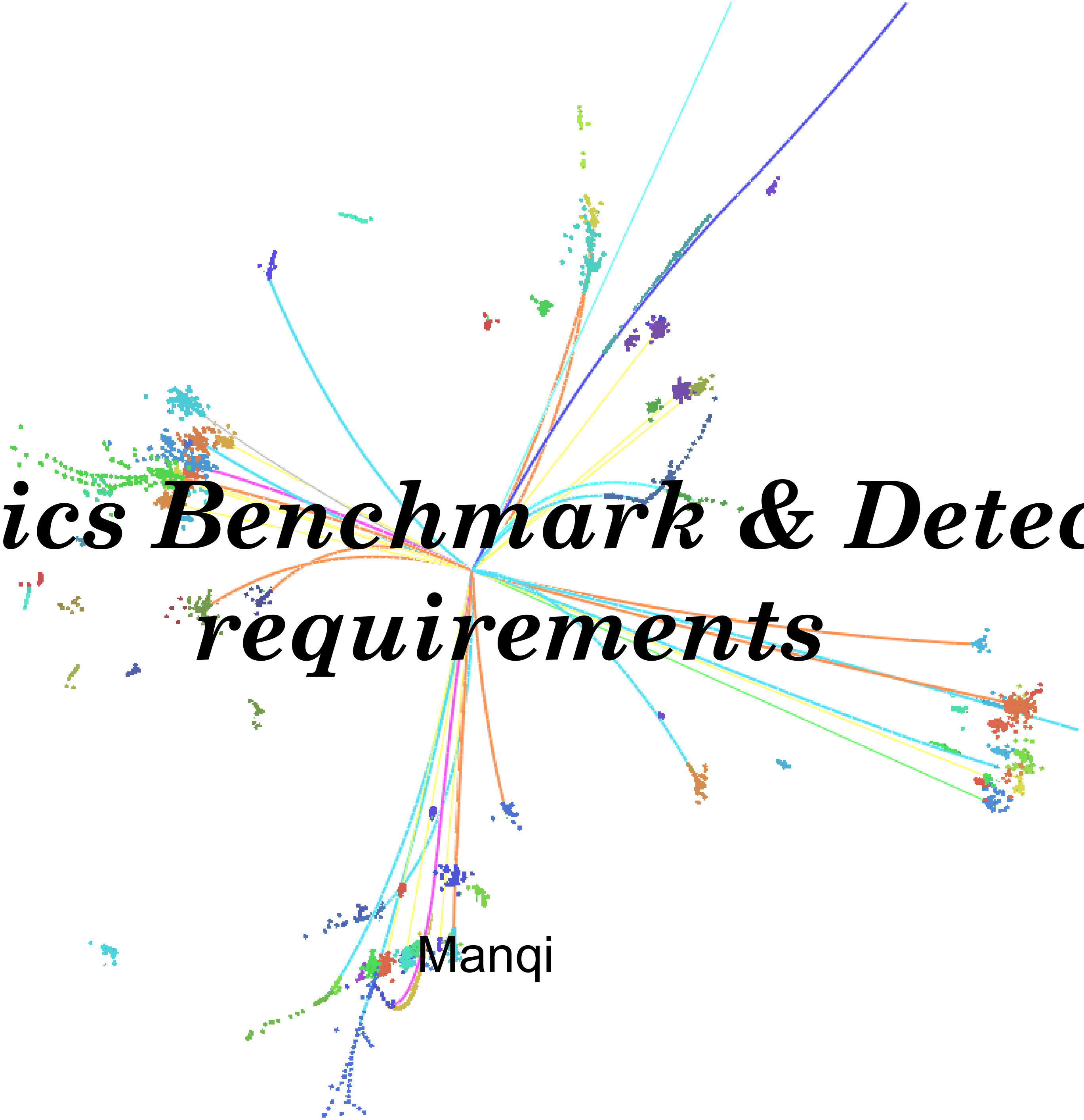
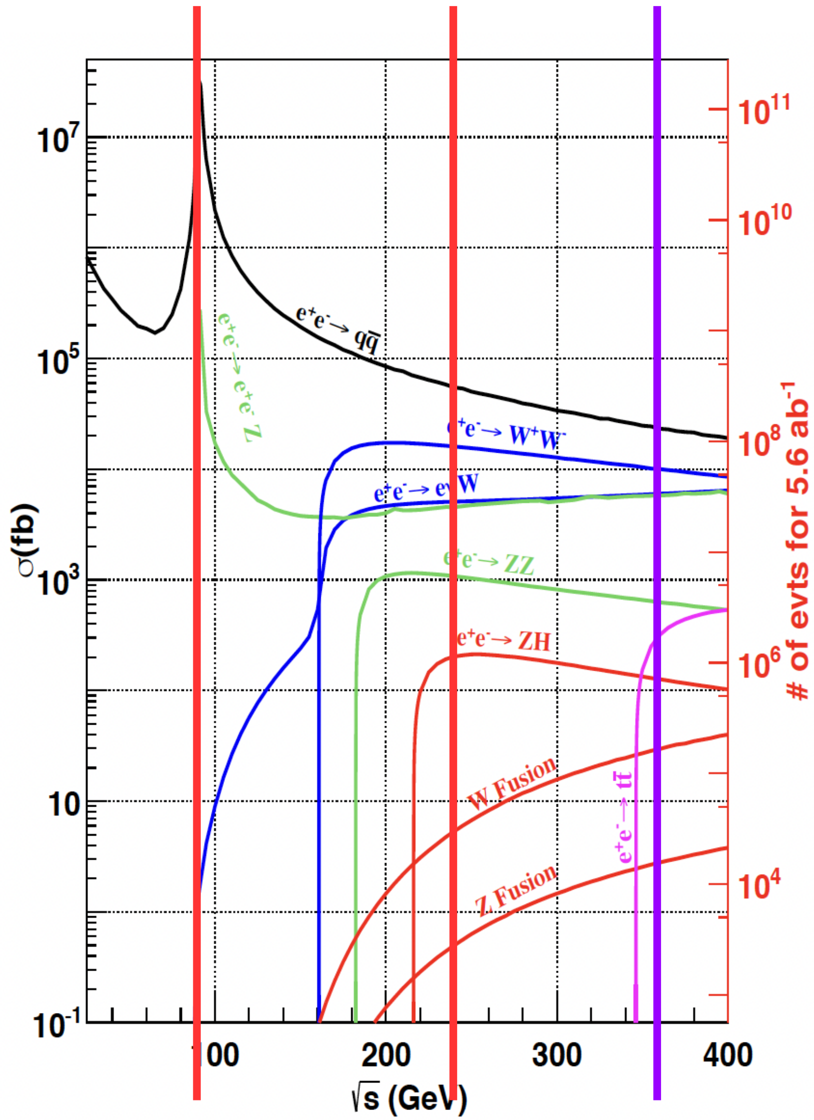
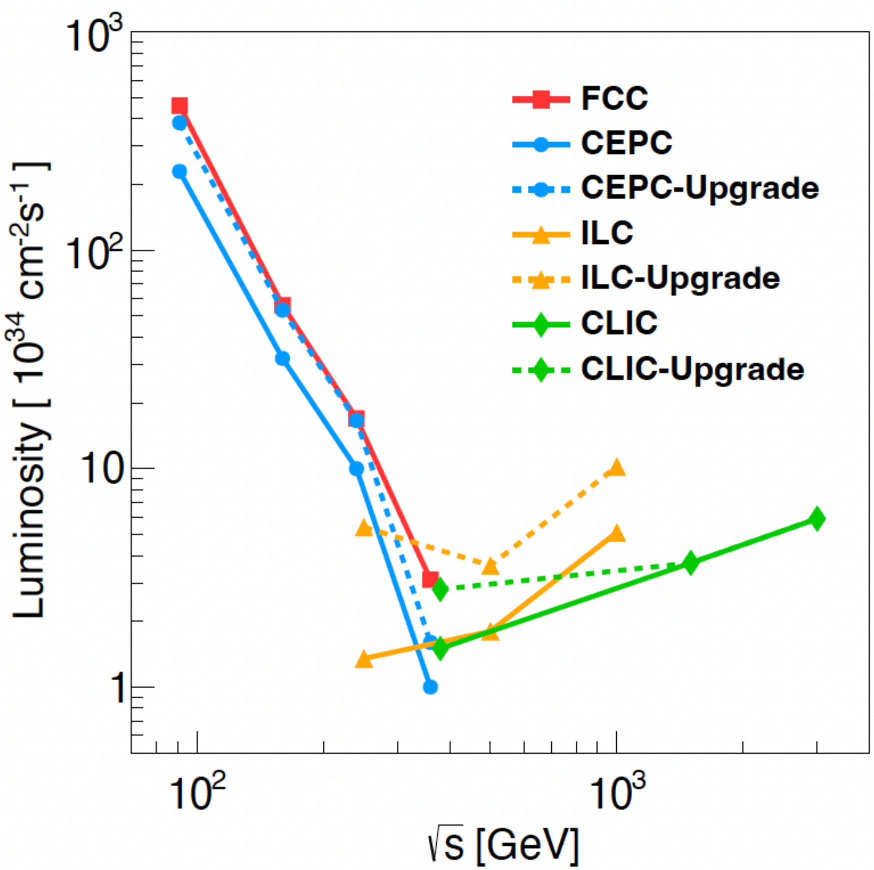
Physics Benchmark & Detector requirements



