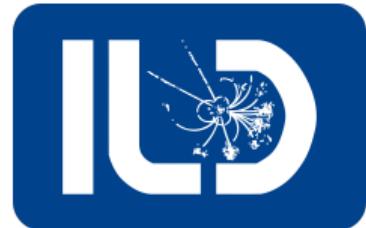




INSTITUT
POLYTECHNIQUE
DE PARIS



INCLUSIVE HIGGSSTRAHLUNG CROSS SECTION MEASUREMENTS WITH THE NEW REFERENCE SAMPLE METHOD

LCWS 2019, Sendai



OUTLINE

Inclusive Higgsstrahlung cross section measurements with the new reference sample method

Motivation:

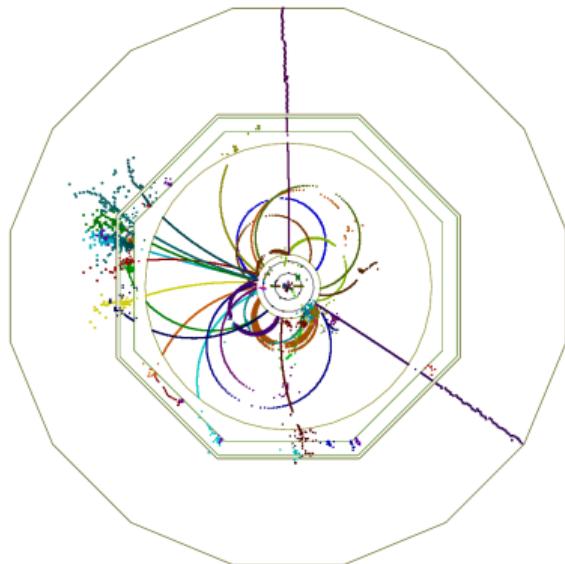
Improve the only (Higgs boson decay) model independent coupling measurement that is possible:

g_{HZZ} .

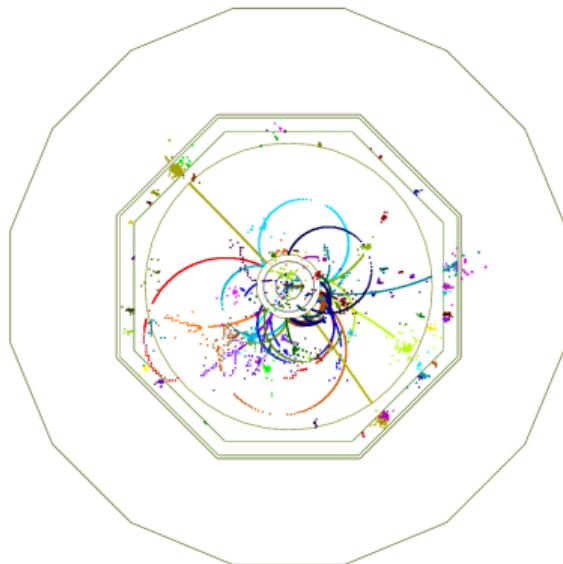
1. Reference sample method
2. The dataset
3. Uncertainty estimation

THE HIGGS-ONLY PART OF A HIGGSSTRAHLUNG EVENT

Nothing has to be removed for $Z \rightarrow \nu_l \bar{\nu}_l$.



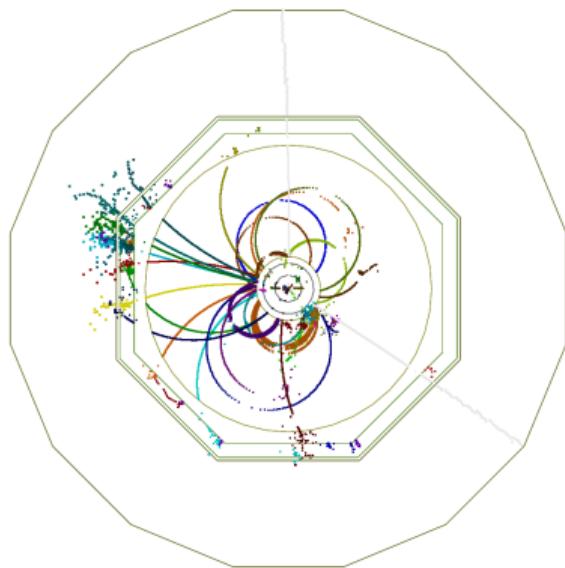
$$e^+ e^- \rightarrow HZ, Z \rightarrow \mu^+ \mu^-$$



