*plus two month

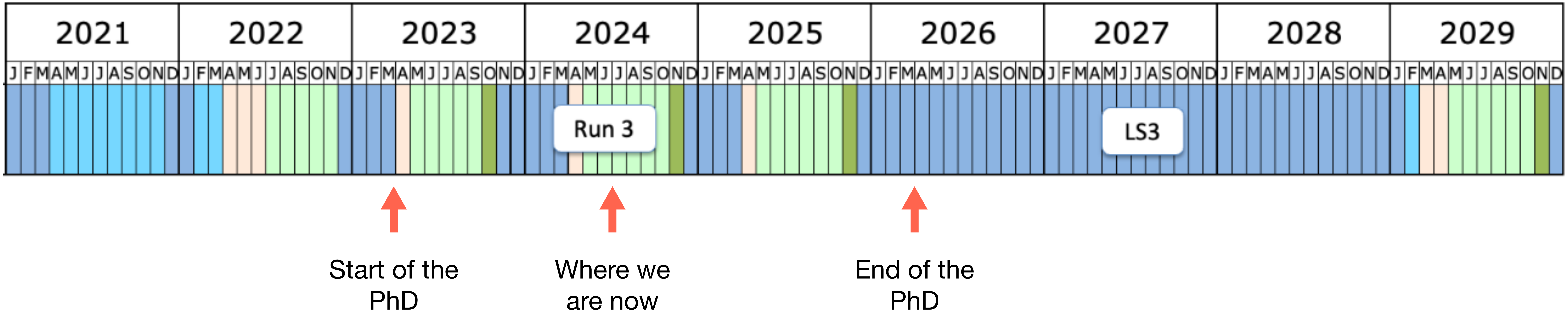
Status update of the 1st* year

Anna Tegetmeier

Laboratoire des 2 Infinis, Toulouse

21.06.2024

Timeline and Objectives



Worked on three main topics in the **first year**:

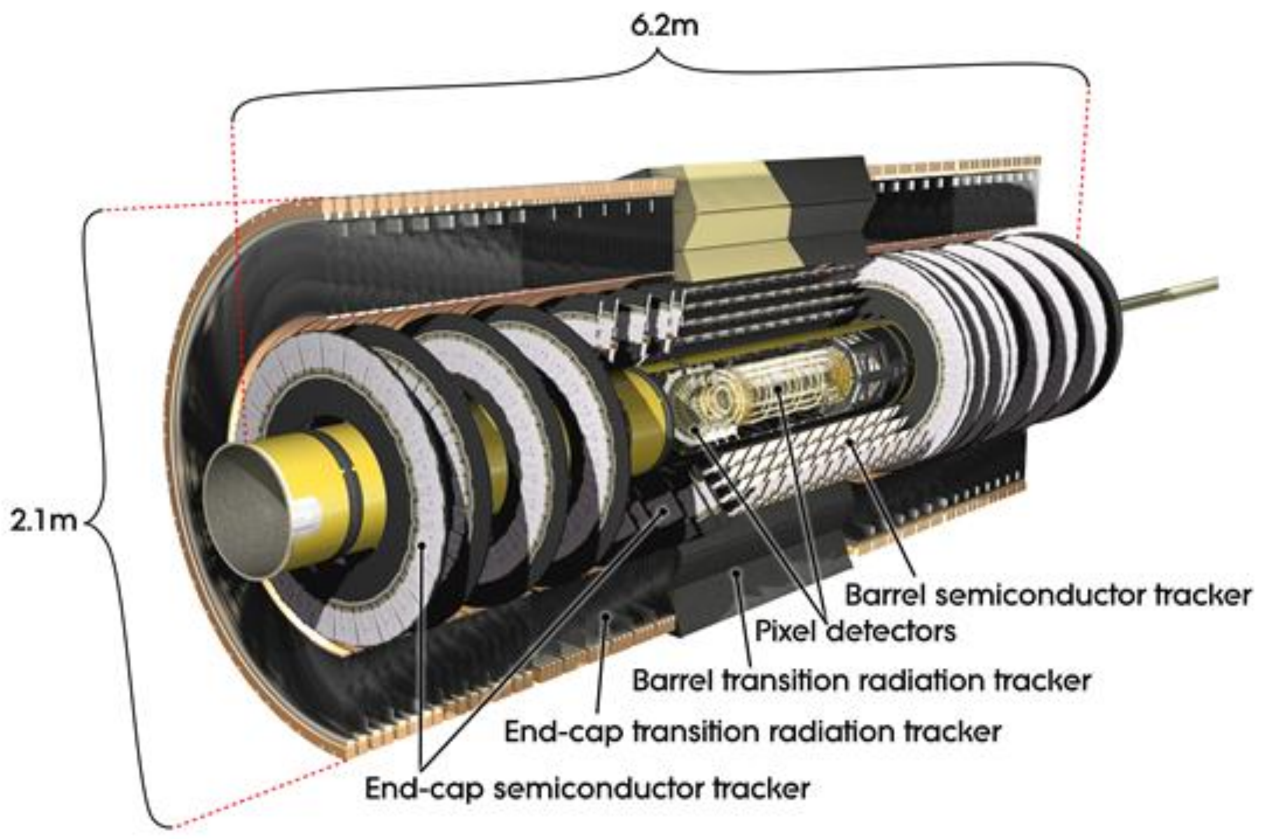
1. Qualification project
2. Polarisation for VBF di-Higgs
3. Effective Field Theories in VBF di-Higgs

1. Qualification Project

Qualification Project: Tracking

- Project for People in the ATLAS collaboration to become an author
- Duration: 1 year

- Topic: Backtracking with the ITk
  - ITk
    - new Silicon based inner detector built to replace the current inner detector in ATLAS for the HL-LHC phase
  - Backtracking algorithm
    - Algorithm to improve reconstruction of converted photons
    - Used to reconstruct tracks originating from electron-positron pairs from photon conversion
    - Such tracks are typically displaced which makes
      - difficult for the standard tracking algorithm to reconstruct them

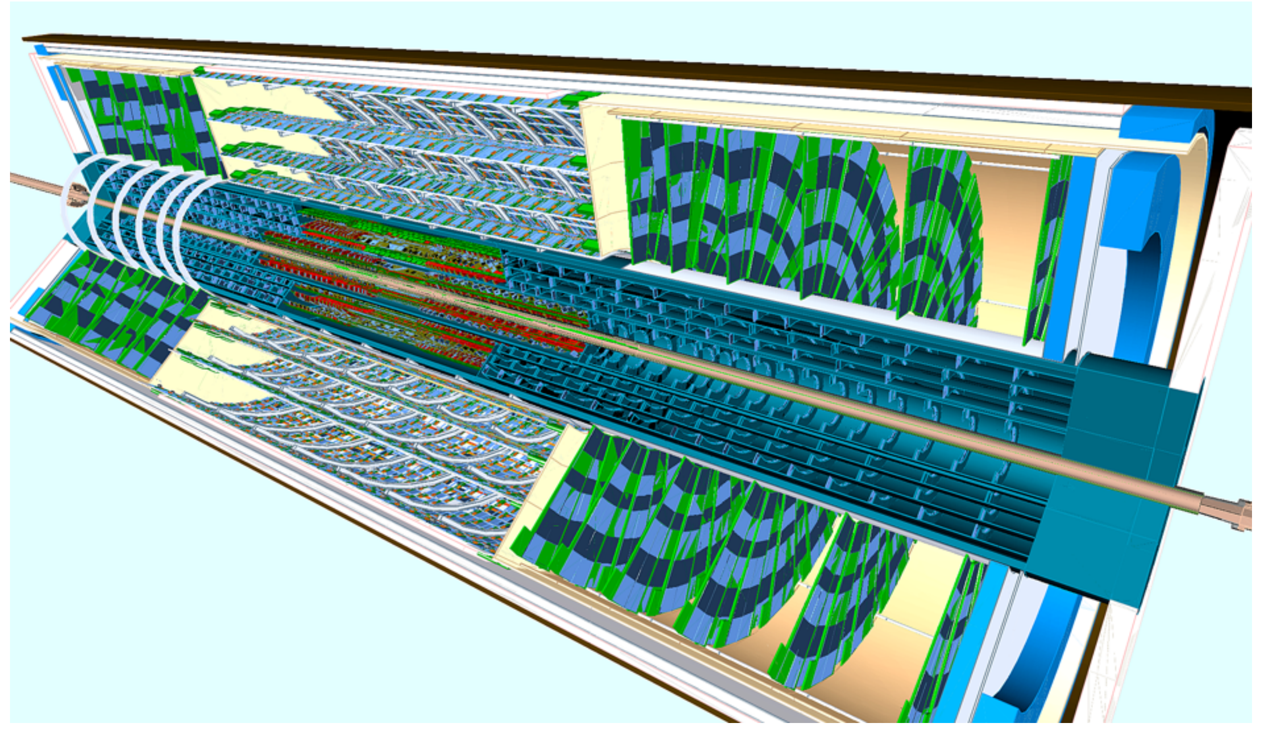


Current inner detector

https://mediaarchive.cern.ch/MediaArchive/Photo/Public/2008/0803014/0803014_01/0803014_01-A5-at-72-dpi.jpg

↓ HL-LHC

ITk



https://cds.cern.ch/record/2850865/files/ATLAS_ITK.png

Qualification Project

- Testing the current implementation of the method in the main development branch
  Status: done

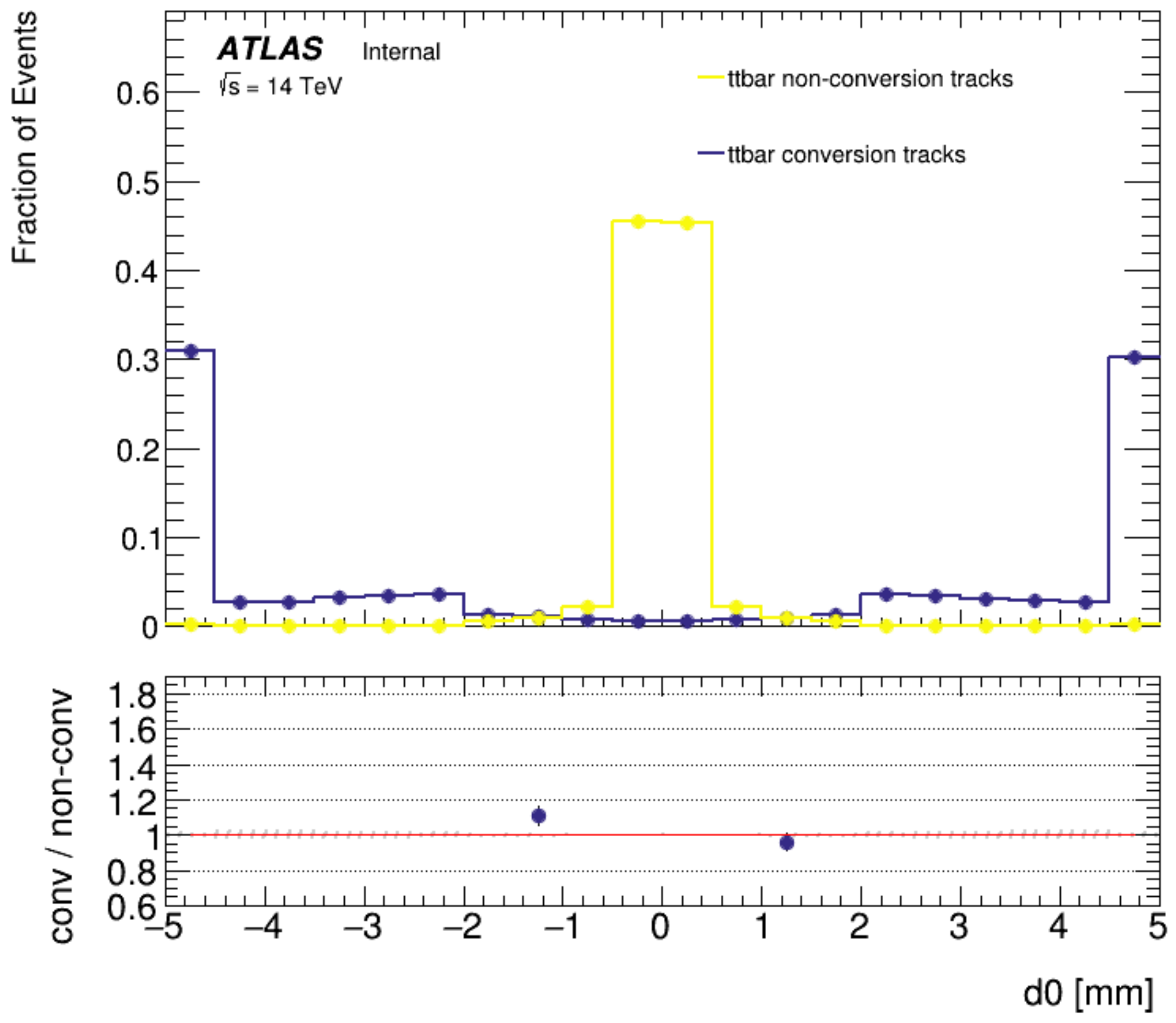
- Characterize the performance of the method to figure out how electron track efficiency is lost and/or track quality is degraded
  Status: done

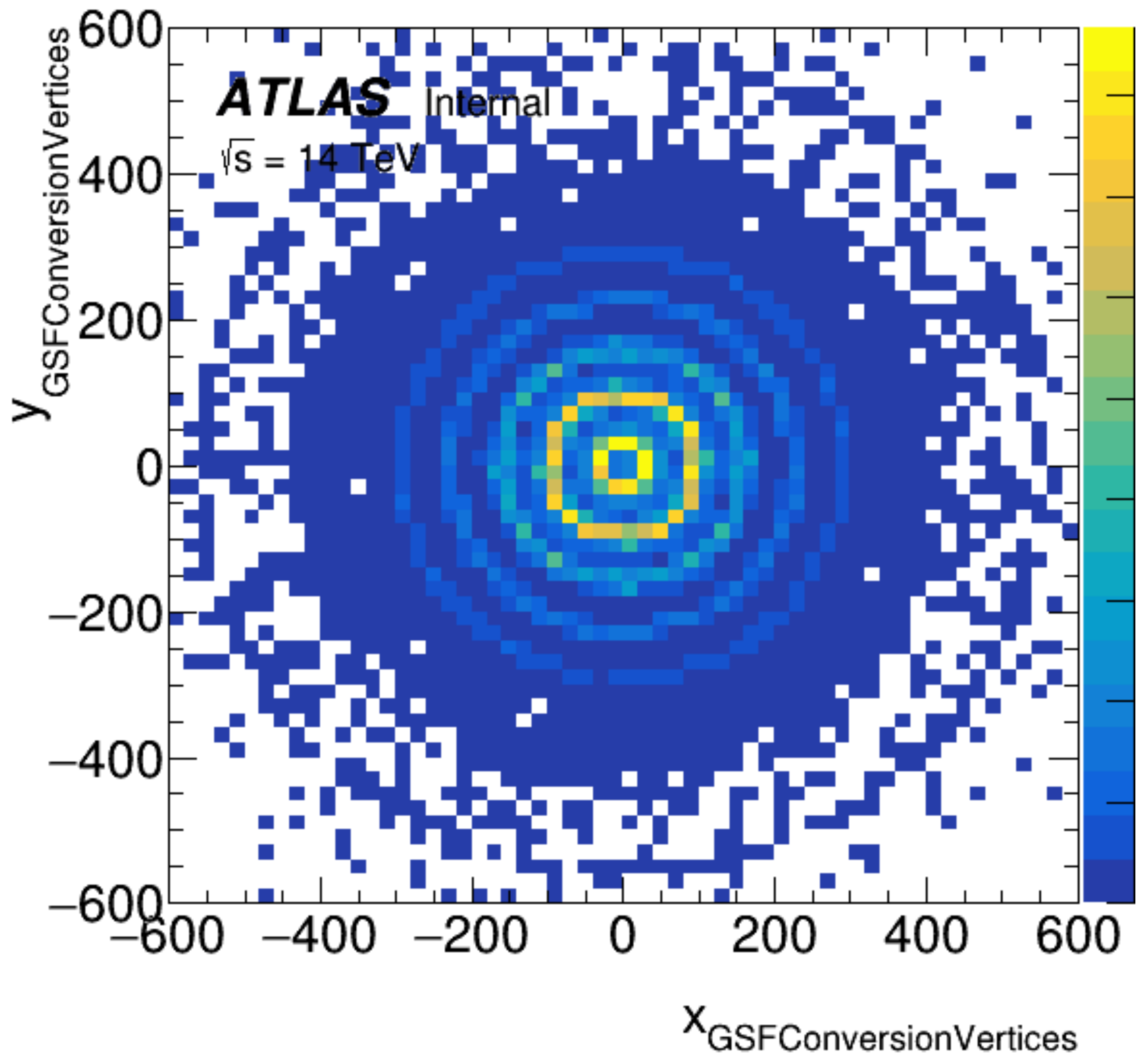
- Improve the method in the context of the ITk
  Status: almost finished

Qualification Project

Testing the current implementation of the method in the main development branch
Status: done

- Confirmed that tracks from the Backtracking algorithm are available and look reasonable
- Can be accessed for different track container
- Conversion vertices are available and look reasonable

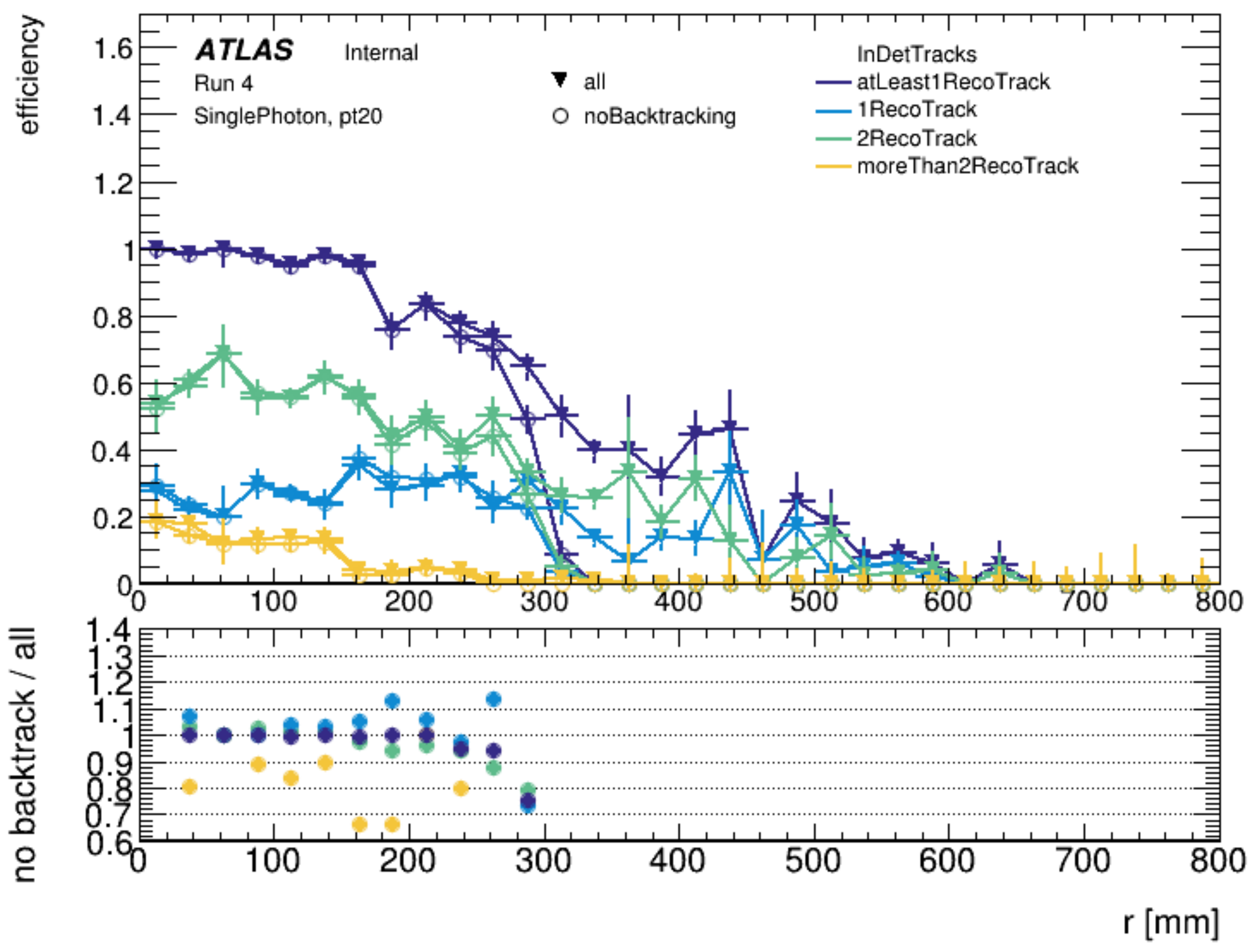


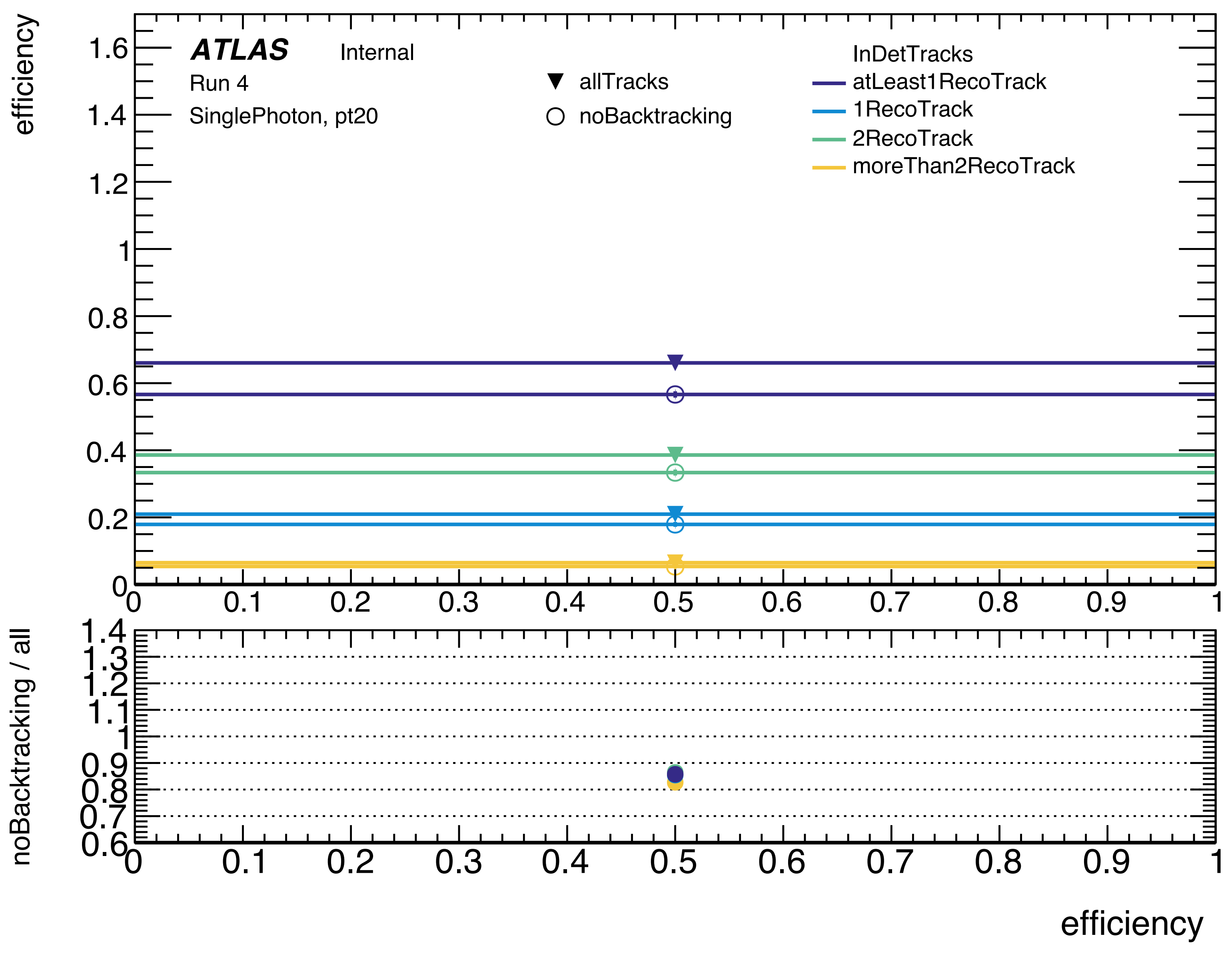


Qualification Project

Characterize the performance of the method to figure out how electron track efficiency is lost and/or track quality is degraded
Status: done

- Studied reconstruction efficiencies for photon conversions
- Found lower efficiency than for the current inner detector (who has efficiency >70%)

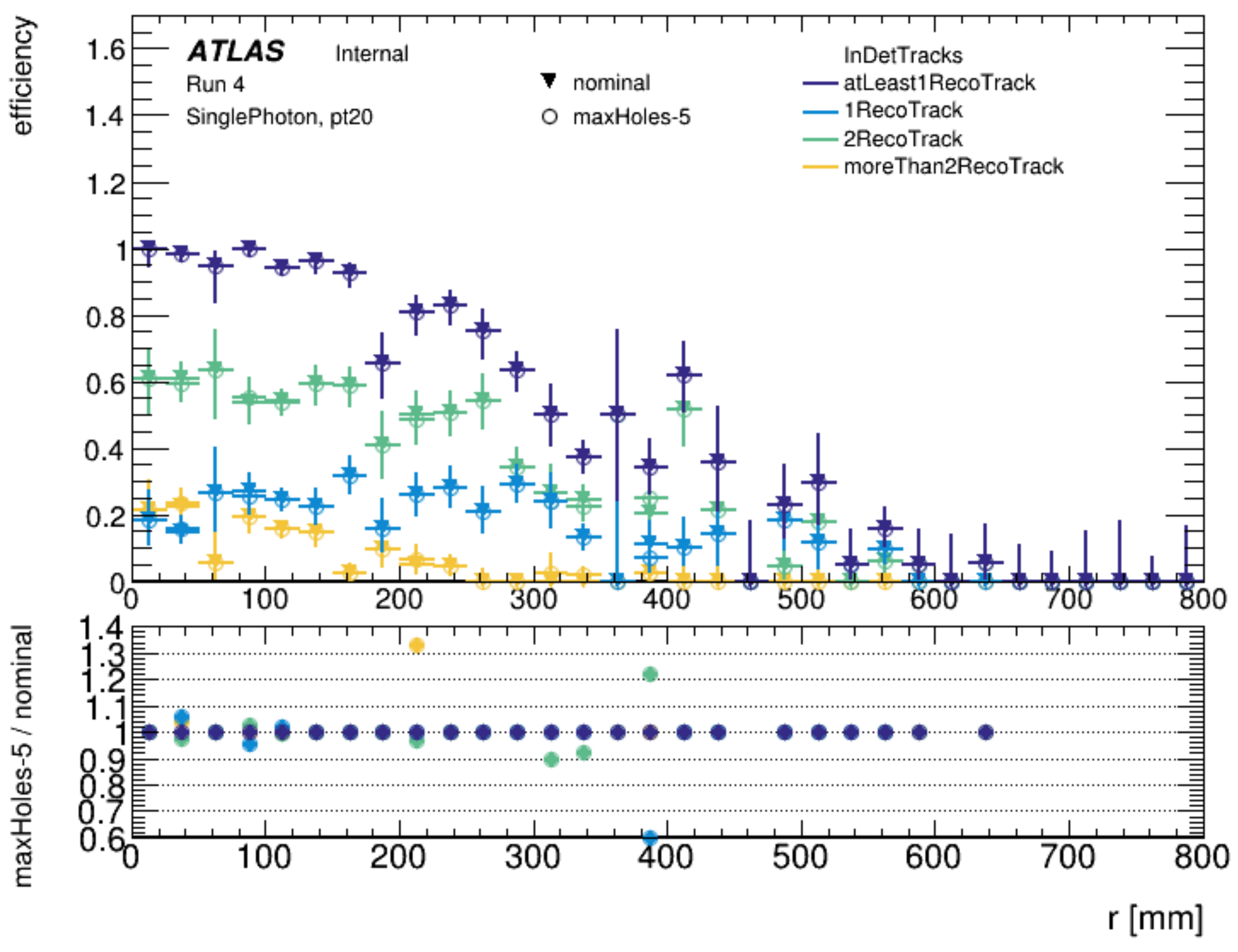


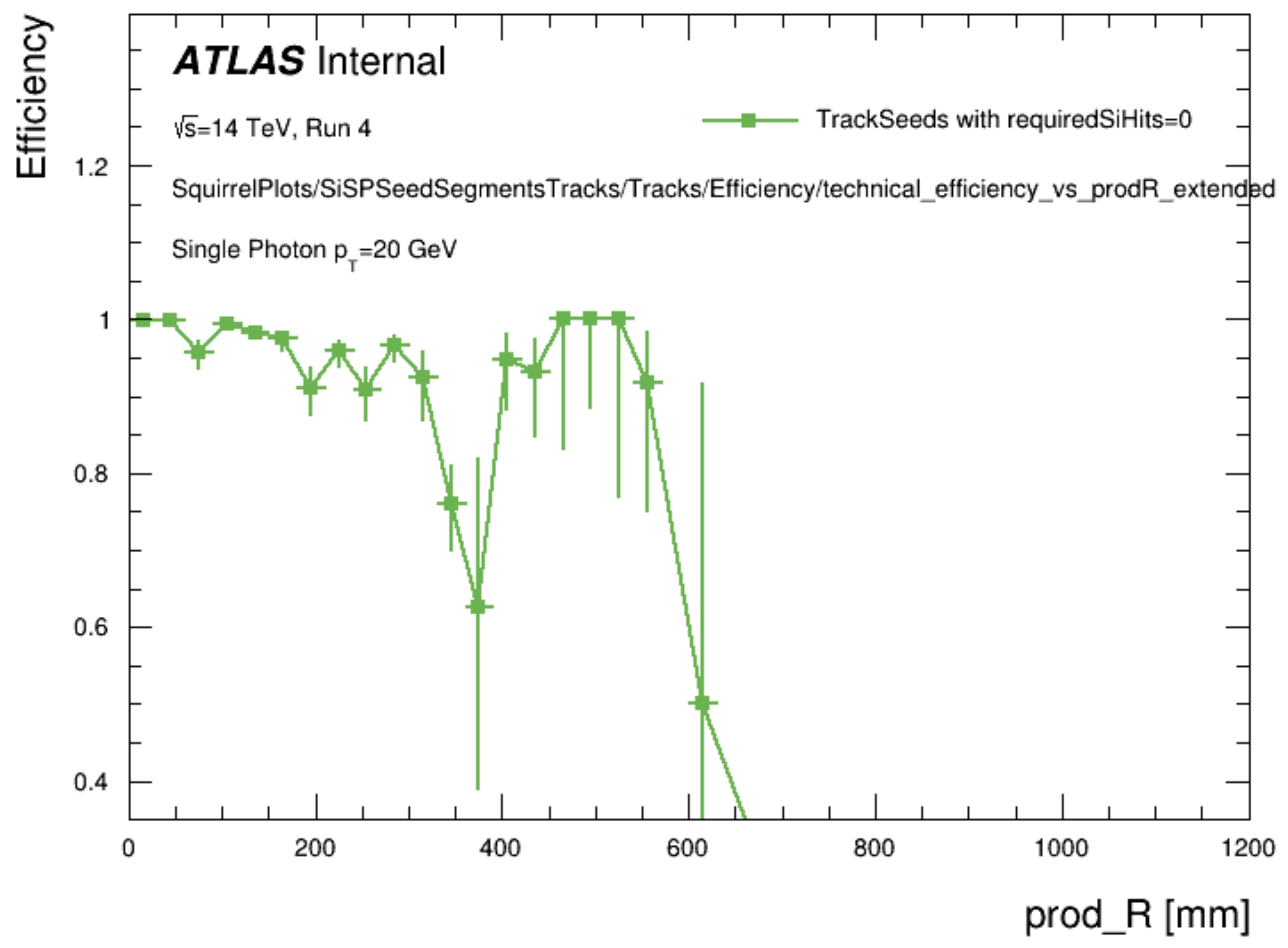


Qualification Project

Improve the method in the context of the ITk
Status: almost finished

- No improvement by modifying the parameters of the algorithm
- Studied seed efficiency
- Investigating truth conversion electrons that are not matched to tracks
- Will finish this in July



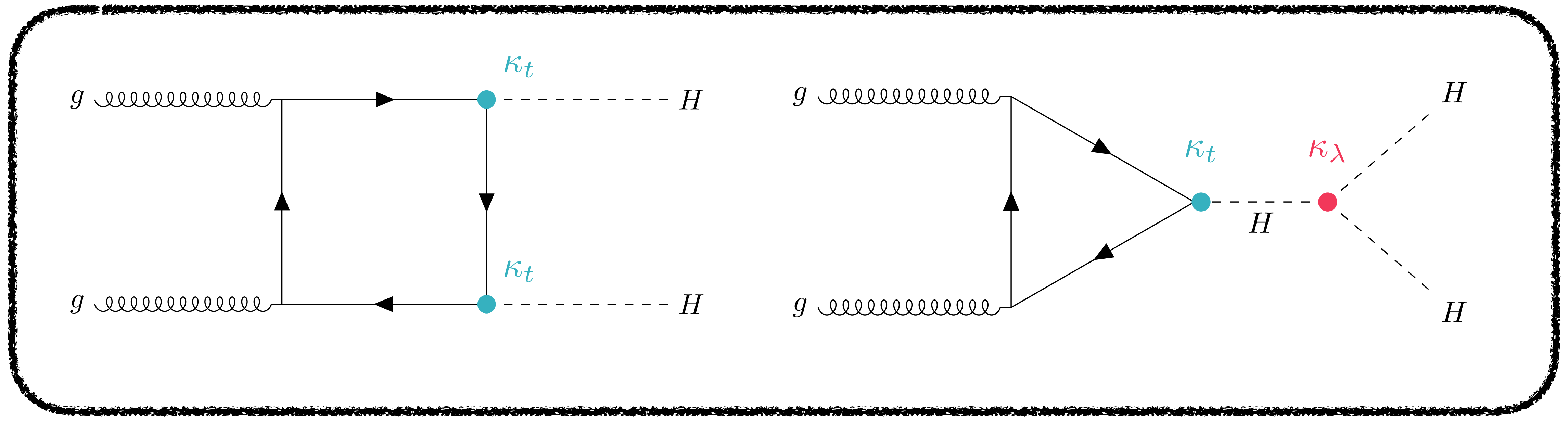


Main Physics Topic

Physics Subject

- Main physics focus of the thesis: **Higgs-boson pair production**
- Two main production modes:

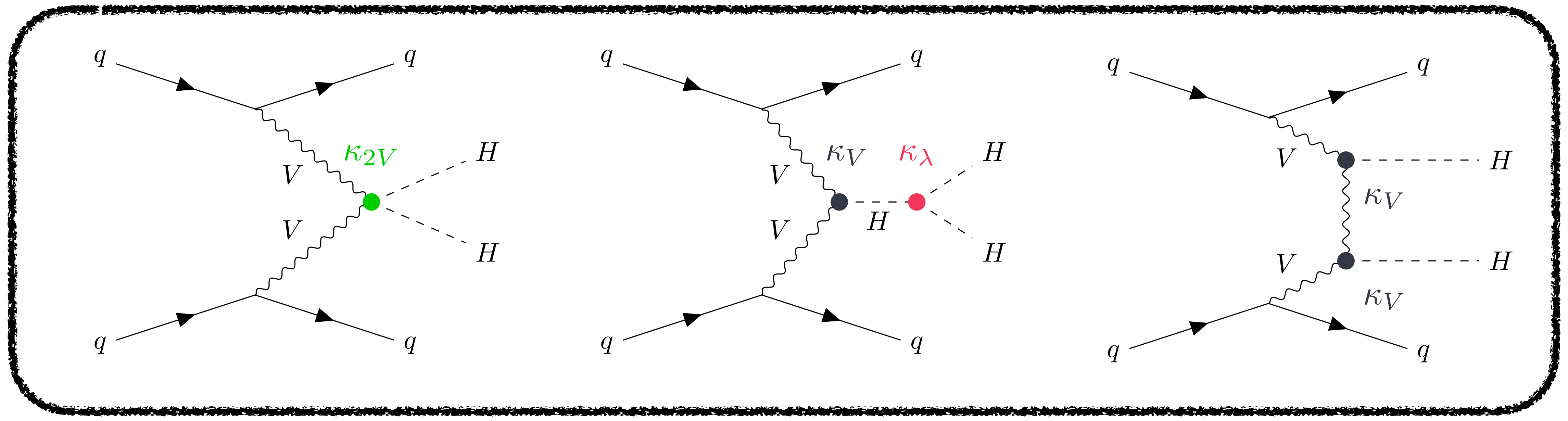
gluon-gluon Fusion (ggF)



Leading Production mode

- Cross section: $\sigma_{ggF} = 31.05$ fb
- Sensitive to the trilinear Higgs self-coupling (κ_λ)

Vector Boson Fusion (VBF)



Subleading Production mode

- Cross section: $\sigma_{VBF} = 1.73$ fb
- Sensitive to the trilinear Higgs self-coupling (κ_λ) and the coupling of two vector bosons to two Higgs bosons (κ_{2V})

2. Polarisation in VBF di-Higgs

Polarization

What is polarization?

- Alignment of a particles spin with its momentum

What are the polarizations of the W and Z boson?

- transversal polarization (T) ➝ Spin (anti)parallel to momentum
- longitudinal polarization (L) ➝ Spin perpendicular to momentum

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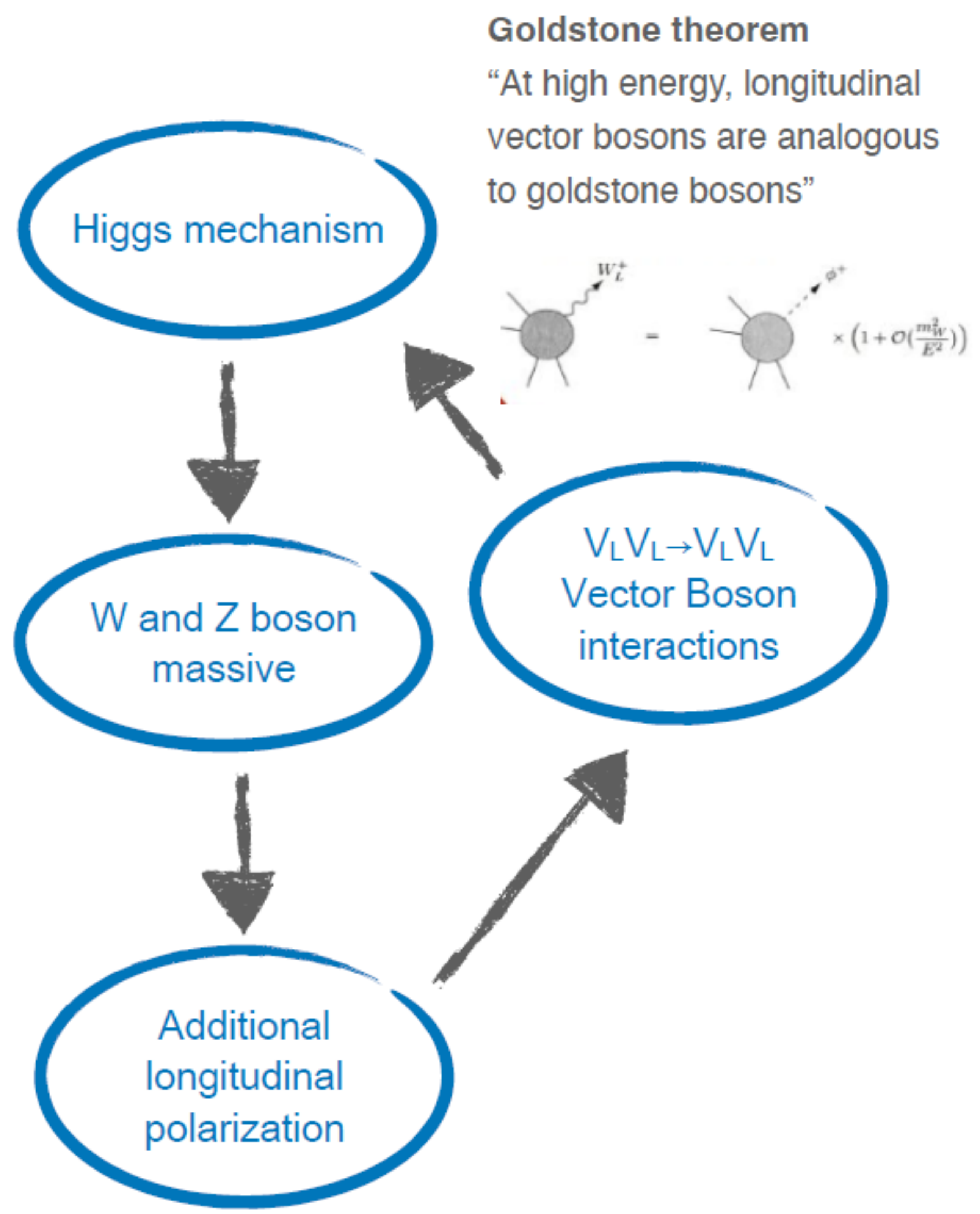
↓

- Direct consequence of the Higgs mechanism

→ Test of the this mechanism



Polarization

What is polarization?

