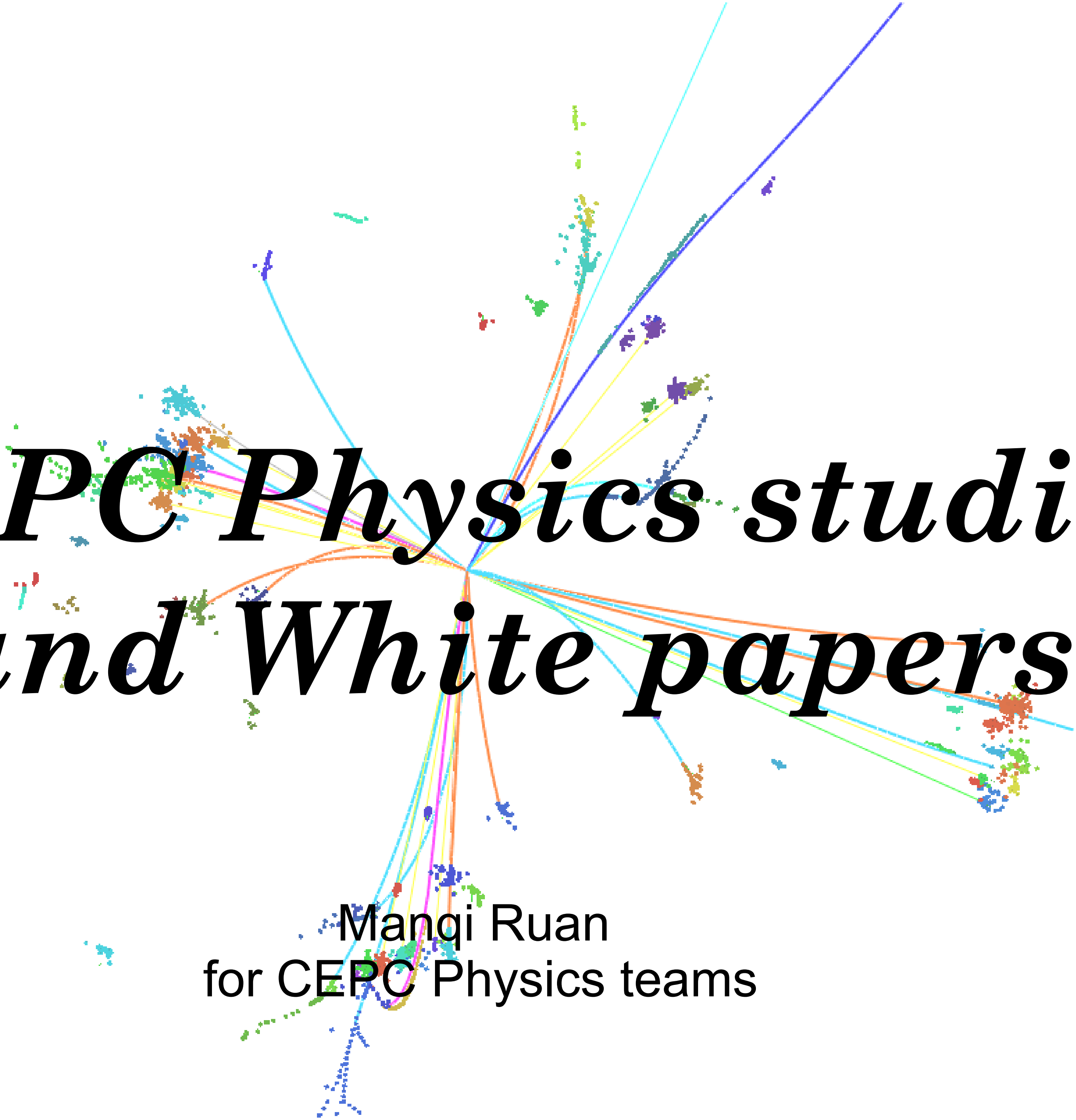
CEPC Physics studies and White papers

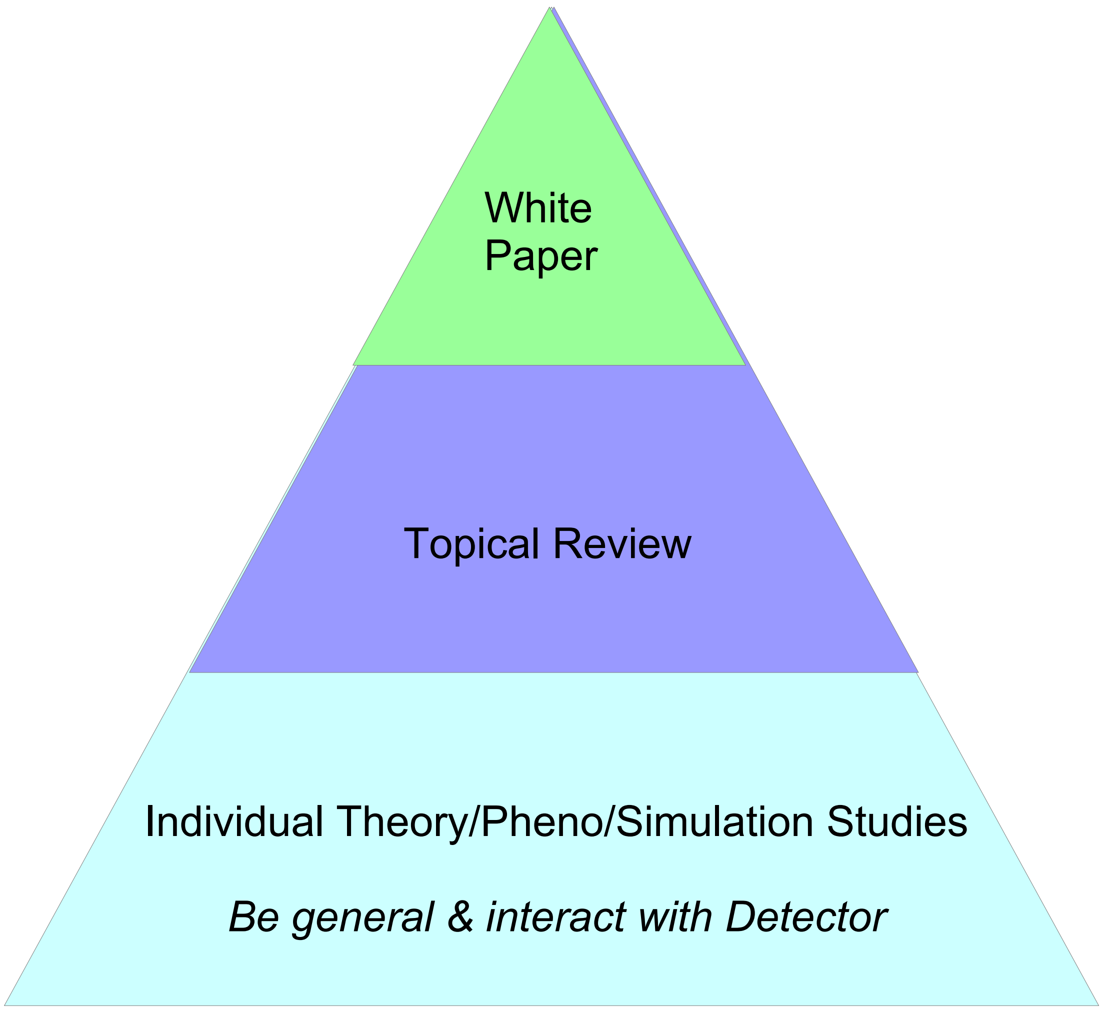


Manqi Ruan
for CEPC Physics teams

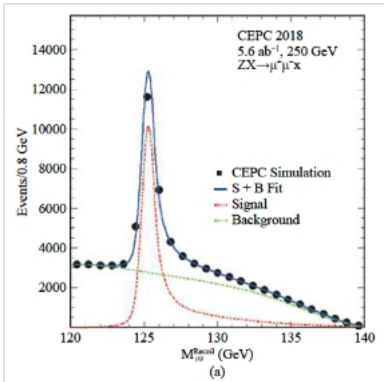
Objectives

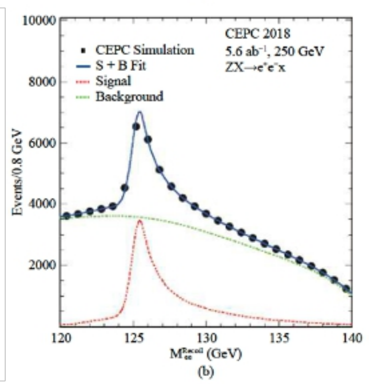
- To understand the physics landscape & science merits
  - Identify benchmarks & quantify reaches
  - Quantify the discovery power, especially NP Smoking guns
  - Added values compared to existing facilities
- To maximize the physics output
  - To iterate with detector/facility Design & optimization
  - To synergies with X-frontier facilities
- To stimulate new ideas/methods
- To actively participate international collaboration & participations
- To be in pace with the project application
- To communicate efficiently with general public & decision maker

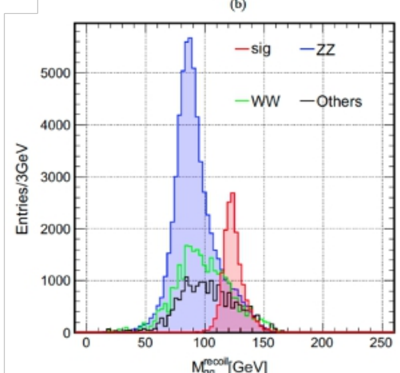
CEPC Physics Study

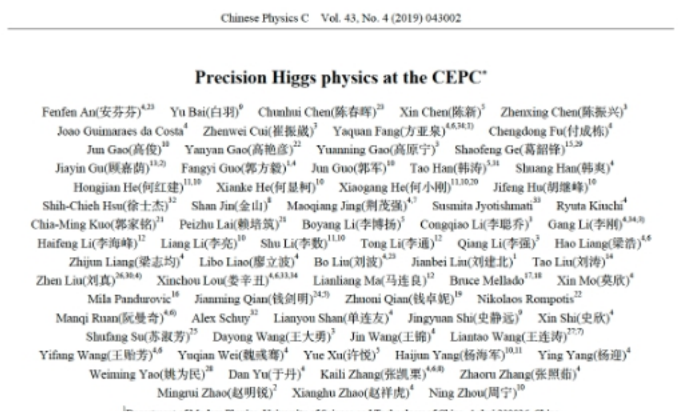


Physics study: 2023





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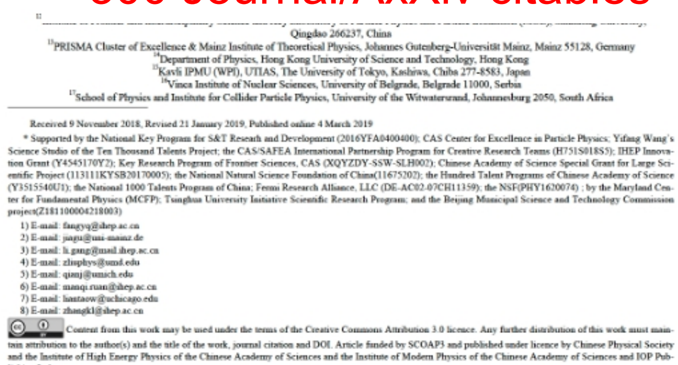
Precision Higgs physics at the CEPC*

White papers +

~300 Journal/AxXiv citables


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

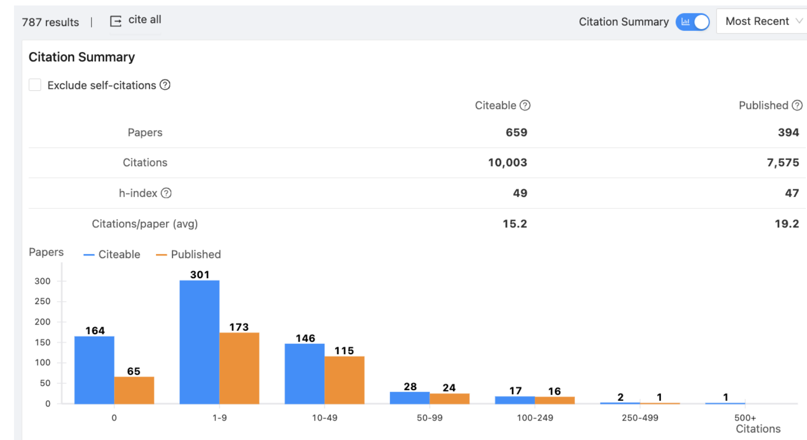


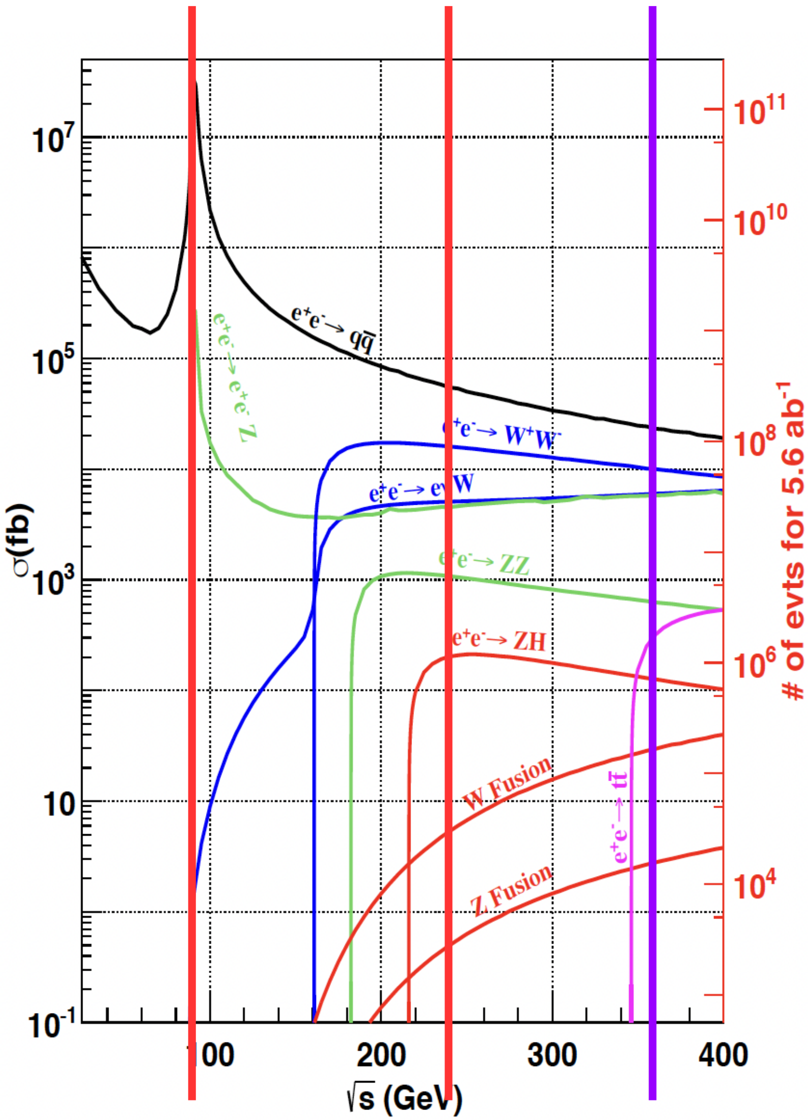
Table 2.1: Precision of the main parameters of interests and observables at the CEPC, from Ref. [1] and the references therein, where the results of Higgs are estimated with a data sample of 20 ab^{-1}. The HL-LHC projections of 3000 fb^{-1} data are used for comparison. [2]

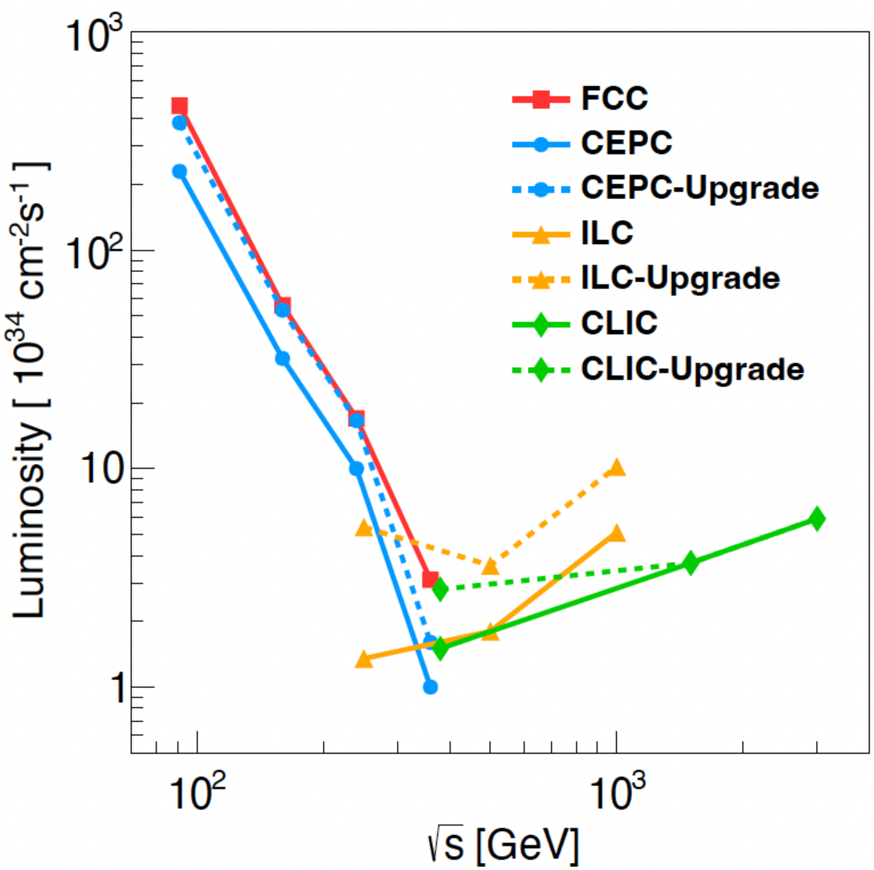
Higgs			W, Z and top		
Observable	HL-LHC projections	CEPC precision	Observable	Current precision	CEPC precision
M_H	20 MeV	3 MeV	M_W	9 MeV	0.5 MeV
Γ_H	20%	1.7%	Γ_W	49 MeV	2 MeV
$\sigma(ZH)$	4.2%	0.26%	M_{top}	760 MeV	$\mathcal{O}(10)$ MeV
$B(H\to bb)$	4.4%	0.14%	M_Z	2.1 MeV	0.1 MeV
$B(H\to cc)$	-	2.0%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

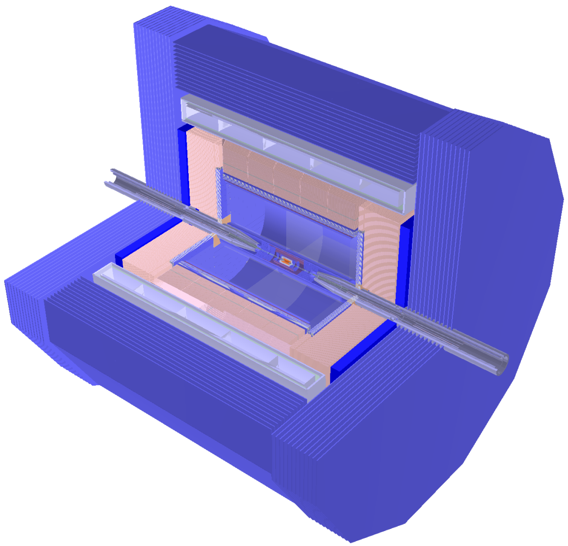
Yields ~ Xsec * Lumi * Time

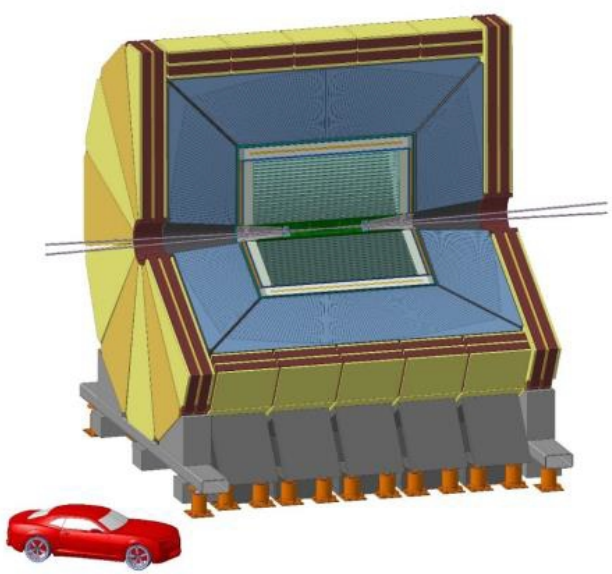


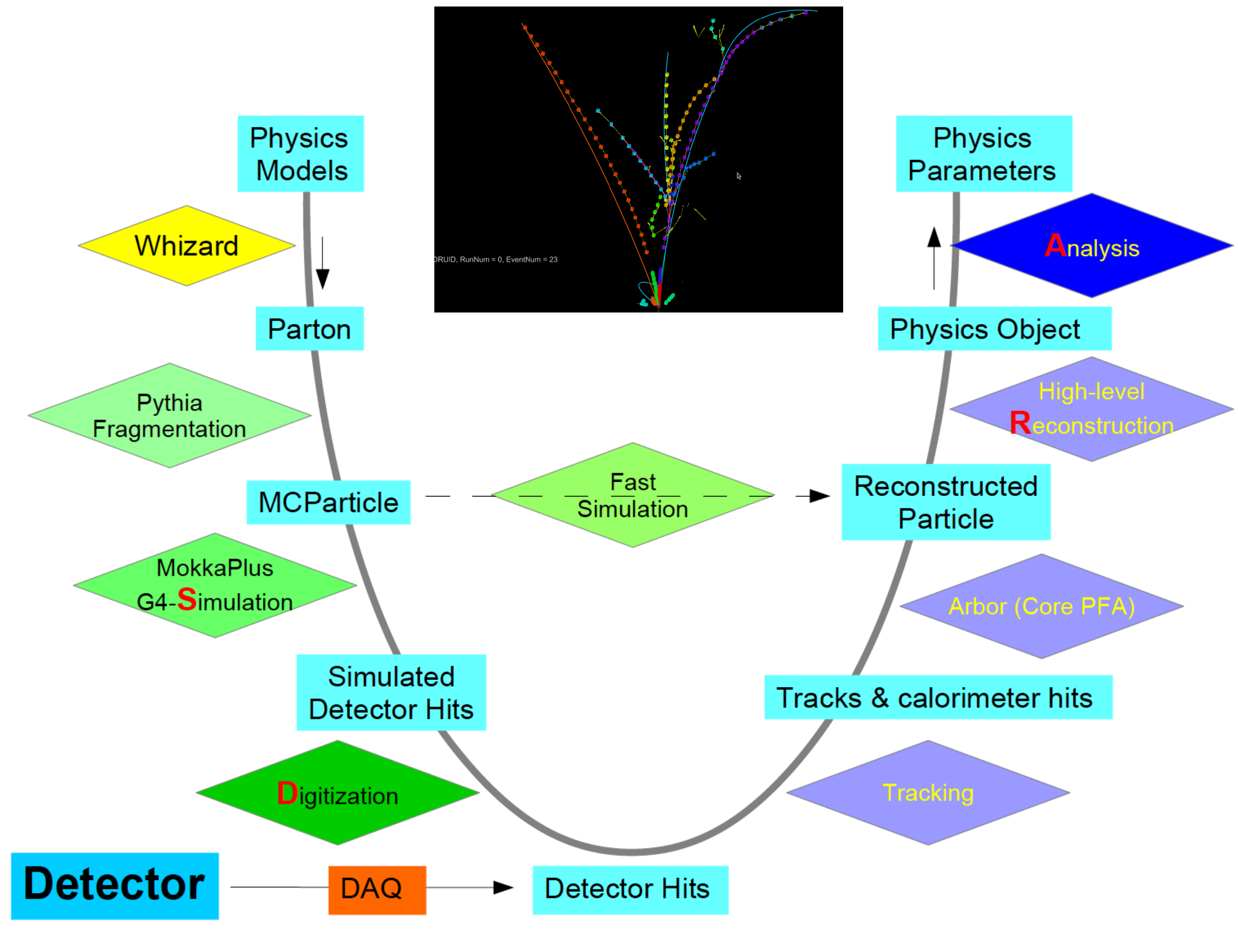


- 4 Million Higgs (10 years)
- ~ 1 Giga W (1 year) + 4 Tera Z (2 years)
- Upgradable: Top factory (500 k ttbar)

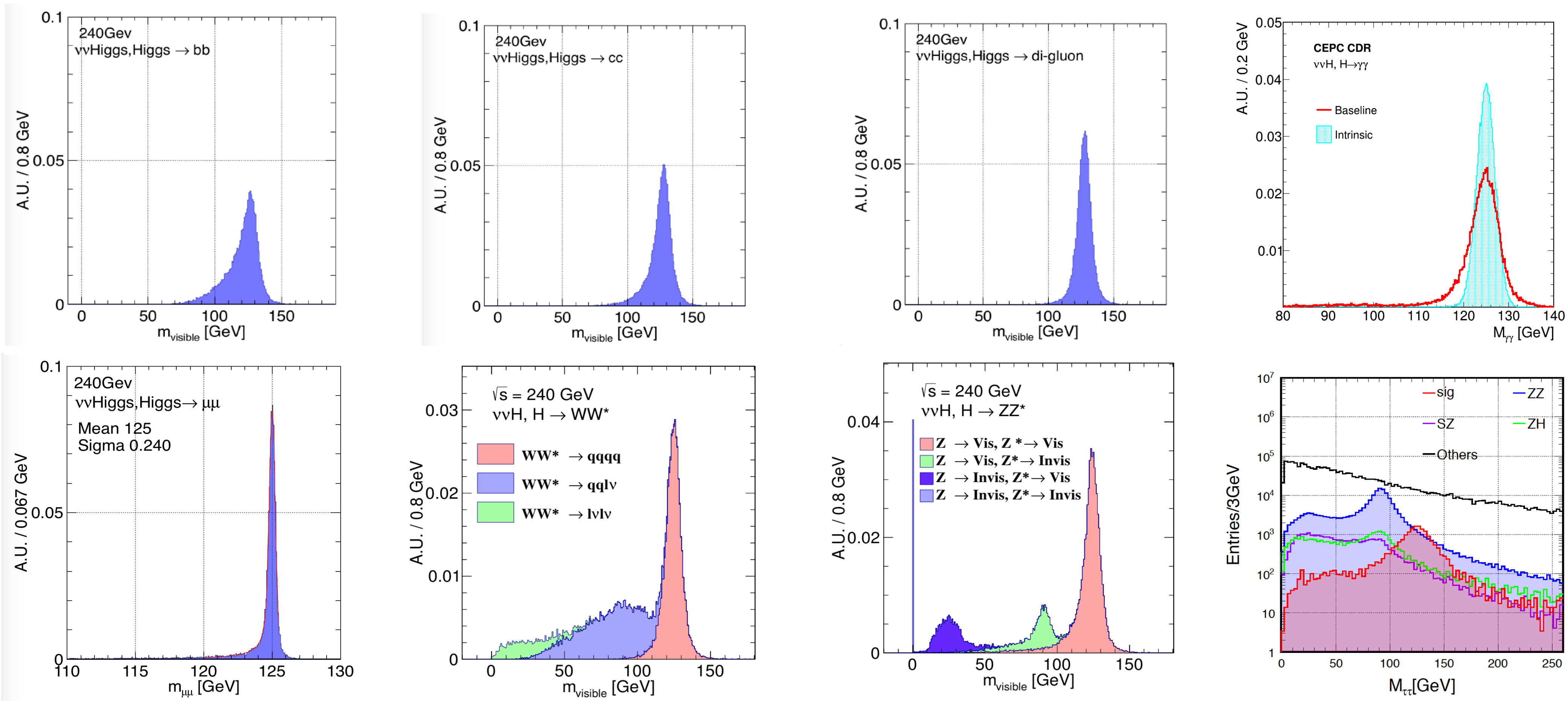
Detector & Software







Reconstructed Higgs Signatures



Clear Higgs Signature in all SM decay modes

Massive production of the SM background (2 fermion and 4 fermions) at the full Simulation level

Right corner: di-tau mass distribution at qqH events using collinear approximation

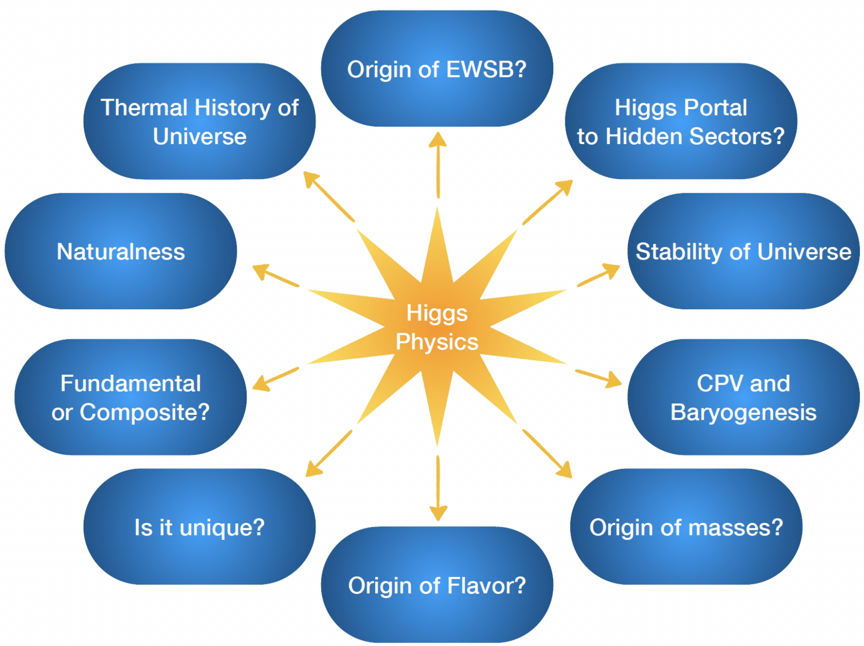
White papers

- Higgs: published in 2019, updated in 2021 Snowmass WP
- Flavor:
  - Main editors: Lingfeng Li (Brown U), TaoLiu (HKUST), Fengkun Guo (ITP), Lorenzo Calibbi (Tianjing U), Qiangxin Li (CCNU), Qin Qin (Huazhong S&T), etc)
  - Phase-I: submit to ArXiv in a few weeks
  - Phase-II: to enhance the measurement with tautau events and CKM measurements
- EW: draft for internal review expected at beginning of 2024 – released at middle 2024
  - Main editors: Jiayin Gu (Fudan U), Zhijun Liang (IHEP)
- NP: same as EW White paper
  - Main editors: Jia Liu (PKU), Liantao Wang(Chicago U), Zhen Liu (Minnesota U), Xuai Zhuang (IHEP), Yu Gao (IHEP), etc
- QCD:
  - Main editors: Huaxing Zhu (PKU), Meng Xiao (ZJU), Jun Gao (SJTU), Zhao Li (IHEP), etc
  - Very rich physics: strong coupling constant measurement + Form Factor + Hadron Fragmentation + QCD Phase transition + accurate calculation + interplay to other measurements especially Flavor & Higgs...