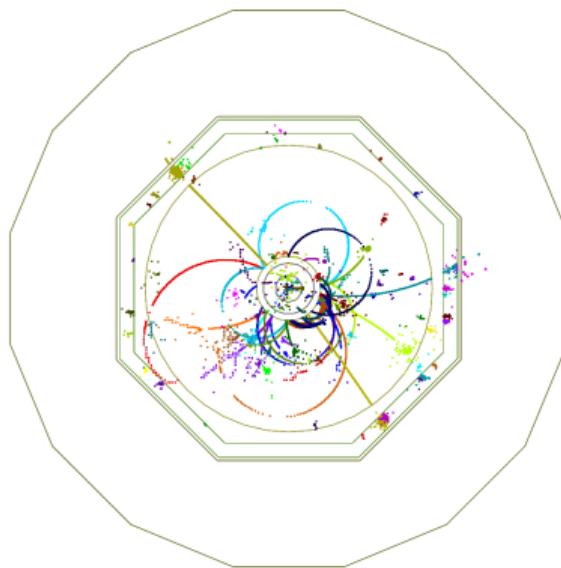
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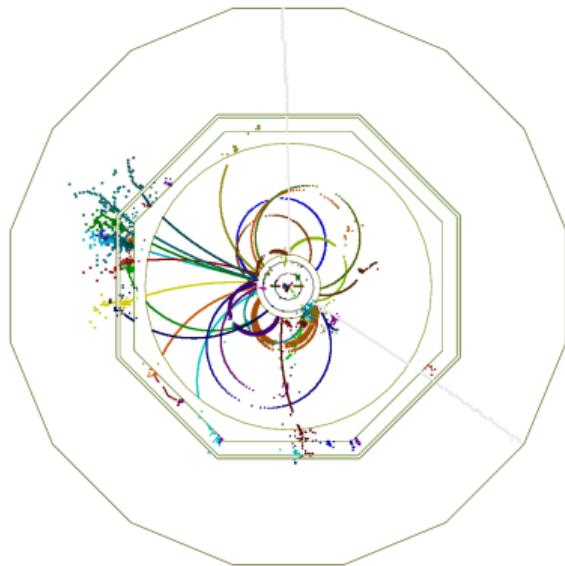
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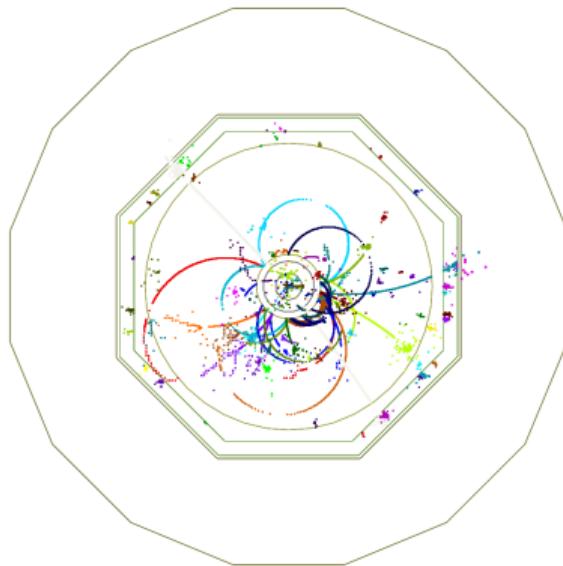
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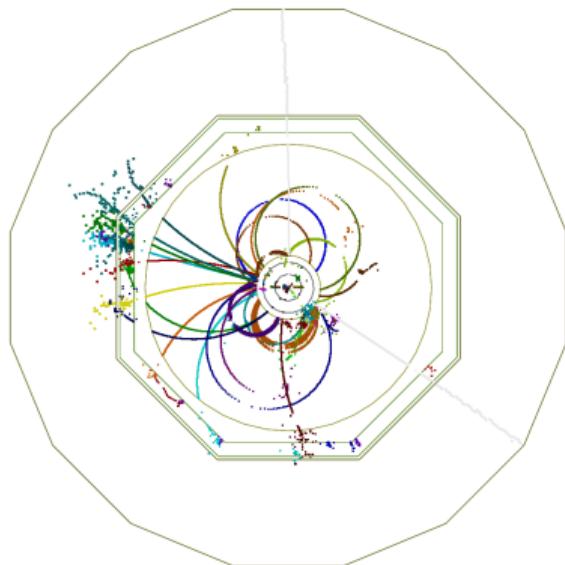
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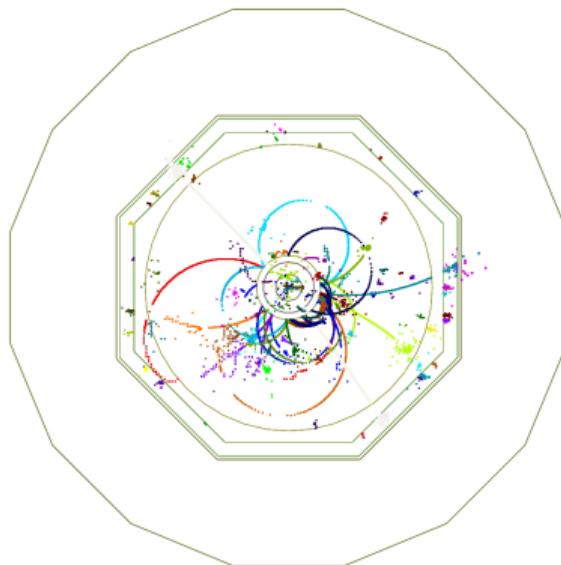
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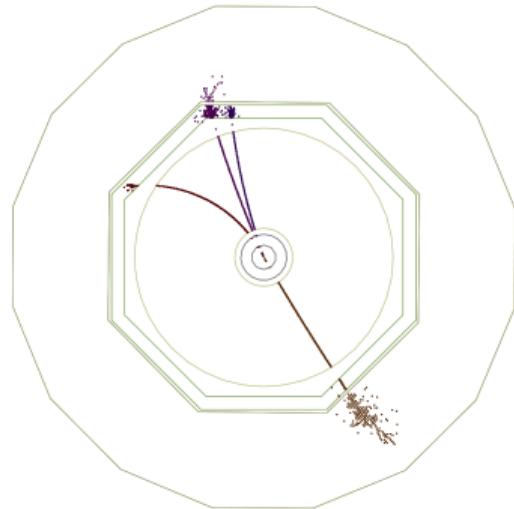
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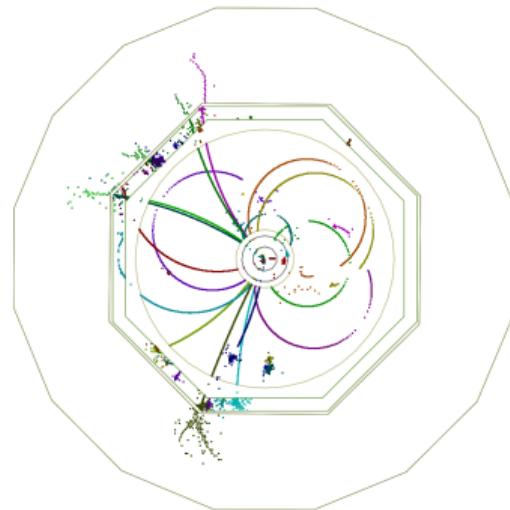
$$e^+ e^- \rightarrow HZ, Z \rightarrow e^+ e^-$$

THE HIGGS-ONLY PART OF A HIGGSSTRAHLUNG EVENT

Correct assignment still realistic for $Z \rightarrow \tau^+\tau^-$. Very difficult for $Z \rightarrow q\bar{q}$.
(Shown here : Invisible Higgs decay events.)



$$\begin{aligned} e^+e^- &\rightarrow HZ \rightarrow (ZZ)(\tau^+\tau^-) \\ &\rightarrow (4\nu)((\bar{\nu}_\tau 2\pi^+\pi^-)(\nu_\tau e^-\bar{\nu}_e)) \end{aligned}$$



$$e^+e^- \rightarrow HZ \rightarrow (4\nu)(d\bar{d})$$

TWO TYPES OF VARIABLES

REFERENCE
SAMPLE
METHOD



It is important to assign each observed momentum to the right parent particle.

Higgs-only variables

- E.g. M_H^{vis} , recoil to M_H^{vis}
- But also **number of charged hadrons**
- Differ between the Higgs decay modes
- Same distr. for all four $Z \rightarrow l\bar{l}$ samples
- Distributions taken from the *reference sample*

Z-only variables

- E.g. M_{recoil} , M_Z
- C.f. recoil mass technique
- Independent of the Higgs boson decay (model)
- Distributions taken from Monte Carlo (MC) generated data

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Counting sample

- Count the number of events in the samples
- Three samples are built : $Z \rightarrow e^+e^-$, $\tau^+\tau^-$ and $\nu_l\bar{\nu}_l$
- Event selection based on both Z-only and Higgs-only variables
- Z-only selection efficiency from MC
- Higgs-only sel. eff. from reference sample

Reference sample

- Extract the fraction of events passing a (Higgs-only) selection
- Employed Higgsstrahlung events : $Z \rightarrow \mu^+\mu^-$
- Event selection based on just the Z-only variables
- Selection efficiency from MC