Manqi

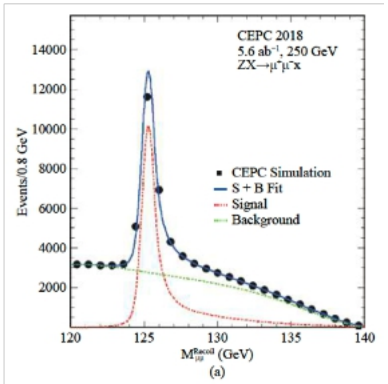
Yields ~ Xsec * Lumi * Time

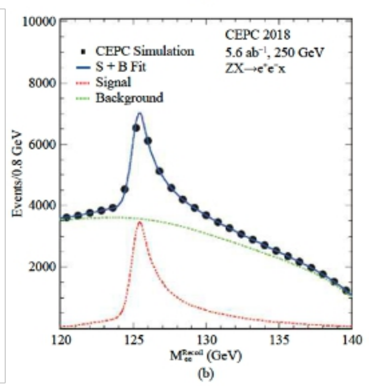


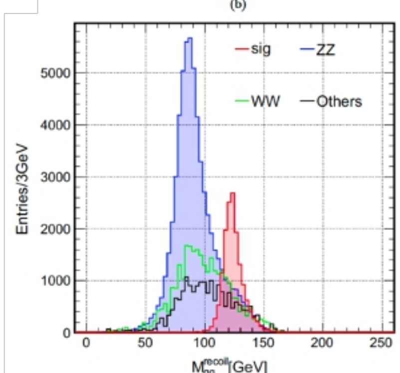


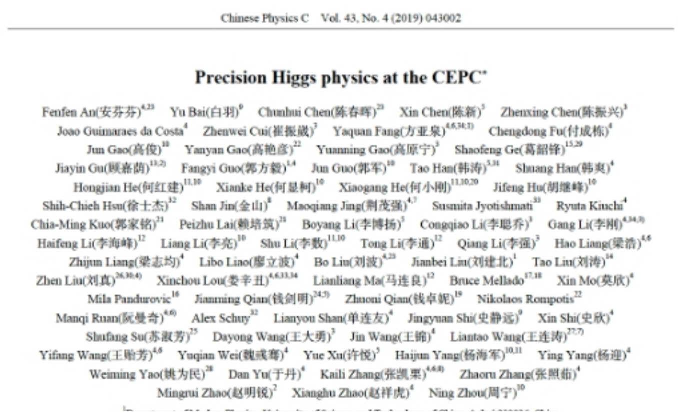
- 4 Million Higgs (10 years)
- ~ 1 Giga W (1 year) + 4 Tera Z (2 years)
- Upgradable: Top factory (500 k ttbar)

Physics study: 2023









White papers +

~300 Journal/AxXiv citables

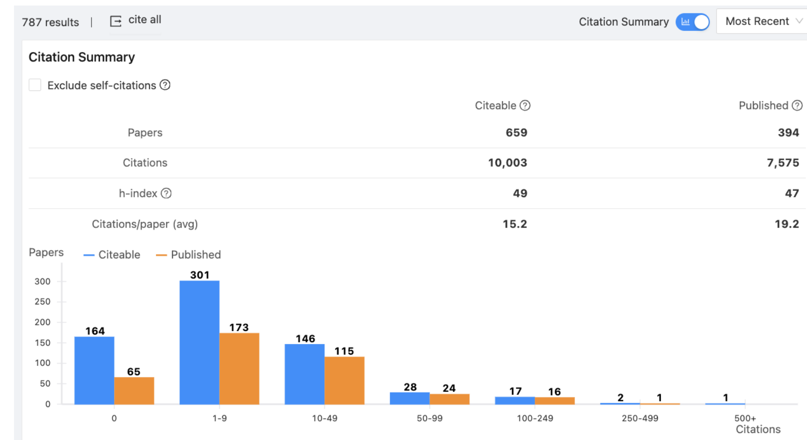


Table 2.1: Precision of the main parameters of interests and observables at the CEPC, from Ref. [1] and the references therein, where the results of Higgs are estimated with a data sample of 20 ab^{-1}. The HL-LHC projections of 3000 fb^{-1} data are used for comparison. [2]

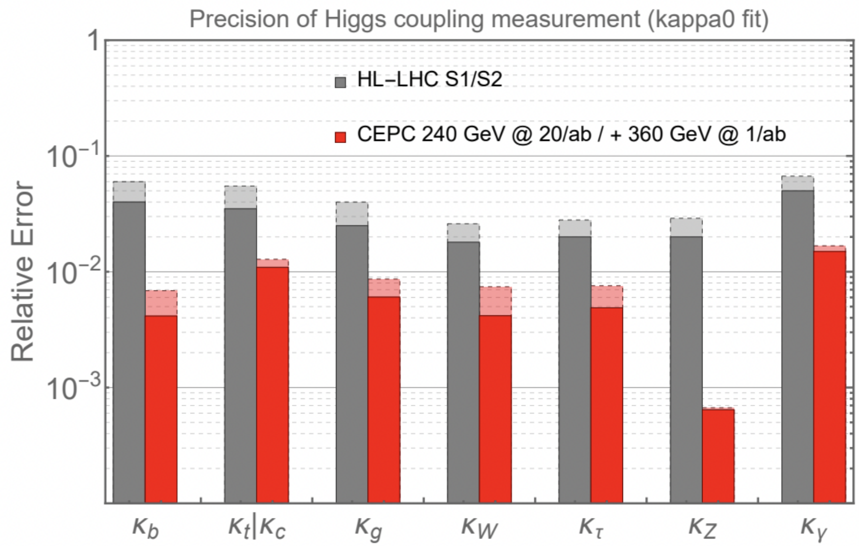
Higgs			W, Z and top		
Observable	HL-LHC projections	CEPC precision	Observable	Current precision	CEPC precision
M_H	20 MeV	3 MeV	M_W	9 MeV	0.5 MeV
Γ_H	20%	1.7%	Γ_W	49 MeV	2 MeV
$\sigma(ZH)$	4.2%	0.26%	M_{top}	760 MeV	$\mathcal{O}(10)$ MeV
$B(H \to bb)$	4.4%	0.14%	M_Z	2.1 MeV	0.1 MeV
$B(H \to cc)$	-	2.0%	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}

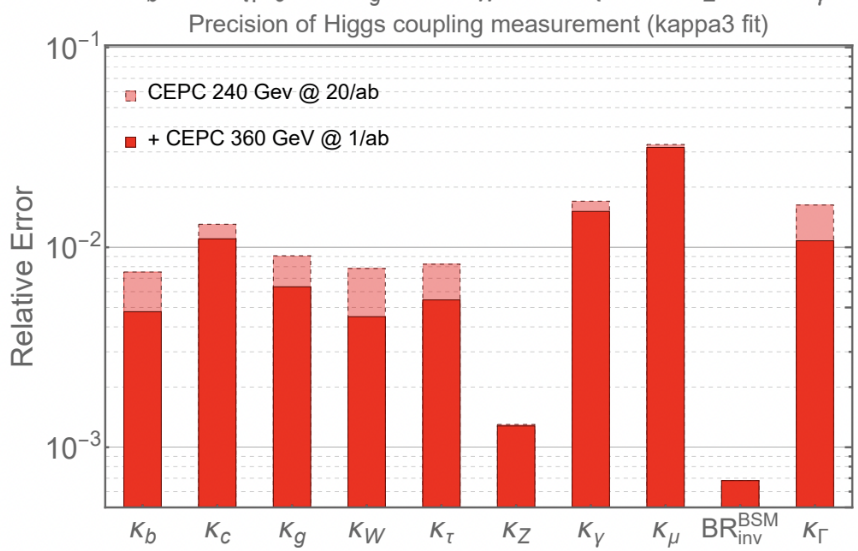
Scientific Significance quantified by **CEPC physics** studies, via full simulation/phenomenology studies:

- 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

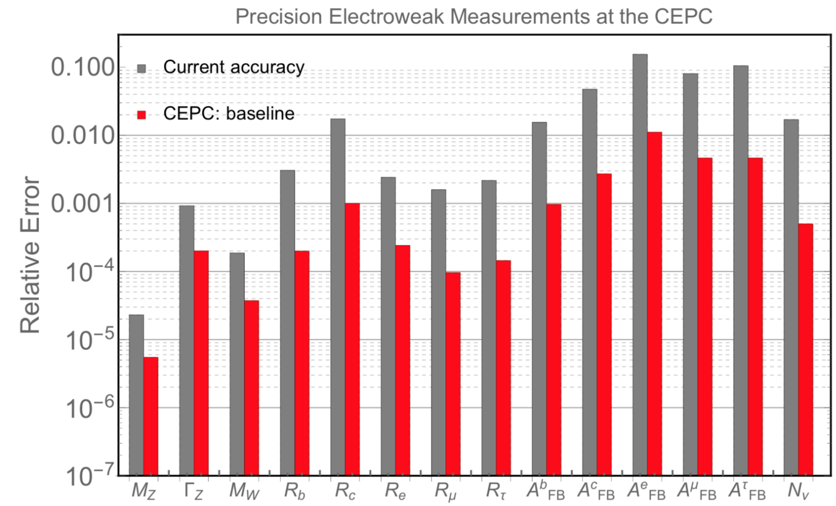
	240 GeV, 20 ab^{-1}		360 GeV, 1 ab^{-1}		
	ZH	**vvH**	ZH	**vvH**	**eeH**
inclusive	**0.26%**		**1.40%**	\	\
H→bb	**0.14%**	**1.59%**	**0.90%**	**1.10%**	**4.30%**
H→cc	**2.02%**		**8.80%**	**16%**	**20%**
H→gg	**0.81%**		**3.40%**	**4.50%**	**12%**
H→WW	**0.53%**		**2.80%**	**4.40%**	**6.50%**
H→ZZ	**4.17%**		**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%**		
$\mathrm{Br}_{upper}(H \to inv.)$	**0.07%**				
Γ_H	**1.65%**		**1.10%**		

