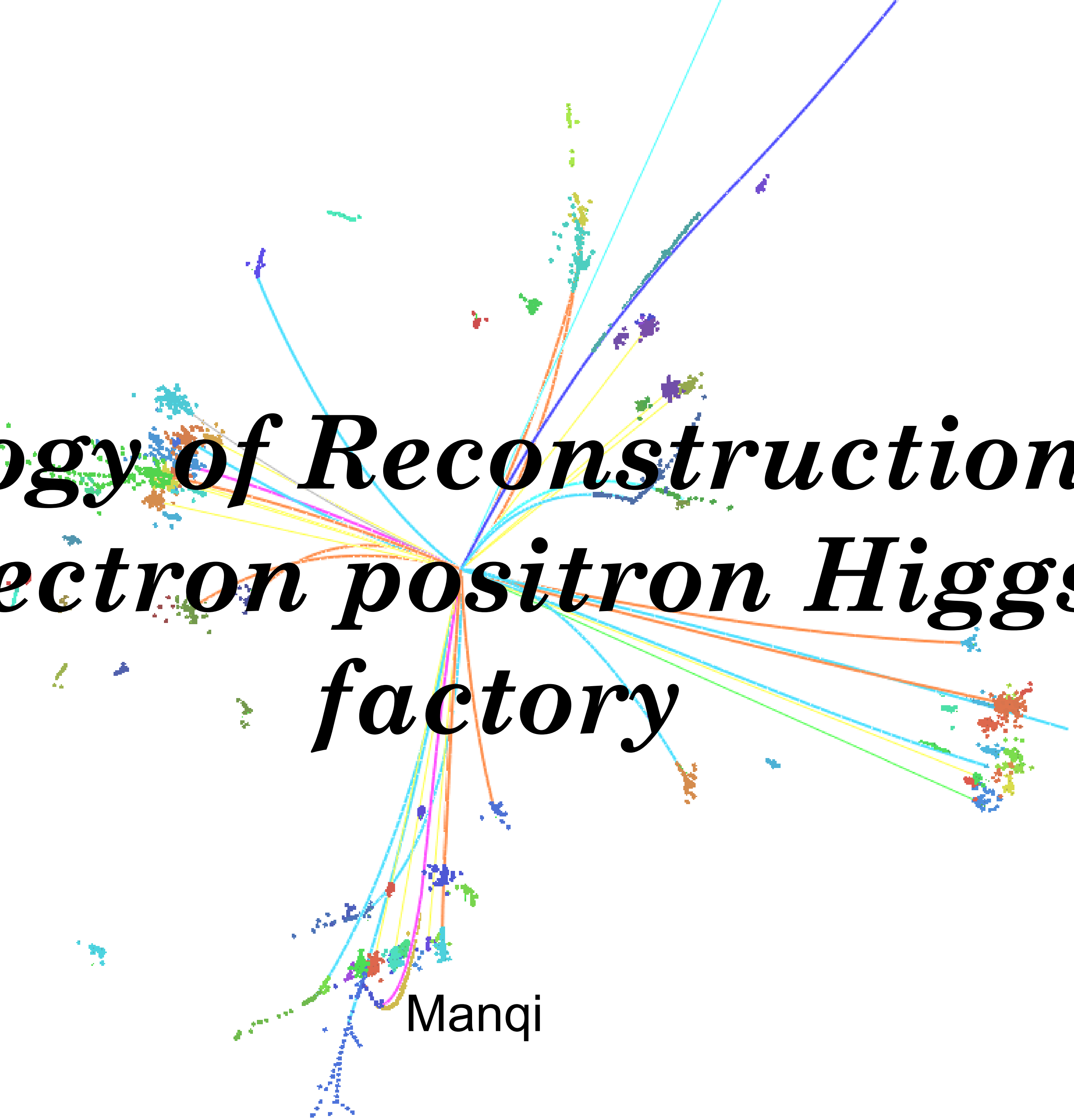
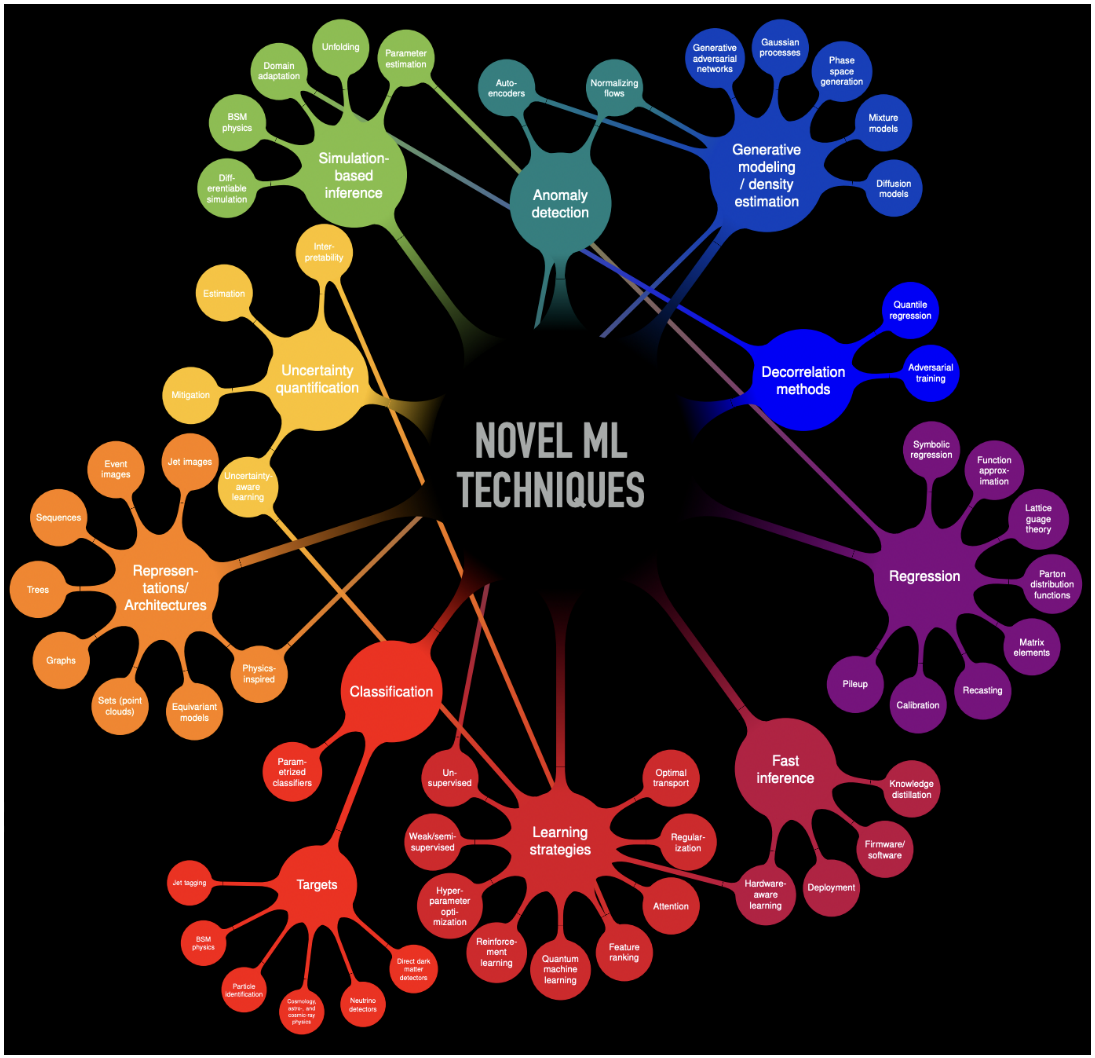
Trilogy of Reconstruction at electron positron Higgs factory



Manqi

AI & HEP

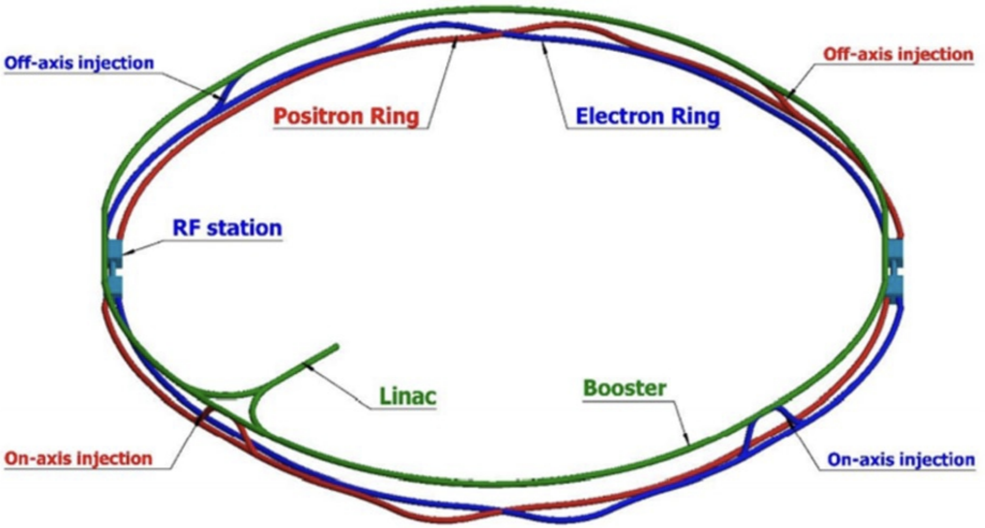


Plot from Javier Mauricio Duarte's talk at ICHEP 2024

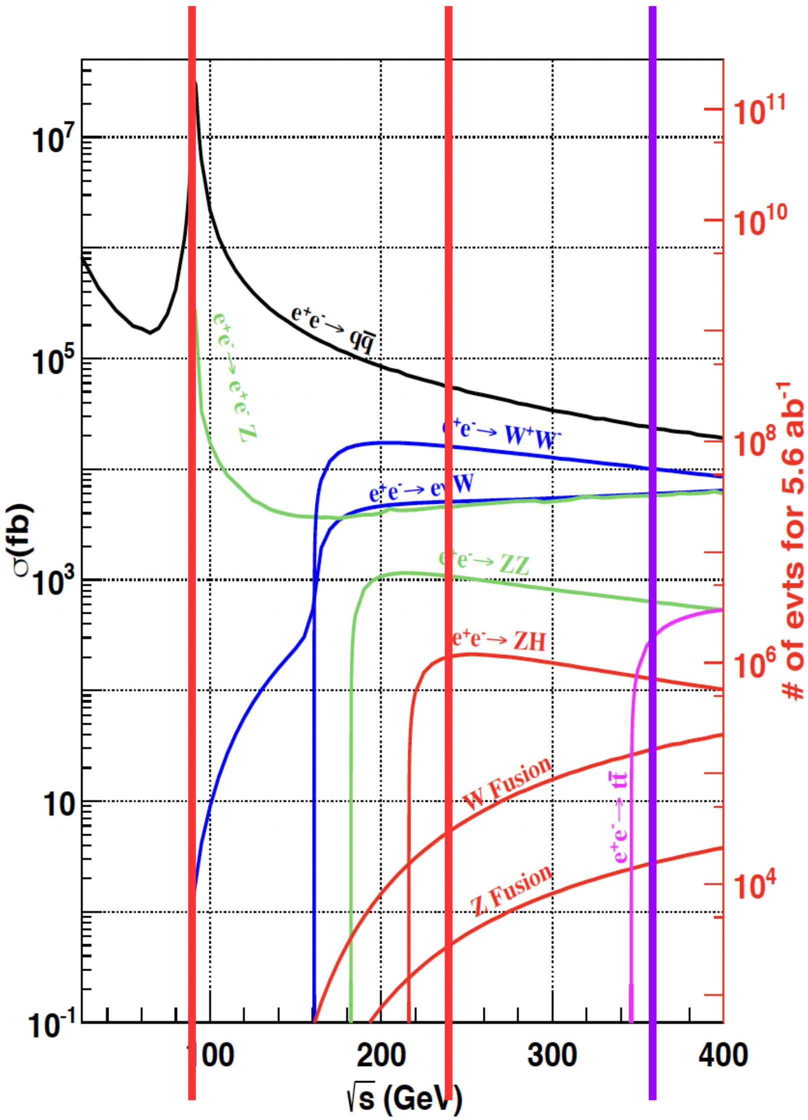
- HEP: data intensive + clear, meaningful & interpretable processing
  - Pioneering for neural network application, i.e., in tracking in 1980s
- An irresistible trend:
  - 17/48 parallel talks of Computing & Data handling session at ICHEP 2024 are relevant to AI: 11 machine learning, 3 deep learning, 3 neural network
  - Many domestic discussions & efforts
- CEPC is actively implementing AI to its data processing:
  - Trigger + DAQ...
  - Simulation: Fast sim.
  - Reconstruction: PFA, Jet Origin id, etc
  - Analysis

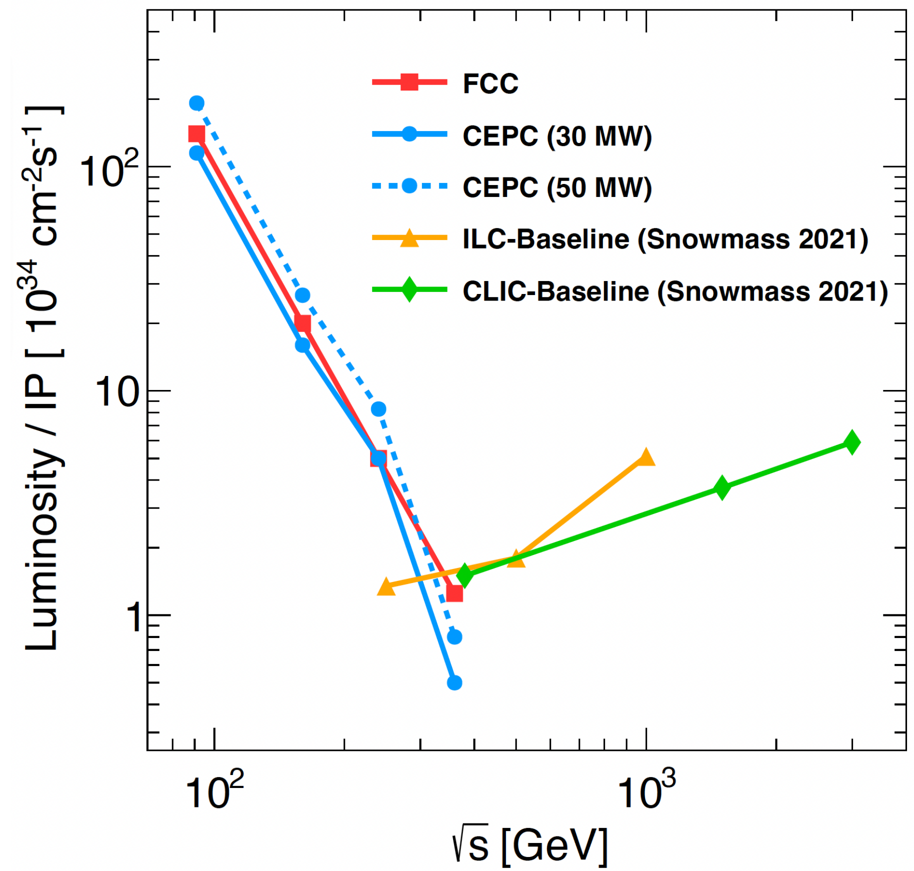
Outline

- *Disclaimer: this talk is not a review talk of all recent progress at Higgs factories, but only focus on a few recent progress that I've been involved*
- CEPC Physics & requirements
- Jet origin identification
- 1-1 correspondence reconstruction
- Progress with LLM and Color Singlet identification
- Discussion



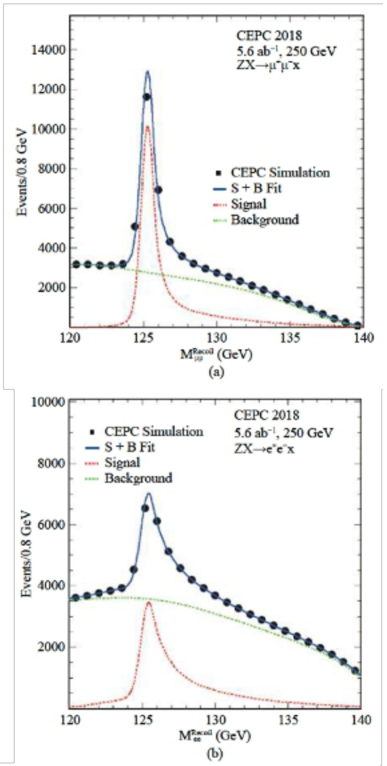
Yields ~ Xsec * Lumi * Time

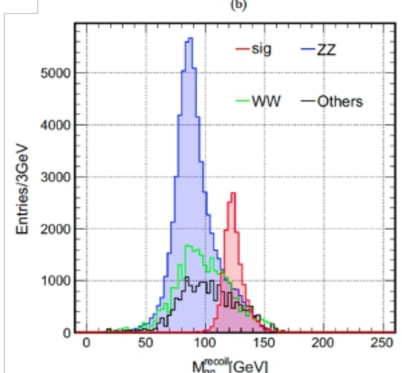




- 4 Million Higgs (10 years)
- ~ 1 Giga W (1 year) + 4 Tera Z (2 years)
- Upgradable: Top factory (500 k ttbar)

CEPC Physics study





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Precision Higgs physics at the CEPC*

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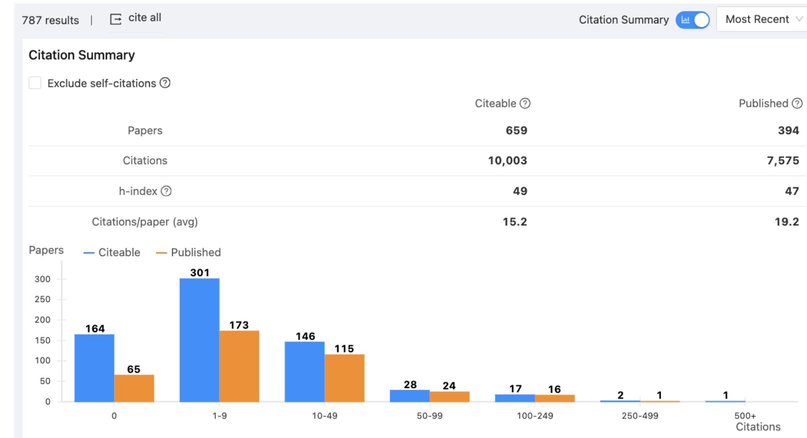


Table 2.1: Precision of the main parameters of interests and observables at the CEPC, from Ref. [1] and the references therein, where the results of Higgs are estimated with a data sample of 20 ab^{-1}. The HL-LHC projections of 3000 fb^{-1} data are used for comparison. [2]

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}

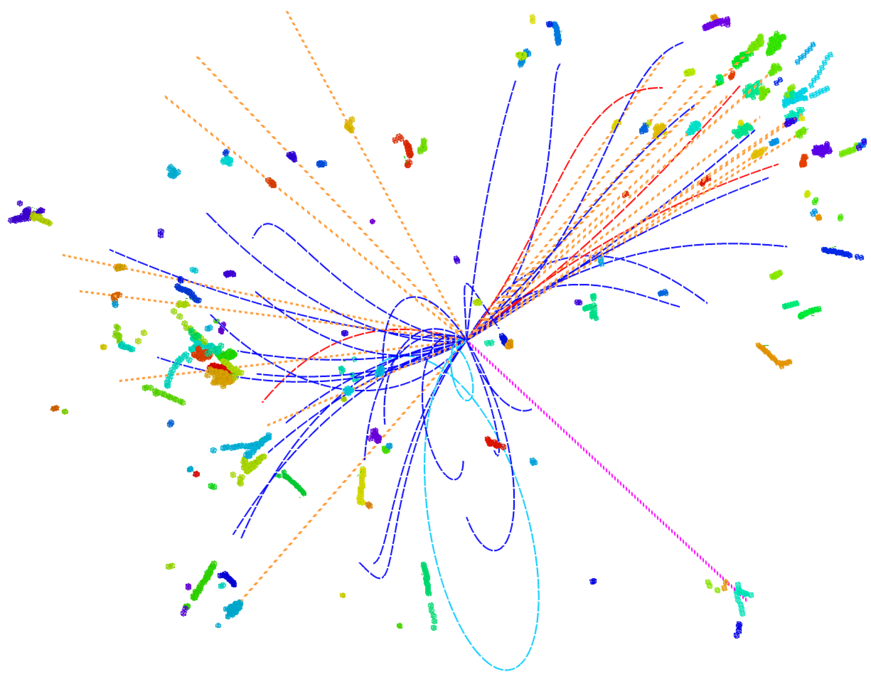
Scientific Significance quantified by **CEPC physics** studies, via full simulation/phenomenology studies:

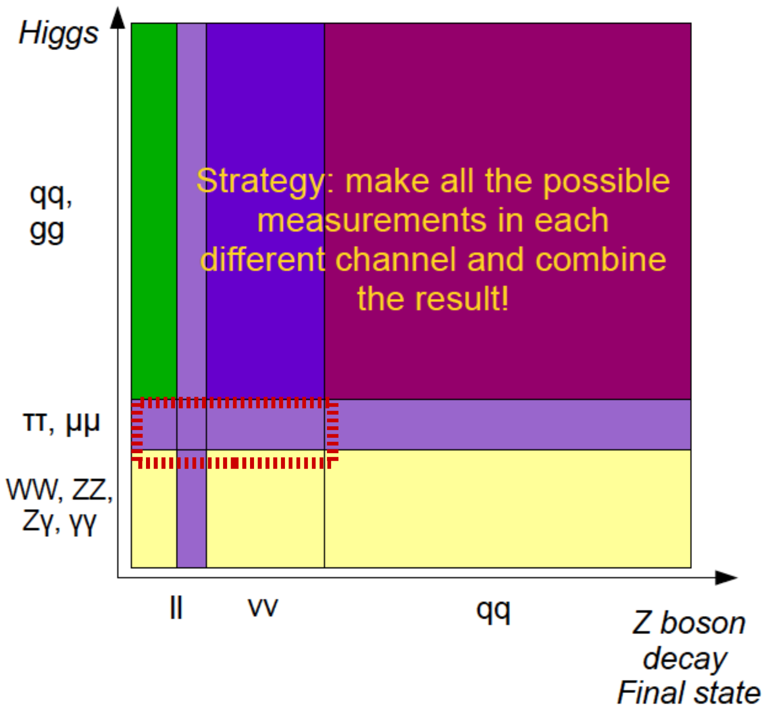
- Higgs: Precisions exceed HL-LHC ~ 1 order of magnitude.
- EW: Precision improved from current limit by 1-2 orders.
- Flavor Physics, sensitive to NP of 10 TeV or even higher.
- Sensitive to varies of NP signal.
- …

White papers +
~300 Journal/AxXiv citables

Performance requirements

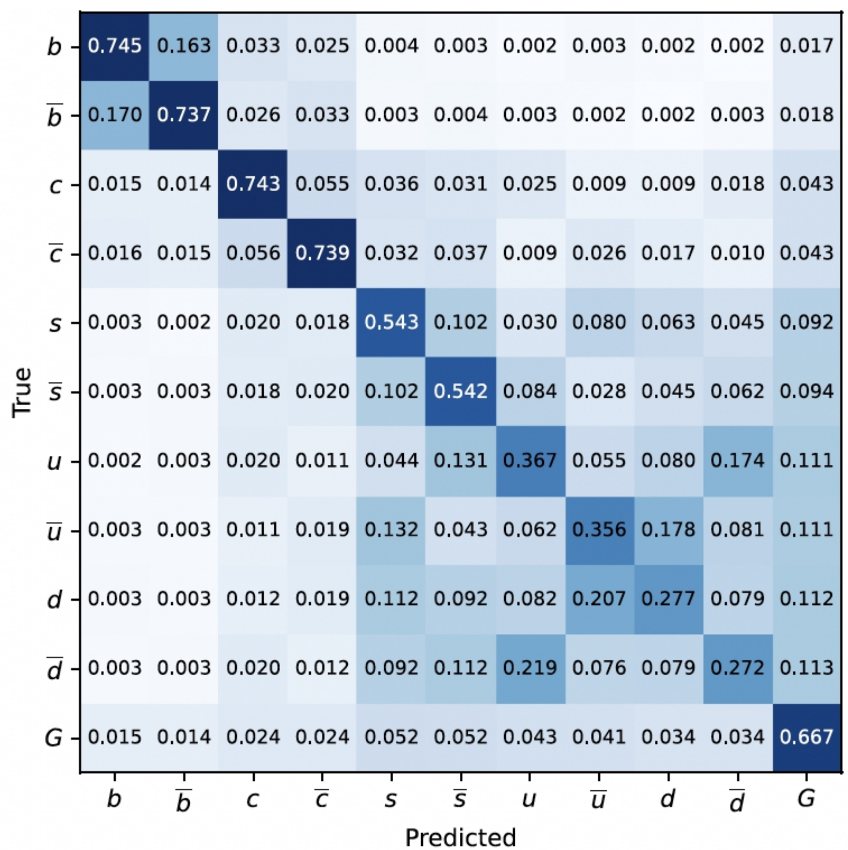
- To well reconstruct all Physics Object, especially Jets
  - Z & W: ~ 70% goes to a pair of jets
  - Higgs: ~97% final state with jets (ZH events)
  - Top: t → W + b

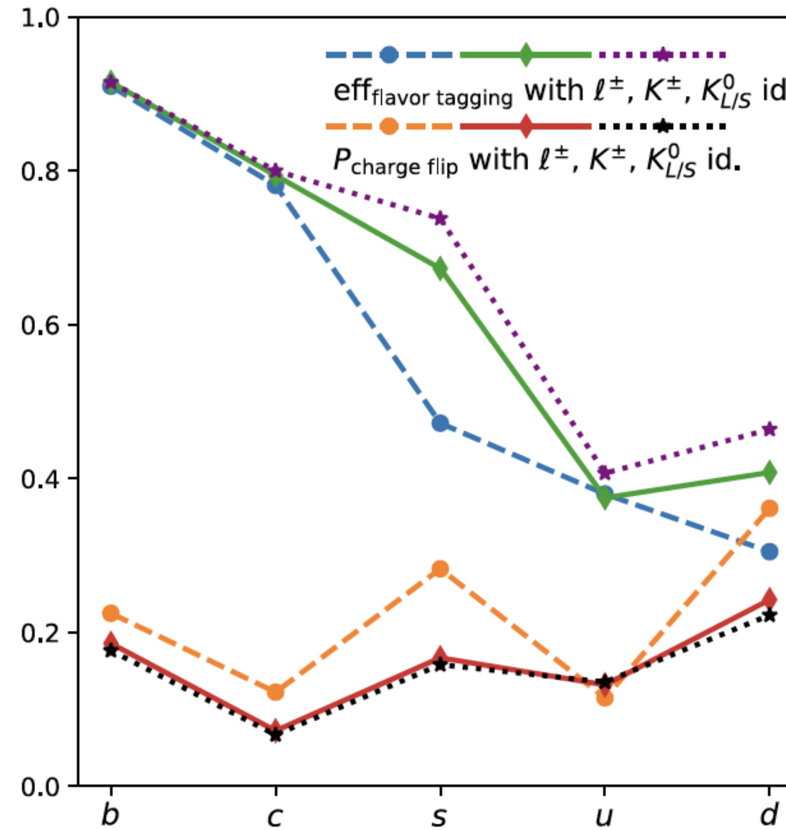




- Look inside the jet: **1-1 correspondence reco.**
  - Larger acceptance...
  - Excellent intrinsic resolutions
  - Extremely stable...
- Be addressed by state-of-art detector design, technology, and reconstruction algorithm!

Jet origin id

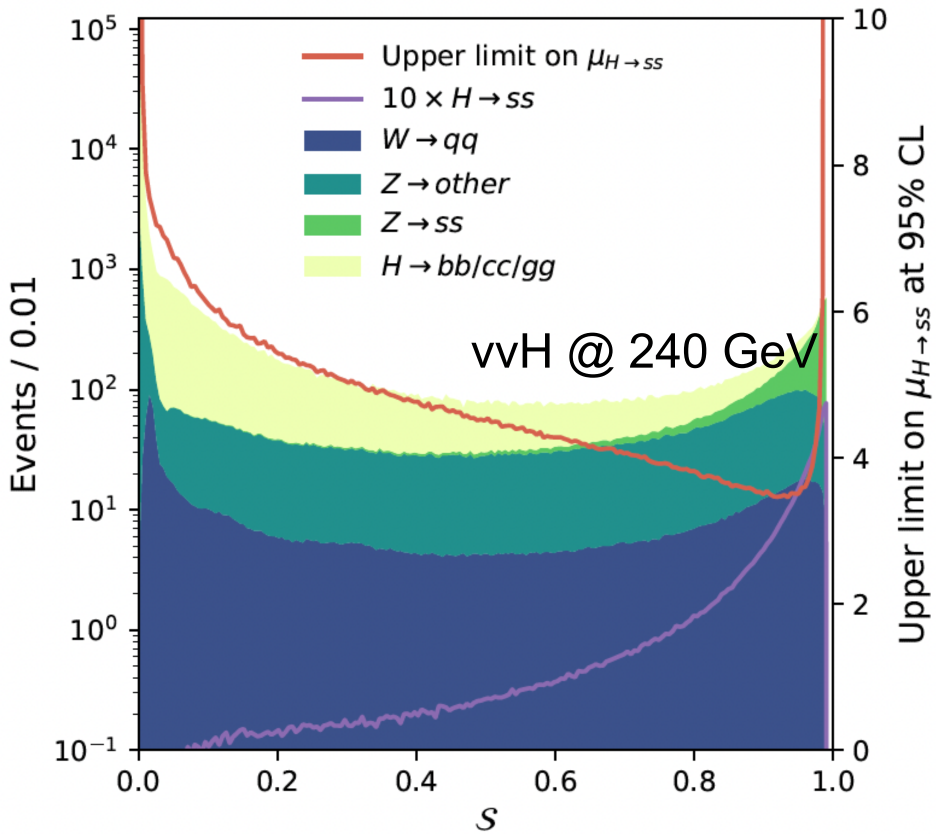


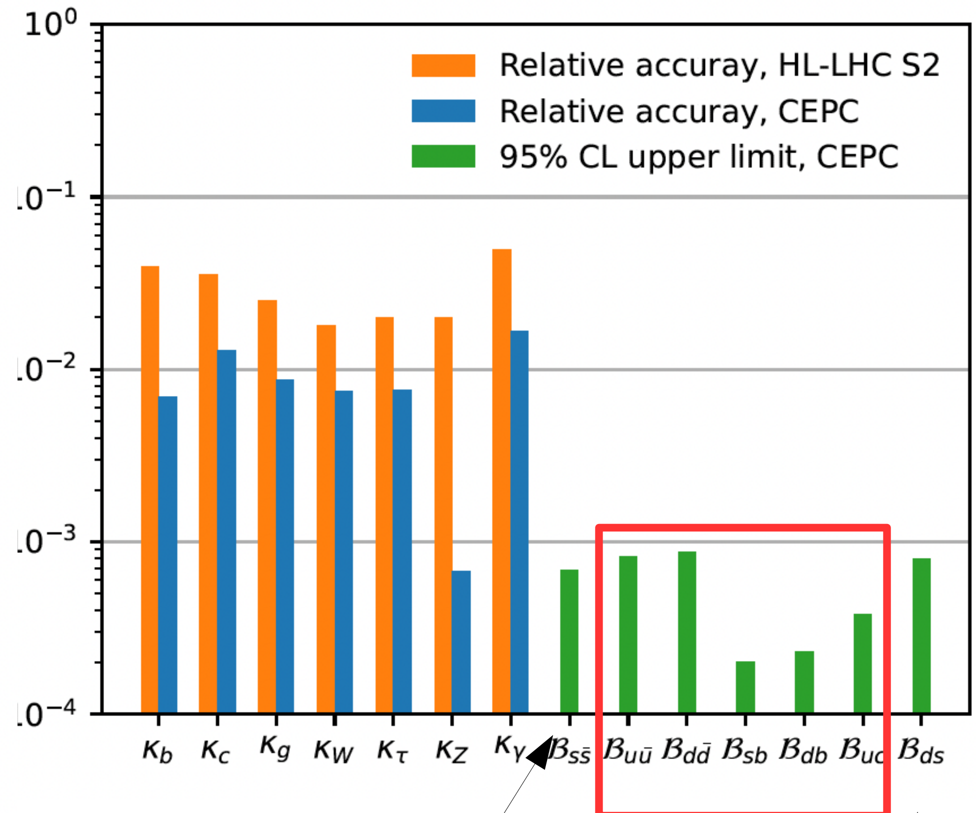


- 11 categories (5 quarks + 5 anti quarks + gluon) identification, realized at Full Simulated di-jet events at CEPC CDR baseline with Arbor + ParticleNet
- Published in PRL *132, 221802 (2024)*. Comment from the referee: *"demonstrate the world-leading performance of tagger", "a "game changer" and opens new horizons for precision flavor studies at all future experiments."*

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

Benchmark analyses: Higgs rare/FCNC



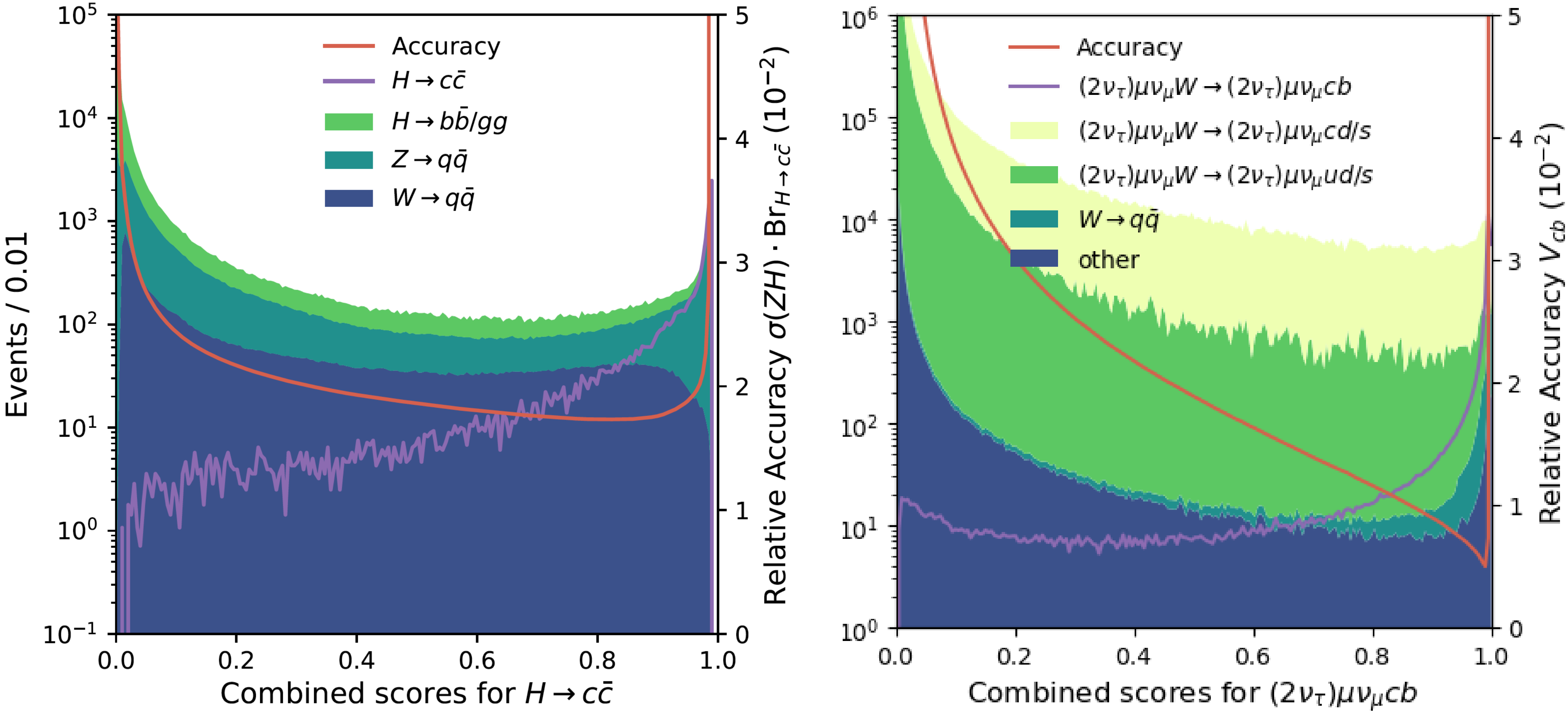


Improved by ~3 times

Improved by 1-2 orders of magnitudes

Presumably... firstly quantified

More benchmarks



- From Jet Flavor Tagging to Jet Origin ID:
  - vvH, H→cc: 3% → 1.7%
  - Vcb: 0.75% → 0.5% (other CKM elements on the target list)

Updated result on $\sin^2\theta^l_{eff}$ measurement

Table 2. Sensitivity S of different final state particles.

