

# CLIC to Probe Dibosons at High Energies

By  
**Davide Maria Lombardo**  
University of Geneva

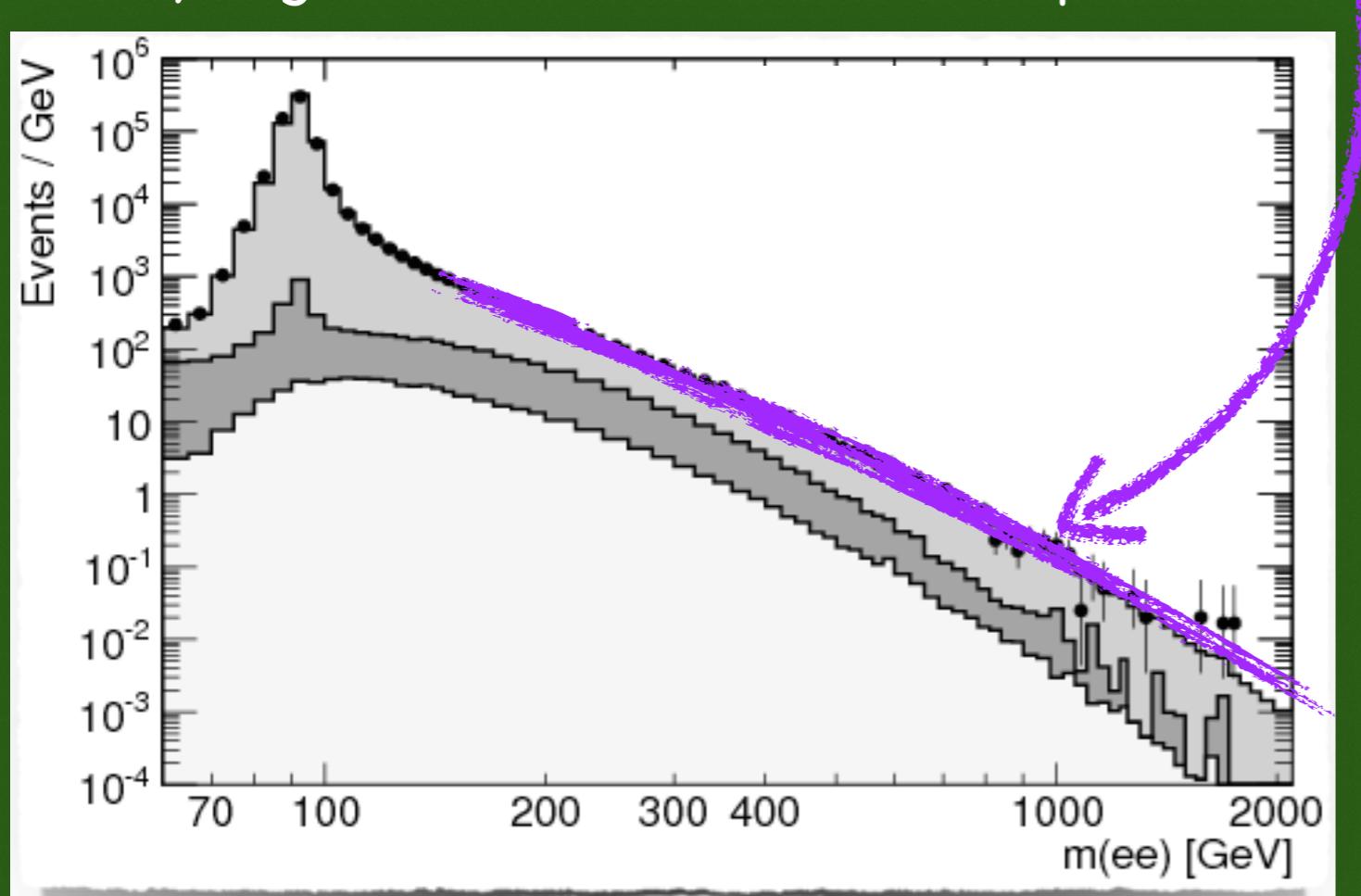
Based on the work in collaboration with Brian Henning and  
Francesco Riva  
(Coming Soon on the Arxiv)



# Aim: Exploring Nature at Smaller Distances

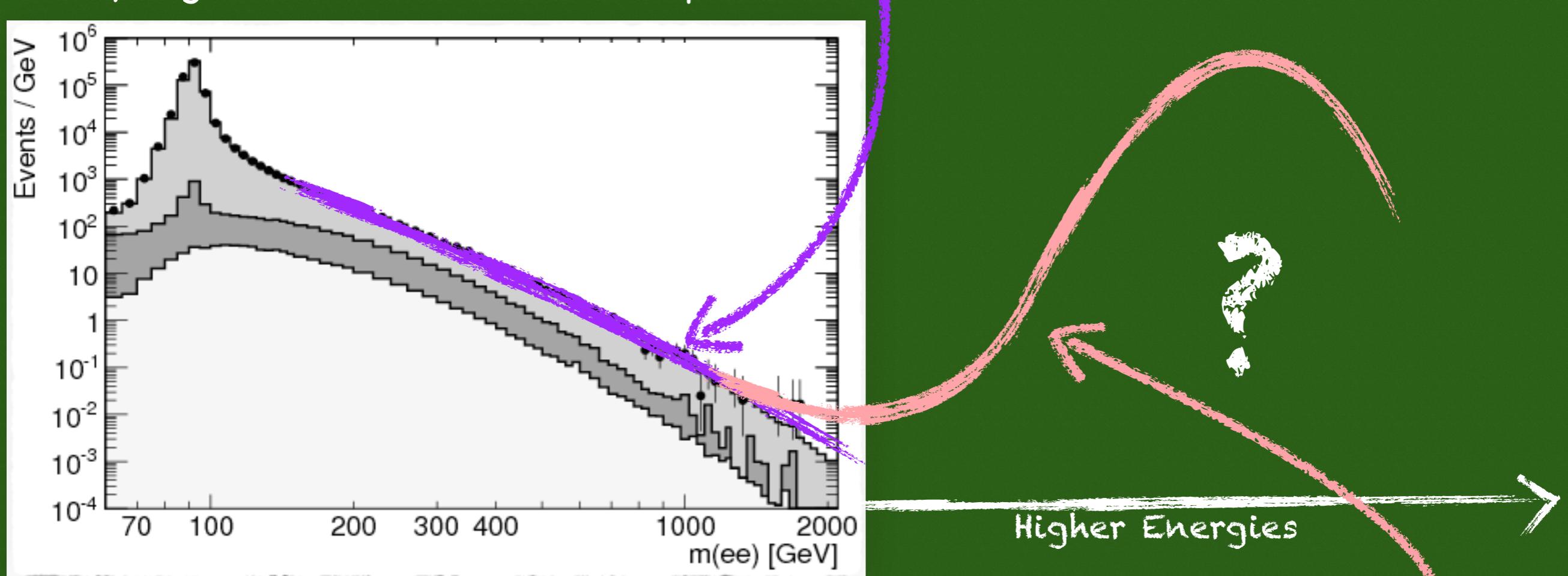
# Aim: Exploring Nature at Smaller Distances

- The Standard Model
  - > Current Interpretation of High-Energy Phenomenology
  - > Very High Confidence Level with Experiments



# Aim: Exploring Nature at Smaller Distances

- The Standard Model
  - > Current Interpretation of High-Energy Phenomenology
  - > Very High Confidence Level with Experiments



- Extending the Current Knowledge

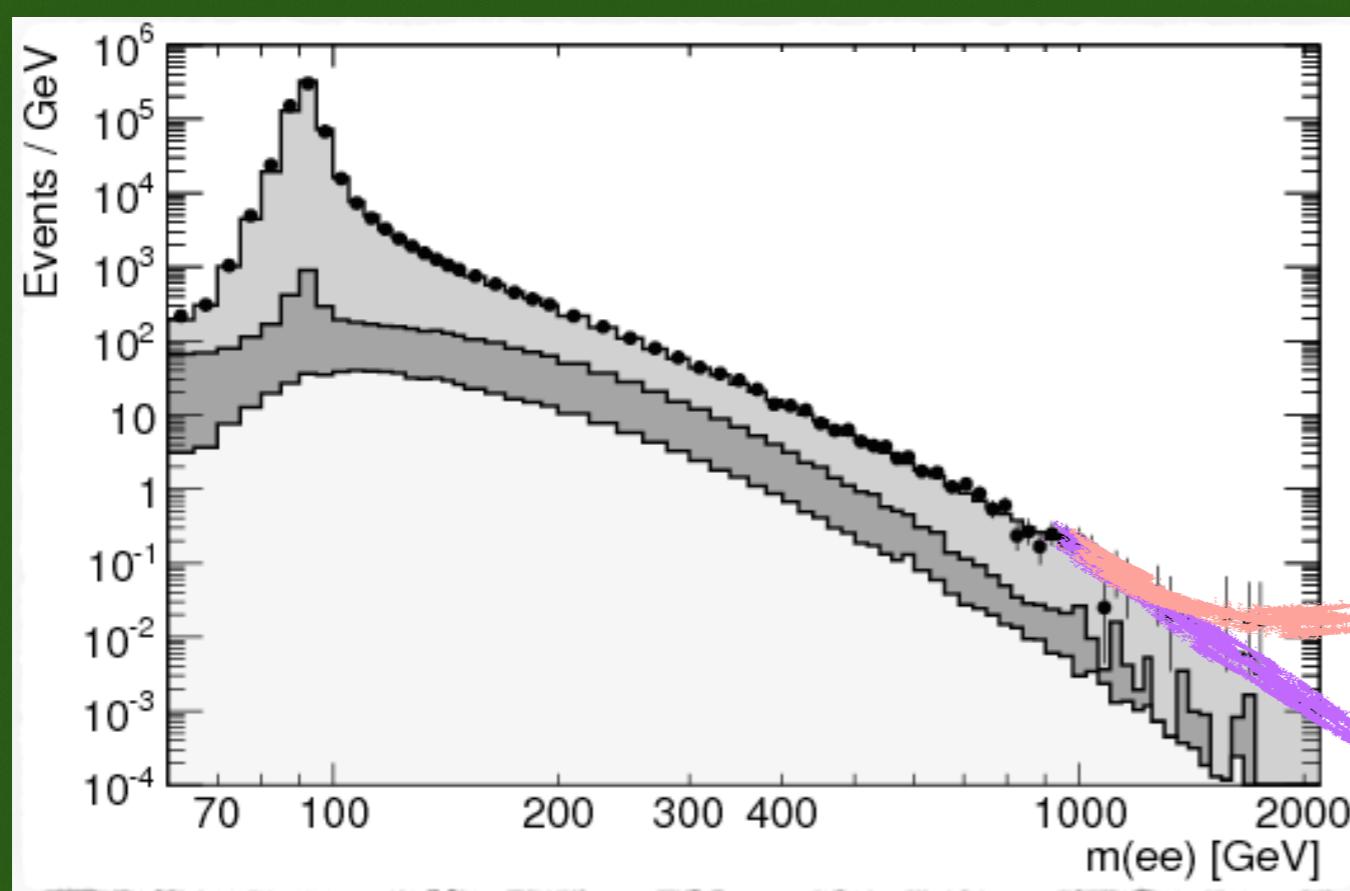
- > Tests at very High-Energy
- > Deviations? New Phenomena?



# How: Higher Energy Tests

# How: Higher Energy Tests

- Energy-Growing Departures

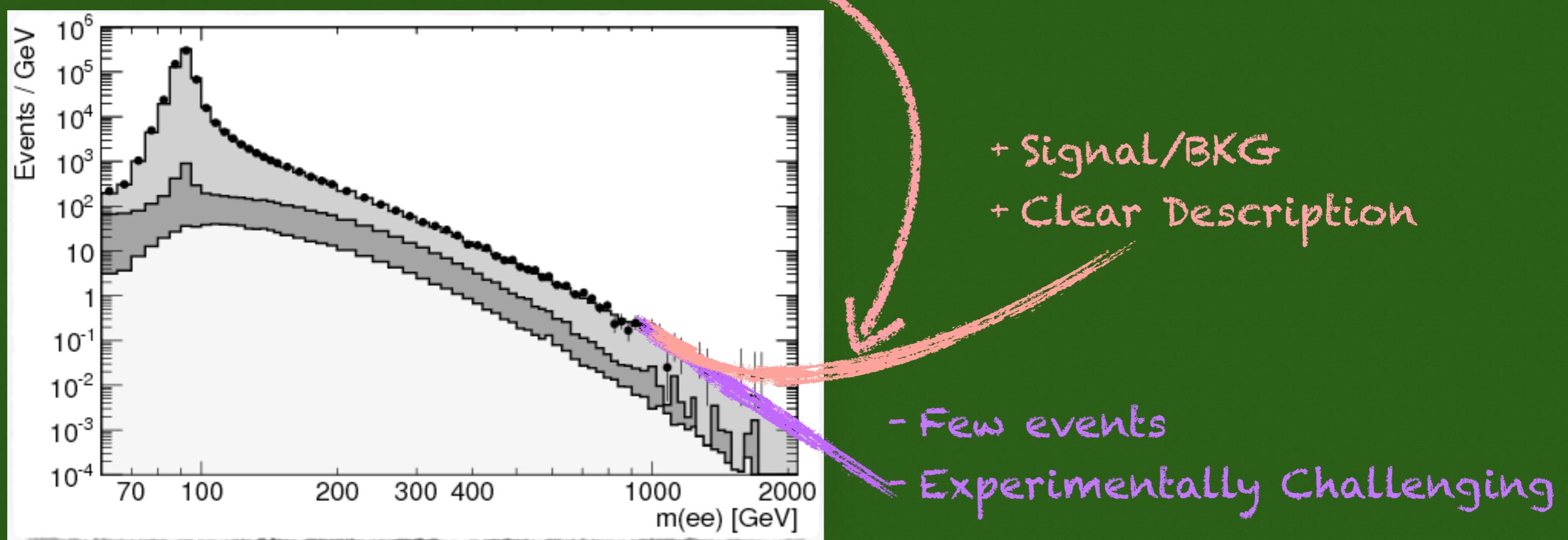


+ Signal/BKG  
+ Clear Description

- Few events  
Experimentally Challenging

# How: Higher Energy Tests

- Energy-Growing Departures

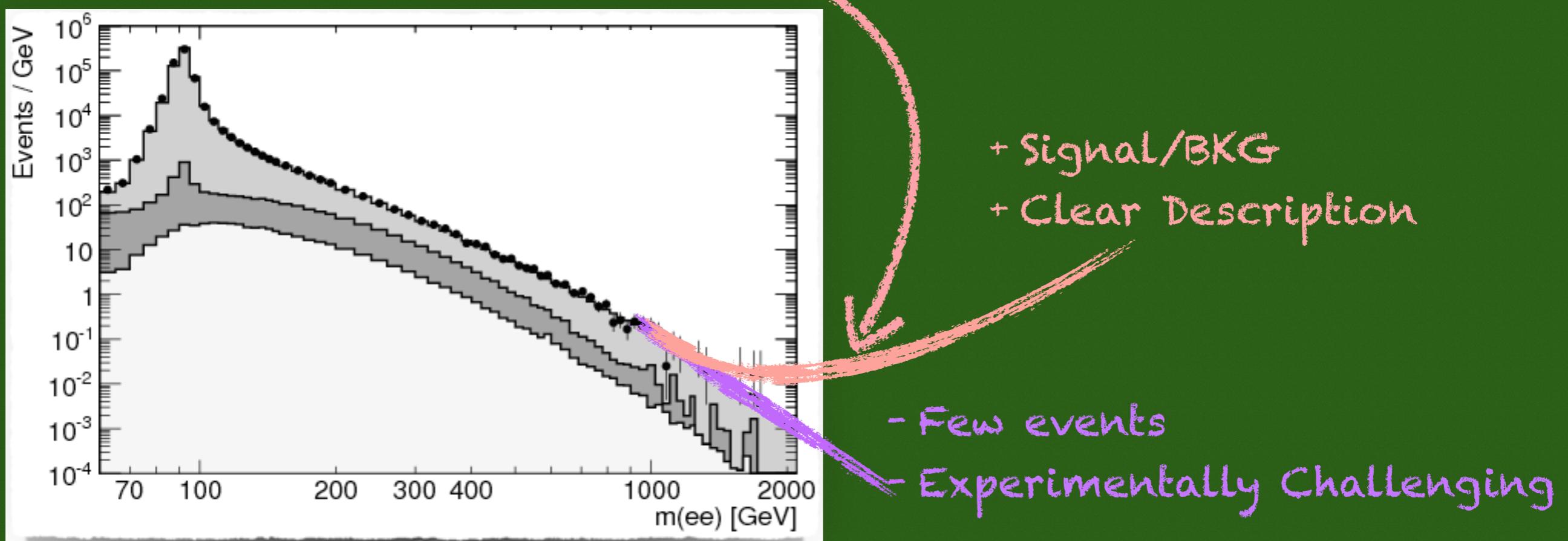


- EFT Framework

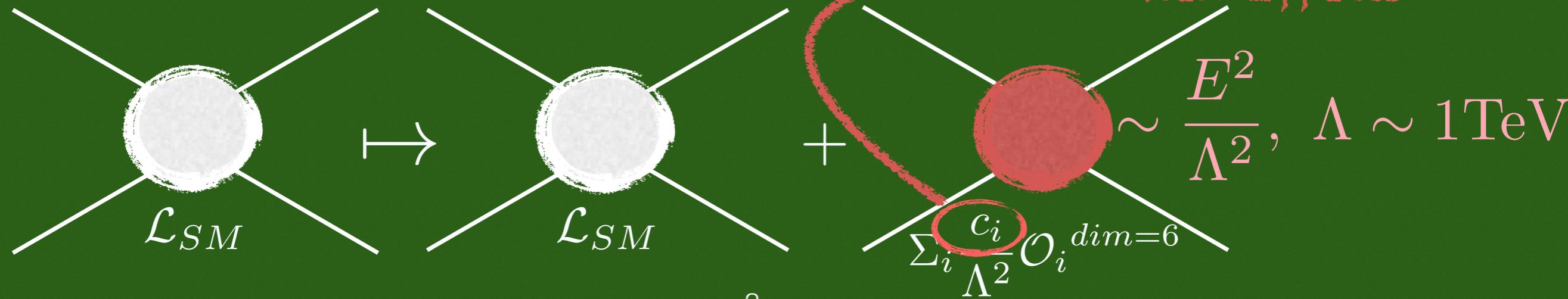


# How: Higher Energy Tests

- Energy-Growing Departures



- EFT Framework

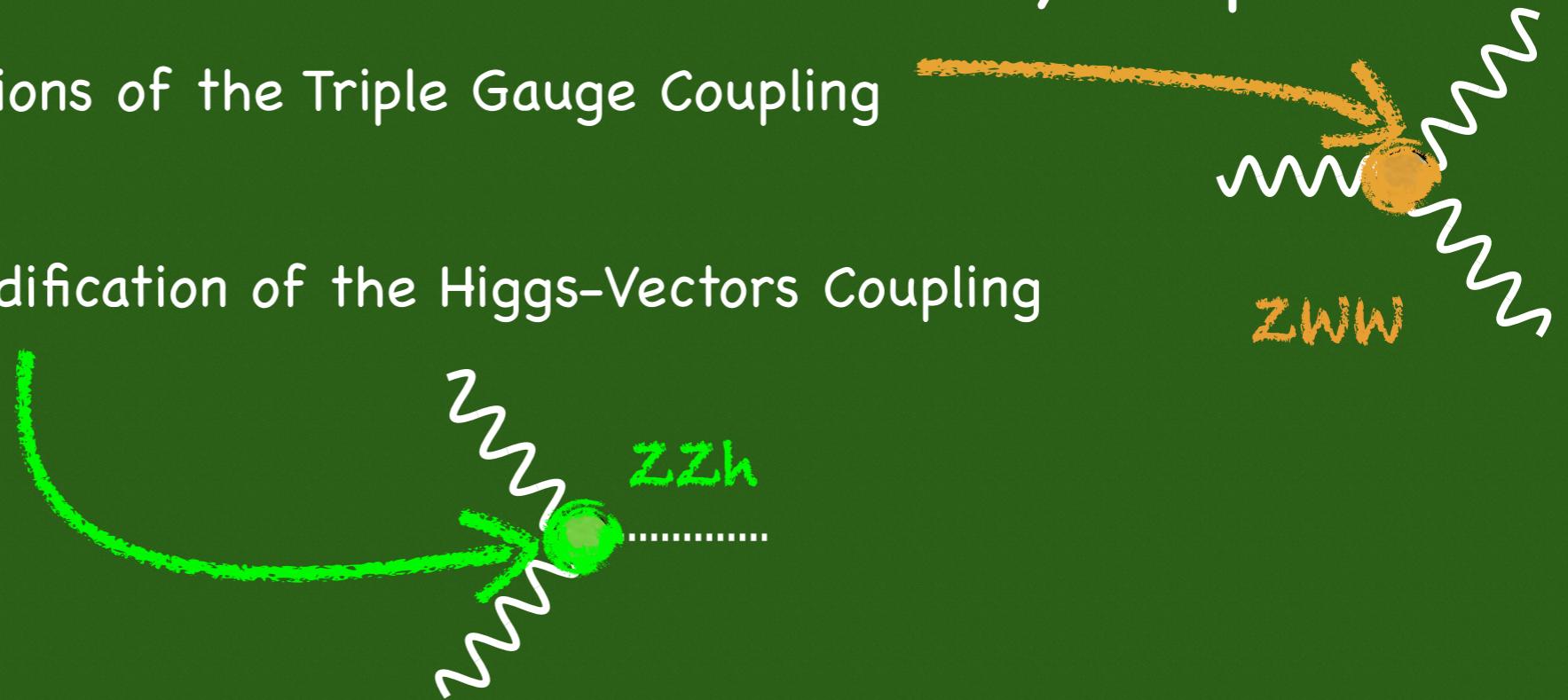




# Where: WW and Zh production @ CLIC

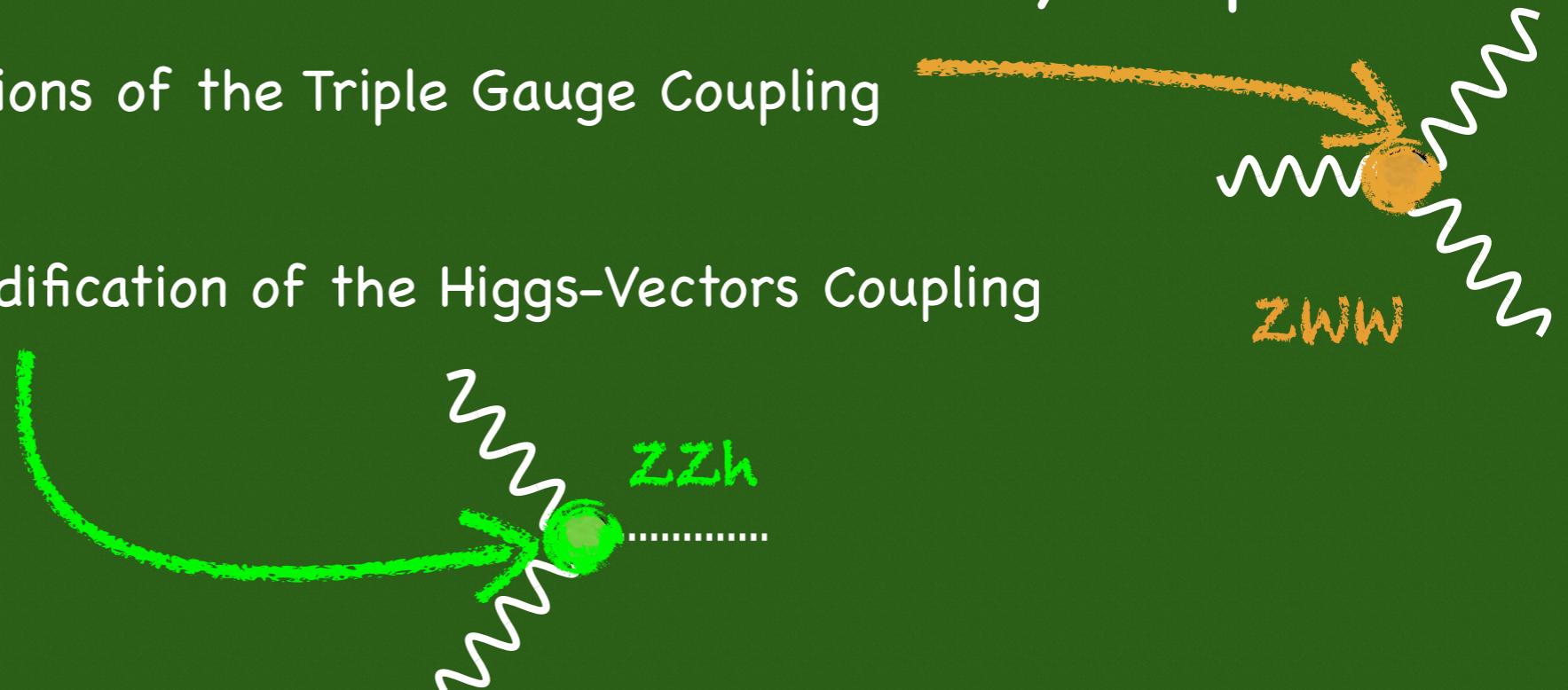
# Where: WW and Zh production @ CLIC

- Dedicated NP-Searches for Different Helicity Amplitudes
  - > WW-Transverse: Modifications of the Triple Gauge Coupling
  - > (Zh,WW)-Longitudinal: Modification of the Higgs-Vectors Coupling



