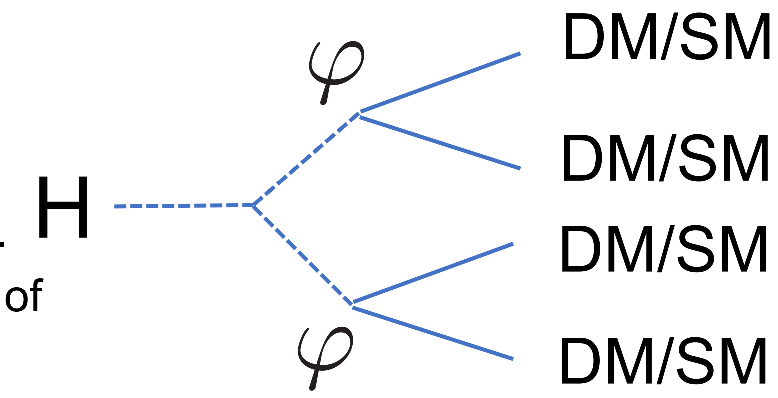
Search for Higgs decaying to exotic scalers at the ILC

Yu Kato
The University of Tokyo

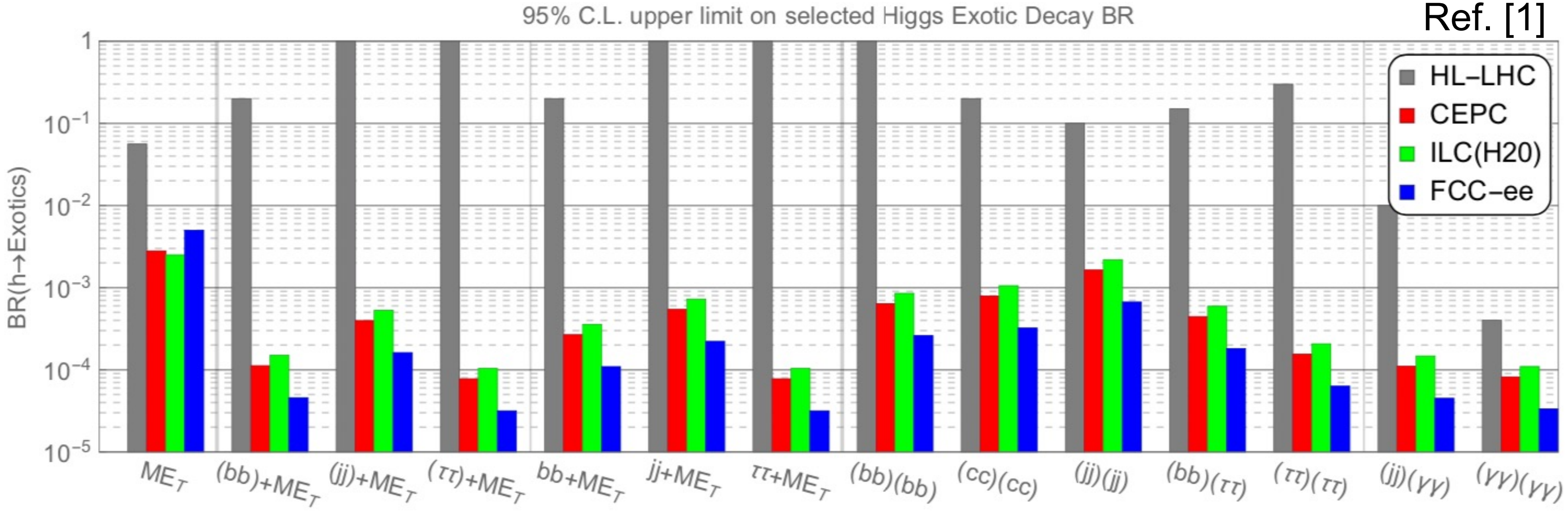
ILC-IDT-WG3 mini-workshop on BSM
Mar. 2, 2022

Higgs exotic decay through scalar mediators

- Higgs can couple to WIMP DM through the scalar mediator.
- The mediator appears as the Higgs exotic decay.
- This study is the first “Full Simulation” analysis for H→φφ at the ILC.
  - The below plot is the prospects from the previous phenomenological study of Higgs exotic decays at future collider experiments[1].

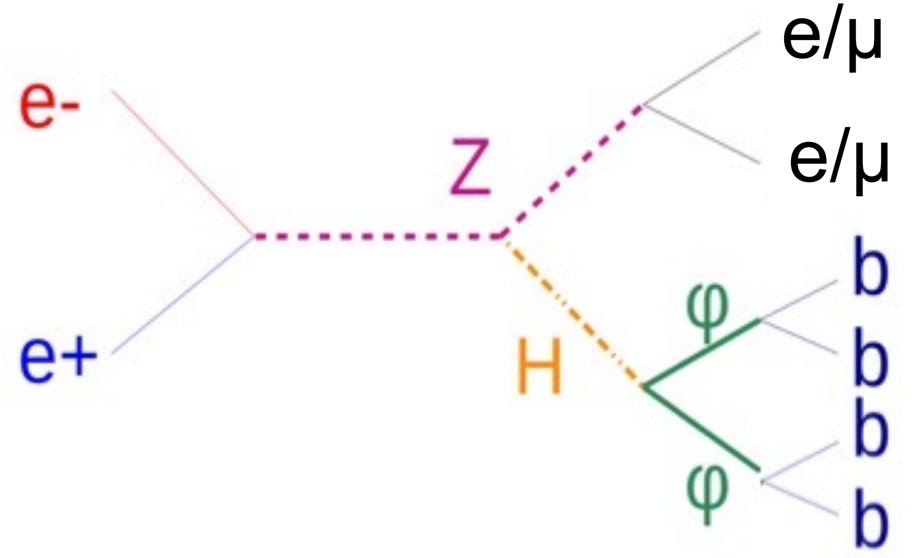


Ref. [1]



[1] Zhen Liu, Lian-Tao Wang, Hao Zhang, “*Exotic decays of the 125 GeV Higgs boson at future e+e− lepton colliders*”, ***Chinese Phys. C* 41 063102, 2017,** [arXiv:1612.09284 [hep-ph]]

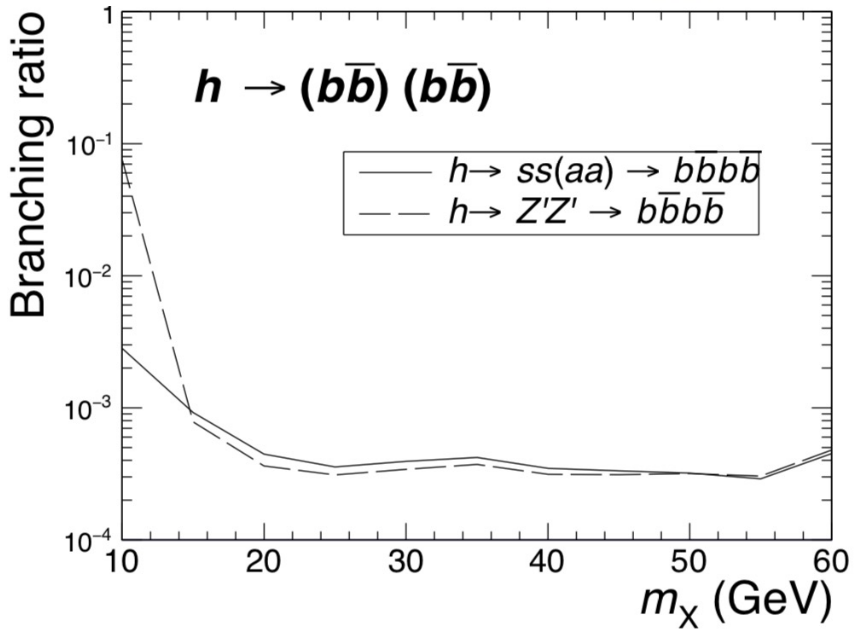
Search for Higgs → φφ → 4b



- Target of this study:

  e+e- → ZH, Z → ee/μμ, H → φφ → 4b
  - with **ILD full detector simulation**
  - Mediator mass range: 15 - 60 GeV
  - Mediators decay promptly.
  - Previous study[1]: 95% C.L. upper limit on BR(H→4b) < 0.1%

- This study is a part of more general study of H → φφ which includes invisible and partially invisible decays.



