Higgs Physics Now and Future

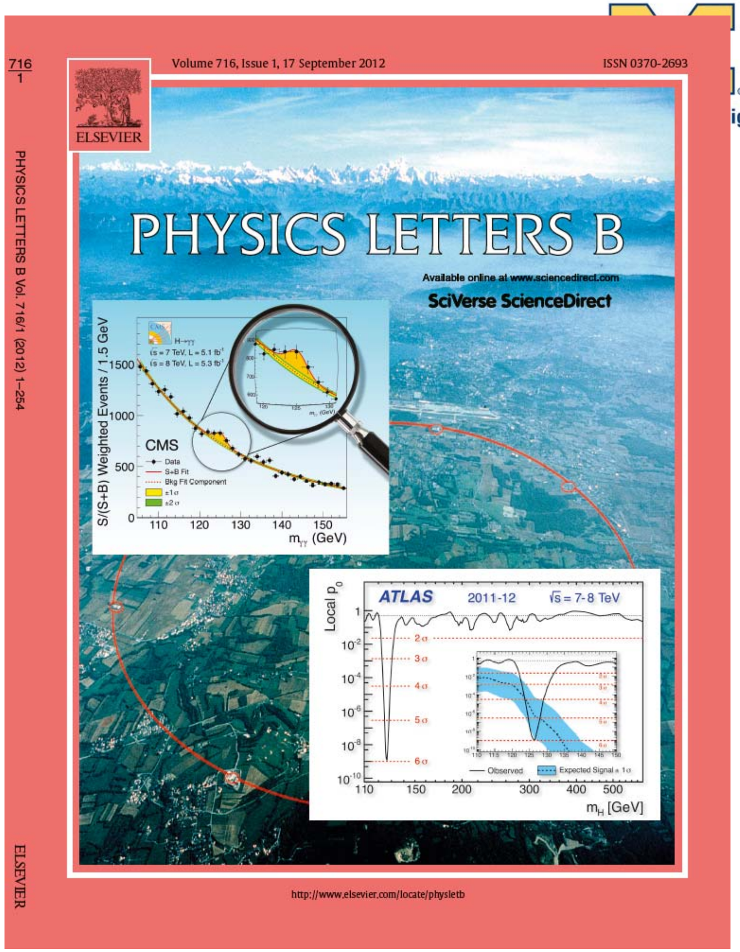
Higgs measurements now
Higgs measurements at CEPC
Notes from Higgs white paper

Jianming Qian
University of Michigan

mini-CEPC workshop, IHEP, Beijing, June 27-29, 2018

The 2012 Discovery

Seminar of July 4, 2012



Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

Phys. Lett. B716 (2012) 1

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

Phys. Lett. B716 (2012) 30

Historical Development

In 1964, three teams published proposals on how mass could arise in local gauge theories. They are now credited for the BEH mechanism and the Higgs boson.

2013 Nobel Prize!

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

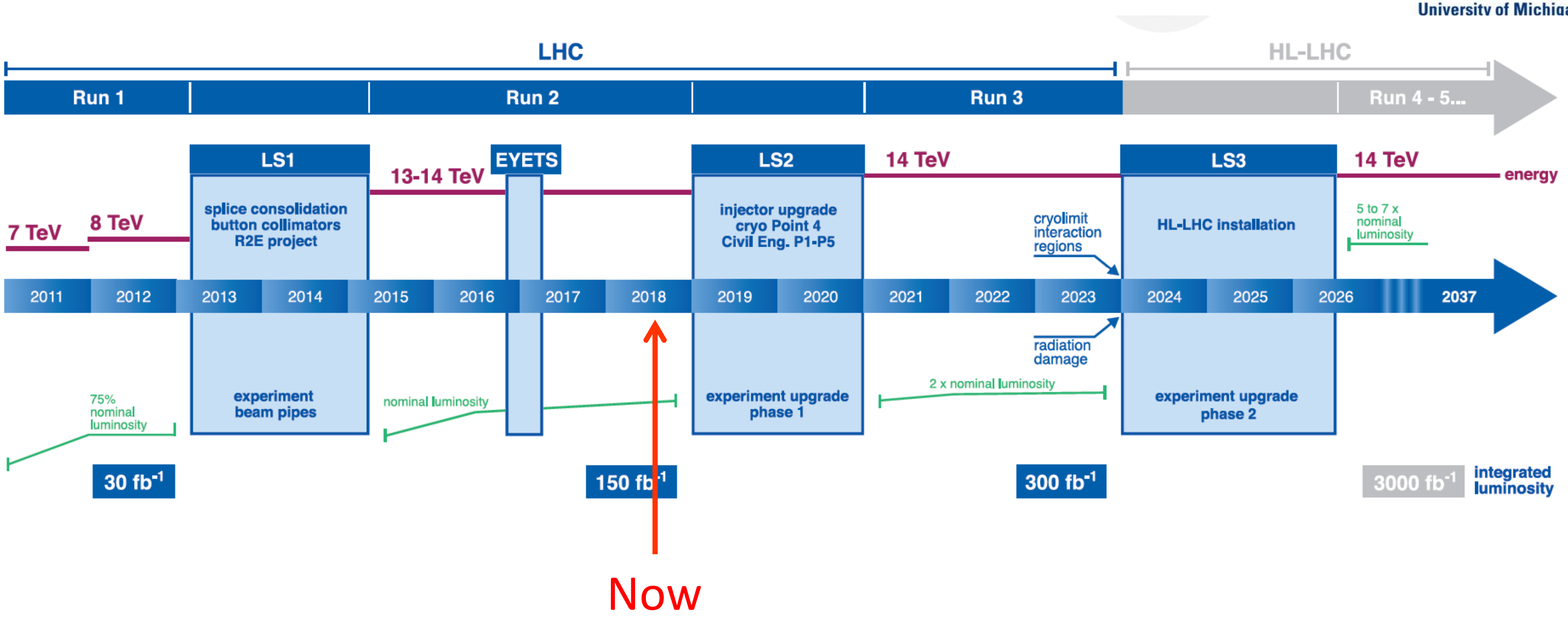
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, S
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

Francois Englert and Peter Higgs

LHC Run Plan



$$\text{Run 1: } 2011-2012,\ 7 \text{ and } 8 \text{ TeV},\ \sim 30\ \text{fb}^{-1}$$

$$\text{Run 2: } 2015-2018,\ 13 \text{ TeV},\ \sim 150\ \text{fb}^{-1}$$

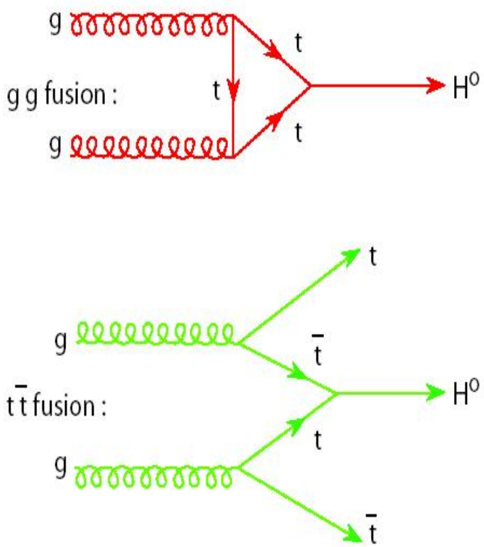
Most of the results are based on Run 1 dataset and partial Run 2 dataset (2015+2016: $\sim 35\ \text{fb}^{-1}$, 2017: $\sim 45\ \text{fb}^{-1}$)

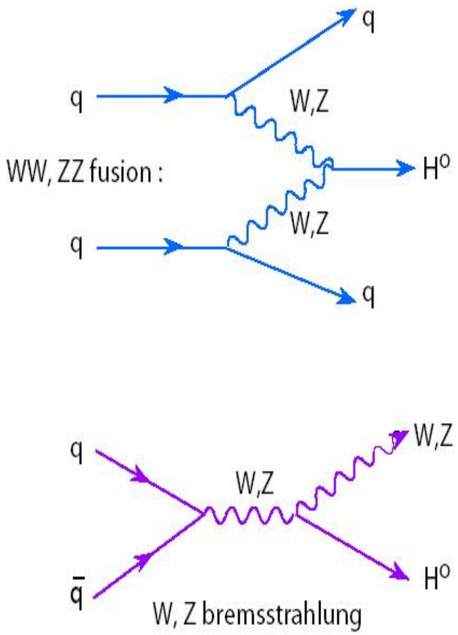
>90% of the data is yet to be taken !

Higgs Boson Production Processes

University of Michigan

Four main processes





ATLAS+CMS Run 1 Combination		
Production process	Significance (σ)	
	Expected	Observed
ggF	5+	5+
VBF	4.6	5.4
WH	2.7	2.4
ZH	2.9	2.3
VH	4.2	3.5
ttH	2.0	4.4

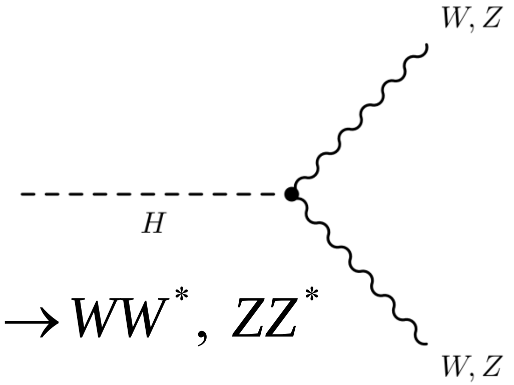
ATLAS and CMS: arXiv:1606.02266

Strong production
Fermion coupling
$y_f \propto m_f$

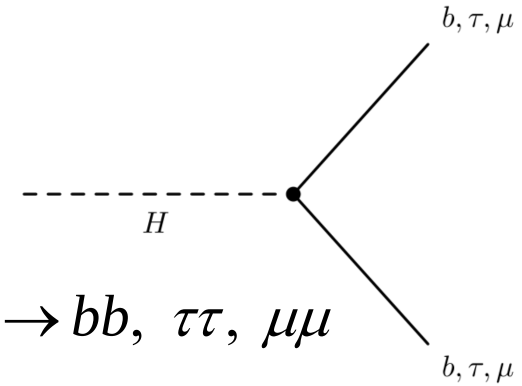
Electroweak production
Vector boson coupling
$y_V \propto m_V^2$

ggF and VBF production were observed with $> 5\sigma$ in Run 1

Higgs Boson Decay



$H \to WW^*,\ ZZ^*$

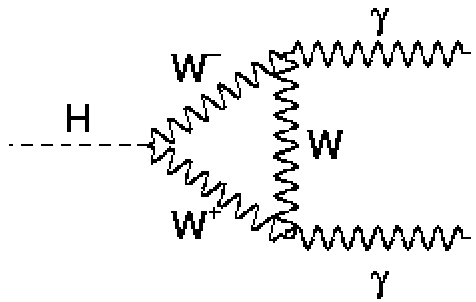


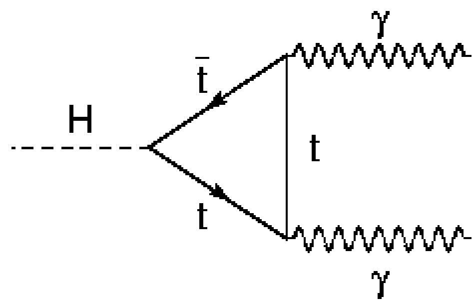
$H \to bb,\ \tau\tau,\ \mu\mu$

Higgs boson couples to particle mass
⇒ decay to heaviest particle possible

Decay mode	Branching ratio
$H \to b\bar{b}$	57.7%
$H \to c\bar{c}$	2.91%
$H \to \tau^+\tau^-$	6.32%
$H \to \mu^+\mu^-$	2.19×10^{-4}
$H \to WW^*$	21.5%
$H \to ZZ^*$	2.64%
$H \to \gamma\gamma$	2.28×10^{-3}
$H \to Z\gamma$	1.53×10^{-3}
$H \to gg$	8.57%
Γ_H	4.07 MeV

