Detector Requirements for Precision Higgs Boson Physics

Status of Higgs property measurements
Difference and complementary of *pp* and *ee* collisions
Physics drivers of detector performances

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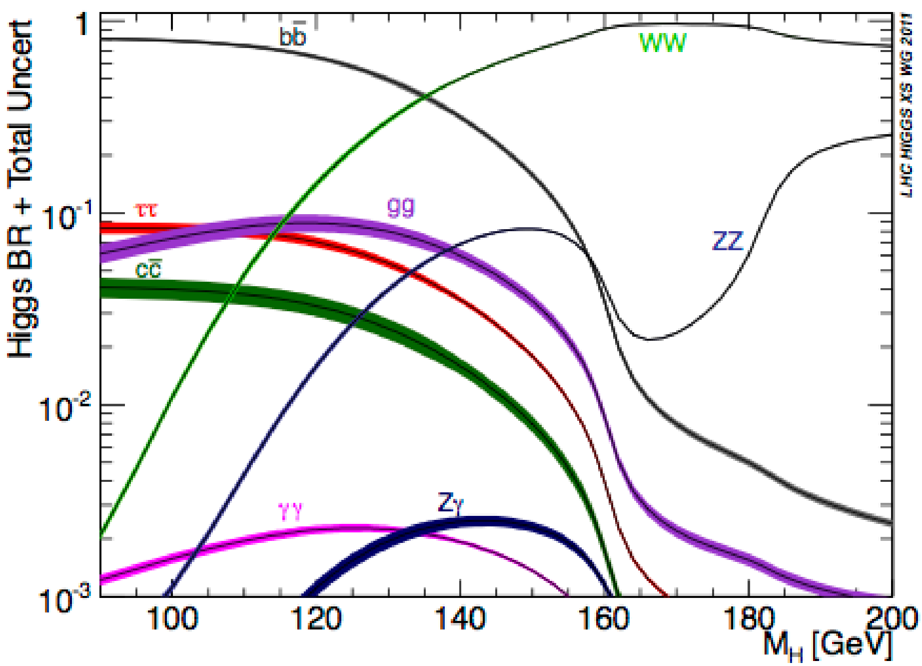
Total Width and Decay Branching Ratios

The Higgs boson mass is the only free parameter in the SM, everything else is predicted in the model…



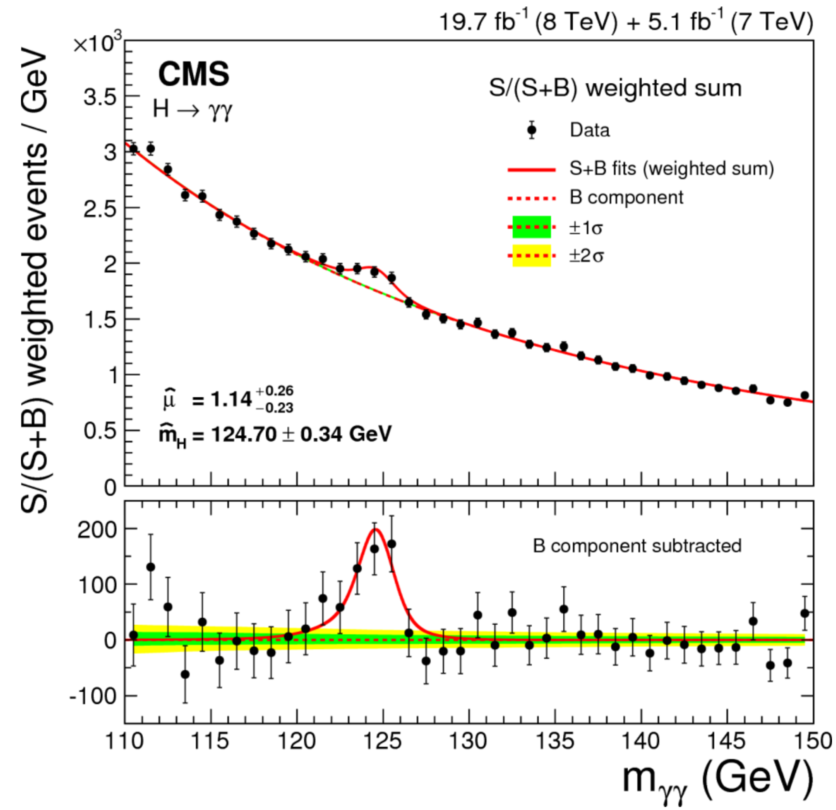
Branching Ratio @ 125 GeV	
$H \to b\bar{b}$	57.7%
$H \to gg$	8.57%
$H \to c\bar{c}$	2.91%
$H \to s\bar{s}$	2.5×10^{-4}
$H \to WW^*$	21.5%
$H \to ZZ^*$	2.64%
$H \to \gamma\gamma$	0.23%
$H \to Z\gamma$	0.15%
$H \to \tau\tau$	6.32%
$H \to \mu\mu$	2.2×10^{-4}

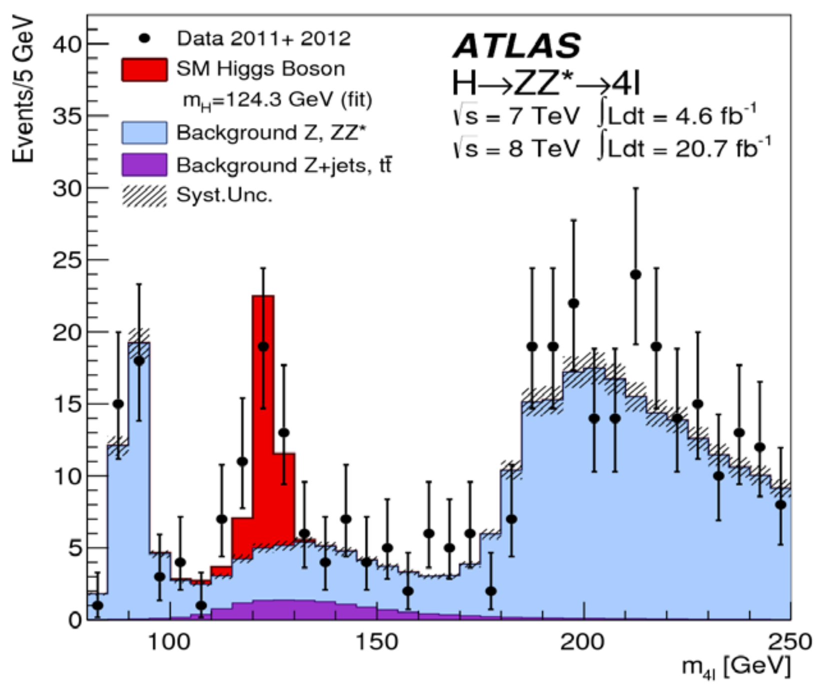
SM @ 125 GeV: $\Gamma_H \approx 4.07$ MeV $\ll$ smaller than the experimental resolutions of direct measurements

Measurements at LHC

Identify Higgs bosons from their decay signature ⇒ only known decays can be studied.

Tag production using information other than the Higgs decay





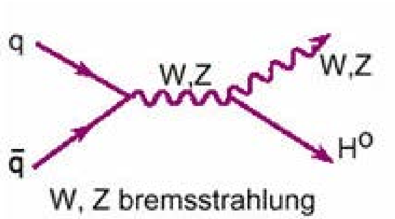
Always measure the product of cross section and branching ratio

$\sigma \times BR$

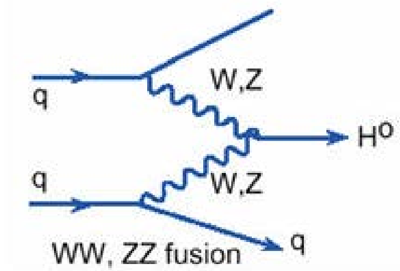
No model independent way to separate σ from BR.

Tagging Production

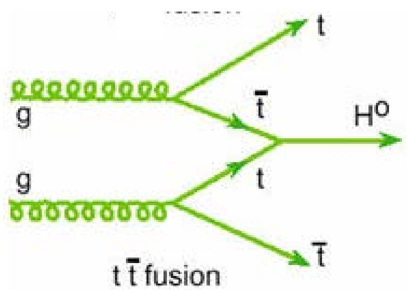
From other activities in candidate events…



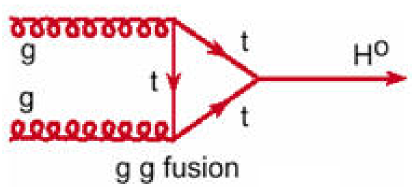
VH
Leptons, missing ET or low-mass dijets from W or Z decays



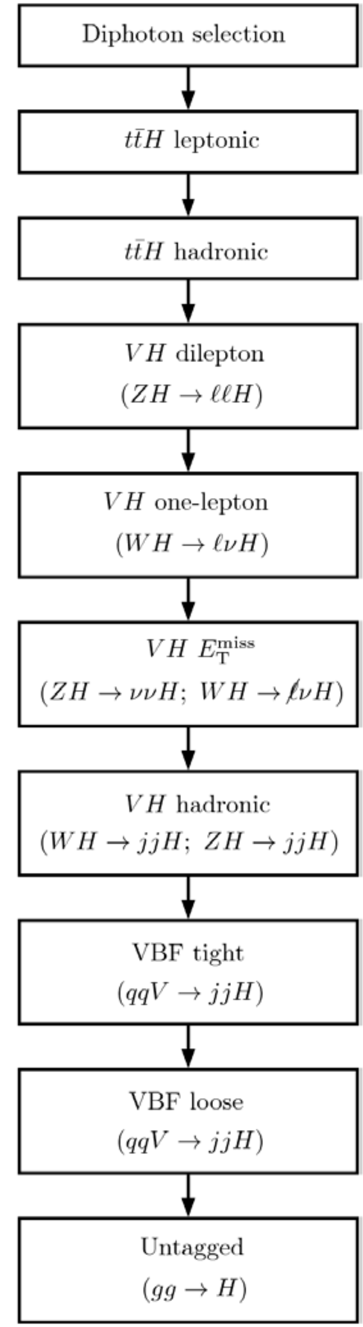
VBF
Two high pT jets with high-mass and large Pseudorapidity separation



ttH
Two top quarks: leptons, missing ET, multijets or b-tagged jets



ggF
the rest

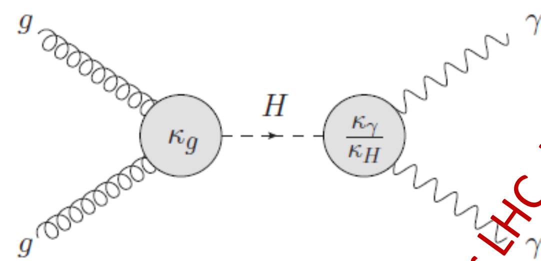


Coupling Extraction

Parametrizing deviations from SM using scale parameters: κ (SM: $\kappa = 1$)

$$g_{Hff} = \frac{m_f}{\upsilon}, \quad g_{HVV} = \frac{2m_V^2}{\upsilon} \quad \Rightarrow$$

$$g_{Hff} = \boxed{\kappa_f} \cdot \frac{m_f}{\upsilon}, \quad g_{HVV} = \boxed{\kappa_V} \cdot \frac{2m_V^2}{\upsilon}$$



For LHC, but same idea for Higgs factories

For example: $(\sigma \cdot BR)(gg \to H \to \gamma\gamma) = \left[\sigma(gg \to H) \cdot BR(H \to \gamma\gamma)\right]_{SM} \times \boxed{\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}}$

