Prospects for longitudinal ZZ scattering

C. Charlot

VBS Polarization workshop, Oct. 10-12, Palaiseau

Outline

- Motivation
- Current result for VBS ZZ
- Polarization study (Phantom)
  - Effect of p_T and η lepton cuts
- Very first look at backgrounds

Why ZZ in fully leptonic?

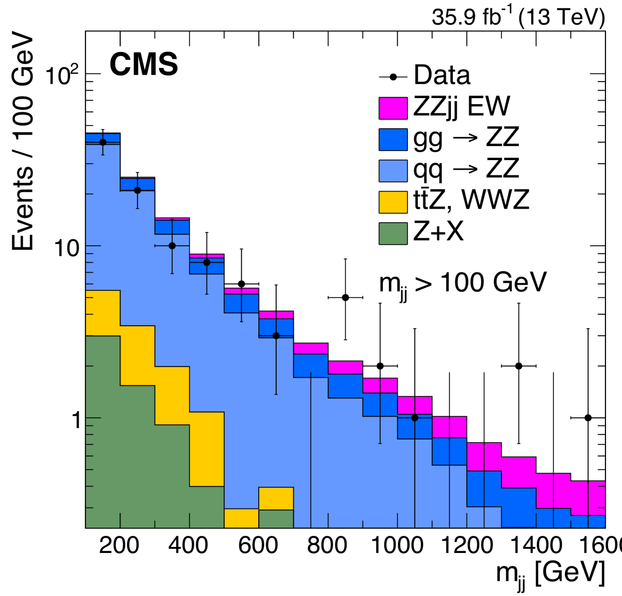
- Precise reconstruction o(%) of Z decays
  - Precise reconstruction of the scattering energy with m_{4l}
  - Precise determination of angular correlations
- Low reducible backgrounds
- Reliable projections from (simplistic) gen level studies
- But very low cross section

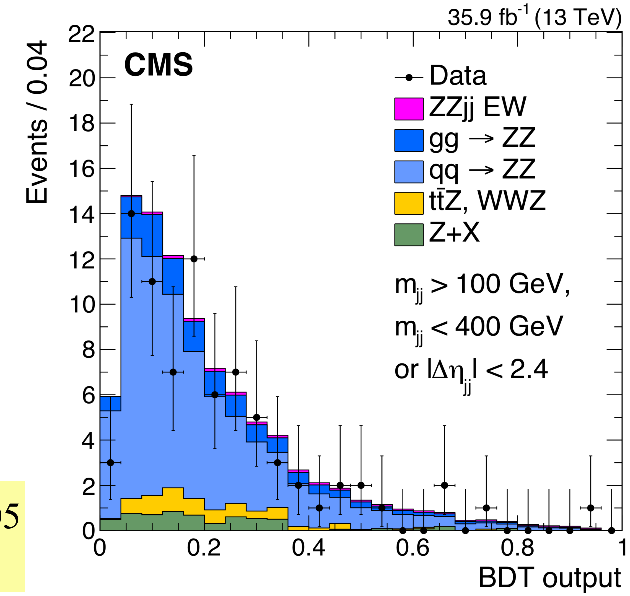
CMS 2016 analysis

- Low statistics, don't want to throw away events => multivariate classifier (BDT)
- $p_{Tj1,2}$>30 GeV, p_T(lepton)>7(5) GeV, $|\eta$(lepton)$|$ <2.5(2.4), m_{jj}>100 GeV
- Input variables: m_{jj}, $\Delta\eta_{jj}$, z_1^*, z_2^*, p_T balance, dijet p_T balance, m_{4l} (no 3[rd] jet veto)
- BDT optimized, performance checked against Matrix Element Approach, also cut based
- Signal extracted from template fit of the BDT distributions to the data
- Background validated in QCD enriched CR (m_{jj}<400 GeV or $|\Delta\eta_{jj}|$<2.4)

P. Pigard's PhD thesis

PLB 774 (2017) 682-705
SMP-17-006





CMS 2016 results

Selection	$t\bar{t}Z$ and WWZ	QCD ZZjj	Z+X	Total bkg.	EW ZZjj	Total expected	Data
ZZjj	7.1 ± 0.8	97 ± 14	6.6 ± 2.5	111 ± 14	6.2 ± 0.7	117 ± 14	99
VBS	0.9 ± 0.2	19 ± 4	0.7 ± 0.3	20 ± 4	4 ± 0.5	25 ± 4	19