Decay through loops for massless particles.
For example: $H \to \gamma\gamma$





Higgs Boson Decays

Run 1 combination

Channel	Signal strength [μ] ATLAS	Signal strength [μ] CMS	Signal significance [σ] ATLAS	Signal significance [σ] CMS
	from results in this paper (Section 5.2)			
$H \to \gamma\gamma$	$1.14^{+0.27}_{-0.25}$ $\left(^{+0.26}_{-0.24}\right)$	$1.11^{+0.25}_{-0.23}$ $\left(^{+0.23}_{-0.21}\right)$	5.0 (4.6)	5.6 (5.1)
$H \to ZZ$	$1.52^{+0.40}_{-0.34}$ $\left(^{+0.32}_{-0.27}\right)$	$1.04^{+0.32}_{-0.26}$ $\left(^{+0.30}_{-0.25}\right)$	7.6 (5.6)	7.0 (6.8)
$H \to WW$	$1.22^{+0.23}_{-0.21}$ $\left(^{+0.21}_{-0.20}\right)$	$0.90^{+0.23}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$	6.8 (5.8)	4.8 (5.6)
$H \to \tau\tau$	$1.41^{+0.40}_{-0.36}$ $\left(^{+0.37}_{-0.33}\right)$	$0.88^{+0.30}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$	4.4 (3.3)	3.4 (3.7)
$H \to bb$	$0.62^{+0.37}_{-0.37}$ $\left(^{+0.39}_{-0.37}\right)$	$0.81^{+0.45}_{-0.43}$ $\left(^{+0.45}_{-0.43}\right)$	1.7 (2.7)	2.0 (2.5)
$H \to \mu\mu$	$-0.6^{+3.6}_{-3.6}$ $\left(^{+3.6}_{-3.6}\right)$	$0.9^{+3.6}_{-3.5}$ $\left(^{+3.3}_{-3.2}\right)$		

Bosons $> 5\sigma$

Fermions $< 5\sigma$

ATLAS and CMS: arXiv:1606.02266

ATLAS and CMS Run 1 Summary

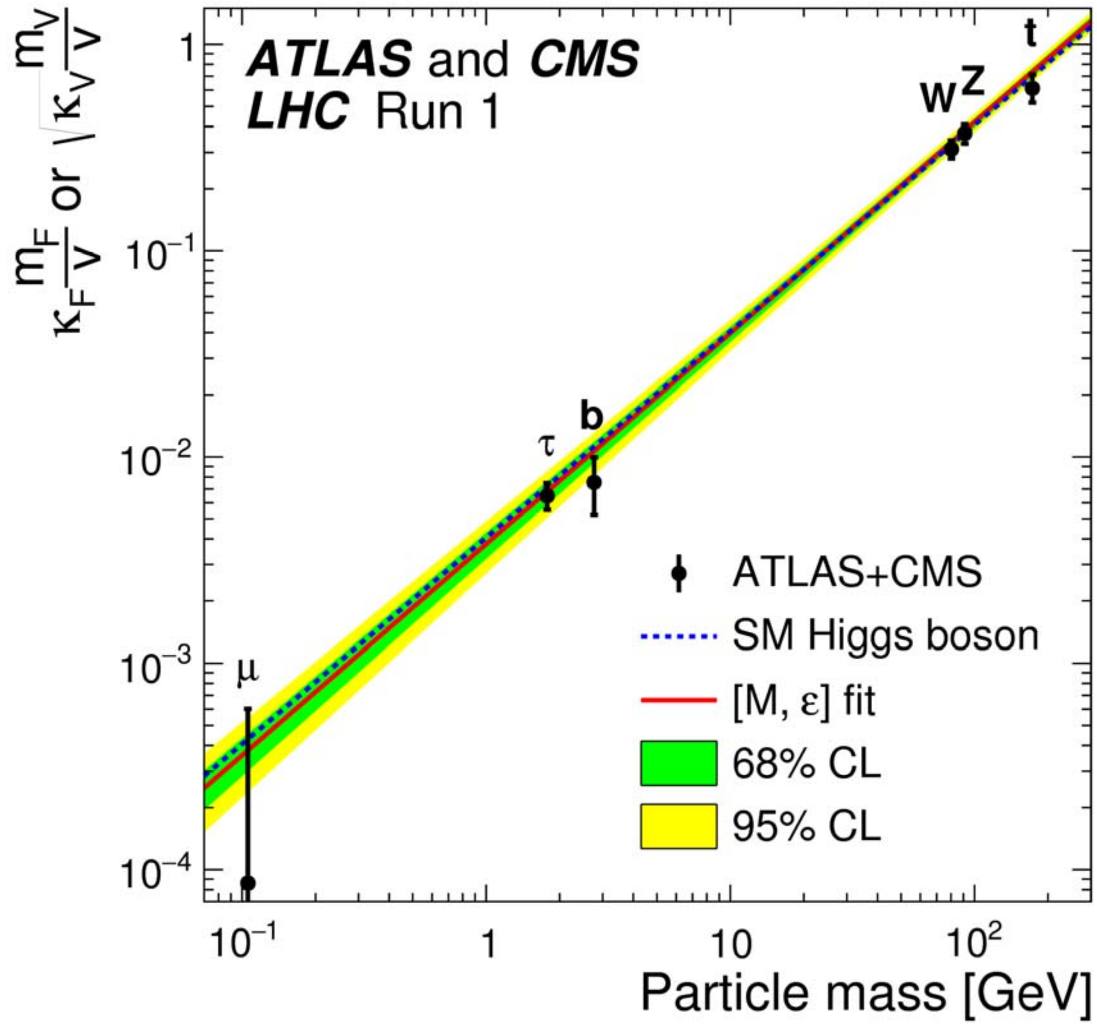
$$g_{Hff} = \frac{\sqrt{2}m_f}{\upsilon},$$

$$g_{HVV} = \frac{2m_V^2}{\upsilon}$$

$$\Downarrow$$

$$g_{Hff} = \boxed{\kappa_F} \cdot \frac{\sqrt{2}m_f}{\upsilon},$$

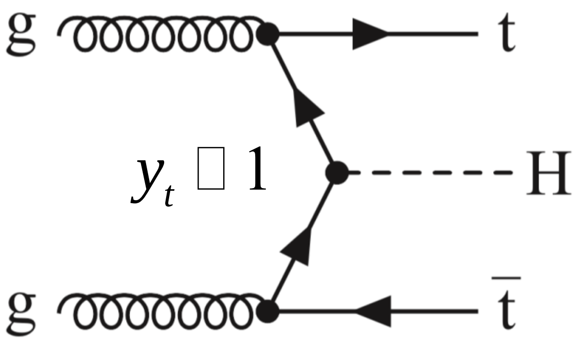
$$g_{HVV} = \boxed{\kappa_V} \cdot \frac{2m_V^2}{\upsilon}$$



Measured couplings are very Standard Model like

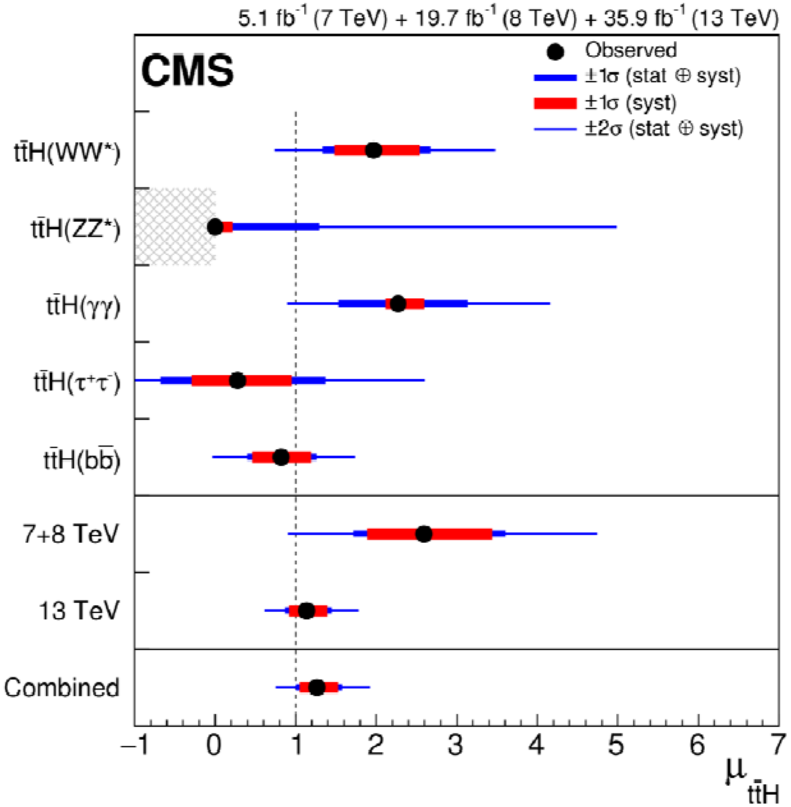
ATLAS & CMS: JHEP 08 (2016) 04

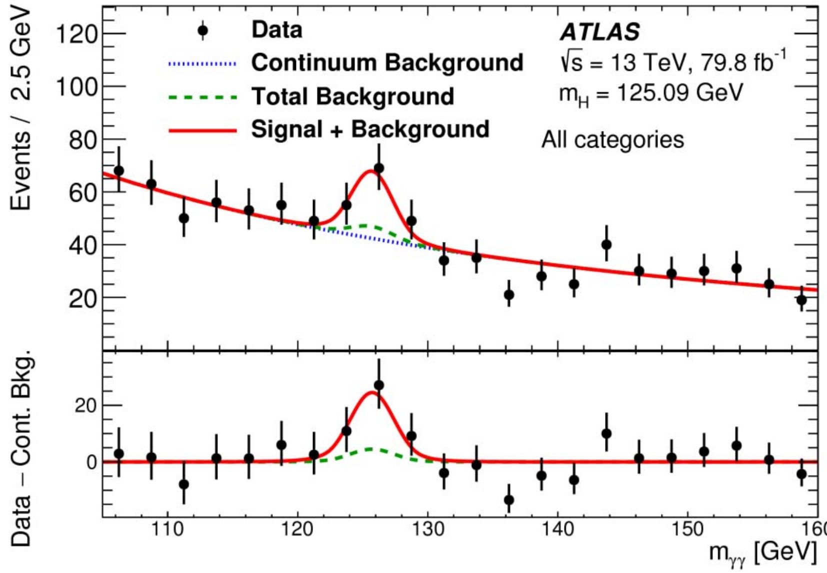
Observation of ttH Production



$$\text{CMS: } \mu = 1.26^{+0.31}_{-0.26} \; (8+13 \text{ TeV data})$$
$$5.2\sigma(4.2\sigma) \text{ observed (expected)}$$
$$\text{ATLAS: } \mu = 1.32^{+0.28}_{-0.26} \; (13 \text{ TeV data only})$$
$$5.8\sigma(4.9\sigma) \text{ observed (expected)}$$