Higgs white paper

Mystery Higgs sector

Snowmass 2021 US Community Study
on the Future of Particle Physics



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Precision Higgs physics at the CEPC*

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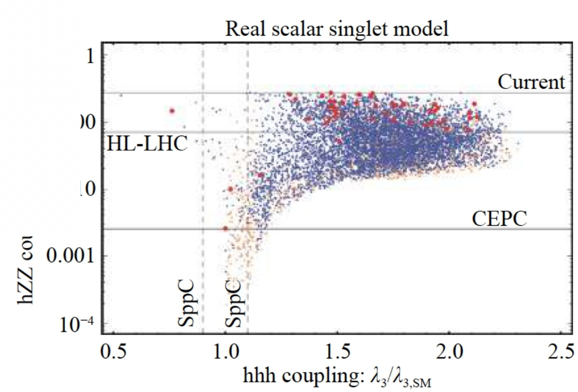

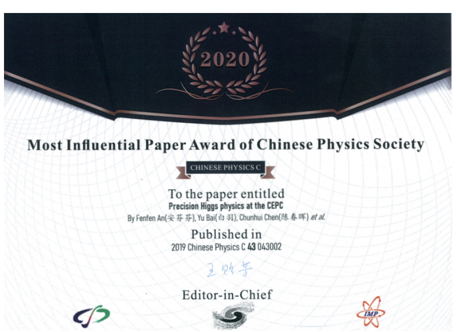

Snowmass White Paper

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

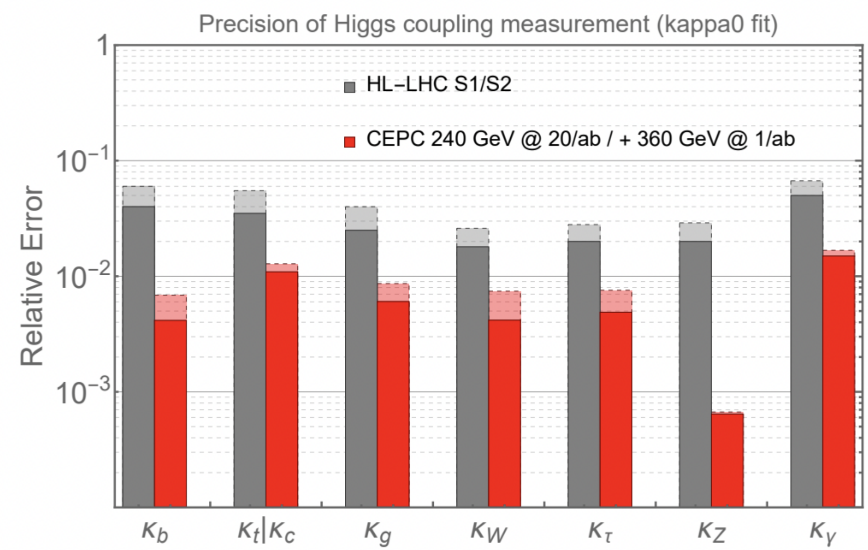
The Circular Electron Positron Collider (CEPC) is a large-scale collider facility that can serve as a factory of the Higgs, Z, and W bosons and is upgradable to run at the $t\bar{t}$ threshold. This document describes the latest CEPC nominal operation scenario and particle yields and updates the corresponding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

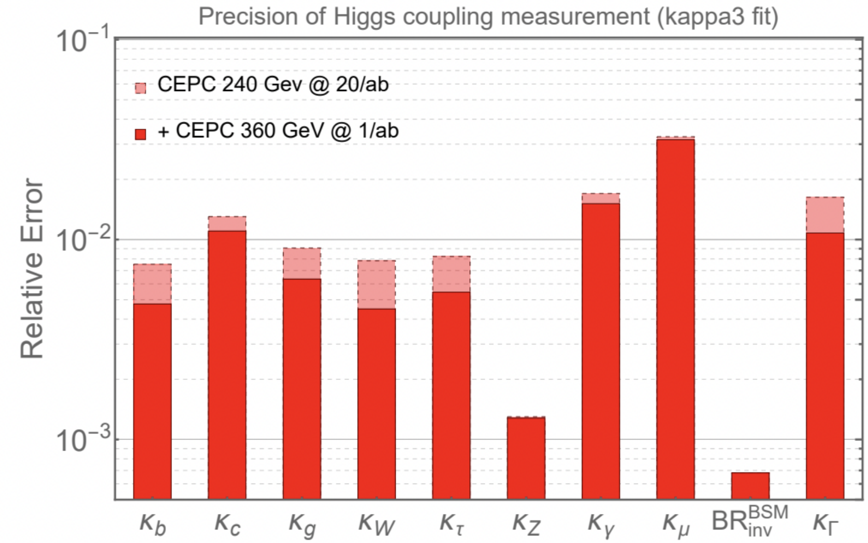
CONTENTS

- Summarize ~ 20 citables for CEPC Snowmass studies

Physics reach via Higgs at CEPC

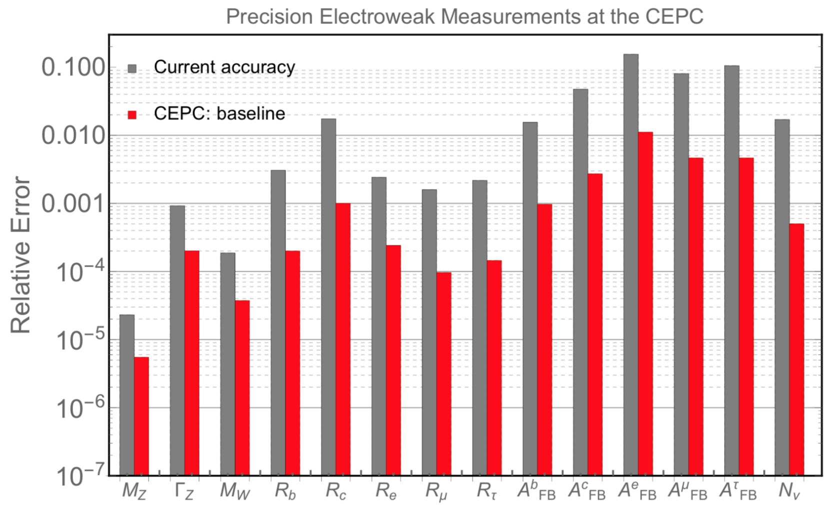
	240 GeV, 20 ab^{-1}		360 GeV, 1 ab^{-1}		
	ZH	**vvH**	ZH	**vvH**	**eeH**
inclusive	**0.26%**		**1.40%**	\	\
H→bb	**0.14%**	**1.59%**	**0.90%**	**1.10%**	**4.30%**
H→cc	**2.02%**		**8.80%**	**16%**	**20%**
H→gg	**0.81%**		**3.40%**	**4.50%**	**12%**
H→WW	**0.53%**		**2.80%**	**4.40%**	**6.50%**
H→ZZ	**4.17%**		**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%**		

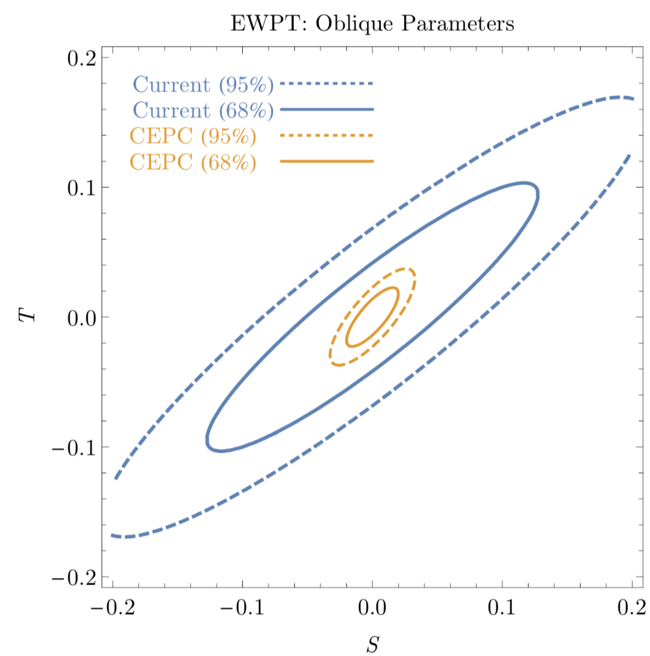


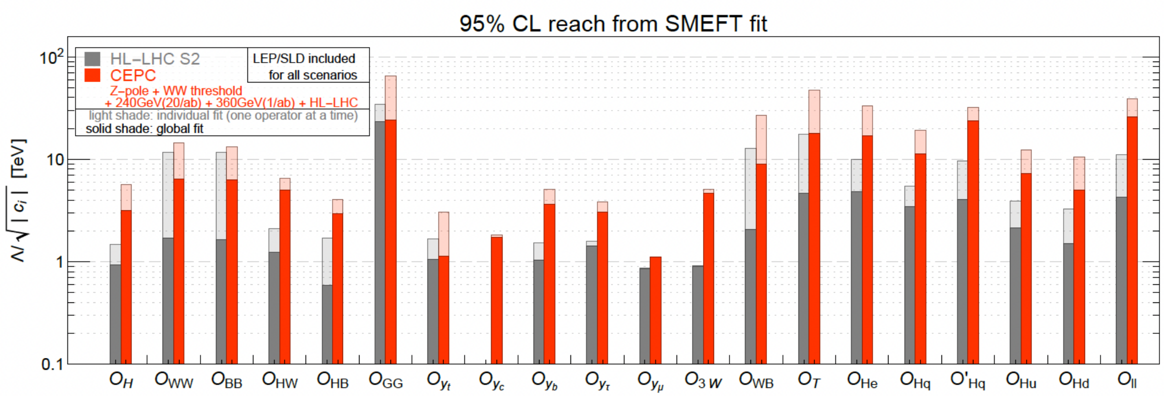


EW measurements & SMEFT

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 White paper

Flavor Physics at CEPC: a General Perspective

Contents

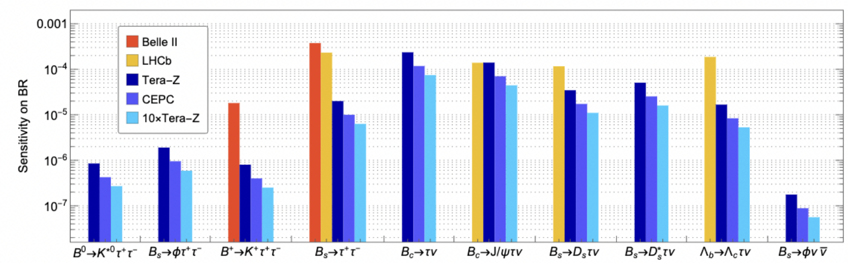


Figure 18: Projected sensitivities of measuring the $b \to s\tau\tau$ [70], $b \to s\nu\bar{\nu}$ [34] and $b \to c\tau\nu$ [35, 62] transitions at the Z pole. The sensitivities at Belle II @ 50 ab^{-1} [6] and LHCb Upgrade II [17, 71] have also been provided as a reference. Note, the LHCb sensitivities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

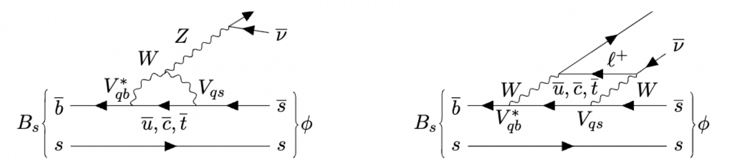


Figure 21: Illustrative Feynman diagrams for the $B_s \to \phi\nu\bar{\nu}$ transitions in the SM. **LEFT**: EW penguin diagram. **RIGHT**: EW box diagram.

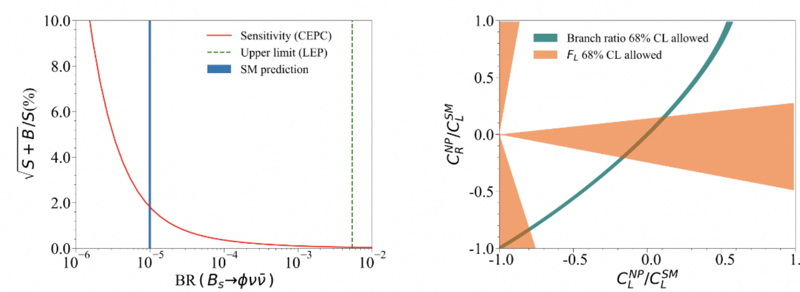
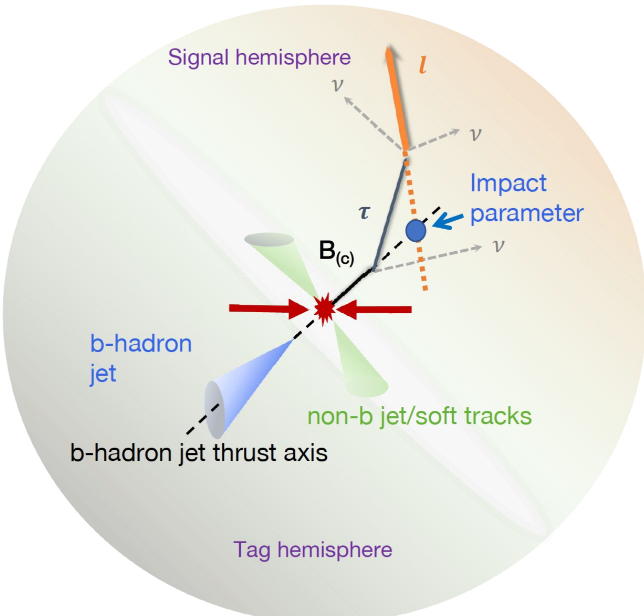
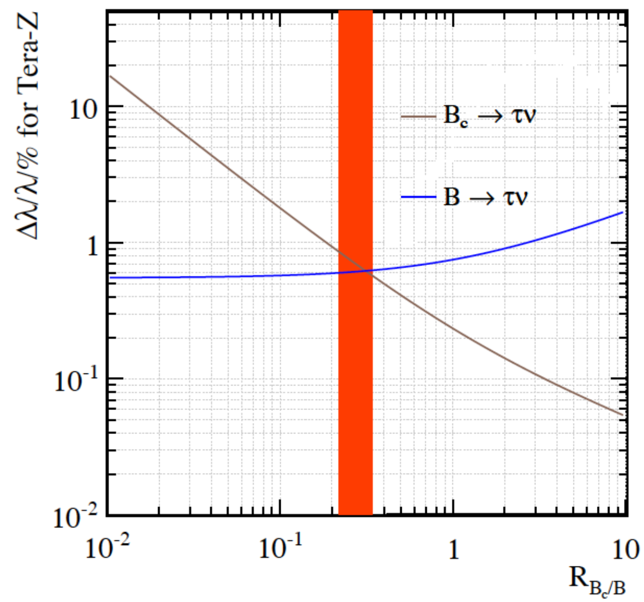


Figure 22: **LEFT**: Relative precision for measuring the signal strength of $B_s \to \phi\nu\bar{\nu}$ at Tera-Z, as a function of its BR. **RIGHT**: Constraints on the LEFT coefficients $C_L^{\rm NP} \equiv C_L - C_L^{\rm SM}$ and C_R with the measurements of the overall $B_s \to \phi\nu\bar{\nu}$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

~ 20+ benchmarks + ... Access to NP at 10 TeV or higher

Bc → τν





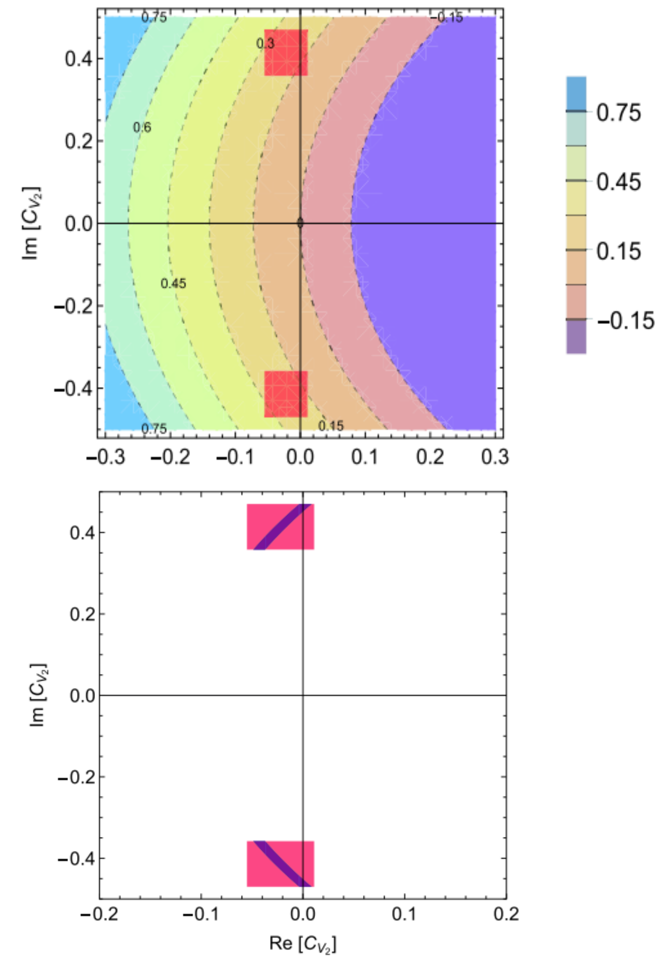


Fig. 10. (color online) Constraints on the real and imaginary parts of C_{V_2}. The red shaded area corresponds to the current constraints using available data on $b \to c\tau\nu$ decays. If the central values in Eq. (9) remain while the uncertainty in $\Gamma(B_c^+ \to \tau^+\nu_\tau)$ is reduced to 1%, the allowed region for C_{V_2} shrinks to the dark-blue regions.

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Analysis of $B_c \to \tau\nu_\tau$ at CEPC*

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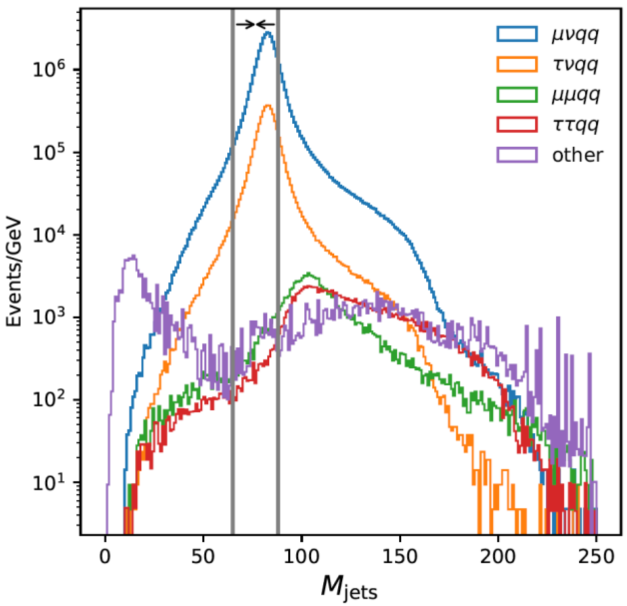
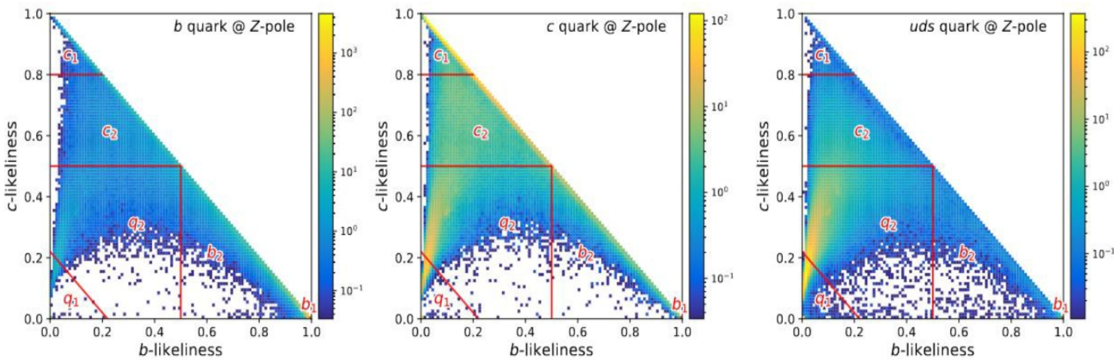
Abstract: Precise determination of the $B_c \to \tau\nu_\tau$ branching ratio provides an advantageous opportunity for understanding the electroweak structure of the Standard Model, measuring the CKM matrix element $|V_{cb}|$, and probing new physics models. In this paper, we discuss the potential of measuring the process $B_c \to \tau\nu_\tau$ with τ decaying leptonically at the proposed Circular Electron Positron Collider (CEPC). We conclude that during the Z pole operation, the channel signal can achieve five-σ significance with $\sim 10^9$ Z decays, and the signal strength accuracies for $B_c \to \tau\nu_\tau$ can reach around 1% level at the nominal CEPC Z pole statistics of one trillion Z decays, assuming the total $B_c \to \tau\nu_\tau$ yield is 3.6×10^6. Our theoretical analysis indicates the accuracy could provide a strong constraint on the general effective Hamiltonian for the $b \to c\tau\nu$ transition. If the total B_c yield can be determined to $O(1\%)$ level of accuracy in the future, these results also imply $|V_{cb}|$ could be measured up to $O(1\%)$ level of accuracy.

Vcb from W decay





quark \ tag	b_1	b_2	c_1	c_2	q_1	q_2
b	0.47	0.378	0.0197	0.0965	0.00397	0.0315
c	0.00042	0.078	0.298	0.373	0.0682	0.182
uds	0.000104	0.00477	0.00145	0.054	0.538	0.401

	$\mu\nu W, W \to$				$\tau(\mu\nu)\nu_\tau W, W \to$				$\tau\nu_\tau qq, \tau \to$					
	cb	ub	$c(d/s)$	$u(d/s)$	cb	ub	$c(d/s)$	$u(d/s)$	$e2\nu$	had.ν_τ	$\tau\tau qq$	$\mu\mu qq$	Higgs	others
w/o slections	40.3K	363	24.2M	24.2M	7.73K	74	4.2M	4.2M	8.66M	31.4M	2.18M	4.47M	4.07M	2.06G
$E_{L\mu} > 12$GeV	37.9K	330	22.6M	22.6M	5.59K	56	2.98M	2.97M	133K	687K	422K	2.82M	645K	186.3M
$R_{L\mu} > 0.85$	35.3K	302	21.1M	21.1M	5.01K	46	2.73M	2.73M	1.55K	43.2K	266K	1.82M	308K	128.8M
$\cos(\theta_{L\mu})$	35.3K	302	21.1M	21.1M	5.01K	46	2.73M	2.73M	1.55K	43.2K	266K	1.82M	308K	128.8M
$q_{L\mu}\cos(\theta_{L\mu}) < 0.20$	32.8K	283	19.6M	19.6M	4.7K	42	2.57M	2.57M	1.26K	39.9K	156K	1.03M	183K	92.6M
2nd isolation ℓ veto	32.8K	283	19.5M	19.6M	4.7K	42	2.57M	2.57M	1.26K	39.9K	154K	526K	138K	43.9M
multiplicity ≥ 15	32.8K	283	19.5M	19.4M	4.7K	42	2.56M	2.55M	1.23K	39.6K	153K	522K	118K	185K
Missing $P_T > 9.5$ GeV/c	31.5K	264	18.7M	18.6M	4.38K	37	2.4M	2.39M	1.18K	37.2K	136K	118K	92.6K	97.7K
$M_{\text{jets}} > 65$ GeV/c^2	29.4K	254	18.1M	18.3M	4.15K	32	2.33M	2.35M	978	36.0K	132K	112K	85.3K	24.5K
$M_{\text{jets}} < 88$ GeV/c^2	24.1K	193	14.3M	14.1M	3.49K	23	1.87M	1.85M	641	24.7K	5.62K	11.5K	6.76K	4.31K
$M_{\text{jets,recoil}} < 115$ GeV/c^2	20.2K	184	13.0M	13.1M	2.96K	23	1.72M	1.73M	505	22.6K	3.57K	6.86K	536	3.02K
$M_{L\mu S\mu} < 75$ GeV/c^2	19.6K	184	12.9M	13.0M	2.95K	23	1.72M	1.73M	505	22.6K	3.56K	5.78K	414	3.0K
$M_{\ell\nu} > 12$ GeV/c^2	19.6K	184	12.9M	13.0M	2.7K	18	1.54M	1.55M	416	19.5K	2.08K	5.16K	390	1.81K
ϵ_{kin} (%)	48.8 (0.7)	50.6 (8.1)	53.5 (0.0)	53.7 (0.0)	34.9 (1.5)	25.0 (12.5)	36.7 (0.1)	36.9 (0.1)	0.0 (0.0)	0.1 (0.0)	0.1 (0.0)	0.1 (0.0)	0.0 (0.0)	0.0 (0.0)
$b_1c_{1,2}$	5.14K	4	2.79K	571	632	0	407	65	0	14	67	228	0	0
$\epsilon_{b_1c_{1,2}}$ (%)	12.8 (0.4)	1.3 (1.3)	0.0 (0.0)	0.0 (0.0)	8.2 (0.7)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)

- Purity > 99.5% at Eff. 50% for $\mu\nu qq$ and 34% for $\tau(\mu 2\nu)\nu qq$
- Main backgrounds include:
  - $W \to c(d/s)$
  - $\mu\mu qq$

Vcb could be measured to a relative uncertainty of 0.4% at CEPC Nominal Set up...

New Physics White paper

The BSM Physics potential of the CEPC

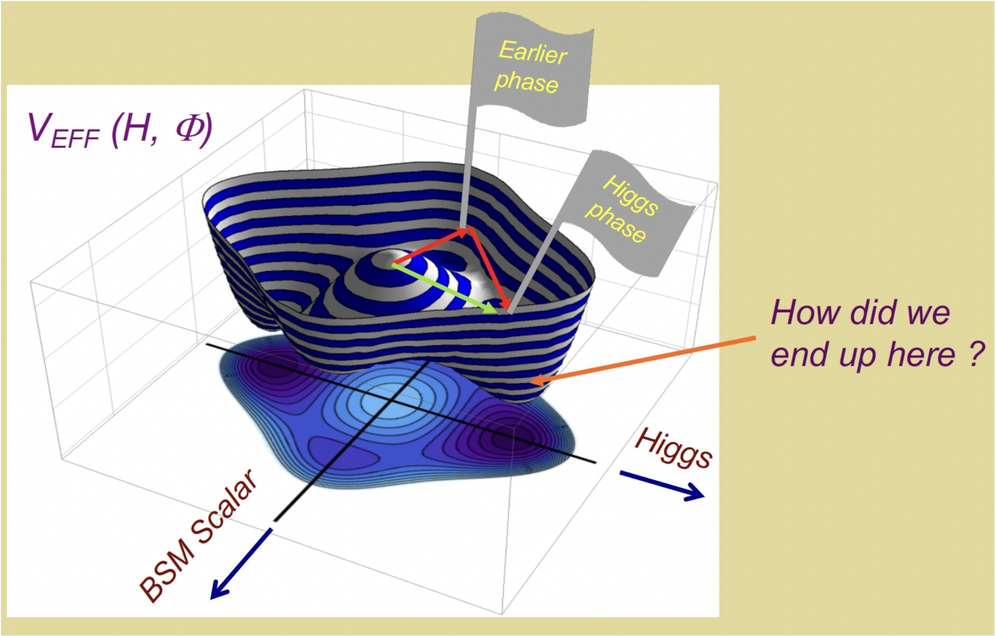
Prepared for the CEPC BSM white paper

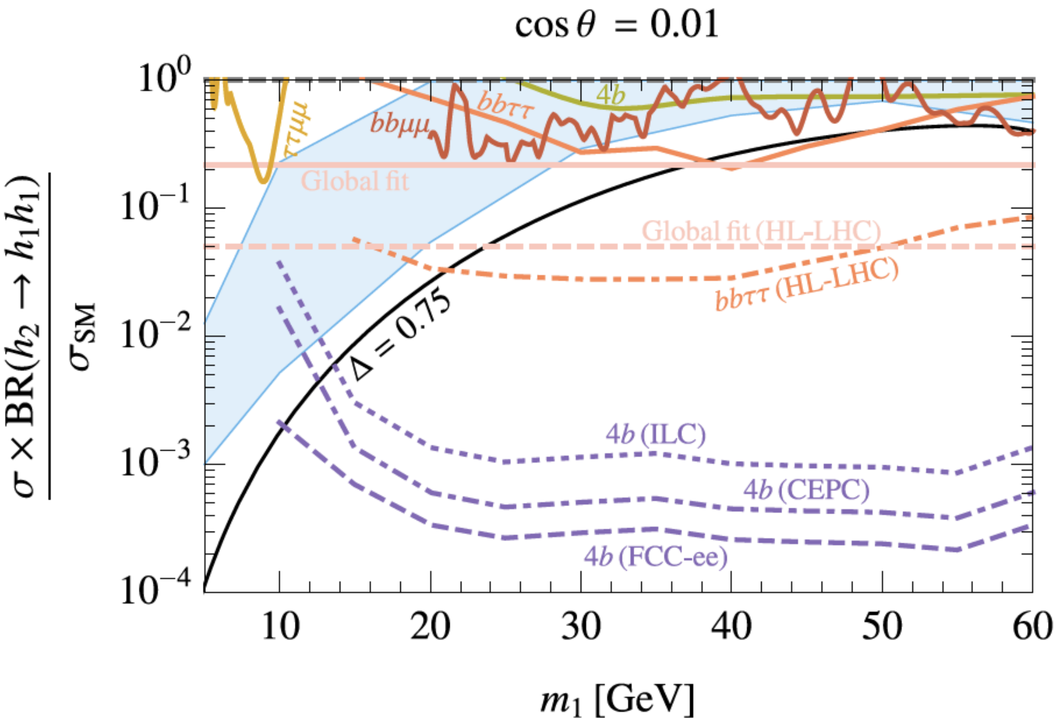
CEPC BSM Physics Study Group

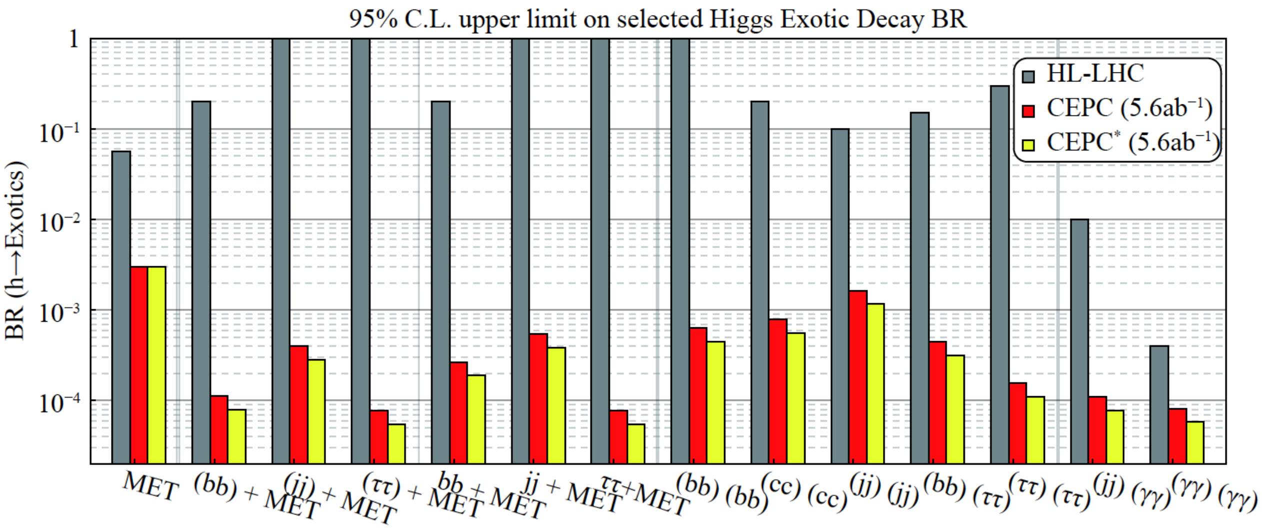
CONTRIBUTORS (TO BE UPDATED)

CONTENTS

Phase Transition in early Universe







Origin of matter -

Synergy with GW detection...

Low mass Higgs bosons...

The Observation of a 95 GeV Scalar at future e^+e^- Colliders

Karabo Mosala[1,2], Anza-Tshilidzi Mulaudzi[1,2], Thuso Mathaha[1,2], Mukesh Kumar[1], Bruce Mellado[1,2], and Manqi Ruan[3]

[1]University of the Witwatersrand, 1 Jan Smuts Avenue, Johannesburg, 2050, South Africa
[2]iThemba LABS, National Research Foundation, PO Box 722, Somerset West 7129, South Africa
[3]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

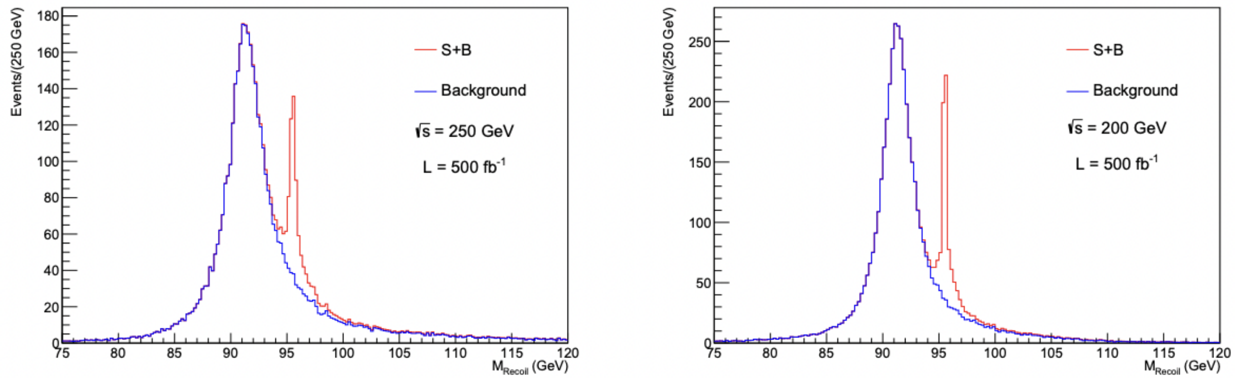


Figure 1. Recoil mass distribution for simulated $e^+e^- \to HZ \to H\mu^+\mu^-$ events with $m_S = 95,5$ GeV and all relevant background events after a pre-selection described in this section for (a) $\sqrt{S} = 250$ GeV and (b) $\sqrt{S} = 200$ GeV both at integrated luminosity $\mathscr{L} = 500$ fb^{-1}; measured with the CLIC_ILD detector concept. This is achieved by considering the BSM signal to be 10% SM Higgs-like.

- *Assume signal Xsec ~ 20 fb*

...Preliminary...