# Where: WW and Zh production @ CLIC

- Dedicated NP-Searches for Different Helicity Amplitudes
  - > WW-Transverse: Modifications of the Triple Gauge Coupling
  - > (Zh,WW)-Longitudinal: Modification of the Higgs-Vectors Coupling
- CLIC
  - > Beam Polarization
  - > Very high-energy Collisions



# Where: WW and Zh production @ CLIC

- Dedicated NP-Searches for Different Helicity Amplitudes
  - > WW-Transverse: Modifications of the Triple Gauge Coupling

> (Zh,WW)-Longitudinal: Modification of the Higgs-Vectors Coupling

- CLIC

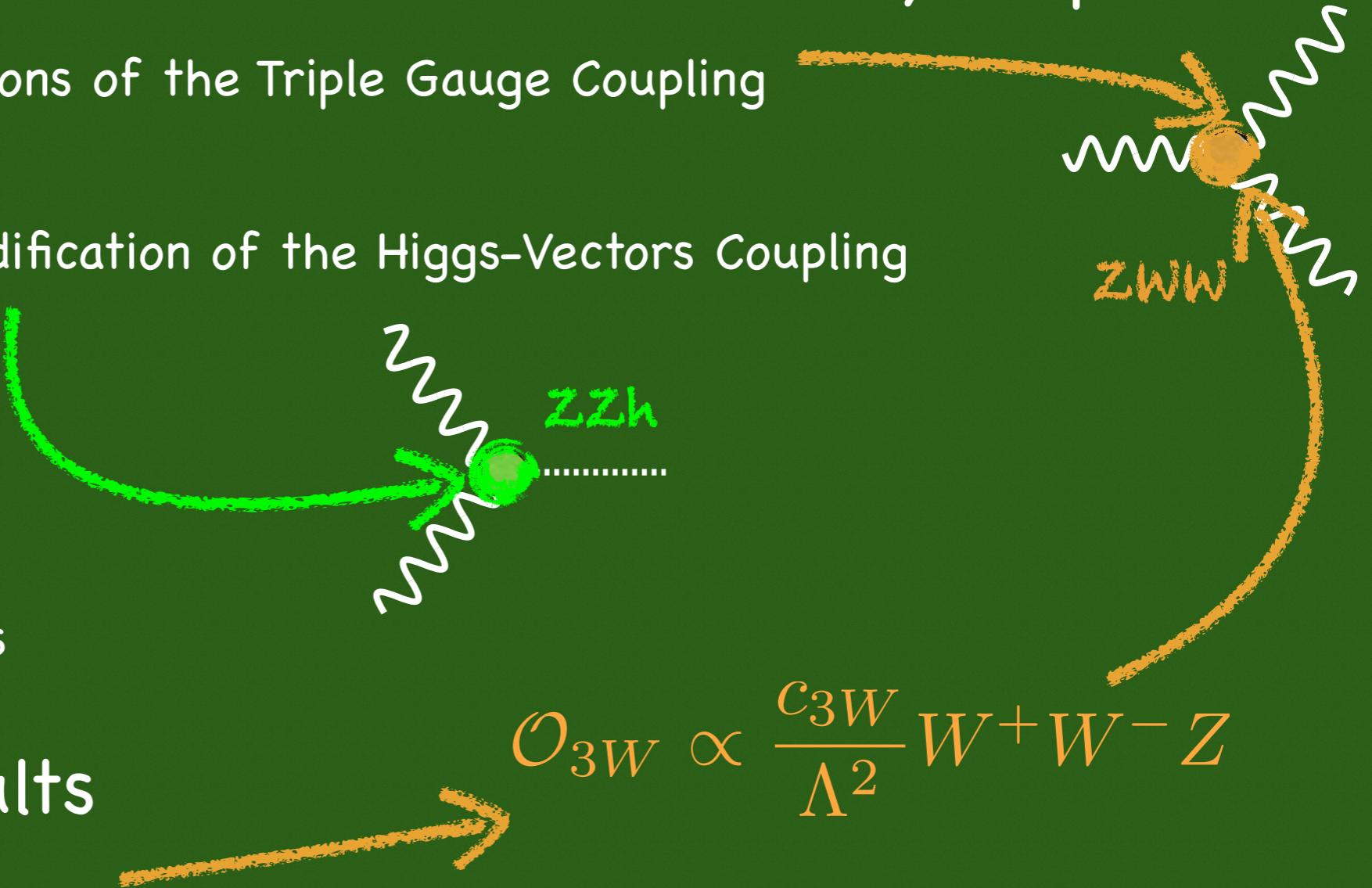
> Beam Polarization

> Very high-energy Collisions

- Analysis and Results

> Searches for NP in Transverses

$$e^+ e^- \rightarrow W_T W_T$$



# Where: WW and Zh production @ CLIC

- Dedicated NP-Searches for Different Helicity Amplitudes
  - > WW-Transverse: Modifications of the Triple Gauge Coupling

- > (Zh,WW)-Longitudinal: Modification of the Higgs-Vectors Coupling

- CLIC

- > Beam Polarization

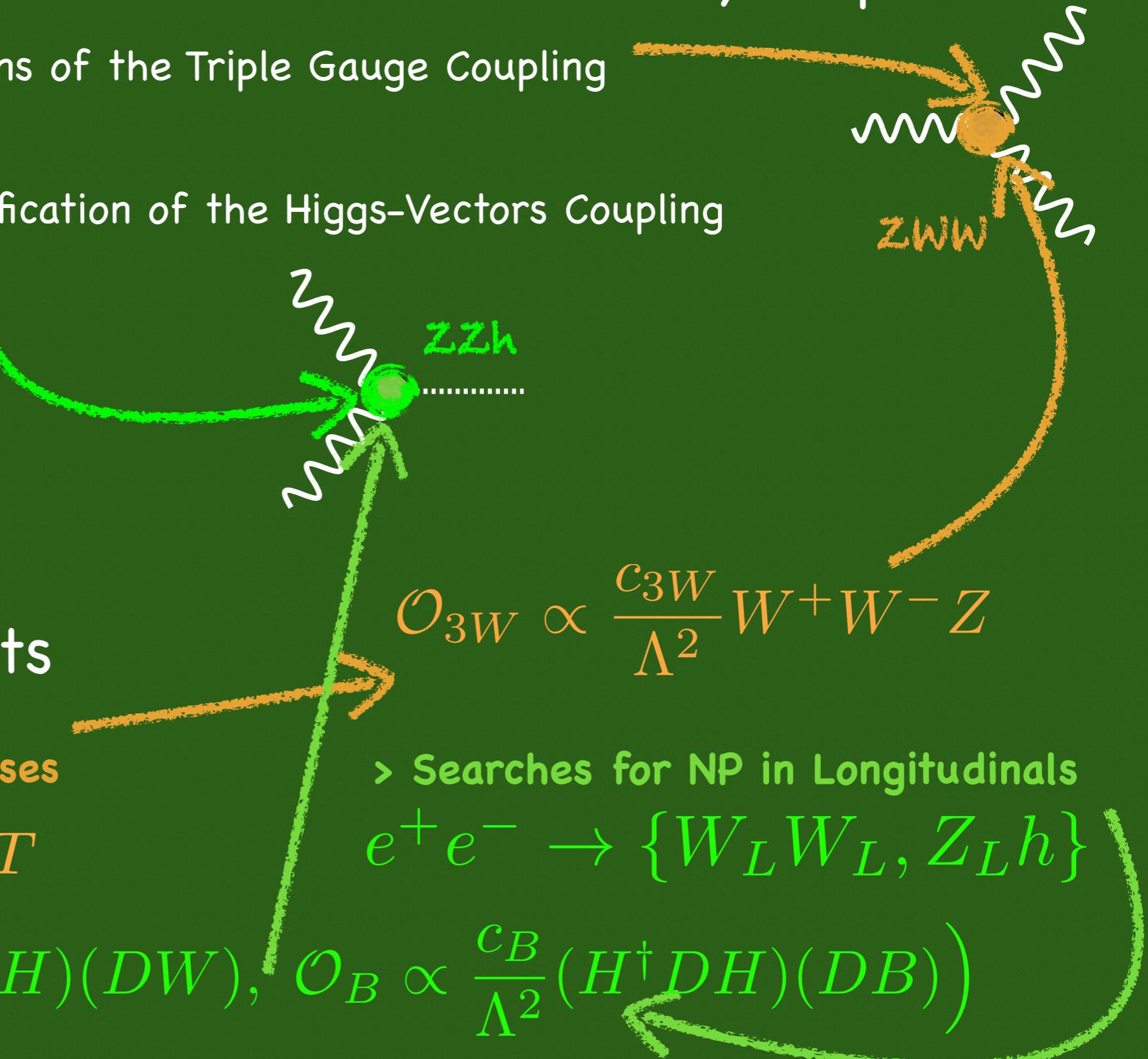
- > Very high-energy Collisions

- Analysis and Results

- > Searches for NP in Transverses

$$e^+ e^- \rightarrow W_T W_T$$

$$\left( \mathcal{O}_W \propto \frac{c_W}{\Lambda^2} (H^\dagger D H)(D W), \quad \mathcal{O}_B \propto \frac{c_B}{\Lambda^2} (H^\dagger D H)(D B) \right)$$





# Study of ee->(WW)Transverse-Analysis1

# Study of ee->(WW)Transverse-Analysis1

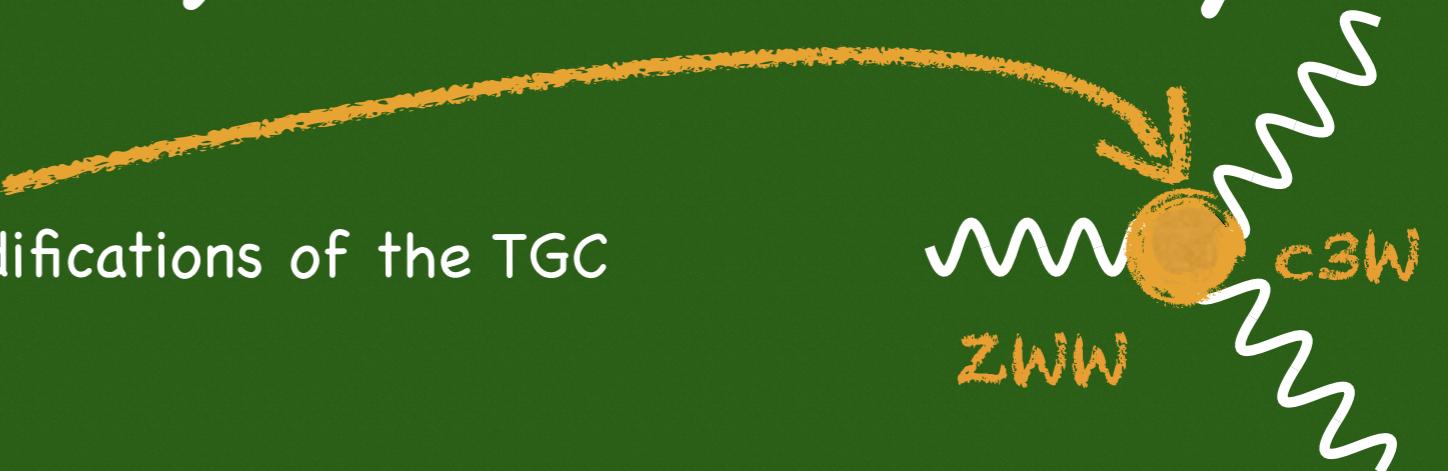
- Target

- > Assessing the reach of CLIC on Modifications of the TGC



# Study of ee->(WW)Transverse-Analysis1

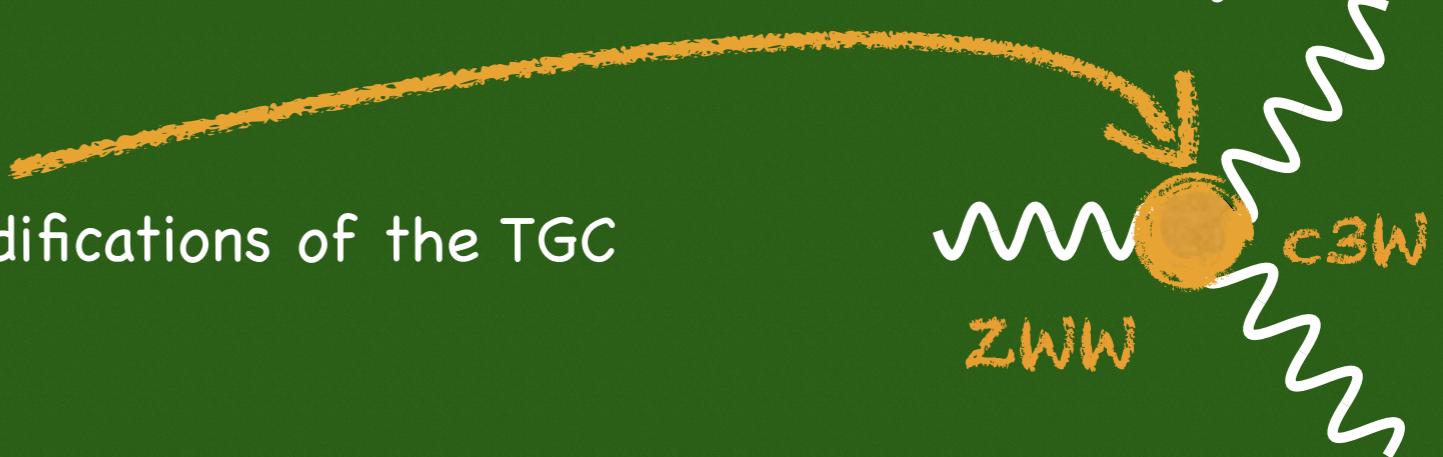
- Target
  - > Assessing the reach of CLIC on Modifications of the TGC
- Pro/Cons



# Study of ee->(WW)Transverse-Analysis1

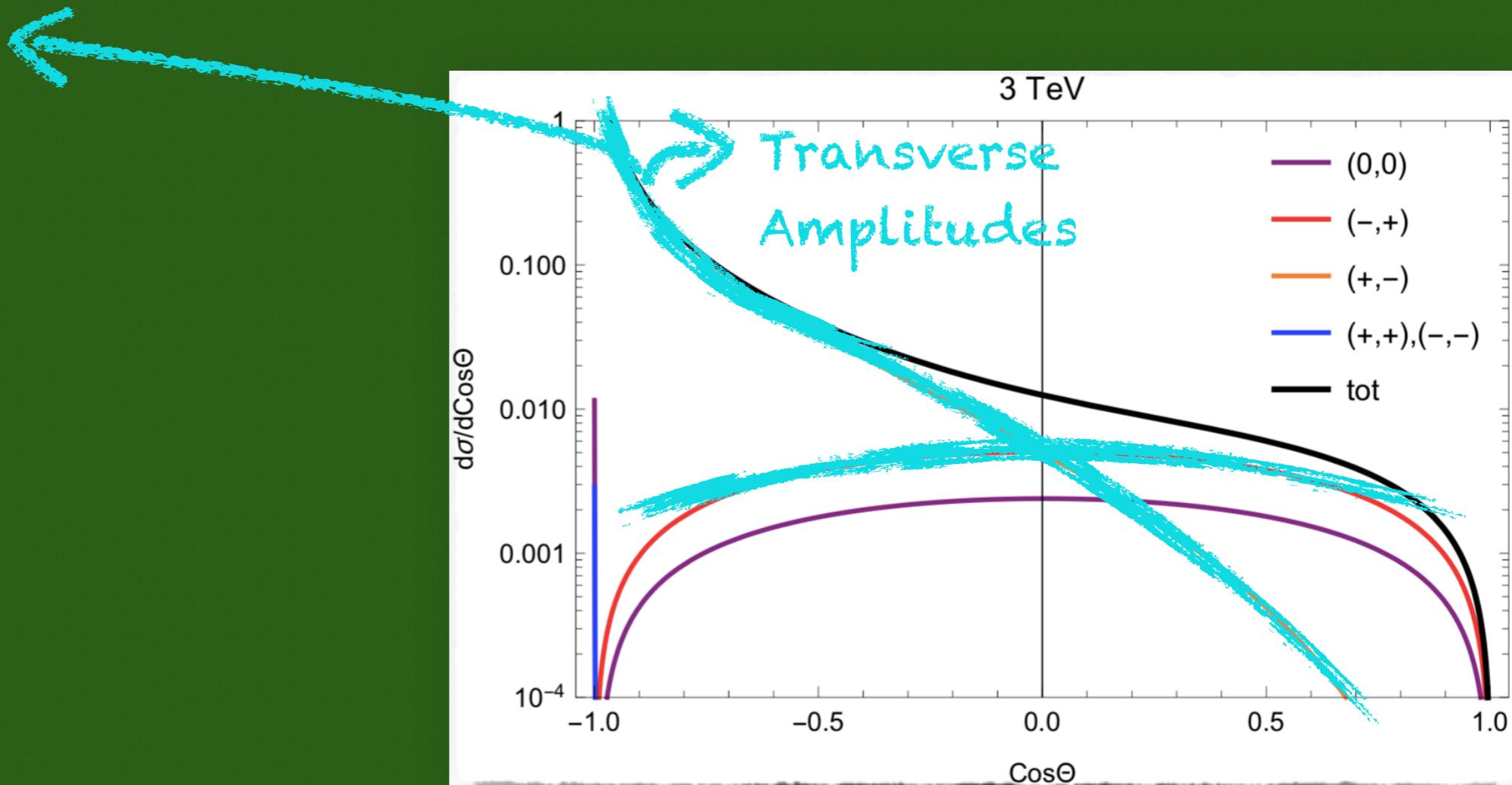
- Target

- > Assessing the reach of CLIC on Modifications of the TGC



- Pro/Cons

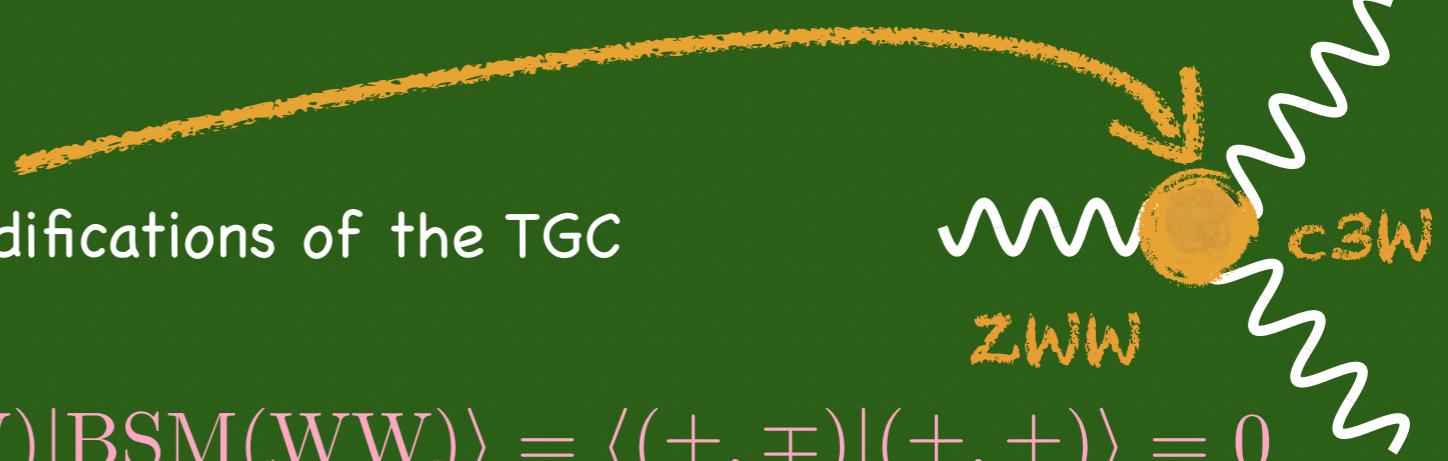
- > Largest Xsections



# Study of ee->(WW)Transverse-Analysis1

- Target

> Assessing the reach of CLIC on Modifications of the TGC



- Pro/Cons

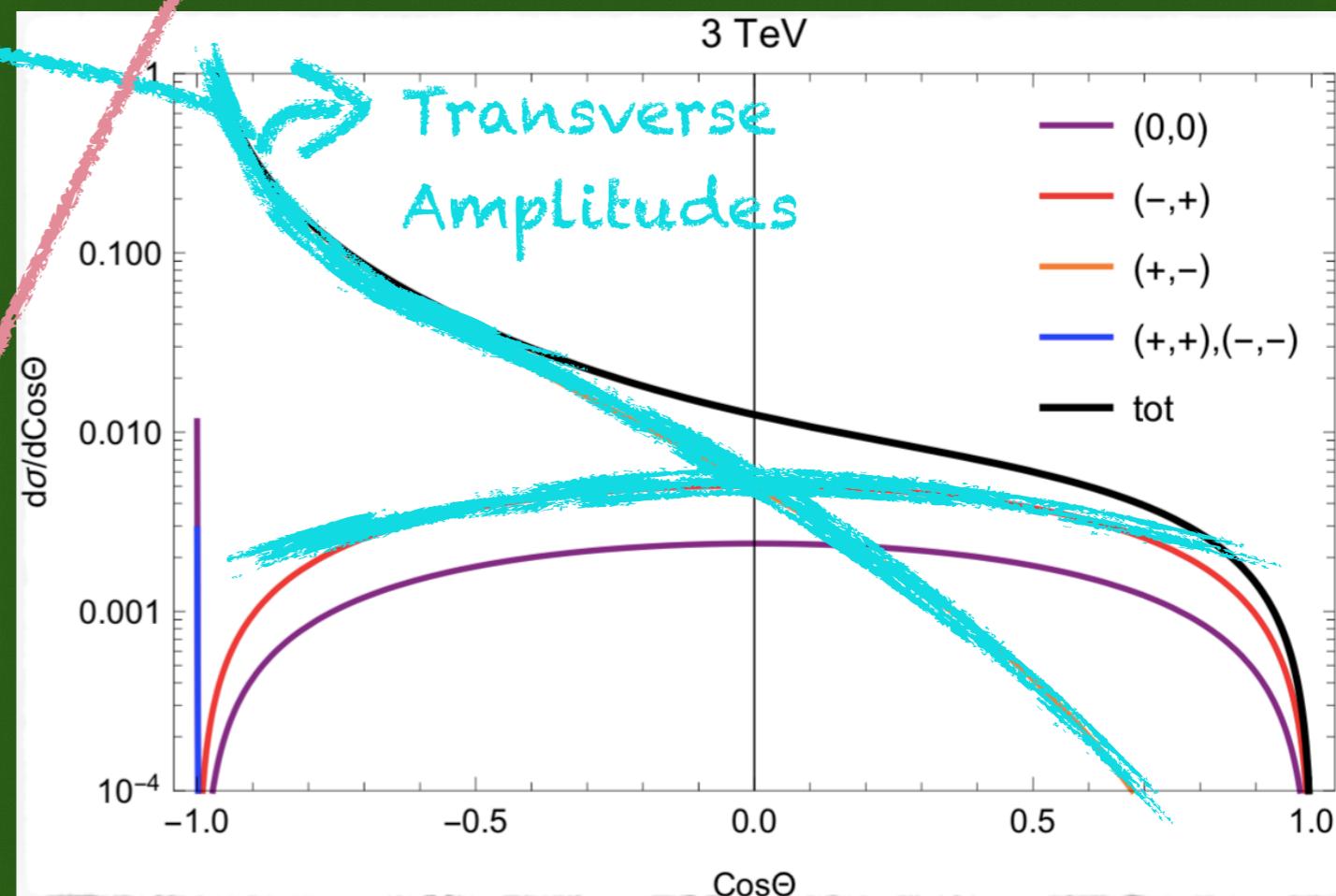
> Largest Xsections

> Non Interference (arXiv:1607.05236)

$$\text{BSM(WW)} \xrightarrow[\text{Helicities}]{\text{Final}} (\pm, \pm)$$

$$\text{SM(WW)} \xrightarrow[\text{Helicities}]{\text{Final}} (\pm, \mp)$$

$$\sigma_{WW} \sim \sigma_{SM} \underbrace{\left(1 + \delta_{SM \times BSM} \sqrt{\left(\frac{E}{\Lambda}\right)^2 + \delta_{BSM \times BSM} \left(\frac{E}{\Lambda}\right)^4}\right)}_{\text{Leading Term}}$$



