Polarized off-shell measurements

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Motivation

- Why is it interesting about the measurement of polarized ggZZ processes?
  - Polarized VBF process already measured (e.g. Measurements of production cross sections of polarized same-sign WWjj)
  - Polarization of ggF processes not yet explored
- Why investigate the Higgs boson off-shell regime?
  - Enables to test the Higgs couplings via their contributions to the physics of **longitudinally** polarised gauge bosons [Higgs Couplings without the Higgs]
  - Novel approach to explore new measurements, EFT interpretations etc

How to generate the polarised ggZZ processes?

- MadGraph model provided by *Richard Ruiz*: **SM_Loop_ZPolar_NLO**
- 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**
    - Auxiliary propagator accounts for the off-shell behaviour of particles
    - on-shell particle: propagator = (transverse part) + (longitudinal part)
    - off-shell particle: propagator = (transverse part) + (longitudinal part) + (auxiliary part)

Event generation with MadGraph5

- MEs calculated up to one additional parton in the final state
  - gg -> ZLZL
  - gg -> ZTZT
  - gg -> ZZ

```
import model SM_Loop_ZPolar_NLO

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

generate    g g > e+ e- mu+ mu-   QED=4 QCD=2 [noborn = QCD] / a z z0 za @0
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```

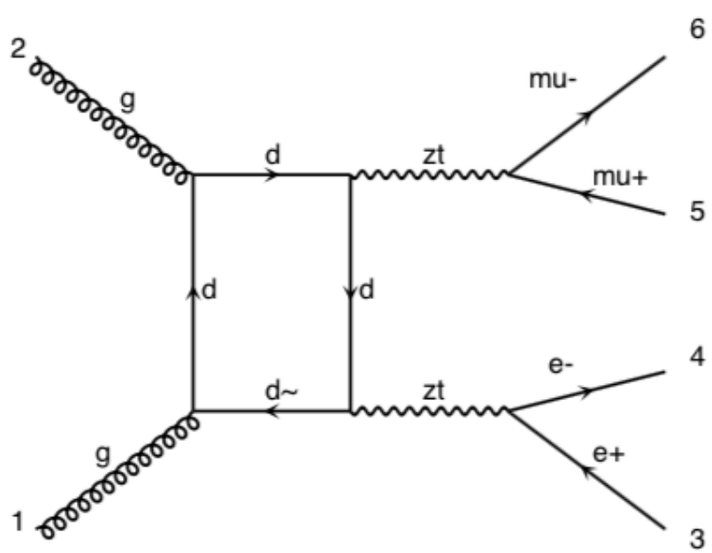


diagram 3 QCD=2, QED=4

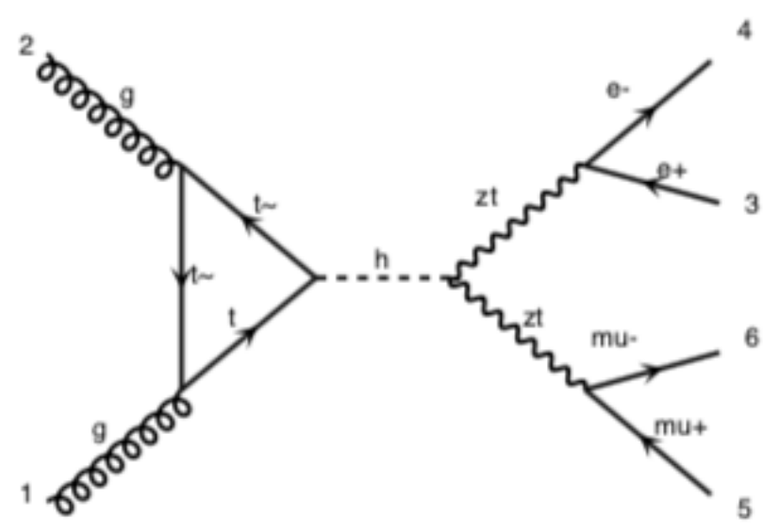


diagram 52 QCD=2, QED=4

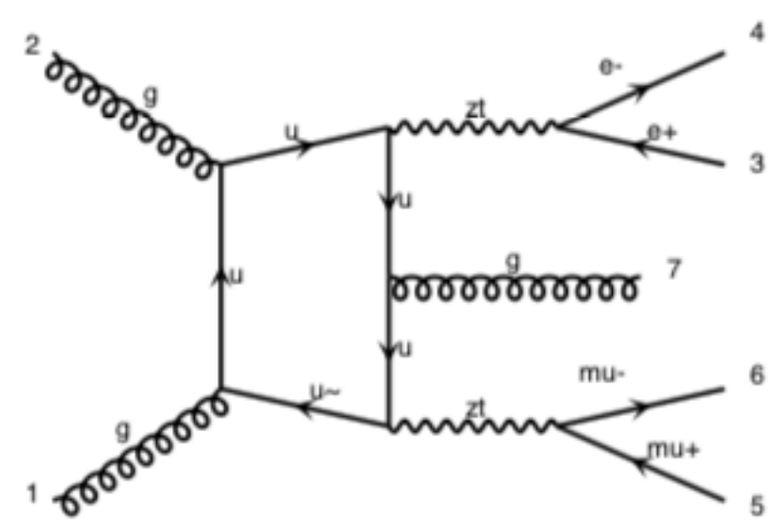


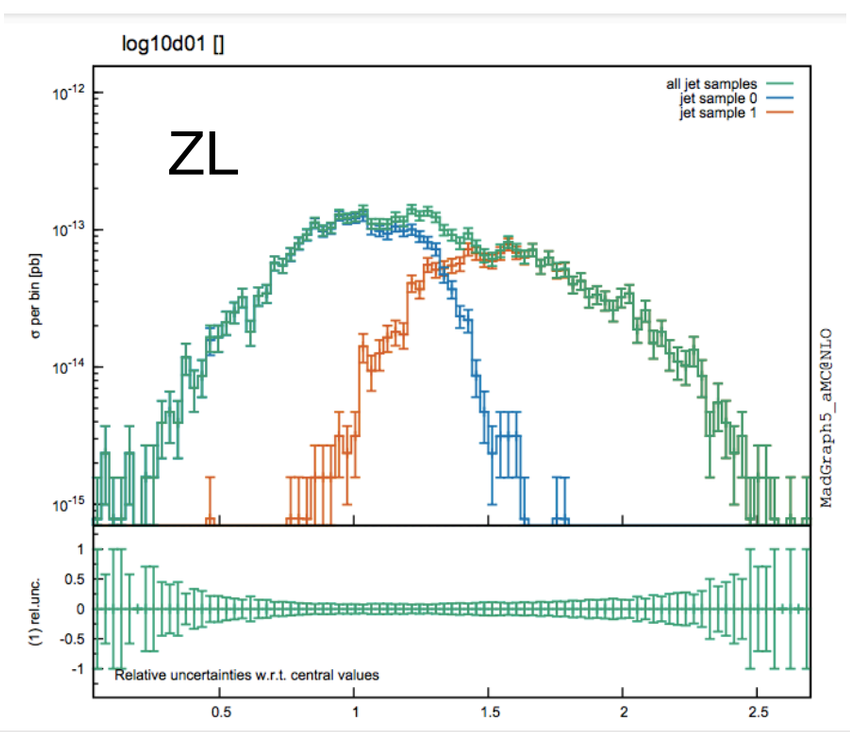
diagram 139 QCD=3, QED=4

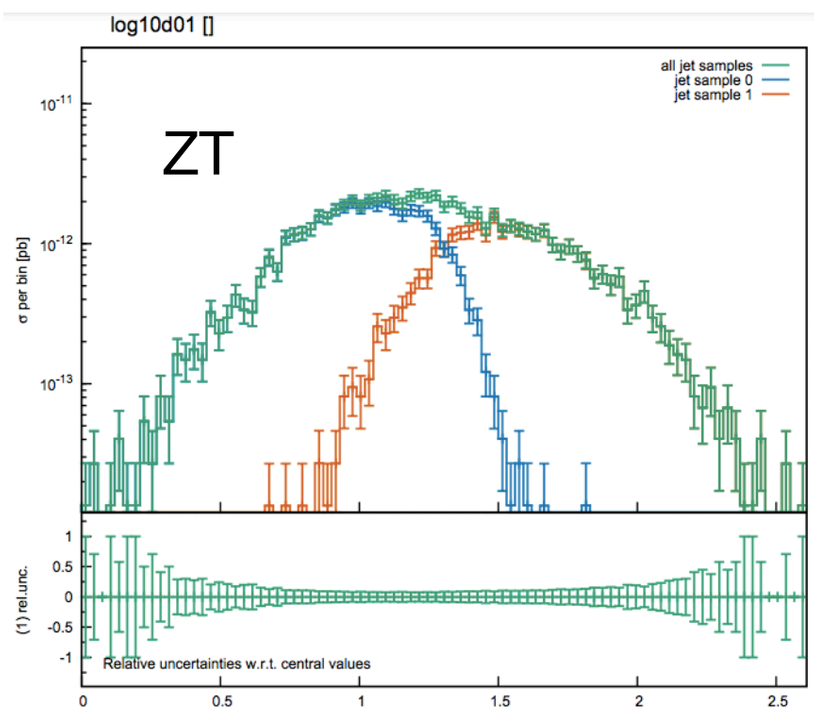
Matching strategy

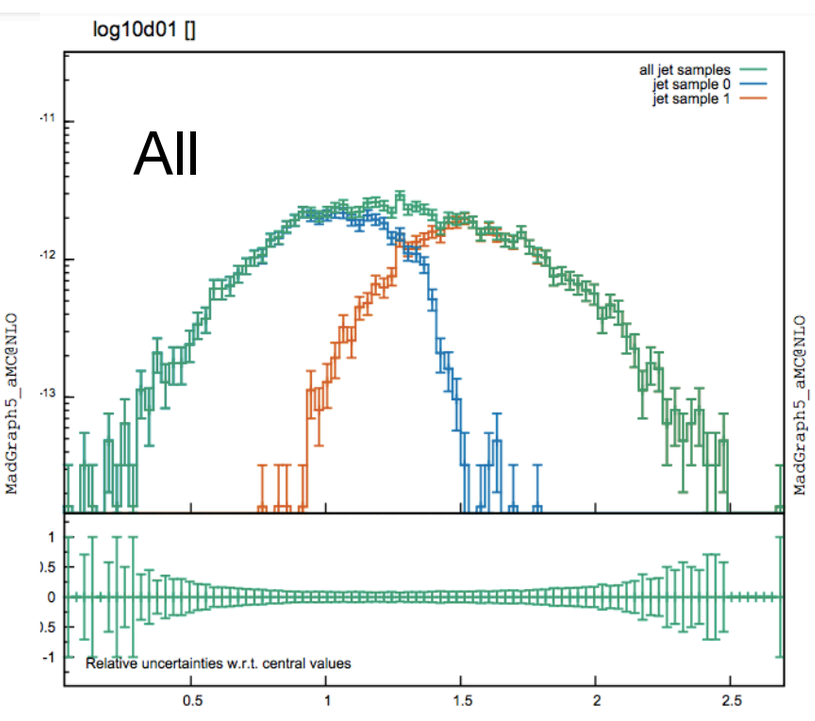
- kT-jet MLM matching scheme used
  - xqCut = 20 (set xqcut 20)
  - qCut = 30 (set JetMatching:qCut 30)
  - nJetMax=1 (set JetMatching:nJetMax 1)

