Probing Anomalous Couplings in Single Higgs Production at *ep* Collider

Pramod Sharma and Ambresh Shivaji, JHEP 10 (2022) 108

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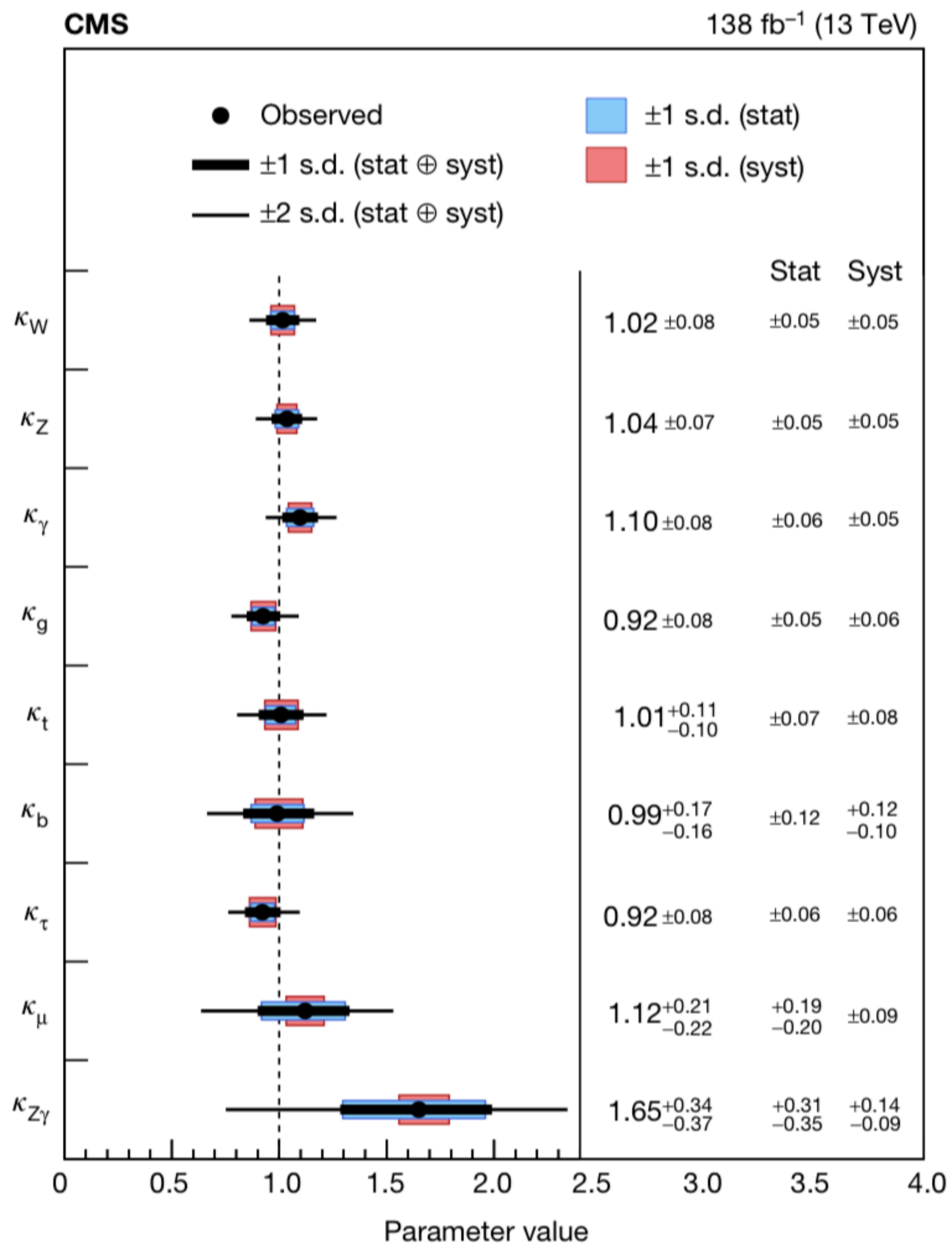
- A particle of 125 GeV discovered by CMS and ATLAS experiments in 2012
- So far measurements of Higgs boson properties are compatible with SM within current uncertainties
- The **KEY** to probe new physics is to verify EWSB (Higgs mechanism)
- Uncertainty $\rightarrow \approx 10\,\%$ in Higgs to gauge boson couplings



Ref. [1] Nature 607, 60-68 (2022)

Anomalous $HVV(V = W^{\pm}, Z)$ coupling

Most general Lagrangian

$$g\left(m_W \kappa_W W^+_\mu W^{-\mu} + \frac{\kappa_Z}{2\cos\theta_W} m_Z Z_\mu Z^\mu\right) H$$

$$-\frac{g}{m_W}\Bigg[\frac{\lambda_{1W}}{2} W^{+\mu\nu} W^-_{\mu\nu} + \frac{\lambda_{1Z}}{4} Z^{\mu\nu} Z_{\mu\nu}$$

$$+\lambda_{2W}(W^{+\nu}\partial^\mu W^-_{\mu\nu} + h.c.) + \lambda_{2Z} Z^\nu \partial^\mu Z_{\mu\nu}$$

$$+\frac{\tilde{\lambda}_W}{2} W^{+\mu\nu} \widetilde{W}^-_{\mu\nu} + \frac{\tilde{\lambda}_Z}{4} Z^{\mu\nu} \tilde{Z}_{\mu\nu}\Bigg] H$$

$g \rightarrow SU(2)$ coupling parameter

$$\tilde{V}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta} V_{\alpha\beta}$$

$$V^{\mu\nu} = \partial^\mu V^\nu - \partial^\nu V^\mu$$

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SM like

$$-\frac{g}{m_W}\left[\frac{\lambda_{1W}}{2} W^{+\mu\nu} W^-_{\mu\nu} + \frac{\lambda_{1Z}}{4} Z^{\mu\nu} Z_{\mu\nu}\right.$$

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Derivative of fields

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CP even

$$\left. + \frac{\tilde{\lambda}_W}{2} W^{+\mu\nu} \widetilde{W}^-_{\mu\nu} + \frac{\tilde{\lambda}_Z}{4} Z^{\mu\nu} \tilde{Z}_{\mu\nu}\right] H$$

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Derivative of fields

Anomalous $HVV(V = W^{\pm}, Z)$ coupling

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Vertex form

$$\Gamma^{\mu\nu}_{HVV}(p_1, p_2)$$

$$g_V m_V \kappa_V g^{\mu\nu}$$

$$+\frac{g}{m_W}\left[\lambda_{1V}(p_1^\nu p_2^\mu - g^{\mu\nu} p_1 . p_2) \right.$$

$$+ \lambda_{2V}\,(p_1^\mu p_1^\nu + p_2^\mu p_2^\nu - g^{\mu\nu} p_1 . p_1 - g^{\mu\nu} p_2 . p_2)$$

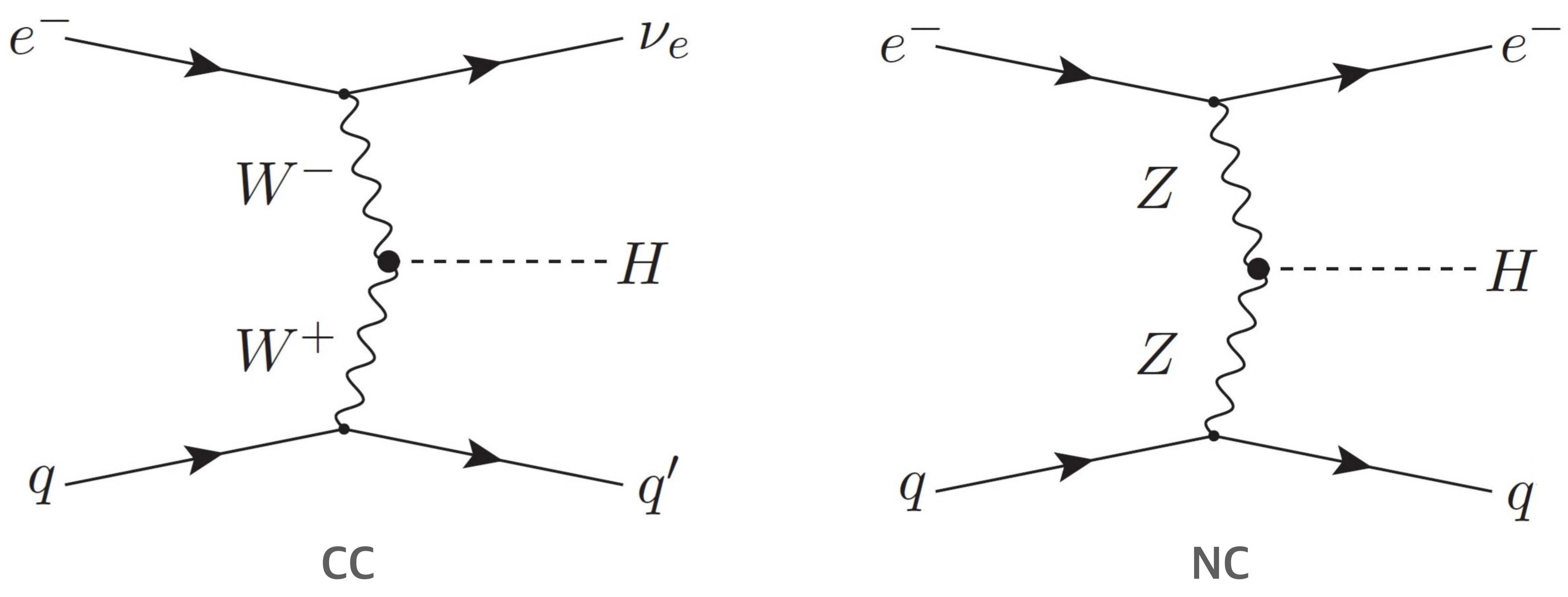
$$\left. + \tilde{\lambda}_V\, \epsilon^{\mu\nu\alpha\beta} p_{1\alpha} p_{2\beta} \right]$$

ep Collider

Collider	Center of mass energy (TeV)	Process	Cross section (pb)
pp	14	$pp \to hjj$	3.7
ILC	1	$e^+e^- \to e^+e^-h$ $e^+e^- \to \nu_e\bar{\nu}_e h$	0.007 0.21
CLIC	3	$e^+e^- \to e^+e^-h$ $e^+e^- \to \nu_e\bar{\nu}_e h$	6×10^{-4} 0.5
LHeC	1.3	$e^-p \to e^-hj$ $e^-p \to \nu_e hj$	0.016 0.088

For this study, $E_e = 60$ GeV, $E_p = 7$ TeV

- **LHeC:** e^- energy 60 to 120 GeV with 7 TeV proton energy
- Sufficiently large cross section as compared to e^+e^- collider
- Clean environment with suppressed background as compared to pp collider



Results and discussion

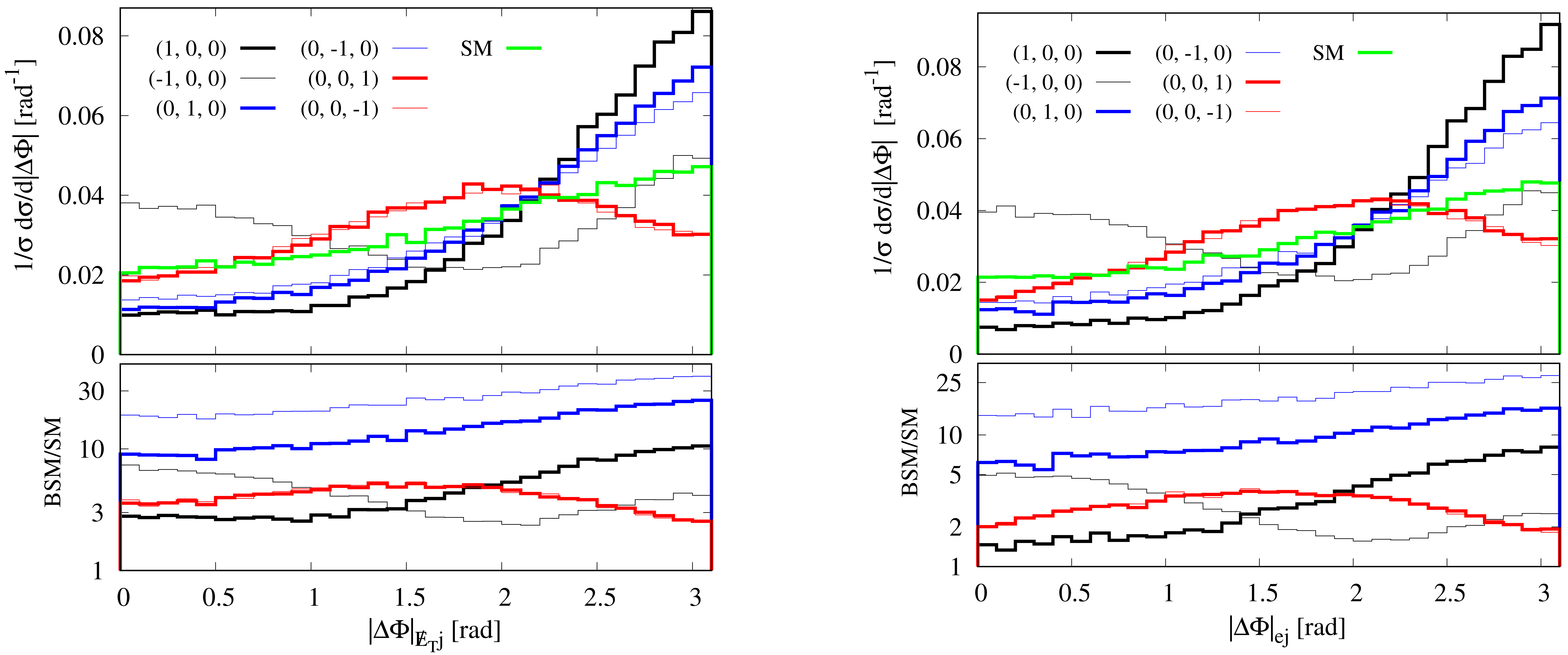
Observables: $|\Delta\phi|$ is azimuthal correlation of two particles 1 and 2

$$|\Delta\phi| = cos^{-1}(\hat{p}_{T1} . \hat{p}_{T2})$$

Motivation: $|\Delta\phi|$ distribution is a good observable to distinguish CP-even and CP-odd couplings of CC process considered in ref. [2]