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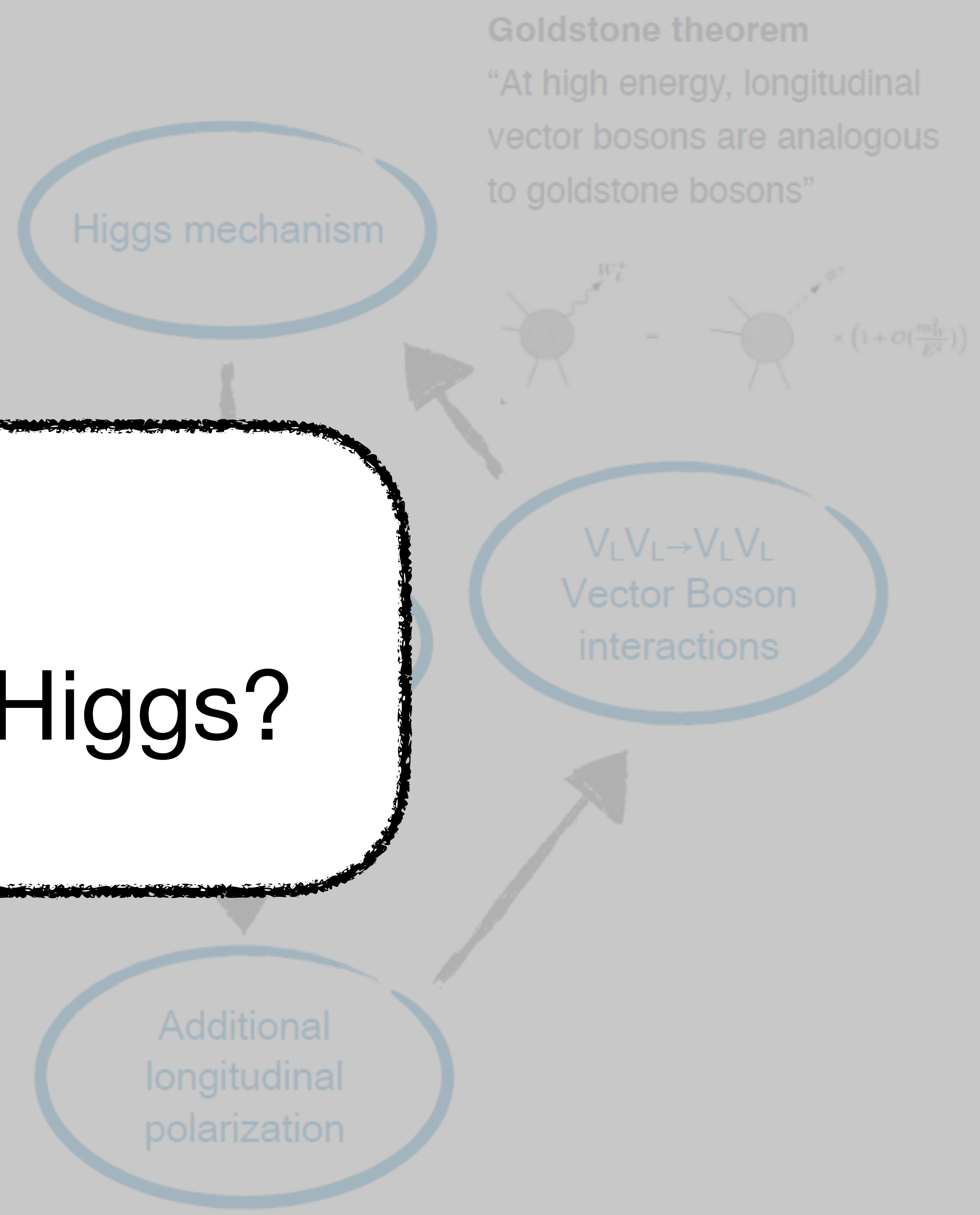
- ! longitudinal

Question:

What is the polarization composition in VBF di-Higgs?

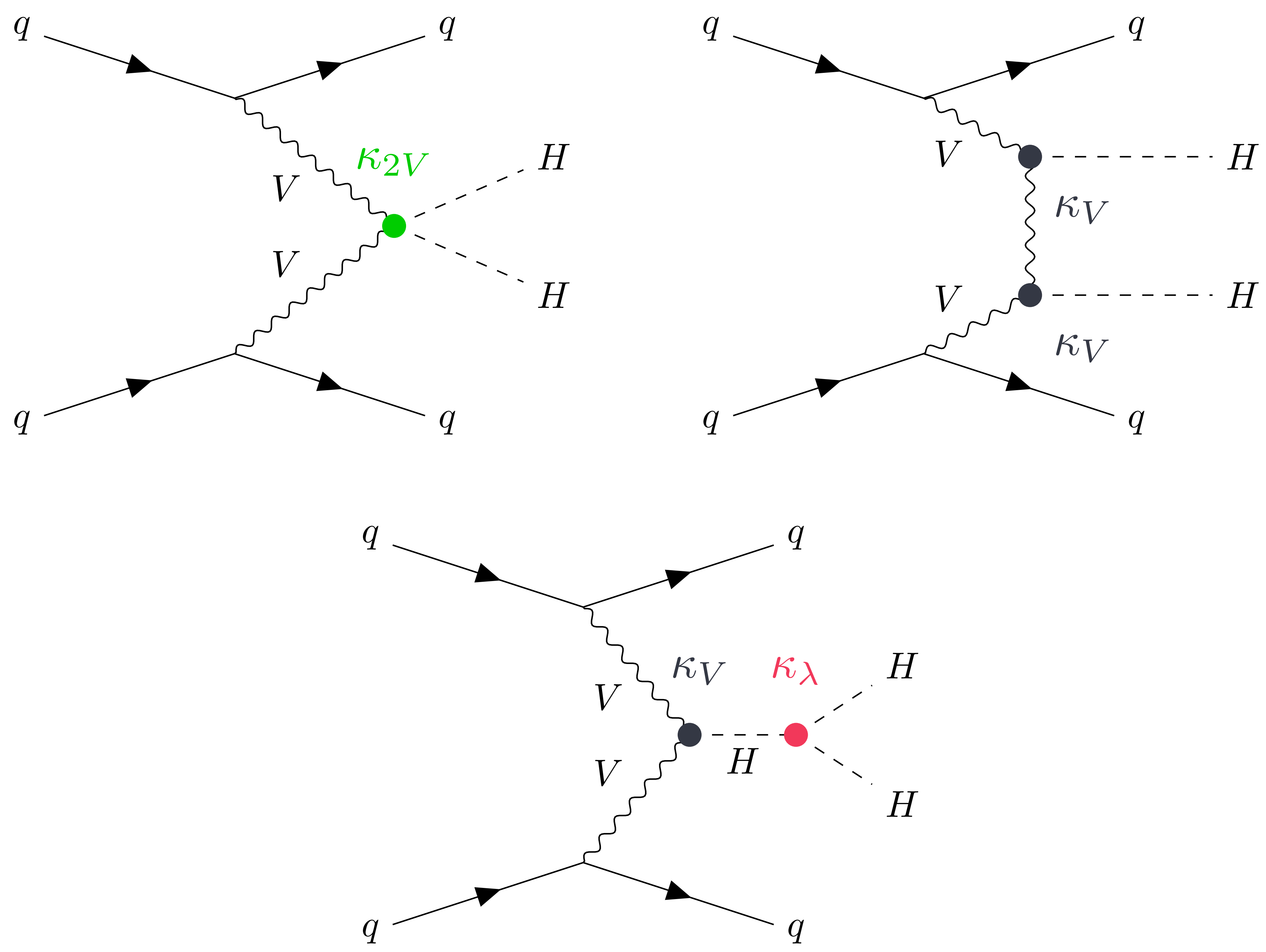
- Direct consequence of the Higgs mechanism

→ Test of the this mechanism



Polarization in VBF di-Higgs

Goal:
- Simulate VBF HH with polarized vector bosons



Polarization in VBF di-Higgs

Goal:

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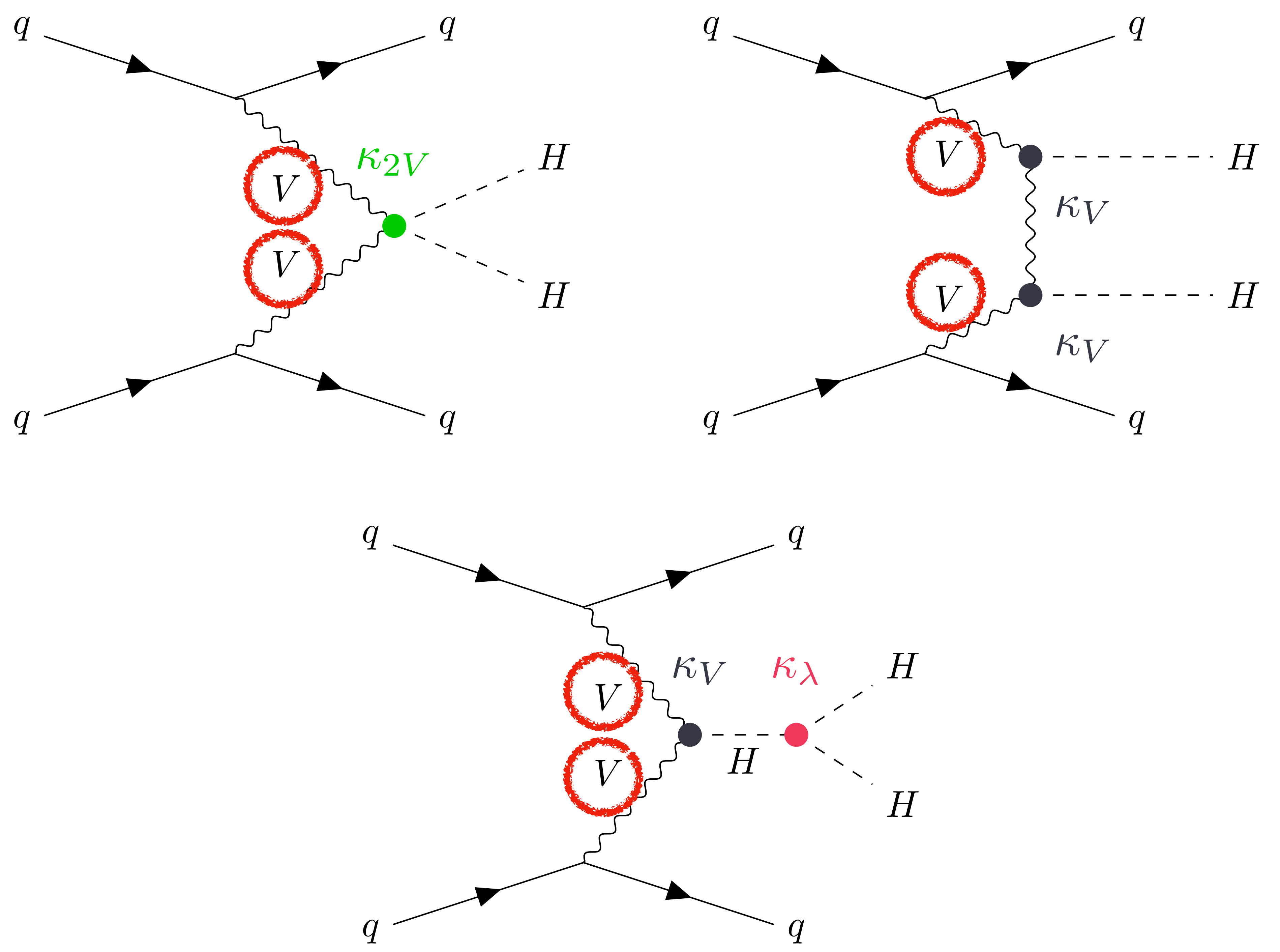
Problem:

- Vector bosons are intermediate particles
- No generator available to simulate the polarization of that at the moment



Polarization in VBF di-Higgs

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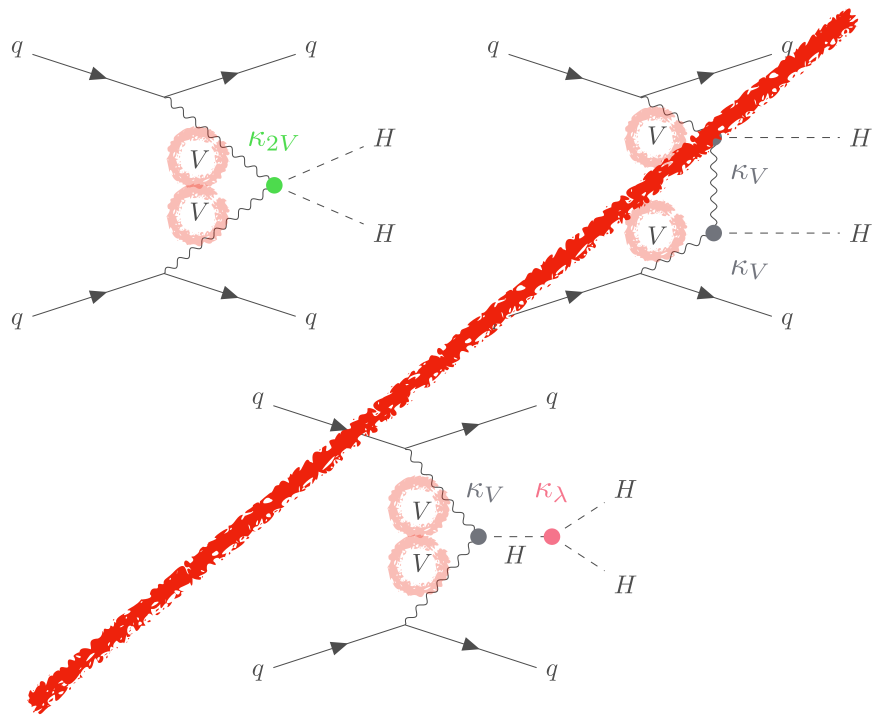
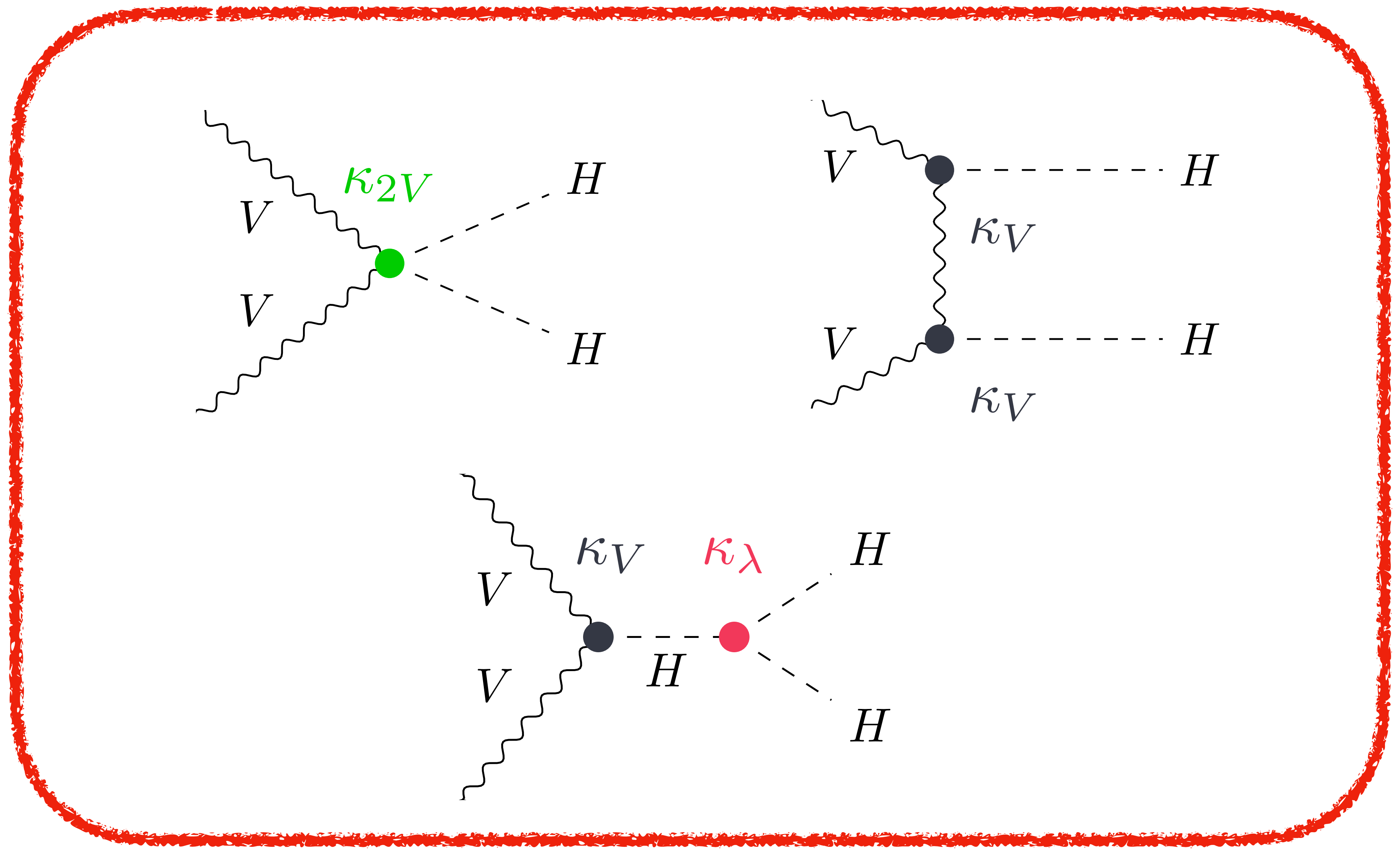
Temporary Fix:

- Simulate the direct collision of the vector bosons:

$$V_X V_X \rightarrow HH$$

- $X =$ longitudinal (L), transversal (T)





Polarization in VBF di-Higgs

Goal:

- Simulate V

- Vector b
- No gene
of that a

How does the cross section depends on:

- the center of mass energy
- different values of the coupling modifiers
- the different polarizations

Temporary Fix:

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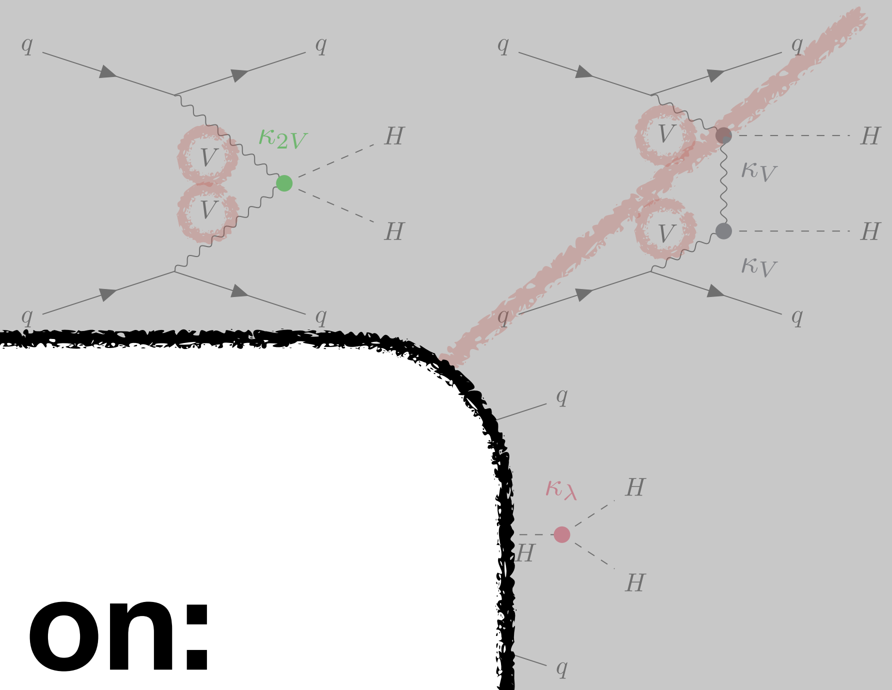
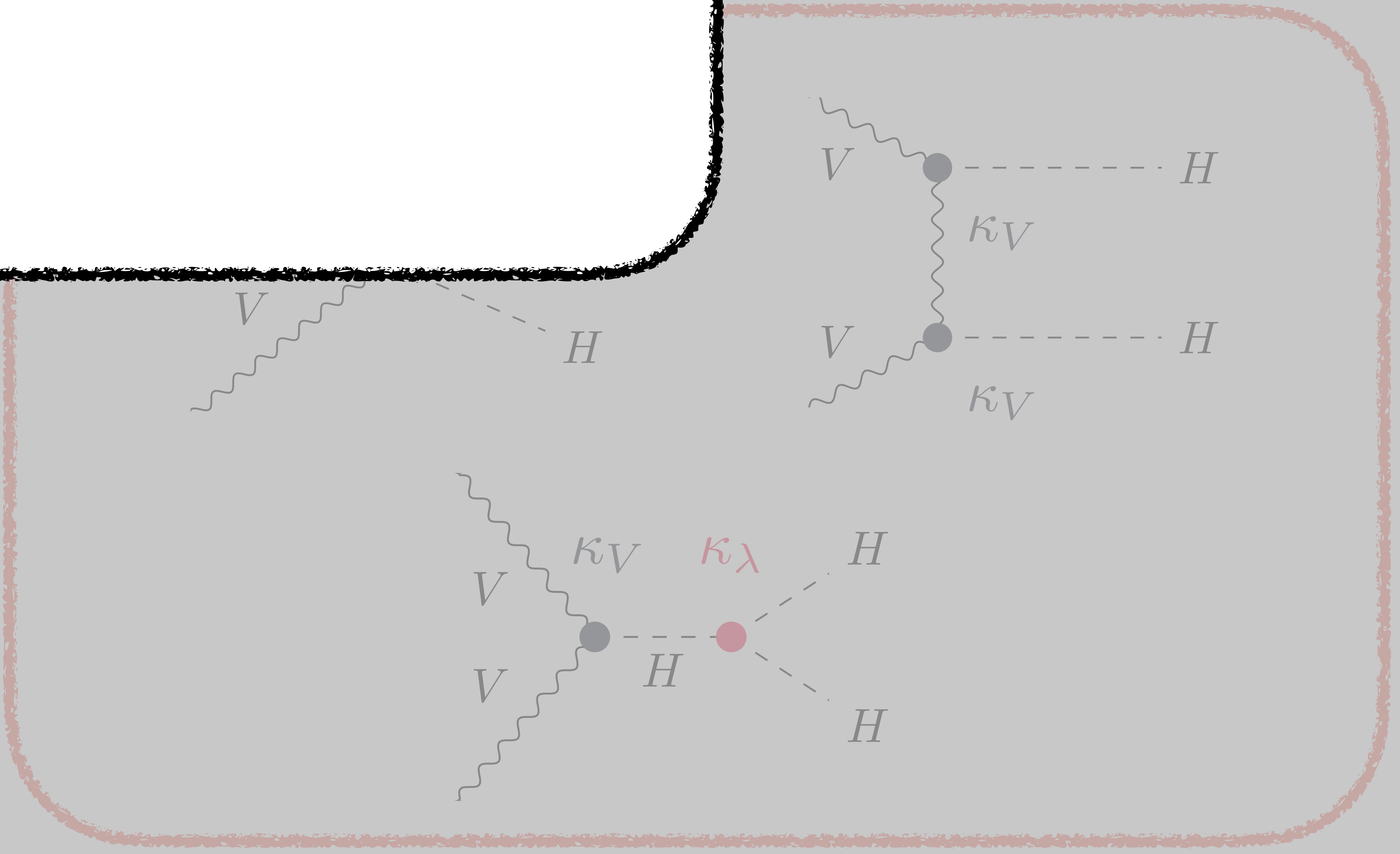
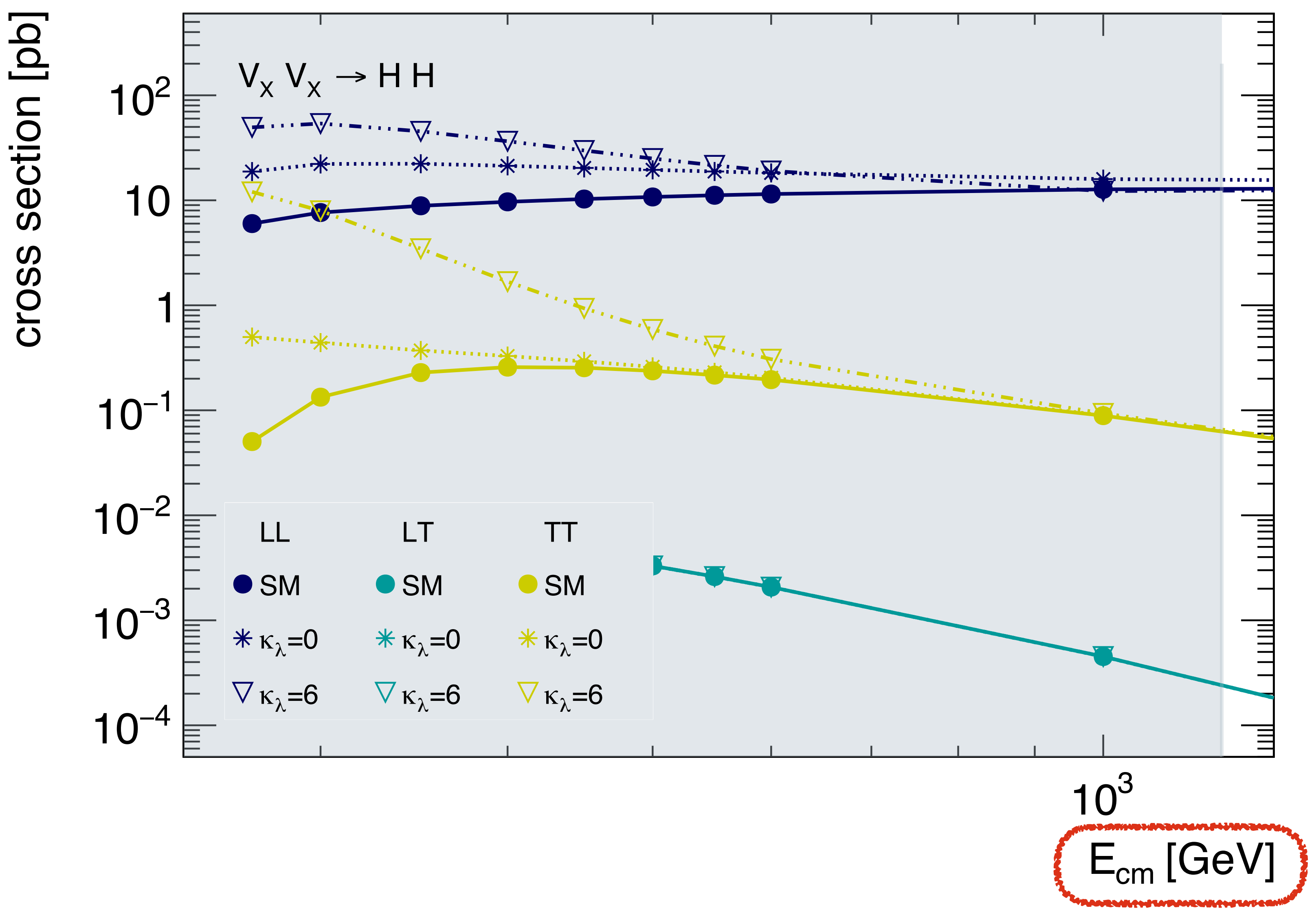


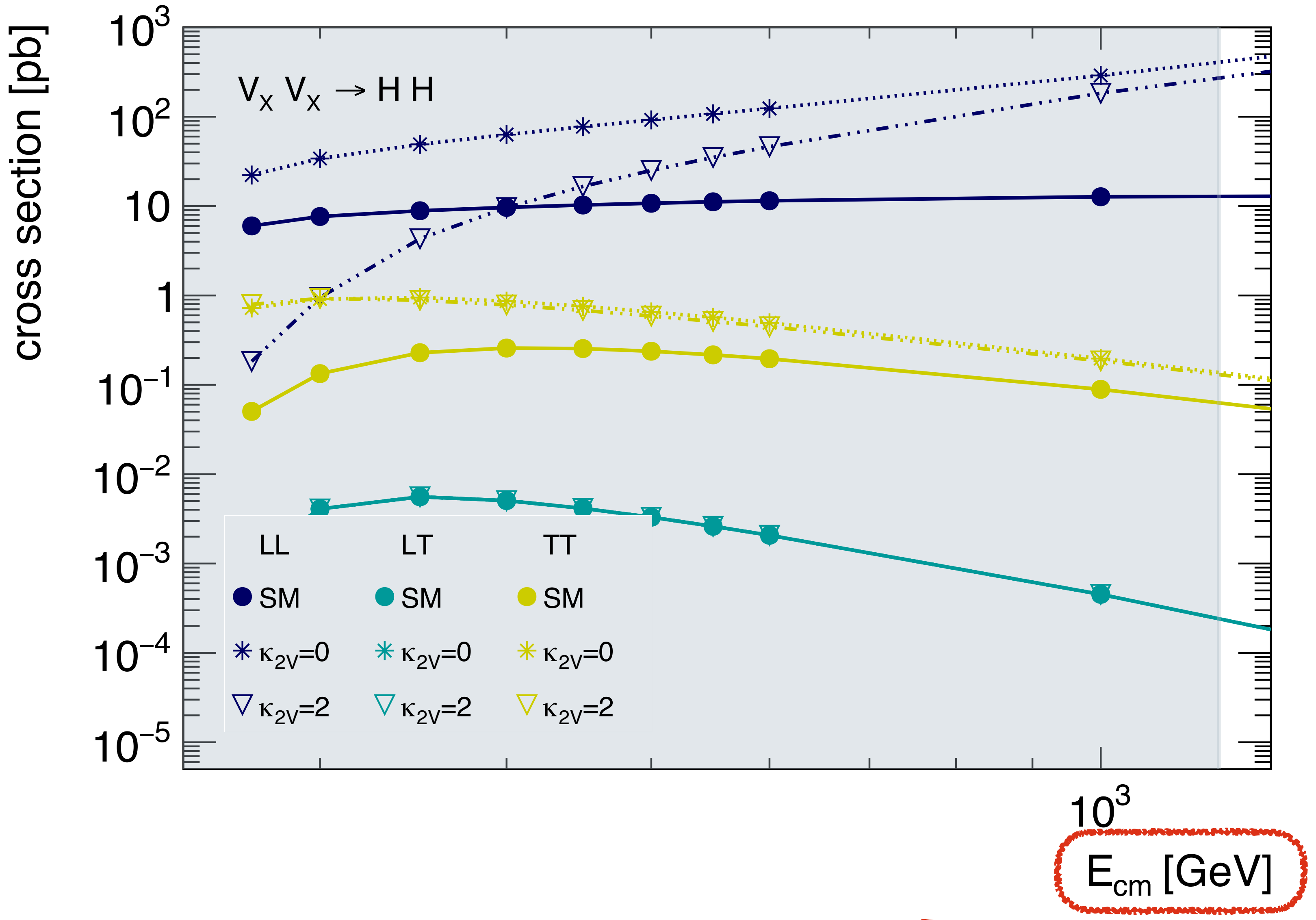


Effect of the Different Coupling Parameters on the Cross Section

Effect of changing κ_λ



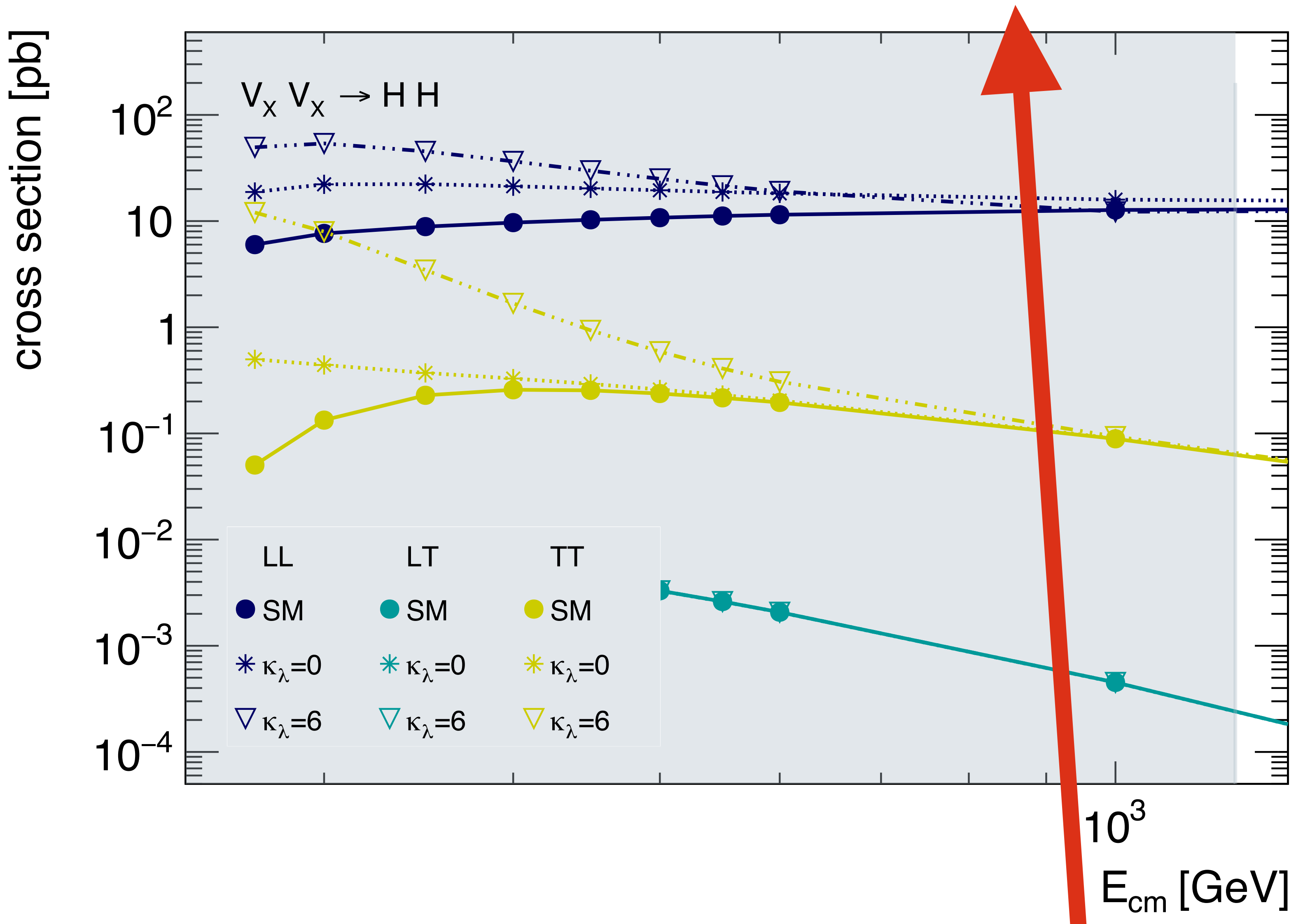
Effect of changing κ_{2V}



Center of mass energy of the vector bosons

Effect of the Different Coupling Parameters on the Cross Section

Effect of changing κ_λ



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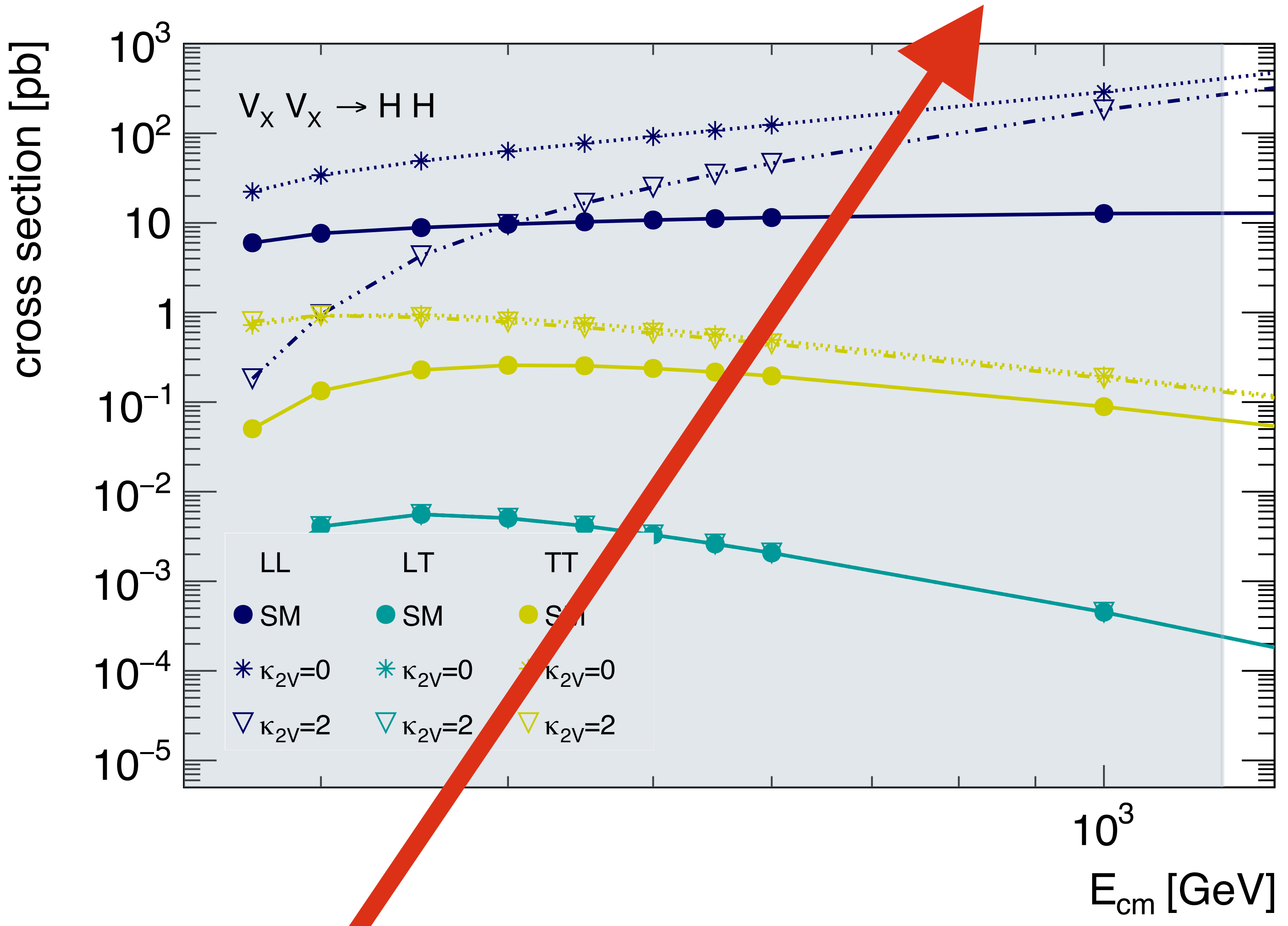
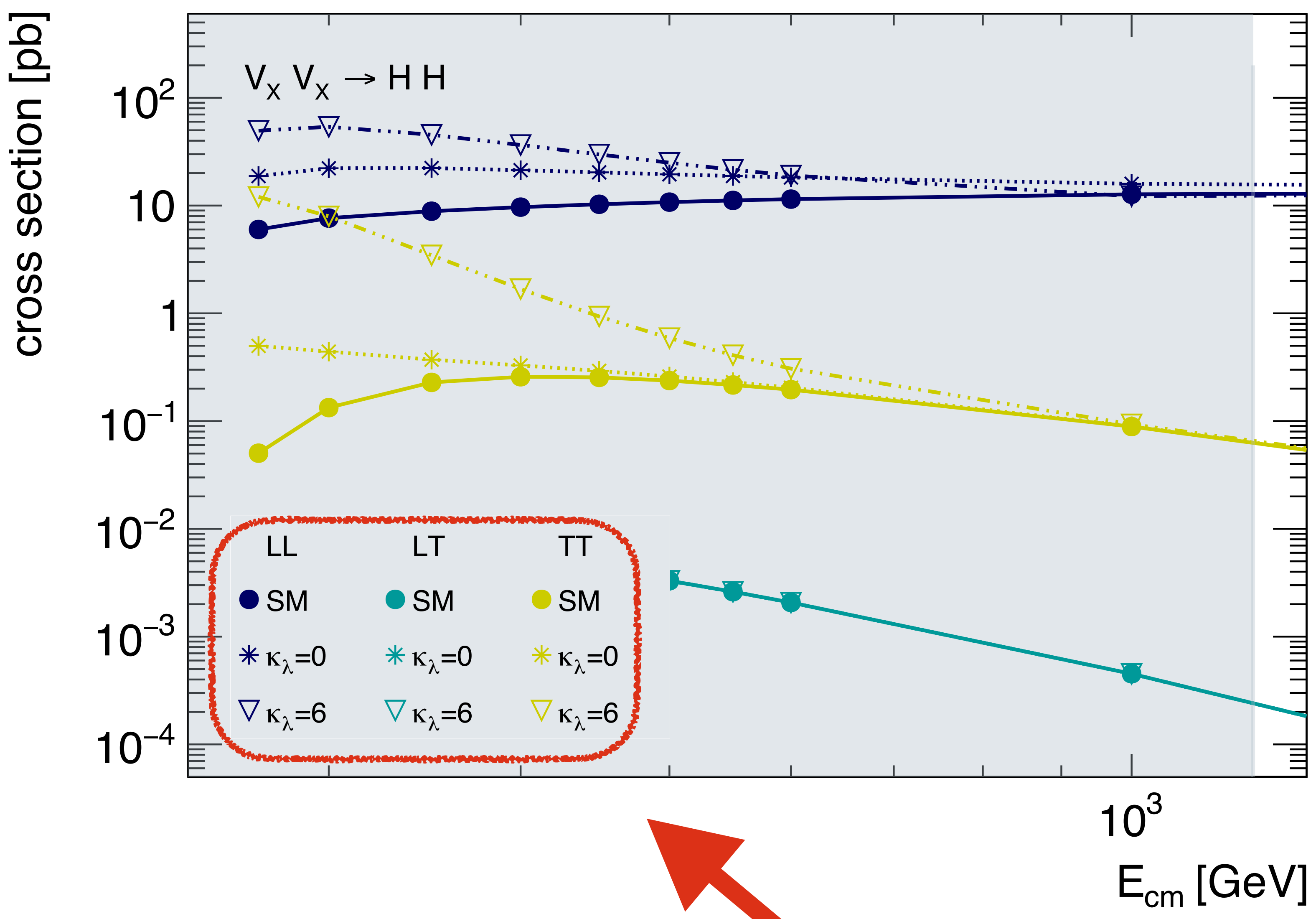