- *CEPC Higgs operation: ~ 6 fb^{-1}/day ~ 2 ab^{-1}/year*

- *Turn-key discovery*

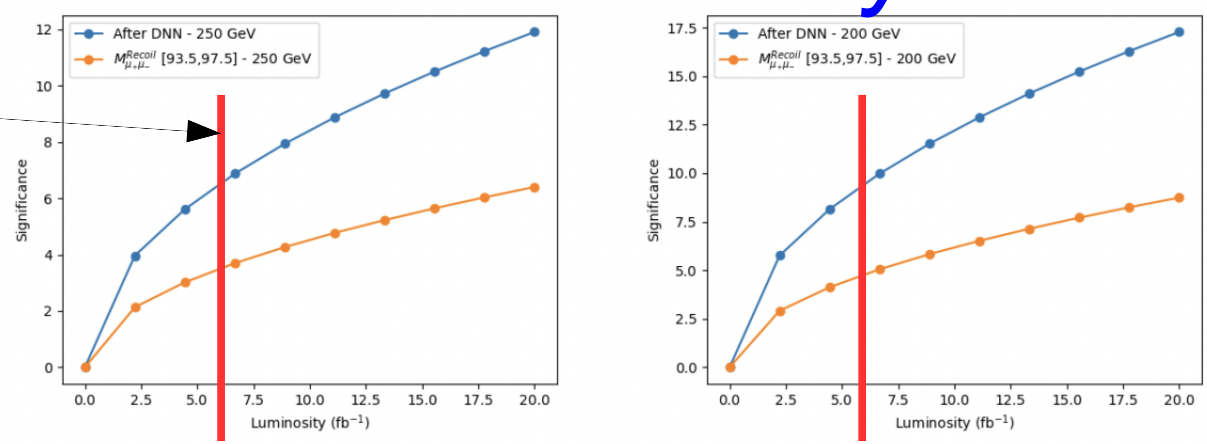
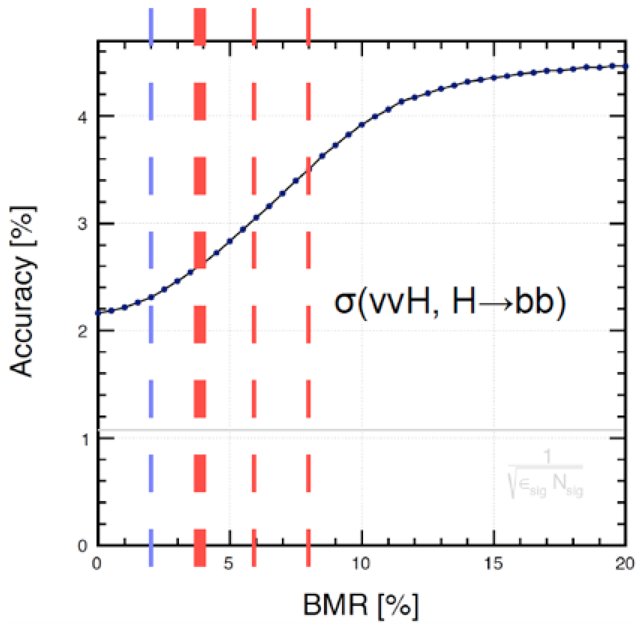


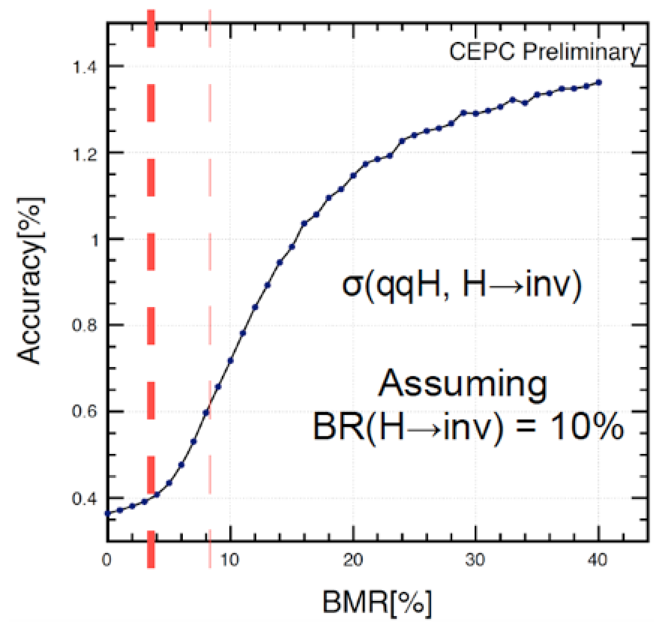
Figure 5. The signal significance as a function of Luminosity ($\mathscr{L}$) for (left) $\sqrt{s} = 250$ GeV before (Orange) and after DNN (Blue), (right) $\sqrt{s} = 200$ GeV before (Orange) and after DNN (Blue) respectively.

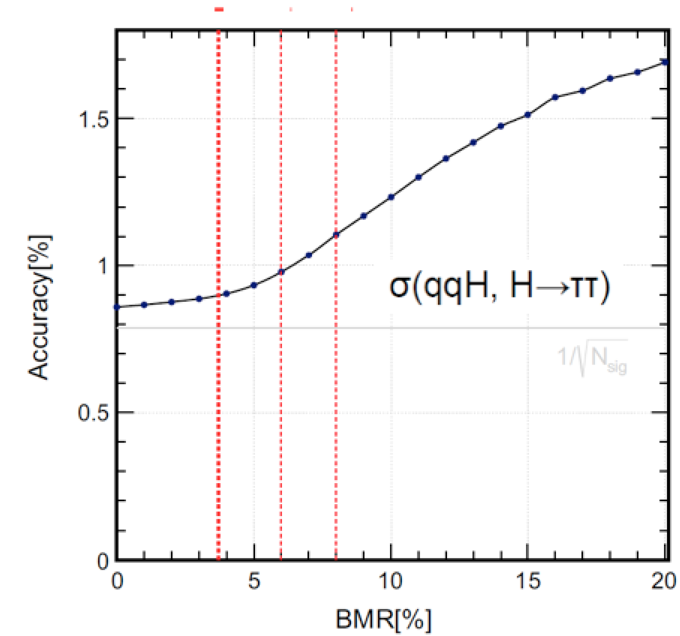
Detector Requirements & Performance

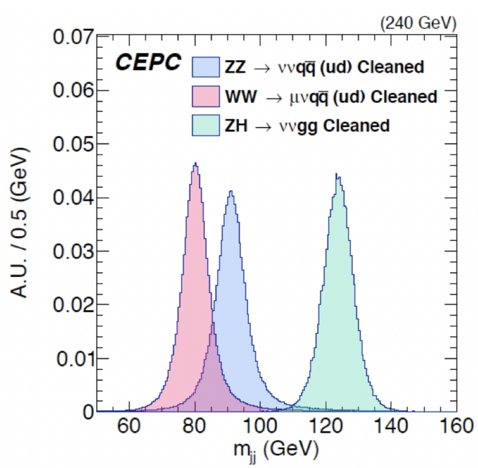
- Suited to the collision environment, especially beam background/MDI
- Trigger-less equivalent: Trigger system works as Trigger-less
- Extremely stable
- Large acceptance: polar angle, energy, time
- PFA compatible (in SpaceTime): final state particle separation – pursue 1-1 correspondence
  - Physics Objects Identification: Isolated, inside jets & jets
    - Single particle objects: Leptons, photons, Charged hadron
    - Composited objects: Pi-0, K-short, Lambda, Phi, Tau, D/B hadron, ..., Jets
  - Improving the E/M resolution for composited objects, especially jets
- BMR (Boson Mass Resolution)
  - < 4% for Higgs measurements, ~3% for NP tagging & Flavor Physics Measurements
- Pid: Pion & Kaon separation > 3σ
- Jet origin identification: Flavor Tagging, Charge Reconstruction, s-tagging...
- Excellent intrinsic resolution E/M/position: per mille level for track, percentage level for EM...

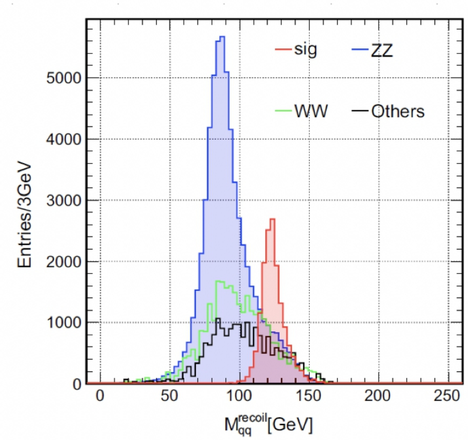
BMR < 4% for Higgs physics











	BMR = 2%	4%	6%	8%
σ(ννH, H→bb)	2.3%	2.6%	3.0%	3.4%
σ(ννH, H→inv)	0.38%	0.4%	0.5%	0.6%
σ(qqH, H→ττ)	0.85%	0.9%	1.0%	1.1%

Bs→Φvv

https://arxiv.org/pdf/2201.07374.pdf

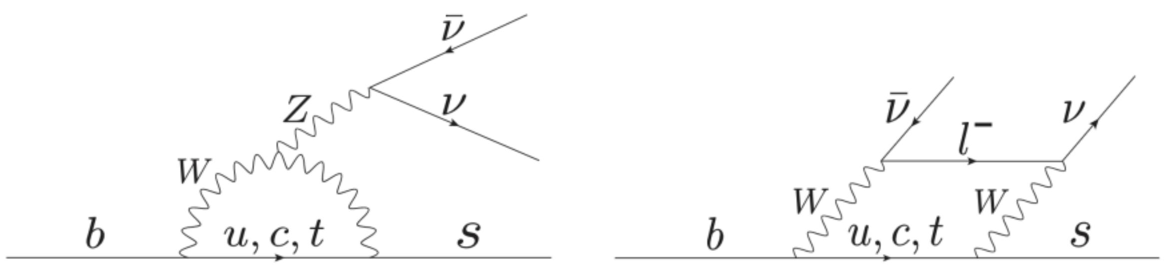
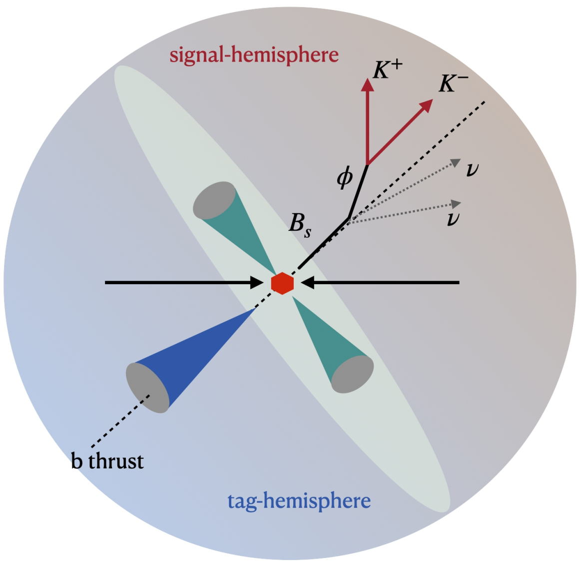
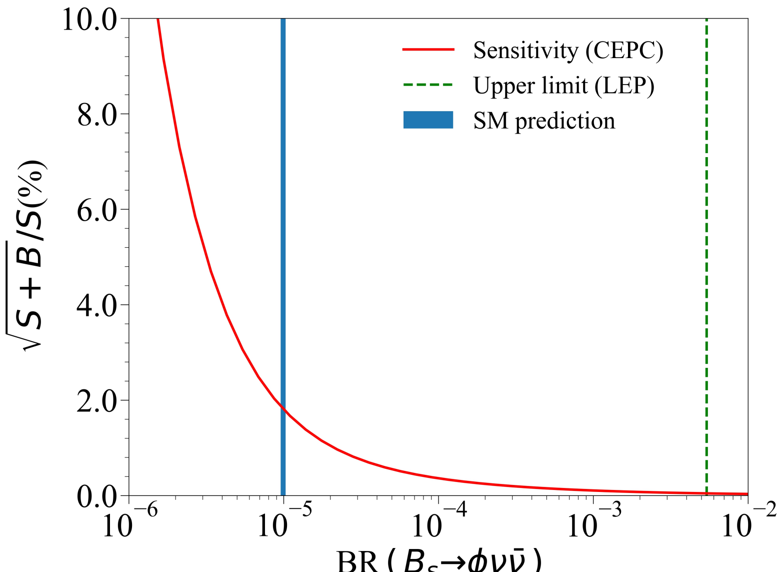


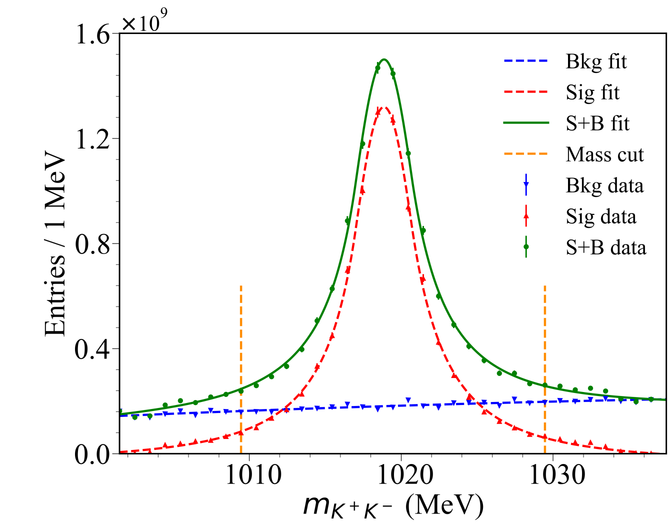
FIG. 1. The penguin and box diagrams of $b \to s\nu\bar{\nu}$ transition at the leading order.

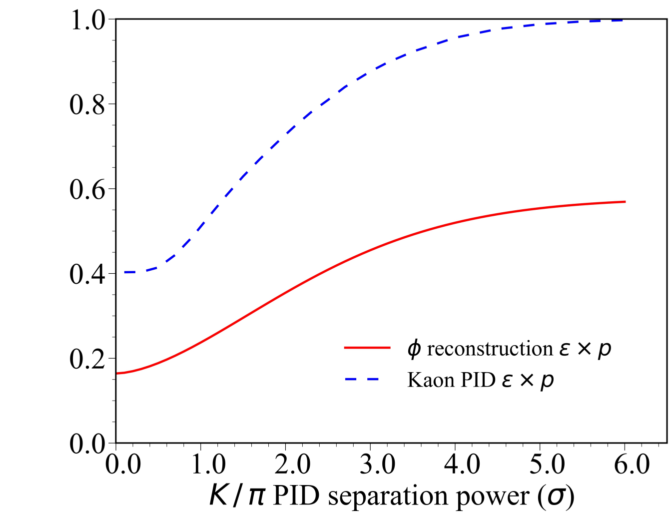


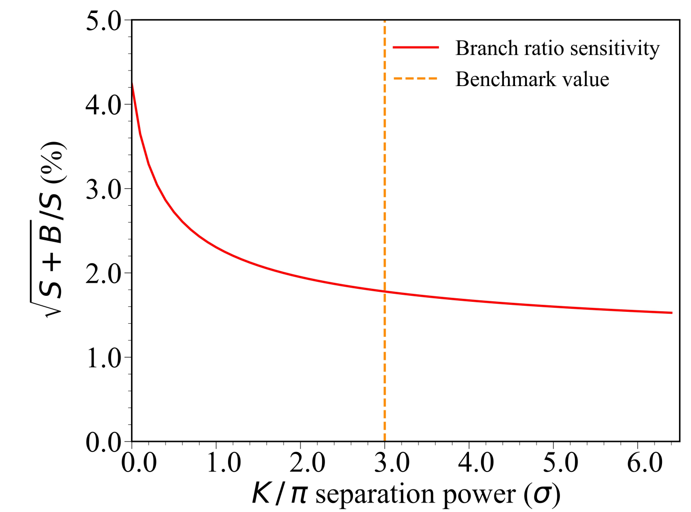
- Key ingredient to understand FCNC anomaly...
- Critical Physics Objects: Phi (and charged Kaon), 2nd VTX, Missing E/P, b-jet at opposite side
- Percentage level accuracy anticipated at Tera-Z

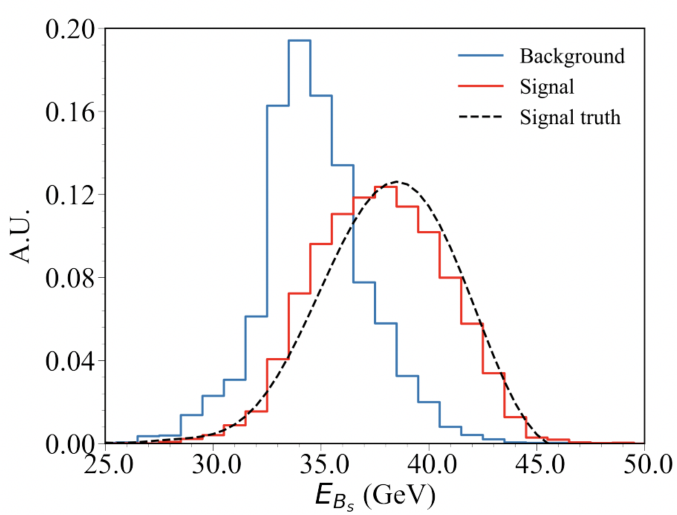


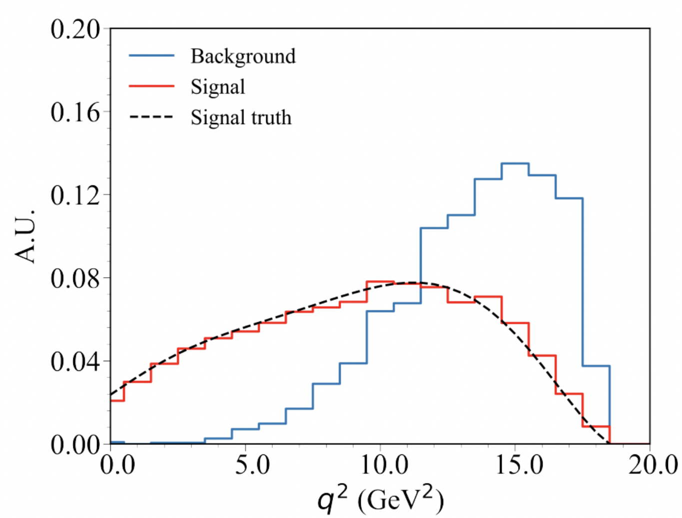
Requirements: Pid & MET











$$M_{\rm tag} = \sqrt{\left(\sum p_{\rm tag}^{\rm vis}\right)^2},$$

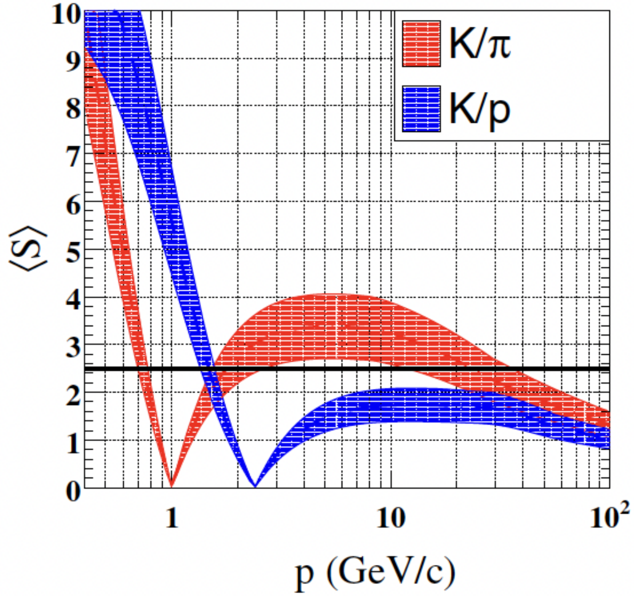
$$M_{\rm sig}^{(i)} = \sqrt{\left(\sum p_{\rm sig}^{\rm vis} + p_{B_s}^{(i-1)} - p_\phi\right)^2},$$

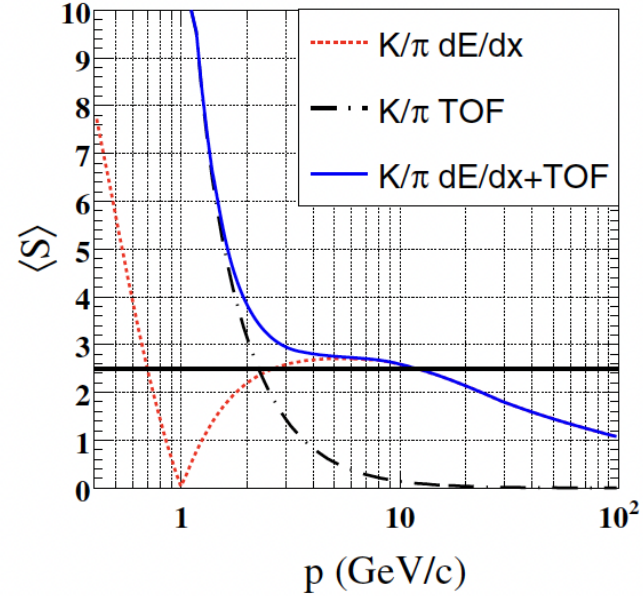
$$E_{B_s}^{(i)} = \frac{s + (M_{\rm sig}^{(i-1)})^2 - M_{\rm tag}^2}{2\sqrt{s}} - E_{\rm sig} + E_\phi\,,$$

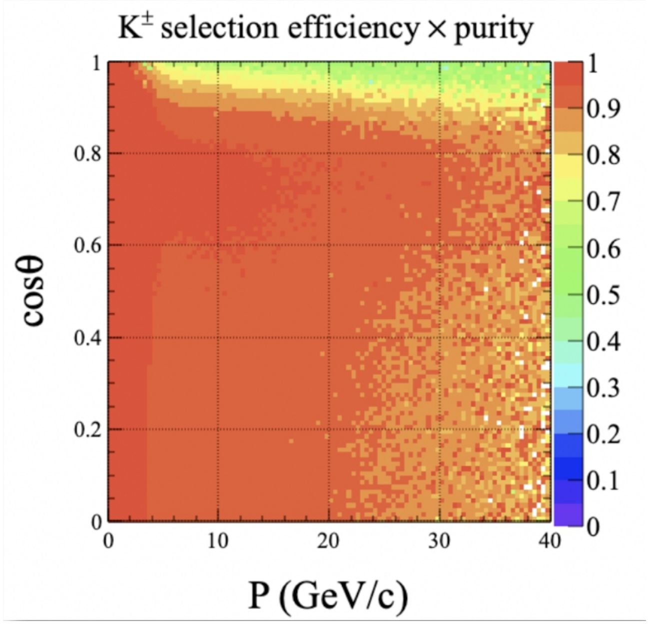
$$(q^2)^{(i)} = (p_{B_s}^{(i-1)} - p_\phi)^2\,,$$

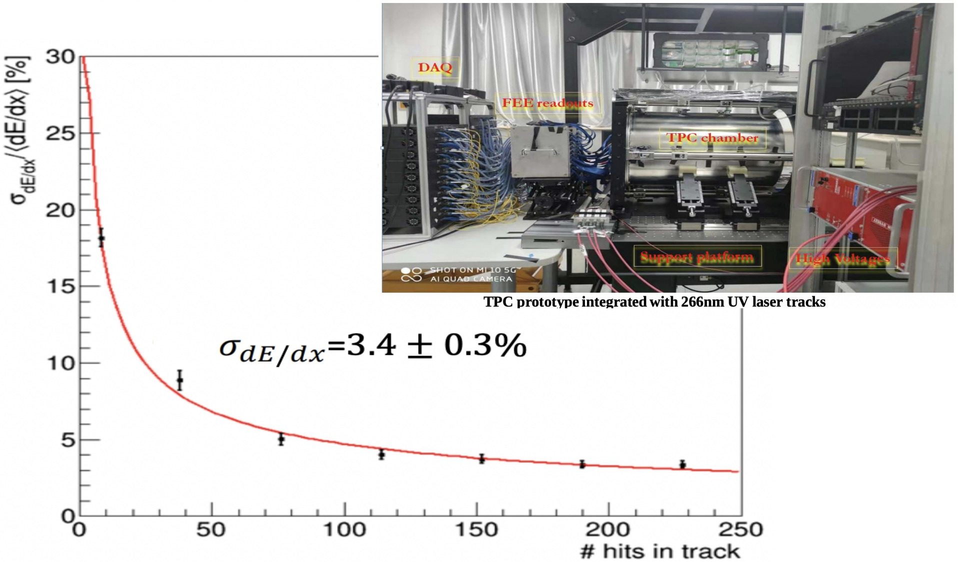
3σ Pion-Kaon separation + Good missing Energy/Momentum (~ BMR) resolution

Tracker: Pid









TPC prototype integrated with 266nm UV laser tracks

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

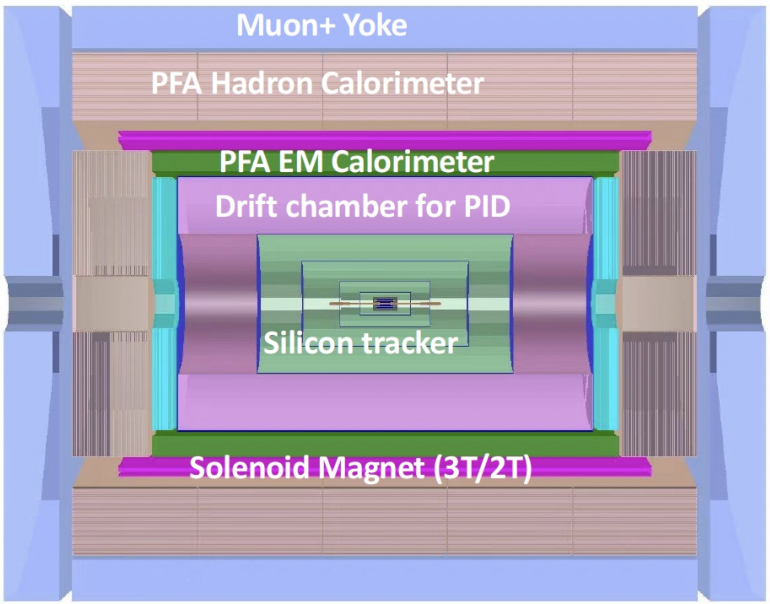
	Factor	1.	1.2	1.5	2.
dE/dx	ε_K (%)	95.97	94.09	91.19	87.09
	$purity_K$ (%)	81.56	78.17	71.85	61.28
dE/dx & TOF	ε_K (%)	98.43	97.41	95.52	92.3
	$purity_K$ (%)	97.89	96.31	93.25	87.33

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

Detector concept studies

Design of experimental facility and technical requirements

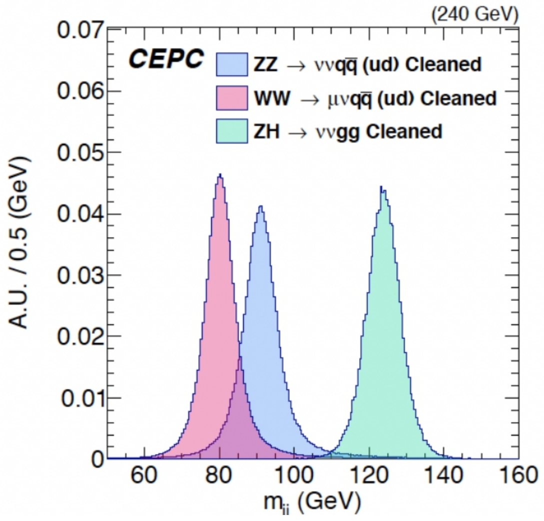
Detector



Requirements
boson mass resolution (BMR ~3%)

→

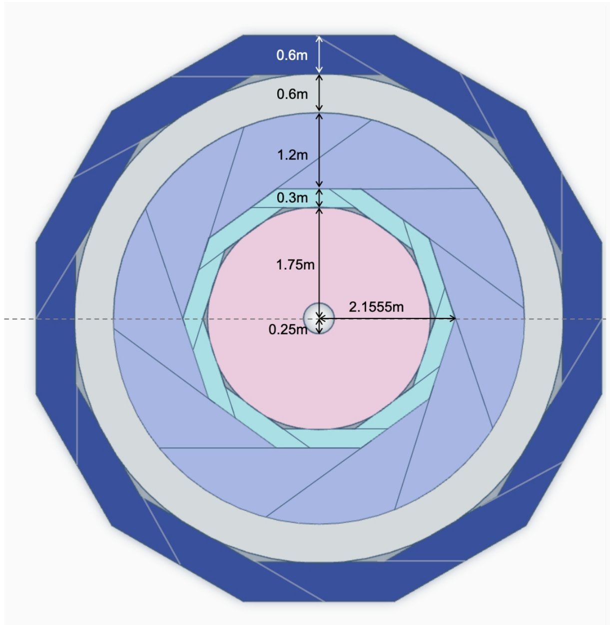
Challenges
- Support Particle flow with
  - High granularity
  - High precision

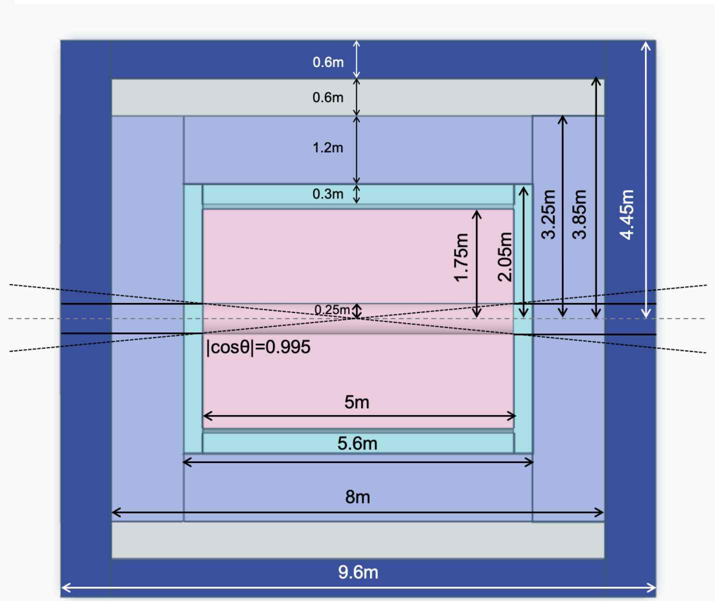


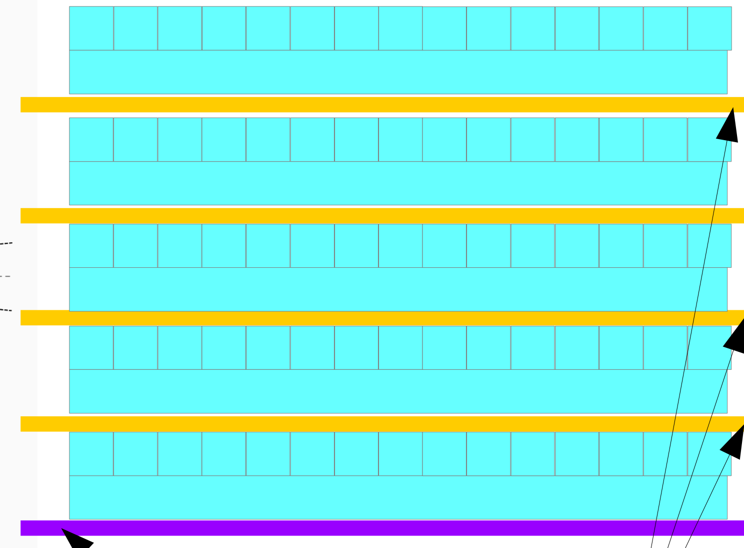
Novel detector design based on PFA calorimeter. Aim at improving BMR from 4% to 3%

Detector	Key parameter	World-class level	CEPC design
PFA based EM calorimeter	EM shower E resolution	~20%/√E	<3%/√E
PFA based Hadron calorimeter	Single hadron E resolution	~50%/√E	~40%/√E

Detector study: CHLOE design

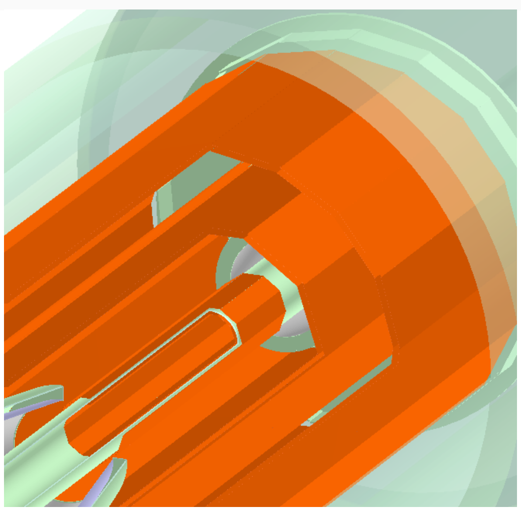


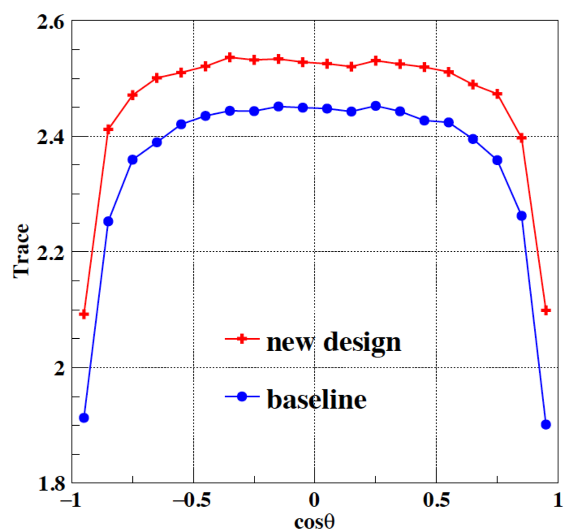


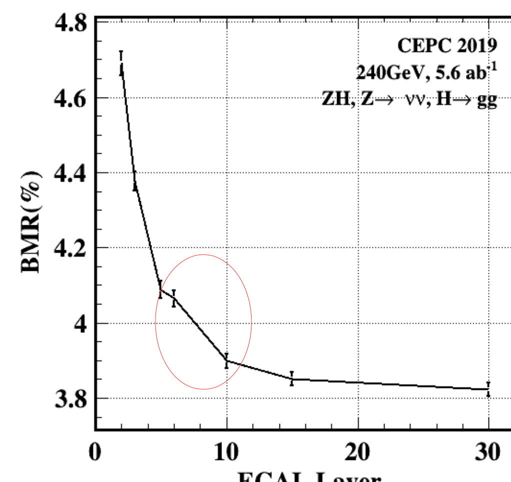


Silicon Tracker

Positioning - timing Layer with 1*1 cm granularity (Si or Alternative)

