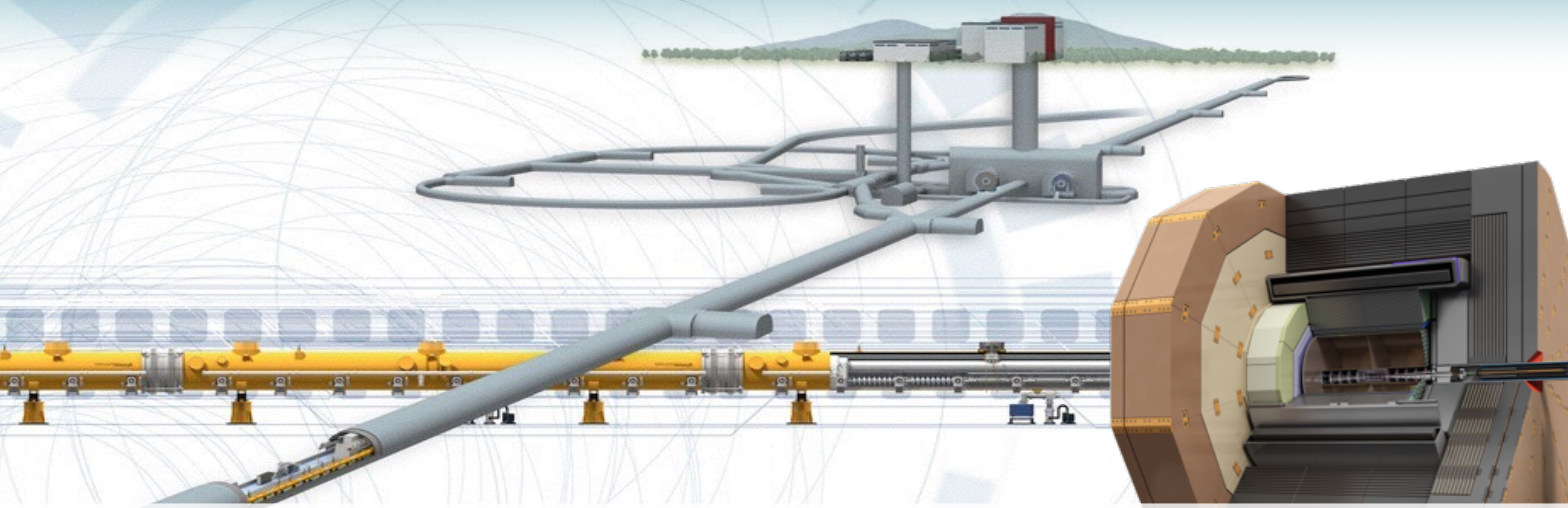
LCWS STRASBOURG 2017

23-27 October

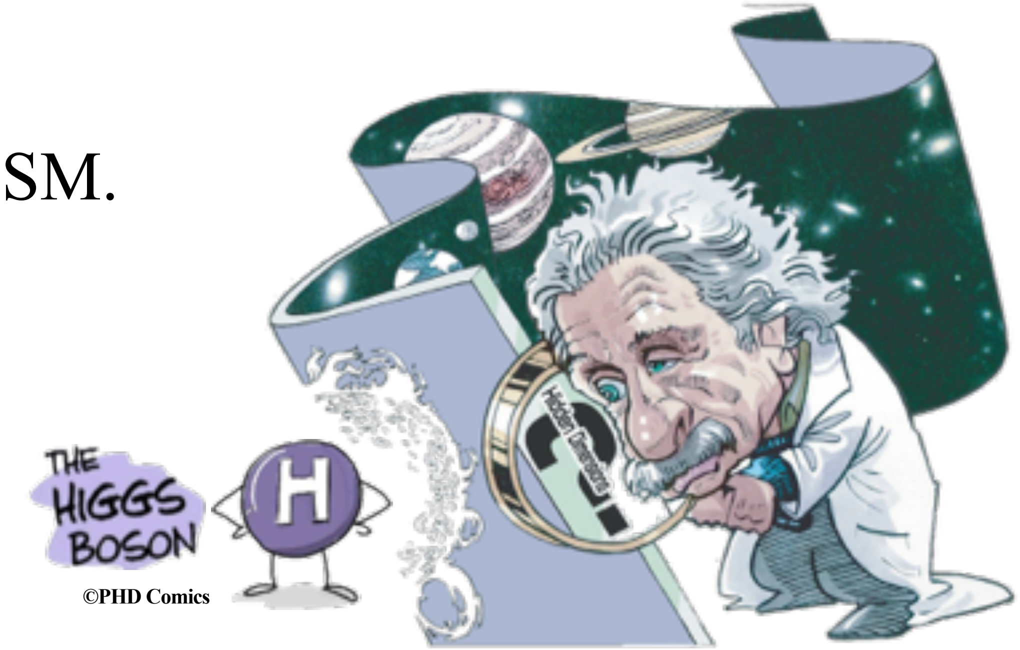
Convention Center (Palais des Congrès) Strasbourg, France

The workshop will be devoted to the study of the physics case for a high energy linear electron-positron collider, taking into account the recent results from LHC, and to review the progress in the detector and accelerator designs for both ILC and CLIC projects.



Study of sensitivity to anomalous VVH couplings at the International Linear Collider

Introduction on VVH couplings



The SM has been successful to describe nature.
Several phenomena can't be explained only with the SM.
(Dark matter, baryon asymmetry, …)

Precise verification of a structure
of the Higgs sector is the next step.
The Higgs is a tool for verification.

The structures and couplings between the Higgs and vectors VVH (V=Z , γ and W) directly relate to Electro-Weak Symmetry Breaking.

One approach is the Effective Field Theory (EFT) which can assume new Lorentz structures as anomalies.

Tim Barklow et al.
https://agenda.linearcollider.org/event/7371/contributions/37884/

$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{\mathrm{v}} + \frac{a_Z}{\Lambda}\right) Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu} H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\widetilde{\hat{Z}}^{\mu\nu} H$$

$$\mathcal{L}_{WWH} = 2M_W^2\left(\frac{1}{\mathrm{v}} + \frac{a_W}{\Lambda}\right) W_\mu^+ W^{-\mu} H + \frac{b_W}{\Lambda}\hat{W}_{\mu\nu}^+\hat{W}^{-\mu\nu} H + \frac{\tilde{b}_W}{\Lambda}\hat{W}_{\mu\nu}^+\widetilde{\hat{W}}^{-\mu\nu} H$$

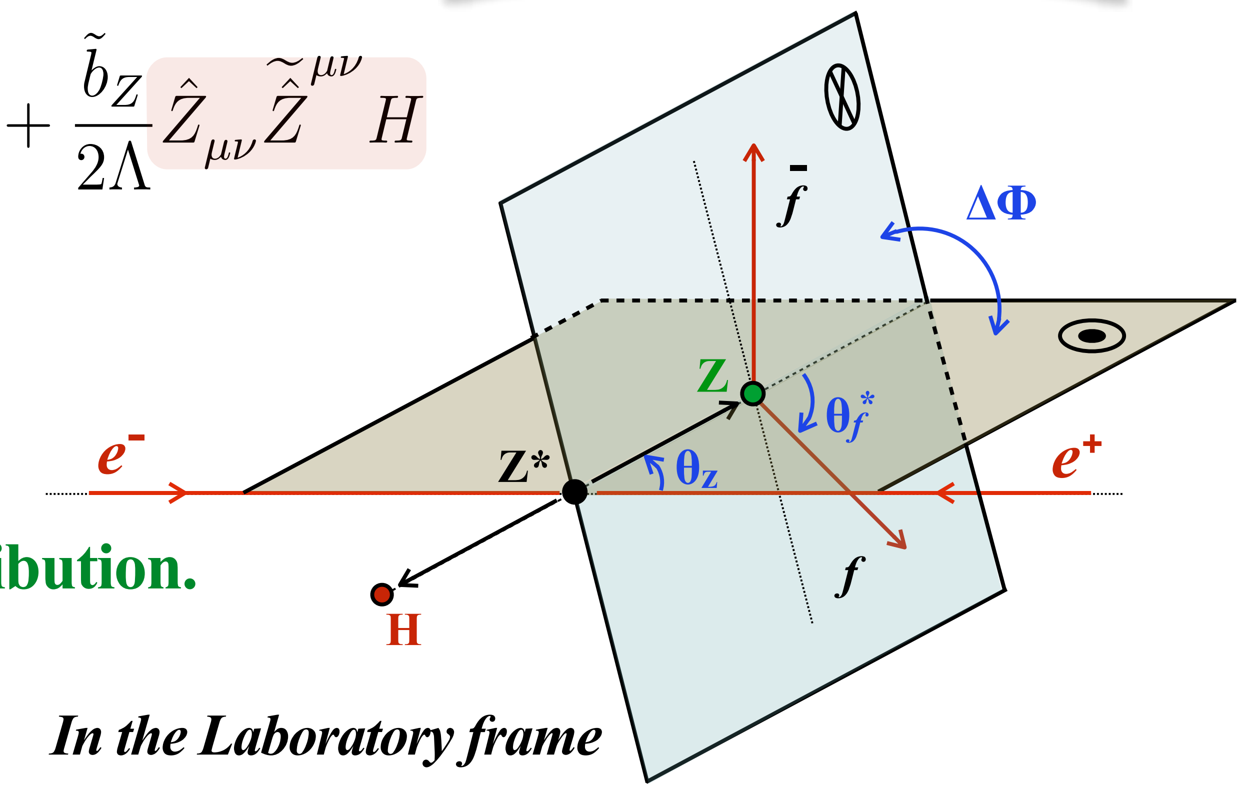
$$\hat{V}_{\mu\nu} \equiv \partial_\mu V_\nu - \partial_\nu V_\mu \text{ and } \widetilde{\hat{V}}_{\mu\nu} \equiv \tfrac{1}{2}\epsilon_{\mu\nu\rho\sigma}\hat{V}^{\rho\sigma}.$$

Anomalous ZZH couplings

The Higgs-straulung

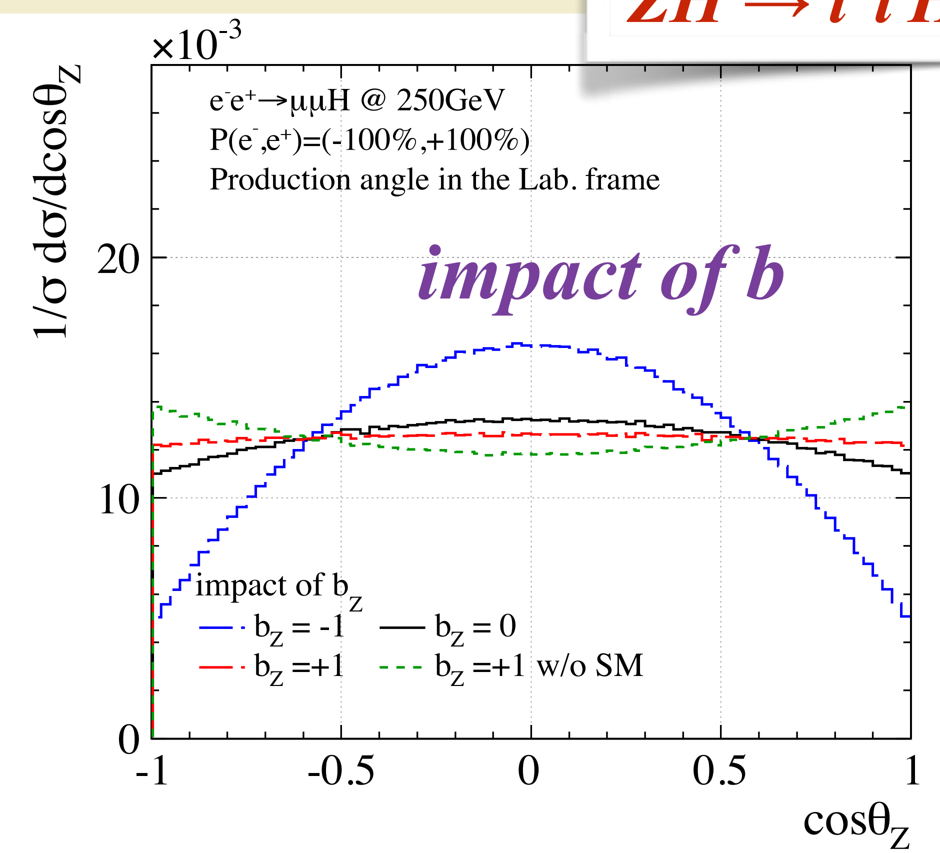
$$\mathcal{L}_{ZZH} \;=\; M_Z^2\left(\frac{1}{\mathrm{v}}+\frac{a_Z}{\Lambda}\right)Z_\mu Z^\mu H+\frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}H+\frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\tilde{\hat{Z}}^{\mu\nu}H$$

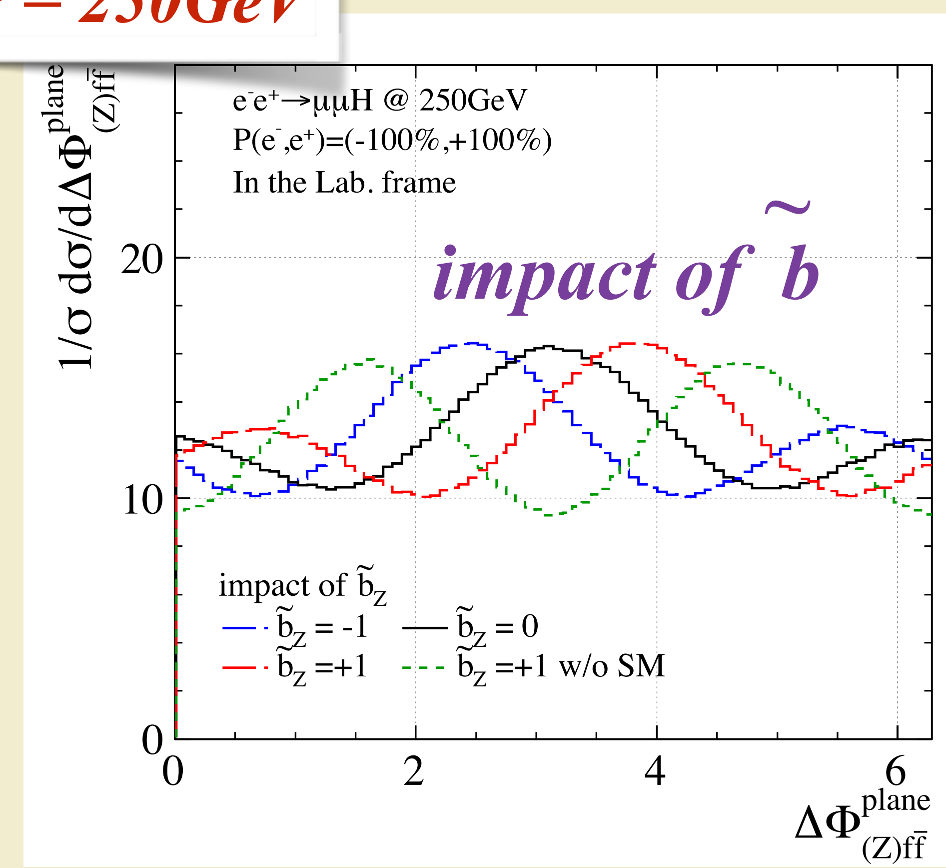
- "a_Z" : a normalization parameter (rescales the SM-coupling)
- "b_Z" : a different CP-even tensor structure affecting **momentum and changes angular distribution.**
- "$\tilde{b}_Z$" : a CP-violating parameter affecting **angular/spin correlations.**



In the Laboratory frame

$ZH \rightarrow l^+l^-H\,,\ \sqrt{s} = 250GeV$

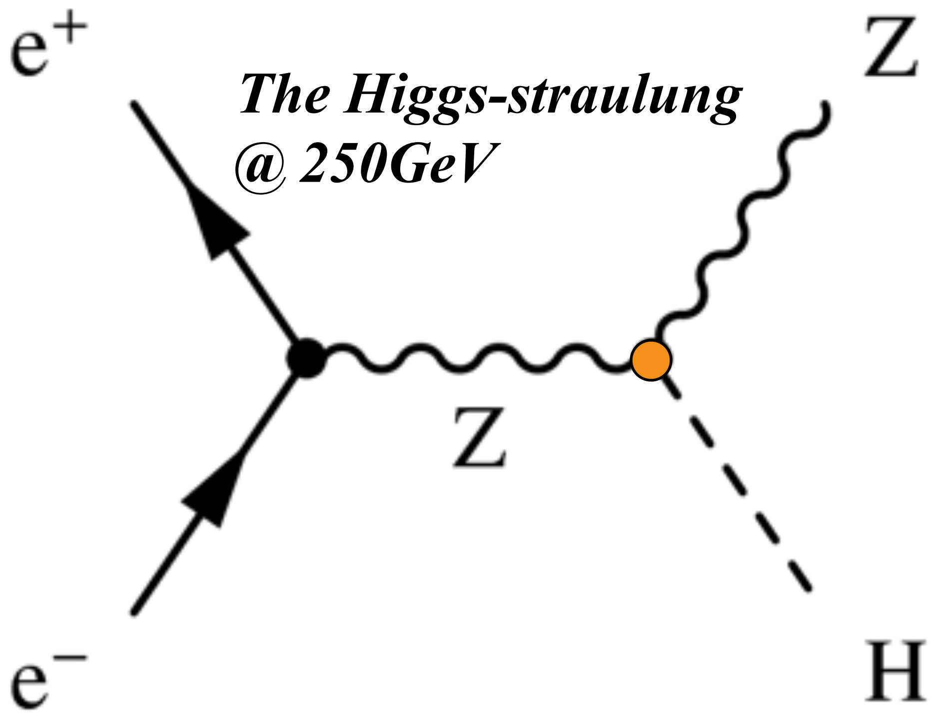




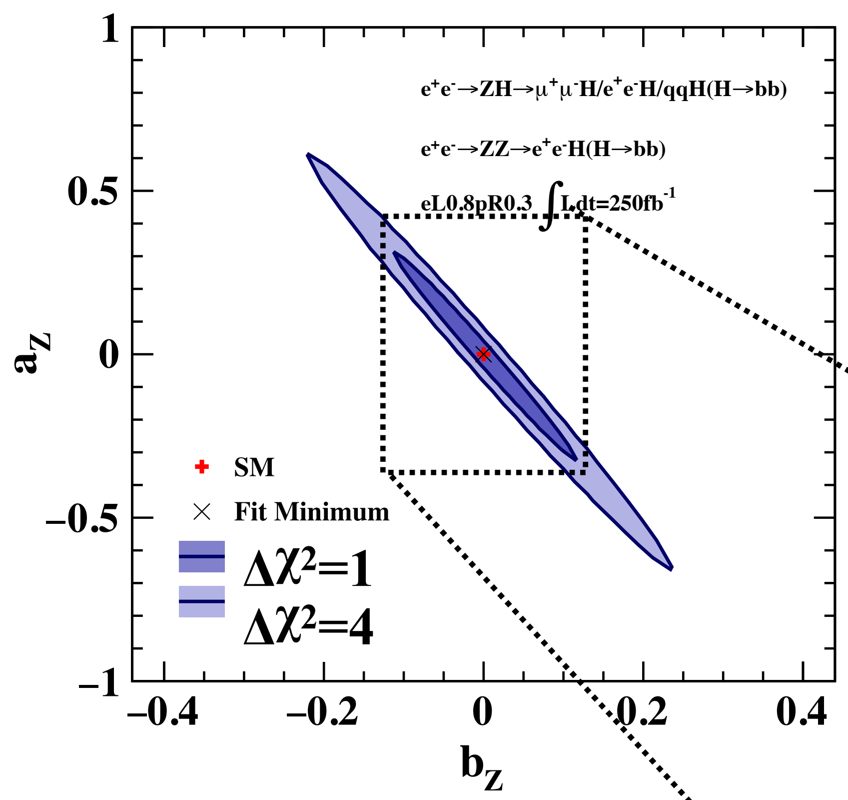
Anomalous ZZH couplings

EPS17 talk
https://indico.cern.ch/event/466934/contributions/2588482/

$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{\mathrm{v}} + \frac{a_Z}{\Lambda}\right) Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu} H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\tilde{\hat{Z}}^{\mu\nu} H$$

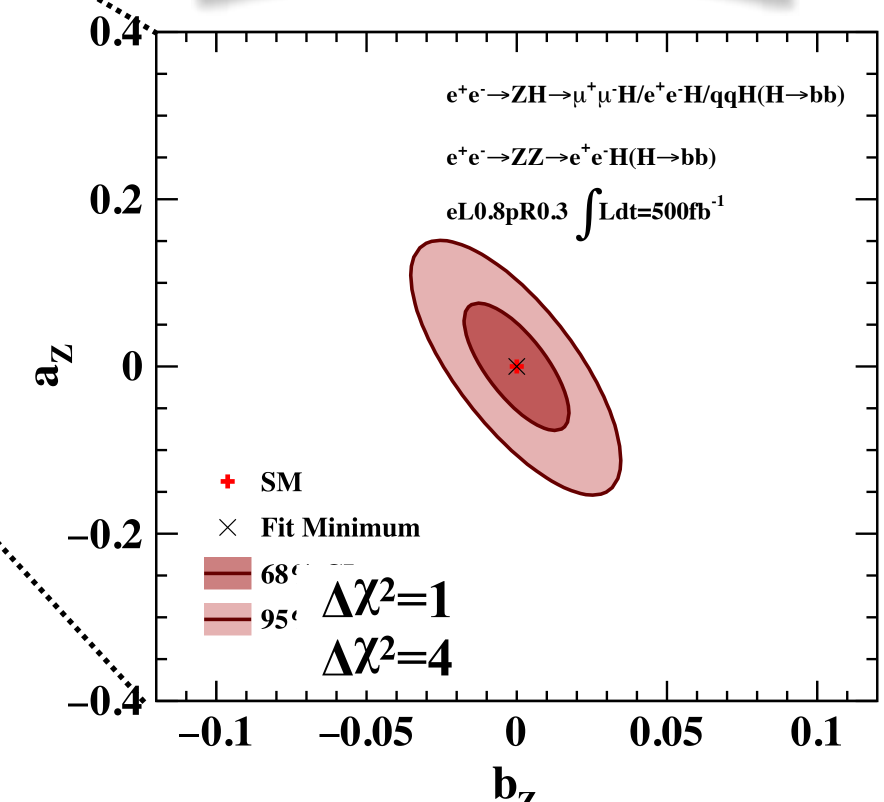


250GeV w/ 250fb-1



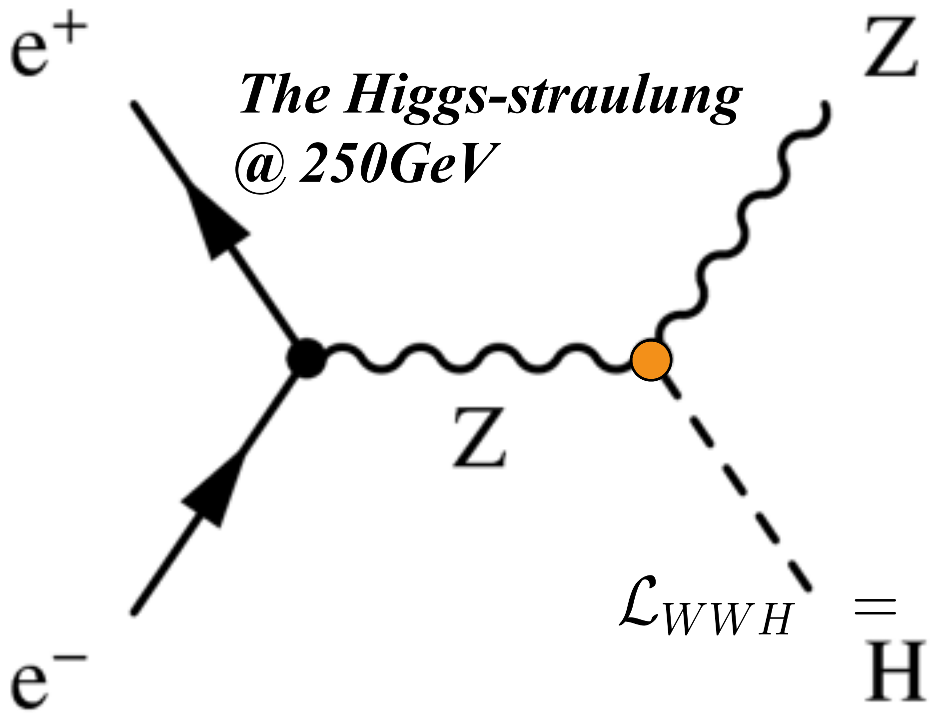
simultaneous fitting, projected on a-b plane

500GeV w/ 500fb-1



Consideration on Anomalous WWH couplings

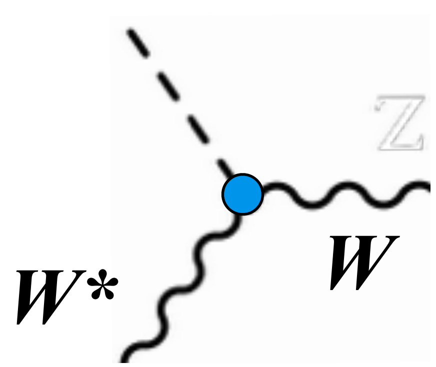
$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{\mathrm{v}}+\frac{a_Z}{\Lambda}\right)Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\widetilde{\hat{Z}}^{\mu\nu}H$$



anomalous WWH couplings using the Higgs decay

The origin of VVH is same, EWSB

$$\mathcal{L}_{WWH} = 2M_W^2\left(\frac{1}{\mathrm{v}}+\frac{a_W}{\Lambda}\right)W_\mu^+ W^{-\mu} H + \frac{b_W}{\Lambda}\hat{W}_{\mu\nu}^+\hat{W}^{-\mu\nu}H + \frac{\tilde{b}_W}{\Lambda}\hat{W}_{\mu\nu}^+\widetilde{\hat{W}}^{-\mu\nu}H$$



Production : incoming and outgoing
Decay : both is outgoing

The difference can be calculated in terms of $|M|$ $\longrightarrow$ back up

When the variation of BR(H→WW) depending on anom-couplings the variation of Γ(H→XX) must be considered. → **Only shape information**

Anomalous WWH couplings

The Higgs-straulung

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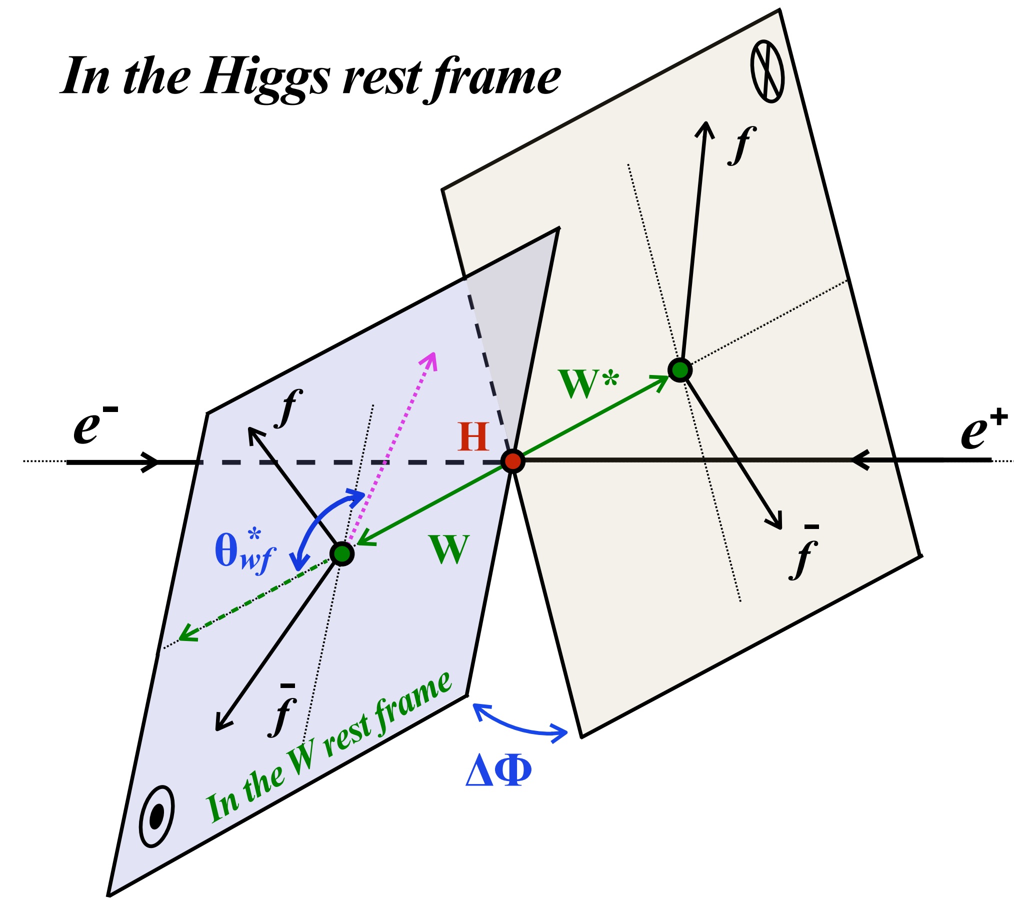

