GO BEYOND JET-LEVEL INFORMATION AT PRECISION ERA

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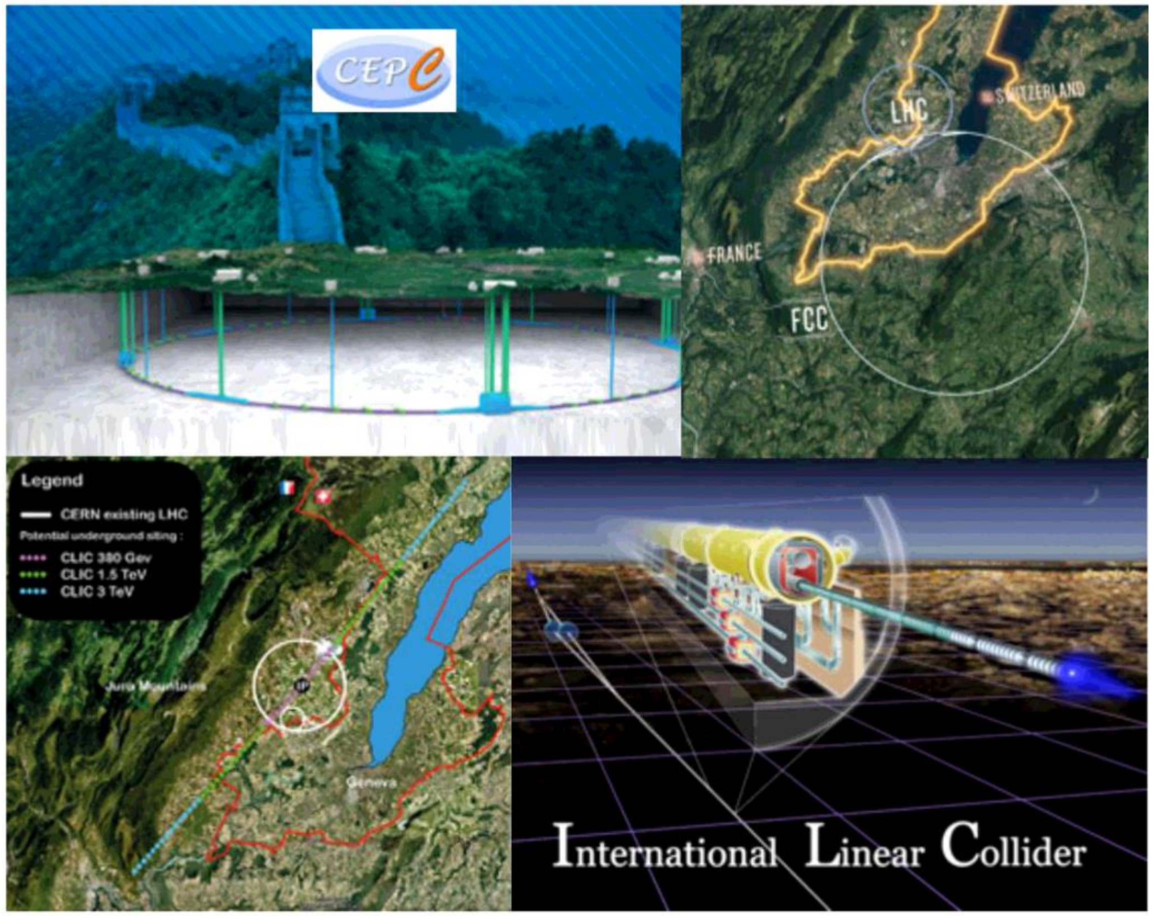

CEPC Detector Meeting
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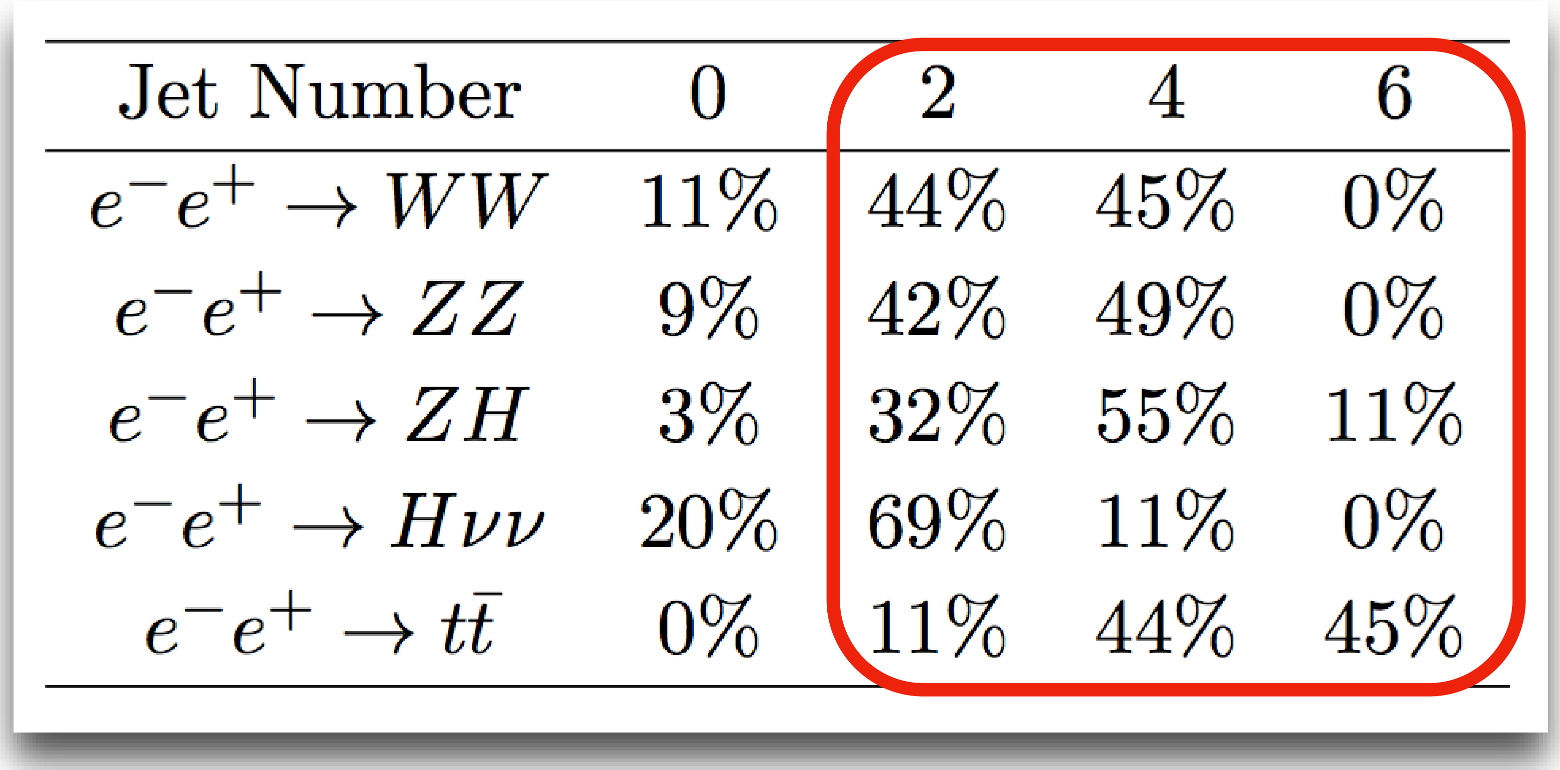
Based on arXiv:2004.15013
in collaboration with Ying-Ying Li, Tao Liu and Sijun Xu

Precision Frontier of Next Decades

Led by future ee colliders (FCC-ee, CEPC, CLIC, ILC)
,measuring Higgs and EW precisely.
[A. Abada et al., (2019); H. Abramowicz et al., 1608.07538, F. An et al., 1810.09037,…]

Primary Higgs and electroweak processes



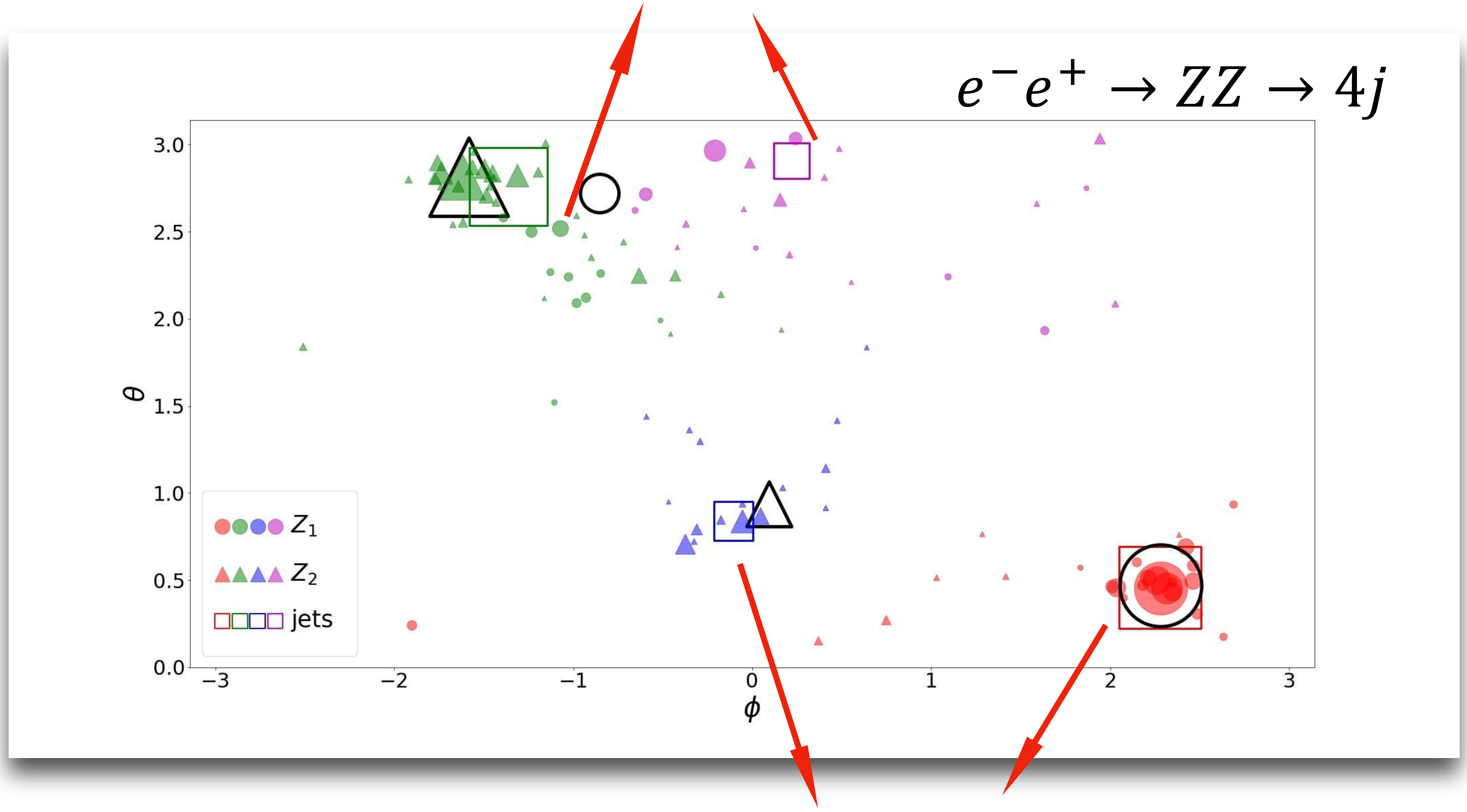
Jet Number	0	2	4	6
$e^-e^+ \to WW$	11%	44%	45%	0%
$e^-e^+ \to ZZ$	9%	42%	49%	0%
$e^-e^+ \to ZH$	3%	32%	55%	11%
$e^-e^+ \to H\nu\nu$	20%	69%	11%	0%
$e^-e^+ \to t\bar{t}$	0%	11%	44%	45%

Hadronic mode dominant

How would jet clustering affect the precisions?

Limitations of jet clustering

Hadrons from different Z clustered in a same jet (info distortion)



$$e^-e^+ \to ZZ \to 4j$$

Detailed structures are gone after clustering (info loss)

Can we recover from these limitations?

First Way: Jet +Event-Level Obs.

- Jet substructure observables: extensively applied in boost kinematics
- Event shape: relatively intuition-based, e.g. thrust [E. Farhi, 1977]
- Fox-Wolfram moments [G. C. Fox and S. Wolfram, 1978]and their extensions: more systematic, but relatively less intuitive.

$$H_{AB;l} = \sum_{m=-l}^{l} H_{AB;l,m} = \frac{4\pi}{2l+1} \sum_{i,j} \frac{A_i B_j}{s} \sum_{m=-l}^{l} \left(Y_l^m(\Omega_i)^* Y_l^m(\Omega_j)\right) = \sum_{i,j} \frac{A_i B_j}{s} P_l(\cos \Omega_{ij})$$

- Pros: Simple framework. Physically intuitive.
- Cons: Less organized.

