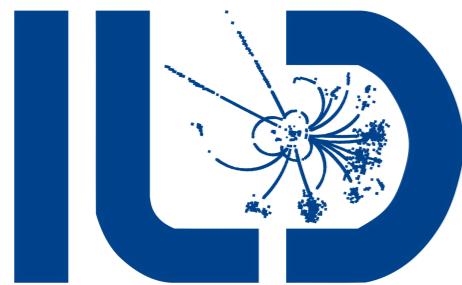


a new method for measuring the Higgs mass at e+e-



Junping Tian (U. Tokyo)



LCWS 2019, Oct. 28-Nov.1, 2019 @ Sendai

outline

- motivation
- traditional method
- new method
- detector benchmark

introduction: why δm_H is important

- partial widths of $H \rightarrow ZZ^*/WW^*$ are very sensitive to the Higgs boson mass (due to phase space)
- δm_H becomes one main source of systematic errors for theory prediction of $\Gamma(H \rightarrow ZZ^*)$ and $\Gamma(H \rightarrow WW^*)$

Peskin et al, 1404.0319

$$\delta_W = 6.9 \cdot \delta m_H \quad \delta_Z = 7.7 \cdot \delta m_H$$

e.g. if $\Delta m_H = 200 \text{ MeV} \rightarrow \delta_Z \sim 1.2\% (\gg \text{other sources})$

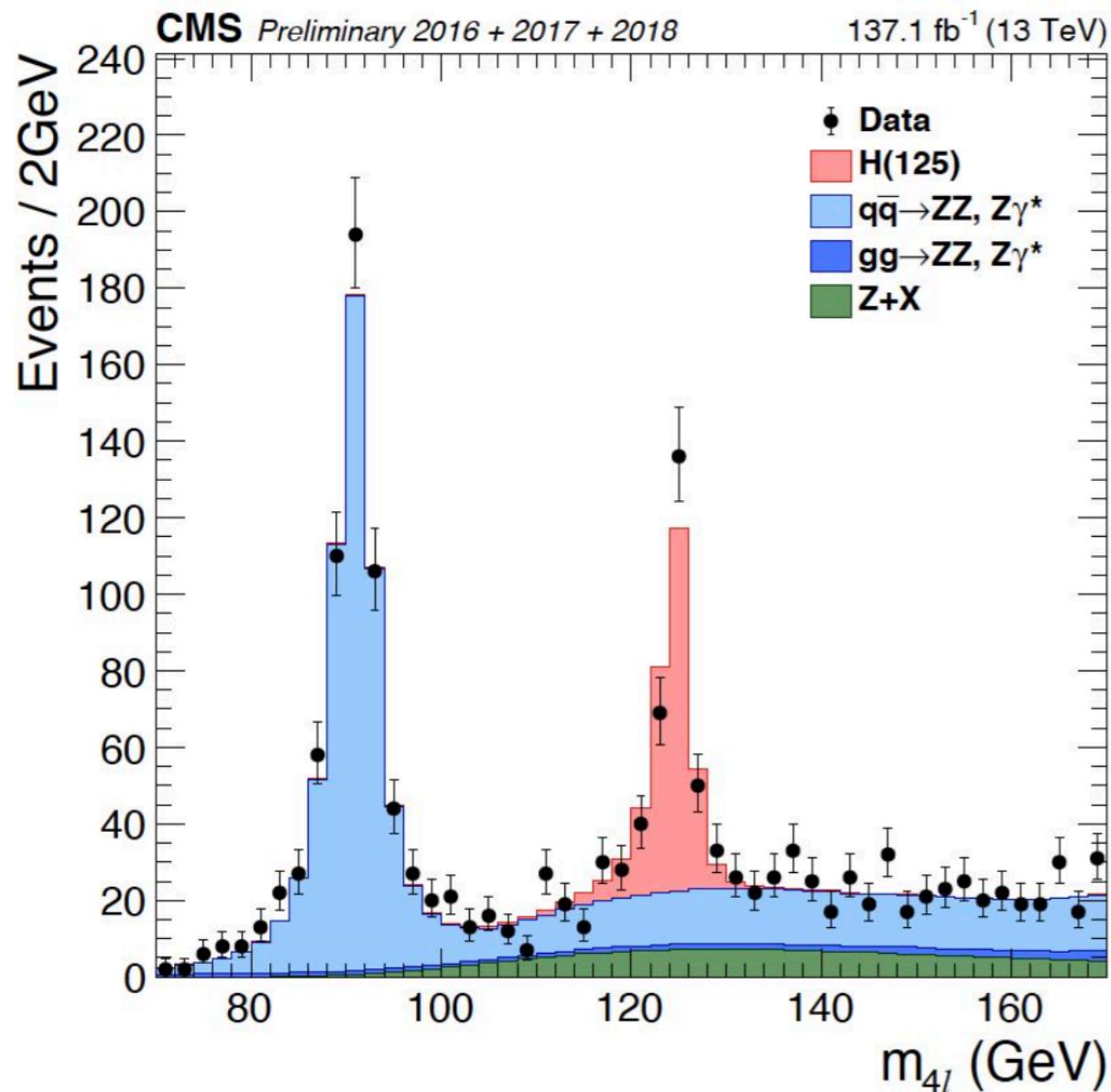
ILC 250: $\Delta m_H = 14 \text{ MeV} \rightarrow \delta_Z \sim 0.1\%$

importance in SMEFT: talk by S. Jung on Tuesday

note: δ_Z is relative error for HZZ coupling, which is defined as
1/2 of relative error of partial width of $H \rightarrow ZZ^*$

introduction: methods to measure Higgs mass

CMS-PAS-HIG-19-001



- at LHC
direct reconstruction from
decay: $H \rightarrow \gamma\gamma$ or $H \rightarrow ZZ \rightarrow 4l$

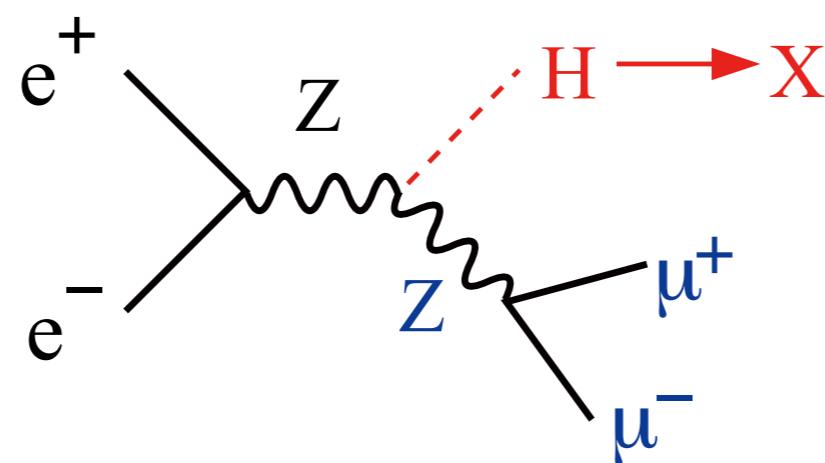
Run1 + 2016 data

$$m_H = 125.35 \pm 0.12(\text{stat}) \pm 0.09(\text{syst}) \text{ GeV}$$

talk by G. Bagliesi yesterday

introduction: methods to measure Higgs mass

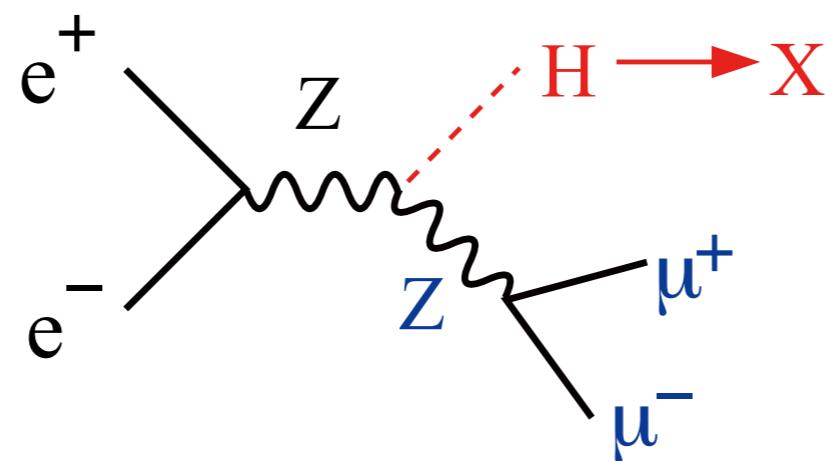
- o at e+e-: recoil mass method (traditional)



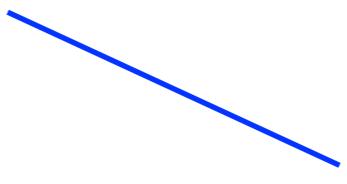
$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-}) \right)^2$$

introduction: methods to measure Higgs mass

- o at e+e-: recoil mass method (traditional)

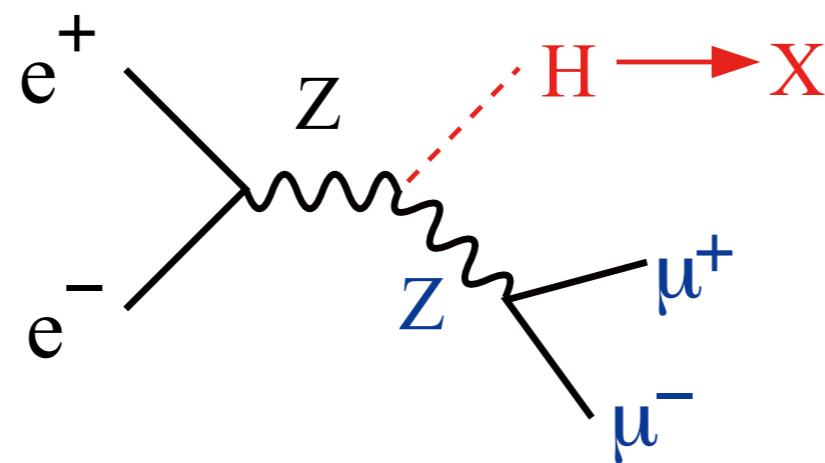


$$M_X^2 = (p_{CM} - (p_{\mu^+} + p_{\mu^-}))^2$$

 momentum uncertainty

introduction: methods to measure Higgs mass

- o at e+e-: recoil mass method (traditional)



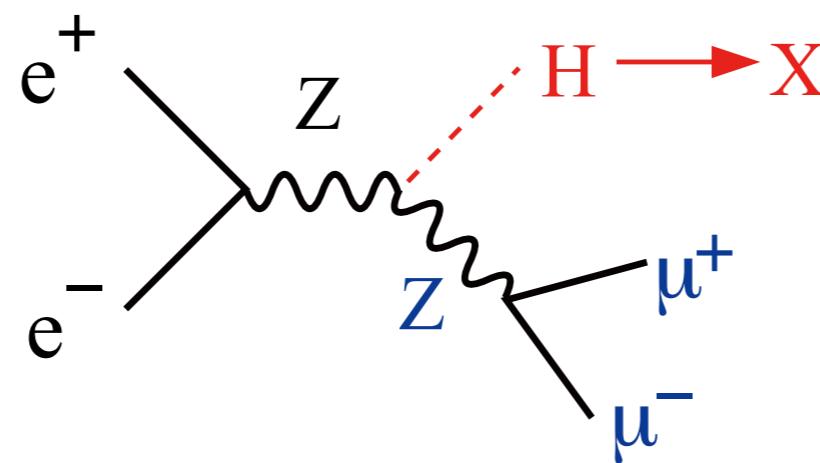
$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-}) \right)^2$$

E_{CM} uncertainty

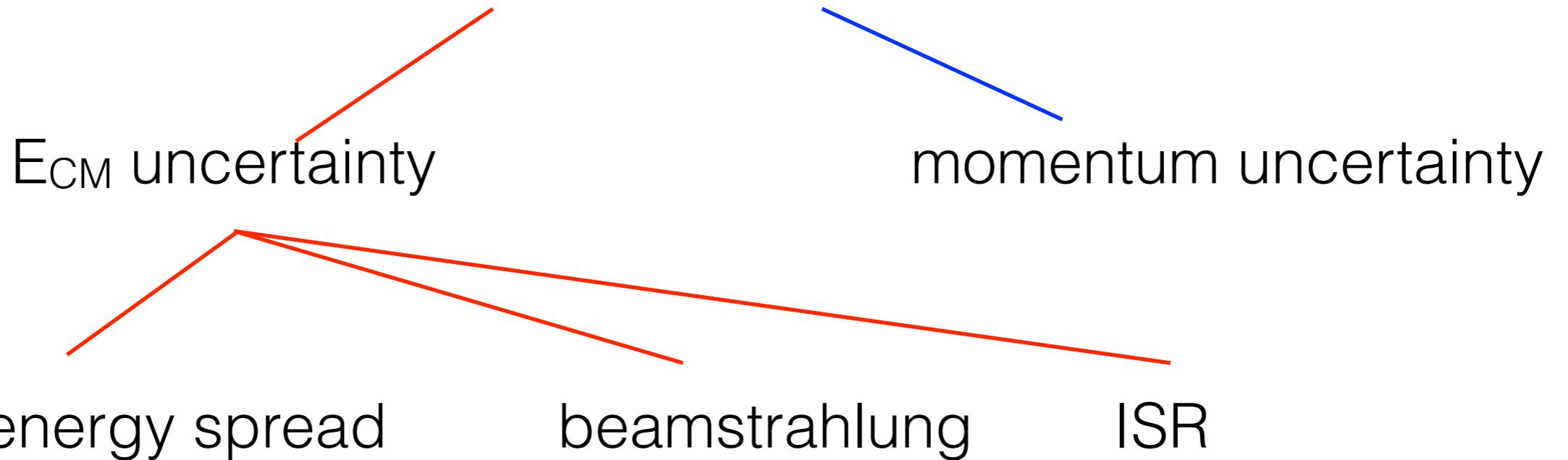
momentum uncertainty

introduction: methods to measure Higgs mass

- o at e+e-: recoil mass method (traditional)

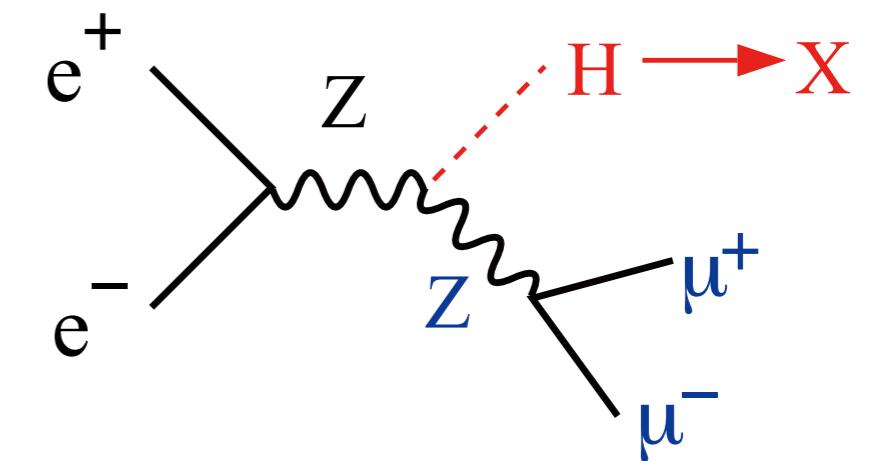
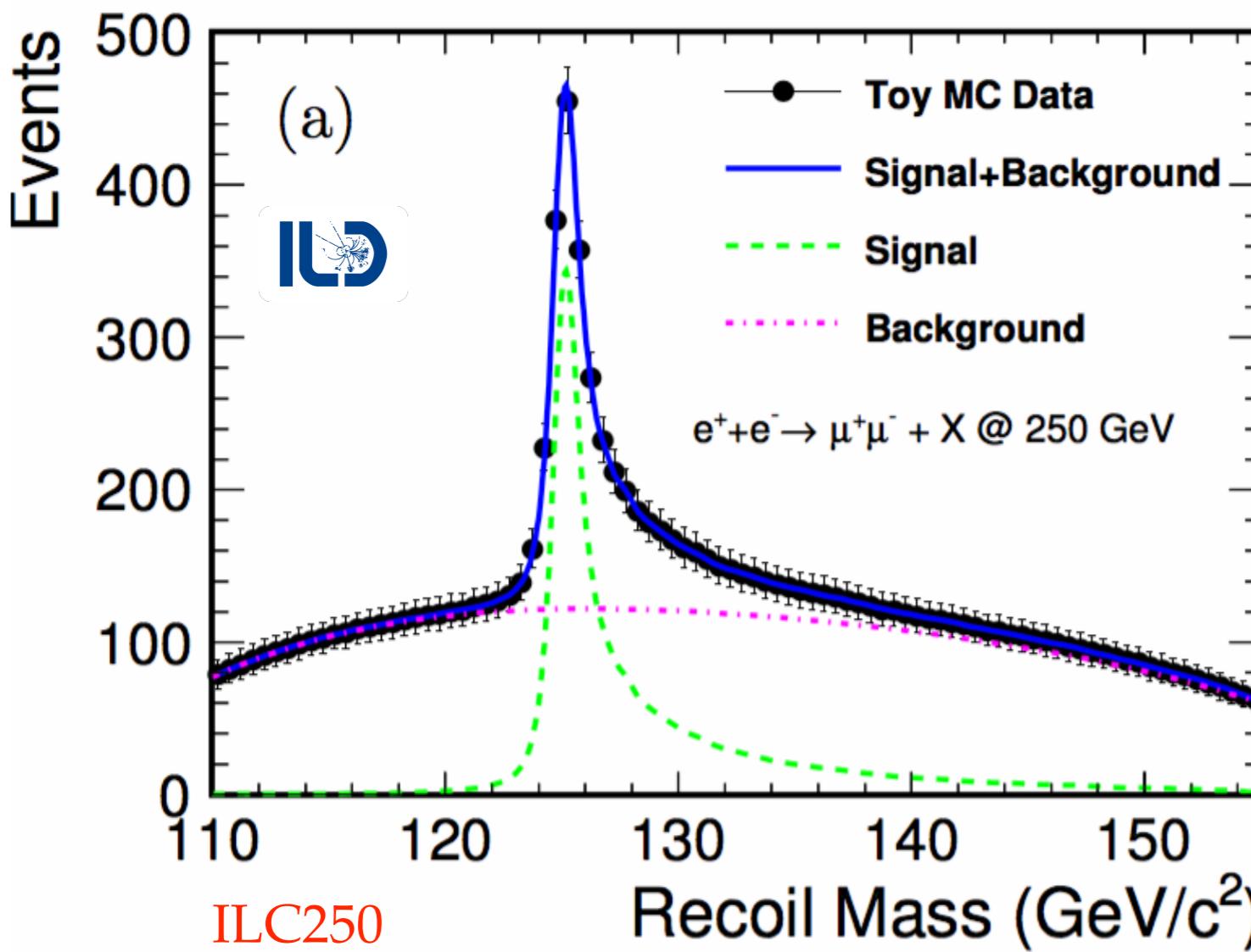


