Measuring the branching ratio of $h \to \mu^+\mu^-$ at the ILC

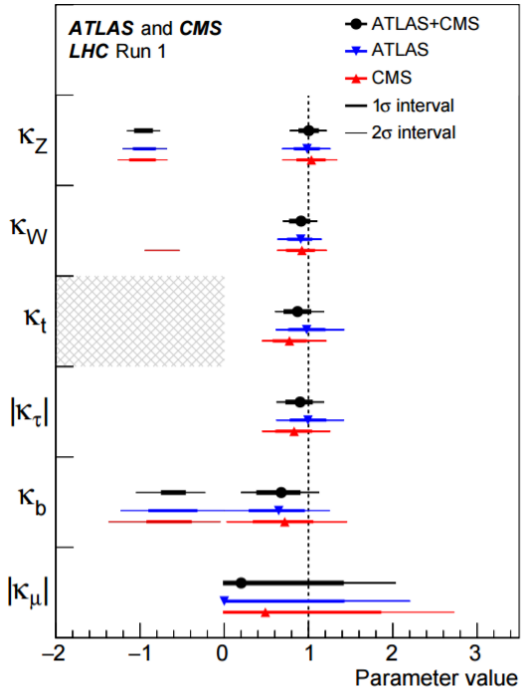
Shin-ichi Kawada, Jenny List, Mikael Berggren (DESY)

2017/June/26

AWLC17

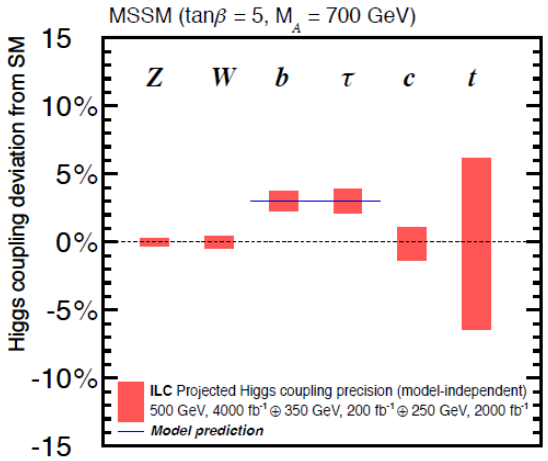
Introduction

Discovery of Higgs-like boson at the LHC
--> Last particle of SM? Or beyond SM?



JHEP **08** (2016) 045

Goal: model-independent determination of
EWSB sector with precise measurements
- mass-coupling relation
- any deviation shows the existence of BSM

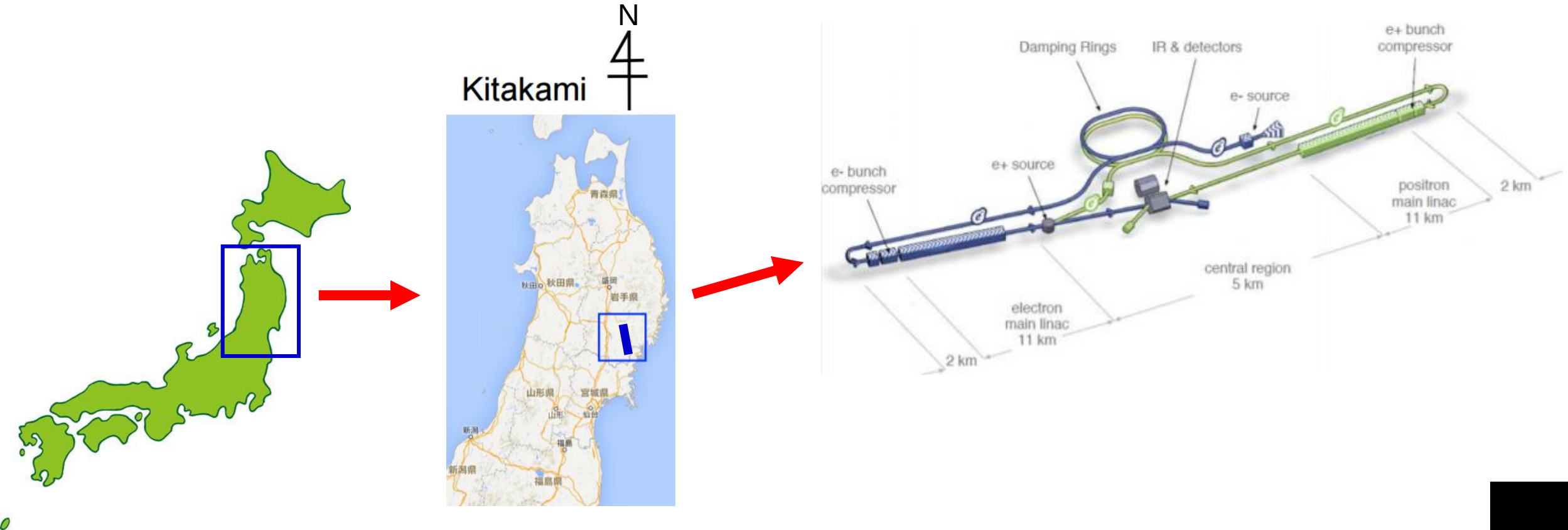


arXiv: 1506.05992 [hep-ex]

ILC

The International Linear Collider

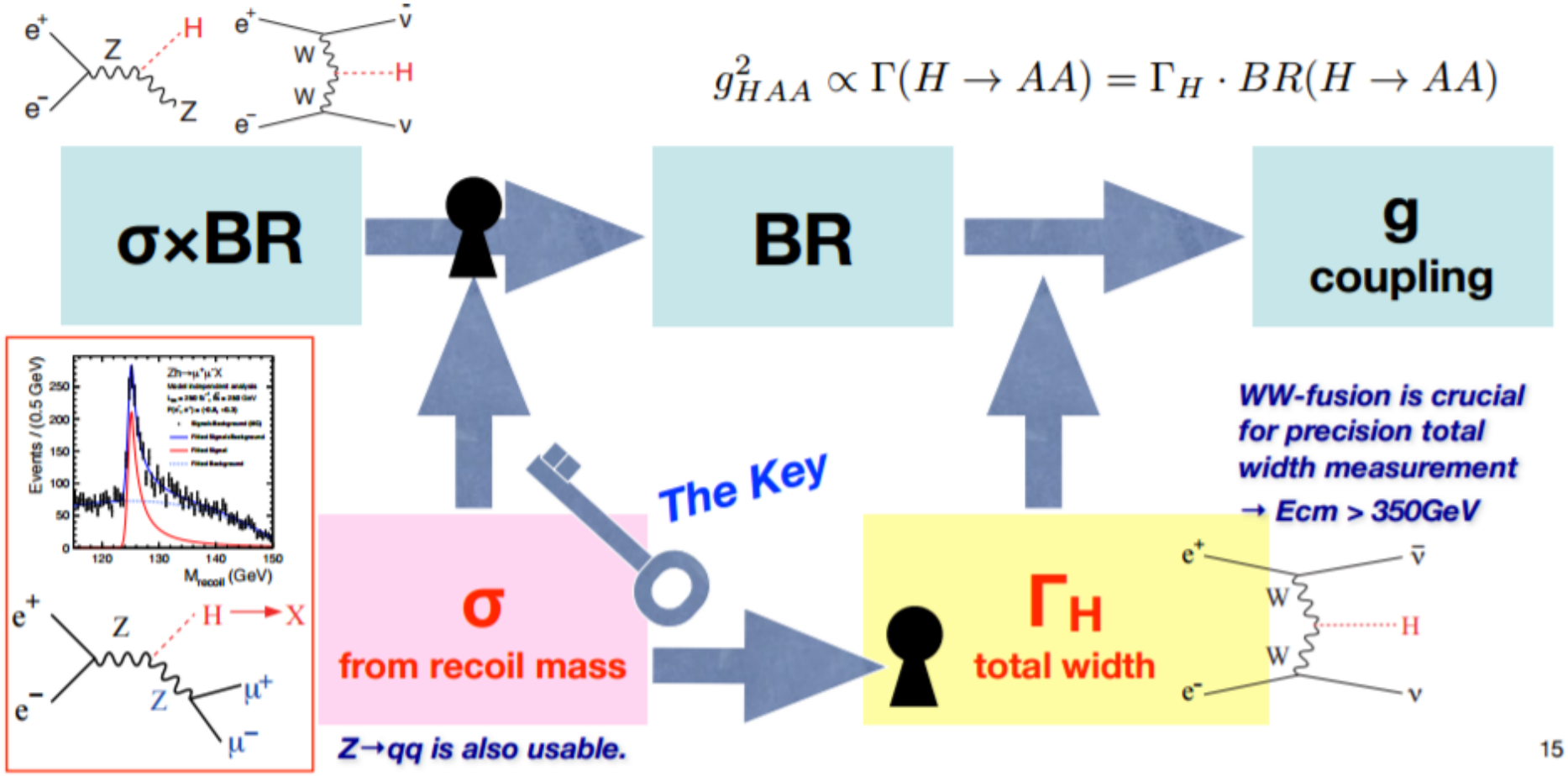
- e^+e^- collider, E_{CM} = 250 - 500 GeV (upgradable to 1 TeV)
- polarized beam (e^-: 0.8, e^+: $\geq$ 0.3(0.6))
- clean environment, known initial state