Ref. [1], CEPC 5 ab^{-1} scenario

Simulation setup

- Generator: WHIZARD 2.8.5

  Signal production
  - Assumption of φ mass: 15, 30, 45, 60 [GeV]

- Collider parameters:
  - ILC H20 scenario of $\sqrt{s}$ = 250 GeV, Luminosity = 2 ab^{-1}
  - Polarization: $P(e^-,e^+)$ = { (-80%,+30%), (+80%,-30%) }

- Detector: Full simulation of latest ILD model

- Samples
  - Signal: 20K events / φ mass / polarization
  - Main backgrounds: Full events of mc-2020 production

    mc-2020: https://ild.ngt.ndu.ac.jp/mc-prod/prodmon/prodsum-mc2020.html
    - Other 2f, 4f, 6f backgrounds are used in small statistics(~100K).

Main backgrounds

μμ + 4b
- μμH (e2e2h)
- llqq (4f_zz_sl)
- qqH (qqh)
- ττH (e3e3h)
- llqqq (6f_llxyyx, 6f_llyyyy)

ee + 4b
- eeH (e1e1h)
- eeqq (4f_sze_sl)
- qqH (qqh)
- ττH (e3e3h)
- eeqqq (6f_eeyyyy)

Analysis flow

Event reconstruction

1. Particle reconstruction: `PandoraPFA`
2. Isolated lepton selection: `IsolatedLeptonTaggingProcessor`
3. Jet clustering & Flavor tagging: `LCFIPlus`

   Durham forced to 4 jets
4. Jet pairing

   Requiring the combination of which invariant masses of paired jets are closest.

Event selection

- The number of isolated [muons / electrons] = 2
- The sum of b-probabilities of 4 jets > 3
- The recoil mass within (124, [160 / 180]) GeV

- We assume BR($H \to \varphi\varphi \to 4b$) = 1 % for the event selection.

Isolated Lepton Tagging

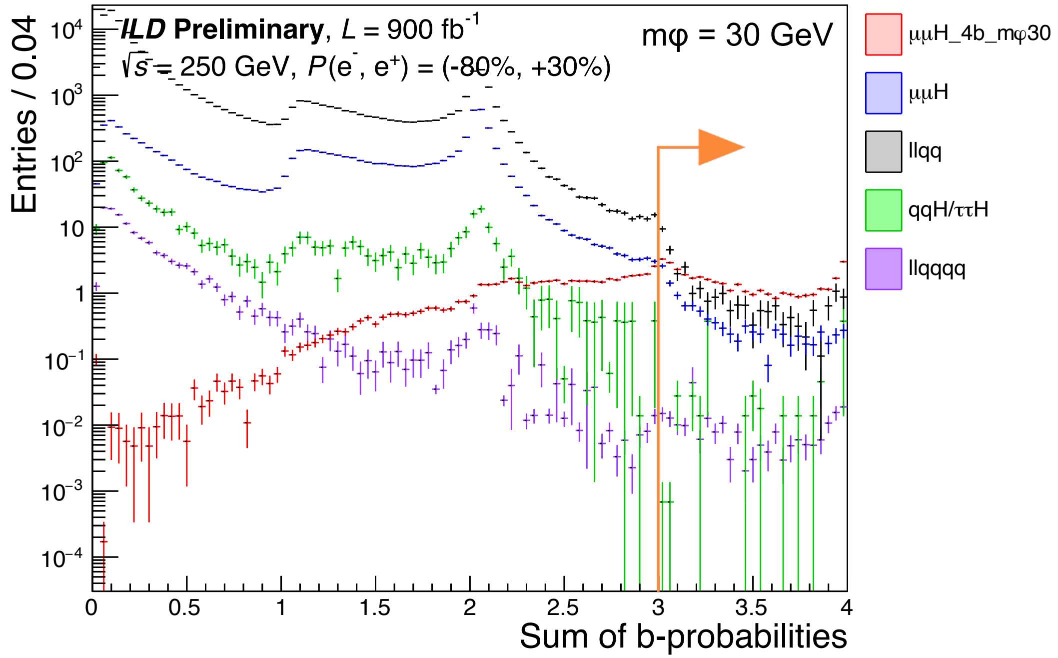
- Processor: `MarlinReco/Analysis/IsolatedLeptonTaggingProcessor`
  - Standard parameters

parameter	requirement e	/ μ
$\cos\theta_L$	0.95	0.95
$\cos\theta_S$	0.98	0.98
E_{Cal} / p	0.5 - 1.3	< 0.3
E_{ECal} / E_{total}	> 0.9	-
E_{Yoke}	-	> 1.2
p	> 5	> 5
d0 significance	< 50	< 20
z0 significance	< 50	< 20
MVA cut	0.5	0.7

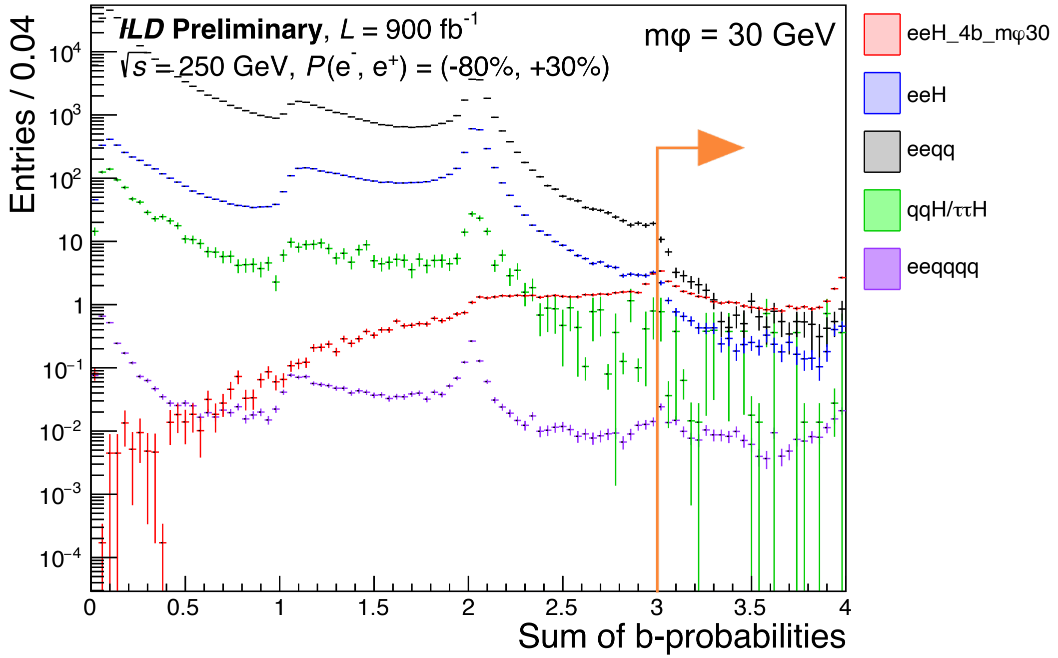
- Selection efficiency for signal samples ($P(e^-,e^+)$ = (-80%,+30%), mφ = 30 GeV)
  - μμ: 93.6%
  - ee: 86.4%

