Performance requirement from the hadronic event/jet

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Jets at 240 GeV Higgs factory

- SM Higgs
 - **0 jets: 3%:** $Z \rightarrow II$, vv (30%); $H \rightarrow 0$ jets (~10%, $\tau\tau$, $\mu\mu$, $\gamma\gamma$, $\gamma Z/WW/ZZ \rightarrow Ieptonic$)
 - 2 jets: 32%
 - *Z*→qq, *H*→0 jets. 70%*10% = 7%
 - *Z*→*II*, *vv*; *H*→2 jets. 30%*70% = 21%
 - $Z \rightarrow II$, vv; $H \rightarrow WW/ZZ \rightarrow semi-leptonic. 3.6\%$
 - 4 jets: 55%
 - *Z*→qq, *H*→2 jets. 70%*70% = 49%
 - *Z*→*II*, *vv*; *H*→*WW*/*ZZ*→4 jets. 30%*15% = 4.5%
 - 6 jets: 11%
 - $Z \rightarrow qq$, $H \rightarrow WW/ZZ \rightarrow 4$ jets. 70%*15% = 11%
- 97% of the SM Higgsstrahlung Signal has Jets in the final state
- **1/3** has only 2 jets: include all the SM Higgs decay modes
- 2/3 need color-singlet identification: grouping the hadronic final sate particles into color-singlets
- Jet is important for EW measurements & jet clustering is essential for differential measurements



Jets at other SM Processes

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- Multi-jet events, especially the dominant 2-jet events, are critical
 - Measurement: TGC, Afb, etc
 - Background control
 - Calibration & in-situ monitoring
- 0 jets:
 - Di-photon events;
 - bhabha, ττ, μμ;
- 2 jets:
 - $ee \rightarrow qq(\gamma)$ (ISR return & full energy)
 - WW/ZZ→semi-leptonic
 - Single W/Z events
- 4 jets:
 - WW/ZZ→Full hadronic
 - $ZH \rightarrow qq+(bb, cc, gg)$
- 6 jets: ZH→qqWW*, qqZZ*→Full hadronic
 28/10/19



Performance quantification on the hadronic event reconstruction

- Visible mass of hadronic system
 - Identify the hadronic system & calculate its visible mass
 - At 2-jets event: the visible mass is the mass of the intermediate boson
 - At fixed c.m.s. energy, the recoil mass of hadronic system is mostly determined by the visible mass.
- Jet: via jet clustering, and match to/interpret as parton
 - Essential for differential measurements
 - Essential for identifying the right combination of jets the color singlet for physics event with jet number > 2
 - The jet clustering can induce significant uncertainties

The performance - requirement benchmark analyses

- 2 jet final state
 - $\sigma(vvH, H \rightarrow bb)$
 - $\sigma(qqH, H \rightarrow inv)$
 - $\sigma(qqH, H \rightarrow tautau)$
- 4 jet final state: ZZ/WW separation at full hadronic final states
- Jet response: Jet Energy/Angluar Resolution/Scale and impact from jet clustering algorithms, see Peizhu Lai's presentation yesterday

https://agenda.linearcollider.org/event/8217/contributions/44662/

CEPC Software & Reconstruction



Starting from the ilcsoft & integrating Arbor/high-level reconstruction algorithms.

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 $H \rightarrow gg$ events, and similar conclusions are obtained with $H \rightarrow bb$ and cc events. The red lines in the plots are the cut values used for event cleaning.

BMR at the CEPC baseline ~ 3.75%





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

	$\alpha \alpha(0/)$	bb(0/)	aa(0/)	WW*(0/)	77*(0/)		0	1	-		
	88(%)	00(70)	CC(70)	<i>W W</i> · (70)	ZZ · (70)		11	$\Pi \rightarrow \infty$	11 H/H/+		Ì
Pt ISR < 1 GeV	95.15	95.37	95.30	95.16	95.24	$H \rightarrow DD$	$H \rightarrow cc$	$H \rightarrow gg$	$H \rightarrow W W^*$	$H \rightarrow ZZ^{*}$	
_						2 (20)	2.020/	2 7 5 9 /	2 0 1 0 /	2 7 48 (
Pt_neutrino < 1 GeV	89.33	39.04	66.36	37.46	41.39	3.63%	3.82%	3.75%	3.81%	3.74%	_
Cos(Theta_Jet) < 0.85	67.30	28.65	49.31	_	_	CWS 2019				8	
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BM1: Massive Boson Mass Resolution



■ W-, Z-, and Higgs-boson masses in dijet final state can be well separated at CEPC.