Another Way: Event-Level ML

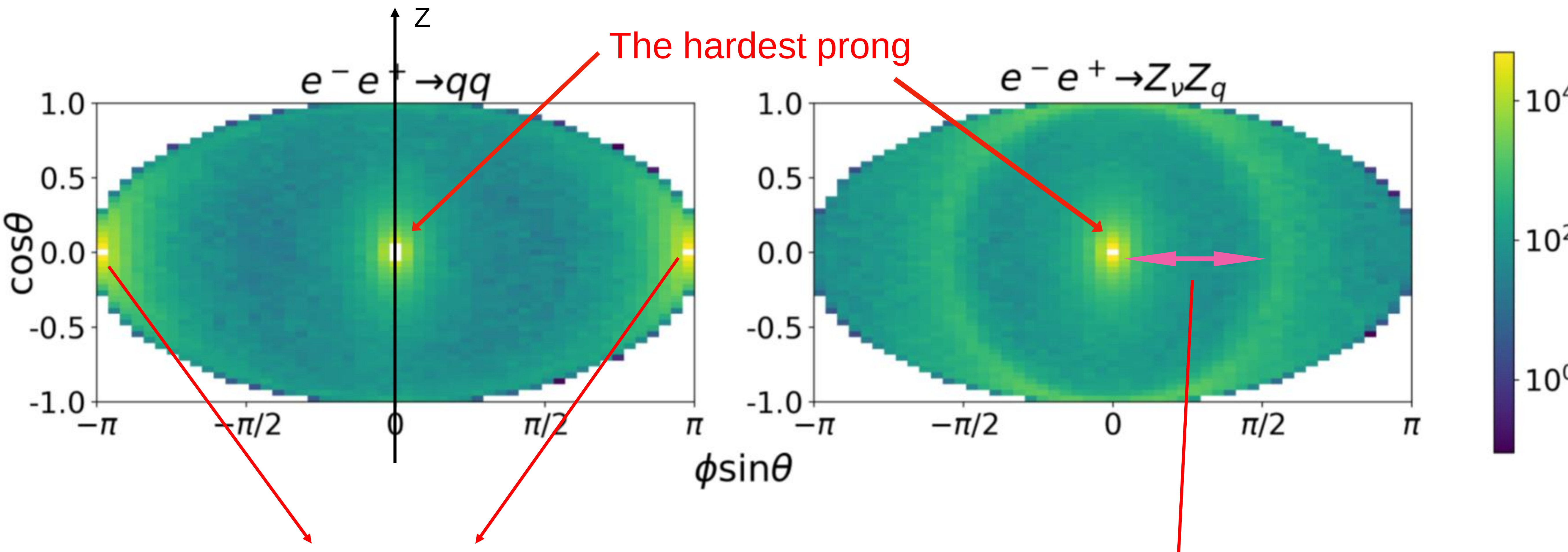
Pursue analysis directly at event level

- Pro: Most information.
  - Lepton Collider: negligible pileups, colorless beam and fixed energy
- Con: Large complexity. -> ML as a solution.

Comparative studies to compare the two approaches using ML as a tool

- Jet Level: Fully Connected Network (FCN) :
  Input: jet momenta (and FW moments l<50 / track info).
- Event Level: Convolutional Neuron Network (CNN)
  Based on ResNet-50 structure.
  Input: 50 × 50 pixelized event-level image (and track info).

Cumulative Mollweide Projection



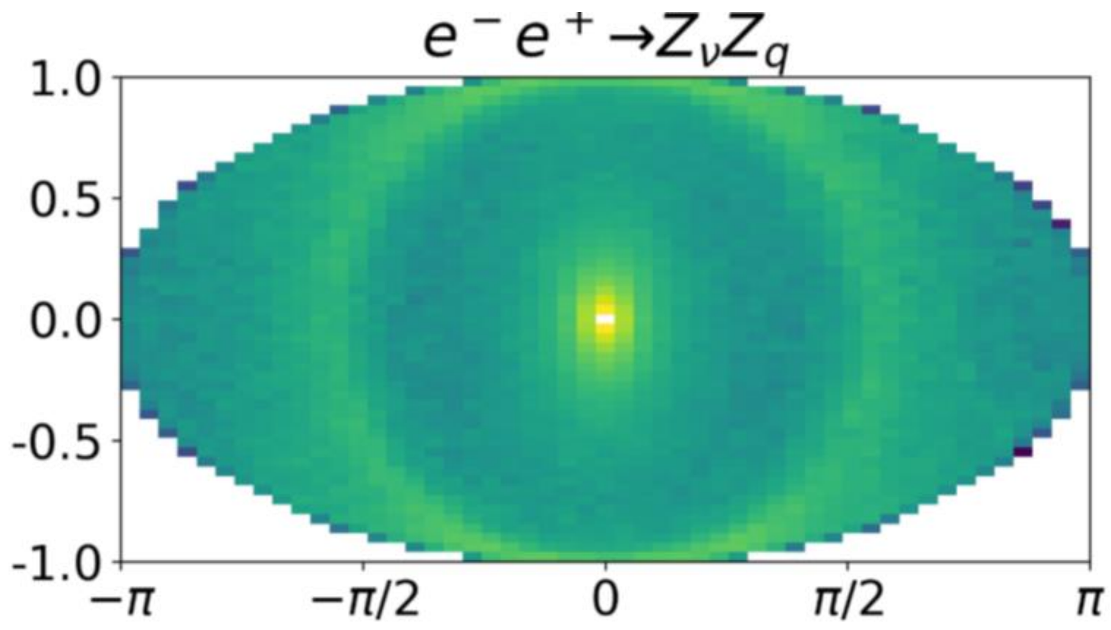
The hardest prong

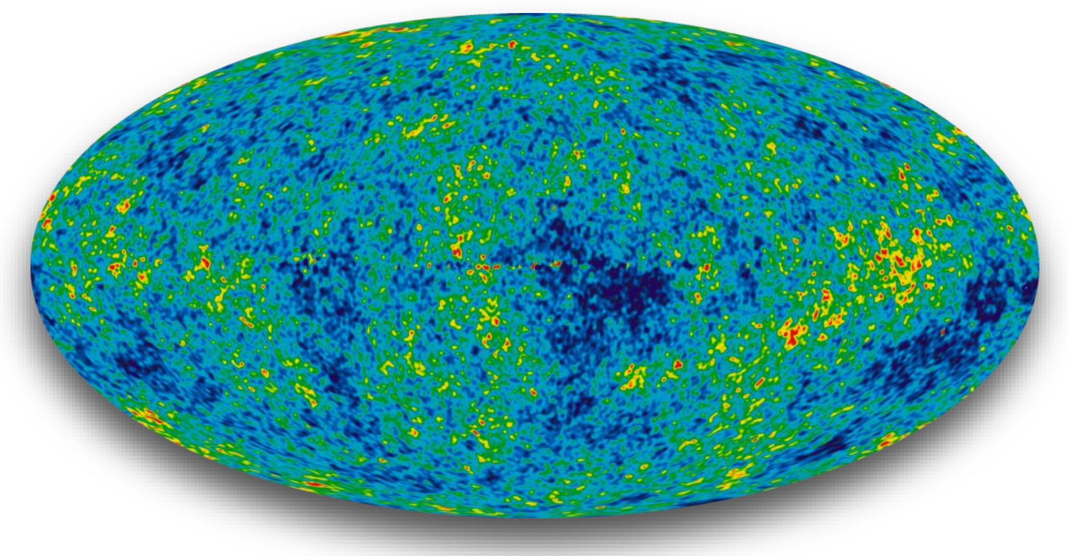
Back to back motion of qq

Halo size and structure: minimal included angle of quarks/ information missing at jet level

- Define a Cartesian coordinate system: z-axis being along beam line and x − y plane (equatorial plane) overlapping with its transverse plane
- Rotate the motion direction of the most energetic particle to be along x-axis.
- Project the particles to ``detector sphere''

“Dictionary” between Event Projection and CMB

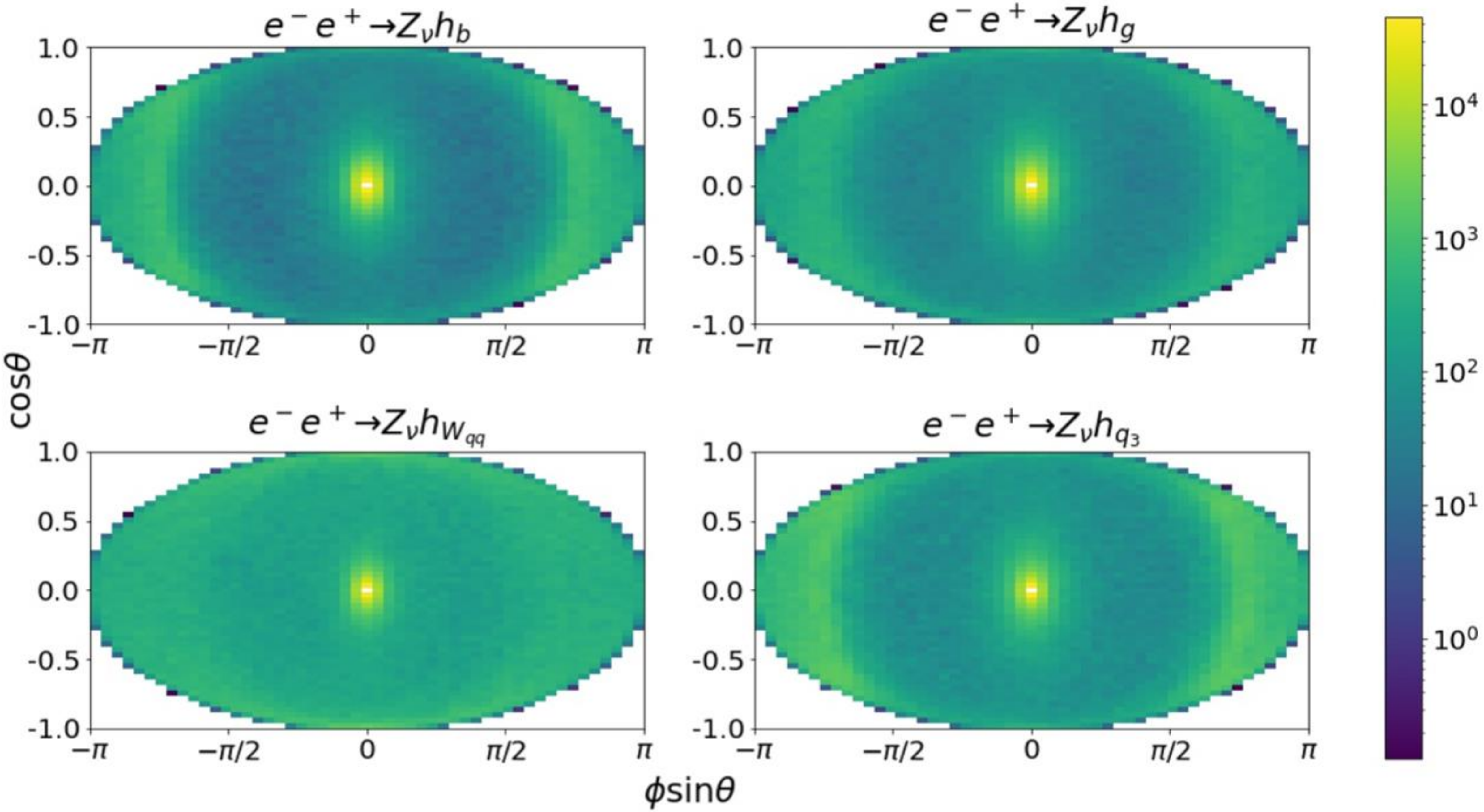




Mollweide projection at e^-e^+ colliders	All-sky CMB map
Projection sphere	Celestial sphere
Equatorial plane	Galactic plane
Energy (p_T, timing, charge, d_0, etc.) projection	Temperature (polarization) map
Event-level kinematics	Anisotropy
Fox-Wolfram moments	Power spectrum (TT, TB, BB, etc.)
Multi-spectra	Bispectrum, trispectrum, etc.
… …	… …

In such CMB-like information scheme, the event-level information is encoded as the FW moments at leading order and multi-spectra at higher orders.

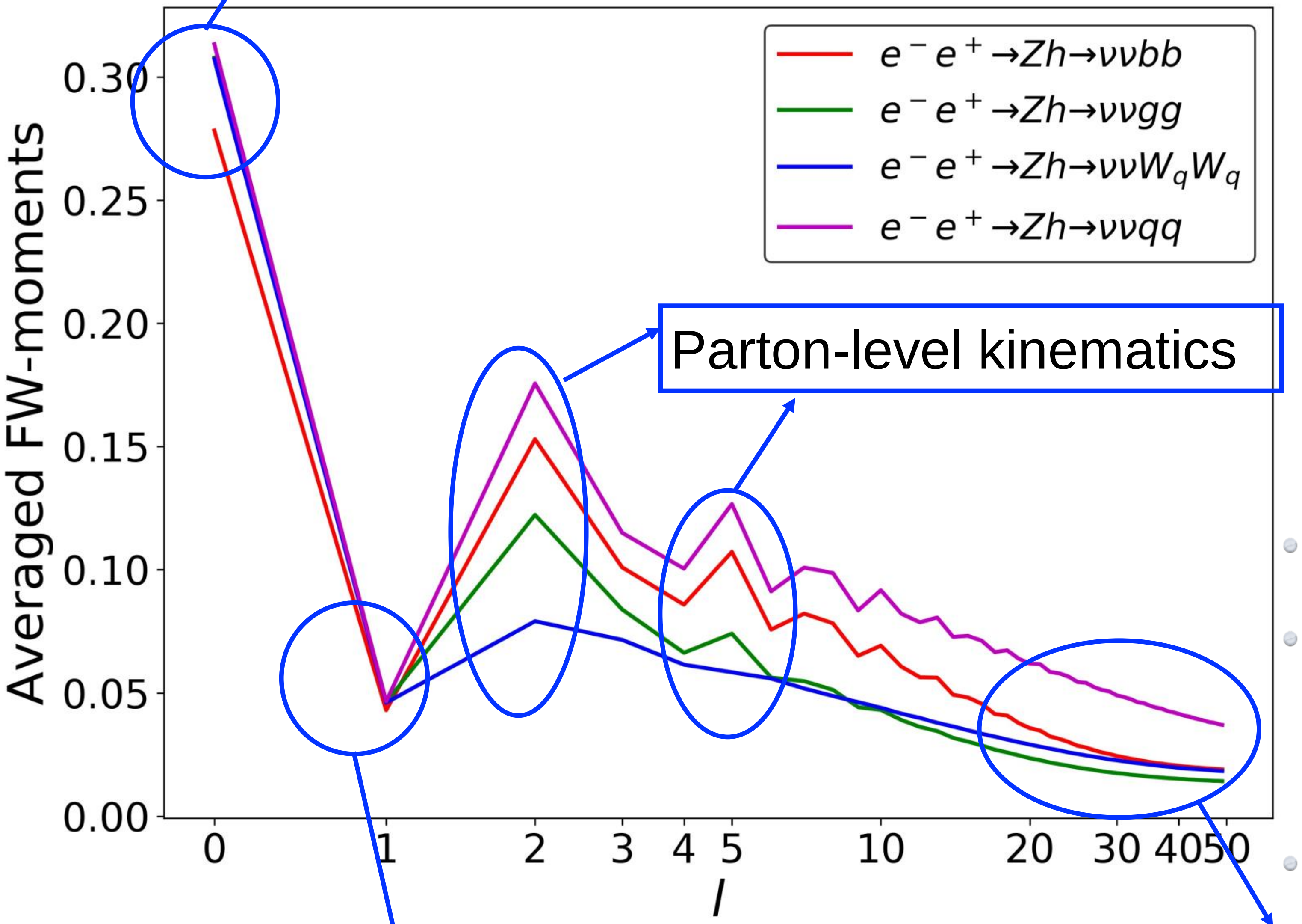
Benchmark Study ("2"j)