Event selection: b-probability

μμ + 4b



ee + 4b



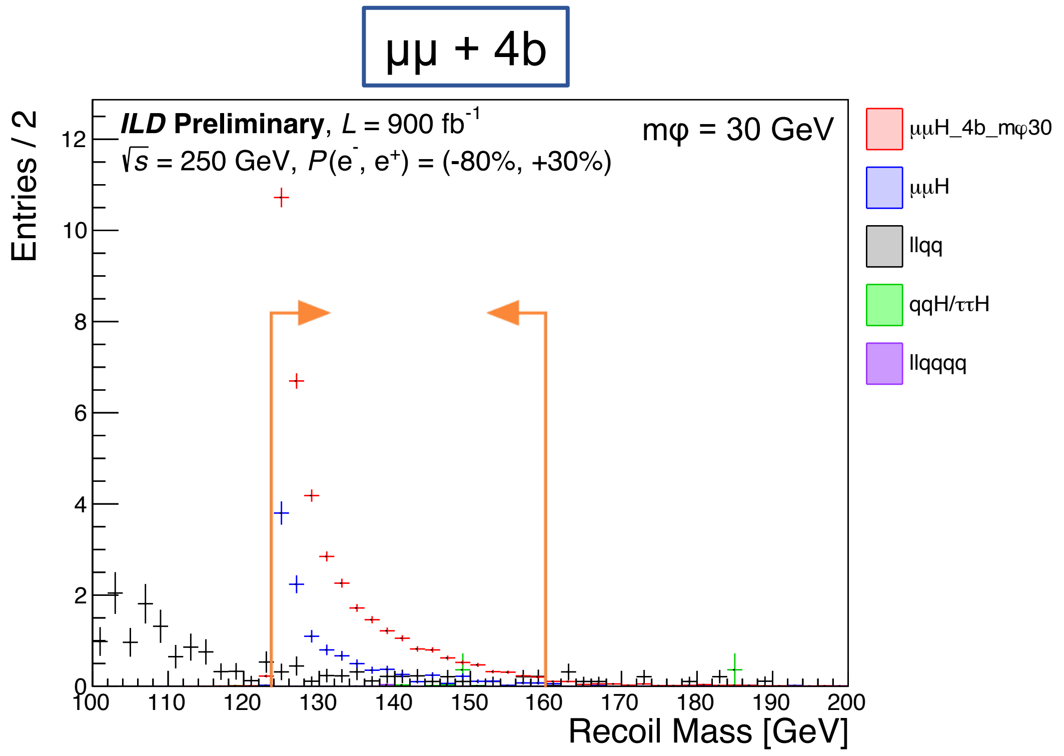
b-probability:

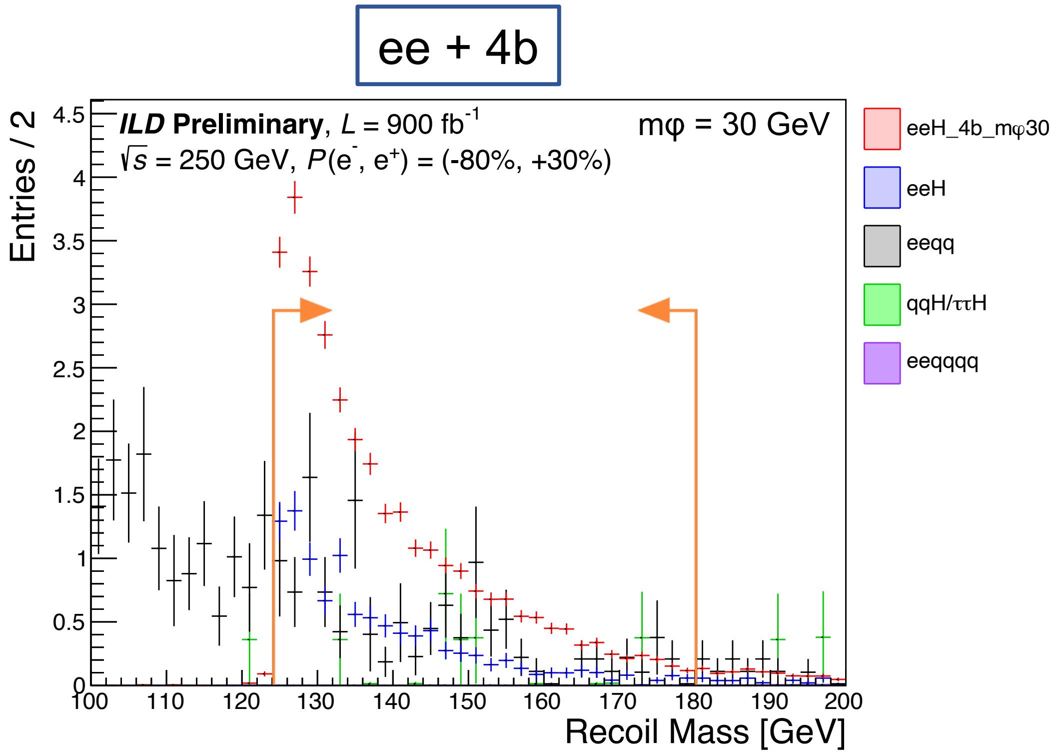
- output from LCFIPlus flavor tagging processor
- defined by each jet

Cut condition:

“Sum of b-probabilities” > 3

Event selection: Recoil mass





Recoil mass:

$$M_{recoil} = \sqrt{(\sqrt{s} - E_{ll})^2 - |\vec{p_{ll}}|^2}$$

Cut conditions:

Muon: 124 GeV < Recoil mass < 160 GeV
Electron: 124 GeV < Recoil mass < 180 GeV

Cut table

μμ + 4b, mφ = 30 GeV, *P*(e[-],e[+]) = (-80%,+30%), √s = 250 GeV, *L* = 900 fb[-1], ***ILD* Preliminary**

