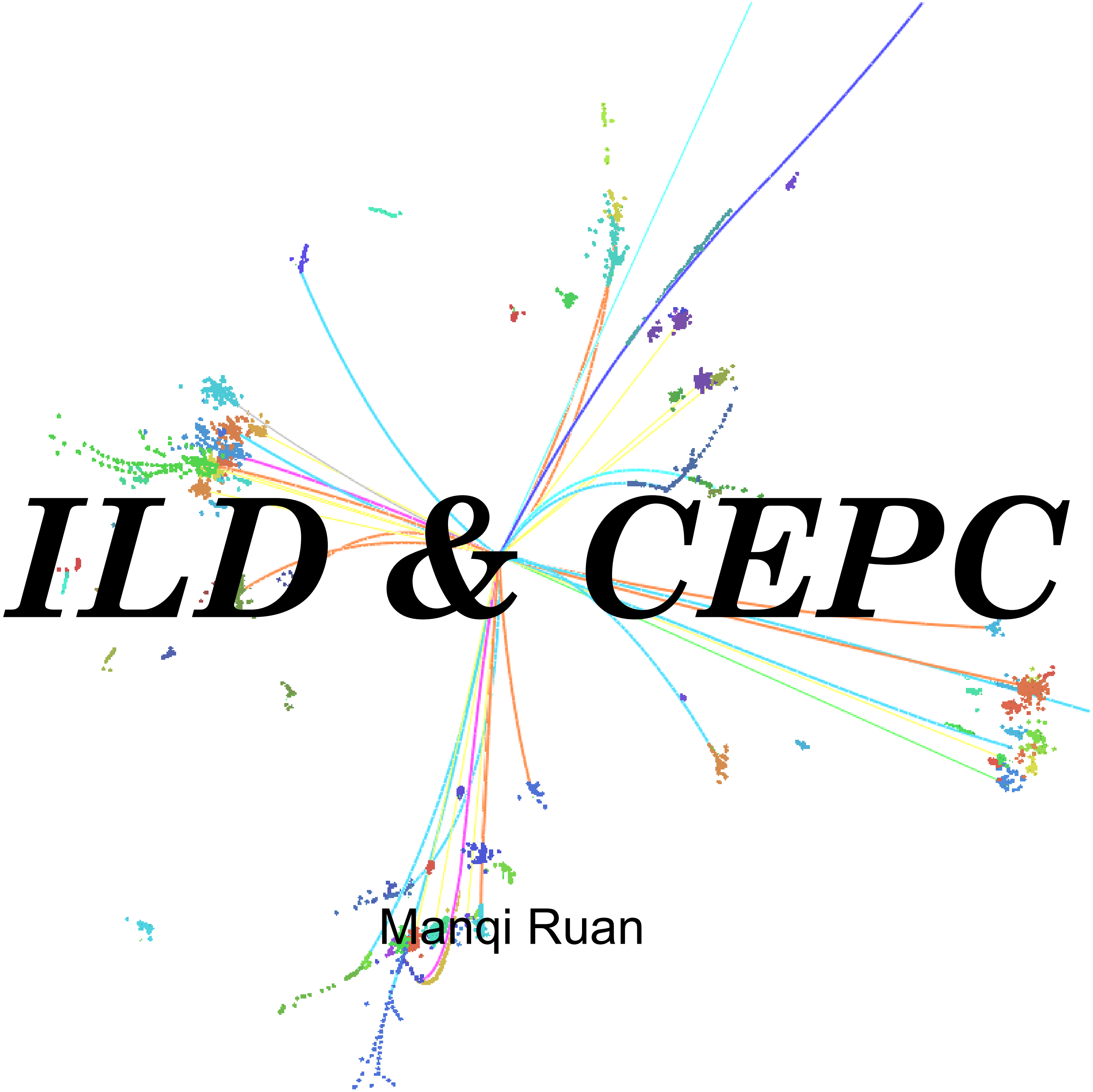
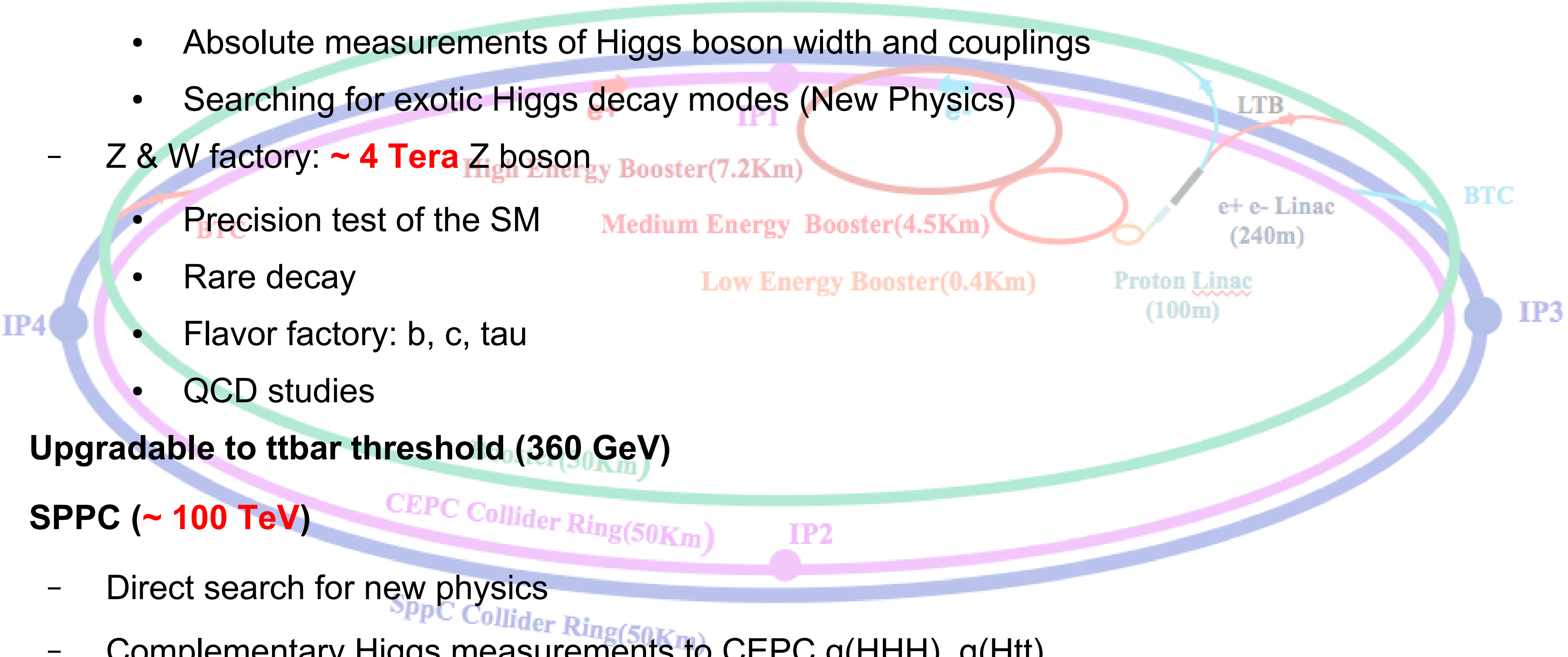


ILD & CEPC

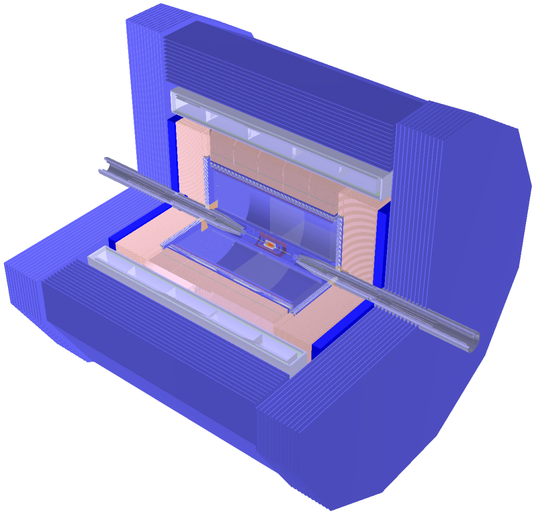
Manqi Ruan

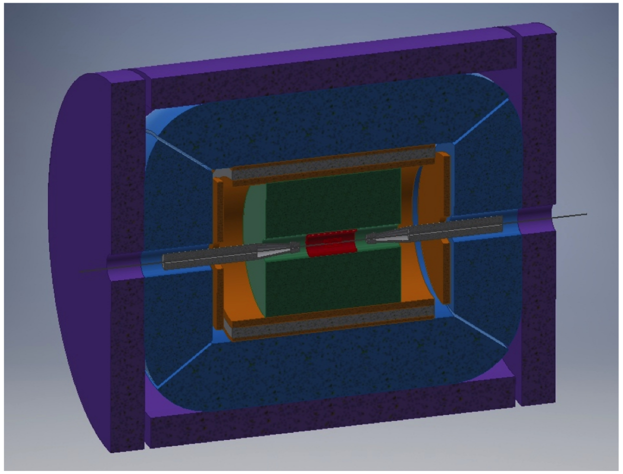
Key figures of the CEPC-SPPC

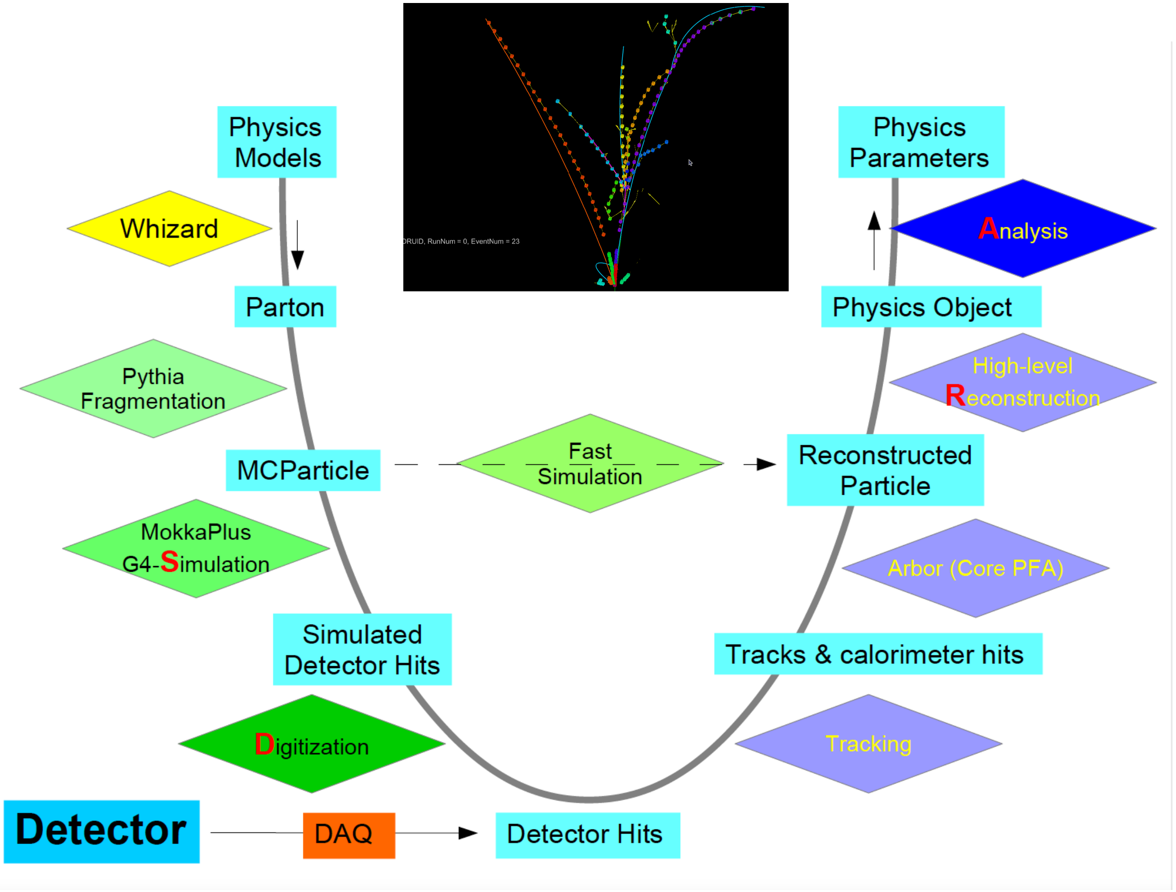


- **Tunnel ~ 100 km**
- **CEPC (90 – 240 GeV)**
  - Higgs factory: **4M** Higgs boson
    - Absolute measurements of Higgs boson width and couplings
    - Searching for exotic Higgs decay modes (New Physics)
  - Z & W factory: **~ 4 Tera** Z boson
    - Precision test of the SM
    - Rare decay
    - Flavor factory: b, c, tau
    - QCD studies
- **Upgradable to ttbar threshold (360 GeV)**
- **SPPC (~ 100 TeV)**
  - Direct search for new physics
  - Complementary Higgs measurements to CEPC g(HHH), g(Htt)
  - ...
- **Heavy ion, e-p collision...**

Detector & Software







Physics Models

Whizard

Parton

Pythia Fragmentation

MCParticle

MokkaPlus G4-Simulation

Simulated Detector Hits

Digitization

Fast Simulation

Detector

DAQ

Detector Hits

Tracking

Tracks & calorimeter hits

Arbor (Core PFA)

Reconstructed Particle

High-level Reconstruction

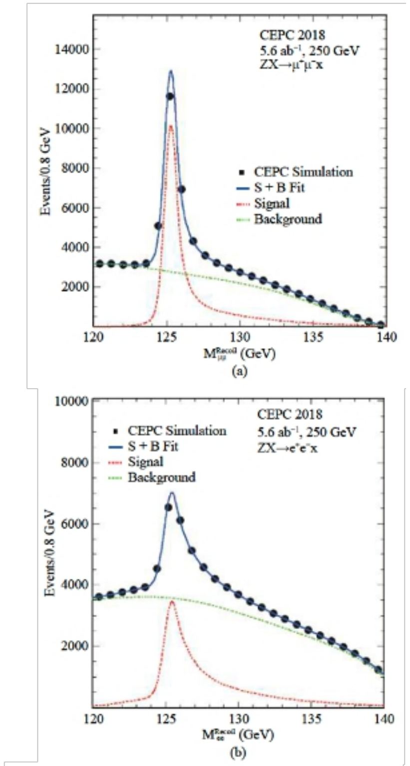
Physics Object

Analysis

Physics Parameters

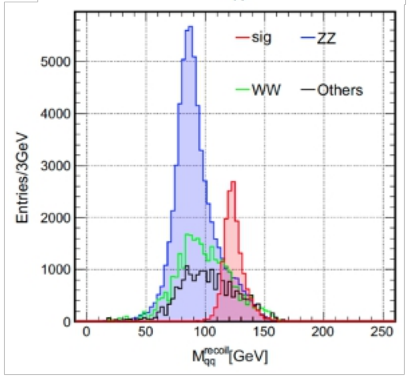
Full simulation reconstruction Chain with Arbor, iterating/validation with hardware studies

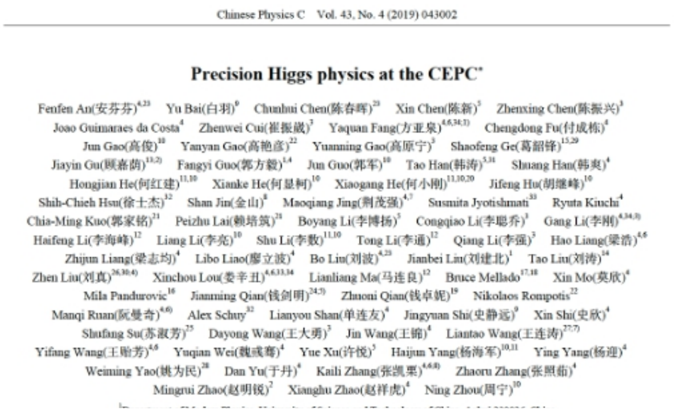
Physics study: 2023



(a)

(b)





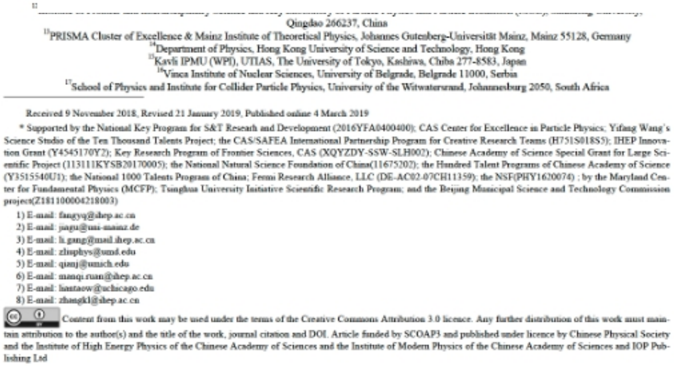
Chinese Physics C Vol. 43, No. 4 (2019) 043002

Precision Higgs physics at the CEPC*

Fenfen An(安芬芬)[4,23] Yu Bai(白羽)[9] Chunhui Chen(陈春晖)[23] Xin Chen(陈新)[5] Zhenxing Chen(陈振兴)[3]
Joao Guimaraes da Costa[4] Zhenwei Cui(崔振崴)[3] Yaquan Fang(方亚泉)[4,6,34;1)] Chengdong Fu(付成栋)[4]
Jun Gao(高俊)[10] Yanyan Gao(高艳彦)[22] Yuanning Gao(高原宁)[3] Shaofeng Ge(葛韶锋)[15,29]
Jiayin Gu(顾嘉荫)[13;2)] Fangyi Guo(郭方毅)[1,4] Jun Guo(郭军)[10] Tao Han(韩涛)[5,31] Shuang Han(韩爽)[4]
Hongjian He(何红建)[11,10] Xianke He(何显柯)[10] Xiaogang He(何小刚)[11,10,20] Jifeng Hu(胡继峰)[10]
Shih-Chieh Hsu(徐士杰)[32] Shan Jin(金山)[8] Maoqiang Jing(荆茂强)[4,7] Susmita Jyotishmati[33] Ryuta Kiuchi[4]
Chia-Ming Kuo(郭家铭)[21] Peizhu Lai(赖培筑)[21] Boyang Li(李博扬)[5] Congqiao Li(李聪乔)[3] Gang Li(李刚)[4,34;3)]
Haifeng Li(李海峰)[12] Liang Li(李亮)[10] Shu Li(李数)[11,10] Tong Li(李通)[12] Qiang Li(李强)[3] Hao Liang(梁浩)[4,6]
Zhijun Liang(梁志均)[4] Libo Liao(廖立波)[4] Bo Liu(刘波)[4,23] Jianbei Liu(刘建北)[1] Tao Liu(刘涛)[14]
Zhen Liu(刘真)[26,30;4)] Xinchou Lou(娄辛丑)[4,6,33,34] Lianliang Ma(马连良)[12] Bruce Mellado[17,18] Xin Mo(莫欣)[4]
Mila Pandurovic[16] Jianming Qian(钱剑明)[24;5)] Zhuoni Qian(钱卓妮)[19] Nikolaos Rompotis[22]
Manqi Ruan(阮曼奇)[4;6)] Alex Schuy[32] Lianyou Shan(单连友)[4] Jingyuan Shi(史静远)[9] Xin Shi(史欣)[4]
Shufang Su(苏淑芳)[25] Dayong Wang(王大勇)[3] Jin Wang(王锦)[4] Liantao Wang(王连涛)[27;7)]
Yifang Wang(王贻芳)[4,6] Yuqian Wei(魏彧骞)[4] Yue Xu(许悦)[5] Haijun Yang(杨海军)[10,11] Ying Yang(杨迎)[4]
Weiming Yao(姚为民)[28] Dan Yu(于丹)[4] Kaili Zhang(张凯栗)[4,6;8)] Zhaoru Zhang(张照茹)[4]
Mingrui Zhao(赵明锐)[2] Xianghu Zhao(赵祥虎)[4] Ning Zhou(周宁)[10]

White papers +

~300 Journal/AxXiv citables



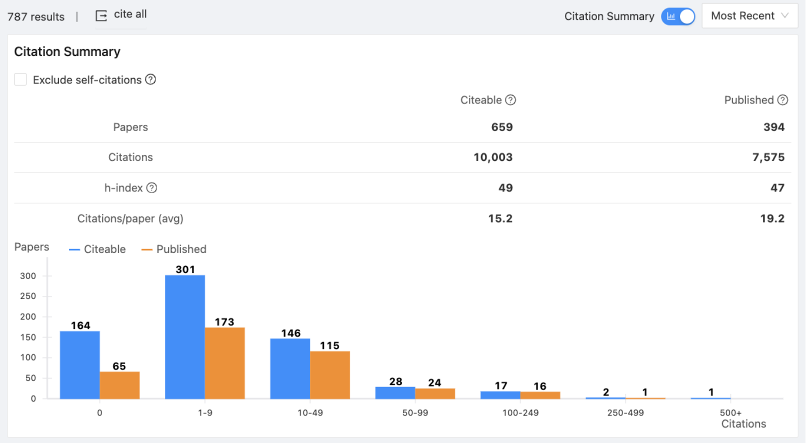
Qingdao 266237, China
[13]PRISMA Cluster of Excellence & Mainz Institute of Theoretical Physics, Johannes Gutenberg-Universität Mainz, Mainz 55128, Germany
[14]Department of Physics, Hong Kong University of Science and Technology, Hong Kong
[15]Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan
[16]Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade 11000, Serbia
[17]School of Physics and Institute for Collider Particle Physics, University of the Witwatersrand, Johannesburg 2050, South Africa

---

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

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

1) E-mail: fangyq@ihep.ac.cn
2) E-mail: jiagu@uni-mainz.de
3) E-mail: li.gang@mail.ihep.ac.cn
4) E-mail: zliuphys@umd.edu
5) E-mail: qianj@umich.edu
6) E-mail: manqi.ruan@ihep.ac.cn
7) E-mail: liantaow@uchicago.edu
8) E-mail: zhangkl@ihep.ac.cn



Citation Summary

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

Citations	Citeable	Published
0	164	65
1-9	301	173
10-49	146	115
50-99	28	24
100-249	17	16
250-499	2	1
500+	1	

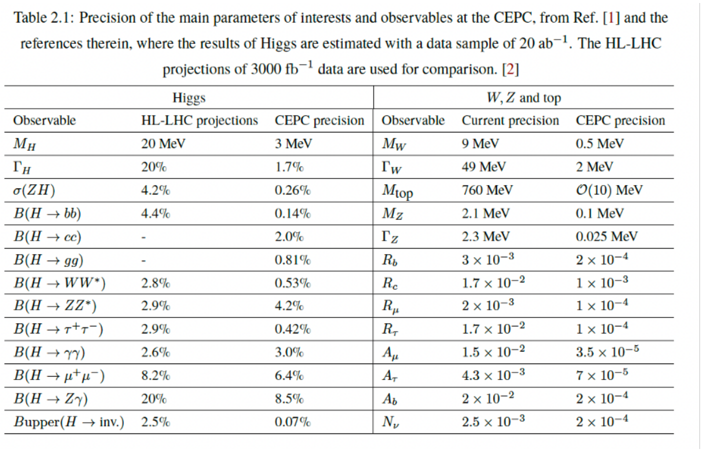


Table 2.1: Precision of the main parameters of interests and observables at the CEPC, from Ref. [1] and the references therein, where the results of Higgs are estimated with a data sample of 20 ab^{-1}. The HL-LHC projections of 3000 fb^{-1} data are used for comparison. [2]

Higgs			W, Z and top		
Observable	HL-LHC projections	CEPC precision	Observable	Current precision	CEPC precision
M_H	20 MeV	3 MeV	M_W	9 MeV	0.5 MeV
Γ_H	20%	1.7%	Γ_W	49 MeV	2 MeV
$\sigma(ZH)$	4.2%	0.26%	M_{top}	760 MeV	$\mathcal{O}(10)$ MeV
$B(H \to bb)$	4.4%	0.14%	M_Z	2.1 MeV	0.1 MeV
$B(H \to cc)$	-	2.0%	Γ_Z	2.3 MeV	0.025 MeV
$B(H \to gg)$	-	0.81%	R_b	3×10^{-3}	2×10^{-4}
$B(H \to WW^*)$	2.8%	0.53%	R_c	1.7×10^{-2}	1×10^{-3}
$B(H \to ZZ^*)$	2.9%	4.2%	R_μ	2×10^{-3}	1×10^{-4}
$B(H \to \tau^+\tau^-)$	2.9%	0.42%	R_τ	1.7×10^{-2}	1×10^{-4}
$B(H \to \gamma\gamma)$	2.6%	3.0%	A_μ	1.5×10^{-2}	3.5×10^{-5}
$B(H \to \mu^+\mu^-)$	8.2%	6.4%	A_τ	4.3×10^{-3}	7×10^{-5}
$B(H \to Z\gamma)$	20%	8.5%	A_b	2×10^{-2}	2×10^{-4}
Bupper$(H \to \text{inv.})$	2.5%	0.07%	N_ν	2.5×10^{-3}	2×10^{-4}

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

- Higgs: Precisions exceed HL-LHC ~ 1 order of magnitude.
- EW: Precision improved from current limit by 1-2 orders.
- Flavor Physics, sensitive to NP of 10 TeV or even higher.
- Sensitive to varies of NP signal.
- …

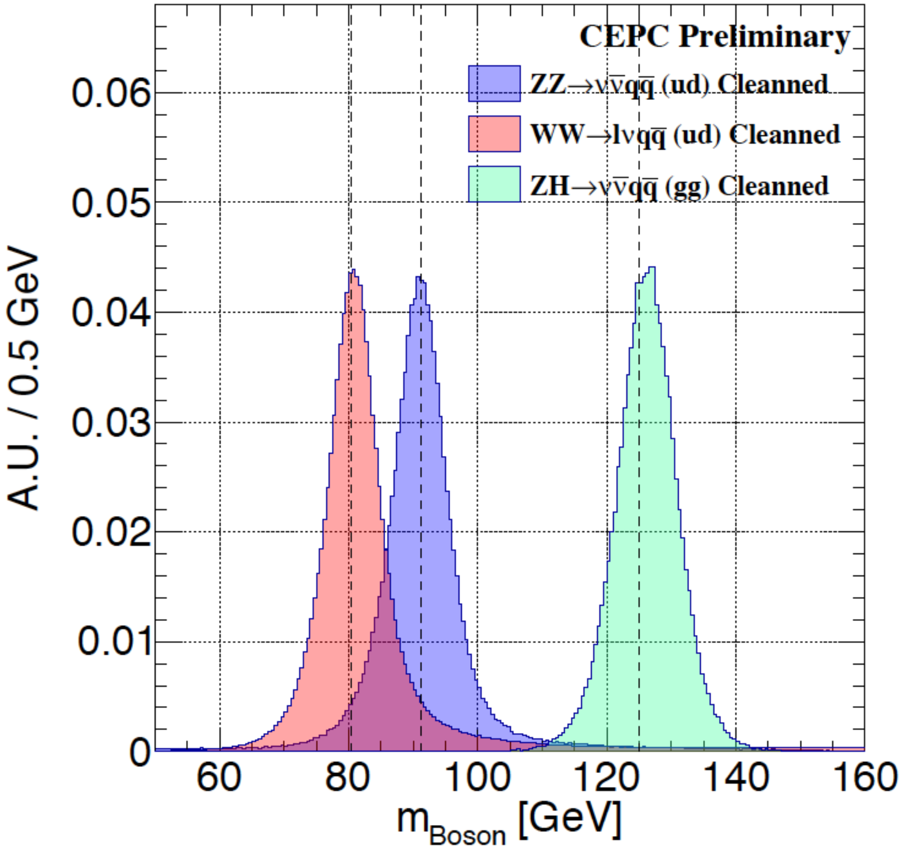
Extreme detector requirements

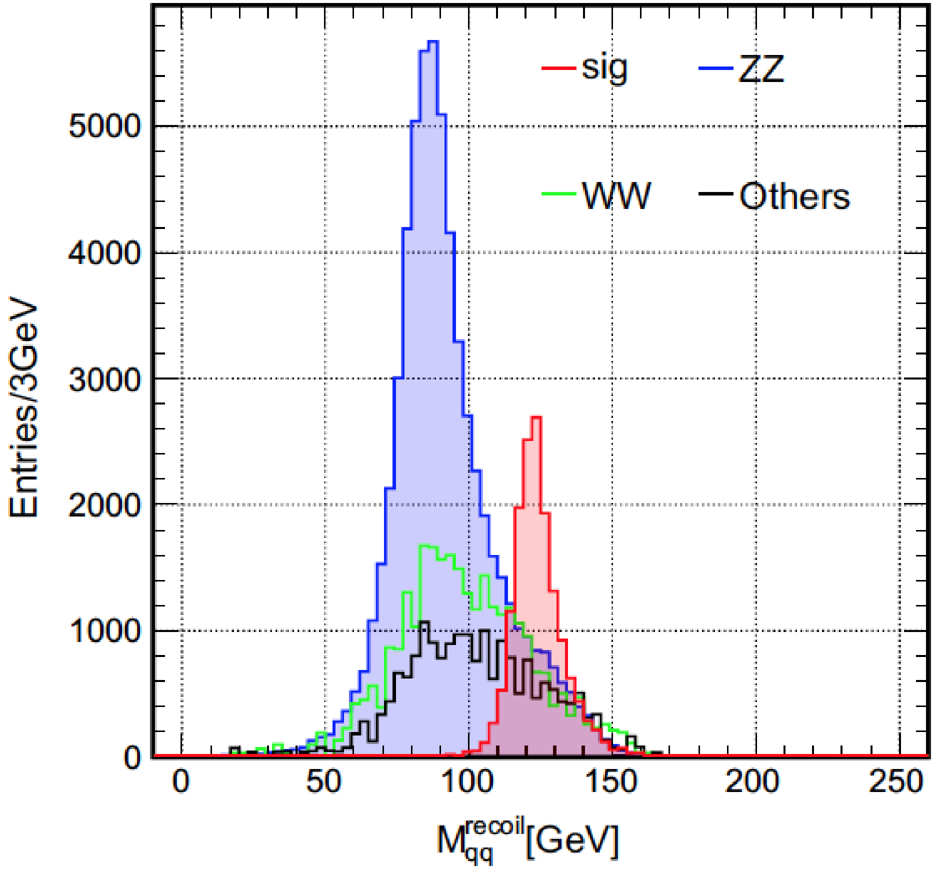
- Suited to the collision environment, especially beam background/MDI
- Trigger-less equivalent: Trigger system works as Trigger-less
- Extremely stable
- Large acceptance: polar angle, energy, time
- **PFA compatible (in SpaceTime): final state particle separation – pursue 1-1 correspondence**
  - Physics 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 (Kaon finding at incl. Z->qq : eff/purity > 95%)
- **Jet origin identification: Flavor Tagging, Charge Reconstruction, s-tagging...**
- Excellent intrinsic resolution E/M/position: per mille level for track, percentage level for EM...