$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-}) \right)^2$$



introduction: methods to measure Higgs mass

o at e^+e^- : recoil mass method (traditional)



$$\Delta m_H = 14 \text{ MeV}$$

Yan et al, 1604.07524

introduction: methods to measure Higgs mass

Collider Scenario	Strategy	δm_H (MeV)	Ref.	$\delta(\Gamma_{ZZ^*})$ [%]
LHC Run-2	$m(ZZ), m(\gamma\gamma)$	160	[96]	1.9
	$m(ZZ)$	10-20	[13]	0.12-0.24
Higgs @ FC 1905.03764	ZH recoil	14	[3]	0.17
	ZH recoil	78	[98]	0.94
	$m(bb)$ in Hvv	30 ¹⁹	[98]	0.36
	$m(bb)$ in Hvv	23	[98]	0.28
	ZH recoil	11	[99]	0.13
	ZH recoil	5.9	[2]	0.07

introduction: methods to measure Higgs mass

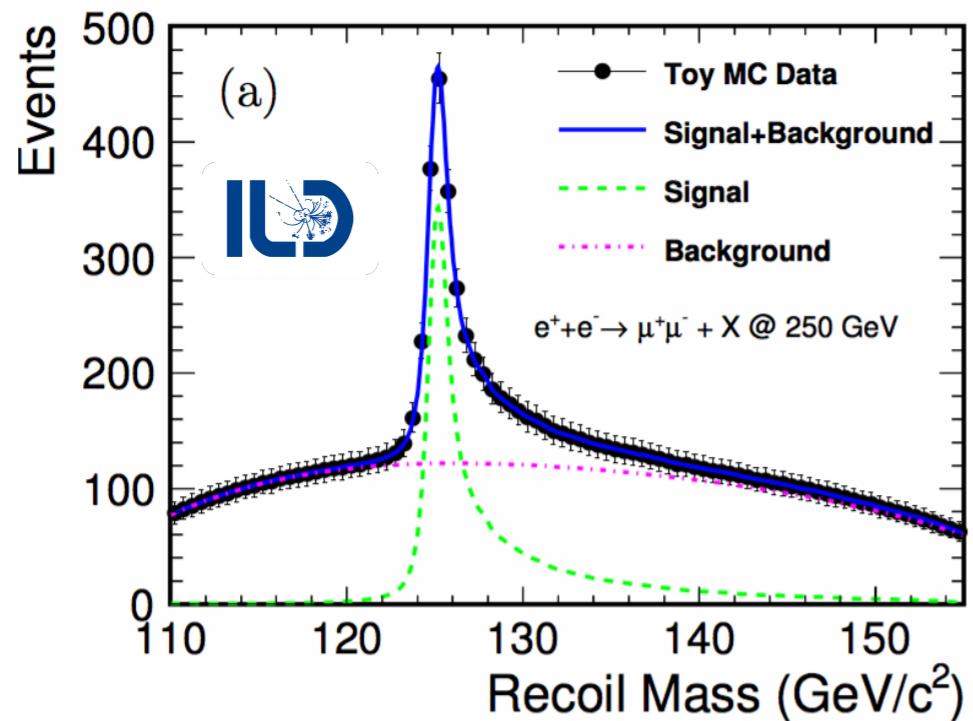
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	FCC-ee	ZH recoil	11	[99] 0.13
	CEPC	ZH recoil	5.9	[2] 0.07

[13] 1902.00134

Detailed studies of the calibration of the muons, electrons and photons with the very large HL-LHC sample have not been done yet, however it is plausible that the mass of the Higgs boson will be measured with a precision of 10-20 MeV, assuming that with the higher statistics the analysis will be further optimised to gain in statistical precision and that systematic uncertainties on the muon transverse momentum scale will significantly improve with the higher statistics.

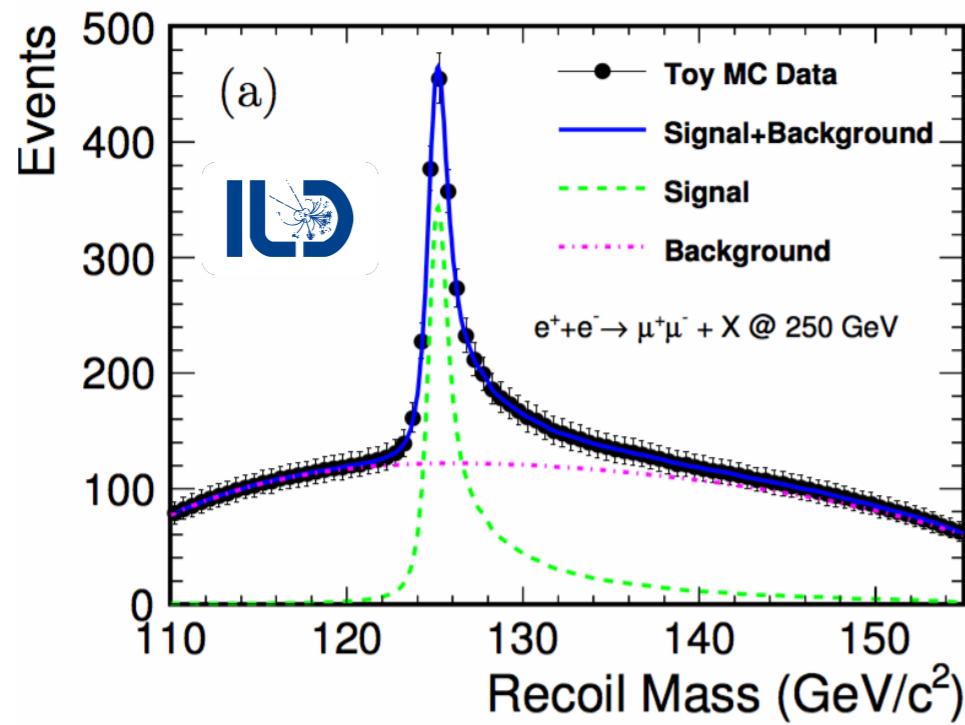
introduction: why a new method?

at $E_{CM}=250$ GeV: $\Delta m_H = 14$ MeV

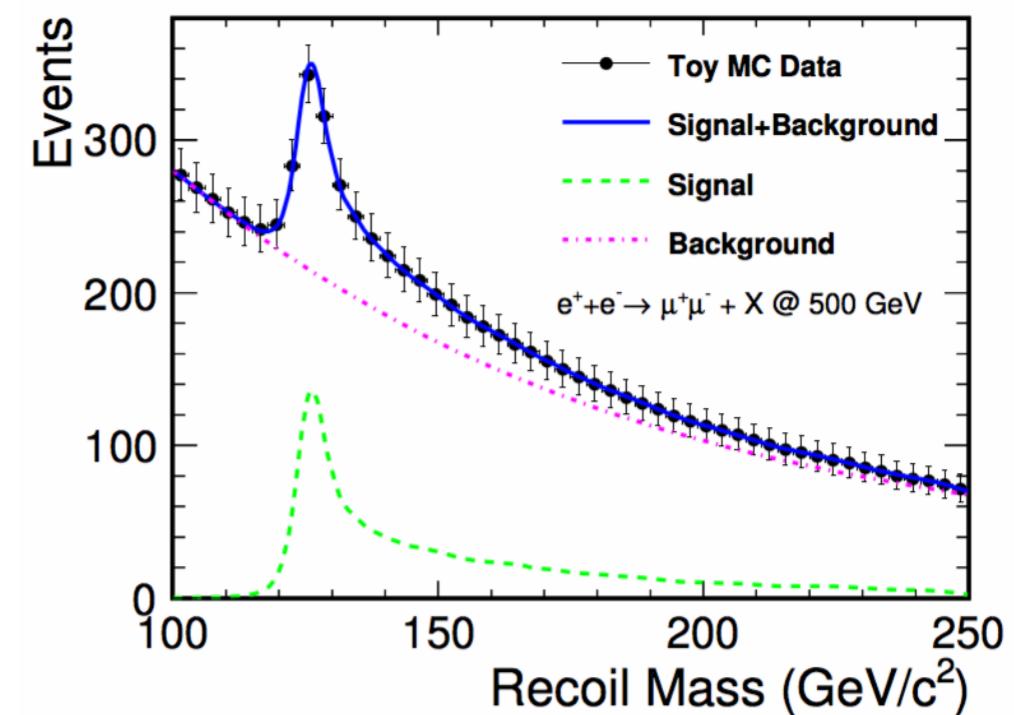


introduction: why a new method?

at $E_{CM}=250$ GeV: $\Delta m_H = 14$ MeV

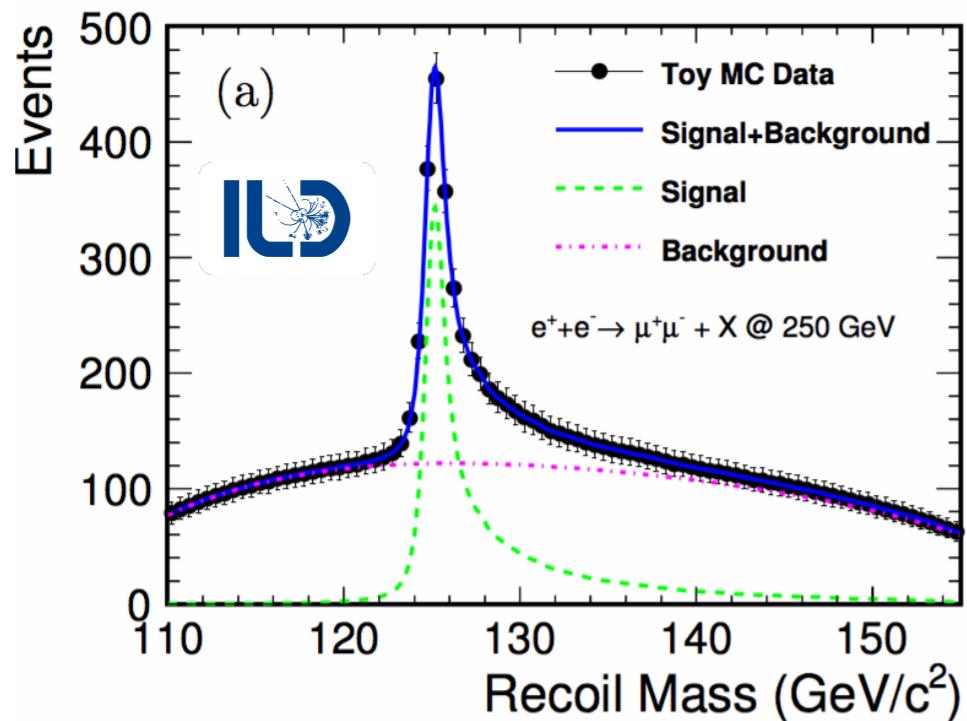


at $E_{CM}=500$ GeV: $\Delta m_H = 218$ MeV

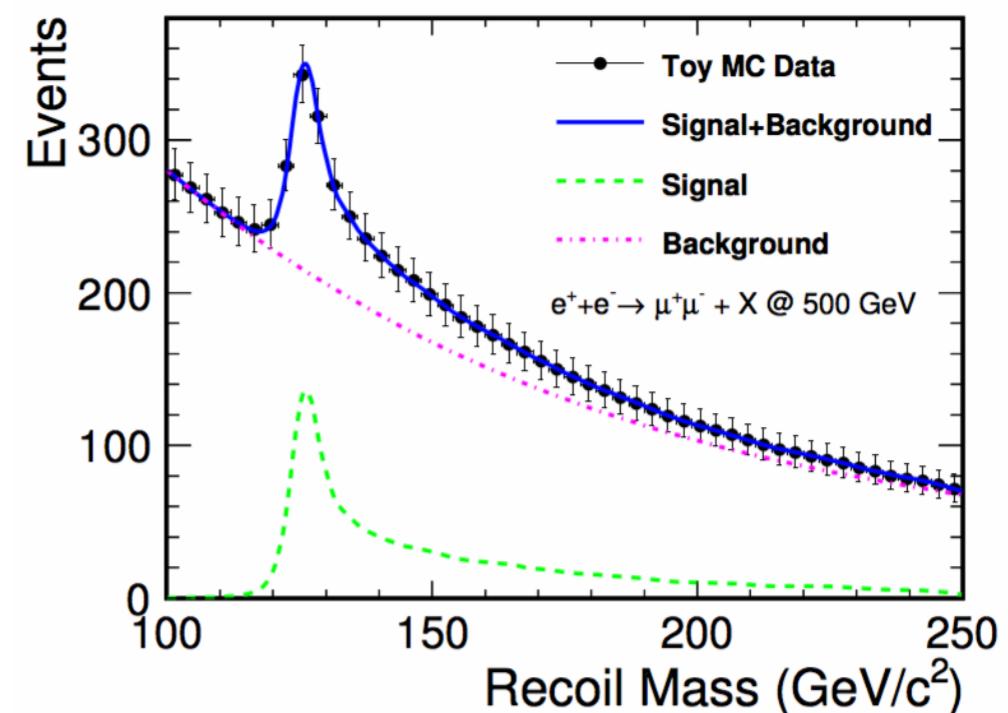


introduction: why a new method?

at $E_{CM}=250$ GeV: $\Delta m_H = 14$ MeV



at $E_{CM}=500$ GeV: $\Delta m_H = 218$ MeV

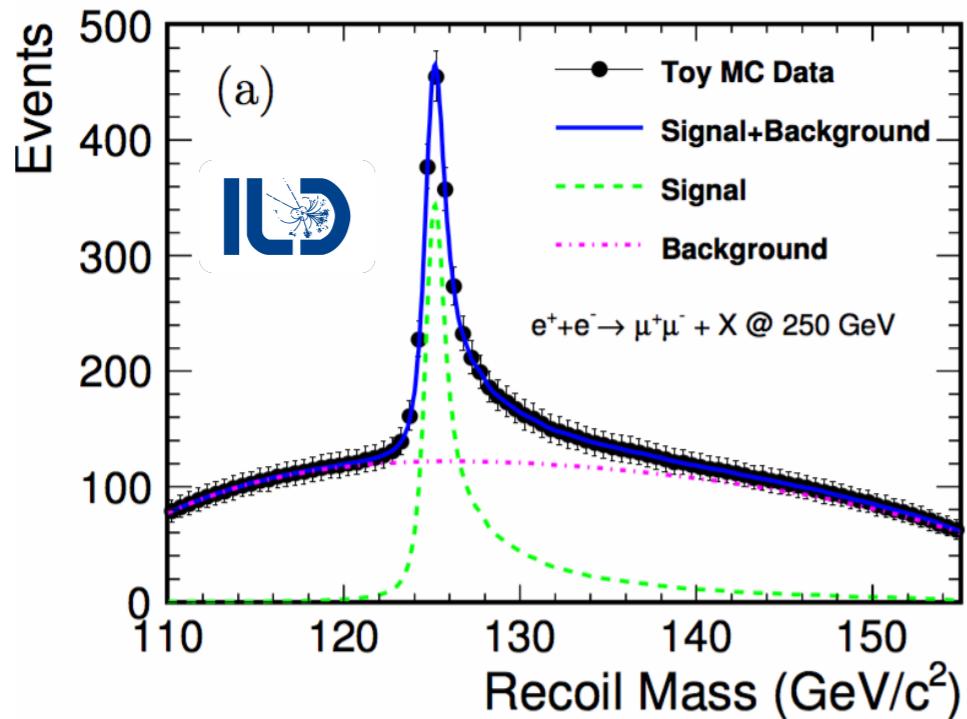


can we improve Δm_H at e.g. $\sqrt{s} \geq 500$ GeV?

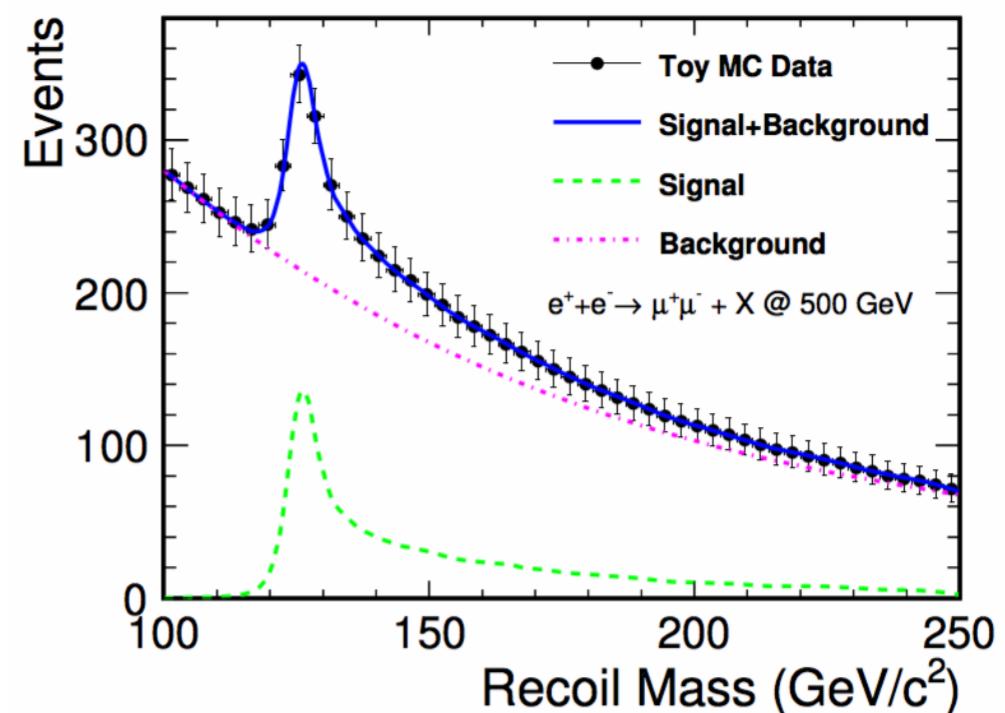
can we calibrate E_{CM} to << 14MeV at 250 GeV?

introduction: why a new method?

at $E_{CM}=250$ GeV: $\Delta m_H = 14$ MeV



at $E_{CM}=500$ GeV: $\Delta m_H = 218$ MeV



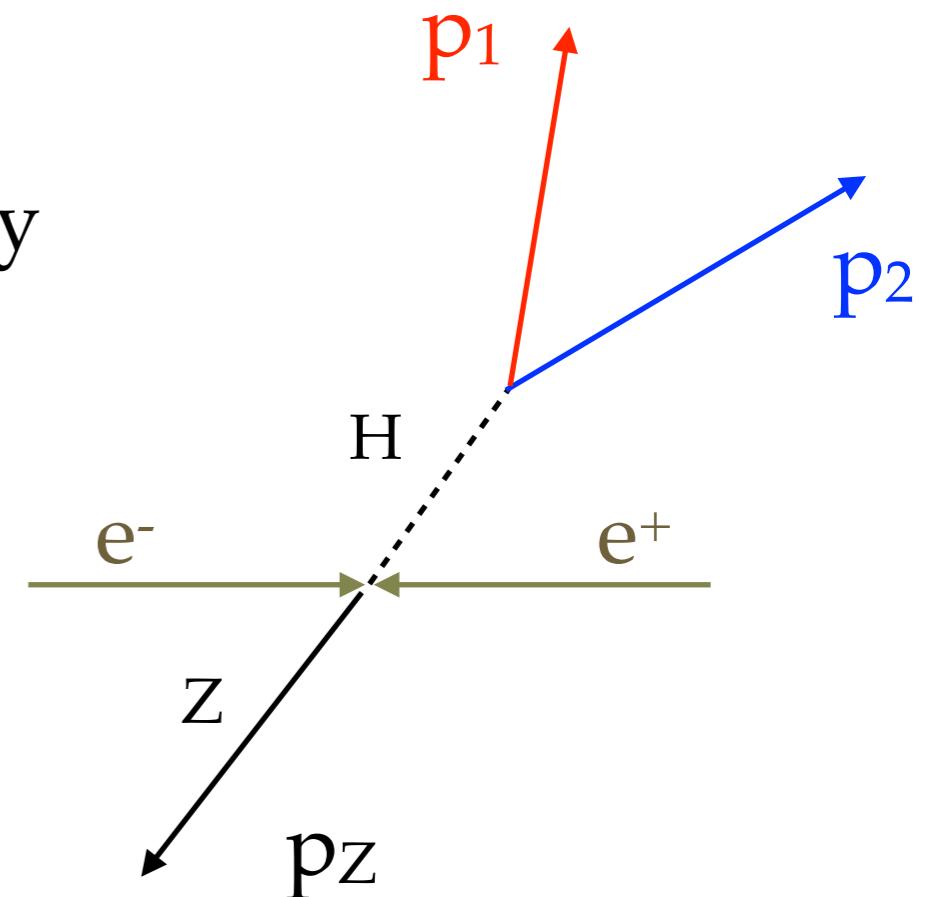
can we improve Δm_H at e.g. $\sqrt{s} \geq 500$ GeV?
can we calibrate E_{CM} to << 14 MeV at 250 GeV?

