Quantum entanglement in $H\to ZZ$ leptonic decay channels

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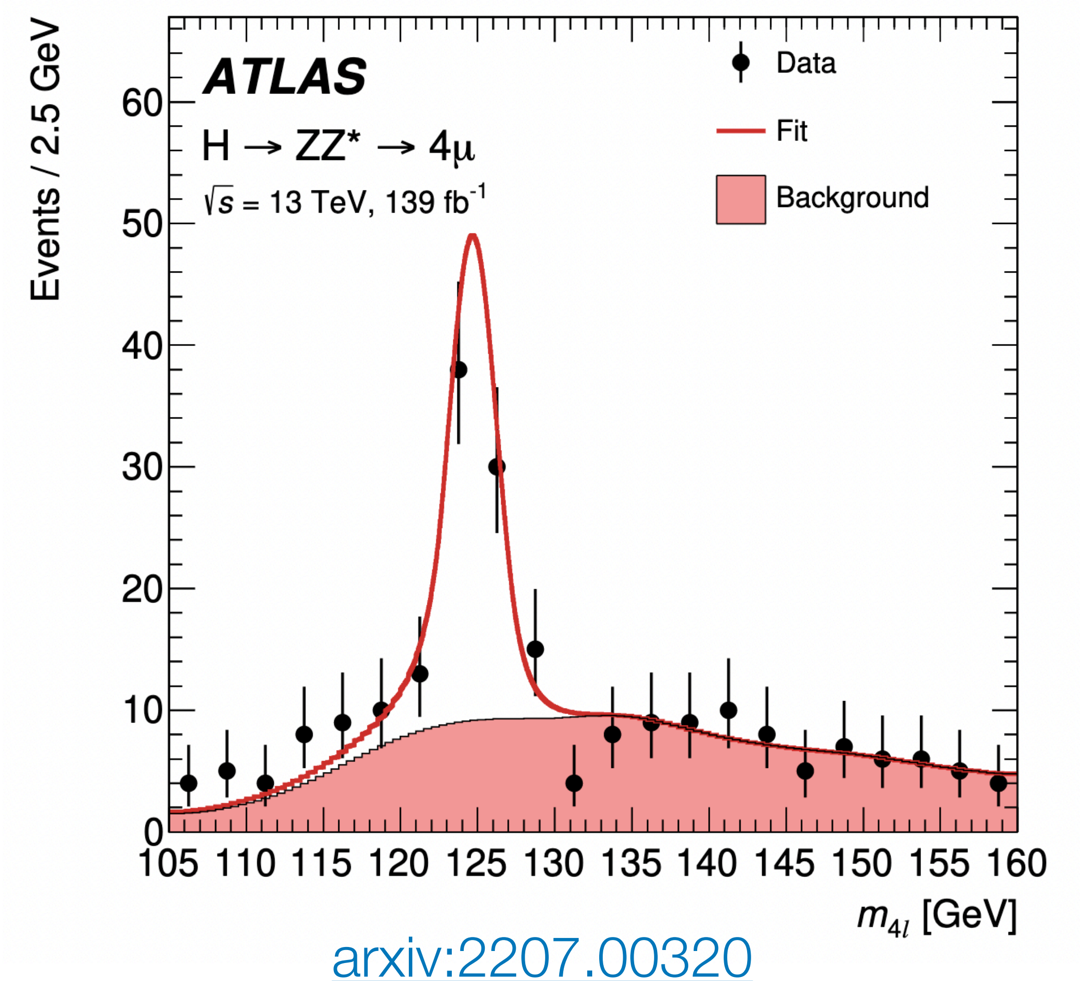
Workshop on the foundational tests of Quantum Mechanics at the LHC

Oxford

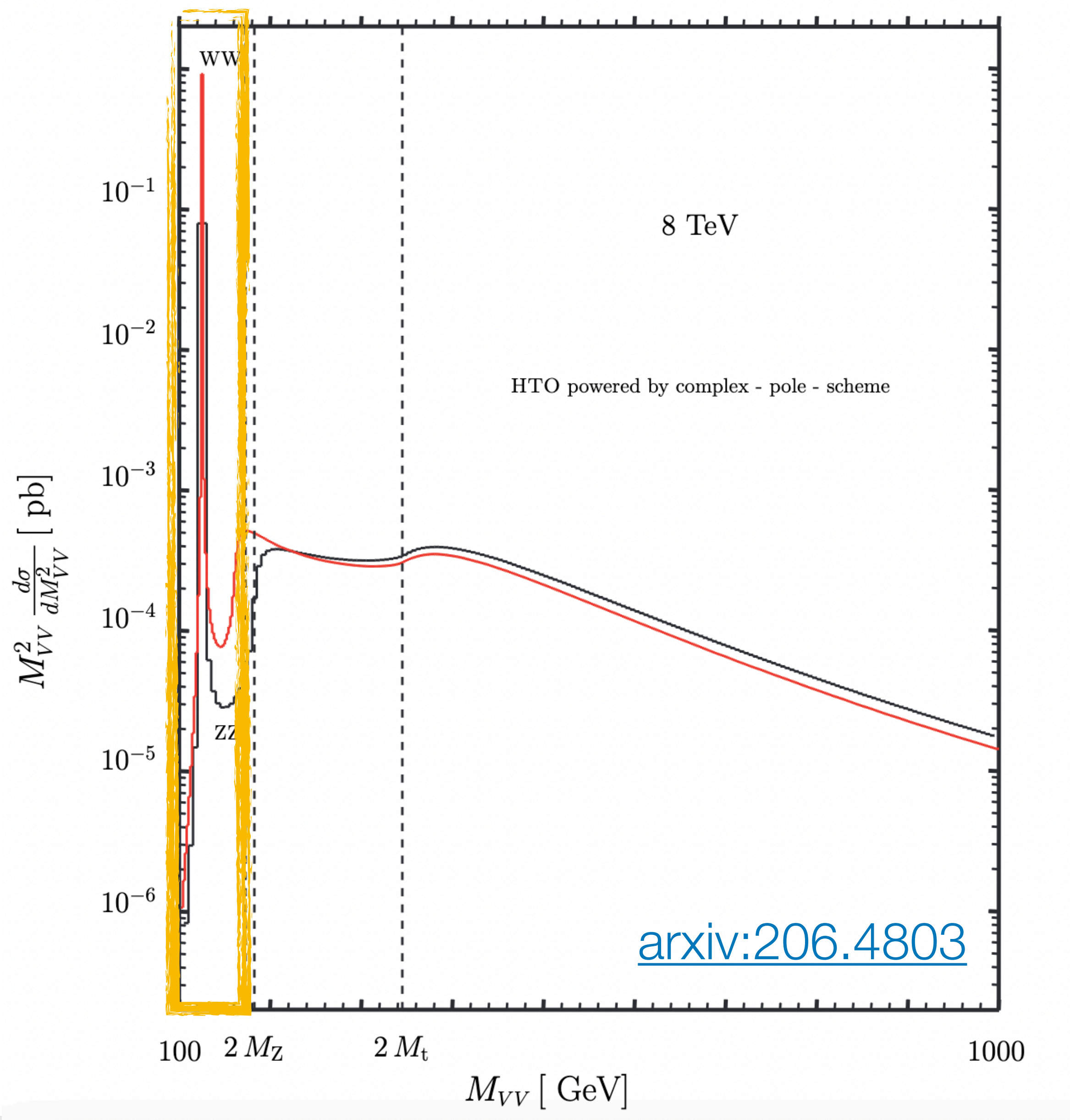
22/03/2023

Overview of H→ZZ measurements at ATLAS

- On-shell $H \rightarrow ZZ^{*} \rightarrow 4\ell$
  - Higgs Boson mass measurement [arxiv:2207.00320]
  - Measurement of the Higgs boson production mode cross-sections [arxiv:2004.03447
  - $115 < m_{4\ell} < 130$ GeV



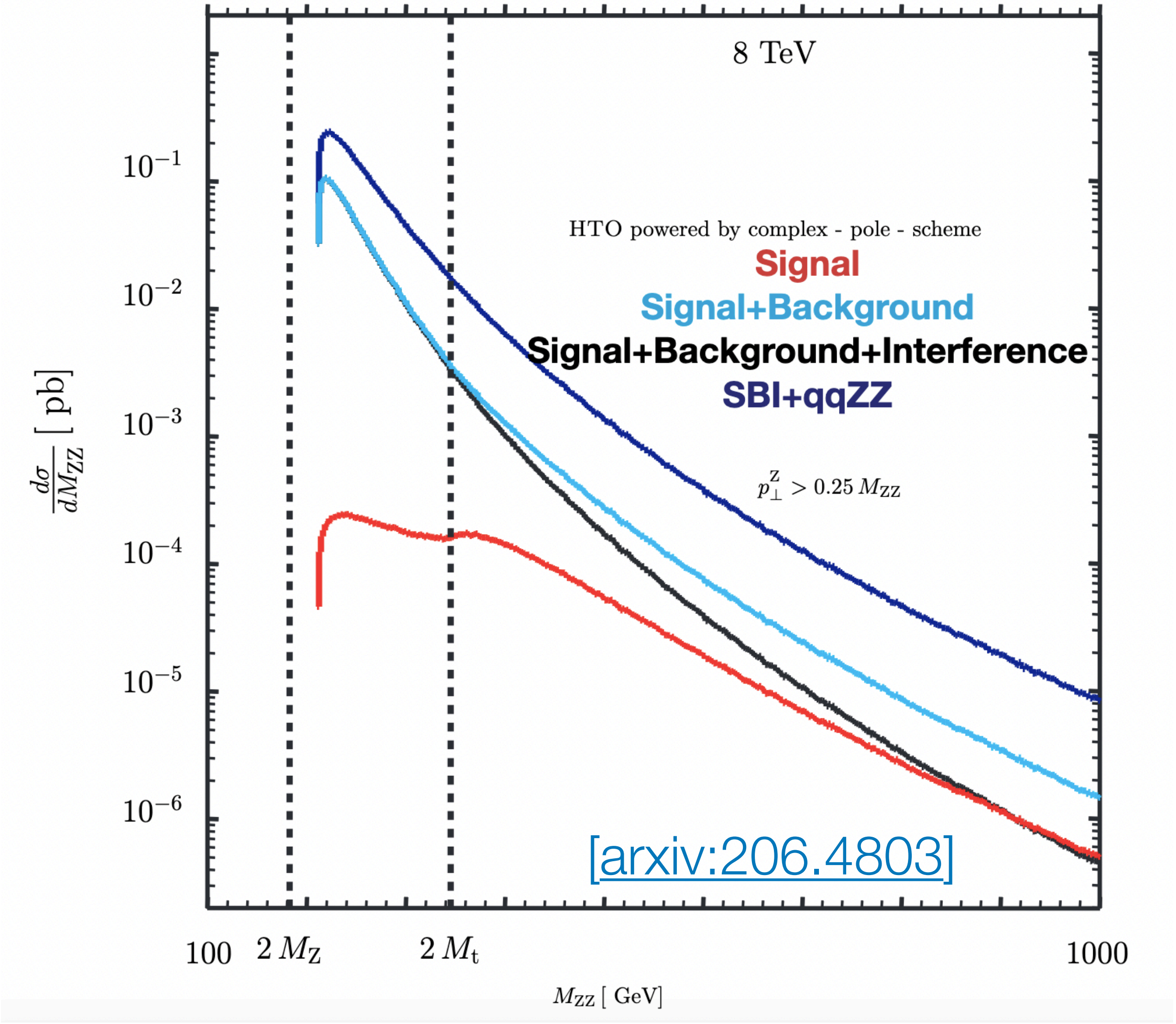
arxiv:2207.00320



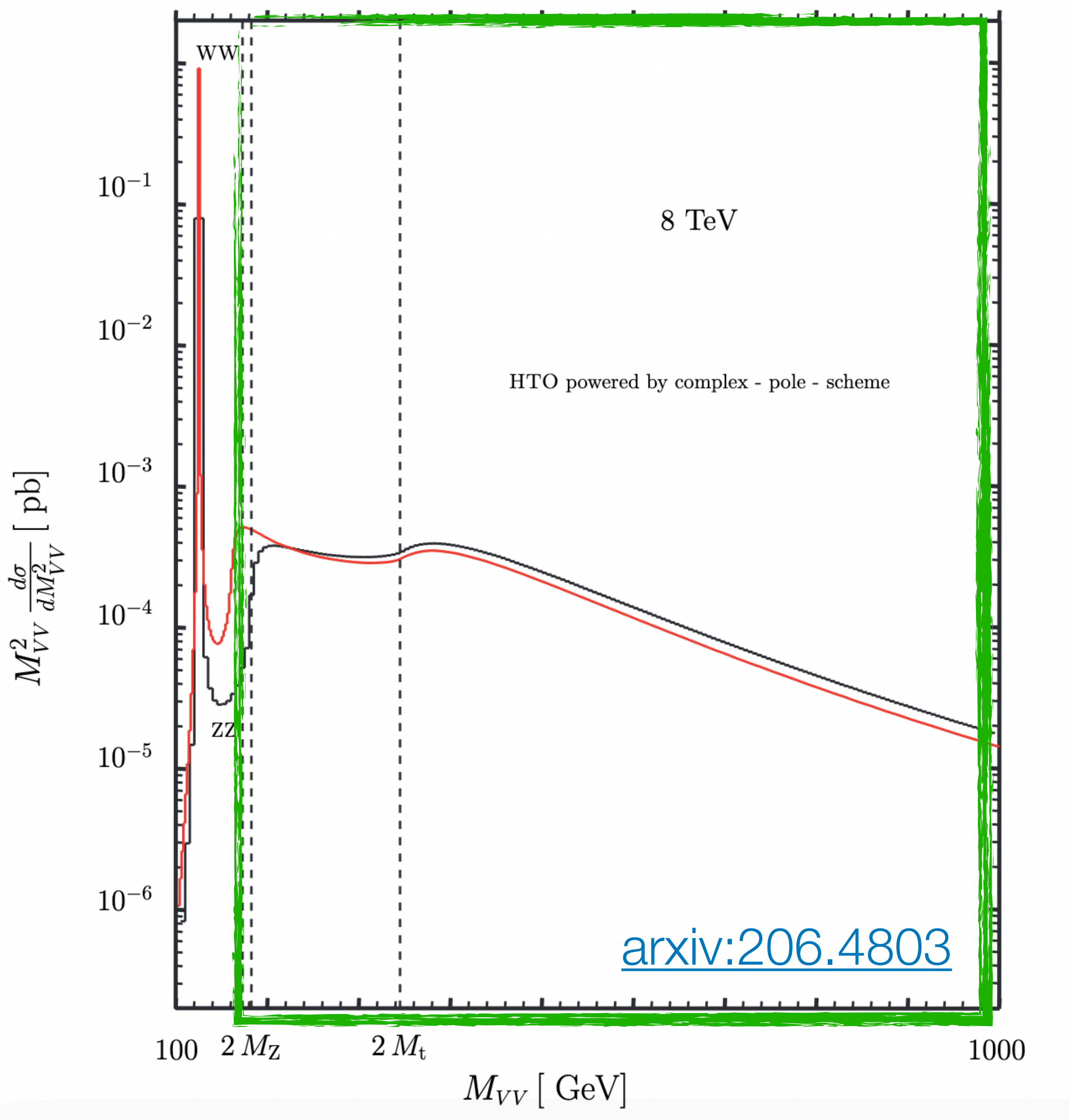
arxiv:206.4803

Overview of H→ZZ measurements at ATLAS

- **Off-shell** $H^* \to ZZ \to 4\ell$
  - Higgs Boson decay width measurement [ATLAS-CONF-2022-068]
  - $m_{4\ell} > 220$ GeV



[arxiv:206.4803]



arxiv:206.4803

How to probe quantum entanglement?