+ with acceptable price: To be addressed by innovative detector design + key tech R&D

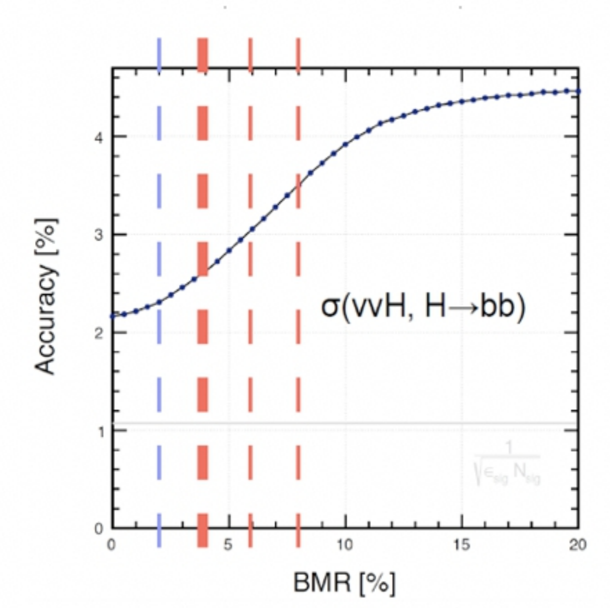
Boson Mass Resolution

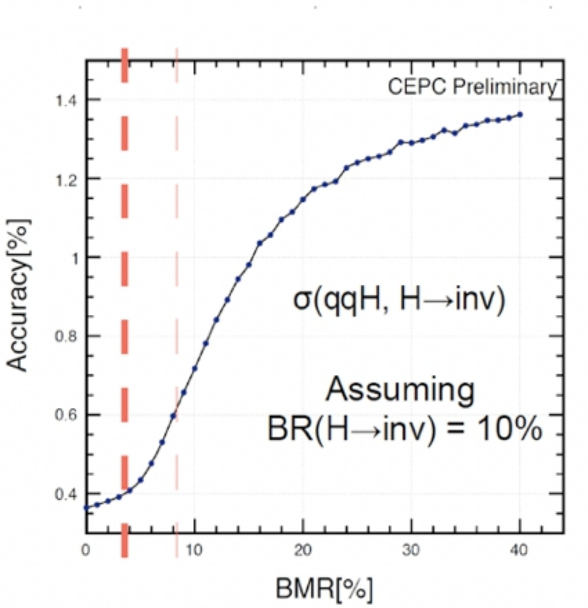
Boson Mass Resolution: Key Per. Para

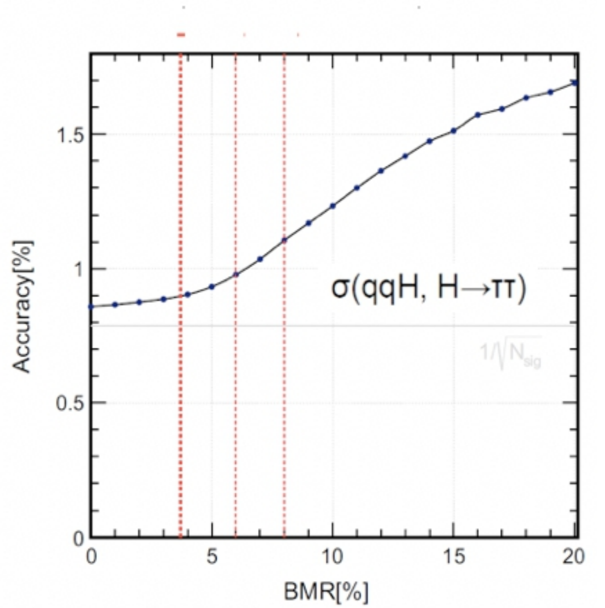


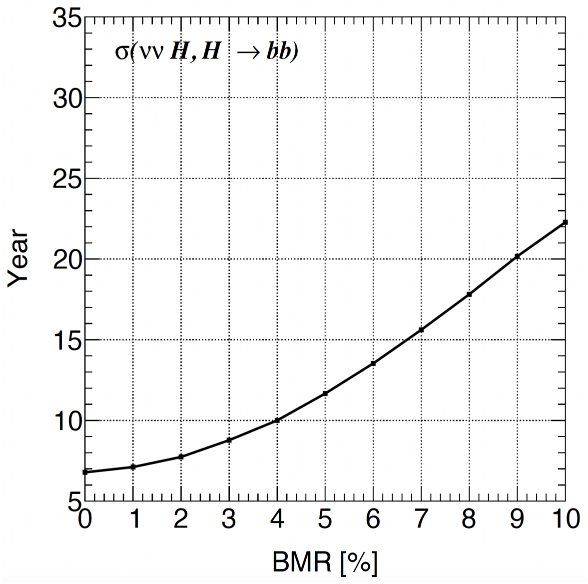


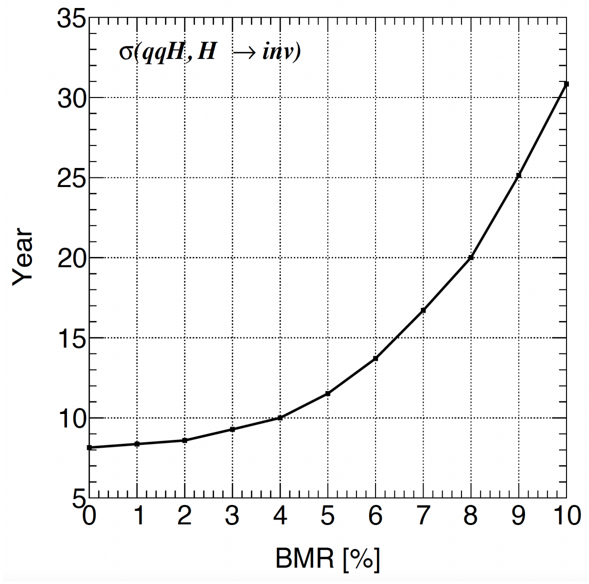
BMR: impact on critical measurements

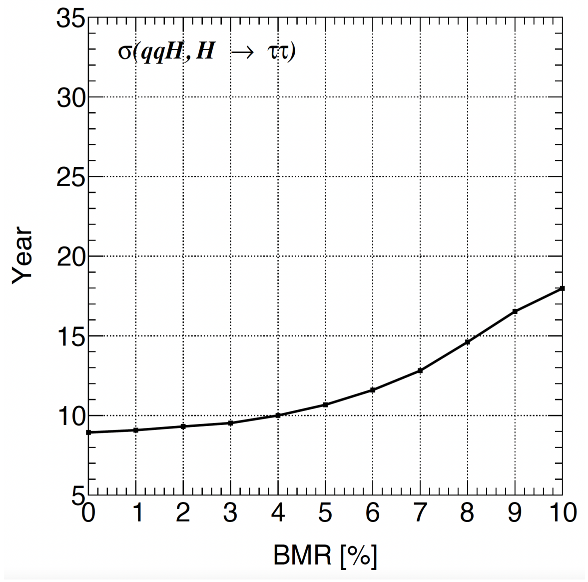




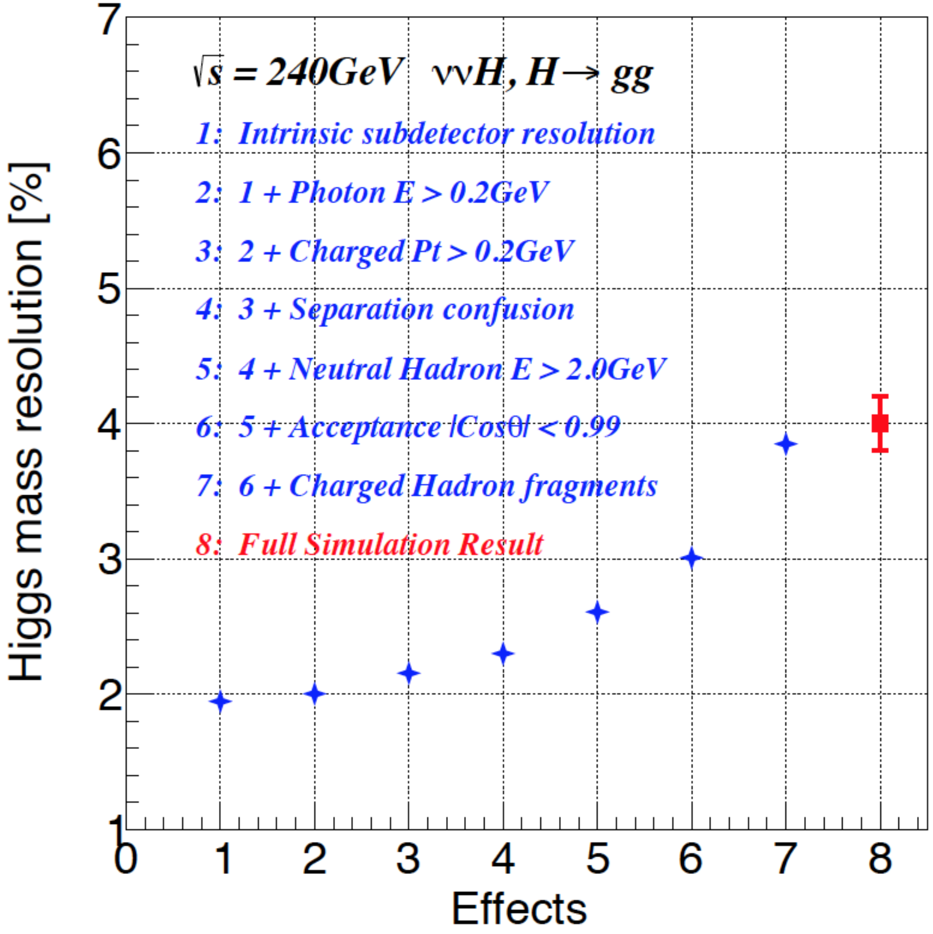




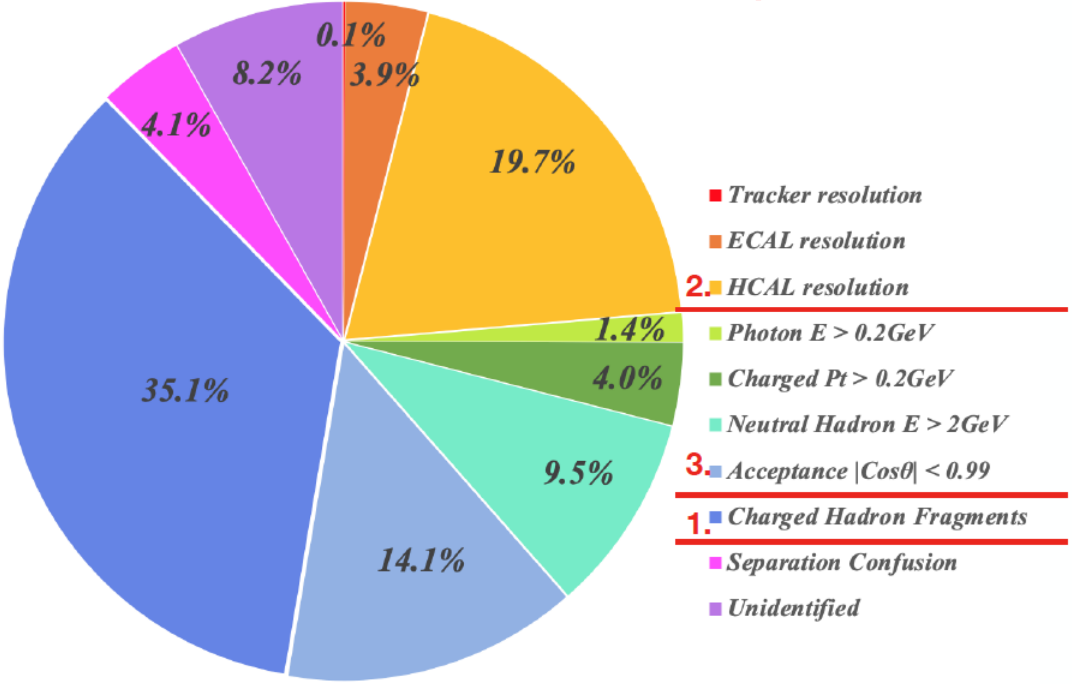




PFA Fast simulation



To be updated!

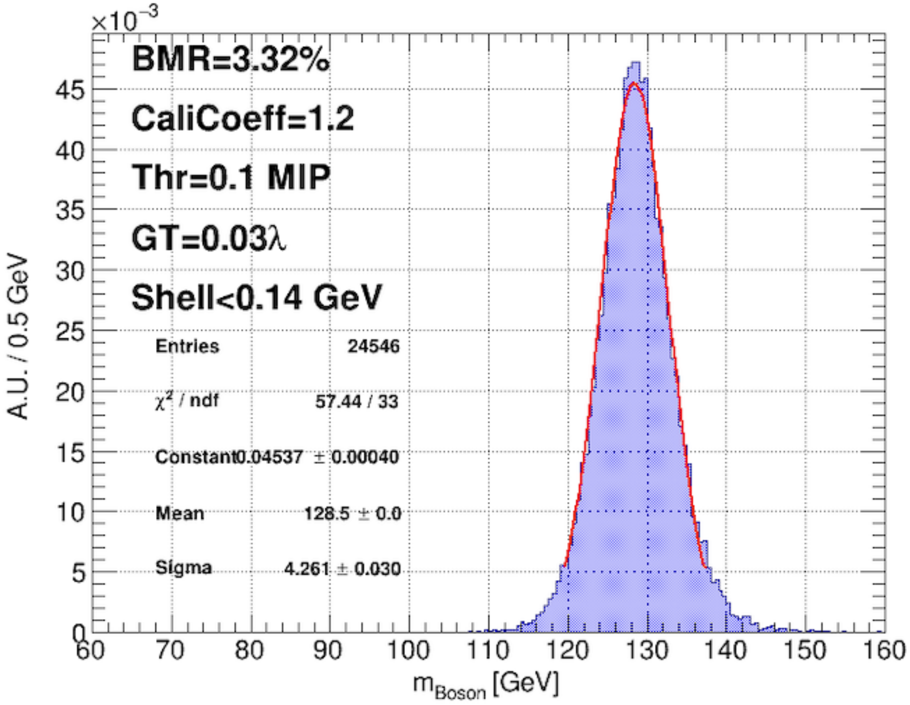


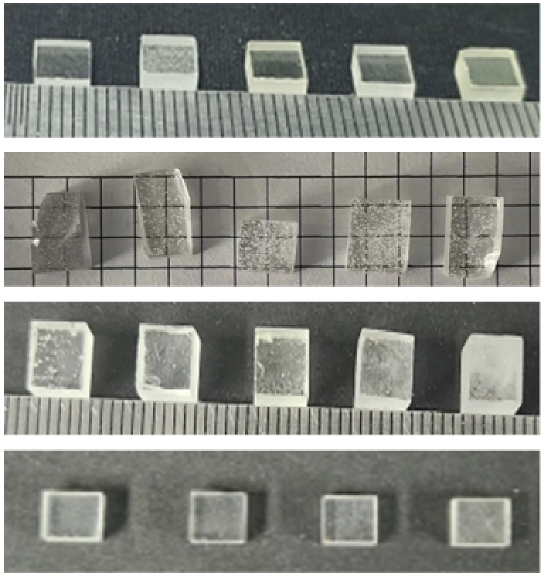
YX. Wang

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

BMR wi GSHCAL

P. Hu & YX. Wang





2021.11
Density ~4.5 g/cm^3

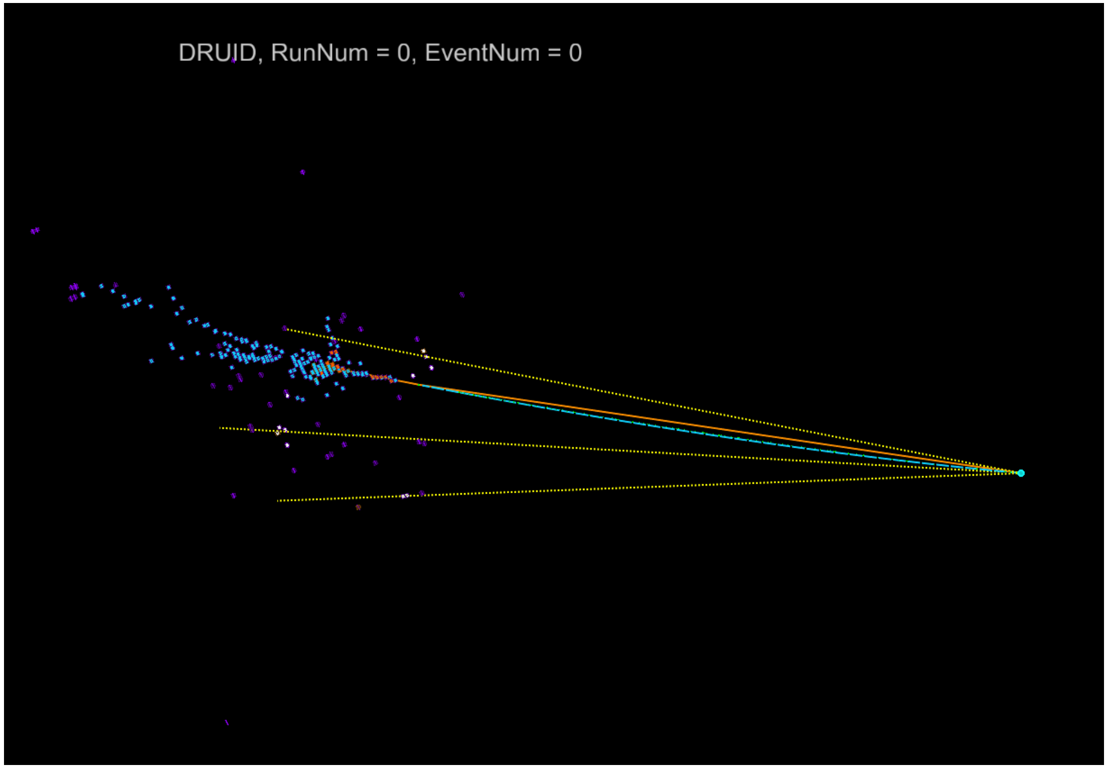
2021.11
Density ~4.0 g/cm^3

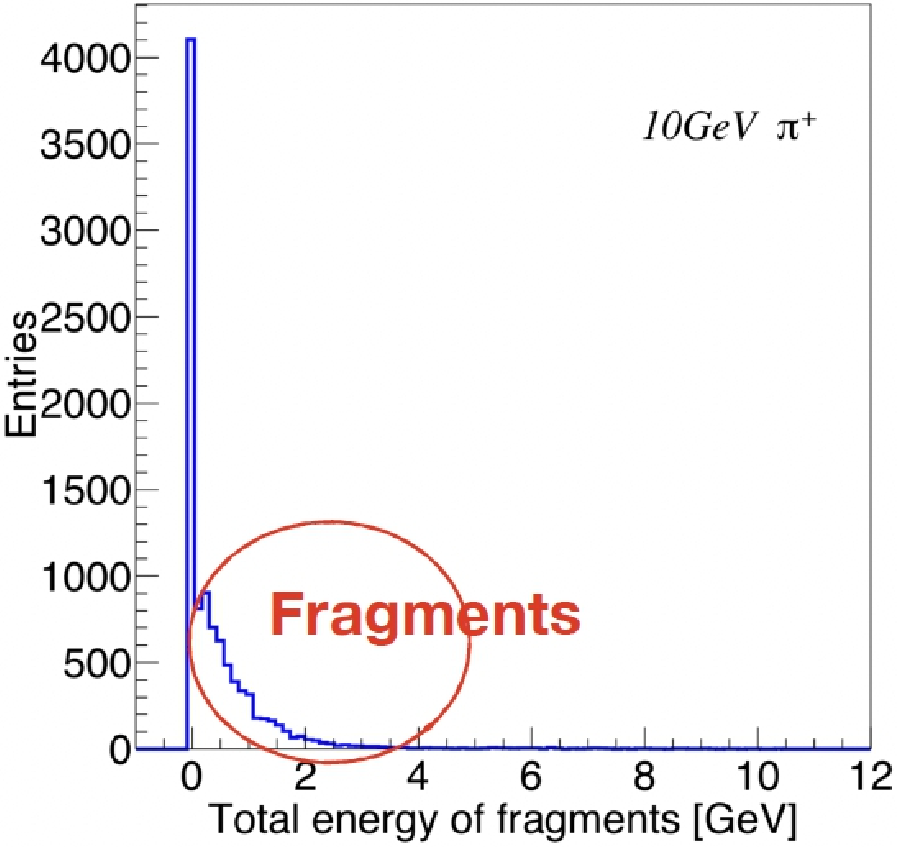
2022.06
Density ~6.0 g/cm^3

2023.02
Density ~6.0 g/cm^3

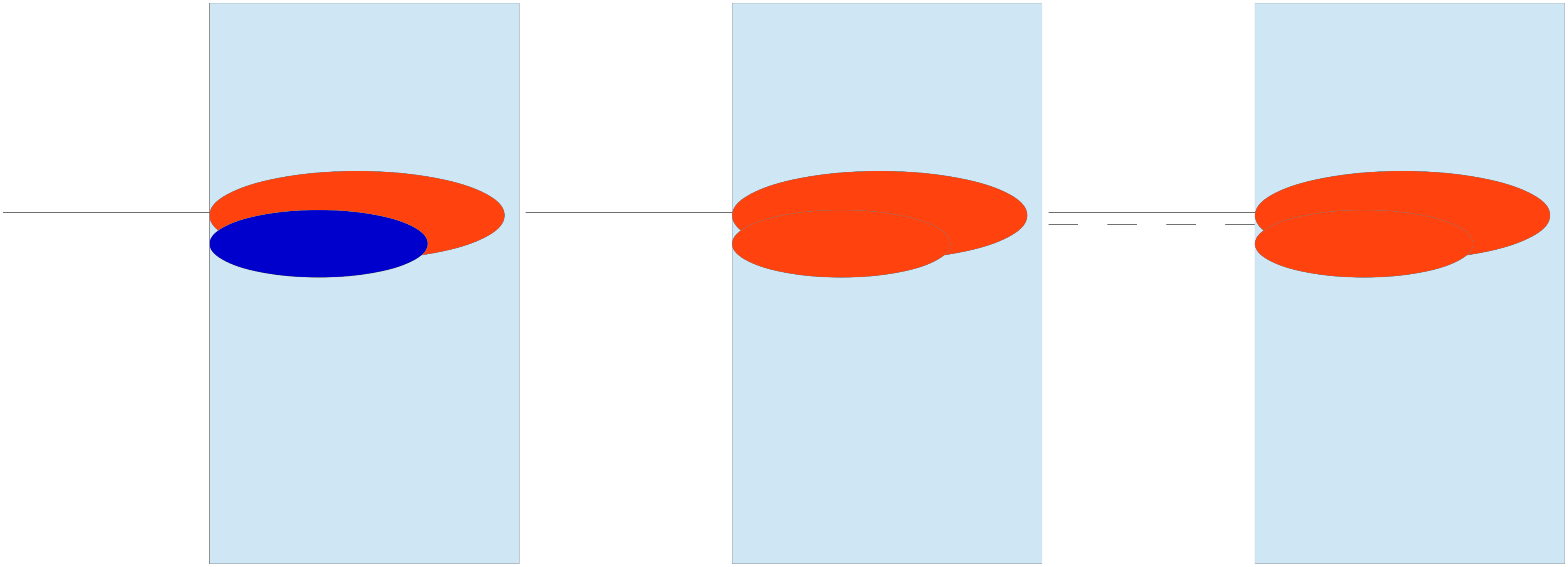
- Baseline + replace DHCAL to GSHCAL + Simple para. optimization
- ~ o(10)% improvement w.r.t. DHCAL

