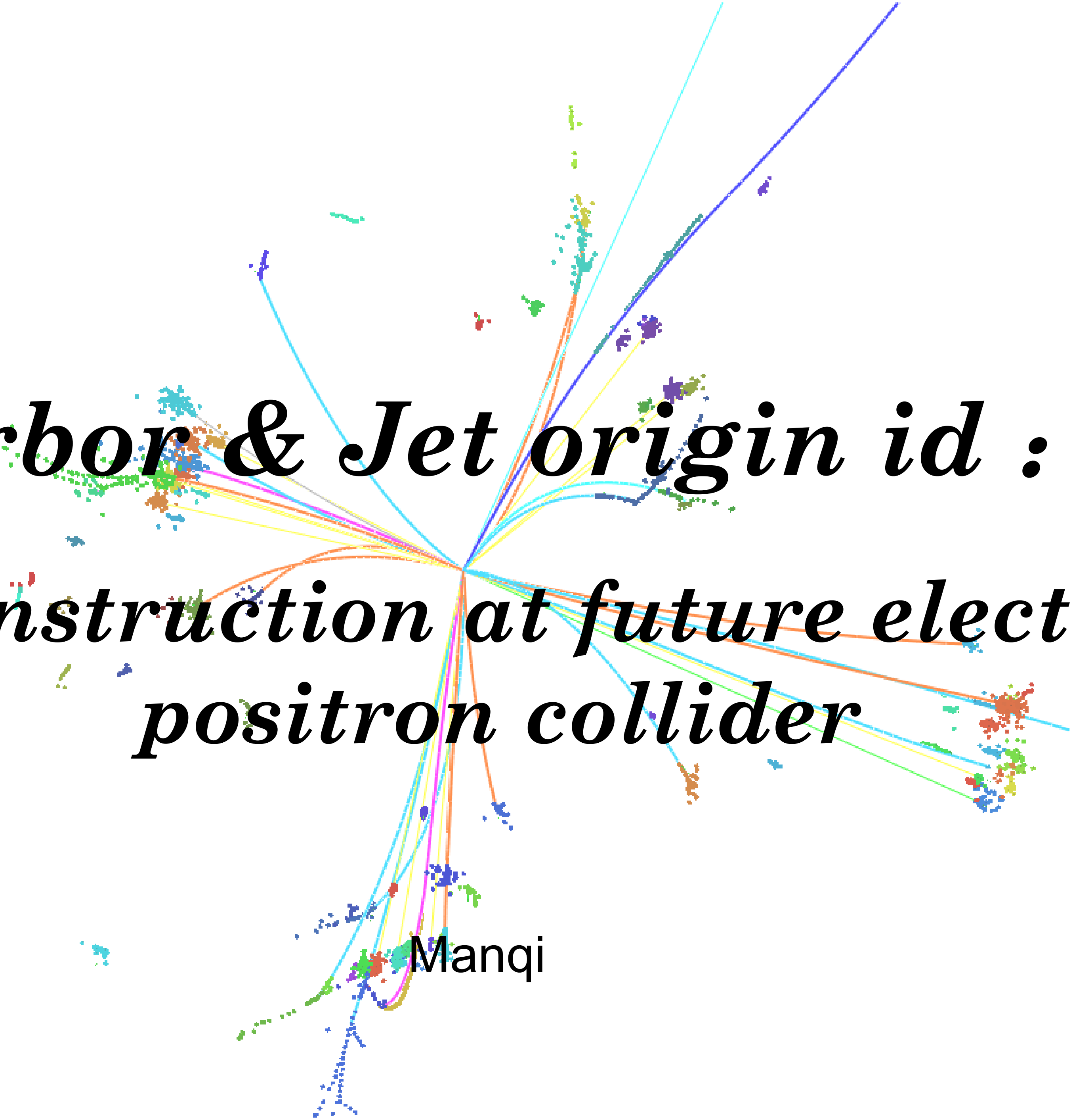


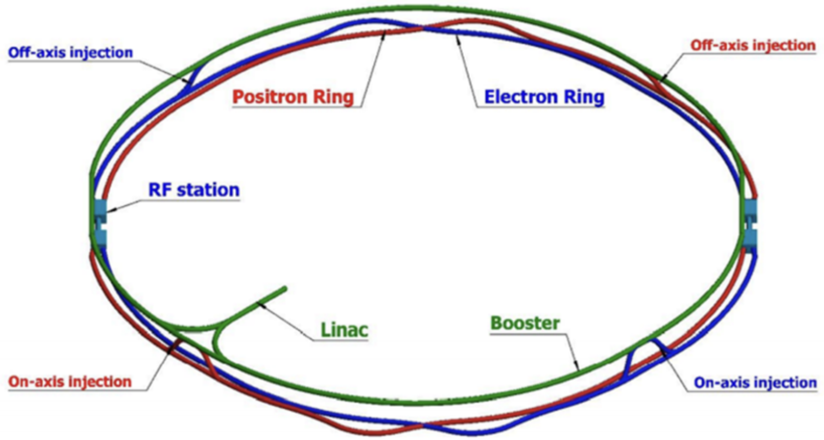
Arbor & Jet origin id : Reconstruction at future electron positron collider

Manqi

A brief introduction to CEPC

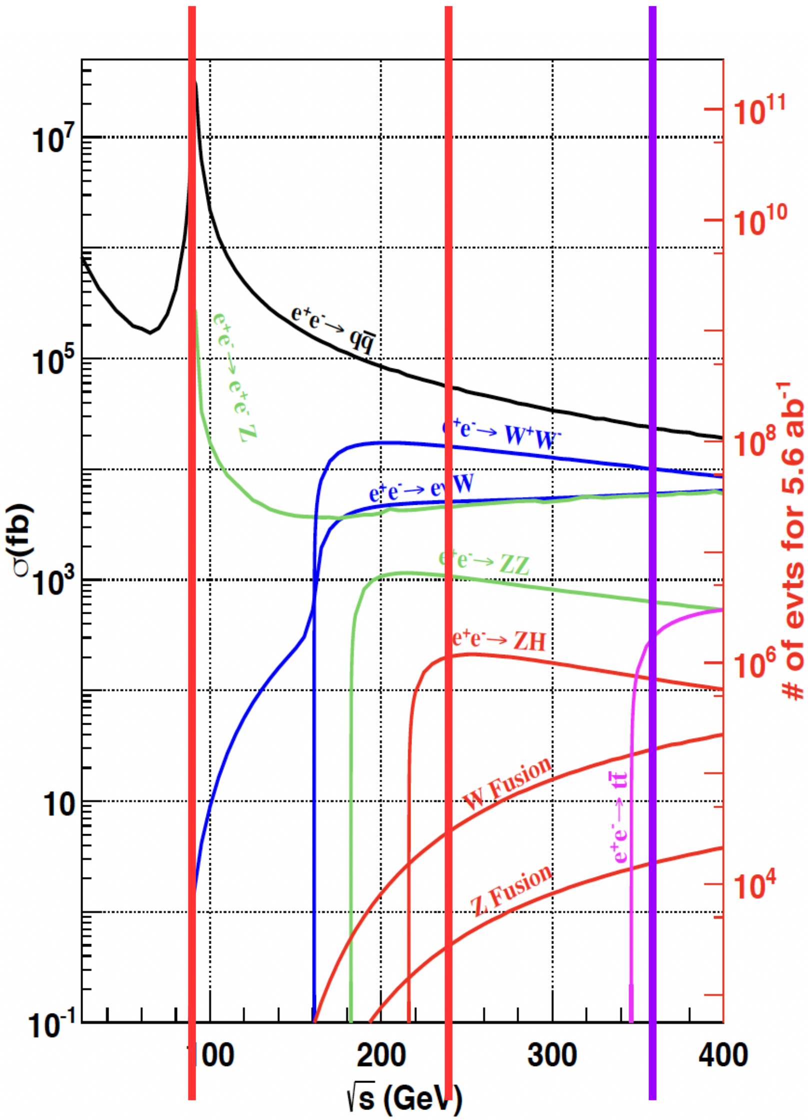
- CEPC: an e^+e^- Higgs factory producing H and W/ Z bosons and top quarks
  aims at discovering new physics beyond the Standard Model
  - CEPC + SppC complex proposed in 2012 right after the Higgs discovery
  - Conceptual Design Report delivered in Nov. 2018, 1st for circular ee Higgs factory
  - R&D reaching maturity, accelerator TDR published at 2023, high-impact innovations

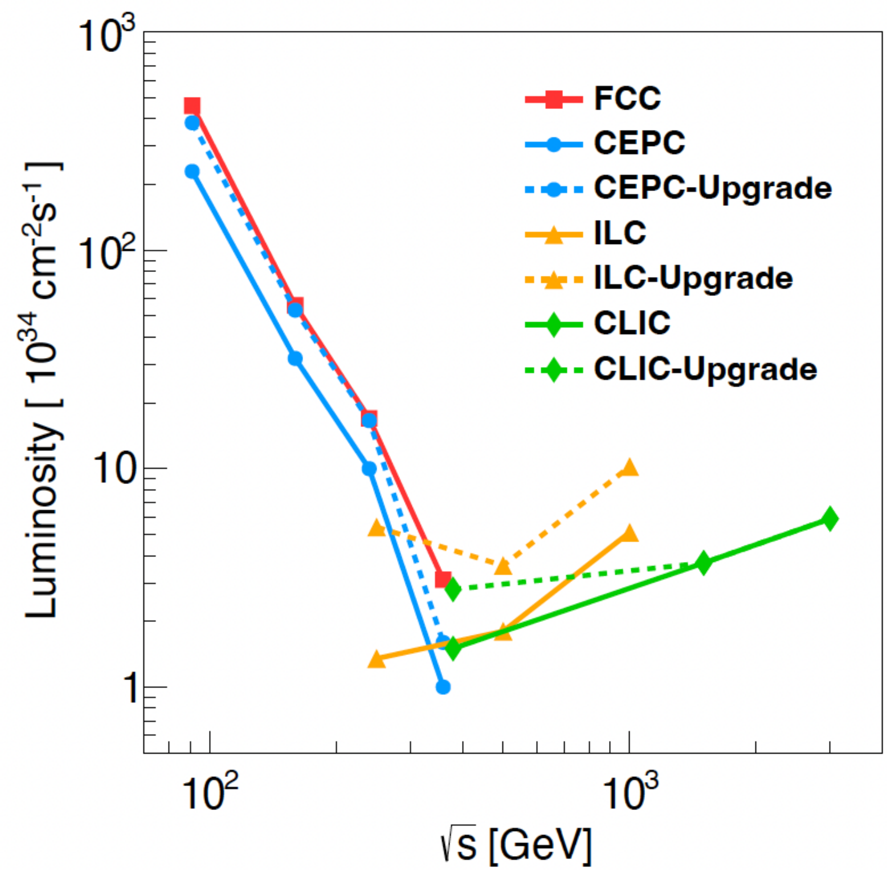
- Proposed to commence the construction in ~2026
  to deliver Higgs data in 2030s



CEPC circumference ~ 100km

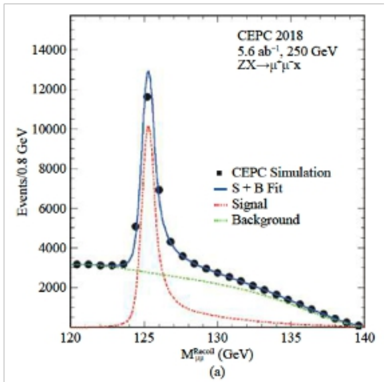
Yields ~ Xsec * Lumi * Time

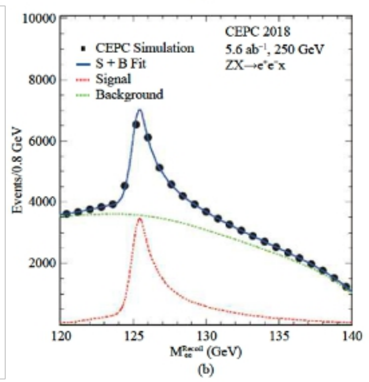


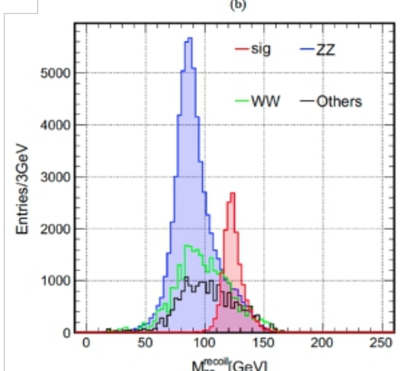


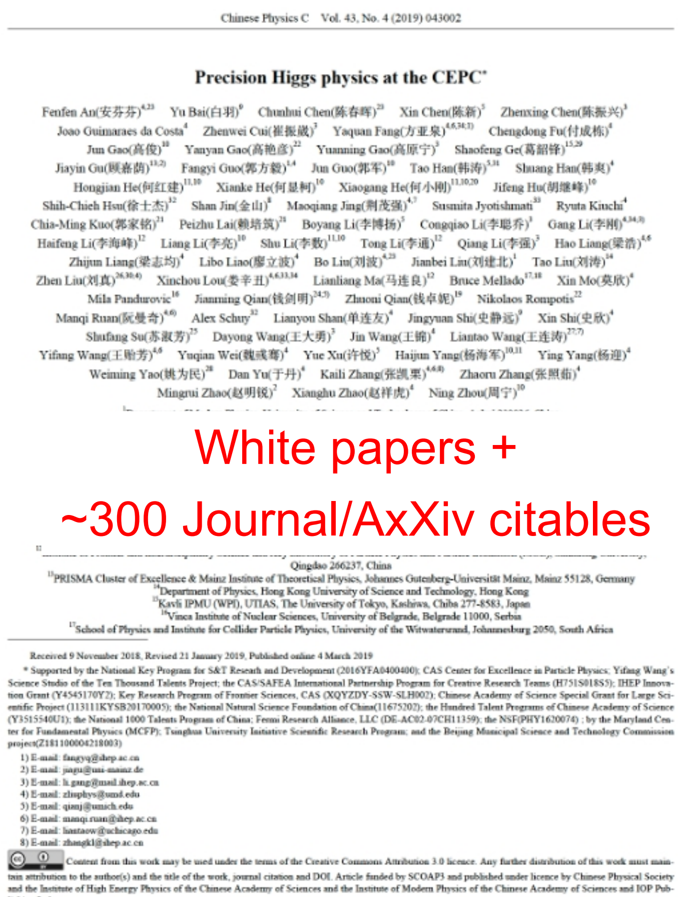
- 4 Million Higgs (10 years)
- ~ 1 Giga W (1 year) + 4 Tera Z (2 years)
- Upgradable: Top factory (500 k ttbar)

Physics study: 2023








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

Precision Higgs physics at the CEPC*

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

White papers +

~300 Journal/AxXiv citables

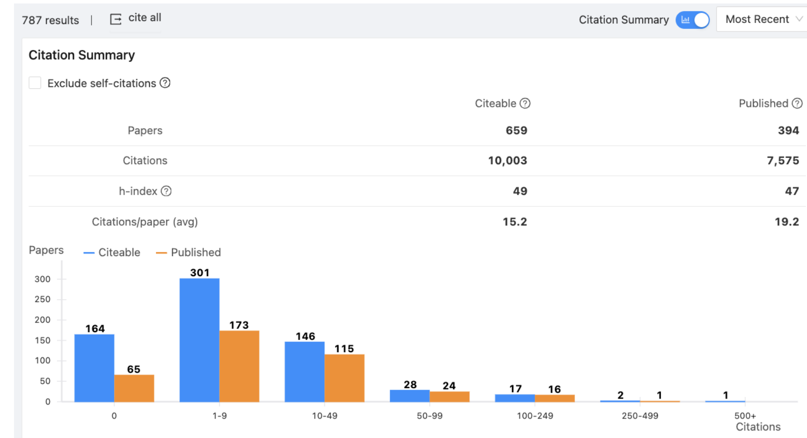


Table 2.1: Precision of the main parameters of interests and observables at the CEPC, from Ref. [1] and the references therein, where the results of Higgs are estimated with a data sample of 20 ab^{-1}. The HL-LHC projections of 3000 fb^{-1} data are used for comparison. [2]

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

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

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

Scientific objectives, significance, and strategic value

The scientific importance and strategical value of an electron positron Higgs factory is clearly identified.

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clear consensus in HEP community

*2013, 2016: **the CEPC is the best approach** and a major historical opportunity for the national development of accelerator-based high-energy physics program.*

2020 European Strategy Update

An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

Report of the Particle Physics Project Prioritization Panel 2023

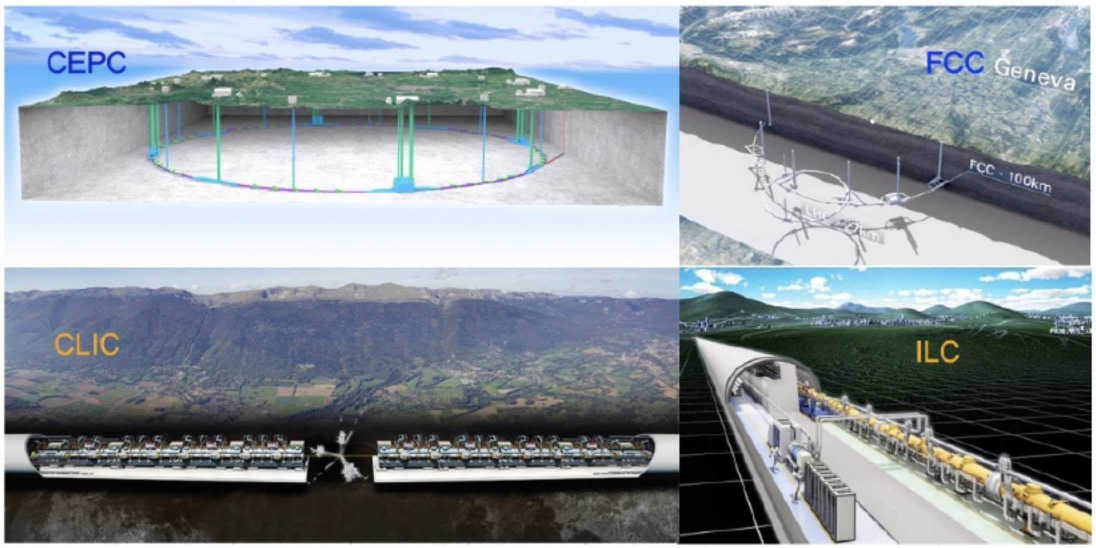
The panel would consider the following:

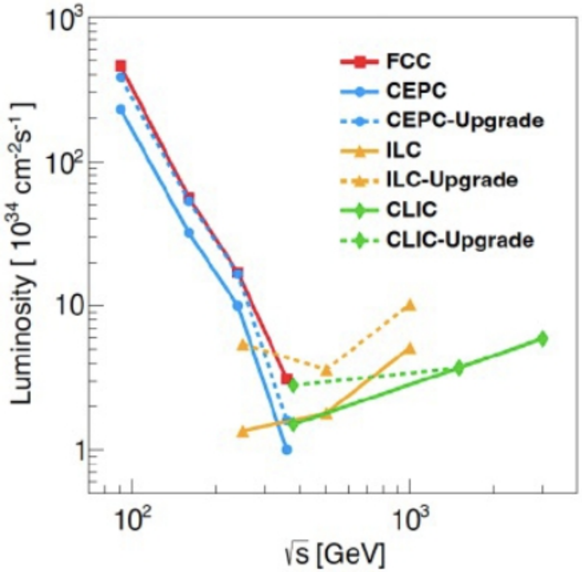
1. The level and nature of **US contribution in a specific Higgs factory** including an evaluation of the associated schedule, budget, and risks once crucial information becomes available.
2. Mid- and large-scale **test and demonstrator facilities** in the accelerator and collider R&D portfolios.
3. A plan for the evolution of the **Fermilab accelerator complex** consistent with the longterm vision in this report, which may commence construction in the event of a more favorable budget situation.

ICFA

*In April 2022, the International Committee for Future Accelerators (ICFA) "reconfirmed the international consensus on the importance of **a Higgs factory as the highest priority for realizing the scientific goals of particle physics**", and expressed support for the above-mentioned Higgs factory proposals. Recently, the United States also proposed a new linear collider concept based on the cool copper collider (C3) technology [31].*

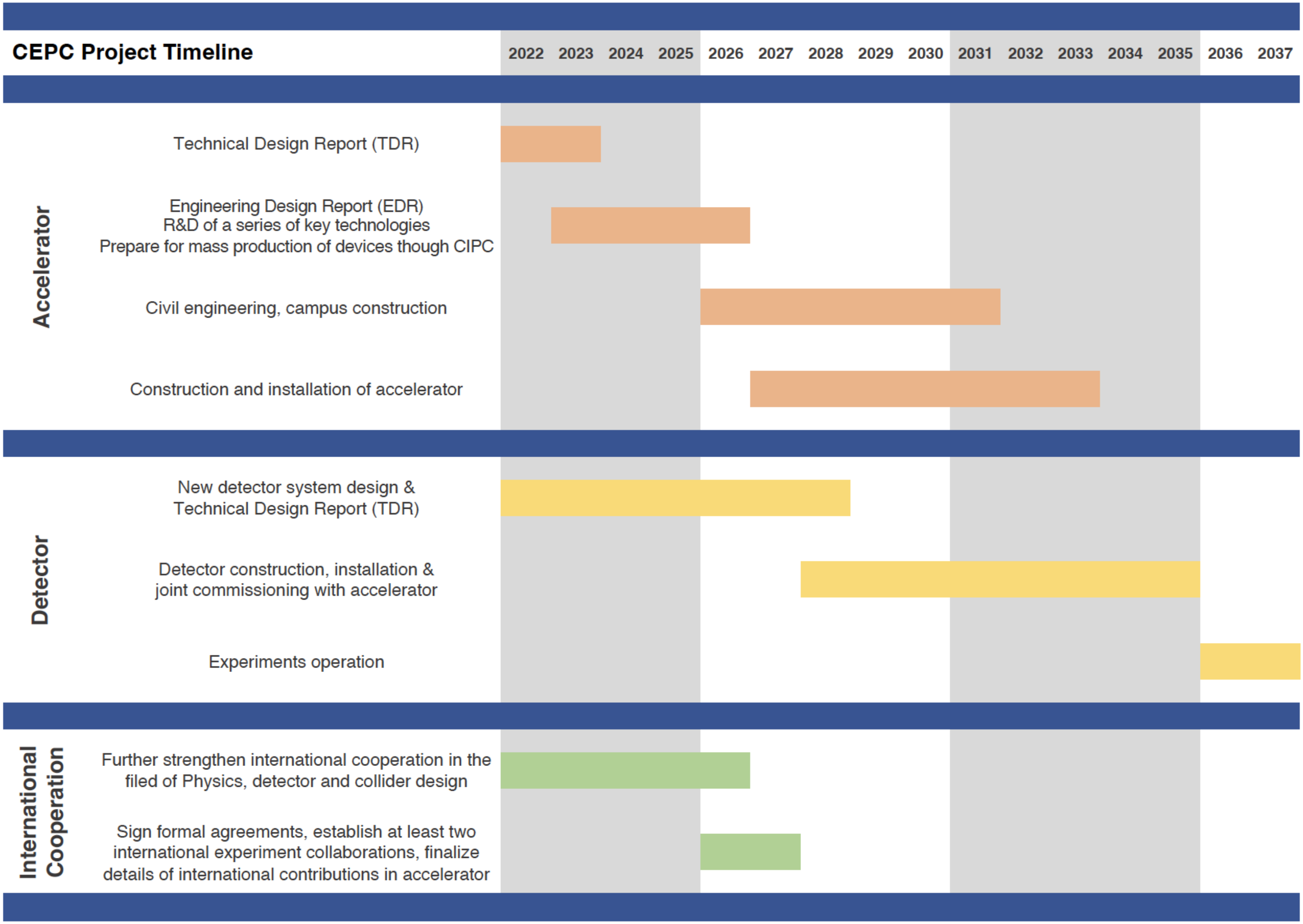
International competition & Comparative advantages





- Electron-positron Higgs factories identified as top priority for future collider (ESPPU).
- CEPC has strong advantages among mature electron-positron Higgs factories (design report delivered),
  - **Earlier data**: collision expected in 2030s (vs. FCC-ee ~ 2040s), **larger tunnel cross section** （ee, pp coexistence)
  - **Higher precision** vs. linear colliders with more Higgs & Z; potential for **proton collider upgrade**.
  - **Lower cost** vs. FCC-ee, ~1/2 the construction cost with similar luminosity up to 240 GeV.
- CEPC is well recognized in particle physics world, as a major choice for the future flagship facility.

CEPC Timeline

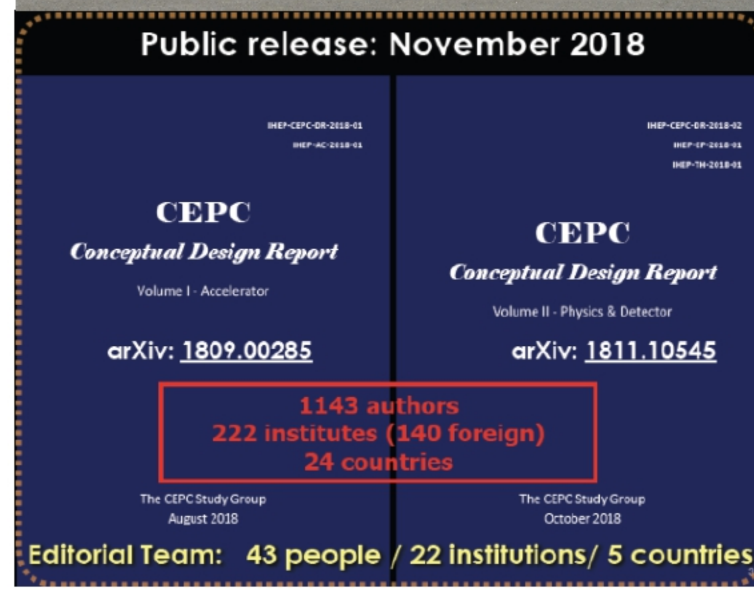


CEPC Major Milestones

CEPC-SPPC Kickoff (2013.9)

First CEPC IAC Meeting (2015.9)

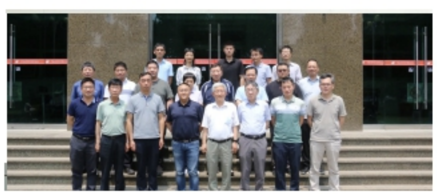
CEPC CDR Released (2018.11)



CEPC Major Milestones

CEPC Accelerator TDR Review
June 12-16, 2023, Hong Kong

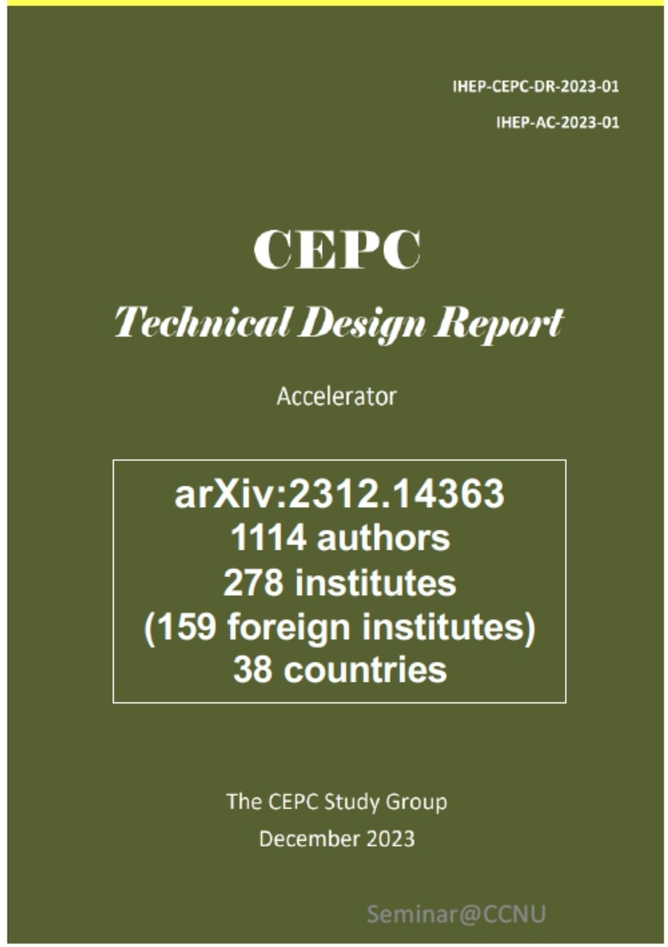
CEPC Accelerator TDR Cost Review
Sept. 11-15, 2023, Hong Kong



Domestic Civil Engineering
Cost Review, June 26, 2023, IHEP

9th CEPC IAC 2023 Meeting
Oct. 30-31, 2023, IHEP

CEPC Accelerator TDR released in December, 2023



IHEP-CEPC-DR-2023-01
IHEP-AC-2023-01

CEPC
Technical Design Report
Accelerator

arXiv:2312.14363
1114 authors
278 institutes
(159 foreign institutes)
38 countries

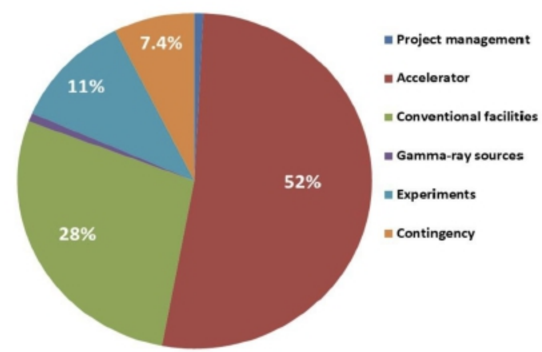
The CEPC Study Group
December 2023

Seminar@CCNU

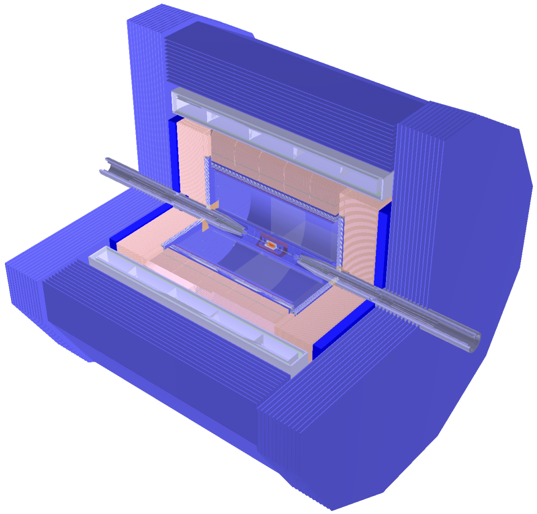
Distribution of CEPC Project TDR cost of 36.4B RMB (~4.7B Euro)