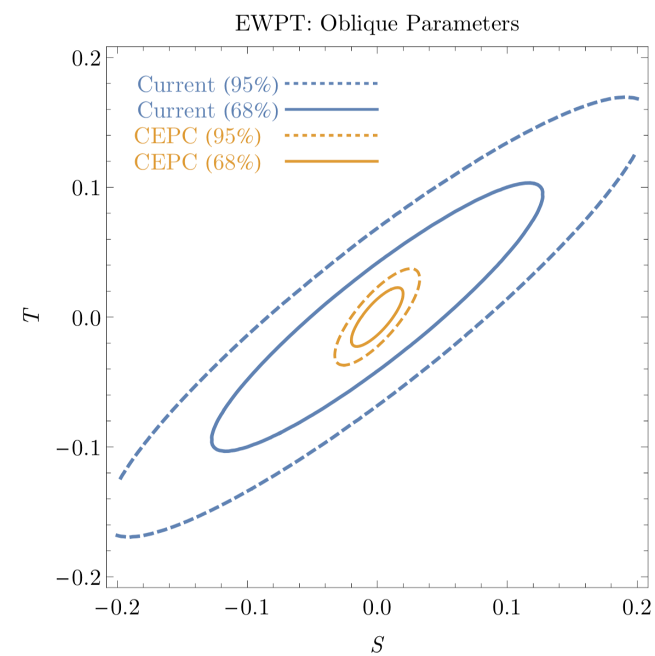


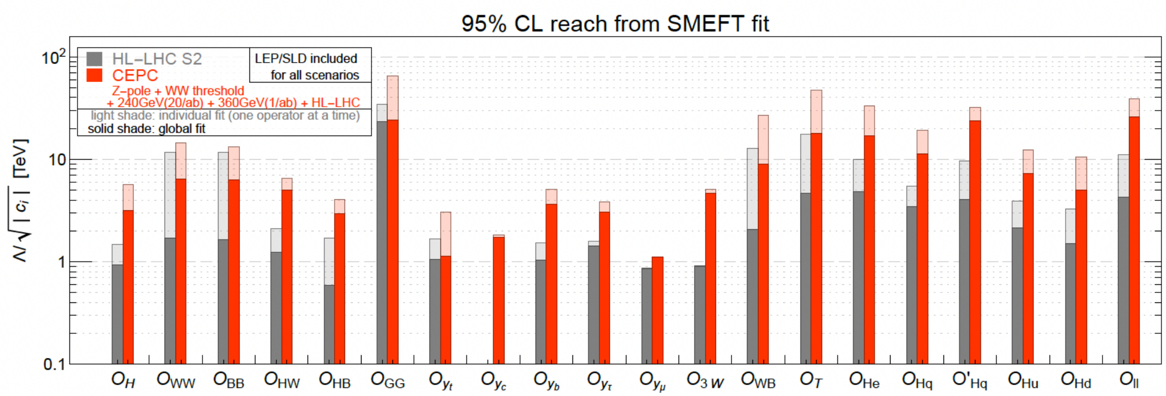


EW measurements & SMEFT

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 White paper

Flavor Physics at CEPC: a General Perspective

Contents

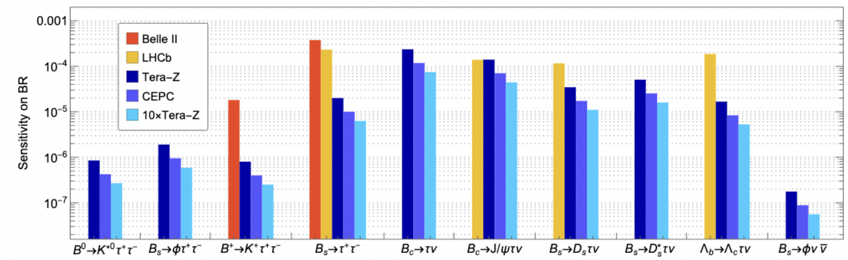


Figure 18: Projected sensitivities of measuring the $b \to s\tau\tau$ [70], $b \to s\nu\bar{\nu}$ [34] and $b \to c\tau\nu$ [35, 62] transitions at the Z pole. The sensitivities at Belle II @ 50 ab^{-1} [6] and LHCb Upgrade II [17, 71] have also been provided as a reference. Note, the LHCb sensitivities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

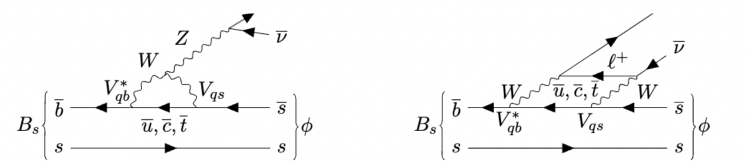


Figure 21: Illustrative Feynman diagrams for the $B_s \to \phi\nu\bar{\nu}$ transitions in the SM. **LEFT**: EW penguin diagram. **RIGHT**: EW box diagram.

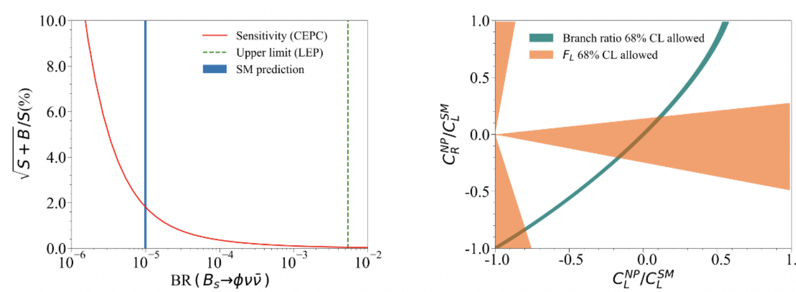


Figure 22: **LEFT**: Relative precision for measuring the signal strength of $B_s \to \phi\nu\bar{\nu}$ at Tera-Z, as a function of its BR. **RIGHT**: Constraints on the LEFT coefficients $C_L^{\rm NP} \equiv C_L - C_L^{\rm SM}$ and C_R with the measurements of the overall $B_s \to \phi\nu\bar{\nu}$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

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

Physics Benchmarks

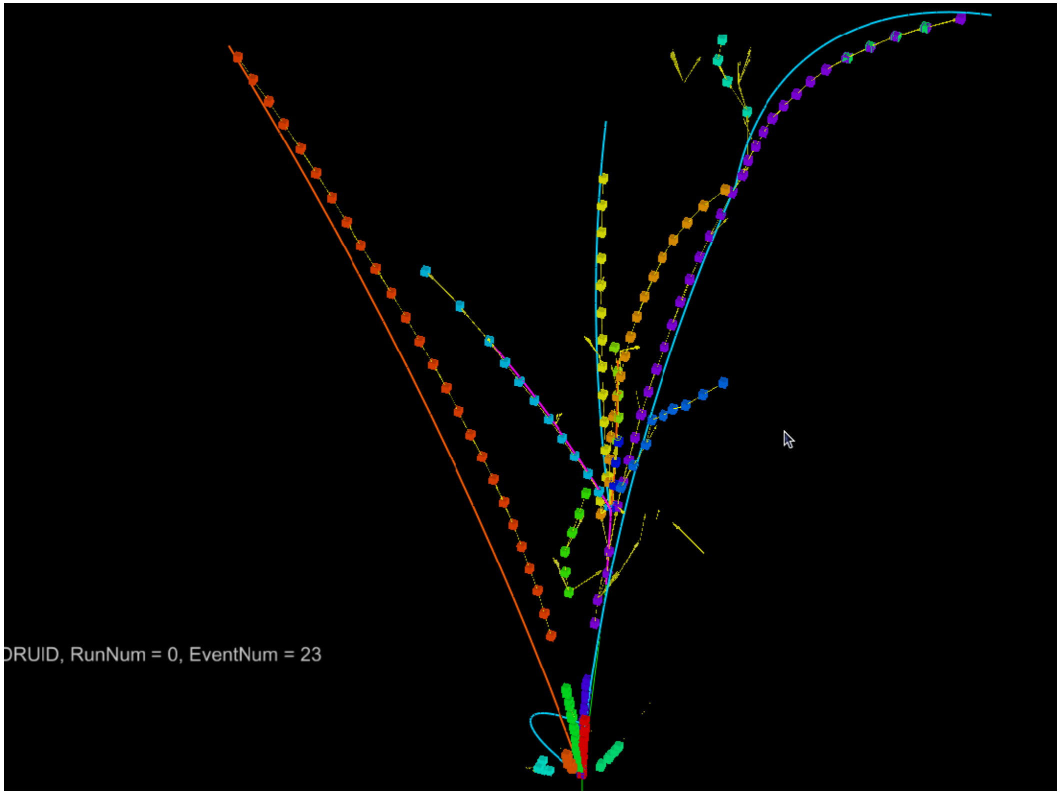
	Processes @ c.m.s.	Domain	Total Det. Performance	Sub-D
H->ss/cc/sb	vvH @ 240 GeV	Higgs	PFA + JOI (Jet origin id)	All sub-D, especially VTX
H->inv	qqH	Higgs/NP	PFA	All
Vcb	WW@ 240/160 GeV	Flavor	JOI + Particle (lepton) id	All
W fusion Xsec	vvH @ 360 GeV	Higgs	PFA + JOI	All
α_S	Z->tautau @ 91.2 GeV	QCD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

Performance requirements

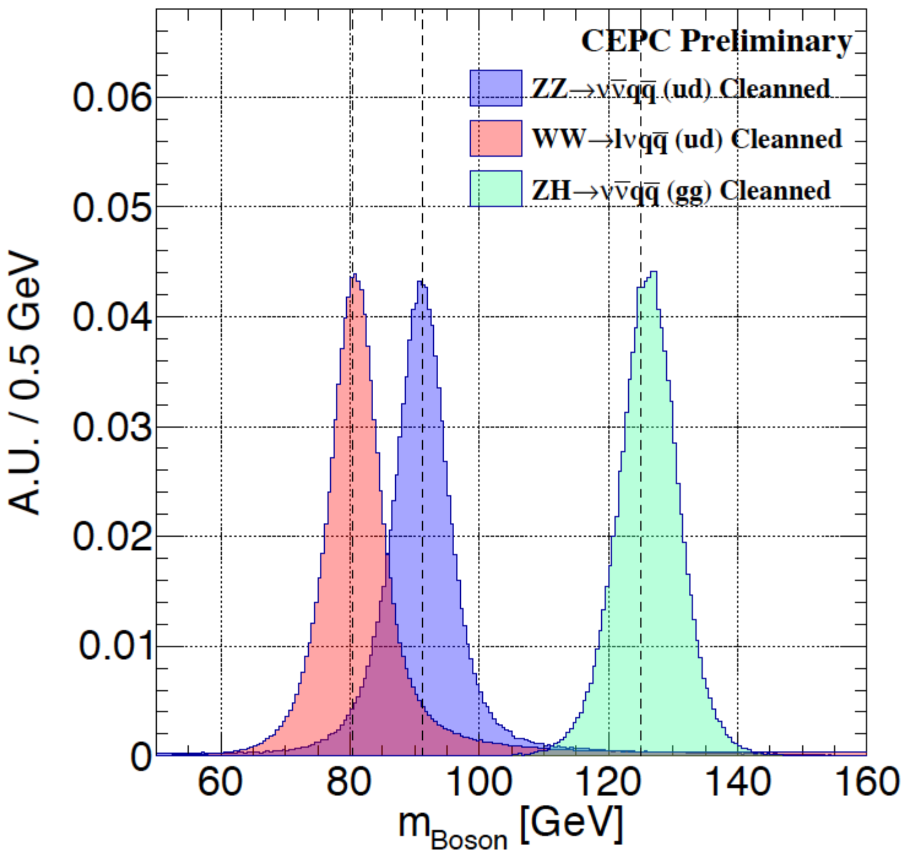
- A clear separation of the final state particles: Identification of Physics Objects, and Improving the E/P resolution for composited objects, especially jets
  - Leptons, especially these inside jets
  - Composited objects:
    - Two/three body objects: Pi-0, K-short, Lambda, Phi, Tau, D meson...
    - More bodies: Tau & Jets
  - **PFA:** pursuing 1-1 correspondence.
    - BMR (Boson Mass Resolution): mass resolution of Hadronic decayed Higgs/Z/W