Ref. [2]: Phys. Rev. Lett. 109 (2012) 261801, [1203.6285]

Results



BSM effects in $|\Delta\phi|$ distribution for CC (left) and NC (right)

$(\lambda_{1V}, \lambda_{2V}, \widetilde{\lambda}_V)$

- $|\Delta\phi|$ is sensitive to individual effect of new couplings
- Deviation in distribution with respect to SM is largest for λ_{2V} and smallest for $\widetilde{\lambda}_V$

Results

Signal for CC (NC) $e^- p \to \nu_e (e^-) hj, h \to b\bar{b}$ $j = g, u, d, s, c$

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- Irreducible background : $e^- p \to \nu_e (e^-) b\bar{b}j$

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- Reducible background:
  - $e^- p \to \nu_e(e^-)jjj$
  - $e^- p \to \nu_e(e^-)bbjj$
  - Photo production from $e^- p \to e^- b\bar{b}j$

$\gamma^* p \to b\bar{b}j$ for CC process

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Background for CC (NC)

Negligible for miss-tagging rates
c jet $\to 0.1$
light jet $\to$0.01

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Reduced by $\not{E}_T$ for a very collinear e^- along the beam pipe

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Negligible for miss-tagging rates
c jet $\to 0.1$
light jet →0.01

Energy smearing of partons by $\frac{\sigma_E}{E} = a/\sqrt{E} \oplus b$

a = 0.6, b= 0.04 for jets, a= 0.12, b=0.02 for electrons [3]

Ref [3]: LHeC, FCC-he Study Group collaboration, J. Phys. G 48 (2021) 110501,[2007.14491].

Results

Signal v/s background

Cuts or **CC**

$$p_T(j) > 30\ GeV,\ p_T(b) > 30\ GeV,\ \not{E}_T > 25GeV$$

$$|M_{b\bar{b}} - m_H| < 15\ GeV$$

$$1 < \eta_j < 5.0,\ -1 < \eta_b < 4.0,\ M_{Hj} > 250\ GeV$$

Process	Events at generation level	Events after cuts
Signal	3011	819
$\nu_e b\bar{b}j$	18883	30
$\nu_e b\bar{b}jj$	10985	38
S/B	0.1	12.0

Cuts or **NC**

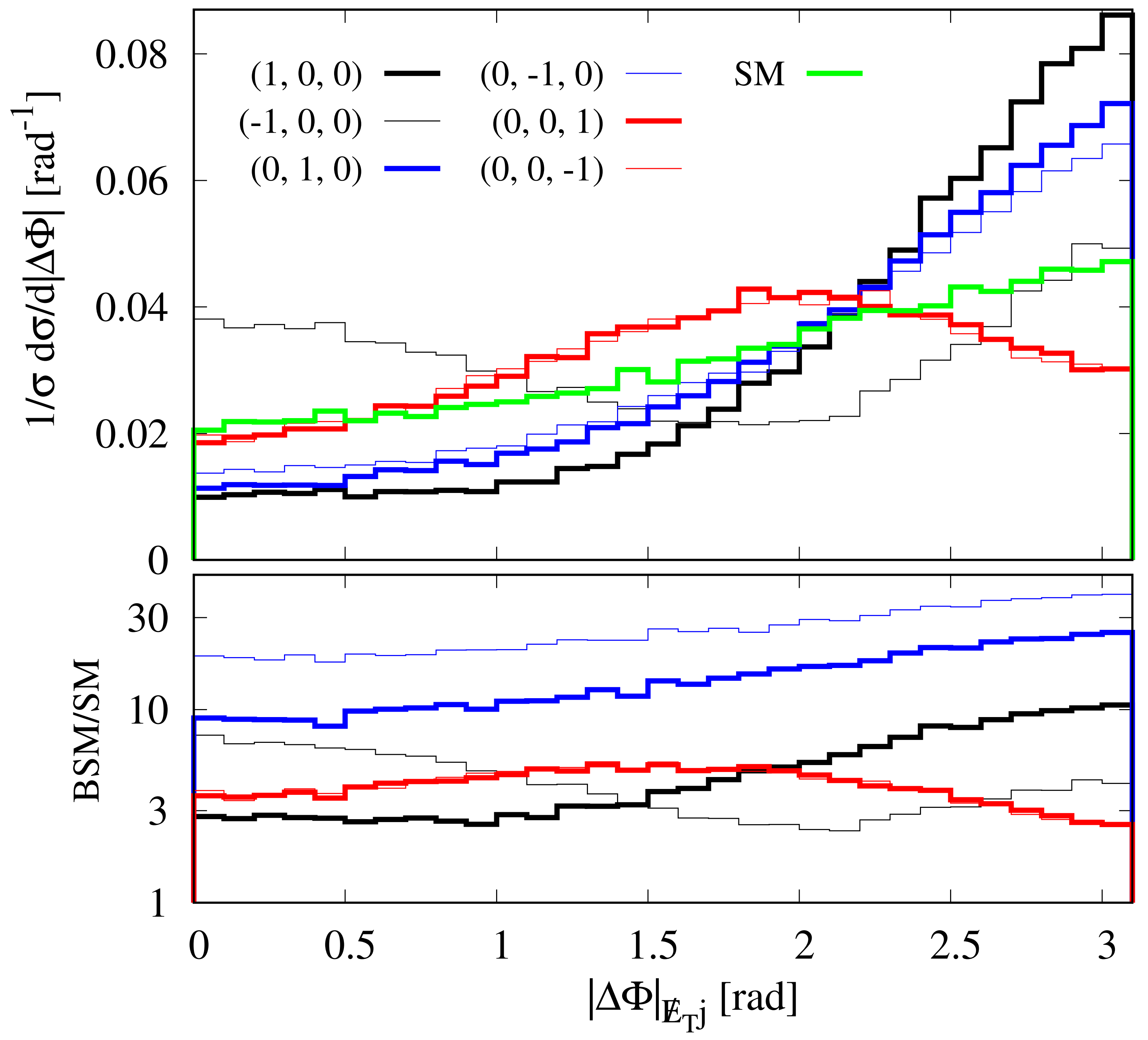
$$p_T(e) > 20\ GeV,\ p_T(j) > 30\ GeV,\ p_T(b) > 30\ GeV$$

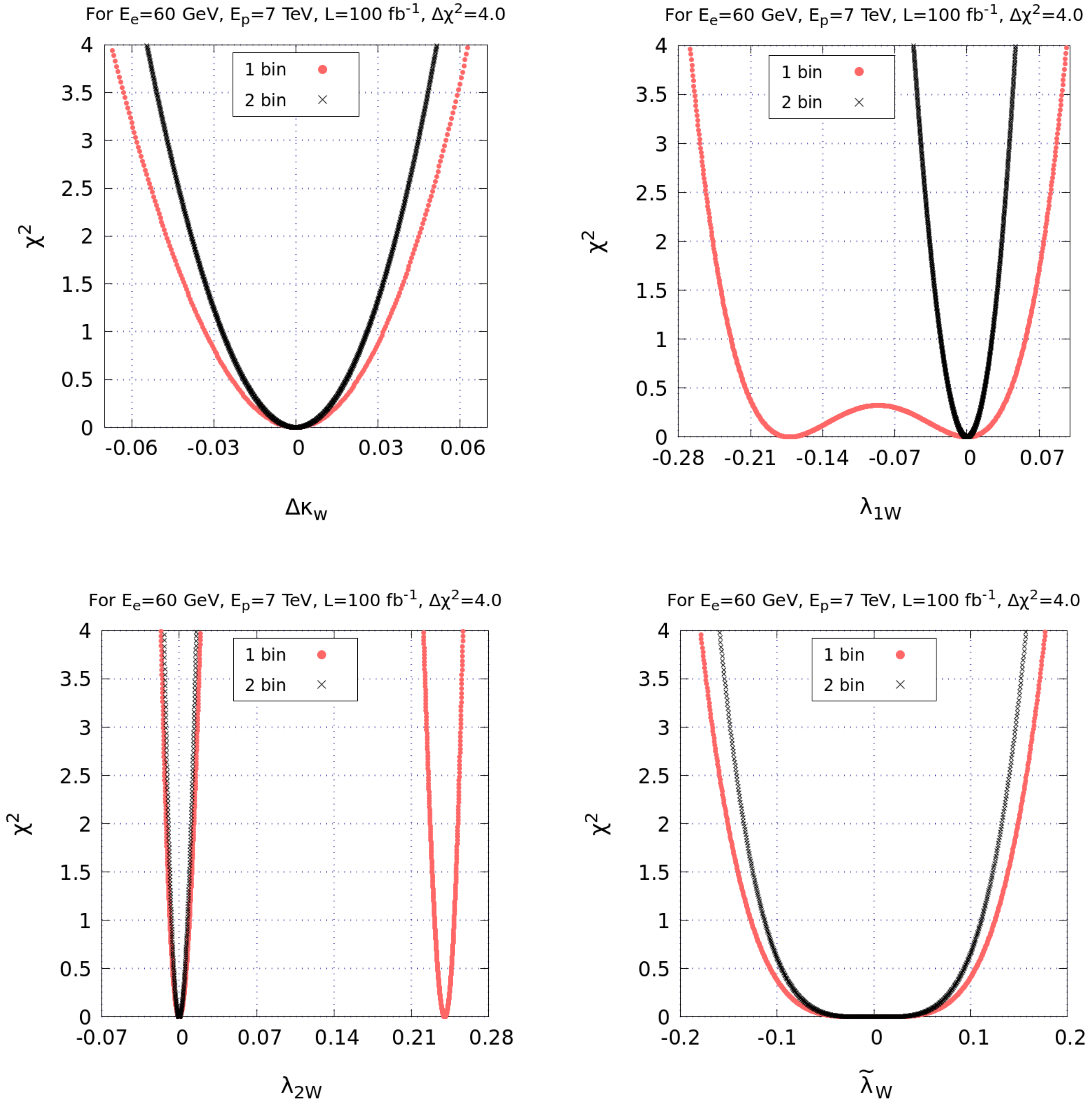
$$|M_{b\bar{b}} - m_H| < 15\ GeV$$

$$|\eta_e| < 2.5,\ 2 < \eta_j < 5.0,\ 0.5 < \eta_b < 4.0,\ M_{Hj} > 300\ GeV$$

Process	Events at generation level	Events after cuts
Signal	534	76
$e^- b\bar{b}j$	2.75×10^6	161
$e^- b\bar{b}jj$	6.3×10^5	24
S/B	0.02×10^{-2}	0.41

