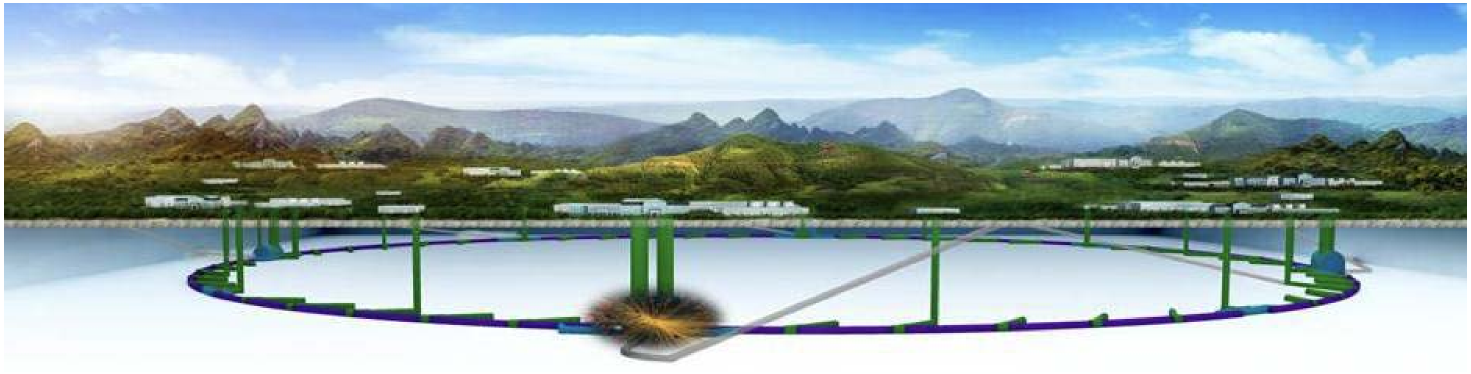
Higgs Physics: Review & Discussion

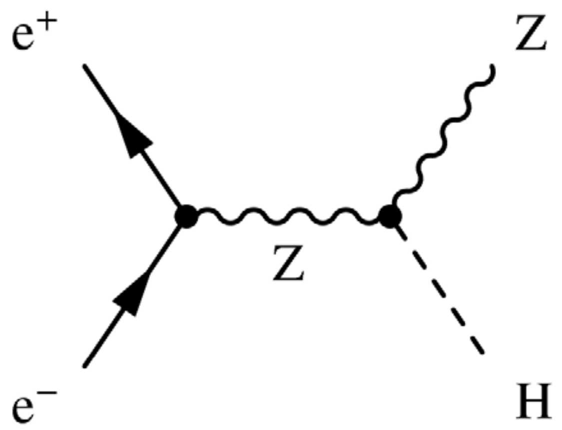


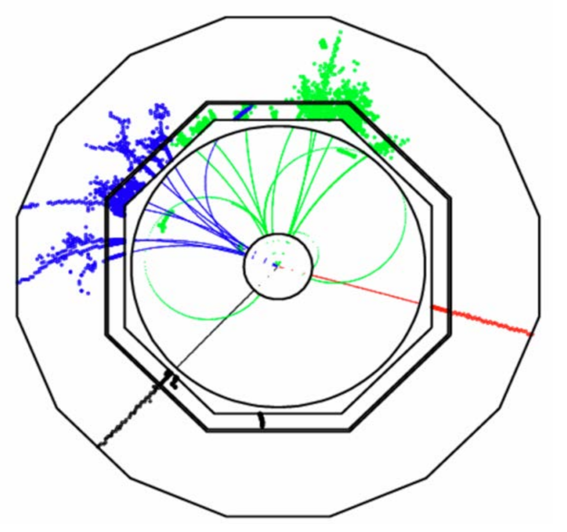
Jianming Qian (University of Michigan)

CEPC Physics Workshop, Peking University
Beijing, July 1-5, 2019

Decay-Blinded Tagging of Higgs Boson

Unique to lepton colliders, the energy and momentum of the Higgs boson in $ee \to ZH$ can be measured by looking at the Z kinematics only: $E_H = \sqrt{s} - E_Z, \quad \vec{p}_H = -\vec{p}_Z$





Recoil mass reconstruction:

$$m^2_{\text{recoil}} = \left(\sqrt{s} - E_Z\right)^2 - \left|\vec{p}_Z\right|^2$$

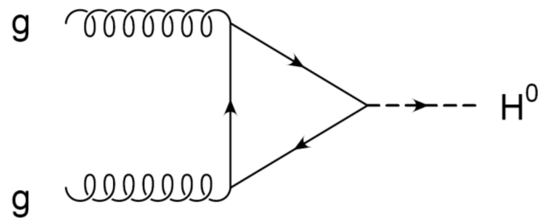
$\Rightarrow$ identify the Higgs boson without looking at the Higgs boson.

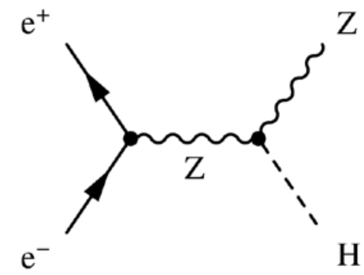
Measure $\sigma(ee \to ZH)$ independent of its decay !