κ_H^2 is the scale factor to the total Higgs decay width

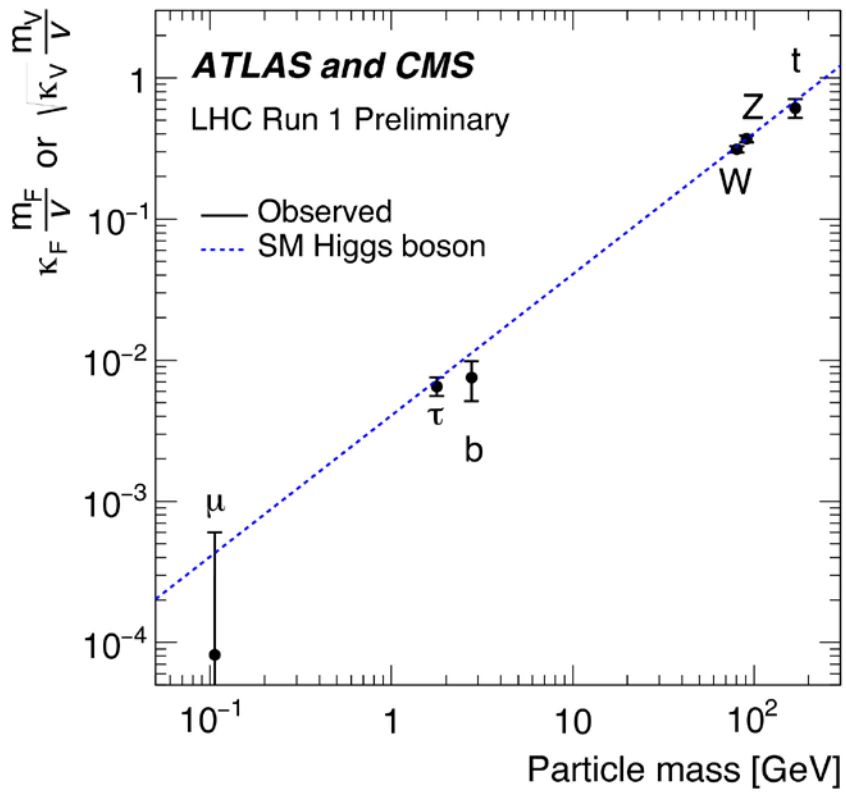
$$\kappa_H^2 = \sum_x \kappa_x^2 \cdot BR(H \to xx) \xrightarrow{\text{No non-SM decays}} \kappa_H^2 = \sum_x \kappa_x^2 \cdot BR_{SM}(H \to xx)$$

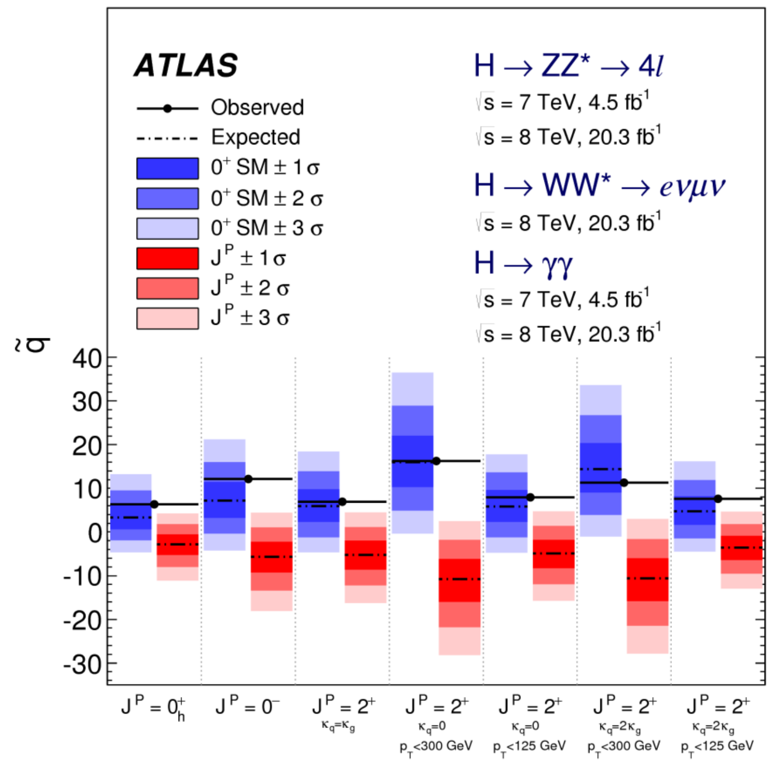
$$\xrightarrow{\text{With non-SM decays}} \kappa_H^2 = \sum \kappa_x^2 \cdot \frac{BR_{SM}(H \to xx)}{1 - BR_{non-SM}}$$

Benchmark models with different assumptions. Most models at LHC assume no non-SM decays $(BR_{non-SM} = 0)$. More generally: $BR_{non-SM} = BR_{inv} + BR_{exotic}$

Status of the LHC Measurements

All measurements are consistent with the expectations of a 125 GeV Standard Model Higgs boson.



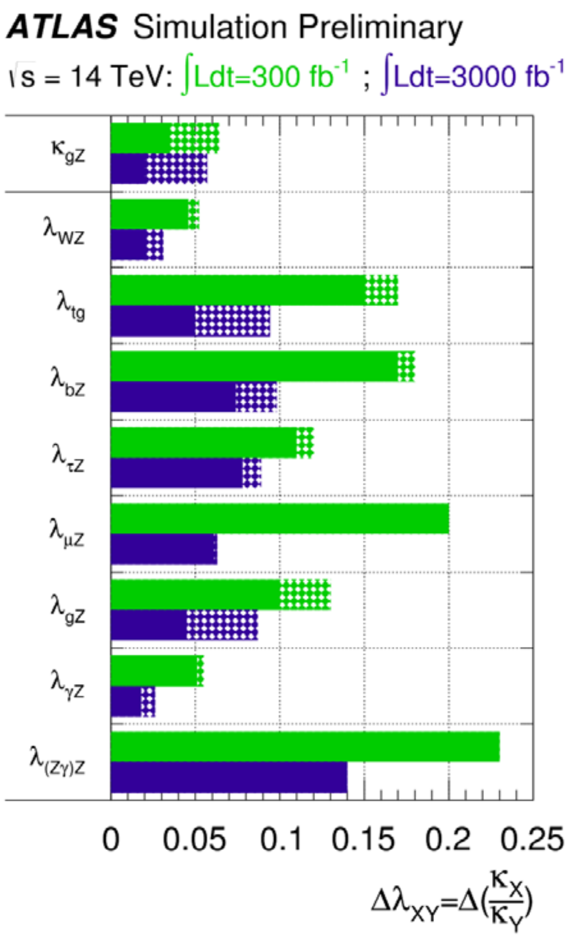


Relevant couplings are measured with a precision of 10-30%. Alternative spin/CP hypotheses tested are disfavored at 95% CL or higher.

See presentation for details by Guido Tonelli yesterday

Prospects at HL-LHC

Significant improvements are expected from the ongoing and future LHC program



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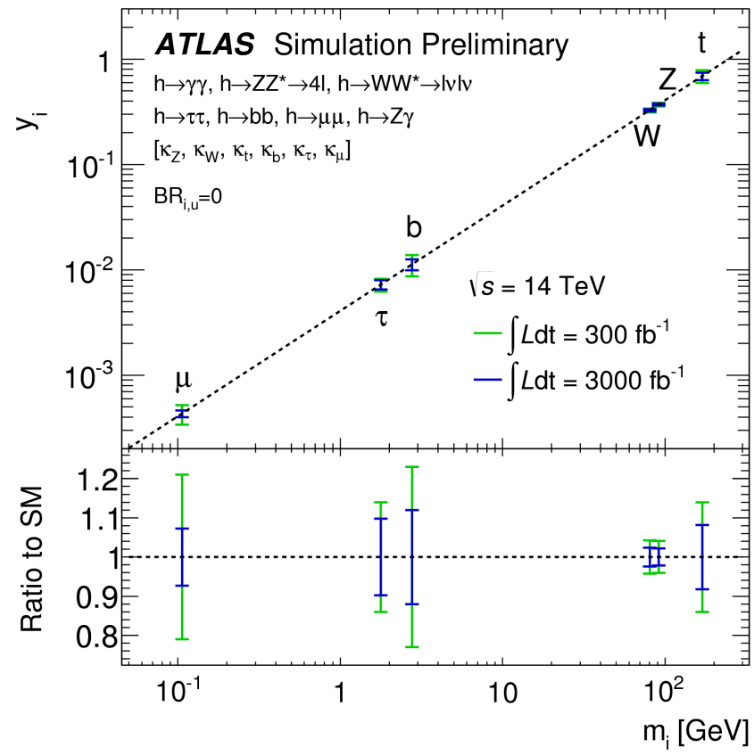


But theoretical and experimental challenges limit the precision to a few percent in the best cases. Percent-level precision possible in some ratios.

Cases for a Precision Higgs Program

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:

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

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

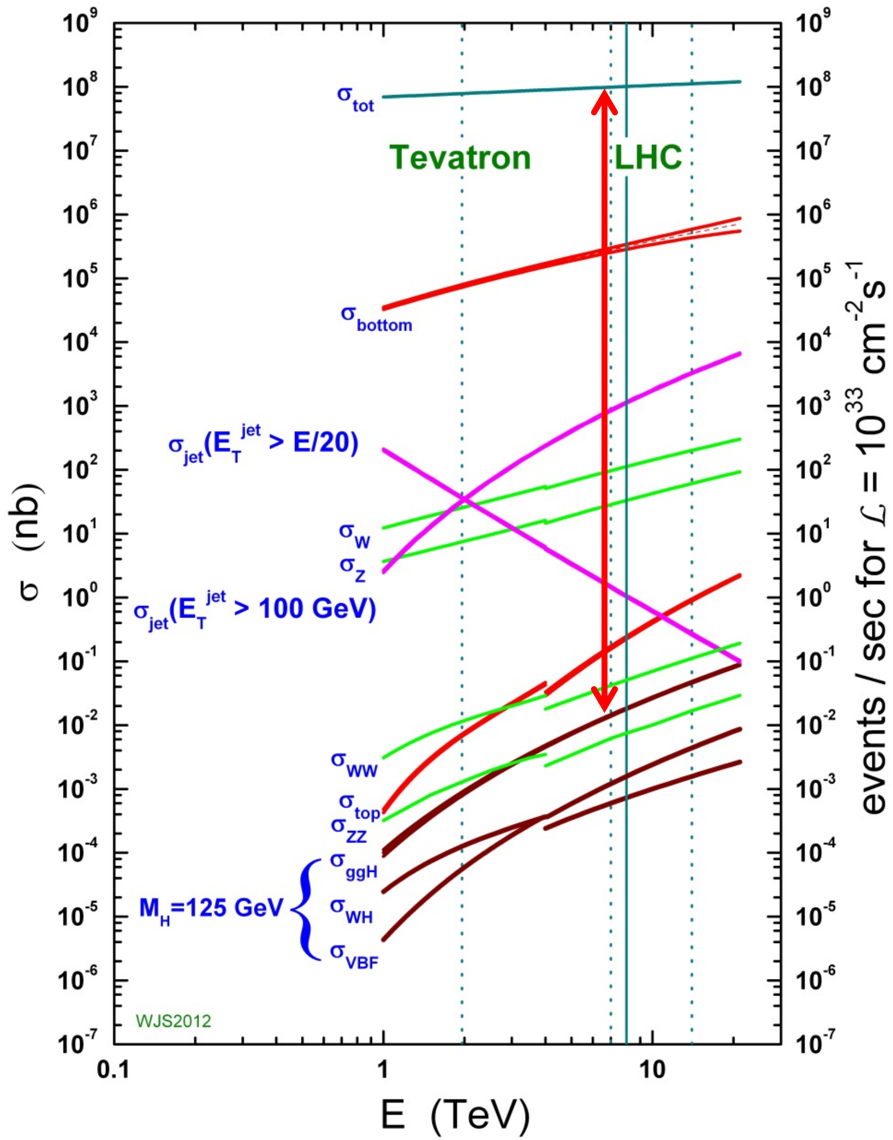
How large are potential deviations from BSM physics? How well do we need to measure them to be sensitive?