Key Point

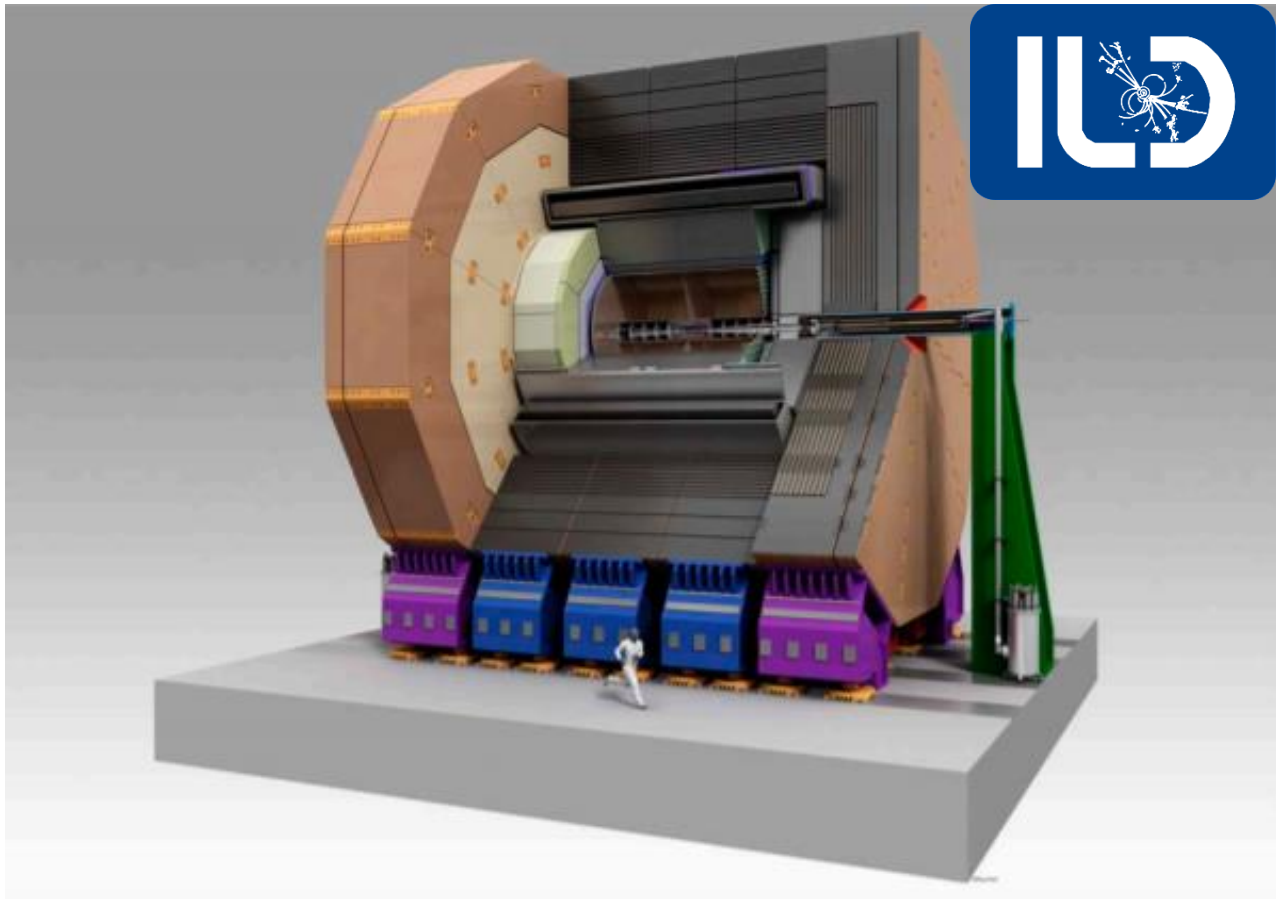
LHC: all measurements are $\sigma \times \mathrm{BR}$

ILC: $\sigma \times \mathrm{BR}$ measurements + σ measurement



Detector Concept at the ILC

ILD (International Large Detector)



Tracker: Vertex, TPC
Calorimeter: ECAL, HCAL
3.5T magnetic field
Yoke for muon, Forward system

Requirements:

- Impact parameter resolution
  $\sigma_{r\phi} < 5 \oplus \frac{10}{p\sin^{3/2}\theta}\ \mu\text{m}$
- Momentum resolution
  $\sigma_{1/p_T} < 2*10^{-5}\ \text{GeV}^{-1}$
- Energy resolution
  σ_E/E = 3 - 4%

In This Talk: $h \to \mu^+\mu^-$

- Challenging analysis: tiny branching ratio (BR($h \to \mu^+\mu^-$) = **$2.2*10^{-4}$** at M_h = 125 GeV)
- Can be used for testing:
  - $y_f \propto m_f$
  - mass generation mechanism between 2nd/3rd leptons (κ_μ/κ_τ) and 2nd lepton/quark (κ_μ/κ_c)
- Today I will show the first results at E_{CM} = 250/500 GeV
- HL-LHC prospects (3000 fb^{-1}): ~14% precision for cross section times branching ratio $\frac{\Delta(\sigma\times\mathrm{BR})}{(\sigma\times\mathrm{BR})}$

Previous Studies

Everything performed at >= 1 TeV

Reference	E_{CM}	beam pol. $P(e^-, e^+)$	$\int Ldt$	$\frac{\Delta(\sigma \times \mathrm{BR})}{(\sigma \times \mathrm{BR})}$	comment
LC-REP-2013-006	1 TeV	(-0.8, +0.2)	500 fb^{-1}	44%	ILC/ILD
arXiv:1306.6329 [hep-ex]	1 TeV	(-0.8, +0.2)	1000 fb^{-1}	32%	ILC/SiD
arXiv:1603.04718 [hep-ex]	1 TeV	(-0.8, +0.2)	500 fb^{-1}	36%	ILC/ILD used TMVA
Eur. Phys. J. **C73**(2), 2290 (2013)	3 TeV	unpol.	2000 fb^{-1}	15%	CLIC_SiD M_h = 120 GeV used TMVA
Eur. Phys. J. **C75**, 515 (2015)	1.4 TeV	unpol.	1500 fb^{-1}	38%	CLIC_ILD used TMVA
		(-0.8, 0)		25%	

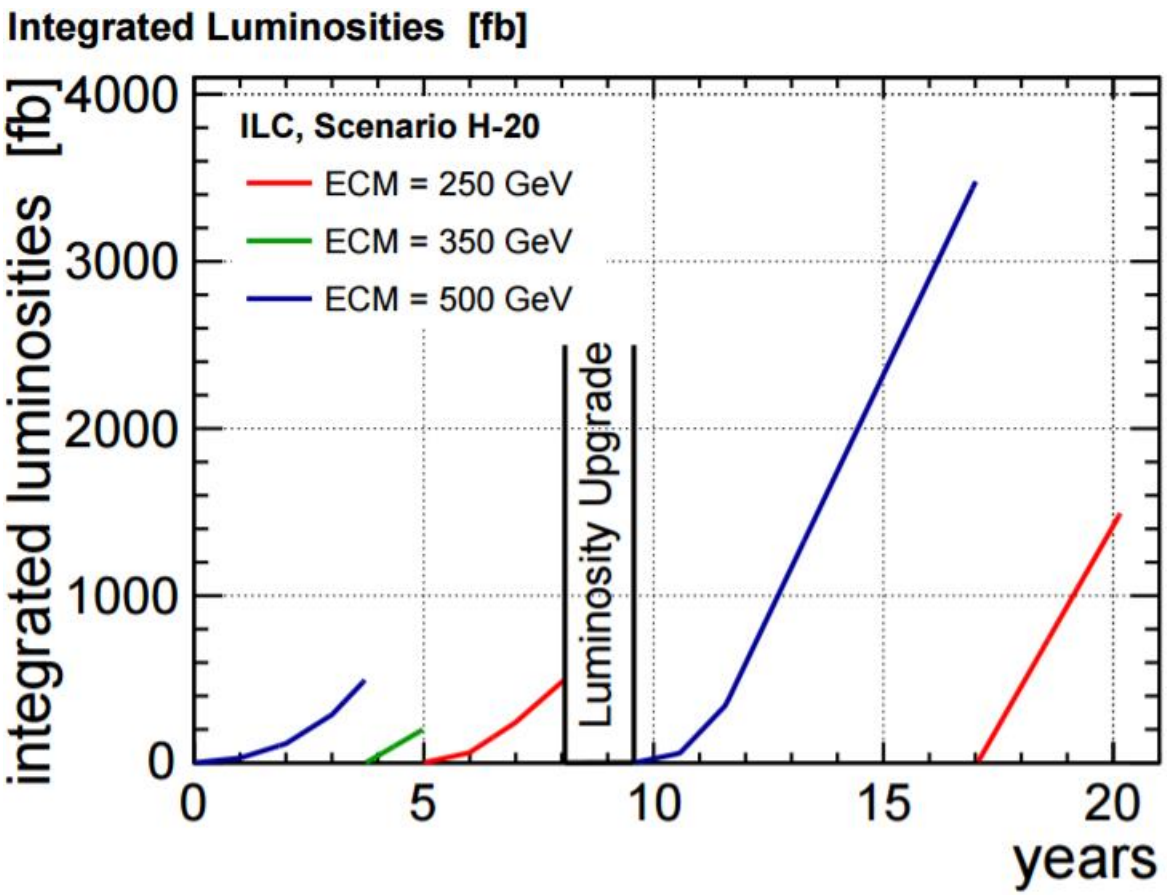
arXiv:1506.07830 [hep-ex],
J. Brau's talk @ ICHEP2016

