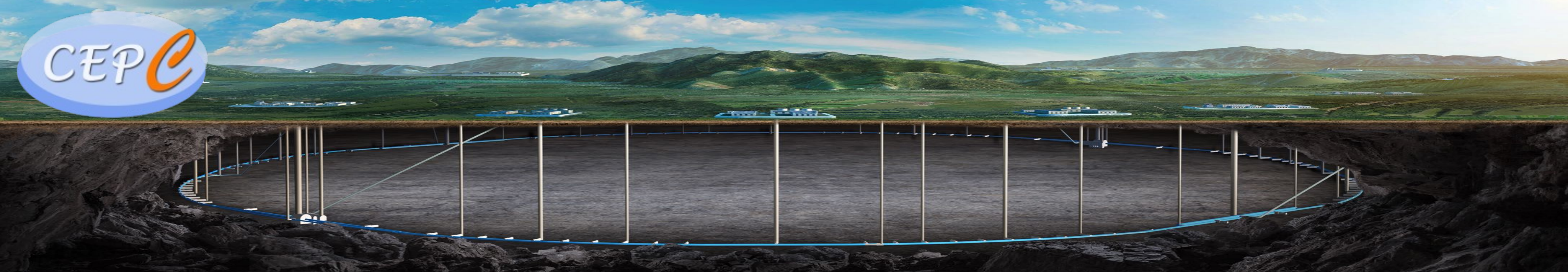

Physics Benchmarks & Global Performance

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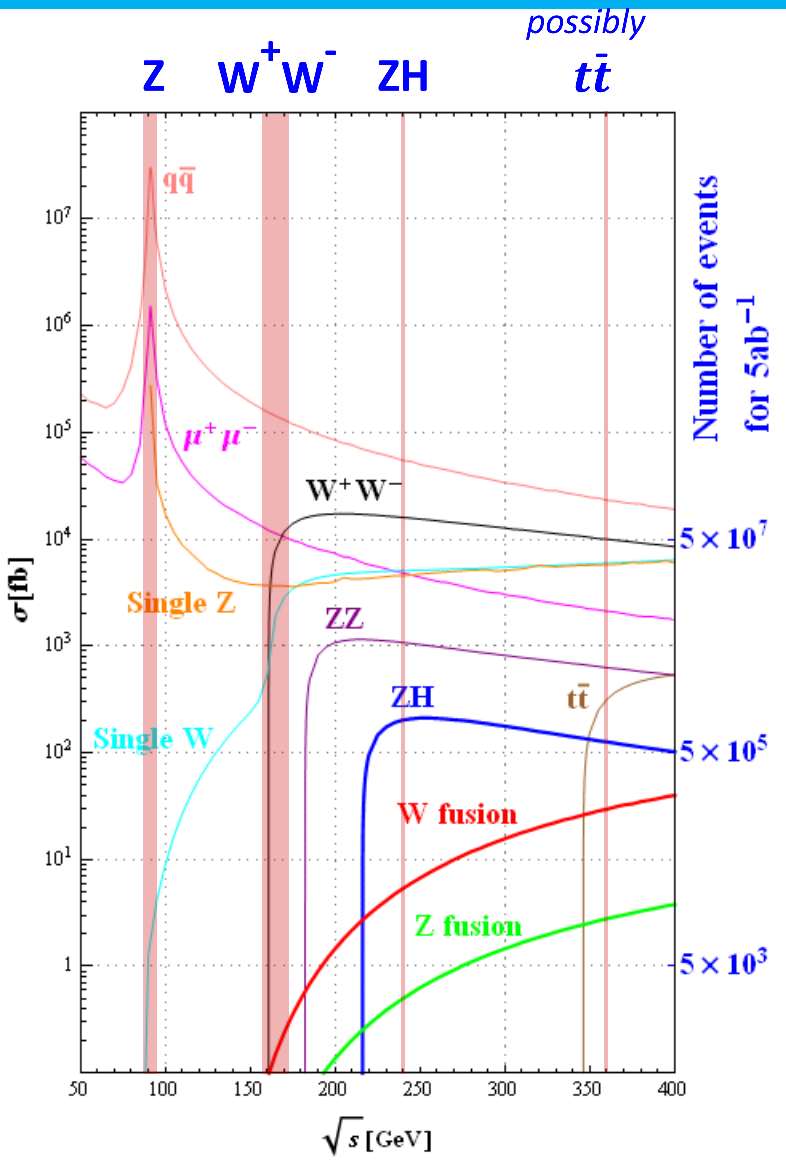
Institute of High Energy Physics
Chinese Academy of Sciences

Content

- Introduction: CEPC Physics
- Physics Benchmarks & Global Performance
  - Key detector requirements
  - Algorithm development: Jet Origin ID & its application
- Physics Benchmarks Reach with CDR detector for reference
- Global Performance of Ref-TDR detector
- Physics Benchmarks Prospect at Ref-TDR
- Challenges, Plan, and Team
- Summary

Operation Plan from Acc. TDR



Operation mode		ZH	Z	W^+W^-	$t\bar{t}$
$\sqrt{s}$ [GeV]		~240	~91	~160	~360
Run Time [years]		10	2	1	5
30 MW	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	**5.0**	**115**	**16**	**0.5**
	$\int L\,dt$ [ab^{-1}, 2 IPs]	13	60	4.2	0.65
	Event yields [2 IPs]	2.6×10^{6}	2.5×10^{12}	1.3×10^{8}	4×10^{5}
50 MW	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	**8.3**	**192**	**26.7**	**0.8**
	$\int L\,dt$ [ab^{-1}, 2 IPs]	21.6	100	6.9	1
	Event yields [2 IPs]	4.3×10^{6}	4.1×10^{12}	2.1×10^{8}	6×10^{5}

CEPC accelerator TDR (Xiv:2312.14363)

While aiming to meet the needs of the whole energy range, emphasizes more on the Higgs operation mode.

CEPC physics

Higgs

m_H, σ, Γ_H
self-coupling
H→ bb, cc, ss, gg
H→inv, H→sb, ...

Flavor

CKM matrix
CPV measurements
LFV, LUV
τ properties (lifetime, BRs..)
$B_c \to \tau\, \nu$, $B_s \to D_s\, K/\pi$
$B_s \to K^* \tau\, \tau$, $B \to K^*\, \nu\, \nu$
$B_s \to \varphi\, \nu\, \nu$ …

4 million Higgs
4 trillion Z bosons
200 million W pairs
600 k ttbar

Top

m_{top}, Γ_{top},
top quark coupling,
...

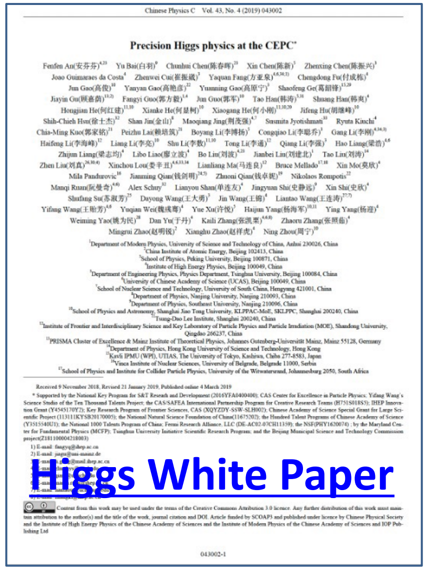
BSM

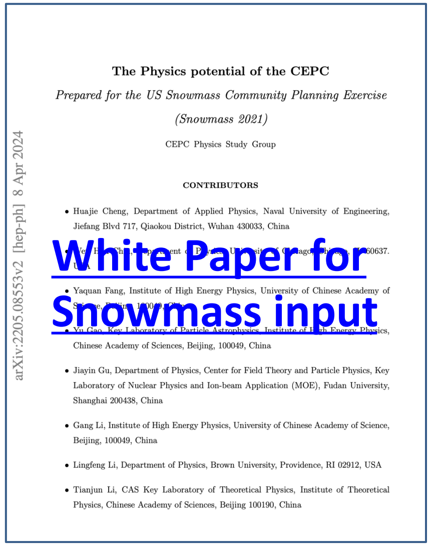
Heavy Neutral Leptons
Dark Photons Z_D
Axion Like Particles
Exotic Higgs decays
...

EWK/QCD

m_Z , Γ_Z , Γ_{inv}
$\sin^2\theta_W$, m_W, Γ_W ,
$A_{FB}^{b,c}$, τ pol.
α_S ,....

CEPC physics





Higgs

m_H, σ, Γ_H
self-coupling
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...

