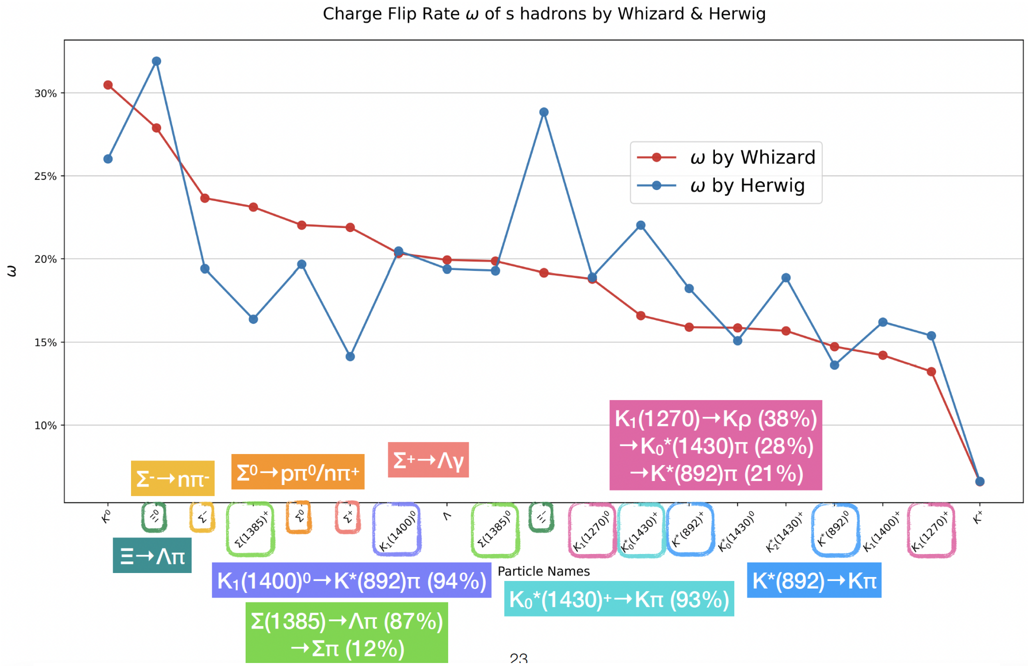

Difference in Percentage of c hadrons between Whizard and Herwig


Difference in Charge Flip Rate ω of $\hat{c}$ hadrons between Whizard and Herwig

s-jet: leading s-hadrons & flip rates



Percentage of s hadrons by Whizard & Herwig



Charge Flip Rate ω of s hadrons by Whizard & Herwig

$K_1(1270) \to K\rho$ (38%)
$\to K_0^*(1430)\pi$ (28%)
$\to K^*(892)\pi$ (21%)

$\Sigma^- \to n\pi^-$

$\Sigma^0 \to p\pi^0 / n\pi^+$

$\Sigma^+ \to \Lambda\gamma$

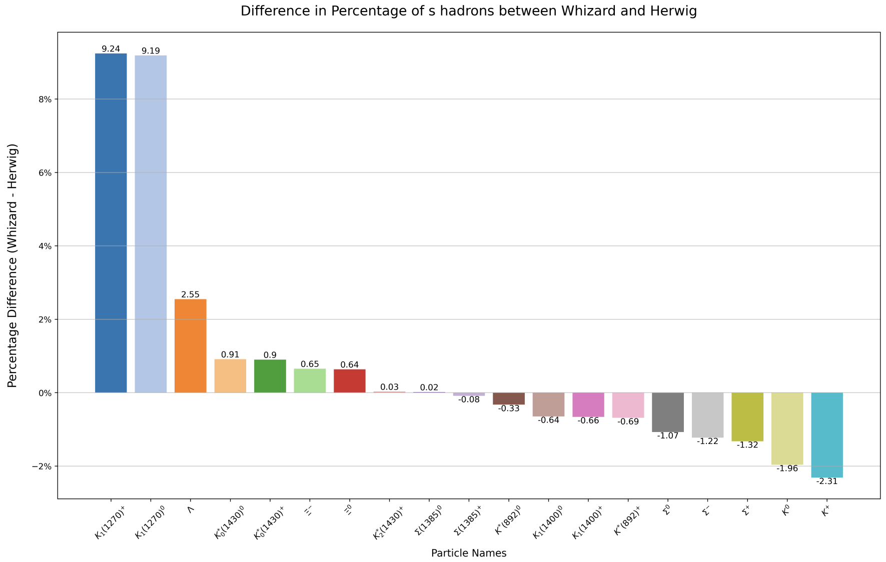
$\Xi \to \Lambda\pi$

$K_1(1400)^0 \to K^*(892)\pi$ (94%)

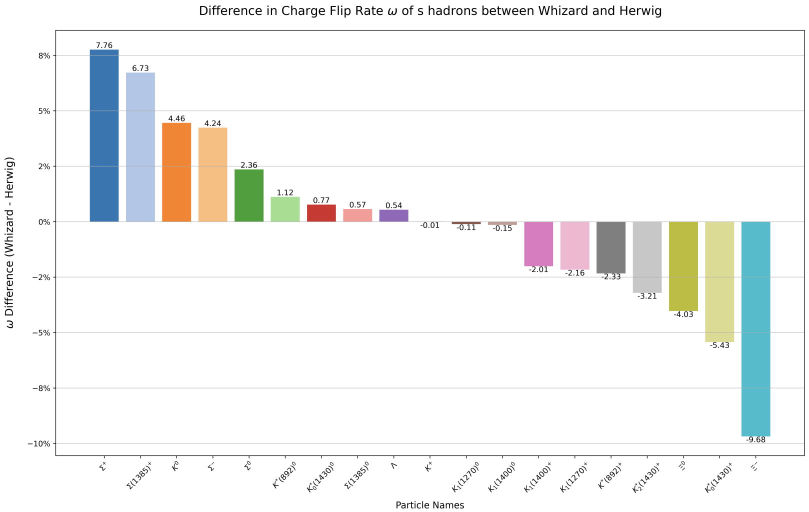
$\Sigma(1385) \to \Lambda\pi$ (87%)
$\to \Sigma\pi$ (12%)

$K_0^*(1430)^+ \to K\pi$ (93%)

$K^*(892) \to K\pi$

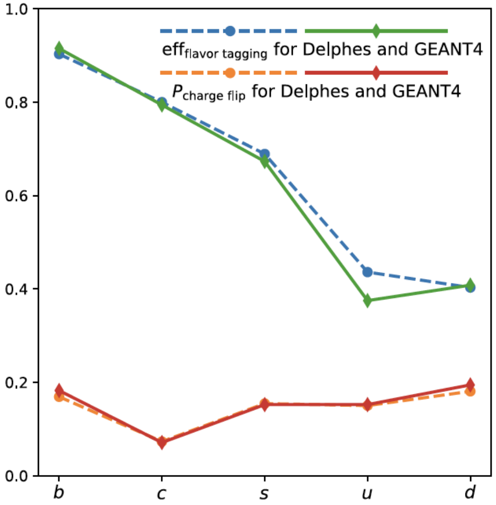


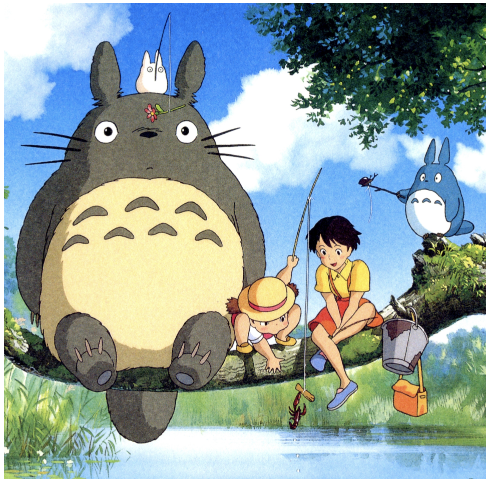
Difference in Percentage of s hadrons between Whizard and Herwig



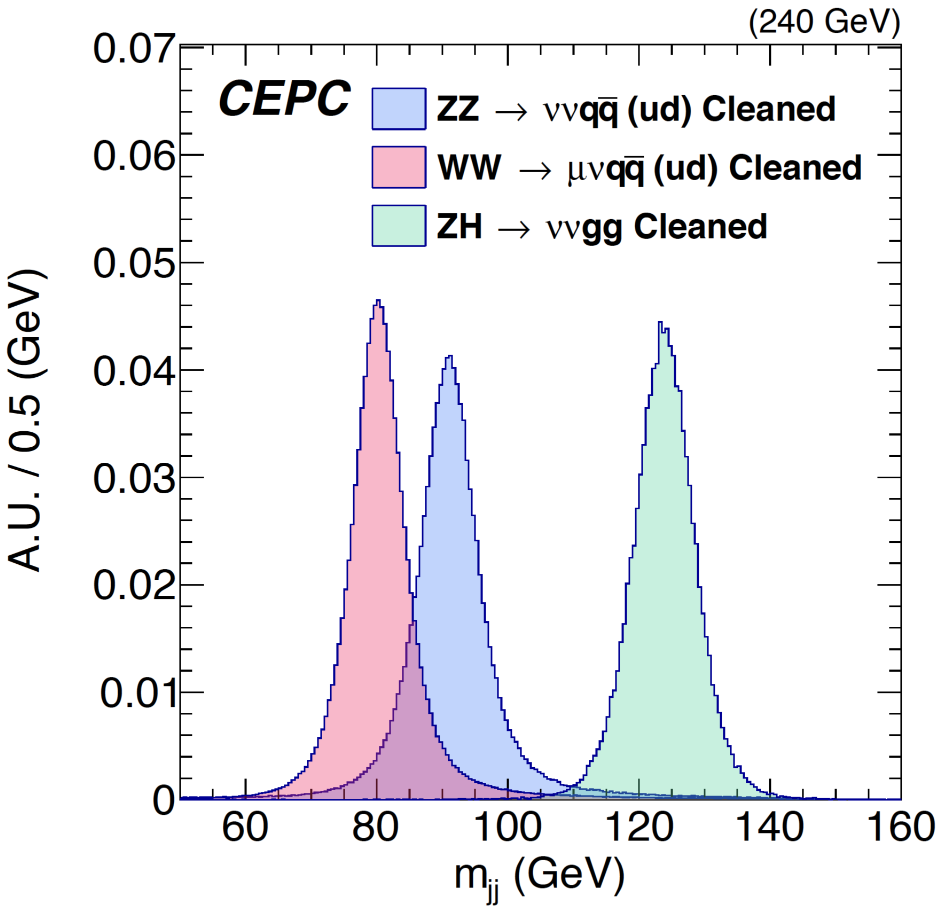
Difference in Charge Flip Rate ω of s hadrons between Whizard and Herwig