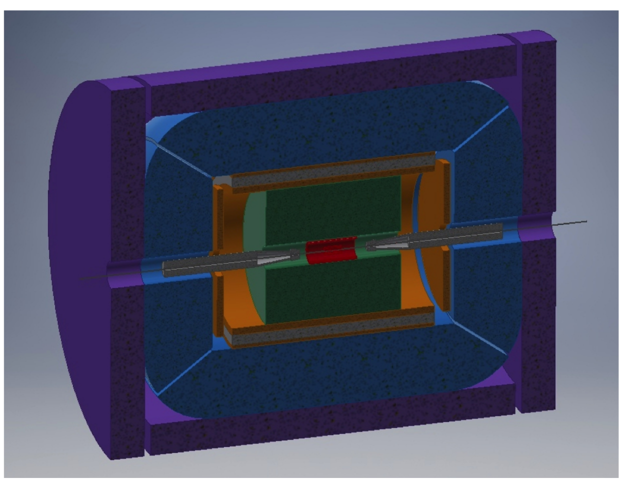
Table 12.1.2: CEPC project cost breakdown, (Unit: 100,000,000 yuan)

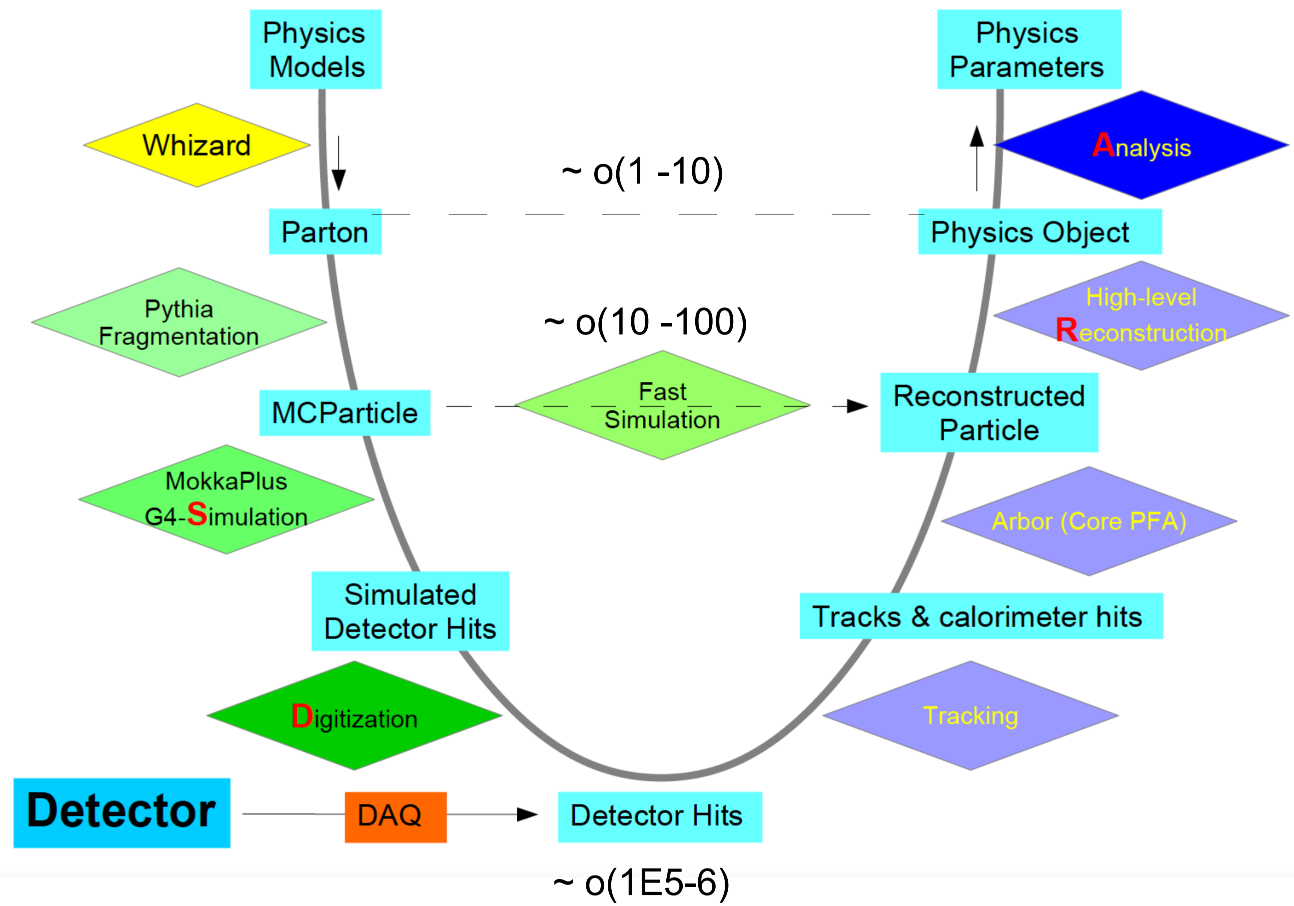
Total	364	100%
Project management	3	0.8%
Accelerator	190	52%
Conventional facilities	101	28%
Gamma-ray beam lines	3	0.8%
Experiments	40	11%
Contingency (8%)	27	7.4%



CEPC Detector & Reconstruction



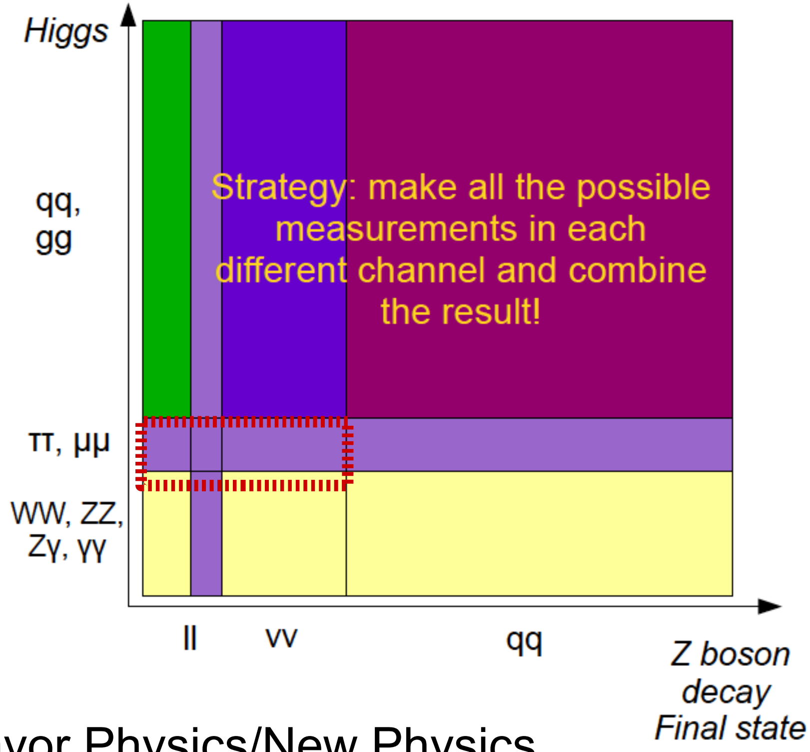




Full simulation reconstruction Chain with Arbor, iterating/validation with hardware studies

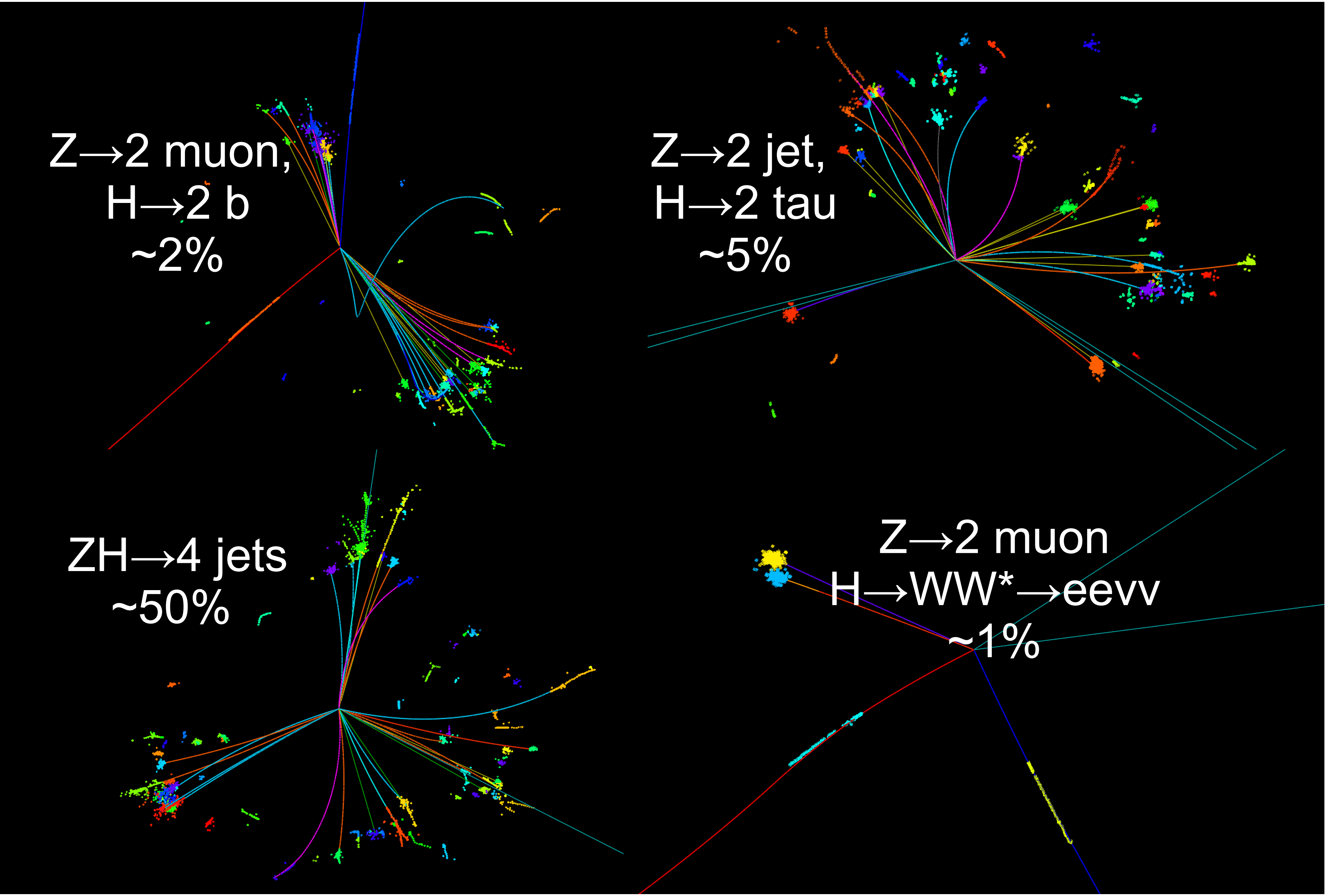
Performance requirements

- Massive Four in Standard Model:
  - Z & W: ~ 70% goes to a pair of jets
  - Higgs: ~90% goes to jet final states
  - Top: t → W + B

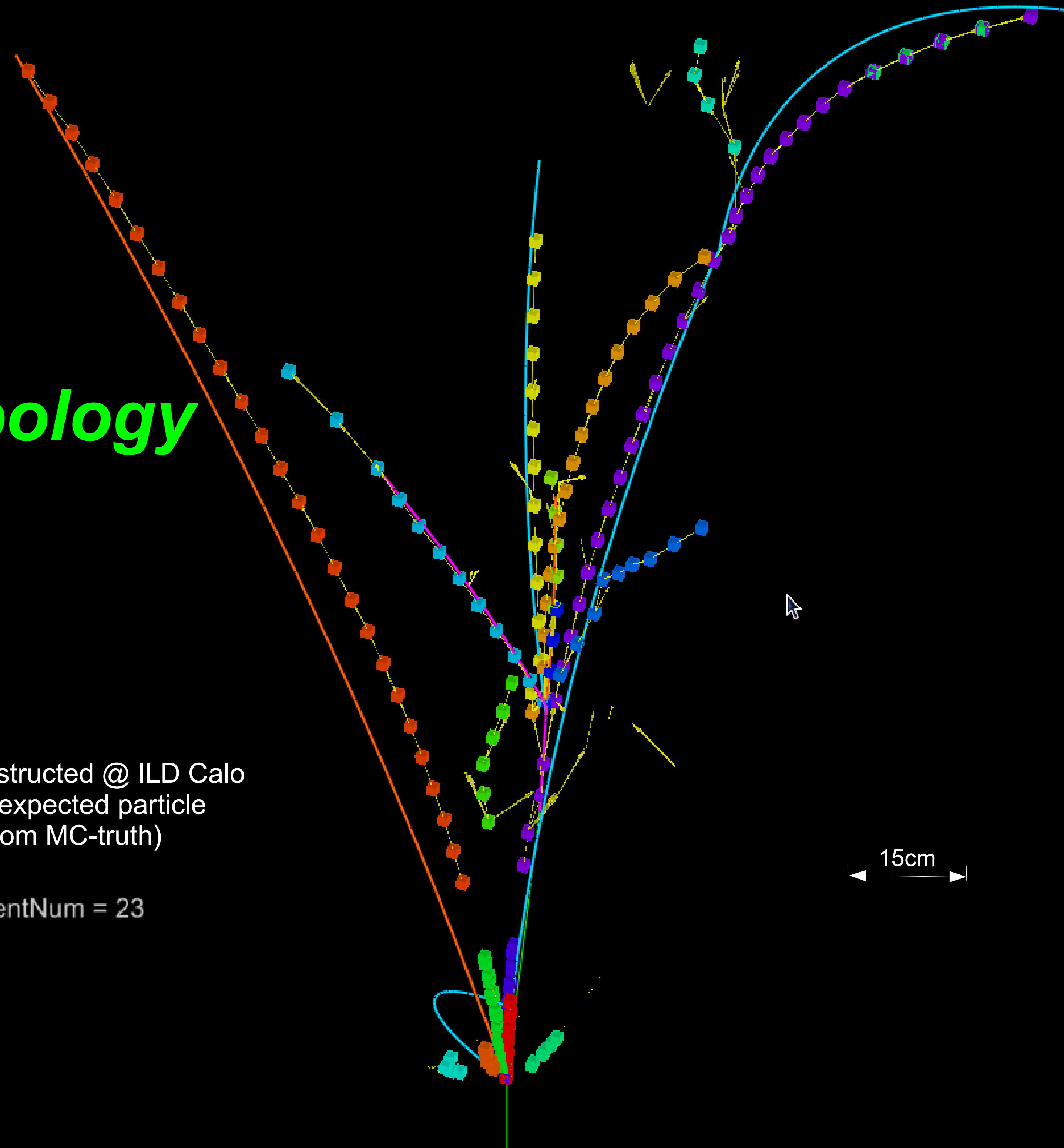


- Arbor: final state particle reconstruction
  - Particle flow, Pursuing 1-1 correspondence...
  - BMR < 4% for Higgs, much demanding for Flavor Physics/New Physics

- Jet origin id: jet ↔ colored SM particle reconstruction.
  - Flavor Tagging & Charge Reconstruction, s/light/gluon-tagging...


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

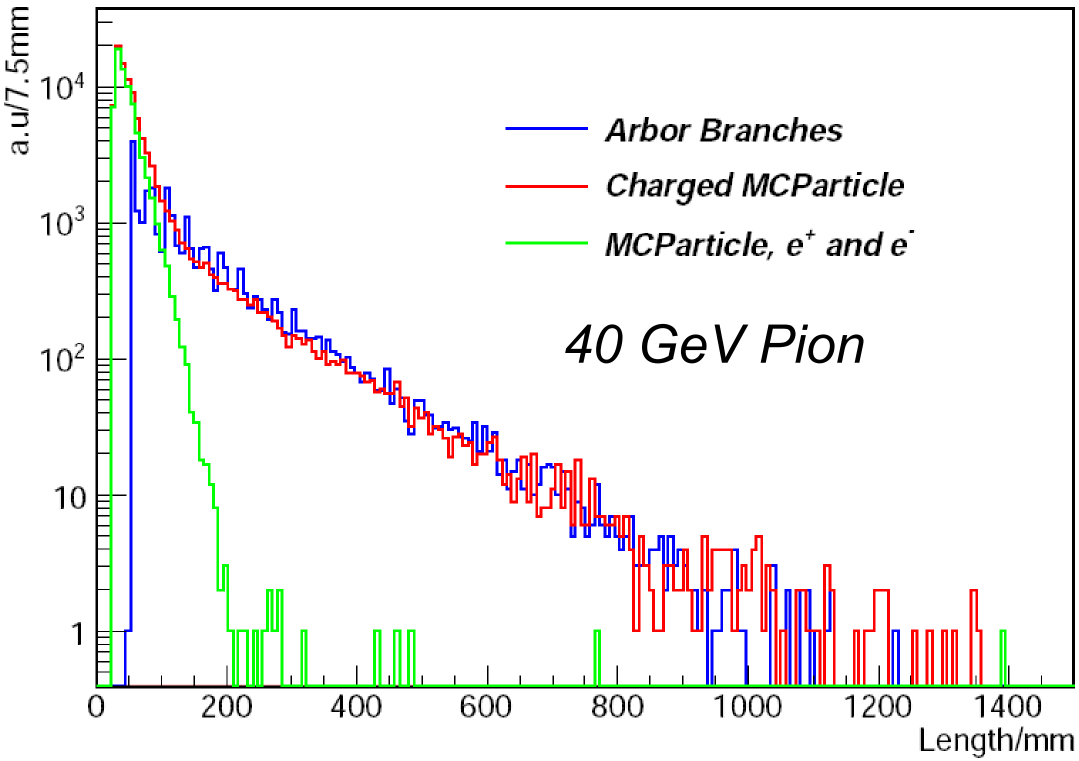
Tree Topology

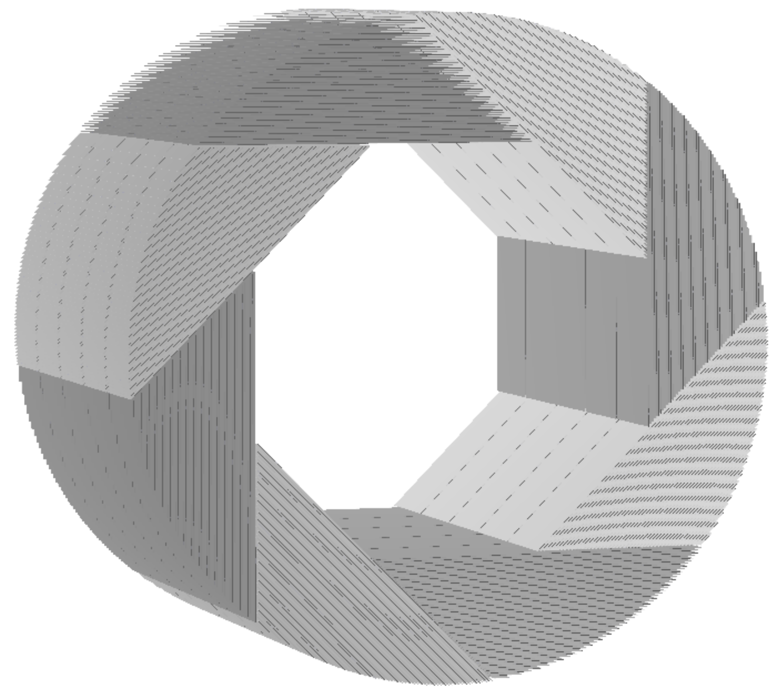


20 GeV Klong reconstructed @ ILD Calo
Curves indicating expected particle
trajectories (from MC-truth)

DRUID, RunNum = 0, EventNum = 23

Validation: Arbor Branch Length Vs MC Truth

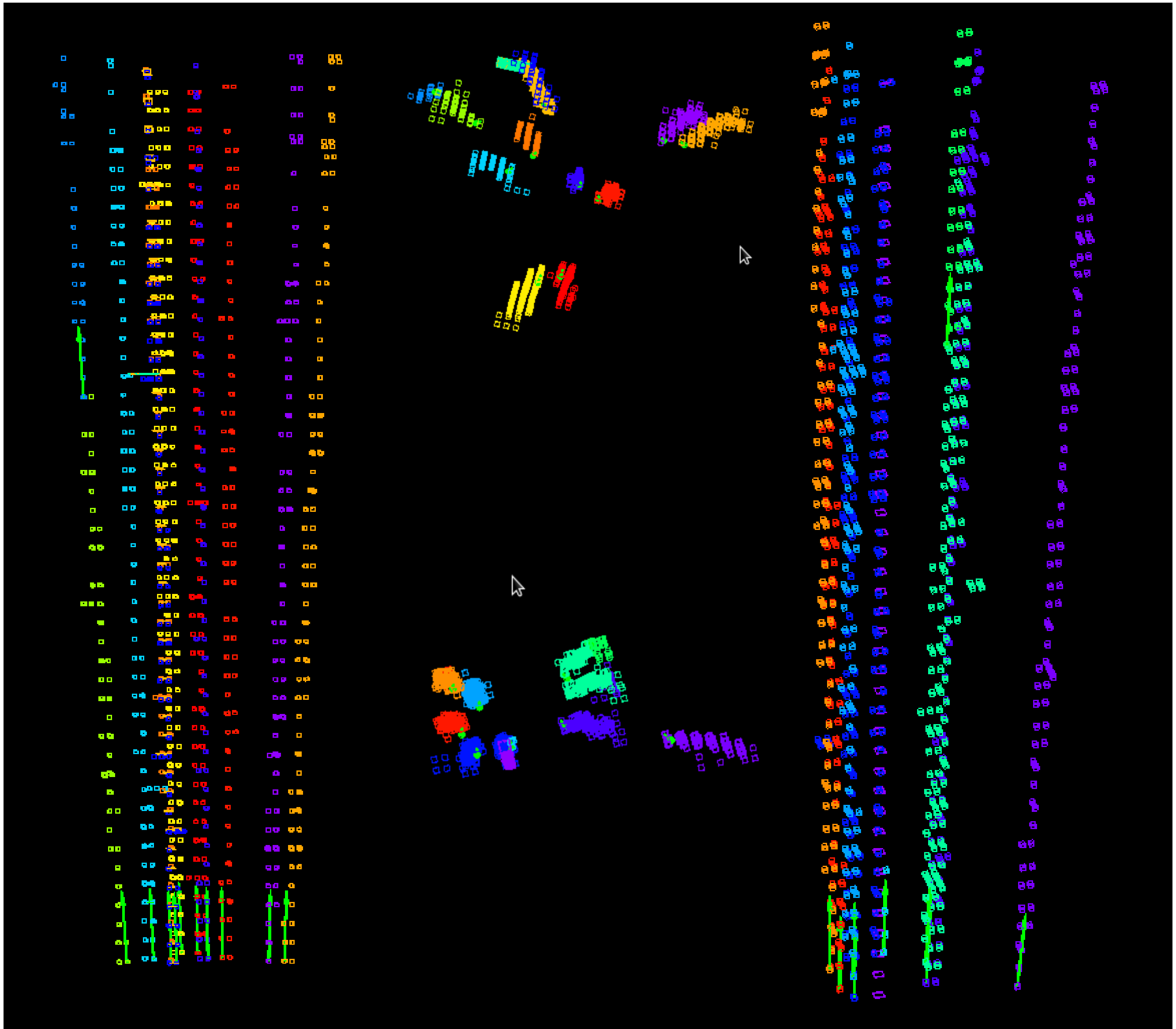


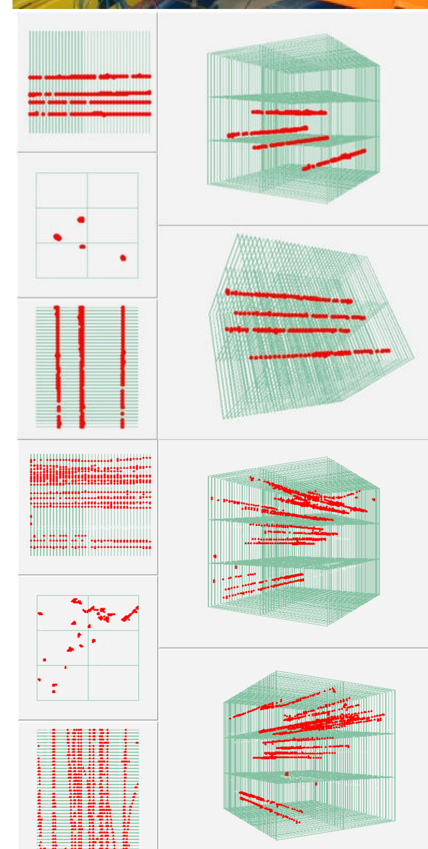


Arbor: successfully tag sub-shower structure

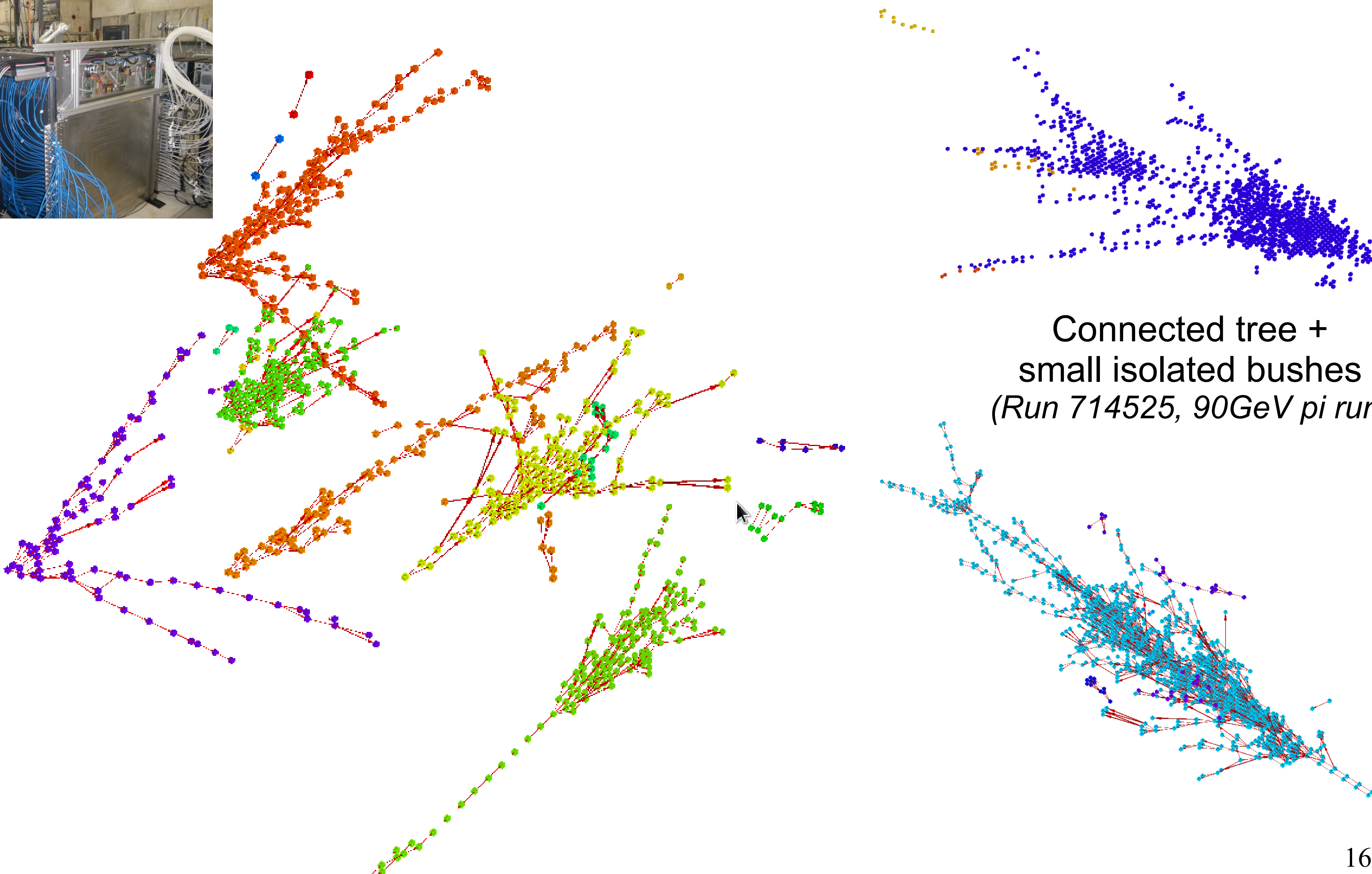
Samples: Particle gun event at ILD HCAL (readout granularity 1cm^2 & layer thickness 2.65cm)
Length:
Charged MCParticle: spatial distance between generation/end points
Arbor branch: sum of distance between neighboring cells

