Branching ratio measurement of $h \to \mu^+\mu^-$ at the ILC

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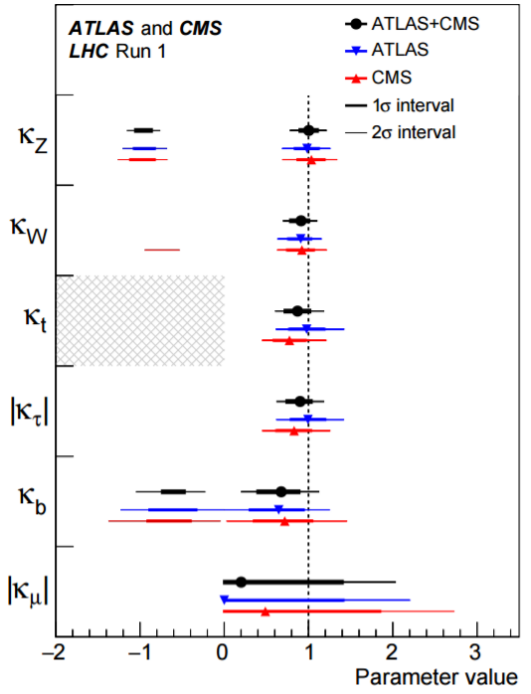
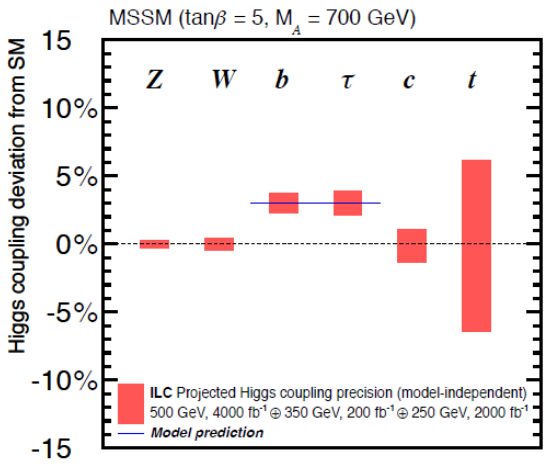
Introduction

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

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



JHEP **08** (2016) 045

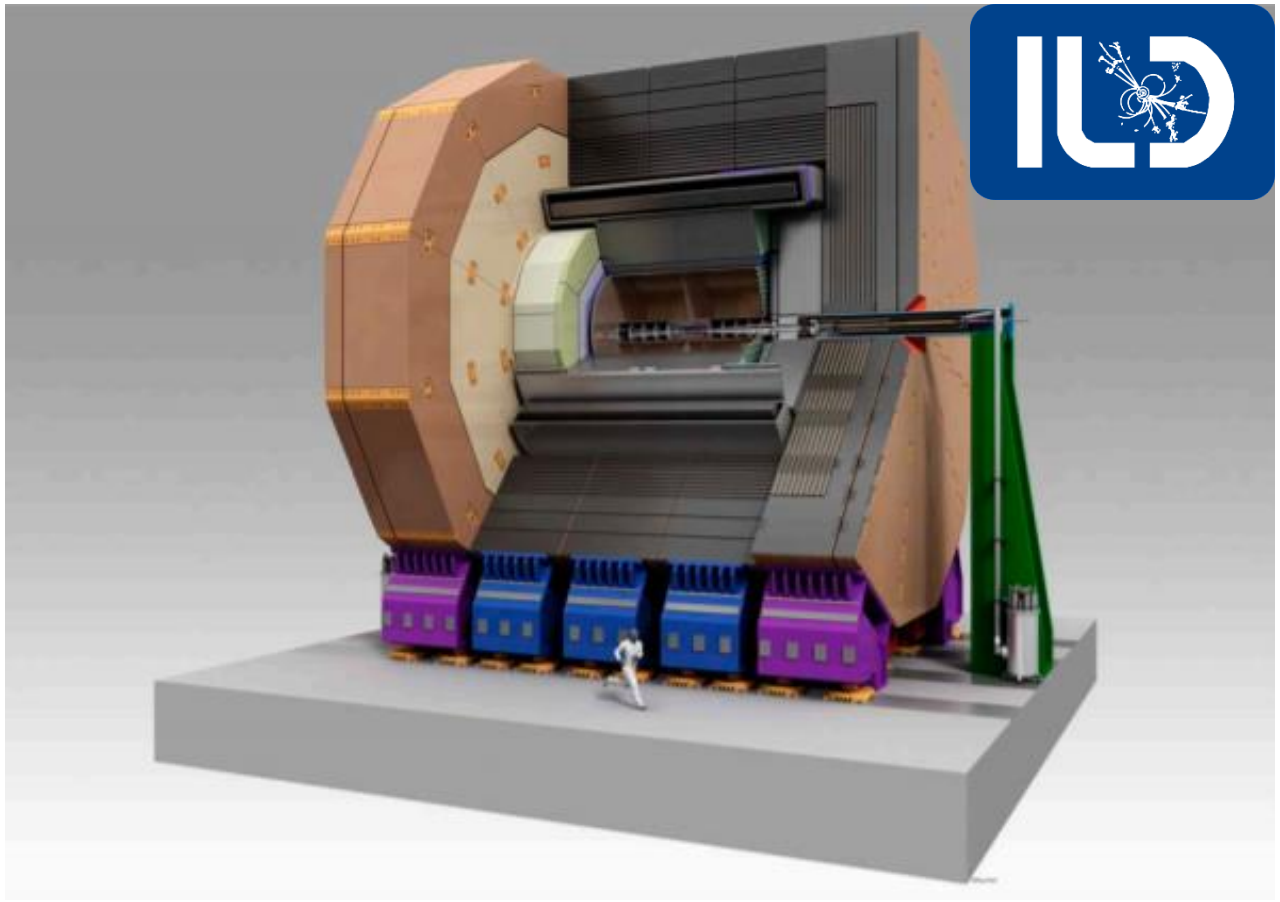


arXiv: 1506.05992 [hep-ex]

ILC

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

  $\sigma_{r\phi} < 5 \oplus \frac{10}{p\sin^{3/2}\theta}\ \mu$m

- Momentum resolution

  $\sigma_{1/p_T} < 2*10^{-5}$ 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)
- HL-LHC prospects (3000 fb^{-1}): ~21% precision for cross section times branching ratio $\frac{\Delta(\sigma\times \mathrm{BR})}{(\sigma\times \mathrm{BR})}$ (ATLAS-PHYS-PUB-2013-014)

Previous Studies

Everything performed at >= 1 TeV, or not realistic

Reference	E_{CM}	beam pol. $P(e^-, e^+)$	$\int Ldt$	$\frac{\Delta(\sigma \times BR)}{(\sigma \times BR)}$	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:0911.0006 [physics.ins-det]	250 GeV	(-0.8, +0.3)	250 fb^{-1}	91%	ILC/SiD M_h = 120 GeV