- direct reconstruction using $H \rightarrow bb$ (and $Z \rightarrow qq$): A.Ebrahimi PhD Thesis
- cross section scan at around threshold: G.Wilson @ LCWS2017
- new method: this study

idea of a new method for measurement of m_H

strategy

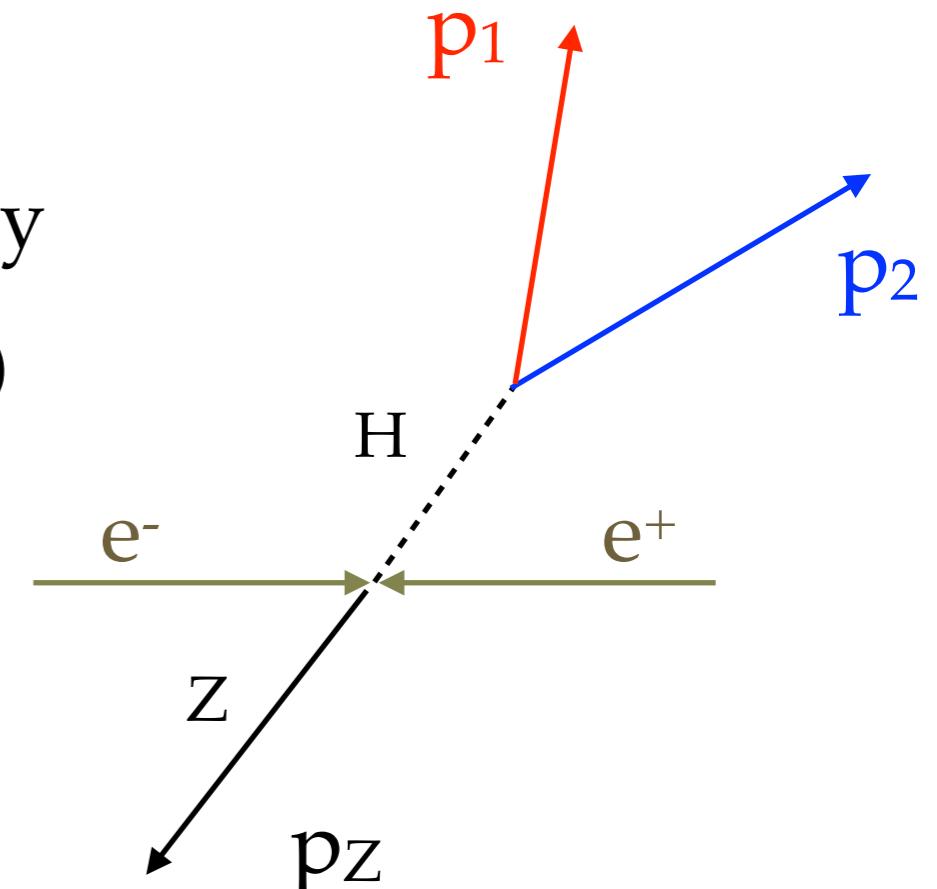
- require momentum balance only in transverse direction
- use measured jet direction, but not energy
- two constraints -> two unknown (p_1, p_2)



idea of a new method for measurement of m_H

strategy

- require momentum balance only in transverse direction
- use measured jet direction, but not energy
- two constraints \rightarrow two unknown (p_1, p_2)



advantage

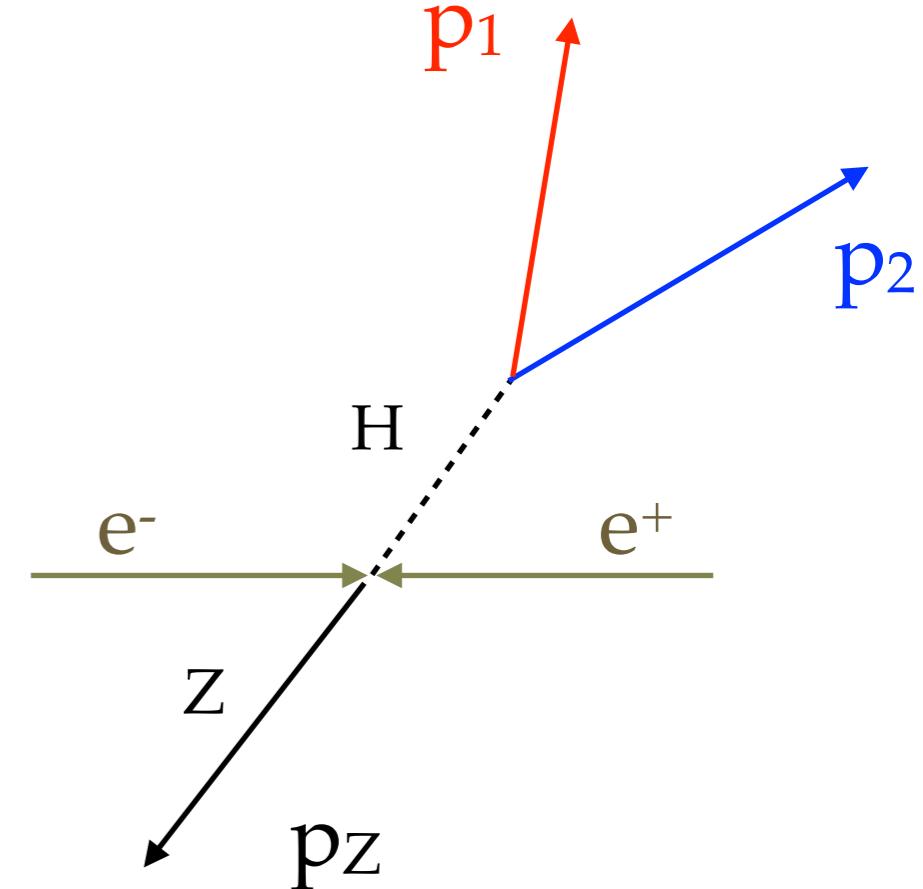
- insensitive to beam energy
- insensitive to beamstrahlung/ISR
- insensitive to (b)-jet energy (scale & resolution)

analytic results

$$p_1 \sin \theta_1 \cos \phi_1 + p_2 \sin \theta_2 \cos \phi_2 = p_x$$

$$p_1 \sin \theta_1 \sin \phi_1 + p_2 \sin \theta_2 \sin \phi_2 = p_y$$

(p_x, p_y : measured from p_z)

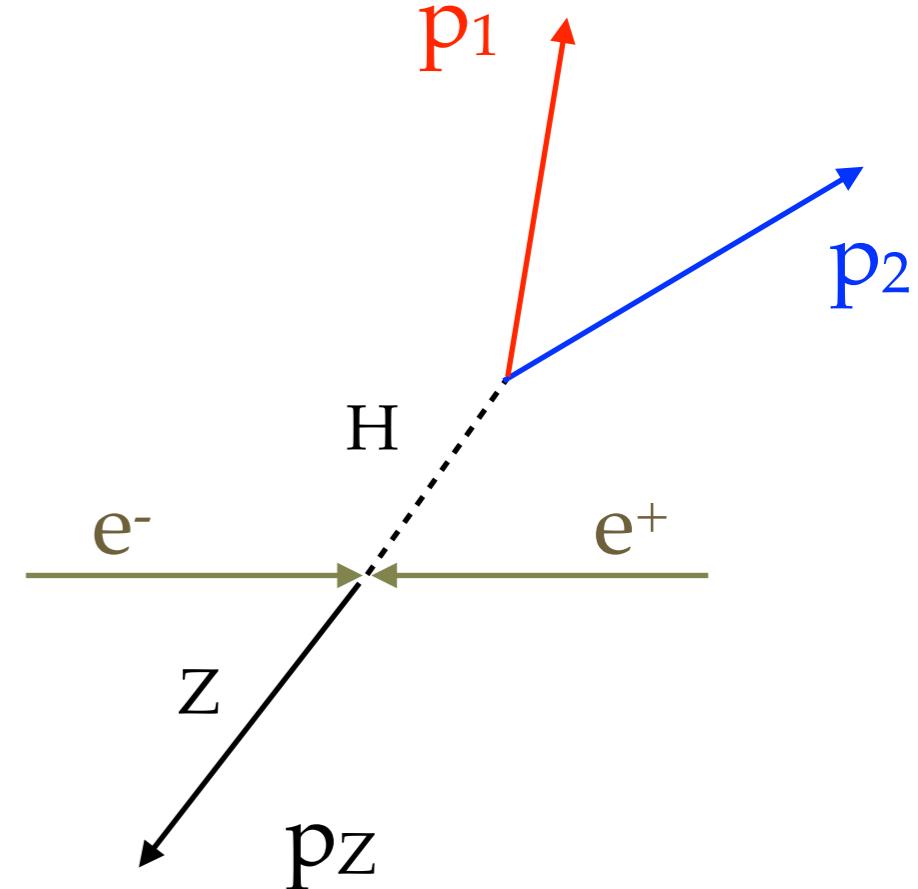


$$\begin{pmatrix} p_1 \\ p_2 \end{pmatrix} = \frac{p_t}{\sin \phi} \begin{pmatrix} \frac{\sin(\phi - \phi_2)}{\sin \theta_1} \\ \frac{\sin(\phi_1 - \phi)}{\sin \theta_2} \end{pmatrix}$$

$$\phi = \phi_1 - \phi_2 \quad p_t = \sqrt{p_x^2 + p_y^2}$$

analytic results

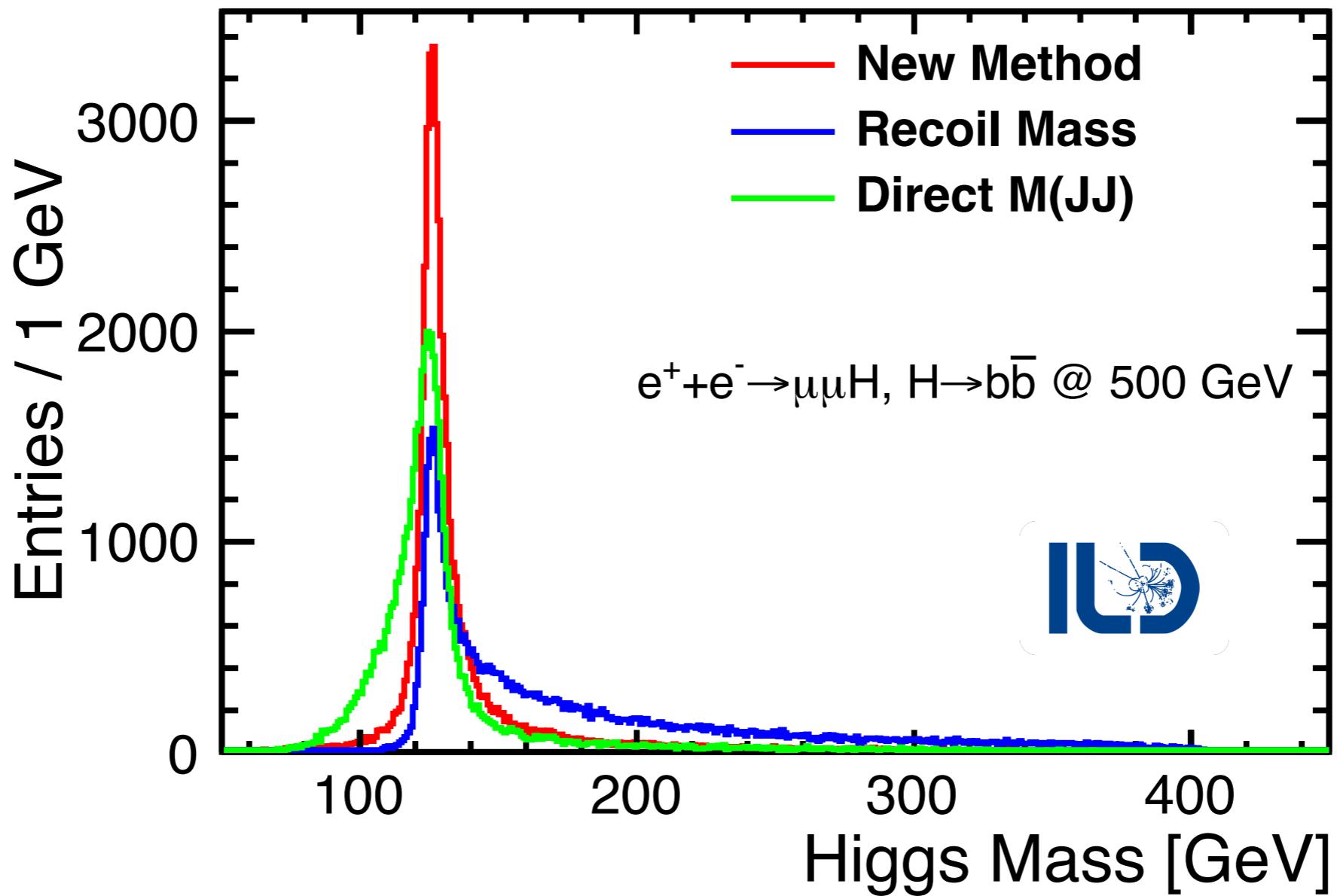
when $m_i/p_i \ll 1$



$$m_H^2 = \left(1 + \frac{p_2}{p_1}\right)m_1^2 + \left(1 + \frac{p_1}{p_2}\right)m_2^2$$

$$+ \frac{2p_t^2 \sin(\phi - \phi_2) \sin(\phi_1 - \phi)}{\sin \theta_1 \sin \theta_2 \sin^2 \phi} (1 - \sin \theta_1 \sin \theta_2 \cos \phi - \cos \theta_1 \cos \theta_2).$$

performance of new method (compared with others)

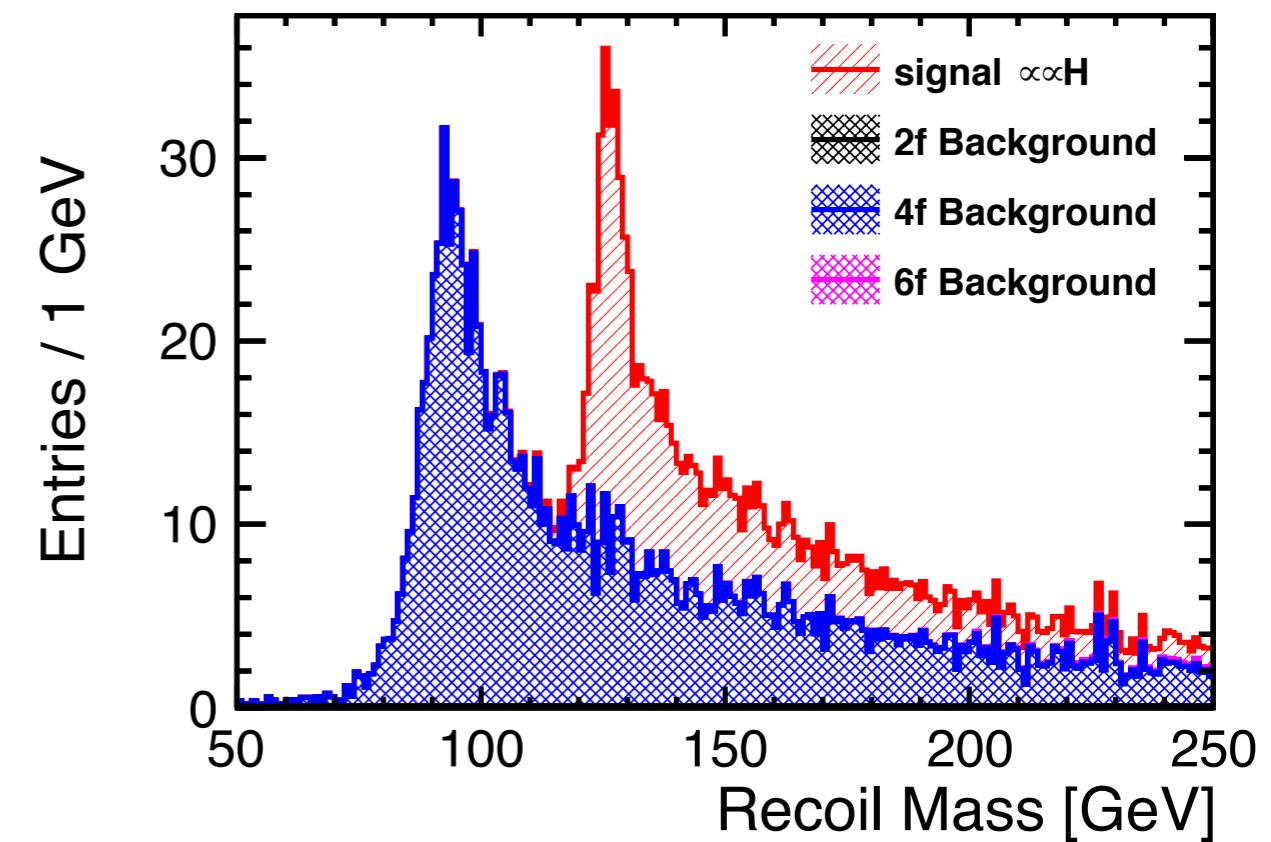
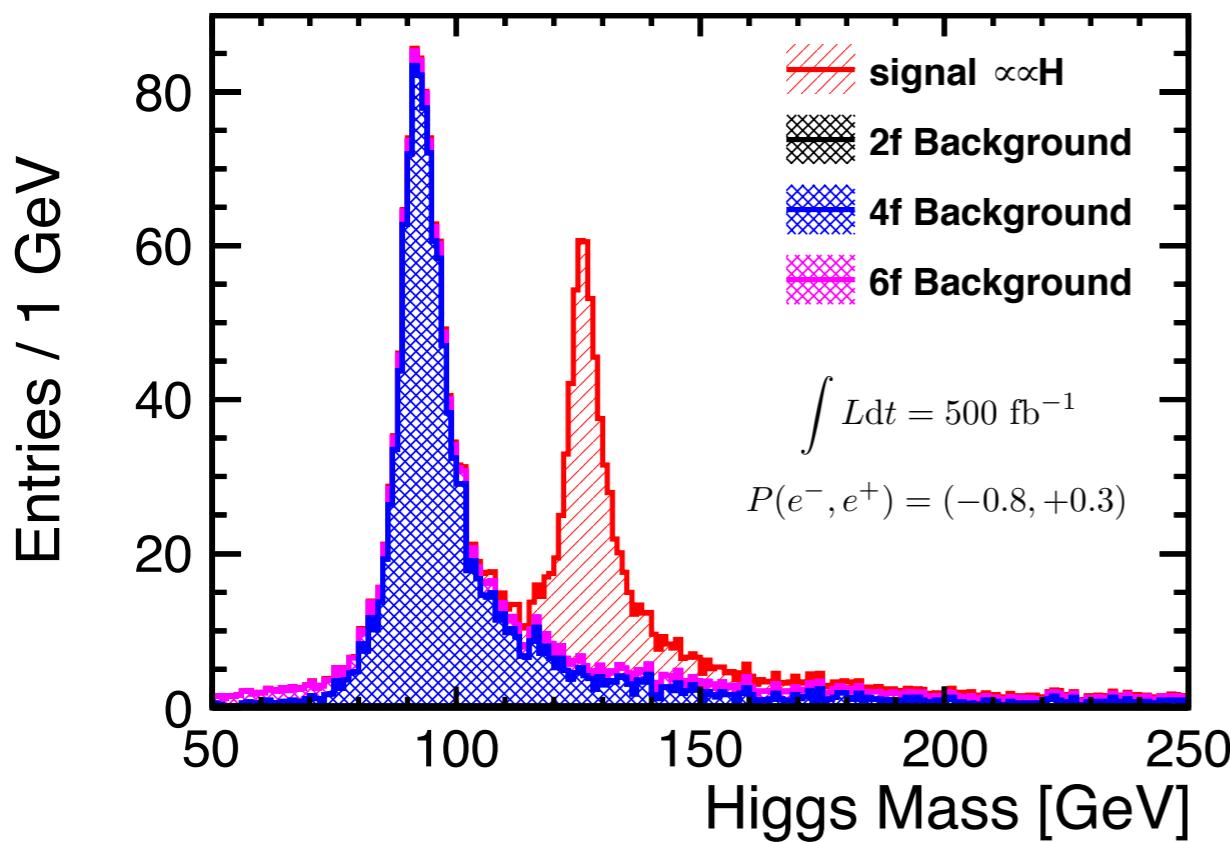