$\sqrt{s}$/GeV	S of $A^{e/\mu}_{FB}$	S of A^{d}_{FB}	S of A^{u}_{FB}	S of A^{s}_{FB}	S of A^{c}_{FB}	S of A^{b}_{FB}
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

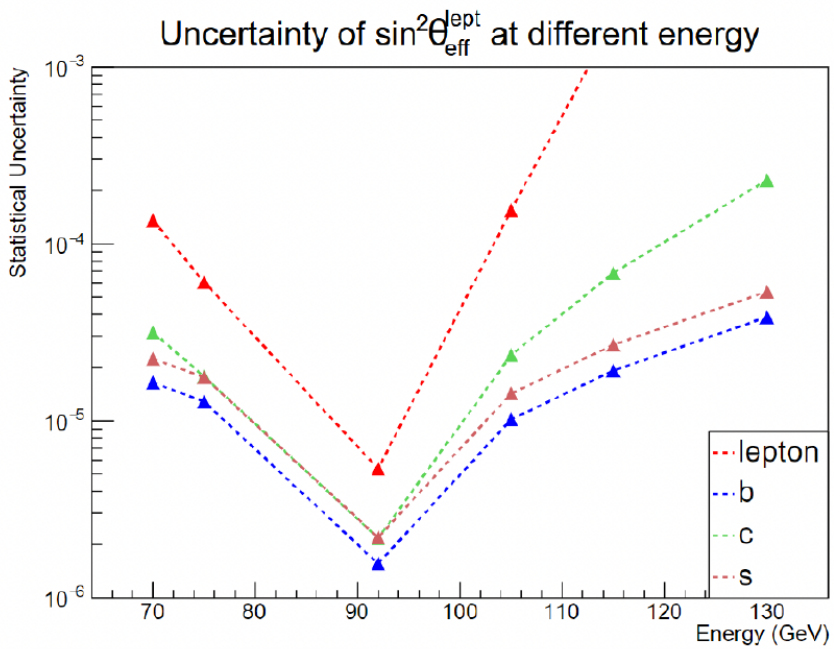
Table 3. Cross section of process $e^+e^- \to f\bar{f}$ calculated using the ZFITTER package. Values of the fundamental parameters are set as $m_Z = 91.1875$ GeV, $m_t = 173.2$ GeV, $m_H = 125$ GeV, $\alpha_s = 0.118$ and $m_W = 80.38$ GeV.

$\sqrt{s}$/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

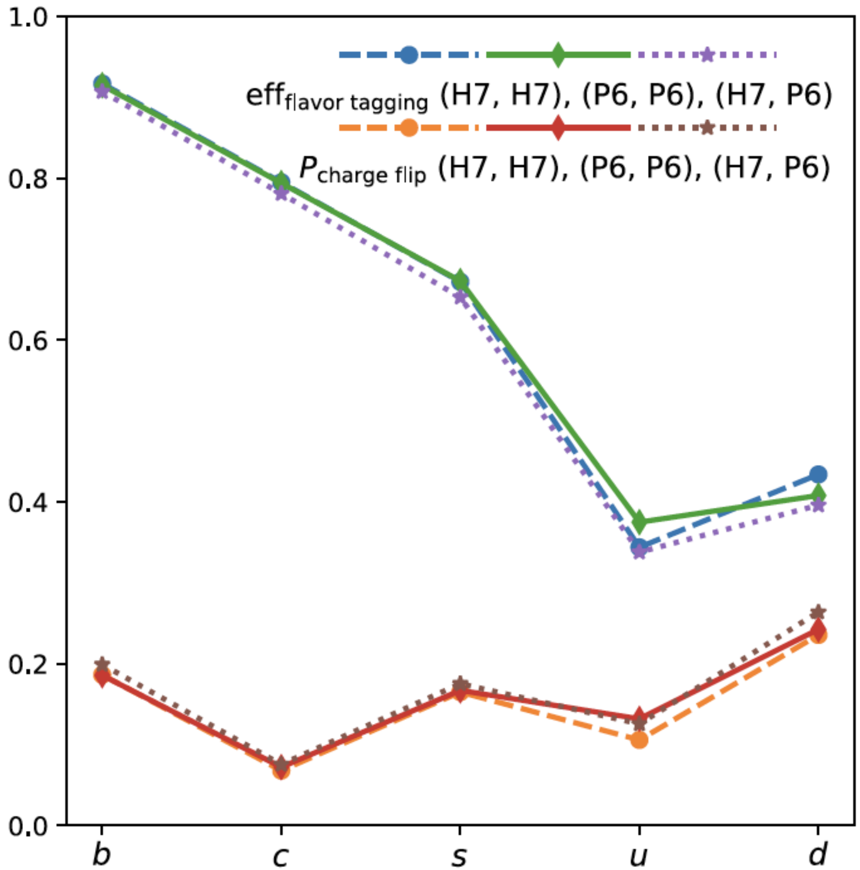
Expected statistical uncertainties on $\sin^2\theta^l_{eff}$ measurement.

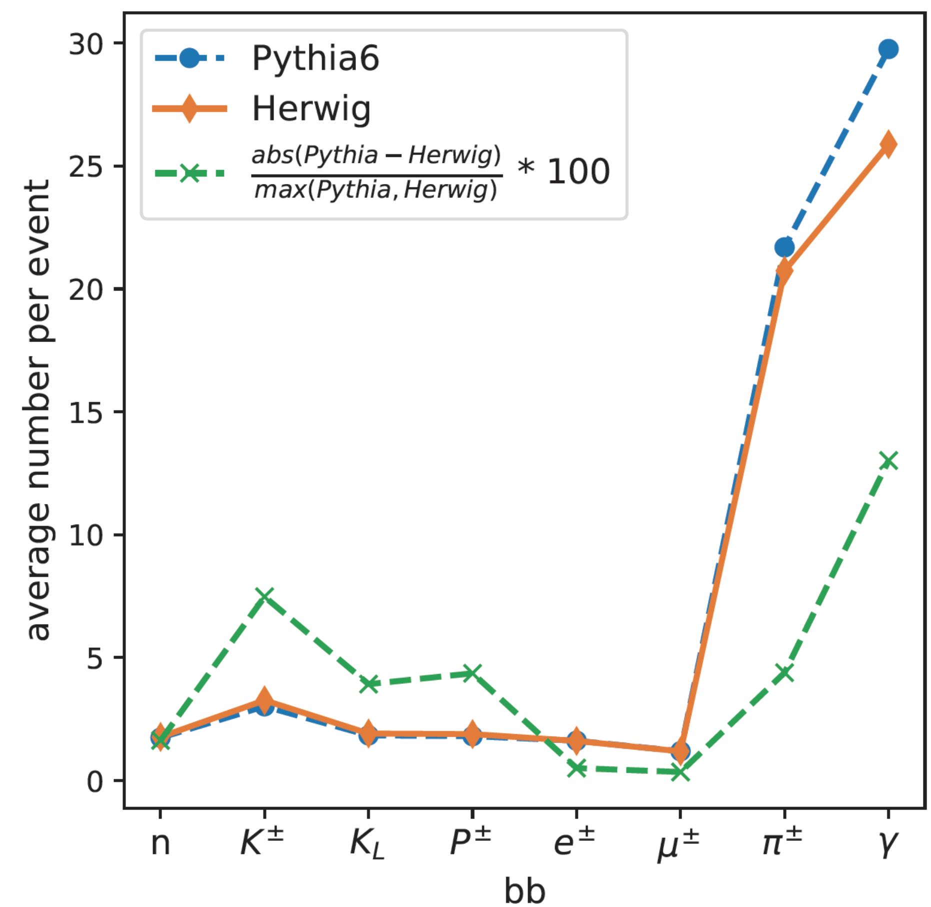
(Using one-month data collection, ~ *4e12/24 Z events* at Z pole)



$\sqrt{s}$	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}

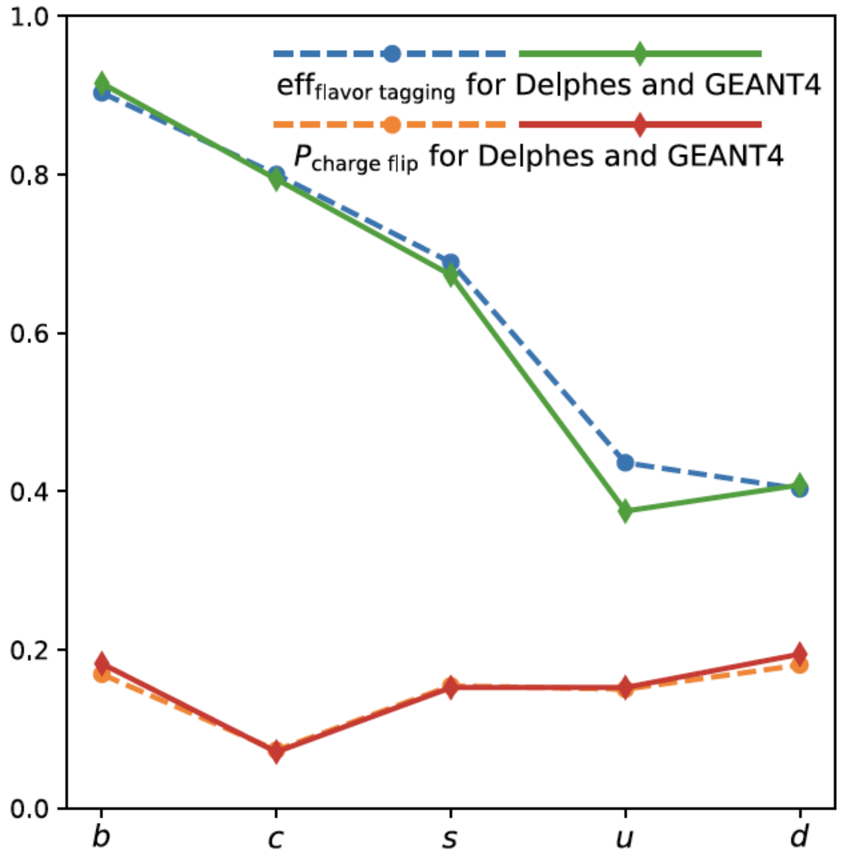
V.S. Hadronization models



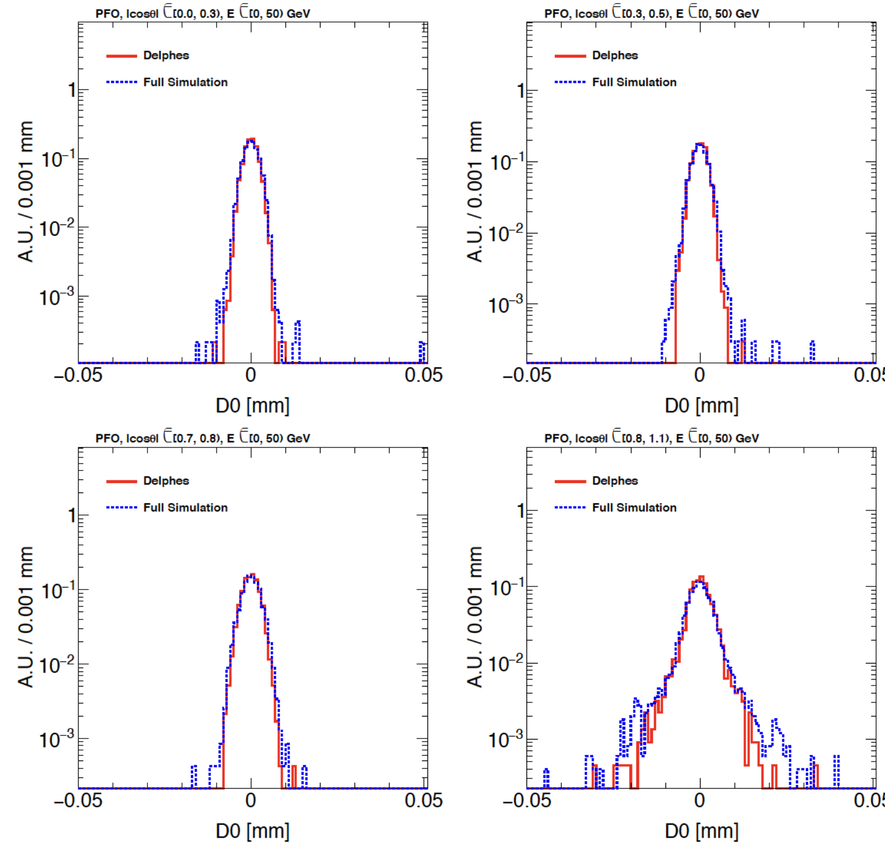


- Different hadronization model have significantly different predictions...

Fast/Full Simulation

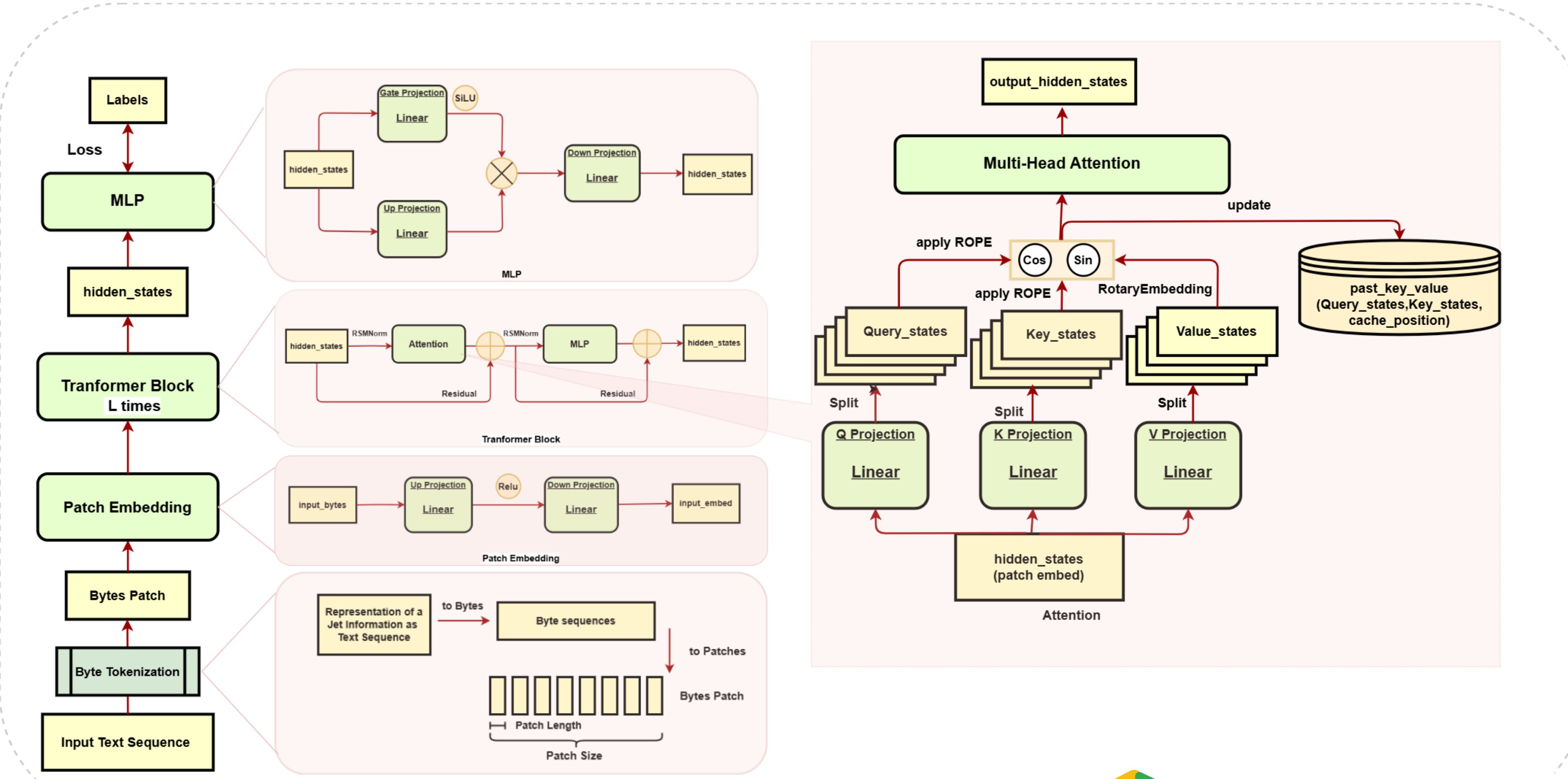


Z->μμ (91.2 GeV)



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

Recent update: from specialized Models to LLM

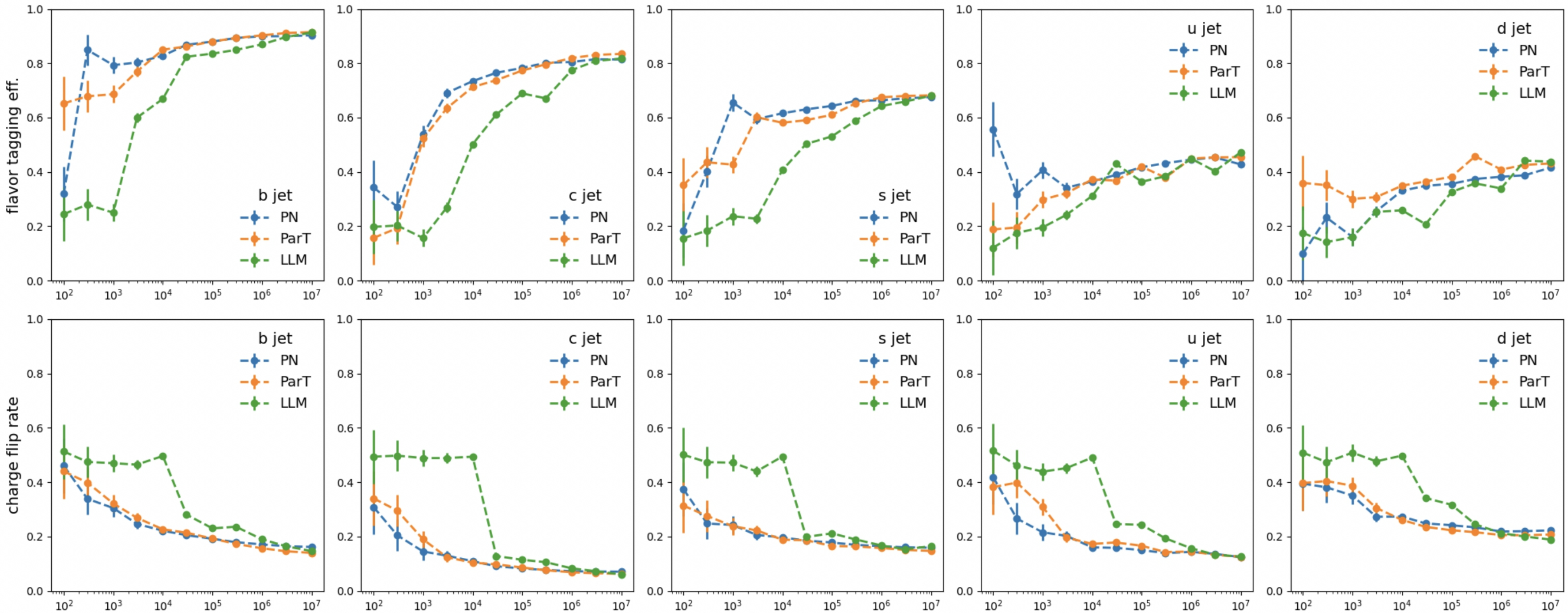


BIN-BBT Model

- New tokenization method to address numeric problems at LLM

超对称
Super Symmetry Technologies

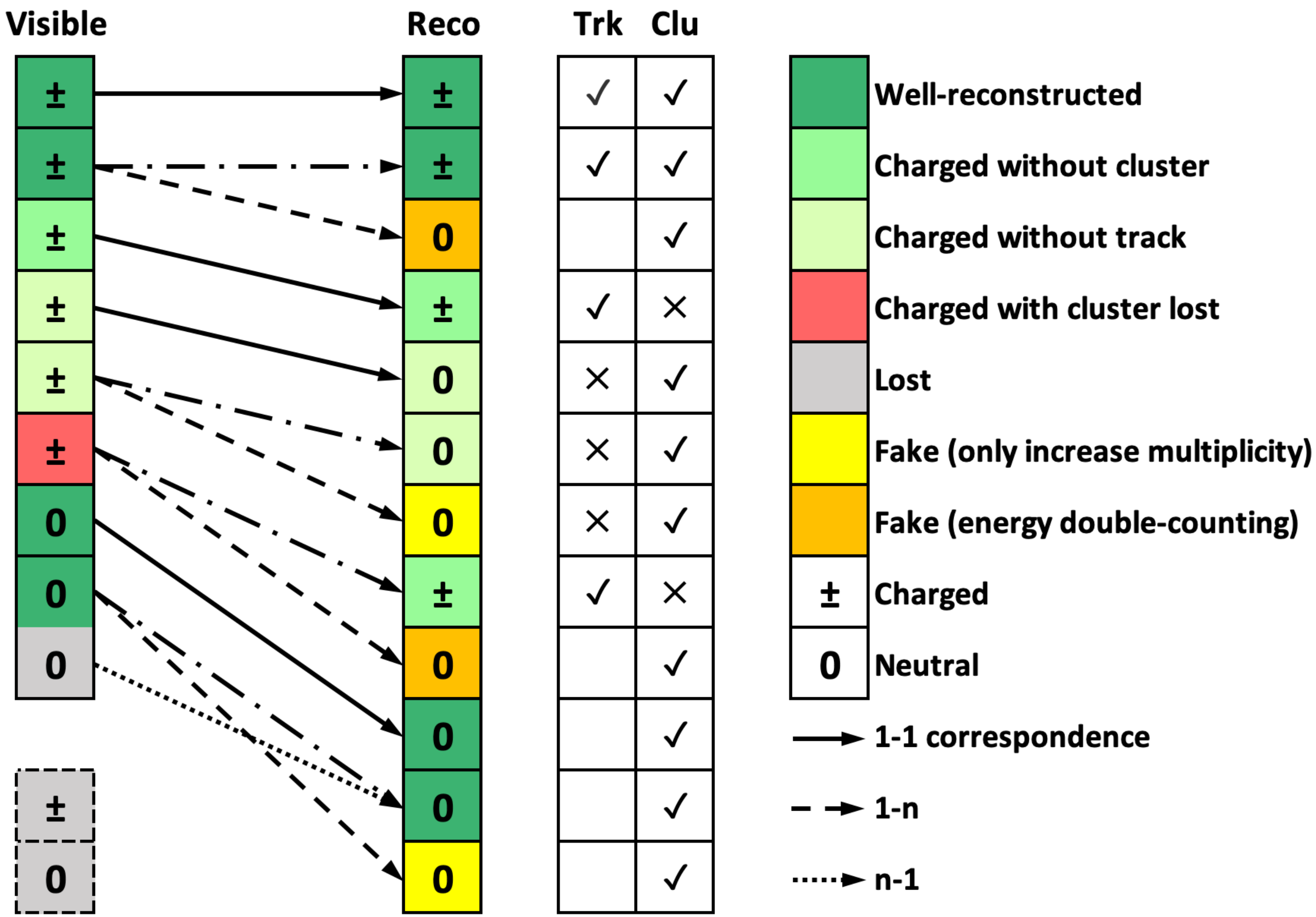
From specialized Models to LLM



- Comparable result with different scaling behavior
- Para. Numbers: PN 360k, ParT 2.4M, BINBBT 150 M
- More details at: *https://arxiv.org/pdf/2412.00129*

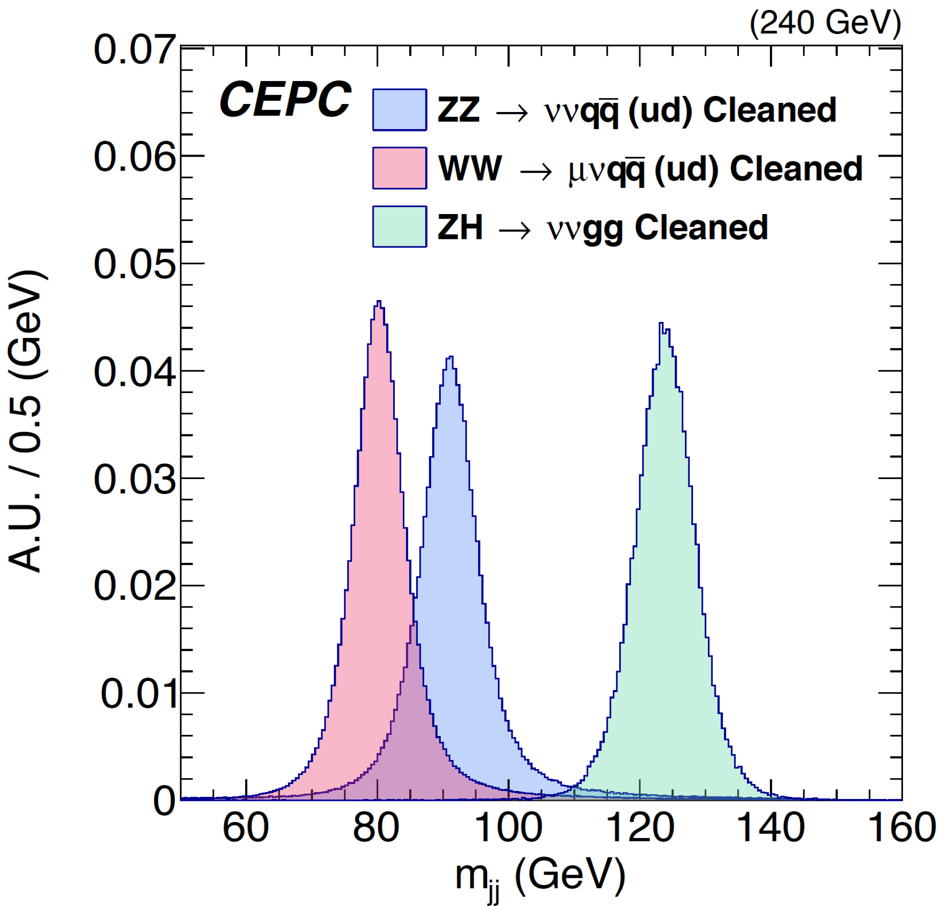
超对称
Super Symmetry Technologies

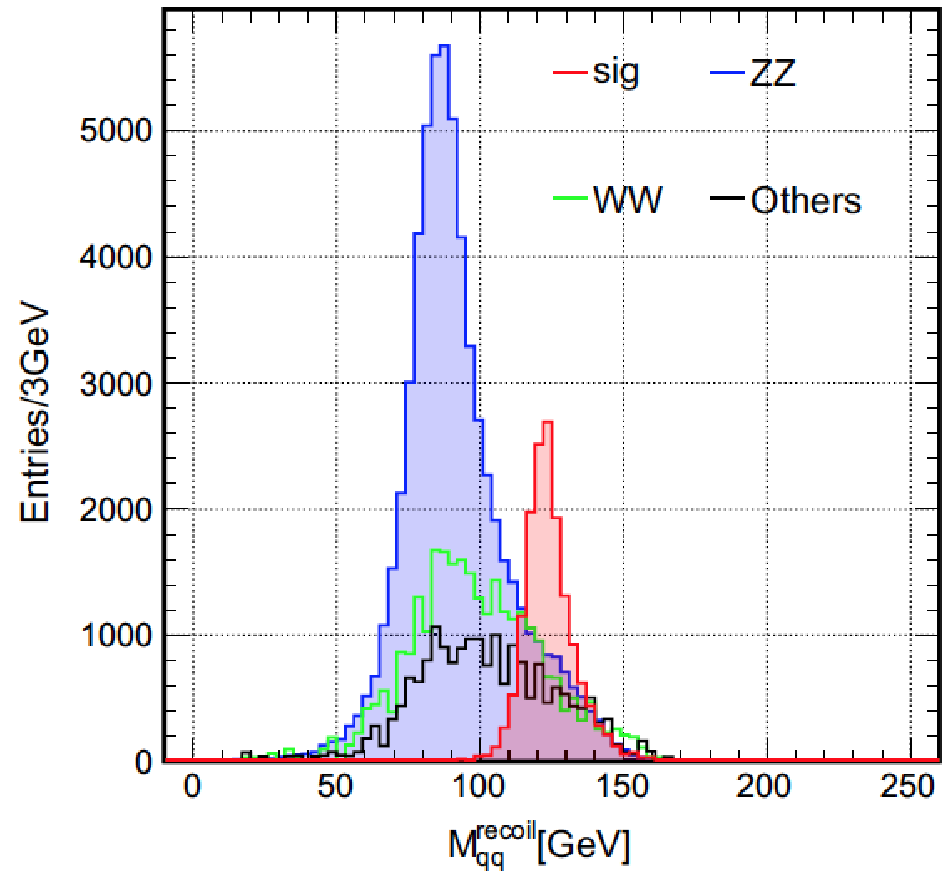
1-1 correspondence: ultimate Mapping between visible & reco



 Yuexin, Yongfeng, etc

Boson Mass Resolution: Key Per. Para



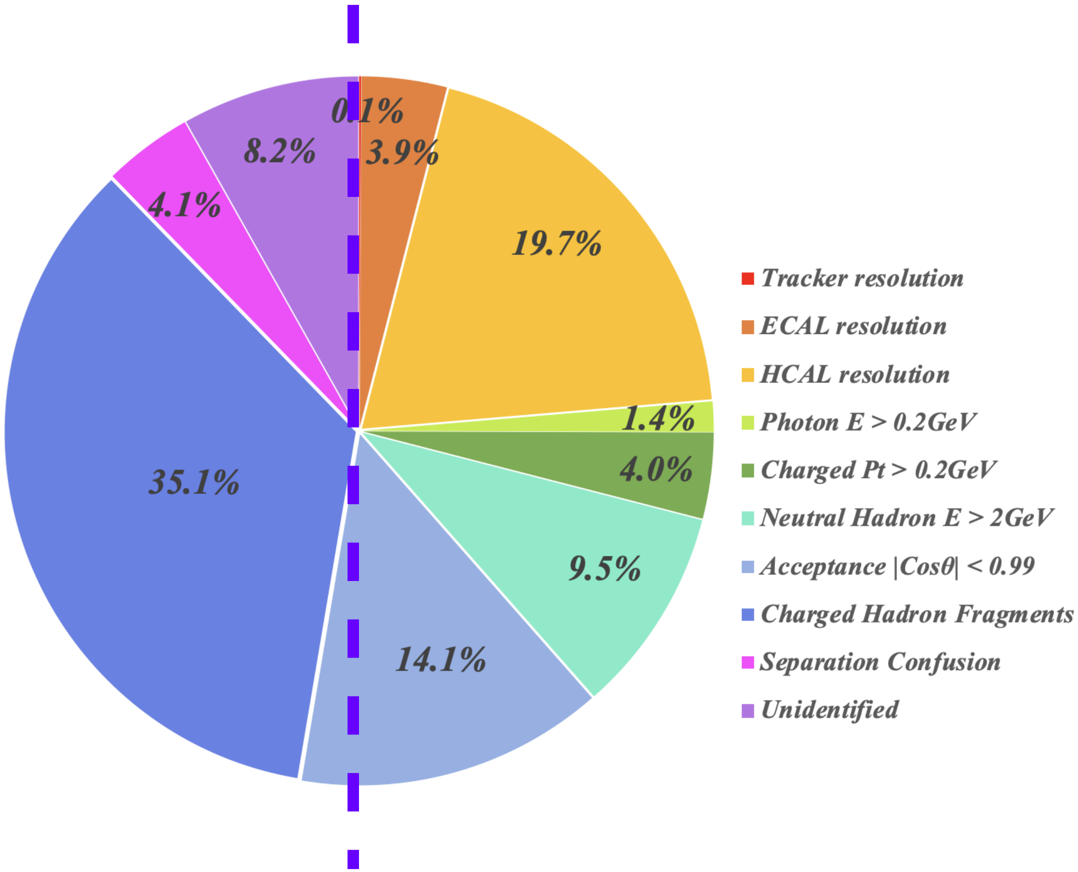


Higgs factory: need BMR < 4% (critical for qqH & qqZ separation using recoil mass to di-jet)

Strongly motivated to improve BMR to 3% or even lower, especially for NP & Flavor

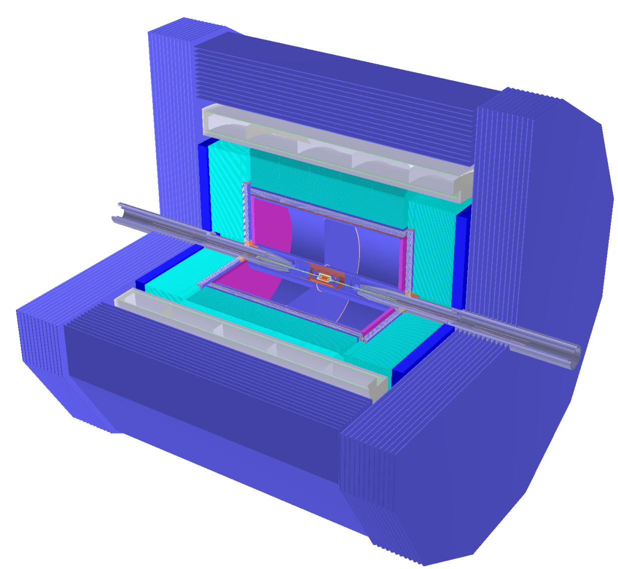
CDR baseline (left plot): BMR = 3.75%

BMR decomposition @ CDR baseline



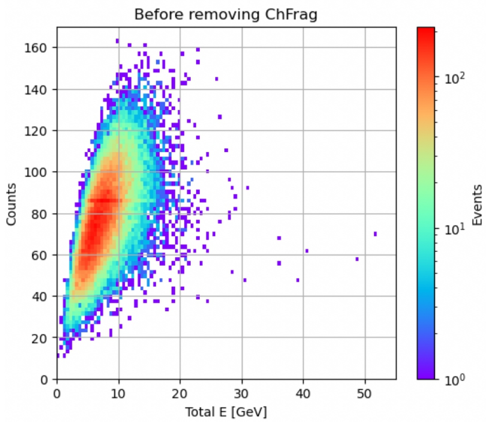
- 1st HCAL resolution dominant the uncertainties from intrinsic detector resolution: need better HCAL → usage of GSHCAL

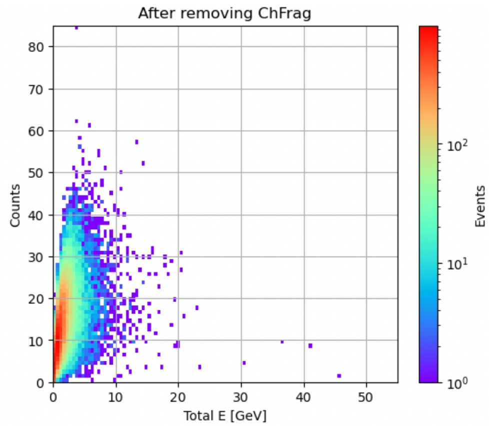
- 2nd Leading contribution: Confusion from shower Fragments (fake particles), need better Pattern Reco.