I) Measuring Z-boson polarisations

i) [Laboratory-frame tests of QE in H → WW]: *J. A. Aguilar-Saavedra*

- Entanglement condition can be reformulated as a binary test: SM versus longitudinal polarisations.

ii) [Vector boson polarizations in the decay of the Standard Model Higgs]: *E. Maina*

- VB polarizations can be reconstructed analyzing the kinematic distributions of the final state leptons.

II) Determine experimentally the spin density matrix coefficients

- Requires measurement of spin correlation observables→ full reconstruction of the event kinematics.

  a) [Testing entanglement and Bell inequalities in H → ZZ]: *J. A. Aguilar-Saavedra , A. Bernal , J. A. Casas and J. M. Moreno*

  b) [Quantum state tomography, entanglement detection and Bell violation prospects in weak decays of massive particles]: *R. Ashby-Pickering, A. Barr, A. Wierzchucka*

I) Z-boson polarizations

Z-boson polarizations

- Why is it interesting to measure **polarized gluon-induced processes**?
  - Polarized VBF process already measured [e.g. Production x-sections of polarized SS WWjj]
  - Polarization of **ggZZ** processes not yet explored
  - Polarized **ggH** processes open new opportunities to probe quantum entanglement
    - Higgs boson is a scalar, thus the ZZ pair is produced in a spin-singlet state, where the quantum entanglement is maximal.
    - The amplitude for the Higgs decay to four fermions can be **analytically** reformulated in terms of the polarizations of the intermediate vector bosons. The vector polarizations can be then **reconstructed** analyzing the kinematic distributions of the final state leptons.
    - QE condition can be reformulated in terms of decay polarisation amplitudes

How to generate the polarized ggZZ processes?

- MadGraph model provided by *Richard Ruiz*[1]: **SM_Loop_ZPolar_NLO**
  - The automation of ***loop-level*** *production* + *polarization* + *decay* is not yet supported officially. This model keeps spin correlation at every step of the simulation.
  - Z is redefined to be: **Z -> ZX + Z0 + ZT + ZA**
    - ZX is just a field redefinition, its mass and width are MZ and WZ (like in other SM UFO)
    - Z0 has a propagator built solely from **longitudinal polarization vectors**
    - ZT has a propagator built from summing over the **2 transverse polarization vectors**
    - ZA has a propagator built solely from an **auxiliary polarization vector**
      - Describes the behavior not captured by the transverse and longitudinal polarization vector
      - Auxiliary propagator vanishes in the on-shell limit

$$\varepsilon^{\mu}(q,\lambda=A)=\frac{q^{\mu}}{M_V}\sqrt{\frac{q^2-M_V^2}{q^2}}$$

[1] [Automated Predictions from Polarized Matrix Elements]: VB polarisations studied in VBS (not ggF)

Polarizations in the Higgs boson off-shell regime?

- **Evidence of off-shell production in the HZZ decay channel**
  - Published by CMS [Nature Phys. 18 (2022) 1329] and ATLAS [ATLAS-CONF-2022-068]
- **Study polarisation in the off-shell regime is interesting**
  - Novel method [Higgs Couplings without the Higgs] enables to **test the Higgs couplings**, off-shell, via their contributions to the physics of *longitudinally* polarised gauge bosons
    - Grows with energy → promising now and increasingly important in the future
    - Independent and complementary to the well-established on-shell measurements
  - Both Z bosons are on-shell → **polarizations are well-defined**
  - Anomalous modifications of the SM necessarily induce E-growth
    - Novel approach to explore **EFT** interpretations, break degeneracies
  - **QE condition** can be formulated in terms of decay polarisation amplitudes

Event generation of polarised samples

- MEs calculated up to one additional parton in the final state for $ee\mu\mu$ final state[1]

- **gg -> ZLZL**
- **gg -> ZTZT**
- **gg -> ZZ**

```
import model SM_Loop_ZPolar_NLO

generate    p p > e+ e- mu+ mu-   QED=4 QCD=2 [noborn = QCD] / a z zt za @0
add process p p > e+ e- mu+ mu- j QED=4 QCD=3 [noborn = QCD] / a z zt za @1

generate    p p > e+ e- mu+ mu-   QED=4 QCD=2 [noborn = QCD] / a z z0 za @0
add process p p > e+ e- mu+ mu- j QED=4 QCD=3 [noborn = QCD] / a z z0 za @1

generate    p p > e+ e- mu+ mu-   QED=4 QCD=2 [noborn = QCD] / a z0 zt za @0
add process p p > e+ e- mu+ mu- j QED=4 QCD=3 [noborn = QCD] / a z0 zt za @1
```

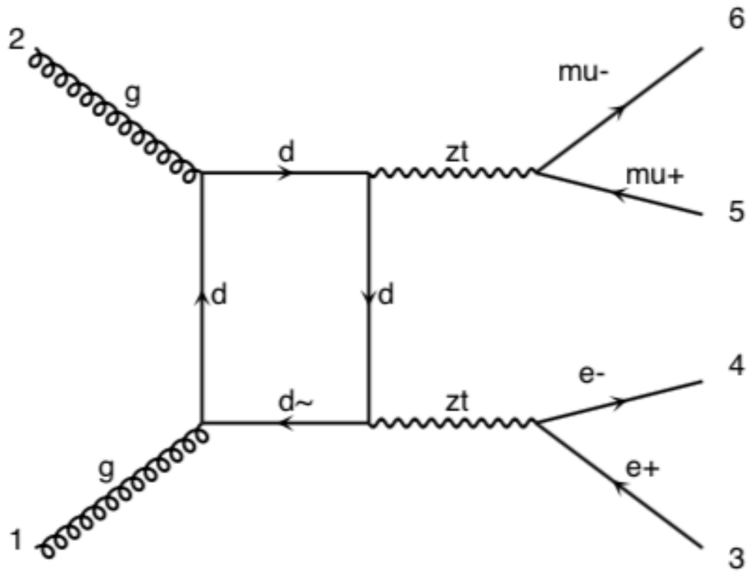


diagram 3 QCD=2, QED=4

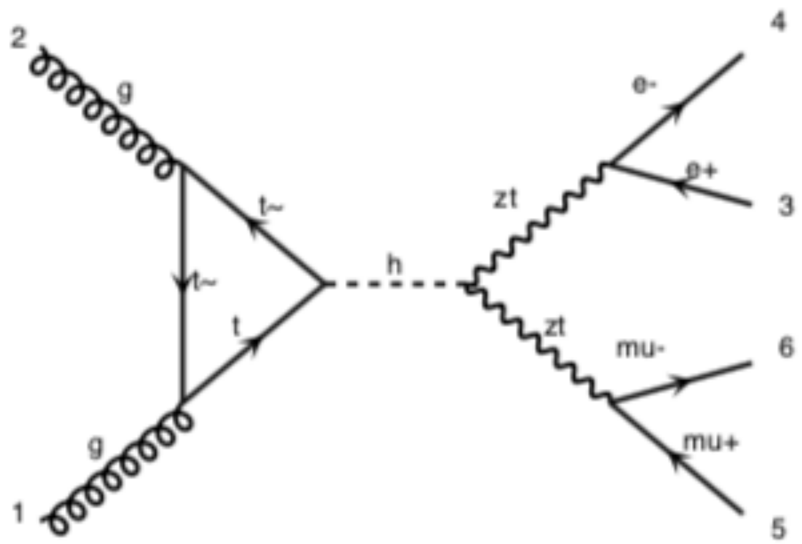


diagram 52 QCD=2, QED=4

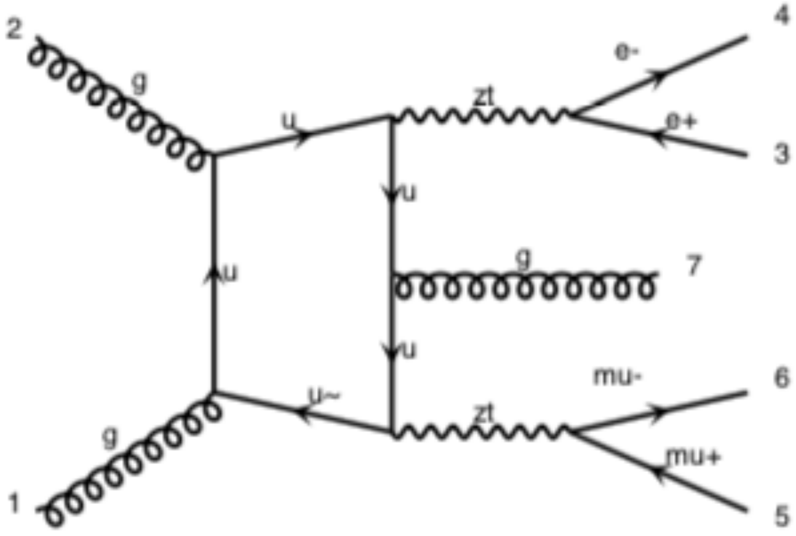


diagram 139 QCD=3, QED=4

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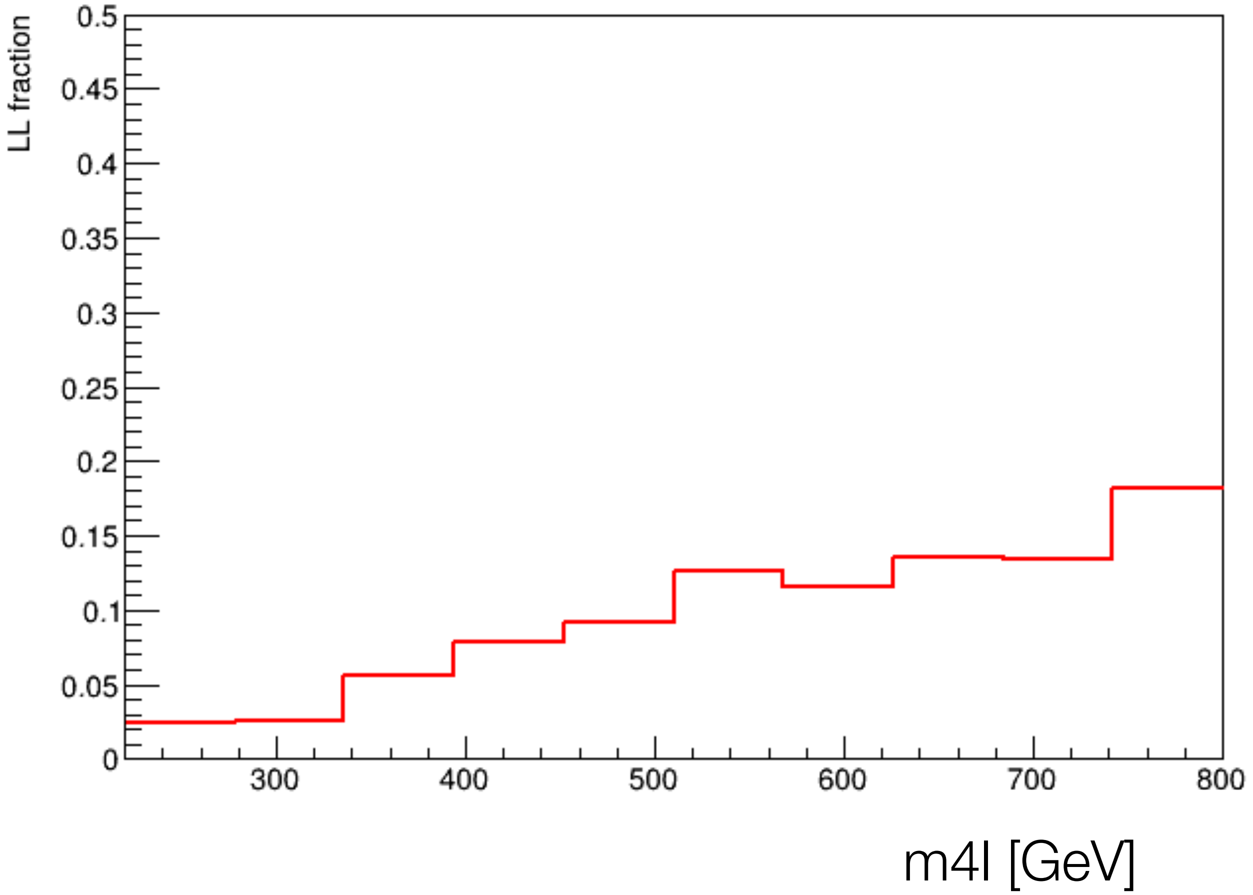
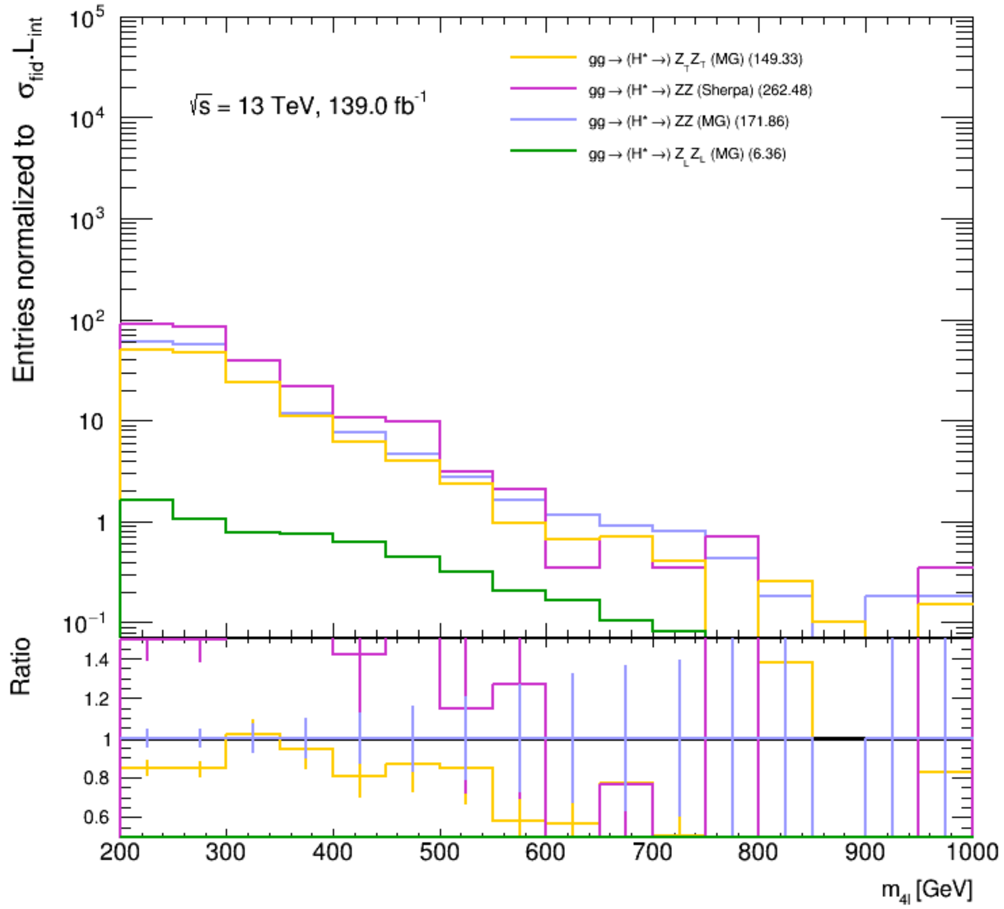
[1] loop diagram filter applied in order to remove NNLO corrections to qqZZ