VBS selection: m_{jj}>400 GeV $|\Delta\eta_{jj}|$>3.6

- Signal strength:

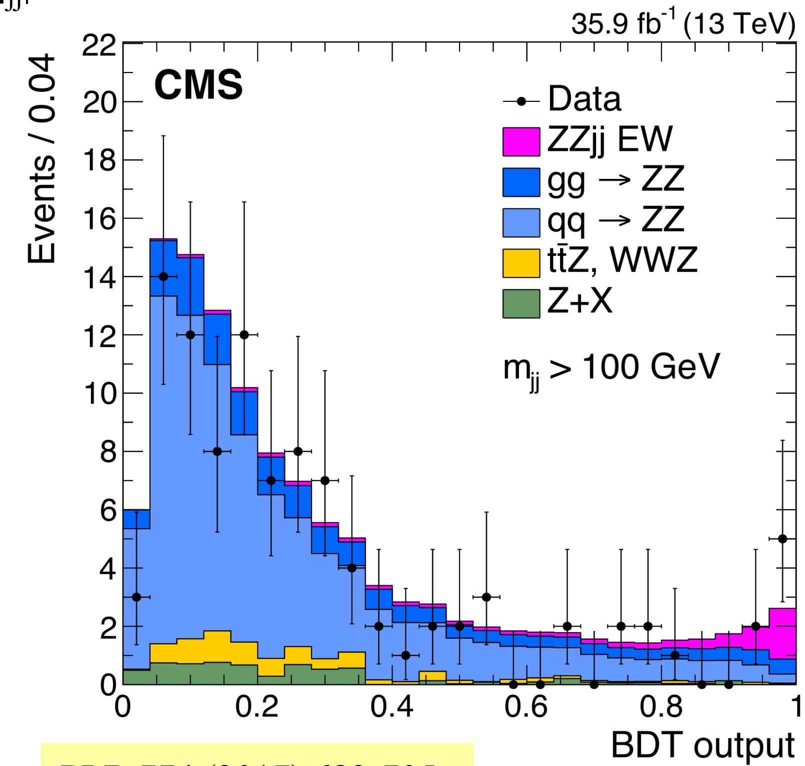
$$\mu = 1.39^{+0.72}_{-0.57}\,(\text{stat})\,^{+0.46}_{-0.31}\,(\text{syst}) = 1.39^{+0.86}_{-0.65}$$

- Observed significance: 2.7σ (expected 1.6σ)

- Fiducial cross section:

$$\sigma_{\text{EW}}(\text{pp} \to \text{ZZjj} \to \ell\ell\ell'\ell'\text{jj}) = 0.40^{+0.21}_{-0.16}\,(\text{stat})\,^{+0.13}_{-0.09}\,(\text{syst})\,\text{fb}$$

Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper
f_{T_0}/Λ^4	−0.53	0.51	−0.46	0.44
f_{T_1}/Λ^4	−0.72	0.71	−0.61	0.61
f_{T_2}/Λ^4	−1.4	1.4	−1.2	1.2
f_{T_8}/Λ^4	−0.99	0.99	−0.84	0.84
f_{T_9}/Λ^4	−2.1	2.1	−1.8	1.8



PLB 774 (2017) 682-705

Constraints on f_{T0} stronger than from ssWW (weaker for f_{T1} and similar for f_{T2})

Polarization study

Final state: $pp \rightarrow e^+e^-\mu^+\mu^-$ jj, generator level study

- Software setup
  - Phantom 1.5b (in collaboration with Phantom authors)
  - $\sqrt{s}$ = 13 TeV
  - NNPDF30_lo_as_130
  - QCD scales: $m_{4l}/\sqrt{2}$

A. Li internship

- Selection:
  - $p_T^j > 20$ GeV, $|\eta_j| < 5$
  - $m_{jj} > 600$ GeV, $|\Delta\eta_{jj}| > 3.6$, $\eta_{j1} \cdot \eta_{j2} << 0$
  - $m_{ZZ} > 2m_Z$
  - $m_{ll} > 40$ GeV
  - $86.2 < m_Z < 96.2$ GeV (as recomended by Phantom authors, see discussion by A. Ballestero)