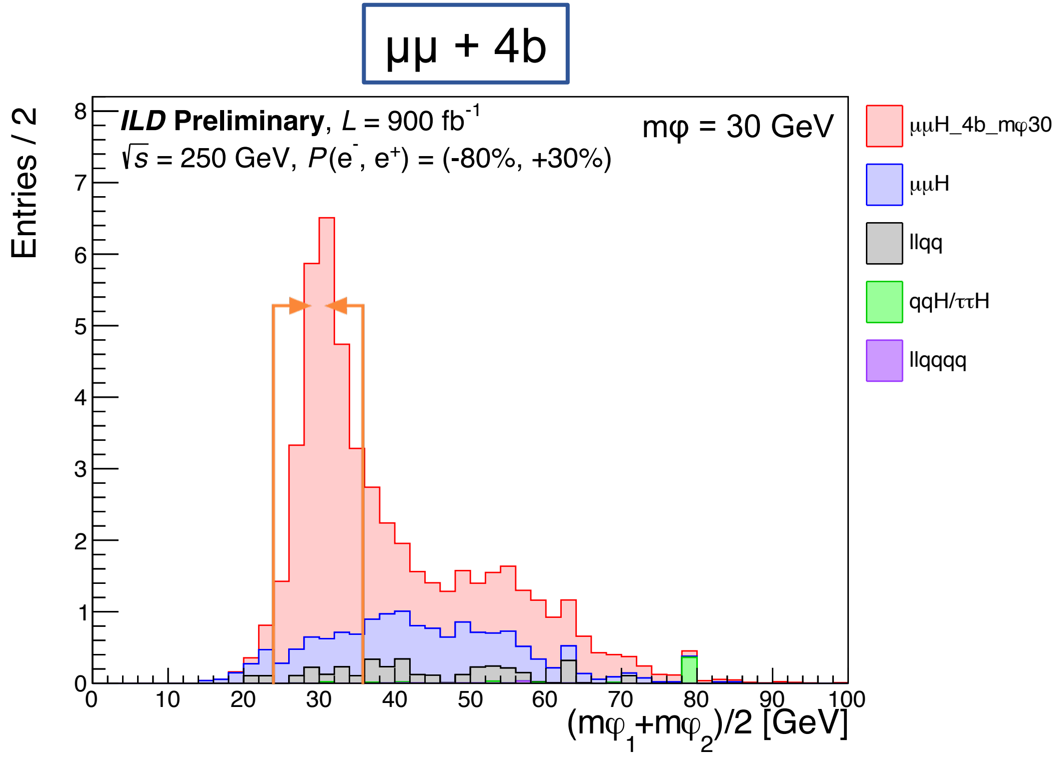
	μμH	llqq (4f_zz_sl)	qqH/ττH	llqqq (6f_llxyyx, 6f_llyyyy)	Signal	Efficiency	Significance
No Cut	9277.43	455954	196780	645.21	92.81		
2 isolated leptons	7894.98	116545	3008.86	122.82	86.92	0.937	0.243
2 isolated muons	7861.08	113424	735.64	120.83	86.84	0.936	0.248
Σ b-prob. > 3.	11.28	31.60	0.97	0.24	37.33	0.402	4.137
M_{recoil} ∈ (124,160) GeV	11.10	3.40	0.46	0.07	36.45	0.393	5.081

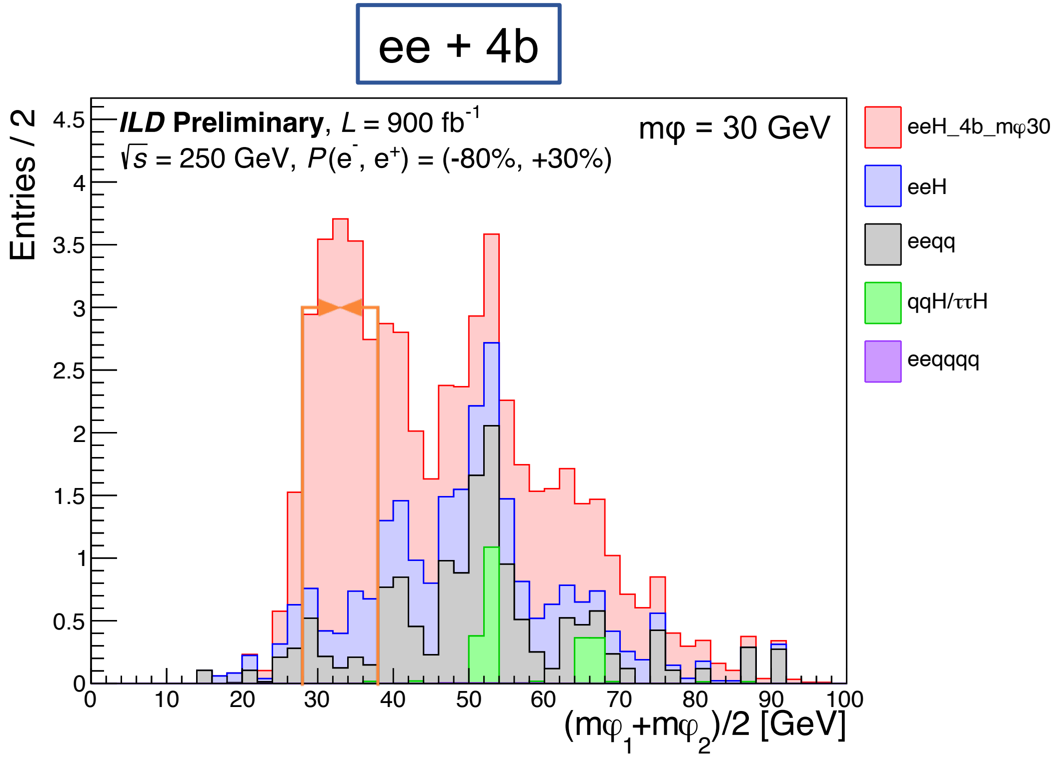
ee + 4b, mφ = 30 GeV, *P*(e[-],e[+]) = (-80%,+30%), √s = 250 GeV, *L* = 900 fb[-1], ***ILD* Preliminary**

	eeH	eeqq (4f_sze_sl)	qqH/ττH	eeqqqq (6f_eeyyyy)	Signal	Efficiency	Significance
No Cut	9868.15	1183160	196780	8.78	92.95		
2 isolated leptons	7792.59	267326	3008.86	4.56	80.38	0.865	0.152
2 isolated electrons	7708.17	263831	989.17	4.54	80.26	0.864	0.154
Σ b-prob. > 3.	10.64	40.63	5.42	0.24	33.07	0.356	3.486
M_{recoil} ∈ (124,180) GeV	10.21	12.45	2.27	0.05	31.79	0.342	4.220

- Other backgrounds are removed at the end of the selection.