CALICE DHCAL TB & FermiLab, multi-muon



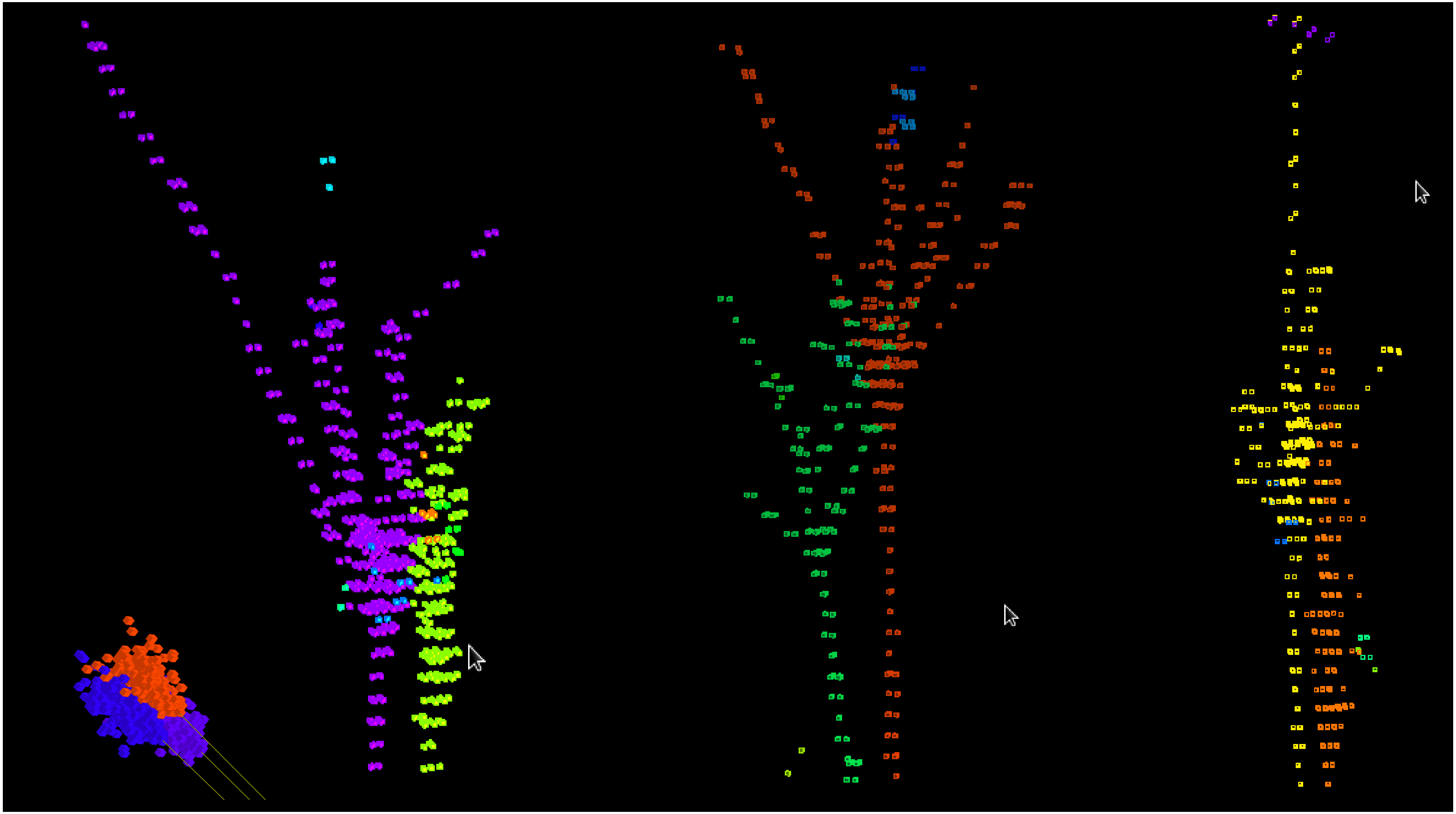


CALICE SDHCAL TB @ CERN: hadronic pre interaction



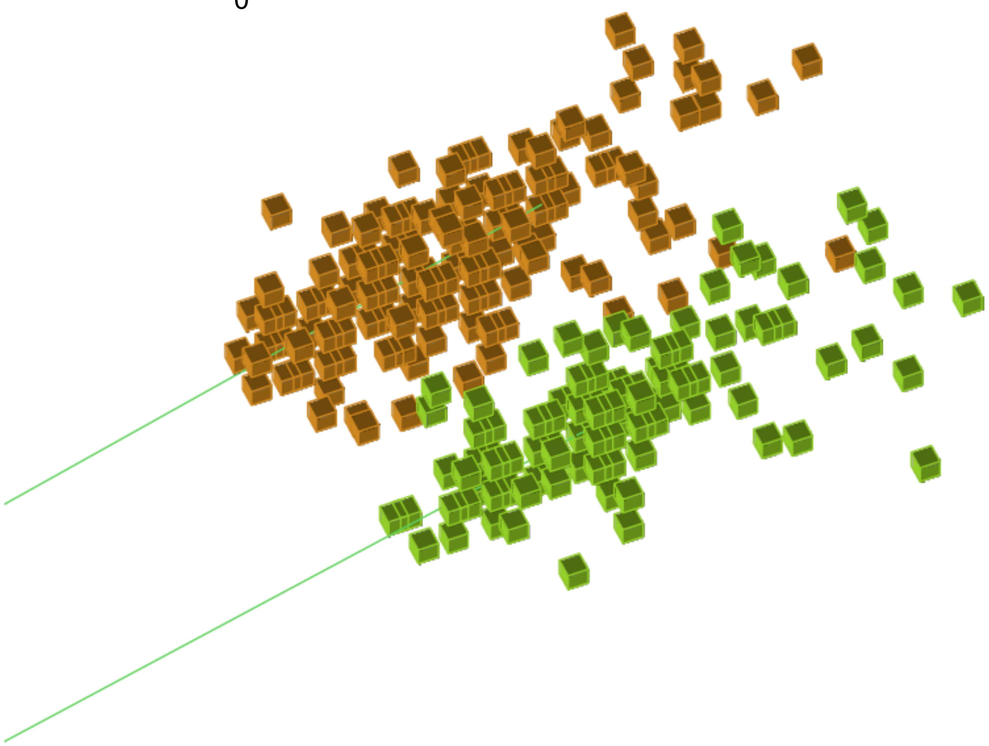
Connected tree +
small isolated bushes
(Run 714525, 90GeV pi run)

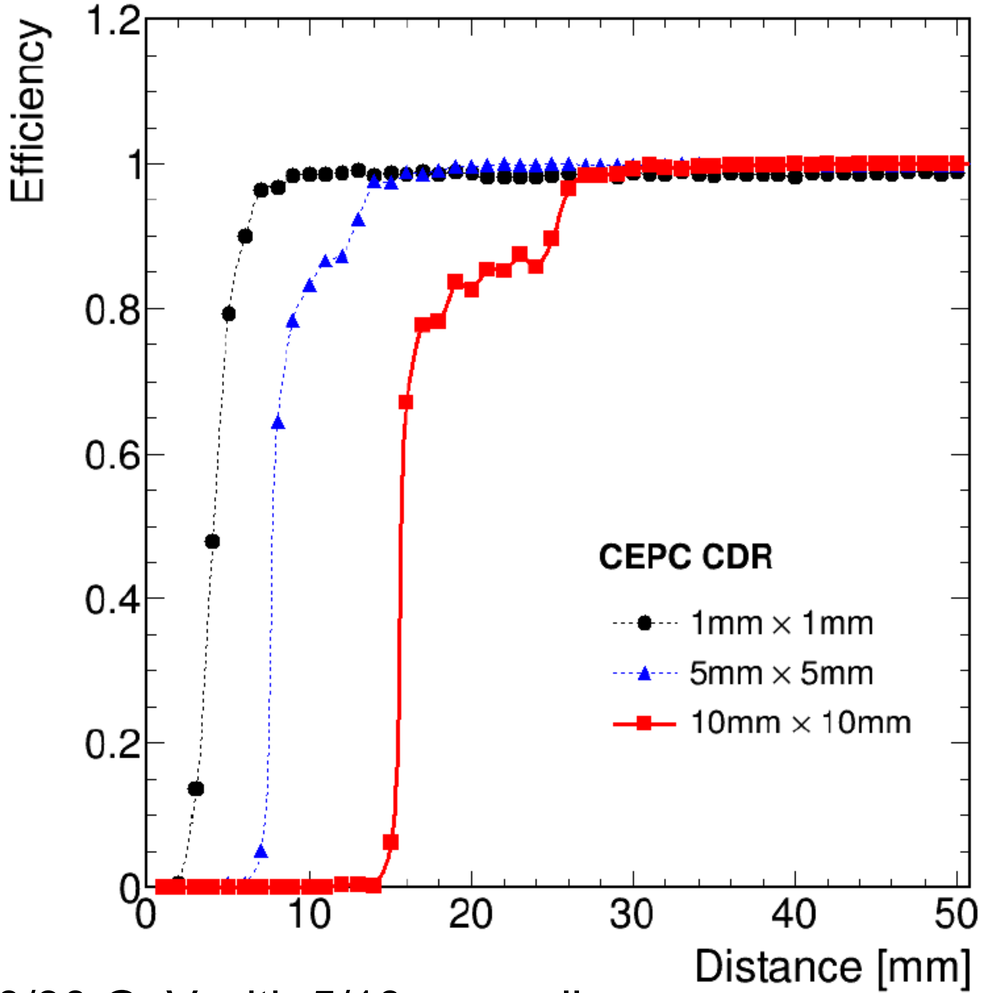
Simulation: nearby particle showers



Clustering - Separation

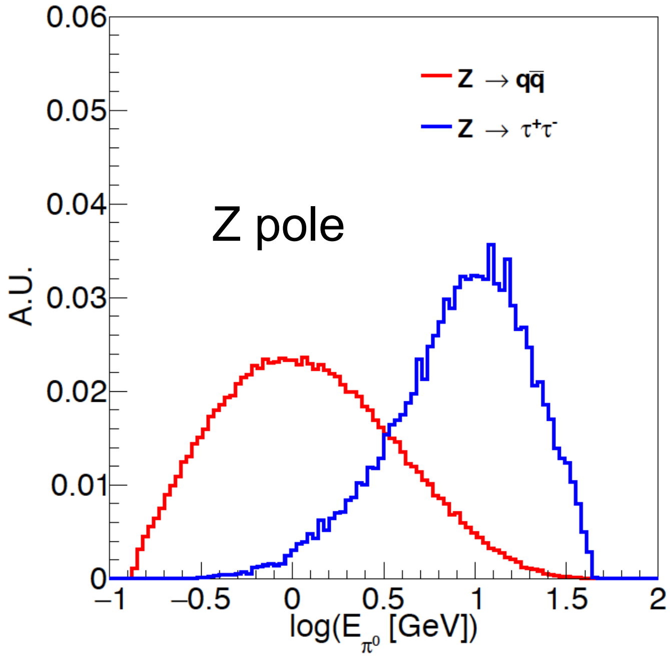
10 GeV π_0

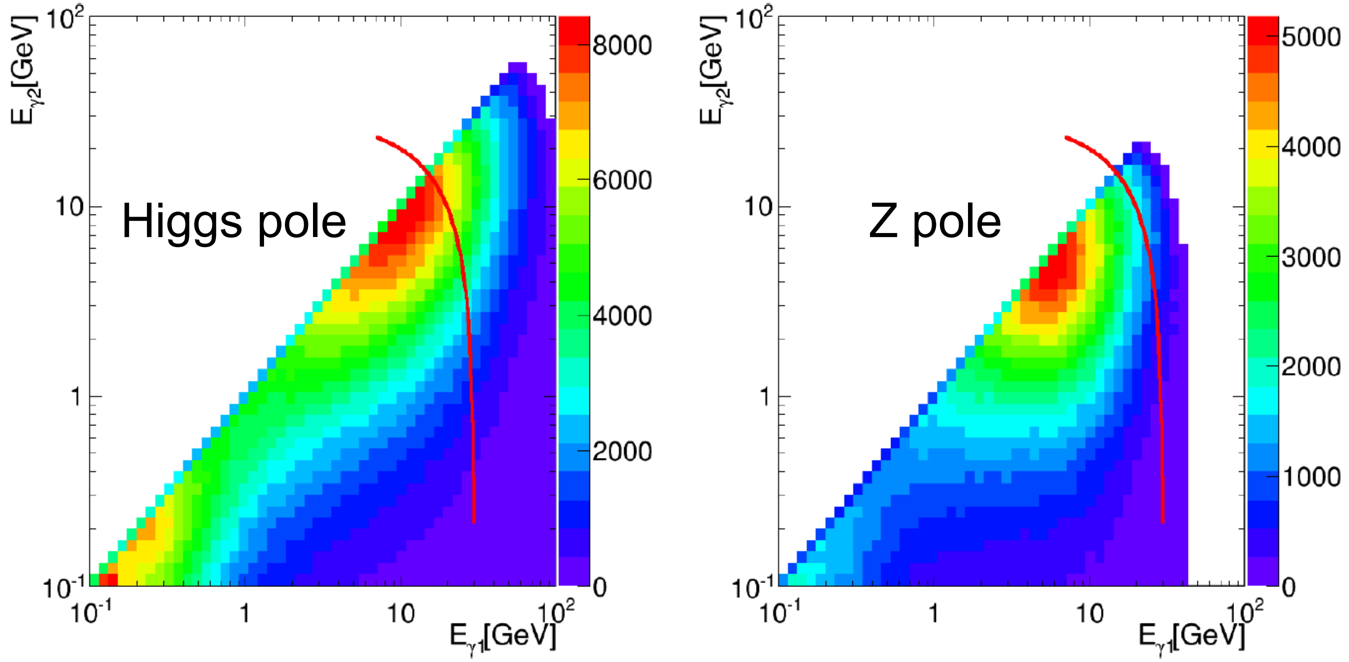




Critical energy to separate an evenly decay π_0: 60/30 GeV with 5/10 mm cell.

π^0: energy range



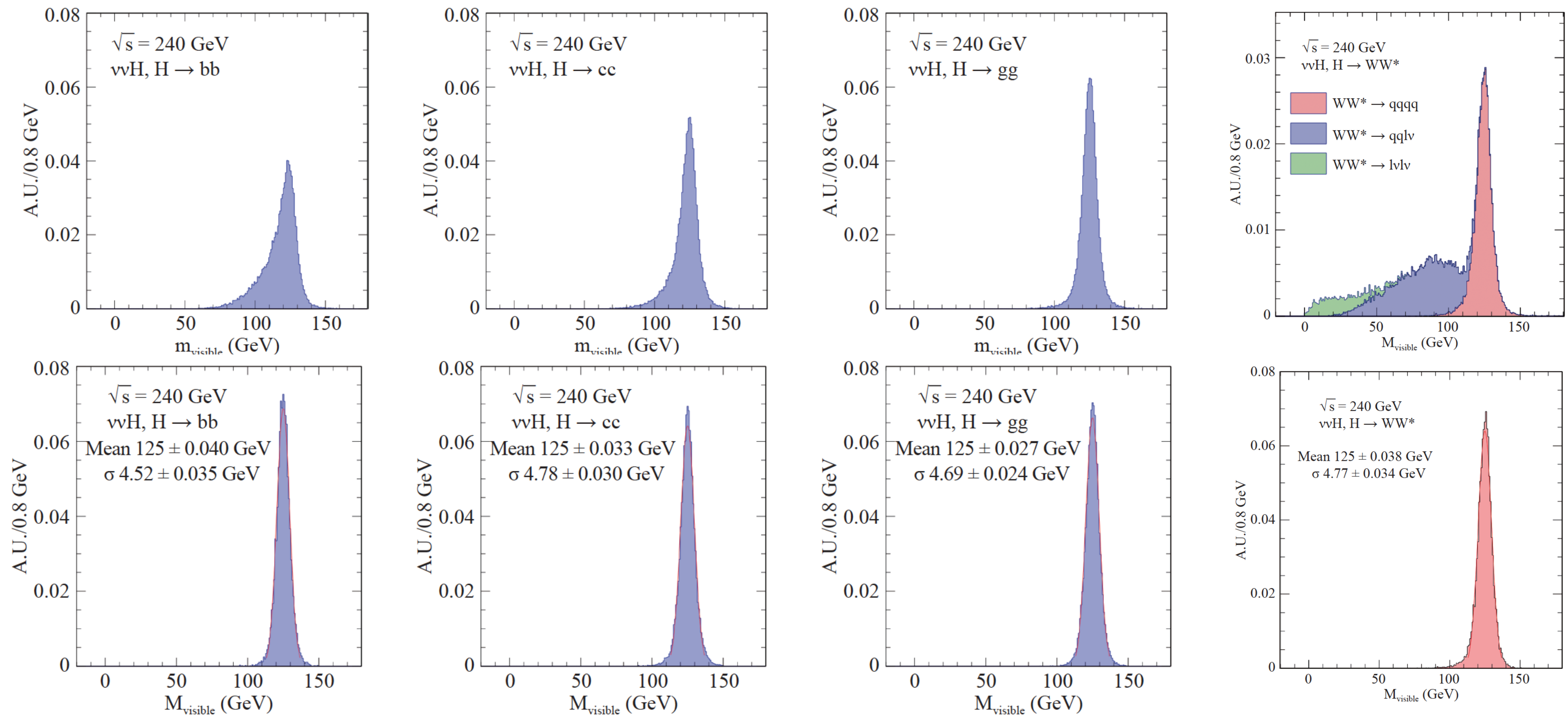


(a) (b)

Fig. 14: The generated π^0 distribution as a function of the energies of di-photons from $\pi^0 \to \gamma\gamma$ in inclusive Higgs (a) and $Z \to \tau\tau$ samples (b). $E_{\gamma 1}$ is the energy of the leading photon. $E_{\gamma 2}$ is the energy of the sub-leading photon. The red line is the function of $E_{\gamma 1} + E_{\gamma 2} = 30$ GeV.

- π^0 energy (rest-mass, 30 GeV – 60 GeV): photon threshold ~ o(100) MeV
- At Z pole: be able to separate photons from Pi-0 decay, up to 30 GeV

BMR: no significant dependence on #jets...



Fi

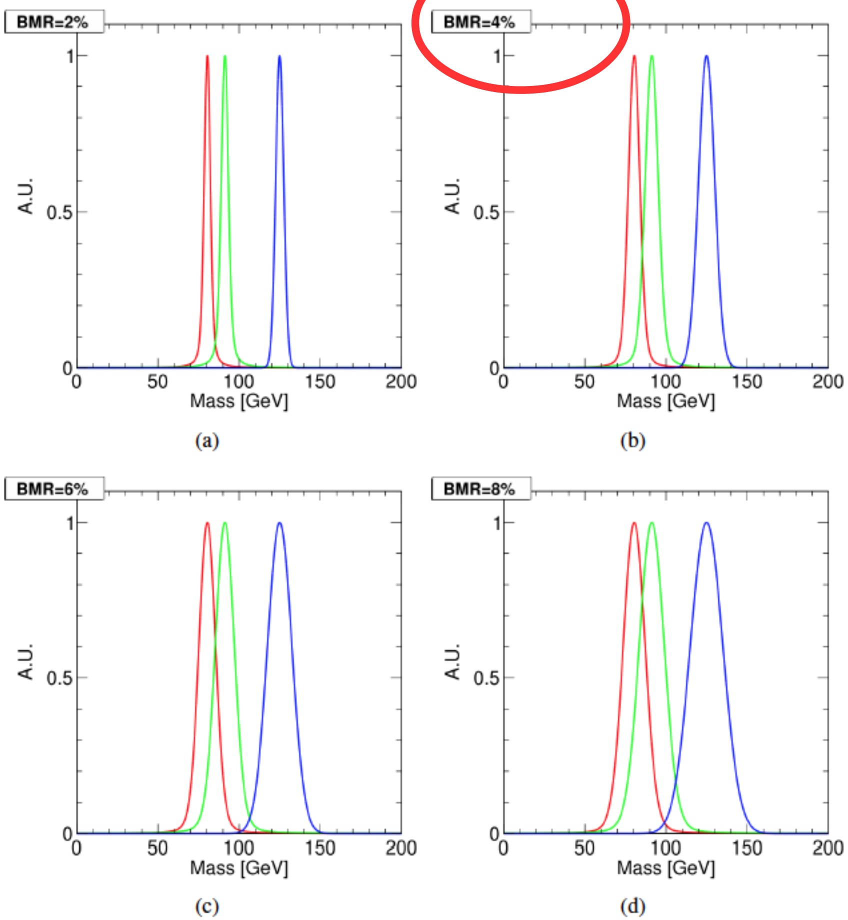
Table 1. Event cumulative efficiency for Higgs boson exclusive decay at the CEPC with $\sqrt{s} = 240$ GeV.

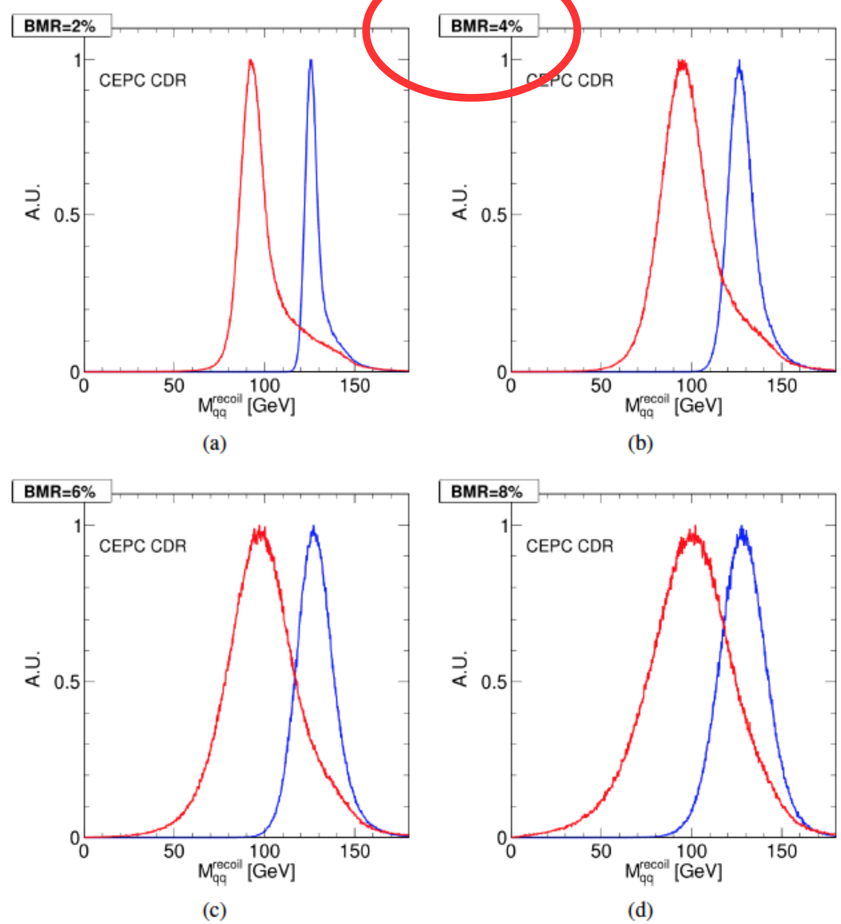
	gg(%)	*bb*(%)	*cc*(%)	*WW**(%)	*ZZ** (%)
Pt_ISR < 1 GeV	95.15	95.37	95.30	95.16	95.24
Pt_neutrino < 1 GeV	89.33	39.04	66.36	37.46	41.39
|Cos(Theta_Jet)| < 0.85	67.30	28.65	49.31	–	–

Table 3. Higgs boson mass resolution (sigma/Mean) for different decay modes with jets as final state particles, after event cleaning.

$H \to bb$	$H \to cc$	$H \to gg$	$H \to WW^*$	$H \to ZZ^*$
3.63%	3.82%	3.75%	3.81%	3.74%

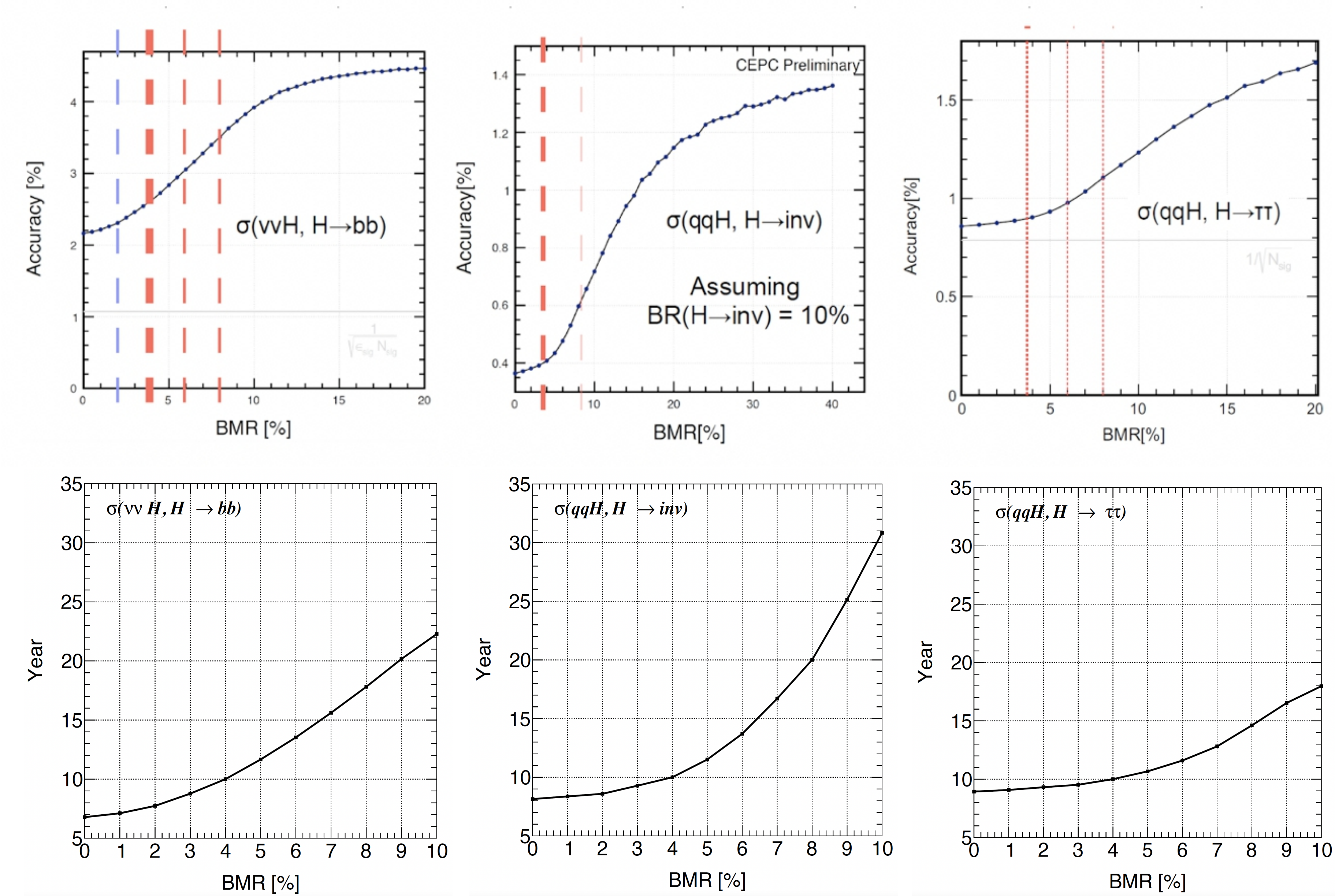
BMR < 4% required...



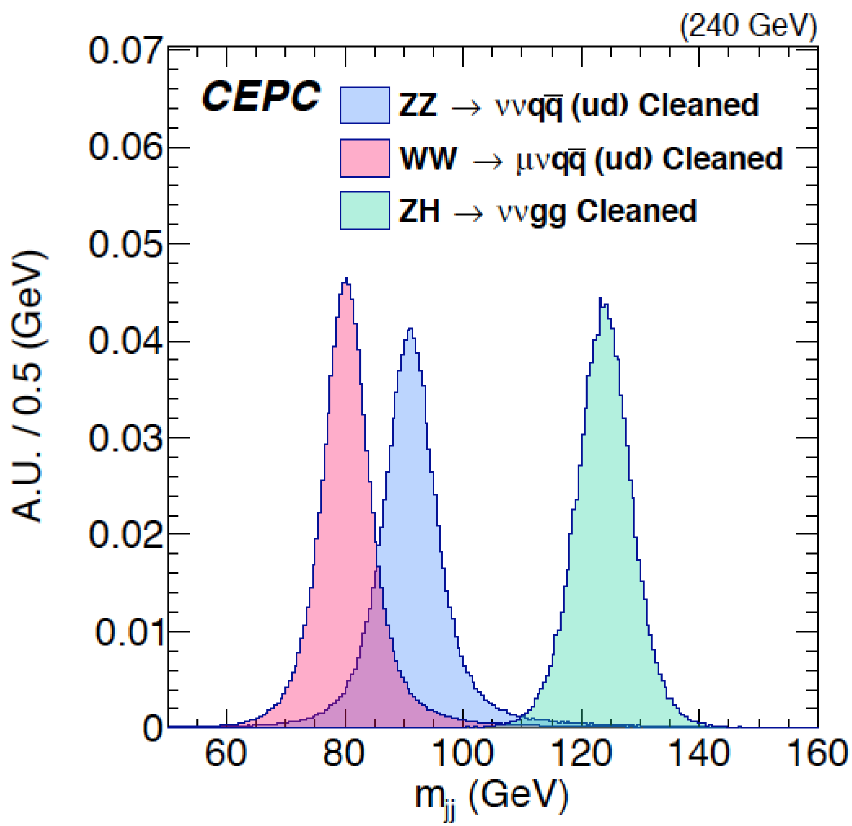


- W, Z, H mass peak separation
- To separate qqH signal from qqX background with recoil mass information

BMR: impact on critical measurements



CEPC Baseline: BMR = 3.75%



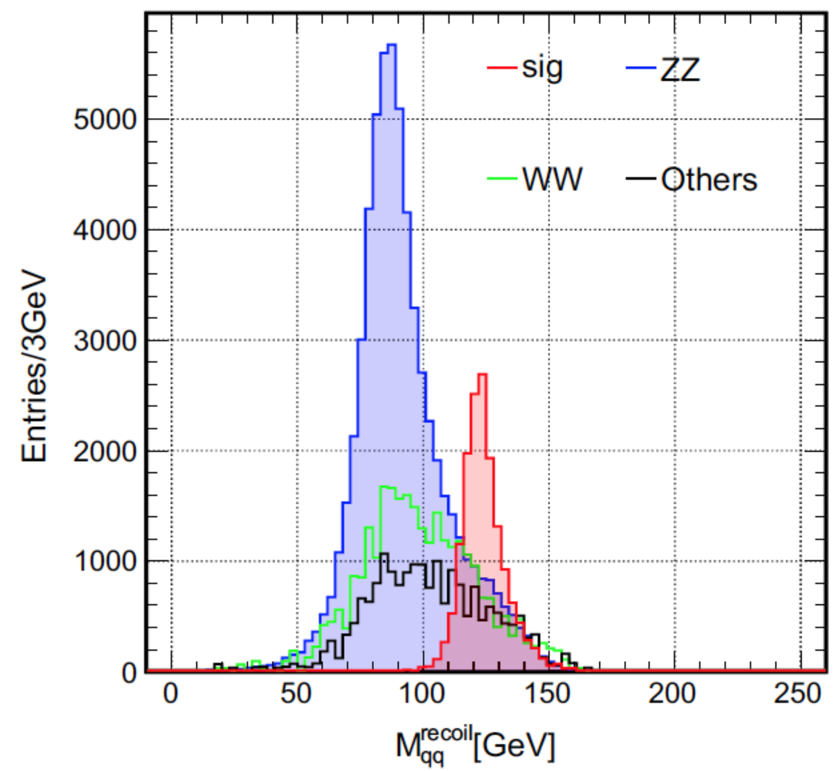
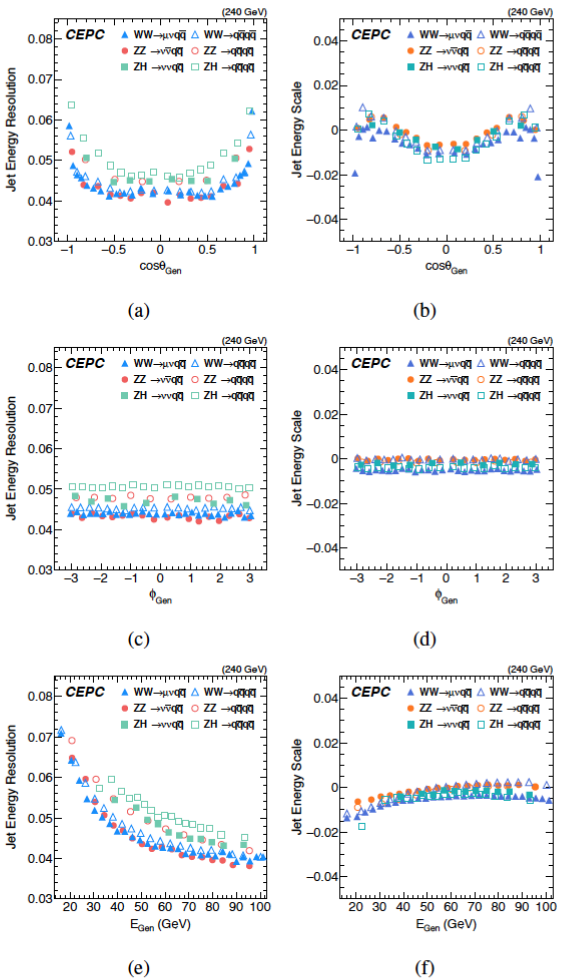
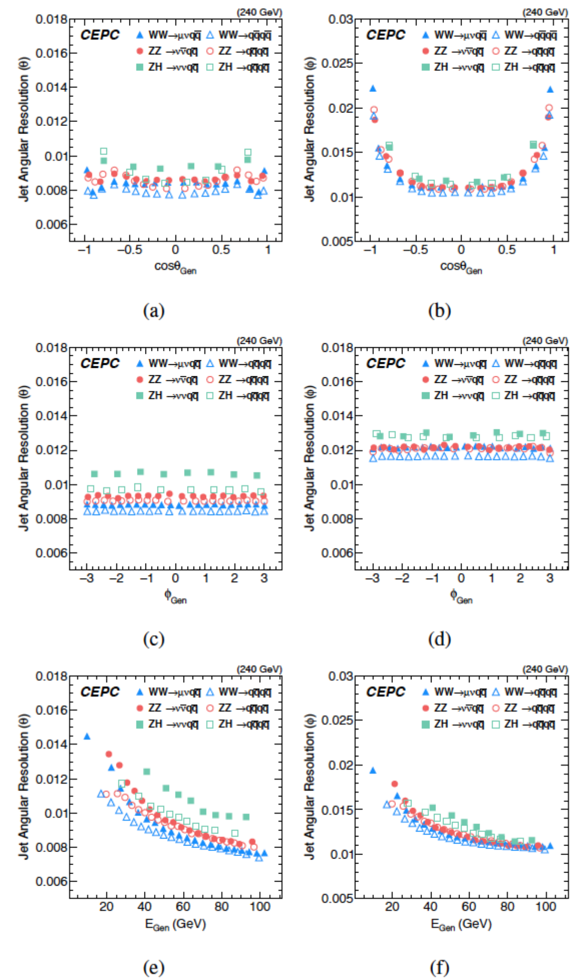