Constraints on HWW parameters at $L = 100\ fb^{-1}$





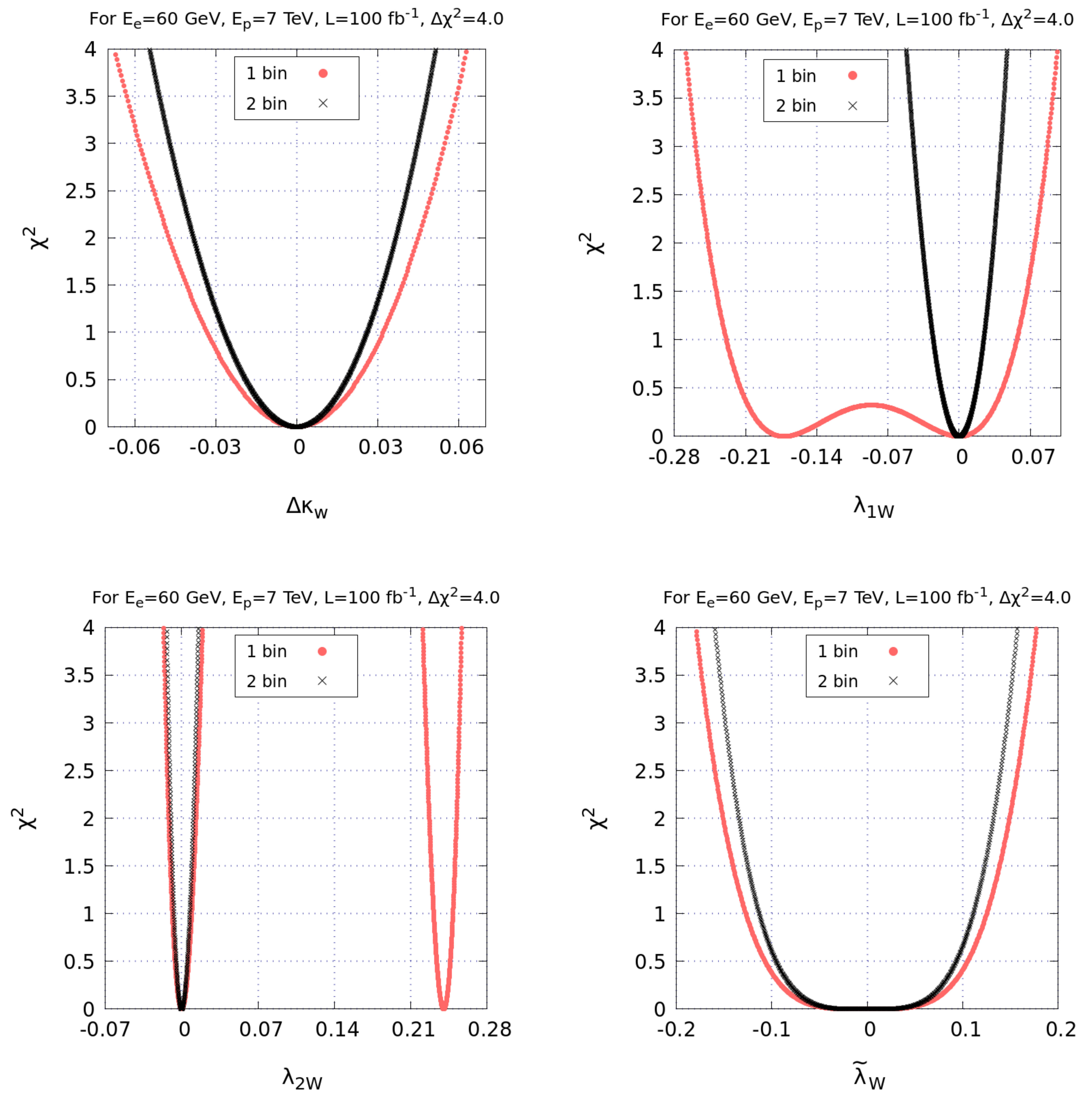
- λ_{2W} is constrained most while $\widetilde{\lambda}_W$ is constrained least
- Very small effect of 2 bin analysis on κ_W and $\widetilde{\lambda}_W$

at 95% C.L.

	Our limits at $L = 100\ fb^{-1}$			
$\kappa_W \rightarrow$	[0.94,1.05]	Run II data [a] $35.9\ fb^{-1}$, 13 TeV [0.76,1.34]	HL LHC [e] 3.4%	
$\widetilde{\lambda}_W \rightarrow$	[-0.16, 0.16]	Run II LHC [b] $[-0.42,0.3]$	FCC eh [d] $1\ ab^{-1}$, 3.5 TeV [-1.2, 1.2]	LHeC [c] $0.5\ ab^{-1}$, $E_e = 140$ GeV, $E_p = 6.5$ GeV [-0.2, 0.3]
$\lambda_{1W} \rightarrow$	[-0.05, 0.05]		FCC eh [d] [-0.56, 0.54]	LHeC [c] [-0.06, 0.1]
$\lambda_{2W} \rightarrow$	[-0.013, 0.015]	FCC eh [d] [-0.05, 0.05]		

[a] Eur. Phys. J. C 79 (2019) 421 [arXiv:1809.10733]
[b] Phys. Lett. B 805 (2020) 135426 [arXiv:2002.05315]
[c] arXiv:1203.6285
[d] arXiv:1509.04016
[e] arXiv:1902.00134

Constraints on HWW parameters at $L = 100\ fb^{-1}$

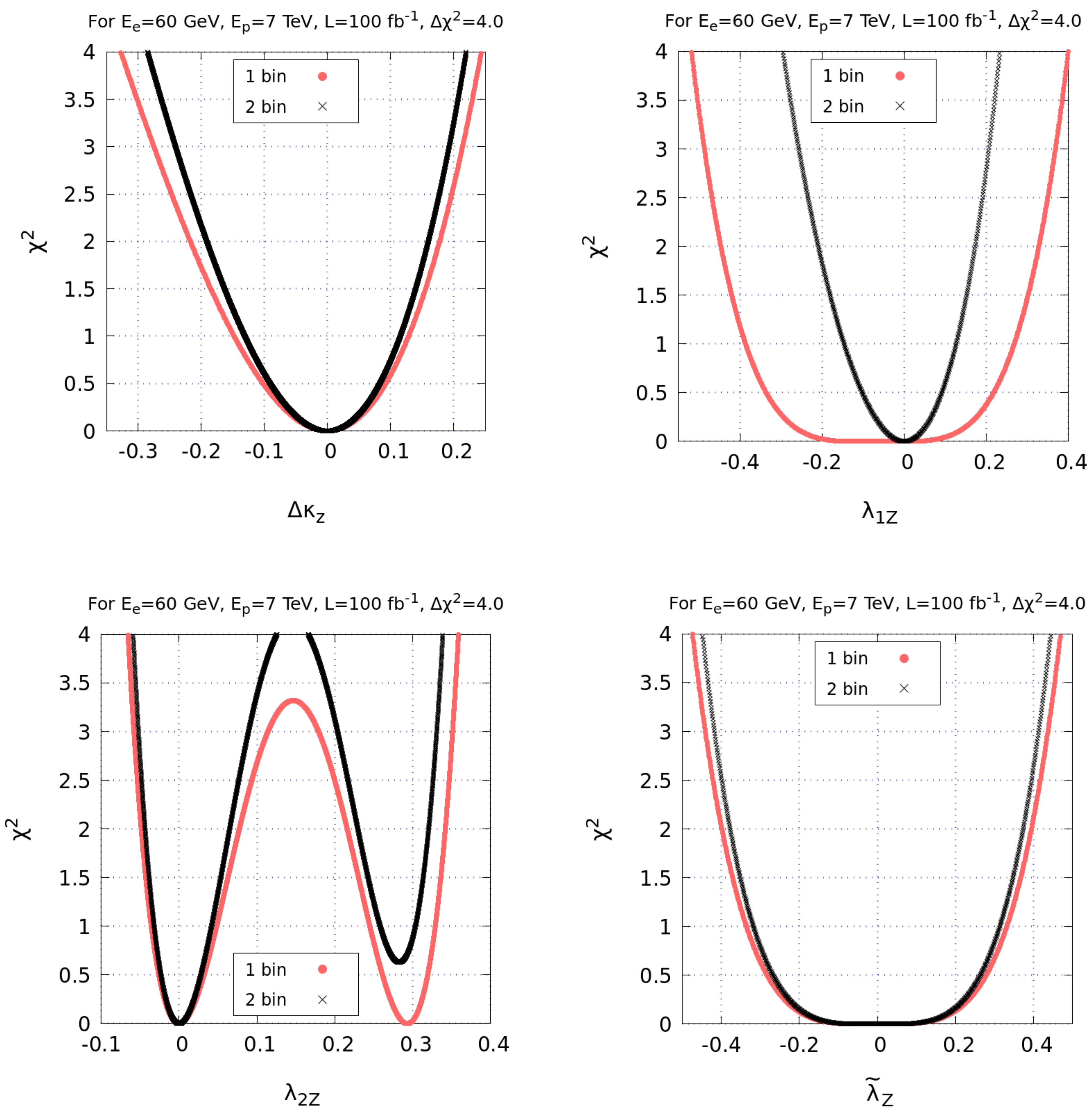


Results

$$\chi^2(c_i) = \sum_{j=1}^{n} \left(\frac{N_j^{\mathrm{BSM}}(c_i) - N_j^{\mathrm{SM}}}{\Delta N_j} \right)^2$$

Suppress χ^2 due to huge background

Constraints on HZZ parameters at $L = 100\ fb^{-1}$



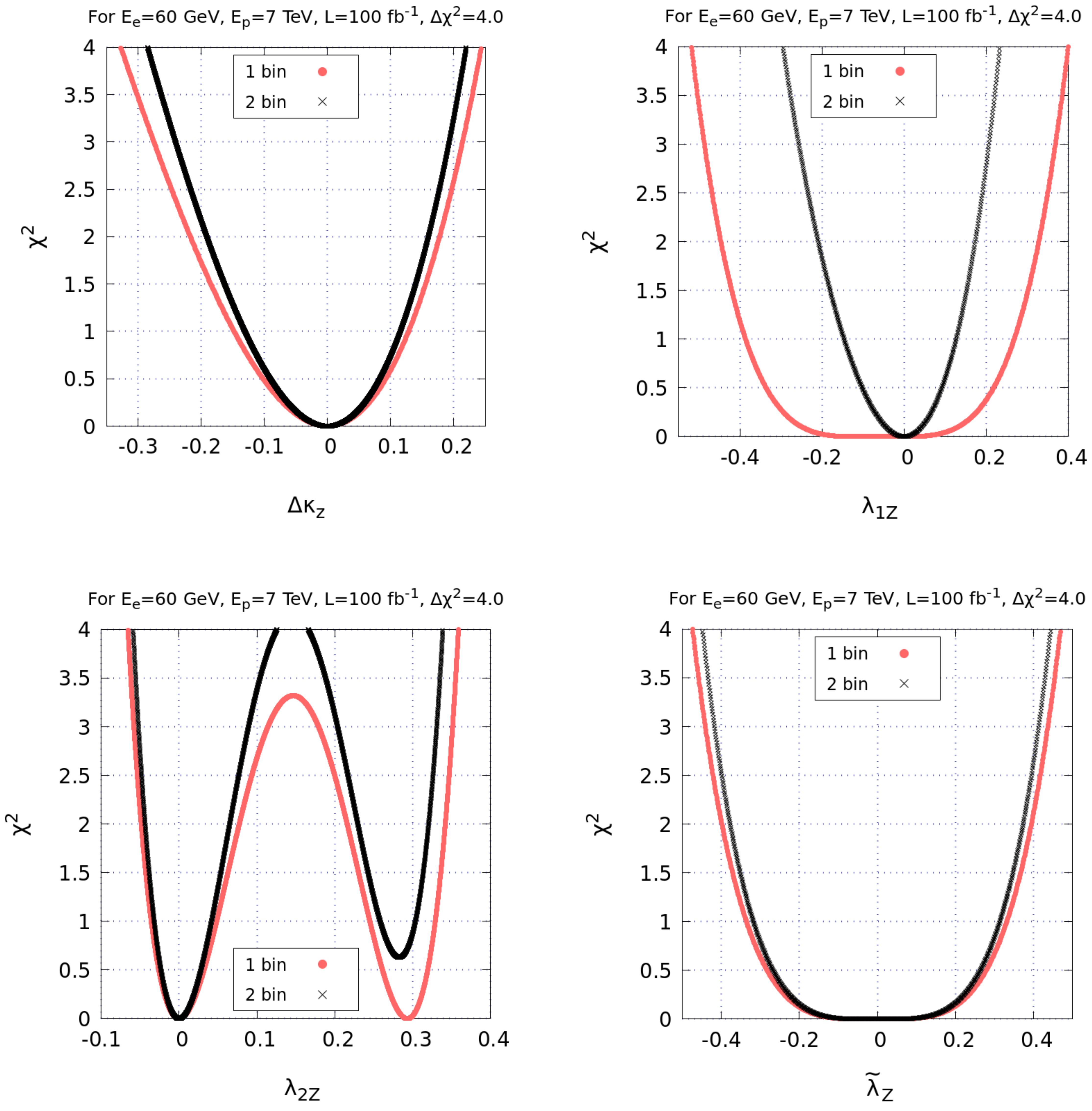
- HZZ parameters less stringent as compared to HWW parameters
- All parameters lie within range [-0.45, 0.45]

at 95% C.L.