[2] no need to generate AA (only for a sanity check)

Validation of polarised samples: cross-sections

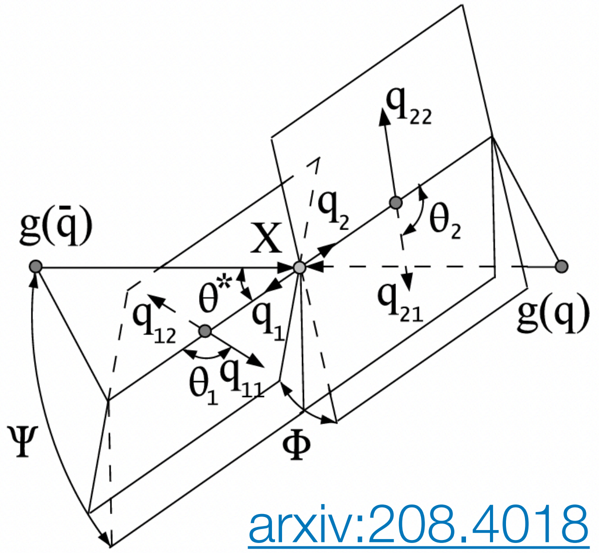
- **Fiducial cross-sections**
  - gg -> ZZ: 1.172 fb
  - gg -> ZTZT 0.9483 fb
  - gg -> ZLZL: 0.0577 fb
  - f^{LL} same order of magnitude as the signal Higgs in [ATLAS-CONF-2022-068] ($f^{LL} = \sigma^{LL}/\sigma^{all} \sim 5\,\%$)



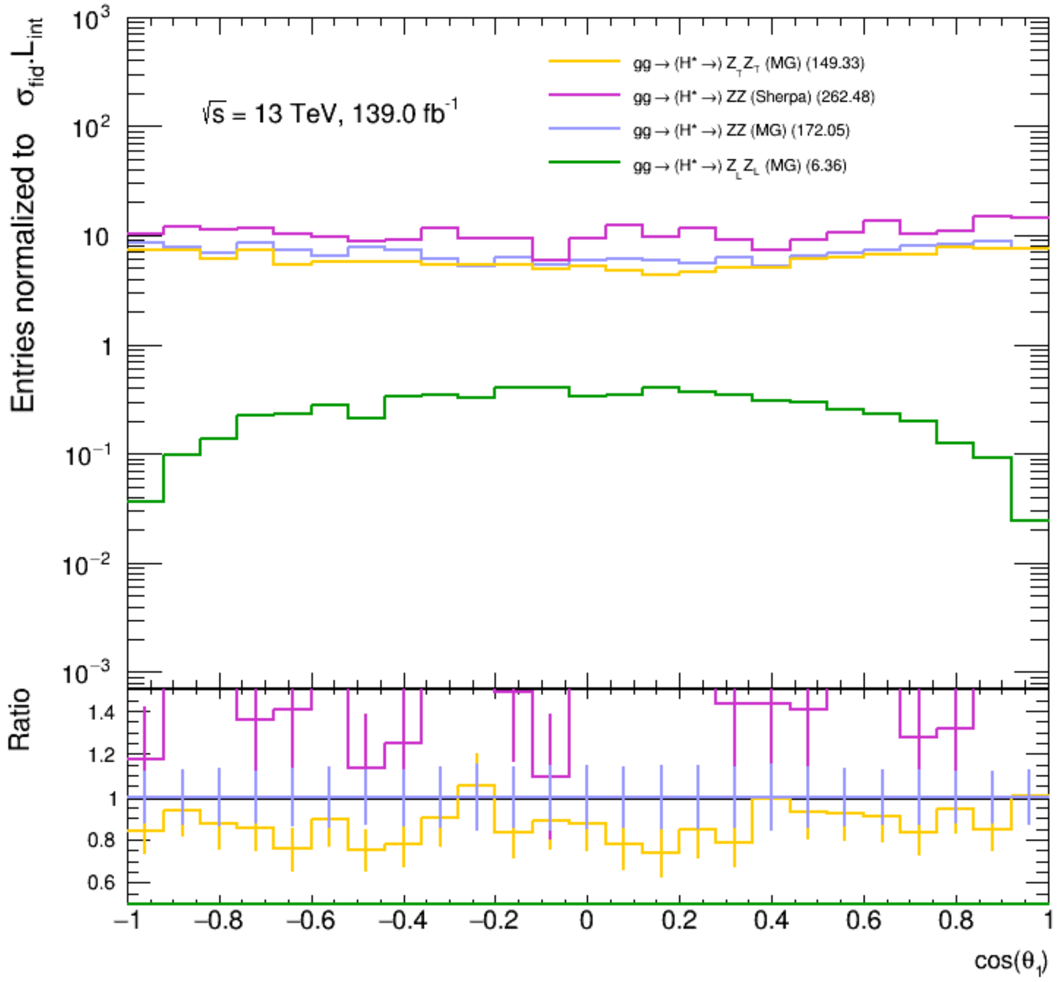


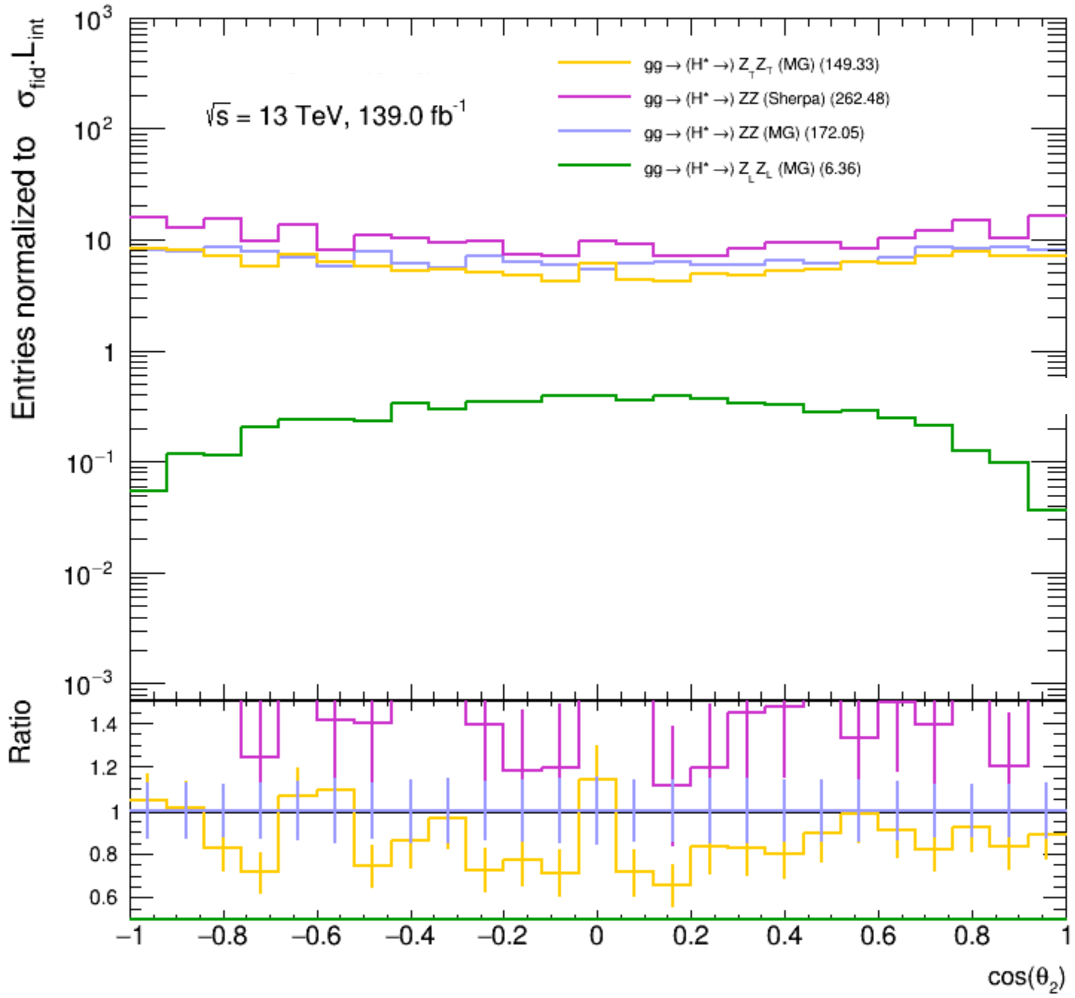
Validation of polarised samples: helicity angles

- **Helicity angles**
  - Spin correlation check
  - $\cos\theta_1$ and $\cos\theta_2$ provide good separation power (LL vs TT)



arxiv:208.4018





Analysis setup

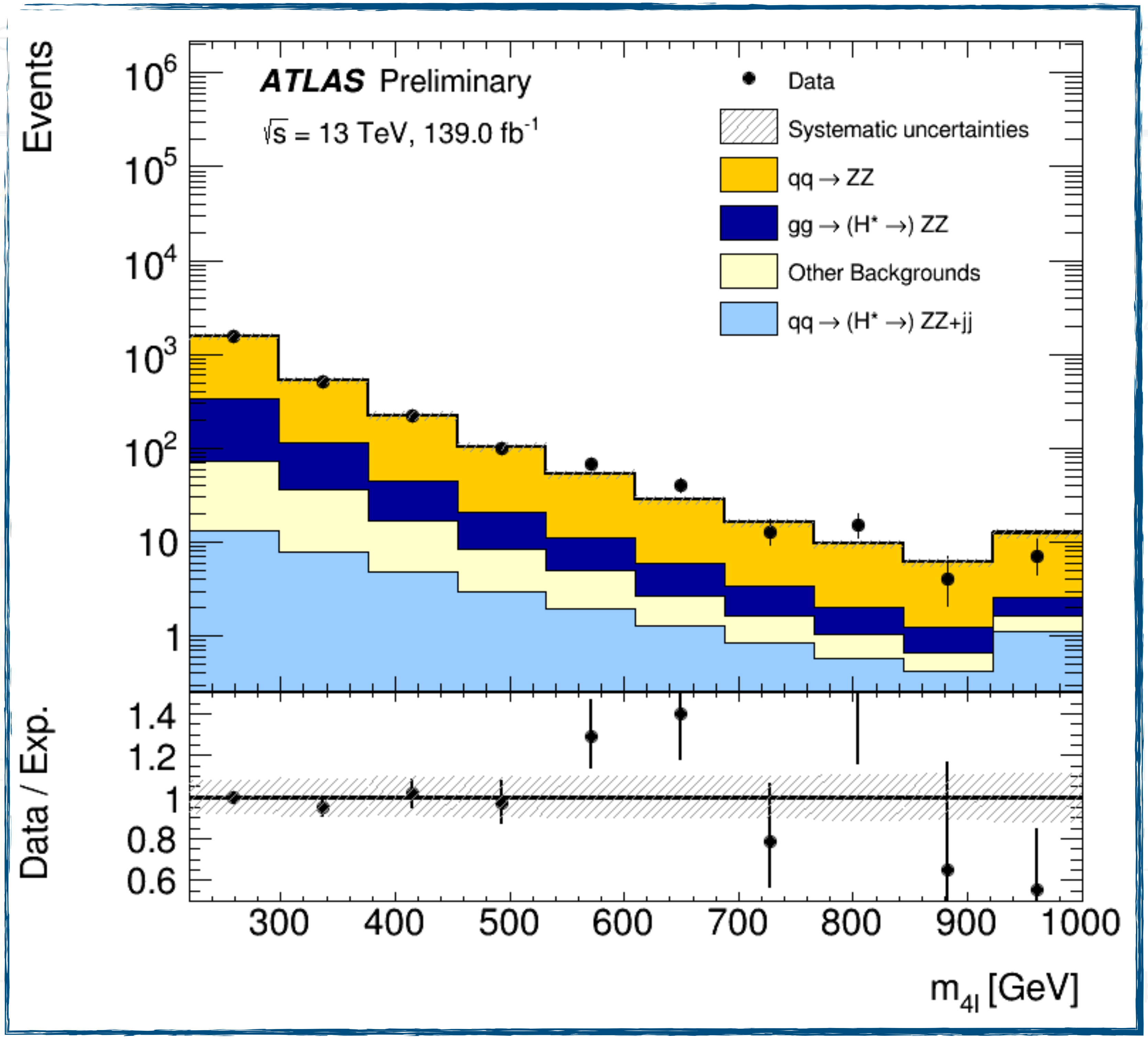
Similar strategy as in the measurement of off-shell Higgs boson production at $\sqrt{s} = 13$ TeV with the data of $139\ \mathrm{fb}^{-1}$

- Main event selections (same as in the off-shell analysis)
  - 4l candidates formed by selecting a lepton-quadruplet made out of 2 SFOS lepton pairs
  - $m_{4\ell} > 220$ GeV, $m_{Z1} \in [50{,}106]$ GeV, $m_{Z2} \in [50{,}115]$ GeV
- **Dominant background**: QCD $q\bar{q} \to ZZ$ process
- Analysis strategy
  - Calculate LO MEs for ggZLZL, ggZTZT and qqZZ processes in the Higgs boson rest frame
  - Construct ME ratio to enhance separation of the longitudinal component
  - Parametrise gg -> ZTZL contribution via: ZZ-ZTZT-ZLZL (in a given observable)
  - Use optimal observable (eventually binned in jets) in a maximum-likelihood fit