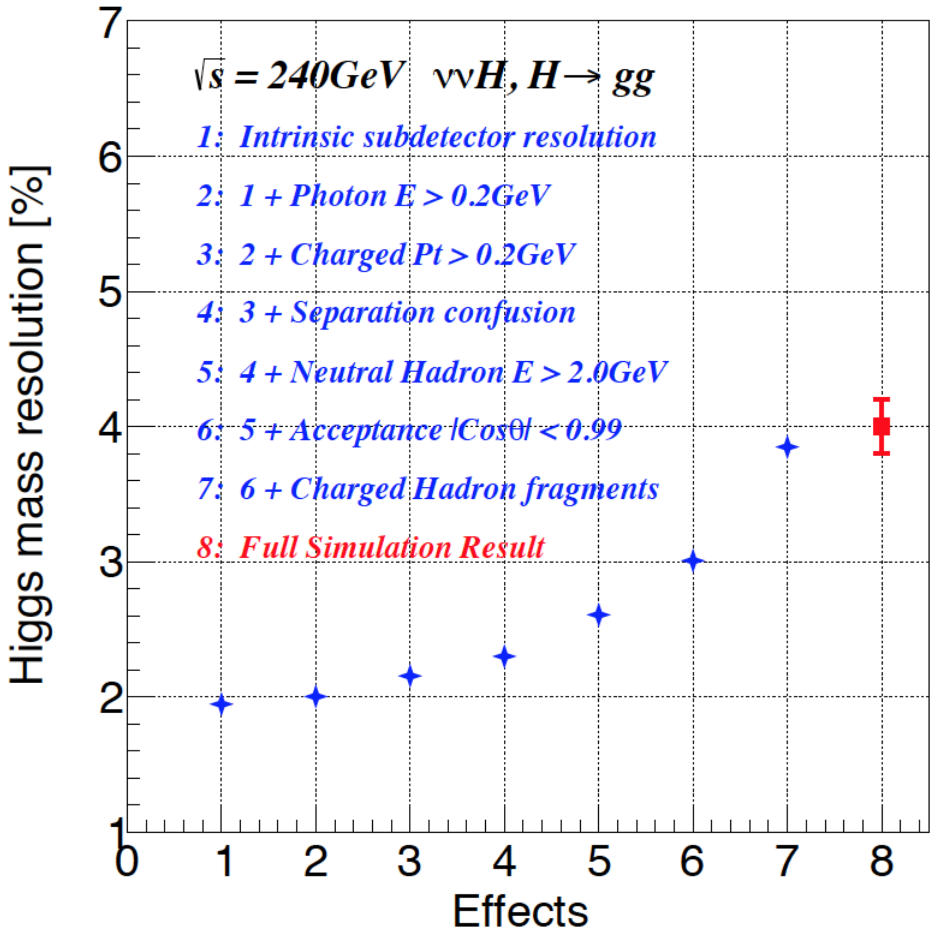


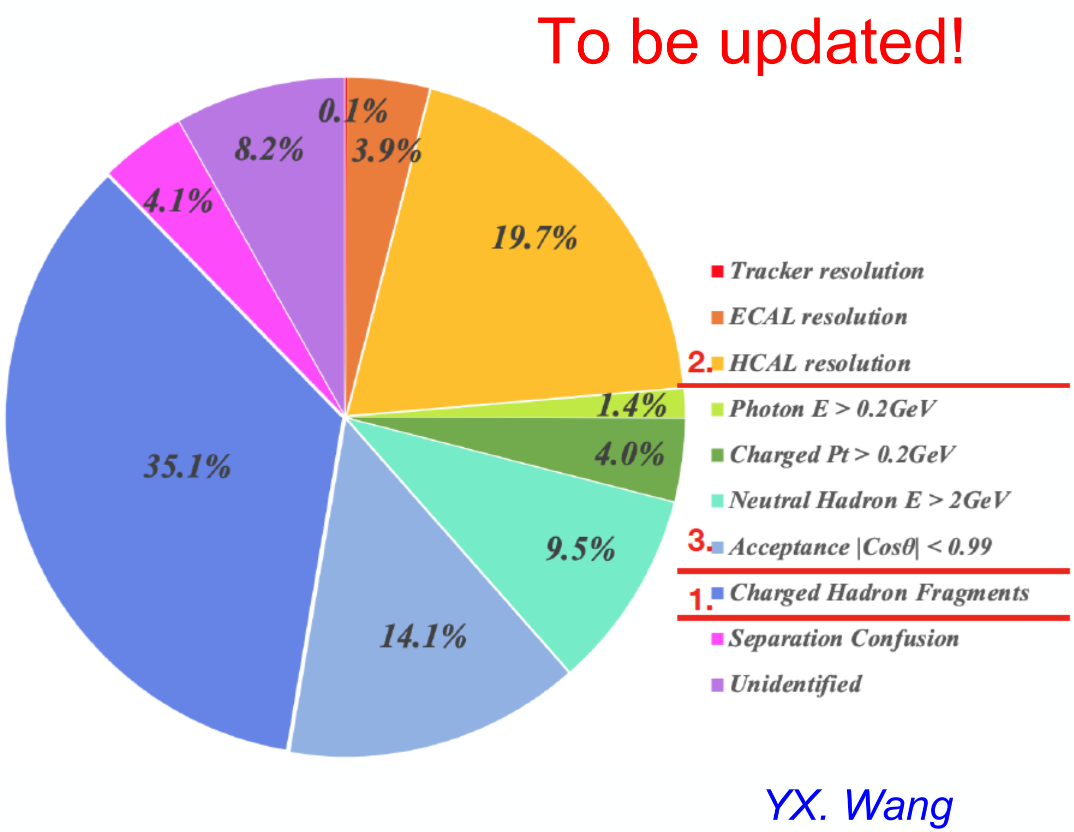




Vin (Vertex inside beam pipe): 20% imp. on Vcb measurements w.r.t. Baseline

PFA Fast simulation

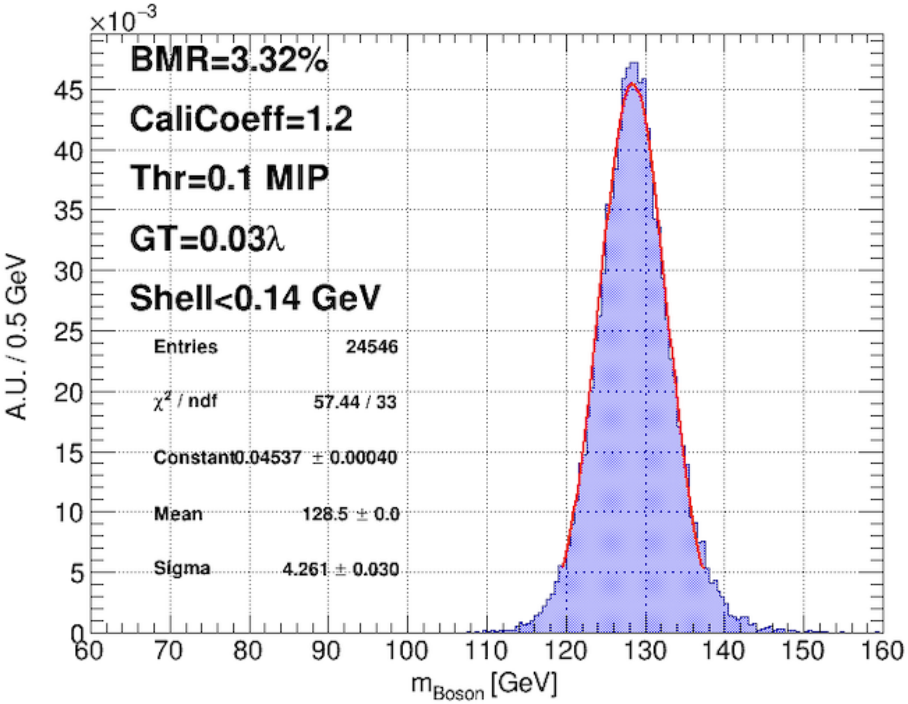


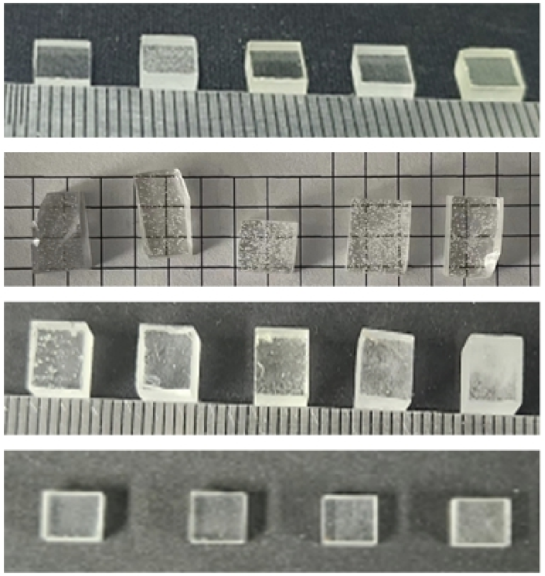


Fast simulation reproduces the full simulation results, factorize/quantifies different impacts

BMR wi GSHCAL

P. Hu & YX. Wang





2021.11
Density ~4.5 g/cm³

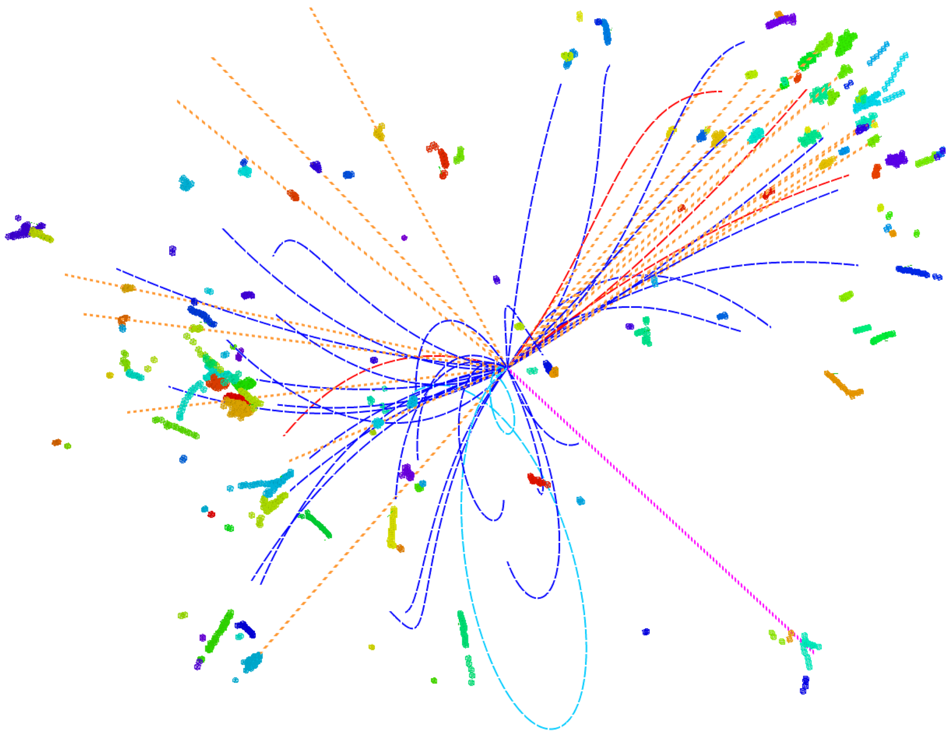
2021.11
Density ~4.0 g/cm³

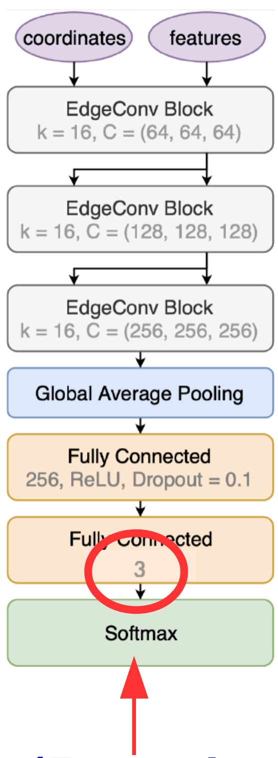
2022.06
Density ~6.0 g/cm³

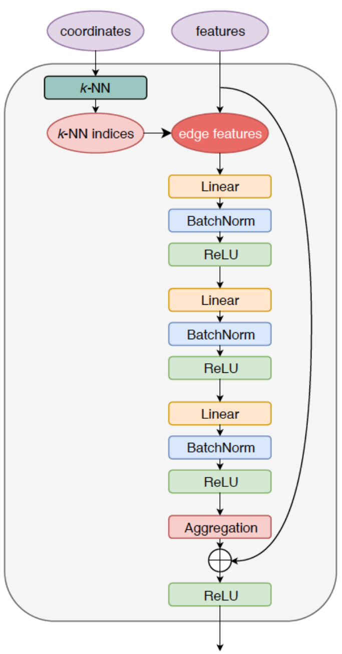
2023.02
Density ~6.0 g/cm³

- Baseline + replace DHCAL to GSHCAL + Simple para. optimization
- ~ o(10)% improvement w.r.t. DHCAL

Recent HL: Jet Origin Identification





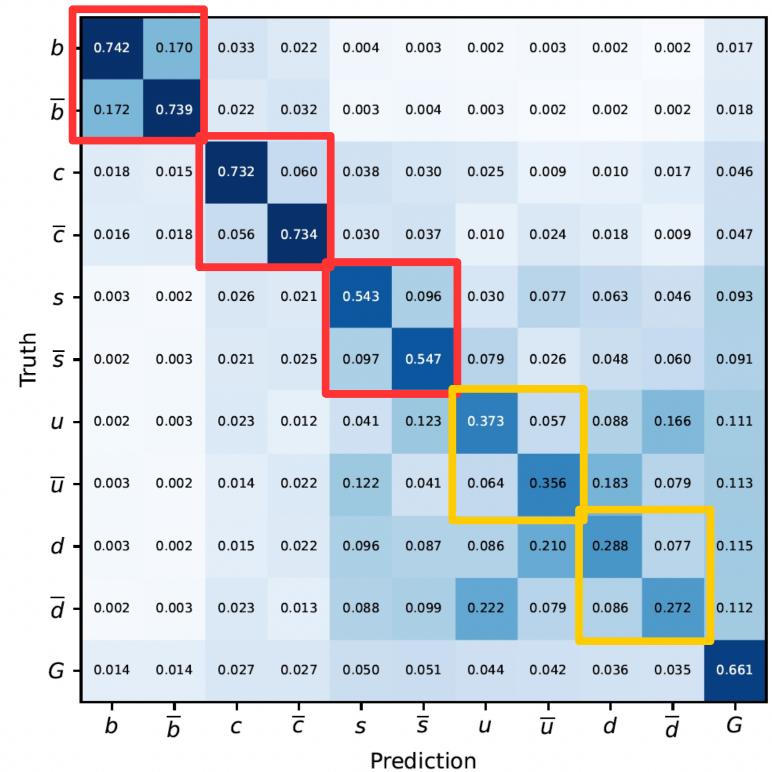


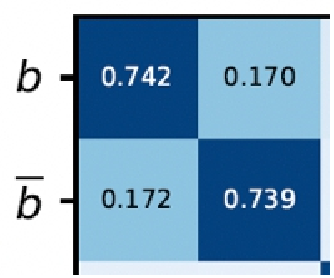
- **Jet origin identification: 11 categories (5 quarks + 5 anti quarks + gluon)**
  - Jet Flavor Tagging + Jet Charge measurements + s-tagging + gluon tagging...
- Full Simulated vvH, Higgs to two jets sample at CEPC baseline configuration: CEPC-v4 detector, reconstructed with **Arbor + ParticleNet (Deep Learning Tech.)**

https://arxiv.org/abs/2310.03440
https://arxiv.org/abs/2309.13231

Jet origin id: 11 categories

- vvH sample, with Higgs decays into different species of colored particle: 5 quark, 5 antiquark & gluon
  - **1 Million** of each type
  - **60/20/20%** for training, validating, and testing, result corresponding to testing sample
- Pid: ideal Pid – three scenarios
  - Lepton identification
  - + Charged hadron identification
  - + Neutral Kaons identification
- Patterns:
  - ~ Diagonal at quark sector...
  - P(g→q) < P(q→g)...
  - Light jet id...

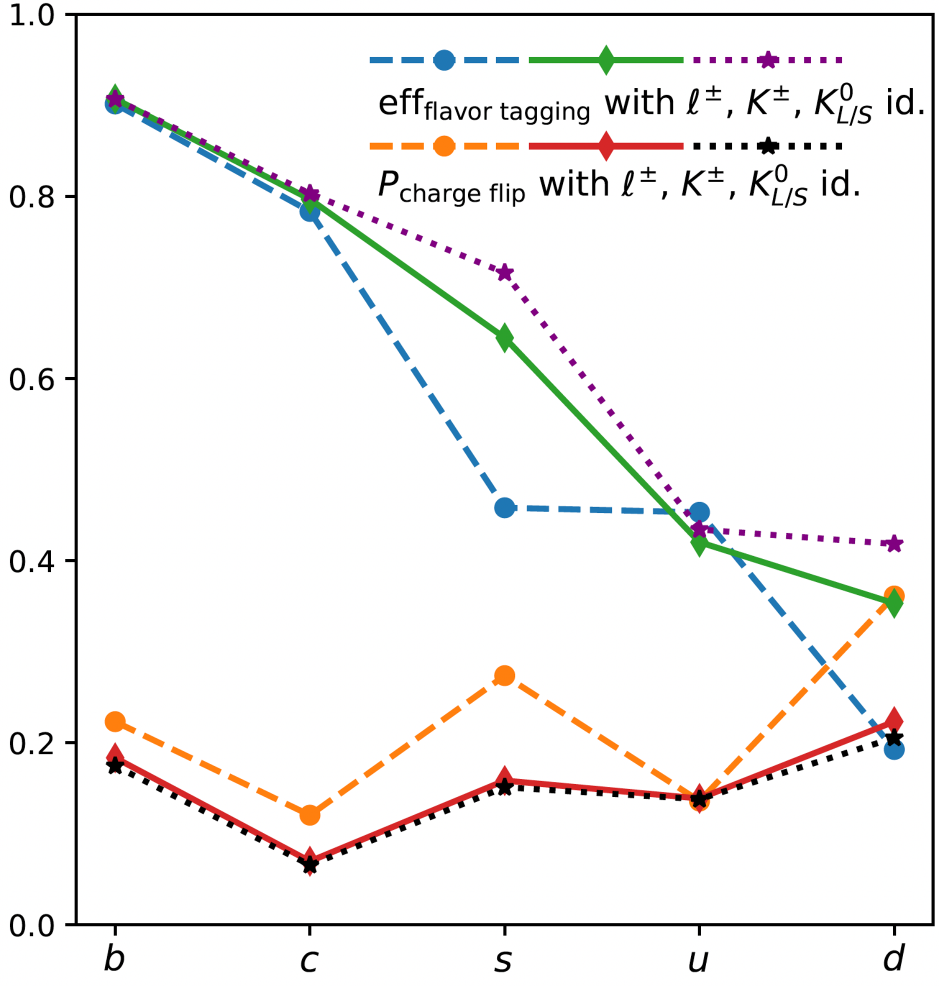


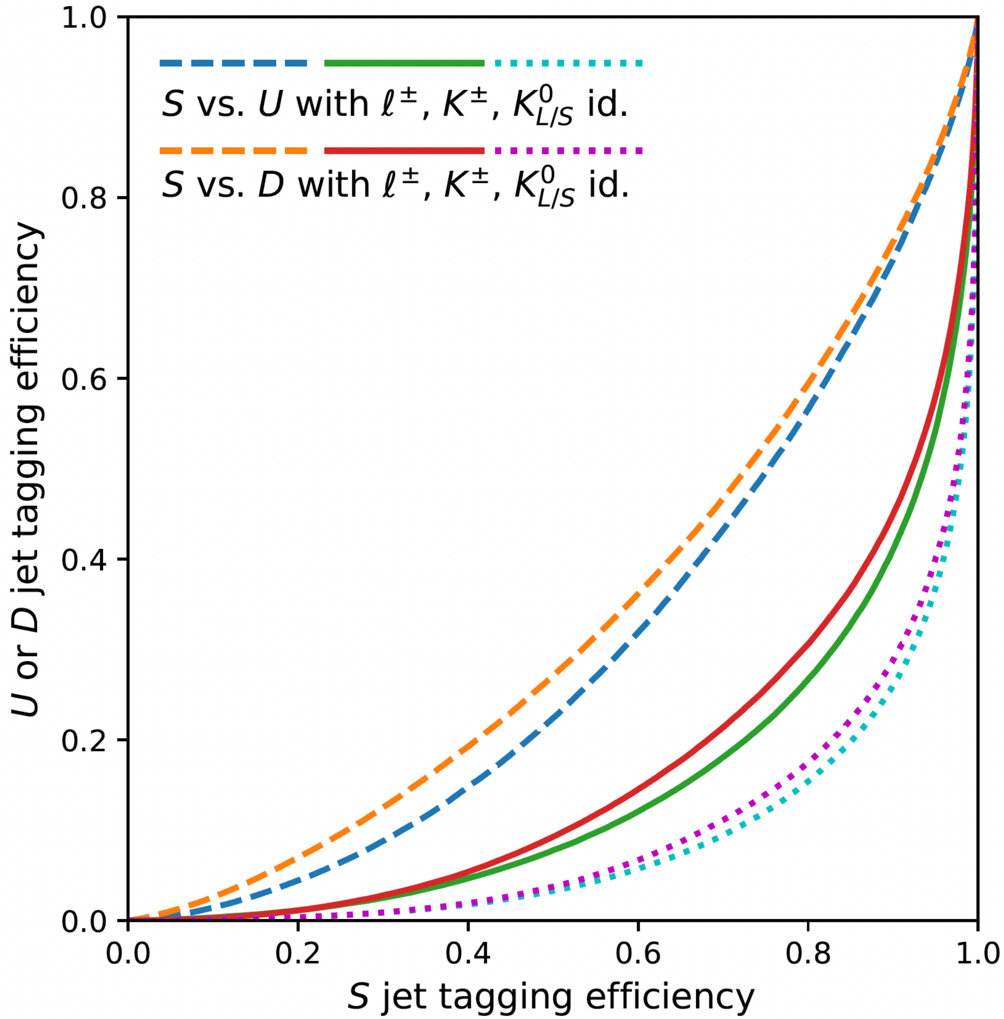


Eff = (0.74 + 0.17 + 0.74 + 0.17)/2 = 0.91

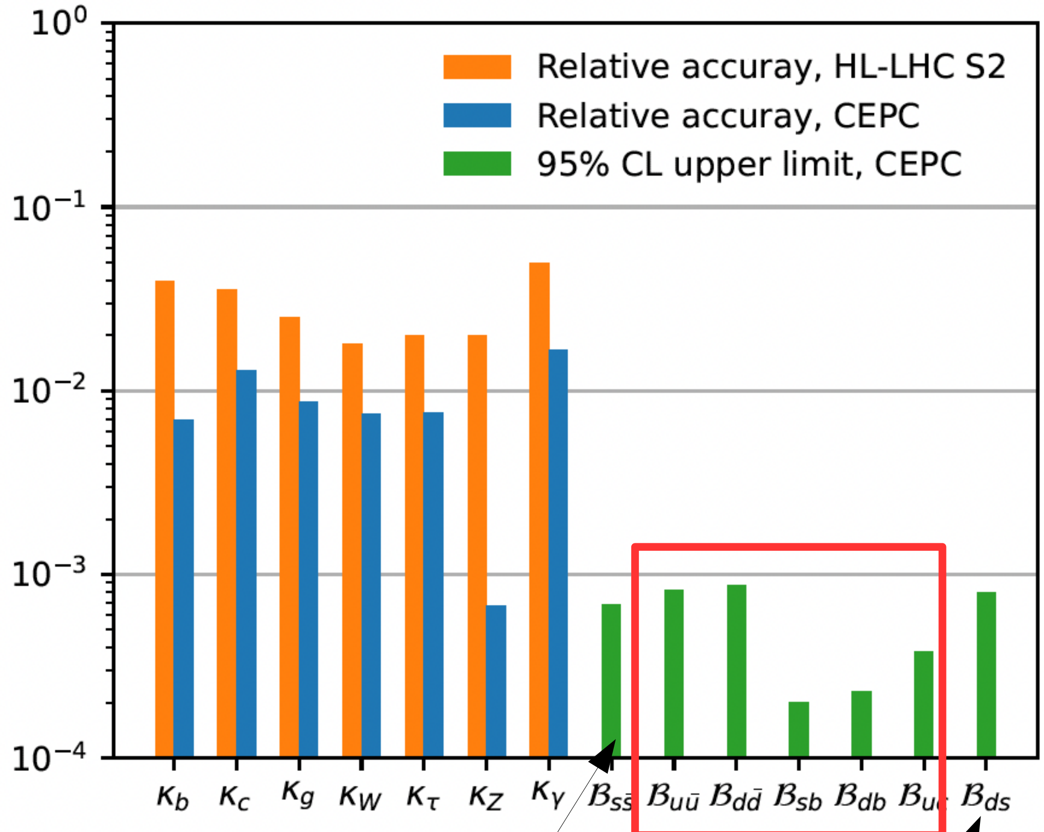
Charge flip rate = 0.17/0.91 = 0.19

Performance with different PID scenarios





Benchmark analyses using Jet origin ID



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

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

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

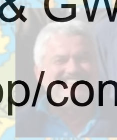
[59] J. de Blas et al. Higgs Boson Studies at Future Particle Colliders. *JHEP*, 01:139, 2020.

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

For H->bb, cc, gg: results in 20 – 40% improvement in relative accuracies (preliminary)...

Collaborations & Communications

- Multiple workshops
  - HKIAS working month (Jan. every year)
  - Phy/Det Workshops (Duality to Nov. Annual Meeting)
    - i.e., Fudan Phy/Det WS Aug. 2024, with ~ 120 talks in 1 weeks
  - Topical Workshops (i.e., with FOPT & GW detection)
- Actively participate international workshop/conferences
  - LCWS, eeFACTs, FCC workshops, ECFA Workshops, etc
  - Hosting relevant conference, i.e., Higgs2023
- In Snowmass/ESPPU Studies
  - Actively provide input (~ 30 citables at Snowmass studies + Snowmass WP)
  - ESPPU input
  - Joins the discussions

Physics WS @ Fudan

https://indico.ihep.ac.cn/event/19839 Many new faces & new ideas!

IAC recommendation & response

Item 26. Aim at having a stronger involvement of Chinese universities to strengthen the simulation effort. Explore avenues to engage international software experts for short-term, targeted visits.

Item 28. Articulate the unique features of the CEPC physics program in the context of the global high-energy physics program and consider submission of a separate whitepaper on this topic.

~~~

MQ:

Community interests arises.

Organization + Services works is critical to facilitate the collaboration & enhance the output.

Central team, especially algorithm/software/computing part need to be strengthened.

For the WP studies, lacking of senior editing power, need to have good theorists/phenologists/experimentalists working together.
~~~

IAC recommendation & response

Item 27. Strengthen the physics case as much as possible through targeted, full simulations of the key physics processes and complete the set of whitepapers, addressing the five science areas, well before the CEPC proposal is due.

Item 29. The flow-down of the physics requirements should be based on the detector performance as a whole and the detector treated as an integrated system rather than a set of subdetectors.

Item 31. For the moment, narrow the number of concept detectors to two and advance the level of maturity of the most promising candidate baseline technologies for the various subdetectors, maximising the complementarity between the two detectors.

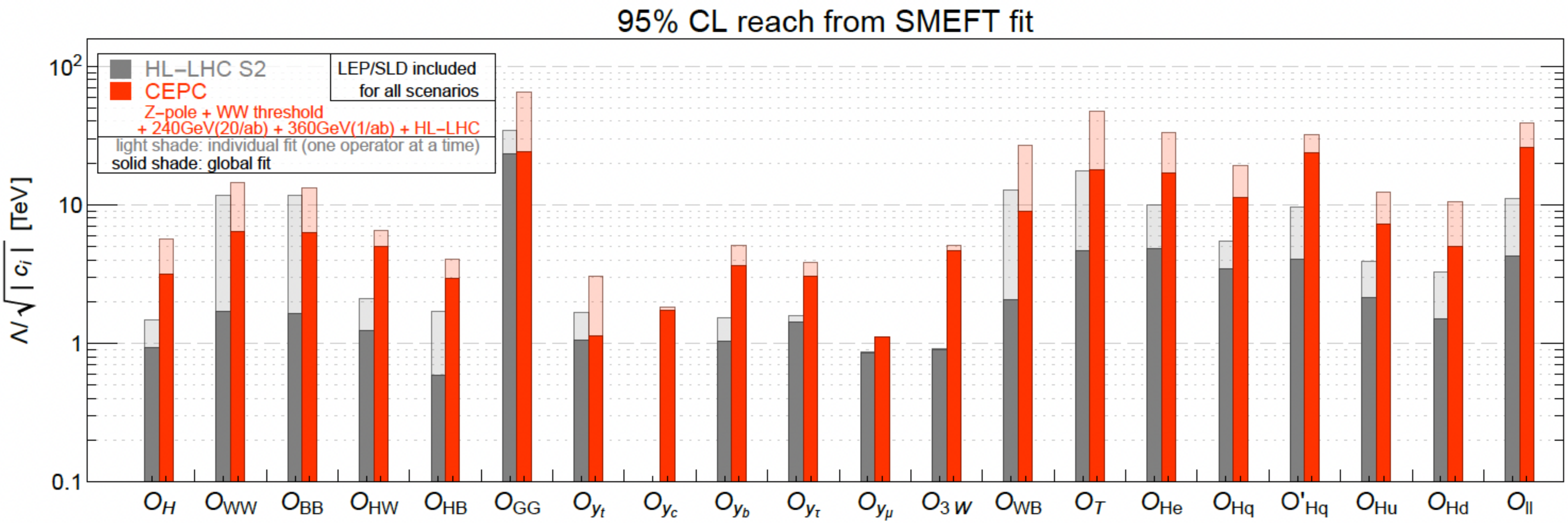
~~~

MQ: I fully agree that full sim. studies towards the reference detector design with adequate simulation/reconstruction is essential. Should be composed of both top-down & bottom-up approaches. From Physics reach/detector requirement to the final design of reference detector. Those efforts include reco. Algorithm development, prototype commissioning & test, Digitization & Validation studies, Fast simulation Validation from Full Simulation, Benchmark studies, Pheno-studies, etc.

Manpower & coordination is essential, while I think the current efforts – especially the manpower is a bit worrisome.

...recruitment, collaboration (esp. International collaboration), training...
~~~

Summary

- Electron Positron Higgs factories: a gigantic boost from LHC
- CEPC physics studies: composed of physics reach/pheno and detector requirement optimization, aims at White papers to be released according to the project paces
  - Community activated, results in multiple new ideas/results
  - Good international communication/collaboration
  - Lots of raw material available, visionary summarization/interpretation is needed
    - Incentives/supports to young people, especially young PIs at China
    - Editing help from senior & visionary experts
- Extremely rich physics program results in stringent requirements on the detector performance, to be addressed by intensive study on detector design, key tech R&D, and algorithms development
  - Significant efforts towards the RDR (reference detector design TDR)
  - Manpower/resource is an issue. Especially the service & communication
- New tools, especially AI, could significantly alter the physics study/detector design.