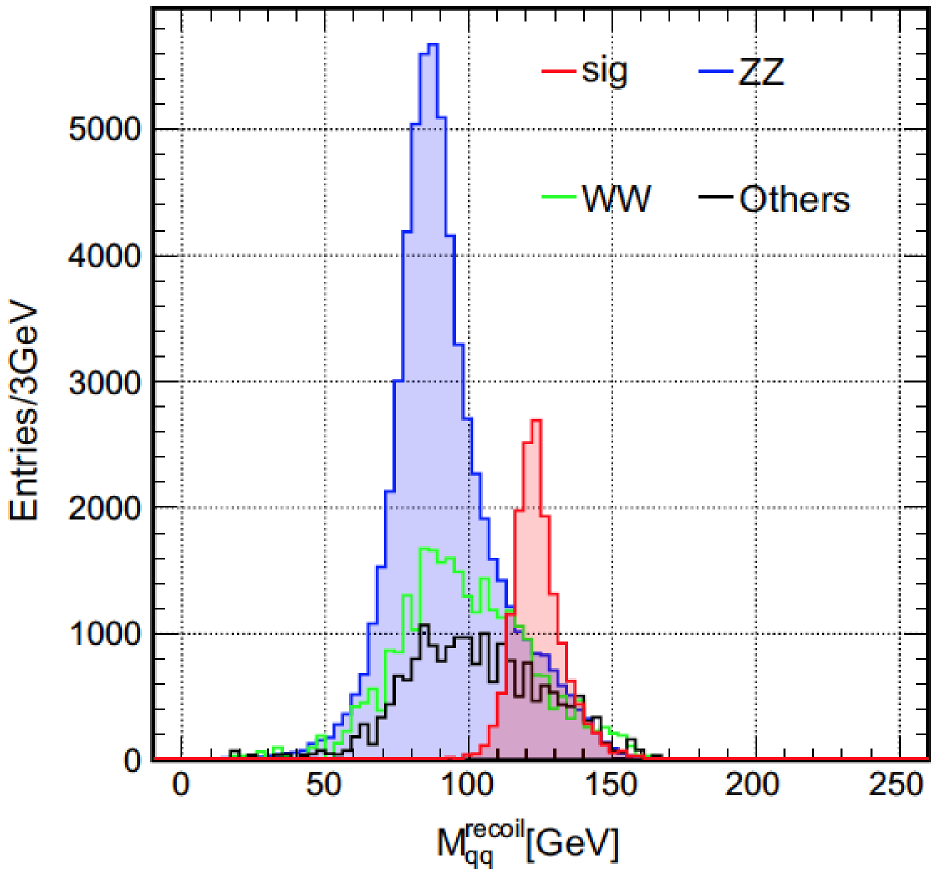
Towards one-to-one correspondence (Totoro)