	Our limits at $L = 100\ fb^{-1}$		
$\kappa_Z \rightarrow$	[0.72 1.22]	Run II data [a] [0.75, 1.21]	HL LHC [e] 3.0%
$\lambda_{1Z} \rightarrow$	[-0.35, 0.25]		HL LHC [g] [-0.01, 0.01]
$\lambda_{2Z} \rightarrow$	[-0.06,0.13] ∪ [0.17, 0.34]		HL LHC [g] [-0.007, 0.007]
$\tilde{\lambda}_Z \rightarrow$	[-0.45, 0.45]	Run II LHC [b] $[-0.21, 0.15]$	HL LHC [g] [-0.08, 0.08]

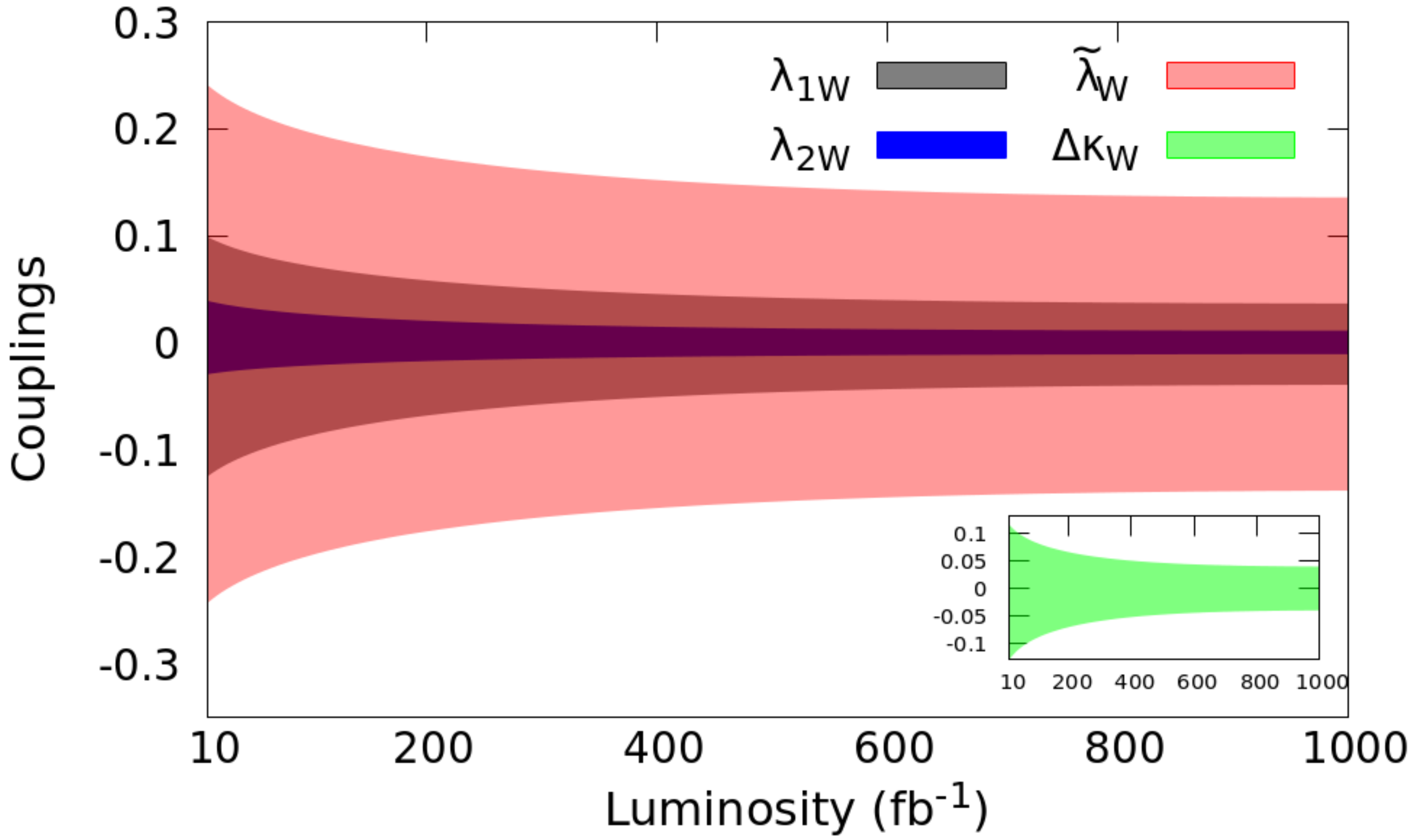
[g] JHEP 01 (2018) 096 [arXiv:1703.06667]

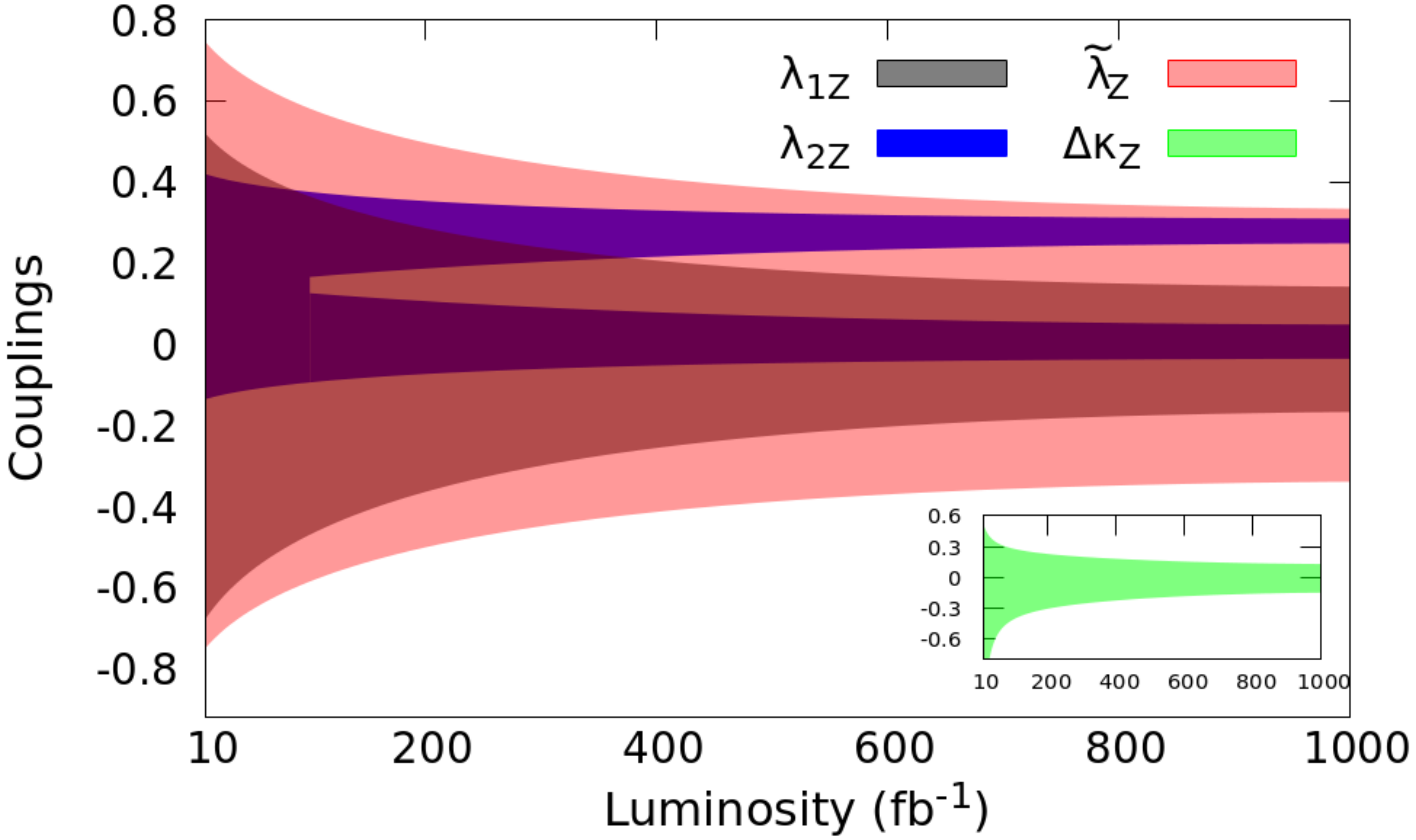
Constraints on HWW parameters at $L = 100\ fb^{-1}$



$\Delta N \approx \sqrt{\sigma L}$ (for $\delta_{sys} = 0$) $\implies \chi^2 \propto L$

at 95% C.L.





Luminosity from 10 to $10^3\ fb^{-1}$

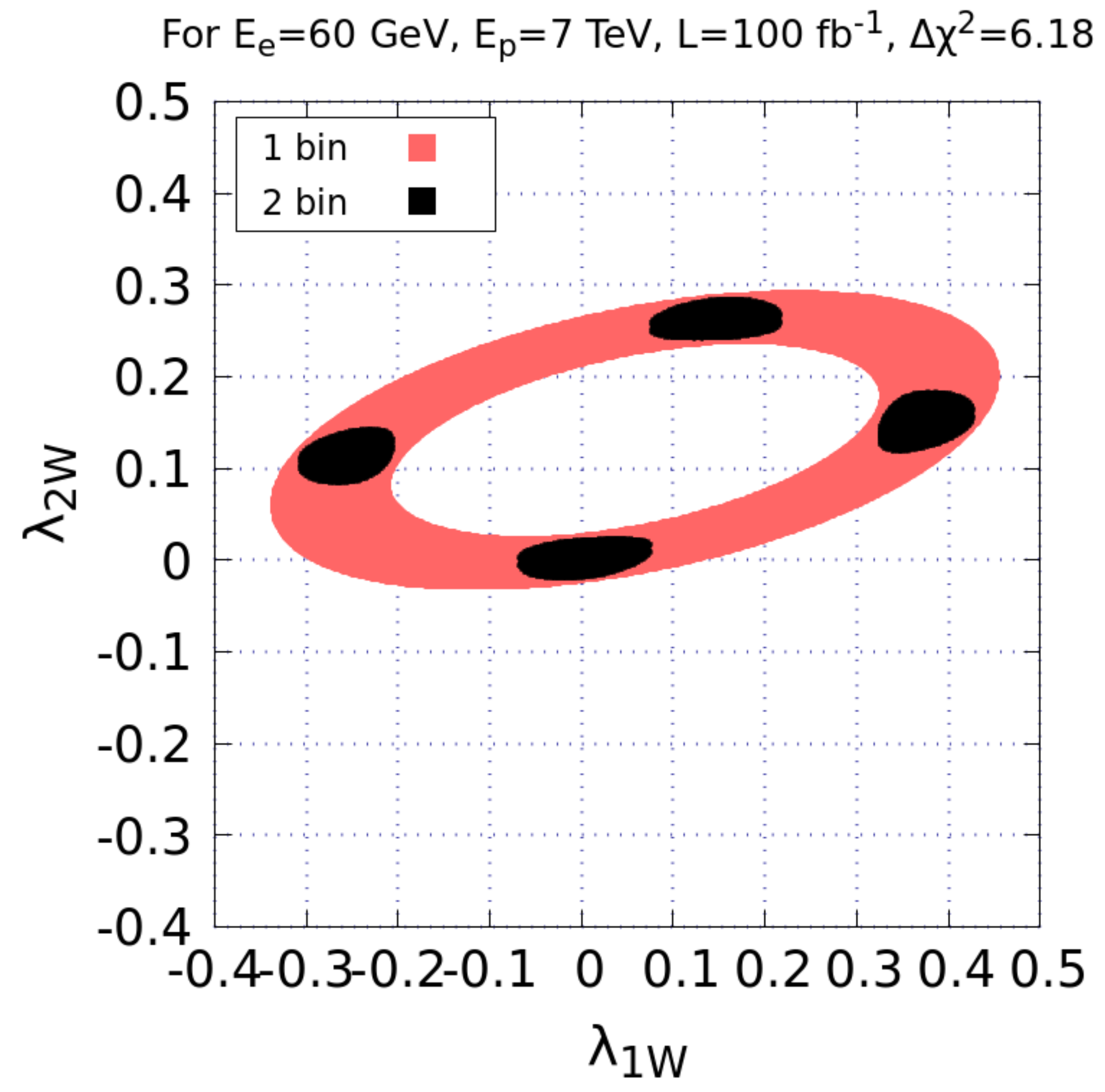
$$\kappa_W,\ \lambda_{1W},\ \lambda_{2W},\ \tilde{\lambda}_W \rightarrow 67\,\%, 40\,\%, 78\,\%, 42\,\%$$