# Study of ee->(WW)Transverse-Analysis1

- Target

> Assessing the reach of CLIC on Modifications of the TGC

- Pro/Cons

> Largest Xsections

> Non Interference (arXiv:1607.05236)

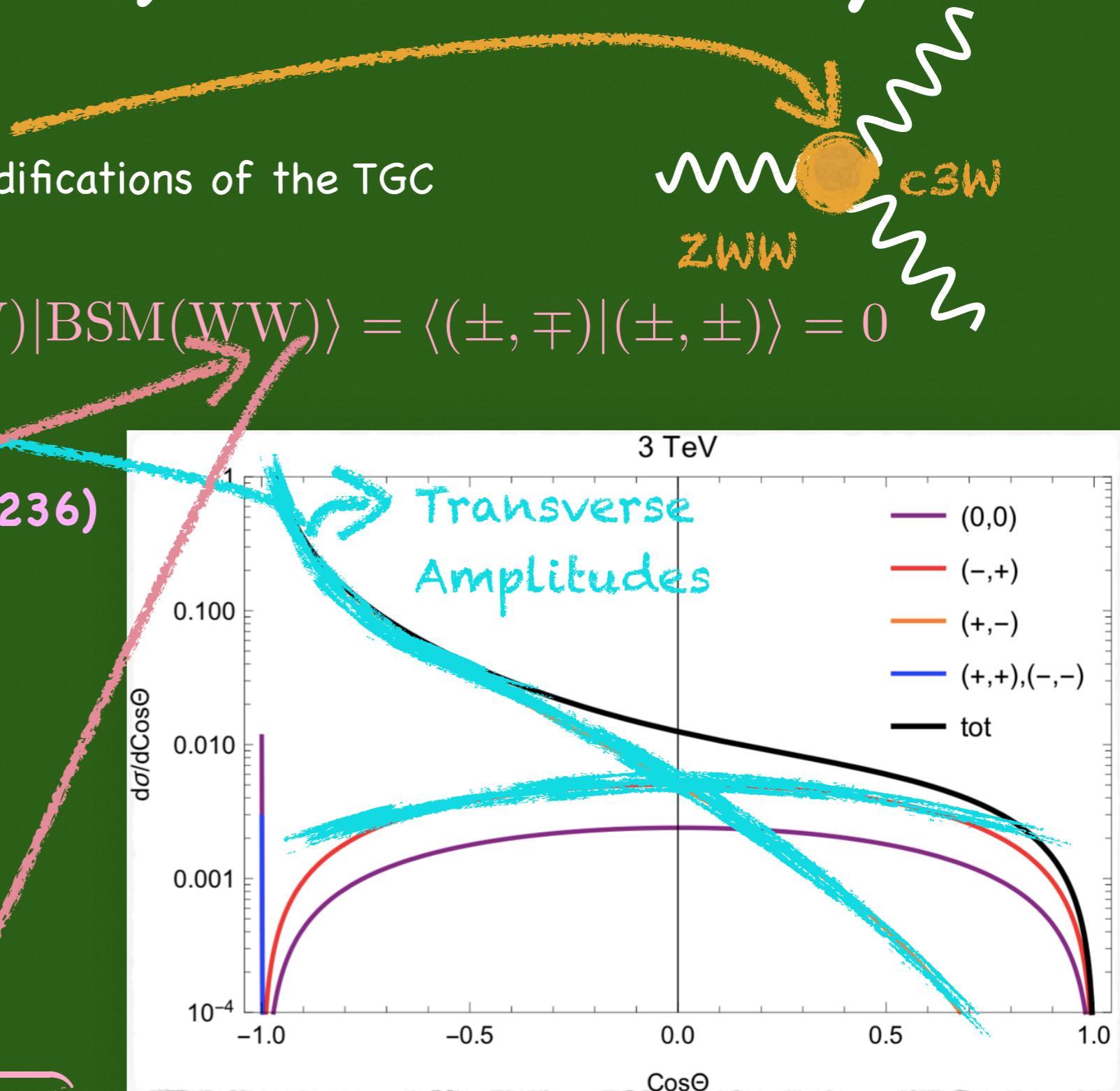
$$\text{BSM}(WW) \xrightarrow[\text{Helicities}]{} (\pm, \pm)$$

$$\text{SM}(WW) \xrightarrow[\text{Helicities}]{} (\pm, \mp)$$

Interference

$$\sigma_{WW} \sim \sigma_{SM} \left( 1 + \delta_{SM \times BSM} \left( \frac{E}{\Lambda} \right)^2 \right) + \delta_{BSM \times BSM} \left( \frac{E}{\Lambda} \right)^4$$

Leading Term





# Study of ee->(WW)Transverse-Analysis2

# Study of ee->(WW)Transverse-Analysis2

- Strategy of Improvement

> Interference Resurrection (arXiv:1708.07823)

$$\left. \begin{array}{l} \text{SM(WW): } (\pm, \mp) \\ \text{BSM(WW): } (\pm, \pm) \end{array} \right\} \rightarrow (f\bar{f})(f\bar{f})$$

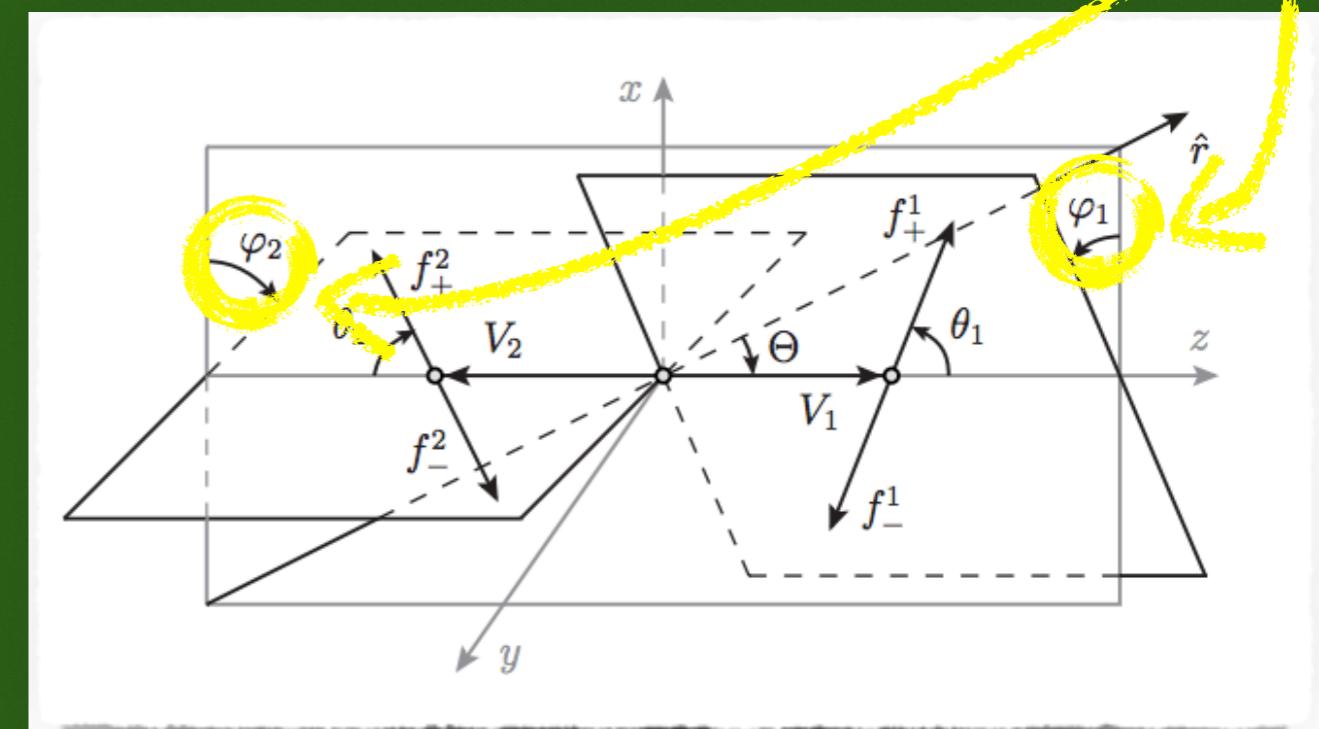

# Study of ee->(WW)Transverse-Analysis2

- Strategy of Improvement

> Interference Resurrection (arXiv:1708.07823)

$$\left. \begin{array}{l} \text{SM(WW): } (\pm, \mp) \\ \text{BSM(WW): } (\pm, \pm) \end{array} \right\} \rightarrow (f\bar{f})(f\bar{f})$$

$$\langle \text{SM(fermions)} | \text{BSM(fermions)} \rangle \propto \mathcal{A}_{++}^{\text{BSM}} [\mathcal{A}_{--}^{\text{SM}} + \mathcal{A}_{+-}^{\text{SM}}] \cos 2\varphi$$



# Study of ee->(WW)Transverse-Analysis2

- Strategy of Improvement

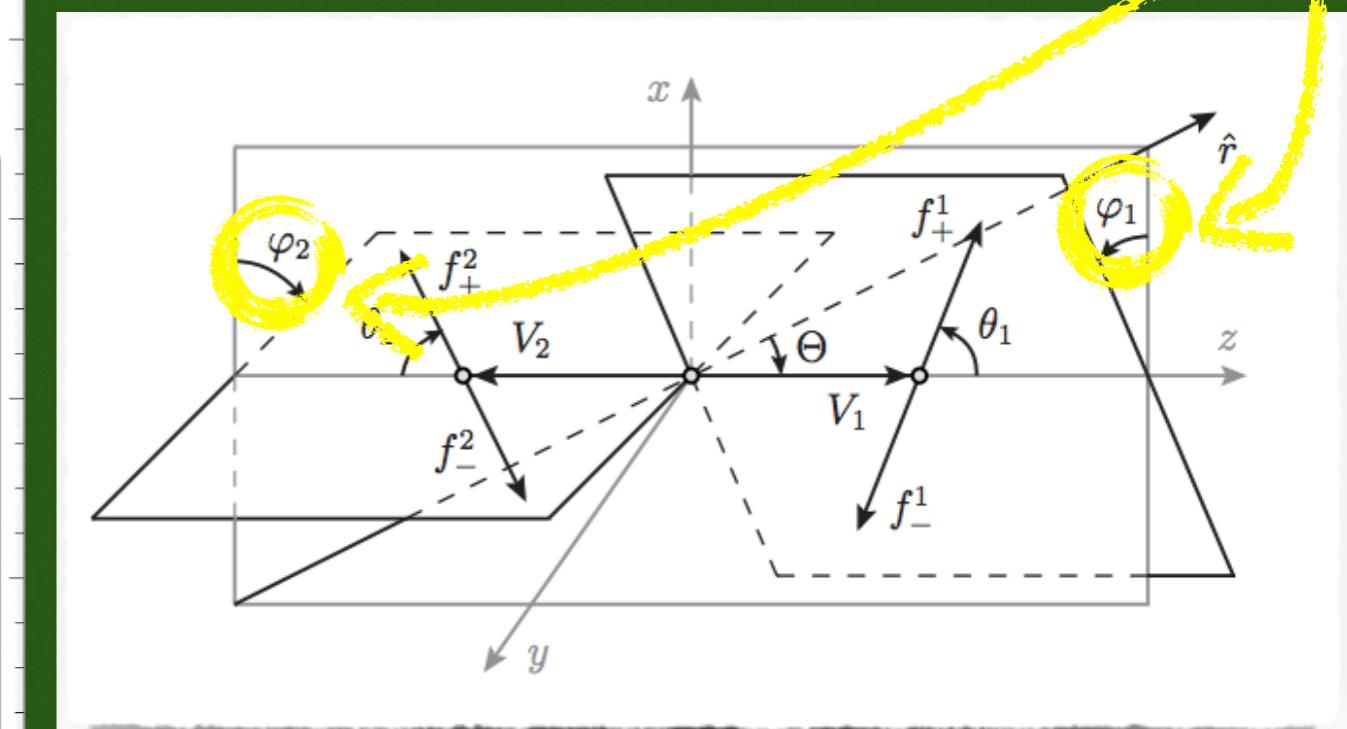
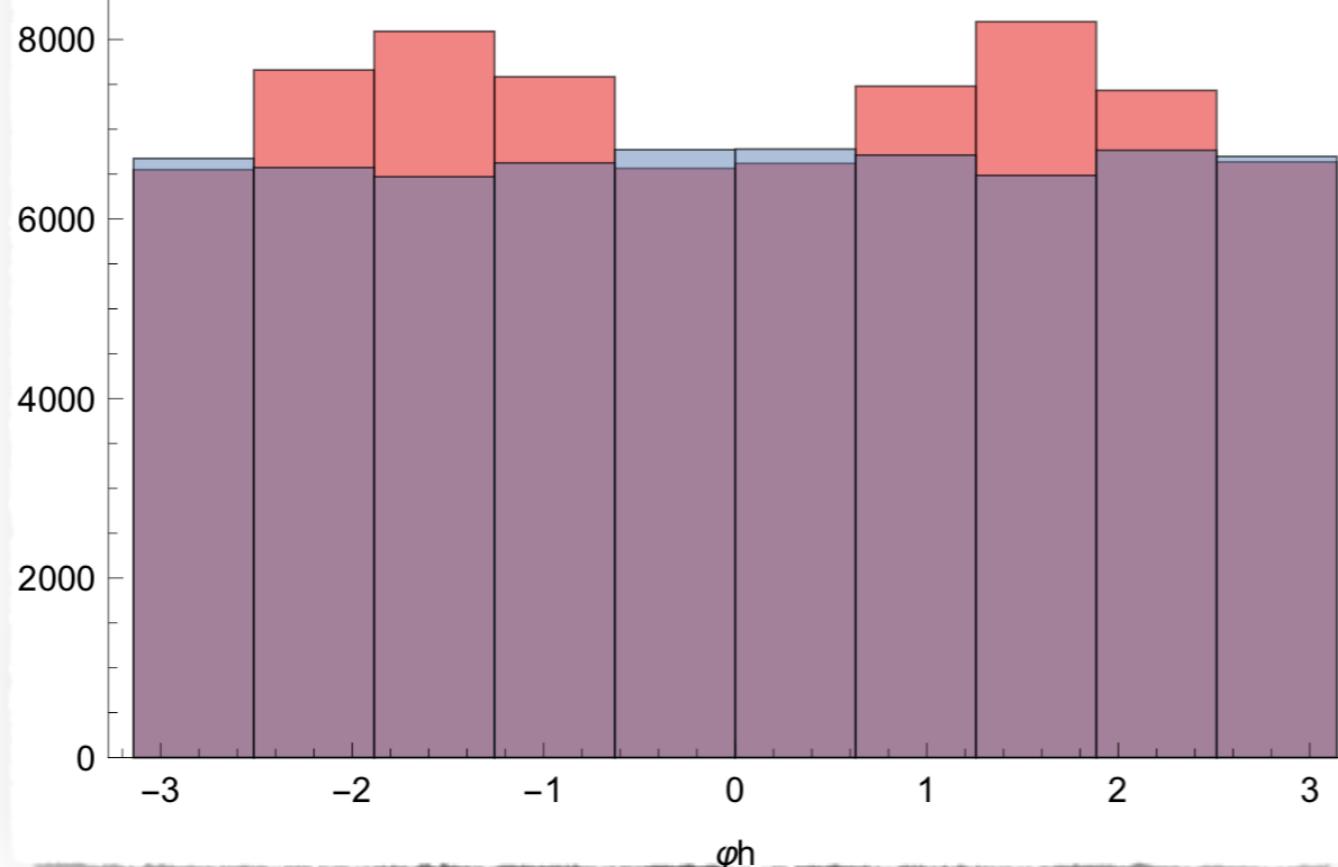
> Interference Resurrection (arXiv:1708.07823)

> Final Fermions Azimuthal Distributions

$$\text{SM(WW): } (\pm, \mp) \\ \text{BSM(WW): } (\pm, \pm) \quad \} \rightarrow (f\bar{f})(f\bar{f})$$

$\langle \text{SM(fermions)} | \text{BSM(fermions)} \rangle \propto \mathcal{A}_{++}^{\text{BSM}} [\mathcal{A}_{--}^{\text{SM}} + \mathcal{A}_{+-}^{\text{SM}}] \cos 2\varphi$

SM Vs BSM( $c_{3W}=0.294$ ),  $\text{Cos}(\theta) \in [0, 0.5]$ , Semileptonic\_Hadronic



# Study of ee->(WW)Transverse-Analysis2

- Strategy of Improvement

> Interference Resurrection (arXiv:1708.07823)

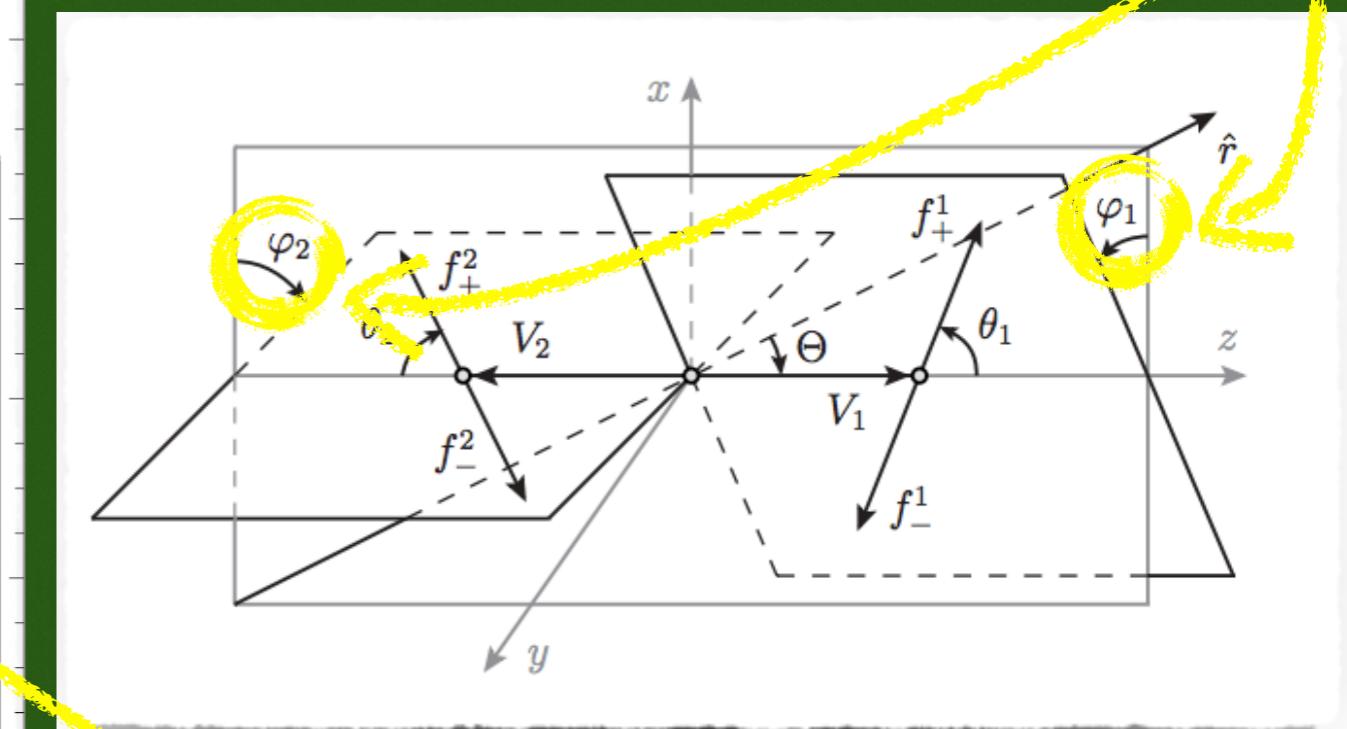
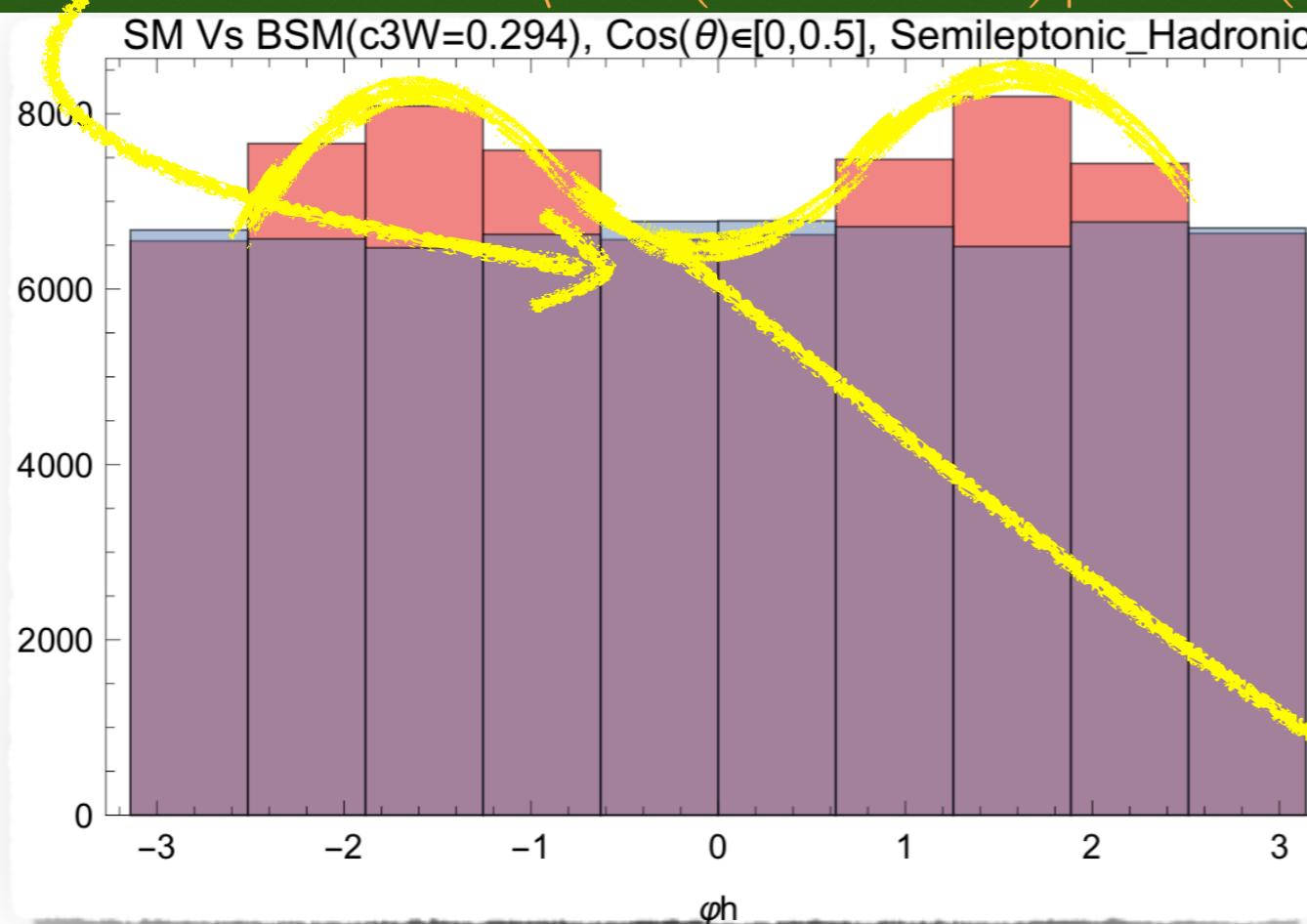
> Final Fermions Azimuthal Distributions

SM(WW): ( $\pm, \mp$ )

BSM(WW): ( $\pm, \pm$ )