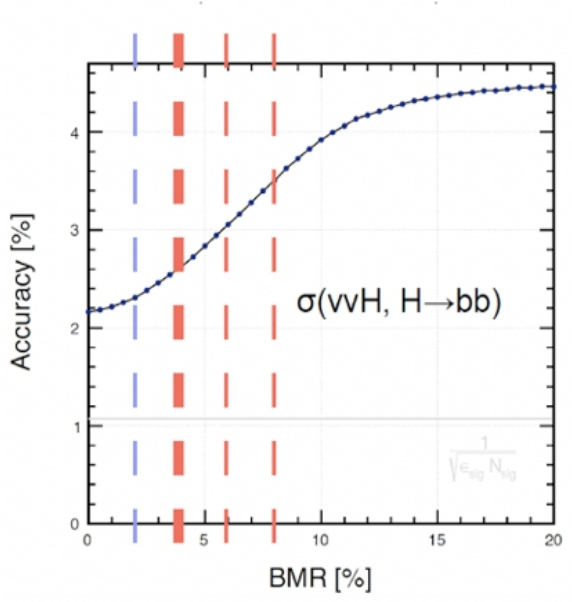


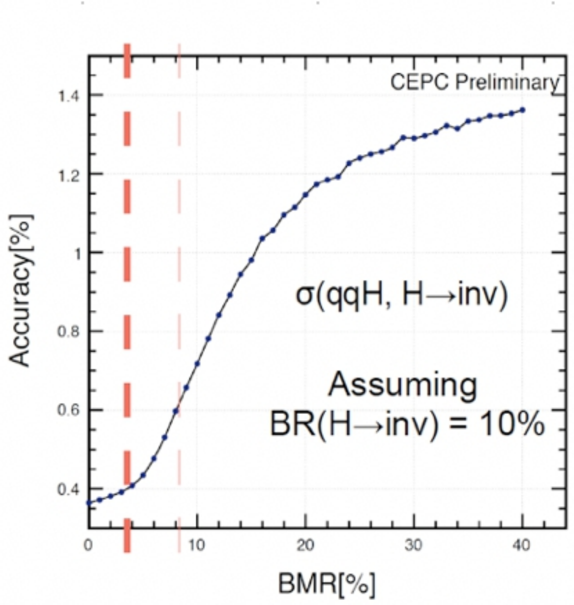
Arbor + AI: @ Boson Mass Resolution

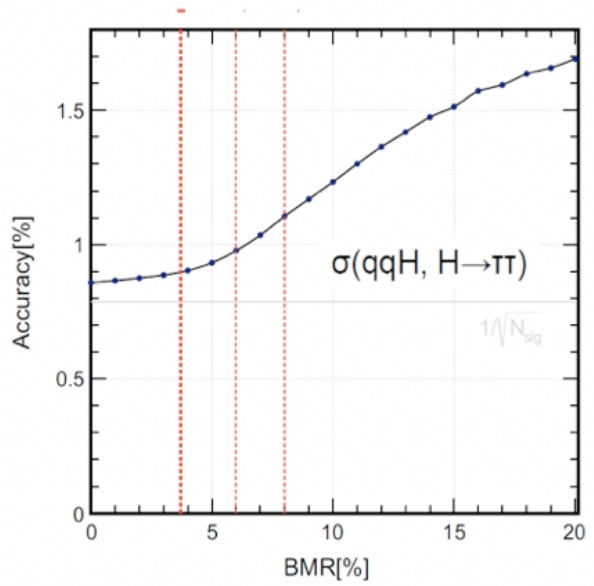


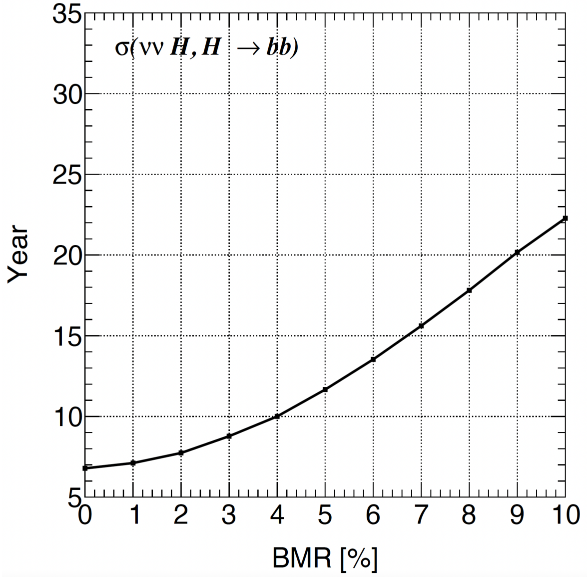


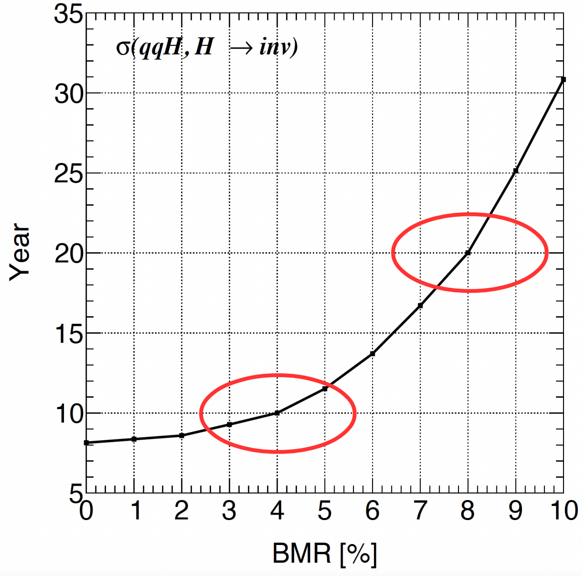
BMR: impact on critical measurements

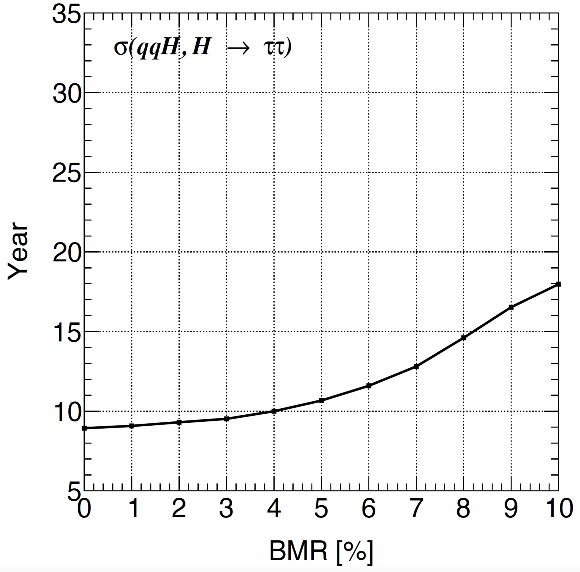




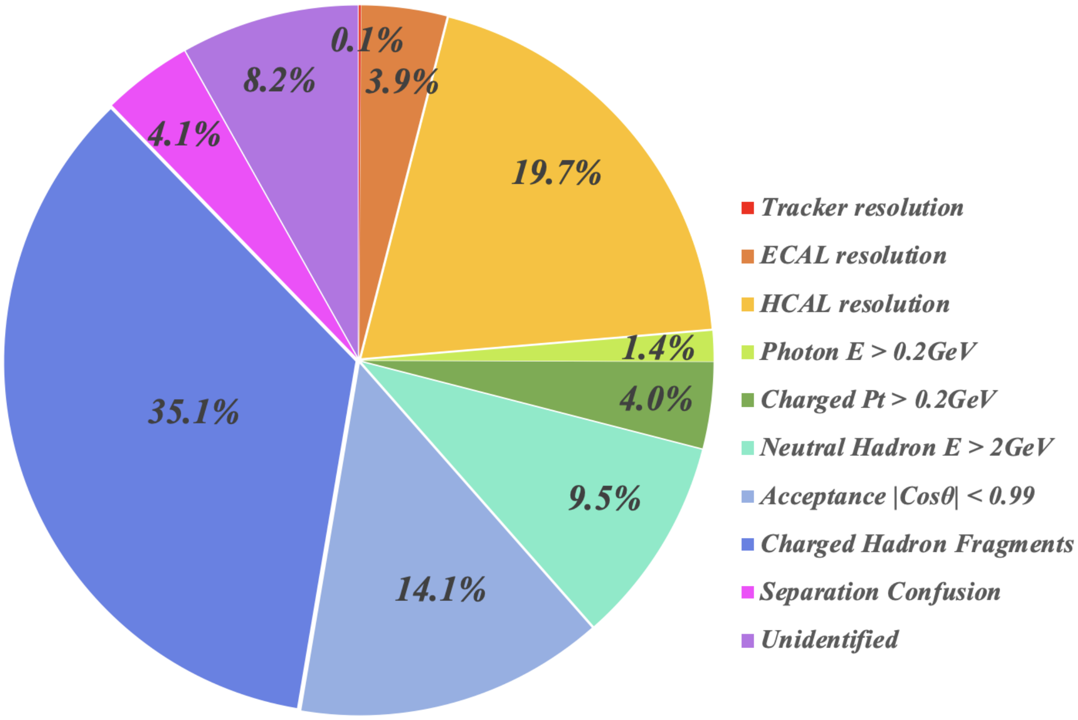






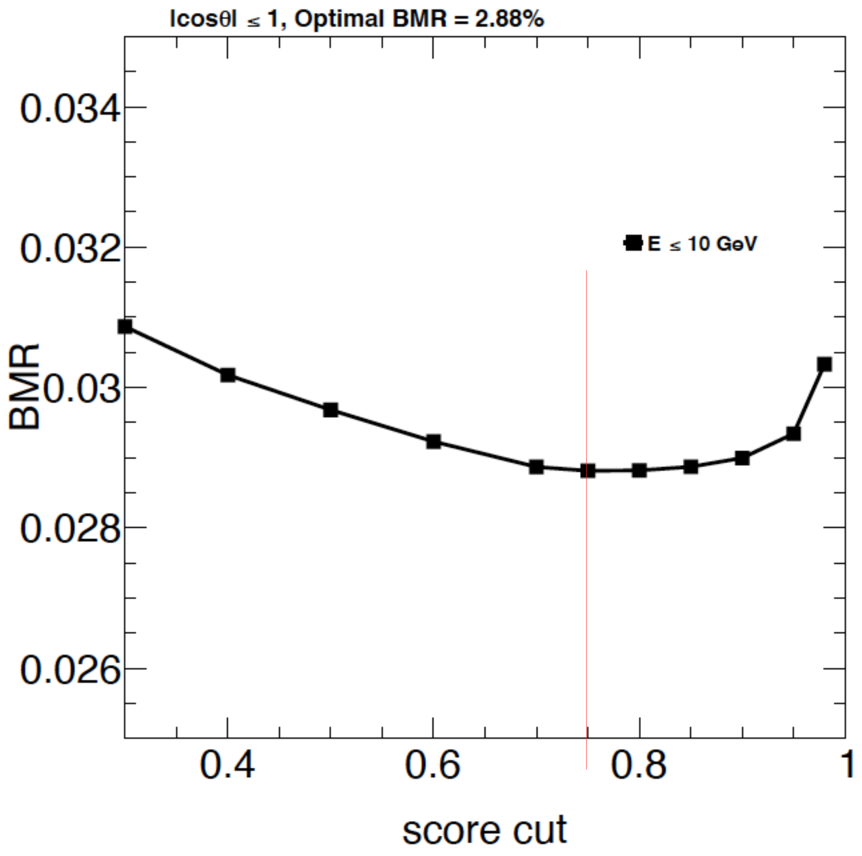


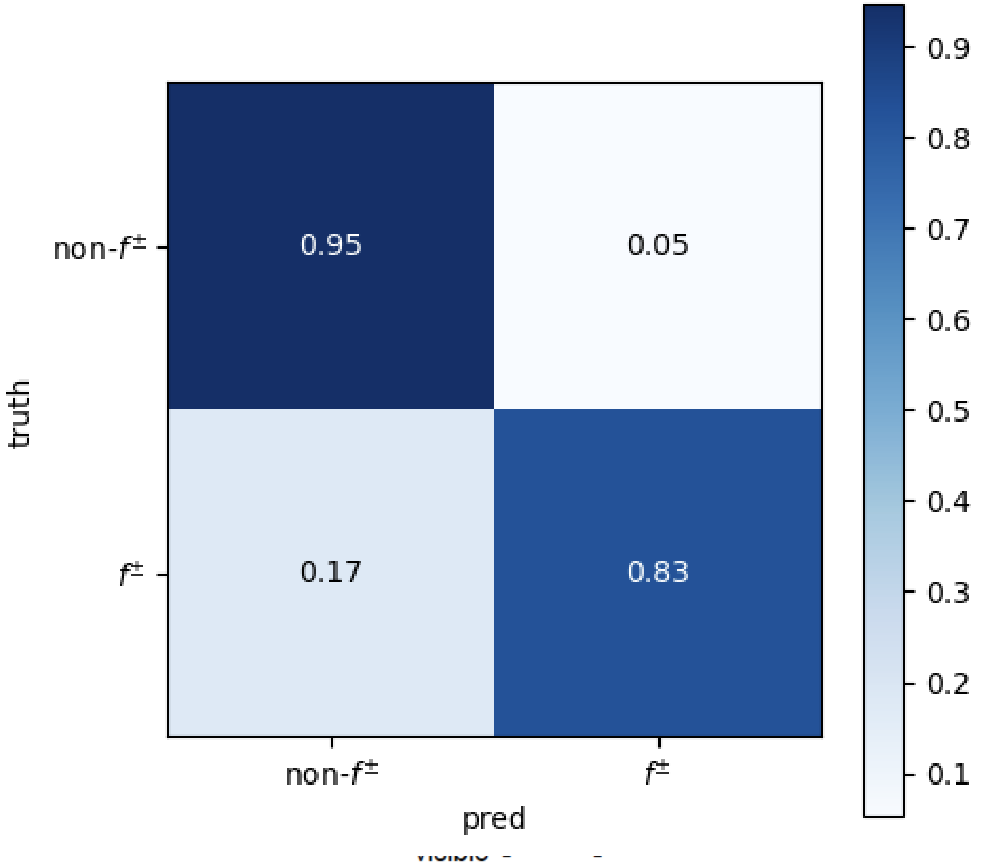
BMR decomposition @ CDR baseline



- *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.*

Preliminary: Identify & veto charged shower fragments using AI



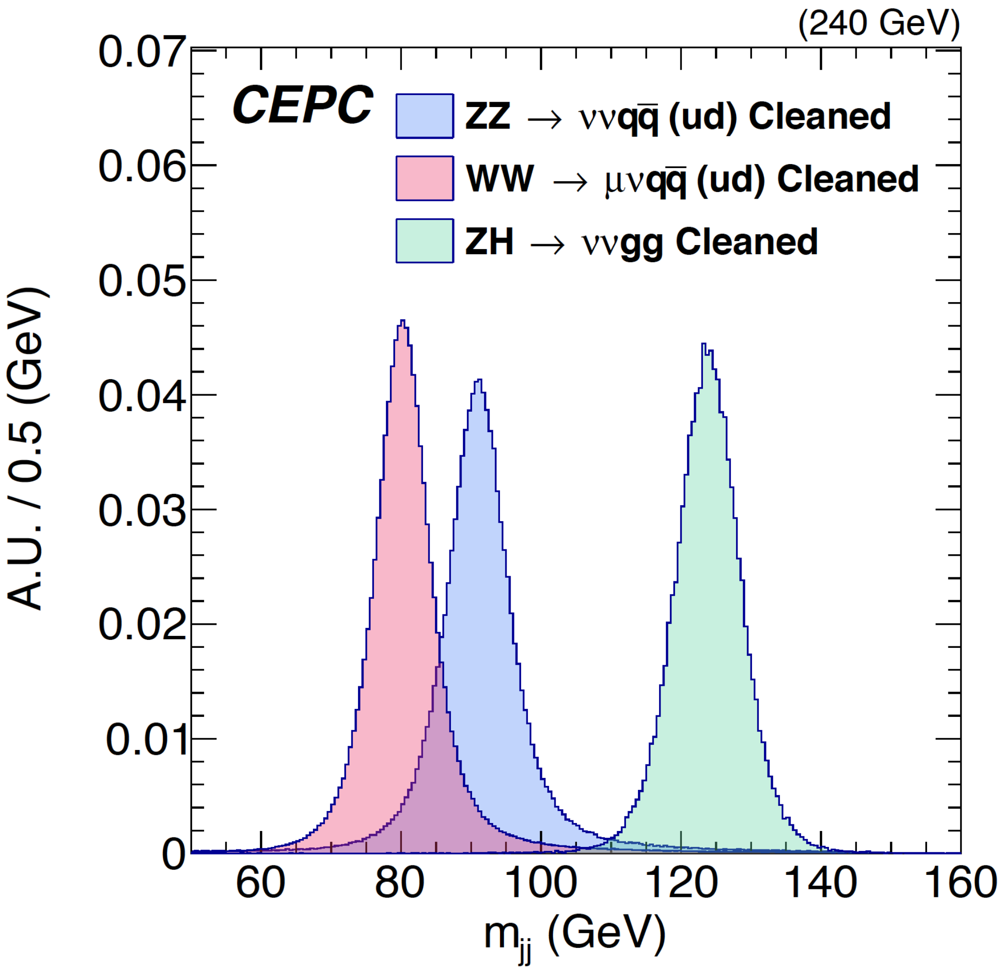


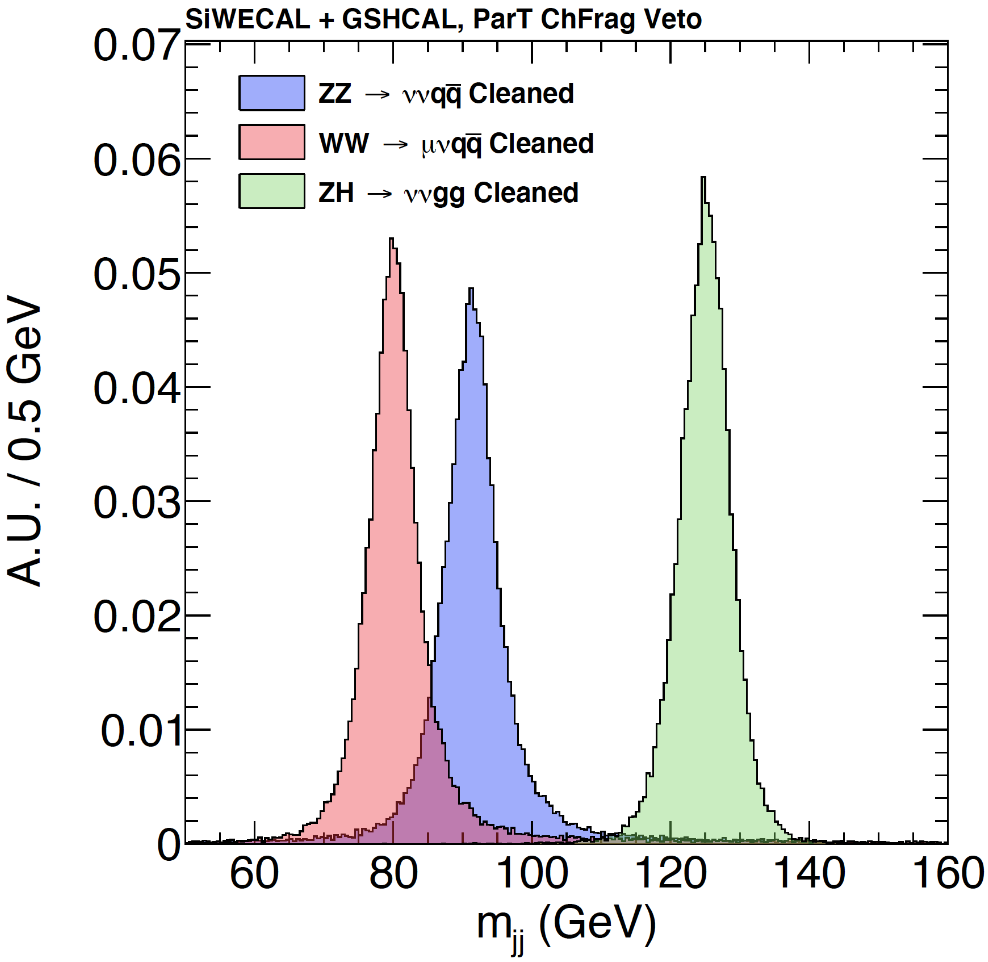
Trained at 12E4 events,

Test & Applied at 4E4 events

score > 0.75
efficiency ~83%
purity ~95%

... At Bosons ...