Confusion-1: charged fragments





Confusion-2: Merged neutral PFO



- If Cluster Energy be significantly larger than associated track (E >> P): reconstructed as a Charged PFO with E = P, and a Neutral one with energy of E-P
- However due to the failure and uncertainty of tracking, ... exist mis-id

Touch base study using MCTruth

Baseline (SiWECAL + DHCAL) with perfect cluster id

0: BMR ~3.70%, original

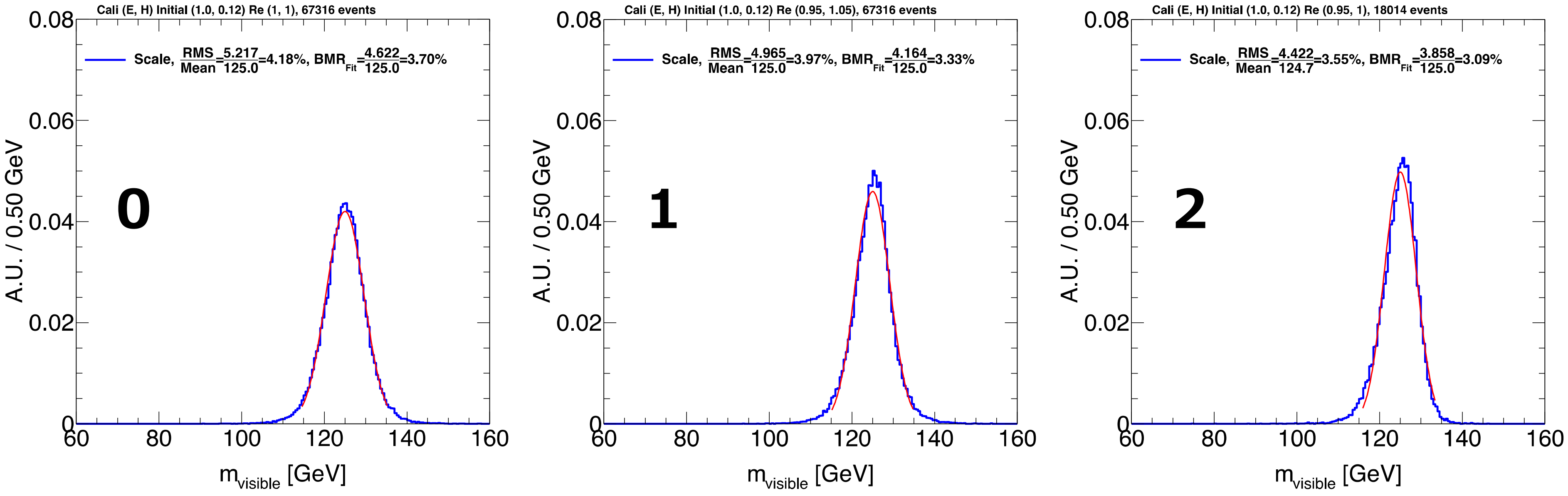
1: BMR ~3.33%, remove charged fragments

2: BMR ~3.09%, remove charged fragments + “Null MCP” event cut

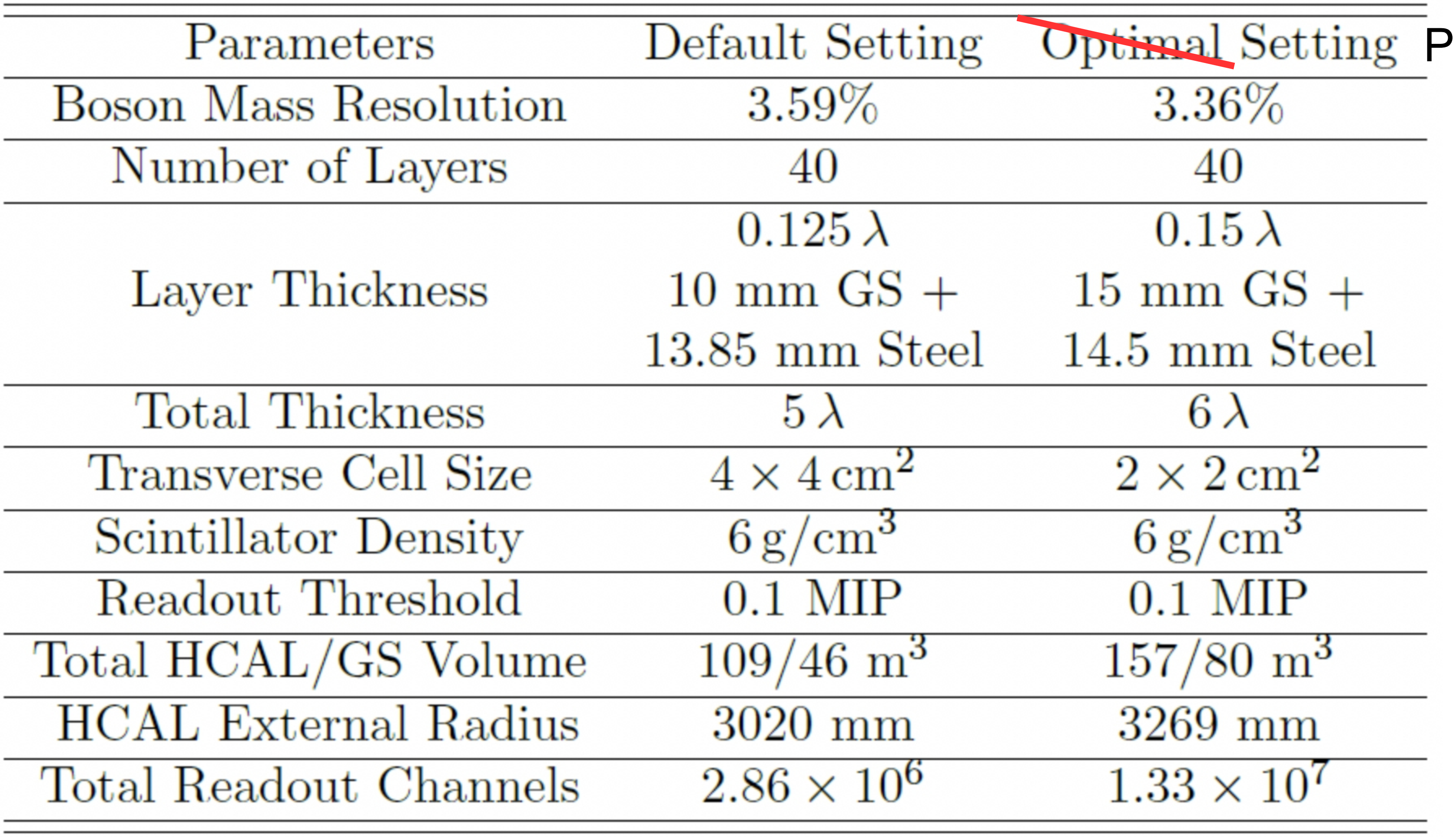
PS: Two cases of “Null MCP” (fail to link to MCTruth Particle)

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

Null MCP Cut eff ~ 25%



Perf & Cost Comparison: 2 scenarios



Parameters	Default Setting	~~Optimal~~ Setting Preferable-1
Boson Mass Resolution	3.59%	3.36%
Number of Layers	40	40
Layer Thickness	$0.125\,\lambda$ 10 mm GS + 13.85 mm Steel	$0.15\,\lambda$ 15 mm GS + 14.5 mm Steel
Total Thickness	$5\,\lambda$	$6\,\lambda$
Transverse Cell Size	$4 \times 4\,\mathrm{cm}^2$	$2 \times 2\,\mathrm{cm}^2$
Scintillator Density	$6\,\mathrm{g/cm}^3$	$6\,\mathrm{g/cm}^3$
Readout Threshold	0.1 MIP	0.1 MIP
Total HCAL/GS Volume	$109/46\ \mathrm{m}^3$	$157/80\ \mathrm{m}^3$
HCAL External Radius	3020 mm	3269 mm
Total Readout Channels	2.86×10^6	1.33×10^7

- Balance between Perf. & Cost.

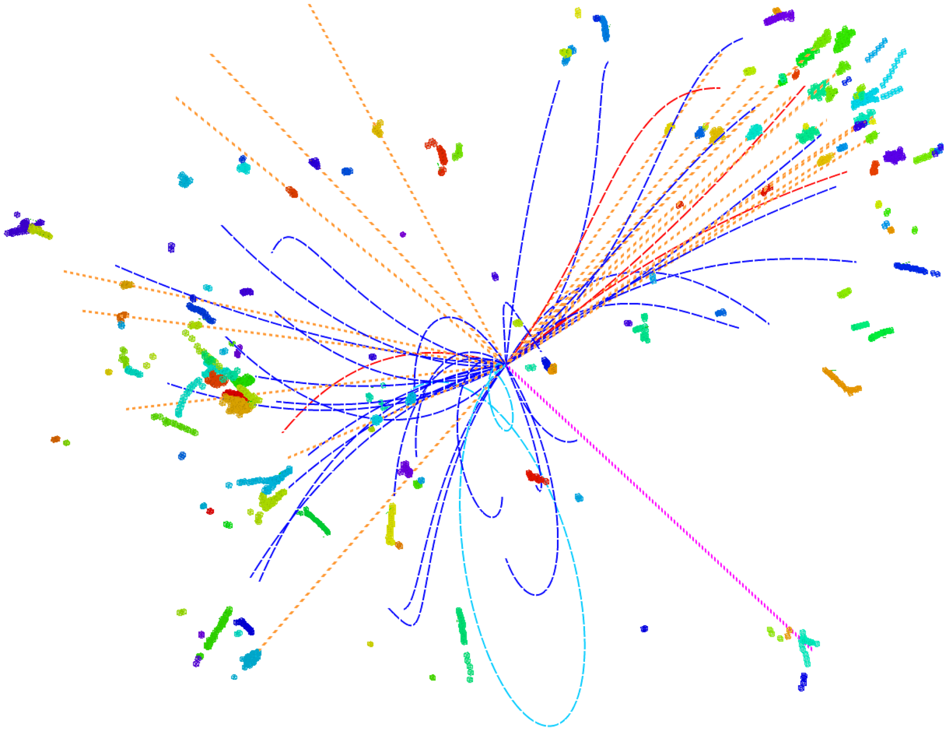
Anticipated BMRs

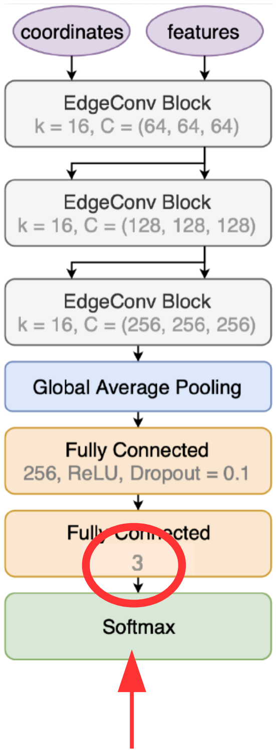
	Current	Leading confusion solved (Fragment & Merging)
CDR Baseline	3.7%	3.1%
GSHCAL (default)	3.6%	2.9%
GSHCAL (Preferable)	3.3%	2.7%
CHLOE expectation	3.4%	2.8%

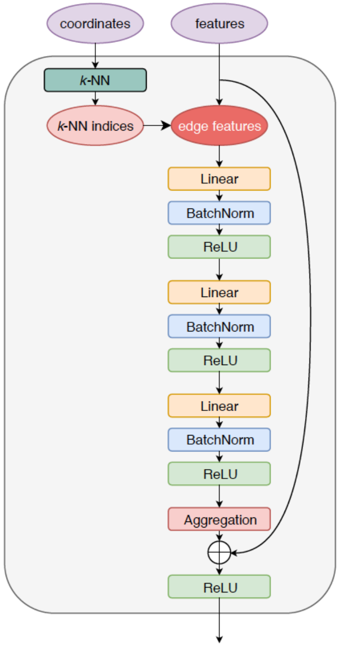
- Achievable BMR estimate: ~ 3.0%
  - *Plan: replace ideal cluster id using realistic – but really good one...*
  - Better energy estimation tech. potentially improve the BMR by 0.2 – 0.3%
  - Realistic pattern recognition may not match ideal level (granularity, space/time resolution, etc): degrade BMR by 0.2%
  - Realistic digitization to account the homogeneity effects: degrade BMR by 0.2%
  - ...

Jet origin id

Recent HL: Jet Origin Identification







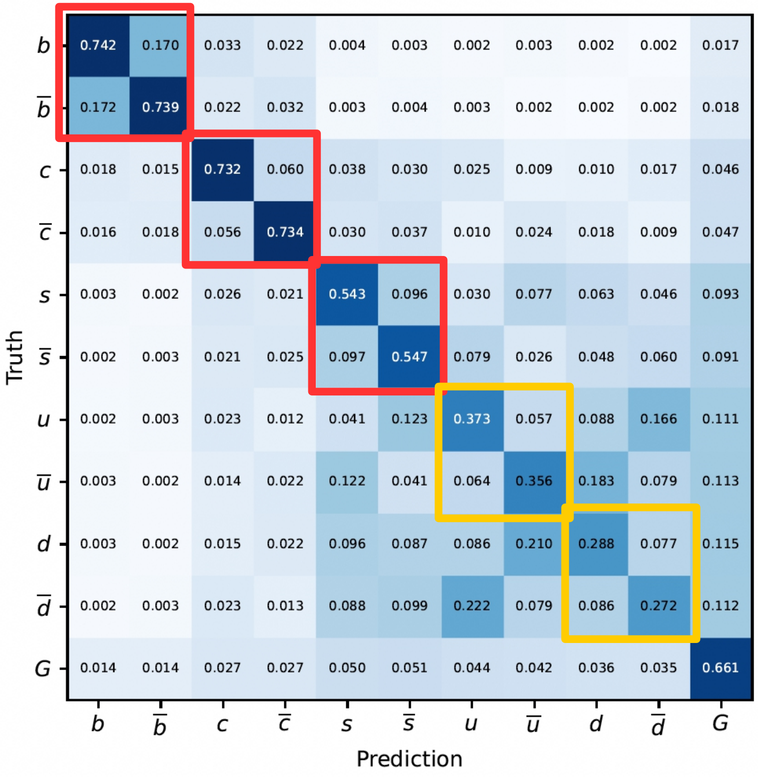
- **Jet origin identification: 11 categories (5 quarks + 5 anti quarks + gluon)**
  - Jet Flavor Tagging + Jet Charge measurements + s-tagging + gluon tagging...
- Full Simulated vvH, Higgs to two jets sample at CEPC baseline configuration: CEPC-v4 detector, reconstructed with **Arbor + ParticleNet (Deep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

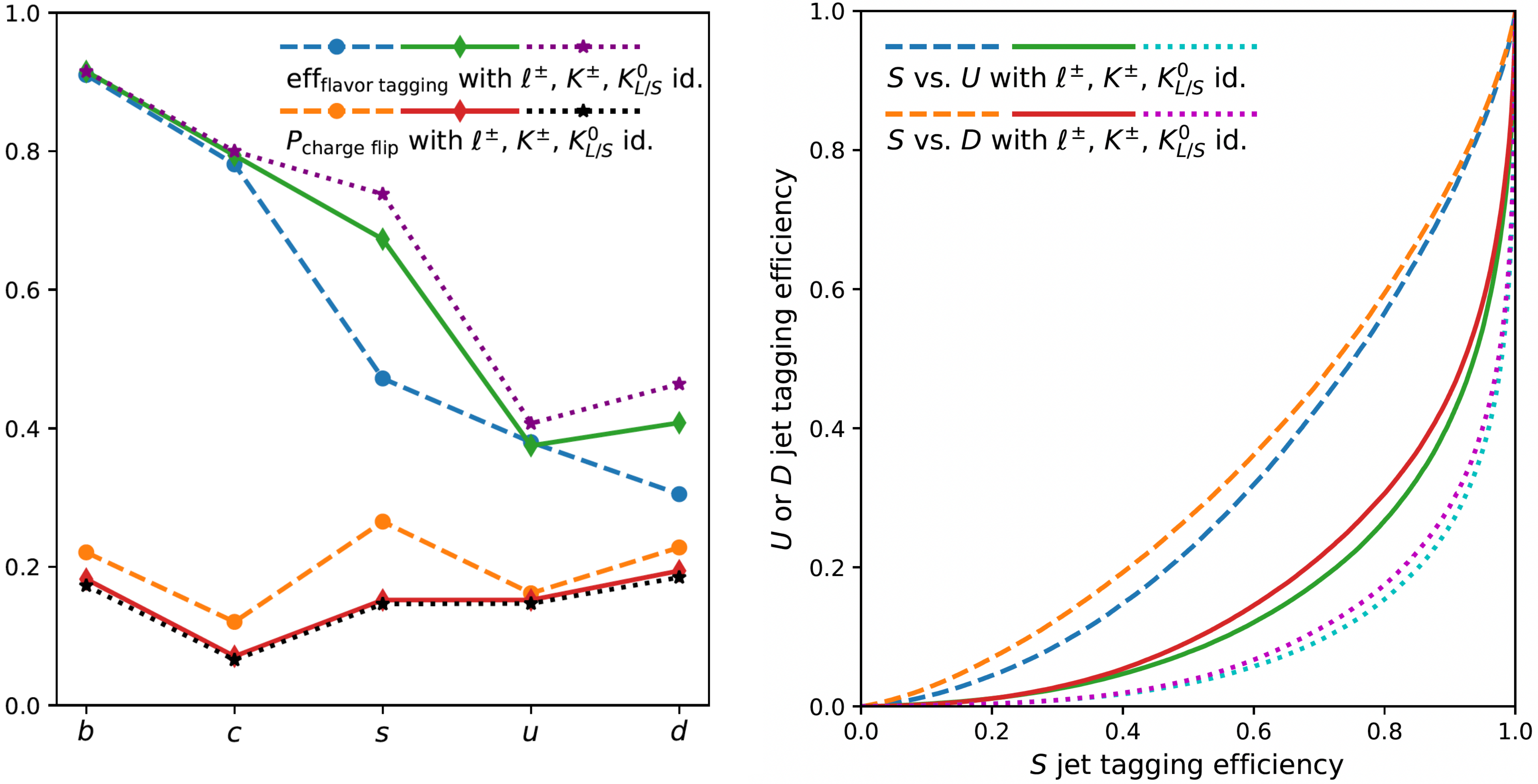


Truth \ Prediction	b	$\bar{b}$	c	$\bar{c}$	s	$\bar{s}$	u	$\bar{u}$	d	$\bar{d}$	G
b	0.742	0.170	0.033	0.022	0.004	0.003	0.002	0.003	0.002	0.002	0.017
$\bar{b}$	0.172	0.739	0.022	0.032	0.003	0.004	0.003	0.002	0.002	0.002	0.018
c	0.018	0.015	0.732	0.060	0.038	0.030	0.025	0.009	0.010	0.017	0.046
$\bar{c}$	0.016	0.018	0.056	0.734	0.030	0.037	0.010	0.024	0.018	0.009	0.047
s	0.003	0.002	0.026	0.021	0.543	0.096	0.030	0.077	0.063	0.046	0.093
$\bar{s}$	0.002	0.003	0.021	0.025	0.097	0.547	0.079	0.026	0.048	0.060	0.091
u	0.002	0.003	0.023	0.012	0.041	0.123	0.373	0.057	0.088	0.166	0.111
$\bar{u}$	0.003	0.002	0.014	0.022	0.122	0.041	0.064	0.356	0.183	0.079	0.113
d	0.003	0.002	0.015	0.022	0.096	0.087	0.086	0.210	0.288	0.077	0.115
$\bar{d}$	0.002	0.003	0.023	0.013	0.088	0.099	0.222	0.079	0.086	0.272	0.112
G	0.014	0.014	0.027	0.027	0.050	0.051	0.044	0.042	0.036	0.035	0.661

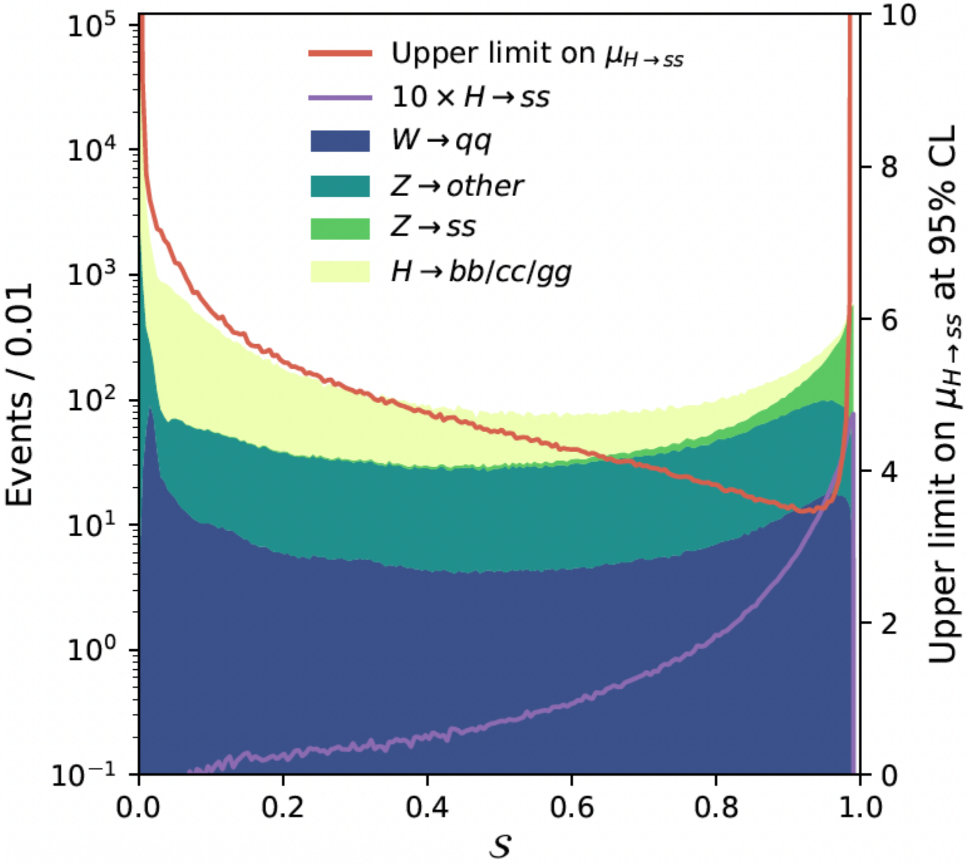
Flavor tagging: type that maximize {L_q + L_q_bar, L_g}

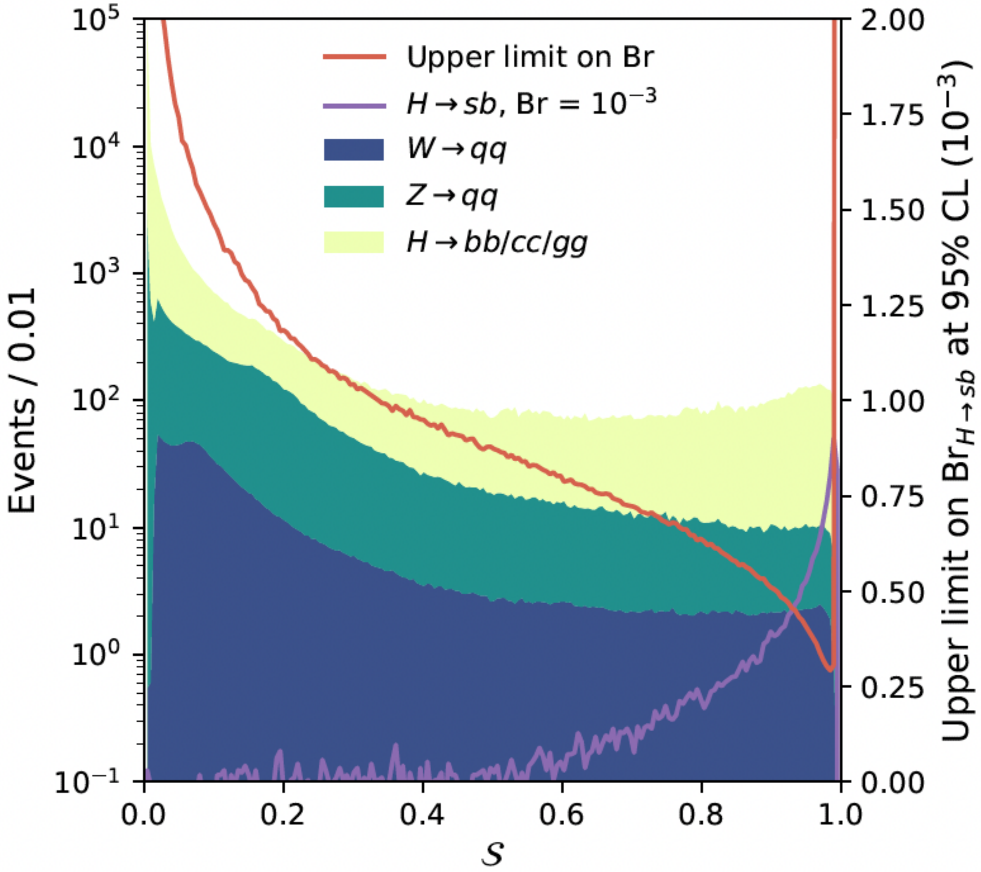
Jet charge (if quark jet): compare {L_q, L_q_bar}

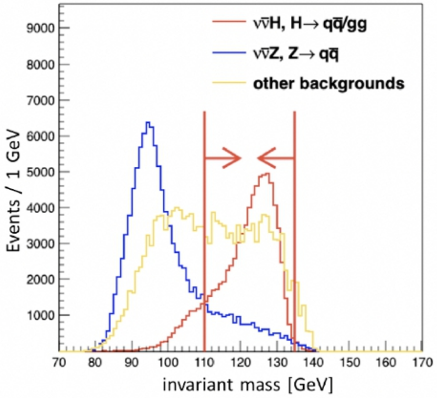
Performance with different PID scenarios



Benchmark analyses using Jet origin ID

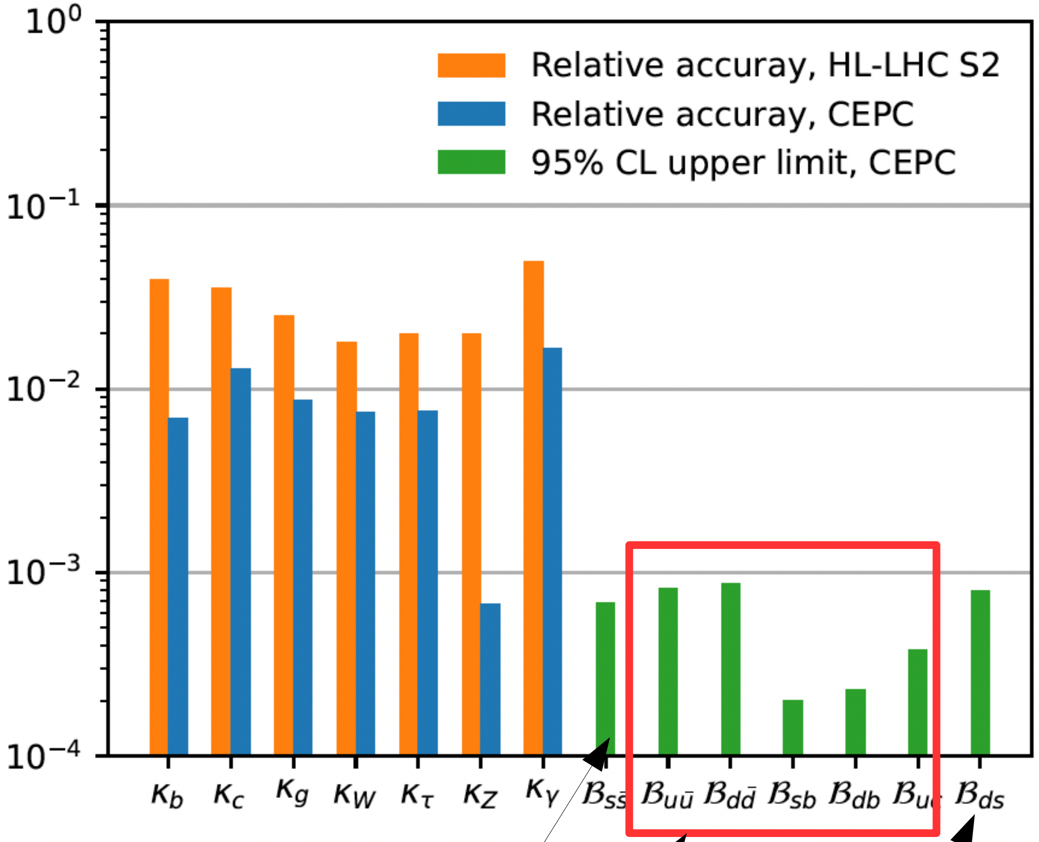






Applied to quasi-data of vvH;
H → ss: be limited to 3*SM using vvH + llH at 20 iab
H → sb: up limit of 2E-4 at 95% C.L.