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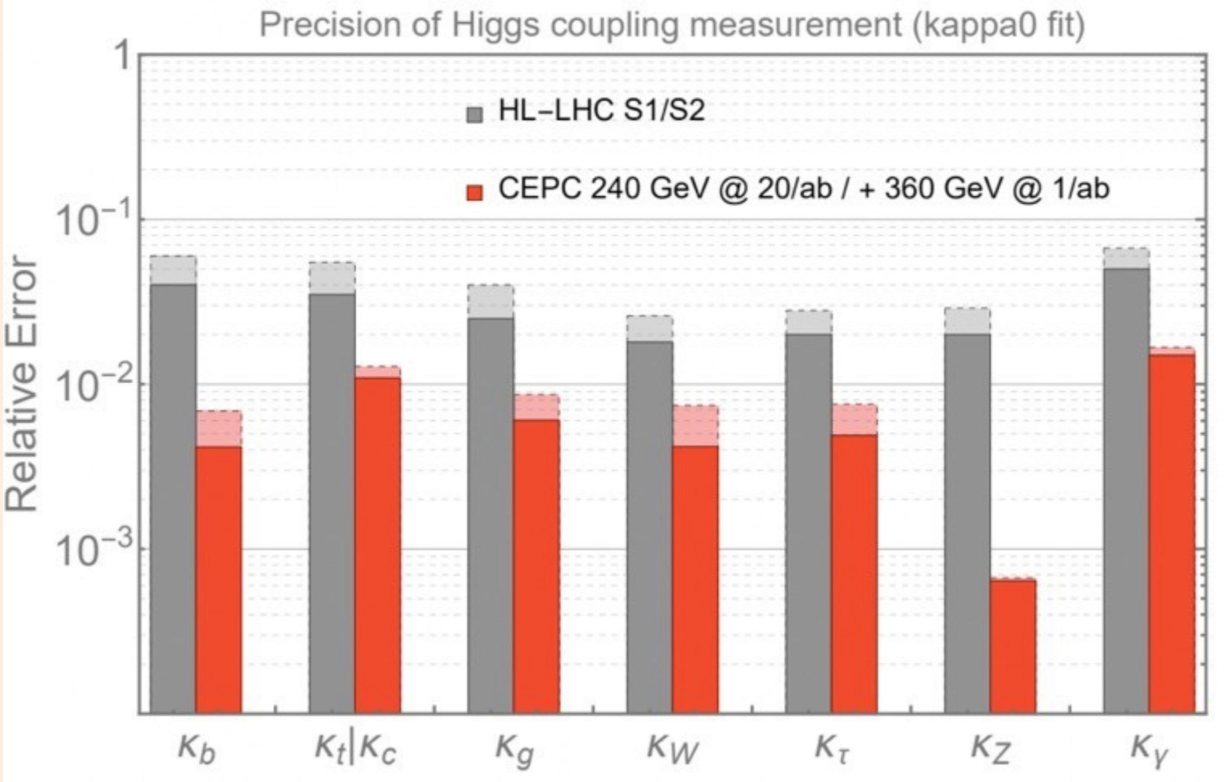
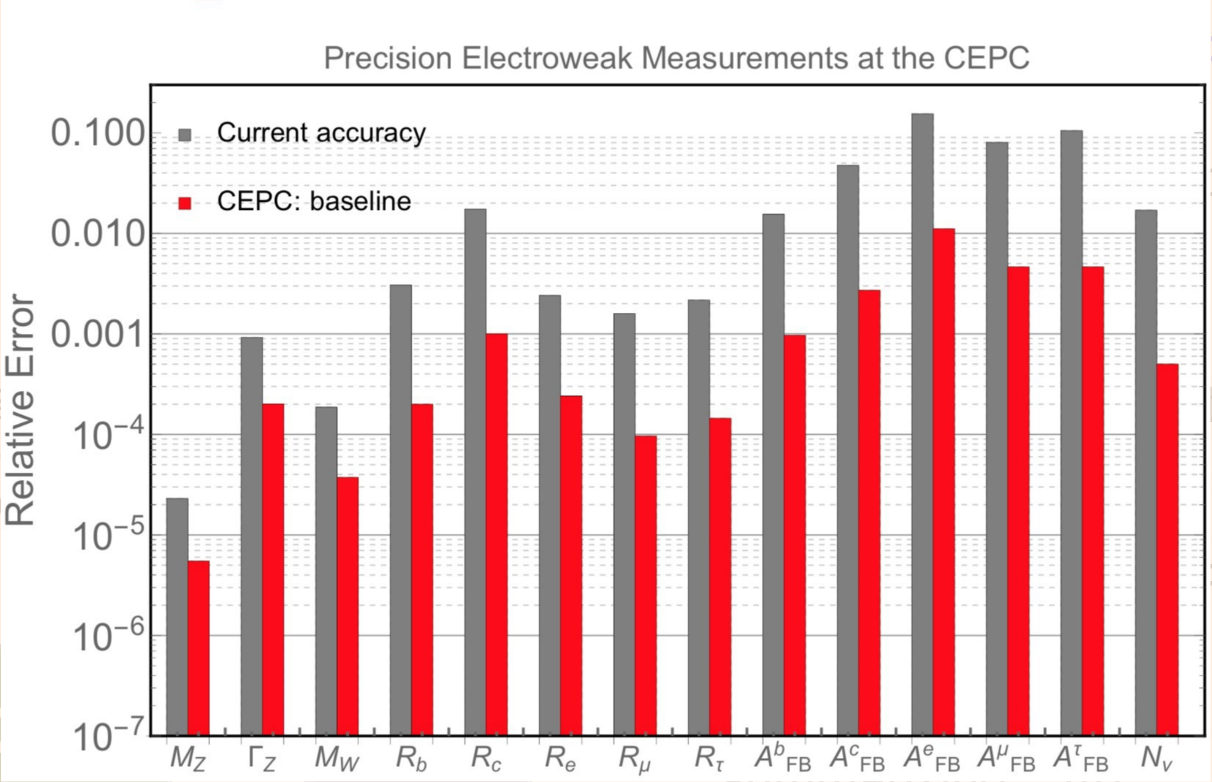
EWK/QCD

m_Z , Γ_Z , Γ_{inv}
$\sin^2\theta_W$, m_W, Γ_W ,
$A_{FB}^{b,c}$, τ pol.
α_S ,....

- Physics merit quantified by simulation & phenomenology studies:
  - Higgs White Paper, etc: Precisions exceed HL-LHC ~ 1 order of magnitude
  - EW: Precision improved from current limit by 1-2 orders of magnitudes
  - Flavor, sensitive to NP of energy scale of 10 TeV or above (Flavor White Paper, summarizing ~ 40 benchmarks)
  - Sensitive to various BSM signals

CEPC physics





arXiv:2205.08553

- Physics merit quantified by simulation &
- benchmarks)
- Sensitive to varies of NP signal

CEPC Detector Requirements

Excellent tracking resolution/
Jet energy resolution
Impact parameter resolution
for b,c,s tagging

Higgs

m_H, σ, Γ_H
self-coupling
H→ bb, cc, ss, gg
H→inv, H→sb, …

Flavor

CKM matrix
CPV measurements
LFV, LUV
τ properties (lifetime, BRs..)
$B_c \to \tau\nu$, $B_s \to D_s K/\pi$
$B_s \to K^* \tau\tau$, $B \to K^* \nu\nu$
$B_s \to \varphi \nu\nu$ …

Superior impact parameter resolution for vertices, tagging;
Energy resolution for π^0 or γ reco;
PID: K/π separation over wide momentum range for b and τ physics

4 million Higgs
4 trillion Z bosons
200 million W pairs
600 k ttbar

Top

m_{top}, Γ_{top},
top quark coupling,
…

BSM

Heavy Neutral Leptons
Dark Photons Z_D
Axion Like Particles
Exotic Higgs decays
…

LLP sensitivity via far detached vertices (mm→m):
Tracking, Calorimetry, Muon

EWK/QCD

m_Z , Γ_Z , Γ_{inv}
$\sin^2\theta_W$, m_W, Γ_W ,
$A_{FB}^{b,c}$, τ pol.
α_S , …

Small systematics:
Absolute normalisation (luminosity， 10^{-4})
Momentum resolution

Physics Benchmarks & Requirements

	Processes @ c.m.s.	Domain	Relevant Det. Performance
H→ss/cc/sb	ννH @ 240 GeV	Higgs	PFA + Jet Origin Id (JoI)
H→inv	qqH	Higgs/NP	PFA
Vcb	WW→lνqq @ 240/160 GeV	Flavor	JoI + Pid (Lepton, tau)
W fusion Xsec	ννH @ 360 GeV	Higgs	PFA + JoI
α_S	Z→tautau @ 91.2 GeV	QCD	PFA: Tau & Tau final state id
CKM angle $\gamma - 2\beta$	Z→bb, B→DK @ 91.2 GeV	Flavor	PFA + JoI + Pid (Kaon)
Weak mixing angle	Z@ 91.2 GeV	EW	JoI
Higgs recoil	llH	Higgs	Pid (Lepton), track dP/P
H→bb, gg	ννH + qqH	Higgs	PFA + JoI + Color Singlet id
H→di muon	qqH	Higgs	PFA, Leptons id, Tracking
H→di photon	qqH	Higgs	PFA, Photons id, EM resolution
W mass & Width	W threshold scan @160 GeV	EW	Beam energy
Top mass & Width	Top threshold scan @360 GeV	EW	Beam energy
Bs→ $\upsilon\upsilon\phi$	91.2 GeV	Flavor	Object (ϕ) in jets; MET
Bc→ $\tau\upsilon$	91.2 GeV	Flavor	Object (τ) in jets; MET
B0→ $2\pi^0$	91.2 GeV	Flavor	π^0 in jets; EM resolution

PFA is required by most of the benchmarks, emphasizing **global reconstruction performance**

- **BMR < 4%** required, to pursue 3%
- Object identification: need to efficient reconstruct and identify final state particles (1-1 correspondence)
- **Kaon ID with eff and purity > 95%**
- Capable to find composited objects in jets

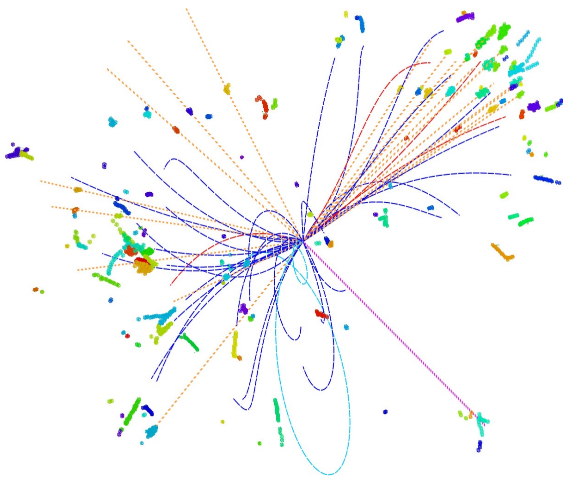
Sub-Det level performance

- **Tracking: ~0.1% momentum resolution**
- **EM resolution: ~1% level**
- **VTX: position resolution ~ 5 μm**

- **Rely on not only sub detector performance, but also excellent global reconstruction algorithms**
  - **CyberPFA** being developed to cope with Xstal bar ECal, and rely on full simulation of the detector
  - **New concepts (Jet origin ID** & color singlet ID) emerge, need to establish their relevance to algorithm & sub-detector configuration & performance