ILC Running Scenario

optimized scenario with considering
- Higgs precise measurements
- Top physics
- New physics search

20 years running with
energy range [250-500] GeV,
beam polarization sharing
---> then possible 1 TeV upgrade

preferred scenario:
2000 fb^{-1} @ 250 GeV
200 fb^{-1} @ 350 GeV
4000 fb^{-1} @ 500 GeV



※staging scenario will start from 250 GeV,
but total luminosities are the same

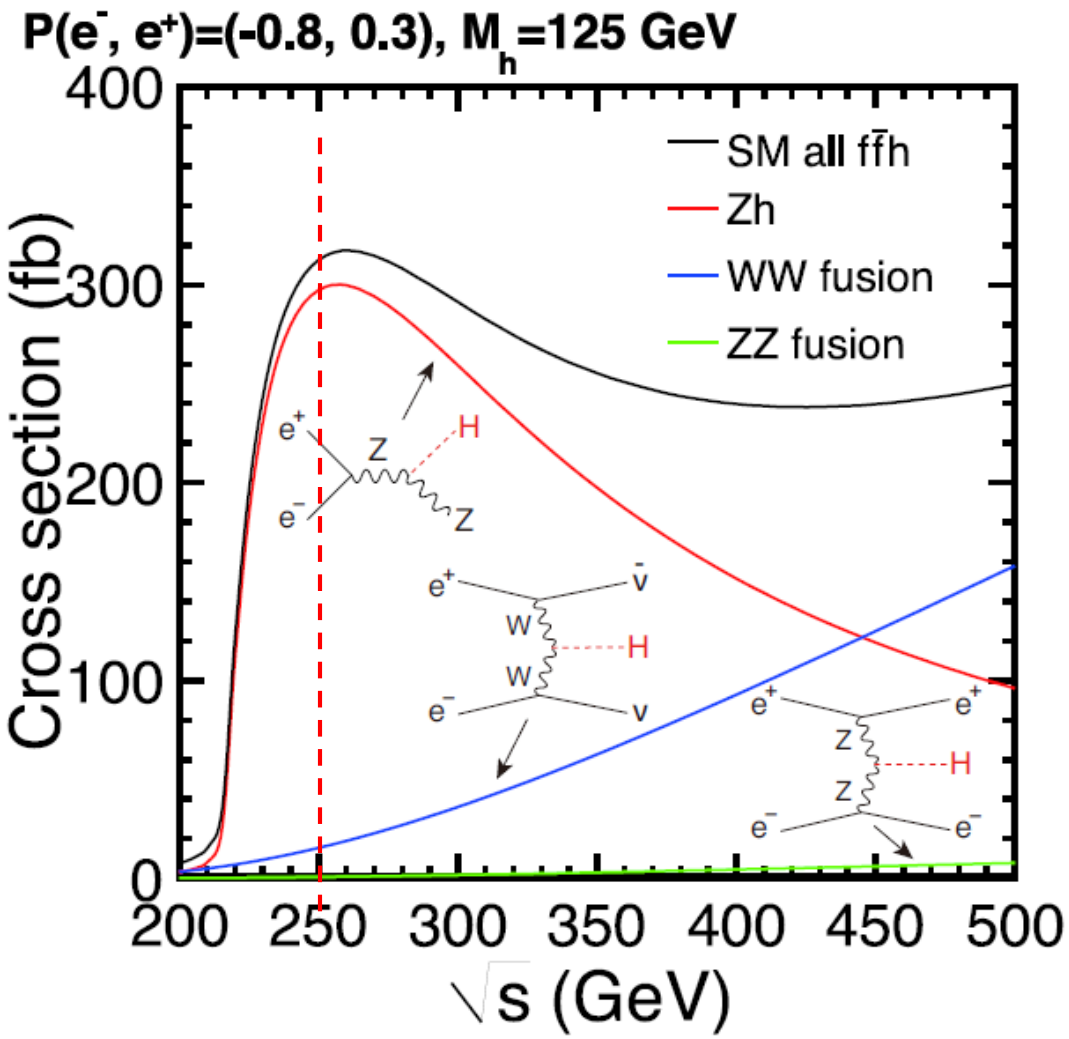
arXiv:1506.05992 [hep-ex]

Single Higgs Production

$\sqrt{s}$ = 250 GeV
Higgs-strahlung (Zh) dominant

$\sqrt{s}$ = 500 GeV
WW-fusion dominant

E_{CM}	process	beam pol.	$\int Ldt$	# events
500	$\nu\bar{\nu}h$	L	1600	58
		R	1600	8
	$q\bar{q}h$	L	1600	25
		R	1600	16
250	$q\bar{q}h$	L	1350	62
		R	450	14



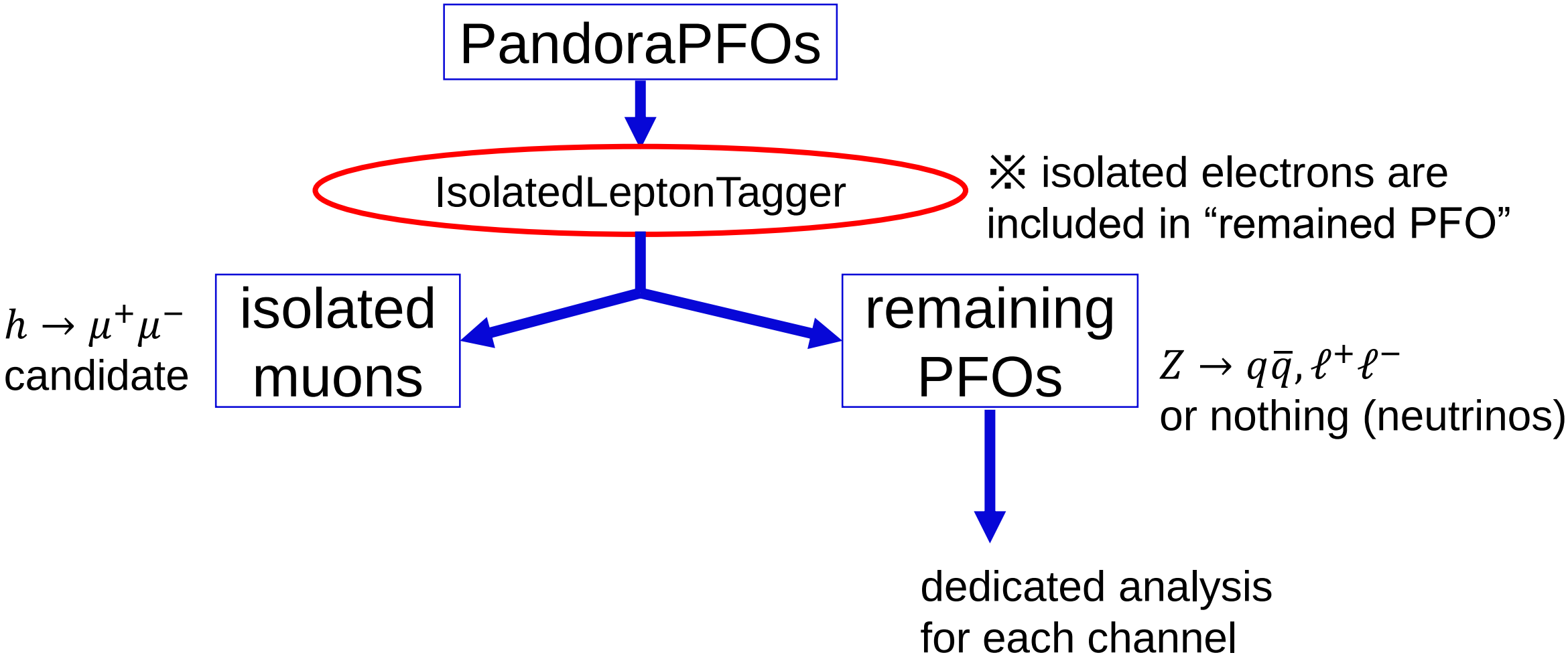
L: (e^-, e^+) = (-0.8, +0.3)
R: (e^-, e^+) = (+0.8, -0.3)

Analysis Settings

- Geant4-based full detector simulation with ILD model
- Included all possible SM backgrounds
  - Still some processes have not enough statistics, need more MC statistics (under production)

