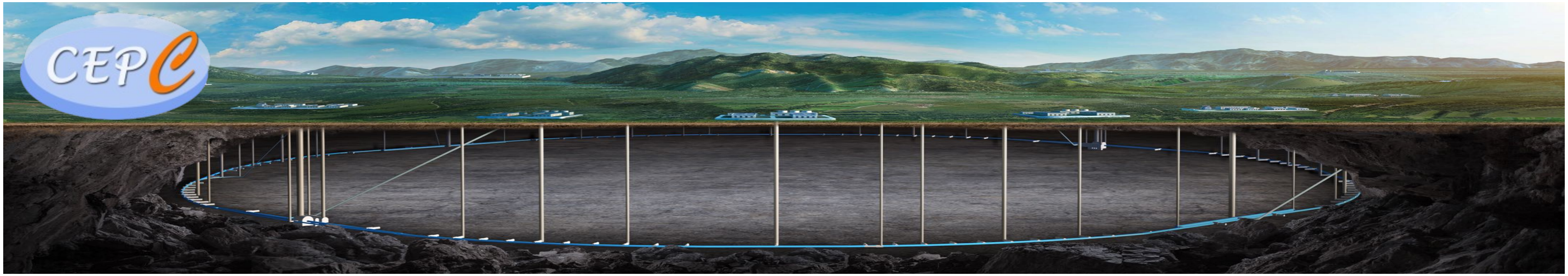

Global Performance

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Institute of High Energy Physics
Chinese Academy of Sciences

Content

- Introduction: Physics benchmarks & relevant Global performance
- Relevant Detector concepts
- Detector global Performance:
  - BMR
  - JoI
  - Pid
  - Outlook: 1-1 correspondence reco.
- Physics Benchmarks
- Challenges & Plan
- Teams
- Summary

Content

- **Introduction: Physics benchmarks & relevant Global performance**
- **Relevant Detector concepts**
- **Detector global Performance:**
  - **BMR**
  - **JoI**
  - **Pid**
  - **Outlook: 1-1 correspondence reco.**
- **Physics Benchmarks**
- **Challenges & Plan**
- **Teams**
- **Summary**

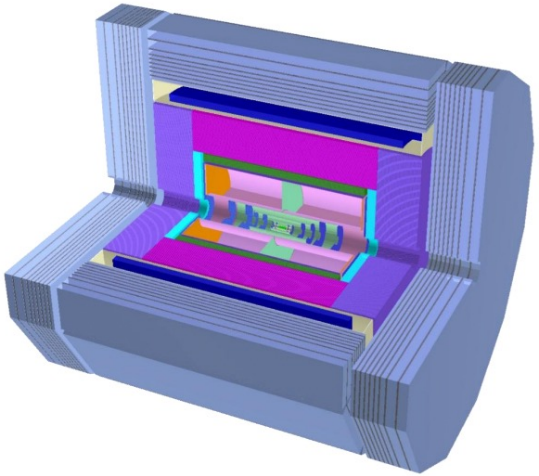
- Introduction
  - Key requirements: BMR, Pid, etc
- Recap of sub-d performance
  - Tracking: efficiency & resolutions as a function of cos(theta) & Pt
  - Calorimeter: efficiency & resolution – linearity of photon, neutral hadron
  - Pid relevant: ToF, dE/dx, dN/dx, etc.
- Global Performance
  - BMR
  - JoI
  - Pid
- Physics Benchmarks
  - Higgs, H->cc/ss
  - NP, H->inv, exotics
  - Flavor, Bs->DK
  - QCD, alpha-s
- Outlook & Plan
  - 1-1 correspondense
  - Physics reach recap

Physics Benchmarks & Global Performances

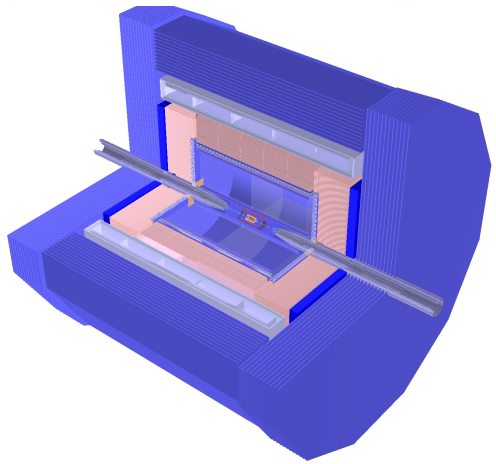
	Processes @ c.m.s.	Domain	Total Det. Performance	Sub-D
H->ss/cc/sb	vvH @ 240 GeV	Higgs	PFA + JOI (Jet origin id)	All sub-D, especially VTX
H->inv	qqH	Higgs/NP	PFA	All
Vcb	WW@ 240/160 GeV	Flavor	JOI + Particle (lepton) id	All
W fusion Xsec	vvH @ 360 GeV	Higgs	PFA + JOI	All
α_S	Z->tautau @ 91.2 GeV	QCD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

Det. Concepts

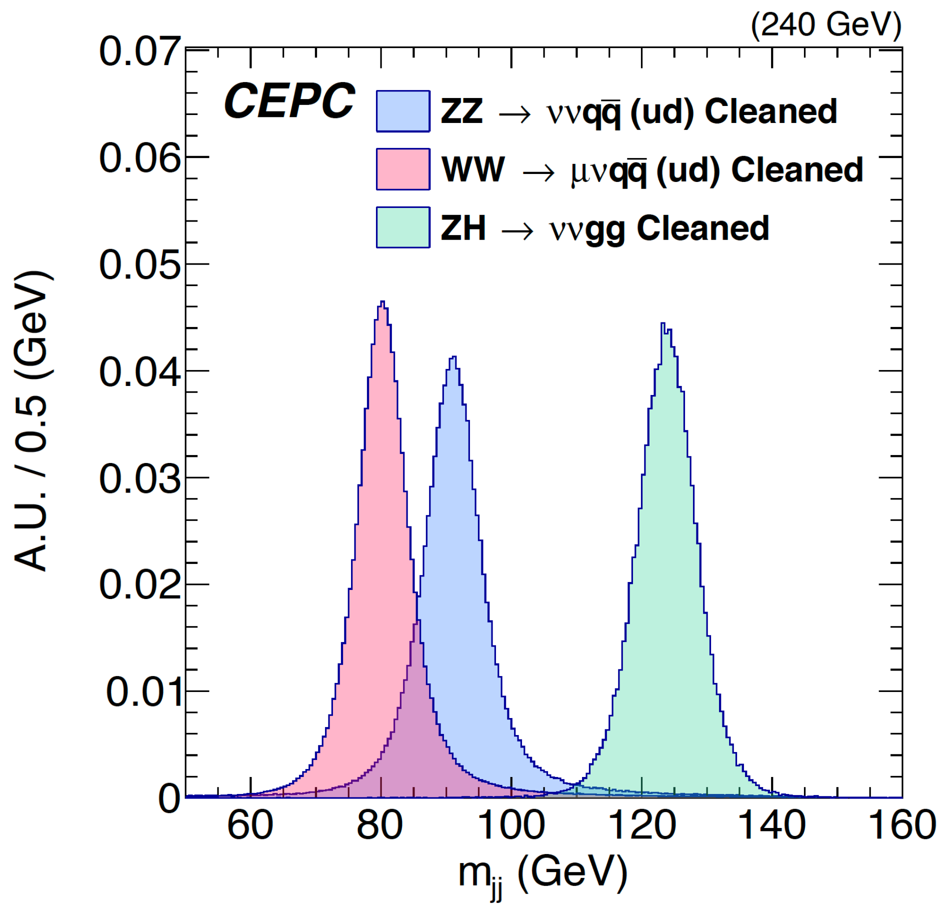
- 4th Det Concept (TDR baseline)

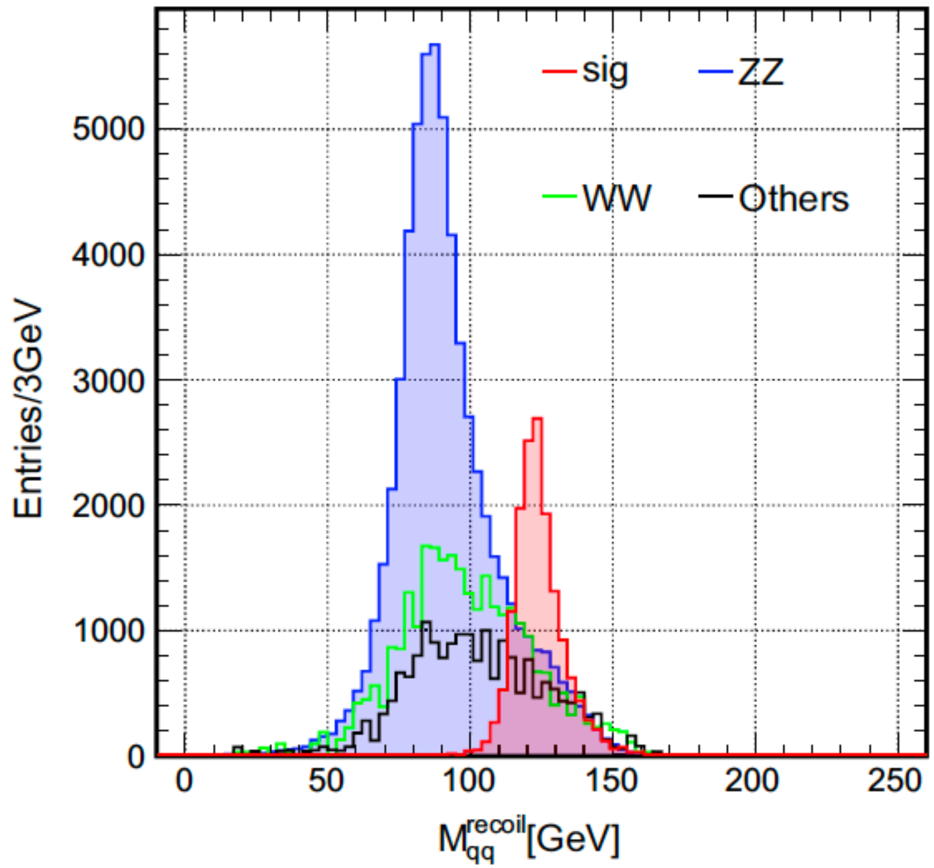


- CEPC-v4 (CDR baseline)
- AURORA: CEPC-v4, with
  - Scintillating Glass HCAL with 6 lambda Thickness + 20 mm*20 mm Readout Cells
  - Calo Cell with ~o(100)ps time resolution.
  - Stitching VTX (to be implemented)