Analysis setup

Similar strate … on at $\sqrt{s} = 13$ TeV

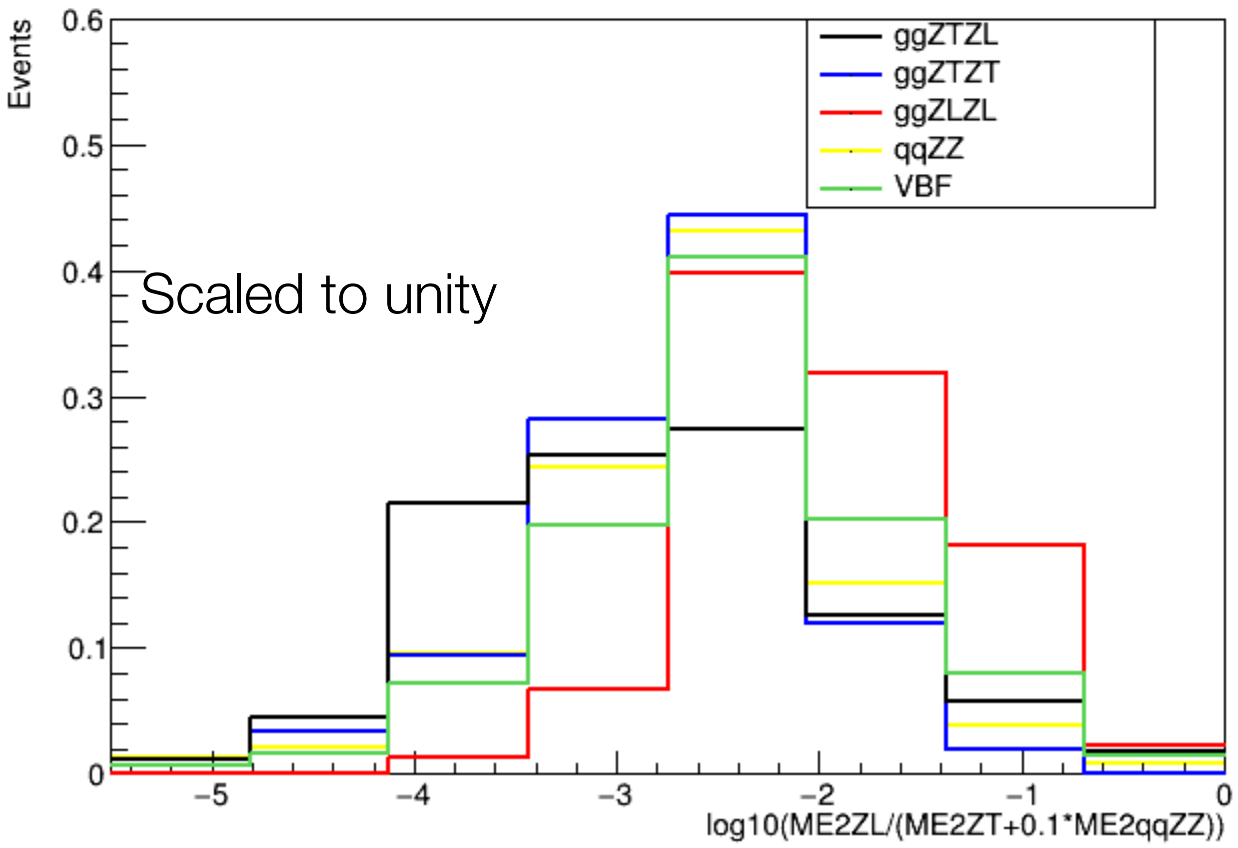
- Main event
  - 4l candi … 2 SFOS lepton pairs
  - $m_{4\ell} > 2$
- Dominant
- Analysis st
  - Calculat … iggs boson rest frame
  - Constru … ent
  - Parame … bservable)
  - Use optimal observable (eve … aximum-likelihood fit

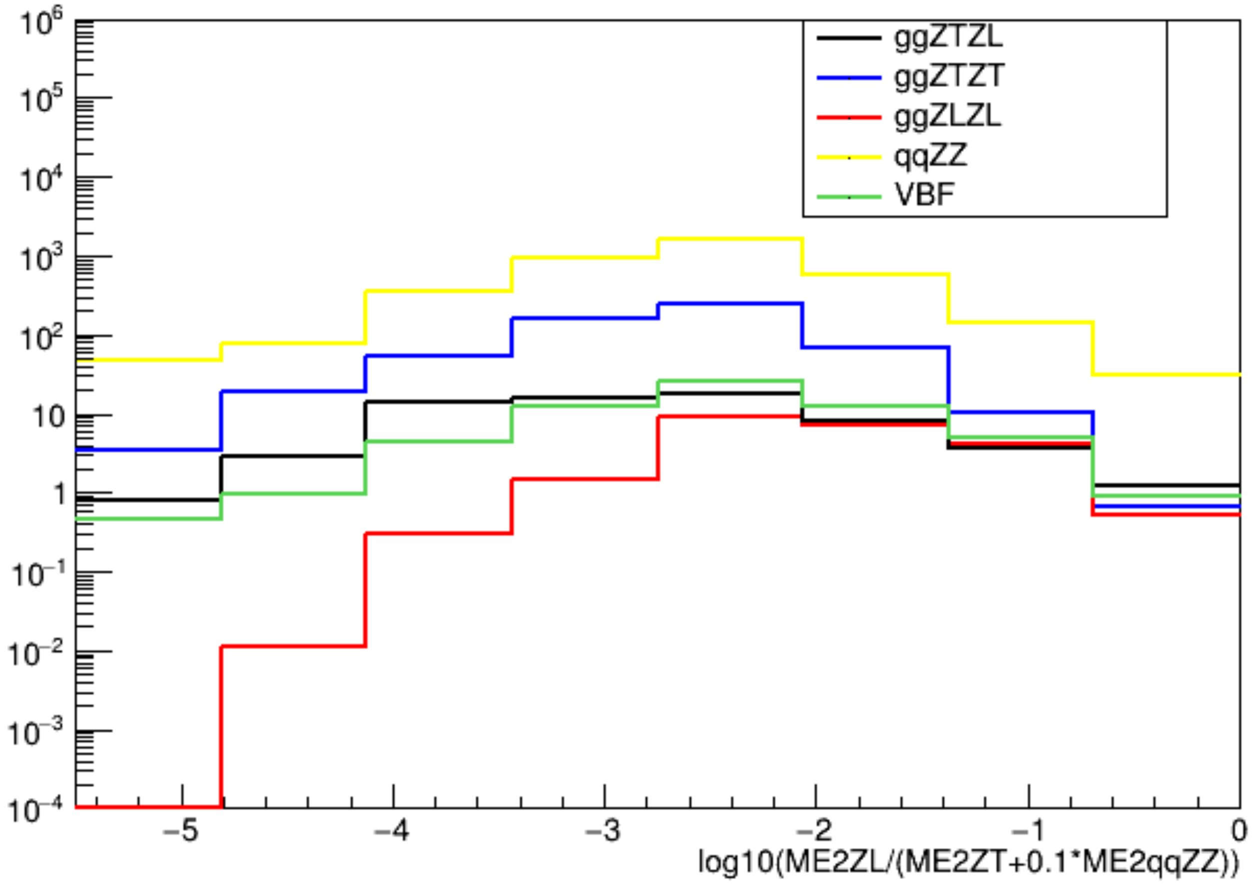


[ATLAS-CONF-2022-068]

Looking for the optimal observable

- Calculated LO MEs for
  - long. (ME2ZL) and trans. (ME2ZT) polarisations in the ggZZ process and qqZZ (ME2qqZZ)
- Defined a ME ratio as follows: **log10(ME2ZL/(ME2ZT+0.1*ME2qqZZ))**
  - For preliminary studies, the same "traditional" ME ratio was used as in the off-shell analysis
  - Per-Event Likelihood Ratios can be applied





Statistical interpretation

- Integrated luminosity of **440 ifb** assumed (proxy for Run 2 + Run 3 luminosity)
- Systematic uncertainty of **25%** estimated
    - [Measurement of off-shell Higgs production]: dominated by parton shower syst. on ggZZ
- Several options

1. Measuring solely the *LL ggZZ component* (everything else treated as background)

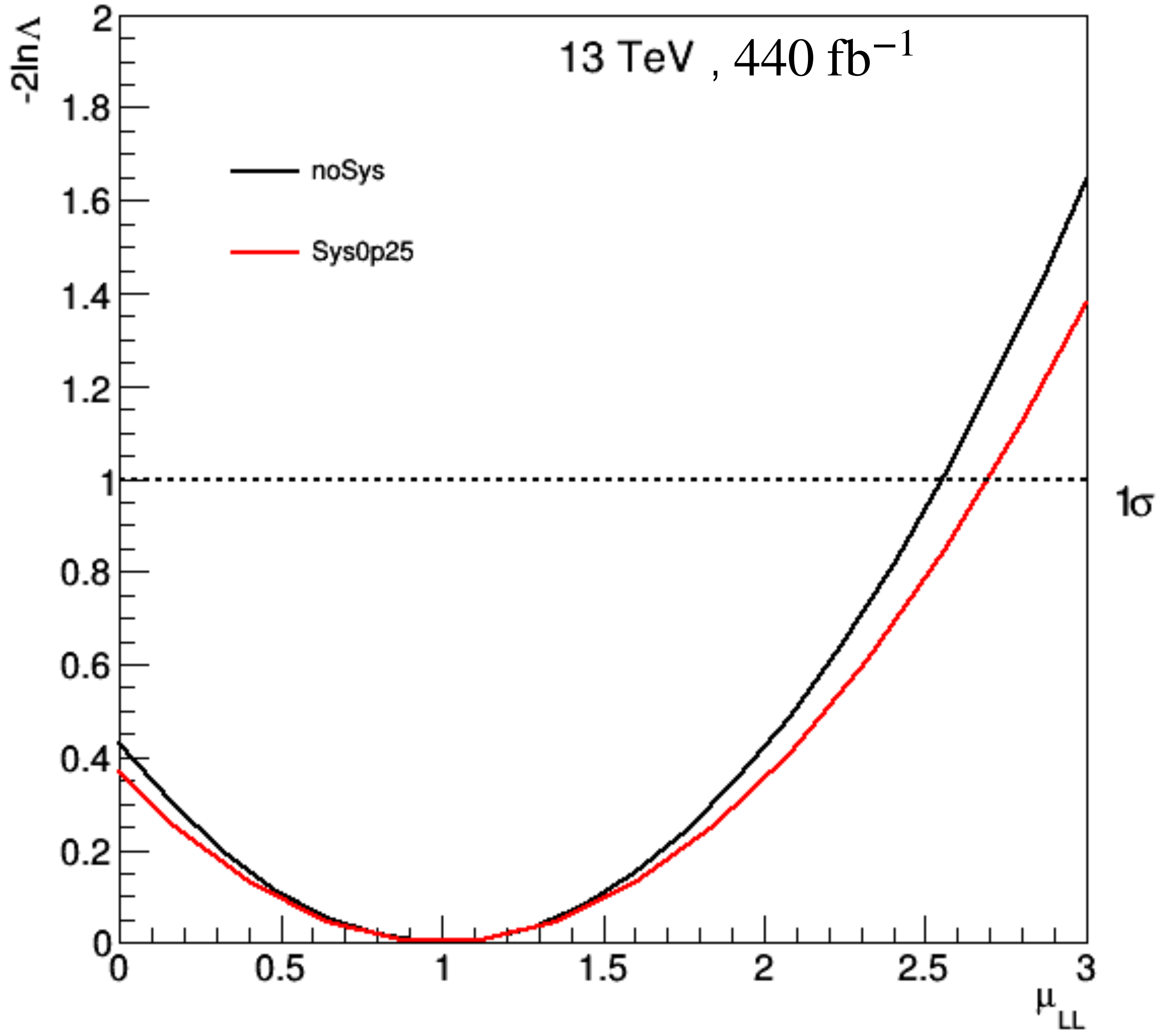
$$N_i^{exp}(\mu) = n_i^{qqZZ} + n_i^{ggZTZL+ggZTZT} + n_i^{VBFZZ} + \mu_{LL} \cdot n_i^{ggZLZL}$$

2. Binning in # jets enables to measure the *LL ggZZ and VBF components separately*

$$N_i^{exp}(\mu) = n_i^{qqZZ} + n_i^{ggZTZL+ggZTZT} + n_i^{VBFZTZL+VBFZTZT} + \mu_{LL}^{ggF} \cdot n_i^{ggZLZL} + \mu_{LL}^{VBF} \cdot n_i^{VBFZLZL}$$

3. Also considering floating the overall ggZZ normalisation and measuring *fractions*

Expected sensitivity for Run 2+3 data



- **Several improvements on the way!**
  - Optimize binning
  - Test 2D optimal observable
  - Build Per-Event Likelihood Ratios
    - Aim to increase *discovery significance* above $1\ \sigma$

Expected *discovery significance* is around $0.6\ \sigma$

Can this be interpreted as a test of QE?

- [Laboratory-frame tests of QE in H → WW]
  - "We can reformulate the entanglement condition as a binary test: **SM versus longitudinal polarisation**. And this binary test can be performed using laboratory-frame observables."