ILD full simulation (DBD)

results for full simulation – including full SM background

$\sqrt{s} = 500 \text{ GeV}$

$e^+e^- \rightarrow \mu\mu H, H \rightarrow b\bar{b}$



new method

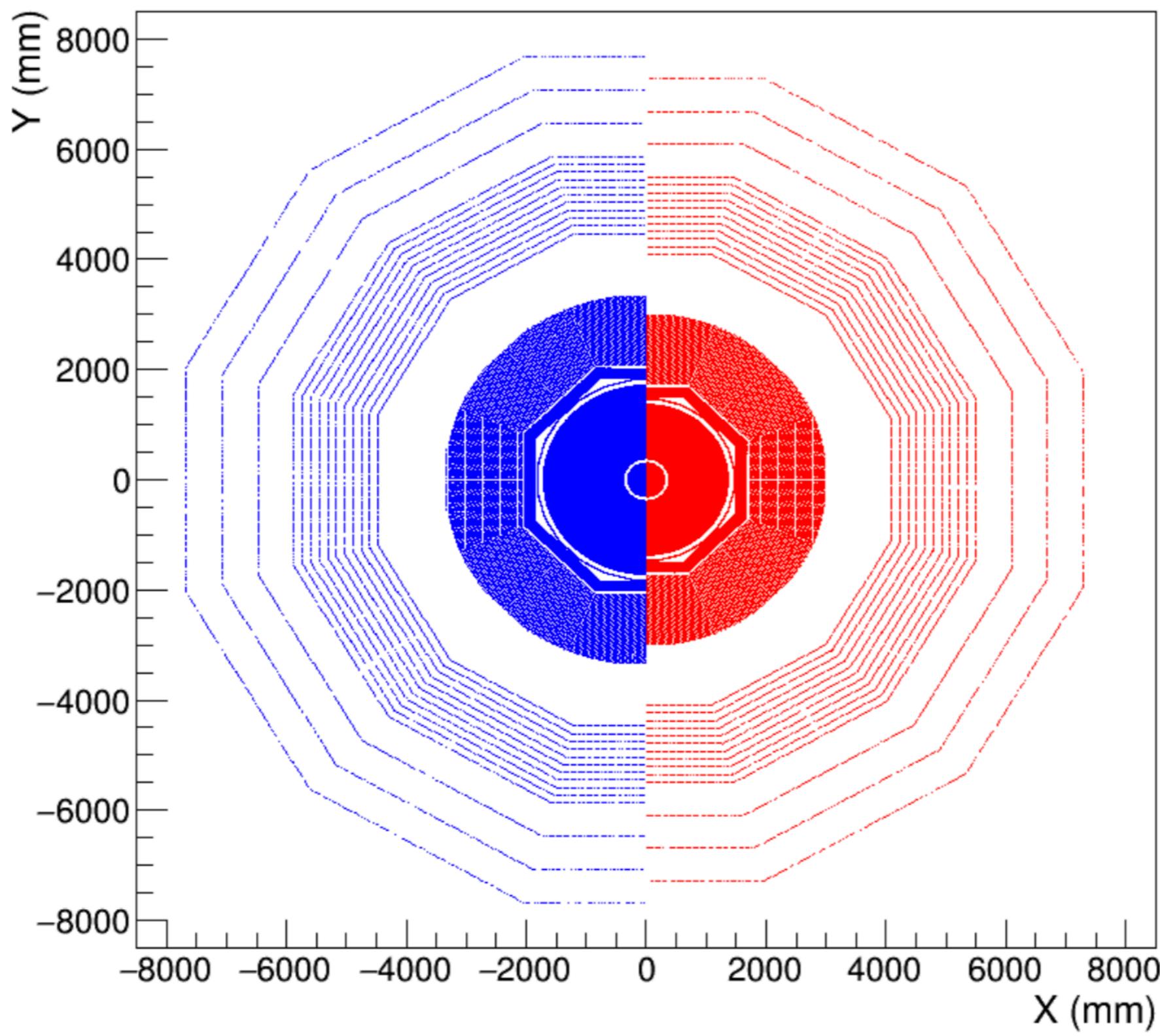
$\Delta m_H \sim 70 \text{ MeV}$

recoil method

$\Delta m_H \sim 218 \text{ MeV}$

(leptonic channels & only 500 GeV data in H20; DBD)

Detector Benchmark: Large .vs. Small



Analysis for Detector Benchmark

- performance to look at

$$m_H^2 = \left(1 + \frac{p_2}{p_1}\right)m_1^2 + \left(1 + \frac{p_1}{p_2}\right)m_2^2 + \frac{2p_t^2 \sin(\phi - \phi_2) \sin(\phi_1 - \phi)}{\sin \theta_1 \sin \theta_2 \sin^2 \phi} (1 - \sin \theta_1 \sin \theta_2 \cos \phi - \cos \theta_1 \cos \theta_2).$$

- final observable: Δm_H
- **intermediate**

Z->ll: resolution on lepton momentum

H->bb: resolution on jet-direction (ϕ, θ)

- basic: selection efficiencies

Isolated Lepton Tagging, Flavor Tagging, etc.

Analysis for Detector Benchmark

- o detector model & event sample

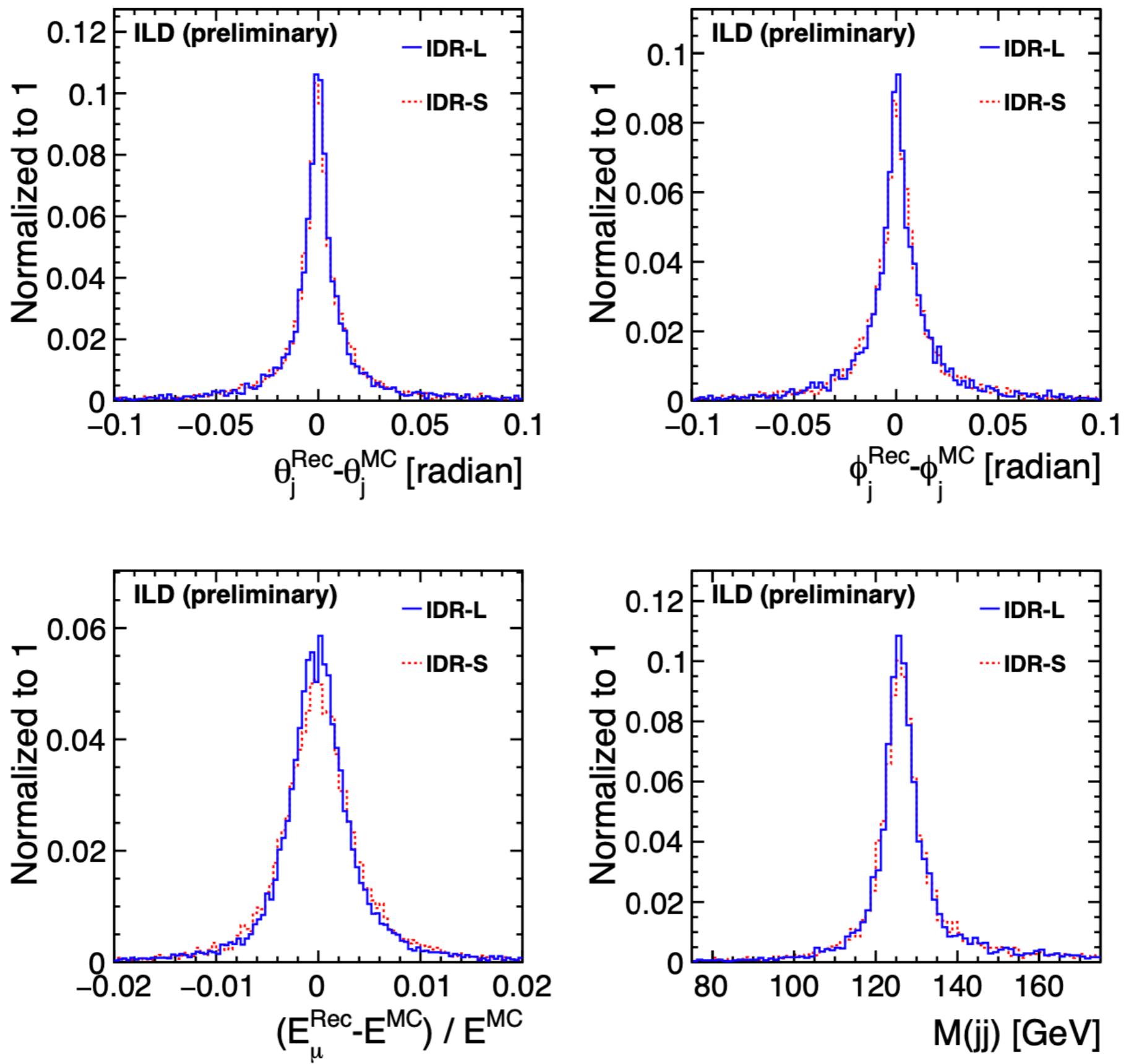
- Large: IDR-L; Small: IDR-S
- common event samples generated by ILD MC group for both signal and SM background processes

signal: $\mu\mu h/eeh$, $h \rightarrow bb$

major background: ZZ semi-leptonic

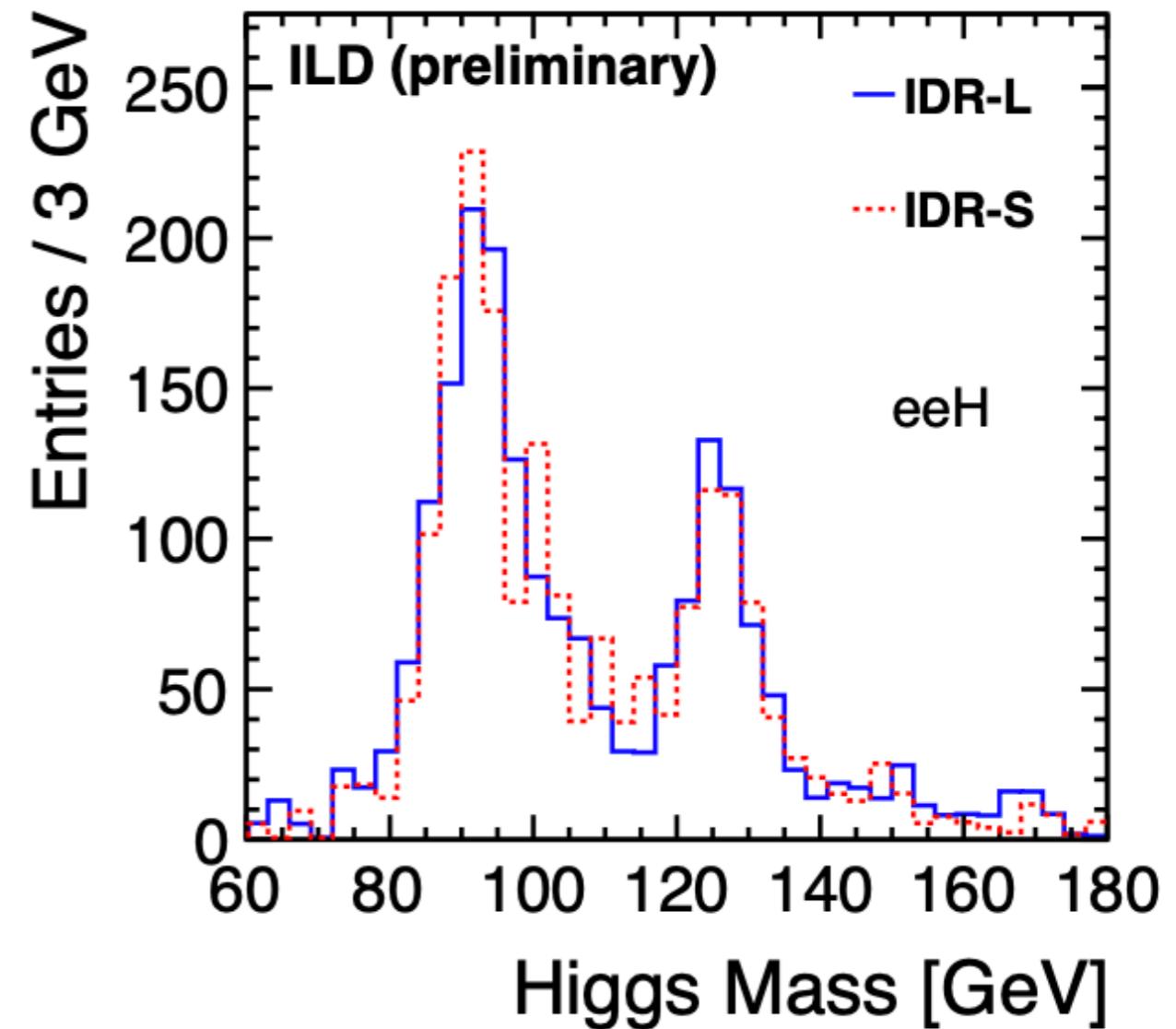
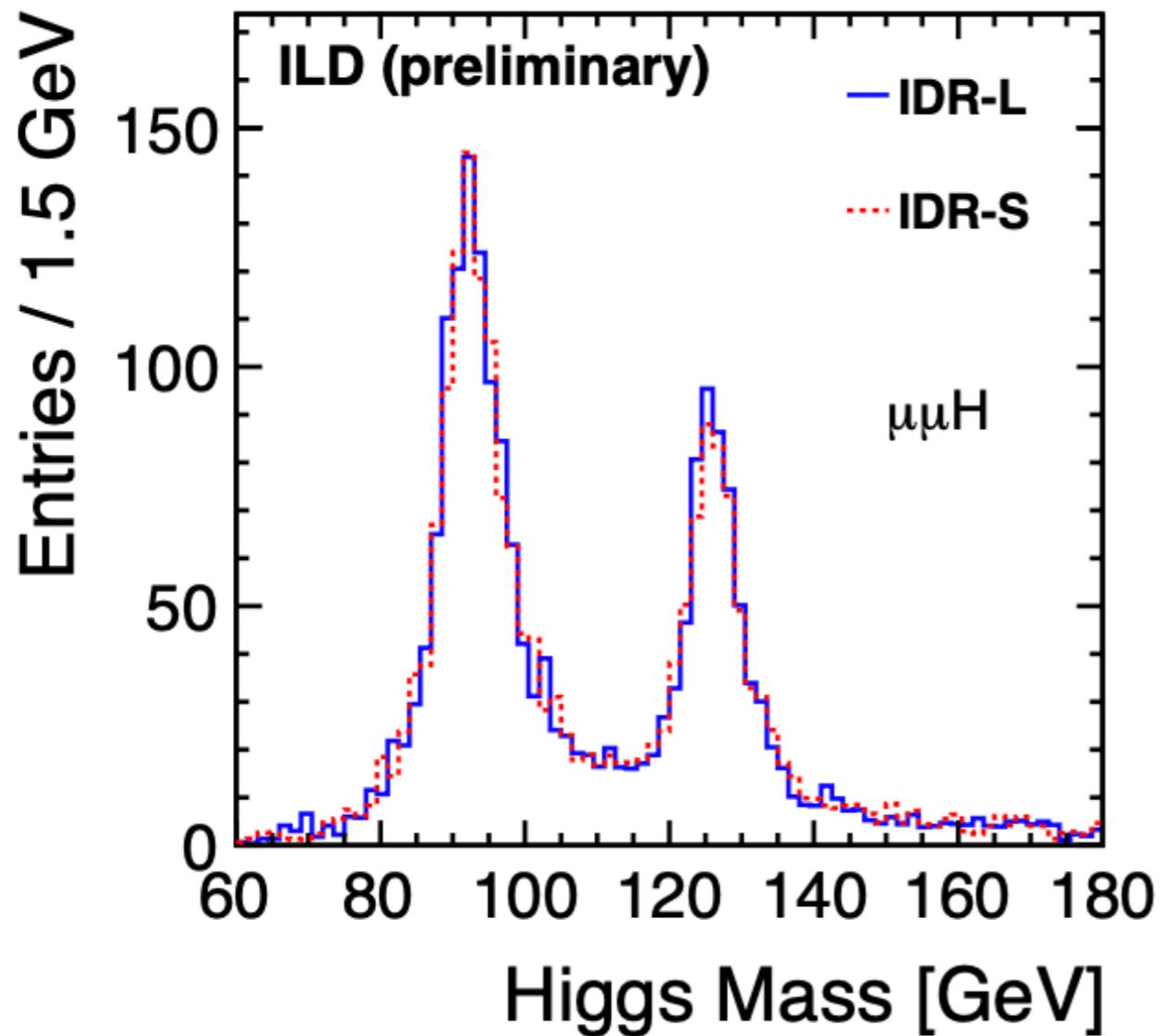
- whizard 1.95; ilcsoft v02-00-01