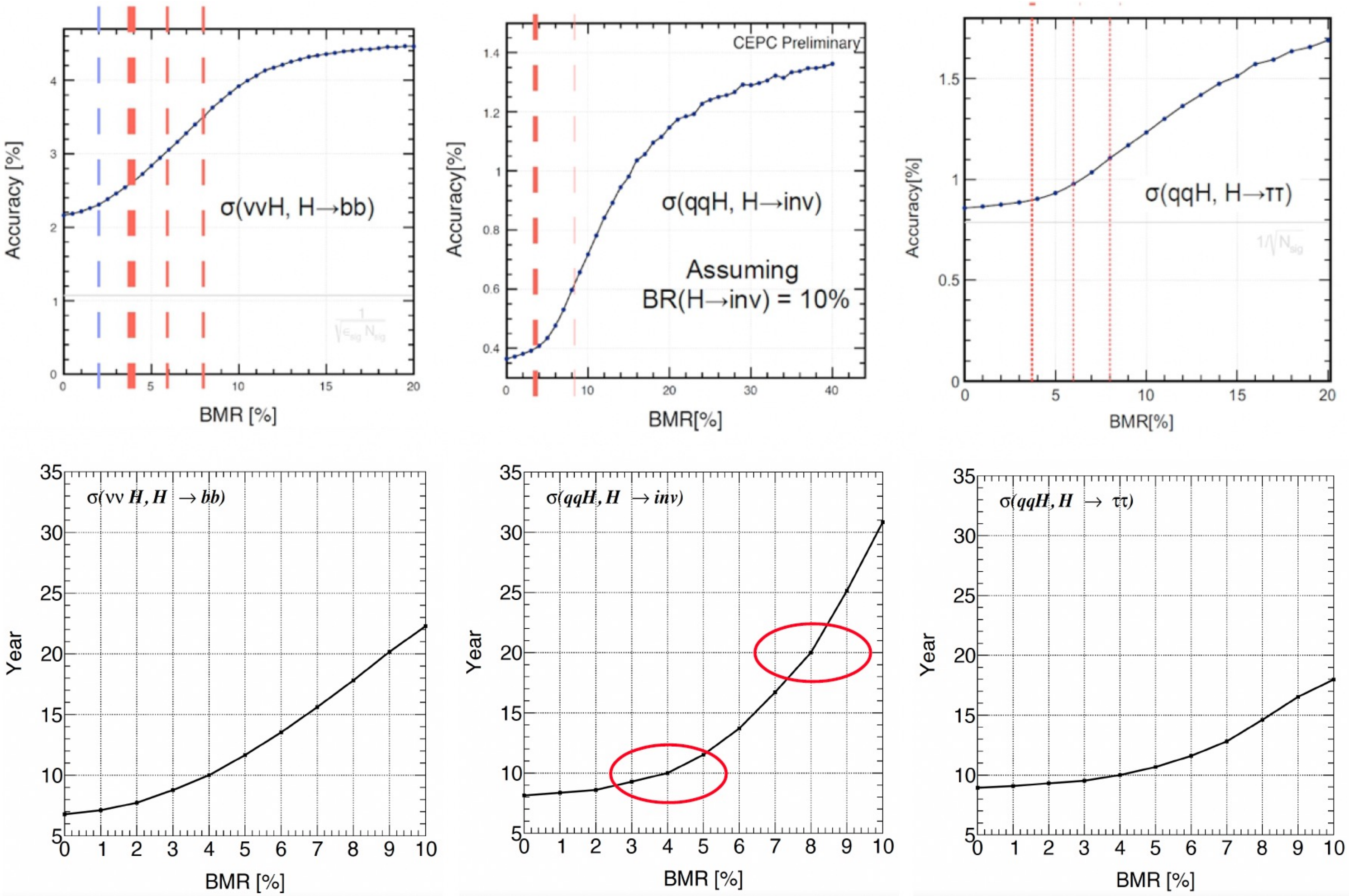


Boson Mass resolution





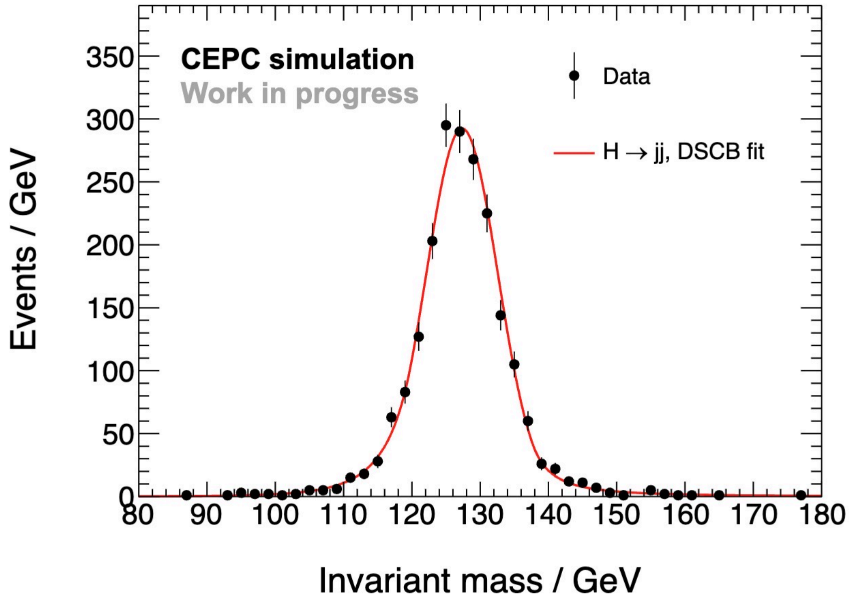
BMR Goal: < 4% & pursue 3%



BMR of ~ 4% at TDR baseline

Physics performance: $H \rightarrow gg$

- **Physics process: $ee \rightarrow ZH \rightarrow \nu\nu gg$ in $\sqrt{s} = 240$ GeV**
  - Full reconstruction in CEPC detector: Silicon + TPC tracker, crystal ECAL, glass tile HCAL.

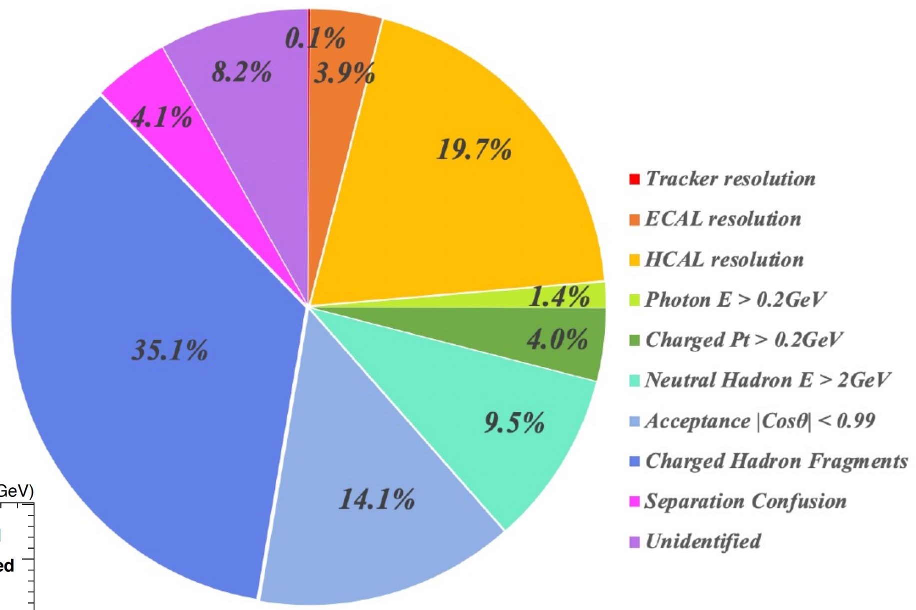


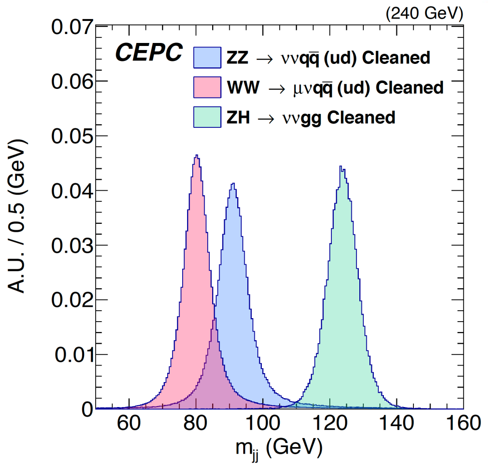
$m_{jj} = 127.3$ GeV, $\sigma(m_{jj}) = 5.23$ GeV

Boson mass resolution (BMR) 4.11%.

With truth track: BMR 3.73%.

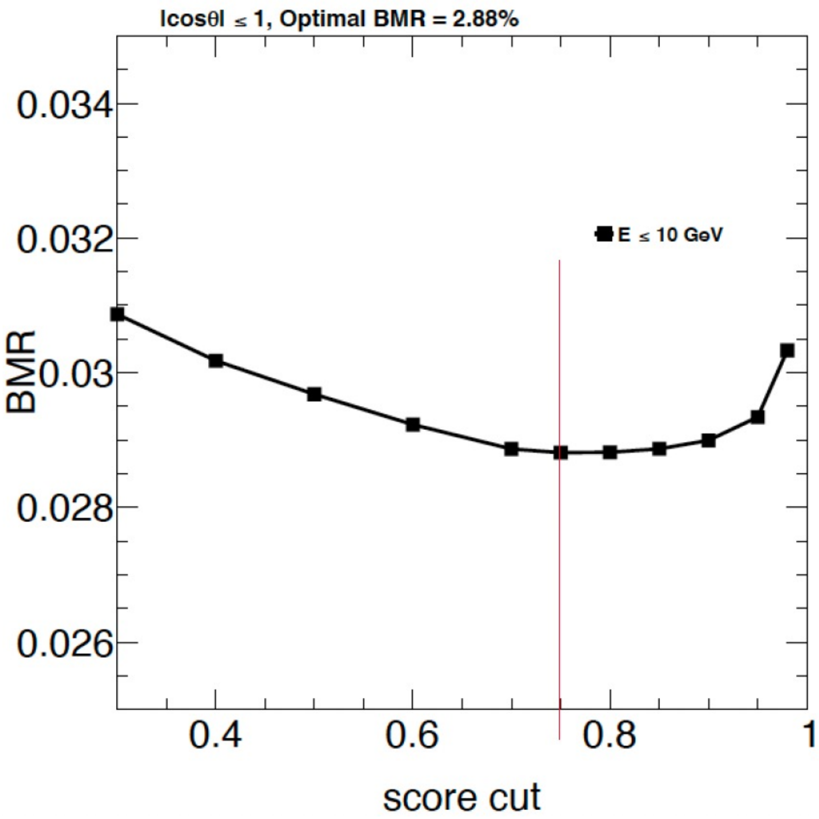
BMR Decomposition for CDR baseline

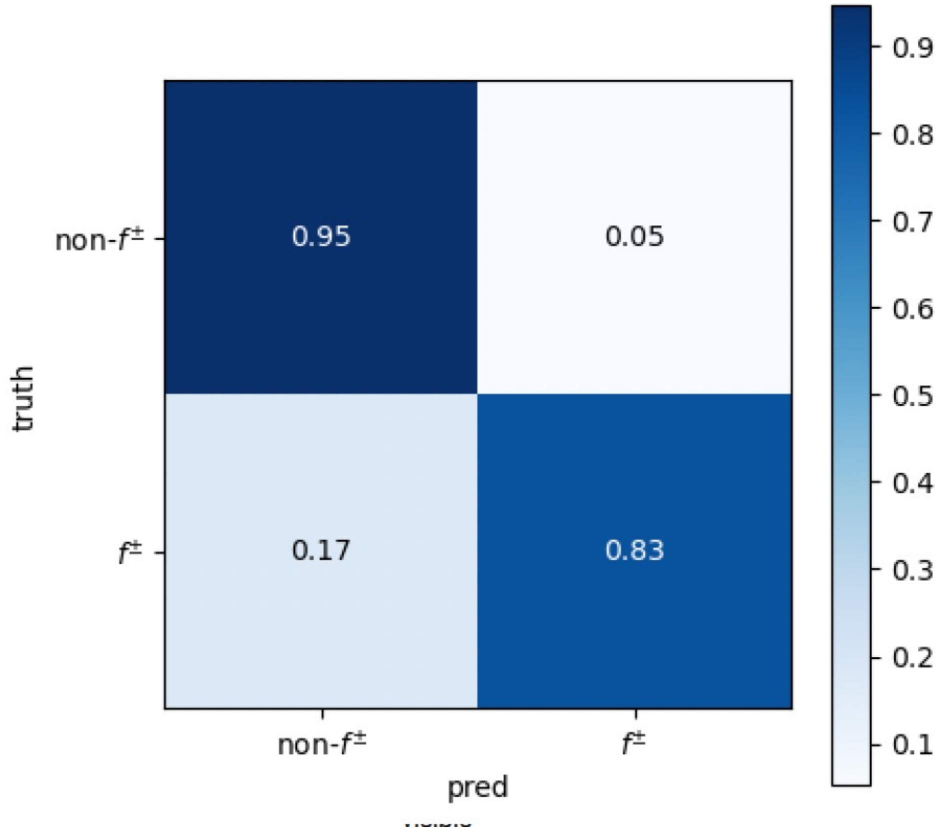




- *1st, Ultimate Precision ~ 2.8 with CDR baseline3rd, HCAL*
- *2nd, HCAL resolution dominant the uncertainties from intrinsic detector resolution: need better HCAL*
- *3rd Leading contribution: Confusion from shower Fragments (fake particles), need better Pattern Reco.*