Benchmark analyses using Jet origin ID



Improved by ~3 times

Improved by 1-2 orders of magnitudes

Presumably... firstly quantified

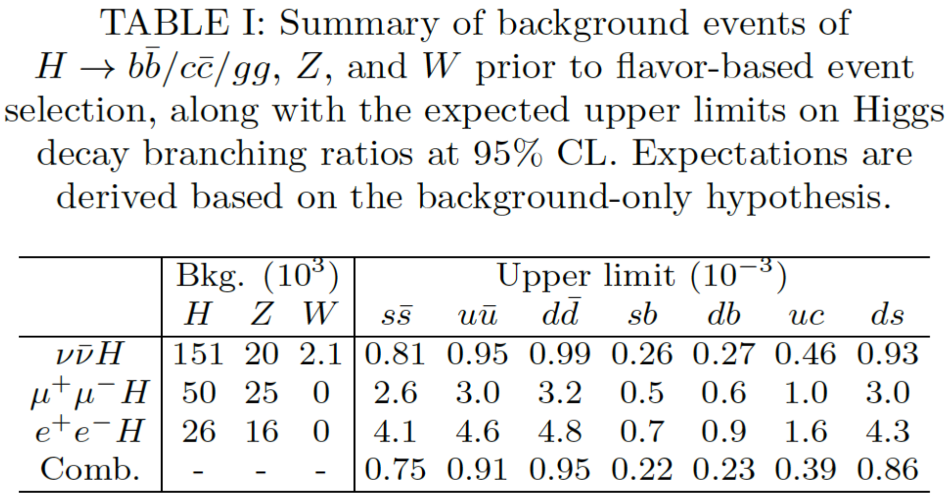
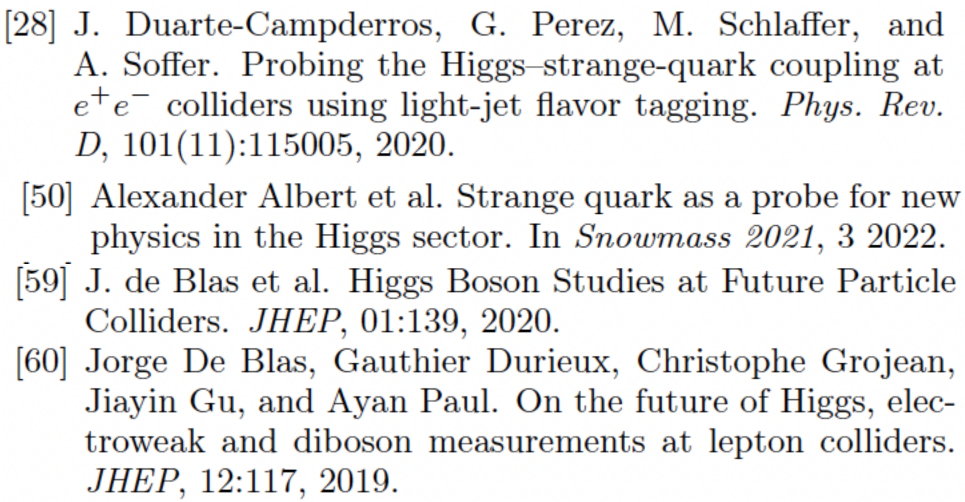


TABLE I: Summary of background events of $H \to b\bar{b}/c\bar{c}/gg$, Z, and W prior to flavor-based event selection, along with the expected upper limits on Higgs decay branching ratios at 95% CL. Expectations are derived based on the background-only hypothesis.

	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.

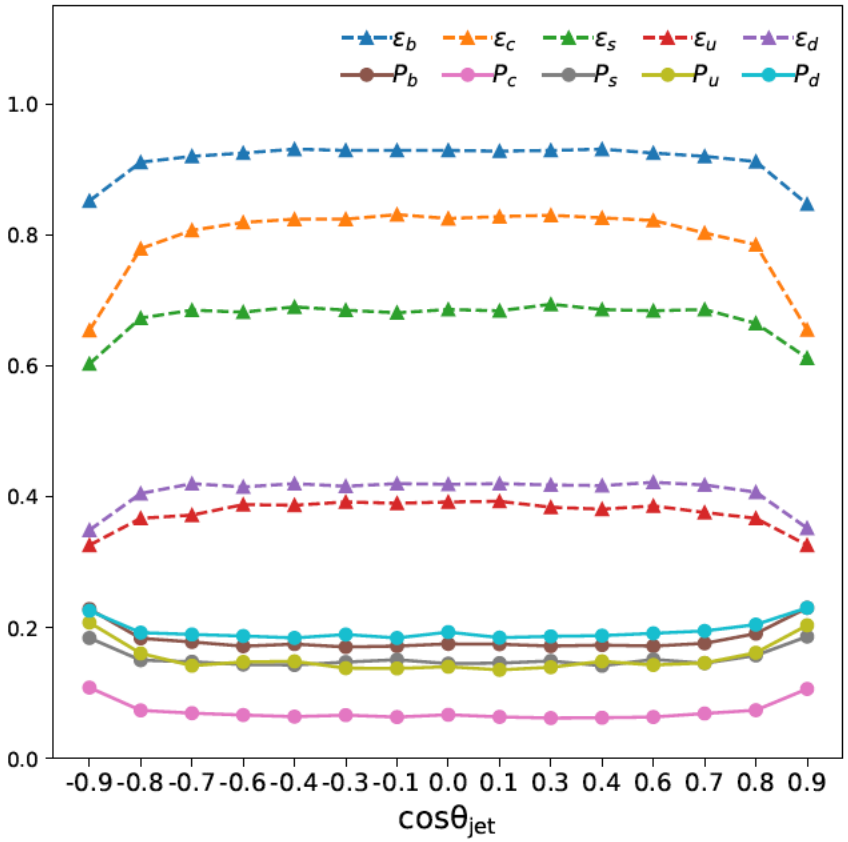
[50] Alexander Albert et al. Strange quark as a probe for new physics in the Higgs sector. In *Snowmass 2021*, 3 2022.

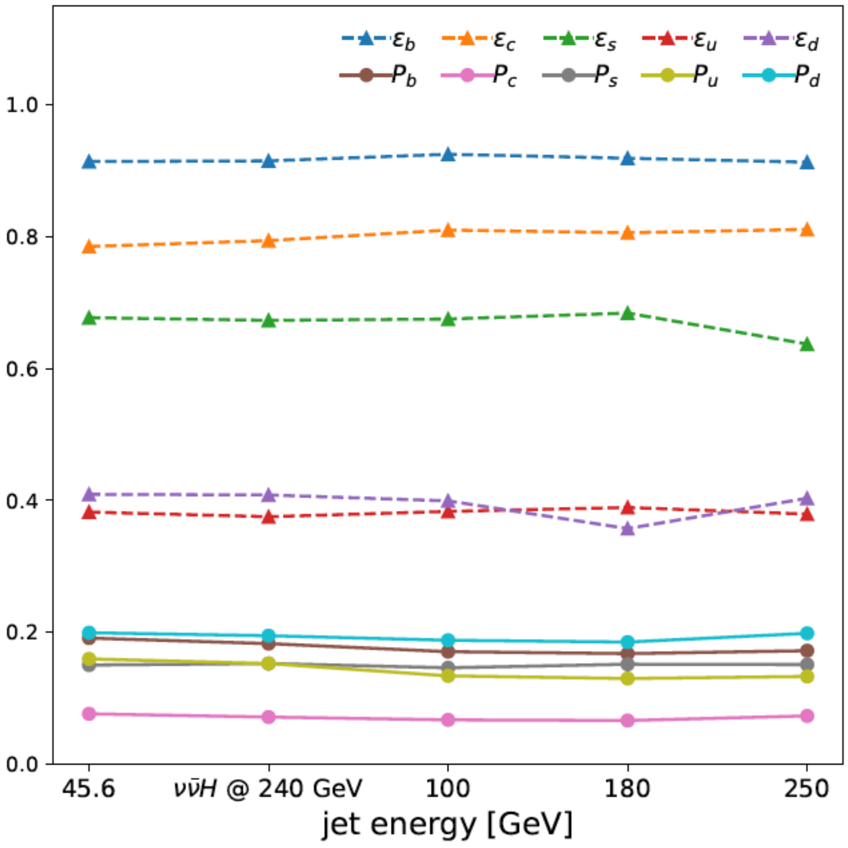
[59] J. de Blas et al. Higgs Boson Studies at Future Particle Colliders. *JHEP*, 01:139, 2020.

[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.

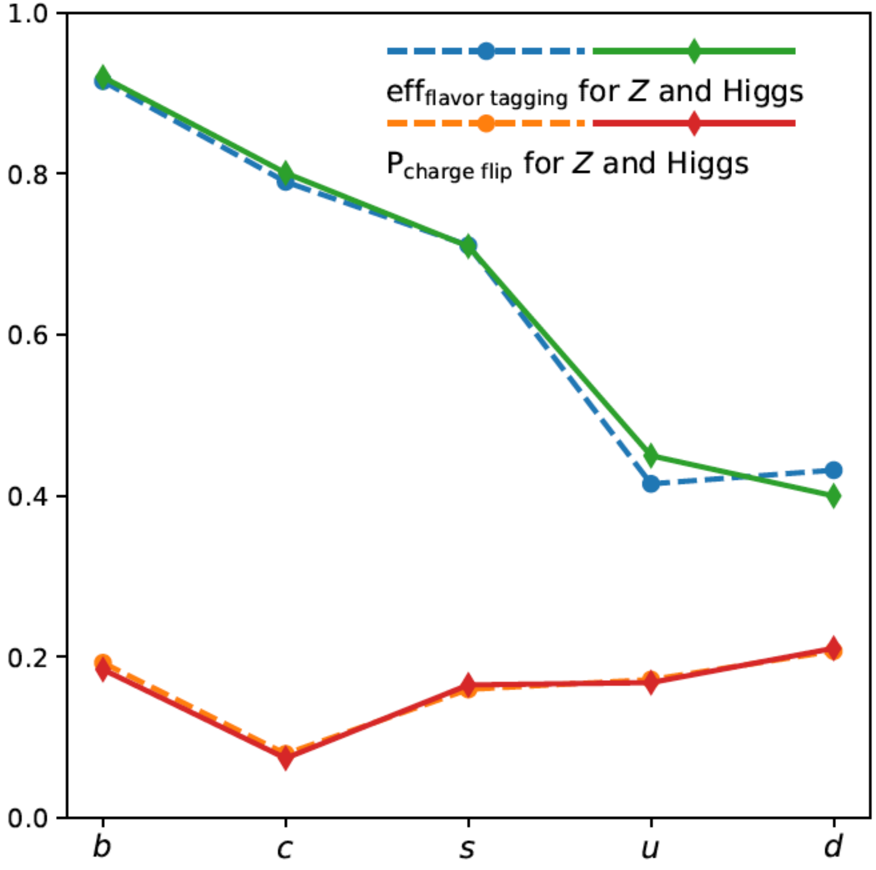
For H->bb, cc, gg: results in 20 – 40% improvement in relative accuracies (preliminary)...

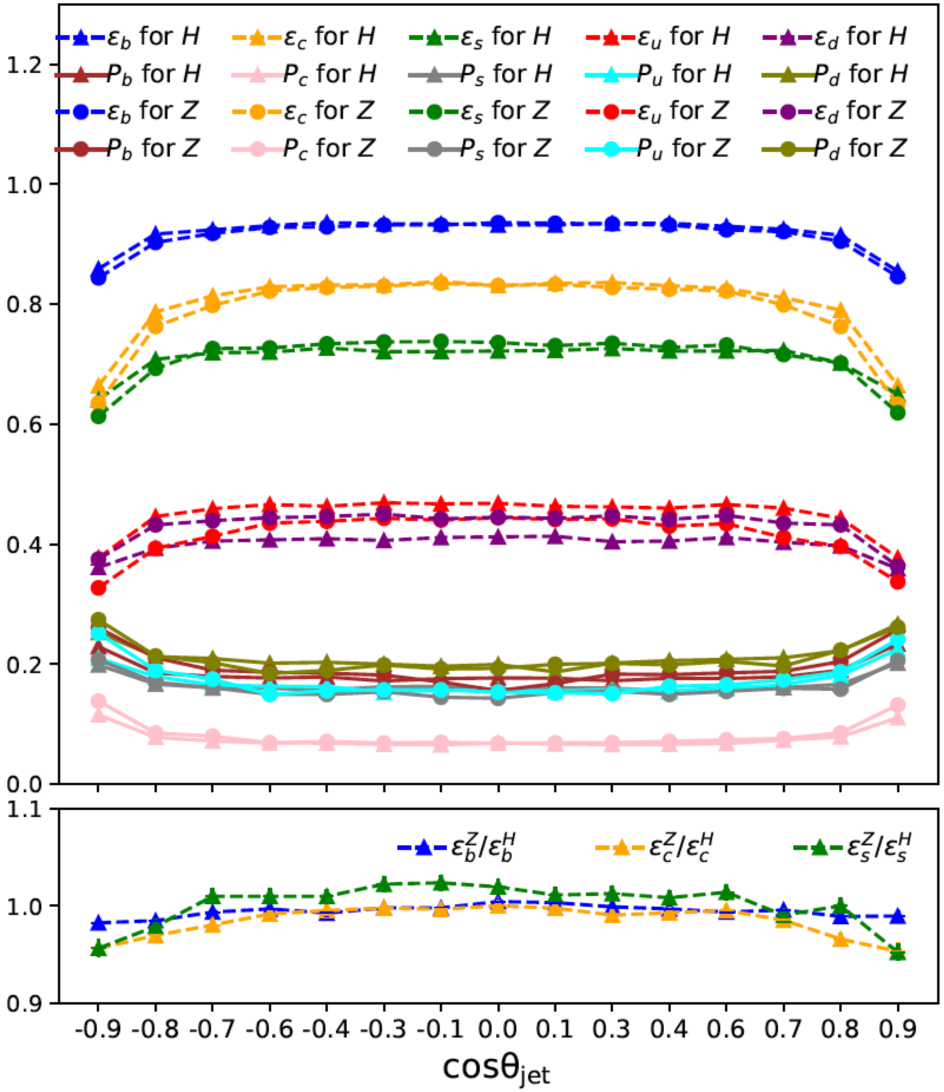
Performance V.S. Jet Kinematics





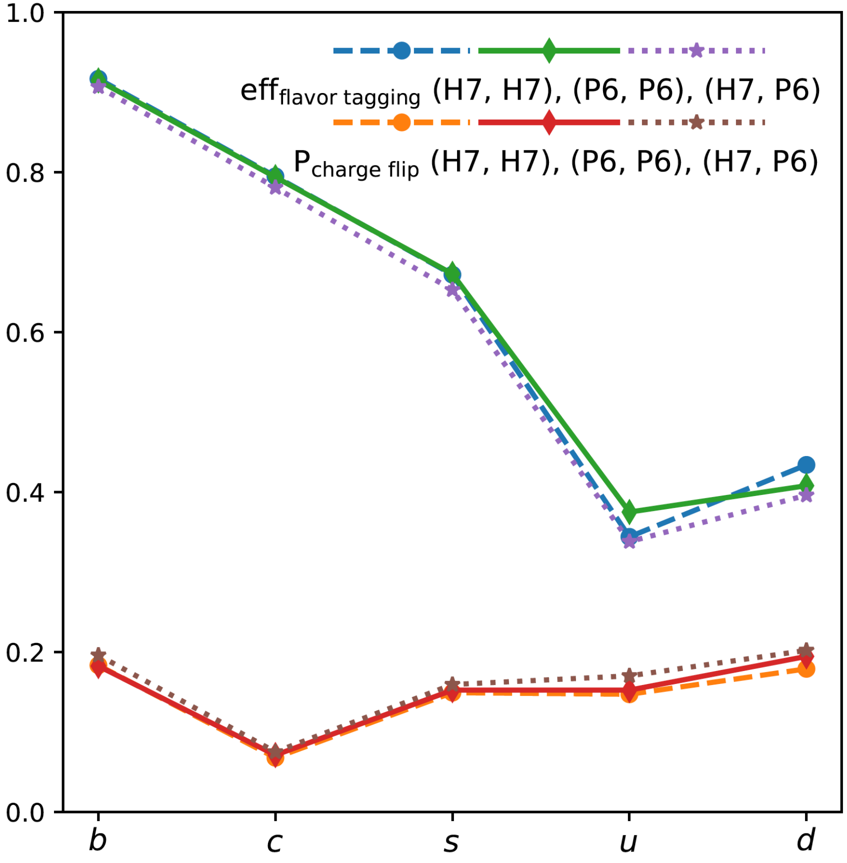
Performance @ Z and Higgs

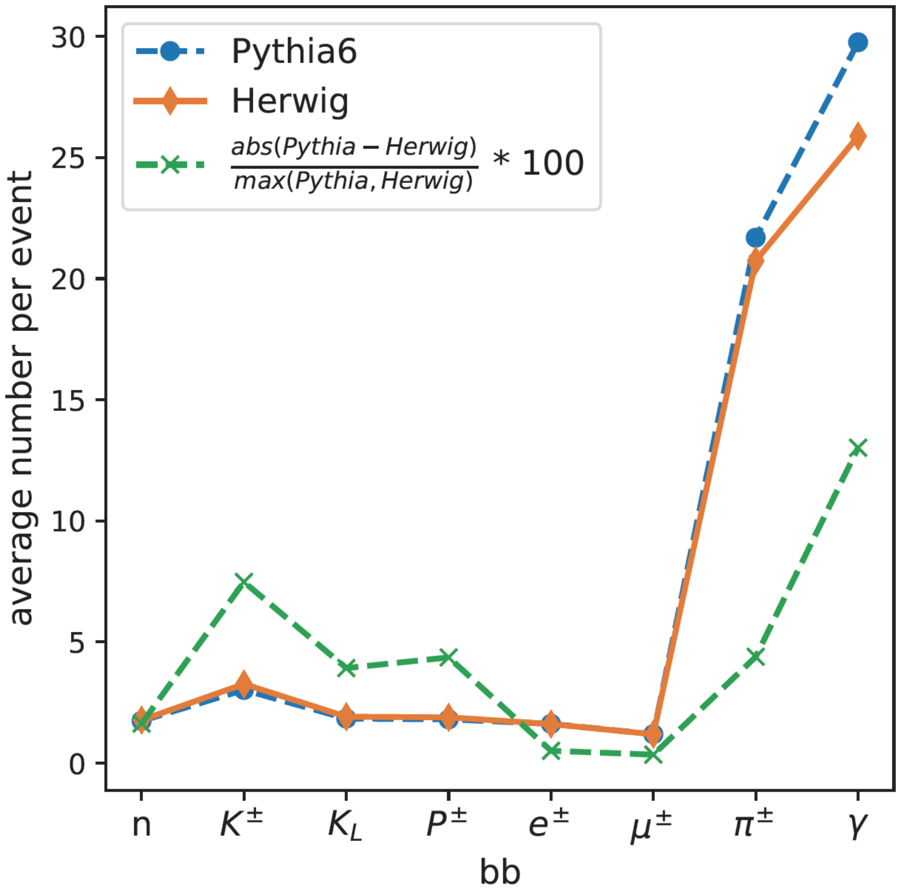




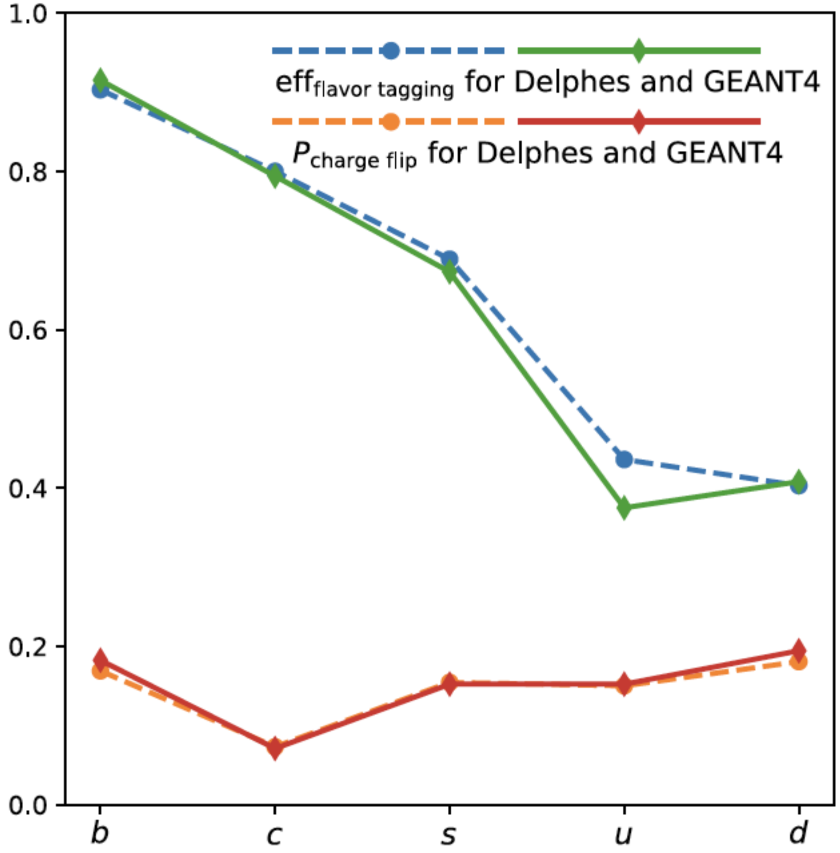
- *M10 instead of M11*

V.S. Hadronization models

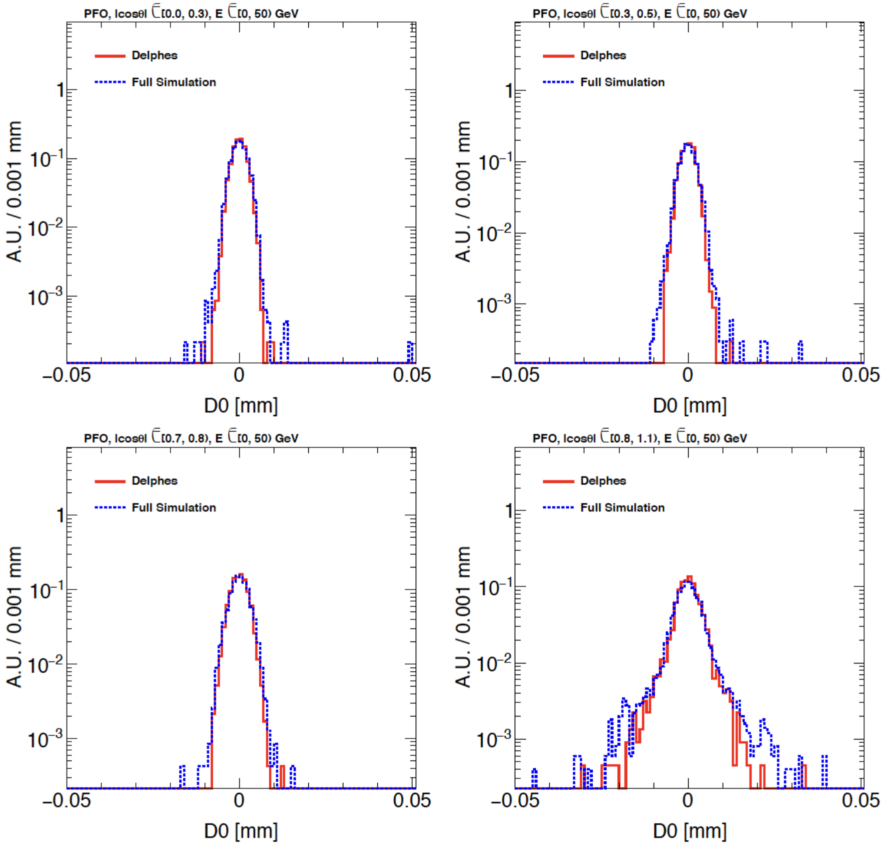




Fast/Full Simulation



Z->μμ (91.2 GeV)



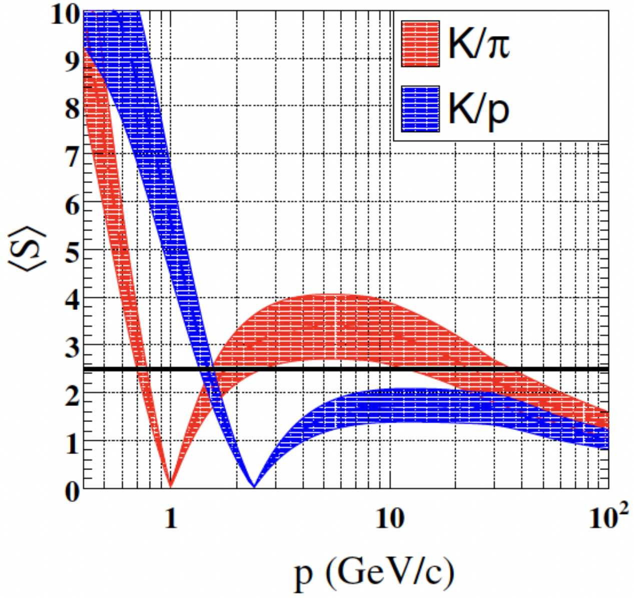
- Delphes ~ Perfect PFA (1 – 1 correspondence..)