Cross sections @ 13 TeV

$pp \to e^+e^-\mu^+\mu^-\, jj$, no lepton cuts

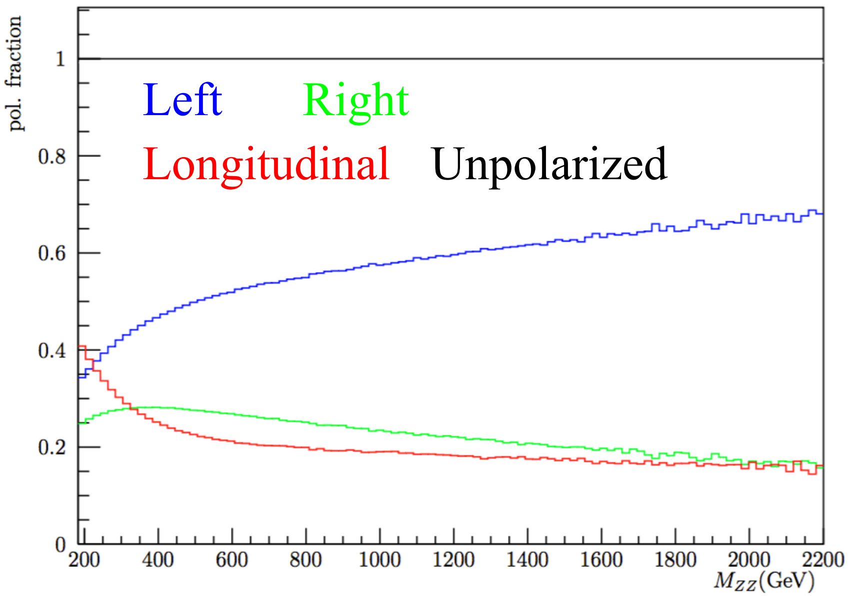
	Full	Z^e Left	Z^e Right	Z^e Long	Long-Long	TT	Long-T + T-Long
Cross section (fb)	0.064	0.029	0.017	0.018	0.005	0.034	0.025
Fraction	1	0.454	0.268	0.278	0.083	0.526	0.391

T = transverse

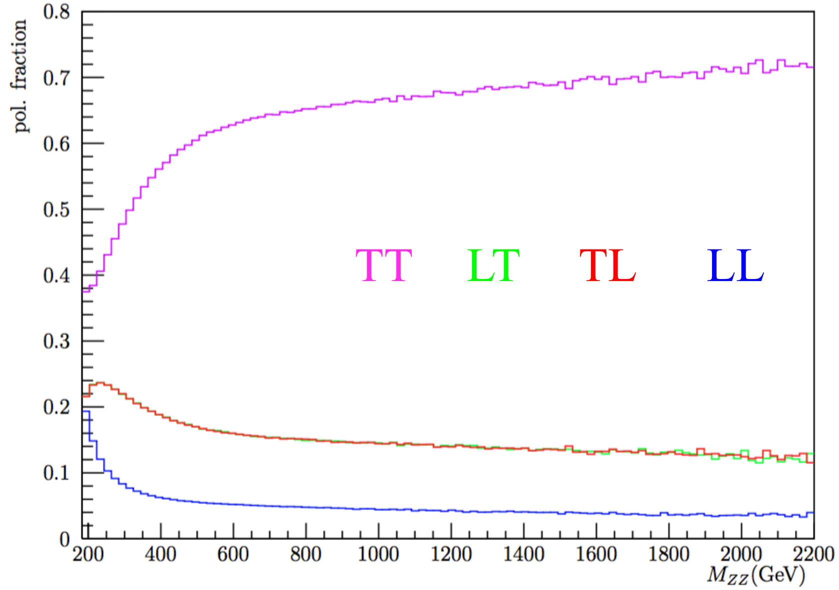
- Cross sections are small o(10^{-2}fb)
- longitudinal-longitudinal fraction: 8.3% (without lepton cuts)

Polarization fractions

Single polarization fractions (ee)