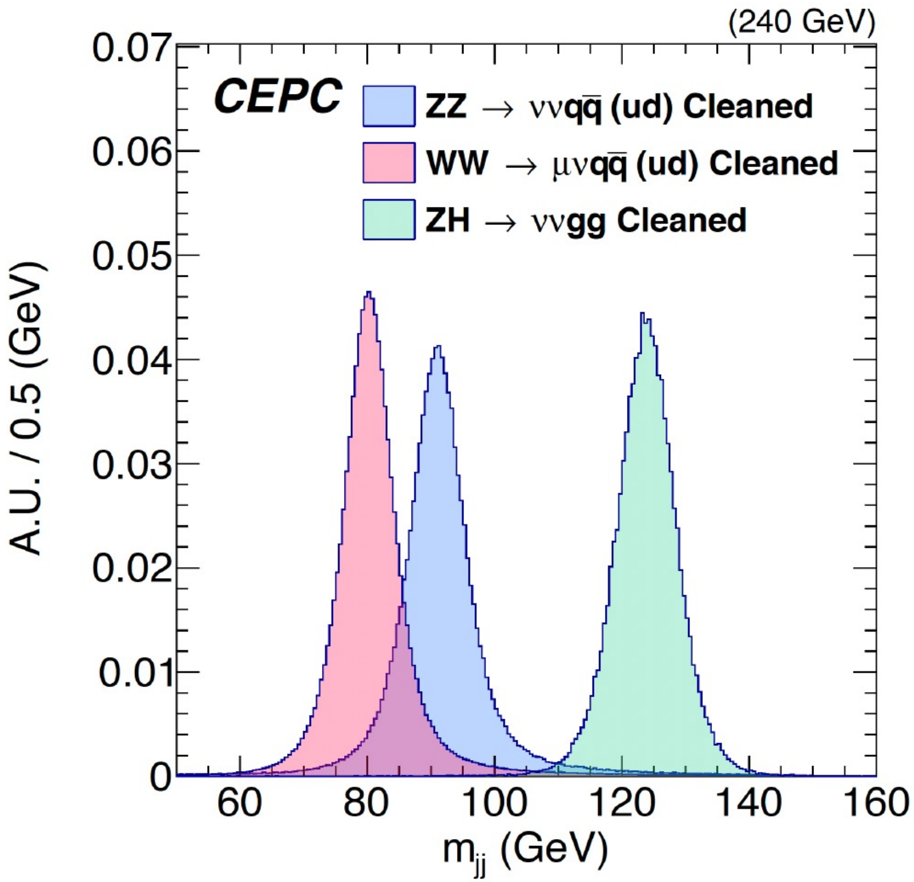
Fake particle veto using AI

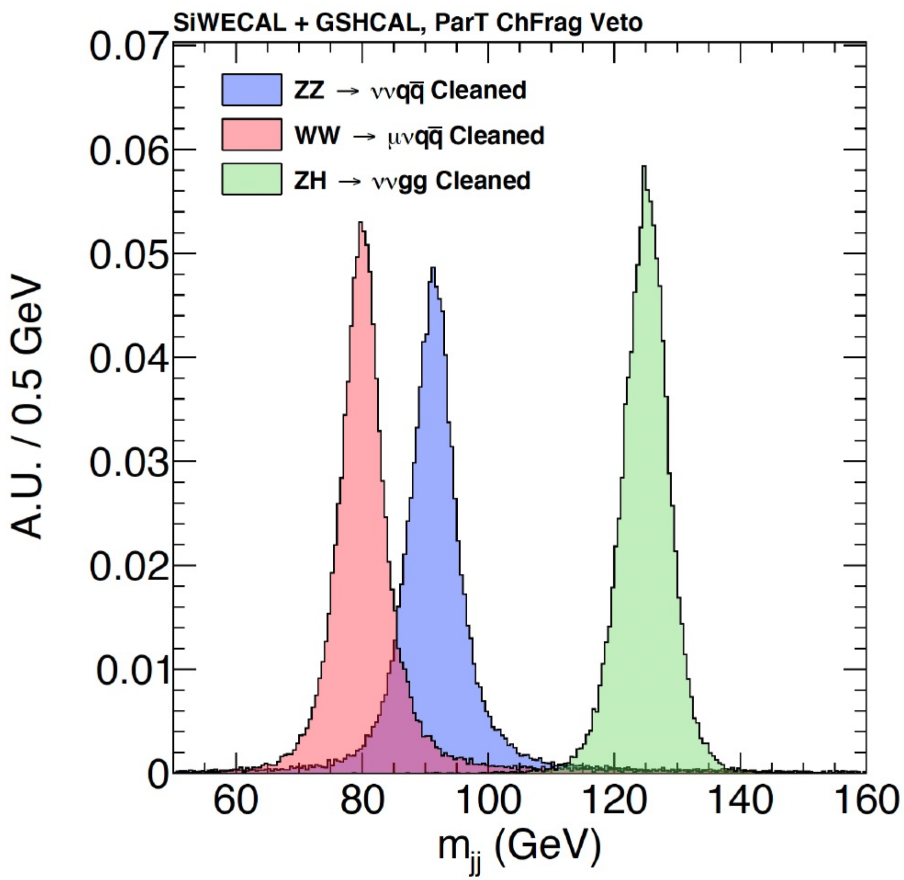




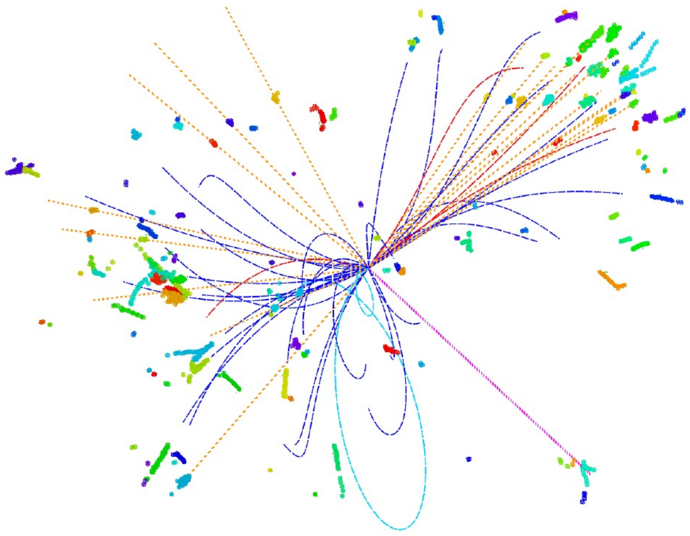
(stemmed from Charge Shower Fragments)

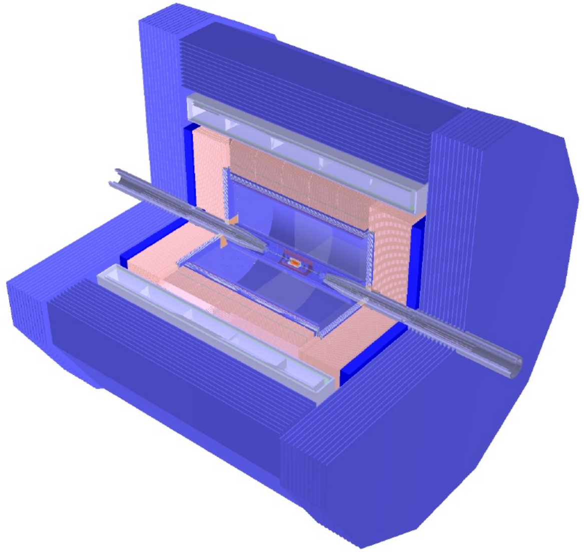
BMR @ CDR & AURORA: 3.7% & 2.9%

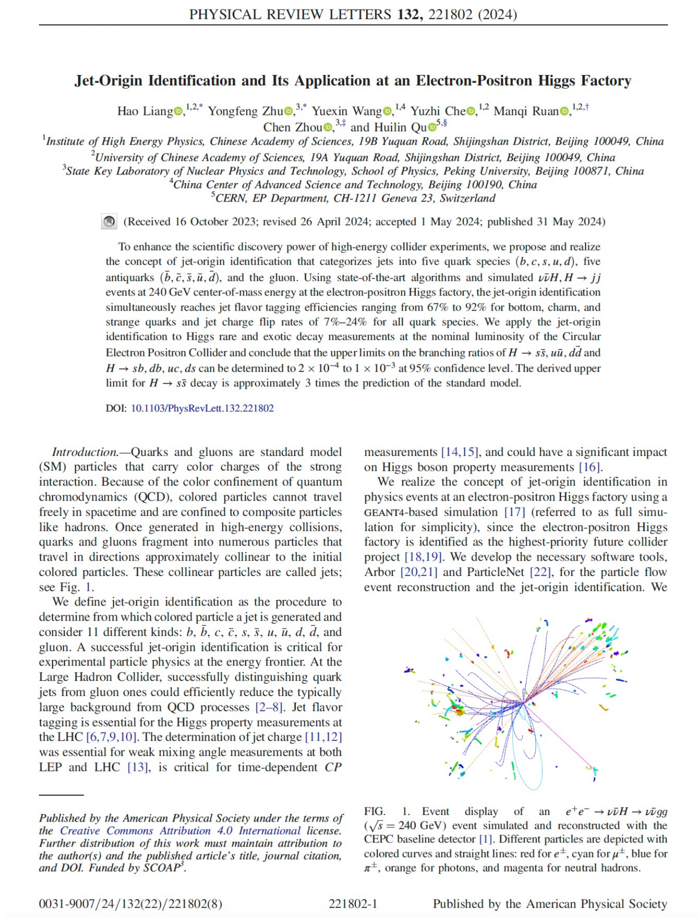




Jet Origin ID







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

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

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

DOI: 10.1103/PhysRevLett.132.221802

Introduction.—Quarks and gluons are standard model (SM) particles that carry color charges of the strong interaction. Because of the color confinement of quantum chromodynamics (QCD), colored particles cannot travel freely in spacetime and are confined to composite particles like hadrons. Once generated in high-energy collisions, quarks and gluons fragment into numerous particles that travel in directions approximately collinear to the initial colored particles. These collinear particles are called jets; see Fig. 1.

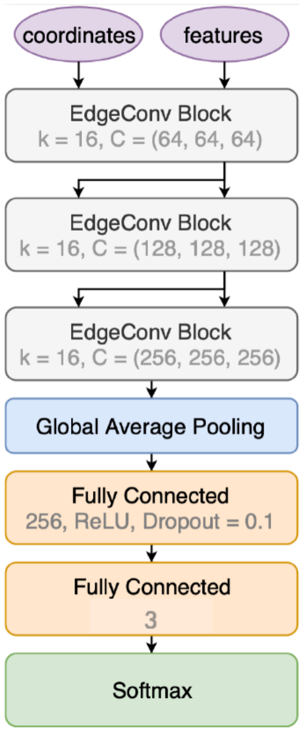
We define jet-origin identification as the procedure to determine from which colored particle a jet is generated and consider 11 different kinds: b, $\bar{b}$, c, $\bar{c}$, s, $\bar{s}$, u, $\bar{u}$, d, $\bar{d}$, and gluon. A successful jet-origin identification is critical for experimental particle physics at the energy frontier. At the Large Hadron Collider, successfully distinguishing quark jets from gluon ones could efficiently reduce the typically large background from QCD processes [2–8]. Jet flavor tagging is essential for the Higgs property measurements at the LHC [6,7,9,10]. The determination of jet charge [11,12] was essential for weak mixing angle measurements at both LEP and LHC [13], is critical for time-dependent *CP* measurements [14,15], and could have a significant impact on Higgs boson property measurements [16].

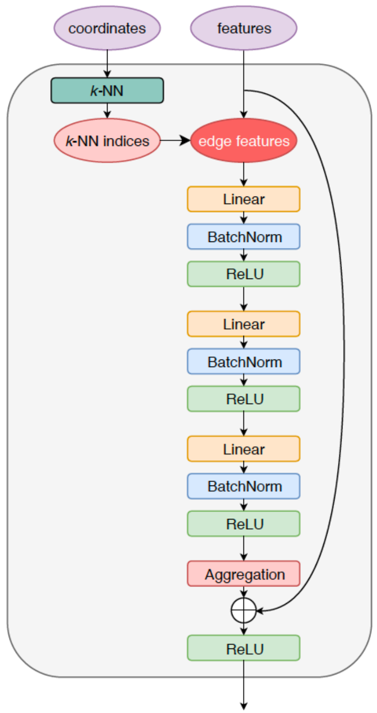
We realize the concept of jet-origin identification in physics events at an electron-positron Higgs factory using a GEANT4-based simulation [17] (referred to as full simulation for simplicity), since the electron-positron Higgs factory is identified as the highest-priority future collider project [18,19]. We develop the necessary software tools, Arbor [20,21] and ParticleNet [22], for the particle flow event reconstruction and the jet-origin identification. We

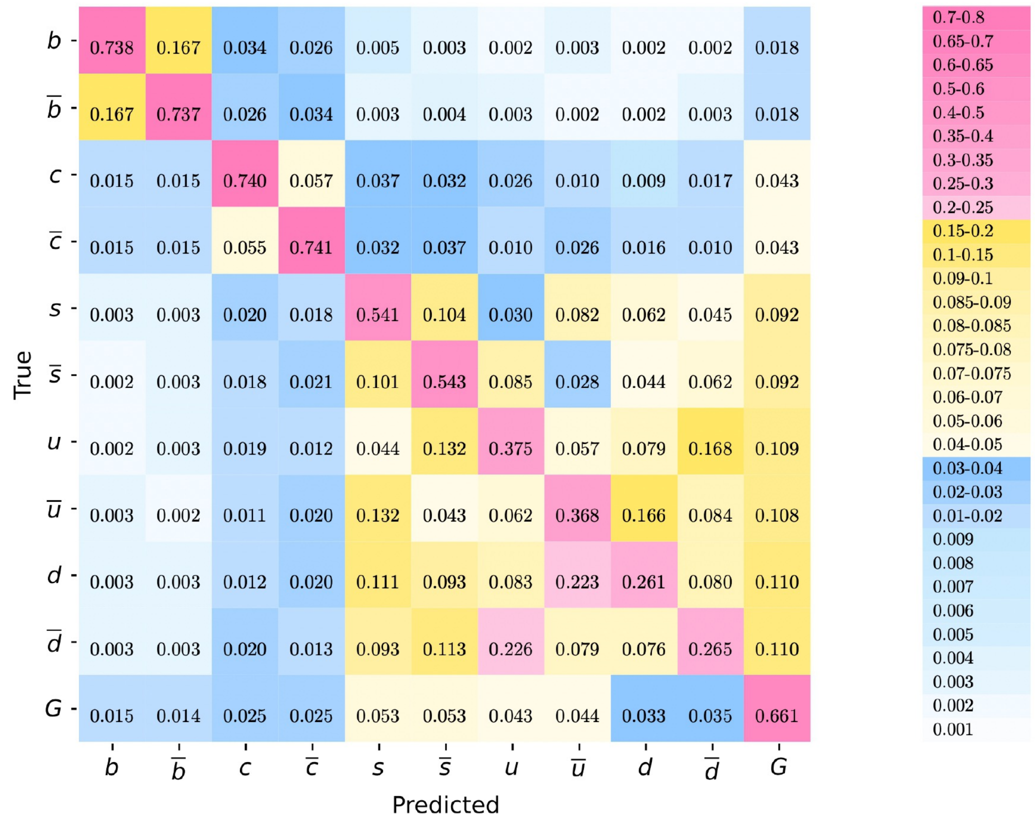
FIG. 1. Event display of an $e^+e^- \to \nu\bar{\nu}H \to \nu\bar{\nu}gg$ ($\sqrt{s} = 240$ GeV) event simulated and reconstructed with the CEPC baseline detector [1]. Different particles are depicted with colored curves and straight lines: red for $e^\pm$, cyan for $\mu^\pm$, blue for $\pi^\pm$, orange for photons, and magenta for neutral hadrons.