➡ We need to go one step further and separate the *LL **signal** component*

1) **Event generation** of signal polarised samples

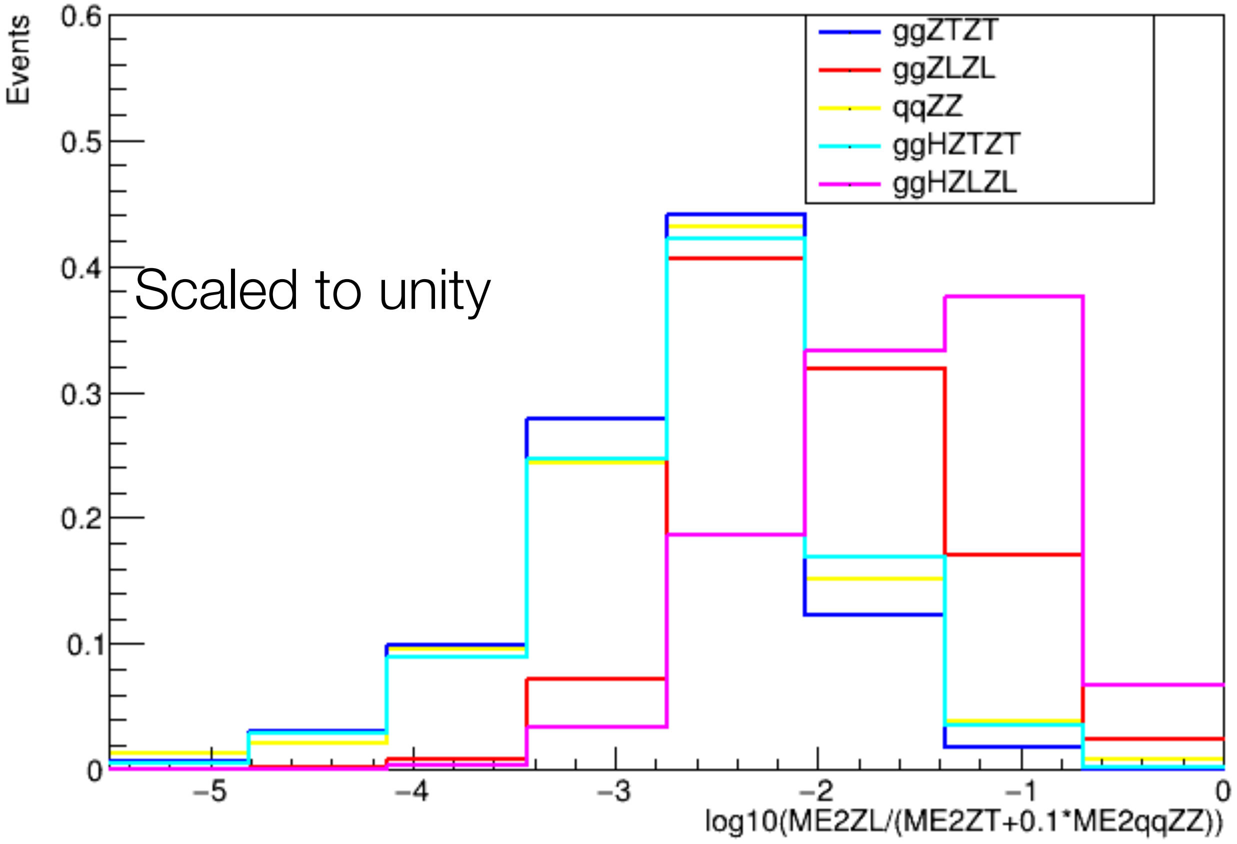
```
import model SM_Loop_ZPolar_NLO

generate    p p > h > e+ e- mu+ mu-   QED=4 QCD=2 [noborn = QCD] / a z zt za @0
add process p p > h > e+ e- mu+ mu- j QED=4 QCD=3 [noborn = QCD] / a z zt za @1
```

2) Looking at the same **optimal observable:** log10(ME2ZL/(ME2ZT+0.1*ME2qqZZ))

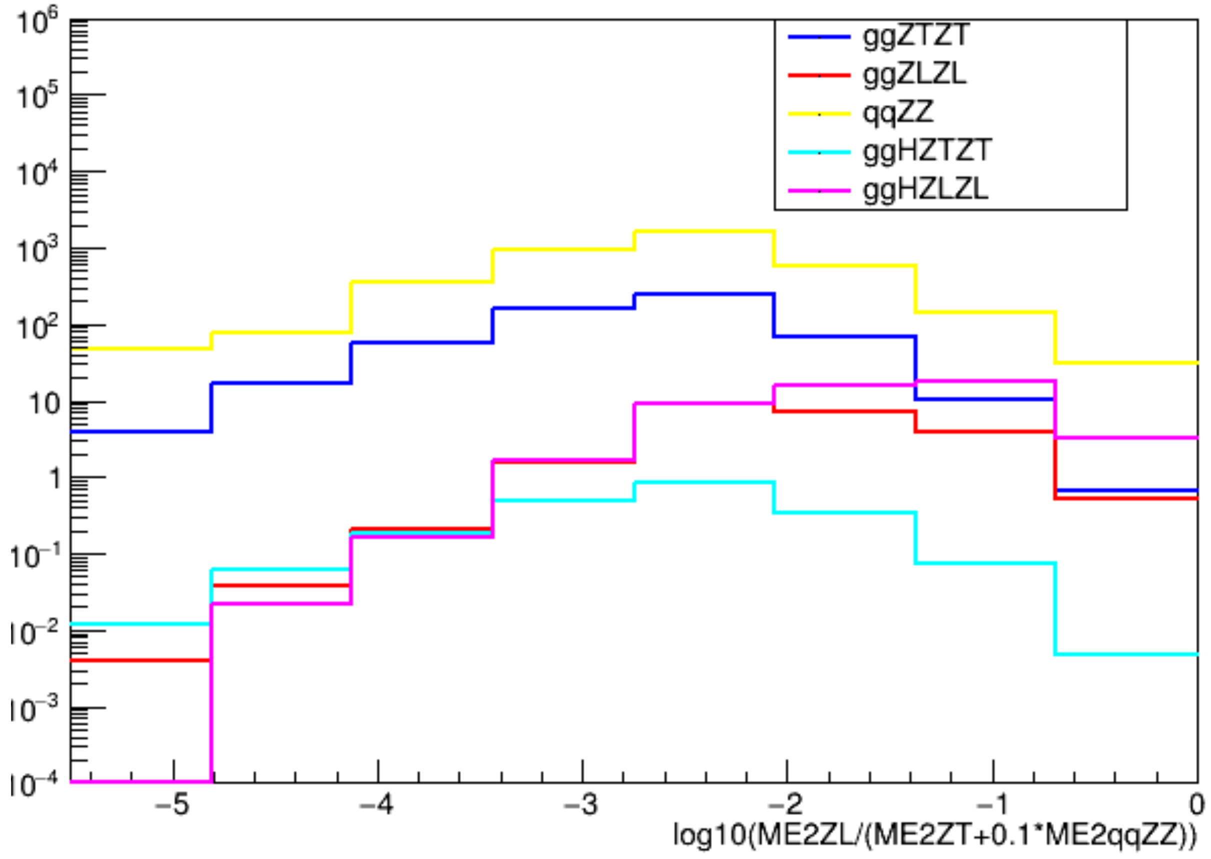
- NB: contributions from NLO corrections are not considered in this observable
- ML methods (e.g. used in Measurement of off-shell Higgs production]) can be employed to better explore these differences

Test of quantum entanglement

- **Fiducial cross-sections**
  - gg -> H* -> ZZ: 0.08375 fb
  - **gg -> H* -> ZTZT:** 0.005435 fb
  - **gg -> H* -> ZLZL:** 0.06884 fb
  - LL component dominates in the off-shell regime: $f_H^{LL} = \sigma_H^{LL} / \sigma_H^{all} \sim 80\,\%$



Scaled to unity



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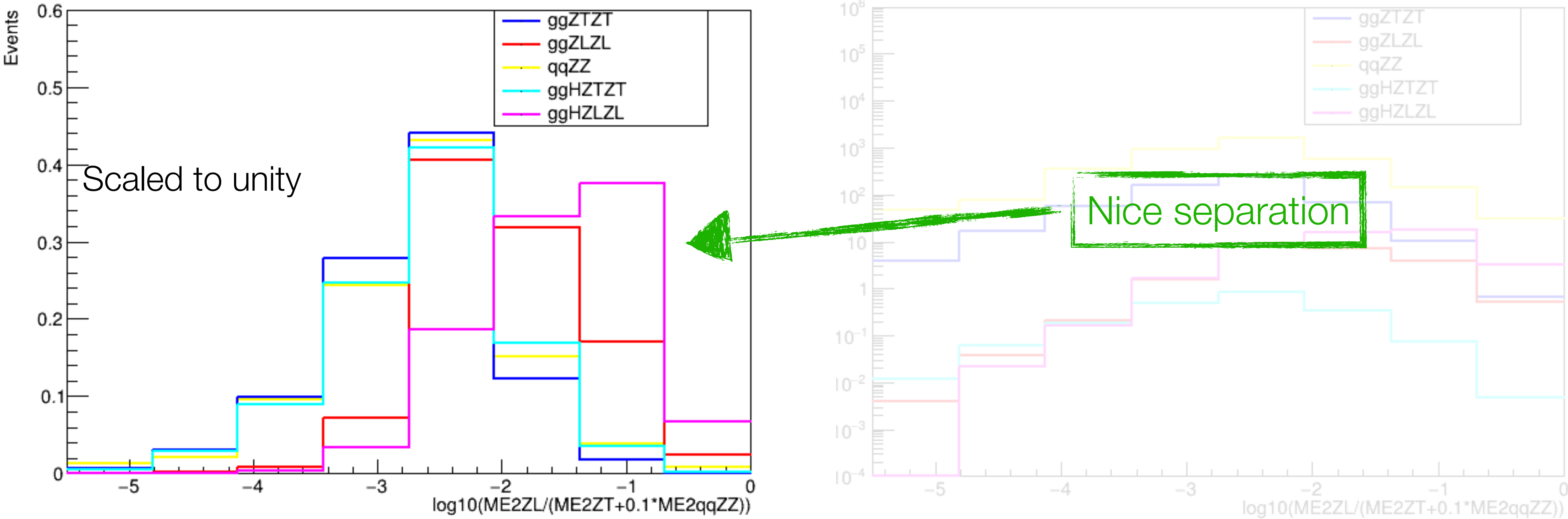

Scaled to unity

Nice separation

Test of quantum entanglement

- **Fiducial cross-sections**
  - gg -> H* -> ZZ: 0.08375 fb
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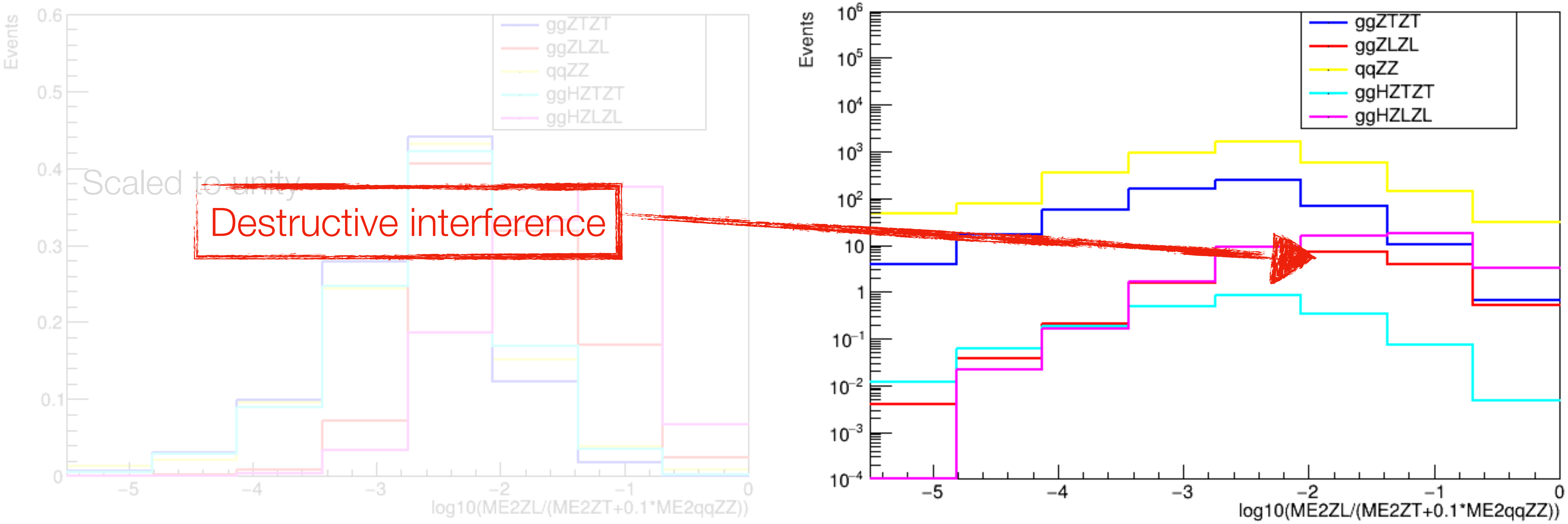
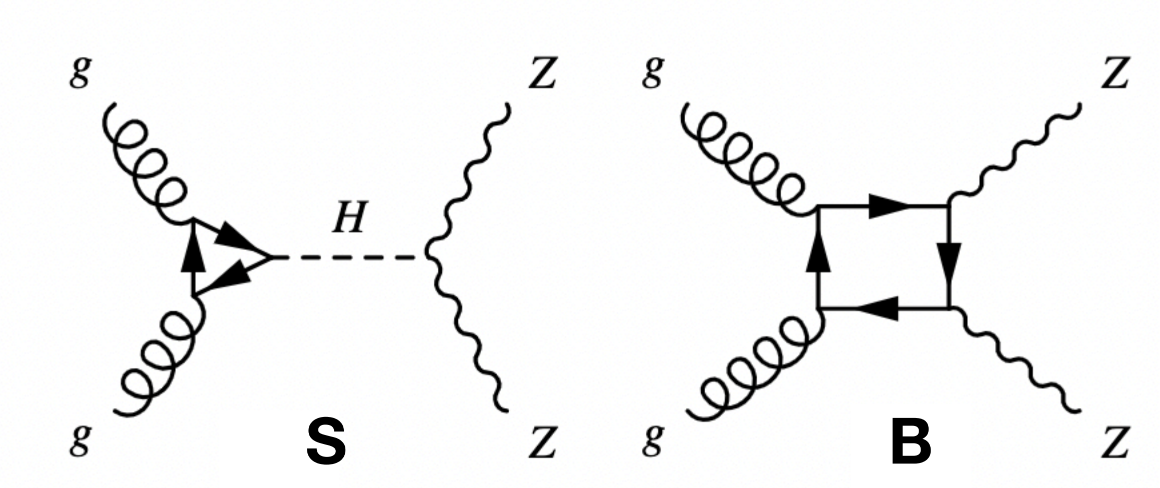


Destructive interference

Statistical interpretation

- Need to deal with sizeable destructive **interference** between the continuum background and the off-shell Higgs boson process
  - Scales as $\sqrt{\mu_{LL}^{\text{Higgs}}}$ (NLL has no longer parabolic shape)
  - Similarly as in [Measurement of off-shell Higgs production]



- SBI = signal + background + interference
- I = SBI - S - B

- Measuring solely the *LL ggH component*

$$N^{exp}(\mu_{LL}^{\text{Higgs}}) = n^{qqZZ} + n^{VBFZZ} + n_{\text{SBI}}^{ggZTZL+ggZTZT} + \mu_{LL}^{\text{Higgs}} \cdot n_{\text{S}}^{ggZLZL} + \sqrt{\mu_{LL}^{\text{Higgs}}} \cdot (n_{\text{SBI}}^{ggZLZL} - n_{\text{S}}^{ggZLZL} - n_{\text{B}}^{ggZLZL}) + n_{\text{B}}^{ggZLZL}$$

Statistical interpretation

- Need to deal with sizeable destructive **interference** between the continuum background and the off-shell Higgs boson process
  - Scales as $\sqrt{\mu_{LL}^{\text{Higgs}}}$ (NLL has no longer parabolic shape)
  - Similarly as in [Measurement of off-shell Higgs production], [Per-event analysis in [illegible] 22-04]

NLL under construction: generation of ggZLZL bkg samples ongoing

- SBI = signal + background + interference
- I = SBI - S - B

- Measuring solely the *LL ggH component*

$$N^{exp}(\mu_{LL}^{\text{Higgs}}) = n^{qqZZ} + n^{VBFZZ} + n_{\text{SBI}}^{ggZTZL+ggZTZT} + \mu_{LL}^{\text{Higgs}} \cdot n_{\text{S}}^{ggZLZL} + \sqrt{\mu_{LL}^{\text{Higgs}}} \cdot (n_{\text{SBI}}^{ggZLZL} - n_{\text{S}}^{ggZLZL} - n_{\text{B}}^{ggZLZL}) + n_{\text{B}}^{ggZLZL}$$

Polarizations in the Higgs boson on-shell regime?