CMS: PRL 120 (2018) 231801





ATLAS: 1806.00425

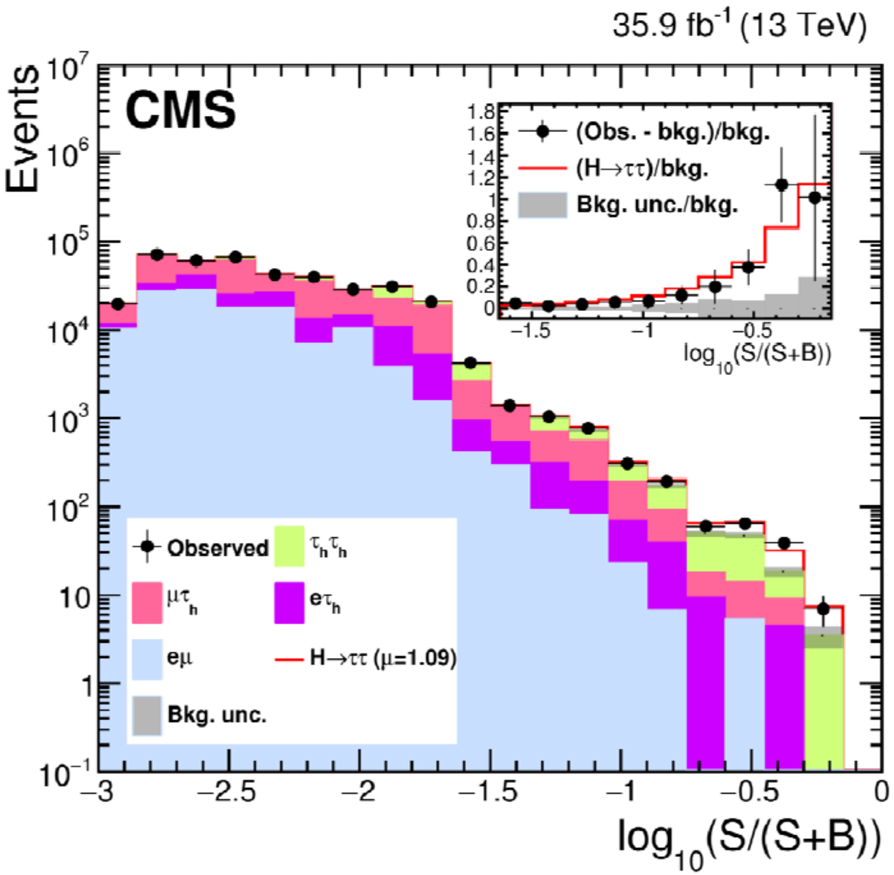
$H \rightarrow \tau\tau$ decay

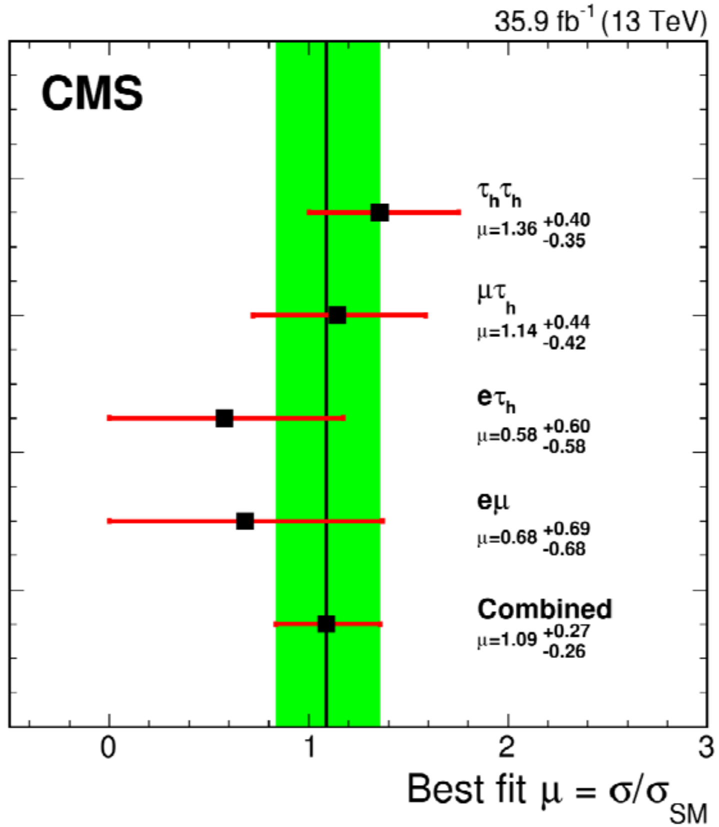
Run 1 + Run 2

Observation from both experiments:

ATLAS: $6.4\sigma\,(5.4\sigma)$ observed (expected)

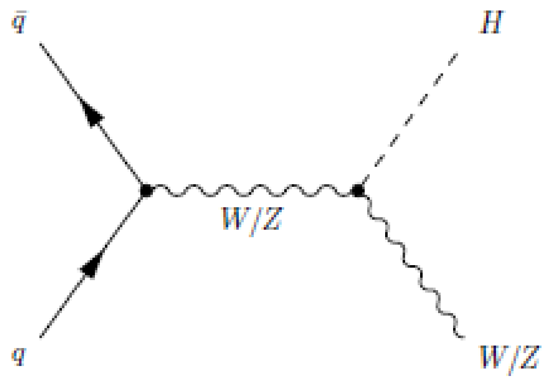
CMS: 5.9 observed





ATLAS: ATLAS-CONF-2018-021; CMS: PLB 779 (2018) 283

VH Production with *H→bb* decay

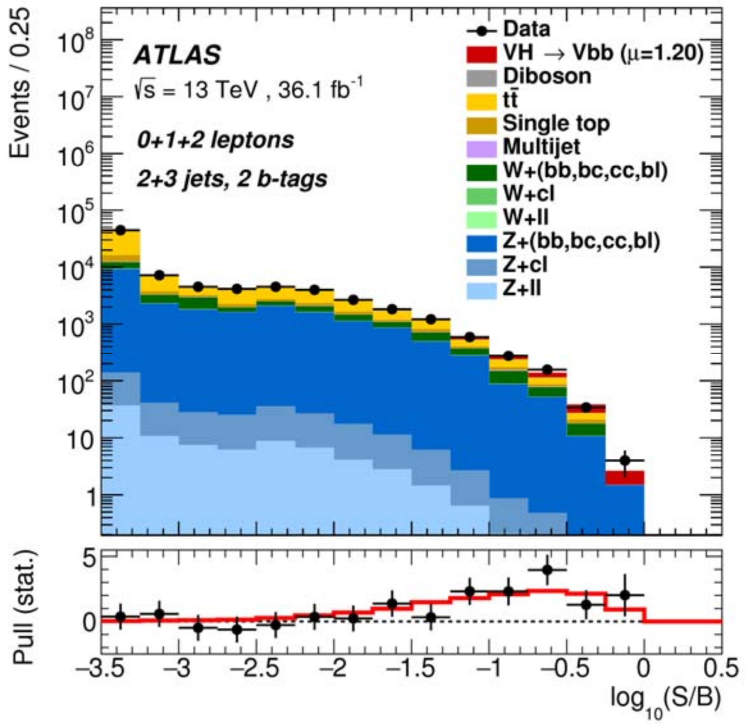


Run 1 + Run 2

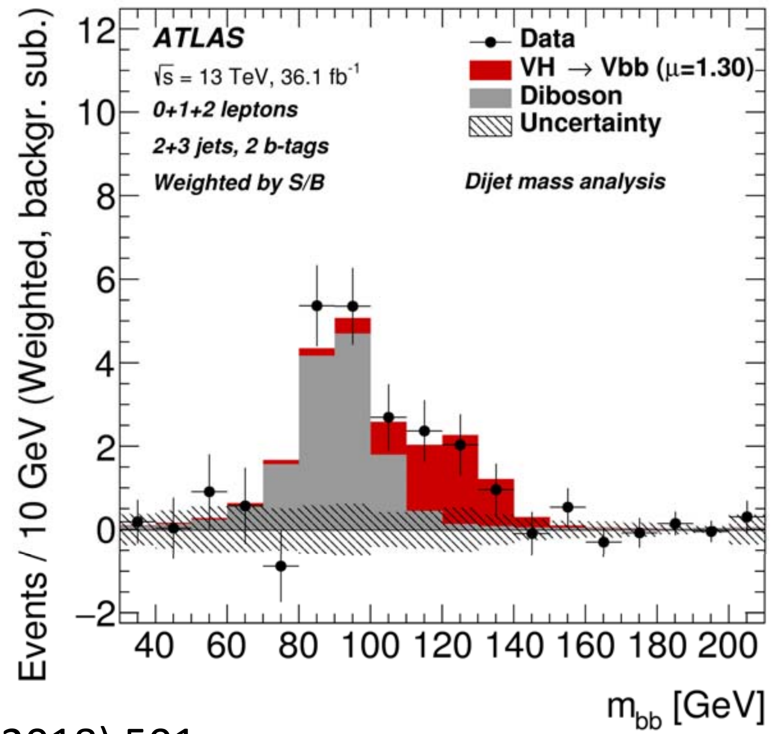
Evidences from both experiments:

ATLAS: $3.6\sigma(4.0\sigma)$ observed (expected)

CMS: $3.8\sigma(3.8\sigma)$ observed (expected)