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

I-O & migration matrix



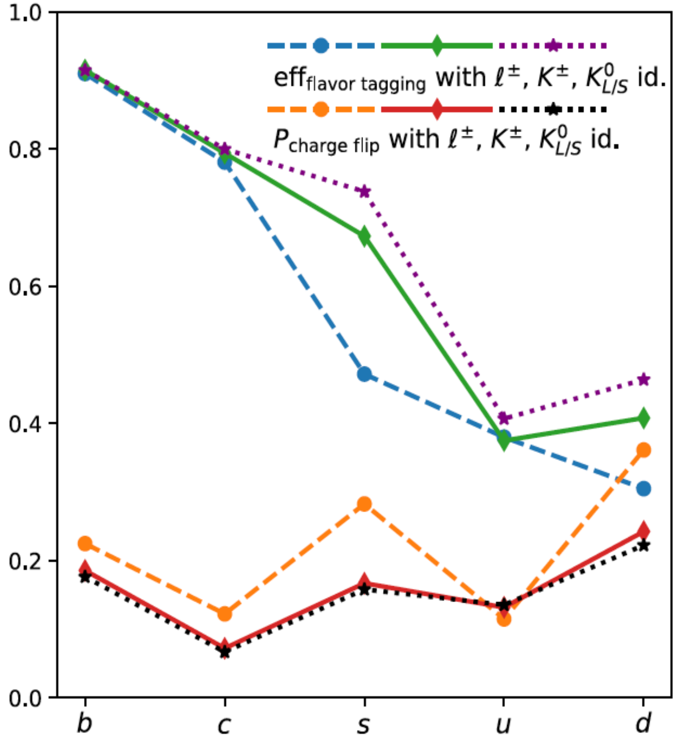


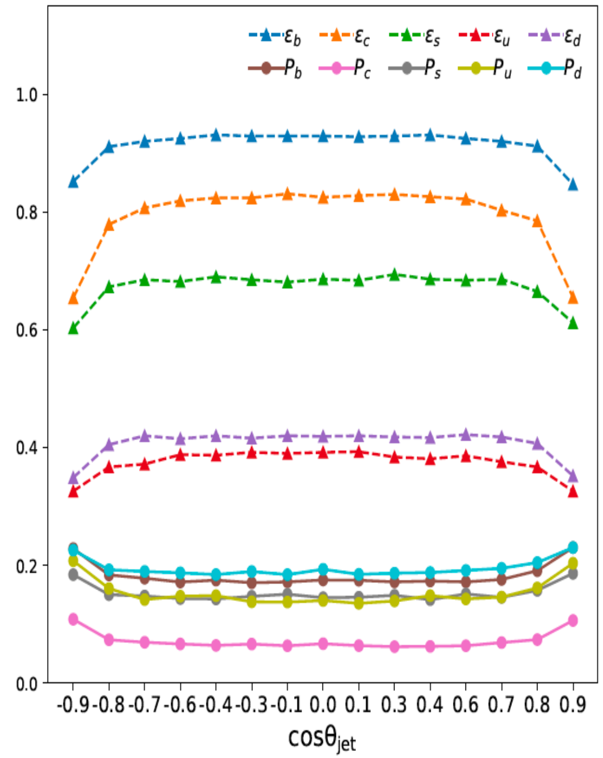


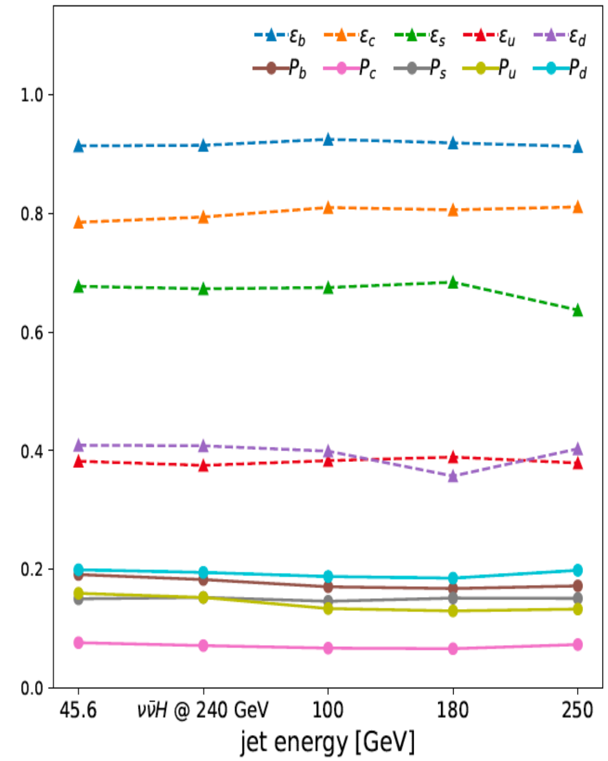
True \ Predicted	b	$\bar{b}$	c	$\bar{c}$	s	$\bar{s}$	u	$\bar{u}$	d	$\bar{d}$	G
b	0.738	0.167	0.034	0.026	0.005	0.003	0.002	0.003	0.002	0.002	0.018
$\bar{b}$	0.167	0.737	0.026	0.034	0.003	0.004	0.003	0.002	0.002	0.003	0.018
c	0.015	0.015	0.740	0.057	0.037	0.032	0.026	0.010	0.009	0.017	0.043
$\bar{c}$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

- Input: ~ 10 numbers (4 momentum, Pid, Impact Para (Charged))*~50 final state particles
- Output: 11/10 likelihoods corresponding to all different jet categories.

JOI: tagging efficiency & flip rates

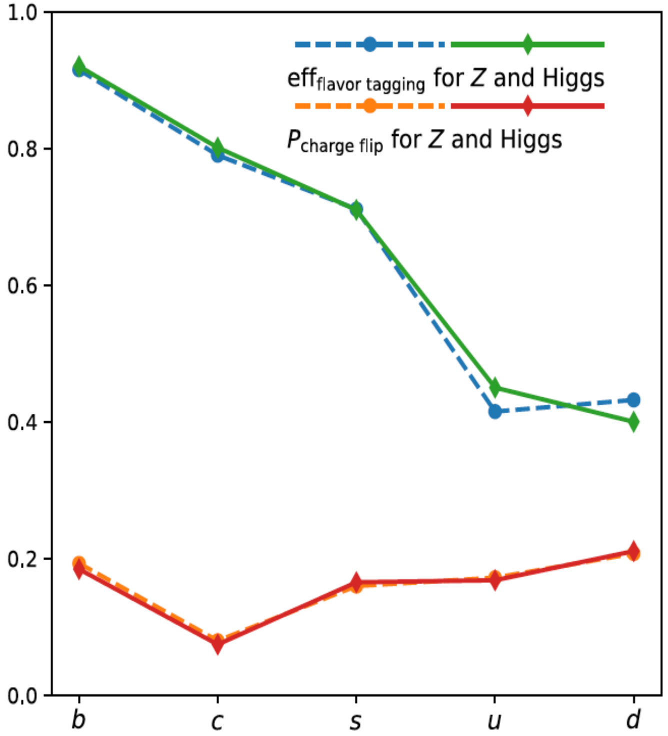


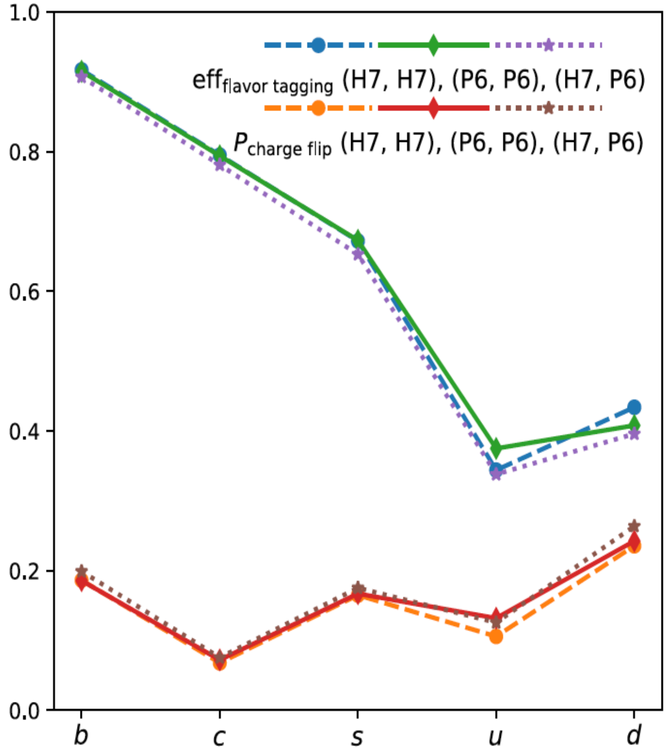


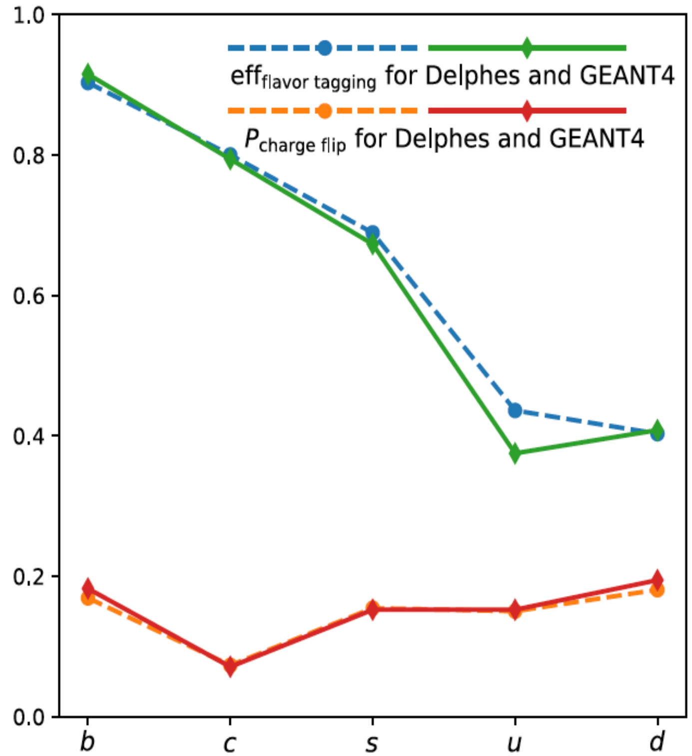


- Kaon id: a must
- Could be calibrated on Z->qq events, and is relatively stable VS hadronization models, etc