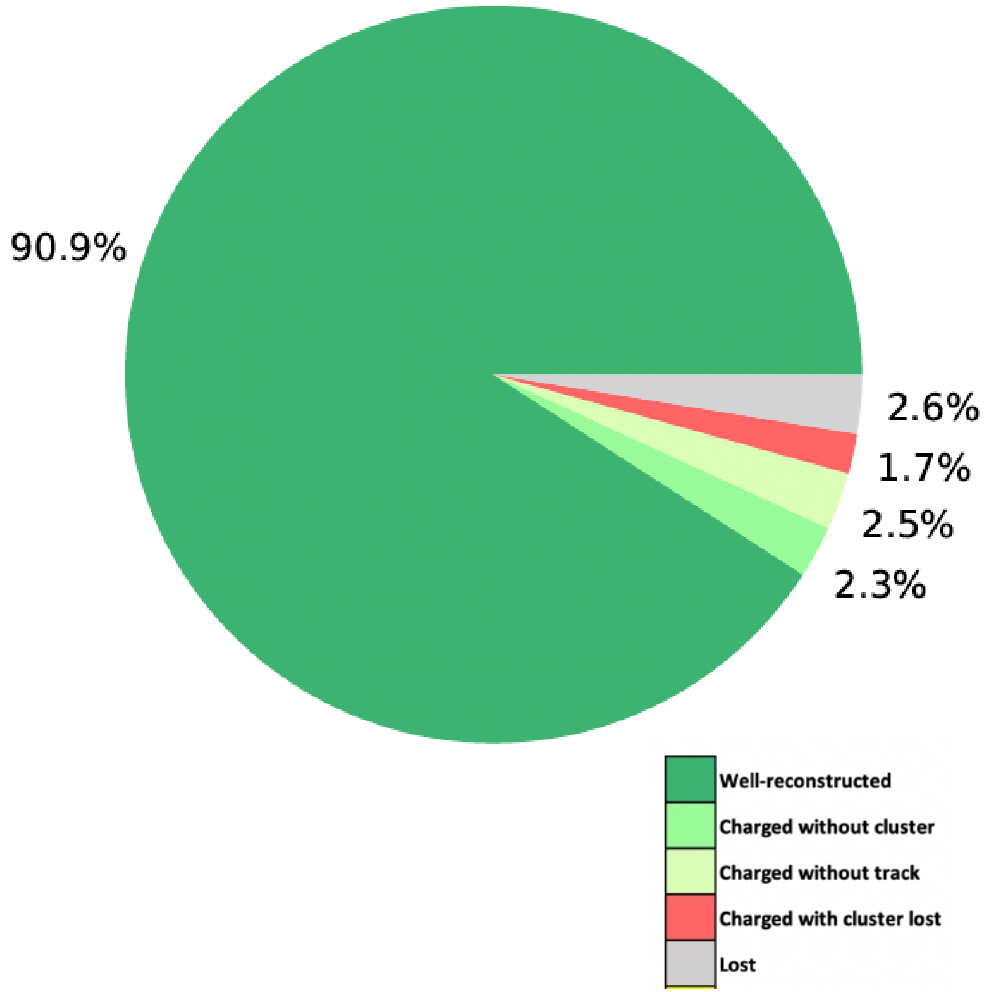


- CDR baseline - GRPC HCAL

Confusion identification & treatment: frag. veto



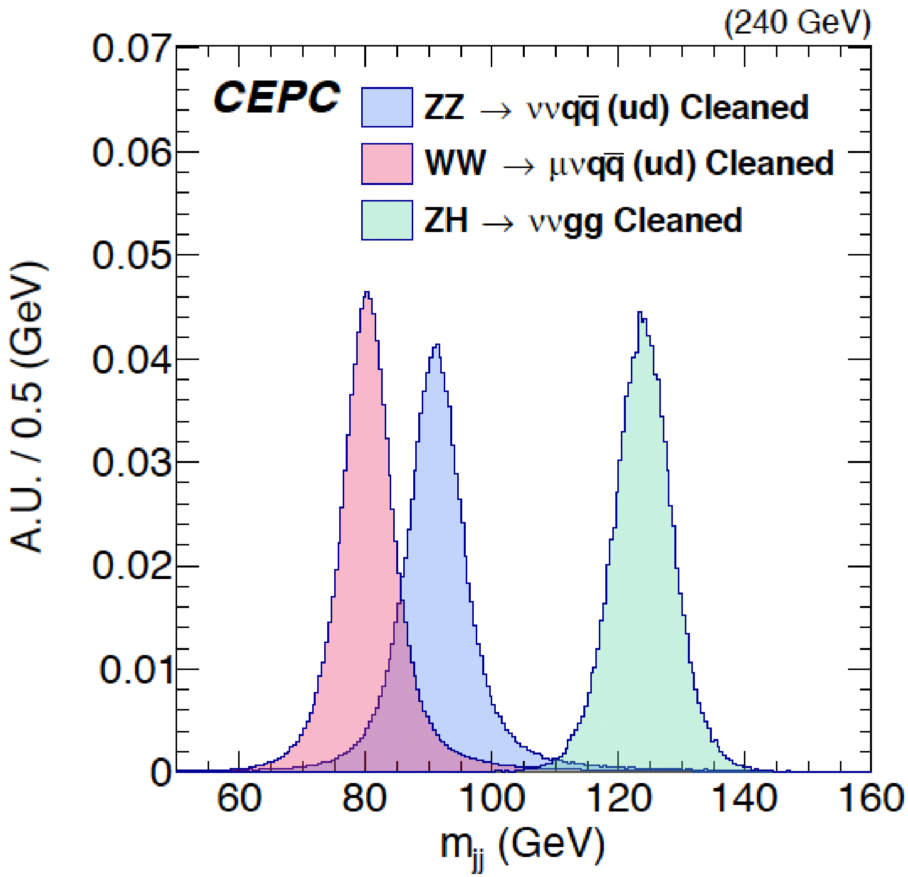


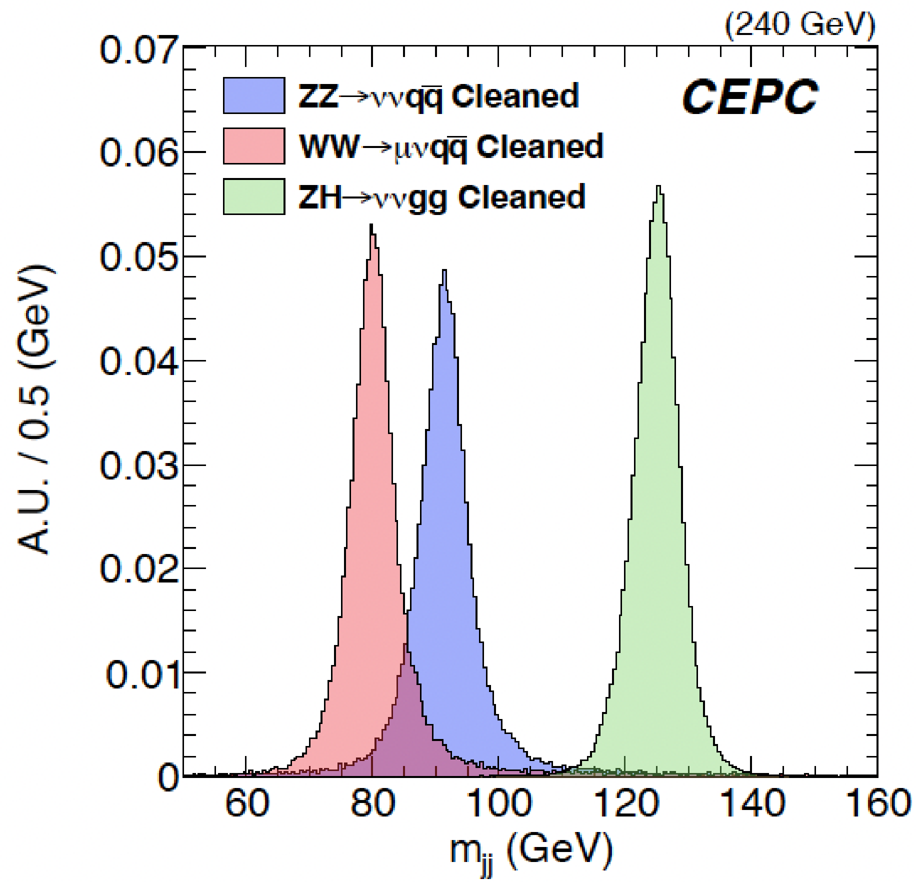


Fake particle originated Confusion reduced by 1 order of magnitude, at nominal ννH, H→gg event

Ignoring the remaining fragments with total E < 1 GeV, more than 95% of the visible energy preserves 1-1 correspondence

BMR of 2.75% reached





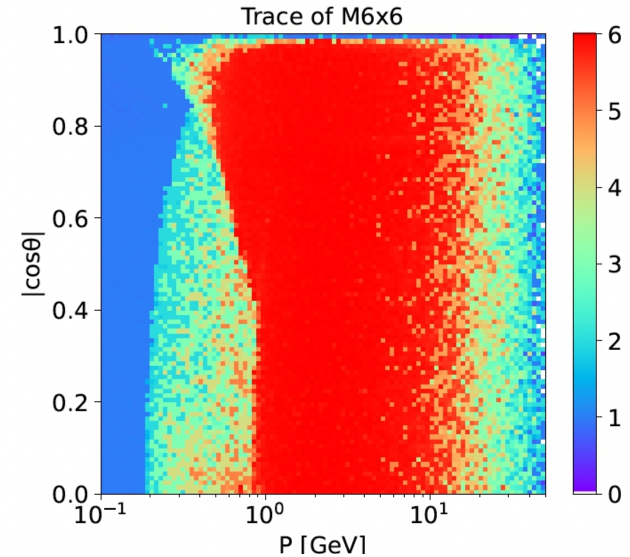
Detector change: BMR 3.7 → 3.4;

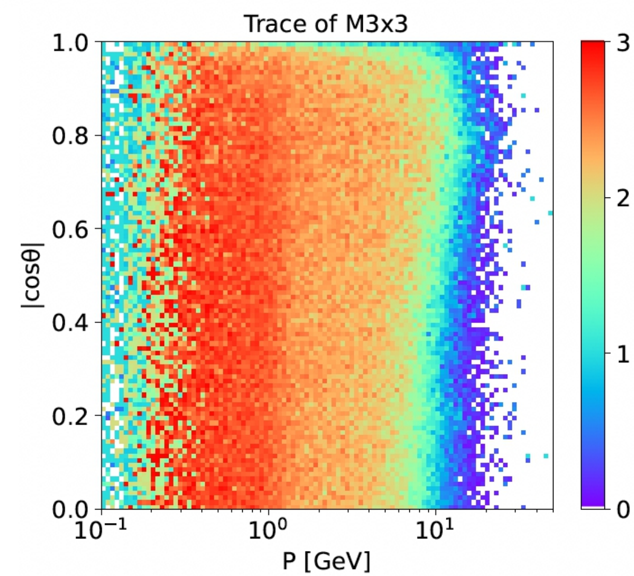
AI enhanced reconstruction: 3.4 → 2.8.

Impact from Beam induced background + impact on objects inside jet reco: to be evaluated.

Pid: differential performance

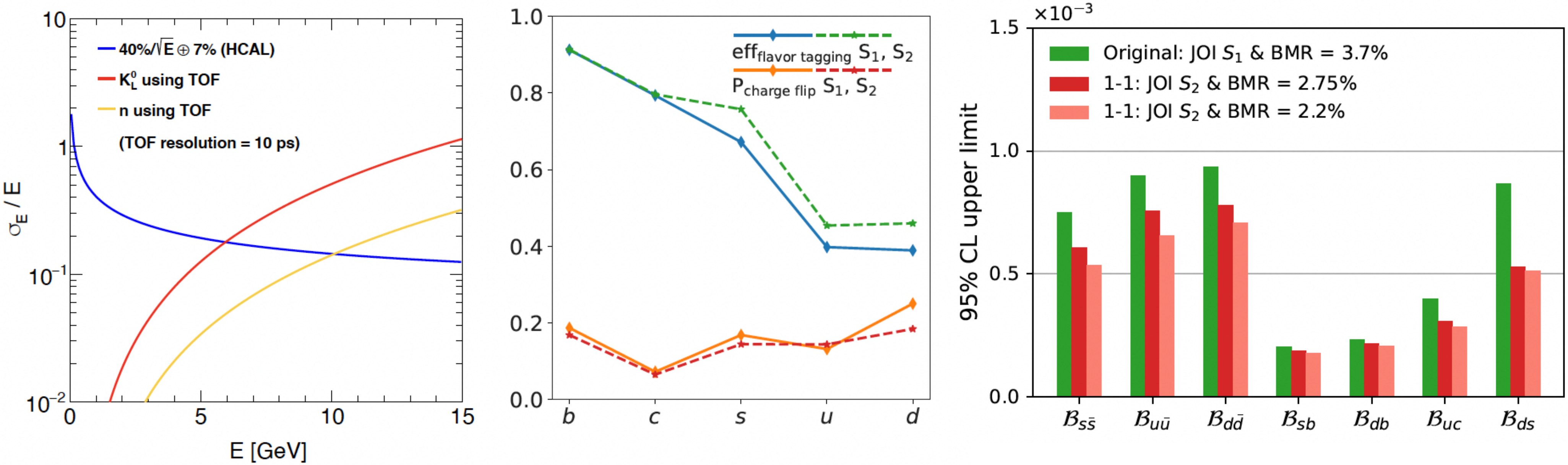
True \ Predicted	$e^{\pm}$	$\mu^{\pm}$	$\pi^{\pm}$	$K^{\pm}$	$p/\bar{p}$	γ	K_L^0	n	$\bar{n}$	others
$e^{\pm}$	0.999	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$\mu^{\pm}$	0.000	0.985	0.015	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$\pi^{\pm}$	0.000	0.019	0.977	0.003	0.000	0.000	0.000	0.000	0.000	0.000
$K^{\pm}$	0.000	0.001	0.003	0.985	0.011	0.000	0.000	0.000	0.000	0.000
$p/\bar{p}$	0.000	0.000	0.001	0.012	0.979	0.000	0.000	0.000	0.000	0.008
γ	0.000	0.000	0.000	0.000	0.000	0.973	0.003	0.004	0.000	0.020
K_L^0	0.000	0.000	0.000	0.000	0.000	0.007	0.756	0.070	0.048	0.119
n	0.000	0.000	0.000	0.000	0.000	0.003	0.083	0.803	0.027	0.084
$\bar{n}$	0.000	0.000	0.000	0.000	0.000	0.003	0.052	0.026	0.796	0.123
others	0.000	0.000	0.000	0.000	0.000	0.014	0.025	0.095	0.011	0.854





Neutral Hadron ID: excellent Calorimetry with ToF capability (δt~100 ps/hit)

Perspectives with 1-1 correspondence



- ToF enhanced energy measurement: BMR: 2.8 → 2.2-2.4
  - Need excellent CALO + ToF ~ o(10 ps)
  - Assume Low energy neutrons & secondary particles can be tamed... still very challenge...
- Strongly Boost the light quark ID.
- Benchmark precision improved... up to nearly two times.

1-1 Correspondence

Holistic description of physics events

Efficient & interpretable information compression: (o(1E5) Hits → o(100) reco particles)

~ Confusion Free PFA + Excellent Particle identification

~ New method for the detector monitoring & measurements

arXiv > hep-ex > arXiv:2411.06939

Search...

Help | Adva

High Energy Physics – Experiment

[Submitted on 11 Nov 2024]

One-to-one correspondence reconstruction at the electron-positron Higgs factory

Yuexin Wang, Hao Liang, Yongfeng Zhu, Yuzhi Che, Xin Xia, Huilin Qu, Chen Zhou, Xuai Zhuang, Manqi Ruan

We propose one-to-one correspondence reconstruction for electron-positron Higgs factories. For each visible particle, one-to-one correspondence aims to associate relevant detector hits with only one reconstructed particle and accurately identify its species. To achieve this goal, we develop a novel detector concept featuring 5-dimensional calorimetry that provides spatial, energy, and time measurements for each hit, and a reconstruction framework that combines state-of-the-art particle flow and artificial intelligence algorithms. In the benchmark process of Higgs to di-jets, over 90% of visible energy can be successfully mapped into well-reconstructed particles that not only maintain a one-to-one correspondence relationship but also associate with the correct combination of cluster and track, improving the invariant mass resolution of hadronically decayed Higgs bosons by 25%. Performing simultaneous identification on these well-reconstructed particles, we observe efficiencies of 97% to nearly 100% for charged particles ($e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, $p/\bar{p}$) and photons (γ), and 75% to 80% for neutral hadrons (K_L^0, n, $\bar{n}$). For physics measurements of Higgs to invisible and exotic decays, golden channels to probe new physics, one-to-one correspondence could enhance discovery power by 10% to up to a factor of two. This study demonstrates the necessity and feasibility of one-to-one correspondence reconstruction at electron-positron Higgs factories.

Color Singlet Identification

JHEP

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The Higgs→ $b\bar{b}, c\bar{c}, gg$ measurement at CEPC

Yongfeng Zhu, Hanhua Cui and Manqi Ruan

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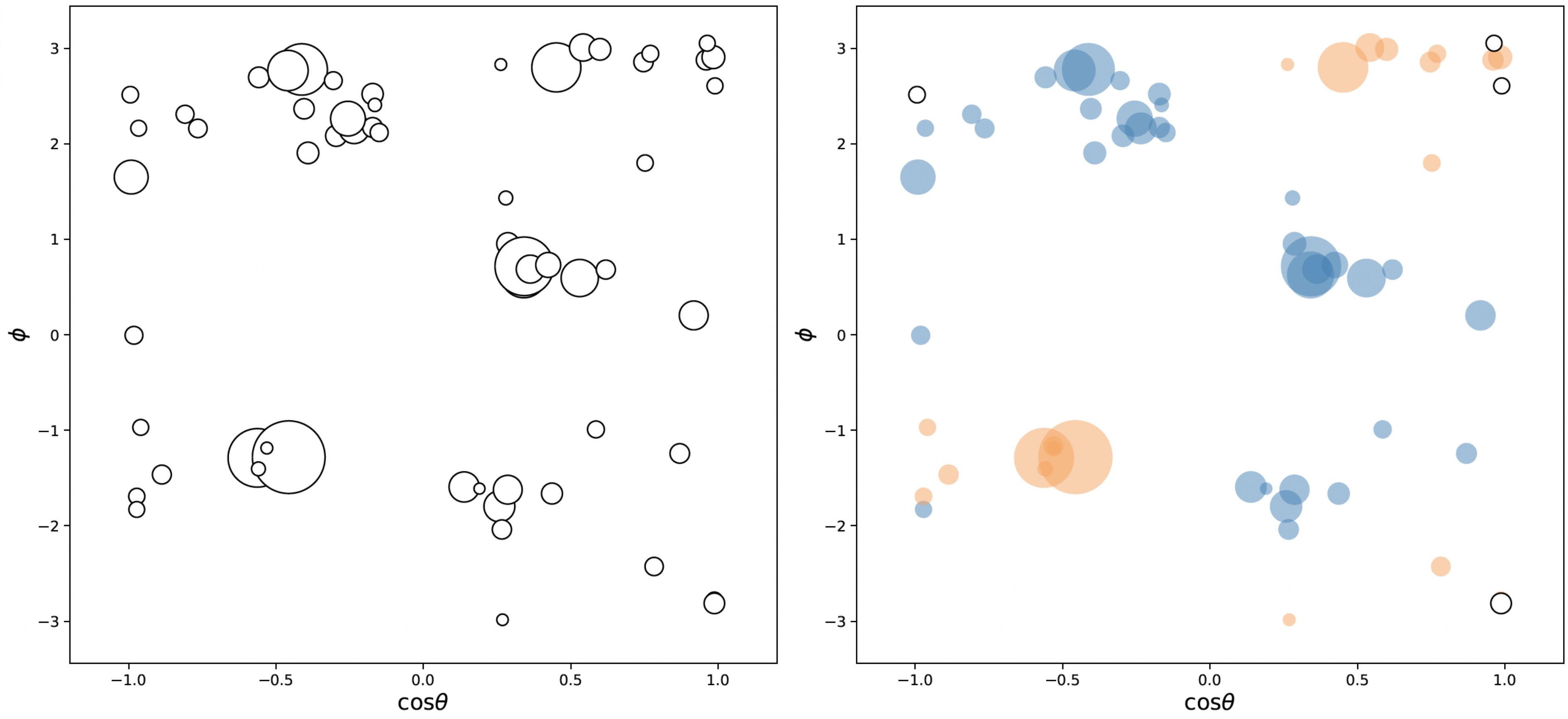
Z decay mode	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$
$Z \to e^+e^-$	1.57%	14.43%	10.31%
$Z \to \mu^+\mu^-$	1.06%	10.16%	5.23%
$Z \to q\bar{q}$	0.35%	7.74%	3.96%
$Z \to \nu\bar{\nu}$	0.49%	5.75%	1.82%
combination	0.27%	4.03%	1.56%

Table 3. The signal strength accuracies for different channels.

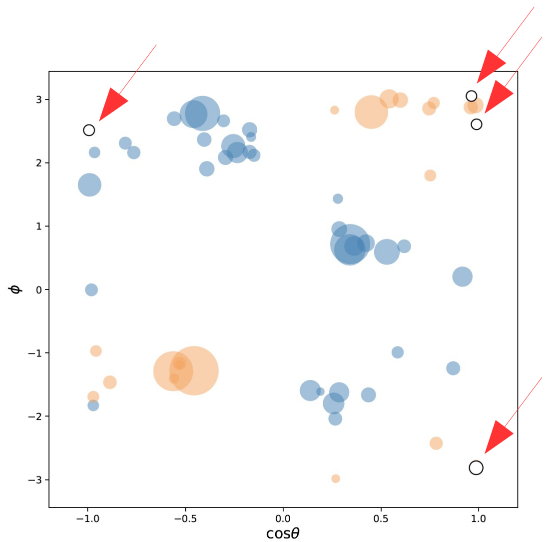
- H→cc & gg measurements at qqH channel is much worse vvH channels, despite the former has 3.5 times more signal statistic
- Reason: Failure of Color Singlet Identification – to distinguish the decay products of each Color Singlet
  - Z & H for 240/250 GeV Higgs factory
  - Which Higgs boson for Higgs self-coupling measurements (i.e., at vvHH events at 500 GeV, etc)

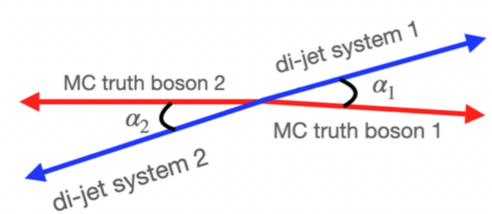
CSI: to group the final state particle

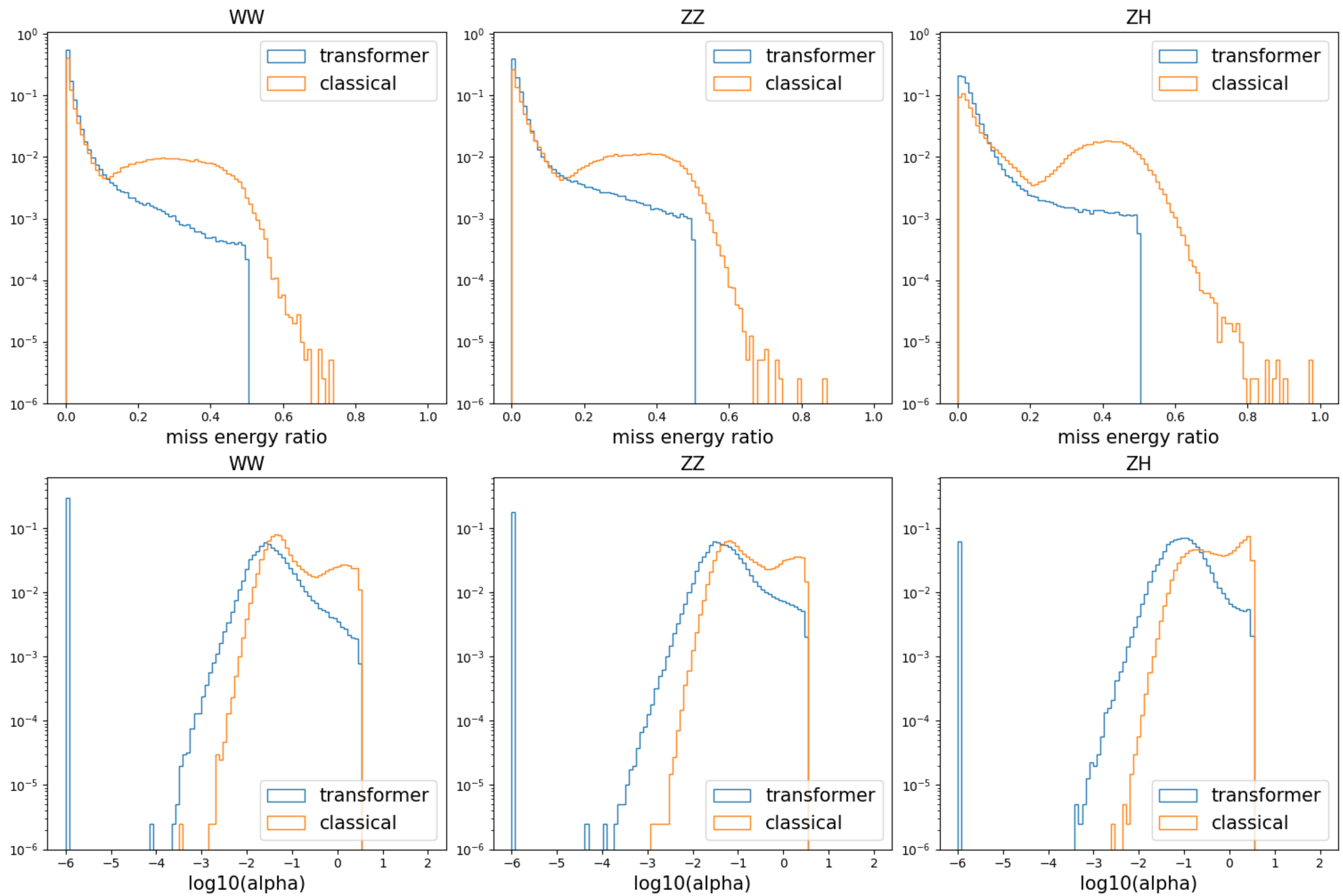


 Yongfeng, Hao, Yuexin, etc

CSI: classical VS AI (Transformer)

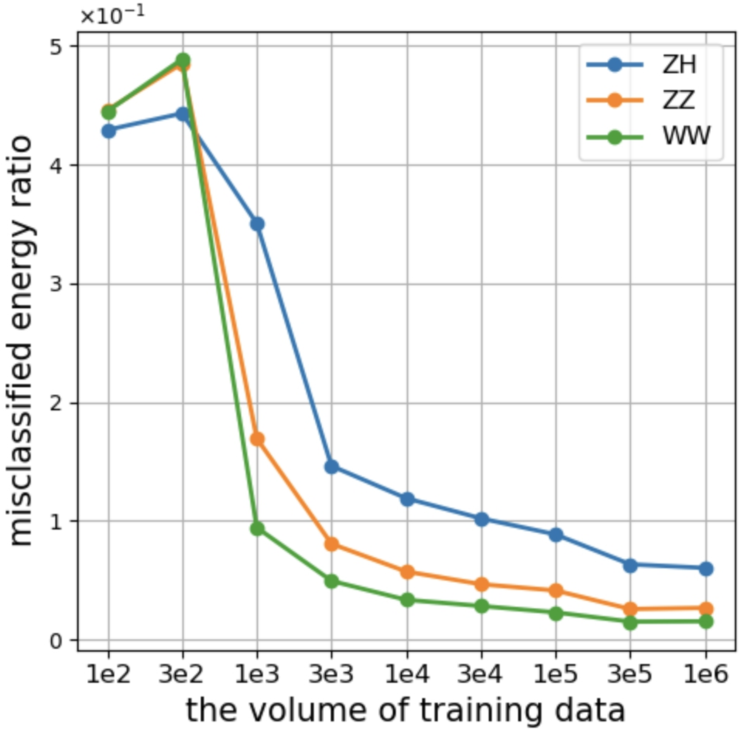


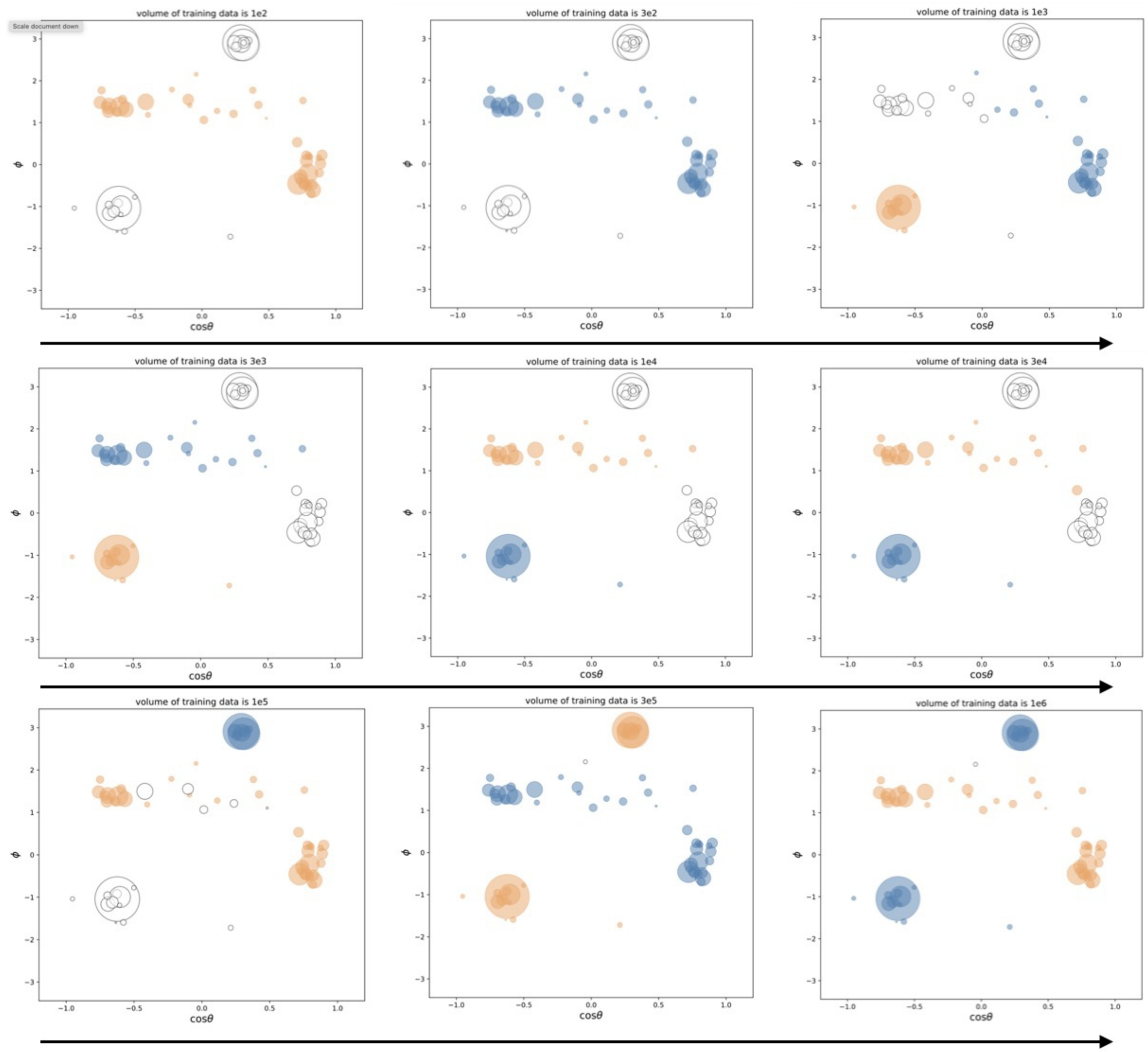




Classical: Jet Clustering + Matching with min(Chi-2)