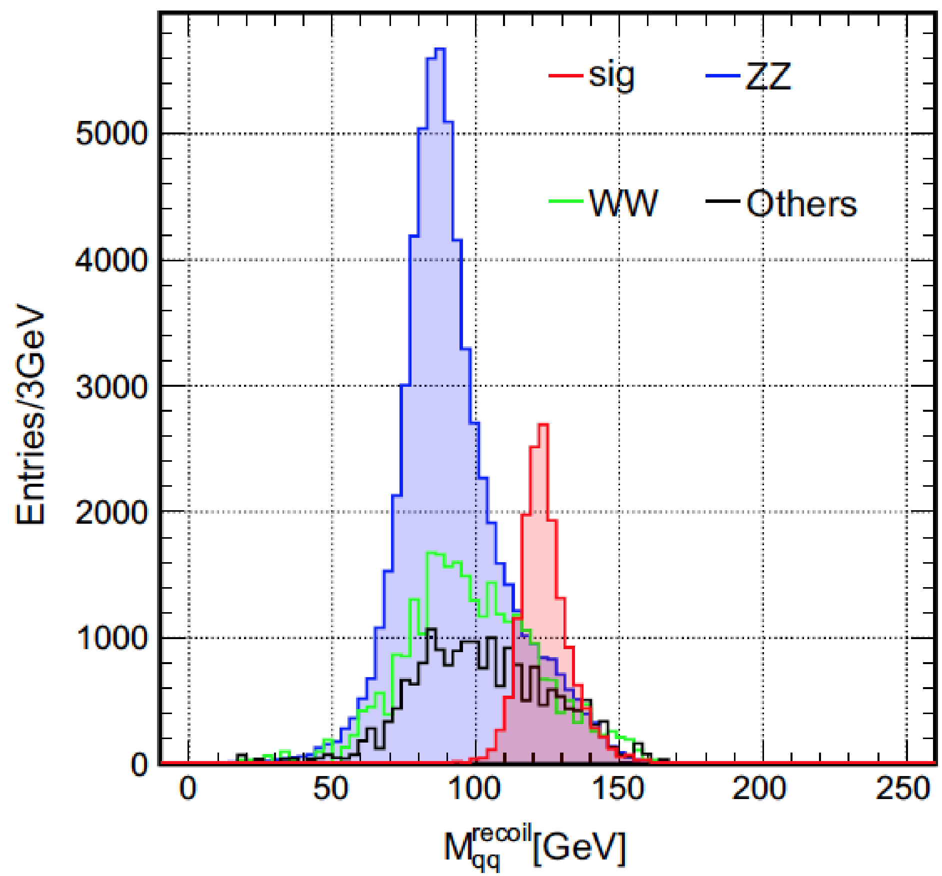
      BMR < 4% for Higgs measurements
    - Much demanding for Flavor Physics/New Physics Hunting
- **Pid:**
  - Pion & Kaon separation > 3 σ
  - Identify species of all charged final state particles: isolated and **in jet**...
- **Jet origin id:** Flavor Tagging & Charge Reconstruction, s-jet id, gluon jet id, etc
- Intrinsic accuracies: momentum, energy, VTX positions...