```
set nevents 15000
set use_syst false
set mmll 45
set mmnl 150
set ptl 3
set etal 2.8
set ptj 5
set ptb 5
set etaj 6.5
set etab 6.5
set mmjj 10
set mmbb 10
set ickkw 1
set xqcut 20
set JetMatching:qCut 30
set JetMatching:nJetMax 1
```

✓Validated by looking at the differential jet rate plots: *smooth*







Adding NLO (via LO 0+1 merged jets) corrections

- Adding partial NLO corrections to ggZZ

```
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
```

- Loop diagram filter applied in order to remove NNLO corrections to qqZZ

```
if any([abs(pdg) not in range(1,7) for pdg in diag.get_loop_lines_pdgs()]) or
(23 not in diag.get_pdgs_attached_to_loop(structs) and 230 not in diag.get_pdgs_attached_to_loop(structs) and
231 not in diag.get_pdgs_attached_to_loop(structs) and 232 not indiag.get_pdgs_attached_to_loop(structs)
and 25 not in diag.get_pdgs_attached_to_loop(structs)):
        valid_diag = False
```

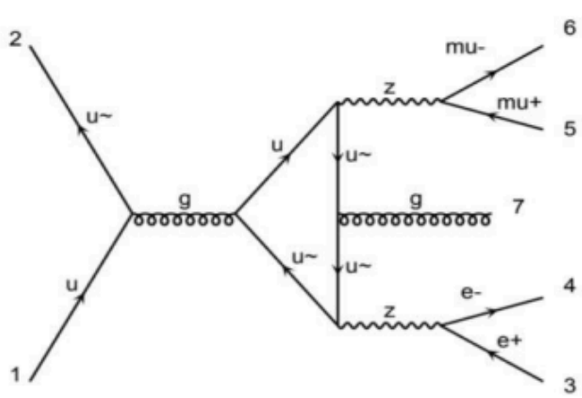


diagram 29 QCD=3, QED=4

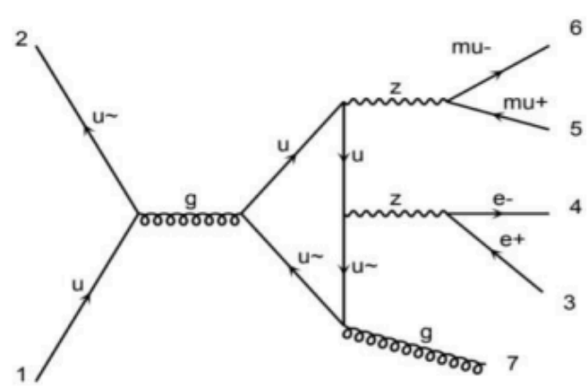


diagram 30 QCD=3, QED=4

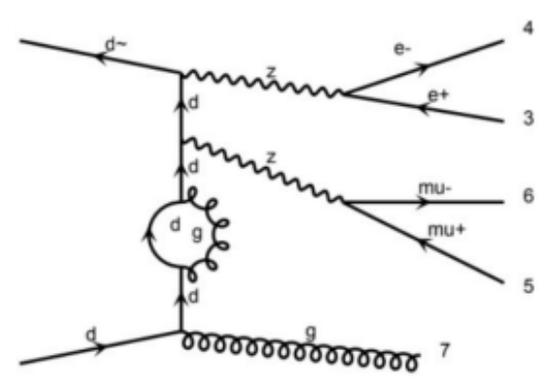


diagram 101 QCD=3, QED=4

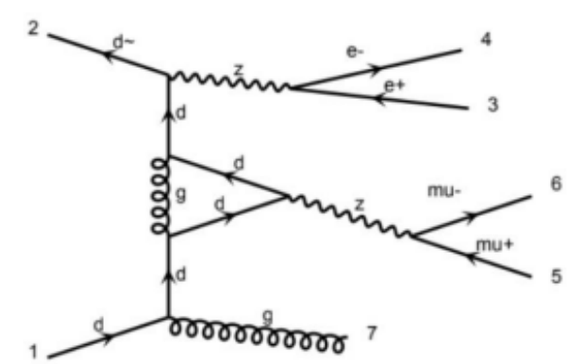


diagram 102 QCD=3, QED=4

Adding NLO (via LO 0+1 merged jets) corrections

- Adding partial NLO corrections to ggZZ

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231 not in diag.get_pdgs_attached_to_loop(structs) and 232 not indiag.get_pdgs_attached_to_loop(structs)
and 25 not in diag.get_pdgs_attached_to_loop(structs)):
        valid_diag = False
```