$$e^-e^+ \to Zh \to \nu\nu + (bb, jj, gg, W_q W_q^*)$$

FW Moments of Energy Distribution

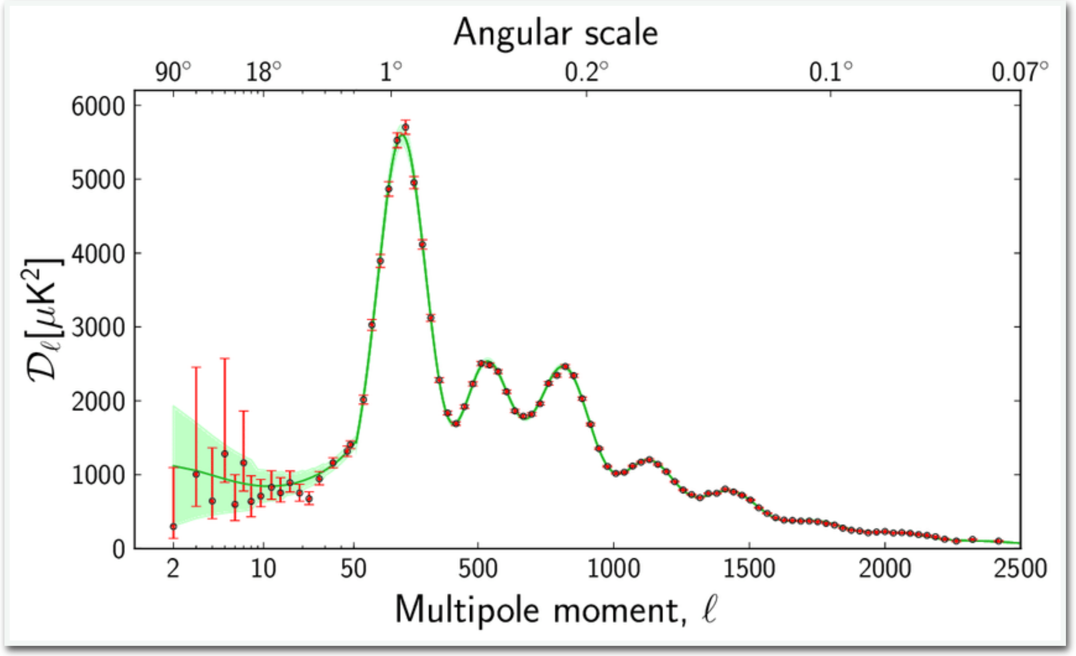
$$H_{EE;0} = \frac{(\sum_i E_i)^2}{s}$$



Parton-level kinematics

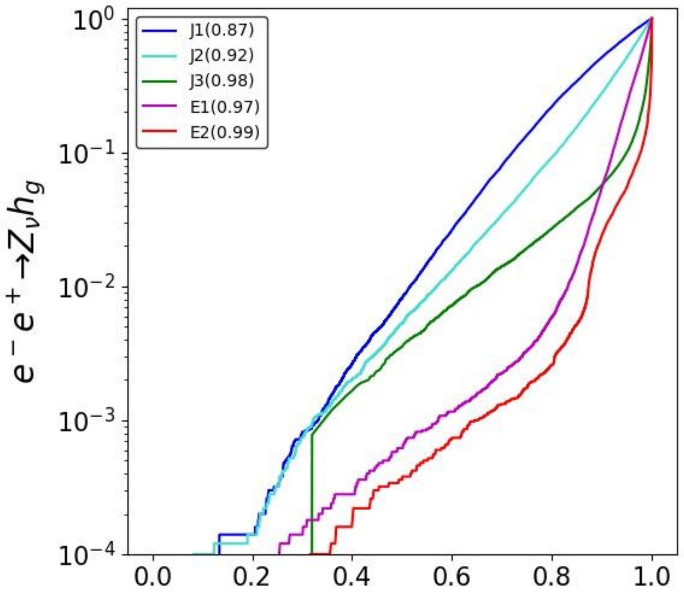
Shower/Hadronizaiton:
Collinear and IR safe

$$H_{EE;1} = \frac{|\sum_i \vec{p}_i|^2}{s}$$

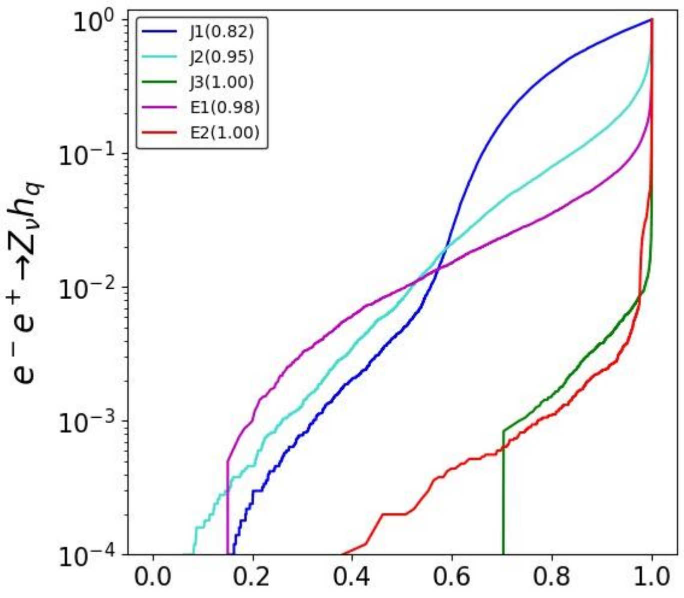


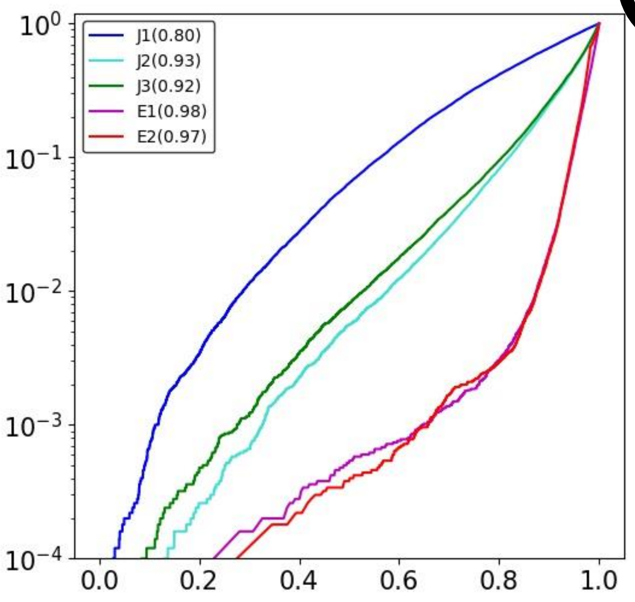
- Analogue to CMB power spectrum
- Difference: suppressed sample (``cosmic'') variance, due to large size of data sample
- Similarity: physics at characteristic sales may result in ``acoustic peaks''

Benchmark Performance

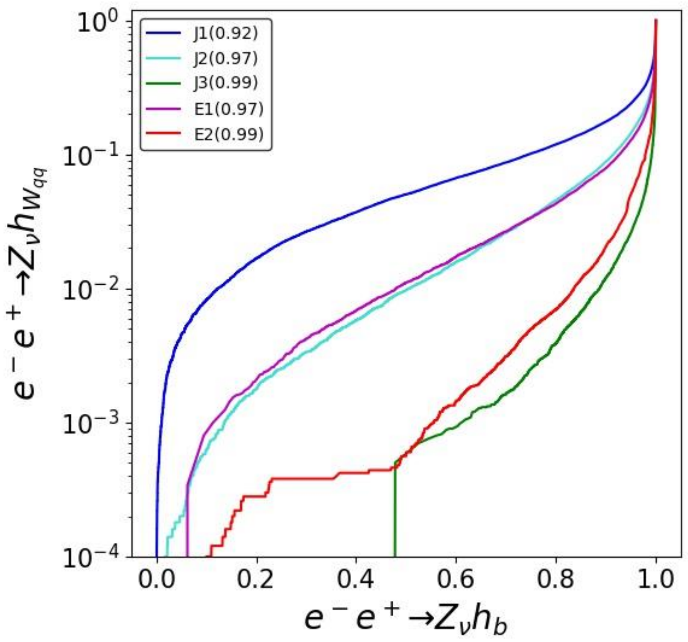


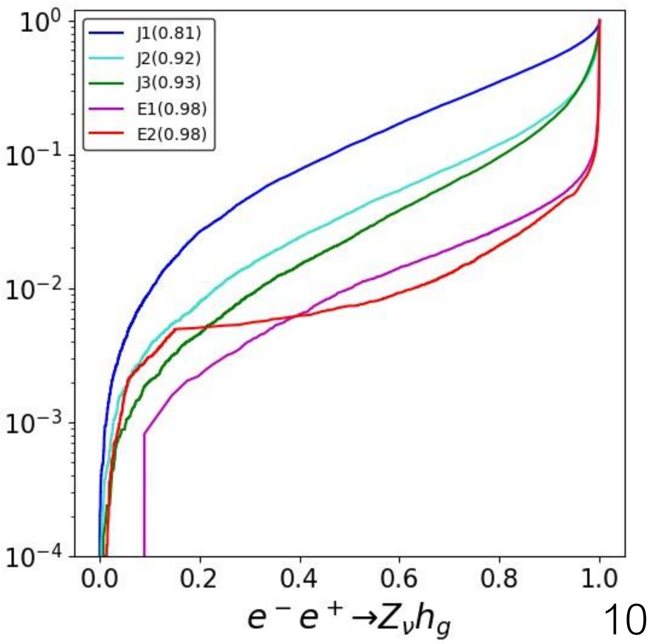
Jet < **Jet + FW** ~ **Image** < **Jet + FW + track** ~ **Image + track**

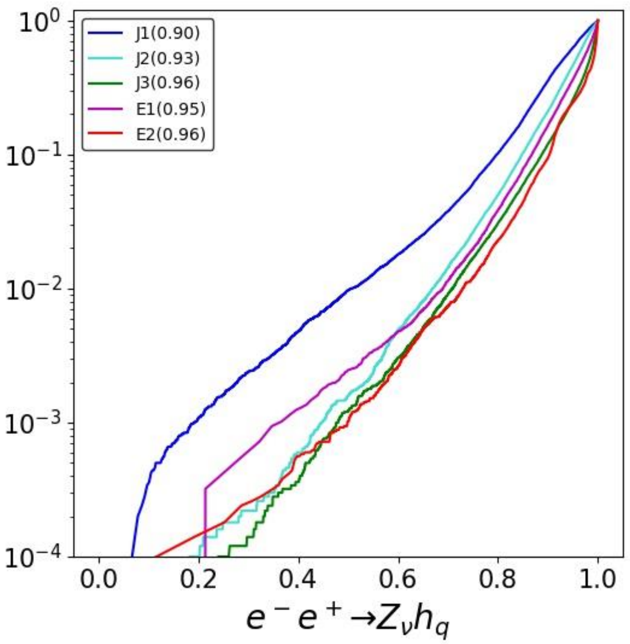




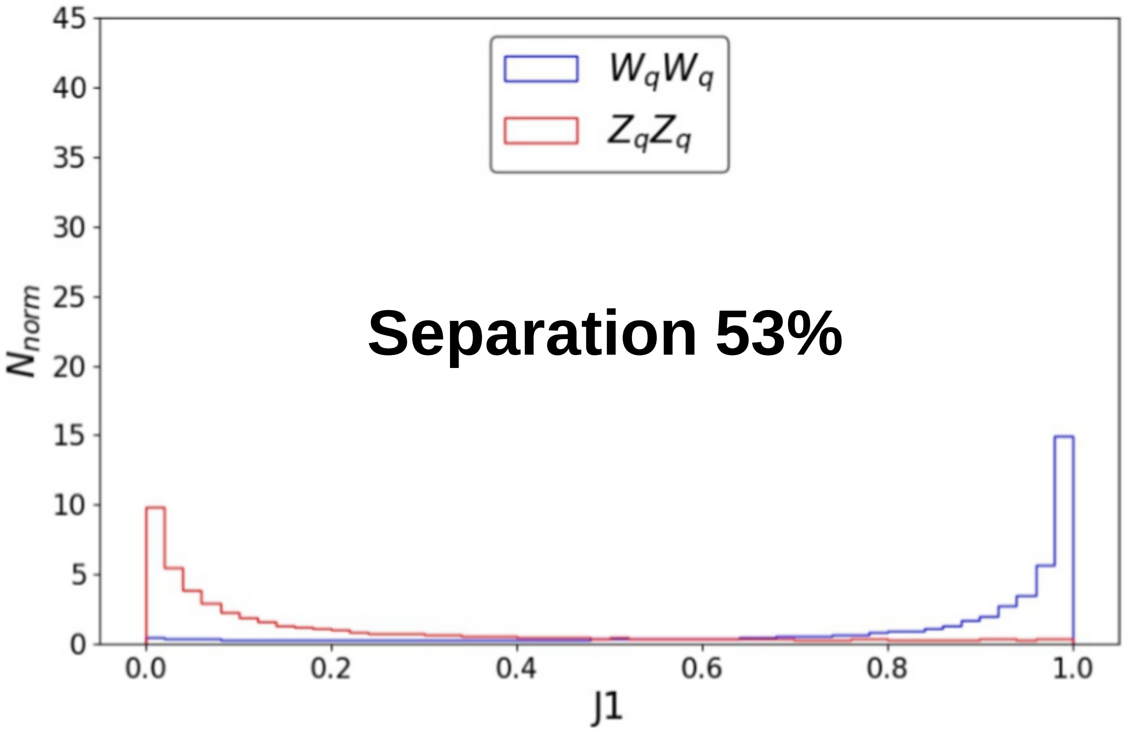
The performance gap between Jet+FW and Image may be explained by higher order correlation terms.