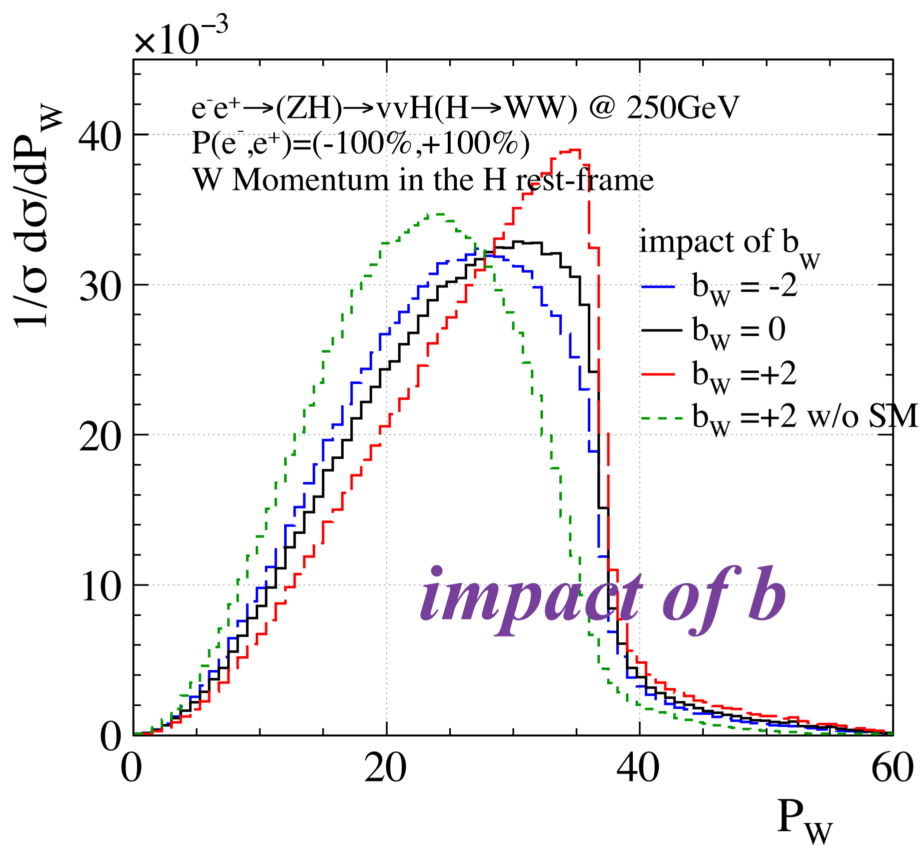

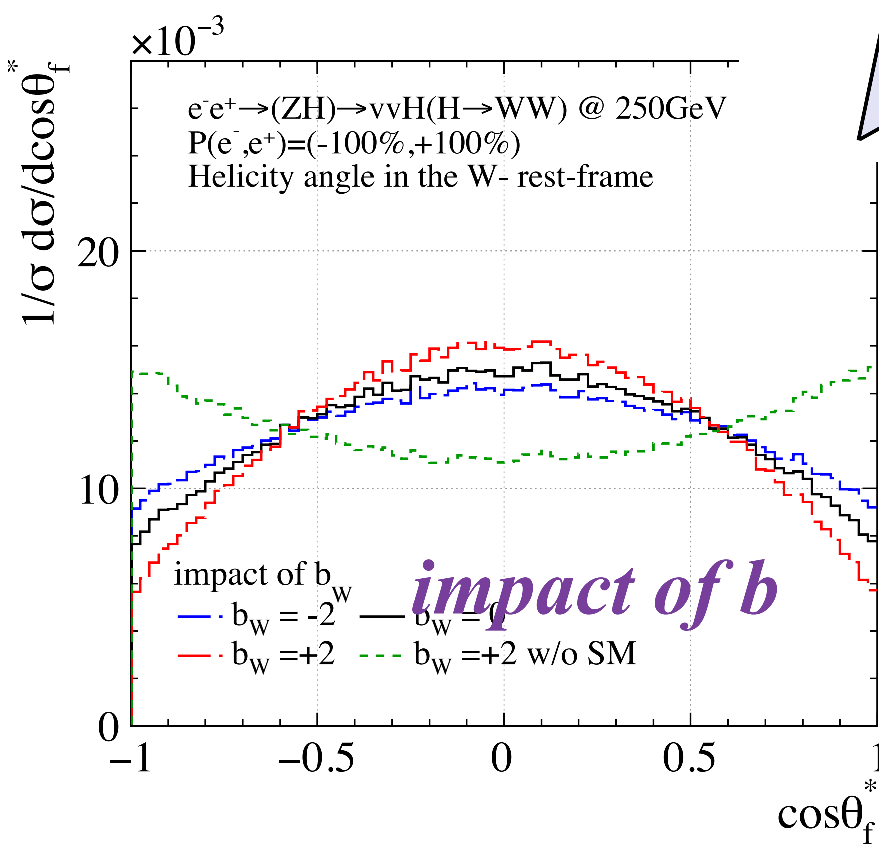

Anomalous WWH couplings

The Higgs-straulung

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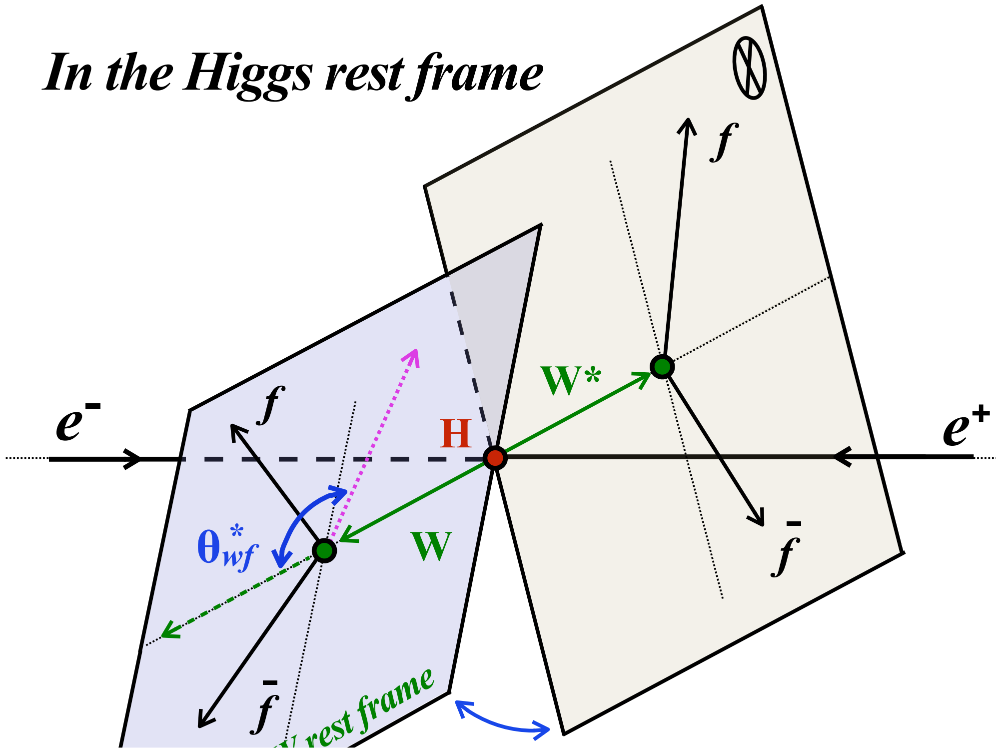
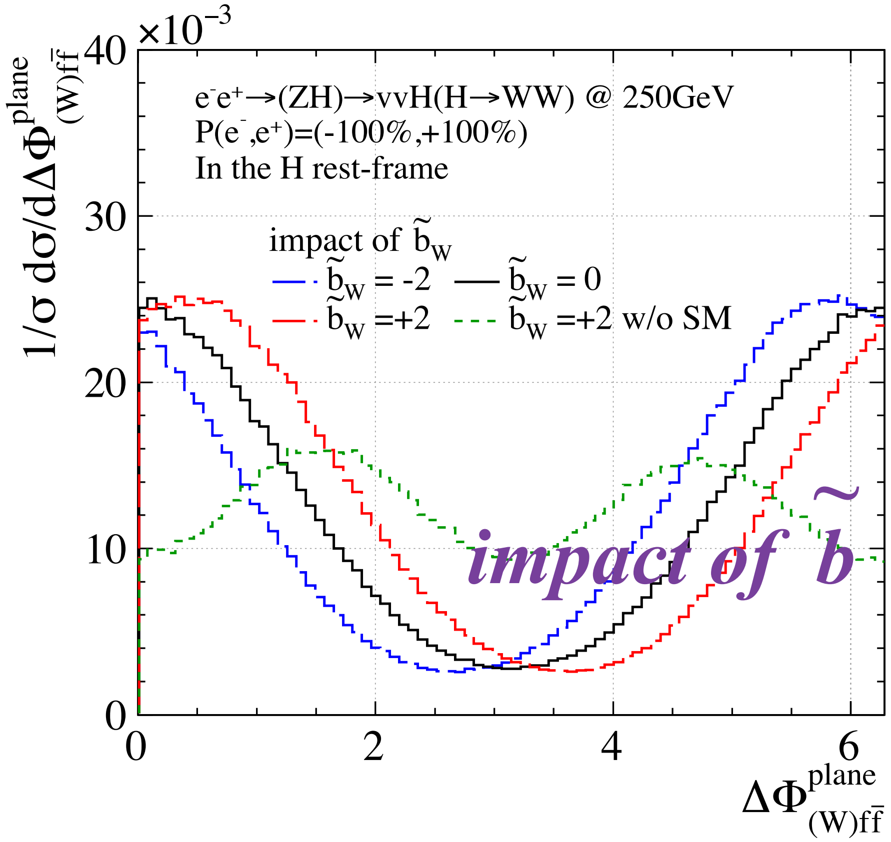
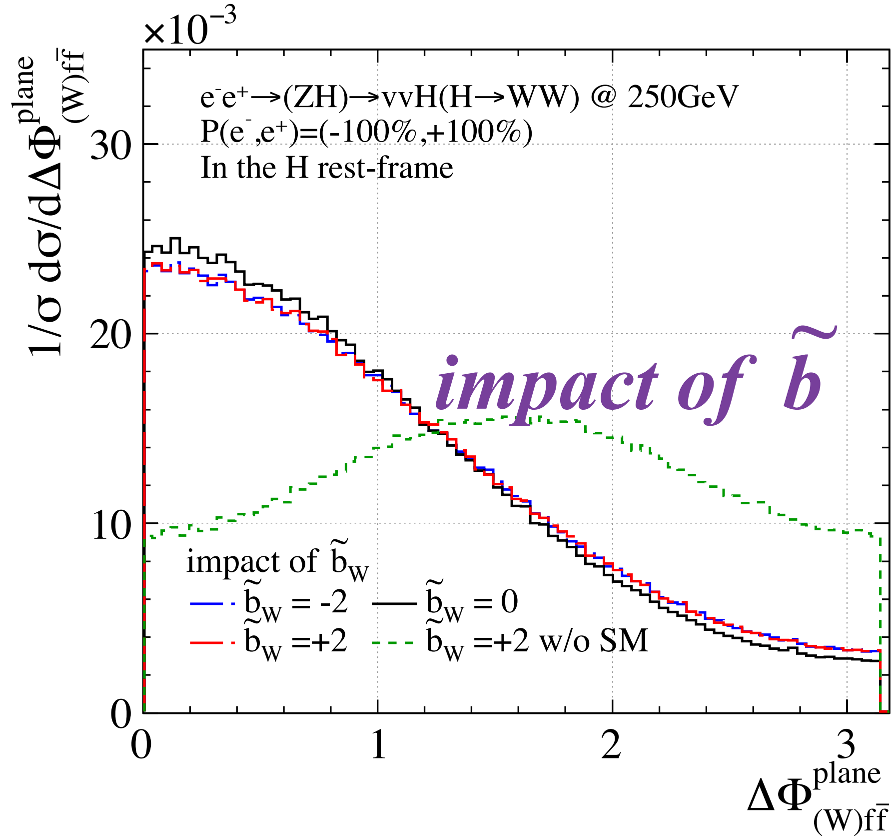




- ***c-jet identification***

$WW^* \to cx\bar{c}\bar{x}$ $[0 \sim 2\pi]$

$WW^* \to cxqq$ $[0 \sim 1\pi]$

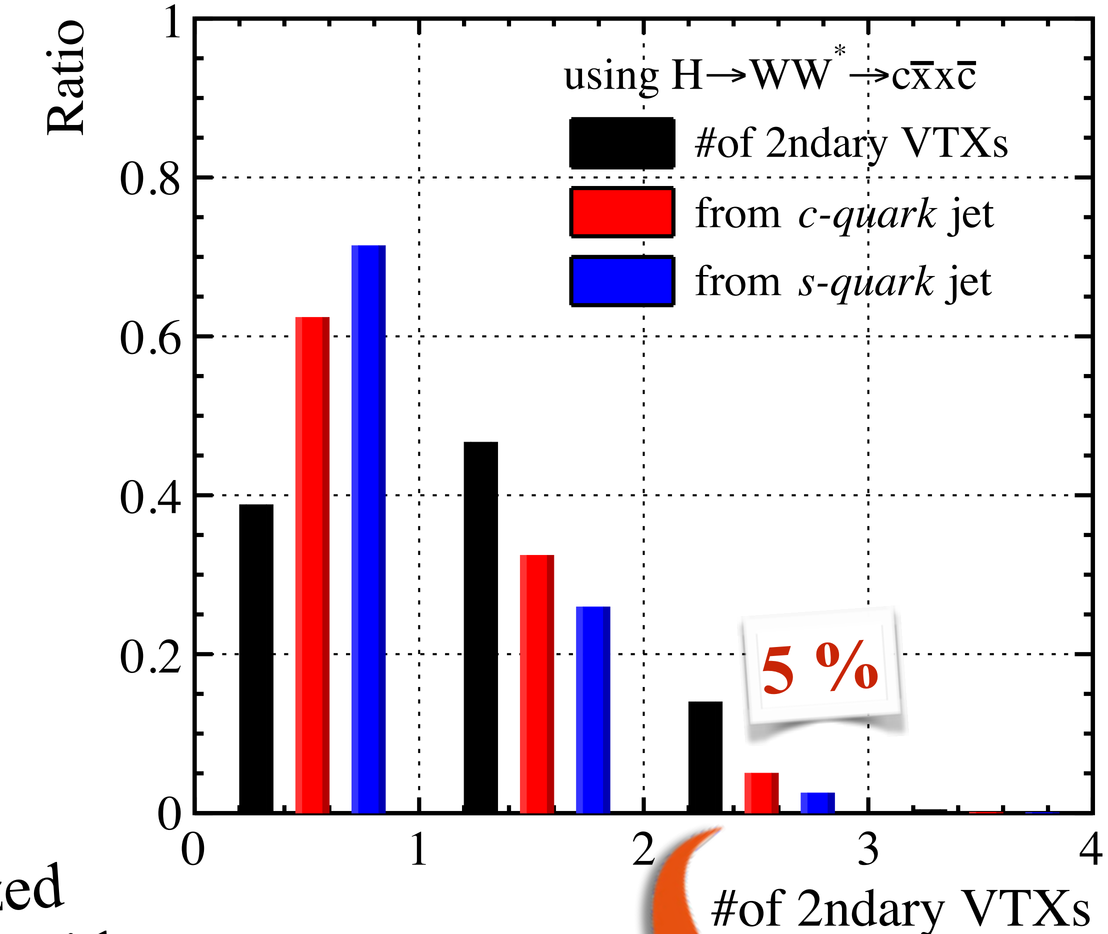


c-tag performance for H→WW*

using H→WW^*→ $cx\bar{c}\bar{x}$

Events which can find two 2ndary vertices

<u>~ 5 % of all events</u>

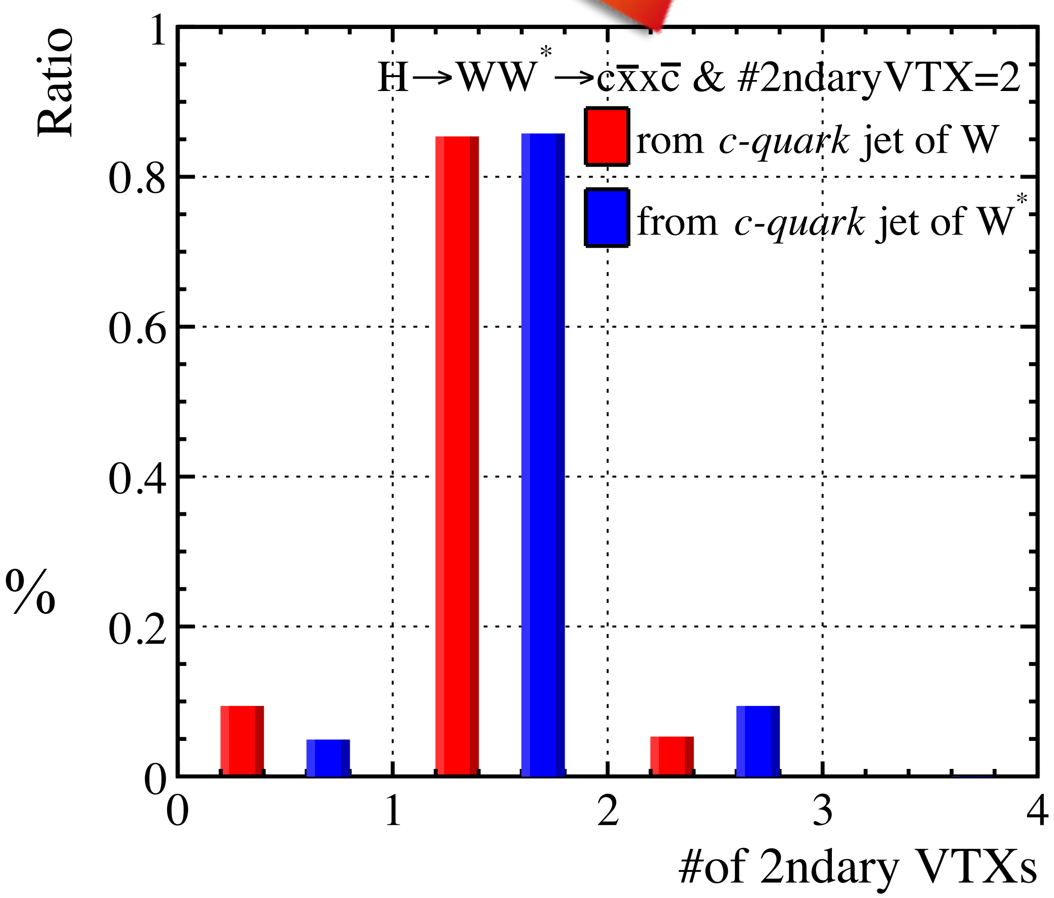


ZH → νν +WW → cxcx w/ 250 fb^{-1}

Before c-tag distinction ~ 100 (cxcx)
After c-tag distinction
c-tag requirement > 0.75
→ 12 (cxcx)

<u>selection efficiency 12%</u>

cut is optimized
→ back up slides



Phys. Rev. D 88, 013010
– Published 18 July 2013
Measuring anomalous couplings in H →WW*

c-tag
selection efficiency 88%

Decay processes for WWH

Focus on the Higgs-straulung @ 250GeV

250GeV w/ 250fb-1

$e^+e^- \rightarrow$ ZH $\rightarrow$ (1). νν +WW (4jets (categorize)

$\rightarrow$ cxcx c-tag essential

qqqq

(2). qq + WW (lνqq)

fully reconstruction is possible

(3). qq + WW (4jets)

huge migration

sensitive info. is almost lost

1. Full standard model backgrounds are taken into account
2. Background suppression is optimized by considering signal-significance

Decay processes for WWH

Focus on the Higgs-straulung @ 250GeV

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$e^+e^- \rightarrow$ ZH $\rightarrow$ (1). νν +WW (4jets (categorize) → back up slides

→ cxcx c-tag essential

qqqq

Nsig = 12.27
Nbkg = 45.53
Signif= 1.61

Nsig = 418.11
Nbkg = 1663.87
Signif= 9.16

(2). qq + WW (lvqq)

fully reconstruction is possible

Nsig = 1037
Nbkg = 1402
Signif= 20.99

(3). qq + WW (4jets)

huge migration

sensitive info. is almost lost

Nsig = 906
Nbkg = 13590
Signif= 7.53

1. Full standard model backgrounds are taken into account
2. Background suppression is optimized by considering signal-significance

Determination of the sensitivity

Our approach for evaluating the sensitivity
to the anomalous couplings is based on a combined chi2.

- **Shape information**

"Generator level" distribution
Calculated dσ/dX with explicit parameters.

$$\chi^2 = \sum_{i=1}^{n} \left[\frac{N_{SM} \cdot \frac{1}{\sigma}\frac{d\sigma}{dx}(x_i) \cdot f_i - N_{SM} \cdot \frac{1}{\sigma}\frac{d\sigma}{dx}(x_i; a_Z, b_Z, \tilde{b}_Z) \cdot f_i}{\Delta n_{SM}^{obs}(x_i)} \right]^2$$

Detector response function
→ Transfer to "Detector level" distribution

Poisson error on each bin
(SM Bkgs are taken into account)

- **Normalization information**

Expected #events
with different models

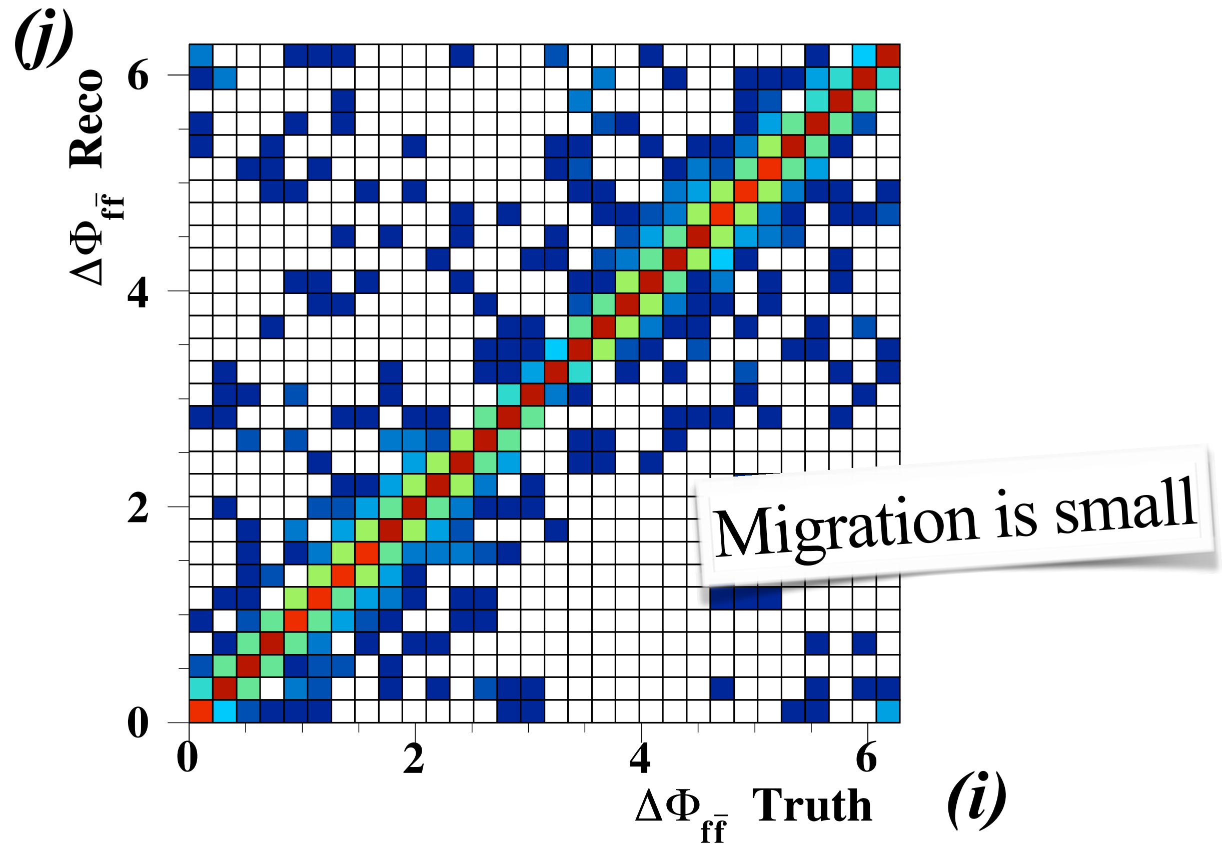
under discussion

Migration effect : example ΔΦ

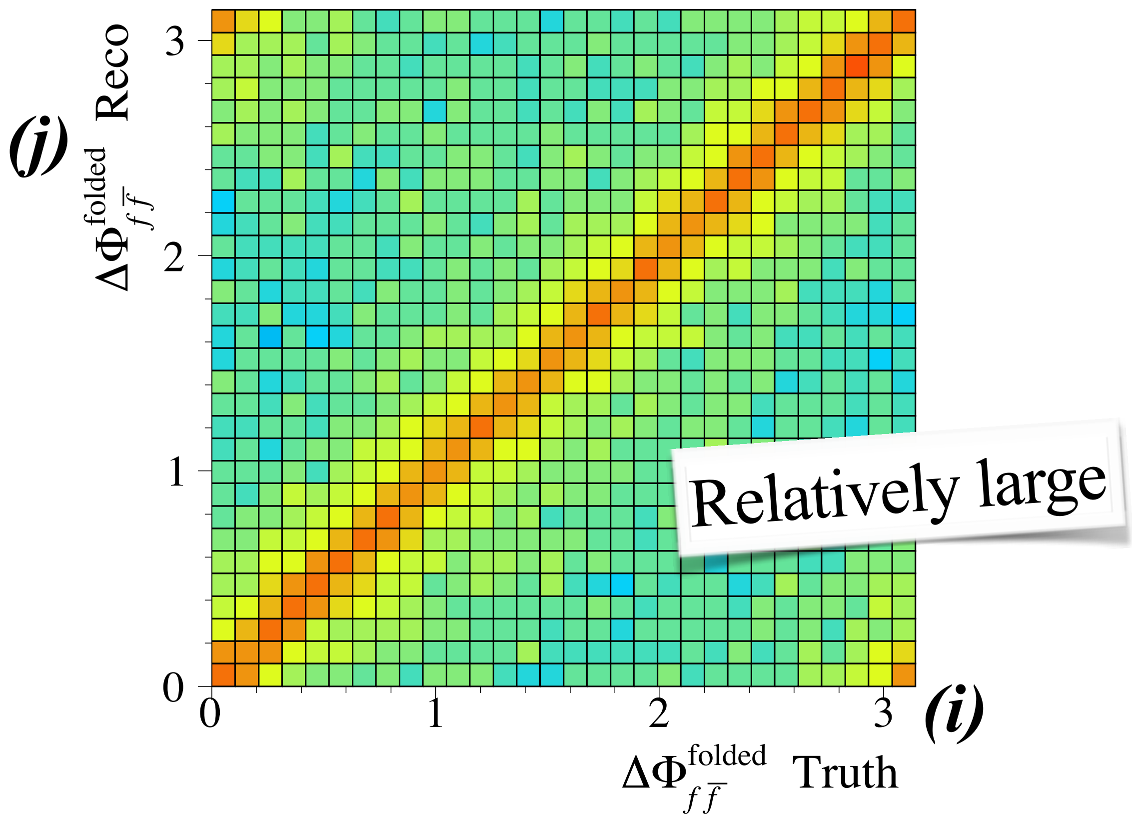
Production plane angle ΔΦ on ZH→ $\mu^+\mu^-$H @250GeV

Distributions are subject to migration effects due to

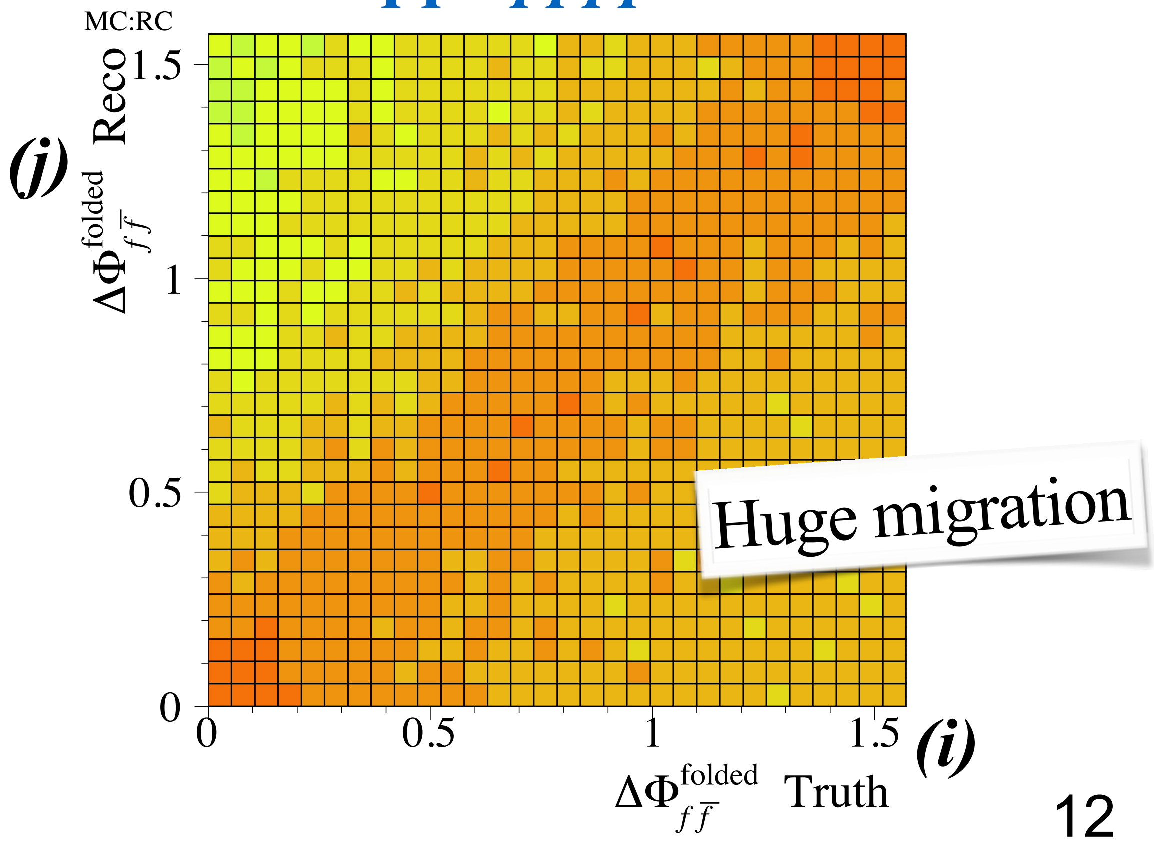
- finite detector resolution
- jet clustering,
- missing particles
- …



Decay plane angle ΔΦ on ZH→ qqWW → qq+ *lνqq*



qq+ *qqqq*



Migration effect ： example ΔΦ

→ detector response f

For a N-binned distribution,
an NxN migration matrix is necessary
to transfer the "generator" level
to the "detector" level.

$$N^{Rec}(x_j^{Rec}) = \sum_i f(x_j^{Rec}, x_i^{Gen}) \cdot N^{Gen}(x_i^{Gen})$$

detector response

$$N^{Rec}(x_j^{Rec}) = \sum_i f_{ji} \cdot N_i^{Gen} = \sum_i \bar{f}_{ji} \cdot \eta_i \cdot N_i^{Gen}$$