JOI: validation & comparison

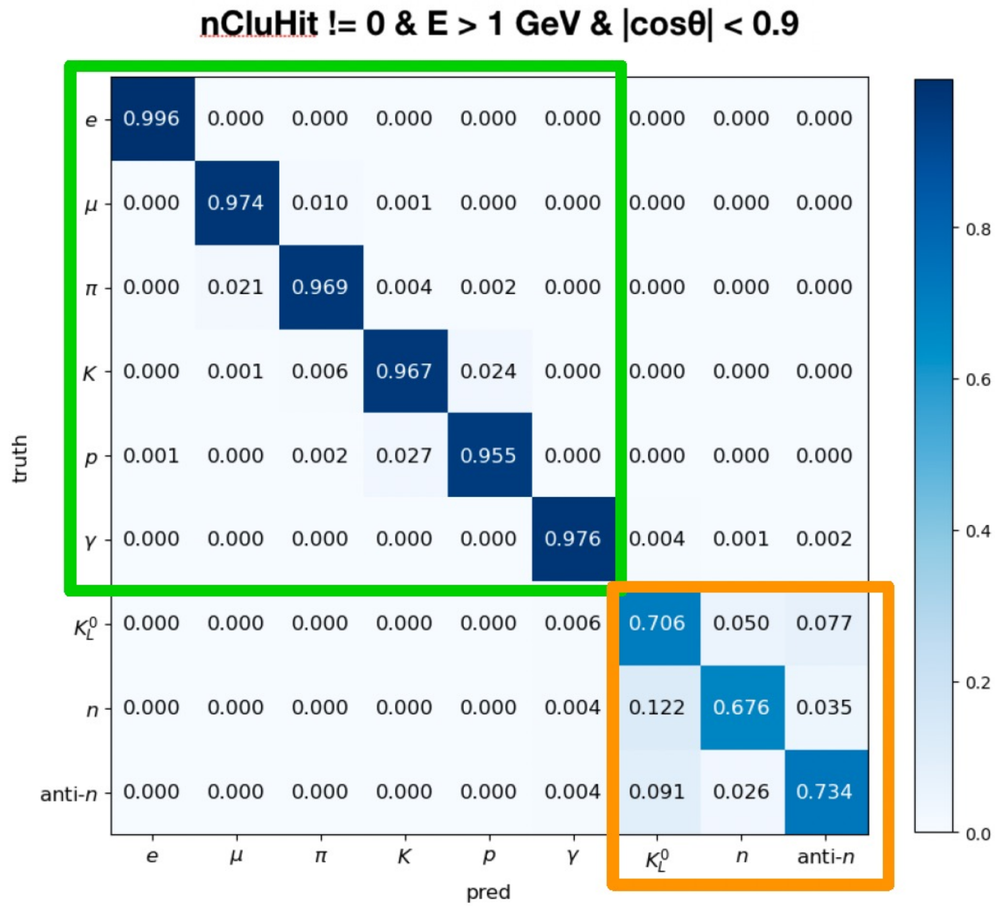


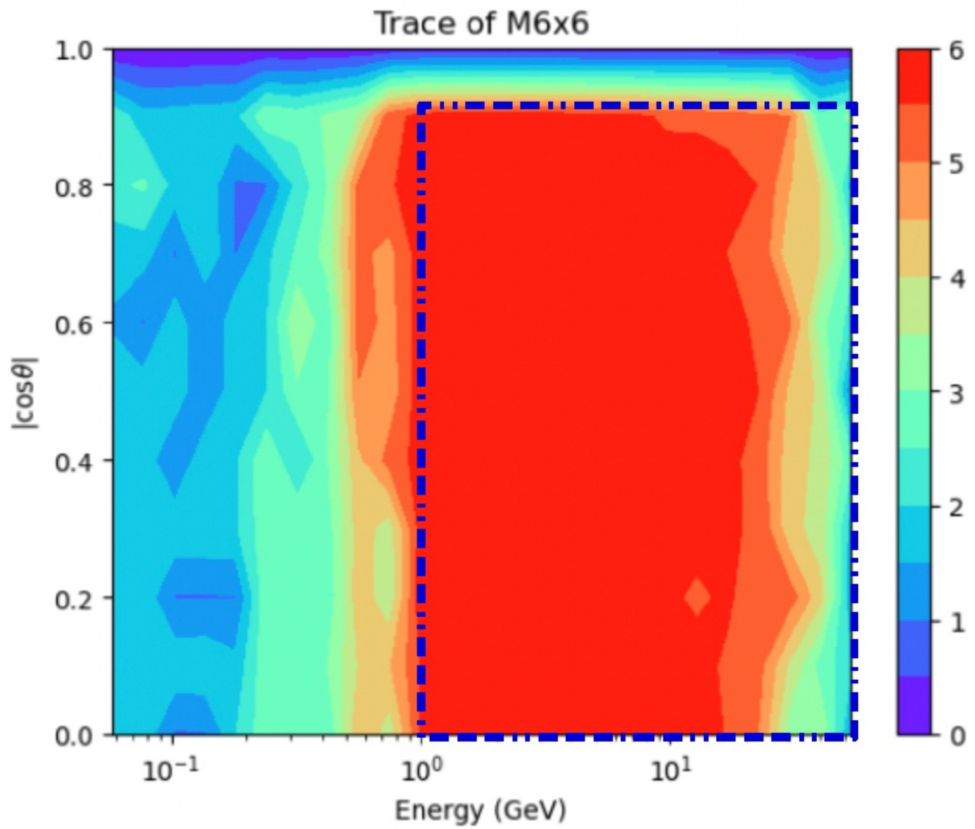




- Could be calibrated using Z->qq. (10 category id, without gluon)
- Stable at different Hadronization model, different simulation method (Geant 4 & Delphes - Fast Sim)
- *Referee: A "game changer" and opens new horizon for precise flavor studies at all future experiments*

Pid of all final state particle…





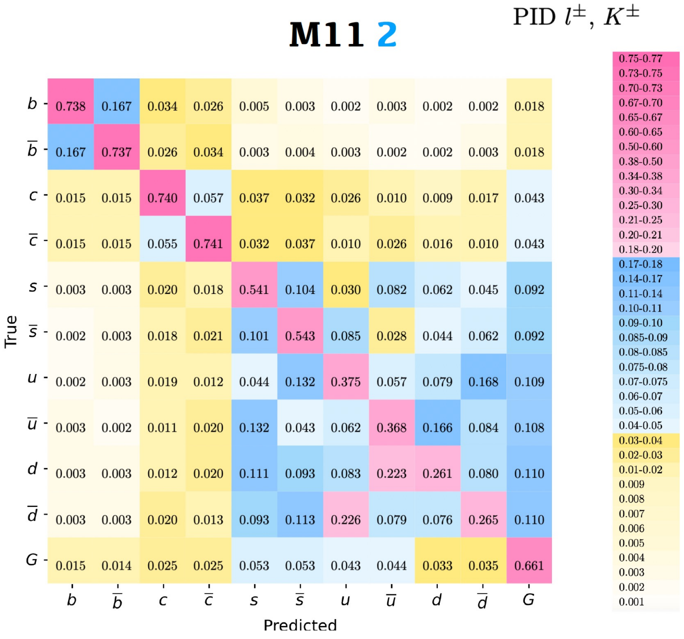
At vvH, H->gg events @ 240 GeV, Using AURORA, No TPC dE/dx Digitization.

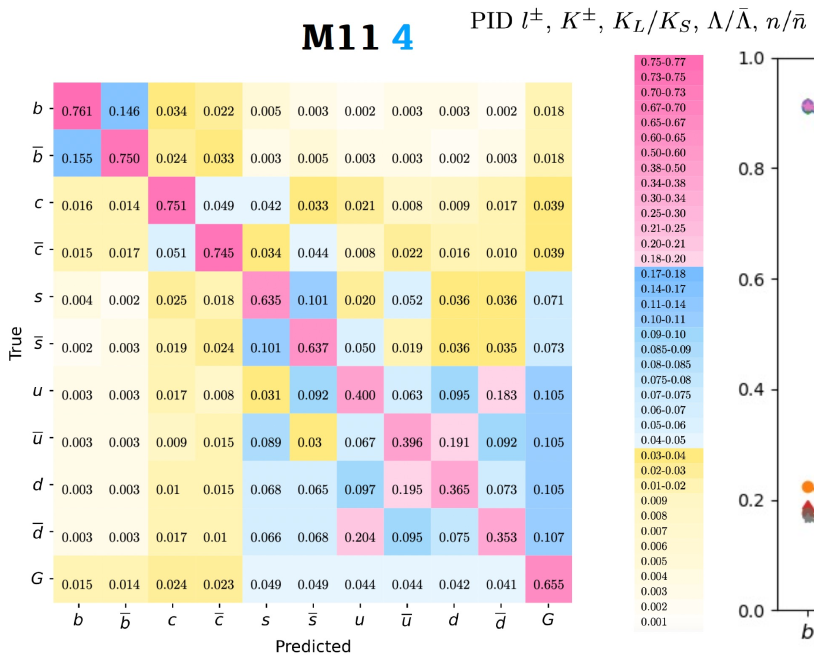
1-1 correspondence between Reco particle & real particle in detector fiducial volume