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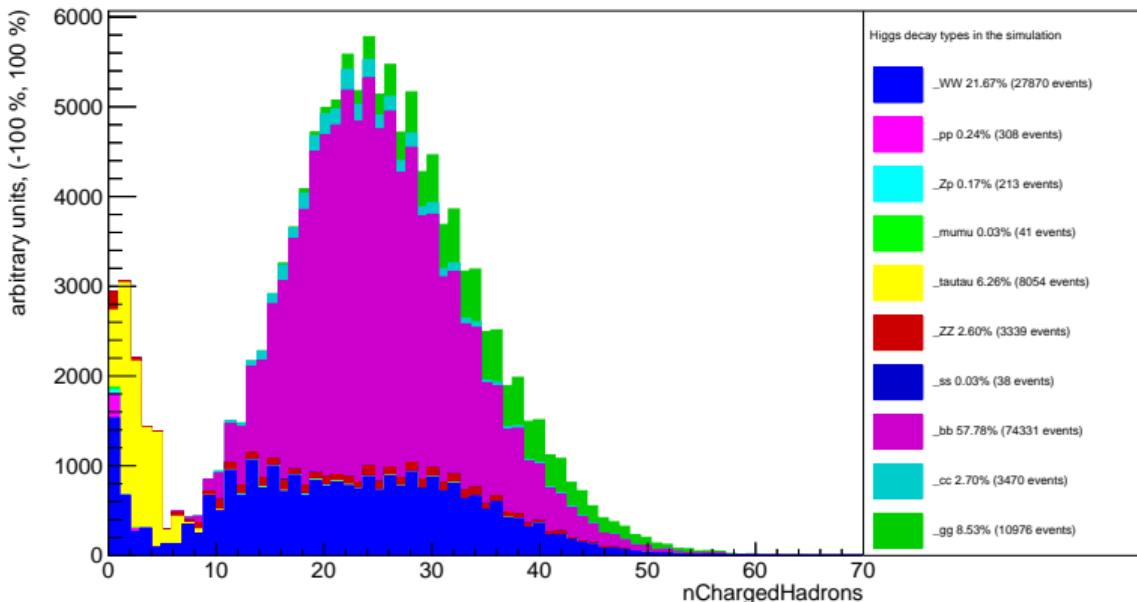
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THE REFERENCE SAMPLE

Extract the (Higgsstrahlung) signal distributions in the Higgs-only variables from it.

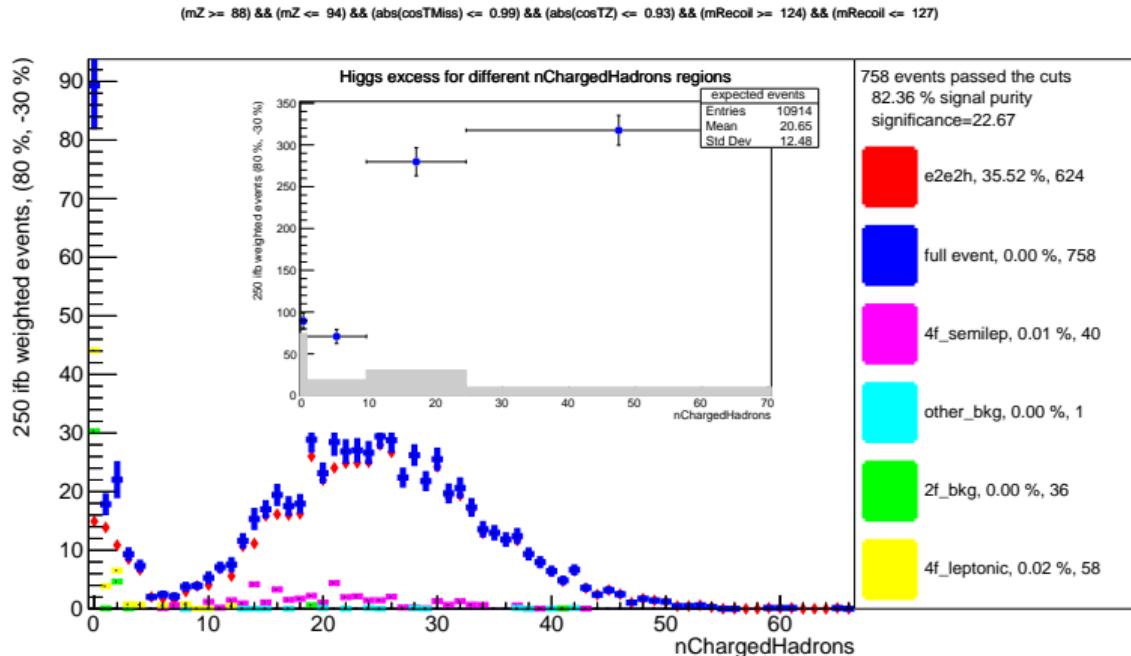
Higgs decay dependent distribution of nChargedHadrons





THE REFERENCE SAMPLE

Build a sample with a selection based on Z-only variables.



FROM MC TRUTH TO A PERFECT DETECTOR

THE
DATASET



So far, the analysis uses the MCParticle collection of the ILD DBD 250 GeV data set. (*Thank you to the ILD Software group!*)

Ignore :

- Neutrinos
- Particles with $|\cos(\theta)| > 0.995$ (beam pipe)
- Charged particles with $p_T < 0.105$ GeV (spiralling)
 - $r > 10$ cm : reach 4 vertex detector layers
 - 5 cm beam pipe, 3.5 T B-field assumed
- $E_\gamma < 0.2$ GeV
- $E < 0.5$ GeV for neutral hadrons

→ A realistic detector but with perfect particle identification (PID), unlimited granularity and without material interactions.

UNCERTAINTY ON THE HIGGSSTRAHLUNG CS

UNCER-
TAINTY



$$\begin{aligned}\sigma_{HZ} &= \frac{N_{HZ}}{L} = \frac{N_C}{BR(Z \rightarrow l\bar{l})\epsilon_Z\epsilon_H L} \\ \frac{\Delta\sigma_{HZ}}{\sigma_{HZ}} &\approx \sqrt{\left(\frac{\Delta N_C}{N_C}\right)^2 + \left(\frac{\Delta\epsilon_H}{\epsilon_H}\right)^2} \\ &= \sqrt{\frac{D_{H(l)}^l}{(N_{H(l)}^l)^2} + \frac{D_{Z(l)}^\mu}{(N_{Z(l)}^\mu)^2} + \frac{D_{H(l)|Z(l)}^\mu}{(N_{H(l)|Z(l)}^\mu)^2} - \frac{2D_{H(l)|Z(l)}^\mu}{N_{H(l)|Z(l)}^\mu N_{Z(l)}^\mu}}\end{aligned}$$