- Cross-sections before / after additional NLO corrections
  - gg -> ZLZL: 0.0512 fb / 0.0577 fb
  - gg -> ZTZT: 0.8443 fb / 0.9483 fb
  - gg -> ZZ: 1.036 fb / 1.172 fb

Analysis strategy

Similar strategy as in the measurement of off-shell Higgs boson production in the $Z \to 4\ell$ at $\sqrt{s} = 13$ TeV with the data of $36.1\ \mathrm{fb}^{-1}$ [ATLAS paper]

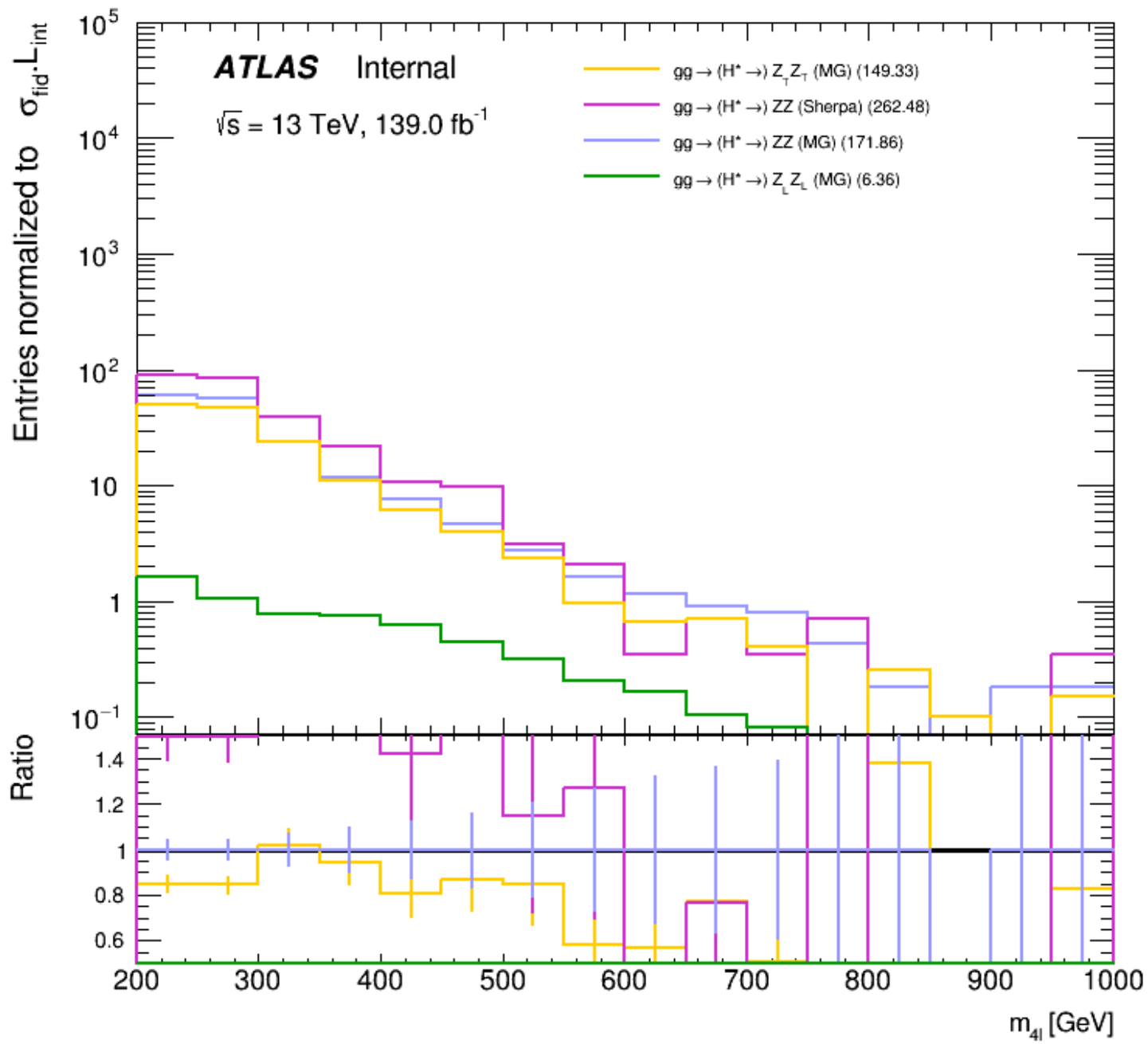
- **Main event selections**
  - Four-lepton candidates are formed by selecting a lepton-quadruplet made out of two same-flavour, opposite-sign lepton pairs
  - $m_{4\ell} > 220$ GeV, $m_{Z1} \in [50,106]$ GeV, $m_{Z2} \in [50,115]$ GeV
- **Discriminant variables**
  - Calculate ME at LO for longitudinally and transverse polarised Z-bosons to enhance the separation between gg -> ZLZL and gg -> ZTZT
  - Parametrise gg -> ZTZL contribution via: ZZ-ZTZT-ZLZL (in a given observable)
  - Use these variables in a binned maximum-likelihood fit for the final result