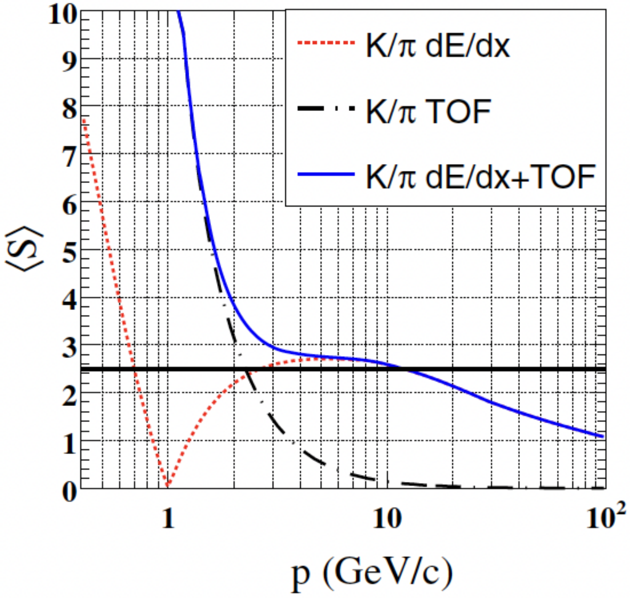
Key challenges

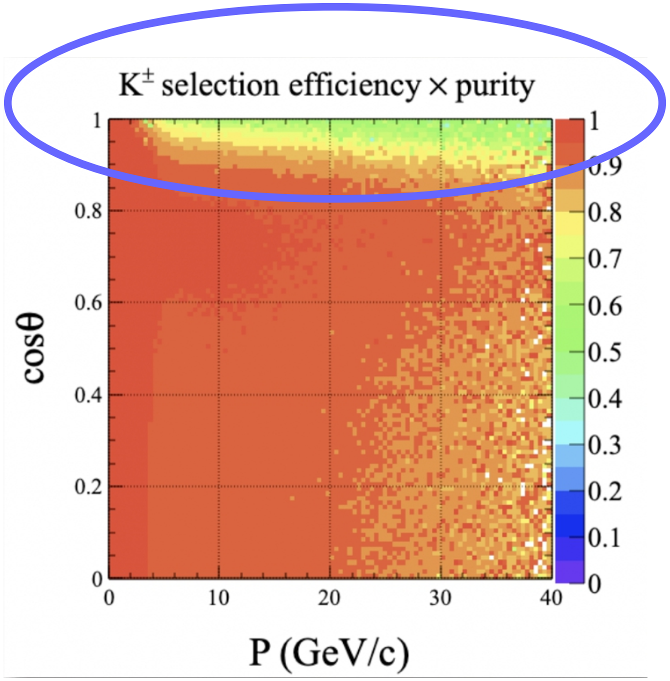
- Suited to the collision environment, especially beam background/MDI
- **Trigger-less equivalent: Trigger system works as Trigger-less**
- Extremely stable
- Large acceptance: polar angle, energy, time
- **PFA compatible (in SpaceTime): final state particle separation – pursue 1-1 correspondence**
  - 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 (Kaon finding at incl. Z->qq : eff/purity > 95%)**
- Jet origin identification: Flavor Tagging, Charge Reconstruction, s-tagging...
- **Excellent intrinsic resolution E/M/position: per mille level for track, percentage level for EM...**

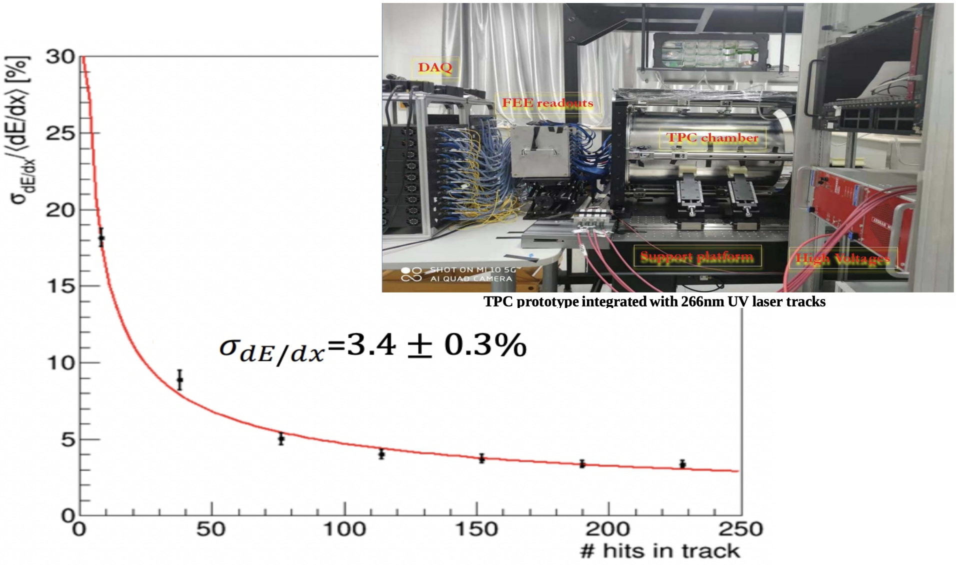
+with acceptable price: To be addressed by innovative detector design + key tech R&D

Tracker: Pid






$K^{\pm}$ selection efficiency × purity



TPC prototype integrated with 266nm UV laser tracks

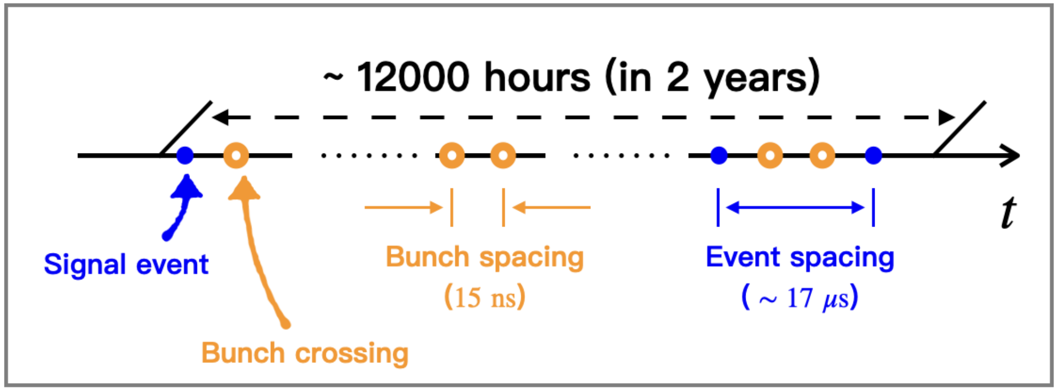
Table 3
The $K^{\pm}$ identification performance with different factors, $\sigma_{actual} = factor \cdot \sigma_{intrinsic}$, with/without combination of TOF information at the Z-pole.

	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

High Rates: Leakage & Overlapping in Time

CEPC Z pole scheme



~ 12000 hours (in 2 years)

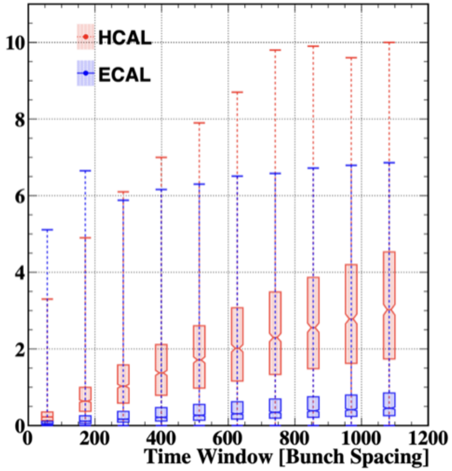
Signal event

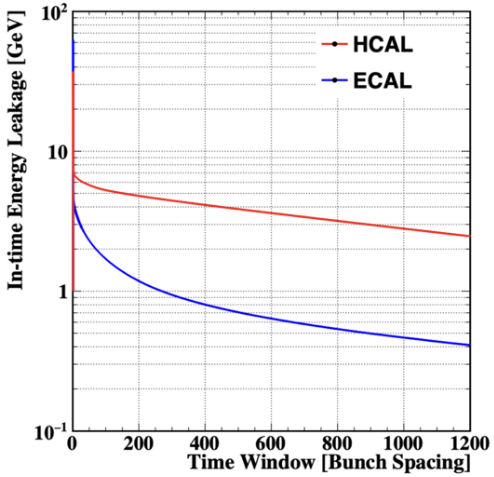
Bunch crossing

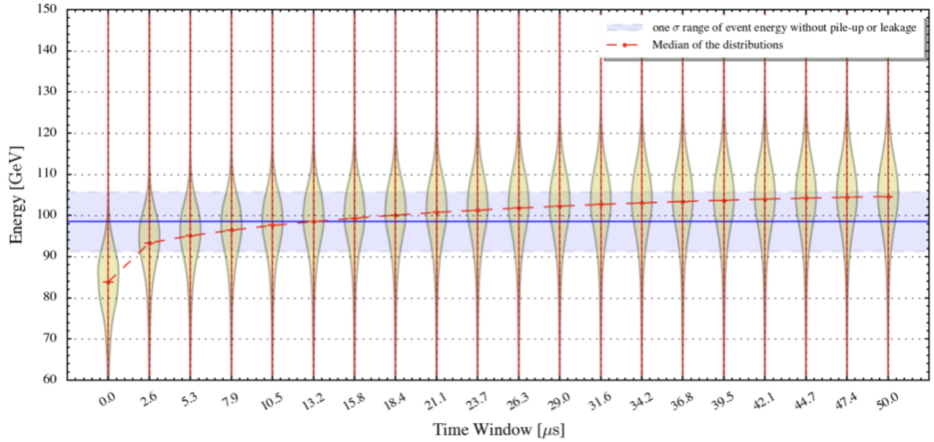
Bunch spacing (15 ns)

Event spacing (~ 17 μs)

t

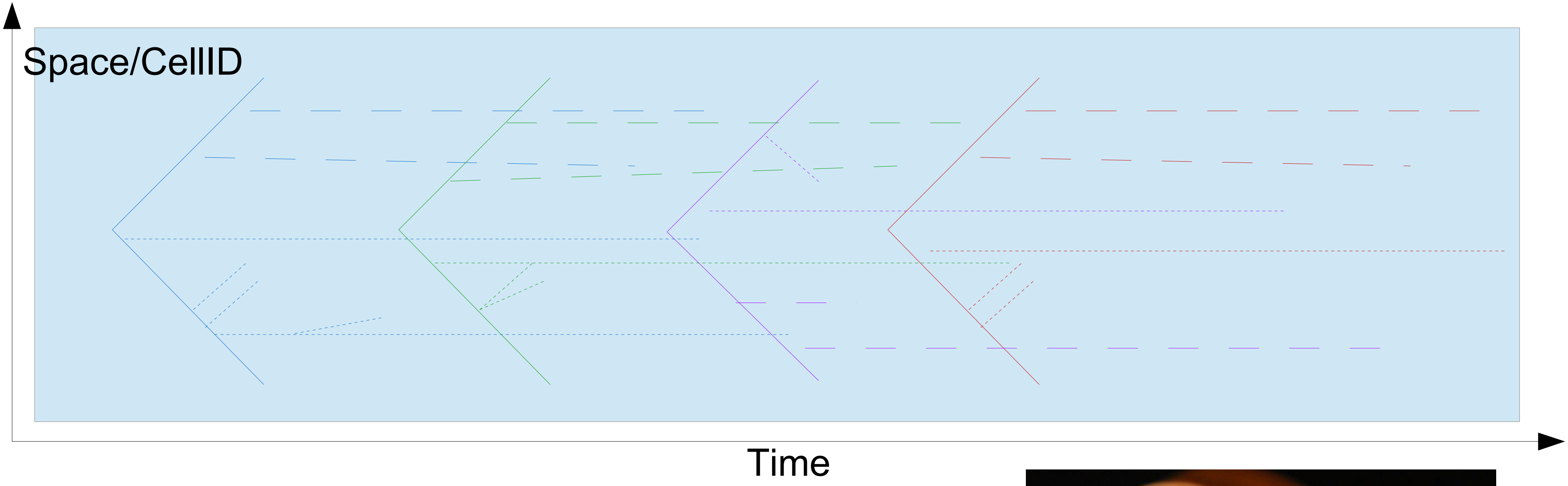






- Hit level ~ With integration time of 13 micro-sec, the energy or in time leakage ~ off time pileup ~ 3 GeV - Comparable to the BMR itself!
- PFA clustering, wi/wo timing information, could ameliorate this effect – awaiting analyses

POST: Particle Origin in Space Time



- Beyond the PFA
  - *To identify every cluster (even every hit) – and associate it with their vertexes – Event Building*
  - *To associate correctly clusters, tracks to reconstructed particle.*
  - *To identify particles (i.e., Kaons) and their origin (including quark/gluons ...).*
  - *posts the critical info from the collision...*

Detector concept studies

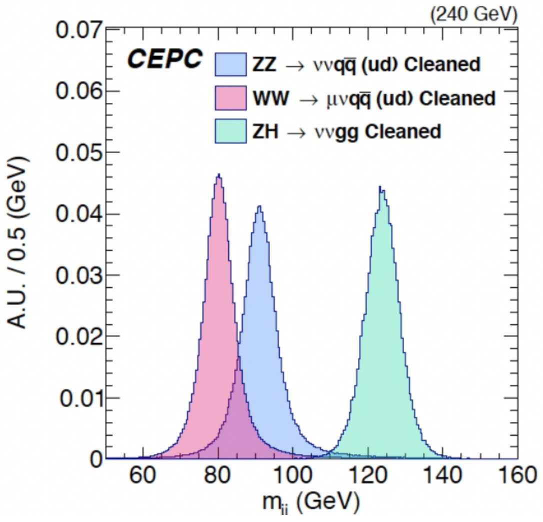
Design of experimental facility and technical requirements

Detector

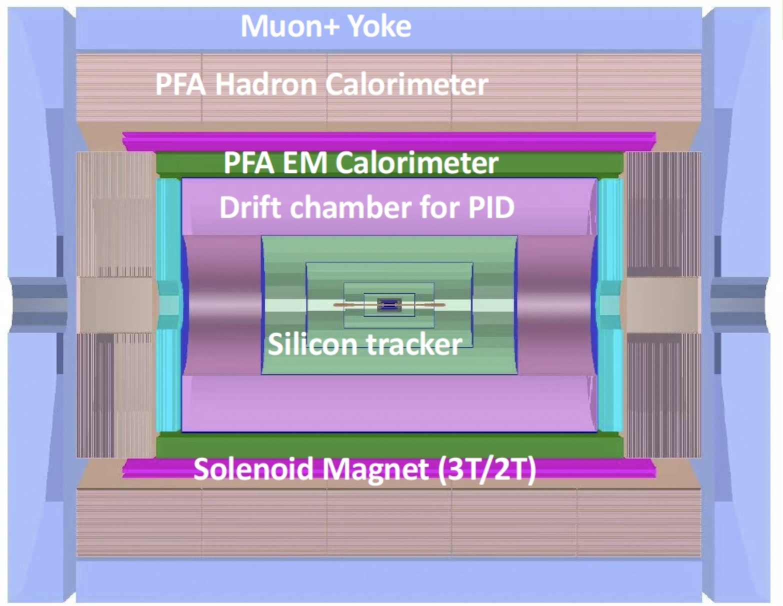
Requirements
boson mass resolution (BMR ~3%)

→

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

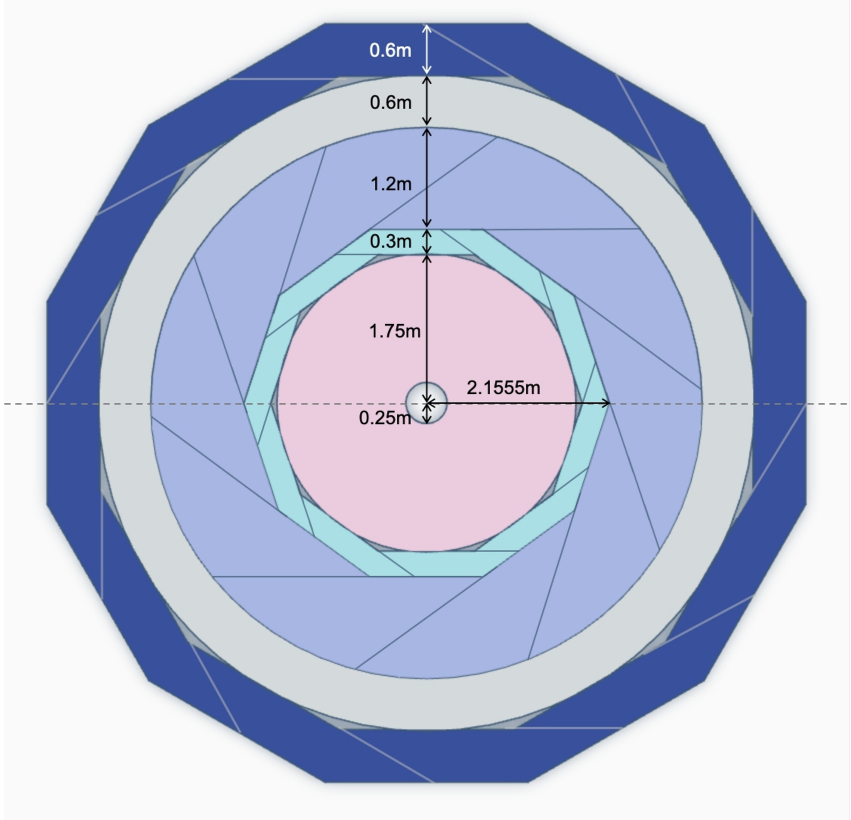


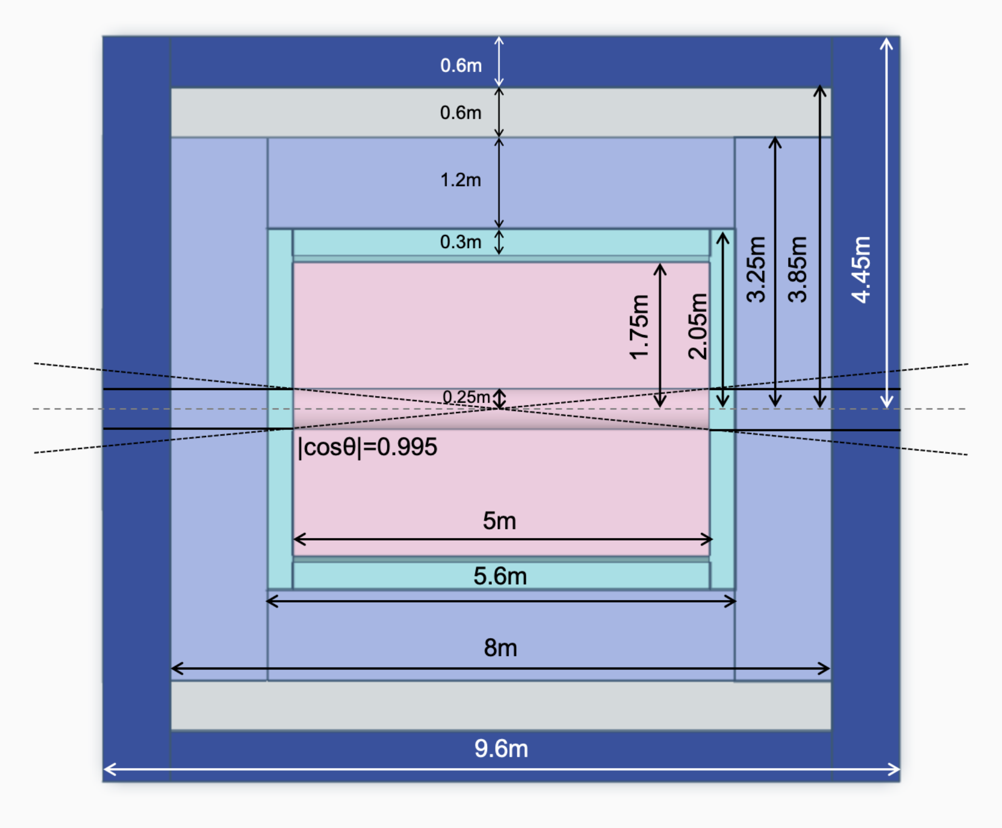
Novel detector design based on PFA calorimeter. Aim at improving BMR from 4% to 3%



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

CHLOE

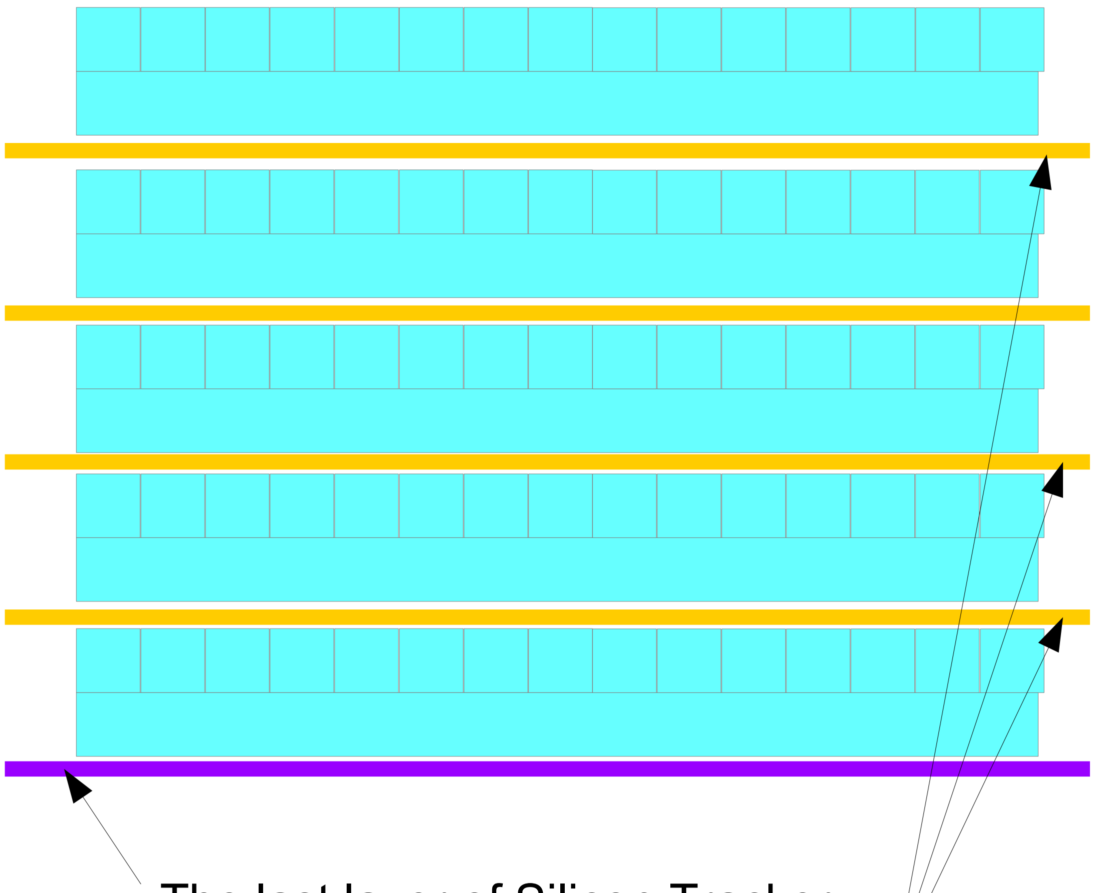




- Main features:
  - Aggressive VTX + Larger Gaseous Tracker to the beam induced background boundary, or, alternatively... *Silicon tracker with Pid capability...*
  - ECAL + HCAL: Xstal/Glass ECAL with Positioning & Timing layer + GSHCAL
  - 12-side polygon Calo

ECAL: Crystal + Position/timing layer

- Geometry
  - Total Crystal Volume: 23.3 m^3
  - Single Crystal Bar Dimension: 2.67cm * 2.67cm * 40cm = 291 cc, In total 80k bars
  - Inner Area: 80 m^2
  - Total Readout Channel:
    - 80000*2 = 160k (Crystal)
    - 800000*4 = 3.2 M (Si)
- Performance
  - EM resolution
  - Anticipated BMR
  - Timing

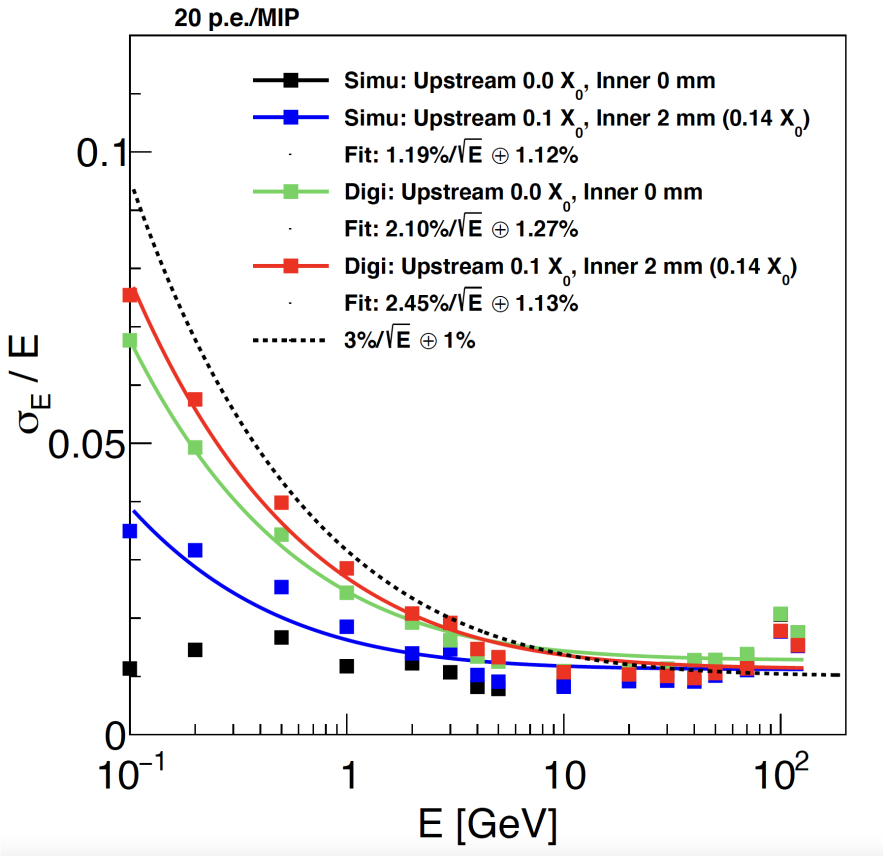


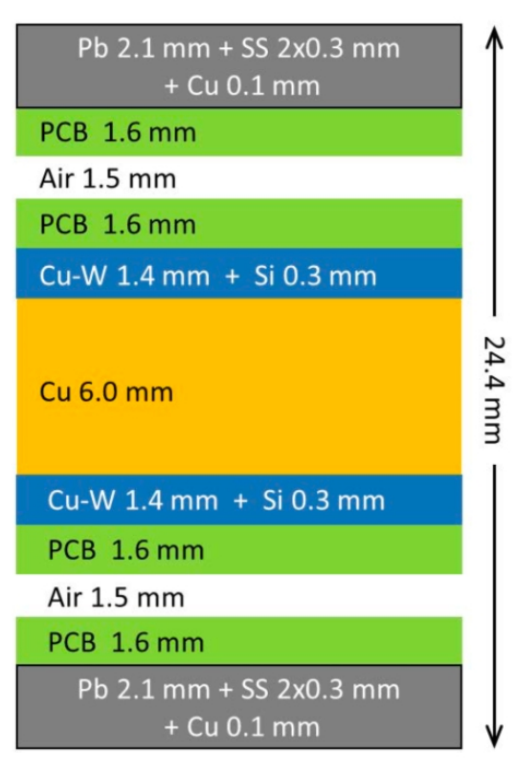
The last layer of Silicon Tracker

Position Layer with 1*1 cm Granularity (Si or Alternative)