Stacked histogram of mediator mass

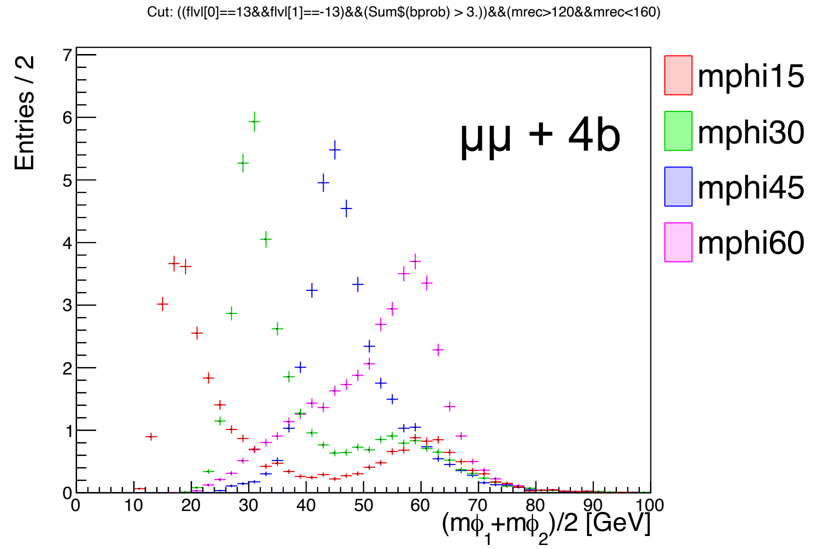


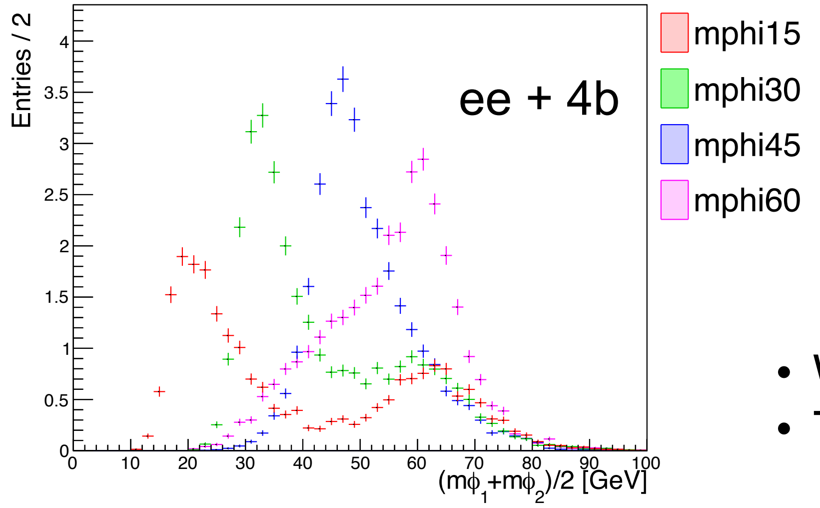


- After the event selection, a clear peak can be seen in the mediator mass distribution on the assumption of BR(H→4b) = 1%.

- The final cut conditions of mediator mass are determined to optimize the significance.
    - See details in backup

Comparison of φ mass and Combined results





ILD Preliminary

μμ + 4b

	95% C.L. upper limit on BR(H→4b)		
mφ	(-0.8,+0.3)	(+0.8,-0.3)	combined
15	0.11%	0.14%	0.09%
30	0.14%	0.17%	0.11%
45	0.15%	0.20%	0.12%
60	0.14%	0.19%	0.11%

ee + 4b

	95% C.L. upper limit on BR(H→4b)		
mφ	(-0.8,+0.3)	(+0.8,-0.3)	combined
15	0.19%	0.24%	0.15%
30	0.21%	0.25%	0.16%
45	0.24%	0.26%	0.18%
60	0.22%	0.26%	0.17%

mφ	ee + μμ
15	0.07%
30	0.09%
45	0.10%
60	0.09%

- We obtained 95% C.L. upper limit on BR(H→4b) ~ 0.1% for all mφ.
- The smaller peaks would be due to mis-pairing of jets.
  - See details in backup

Summary

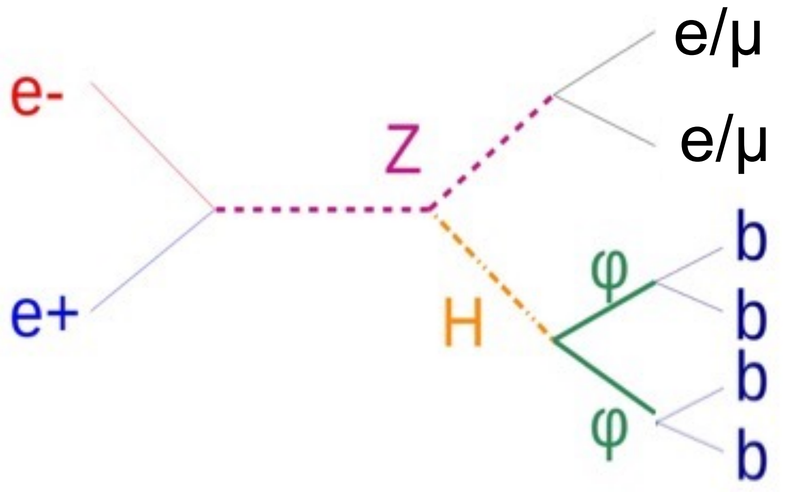
- The ILC has the possibility to search for Higgs exotic decays to the scalar mediators.
- We performed **the first full simulation study of $H \to \varphi\varphi$ at the 250 GeV ILC using ILD concept**.
- The target channels of this talk are **$e^+e^- \to ZH$, $Z \to ee/\mu\mu$, $H \to \varphi\varphi \to 4b$**.
- We obtained **95% C.L. upper limit on BR($H \to \varphi\varphi \to 4b$) ~ 0.1% in the range of m_φ from 15 - 60 GeV** which is consistent with the previous phenomenological study.

backup

Short Summary

This is the first “full simulation” analysis for H→φφ at the ILC.

- φ: scalar mediator



Target of this study

e+e- → ZH, Z → ee/μμ, H → φφ → 4b

- with **ILD full detector simulation**
- Mediator mass range: 15 - 60 GeV
- ILC H20 scenario of √s = 250 GeV, Luminosity = 2 ab^{-1}
- Polarization: $P(e^-,e^+)$ = { (-80%,+30%), (+80%,-30%) }
- Previous study[1]: 95% C.L. upper limit on BR(H→4b) < 0.1%

This study is a part of more general study of H → φφ which includes invisible and partially invisible decays.

Analysis flow

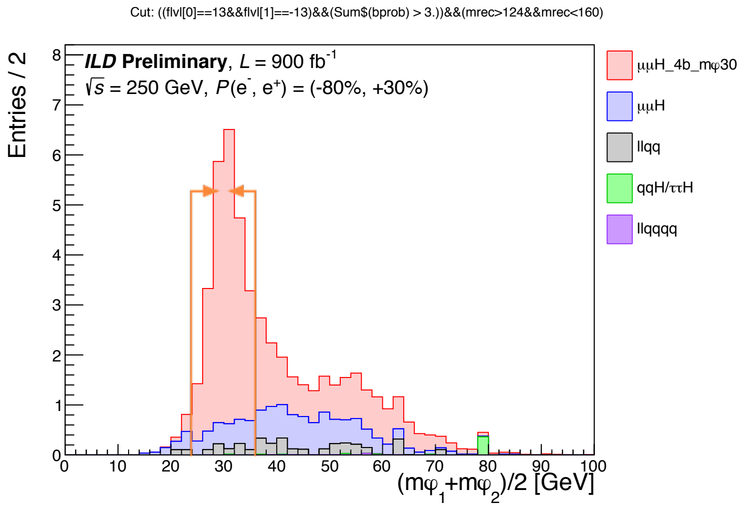
Event reconstruction

1. Particle reconstruction
2. Isolated lepton selection
3. Jet clustering & Flavor tagging
4. Jet pairing

Event selection

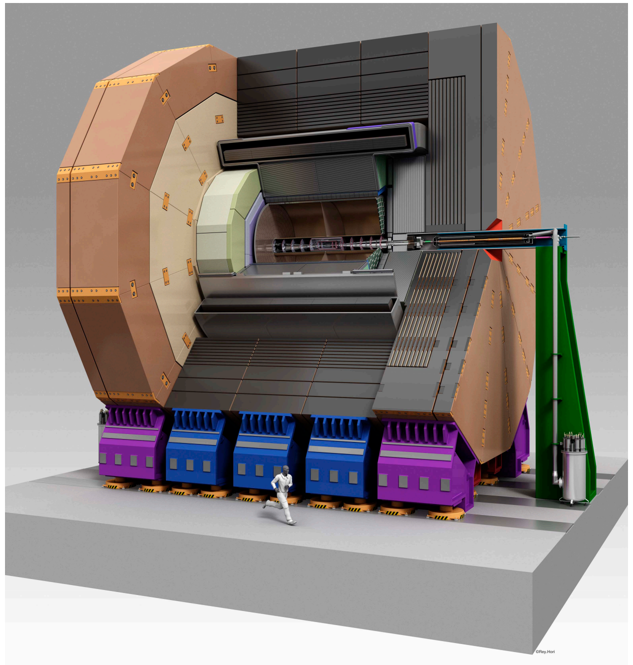
- The number of isolated [muons / electrons] = 2
- The sum of b-probabilities of 4 jets > 3
- The recoil mass within (124, [160 / 180]) GeV