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 $gg \to (H^* \to)ZZ$
    - m_{ZZ} differential **NLO/LO K-factors**
  - **NNLO QCD** corrections [Passarino], [Handbook of LHC Higgs x-sections]
    - Available only for the signal process $gg \to H^* \to ZZ$ as a function of m_{ZZ}
    - Additional flat **NNLO/NLO K-factor** of 1.2

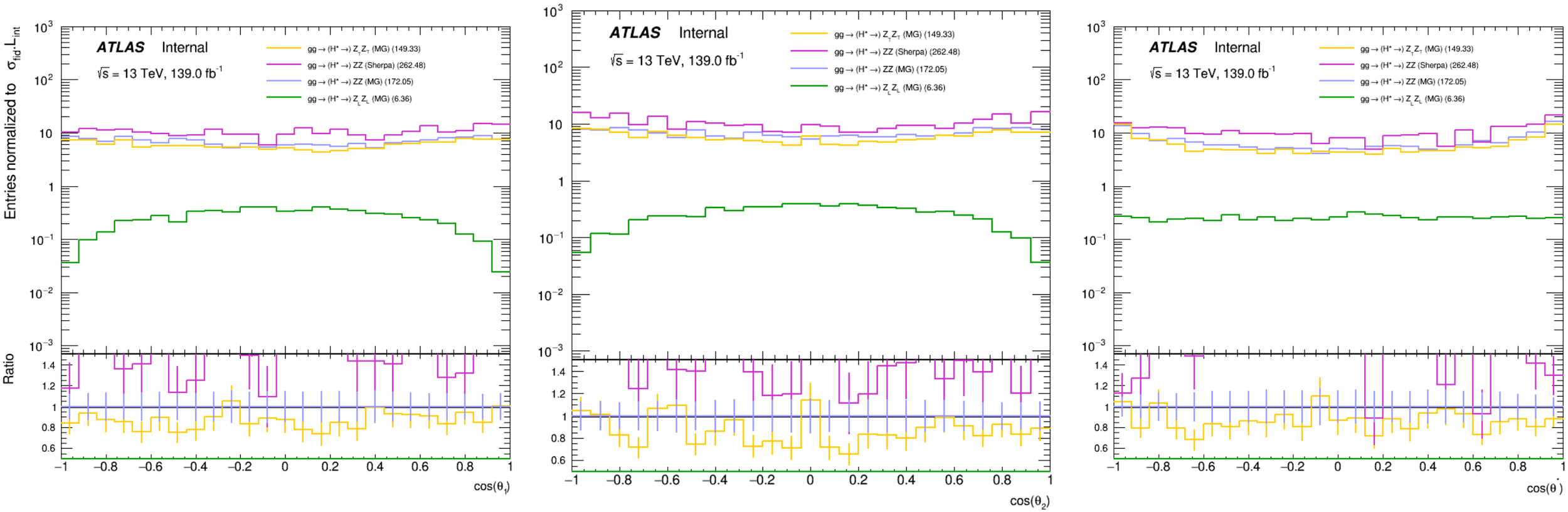
▸ **Plan to derive similar K-factors for MadGraph samples as well**