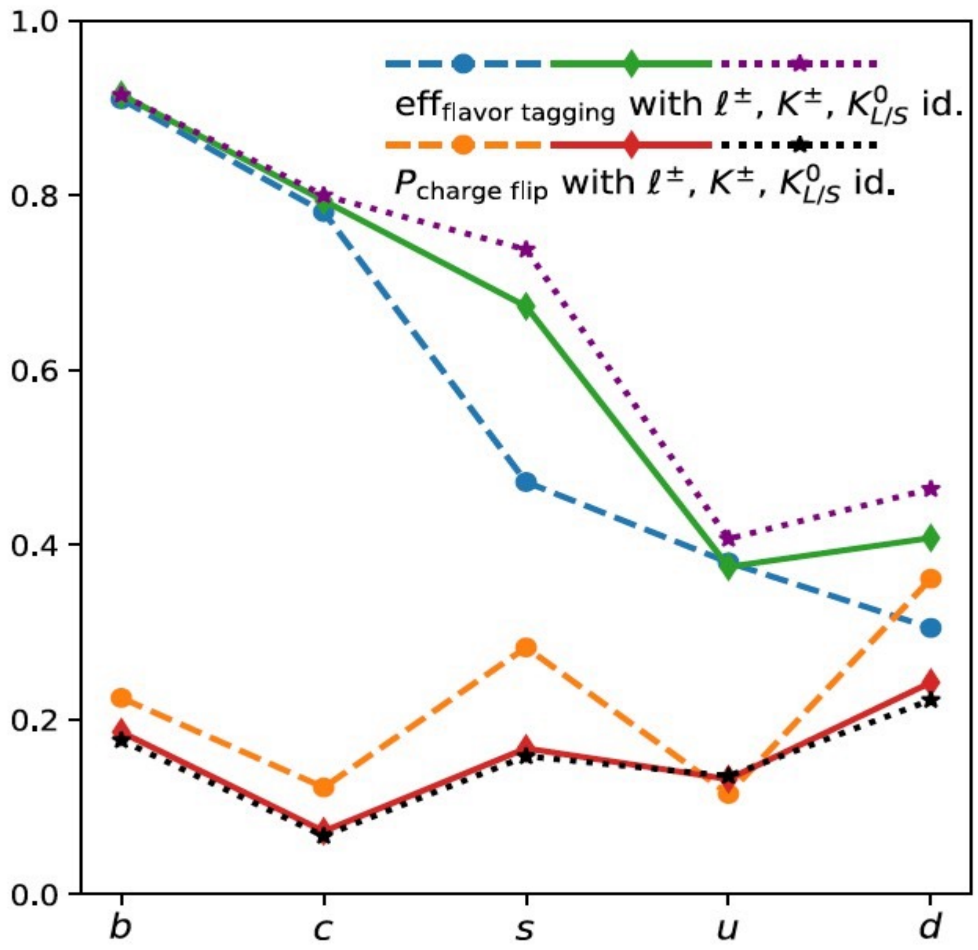
Jet Origin ID

PRL 132, 221802 (2024)



True \ Predicted	b	$\bar{b}$	c	$\bar{c}$	s	$\bar{s}$	u	$\bar{u}$	d	$\bar{d}$	G
b	0.745	0.163	0.033	0.025	0.004	0.003	0.002	0.003	0.002	0.002	0.017
$\bar{b}$	0.170	0.737	0.026	0.033	0.003	0.004	0.003	0.002	0.002	0.003	0.018
c	0.015	0.014	0.743	0.055	0.036	0.031	0.025	0.009	0.009	0.018	0.043
$\bar{c}$	0.016	0.015	0.056	0.739	0.032	0.037	0.009	0.026	0.017	0.010	0.043
s	0.003	0.002	0.020	0.018	0.543	0.102	0.030	0.080	0.063	0.045	0.092
$\bar{s}$	0.003	0.003	0.018	0.020	0.102	0.542	0.084	0.028	0.045	0.062	0.094
u	0.002	0.003	0.020	0.011	0.044	0.131	0.367	0.055	0.080	0.174	0.111
$\bar{u}$	0.003	0.003	0.011	0.019	0.132	0.043	0.062	0.356	0.178	0.081	0.111
d	0.003	0.003	0.012	0.019	0.112	0.092	0.082	0.207	0.277	0.079	0.112
$\bar{d}$	0.003	0.003	0.020	0.012	0.092	0.112	0.219	0.076	0.079	0.272	0.113
G	0.015	0.014	0.024	0.024	0.052	0.052	0.043	0.041	0.034	0.034	0.667

Confusion matrix M_{11}



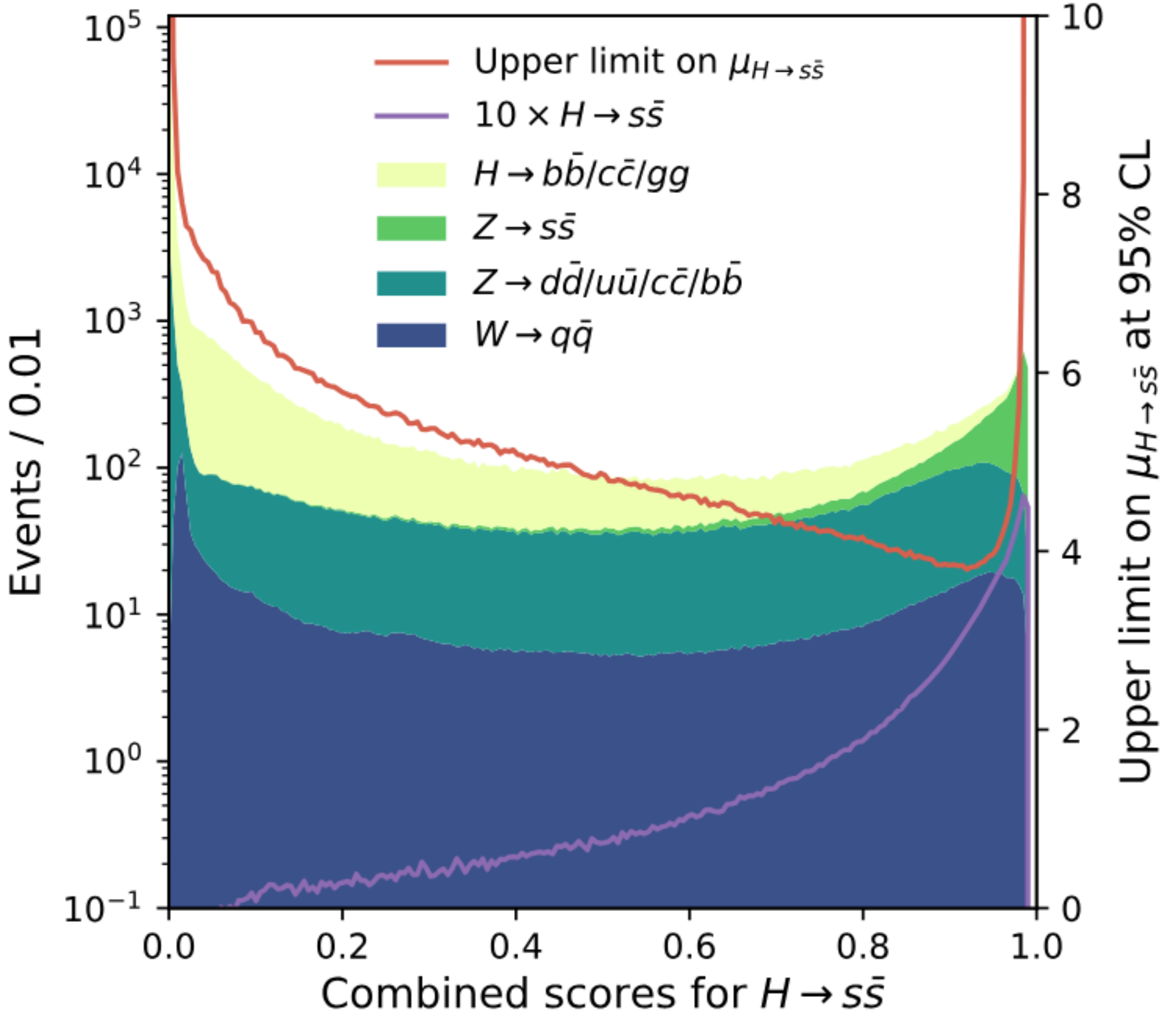
Jet flavor tagging efficiencies and charge flip rates with perfect identifications

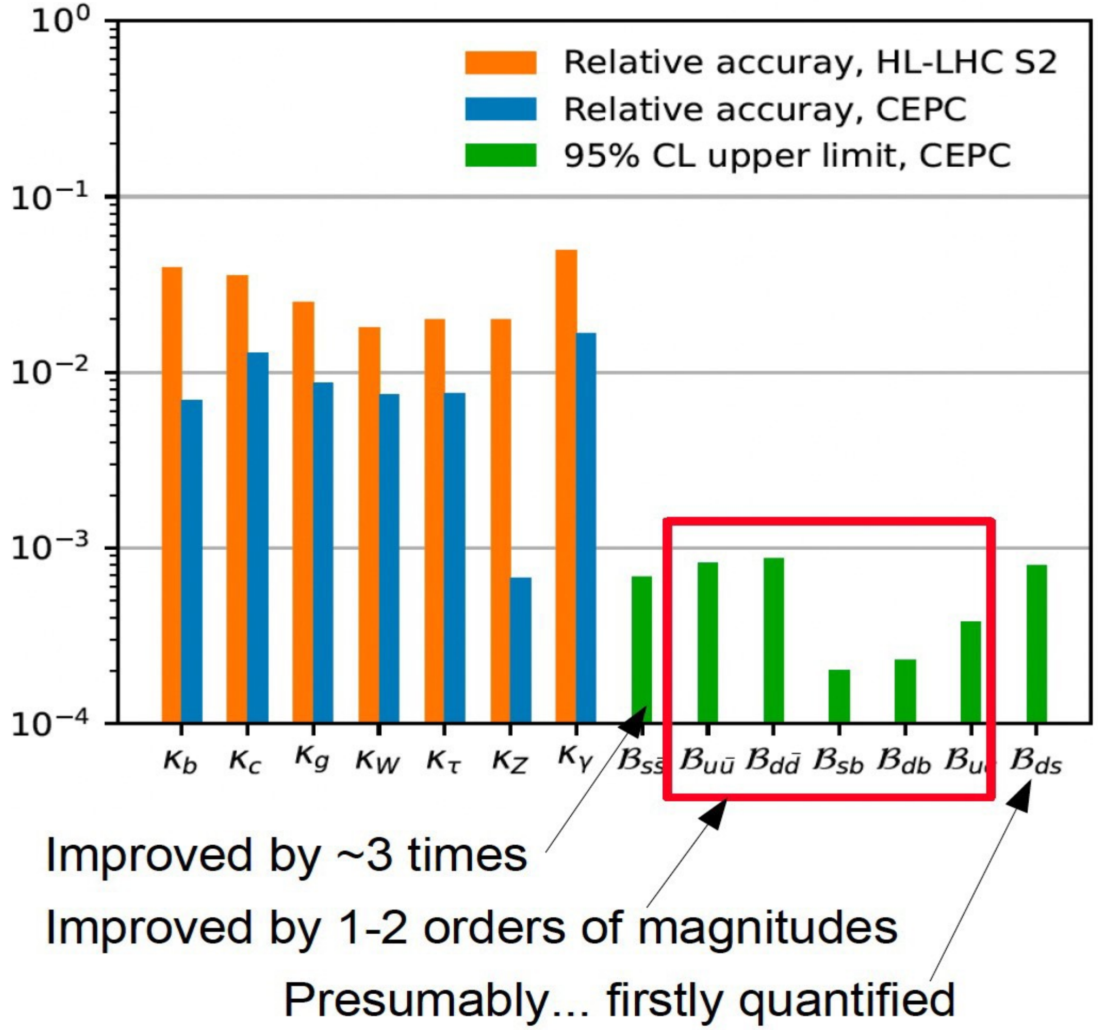
- Jet Origin ID: 11 categories (5 quarks + 5 antiquarks, + gluon)
  - Jet Flavor Tagging + Jet Charge measurement, s, gluon, u & d –tagging
  - Input: PID & 4-momentum of all reconstructed particles + impact parameters for charged ones (~o(50) particles)