resolutions: $e^+e^- \rightarrow \mu\mu H, H \rightarrow b\bar{b}$



results:

$$e^+ e^- \rightarrow \mu\mu H, H \rightarrow b\bar{b}$$



observed difference (L&S) in Δm_H : ~22% (preliminary)

summary

- m_H measurement is important: $\Delta m_H = 14 \text{ MeV} \rightarrow 0.1\%$ systematic error for HZZ, HWW couplings
- a new method for m_H measurement is proposed
 - ▶ insensitive to beam energy, beam strahlung
 - ▶ a factor of 3 better at $\sqrt{s} \geq 500 \text{ GeV}$ than recoil method
 - ▶ a combined approach is promising at $\sqrt{s} = 250 \text{ GeV}$
- impact of detector performance for IDR-L & IDR-S
- next step: include $Z \rightarrow q\bar{q}$; systematic errors, e.g. jet direction and jet mass; apply with new beam parameters

backup

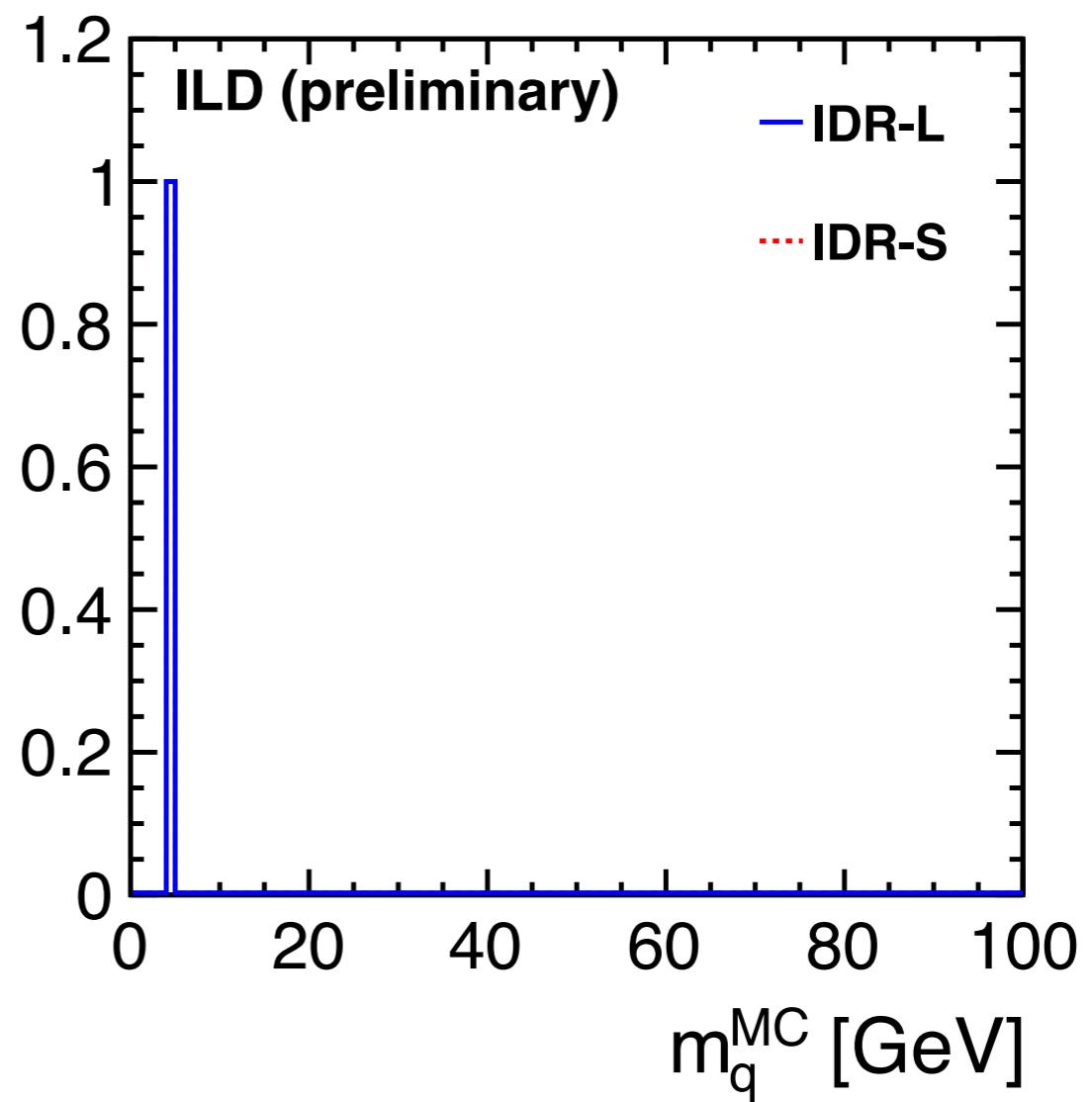
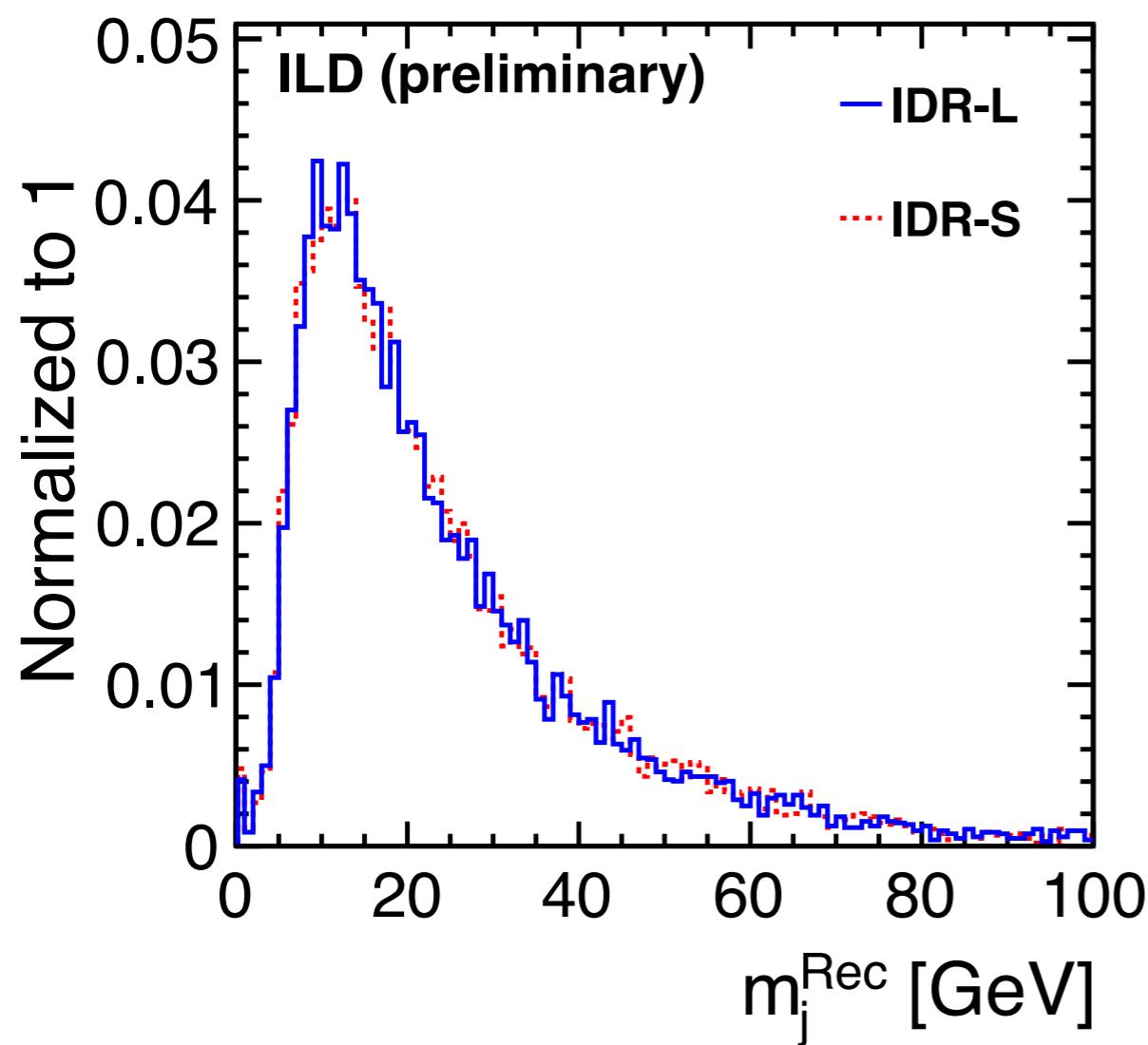
Analysis for Detector Benchmark

- o event selection

- Isolated Lepton Tagging: a pair of $\mu/e \sim m_Z$ + FSR recovery
- overlay removal: for the time being using MCTruth (focus on detector performance, will be replaced by Kt/Valencia algorithm later on)
- 2-jet clustering and Flavor Tagging: LCFIPlus (still using weight/configuration as DBD, can be easily updated with the latest ones)

what MC truth should we compare to?

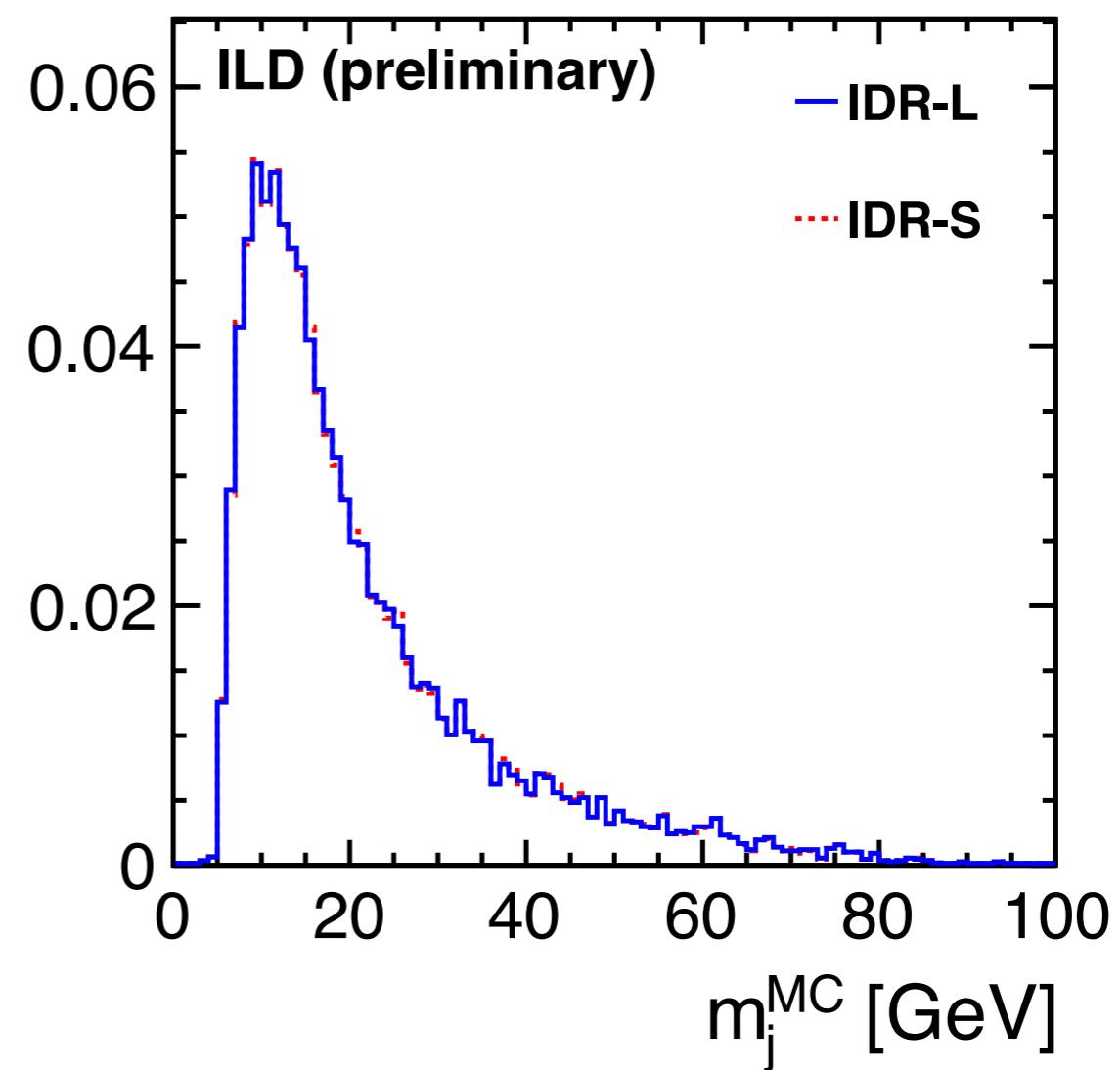
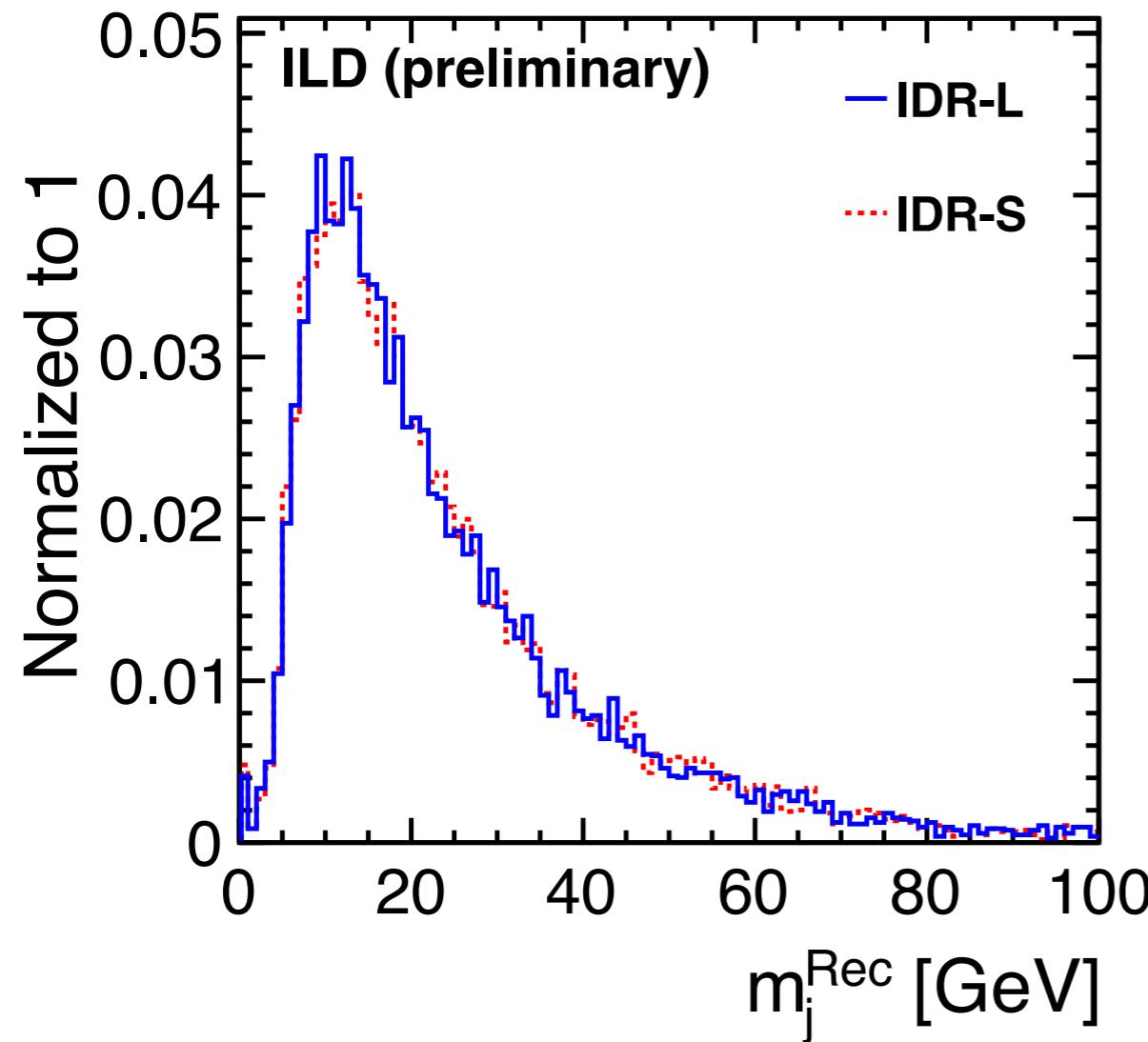
$$e^+ e^- \rightarrow \mu\mu H, H \rightarrow b\bar{b}$$



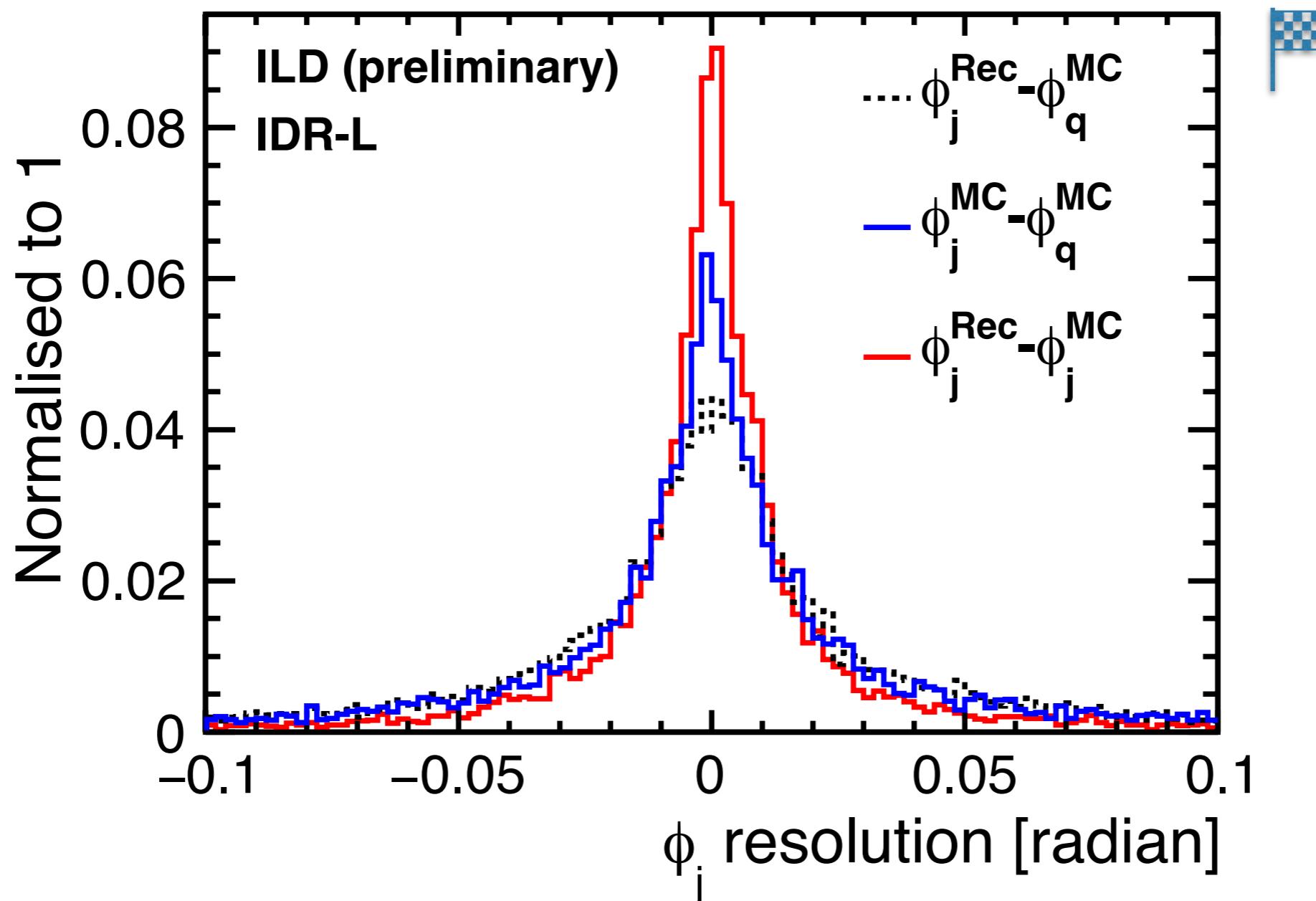
reconstructed jet mass is totally different with quark mass

what MC truth should we compare to?