$\{ \rightarrow (f\bar{f})(f\bar{f})$

$$\langle \text{SM(fermions)} | \text{BSM(fermions)} \rangle \propto \mathcal{A}_{++}^{\text{BSM}} [\mathcal{A}_{-+}^{\text{SM}} + \mathcal{A}_{+-}^{\text{SM}}] \cos 2\varphi$$



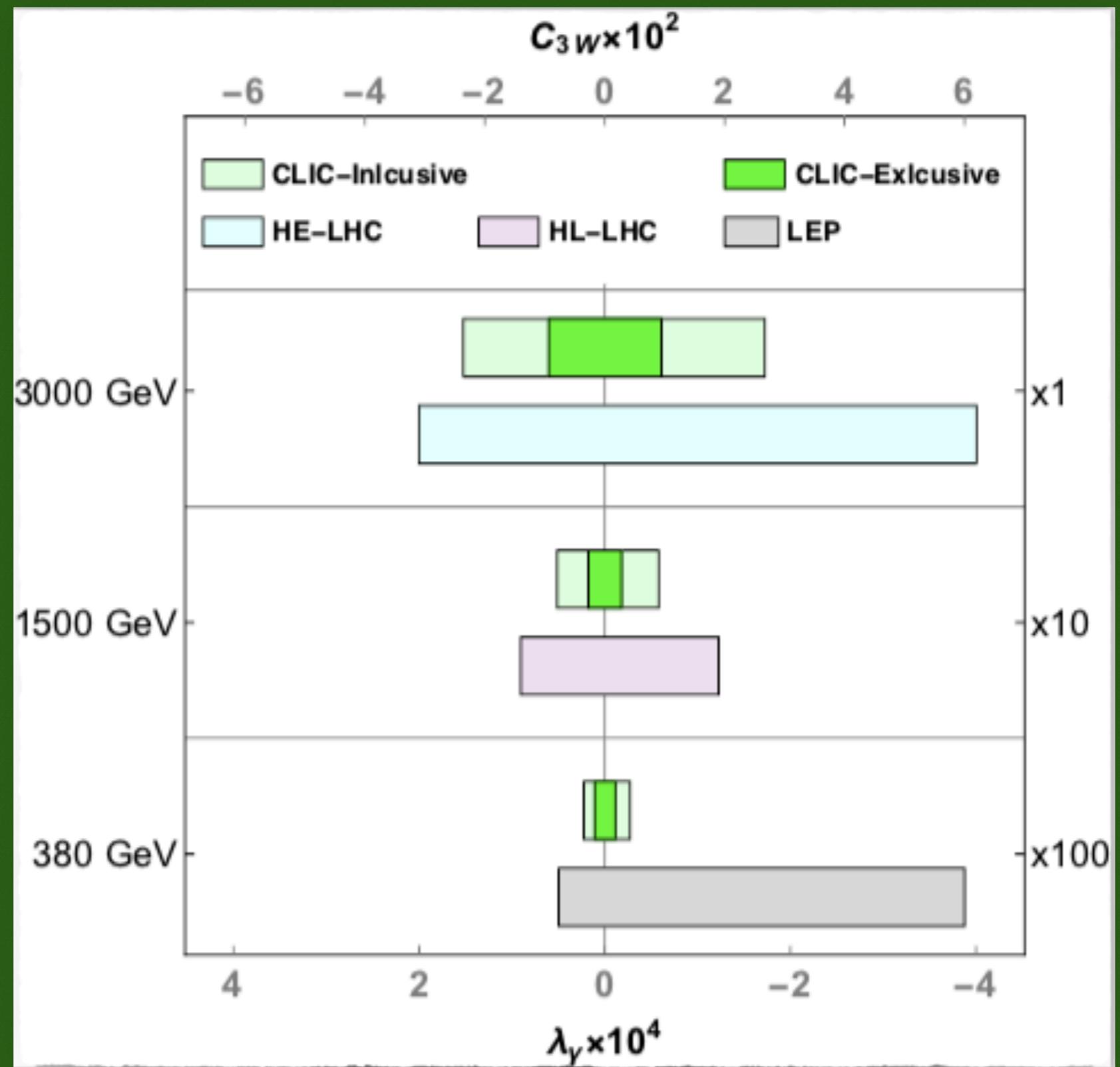
> Exclusive Measurements to improve the BSM-reach



# Study of ee->(WW)Transverse-Results

# Study of ee->(WW)Transverse-Results

- Reach of CLIC on modifications of the TGC

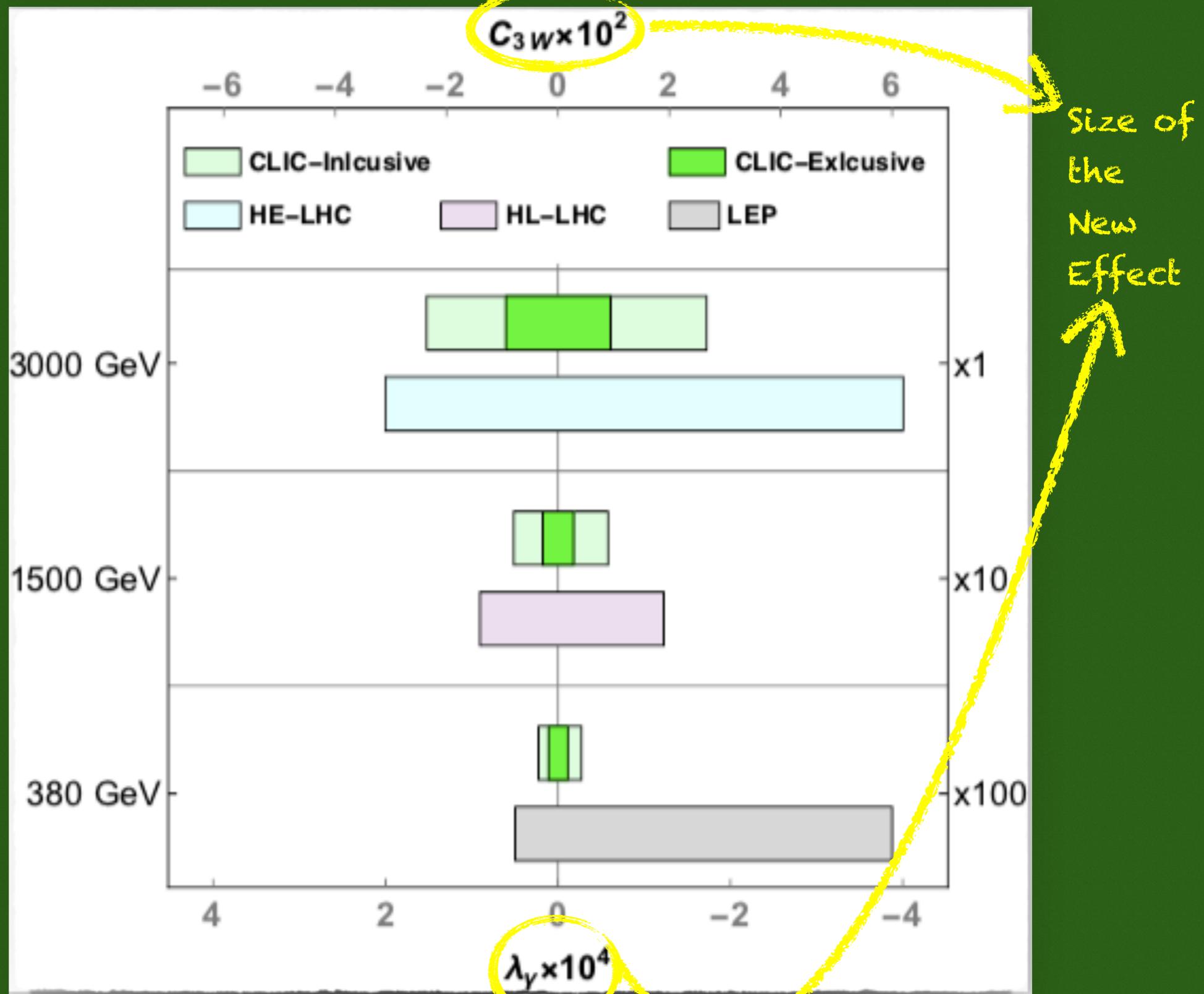


>  $1\sigma$ -Reach from  
a  $\chi^2$ -analysis

# Study of ee->(WW)Transverse-Results

- Reach of CLIC on modifications of the TGC

>  $1\sigma$ -Reach from  
 $\chi^2$ -analysis

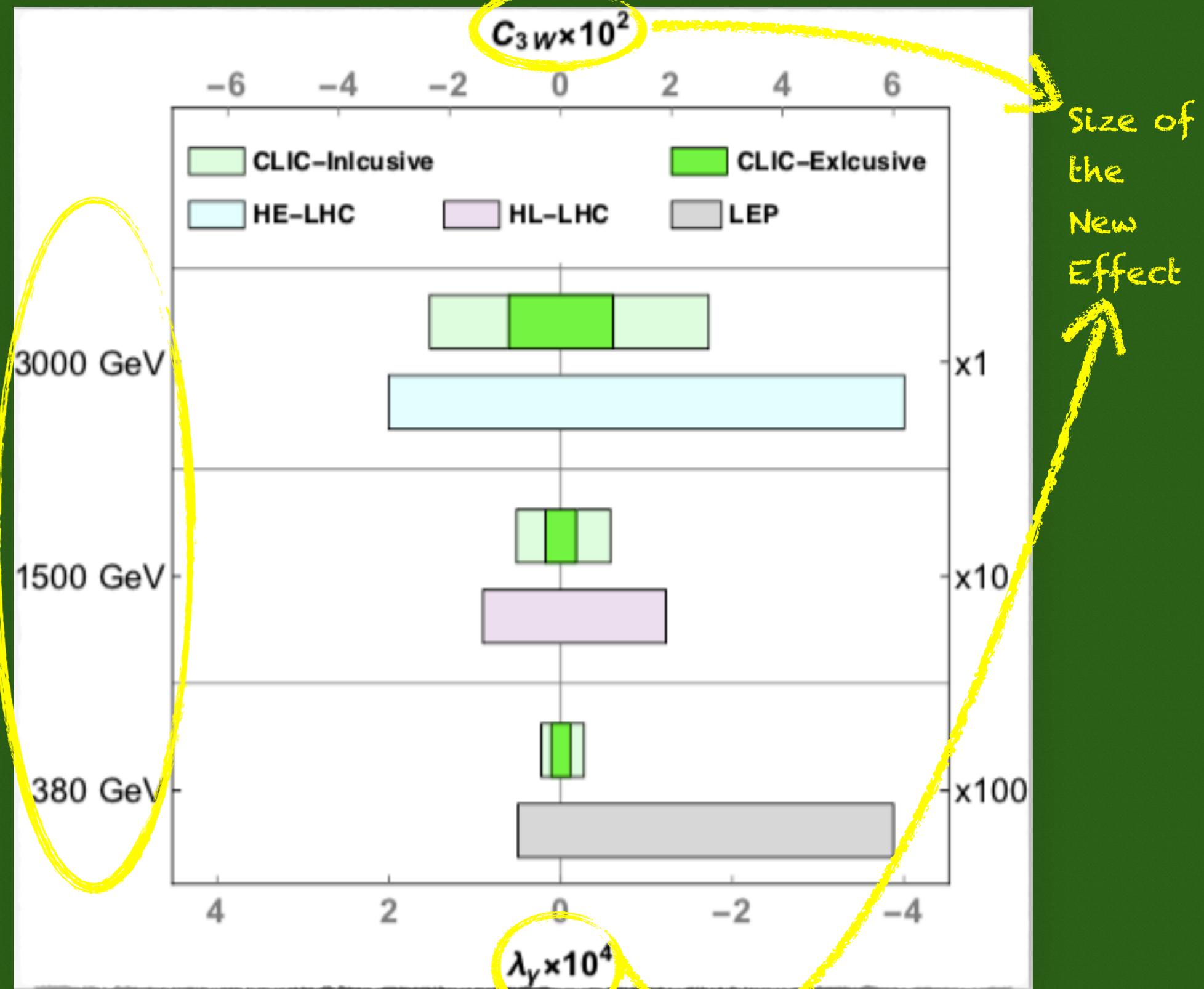


# Study of ee->(WW)Transverse-Results

- Reach of CLIC on modifications of the TGC

>  $1\sigma$ -Reach from  
 $\chi^2$ -analysis

> CLIC Baseline  
for the Specifics

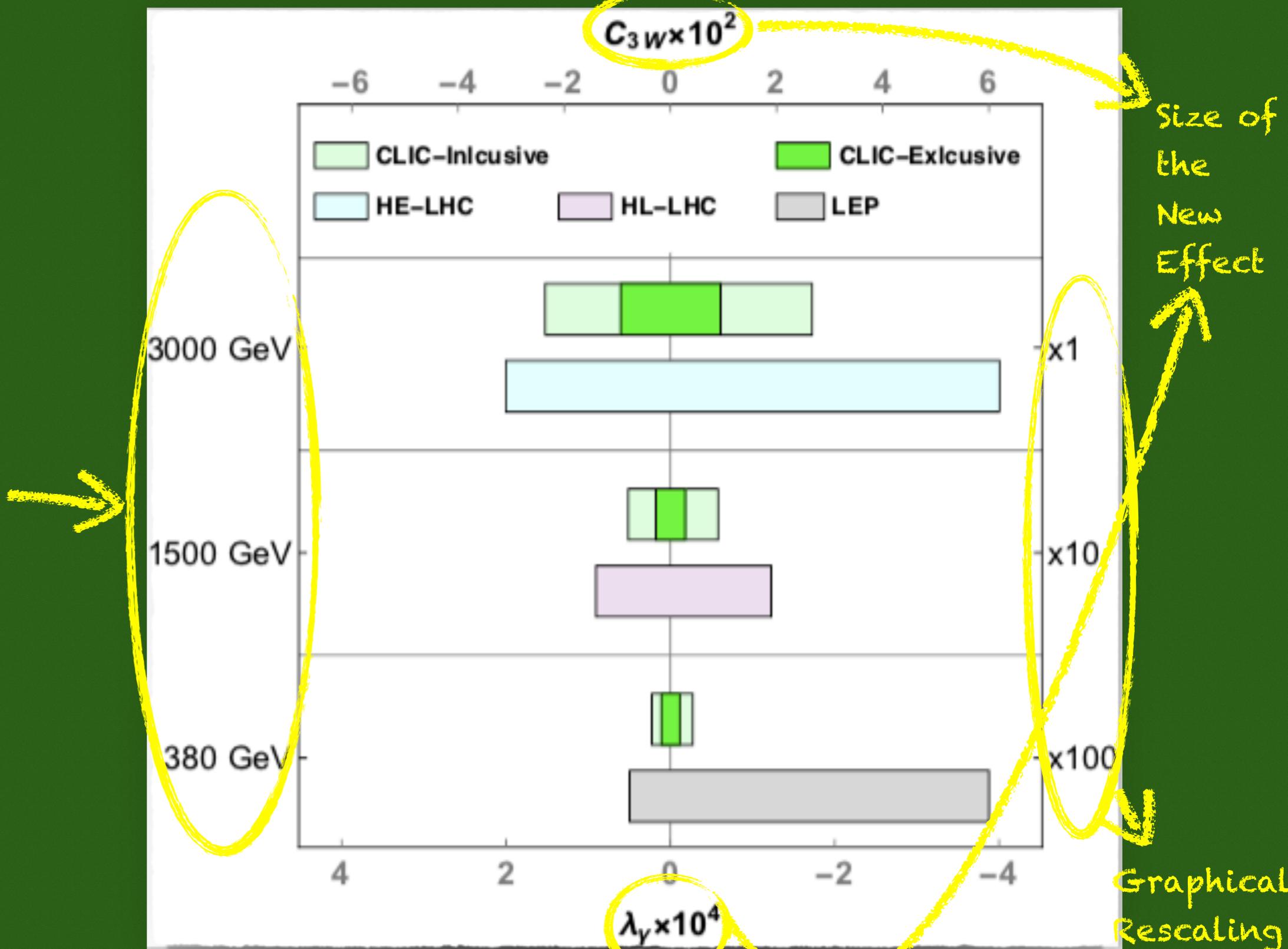


# Study of ee->(WW)Transverse-Results

- Reach of CLIC on modifications of the TGC

>  $1\sigma$ -Reach from  
 $\chi^2$ -analysis

> CLIC Baseline  
for the Specifics



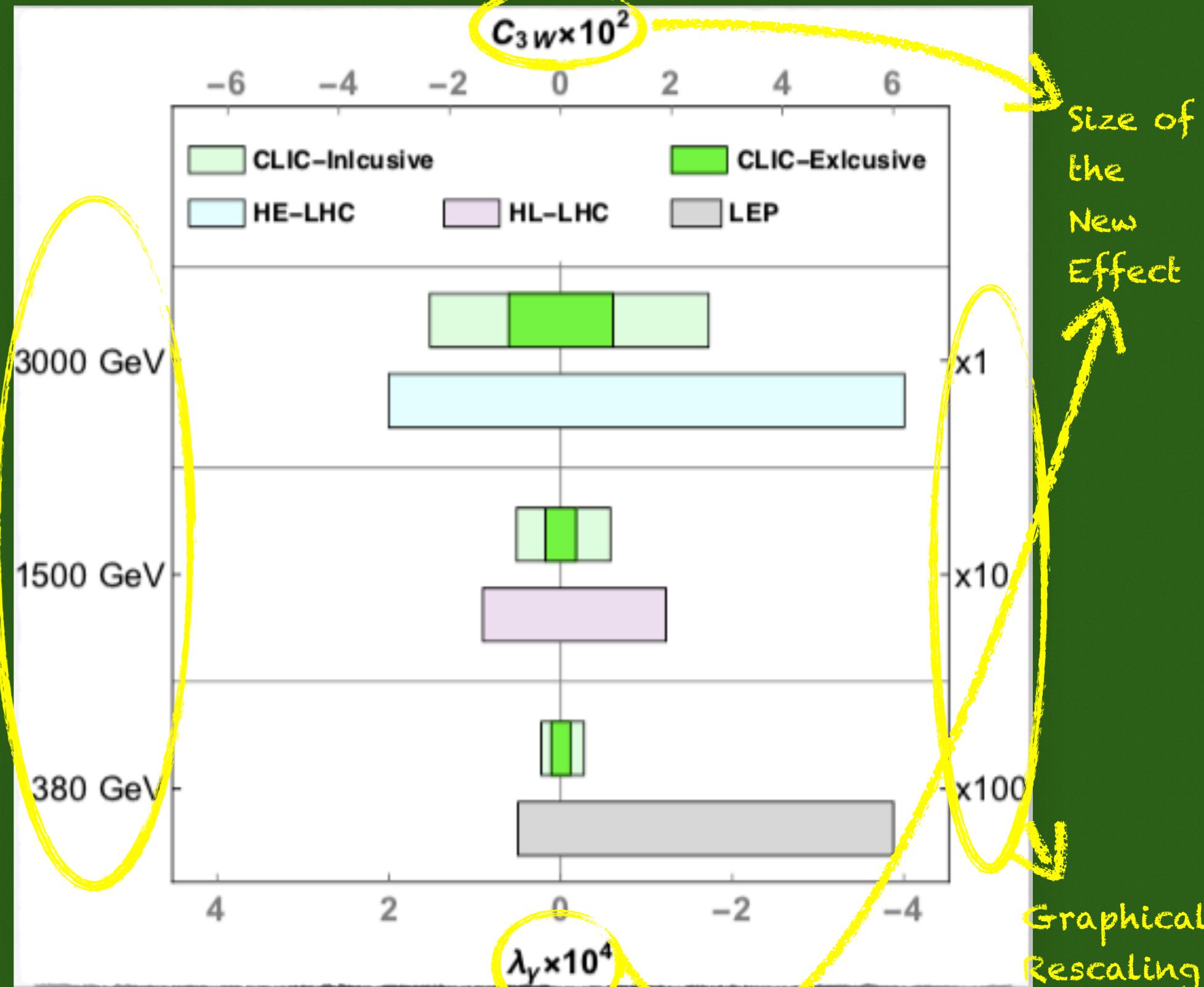
# Study of ee->(WW)Transverse-Results

- Reach of CLIC on modifications of the TGC

>  $1\sigma$ -Reach from  
 $\chi^2$ -analysis

> CLIC Baseline  
for the Specifics

> Radiation  
Effects Included



# Study of ee->(WW)Transverse-Results

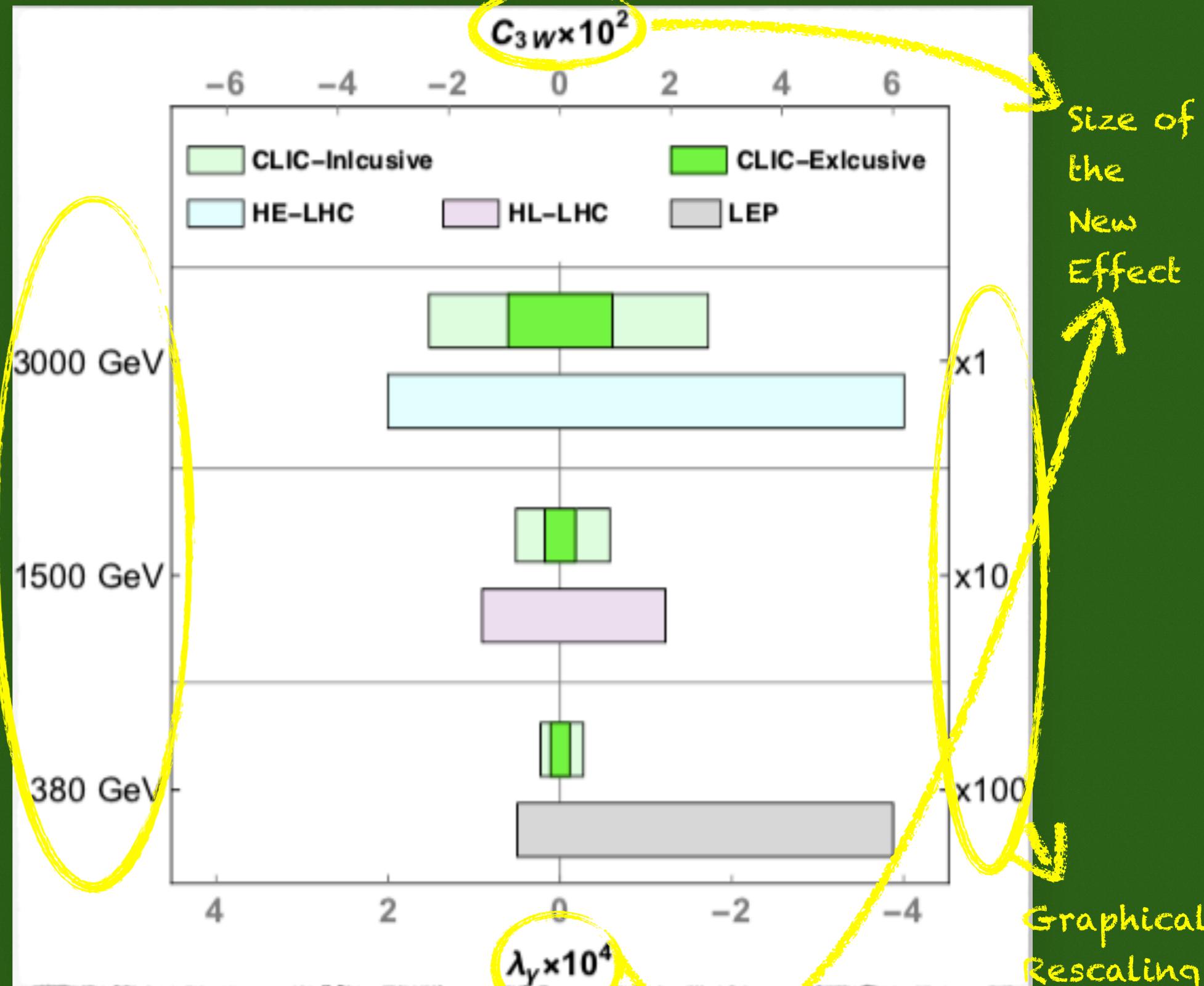
- Reach of CLIC on modifications of the TGC