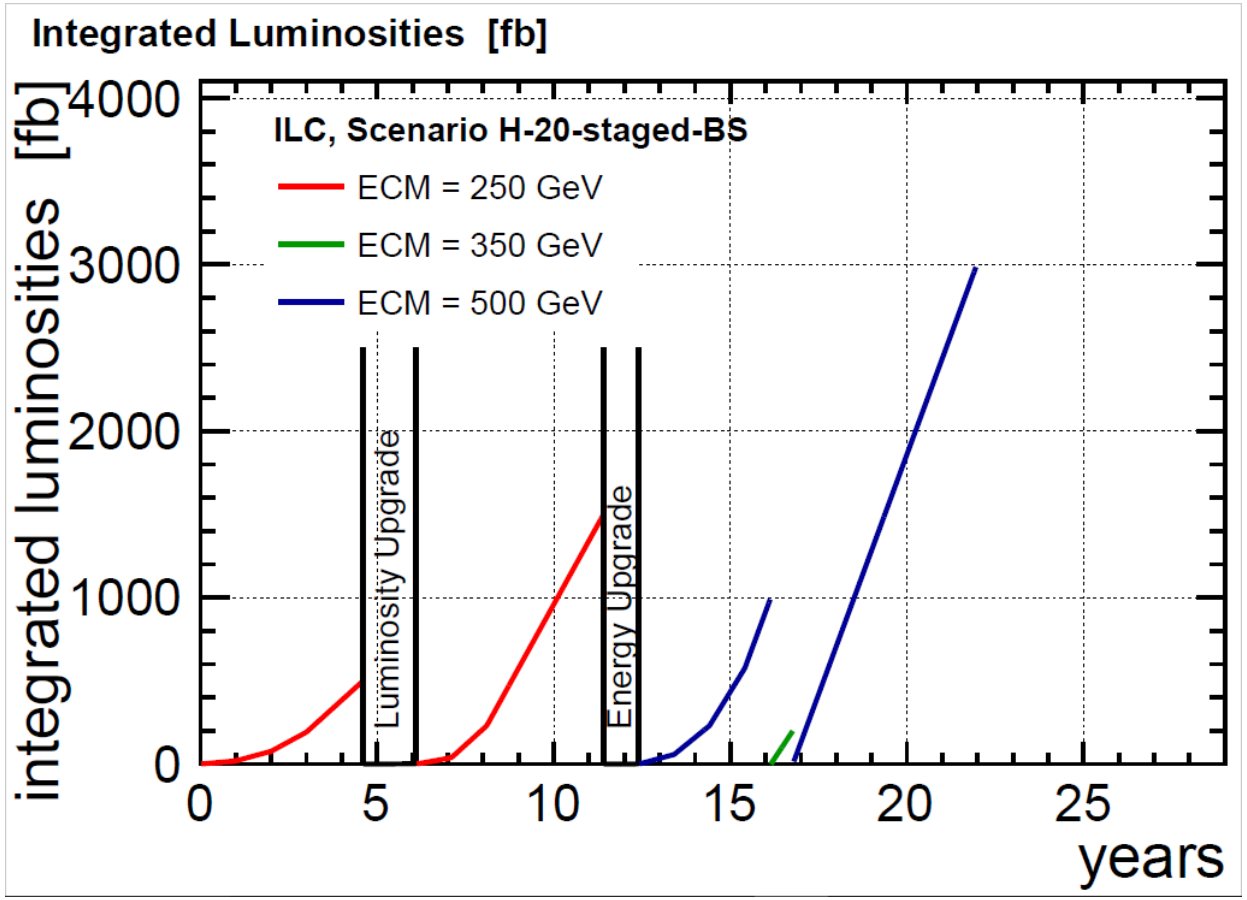
arXiv:1710.07621 [hep-ex]

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 running scenario

arXiv:1506.05992 [hep-ex]

Single Higgs Production

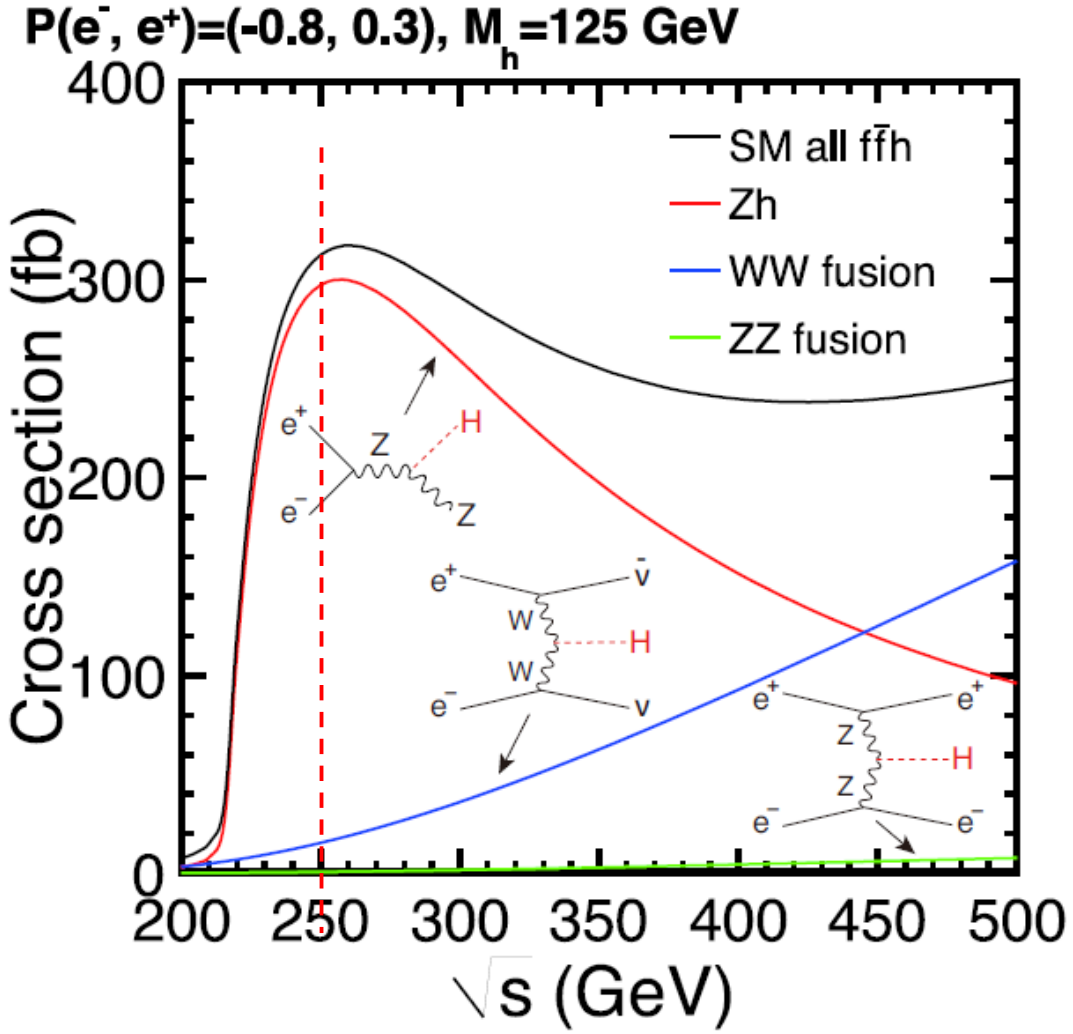
$\sqrt{s}$ = 250 GeV

Higgs-strahlung (Zh) dominant

$\sqrt{s}$ = 500 GeV

WW-fusion dominant

E_{CM}	process	beam pol.	$\int Ldt$ (fb^{-1})	# events
500	$\nu\bar{\nu}h$	L	1600	58
		R	1600	8
	$q\bar{q}h$	L	1600	25
		R	1600	16
250	$\nu\bar{\nu}h$	L	1350	22
		R	450	4
	$q\bar{q}h$	L	1350	62
		R	450	14