jet obtained with MC particles using same jet-clustering algorithm



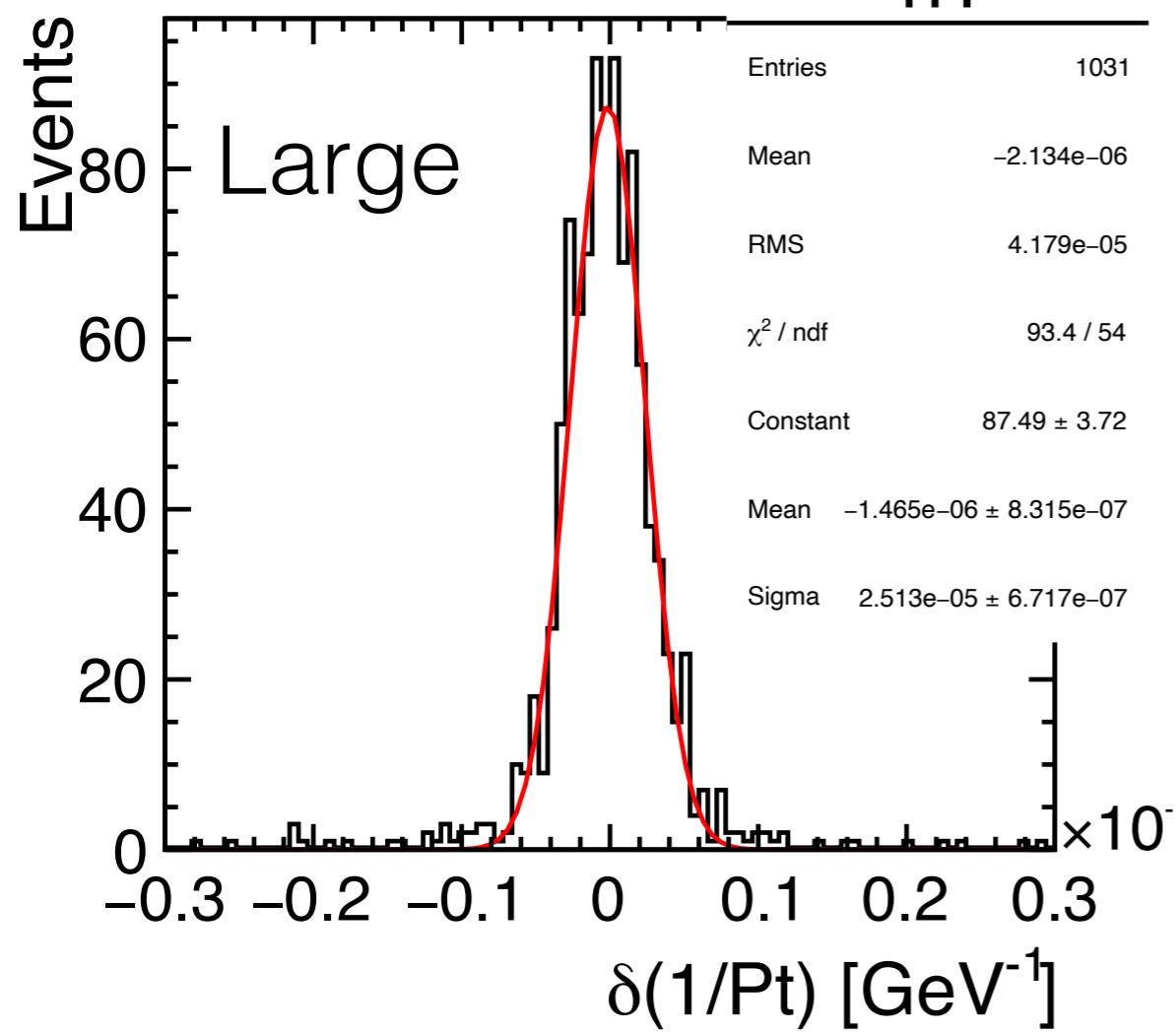
resolutions: why didn't see the difference before



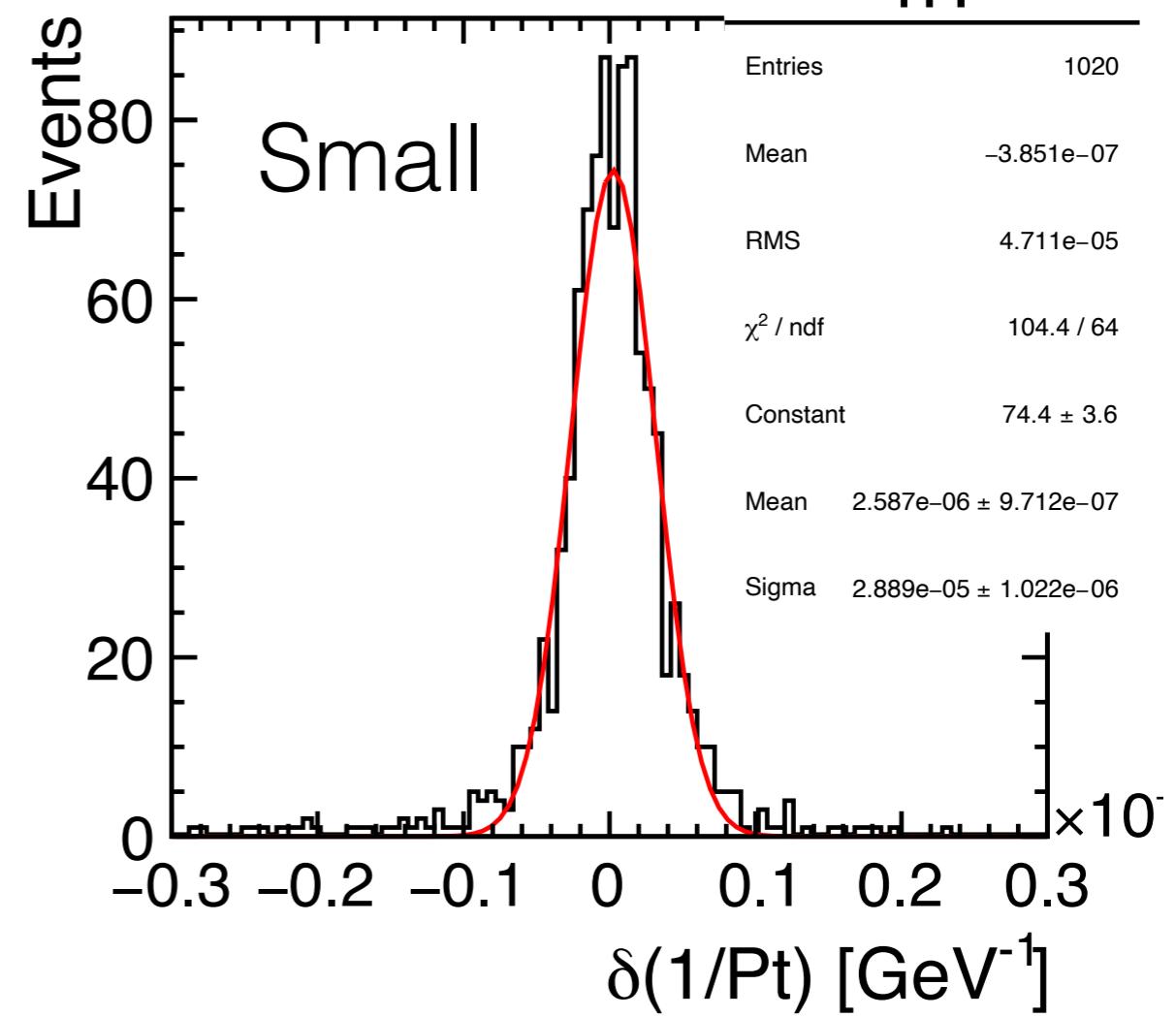
note the different color code

resolution: lepton momentum

$$\Delta \frac{1}{P_t} \sim 2.5 \times 10^{-5}$$

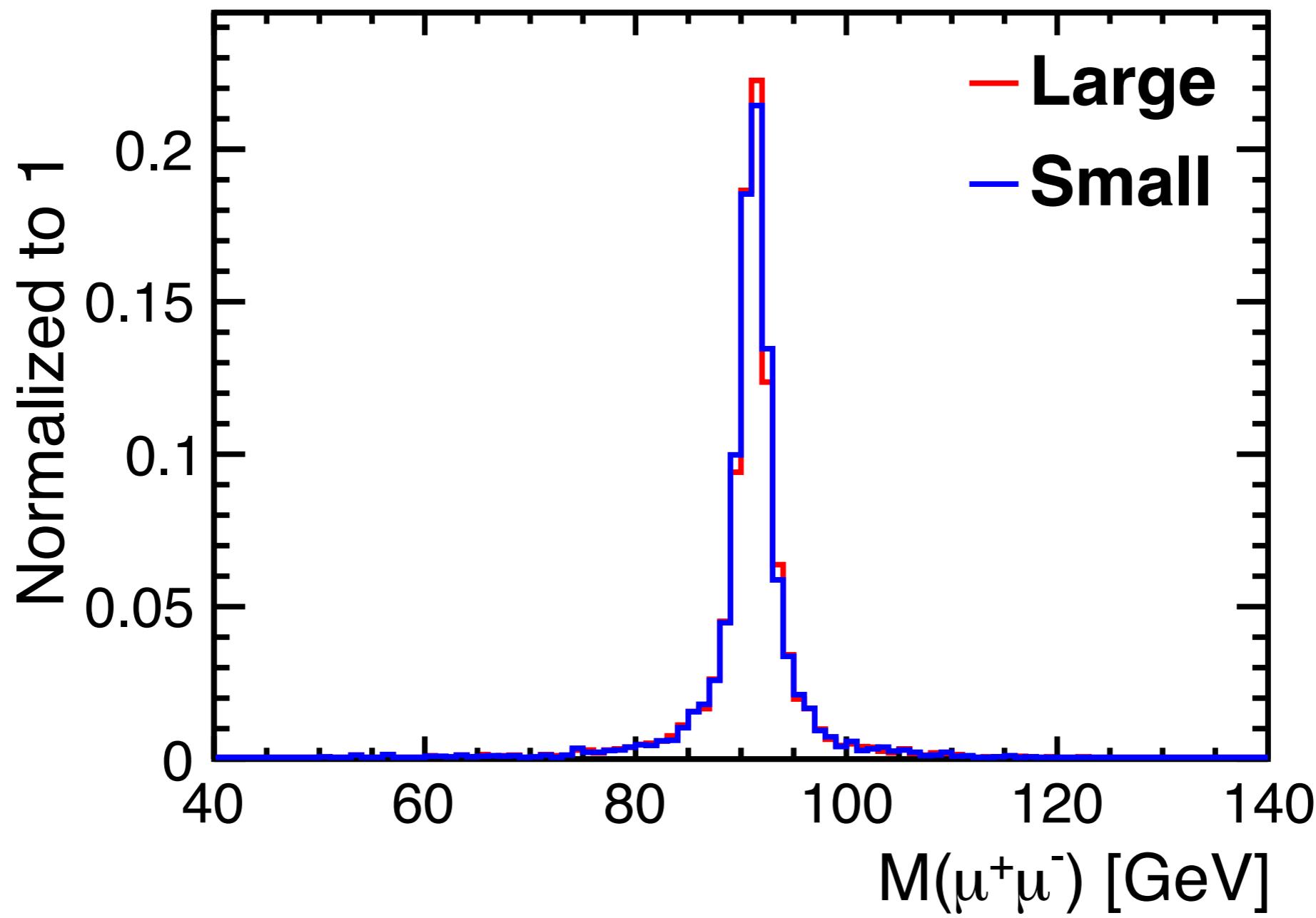


$$\Delta \frac{1}{P_t} \sim 2.9 \times 10^{-5}$$



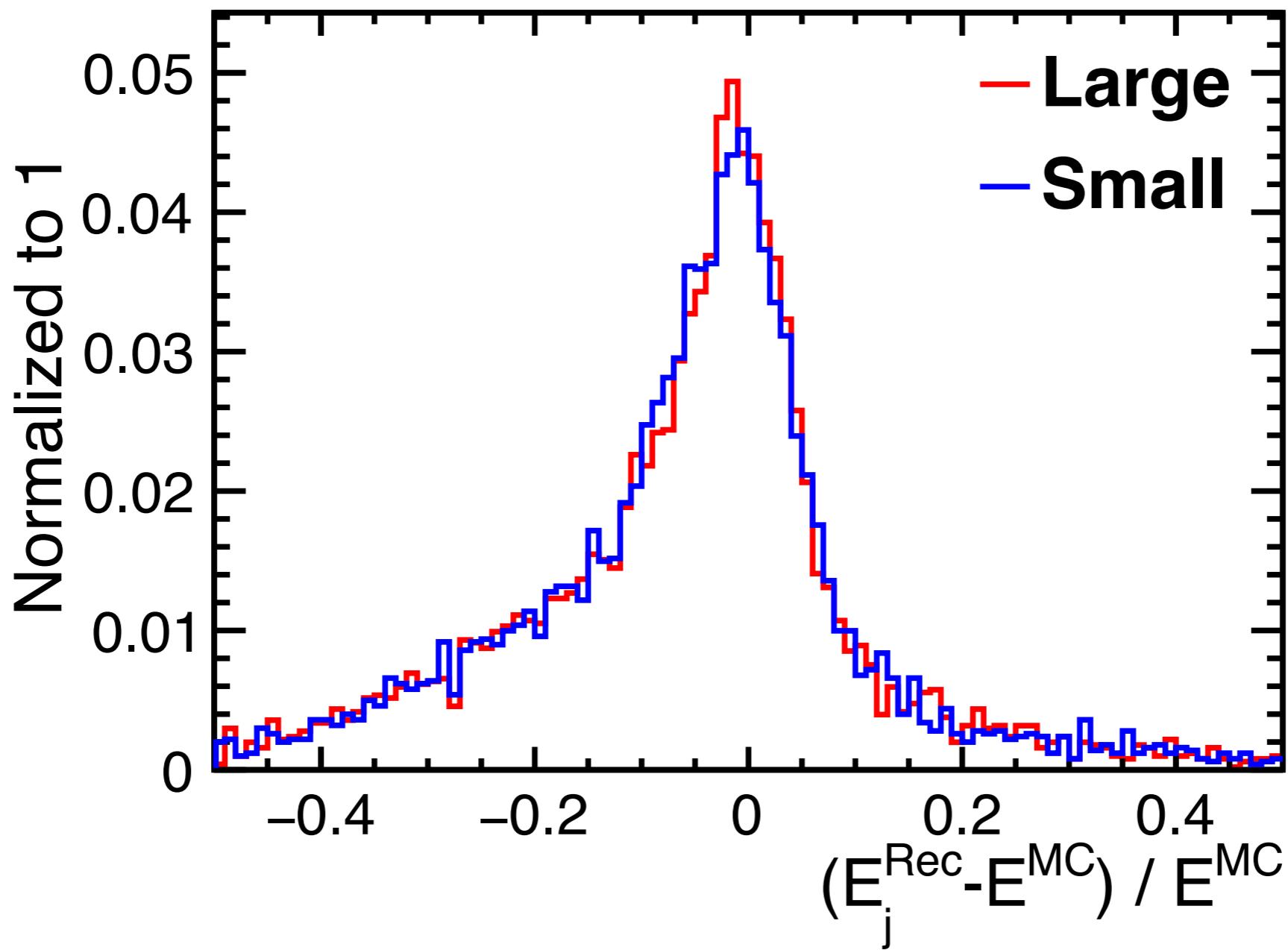
for illustration: $P_\mu > 100\text{GeV}$, $|\cos\theta| < 0.3$

resolution: lepton momentum (Z mass)