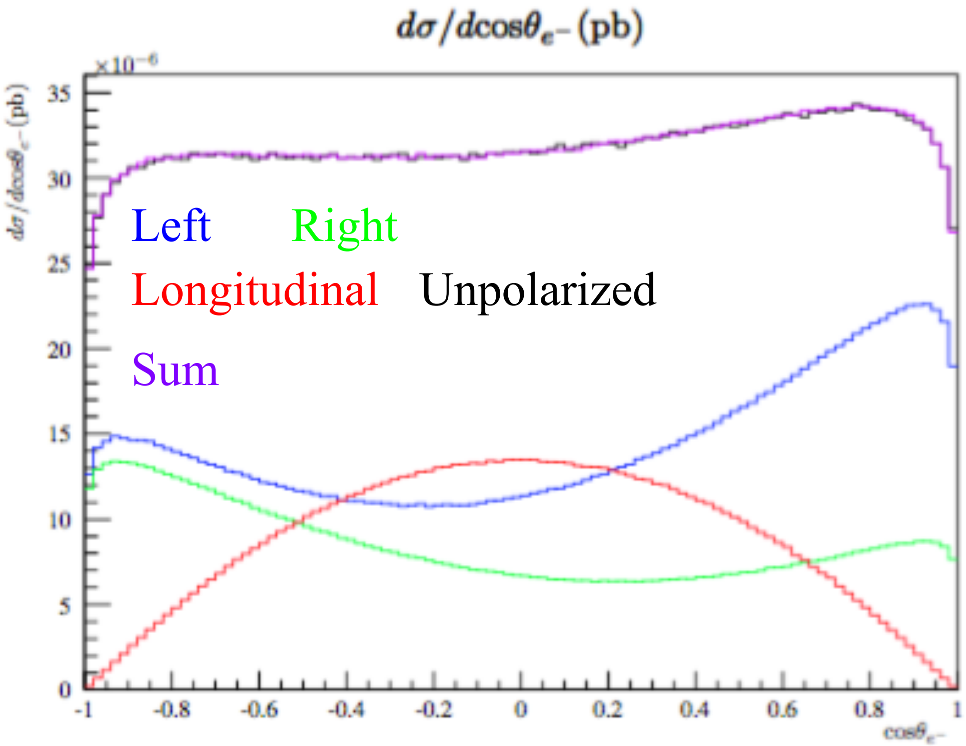
Double polarizations fraction



- long-long fraction: 8.3% integrated
- Peaks at ~2m_Z, decreases with increasing m_{ZZ}: ~5% for m_{ZZ}> 500 GeV

TT: transverse-transverse LT: longitudinal-transverse TL: transverse-longitudinal LL: longitudinal-longitudinal