The different coupling modifiers

Effect of the Different Coupling Parameters on the Cross Section

Effect of changing κ_λ



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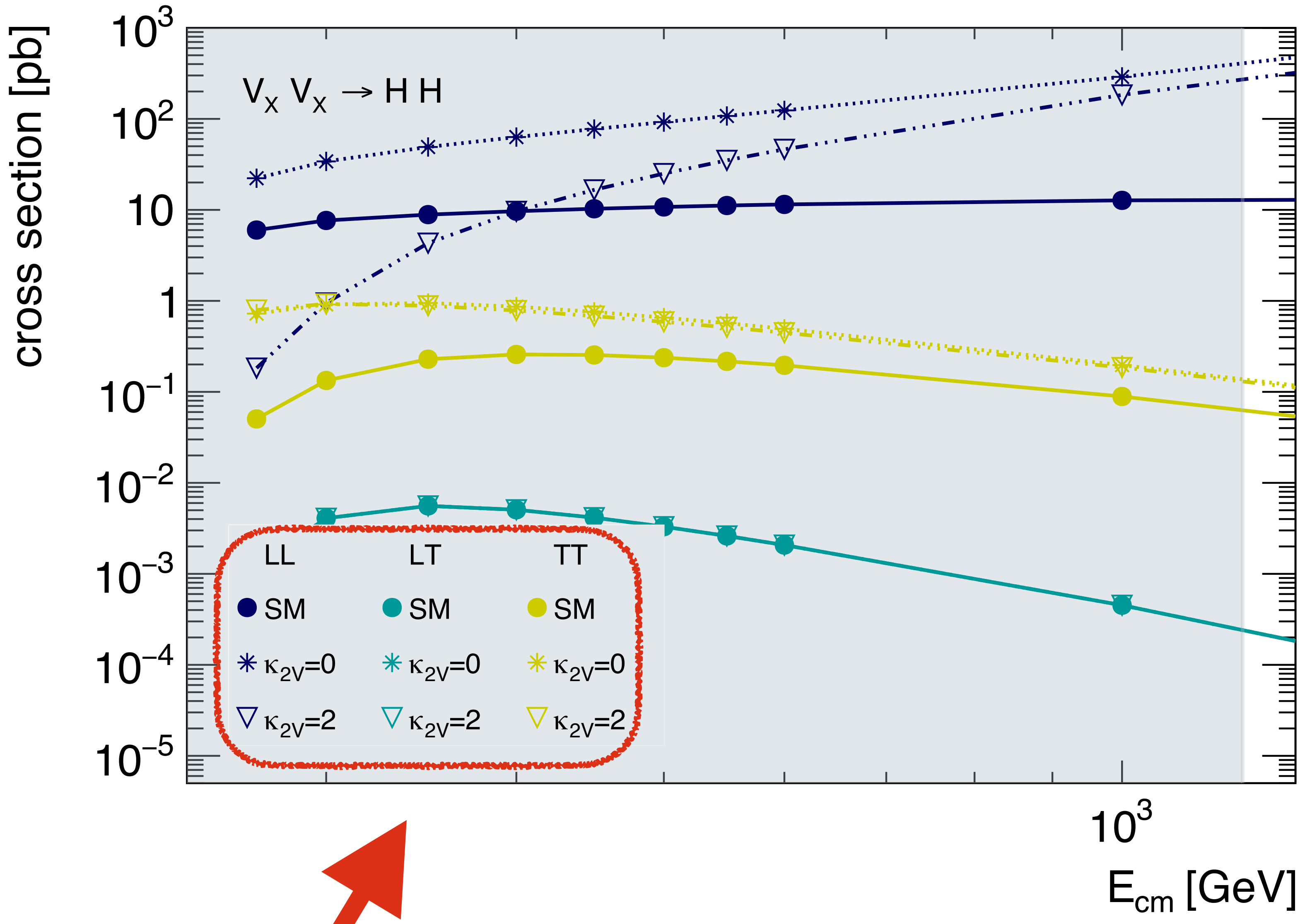
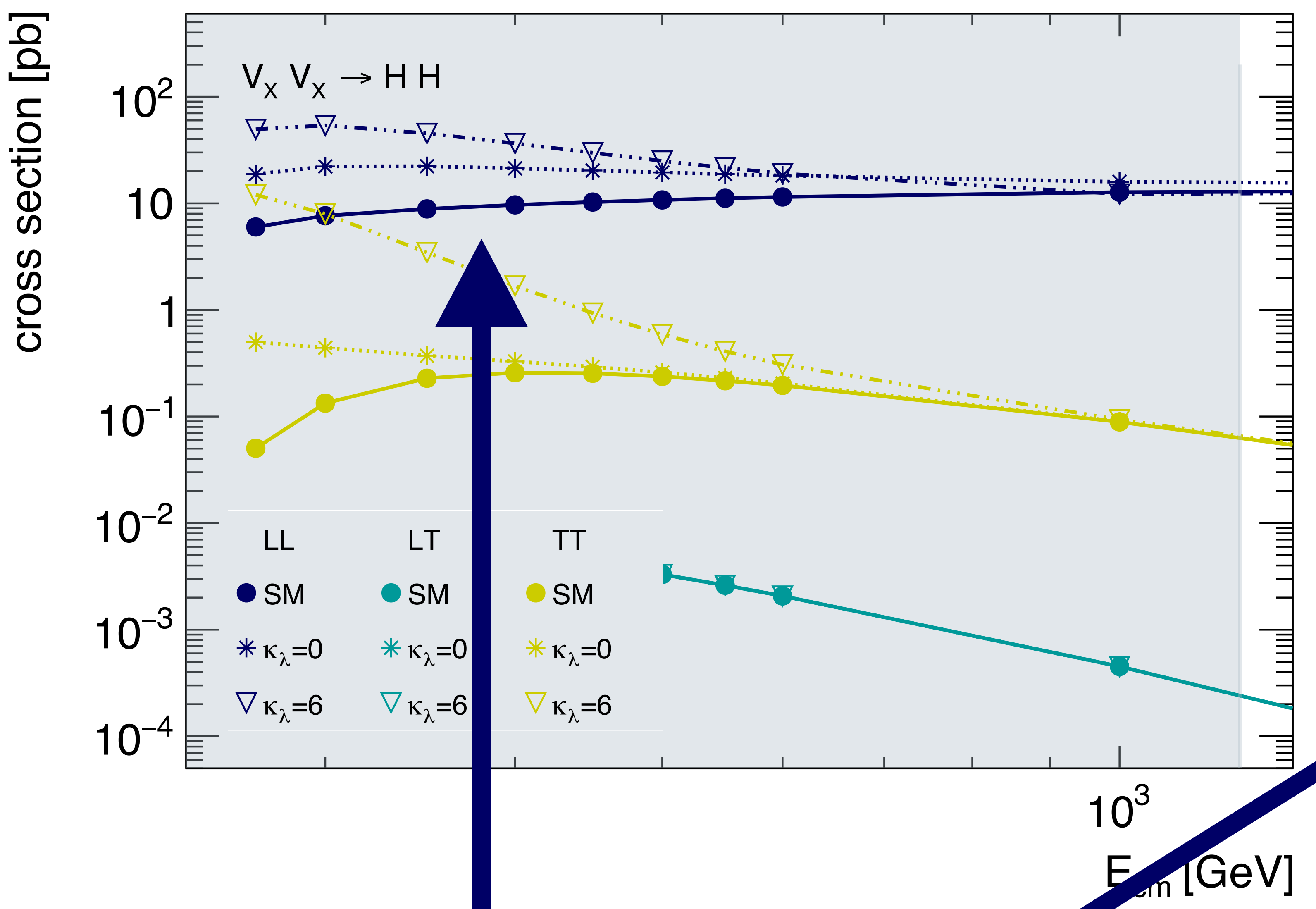


Values of the coupling parameters chosen to be close to the limits

Effect of the Different Coupling Parameters on the Cross Section

Effect of changing κ_λ



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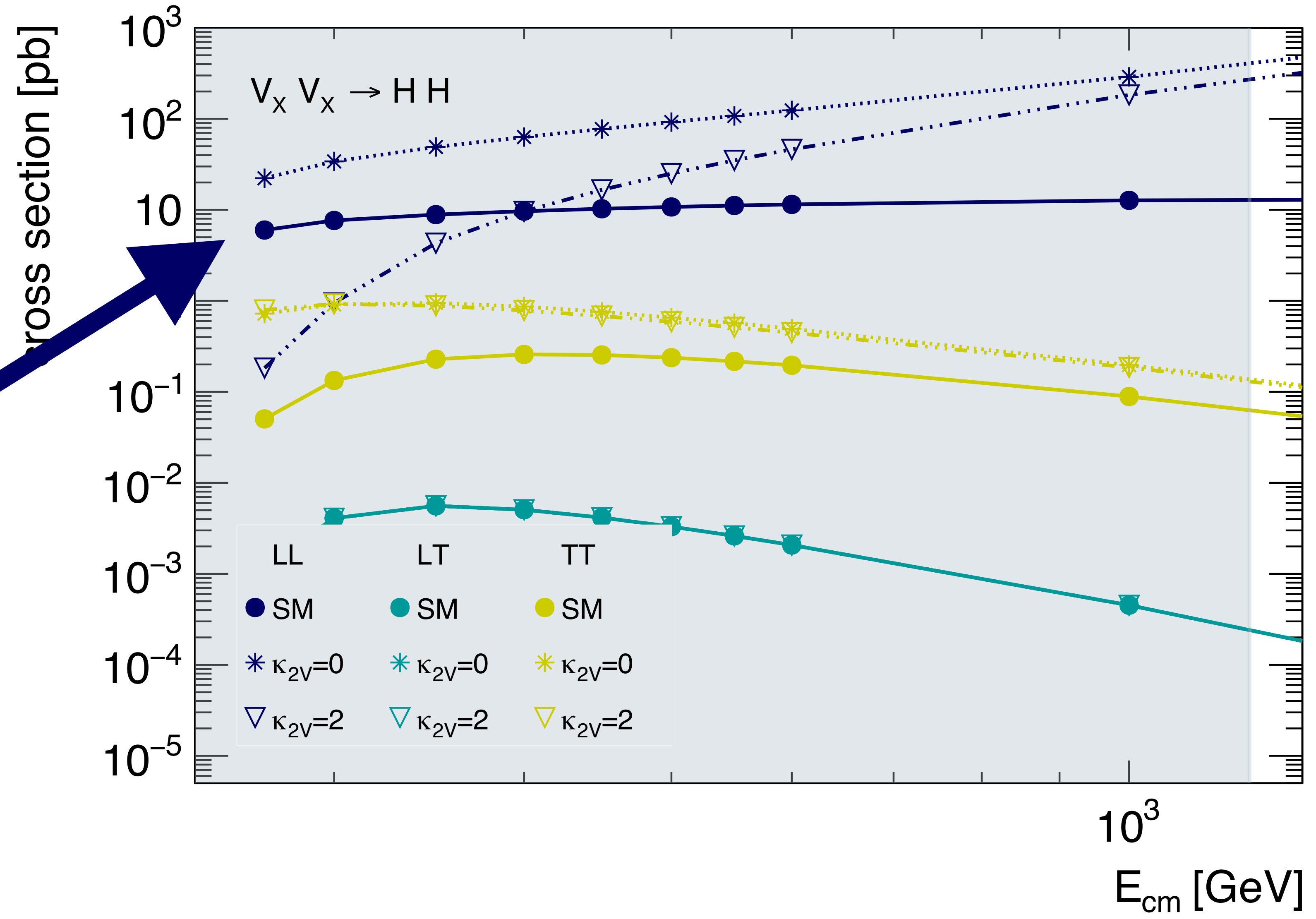


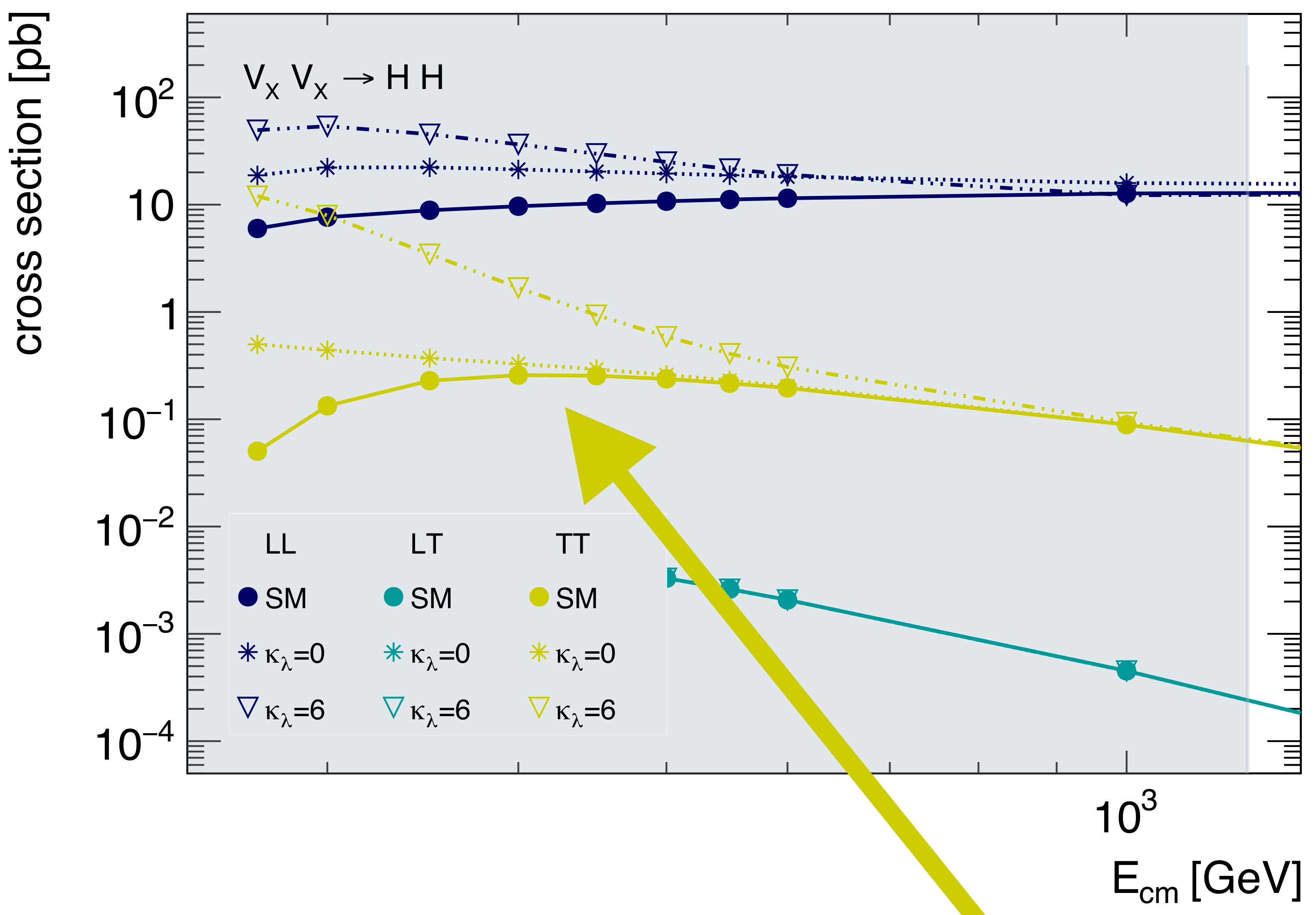
Longitudinal longitudinal (LL)

Transversal transversal (TT)

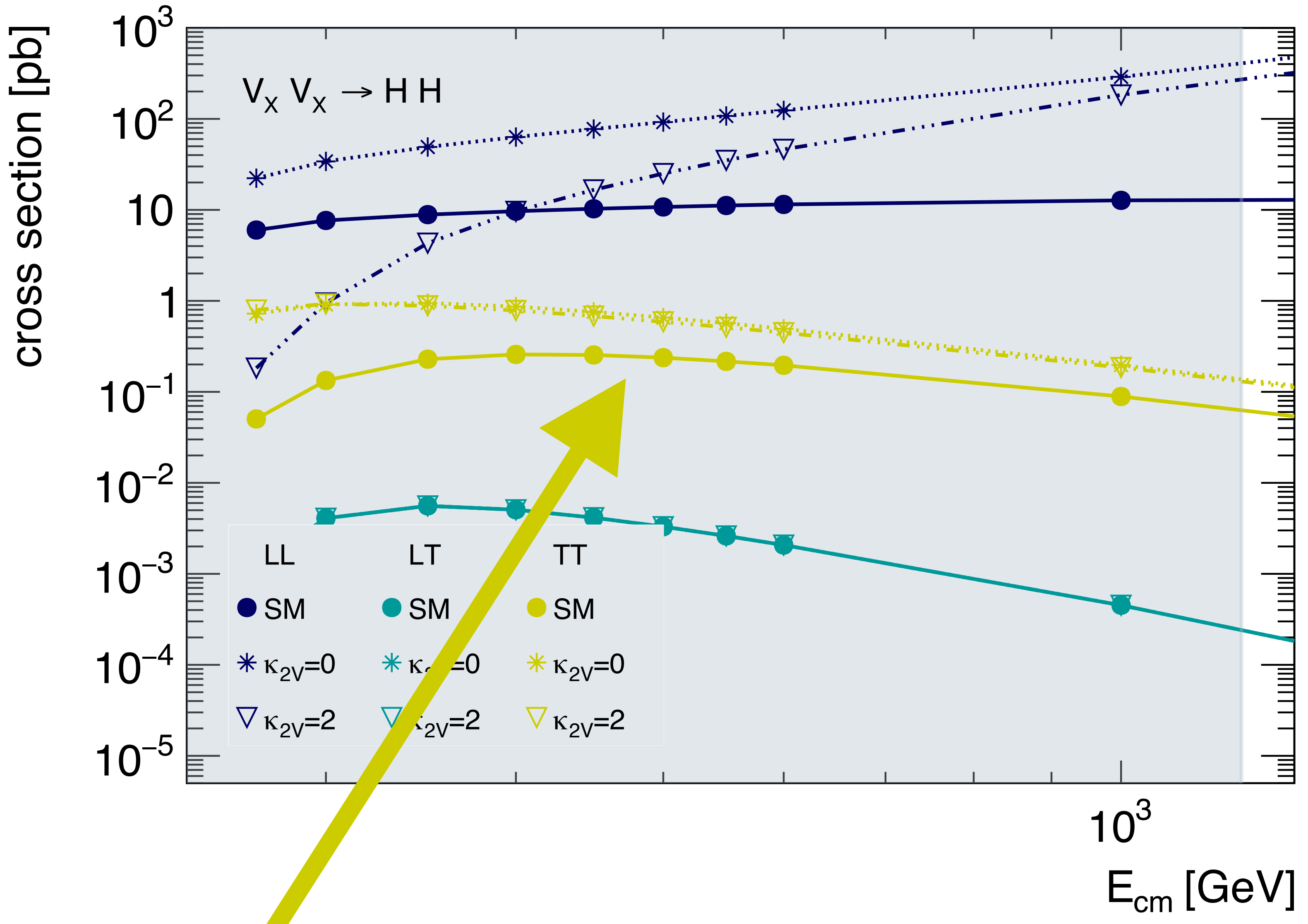
mixed (LT)

Effect of the Different Coupling Parameters on the Cross Section

Effect of changing κ_λ



Effect of changing κ_{2V}



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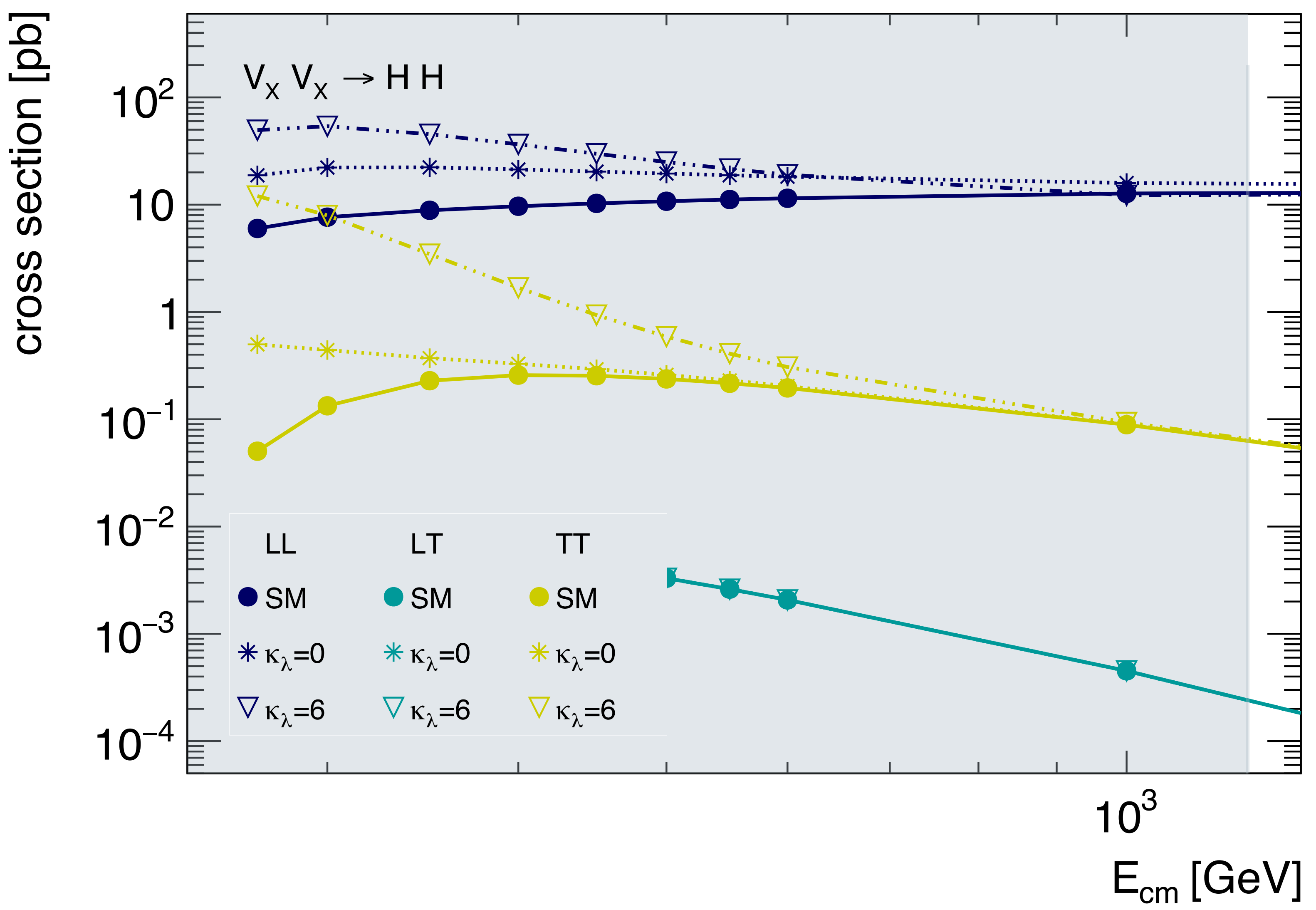
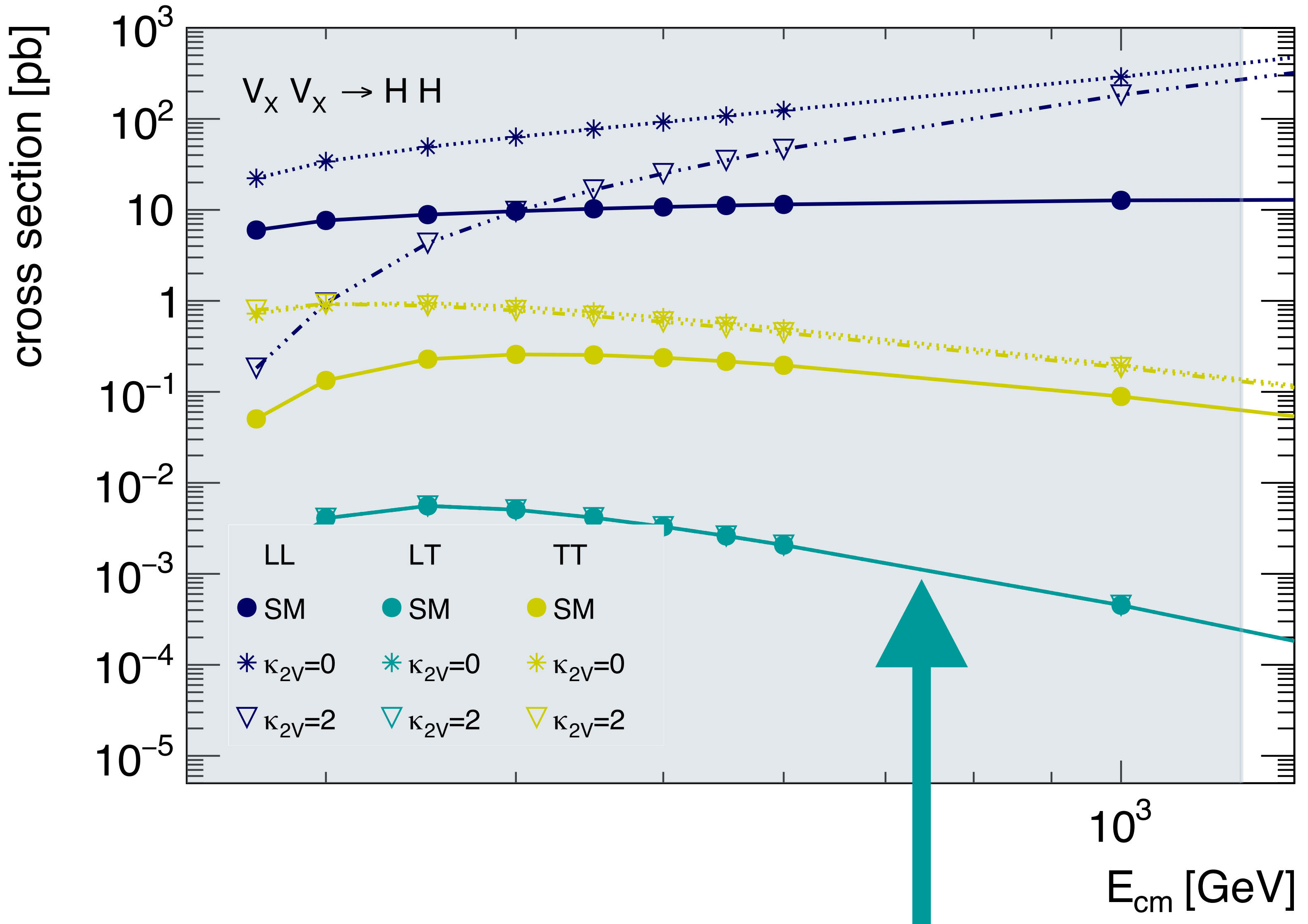


Effect of changing κ_{2V}



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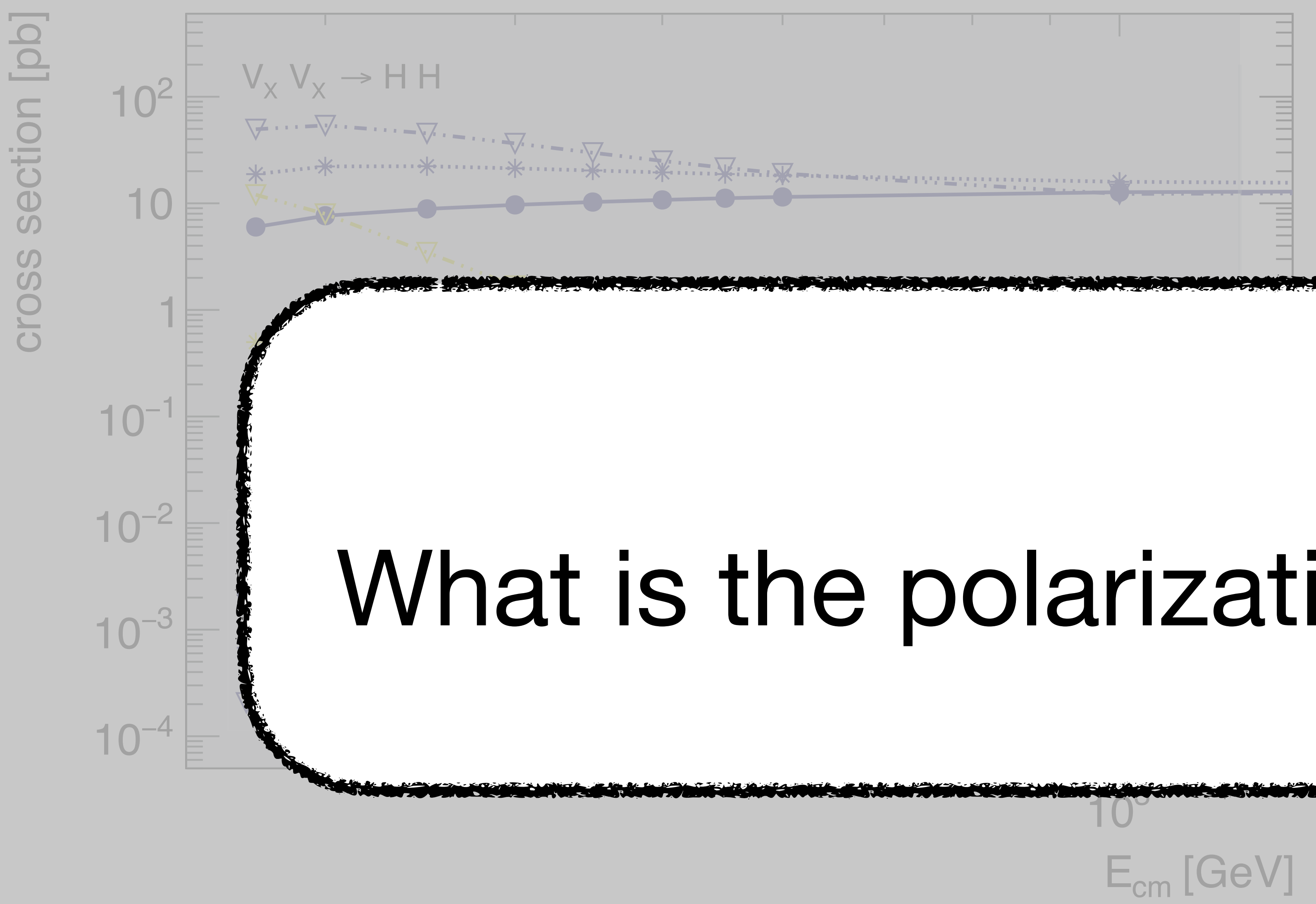
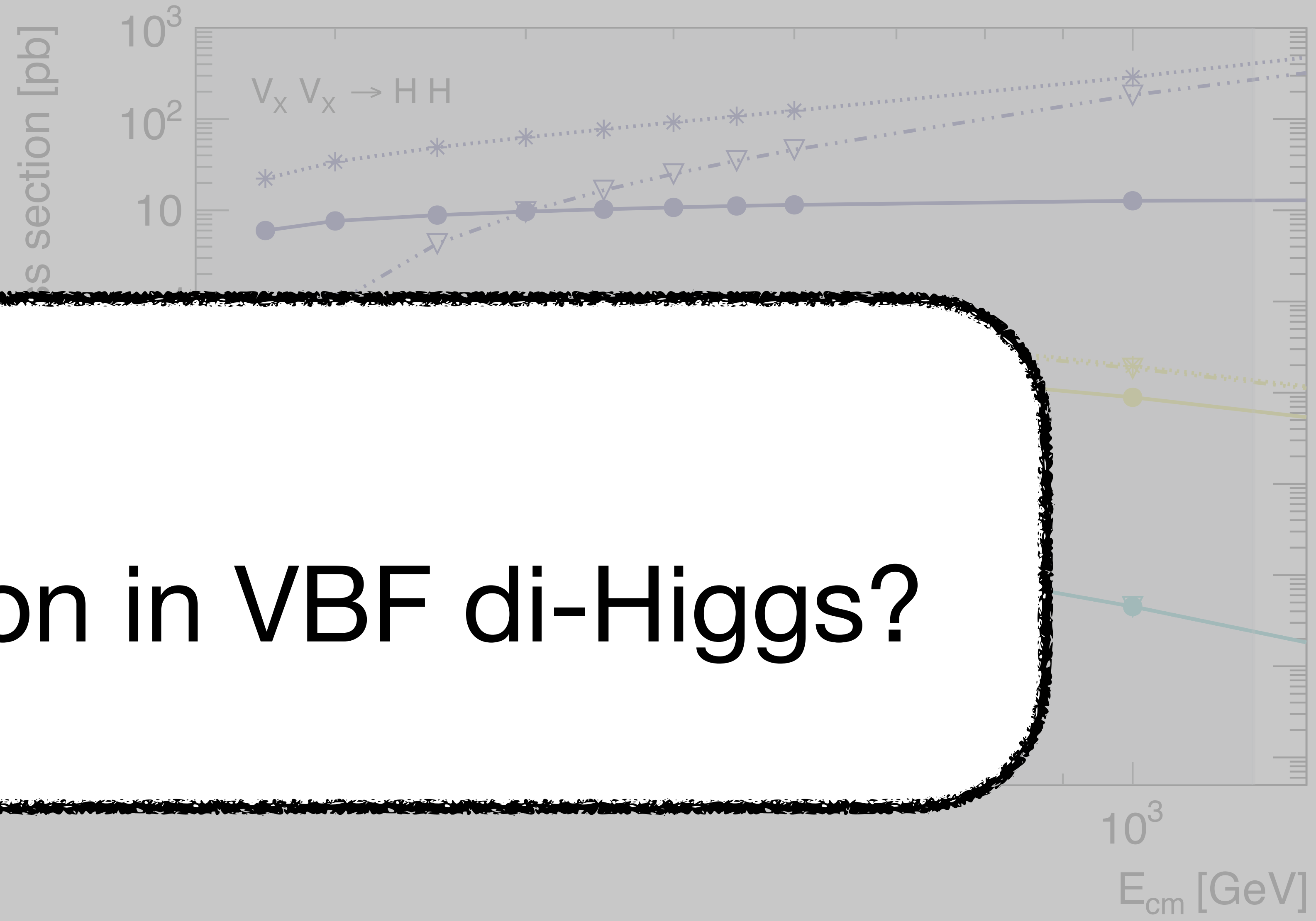


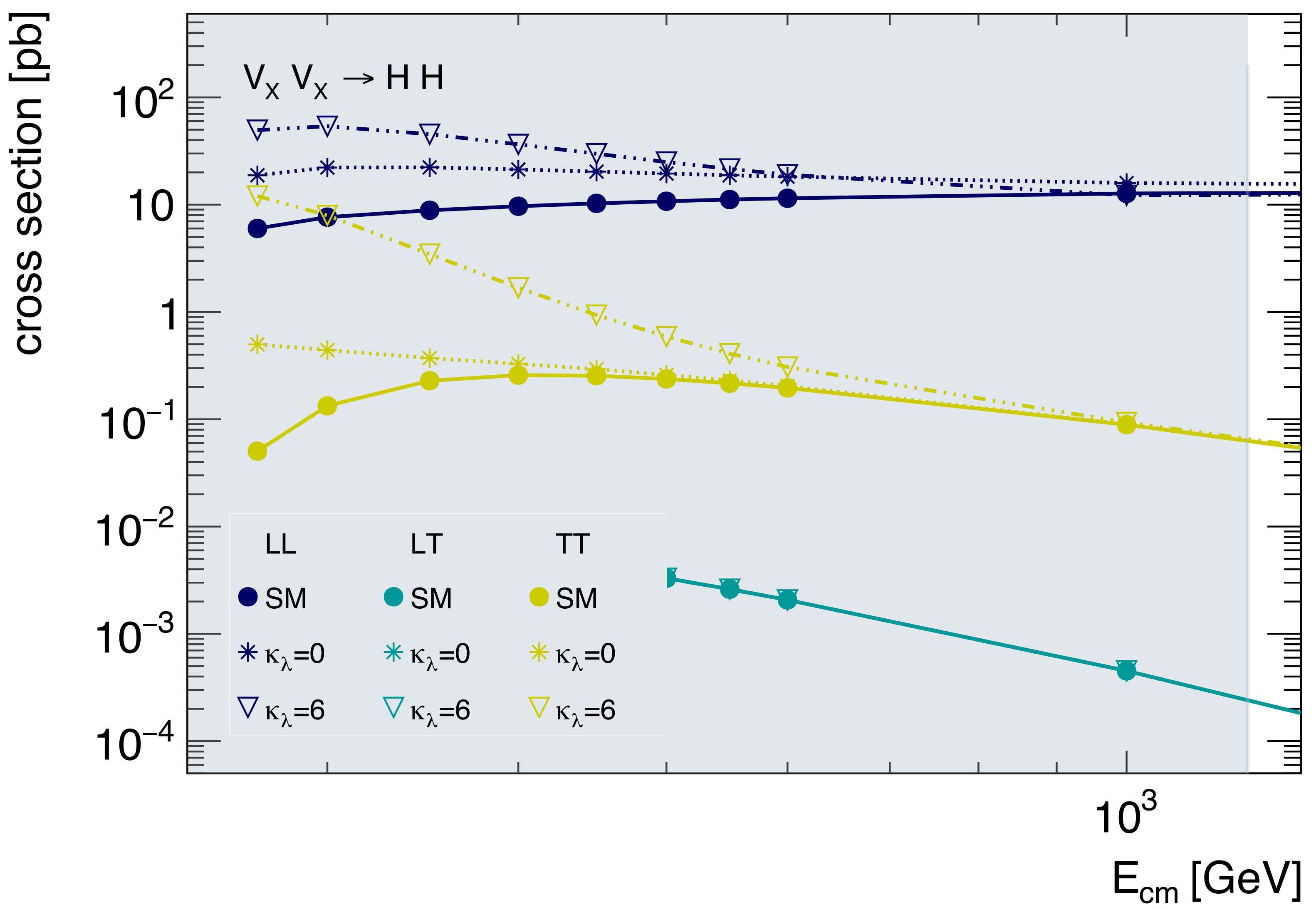
Effect of changing κ_{2V}



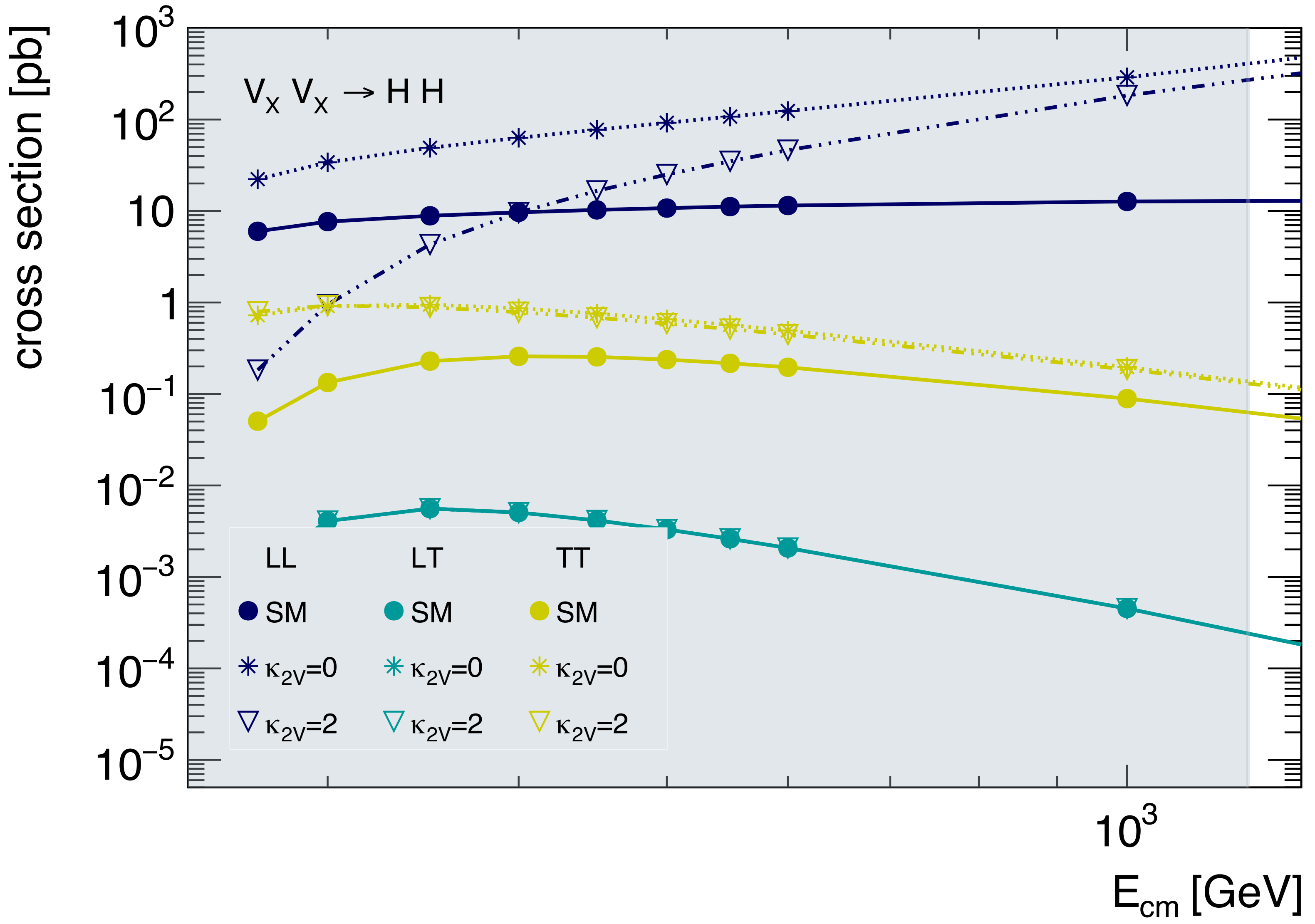
Question:
What is the polarization composition in VBF di-Higgs?