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

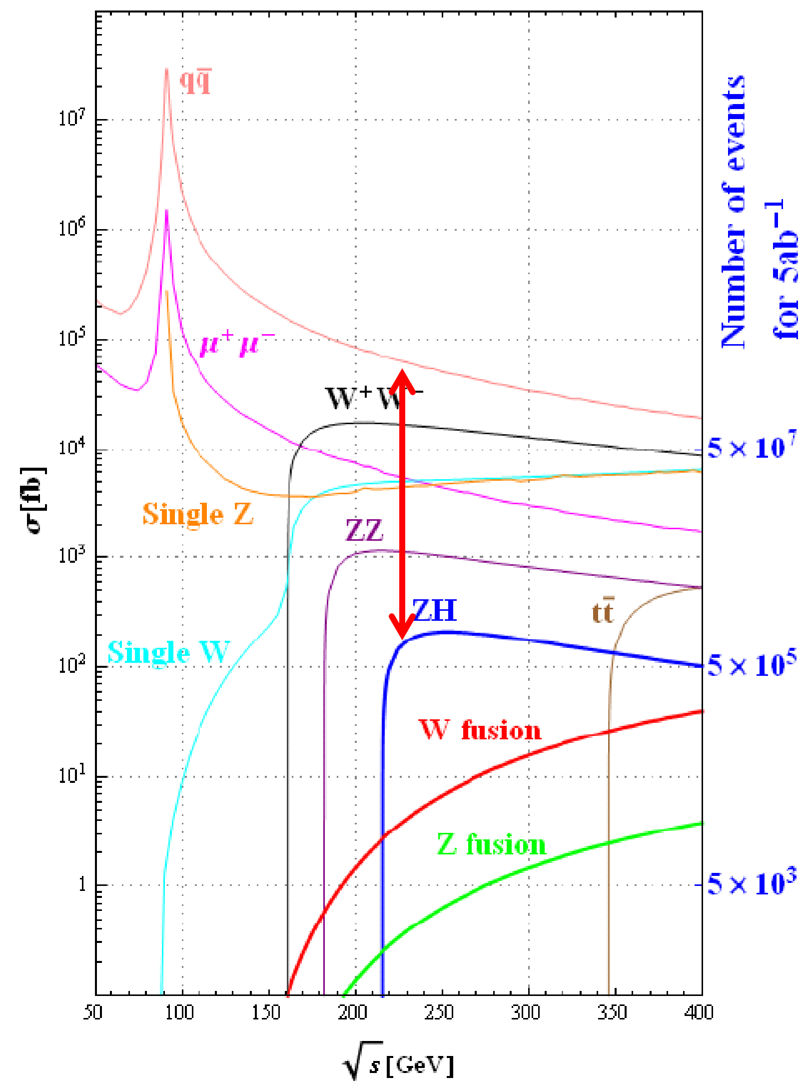
$\Rightarrow$ Need percent-level or better measurements!

Cross Sections

proton - (anti)proton cross sections



e^+e^- cross sections



Production Rates

ee compared with *pp* collisions

Smaller production cross sections, cleaner events and better signal-to-background ratios.

pp collisions at 14 TeV, 3 ab^{-1}

Process	σ (pb)	Events (10^6)
ggF	49.5	148
VBF	4.23	12.7
VH	2.62	7.8
$t\bar{t}$H	0.61	1.8

e^+e^- collisions at 250 GeV, 5 ab^{-1}

Process	σ (fb)	Events
ZH	212	1.06×10^6
$\nu\bar{\nu}H$	6.72	3.36×10^4
e^+e^-H	0.63	3.15×10^3

Running at ZH with an instantaneous luminosity of $2 \times 10^{34}\ cm^{-2}s^{-1}$:

Higgs processes $\sim$ 0.004 Hz

All other processes $\sim$ 2 Hz (not including $\gamma\gamma$ processes)

Running at Z pole with an instantaneous luminosity of $5 \times 10^{35}\ cm^{-2}s^{-1}$:

Event rate $\sim$ 20 kHz

(For comparison, ATLAS aims an average data-recording rate of 10 kHz for HL-LHC).

Higgs Samples

Numbers of Higgs bosons produced:

pp collisions in 3000 fb^{-1}: 170 millions ($2\times$ for two experiments)

ee collisions in 5 ab^{-1}: 1 million

Only a small faction of events produced at the LHC will be recorded and analyzable. This rate is estimated to be about 0.5% from Run 1 experiences. In comparison, every Higgs event (almost) will be recorded and contribute to the Higgs measurements.

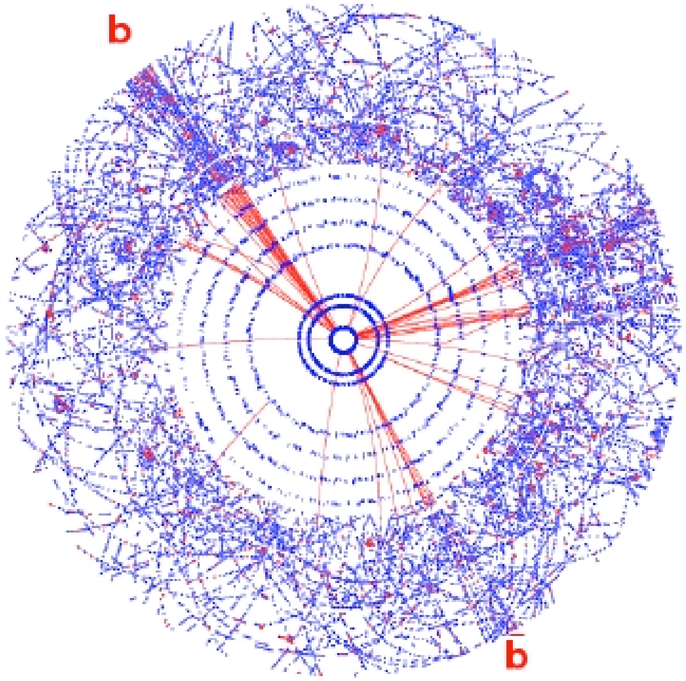
At the end, the statistics of Higgs samples are not so much different between the LHC and CEPC for example. What is different is the "flavor" composition of the sample:

pp collisions: dominated by Higgs decay final states with ℓ or γ

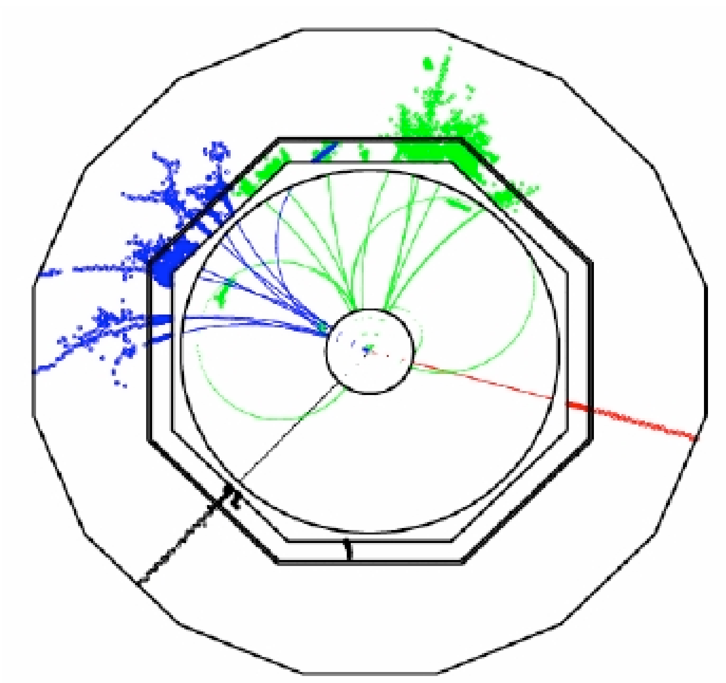
ee collisions: demoncratically distributed according to BR

Clean: Events and Theory

$$pp \rightarrow H + X \rightarrow b\bar{b} + X$$



$$e^+e^- \rightarrow ZH \rightarrow \mu\mu b\bar{b} + X$$



$\Delta\sigma/\sigma$ for pp at 14 TeV

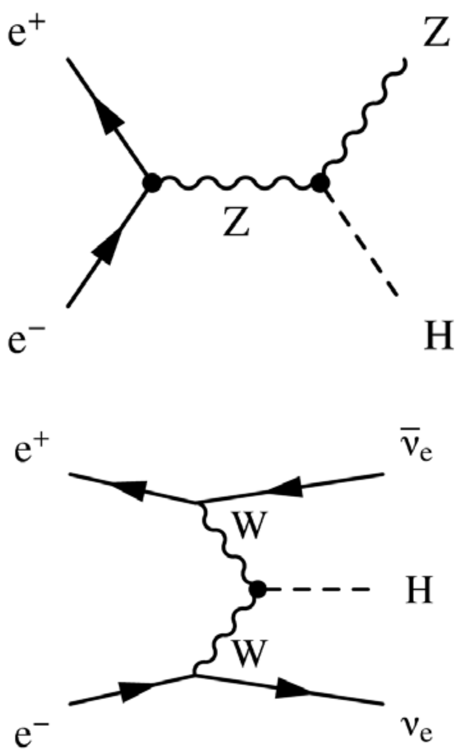
Process	QCD scale	PDF+α_s	Total (linear sum)
ggF	±8%	±7%	±15%
$t\bar{t}$H	±8%	±9%	±17%
VBF	±0.5%	±3%	±4%
VH	±3%	±2%	±5%

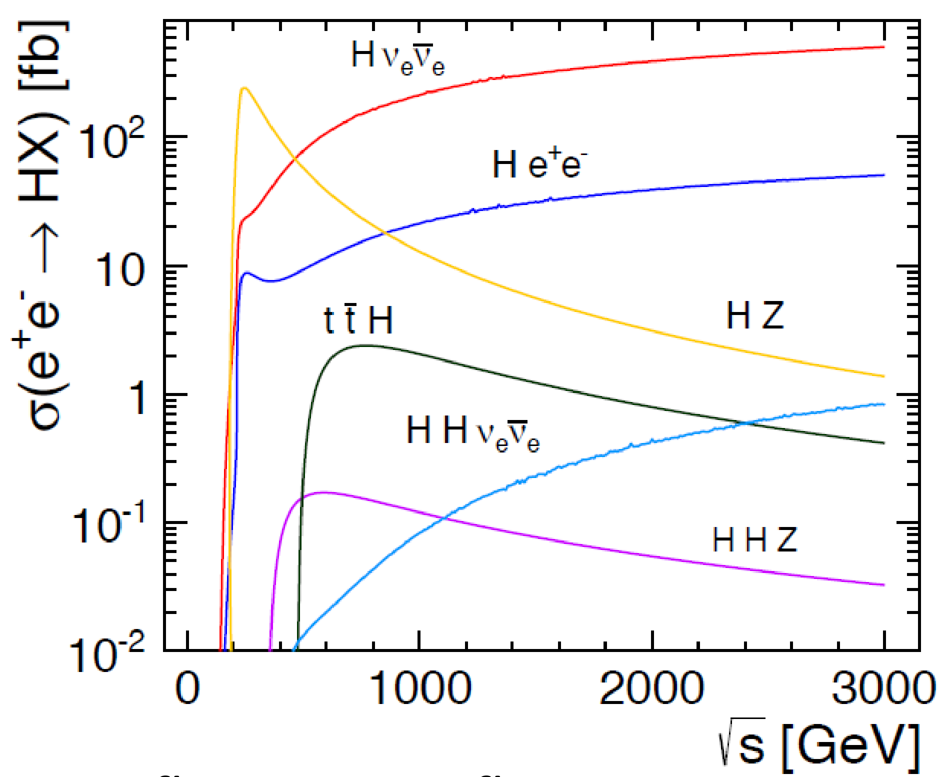
Theoretical uncertainties are large or dominant for *pp* collisions, but are much smaller than experimental uncertainties in *ee* collisions

Higgs Boson Production in *ee* Collisions

At $\sqrt{s} \sim 240-250$ 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 $ee \to \nu\nu H$.