Scaling behavior



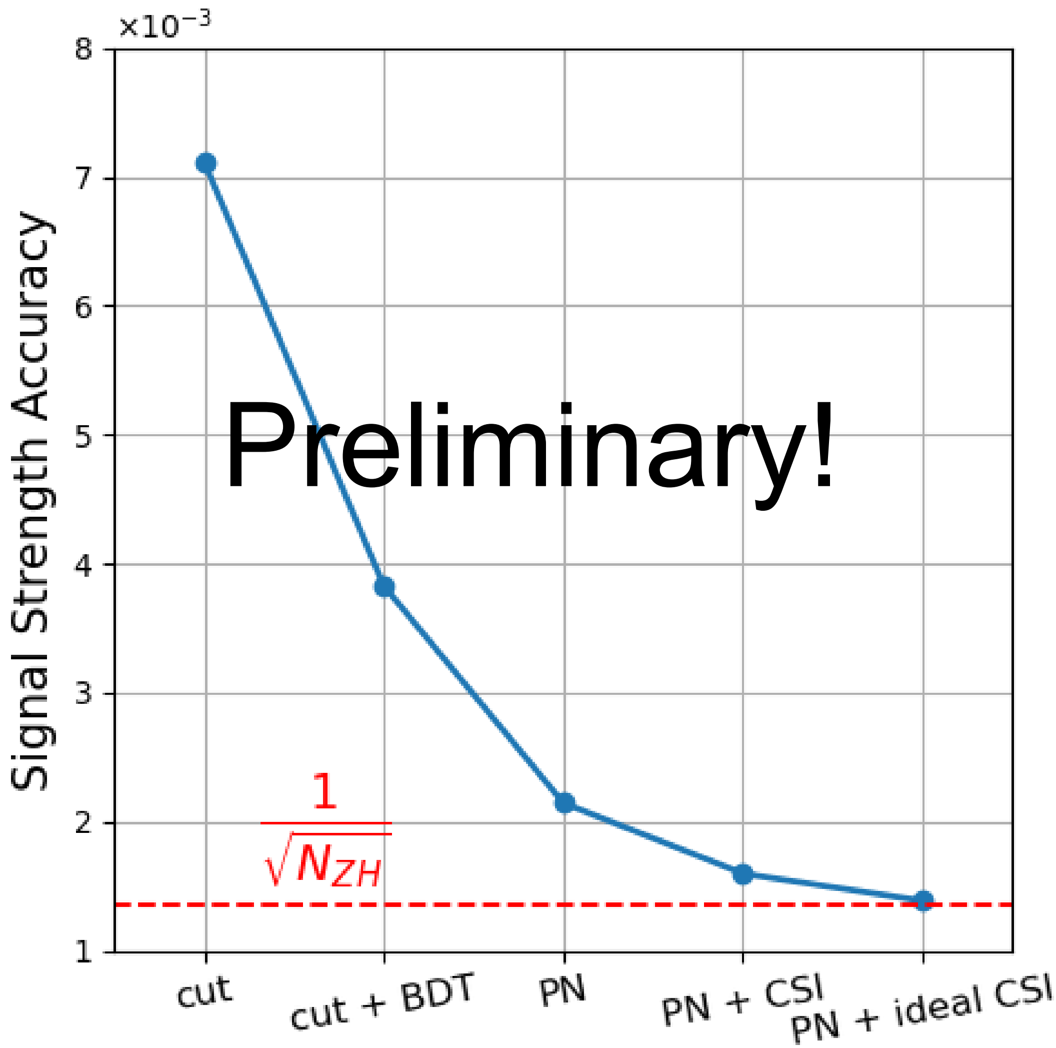


A toy analysis: identify full hadronic ZH signal from ZZ + WW background

- Cut based
- BDT
- 1-1 correspondence
- 1-1 correspondence with reconstructed CSI
- 1-1 correspondence with truth level CSI

- 5.6 iab: 540k ZH + 3.1M ZZ + 47 M WW full hadronic events

Comparison of different analysis methods



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

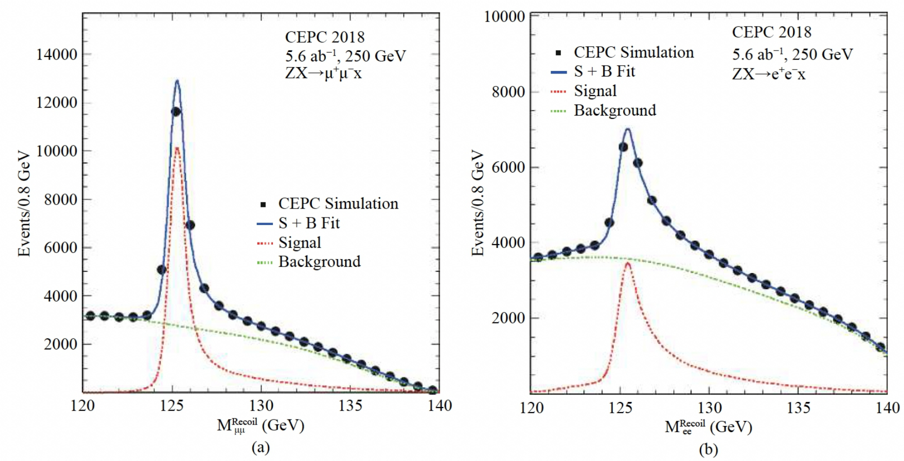
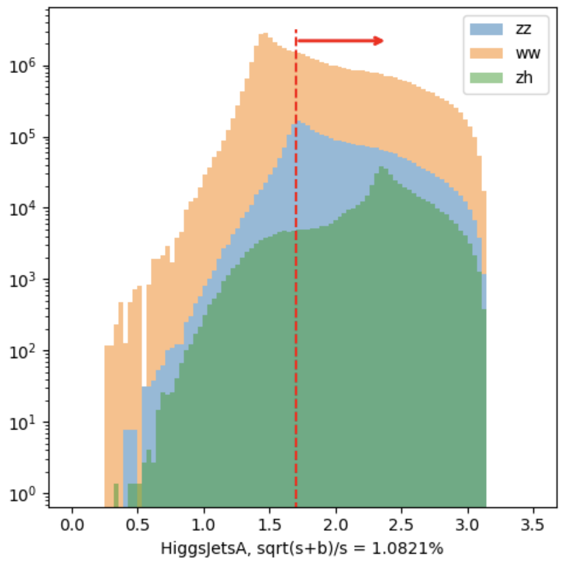


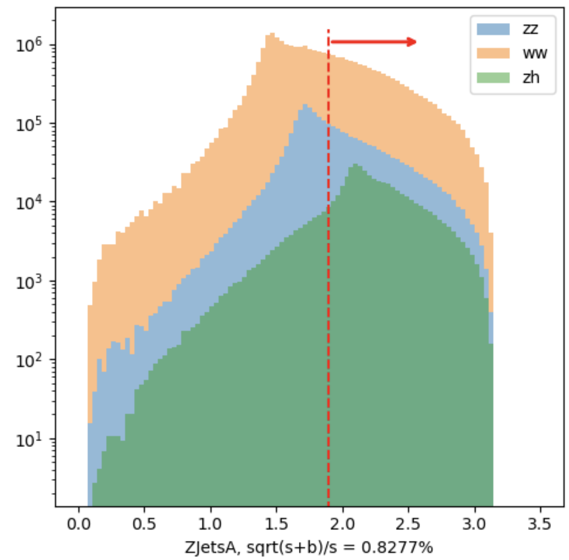
Table 5. Estimated measurement precision for the Higgs boson mass m_H and the $e^+e^- \to ZH$ production cross section $\sigma(ZH)$ from a CEPC dataset of 5.6 ab^{-1}.

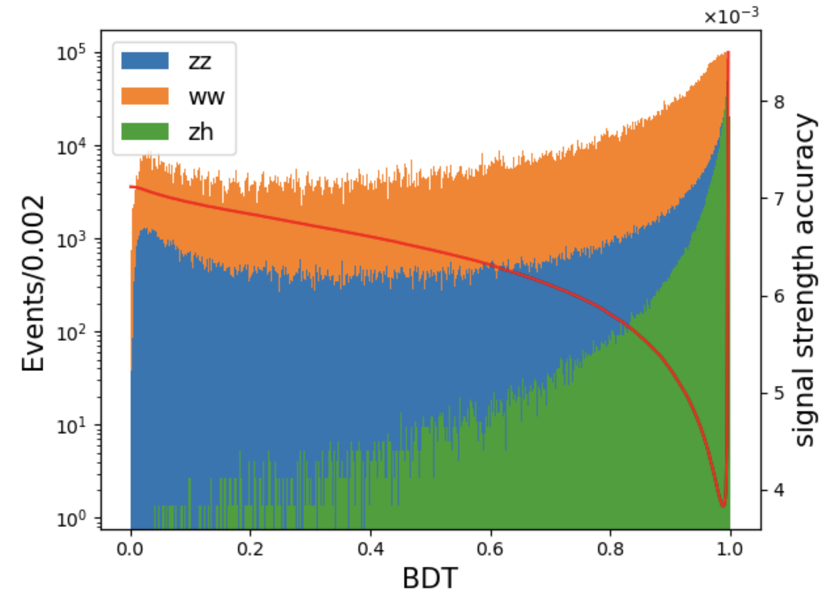
Z decay mode	Δm_H/MeV	$\Delta\sigma(ZH)/\sigma(ZH)$
e^+e^-	14	1.4%
$\mu^+\mu^-$	6.5	0.9%
$q\bar{q}$	–	0.6%
combination	5.9	0.5%

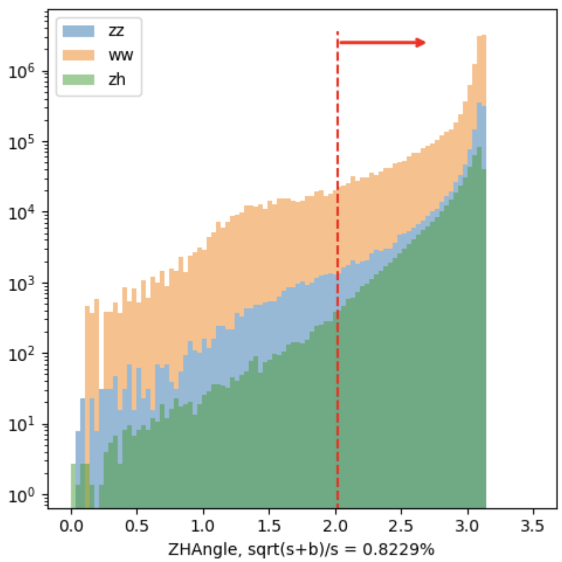
Optimistic Guesstimate:
Applied to Higgs recoil analysis with qqH channel, sigma(ZH) measurements could be improved by more than 2 times...

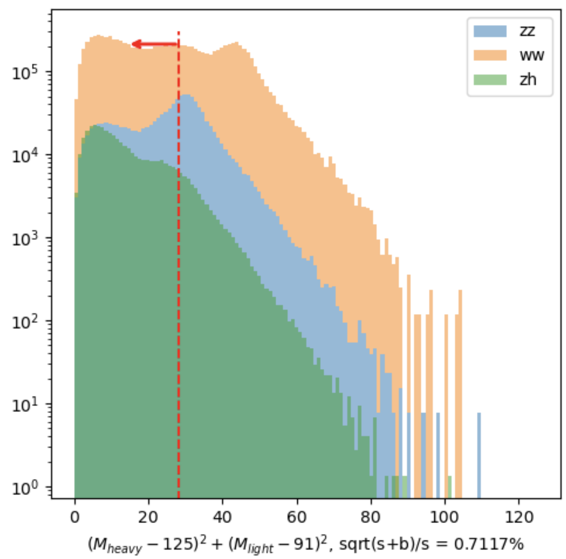
Cut & BDT based analysis





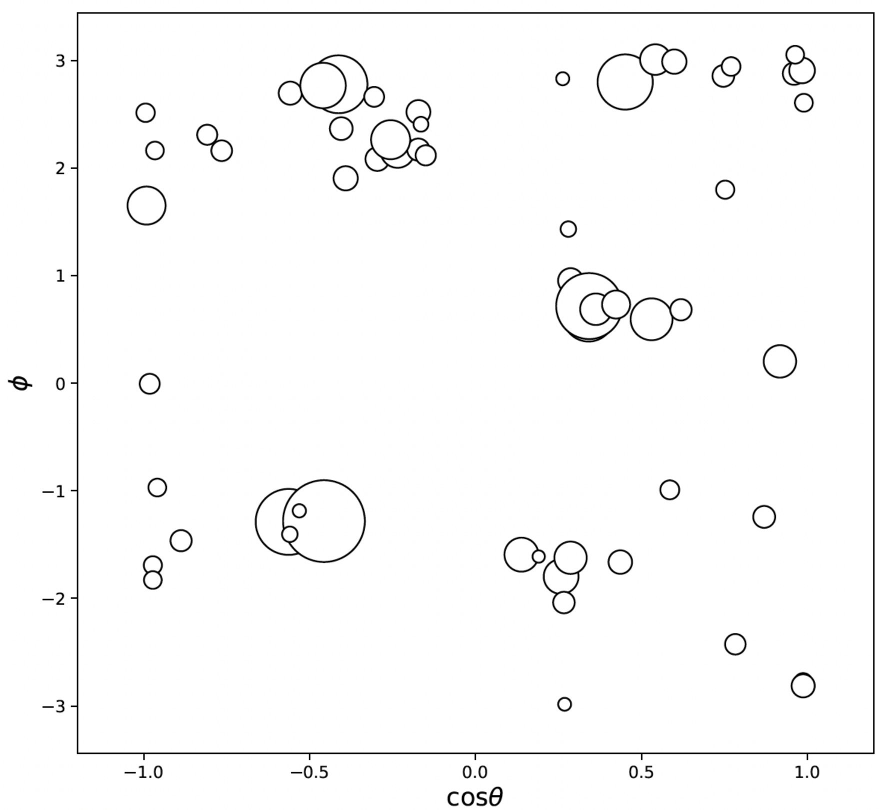


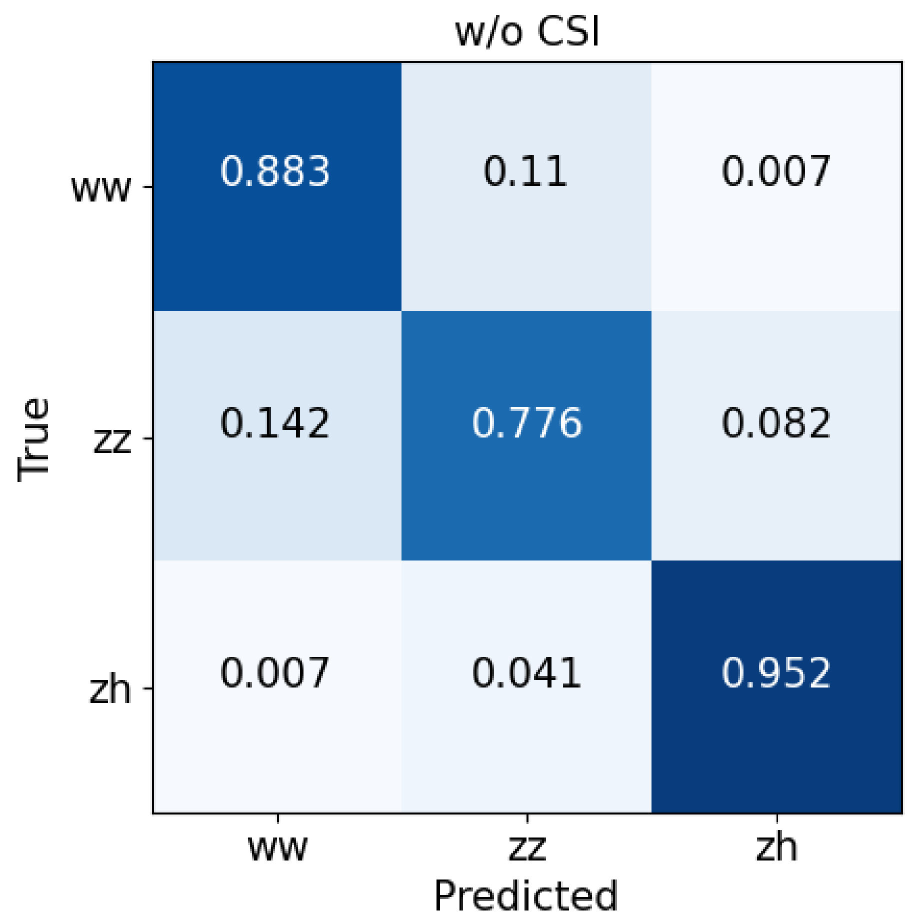




	WW	ZZ	ZH	signal strength accuracy (%)
total	46760000.0	3080000.0	536295.0	
HJetsAngle	25237307.0	2517908.0	483375.0	1.08
ZJetsAngle	9688088.0	1172856.0	404320.0	0.83
ZHAngle	9313657.0	1152690.0	400580.0	0.82
mass	5232210.0	648178.0	350720.0	0.71
BDT	697075.0	199992.0	265256.0	0.38

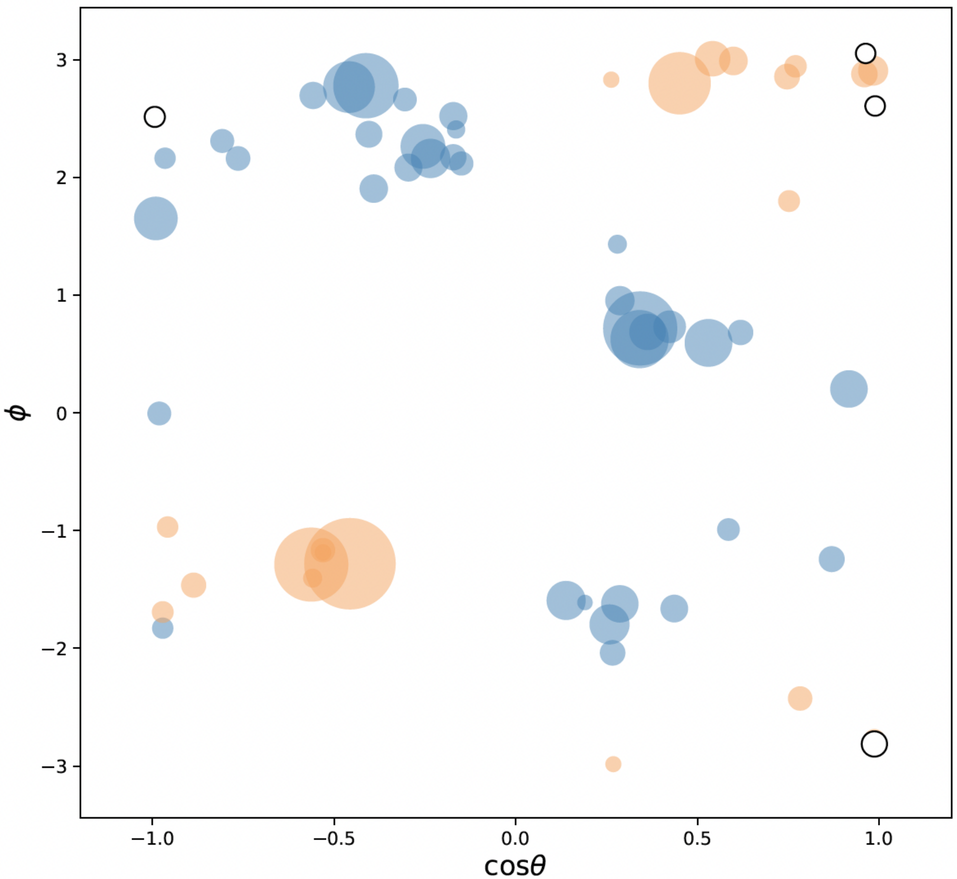
Analysis with 1-1 corresponding

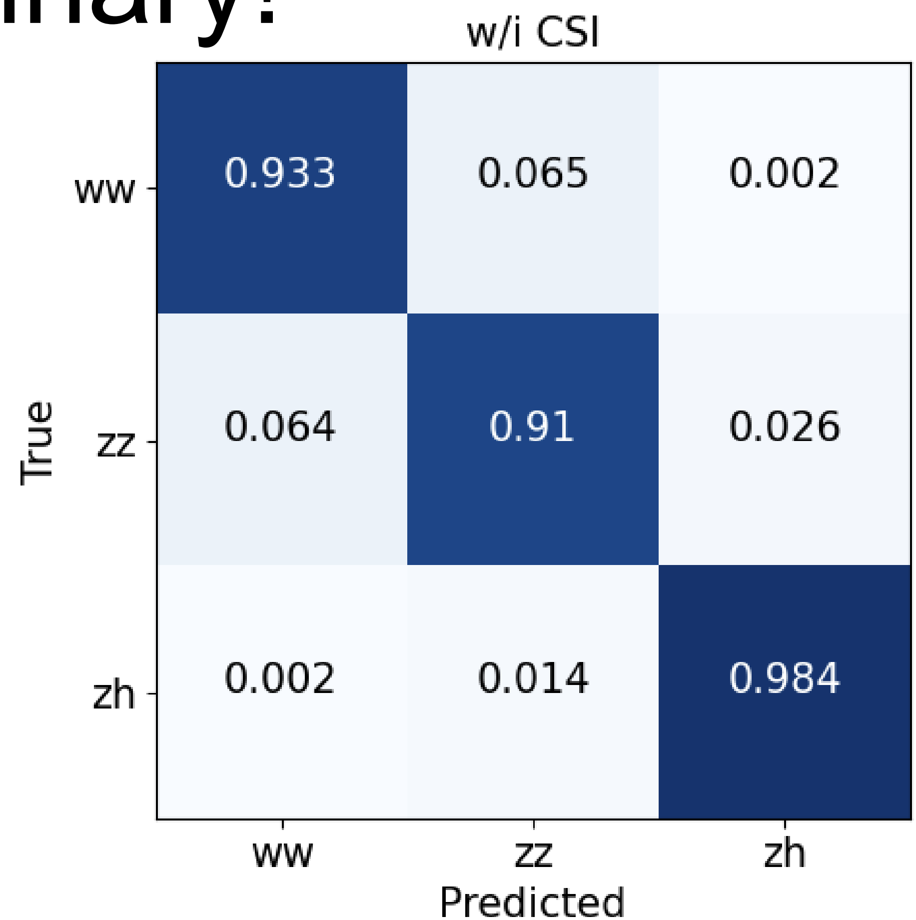




- Input all the reconstructed particles... and distinguish ZH, WW & ZZ events

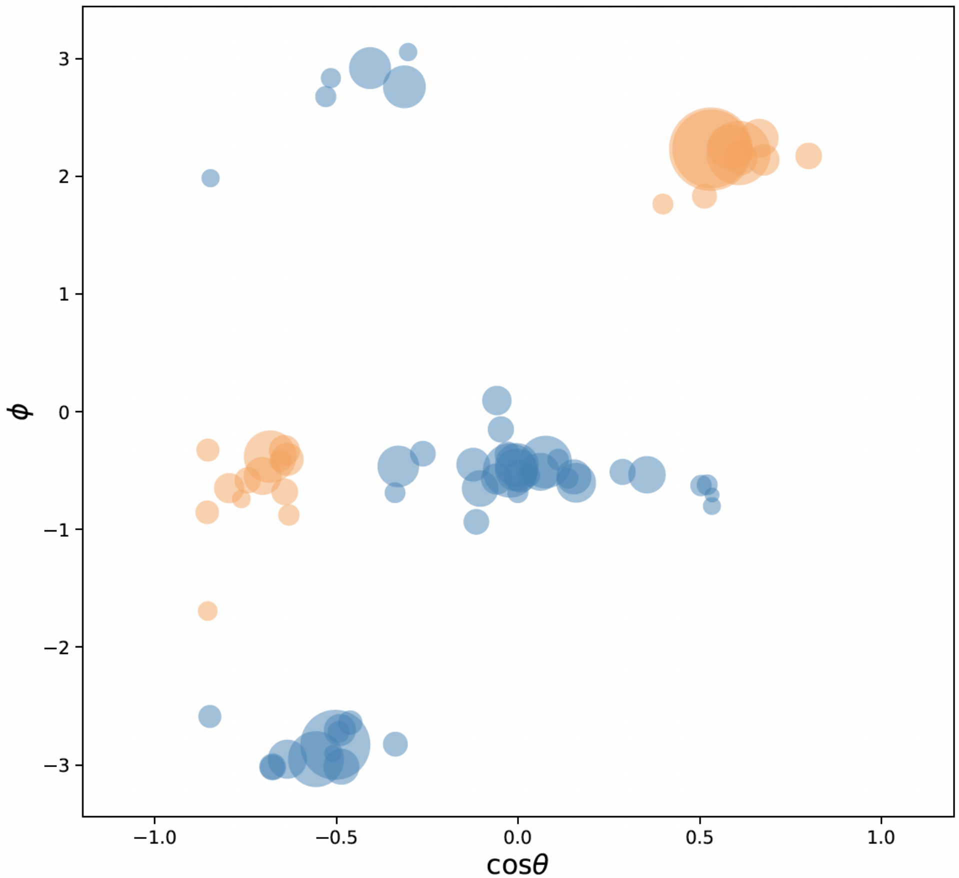
Analysis with 1-1 + CSI (reco) – Preliminary!

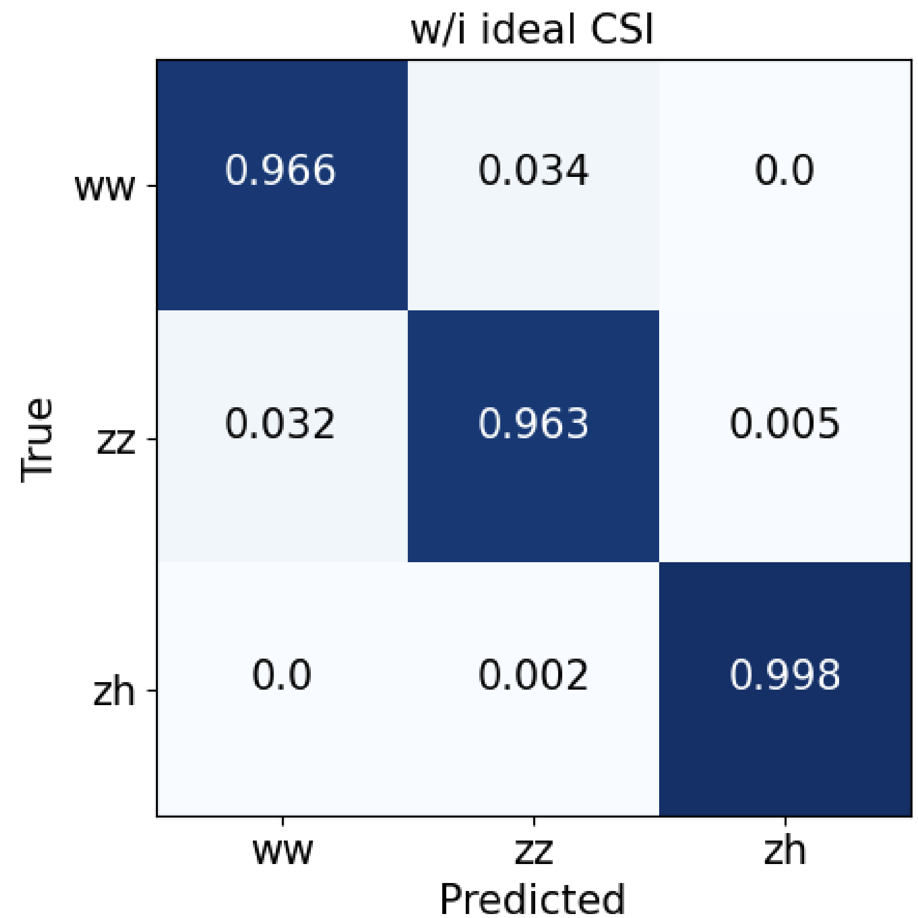




- Input all the reconstructed particles, each associated with one reconstructed CSI index.