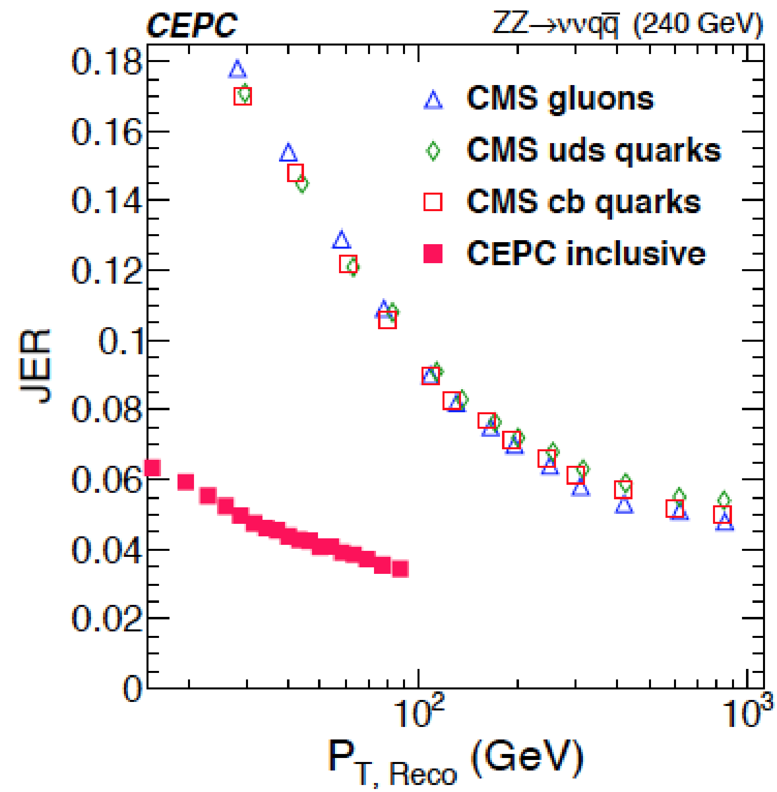
Fig. 7 Distribution of the recoil mass of the qq, M_{qq}^{recoil} for $Z \to qq$, $H \to \tau\tau$ and each background at $\sqrt{s} = 240$ GeV after the previous cuts

@ Hadronically decayed Higgs boson: not sensitive to different modes it decays into
BMR 3.6 – 3.8% for H->bb, cc, gg, WW*/ZZ*->4 jets

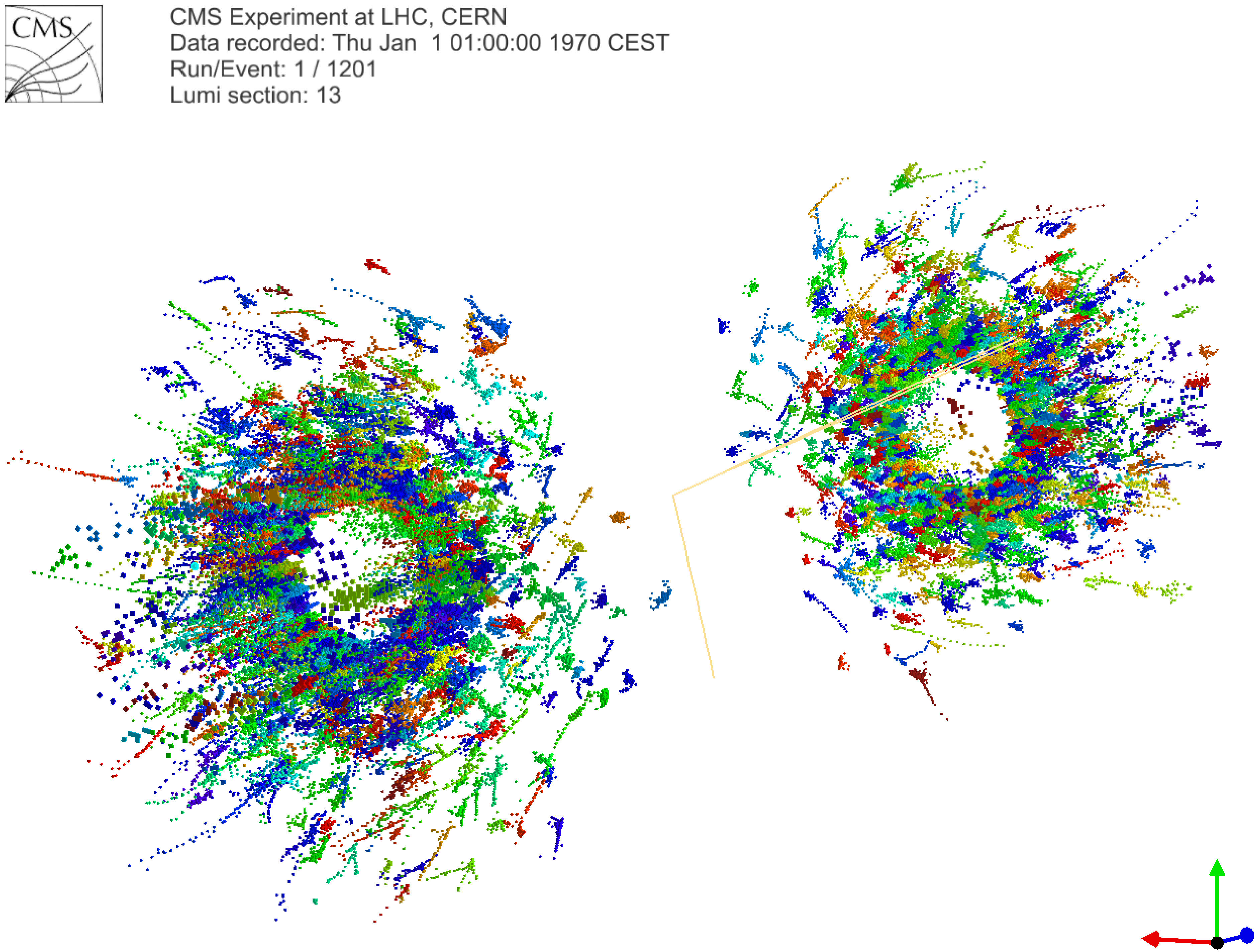
Individual Jet Responses







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


CMS Experiment at LHC, CERN
Data recorded: Thu Jan 1 01:00:00 1970 CEST
Run/Event: 1 / 1201
Lumi section: 13

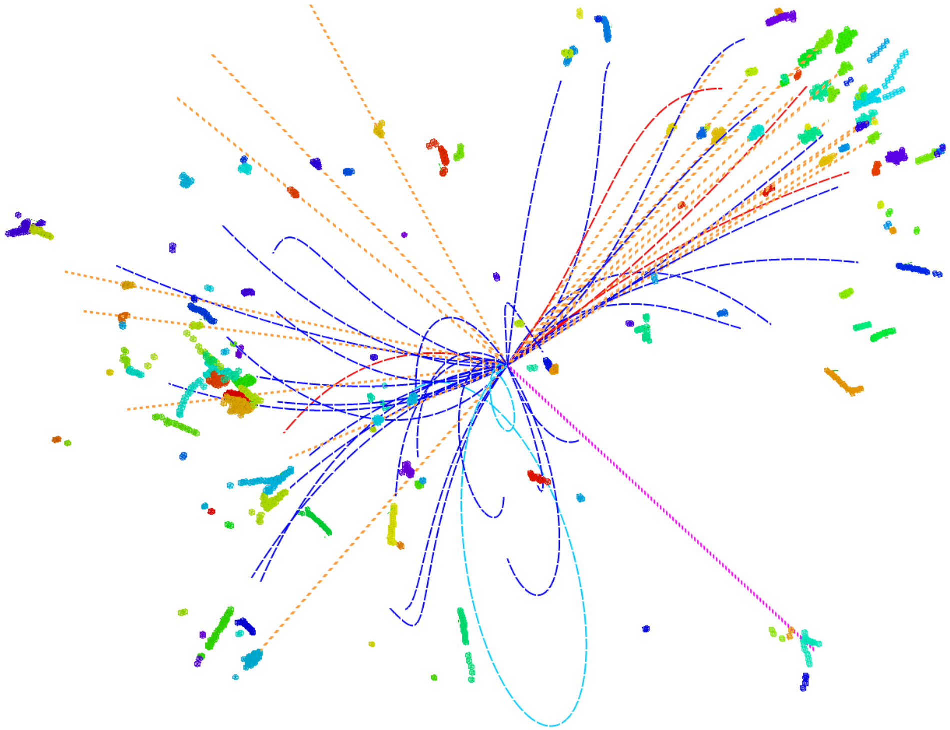
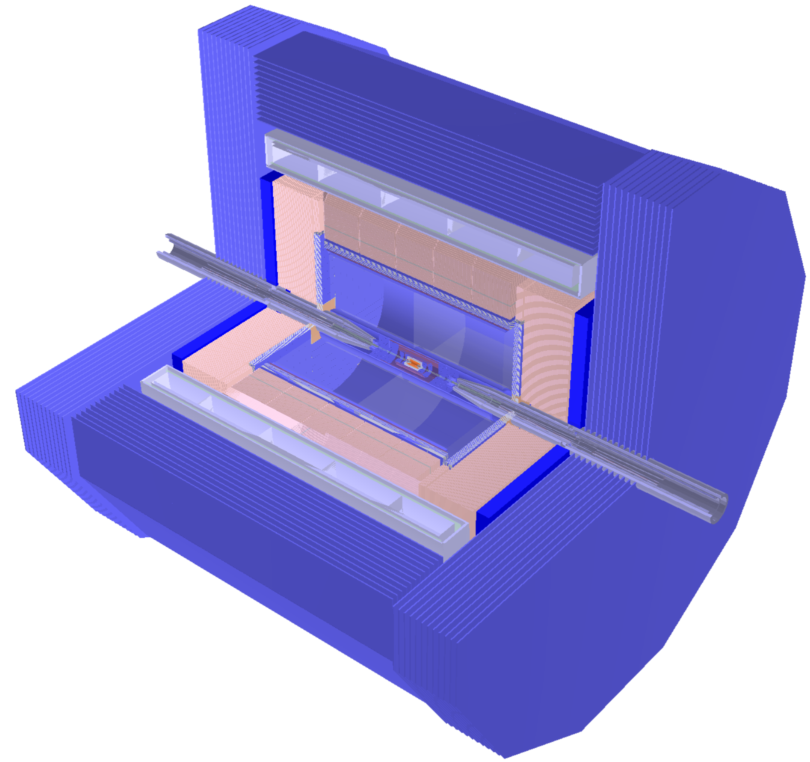
Jet origin id

Hao Liang, Yongfeng Zhu, Yuzhi Che, Yuexin Wang, Huiling Qu, Cen Zhou, etc

https://arxiv.org/abs/2310.03440

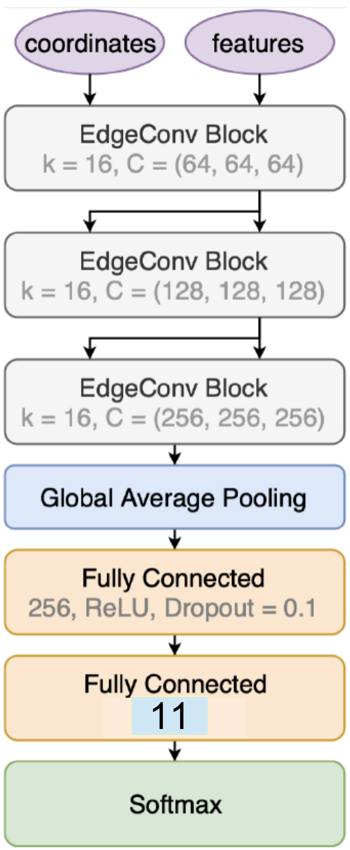
https://arxiv.org/abs/2309.13231

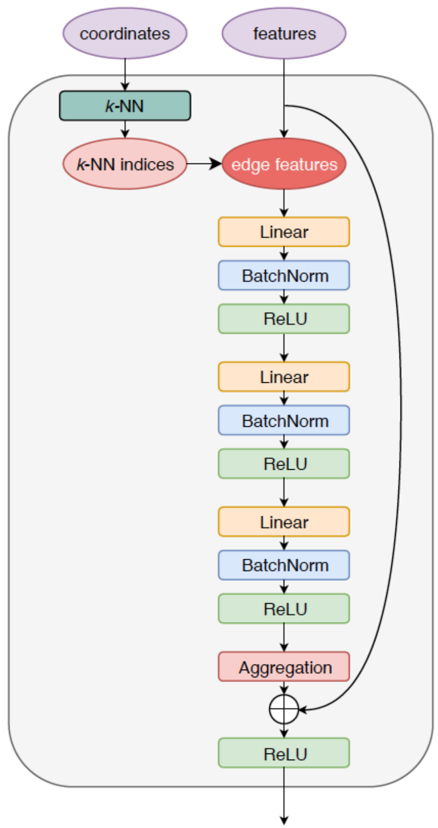
Geo. & Tools

- **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

Particle Net: IO





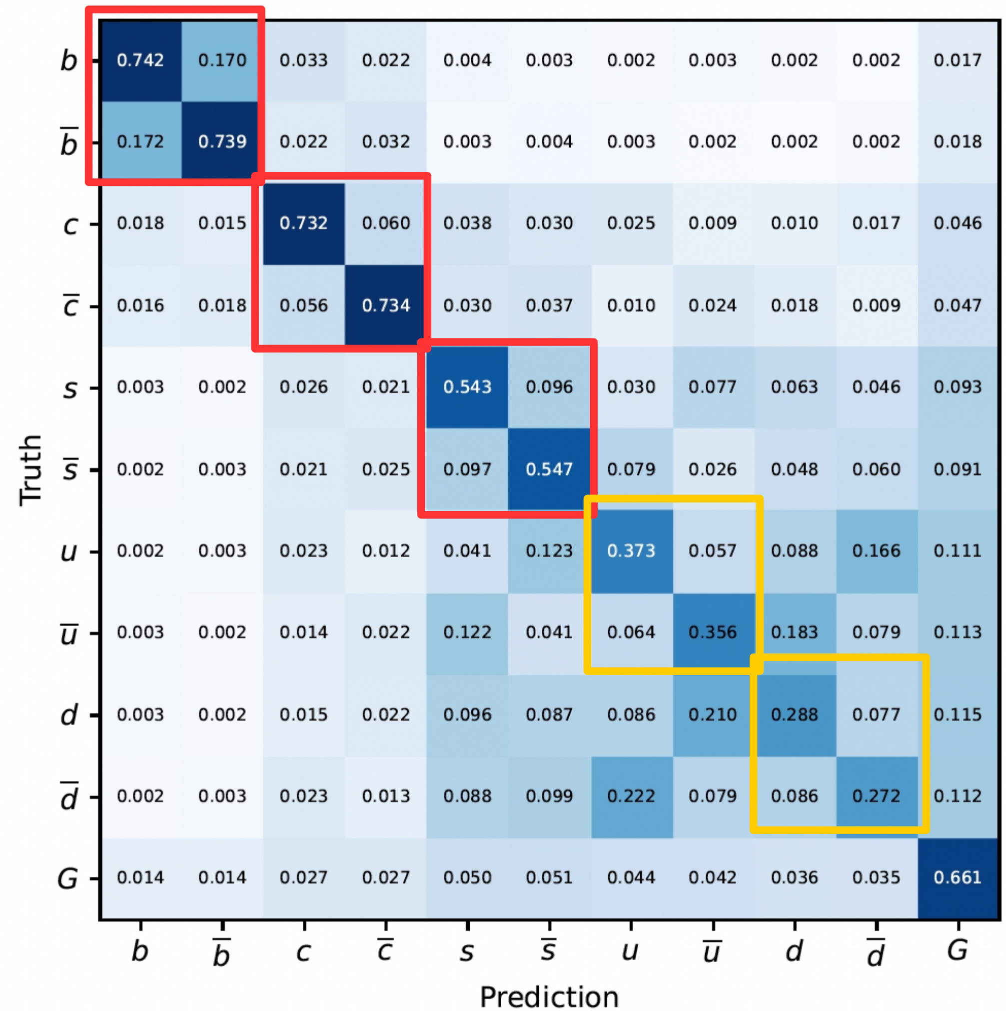
Variable	Definition
$\Delta\eta$	difference in pseudorapidity between the particle and the jet axis
$\Delta\phi$	difference in azimuthal angle between the particle and the jet axis
$logp_T$	logarithm of the particle's p_T
$logE$	logarithm of the particle's energy
$log\frac{p_T}{p_T(jet)}$	logarithm of the particle's p_T relative to the jet p_T
$log\frac{E}{E(jet)}$	logarithm of the particle's energy relative to the jet energy
ΔR	angular separation between the particle and the jet axis ($\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$)
d0	transverse impact parameter of the track
d0err	uncertainty associated with the measurement of the d0
z0	longitudinal impact parameter of the track
z0err	uncertainty associated with the measurement of the z0
charge	electric charge of the particle
isElectron	if the particle is an electron
isMuon	if the particle is a muon
isChragedKaon	if the particle is a charged Kaon
isChragedPion	if the particle is a charged Pion
isProton	if the particle is a proton
isNeutralHadron	if the particle is a neutral hadron
isPhoton	if the particle is a photon

Table 3. The input variables used in ParticleNet for jet flavor tagging at the CEPC.

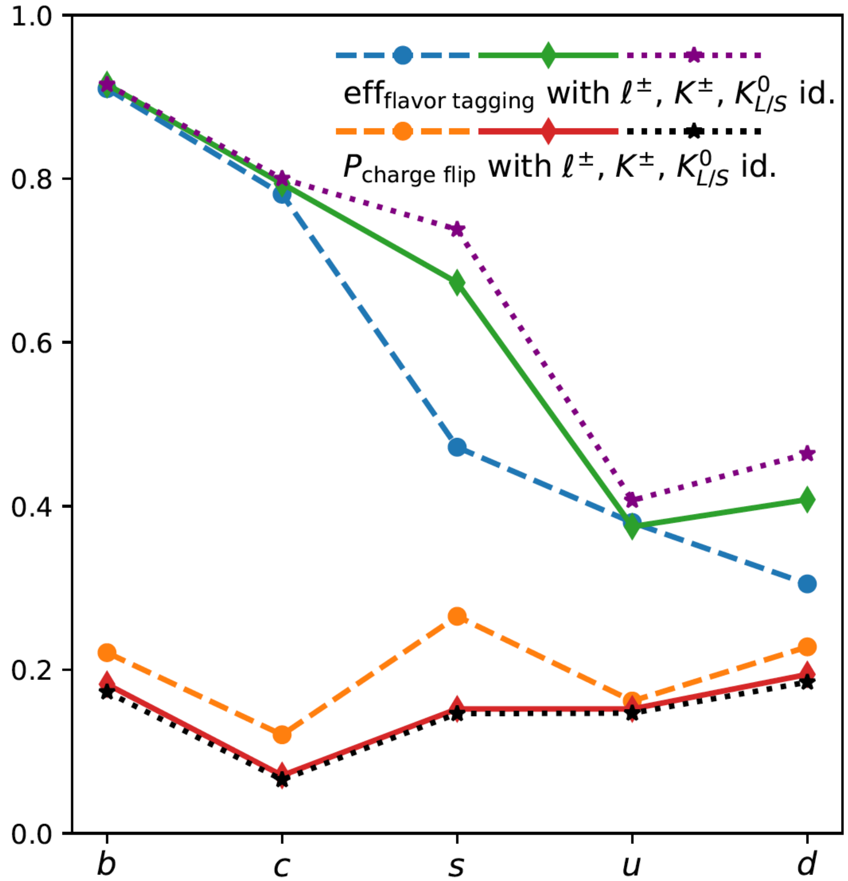
- Output: likelihoods to different categories

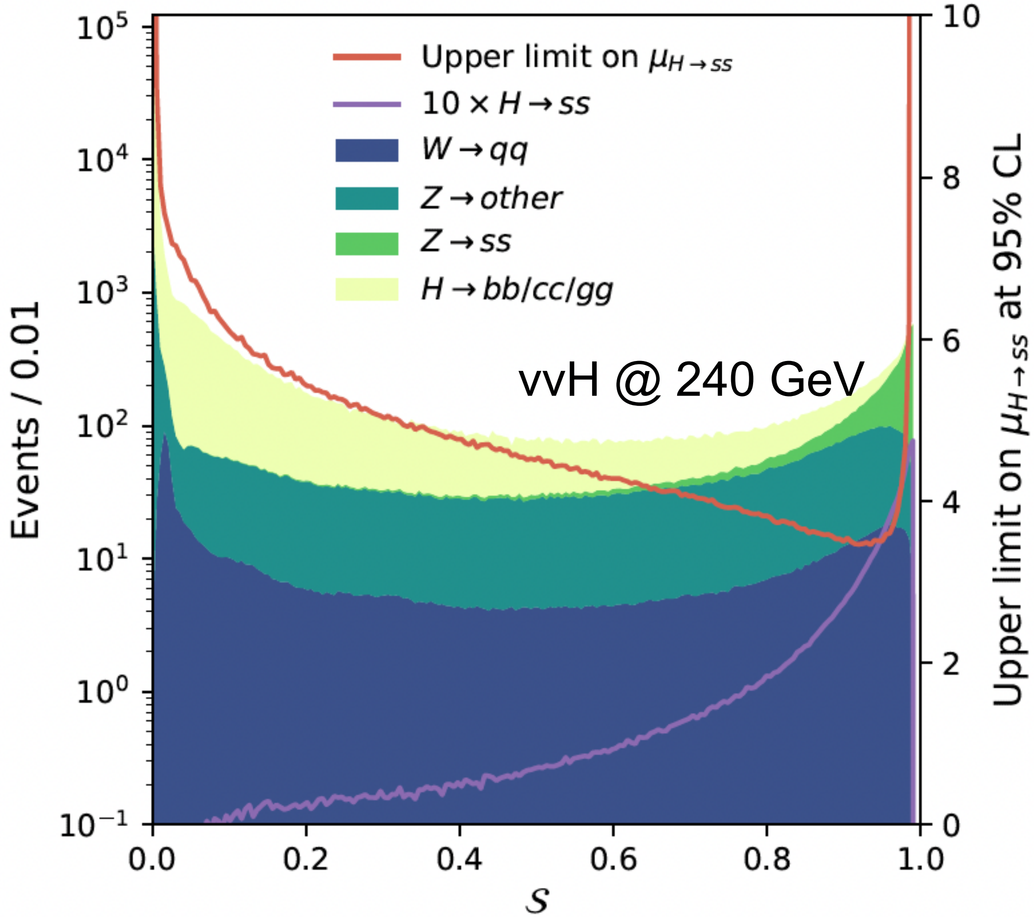
11-dim migration behavior

- Let the jet be identified as the category with highest likelihood:
- Pid: ideal Pid – three categories
  - Lepton identification
  - Charged Kaon identification
  - Neutral Kaon identification
- Patterns:
  - ~ Diagonal at quark sector...
  - P(g→q) < P(q→g)...
  - Light jet id...



Performance with different PID scenarios & H→ss measurements





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

If quark jet: jet charge ~ compare {L_q, L_q_bar}

Remark: current jet flavor tagging efficiency & jet charge flip rates are projections of the 11-dim arrays produced by Jet origin id

Benchmark analyses: Higgs rare/FCNC

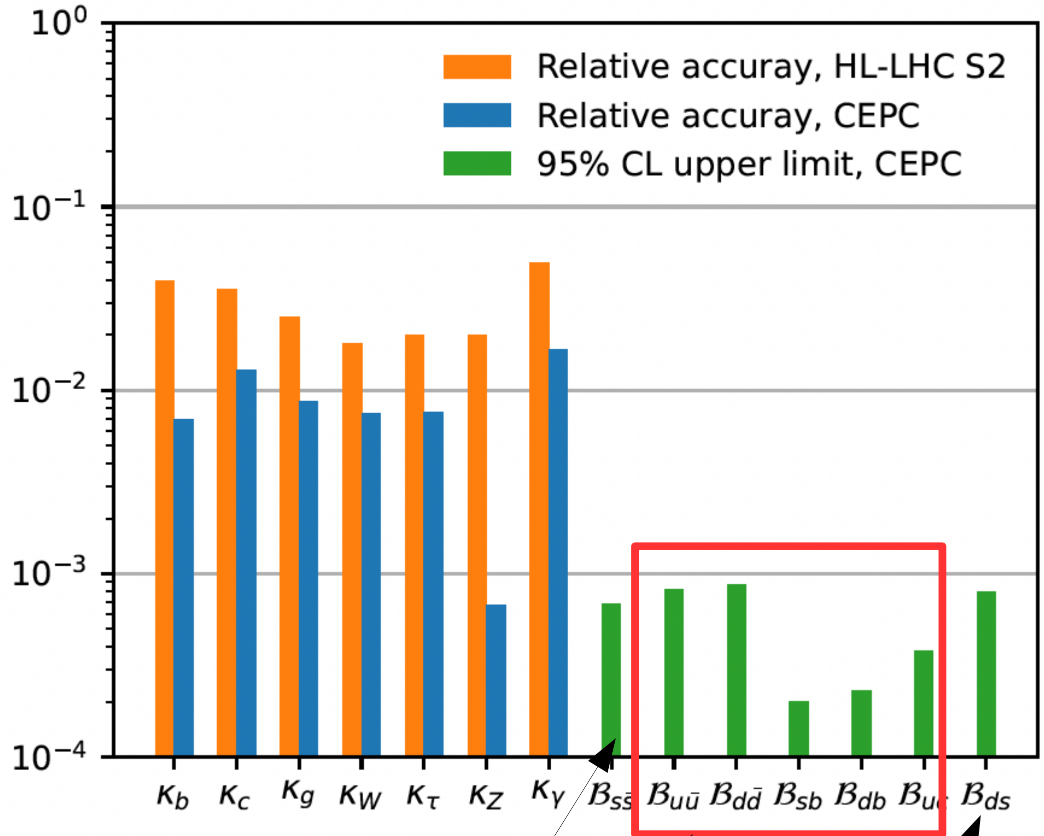


TABLE I: Summary of background events of $H \to b\bar{b}/c\bar{c}/gg$, Z, and W prior to flavor-based event selection, along with the expected upper limits on Higgs decay branching ratios at 95% CL. Expectations are derived based on the background-only hypothesis.

	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

Improved by ~3 times

Improved by 1-2 orders of magnitudes

Presumably... firstly quantified

[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.

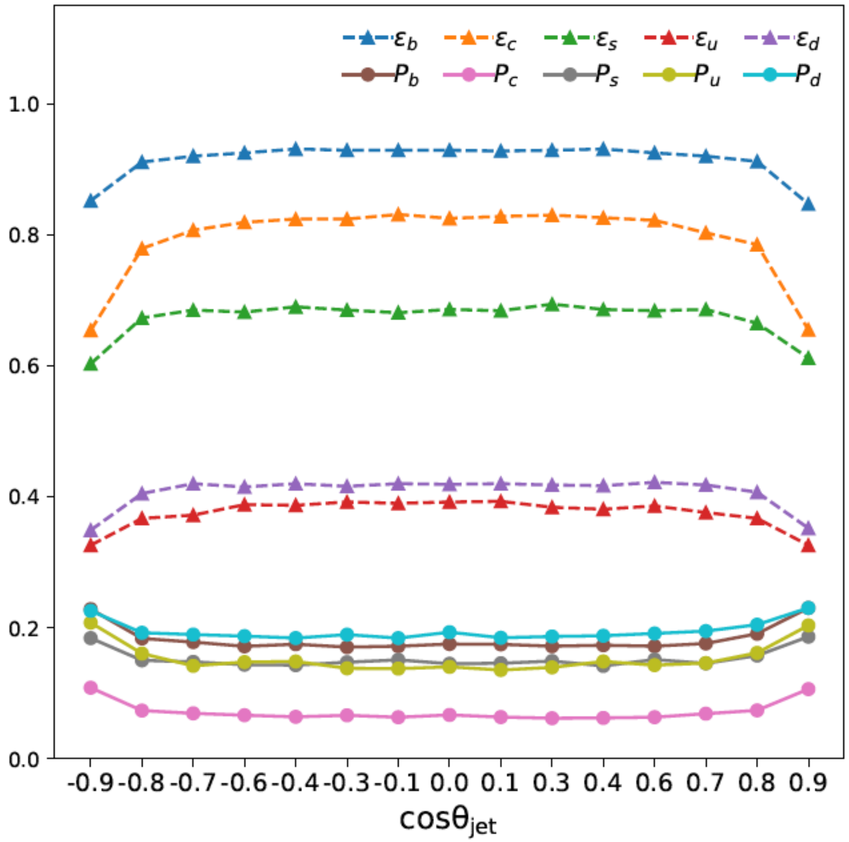
[50] Alexander Albert et al. Strange quark as a probe for new physics in the Higgs sector. In *Snowmass 2021*, 3 2022.