Costheta



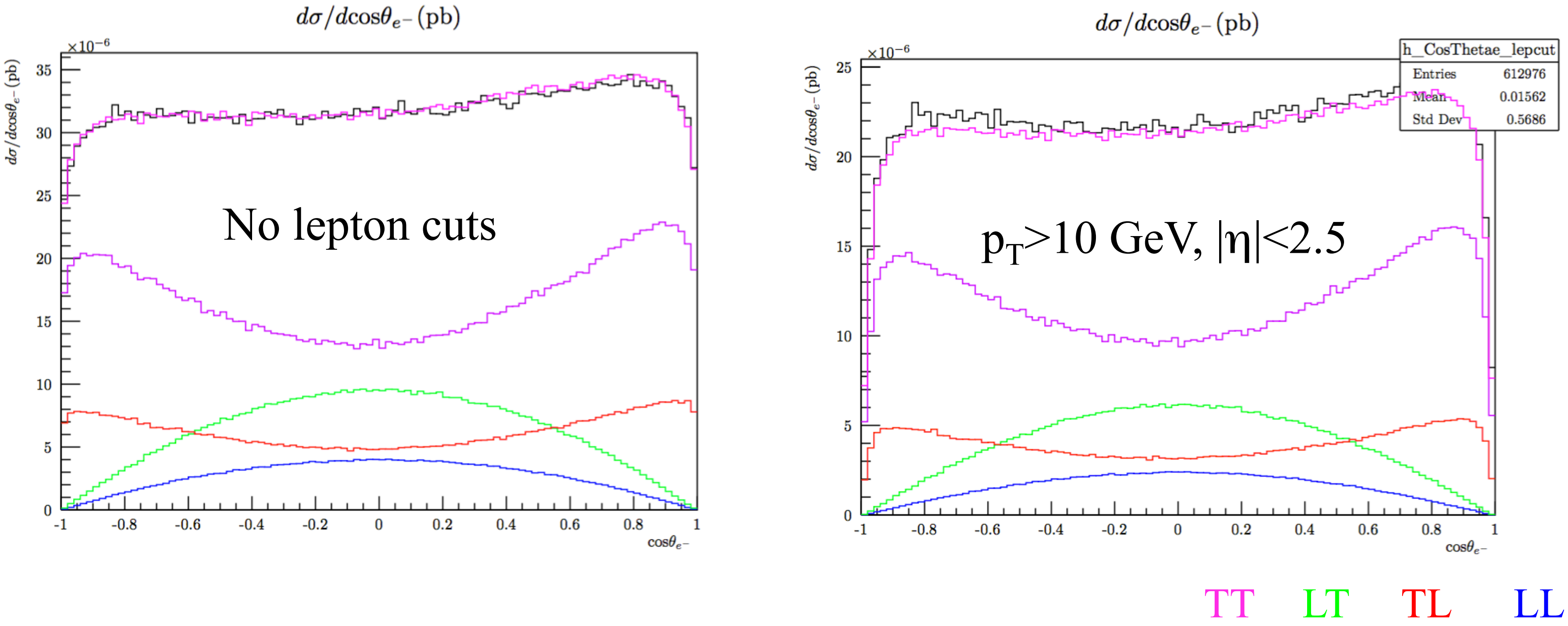
- ❑ Angle between the electron momentum direction in the Z rest frame and the Z momentum direction in the lab frame

No lepton cuts

- ❑ Typical distribution for the longitudinal polarization
- ❑ Good discrimination potential long vs right and left