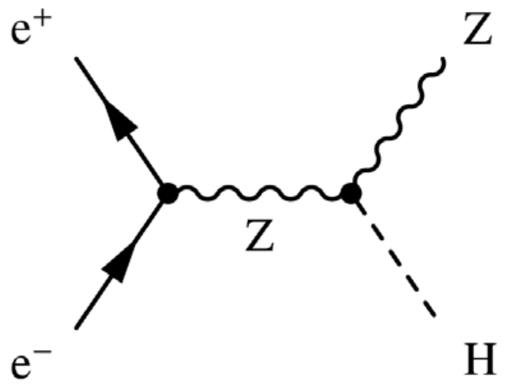


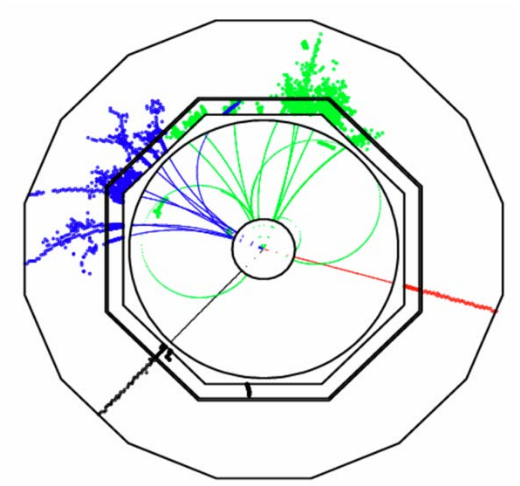


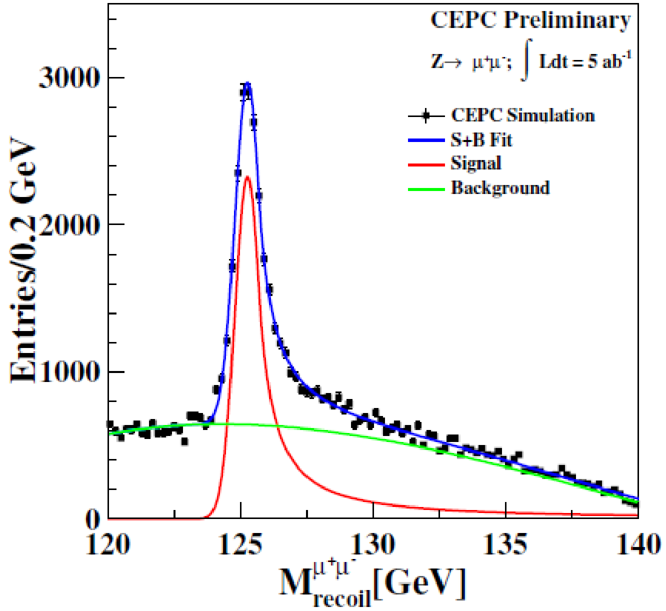
$\sqrt{s} = 250$ GeV: $\sigma_{ZH} \approx 200$ fb, $\sigma_{\nu\nu H} \approx 10$ fb

Decay-Blind Tagging 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 Higgs without looking at Higgs.

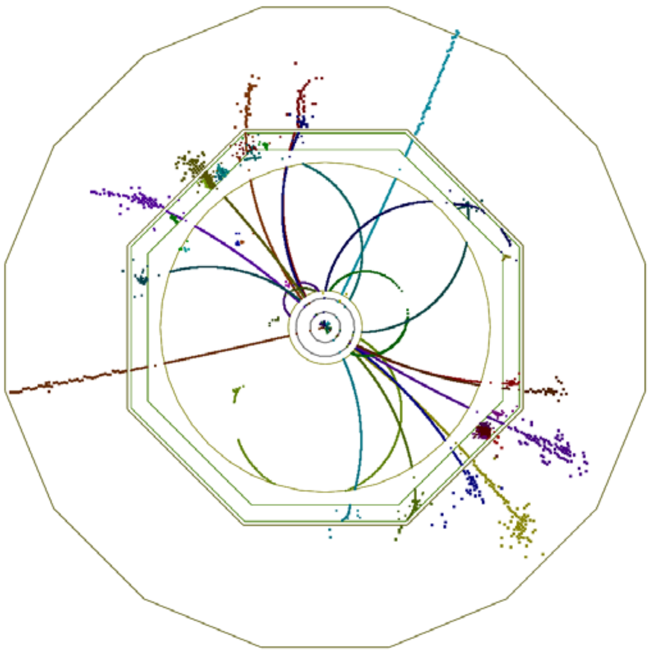
Measure $\sigma(ee \to ZH)$ independent of its decay !

Higgs Decay Classifications

Examining the other activities in the events to study Higgs boson decays and measure

$$\sigma\left(ee \to ZH\right)\times BR\left(H \to XX\right)$$

thus allowing the measurements of Higgs decay BR without assumptions.



Identify expected decay modes and search for unexpected ones;

Key performance for the analyses are:

- Lepton identification and measurements;
- Jet angular and momentum resolutions;
- Jet flavor tagging;
- .....

Accessible Decay Modes

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

CEPC Expected Precisions

Event rate & Branching ratio measurements

Table 3.12 Estimated precisions of Higgs boson property measurements at the CEPC. All the numbers refer to relative precision except for M_H and $BR(H \to inv)$ for which ΔM_H and 95% CL upper limit are quoted respectively.

ΔM_H	Γ_H	$\sigma(ZH)$	$\sigma(\nu\nu H) \times BR(H \to bb)$
5.9 MeV	2.8%	0.51%	2.8%

Decay mode	$\sigma(ZH) \times BR$	BR
$H \to bb$	0.28%	0.57%
$H \to cc$	2.2%	2.3%
$H \to gg$	1.6%	1.7%
$H \to \tau\tau$	1.2%	1.3%
$H \to WW$	1.5%	1.6%
$H \to ZZ$	4.3%	4.3%
$H \to \gamma\gamma$	9.0%	9.0%
$H \to \mu\mu$	17%	17%
$H \to inv$	–	0.28%

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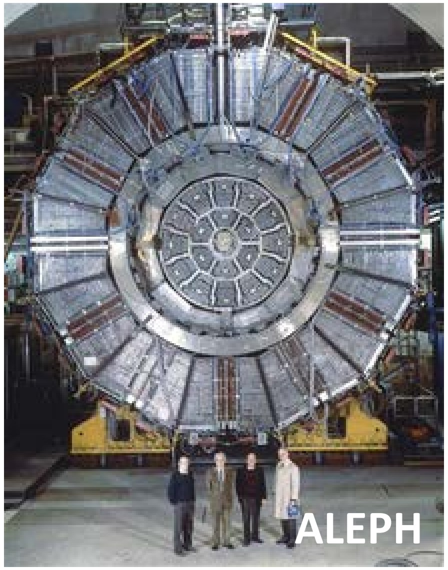
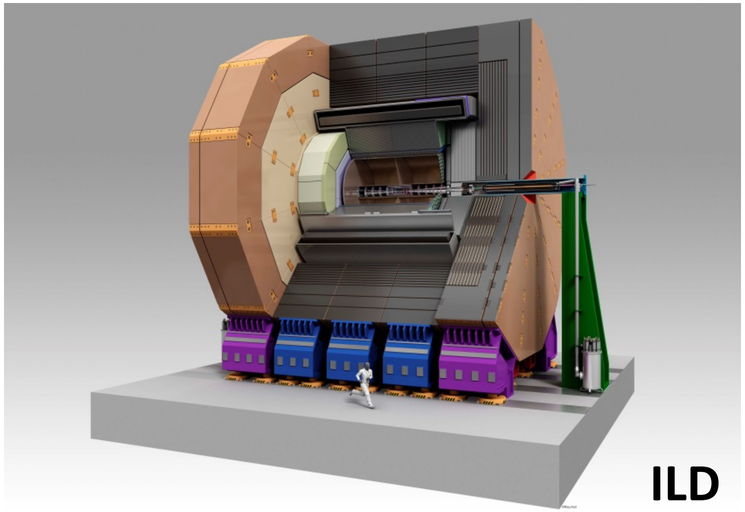
See the presentation by Manqi Ruan yesterday for details.

Detectors for *ee* Colliders

We know how to build detectors for *ee* colliders:

- Collision environment at a Higgs factory is not that much different than that at LEP – low rates and low occupancies;
- Significant progress since LEP – detector R&D, design studies for ILC and experiences at LHC.





The challenge is to build them to maximize physics potential at a reasonable cost.

See the presentations yesterday afternoon and the presentation by Yuanning Gao this afternoon for detailed detector designs for ee colliders.

Requirements for Precision Measurements

Hermeticity and 4π coverage

Good tracking momentum resolution ⇒ low mass, large and strong fields

Efficient and accurate flavor tagging ⇒ precision vertex detector;

Good jet angular and momentum resolutions for S-B separations
⇒ Fine calorimeter granularity to facilitate particle flow reconstructions

Model-independent measurements ⇒ inclusiveness of triggers

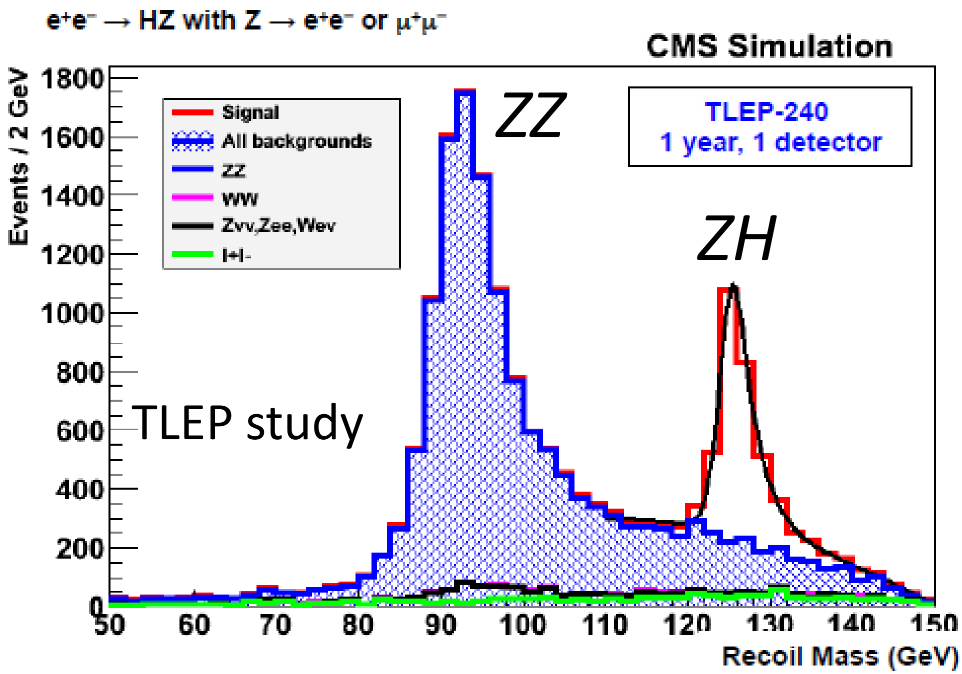
Excellent lepton identification and measurement, …