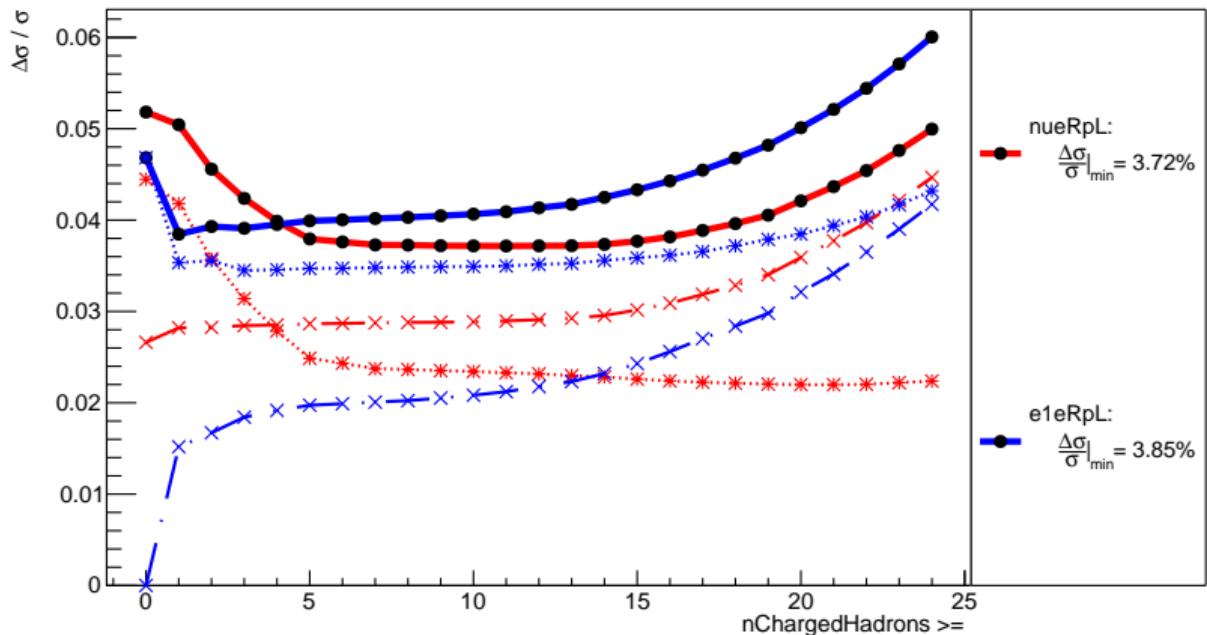
Includes the systematic uncertainty from the selection (e.g. cut on $N_{\text{ch. hadr.}}$).
Assumption : Background distributions well known.

BEHAVIOR OF THE TWO UNCERTAINTY CONTRIBUTIONS

UNCER-
TAINTY



Discriminant evaluator

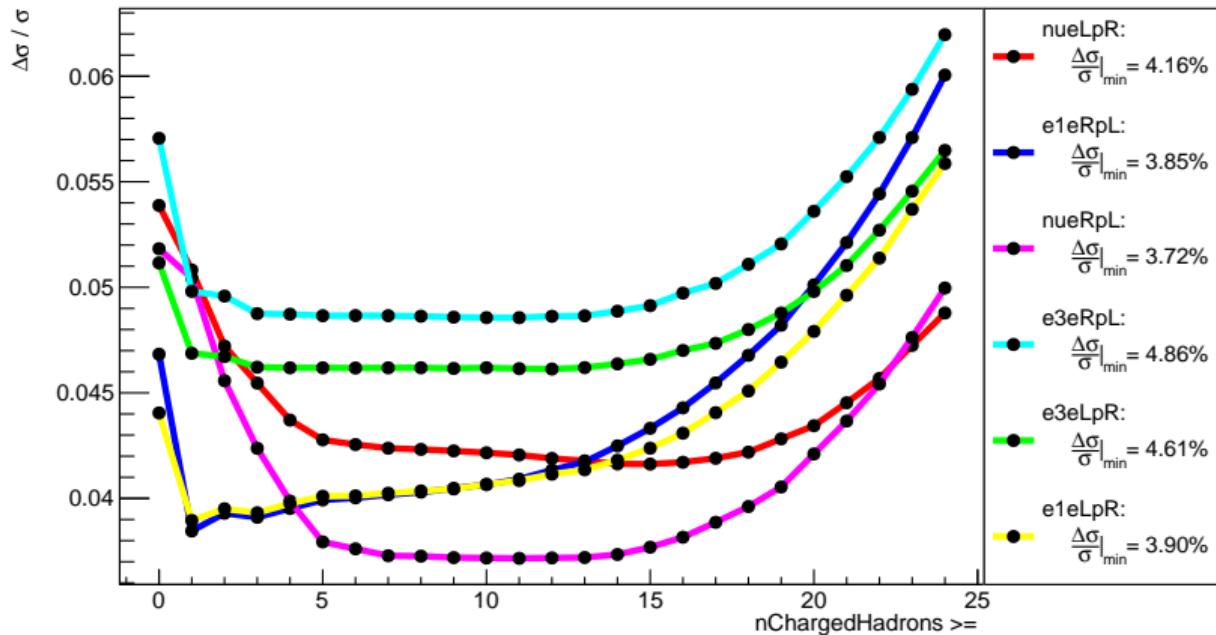


$N_{\text{ch. hadr.}} \geq 1$: Removes the important purely leptonic backgrounds.

SELECT THE OPTIMAL CUT VALUE FOR EACH SAMPLE

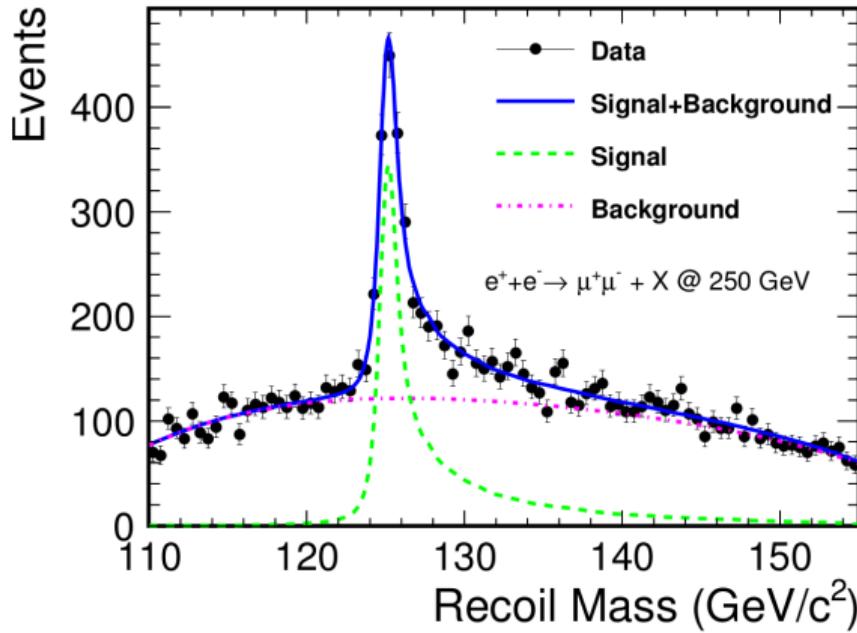


Discriminant evaluator



Two ILC polarization scenarios are considered.

COMPARISON WITH RECOIL MASS SHAPE METHOD



Shape extraction relies on $\frac{\Delta p_T}{p_T^2} = 2 \cdot 10^{-5}$ GeV⁻¹. (Figure from arXiv:1604.07524)

Here : Instead need good tagging efficiency for charged hadrons and leptons inside jets.

COMPARISON WITH RECOIL MASS SHAPE METHOD

UNCER-
TAINTY



250 GeV, 250 fb ⁻¹ , $e_L^- e_R^+$	recoil shape	new
$H\mu^+\mu^-$	3.2%	x
He^+e^-	4.0%	3.9%
$H\tau^+\tau^-$	x	4.6%
$H\nu\bar{\nu}$	x	4.2%
combined	2.5%	3.0%

COMBINATION WITH RECOIL MASS SHAPE METHOD

UNCER-
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combined	2.5%	3.0%
μ from recoil	2.4%	
μ and e from recoil	2.1%	

The reference sample analyses use $H\mu^+\mu^-$ only for the ratio of events passing a selection. → Can combine with its recoil mass shape result.