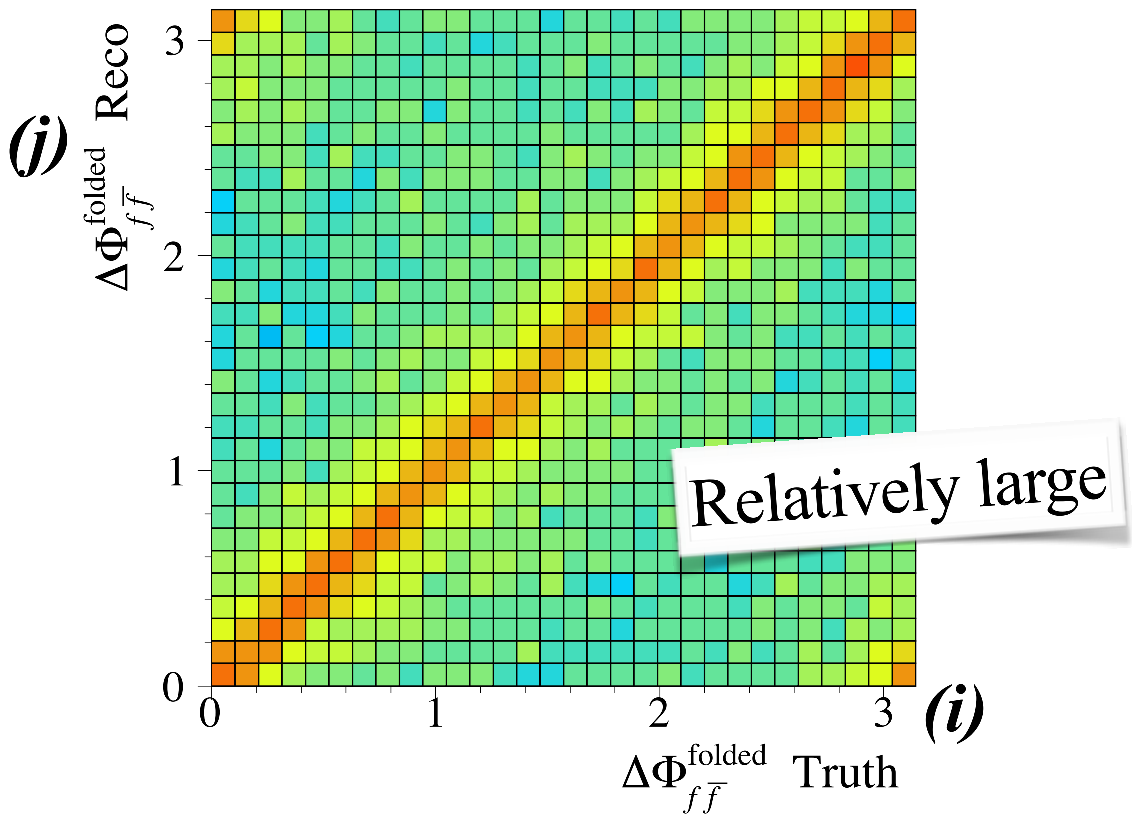
Normalized to 1

$$\eta_i \equiv \frac{N_i^{Accept}}{N_i^{Gene}} \quad \text{(Event Acceptance)}$$

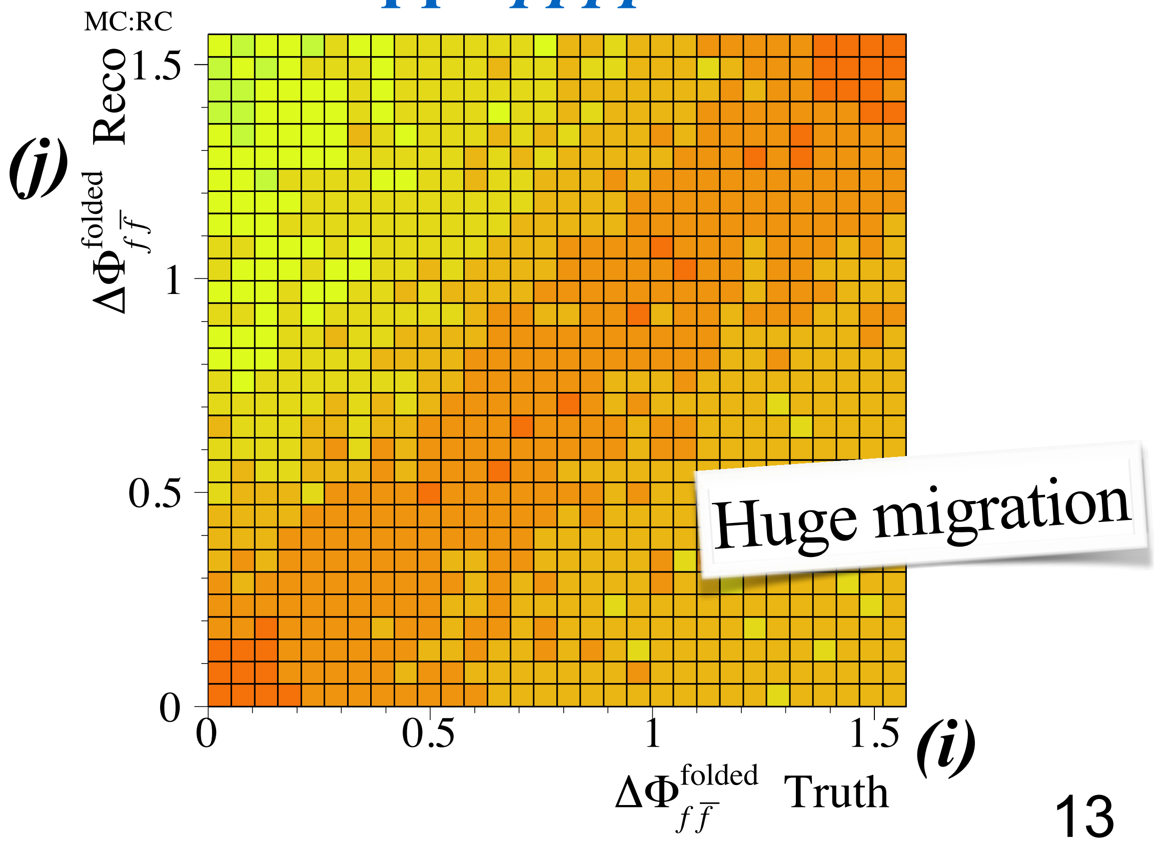
$$\bar{f}_{ji} \equiv \frac{N_{ji}^{Accept}}{N_i^{Accept}} \quad \text{(Migration Matrix)}$$

Decay plane angle ΔΦ

on ZH→ qqWW → qq+ *lvqq*



qq+ *qqqq*



Migration effect ： example ΔΦ

→ **detector response** ***f***

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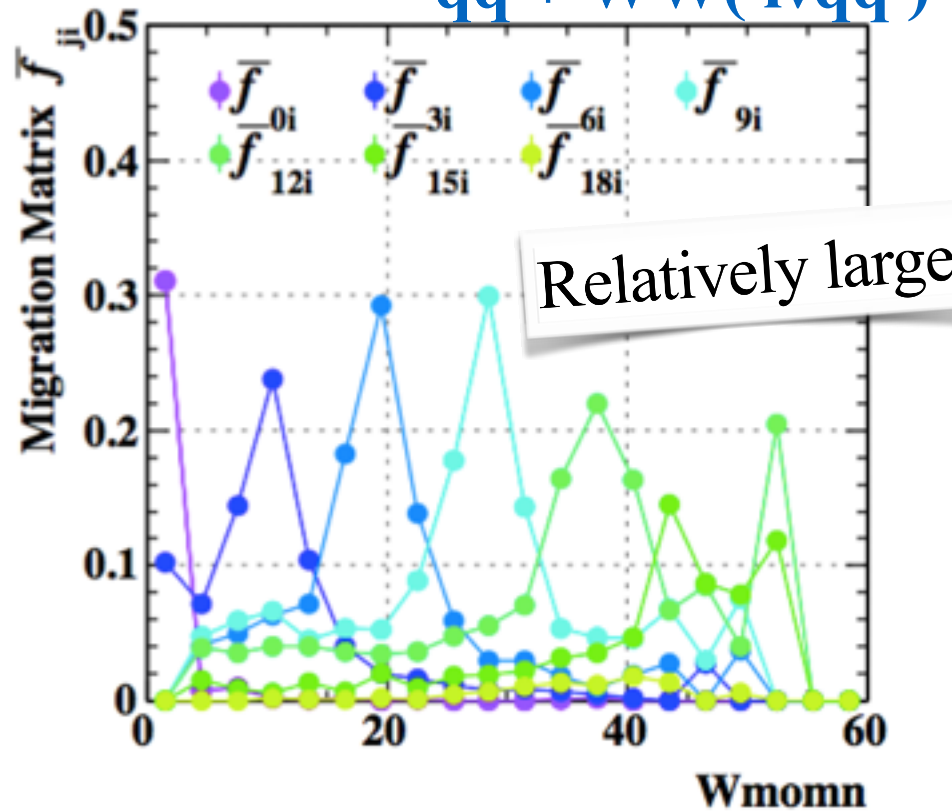
$$\bar{f}_{ji} \equiv \frac{N_{ji}^{Accept}}{N_i^{Accept}} \quad \text{(Migration Matrix)}$$

clear

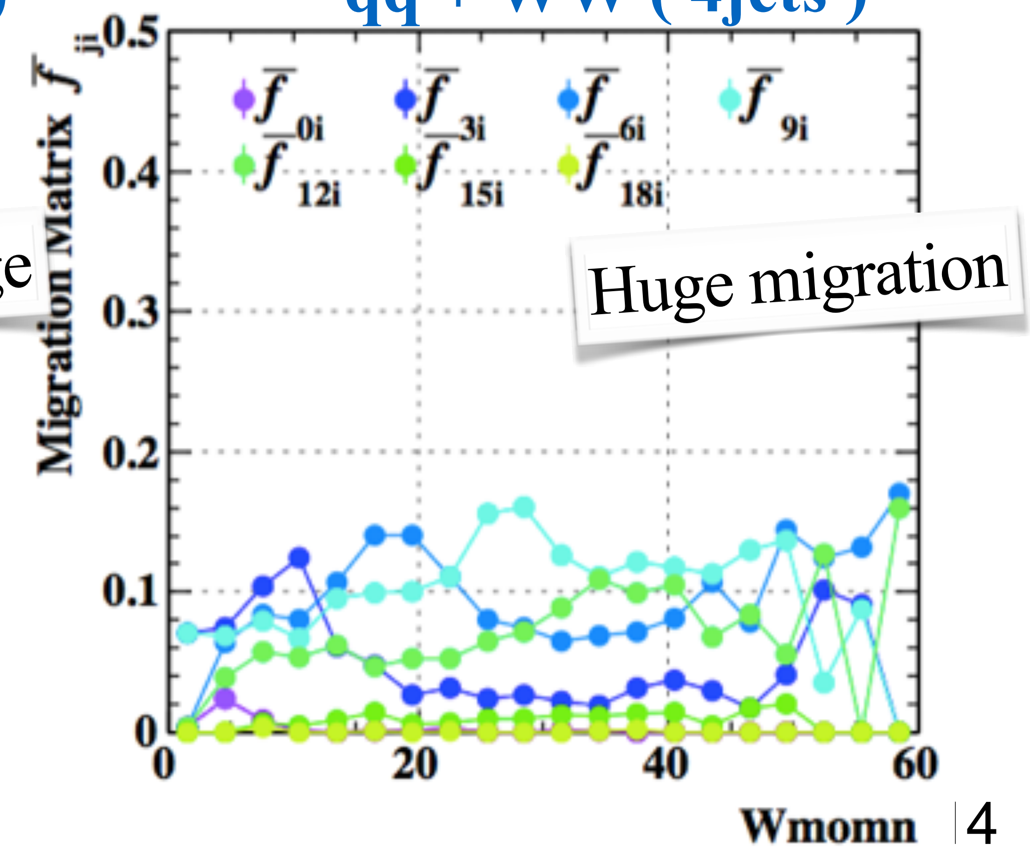
Another example Pw

Example :
Situation of the migration
e.g. Pw distribution

qq + WW(lνqq)



qq + WW (4jets)

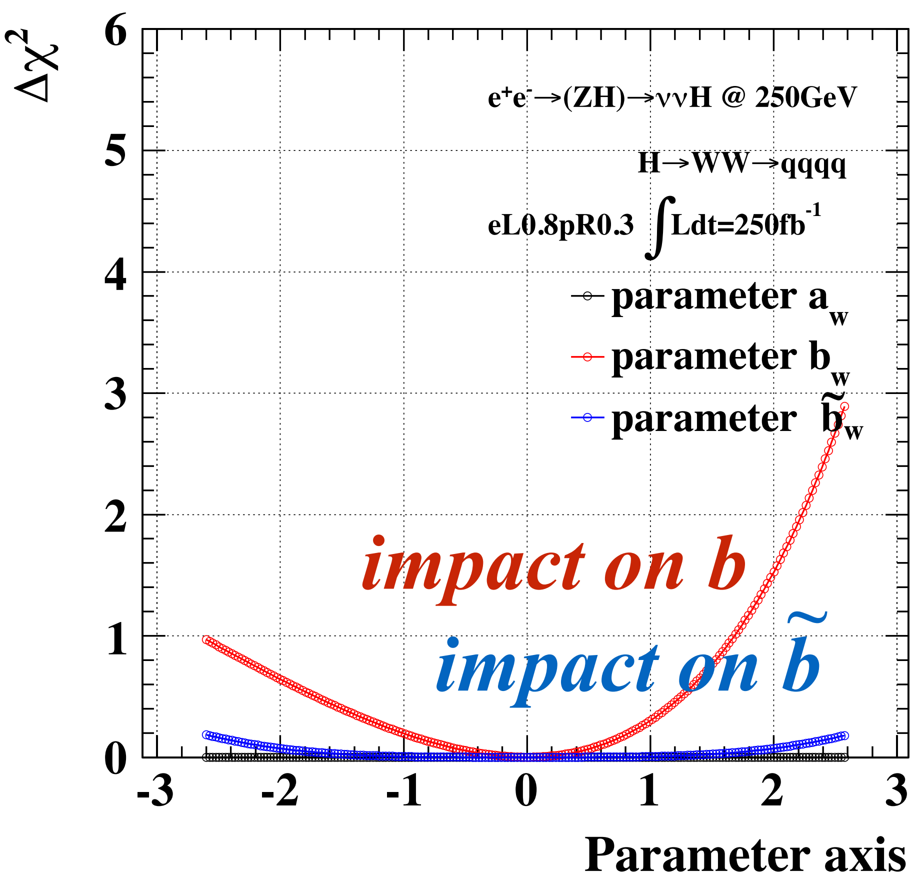


Power of the shape for determining anomalous WWH

Only shape information is considered.

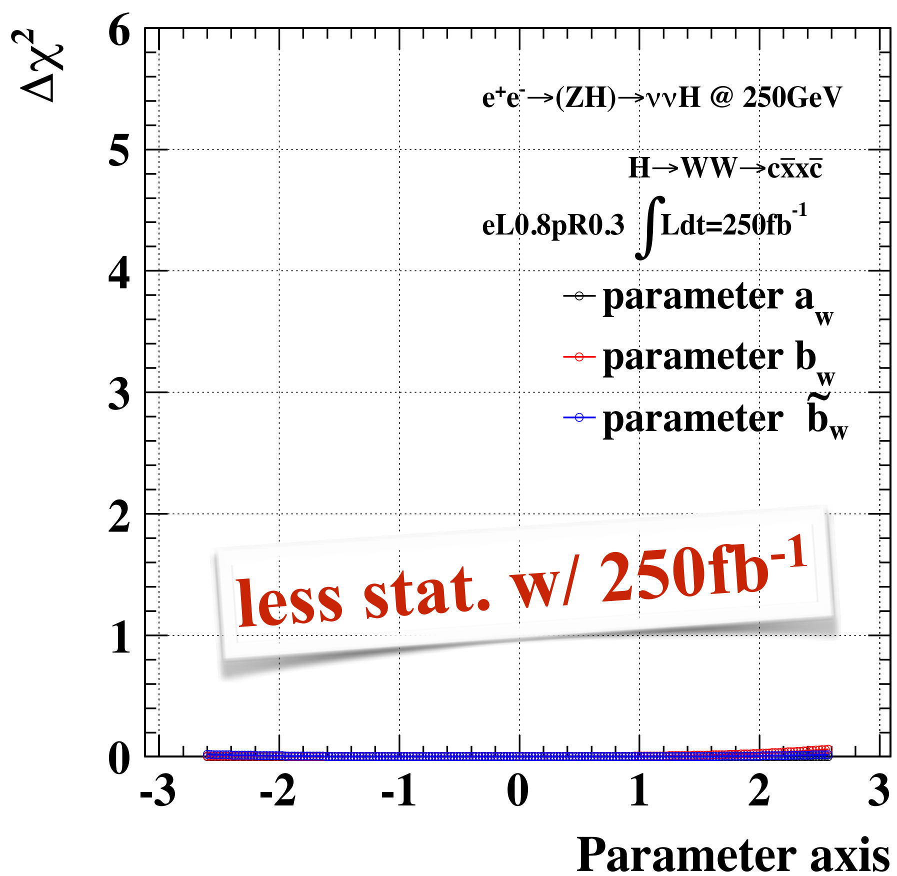
@ 250 GeV w/ 250 fb-1 is assumed.

$\Delta\chi 2 = \chi 2 \ (\chi 2_{min} = 0)$



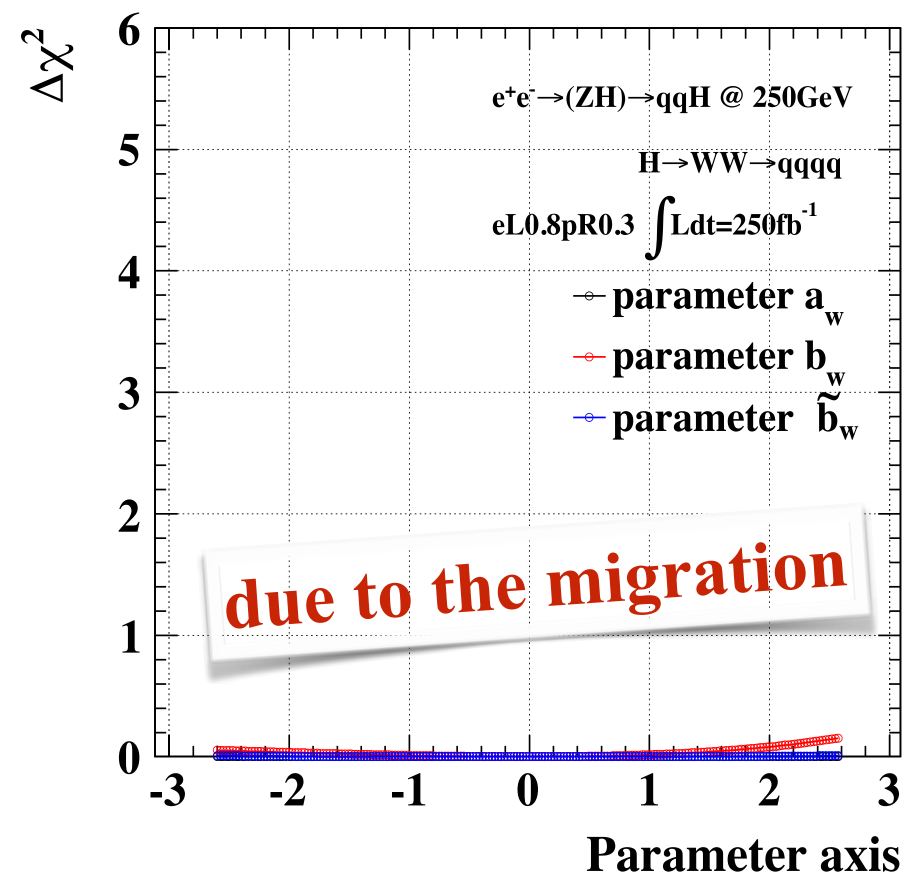
νν +WW
(4jets → qqqq) categorized

3d shape information
x(Pw, cosθwf, ΔΦ[0~π])



νν +WW
(4jets→cxcx) categorized

1d shape information
x(ΔΦ[0~π])



qq +WW (4jets)
full hadronic

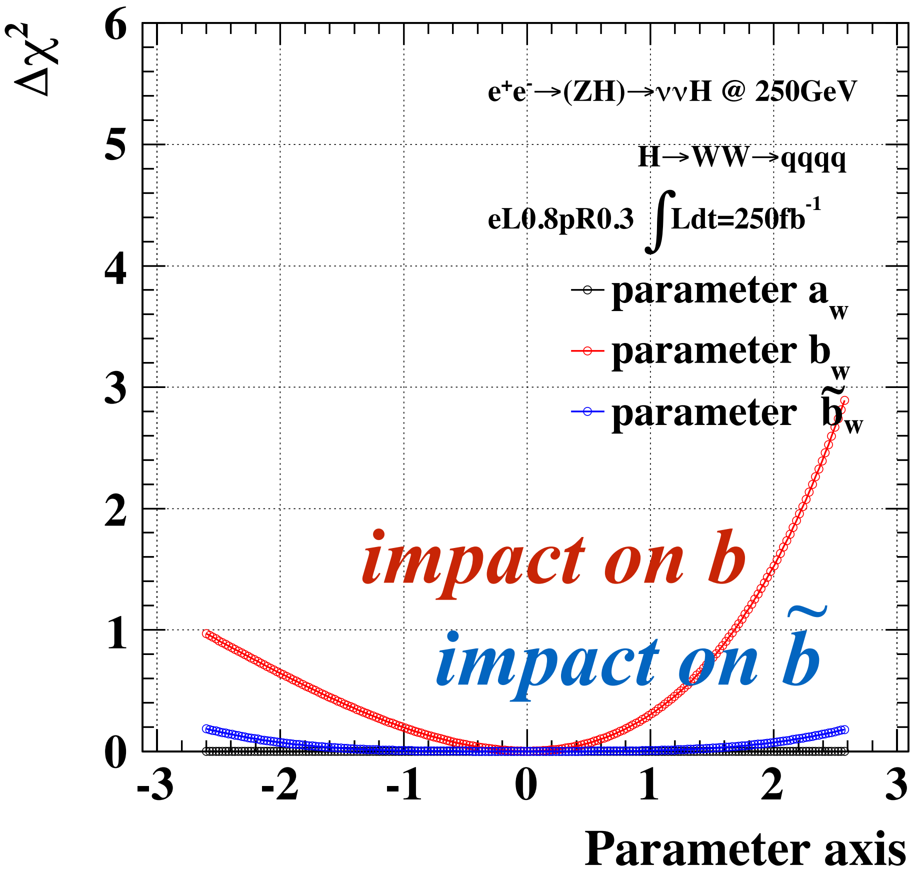
3d shape information
x(Pw, cosθwf, ΔΦ[0~1/2π])

Power of the shape for determining anomalous WWH

Only shape information is considered.

@ 250 GeV w/ 250 fb-1 is assumed.

$\Delta\chi 2 = \chi 2$ ($\chi 2_{min}=0$)

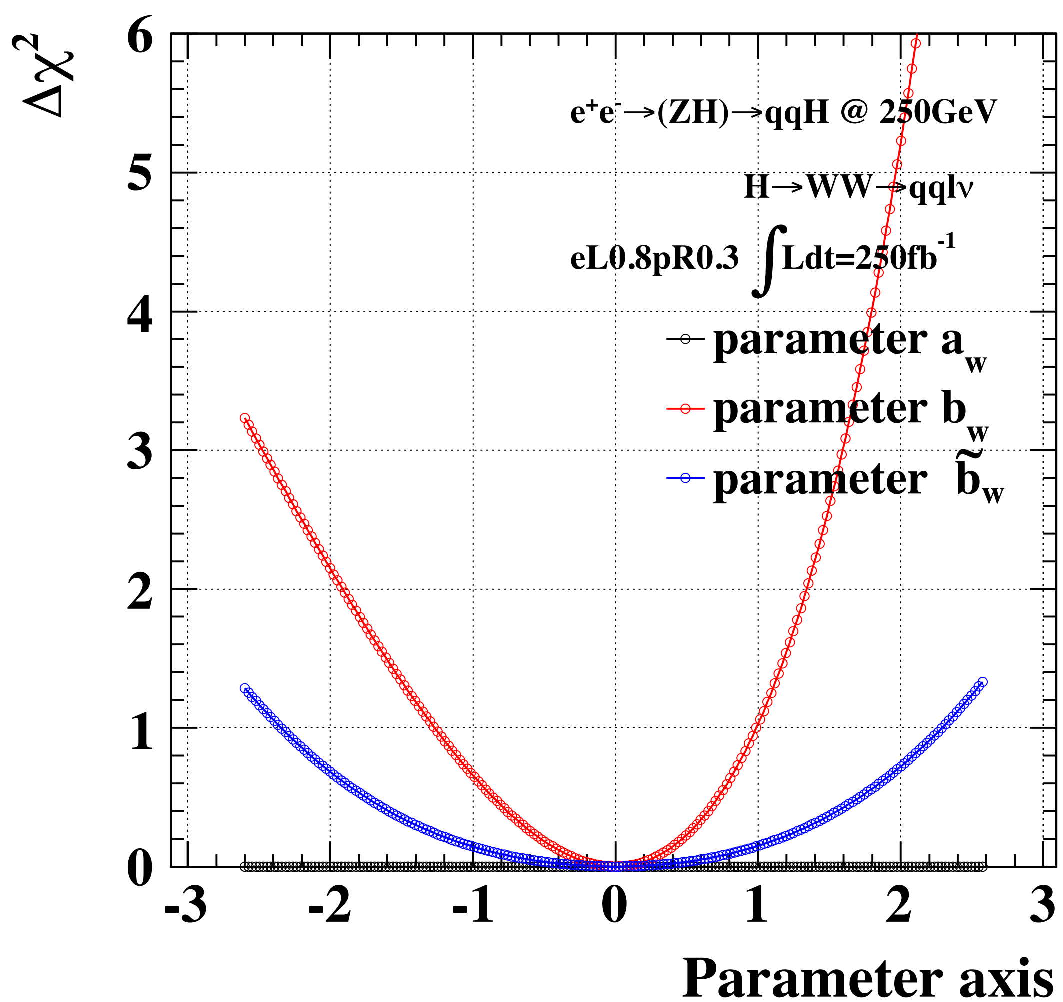


νν +WW

(4jets → qqqq) categorized

3d shape information

x(Pw, cosθwf, ΔΦ[0~π])



qq + WW (lνqq)

3d shape information

x(Pw, cosθwf, ΔΦ[0~π])

Comparison of the sensitivity to anom-ZZH and -WWH

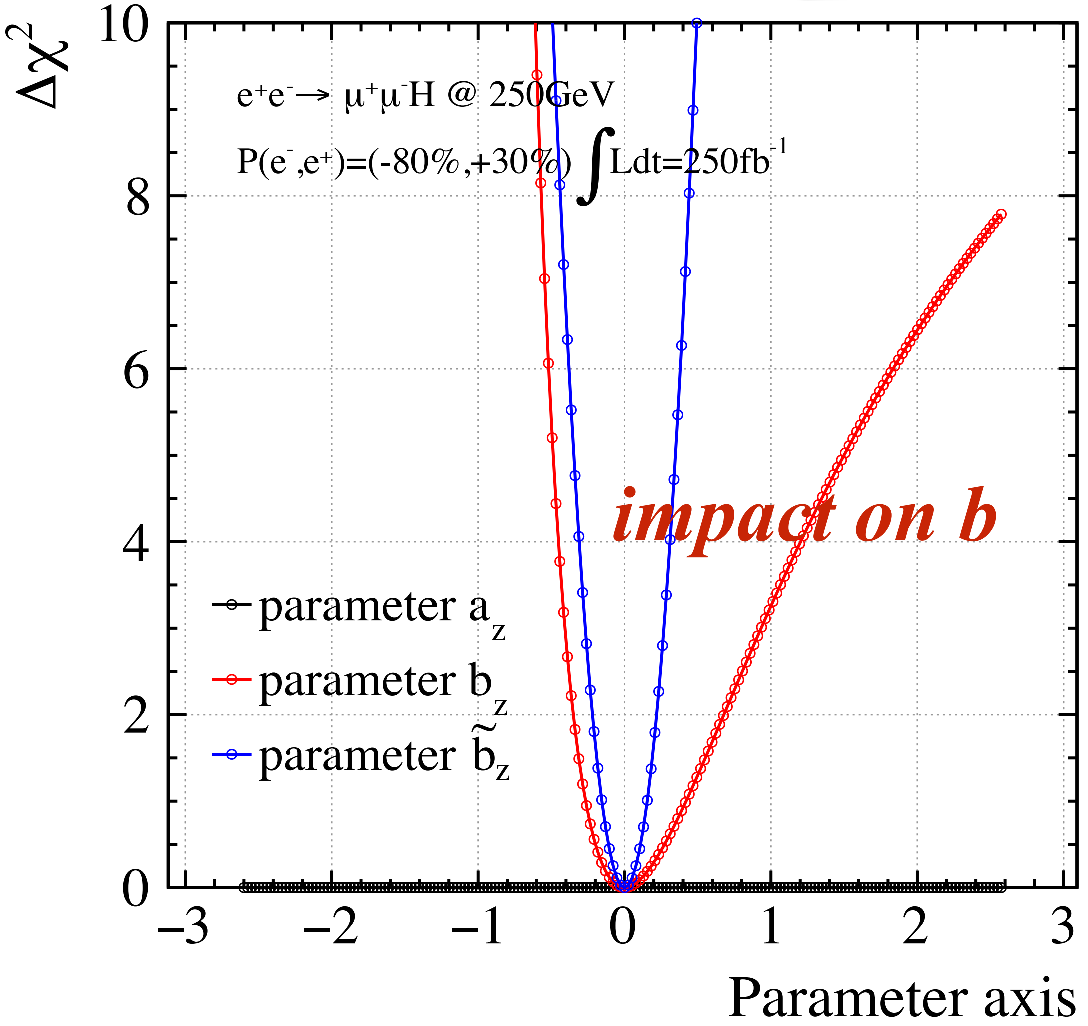
Only shape information is considered.