(LHC always measures $\sigma \times \text{BR}$)

Main differences with LHC

- **Production:**
  LHC: dominated by the QCD process $\Rightarrow$ large theoretical uncertainties
  CEPC: pure electroweak process $\Rightarrow$ precise theory calculations



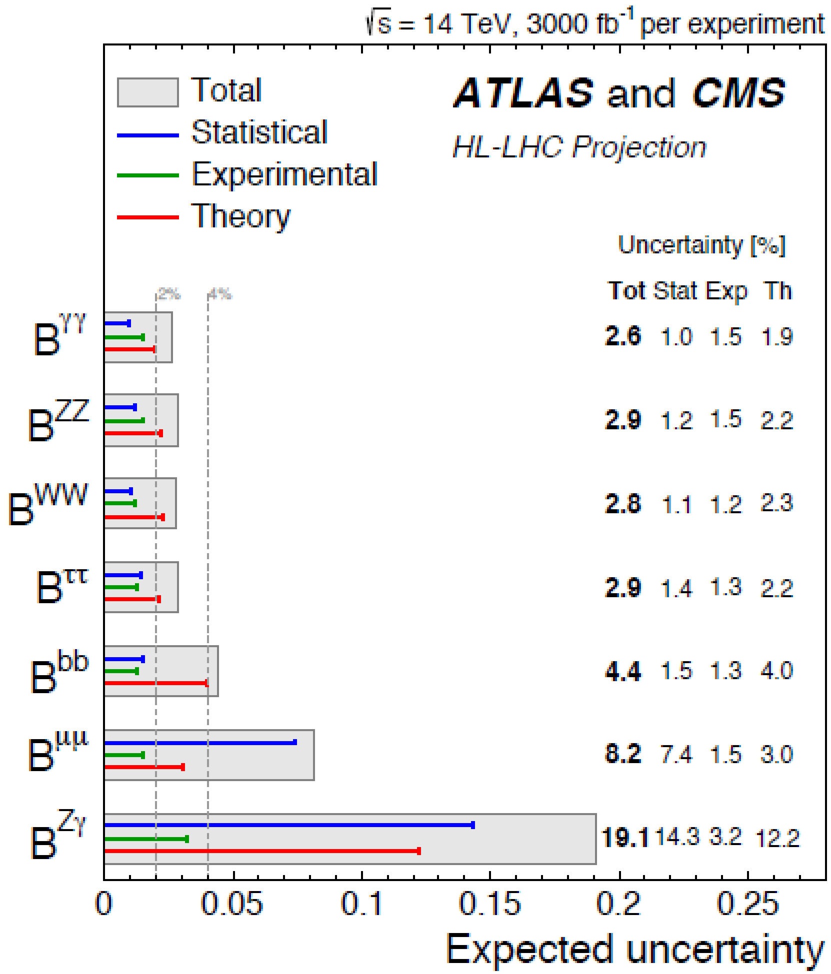


- **Trigger and identification:**
  LHC: based on specific Higgs boson decay signatures $\Rightarrow$ *measure $\sigma\times$BR*
  CEPC: Higgs boson decay blinded $\Rightarrow$ *measure σ and BR*

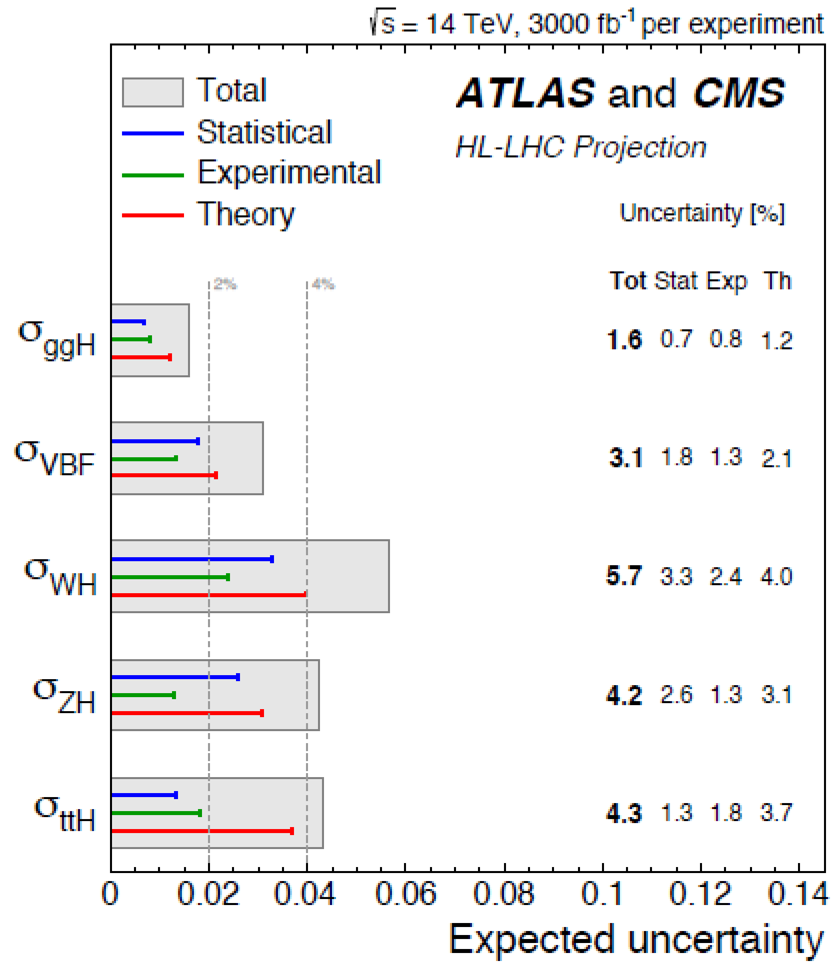
- **Environment:**
  LHC: suffer from underlying event and pileup effects
  CEPC: clean

- **Statistics**
  HL-LHC: ~ 300 million Higgs bosons, recording about ~2%
  CEPC: ~ 1 million Higgs bosons, every event is gold

Updated LHC Projections



Assuming SM production cross sections



Assuming SM decay branching ratios

These are model-dependent projections !