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

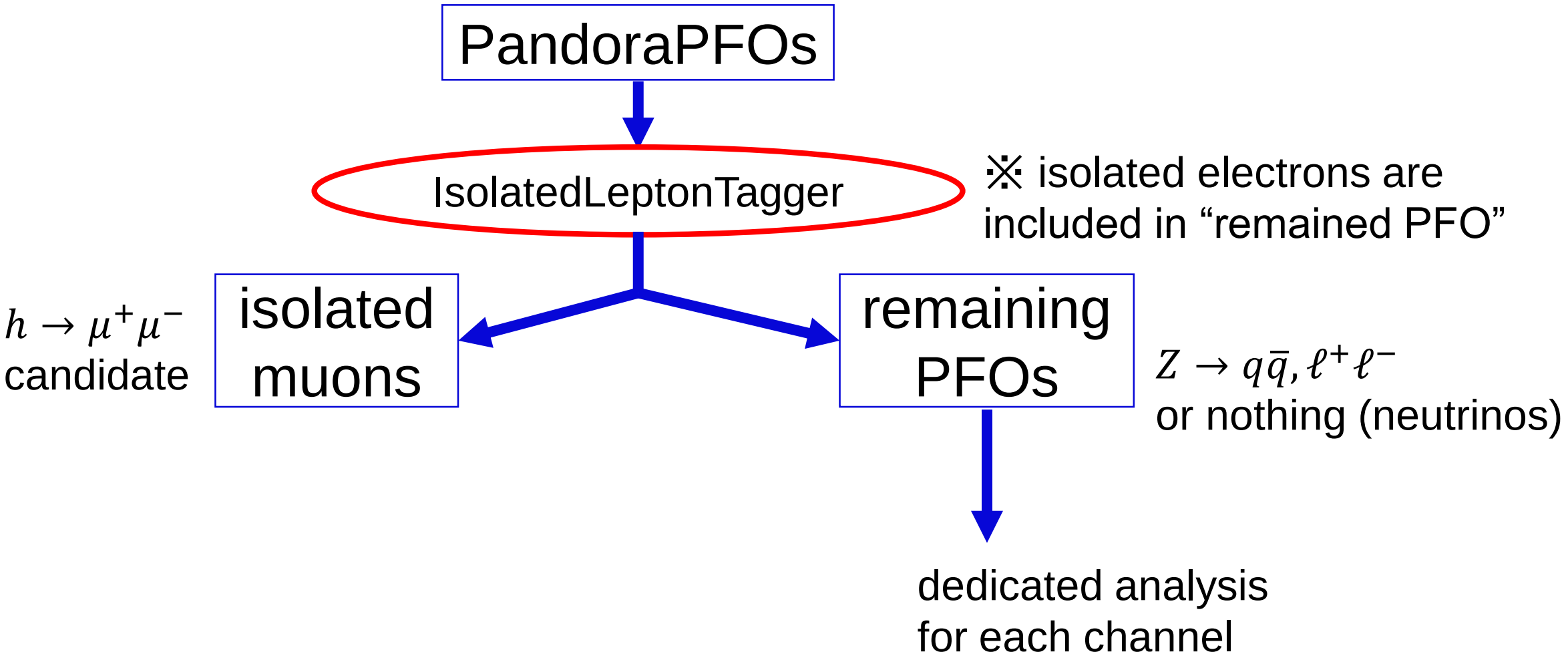
R: (e^-, e^+) = (+0.8, -0.3)

※assumed H20 scenario in this talk, not staging scenario

Analysis Settings

- Geant4-based full detector simulation with ILD model
- Included all possible SM backgrounds
  - Performed toy MC in the end to extract the precision, because some SM background processes (ex: e^+e^- ---> 2f/4f) have not enough MC statistics

General Event Reconstruction



signal
other colors: SM background
plots from nnh500-L

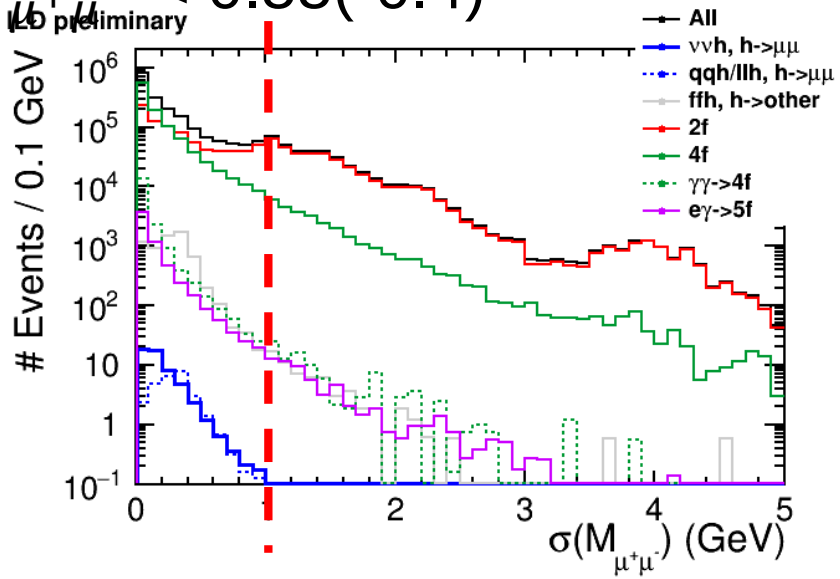
General Event Selection

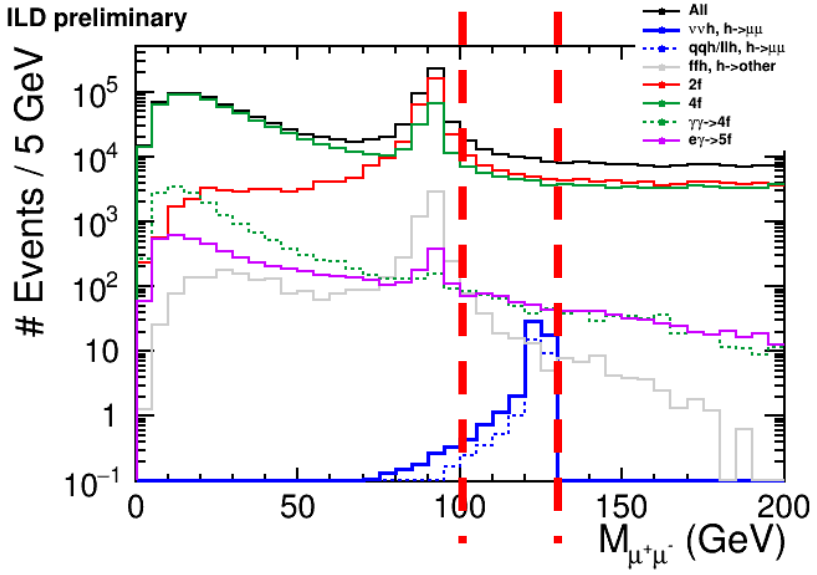
Selections at 500(250) GeV:

- $\#\,\mu^+ == 1, \#\,\mu^- == 1$
- $0.5 < \chi^2(\mu^\pm)/\mathrm{Ndf} < 1.5$ ⟶ only select well-measured tracks
- $\sigma\left(M_{\mu^+\mu^-}\right) < 1(0.5)$ GeV ⟶ only select well-measured muon pair
- $\left|d_0(\mu^\pm)\right| < 0.02$ mm, $|d_0(\mu^-) - d_0(\mu^+)| < 0.02$ mm
- $\left|z_0(\mu^\pm)\right| < 0.5$ mm, $|z_0(\mu^-) - z_0(\mu^+)| < 0.5$ mm