COMBINATION WITH RECOIL MASS SHAPE METHOD

UNCER-
TAINTY

250 GeV, 250 fb ⁻¹	$e_L^- e_R^+$ recoil shape	$e_L^- e_R^+$ new	$e_R^- e_L^+$ recoil shape	$e_R^- e_L^+$ new
$H\mu^+\mu^-$	3.2%	x	3.6%	x
He^+e^-	4.0%	3.9%	4.7%	3.8%
$H\tau^+\tau^-$	x	4.6%	x	4.9%
$H\nu\bar{\nu}$	x	4.2%	x	3.7%
combined	2.5%	3.0%	2.9%	2.8%
μ from recoil	2.4%		2.2%	
μ and e from recoil	2.1%		2.2%	

- New results without detector simulation & reconstruction.
- But also without cut variable and value optimization.
- Access to new channels improves the uncertainties (20% for $e_L^- e_R^+$, 30% for $e_R^- e_L^+$) without additional data taking.





Goal :

Improve the only (Higgs boson decay) model independent coupling measurement that is possible :

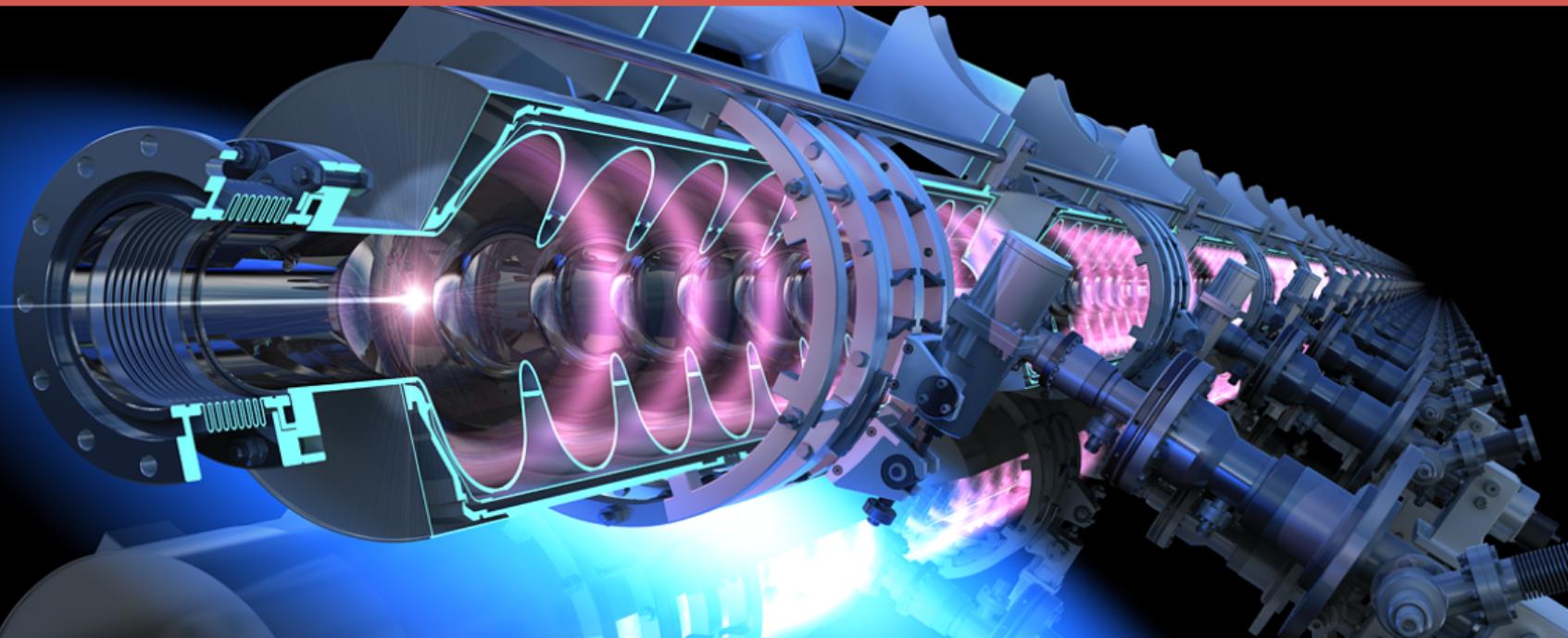
g_{HZZ} . ✓
(Almost equivalent to 2×luminosity)

Next steps :

- Add $Z \rightarrow e^+e^-$ events to the reference sample
- Repeat with ILD detector simulation & reconstruction (see slides 8 and 12 : should not change much)
- New selection variables, MVA selection
- Move on to contents of Jean-Claude's talk

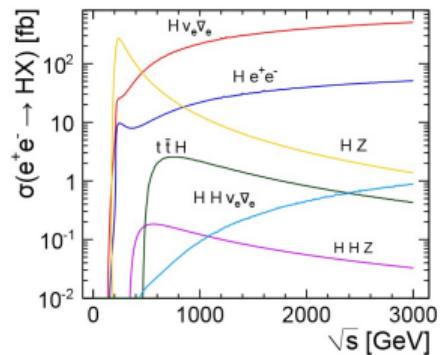
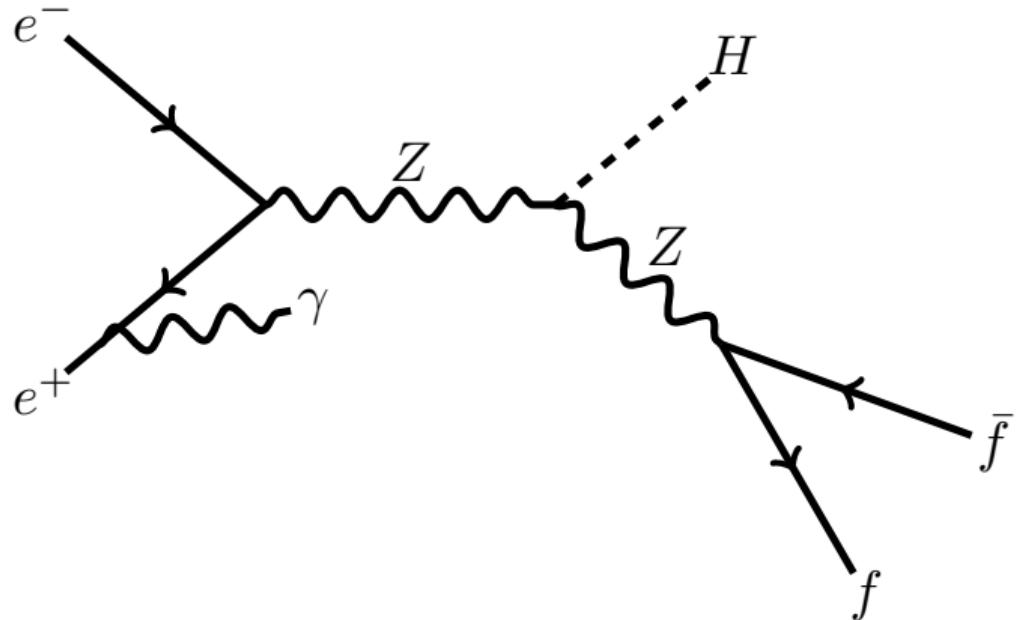
3

BACK-UP



HIGGS BOSON PRODUCTION AT A LEPTON COLLIDER

BACK-UP



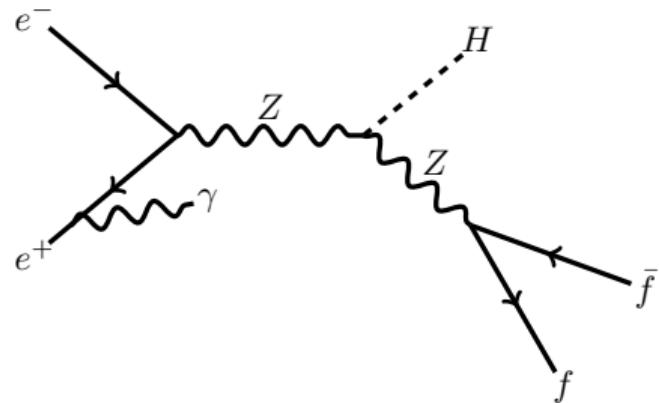
THE RECOIL MASS TECHNIQUE

BACK-UP



Event selection without looking at the Higgs boson (decay products).