CEPC performance assumption

Detector acceptance	TPC (97%), FTD, ECAL, HCAL (99.5%)
Tracking efficiency	$\sim 100\%$ within geometry acceptance
Tracking performance	$\Delta(1/p_T) \sim 2 \times 10^{-5}$ (1/GeV)
ECAL energy resolution	$16\%/\sqrt{E} \oplus 1\%$
HCAL energy resolution	$60\%/\sqrt{E} \oplus 1\%$
Jet energy resolution	$3-4\%$ $\Rightarrow \frac{\Delta E}{E} \sim \frac{30\%}{\sqrt{E}}$ @ $E = 50$ GeV
Impact parameter resolution	$5\ \mu$m

(take ILD as a reference design)

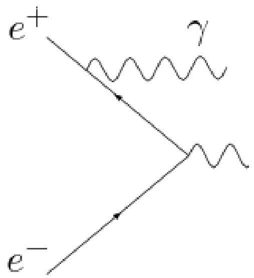
Recoiling Mass Distributions



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

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

$S/B \sim X$ for $m \in [120,130]$ GeV



ZH: detector resolution dominates the width, radiation dominates the high-mass tail.

Key performance issues:

Lepton momentum resolution (detector);

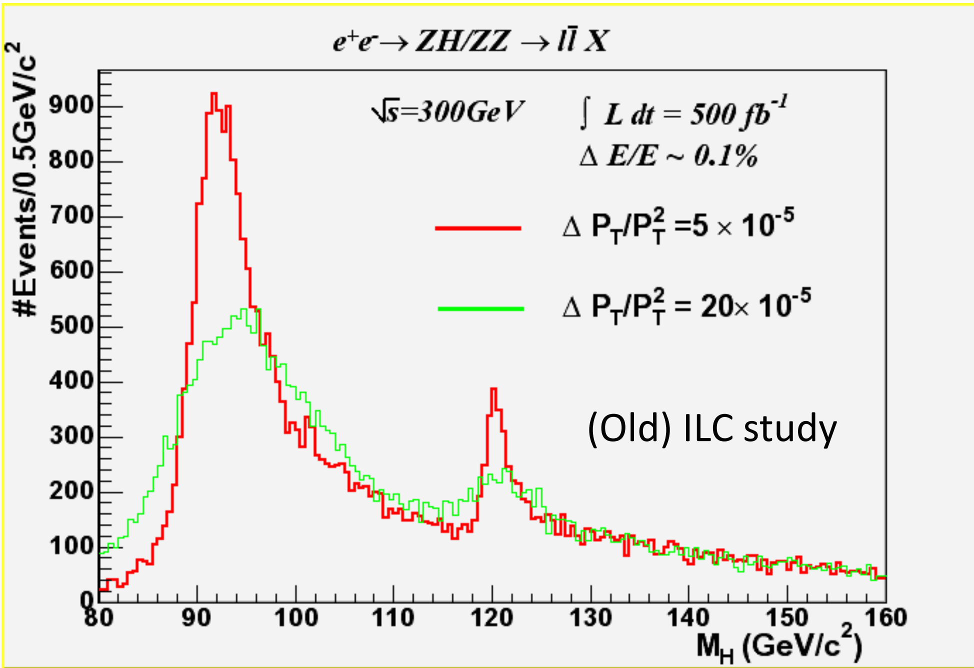
Minimize the impact of the radiations:

e.g. small angle ECAL coverage will be important.

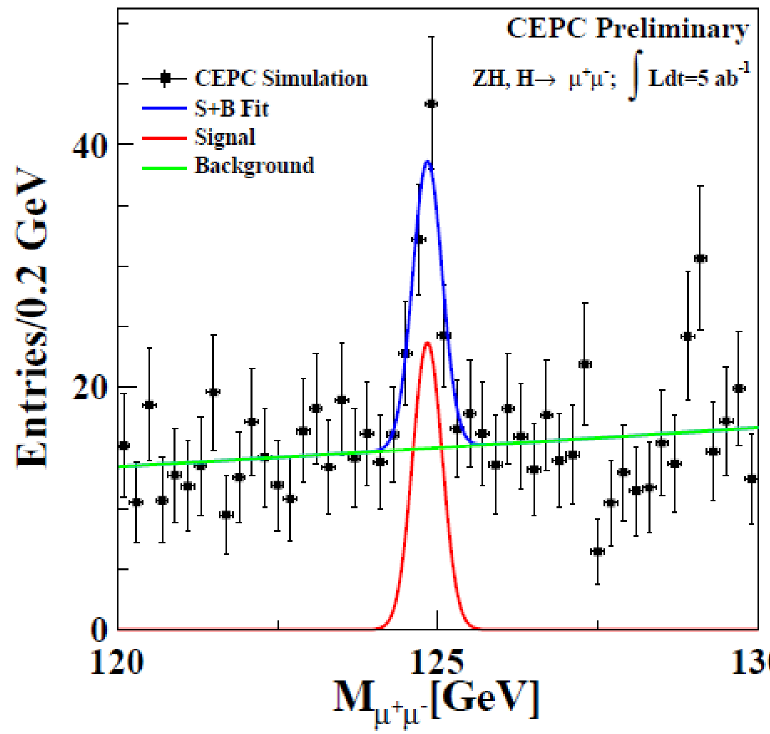
Track Momentum Resolution

Separation of ZH and ZZ through $Z \to \ell\ell$ recoil mass reconstruction

Reconstruction and identification of $H \to \mu\mu$ decay



$BR(H \to \mu\mu) = 2.4 \times 10^{-4}$

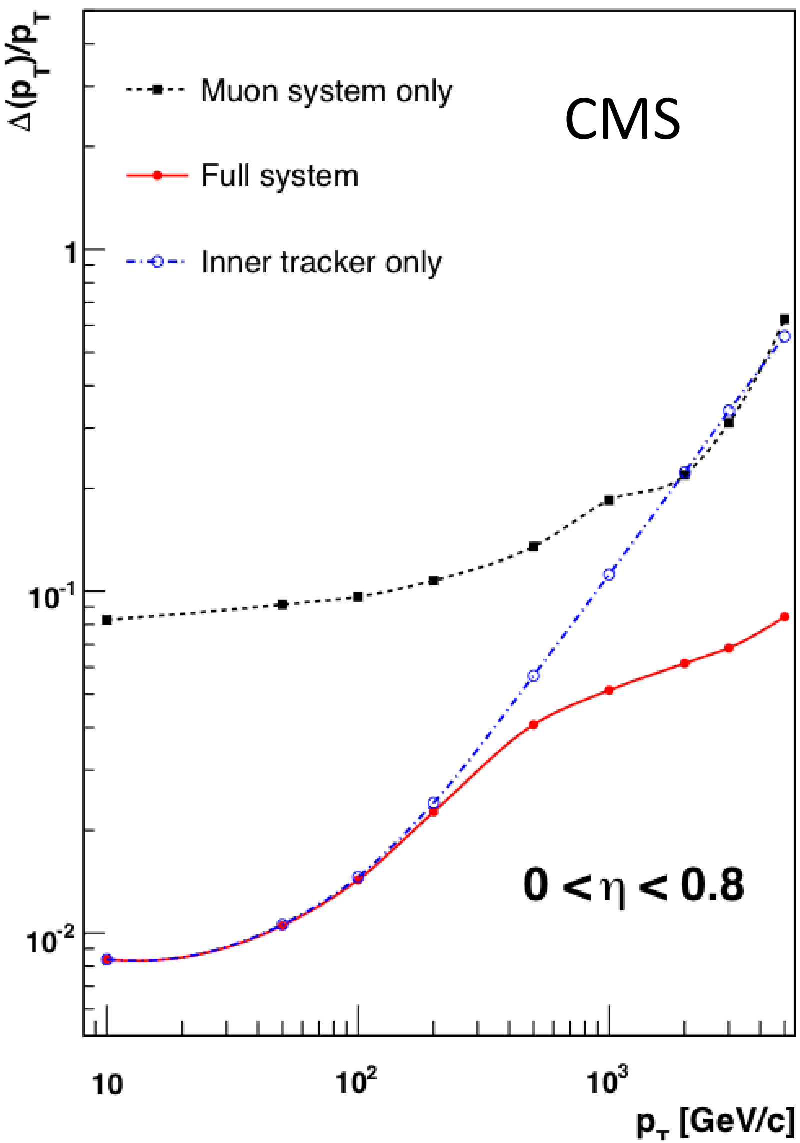


$$\frac{S}{B} \sim 1 \ \text{ for } \ \frac{\Delta p_T}{p_T^2} = 5 \times 10^{-5}\ \text{GeV}^{-1}$$