>  $1\sigma$ -Reach from  
 $\chi^2$ -analysis

> CLIC Baseline  
for the Specifics

> Radiation  
Effects Included

> 1%-Systematics  
and Detectors  
Uncertainties



# Study of ee->(WW)Transverse-Results

- Reach of CLIC on modifications of the TGC

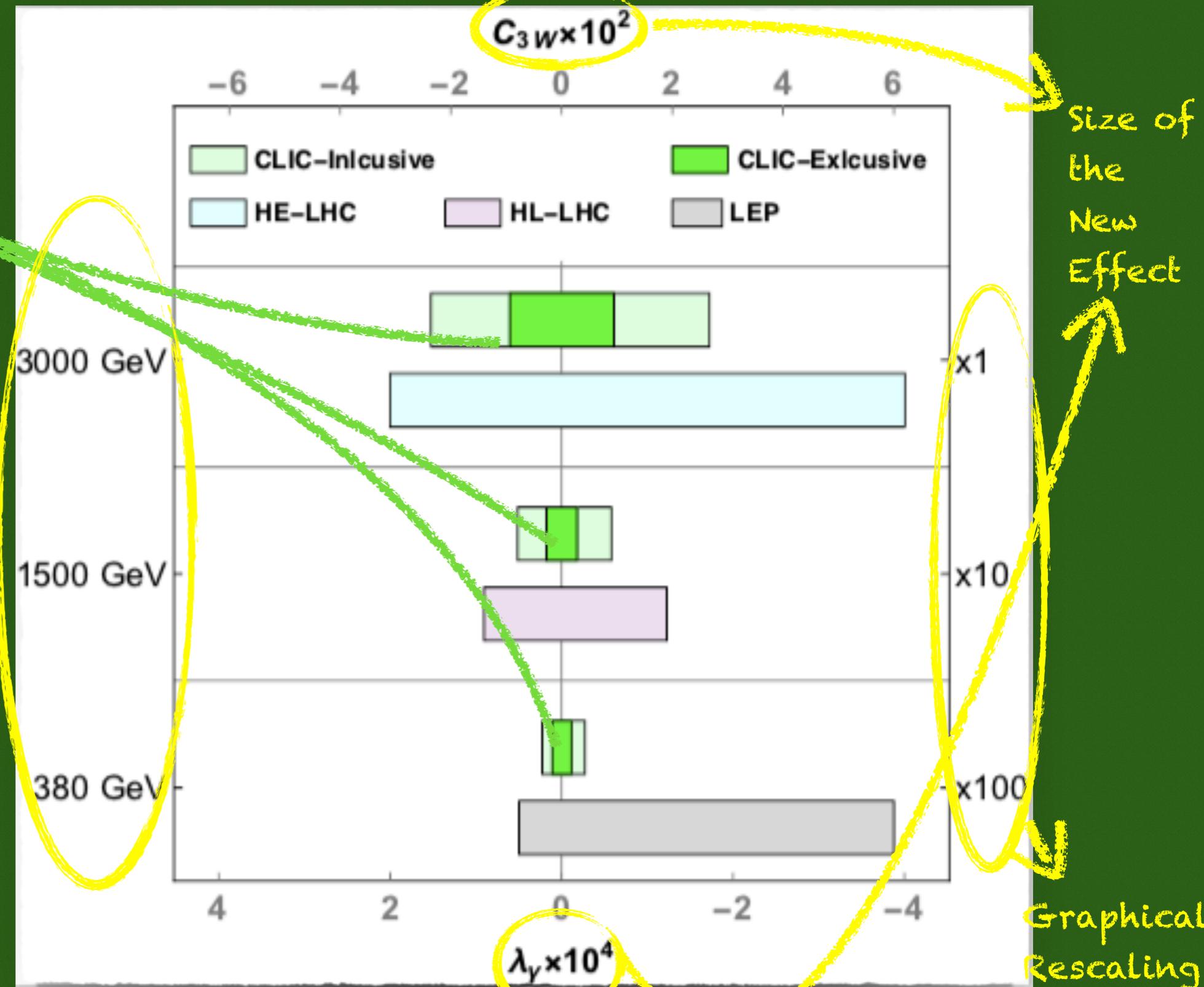
Roughly  
like  
4times the  
luminosity

>  $1\sigma$ -Reach from  
 $\chi^2$ -analysis

> CLIC Baseline  
for the Specifics

> Radiation  
Effects Included

> 1%-Systematics  
and Detectors  
Uncertainties

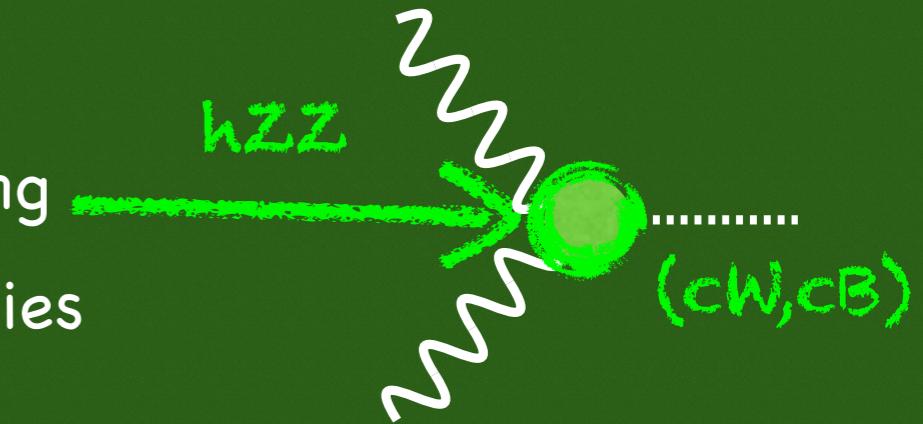




# Study of ee->(WW,Zh)Longitudinals-Analysis

# Study of ee->(WW,Zh)Longitudinals-Analys

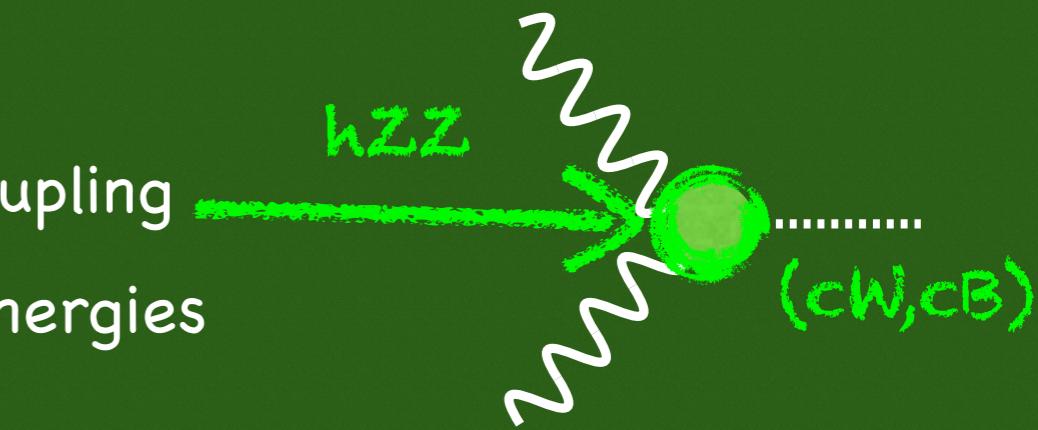
- Main Idea
  - > Assessing the reach of CLIC on anomalous Higgs coupling
  - > Non-Higgs Tests of the Higgs sector at very high energies



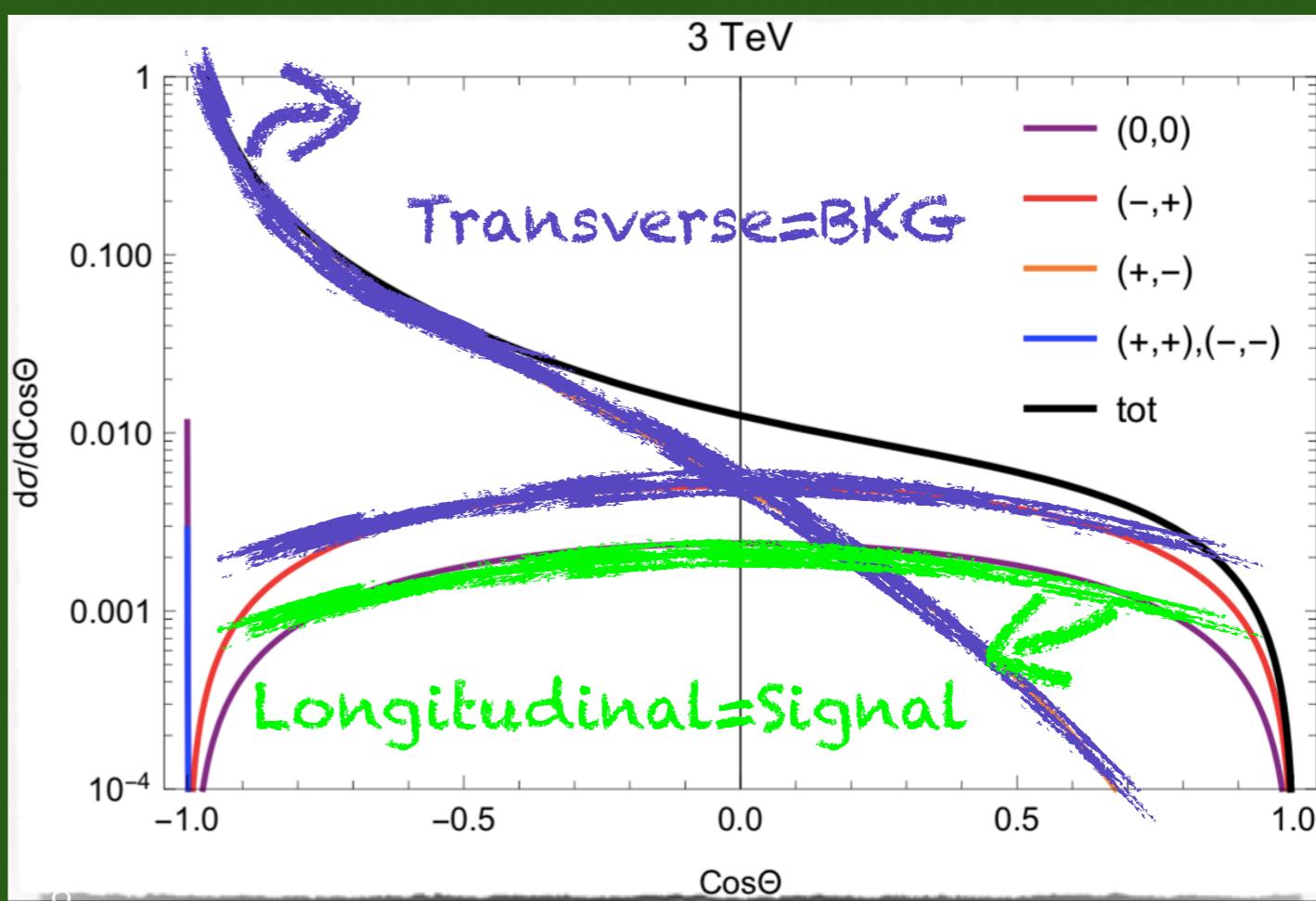
# Study of ee->(WW,Zh)Longitudinals-Analysis

- Main Idea

- > Assessing the reach of CLIC on anomalous Higgs coupling
- > Non-Higgs Tests of the Higgs sector at very high energies



- WW: Strategy



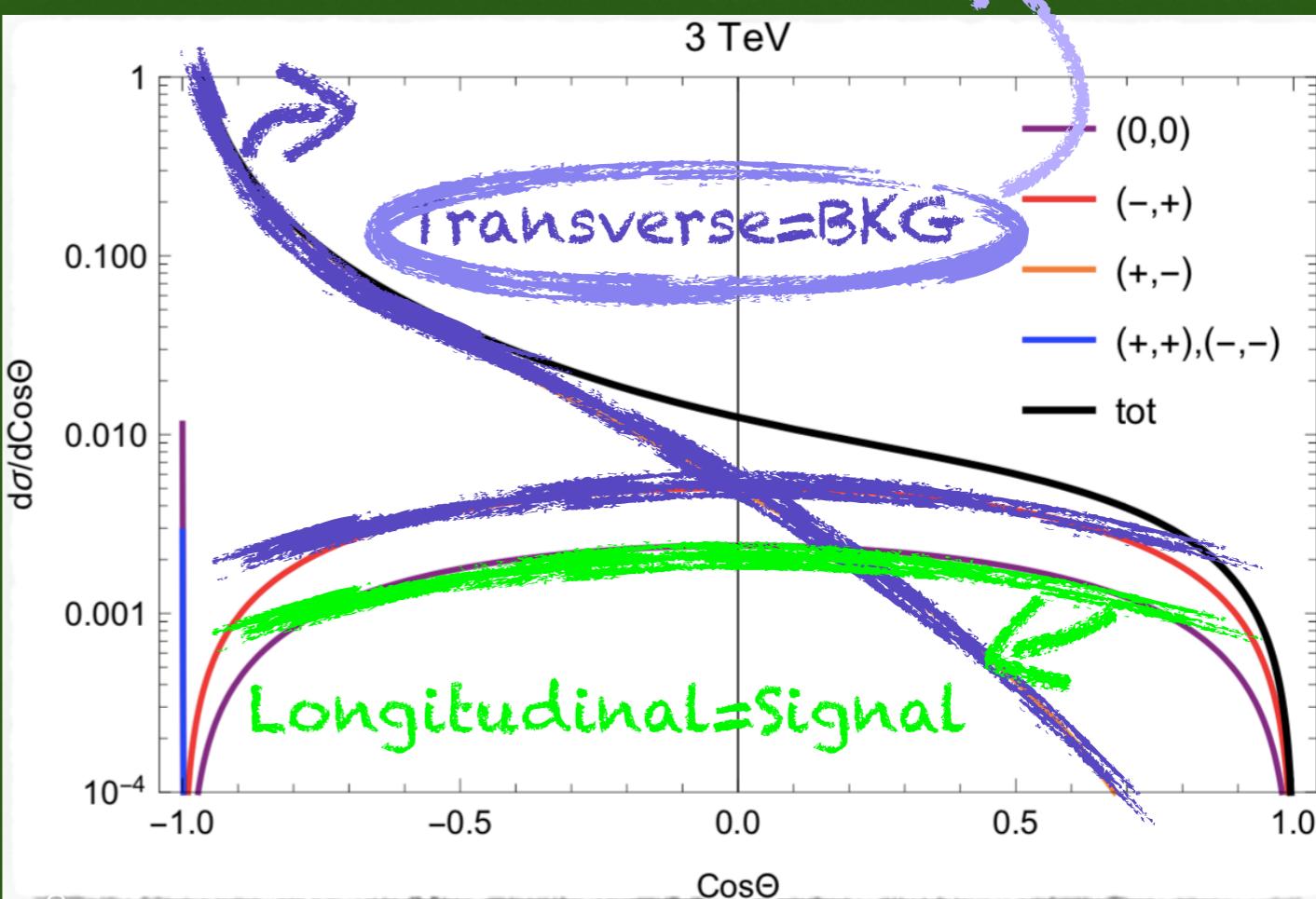
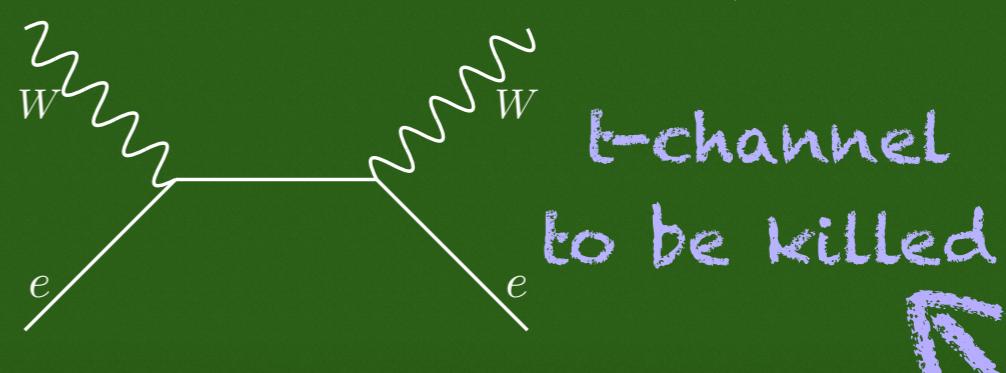
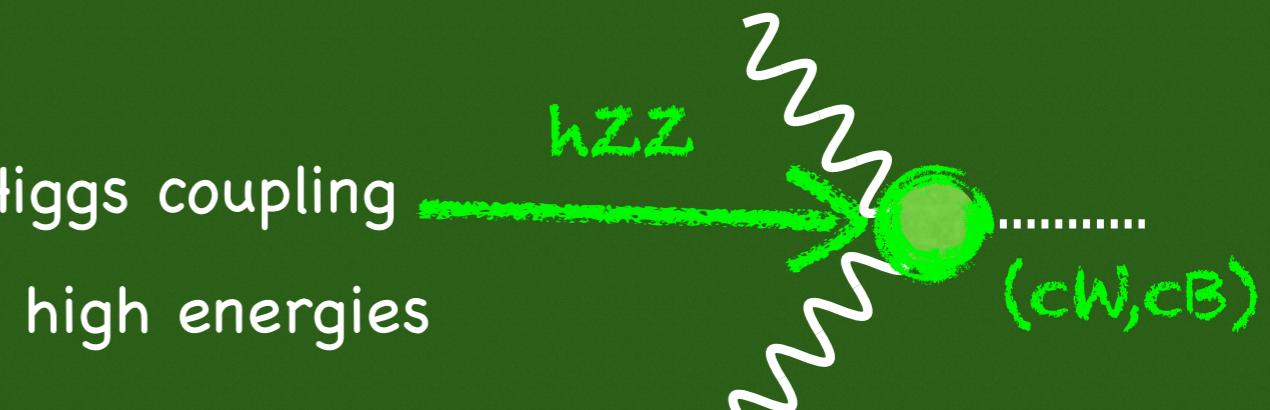
# Study of ee->(WW,Zh)Longitudinals-Analysis

- Main Idea

- > Assessing the reach of CLIC on anomalous Higgs coupling

- > Non-Higgs Tests of the Higgs sector at very high energies

- WW: Strategy

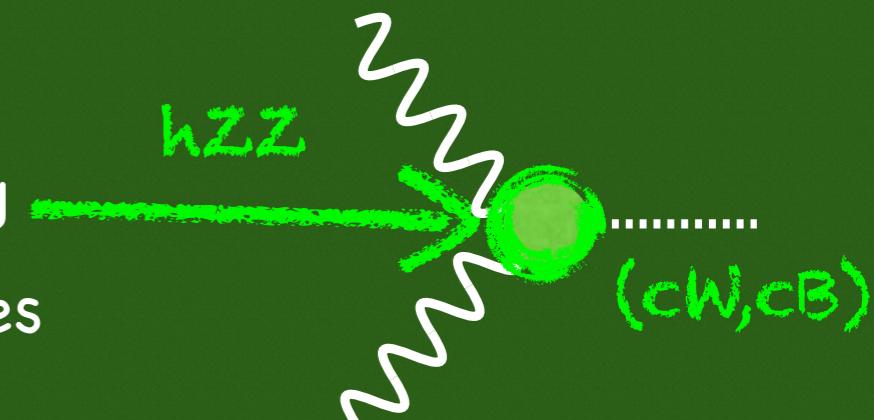


# Study of ee->(WW,Zh)Longitudinals-Analysis

- Main Idea

- > Assessing the reach of CLIC on anomalous Higgs coupling

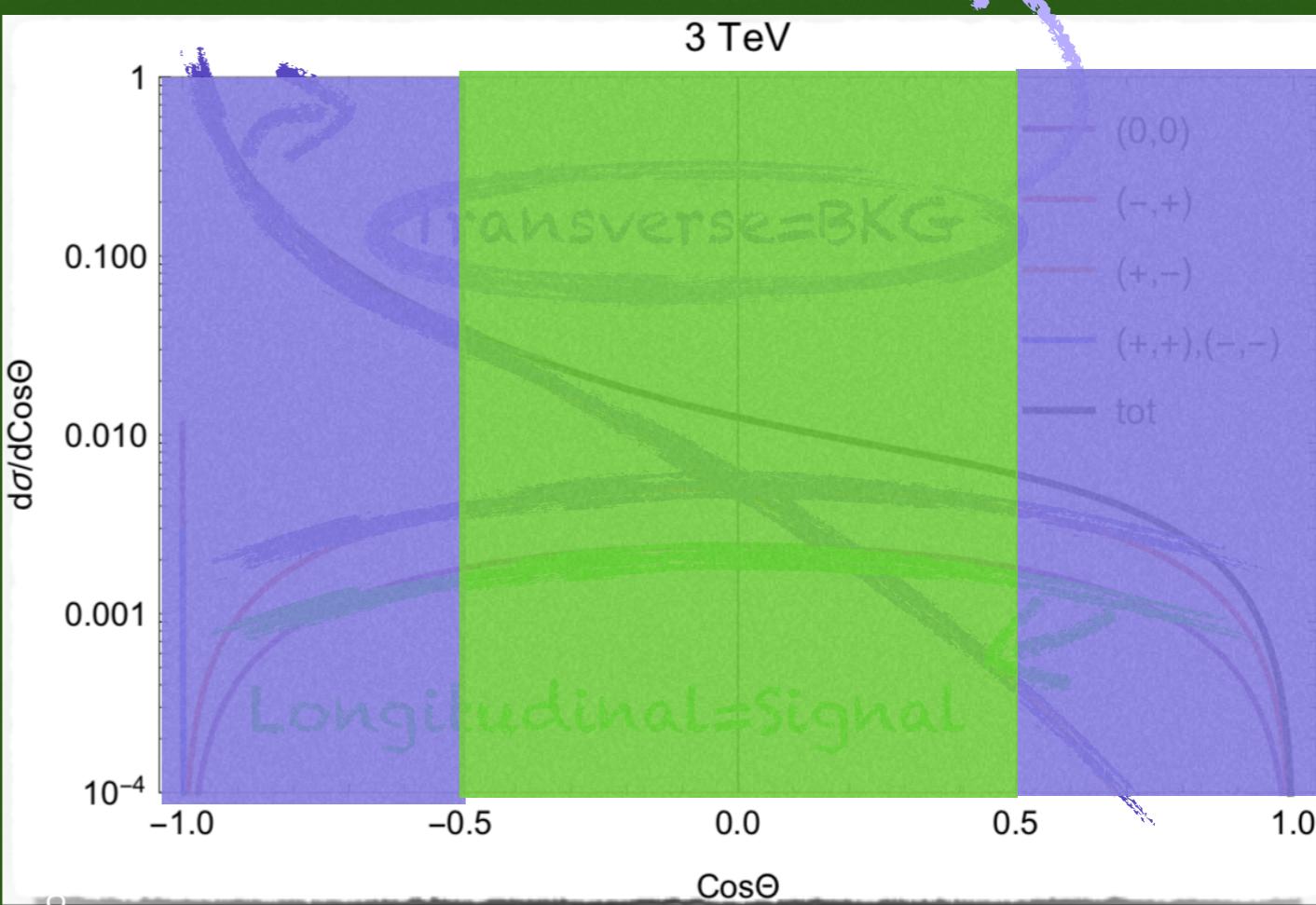
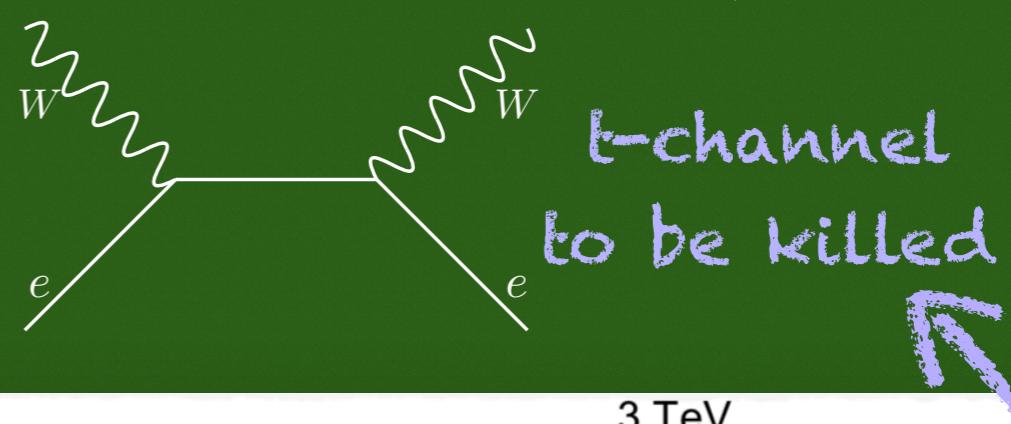
- > Non-Higgs Tests of the Higgs sector at very high energies