Effect of the Different Coupling Parameters on the Cross Section

Effect of changing κ_λ



Effect of changing κ_{2V}

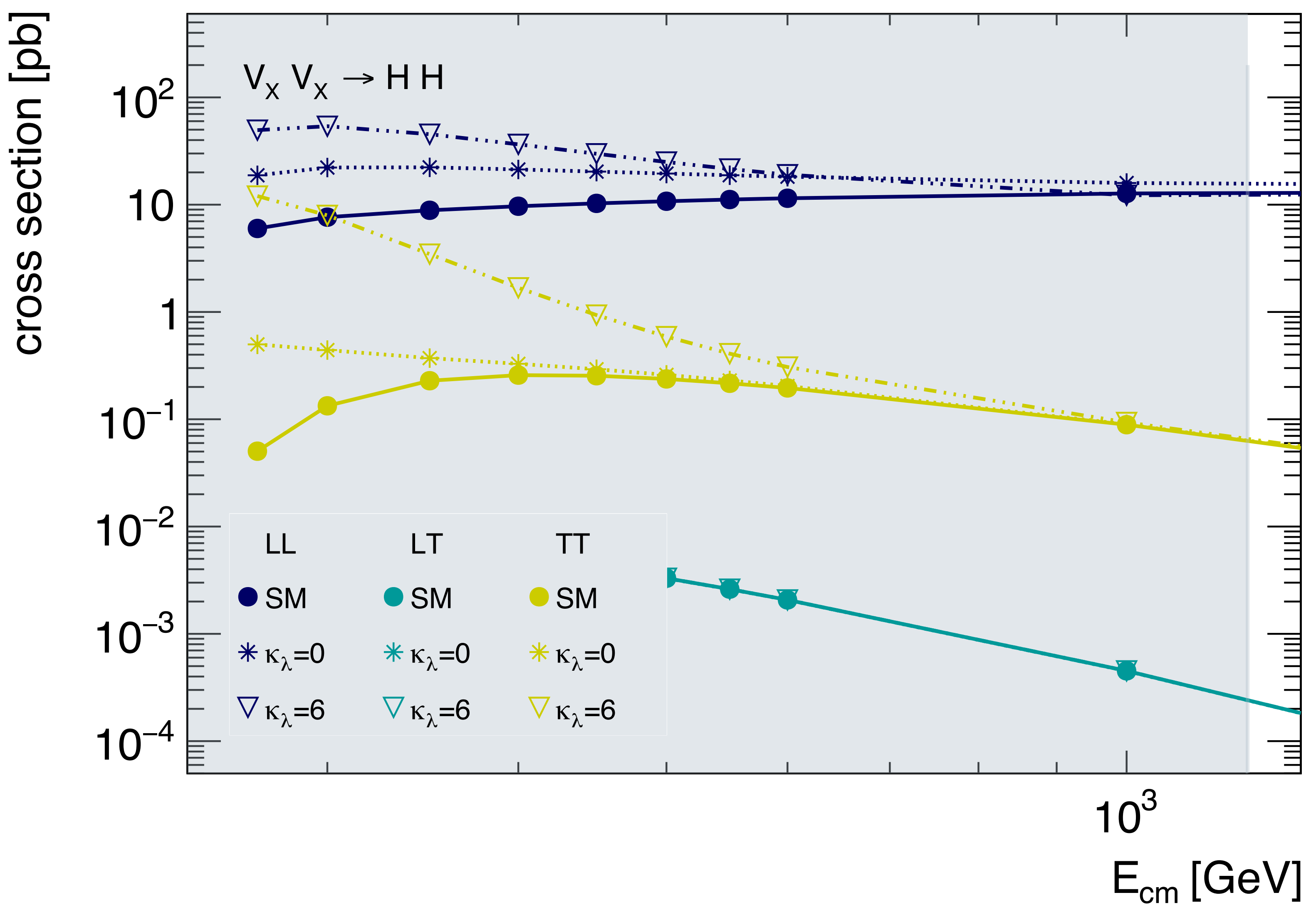


Results:

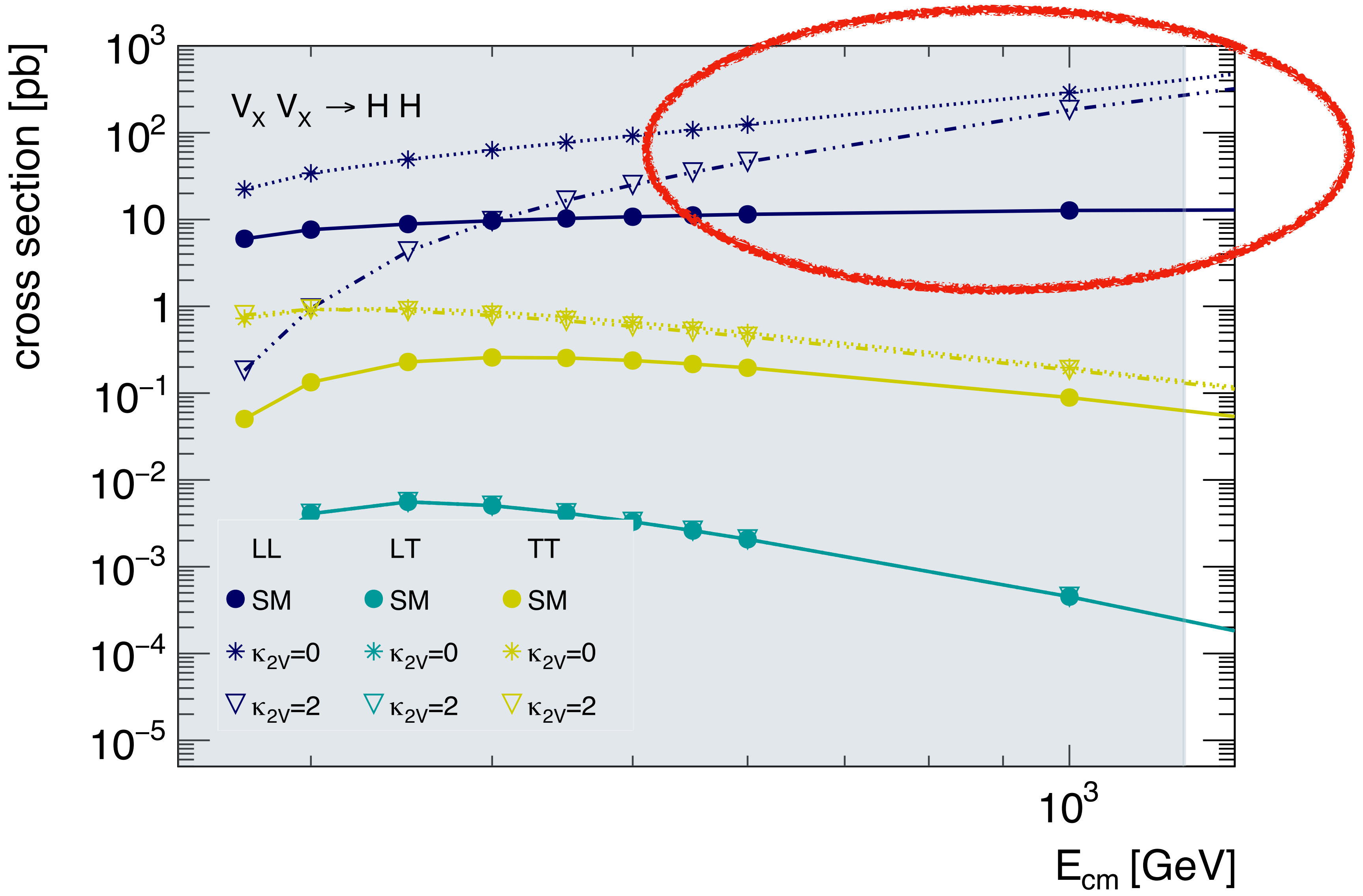
- Strongly dominated by the LL polarization

Effect of the Different Coupling Parameters on the Cross Section

Effect of changing κ_λ



Effect of changing κ_{2V}

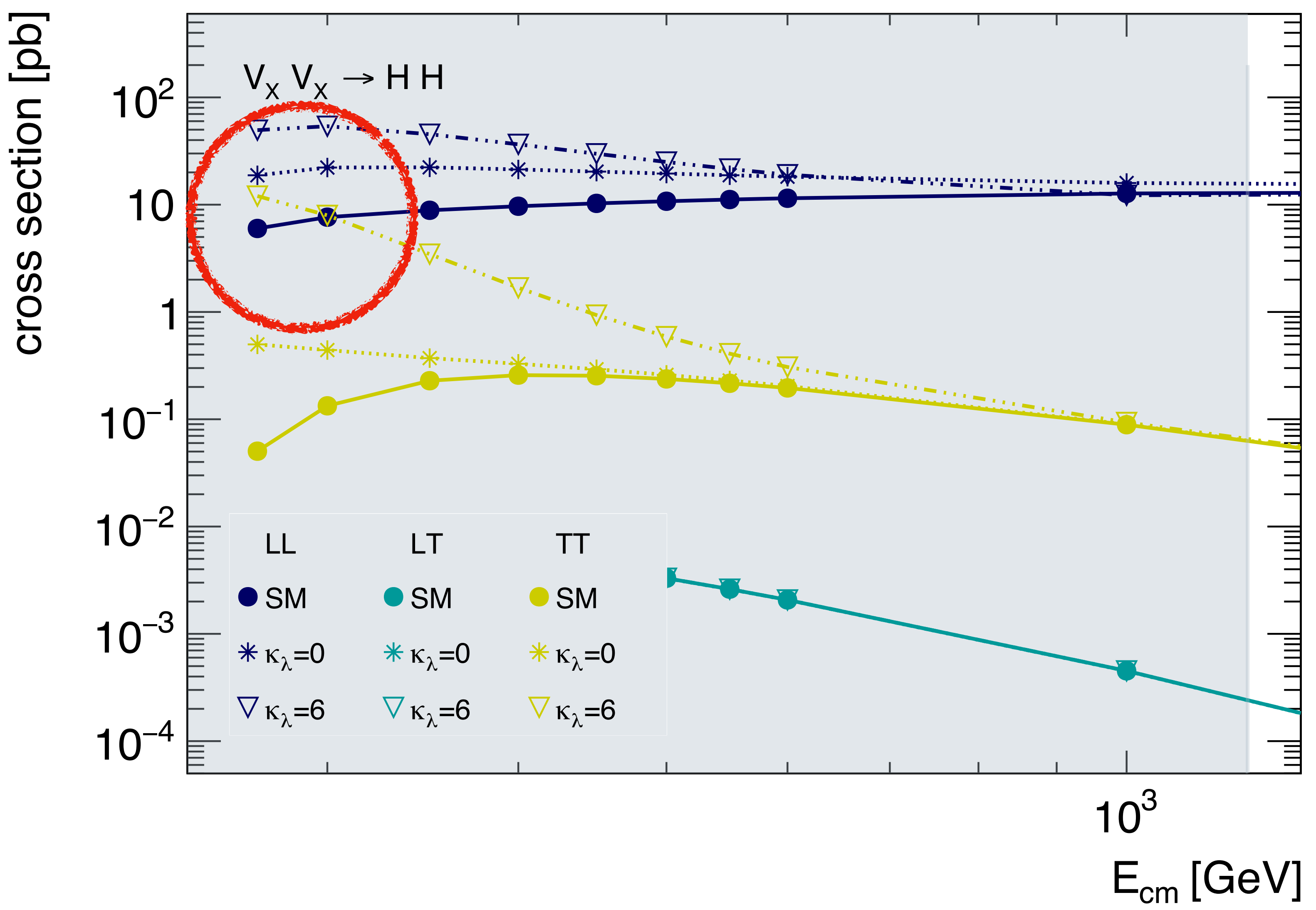


Results:

- As expected: Unitarity violation only visible for the LL case

Effect of the Different Coupling Parameters on the Cross Section

Effect of changing κ_λ



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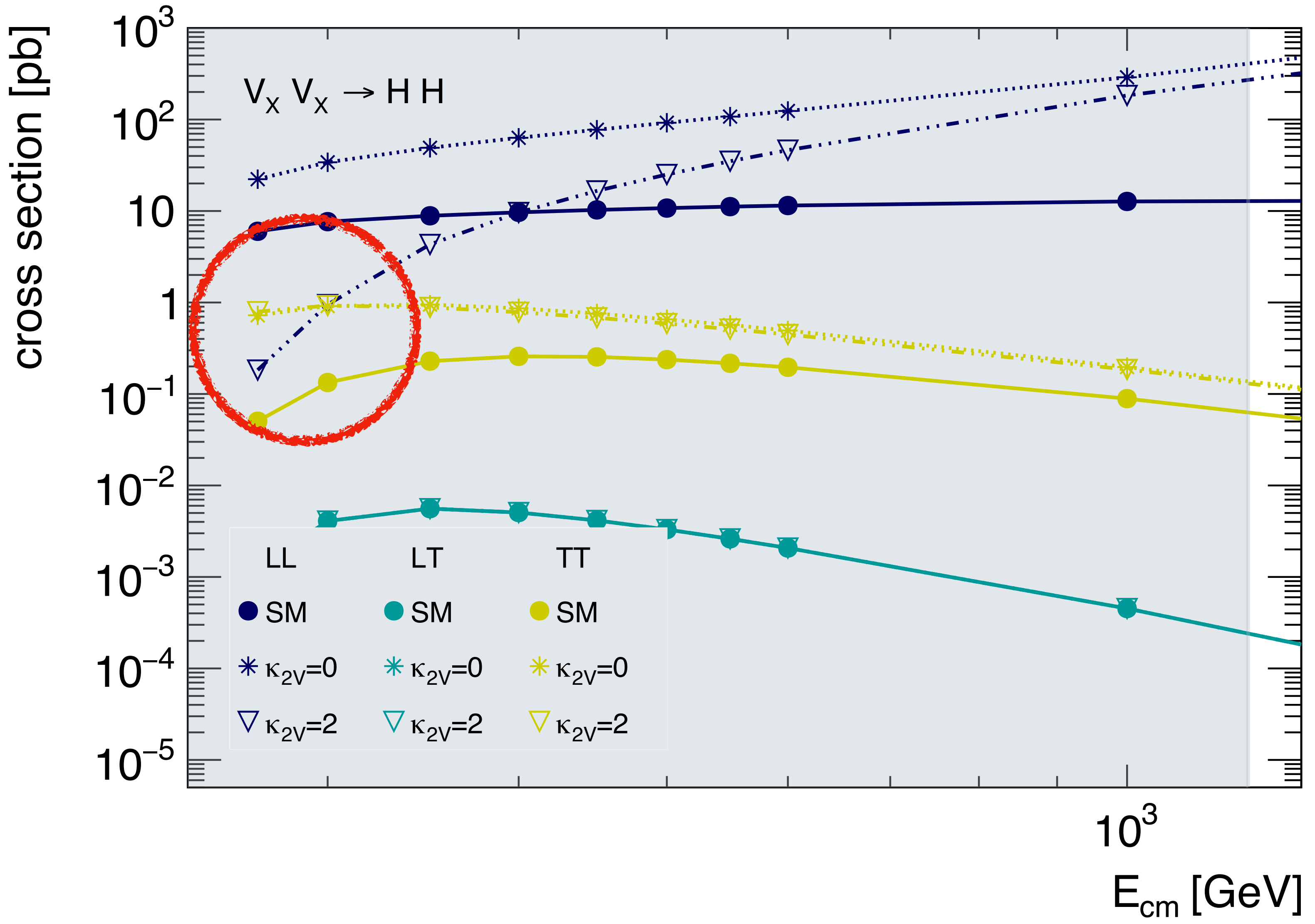


Results:

- Very low energies: TT fraction can get close to LL
- Strongest for $\kappa_\lambda, \kappa_{2V} \approx 2$

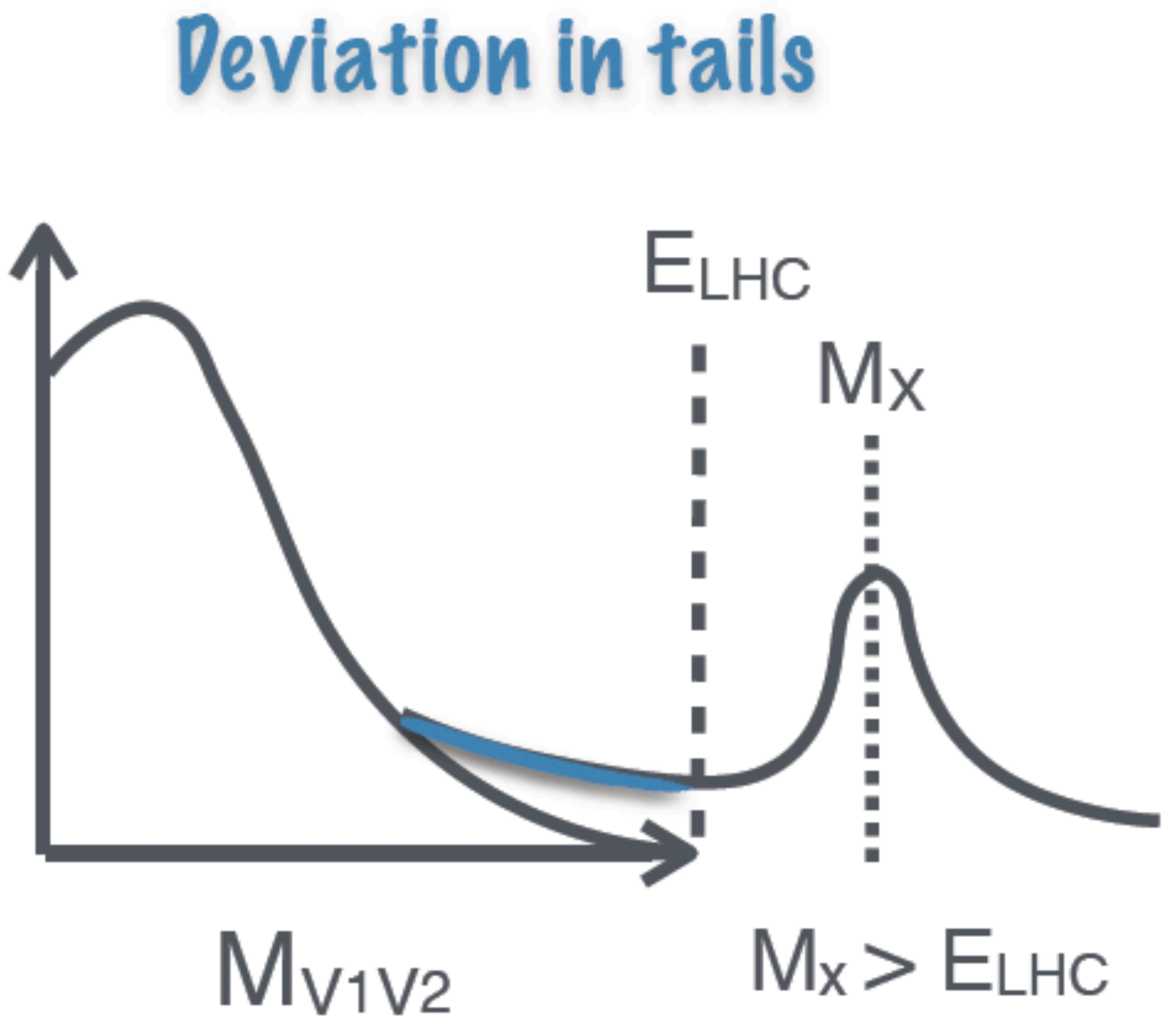
3. Effective Field Theories

Effective Field Theory

- BSM physics at energy scales above the range of the LHC can lead to deviations in the tale of distributions

- These can be parametrized by higher order operators in SM EFT models:

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{f_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)}$$



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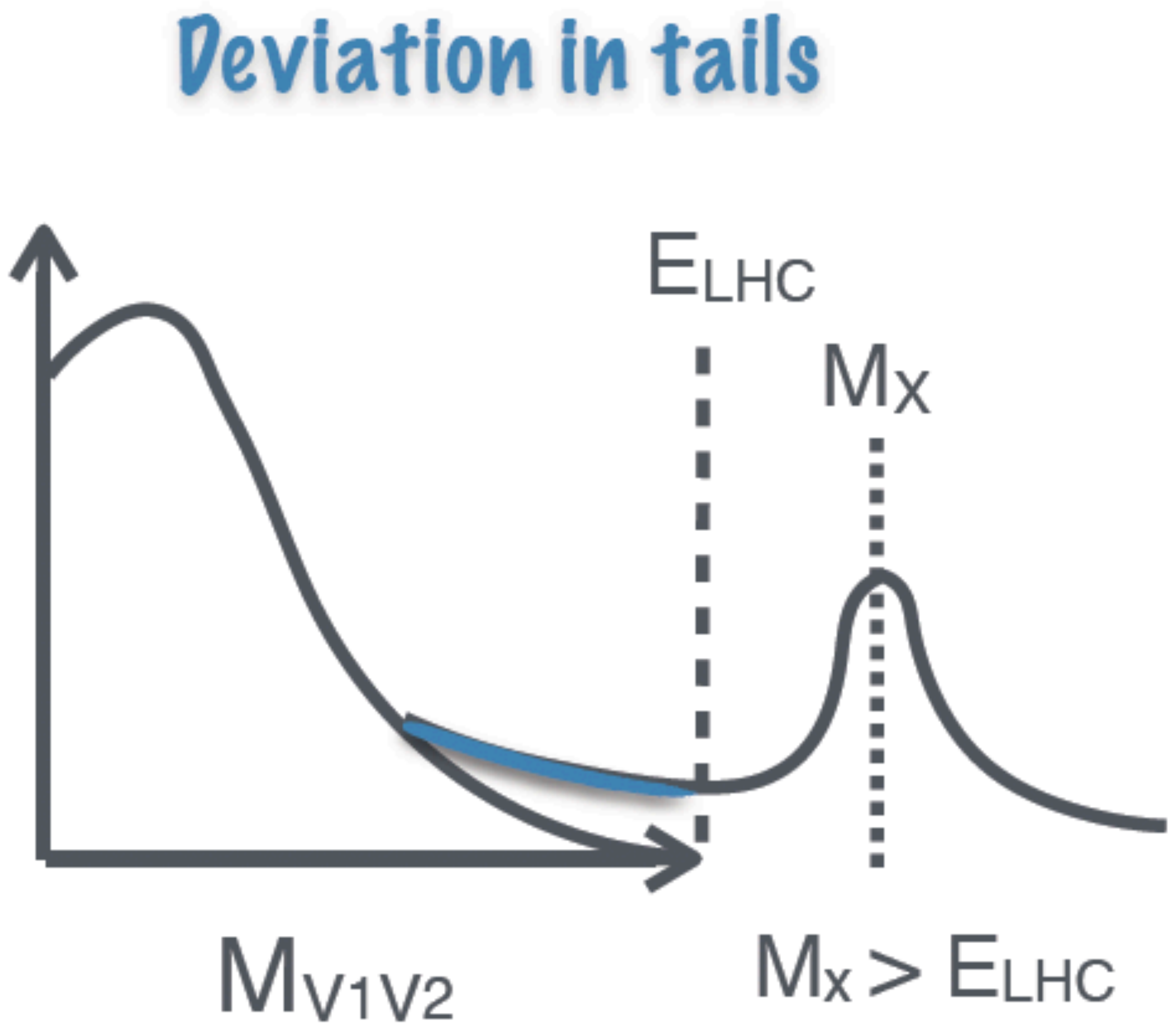
The EFT studies in Run 2 di-Higgs analysis were done looking at dimension-6 operators



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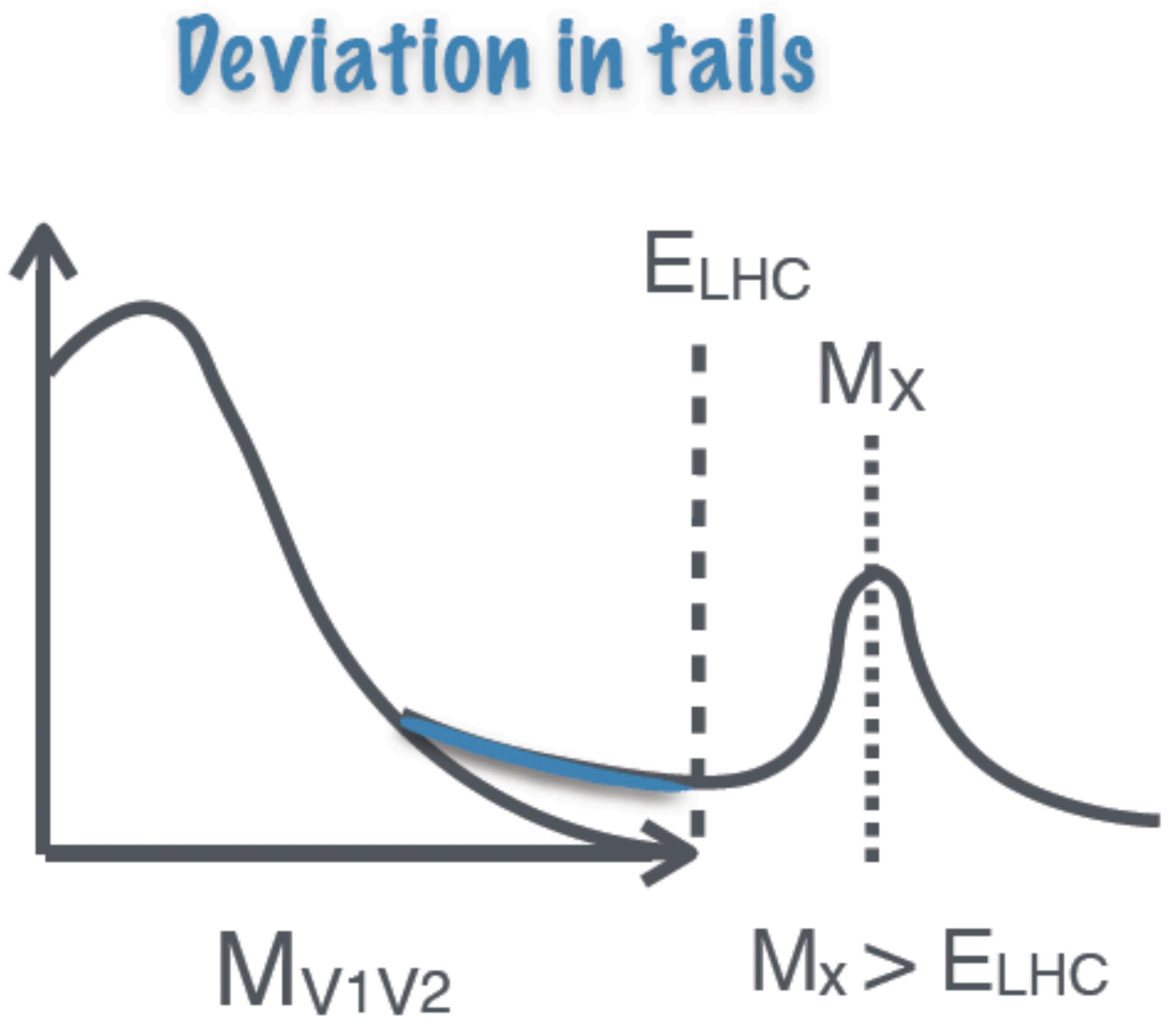
This is what we will look at in this presentation



The Eboli Model

- The Eboli model (https://arxiv.org/pdf/1604.03555.pdf) is a dimension-8 EFT model used by VBS analysis

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{f_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)}$$

- Affects only genuine quartic couplings without effects on the triple couplings
- Contains 18 independent operators
  - **S operators**: affecting only quartic vertices with only longitudinally polarised vector boson
  - **M operators**: affecting the quartic vertices with mixed longitudinally and transversally polarised vector bosons
  - **T operators**: affecting only quartic vertices with only transversally polarised vector bosons

	$WWWW$	$WWZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZZ$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$, $\mathcal{O}_{S,2}$	✓	✓			✓				
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$					✓	✓	✓	✓	✓

Allowed by the SM

- Study from A. Cappati, R. Covarelli, P. Torrielli & M. Zaro about the Eboli Model in VBF di-Higgs (https://link.springer.com/article/10.1007/JHEP09(2022)038)
  - VBF di-Higgs is also sensitive to the operators and expected to give similar or stronger constraints as VBS processes

The Eboli Model for VBF di-Higgs

- Performed tests using the Eboli model with the VBF di-Higgs process to looked at the cross sections

	$WWWW$	$WWZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZZ$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$	$ZZHH$	$WWHH$	$Z\gamma HH$	$\gamma\gamma HH$
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$, $\mathcal{O}_{S,2}$	✓	✓			✓					✓	✓		
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		✓	✓	✓	✓	✓	✓			✓		✓	✓
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓				
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		✓	✓	✓	✓	✓	✓	✓	✓				
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$					✓	✓	✓	✓	✓				

Allowed by the SM

The Eboli Model for VBF di-Higgs

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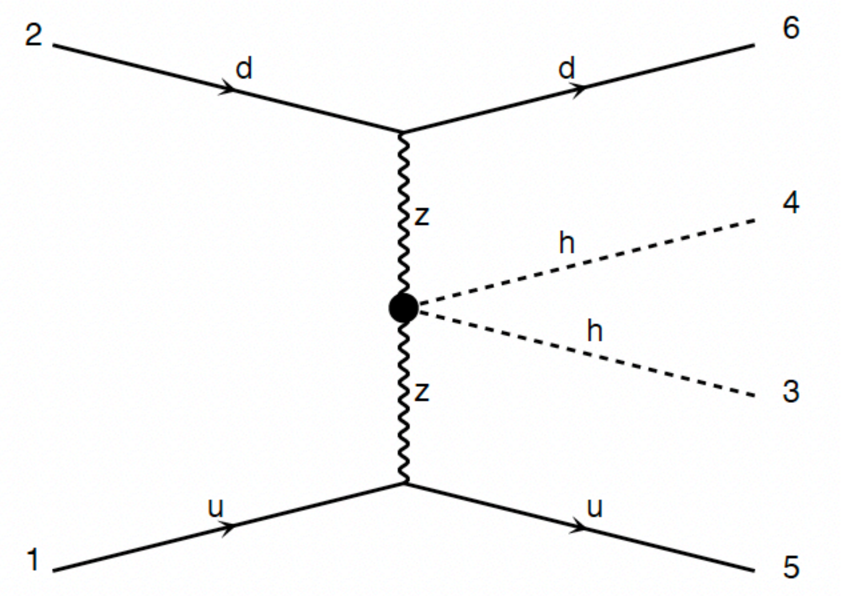
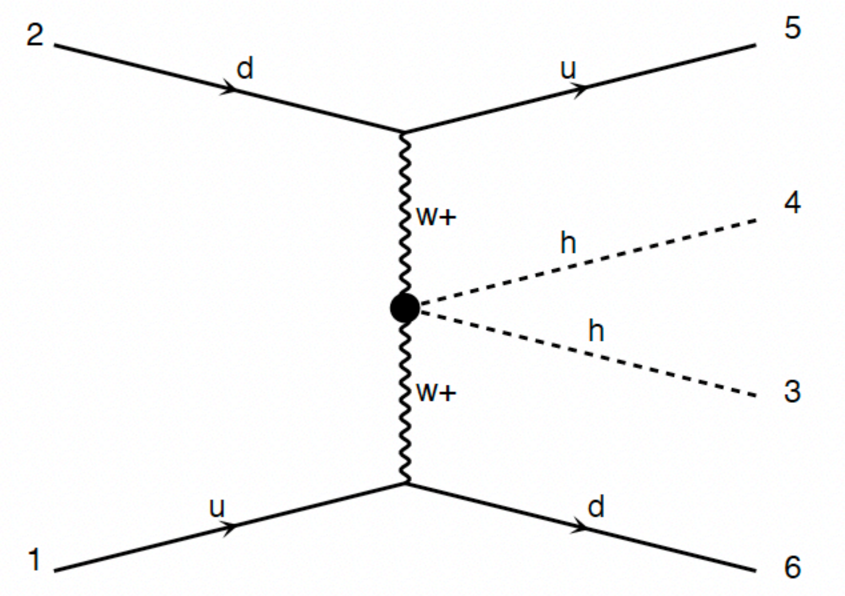
	$WWWW$	$WWZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZZ$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$	$ZZHH$	$WWHH$	$Z\gamma HH$	$\gamma\gamma HH$
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$, $\mathcal{O}_{S,2}$	✓	✓			✓					✓	✓		
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		✓	✓	✓	✓	✓	✓			✓		✓	✓
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓				
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		✓	✓	✓	✓	✓	✓	✓	✓				
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$					✓	✓	✓	✓	✓				

Allowed by the SM

- S operators only affect SM vertices with longitudinally polarised vector boson





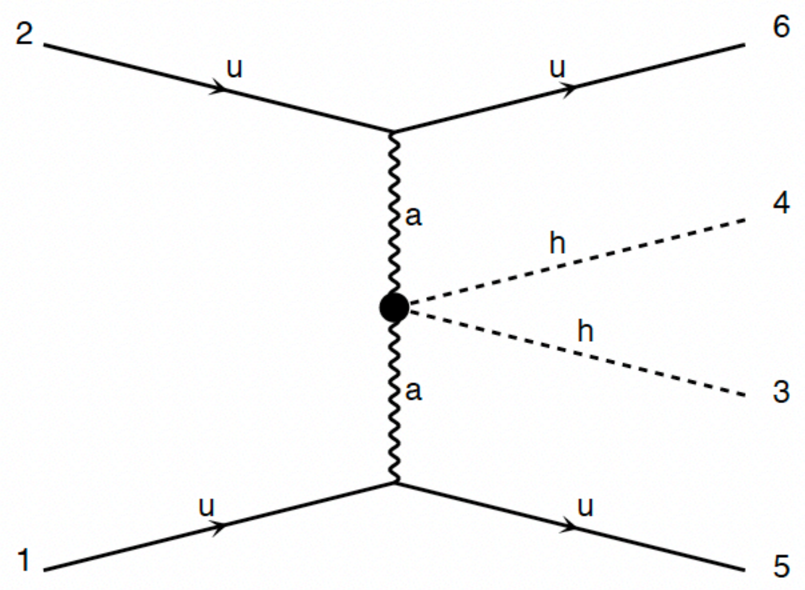
The Eboli Model for VBF di-Higgs

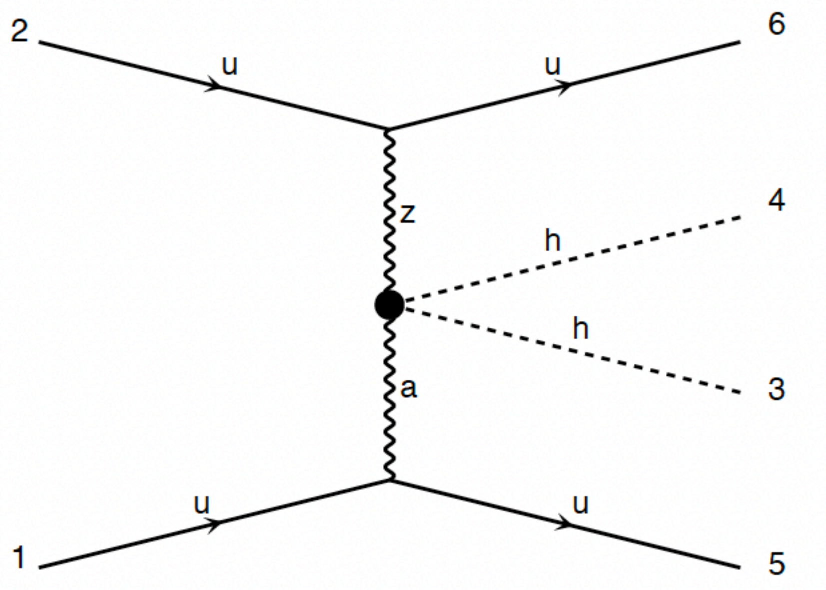
- Performed tests using the Eboli model with the VBF di-Higgs process to looked at the cross sections

	$WWWW$	$WWZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZZ$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$	$ZZHH$	$WWHH$	$Z\gamma HH$	$\gamma\gamma HH$
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$, $\mathcal{O}_{S,2}$	✓	✓			✓					✓	✓		
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		✓	✓	✓	✓	✓	✓			✓		✓	✓
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓				
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		✓	✓	✓	✓	✓	✓	✓	✓				
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$					✓	✓	✓	✓	✓				

Allowed by the SM

- S operators only affect SM vertices with longitudinally polarised vector boson
- M operators additionally lead to new vertices that are forbidden by the SM





The Eboli Model for VBF di-Higgs

- Performed tests using the Eboli model with the VBF di-Higgs process to looked at the cross sections

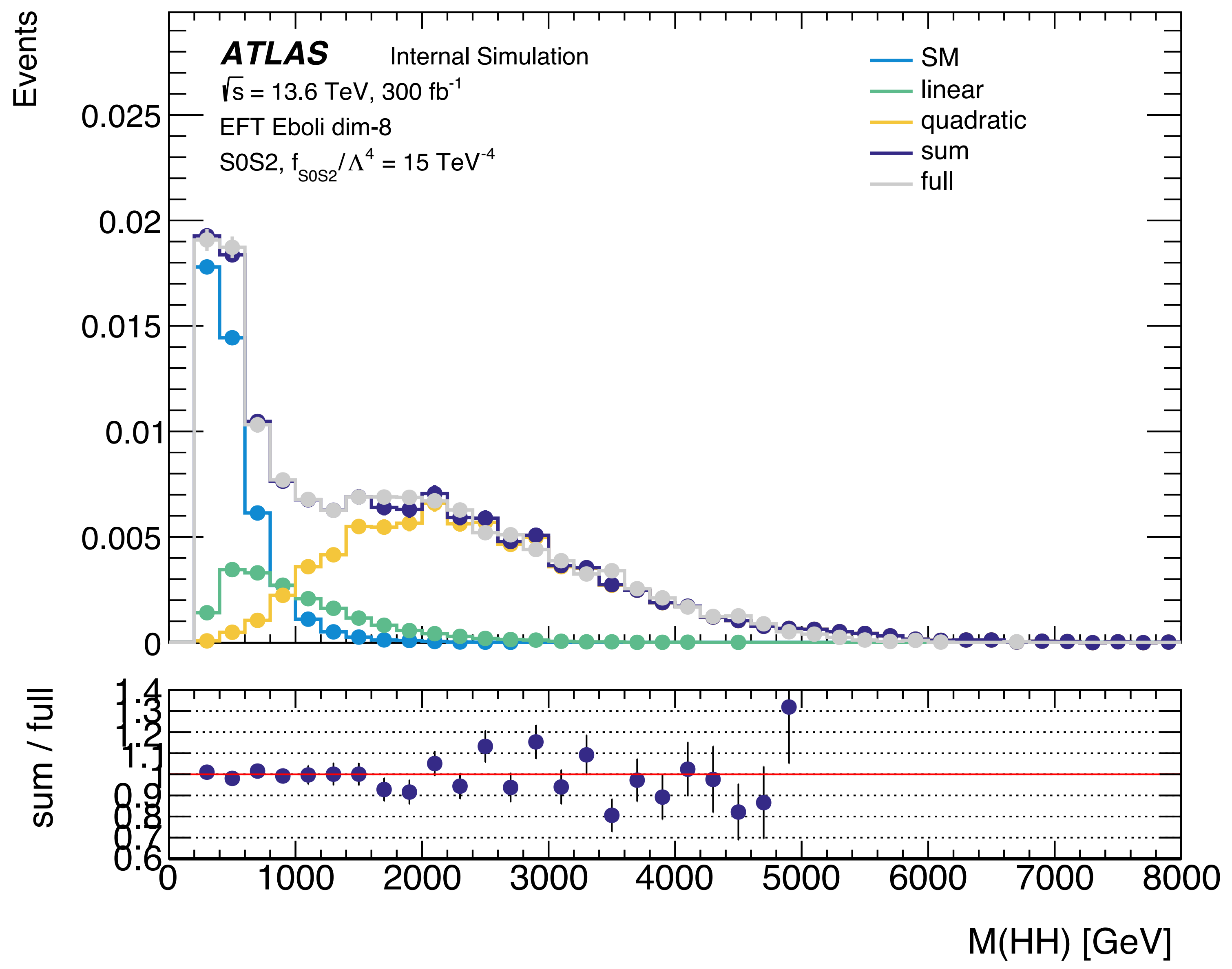
	$WWWW$	$WWZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZZ$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$	$ZZHH$	$WWHH$	$Z\gamma HH$	$\gamma\gamma HH$
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$, $\mathcal{O}_{S,2}$	✓	✓			✓					✓	✓		
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		✓	✓	✓	✓	✓	✓			✓		✓	✓
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓				
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		✓	✓	✓	✓	✓	✓	✓	✓				
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$					✓	✓	✓	✓	✓				

Allowed by the SM

- S operators only affect SM vertices with longitudinally polarised vector boson
- M operators additionally lead to new vertices that are forbidden by the SM
- Not sensitive to the T operators

The Eboli Model for VBF di-Higgs

- Distributions of generated sample look good
- First rough estimation of limits
  - In optimistic calculation comparable with best limits from VBS analysis
  - Even if 1D limits are less strong the analysis might still be interesting for combinations when constraining different parameters at the same time



coefficient $[TeV^{-4}]$	VBS semileptonic from *	VBF HH estimated limit conservative	VBF HH estimated limit optimistic
f_{M0}/Λ^4	[-1.13, 1.13]	[-3.69, 3.69]	[-0.61, 0.60]
f_{M1}/Λ^4	[-3.24, 3.24]	[-14.89, 14.81]	[-2.47, 2.40]
f_{M2}/Λ^4	[-1.66, 1.67]	[-5.16, 5.16]	[-0.85, 0.85]
f_{M3}/Λ^4	[-5.29, 5.29]	[-20.48, 20.47]	[-3.36, 3.35]
f_{M4}/Λ^4	[-2.62, 2.62]	[-15.43, 15.44]	[-2.52, 2.54]
f_{M5}/Λ^4	[-3.81, 3.84]	[-27.65, 27.74]	[-4.50, 4.58]
f_{M7}/Λ^4	[-5.33, 5.21]	[-29.63, 29.78]	[-4.80, 4.95]
f_{S0S2}/Λ^4	[-3.22, 3.23]	[-64.90, 61.36]	[-12.26, 8.73]
f_{S1}/Λ^4	[-6.86, 6.88]	[-45.08, 43.21]	[-8.23, 6.36]

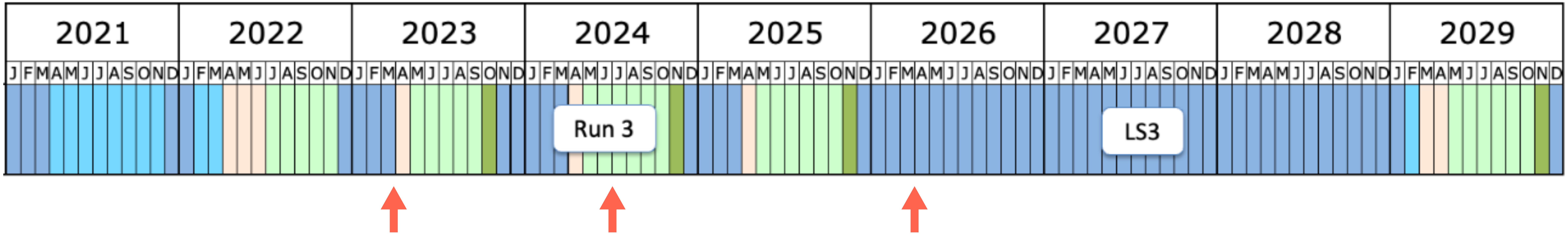
* D. Carlton et al., Study of electroweak WW/WZ/ZZ production in 3 semileptonic final states and limits on anomalous 4 quartic gauge couplings with 13 TeV ATLAS full 5 Run-2 data, ANA-STDM-2018-27-INT1

Non-Scientific Topics

Requirements for the PhD Thesis

- **Non-Scientific Training (require 40h)**
  - Completed 32h of training
  - To do: Ethics training (6h)
- **Scientific training (require 40h)**
  - Introductory Tutorial on Data Analysis with Deep Neural Networks (4h)
  - Desy Statistics School (4 days, 18h)
  - Presentations (12h)
    - 15.11.2023: “Vector-boson polarization in VBF di-Higgs production”, 20th Workshop of the LHC Higgs working group (CERN)
    - 25.01.2024: “Vector-boson polarization in VBF di-Higgs production”, ATLAS di-Higgs workshop (CERN)
    - 13.03.2024: “A look into Polarisation and EFT for VBF di-Higgs”, Clermont-Ferrand
  - To do: 6h of scientific training
  - Plans:
    - 26.09.2024: presentation “EFT interpretations in HH”, MBI, Toulouse
    - Attending the European School of High-Energy Physics 2025
- **English test (TOEIC)**
  - 11.12.2023: Training test, score: 980 (750 needed)
  - 11.06.2024: Official test, score: not yet received

Timeline and Objectives



Start of the PhD

Where we are now

End of the PhD

Worked on three main topics in the **first year**:

1. Qualification project
2. Polarisation for VBF di-Higgs
3. Effective Field Theories in VBF di-Higgs

Plans for the **next year**:

- Contribute to the di-Higgs bbyy analysis
    - Building VBF specific tagger/categories to select the interesting events on data
    - Perform new VBF BDT/NN training
    - Perform FS vs AF3 comparison for Run2 and Run3 signal samples
    - Perform the dim-8 VBF EFT analysis at detector level and set limits on the operators

Backup

EFT

The Eboli Model for VBF di-Higgs

- Amplitude decomposition approach

$$\sigma_{\mathrm{SM+EFT}} \sim \left|\mathcal{M}_{\mathrm{SM}} + \sum_i \frac{f_i}{\Lambda^4}\mathcal{M}_i\right|^2 = \underbrace{|\mathcal{M}_{\mathrm{SM}}|^2}_{\text{SM}} + \underbrace{\sum_i 2\frac{f_i}{\Lambda^4}\mathcal{R}e(\mathcal{M}_i^*\mathcal{M}_{\mathrm{SM}})}_{\text{Interference SM - EFT operator}} + \underbrace{\sum_i \frac{f_i}{\Lambda^8}|\mathcal{M}_i|^2}_{\text{Quadratic Pure EFT}} + \underbrace{\sum_{i,j;i\neq j} 2\frac{f_i f_j}{\Lambda^8}\mathcal{R}e(\mathcal{M}_i^*\mathcal{M}_j)}_{\text{Interference EFT operator - EFT operator}}$$