■ After cleaned, Z- and W-boson could be separated ≈ 2σ, and the Higgs Boson Mass Resolution = 3.8% achieving the CEPC baseline.

Cleaned: Select the light flavor jet event with low energy ISR, low energy neutrino inside jet, and within |cosθ| < 0.85.</th>Pei-Zhu Lai (NCU, Taiwan)11LCWS201928/10/19LCWS 20199

BM3: JER (Reco-Gen)





- JER also depends on jet flavors.
- For light-flavor jets with high energy and within central region of barrel, JER could reach 3%.

https://agenda.linearcollider.org/event/8217/contributions/44662/

1st Benchmark: $\sigma(vvH, H\rightarrow bb) \sim Higgs$ width

• $g^{2}(HXX) \sim \Gamma_{H \rightarrow XX} = \Gamma_{total}^{*}Br(H \rightarrow XX)$

- Γ_{total} : determined by combining:
 - − 1st, σ (ZH) (~g²(HZZ)), σ (ZH, H→ZZ) (~g⁴(HZZ)/Γ_{total})
 - 2nd, σ (ZH, H→bb), σ (ZH, H→WW), σ (ZH), σ (VVH|_{w fusion}, H→bb), (bb can be replaced by X)
 - The 2nd method dominant the accuracy
- Critical to identify the W fusion events from the Higgsstrahlung ones with vvH final state: rely on the recoil mass agains the Higgs (and the Higgs direction).



Hao Liang

$\sigma(vvH, H \rightarrow bb)$: Accuracy V.S. BMR



If the BMR degrades from 4% to 6/8%: the Higgs width measurement degrades by 20/40% improves to 2%: the width measurement will improve by 15% 28/10/19 LCWS 2019 12

2^{nd} Benchmark: qqH, H \rightarrow invisible

- Portal to DM...
- qqH dominants the precision & rely on the recoil mass to separate the ZZ bkg
- Essential for qqH analysis, especially H→non jet final state





If the BMR degrades from 4% to 6/8%: the Higgs invisible measurement degrades by 20/50%

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3rd Benchmark: g(HTT) at qqH



- TAURUS: di-tau system identification
- The rest particles are identified as the di-jet: to distinguish the ZZ/ZH background & Improves the accuracy by more than a factor of 2: BMR < 4% is crucial
- Isolated tracks are intensionally defined as tau candidate: be distinguished by the VTX
- Relative accuracy of 0.9% at 5.6 ab⁻¹ integrated luminosity, dominate the combined accuracy (0.8%)
- Changing BMR from 4% to 6/10%, the Accuracy degrades by 10/20%

Requirement from benchmark analysis: BMR < 4%



- 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→тт)	0.85%	0.9%	1.0%	1.1%

BMR factorization

- BMR is composed of
 - Sub detector responses
 - Intrinsic resolutions
 - Thresholds
 - Acceptance
 - Confusions
 - Overlapping between nearby clusters
 - Cluster splitting: double counting
 - Back scattering, interactions inside tracker
 - ...
- A fast simulation tool is developed to quantify individual impact

PFA Fast simulation (Preliminary)



Fast simulation reproduces the full simulation results, factorize/quantifies different impactsSame cleaning condition as in the Full simulation appliedEarly phase of modeling/tuning28/10/19LCWS 201917

Cluster splitting: the most severe confusions



Time/pattern recognition may help a lot, in identify the charged cluster fragmentations without arise the threshold for the neutral hadron significantly...

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

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

overlapping ratio = $\sum min(a_i, b_i)$

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 V.S. clustering



Eur. Phys. J. C (2019) 79:274

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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.



it has been studied if a color singlet jet clustering can be implemented for both signal and BG, $\lambda_{\rm HHH}$ measurement improved by 40%, which means 20% $\delta\lambda_{\rm HHH}/\lambda$ (5 σ) would already be possible at 500 GeV ILC with the H20 scenario

Summary

Future lepton colliders:

- an opportunity to understand the process from parton to jet.