Resolution of $\frac{\Delta p_T}{p_T^2} < 5 \times 10^{-5}$ will be needed

$$\frac{\Delta p_T}{p_T^2} = 2 \times 10^{-5}\ \text{GeV}^{-1}$$

Track Resolution of Existing Detectors



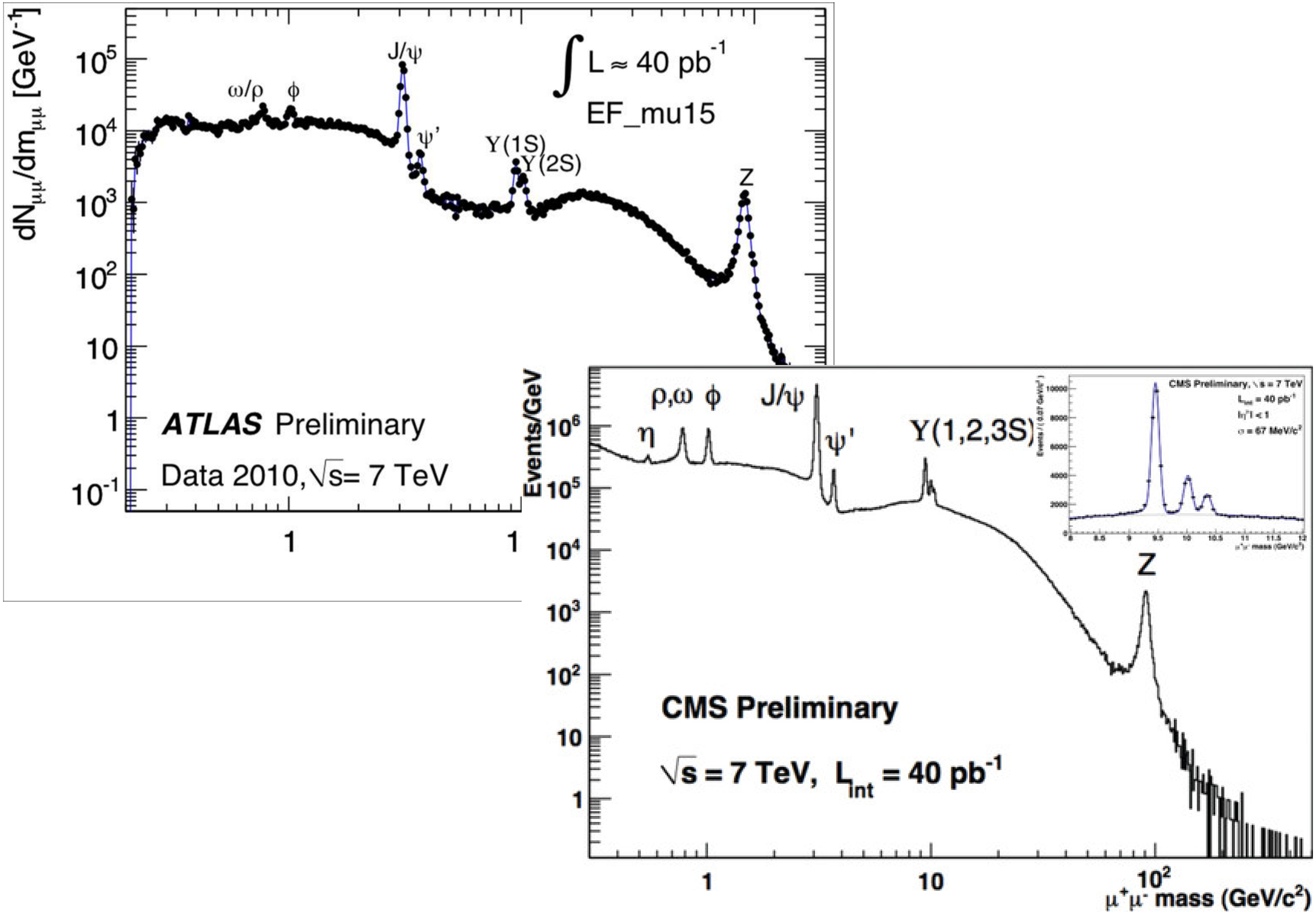
ALEPH: $\frac{\Delta p_T}{p_T^2} \sim 8\times10^{-4}\ \text{GeV}^{-1}$

ATLAS: $\frac{\Delta p_T}{p_T^2} \sim 3\times10^{-4}\ \text{GeV}^{-1}$

CMS: $\frac{\Delta p_T}{p_T^2} \sim 1\times10^{-4}\ \text{GeV}^{-1}$

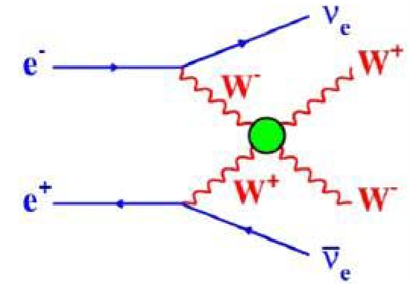
A factor of five improvement over the best resolution of existing detectors.

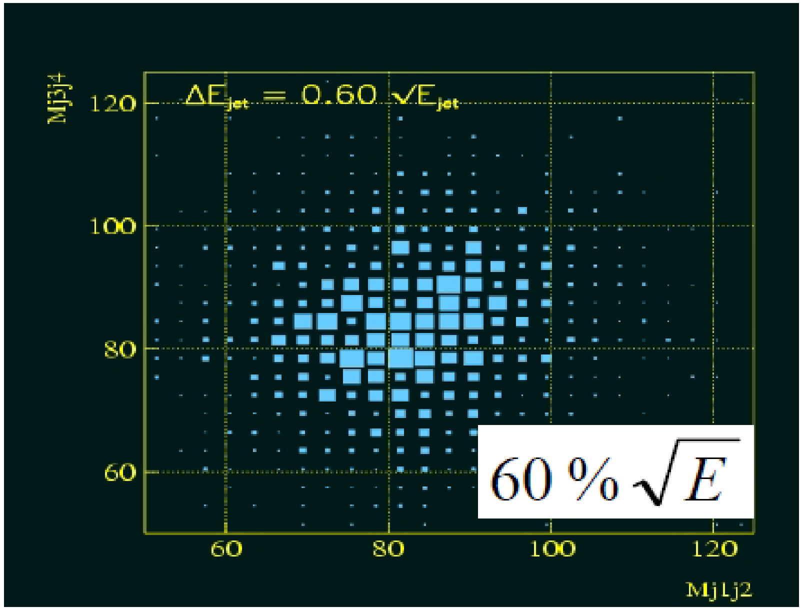
Track Momentum Resolution

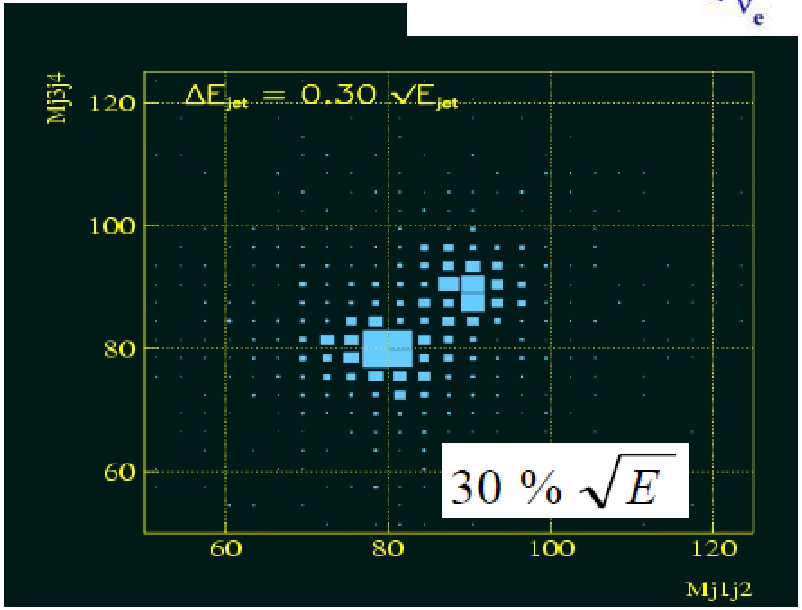


Jet Energy Resolution

The argument is often made based on the separation of $ee \to WW\nu\nu$ and $ee \to ZZ\nu\nu$ in hadronic final states.







ΔE/E = 30%/Sqrt(E [GeV]) makes W-Z separation possible

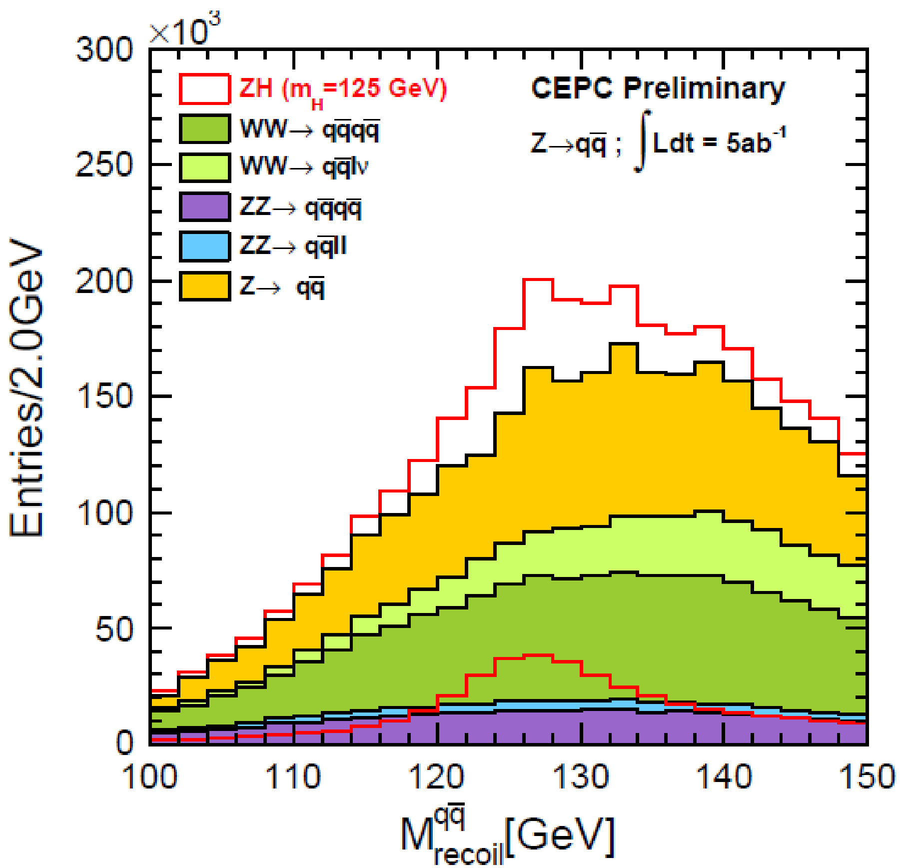
These processes are not really relevant for CEPC running at $\sqrt{s} \sim 250$ GeV.
But good jet energy resolution is critical for precision Higgs physics.

Jet Energy Resolution

At $\sqrt{s} \sim 250$ GeV, jet energy resolutions are critical for

- $H \rightarrow WW^*$ and ZZ^* decays in hadronic final states;
- $ZH \rightarrow q\bar{q}H$ recoil mass reconstruction;
- separation of $\nu\bar{\nu}H \rightarrow \nu\bar{\nu}b\bar{b}$ and $ZH \rightarrow \nu\bar{\nu}b\bar{b}$ processes

……



ZH with $Z \rightarrow q\bar{q}$

Large branching ratio ~ 70%

Critical for the σ_{ZH} measurement:

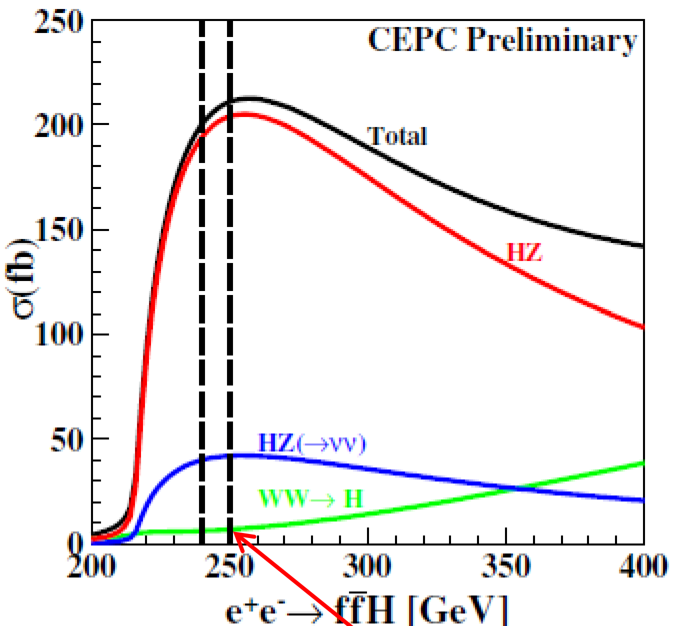
$$\frac{\Delta\sigma_{ZH}}{\sigma_{ZH}} \sim 0.65\%$$

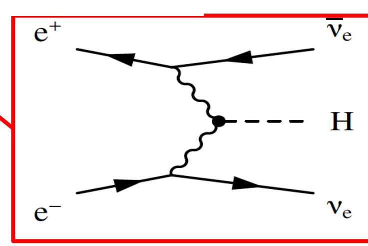
Good recoiling mass distribution is important to reduce the impact of large single- and di-boson backgrounds.