Concept demonstrated with CEPC CDR baseline detector & Arbor PFA, and perfect PID : di-jet events (vvH(qq) & Z→qq) simulated

Physics Benchmarks: H→ss

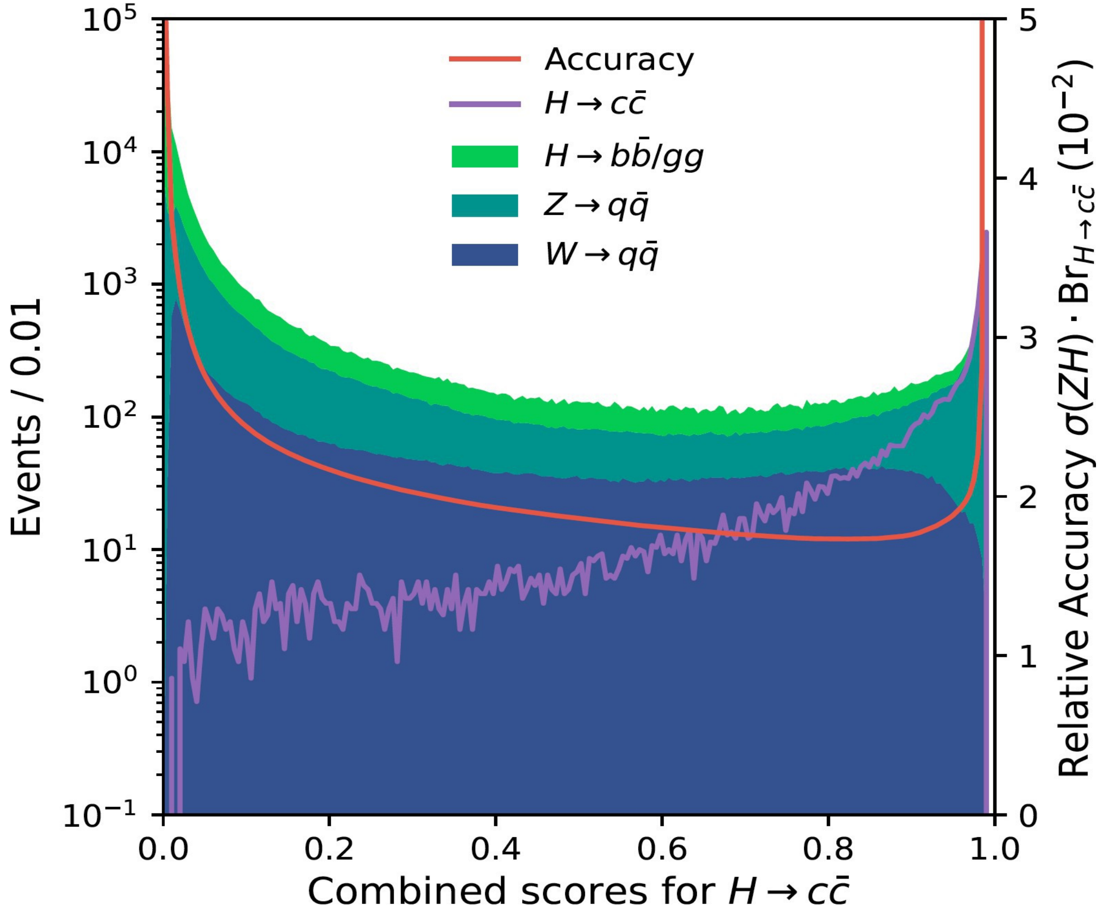
PRL 132, 221802 (2024)

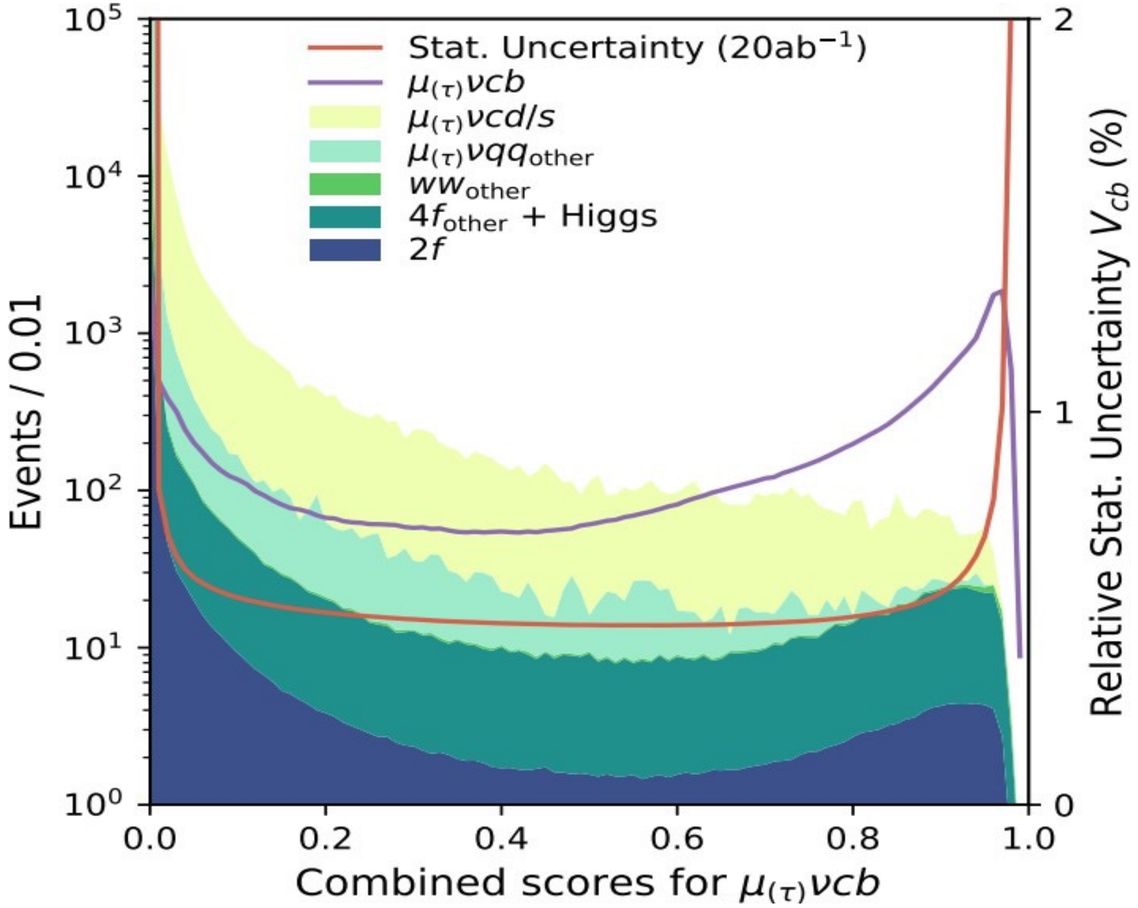




Physics Benchmarks: H→cc & Vcb

PRL 132, 221802 (2024)





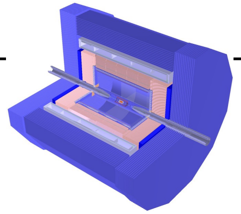
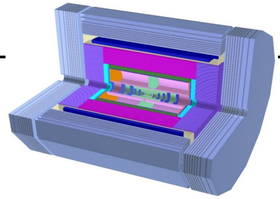
- From Jet Flavor Tagging to Jet Origin ID:
  - vvH, H→cc: 3% → 1.7% (preliminary)
  - Vcb: 0.75% → 0.45% (mvqq channel, evqq: 0.6%, combined 0.4%)