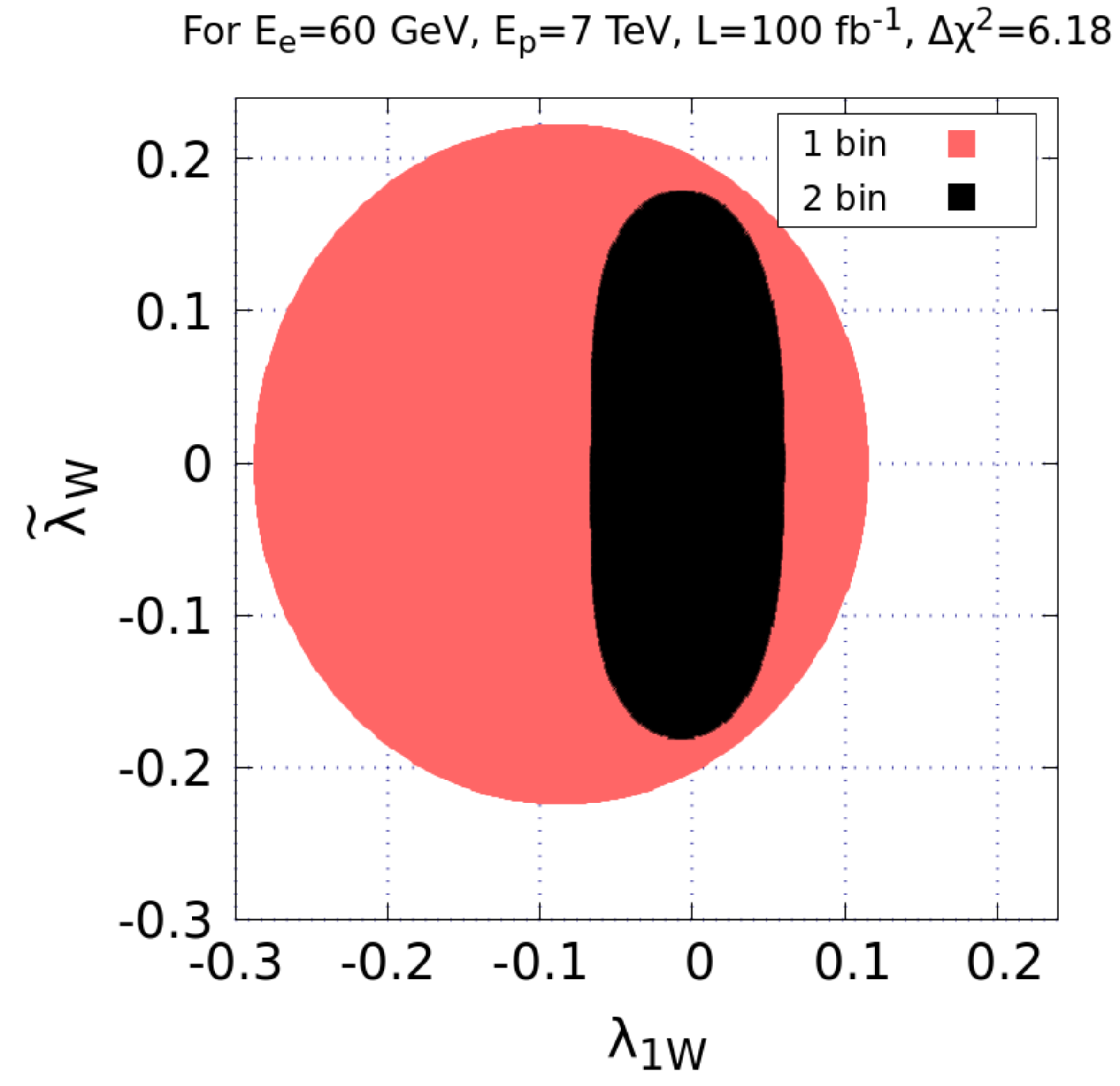
$$\kappa_Z,\ \lambda_{1Z},\ \lambda_{2Z},\ \tilde{\lambda}_Z \rightarrow 91\,\%, 74\,\%, 73\,\%, 55\,\%$$

two parameter analysis for HWW coupling

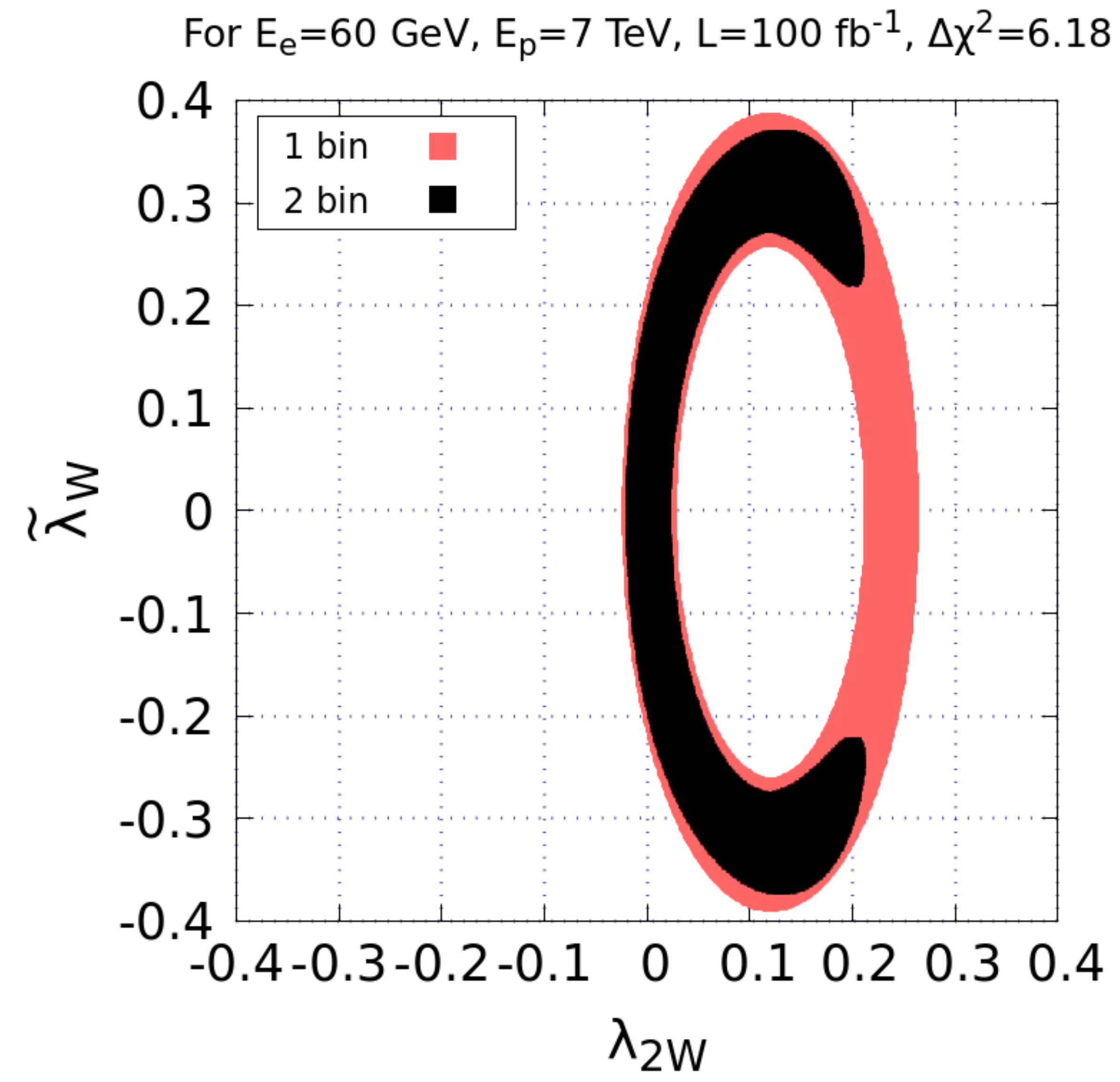
$$X^{\mathrm{BSM}} = X^{\mathrm{SM}} + \sum_i X_i c_i + \sum_{i,j} X_{ij} c_i c_j \,.$$

Correlation of two BSM parameters





- Parameter space increases as going from one parameter to two parameter analysis
- $(\lambda_{1W}, \lambda_{2W})$ region is strongly correlated
- $(\lambda_{2W}, \widetilde{\lambda}_W)$ region has least effect of 2 bin analysis



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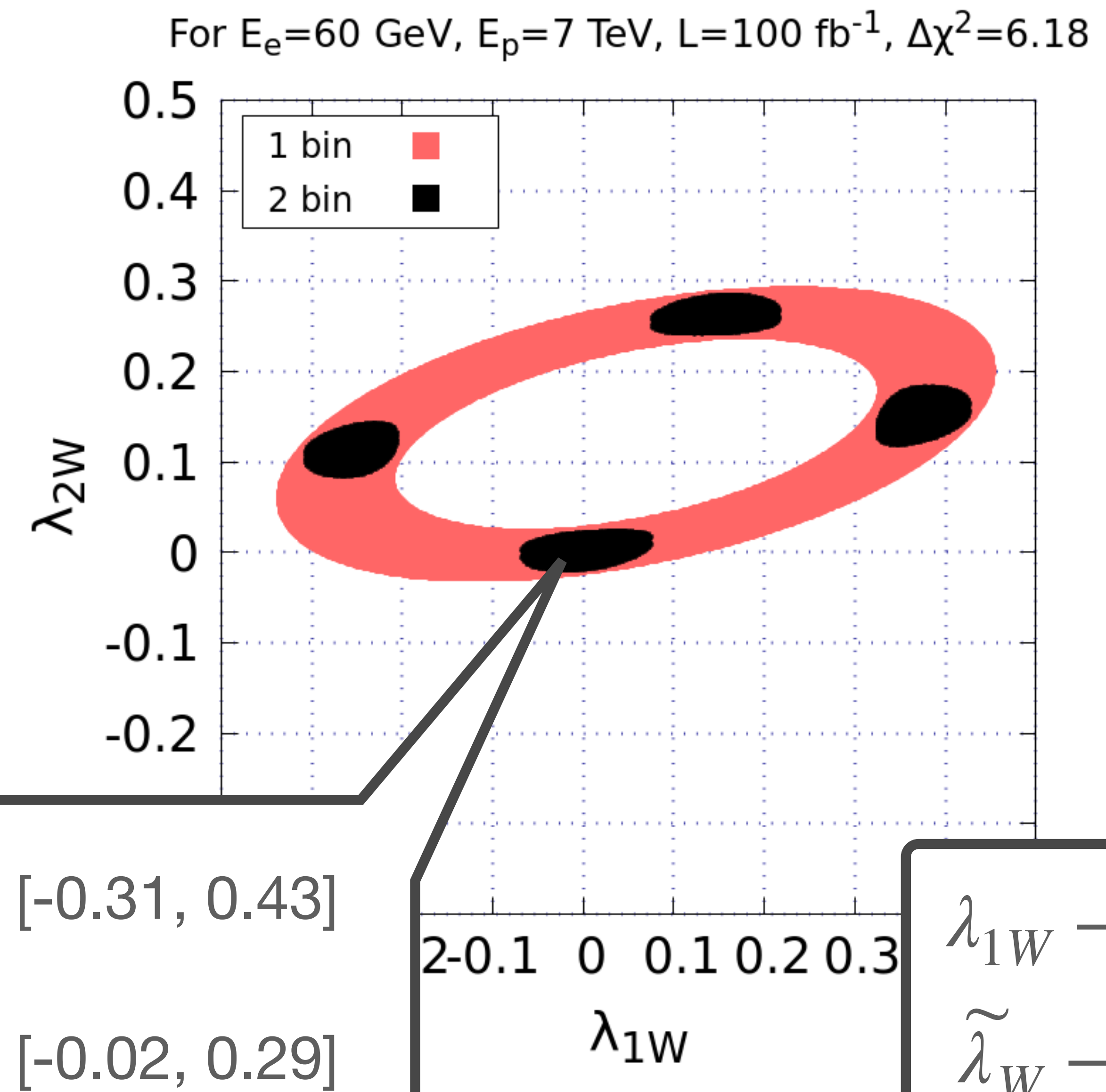