Cut effects on costheta

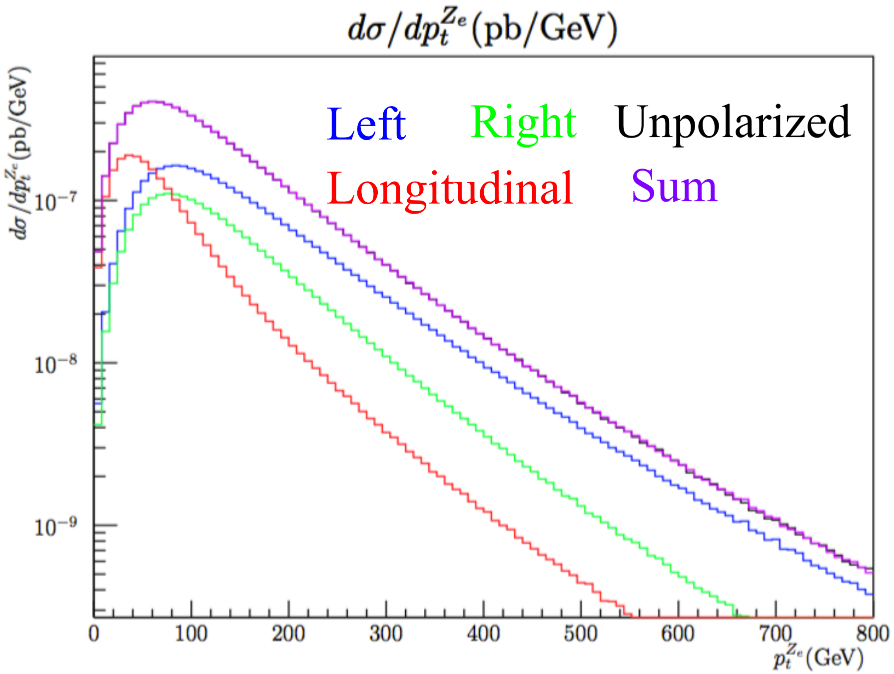
Double polarization distributions

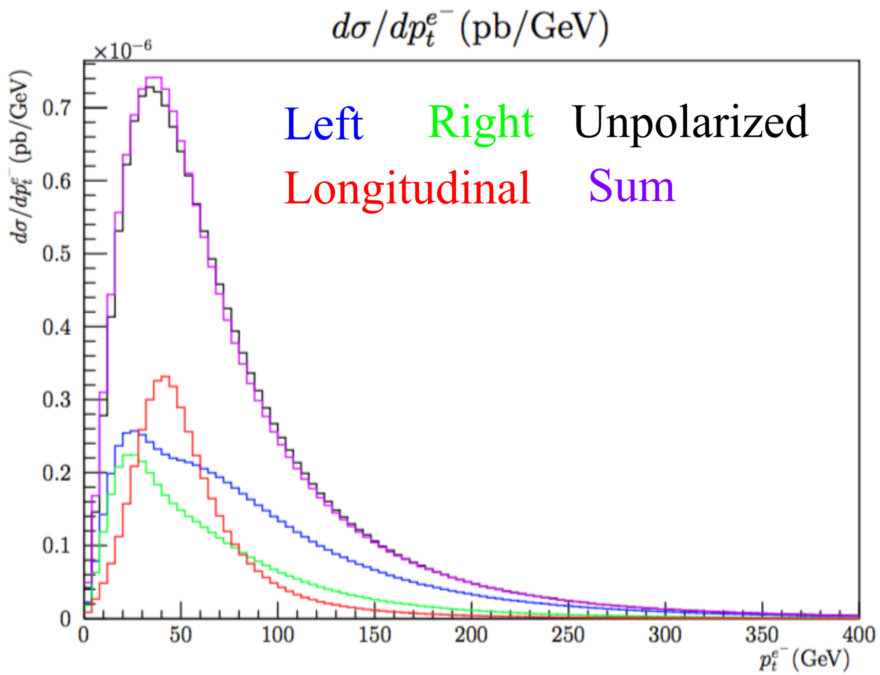


- Visible cut effects at the edges of the costheta distribution
- In the region where the most difference long vs transverse, although very localized