Back up

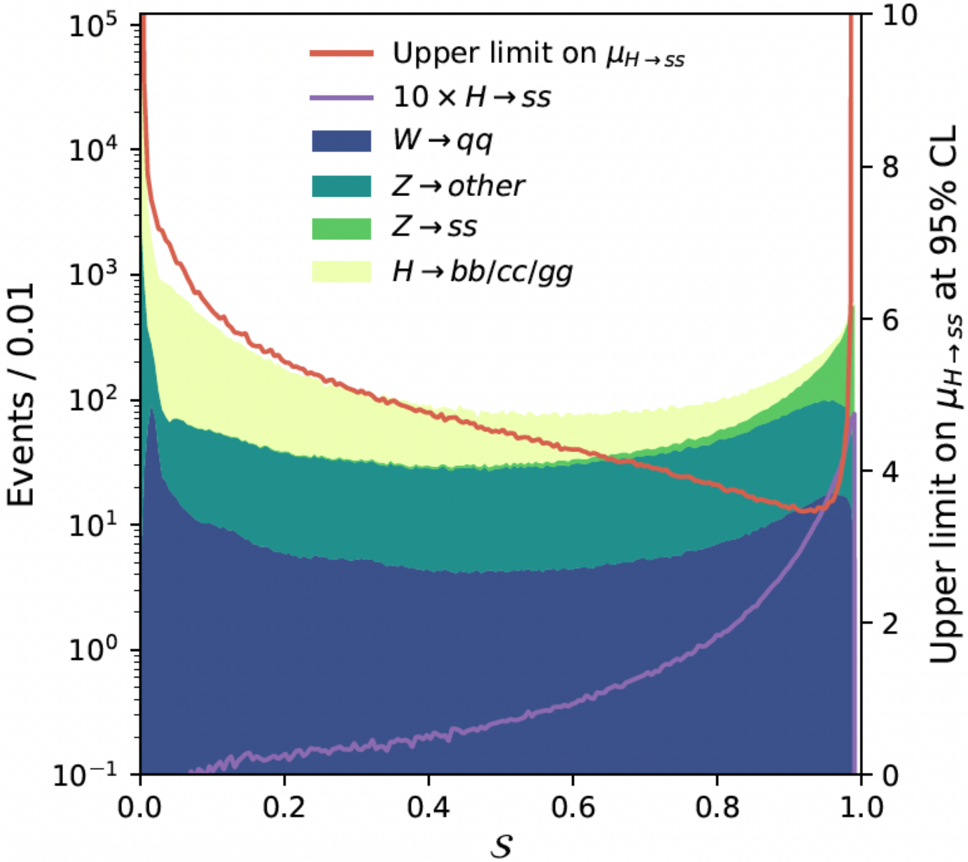
Physics reach via EFT

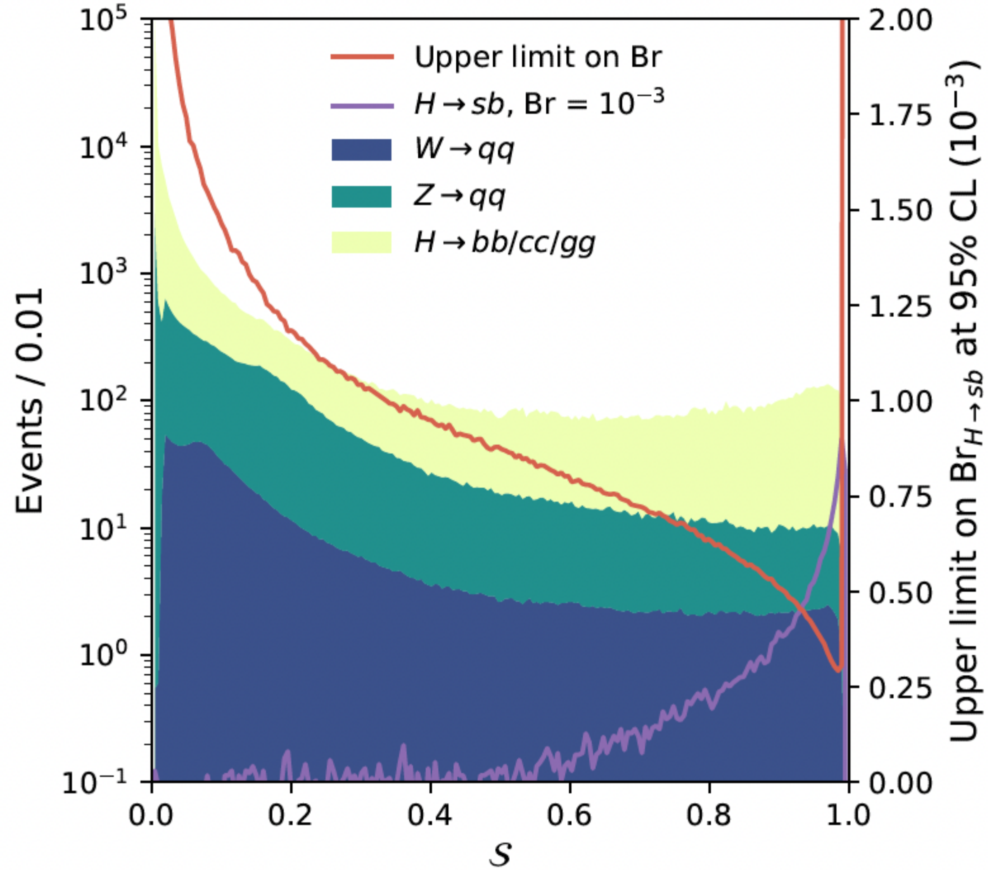


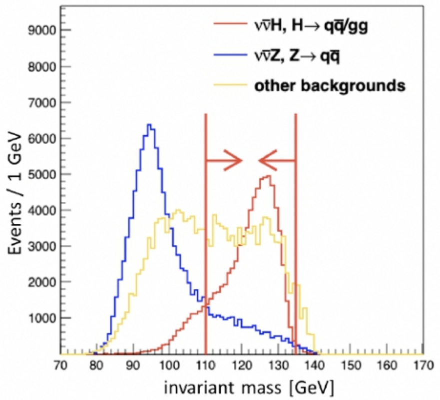
Challenges

- Physics: To be addressed by Physics studies & Summarized into White papers
  - Identify the Smoking gun for discovery -
  - Physics landscape & Synergies @ X-frontier (i.e., GW + Collider)
  - Interpretations
  - High precision calculation
- Accelerator: Engineering Design Report & Feasibility studied
  - Prototype & commissioning at integrated level (large scale test facility, test with beam load)
  - Integration & alignments
  - Civil Engineering
- Detector: Innovative detector design + A3 (AI Assistant Algorithms) + Key tech R&D
  - PFA oriented
  - Extremely stable
  - Trigger-less equivalent at Tera Z
  - Sub-detectors – state of art + pursue excellent intrinsic resolutions
- International collaboration!

Benchmark analyses using Jet origin ID



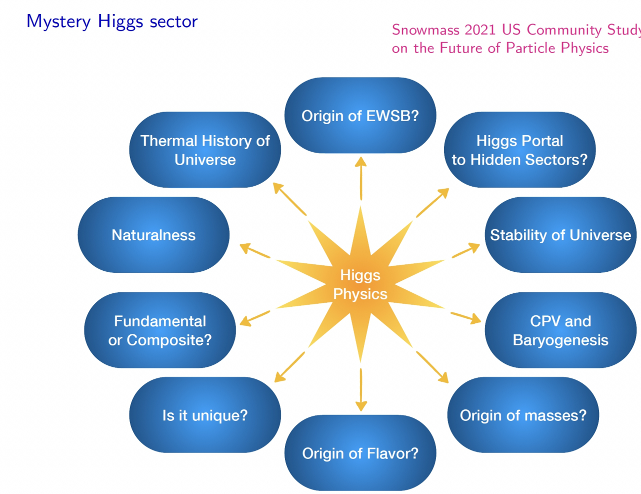




Applied to quasi-data of vvH;
H → ss: be limited to 3*SM using vvH + llH at 20 iab
H → sb: up limit of 2E-4 at 95% C.L.

Circular Electron Positron Collider: Status

- 11 years of endeavor: Technologically ready to construct (TDR)
- CEPC, via multiple observation window especially the Higgs
  - Explore two new interactions beyond Gauge + Gravity
  - Could identify new ingredient of matter, discover New Physics, and reveal the known unknowns of SM
- Boost technologies: High Field Super Conducting, RF, Medical technologies, AI, ...
- A platform for profound International Collaboration



The SM Higgs Lagrangian (schematically)

$$\mathcal{L}_{\rm Higgs} = \underbrace{|D\phi|^2}_{\text{gauge interactions}} + \underbrace{(y_{jk}\overline{\psi}_j\psi_k\phi + \text{h.c.})}_{\text{Yukawa interactions}} - \underbrace{V(\phi^\dagger\phi)}_{\text{Higgs potential}}$$

gauge interactions, HWW/HZZ couplings
$\hookrightarrow$ well tested after LHC

Yukawa interactions, $H\bar{f}f$, CKM matrix, $\not{CP}$
$\hookrightarrow$ studied since $\sim$ 2018

"5th force"

Higgs potential, $HHH/HHHH$ coupl.
$\hookrightarrow$ not yet tested

"6th force"

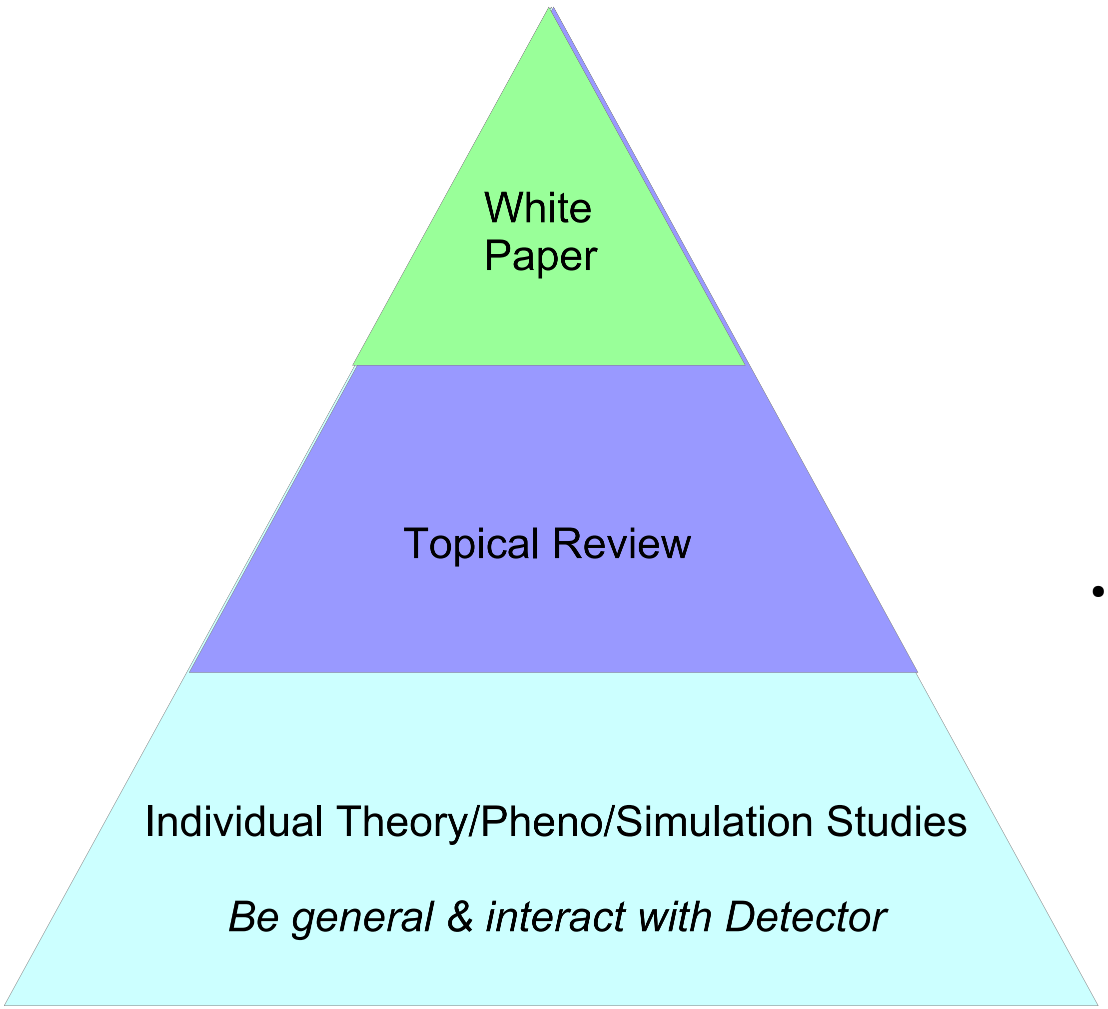
- The immense science merit & profound influence on mankind, we hope Higgs factories could be approved for construction soon

Challenges

- Manpower and resources is worrisome.
- From the physics requirement to its resolution as in a detector TDR, requires
  - Reliable quantification of boundary condition (Beam induced bkg, etc)
  - Detector hardware R&D
  - Detector prototype testing + modeling of Digitization
  - Full Detector Simulation & Modeling in fast simulation
  - Software:
    - framework,
    - full simulation,
    - algorithm development
  - Active user community, training program
- Profound international collaborations

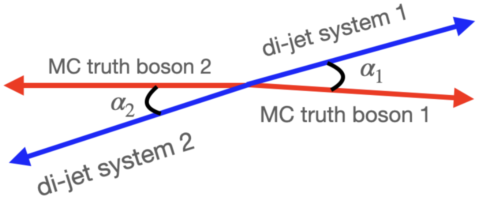
- Recruitments + Visitings

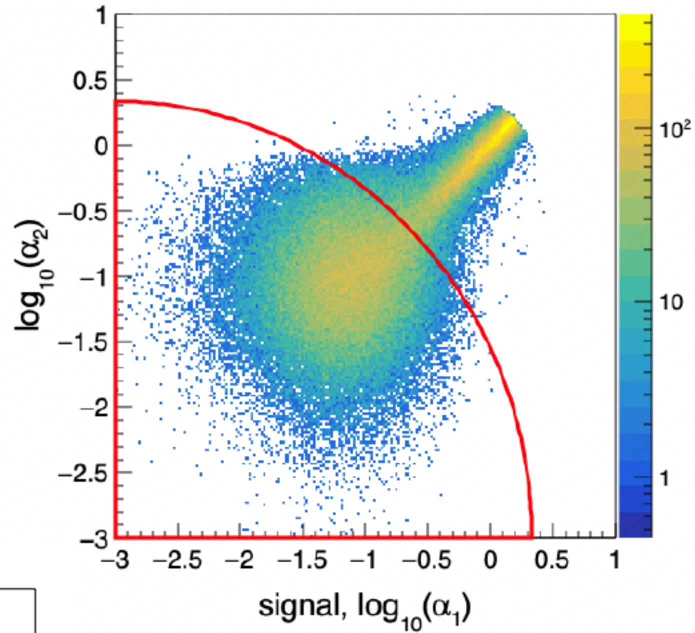
CEPC Physics Study

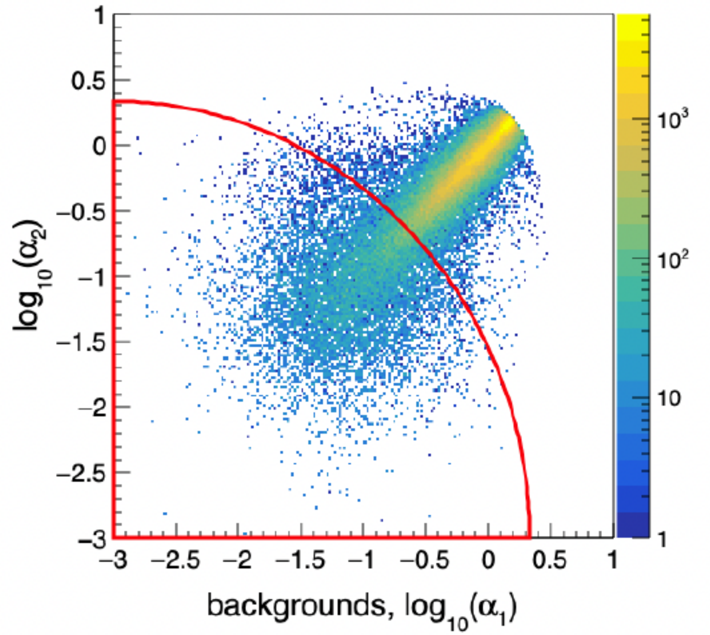


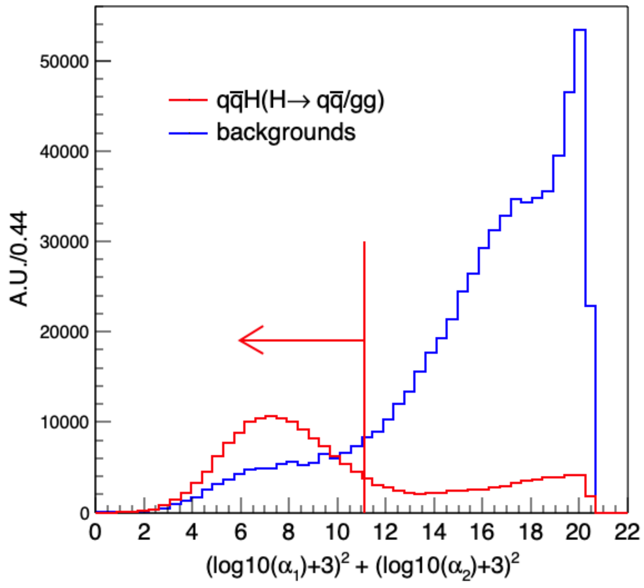
- Contacts
  - NP: Xuai, Jia Liu...
  - EW: Jiayin, Zhijun...
  - Flavor: Lingfeng, Lorenzo...
  - QCD: Huaxing, Meng Xiao...
  - Higgs: Yaquan, Gang...
  - Manqi, Liantao
- Topical reviews
  - PFA
  - EWPT & Early Universe
  - Mono photon
  - LLP
  - Exotica (in. With Flavor)
  - ...

Impact of CSI









- If we find an observable that evaluates the performance of CSI – and eventually veto events with bad CSI, we can improve the accuracy on H->bb, cc, gg by ~ 2 times at qqH channel.
- Need profound understanding of QCD picture, and developments of new tools

Vcb from W decay

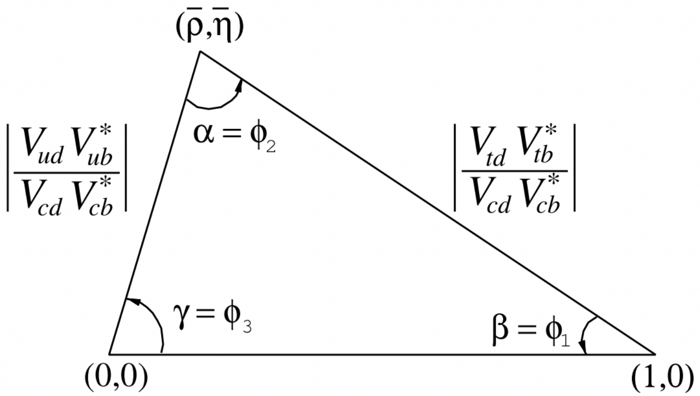


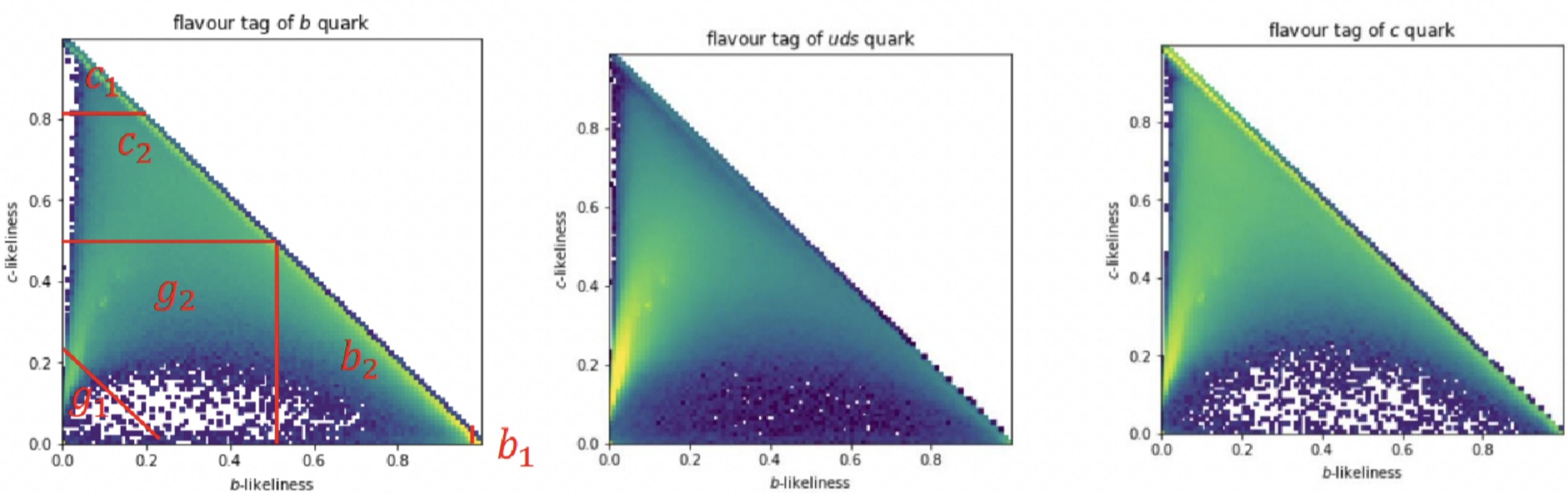
Figure 12.1: Sketch of the unitarity triangle.

$$|V_{cb}| = (41.0 \pm 1.4) \times 10^{-3}\,.$$

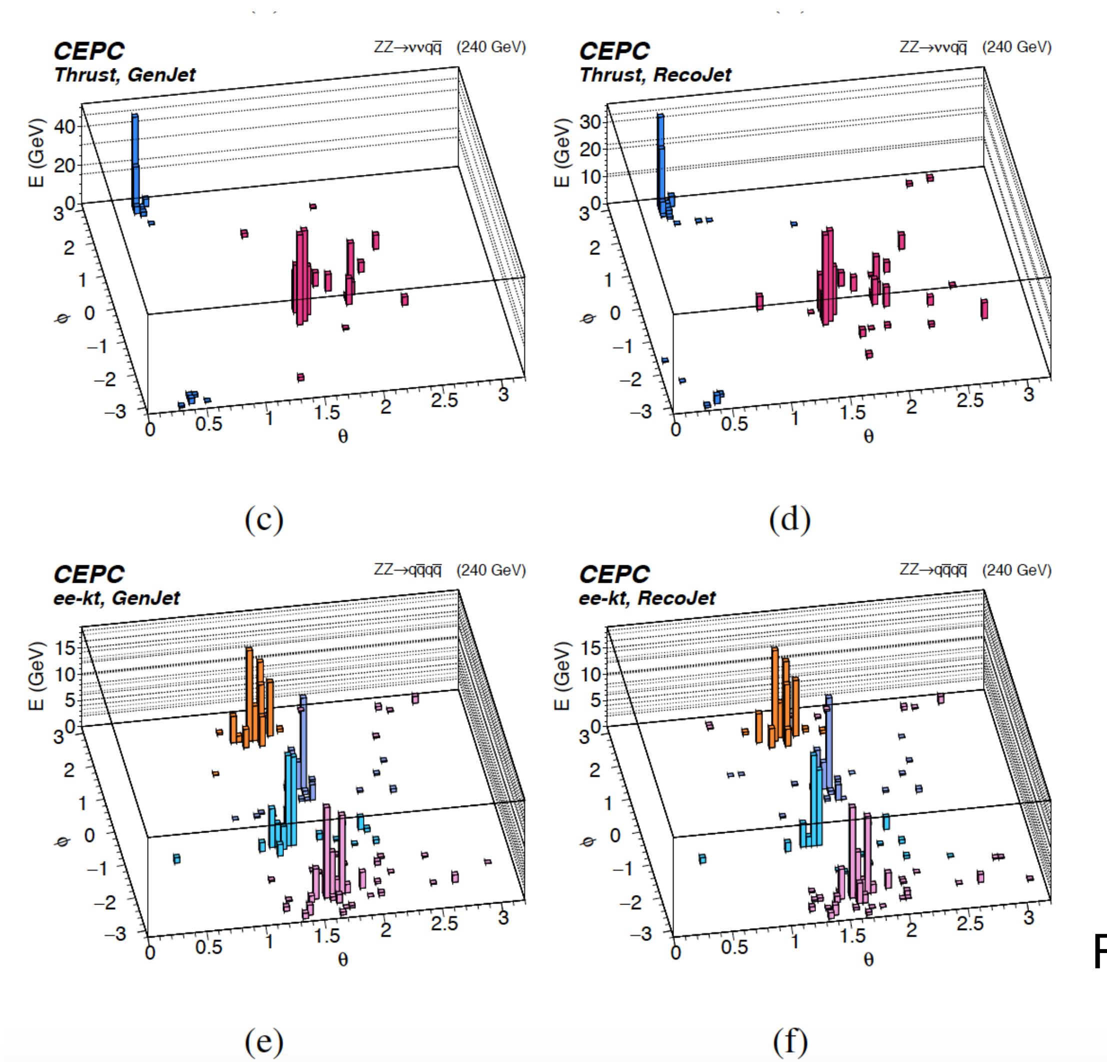
$M =$

	b1	b2	c1	c2	g1	g2
b	0.47	0.378	0.0197	0.0965	0.00397	0.0315
c	0.00042	0.078	0.298	0.373	0.0682	0.182
uds	0.000104	0.00477	0.00145	0.054	0.538	0.401

Flavour tagging at Z-pole



Individual jet: jet clustering - matching



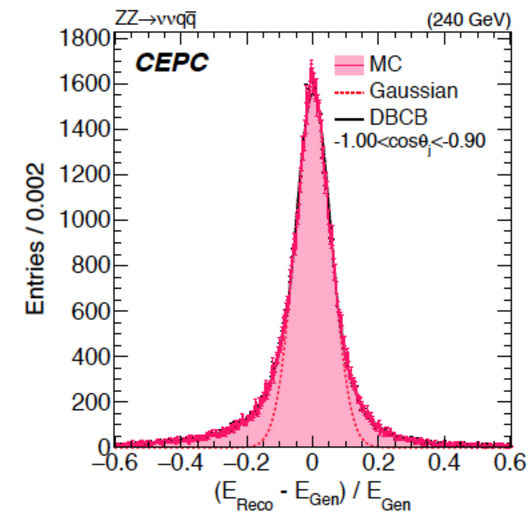
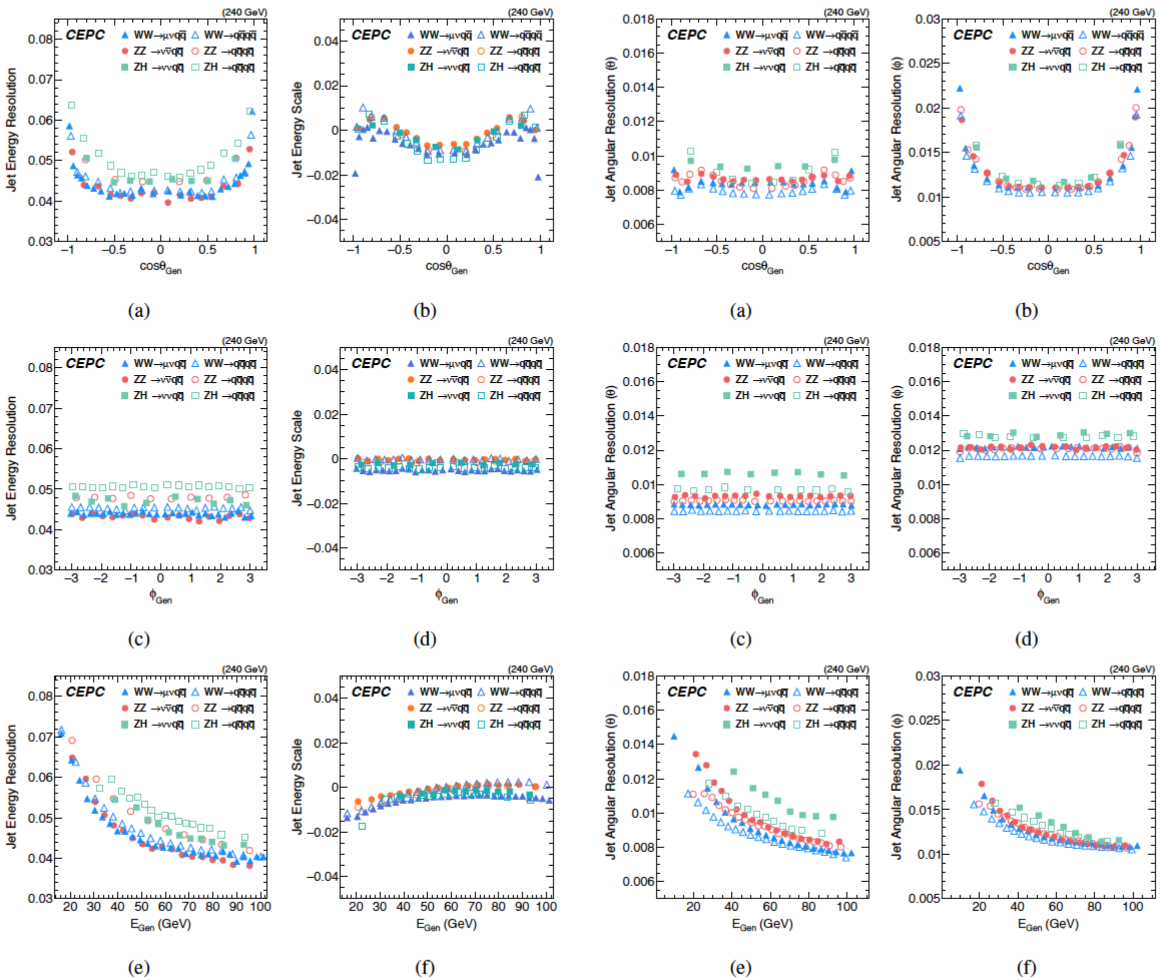


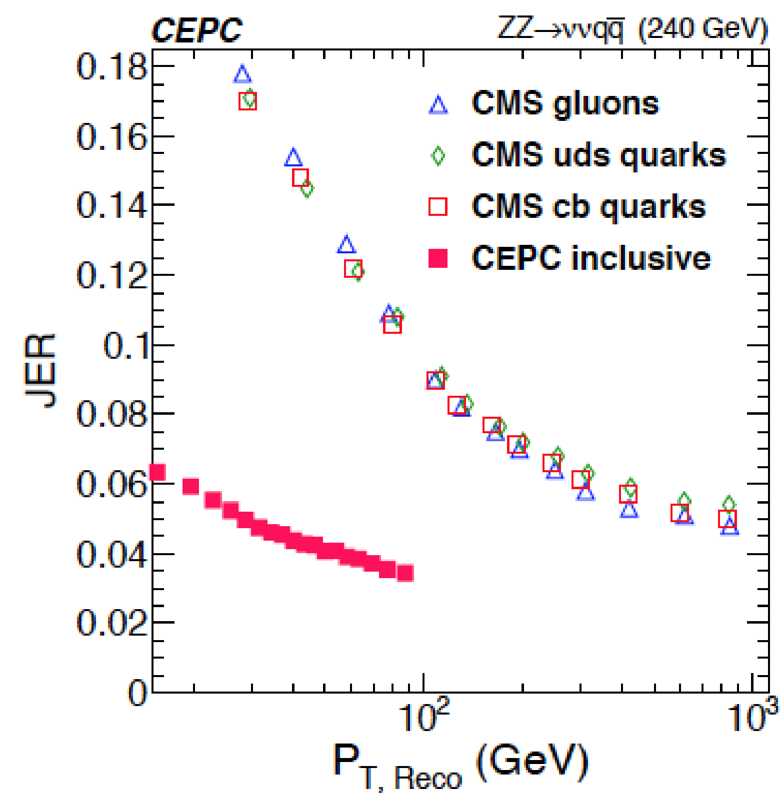
Fig. 7: σ and $\bar{x}$ from the core of the DBCB fit to R are defined as JER/S, respectively. The $cos\theta_j$ indicates the specific polar angle of the jets.