} only select prompt muons

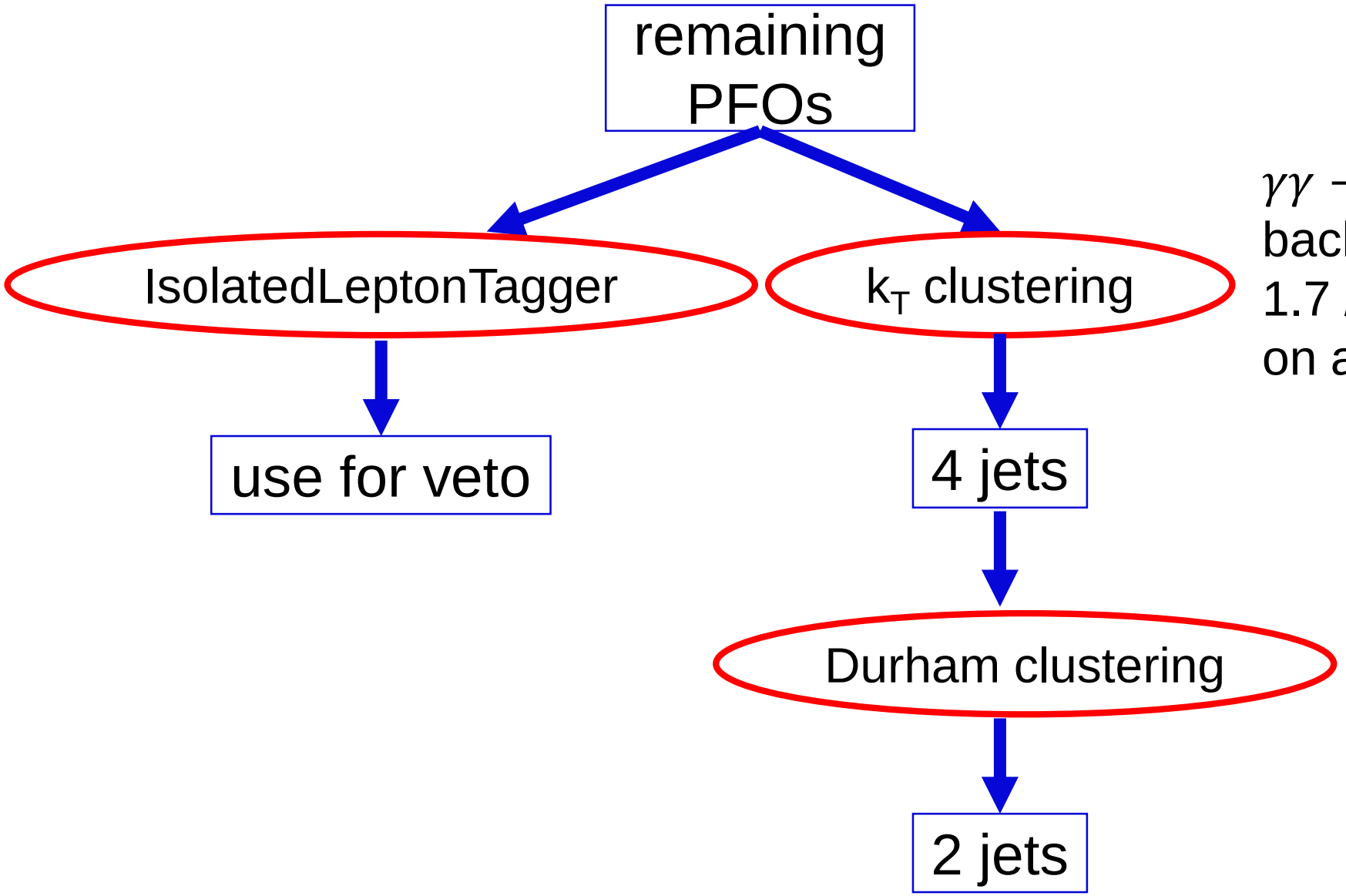
- $100 < M_{\mu^+\mu^-} < 130$ GeV ⟶ $h \to \mu^+\mu^-$ candidate
- $\cos\theta_{\mu^+\mu^-} < 0.55(-0.4)$





One Example: qqh500-L/R

Event Reconstruction

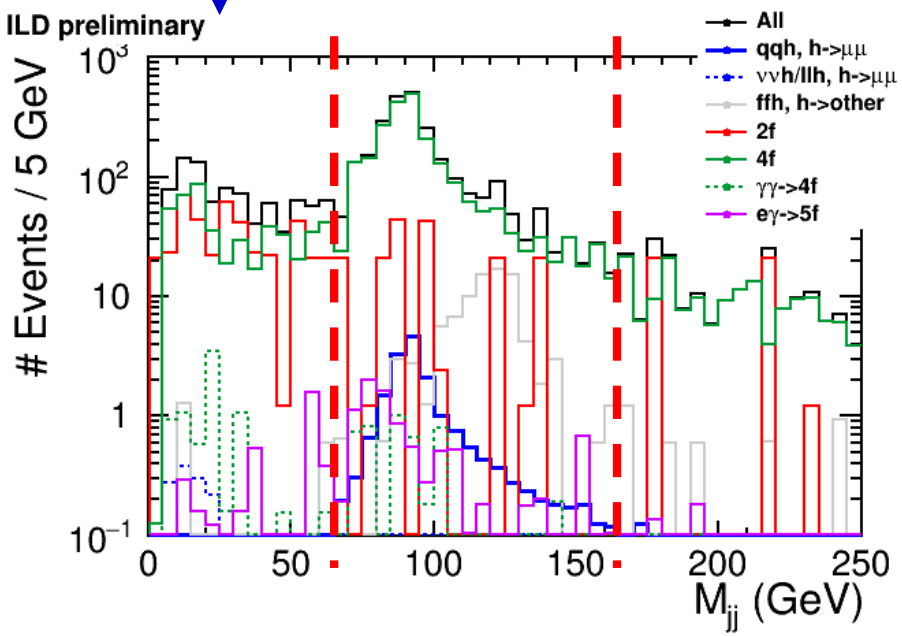


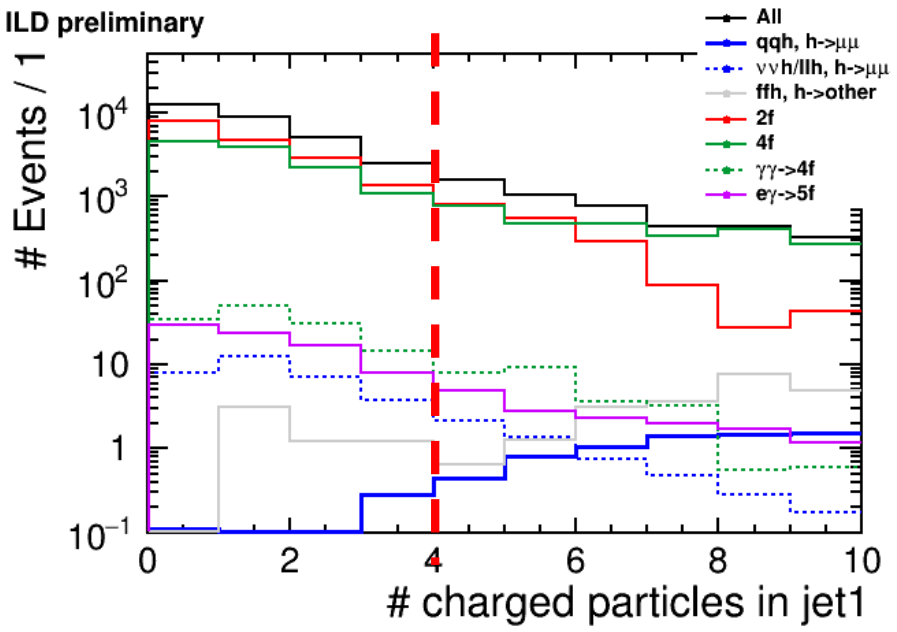
$\gamma\gamma \rightarrow$ low P_t hadron backgrounds are overlaid
1.7 / bunch crossing
on average at 500 GeV

signal
other colors: SM background
plots from qqh500-L

Precuts

- veto: require no isolated leptons in the remaining particles after IsolatedLeptonTagger
- exact 4 jets after k_T clustering
- jet1 and jet2 after Durham clustering should contain 4 or more charged particles ($E_{\text{jet1}} > E_{\text{jet2}}$)
- $60 < M_{jj} < 160$ GeV