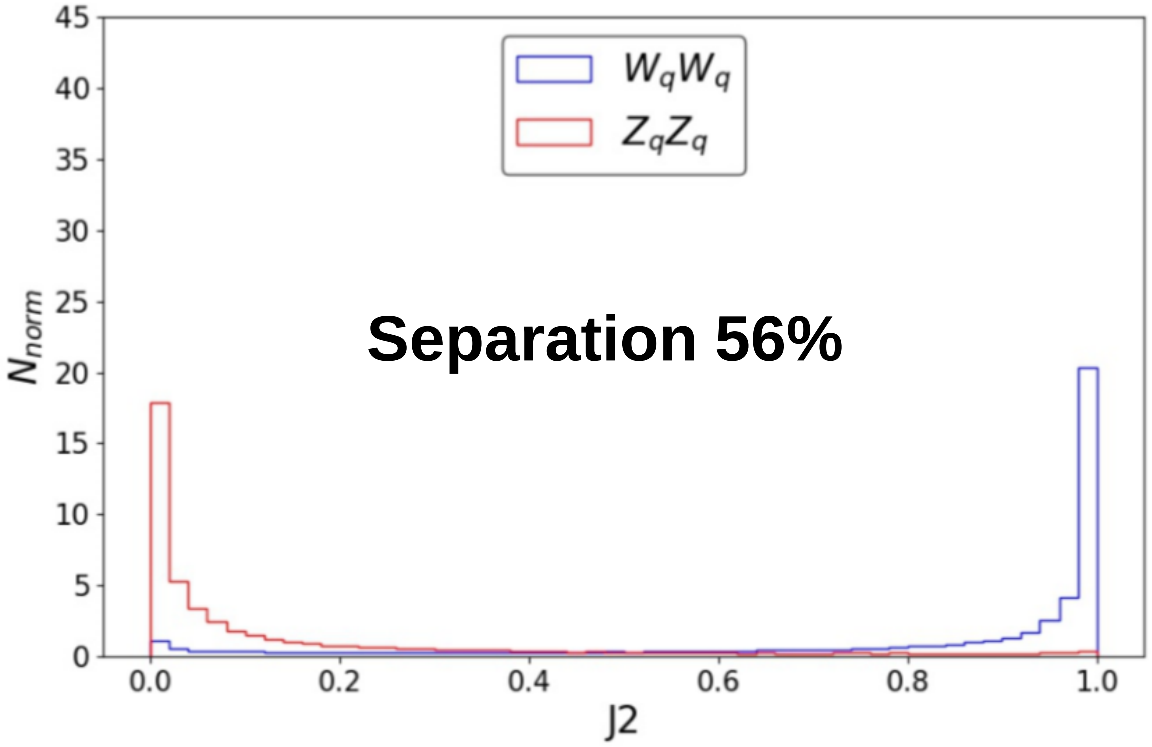


Benchmark Study (WW vs ZZ, 4j)



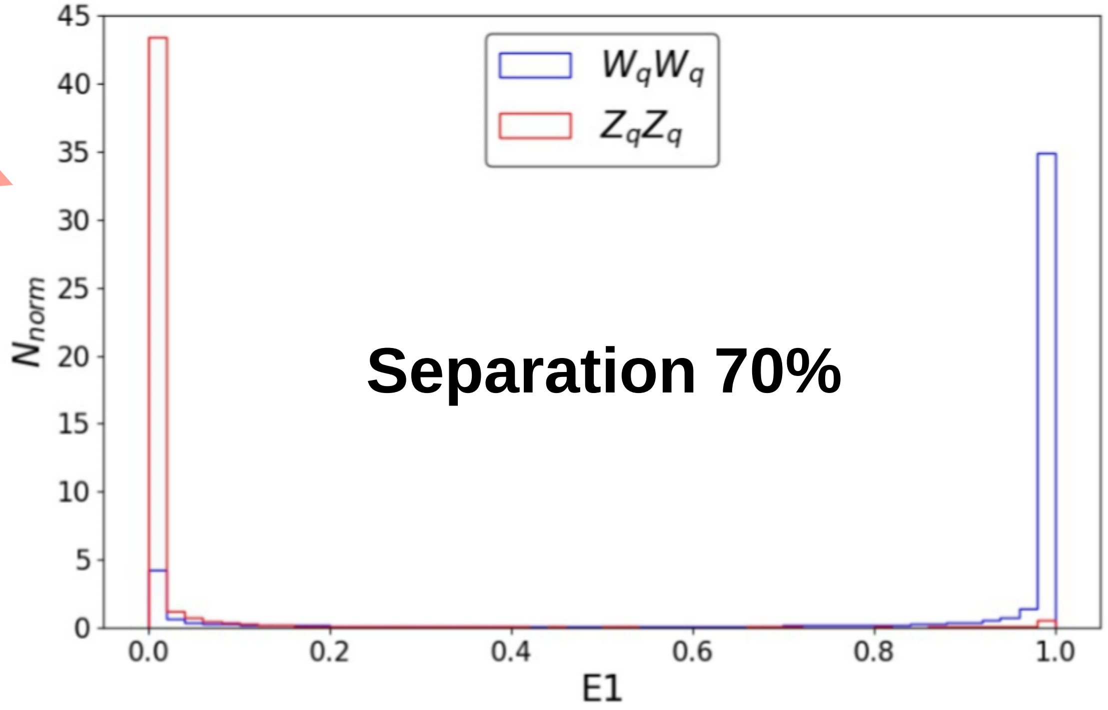
Separation 53%

+ FW



Separation 56%

To image



Separation 70%

Application: Measurement of Γ(h) @ 240 GeV, 5 ab^{-1}

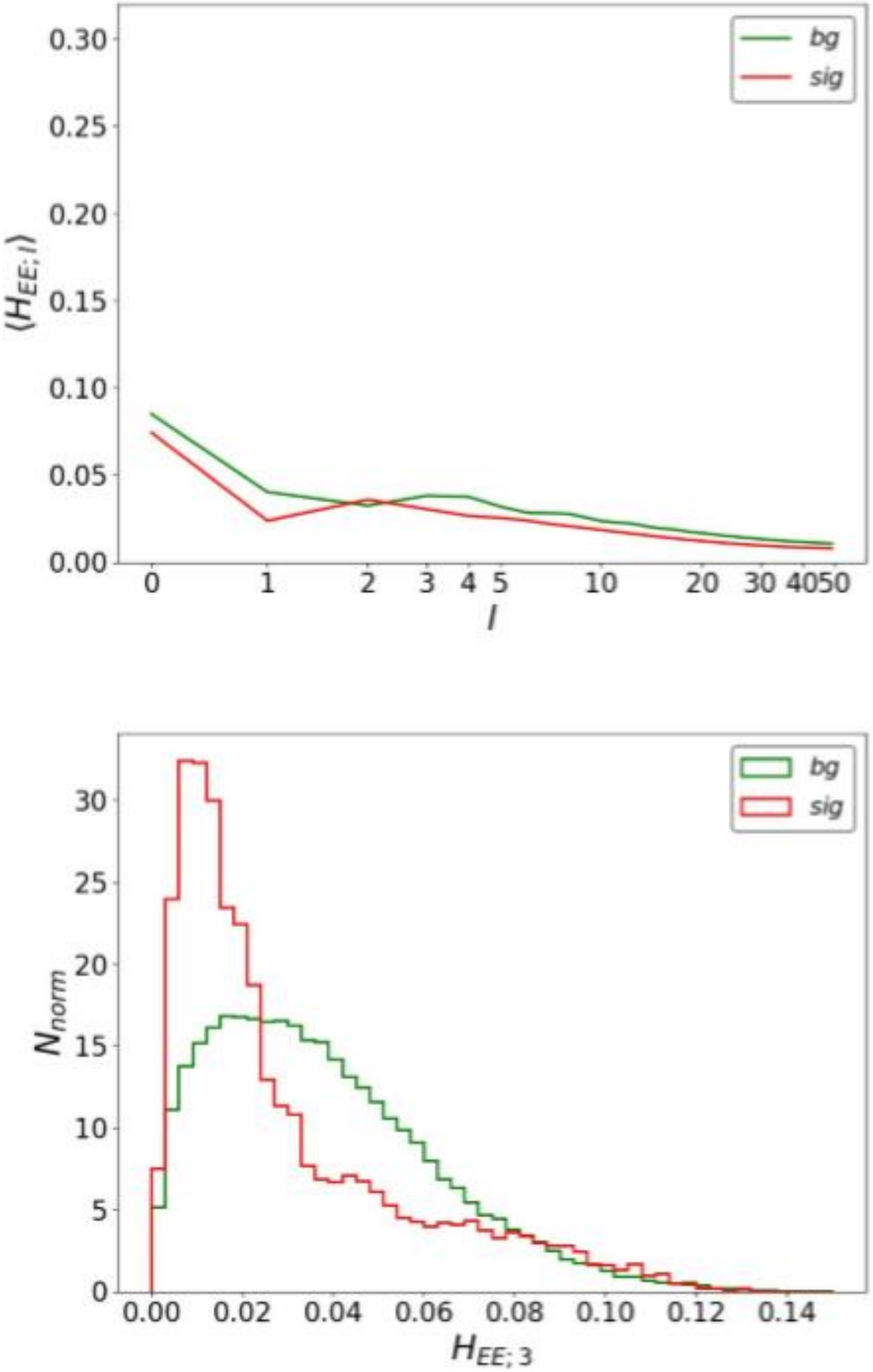
The most important method for the Higgs factory mode:
Limitation mostly arise from BR(h->WW*) and σ(νvh) rate measurements

$$\Gamma_h^* = \frac{\Gamma(h \to WW^*)}{\mathrm{BR}(h \to WW^*)} \propto \frac{\sigma(\nu\nu h)}{\mathrm{BR}(h \to WW^*)} = \frac{[\sigma(\nu\nu h_b)][\sigma(Zh)]^2}{[\sigma(Zh_b)][\sigma(Zh_W)]}$$

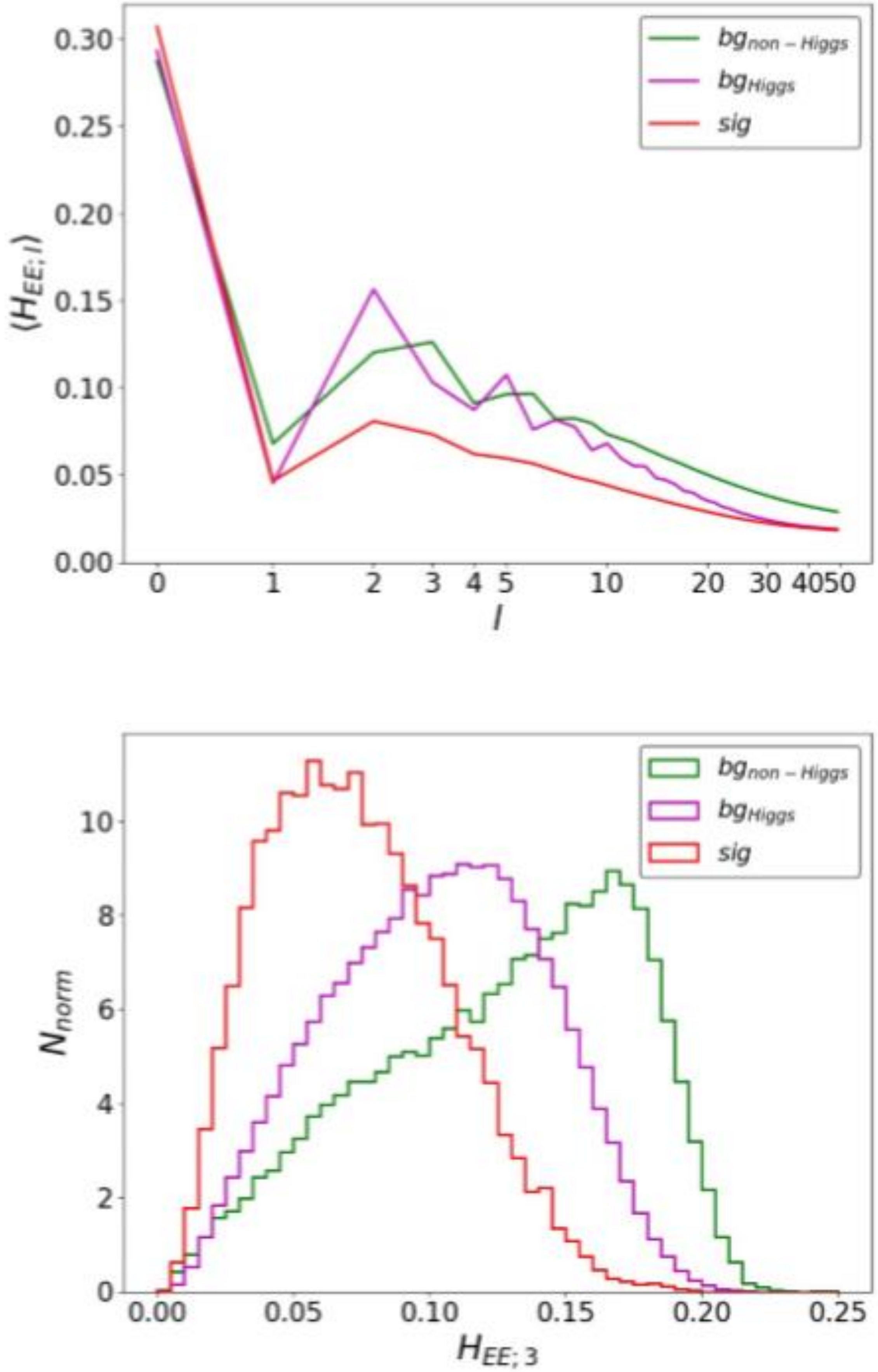
Γ_h (%)	CEPC$_{240(250)}$ [14, 65]	FCC$_{240}$ [15]	FCC$_{240+365}$ [15]	CLIC$_{350}$ [66]	ILC$_{250}$ [64, 67, 68]
Method A	5.1 (5.0)	4.5*	4.2*	-	20*
Method B	3.5 (3.2)	3.5*	1.7*	6.7	13
Method C	-	-	3.4*	-	-
Combined	2.8 (2.7)	2.7	1.3	6.7	11

*In our study, we also include h-> cc/gg/ττ decays to take the advantage of machine learning (~ 20% increase in net signal rate.)