Physics Benchmarks using CDR det. + TDR lumi

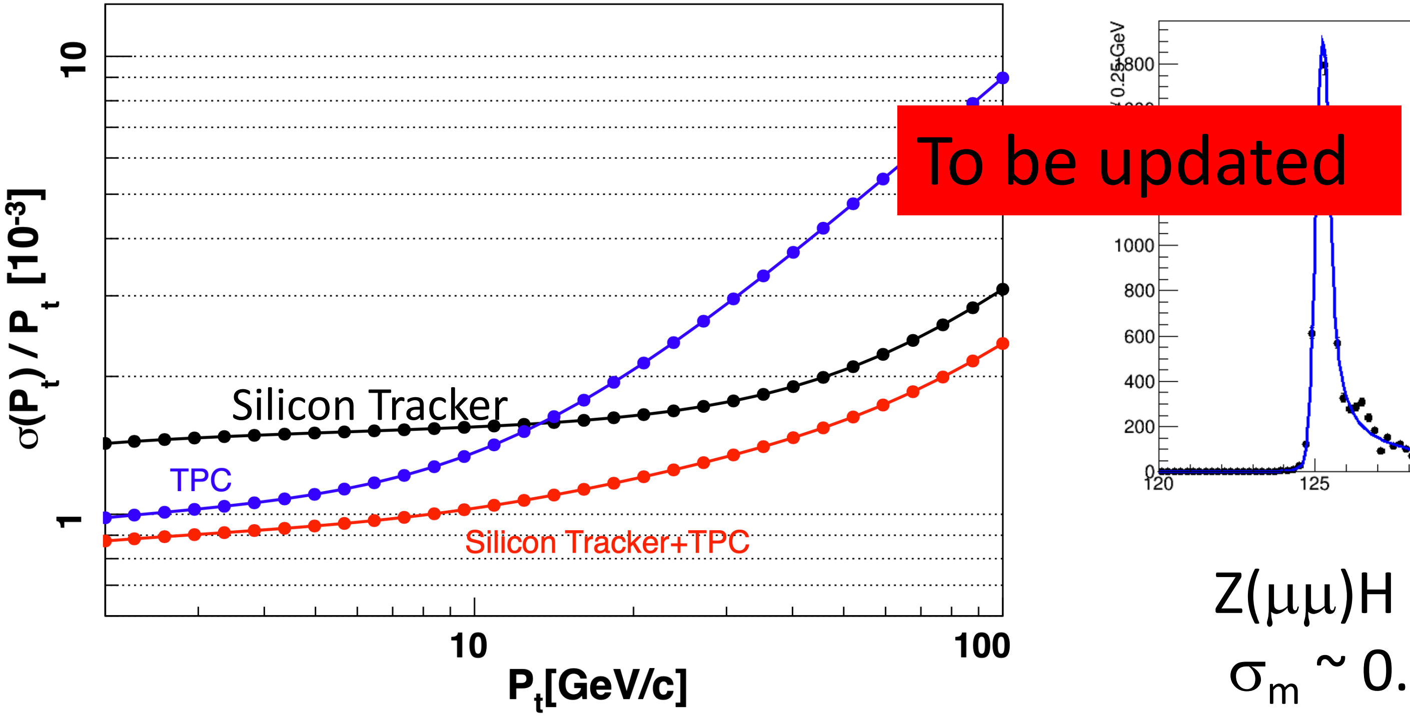
	Processes @ c.m.s.	Domain	Anticipated relative accuracies/up limit with CDR baseline detector + TDR Luminosity, with JoI
H→cc	ννH @ 240 GeV	Higgs	1.7%
H→ss [1]			95% up limit of 0.75E-3
H→sb [1]			95% up limit of 0.22E-3
H→inv [2]	qqH	Higgs/NP	95% up limit of 0.13%
Vcb [3]	WW→lνqq @ 240/160 GeV	Flavor	0.4%
W fusion Xsec [2]	ννH @ 360 GeV	Higgs	1.1%
α_S	Z→tautau @ 91.2 GeV	QCD	NAN
CKM angle $\gamma - 2\beta$	Z→bb, B→DK @ 91.2 GeV	Flavor	NAN
Weak mixing angle [4]	Z@ 91.2 GeV	EW	2.4E-6 using 1 month of Z pole data (~ 2E11 Z)
Higgs recoil [5]	llH	Higgs	δm = 2.5 MeV $\delta\sigma/\sigma$ = 0.25%/0.4% (wi/wo qqH)
H→bb, gg [2]	ννH + qqH	Higgs	bb: 0.14% -> 0.13% gg: 0.81% -> 0.65% (wi/wo JoI)
H→di muon [2]	qqH	Higgs	6.4%
H→di photon [2]	qqH	Higgs	3%
W mass & Width [6]	W threshold scan @160 GeV	EW	0.7 MeV & 2.4 MeV @ 6 iab
Top mass & Width [7]	Top threshold scan @360 GeV	EW	9 MeV & 26 MeV @ 100 ifb
Bs→ $\nu\nu\phi$ [8]	91.2 GeV	Flavor	0.9% (1.8%@Tera-Z)
Bc→ $\tau\nu$ [9]	91.2 GeV	Flavor	0.35% (0.7%@Tera-Z)
B0→ $2\pi^0$ [10]	91.2 GeV	Flavor	NAN

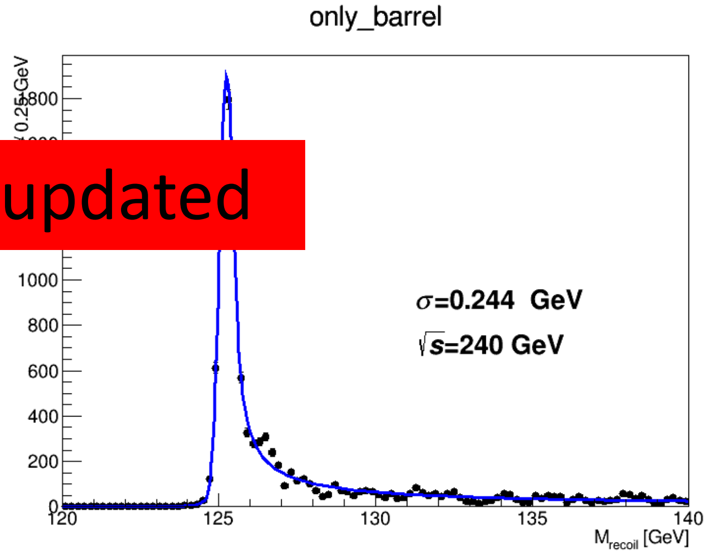
1. H. Liang, et al, PHYSICAL REVIEW LETTERS 132, 221802 (2024)
2. CEPC Phy-Det Snowmass White Paper, arXiv:2205.08553v1
3. H. Liang, Ph.D thesis
4. Z. Zhao, et al., Chinese Physics C Vol. 47, No. 12 (2023) 123002
5. Z. Yang, et al., Chinese Physics C Vol. 41, No. 2 (2017) 023003
6. P. Shen, et al., Eur. Phys. J. C (2020) 80:66
7. Z. Li, et al., arXiv:2207.12177
8. Y. Wang, et al., PHYSICAL REVIEW D 105, 114036 (2022)
9. T. Zheng, et al., Chinese Physics C Vol. 45, No. 2 (2021) 023001
10. Y. Wang, et al., JHEP12(2022)135

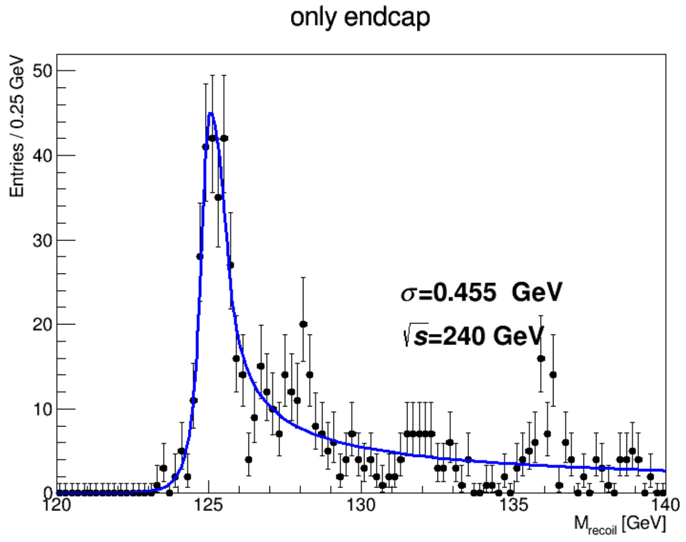
Detector Concepts: CDR to refTDR

	CDR 	Ref-TDR 
VTX	Inner radius of 16 mm	Inner radius of **11 mm**
	Material Budget: 0.15%*6+0.14%(beampipe)= 1.05% X0	Material Budget: 0.06%*4(inner)+0.25%*2(outer)+0.16%(beampipe)= **0.9% X0**
Gaseous Tracker	TPC with 1 mm* 6 mm readout	TPC with **0.5 mm* 0.5 mm** readout To have **dE/dx or dN/dx resolution 3%** (Drift Chamber with the capability of dN/dx as alternative)
ToF	-	AC-LGAD, with **50 ps** per MIP
ECAL	Si-W-ECAL: 17%/√E ⊕ 1%	Crystal Bar-ECAL: **3%**/√E ⊕ 1%
HCAL	RPC-Iron: 60%/√E ⊕ 2%	Glass-Iron: **40%**/√E ⊕ 2%

Tracking @ full simulation







Z(μμ)H – recoil mass
σ_m ~ 0.1% @ Barrel

Z(μμ)H – recoil mass
σ_m ~ 0.2% @ Endcap

- To be updated with full tracking system Vertex + ITK + TPC + OTK, and also versus costheta
- ~0.1% for bulk of tracking resolution reachable

VTX and Jet Flavor/Charge measurement

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THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Experimental Physics

ParticleNet and its application on CEPC jet flavor tagging

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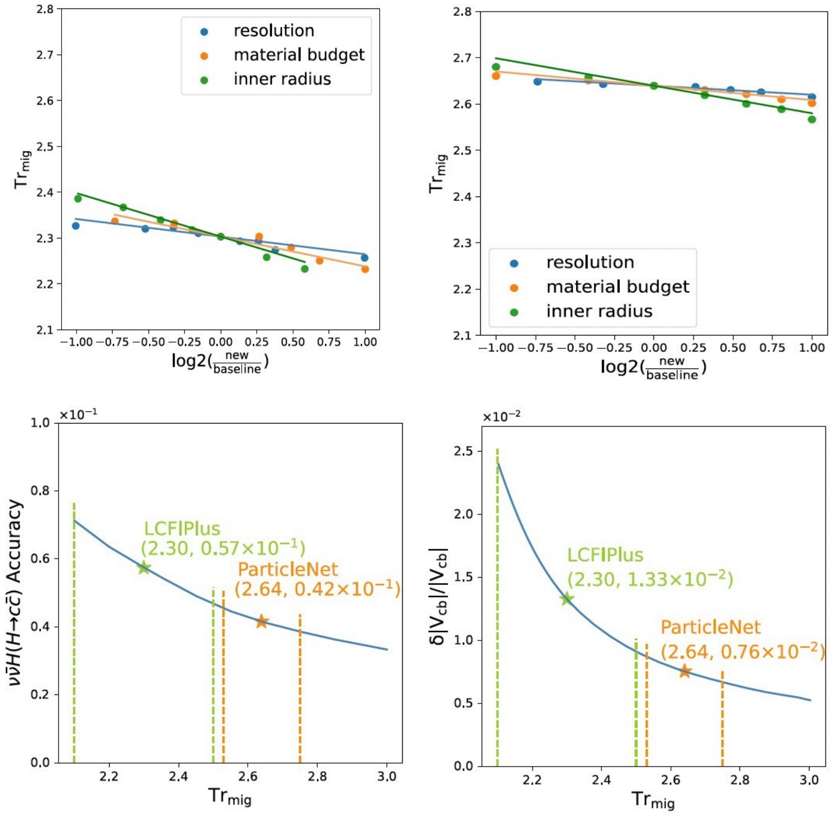