PFA

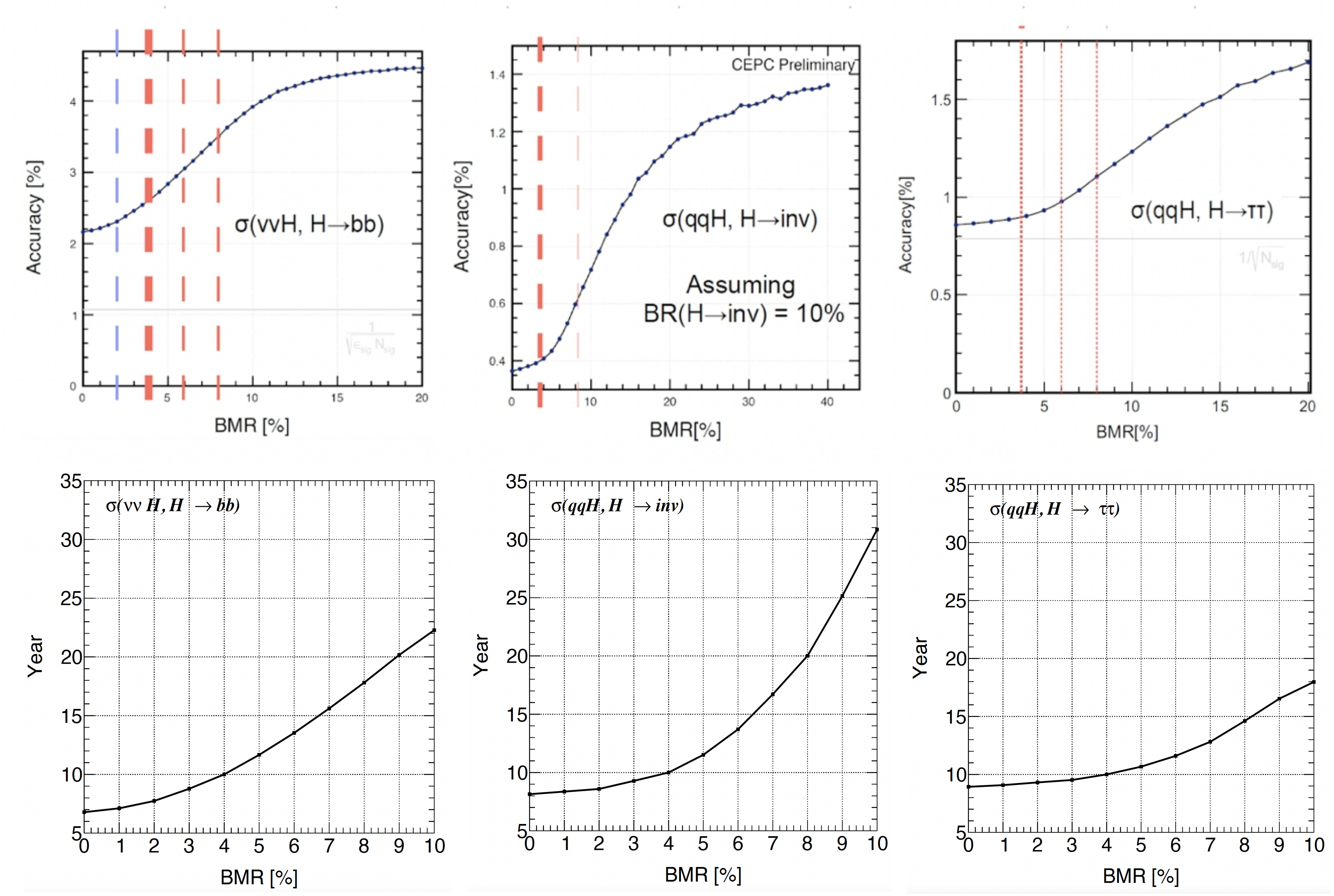


Boson Mass Resolution: Key Per. Para

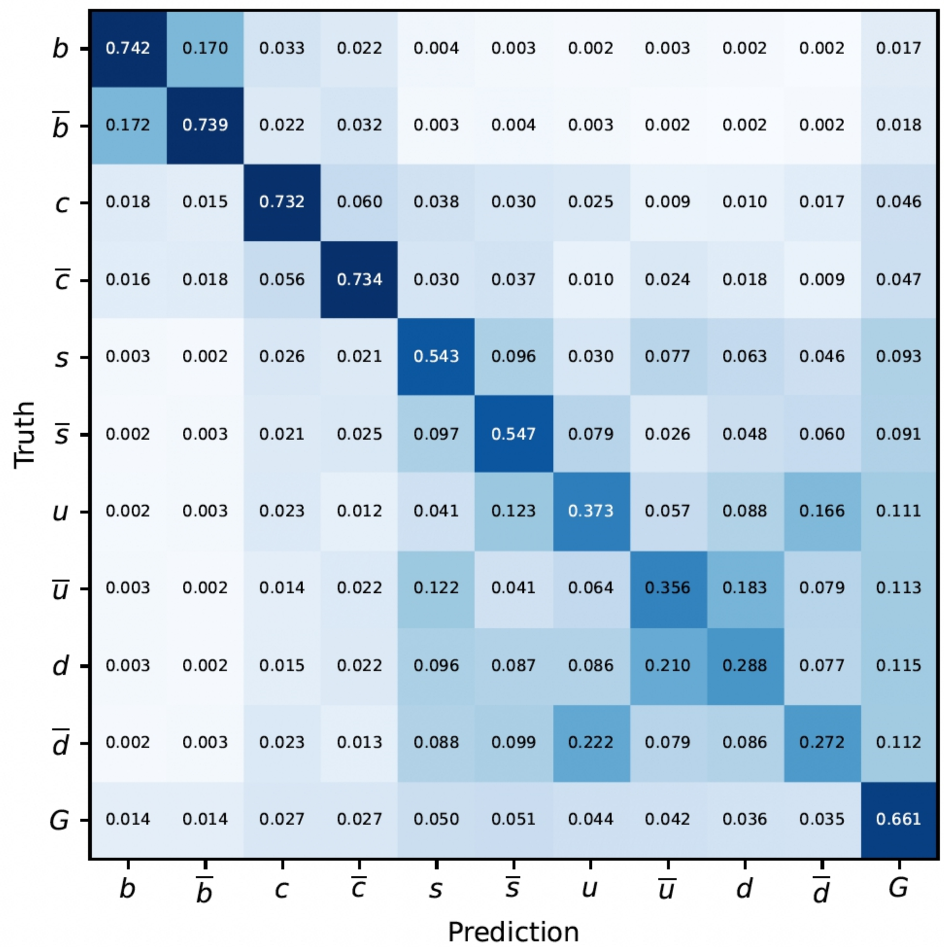




BMR: impact on critical measurements



Jet origin id



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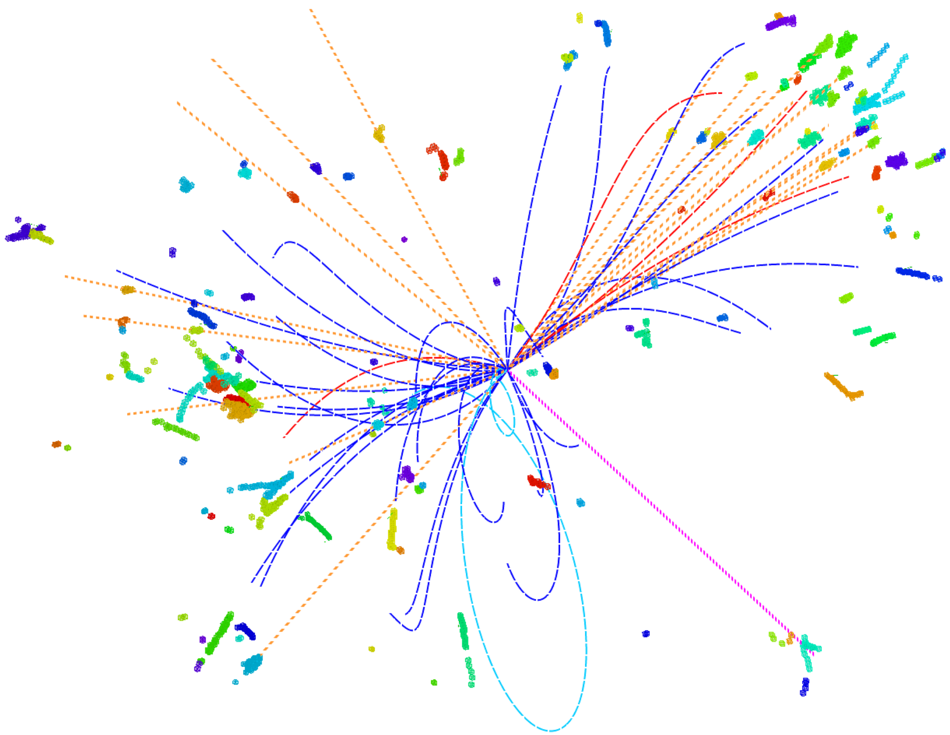
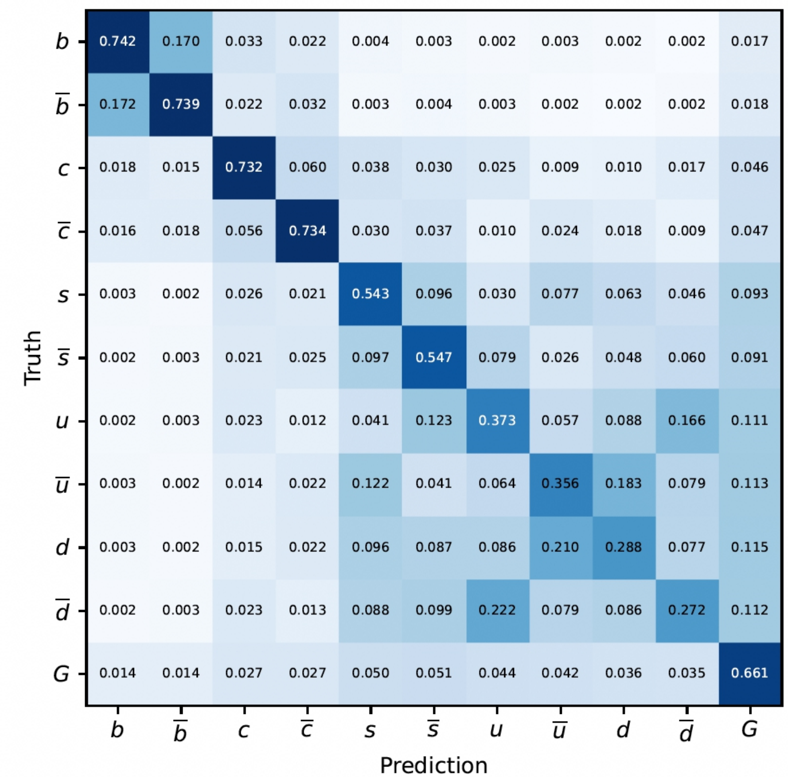
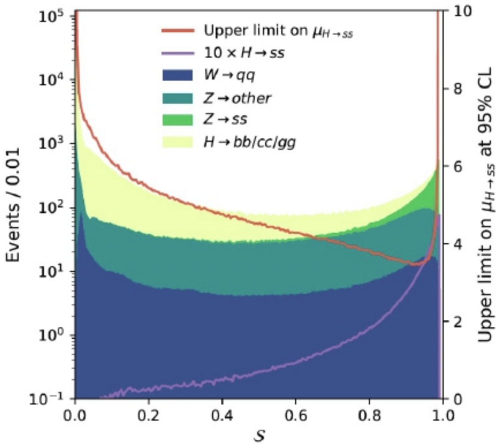
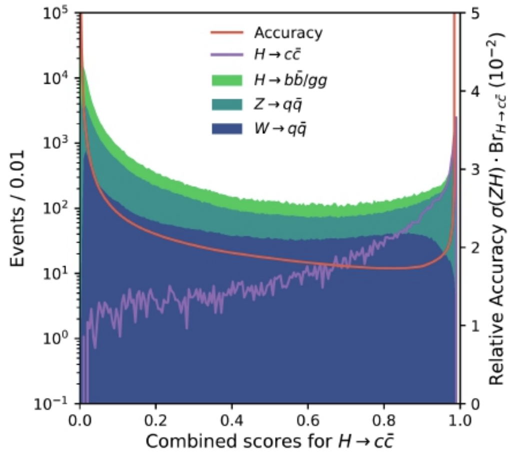


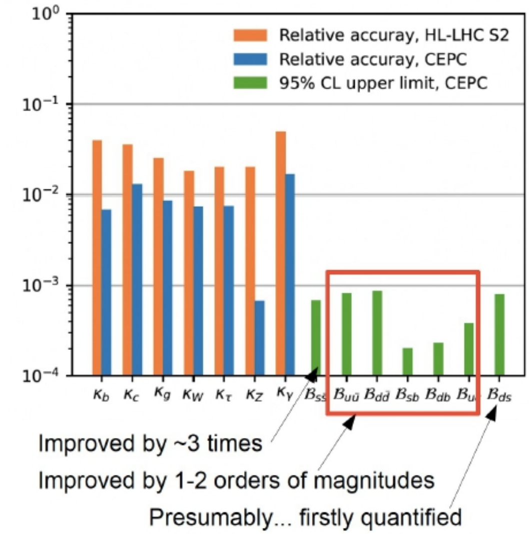


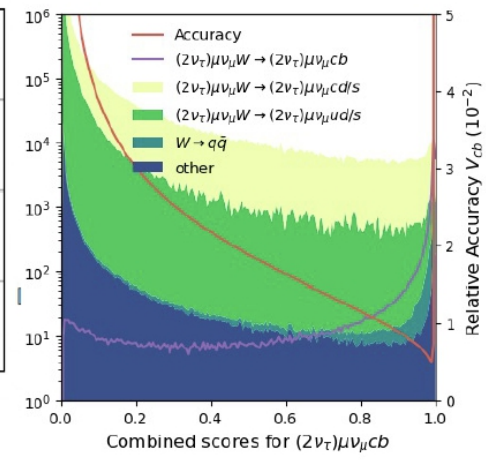
- **Jet origin identification: 11 categories (5 quarks + 5 anti quarks + gluon)**
  - Jet Flavor Tagging + Jet Charge measurements + s-tagging + gluon tagging...
- Full Simulated vvH, Higgs to two jets sample at CEPC baseline configuration: CEPC-v4 detector, reconstructed with **Arbor + ParticleNet (Deep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

Impact on Physics

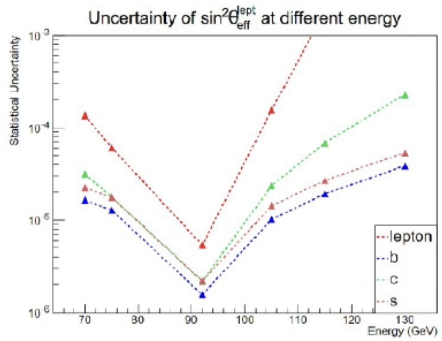




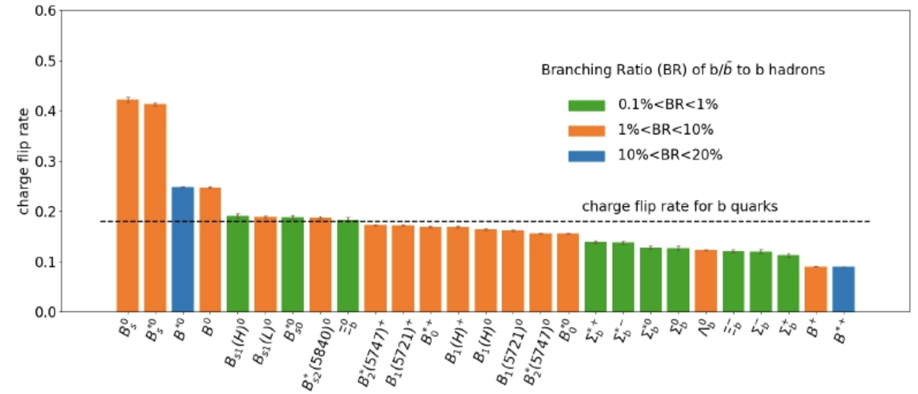




Expected statistical uncertainties on $\sin^2\theta^l_{eff}$ measurement.
(Using one-month data collection, ~*4e12/24 Z events* at Z pole)