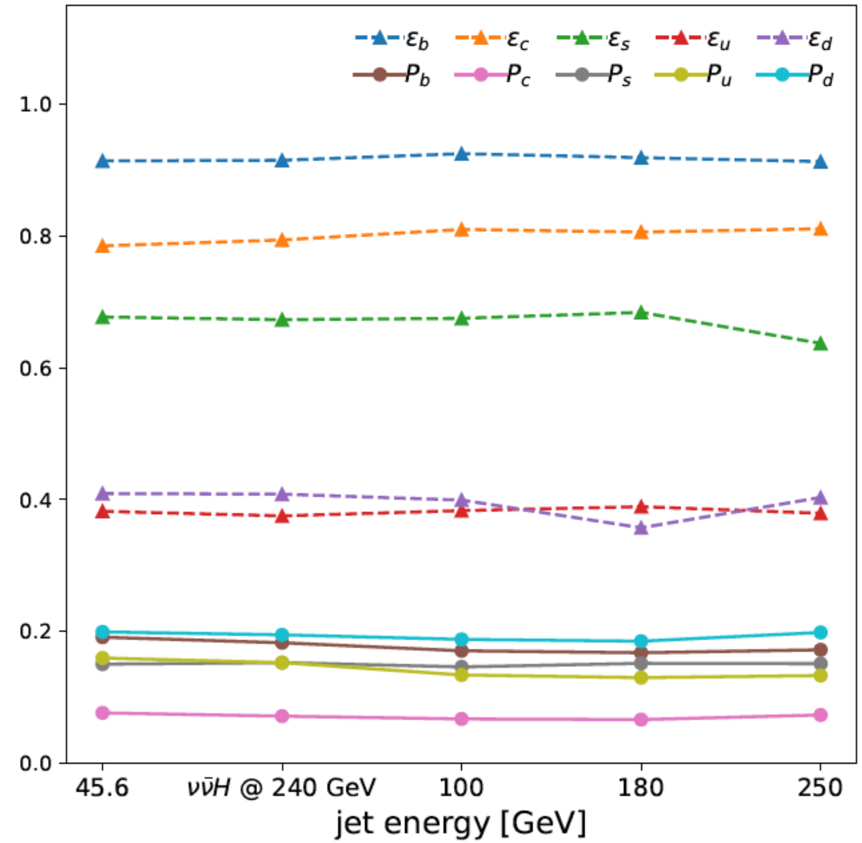
[59] J. de Blas et al. Higgs Boson Studies at Future Particle Colliders. *JHEP*, 01:139, 2020.

[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.

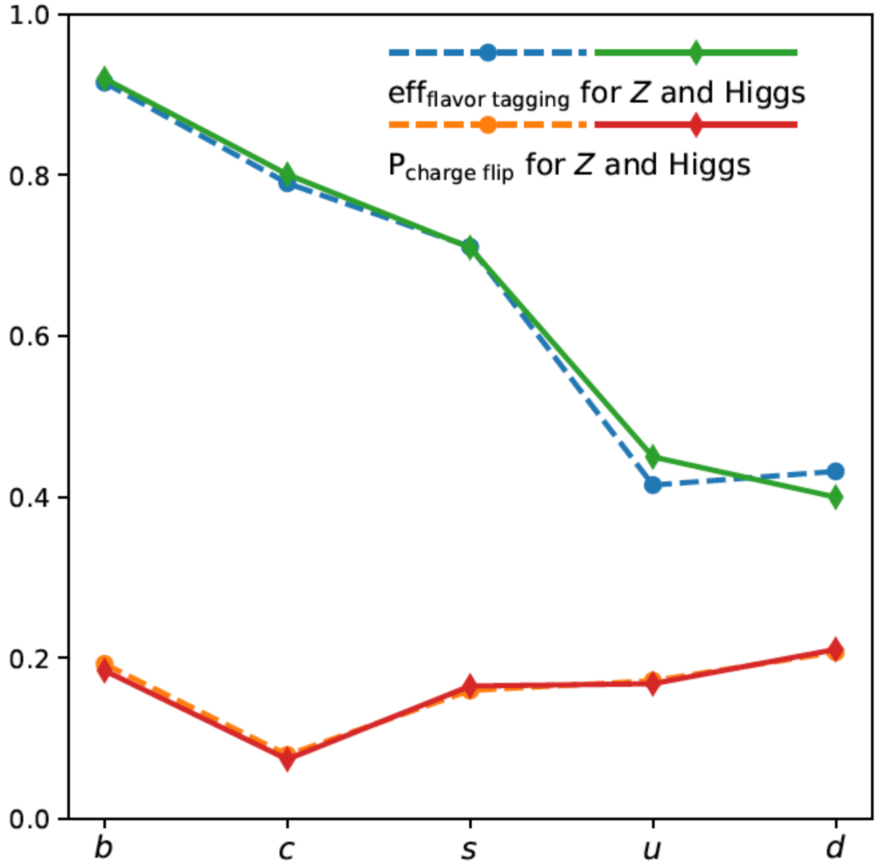
For H->bb, cc, gg: results in 20 – 40% improvement in relative accuracies (preliminary)...

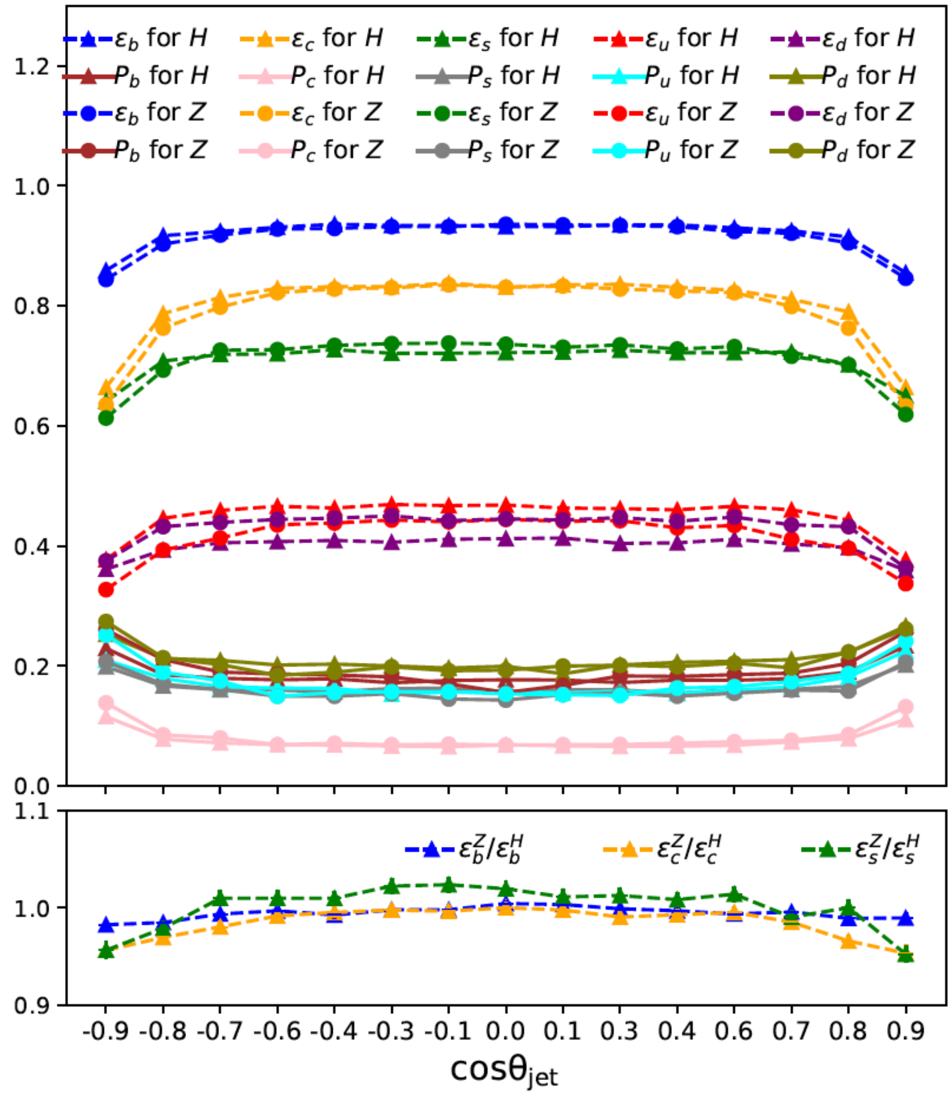
Performance V.S. Jet Kinematics





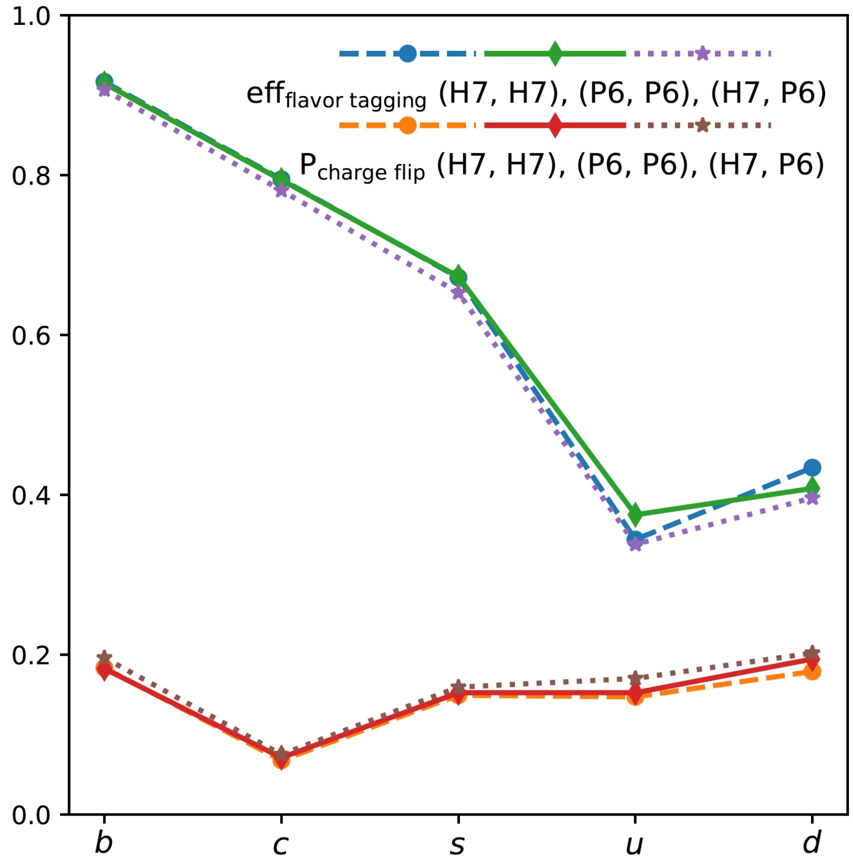
Performance @ Z and Higgs

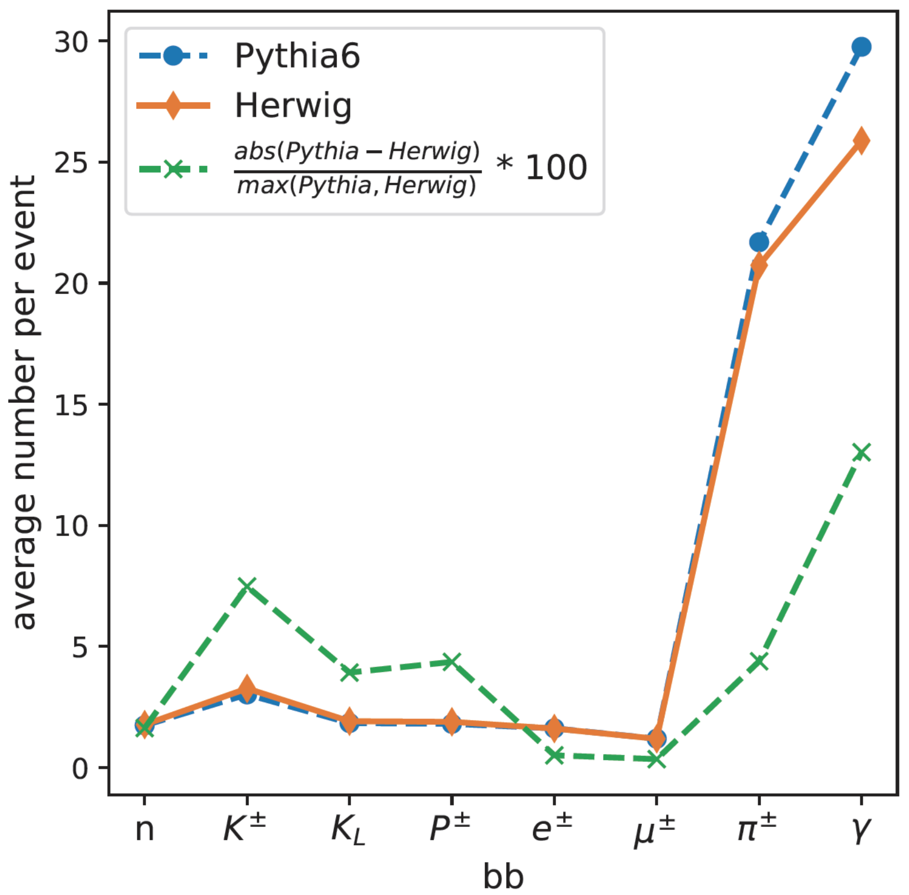




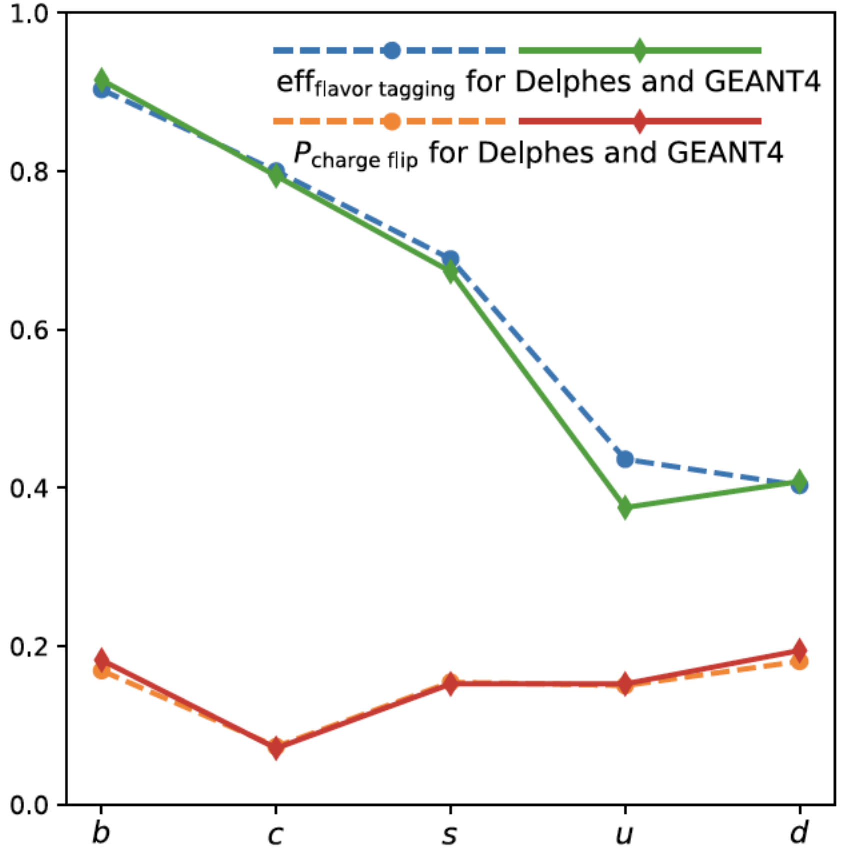
- *M10 instead of M11*

V.S. Hadronization models

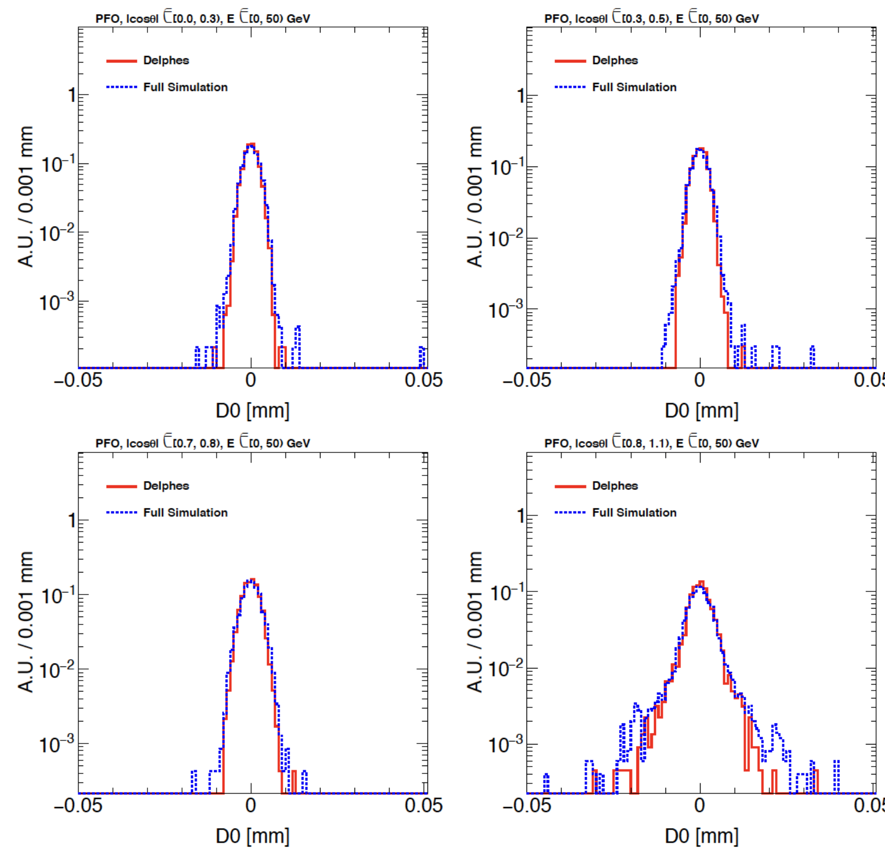




Fast/Full Simulation

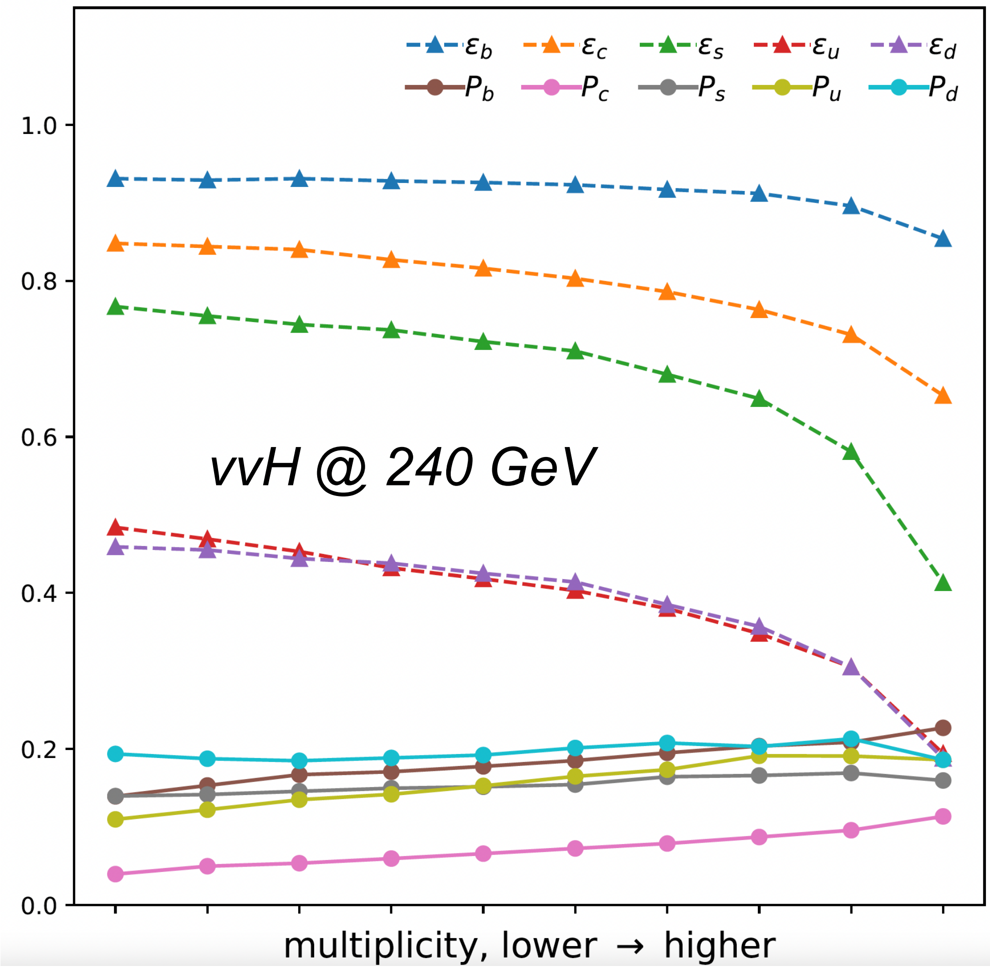


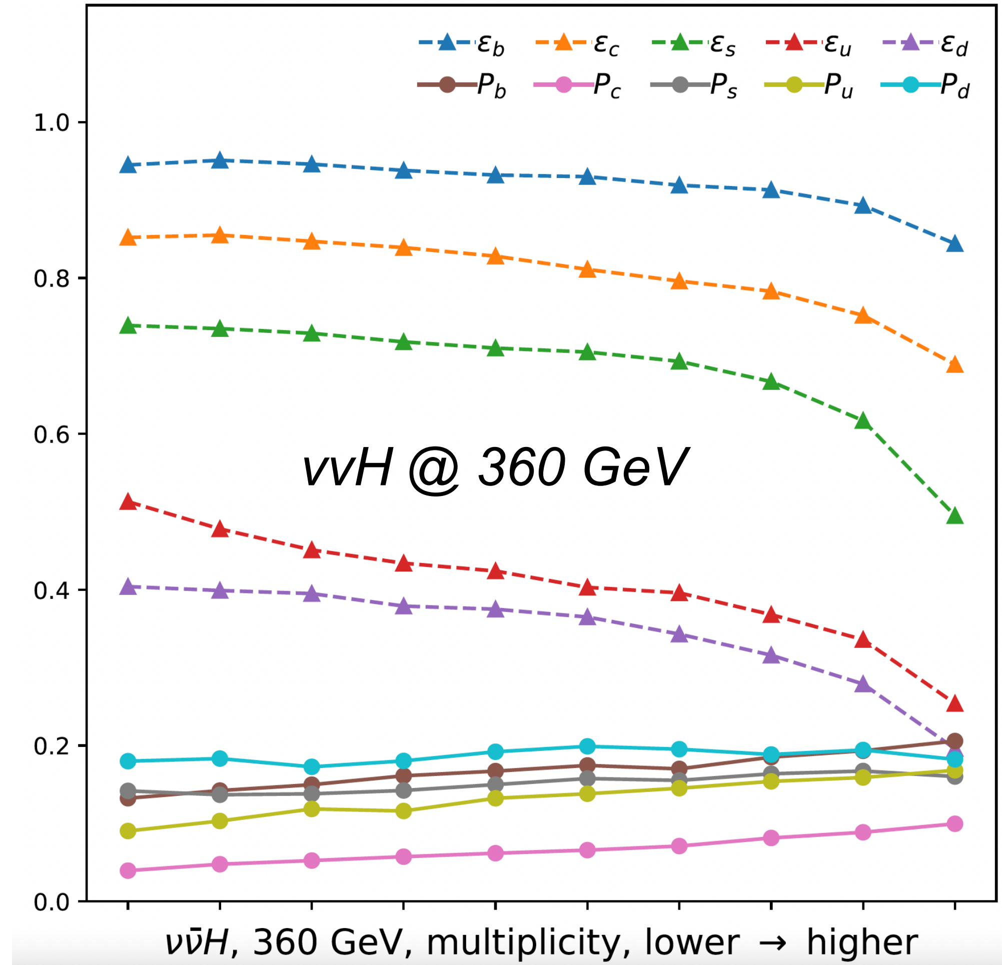
Z->μμ (91.2 GeV)



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

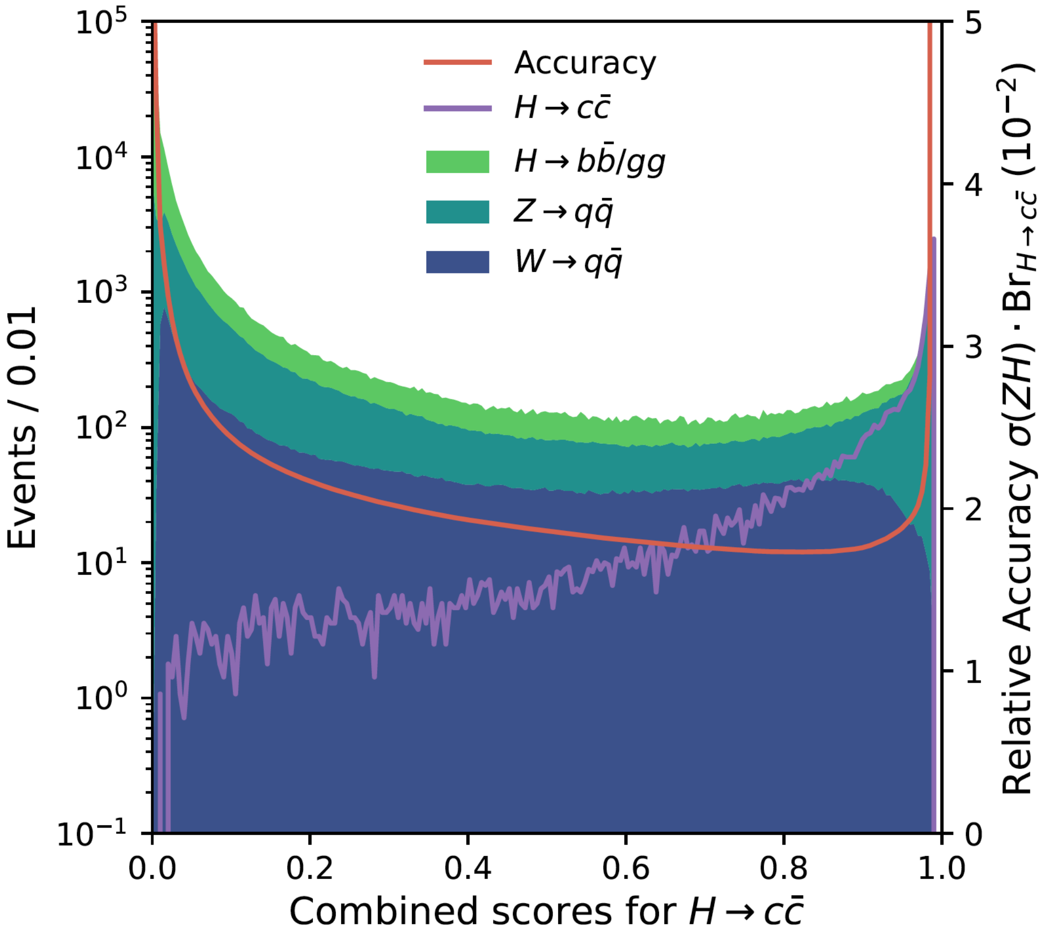
V.S. Multiplicity

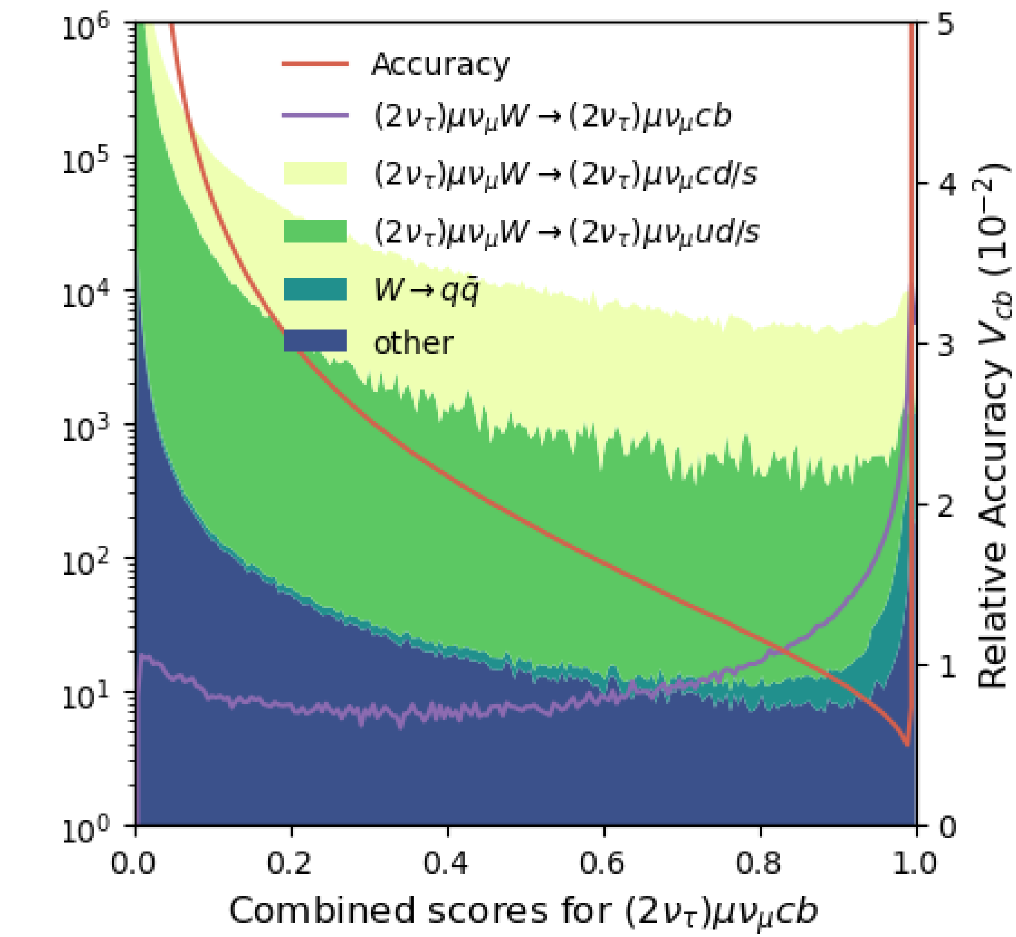




- *...many patterns need further understanding & towards further optimization...*

Recent update at more benchmarks





- From Jet Flavor Tagging to Jet Origin ID (**Preliminary**):
  - vvH, H→cc: 3% → 1.7%
  - Vcb: 0.75% → 0.5%

Updated result on $\sin^2\theta_{eff}^{l}$ measurement

Table 2. Sensitivity S of different final state particles.