- The helicity polarization of an off-shell Z boson is **not well-defined** because helicity a label of an eigenstate in the mass basis and off-shell states are not eigenstates in this basis.

- However, for massless leptons, the decay amplitude for the **auxiliary polarization is zero** because is proportional to the four–momentum of the virtual boson.

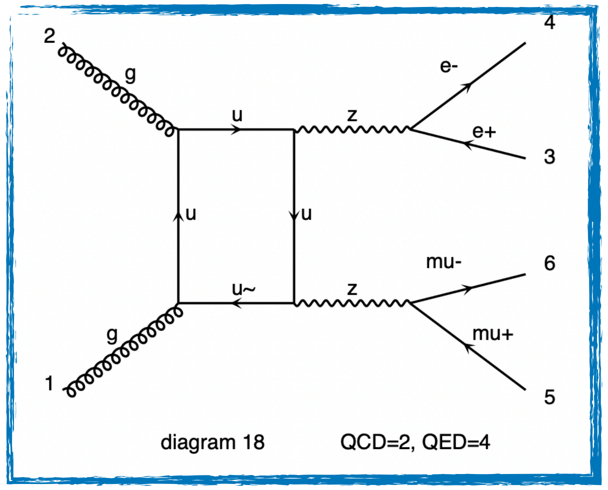
- **Work ongoing** to understand if it is still a good approximation:

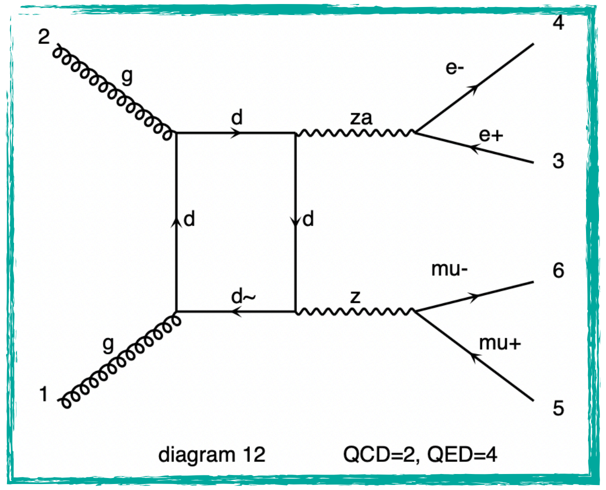
  i) LO process generated with MG including all polarizations:

  - generate g g > e+ e- mu+ mu- QED=4 QCD=2 [noborn = QCD] / a zt z0 za (x-section = 2.311 fb)

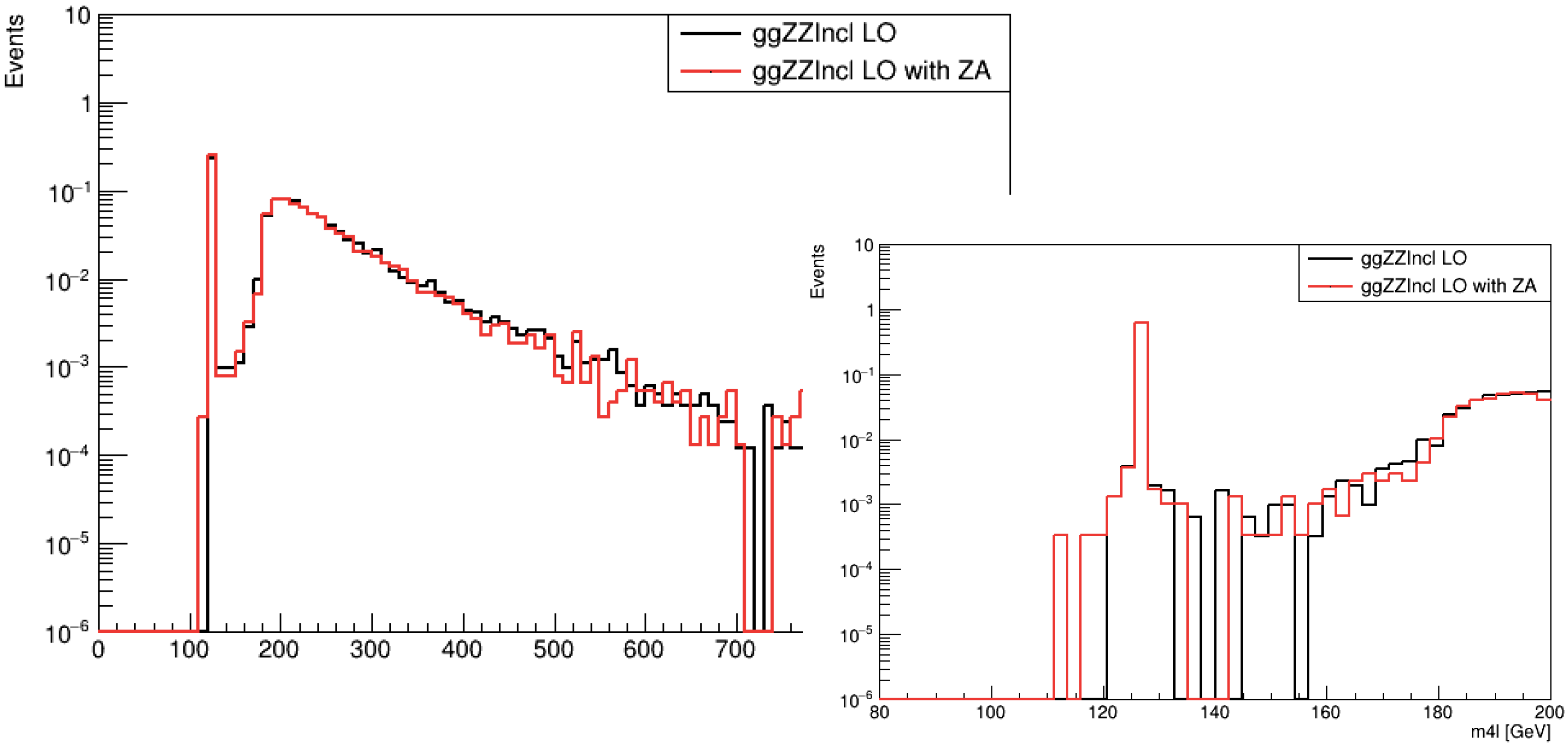
  ii) LO process generated with MG including all polarizations and ZA (ZA is double counted):

  - generate g g > e+ e- mu+ mu- QED=4 QCD=2 [noborn = QCD] / a zt z0 (x-section = 2.323 fb)





Polarizations at the Higgs boson on-shell regime?



- This can change with NLO corrections → work ongoing

II) Spin Density Matrix

Test of entanglement and Bell inequalities in H→ZZ

a) [Testing entanglement and Bell inequalities in H → ZZ]

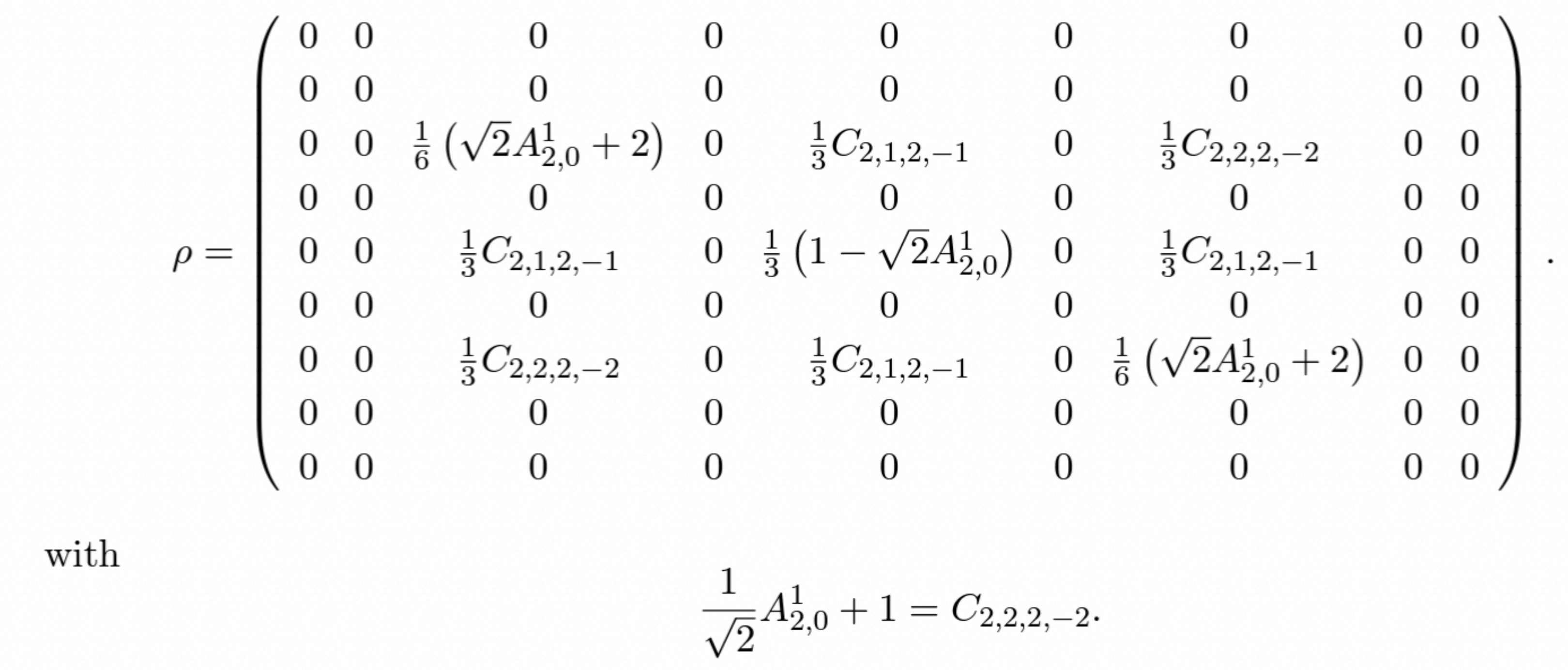
- Parameterisation based on the *irreducible tensor operators.*
- Measurement of the density matrix coefficients can be done by **integration with spherical harmonics**, which in turn requires knowledge of the angles θ_i and ϕ_i in the respective Z_i rest frames.

b) [Quantum state tomography, entanglement detection and Bell violation prospects in weak decays of massive particles]

- Parameterisation based on the generalised d-dimensional *Gell-Mann operators.*
- Density matrix parameters can be found experimentally from **averages of products of Wigner P functions**.

a) Test of entanglement and Bell inequalities in H→ZZ

- [Testing entanglement and Bell inequalities in H → ZZ]: *J. A. Aguilar-Saavedra , A. Bernal , J. A. Casas and J. M. Moreno*
  - Due to the symmetric form of the possible final states, (ZZ pair in a singlet spin state), the theoretical form of the spin density matrix has a very defined structure



$$\rho = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{6}\left(\sqrt{2}A^1_{2,0}+2\right) & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}\left(1-\sqrt{2}A^1_{2,0}\right) & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{6}\left(\sqrt{2}A^1_{2,0}+2\right) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}.$$

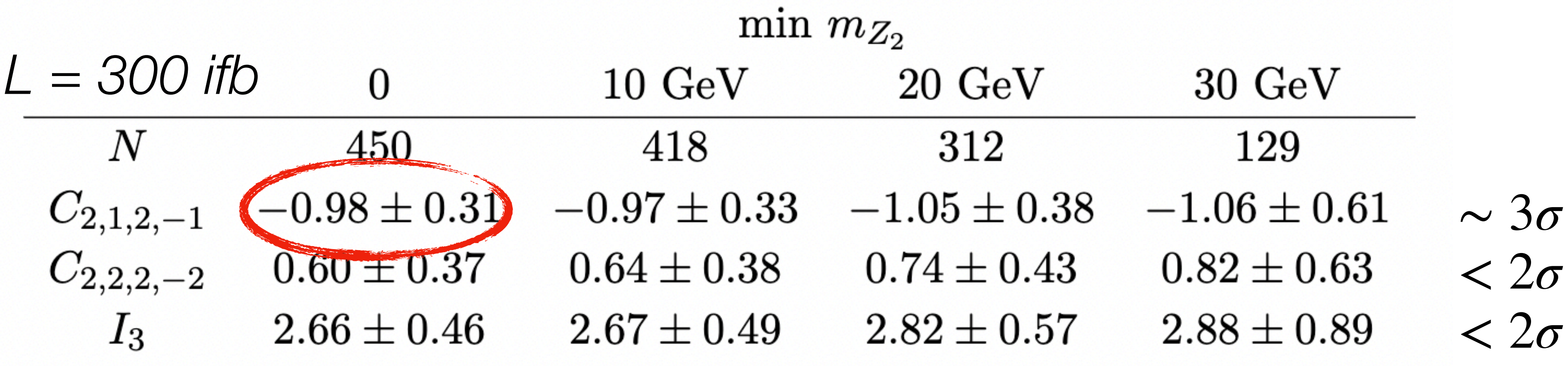
with

$$\frac{1}{\sqrt{2}}A^1_{2,0} + 1 = C_{2,2,2,-2}.$$

  - The coefficients can be experimentally determined by measuring **angular coefficients** of H → ZZ decay and **integrating with spherical harmonics**.