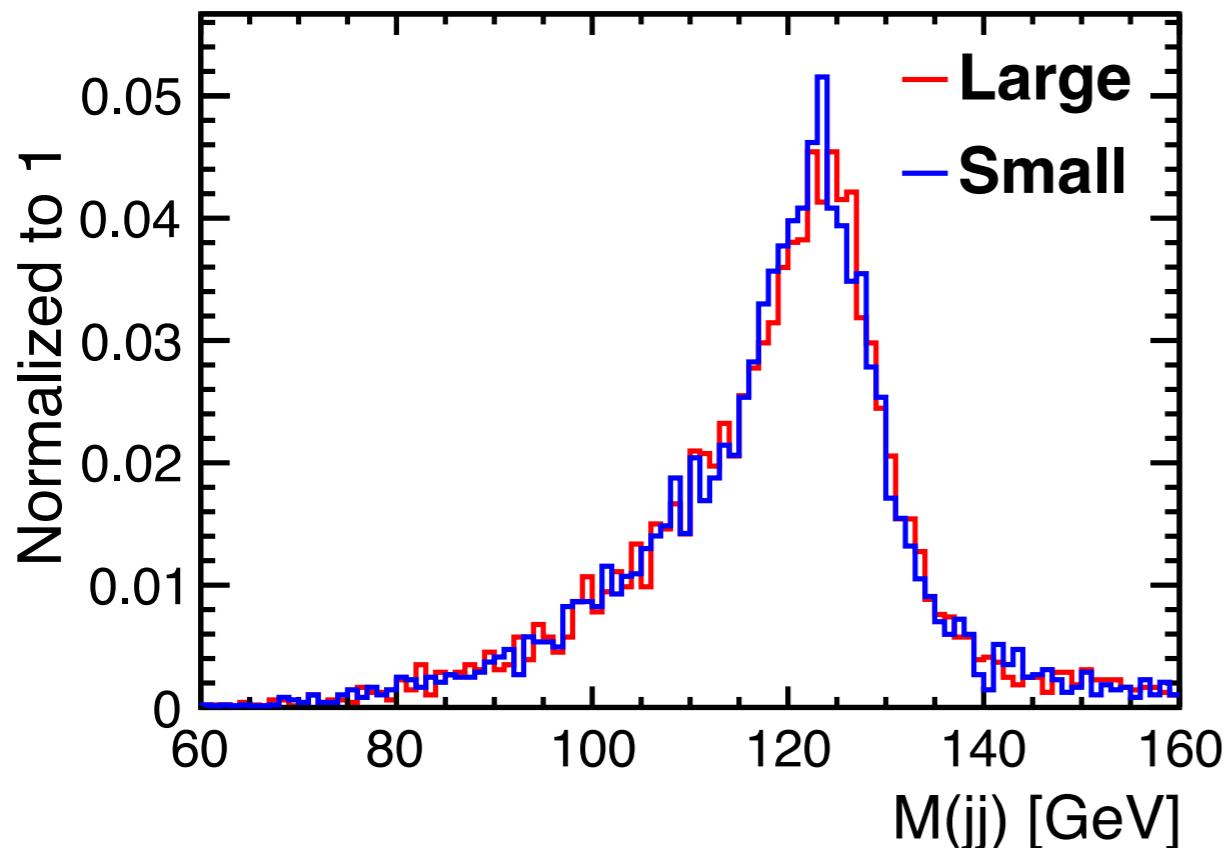
difference becomes much smaller; dominated by Z natural width

resolution: jet-energy

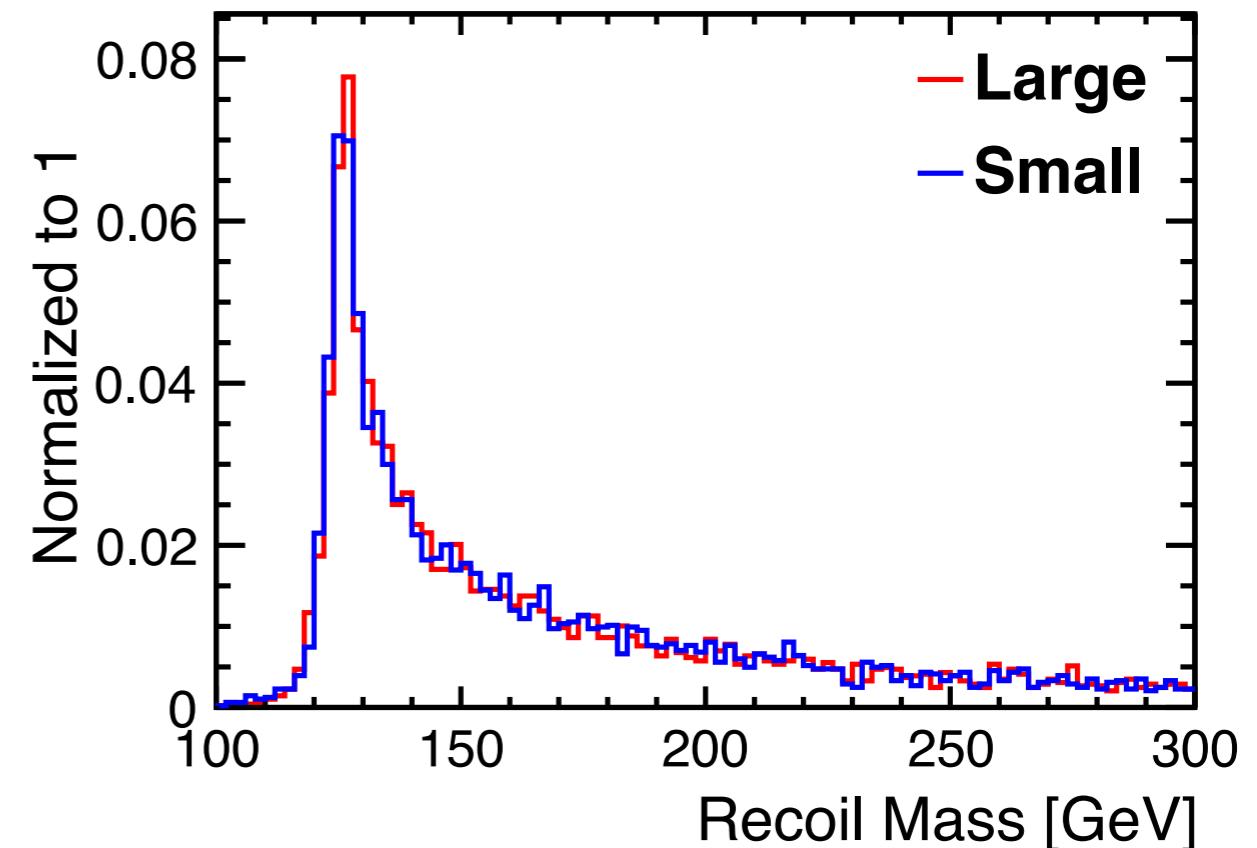


final: Higgs mass (conventional)

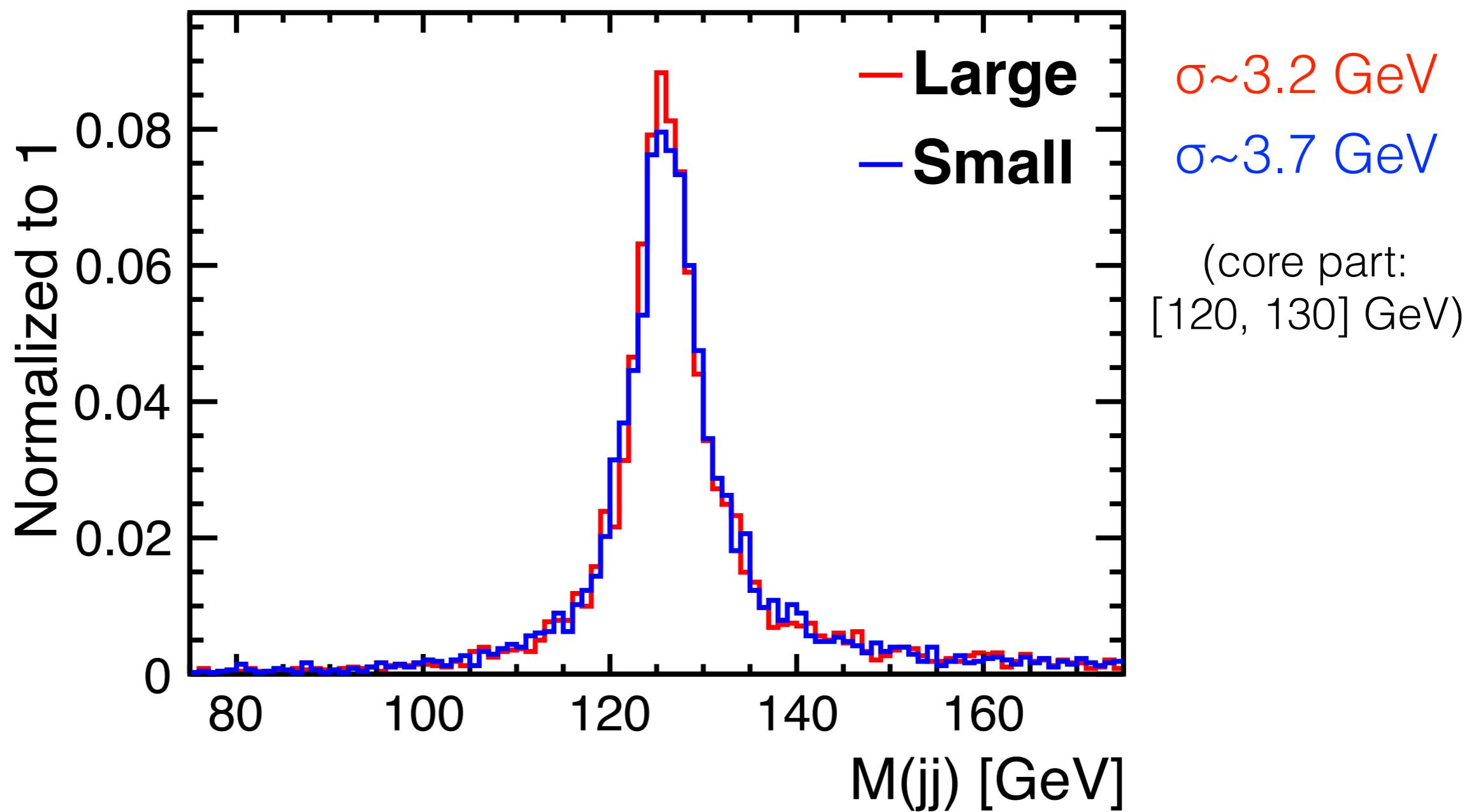
direct reconstruction



leptonic recoil

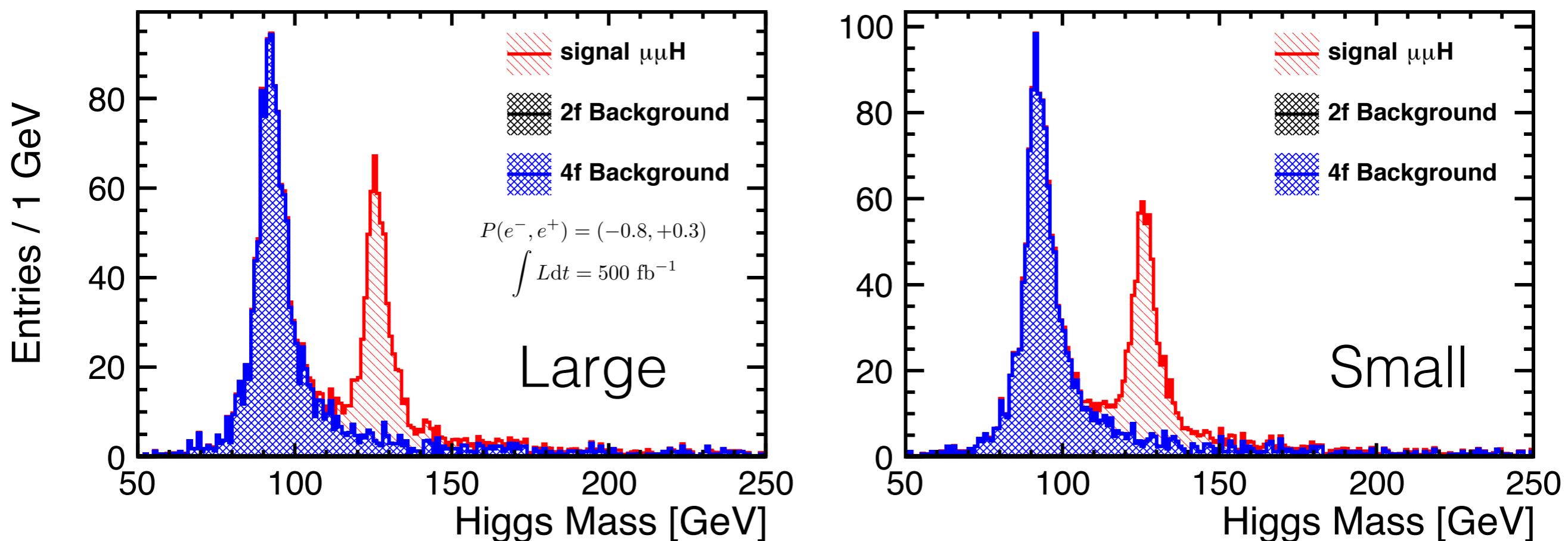


final: Higgs mass (new method)



final physical observable: Δm_H from full analysis

Preliminary $\sqrt{s} = 500 \text{ GeV}$ $e^+e^- \rightarrow \mu\mu H, H \rightarrow b\bar{b}$



$$\int Ldt = 4 \text{ ab}^{-1}$$

$$P(e^-, e^+) = (-0.8, +0.3)$$

Large:

$\Delta m_H = 66 \text{ MeV}$

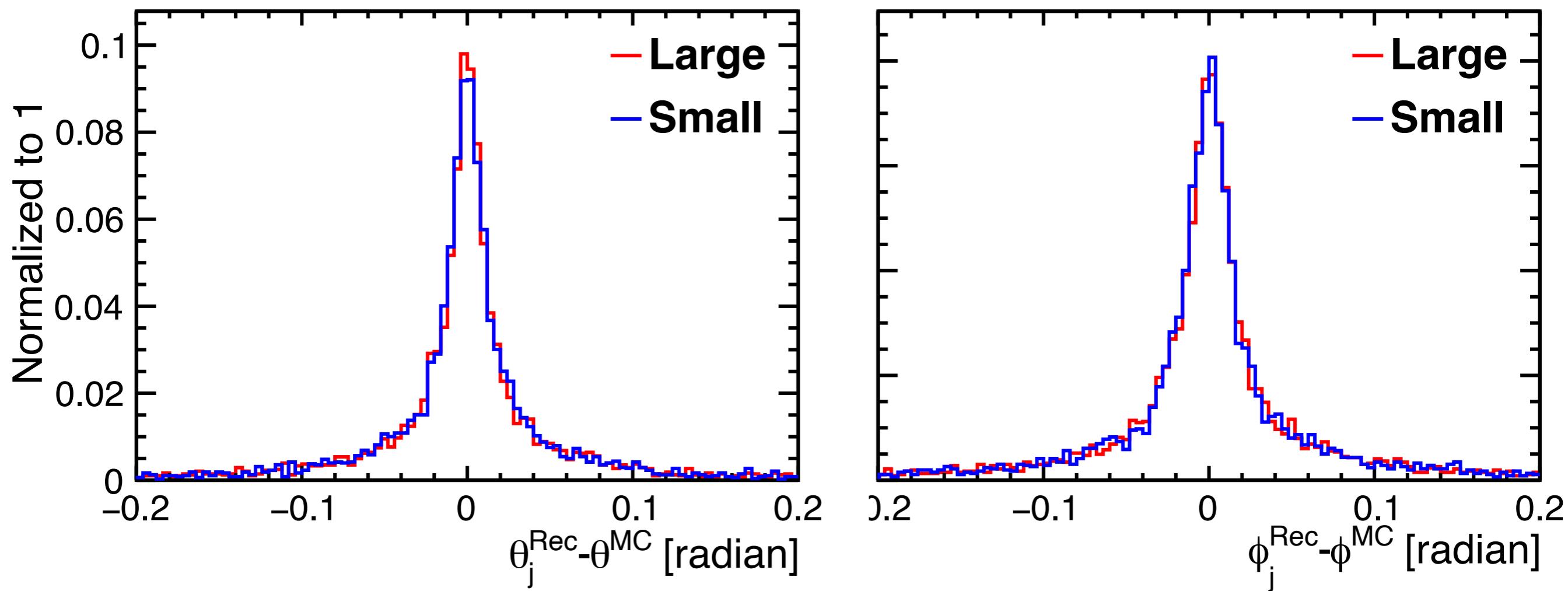
Small:

$\Delta m_H = 81 \text{ MeV}$

22% diff.