- The initial states at a lepton collider are known (momenta and particle types) $\rightarrow \sqrt{s}$
- Identify the Z boson decay products $\rightarrow M_Z, E_Z$
- For a Higgsstrahlung event :
$$M_{\text{recoil}}^2 = s + M_Z^2 - 2\sqrt{s} \cdot E_Z \approx M_H^2$$

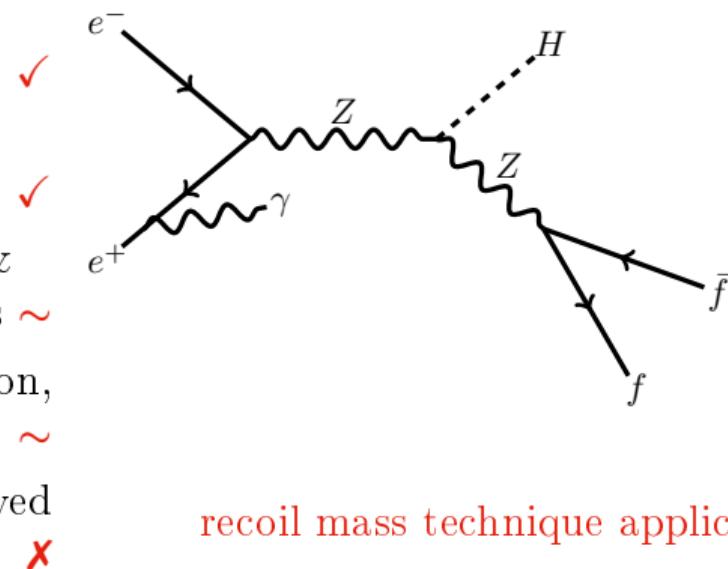




Z BOSON DECAYS

Decay product identification and momentum reconstruction procedure differ between the channels :

1. $BR(Z \rightarrow \mu^+ \mu^-) \approx 3.4\%$: The simplest channel
2. $BR(Z \rightarrow e^+ e^-) \approx 3.4\%$: Final state radiation important
3. $BR(Z \rightarrow q\bar{q}) \approx 69.9\%$: Hadronization & jets \rightarrow many different detector signatures \sim
4. $BR(Z \rightarrow \tau^+ \tau^-) \approx 3.4\%$: τ reconstruction, momentum carried by ν_τ invisible \sim
5. $BR(Z \rightarrow \nu_l \bar{\nu}_l) \approx 20.0\%$: Nothing observed in the detector \times



recoil mass technique applicable

THE ILD DBD 250 GEV DATA SET

BACK-UP

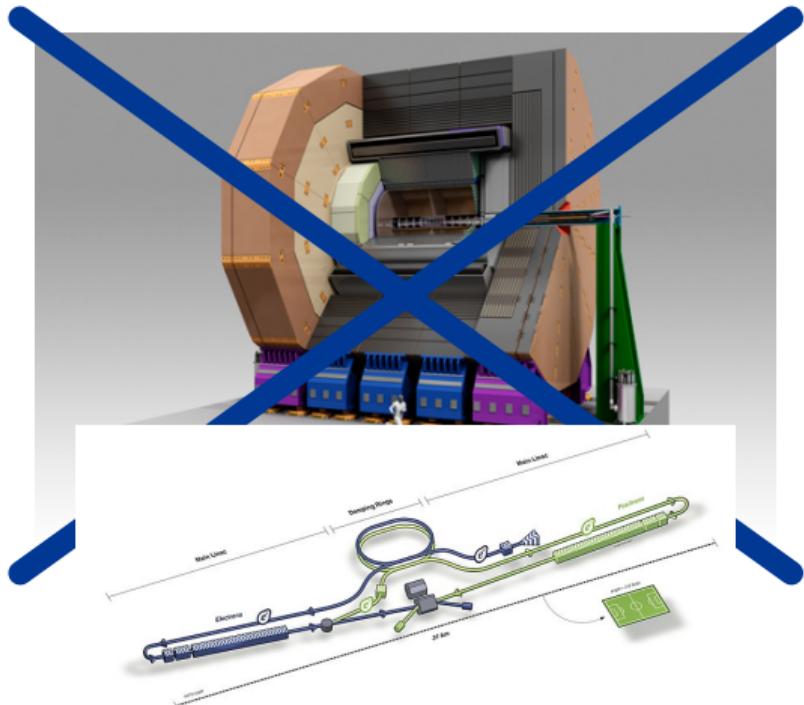


$\sqrt{s} = 250$ GeV	cross section		N_{Gen}	
e^- polarisation	left	right	left	right
$\mu^+ \mu^- H$	17.1 fb	11.0 fb	17.1k	11.0k
$e^+ e^- H$	17.6 fb	11.2 fb	17.6k	11.2k
$\tau^+ \tau^- H$	17.1 fb	11.0 fb	17.1k	11.0k
$\nu_l \bar{\nu}_l H$	128.6 fb	65.1 fb	0.13M	65.1k
2f_h	129.15 pb	71.27 pb	1.75M	1.43M
2f_l	46.51 pb	40.70 pb	2.63M	2.13M
4f_h	28.66 pb	966.2 fb	2.50M	0.24M
4f_l	8.89 pb	1.28 pb	2.25M	0.35M
4f_sl	31.12 pb	1.42 pb	4.43M	0.36M
$q\bar{q}H$	346.0 fb	222.0 fb	0.35M	0.22M
sum	244.86 pb	115.95 pb	14.09M	4.83M

- Large Standard Model event generation and detector simulation
→ for Detailed Baseline Design (DBD)
- A particle flow algorithm (PandoraPFA) was run on simulated events in 2013
- Process luminosities between $\sim 20 \text{ fb}^{-1}$ (Bhabha) and 1000 fb^{-1} (Higgs)



THE ILD DBD 250 GEV DATA SET



- ILD is a detector concept for the *International Linear Collider* (ILC)
- Event **generation** depends on the accelerator (ILC) :
 - Design \sqrt{s} , polarization
 - Beam energy spread
 - Beamstrahlung, event overlay
- Detector **simulation** adds :
 - Material interaction (backscattering)
 - Tracker and calorimeter hits
 - Resolution