VZ/VH with $Z/H \to bb$



ATLAS: JHEP 12 (2017) 024; CMS: PLB 780 (2018) 501

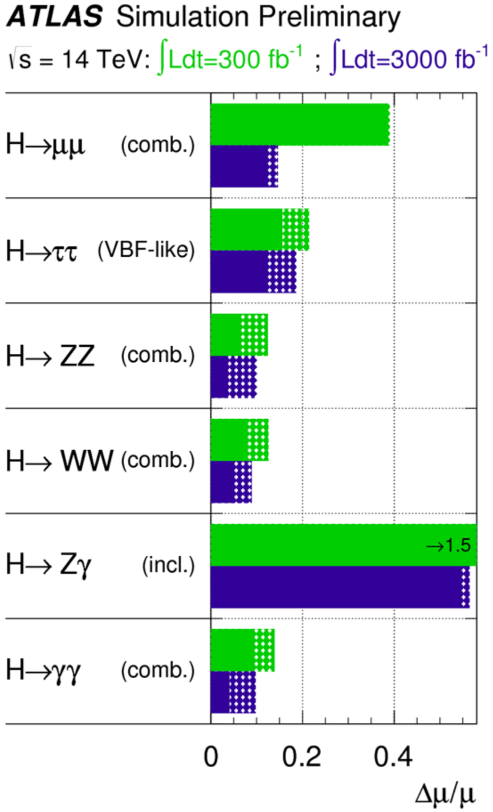
HL-LHC Coupling Projections

University of Michigan

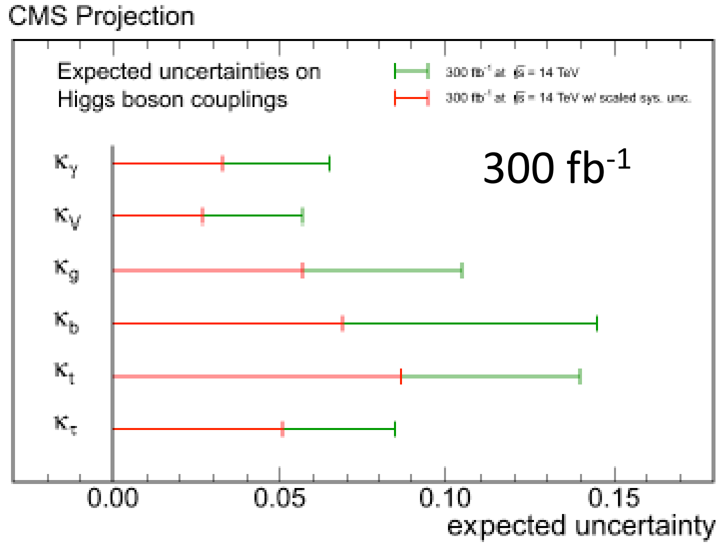
Many studies done for US Snowmass process, Europe ECFA studies.

150 millions of Higgs bosons produced per experiment

Snowmass Higgs report, arXiv:1310.8361



(Based on parametric simulation)



(Extrapolated from 2011/2012 results)

Two assumptions on systematics:

1. no change

2. $\Delta(\text{theory})/2$, rest $\propto 1/\sqrt{Lumi}$

Even with the projected precisions at HL-LHC, the couplings are not expected to be constrained better than □ 5%.

Cases for a Precision Higgs Program

University of Michigan

How large are potential deviations from BSM physics? How well do we need to measure them to be sensitive?

To be sensitive to a deviation Δ, the measurement precision needs to be much better than Δ, at least $\Delta/3$ and preferably $\Delta/5$!

Since the couplings of the 125 GeV Higgs boson are found to be very close to SM $\Rightarrow$ deviations from BSM physics must be small.

Typical effect on coupling from heavy state M or new physics at scale M:

$$\Delta \,\square\, \left(\frac{\upsilon}{M}\right)^2 \,\square\, 6\% \text{ @ } M \,\square\, 1 \text{ TeV}$$

(Han et al., hep-ph/0302188, Gupta et al. arXiv:1206.3560, …)

MSSM decoupling limit

Δ at sub-percent to a few percent, will be challenging to distinguish the MSSM decoupling limit from the SM in the case of no direct discovery.

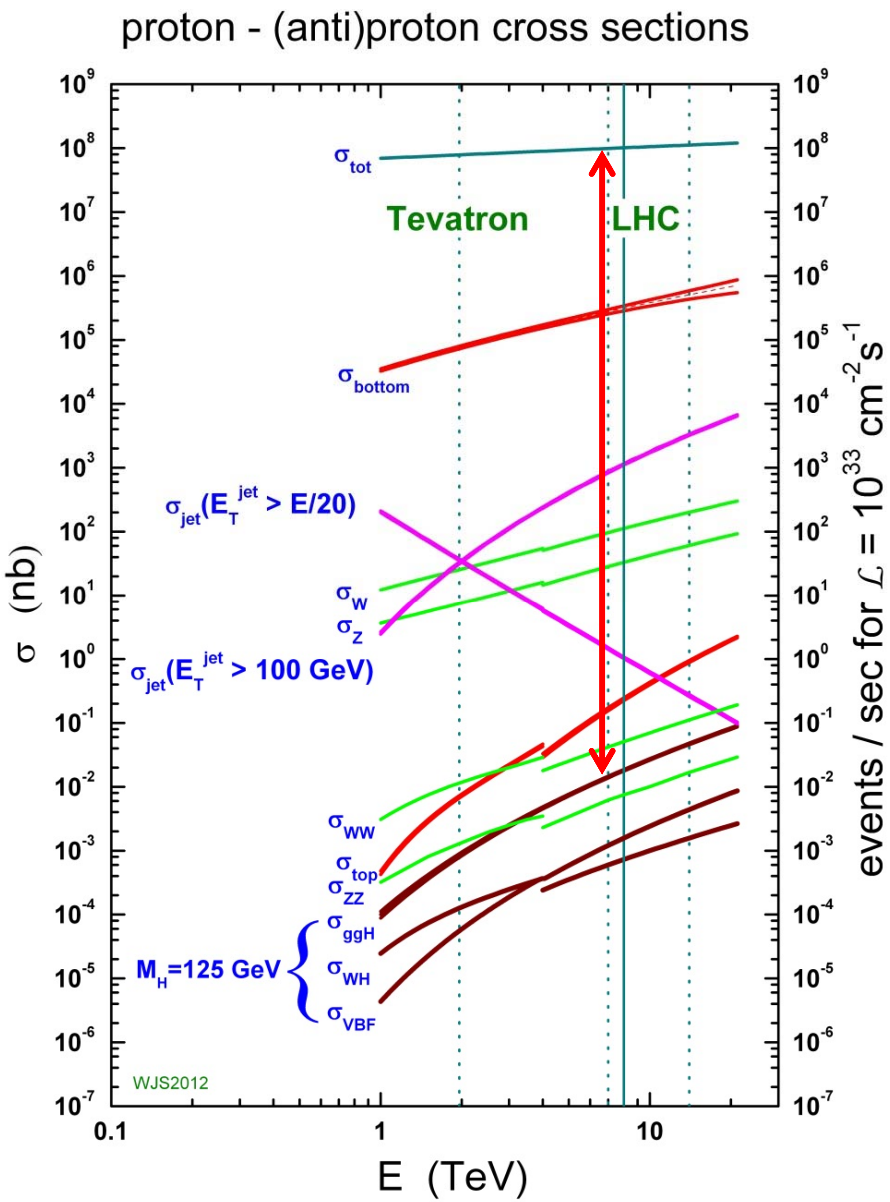
$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} \simeq 1 - 0.3\% \left(\frac{200\ \text{GeV}}{m_A}\right)^4$$
$$\frac{g_{htt}}{g_{h_{\rm SM}tt}} = \frac{g_{hcc}}{g_{h_{\rm SM}cc}} \simeq 1 - 1.7\% \left(\frac{200\ \text{GeV}}{m_A}\right)^2$$
$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 40\% \left(\frac{200\ \text{GeV}}{m_A}\right)^2.$$

(ILC DBDPhysics)

$\Rightarrow$ Need percent-level or better measurements!

Hadron Colliders

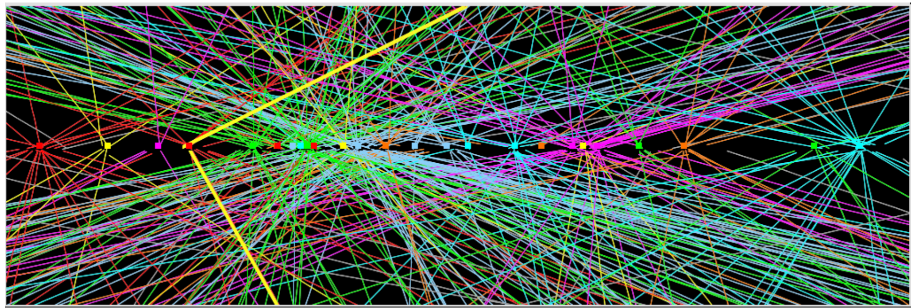
University of Michigan



Huge background

- QCD production dominates σ
- tiny S/B ratio: $\sigma_h / \sigma_{tot} \sim 10^{-11}$
- unknow event level $\sqrt{\hat{s}}$
- messy collision environment

Trigger is the key!



On the other hand…

- broad band in $\sqrt{\hat{s}}$
- much large Higgs cross section

HL-LHC will deliver 150 millions of Higgs events per experiment !