mφ	UL on BR(H→4b)
15 GeV	0.07%
30 GeV	0.09%
45 GeV	0.10%
60 GeV	0.09%



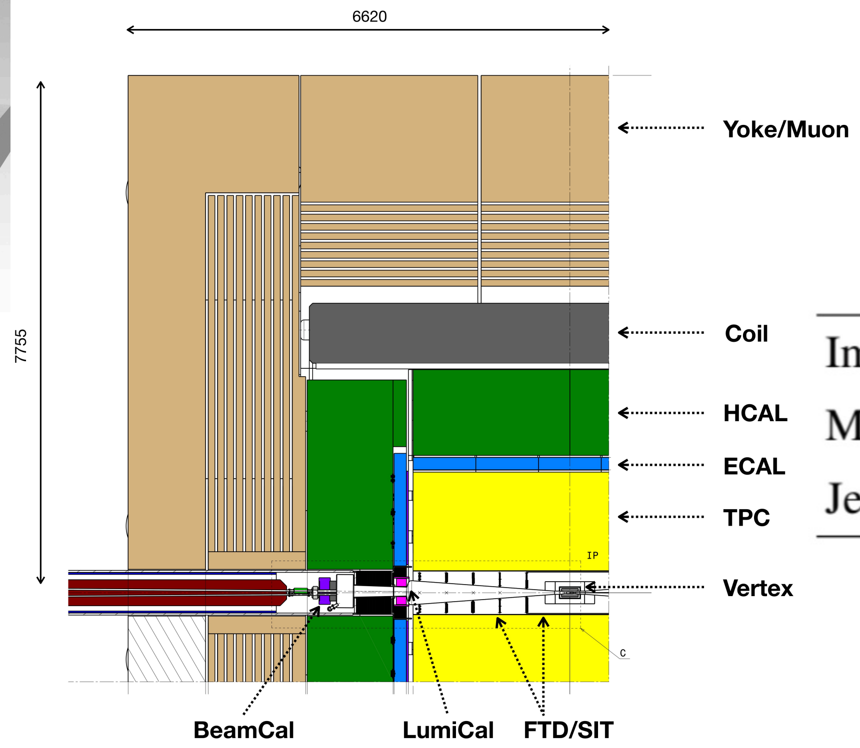
We obtained 95% C.L. upper limit on BR(H→φφ→4b) ~ 0.1% with ILD full simulation.

International Large Detector



- One of the detector concepts at the ILC
- Optimized for **Particle Flow Algorithm**
  - Reconstruct & identify all the particles, especially hadron jets in this study

(see details in backup)



Resolutions as the key detector performance	
Impact parameter	$\sigma_{r\phi} = 5 \oplus 10/p \cdot \sin^{3/2}\theta \ [\mu\mathrm{m}]$
Momentum	$\sigma_{1/p_T} \sim 2 \times 10^{-5} \ [\mathrm{GeV}^{-1}]$
Jet energy	$\sigma_{E_{\mathrm{jet}}}/E_{\mathrm{jet}} \sim 3\,\% \ (E_{\mathrm{jet}} < 100\mathrm{GeV})$

The ILD Concept

From key requirements from physics:

- **p_t resolution** (total ZH x-section)
  $\sigma(1/p_t) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$

  ≈ CMS / 40

- **vertexing** (H → bb/cc/ττ)
  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu\mathrm{m}$

  ≈ CMS / 4

- **jet energy resolution** 3-4%
  (H → invisible)

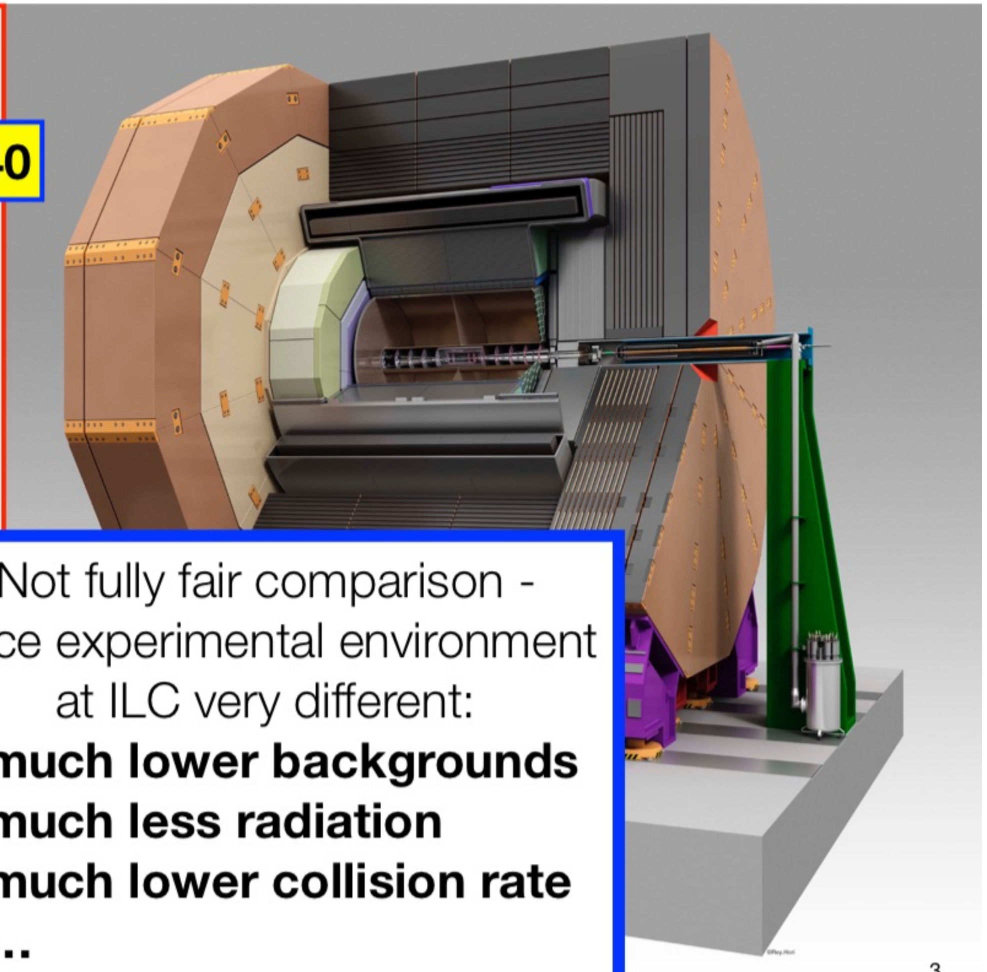
  ≈ ATLAS / 2

- **hermeticity** θ_{min} = 5 mrad
  (H → invis, BSM)

  ≈ ATLAS / 3

To key features of the **detector**:

- **low mass tracker:**
  - main device: **Time Projection Chamber** (dE/dx !)
  - add. silicon: eg VTX: 0.15% rad. length / layer)
- **high granularity calorimeters**
  optimised for particle flow



Not fully fair comparison - since experimental environment at ILC very different:

- **much lower backgrounds**
- **much less radiation**
- **much lower collision rate**
- **...**