What We Have Done

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Precision Higgs Physics at the CEPC*

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Abstract: The discovery of the Higgs boson with its mass around 125 GeV by the ATLAS and CMS Collaborations marked the beginning of a new era in high energy physics. The Higgs boson will be the subject of extensive studies of the ongoing LHC program. At the same time, lepton collider based Higgs factories have been proposed as a possible next step beyond the LHC, with its main goal to precisely measure the properties of the Higgs boson and probe potential new physics associated with the Higgs boson. The Circular Electron Positron Collider (CEPC) is one of such proposed Higgs factories. The CEPC is an e^+e^- circular collider proposed by and to be hosted in China. Located in a tunnel of approximately 100 km in circumference, it will operate at a center-of-mass energy of 240 GeV as the Higgs factory. In this paper, we present the first estimates on the precision of the Higgs boson property measurements achievable at the CEPC and discuss implications of these measurements.

Key words: CEPC, Higgs boson, Higgs boson properties, Higgs boson couplings, Higgs factory, Effective Field Theory, EFT

PACS: 1–3 PACS(Physics and Astronomy Classification Scheme, http://www.aip.org/pacs/pacs.html/)

Final States Studied

$H \to bb / cc / gg$

Z decay mode	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$
$Z \to e^+e^-$	1.3%	12.8%	6.8%
$Z \to \mu^+\mu^-$	1.0%	9.4%	4.9%
$Z \to q\bar{q}$	0.5%	10.6%	3.5%
$Z \to \nu\bar{\nu}$	0.4%	3.7%	1.4%
Combined	0.3%	3.1%	1.2%

$H \to ZZ^*$

ZH final state		Precision
$Z \to \mu^+\mu^-$	$H \to ZZ^* \to \nu\bar{\nu}q\bar{q}$	7.2%
$Z \to \nu\bar{\nu}$	$H \to ZZ^* \to \ell^+\ell^- q\bar{q}$	7.9%
Combined		4.9%

$H \to$ Invisible

ZH final state studied		Relative precision on $\sigma \times$ BR	Upper limit on BR($H \to$ inv)
$Z \to e^+e^-$	$H \to$ inv	339%	0.82%
$Z \to \mu^+\mu^-$	$H \to$ inv	232%	0.60%
$Z \to q\bar{q}$	$H \to$ inv	217%	0.57%
Combined		143%	0.41%

$H \to WW^*$

ZH final state		Precision
$Z \to e^+e^-$	$H \to WW^* \to \ell\nu\ell'\nu, \ell\nu q\bar{q}$	2.6%
$Z \to \mu^+\mu^-$	$H \to WW^* \to \ell\nu\ell'\nu, \ell\nu q\bar{q}$	2.4%
$Z \to \nu\bar{\nu}$	$H \to WW^* \to \ell\nu q\bar{q}, q\bar{q}q\bar{q}$	1.5%
$Z \to q\bar{q}$	$H \to WW^* \to q\bar{q}q\bar{q}$	1.7%
Combined		0.9%

$H \to \tau\tau$

ZH final state		Precision
$Z \to \mu^+\mu^-$	$H \to \tau^+\tau^-$	2.6%
$Z \to e^+e^-$	$H \to \tau^+\tau^-$	2.6%
$Z \to \nu\bar{\nu}$	$H \to \tau^+\tau^-$	2.5%
$Z \to q\bar{q}$	$H \to \tau^+\tau^-$	0.9%
Combined		0.79%

Other final states:

$H \to \gamma\gamma: Z \to \mu\mu, \tau\tau, \nu\nu, qq$

$H \to Z\gamma: ZZ \to \nu\nu qq$

$H \to \mu\mu: Z \to \ell\ell, \nu\nu, qq$

$ee \to \nu\nu H \to \nu\nu bb$

A lot final states have been studied, many more remain unexplored…

Future Colliders in a chart

European Strategy Update

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]$ $\text{cm}^{-2}\text{s}^{-1}$	$\mathscr{L}$ $[\text{ab}^{-1}]$	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[10]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[10]	HE-LHC
FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee_{240}
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee_{365}
							(+1)		(1y SD before $2m_{top}$ run)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[[illegible], 11]	ILC_{250}
		350 GeV	±80/±30	1	1.6	0.2	1		ILC_{350}
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC_{500}
							(+1)		(1y SD after 250 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[12]	CLIC_{380}
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC_{1500}
		3.0 TeV	±80/0	1	6.0	5.0	8		CLIC_{3000}
							(+4)		(2y SDs between energy stages)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[9]	LHeC
HE-LHeC	ep	1.8 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

- The values for $\sqrt{s}$ are approximate: when a scan is proposed: included in the closest value
- When the entire programme is discussed, the highest energy value label is used inclusively

Higgs@Future Colliders Report

Higgs Boson studies at future particle colliders

- Preliminary Version -

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ABSTRACT

This document aims to provide an assessment of the potential of future colliding beam facilities to perform Higgs boson studies. The analysis builds on the submissions made by the proponents of future colliders to the European Strategy Update process, and takes as its point of departure the results expected at the completion of the HL-LHC program. This report presents quantitative results on many aspects of Higgs physics for future collider projects using uniform methodologies for all proposed machine projects of sufficient maturity. This report is still preliminary and is distributed for the purposes of discussion at the Open Symposium in Granada (13-16/05/2019).