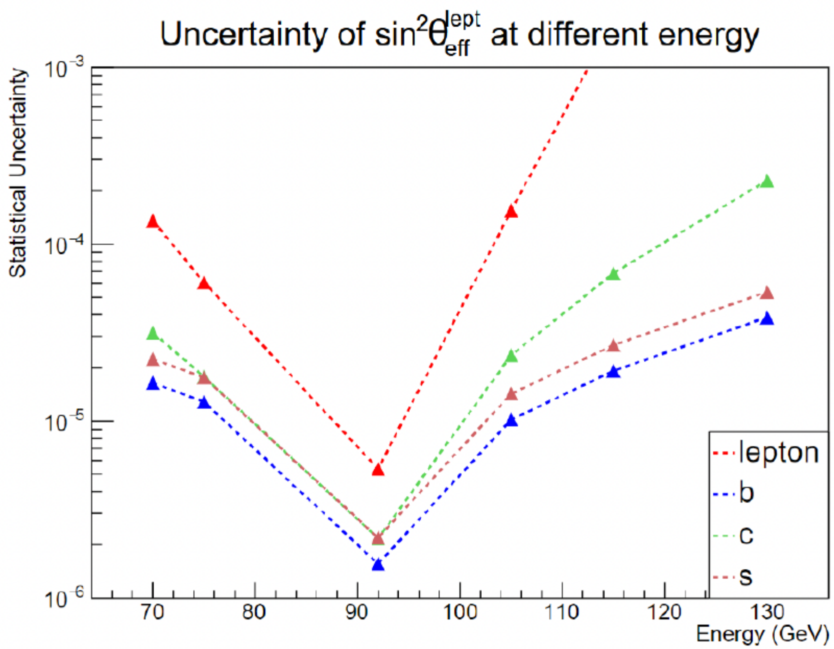
$\sqrt{s}$/GeV	S of $A_{FB}^{e/\mu}$	S of A_{FB}^{d}	S of A_{FB}^{u}	S of A_{FB}^{s}	S of A_{FB}^{c}	S of A_{FB}^{b}
70	0.224	4.396	1.435	4.403	1.445	4.352
75	0.530	5.264	2.598	5.269	2.616	5.237
92	1.644	5.553	4.200	5.553	4.201	5.549
105	0.269	4.597	1.993	4.598	1.994	4.586
115	0.035	3.956	1.091	3.958	1.087	3.942
130	0.027	3.279	0.531	3.280	0.520	3.261

Table 3. Cross section of process $e^+e^- \to f\bar{f}$ calculated using the ZFITTER package. Values of the fundamental parameters are set as $m_Z = 91.1875$ GeV, $m_t = 173.2$ GeV, $m_H = 125$ GeV, $\alpha_s = 0.118$ and $m_W = 80.38$ GeV.

$\sqrt{s}$/GeV	σ_μ/mb	σ_d/mb	σ_u/mb	σ_s/mb	σ_c/mb	σ_b/mb
70	0.039	0.032	0.066	0.031	0.058	0.028
75	0.039	0.047	0.073	0.046	0.065	0.043
92	1.196	5.366	4.228	5.366	4.222	5.268
105	0.075	0.271	0.231	0.271	0.227	0.265
115	0.042	0.135	0.122	0.135	0.118	0.132
130	0.026	0.071	0.068	0.071	0.066	0.069

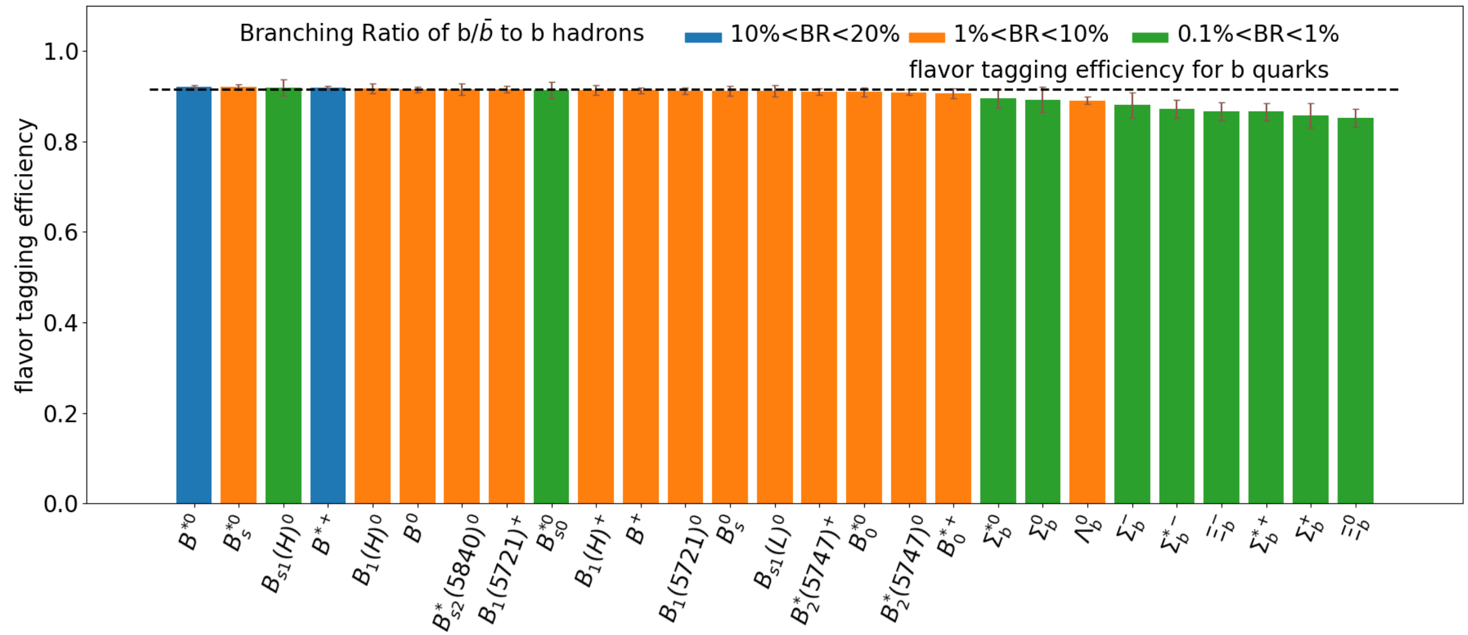
Verify the RG behavior… using ~1 month of data taking

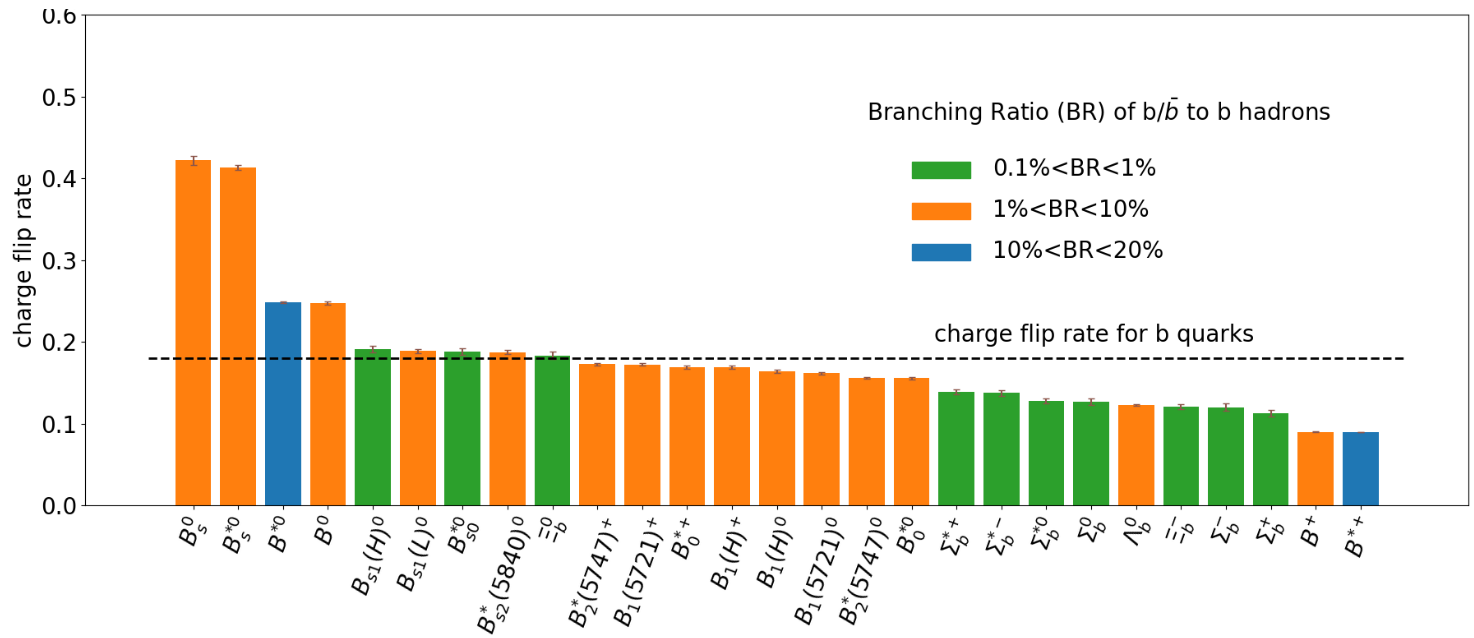
Expected statistical uncertainties on $\sin^2\theta_{eff}^{l}$ measurement.
(Using one-month data collection, ~ *4e12/24 Z events* at Z pole)



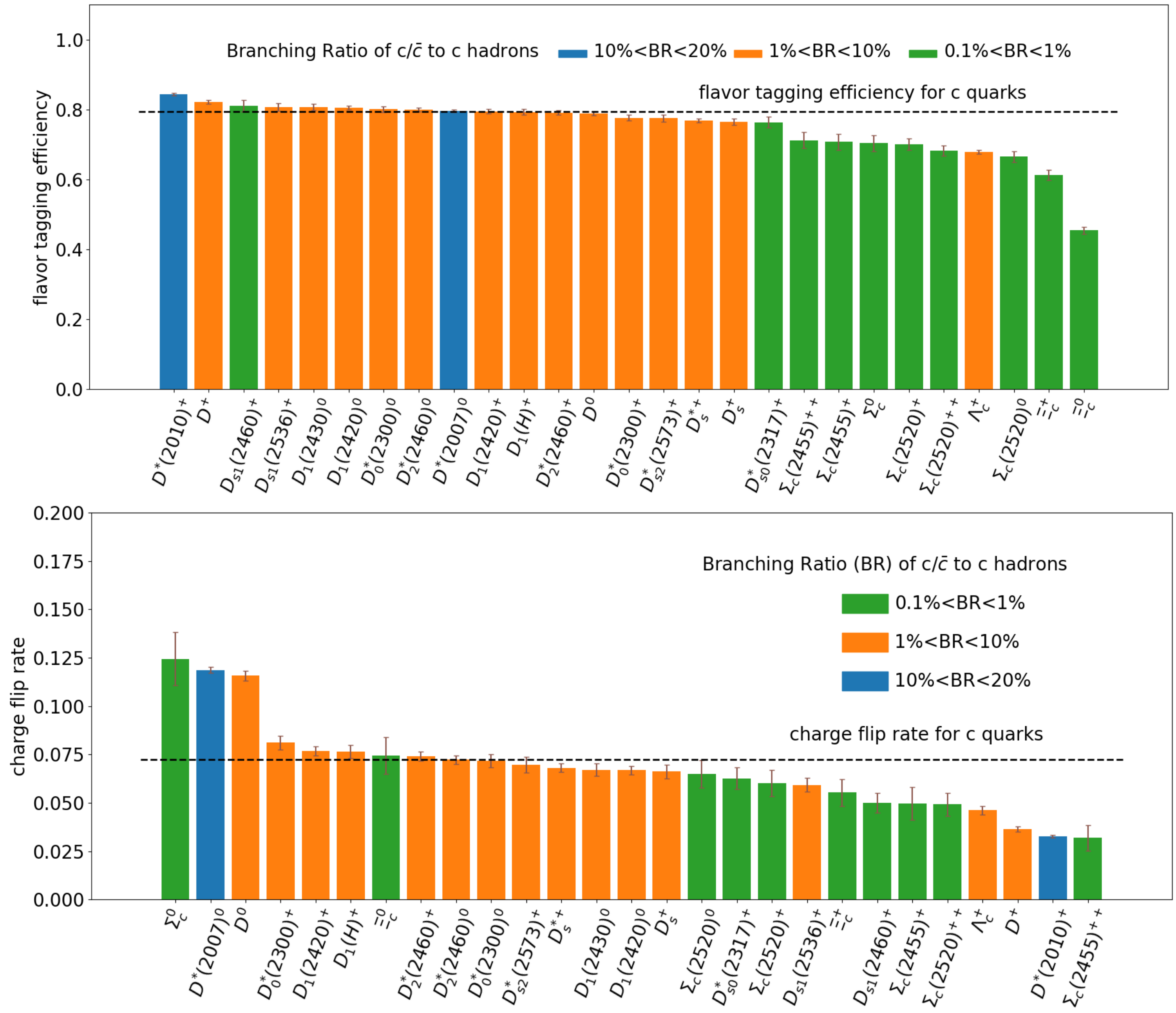
$\sqrt{s}$	b	c	s
70	1.6×10^{-5}	3.2×10^{-5}	2.2×10^{-5}
75	1.3×10^{-5}	1.8×10^{-5}	1.8×10^{-5}
92	1.6×10^{-6}	2.2×10^{-6}	2.2×10^{-6}
105	1.0×10^{-5}	2.4×10^{-5}	1.4×10^{-5}
115	1.9×10^{-5}	6.8×10^{-5}	2.7×10^{-5}
130	3.9×10^{-5}	2.3×10^{-4}	5.4×10^{-5}

b-jets: dependency on Leading hadron

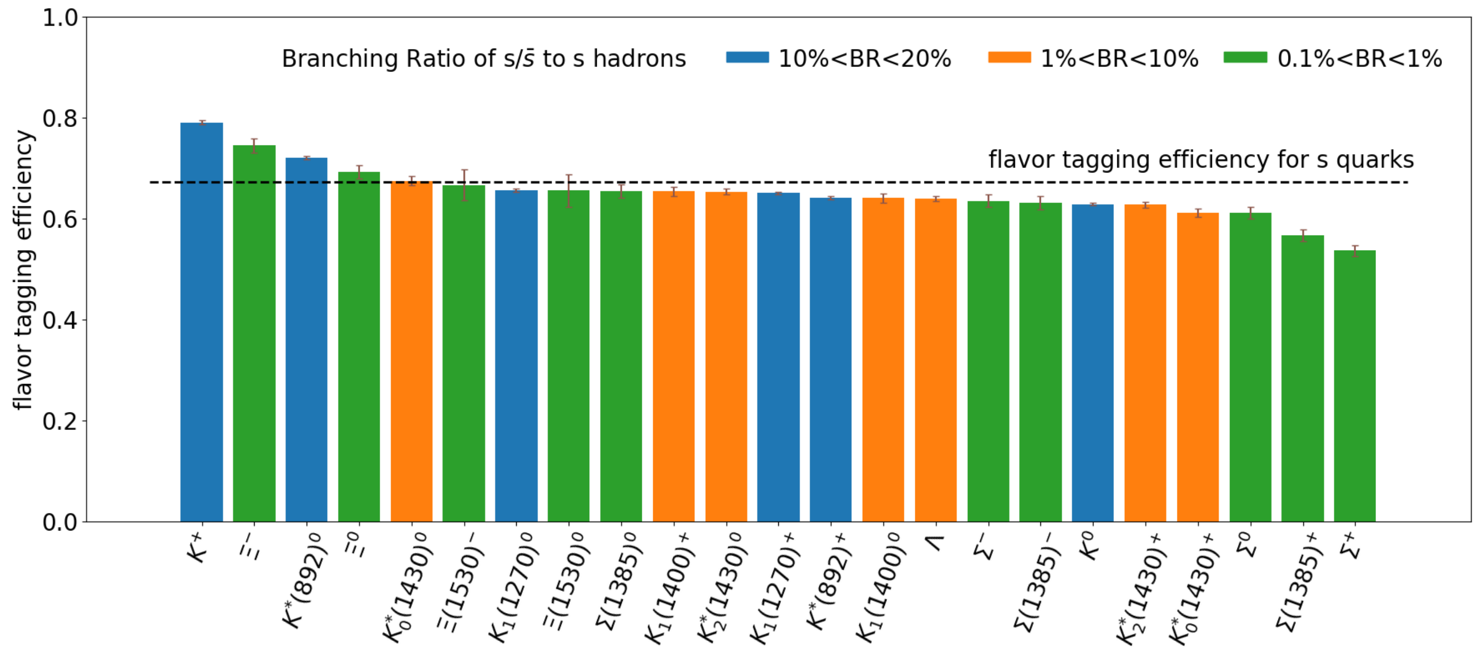


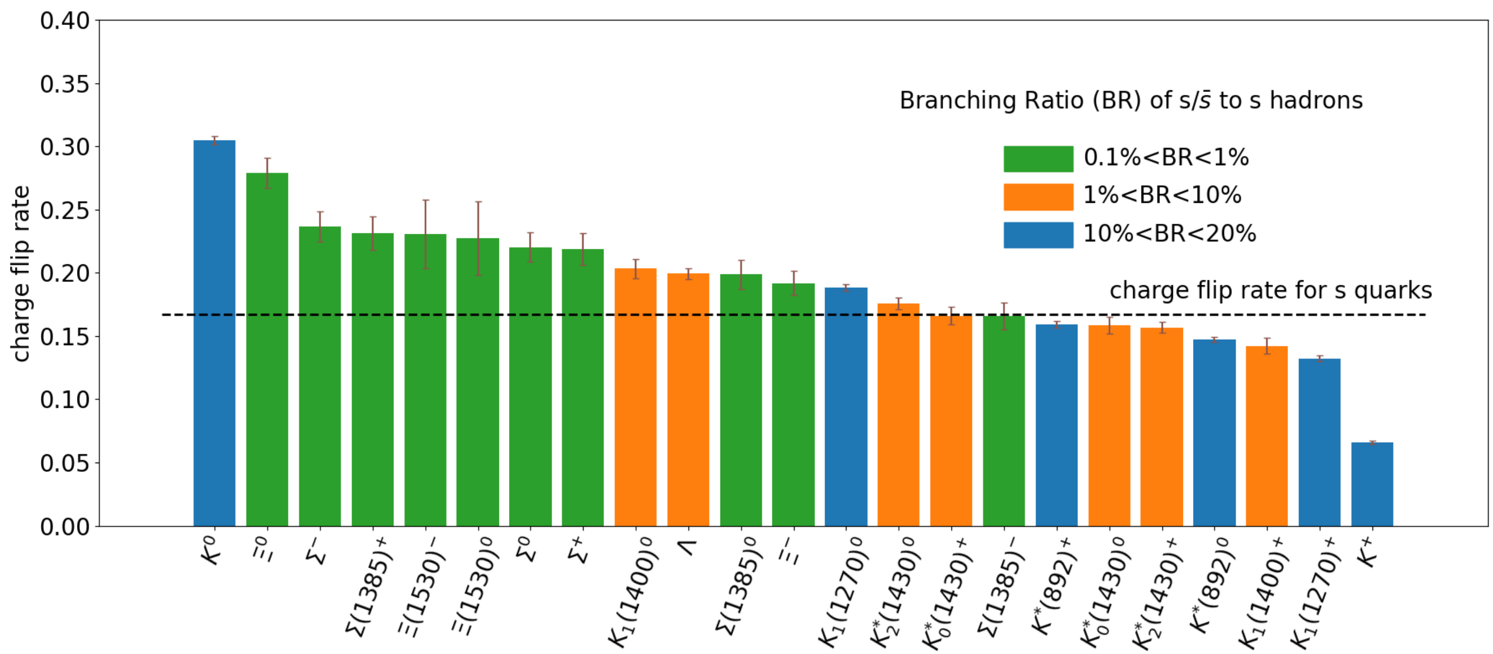


c-jets: dependency on Leading hadron



s-jets: dependency on Leading hadron

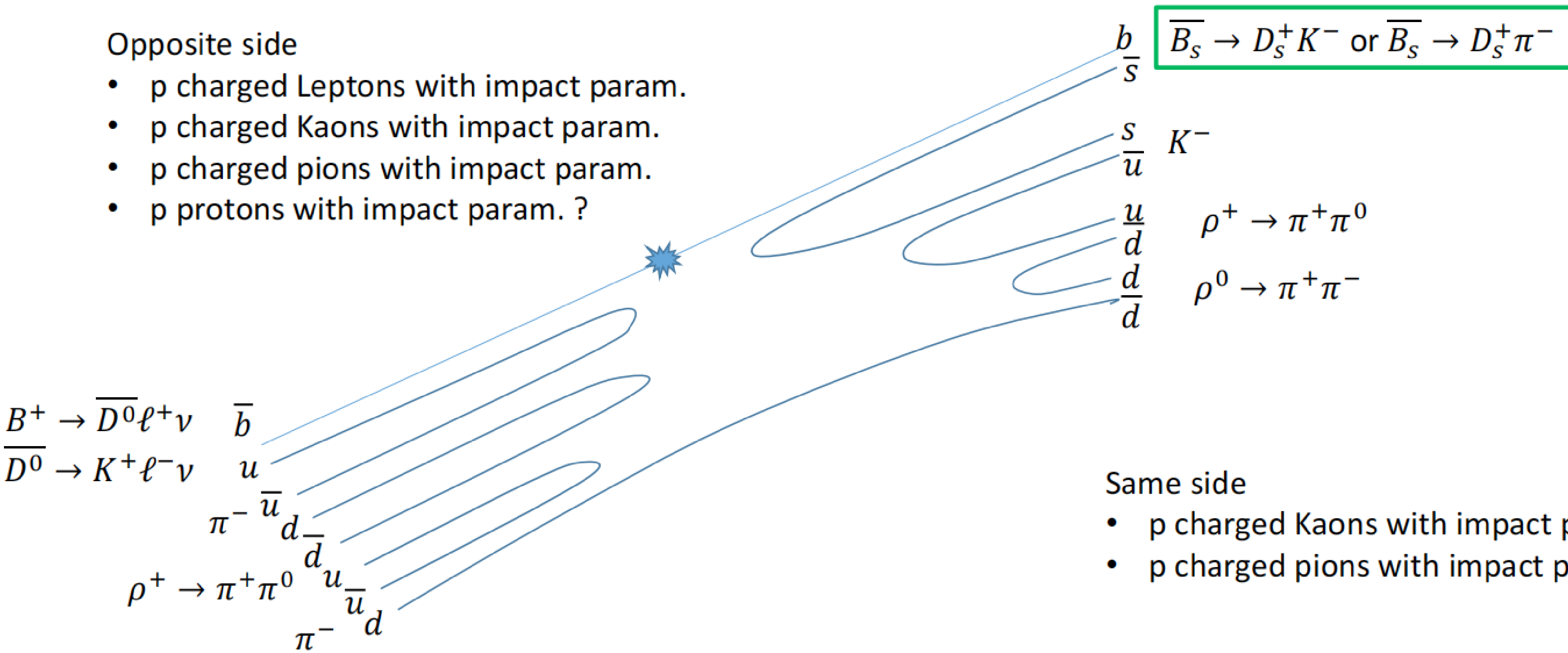




B-charge flip rate: Bs oscillations

Opposite side

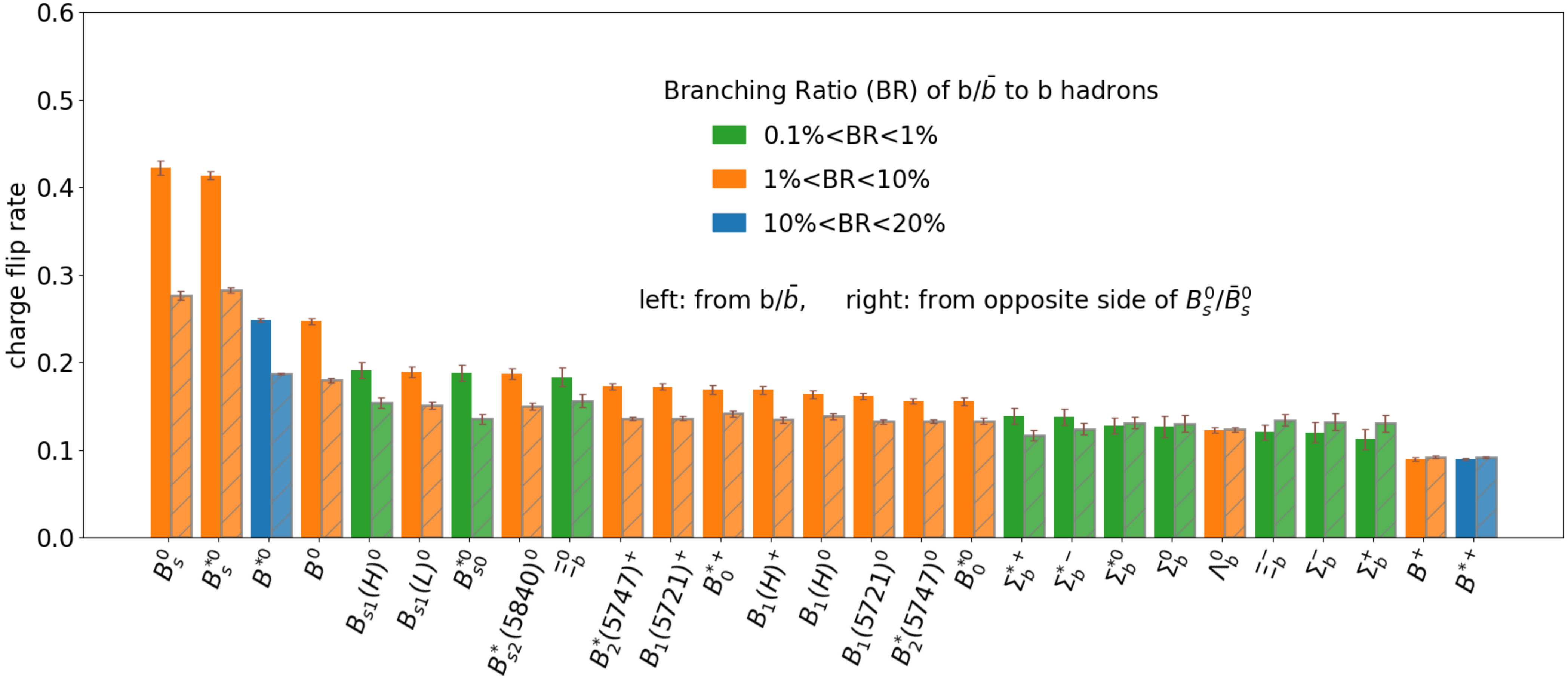
- p charged Leptons with impact param.
- p charged Kaons with impact param.
- p charged pions with impact param.
- p protons with impact param. ?



Same side

- p charged Kaons with impact param
- p charged pions with impact param.

B-charge flip rate: Bs oscillations



Summary

- Final State Particles
  - Abb. Layer of information: High energy processes at collider interaction point is in principle independent of Shower development
  - Successful reco, i.e., separation - identification & measurements are critical for HEP experiments

- Arbor: Backbone of CEPC reconstruction.
  - Particle Flow algorithm that interpret detector hits into final state particles
    - CalorimeterHits → Clusters,
    - Clusters + Tracks → Reconstructed Final state particles)
  - Resolve shower tree topology, emphasize on separation & identification
  - Applied to multiple cases: TB, electron positron & pp colliders

Summary

- Jet origin id: realized using Arbor + PN/Transformer
  - Efficiently separate different species of colored SM particle
  - Stable & Health
    - Jet kinematic & Physics Processes: Calibration
    - Hadronization models
    - Det. Geometry, Fast & Full Sim: reference for det. Optimization
- Significantly impact on physics
  - Higgs: boost precision on hadronic, especially rare/exotic final state (3 – 100 times)
  - EW: Weak mixing angle
  - *Flavor: Time dependent CP measurements...*
  - *QCD: Quark Fragmentation*
- Long term version: identify quark & gluons... as lepton & photons.

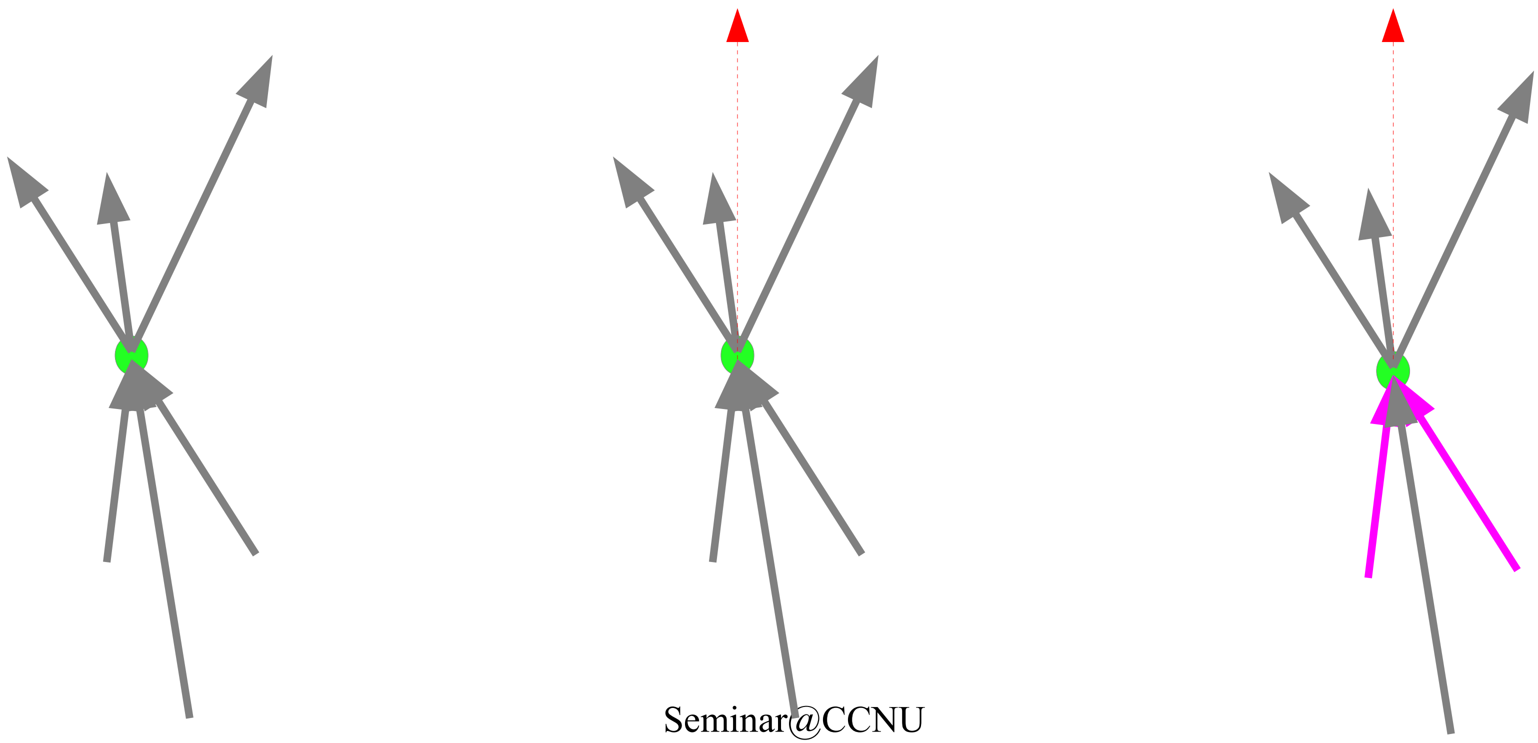
Back up: related physics performance studies

Performance requirements

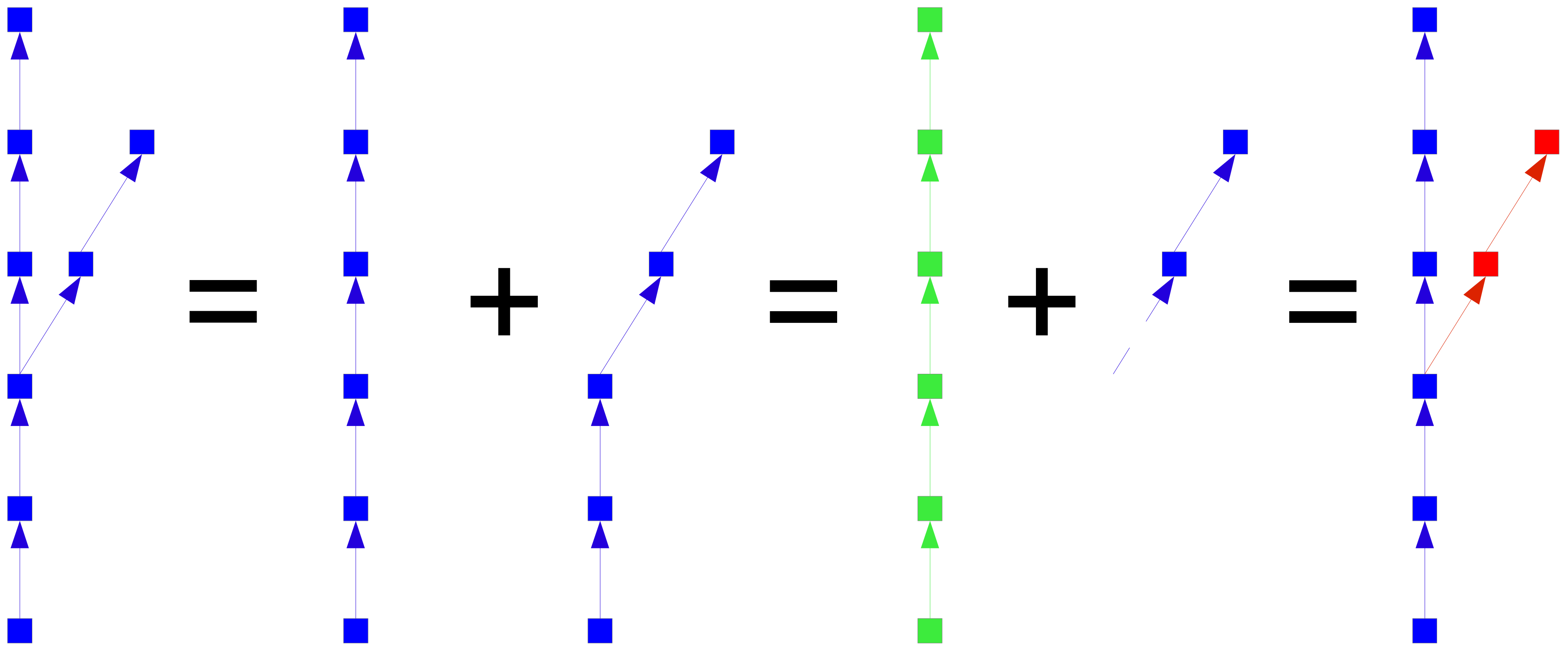
- A clear separation of the final state particles: Identification of Physics Objects, and Improving the E/P resolution for composited objects, especially jets
  - Leptons, especially these inside jets
  - Composited objects:
    - Two/three body objects: Pi-0, K-short, Lambda, Phi, Tau, D meson...
    - More bodies: Tau & Jets
  - PFA: pursuing 1-1 correspondence...
- BMR (Boson Mass Resolution): mass resolution of Hadronic decayed Higgs/Z/W
  - < 4% for Higgs measurements
  - Much demanding for Flavor Physics/New Physics Hunting
- Pid: Pion & Kaon separation > 3 σ (eff*purity of Kaon at Key processes > 60%...)
- Jet origin id: Flavor Tagging & Charge Reconstruction, s/light/gluon-tagging...
- Intrinsic accuracies: momentum, energy, VTX positions...