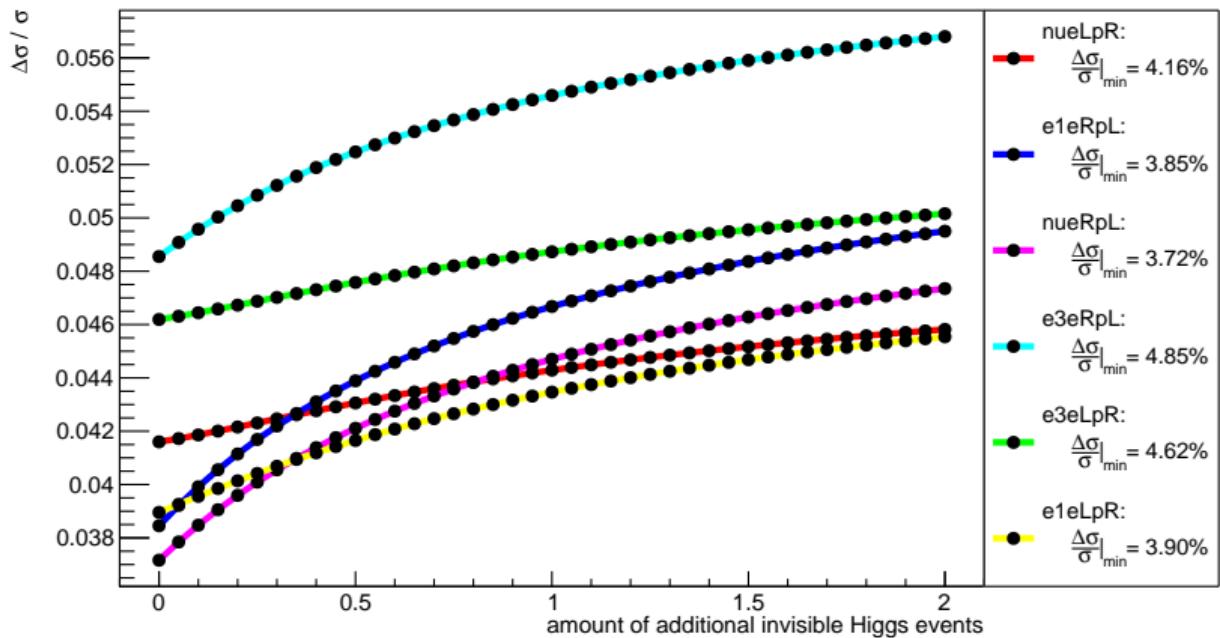
UNCERTAINTY INCREASE FROM INVISIBLE HIGGS DECAYS

BACK-UP

Assume invisible Higgs boson decay events additional to the expected events.



Uncertainty for different Higgs models



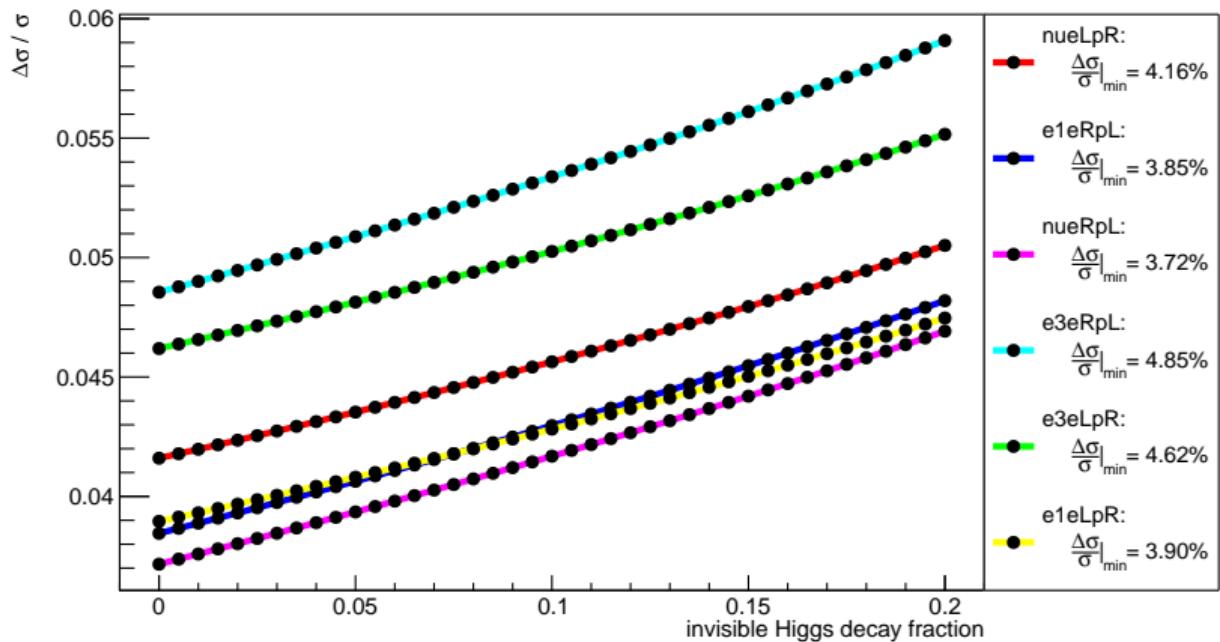
UNCERTAINTY INCREASE FROM INVISIBLE HIGGS DECAYS

BACK-UP

Assume some of the expected Higgs boson events actually decay invisibly.