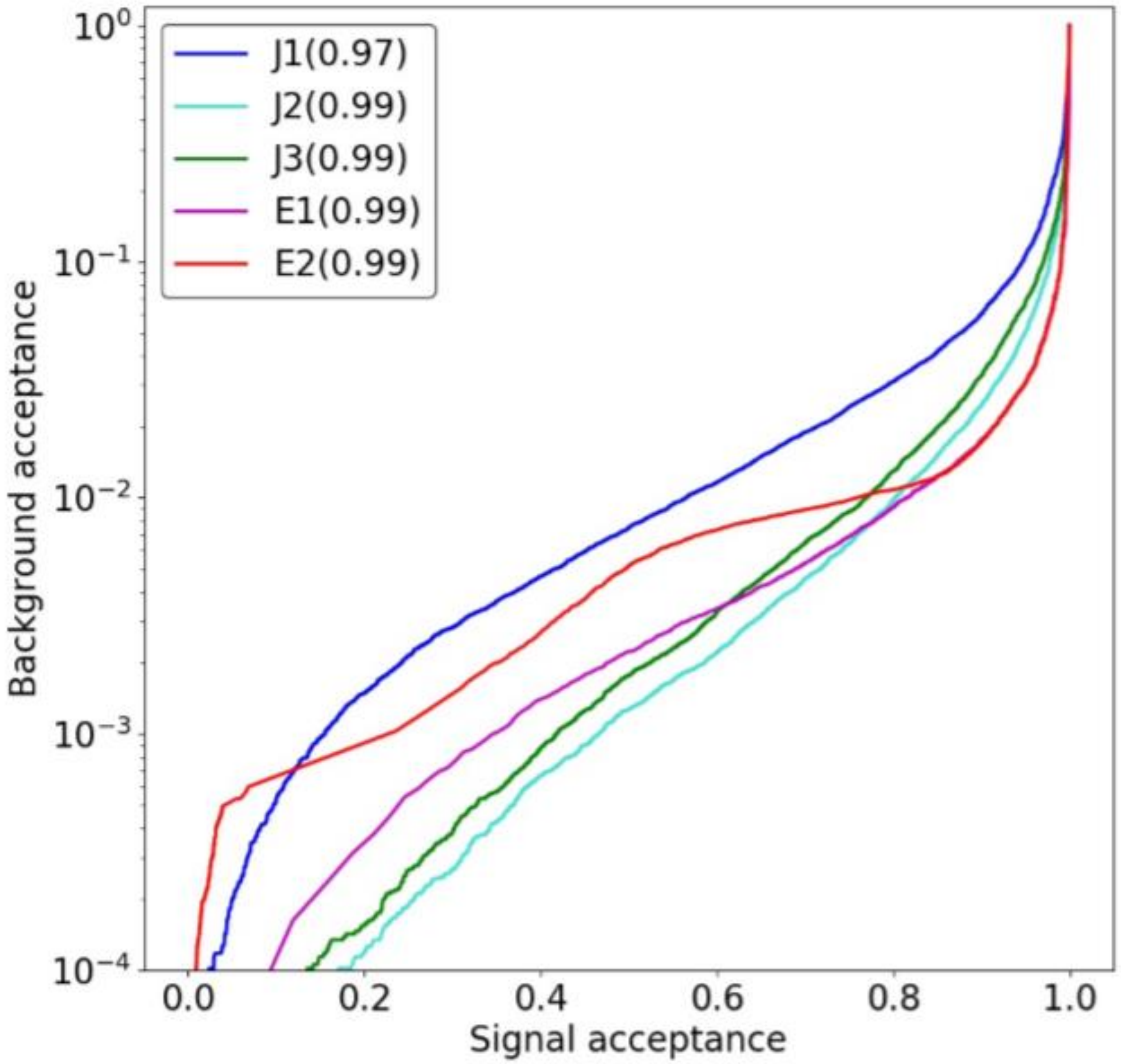
Zh->vvWW* (2j1l)



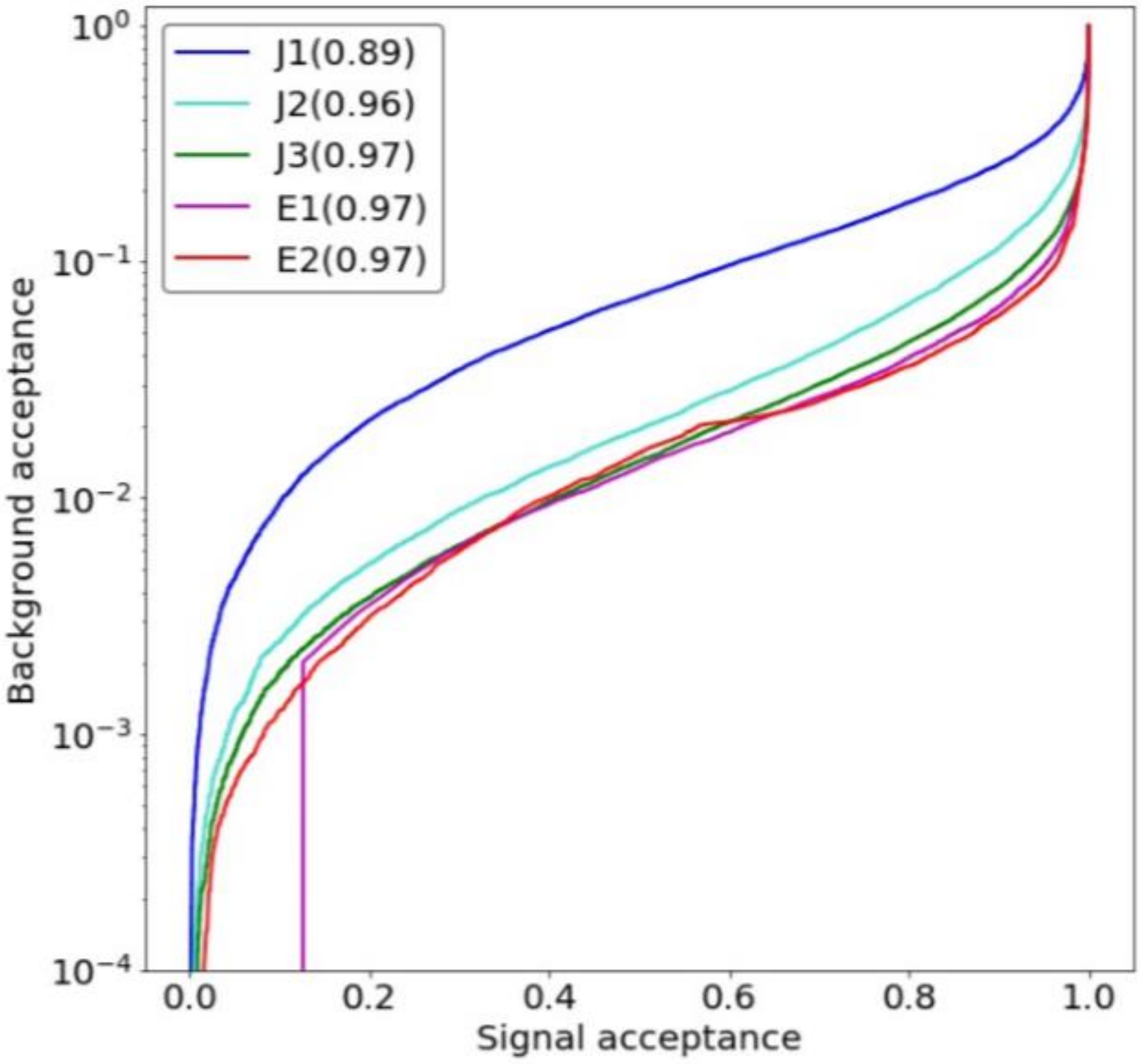
Zh->vvWW* (4j)



Zh->vvWW* (2j1l)



Zh->vvWW* (4j)

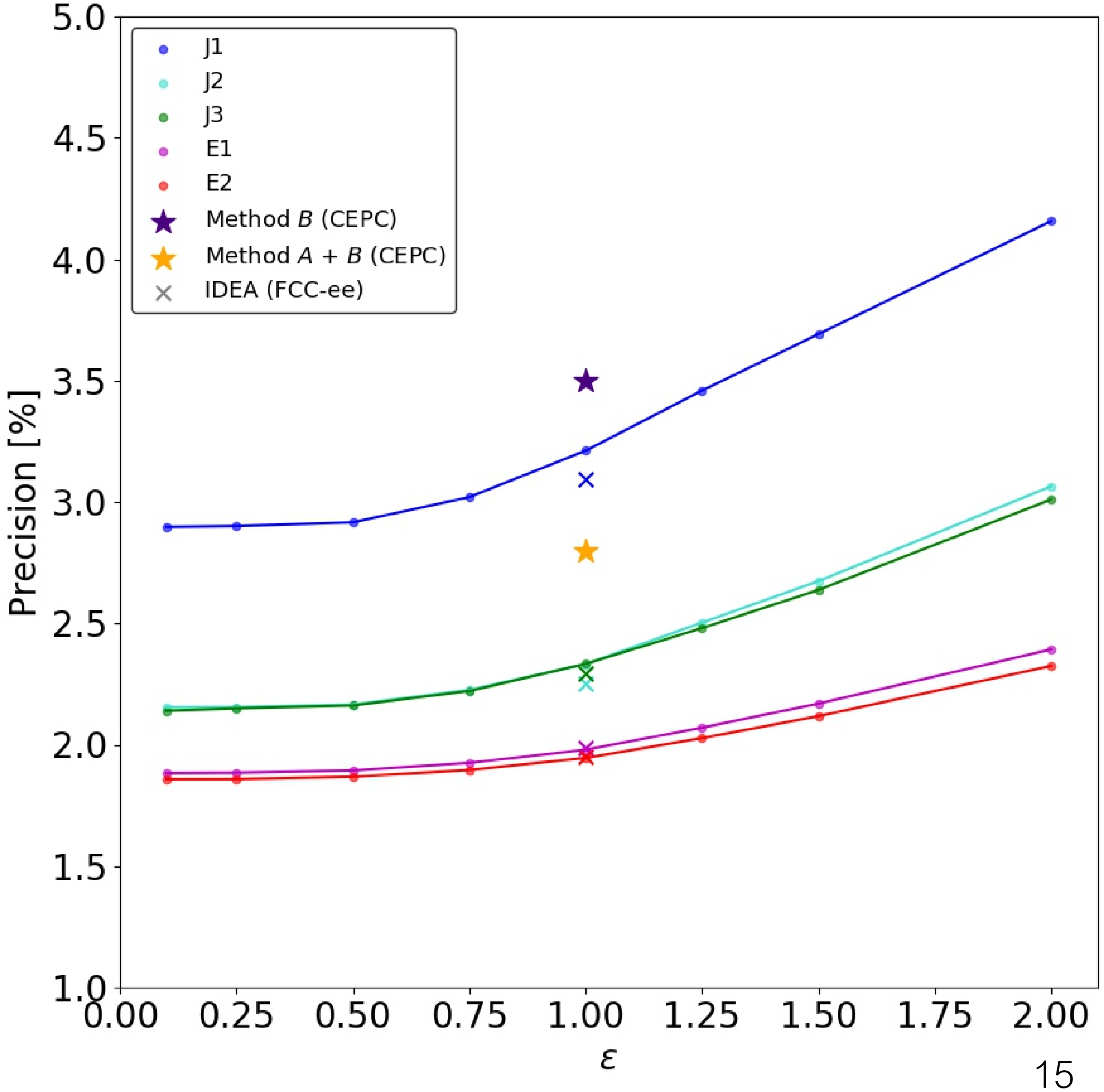


Gain may come from when jets from W* are crowded together:

Strong confusion effect at jet-level

Event level results @ 240 GeV, 5 ab^{-1}

	Jet	**Jet+FW**	**Jet+FW+track**	**Image**	**Image+track**
Precision (%)	J1	J2	J3	E1	E2
$\sigma(Z_\nu h_{W_{lq}})$	1.7 (1.6)	1.4 (1.6)	1.5 (1.6)	1.5 (1.4)	1.5 (1.4)
$\sigma(Z_\nu h_{W_{qq}})$	1.6 (1.6)	1.2 (1.2)	1.1 (1.1)	1.1 (1.1)	1.1 (1.1)
$\sigma(\nu\nu h_h)$	2.8 (2.7)	1.8 (1.7)	1.9 (1.8)	1.4 (1.4)	1.3 (1.3)
Γ_h	$3.2^{+0.9}_{-0.3}$ (3.1)	$2.3^{+0.7}_{-0.2}$ (2.2)	$2.3^{+0.7}_{-0.2}$ (2.3)	$1.9^{+0.5}_{-0.1}$ (1.9)	$1.9^{+0.4}_{-0.1}$ (1.9)



2.3% with jet level inputs + FW moments

1.9% with event-level inputs

The precision achieved is robust against the rescaling of detector resolutions and different detector templates

Outlook

Can the Higgs decay width be measured at sub percent level @ 240+365 GeV or even @ 240 GeV, given the currently proposed detector baseline?

- Apply event-level ML to multiple channels
- Extra information: charge, pid, displacement, etc.
- Advanced ML techniques
- … …

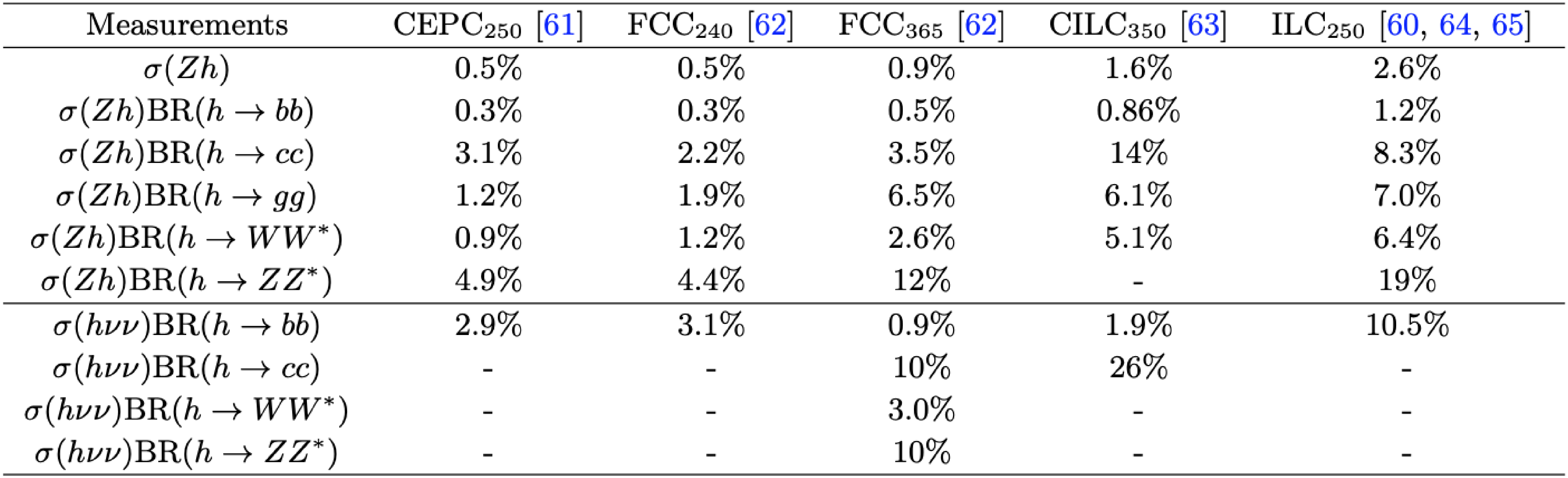
We expect event-level analysis with ML to be broadly applied to other hadronic-event measurements at future e-e+ colliders. To what extent one can benefit from it?