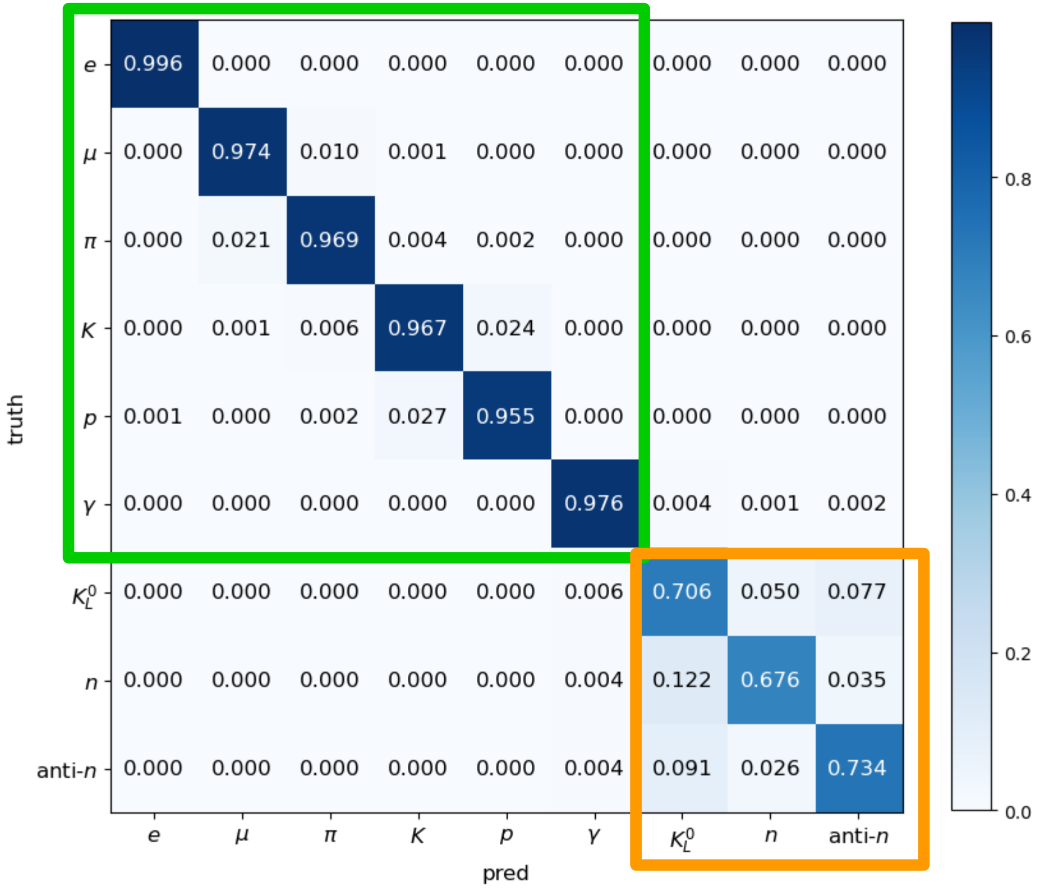




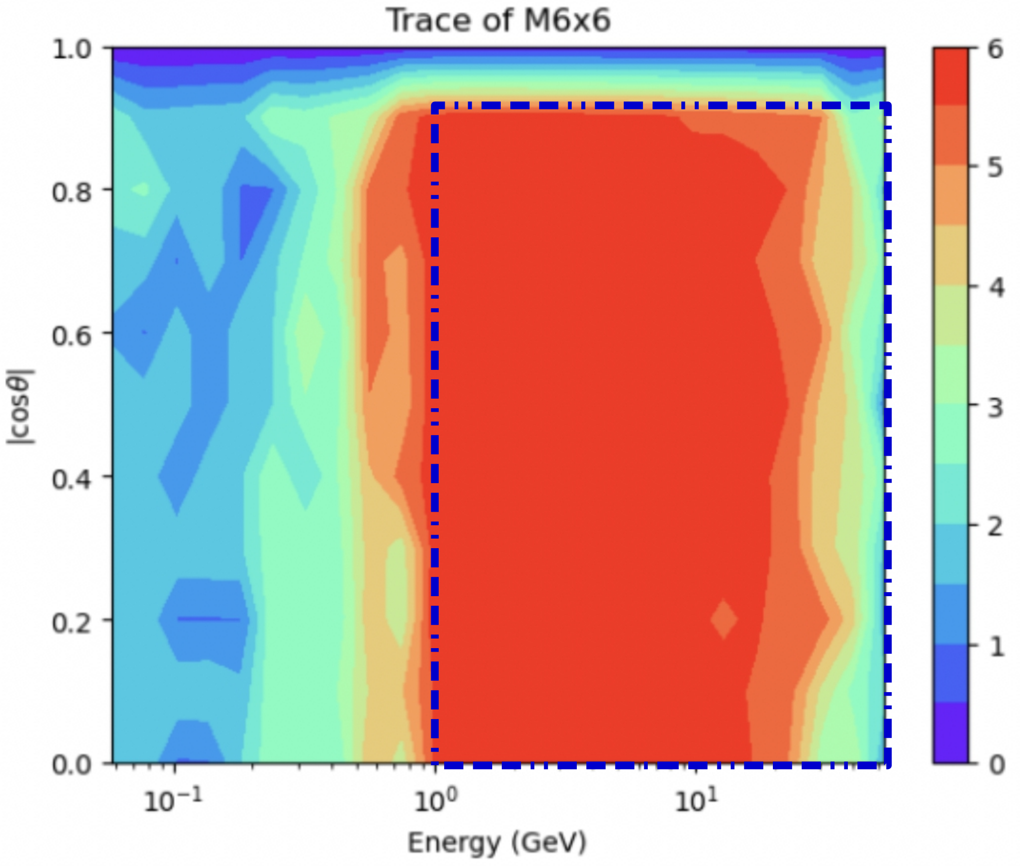
Improvement from Det. Opt. 10%; from Frag veto: 20%

1-1 correspondence: preliminary

nCluHit != 0 & E > 1 GeV & |cosθ| < 0.9



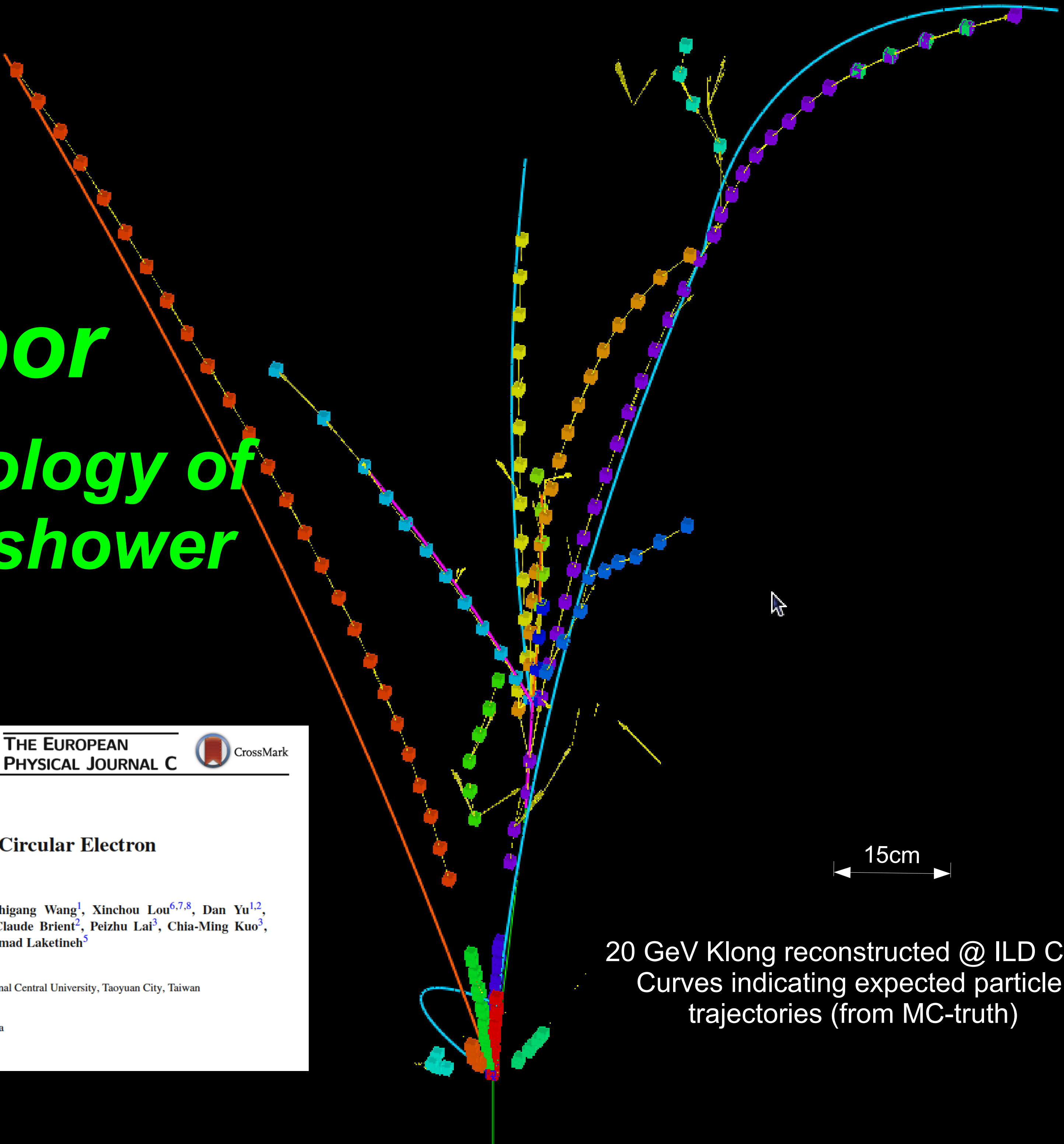
truth \ pred	e	μ	π	K	p	γ	K_L^0	n	anti-n
e	0.996	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
μ	0.000	0.974	0.010	0.001	0.000	0.000	0.000	0.000	0.000
π	0.000	0.021	0.969	0.004	0.002	0.000	0.000	0.000	0.000
K	0.000	0.001	0.006	0.967	0.024	0.000	0.000	0.000	0.000
p	0.001	0.000	0.002	0.027	0.955	0.000	0.000	0.000	0.000
γ	0.000	0.000	0.000	0.000	0.000	0.976	0.004	0.001	0.002
K_L^0	0.000	0.000	0.000	0.000	0.000	0.006	0.706	0.050	0.077
n	0.000	0.000	0.000	0.000	0.000	0.004	0.122	0.676	0.035
anti-n	0.000	0.000	0.000	0.000	0.000	0.004	0.091	0.026	0.734



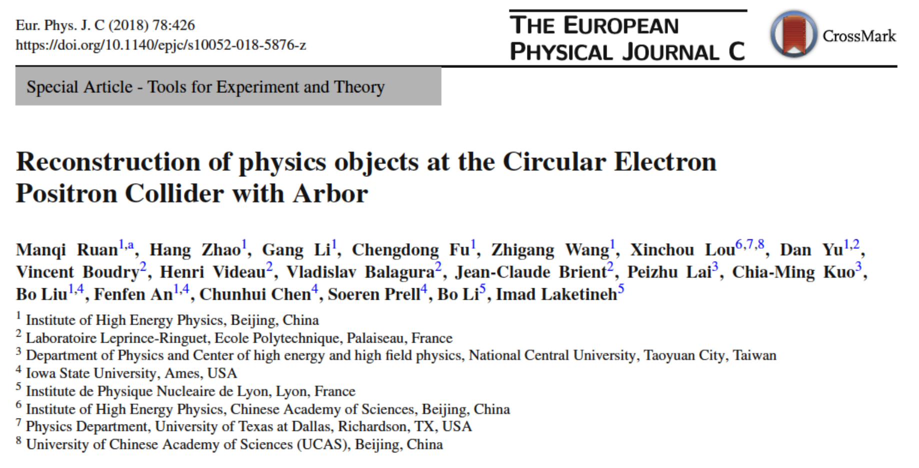
- Next step: to improve the neutral hadron reco & to optimize the detector configuration

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 Laketineh[5]