Algorithm: hits → connectors

- Preparation: hits cleaning, pre-clustering, etc
- Create connector set between hits
  - Create all possible connectors (according to geometry constrains)
  - Clean: keep at most one connector end at a given hit
  - Iterate: change geometry constrain, add new connectors, and clean

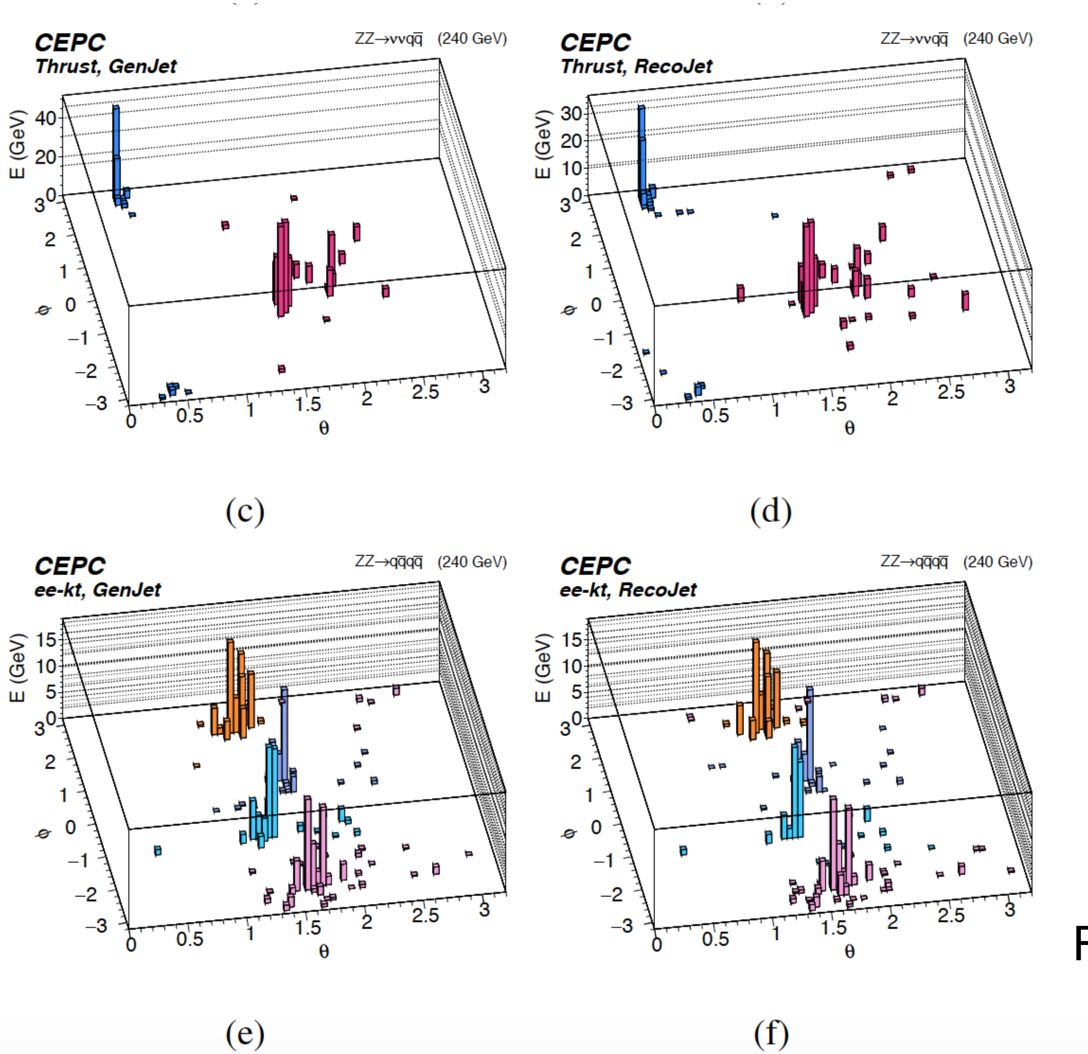


Algorithm: connectors → branches



- Tag the unique branch set from connectors
  - Create all the possible branches (*from leaves to seed*)
  - Loop the branches with length order, flag hit, end the branch at the flagged hits

Individual jet: jet clustering - matching



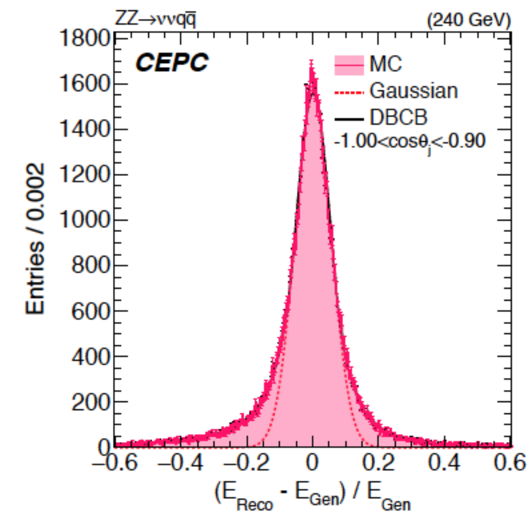


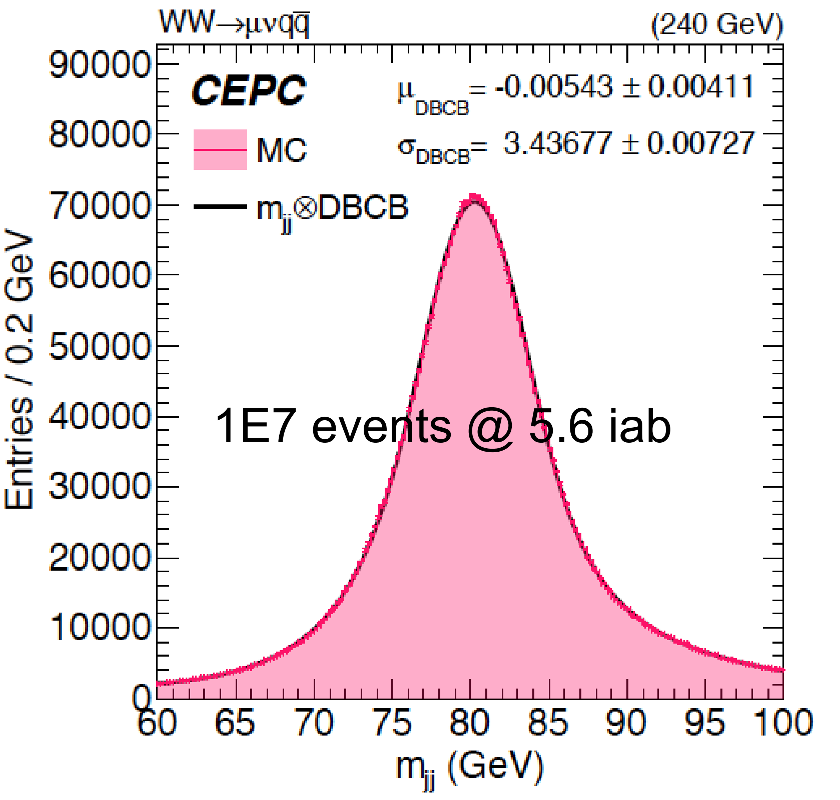
Fig. 7: σ and $\bar{x}$ from the core of the DBCB fit to R are defined as JER/S, respectively. The $cos\theta_j$ indicates the specific polar angle of the jets.

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

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

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

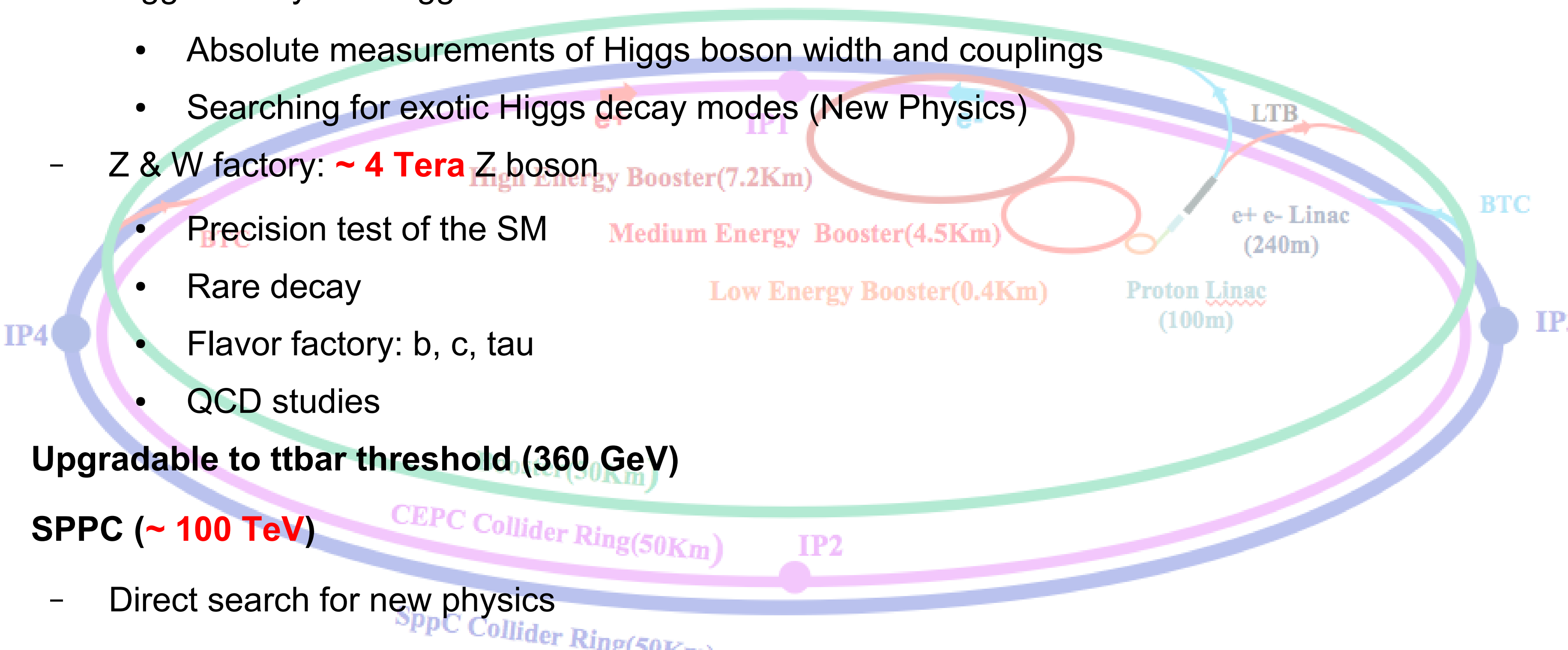
- W mass measurement at 240 GeV:
  - Statistic uncertainty @ 20 iab~
    - *0.3 MeV using only μvqq final state*
    - *Bias ~ 2.5 MeV once Z mass calibrated to known value*
  - Ultimate accuracy?
    - *Can we better control the systematic using the differential information?*
    - *Control the jet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



Quasi analysis: JES calibrated to pure ISR return qq sample

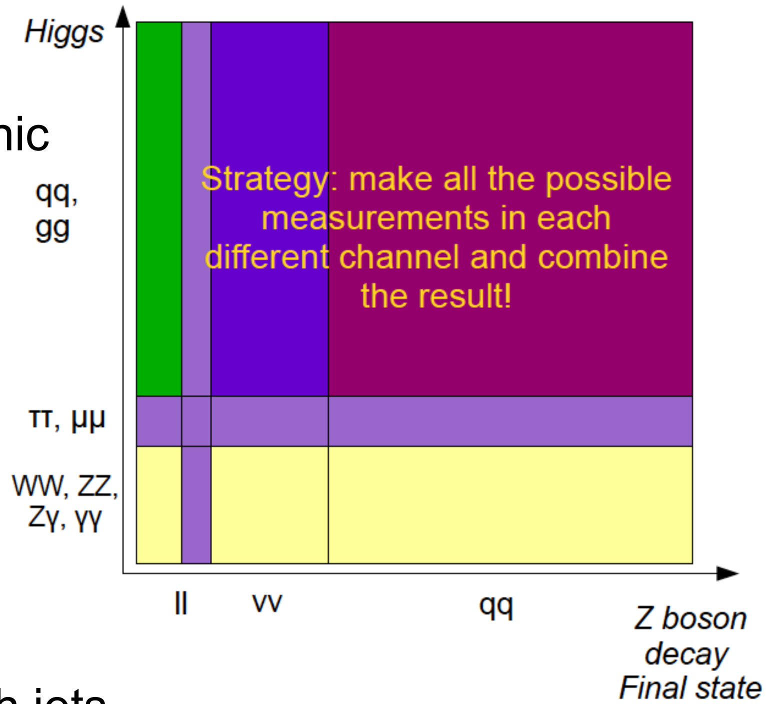
Key figures of the CEPC-SPPC

- **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...**



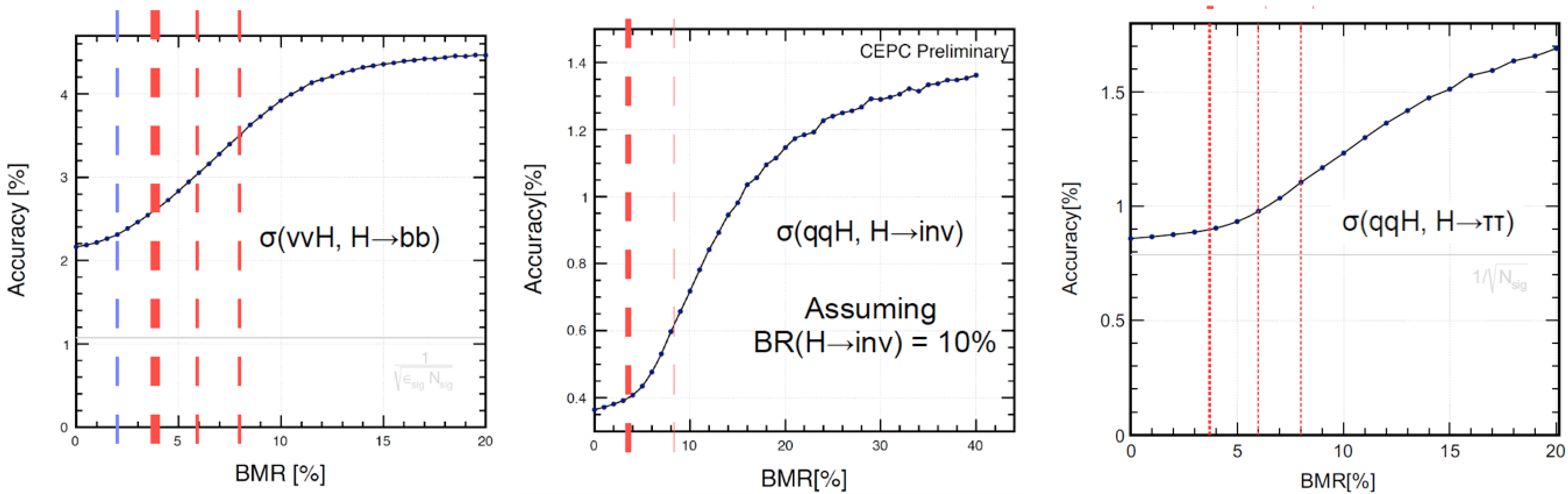
Hadronic system (jet)

- Core of e+e- Higgs factory Physics measurements
  - 97% of CEPC Higgs events are hadronic/semi-leptonic
- Identify the hadronic system in semi-leptonic events
  - lepton identification & missing energy
- 4-momentum measurement of the hadronic system
  - BMR: Invariant Mass Resolution of Hadronic system



- Jet response: essential for differential measurements with jets
  - Applied to events with more than one color singlet fragment into jets: WW/ZZ/ZH event separation in 4-jet final state
  - Color-singlet identification Identify the origin of each final state particle: Jet Clustering & Matching, or beyond?

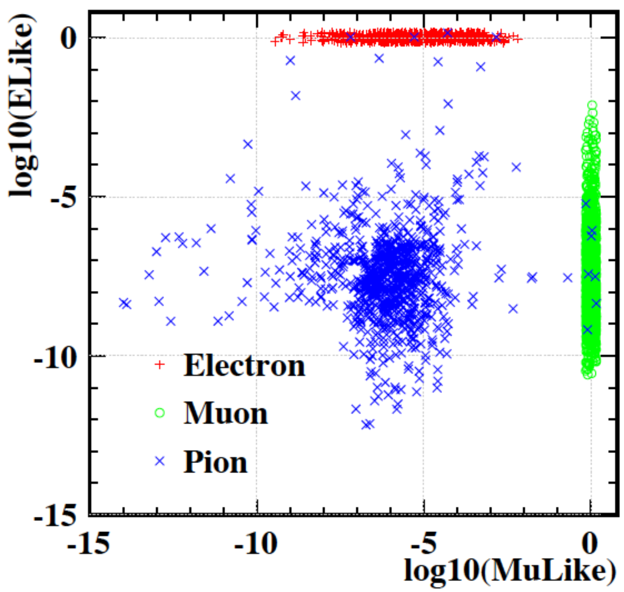
Confirmed with benchmark analyses

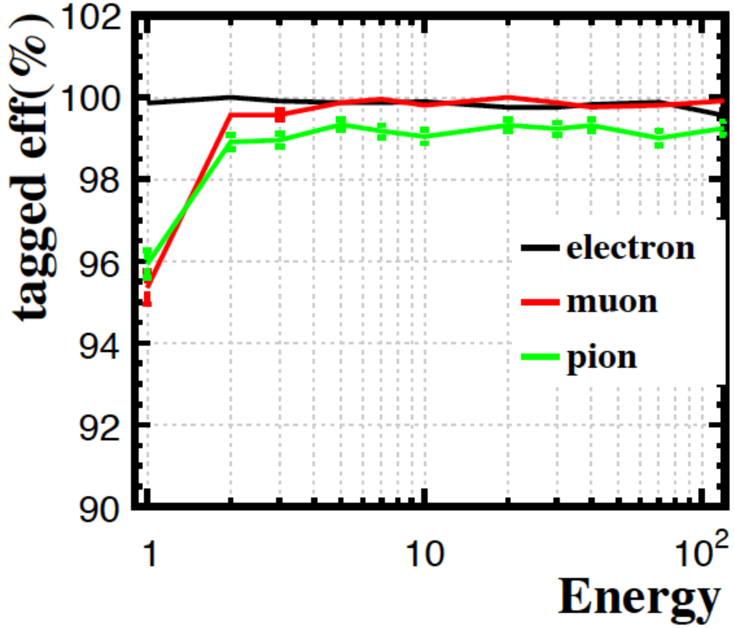


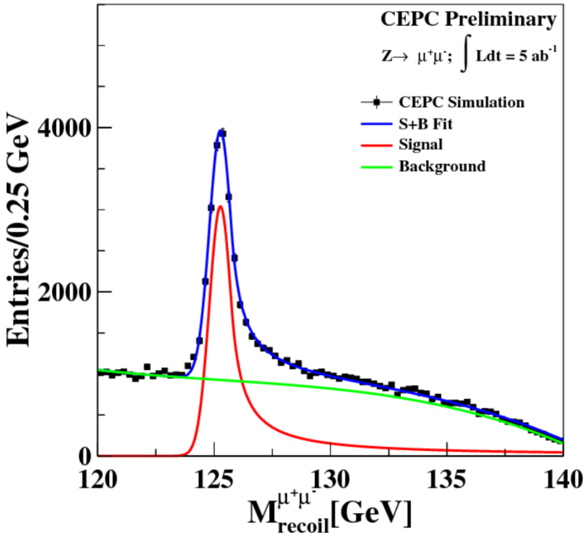
- Boson Mass Resolution: relative mass resolution of vvH, H→gg events
  - Free of Jet Clustering
  - Be applied directly to the Higgs analyses
- The CEPC baseline reaches 3.8%

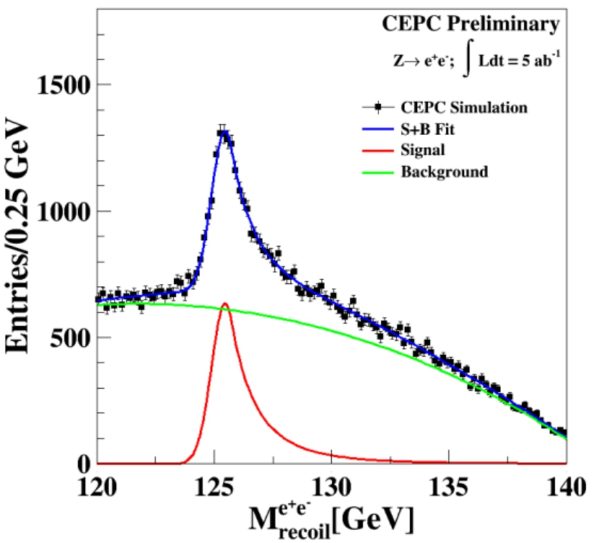
	BMR = 2%	4%	6%	8%
σ(vvH, H→bb)	2.3%	2.6%	3.0%	3.4%
σ(vvH, H→inv)	0.38%	0.4%	0.5%	0.6%
σ(qqH, H→ττ)	0.85%	0.9%	1.0%	1.1%

Lepton: isolated







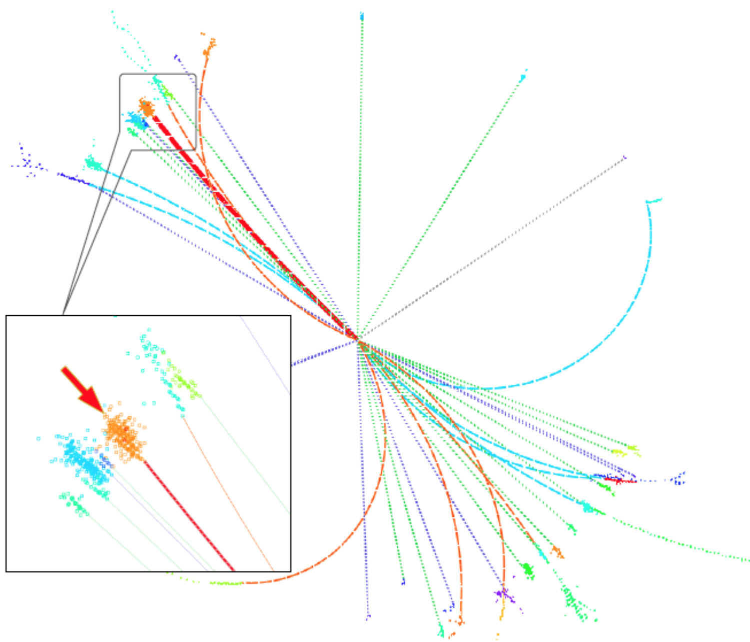


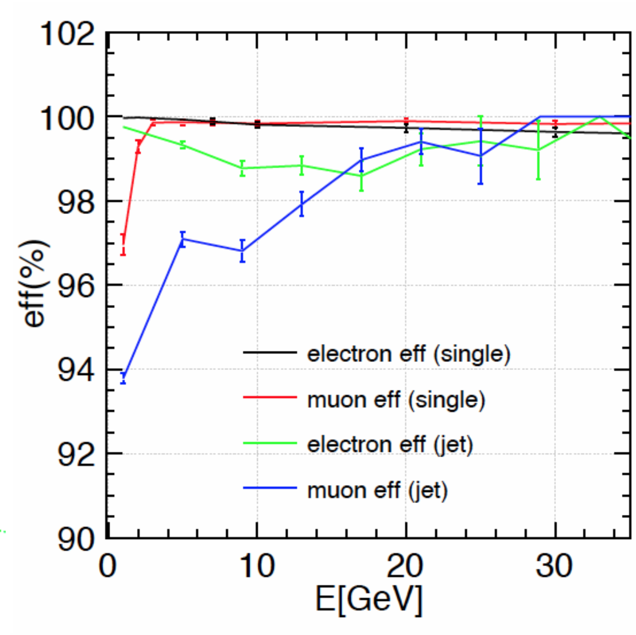
BDT method using 4 classes of 24 input discrimination variables.

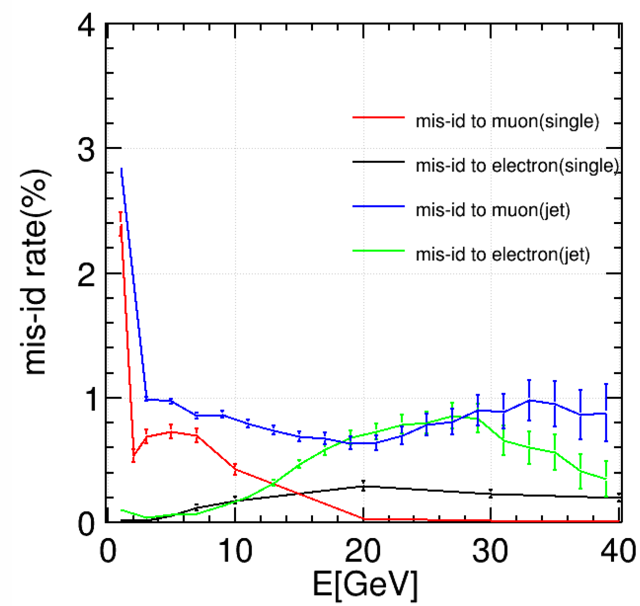
Test performance at: Electron = E_likeness > 0.5 ;
Muon = Mu_likeness > 0.5
Single charged reconstructed particle, for E > 2 GeV:
lepton efficiency > 99.5% && Pion mis id rate ~ 1%

https://link.springer.com/article/10.1140/epjc/s10052-017-5146-5
CEPC-DocDB-id:148, Eur. Phys. J. C (2017) 77: 591

Lepton: inside jet



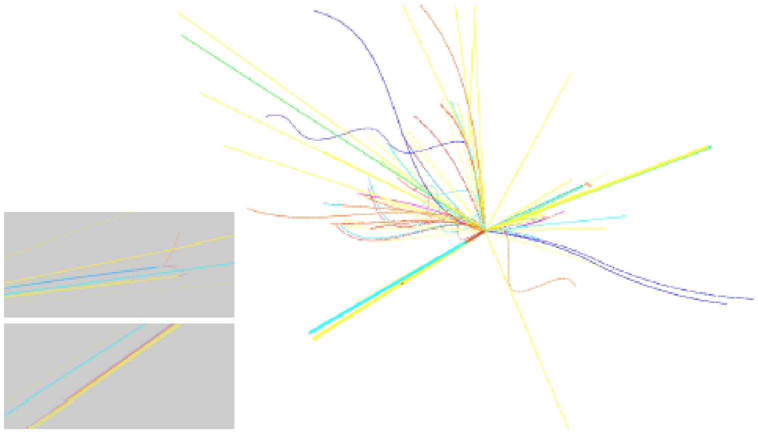




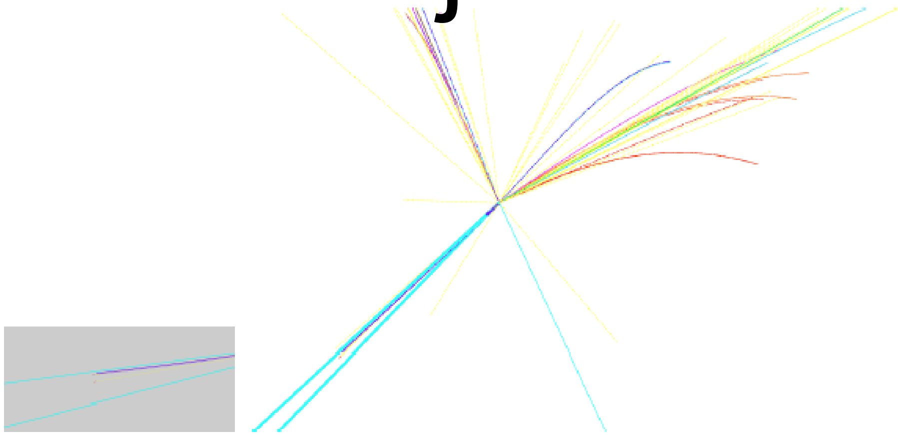
Compared the single particle sample, the jet lepton (at Z->bb sample at sqrt = 91.2 GeV) Performance will be slightly degraded – Due to the limited clustering performance (splitting & containmination).