Jet Clustering & Matching is critical:
ee-kt is used as CEPC baseline

Relative difference between Gen/Recojet is define to be the detector jet response

Individual Jet Responses

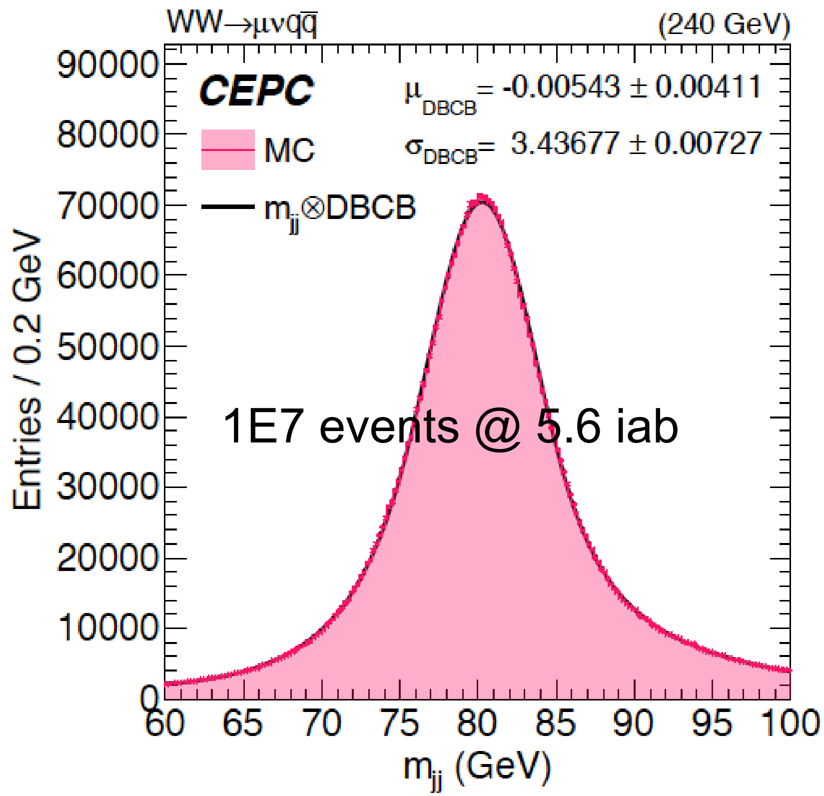




Jet Energy Response: 2.5 – 4 times better than LHC in the same Pt range,
Jet Energy Scale: 3 times better before sophisticated calibration

W-mass direct reconstruction at 240 GeV. Challenge & interesting

- W mass measurement at 240 GeV:
  - Statistic uncertainty @ 20 iab~
    - *0.3 MeV using only μvqq final state*
    - *Bias ~ 2.5 MeV once Z mass calibrated to known value*
  - Ultimate accuracy?
    - *Can we better control the systematic using the differential information?*
    - *Control the jet confusion?...*
    - *Identify & tame ISR?*
    - *Better calibrate?*
    - *Can we maintain sufficient stability over 7/10 years? ...*

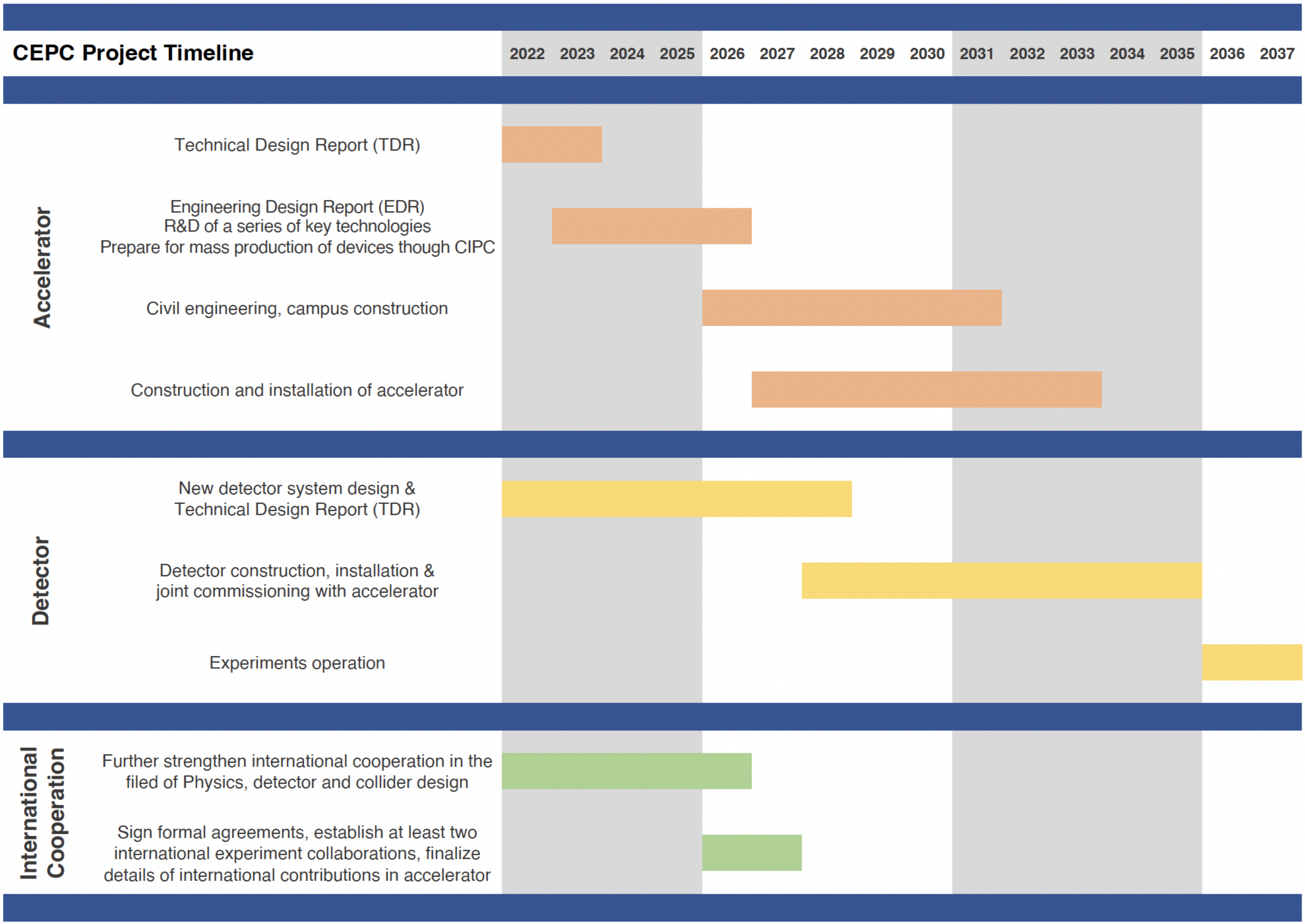


Quasi analysis: JES calibrated to pure ISR return qq sample

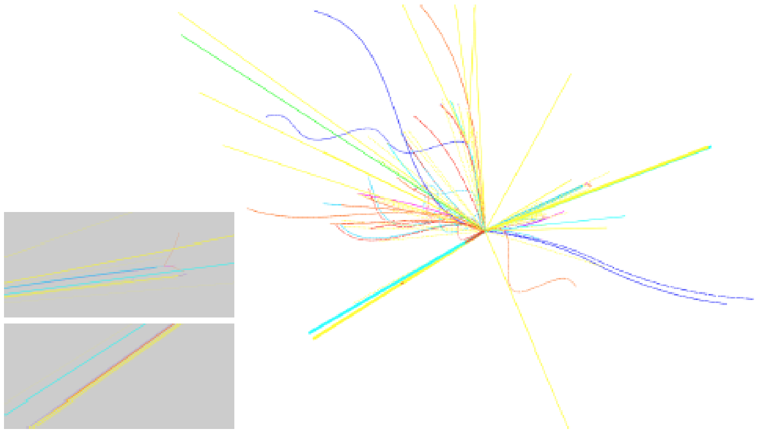
Flavor Physics @ Z pole

- Extremely rich physics & strong competition from Belle-II & LHCb
- Comparative advantages of a Tera-Z
  - V.S. BelleII, Access to particles heavier than Bs, large boost
  - V.S. LHCb, much lower yields (2 orders of magnitudes) Better Acceptance, better reconstruction of neutral final state (photon, missing energy, and even Klong, neutron) and Jet Charge
- Observations
  - For CP measurement, a Tera-Z can compete with LHCb @ HL-LHC thanks to the capability of precise Jet Charge measurements...
  - Brings lots of critical information on measurements with neutral final states...
  - Yet, Pid is essential.

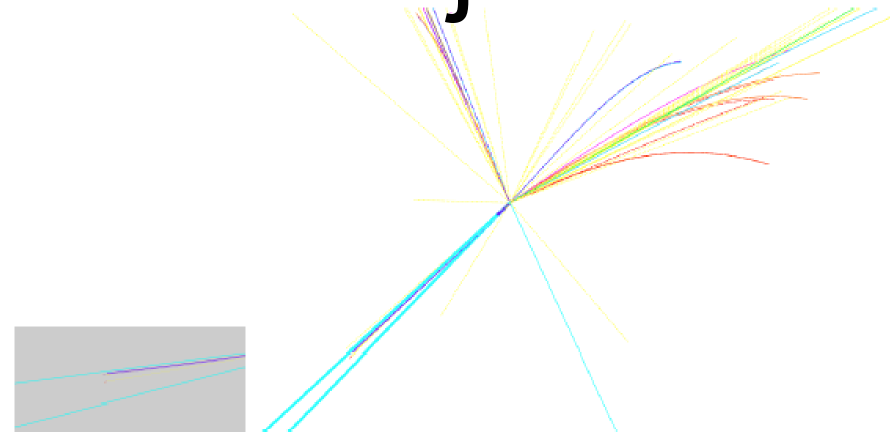
Timeline


CEPC Project Timeline
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
Accelerator
Technical Design Report (TDR)
Engineering Design Report (EDR)
R&D of a series of key technologies
Prepare for mass production of devices though CIPC
Civil engineering, campus construction
Construction and installation of accelerator
Detector
New detector system design &
Technical Design Report (TDR)
Detector construction, installation &
joint commissioning with accelerator
Experiments operation
International Cooperation
Further strengthen international cooperation in the
filed of Physics, detector and collider design
Sign formal agreements, establish at least two
international experiment collaborations, finalize
details of international contributions in accelerator

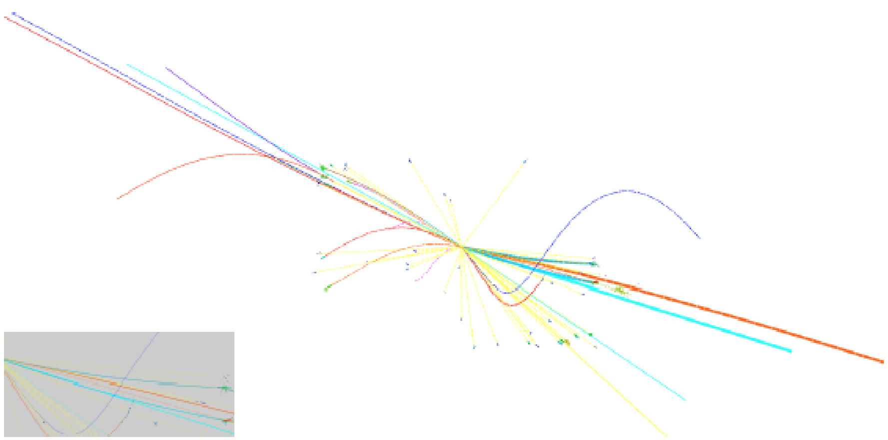
Taus: isolated or inside jets



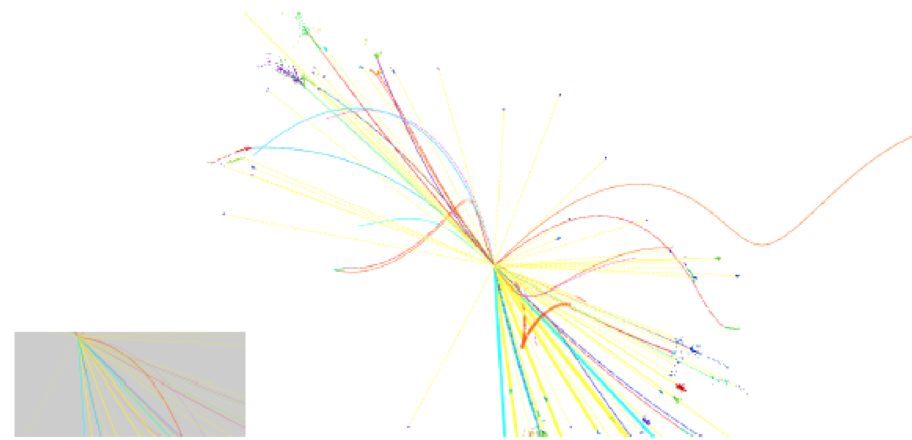
(a) $Z \to qq, H \to \tau\tau$ with two hadronic decay.



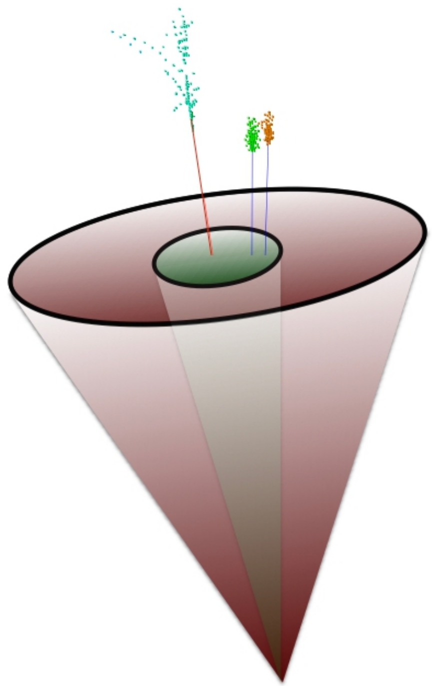
(b) $WW \to \tau\nu qq$ with one leptonic decay.

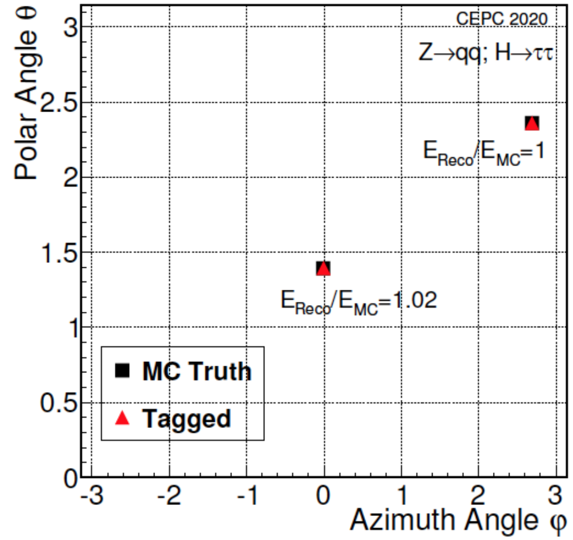


(c) $Z \to b\overline{b}, B_c \to \tau\nu$ with one hadronic dacay.

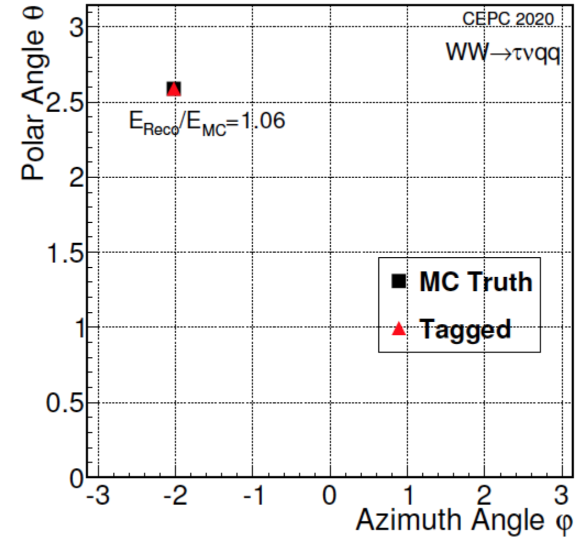


(d) $Z \to b\overline{b}, B_s \to \tau\tau$ with two hadronic decay mixed together.

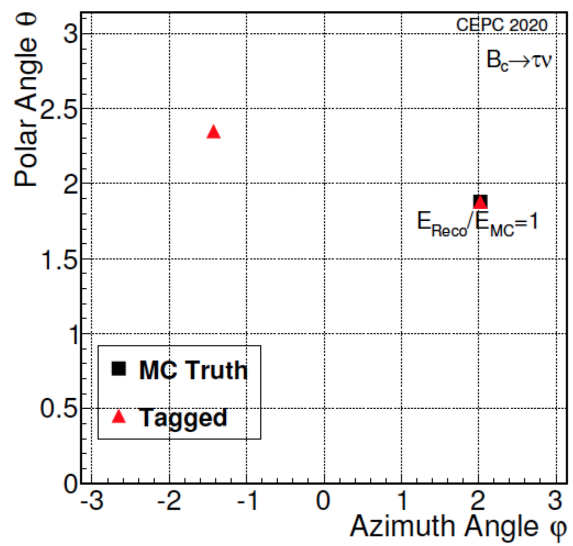




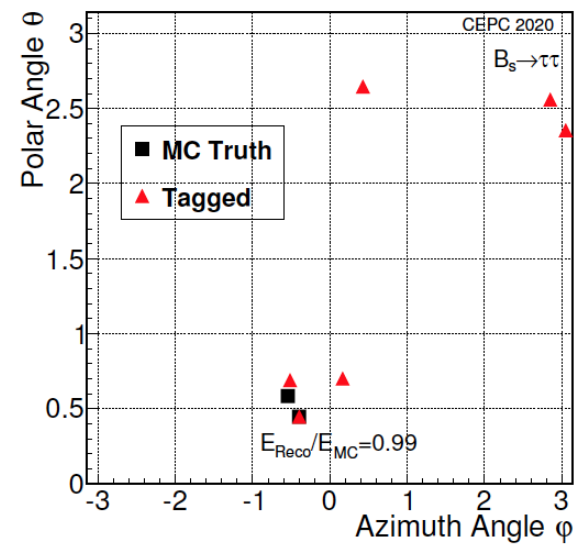
(a) $Z \rightarrow qq, H \rightarrow \tau\tau$, efficiency=1, purity=1



(b) $WW \rightarrow \tau\nu qq$, efficiency=1, purity=1

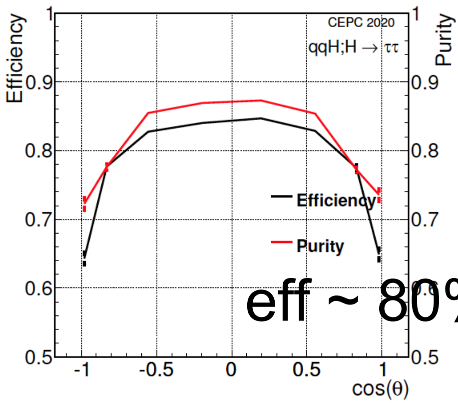


(c) $Z \rightarrow b\overline{b}, B_c \rightarrow \tau\nu$, efficiency=1, purity=0.5

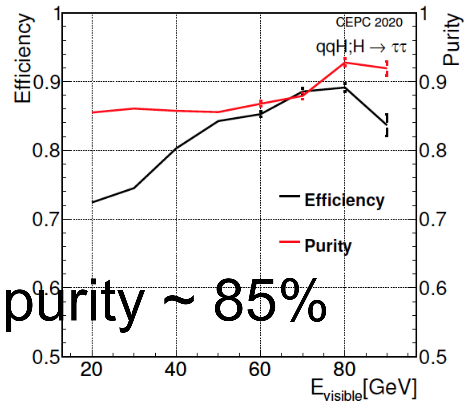


(d) $Z \rightarrow b\overline{b}, B_s \rightarrow \tau\tau$, efficiency=0.5, purity=0.167

Tau id

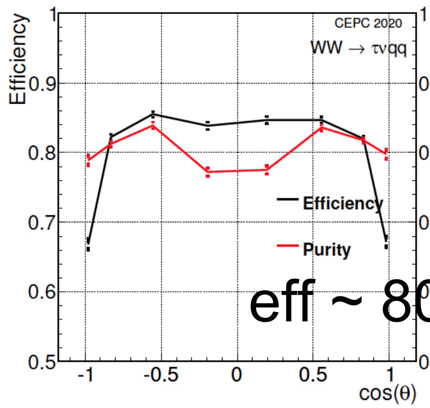


(a) Efficiency and purity performance along with polar angle θ, parameters fixed.

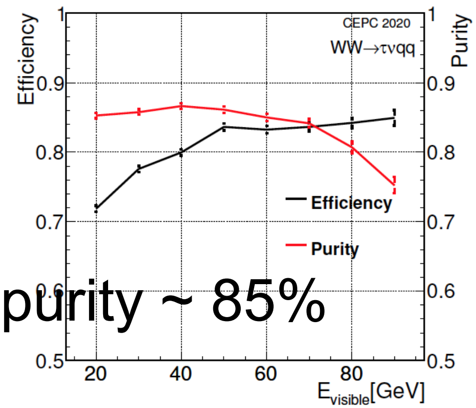


(b) Efficiency and purity performance along with visible energy. The performance above 80 GeV falls as a result of stringent cone selection.

eff ~ 80%, purity ~ 85%

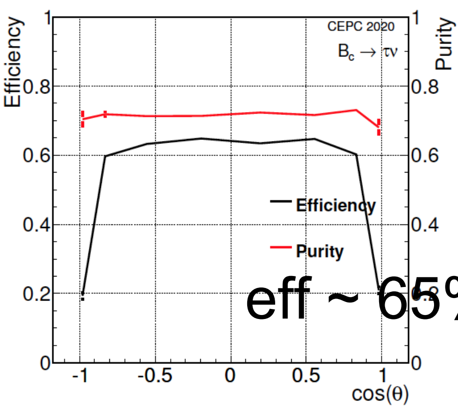


(a) Efficiency and purity performance along with polar angle θ, parameters fixed.

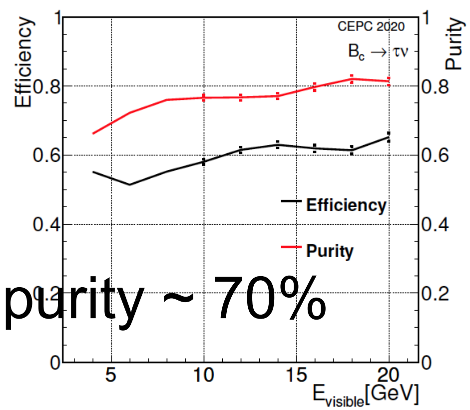


(b) Efficiency and purity performance along with visible energy

eff ~ 80%, purity ~ 85%

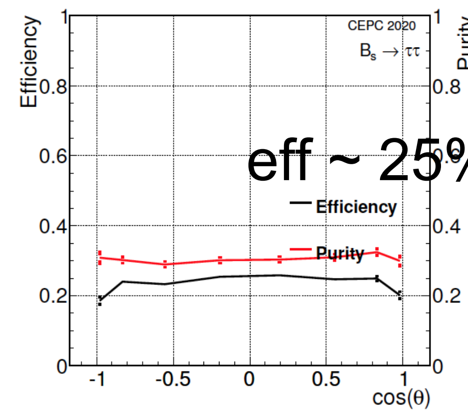


(a) Efficiency and purity performance along with polar angle θ, parameters fixed.

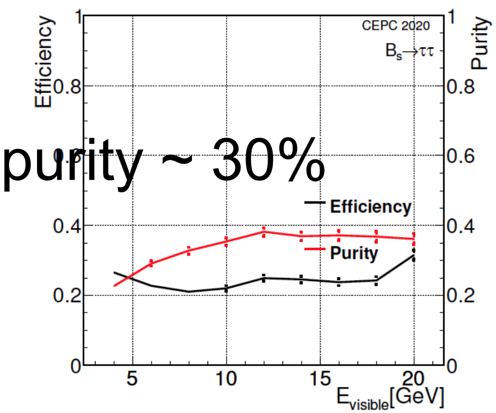


(b) Efficiency and purity performance along with visible energy

eff ~ 65%, purity ~ 70%



(a) Efficiency and purity performance along with polar angle θ, parameters fixed.



(b) Efficiency and purity performance along with visible energy

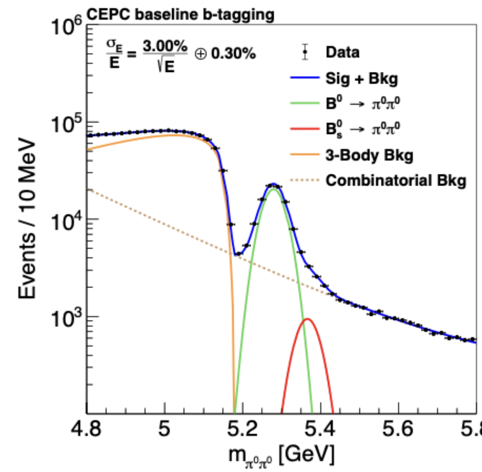
eff ~ 25%, purity ~ 30%

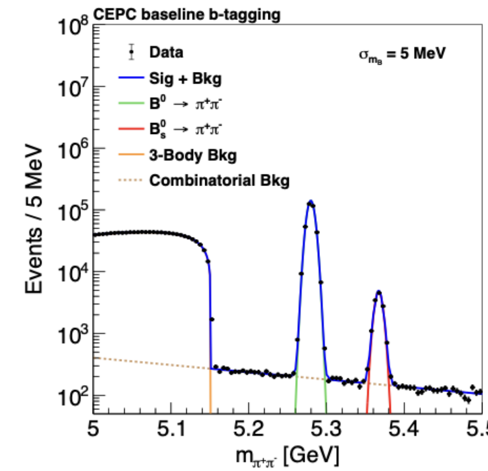
Measurement of α using B0 → 2pi0

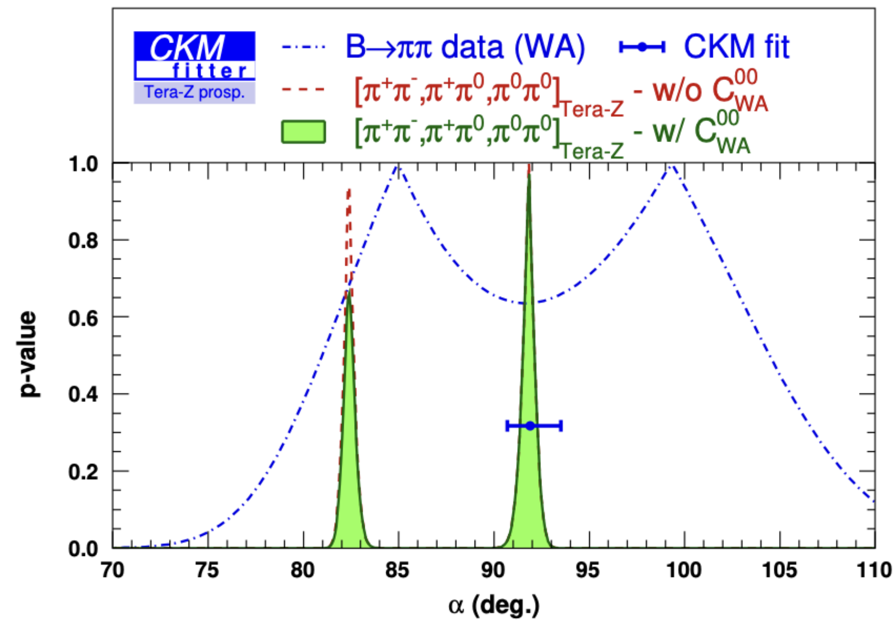
- $B \to \pi\pi$ [JHEP12(2022)135]
  - Z-factory advantages
    - Lower bkg level & better Neutral final state reconstruction (vs LHC)
    - Larger boost of b-hadrons (vs B-factory)
    - Complementary with B-factory in
      - extracting S_{CP}^{00}
      - reducing mirror solutions in α
  - Tera-Z precisions

Parameters	Tera-Z Projection
$\sigma_{\mathcal{B}^{00}}/\mathcal{B}^{00}$	0.45%
$\sigma_{\mathcal{B}^{+0}}/\mathcal{B}^{+0}$	0.19%
$\sigma_{\mathcal{B}^{+-}}/\mathcal{B}^{+-}$	0.18%
$\sigma_{a_{CP}^{00}}$	$\pm$ (0.014–0.018)
$\sigma_{C_{CP}^{+-}}$	$\pm$ (0.004–0.005)
$\sigma_{S_{CP}^{+-}}$	$\pm$ (0.004–0.005)

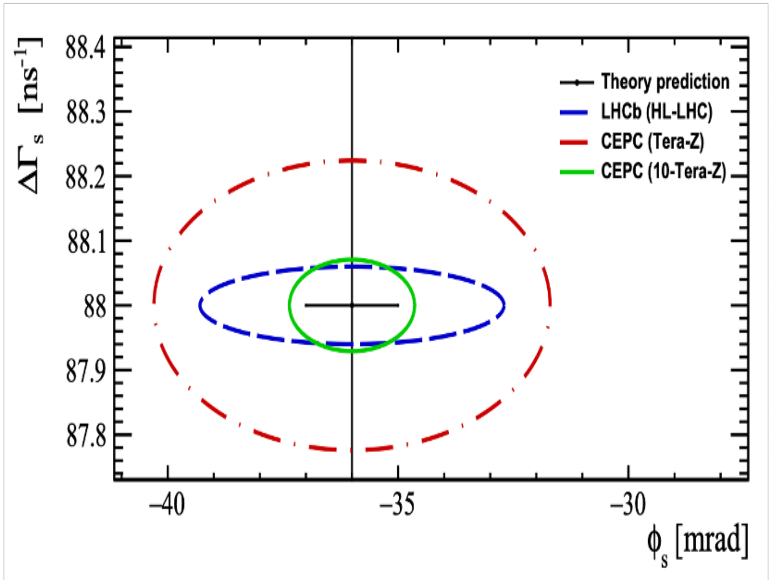
  - σ(α) ≈ 0.4°
  - Prospects
    - Direct extraction of $S_{\pi\pi}^{00}$ via π^0 Dalitz decay or photon conversion



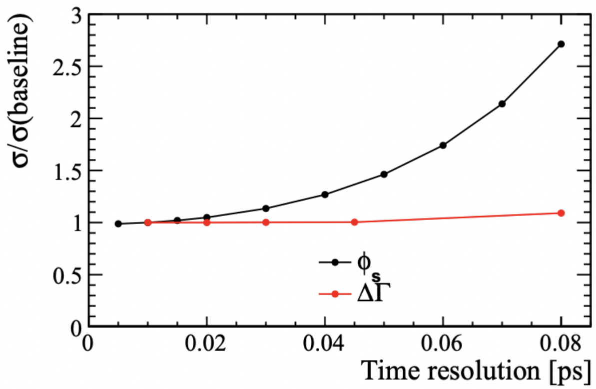


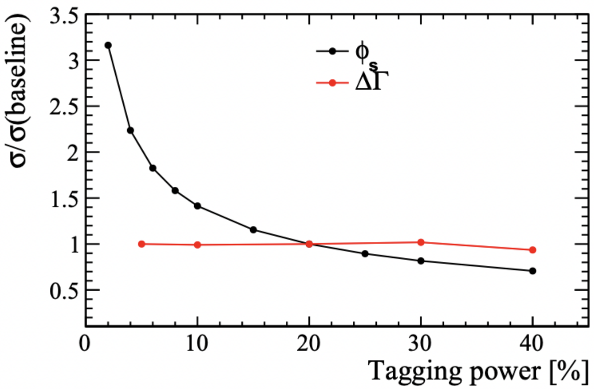


Bs→J/ψϕ



	LHCb(HL-LHC)	CEPC(Tera-Z)	CEPC/LHCb
$b\bar{b}$ statics	43.2×10^{12}	0.152×10^{12}	1/284
Acceptance×efficiency	7%	75%	10.7
Br	6×10^{-6}	12×10^{-6}	2
Flavour tagging	4.7%	20%	4.3
Time resolution $(\exp(-\frac{1}{2}\Delta m_s^2 \sigma_t^2{}^2)$	0.52	1	1.92
scaling factor ξ	0.0014	0.0019	0.8
$\sigma(\phi_s)$	3.3 mrad	4.3 mrad	

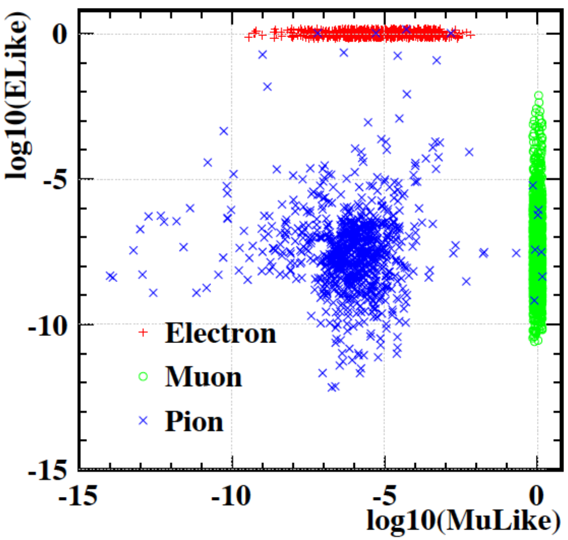


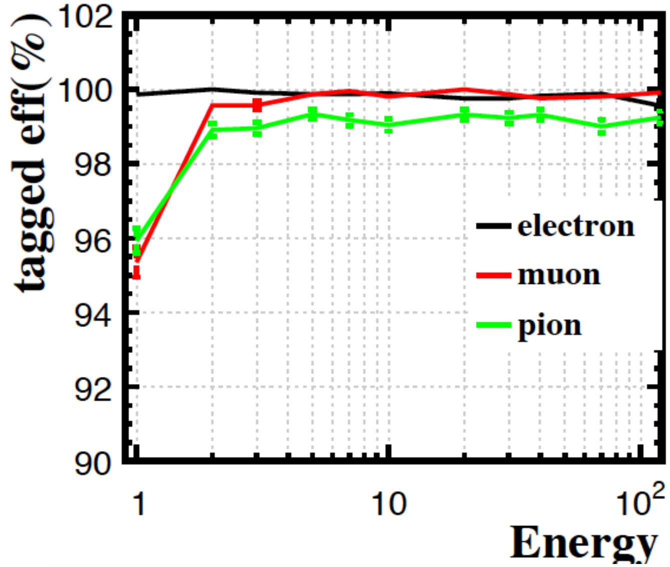


- $B_s \to J/\psi\phi \to \mu\mu KK$ [2205.10565]
  - $\phi_s = -2\beta_s$
  - $\sigma(\phi_s)$ = 4.3 mrad
  - $\sigma(\Delta\Gamma_s)$ = 0.24 ns^{-1}
  - $\sigma(\Gamma_s)$ = 0.072 ns^{-1}