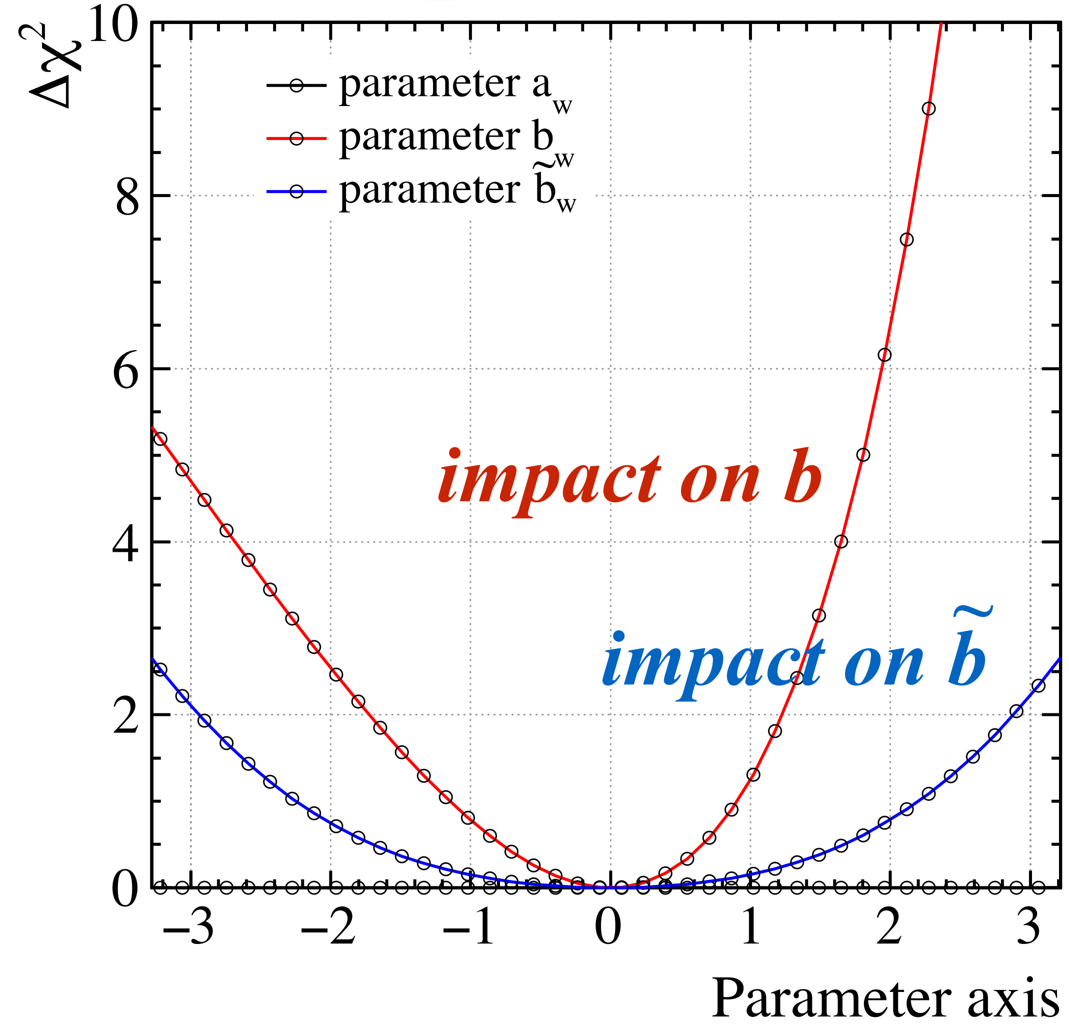
@ 250 GeV w/ 250 fb-1 is assumed.

for the 1- parameter space

The other 2 params are fixed to 0.

$\Delta\chi 2 = \chi 2$ ($\chi 2_{min}$=0)





ZH→ $\mu^+\mu^-$H
@250GeV w/ 250 fb-1

H→WW @250GeV w/ 250 fb-1

νν +WW

(4jets→cxcx) categorized

(4jets→qqqq) categorized

qq + WW(lνqq)

Comparison of the sensitivity to anom-ZZH and -WWH

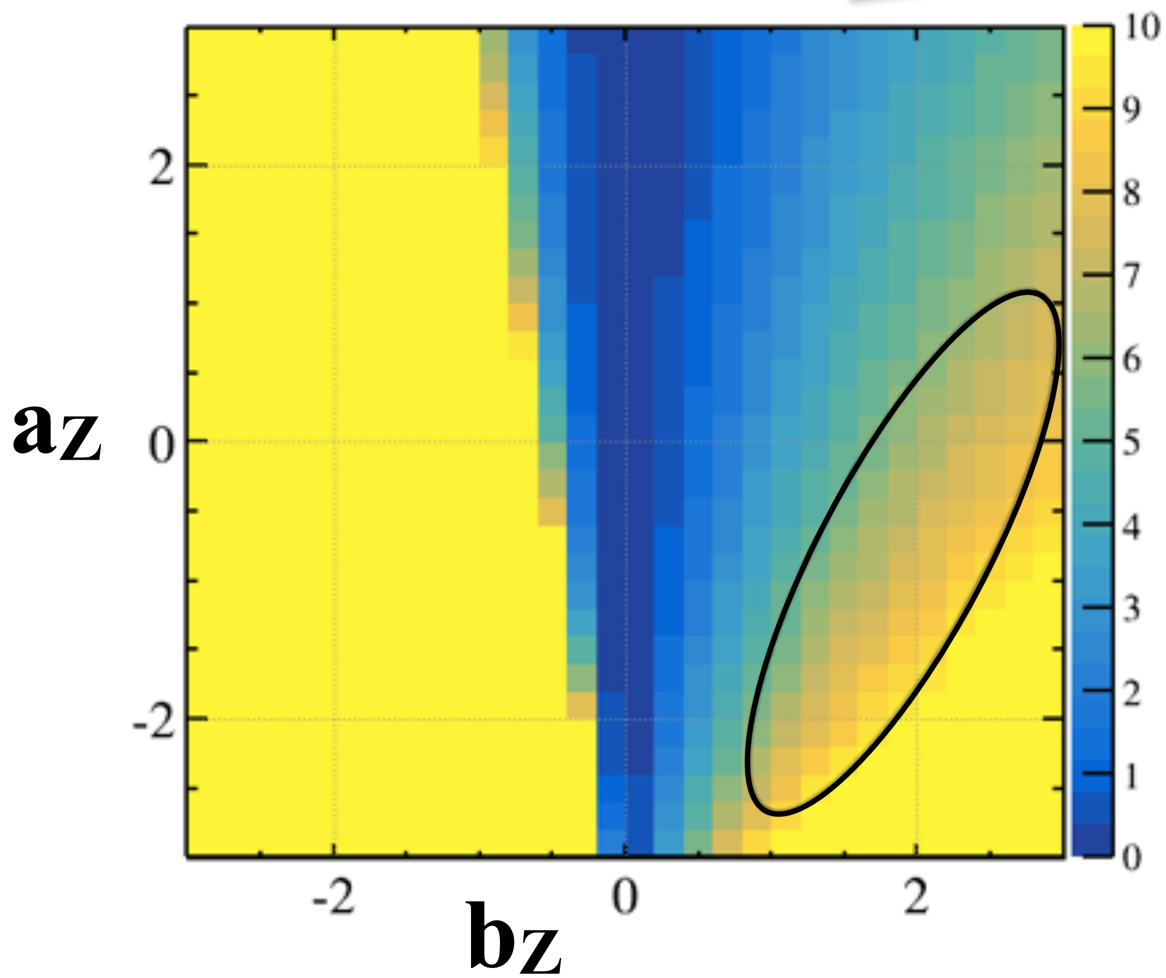
Only shape information is considered.

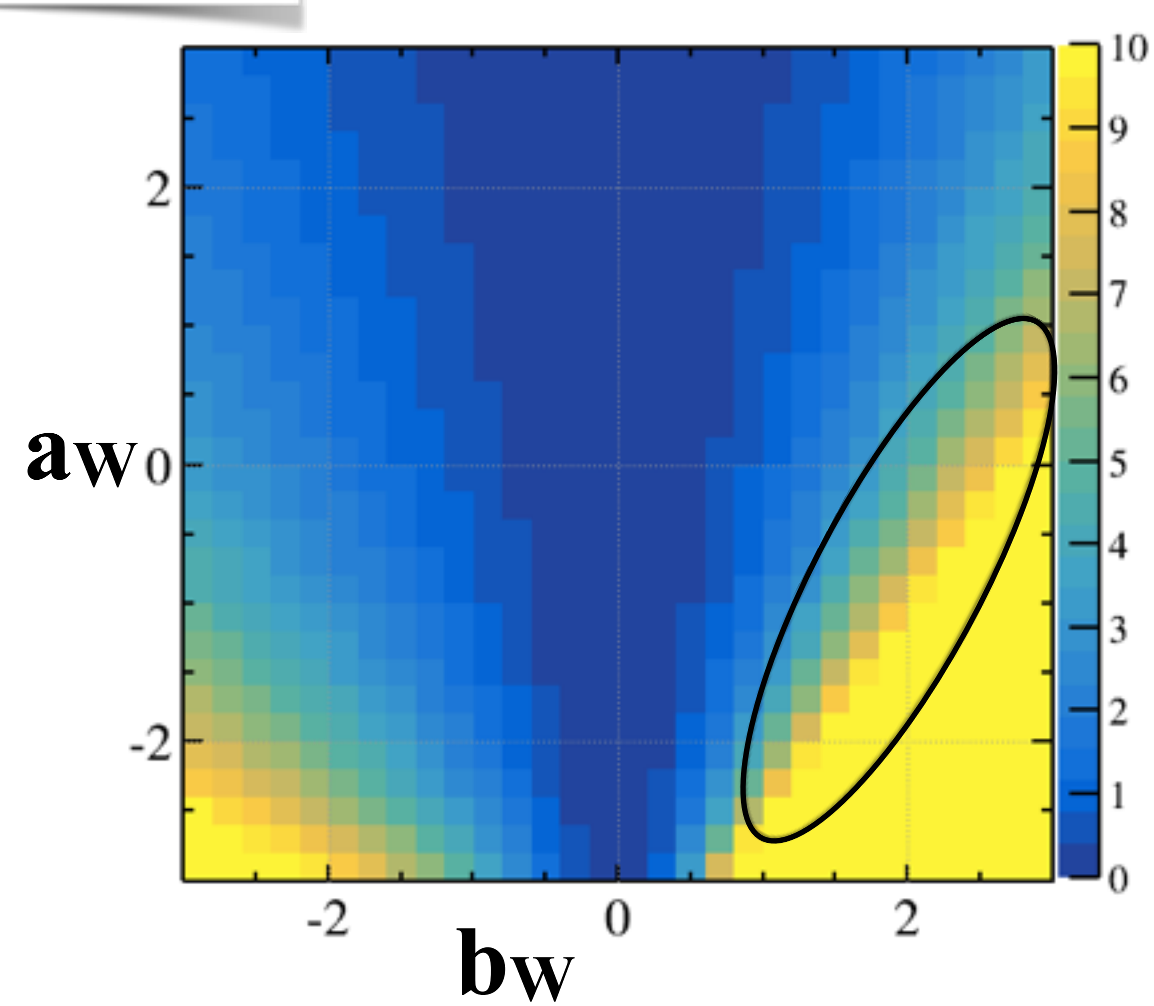
@ 250 GeV w/ 250 fb-1 is assumed.

Another params is free.
Δχ2 dist. is projected on to a-b

for 3-parameter space

$\Delta\chi 2 = \chi 2$ ($\chi 2_{min}=0$)





ZH→ $\mu^+\mu^-$H
@250GeV w/ 250 fb-1

H→WW @250GeV w/ 250 fb-1
νν +WW
(4jets→cxcx) categorized
(4jets→qqqq) categorized
qq + WW(lνqq)

Summary

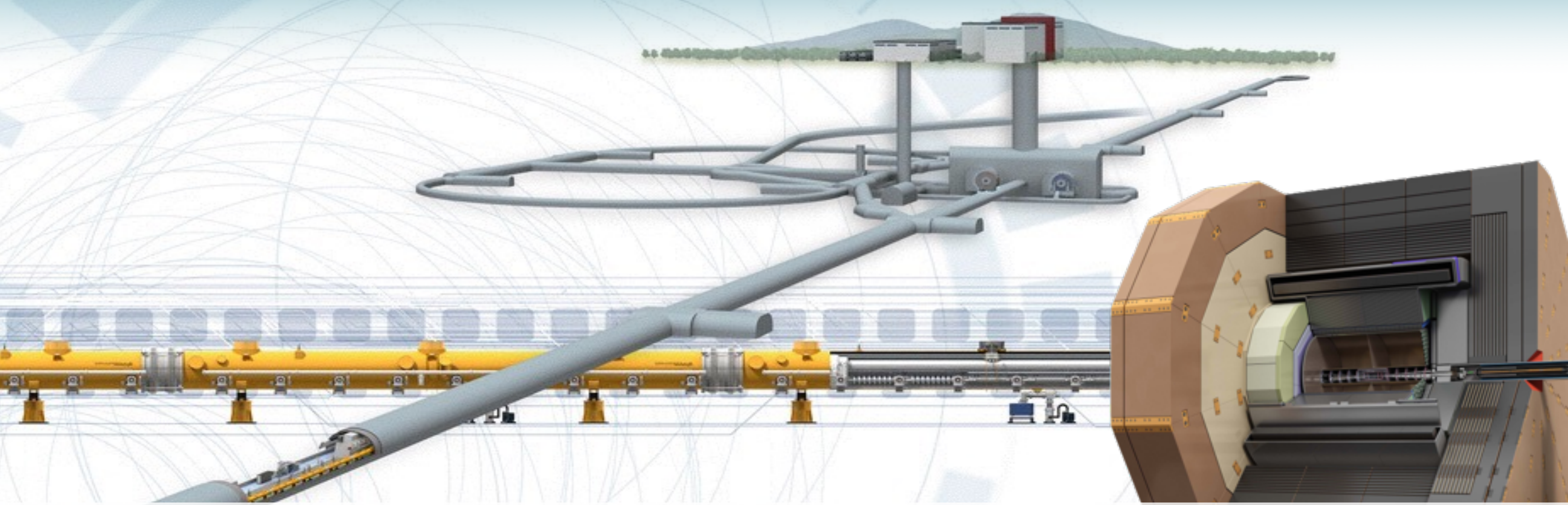
The Higgs boson is the tool to new physics.
The new physics might appear
in the Lorentz structure of the VVH couplings.

The anomalous ZZH couplings has been studied
and the sensitivity are given under the framework
of the Effective Field Theory.

The study of the anomalous WWH couplings is ongoing,
preliminary results indicate that sensitivity to b
using shape information in $H \rightarrow WW$ channels would be very useful.

Evaluation of the combined sensitivity
for anomalous HZZ and HWW couplings are ongoing,
the connection (η_Z and η_W, ζ_Z and ζ_W) under discussion.

the EFT talk:
Tim Barklow et al.
https://agenda.linearcollider.org/event/7371/contributions/37884/



Thank you for listening

ogawat@post.kek.jp

ZH → ννH (H→WW → qqqq) @ 250GeV with 250^{fb-1}

Cross section of the ZH → ννH (H→WW)
~ 16.7

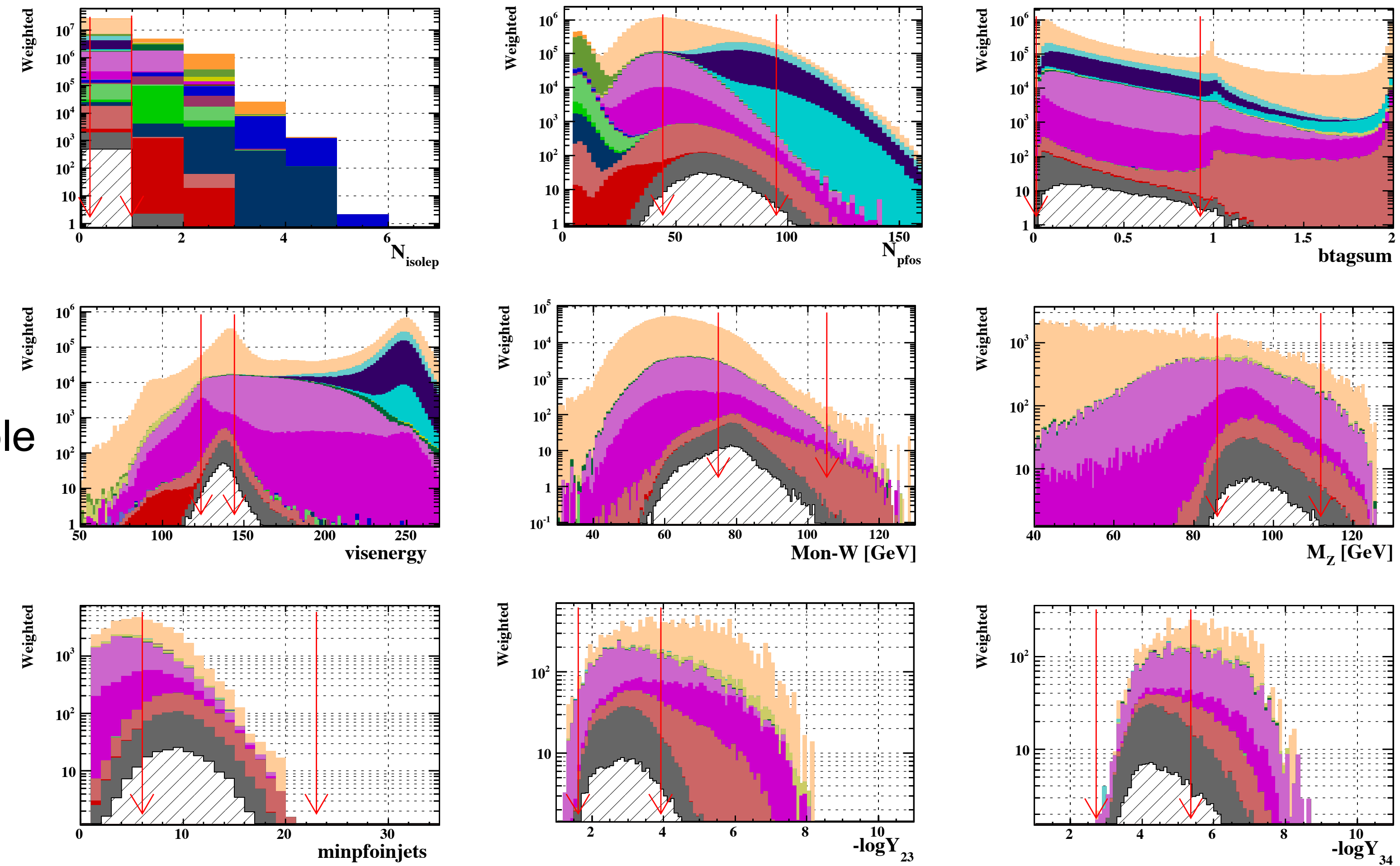
H → WW → qqqq ~ 7.6 *L ~ 1916 events
(H → WW → cxcx ~ 1.9 *L ~ 479 events)

Using several observable except angular observable
Bkgs are suppressed. (scanned to get S_{sig})

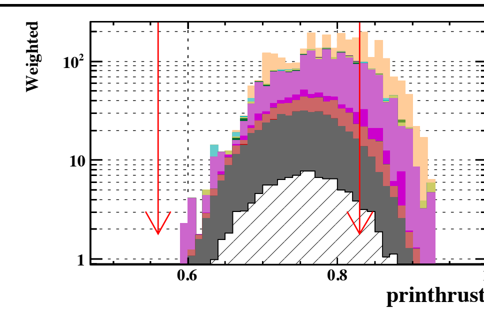
selection ~ 20%

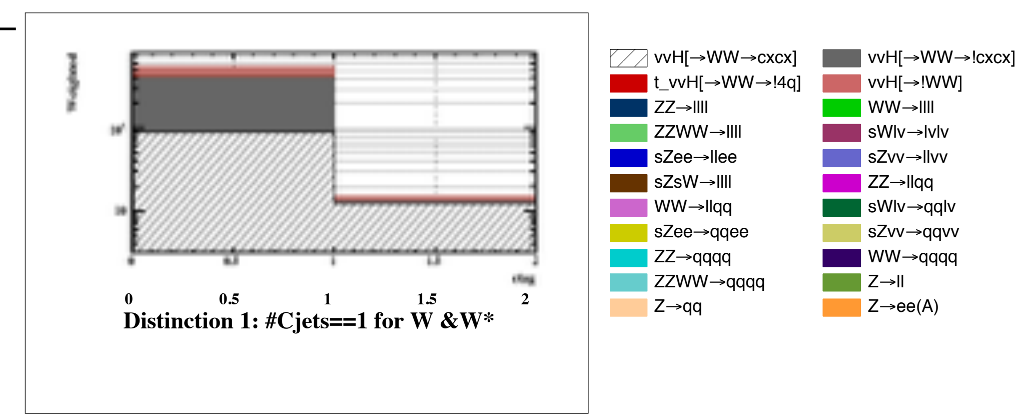
Before c-tag distinction ~ 430

Categorization



After c-tag distinction
H → WW → qqqq * L *ε ~ 420
H → WW → cxcx * L *ε ~ 12



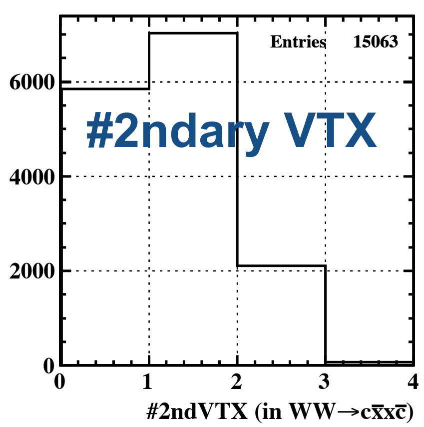


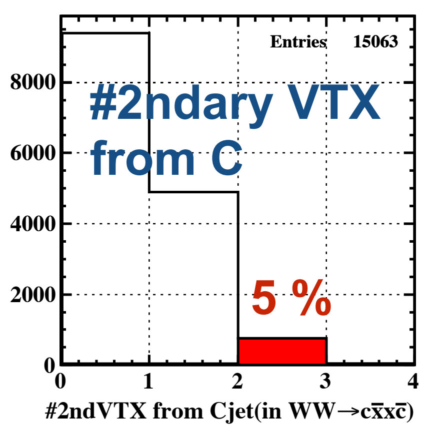

```
Nsig   = 12.27       Nsig   = 418.11
Nbkg   = 45.53       Nbkg   = 1663.87
Signif= 1.61         Signif= 9.16
```

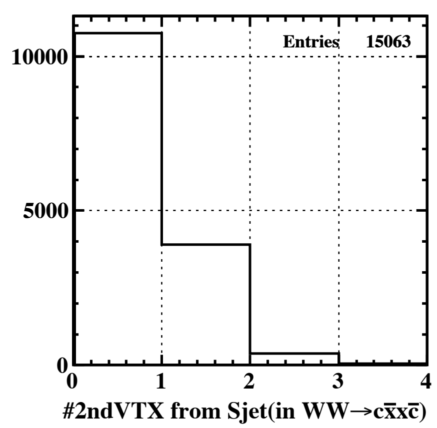
ZH → ννH (H→WW → qqqq) @ 250GeV with 250^{fb-1}

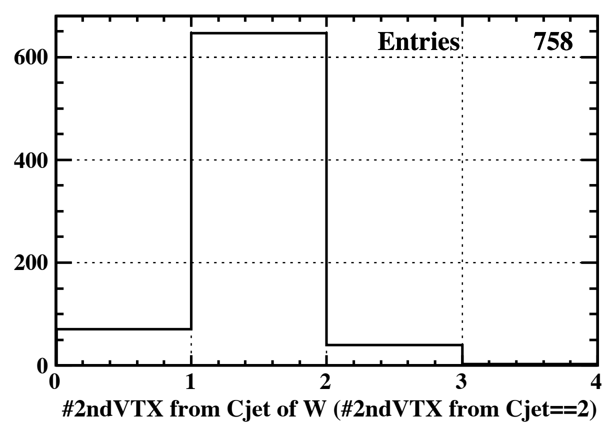
A crucial thing is c-tag:

Check the performance after
extracting only **WW→cxcx** decay events

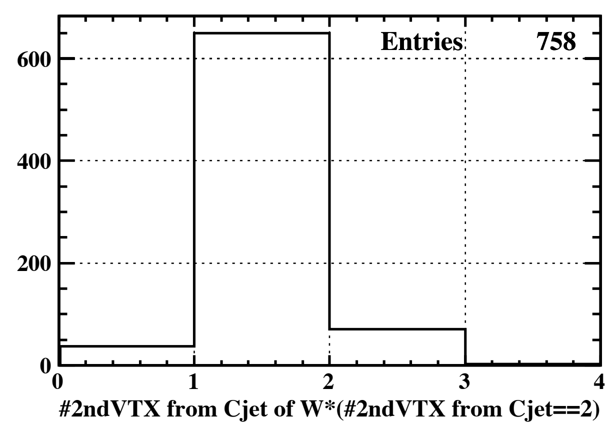








#2ndary VTX
from C of W
in the case #2ndary VTX==1

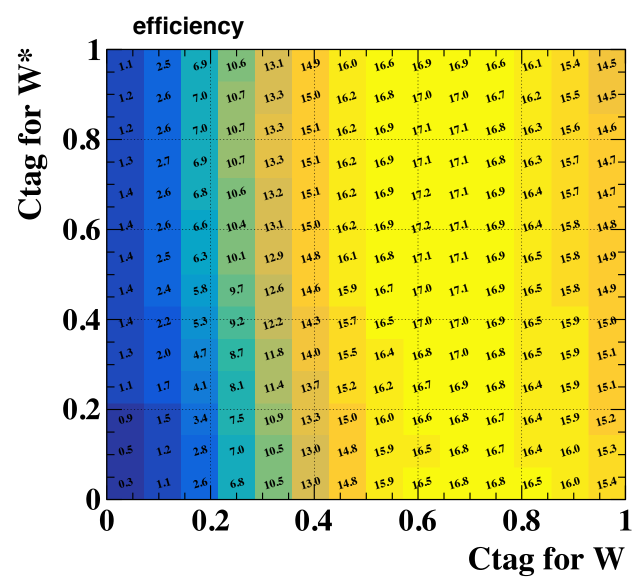


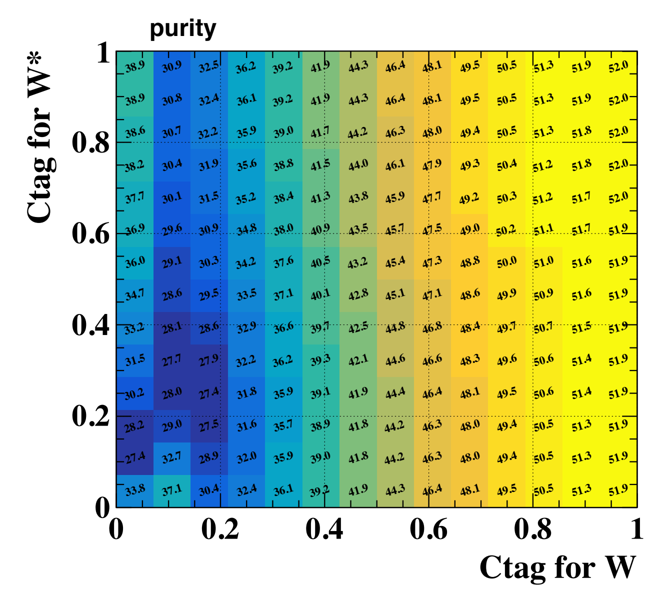
#2ndary VTX
from C of W*
in the case #2ndary VTX==1

Decision of c-tag requirement

$$\text{Efficiency} = \frac{N^{acpt} \cap MC_{c\bar{x}x\bar{c}}}{MC_{c\bar{x}x\bar{c}}}$$

$$\text{Purity} = \frac{N^{acpt} \cap MC_{c\bar{x}x\bar{c}}}{N^{acpt}}$$





c-tag requirement > 0.75

ZH → ννH (H→WW → qqqq) @ 250GeV with 250^{fb-1}

(4jets→cxcx) categorized

----- Cut Table Summary

cut&process	vvh_cc	vvh_!cc	vvh_!4q	vvH_!ww	ZZ_l	WW_l	ZZWW_l	sW_l	sZee_l	sZvv_l	sZsW_l	ZZ_sl	WW_sl	sW_sl	sZee_sl	Zvv_sl	ZZ_h	WW_h	ZZWW_h	Z_l	Z_h	Z_ee(A)
raw data	30002	90818	138360	151710	69994	409167	430167	865553	1035718	79997	254981	528110	1949032	1987519	319496	142858	500963	1106844	1128752	3772010	2963225	1995739
used data	30002	90818	138360	151710	69994	409167	430167	865553	1035718	79997	254981	528110	1949032	1987519	319496	142858	500963	1106844	1128752	3772010	2963225	1995739
passed data	769	45	1	24	0	0	0	0	0	0	0	2	18	0	0	3	0	0	1	0	2	0
passed/used	2.563	0.050	0.001	0.016	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000
xsection	1.91	5.75	9.09	60.79	95.89	915.58	958.97	1966.97	1053.45	114.14	550.67	856.93	10992.92	5898.17	378.28	271.81	841.38	8706.23	7252.10	12993.87	78046.47	25183.36
xsection*L	479	1437	2271	15196	23972	228894	239742	491743	263361	28534	137667	214232	2748229	1474542	94570	67951	210344	2176557	1813025	3248467	19511617	6295840
sucsess:	479	1437	1975	14831	12877	99095	102531	142360	156545	9743	20912	214172	2748228	1474541	94523	67928	210344	2176557	1813025	1531414	19511038	2788141
+nisoleptons	478	1435	746	14670	6529	5851	79662	13503	28566	8132	698	156216	1300981	110697	7124	67830	209881	2172234	1809374	1131566	19345317	404624
+allpfos	451	1334	179	11101	8	5	59	4	16	11	1	81679	637950	52373	1411	29811	151652	1786617	1484567	965	10940366	230
+j2btagsum	419	1310	173	2402	4	4	36	3	15	9	1	57287	596762	50561	1082	20911	92330	1695989	1375359	642	8247013	192
+visenergy	345	1071	18	1854	0	0	8	1	0	1	0	17787	135162	6368	9	8135	85	41	90	63	2071156	3
+onwmass	215	698	8	1238	0	0	5	0	0	0	0	5148	29588	752	4	2473	46	24	50	31	267854	0
+missmass	189	614	6	1045	0	0	3	0	0	0	0	2756	10825	228	3	1561	16	10	29	18	17219	0
+minpfoinjets	165	528	2	905	0	0	1	0	0	0	0	1323	3517	79	0	752	14	6	24	10	9192	0
+logy23	144	464	2	396	0	0	1	0	0	0	0	307	2421	50	0	169	10	6	21	5	2719	0
+logy34	111	366	1	182	0	0	0	0	0	0	0	93	1094	22	0	47	6	6	18	2	988	0
+printhrust	100	331	1	152	0	0	0	0	0	0	0	67	818	20	0	37	4	6	11	0	593	0
+ctagdummy	12	1	0	2	0	0	0	0	0	0	0	1	25	0	0	1	0	0	2	0	13	0
+hmass	12	1	0	2	0	0	0	0	0	0	0	1	25	0	0	1	0	0	2	0	13	0