arXiv:1905.03764

European Strategy Update

European Strategy Update

CEPC Higgs physics sensitivity projections were fairly presented at the open symposium: https://cafpe.ugr.es/eppsu2019/

kappa-3 scenario	HL-LHC+								
	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	FCC-ee_{240}	FCC-ee_{365}	FCC-ee/eh/hh
κ_W (%)	1.1	0.29	0.75	0.4	0.38	0.95	0.95	0.41	0.2
κ_Z(%)	0.29	0.23	0.44	0.39	0.39	0.18	0.19	0.17	0.17
κ_g(%)	1.4	0.84	1.5	1.1	0.86	1.1	1.2	0.89	0.53
κ_γ (%)	1.3	1.2	1.5*	1.3	1.1	1.2	1.3	1.2	0.36
$\kappa_{Z\gamma}$ (%)	11.*	11.*	11.*	8.4	5.7	6.3	11.*	10.	0.7
κ_c (%)	2.	1.2	4.1	1.9	1.4	2.	1.6	1.3	0.97
κ_t (%)	2.7	2.4	2.7	1.9	1.9	2.6	2.6	2.6	0.95
κ_b (%)	1.2	0.57	1.2	0.61	0.53	0.92	1.	0.64	0.48
κ_μ (%)	4.2	3.9	4.4*	4.1	3.5	3.9	4.	3.9	0.44
κ_τ (%)	1.1	0.64	1.4	0.99	0.82	0.96	0.98	0.66	0.49
BR_{inv} (<%, 95% CL)	0.26	0.22	0.63	0.62	0.61	0.27	0.22	0.19	0.024
BR_{unt} (<%, 95% CL)	1.8	1.4	2.7	2.4	2.4	1.1	1.2	1.	1.

FCC-ee at 240 GeV and CEPC have very similar projections

Recommendations from CDR review

Higgs physics.

Findings: At a center-of-mass energy of 240 GeV the CEPC operates as a Higgs boson factory. In seven years the facility is expected to produce approximately 1 million $e^+e^- \rightarrow ZH$ events that allow a direct and model-independent scrutiny of its properties and its interactions with nearly all other elementary particles. The capabilities of CEPC as a Higgs factory are carefully evaluated and convincingly presented. The potential for precise Higgs coupling measurements significantly exceeds the precision that can be achieved at the Large Hadron Collider and is very competitive compared to other proposals for electron-positron colliders. The main modes, $\tau\tau/b\bar{b}/c\bar{c}/gg$, are well covered. In the WW/ZZ channels, it would be helpful to report separately all the leptonic and hadronic channels.

R1: The Higgs analyses and the sensitivities in the measurement of the Higgs couplings are well documented and studied in the context of various prominent models of new physics. It would be helpful to establish what is the CEPC power in discriminating among these different models through a global fit.

R2: Highlight the capability of CEPC to establish the Higgs couplings to the second generation of quarks (and leptons).

R3: Understand the indirect sensitivity to the top quark Yukawa coupling and Higgs self coupling in a global analysis at next-to-leading order accuracy of low-energy Higgs data

R4: In the $H \rightarrow$ invisible channel, it would be helpful to report the relative importance of the leptonic and hadronic Z decay channels as the latter one fixes the goal of the jet energy resolution.

R5: In the $ZH \rightarrow ZZ\gamma$ channel, we recommend to consider the decay of one Z into charged leptons in addition to the neutrino channel.

Towards TDR

Examples of possible improvements

- Maximum use of detector information
  - Improving electron energy measurement;
  - Estimate sensitivities of missing final states;
- Improve (some) existing analyses
  - Fully exploit kinematic information of both signal and background events;
  - Use advanced analysis techniques for signal and background separation;
  - Global (combined) analysis approaches;
- Moving beyond
  - Spin/CP property studies;
  - Differential cross section measurements
  - BSM studies;

What performance requirements that may impact detector design changes from the baseline? Jet energy resolution?

Missing Channels

$H \to ZZ*$

ZH final state		Precision
$Z \to \mu^+\mu^-$	$H \to ZZ^* \to \nu\bar{\nu}q\bar{q}$	7.2%
$Z \to \nu\bar{\nu}$	$H \to ZZ^* \to \ell^+\ell^- q\bar{q}$	7.9%
Combined		4.9%

Missing: $Z \to qq$

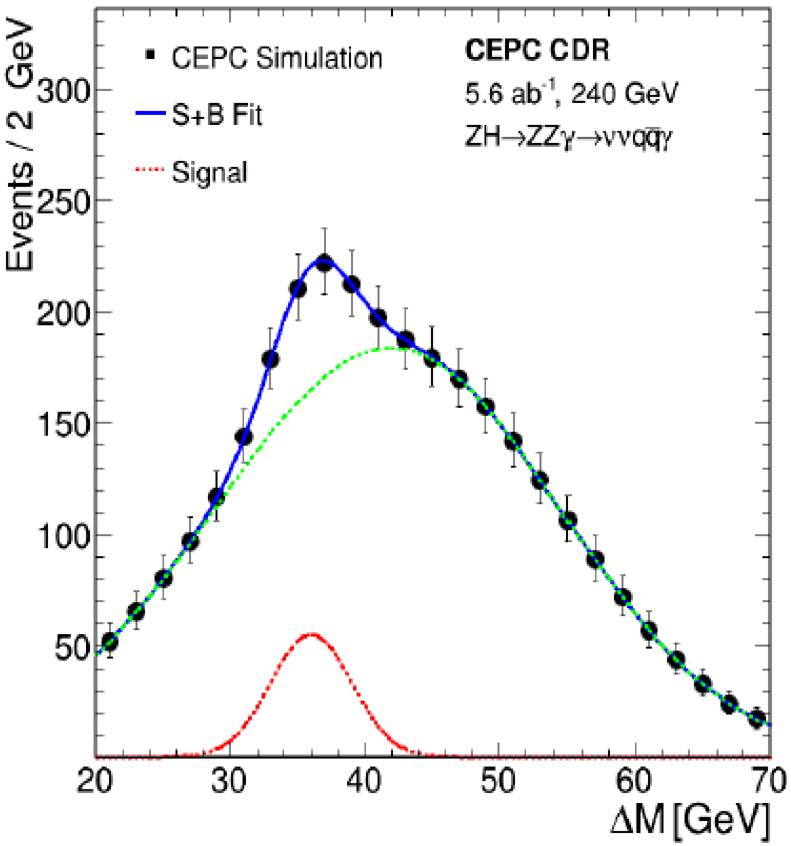
Might be important (relatively)