Time resolution ~ o(10) fs

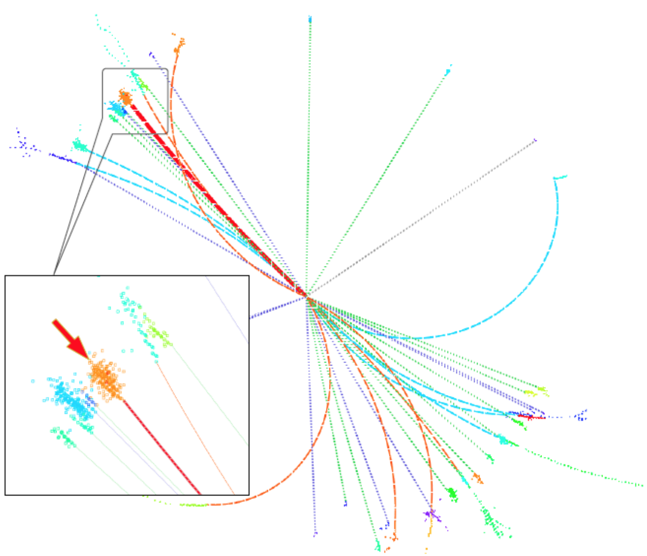
Lepton: isolated & Inside jet

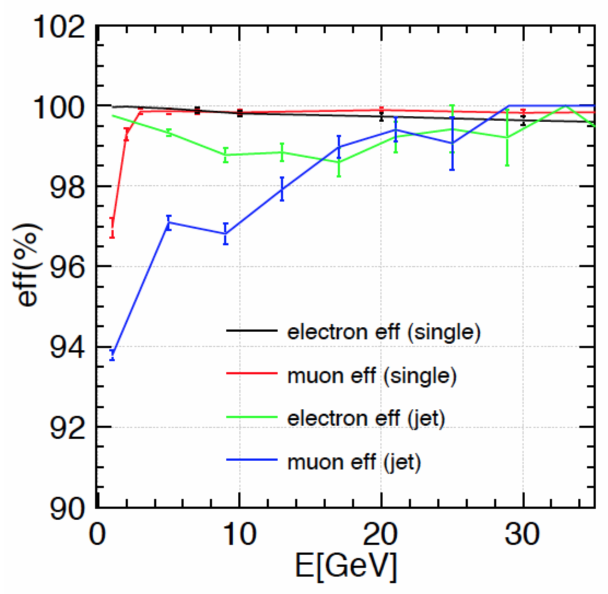


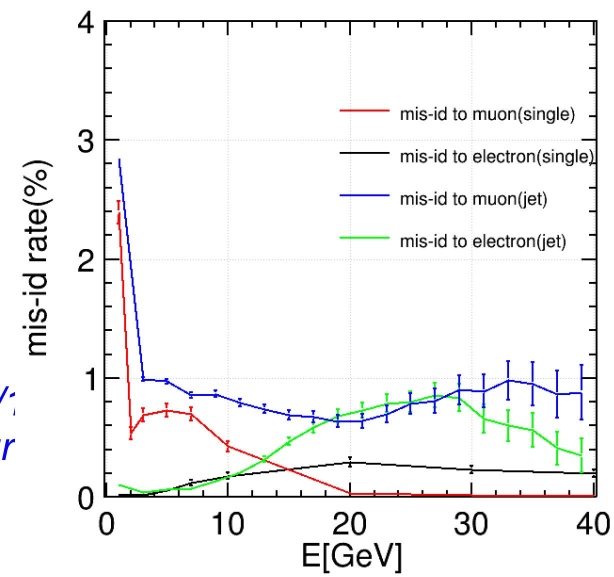


Isolated: for E > 2 GeV:
lepton efficiency > 99.5% &&
Pion mis id rate ~ 1%

Inside Jet: percentage level degrading







Kshort & Lambda

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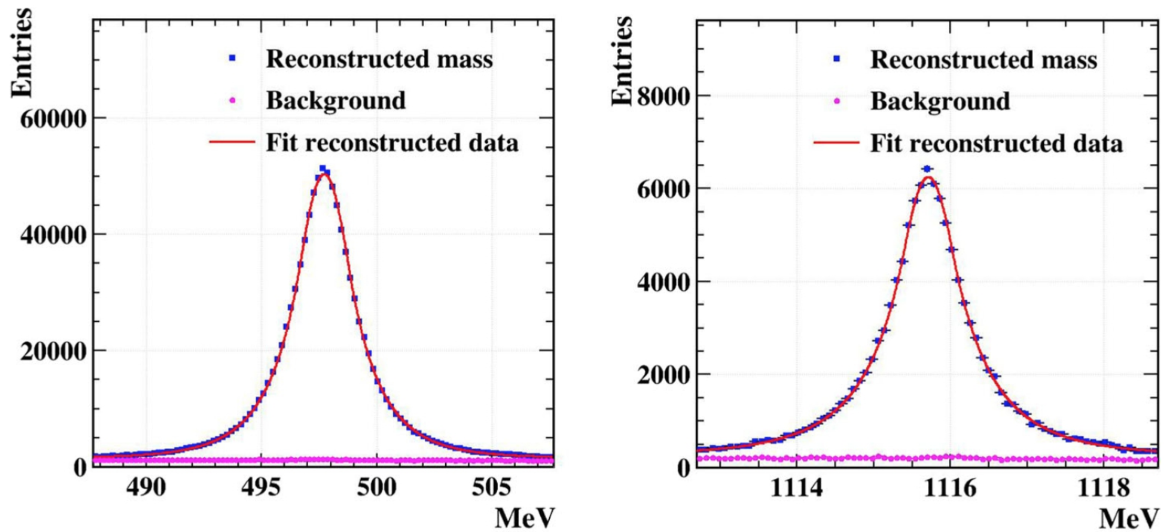
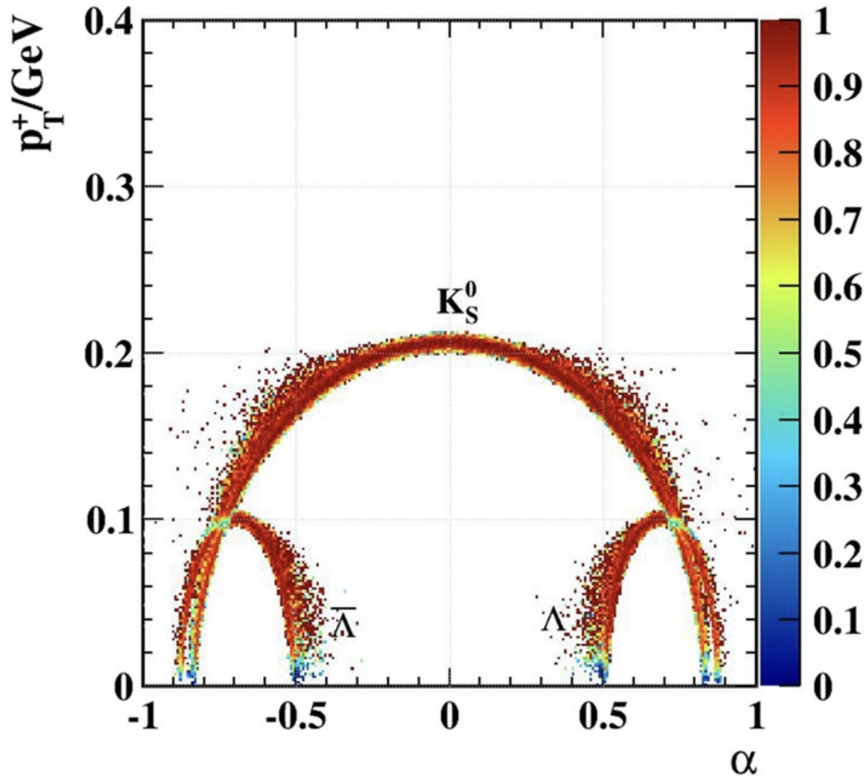


(a) K_S^0 (b) Λ

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

Table 3 K_S^0 and Λ reconstruction performance

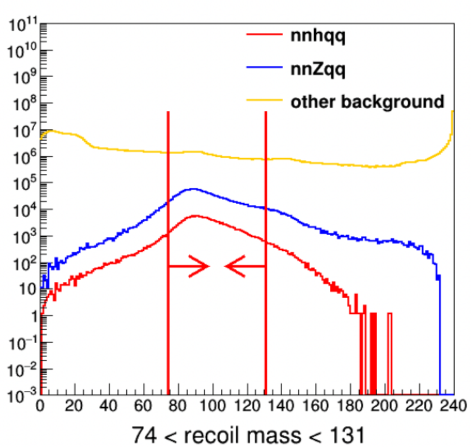
Particle	K_S^0 (%)	Λ (%)
ϵ_R	81.3	70.1
ϵ_T	40.6	27.3
P	92.4%	86.4%
$\epsilon_R \cdot P$	0.751	0.606
$\epsilon_T \cdot P$	0.375	0.236

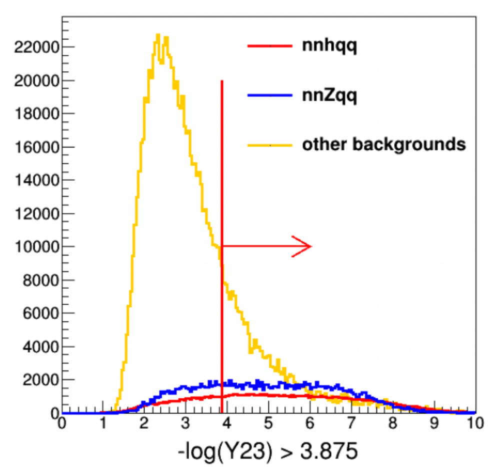


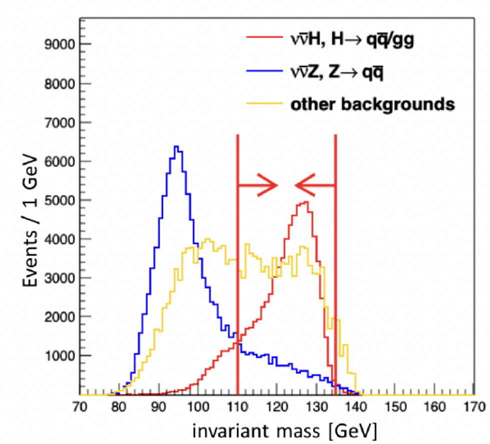
High eff/purity reco. of charged
Final states at least...

Impact on benchmark: ννH, H→jets

	$\nu\nu Hq\bar{q}/gg$	2f	SW	SZ	WW	ZZ	Mixed	ZH	$\frac{\sqrt{S+B}}{S}$ (%)
total	178890	$8.01E8$	$1.95E7$	$9.07E6$	$5.08E7$	$6.39E6$	$2.18E7$	961606	16.86
recoilMass (GeV) $\in (74, 131)$	157822	$5.11E7$	$2.17E6$	$1.38E6$	$4.78E6$	$1.30E6$	$1.08E6$	74991	4.99
visEn (GeV) $\in (109, 143)$	142918	$2.37E7$	$1.35E6$	$8.81E5$	$3.60E6$	$1.03E6$	$6.29E5$	50989	3.92
leadLepEn (GeV) $\in (0, 42)$	141926	$2.08E7$	$3.65E5$	$7.24E5$	$2.81E6$	$9.72E5$	$1.34E5$	46963	3.59
multiplicity $\in (40, 130)$	139545	$1.66E7$	$2.36E5$	$5.24E5$	$2.62E6$	$9.07E5$	4977	42751	3.29
leadNeuEn (GeV) $\in (0, 41)$	138653	$1.46E7$	$2.24E5$	$4.72E5$	$2.49E6$	$8.69E5$	4552	42303	3.12
Pt (GeV) $\in (20, 60)$	121212	248715	$1.56E5$	$2.48E5$	$1.51E6$	$4.31E5$	999	35453	1.37
Pl (GeV) $\in (0, 50)$	118109	52784	$1.05E5$	74936	$7.30E5$	$1.13E5$	847	34279	0.94
-log10(Y23) $\in (3.375, +\infty)$	96156	40861	26088	60349	$2.25E5$	82560	640	10691	0.76
InvMass (GeV) $\in (116, 134)$	71758	22200	11059	6308	77912	13680	248	6915	0.64
BDT $\in (-0.02, 1)$	60887	9140	266	2521	3761	3916	58	1897	0.47

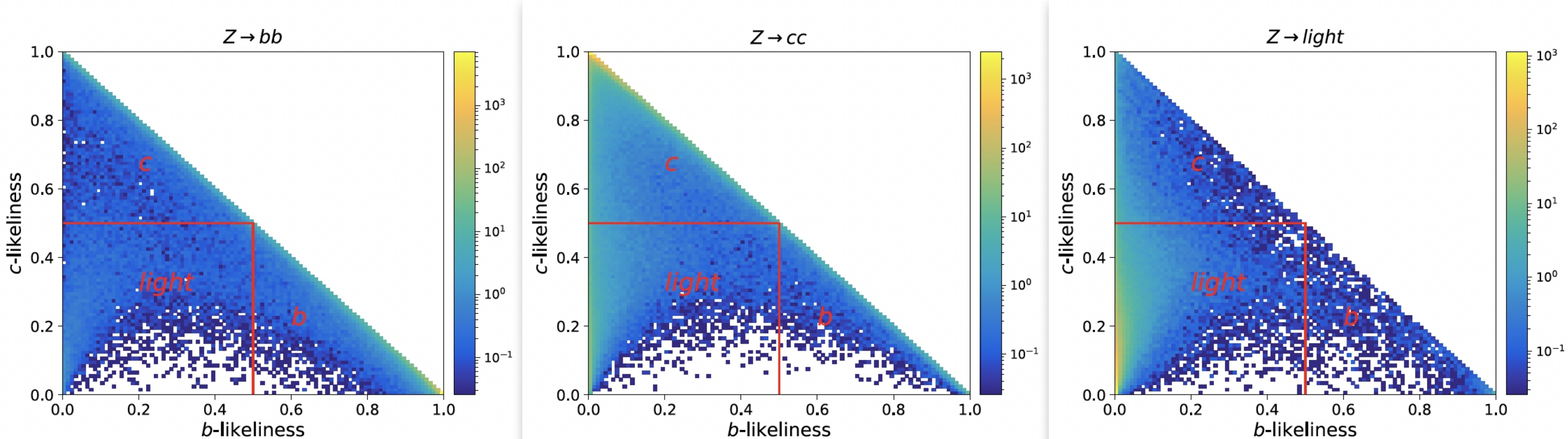






Thanks to BMR ~ 3.8%!

Three categories: b, c, & light



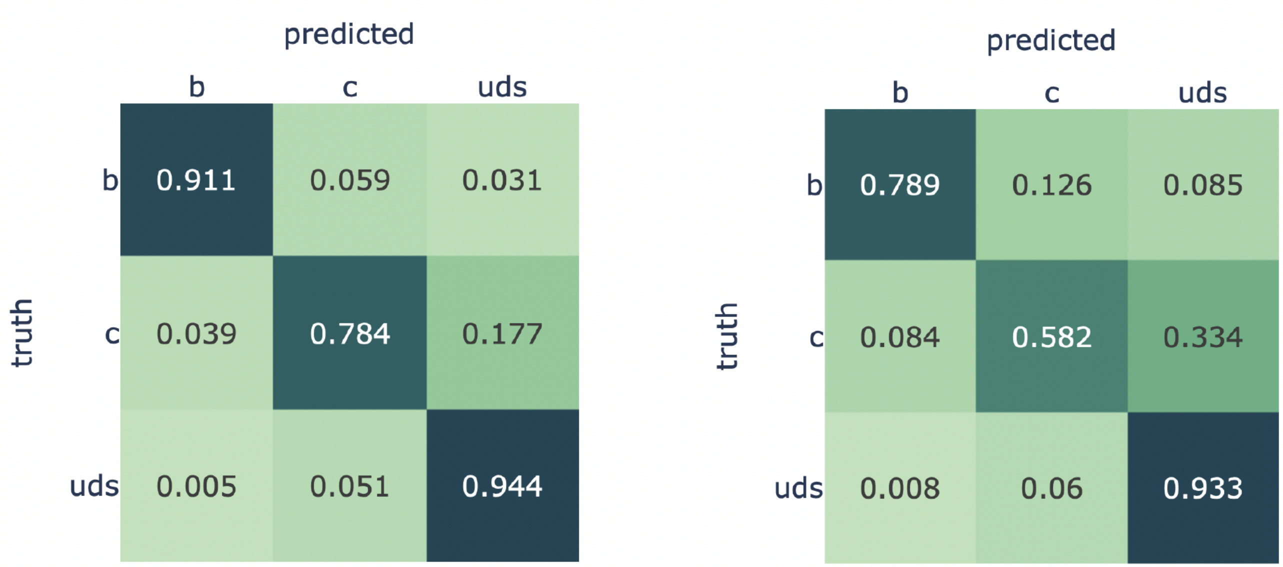
Hadronic Z pole sample

1 M Z→bb, cc, (uds) each

60/20/20% for

training/validating/testing.

Result on Testing sample



ParticleNet (left):

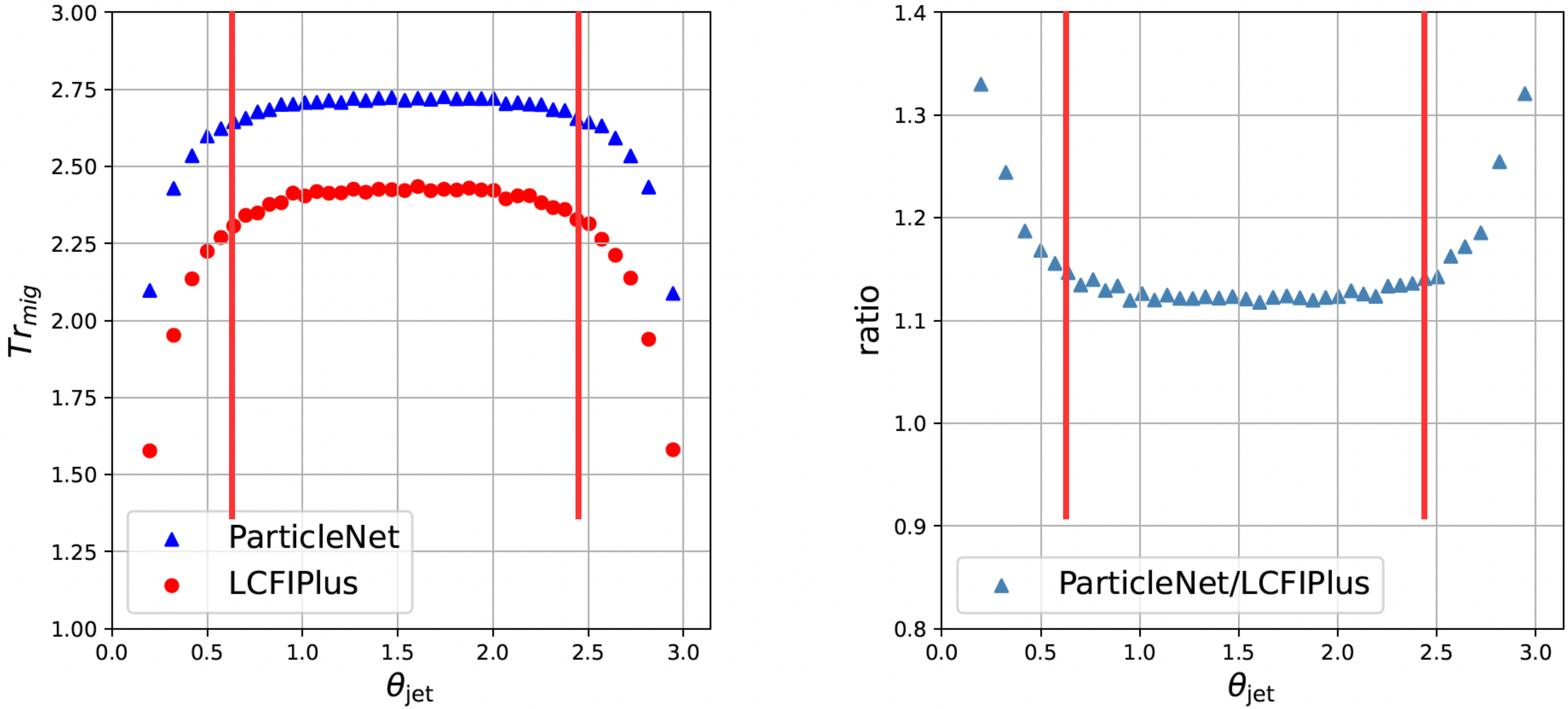
truth \ predicted	b	c	uds
b	0.911	0.059	0.031
c	0.039	0.784	0.177
uds	0.005	0.051	0.944

LCFIPlus (right):

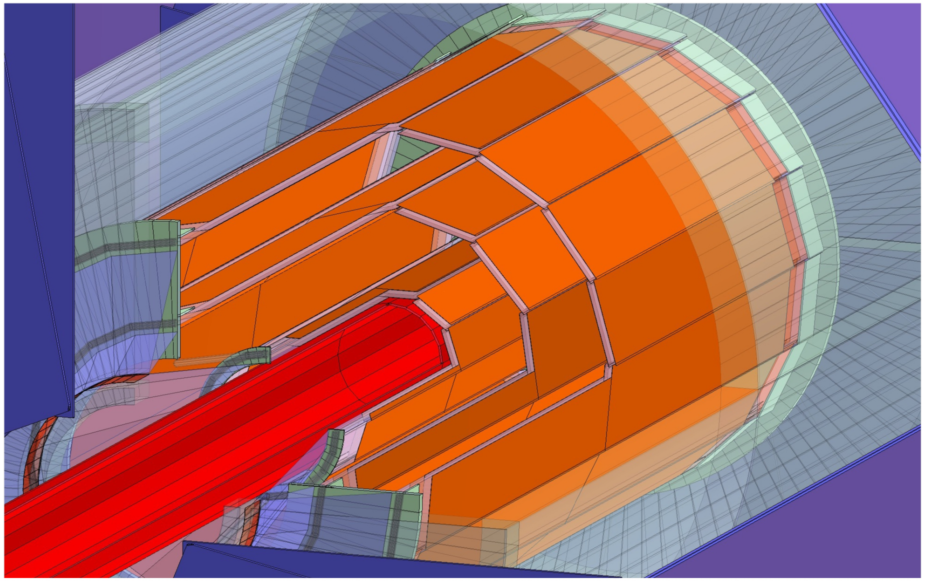
truth \ predicted	b	c	uds
b	0.789	0.126	0.085
c	0.084	0.582	0.334
uds	0.008	0.06	0.933

Figure 7. The migration matrix of ParticleNet (left) and LCFIPlus (right) at the CEPC.

Dependence on polar angle

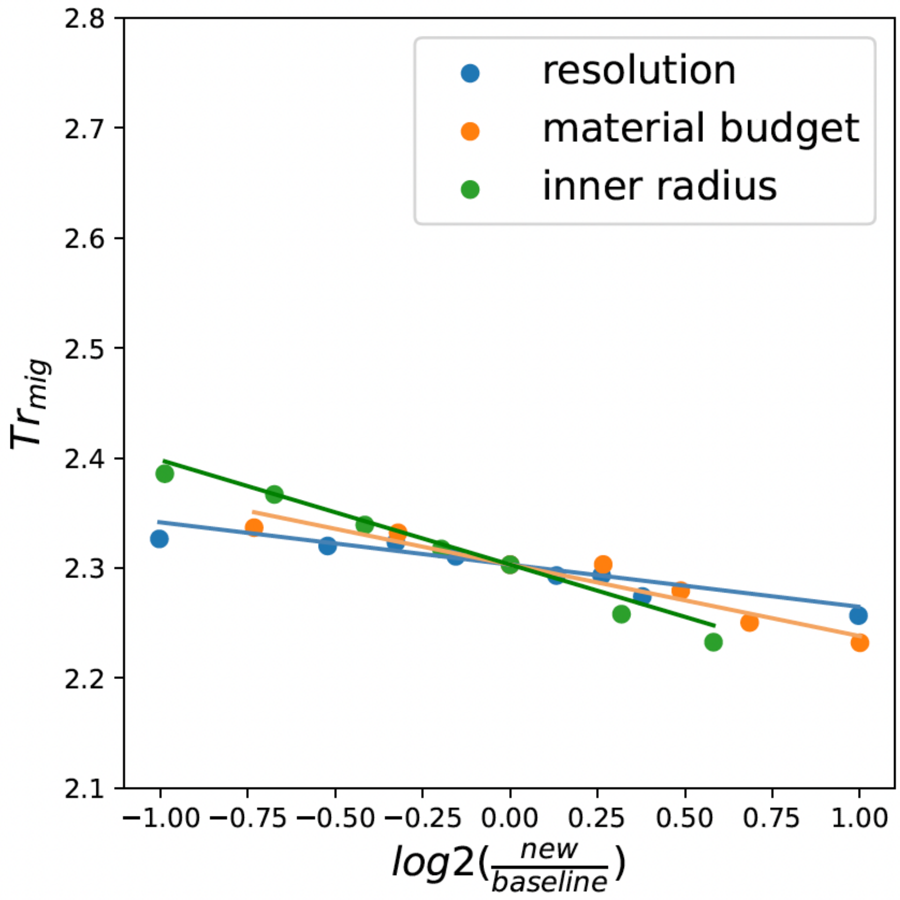


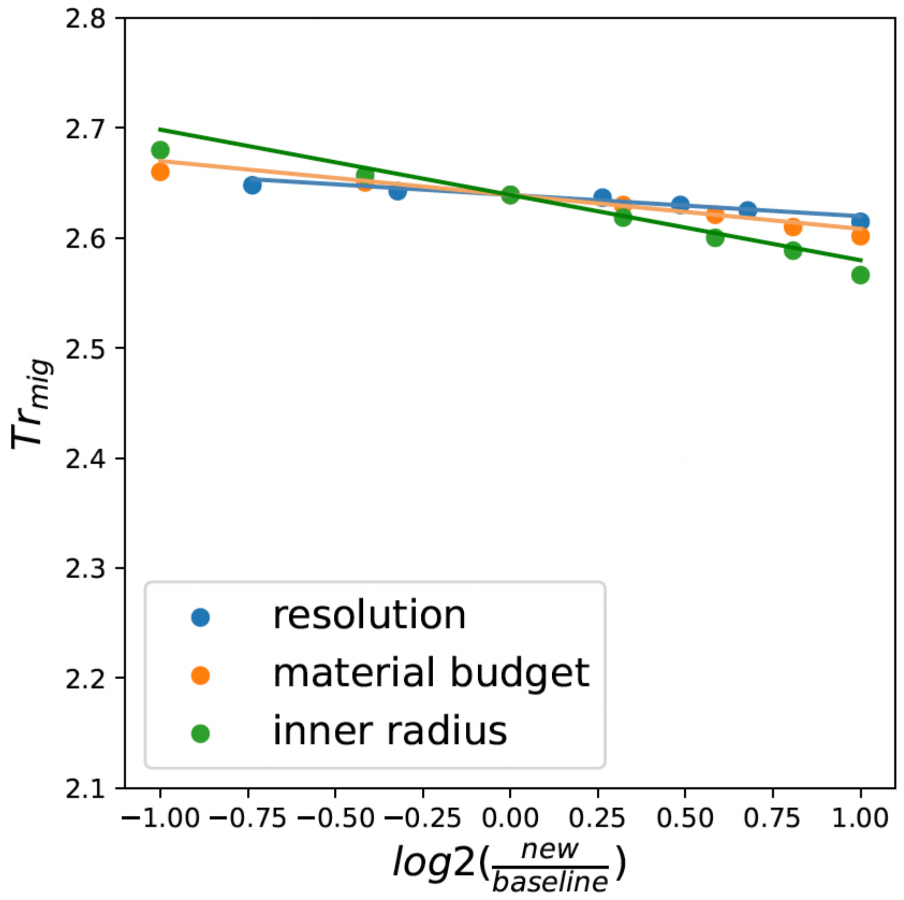
Comparison on Det. Optimization



	R (mm)	sigle-point resolution (μm)	material budget
Layer 1	16	2.8	$0.15\%/X_0$
Layer 2	18	6	$0.15\%/X_0$
Layer 3	37	4	$0.15\%/X_0$
Layer 4	39	4	$0.15\%/X_0$
Layer 5	58	4	$0.15\%/X_0$
Layer 6	60	4	$0.15\%/X_0$

Comparison on Det. Optimization



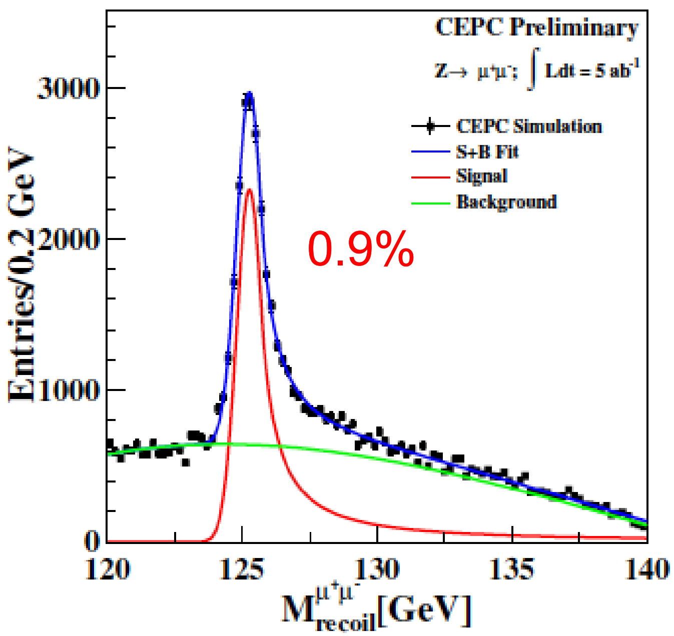


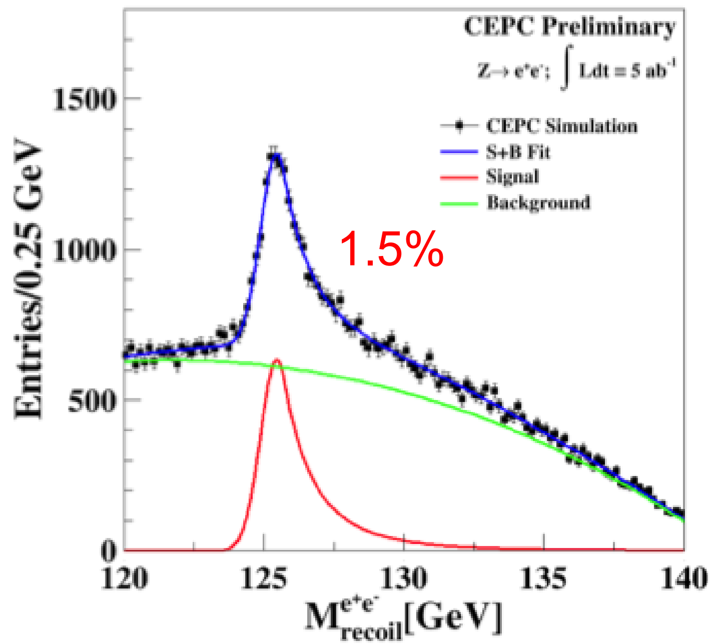
$$Tr_{mig} = 2.30 + 0.06 \cdot log_2 \frac{R^0_{material}}{R_{material}} + 0.04 \cdot log_2 \frac{R^0_{resolution}}{R_{resolution}} + 0.10 \cdot log_2 \frac{R^0_{radius}}{R_{radius}} \quad (4.1)$$

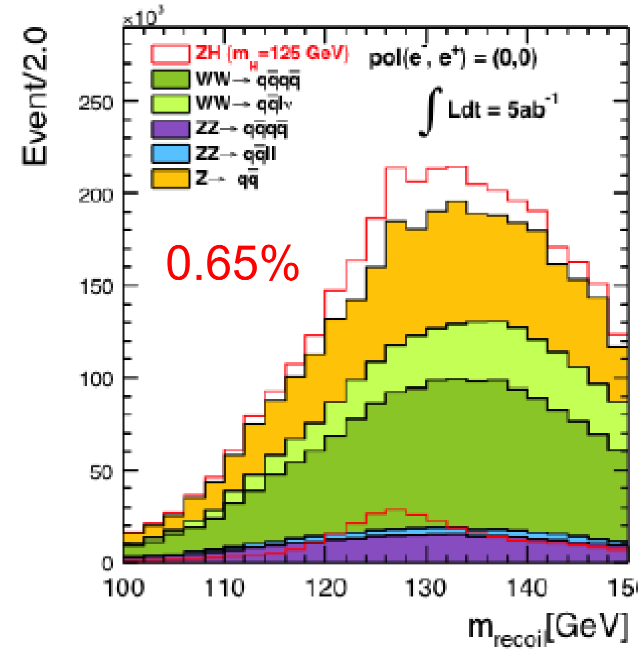
$$Tr_{mig} = 2.64 + 0.03 \cdot log_2 \frac{R^0_{material}}{R_{material}} + 0.02 \cdot log_2 \frac{R^0_{resolution}}{R_{resolution}} + 0.06 \cdot log_2 \frac{R^0_{radius}}{R_{radius}} \quad (4.2)$$

Model-independent measurement of σ(ZH)

Zhenxing Chen & Yacine Haddad

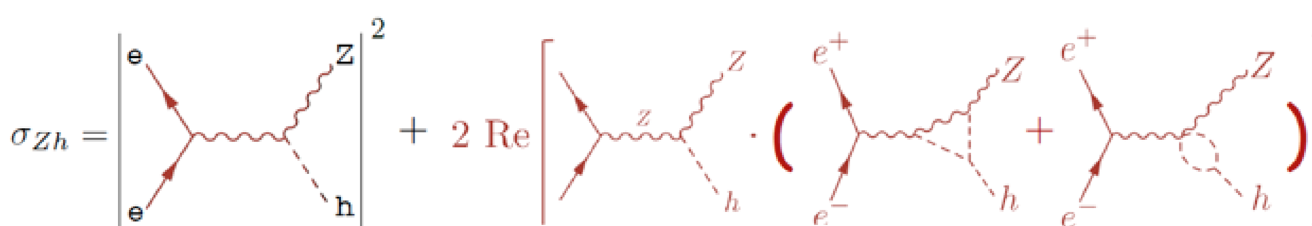






- Recoil mass method. Combined precision:
  δσ(ZH)/σ(ZH) = 0.5% -
  δg(HZZ)/g(HZZ) = 0.25%

- Indirect Access to g(HHH)