- Higgs couplings to quarks/gluons
- CP properties of Higgs boson
- Flavor physics
- … …

Thank you!

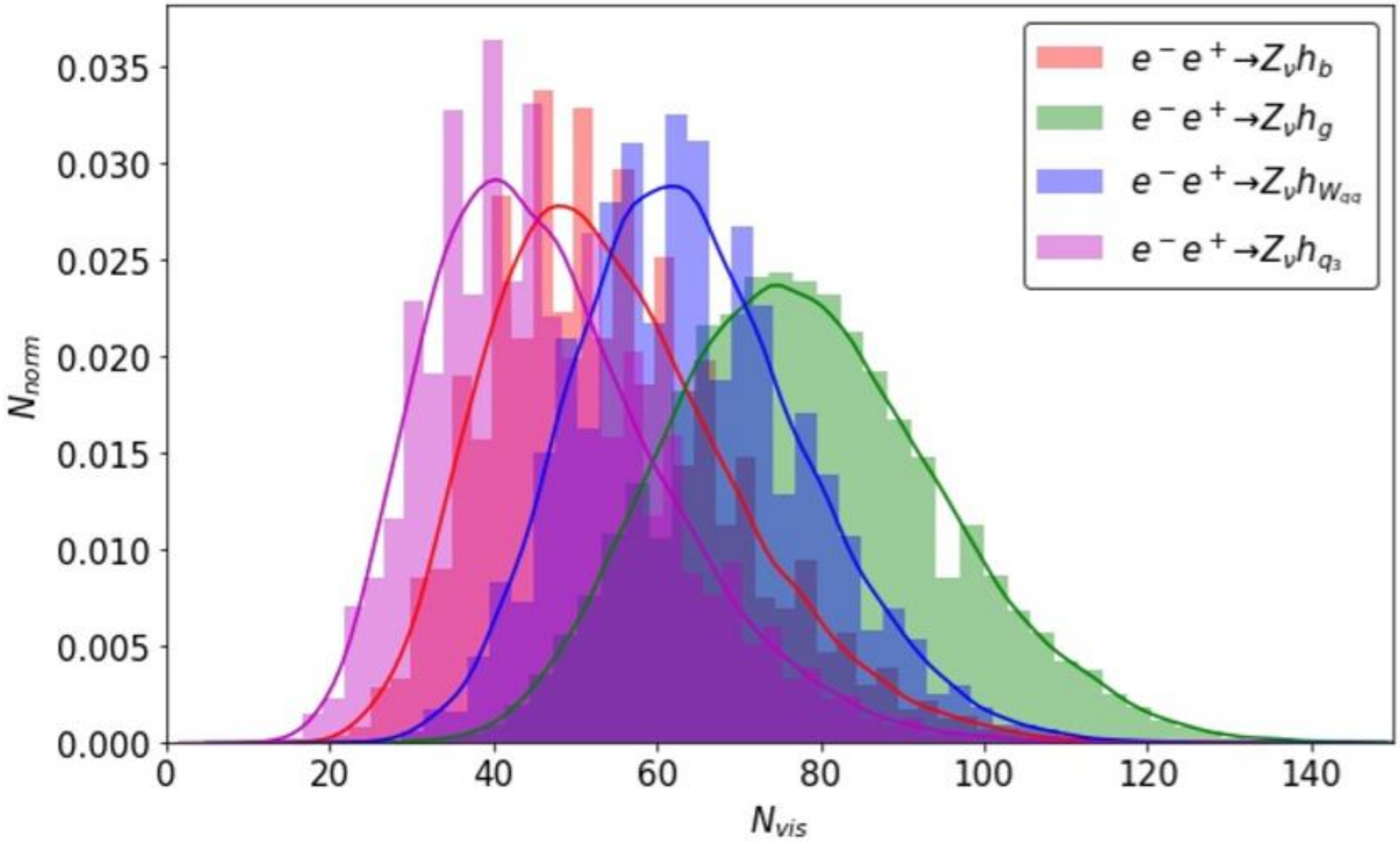
Precision Frontier of Next Decades

The precision frontier of next decades in Higgs and electroweak physics is expected to be defined by a future e^-e^+ collider.



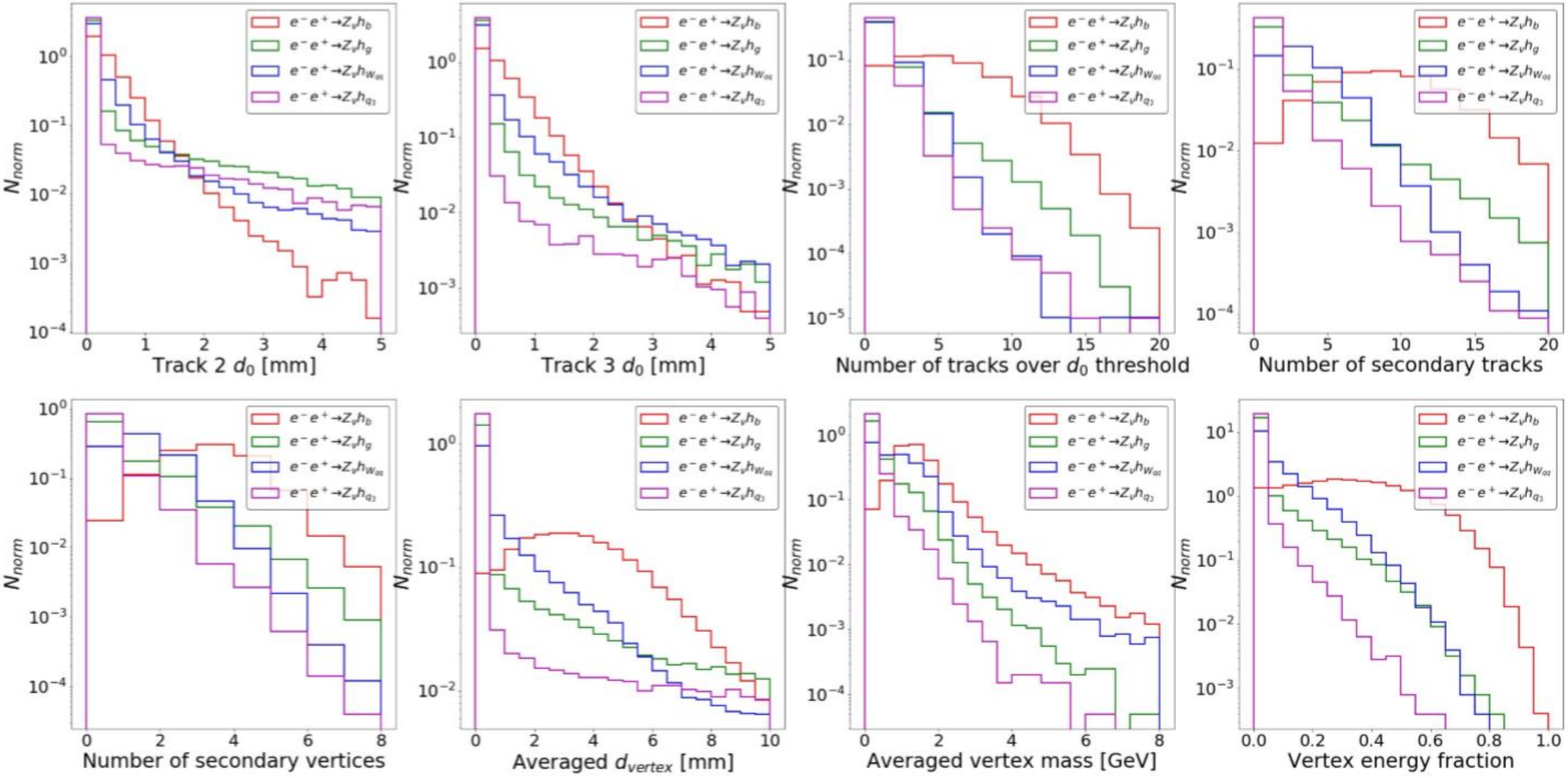
Measurements	CEPC_{250} [61]	FCC_{240} [62]	FCC_{365} [62]	CILC_{350} [63]	ILC_{250} [60, 64, 65]
$\sigma(Zh)$	0.5%	0.5%	0.9%	1.6%	2.6%
$\sigma(Zh)\text{BR}(h \to bb)$	0.3%	0.3%	0.5%	0.86%	1.2%
$\sigma(Zh)\text{BR}(h \to cc)$	3.1%	2.2%	3.5%	14%	8.3%
$\sigma(Zh)\text{BR}(h \to gg)$	1.2%	1.9%	6.5%	6.1%	7.0%
$\sigma(Zh)\text{BR}(h \to WW^*)$	0.9%	1.2%	2.6%	5.1%	6.4%
$\sigma(Zh)\text{BR}(h \to ZZ^*)$	4.9%	4.4%	12%	-	19%
$\sigma(h\nu\nu)\text{BR}(h \to bb)$	2.9%	3.1%	0.9%	1.9%	10.5%
$\sigma(h\nu\nu)\text{BR}(h \to cc)$	-	-	10%	26%	-
$\sigma(h\nu\nu)\text{BR}(h \to WW^*)$	-	-	3.0%	-	-
$\sigma(h\nu\nu)\text{BR}(h \to ZZ^*)$	-	-	10%	-	-

[F. An et al., 1810.09037; A. Abada et al., (2019); H. Abramowicz et al., 1608.07538]

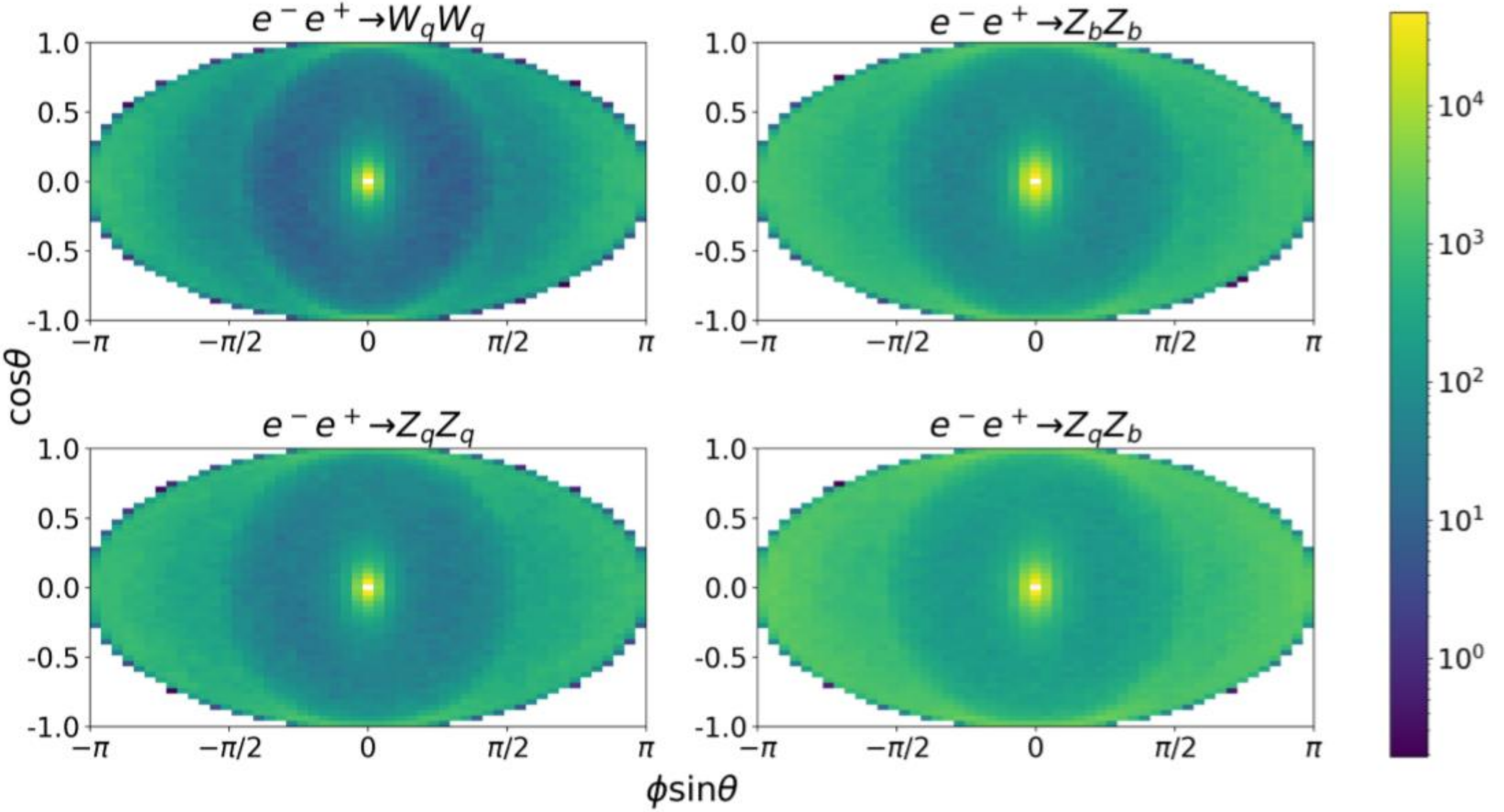


$e^-e^+ \to Z_\nu h_b$
$e^-e^+ \to Z_\nu h_g$
$e^-e^+ \to Z_\nu h_{W_{qq}}$
$e^-e^+ \to Z_\nu h_{q_3}$
N_{norm}
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0
20
40
60
80
100
120
140
N_{vis}