based on the $H \to WW^*$ studies

$H \to WW*$

ZH final state		Precision
$Z \to e^+e^-$	$H \to WW^* \to \ell\nu\ell'\nu, \ell\nu q\bar{q}$	2.6%
$Z \to \mu^+\mu^-$	$H \to WW^* \to \ell\nu\ell'\nu, \ell\nu q\bar{q}$	2.4%
$Z \to \nu\bar{\nu}$	$H \to WW^* \to \ell\nu q\bar{q}, q\bar{q}q\bar{q}$	1.5%
$Z \to q\bar{q}$	$H \to WW^* \to q\bar{q}q\bar{q}$	1.7%
Combined		0.9%

$ZH \to ZZ\gamma \to \nu\bar{\nu}q\bar{q}\gamma$

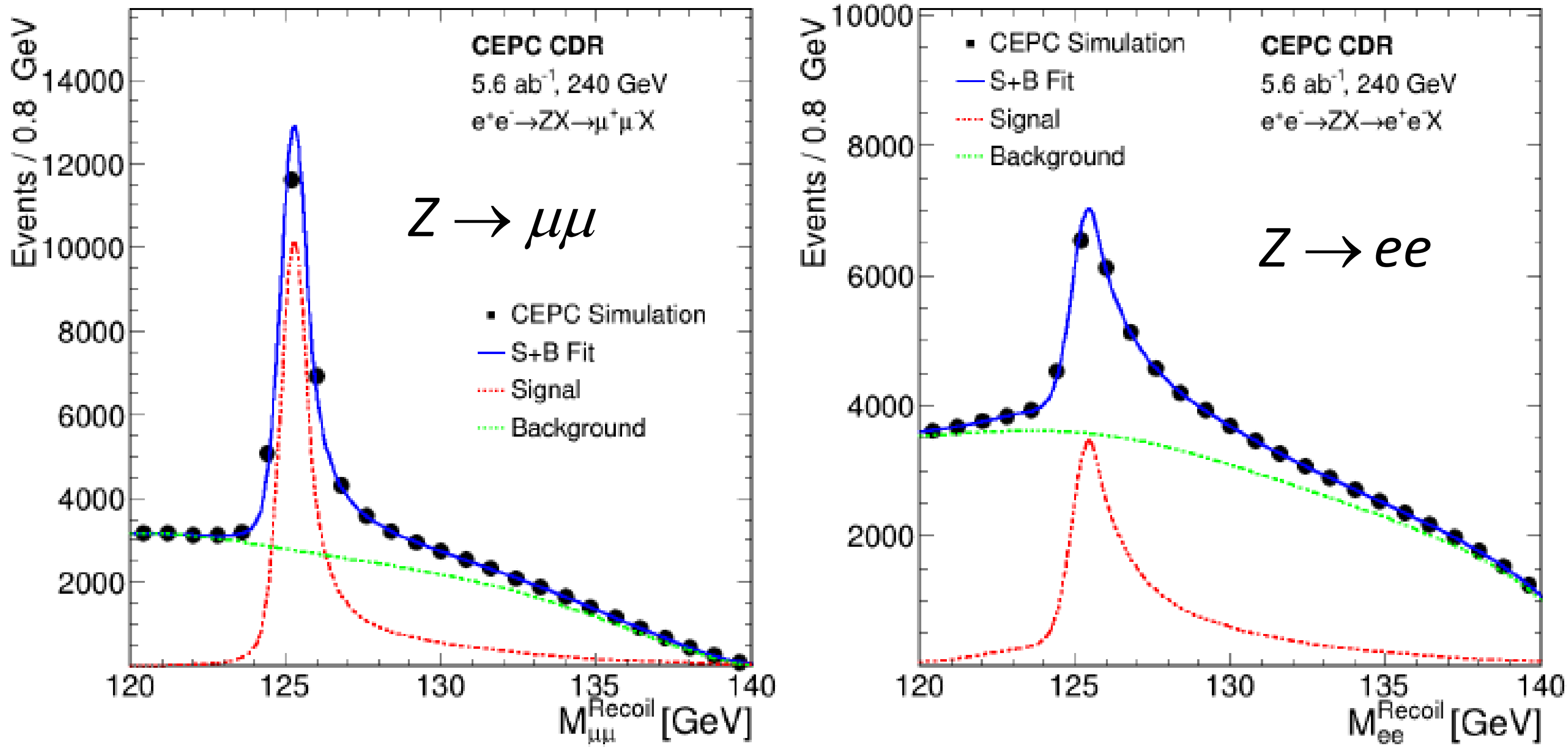


$\Delta M = M(q\bar{q}\gamma) - M(q\bar{q})$ or $M(\nu\bar{\nu}\gamma) - M(\nu\bar{\nu})$

What about other decay final states

such as $ZH \to ZZ\gamma \to qqqq\gamma, \ell\ell qq\gamma$?