Eur.Phys.J.C 84 (2024) 2, 152

predicted

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

$$Tr_{mig} = 2.30 + 0.06 \cdot \log_2 \frac{R^0_{material}}{R_{material}} + 0.04 \cdot \log_2 \frac{R^0_{resolution}}{R_{resolution}} + 0.10 \cdot \log_2 \frac{R^0_{radius}}{R_{radius}} \quad (1)$$

$$Tr_{mig} = 2.64 + 0.03 \cdot \log_2 \frac{R^0_{material}}{R_{material}} + 0.02 \cdot \log_2 \frac{R^0_{resolution}}{R_{resolution}} + 0.06 \cdot \log_2 \frac{R^0_{radius}}{R_{radius}} \quad (2)$$

- Compared to CDR, VTX at TDR:
  - Inner radius reduced by 40% (16 mm -> 11 mm)
  - Material reduced by 10% (1.05 -> 0.9 X0)
- Trace(Migration Matrix): 2.64 -> 2.68
  - H->cc accuracy improved by ~5%
  - Vcb accuracy improved by ~10%

PID: dE/dx or dN/dx + TOF

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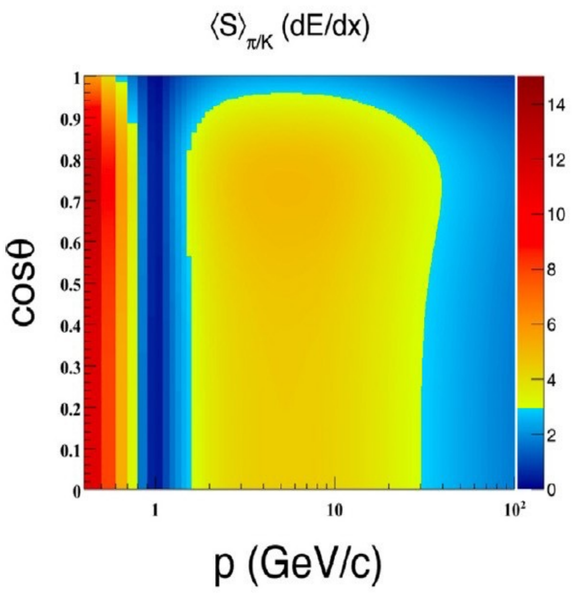

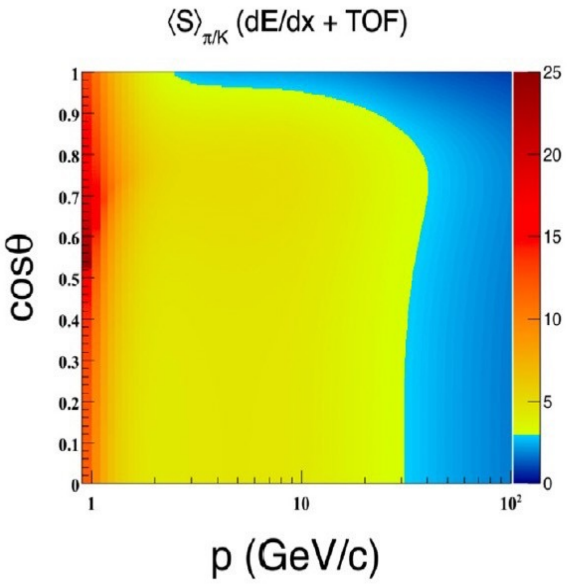

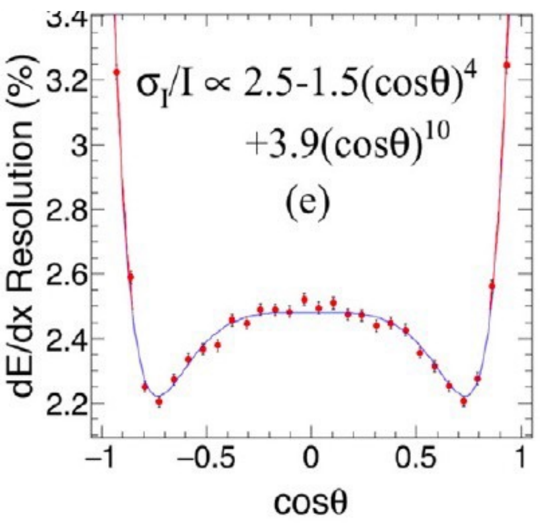

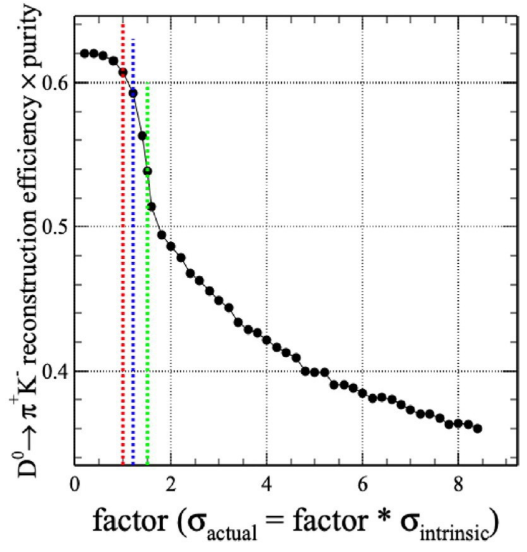

Nuclear Inst. and Methods in Physics Research, A 1047 (2023) 167835

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

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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.

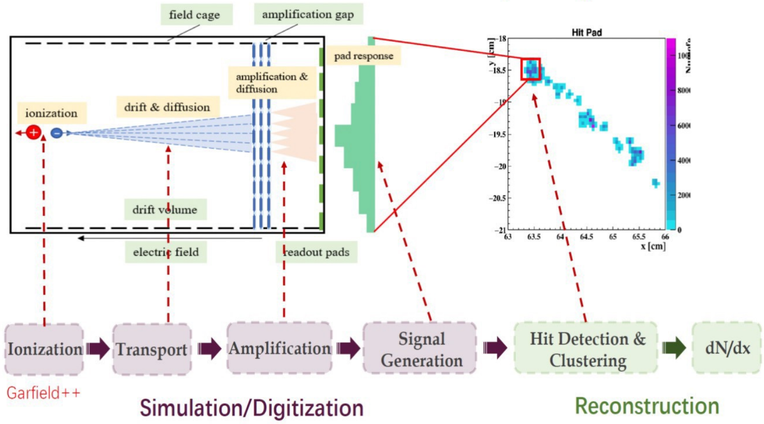
	Factor	1.	1.2	1.5	2.
dE/dx	ϵ_K (%)	95.97	94.09	91.19	87.09
	$purity_K$ (%)	81.56	78.17	71.85	61.28
dE/dx & TOF	ϵ_K (%)	98.43	97.41	95.52	92.3
	$purity_K$ (%)	97.89	96.31	93.25	87.33

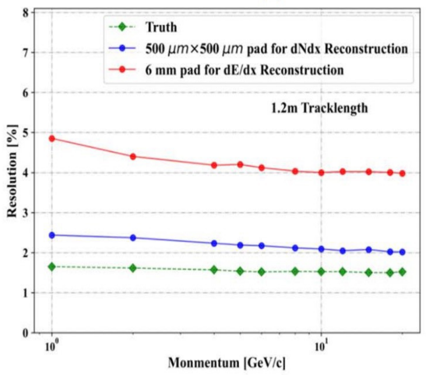
- dE/dx or dN/dx with relevant uncertainty of **3%** + TOF of **50 ps**: **eff & purity of Kaon ID > 95%**

dE/dx or dN/dx @ ref-TDR goal

Performance from simulation

- Full simulation framework of pixelated TPC developed using Garfied++ and Geant4 at IHEP
- Investigating the π/κ separation power using reconstructed clusters, **a 3σ separation at 20GeV** with 50cm drift length can be achieved
- dN/dx has significant potential for **improving PID resolution**



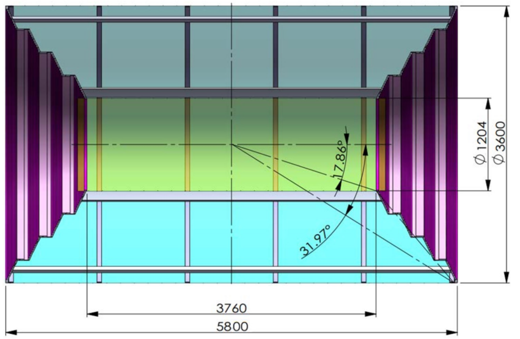


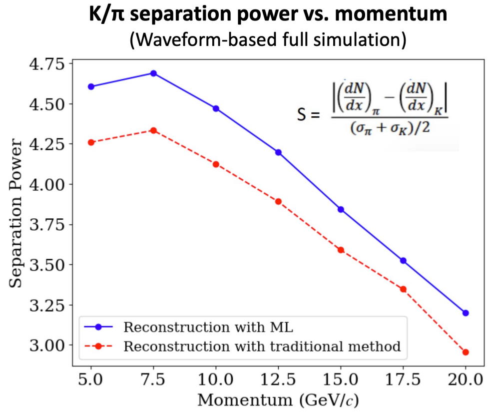
Cite#11: DOI: 10.22323/1.449.0553
Cite#12: EPS-HEP 2023 talk by Yue Chang

Simulation of TPC detector under 3T/2T and T2K mixture gas

26

Detailed design of DC for Tera-Z





$$S = \frac{\left|\left(\frac{dN}{dx}\right)_\pi - \left(\frac{dN}{dx}\right)_K\right|}{(\sigma_\pi + \sigma_K)/2}$$

- CF frame structure
- Length: 5800 mm; Outer diameter: 3600 mm; Inner diameter: 1200 mm
- Thickness of each end plate: 20 mm, weight: 880 kg
- Gas mixture: He + iC_4H_{10} (90/10)
- Cell size: 18mm x 18mm, number of cells: 26483
- Material: 0.16% X_0 for Gas+Wires, 0.21%X_0 for inner and outer cylinders
- Finite element analysis: Endplate deformation 2.7mm, CF frame deformation 1.1mm