Process	# total MC events
500 GeV	$1.4*10^7$
250 GeV	$7.1*10^7$

General Event Reconstruction

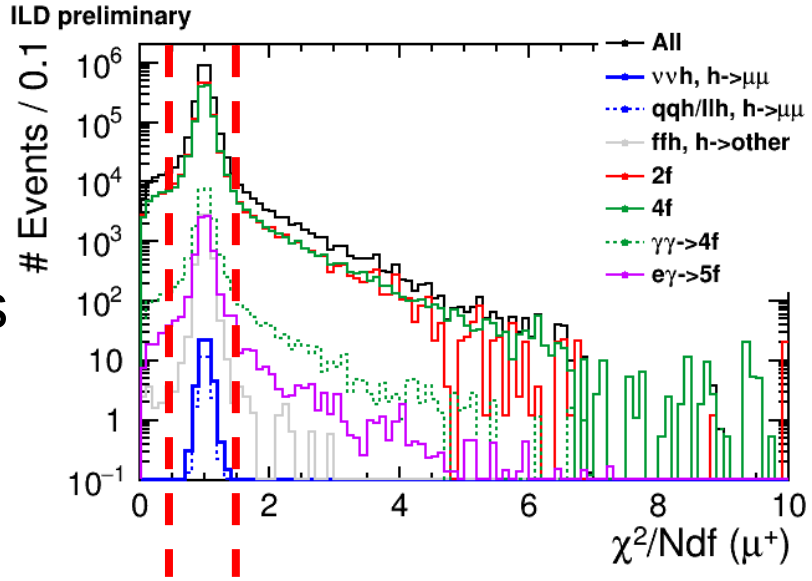


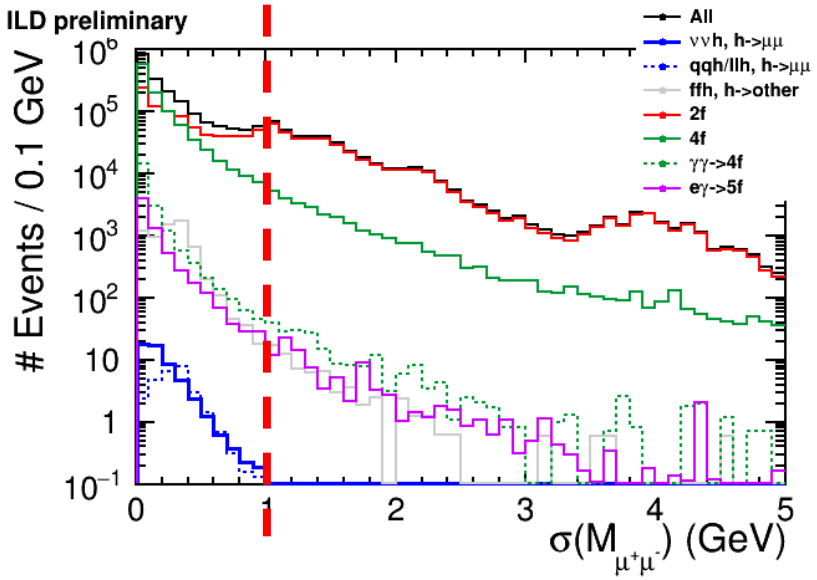
signal
other colors: SM background
plots from nnh500-L

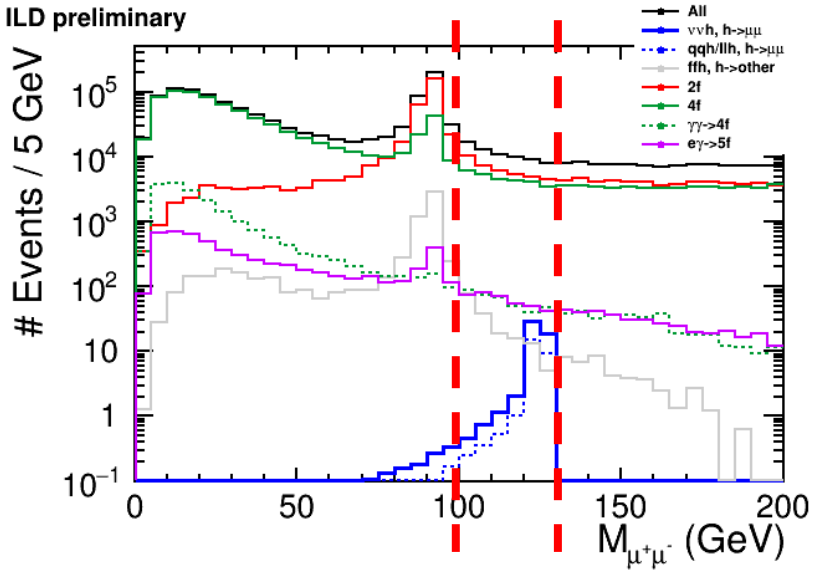
General Event Selection

Selections at 500(250) GeV:

- $\# \mu^+ == 1, \# \mu^- == 1$
- $0.5 < \chi^2(\mu^\pm)/\mathrm{Ndf} < 1.5$ only select well-measured muons
- $\sigma\left(M_{\mu^+\mu^-}\right) < 1(0.5)$ GeV
- $100 < M_{\mu^+\mu^-} < 130$ GeV $h \to \mu^+\mu^-$ candidate
- $\cos\theta_{\mu^+\mu^-} < 0.55(-0.4)$







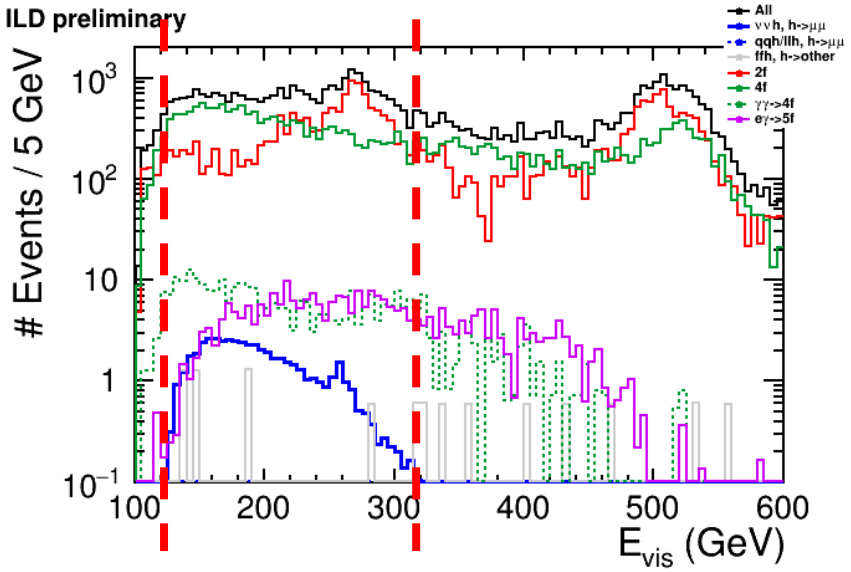
$e^+e^- \to \nu\bar{\nu}h$

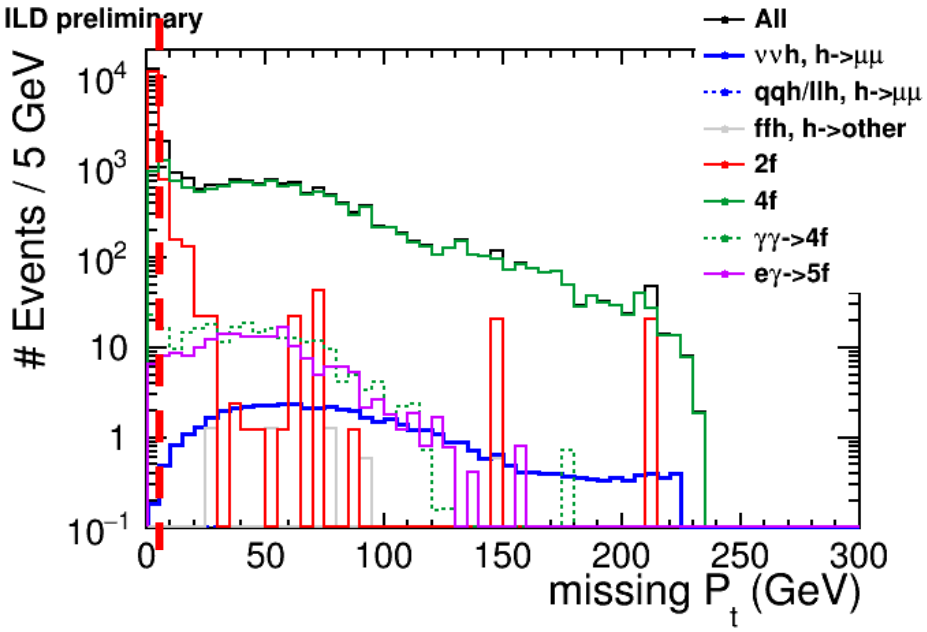
nnh500-L/R

signal
other colors: SM background
plots from nnh500-L

Precuts

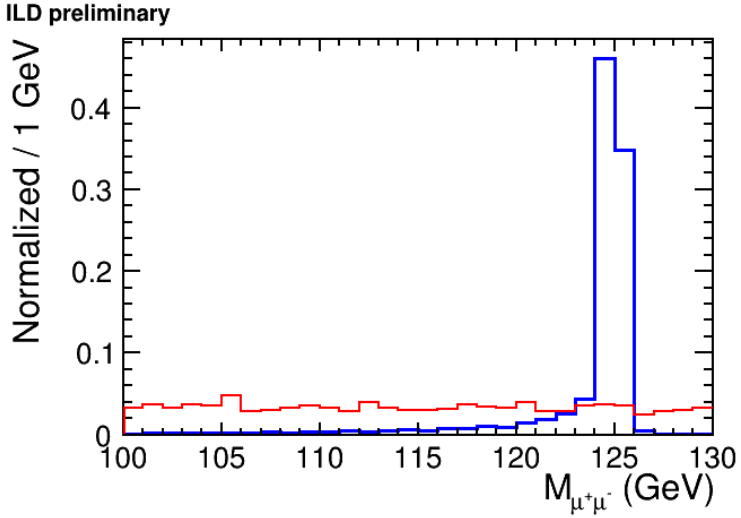
- $N_{P_t > 5\mathrm{GeV}} \leq 1$
- $125 < E_{\mathrm{vis}} < 320$ GeV
- missing $P_t > 5$ GeV
- $|\cos\theta_{\mathrm{miss}}| < 0.99$