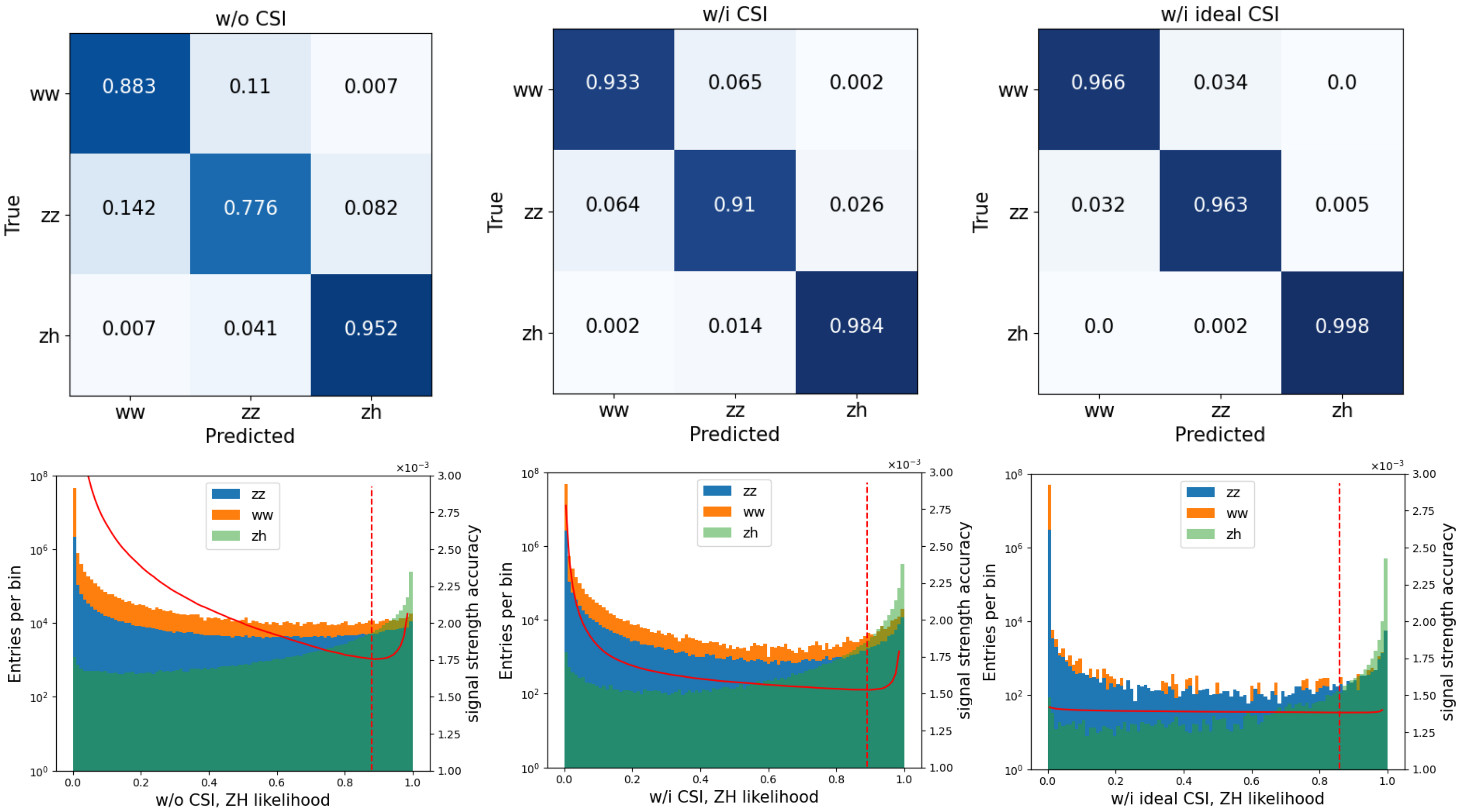
Analysis with 1-1 + CSI (truth)

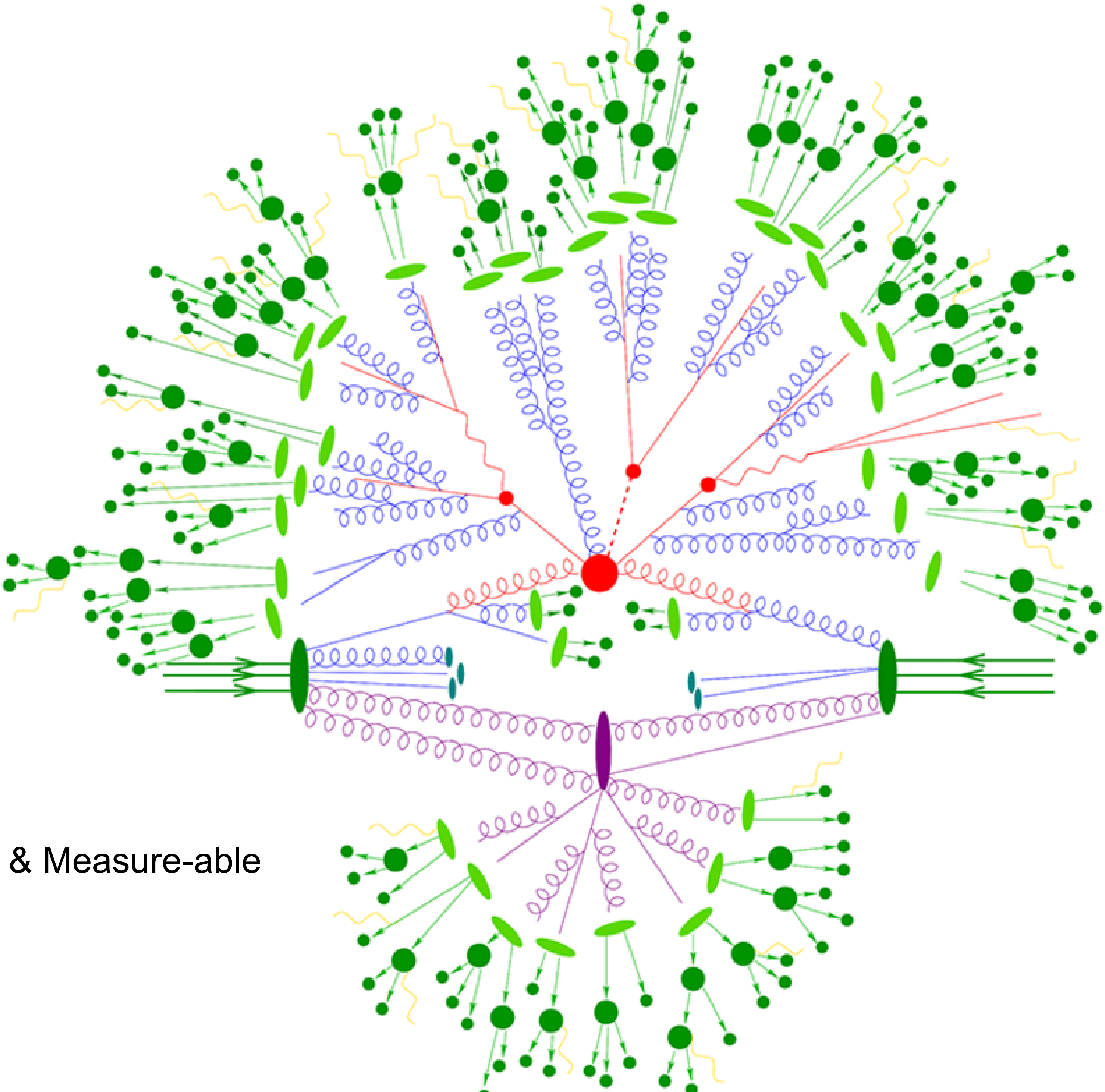




- If mark the CSI origin of each final state particle according to truth level info... almost background free with eff. ~ 1.
- *Left plot: a reconstructed event with perfect CSI, not truth labeled.*

Analysis with 1-1 & CSI: Preliminary!





Calculable & Measure-able

Meta questions

- Problem categorization
  - Identification problem: JoI, Pid, 1-1 correspondence (from Arbor)
  - Grouping problem: Color singlet id, tracking, clustering, ...
  - Assessment/regression problem: such as energy/momentum/time estimation, fitting
  - What's the most suited corresponding AI architecture, or general AI, and Why?

- AI for HEP, and HEP for AI (HEP → Science)
  - HEP, as a mature & vivid field, has the potential to impact the AI development, i.e., interpretability analysis

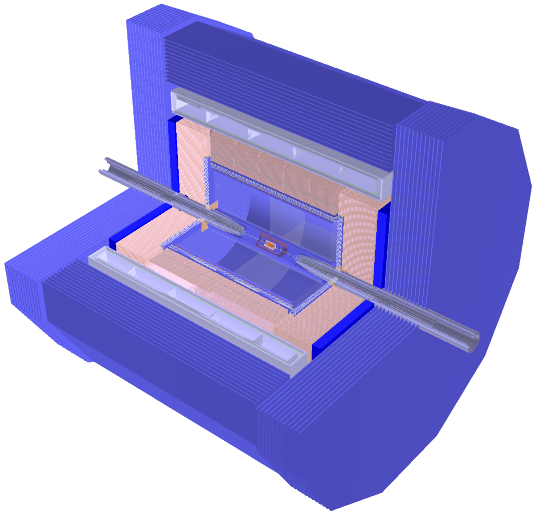
- Be relax, and have fun!...

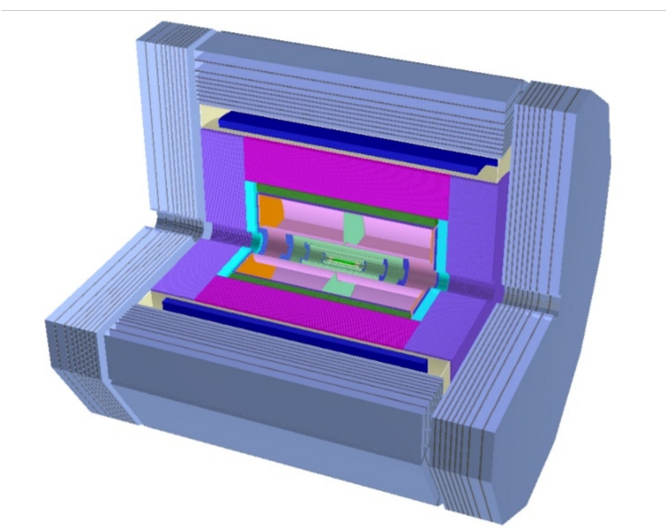
Summary

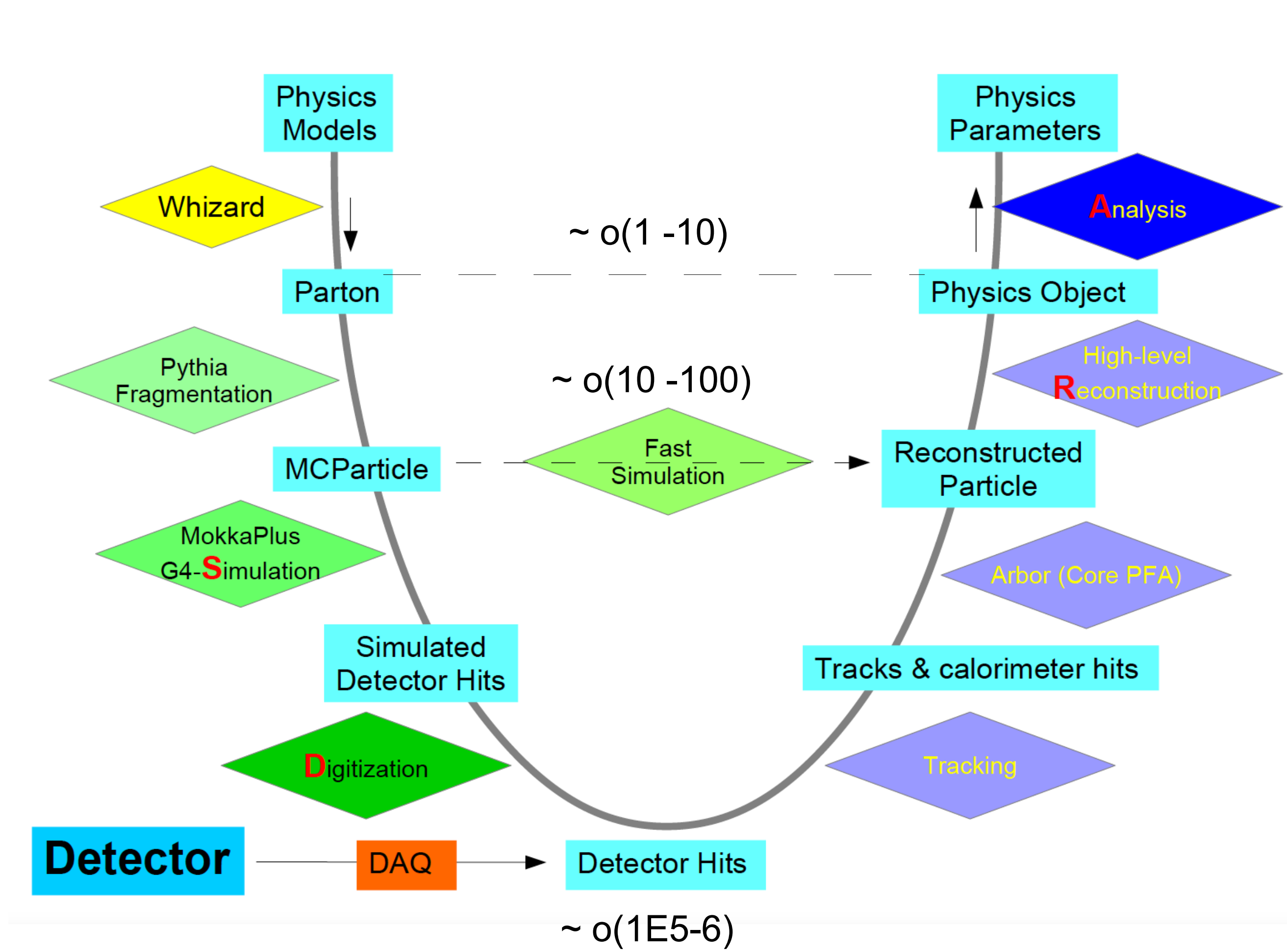
- Higgs factory: extremely rich physics requires excellent performance
- **Trilogy**: Significantly enhance the discovery power & alter the experiments design
  - Jet Origin ID: 'see' quark & gluon as lepton & photon
    - *...A "game changer" and opens new horizon for precise flavor studies at all future experiments...*
  - 1-1 correspondence, at least at Higgs factory: Should & Could
    - New paradigm for analyses:
      - Forget about artificial variable definition – feed all the reconstructable
      - Provide much more detailed info for system monitoring & systematic control
  - Color Singlet Id: decently addressed
- Bottleneck Shifts & Lots to be explored
  - Confusion → Det. Acceptance
  - Clever variable selection → High Quality MC: better QCD modeling, high precision calculation, detector calibration – monitoring, event building...
  - Particle Physics Provides excellent benchmarks to quantify the AI performance & interpretability study...

Back up

CEPC Detector & Reconstruction



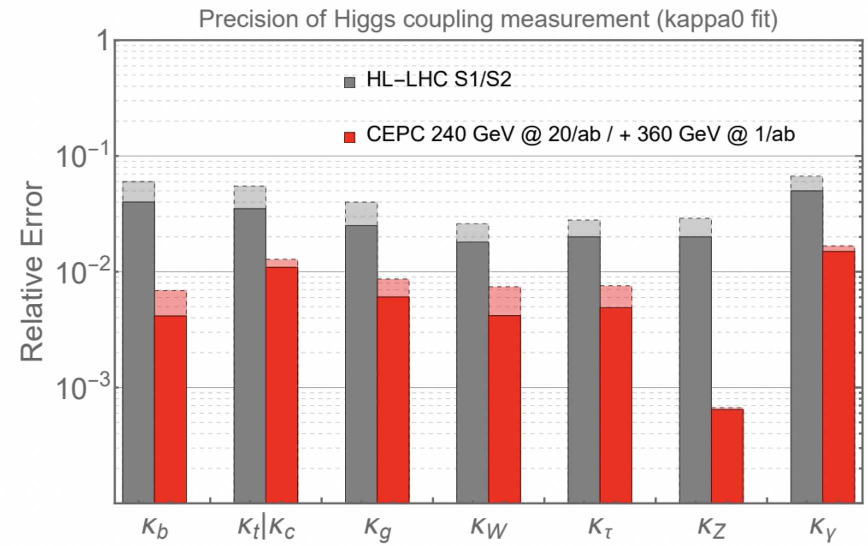


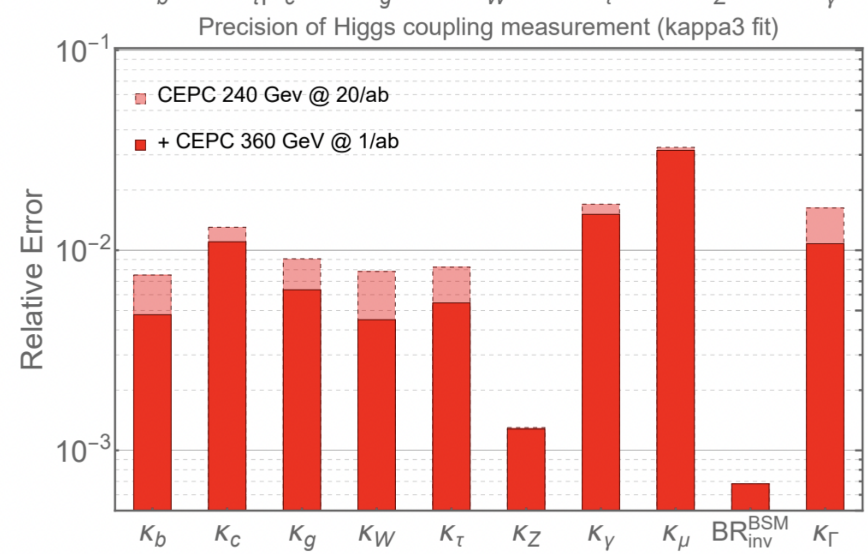


Full simulation reconstruction Chain with **Arbor, etc**

Higgs & Snowmass White Paper

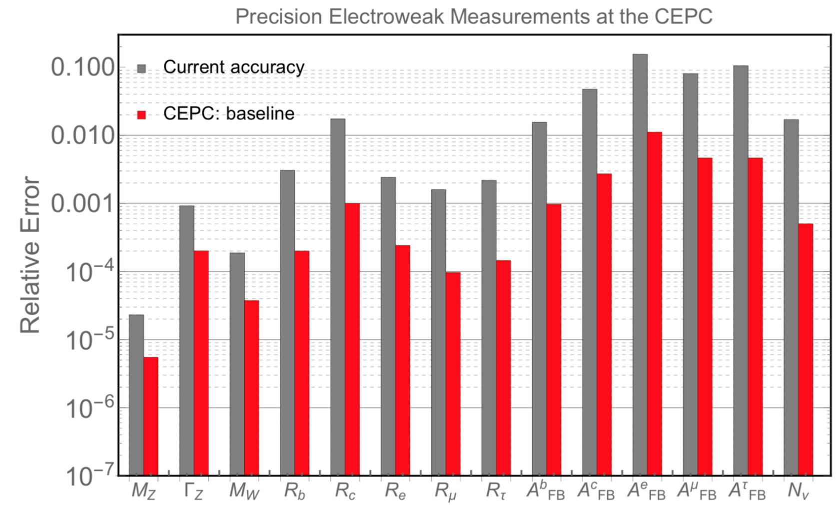
	240 GeV, 20 ab^{-1}		360 GeV, 1 ab^{-1}		
	ZH	**vvH**	ZH	**vvH**	**eeH**
inclusive	**0.26%**		**1.40%**	\	\
H→bb	**0.14%**	**1.59%**	**0.90%**	**1.10%**	**4.30%**
H→cc	**2.02%**		**8.80%**	**16%**	**20%**
H→gg	**0.81%**		**3.40%**	**4.50%**	**12%**
H→WW	**0.53%**		**2.80%**	**4.40%**	**6.50%**
H→ZZ	**4.17%**		**20%**	**21%**	
$H \rightarrow \tau\tau$	**0.42%**		**2.10%**	**4.20%**	**7.50%**
$H \rightarrow \gamma\gamma$	**3.02%**		**11%**	**16%**	
$H \rightarrow \mu\mu$	**6.36%**		**41%**	**57%**	
$H \rightarrow Z\gamma$	**8.50%**		**35%**		
$\text{Br}_{upper}(H \rightarrow inv.)$	**0.07%**				
Γ_H	**1.65%**		**1.10%**		

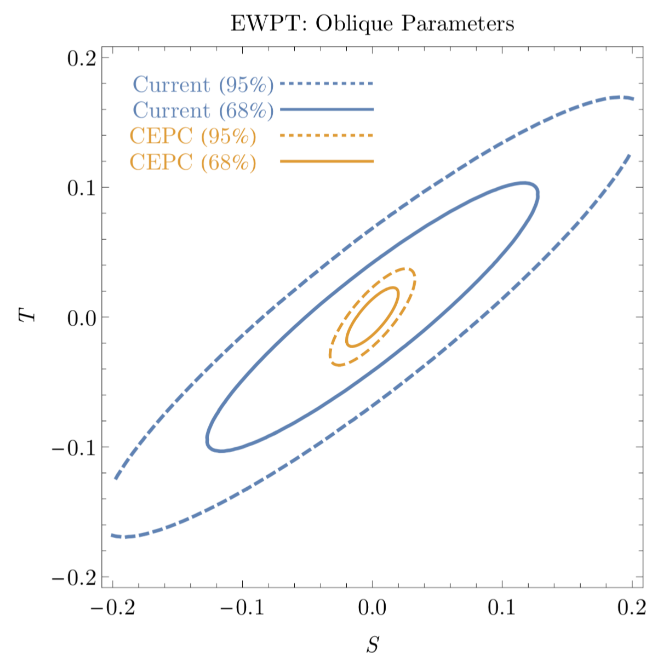


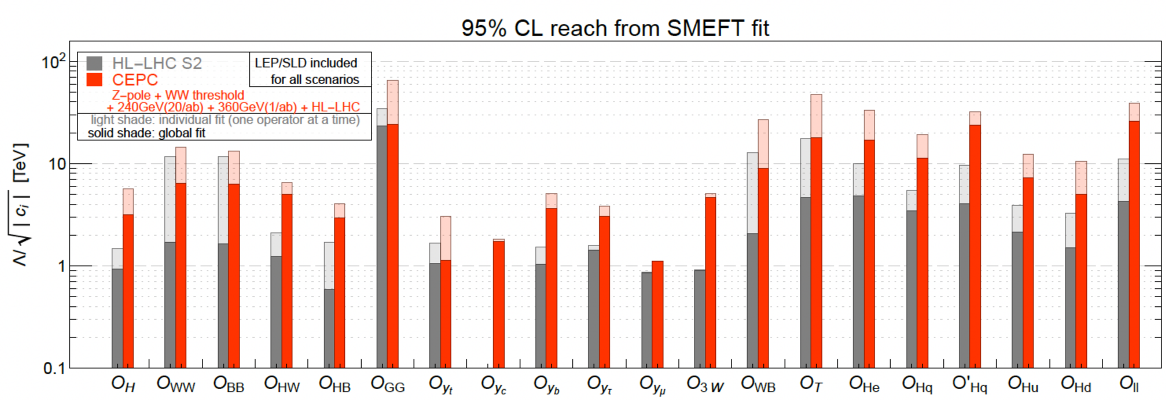


EW measurements & SMEFT

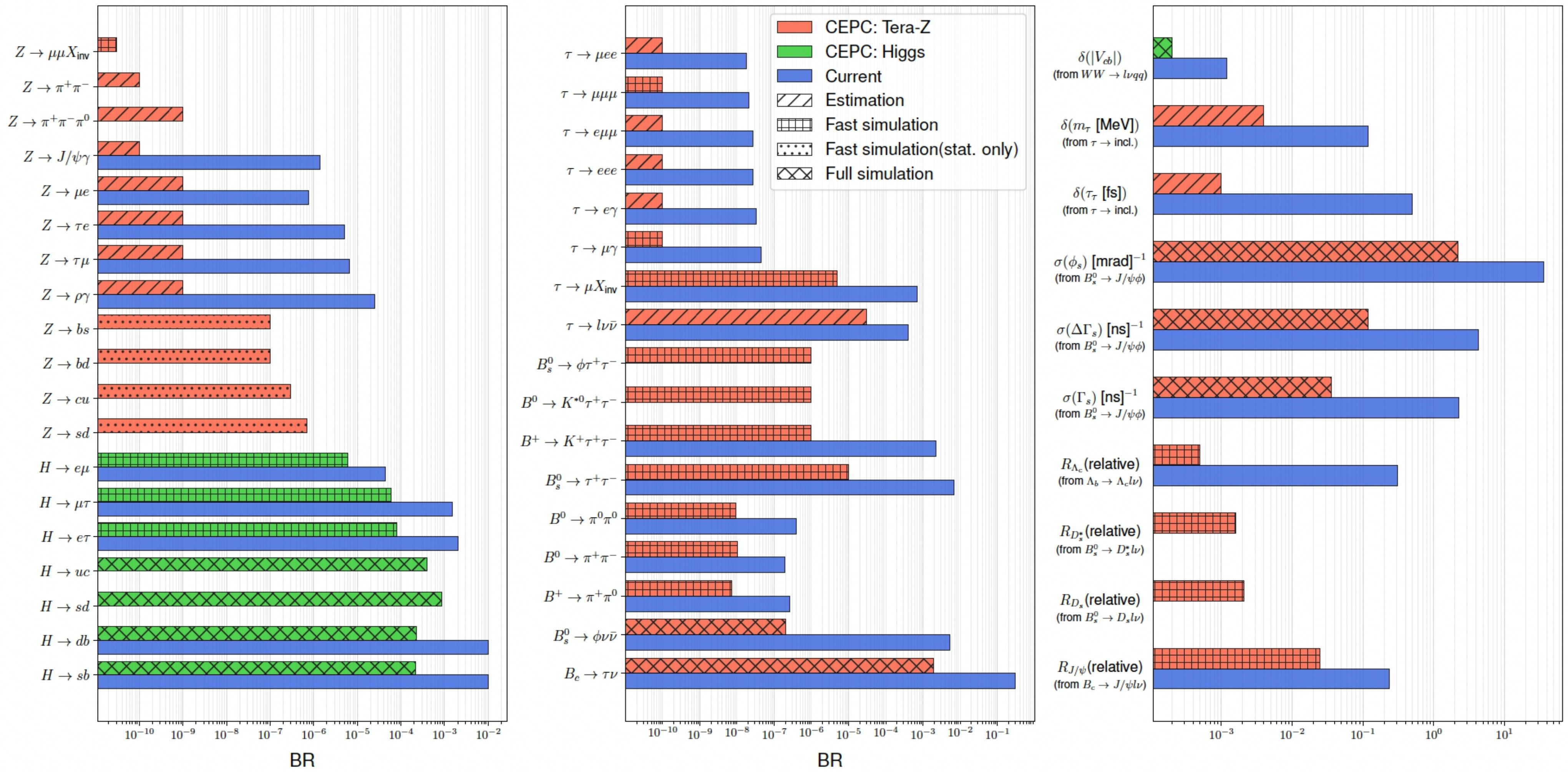
Observable	current precision	CEPC precision (Stat. Unc.)	CEPC runs	main systematic
Δm_Z	2.1 MeV [37–41]	0.1 MeV (0.005 MeV)	Z threshold	E_{beam}
$\Delta\Gamma_Z$	2.3 MeV [37–41]	0.025 MeV (0.005 MeV)	Z threshold	E_{beam}
Δm_W	9 MeV [42–46]	0.5 MeV (0.35 MeV)	WW threshold	E_{beam}
$\Delta\Gamma_W$	49 MeV [46–49]	2.0 MeV (1.8 MeV)	WW threshold	E_{beam}
Δm_t	0.76 GeV [50]	$\mathcal{O}(10)$ MeV[a]	$t\bar{t}$ threshold	
ΔA_e	4.9×10^{-3} [37, 51–55]	1.5×10^{-5} (1.5×10^{-5})	Z pole ($Z\to\tau\tau$)	Stat. Unc.
ΔA_μ	0.015 [37, 53]	3.5×10^{-5} (3.0×10^{-5})	Z pole ($Z\to\mu\mu$)	point-to-point Unc.
ΔA_τ	4.3×10^{-3} [37, 51–55]	7.0×10^{-5} (1.2×10^{-5})	Z pole ($Z\to\tau\tau$)	tau decay model
ΔA_b	0.02 [37, 56]	20×10^{-5} (3×10^{-5})	Z pole	QCD effects
ΔA_c	0.027 [37, 56]	30×10^{-5} (6×10^{-5})	Z pole	QCD effects
$\Delta\sigma_{had}$	37 pb [37–41]	2 pb (0.05 pb)	Z pole	lumiosity
δR_b^0	0.003 [37, 57–61]	0.0002 (5×10^{-6})	Z pole	gluon splitting
δR_c^0	0.017 [37, 57, 62–65]	0.001 (2×10^{-5})	Z pole	gluon splitting
δR_e^0	0.0012 [37–41]	2×10^{-4} (3×10^{-6})	Z pole	E_{beam} and t channel
δR_μ^0	0.002 [37–41]	1×10^{-4} (3×10^{-6})	Z pole	E_{beam}
δR_τ^0	0.017 [37–41]	1×10^{-4} (3×10^{-6})	Z pole	E_{beam}
δN_ν	0.0025 [37, 66]	2×10^{-4} (3×10^{-5})	ZH run ($\nu\nu\gamma$)	Calo energy scale







Flavor Physics



See the non-seen: i.e, Bc→tauv, Bs→Phivv
Orders of magnitudes improvements (1 – 2.5 orders...).
Access New Physics with energy scale of 10 TeV, or even above

New Physics white paper

5

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2024

Contents extends from 40 pages → 200 pages...

- Credit: hanhua Cui, Yu Gao, Xuai Zhuang

Arbor

Tree topology of particle shower

Ori. Idea from Henri Videau @ ALEPH

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https://doi.org/10.1140/epjc/s10052-018-5876-z

THE EUROPEAN PHYSICAL JOURNAL C

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Special Article - Tools for Experiment and Theory

Reconstruction of physics objects at the Circular Electron Positron Collider with Arbor

Manqi Ruan[1,a], Hang Zhao[1], Gang Li[1], Chengdong Fu[1], Zhigang Wang[1], Xinchou Lou[6,7,8], Dan Yu[1,2], Vincent Boudry[2], Henri Videau[2], Vladislav Balagura[2], Jean-Claude Brient[2], Peizhu Lai[3], Chia-Ming Kuo[3], Bo Liu[1,4], Fenfen An[1,4], Chunhui Chen[4], Soeren Prell[4], Bo Li[5], Imad Laktineh[5]

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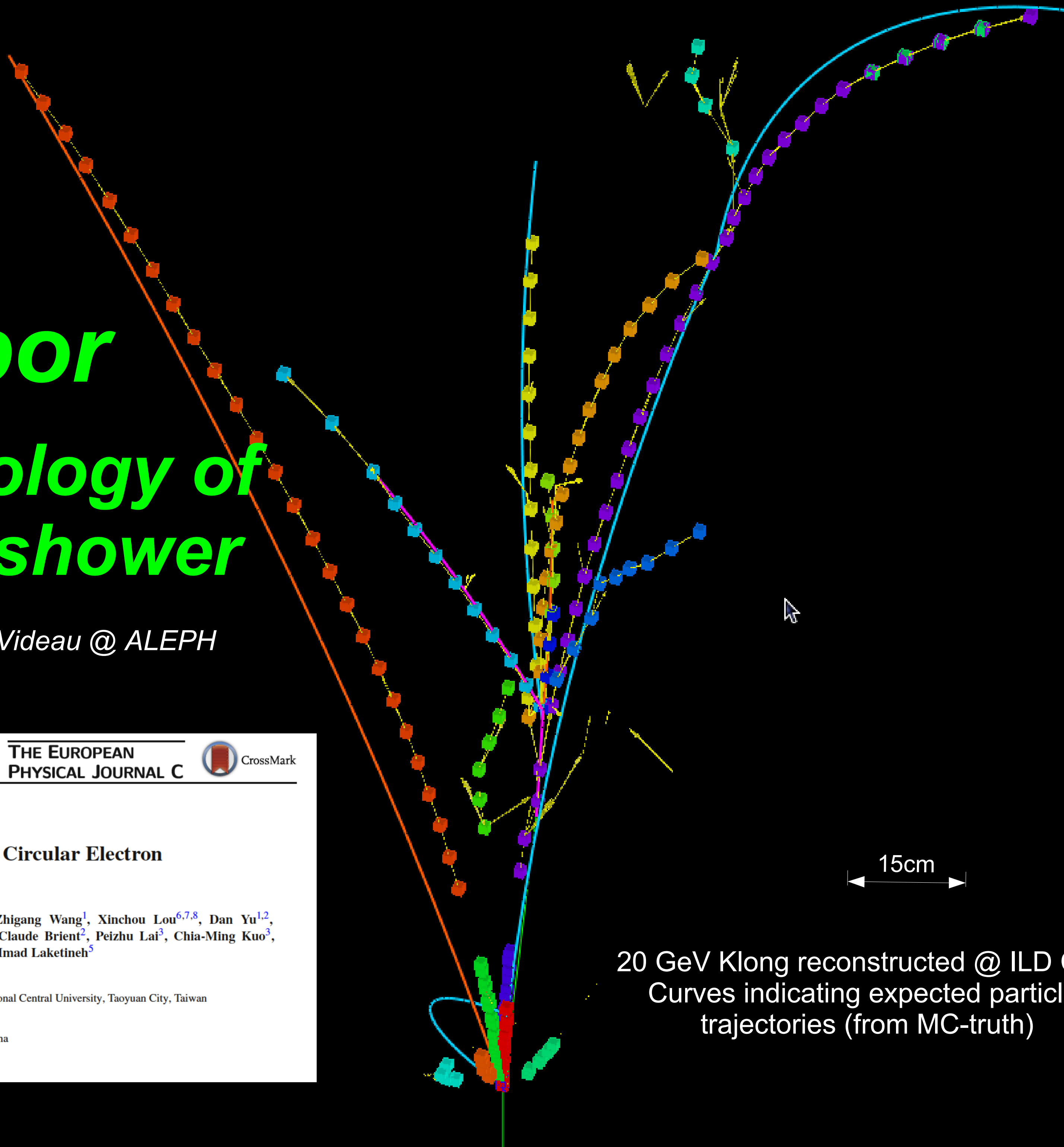
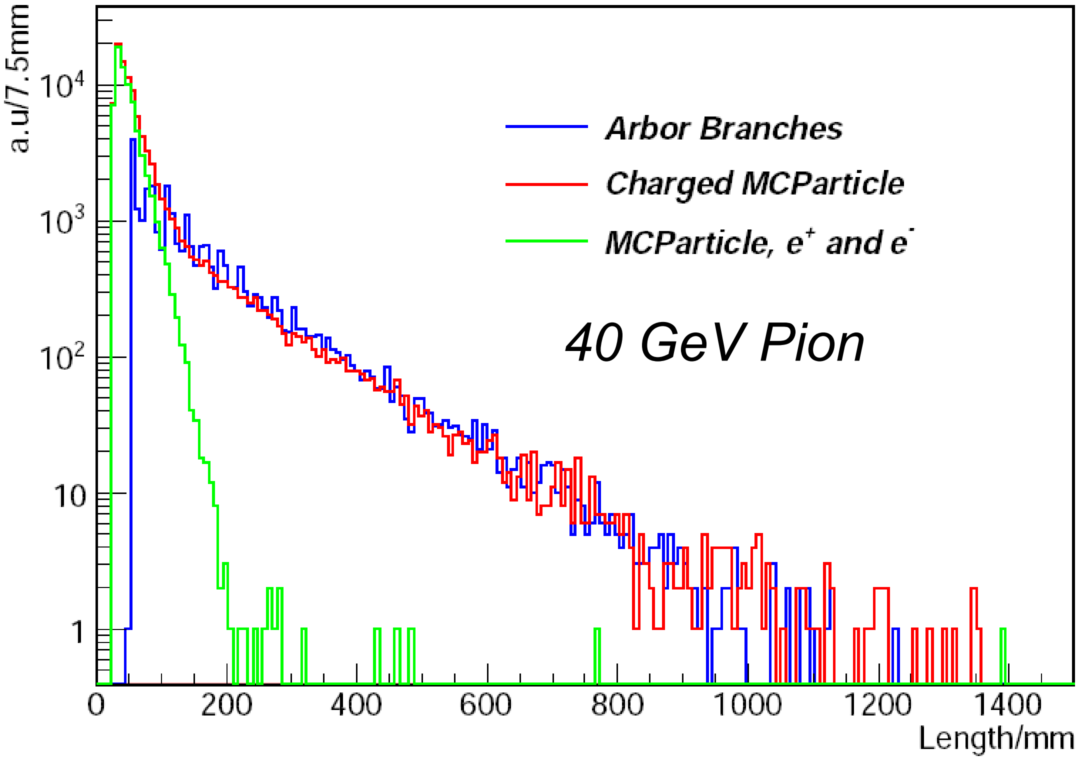
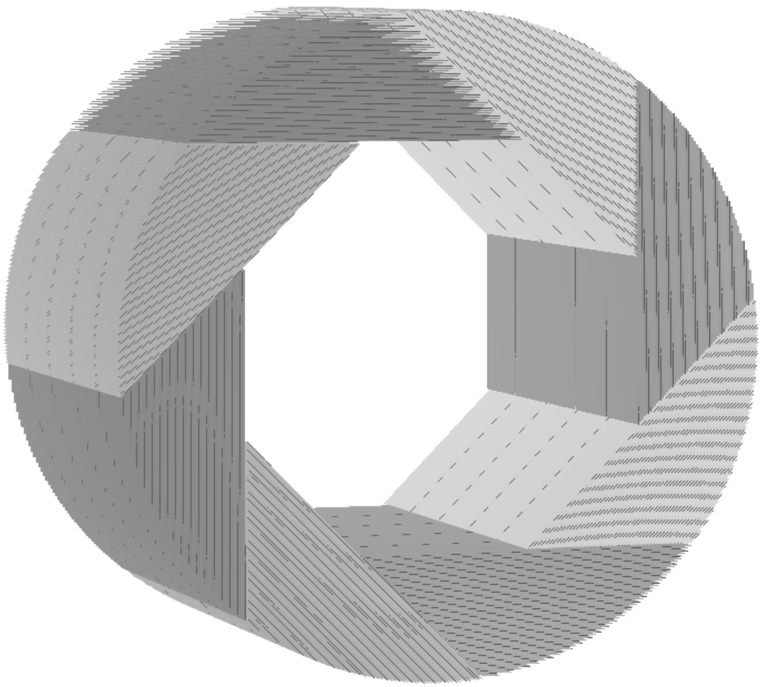
7 Physics Department, University of Texas at Dallas, Richardson, TX, USA
8 University of Chinese Academy of Sciences (UCAS), Beijing, China