*Compared to 1*1*40 cm crystal bars*
With in total 570 k bars and 1.14 M readout

EM resolution





CMS HGC Project:

600 m^2 Si + 300 m^2 Sci

Total cost:
69 M CHF ~ 500 M CNY

~~

CEPC:

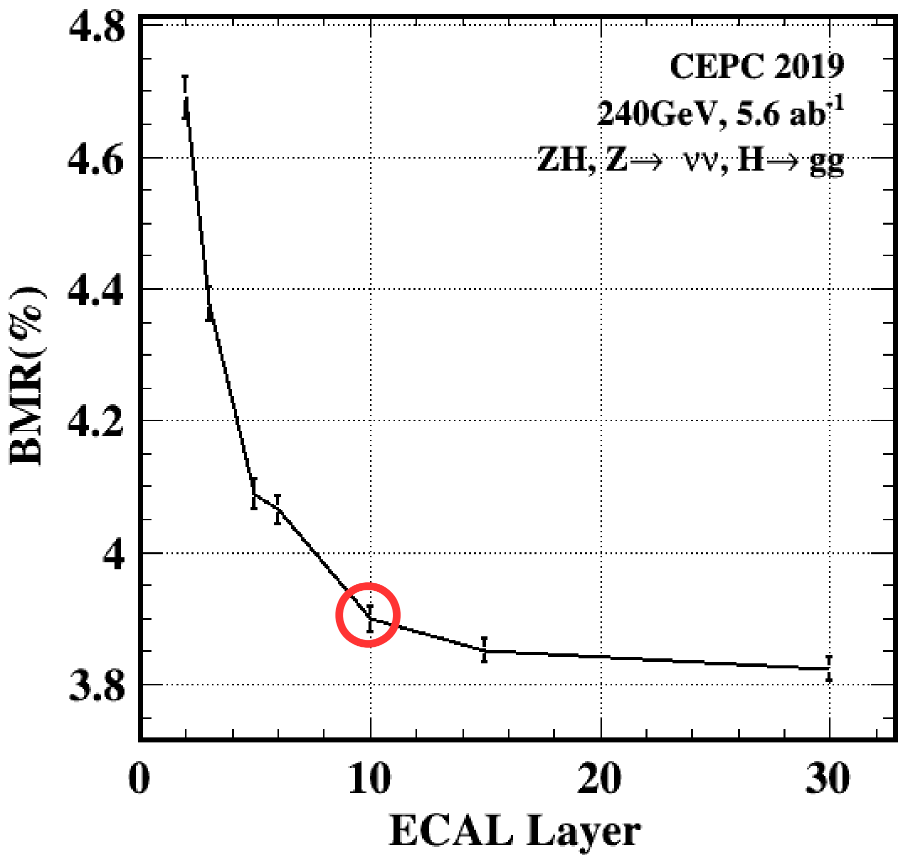
~ 300 m^2 Positioning Layer

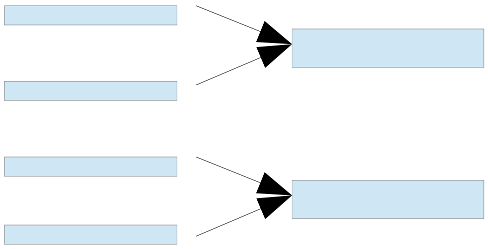
~ o(100) M CNY

- Positioning layer: material budget of ~ 0.2 X0 (3 mm Cu), fraction < 3%
- Compatible with CMS HGC Silicon layer wi cooling; which has much higher data rate & requirement on energy reco. -> further optimization is possible

BMR

- Optimization study at Baseline – Merge Hits of neighboring layers in longitudinal direction. Compared to 30 Si-W layers, 10 layers has a relative degrading of 2% (3.82 → 3.9)
- 5 double-layers + 4 silicon sensors + advanced algorithm shall comparable to 10 layers... if not better
- Better EM resolution of Xstal ECAL has positive impact on BMR
- BMR shall be comparable to baseline





Summary

- PFA oriented detector ~ ILD has excellent performance for the Higgs factory
  - BMR: should always pursue better BMR
  - Jet origin id: improve g(Hcc) ~ 2 times & access to g(Hss)
  - ...
- Higgs factory is not only about Higgs: challenges from Flavor, NP, QCD & EW...
  - Look inside the jet – especially for flavor, QCD, etc.
  - Trigger system as trigger less: background rate < 10% & signal eff > ? (~99.9%?)
  - Be in cope with high rates – PFA in space time
    - Gas tracker VS beam background...
  - Excellent intrinsic resolution & Pid
  - Extremely stable – for EW, etc, Mechanic, integration, cooling, aging & monitoring...
  - ...
- Need active design & optimization study + R&D efforts.
  - Advanced reconstruction is critical: **PFA → POST: Particle Origin in SpaceTime**

Back up

Particle identification

Bs→Φνν

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

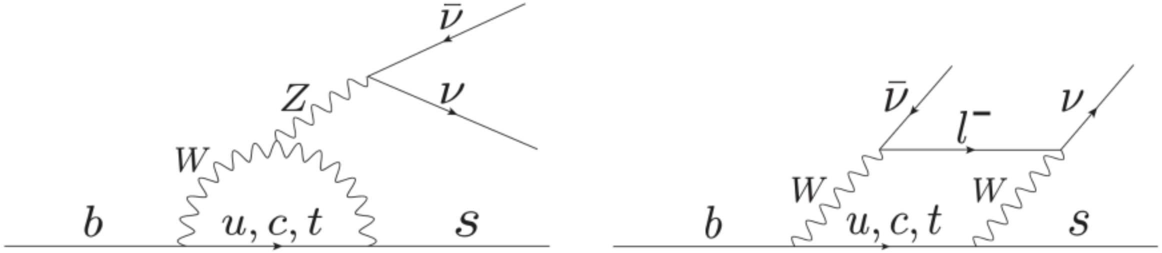
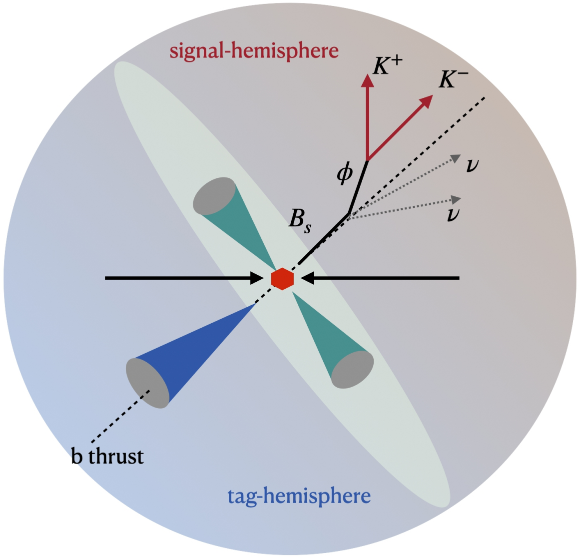
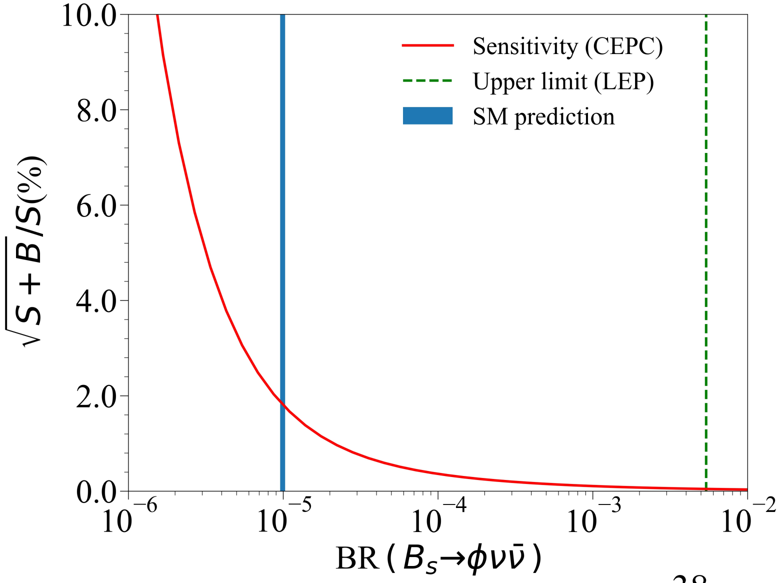


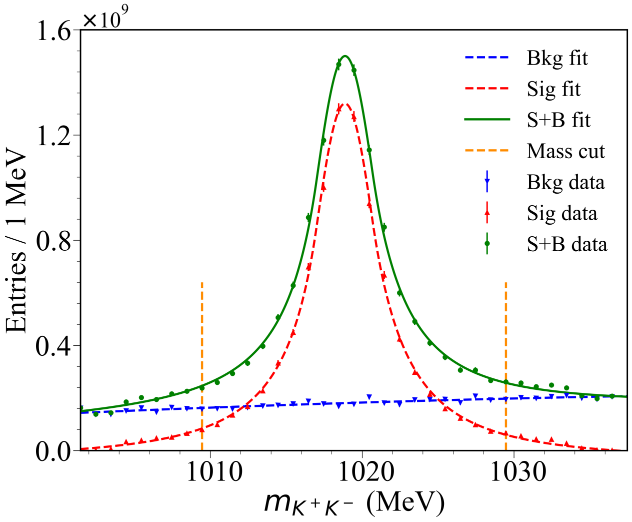
FIG. 1. The penguin and box diagrams of $b \to s\nu\bar{\nu}$ transition at the leading order.

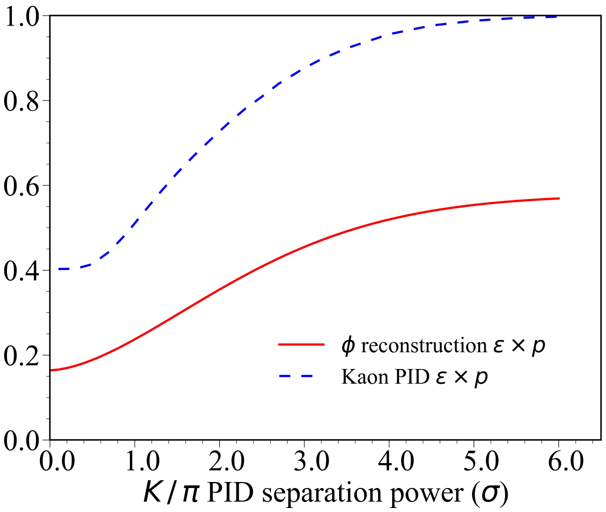


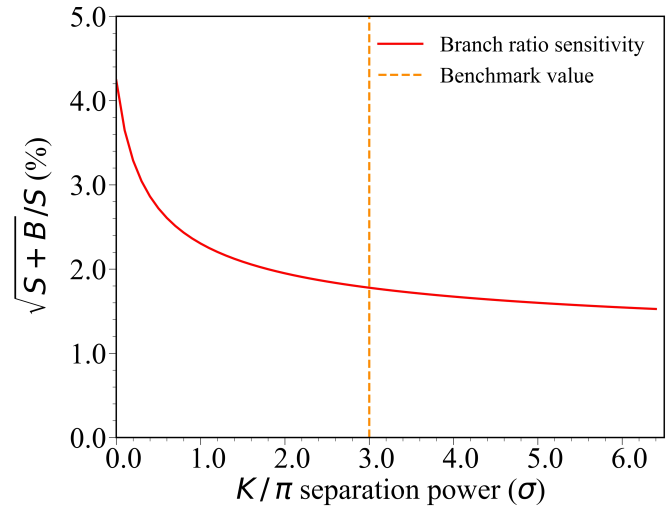
- Key ingredient to understand FCNC anomaly...
- Critical Physics Objects: Phi (and charged Kaon), 2nd VTX, Missing E/P, b-jet at opposite side
- Percentage level accuracy anticipated at Tera-Z

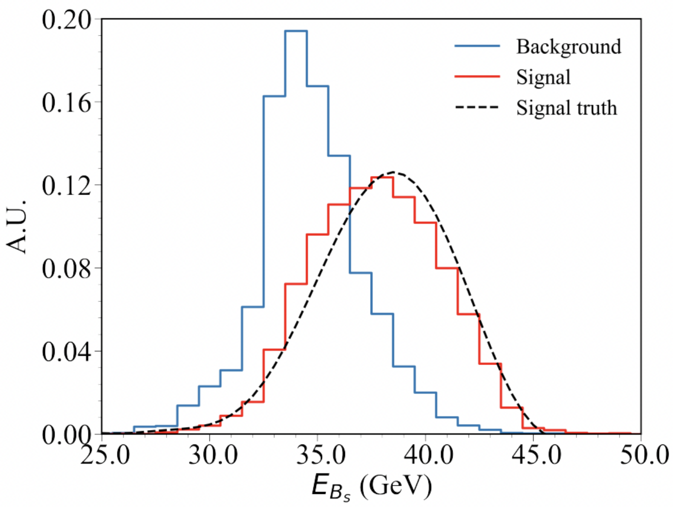


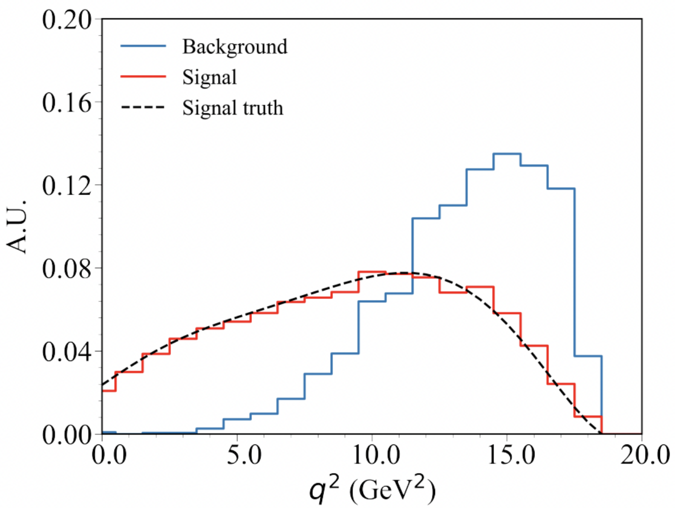
Requirements: Pid & MET











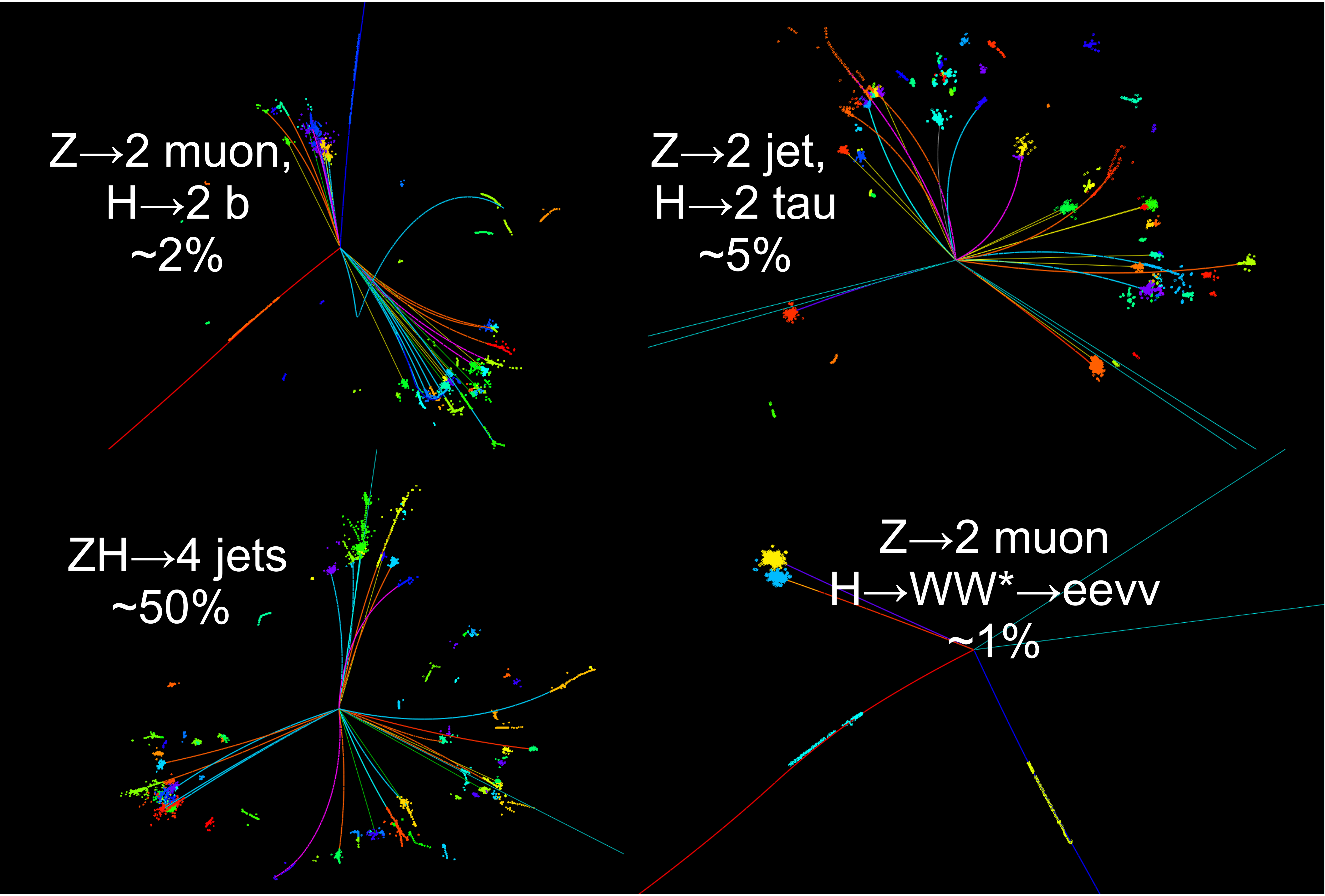
$$M_{\text{tag}} = \sqrt{\left(\sum p^{\text{vis}}_{\text{tag}}\right)^2}\,,$$

$$M^{(i)}_{\text{sig}} = \sqrt{\left(\sum p^{\text{vis}}_{\text{sig}} + p^{(i-1)}_{B_s} - p_\phi\right)^2}\,,$$

$$E^{(i)}_{B_s} = \frac{s + (M^{(i-1)}_{\text{sig}})^2 - M^2_{\text{tag}}}{2\sqrt{s}} - E_{\text{sig}} + E_\phi\,,$$

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

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



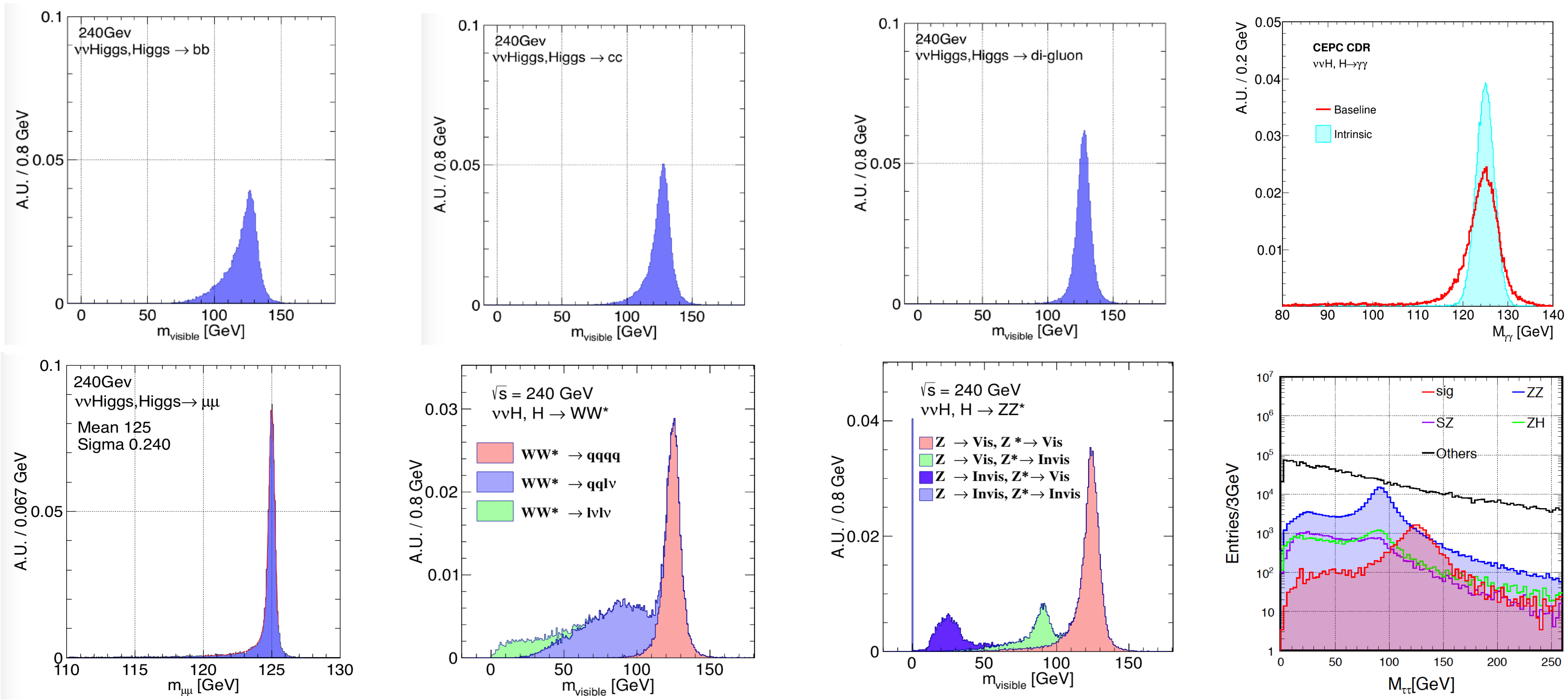
Z→2 muon,
H→2 b
~2%

Z→2 jet,
H→2 tau
~5%

ZH→4 jets
~50%

Z→2 muon
H→WW*→eeνν
~1%

Reconstructed Higgs Signatures



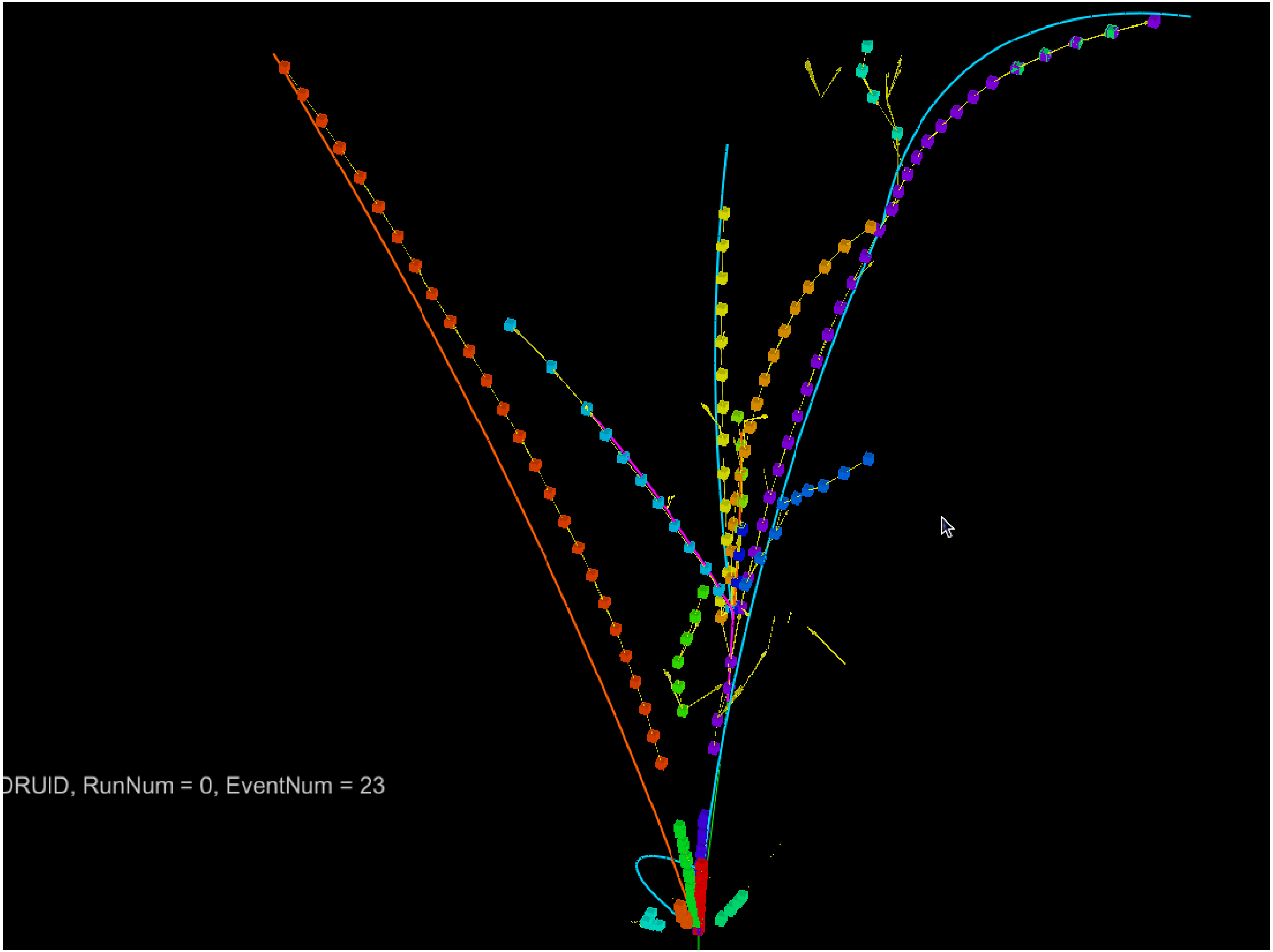
Clear Higgs Signature in all SM decay modes