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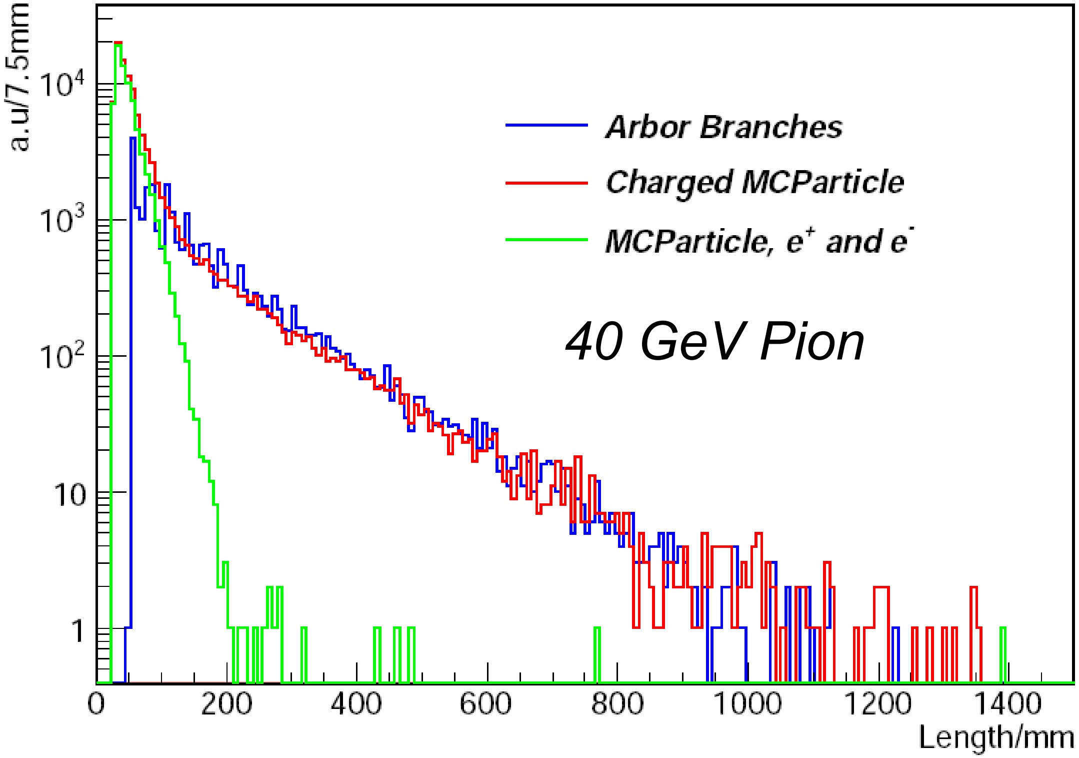
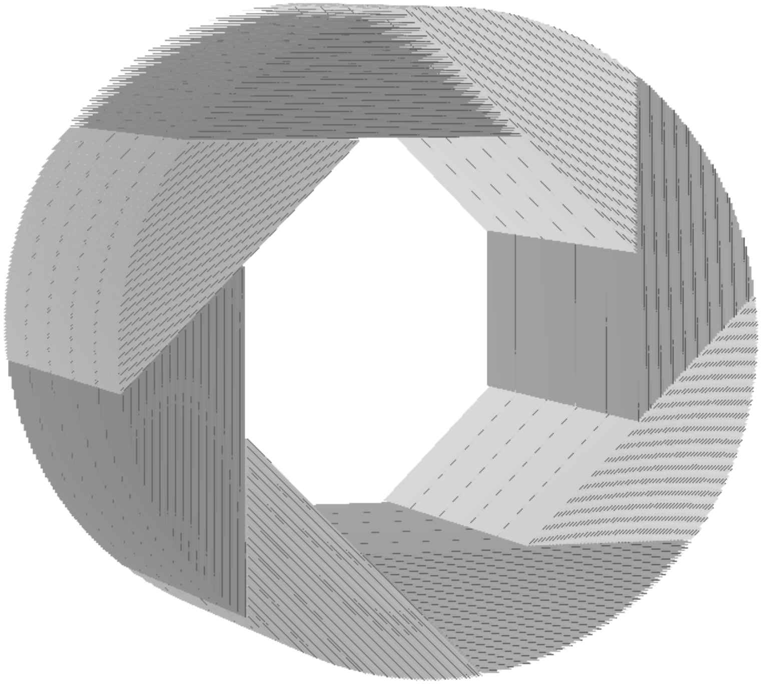
[4] Iowa State University, Ames, USA
[5] Institute de Physique Nucleaire de Lyon, Lyon, France
[6] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
[7] Physics Department, University of Texas at Dallas, Richardson, TX, USA
[8] University of Chinese Academy of Sciences (UCAS), Beijing, China

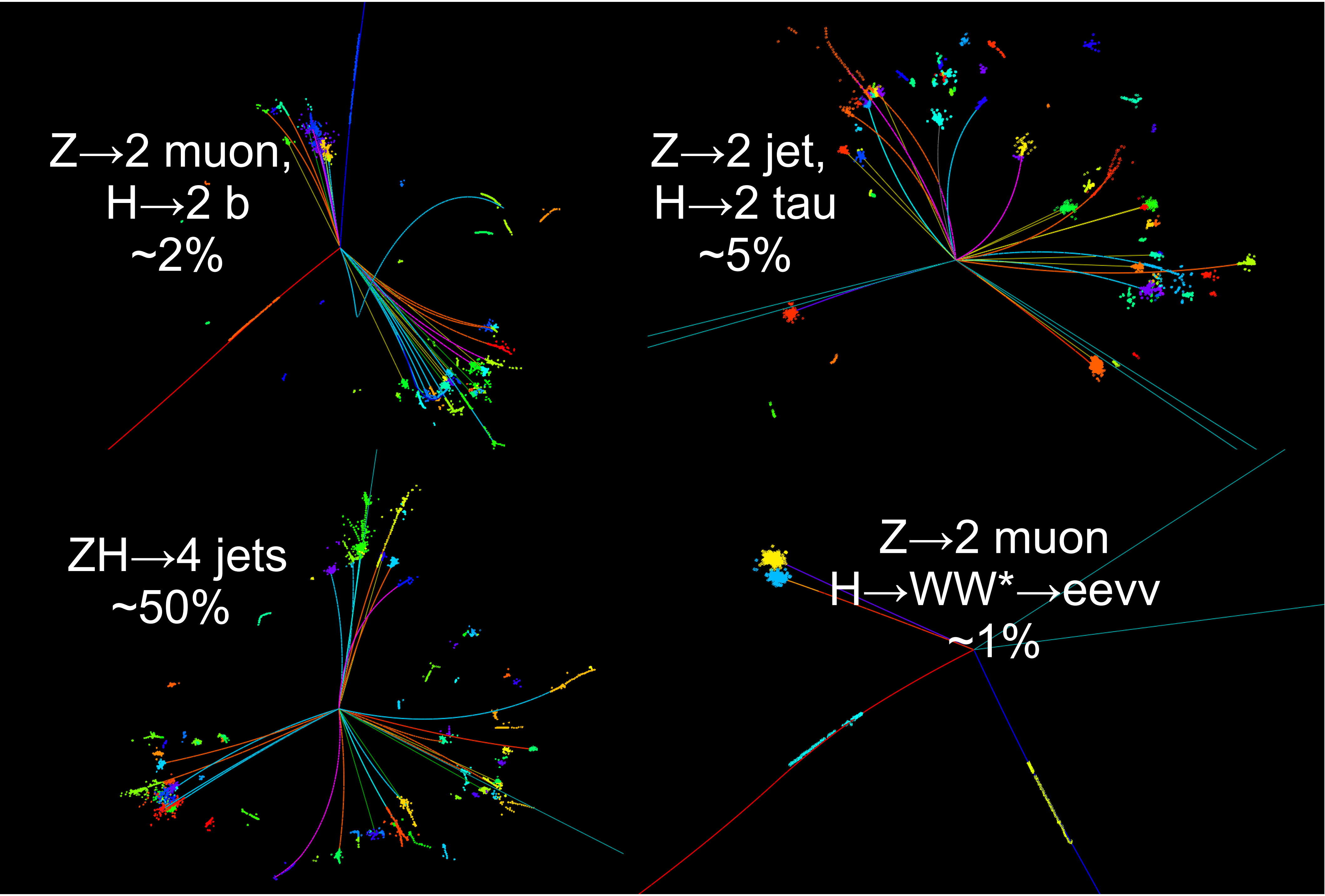
Validation: Arbor Branch Length Vs MC Truth