$\sqrt{s}$	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}

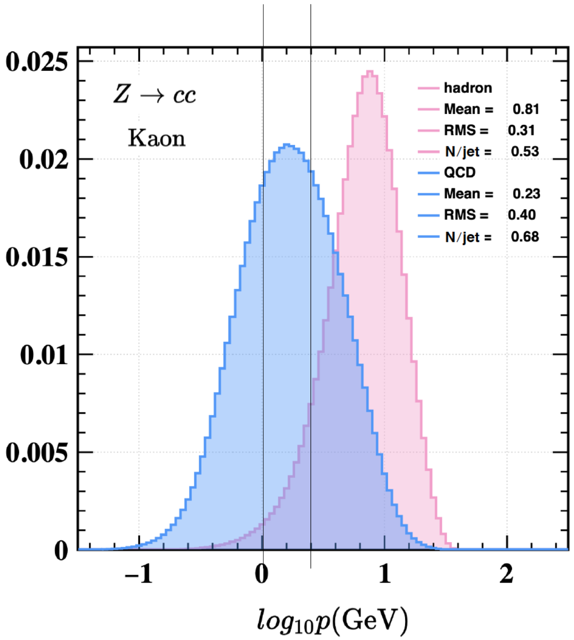


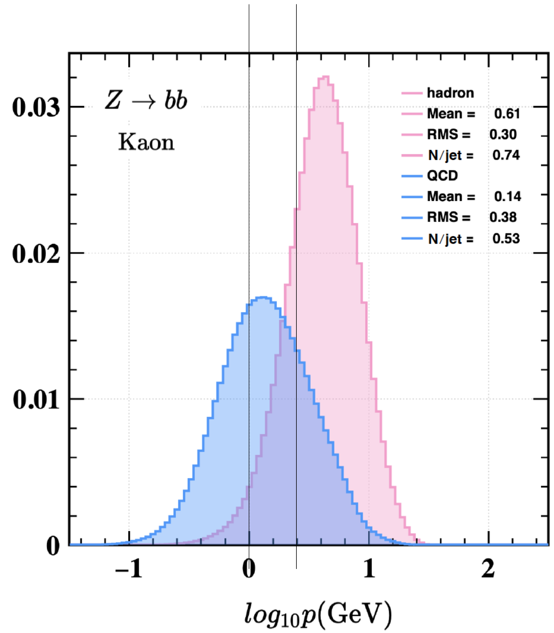
Particle identification

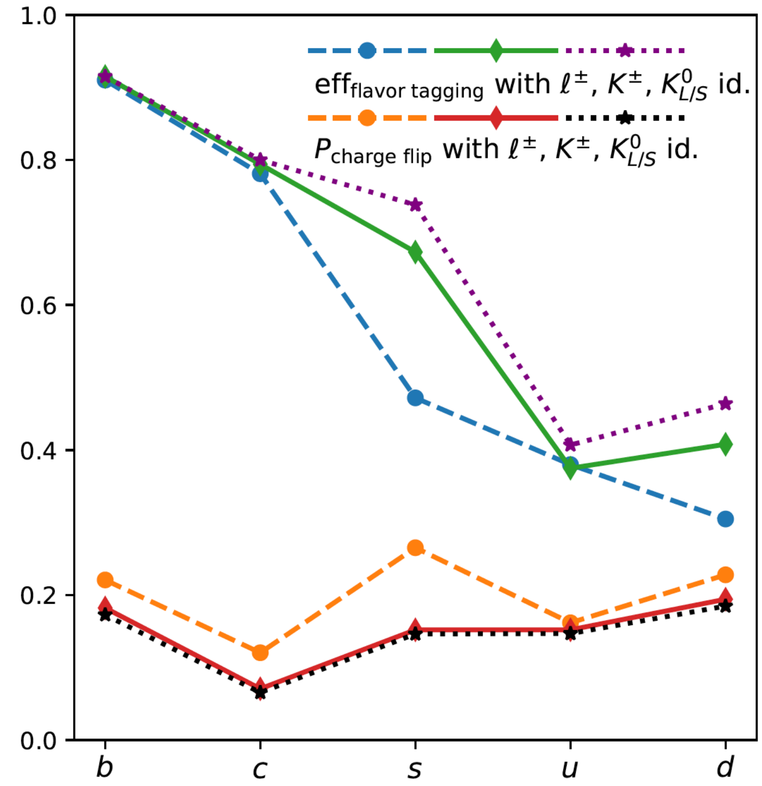
1. Kaon id

2. all species... + inside jets

Momentum spectrum of Kaon...





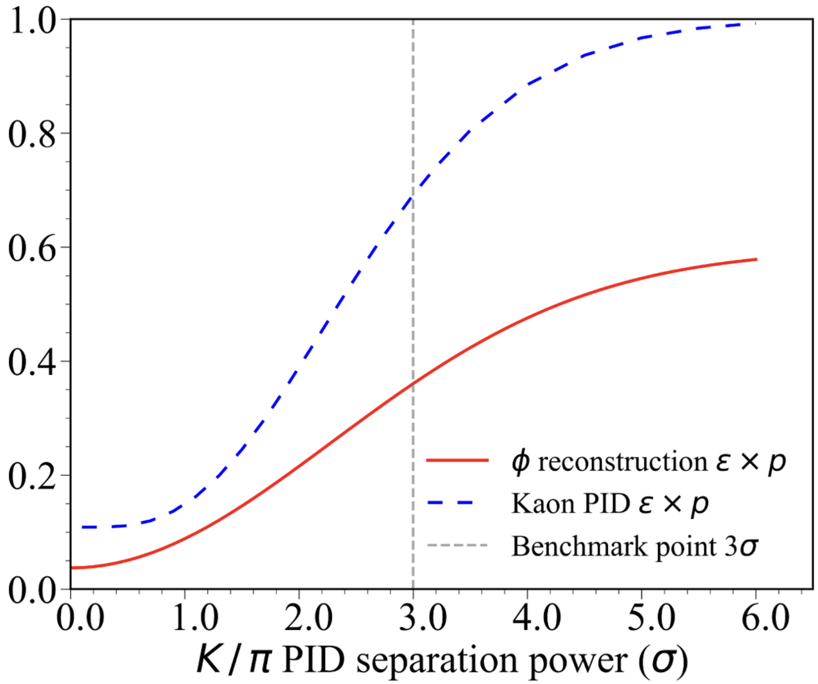


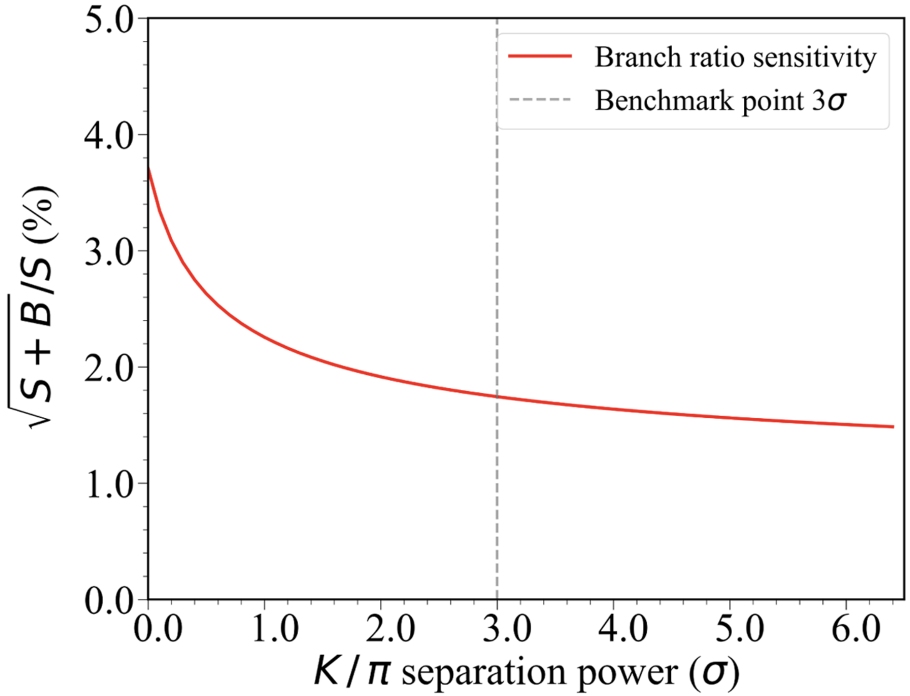
Charged Kaons from B/D hadrons → Flavor Physics

Charged Kaon from QCD → QCD

Both Contributed significantly to Jet Origin ID

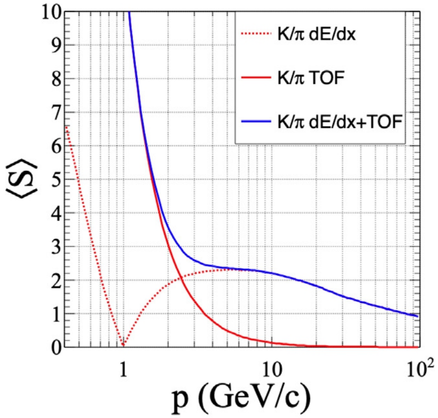
Sep power < 3 sigma



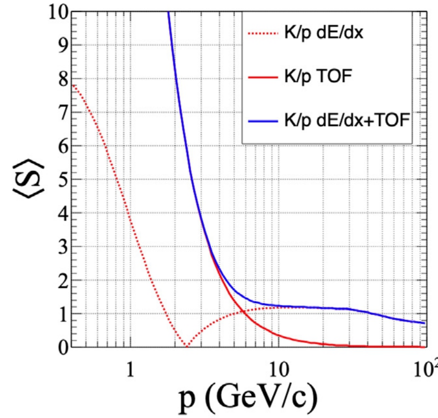


values $\mu_{K(\pi)}$ and corresponding standard deviations $\sigma_{K(\pi)}$. The separation power is defined as $2|\mu_\pi - \mu_K|/(\sigma_\pi + \sigma_K)$.