- Makes it possible to rescale an individual sample to an arbitrary Wilson coefficient
- With that we do a rough estimation of the limits of the operators
  - $\mu_{HH}^{limit}\ \sigma_{SM} = \sigma_{SM} + f_i/\Lambda^4\ \sigma_{lin} + (f_i/\Lambda^4)^2\ \sigma_{quad}$
  - Conservative approach: $\sigma_{SM} = \sigma_{ggF} + \sigma_{VBF}$ and μ_{HH} is current upper limit on sigmal strength: $\mu_{HH} = 2.4$
  - Optimistic approach: $\sigma_{SM} = \sigma_{SM}^{VBF}$ and $\mu_{HH}^{limit}\ \sigma_{SM}$ is cross section that corresponds to the current upper limit on κ_{2V} (1.5)

The Eboli Model for VBF di-Higgs

Preliminary results

- Comparison of the relative increase of the cross sections with respect to the SM between VBF di-Higgs and VBS WZ

operator		M							S			SM
quadratic term		M0	M1	M2	M3	M4	M5	M7	S0	S1	S2	
VBF HH	σ [pb]	3.1E+05	2.0E+04	1.6E+05	1.1E+04	1.8E+04	5.4E+03	5.0E+03	254	2.2E+03	862	0.001348
VBS WZ	σ [pb]	3.8E+04	1.6E+04	1.3E+04	5.5E+03	6.2E+04	3.4E+04	1.1E+04	2.9E+03	1.4E+03	2.9E+03	1.335
VBF HH	σ_{EFT} / σ_{SM}	2.3E+08	1.5E+07	1.2E+08	7.8E+06	1.3E+07	4.0E+06	3.7E+06	1.9E+05	1.6E+06	6.4E+05	1
VBS WZ	σ_{EFT} / σ_{SM}	2.8E+04	1.2E+04	9.7E+03	4.1E+03	4.6E+04	2.5E+04	8.4E+03	2.1E+03	1.1E+03	2.1E+03	1

- Relative increase of the cross section with respect to the SM is about 3-4 orders of magnitudes higher for VBH di-Higgs than for VBS processes
  - This leads to expected similar sensitivity of VBF di-Higgs despite its lower cross section

Polarization

Closure Test of the Cross Sections

SM

Center of mass energy [GeV]	Sum	Full	Ratio sum/full
270	6,05	6,091	0,9938
300	7,78	7,844	0,9924
350	9,10	9,21	0,9880
400	9,93	10,06	0,9872
450	10,54	10,68	0,9868
500	11,00	11,14	0,9877
550	11,38	11,54	0,9865
600	11,67	11,82	0,9877
1000	12,811	13,06	0,9810
5000	13,71	13,78	0,9953
10000	13,77	13,8	0,9977
50000	10,43	13,85	0,75230
100000	10,41	6,224	1,6729

$\kappa_\lambda = 0$

Center of mass energy [GeV]	Sum	Full	Ratio sum/full
270	19,29	19,14	1,0078
300	22,63	22,48	1,0069
350	22,67	22,53	1,0060
400	21,62	21,61	1,0006
450	20,63	20,58	1,0024
500	19,76	19,71	1,0027
550	19,04	19	1,0023
600	18,44	18,4	1,0021
1000	16,01	15,83	1,0115
5000	14,03	14,09	0,9955
10000	13,82	14,03	0,9853
50000	12,68	13,92	0,9108
100000	6,22	10,66	0,5839

$\kappa_\lambda = 6$

Center of mass energy [GeV]	Sum	Full	Ratio sum/full
270	61,57	61,5	1,0012
300	61,80	61,82	0,9997
350	48,85	48,9	0,9991
400	38,20	38,27	0,9981
450	30,76	30,84	0,9975
500	25,59	25,6	0,9997
550	21,93	21,95	0,9993
600	19,34	19,37	0,9986
1000	12,34	12,87	0,9587
5000	13,30	13,37	0,9951
10000	13,70	13,72	0,9986
50000	10,39	13,83	0,7515
100000	10,43	6,22	1,6776

$\kappa_{2V} = 0$

Center of mass energy [GeV]	Sum	Full	Ratio sum/ full
270	23,00	23,25	0,9893
300	35,01	35,34	0,9908
350	50,05	50,31	0,9948
400	64,00	64,2	0,9969
450	78,10	78,45	0,9956
500	92,84	92,93	0,9991
550	108,21	108,4	0,9983
600	124,49	124,6	0,9992
1000	289,64	289,5	1,0005
5000	5955,56	5950	1,0009
10000	23622,22	2,354E+04	1,0035
50000	587000,00	5,87E+05	1,0000
100000	2342222,22	2,342E+06	1,0001

$\kappa_{2V} = 2$

Center of mass energy [GeV]	Sum	Full	Ratio sum/ full
270	0,98	0,98	0,9973
300	1,88	1,87	1,0016
350	5,20	5,16	1,0073
400	10,42	10.39	1,0029
450	17,28	17.24	1,0025
500	25,67	25.64	1,0011
550	35,54	35.47	1,0018
600	46,75	46.68	1,0015
1000	183,52	182.8	1,0039
5000	5762,23	5758	1,0007
10000	23311,11	2.331e+04	1,0000
50000	585222,22	5.852e+05	1,0000
100000	2342222,22	2.342e+06	1,0001

- Compare the cross sections of the sum of the individual polarization combinations with the cross section of the unpolarized (full) sample
  - Individual polarizations are divided by a factor (see next slide) to account to Madgraph averaging over initial state polarizations
- Good agreement for most energies
- For some coupling parameters differences can be seen at very high energies
  - These energies are out of the reach of the LHC at the moment

Comparison of the sum of the polarizations and the full sample

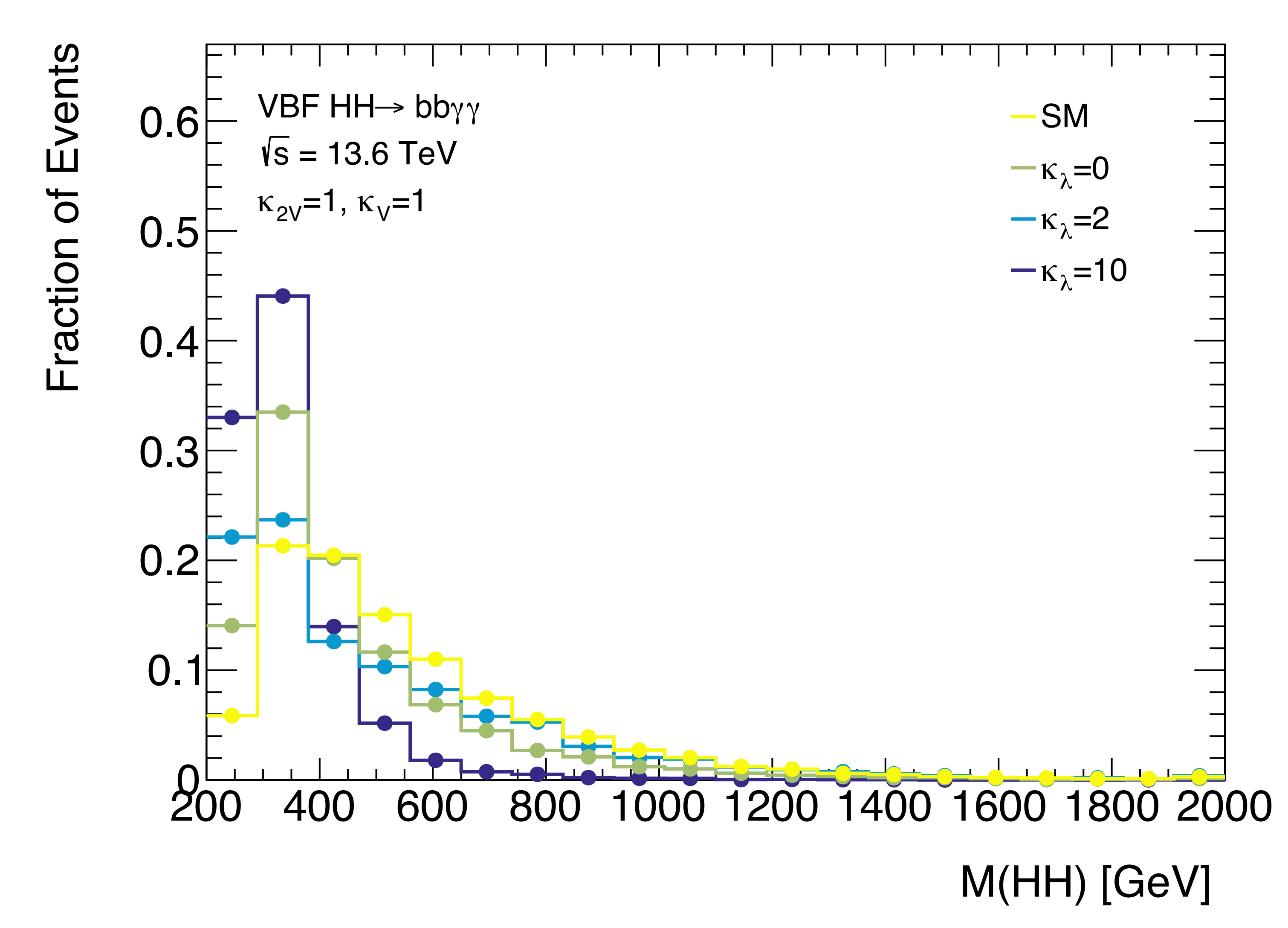
- Compare the cross section of the sum of all the polarizations to the cross section of the unpolarized sample (full)
- Need to account for the fact that Madgraph averages over the initial state polarizations
  - Need to apply an averaging factor to the individual polarizations before adding them
- There are three polarizations for the VV->HH process
  - Longitudinal (L), left-handed (l) and right-handed (r)
  - This means that there are 9 polarization combinations in the initial state
    - LL, Ll, lL, Lr, rL, ll, lr, rl, rr
    - Need to divide each polarization combination by 9
  - In my samples the left- and right-handed polarization are combined into the transversal (T) polarization
    - Likely in the transversal sample Madgraph already averages over the left- and right-handed polarizations, meaning 4 combinations of the polarizations for LT and TT each
    - That means that the averaging factor needs to be adjusted
      - LL: 1/9
      - LT: 1/2.25 = 1/4 * 1/9
    - Contacted Madgraph authors to confirm these fractions (https://answers.launchpad.net/mg5amcnlo/+question/708414)
    - Test with simulating the left- and right-handed polarizations separately seems to confirm that
      - In this case dividing all the polarizations by 9 leads to a good closure with the cross section of the full sample

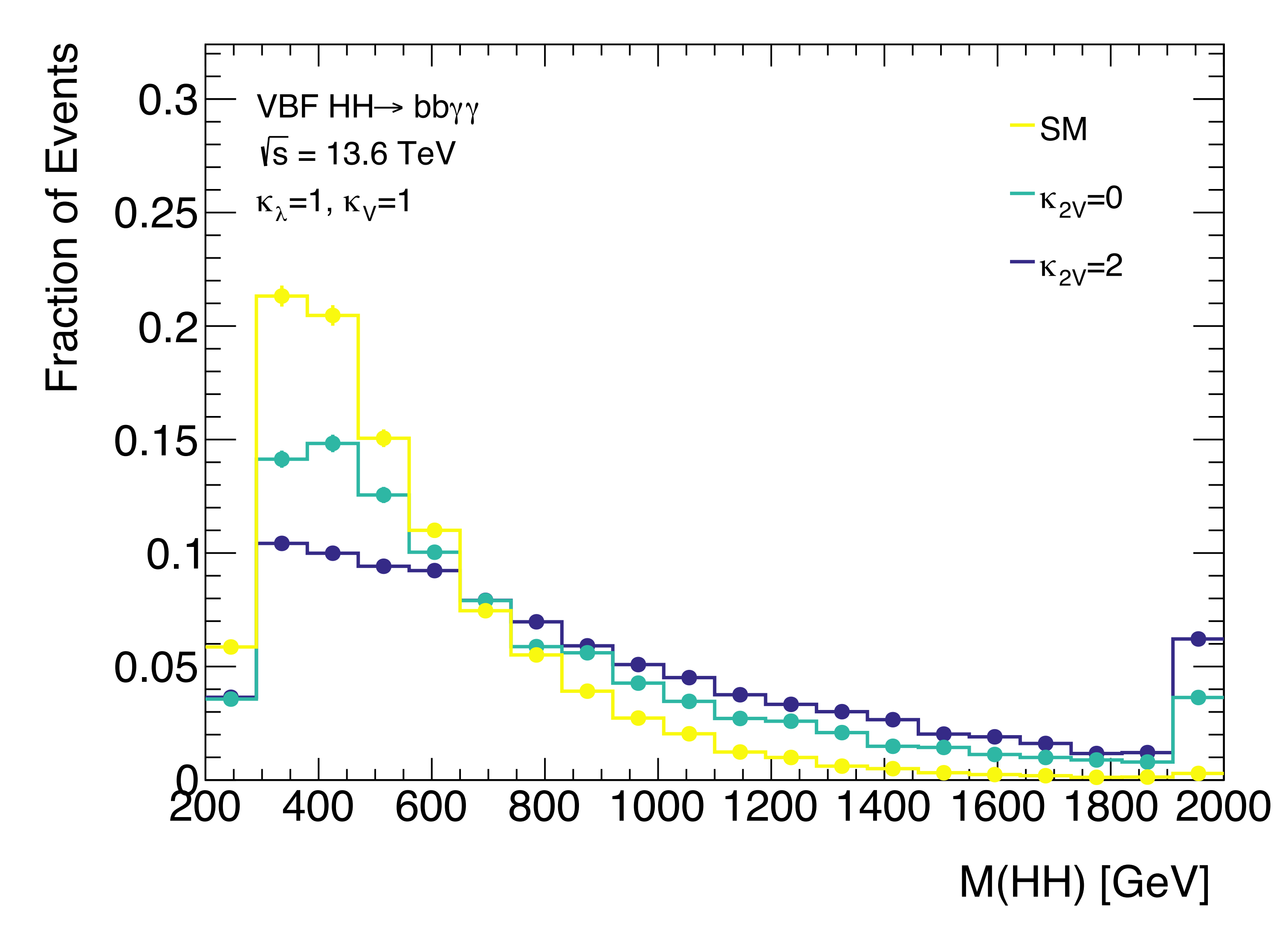
Effect of the Different Coupling Parameters on the Cross Section

How does the center of mass energy of the vector bosons relate to what is happening at the LHC?

Effect of changing κ_λ

Effect of changing κ_V



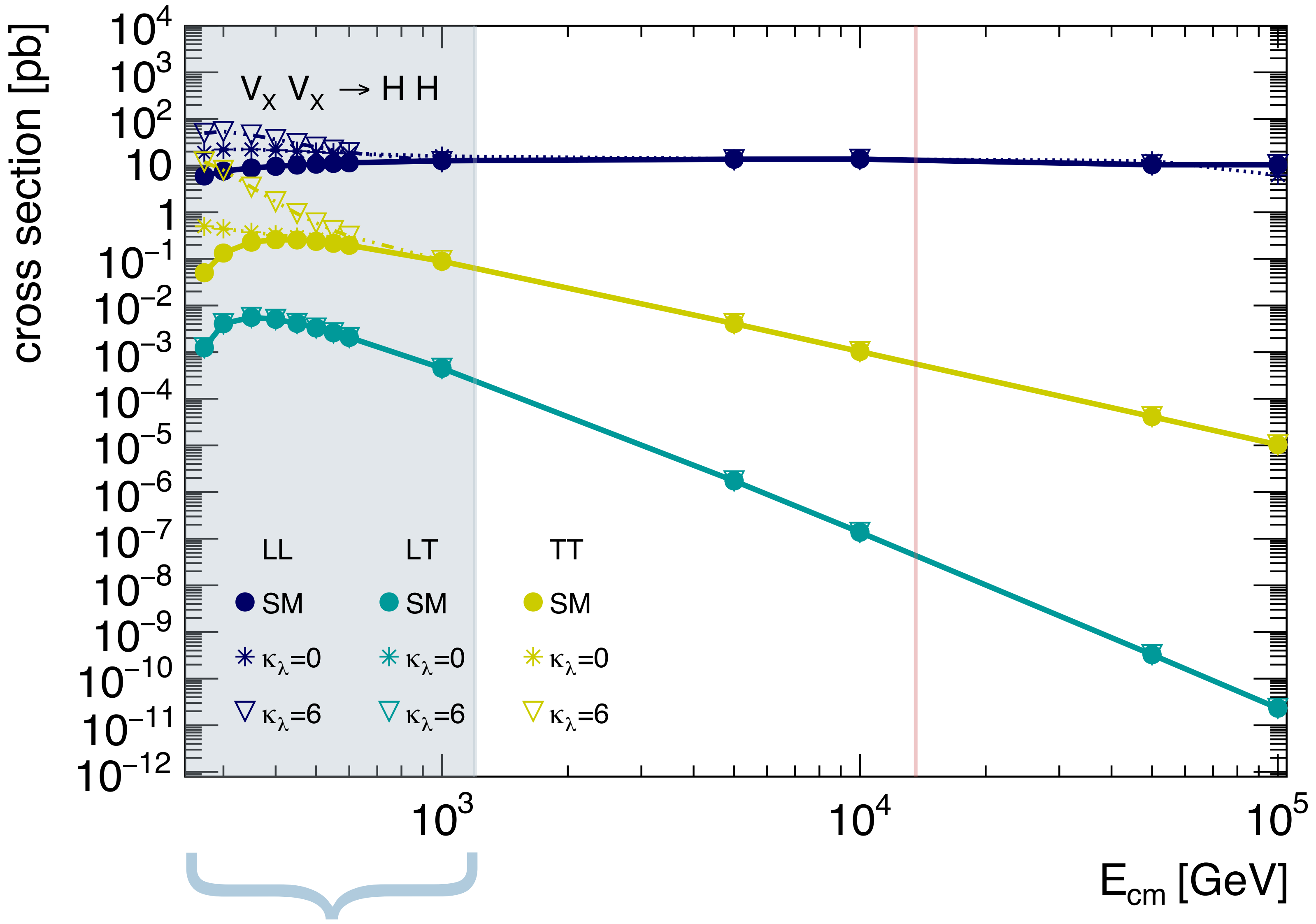


Look at the normalized truth m_{HH} distributions of the VBF di-Higgs process (here for $HH \to bb\gamma\gamma$) at center of mass energy for Run 3

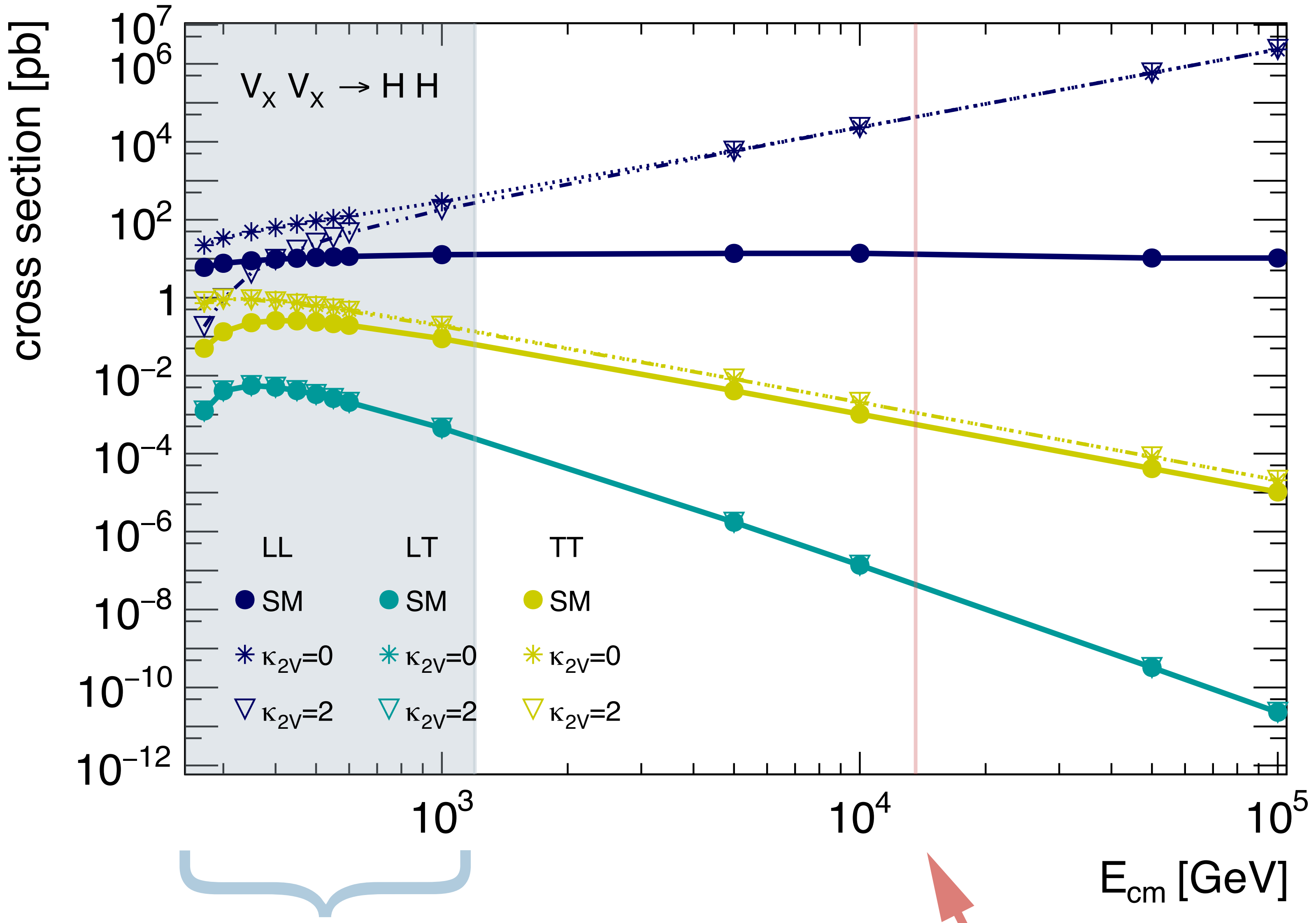
Expect most of the events to be lower than $m_{HH} \approx 1200\ GeV$

Effect of the Different Coupling Parameters on the Cross Section

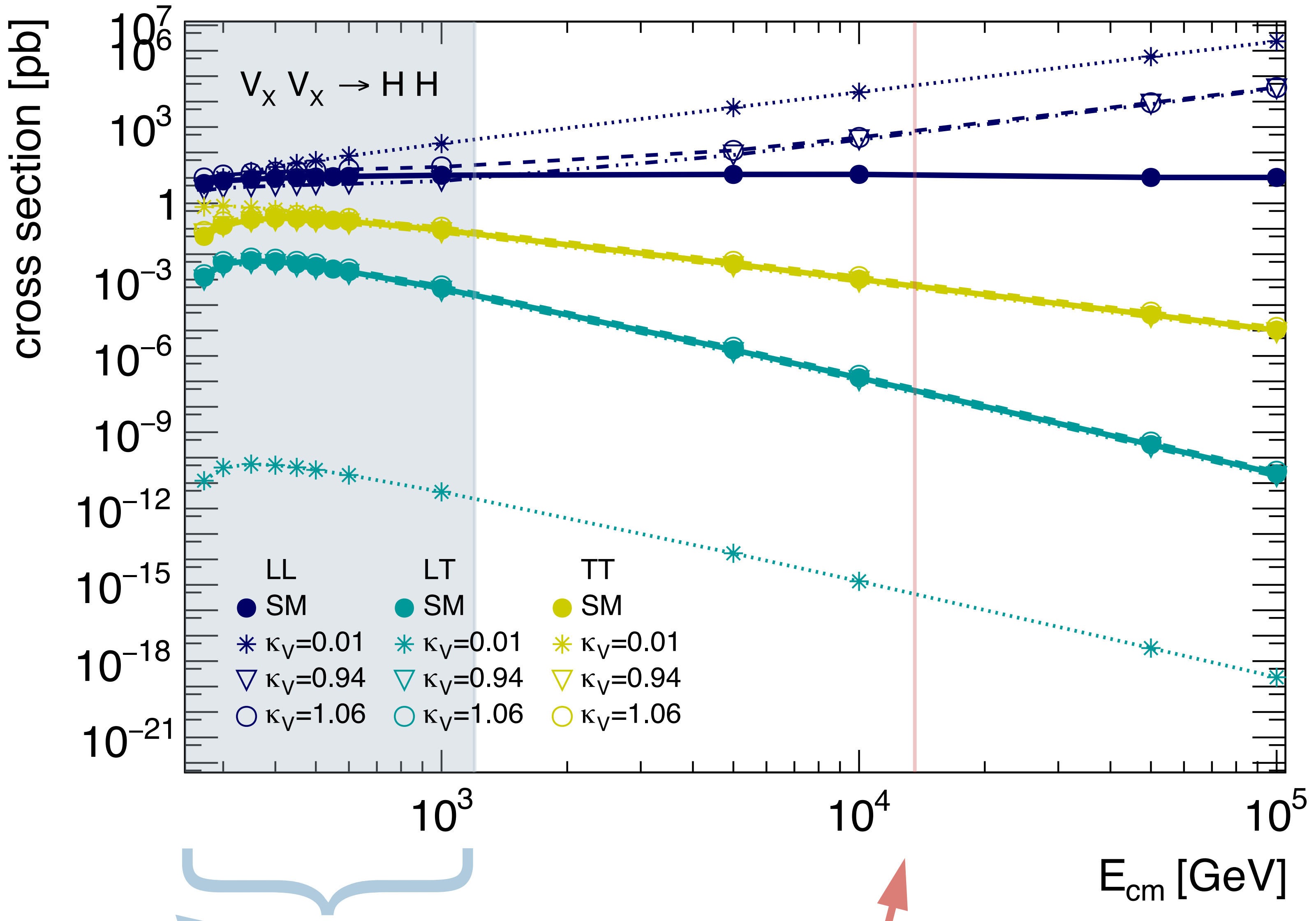
Effect of changing κ_λ



Effect of changing κ_{2V}



Effect of changing κ_V

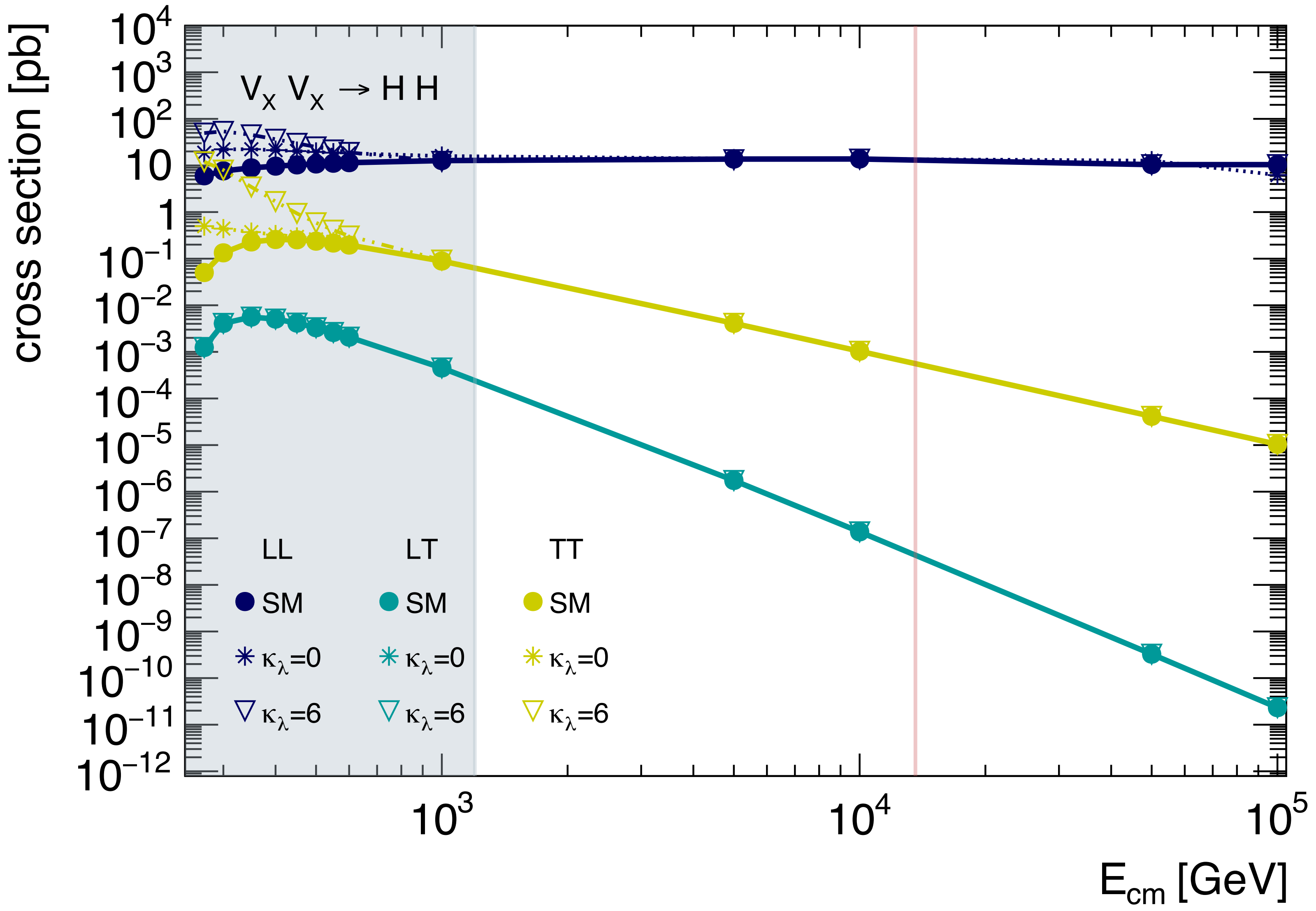


Highlighted Area:
Energy range where the di-Higgs mass of most of the events at the LHC is expected to be for Run 3

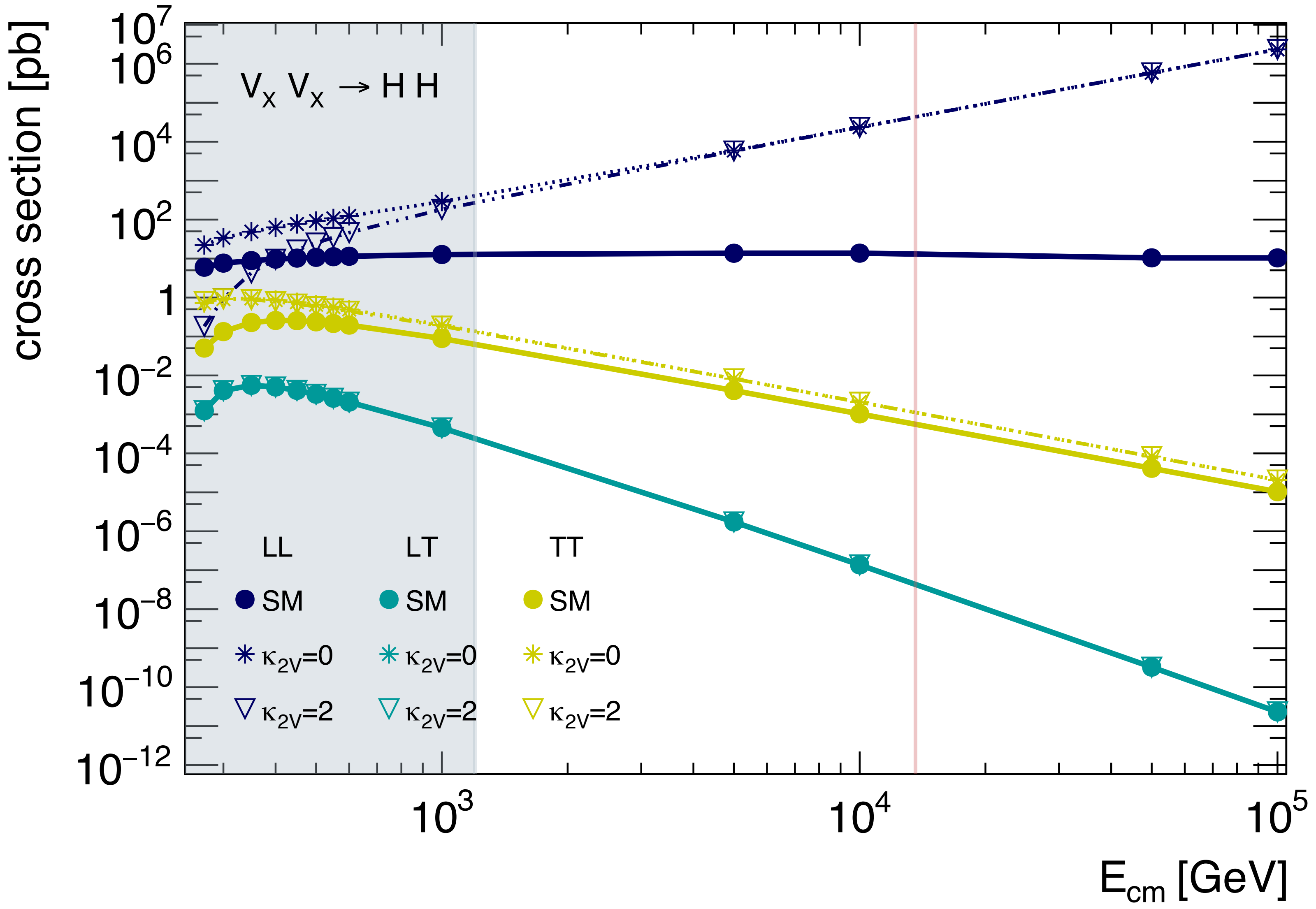
Red Line:
Center of mass energy of the LHC for Run 3 : $\sqrt{s} = 13.6$ TeV

Effect of the Different Coupling Parameters on the Cross Section

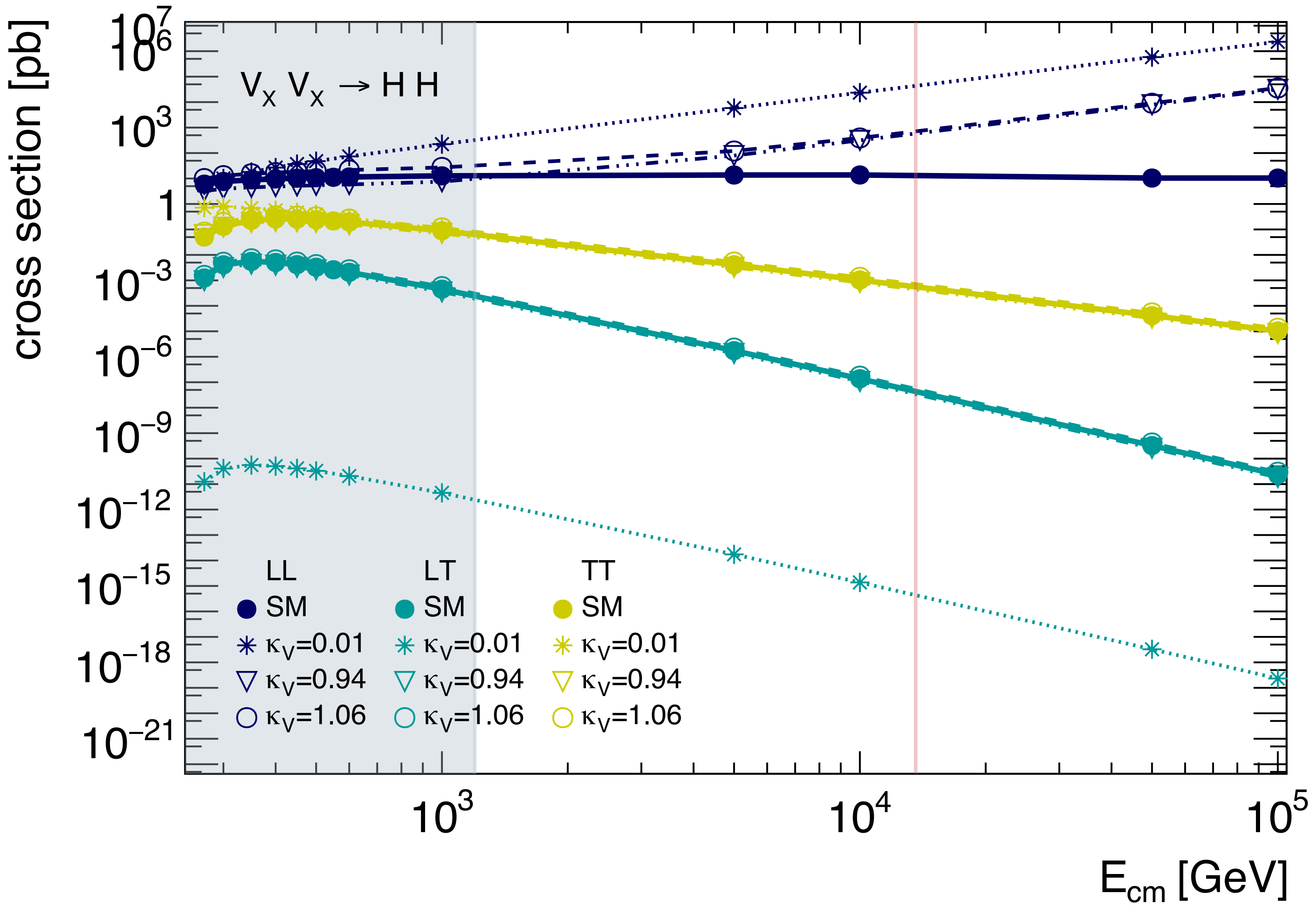
Effect of changing κ_λ



Effect of changing κ_{2V}



Effect of changing κ_V



Longitudinal longitudinal polarization (LL):

- κ_{2V}, κ_V : Unitarity violation visible for deviations from the SM
  - Large cancellations $\kappa_{2V} - \kappa_V$ are expected
- κ_λ : No Unitarity violation visible
  - s-channel diagram with off-shell Higgs disappears for high energies

Other polarizations (LT and TT):

- No unitarity violation

Mixed polarization (LT):