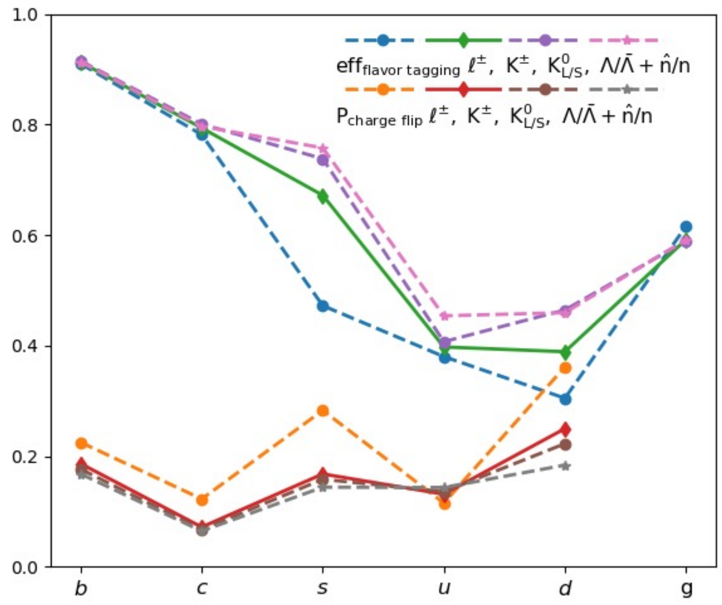
=

Confusion free PFA + Particle Identification

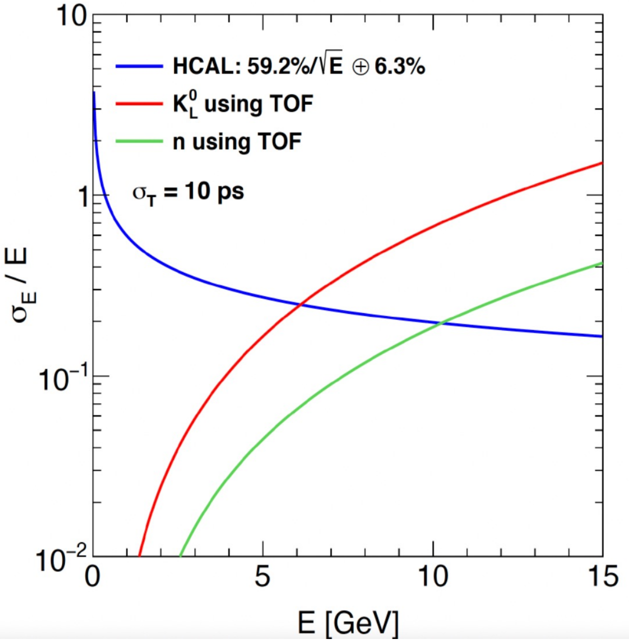
Impact on JoI

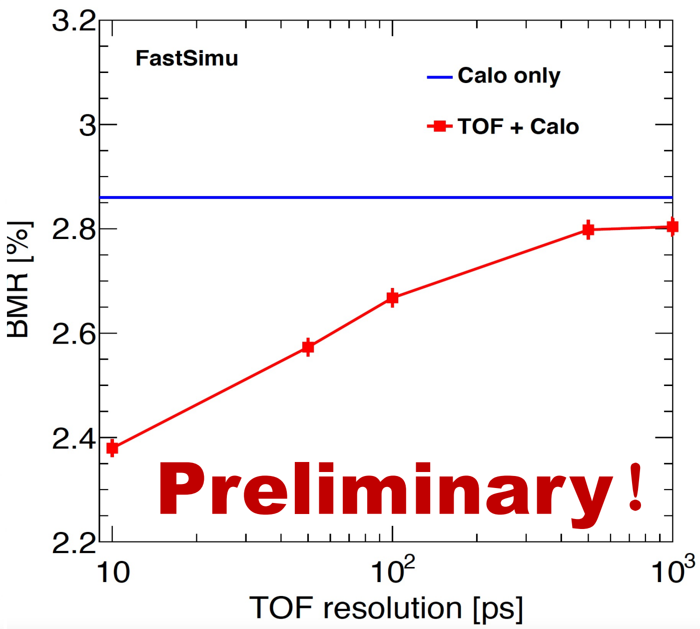






BMR with perfect Neutral hadron id

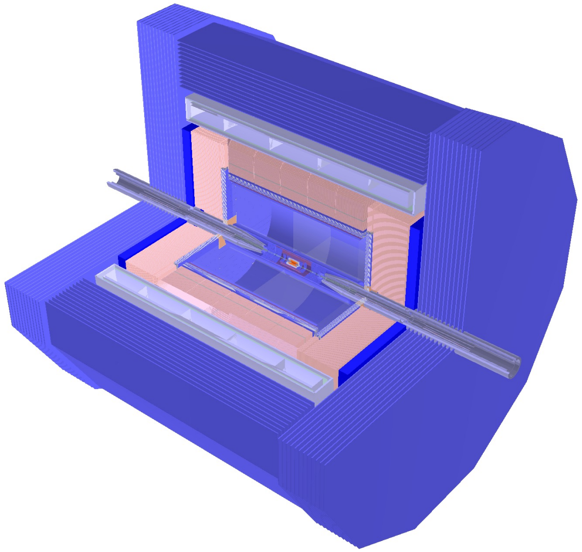




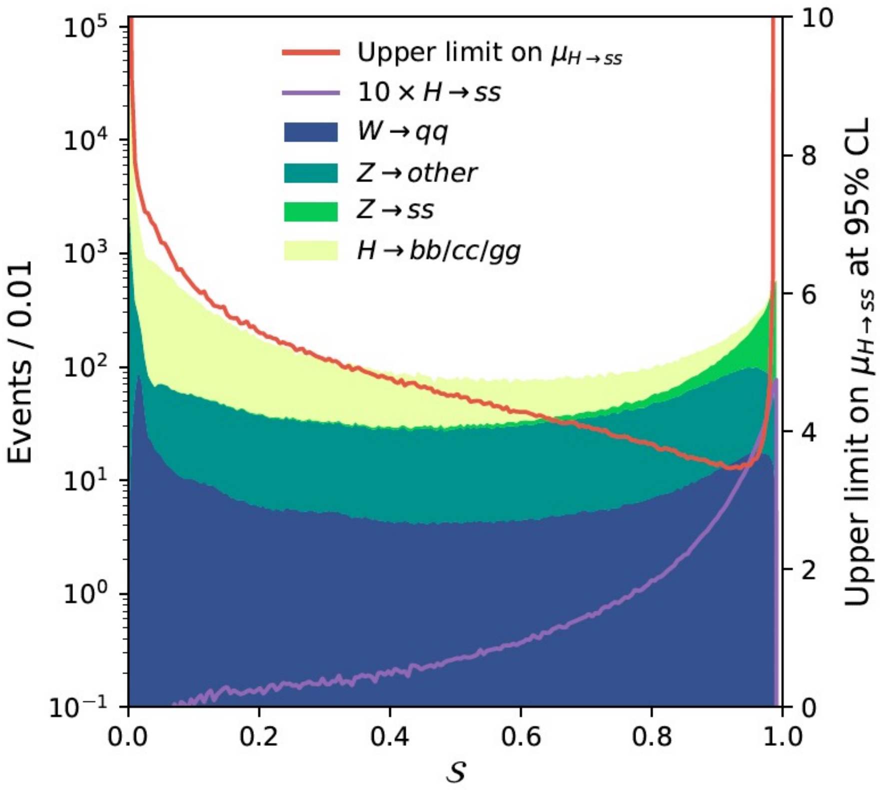
	Charged	Neutral
Non-PFA	Calorimeter	
PFA	Track + Calo (Calo for Pid & Energy matching)	Calorimeter
Future (1-1)	Track + Calo with Time (ToF)	Calo with Time (5D Calo.)

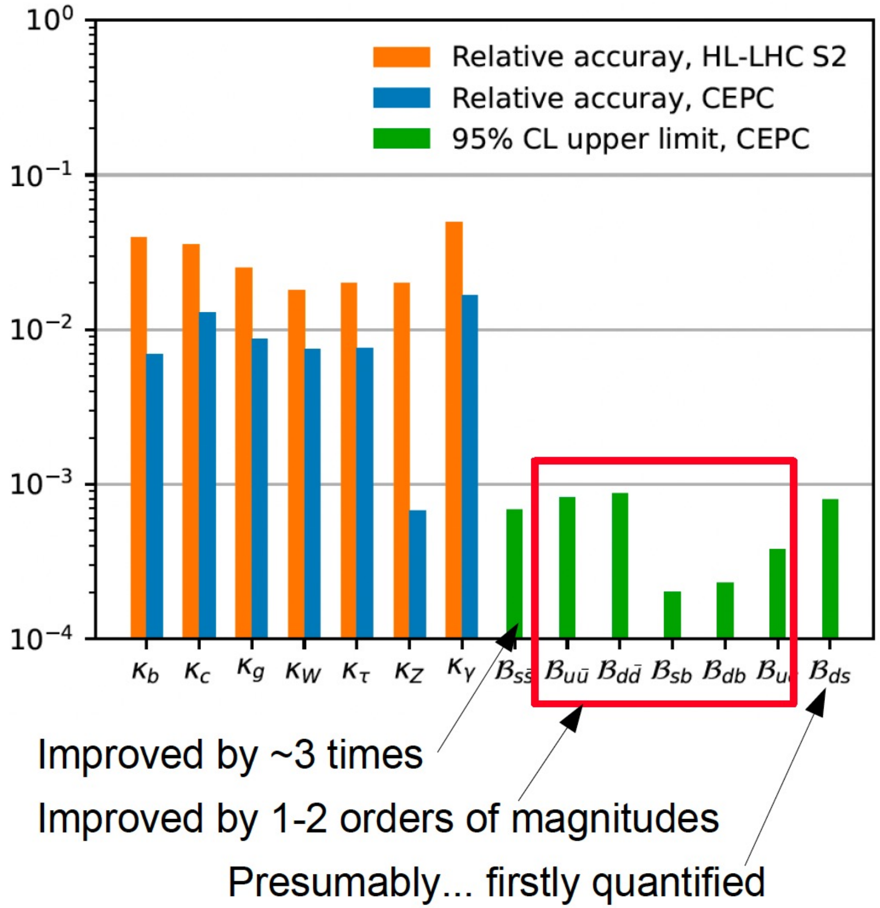
- 5D Calorimeter is essential for
  - Pid, including neutral hadron (~ o(10 ps))
  - PFA Confusion id & Control (~ ns)
  - Event Overlap at Z pole (~ ns)

Physics benchmarks: processed with CDR baseline

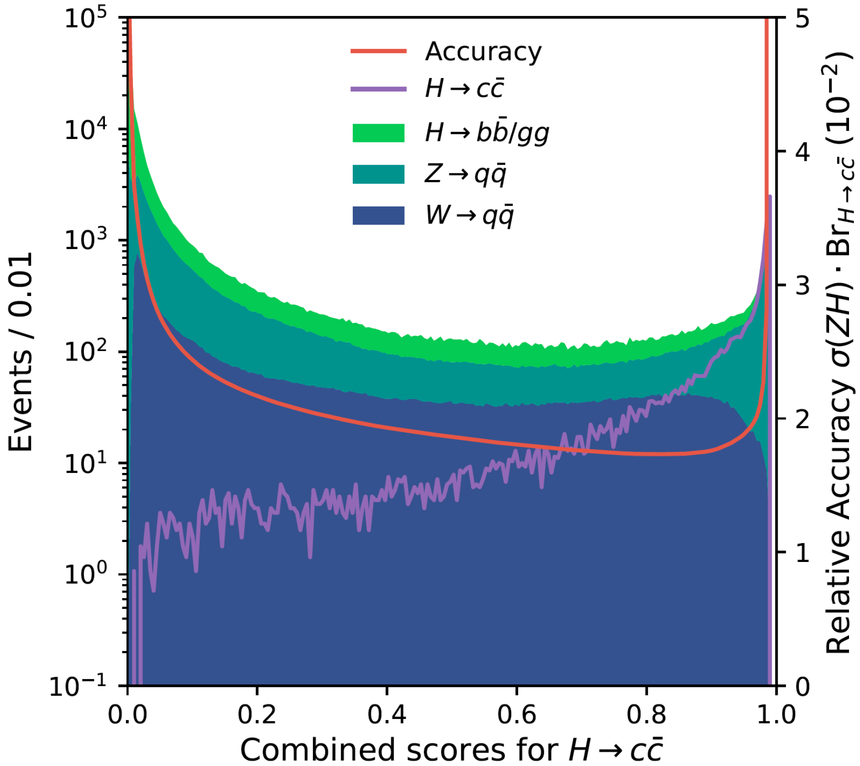


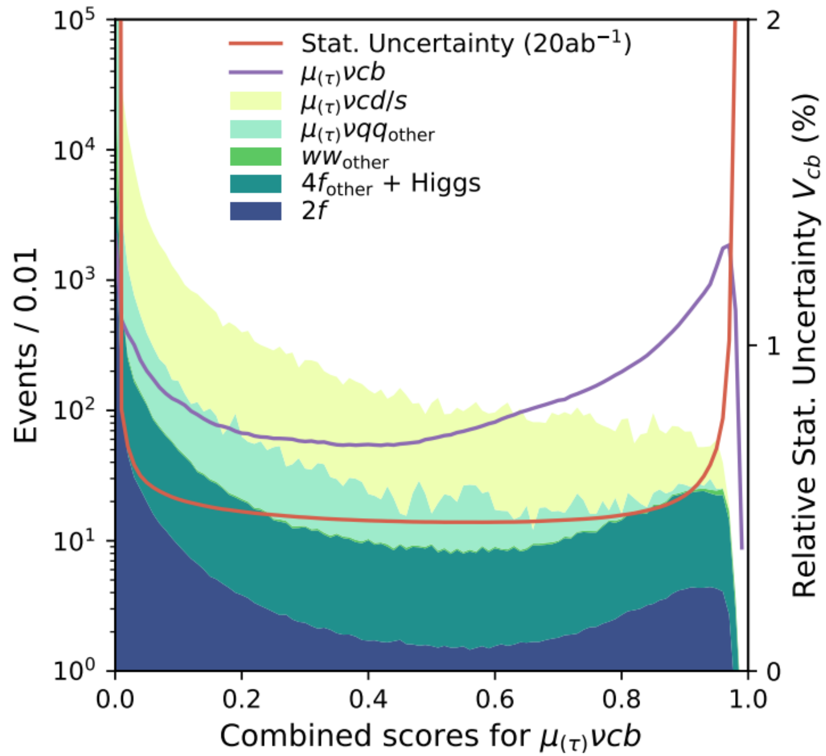
Physics benchmarks: H->ss





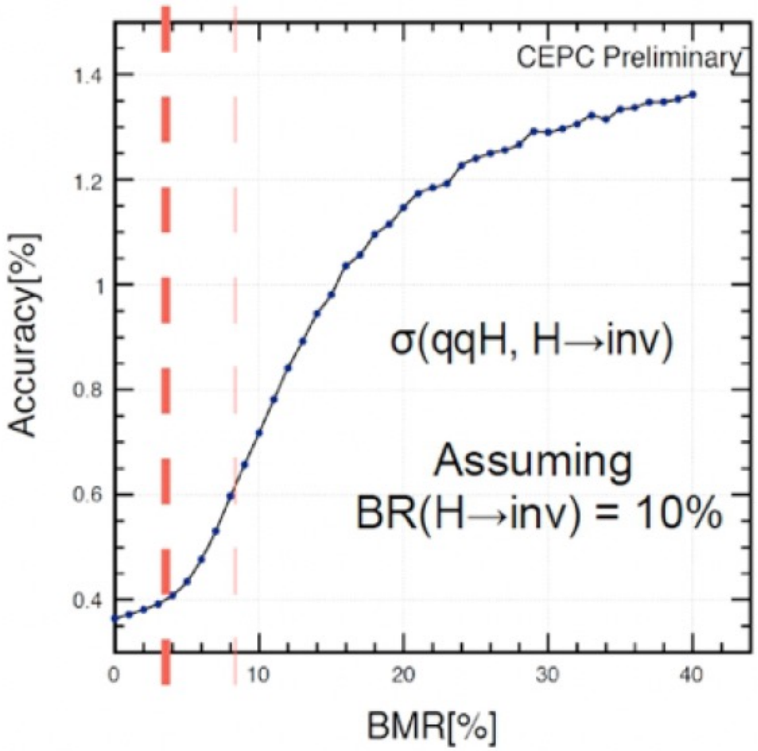
Physics benchmarks: H->cc & Vcb





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

Physics benchmarks: H->inv



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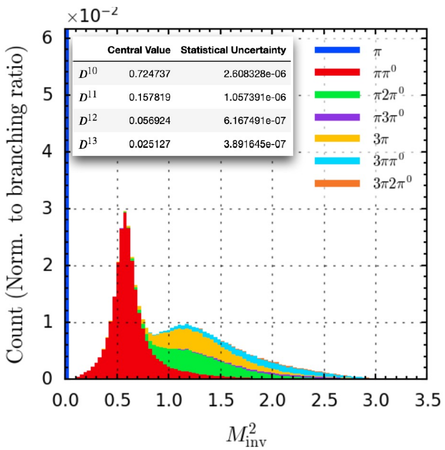
channels $ZH(Z \to qq, H \to \text{inv})$, $ZH(Z \to \mu^+\mu^-, H \to \text{inv})$, and $ZH(Z \to e^+e^-, H \to \text{inv})$. The combined result for the 95% CL upper limit of BR($H \to$ inv) was 0.26% for the