- WW: Strategy

- > Binning in the Polar Angle

- > Beam Polarization

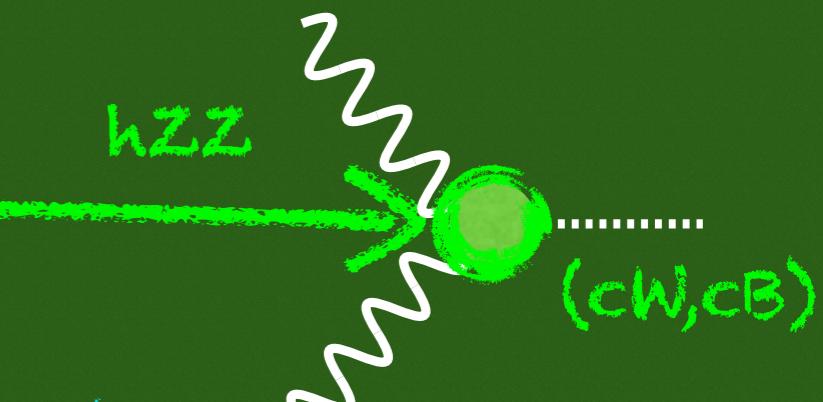


# Study of ee->(WW,Zh)Longitudinals-Analysis

- Main Idea

- > Assessing the reach of CLIC on anomalous Higgs coupling

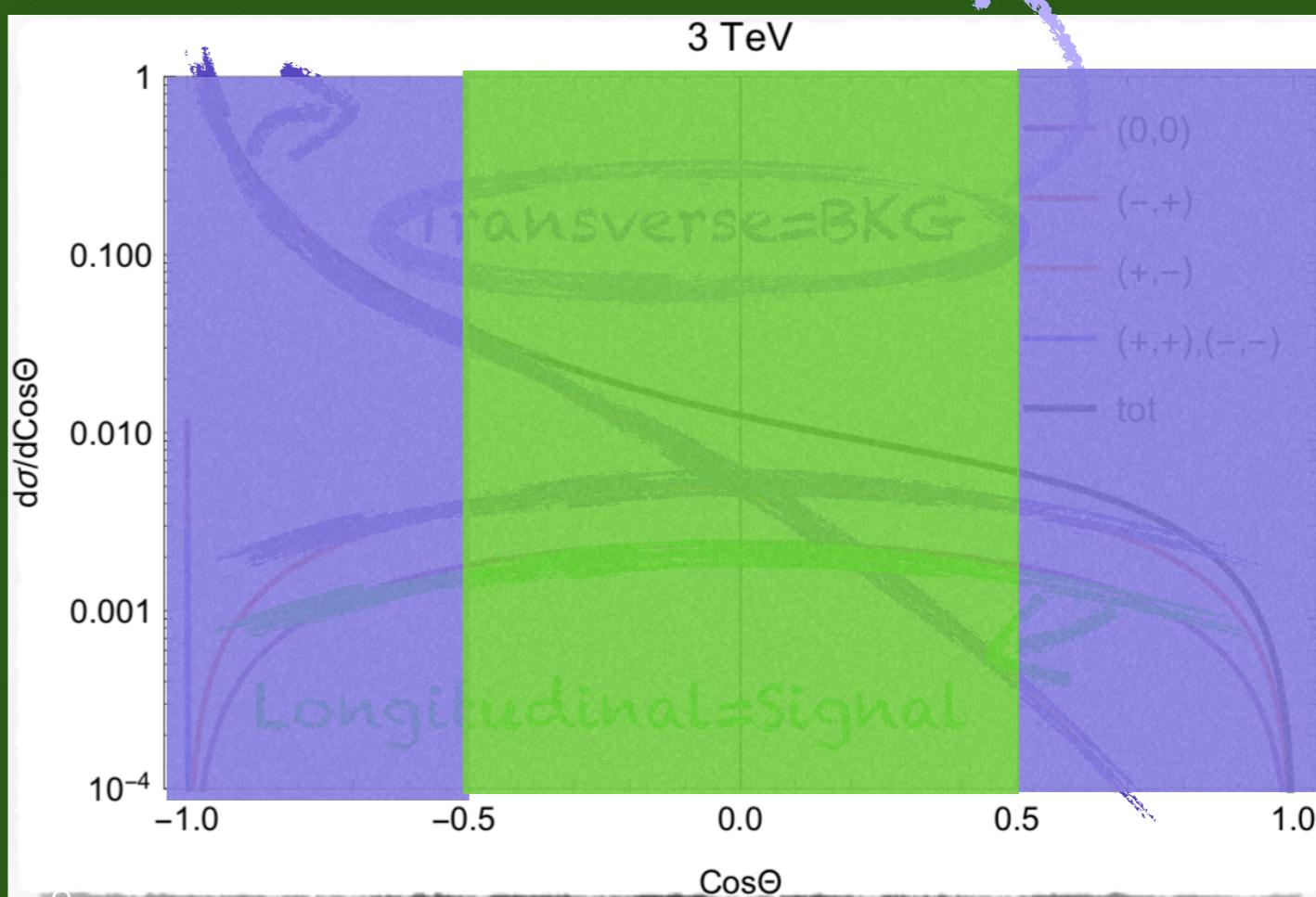
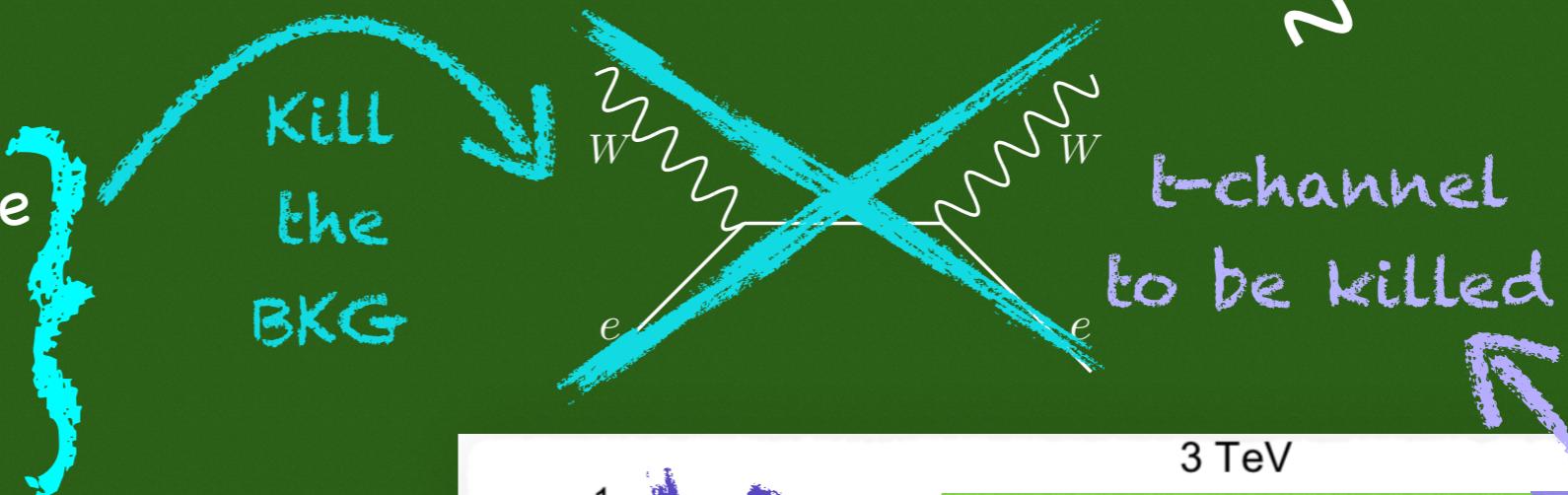
- > Non-Higgs Tests of the Higgs sector at very high energies



- WW: Strategy

- > Binning in the Polar Angle

- > Beam Polarization

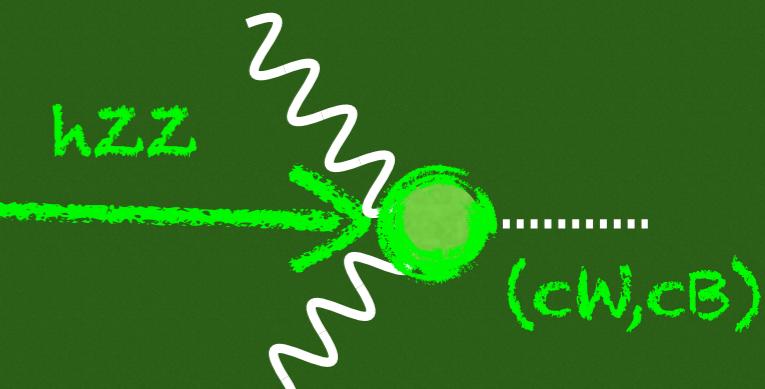


# Study of ee->(WW,Zh)Longitudinals-Analysis

- Main Idea

- > Assessing the reach of CLIC on anomalous Higgs coupling

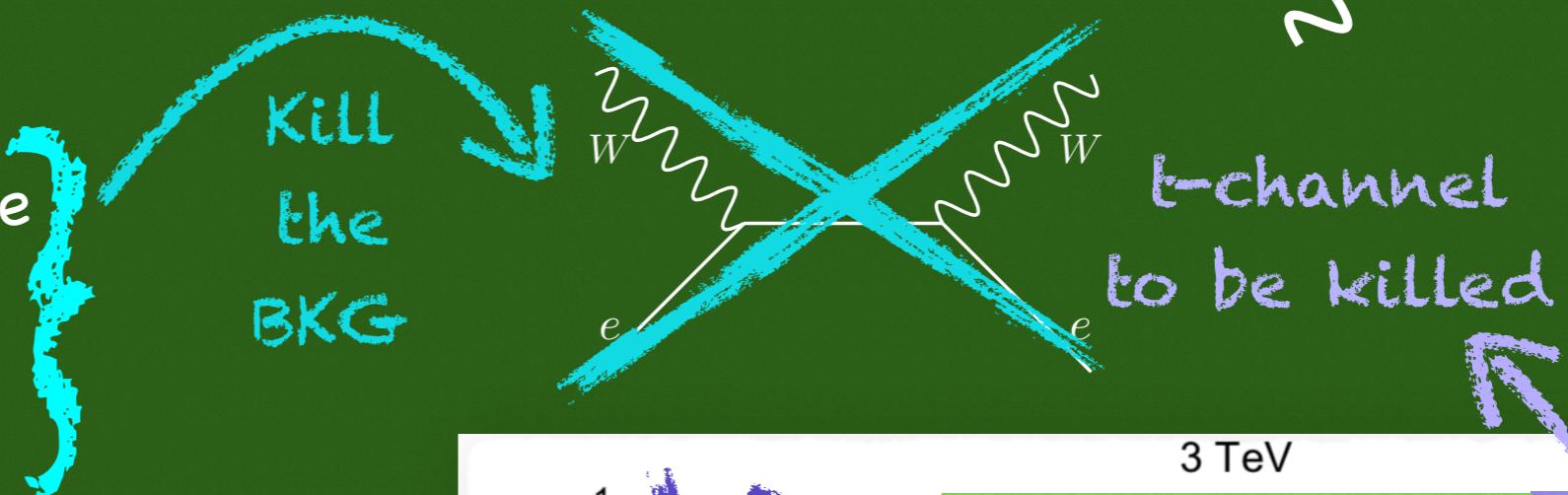
- > Non-Higgs Tests of the Higgs sector at very high energies



- WW: Strategy

- > Binning in the Polar Angle

- > Beam Polarization

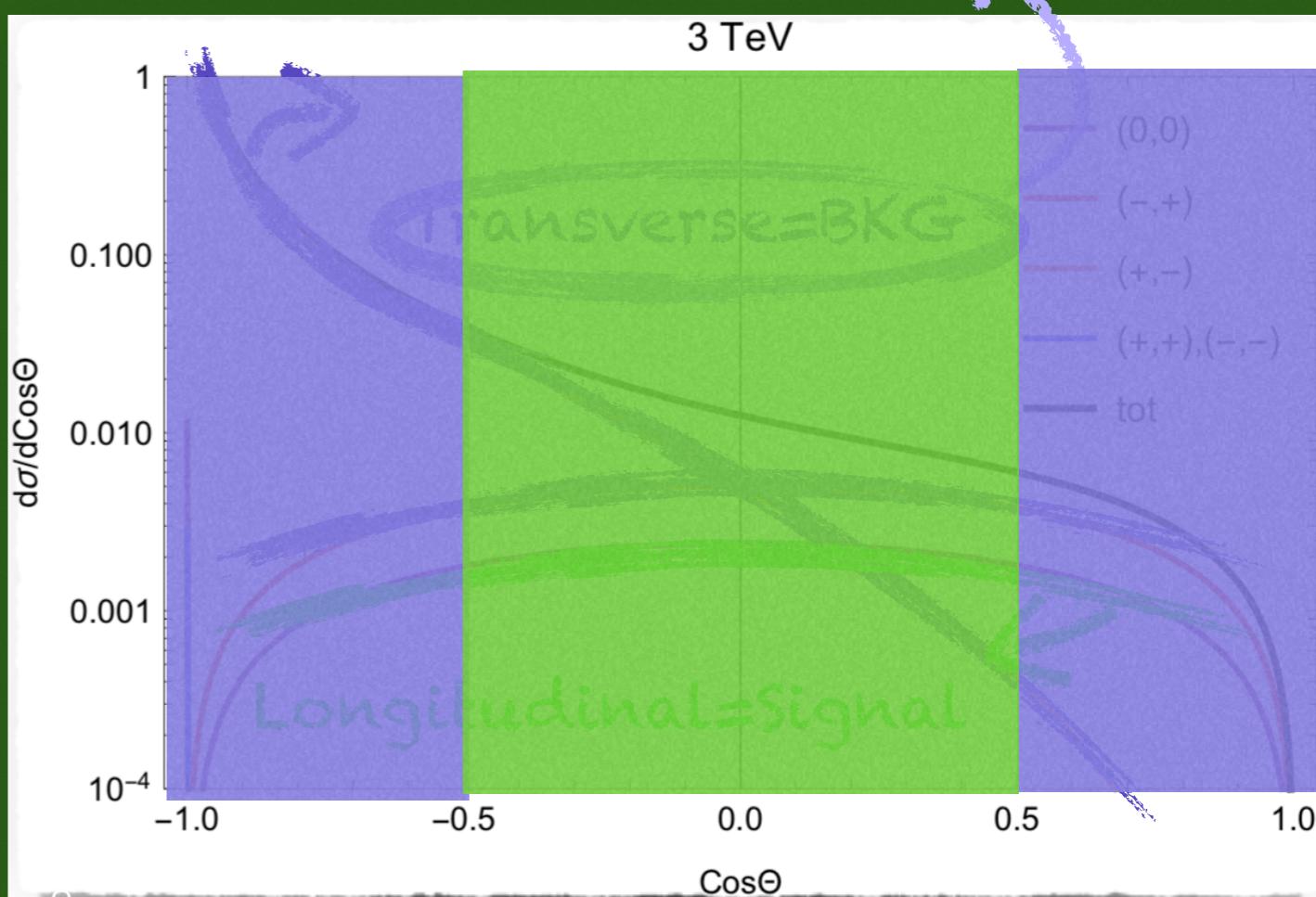


- Zh: Strategy

- > No Relevant BKG

- > SM&BSM have the same angular shape

- > Simply Counting the Events

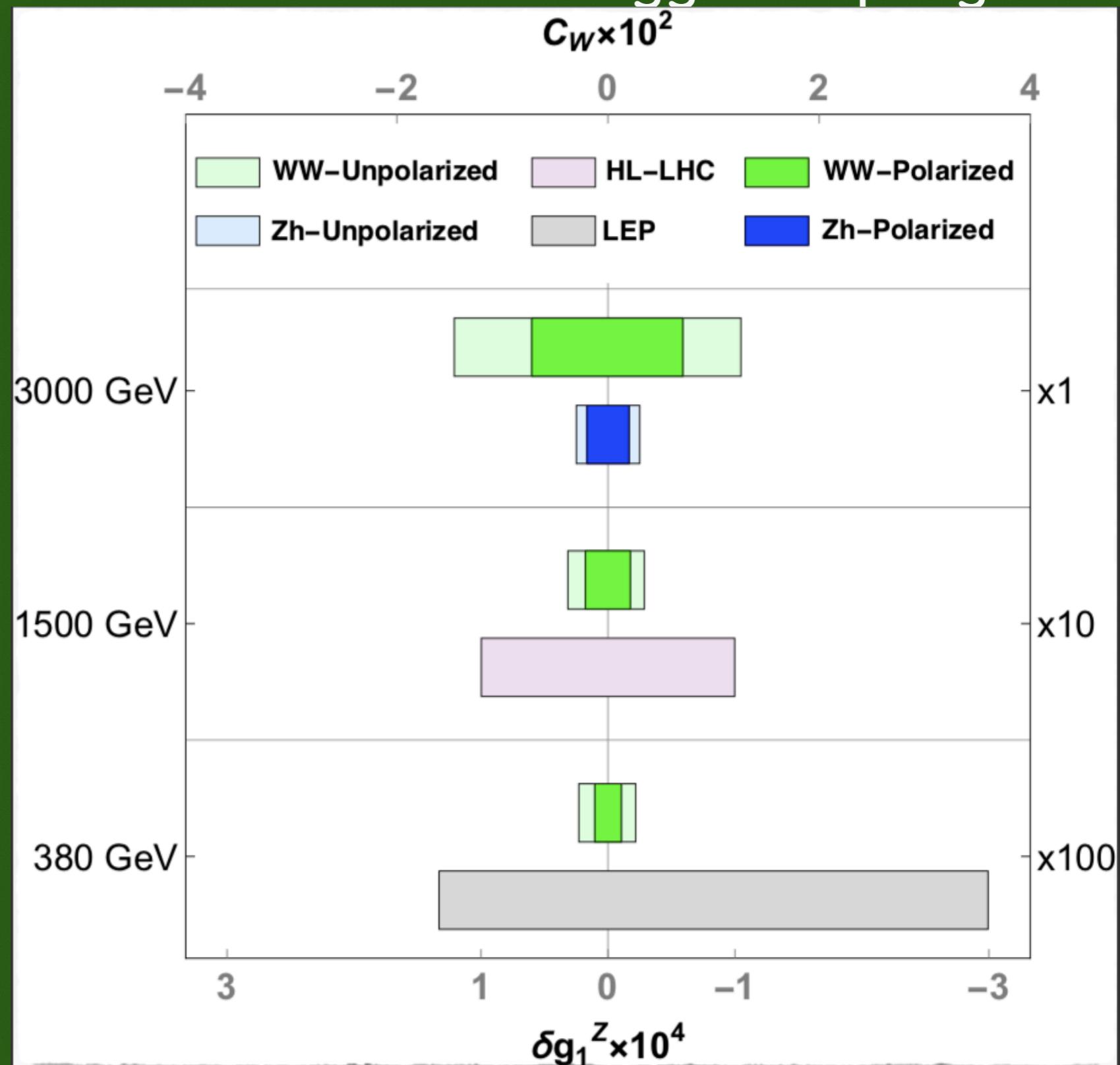




# Study of ee->(WW,Zh)Longitudinals-Results1

# Study of ee->(WW,Zh)Longitudinals-Results1

- Reach of CLIC on Deviations in the Higgs Couplings



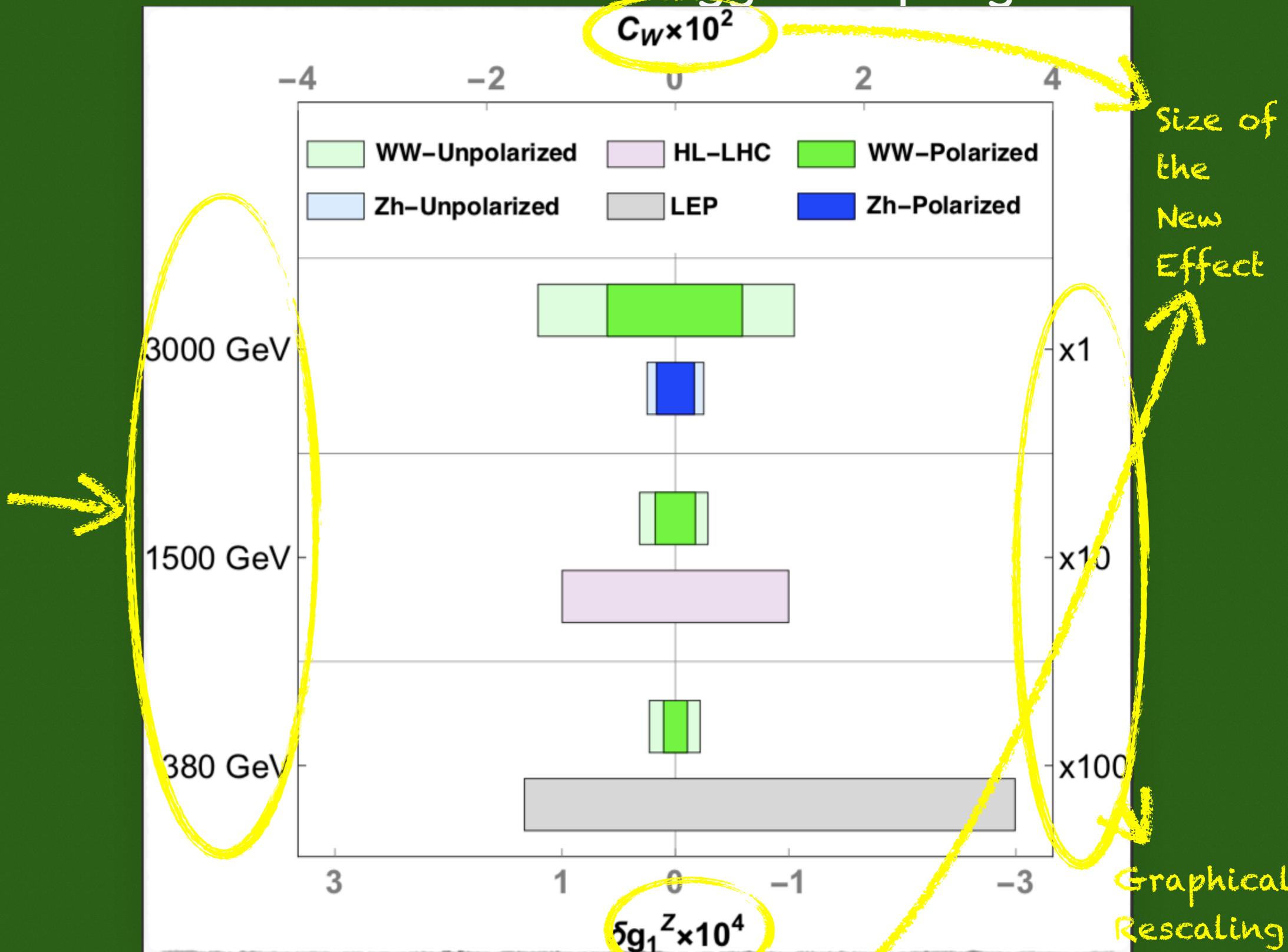
>  $1\sigma$ -Reach from  
 $\chi^2$ -analysis