$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

- *M. McCullough, 1312.3322*

Higgs benchmark analyses

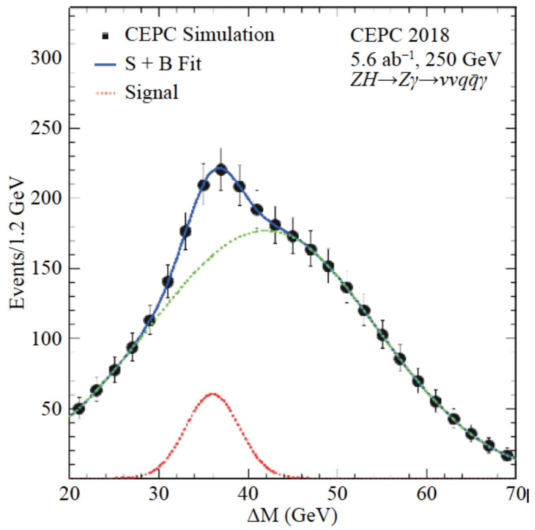
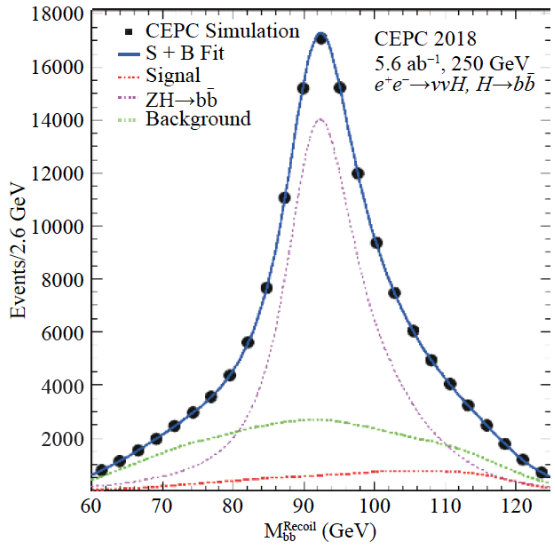
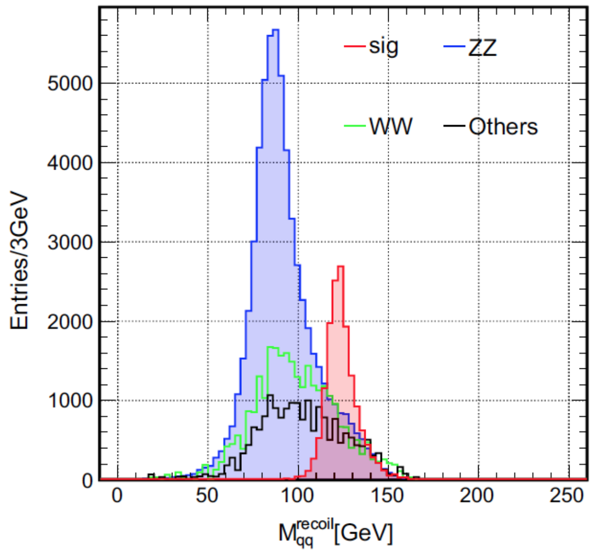
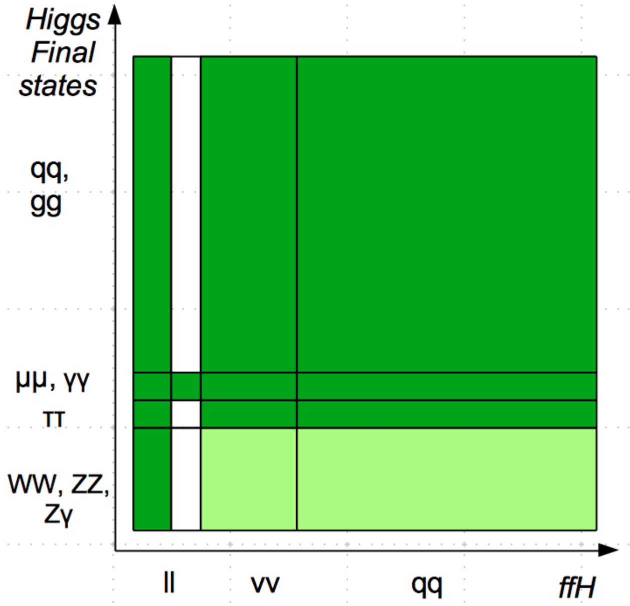
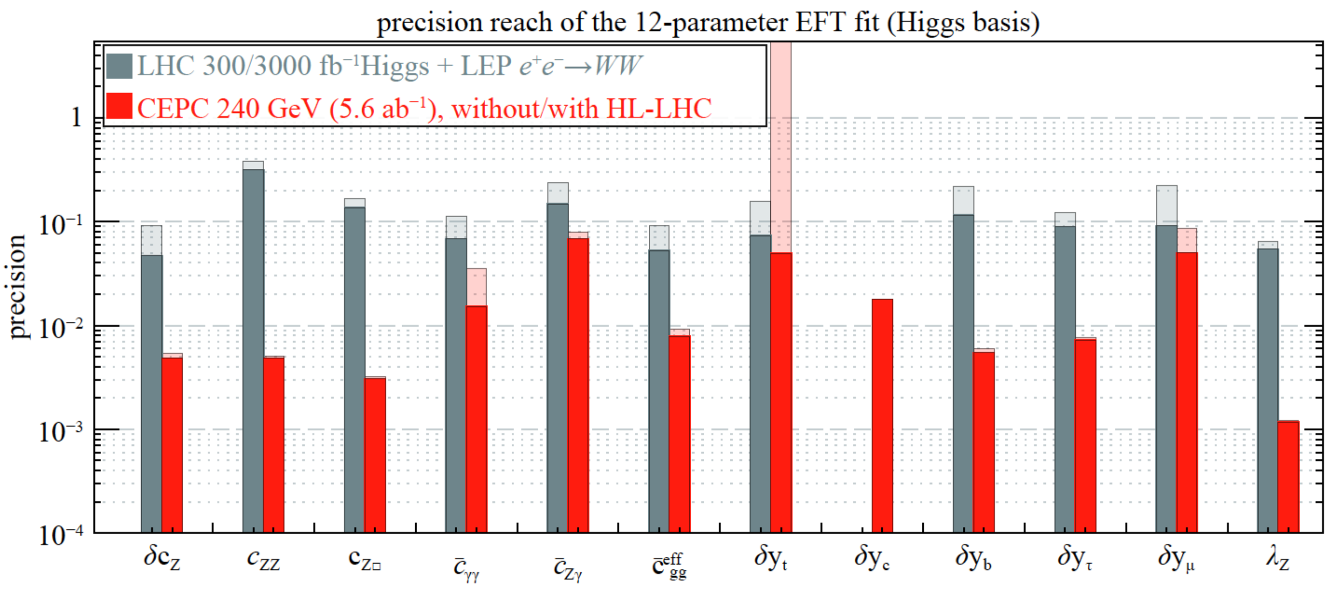


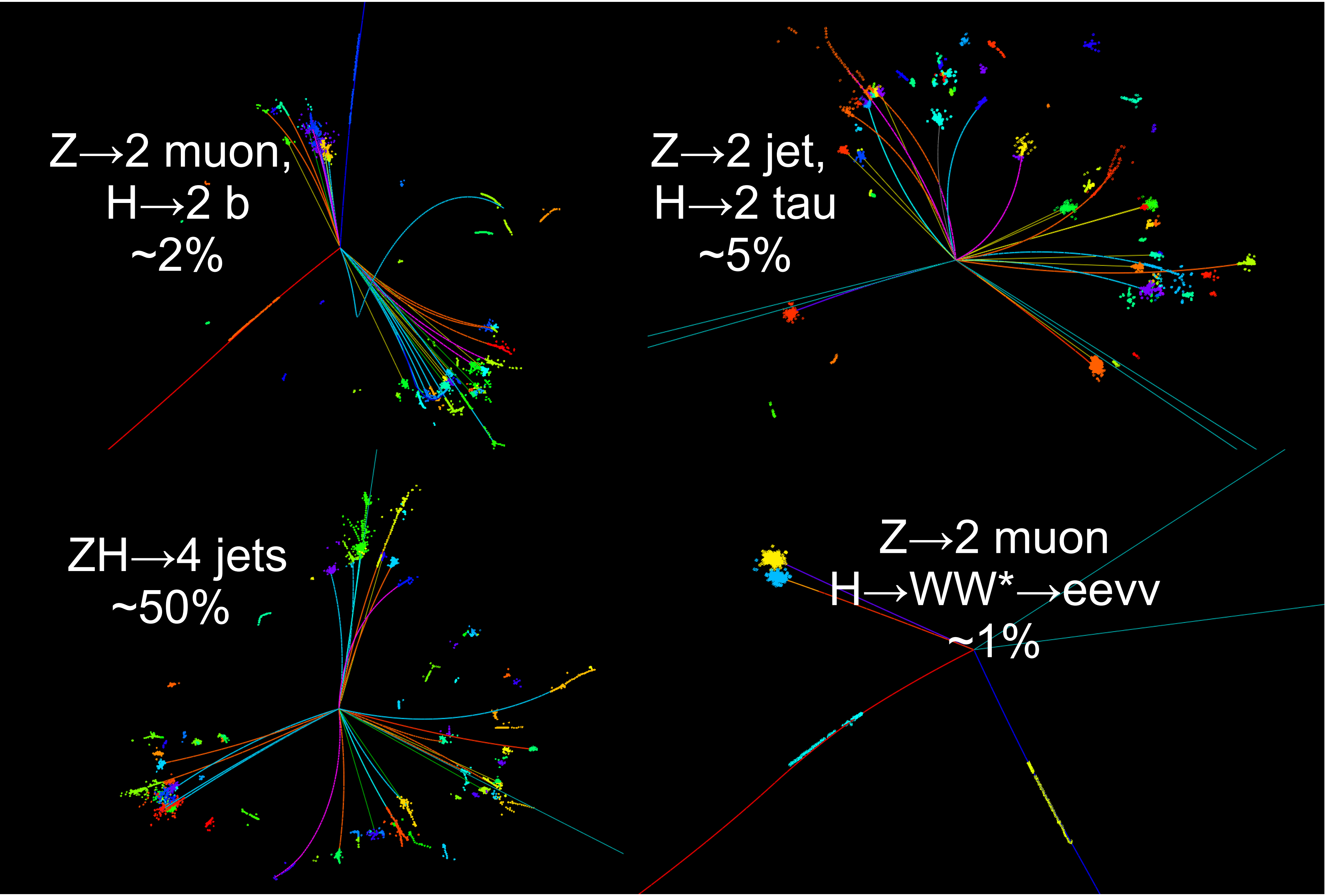
Fig. 15. (color online) The distribution of the mass differ-







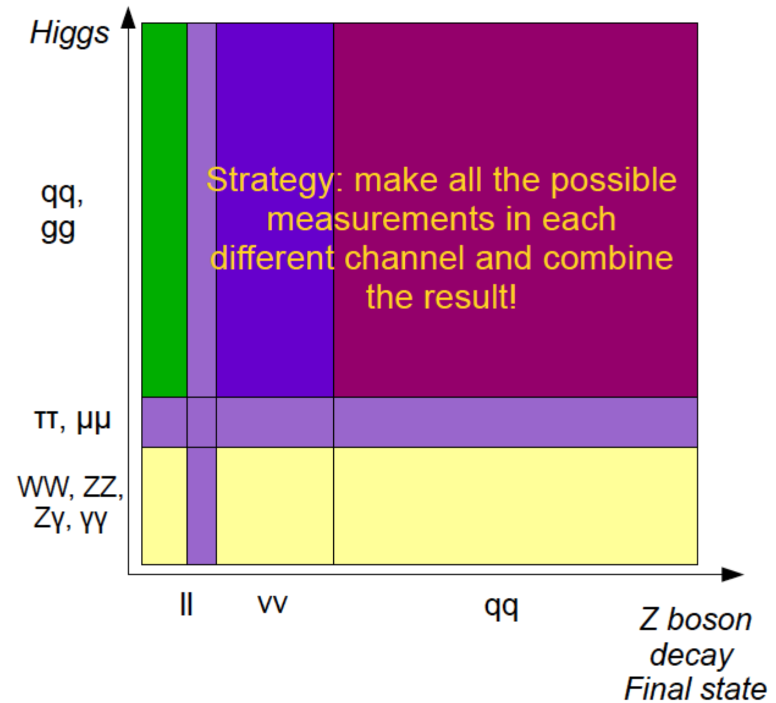


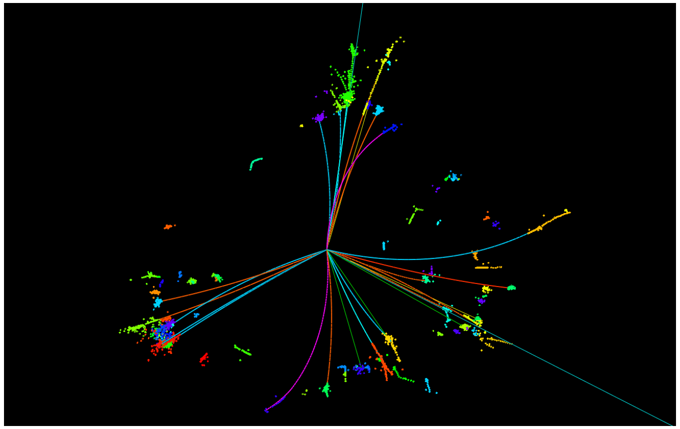


Z→2 muon,
H→2 b
~2%
Z→2 jet,
H→2 tau
~5%
ZH→4 jets
~50%
Z→2 muon
H→WW*→eevv
~1%

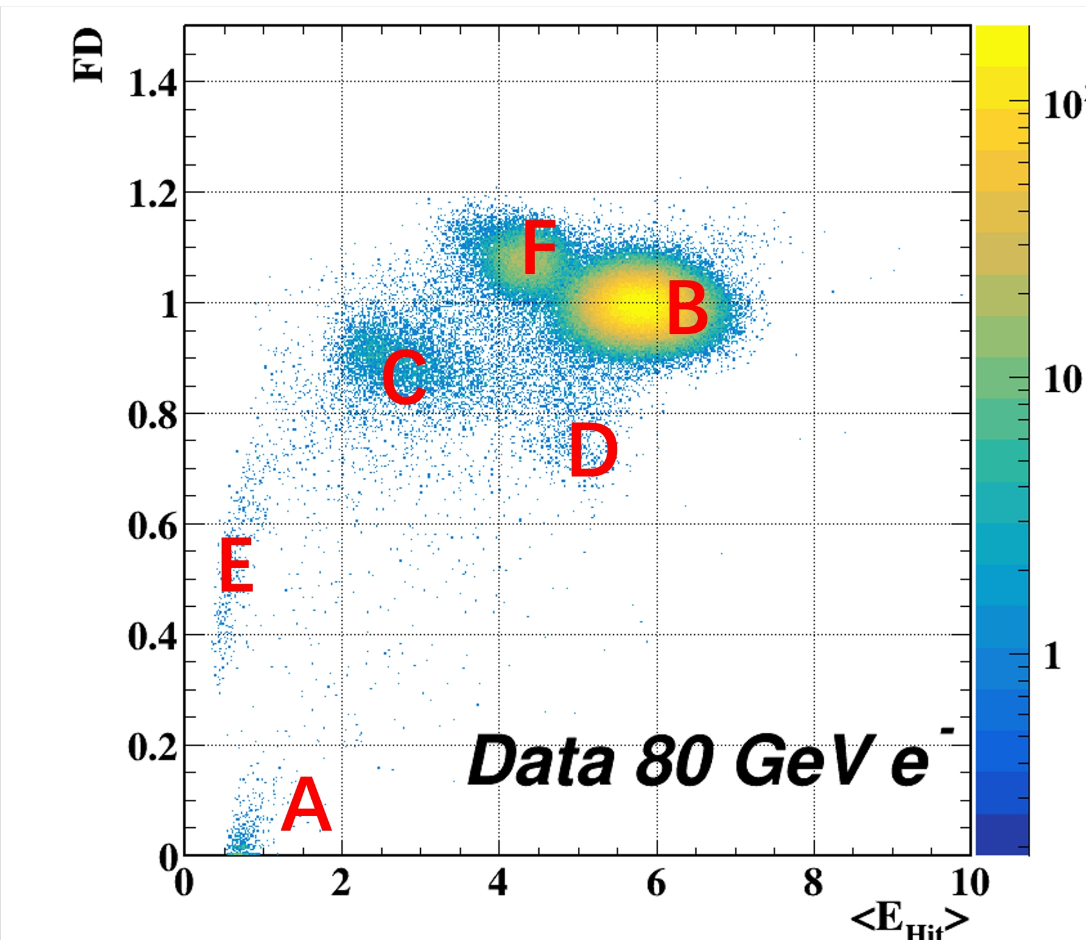
Hadronic system (jet)

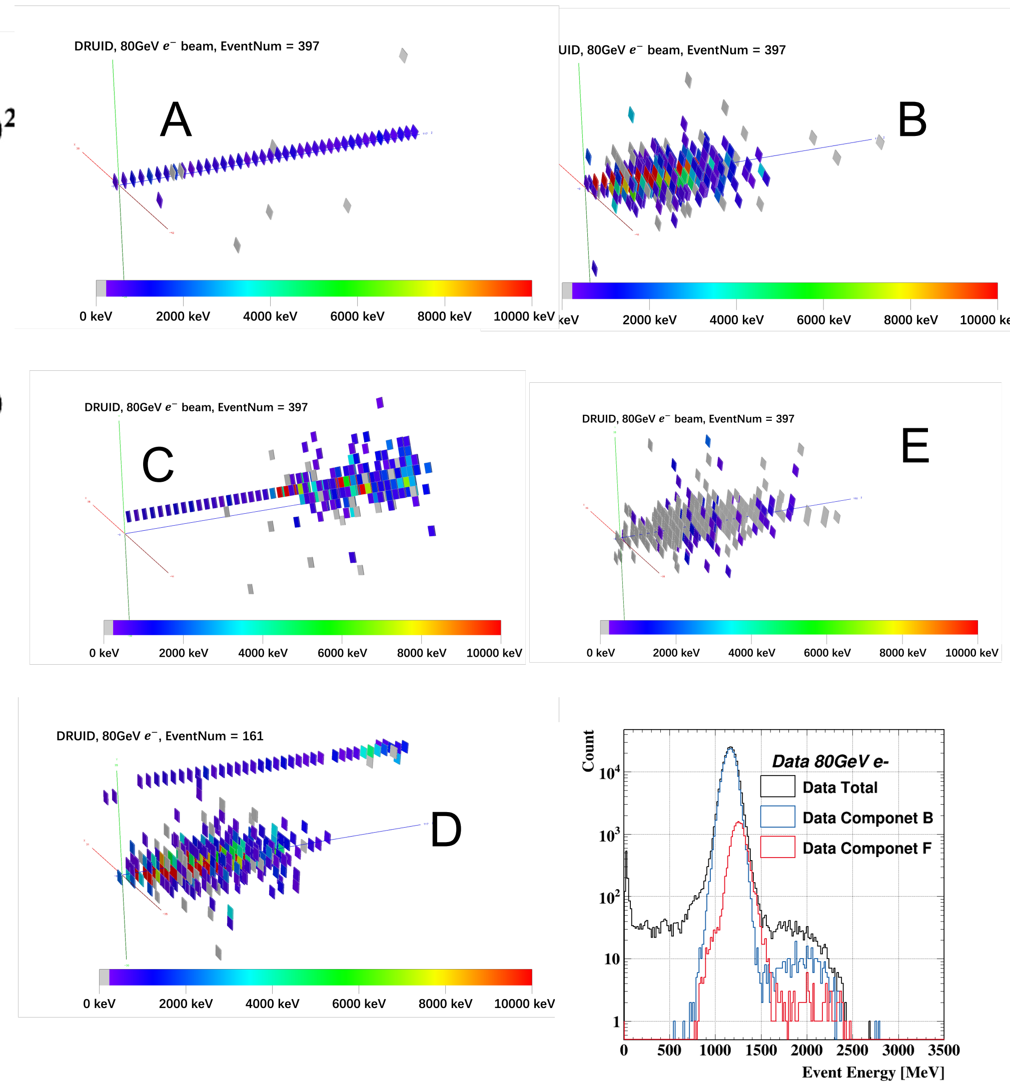
- Core of e+e- Higgs factory Physics measurements
  - 97% of CEPC Higgs events are hadronic/semi-leptonic
- Identify the hadronic system in semi-leptonic events
  - lepton identification & missing energy
- 4-momentum measurement of the hadronic system: BMR: Invariant Mass Resolution
- Jet response: essential for differential measurements
  - Color-singlet identification Identify the origin of each final state particle: Jet Clustering & Matching, or beyond?





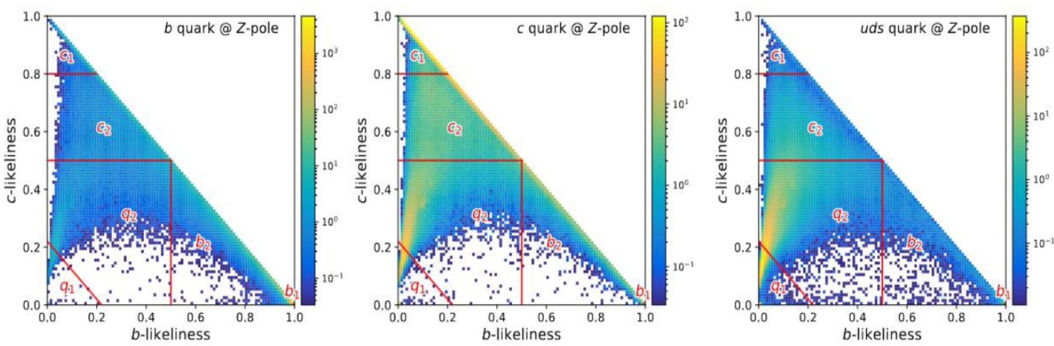
Test beam at CERN





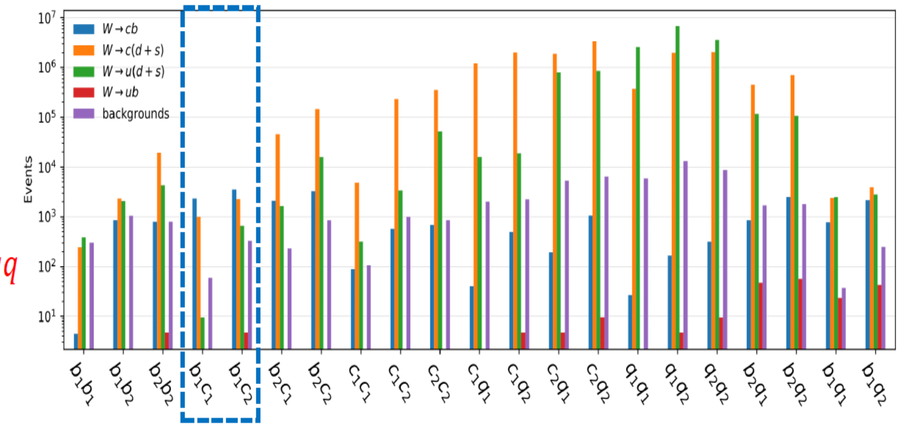
- CALICE

Vcb from W decay

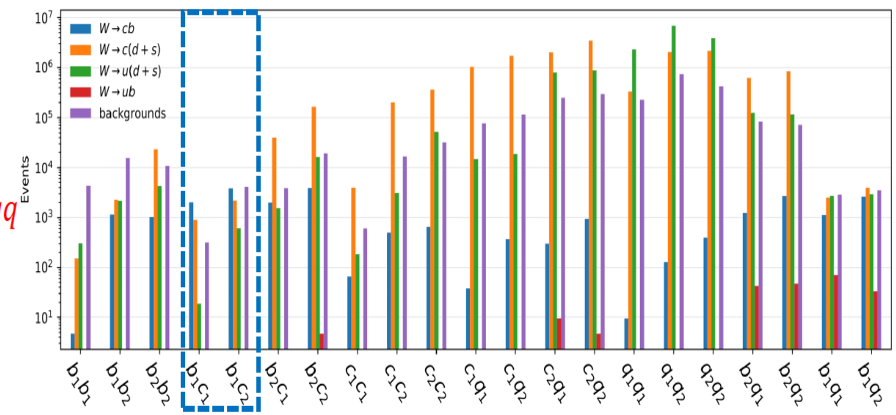


quark \ tag	b_1	b_2	c_1	c_2	q_1	q_2
b	0.47	0.378	0.0197	0.0965	0.00397	0.0315
c	0.00042	0.078	0.298	0.373	0.0682	0.182
uds	0.000104	0.00477	0.00145	0.054	0.538	0.401

$\mu\nu qq$



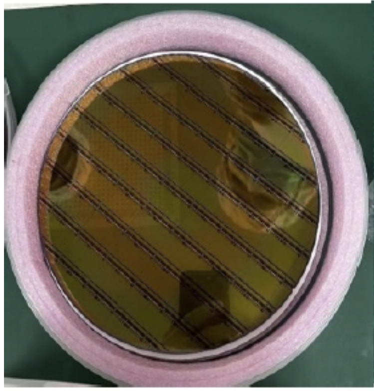
$e\nu qq$

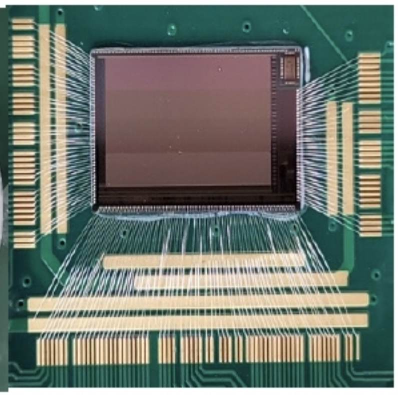


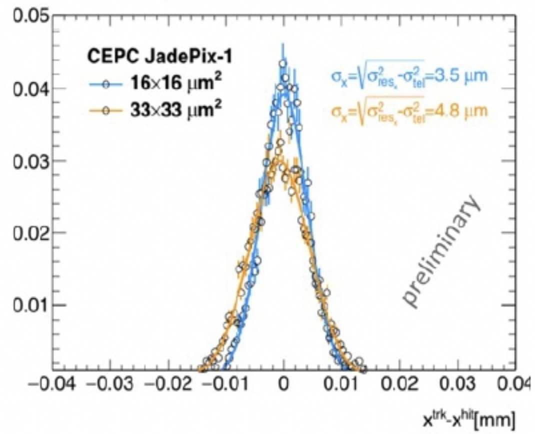
- $\mu\nu qq$
  - Statistical (relative) error: 1.5%, 3.4E-4, 3.4E-4
  - $|V_{cb}|$ Statistical error: 0.75%
- $e\nu qq$
  - statistical (relative) error: 1.7%, 3.7E-4, 3.7E-4
  - $|V_{cb}|$ Statistical error: 0.85%

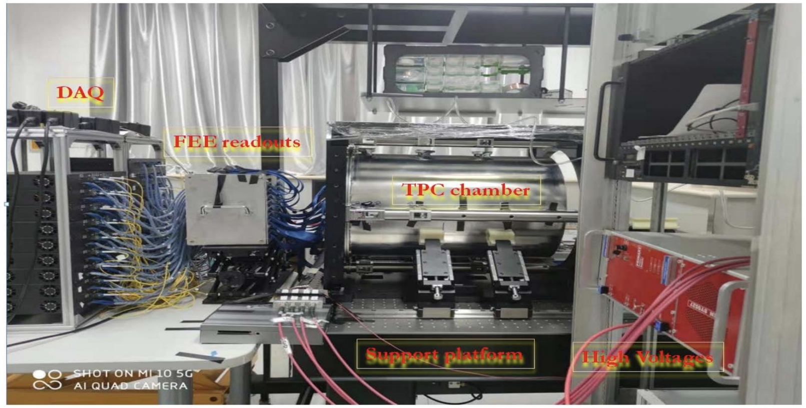
Detector study

Vertex detector R & D (3- 5 μm reso.)



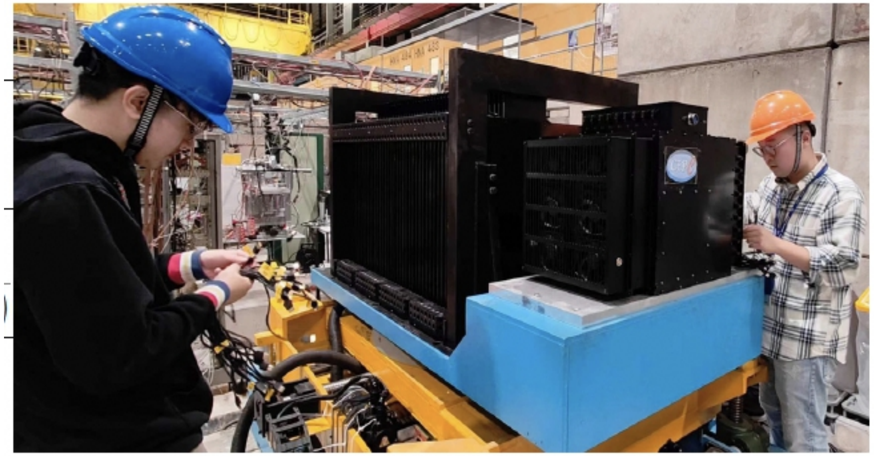




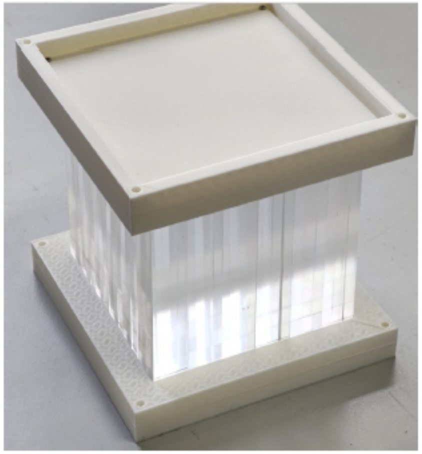


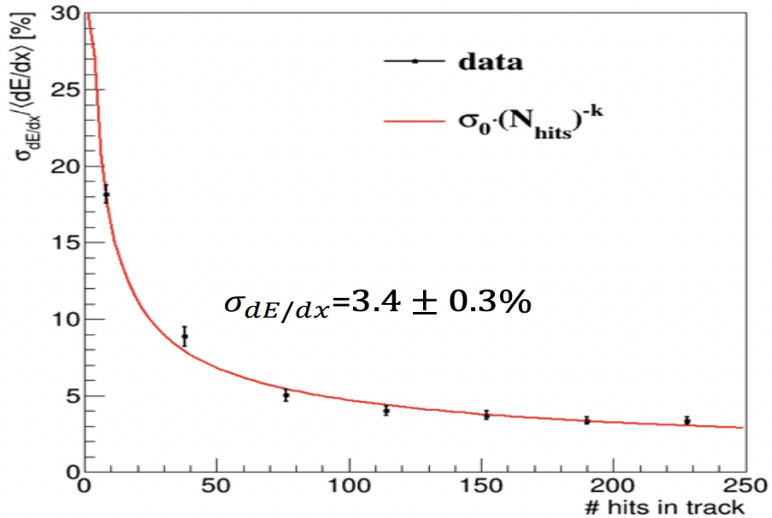
TPC prototype integrated with 266nm UV laser tracks

PFA scintillator-W ECAL

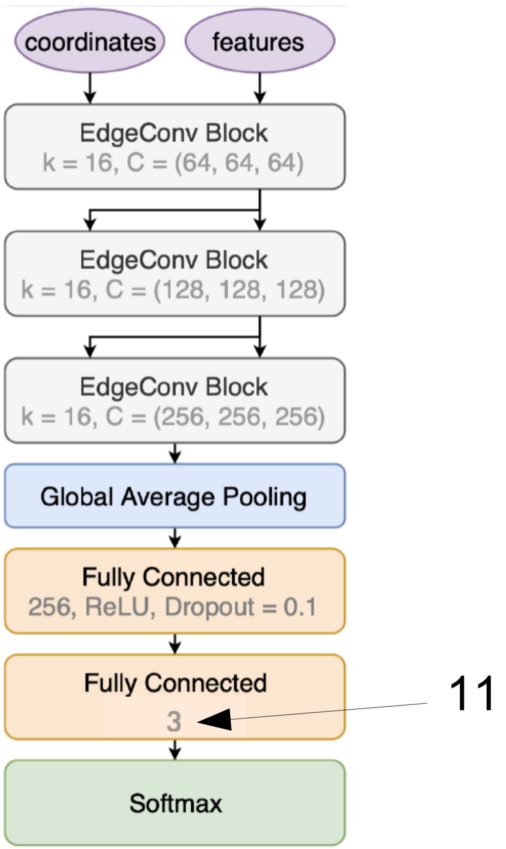


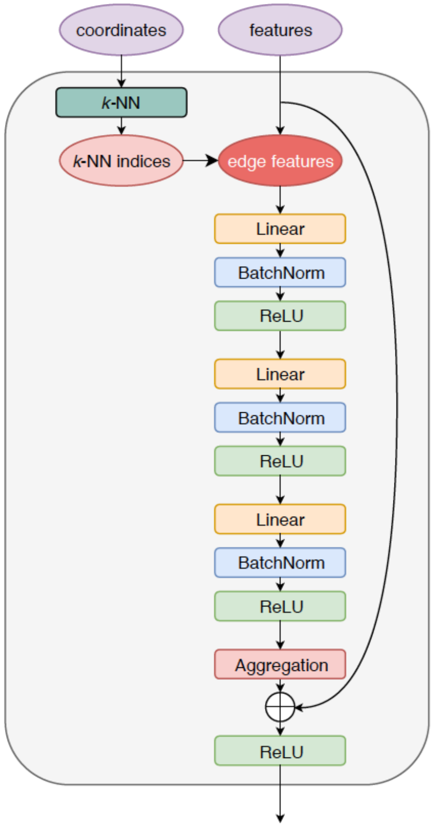
4D crystal ECAL





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: reco particles corresponding to 1 jet...
- Output: likelihoods to 11 different categories (sum =1)