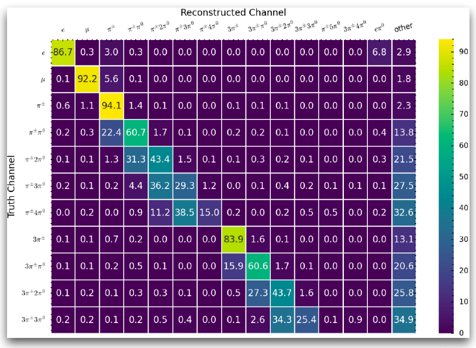
BMR	2.9%	3.7%
L = 5.6 iab		0.26%
L = 20 iab	0.12%	0.13%

- …Benchmark for the impact of beam induced background…

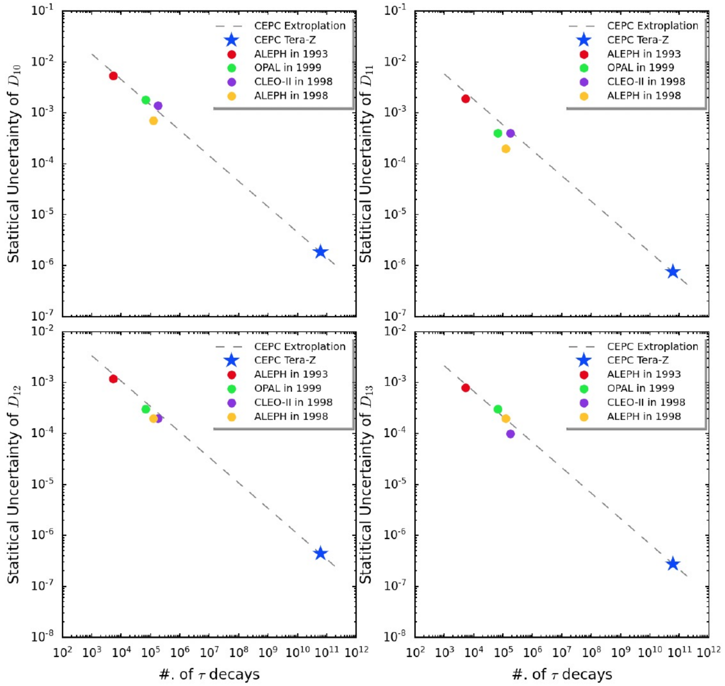
Physics benchmarks: alpha-s



Inclusive $M^2_{\rm inv}$ spectrum merged from exclusive ture $M^2_{\rm inv}$ spectra by associated branching ratio.



Confusion matrix of leptonic and pionic τ decay modes. The migration chance are normalized to truth channel.



Extracting α_S at future e^+e^- Higgs factory with energy correlators

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ABSTRACT: The prospected sensitivity in α_S determination using an event shape observable, ratio of energy correlators at future electron-positron collider is presented. The study focuses on the collinear region which has suffered from large theoretical and hadronization uncertainty in the past. The ratio effectively reduces the impacts of the uncertainties. With the amount of data that future electron-positron collider could produce in 1 minute (40 pb^{-1}) and 0.5 hour (1 fb^{-1}), a 1% and 0.2% precision of α_S could be reached.

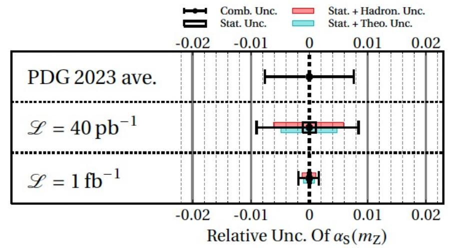
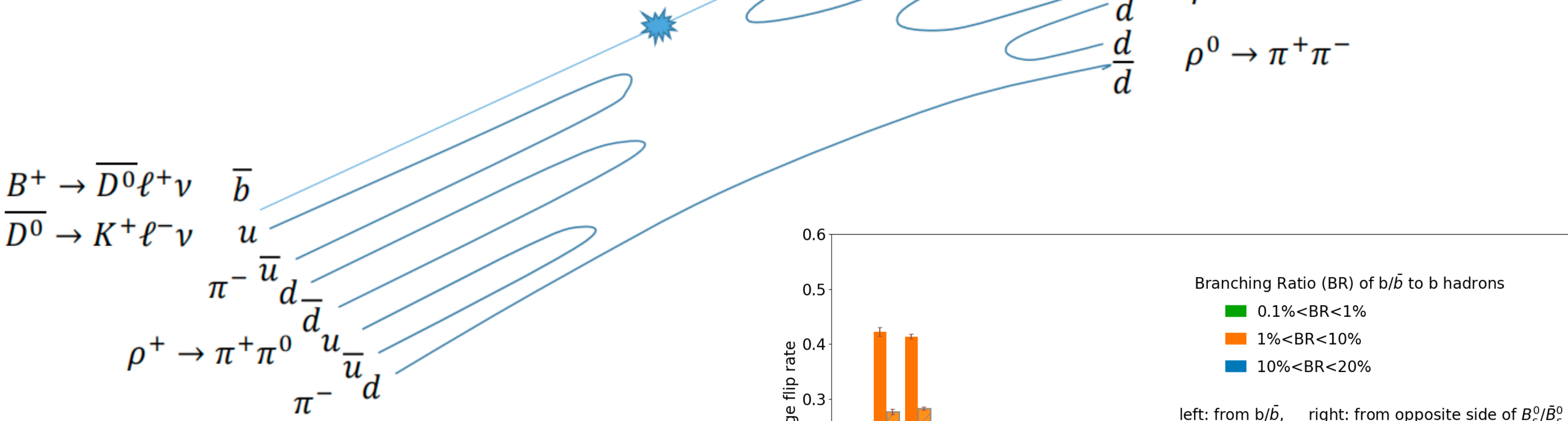


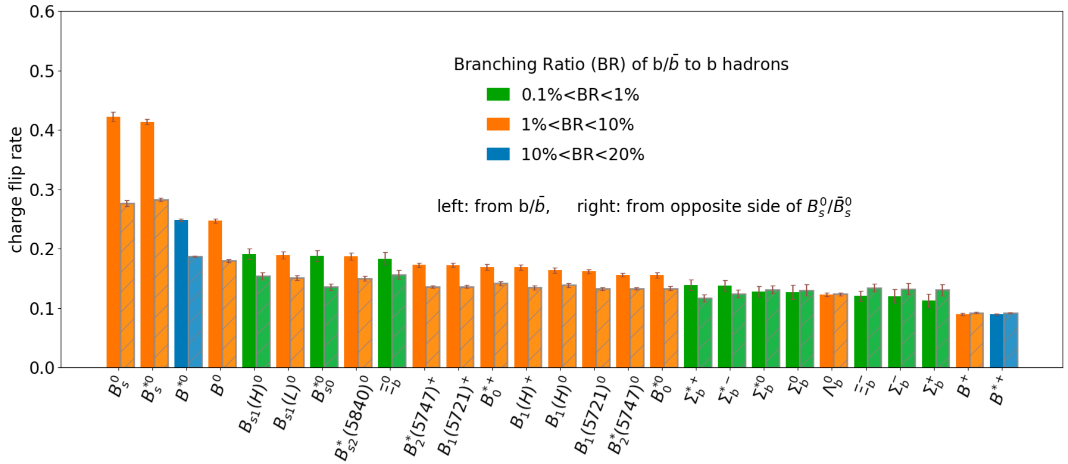
Figure 3: The expected sensitivity to $\alpha_S(m_Z)$ using E3C/E2C at CEPC in different luminosity scenarios. The world average precision for α_S extraction is shown for a comparison [1]. The breakdown of statistical, hadronization, and theoretical uncertainties is shown.

Physics benchmarks: Bs oscillation

Opposite side

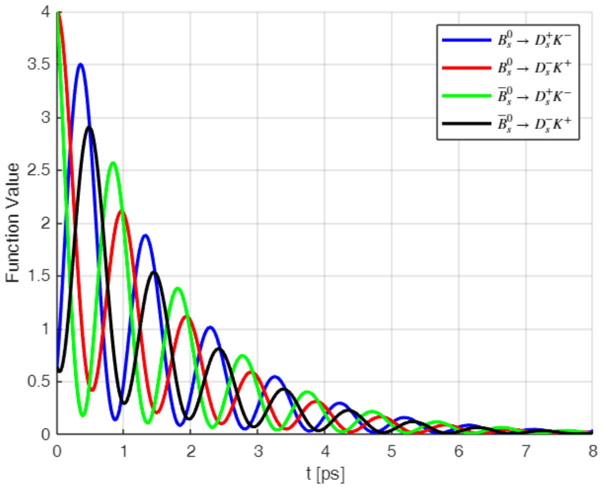
- p charged Leptons with impact param.
- p charged Kaons with impact param.
- p charged pions with impact param.
- p protons with impact param. ?

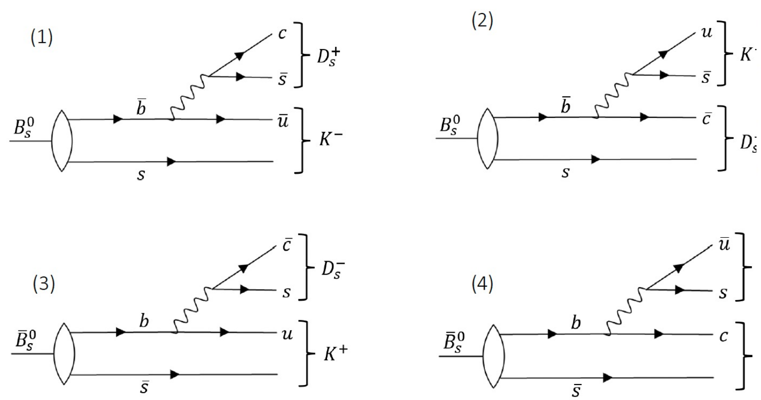




Effective tagging power (eff*(1-2*ω)^2) ~ 40%,
one order of magnitude better than LHCb

Physics benchmarks: Bs oscillation





$$P_{++} \propto e^{-\Gamma t}\left(\cosh\left(\frac{\Delta\Gamma}{2}t\right) - C\cos(\Delta m t) + D_{\bar f}\sinh\left(\frac{\Delta\Gamma}{2}t\right) - S_{\bar f}\sin(\Delta m t)\right) \quad (19)$$

$$P_{+-} \propto e^{-\Gamma t}\left(\cosh\left(\frac{\Delta\Gamma}{2}t\right) + C\cos(\Delta m t) + D_{\bar f}\sinh\left(\frac{\Delta\Gamma}{2}t\right) - S_{\bar f}\sin(\Delta m t)\right) \quad (20)$$

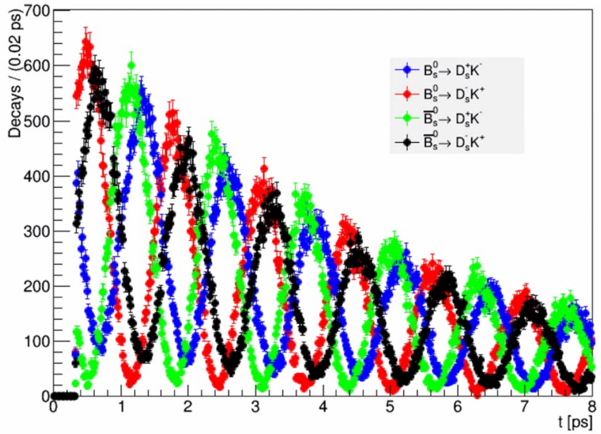
$$P_{-+} \propto e^{-\Gamma t}\left(\cosh\left(\frac{\Delta\Gamma}{2}t\right) + C\cos(\Delta m t) + D_{\bar f}\sinh\left(\frac{\Delta\Gamma}{2}t\right) + S_{\bar f}\sin(\Delta m t)\right) \quad (21)$$

$$P_{--} \propto e^{-\Gamma t}\left(\cosh\left(\frac{\Delta\Gamma}{2}t\right) - C\cos(\Delta m t) + D_{\bar f}\sinh\left(\frac{\Delta\Gamma}{2}t\right) + S_{\bar f}\sin(\Delta m t)\right) \quad (22)$$

$$C = \frac{1-r^2}{1+r^2}, \quad (23)$$

$$D_f = \frac{-2r\cos(\delta-(\gamma-2\beta_s))}{1+r^2}, \qquad D_{\bar f} = \frac{-2r\cos(\delta+(\gamma-2\beta_s))}{1+r^2}, \quad (24)$$

$$S_f = \frac{2r\sin(\delta-(\gamma-2\beta_s))}{1+r^2}, \qquad S_{\bar f} = \frac{-2r\sin(\delta+(\gamma-2\beta_s))}{1+r^2}. \quad (25)$$



From Peng Ji (IHEP), Xiaoling Wang (SCNU), Mingrui Zhao (CIAE), etc

Preliminary Estimation based on Yield & Key Performance comparison:

measure $\gamma - 2\beta_s$ to precision of o(0.1 degree)

~ 20 times better than current precision…

~ 4 times better than LHCb @ HL-LHC

...Challenges...