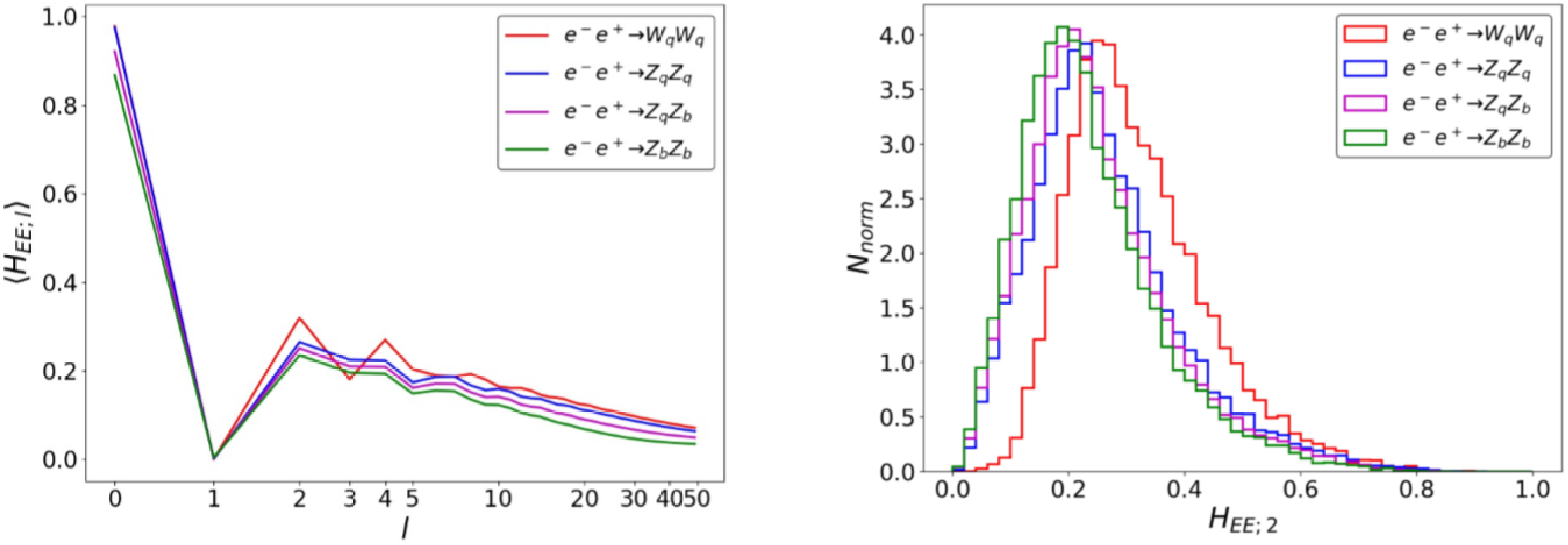
Track Variables Defined at Event-Level



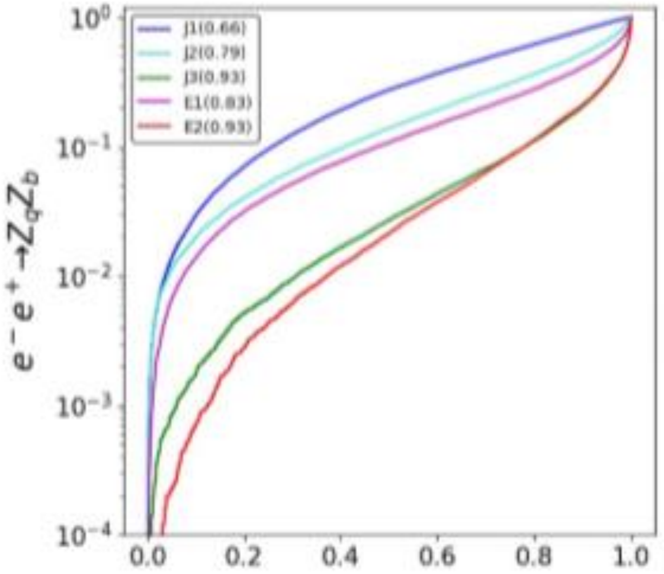
Benchmark Study (4j)

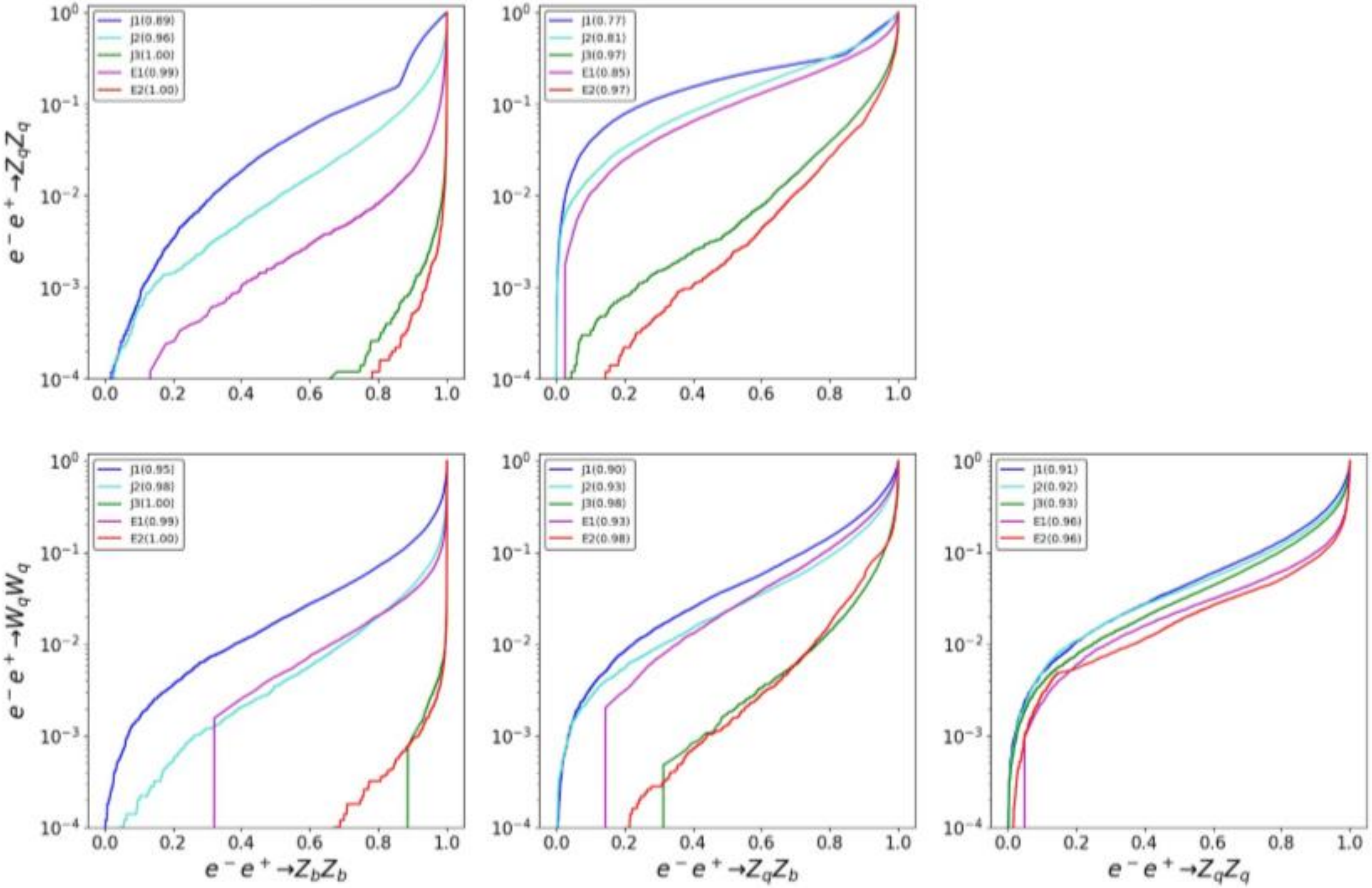


Benchmark Study (4j)



Benchmark Study (4j)

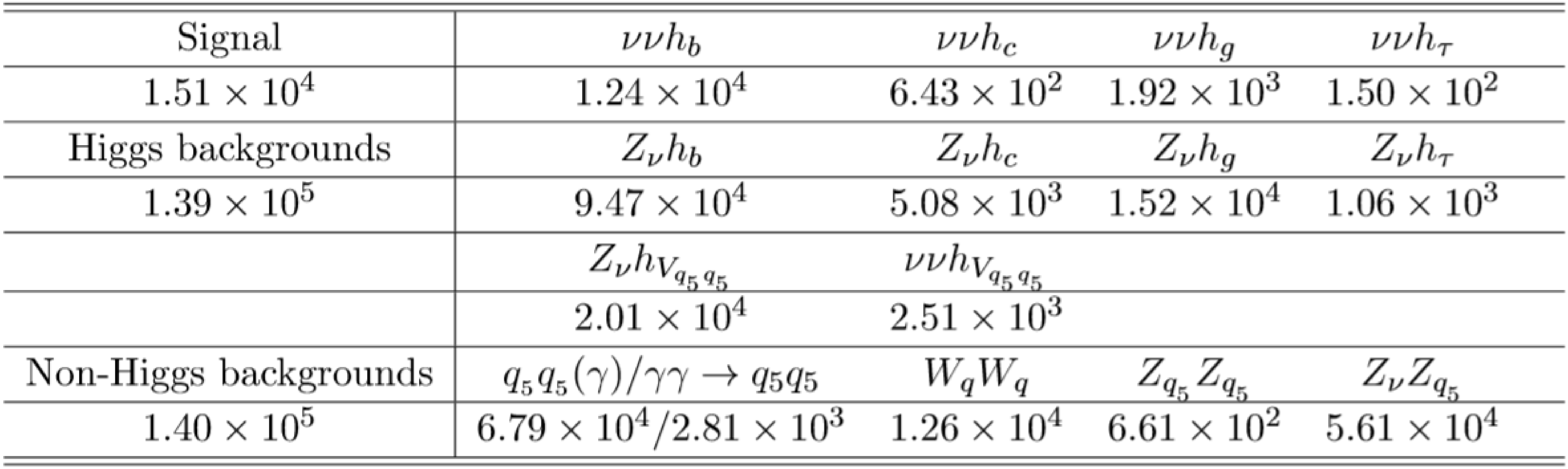




Signal	Backgrounds			
$Z_\nu h_{W_{lq}}$	$W_l W_q$	$Z_l Z_{q_5}$	$Z_\nu h_\tau$	
8.57×10^3	2.41×10^5	1.04×10^3	3.22×10^3	
$Z_\nu h_{W_{qq}}$	$Z_\nu Z_{q_5}$	$q_5 q_5(\gamma)$	$\gamma\gamma \to q_5 q_5$	$W_q W_q / Z_{q_5} Z_{q_5}$
1.65×10^4	5.61×10^4	4.01×10^4	4.41×10^2	1.42×10^4
	$Z_\nu h_b$	$Z_\nu h_c$	$Z_\nu h_g$	$Z_\nu h_{Z_{q_5 q_5}}$
	8.78×10^4	4.71×10^3	1.41×10^4	2.10×10^3

Signal	$\nu\nu h_b$	$\nu\nu h_c$	$\nu\nu h_g$	$\nu\nu h_\tau$
1.51×10^4	1.24×10^4	6.43×10^2	1.92×10^3	1.50×10^2
Higgs backgrounds	$Z_\nu h_b$	$Z_\nu h_c$	$Z_\nu h_g$	$Z_\nu h_\tau$
1.39×10^5	9.47×10^4	5.08×10^3	1.52×10^4	1.06×10^3
	$Z_\nu h_{V_{q_5 q_5}}$	$\nu\nu h_{V_{q_5 q_5}}$		
	2.01×10^4	2.51×10^3		
Non-Higgs backgrounds	$q_5 q_5(\gamma)/\gamma\gamma \to q_5 q_5$	$W_q W_q$	$Z_{q_5} Z_{q_5}$	$Z_\nu Z_{q_5}$
1.40×10^5	$6.79 \times 10^4 / 2.81 \times 10^3$	1.26×10^4	6.61×10^2	5.61×10^4