Nsig = 12.27
Nbkg = 45.53
Signif= 1.61

(4jets→qqqq) categorized

----- Cut Table Summary

cut&process	vvh_cc	vvh_!cc	vvh_!4q	vvH_!ww	ZZ_l	WW_l	ZZWW_l	sW_l	sZee_l	sZvv_l	sZsW_l	ZZ_sl	WW_sl	sW_sl	sZee_sl	Zvv_sl	ZZ_h	WW_h	ZZWW_h	Z_l	Z_h	Z_ee(A)
raw data	30002	90818	138360	151710	69994	409167	430167	865553	1035718	79997	254981	528110	1949032	1987519	319496	142858	500963	1106844	1128752	3772010	2963225	1995739
used data	30002	90818	138360	151710	69994	409167	430167	865553	1035718	79997	254981	528110	1949032	1987519	319496	142858	500963	1106844	1128752	3772010	2963225	1995739
passed data	5505	20876	58	1498	0	0	0	0	0	0	0	162	562	27	1	74	10	3	6	0	88	0
passed/used	18.349	22.987	0.042	0.987	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.031	0.029	0.001	0.000	0.052	0.002	0.000	0.001	0.000	0.003	0.000
xsection	1.91	5.75	9.09	60.79	95.89	915.58	958.97	1966.97	1053.45	114.14	550.67	856.93	10992.92	5898.17	378.28	271.81	841.38	8706.23	7252.10	12993.87	78046.47	25183.36
xsection*L	479	1437	2271	15196	23972	228894	239742	491743	263361	28534	137667	214232	2748229	1474542	94570	67951	210344	2176557	1813025	3248467	19511617	6295840
sucsess:	479	1437	1975	14831	12877	99095	102531	142360	156545	9743	20912	214172	2748228	1474541	94523	67928	210344	2176557	1813025	1531414	19511038	2788141
+nisoleptons	478	1435	746	14670	6529	5851	79662	13503	28566	8132	698	156216	1300981	110697	7124	67830	209881	2172234	1809374	1131566	19345317	404624
+allpfos	451	1334	179	11101	8	5	59	4	16	11	1	81679	637950	52373	1411	29811	151652	1786617	1484567	965	10940366	230
+j2btagsum	419	1310	173	2402	4	4	36	3	15	9	1	57287	596762	50561	1082	20911	92330	1695989	1375359	642	8247013	192
+visenergy	345	1071	18	1854	0	0	8	1	0	1	0	17787	135162	6368	9	8135	85	41	90	63	2071156	3
+onwmass	215	698	8	1238	0	0	5	0	0	0	0	5148	29588	752	4	2473	46	24	50	31	267854	0
+missmass	189	614	6	1045	0	0	3	0	0	0	0	2756	10825	228	3	1561	16	10	29	18	17219	0
+minpfoinjets	165	528	2	905	0	0	1	0	0	0	0	1323	3517	79	0	752	14	6	24	10	9192	0
+logy23	144	464	2	396	0	0	1	0	0	0	0	307	2421	50	0	169	10	6	21	5	2719	0
+logy34	111	366	1	182	0	0	0	0	0	0	0	93	1094	22	0	47	6	6	18	2	988	0
+printhrust	100	331	1	152	0	0	0	0	0	0	0	67	818	20	0	37	4	6	11	0	593	0
+ctagdummy	88	330	1	150	0	0	0	0	0	0	0	66	792	20	0	35	4	6	10	0	579	0
+hmass	88	330	1	150	0	0	0	0	0	0	0	66	792	20	0	35	4	6	10	0	579	0

Nsig = 418.11
Nbkg = 1663.87
Signif= 9.16

Difference of the signature b/w Higgs production & decay

$Z^\mu = \epsilon^\mu$ — Boson wave function, polarization four-vector ε^μ

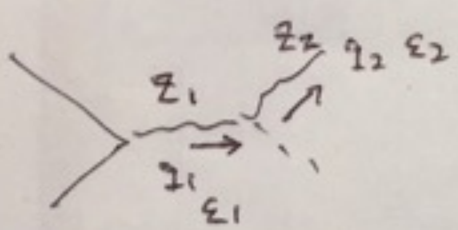
$Z^{\mu\nu} = \partial^\mu \varepsilon^\nu - \partial^\nu \varepsilon^\mu$

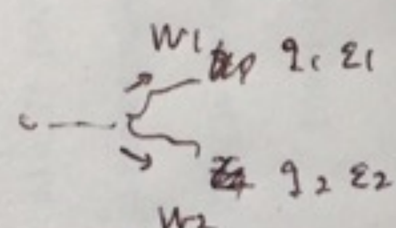
$= [\partial^\mu = -i(i\partial^\mu)] = -i(q^\mu\varepsilon^\nu - q^\nu\varepsilon^\mu)$

$\mathcal{M}_a$: $Z_{1\mu} Z_2^\mu = \varepsilon_{1\mu}^{*} \varepsilon_2^\mu$

$\mathcal{M}_b$: $Z_{1\mu\nu} Z_2^{\mu\nu} = (-i)^2[(q_{1\mu}\varepsilon_{1\nu} - q_{1\nu}\varepsilon_{1\mu})(q_2^\mu\varepsilon_2^\nu - q_2^\nu\varepsilon_2^\mu)]$

$= -2[(q_1 q_2)(\varepsilon_1 \varepsilon_2) - (q_1\varepsilon_2)(q_2\varepsilon_1)]$





$q_1 = (-\sqrt{s}, 0)$ — Lorentz terms

$q_1 \varepsilon_1 = 0$

$-\sqrt{s}\,\varepsilon_1^0 = 0$

$\varepsilon_1^0 = 0$

$\varepsilon_1 = (0, \boldsymbol{\varepsilon}_1)$

$q_2 = (E_2, \mathbf{q}_2) \to$ [out going $-q_2$]

$\varepsilon_2 = (\varepsilon_2^0, \boldsymbol{\varepsilon}_2)$

↳ transverse (z direction)

$\varepsilon_2 = (0, \boldsymbol{\varepsilon}_2)$

$\mathcal{M}_a = -\boldsymbol{\varepsilon}_1 \cdot \boldsymbol{\varepsilon}_2$

$\mathcal{M}_b = -2[-E_2\sqrt{s}\,(-\boldsymbol{\varepsilon}_1 \cdot \boldsymbol{\varepsilon}_2)]$

$= -2[E_2\sqrt{s}\,\boldsymbol{\varepsilon}_1 \cdot \boldsymbol{\varepsilon}_2]$

} same sign

$q_1^2 = m_W^2$

$q_1 = (E_1, \mathbf{q})$

Lorentz terms.

$\varepsilon_1 \cdot \mathbf{q} = 0$.

$\to \varepsilon_1 = (0, \boldsymbol{\varepsilon}_1)$

$q_2 = (m_h - E_1, -\mathbf{q})$

$\varepsilon_2 = (0, \boldsymbol{\varepsilon}_2)$

opposite sign:

$\mathcal{M}_a = -\boldsymbol{\varepsilon}_1 \cdot \boldsymbol{\varepsilon}_2$

$\mathcal{M}_b = -2\left[\left[\frac{1}{2} m_h^2 - m_W^2 - \mathbf{q}_2^2\right](-\boldsymbol{\varepsilon}_1 \cdot \boldsymbol{\varepsilon}_2)\right]$

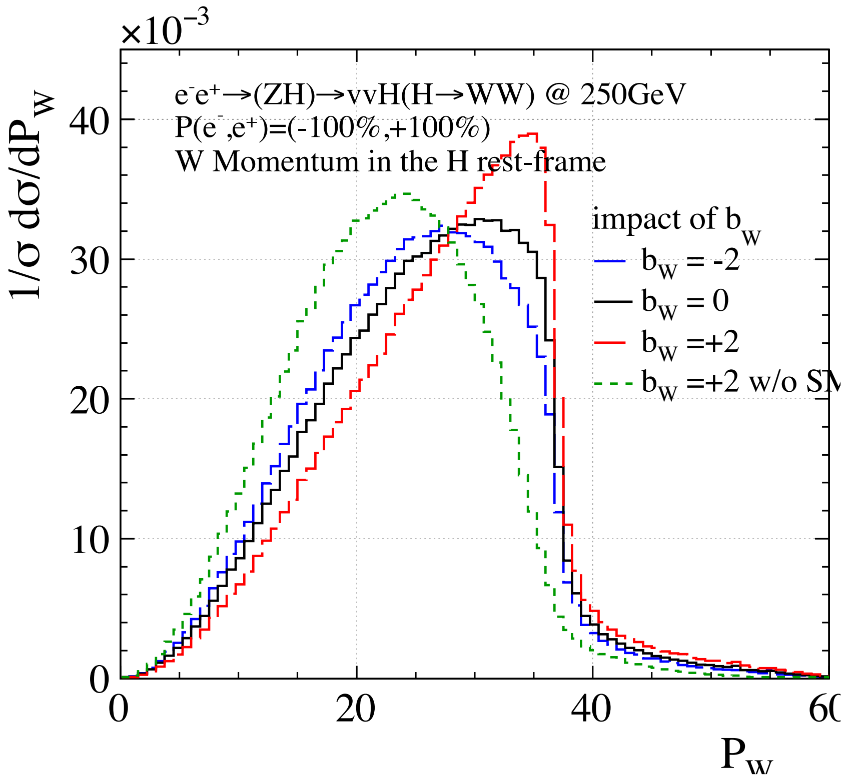
$= (m_h^2 - 2m_W^2 - 2\mathbf{q}_2^2)(\boldsymbol{\varepsilon}_1 \cdot \boldsymbol{\varepsilon}_2)$

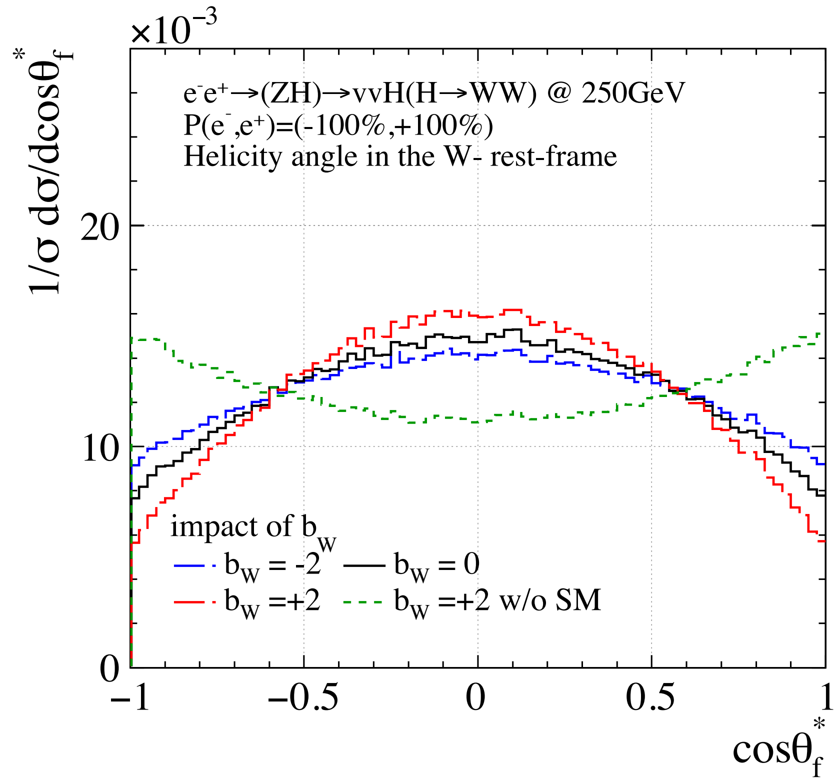
$q_1 q_2 = \frac{1}{2}(|q_1 + q_2|^2 - q_1^2 - q_2^2)$

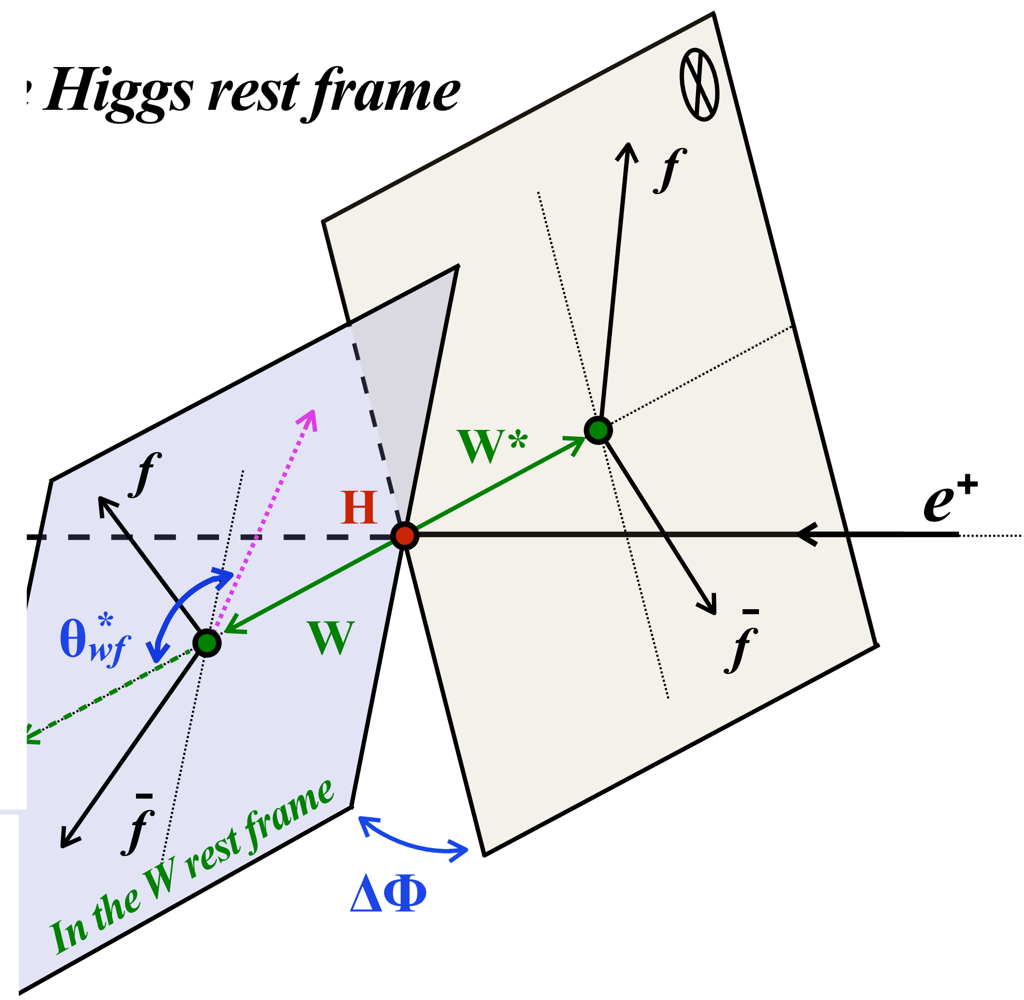
15625 − 12800

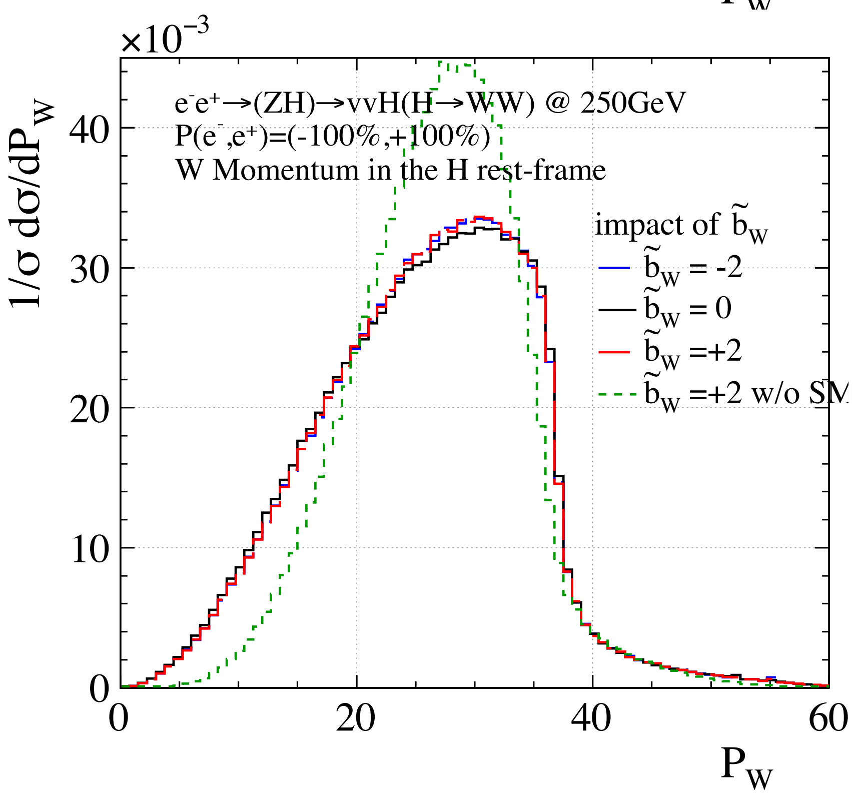
Verification of the Lorentz structures

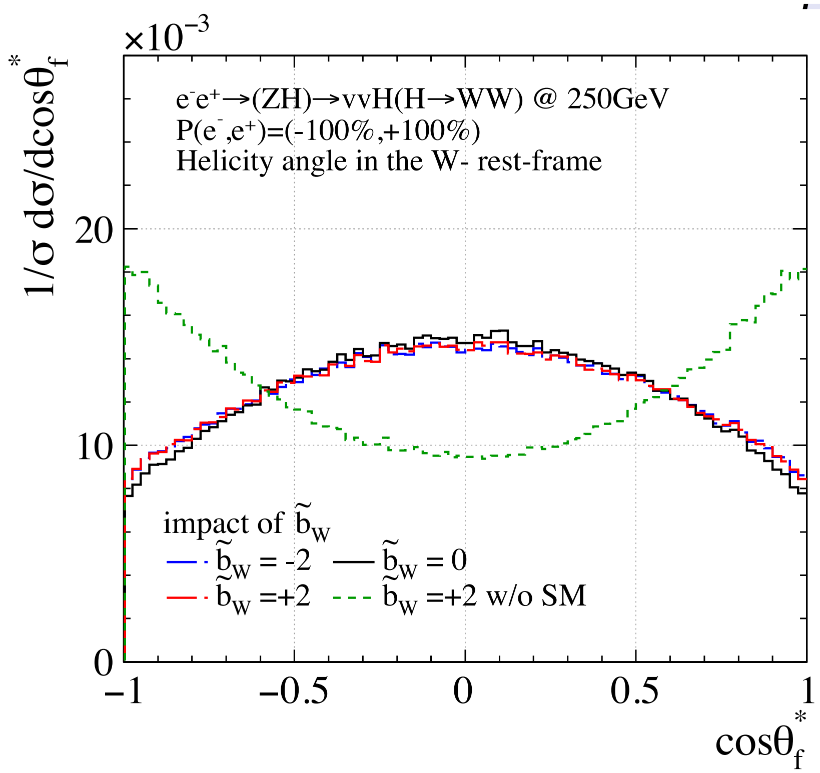
$$\mathcal{L}_{WWH} = 2M_W^2\left(\frac{1}{v}+\frac{a_W}{\Lambda}\right)W^+_\mu W^{-\mu}H + \frac{b_W}{\Lambda}\hat{W}^+_{\mu\nu}\hat{W}^{-\mu\nu}H + \frac{\tilde{b}_W}{\Lambda}\hat{W}^+_{\mu\nu}\widetilde{\hat{W}}^{-\mu\nu}H$$









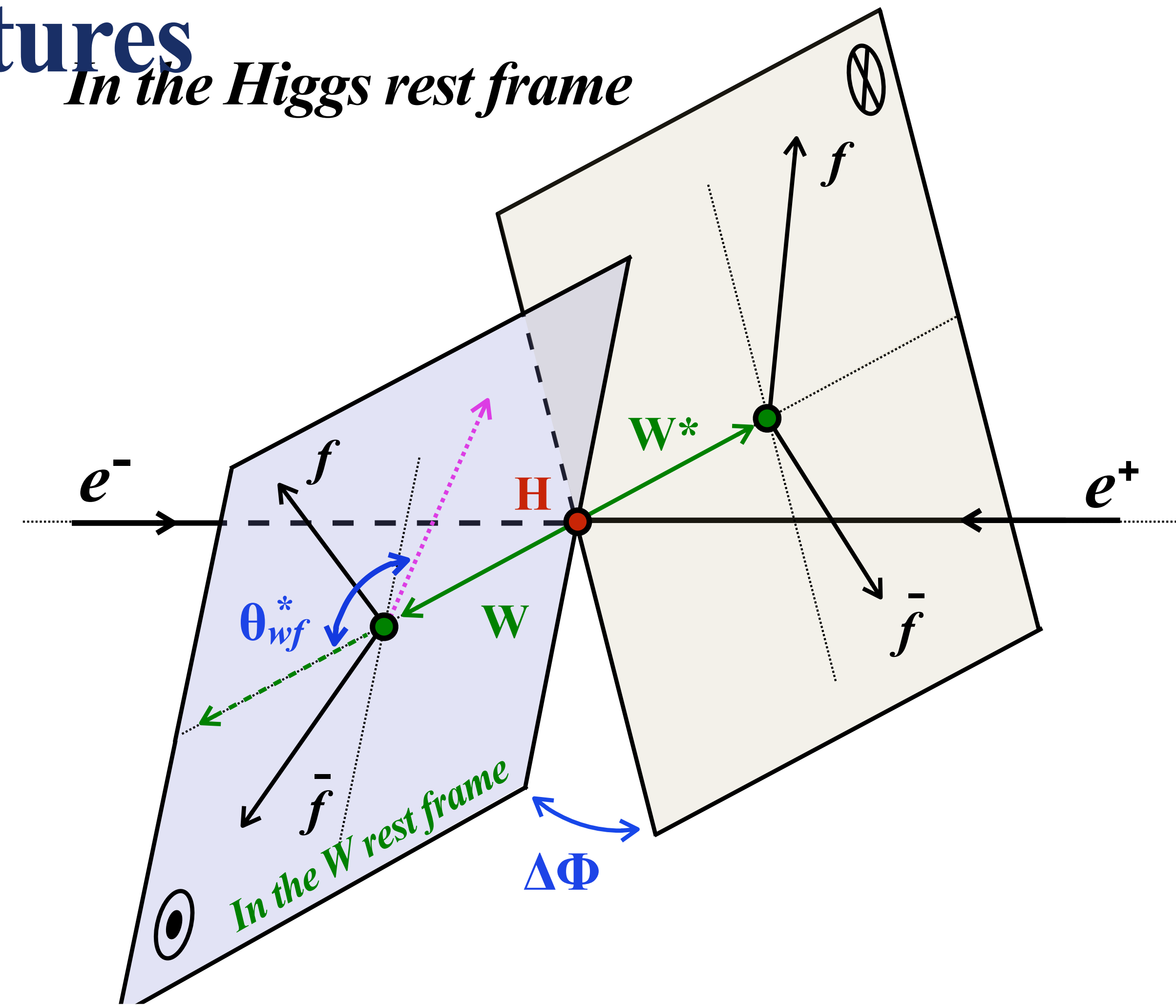


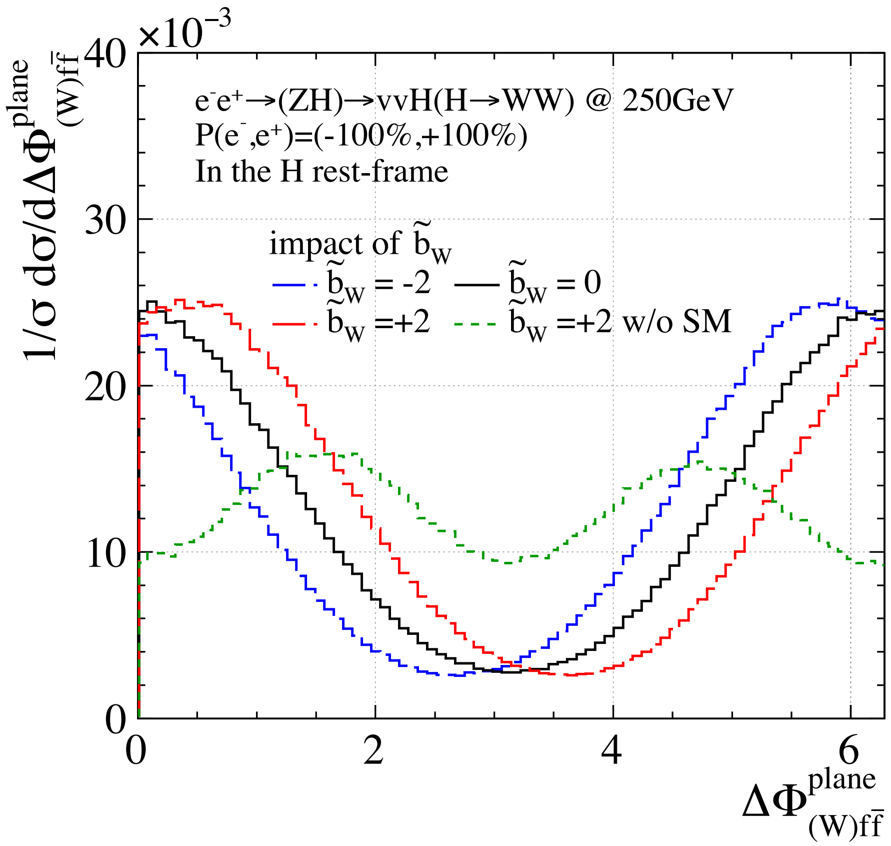
Verification of the Lorentz structures

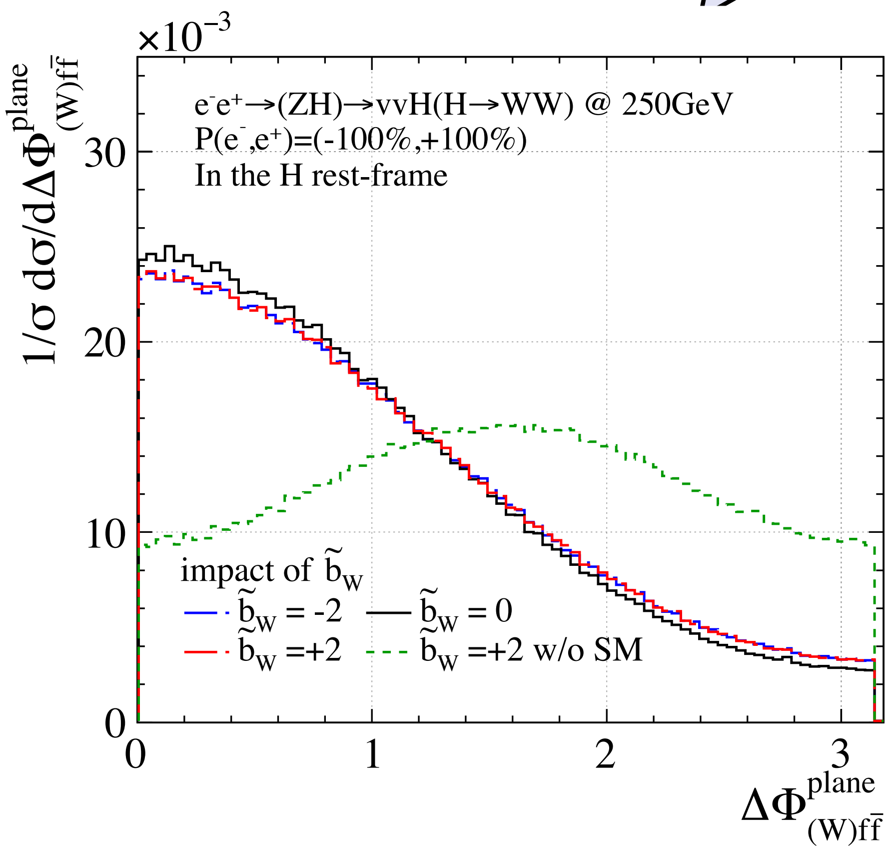
$$\mathcal{L}_{WWH} = 2M_W^2\left(\frac{1}{v}+\frac{a_W}{\Lambda}\right)W_\mu^+W^{-\mu}H + \frac{b_W}{\Lambda}$$

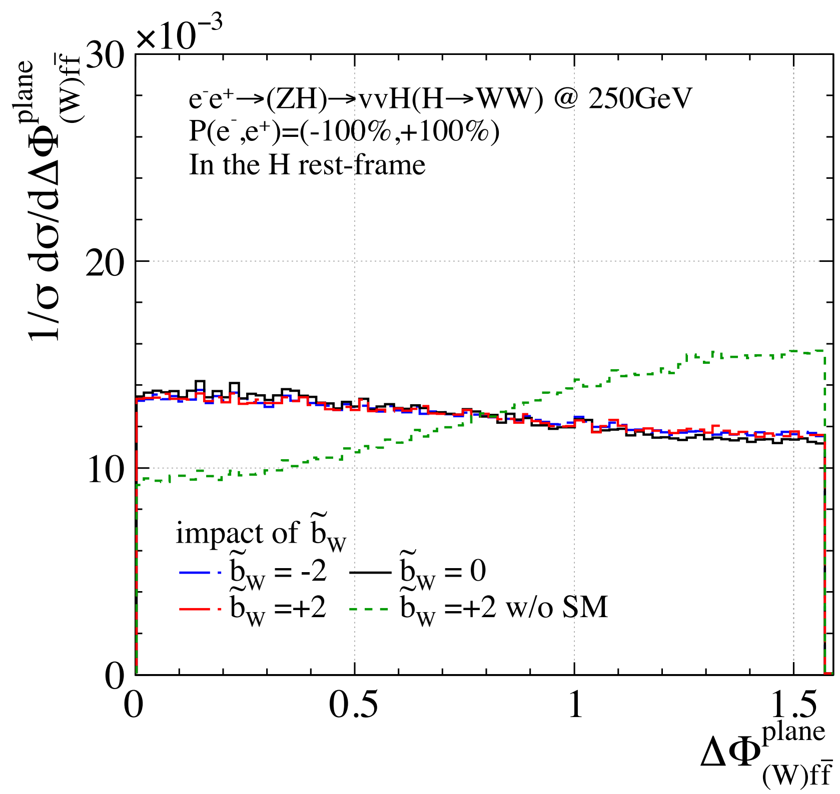
@250GeV $e^+e^- \rightarrow ZH \rightarrow ff + WW$