# Study of ee->(WW,Zh)Longitudinals-Results1

- Reach of CLIC on Deviations in the Higgs Couplings

>  $1\sigma$ -Reach from  
 $\chi^2$ -analysis

> CLIC Baseline  
for the Specifics



# Study of ee->(WW,Zh)Longitudinals-Results1

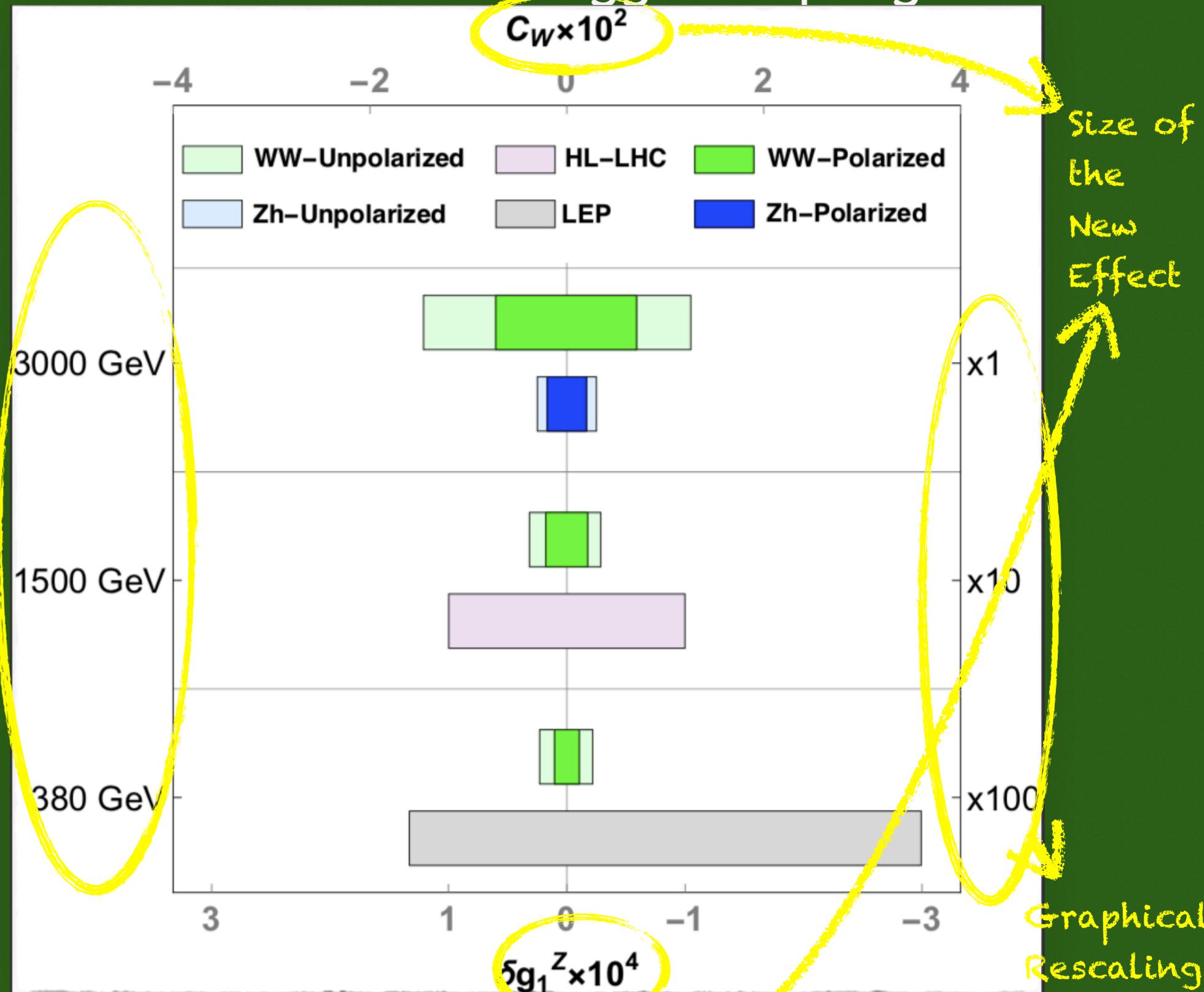
- Reach of CLIC on Deviations in the Higgs Couplings

>  $1\sigma$ -Reach from  
 $\chi^2$ -analysis

> CLIC Baseline  
for the Specifics

> Radiation  
Effects Included

> 1%-Systematics  
and Detectors  
Errors



# Study of ee->(WW,Zh)Longitudinals-Results1

- Reach of CLIC on Deviations in the Higgs Couplings

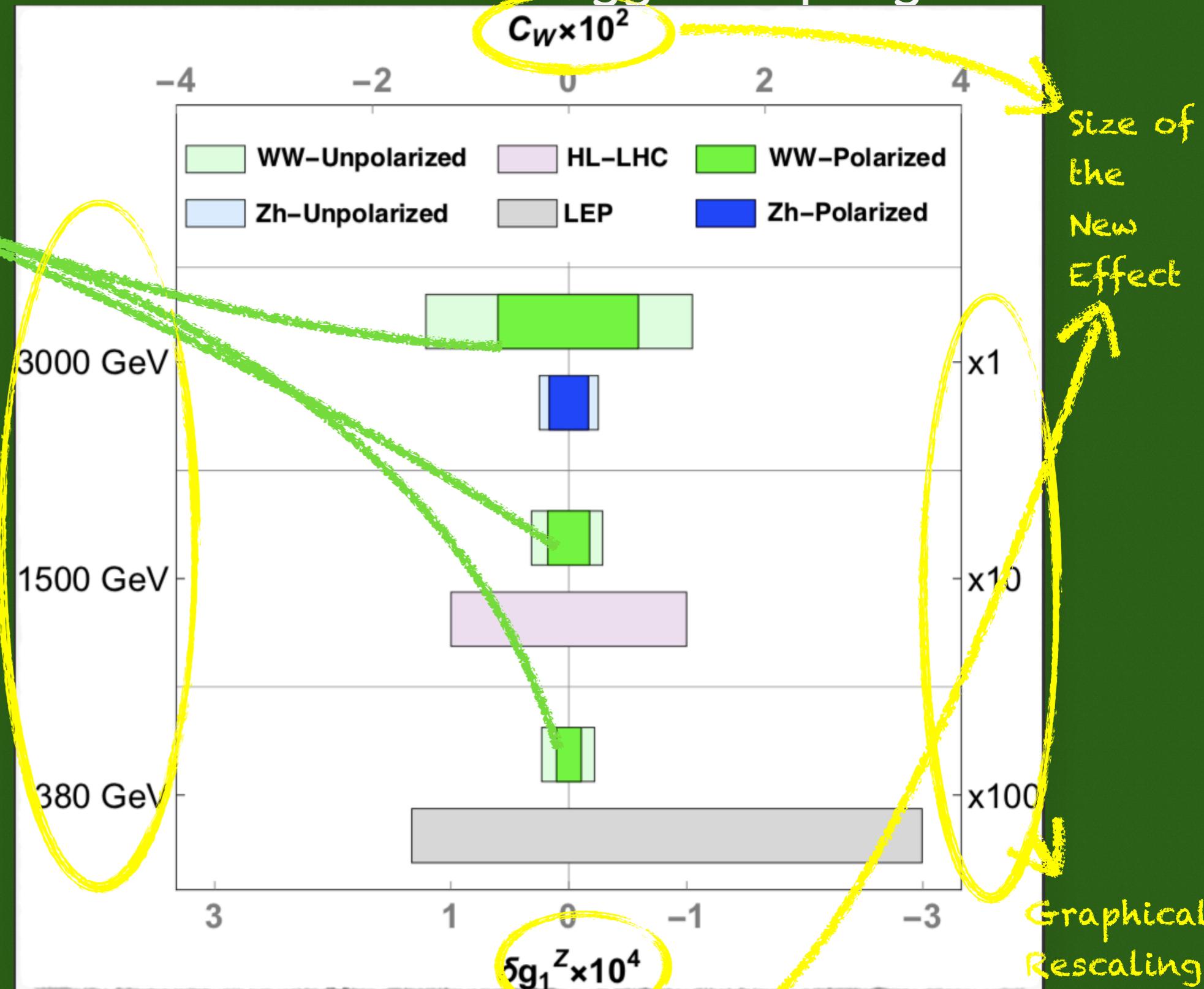
Benefit from  
the  
Polarization

>  $1\sigma$ -Reach from  
 $\chi^2$ -analysis

> CLIC Baseline  
for the Specifics

> Radiation  
Effects Included

> 1%-Systematics  
and Detectors  
Errors



# Study of ee->(WW,Zh)Longitudinals-Results1

- Reach of CLIC on Deviations in the Higgs Couplings

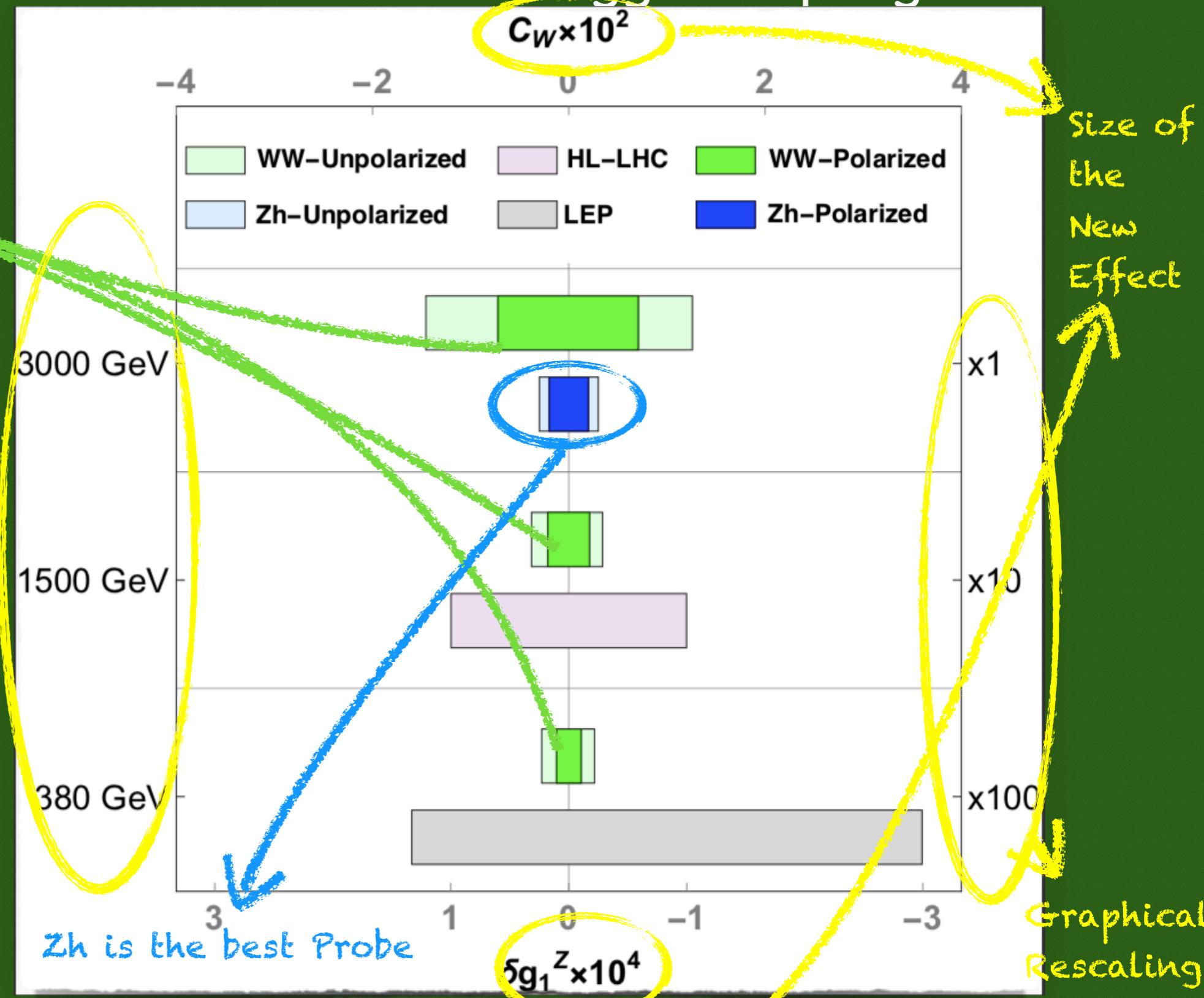
Benefit from  
the  
Polarization

>  $1\sigma$ -Reach from  
 $\chi^2$ -analysis

> CLIC Baseline  
for the Specifics

> Radiation  
Effects Included

> 1%-Systematics  
and Detectors  
Errors

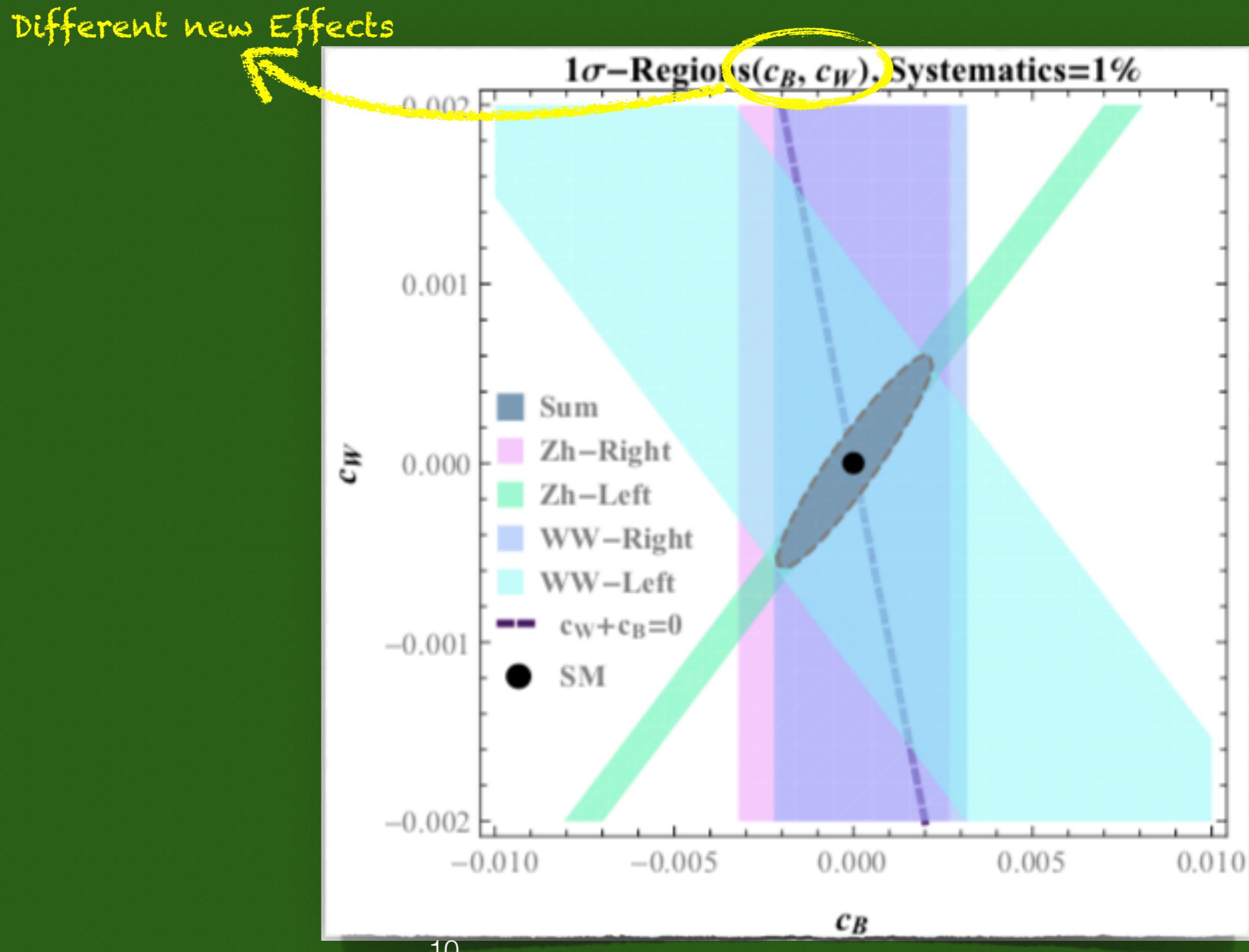




# Study of ee->(WW,Zh)Longitudinals-Results2

# Study of ee->(WW,Zh)Longitudinals-Results2

- Dibosons Reach to Disentangle BSM parameters

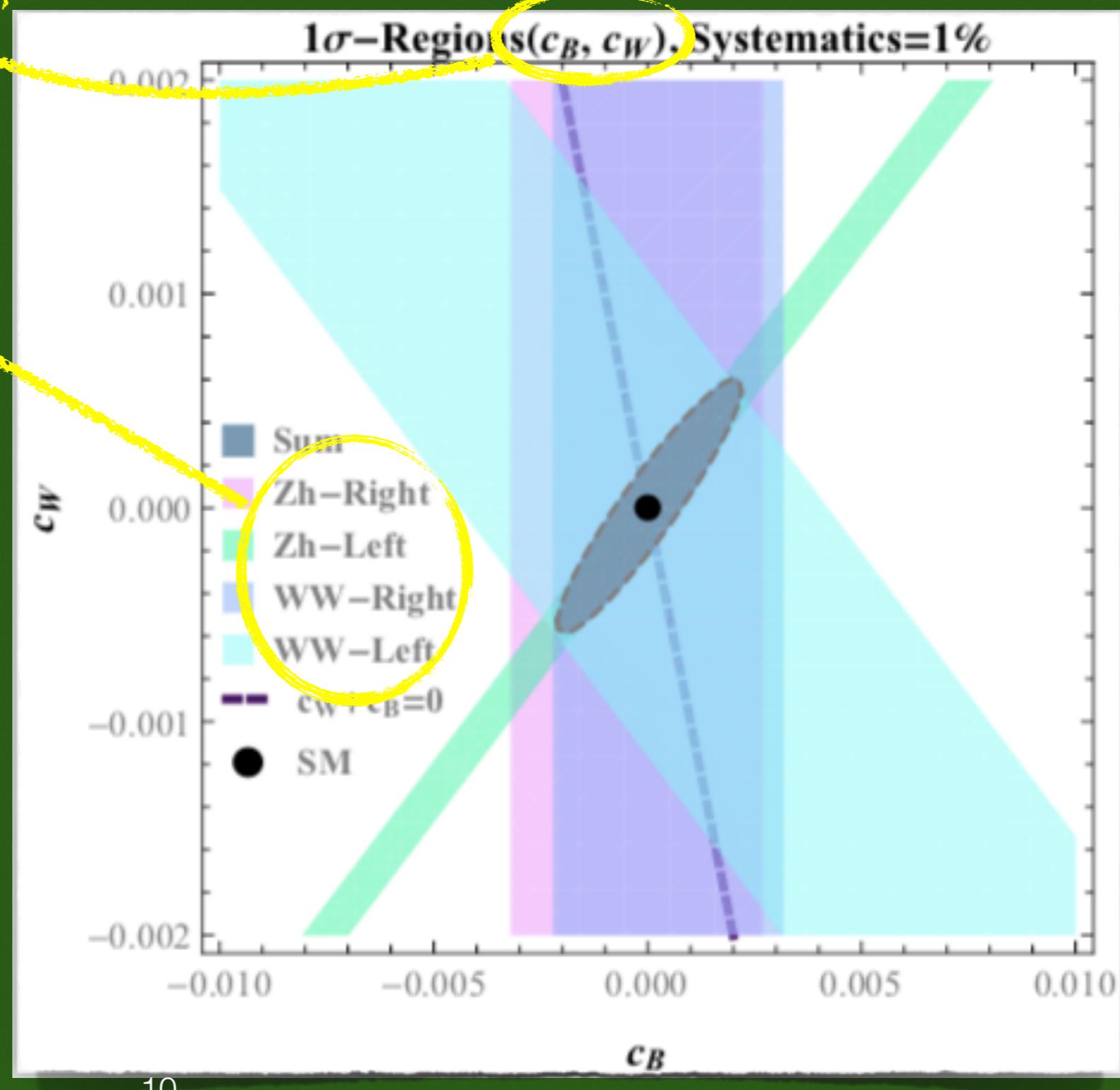


# Study of ee- $\rightarrow$ (WW,Zh)Longitudinals-Results2

- Dibosons Reach to Disentangle BSM parameters

> Different Stages as different Probes

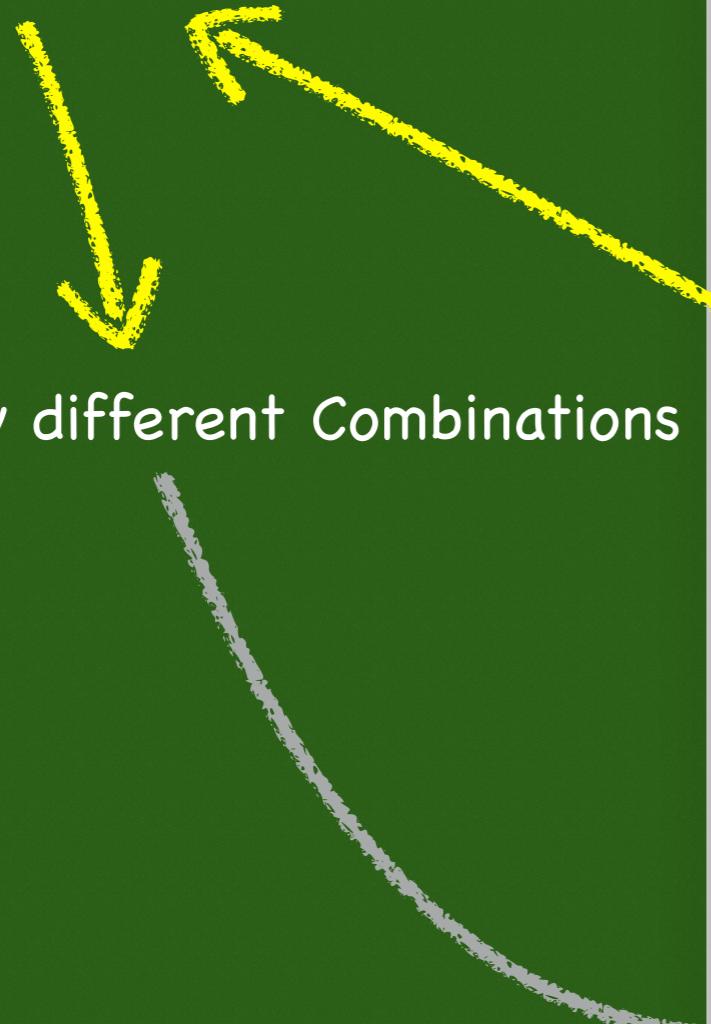
Different new Effects



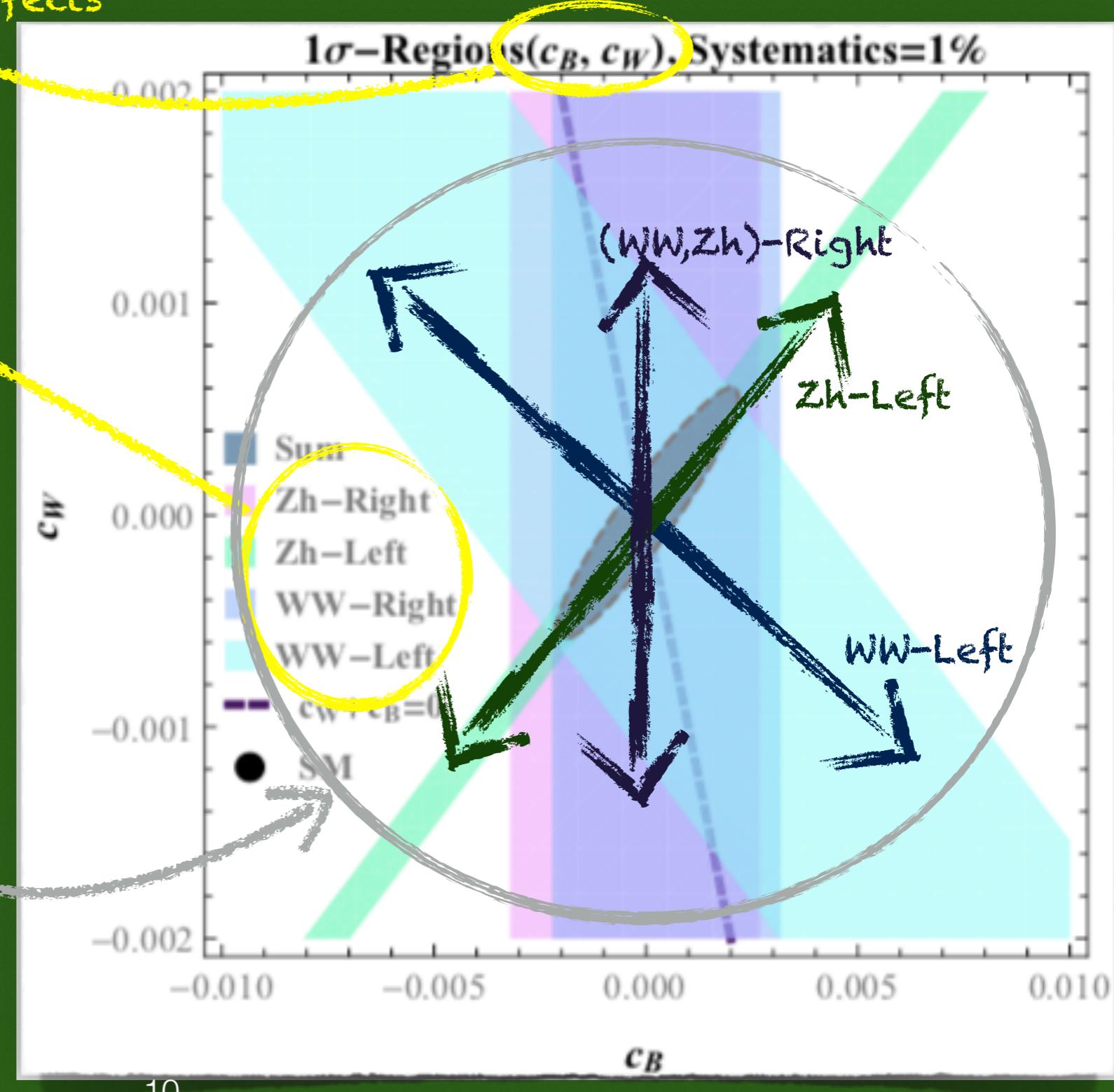
# Study of ee- $\rightarrow$ (WW,Zh)Longitudinals-Results2