3

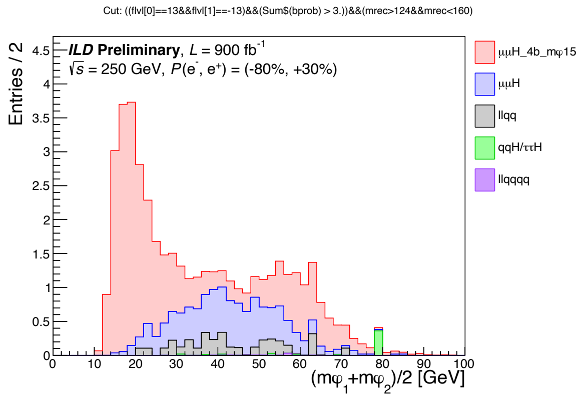
Jenny List, LCWS2018

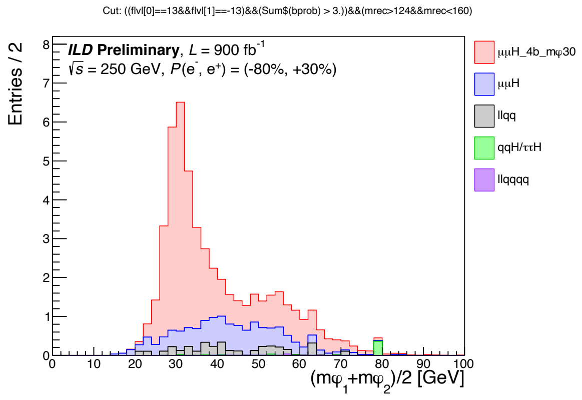
Parameters for Isolated Lepton Tagging

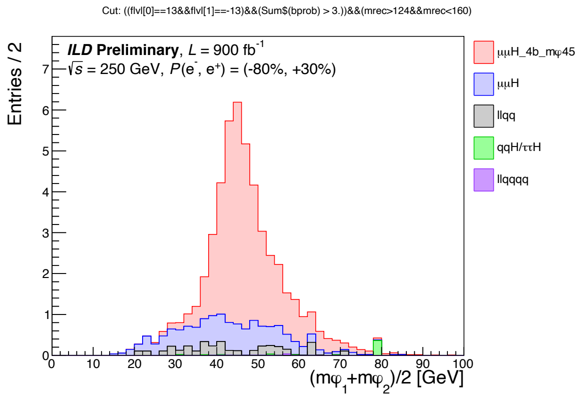
- Processor: MarlinReco / Analysis / IsolatedLeptonTaggingProcessor

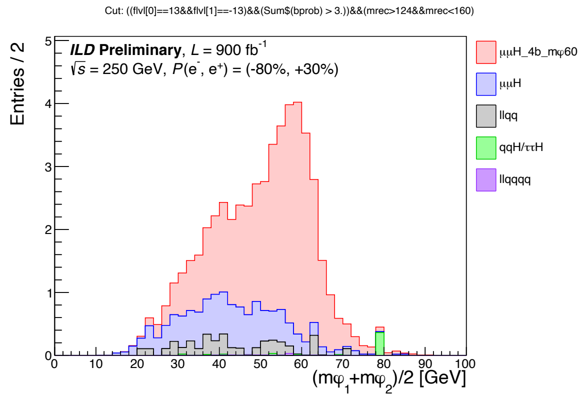
parameter	value	description
CosConeLarge	0.95	cosine of the larger cone
CosConeSmall	0.98	cosine of the smaller cone
MaxEOverPForElectron	1.3	maximum ratio of energy in calorimeters over momentum for electron
MaxEOverPForMuon	0.3	maximum ratio of energy in calorimeters over momentum for muon
MinEOverPForElectron	0.5	minimum ratio of energy in calorimeters over momentum for electron
MinEecalOverTotEForElectron	0.9	minimum ratio of energy in ecal over energy in ecal+hcal
MinEyokeForMuon	1.2	minimum energy in yoke for electron
MinPForElectron	5	minimum momentum for electron
MinPForMuon	5	minimum momentum for muon
MaxD0SigForElectron	50	maximum d0 significance for electron
MaxD0SigForMuon	20	maximum d0 significance for muon
MaxZ0SigForElectron	50	maximum z0 significance for electron
MaxZ0SigForMuon	20	maximum z0 significance for muon
CutOnTheISOElectronMVA	0.5	cut on the MVA output of isolated electron selection
CutOnTheISOMuonMVA	0.7	cut on the MVA output of isolated muon selection