$WW \rightarrow jets$



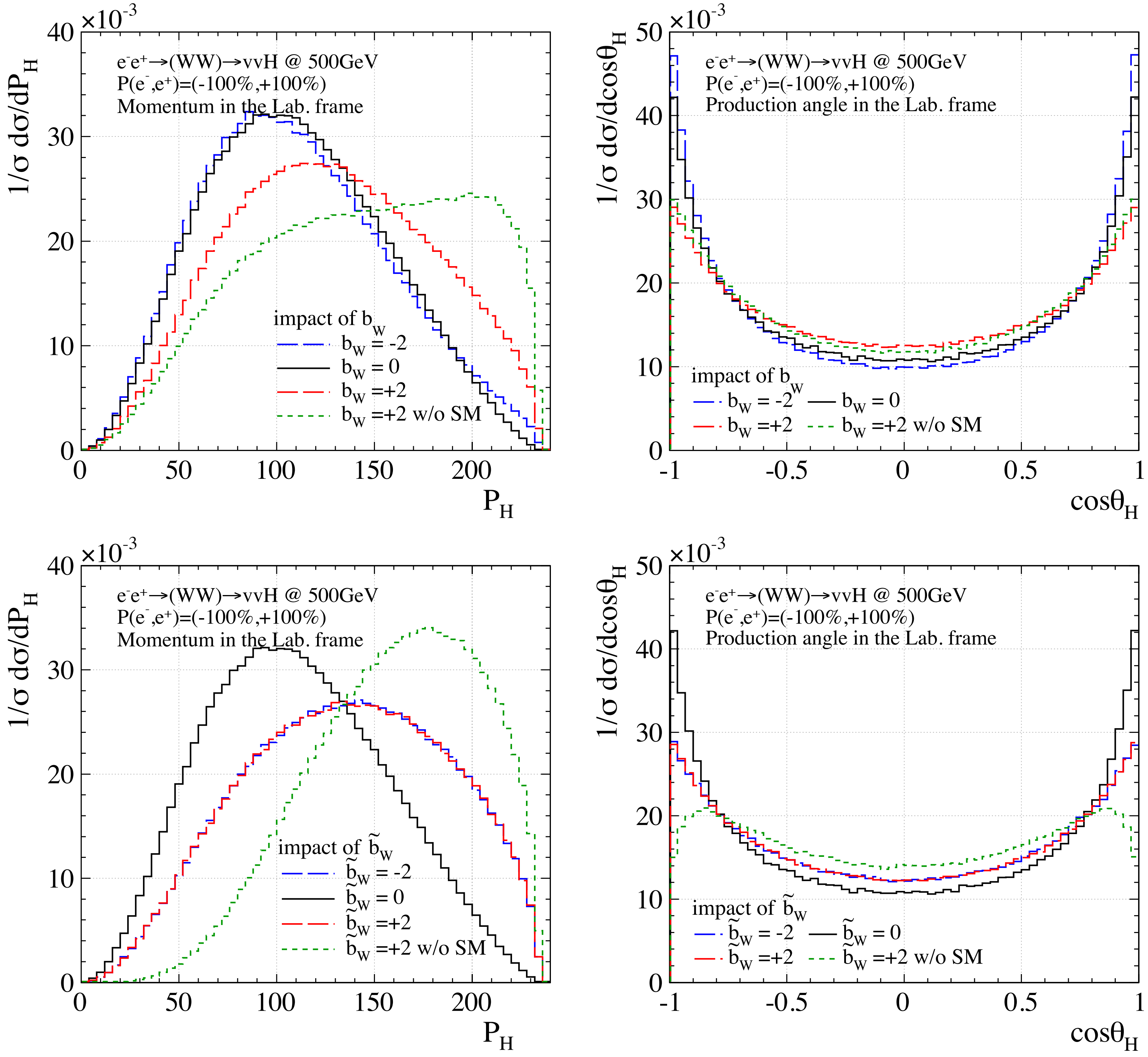


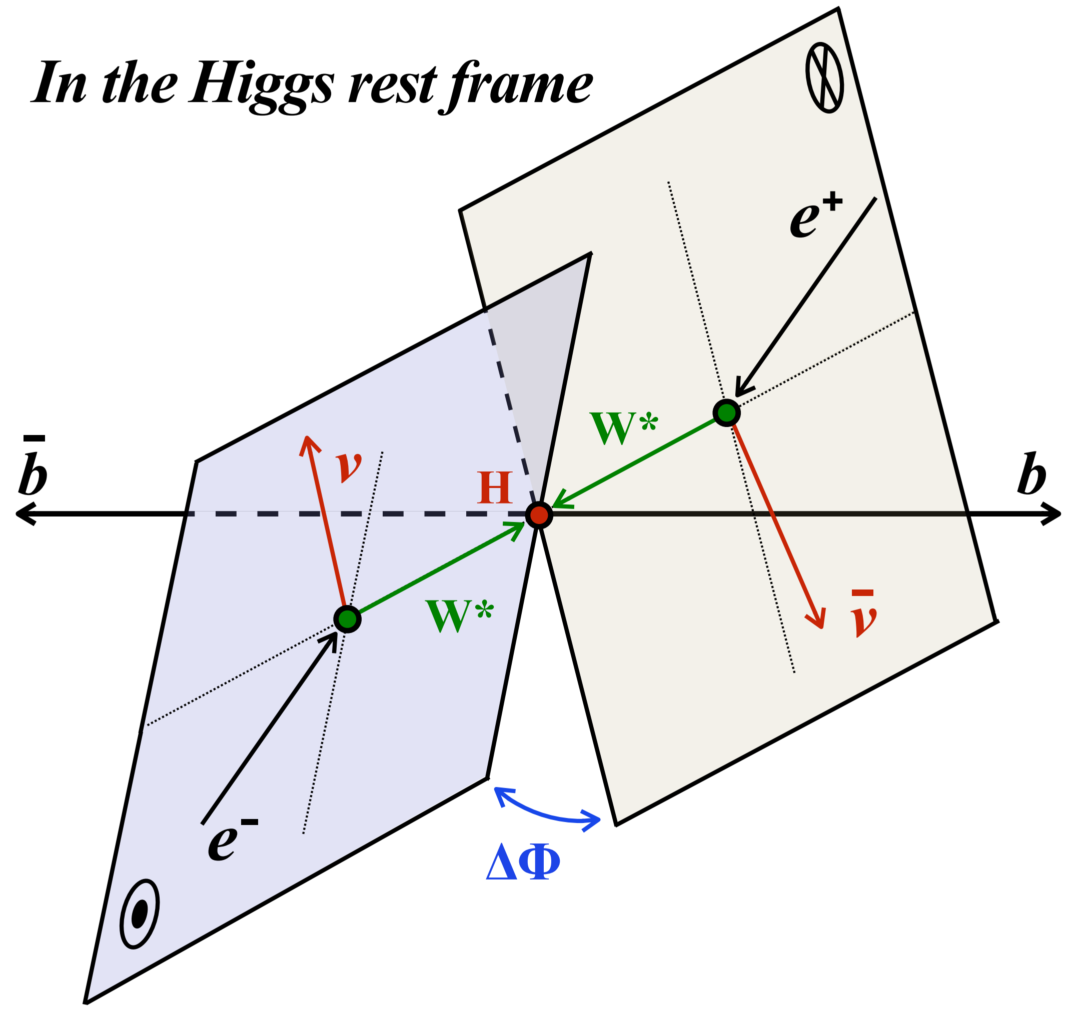




Verification of the Lorentz structures

@500GeV $e^+e^- \rightarrow$ WW-fusion $\rightarrow \nu\nu + H(\rightarrow WW)$
$\nu\nu + H(\rightarrow bb)$





Verification of the Lorentz structures

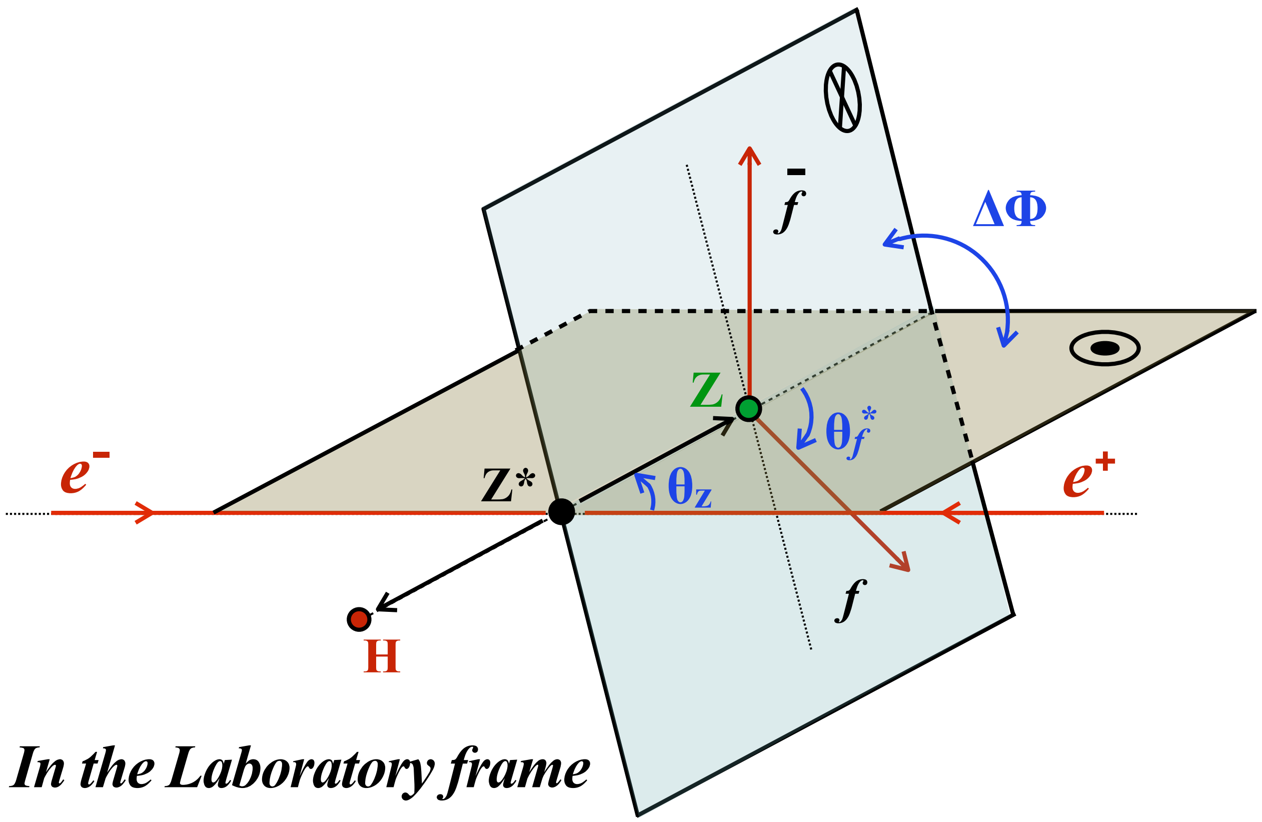
- "a_z" : a normalization parameter affecting the overall cross section. (rescales the SM-coupling)

$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{v} + \frac{a_Z}{\Lambda}\right) Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\tilde{\hat{Z}}^{\mu\nu}H$$

- "b_z" : a different CP-even tensor structure affecting **momentum and changes angular distribution.**

- "$\tilde{b}_z$" : a CP-violating parameter affecting **angular/spin correlations.**

$$e^+e^- \rightarrow ZH \rightarrow l^+l^-H$$



cosθz : a production angle of the Z.

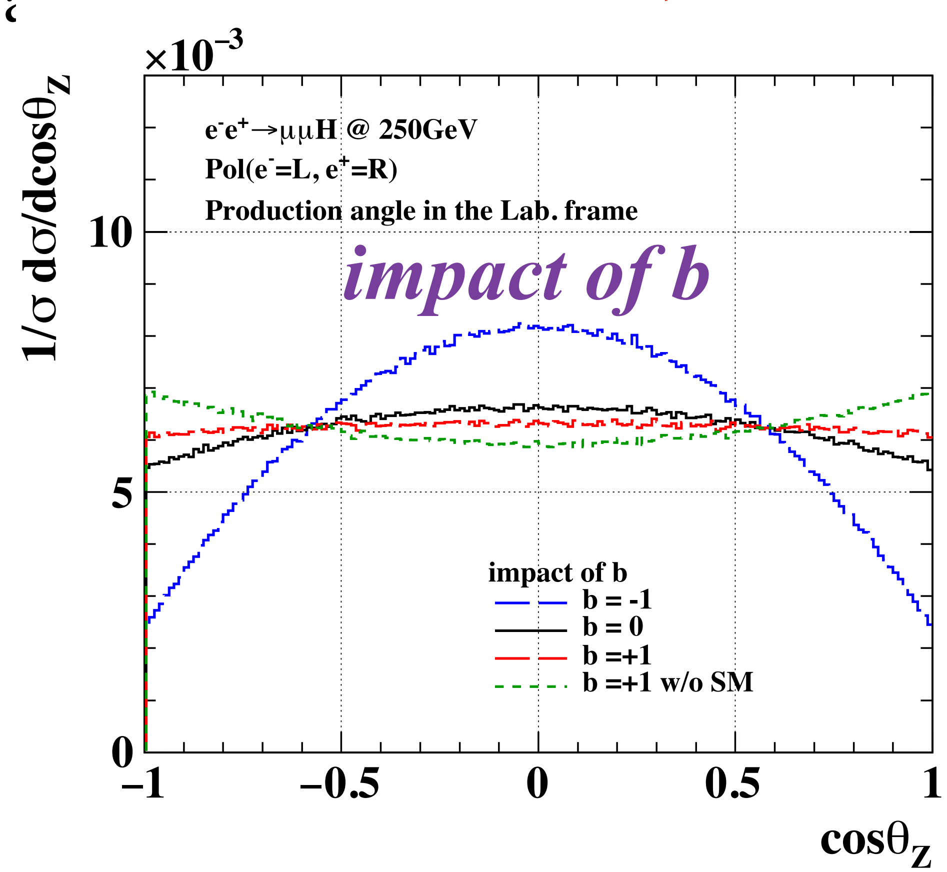
cosθf*: a helicity angle of a Z's daughter.

ΔΦ : an angle between two production plane.

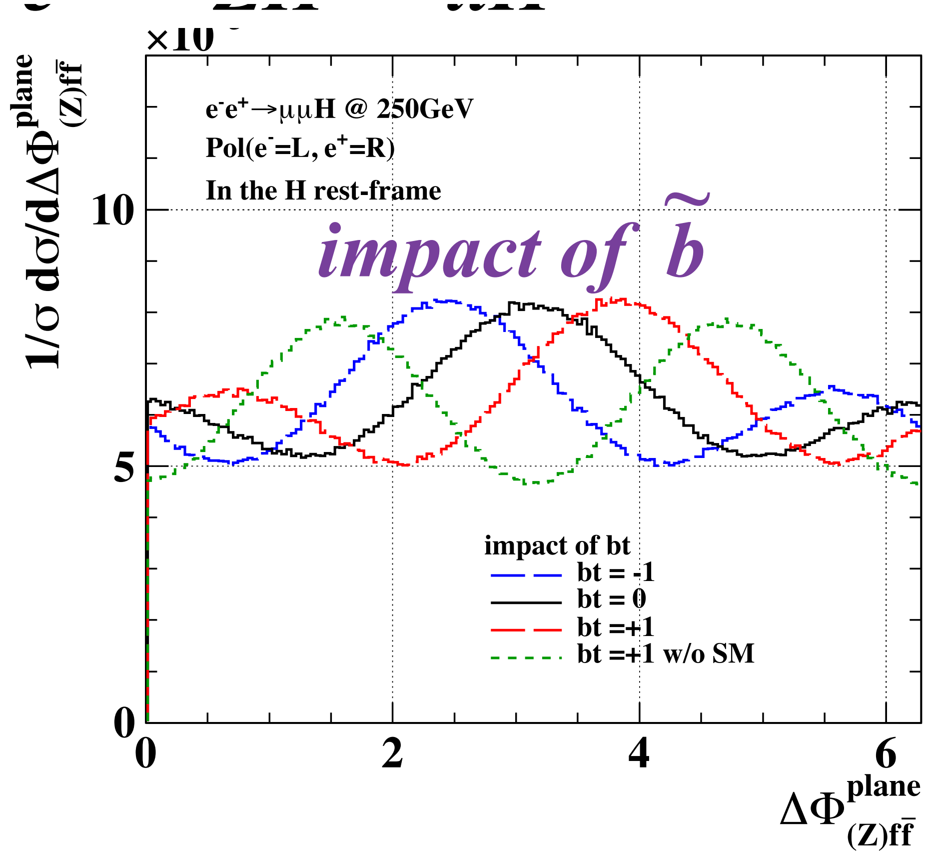
Verification of the Lorentz structures

$ZH \rightarrow l^+l^-H$, $\sqrt{s} = 250GeV$

- "a_Z" : a
  affecti
  (resca
- "b_Z" :
  affec
  chang
- "$\tilde{b}_Z$" :
  angu



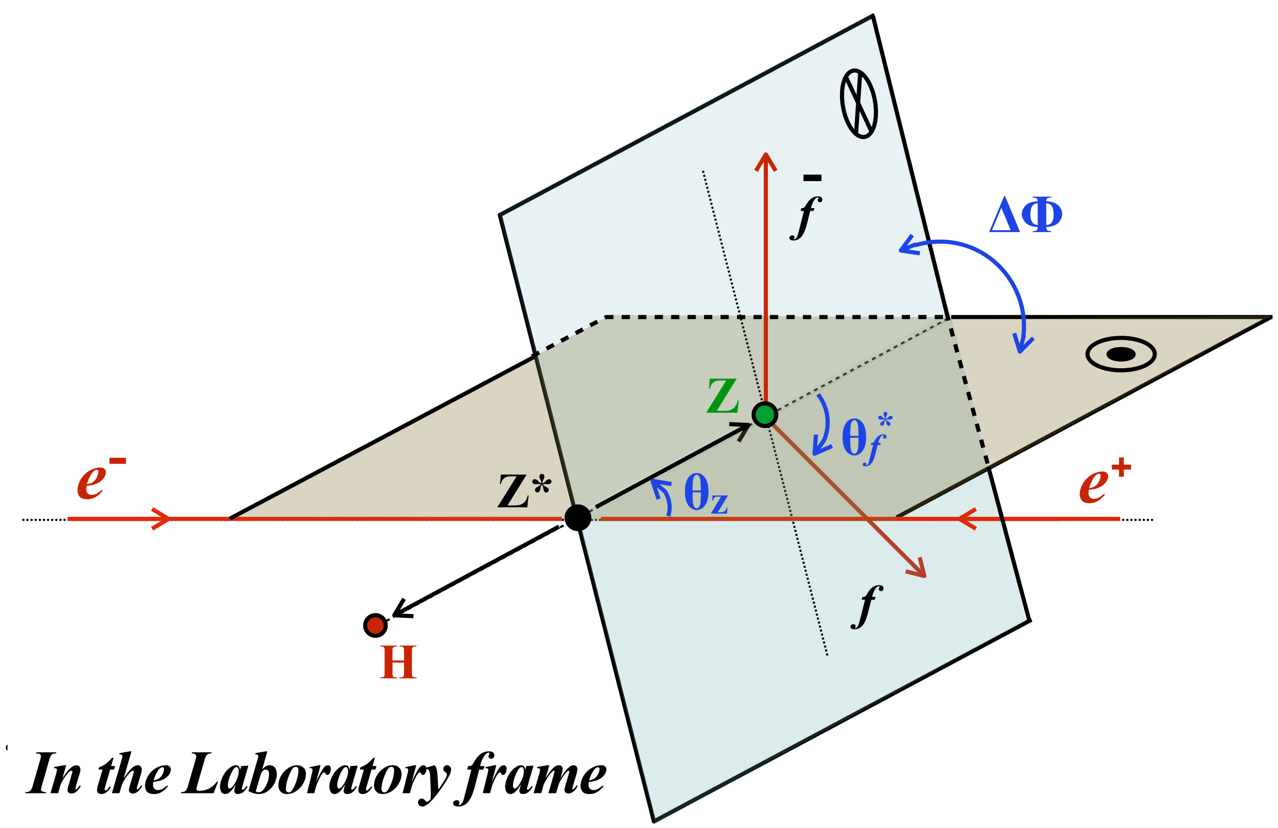
$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{v} + \frac{a_Z}{\Lambda}\right)Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\tilde{\hat{Z}}^{\mu\nu}H$$



$\cos\theta z$:

$\cos\theta f^*$:

$\Delta\Phi$: ... ane.

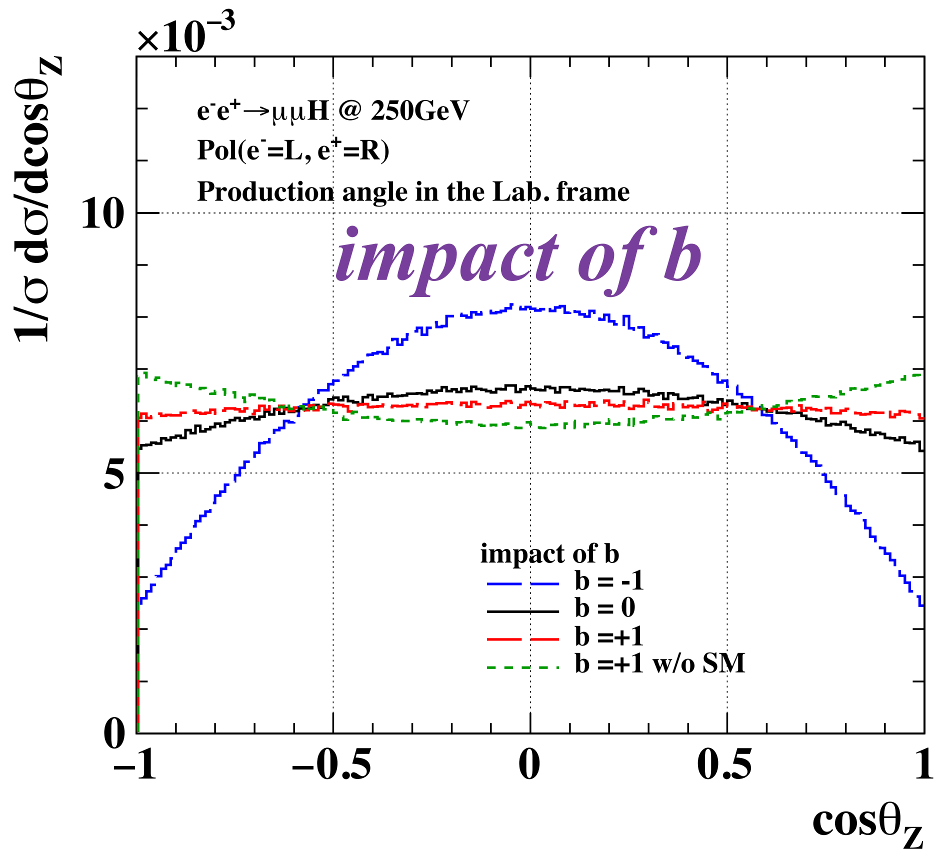


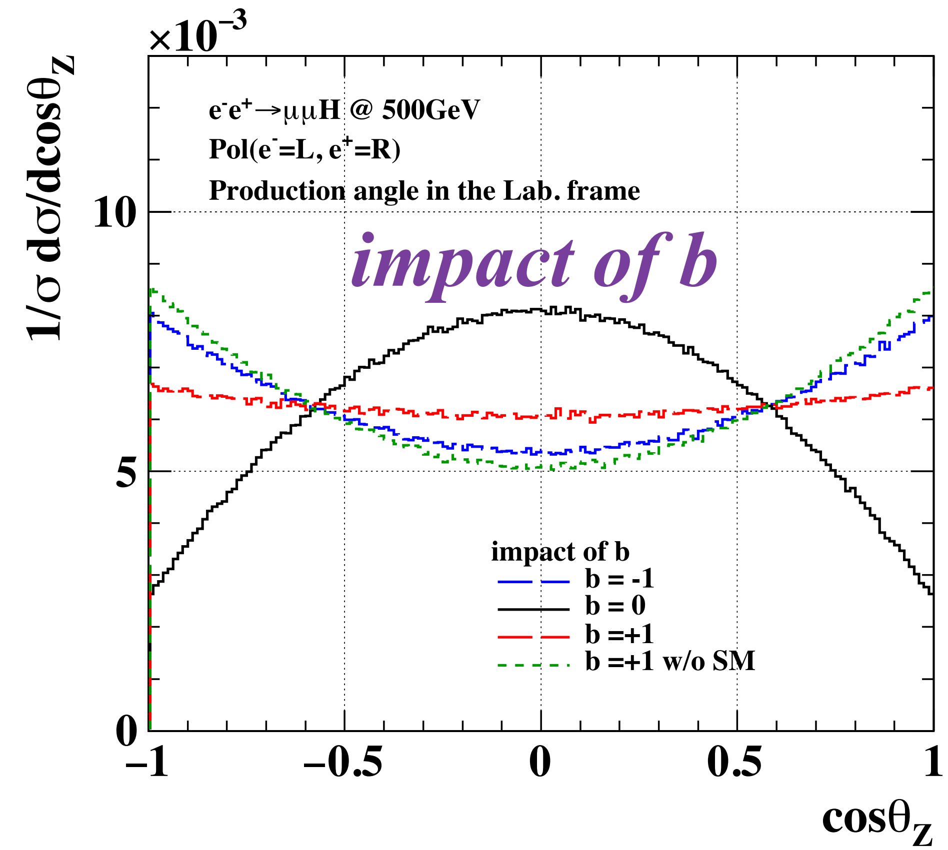
In the Laboratory frame

Verification of the Lorentz structures

$ZH \rightarrow l^+l^-H$, $\sqrt{s} = 250GeV$ $\sqrt{s} = 500GeV$

- "a_Z" :
  affect
  (resca
- "b_Z" :
  affec
  chan
- "$\tilde{b}_Z$" :
  angu



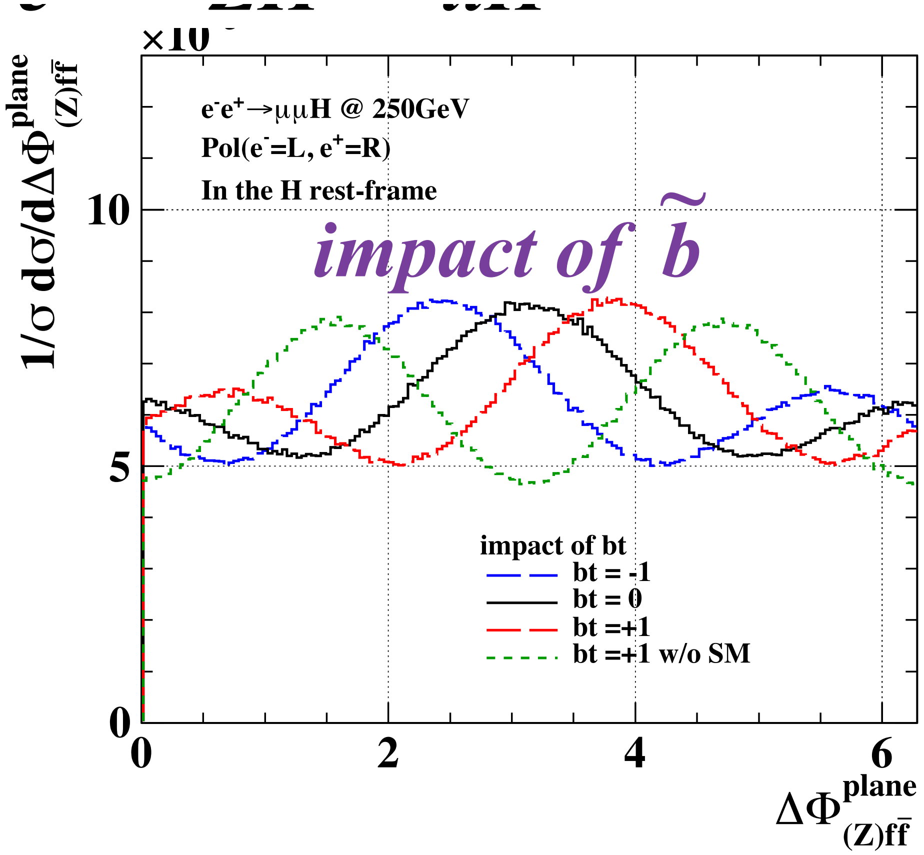


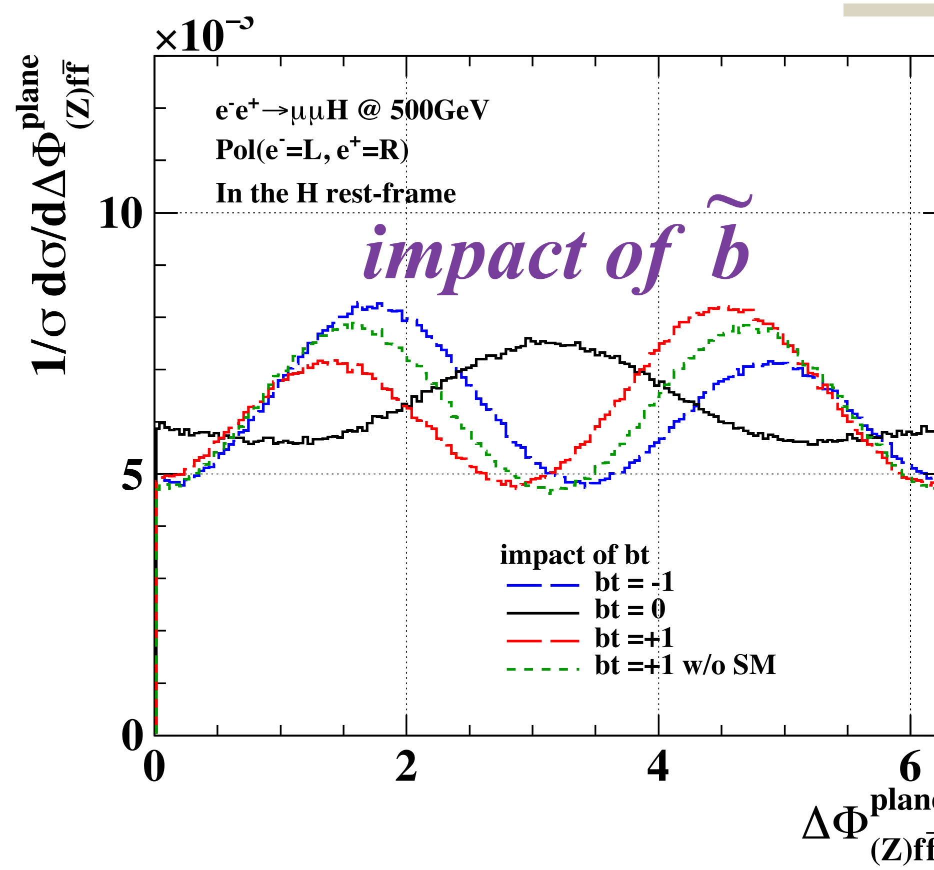
cosθz :

cosθf*:

ΔΦ :

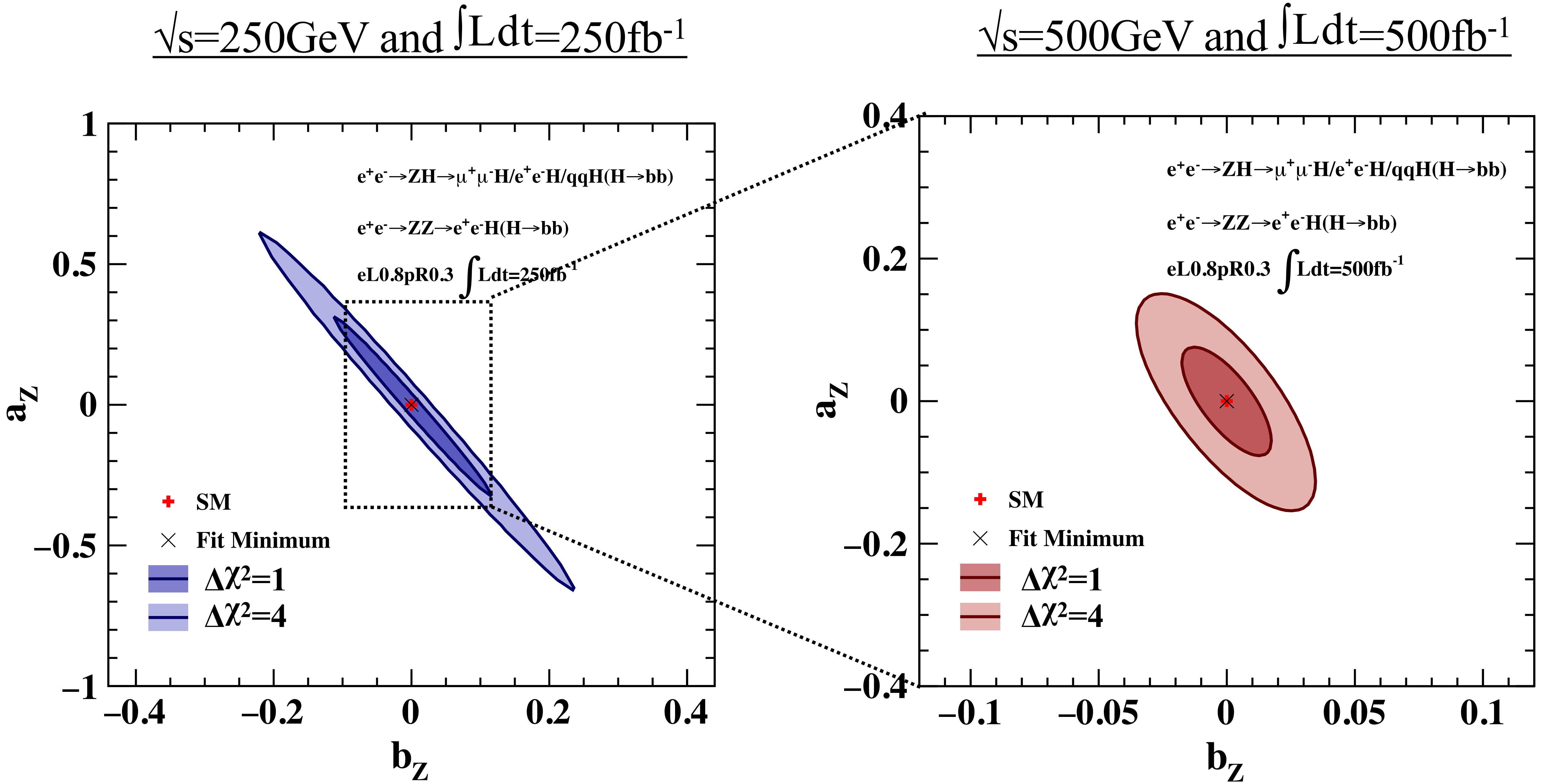
an





Sensitivity to ZZH couplings 250 GeV vs 500 GeV

Simultaneous fitting is performed
in three-parameter space.



The shape distributions quickly change at 500GeV
the correlation between "a_Z" and "b_Z" can be disentangled.

Sensitivity to ZZH couplings 250 GeV + 500 GeV

A realistic ILC full operation is assumed

T. Barklow and J. Brau et al., "ILC Operating Scenarios", arXiv:1506.07830 [hep-ex]

H20 scenario :

Total luminosities of 2000 f b^{-1} and 4000 f b^{-1} are planned to be accumulated at $\sqrt{s}$ =250 and 500 GeV, respectively.

New physics scale Λ is assumed to be 1 TeV.

A table showing sensitivity to ZZH at 250 + 500 GeV.

1σ bounds		a_Z	b_Z	$\tilde{b}_Z$
ZH				
with shape	total	-	±0.0080	±0.0070
ZH				
with shape+σ	total	±0.0307	±0.0074	±0.0070
ZH+ZZ-fusion				
with shape	total	-	±0.0079	±0.0067
ZH+ZZ-fusion				
with shape+σ	total	±0.0218	±0.0058	±0.0067

For the parameter "a" (SM-like couplings) **precision is a_Z few %.**

For new tensor structures **precision of less than 1% or better is possible to achieve.**

Precision on $\tilde{b}_Z$ **is decided by angular info.**

Sensitivities to the a, b and bt with only the *Higgsstrahlung*

Nominal energies and luminosities

√s=250GeV and ∫Ldt=250fb^{-1}

TABLE V. The sensitivity to the anomalous ZZH couplings at $\sqrt{s}$ =250 GeV assuming the benchmark integrated luminosity of 250 fb^{-1} with both beam polarizations. The values correspond to one sigma bounds. The words, with shape and $+\sigma$, in the table indicate that the only shape information is used for the evaluation, and the shape information together with the cross section information are used.

		a_Z	b_Z	$\tilde{b}_Z$
ZH	$e^-_L e^+_R$	-	±0.110	±0.051
with shape	$e^-_R e^+_L$	-	±0.129	±0.061
ZH	$e^-_L e^+_R$	±0.309	±0.109	±0.051
with shape+σ	$e^-_R e^+_L$	±0.356	±0.125	±0.061

correlation matrix (w/ shape+σ P(LR))

$$\rho = \begin{pmatrix} 1 & -0.9917 & 0.0064 \\ & 1 & -0.0051 \\ & & 1 \end{pmatrix}$$

√s=500GeV and ∫Ldt=500fb^{-1}

TABLE VI. The sensitivity to the anomalous ZZH couplings at $\sqrt{s}$ =500 GeV assuming the benchmark integrated luminosity of 500 fb^{-1} with both beam polarizations. The values correspond to one sigma bounds. The words in the table, with shape and $+\sigma$, indicate that the only shape information is used, and the shape information together with the cross section information are used for the evaluation of the sensitivity.

		a_Z	b_Z	$\tilde{b}_Z$
ZH	$e^-_L e^+_R$	-	±0.0199	±0.0183
with shape	$e^-_R e^+_L$	-	±0.0215	±0.0198
ZH	$e^-_L e^+_R$	±0.116	±0.0201	±0.0183
with shape+σ	$e^-_R e^+_L$	±0.130	±0.0217	±0.0198

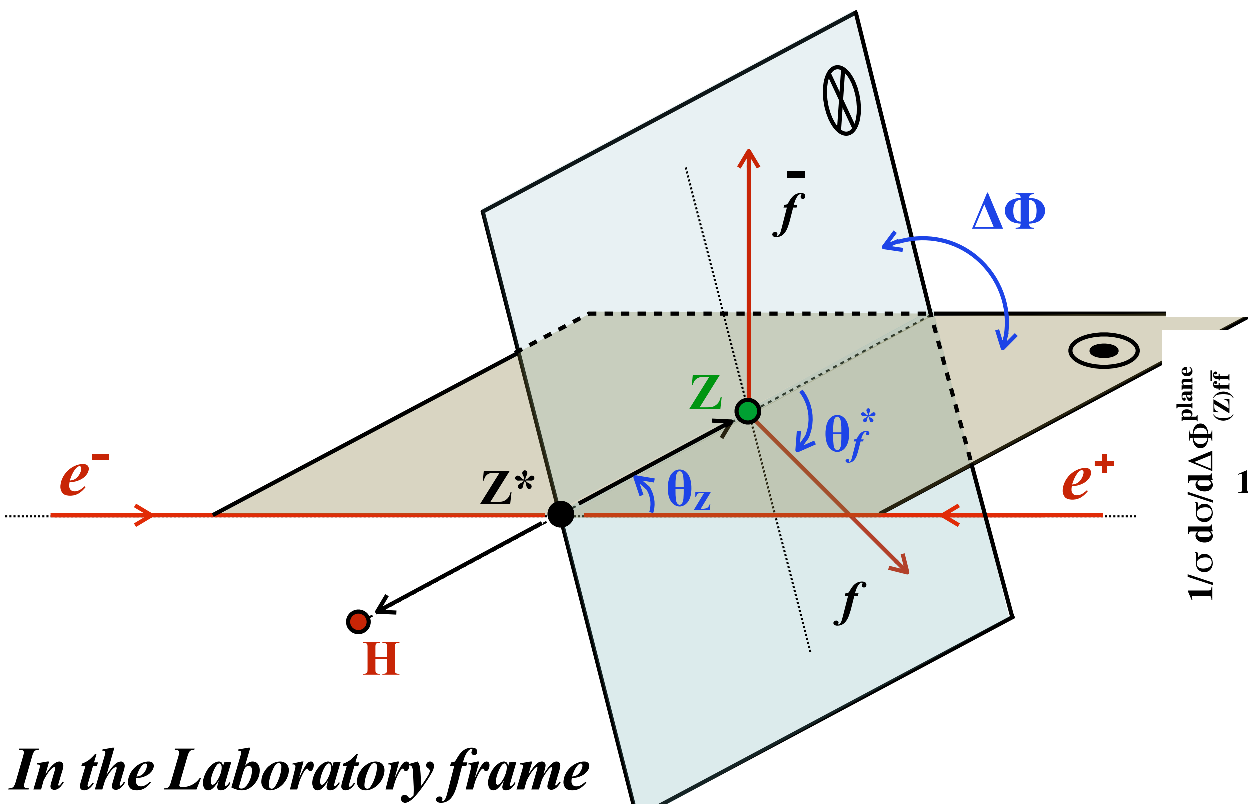
correlation matrix (w/ shape+σ P(LR))

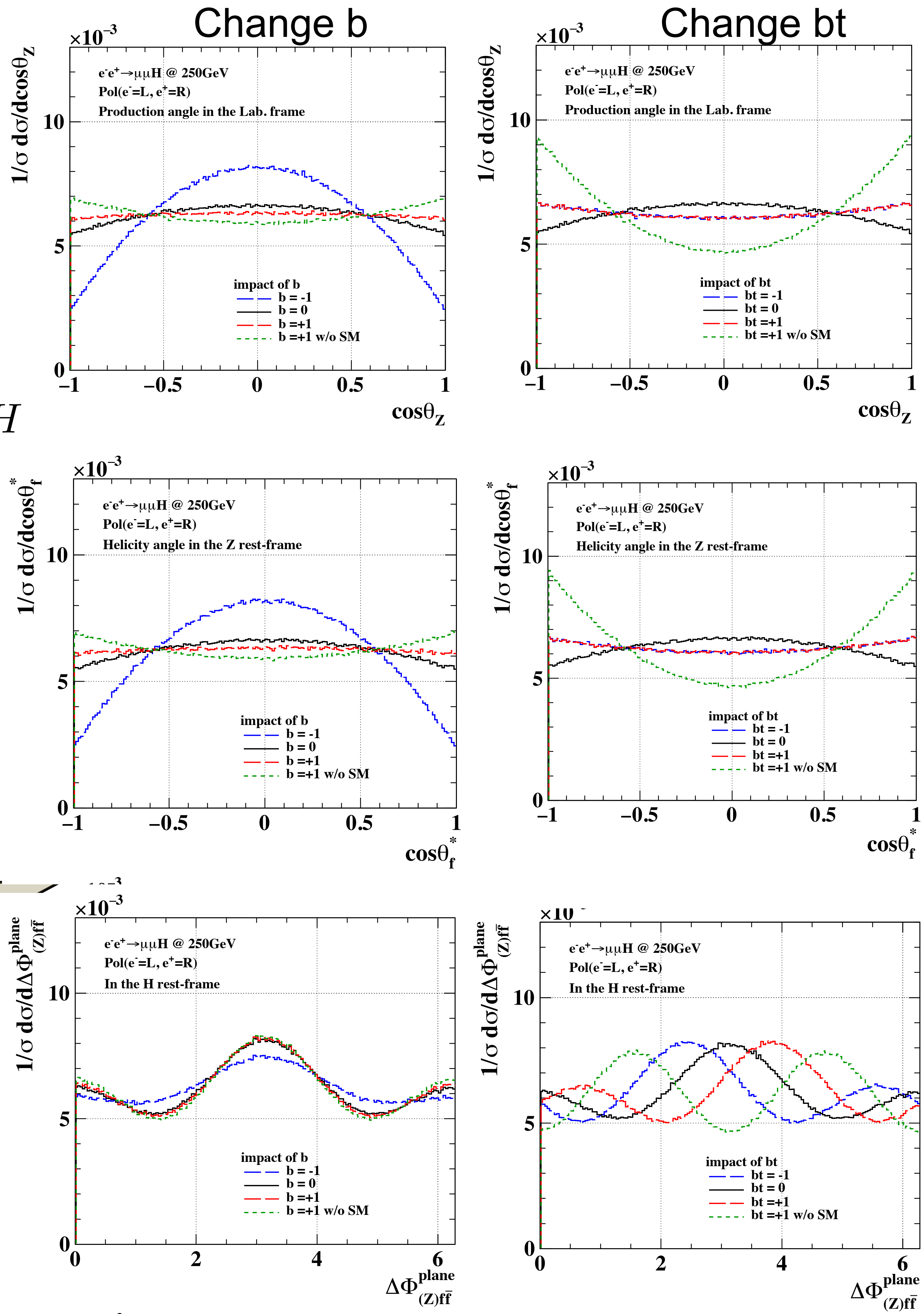
$$\rho = \begin{pmatrix} 1 & -0.848 & 0.0136 \\ & 1 & -0.0124 \\ & & 1 \end{pmatrix}$$

Angular Asymmetry : 250GeV

The Lorentz structure

$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{v}+\frac{a_Z}{\Lambda}\right)Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\tilde{\hat{Z}}^{\mu\nu}H$$

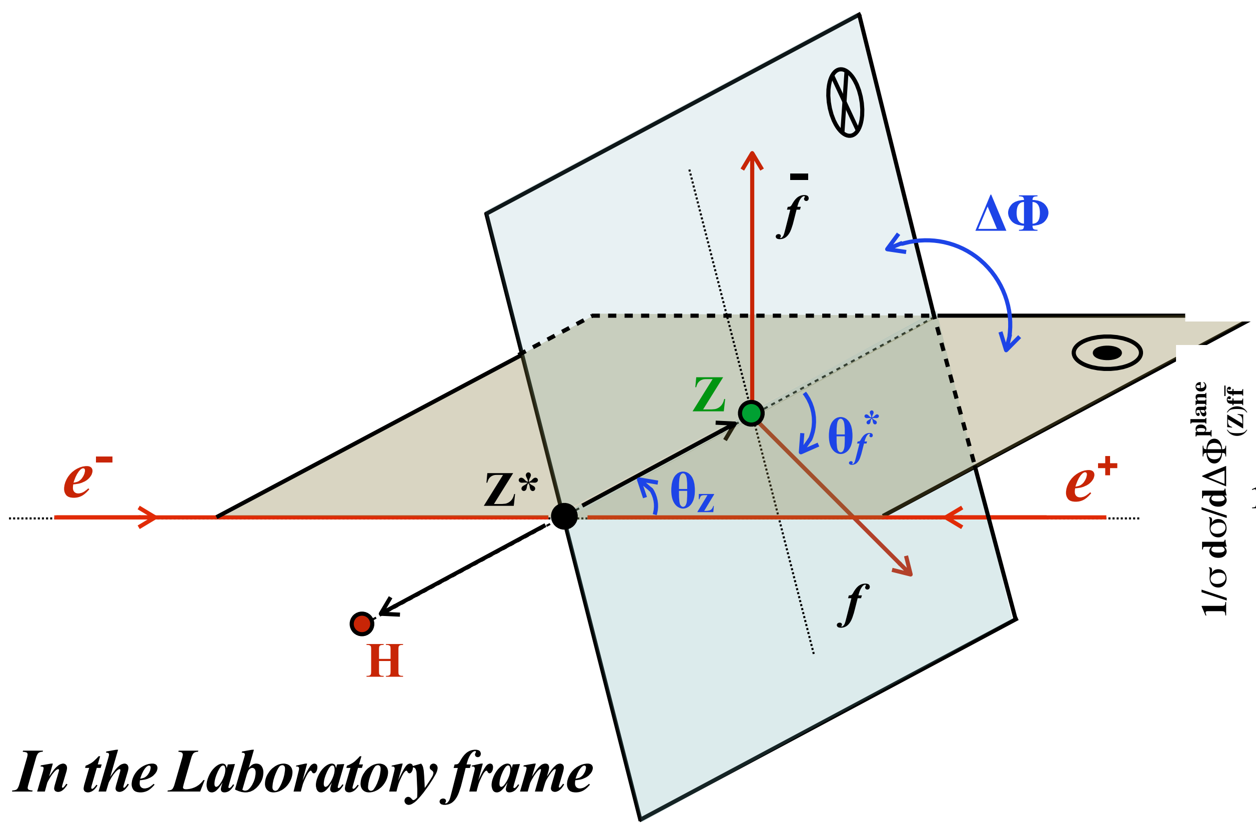




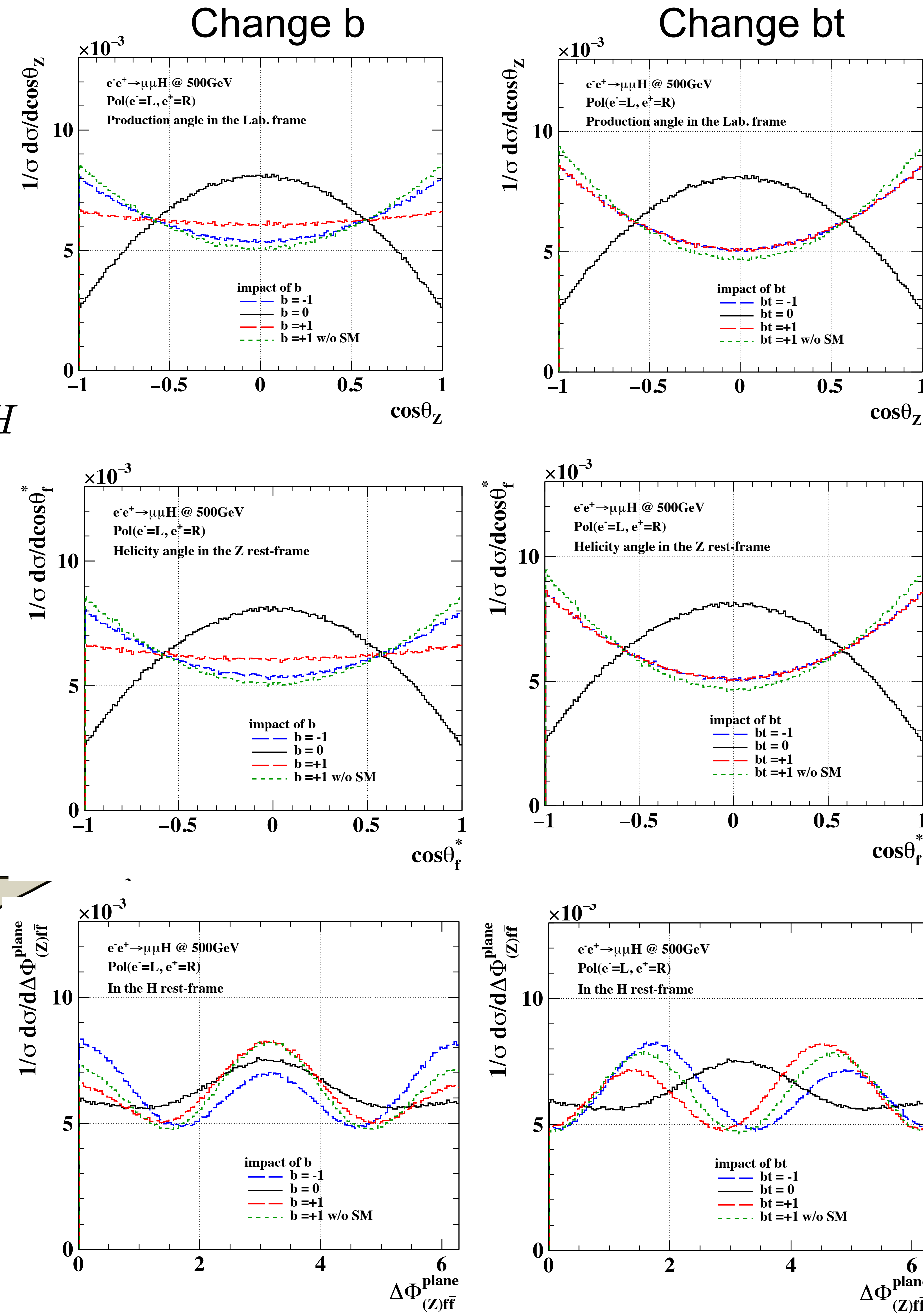
Angular Asymmetry : 500GeV

The Lorentz structure

$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{v} + \frac{a_Z}{\Lambda}\right) Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu} H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\widetilde{\hat{Z}}^{\mu\nu} H$$

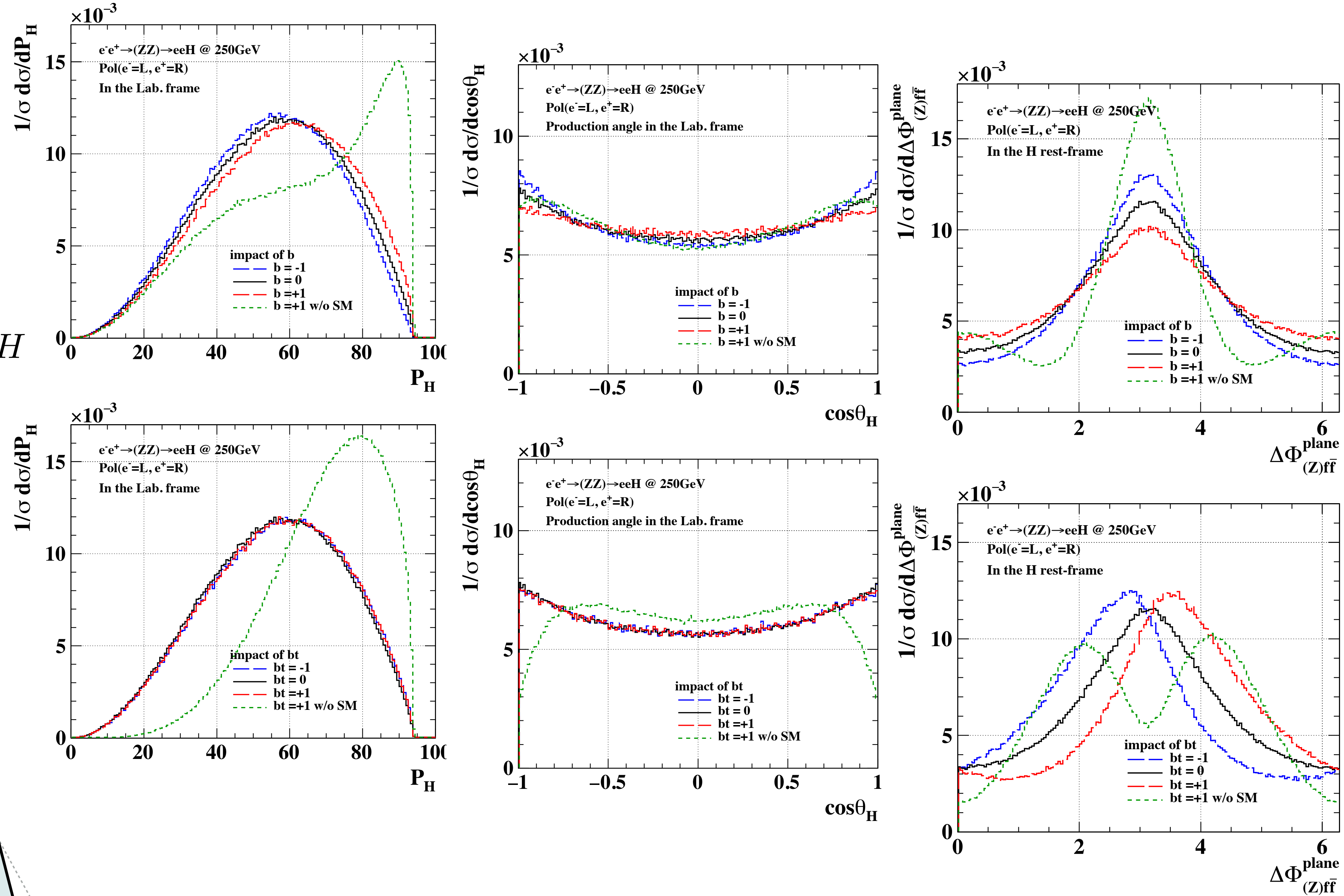


In the Laboratory frame

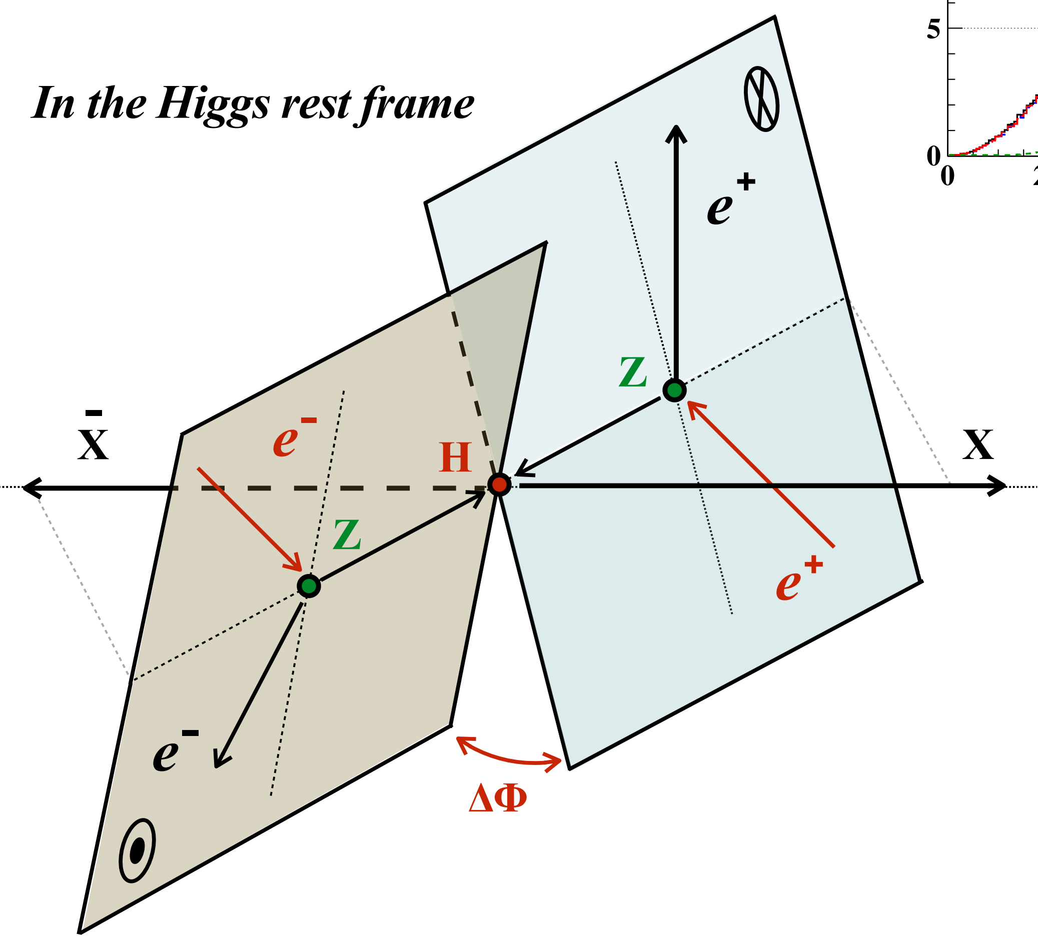


Kinematical distribution with the ZZ-fusion : 250GeV

$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{v}+\frac{a_Z}{\Lambda}\right)Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\widetilde{\hat{Z}}^{\mu\nu}H$$