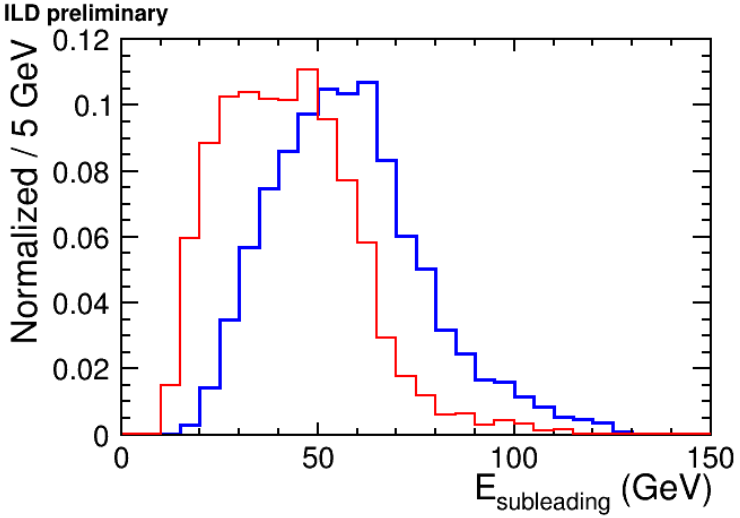




signal
background
plots from nnh500-L

TMVA (BDTG) Analysis

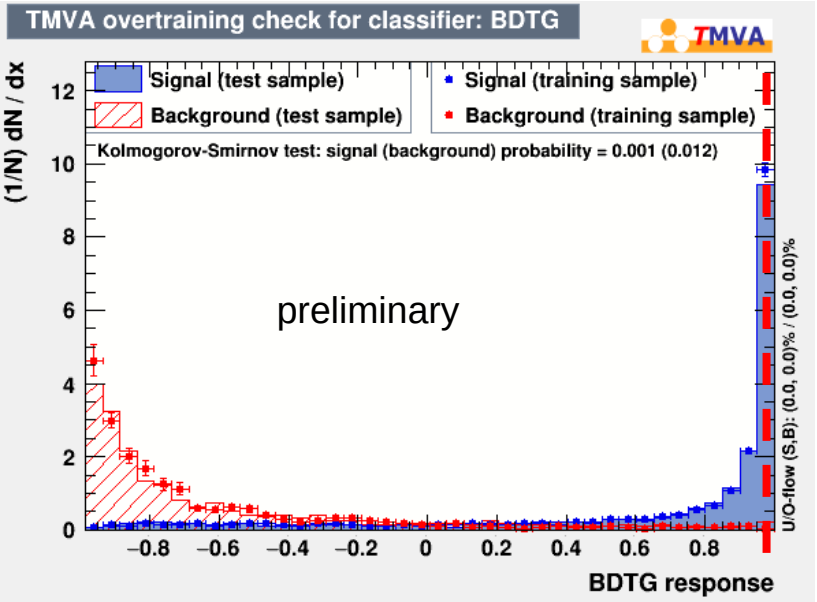


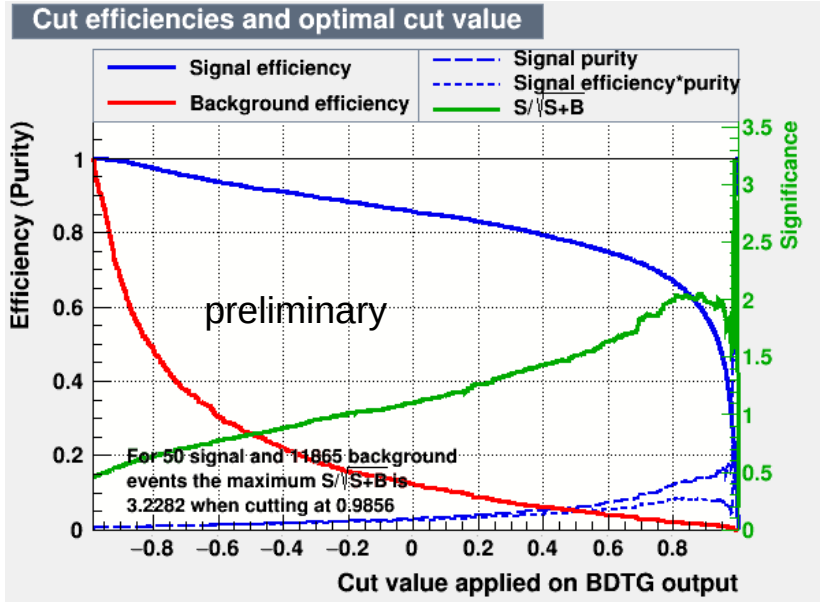


5 input variables:
missing P_t, $M_{\mu^+\mu^-}$,
charge * $\cos\theta_{\mu^\pm}$, $E_{subleading}$

	L	R
N_{sig}	11.66	2.69
N_{bkg}	1.39	0.01
$\frac{S}{\sqrt{S+B}}$	3.2	1.6
$\frac{\Delta(\sigma \times \mathrm{BR})}{(\sigma \times \mathrm{BR})}$	31%	61%

※still overtrained
need more MC (under production)