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

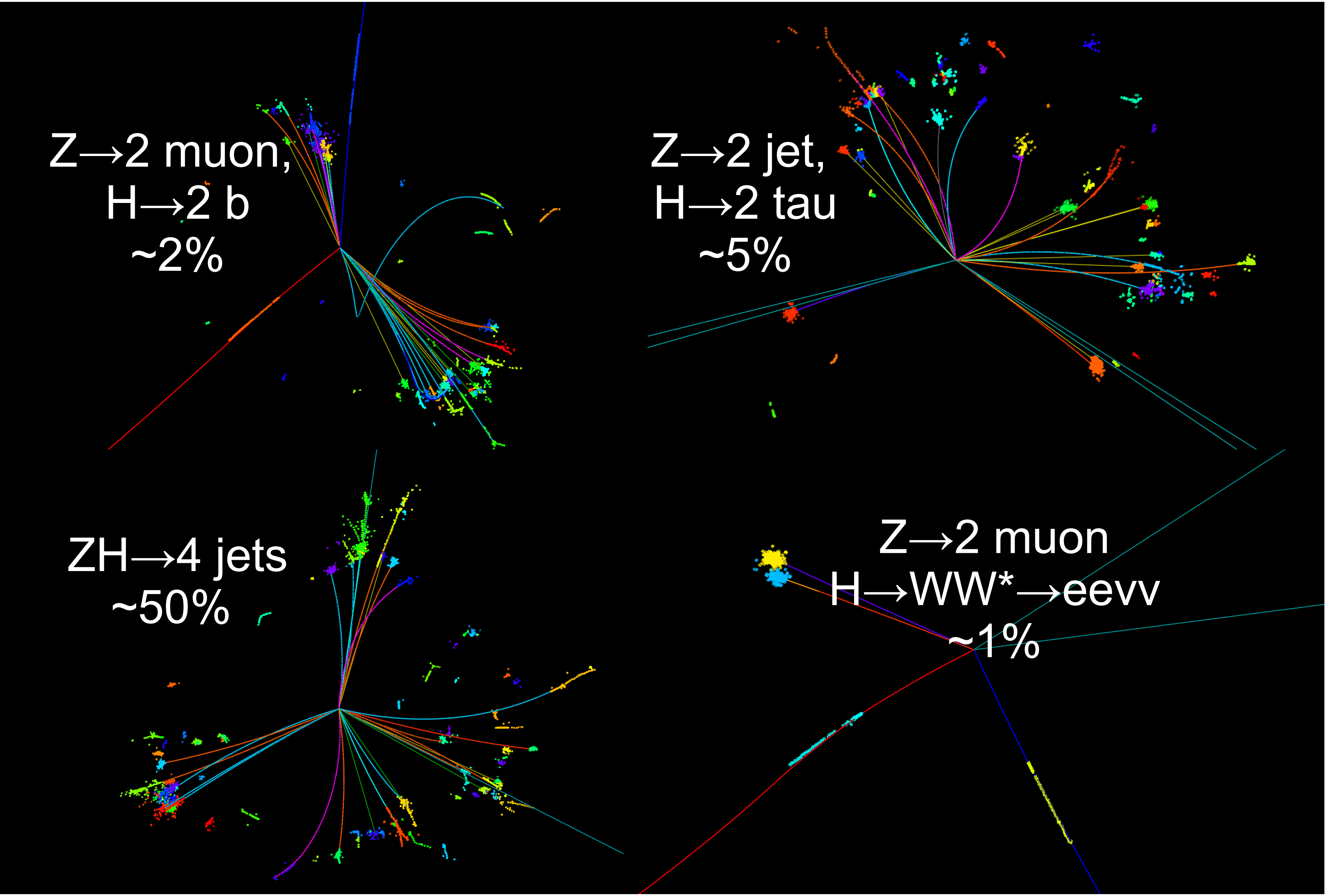
Validation: Arbor Branch Length Vs MC Truth

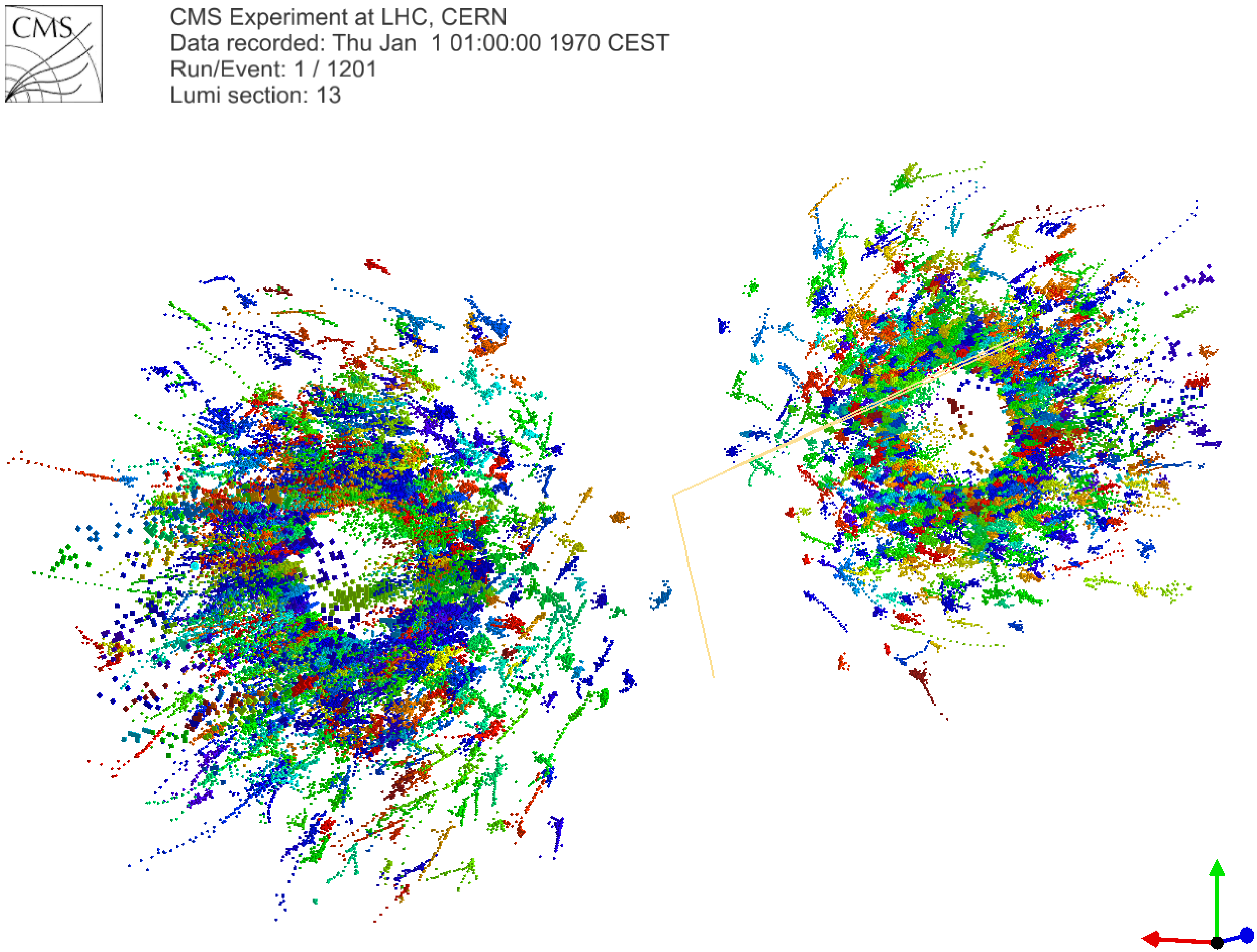




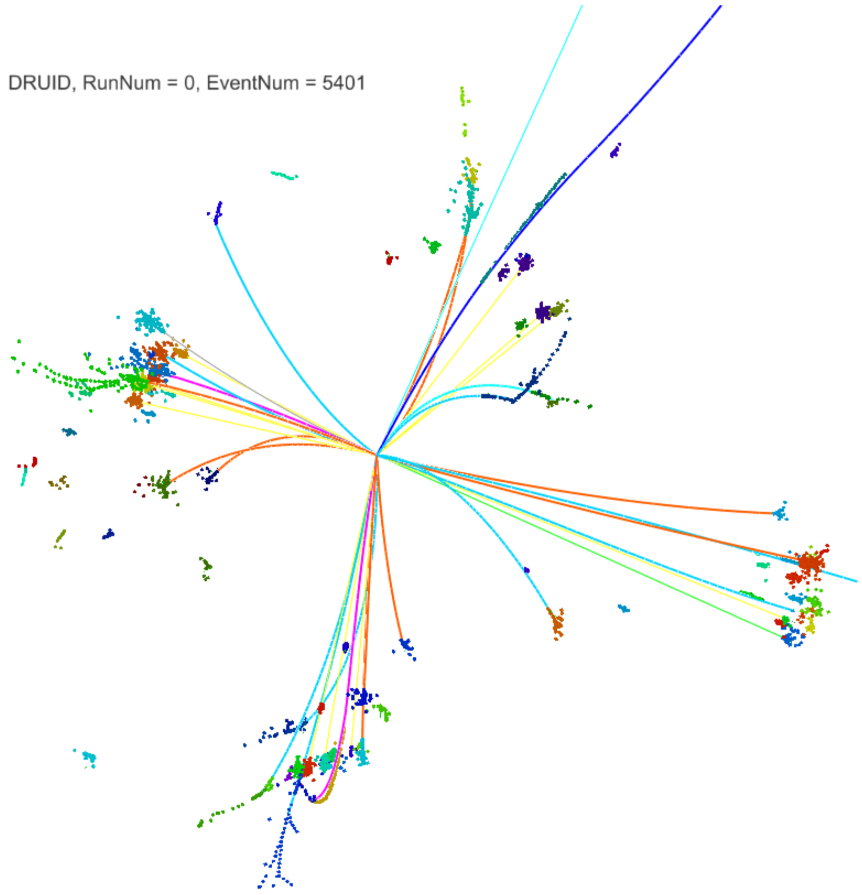
Arbor: successfully tag sub-shower structure

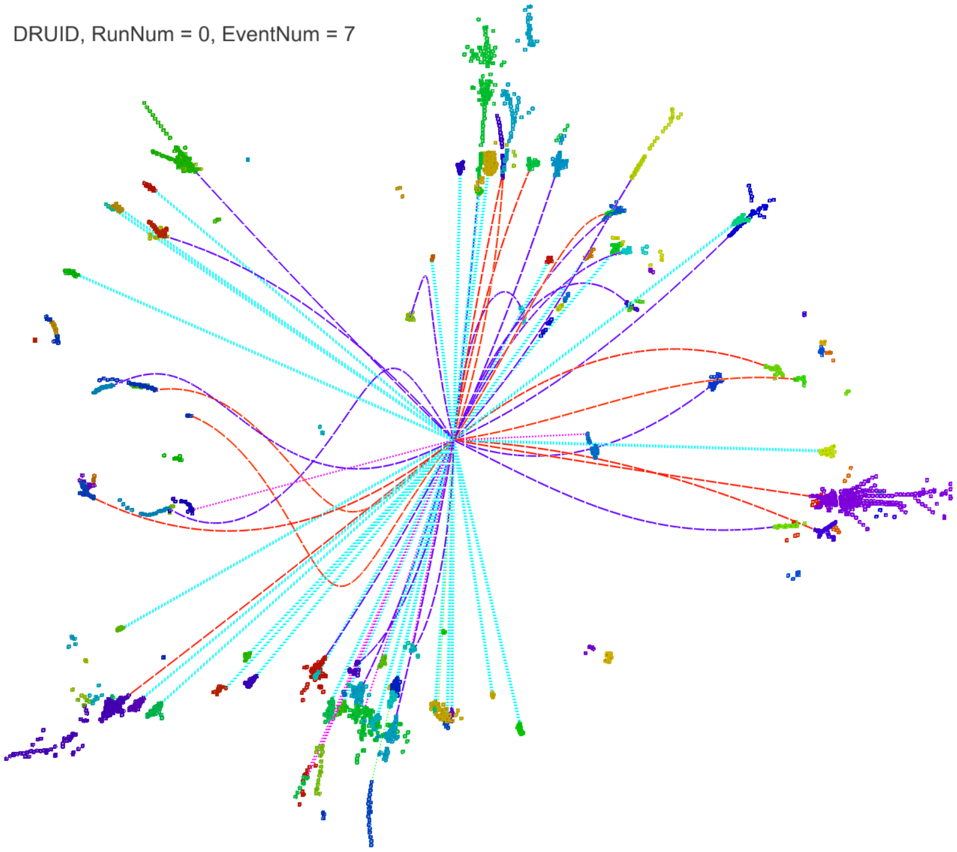
Samples: Particle gun event at ILD HCAL (readout granularity 1cm^2 & layer thickness 2.65cm)
Length:
Charged MCParticle: spatial distance between generation/end points
Arbor branch: sum of distance between neighboring cells


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%

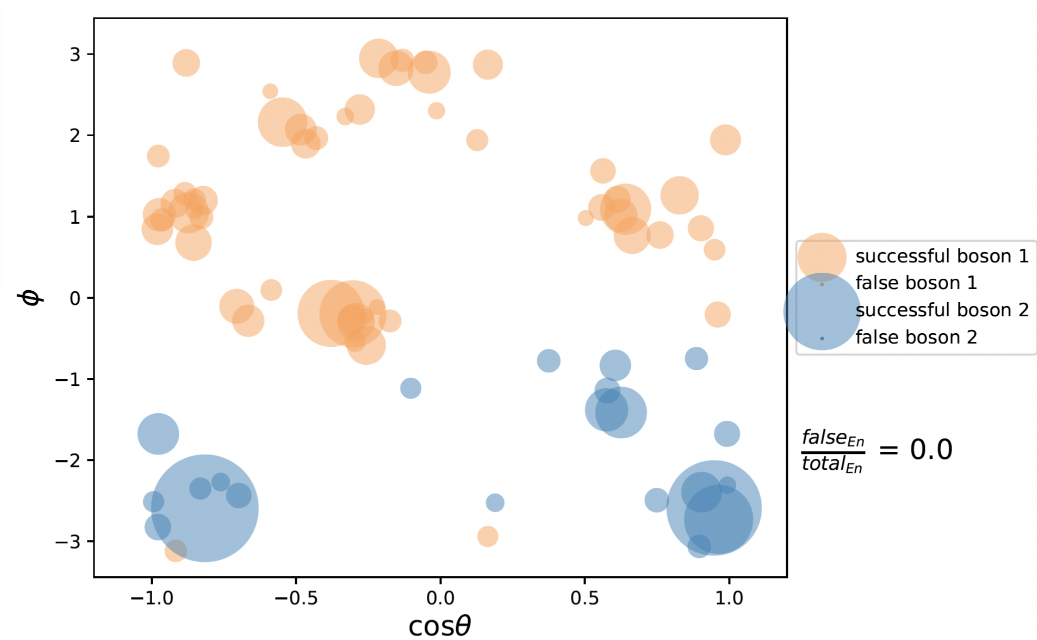

CMS Experiment at LHC, CERN
Data recorded: Thu Jan 1 01:00:00 1970 CEST
Run/Event: 1 / 1201
Lumi section: 13

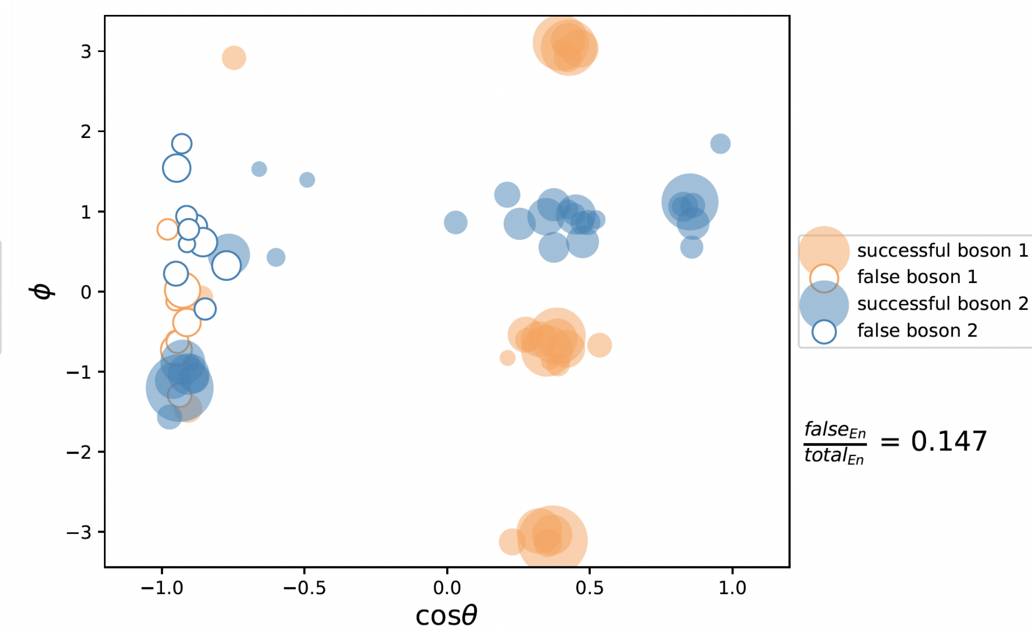
Color Singlet Identification





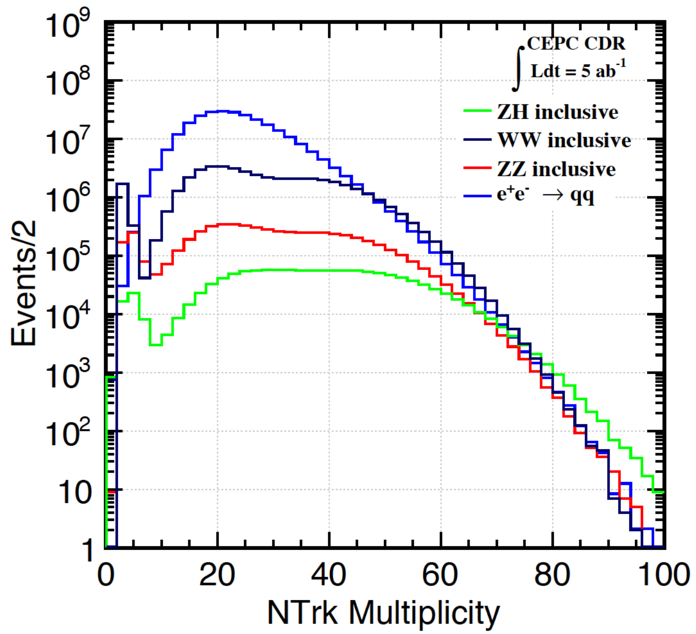
Color Singlet Identification

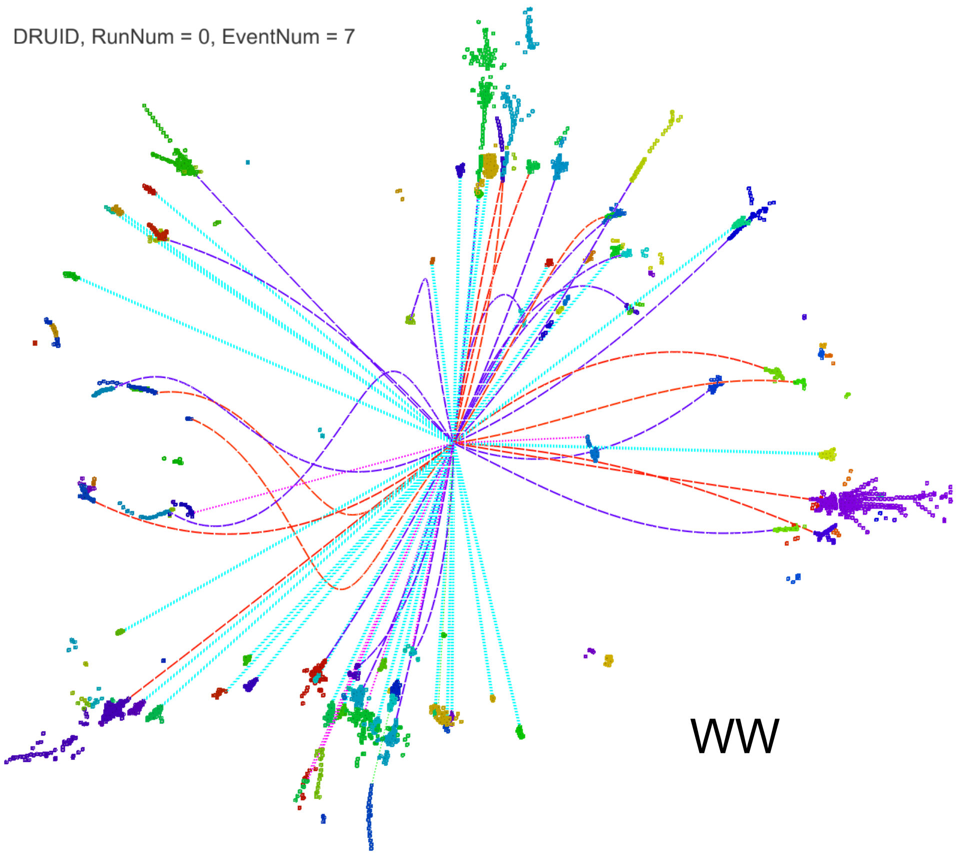




- CSI: identify the color single origin of each final state particle
- Grouping problem: essential for the physics measurements with multi-jet events, i.e., measurements with full hadronic ZH events
- AI might well strongly enhance its performance: compared to conventional jet clustering & matching

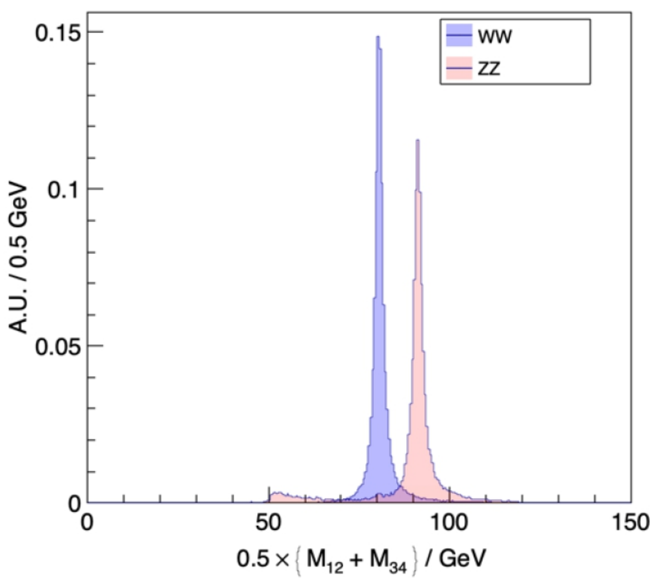
BM-III: full hadronic WW-ZZ separation

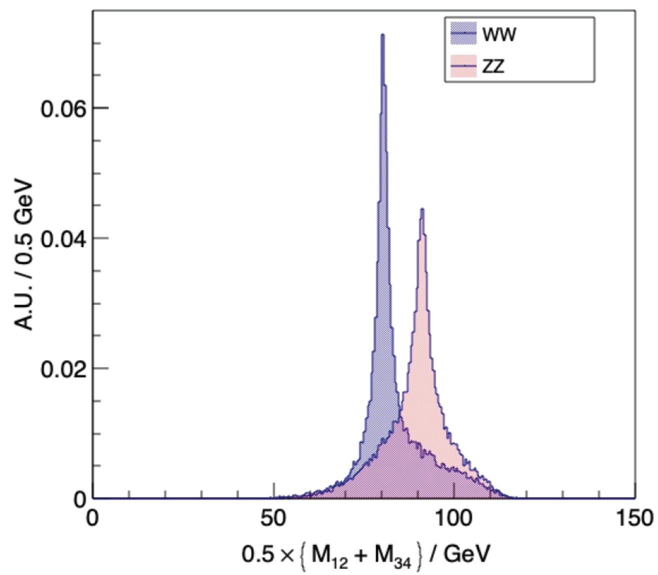


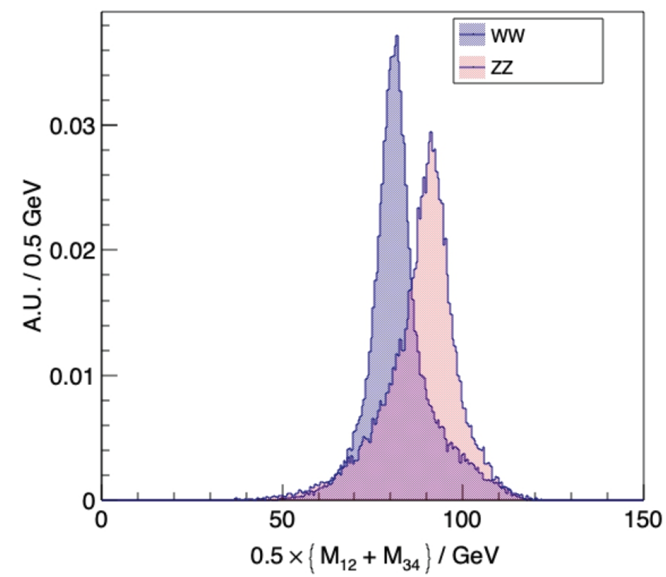


- Low energy jets! (20 – 120 GeV)
- Typical multiplicity ~ o(100)
- WW-ZZ Separation: determined by
  - Intrinsic boson mass/width
  - Jet confusion from color single reconstruction – jet clustering & pairing
  - Detector response

Jet confusion: the leading term







- Separation be characterized by

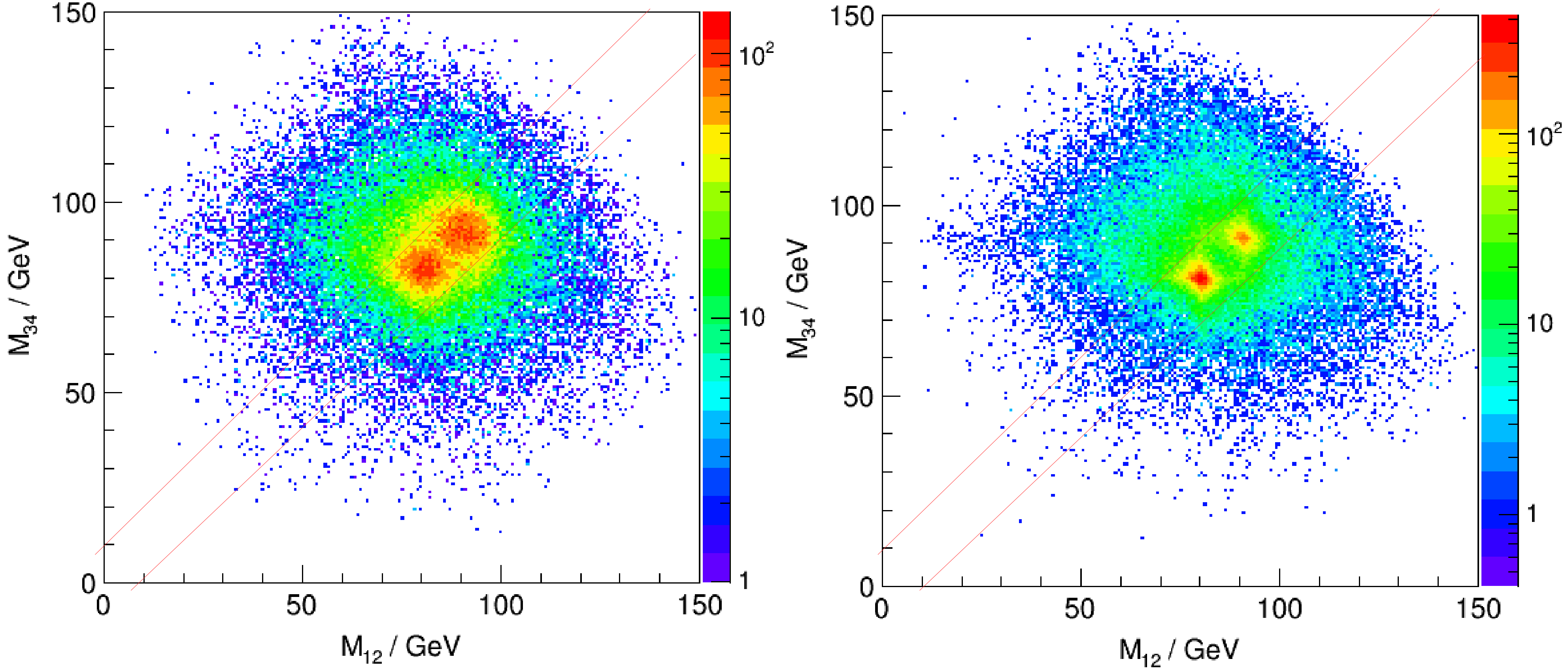
$$overlapping\ ratio = \sum_{bins} min(a_i, b_i)$$

- Final state/MC particles are clustered into Reco/Genjet with ee-kt, and paired according to chi2

$$\chi^2 = \frac{(M_{12} - M_B)^2 + (M_{34} - M_B)^2}{\sigma_B^2}$$

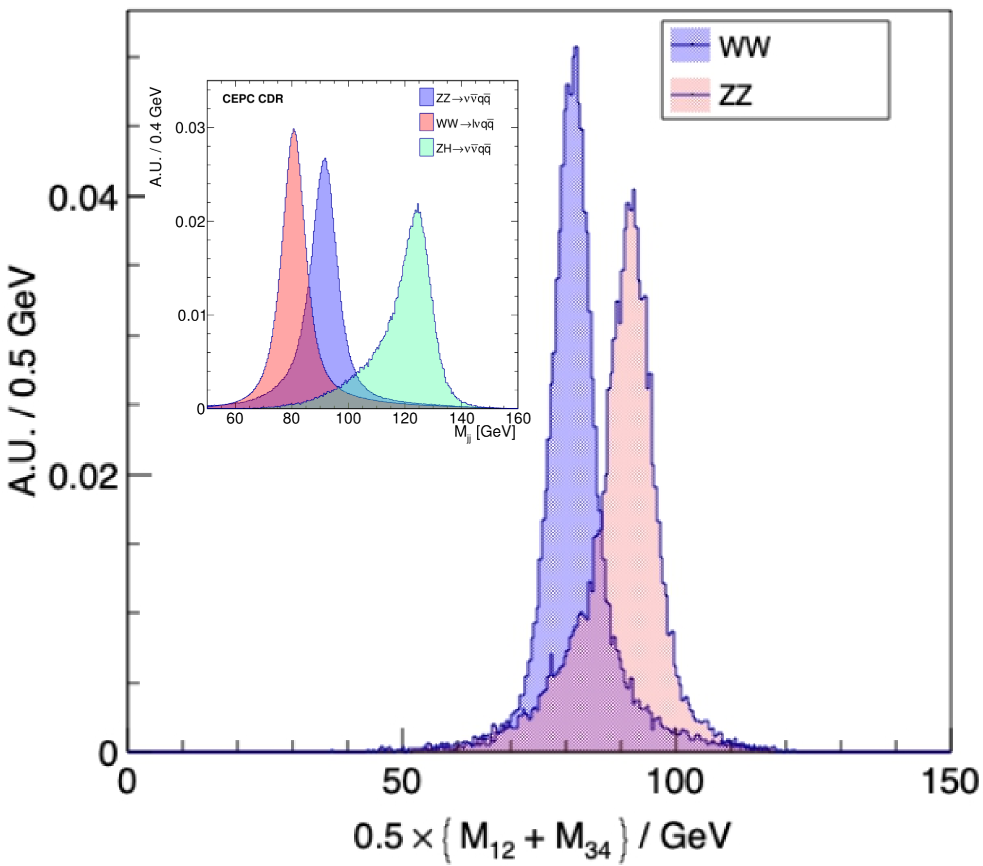
- WW-ZZ Separation at the inclusive sample:
  - Intrinsic boson mass/width - lower limit: Overlapping ratio of 13%
  - \+ Jet confusion – Genjet: Overlapping ratio of **53%**
  - \+ Detector response – Recojet: Overlapping ratio of 58%

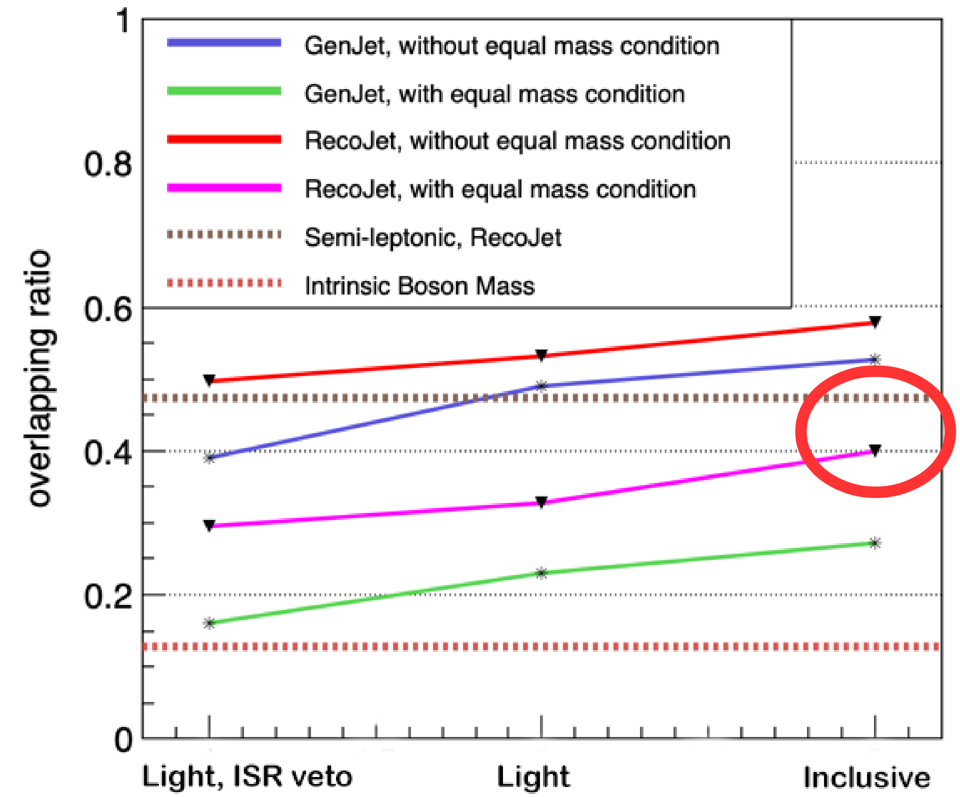
Reconstructed mass of the two di-jet system



Equal mass condition |M12 – M34| < 10 GeV: At the cost of half the statistic, the overlapping ratio can be reduced from 58%/53% to 40%/27% for the Reco/Genjet

Separation of full hadronic WW-ZZ event





The CEPC Baseline could separate efficiently the WW-ZZ with full hadronic final state.