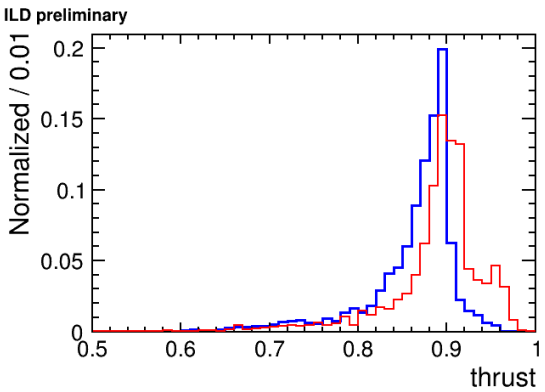


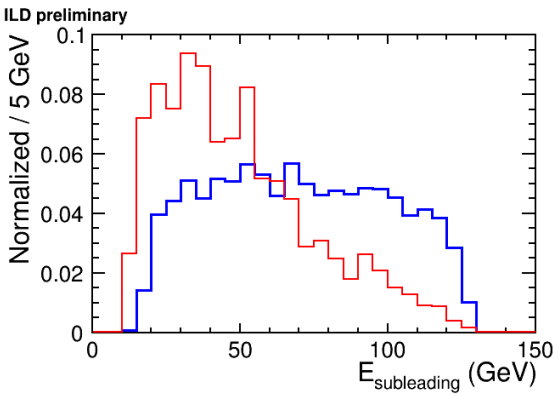


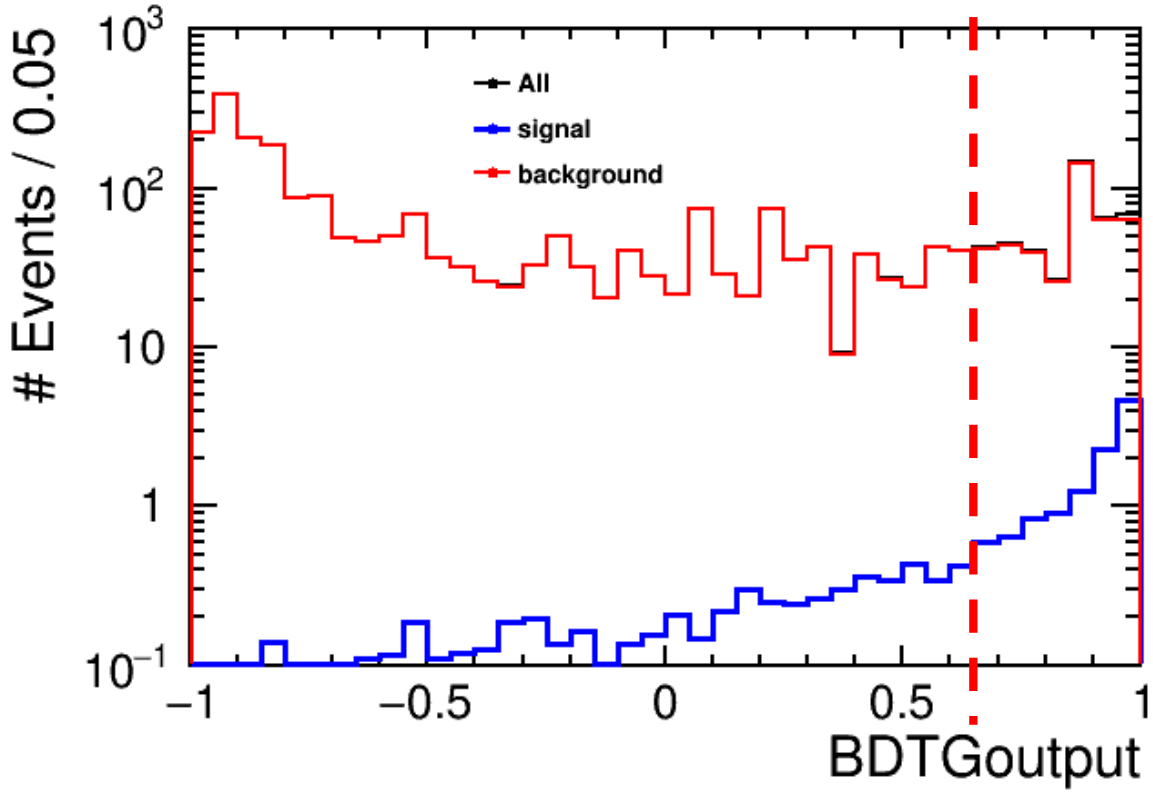
TMVA(BDTG) Analysis

signal
background
plots from qqh500-L

7 input variables:
thrust, $\cos\theta_h$, charge * $\cos\theta_{\mu^\pm}$,
$E_{leading}$, $E_{subleading}$, M_{jj}

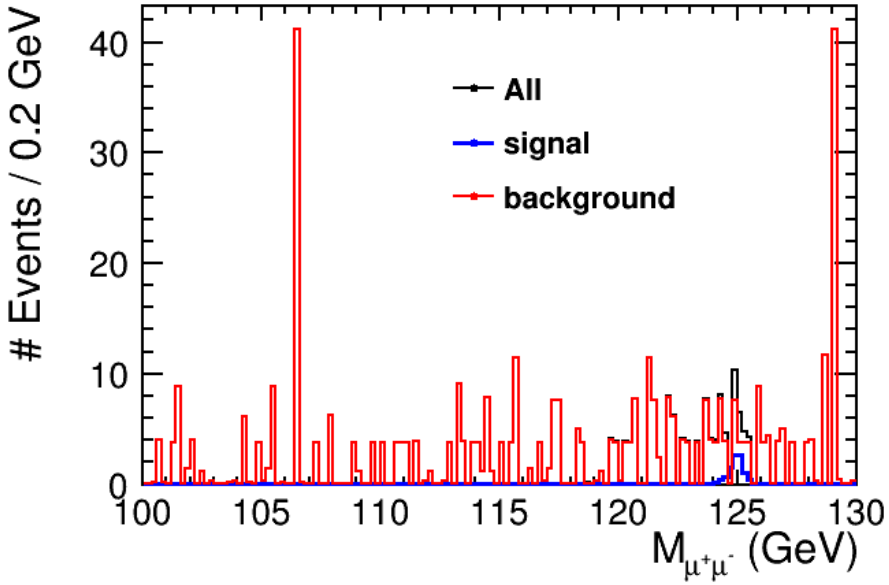






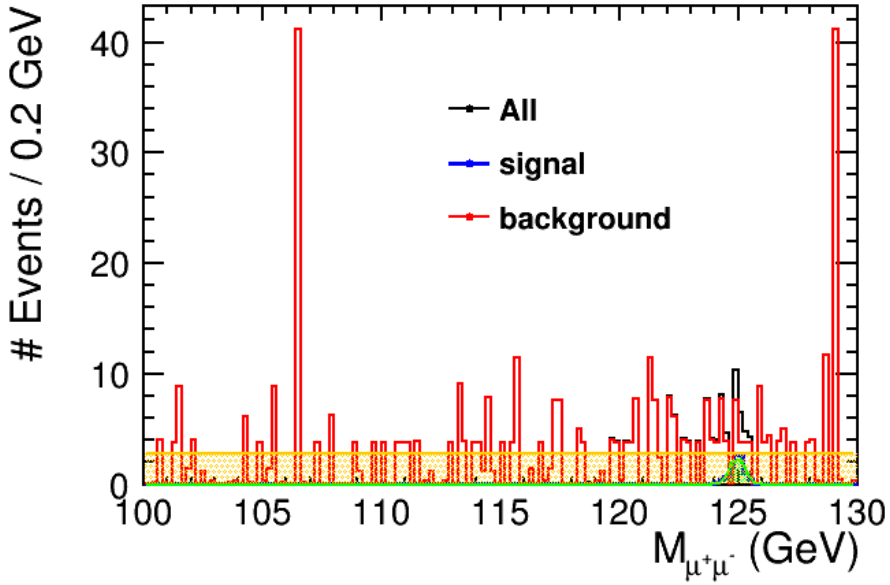
plots from qqh500-L

Toy MC Study (1)