At the same working point, the efficiency can be reduced by up to 3%; while mis-id rate increases up to 1%. Marginal Impact on Flavor Physics measurements as Bc->tauv.

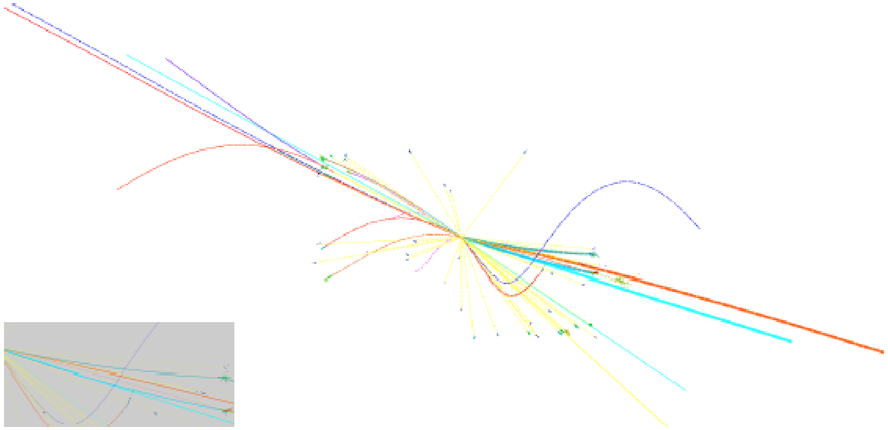
Taus: isolated or inside jets



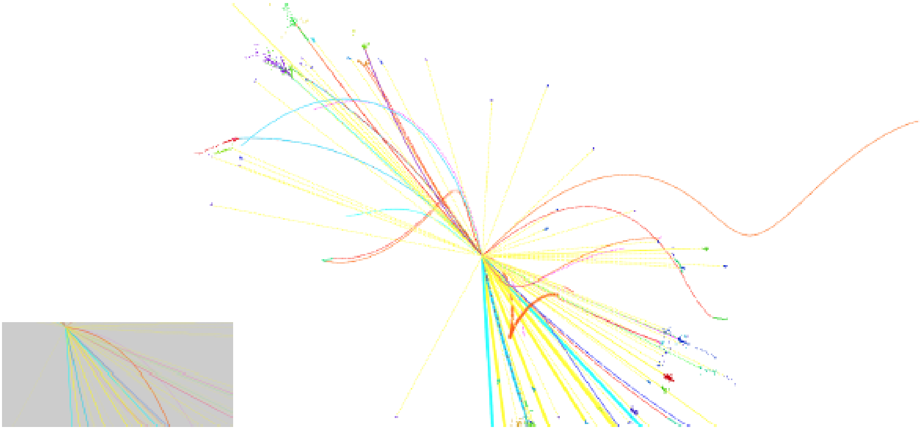
(a) $Z \to qq, H \to \tau\tau$ with two hadronic decay.



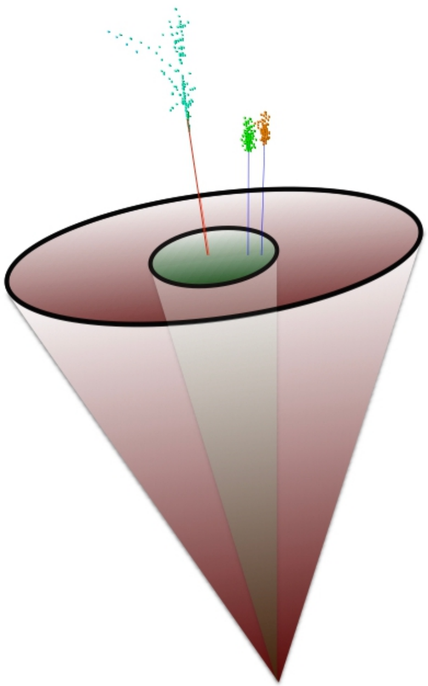
(b) $WW \to \tau\nu qq$ with one leptonic decay.

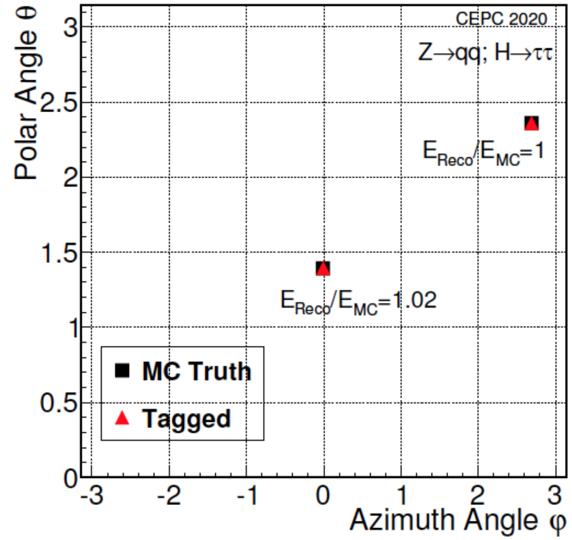


(c) $Z \to b\overline{b}, B_c \to \tau\nu$ with one hadronic dacay.

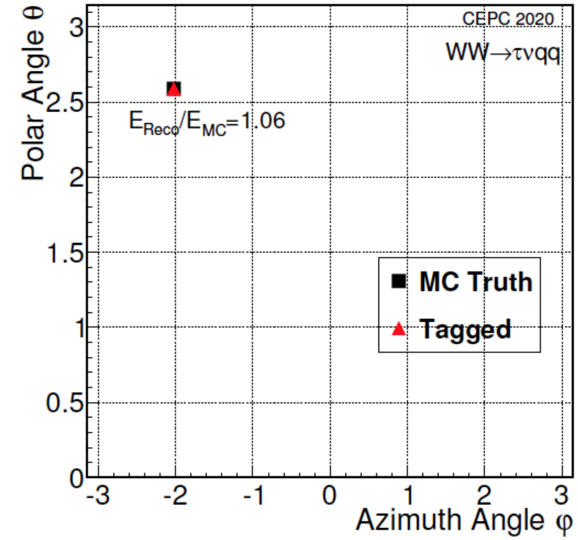


(d) $Z \to b\overline{b}, B_s \to \tau\tau$ with two hadronic decay mixed together.

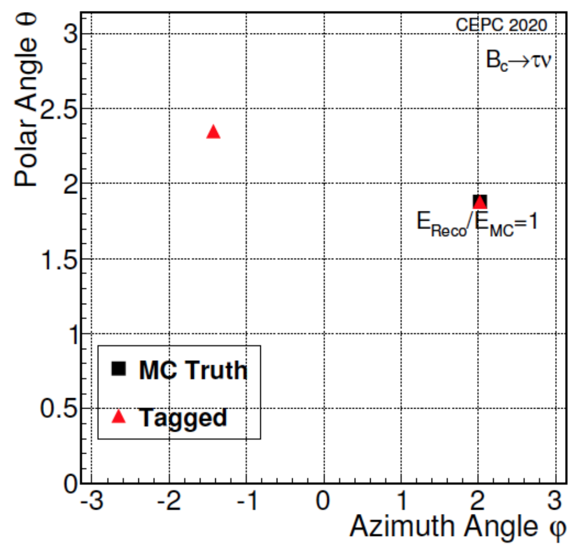




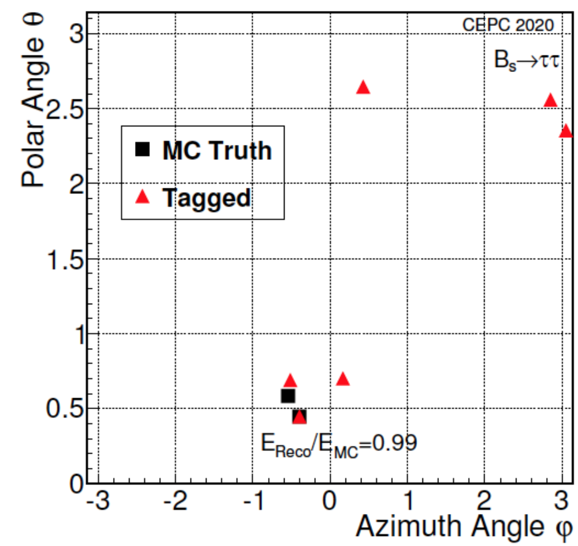
(a) $Z \to qq, H \to \tau\tau$, efficiency=1, purity=1



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

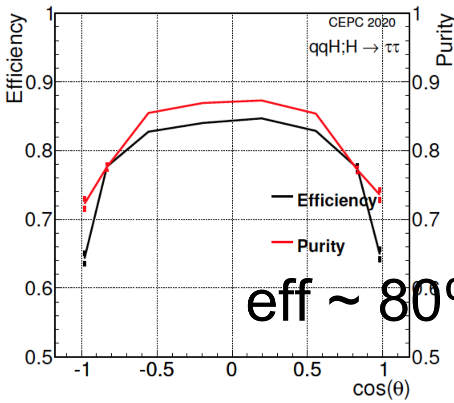


(c) $Z \to b\overline{b}, B_c \to \tau\nu$, efficiency=1, purity=0.5

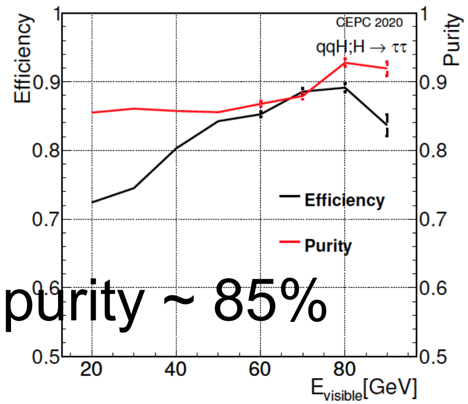


(d) $Z \to b\overline{b}, B_s \to \tau\tau$, efficiency=0.5, purity=0.167

Tau id

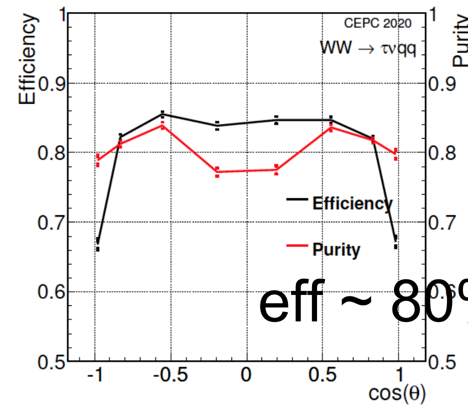


(a) Efficiency and purity performance along with polar angle θ, parameters fixed.

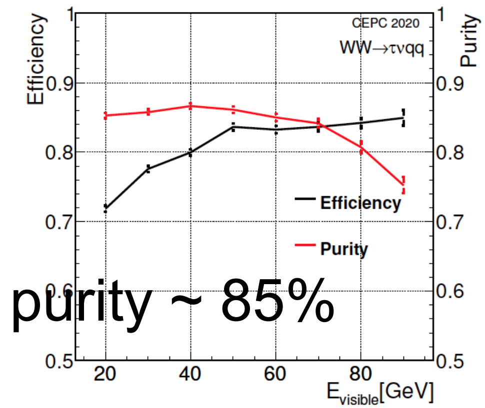


(b) Efficiency and purity performance along with visible energy. The performance above 80 GeV falls as a result of stringent cone selection.

eff ~ 80%, purity ~ 85%

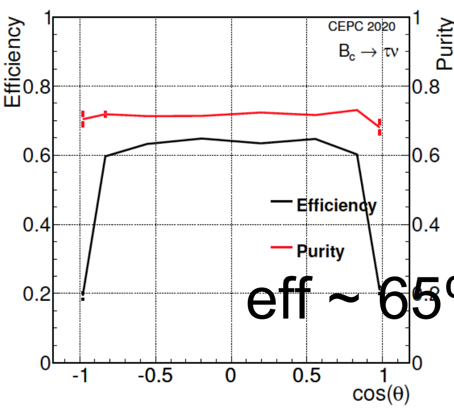


(a) Efficiency and purity performance along with polar angle θ, parameters fixed.

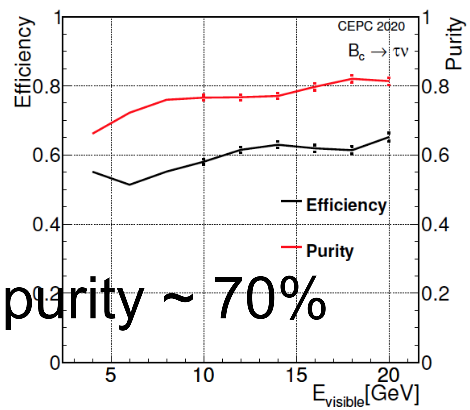


(b) Efficiency and purity performance along with visible energy

eff ~ 80%, purity ~ 85%

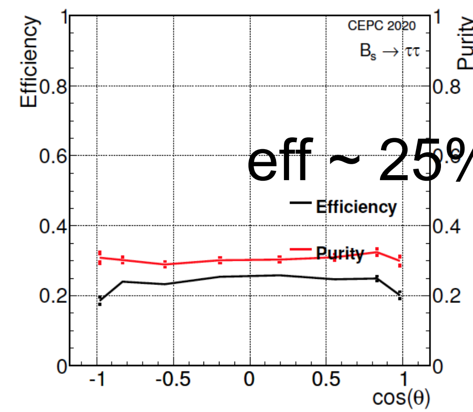


(a) Efficiency and purity performance along with polar angle θ, parameters fixed.

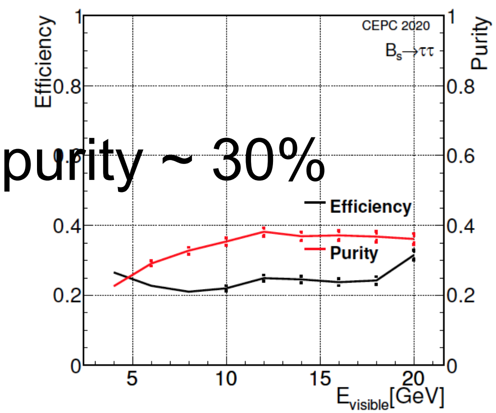


(b) Efficiency and purity performance along with visible energy

eff ~ 65%, purity ~ 70%



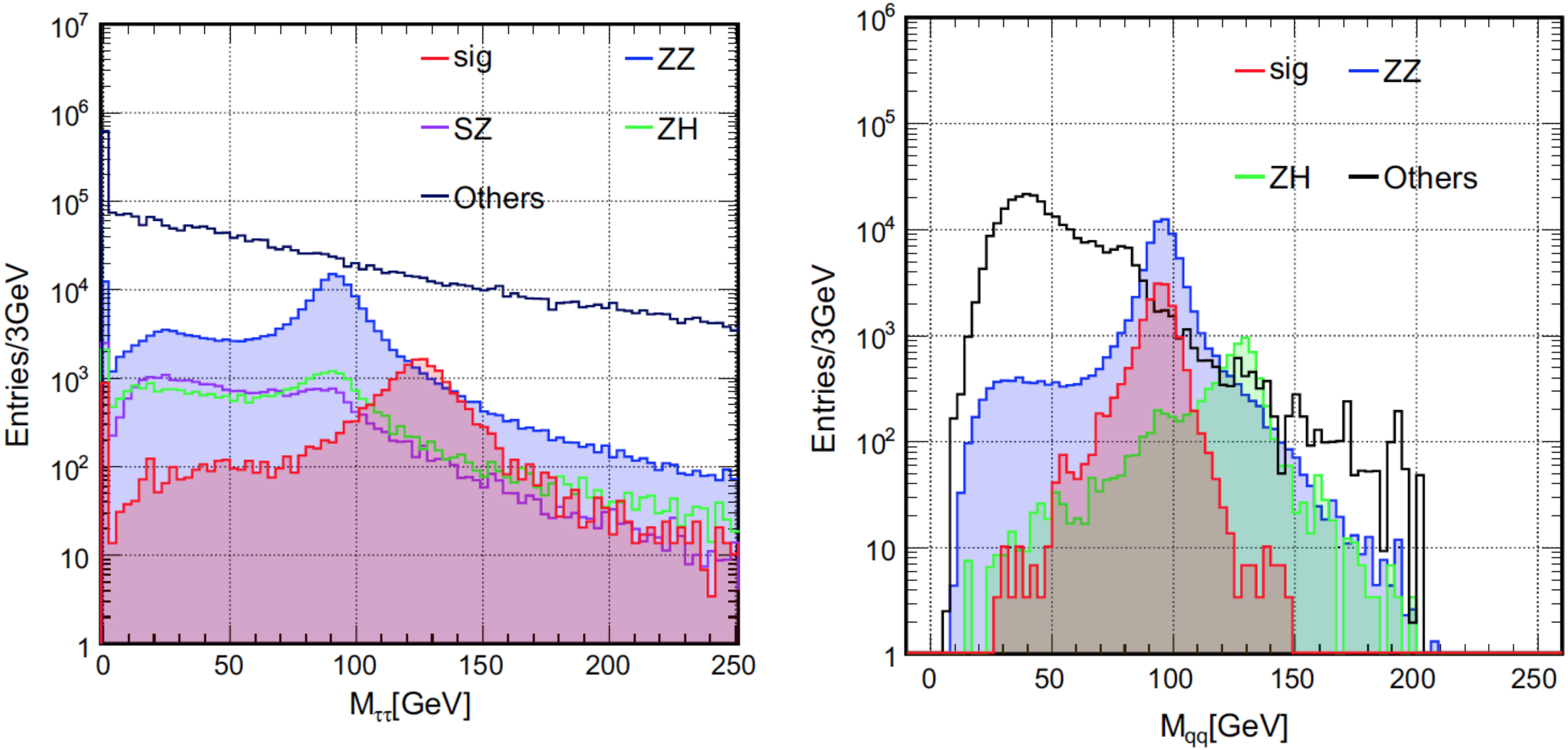
(a) Efficiency and purity performance along with polar angle θ, parameters fixed.



(b) Efficiency and purity performance along with visible energy

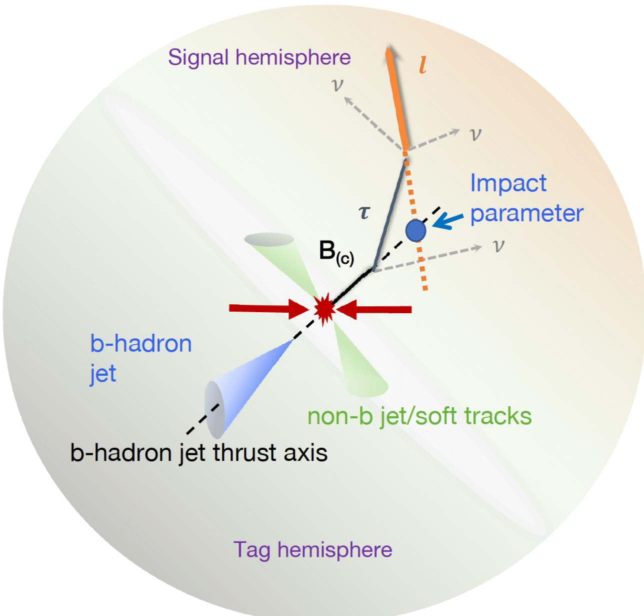
eff ~ 25%, purity ~ 30%

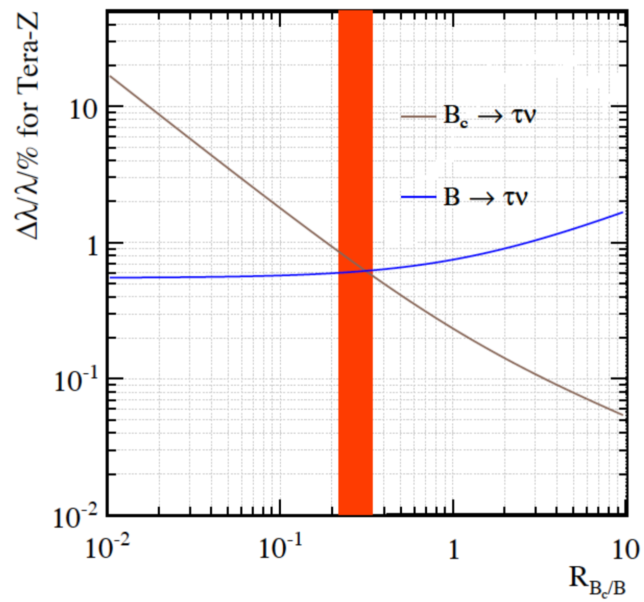
Signal strength measurement of qqH, H→ττ @ 240 GeV



Invariant mass of di-tau: collinear approximation that assumes the neutrinos aligns with the direction of visible tau decay product

Bc → τν





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

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

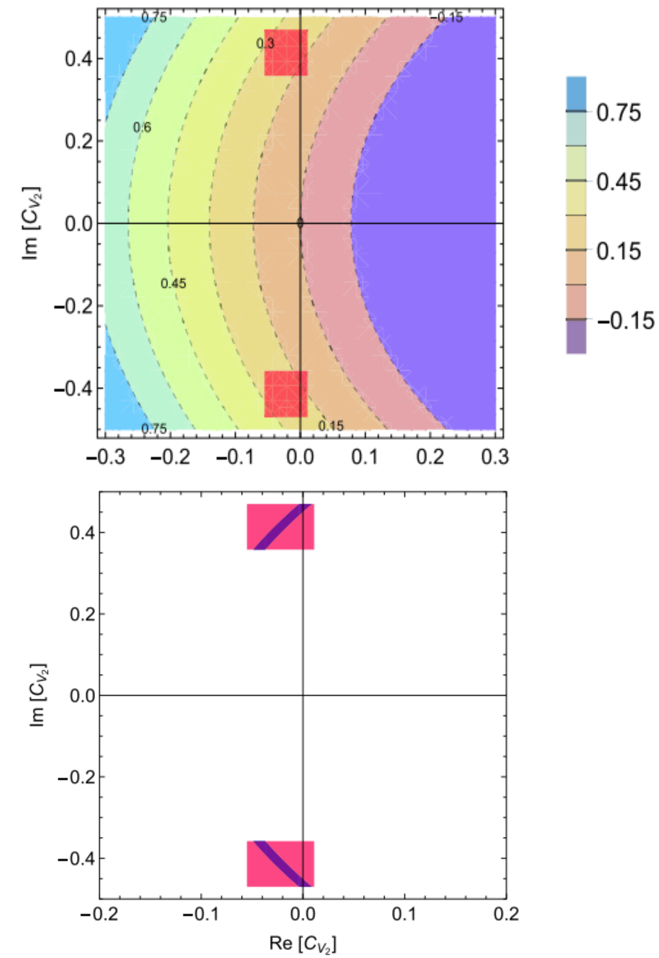
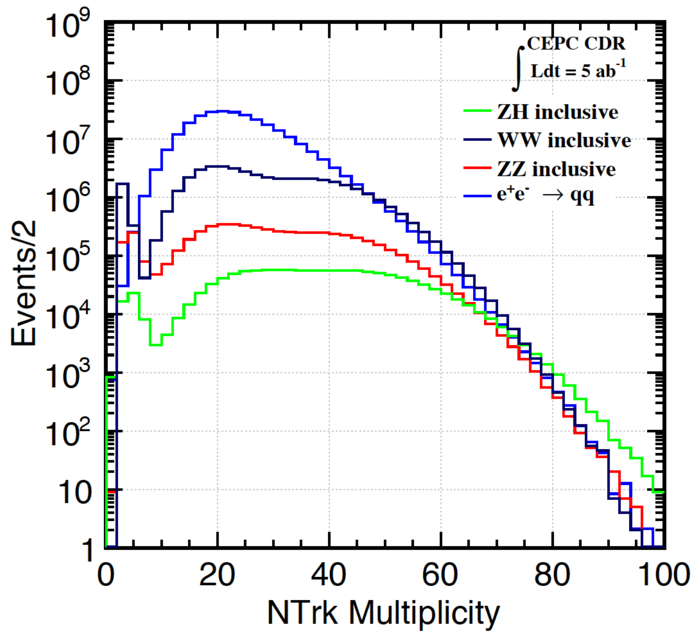
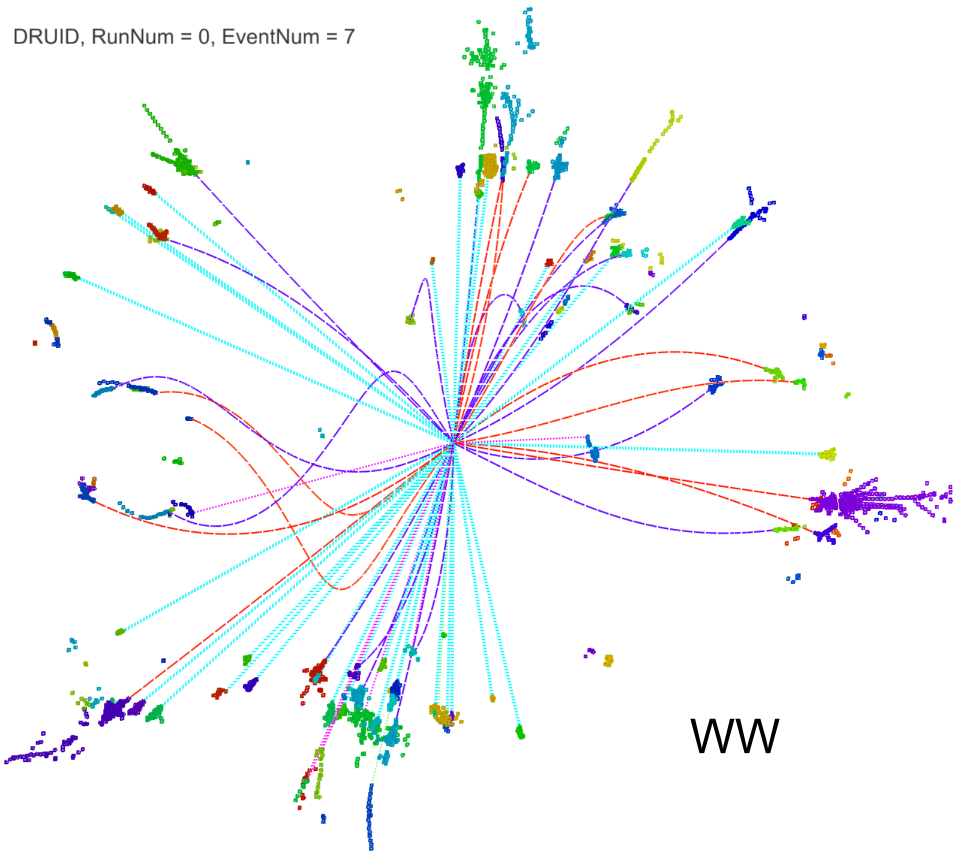


Fig. 10. (color online) Constraints on the real and imaginary parts of C_{V_2}. The red shaded area corresponds to the current constraints using available data on $b \to c\tau\nu$ decays. If the central values in Eq. (9) remain while the uncertainty in $\Gamma(B_c^+ \to \tau^+\nu_\tau)$ is reduced to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

Full hadronic WW-ZZ separation





WW

- Low energy jets! (20 – 120 GeV)
- Typical multiplicity ~ o(100)
- WW-ZZ Separation: determined by
  - Intrinsic boson mass/width
  - Jet confusion from color single reconstruction – jet clustering & pairing
  - Detector response

Visible mass of hadronic system

- Quantified by BMR (Boson Mass Resolution): the relative mass resolution on fully hadronic decay Higgs
- At CEPC, the BMR is determined on vvH event, with a standard cleaning procedure to control the effect of ISR photon, neutrinos generated in Higgs decay, and detector acceptance

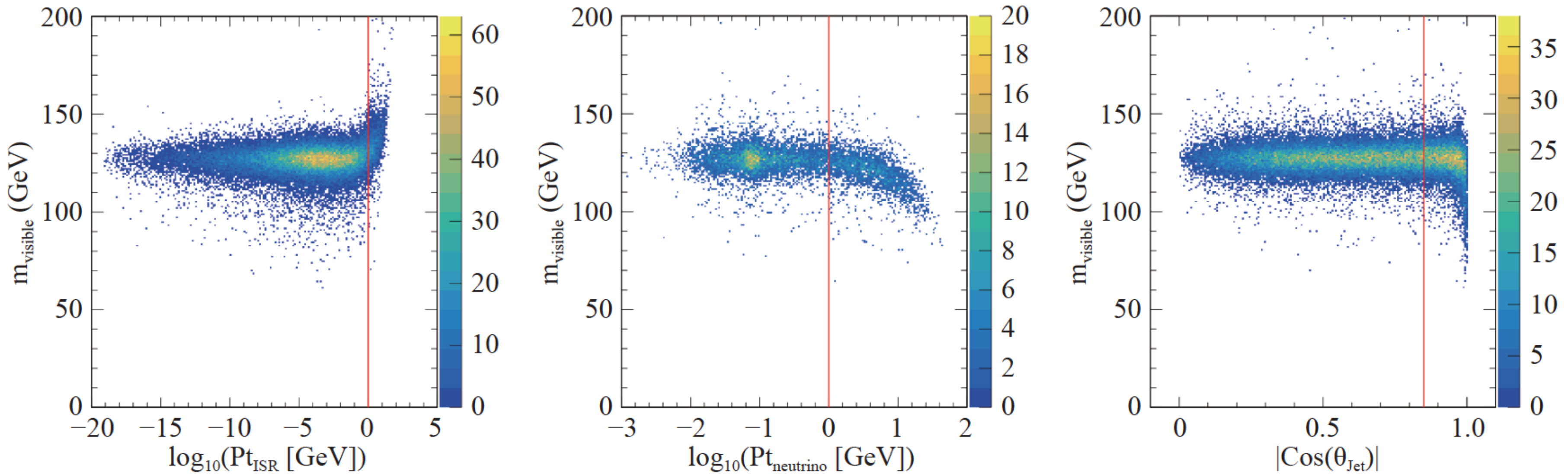


Fig. 4. (color online) Correlation between the reconstructed Higgs boson mass and the sum of the transverse momentum of the ISR photons (Pt_{ISR}) (left); the sum of the transverse momentum of the neutrinos generated by the Higgs bosons decay products ($Pt_{neutrino}$) (center); and the minimum angle between jets and the beam pipe ($|\cos\theta_{Jet}|$) (right). These plots are based on the $H \to gg$ events, and similar conclusions are obtained with $H \to bb$ and cc events. The red lines in the plots are the cut values used for event cleaning.