e^+e^- Collider

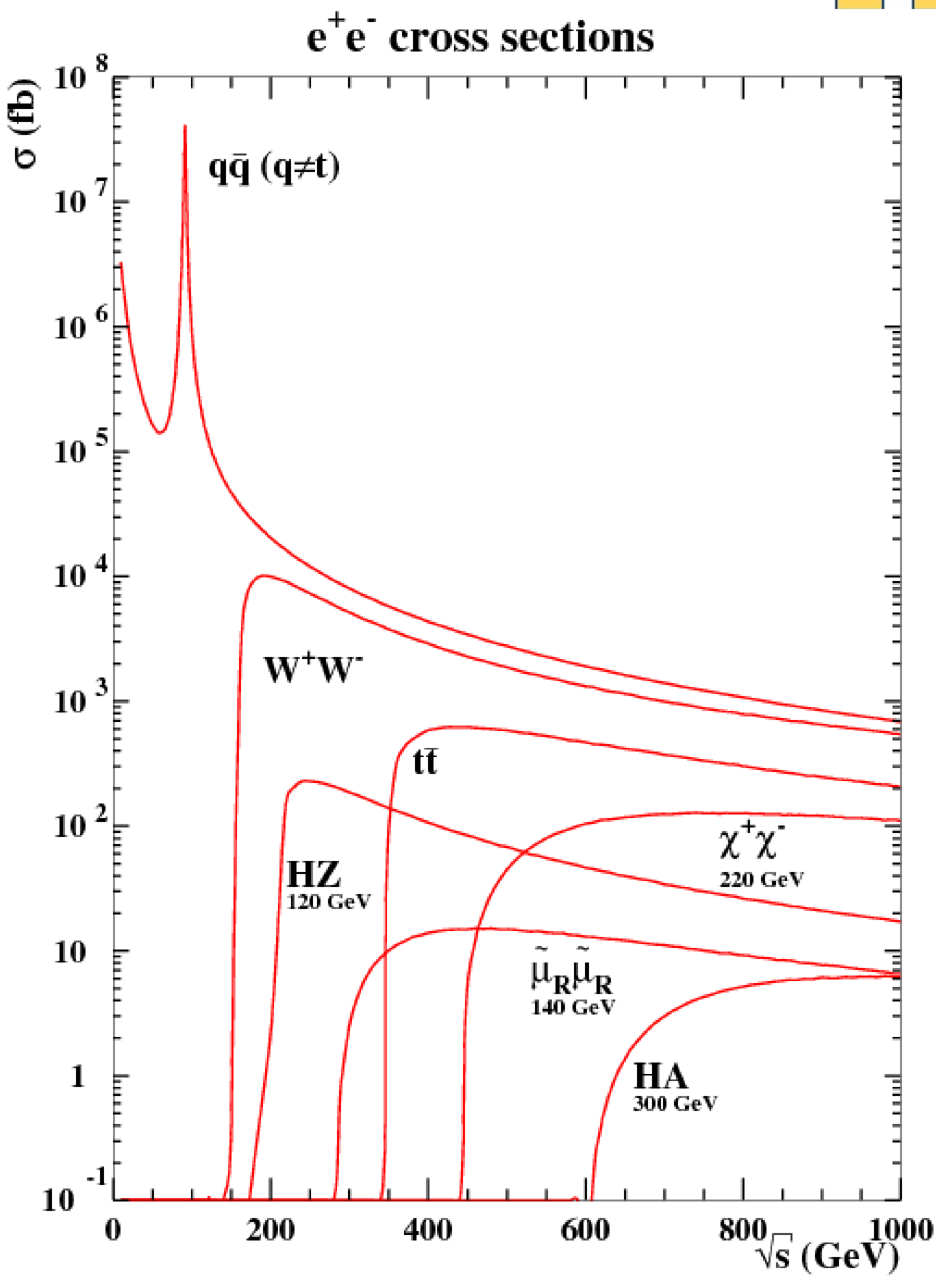
Electroweak production
cross sections are predicted with (sub)percent level precisions in most cases

Relative low rate
can trigger on every event

Well defined collision energy
allow for the “missing” mass reconstruction (*eg* recoiling mass)

Clean events, smaller background
small number of processes

Lepton colliders have unique role in precision measurements

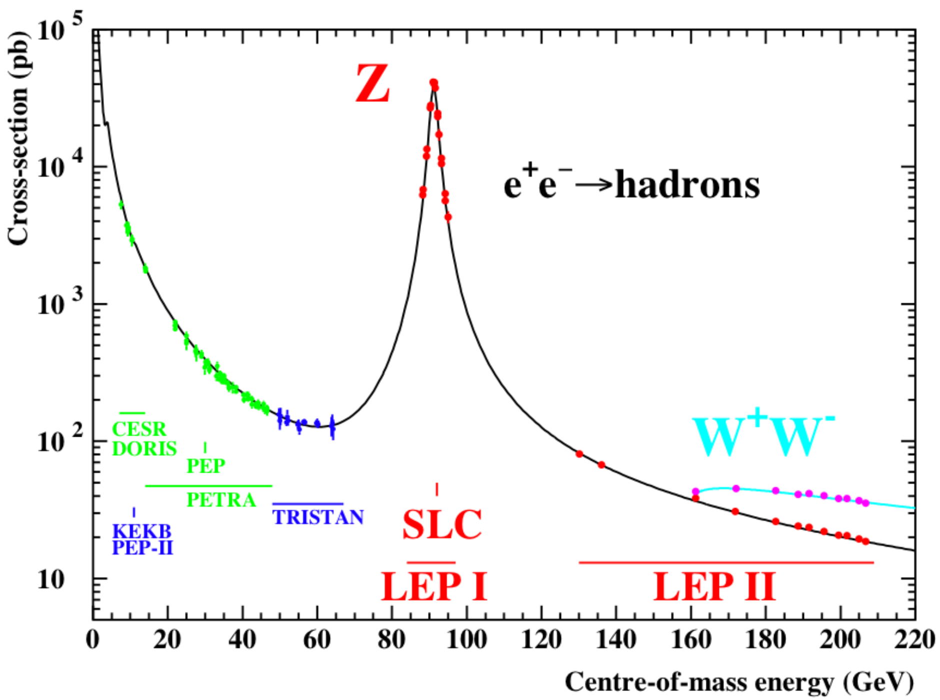


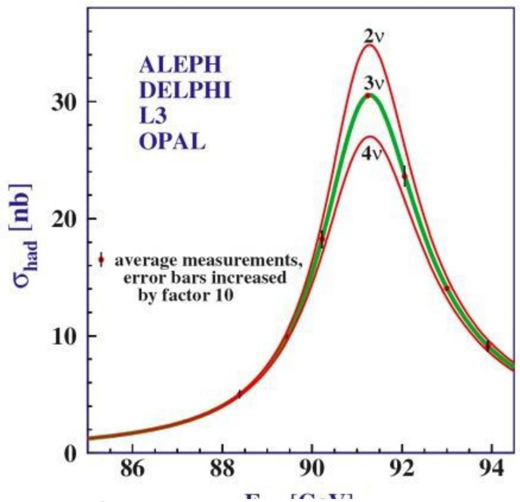
A Success Story: LEP

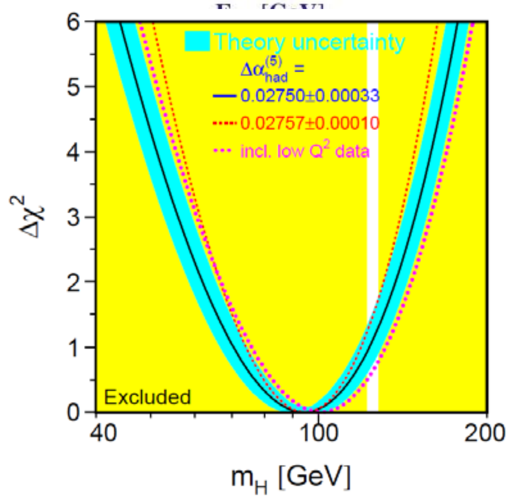
LEP-1 was first built as a Z factory (though it initially had top quark in sight), it was widely successful…

About 17 millions of Z bosons were produced, key physics

- Number of light neutrino species;
- Precision electroweak measurements;
- Direct search and indirect constraint on the Higgs boson; ...



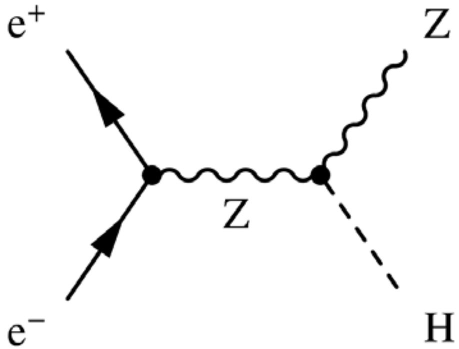


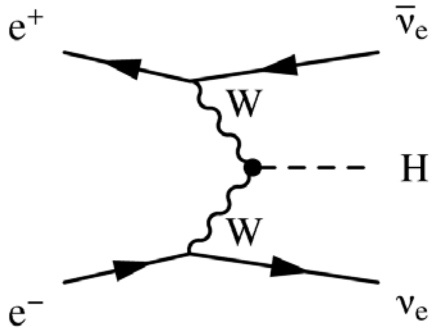


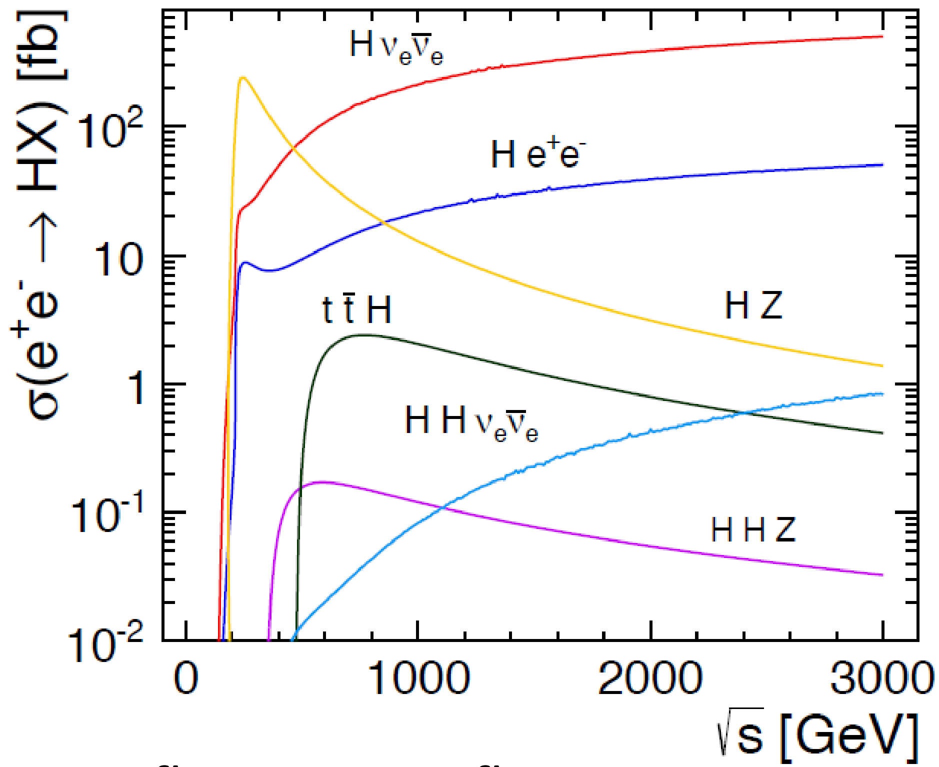
Higgs Boson Production

At $\sqrt{s}$ □ $240-250$ GeV, $ee \to ZH$ production is maximum and dominates with a smaller contribution from $ee \to \nu\nu H$.

Beyond that, the cross section decreases asymptotically as $1/s$ for $ee \to ZH$ and increases logarithmically for $ee \to \nu\nu H$.