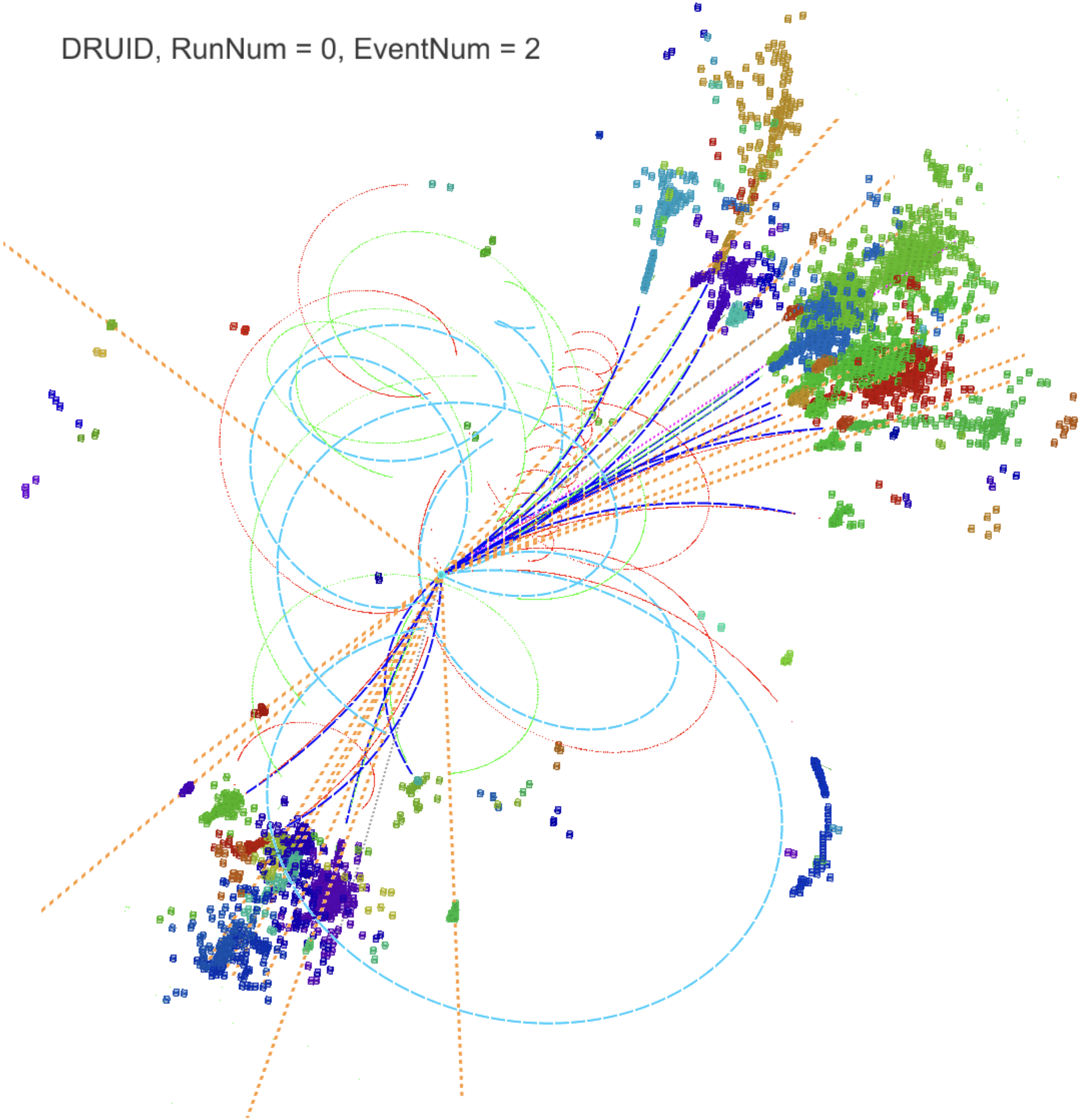
Massive production of the SM background (2 fermion and 4 fermions) at the full Simulation level

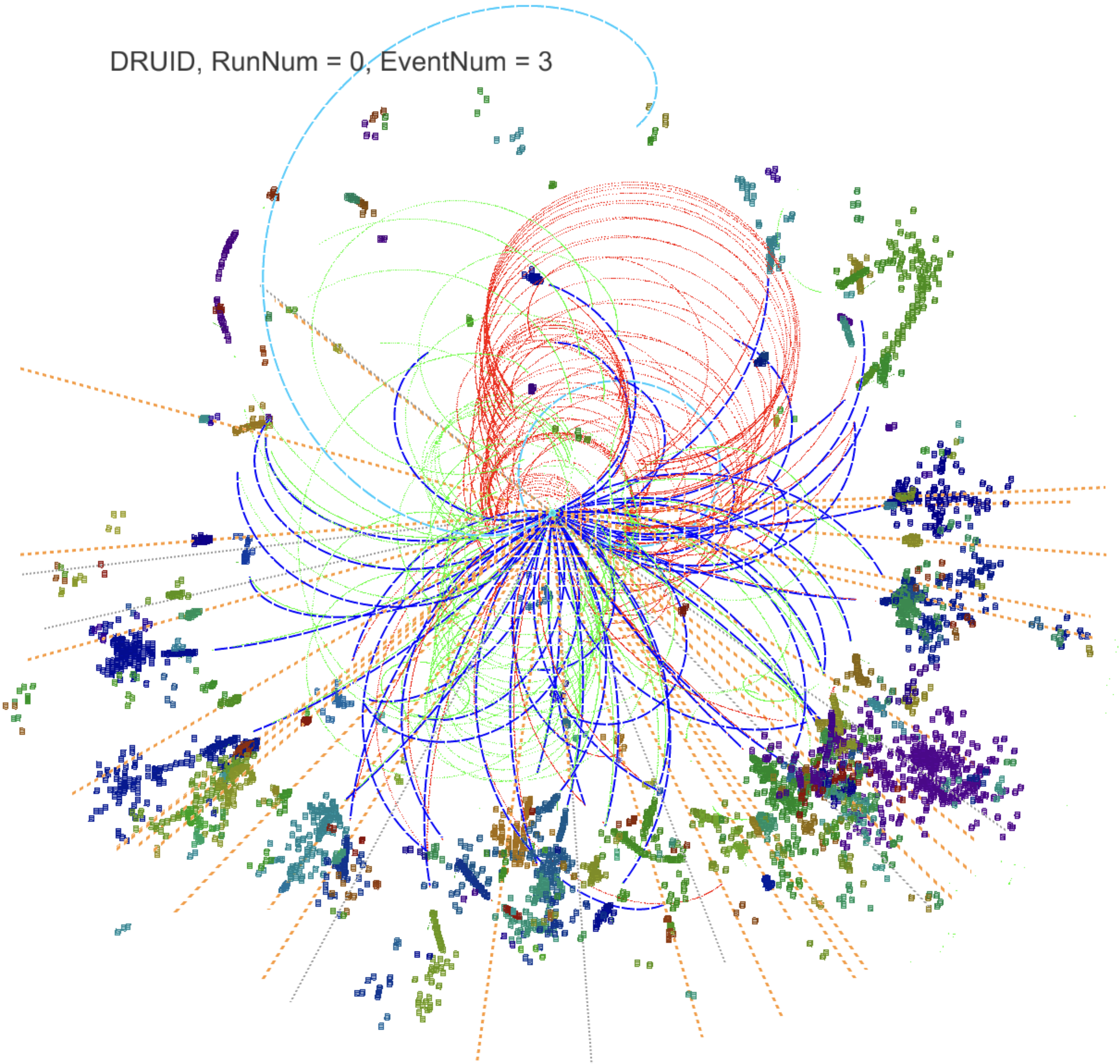
Right corner: di-tau mass distribution at qqH events using collinear approximation

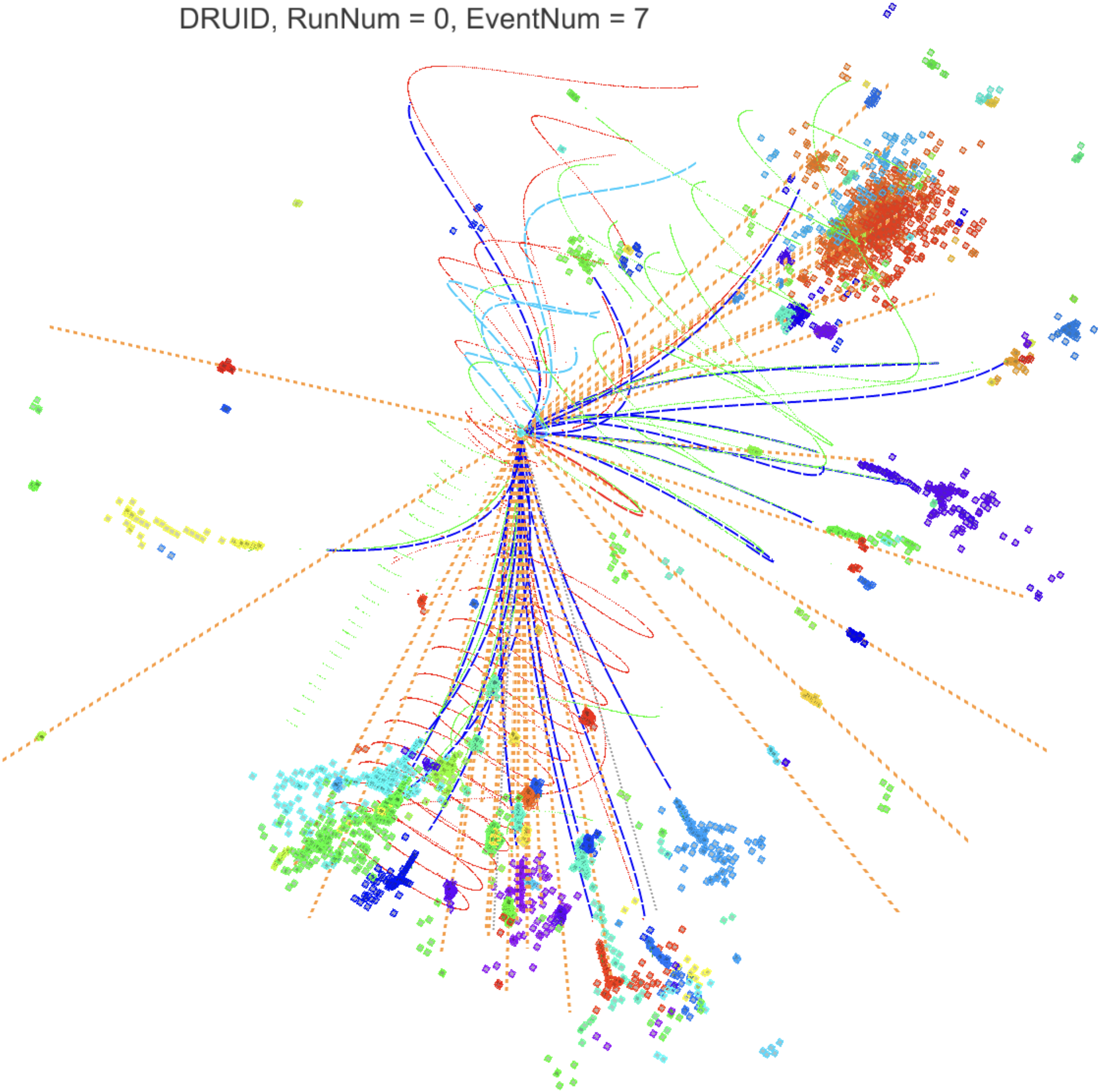
Summary

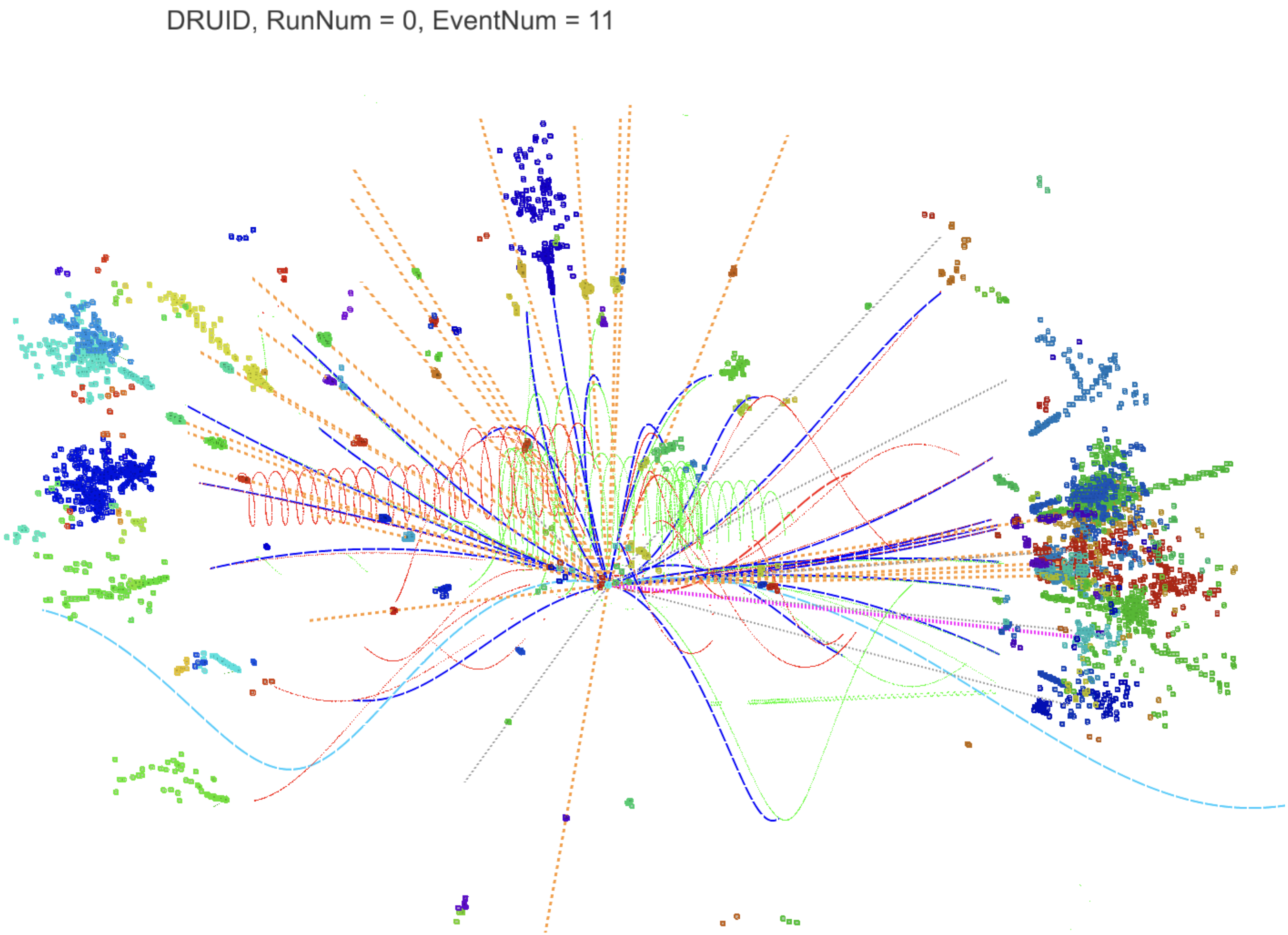
- A lot to be understood...
  - V.S. Scaling of Jet energy, Polar angle/eta,
  - V.S. Collision environment: beam background, # PU
  - V.S. Detector geometry: VTX configuration, acceptance, etc
  - V.S. Jet Clustering algorithm, interactions with jet finding & Color Singlet identification
  - V.S. Different hadronization & fragmentation modes...
  -
  - V.S. algorithm architecture
  - V.S. training & implementation procedure...


DRUID, RunNum = 0, EventNum = 23

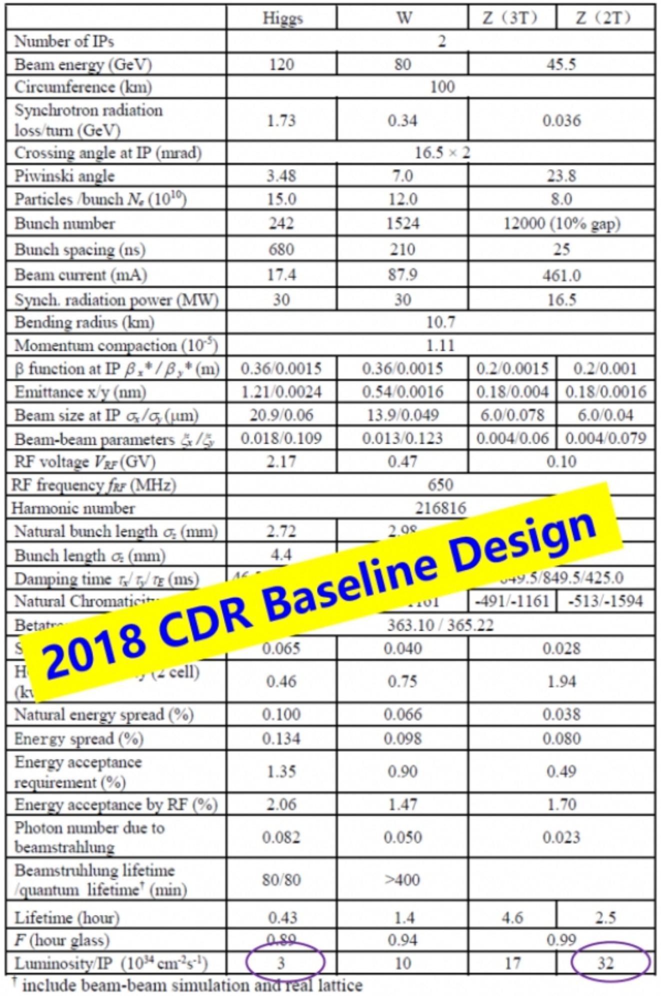

DRUID, RunNum = 0, EventNum = 2


DRUID, RunNum = 0, EventNum = 3


DRUID, RunNum = 0, EventNum = 7


DRUID, RunNum = 0, EventNum = 11

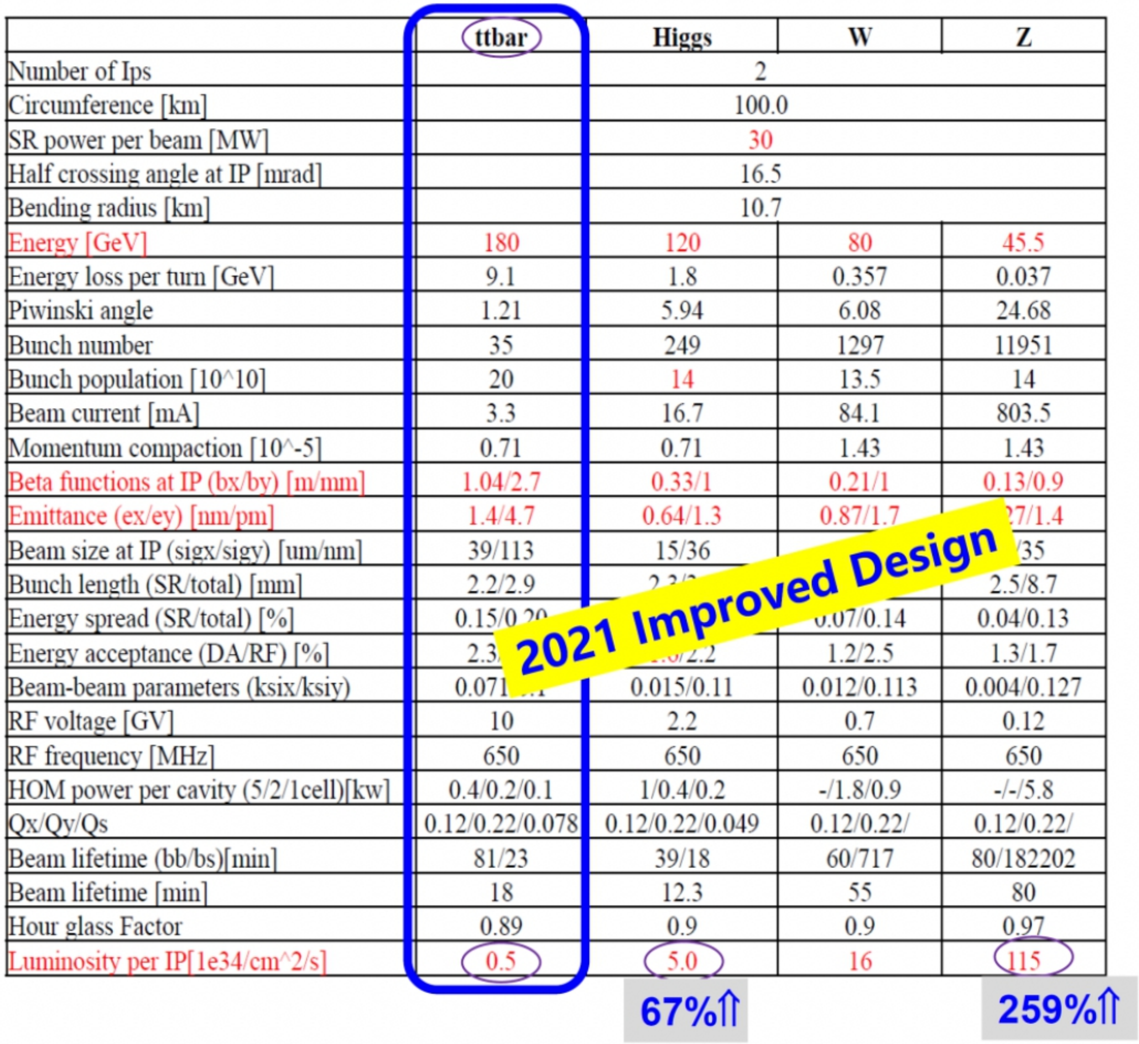
CEPC Accelerator TDR Design



2018 CDR Baseline Design

	Higgs	W	Z（3T）	Z（2T）
Number of IPs	2			
Beam energy (GeV)	120	80	45.5	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5 × 2			
Piwinski angle	3.48	7.0	23.8	
Particles /bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number	242	1524	12000 (10% gap)	
Bunch spacing (ns)	680	210	25	
Beam current (mA)	17.4	87.9	461.0	
Synch. radiation power (MW)	30	30	16.5	
Bending radius (km)	10.7			
Momentum compaction (10^{-5})	1.11			
β function at IP β_x^* / β_y^* (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015	0.2/0.001
Emittance x/y (nm)	1.21/0.0024	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.06	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.018/0.109	0.013/0.123	0.004/0.06	0.004/0.079
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz)	650			
Harmonic number	216816			
Natural bunch length σ_z (mm)	2.72	2.98	[illegible]	
Bunch length σ_z (mm)	4.4	[illegible]	[illegible]	
Damping time $\tau_x/\tau_y/\tau_E$ (ms)	[illegible]	[illegible]	49.5/849.5/425.0	
Natural Chromaticit	[illegible]	[illegible]	-491/-1161	-513/-1594
Betatr	363.10 / 365.22			
S	0.065	0.040	0.028	
H (2 cell) (k	0.46	0.75	1.94	
Natural energy spread (%)	0.100	0.066	0.038	
Energy spread (%)	0.134	0.098	0.080	
Energy acceptance requirement (%)	1.35	0.90	0.49	
Energy acceptance by RF (%)	2.06	1.47	1.70	
Photon number due to beamstrahlung	0.082	0.050	0.023	
Beamstruhlung lifetime /quantum lifetime[†] (min)	80/80	>400		
Lifetime (hour)	0.43	1.4	4.6	2.5
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP (10^{34} cm^{-2}s^{-1})	3	10	17	32

[†] include beam-beam simulation and real lattice



2021 Improved Design

	ttbar	Higgs	W	Z
Number of Ips		2		
Circumference [km]		100.0		
SR power per beam [MW]		30		
Half crossing angle at IP [mrad]		16.5		
Bending radius [km]		10.7		
Energy [GeV]	180	120	80	45.5
Energy loss per turn [GeV]	9.1	1.8	0.357	0.037
Piwinski angle	1.21	5.94	6.08	24.68
Bunch number	35	249	1297	11951
Bunch population [10^10]	20	14	13.5	14
Beam current [mA]	3.3	16.7	84.1	803.5
Momentum compaction [10^-5]	0.71	0.71	1.43	1.43
Beta functions at IP (bx/by) [m/mm]	1.04/2.7	0.33/1	0.21/1	0.13/0.9
Emittance (ex/ey) [nm/pm]	1.4/4.7	0.64/1.3	0.87/1.7	27/1.4
Beam size at IP (sigx/sigy) [um/nm]	39/113	15/36	[illegible]	/35
Bunch length (SR/total) [mm]	2.2/2.9	2.3/	[illegible]	2.5/8.7
Energy spread (SR/total) [%]	0.15/0.20	[illegible]	0.07/0.14	0.04/0.13
Energy acceptance (DA/RF) [%]	2.3	/2.2	1.2/2.5	1.3/1.7
Beam-beam parameters (ksix/ksiy)	0.071	0.015/0.11	0.012/0.113	0.004/0.127
RF voltage [GV]	10	2.2	0.7	0.12
RF frequency [MHz]	650	650	650	650
HOM power per cavity (5/2/1cell)[kw]	0.4/0.2/0.1	1/0.4/0.2	-/1.8/0.9	-/-/5.8
Qx/Qy/Qs	0.12/0.22/0.078	0.12/0.22/0.049	0.12/0.22/	0.12/0.22/
Beam lifetime (bb/bs)[min]	81/23	39/18	60/717	80/182202
Beam lifetime [min]	18	12.3	55	80
Hour glass Factor	0.89	0.9	0.9	0.97
Luminosity per IP[1e34/cm^2/s]	0.5	5.0	16	115

67%⇑

259%⇑

CEPC TDR Parameters - 50MW upgrade

	ttbar	**Higgs**	**W**	**Z**
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	50			
Half crossing angle at IP [mrad]	16.5			
Bending radius [km]	10.7			
Energy [GeV]	180	120	80	45.5
Energy loss per turn [GeV]	9.1	1.8	0.357	0.037
Bunch number	58	415	2162	19918
Bunch spacing [ns]	2640	385	154	15 (10% gap)
Bunch population [10^{10}]	20	14	13.5	14
Beam current [mA]	5.5	27.8	140.2	1339.2
Momentum compaction [10^{-5}]	0.71	0.71	1.43	1.43
Beta functions at IP (βx/βy) [m/mm]	1.04/2.7	0.33/1	0.21/1	0.13/0.9
Emittance (εx/εy) [nm/pm]	1.4/4.7	0.64/1.3	0.87/1.7	0.27/1.4
Betatron tune ν_x/ν_y	445.10/445.22	445.10/445.22	266.10/267.22	266.10/267.22
Beam size at IP (σx/σy) [um/nm]	39/113	15/36	13/42	6/35
Bunch length (SR/total) [mm]	2.2/2.9	2.3/3.9	2.5/4.9	2.5/8.7
Energy spread (SR/total) [%]	0.15/0.20	0.10/0.17	0.07/0.14	0.04/0.13
Damping time (ms)	14/14/7	44/44/22	156/156/78	849.5/849.5/425.0
Energy acceptance (DA/RF) [%]	2.3/2.6	1.7/2.2	1.2/2.5	1.3/1.7
Beam-beam parameters (ξx/ξy)	0.071/0.1	0.015/0.11	0.012/0.113	0.004/0.127
RF voltage [GV]	10	2.2	0.7	0.12
RF frequency [MHz]	650	650	650	650
Longitudinal tune νs	0.078	0.049	0.062	0.035
Luminosity per IP[10^{34}/cm^2/s]	0.83	8.3	26.6	191.7

From Prof. J. Gao

CEPC: operation scenario

- CEPC emphasize on the Higgs factory & Z factory

- Upgradable:
  - In energy: to 360 GeV
  - In SR beam power: 30 to 50 MW

- Tentative Operation Plan & Yields (2 IP, with 50 MW)
  - 2 year in Z: 100 ab^{-1}, 3 Tera $Z \rightarrow qq$ events
  - 1 year in W: 6 ab^{-1}, ~ 100 Million WW events
  - 10 year in Higgs: 20 ab^{-1}, 4 Million Higgs
  - ~ 5 years at top: 1 ab^{-1}, 0.5 Million ttbar events, 150 k Higgs

Challenge: Collision/Event Rate

- Z→qq event rate higher than 100 k Hz.