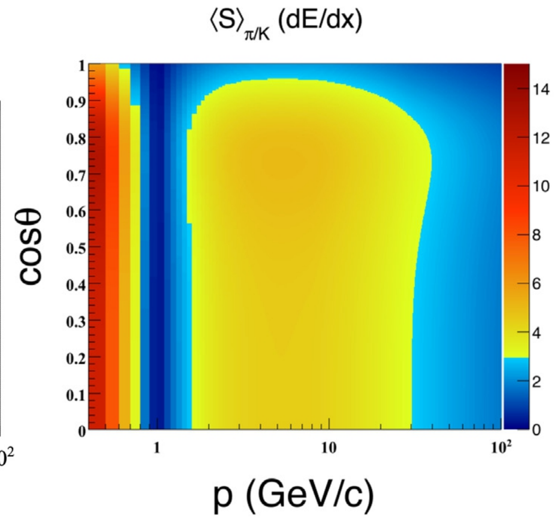
Sep. power



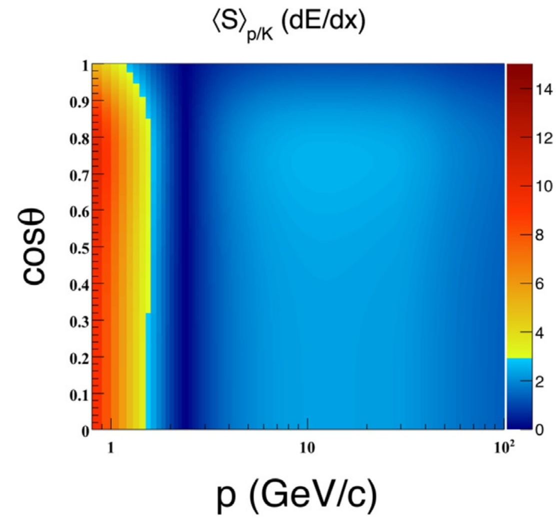
(a)



(b)



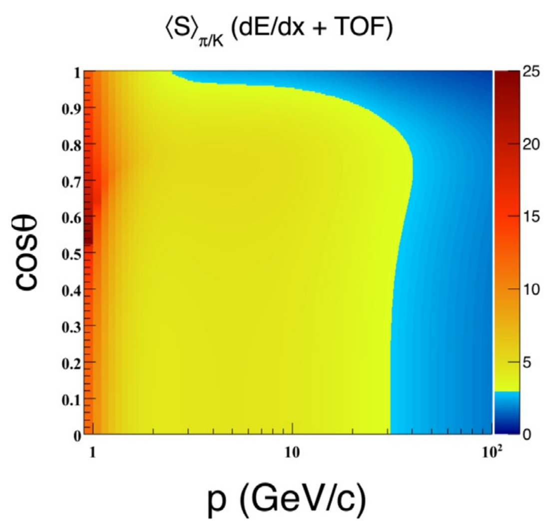
(a)



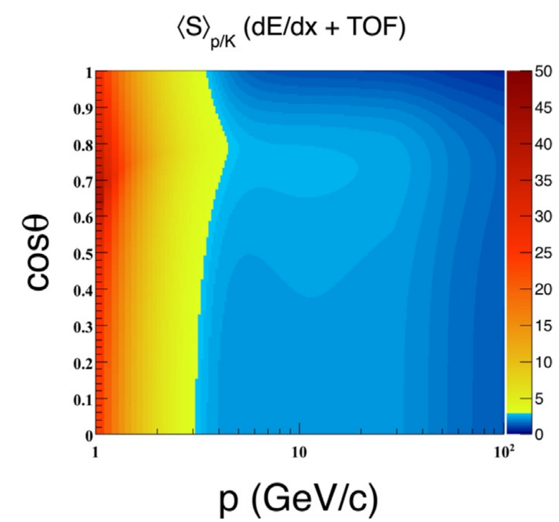
(b)

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

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



(a)



(b)

Requirement on dE/dx & dN/dx

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

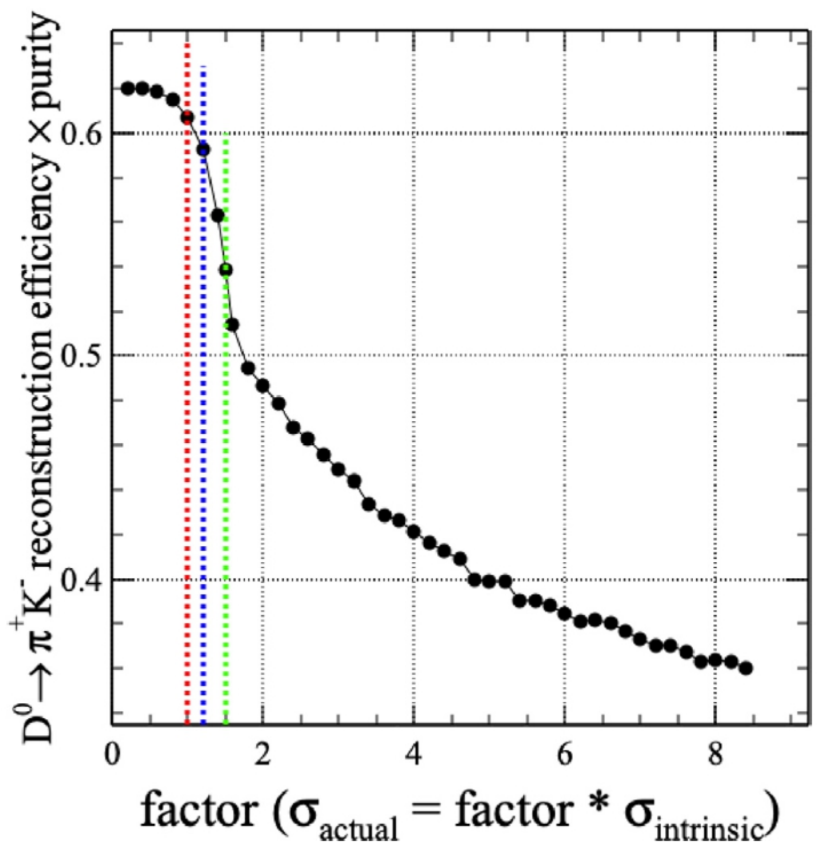


Fig. 12. The distribution of $D^0 \rightarrow \pi^+ K^-$ reconstruction performance as a function of the factor defined in $\sigma_{actual} = factor \cdot \sigma_{intrinsic}$. The red/blue/green line corresponds to the 0%/20%/50% degradation of dE/dx resolution.

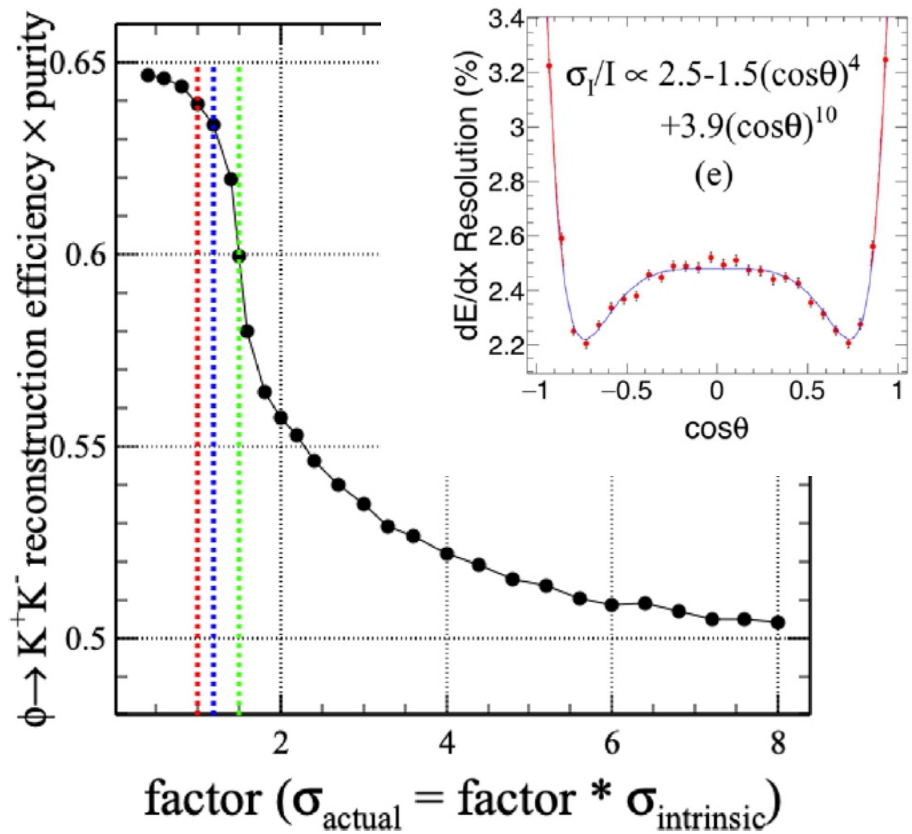
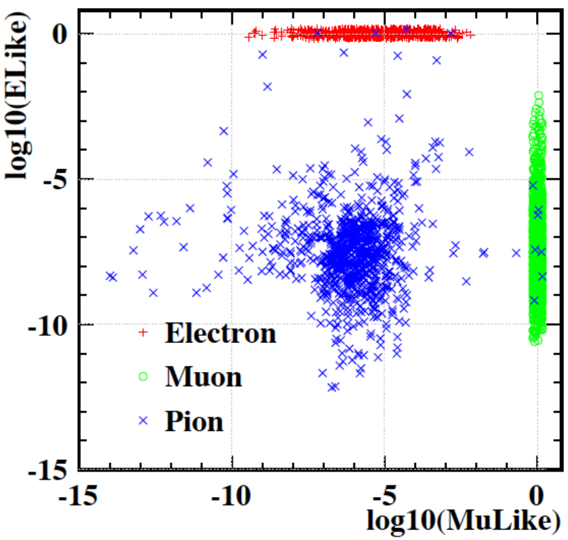
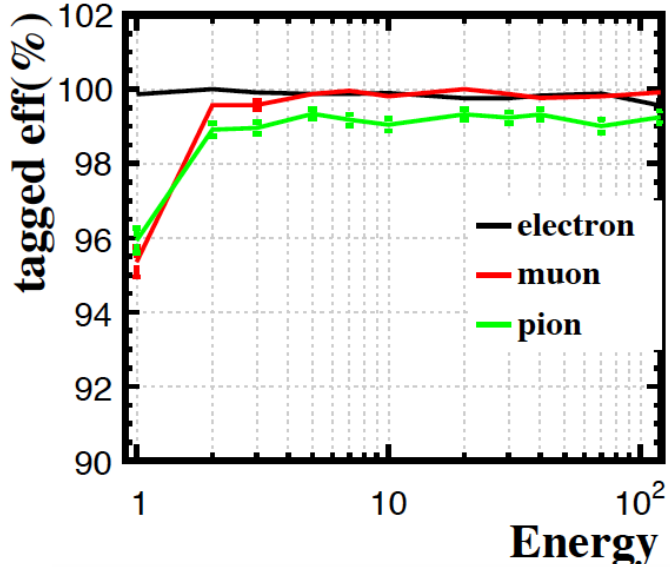