$\sqrt{s} = 250$ GeV: $\sigma_{ZH} \approx 200$ fb, $\sigma_{\nu\nu H} \approx 10$ fb

Cross Sections and Event Rates

Process	Cross section	Events in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\bar{\nu}H$	6.72	3.36×10^4
$e^+e^- \to e^+e^-H$	0.63	3.15×10^3
Total	219	1.10×10^6
Background processes, cross section in pb		
$e^+e^- \to e^+e^-$ (Bhabha)	25.1	1.3×10^8
$e^+e^- \to q\bar{q}\,(\gamma)$	50.2	2.5×10^8
$e^+e^- \to \mu^+\mu^-\,(\gamma)$ [or $\tau^+\tau^-\,(\gamma)$]	4.40	2.2×10^7
$e^+e^- \to WW$	15.4	7.7×10^7
$e^+e^- \to ZZ$	1.03	5.2×10^6
$e^+e^- \to e^+e^-Z$	4.73	2.4×10^7
$e^+e^- \to e^+\nu W^-/e^-\bar{\nu}W^+$	5.14	2.6×10^7

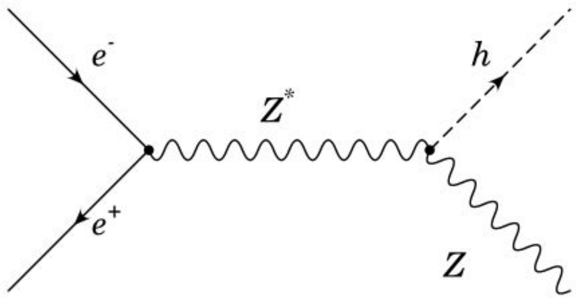
Know your process

For energy above the threshold, $ee \to ZH$ has a Born-level cross section:

$$\sigma\left(e^+e^- \to ZH\right) = \frac{\left(G_F M_Z^2\right)^2}{3\pi}\left(V_e^2 + A_e^2\right)\cdot\frac{3M_Z^2 + p^2}{\left(s - M_Z^2\right)^2}\cdot\frac{p}{\sqrt{s}}$$

$\Rightarrow \sigma \approx 238$ fb at $\sqrt{s} = 250$ GeV

where p is the momentum of Z or H boson:



$$p^2 = \frac{1}{4s}\left(s^2 + M_Z^4 + M_H^4 - 2sM_Z^2 - 2sM_H^2 - 2M_Z^2 M_H^2\right)$$

Moreover, the energies of the Z and Higgs bosons are given by

$$E_Z = \frac{s + m_Z^2 - m_H^2}{2\sqrt{s}} \quad \text{and} \quad E_H = \frac{s + m_H^2 - m_Z^2}{2\sqrt{s}}$$

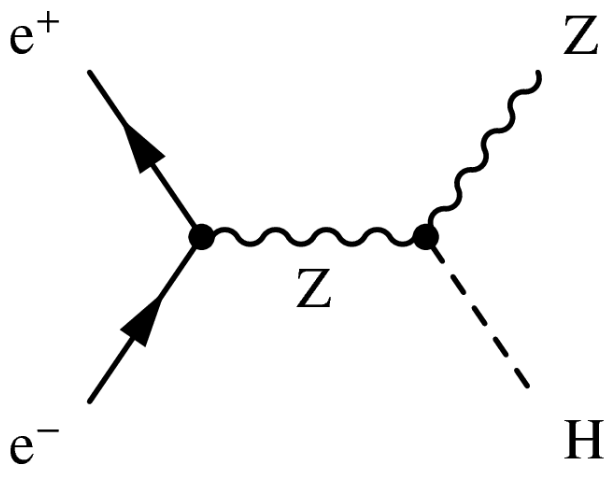
At $\sqrt{s} = 250$ GeV ($m_Z = 91.2$ GeV, $m_H = 125$ GeV):

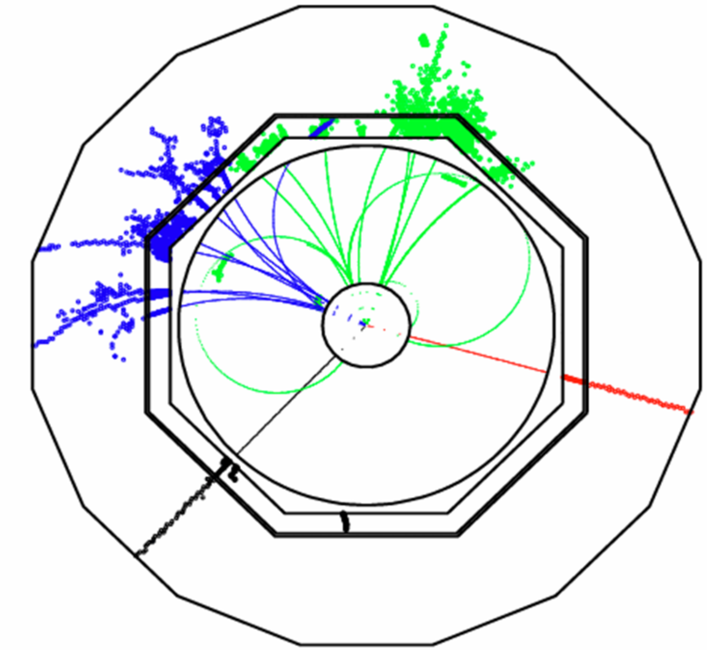
$E_Z = 110.4$ GeV, $E_H = 139.6$ GeV and $p = 62.2$ GeV

The energy and momentum of the Z and H bosons are fixed. However, both radiations and Z boson width will change these values.

Higgs Tagging

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: $E_H = \sqrt{s} - E_Z$, $\vec{p}_H = -\vec{p}_Z$





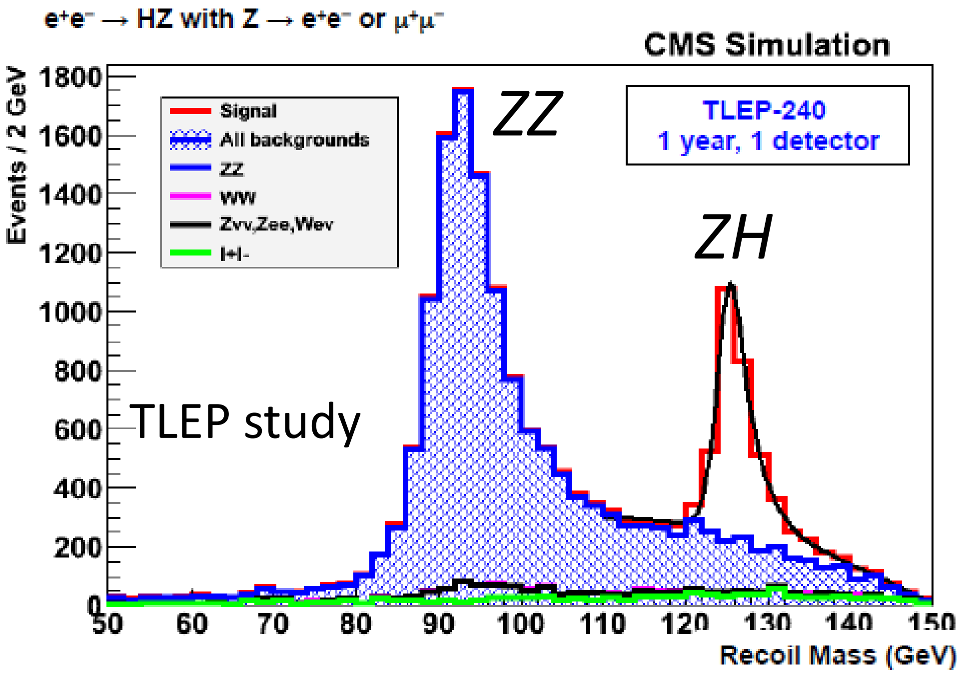
Recoil mass reconstruction:

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

$\Rightarrow$ identify Higgs without looking at Higgs.

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

Recoiling Mass Distributions

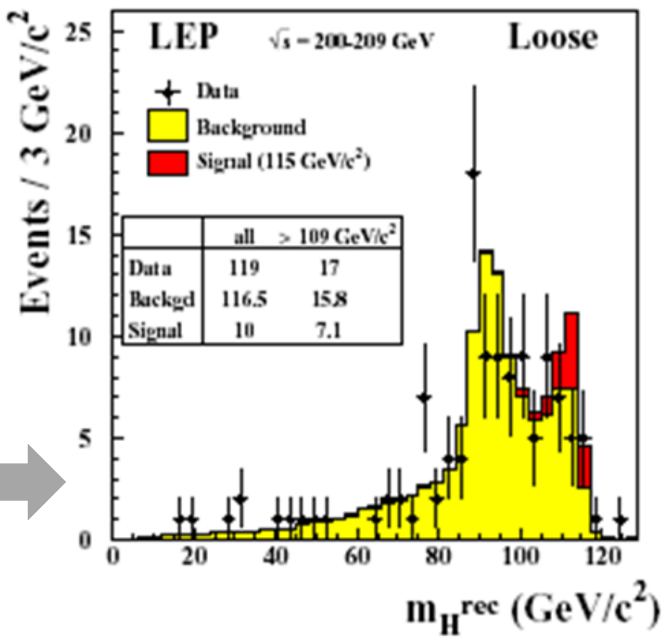


Good recoil mass resolution for $Z \to \ell\ell$

A perfect validation sample in $ZZ \to \ell\ell + X$

ZH : detector resolution dominates the width, radiation dominates the tail

Utilized extensively for Higgs searches at LEP



Accessible Decay Modes

Numbers of Higgs events: □ 10^6 at Higgs factories, □ 10^8 at HL-LHC

SM decay		Accessible?	
mode	branching ratio	(HL-)LHC	Higgs factories
$H \to bb$	57.7%	✓, × *	✓
$H \to gg$	8.57%	×	✓
$H \to cc$	2.91%	×	✓
$H \to ss$	2.46×10^{-4}	×	?
$H \to \tau\tau$	6.32%	✓	✓
$H \to \mu\mu$	2.19×10^{-4}	✓	✓
$H \to WW$	21.5%	✓	✓
$H \to ZZ$	2.64%	✓	✓
$H \to \gamma\gamma$	0.23%	✓	✓
$H \to Z\gamma$	0.15%	✓	✓

* Not all production mode.