- Dibosons Reach to Disentangle BSM parameters

> Different Stages as different Probes

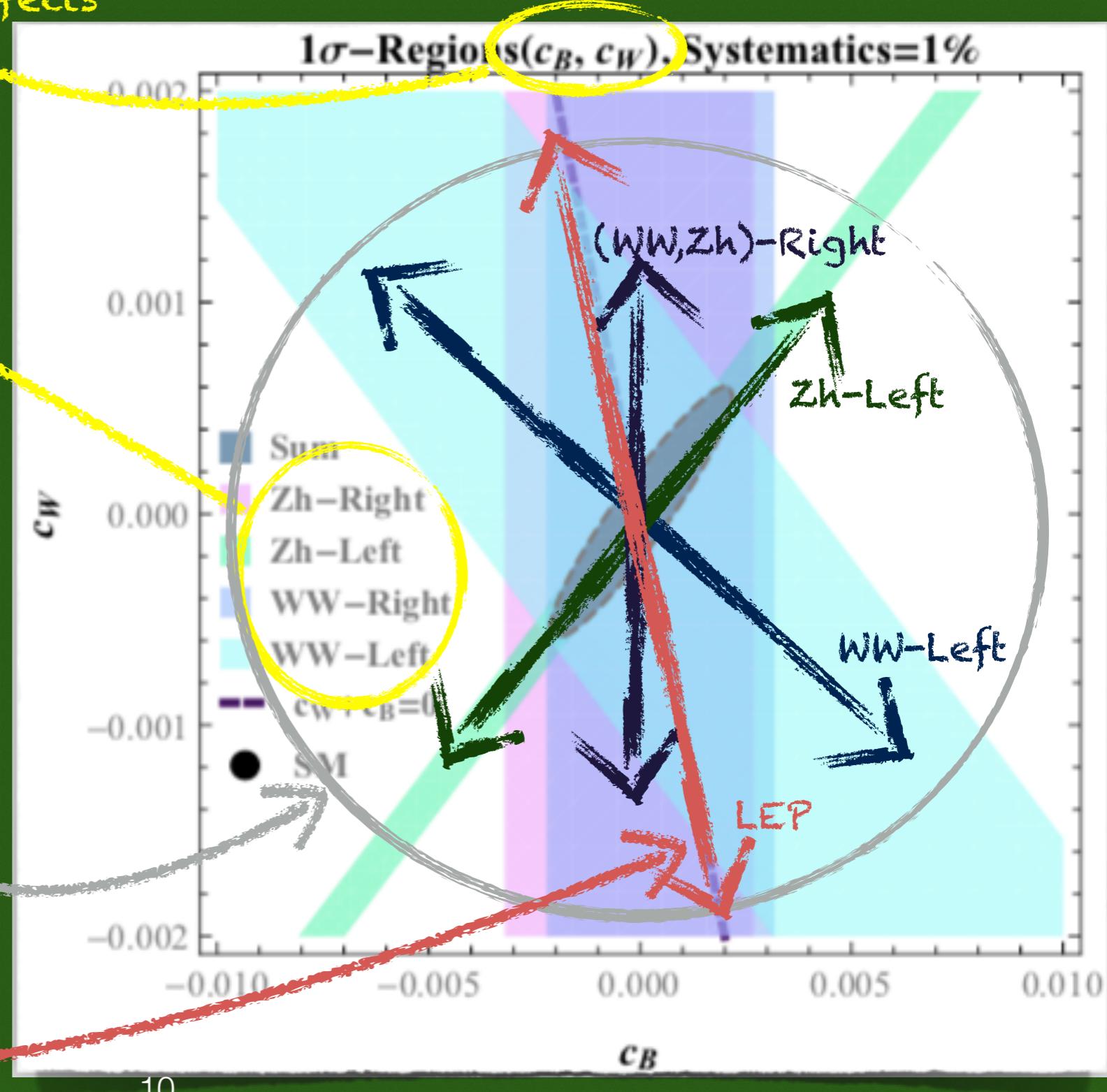
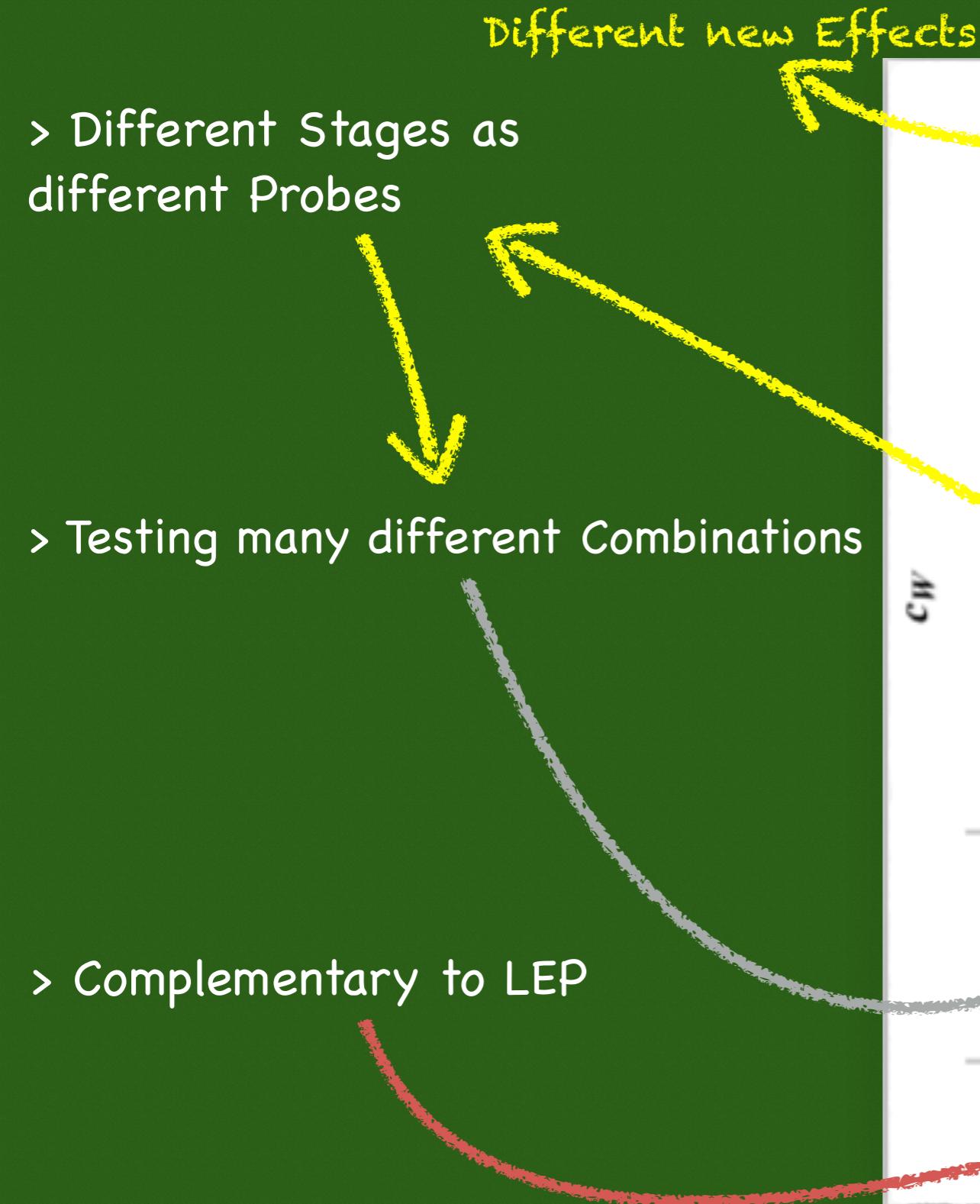


> Testing many different Combinations



# Study of ee- $\rightarrow$ (WW,Zh)Longitudinals-Results2

- Dibosons Reach to Disentangle BSM parameters





# Conclusions

# Conclusions

- CLIC to Search for New Physics in High-Energy Dibosons

# Conclusions

- CLIC to Search for New Physics in High-Energy Dibosons
  - > Different Final States and Helicities for different BSM searches

# Conclusions

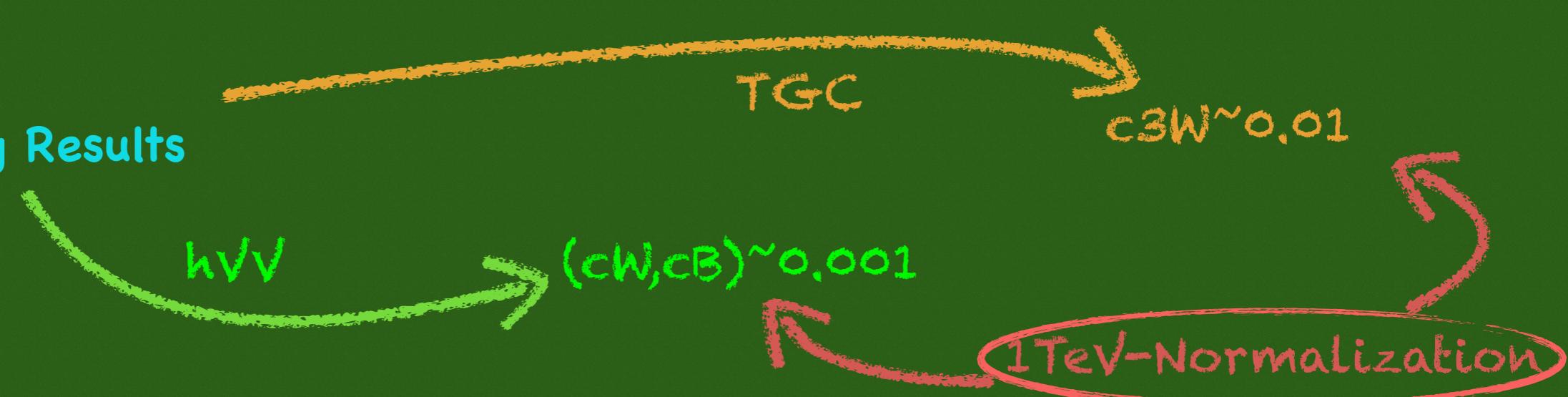
- CLIC to Search for New Physics in High-Energy Dibosons
  - > Different Final States and Helicities for different BSM searches
  - > Triple Gauge Couplings study in (WW)Transverse
    - Exclusive measurements of the azimuthal Angles to resurrect Interference
  - > Higgs Couplings in (WW,Zh)Longitudinals
    - Complementarity of WithoutHiggs/WithHiggs to probe the Higgs Sector (Talk by Marc Riembau)

# Conclusions

- CLIC to Search for New Physics in High-Energy Dibosons
  - > Different Final States and Helicities for different BSM searches
  - > Triple Gauge Couplings study in (WW)Transverse
    - Exclusive measurements of the azimuthal Angles to resurrect Interference
  - > Higgs Couplings in (WW,Zh)Longitudinals
    - Complementarity of WithoutHiggs/WithHiggs to probe the Higgs Sector (Talk by Marc Riembau)
  - + / -

# Conclusions

- CLIC to Search for New Physics in High-Energy Dibosons
  - > Different Final States and Helicities for different BSM searches
  - > Triple Gauge Couplings study in (WW)Transverse
    - Exclusive measurements of the azimuthal Angles to resurrect Interference
  - > Higgs Couplings in (WW,Zh)Longitudinals
    - Complementarity of WithoutHiggs/WithHiggs to probe the Higgs Sector (Talk by Marc Riembau)
  - + / -
- > Very Promising Results



# Conclusions

- CLIC to Search for New Physics in High-Energy Dibosons
    - > Different Final States and Helicities for different BSM searches
    - > Triple Gauge Couplings study in (WW)Transverse
      - Exclusive measurements of the azimuthal Angles to resurrect Interference
    - > Higgs Couplings in (WW,Zh)Longitudinals
      - Complementarity of WithoutHiggs/WithHiggs to probe the Higgs Sector (Talk by Marc Riembau)
    - + / -
    - > Very Promising Results
    - > Could Benefit from Vectors-Polarization Tagging
- 
- TGC
- $c_{3W} \sim 0.01$
- $hVv$
- $(c_W, c_B) \sim 0.001$
- 1TeV-Normalization

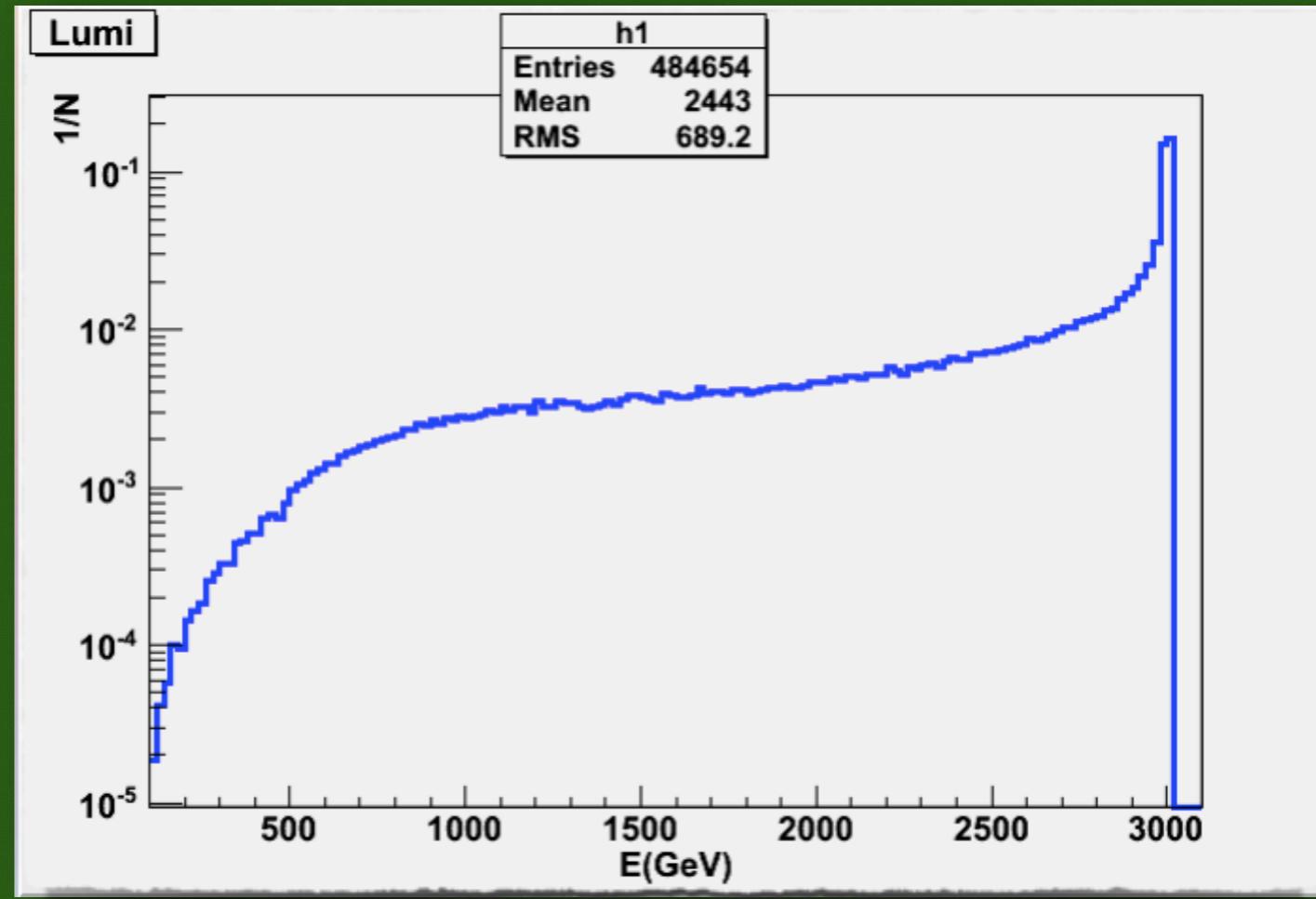
# Thanks!



# Inclusion of Radiation Effects

# Inclusion of Radiation Effects

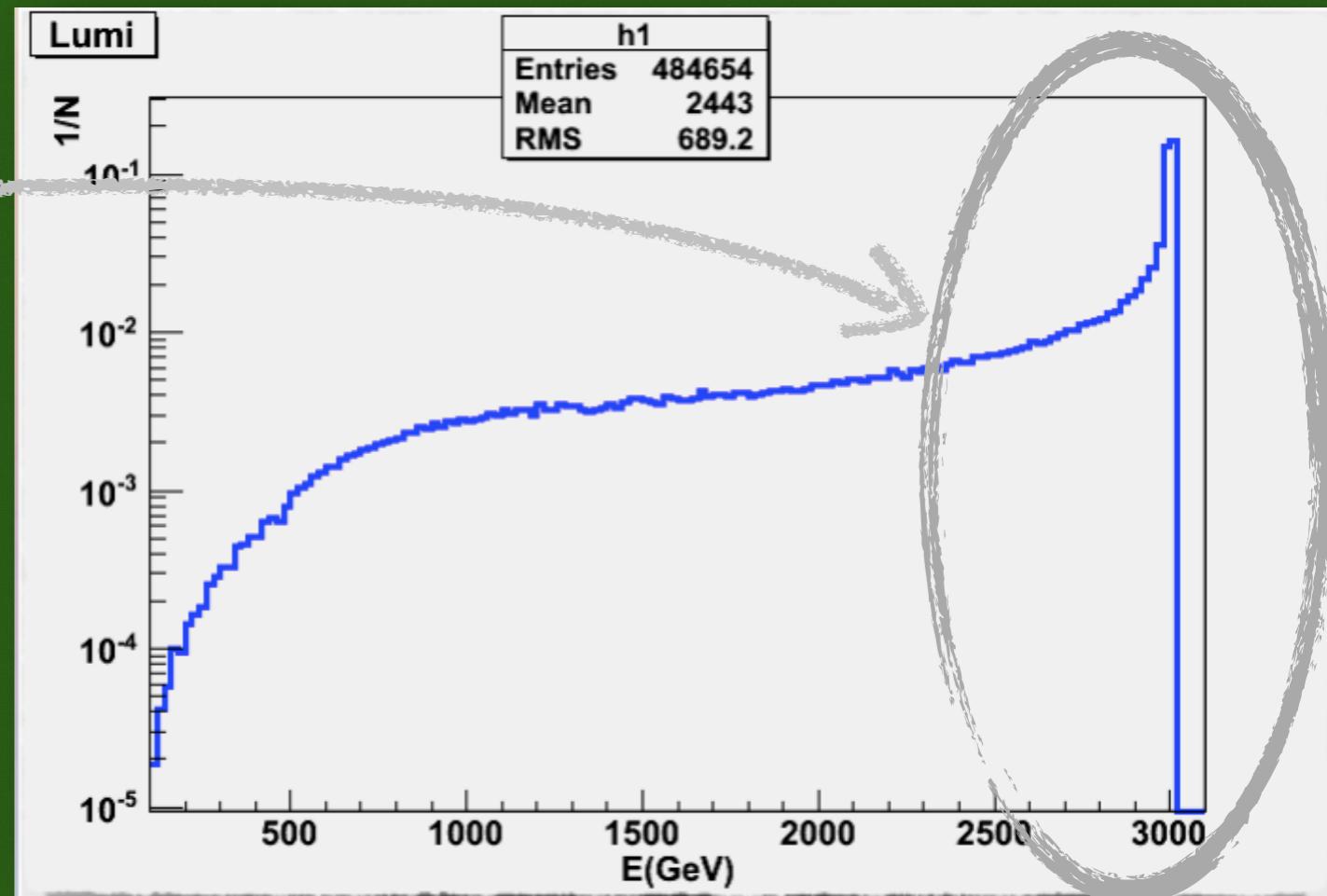
- Loss of Initial Energy due to Radiation



# Inclusion of Radiation Effects

- Loss of Initial Energy due to Radiation

Lower  
Effective  
Luminosity at  
high energy



# Inclusion of Radiation Effects

- Loss of Initial Energy due to Radiation

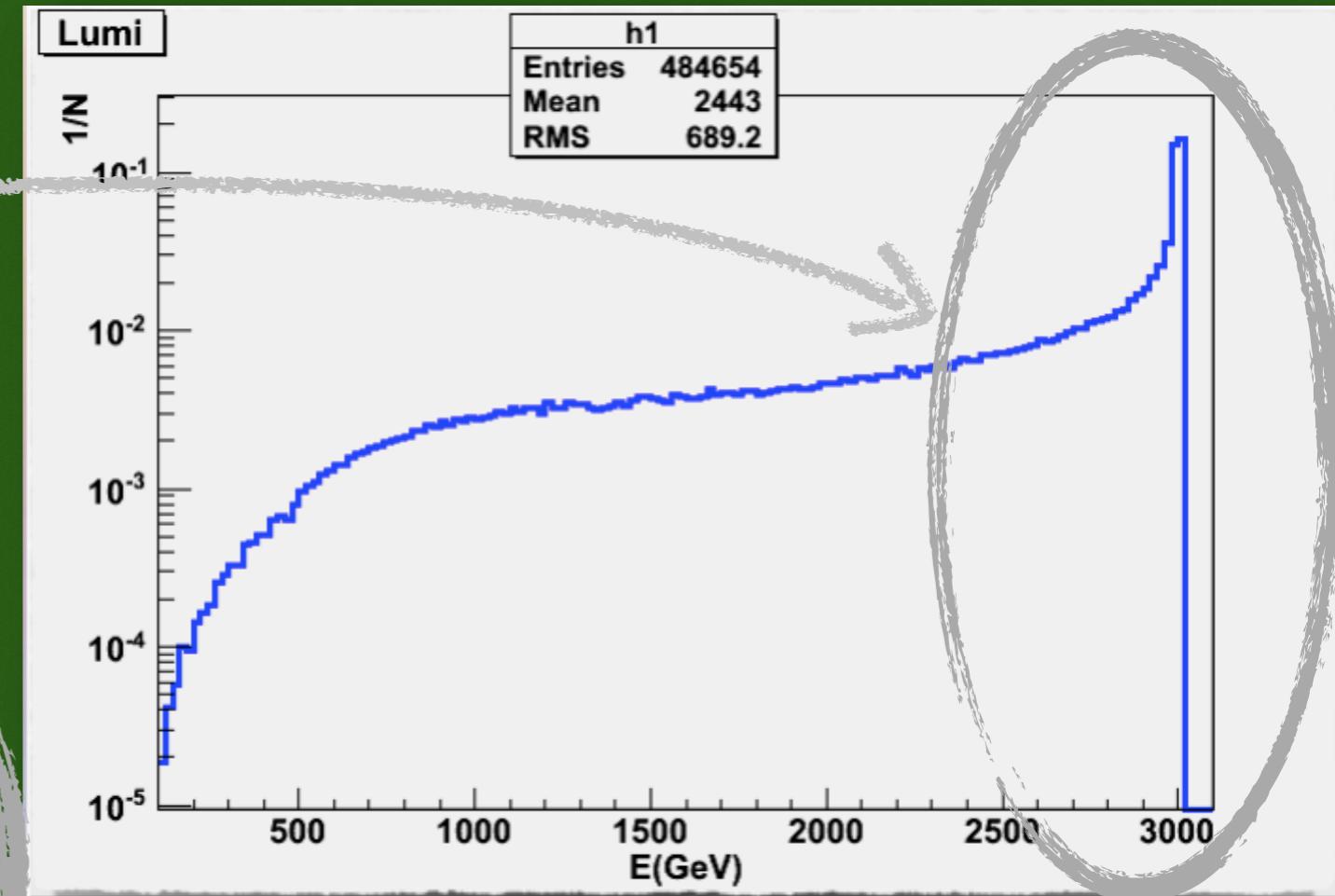
Lower  
Effective  
Luminosity at  
high energy

Energy (GeV)

3000
1500
380

Cut (GeV)

2600
1300
330



- Cut to keep only the High-Energy Events