Uncertainty for different Higgs models

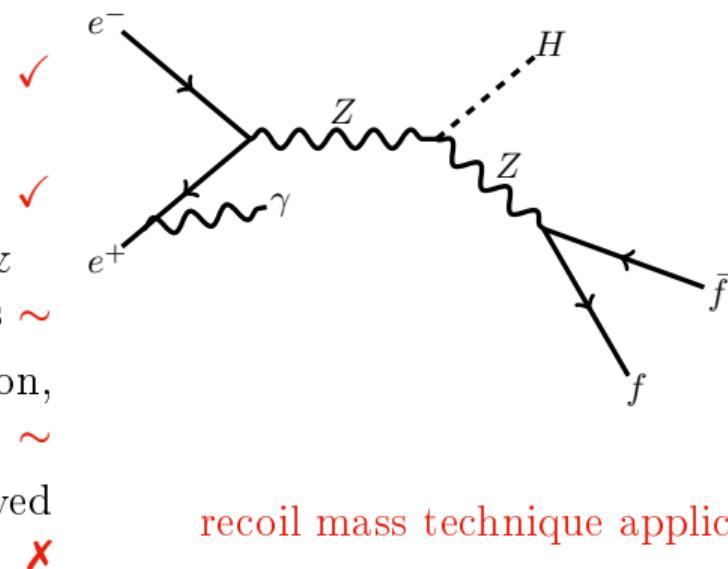




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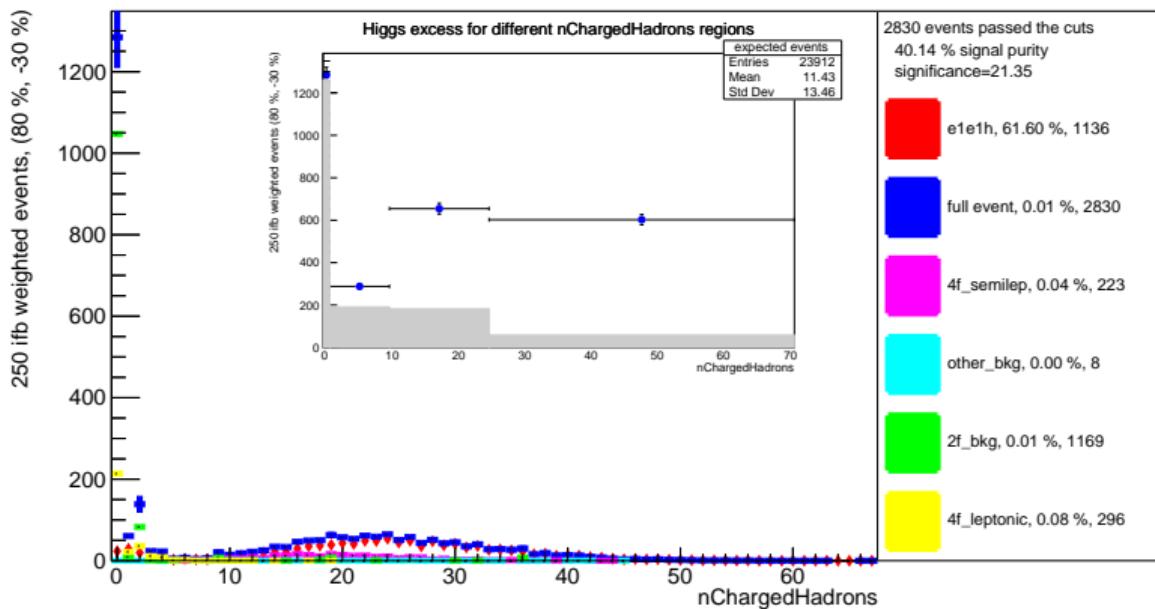


recoil mass technique applicable



ELECTRON SAMPLE (+80%, -30%)

$(mZ \geq 86) \& (mZ \leq 96) \& (\text{abs}(\cos T\text{Miss}) \leq 0.99) \& (\text{abs}(\cos TZ) \leq 0.98) \& (m\text{Recoil} \geq 124) \& (m\text{Recoil} \leq 134)$

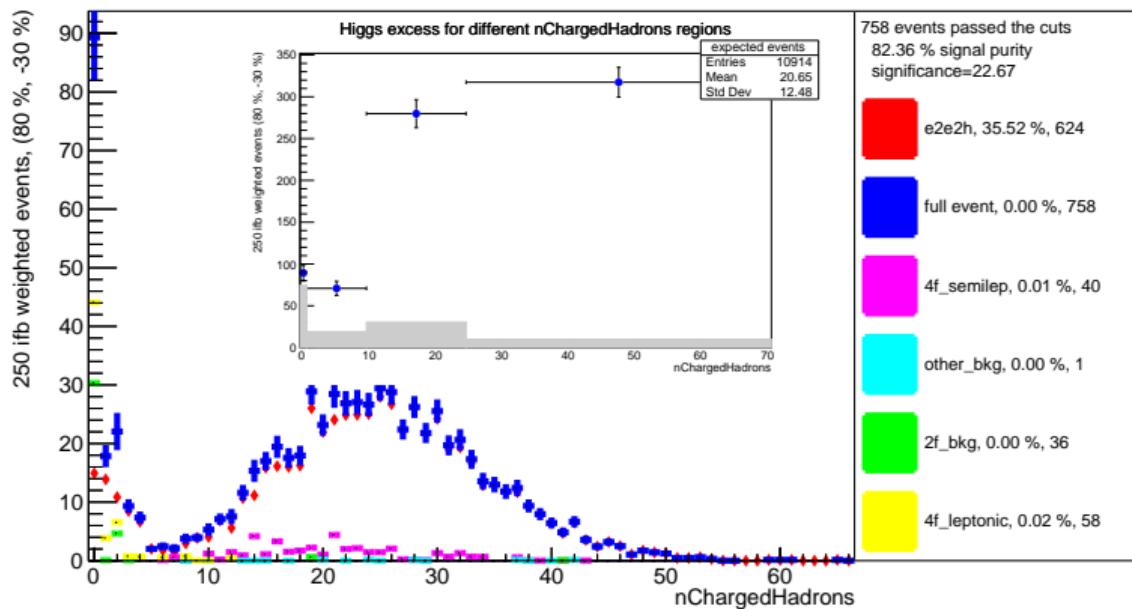


MUON SAMPLE (+80%, -30%)

BACK-UP



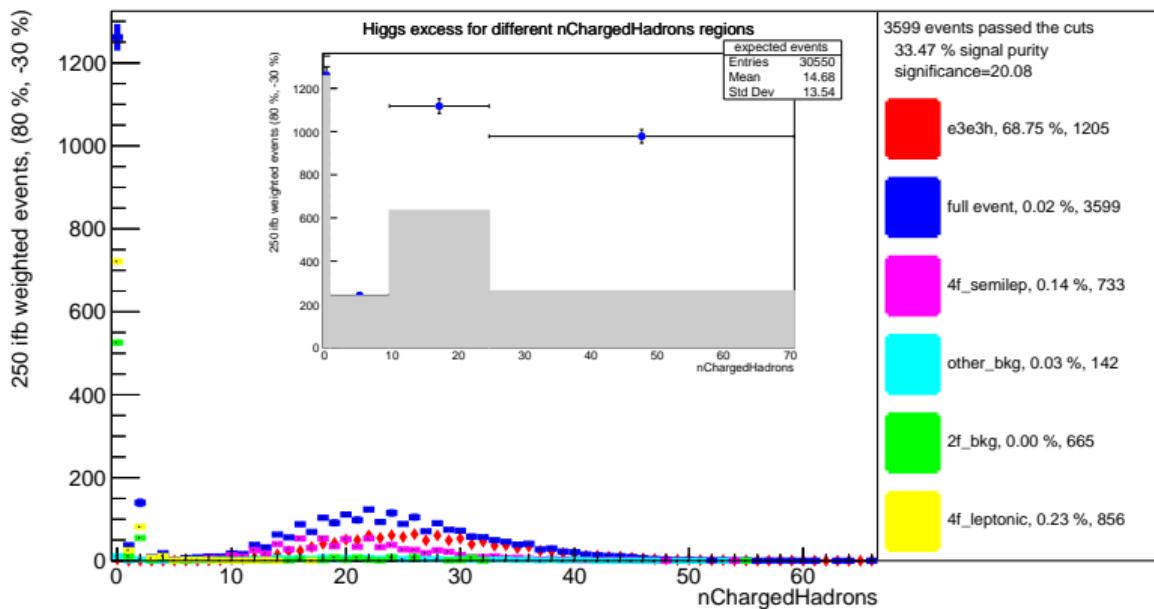
(mZ >= 88) && (mZ <= 94) && (abs(cosTmiss) <= 0.99) && (abs(cosTZ) <= 0.93) && (mRecoil >= 124) && (mRecoil <= 127)





TAU SAMPLE (+80%, -30%)

(mHrecoil >= 80) && (mH <= 132) && (mH >= 103) && (abs(cosTmiss) <= 0.99) && (mZ != 0)





NEUTRINO SAMPLE (+80%, -30%)