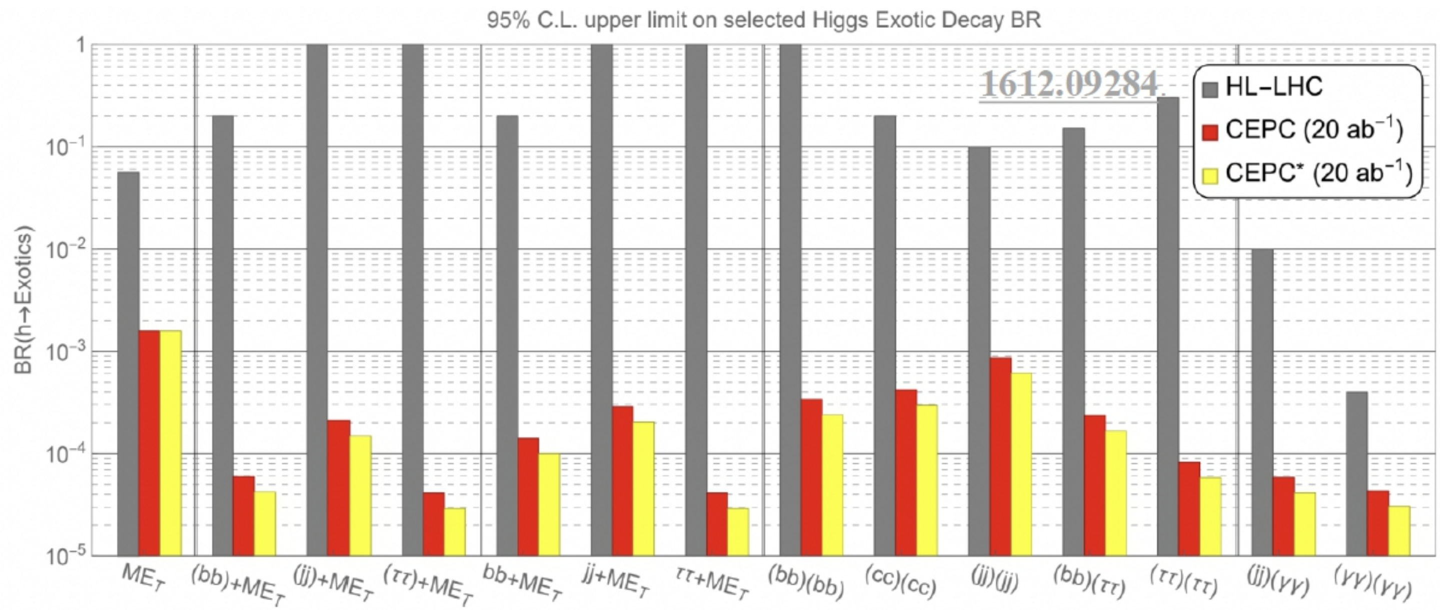
Critical to develop color singlet reconstruction: improve from the naive Jet clustering & pairing.

Quantified by differential overlapping ratio.

Control of ISR photon/neutrinos from heavy flavor jet is important.

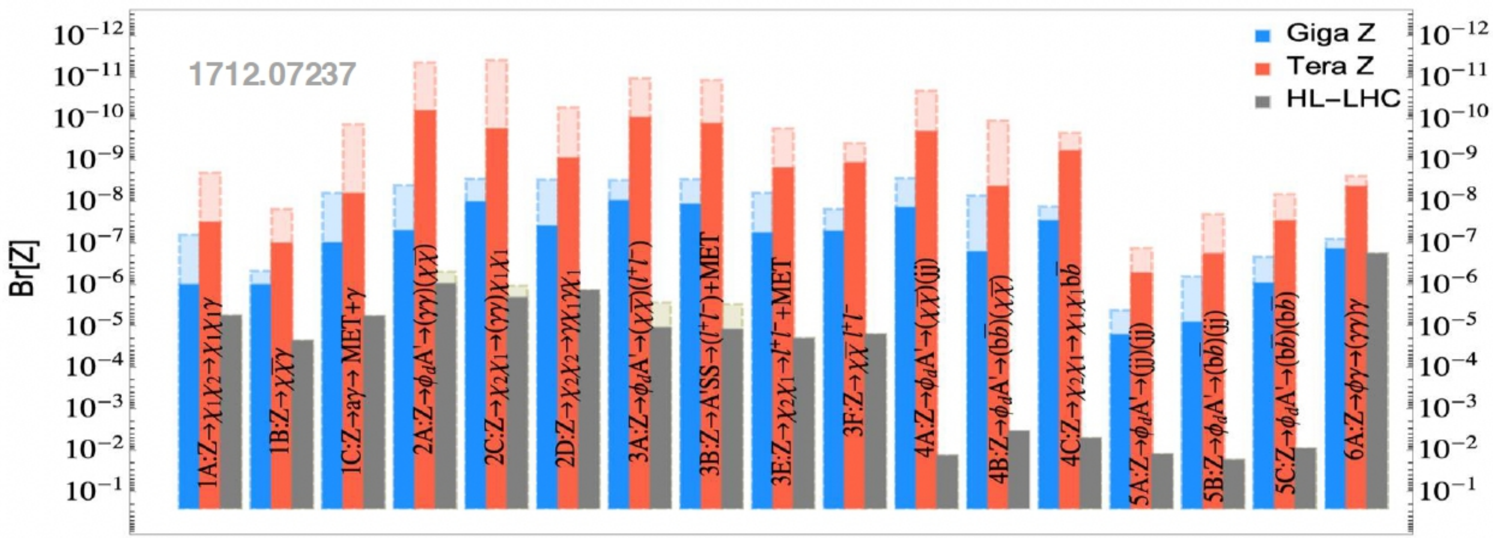
https://arxiv.org/abs/1812.09478

Exotic decays



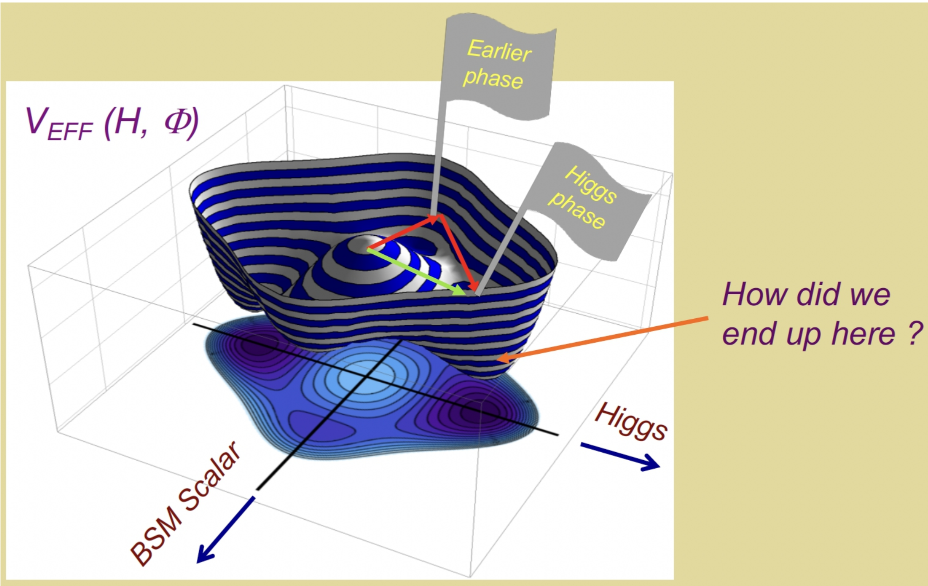
The 95% C.L. upper limit on selected Higgs exotic decay BR

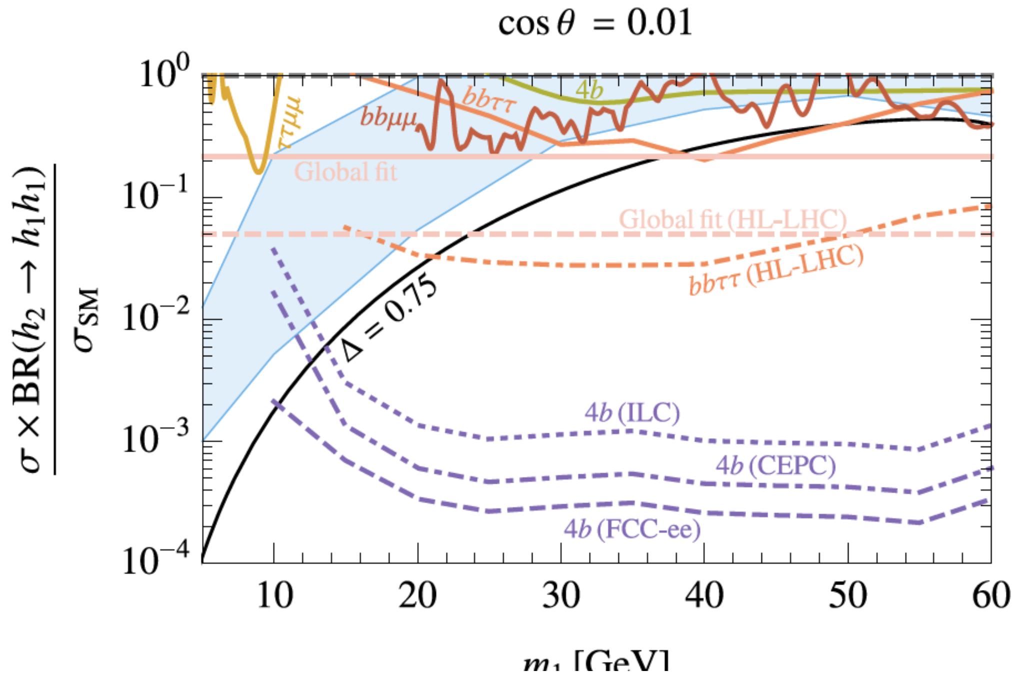
- Credit: Zhen Liu, Jia Liu, Xuai Zhuang, etc

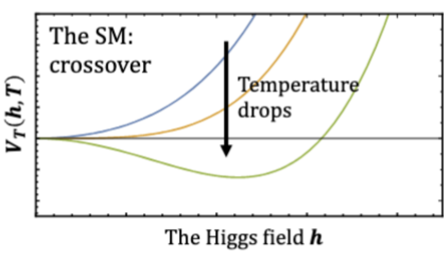


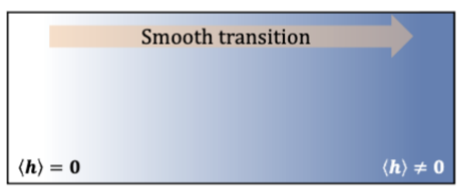
The reach for the branching ratio of various exotic Z decay modes

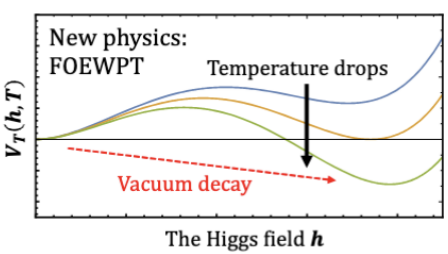
Phase Transition in early Universe

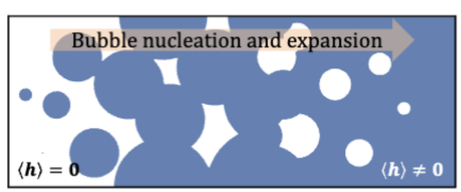


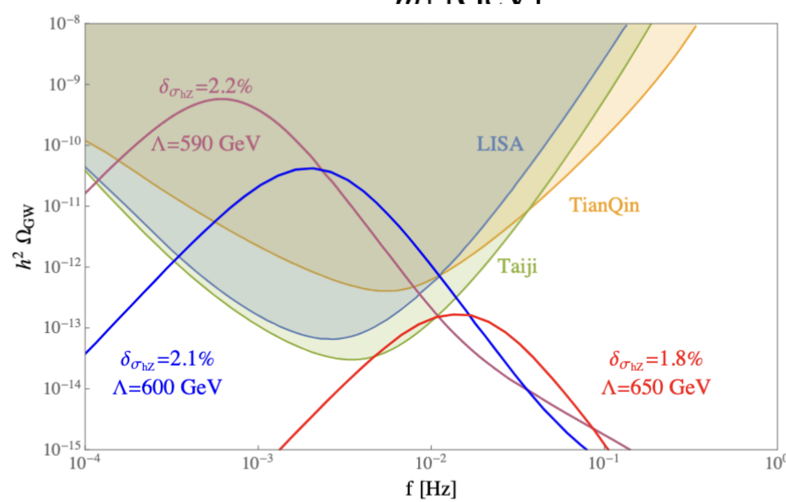








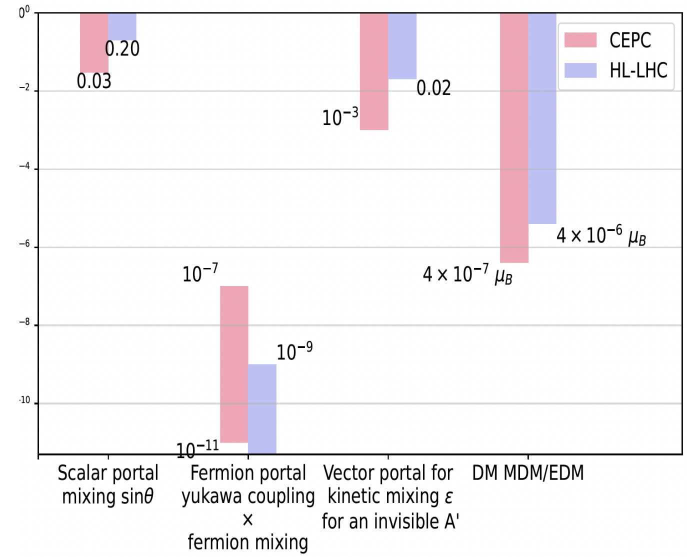


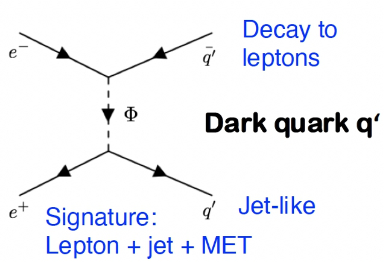


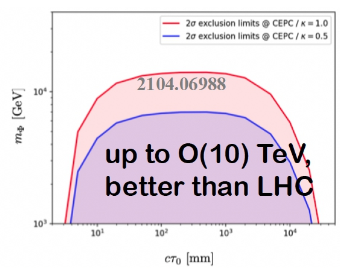
- Credit: Michael Ramse Musolfy, Kepan Xie, etc

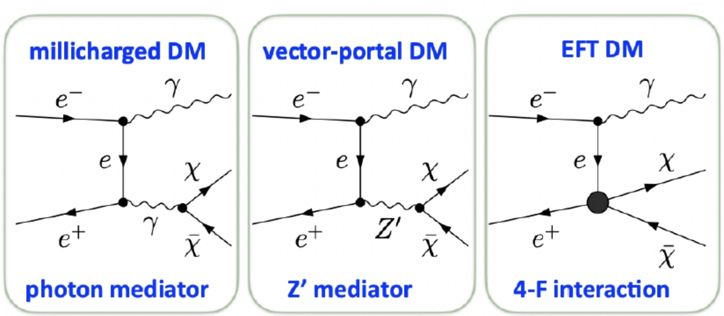
Dark sector

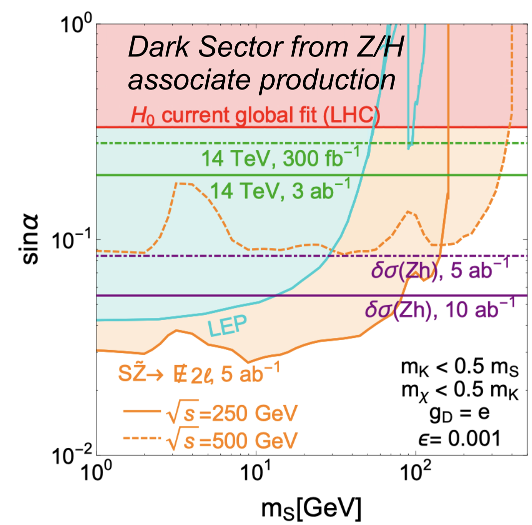
Portal	Effective operator	$\sqrt{s}$ [GeV]	$\mathcal{L}[ab^{-1}]$	Sensitivity of CEPC (HL-LHC)	Figs.	Ref.
Scalar	$\lambda_{HP}\lvert H\rvert^2 S^2 \to$ scalar mixing $\sin\theta$	250	5	invisible S, $\sin\theta \approx 0.03$ (0.20 global-fits)	22	[108]
Fermion	$y_\ell \bar{\chi}_L S^\dagger \ell_R$ + H.c.	250	5	covering 100 GeV $< m_S <$ 170 GeV	23	[56]
	$\kappa \Phi \bar{q}'_L \ell_R$ + H.c. (dark QCD)	250	5	$m_\Phi \sim 10$ TeV for $c\tau_{\text{darkpion}} \in [1, 10^3]$ cm (Null)	25	[109]
	$y \Phi \bar{F}_L \ell_R$ + H.c.	240	5.6	$y\theta_L \in [10^{-11},\ 10^{-7}]$ ($\lesssim 10^{-8} - 10^{-9}$)	26	[110]
Vector	$A'_\mu\left(e\epsilon J^\mu_{\text{em}} + g_D \bar{\chi}\gamma^\mu\chi\right)$	250	5	$\epsilon \sim 10^{-3}$ for $g_D = e$ and $m_{A'} < 125$ GeV ($\epsilon \sim 0.02$)	27, 28	[108]
	$\varepsilon A_\mu \bar{\chi}\gamma^\mu\chi$, (millicharge DM)	250	5	$\epsilon \sim 0.1$ for $m_\chi \sim 50$ GeV	29	[111]
		91.2	2.6	$\epsilon \sim 0.02$ for $m_\chi \sim 5$ GeV		
		160	16	$\epsilon \sim 0.5$ for $m_\chi \sim 10$ GeV		
	$\frac{1}{2}\mu_\chi \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} + \frac{i}{2} d_\chi \bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu}$	91.2	100	$\mu_\chi, d_\chi \sim 4 \times 10^{-7}$ $(4 \times 10^{-6})\mu_B$ for $m_\chi < 25$ GeV	30	[112]
	$-a_\chi \bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu} + b_\chi \bar{\chi}\gamma^\mu\chi\partial^\nu F_{\mu\nu}$	240	20	$a_\chi, b_\chi \sim 10^{-6}$ (2×10^{-6}) GeV^{-2} for $m_\chi < 80$ GeV		
EFT	$\frac{1}{\Lambda^2}\sum_i \left(\bar{\chi}\gamma_\mu(1-\gamma_5)\chi\right)\left(\bar{\ell}\gamma^\mu(1-\gamma_5)\ell\right)$	250	5	$\Lambda_i \sim 2$ TeV ($m_\chi = 0$) (Null)	31	[113]
	$\frac{1}{\Lambda_A^2}\bar{\chi}\gamma_\mu\gamma_5\chi\bar{\ell}\gamma^\mu\gamma_5\ell$	250	5	$\Lambda_A \sim 1.5$ TeV (Null)	32	[111]
	$\sum_i \frac{1}{\Lambda_i^2}(\bar{e}\Gamma_\mu e)(\bar{\nu}_L\Gamma^\mu\chi_L)$ + H.c. $\Gamma_\mu = 1, \gamma_5, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu}$	240	20	$\Lambda_i \sim 1$ TeV ($m_\chi = 0$) (Null)	33	[114]

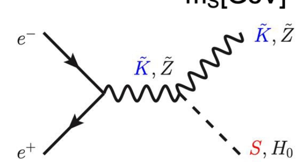


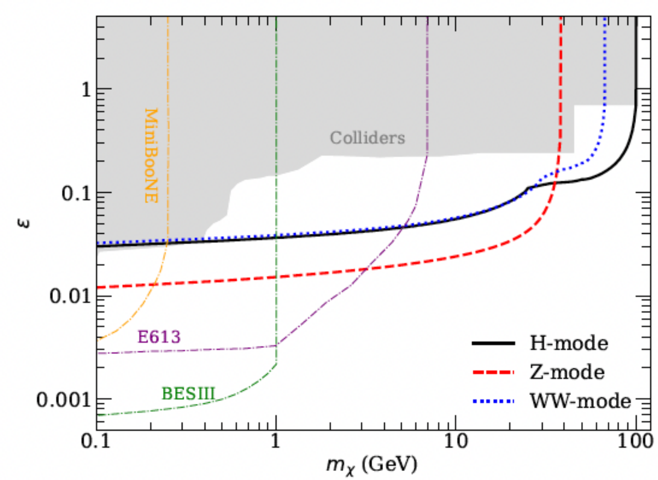








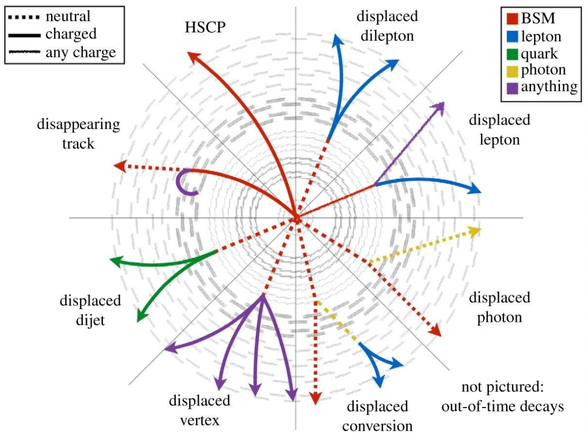




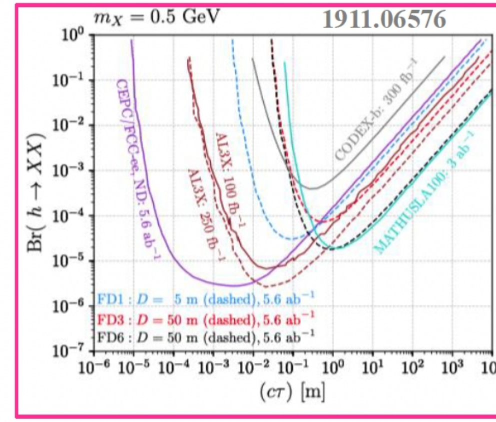
Vector portal DM

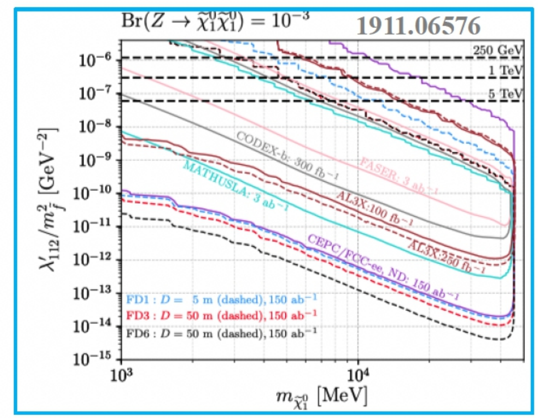
- Credit: Jia Liu, etc

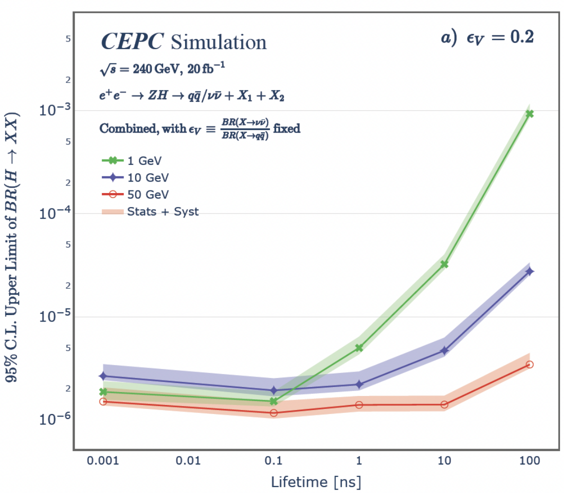
LLP, especially with Far detector



LLP Type	Signal Signature	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [ab^{-1}]	Detector	Sensitivities on parameters [Assumptions]	Figs.	Refs.
New scalar particles (X)	$Z(\to \text{incl.})\, h(\to XX)$, $X \to q\bar{q}/\nu\bar{\nu}$	240	20	ND	$\text{Br}(h \to XX) \sim 10^{-6}$ [$m \in (1,50)$ GeV, $\tau \in (10^{-3}, 10^{-1})$ ns]	37	[80]
	$Z(\to \text{incl.})\, h(\to XX)$, $X \to \text{incl.}$	240	5.6	ND	$\text{Br}(h \to XX) \sim 3 \times 10^{-6}$ [$m = 0.5$ GeV, $c\tau \sim 5 \times 10^{-3}$ m]	49	[86]
				FD3	$\text{Br}(h \to XX) \sim 7 \times 10^{-5}$ [$m = 0.5$ GeV, $c\tau \sim 1$ m]	49	[86]
				LAYCAST	$\text{Br}(h \to XX) \sim 5 \times 10^{-6}$ [$m = 0.5$ GeV, $c\tau \sim 10^{-1}$ m]	49	[241]
RPV-SUSY neutralinos ($\tilde{\chi}_1^0$)	$Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to \text{incl.}$	91.2	150	ND	$\lambda'_{112}/m_{\tilde{f}}^2 \in (2 \times 10^{-14}, 10^{-8})$ GeV^{-2} [$m \sim 40$ GeV, $\text{Br}(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) = 10^{-3}$]	43	[86]
				FD3	$\lambda'_{112}/m_{\tilde{f}}^2 \in (10^{-14}, 10^{-9})$ GeV^{-2} [$m \sim 40$ GeV, $\text{Br}(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) = 10^{-3}$]	50	[86]
				LAYCAST	$\lambda'_{112}/m_{\tilde{f}}^2 \in (7 \times 10^{-15}, 10^{-9})$ GeV^{-2} [$m \sim 40$ GeV, $\text{Br}(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) = 10^{-3}$]	50	[241]
ALPs (a)	$Z^{(*)} \to \mu^- \mu^+ a$	91	150	ND	$f_a/C_{\mu\mu}^A \lesssim 950$ GeV	44	[85]
	γa, $a \to \gamma\gamma$	91.2	150	ND	$C_{\gamma\gamma}/\Lambda \sim 10^{-3}$ TeV^{-1} [$C_{\gamma Z} = 0$, $m \sim 2$ GeV]	51	[241]
				FD3	$C_{\gamma\gamma}/\Lambda \sim 6 \times 10^{-3}$ TeV^{-1} [$C_{\gamma Z} = 0$, $m \sim 0.3$ GeV]	51	[242]
				LAYCAST	$C_{\gamma\gamma}/\Lambda \sim 2 \times 10^{-3}$ TeV^{-1} [$C_{\gamma Z} = 0$, $m \sim 0.7$ GeV]	51	[241]
Hidden valley particles (π_V^0)	$Z\, h(\to \pi_V^0 \pi_V^0)$, $\pi_V^0 \to b\bar{b}$	350	1.0	ND	$\sigma(h) \times \text{BR}(h \to \pi_v^0 \pi_v^0) \sim 10^{-4}$ pb [$m \in (25,50)$ GeV, $\tau \sim 10^2$ ps]	41	[243]
Dark photons (γ_D)	$Z(\to q\bar{q})\, h(\to \gamma_D \gamma_D)$, $\gamma_D \to \ell^- \ell^+/q\bar{q}$	250	2.0	ND	$\text{Br}(h \to \gamma_D \gamma_D) \sim 10^{-5}$, [$m \in (5,10)$ GeV, $\tau \sim 10^2$ ps, $\epsilon \in (10^{-6}, 10^{-7})$]	42	[83]



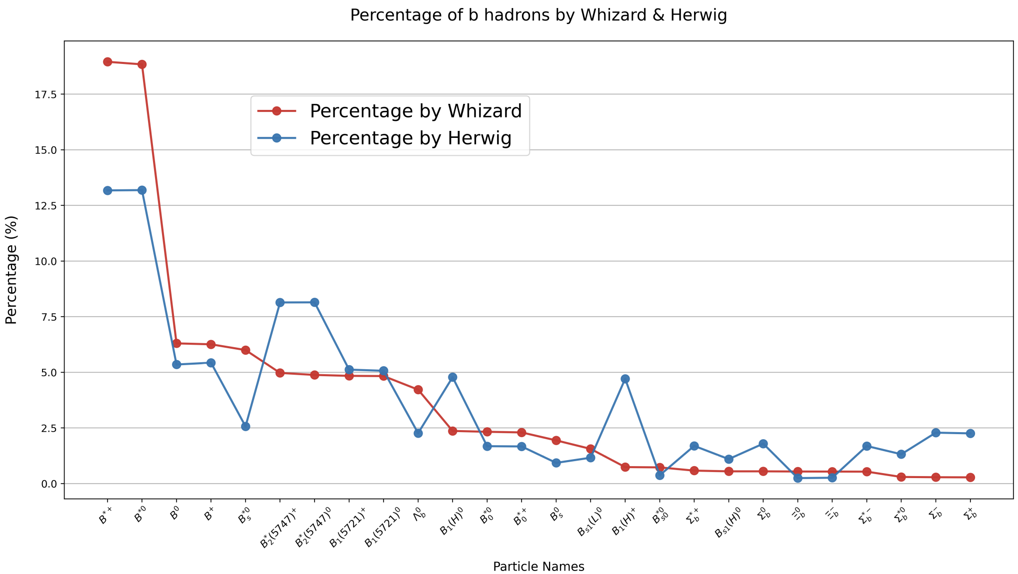


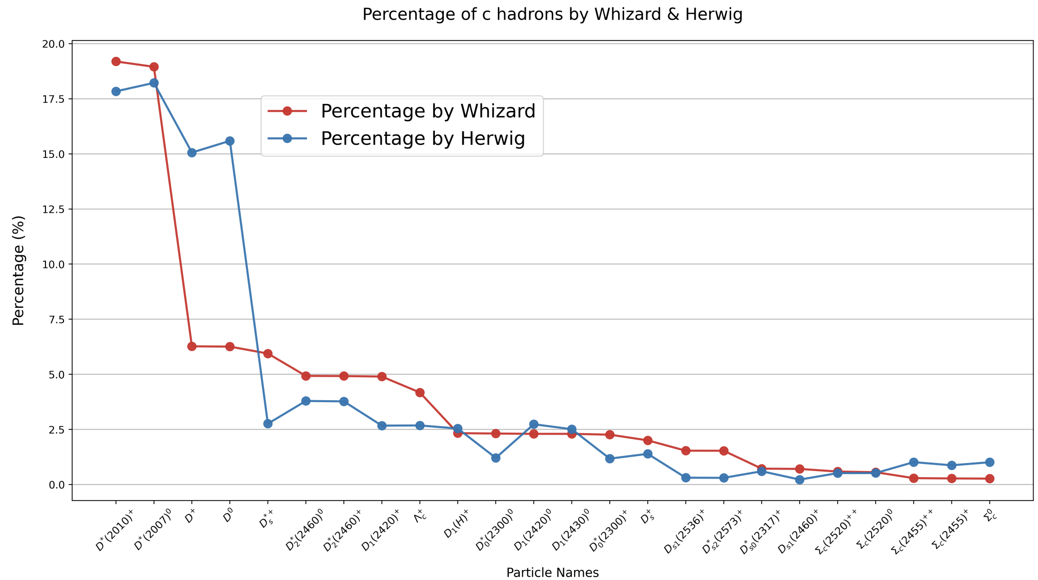


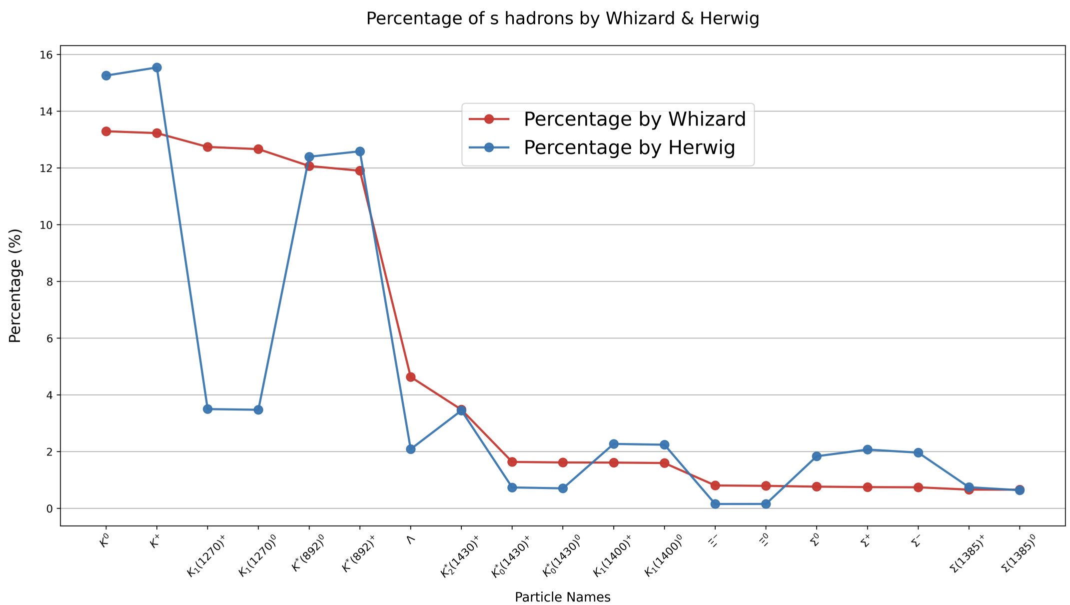
Far detector could enhance & complement the near detector (main detector) sensitivities;
While the understanding of background is the key issue.