a) Test of entanglement and Bell inequalities in H→ZZ

- [Testing entanglement and Bell inequalities in H → ZZ]: *J. A. Aguilar-Saavedra , A. Bernal, J. A. Casas and J. M. Moreno*
  - Due to the symmetric form of the possible final states, (ZZ pair in a singlet spin state), the theoretical form of the spin density matrix has a very defined structure
  - The coefficients can be experimentally determined by measuring **angular coefficients** of H → ZZ decay and **integrating with spherical harmonics**.
  - **Conditions for entanglement** $C_{2,1,2,-1} \neq 0 \quad \text{or} \quad C_{2,2,2,-2} \neq 0\,.$
  - **Bell inequality** $I_3 = \frac{1}{36}\left(18 + 16\sqrt{3} - \sqrt{2}\left(9 - 8\sqrt{3}\right) A^1_{2,0} - 8\left(3 + 2\sqrt{3}\right) C_{2,1,2,-1} + 6\, C_{2,2,2,-2}\right) \leq 2$



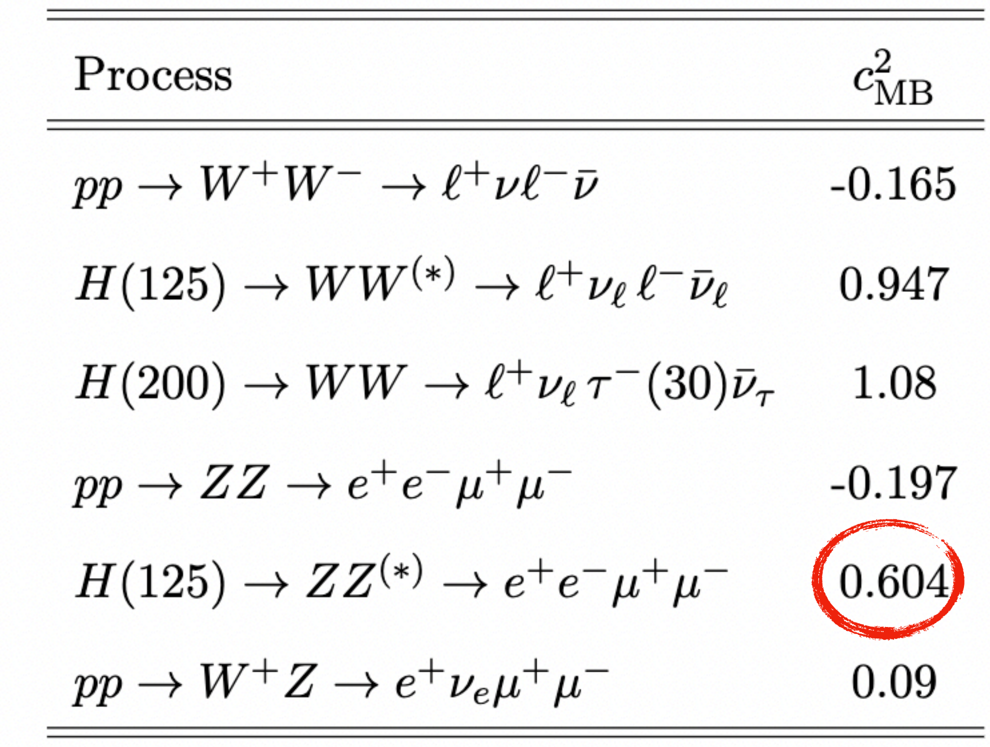
L = 300 ifb	min m_{Z_2}				
	0	10 GeV	20 GeV	30 GeV	
N	450	418	312	129	
$C_{2,1,2,-1}$	-0.98 ± 0.31	-0.97 ± 0.33	-1.05 ± 0.38	-1.06 ± 0.61	$\sim 3\sigma$
$C_{2,2,2,-2}$	0.60 ± 0.37	0.64 ± 0.38	0.74 ± 0.43	0.82 ± 0.63	$< 2\sigma$
I_3	2.66 ± 0.46	2.67 ± 0.49	2.82 ± 0.57	2.88 ± 0.89	$< 2\sigma$

b) Test of entanglement and Bell inequalities in H→ZZ

- [Quantum state tomography, entanglement detection and Bell violation prospects in weak decays of massive particles]: *R. Ashby-Pickering, A. Barr, A. Wierzchucka*

  - Experimental measurement of the density matrix parameter can be obtained by a simple **angular average** (expectation values) **of the Wigner P functions**

  - **Entanglement** may be demonstrated by evaluating a lower bound on the square of the concurrence: $(c(\rho))^2 \geq 2\,\mathrm{tr}(\rho^2) - \mathrm{tr}(\rho_A^2) - \mathrm{tr}(\rho_B^2) \equiv c_{\mathrm{MB}}^2.$



Process	c_{MB}^2
$pp \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$	-0.165
$H(125) \to WW^{(*)} \to \ell^+\nu_\ell\ell^-\bar{\nu}_\ell$	0.947
$H(200) \to WW \to \ell^+\nu_\ell\tau^-(30)\bar{\nu}_\tau$	1.08
$pp \to ZZ \to e^+e^-\mu^+\mu^-$	-0.197
$H(125) \to ZZ^{(*)} \to e^+e^-\mu^+\mu^-$	0.604
$pp \to W^+Z \to e^+\nu_e\mu^+\mu^-$	0.09

- Quantum mechanical maximum for an entangled pair of qutrits is 4/3
- System is entangled is $c_{MB}^2 > 0$

- **Bell inequality** $\mathcal{B}^{xy}_{\mathrm{CGLMP}} = -\frac{2}{\sqrt{3}}\left(S_x \otimes S_x + S_y \otimes S_y\right) + \lambda_4 \otimes \lambda_4 + \lambda_5 \otimes \lambda_5$

- More info in [Alan's talk given on Monday]

b) Test of entanglement and Bell inequalities in H→ZZ

- [Quantum state tomography, entanglement detection and Bell violation prospects in weak decays of massive particles]: *R. Ashby-Pickering, A. Barr, A. Wierzchucka*
  - Experimental measurement of the density matrix parameter can be obtained by a simple **angular average** (expectation values) **of the Wigner P functions**
  - **Entanglement** may be demonstrated by evaluating a lower bound on the square of the concurrence: $(c(\rho))^2 \geq 2\,\mathrm{tr}(\rho^2) - \mathrm{tr}(\rho_A^2) - \mathrm{tr}(\rho_B^2) \equiv c_{\mathrm{MB}}^2.$
  - How does it look in the previously mentioned **off-shell samples**?

Process	c_{MB}^2	I_3
$gg \to ZZ \to 4\ell$	0.30	0.32
$gg \to H^* \to ZZ \to 4\ell$	0.53	1.1

- Final state kinematics fed into scripts provided by Alan Barr and George Barker. *Thank you!*
- Both productions yield a positive c_{MB}^2

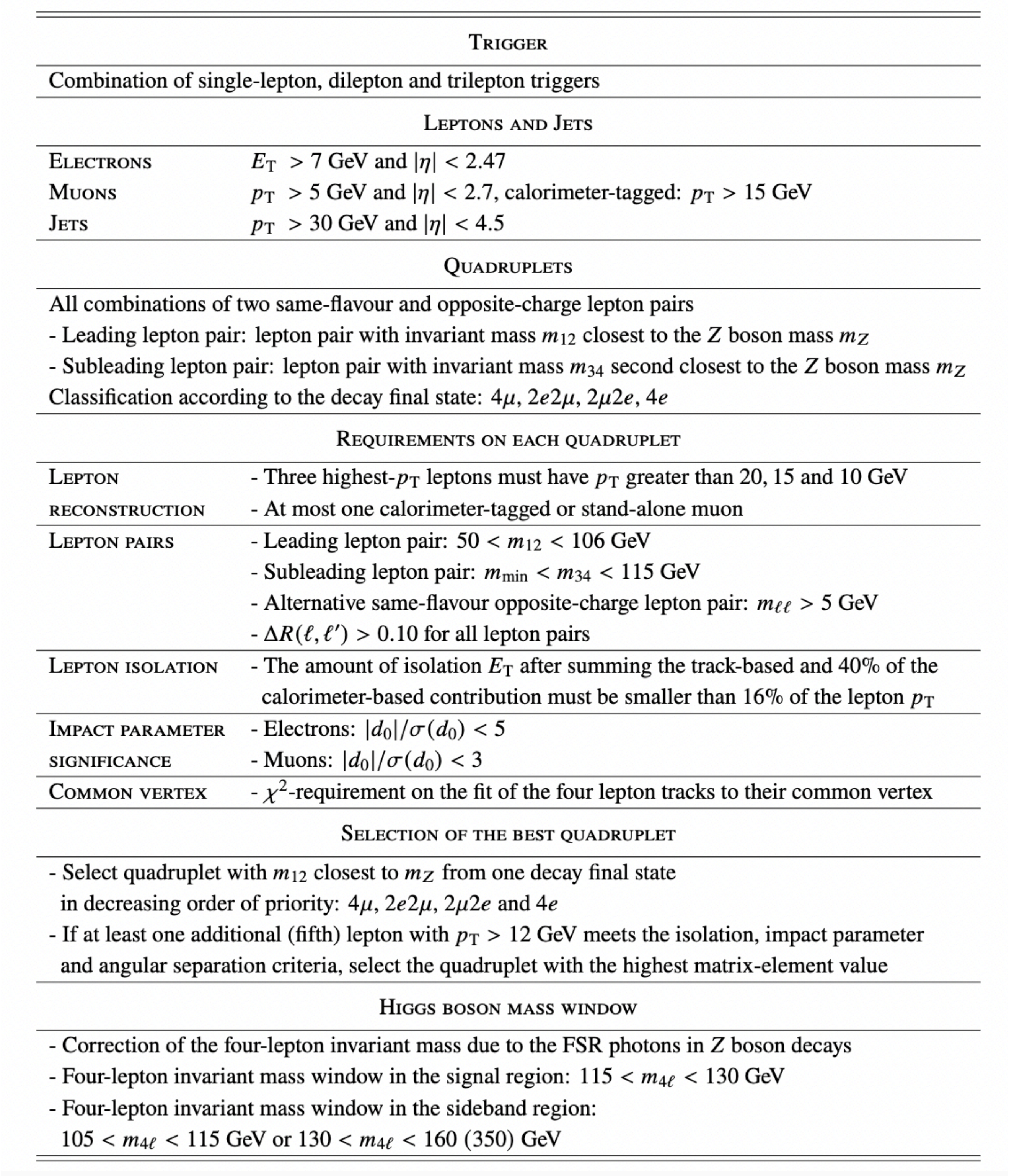
Conclusions

Conclusion/Discussion

- Two approaches of probing quantum entanglement in H→ZZ(*) processes presented:
    - Off-shell Higgs boson regime: measuring the LL polarisations
        - Crucial is to have reliable MC model
        - Crucial is to separate the LL component from other polarisations and the background
    - On-shell Higgs boson regime: measuring the spin density matrix coefficients from the full reconstruction of the relevant event kinematics
        - Crucial is to understand how the measurement is affected by the presence of detector effects, event selections, HO corrections, PS, UE, PDF, FSR, etc
            - Apply unfolding?
            - Build templates?
            - Use unbinned data?

Backup

Event selections in on-shell Higgs regime



TRIGGER	
Combination of single-lepton, dilepton and trilepton triggers	
LEPTONS AND JETS	
ELECTRONS	$E_{\mathrm{T}} > 7$ GeV and $\lvert\eta\rvert < 2.47$
MUONS	$p_{\mathrm{T}} > 5$ GeV and $\lvert\eta\rvert < 2.7$, calorimeter-tagged: $p_{\mathrm{T}} > 15$ GeV
JETS	$p_{\mathrm{T}} > 30$ GeV and $\lvert\eta\rvert < 4.5$
QUADRUPLETS	
All combinations of two same-flavour and opposite-charge lepton pairs - Leading lepton pair: lepton pair with invariant mass m_{12} closest to the Z boson mass m_Z - Subleading lepton pair: lepton pair with invariant mass m_{34} second closest to the Z boson mass m_Z Classification according to the decay final state: 4μ, $2e2\mu$, $2\mu2e$, $4e$	
REQUIREMENTS ON EACH QUADRUPLET	
LEPTON RECONSTRUCTION	- Three highest-p_{T} leptons must have p_{T} greater than 20, 15 and 10 GeV - At most one calorimeter-tagged or stand-alone muon
LEPTON PAIRS	- Leading lepton pair: $50 < m_{12} < 106$ GeV - Subleading lepton pair: $m_{\mathrm{min}} < m_{34} < 115$ GeV - Alternative same-flavour opposite-charge lepton pair: $m_{\ell\ell} > 5$ GeV - $\Delta R(\ell,\ell') > 0.10$ for all lepton pairs
LEPTON ISOLATION	- The amount of isolation E_{T} after summing the track-based and 40% of the calorimeter-based contribution must be smaller than 16% of the lepton p_{T}
IMPACT PARAMETER SIGNIFICANCE	- Electrons: $\lvert d_0\rvert/\sigma(d_0) < 5$ - Muons: $\lvert d_0\rvert/\sigma(d_0) < 3$
COMMON VERTEX	- χ^2-requirement on the fit of the four lepton tracks to their common vertex
SELECTION OF THE BEST QUADRUPLET	
- Select quadruplet with m_{12} closest to m_Z from one decay final state in decreasing order of priority: 4μ, $2e2\mu$, $2\mu2e$ and $4e$ - If at least one additional (fifth) lepton with $p_{\mathrm{T}} > 12$ GeV meets the isolation, impact parameter and angular separation criteria, select the quadruplet with the highest matrix-element value	
HIGGS BOSON MASS WINDOW	
- Correction of the four-lepton invariant mass due to the FSR photons in Z boson decays - Four-lepton invariant mass window in the signal region: $115 < m_{4\ell} < 130$ GeV - Four-lepton invariant mass window in the sideband region: $105 < m_{4\ell} < 115$ GeV or $130 < m_{4\ell} < 160$ (350) GeV	

[arxiv:2004.03447]

Event selections in off-shell Higgs regime

- 4l channel
    - ZZ->4l selection
        - 2 same-flavor, opposite-charge lepton pairs
        - Leading $p_T^{\text{lepton}} >$ 20,15,10 GeV
        - $220 < m_{4\ell} < 2000$ GeV / $180 < m_{4\ell} < 220$ GeV (for CRs)
        - $50 < m_{12} < 106$ GeV and $50 - \max(0,(190 - m_{4\ell})/2) < m_{34} < 115$ (pair 12 defined as the pair closest to m_Z)

- 2l2v channel
    - ZZ->4l selection
        - 1 same-flavor, opposite-charge lepton pair
        - Leading $p_T^{\text{lepton}} >$ 30, 20 GeV
        - $76 < m_{\ell\ell} < 106$ GeV
        - $E_T^{\text{miss}} > 120$ GeV
    - Bkg rejection cuts
        - 3th lepton veto
        - $\Delta R_{\ell\ell} < 1.8$
        - $\Delta\phi(Z, E_T^{\text{miss}}) > 2.5$ and $\Delta\phi(\text{jetp}_T > 100\text{GeV}, \text{E}_T^{\text{miss}}) > 0.4$
        - E_T^{miss} significance >10
        - B-jet veto