$M_{\mu^+\mu^-}$ spectrum after all cuts

spiky due to low MC statistics

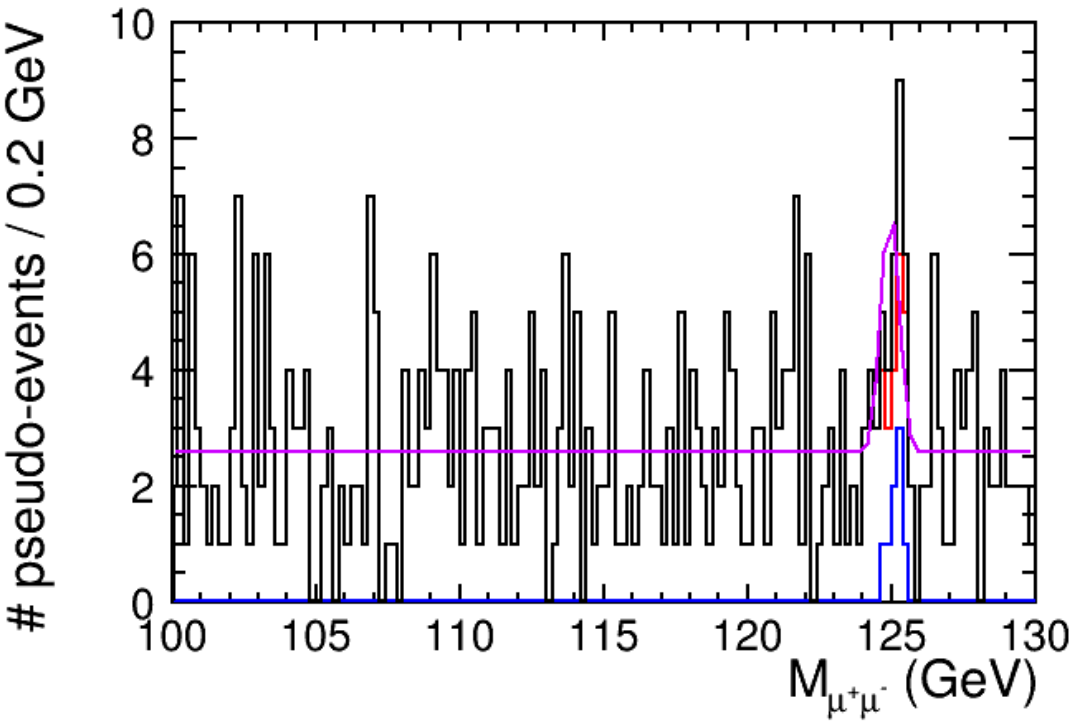


fitting for toy MC

f_S: normalized Gaussian (green)

f_B: constant (yellow)

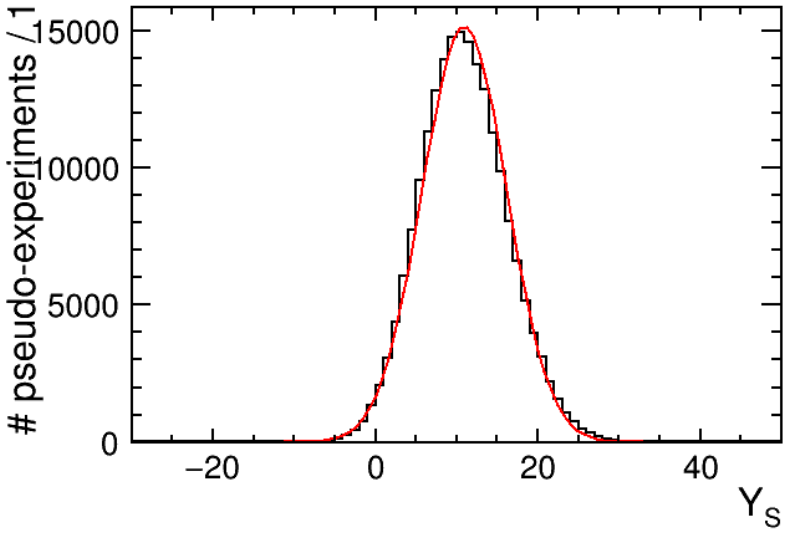
Toy MC Study (2)

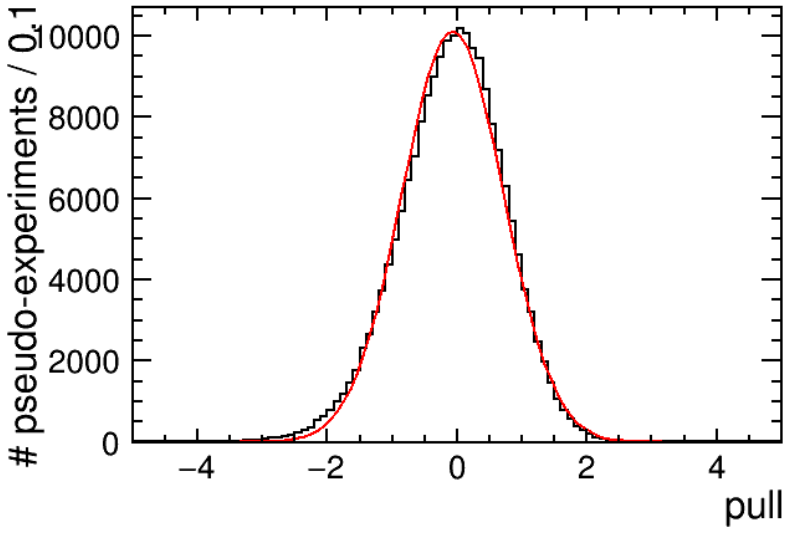


pseudo experiment
blue: signal pseudo data
red: background pseudo data
black = blue + red
purple: result of fit with $f = Y_S f_S + Y_B f_B$
free parameter: Y_S and Y_B
normalization considered

repeat 200000 times
obtain Y_S distribution

Toy MC Study (3)





Y_S distribution
mean: 10.93 +- 0.01
sigma: 5.227 +- 0.008
precision: 47.8%

pull distribution
mean: -0.071 +- 0.002
sigma: 0.779 +- 0.001

Found asymmetric distribution
- small number of events?
- not suitable fitting function?

※100% signal efficiency, no backgrounds, no detector effects

Results

250 GeV	$q\bar{q}h$	$\nu\bar{\nu}h$
L	30.0%	123.5%
R	52.5%	125.4%

500 GeV	$q\bar{q}h$	$\nu\bar{\nu}h$
L	47.8%	39.2%
R	52.1%	71.5%

ILC250 combined = 25.0%

All combined precision = **17.5%** (※“theoretical limit” = 6.9%)

HL-LHC: 21%　similar precision can be achieved

ILC + LHC combined: 14%

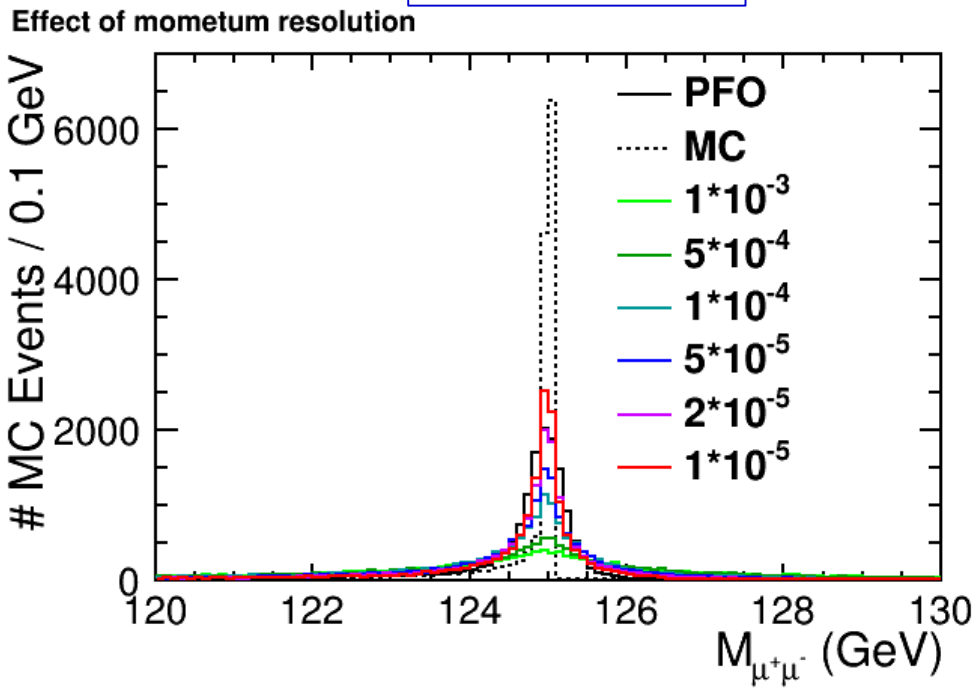
Impact of Momentum Resolution

- 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.
- Checked what happens if we change momentum resolution artificially.
  - Used smearing to MCParticle (MC information)
  - Only signal process