- Credit: Kechen Wang, Yongchao Zhang, etc

Fragmentation comparison

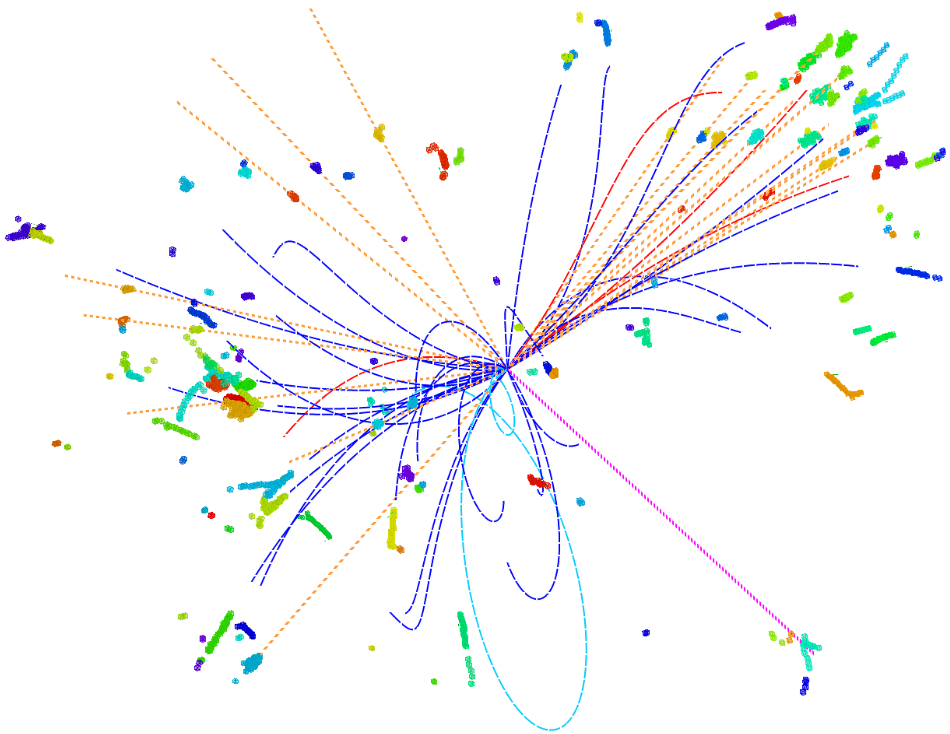


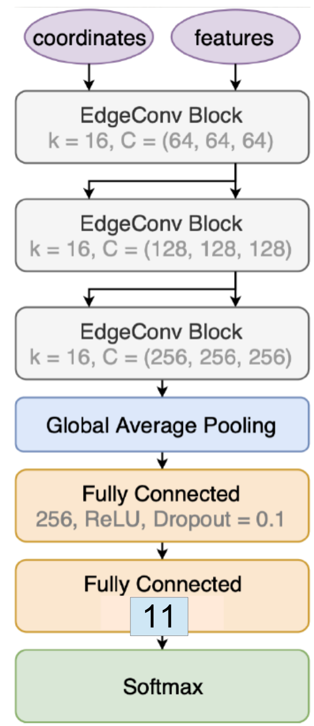


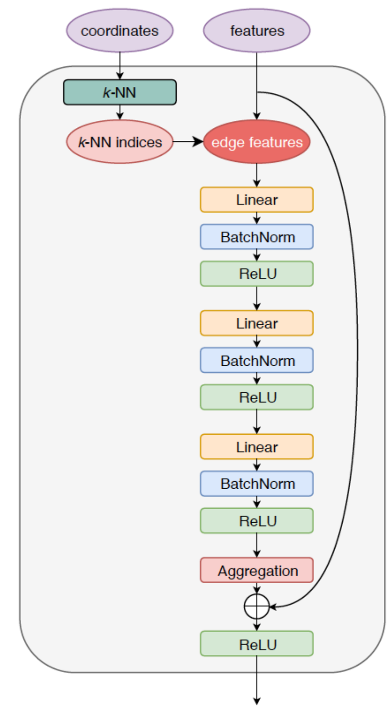


Lots to be studied...

Geo. & Tools

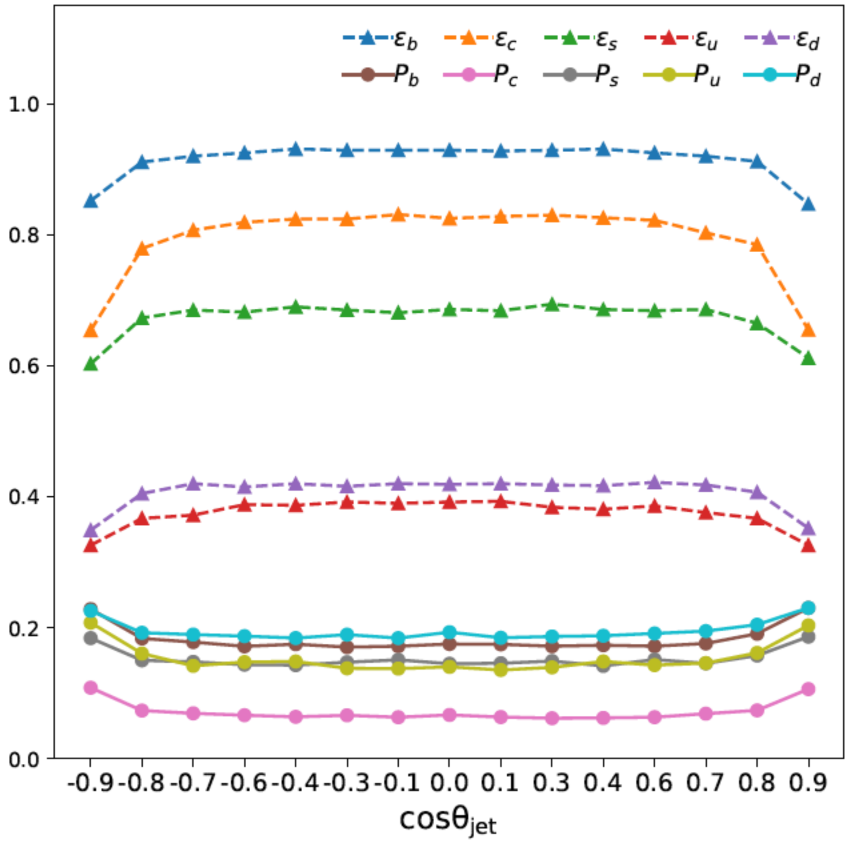


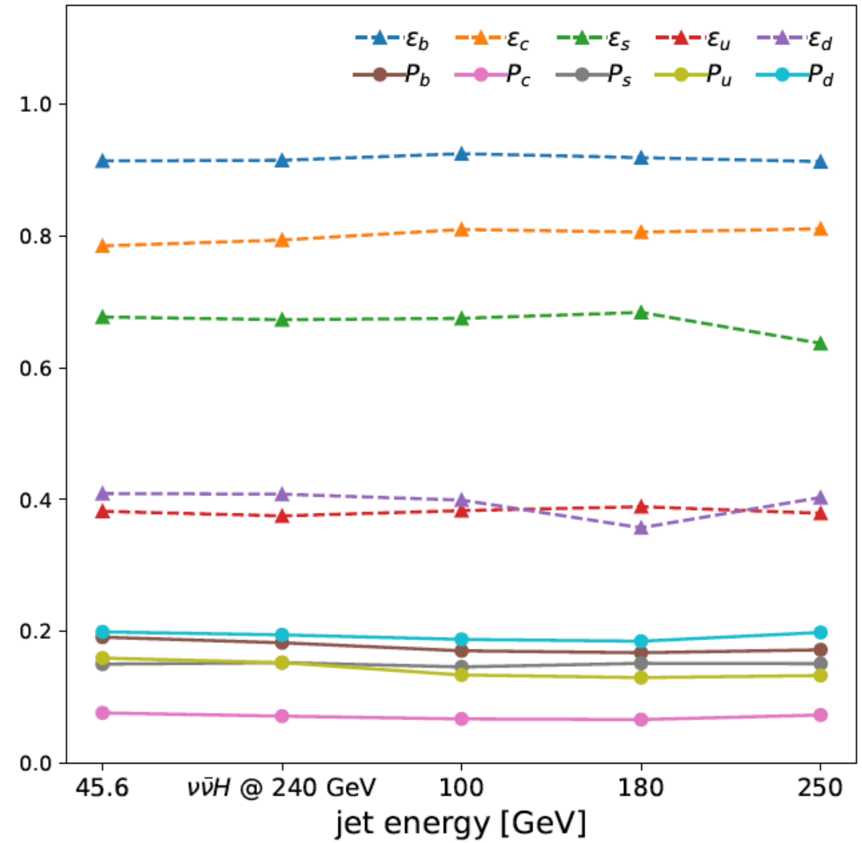




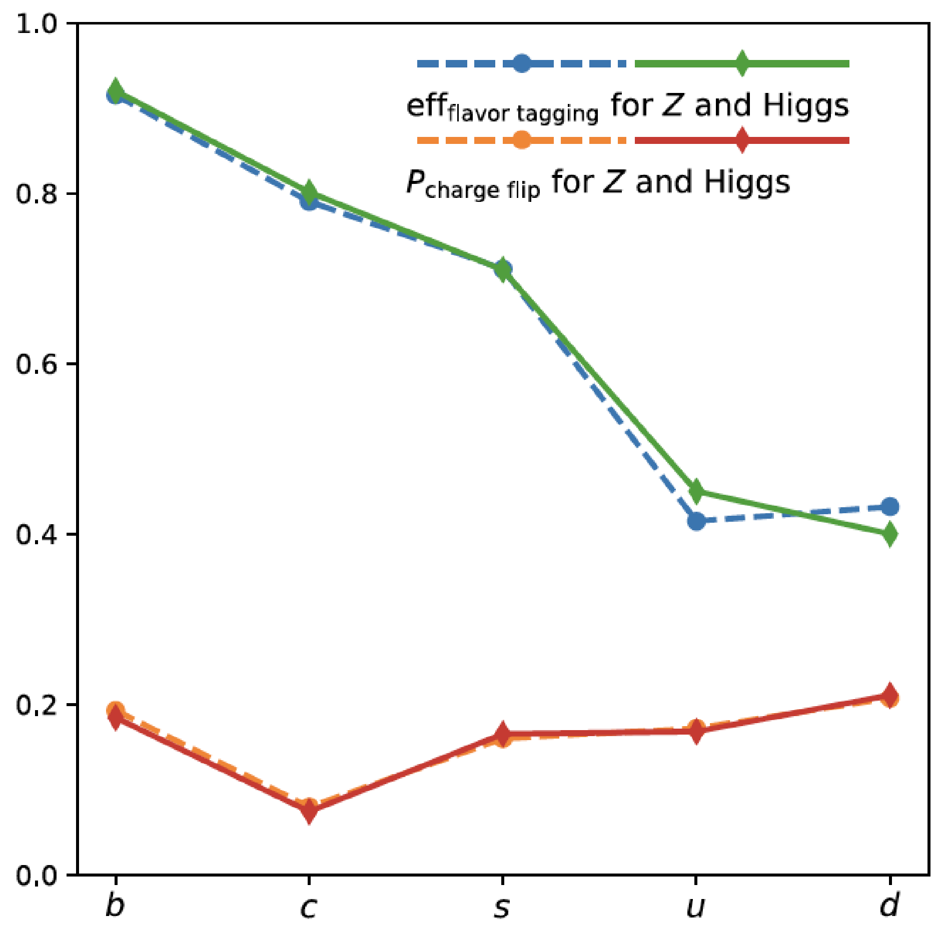
- **Jet origin identification: 11 categories (5 quarks + 5 anti quarks + gluon)**
- Full Simulated vvH, Higgs to two jets sample at CEPC baseline configuration: CEPC-v4 detector, reconstructed with **Arbor + ParticleNet (Deep Learning Tech.)**
  - Input: measurable information of all reconstructed jet particles (~ 10 float)
  - Output: 10(11)-likelihoods to different categories
- 1 Million samples each, 60/20/20% for training, validation & test

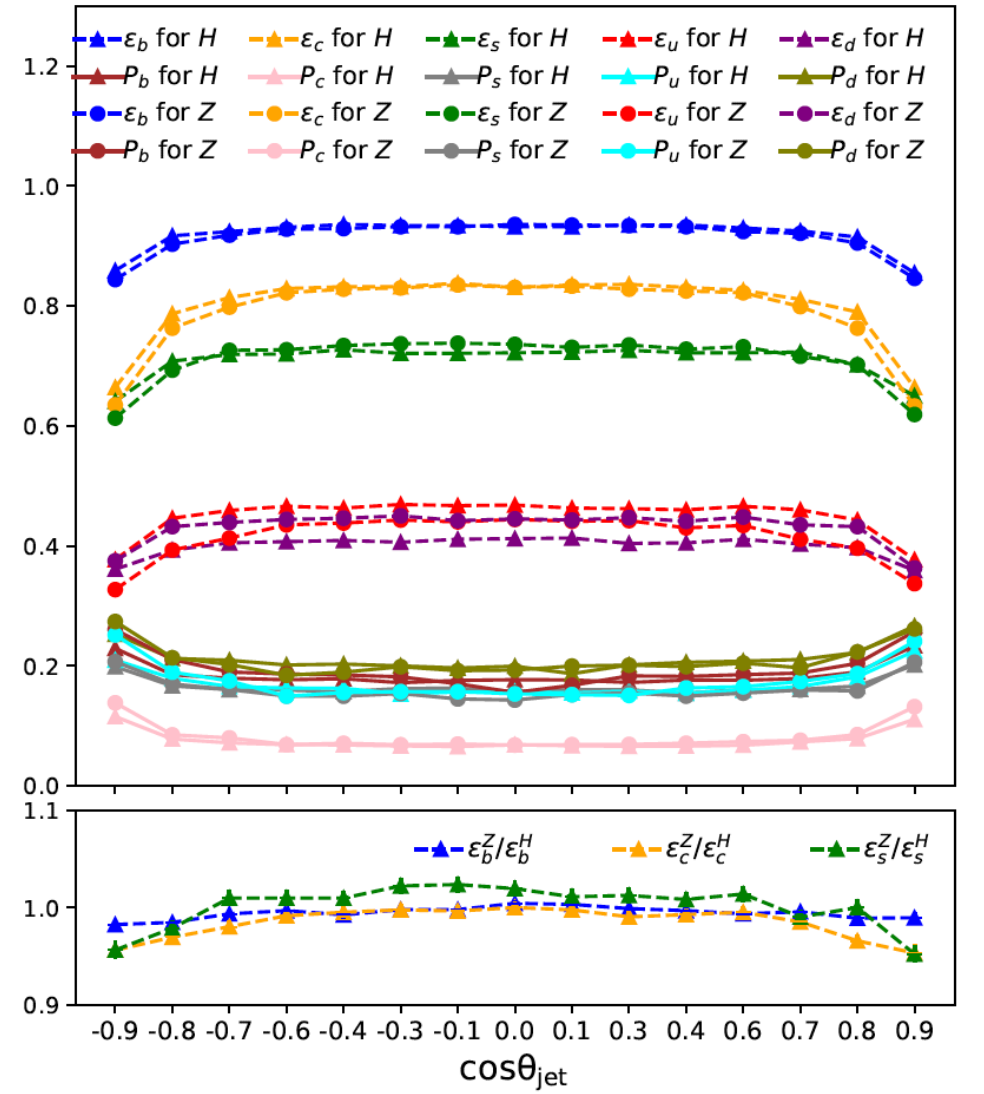
Performance V.S. Jet Kinematics





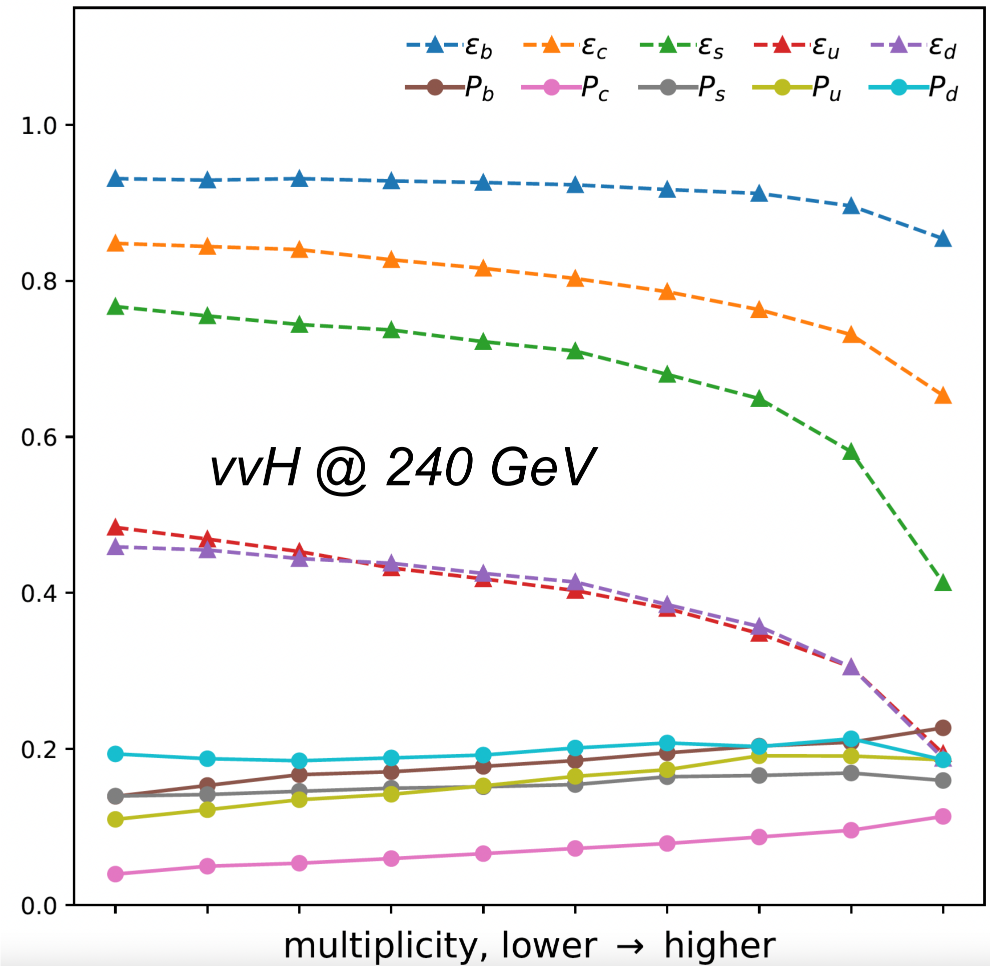
Performance @ Z and Higgs

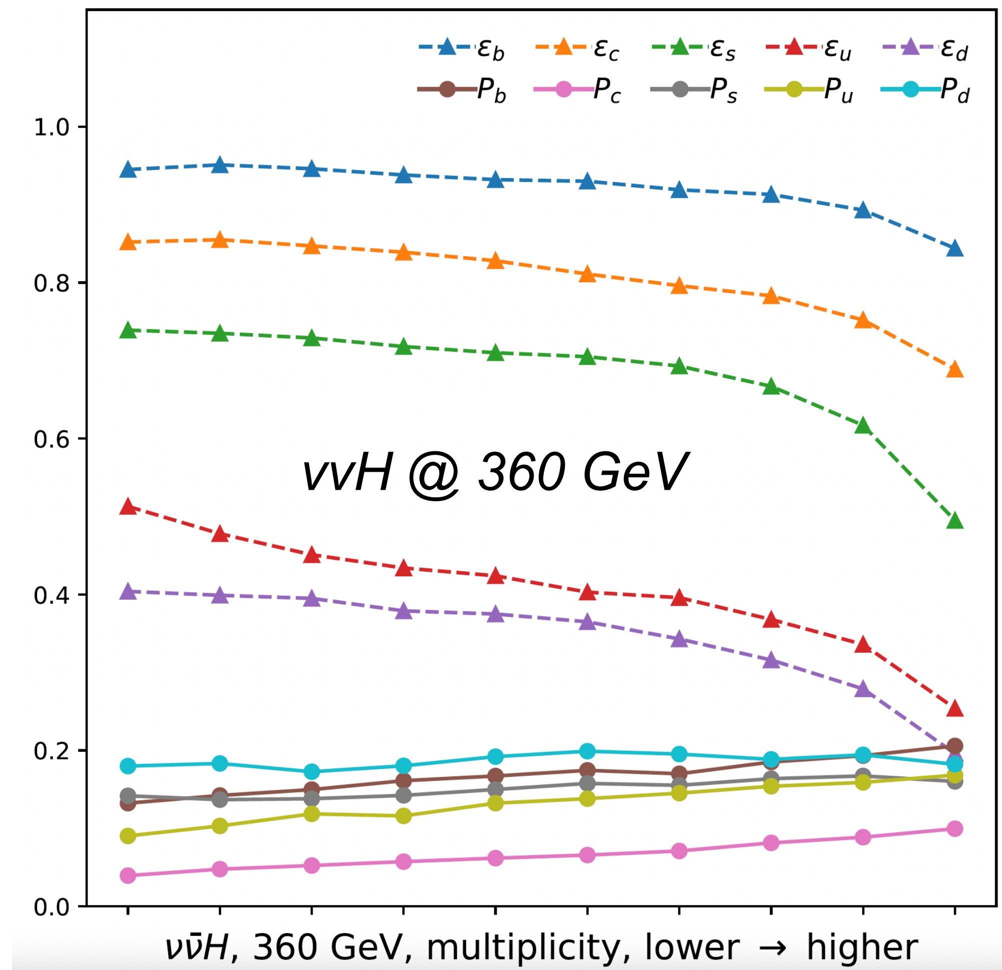




- *M10 instead of M11*

V.S. Multiplicity



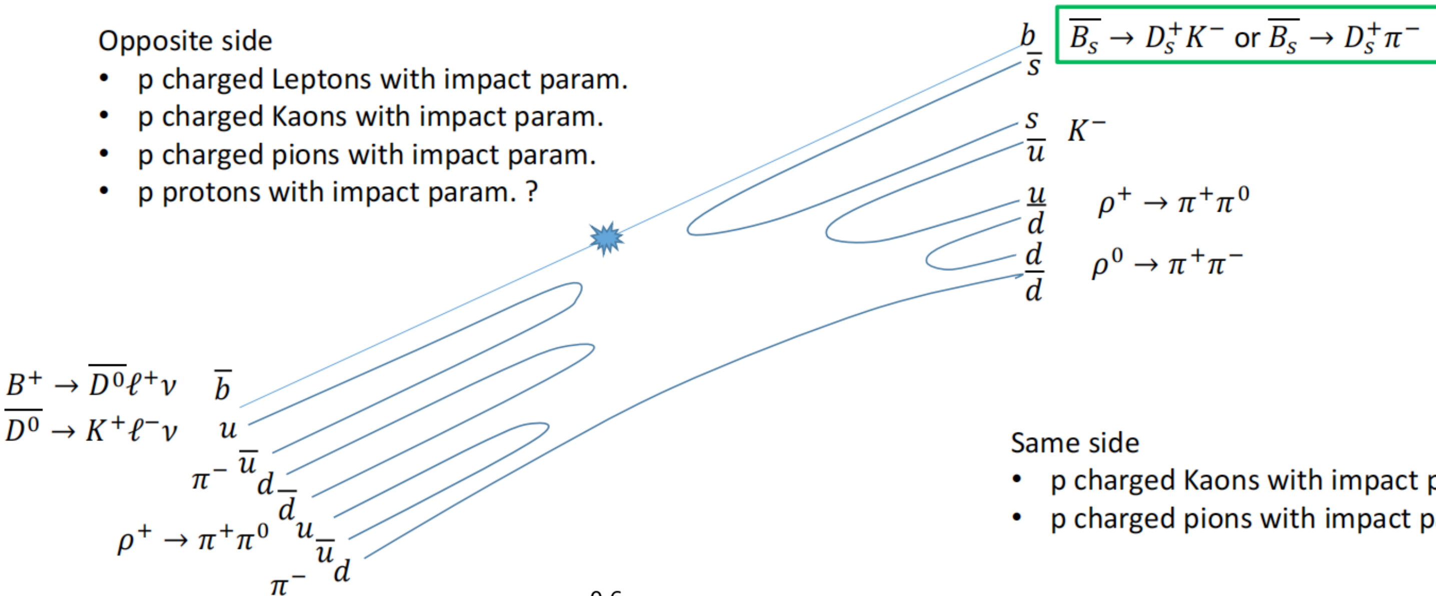


- *...many patterns need further understanding & towards further optimization...*

B-charge flip rate: Bs oscillations

Opposite side

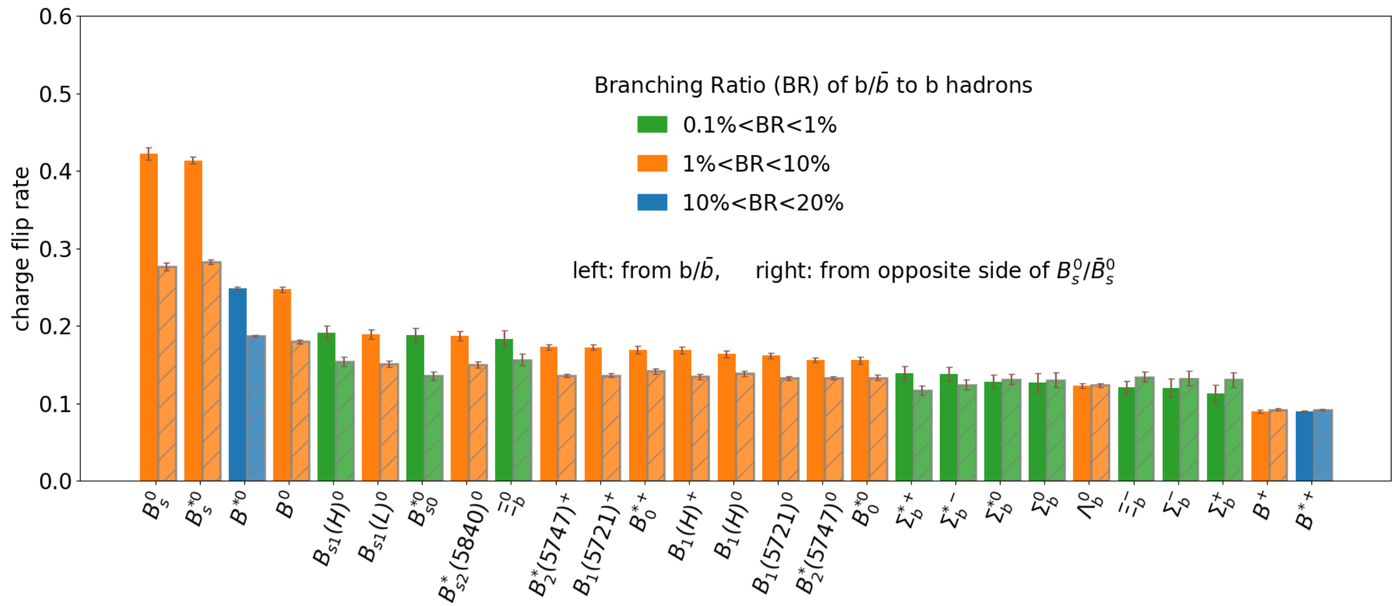
- p charged Leptons with impact param.
- p charged Kaons with impact param.
- p charged pions with impact param.
- p protons with impact param. ?



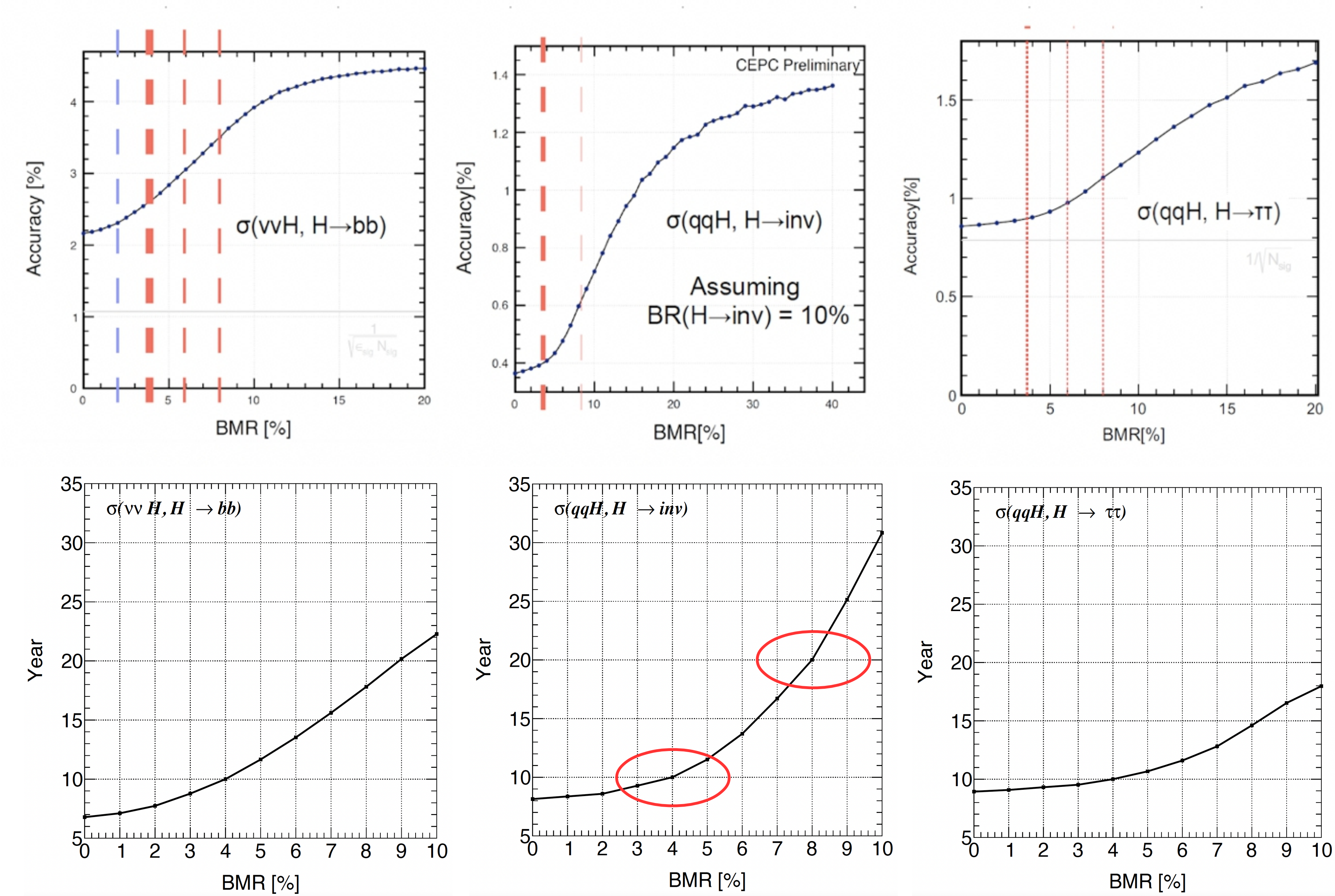
- Using all reco P (exc. Bs decay final state):
- Flip rate ~ 15%, Eff. Tagging power > 40%

Same side

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



BMR: impact on critical measurements



s-jets: dependency on Leading hadron