Electron Energy Measurement



Much worse recoil mass resolution in the electron channel due to Bremstrahlung radiation, should be able to improve with radiation recovery.

Event Kinematics

Can analyses be improved through the exploitation of kinematics of both signal and background events?

Example:

- qqH, Higgs→invisible;
  - Key measurement for the DM search, significant … ...tage … LHC

Physics benchmarks

Manqi Ruan

Signal: $ZH \to qq\ inv$

Background: $ZZ \to qq\ \nu\nu$

Both signal and background events have the same dijet mass, but different recoil masses: M_Z vs M_H.

Can the qq mass constraint improve the recoil mass resolution?

Another example, $ZH \to qq\mu\mu$ is ideal final state for kinematic fitting

Kunlin Ran

Advanced Analysis Techniques

Many analyses have dozen of cuts on different observables

Example:

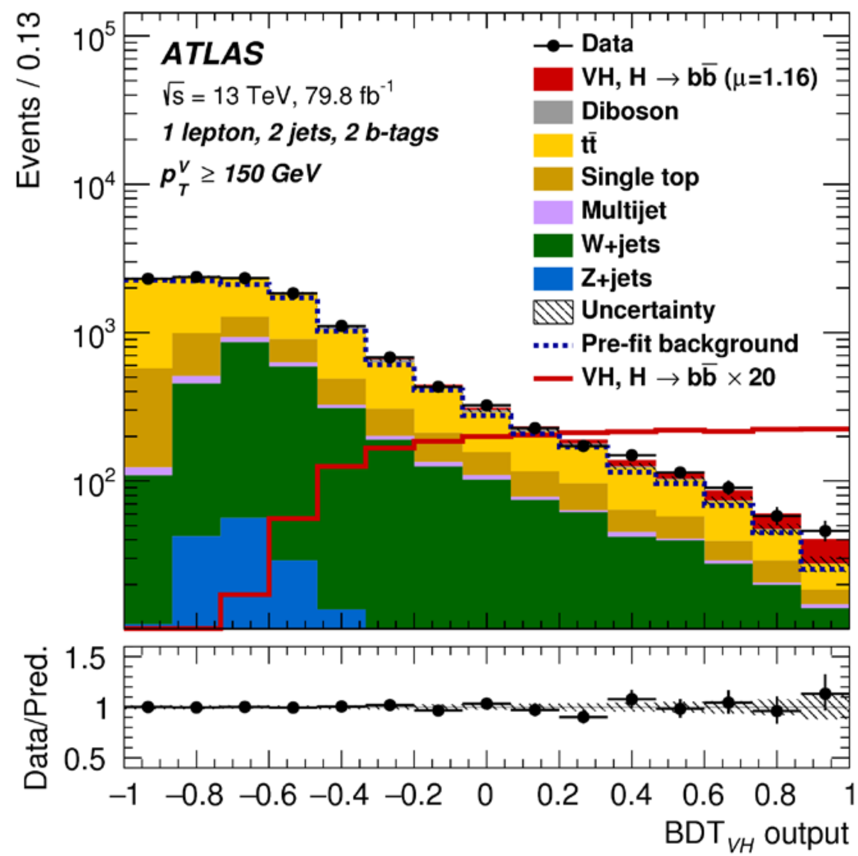
Hao Liang: $\nu\nu H \rightarrow \nu\nu bb$ @ 360 GeV

	$\nu\nu bb(W\text{fusion})$	$\nu\nu bb(ZH)$
No.	34.5k	29.5k
$N_{\text{PFOs}} \leq 17$	100.0%	100.0%
100 <E< 200	96.3%	85.9%
$15 < P_T < 150$	91.3%	84.6%
$N_{\text{lep}} \leq 1$	87.6%	81.6%
$104 < M < 145$	77.0%	70.2%
$M_{\text{rec}} < 255$	76.5%	65.0%
$y_{12} < 0.1$	74.2%	54.9%
$y_{23} < 0.07$	70.6%	54.1%
$y_{34} < 0.01$	69.0%	53.5%
$\cos(\theta_{\text{di-jet}}) < 0.2$	68.1%	47.0%
di-b likeness > 0.5	64.9%	45.0%
No.	22.4k	13.3k

Multivariate Analysis Techniques are ideal suited for this type of analyses.

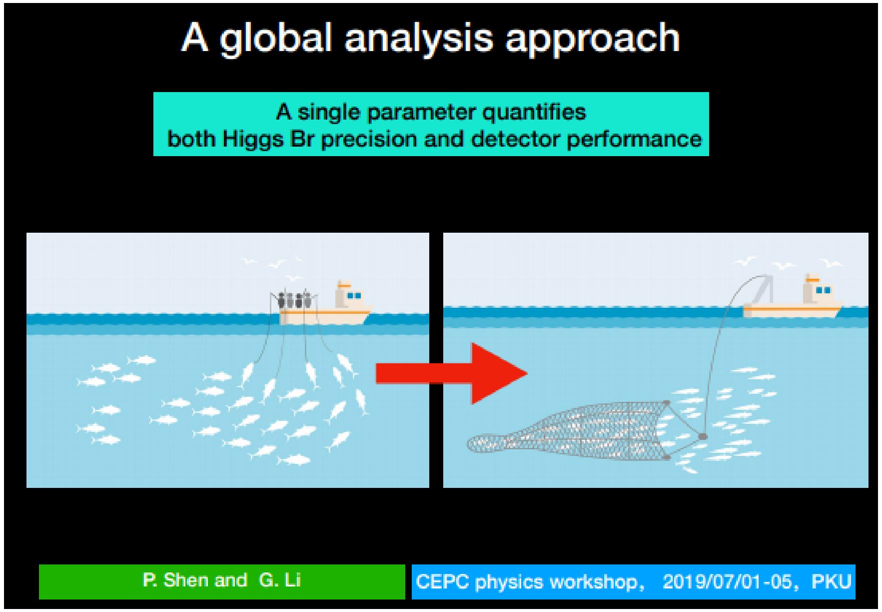
At LHC, complex analyses are done almost *exclusively* using MVA techniques (NN, BDT, …)