Jet Energy Resolution

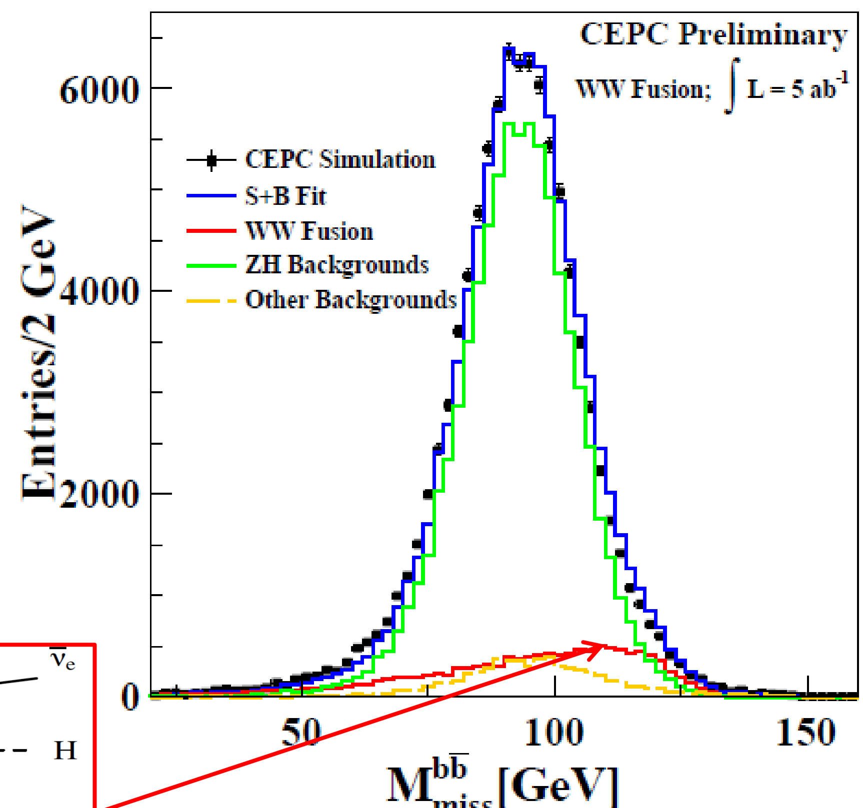
Measurement of $ee \to \nu\bar{\nu}H$ is an important part of the Higgs physics program at CEPC, but it suffers from large $ZH \to \nu\bar{\nu}H$ background.

$$\text{At } \sqrt{s} = 250 \text{ GeV: } \sigma(\nu\bar{\nu}H) = 6.7 \text{ fb}, \ \sigma(ZH \to \nu\bar{\nu}H) = 42.4 \text{ fb}$$





$\nu\bar{\nu}b\bar{b}$ final state

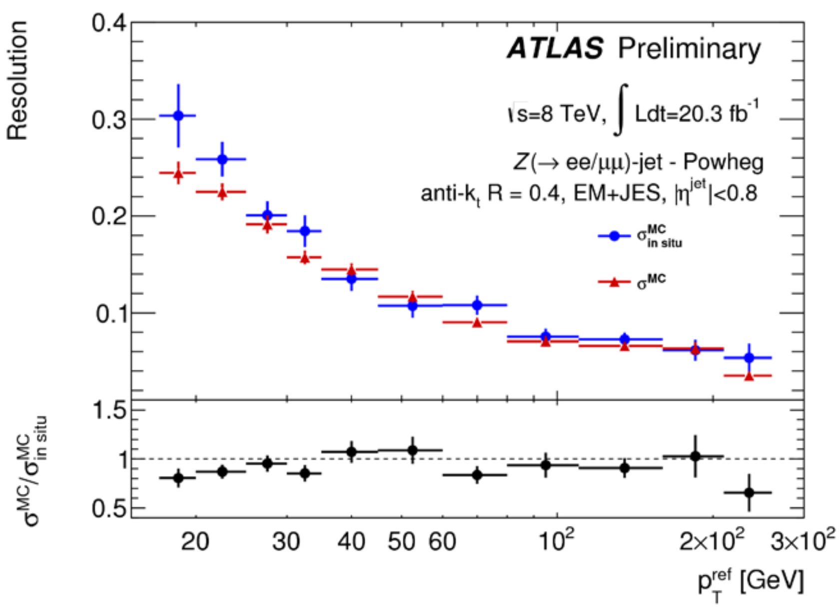


Jet Energy Resolution

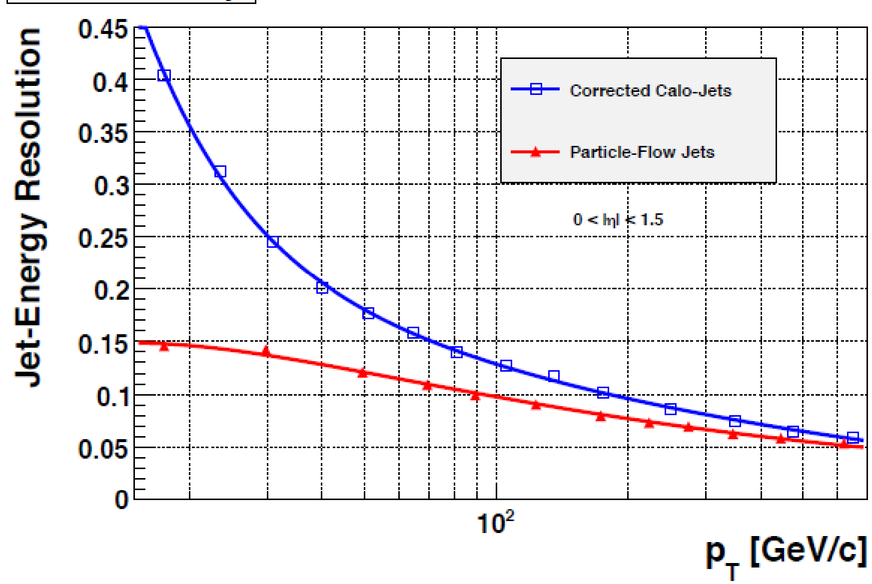
ATLAS and CMS have a similar jet energy resolution

$$\frac{\Delta E_T}{E_T} \sim 10\% \text{ at } E_T = 100 \text{ GeV}$$

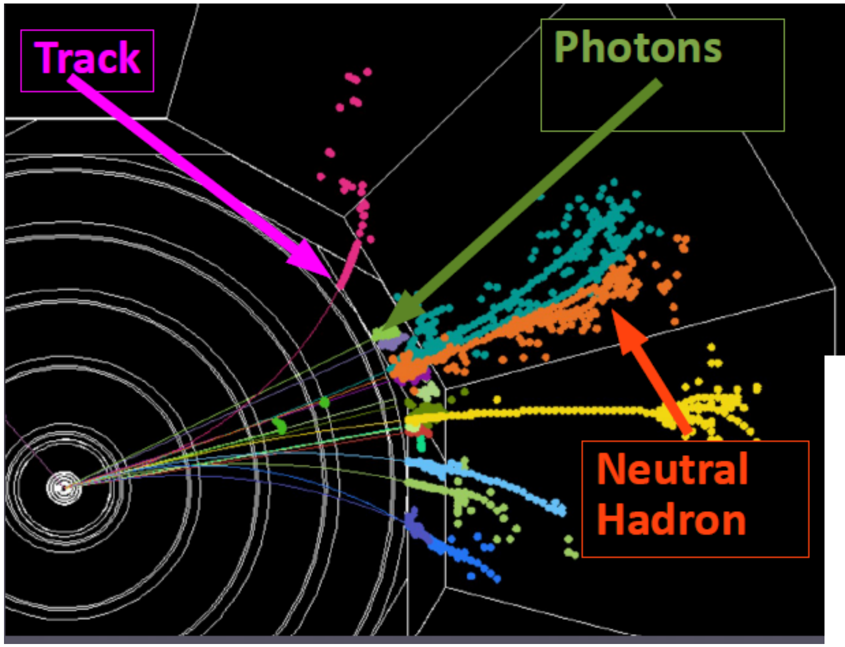
ATLAS-CONF-2015-057



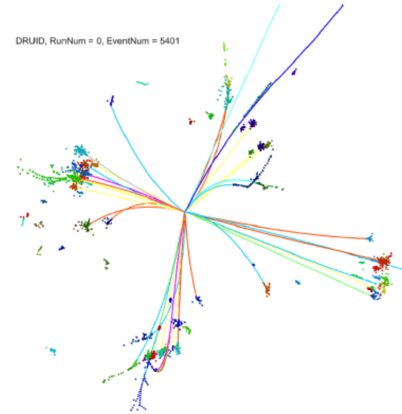
CMS Preliminary arXiv:1401.8155



Jet Energy Resolution

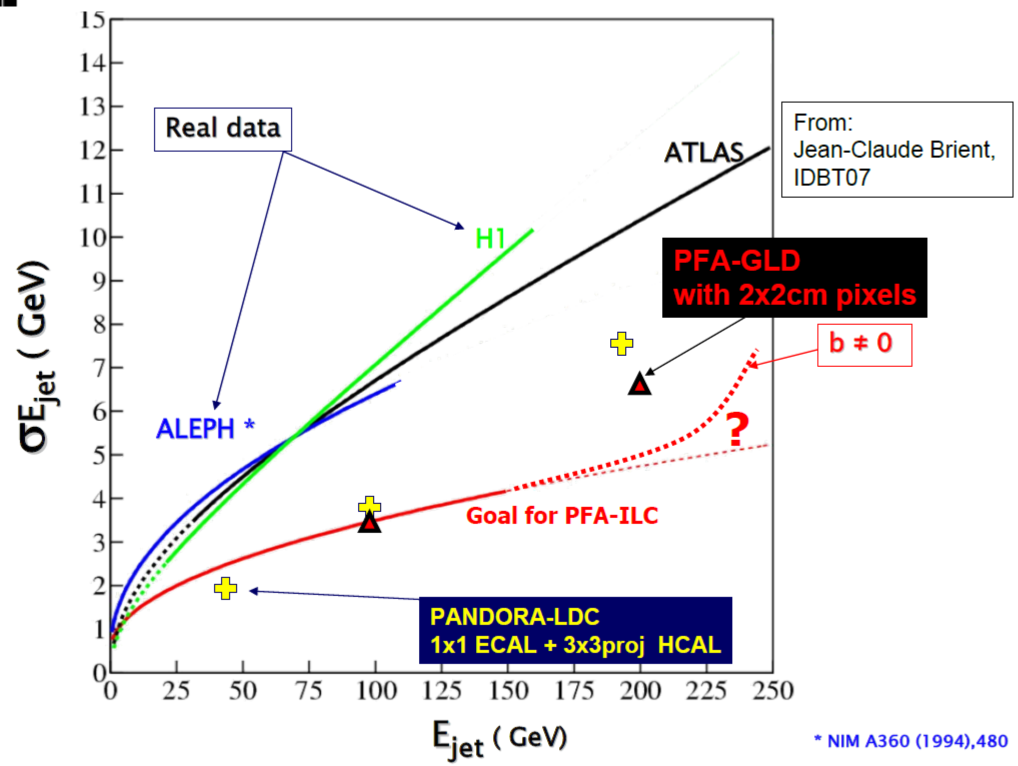


Marcel Stanitzki @ Vertex'15



CEPC simulation

$ee \rightarrow ZH \rightarrow q\bar{q}\ b\bar{b}$



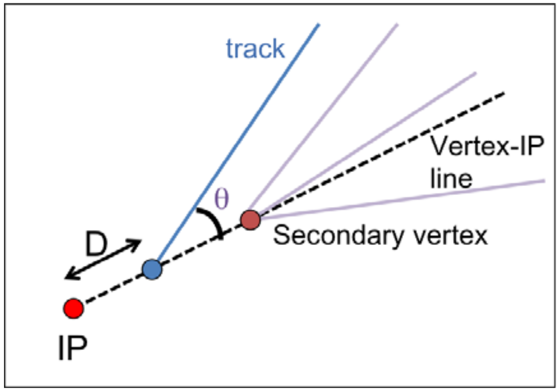
R. Tschirhart

At least a factor of three better than the performance of the past and current collider detectors.