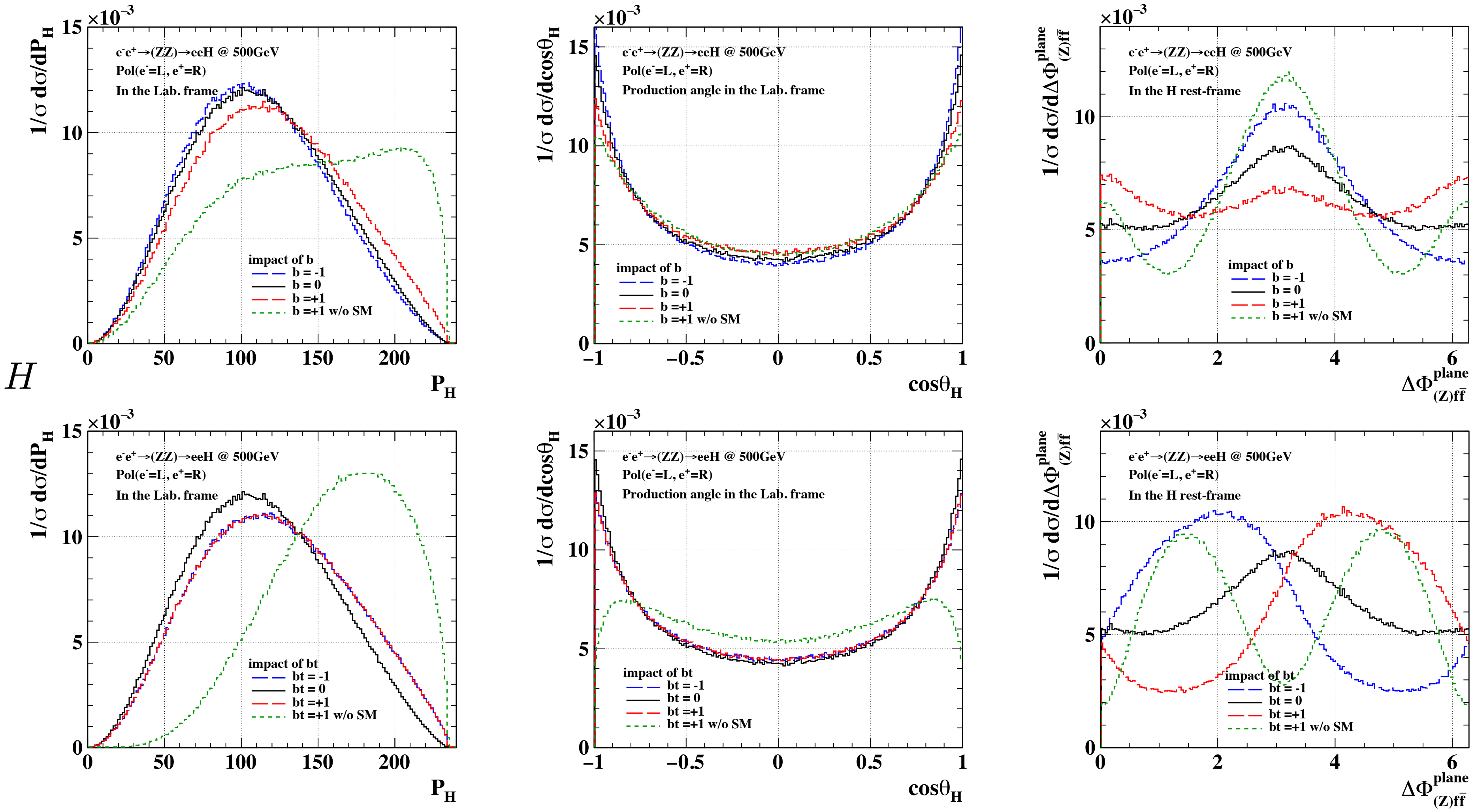


In the Higgs rest frame

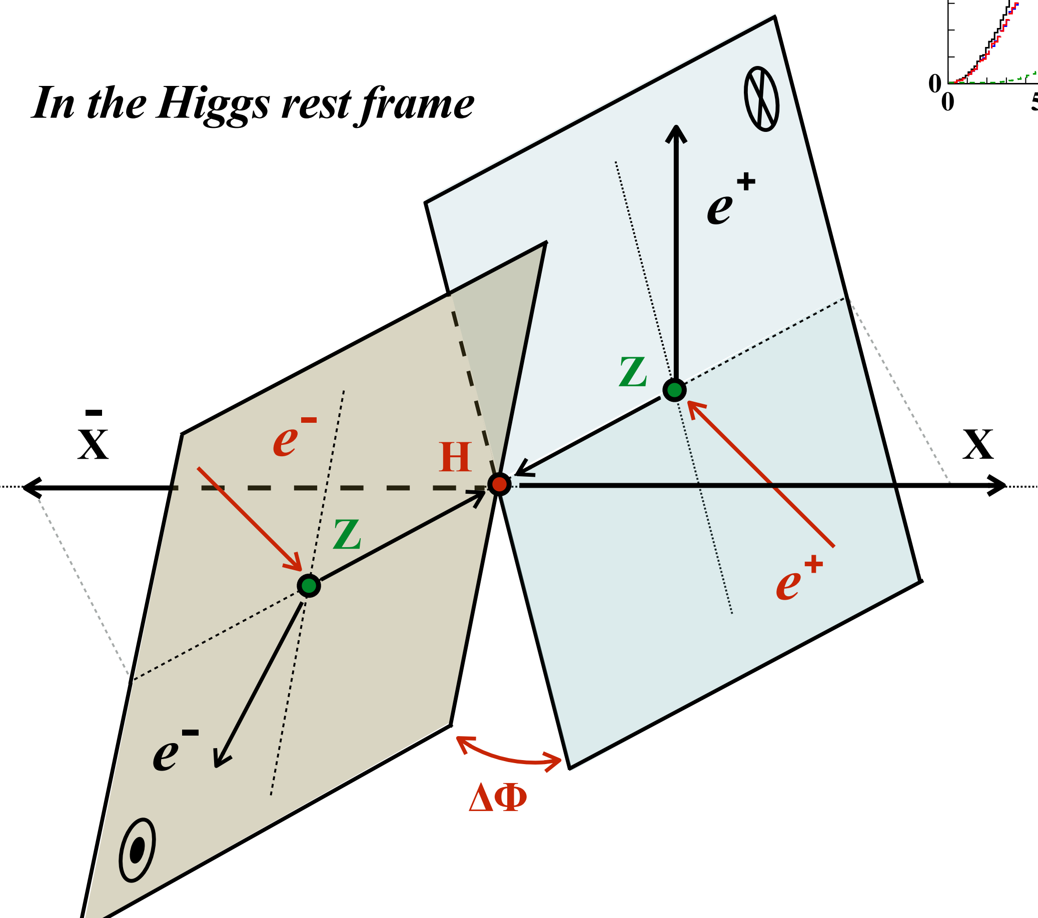


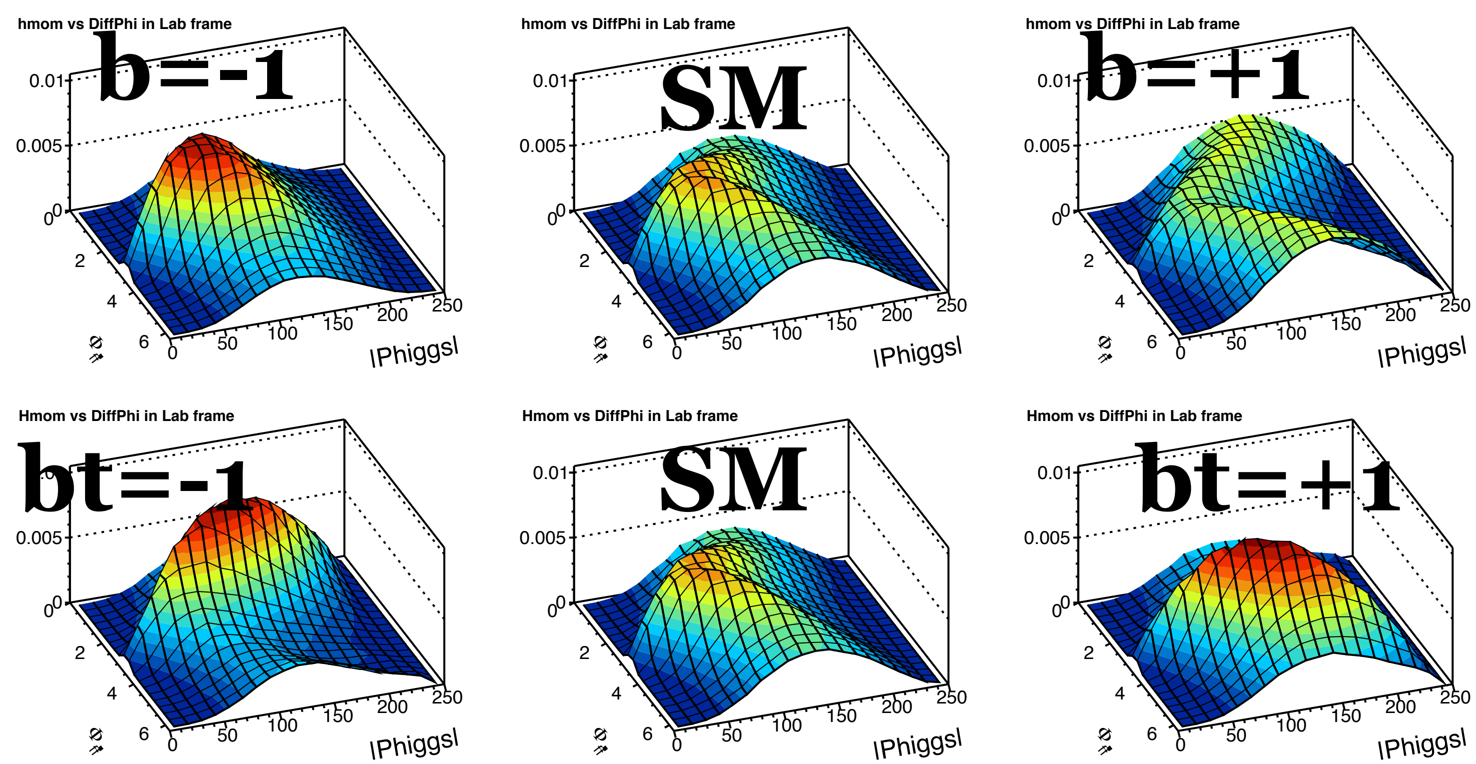
Kinematical distribution with the ZZ-fusion : 500GeV

$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{v}+\frac{a_Z}{\Lambda}\right)Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\widetilde{\hat{Z}}^{\mu\nu}H$$



In the Higgs rest frame



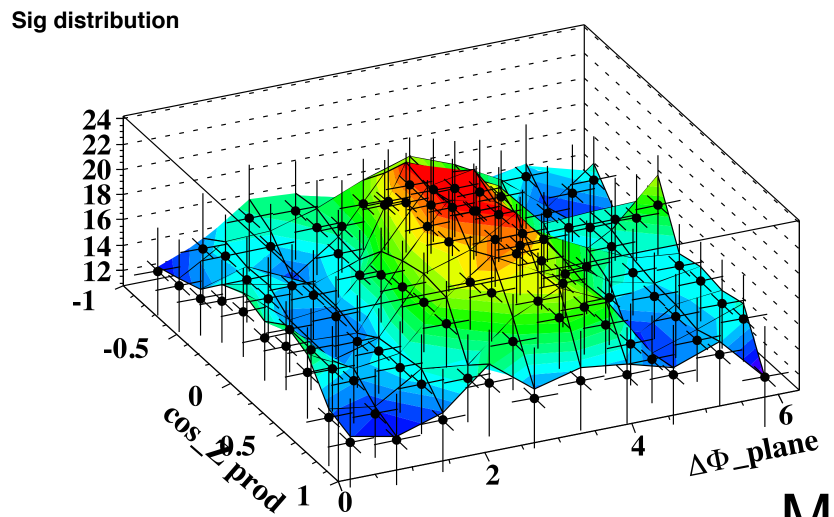


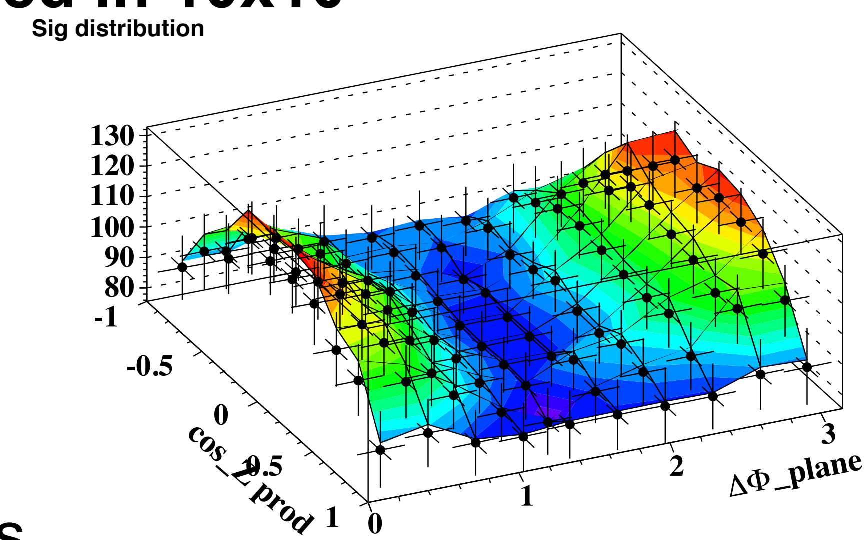
Examples : Reconstructed angular distribution & Migration matrix

ZH → μμH @ 250GeV

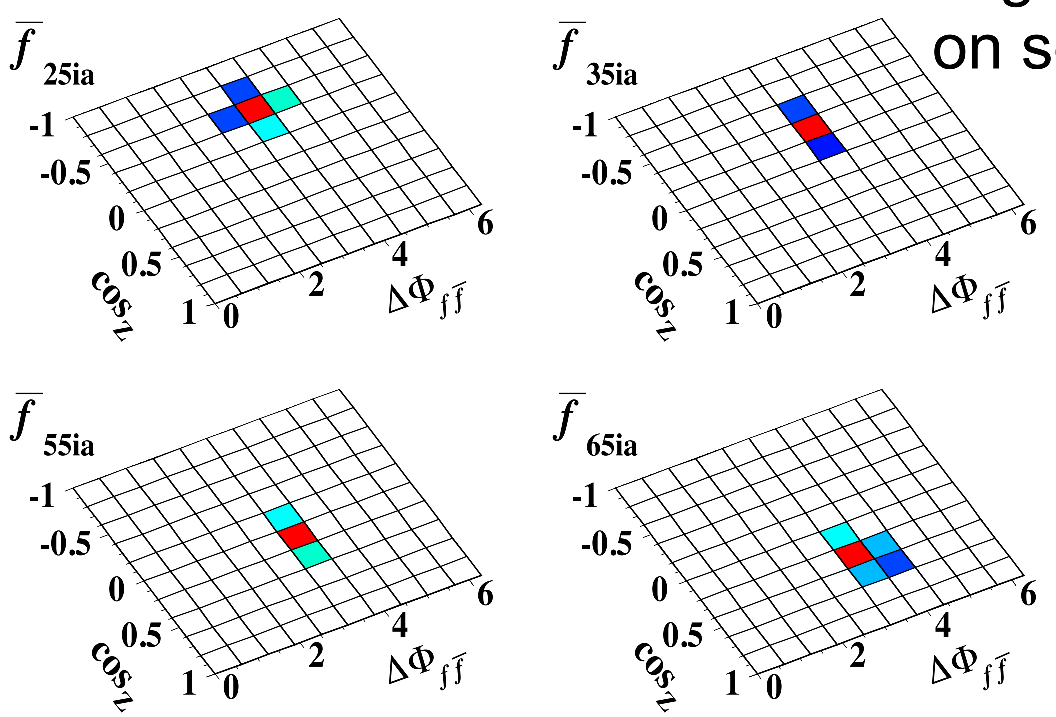
ZH → qqH(H→bb) @ 250GeV

Reconstructed distribution of **ΔΦ vs cosθz binned in 10x10**

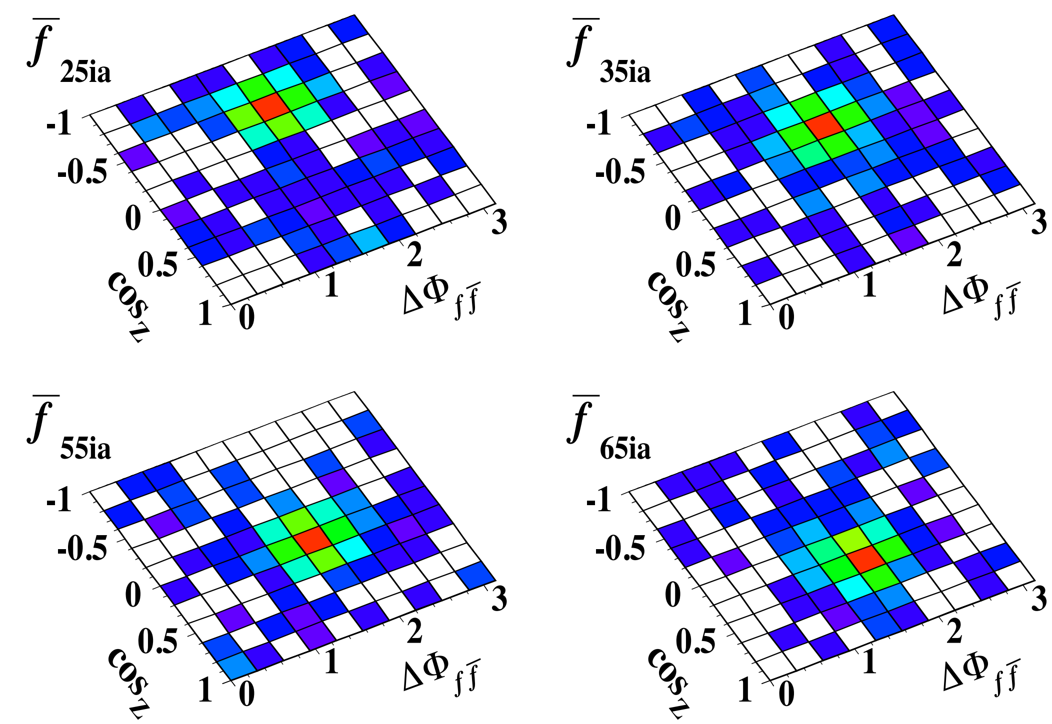




Migration matrices on several bins



Matrix element [0~1]

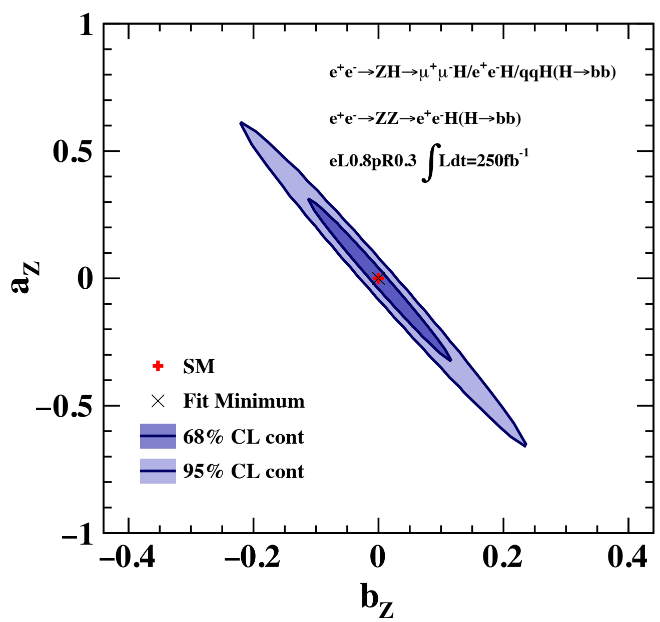


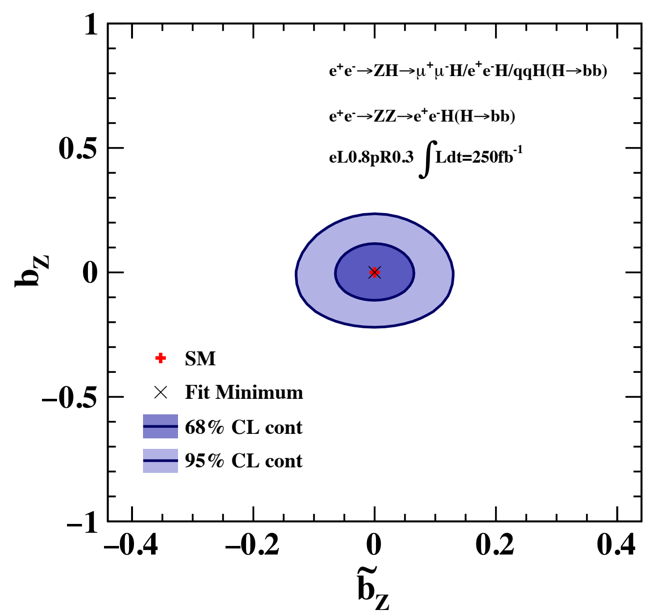
Lepton channel is very clean signature.
Hadron channel has relatively large migration.

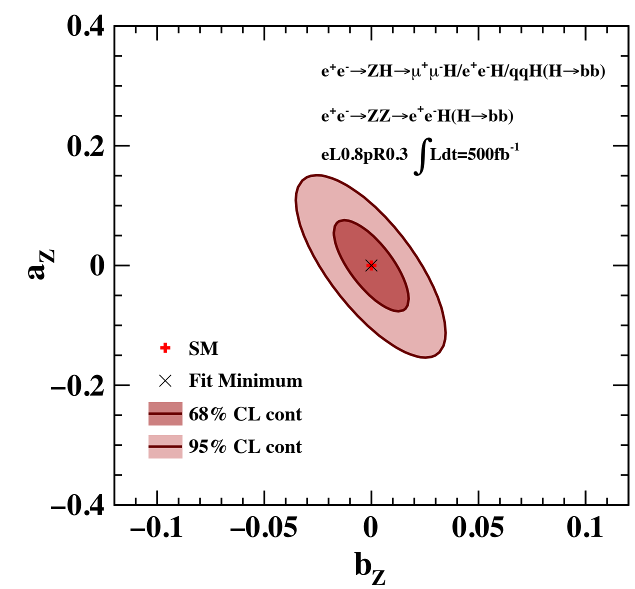
Sensitivity to ZZH couplings

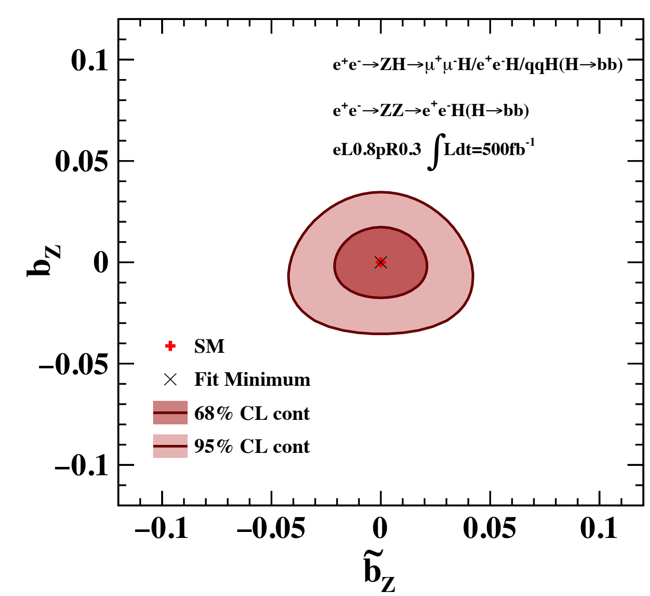
Contours showing sensitivities with three parameter space.

250fb^{-1} and 500fb^{-1} are assumed as the integrated luminosity for 250 and 500GeV.









		a_Z	b_Z	$\tilde{b}_Z$
ZH	$e^-_L e^+_R$	-	± 0.110	± 0.051
with shape	$e^-_R e^+_L$	-	± 0.129	± 0.061
ZH	$e^-_L e^+_R$	± 0.309	± 0.109	± 0.051
with shape+σ	$e^-_R e^+_L$	± 0.356	± 0.125	± 0.061
ZH+ZZ-fusion	$e^-_L e^+_R$	-	± 0.110	± 0.051
with shape	$e^-_R e^+_L$	-	± 0.129	± 0.061
ZH+ZZ-fusion	$e^-_L e^+_R$	± 0.238	± 0.084	± 0.050
with shape+σ	$e^-_R e^+_L$	± 0.278	± 0.098	± 0.060

		a_Z	b_Z	$\tilde{b}_Z$
ZH	$e^-_L e^+_R$	-	± 0.0199	± 0.0183
with shape	$e^-_R e^+_L$	-	± 0.0215	± 0.0198
ZH	$e^-_L e^+_R$	± 0.116	± 0.0201	± 0.0183
with shape+σ	$e^-_R e^+_L$	± 0.130	± 0.0217	± 0.0198
ZH+ZZ-fusion	$e^-_L e^+_R$	-	± 0.0200	± 0.0174
with shape	$e^-_R e^+_L$	-	± 0.0214	± 0.0190
ZH+ZZ-fusion	$e^-_L e^+_R$	± 0.061	± 0.0134	± 0.0174
with shape+σ	$e^-_R e^+_L$	± 0.071	± 0.0156	± 0.0188

bt can be evaluated through
only shape information @ 250 and 500GeV

Correlation a and b is strong
because σ info. is much stronger than that of the shape

@ 500GeV the shape quickly changes
the correlation can be disentangled.

Power of each process for the anomalous couplings

ZH : leptonic(e/μ) / hadronic (q)

ZZ : H → bb

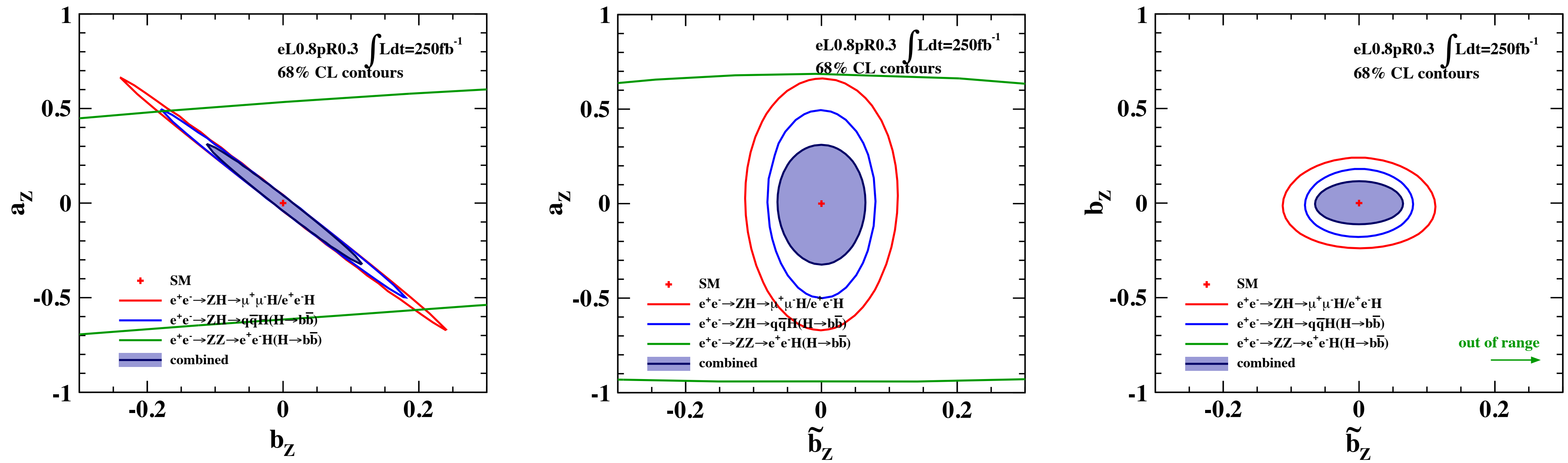


FIG. 25. A plot shows the sensitivity to the anomalous ZZH couplings. Fitting is performed with simultaneous fitting in three free parameter space, and each contour showing impact of each channel are projected into the a_Z-b_Z parameter space. The integrated luminosity is assumed to be 250 fb^{-1} with left-handed polarization $e^-_L e^+_R$.

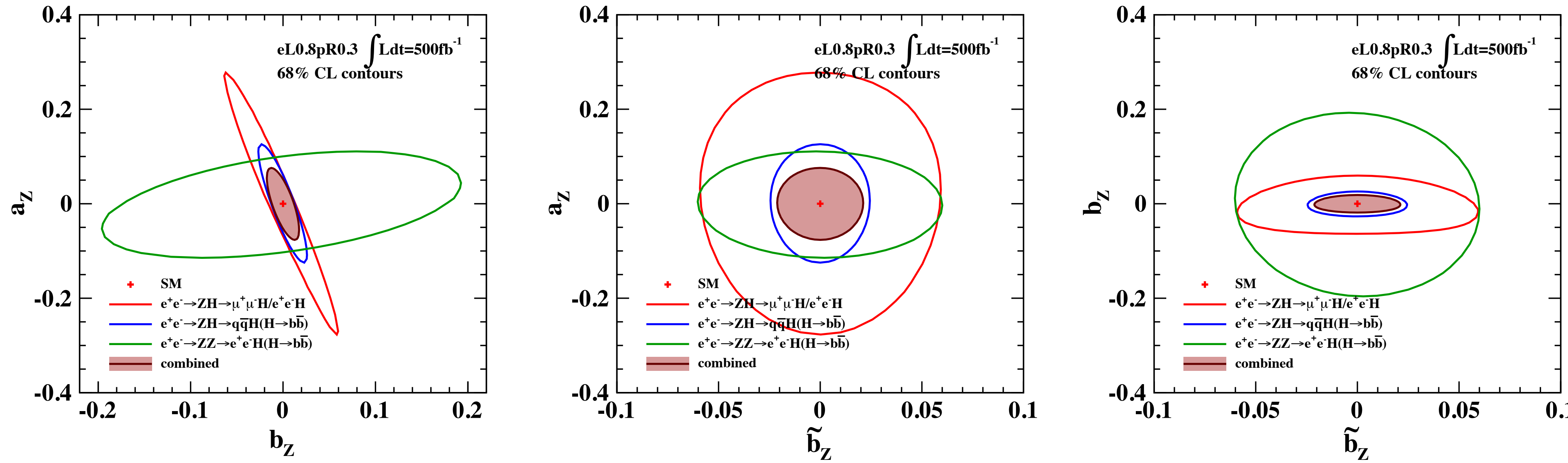


FIG. 26. A plot shows the sensitivity to the anomalous ZZH couplings. Fitting is performed with simultaneous fitting in three free parameter space, and each contour showing impact of each channel are projected into the a_Z-b_Z parameter space. The integrated luminosity is assumed to be 500 fb^{-1} with left-handed polarization $e^-_L e^+_R$.