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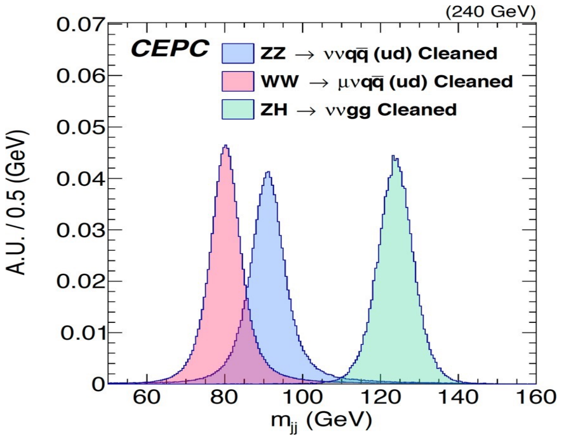
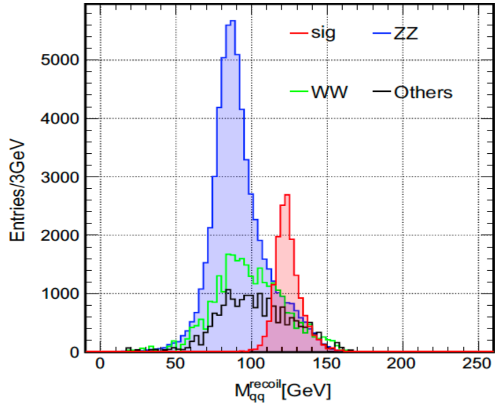
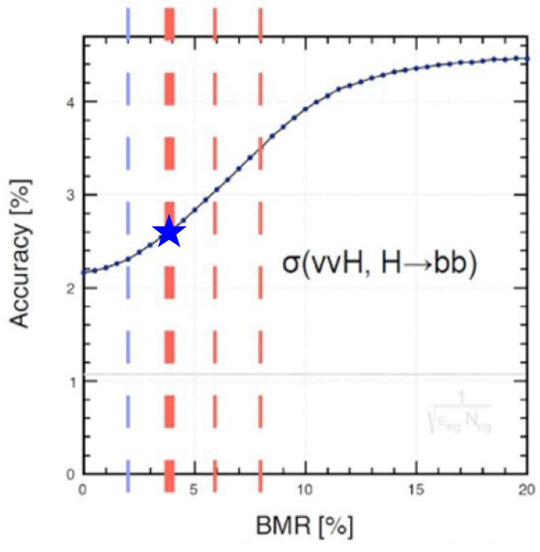
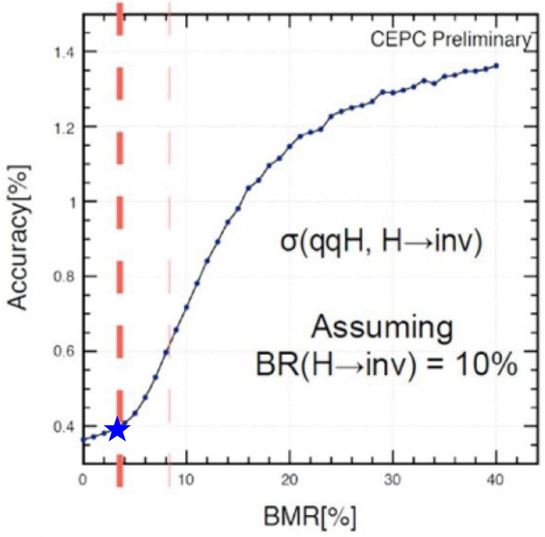
- A major goal for the Ref-TDR Gaseous Tracker is the PID: to achieve 3% dE/dx or dN/dx performance
- Promising results, to be validated with further studies, especially test beam.
- Gaseous Tracker inner radius: to be optimized – for endcap performance

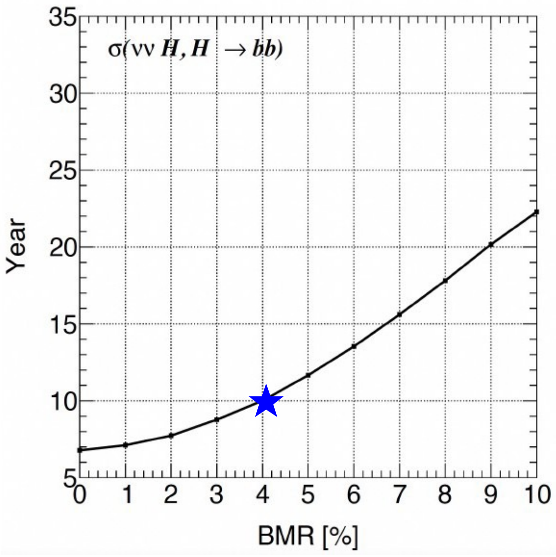
PFA Goal: BMR < 4% & pursue 3%

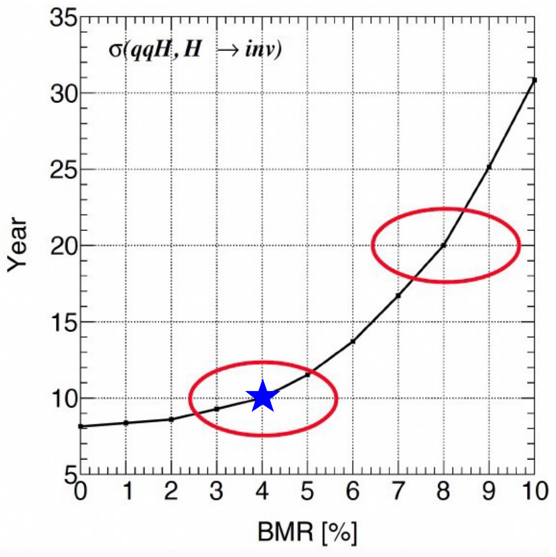






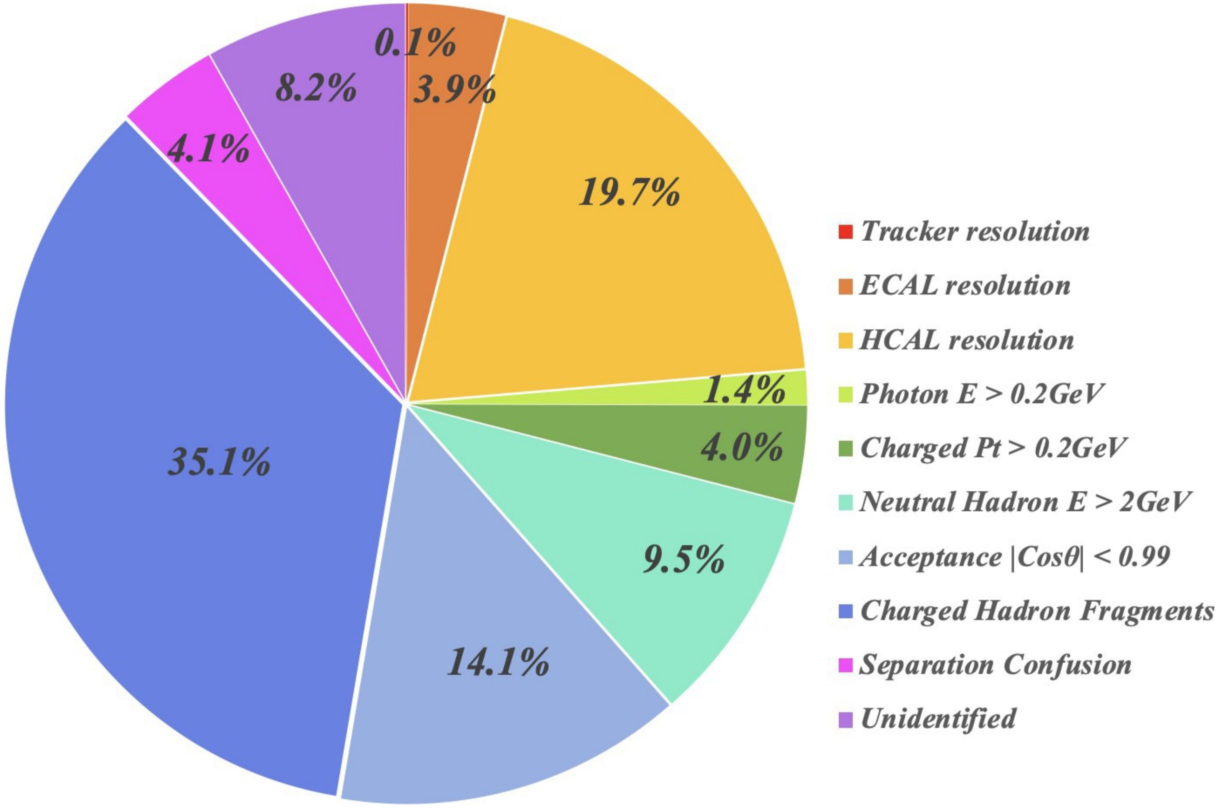






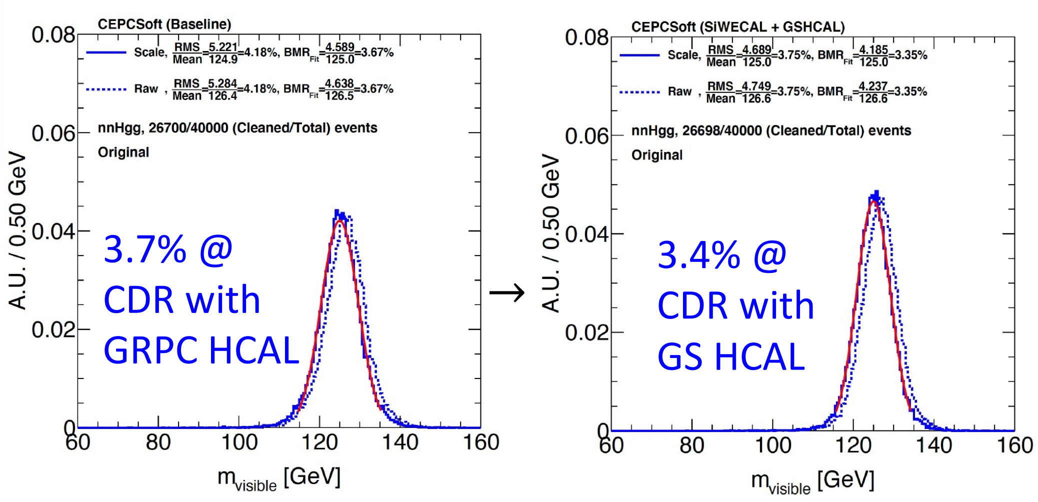
- BMR used to quantify jet reconstruction: 4% will well separate W/Z and Higgs, and separate ZH from the ZZ
  - Accuracies of different physics benchmarks as a function of the BMR show a turning point at roughly BMR of 4%
- H->inv as an example:
  - BMR from **4% to 8%** (typical LHC experiment performance), one need to **double the luminosity** to reach same accuracy
  - BMR from **4% to 3%, save roughly one year** of operation