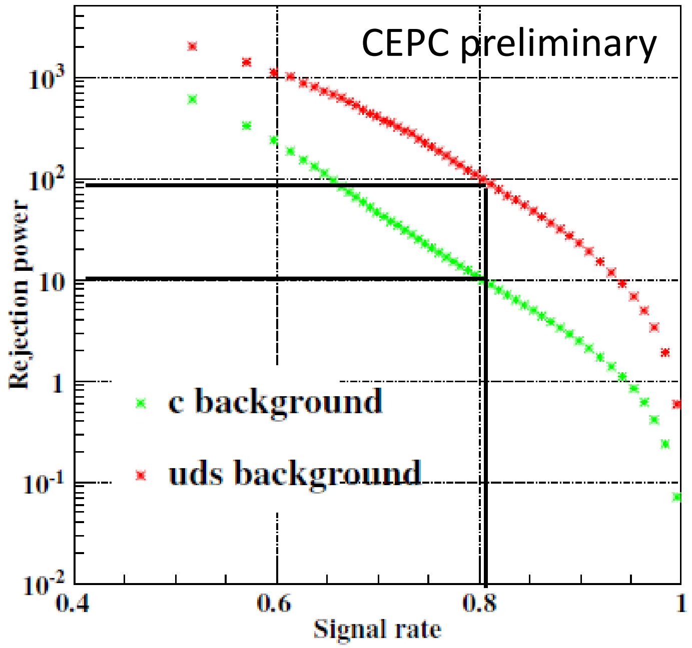
Jet Flavor Tagging

Tagging heavy flavor jets using information

- secondary vertex,
- semi-leptonic decays;
- jet kinematic variables (mass, ...)



Essential for the BR measurements of $H \to b\bar{b}$, $c\bar{c}$ and gg decays. Moreover, they are backgrounds to each other. Precise knowledge of tagging rates are important to correct for cross contaminations.



Branching Ratio @ 125 GeV	
$H \to bb$	57.7%
$H \to gg$	8.57%
$H \to c\bar{c}$	2.91%

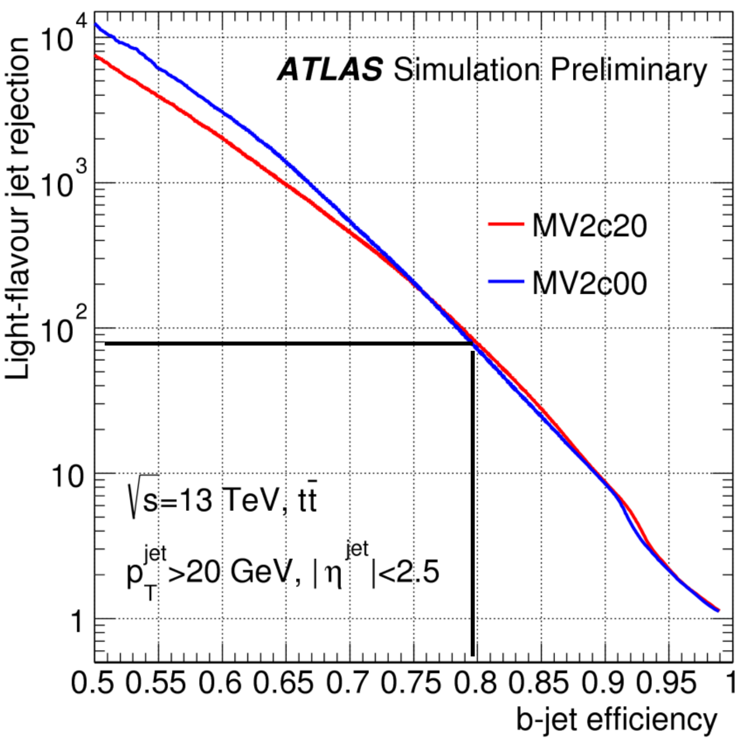
b and c-quark separation is particularly important due to the large $\mathrm{BR}(H \to b\bar{b})$ and small $\mathrm{BR}(H \to c\bar{c})$.

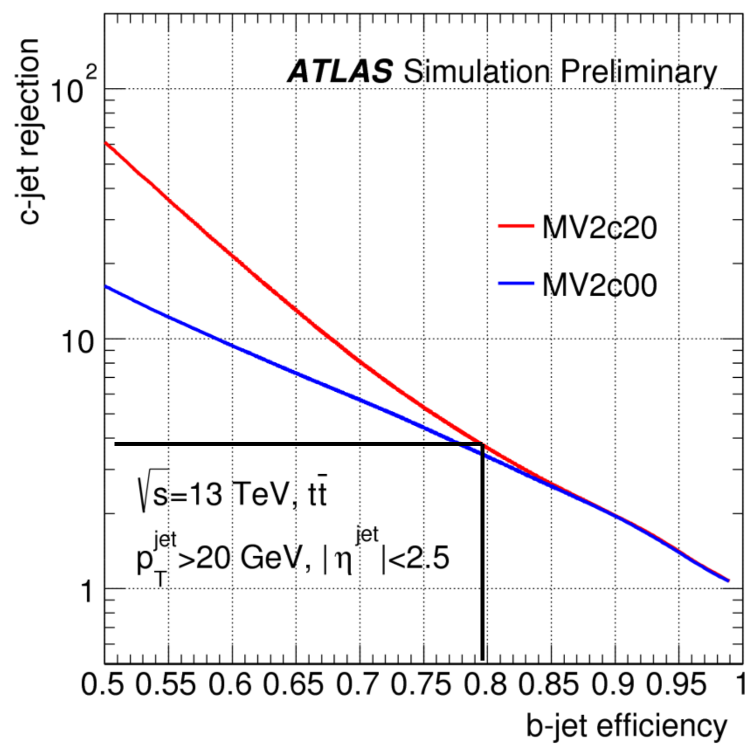
Jet Flavor Tagging

Current b-jet tagging is optimized for light-jet rejection.

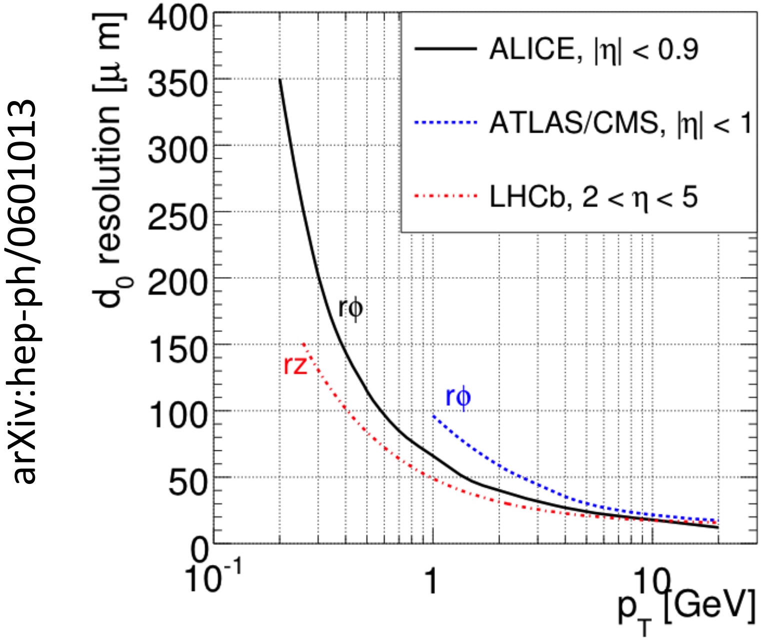
In ATLAS, for a b-jet tagging efficiency of 80%, the rejection factors are about 100 for light-jets and only a factor of 4 for c-jets.

Such low c-jet rejection will lead to a 125% contamination of $H \to b\bar{b}$ in $H \to c\bar{c}$ candidate sample!





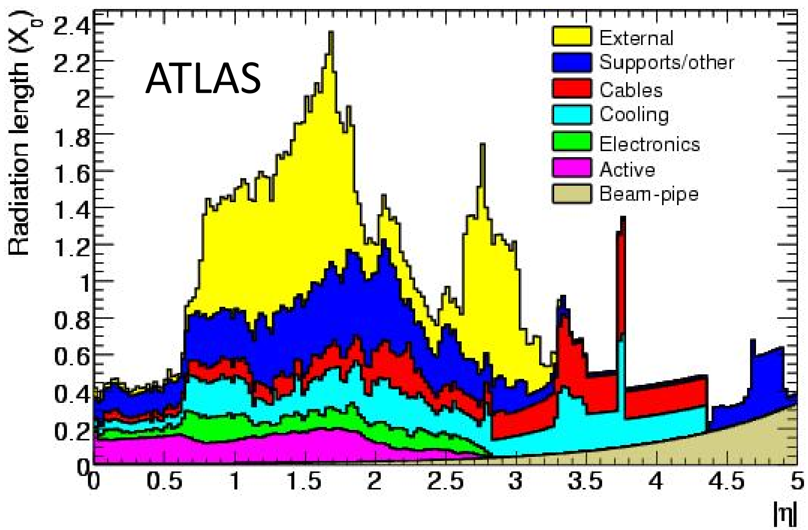
IP Resolution and Tracking Material

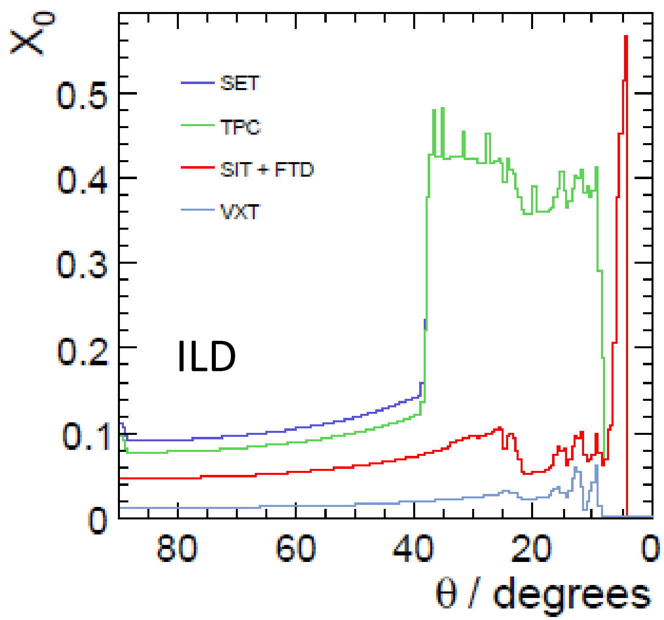


LHC detectors: $\sigma_{r\phi} \sim 20\ \mu\text{m}$ @ 20 GeV

The future e^+e^- detectors call for $\sigma_{r\phi} \sim 5\ \mu m$, a factor of 4 improvement

The main challenge is to build a low material budget tracker, $< 0.1X_0$ in the central region!





Summary

A lepton collider Higgs factory complements to the LHC and its physics case is compelling. It allows for model-independent measurements of the Higgs boson properties and can significantly improve their precisions.

Precision measurements require precision detectors. Significant improvements in performance over past and current detectors are needed, but there are no insurmountable issues.

A lot has been done in understanding the detector requirements for a precision Higgs physics program, but more need to be done.