Limitations: statistics at Higgs factories,
trigger and systematics at (HL-)LHC

Higgs factories are sensitive to *unknown unknown* decays while HL-LHC *may* be sensitive to *known unknown* decays (*eg H→inv*).

pre-CDR and CDR Comparison

University of Michigan

Comparisons of pre-CDR and CDR estimates

Measurement	pre-CDR	CDR
ΔM_H	5.5 MeV	0.5 MeV
σ_{ZH}	0.5%	0.5%
$\sigma_{ZH} \times \mathrm{BR}(H \to bb)$	0.28%	0.29%
$\sigma_{ZH} \times \mathrm{BR}(H \to cc)$	2.2%	3.5%
$\sigma_{ZH} \times \mathrm{BR}(H \to gg)$	1.6%	1.4%
$\sigma_{ZH} \times \mathrm{BR}(H \to \tau\tau)$	1.2%	0.8%
$\sigma_{ZH} \times \mathrm{BR}(H \to \mu\mu)$	17%	16%
$\sigma_{ZH} \times \mathrm{BR}(H \to WW)$	1.5%	1.0%
$\sigma_{ZH} \times \mathrm{BR}(H \to ZZ)$	4.3%	5.0%
$\sigma_{ZH} \times \mathrm{BR}(H \to \gamma\gamma)$	9.0%	8.2%
$\sigma_{ZH} \times \mathrm{BR}(H \to Z\gamma)$		21%
$\mathrm{BR}_{\mathrm{BSM}}(H \to \mathrm{inv})$	0.28%	0.32%

Worse: $H \to cc$, $H \to ZZ$, Improved: $H \to \tau\tau$

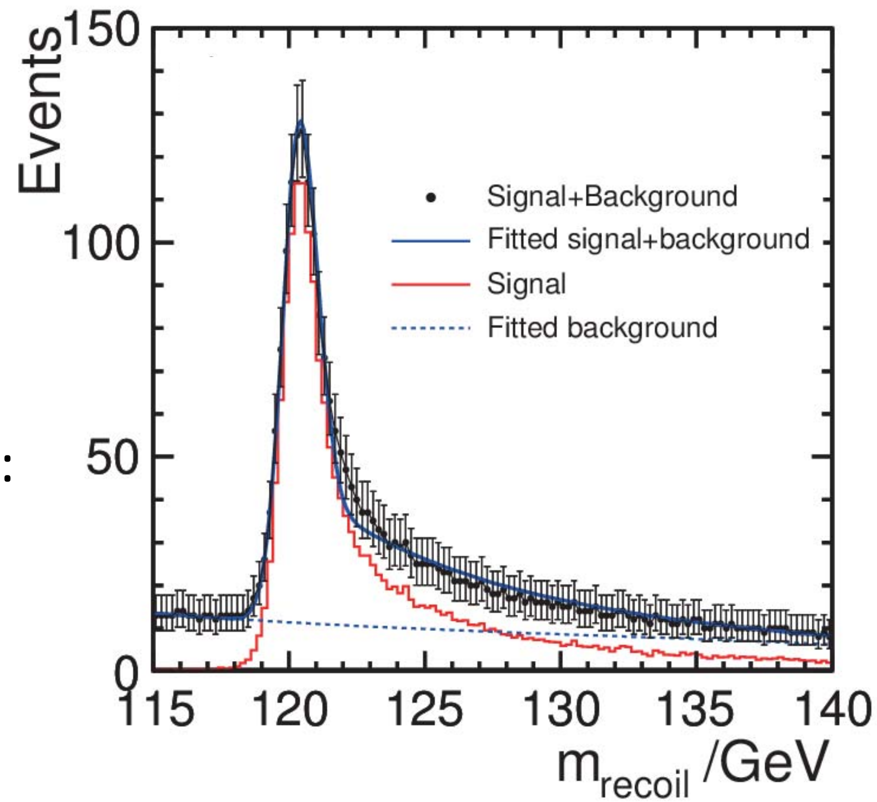
Sensitivity Estimates

The goal of CEPC studies is to estimate expected precision on physical quantifies of interest, not the values of physical quantities.

- The central values or distributions should always be the those expected in the model of interest.
- Estimate the statistical and systematic uncertainties expected from CEPC

Ideally, MC statistics should be far greater than the expected data statistics to minimize fluctuations as illustrated by the plot on the right:

- The histogram is smooth from large MC statistics;
- The error bars are expected uncertainties from expected data (not MC) statistics



Event Selections

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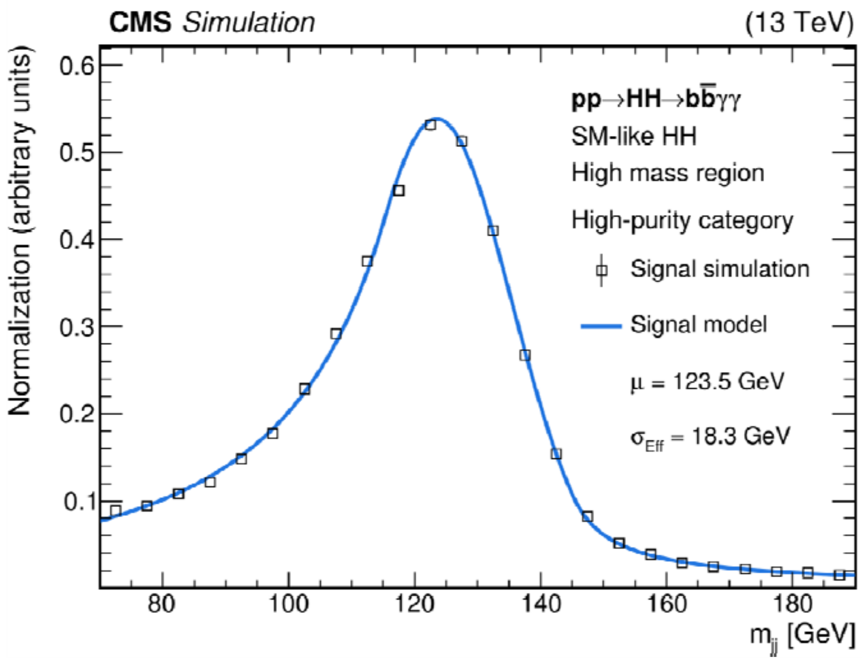
- Know your signal and background processes: what are their most important differences, what are key detector performance requirements, …
  Example: $\nu\nu H$ and $Z(\nu\nu)H$, the missing mass has a continuum distribution for the former and a resonance structure for the later.
- Selections should be logical (and factorized if possible), cuts should be simple and easy to explain;
- Should always have a cut-flow table of expected events or cross sections, plot distributions of key variables before cutting on them
- Consider to use MVAs to explore subtle S/B differences and use shape information to improve sensitivities
- Every analysis should have at least one PR/money plot!
  Some are obvious: $m_{\gamma\gamma}$ distribution for $H\rightarrow\gamma\gamma$ analysis;
  Some are more complicated:

Examples

CMS $HH \to bb\gamma\gamma$ search:

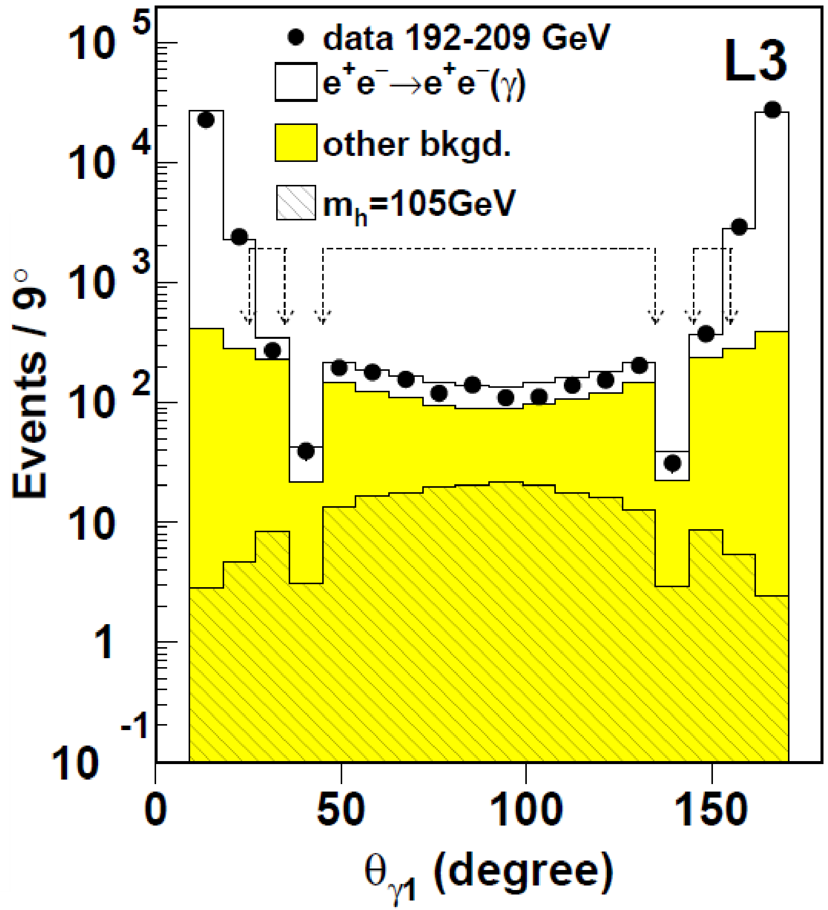
$\gamma\gamma$+jets is the main background with continuum $\gamma\gamma$ and *jj* mass distributions compared with resonant distributions of the signal.

$\Rightarrow$ critical to understand the $m_{\gamma\gamma}$ and m_{bb} resolutions.



L3 $H \to \gamma\gamma$ search:

Compare distributions of signal and background of the variable before cutting on it.