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

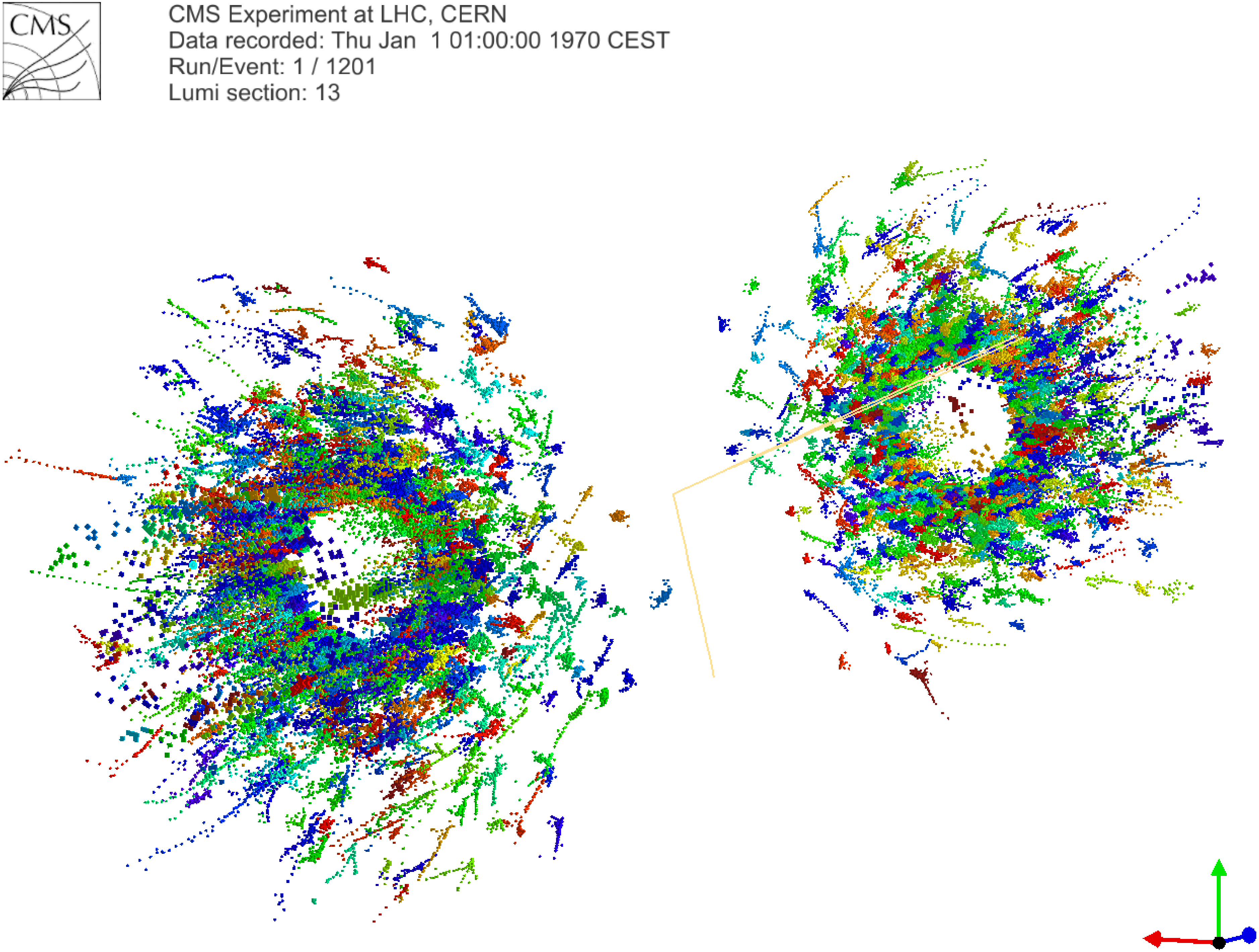


Z→2 muon,
H→2 b
~2%

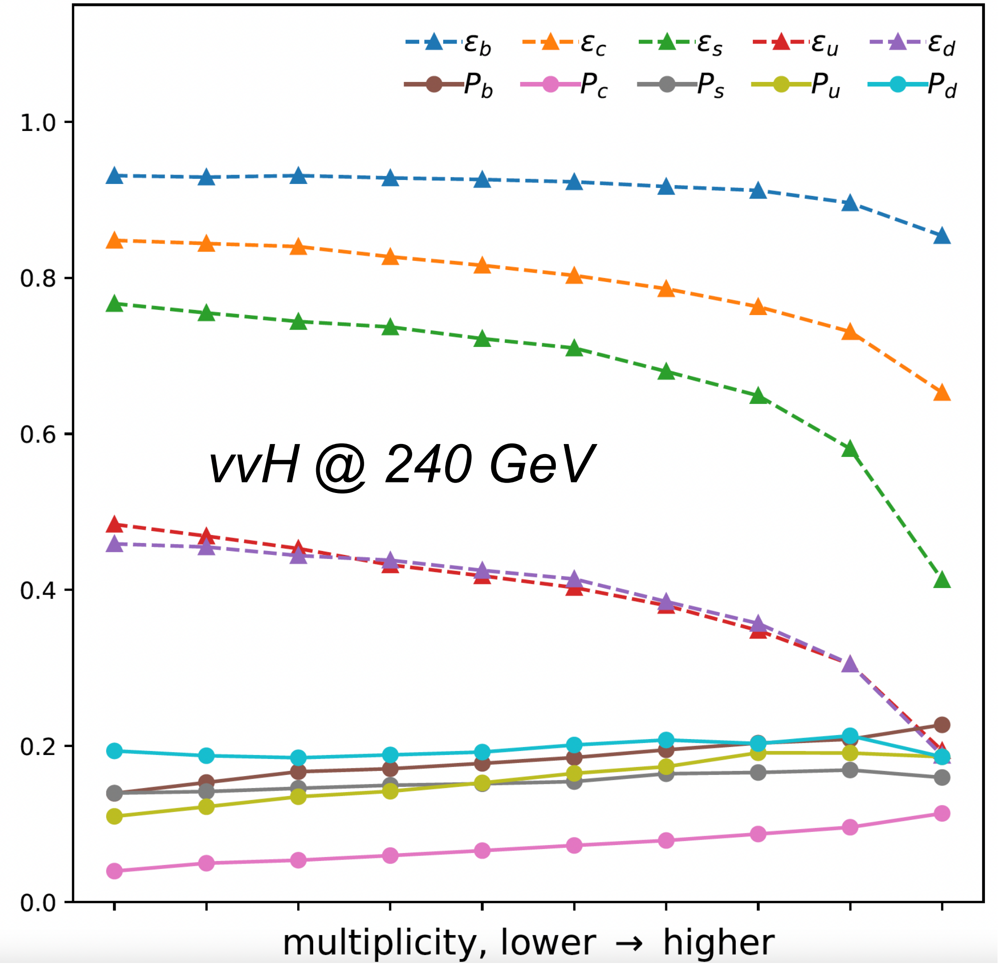
Z→2 jet,
H→2 tau
~5%

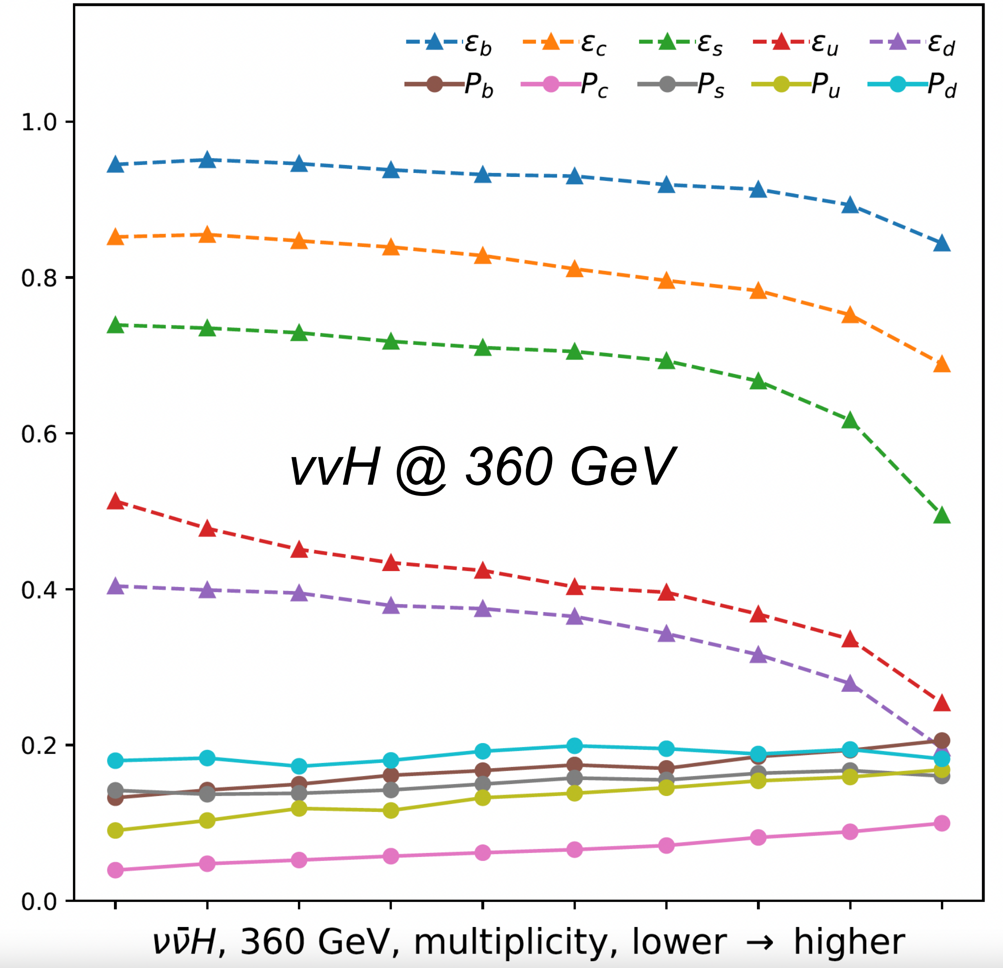
ZH→4 jets
~50%

Z→2 muon
H→WW*→eevv
~1%


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

V.S. Multiplicity



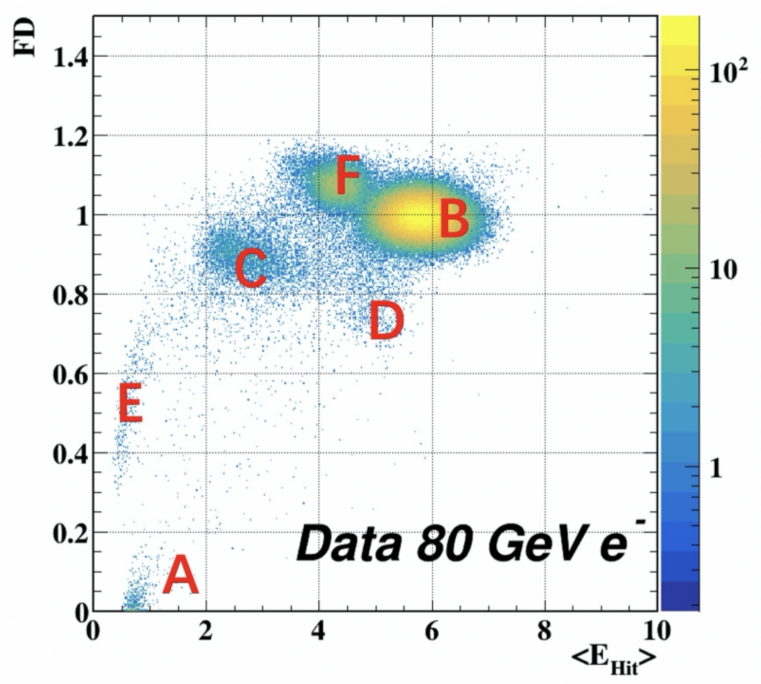


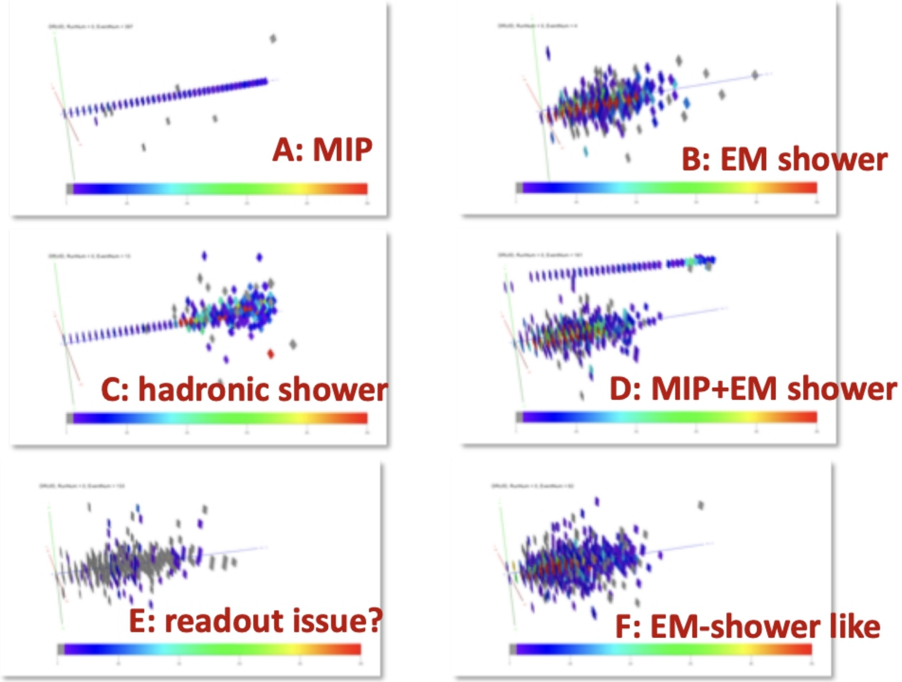
- *...many patterns need further understanding & towards further optimization...*

PID studies with beamtest data

Xin Xia (IHEP)