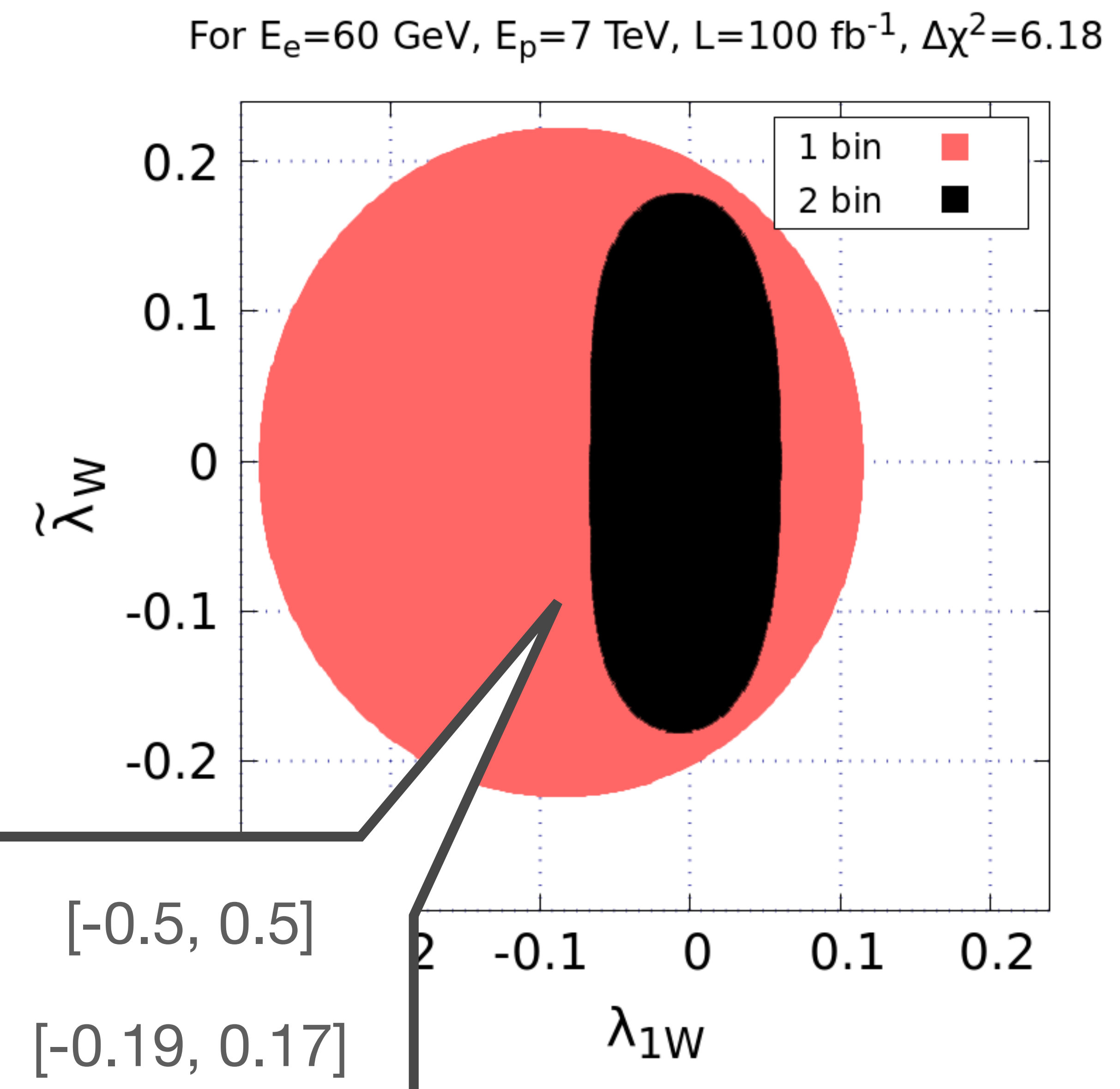

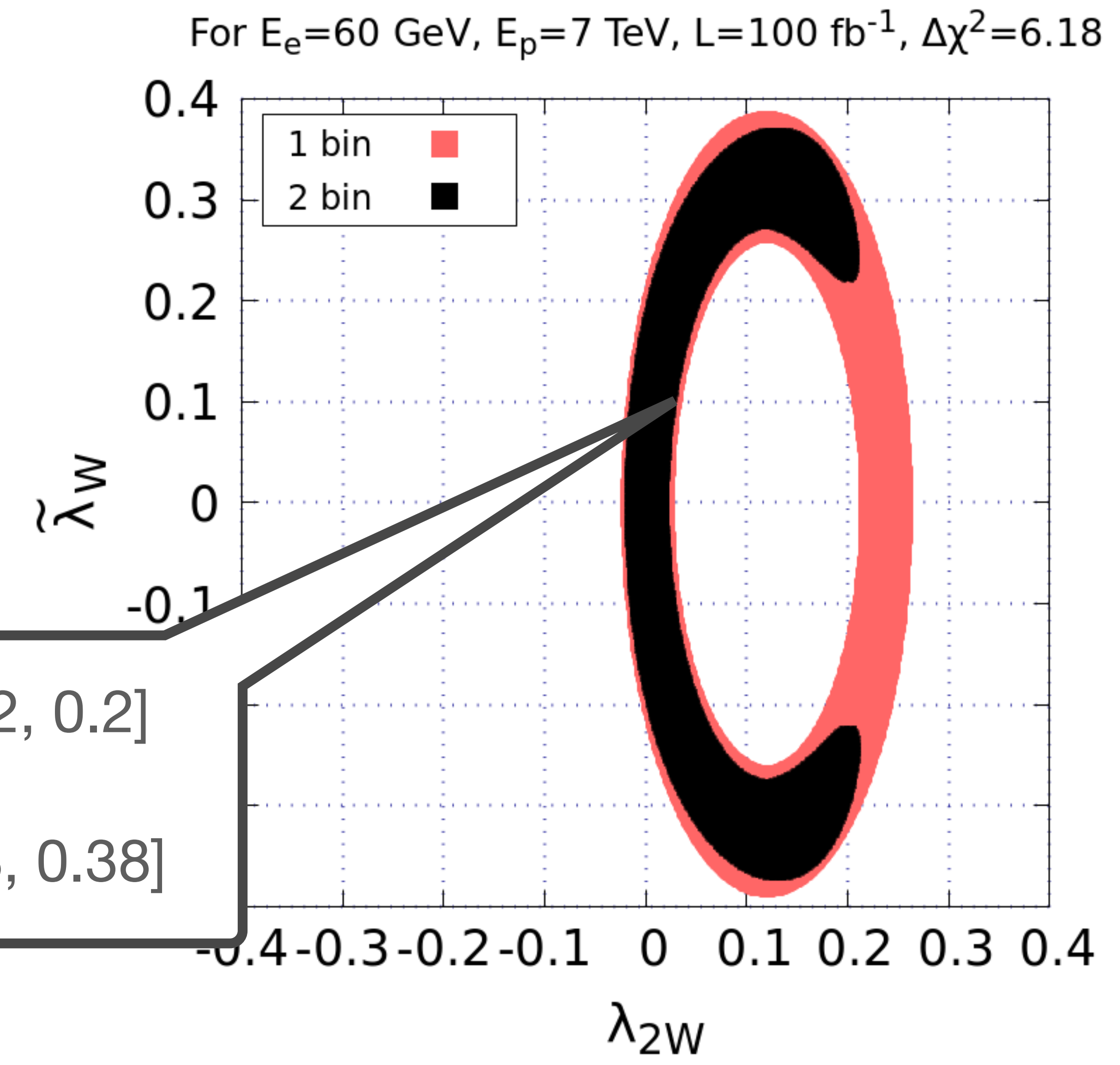

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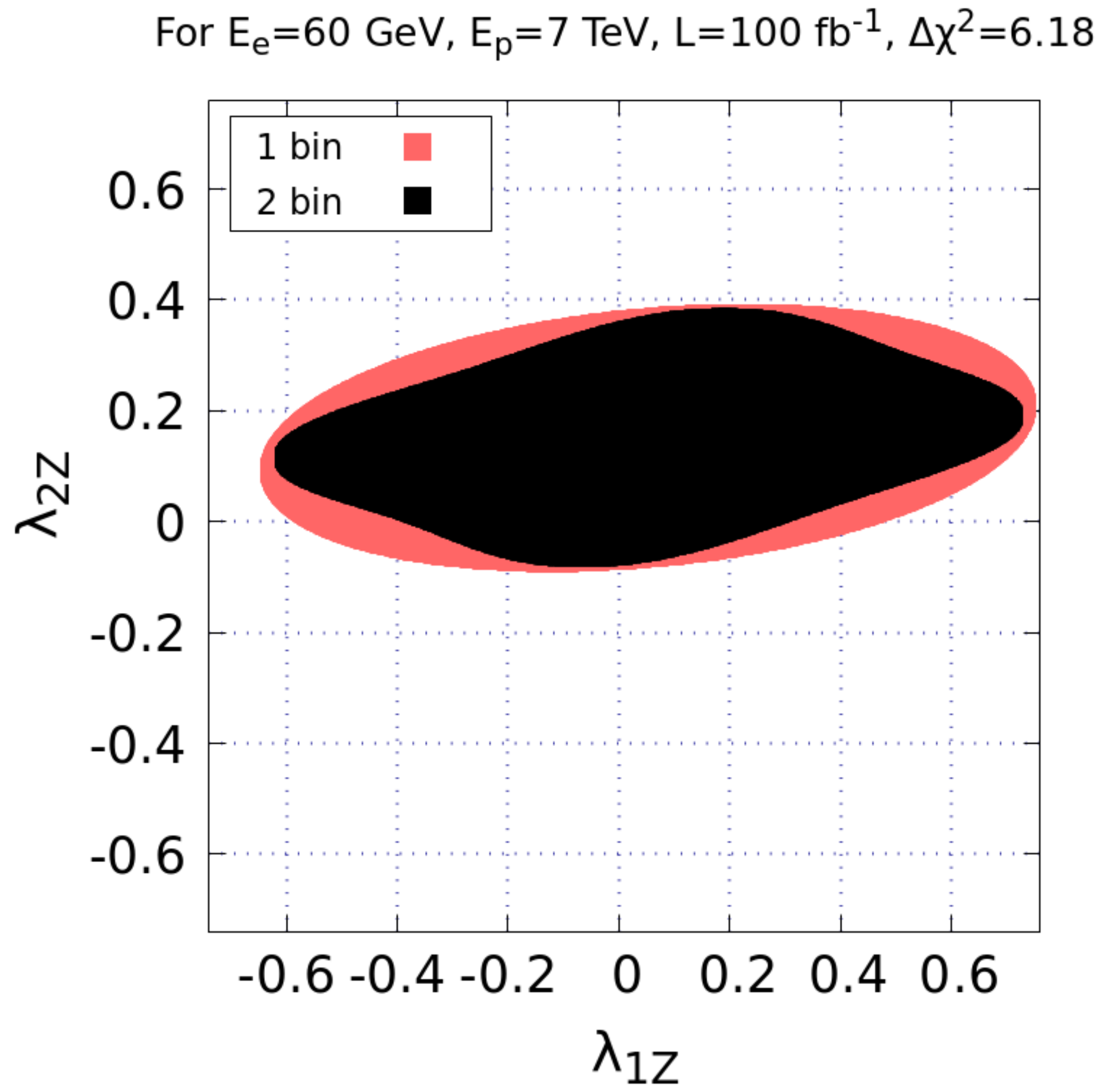
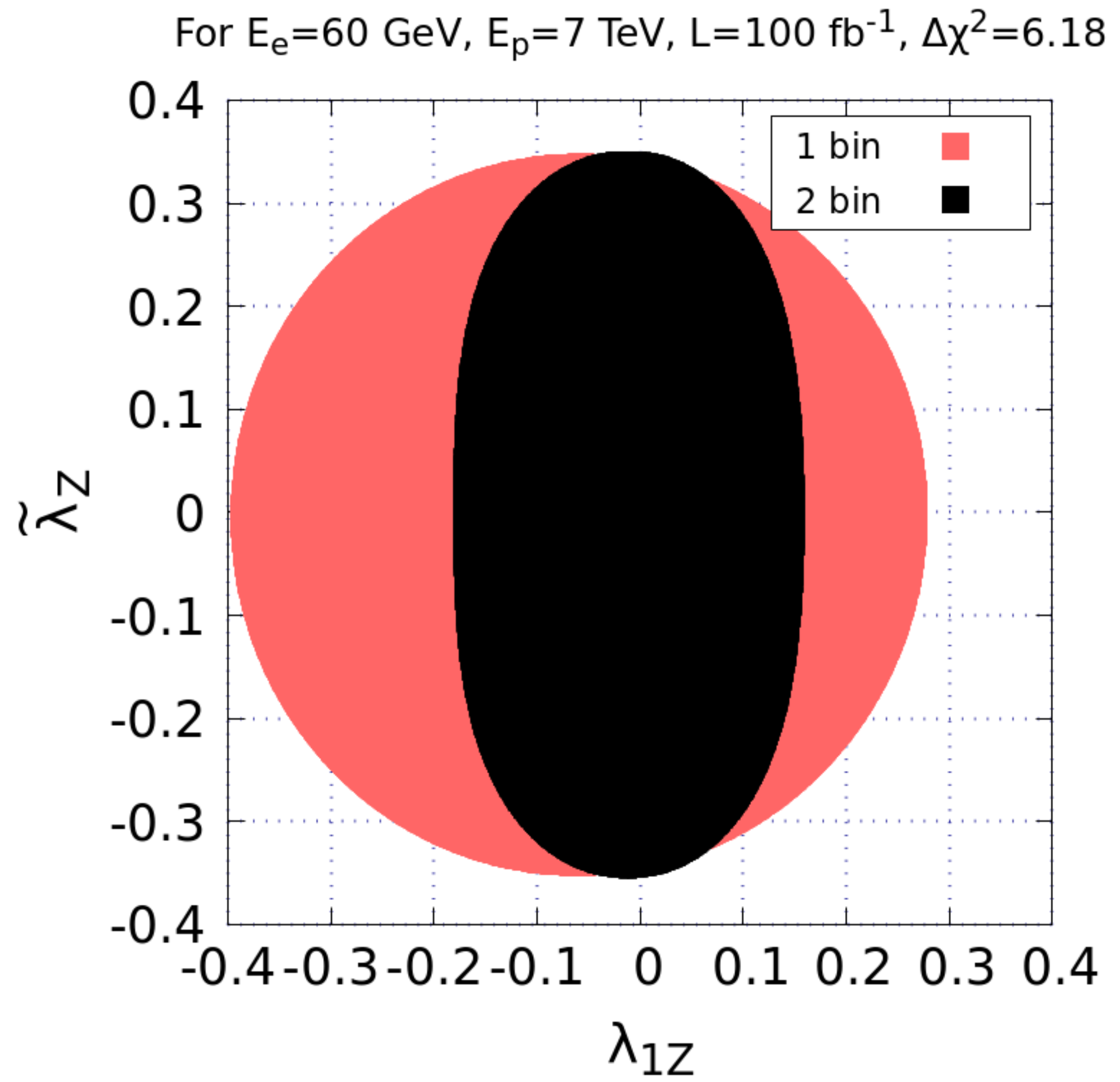
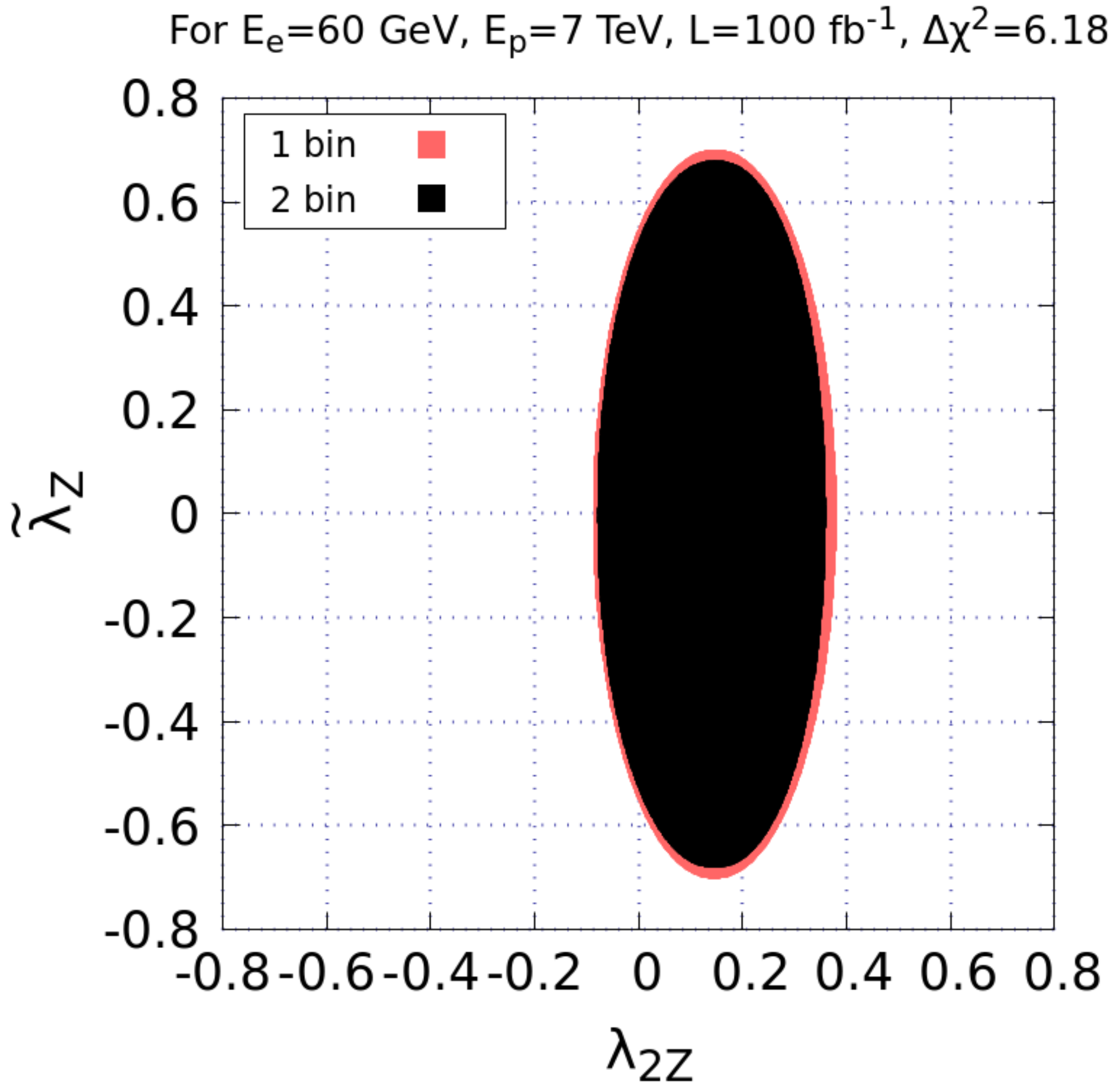
two parameter analysis for HZZ coupling