- a challenge to jet reconstruction (better detectors, complex final states, enhanced phase space, background, tighter control over systematics)

Traditional lepton collider algorithms fail to cope with the background level expected at future linear (circular?) colliders

Longitudinally invariant algorithms work well... and we understand why

Refurbished e⁺e⁻ algorithms can be better still: VLC is currently the most robust algorithm on the market

Non-perturbative corrections are less important than at LEP, but non-trivial differences between algorithms merit further study

Conclusion

- Hadronic events are critical
- To disentangle the impact of detector/PFA and jet algorithms (clusteringmatching), we uses BMR and full hadronic WW-ZZ overlapping ratio
- Benchmark analyses shows BMR < 4% is required for the detector/PFA
 - The recoil mass of di-jet system is an important observable to separate the signal from major backgrounds (ZZ, ZH)
 - BMR decomposition: At the CEPC baseline reconstruction: mainly limited by hadronic shower fragmentation, may potentially be improved using time information - better algorithms – need further quantification...
- Jet algorithms can dominate the uncertainty for the measurement on multi-jet event: need better algorithms.
 - Clear consensus, and need further collaboration with QCD/pheno-theory!...

Back up: related physics performance studies

A test: thrust algorithm (Preliminary)

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Resolution

0.08

0.07

VS eekt (the baseline, recommended by

the full hadronic WW/ZZ study): up to 20%

0.08

0.07

improvement in Jet Angular/Energy

ee-kt

CEPC Preliminary

- Thrust based
 - Boost the hadronic system back to its rest frame
 - Divide into 2 hemisphere with a plane perpendicular to the thrust, each identified as a jet (applicable only to 2 jet state)
 - Resolution (0.06 0.06 0.05 0.05 0.04 Jet Angular 0.04 0.03 0.03 0.02 0.02 0.01 0.0 **Trying axis** -0.50.5 -0.50 0.5 n**T: The thrust axis** cos_θ cos_θ 0.14 0.14 CEPC Preliminary CEPC Preliminar Thrust ee-kt 0.12 0.12 -eading Jet Energy Resolution Leading Jet Energy Resolution WW→uvaa →Z→aā ZH →vva 0.1 0.1 0.08 0.08 0.06 0.06 0.04 0.04 Separate the particles into two jets 0.02 0.02 0 0 -0.8-0.6-0.4-0.2 0 0.2 0.4 0.6 0.8 -0.8-0.6-0.4-0.2 0 0.2 0.4 0.6 0.8 cos_θ cose LCWS 2019

CEPC Prelimina

Thrust

Science at CEPC-SPPC

- Tunnel ~ 100 km
- CEPC (90 250 GeV)
 - Higgs factory: 1M Higgs boson
 - Absolute measurements of Higgs boson width and couplings
 - Searching for exotic Higgs decay modes (New Physics)
 - Z & W factory: 100M W Boson, 100B 1 Tera Z boson

Booster(50Km

- Precision test of the SM Low Energy
 - Low Energy Booster(0.4Km)

IP₂

Proton Linac

e+ e- Linac (240m)

IP3

- Rare decay
- Flavor factory: b, c, tau and QCD studies
- SPPC (~ 100 TeV)

IP4

- Direct search for new physics
- Complementary Higgs measurements to CEPC g(HHH), g(Htt)
- Heavy ion, e-p collision... 28/10/19

Complementary



Observables: Higgs mass, CP, $\sigma(ZH)$, event rates ($\sigma(ZH, vvH)^*Br(H \rightarrow X)$), Diff. distributions

Derive: Absolute Higgs width, branching ratios, couplings



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Derive: Absolute Higgs width, branching ratios, couplings

Physics Requirements



Detector:

To reconstruct all the physics objects with high efficiency, purity & resolution Homogenous & Stable enough to control the systematic

This talk quantifies the requirement/key questions of Jet reconstruction at CEPC/ILC

Two classes of Concepts

- PFA Oriented concept using High Granularity Calorimeter
 - + TPC (ILD-like, Baseline)
 - + Silicon tracking (SiD-like)



- Wire Chamber + Dual Readout Calorimeter





https://indico.ihep.ac.cn/event/6618/

https://agenda.infn.it/conferenceOtherViews.py?view=standard&confld=14816



Particle separation (2 m track)



Physics Objects



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The Simu-Reco Chain at CEPC



Higgs benchmark analyses