- More realistic collision environments: Beam induced background, Primary IP reco, etc
  - To be addressed by a few benchmark performance study wi. Beam induced background & to be included in TDR

- Event overlap in time (Z pole):
  - To be solved by **PFA in Space time: Future Plan.**

- More Realistic Digitization, including Noise & TDAQ effects

+

- Further Optimization (5D Calorimerter, Time resolution, cell configuration, etc)
  - To be addressed by joint study with Sub-detector & Software team (Long term plan)
  - AI enhanced reco. will be the key.

...Challenges...

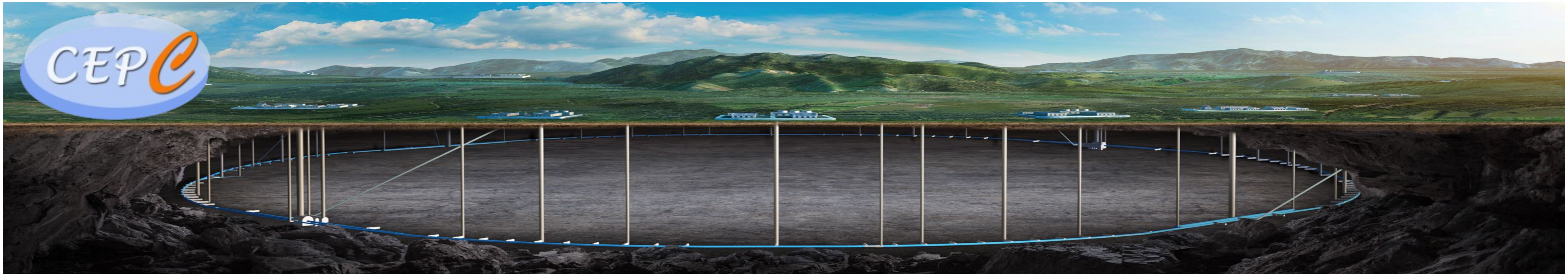
- Geometry not fully converged yet.
- Sophisticated Reco. yet to be established for baseline design.
- Computing: CPU efficiency & total resource.
- Is extrapolating from results using CDR baseline an option??

Team

- Core team: ~ 2 staff (FTE) + 2 PostDoc + 4 Students + 2 Visitors
- Performance: with sub-detector team
- Advanced Algorithms: collaboration with PKU, LLR & CERN
- Benchmark: in pace with physics white paper efforts
  - Higgs: Yaquan Fang (IHEP)
  - Flavor Physics: Tao Liu (HKUST), Lorenzo (NKU), Shanzhen Chen(IHEP) etc
  - New Physics: Xuai Zhuang (IHEP), Mengchao Zhang ()
  - EW: Zhijun Liang (IHEP), Jiayin Gu (FuDan U), Siqi Yang (USTC)
  - QCD: Zhao Li (IHEP), Meng Xiao (ZJU), Huaxing Zhu (PKU)

Summary

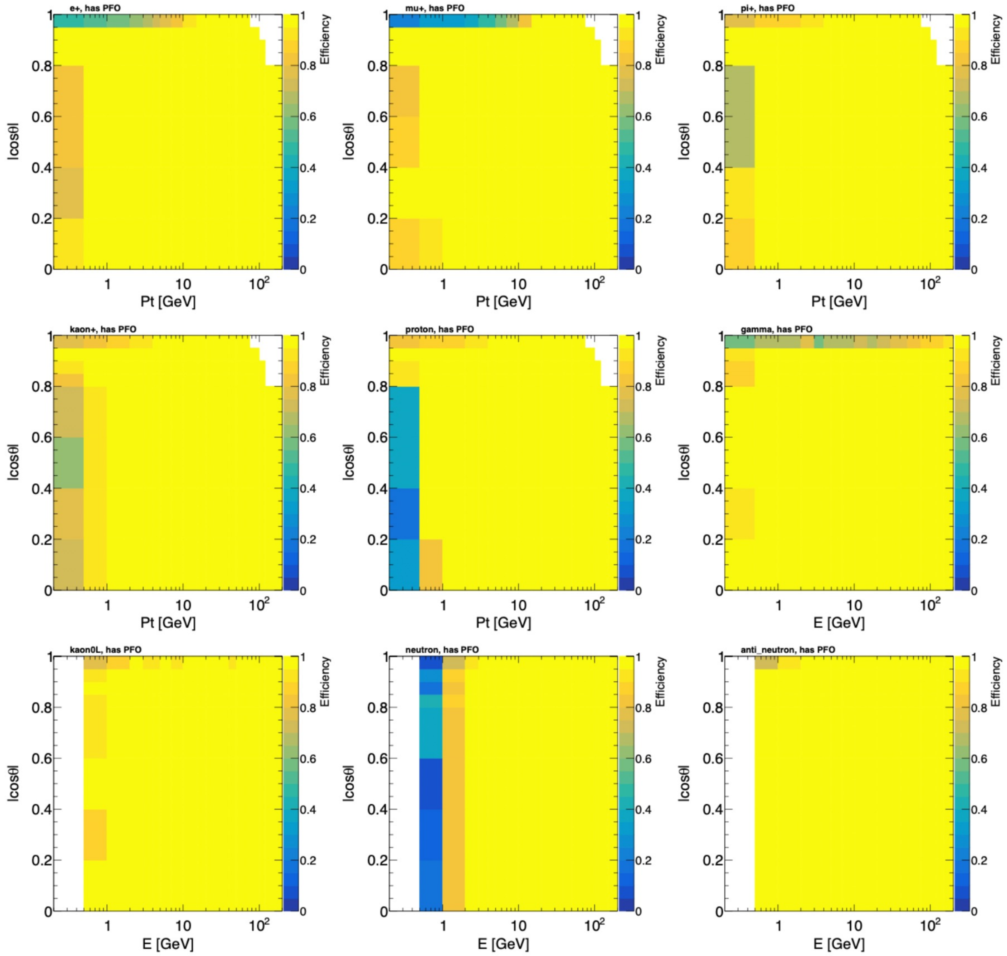
- Global Performance:
  - BMR: 2.9%, (4% as a must; to pursue 3% or better)
  - JoI: idnetify different colored SM particle
  - Pid: efficiently identify final state particles
- 1-1 correspondense at the horizon: a should and a could.
- Physics Benchmarks: quantified at CEPC-v4
- To do:
  - iterated with detector tech/geometry evolution,
  - to include beam background & more realistic sub-d/DAQ modeling,
  - to develop smart algorithms.



Thank you for your attention!

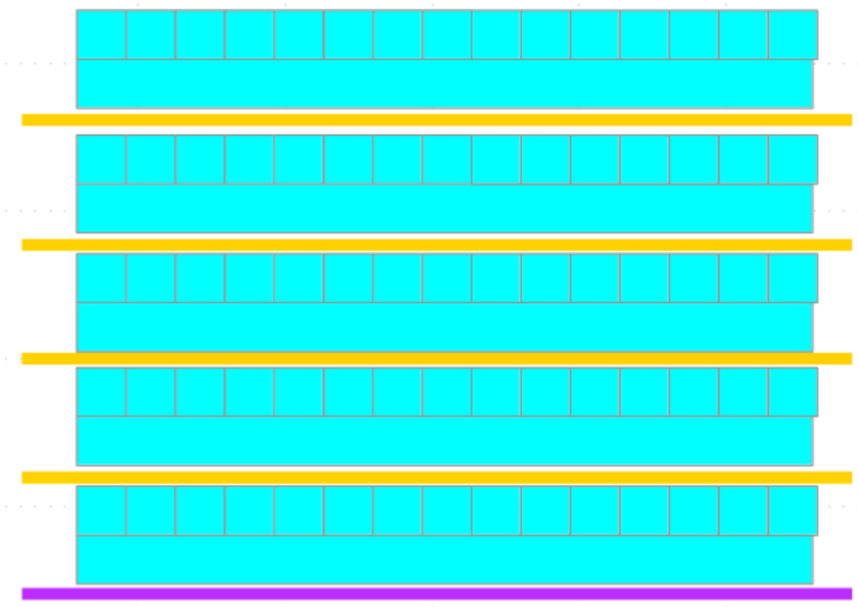
中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Single Particle: differential efficiency



Alternatives

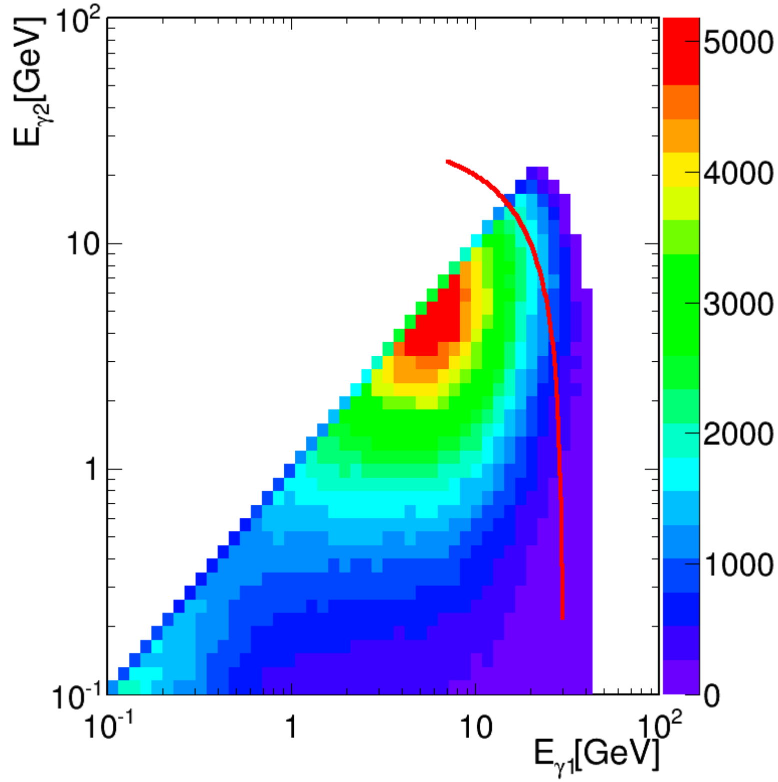
- CDR baseline: all done
- AURORA (GSHCAL + Stitching VTX)
- AURORA+ (Xstal ECAL + Positioning Layers)
- TDR baseline



Sep. power.

Sub-detector	Key technology	Key Specifications
Silicon vertex detector	Spatial resolution and materials	$\sigma_{r\phi} \sim 3\ \mu\text{m}$, $X/X_0 < 0.15\%$ (per layer)
Silicon tracker	Large-area silicon detector	$\sigma(\frac{1}{p_T}) \sim 2 \times 10^{-5} \oplus \frac{1\times10^{-3}}{p\times\sin^{3/2}\theta}(\text{GeV}^{-1})$
TPC/Drift Chamber	Precise dE/dx (dN/dx) measurement	Relative uncertainty 2%
Time of Flight detector	Large-area silicon timing detector	$\sigma(t) \sim 30$ ps
Electromagnetic Calorimeter	High granularity 4D crystal calorimeter	EM energy resolution $\sim 3\%/\sqrt{E(\text{GeV})}$ Granularity $\sim 2 \times 2 \times 2\ \text{cm}^3$
Magnet system	Ultra-thin High temperature Superconducting magnet	Magnet field $2 - 3$ T Material budget $< 1.5X_0$ Thickness < 150 mm
Hadron calorimeter	Scintillating glass Hadron calorimeter	Support PFA jet reconstruction Single hadron $\sigma_E^{had} \sim 40\%/\sqrt{E(\text{GeV})}$ Jet $\sigma_E^{jet} \sim 30\%/\sqrt{E(\text{GeV})}$

These specifications continue to be optimized



Pi0 energies at Z->tautau events at Z pole.

Sep power ~ 1.6 cm ~ 30 GeV Pi0

Sub D recap

- Tracking: efficiency & resolutions as a function of cos(theta) & Pt
- Calorimeter: efficiency & resolution – linearity of photon, neutral hadron
- Pid relevant: ToF, dE/dx, dN/dx, etc.

Performance Chapter: ToC

- Introduction (recall the requirements)
- Recap of sub-d performance
  - Tracking: efficiency & resolutions as a function of cos(theta) & Pt
  - Calorimeter: efficiency & resolution – linearity of photon, neutral hadron
  - Pid relevant: ToF, dE/dx, dN/dx, etc.
- Global Performance
  - BMR
  - JoI
  - Pid
- Physics Benchmarks
  - Higgs, EW, Flavor, NP
- Outlook (1-1 correspondense)