Fig. 13. The distribution of $\phi \rightarrow K^+ K^-$ reconstruction as a function of the factor defined in $\sigma_{actual} = factor \cdot \sigma_{intrinsic}$. The red/blue/green line corresponds to the 0%/20%/50% degradation of the dE/dx resolution.

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

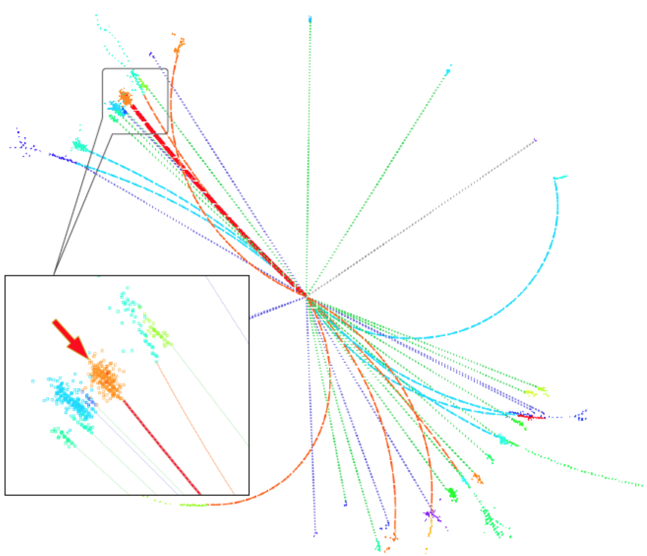
Lepton: isolated & Inside jet

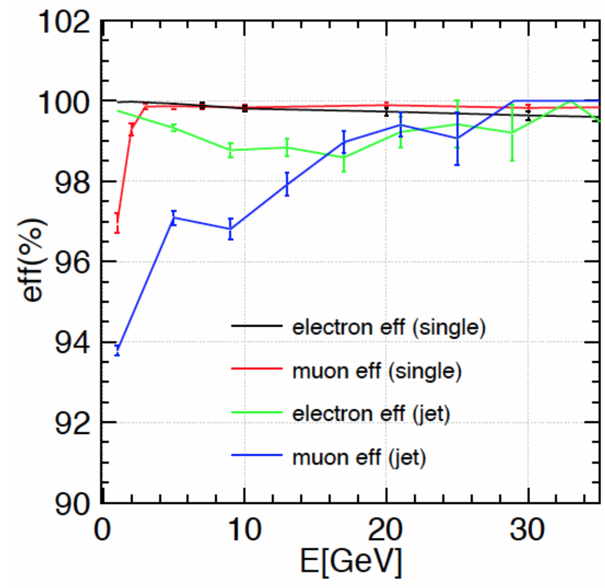


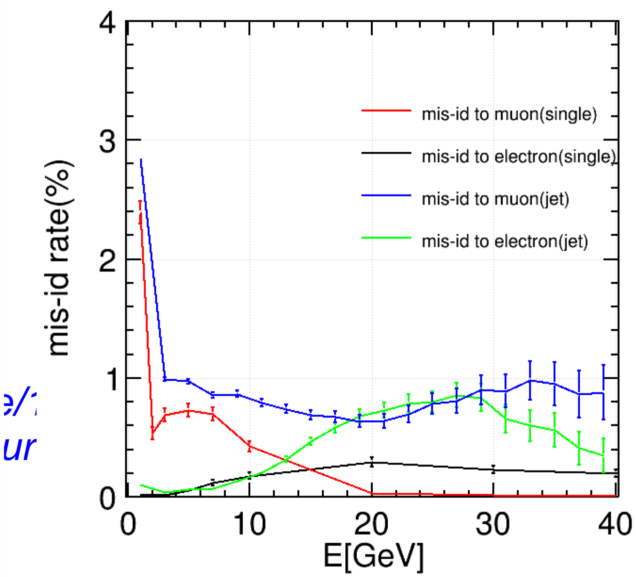


Isolated: for E > 2 GeV: lepton efficiency > 99.5% && Pion mis id rate ~ 1%

Inside Jet: percentage level degrading







Summary

- Physics Benchmarks selected, while new proposals are welcome
  - Based on existing study
  - Emphasize on Higgs (inc. Dark matter), and covers all observation channels.

- Corner stone performances
  - BMR: < 4% as a must... and shall pursue 3%
  - JoI: ~ baseline performance: b/c/s jet eff of 90/80/70% & charge flip rate of 10 - 20%
  - Pid: to identify all species of final state particles, inside jets, especially for charged Kaons.

- Sub-d performance:
  - Tracker dP/P ~ o(0.1%),
  - EM energy resolution ~ 3%/sqrt(E) \conv 0.3% ,
  - Had energy resolution ~ 50%/sqrt(E) \conv 2% .

Back up

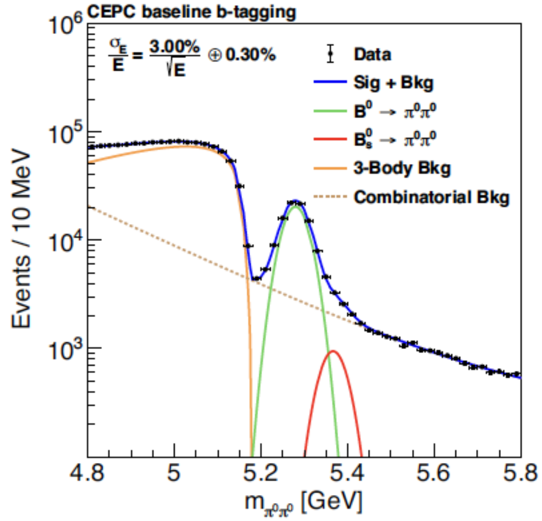


Figure 6. The reconstructed $m_{\pi^0\pi^0}$ distributions of $B^0 \to \pi^0\pi^0$, $B_s^0 \to \pi^0\pi^0$, and $Z \to q\bar{q}$ background after applying the baseline b-tagging and selections on energy and opening angle of π^0 pairs when the ECAL energy resolution is $\frac{3\%}{\sqrt{E}} \oplus 0.3\%$.

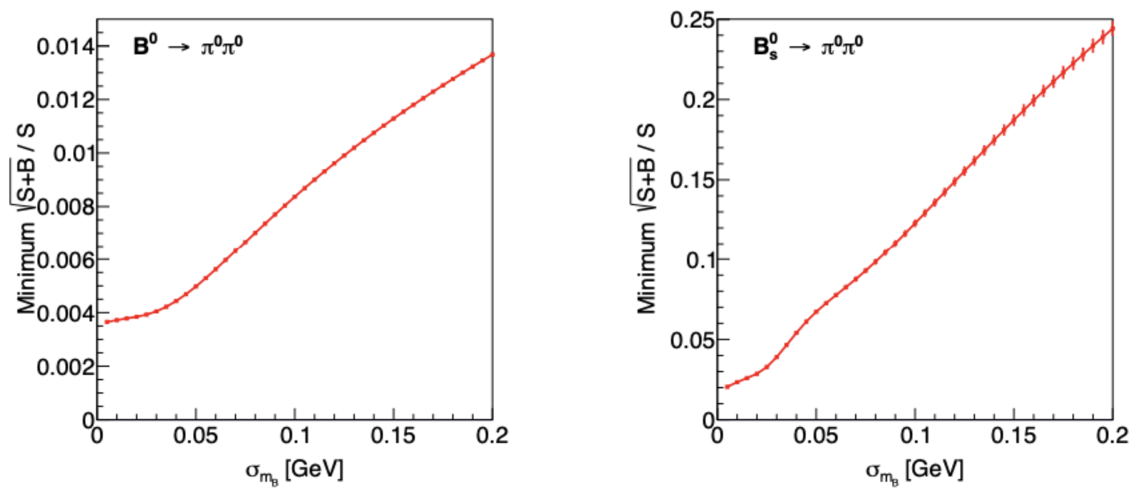


Figure 26: Relative statistical uncertainties of BR($B^0 \to \pi^0\pi^0$) (left) and BR($B_s^0 \to \pi^0\pi^0$) (right) versus B-meson mass resolution σ_{m_B} with four-photon final states. Plots taken from [32].

Charged fragment veto at Truth level

SiWECAL + GSHCAL (ideal parameter)

0: BMR ~3.32%, original

1: BMR ~2.98%, remove charged fragments

2: BMR ~2.73%, remove charged fragments + “Null MCP” event cut

PS: Two cases of “Null MCP” (fail to link to MCTruth Particle)

- PFO reconstructed by Energy Flow
- PFO caused by LumiCal Hits