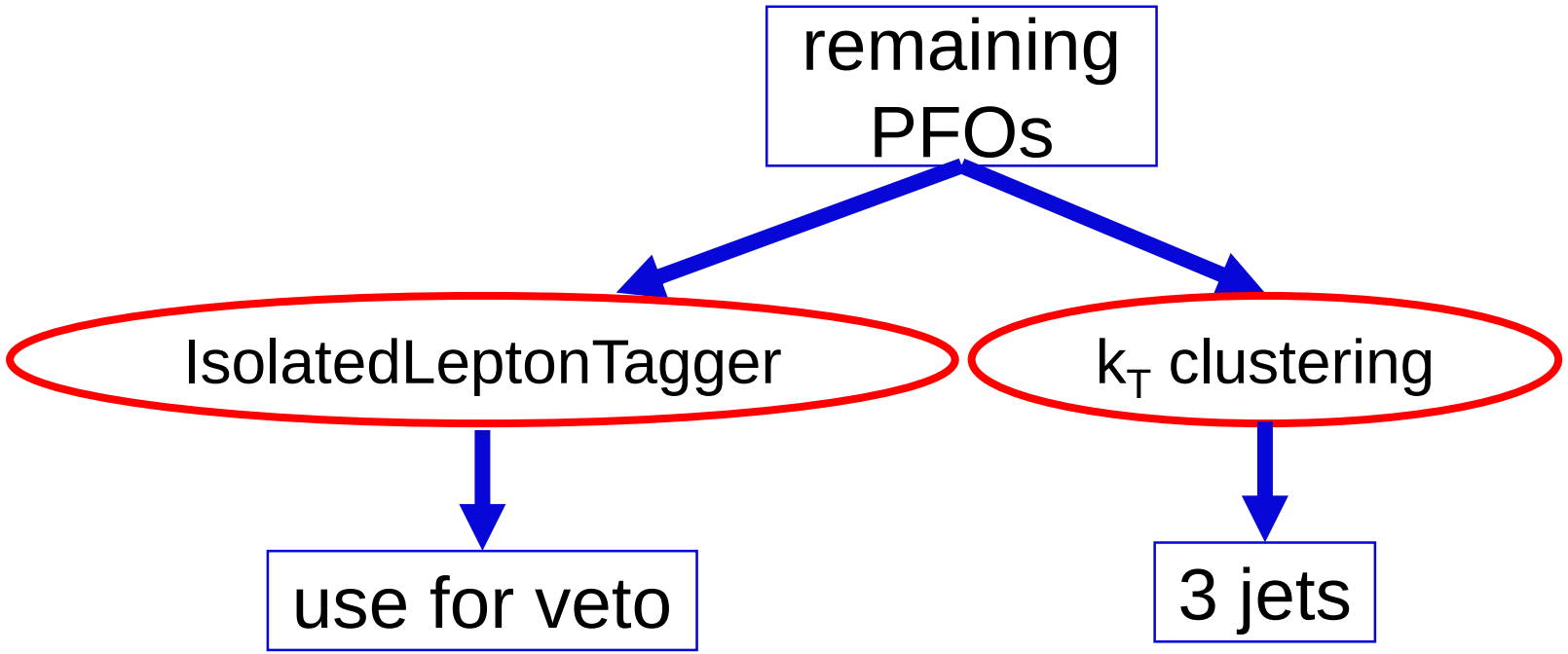




$e^+e^- \to q\bar{q}h$

qqh500-L/R

Event Reconstruction

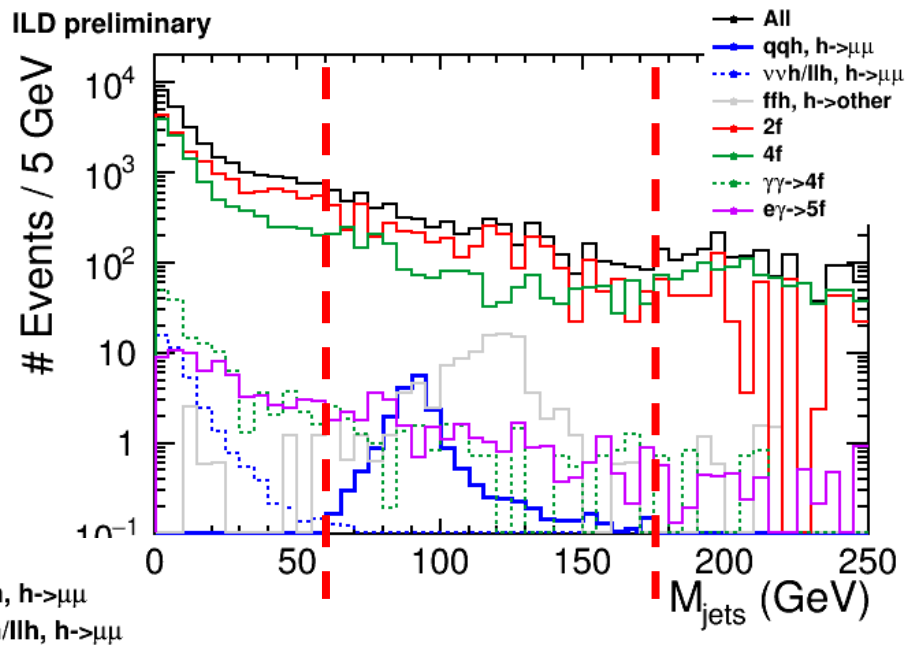


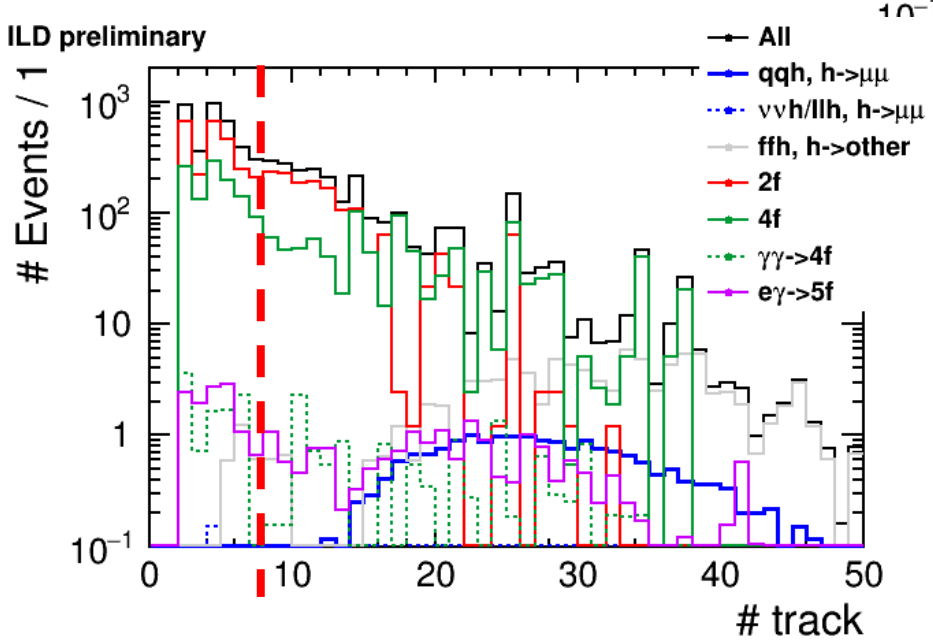
$\gamma\gamma \rightarrow$ low P_t hadron backgrounds are overlaid 1.7 / bunch crossing on average at 500 GeV

signal
other colors: SM background
plots from qqh500-L

Precuts

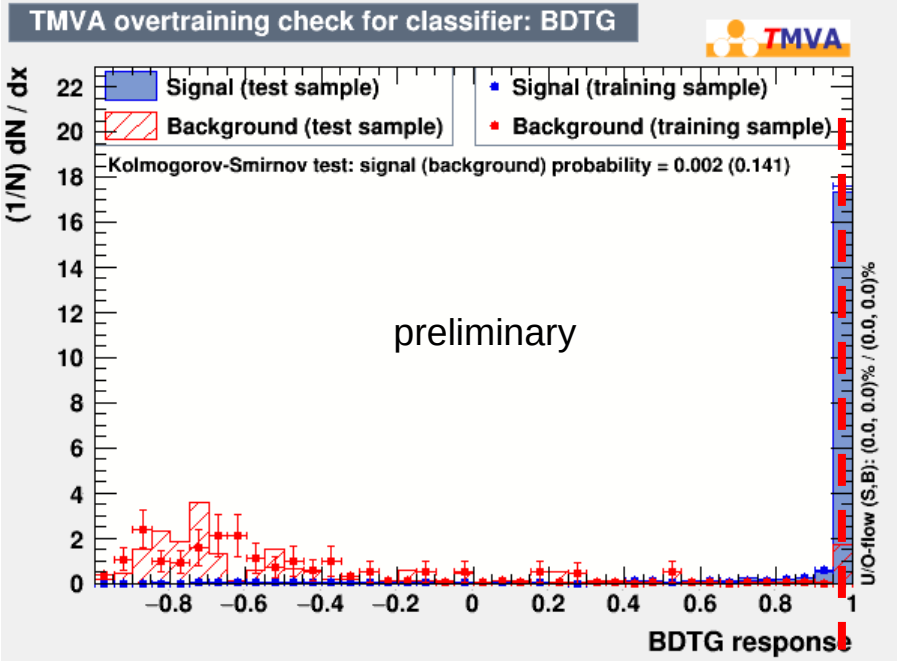
- veto: no isolated lepton in "remaining PFO"
- exactly 3 jets
- $60 < M_{\text{jets}} < 180$ GeV
- number of tracks should be grater or equal to 8
- thrust < 0.95

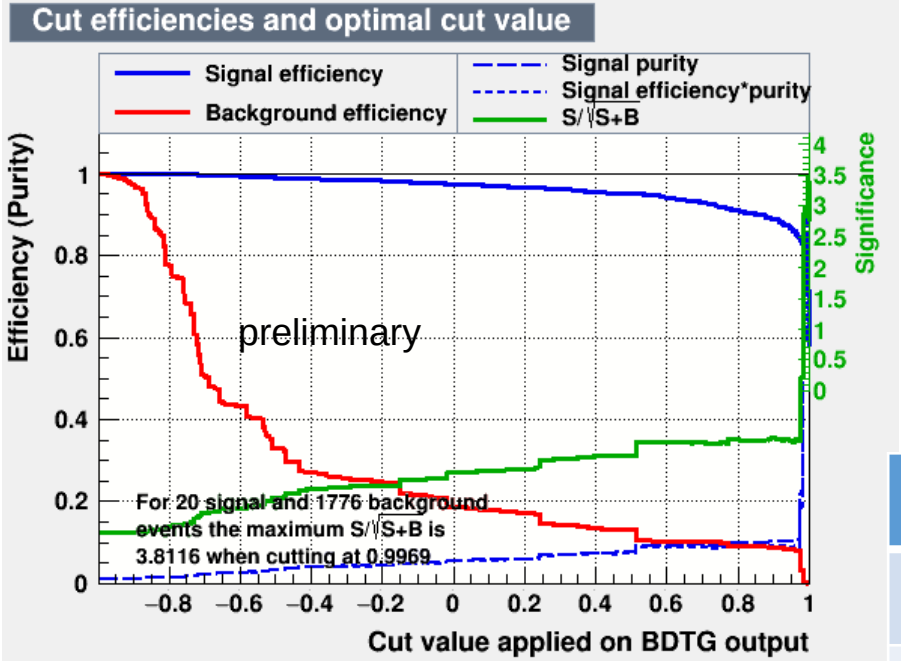




signal
background
plots from qqh500-L

TMVA Analysis





※still overtrained
need more MC (under production)

	L	R
N_{sig}	14.84	9.39
N_{bkg}	0.31	2.34
$\frac{S}{\sqrt{S+B}}$	3.8	2.7
$\frac{\Delta(\sigma \times \mathrm{BR})}{(\sigma \times \mathrm{BR})}$	26%	36%

7 input variables:
thrust, $M_{\mu^+\mu^-}$, charge * $\cos\theta_{\mu^\pm}$,
$E_{subleading}$, M_{jets}, $M_{recoil} = M_h$