- Collision rate: can be comparable to that of LHC.
  - 2.6 ms for ttbar operation
  - 385/154 ns for Higgs/WW scan
  - 15 ns for Z pole

- Compatibility of the sub-detectors: especially
  - Feasibility of the TPC:
    - Track distortion & correction induced by even the primary ionization
  - Power pulsing is difficult... more efficient cooling + optimization?
  - DAQ: Triggerless mode, or at least software trigger (as LHCb upgrade)

Challenge: Beam condition

- Beam energy calibration
  - ~ 0.1 MeV at Z pole
  - ~ sub MeV at W threshold
  - ~ MeV at Higgs operation
  - ...with nature beam energy spread of ~ o(1E-3)

- Beam polarization monitoring
  - Transverse... (essential for the Resonance depolarization Method) and even longitudinal...

- Beam Luminosity Spectrum Monitoring, especially at top

Challenge: Forward region & MDI

- CEPC has very compact & difficult forward region design
  - Luminosity measurement requirement
    - At least 1E-4 for Z pole,
    - 1E-3 for W threshold scan, Higgs operation, and top runs
    - Micrometer level position stability & accuracy for Luminometer, et.al.
  - Very short L* (varies from 1.4 – 2 meter), but seems to be definitely installed inside the tracker volume
  - The beam background condition at the CEPC is yet to be quantified. While better flavor tagging performance strongly prefers small inner radius of the vertex system.

- Low material VTX system, with R_in as small as 20 mm, radiation hard...

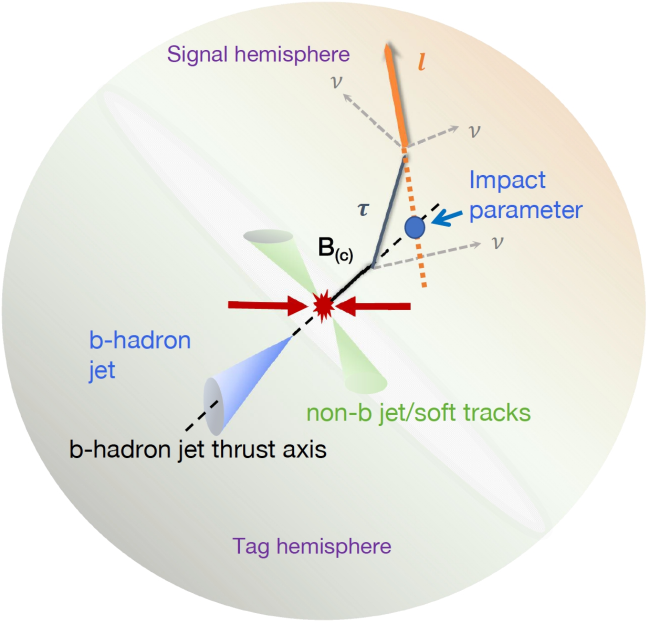
Challenge: Solenoid

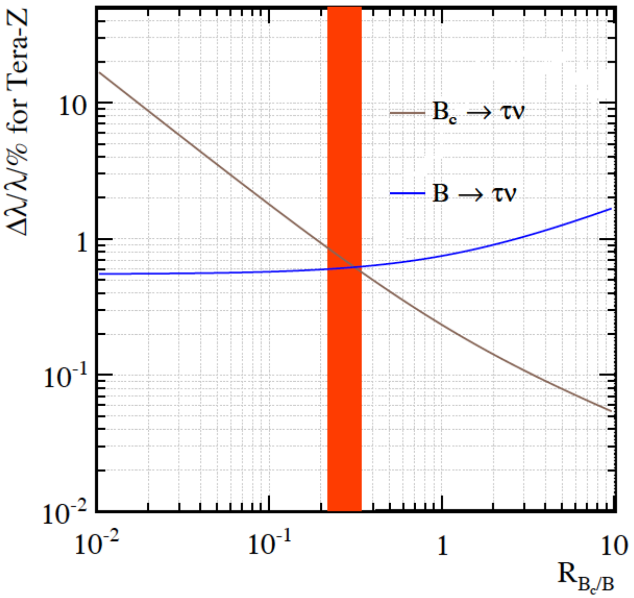
- To reach high luminosity at the Z pole operation, the B-Field of the main Solenoid shall not be higher than 2 Tesla
  - The beam X-angle (2*16.5 mrad) at the collision point induces correlations between the vertical & horizontal emittance..
  - Compared to 3 Tesla B-Field, 2 Tesla B-Field doubles the maximal Z pole luminosity

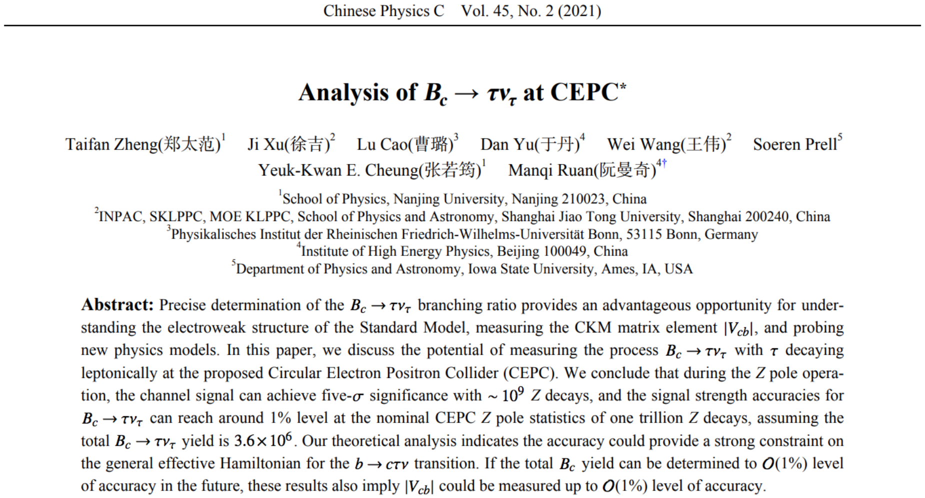
- However, a larger B-Field is strongly favored for Higher Energies.
  - Provide better momentum resolution, especially for the benchmark of Higgs to di-muon.
  - Constrains the beam background.

- Thus, a tunable Solenoid (2 to 3, or even higher) system, whose B-Field map can be monitored to a relative precision of 1E-4, and stable enough...

Bc→Tauv







Chinese Physics C Vol. 45, No. 2 (2021)

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

Taifan Zheng(郑太范)[1] Ji Xu(徐吉)[2] Lu Cao(曹璐)[3] Dan Yu(于丹)[4] Wei Wang(王伟)[2] Soeren Prell[5]
Yeuk-Kwan E. Cheung(张若筠)[1] Manqi Ruan(阮曼奇)[4†]

[1]School of Physics, Nanjing University, Nanjing 210023, China
[2]INPAC, SKLPPC, MOE KLPPC, School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China
[3]Physikalisches Institut der Rheinischen Friedrich-Wilhelms-Universität Bonn, 53115 Bonn, Germany
[4]Institute of High Energy Physics, Beijing 100049, China
[5]Department of Physics and Astronomy, Iowa State University, Ames, IA, USA

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.

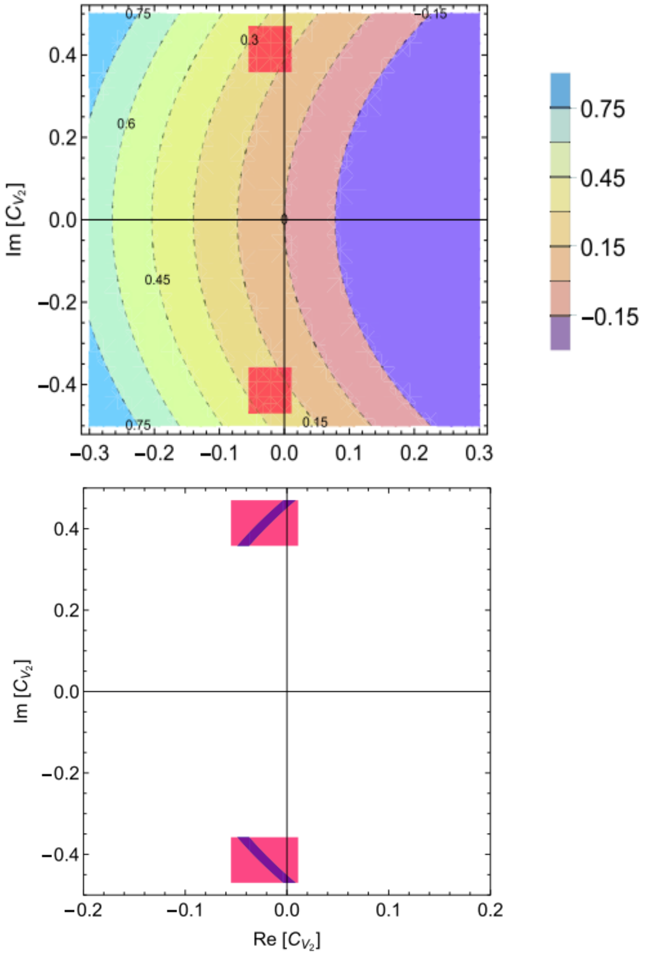
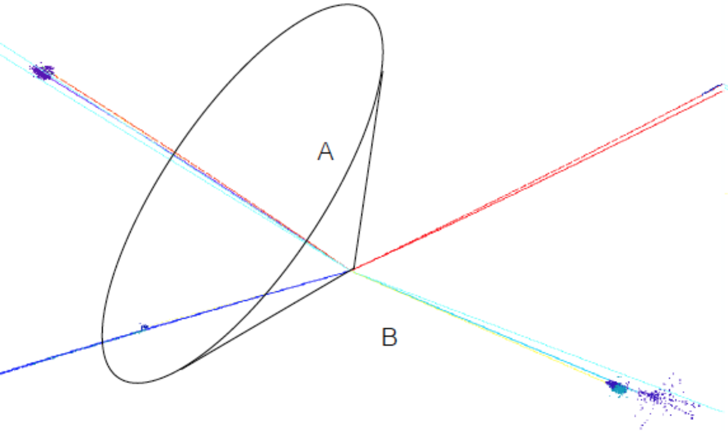


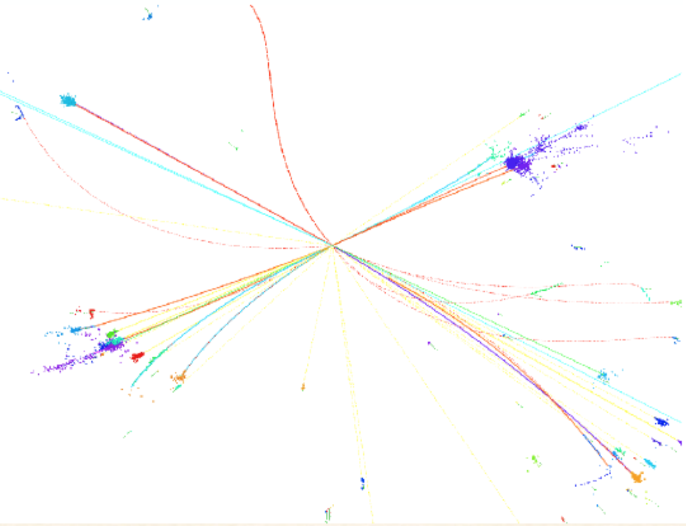
Fig. 10. (color online) Constraints on the real and imaginary parts of C_{V_2}. The red shaded area corresponds to the current constraints using available data on $b \to c\tau\nu$ decays. If the central values in Eq. (9) remain while the uncertainty in $\Gamma(B_c^+ \to \tau^+\nu_\tau)$ is reduced to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

Taus at the CEPC

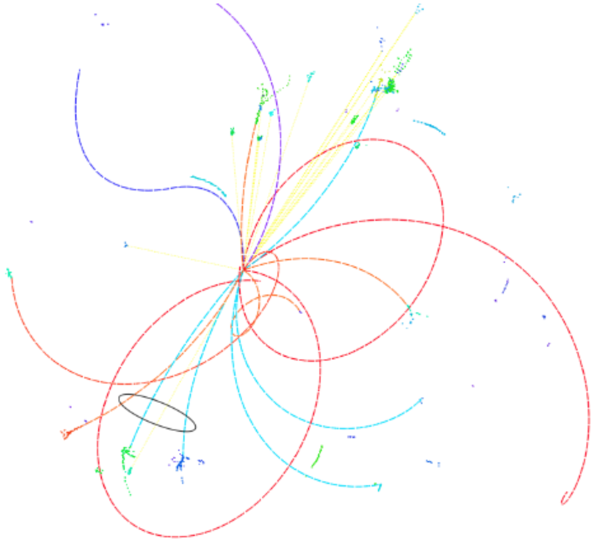
Leptonic:
ZH, Z→ll/vv, H→ττ
Z→ττ



Semi-Leptonic:
ZH, Z→qq, H→ττ
WW→τvqq

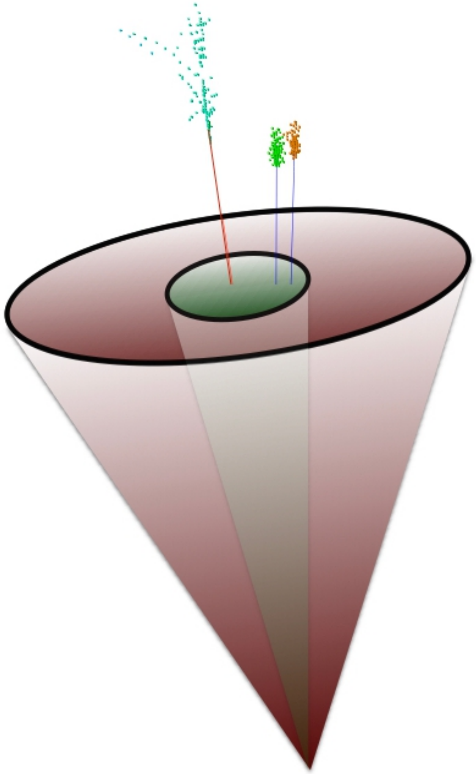


Full-Hadronic:
Z→qq→τ + X

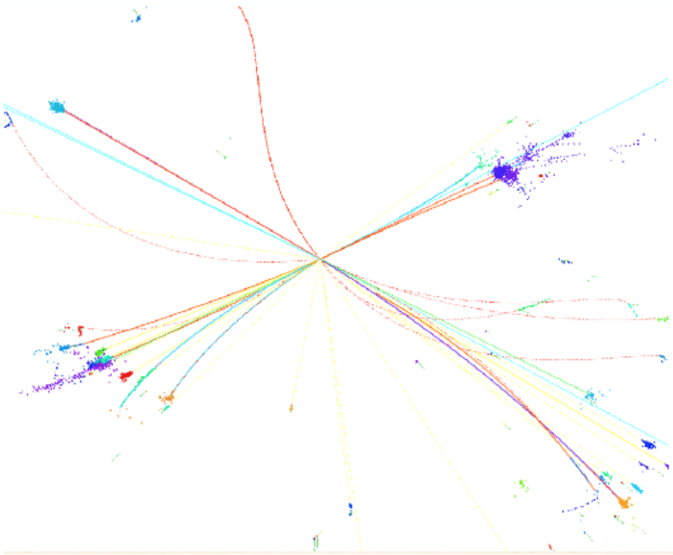


- Finding Tau
- Specify Tau decay product

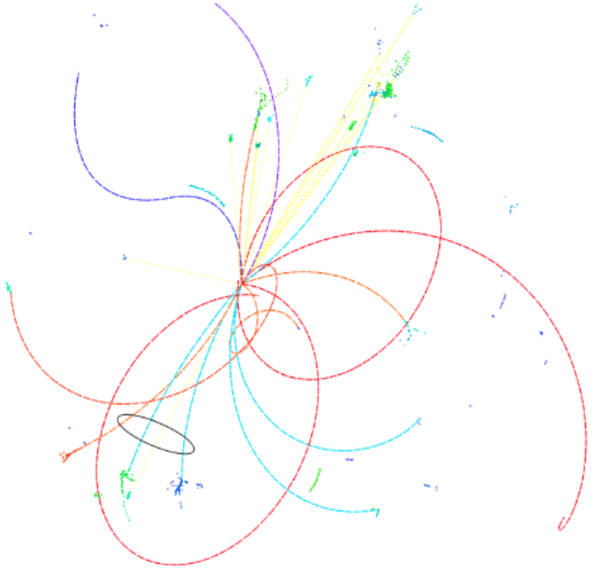
Taus at the CEPC



Semi-Leptonic:
ZH, Z→qq, H→ττ
WW→τνqq



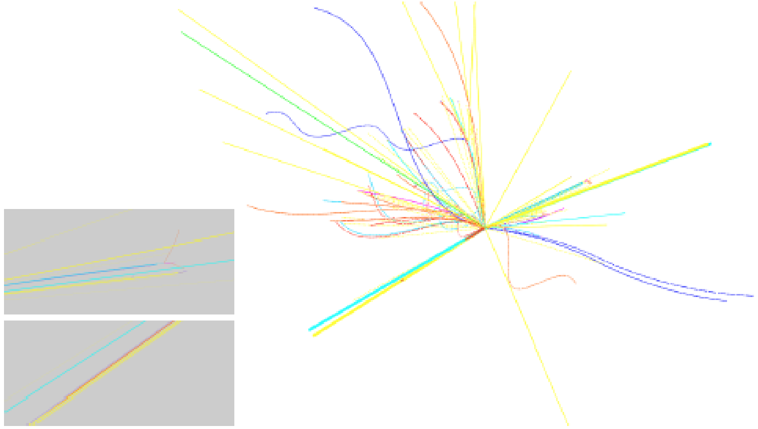
Full-Hadronic:
Z→qq→τ + X



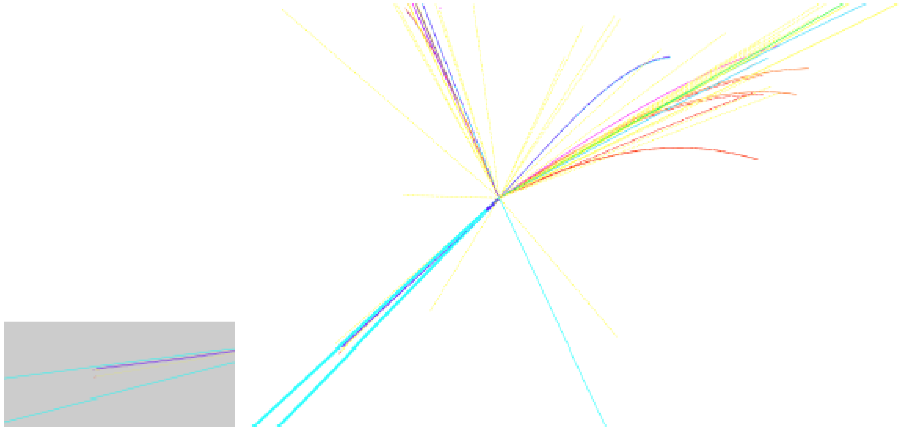
TAURUS (Tau ReconstrUction toolS):
an overall efficiency*purity higher than 70% is achieved for qqττ, and qqτν events

TAURUS/Specify Tau decay product

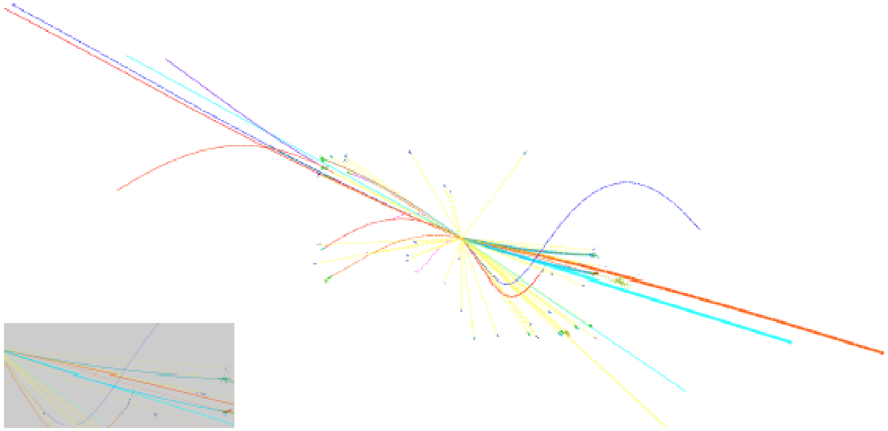
Benchmarks



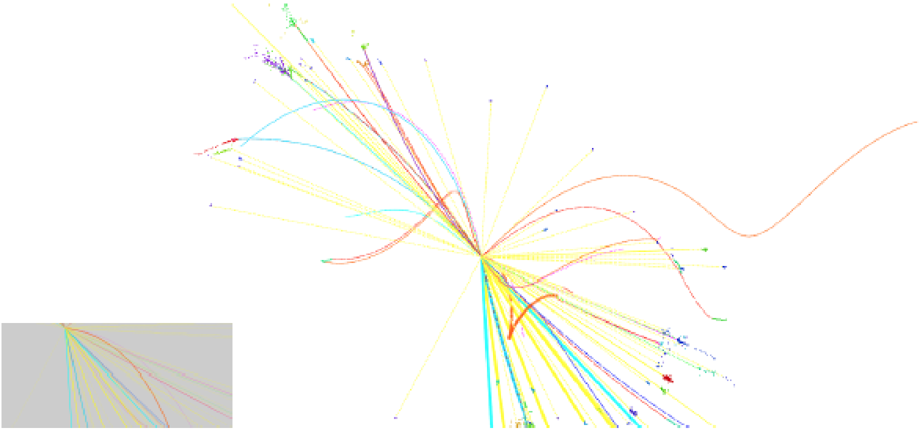
(a) $Z \to qq, H \to \tau\tau$ with two hadronic decay.



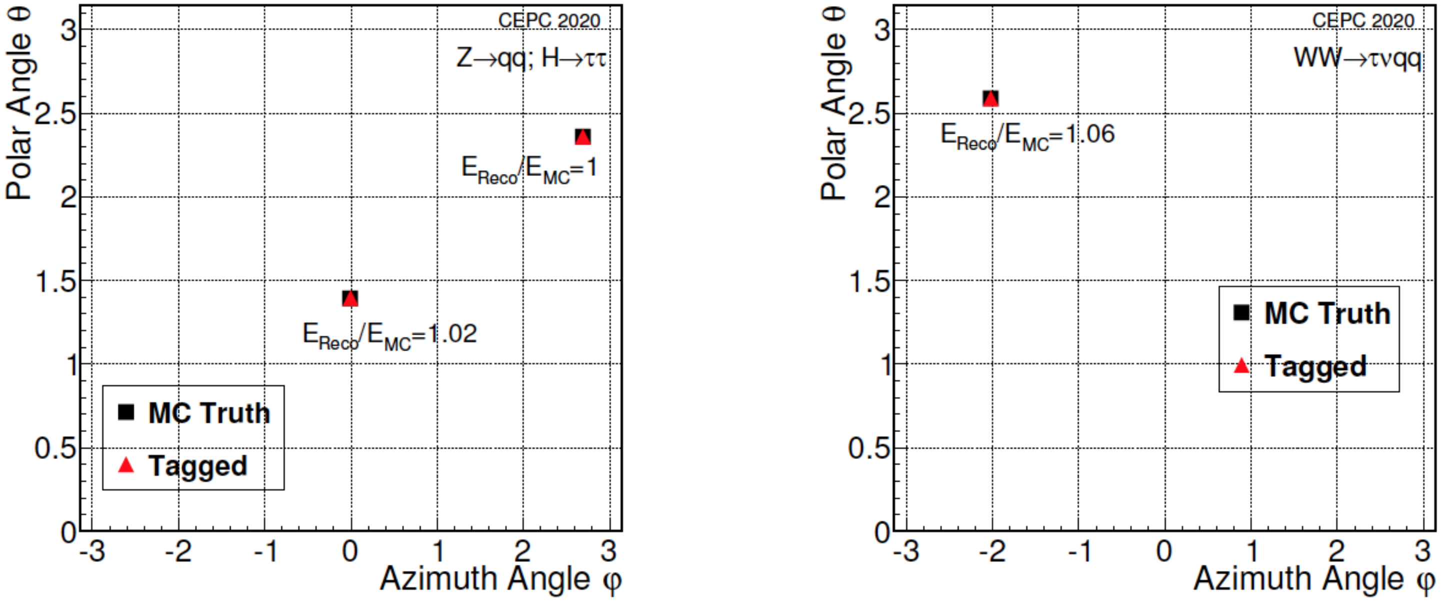
(b) $WW \to \tau\nu qq$ with one leptonic decay.



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

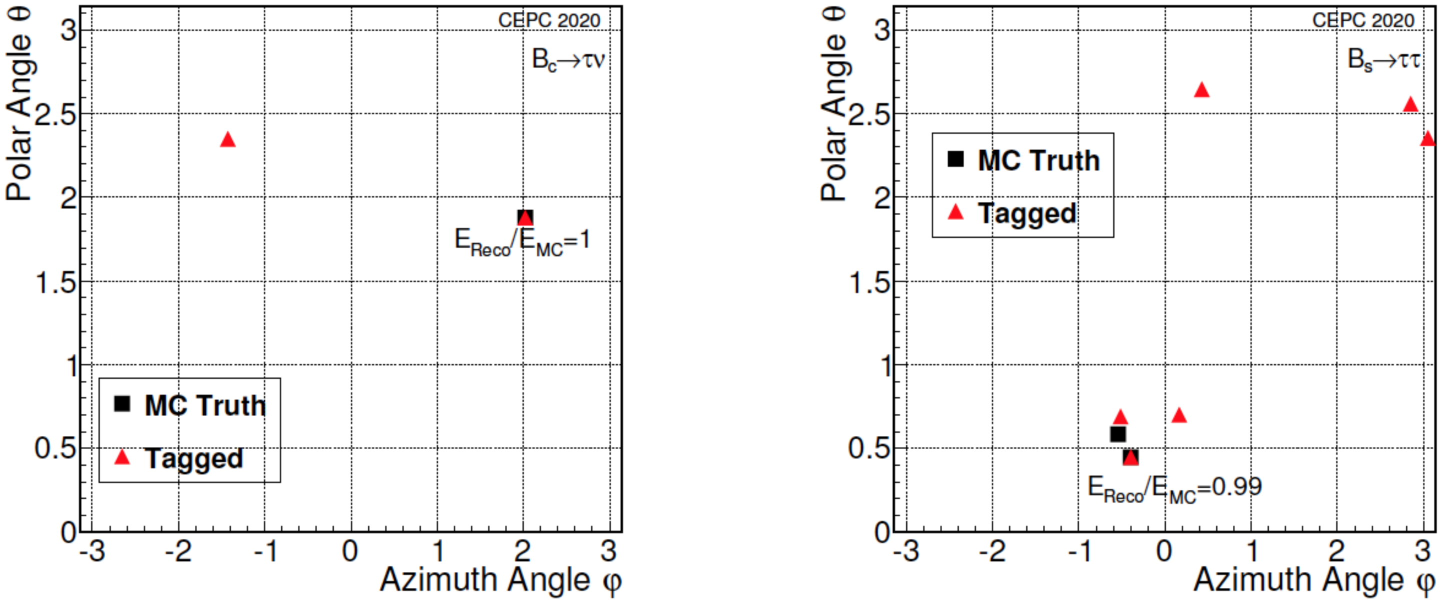


(d) $Z \to b\overline{b}, B_s \to \tau\tau$ with two hadronic decay mixed together.



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

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



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

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