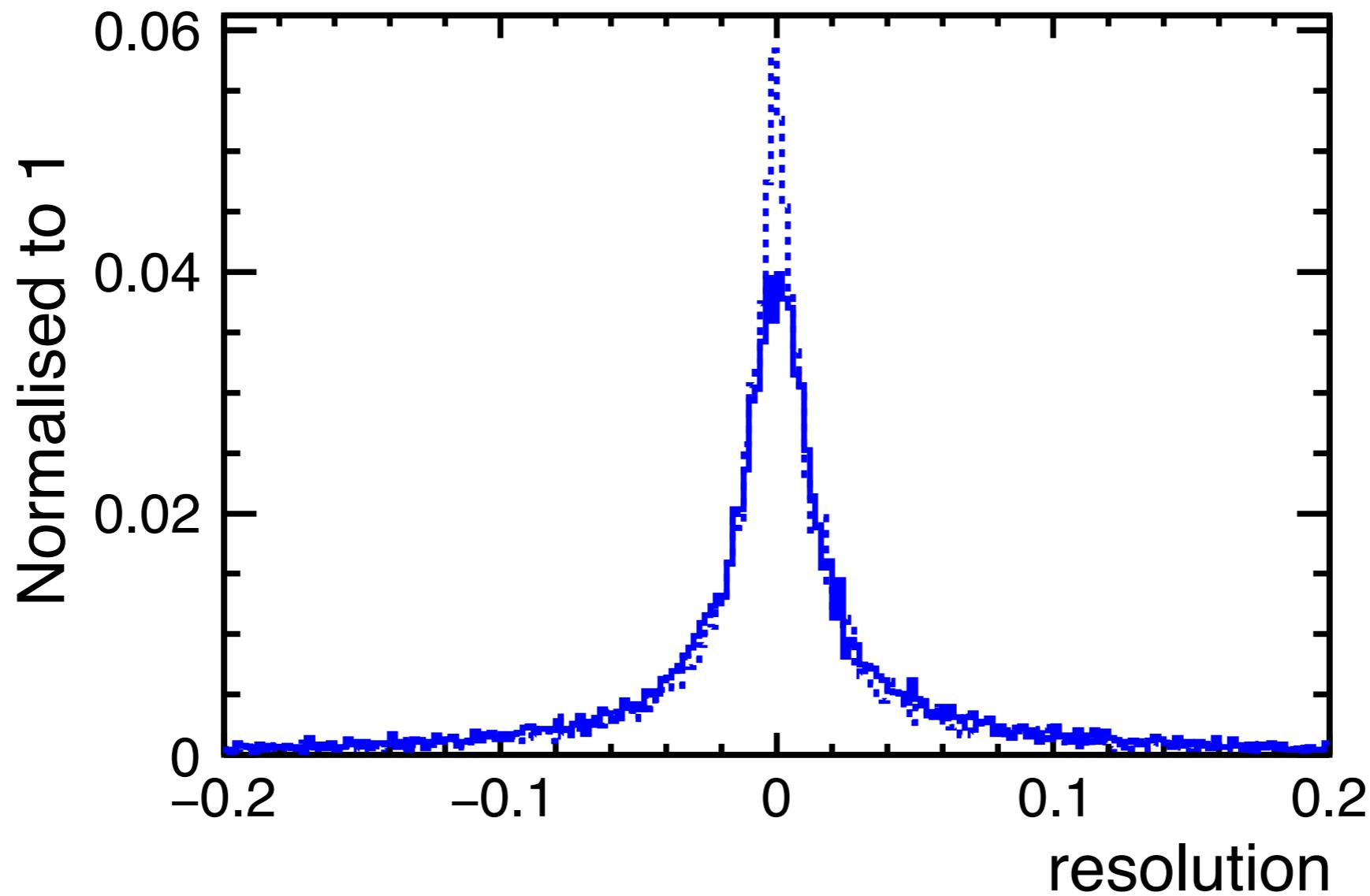
resolution: jet-direction

$\Delta\theta \sim \Delta\phi \sim 1$ degree; almost same for L&S

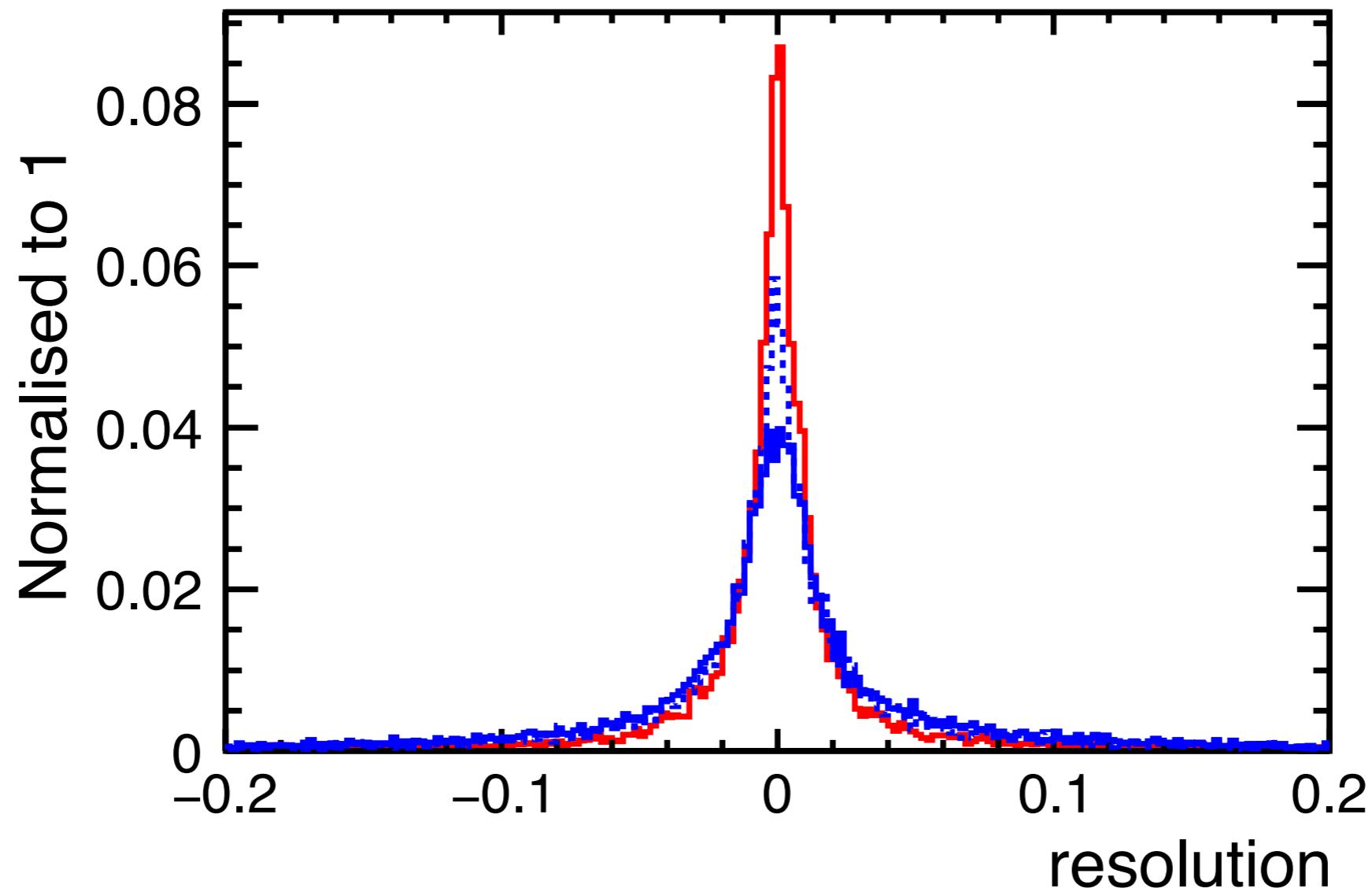


question from Arlington: what happens in case of cheating

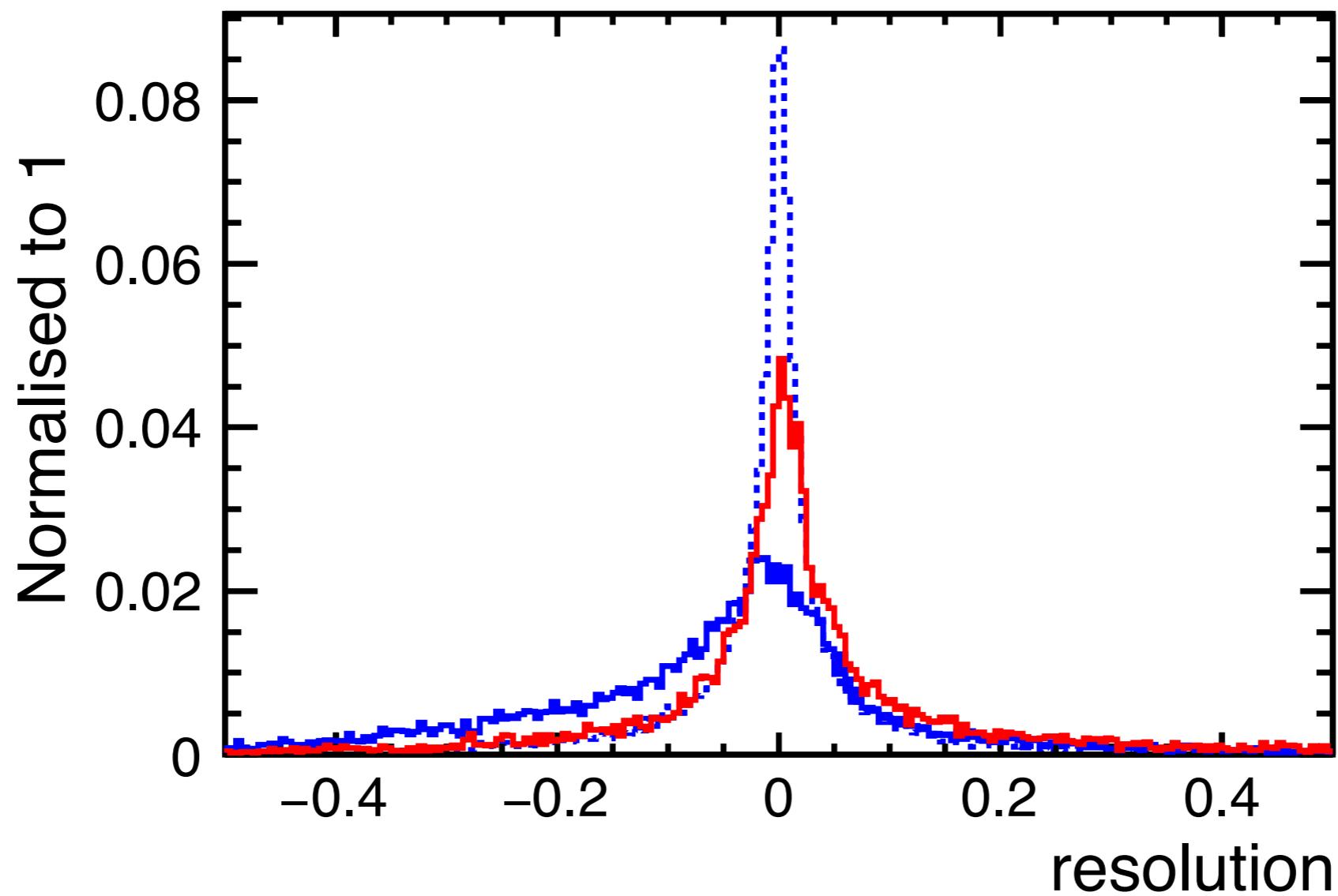
update: phi resolution



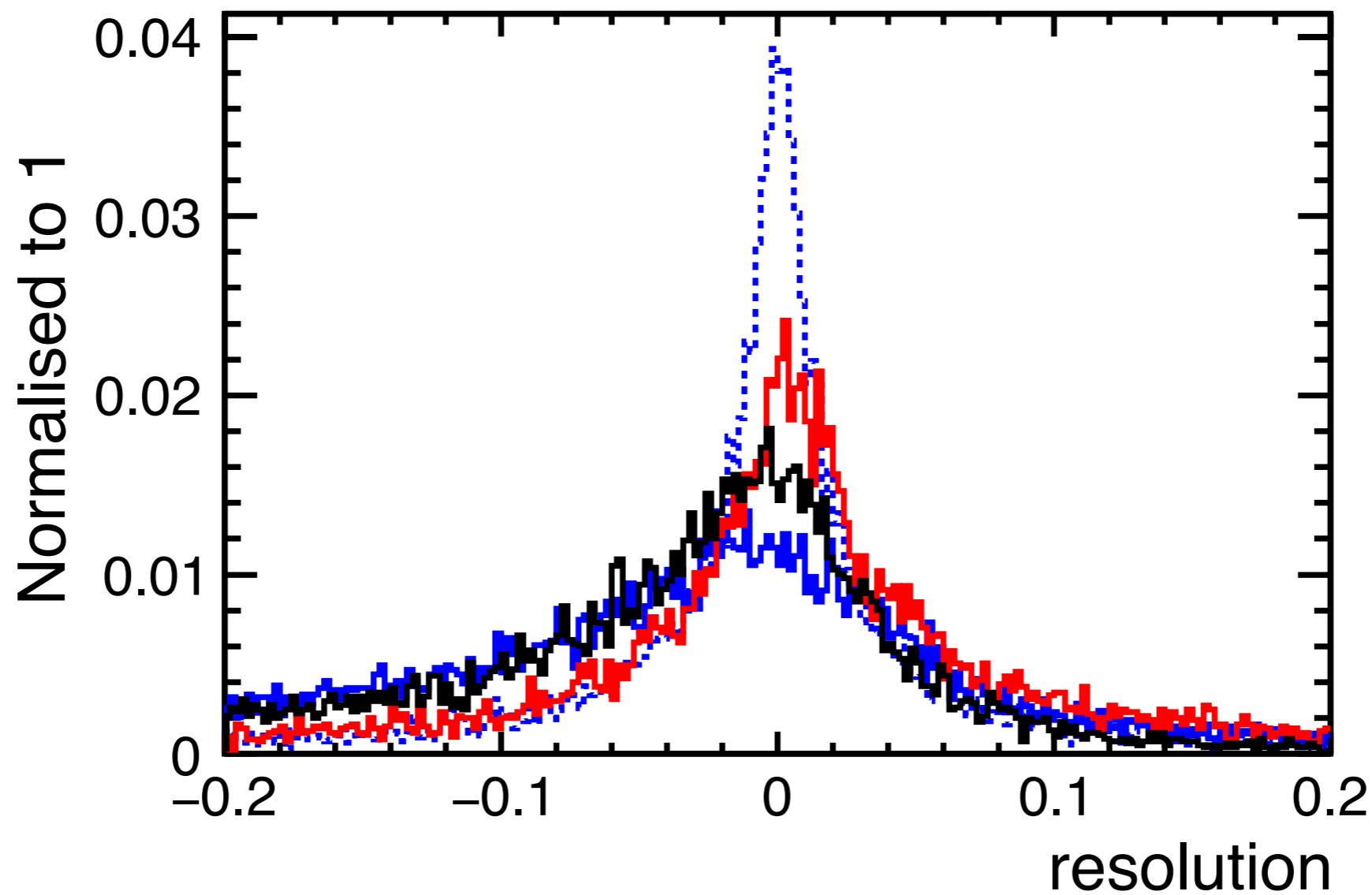
update: phi resolution



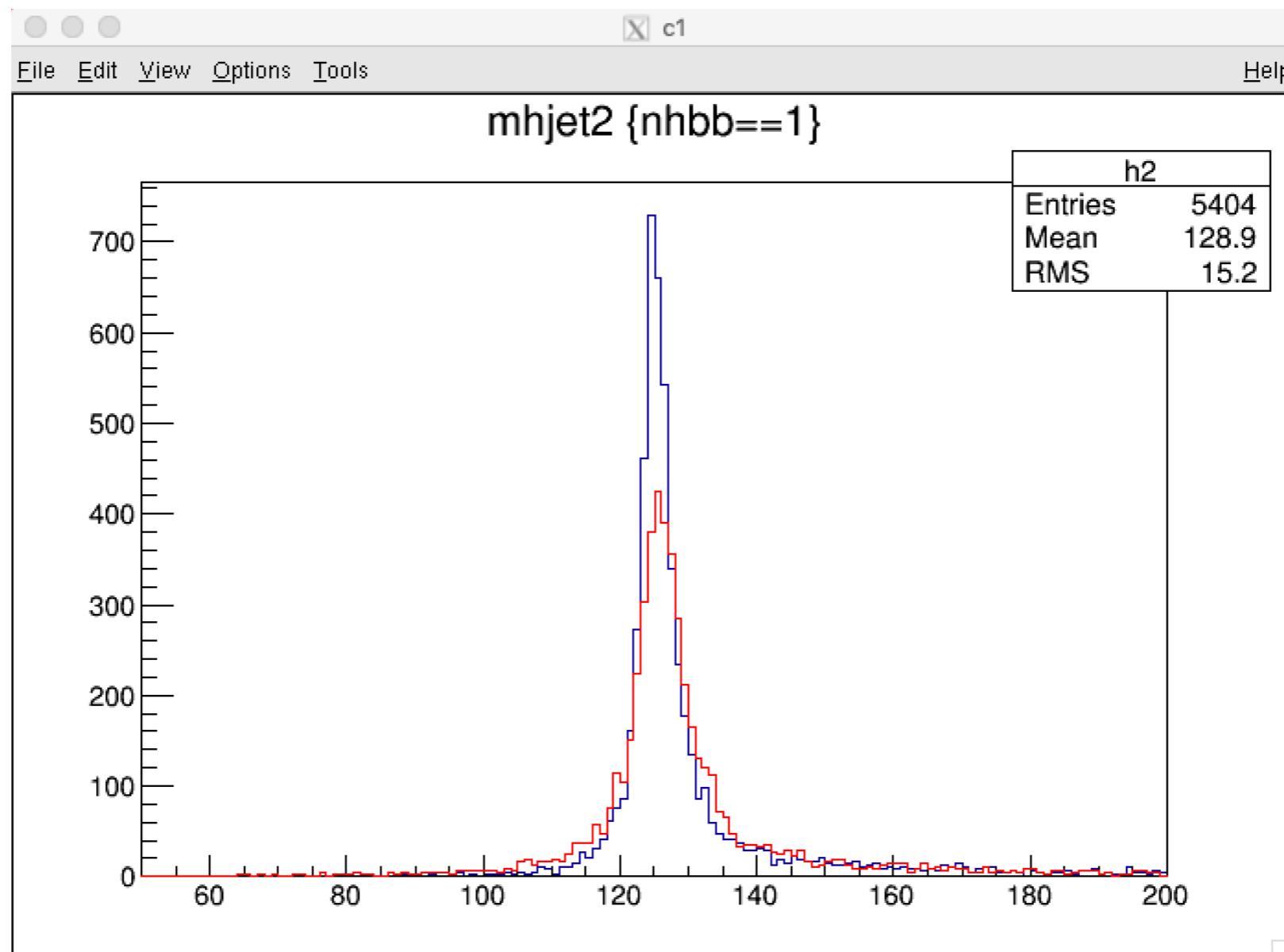
update: Ej resolution



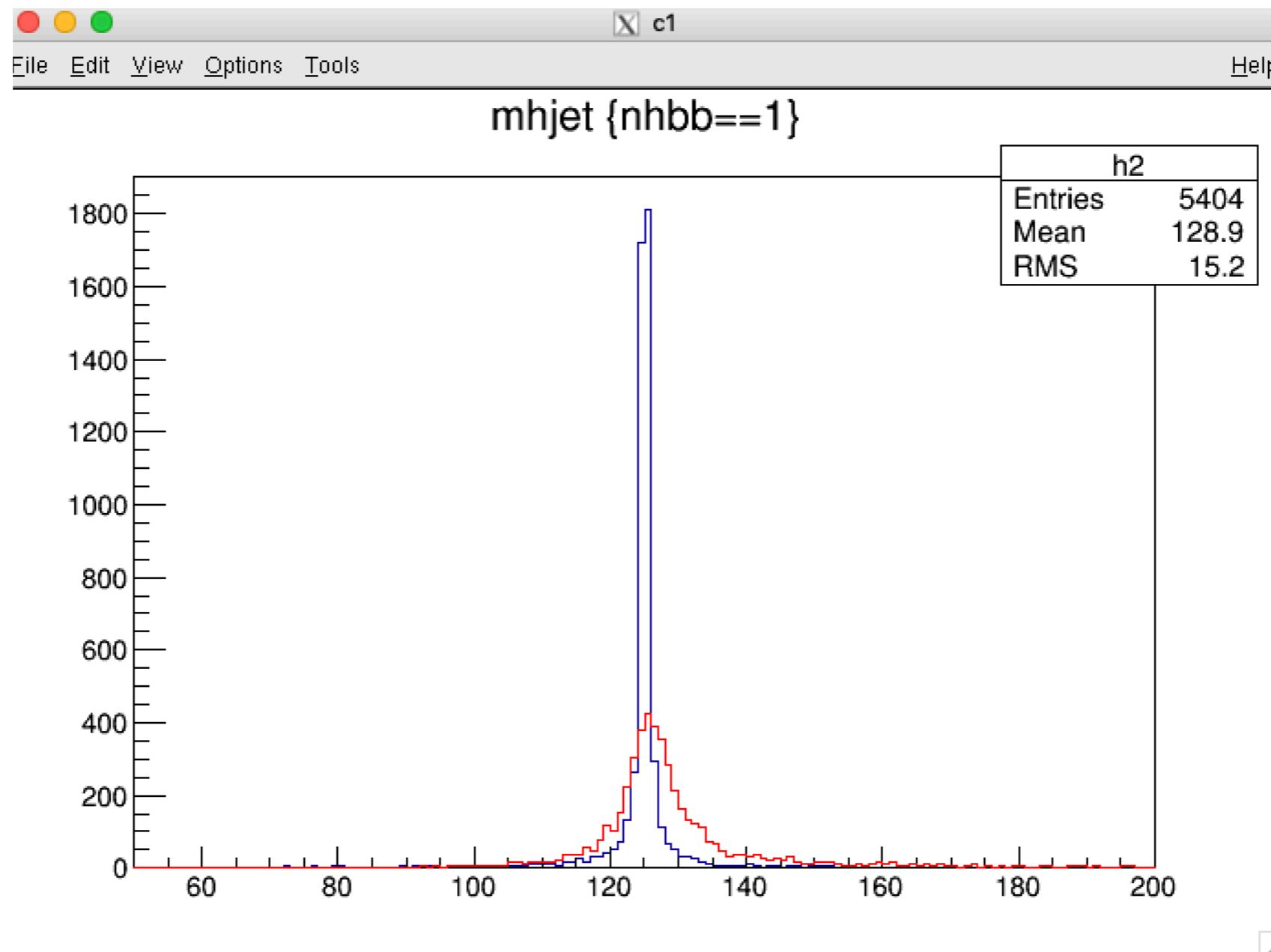
update: Ej resolution



update: mass, with cheated jet direction



update: mass, with cheated jet direction+jet mass



update: mass, with cheated muons