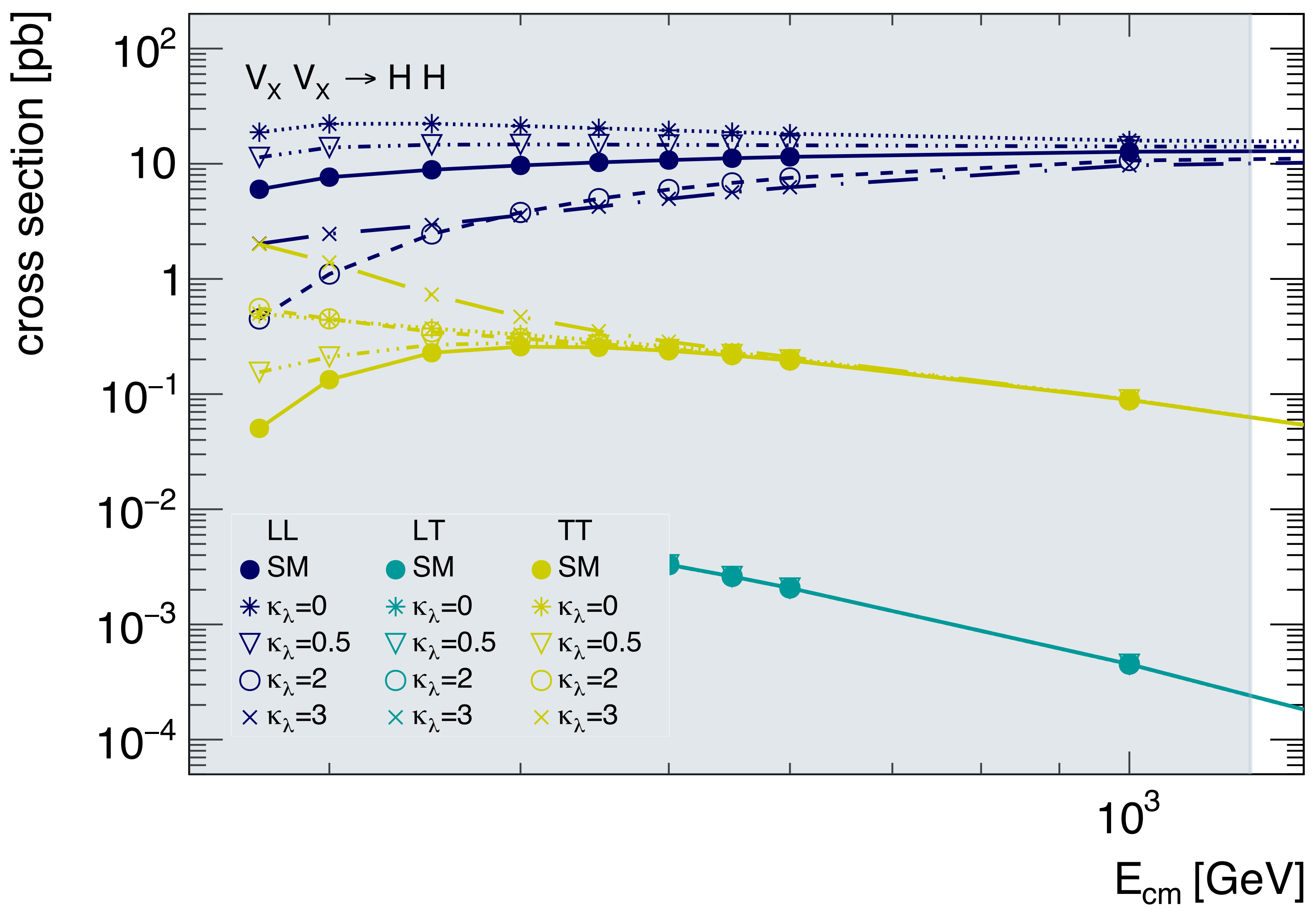
- Very strongly suppressed

Effect of the Different Coupling Parameters on the Cross Section

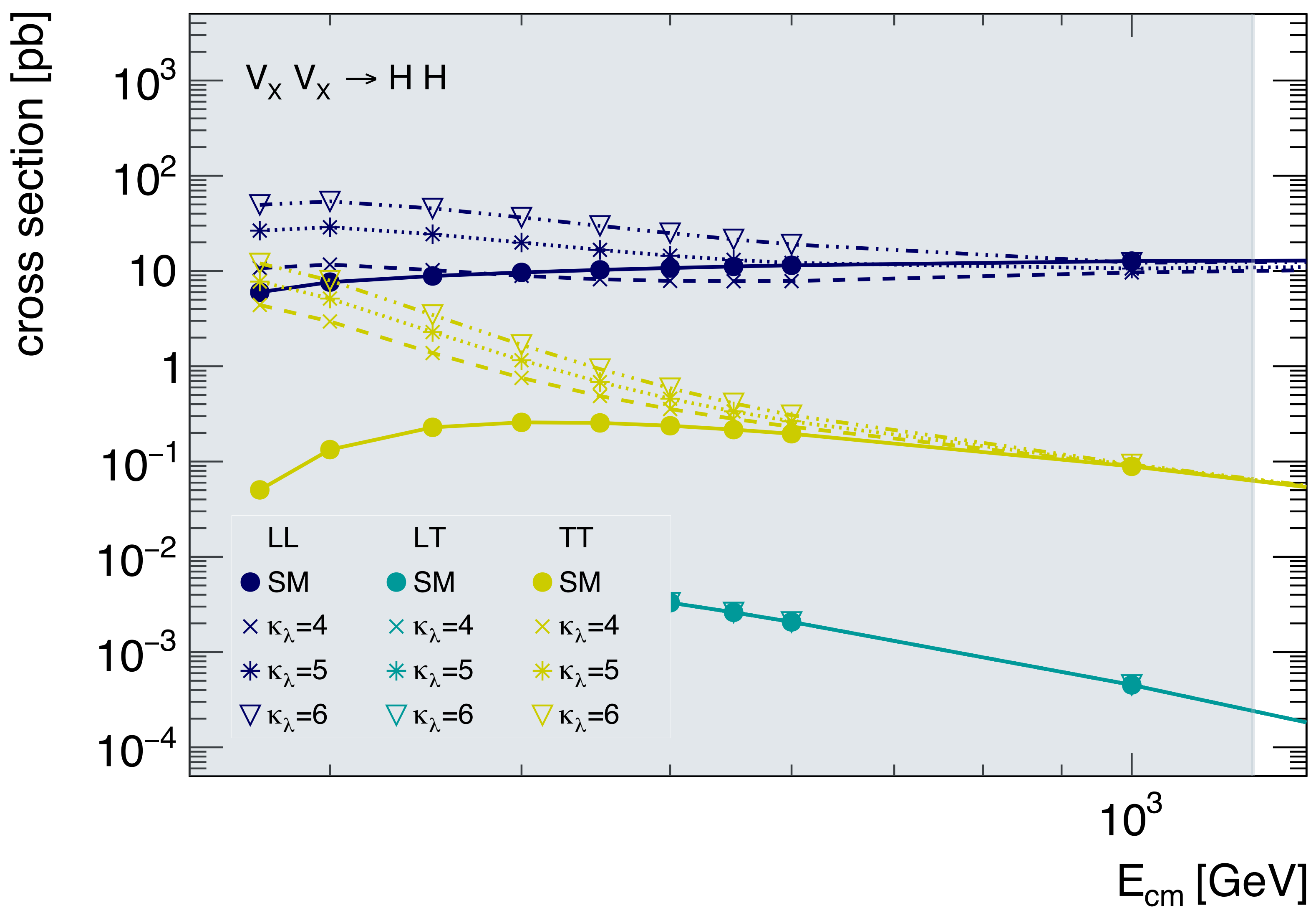
Zoomed in

More values between the limits

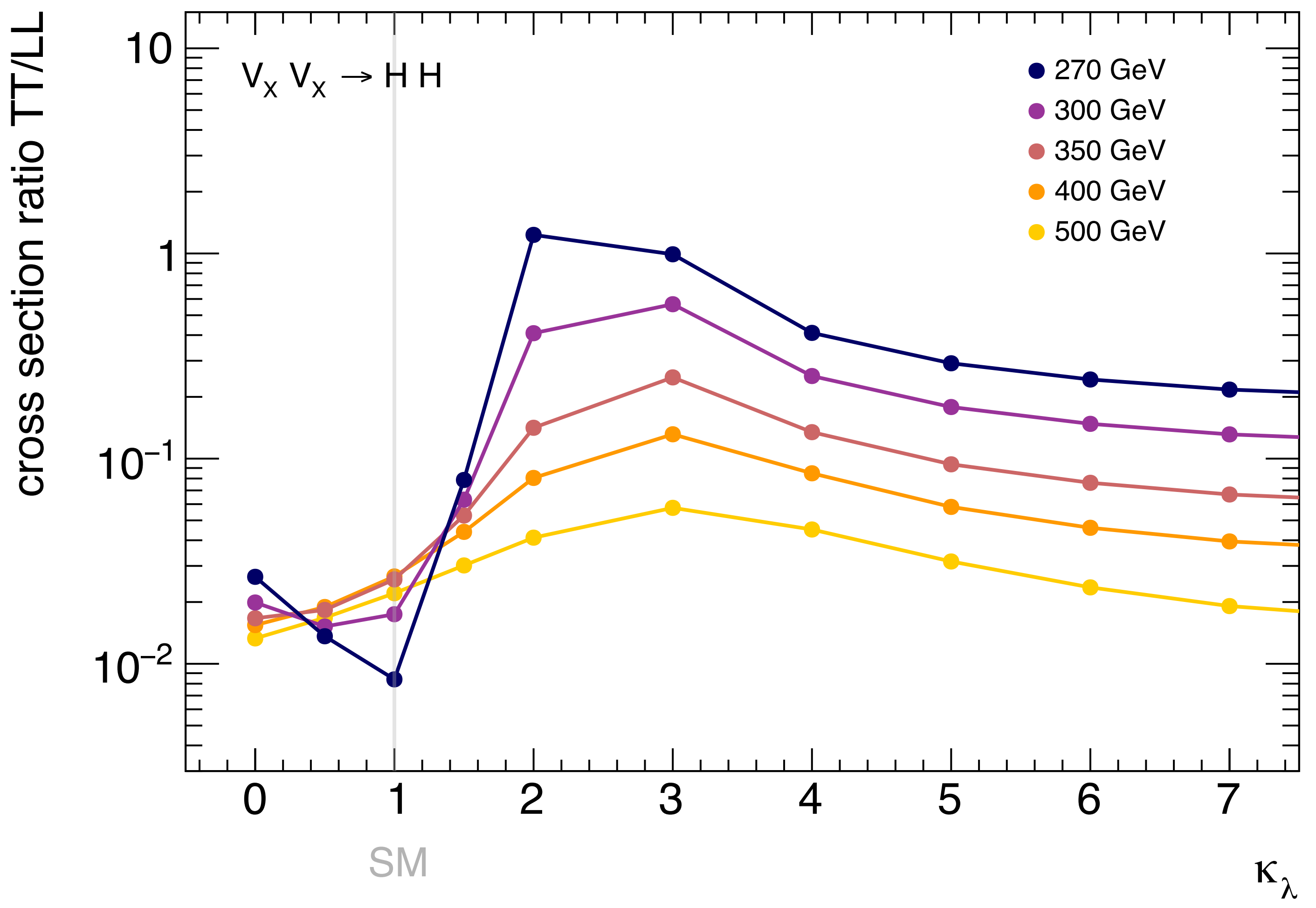
Effect of changing κ_λ at low energies
Low values



Effect of changing κ_λ at low energies
High values



Cross section ratio TT/LL



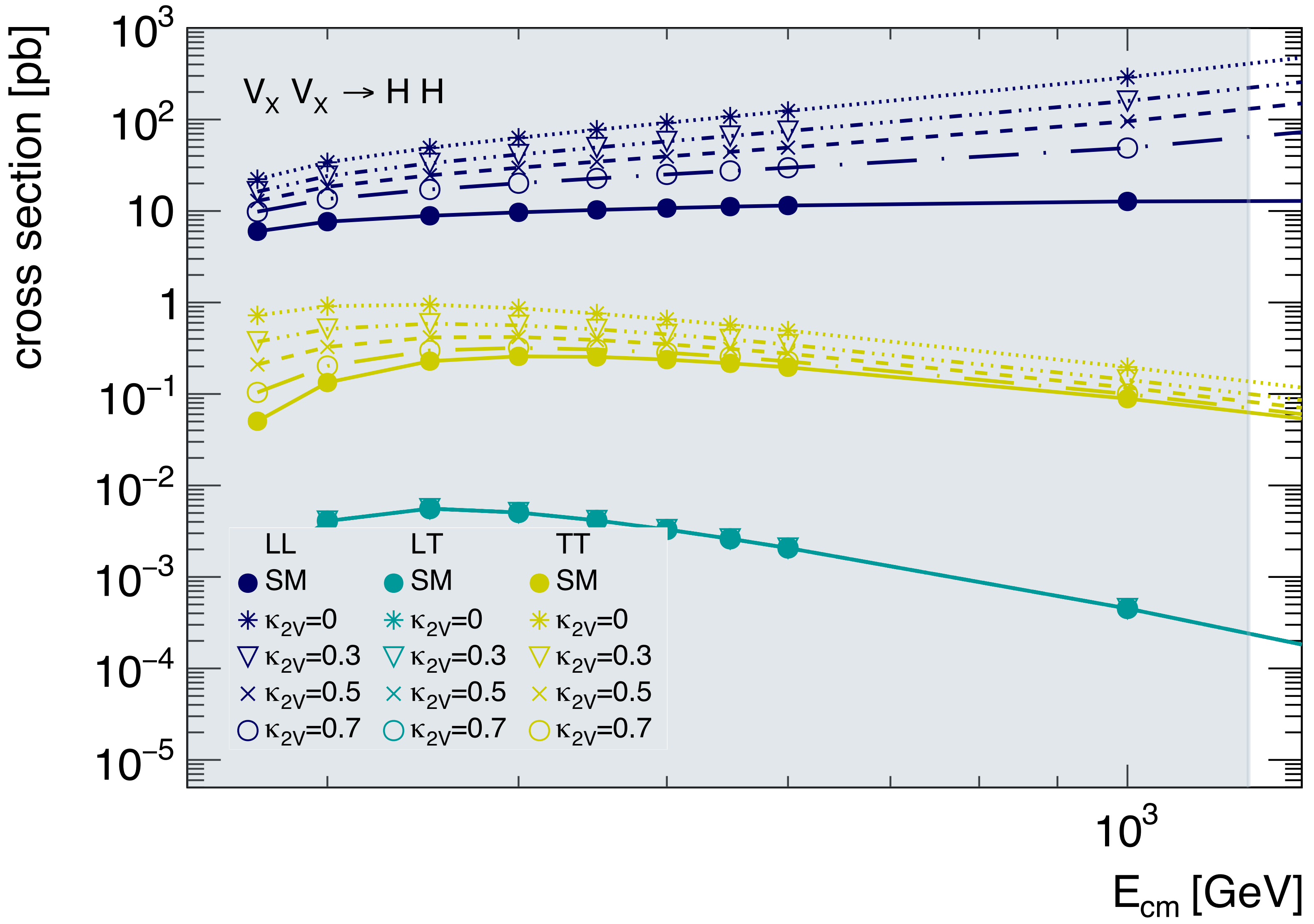
- The LL polarization dominates for most of the coupling values over large energy regimes
- But for some values of the coupling parameters the relative fraction of TT compared to LL gets larger at low energies
- Closer look at more coupling values of κ_λ between the limits
  - Relative fraction of TT at very low energies seems to be largest for $\kappa_\lambda \approx 2$
  - For values of κ_λ between 2 and 6 the cross sections of LL and TT gets close

Effect of the Different Coupling Parameters on the Cross Section

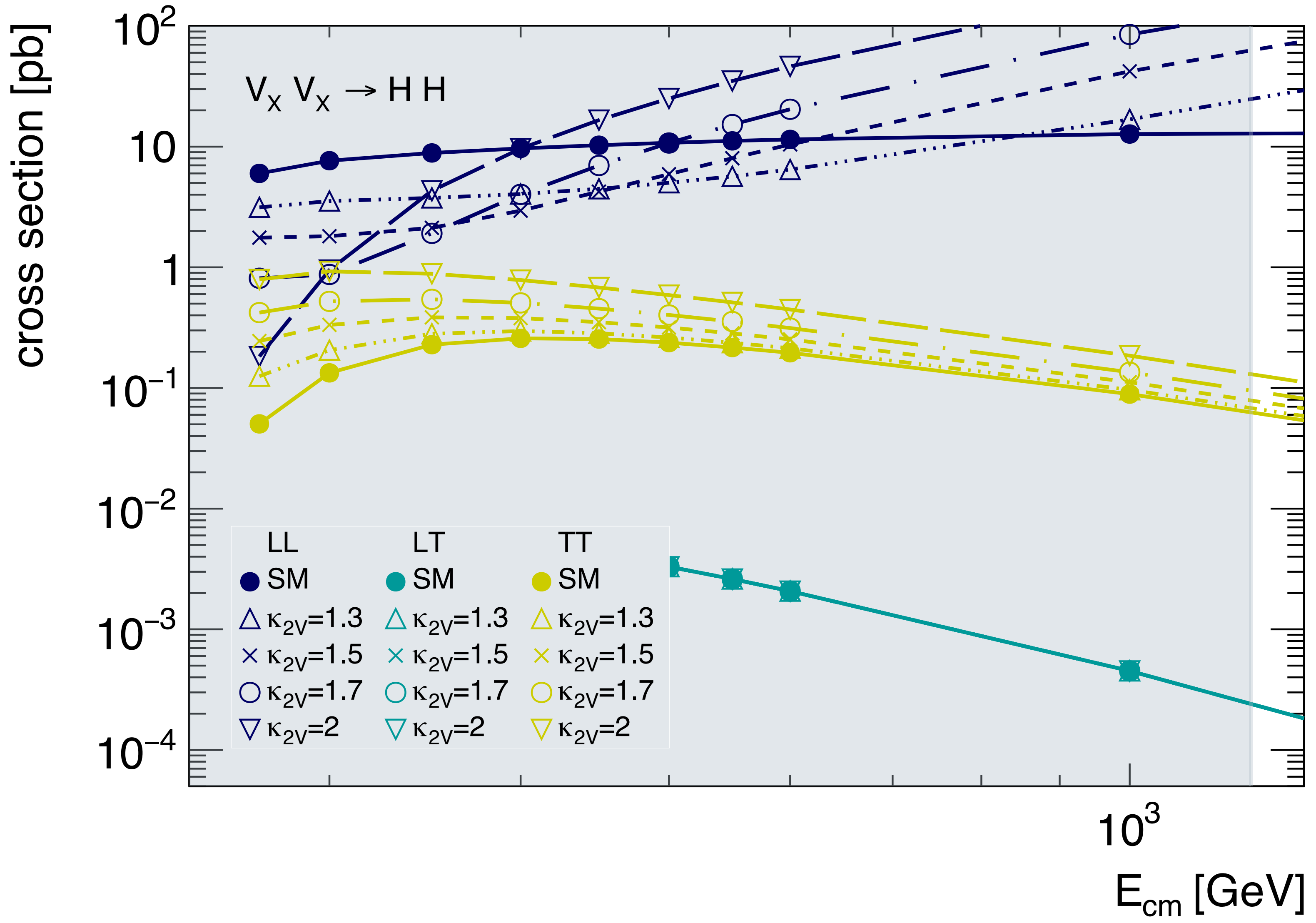
Zoomed in

More values between the limits

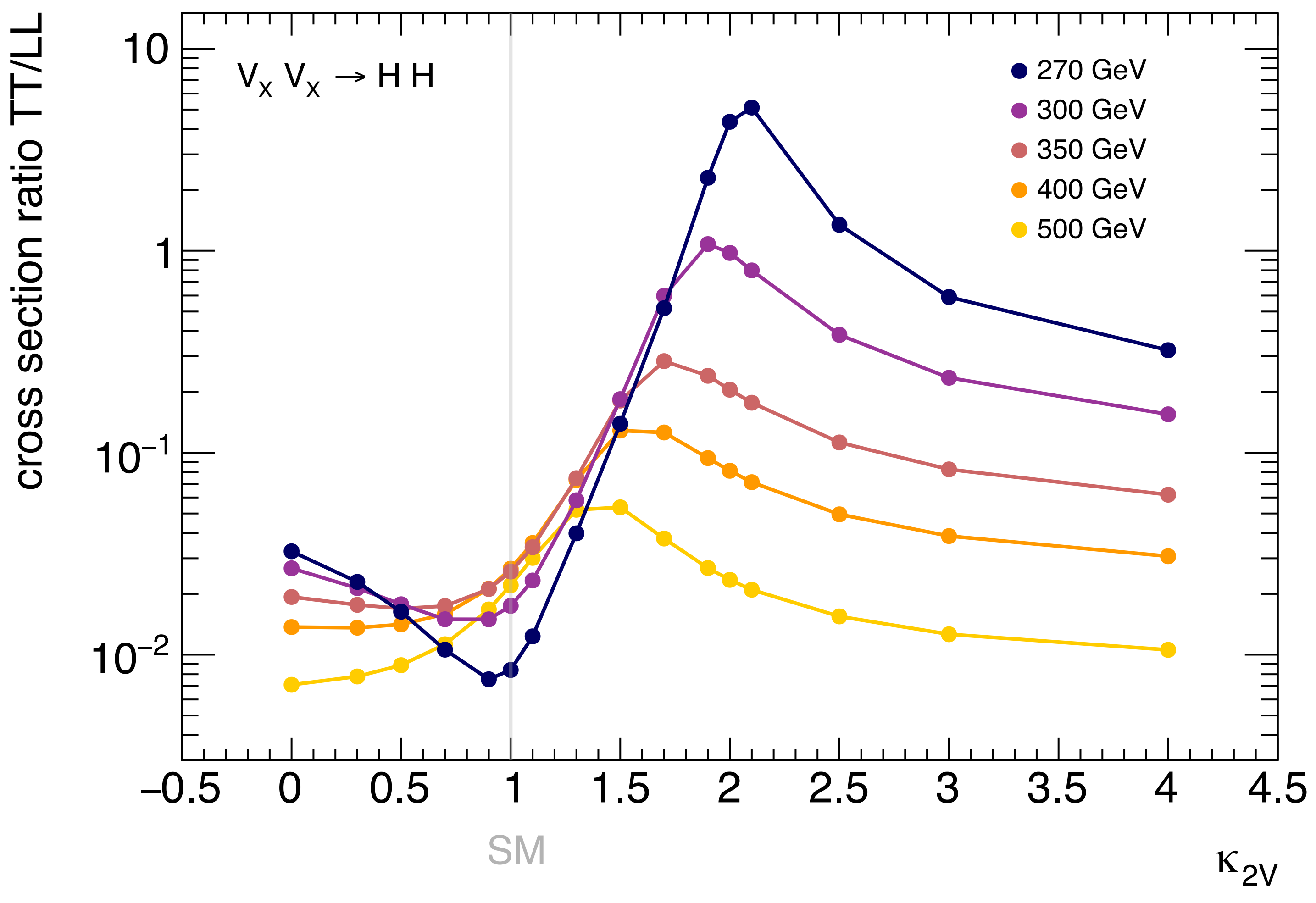
Effect of changing κ_{2V} at low energies
Low values



Effect of changing κ_{2V} at low energies
High values



Cross section ratio TT/LL



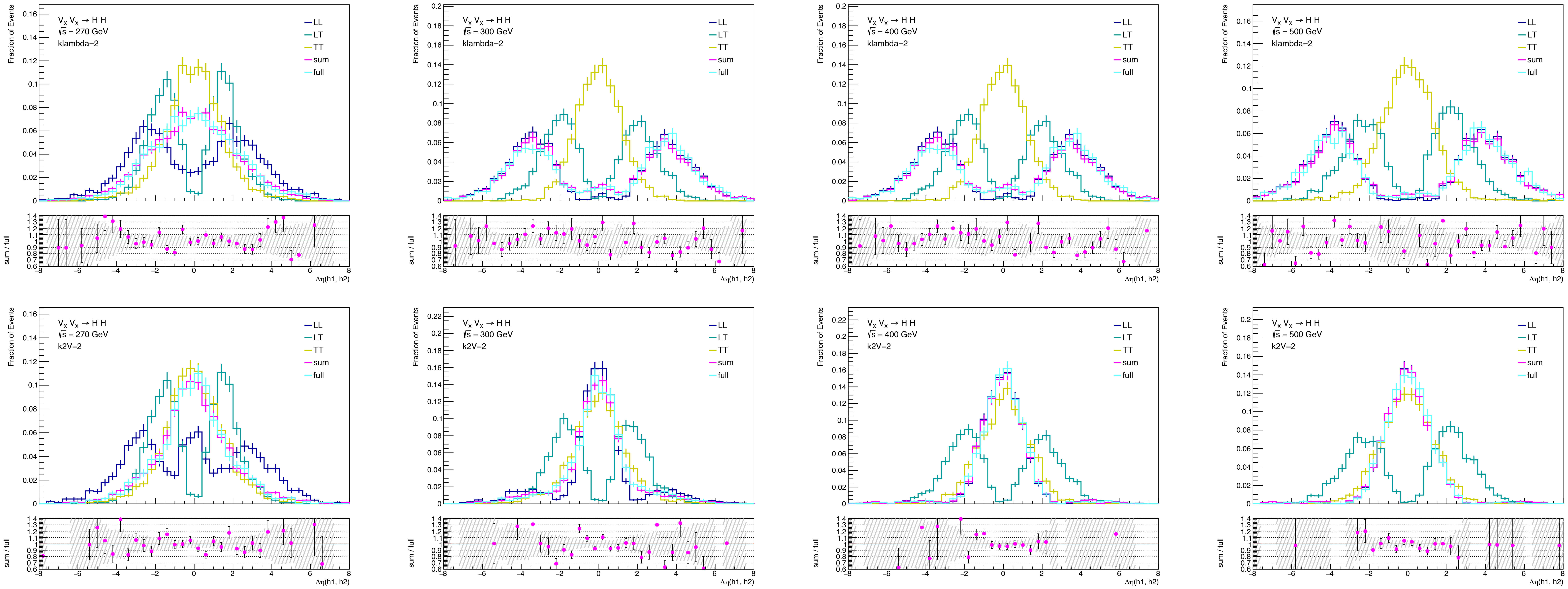
- The LL polarization dominates for most of the coupling values over large energy regimes
- But for some values of the coupling parameters the relative fraction of TT compared to LL gets larger at low energies
- Closer look at more coupling values of κ_{2V} between the limits
  - Relative fraction of TT at very low energies seems to be largest for $\kappa_{2V} \approx 2$
  - Large difference of the cross sections for $\kappa_{2V} < 1$

Polarization Distributions

270 GeV | 300 GeV | 350 GeV | 500 GeV

$\kappa_\lambda = 2$

$\kappa_{2V} = 2$

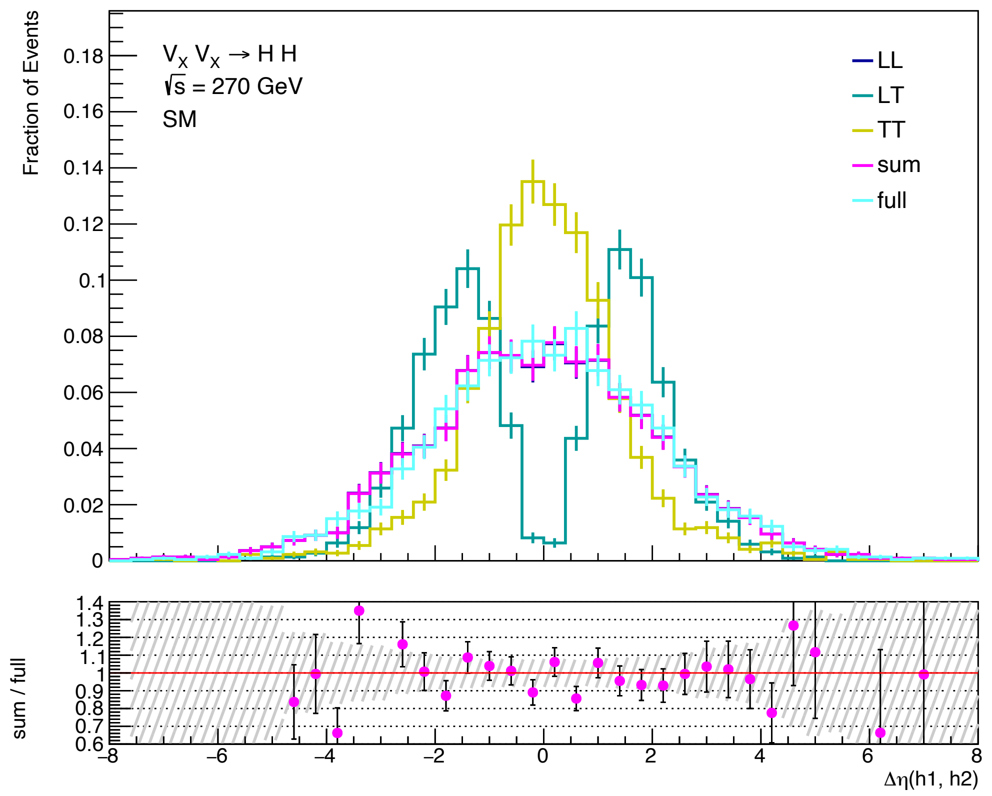


- Good agreement of shape of the distribution of the sum of the polarizations and the unpolarized (full) sample
- $\kappa_\lambda = 2$: Some shape differences visible between LL and TT
- $\kappa_{2V} = 2$: Distributions of LL and TT very similar

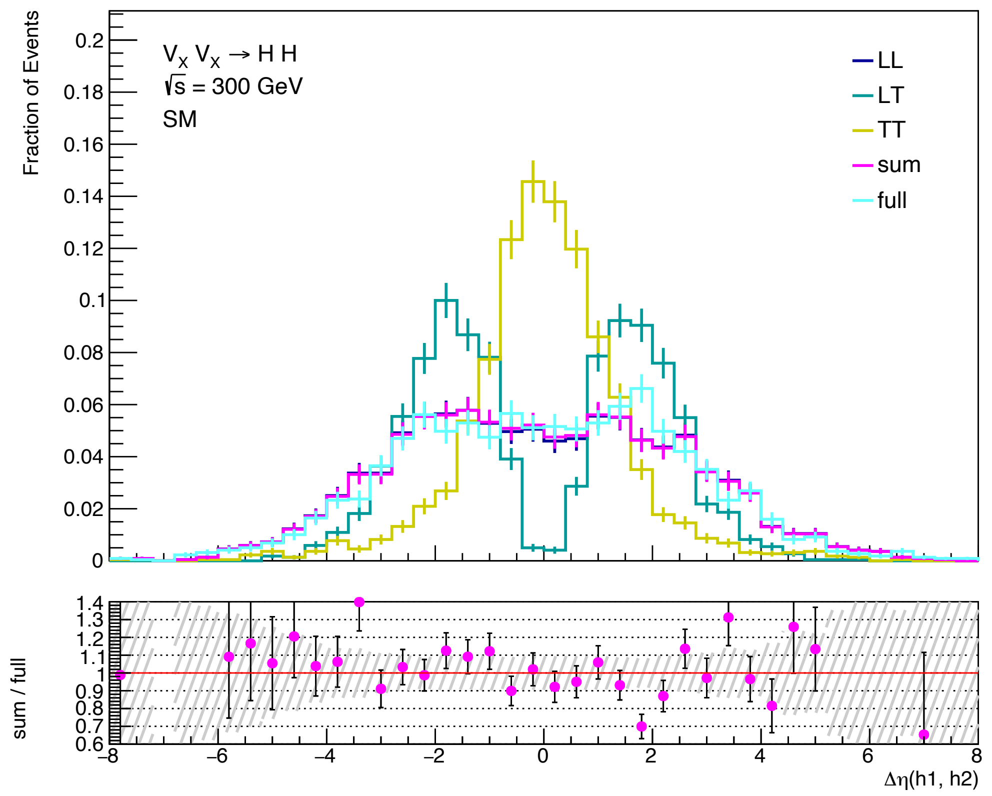
Distributions for the SM case

Center of mass energy

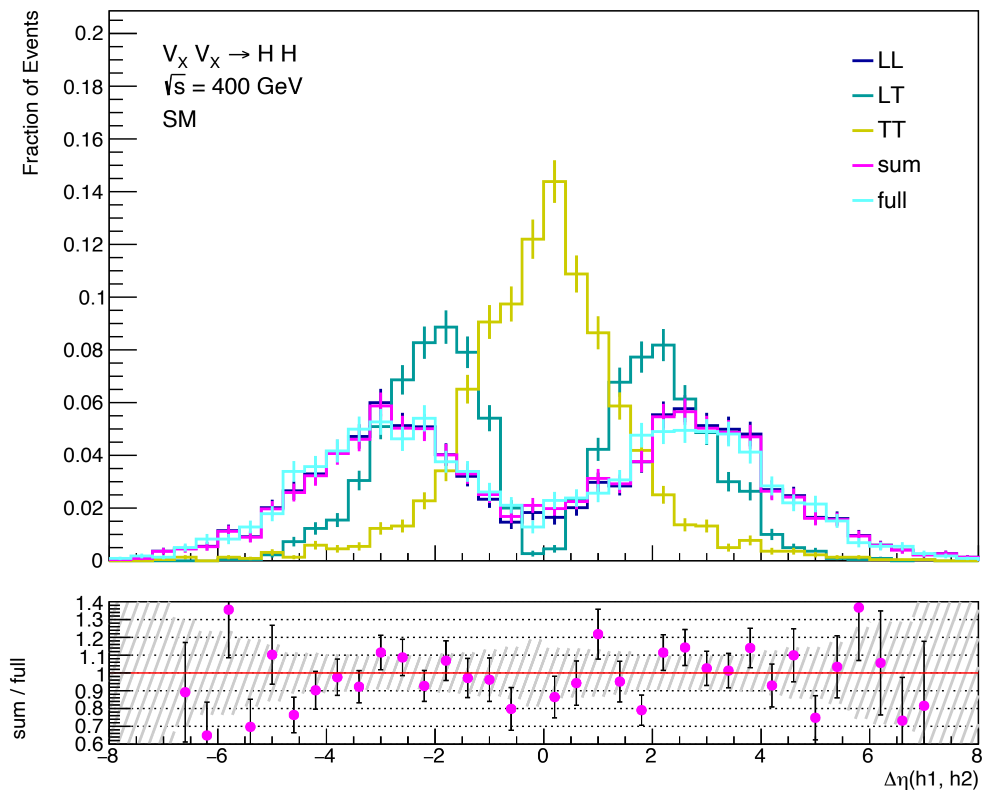
270 GeV



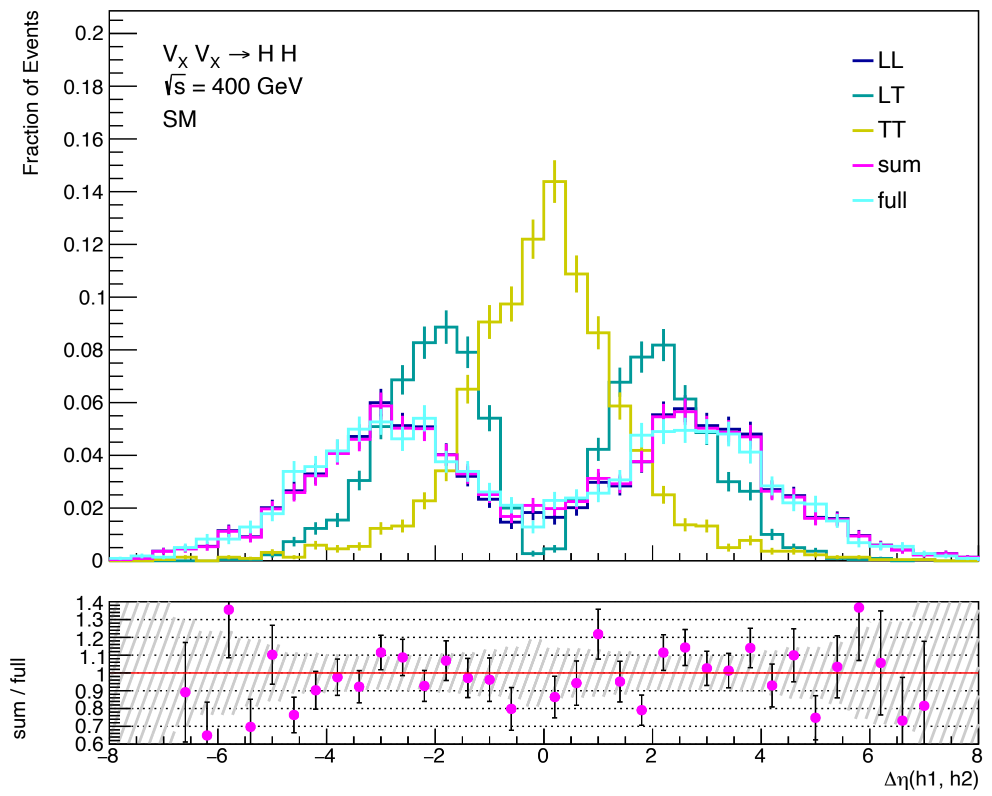
300 GeV



400 GeV

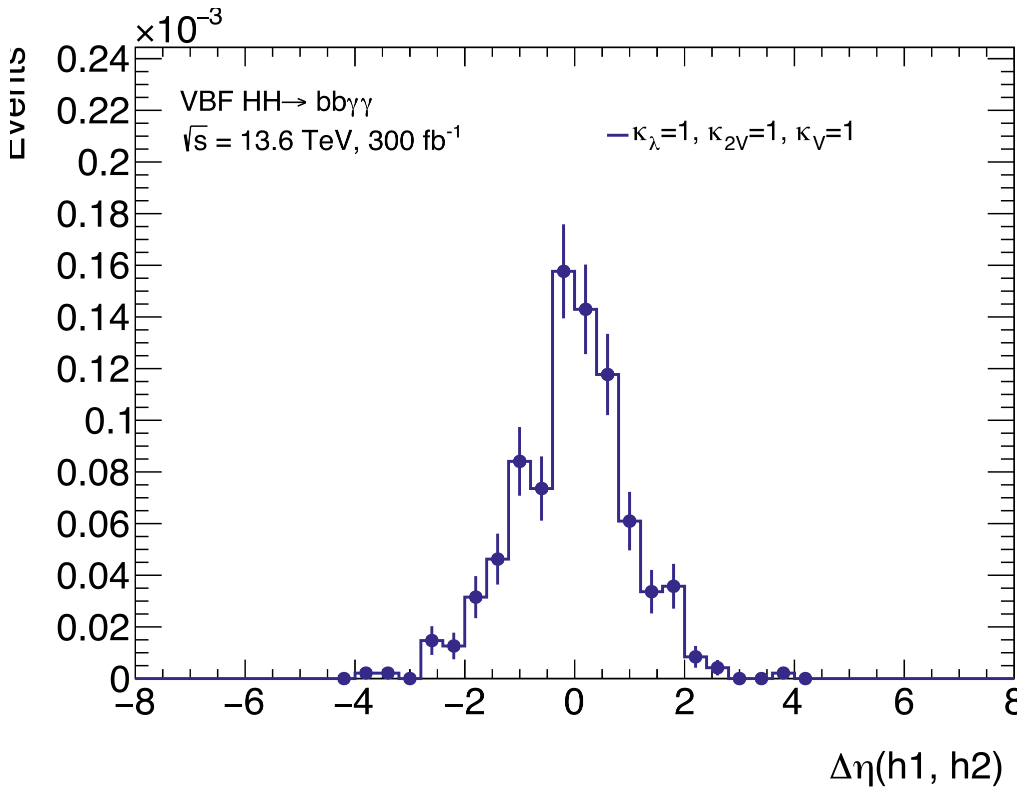


500 GeV

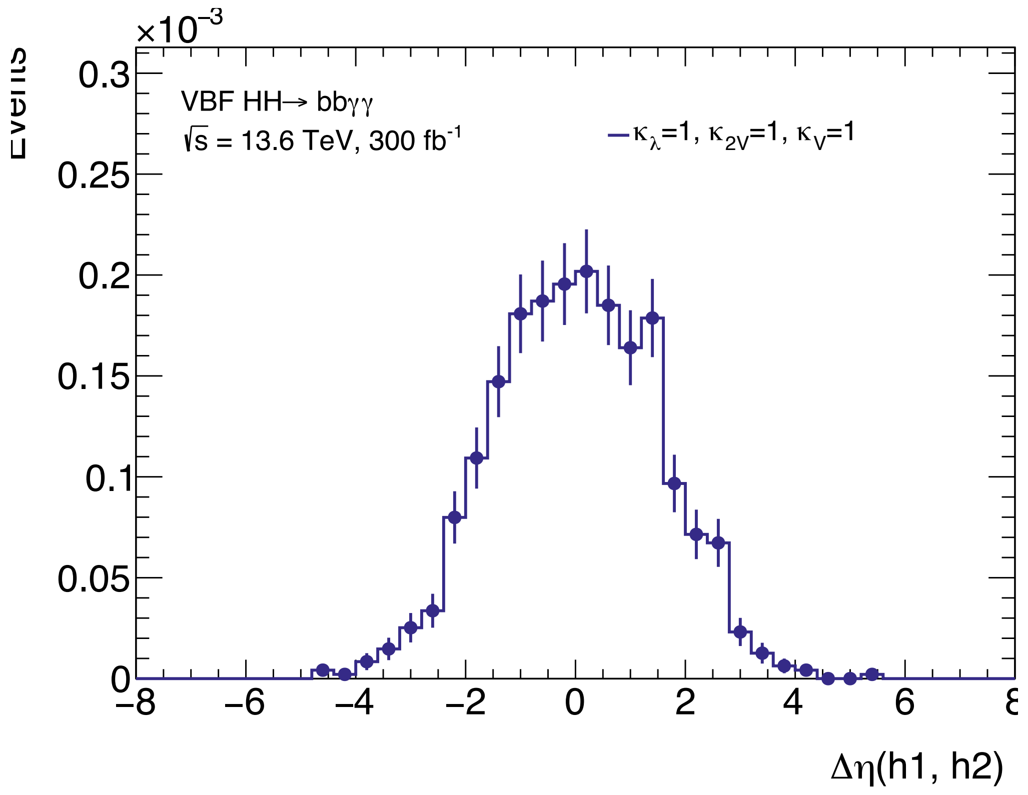


m_{HH}

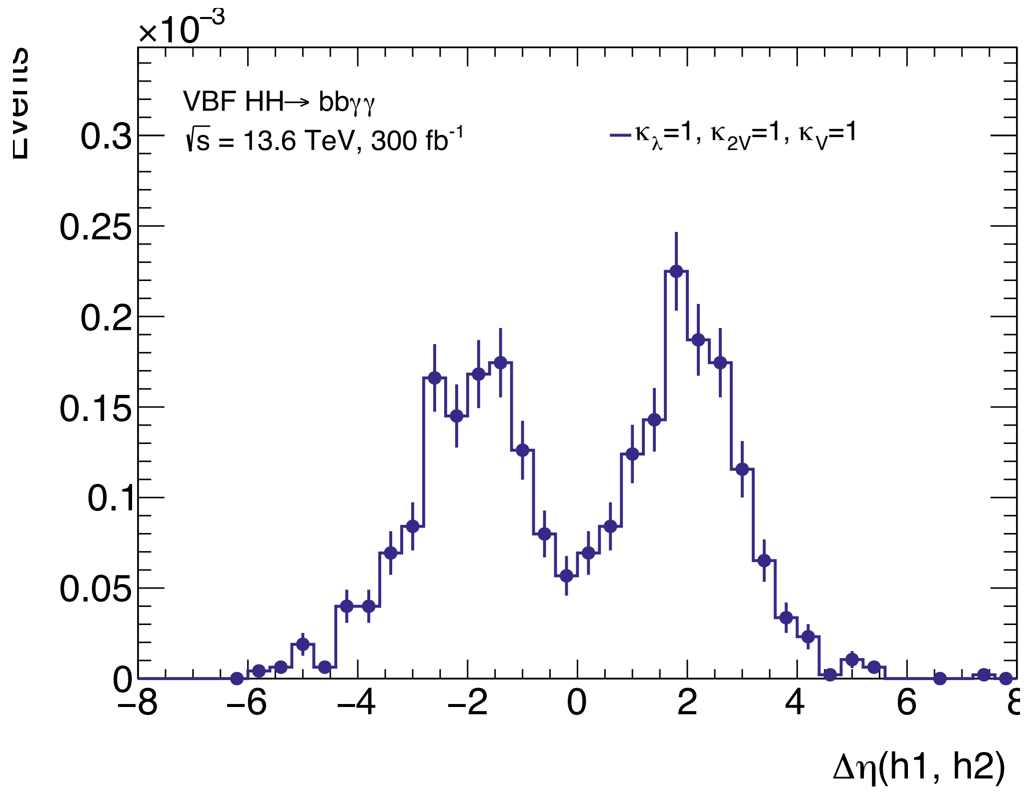
0 - 280 GeV



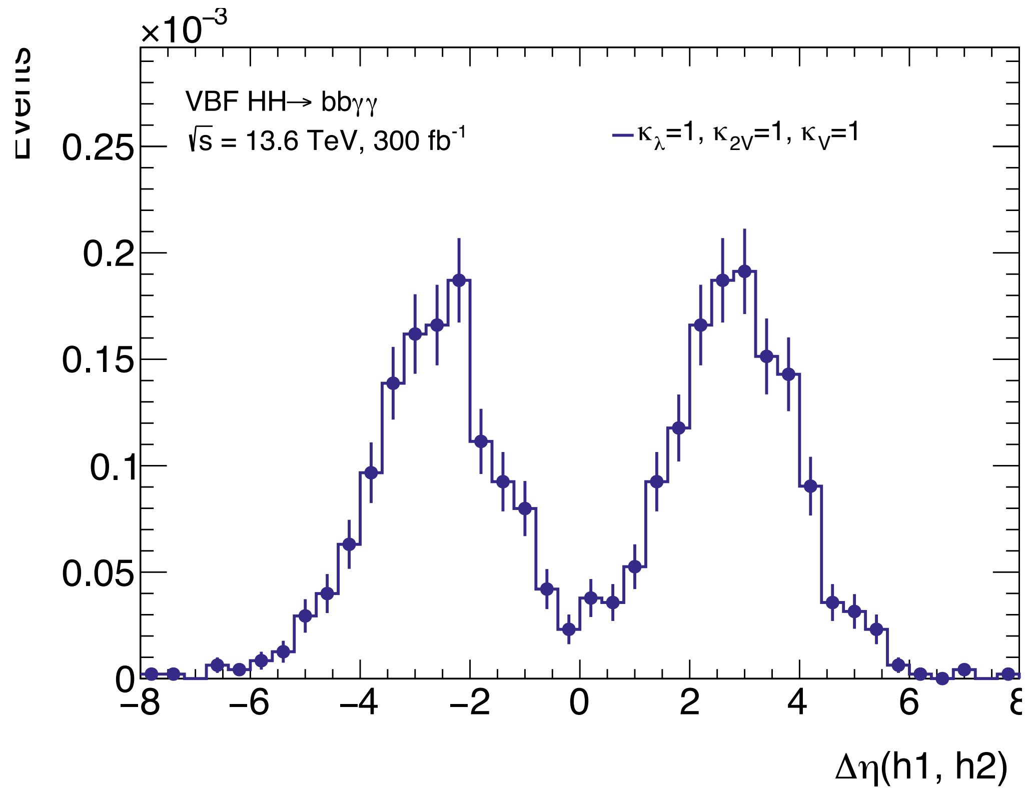
280 - 325 GeV



375-425 GeV



475 - 550 GeV

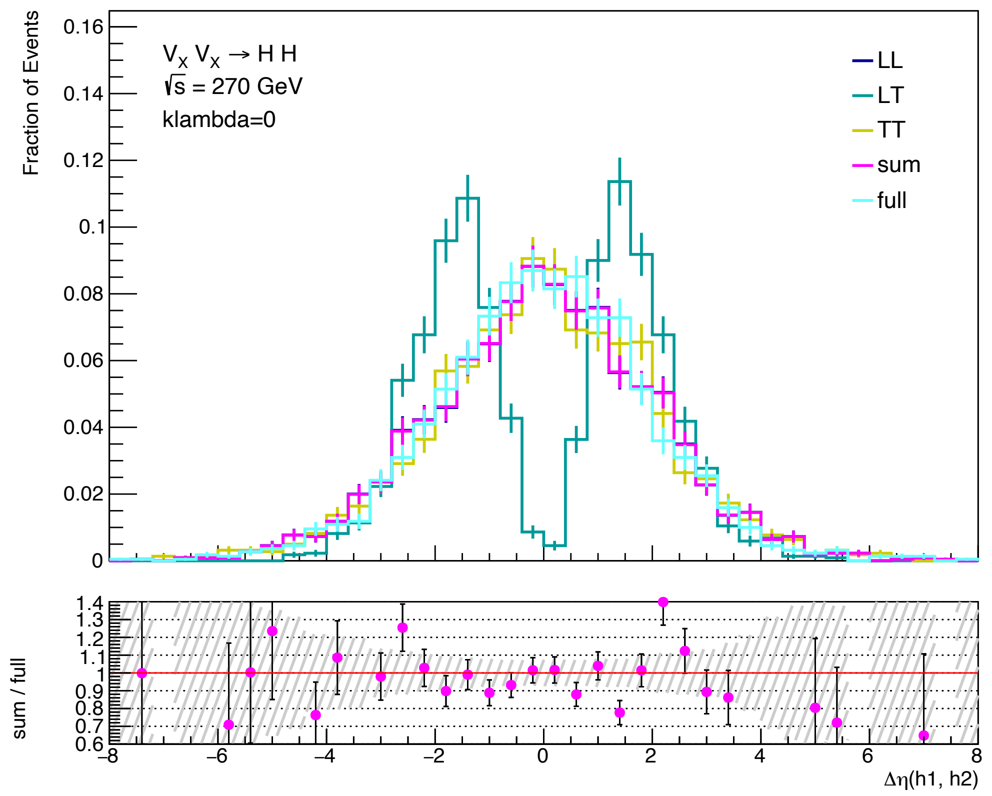


- Distribution of LL and sum almost identical due to dominating cross section of LL
- Comparison to Run 3 VBF $HH \rightarrow bb\gamma\gamma$ distribution in slices of m_{HH}
  - The shapes of the distributions follow a similar trend as the shapes of the distributions of the full sample