$e^+e^- \to q\bar{q}h$

qqh250-L/R

signal
other colors: SM background
plots from qqh250-L

Event Reconstruction / Precuts

remaining PFOs

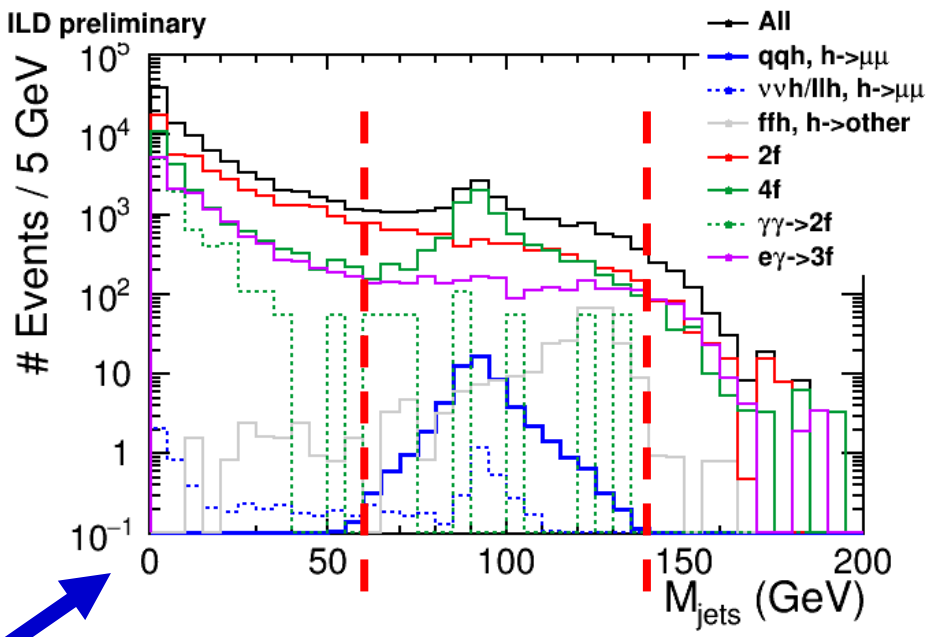
↓

Durham clustering

↓

2 jets

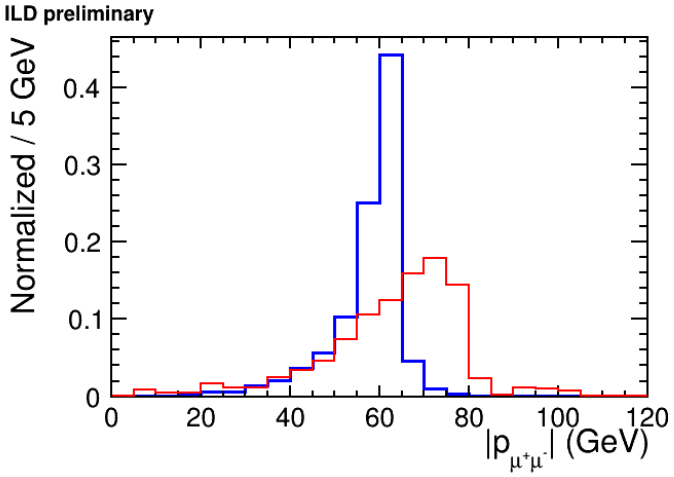
$\gamma\gamma \rightarrow$ low P_t hadron
backgrounds are overlaid
0.4 / bunch crossing
on average at 250 GeV

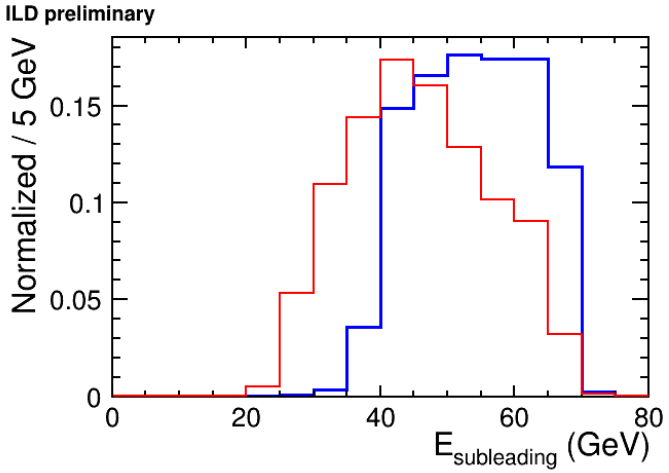


- exactly 2 jets
- $60 < M_{\text{jets}} < 140$ GeV
- $\cos\theta_{\text{jets}} < -0.1$
- number of tracks should be grater or equal to 8

signal
background
plots from qqh250-L

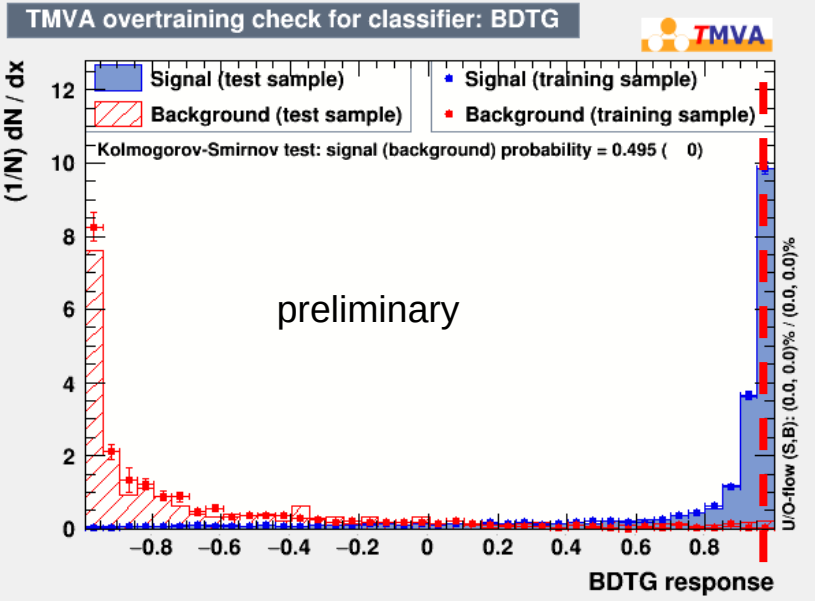
TMVA Analysis

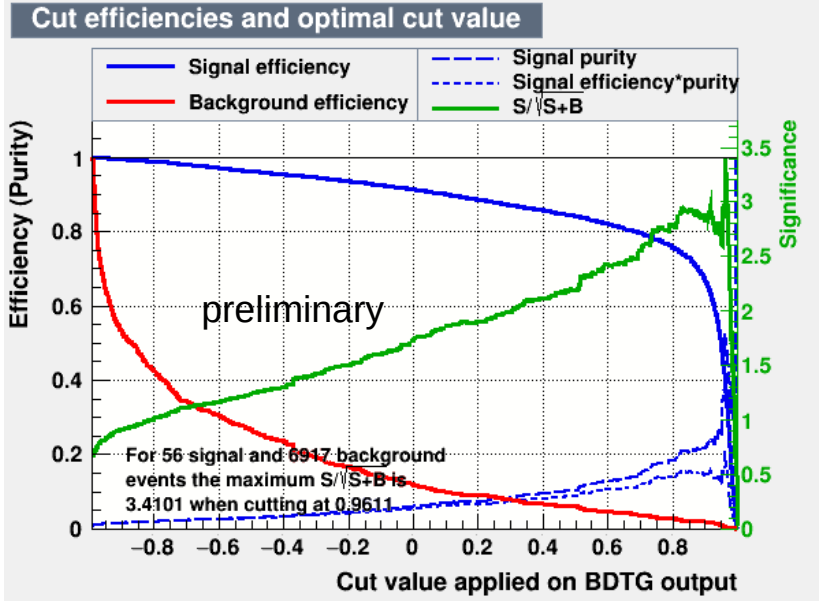




7 input variables:
$\cos\theta_{\mathrm{miss}}$, $M_{\mu^+\mu^-}$, $|p_{\mu^+\mu^-}|$,
charge * $\cos\theta_{\mu^\pm}$, $E_{subleading}$, M_{jets}

	L	R
N_{sig}	22.18	5.81
N_{bkg}	20.13	1.03
$\frac{S}{\sqrt{S+B}}$	3.4	2.2
$\frac{\Delta(\sigma \times \mathrm{BR})}{(\sigma \times \mathrm{BR})}$	29%	45%





※still overtrained
need more MC (under production)

Comparison with Extrapolation

$\int \mathscr{L} dt$ at $\sqrt{s}$	250 fb^{-1} at 250 GeV		330 fb^{-1} at 350 GeV		500 fb^{-1} at 500 GeV		
$P(e^-, e^+)$	(-80%,+30%)						
production	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$t\bar{t}h$
decay	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$						
$h \to \mu^+\mu^-$ [45]	72%	-	76%	140%	88%	72%	-

[45] C. Calancha, private communication.

scale to 1350 fb^{-1}: 31%

My results: 29%, only qqh250-L

scale to 1600 fb^{-1}: 49%/40%

My results: 26%/31%
(for Zh, only qqh500-L)

Everything is similar/better than extrapolation!

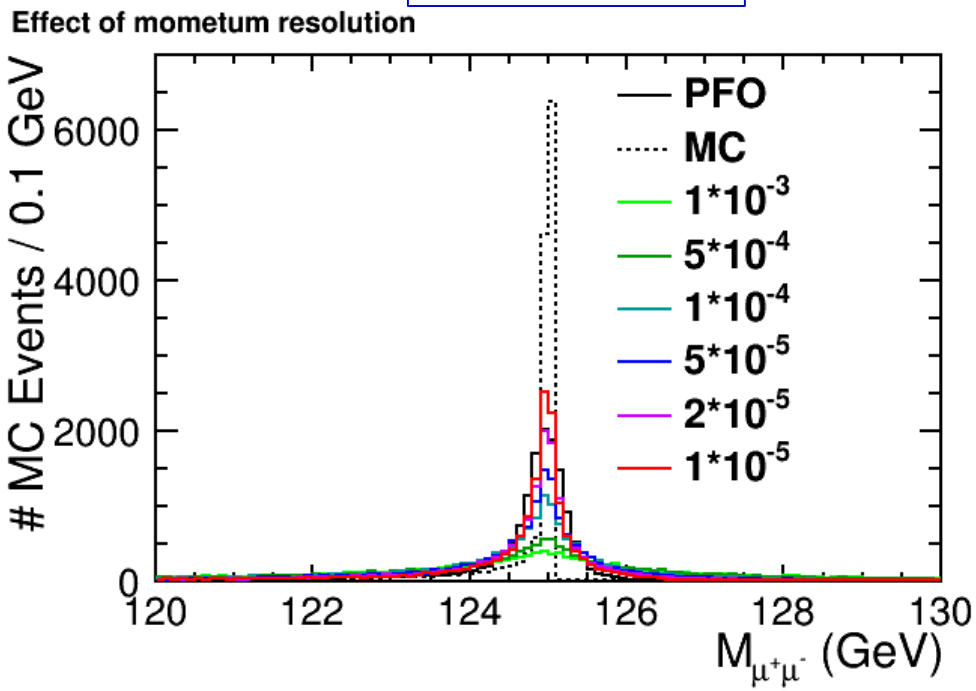
Impact of Momentum Resolution

- In this analysis, momentum resolution (P_t resolution) is most important.
  - For high P_t muons
  - This affects $M_{\mu^+\mu^-}$ which is most important variable for physics analysis.
- Checked what happens if we change momentum resolution artificially.
  - Used smearing to MCParticle (MC information)
  - Only signal process