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



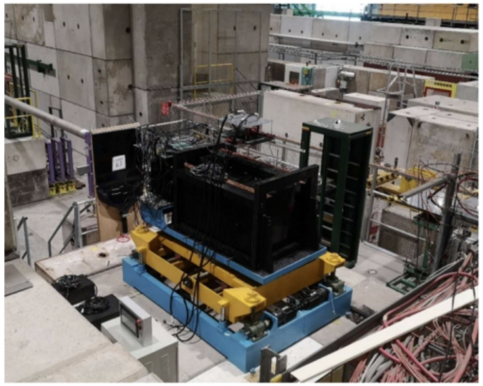


Oct 19 – Nov 2, 2022
SPS H8 beamline

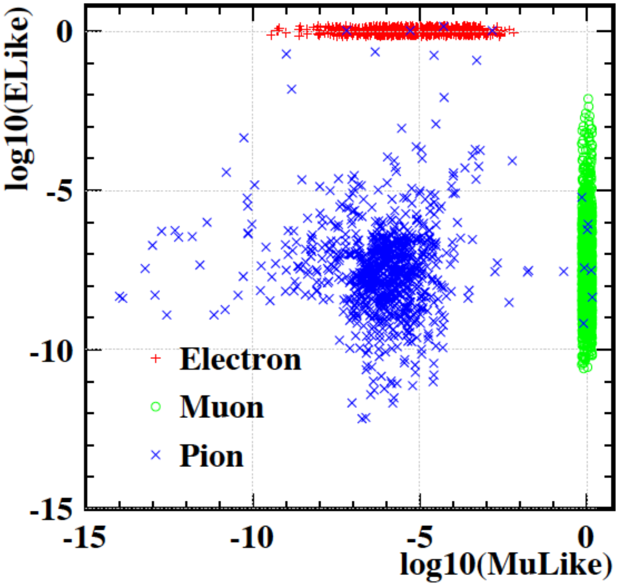
Apr 26 – May 10, 2023
SPS H2 beamline

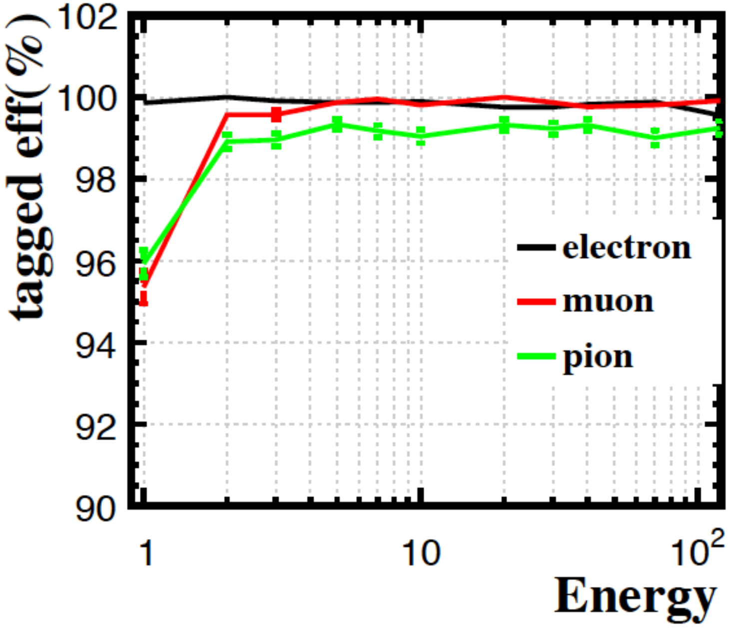
May 17 – 31, 2023
PS T9 beamline

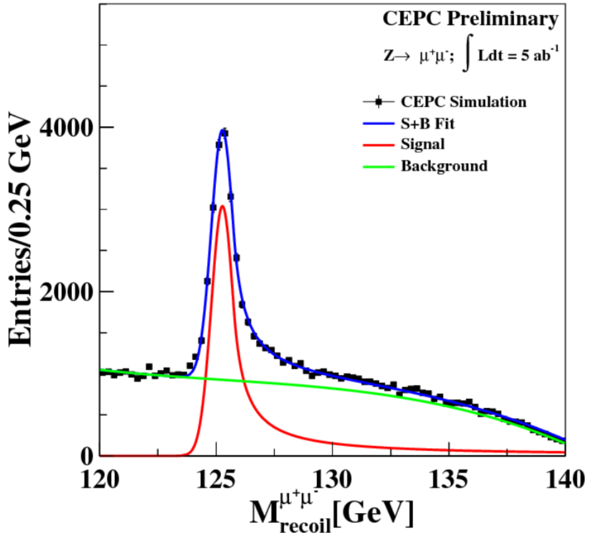


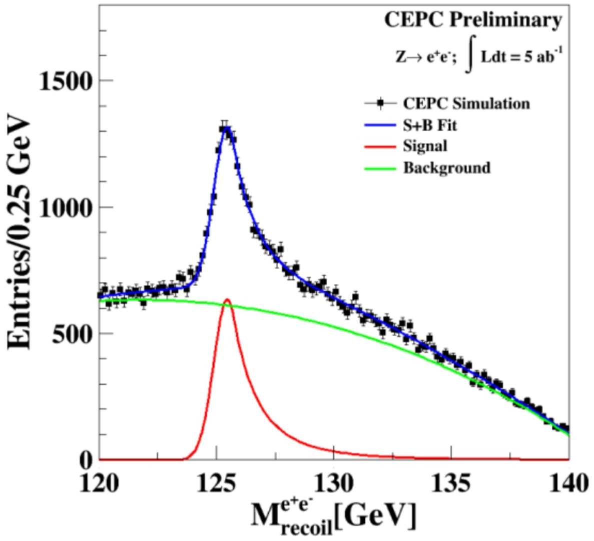



Lepton: isolated







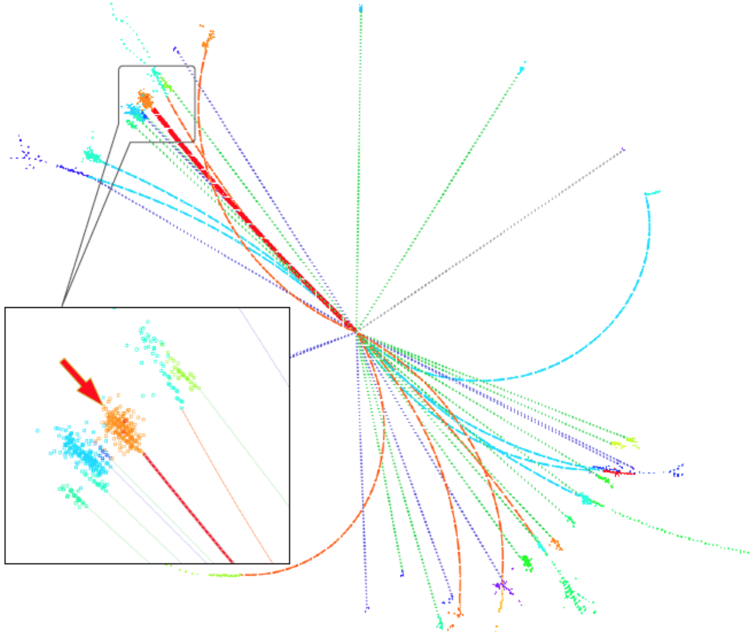


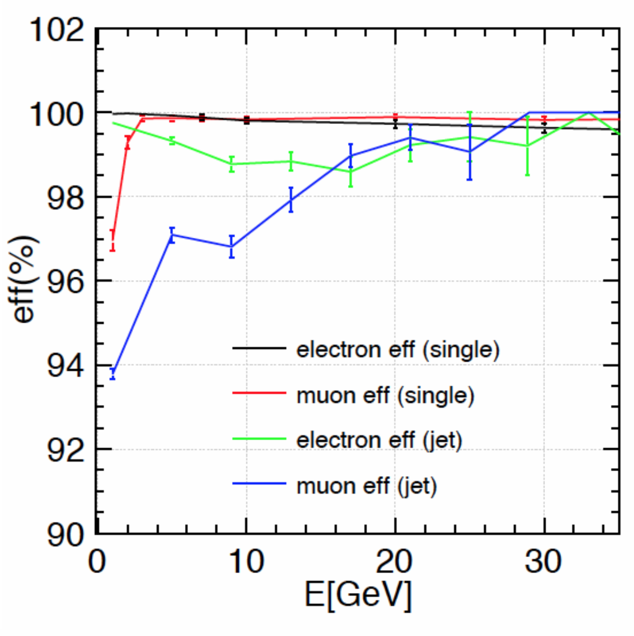
BDT method using 4 classes of 24 input discrimination variables.

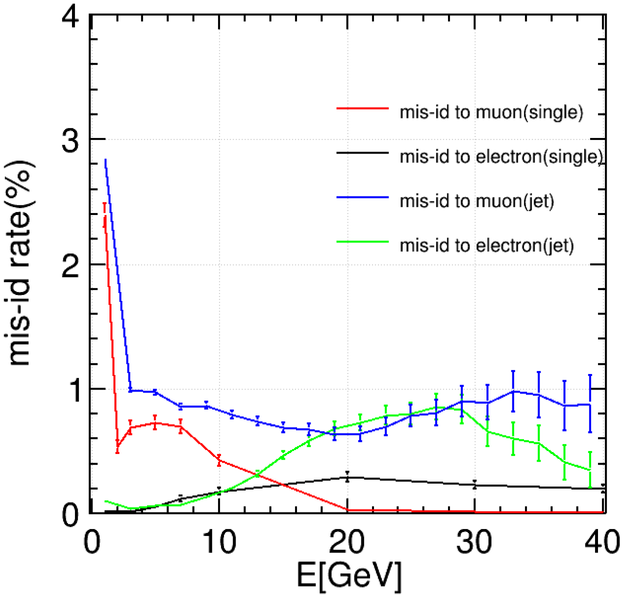
Test performance at: Electron = E_likeness > 0.5 ;
Muon = Mu_likeness > 0.5
Single charged reconstructed particle, for E > 2 GeV:
lepton efficiency > 99.5% && Pion mis id rate ~ 1%

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



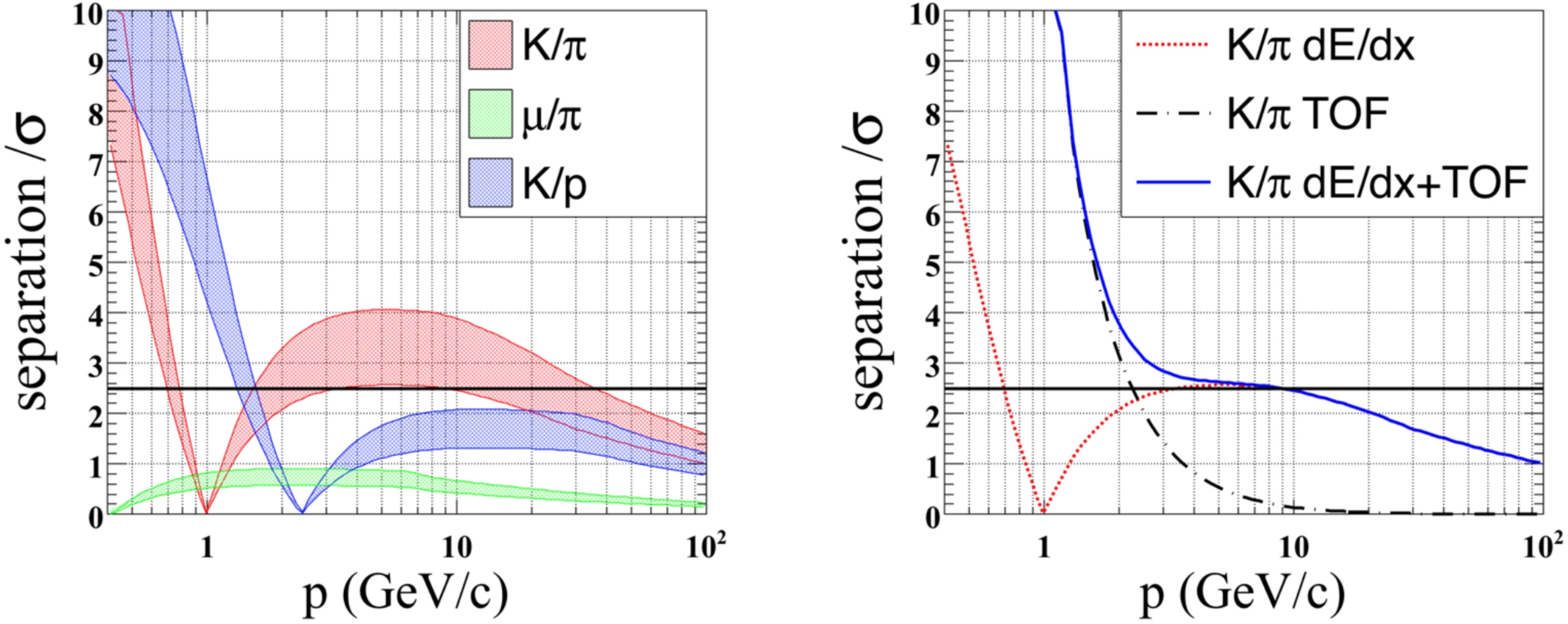




Compared the single particle sample, the jet lepton (at Z->bb sample at sqrt = 91.2 GeV) Performance will be slightly degraded – Due to the limited clustering performance (splitting & containimation).