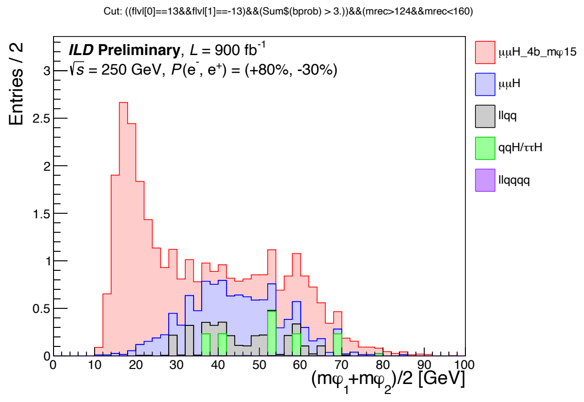
Mediator mass: muon channel

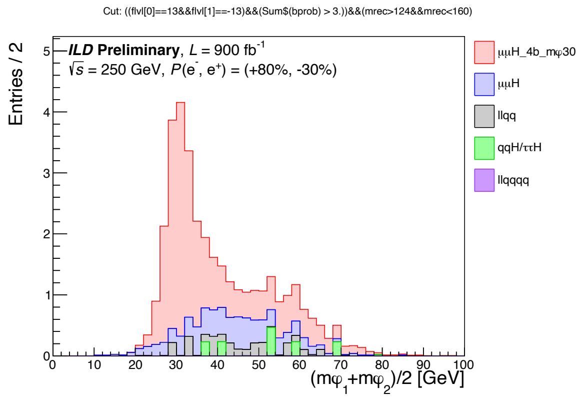


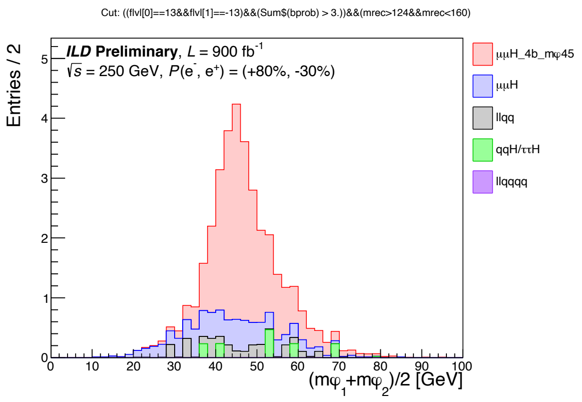


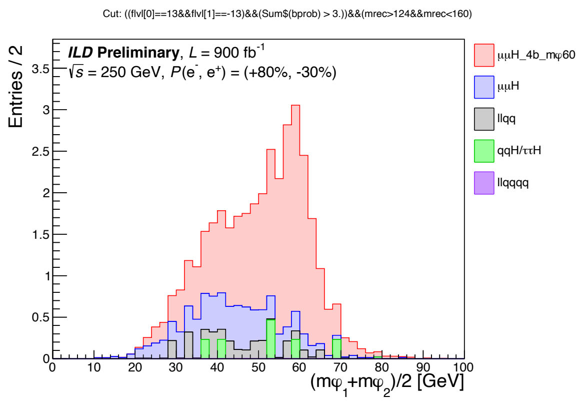




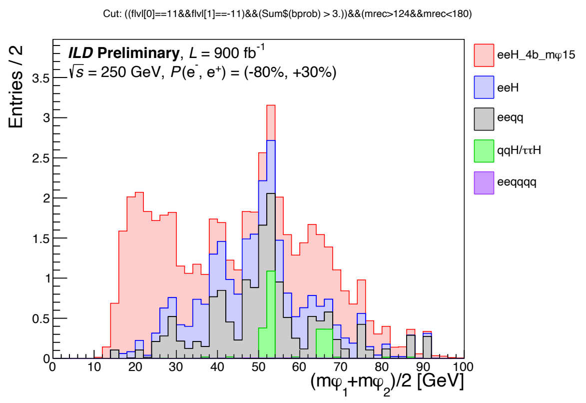


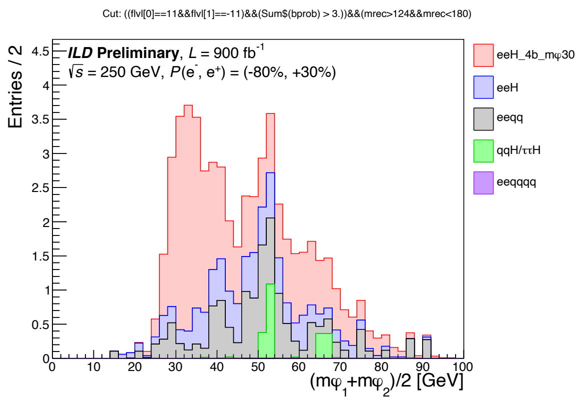


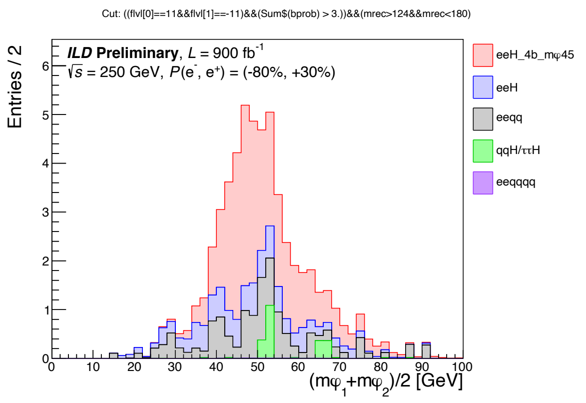


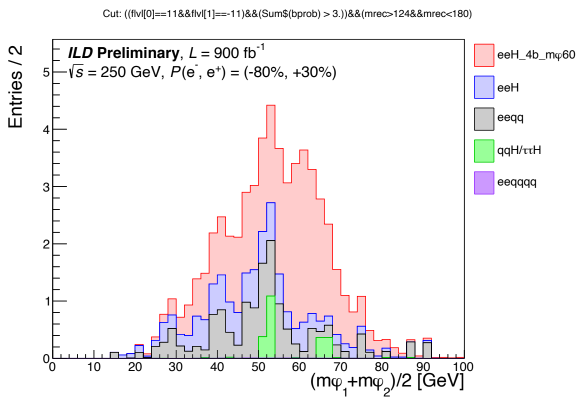


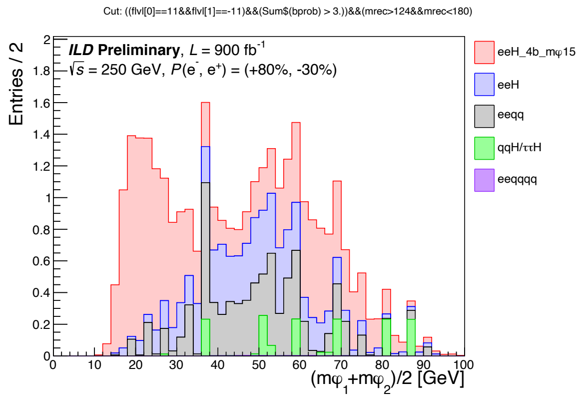
Mediator mass: electron channel

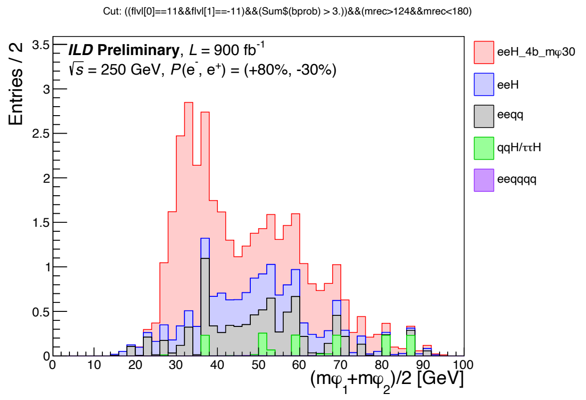


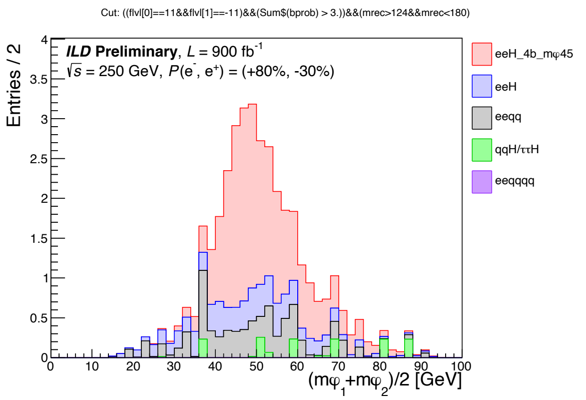


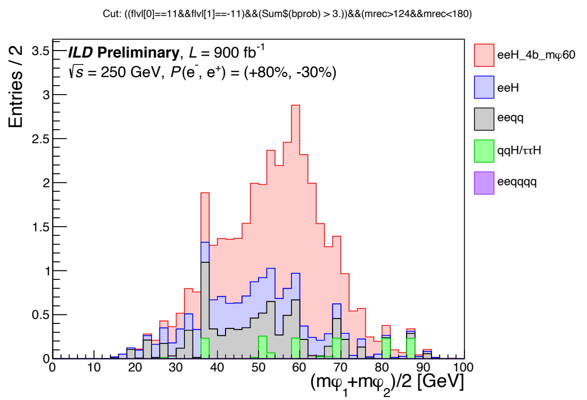












The final cut conditions of mediator mass

μμ, (-0.8,+0.3)	xl	xu	Ns	Nb	UL
15 GeV	10	26	17.0	1.3	0.11
30	24	36	21.7	3.4	0.14
45	38	78	33.9	9.3	0.15
60	52	78	21.9	3.6	0.14

μμ, (+0.8,-0.3)	xl	xu	Ns	Nb	UL
15 GeV	10	30	13.0	1.3	0.14
30	24	36	14.3	2.3	0.17
45	38	58	20.5	6.1	0.20
60	54	68	11.9	1.9	0.19

ee, (-0.8,+0.3)	xl	xu	Ns	Nb	UL
15 GeV	10	28	10.4	1.4	0.19
30	28	38	13.5	3.0	0.21
45	40	86	30.3	18.6	0.24
60	56	74	17.0	5.0	0.22

ee, (+0.8,-0.3)	xl	xu	Ns	Nb	UL
15 GeV	10	30	7.6	1.2	0.24
30	28	36	7.7	1.4	0.25
45	38	80	21.2	11.0	0.26
60	42	80	19.6	9.6	0.26

Jet pairing effect

Muon channel