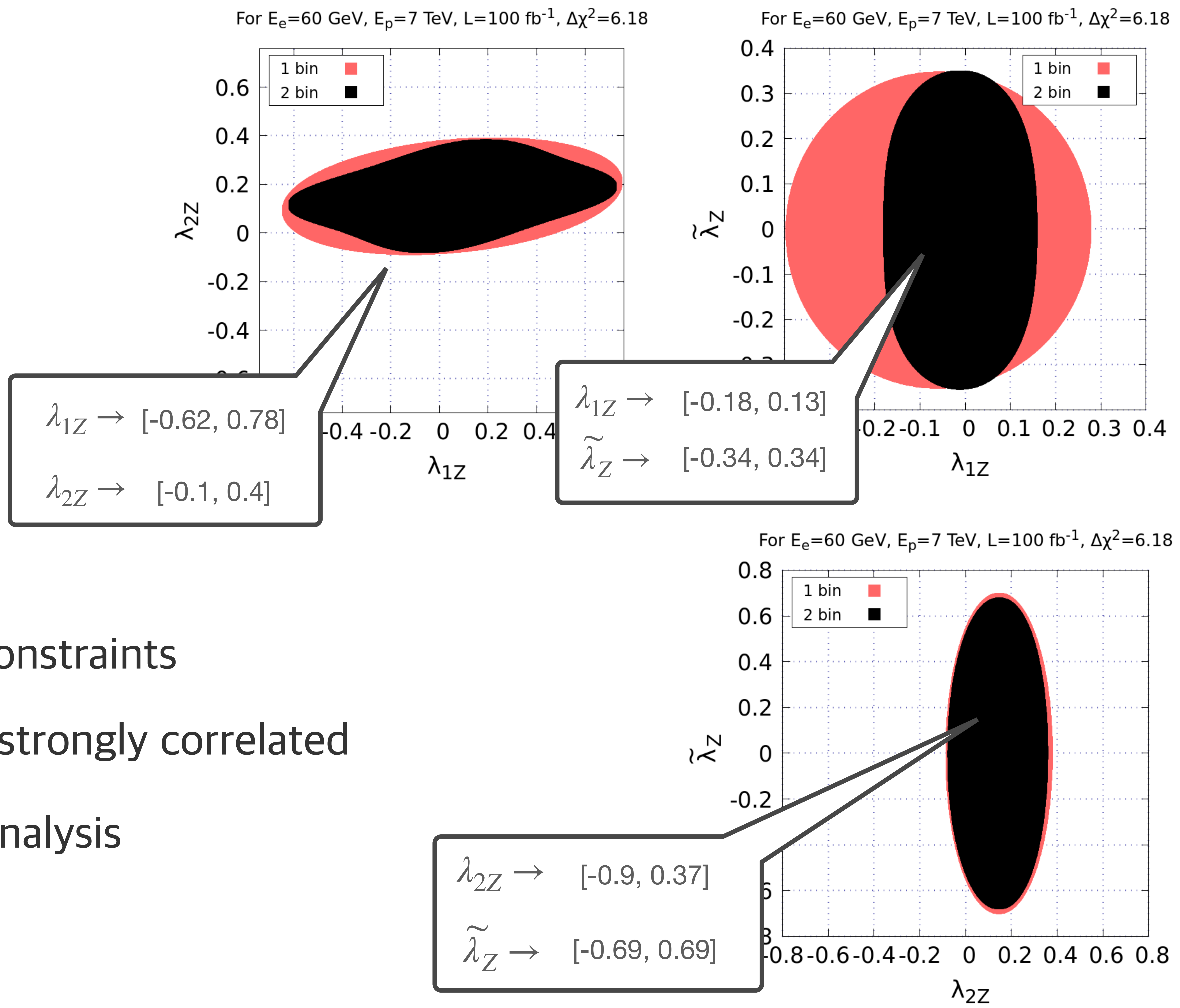






- 2 bin analysis is not efficient to improve constraints
- Like HWW case, $(\lambda_{1Z}, \lambda_{2Z})$ region is also strongly correlated
- $(\lambda_{2Z}, \widetilde{\lambda}_Z)$ region has least effect of 2 bin analysis

two parameter analysis for HZZ coupling



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Conclusion

- $|\Delta\phi|$ distribution is sensitive to $HVV(V = W^{\pm}, Z)$ coupling.
- Using $|\Delta\phi|$ distribution, constraints are obtained keeping one parameter and two parameters non zero at a time.
- Constraints on BSM parameters are improved as going from 1 bin to 2 bin.
- Change in constraints as a function of luminosity is discussed.
- Constraints from two parameter analysis are loose as compared to one parameter analysis.

Back up

For BSM parameter c_i, χ^2 function is

$$\chi^2(c_i) = \sum_{j=1}^{n} \left(\frac{N_j^{\mathrm{BSM}}(c_i) - N_j^{\mathrm{SM}}}{\Delta N_j} \right)^2$$

N_j^{SM} and N_j^{BSM} → SM and BSM events in j^{th} bin

uncertainty (Statistical + systematic) $\quad \Delta N_j = \sqrt{N_j^{\mathrm{SM+Bkg}} \left(1 + \delta_{sys}^2 N_j^{\mathrm{SM+Bkg}}\right)}$

↓ (systematic) 5%

↓ (Statistical)

$$\sqrt{N_j^{SM+Bkg}} = \sqrt{\sigma_j^{SM+Bkg}\ L}$$

Back up

- $e^- p \to \nu_e b\bar{b}jj$ has 2 events after cuts

- $e^- p \to e^- jjj$ has 15 events and S/B changes 0.41 to 0.38

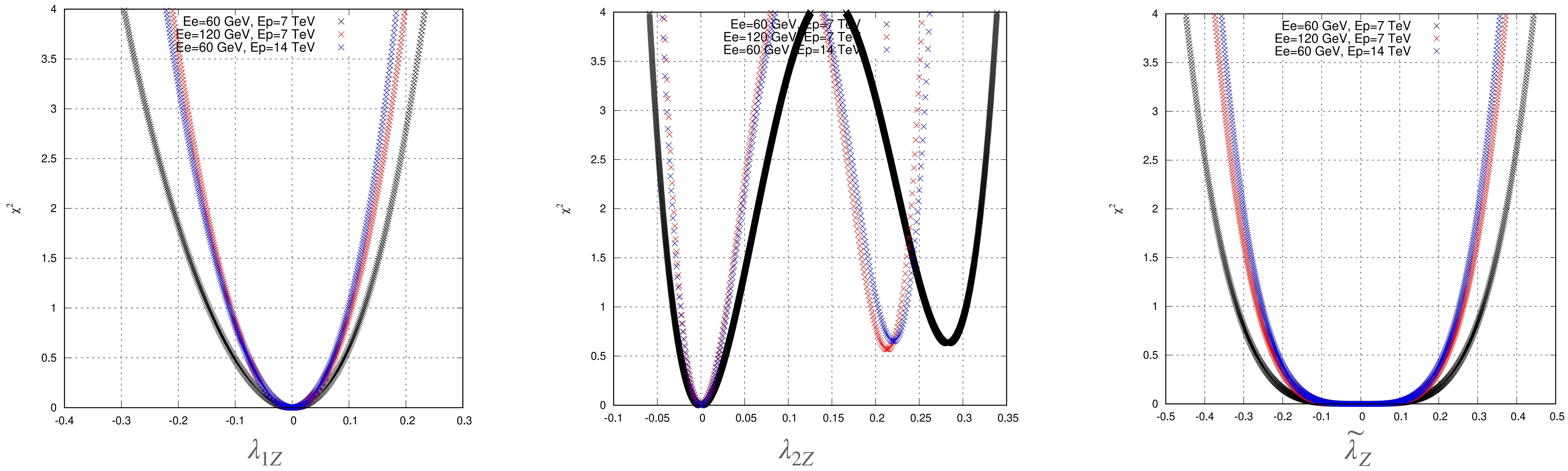
- PDF: NN23LO1

Uncertainty: 2.5%

- Renormalisation factorisation scale choice: -1 in MadGraph which is related to the transverse energy of the final state particles