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

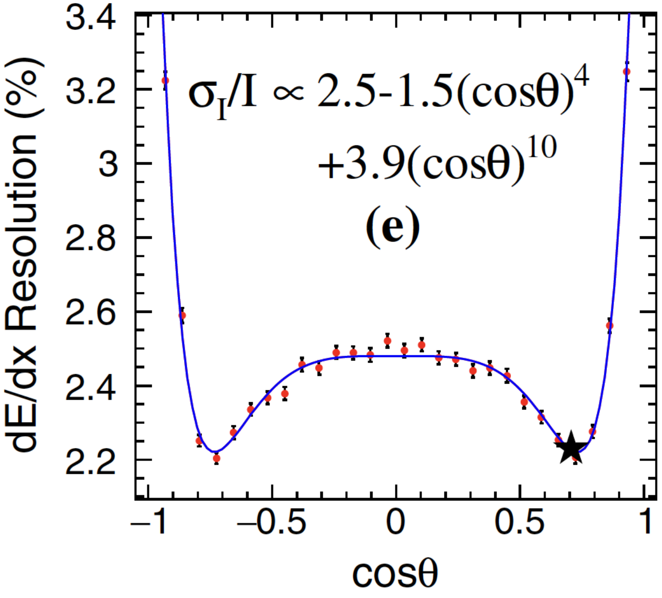
At inclusive Z pole sample:

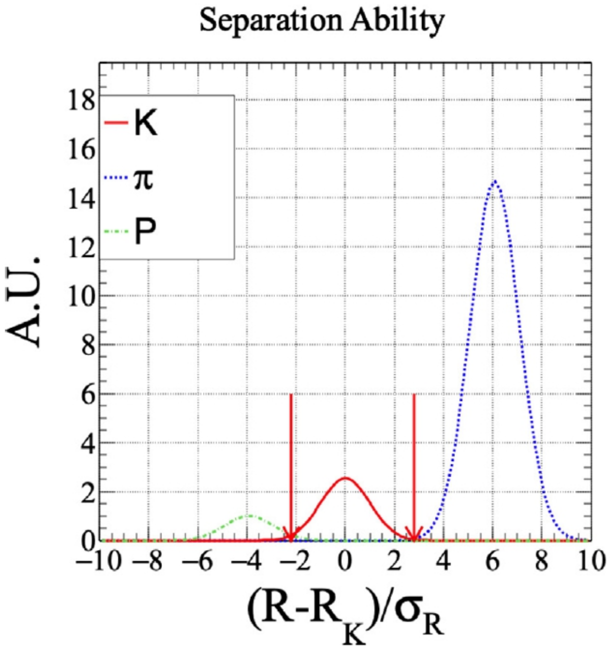
Conservative estimation gives efficiency/purity of 91%/94% (2-20 GeV, 50% degrading +50 ps ToF)

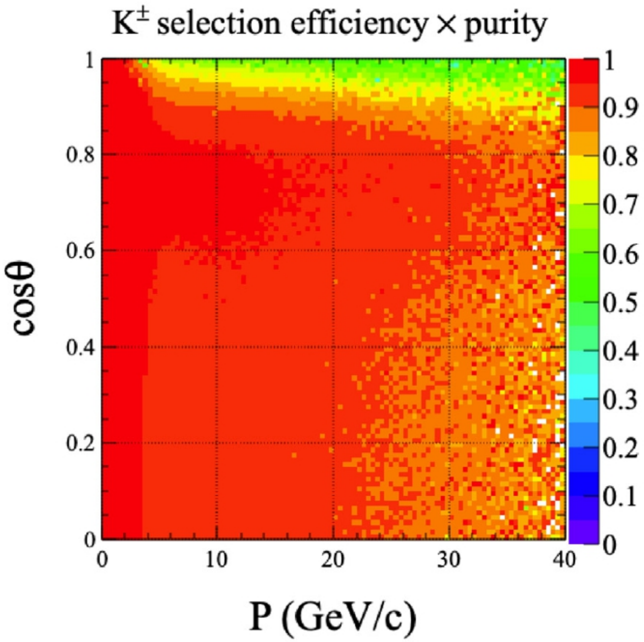
Could be improved to 96%/96% by better detector/DAQ performance (20% degrading + 50 ps ToF)

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

Pid performance





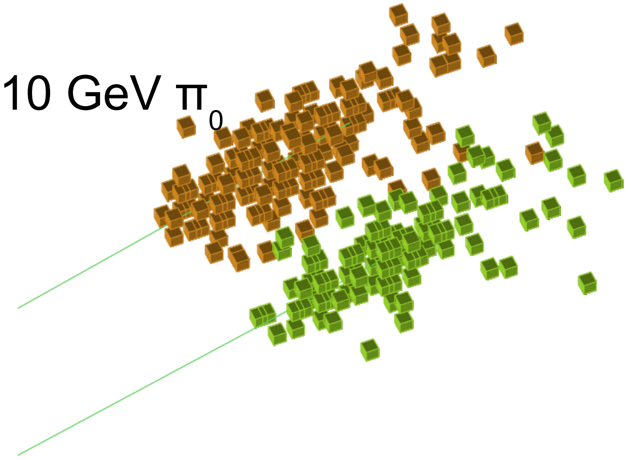


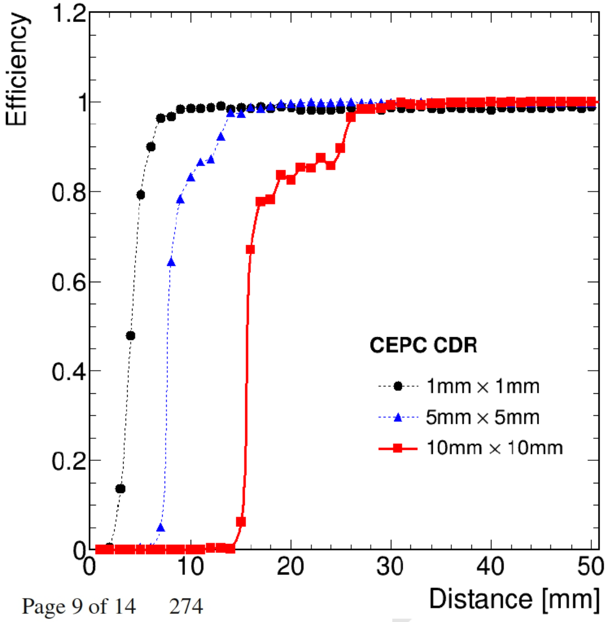
(b)

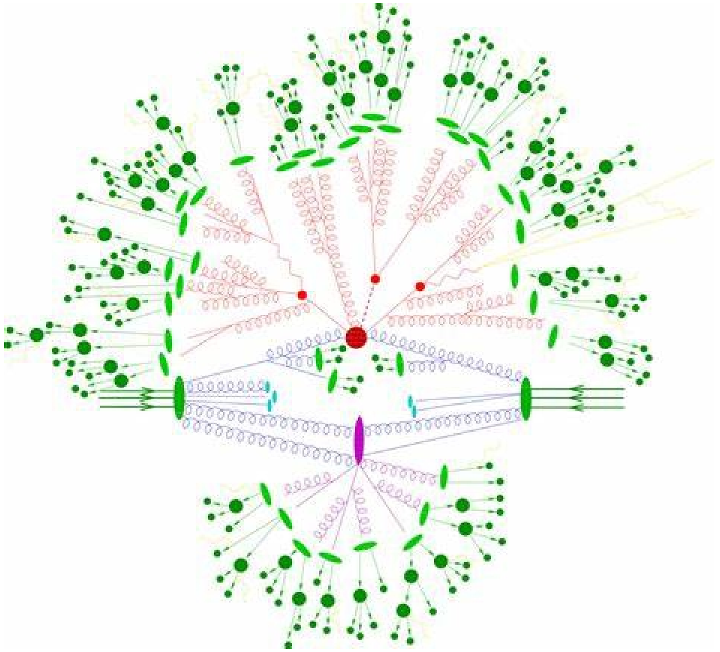
	factor	1.	1.2	1.5	2.
dE/dx	ε_K (%)	95.97	94.09	91.19	87.09
	$purity_K$ (%)	81.56	78.17	71.85	61.28
dE/dx & TOF	ε_K (%)	98.43	97.41	95.52	92.3
	$purity_K$ (%)	97.89	96.31	93.25	87.33

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

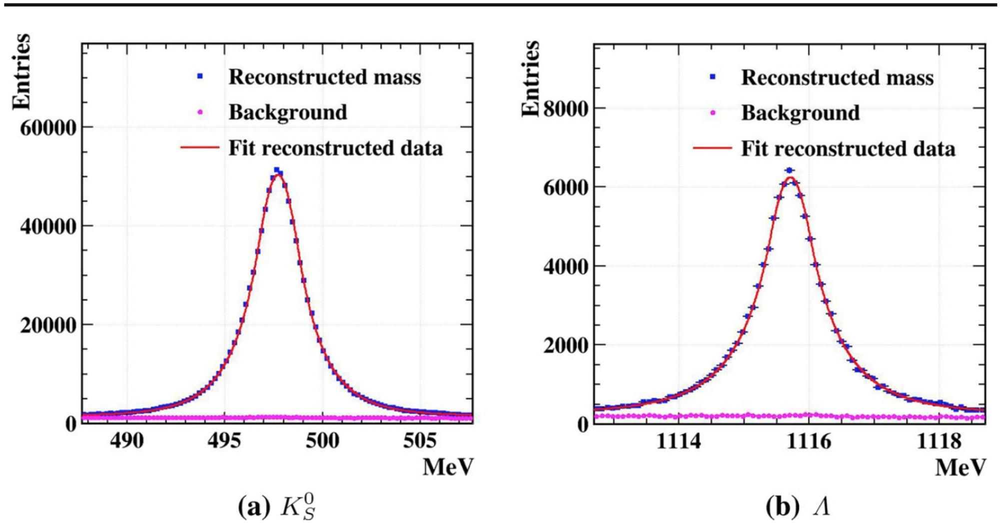
2-body decay particles and tau leptons


10 GeV π_0





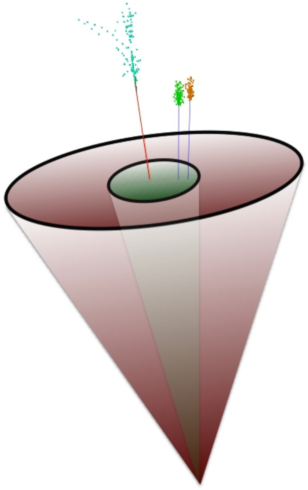
Eur. Phys. J. Plus (2020) 135:274 Page 9 of 14 274



(a) K_S^0

(b) Λ

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...