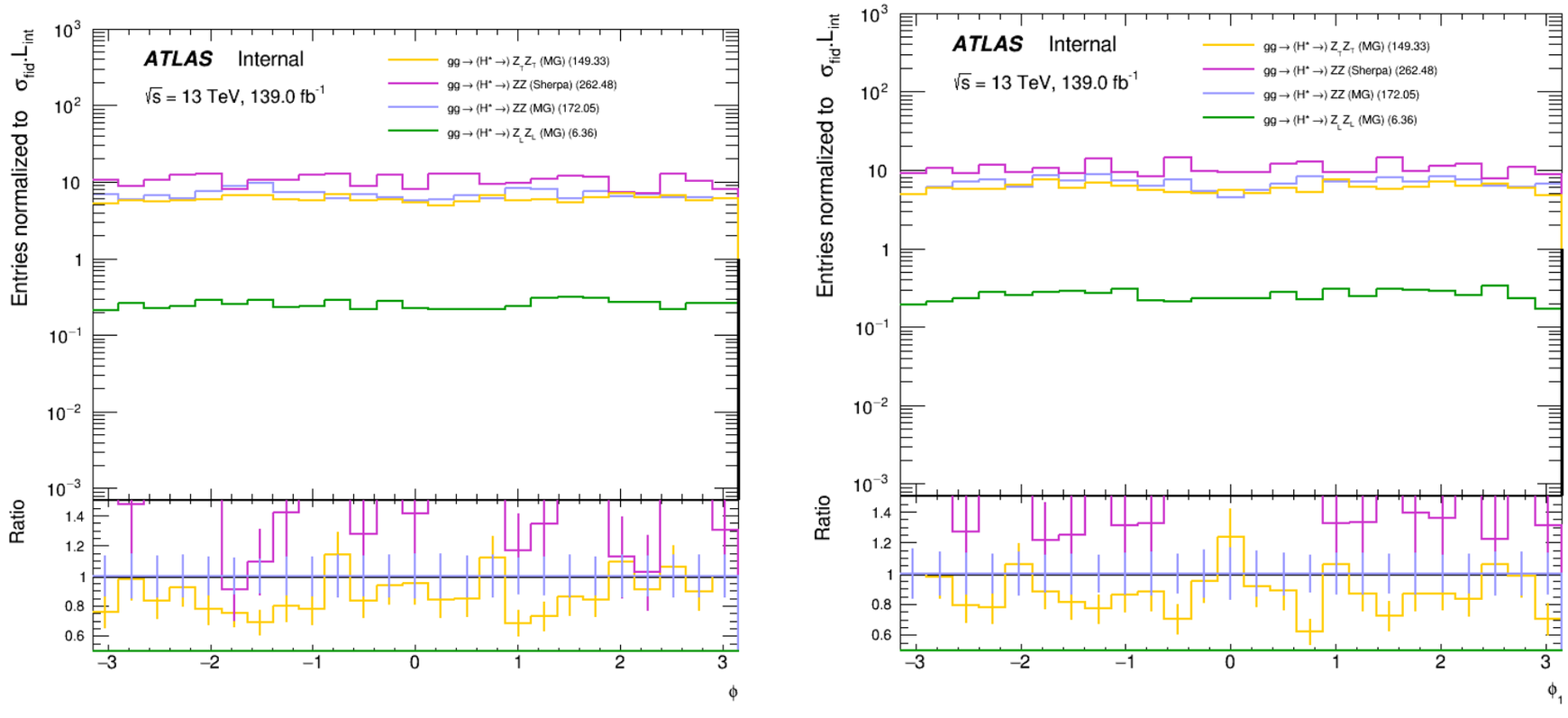
Distributions: m4l



- For a fair comparison, Sherpa sample not weighted to NNLO

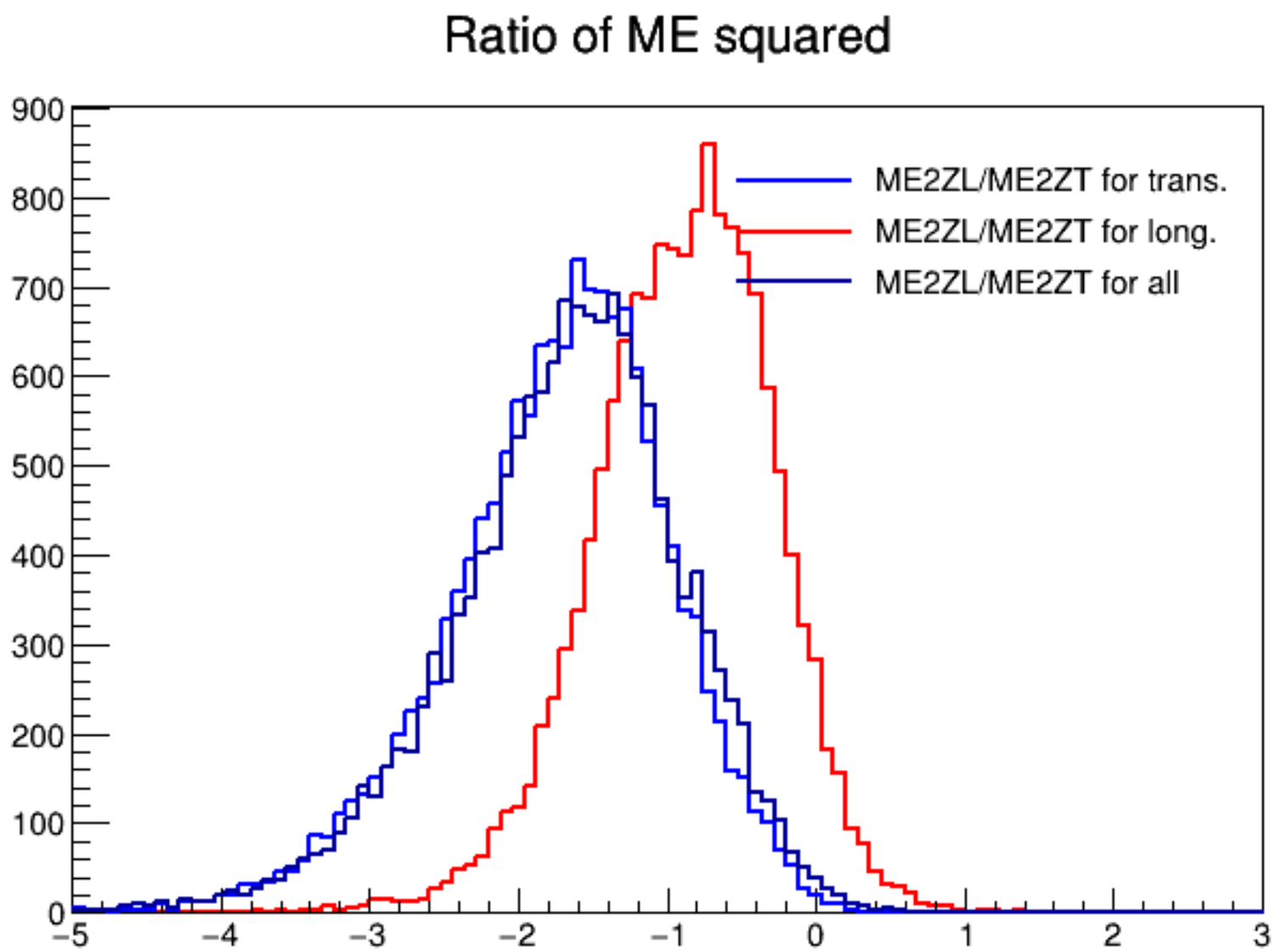
Distributions: helicity angles





Distributions: matrix element ratio

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



Conclusions

- Generated polarized ggZZ samples with MadGraph5
- Validated MLM matching
- Additional (only partial) NLO corrections increased the x-sections by ~13%
- Need to apply m_{ZZ} differential K-factors to account for higher order theory corrections (similarly as for the Sherpa samples)
- Constructed ME-based discriminant to enhance the separation between longitudinal and transverse contributions
- Ability to measure longitudinal ggZZ states opens the door to explore new SM measurements and EFT interpretations