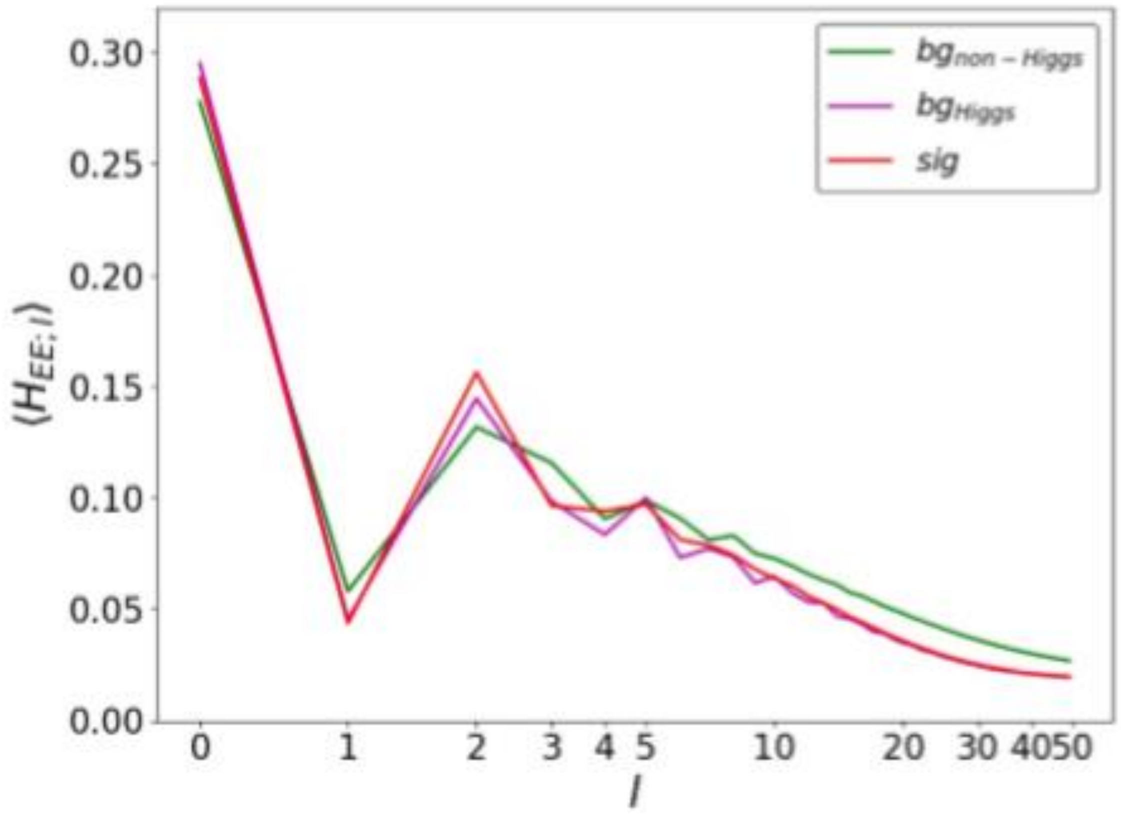
VBF Higgs Measurement

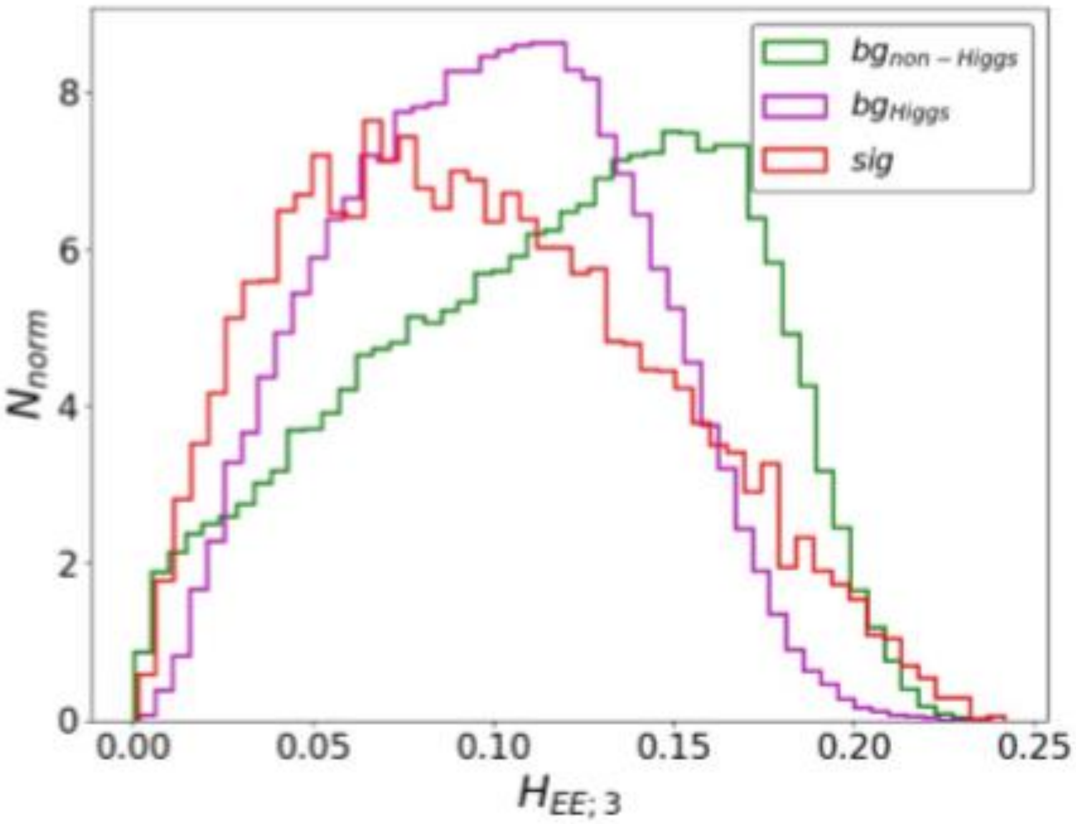


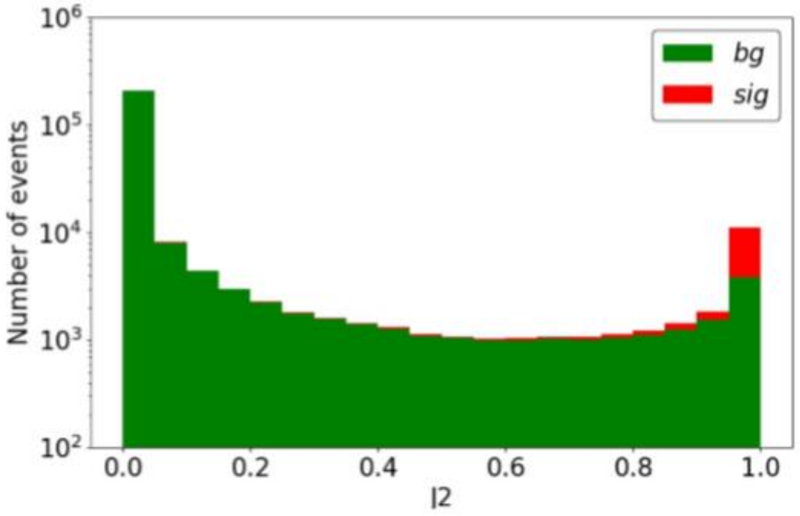
Signal	$\nu\nu h_b$	$\nu\nu h_c$	$\nu\nu h_g$	$\nu\nu h_\tau$
1.51×10^4	1.24×10^4	6.43×10^2	1.92×10^3	1.50×10^2
Higgs backgrounds	$Z_\nu h_b$	$Z_\nu h_c$	$Z_\nu h_g$	$Z_\nu h_\tau$
1.39×10^5	9.47×10^4	5.08×10^3	1.52×10^4	1.06×10^3
	$Z_\nu h_{V_{q_5 q_5}}$	$\nu\nu h_{V_{q_5 q_5}}$		
	2.01×10^4	2.51×10^3		
Non-Higgs backgrounds	$q_5 q_5(\gamma)/\gamma\gamma \to q_5 q_5$	$W_q W_q$	$Z_{q_5} Z_{q_5}$	$Z_\nu Z_{q_5}$
1.40×10^5	$6.79 \times 10^4/2.81 \times 10^3$	1.26×10^4	6.61×10^2	5.61×10^4

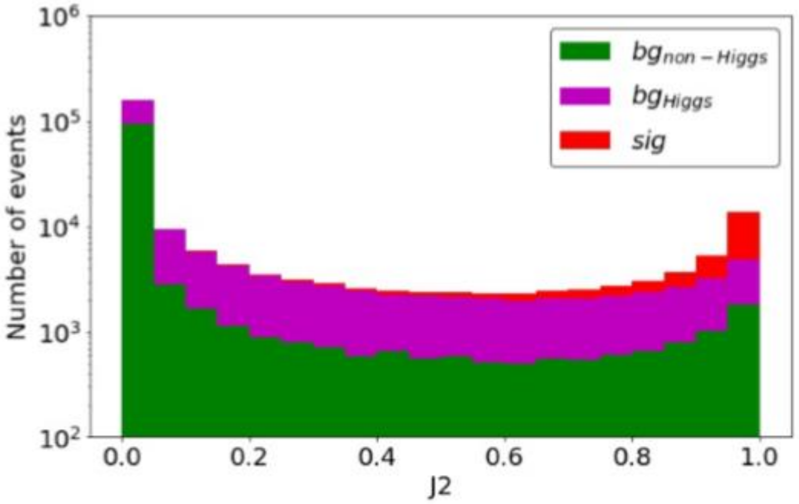
Event yield after simple cuts: total energy ∈ [105,155] GeV, invariant mass ∈ [100,135]GeV, recoil mass ∈ [65,135]GeV, MET>10 GeV and pz < 60GeV.

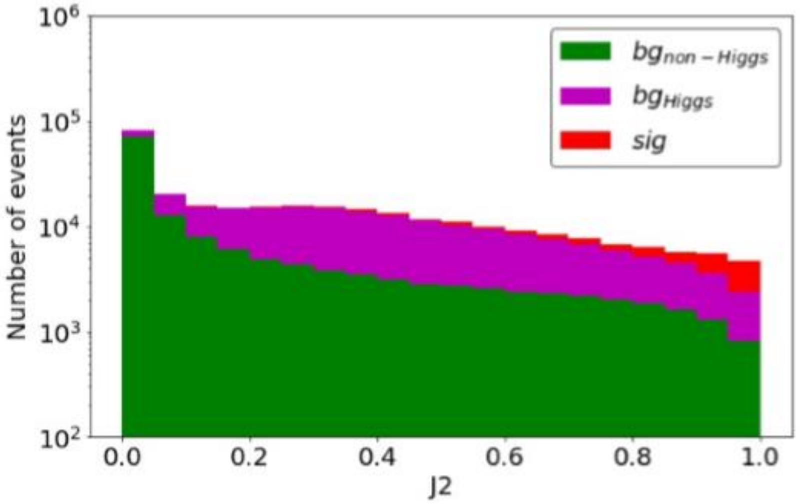
vvh (2j)

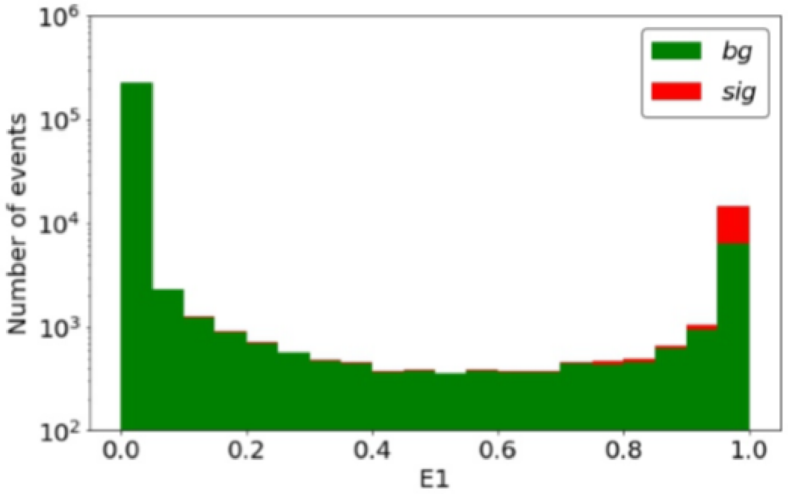

$bg_{non-Higgs}$
bg_{Higgs}
sig
$\langle H_{EE;l} \rangle$
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0
1
2
3
4
5
10
20
30
40
50
l

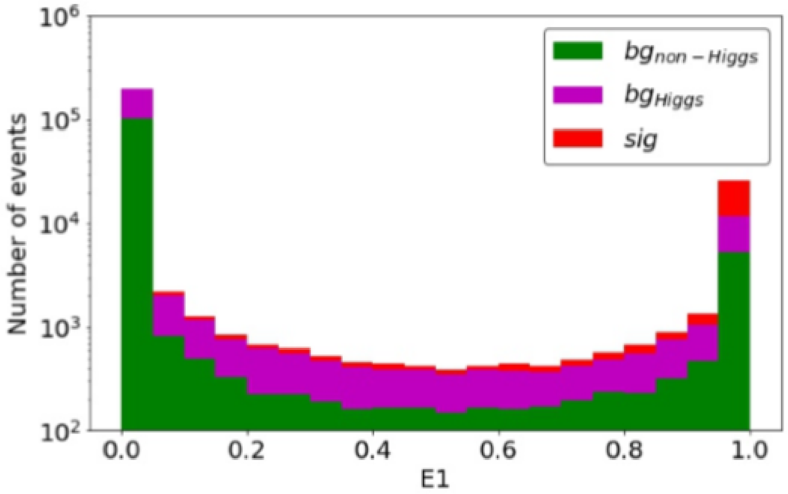

$bg_{non-Higgs}$
bg_{Higgs}
sig
N_{norm}
0
2
4
6
8
0.00
0.05
0.10
0.15
0.20
0.25
$H_{EE;3}$

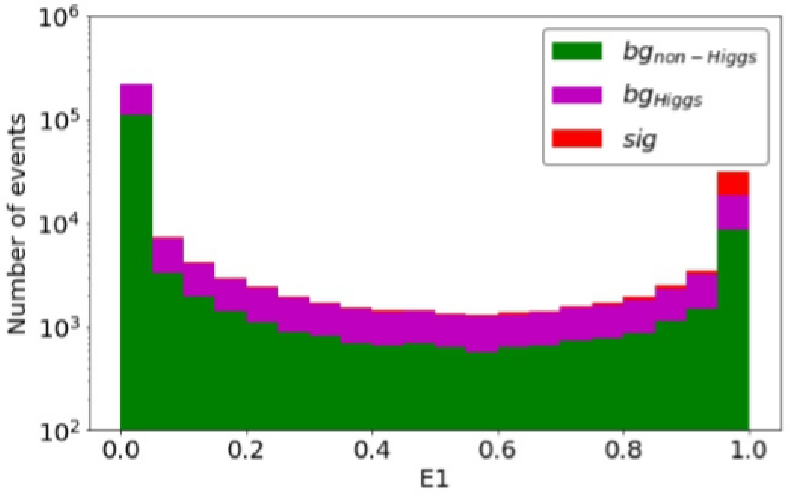

10^6
10^5
10^4
10^3
10^2
Number of events
0.0
0.2
0.4
0.6
0.8
1.0
J2
bg
sig


10^6
10^5
10^4
10^3
10^2
Number of events
0.0
0.2
0.4
0.6
0.8
1.0
J2
$bg_{non-Higgs}$
bg_{Higgs}
sig


10^6
10^5
10^4
10^3
10^2
Number of events
0.0
0.2
0.4
0.6
0.8
1.0
J2
$bg_{non-Higgs}$
bg_{Higgs}
sig


10^6
10^5
10^4
10^3
10^2
Number of events
0.0
0.2
0.4
0.6
0.8
1.0
E1
bg
sig


10^6
10^5
10^4
10^3
10^2
Number of events
0.0
0.2
0.4
0.6
0.8
1.0
E1
$bg_{non-Higgs}$
bg_{Higgs}
sig


10^6
10^5
10^4
10^3
10^2
Number of events
0.0
0.2
0.4
0.6
0.8
1.0
E1
$bg_{non-Higgs}$
bg_{Higgs}
sig