Uncertainty: 5%

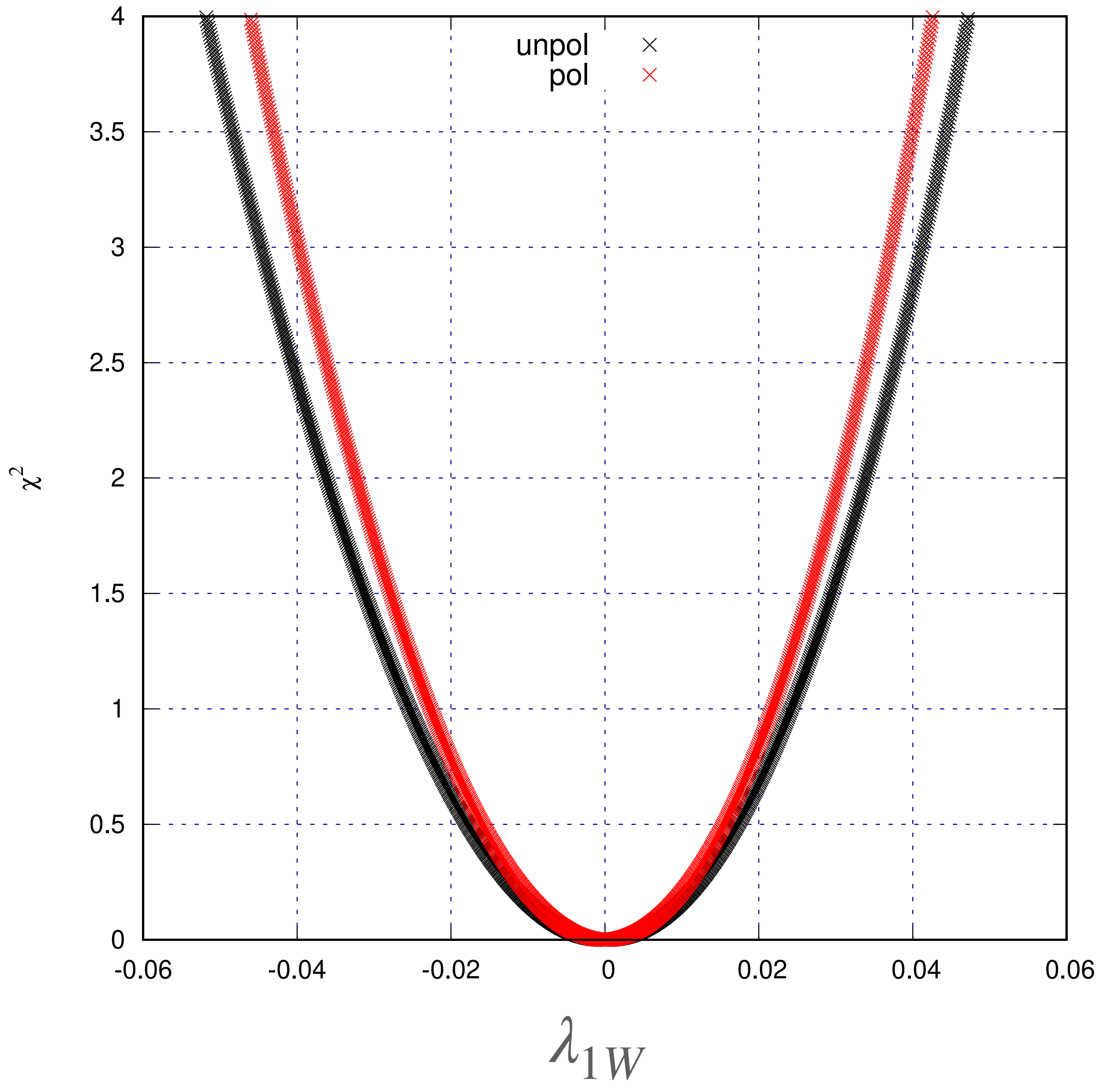
Back up

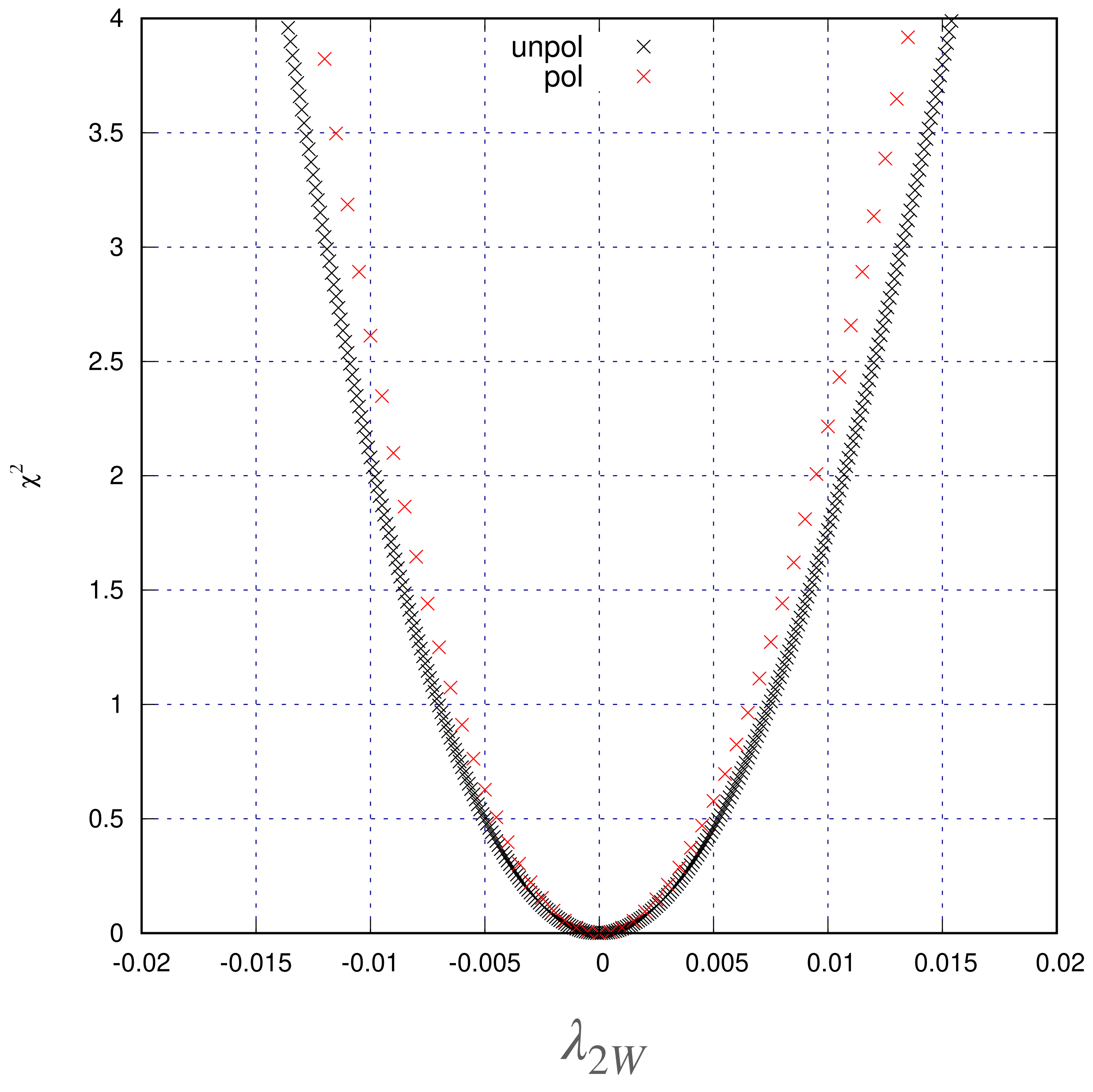


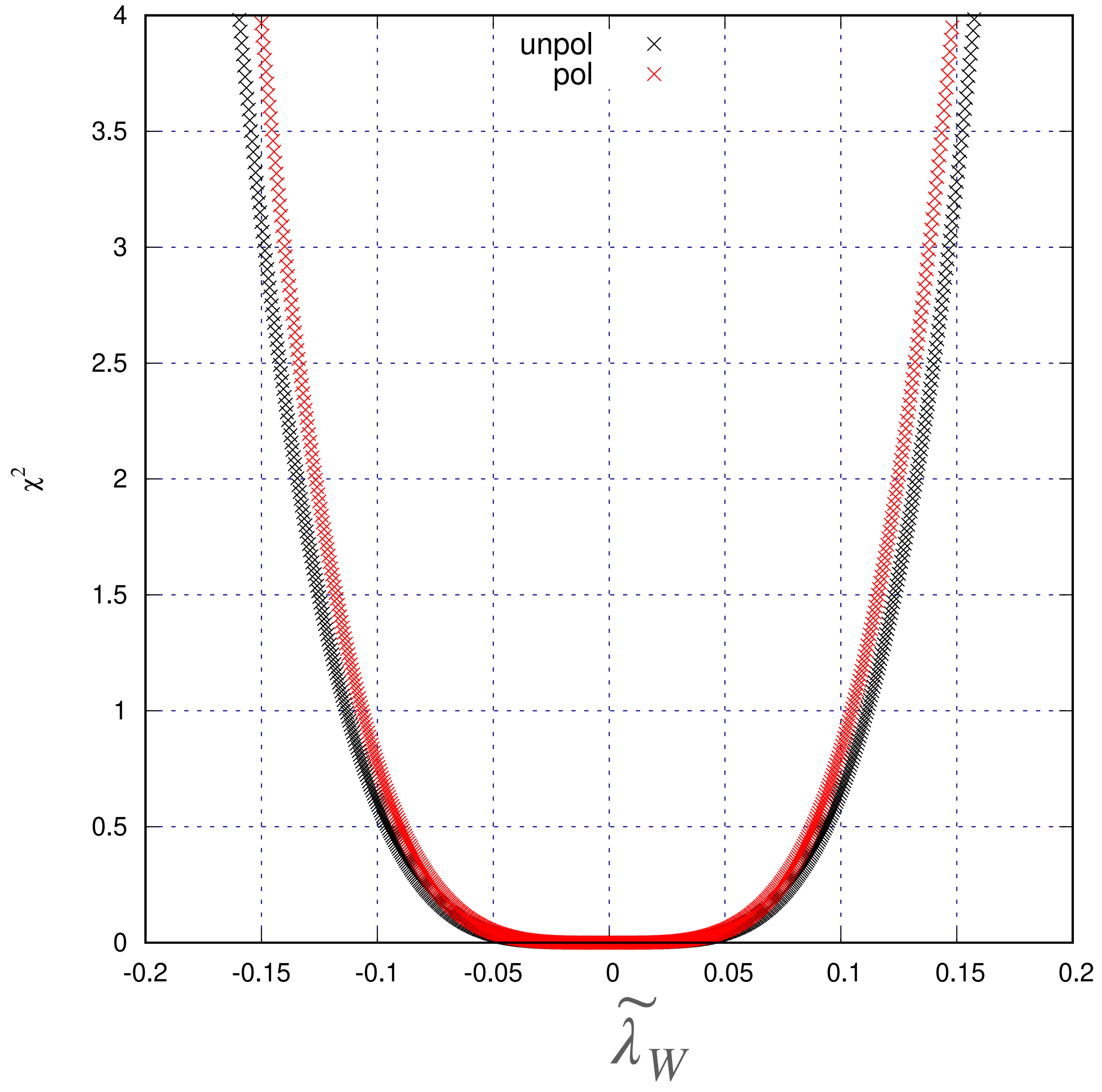
Constraints on HZZ parameters with respect to energy

- Constraints are improved by increasing energy

Back up







Constraints on HWW parameters for -80% e-beam polarisation

- For -80% e-beam polarization S/B =11.0 (CC) and 0.3 (NC)

No significant improvement in NC but constraints improved by 7-10% in CC case.