Example: ATLAS $H \rightarrow b\bar{b}$ analysis



"Global" Analyses

Instead of Higgs decay mode oriented analyses, we should perhaps focus more on final-state oriented analyses

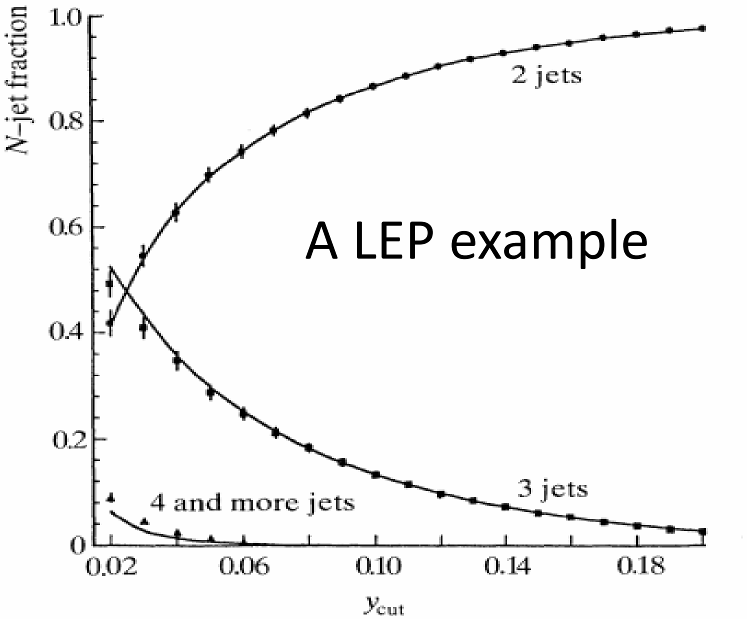


Hadronic final state is a good final state to exercise the global analysis

$$ZH \to (qq, \nu\nu)(bb, cc, gg, WW, ZZ)$$

$$WW \to qqqq$$

$$ZZ \to qq\nu\nu, qqqq$$



A LEP example

Majority of the events at CEPC !
Need good iterative jet algorithm to classify events into 2, 3, 4, 5, 6, … jets !