Examples

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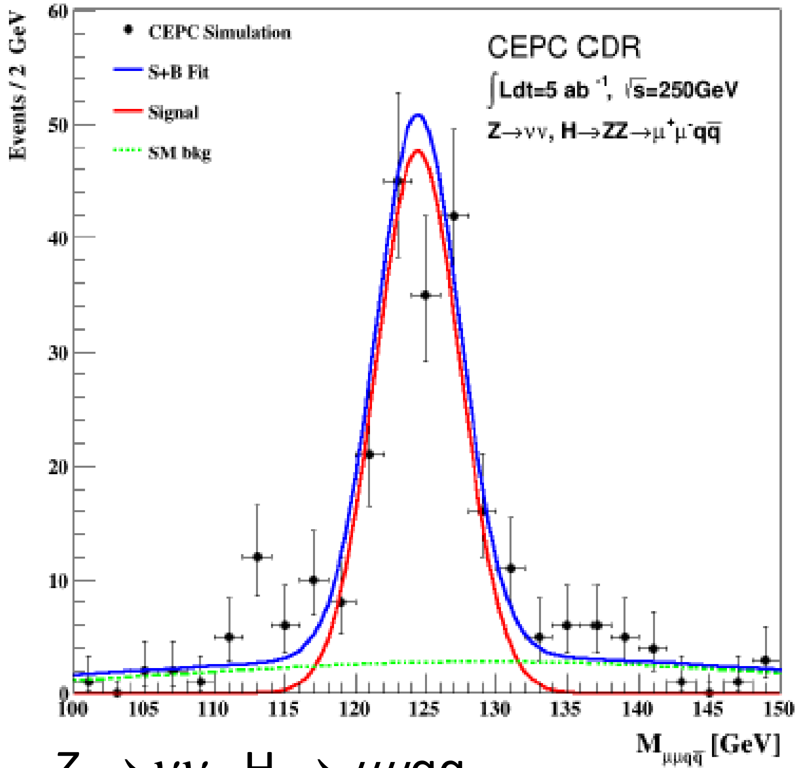
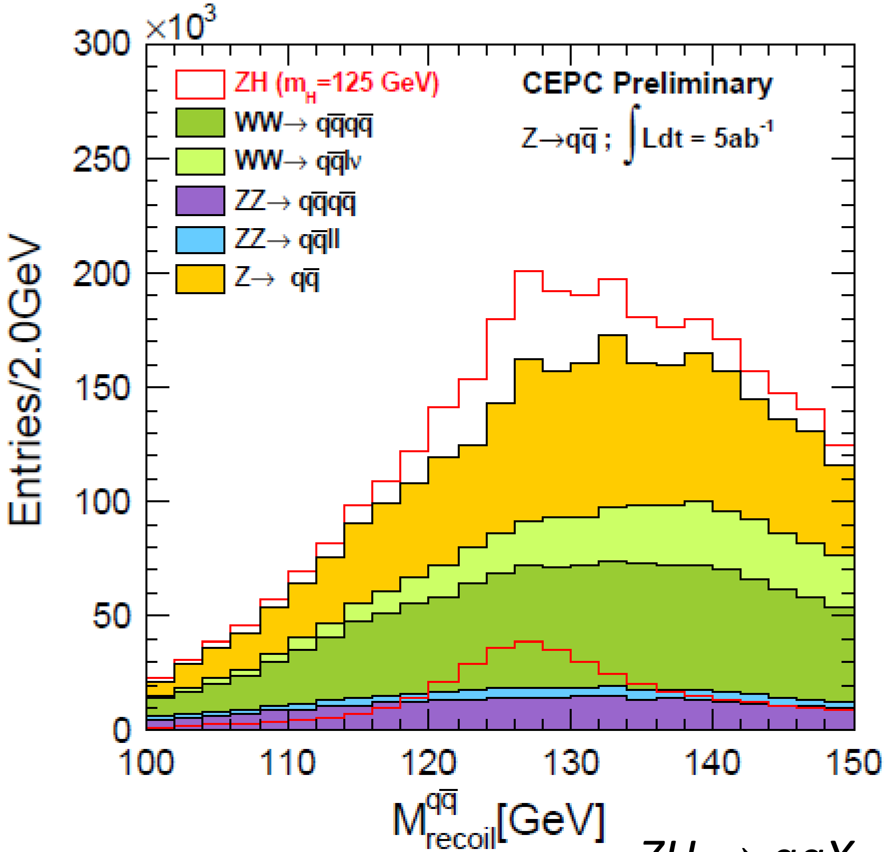


$Z \to \nu\nu$, $H \to \mu\mu qq$



$ZH \to qqX$

This analysis suffers from low MC statistics, resulting in large fluctuations unrelated to the expected data statistics.

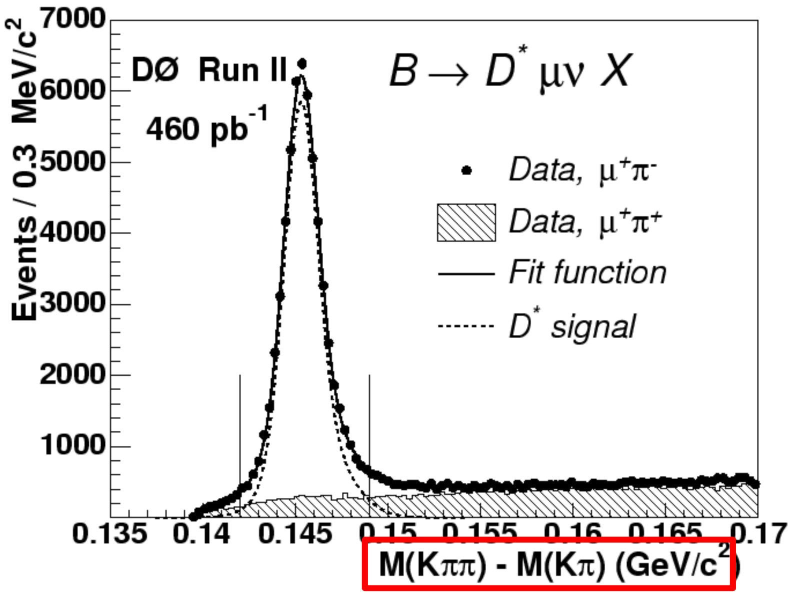
Consider smearing or fit the distribution to generate Asimov data if increasing MC statistics is not practical.

The upper range of this plot should be extended to show more sidebands

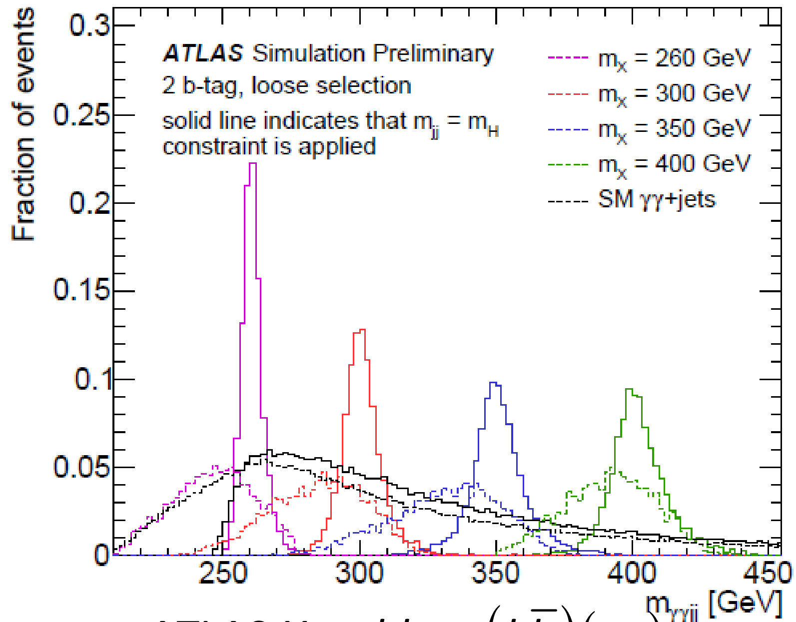
Event Kinematics

- Use polar angle θ or $\cos\theta$, not η! η is a creation for hadron colliders for which the initial longitudinal momentum is unknown. Minimize the usage of E_T or p_T .

- Use known resonance mass to improve the mass resolution of parent particles:
  - add a correction: $\Delta M = M_{PDG} - M_{meas.}$
  - scale 4-momentum by: $M_{PDG} / M_{meas.}$
  - kinematic fitting (more complicated)



$M(D^*) - M(D)$



ATLAS $X \to hh \to (b\bar{b})(\gamma\gamma)$

Standardization

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- Many of the analyses for CDR were done independently and through times led to differences that are hard to justify.

  Example, $Z\rightarrow\mu\mu$ mass window used are 80-100, 81-101, 76-106 GeV

- It will be good to have some common starting points for new people and to ensure some consistencies among different analyses. We can start with simple ones such as

  Mass windows for $Z\rightarrow ee$, $Z\rightarrow\mu\mu$, $Z\rightarrow qq$ (on-shell)

  Recoil mass windows for $Z\rightarrow ee$, $Z\rightarrow\mu\mu$, ...

  and expand the list as we gain experience.

- The standardization should not limit analysis sensitivity. Those benefiting from non-standard selections should be free to do so with some justification.

Analysis Final States

- Electron-positron collisions are clean, but it does not mean that analyses are easy! While HL-LHC will deliver ~150 millions Higgs events per experiment, CEPC will only produce ~1 million two experiments combined.
- What CEPC lacks in quantity is made up by quality. Most of the Higgs events produced at the LHC are indistinguishable from backgrounds, practically every event at CEPC counts.
- A large number of final states need to be analyzed to fully realize CEPC's potential.

$$ee \rightarrow ZH \text{ final states}: \; Z \rightarrow ee,\ \mu\mu,\ \tau\tau,\ \nu\nu,\ qq(bb)$$

$$H \rightarrow WW,\ ZZ,\ gg,\ \gamma\gamma,\ Z\gamma,\ bb,\ cc,\ \tau\tau,\ \mu\mu,\ \text{inv.}$$

5×10 final states already without taking into account different final states of Higgs decay cascades.

Analysis Final States

- For the Higgs white paper, sensitivities from ~32 final states (counting different W and Z decay modes) are quoted. Probably less than half of all final states, though likely the most sensitive ones.

- A mixed approach of final states and Higgs decay modes driven:

  Final states driven: $H \to bb,\ cc,\ gg$

  Higgs decay mode driven: $H \to WW \to 4q,$ but not $H \to ZZ \to 4q$

- Are there other ways to organize the analyses with the aim to improve efficiencies and cover more final states?

A few other thoughts

- Cross contaminations of different Higgs boson decay modes are real issues for many analyses. Need to treat them consistently without complicating individual analyses.
- Suggest to treat contributions from other Higgs boson decay modes as part of the SM background in most cases, but with separate handlers to facilitate combination.
- In a few cases in which contributions from other Higgs processes are larger than the signal itself, e.g. $Z(\nu\nu)H$ contribution to $\nu\nu H$, combined analysis may be necessary.
- Always compare your results with those of ILC and FCC-ee, if available, to check if they are consistent. If not, understand why.
- Individual analysis measure $\sigma\times$BR, so quote precision on it, not on BR (need independent measurement of σ to extract BR)

Discussion

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What's our plan next?

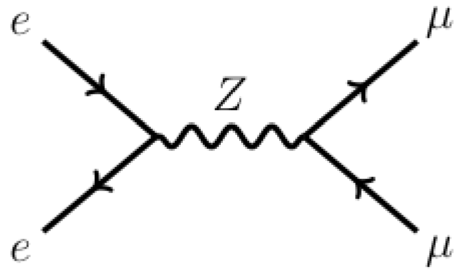
What can we improve?

How do we go from here to there?

Physics processes

Born cross section for $ee \to Z \to ff$:

$$\sigma\left(ee \to Z \to ff\right) = \frac{12\pi}{m_Z^2} \frac{s\Gamma_Z^2}{\left(s - m_Z^2\right)^2 + m_Z^2\Gamma_Z^2} \frac{\Gamma_{ee}\Gamma_{ff}}{\Gamma_Z^2}$$



At the pole $\sqrt{s} = m_Z$:

$$\sigma^0\left(ee \to Z \to ff\right) = \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{ff}}{\Gamma_Z^2}$$

For $\sqrt{s} \gg m_Z$:

$$\sigma \approx \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{ff}}{s}$$

Cross section for $ee \to \gamma^* \to ff$:

$$\sigma\left(ee \to \gamma^* \to ff\right) = \frac{4\pi\alpha^2}{3s} N_f Q_f^2$$