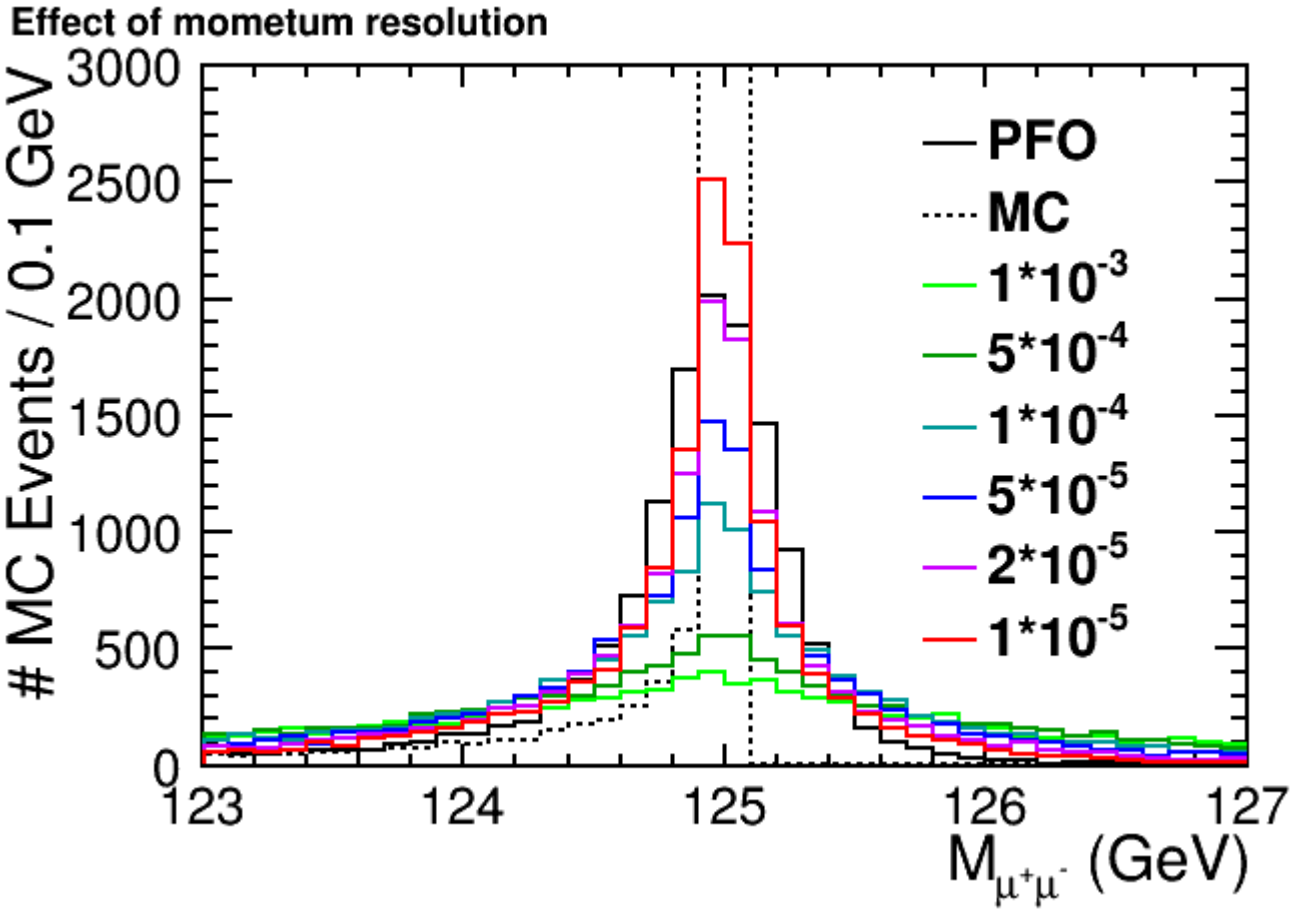
※not luminosity weighted

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

overview



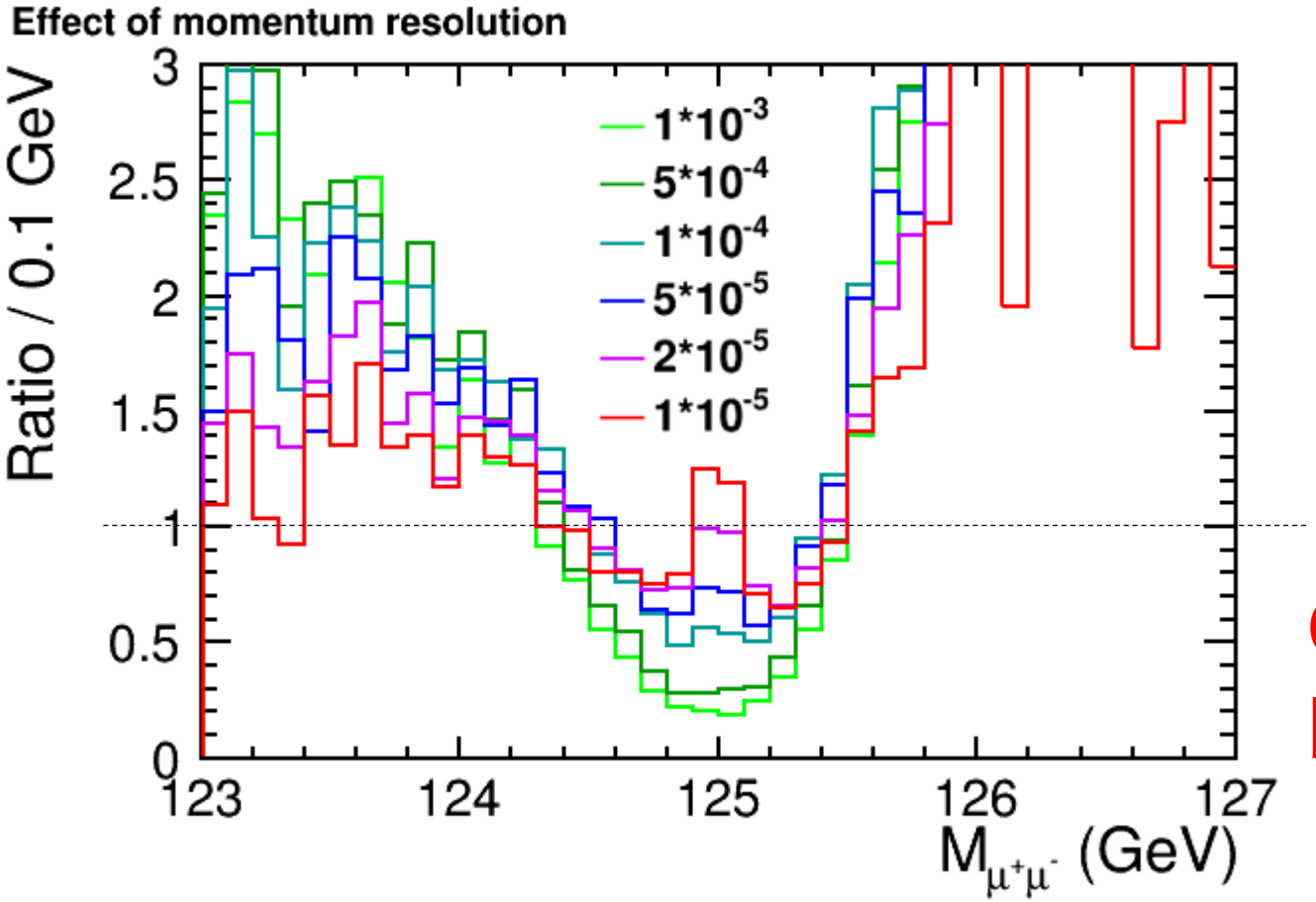
zoom up



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 & Plan

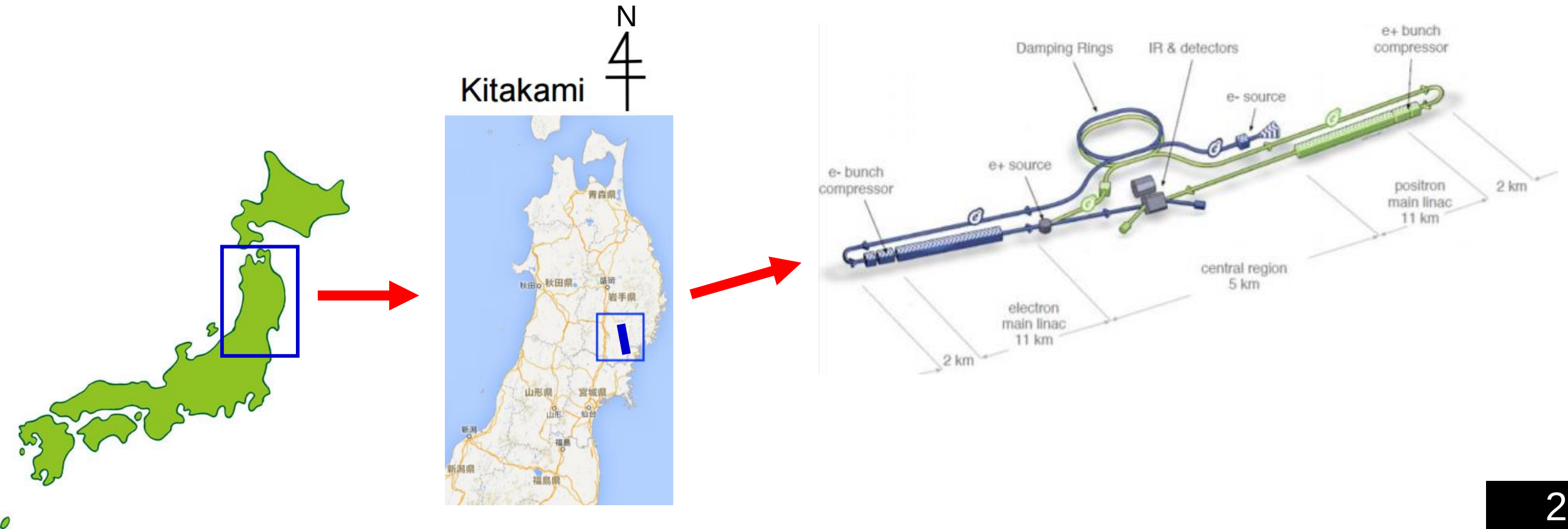
- Studied $h \to \mu^+\mu^-$ channel with E_{CM} = 250/500 GeV based on real analysis, with final states of $q\bar{q}h$ and $\nu\bar{\nu}h$
  - Combined precision = **17.5%** for cross section times branching ratio
    - 25.0% for ILC250
    - better than SiD result with extrapolation (in p5, ~39%)
    - similar precision compare to HL-LHC
    - ILC + LHC will give 14% precision