Potential of the 360 GeV Running

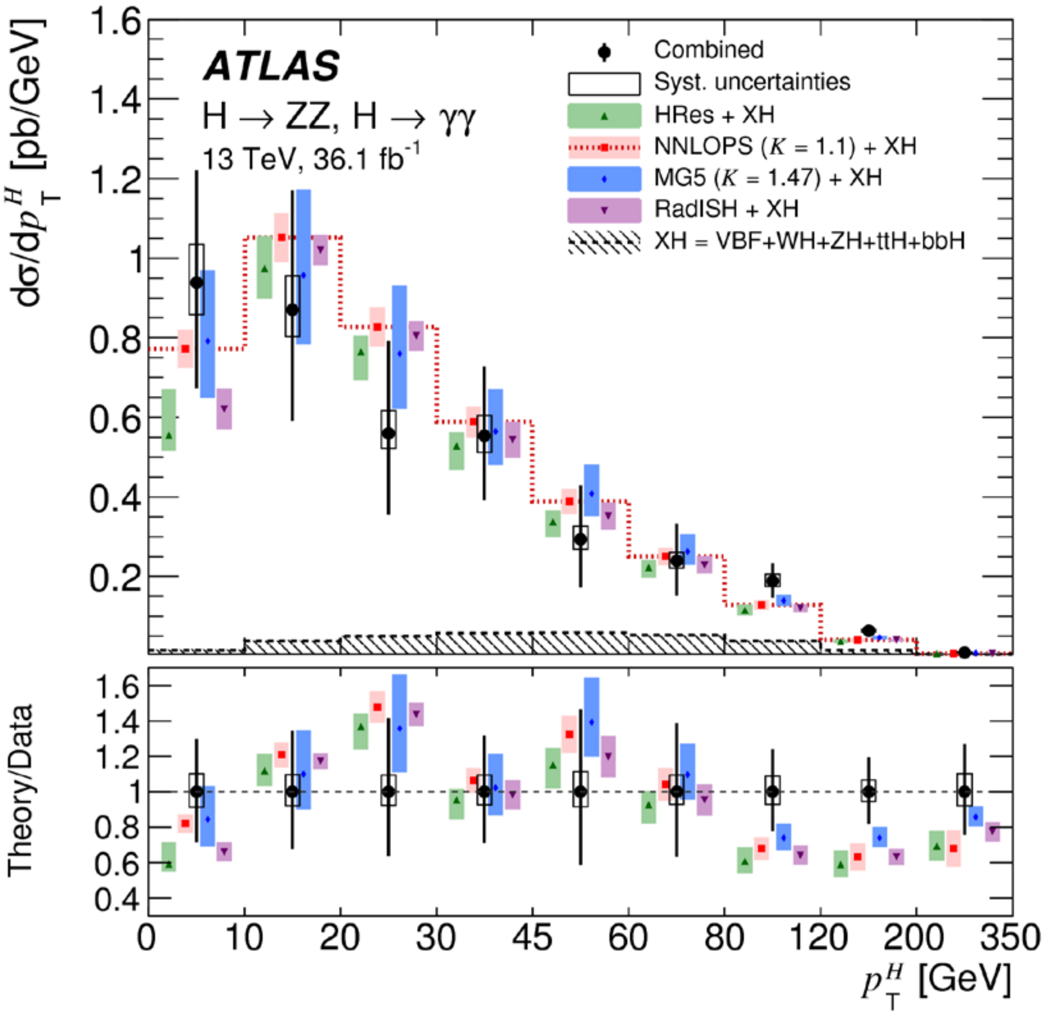
Kaili Zhang

	$5.6ab^{-1}$, 240	$2ab^{-1}$, 360	$1.5ab^{-1}$, 360
$\sigma(ZH)$	0.50%	1% ?	
$\sigma(ZH) * Br(H \to bb)$	0.27%	0.63%	0.71%
$\sigma(ZH) * Br(H \to cc)$	3.3%	6.2%	7.2%
$\sigma(ZH) * Br(H \to gg)$	1.3%	2.4%	2.7%
$\sigma(ZH) * Br(H \to WW)$	1.0%	2.0%	2.3%
$\sigma(ZH) * Br(H \to ZZ)$	5.1%	12%	14%
$\sigma(ZH) * Br(H \to \tau\tau)$	0.8%	1.5%	1.7%
$\sigma(ZH) * Br(H \to \gamma\gamma)$	5.4%	8%	9.2%
$\sigma(ZH) * Br(H \to \mu\mu)$	12%	29%	33%
$\sigma(vvH) * Br(H \to bb)$	3%	0.79%	0.91%
$Br_{upper}(H \to inv.)$	0.2%	\	\
$\sigma(ZH) * Br(H \to Z\gamma)$	16%	25%	29%
Width	2.8%	~0.8%	

- Solidify σ(ZH) precision estimate
- Combined 240 and 360 coupling analyses
- Are other Higgs decay modes in vvH useful?
- Is eeH useful?

Anything else?

Differential Distributions



A few canonical Higgs differential distributions

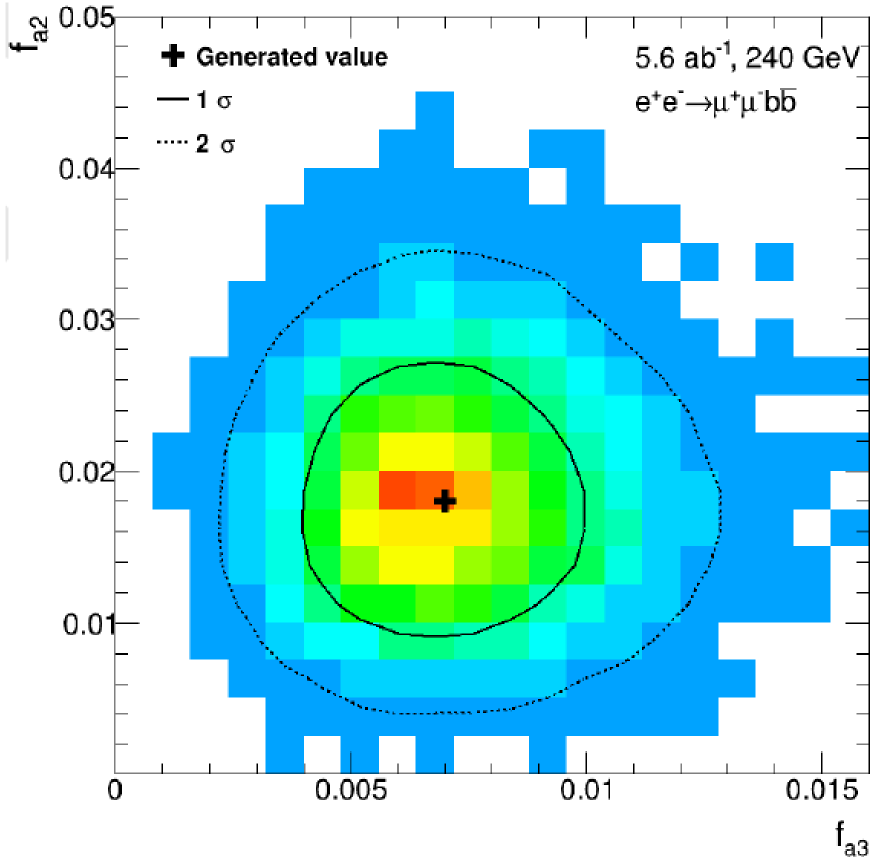
- ❖ Transverse momentum
- ❖ Polar angle

What are other important distributions?

Likely need to combine multiple analyses or through the global analysis

Higgs Boson CP Studies

Extrapolated from phenomenological studies for Higgs white paper



f_{a2} : fraction of high-order CP-even contribution due to SM or BSM physics

f_{a3} : fraction of CP-odd contribution due to BSM physics

Anything else worth doing at this point?

Discussion

Limited resources, cannot be too ambitious, need to choose a few well-defined topics which are either important or good benchmarks

- What are things that are essential?
- What are things that are nice to have?

What should be the deliverable?
An update paper? If so, what time scale?