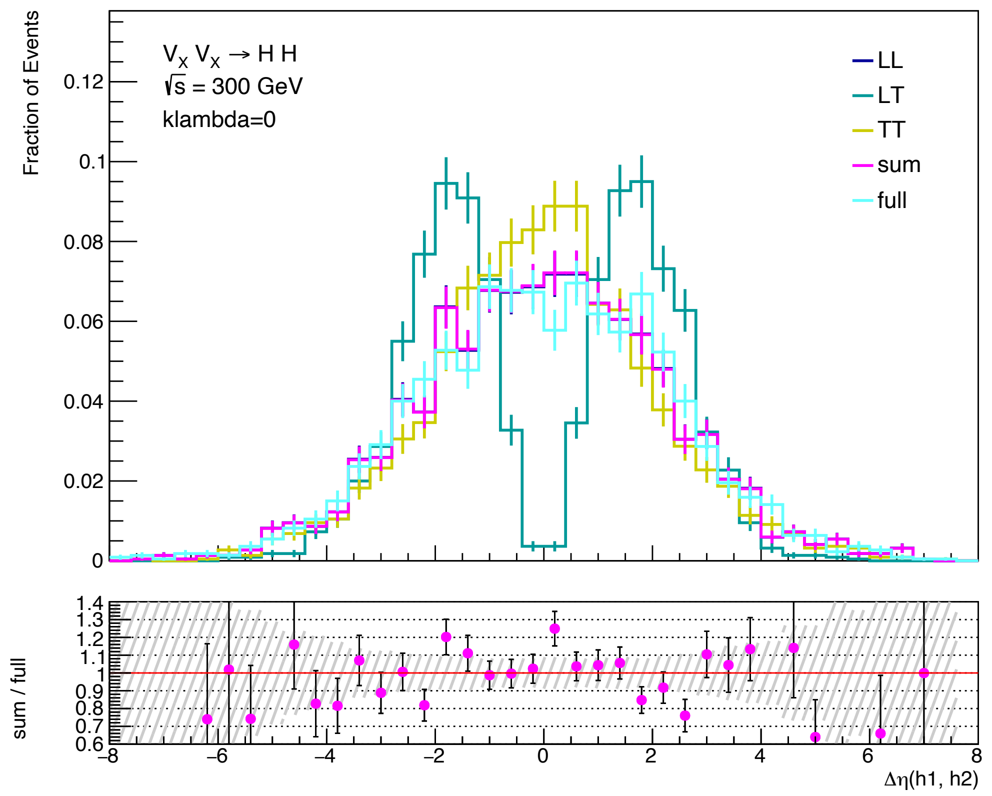
Distributions for $\kappa_\lambda = 0$

Center of mass energy

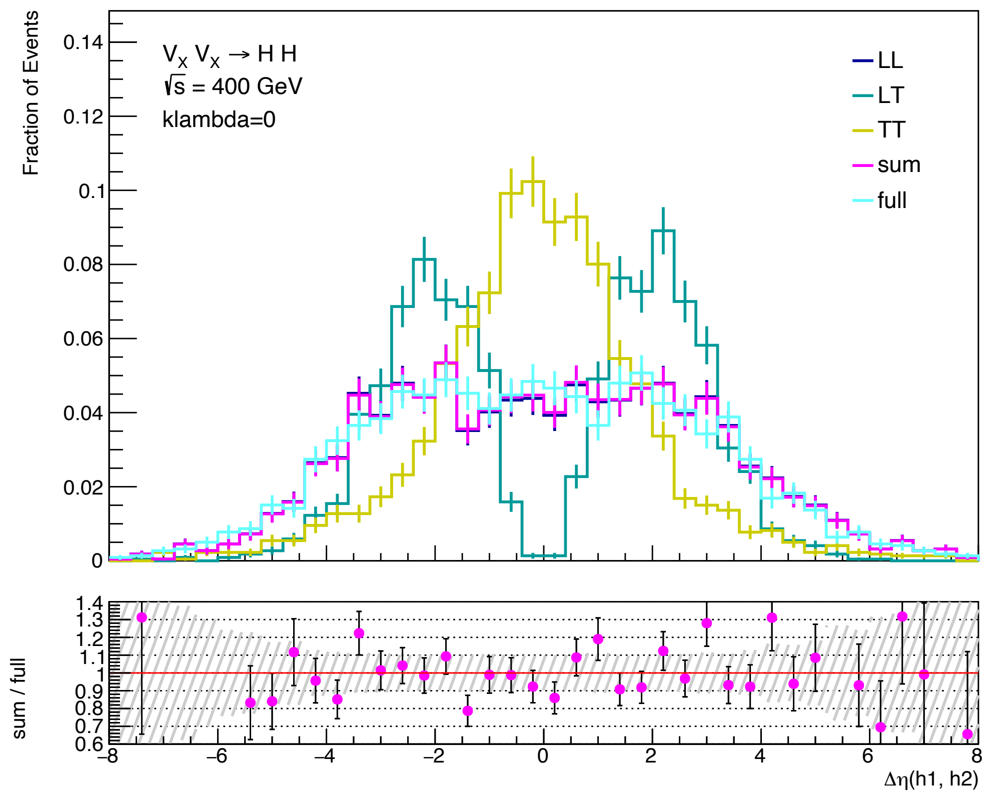
270 GeV



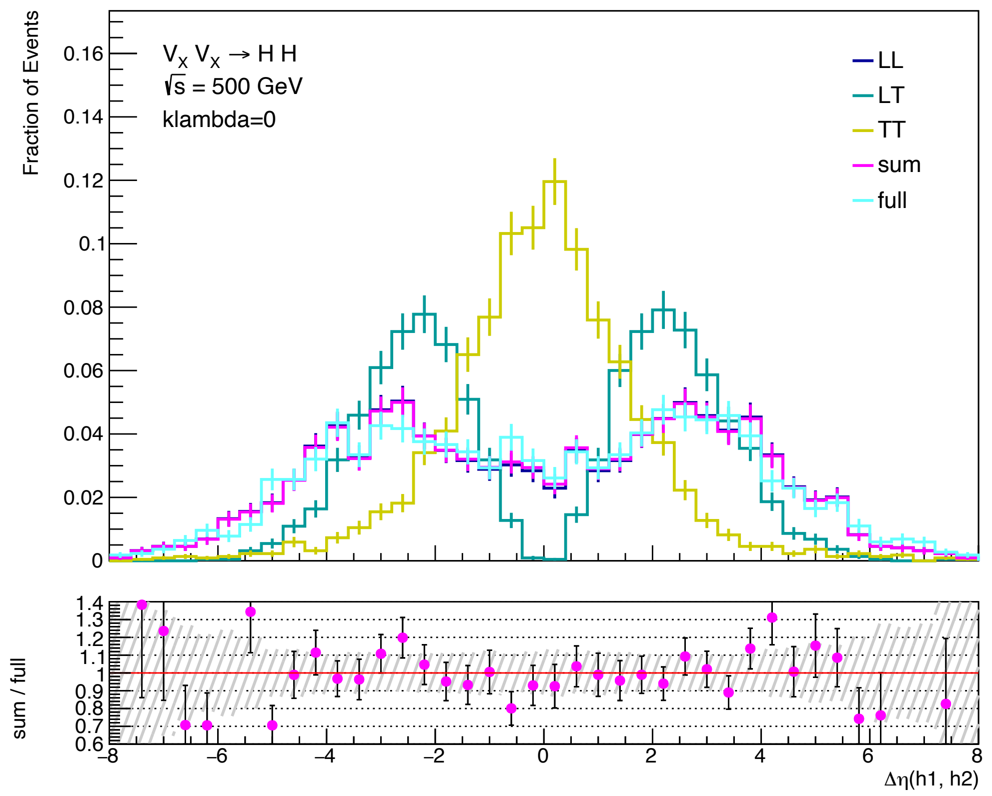
300 GeV



400 GeV

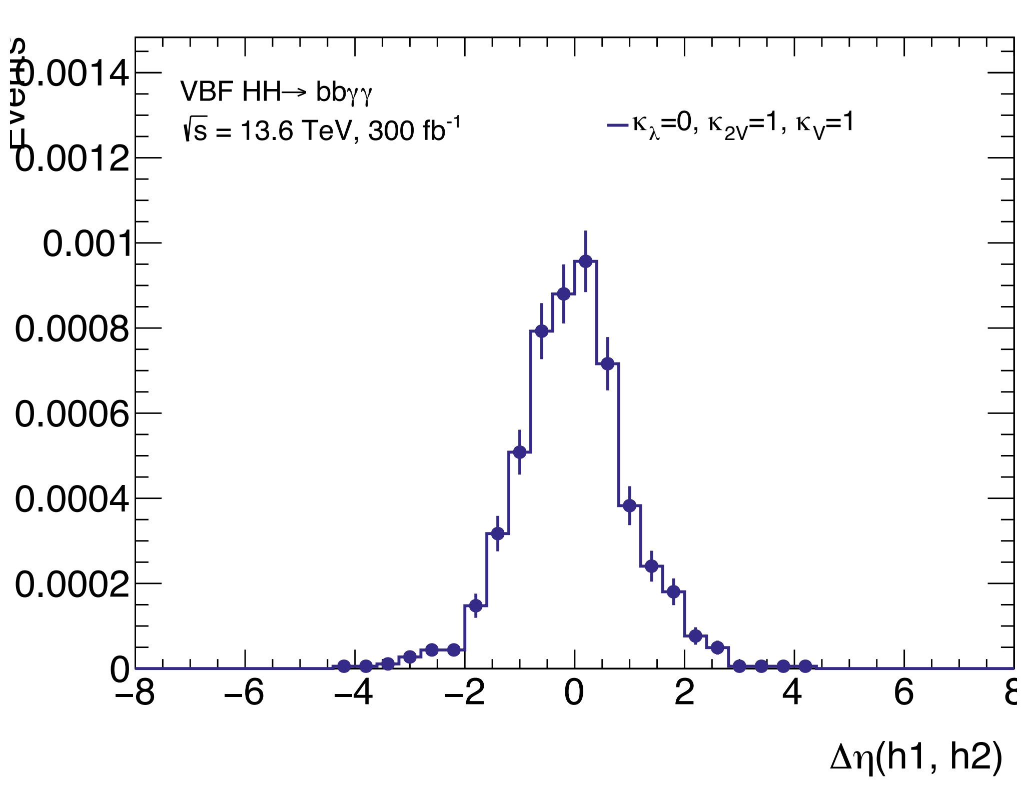


500 GeV

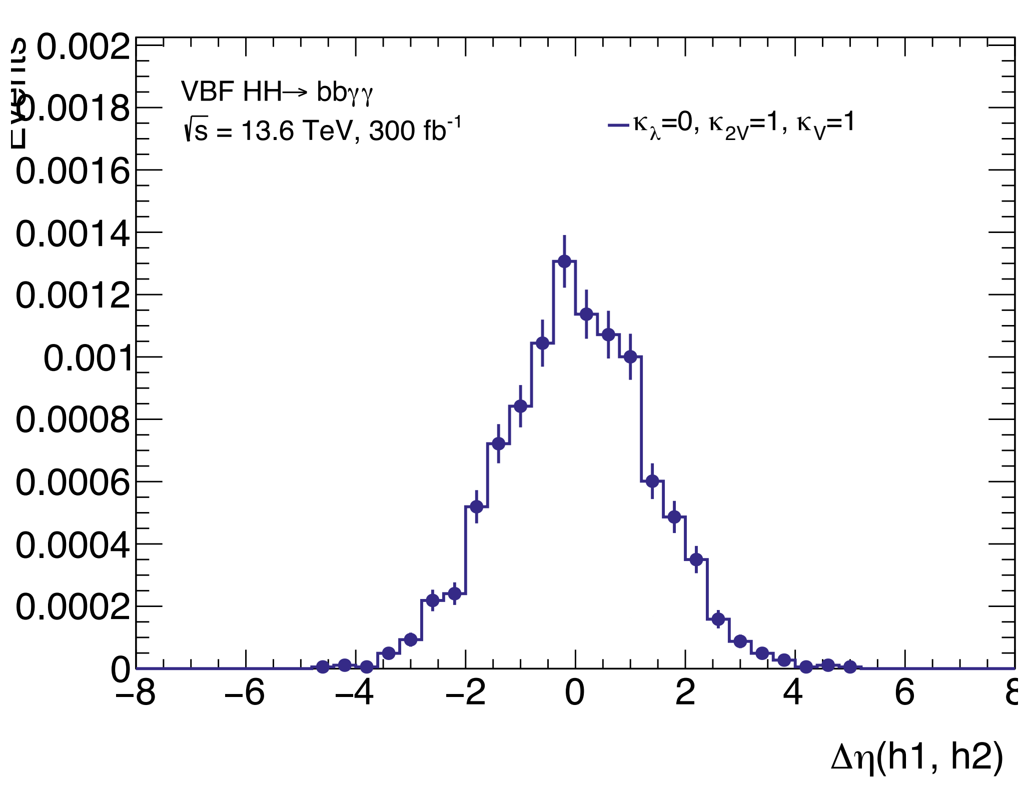


m_{HH}

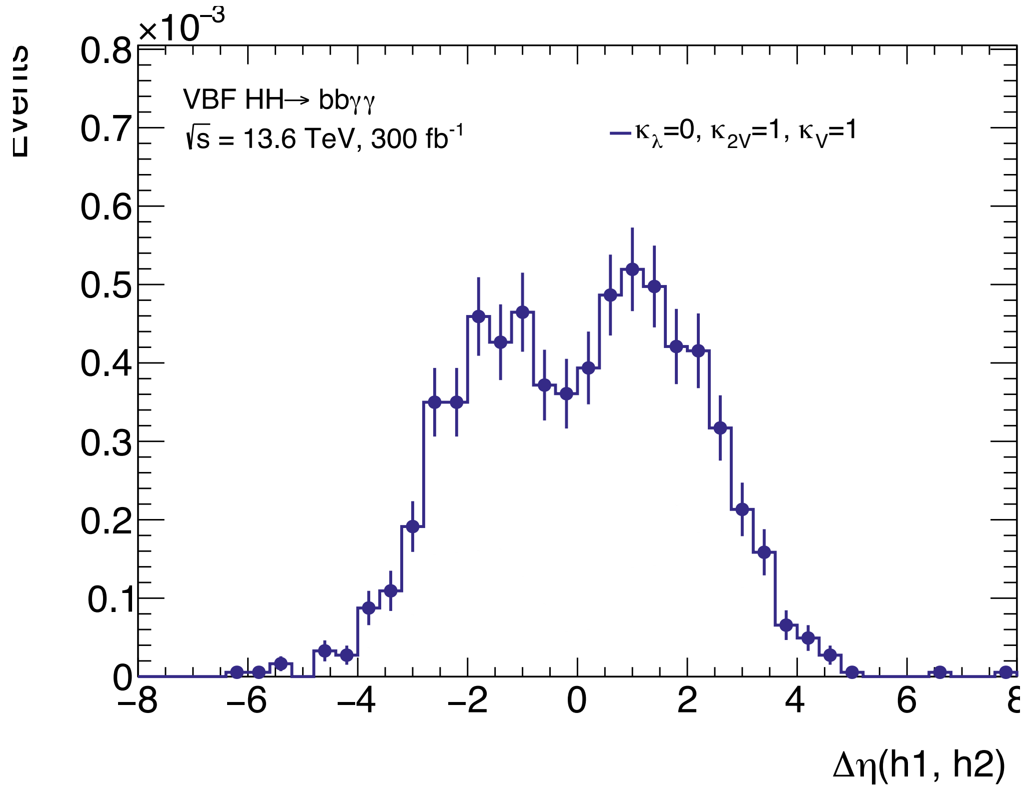
0 - 280 GeV



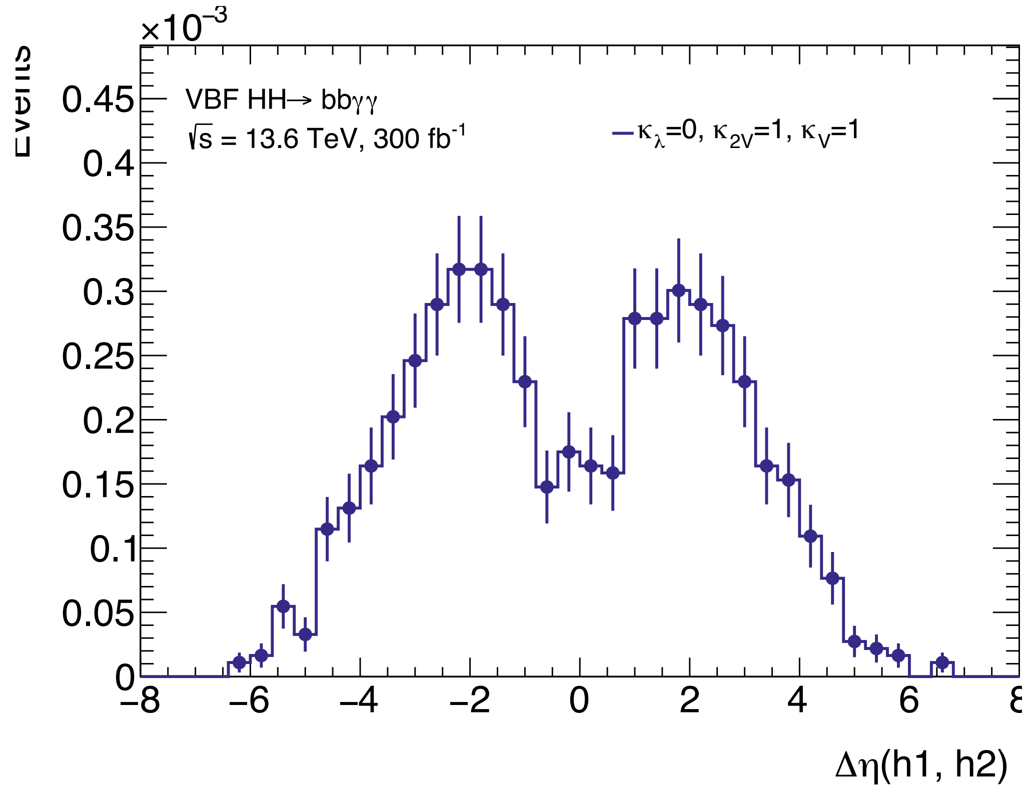
280 - 325 GeV



375-425 GeV



475 - 550 GeV

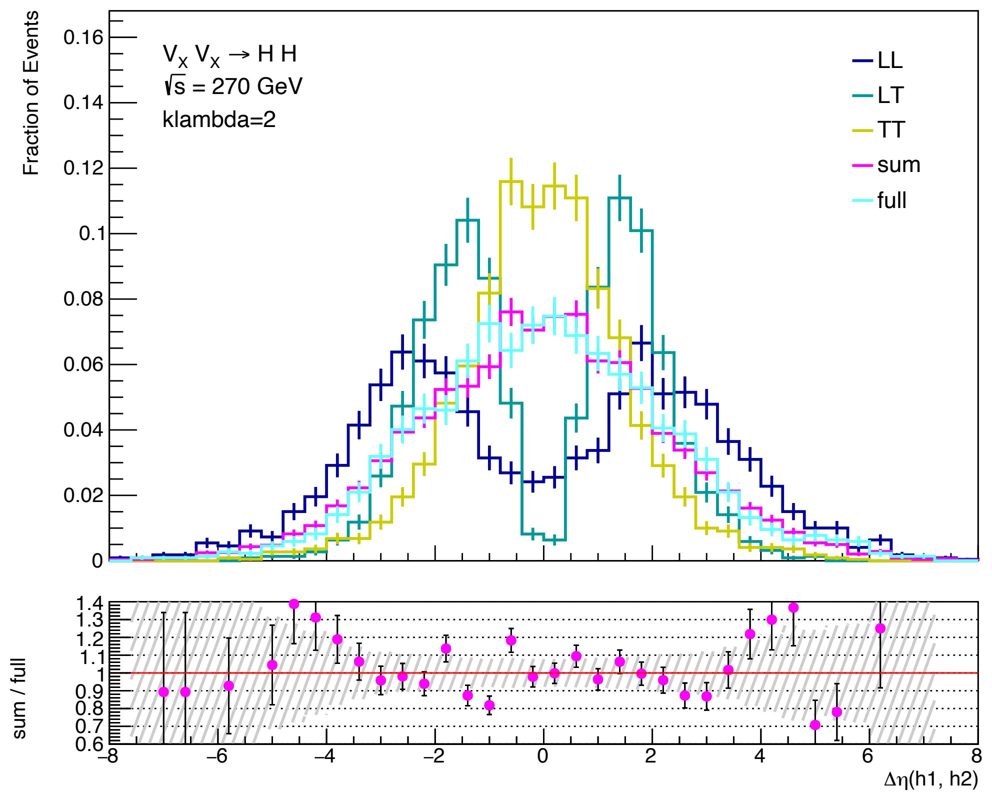


- Distributions of LL and TT very similar
- Comparison to Run 3 VBF $HH \to bb\gamma\gamma$ distribution in slices of m_{HH}
  - The shapes of the distributions follow a similar trend as the shapes of the distributions of the full sample

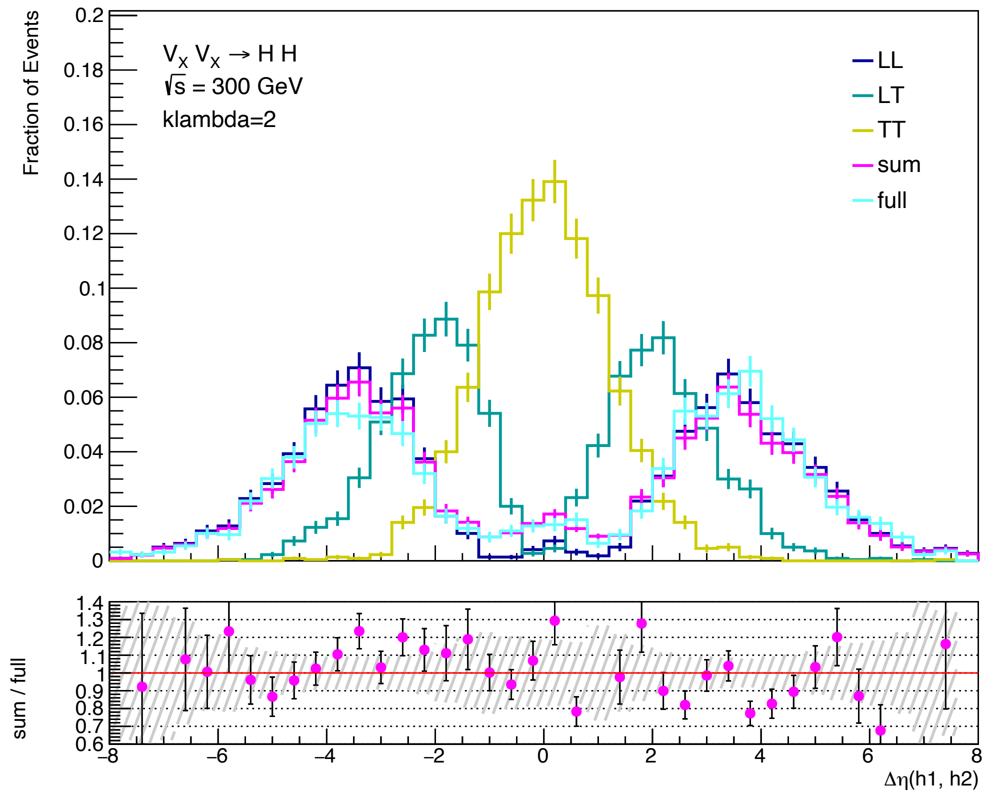
Distributions for $\kappa_\lambda = 2$

Center of mass energy

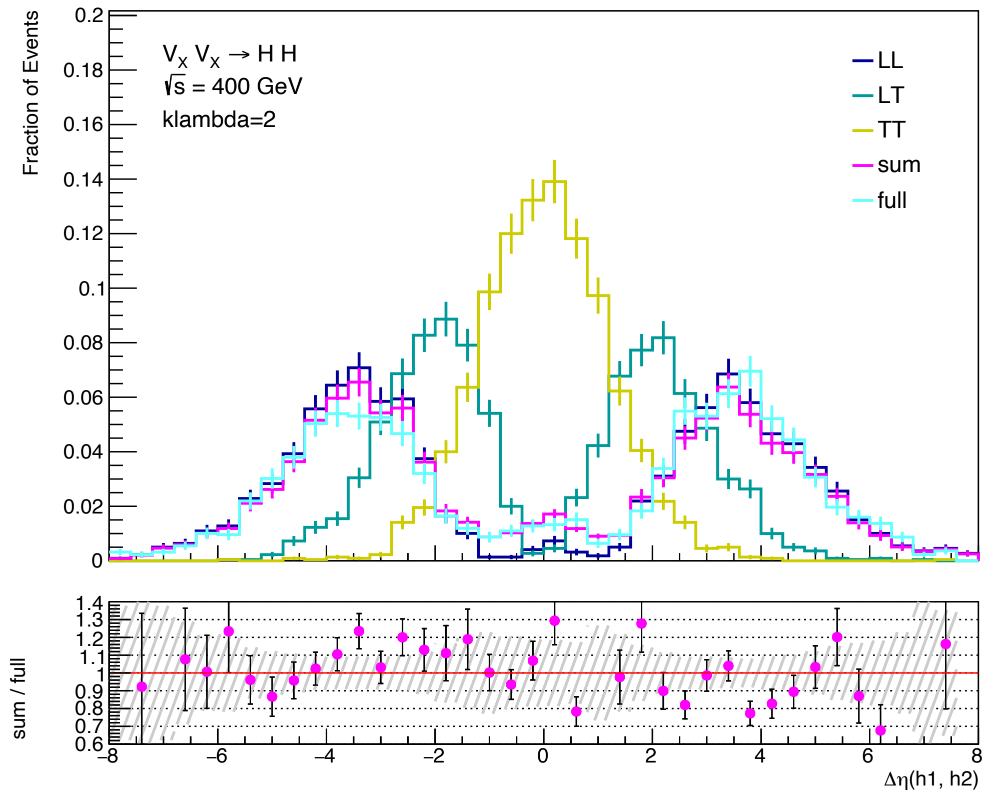
270 GeV



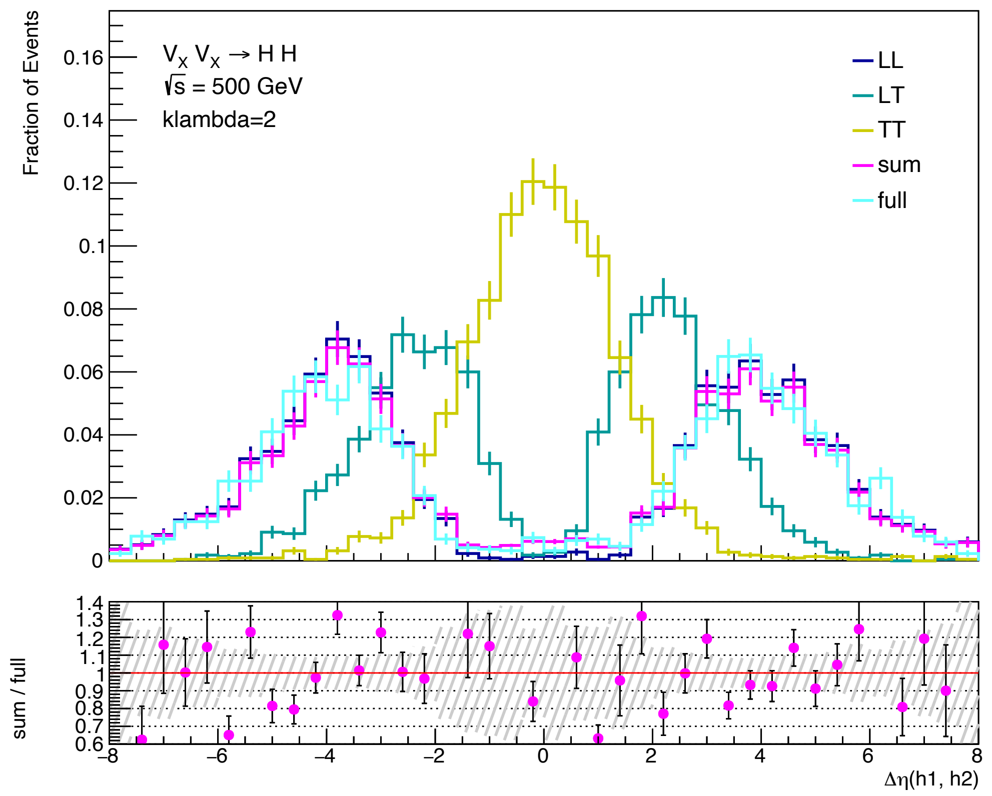
300 GeV



400 GeV

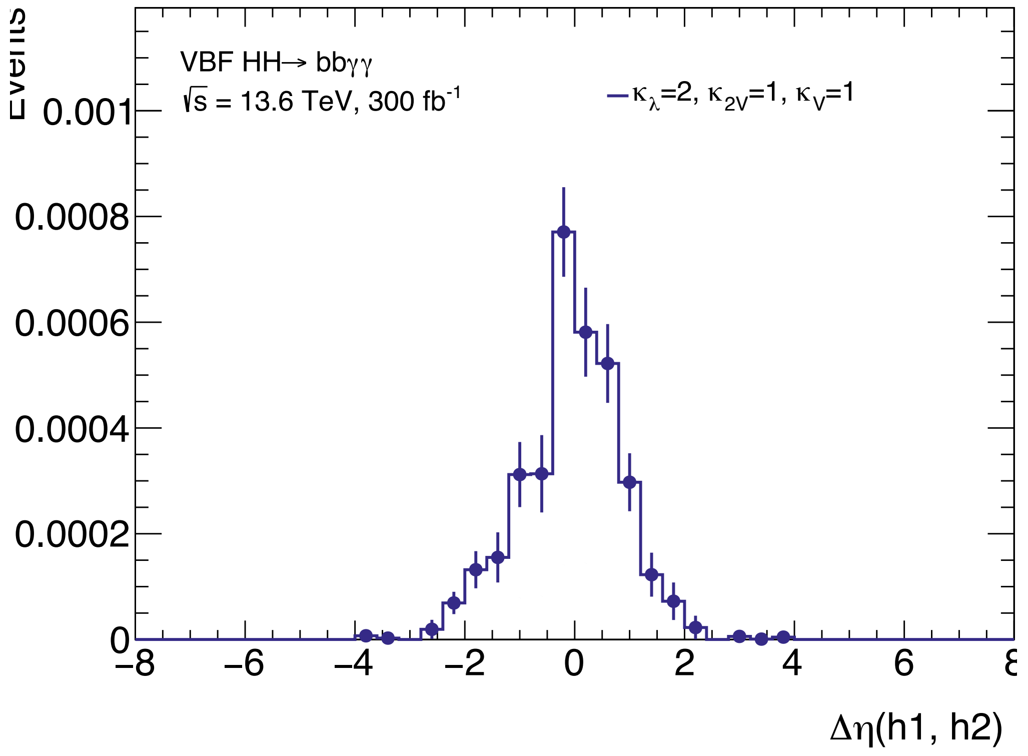


500 GeV

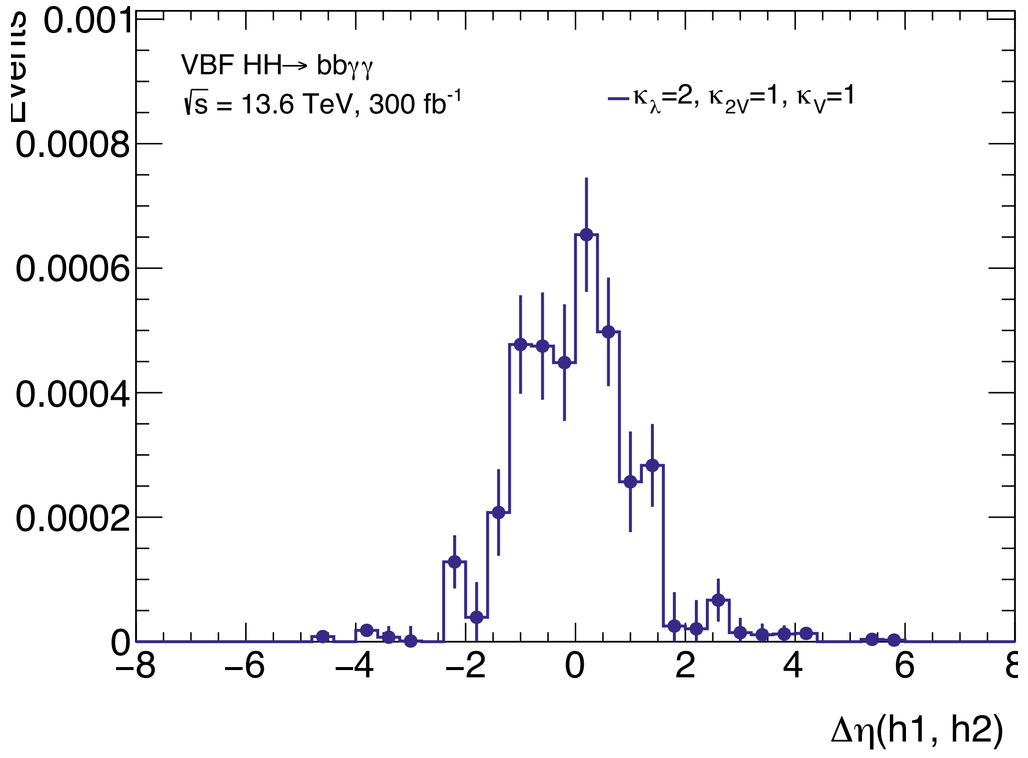


m_{HH}

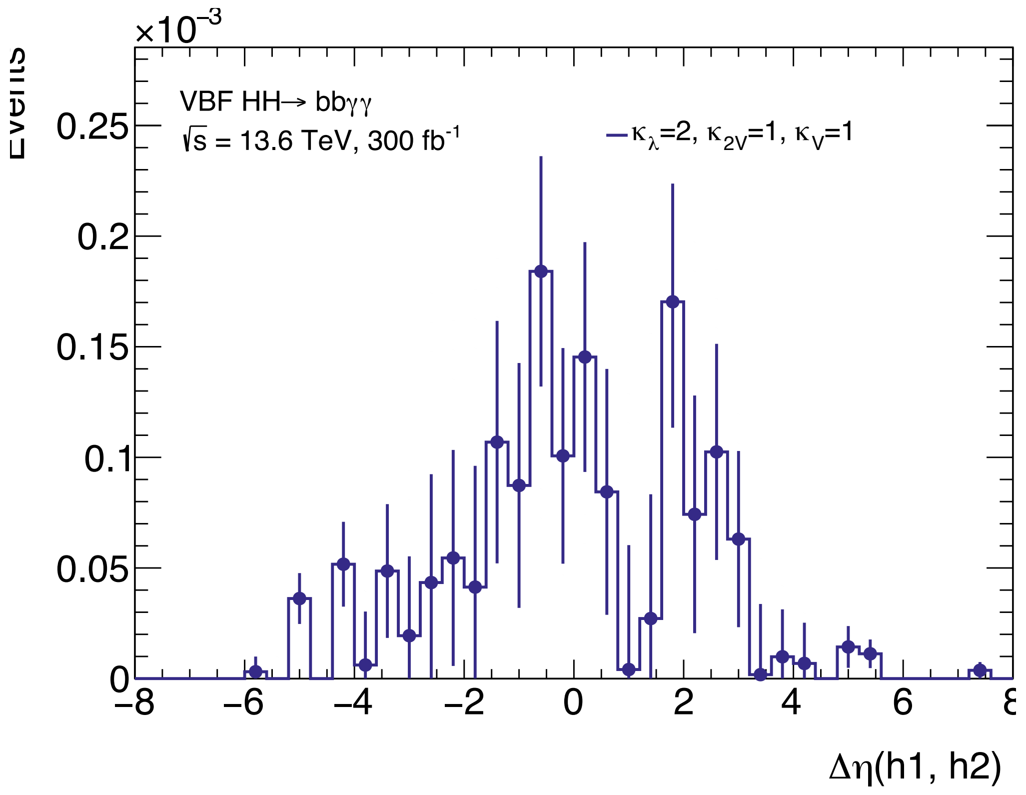
0 - 280 GeV



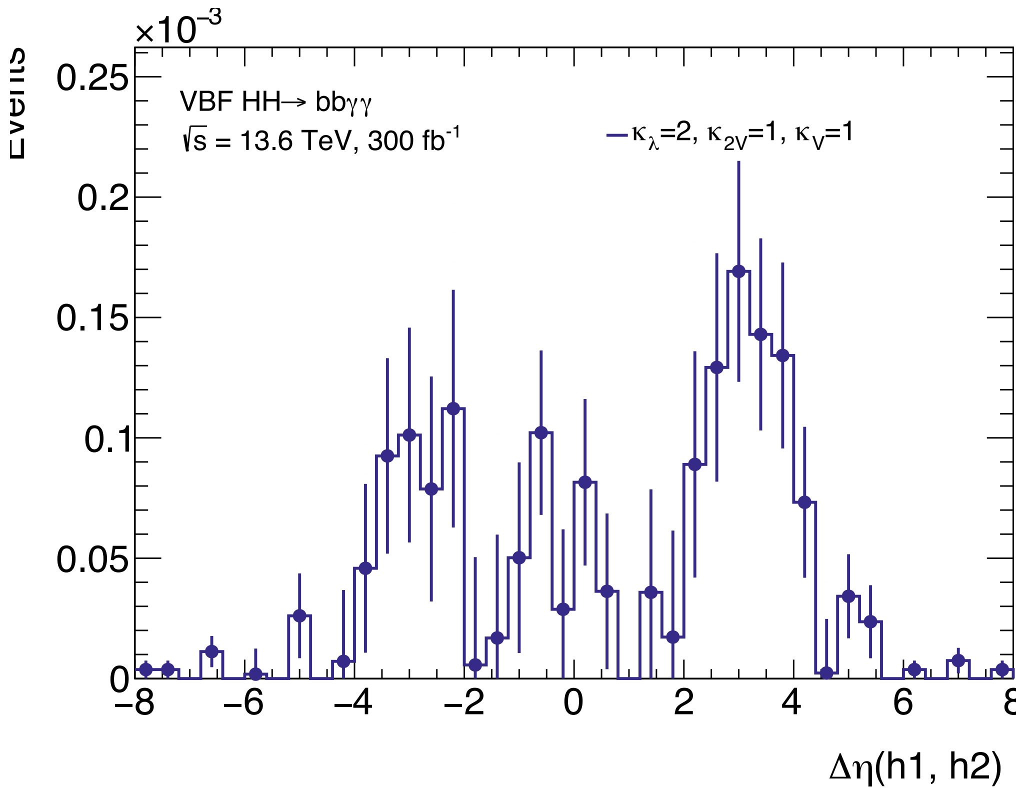
280 - 325 GeV



375-425 GeV



475 - 550 GeV

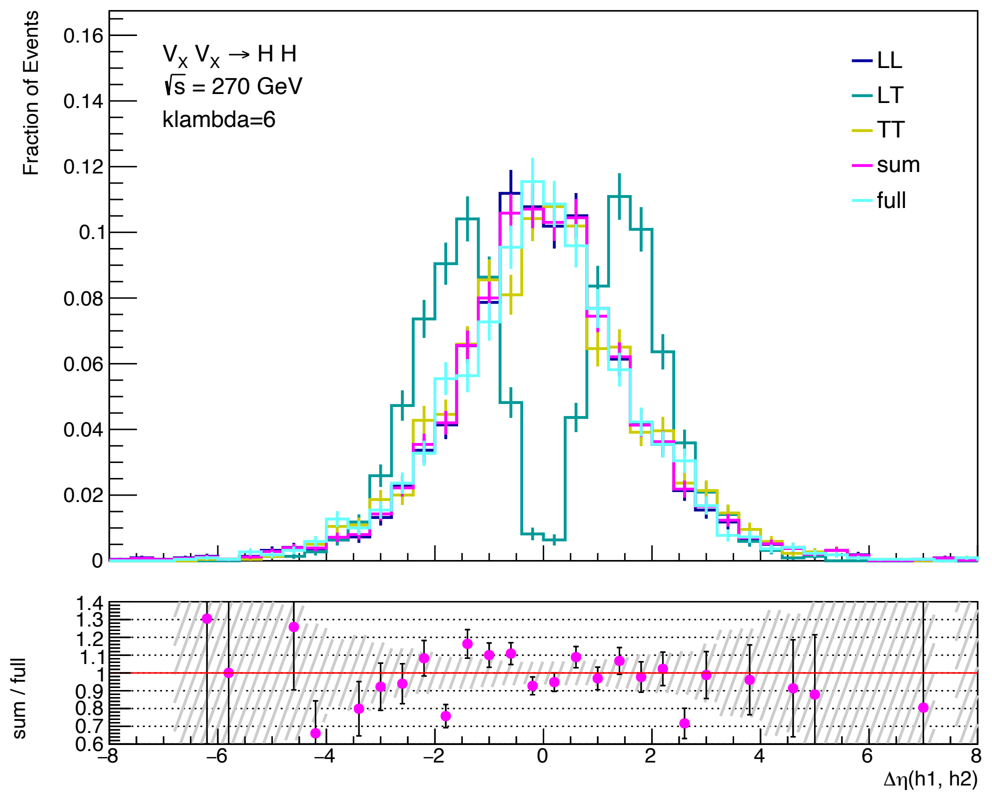


- Some shape differences visible between LL and TT
- Comparison to Run 3 VBF $HH \rightarrow bb\gamma\gamma$ distribution in slices of m_{HH}
  - Distributions of the Run 3 VBF $HH \rightarrow bb\gamma\gamma$ sample more central
  - Possible that the vector bosons that are scattered off from the protons are preferably transversal polarized