BMR Decomposition



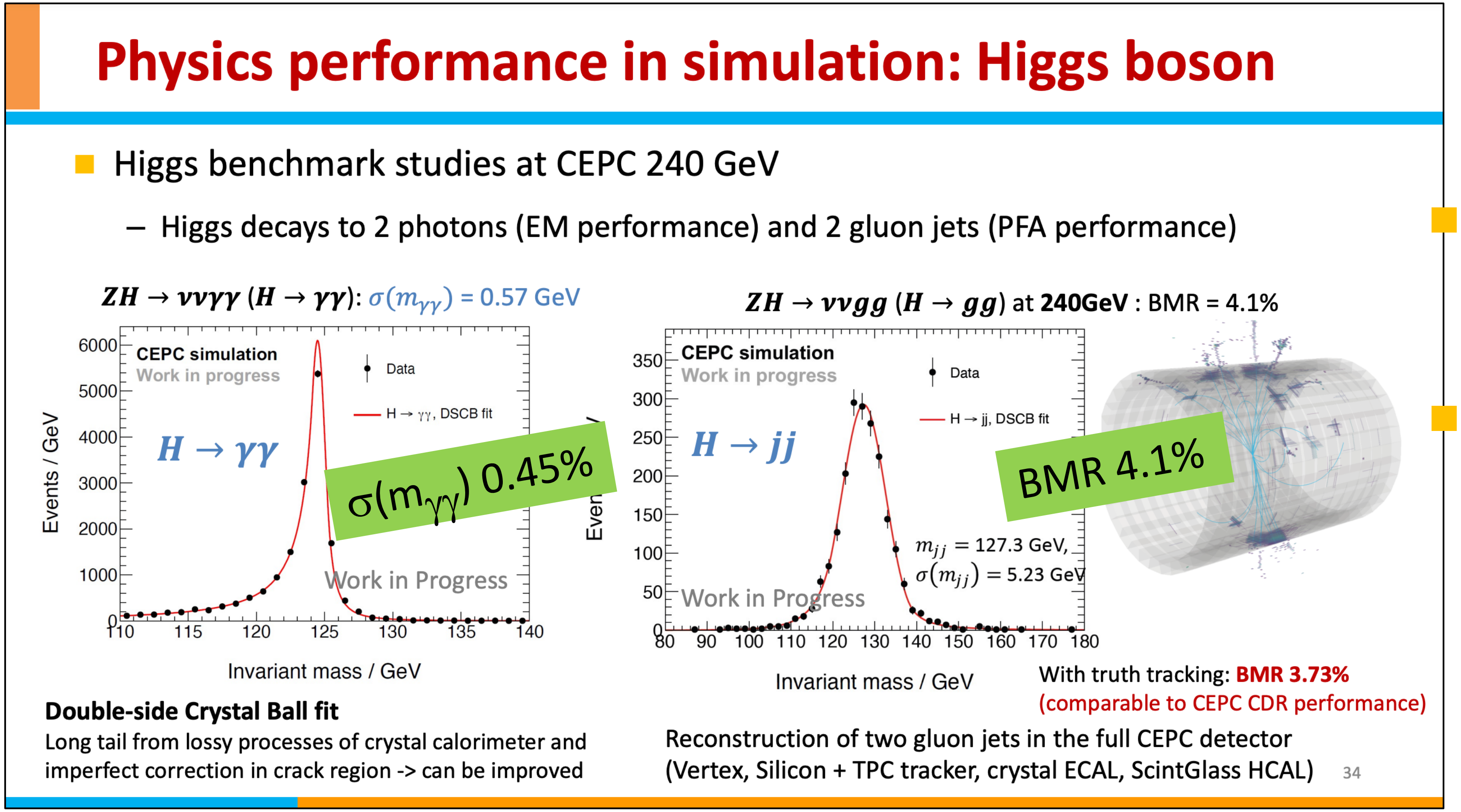
(for BMR of 3.7% at CDR)

- ~50% from confusion
- ~25% from detector resolution
- ~25% from acceptance



- HCAL resolution dominates among the uncertainties from detector resolutions:
  - Using Glass Scintillator (TDR HCAL) - Iron with thickness of 6 lambda (compared to GRPC - Iron of 5 lambda) → BMR of 3.4%

BMR of ~ 4% at refTDR



- Preliminary BMR at ref-TDR: 4.1%, not far from CDR (BMR of 3.7%).
- To control the confusion (fake particles, etc) is critical: need optimization + reconstruction development

Physics Benchmarks at CDR & refTDR

	Processes @ c.m.s.	Domain	Anticipated relative accuracies/up limit with CDR baseline detector + TDR Luminosity, with JoI	@Ref TDR
H→cc	ννH @ 240 GeV	Higgs	1.7%	1.6%
H→ss [1]			95% up limit of 0.75E-3	95% up limit of 0.70E-3
H→sb [1]			95% up limit of 0.22E-3	95% up limit of 0.20E-3
H→inv [2]	qqH	Higgs/NP	95% up limit of 0.13%	Same
Vcb [3]	WW→lνqq @ 240/160 GeV	Flavor	0.4%	0.36%
W fusion Xsec [2]	ννH @ 360 GeV	Higgs	1.1%	Same
α_S	Z→tautau @ 91.2 GeV	QCD	NAN	Theoretical Uncertainty Dominant
CKM angle $\gamma - 2\beta$	Z→bb, B→DK @ 91.2 GeV	Flavor	NAN	~o(0.1 - 1) degree
Weak mixing angle [4]	Z@ 91.2 GeV	EW	2.4E-6 using 1 month data (~ 2E11 Z)	~ tiny improvement due to VTX
Higgs recoil [5]	llH	Higgs	δm = 2.5 MeV $\delta\sigma/\sigma$ = 0.25%/0.4% (wi/wo qqH)	Same
H→bb, gg [2]	ννH + qqH	Higgs	bb: 0.14% -> 0.13% gg: 0.81% -> 0.65% (wi/wo JoI)	bb: 0.12% gg: 0.62%
H→di muon [2]	qqH	Higgs	6.4%	Same
H→di photon [2]	qqH	Higgs	3%	1.8%
W mass & Width [6]	W threshold scan @160 GeV	EW	0.7 MeV & 2.4 MeV @ 6 iab	Same
Top mass & Width [7]	Top threshold scan @360 GeV	EW	9 MeV & 26 MeV @ 100 ifb	Same
Bs→ $\nu\nu\phi$ [8]	91.2 GeV	Flavor	0.9% (1.8%@Tera-Z)	Same, if object recon. ~ CDR
Bc→ $\tau\nu$ [9]	91.2 GeV	Flavor	0.35% (0.7%@Tera-Z)	Same, if object recon. ~ CDR
B0→ $2\pi^0$ [10]	91.2 GeV	Flavor	NAN	0.3%, need to validate photons finding

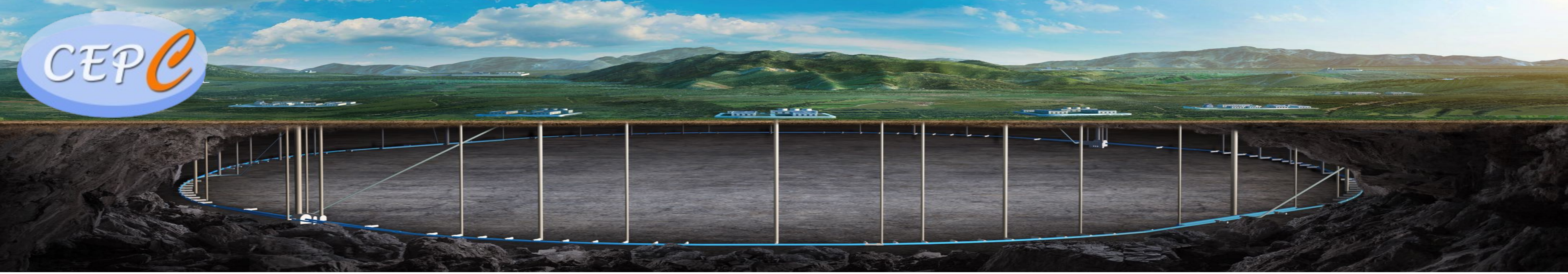
- H->γγ precisions improves significantly, if low mass tail tamed.
- Physics measurements using JoI, etc, benefit from better VTX and have 5-10% improvements，and assuming that the TDR BMR could eventually reach 3.7%
  - If BMR of 3% achieved, precisions of most benchmarks could be further improved by 5-10%
  - Need further development on pattern recognition capability of Crystal Bar ECAL

Challenges & Team

- Challenges:
  - Impact of beam induced background (~ Nov. 2024)
  - High data rate @ Z pole: need to reconstruct in Space time (PFA in space time)
  - New CyberPFA development: rely on full simulation, as it significantly impacts the final resolution on hadronic objects
    - To further validate & verify the pattern recognition performance (~ Dec. 2024)
- Physics Performance Team: ~ 10 staffs + 4 Postdocs + ~10 Students
  - Synergies with sub-detector team
  - Also collaboration with PKU, LLR & CERN on ML algorithms
- Physics white paper efforts: IHEP team + ~ > 20 staffs from ~ 10 Universities
  - Flavor Physics: Tao Liu (HKUST), Lorenzo (NKU), Shanzhen Chen(IHEP) etc
  - New Physics: Xuai Zhuang (IHEP), Mengchao Zhang (JNU)
  - EW: Zhijun Liang (IHEP), Jiayin Gu (FuDan U), Siqi Yang (USTC)
  - QCD: Zhao Li (IHEP), Meng Xiao (ZJU), Huaxing Zhu (PKU)
- Physics studies in pace with ECFA physics focus studies

Summary

- Intensive CEPC Physics studies
  - Well quantified Physics Merits
  - Iterates with Detector R&D
- CEPC Ref-TDR detector provides
  - PID: critical for Higgs/Flavor physics
  - Better VTX: improves precisions on benchmark analysis by 10-20%
  - PFA Compatible Calorimeter with larger sampling:
    - HCAL improves the BMR by ~10%,
    - Crystal Bar ECAL: pattern recognition is challenging.
- To do:
  - Quantify the impact of beam induced background, the readout, especially at Z pole
  - Further develop reconstruction algorithms, and validate with full simulation
    - PFA, smarter algorithm with AI tools
  - Physics benchmarks analyses with full simulation (H measurements) + fast simulation
  - Involve more efforts from theory community to ensure that theoretical uncertainties will be under control



Thank you for your attention!

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