  - Found asymmetric Y_S/pull distribution, more studies are needed

- 250 GeV results should be modified with staging scenario

BACKUP SLIDES

The International Linear Collider

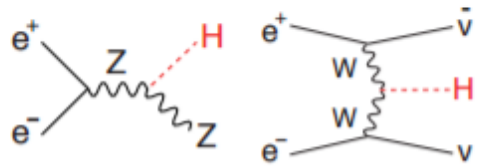
- e^+e^- collider, E_{CM} = 250 - 500 GeV (upgradable to 1 TeV)
- polarized beam (e^-: 0.8, e^+: ≥ 0.3(0.6))
- clean environment, known initial state



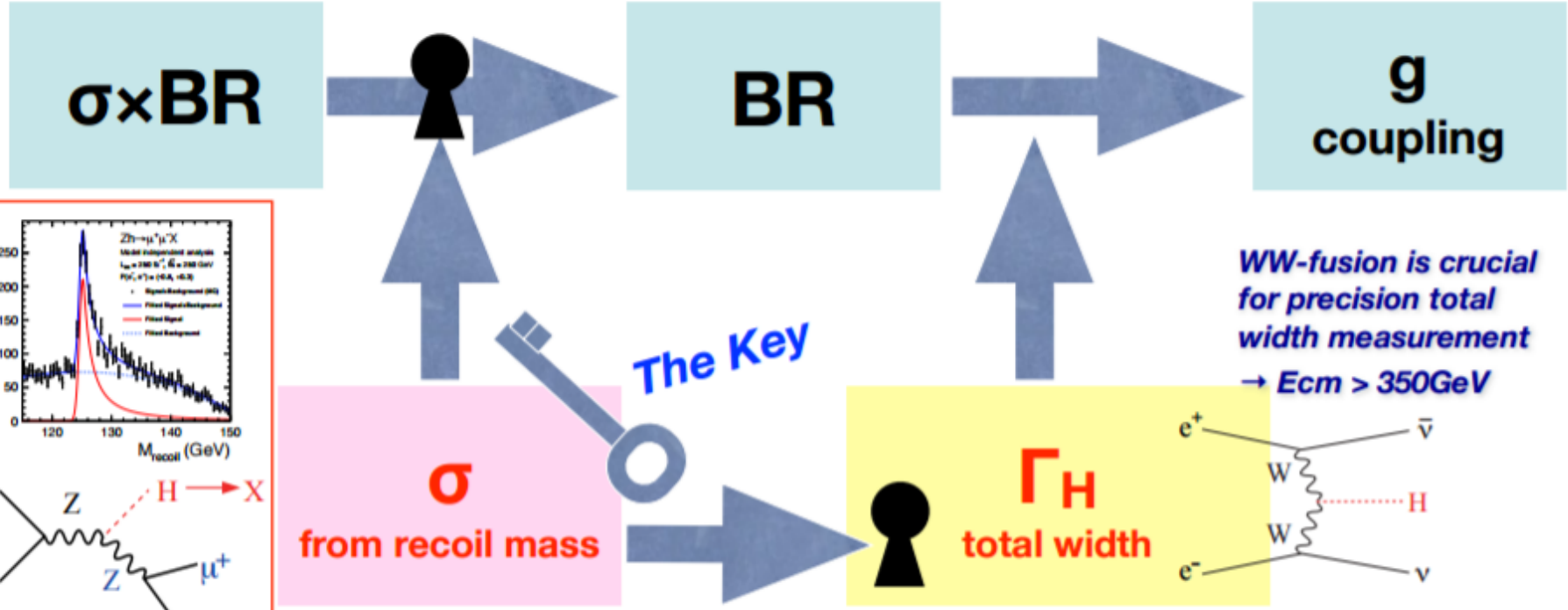
Key Point

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

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



$$g^2_{HAA} \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$



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