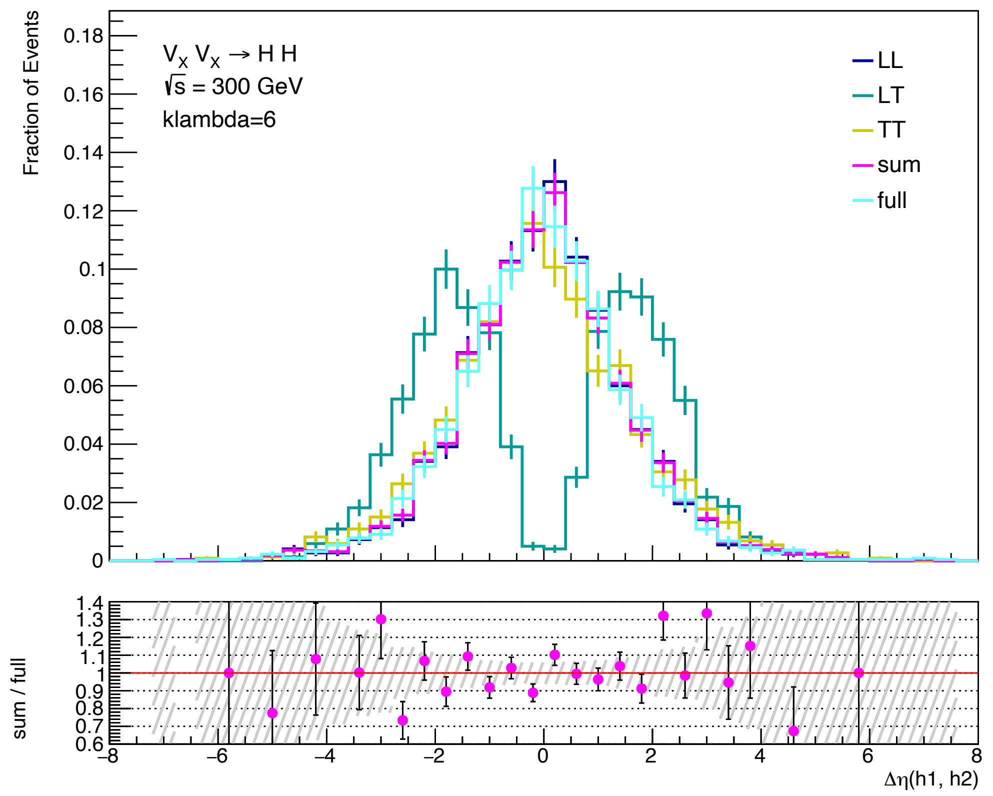
Distributions for $\kappa_\lambda = 6$

Center of mass energy

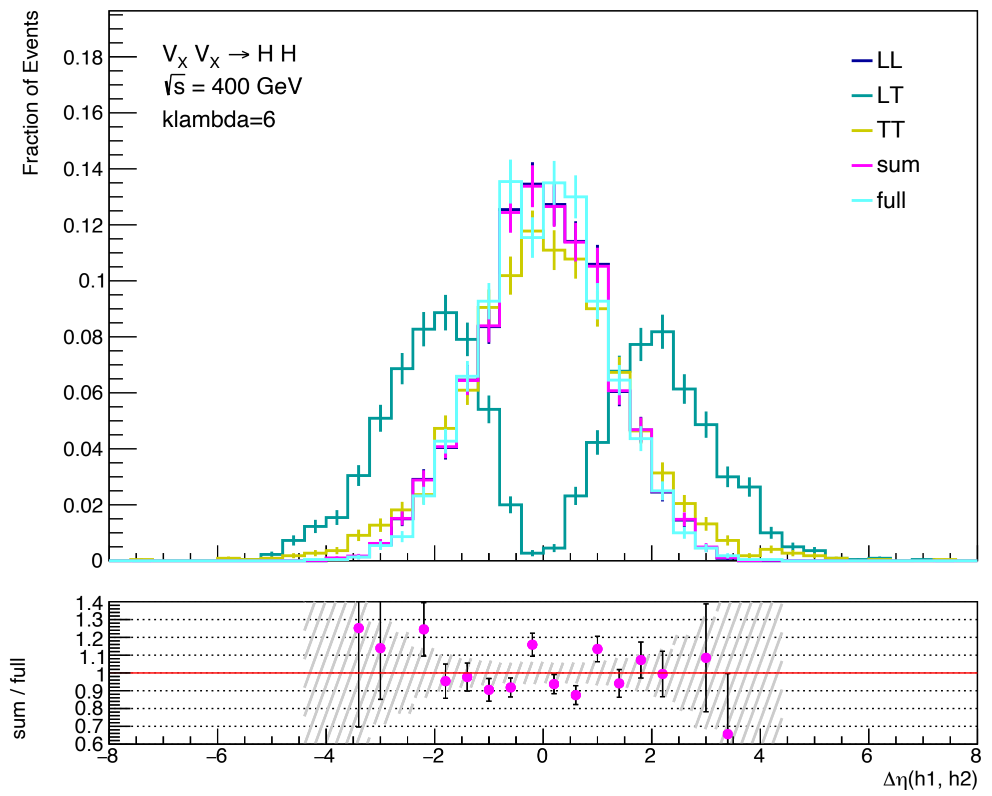
270 GeV



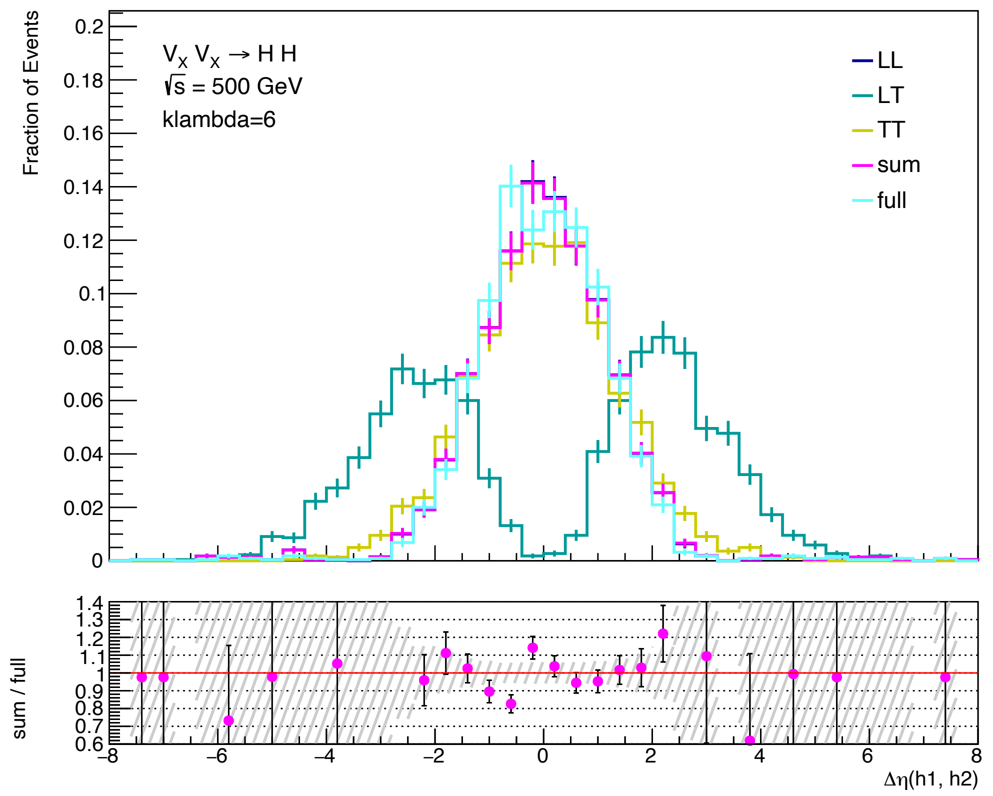
300 GeV



400 GeV

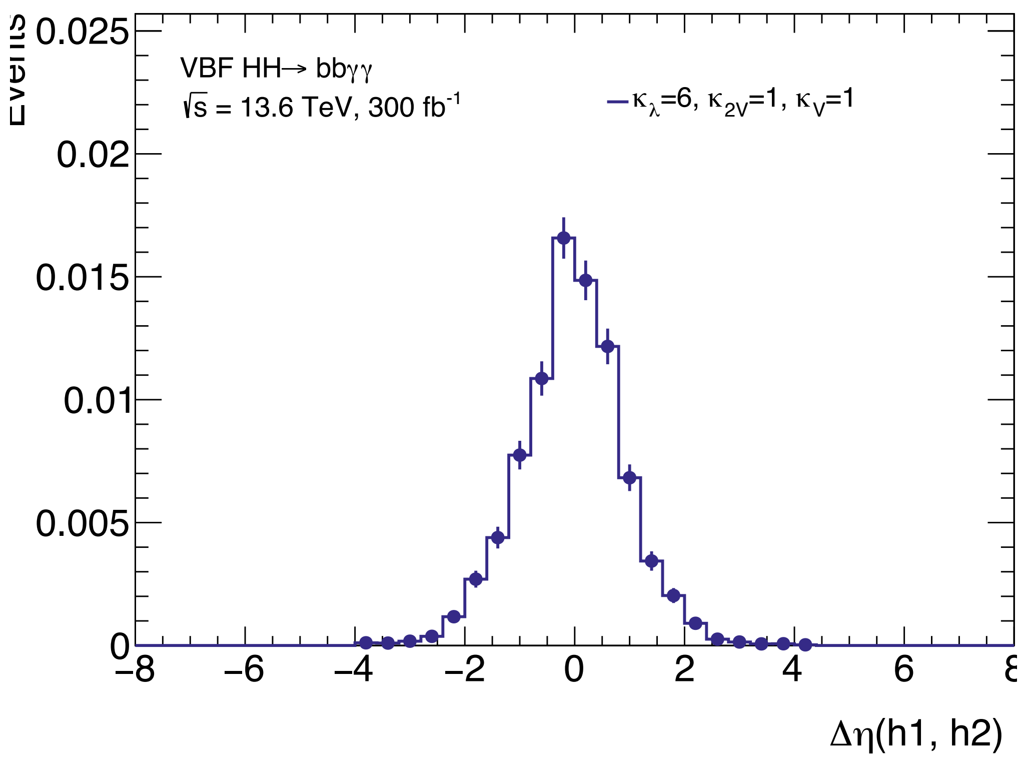


500 GeV

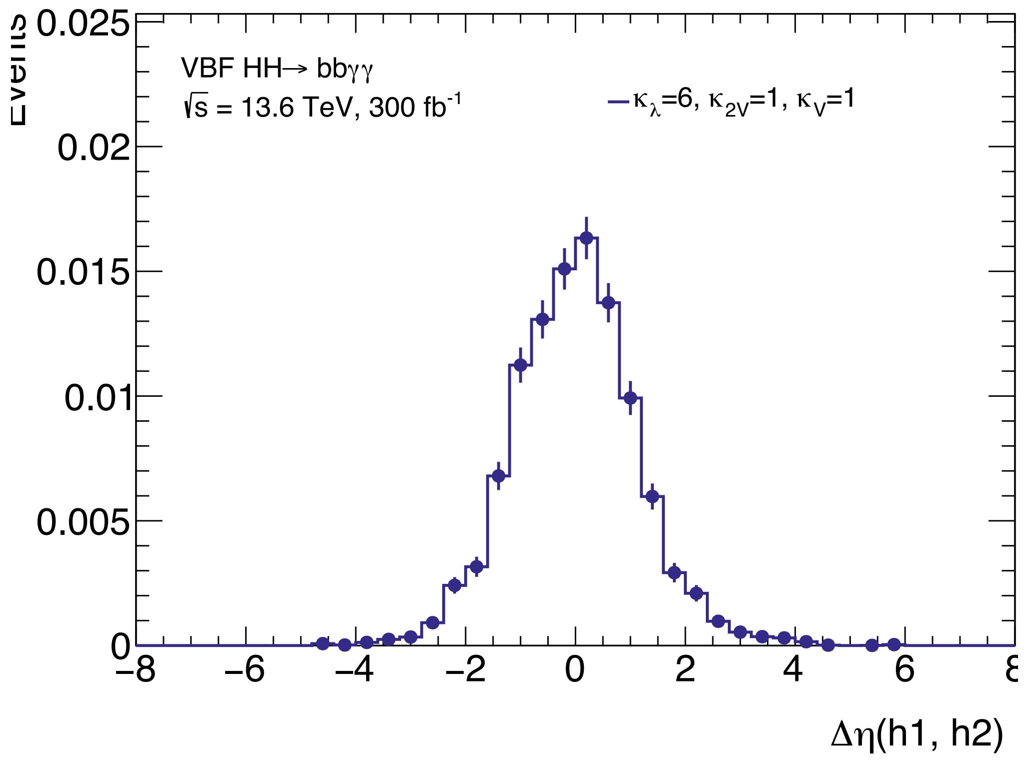


m_{HH}

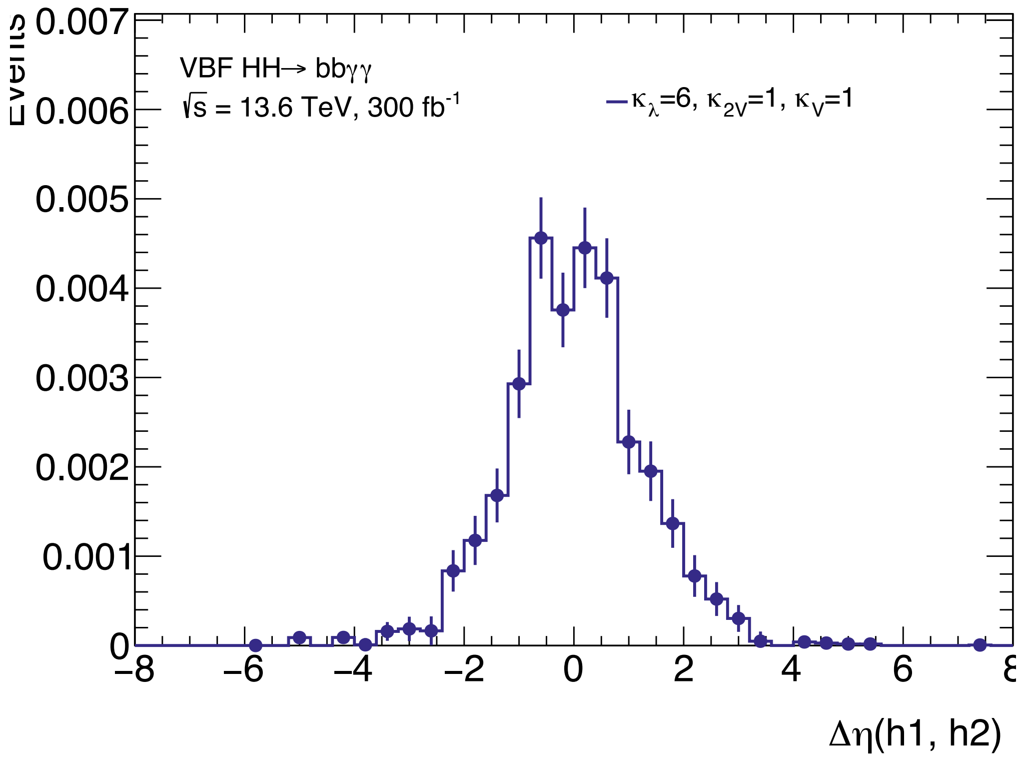
0 - 280 GeV



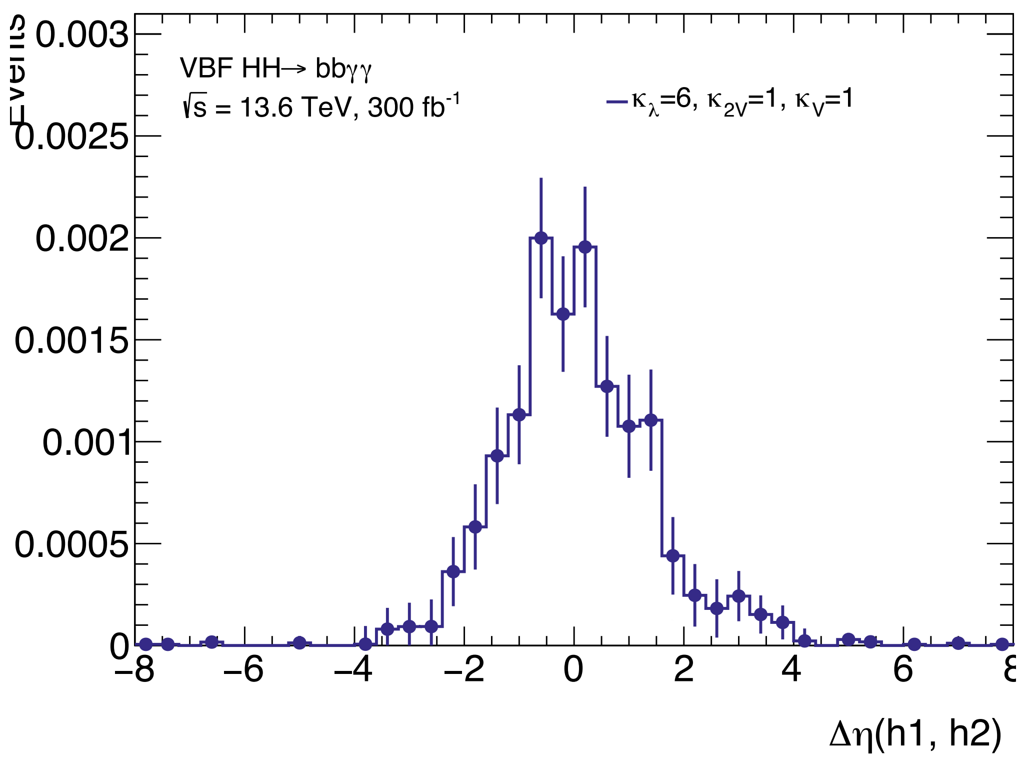
280 - 325 GeV



375-425 GeV



475 - 550 GeV

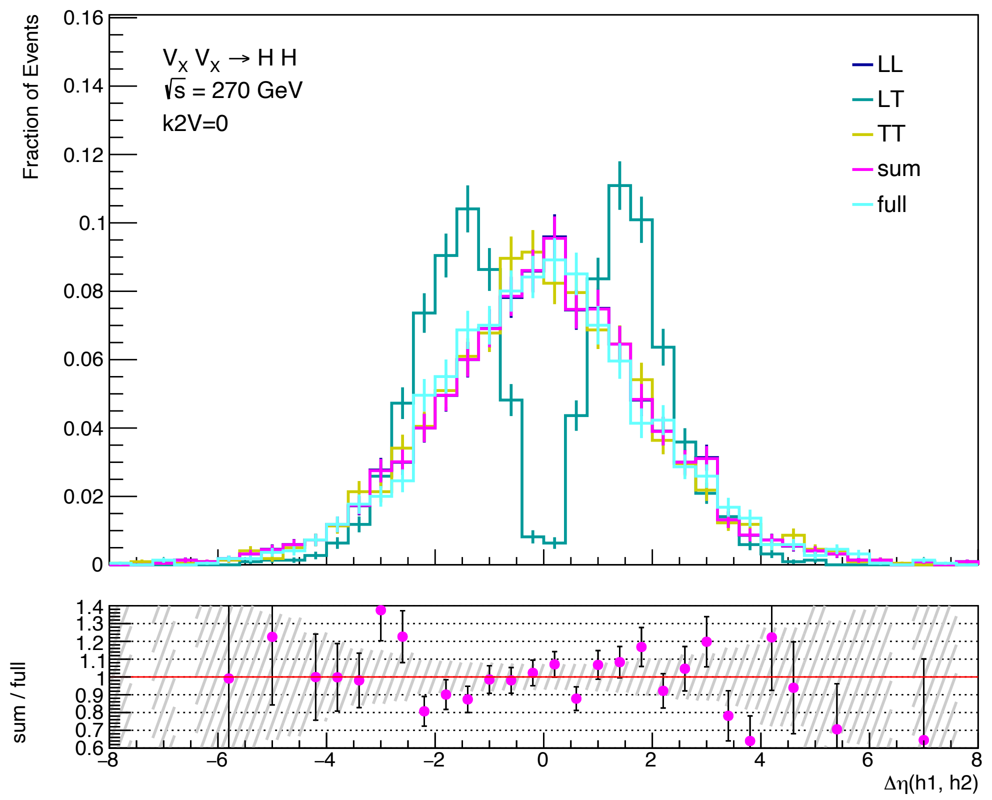


- Distributions of LL and TT very similar
- Comparison to Run 3 VBF $HH \rightarrow bb\gamma\gamma$ distribution in slices of m_{HH}
  - The shapes of the distributions follow a similar trend as the shapes of the distributions of the full sample

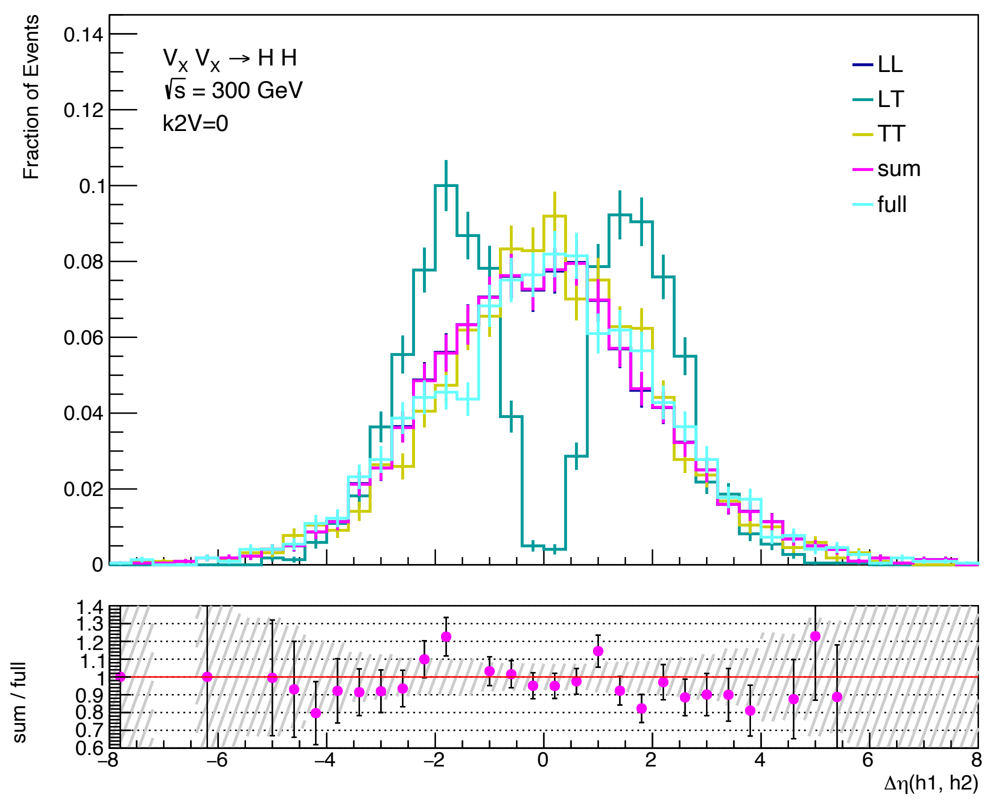
Distributions for $\kappa_{2V} = 0$

Center of mass energy

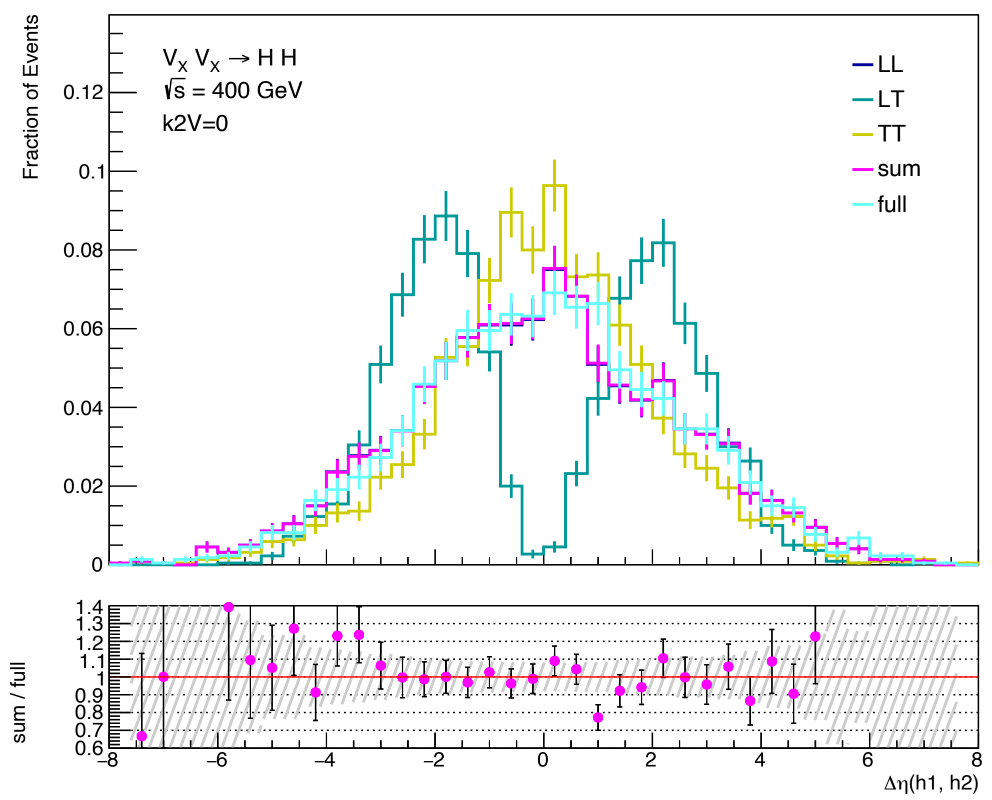
270 GeV



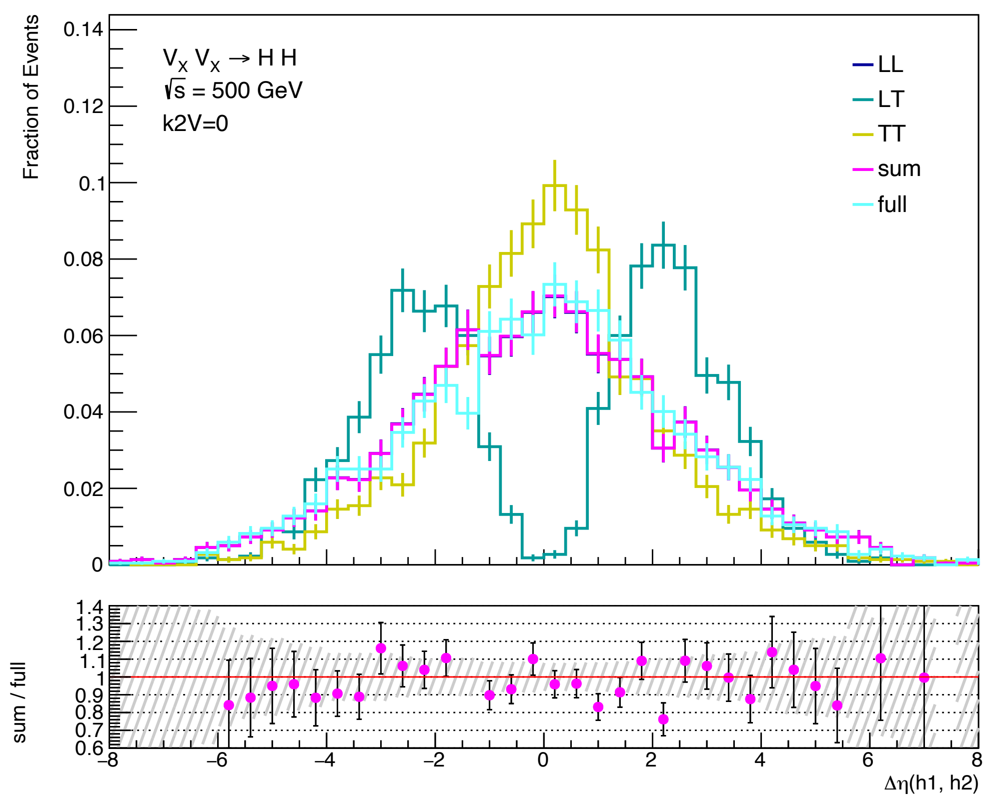
300 GeV



400 GeV

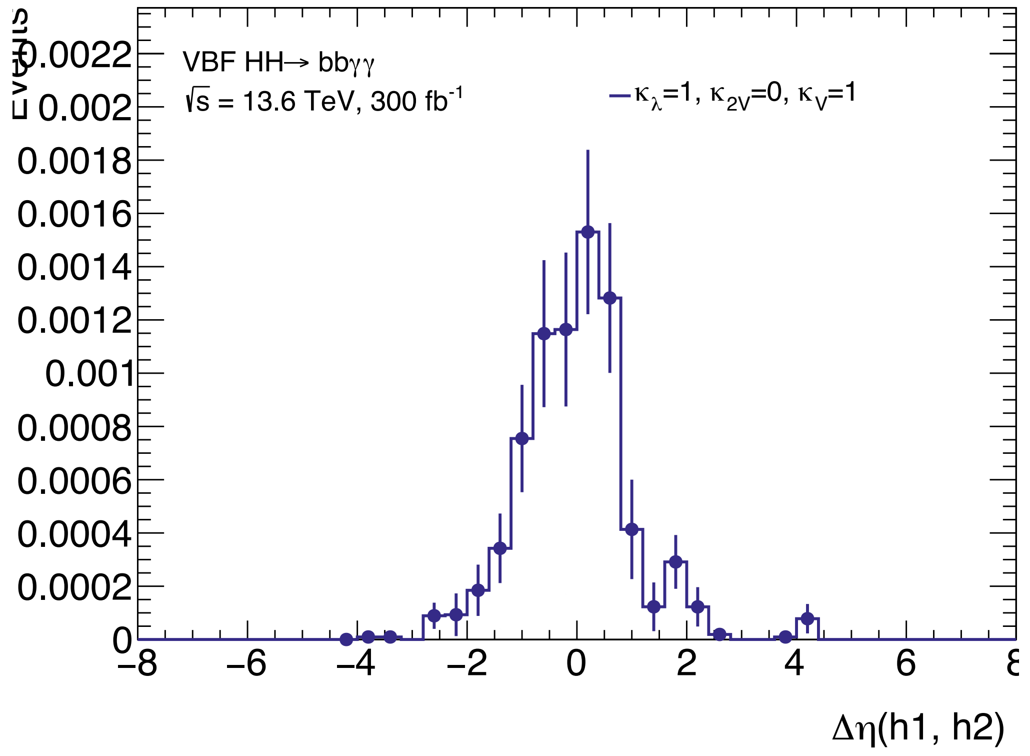


500 GeV

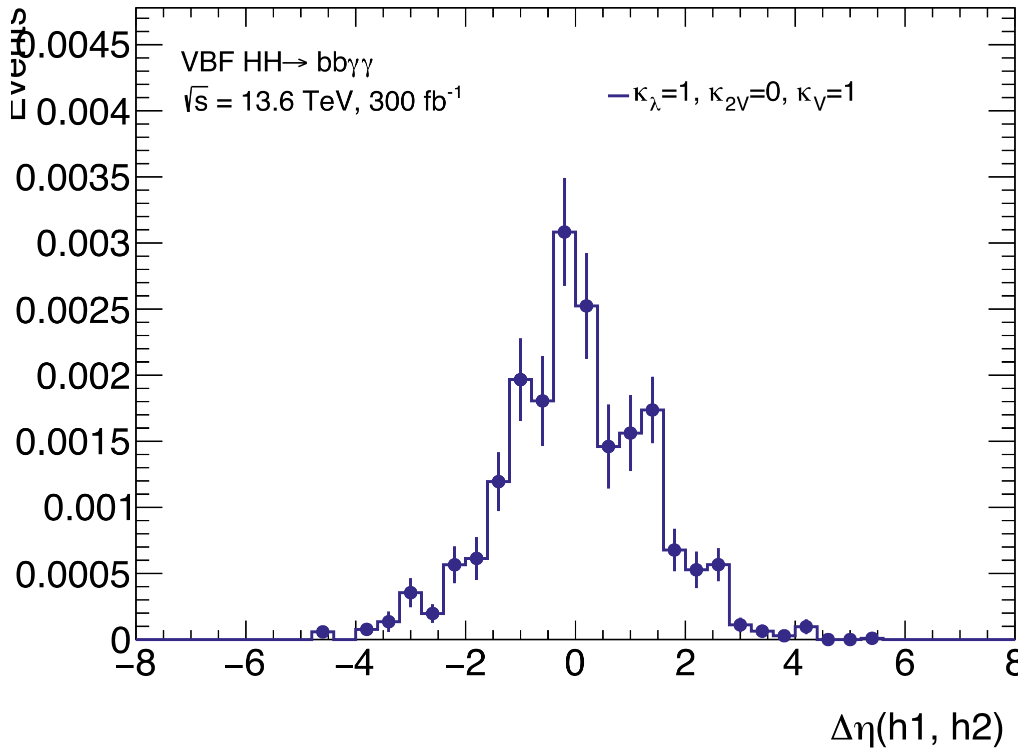


m_{HH}

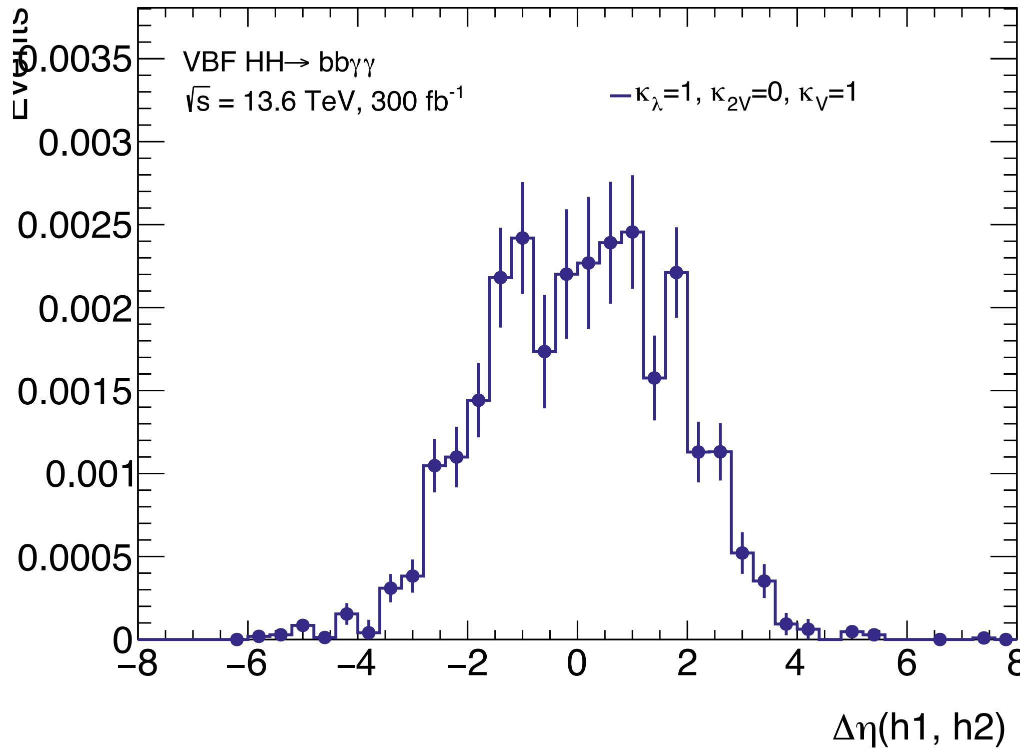
0 - 280 GeV



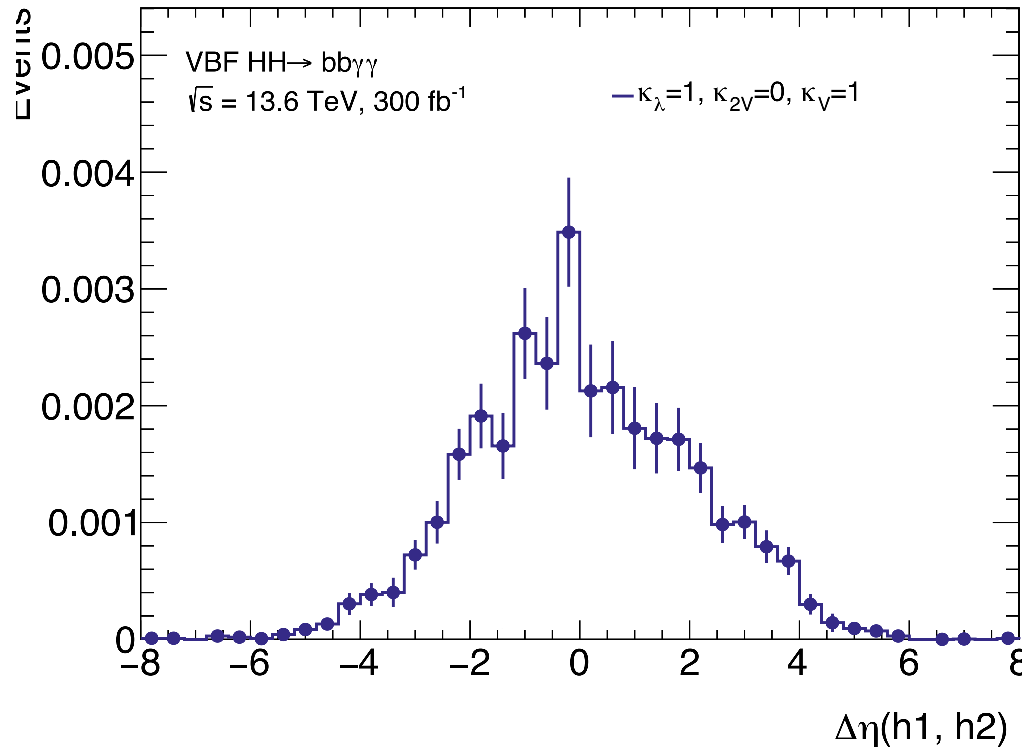
280 - 325 GeV



375-425 GeV



475 - 550 GeV

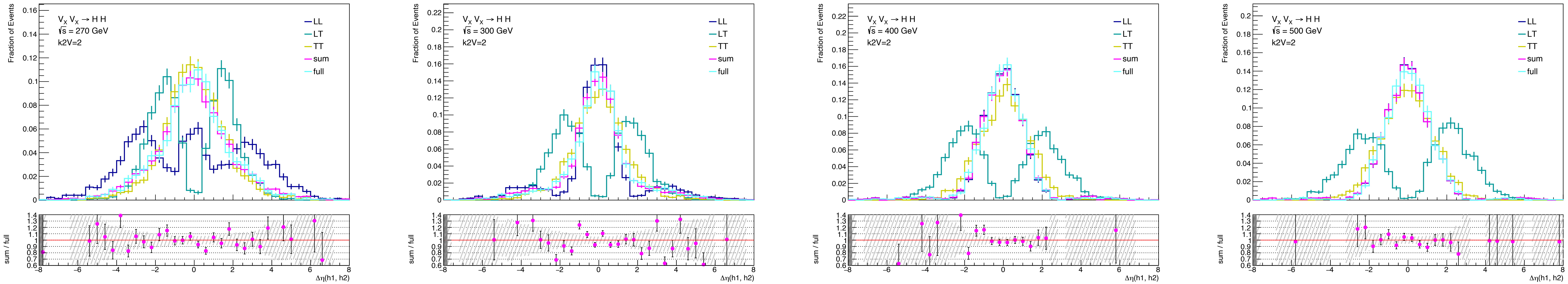


- Distributions of LL and TT very similar
- Comparison to Run 3 VBF $HH \rightarrow bb\gamma\gamma$ distribution in slices of m_{HH}
  - The shapes of the distributions follow a similar trend as the shapes of the distributions of the full sample

Distributions for $\kappa_{2V} = 2$

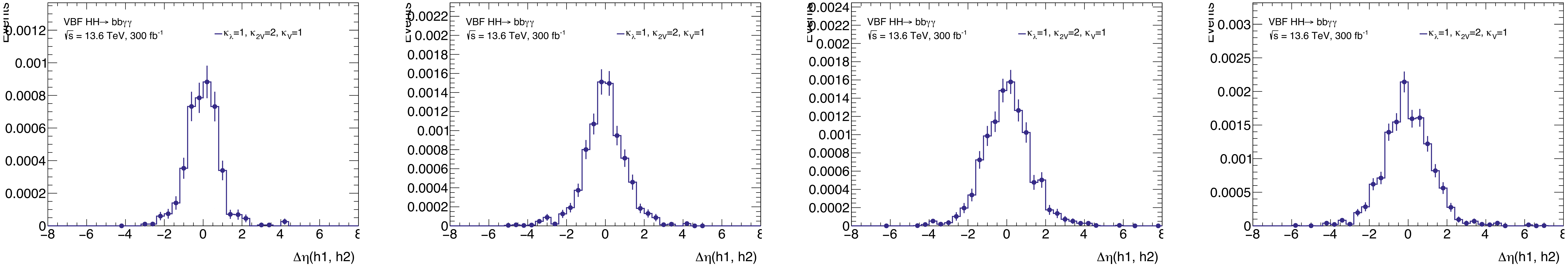
Center of mass energy

270 GeV | 300 GeV | 400 GeV | 500 GeV



m_{HH}

0 - 280 GeV | 280 - 325 GeV | 375-425 GeV | 475 - 550 GeV



- Distributions of LL and TT very similar
- Comparison to Run 3 VBF $HH \to bb\gamma\gamma$ distribution in slices of m_{HH}
  - The shapes of the distributions follow a similar trend as the shapes of the distributions of the full sample

The Eboli Model for VBF di-Higgs

Preliminary results

- Done first tests using the Eboli model with the VBF di-Higgs process to looked at the cross sections

- Large cross section due to EFT effects in comparison to the SM cross section indicates sensitivity to the operator
  - Only looked at one operator at the time
  - All Wilson coefficients set to 1 GeV^{-4} in order to compare the increase in the cross sections

operator				M					S		T	SM
quadratic term	M0	M1	M2	M3	M4	M5	M7	S0	S1	S2	T0-T9	
σ [pb]	3.1E+05	2.0E+04	1.6E+05	1.1E+04	1.8E+04	5.4E+03	5.0E+03	254	2.2E+03	862	no amplitude	0.001348

Sensitive to the M operators (M0–M7)

Sensitive to the S operators (S0–S2)

Not sensitive to the T operators (T0-T9)