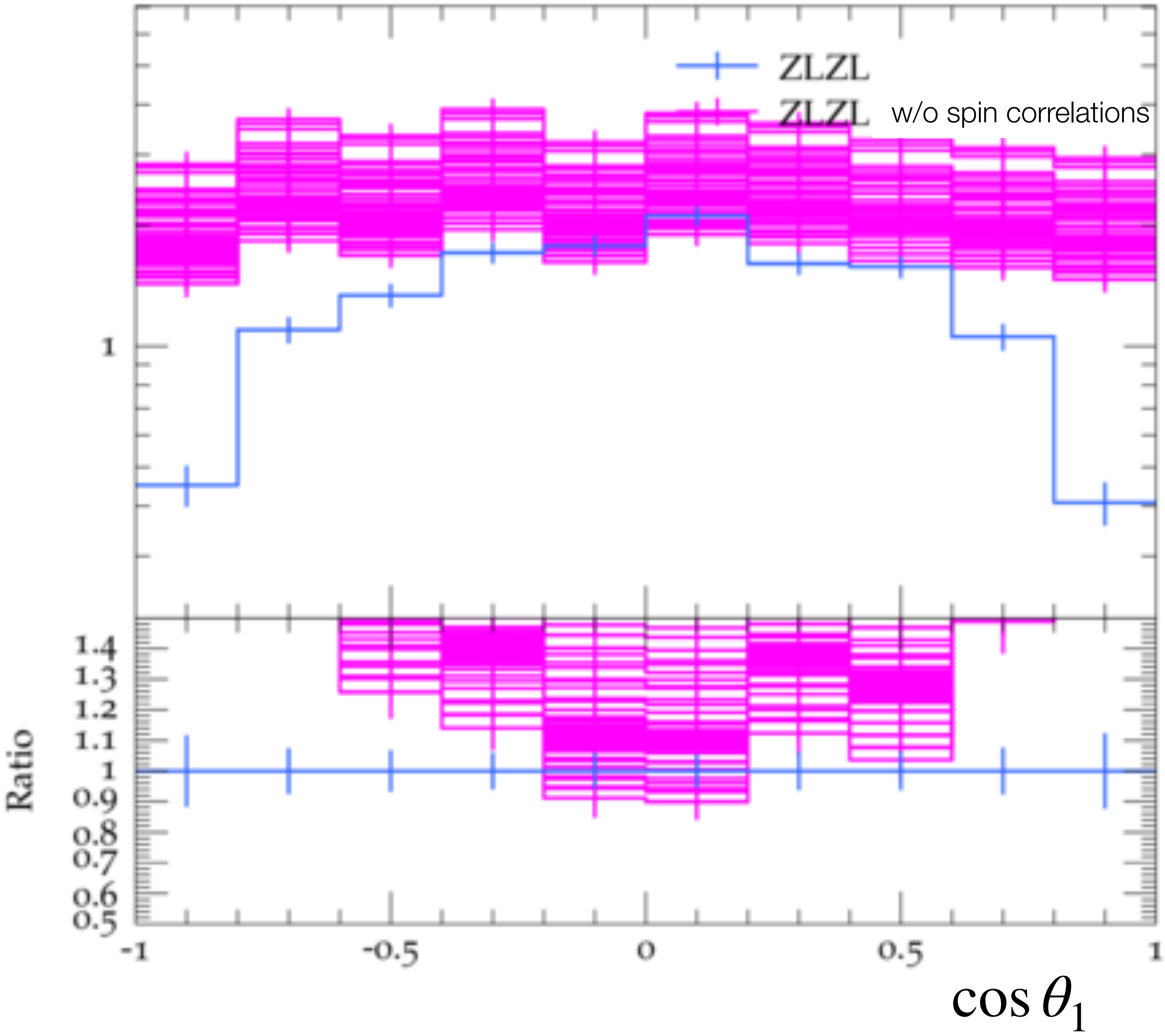
[ATLAS-CONF-2022-068]

ggZZ sample used in the off-shell analysis

- Generated with Sherpa v2.2.2 + OpenLoops
  - MEs calculated for 0 jets and 1 jet at LO and merged with Sherpa parton shower
- Higher order theory corrections
  - **NLO QCD** corrections [Caola et al., 2015] [Caola et al., 2016]
    - Available for the full process $gg \rightarrow (H^* \rightarrow)ZZ$
    - m_{ZZ} differential **NLO/LO k-factors**
    - **No such k-factors for the polarisation states available: in contact with the authors**
  - **NNLO QCD** corrections [Passarino], [Handbook of LHC Higgs x-sections]
    - Available only for the signal process $gg \rightarrow H^* \rightarrow ZZ$ as a function of m_{ZZ}
    - Additional flat **NNLO/NLO K-factor** of 1.2

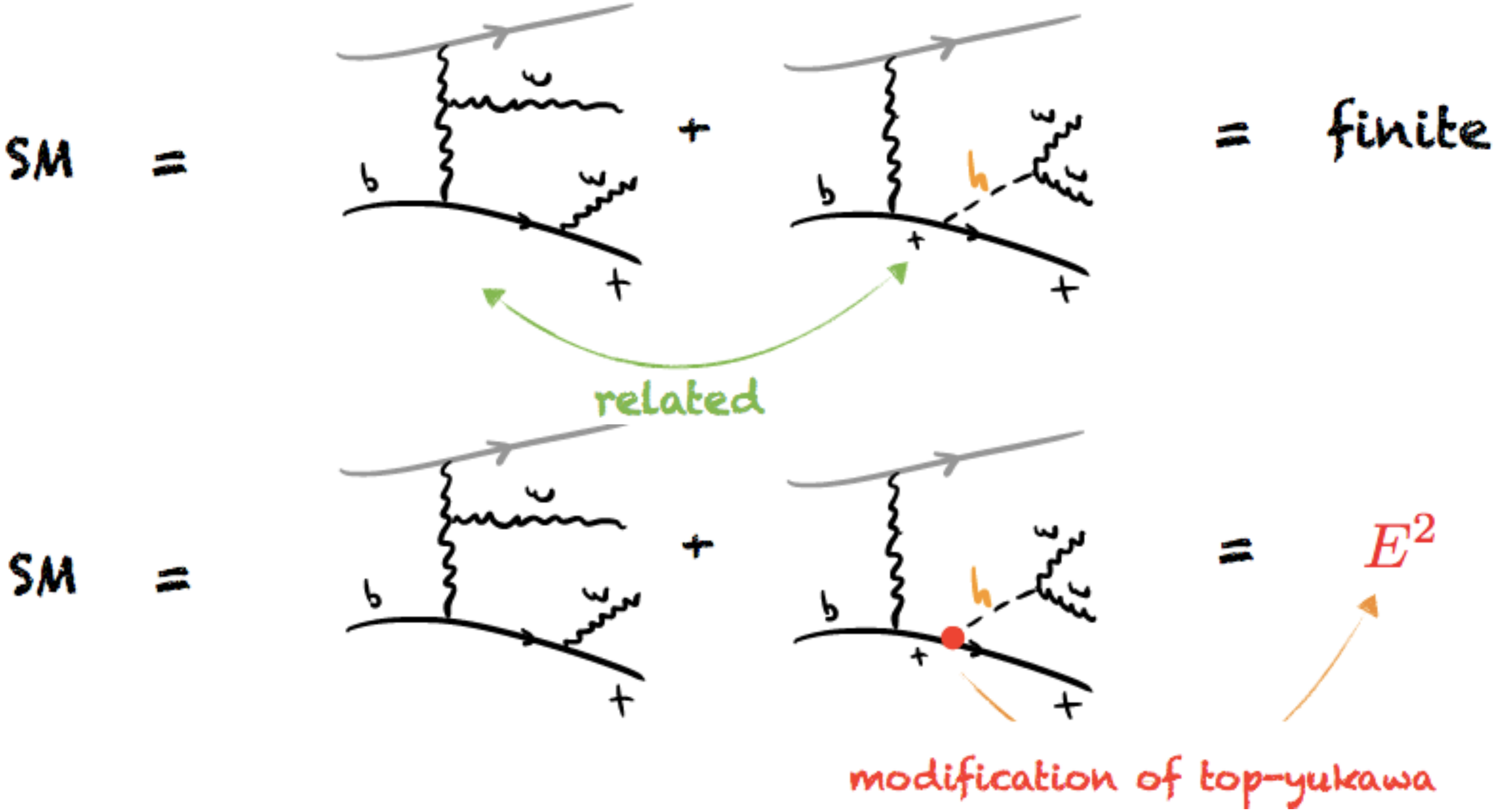
Spin correlations

- The shape of $\cos\theta_1$ distribution is sensitive to spin correlations



Longitudinally polarised vector bosons

Test the Higgs couplings in the off-shell region via their contributions to the physics of **longitudinally** polarised gauge bosons [Higgs Couplings without the Higgs]

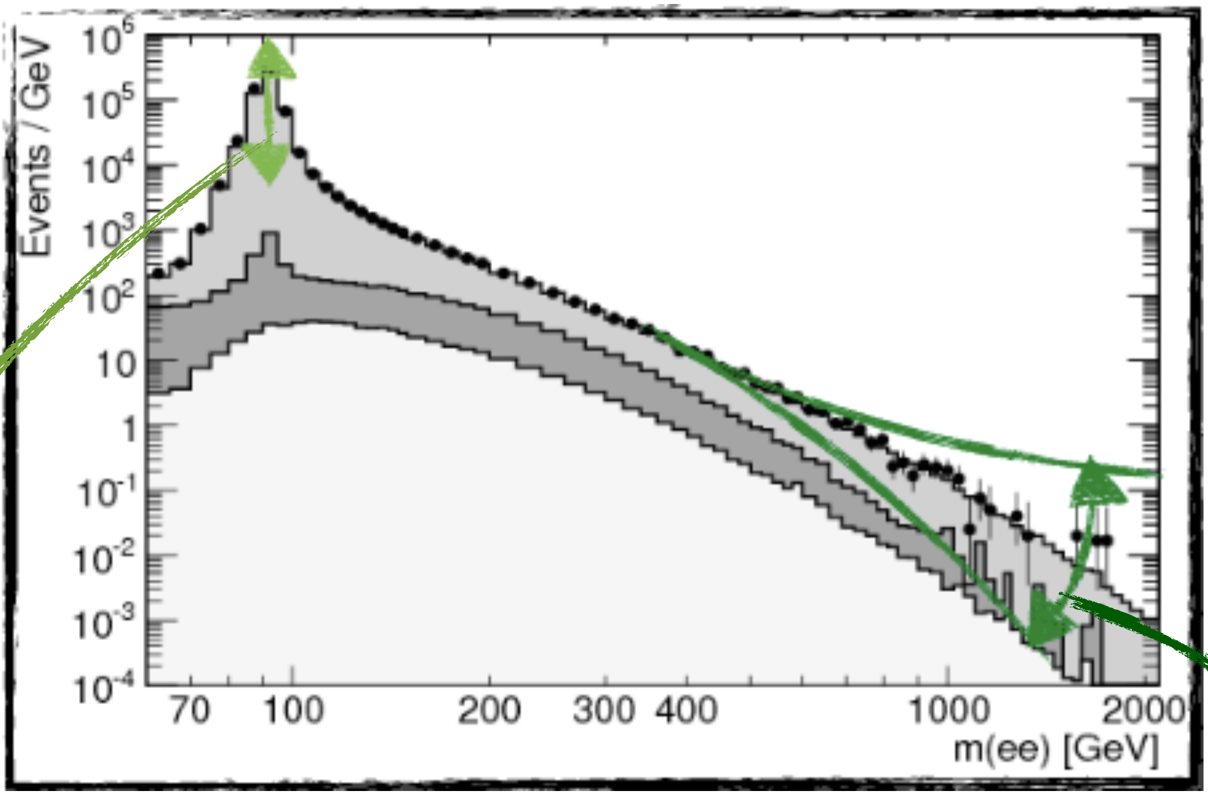


From Francesco Riva’s slides

Longitudinally polarised vector bosons

Longitudinally polarised vector bosons

Test the Higgs couplings in the off-shell region via their contributions to the physics of **longitudinally** polarised gauge bosons [Higgs Couplings without the Higgs]



$$\sigma = \sigma_{\mathrm{SM}}\left(1 + c\frac{E^2}{\Lambda^2} + \dots\right)$$

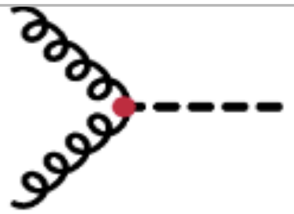
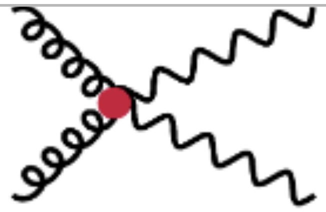
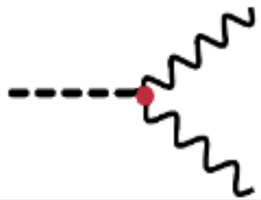
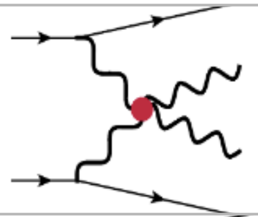
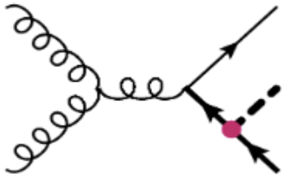
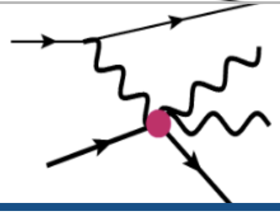
$$\left.\frac{\delta\sigma}{\sigma_{\mathrm{SM}}}\right|_{\sqrt{s}=m_H} \sim 1\,\%$$

$$\left.\frac{\delta\sigma}{\sigma_{\mathrm{SM}}}\right|_{\sqrt{s}=1\mathrm{TeV}} \sim \mathcal{O}(1)$$

From Francesco Riva’s slides

Longitudinally polarised vector bosons

Which coupling constants we can probe?

Interpretation		Energy growth	
κ – framework	EFT approach	$\sim$ const	$\sim E^2$
κ_G	$\lvert H\rvert^2 G^a_{\mu\nu}G^{a,\mu\nu}$		
κ_V	$\lvert H\rvert^2 \partial_\mu H^\dagger \partial^\mu H$		
κ_t	$\lvert H\rvert^2 Q\tilde{H}t_R$		

Longitudinally polarised vector bosons

ME ratio at LHE level

- ME ratio: $D_{ME} = \log10(\mathrm{ME2}_{ZL}/\mathrm{ME2}_{ZT})$