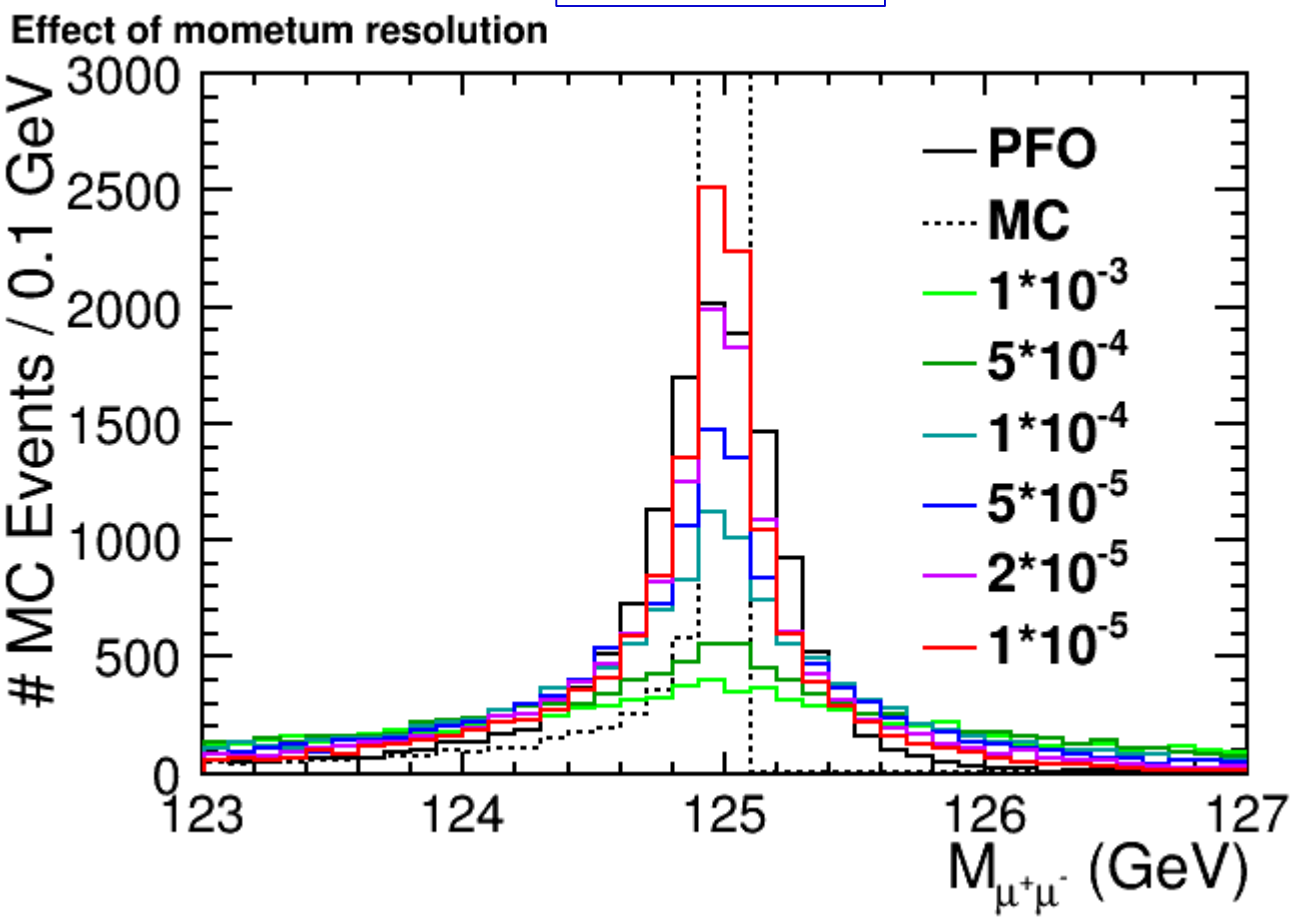
※not luminosity weighted

$M_{\mu^+\mu^-}$ Spectrum

overview



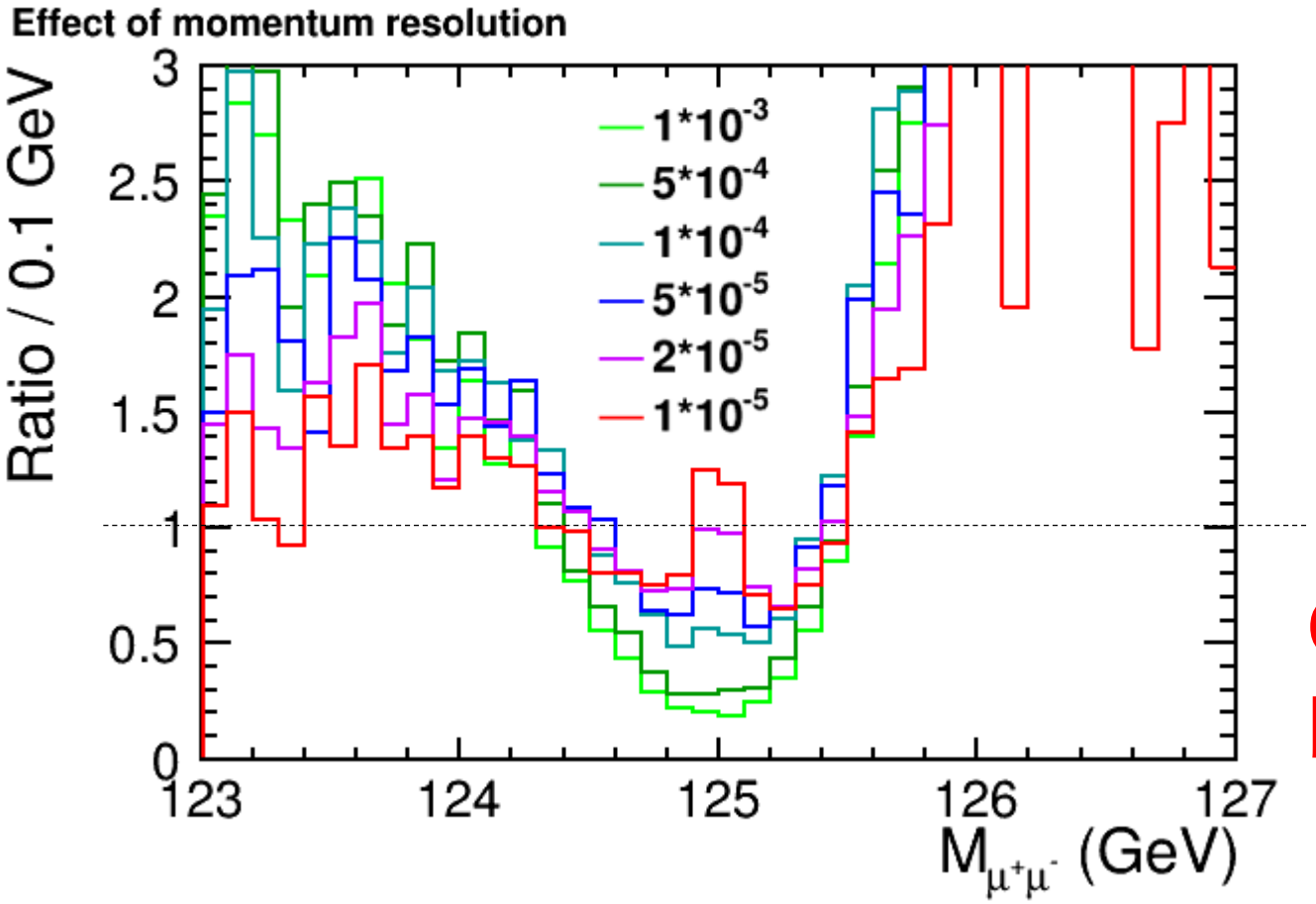
zoom up



MCParticle is smeared with artificial P_t resolution

※not luminosity weighted

Ratio Spectrum



$$\text{Ratio} \equiv \frac{\text{smeared histogram}}{\text{PFO histogram}}$$

Clearly worse in bad momentum resolutions

Summary

Showed first results of $h \to \mu^+\mu^-$ at 250/500 GeV based on ILD full simulation for the first time

Table 7: Obtained precision $\frac{\Delta(\sigma \times \mathrm{BR})}{(\sigma \times \mathrm{BR})}$

500 GeV	$q\bar{q}h$	$\nu\bar{\nu}h$
left-handed	26% (1600 fb^{-1})	31% (1600 fb^{-1})
right-handed	36% (1600 fb^{-1})	61% (1600 fb^{-1})
250 GeV	$q\bar{q}h$	$\nu\bar{\nu}h$
left-handed	29% (1350 fb^{-1})	—
right-handed	45% (450 fb^{-1})	—

preliminary

Everything is better than extrapolation results
Combine everything gives **14%** precision:
almost same precision expected at the HL-LHC