Z transverse momentum

No lepton cuts



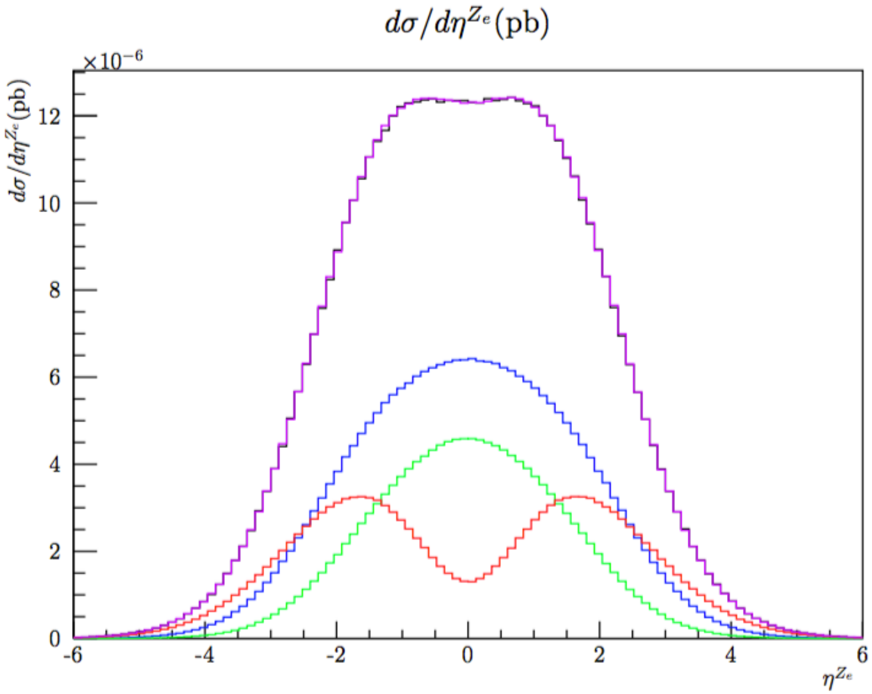


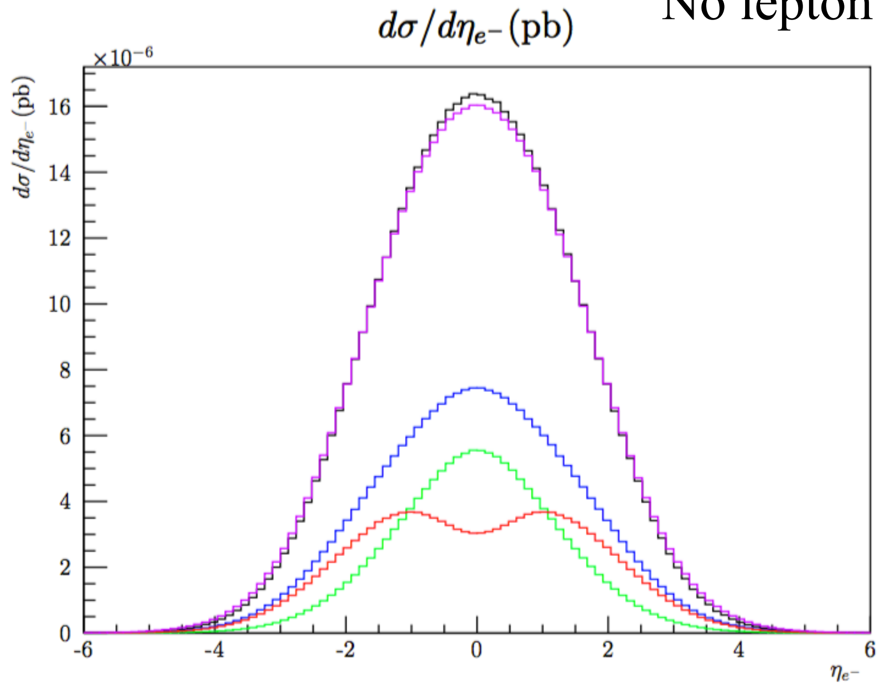
- Softer Z boson p_T distribution for the longitudinal case
- Less separation for the decay electron (costheta folded in) => there is interest to reconstruct the Z momentum

Z pseudorapidity

Left Right Longitudinal Sum Unpolarized

No lepton cuts

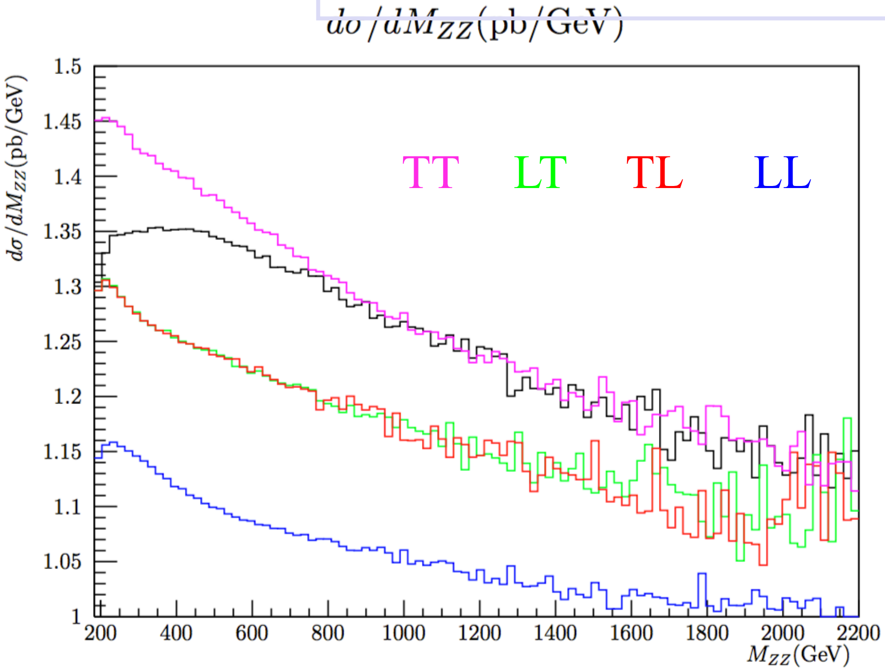




- Longitudinal Zs have a very different η distribution, peaks at |η|~2
  - The effect increases with increasing m_{ZZ} (relates to Higgs interference)
- Consequence for HL-LHC detectors: forward region is important for $V_L V_L$!
- Less separation for the decay electron (costheta folded in) => there is interest to reconstruct the Z momentum

Impact of lepton p_T cut

Ratio of cross section p_T>20,10,10,10 GeV / 20,20,20,20 GeV



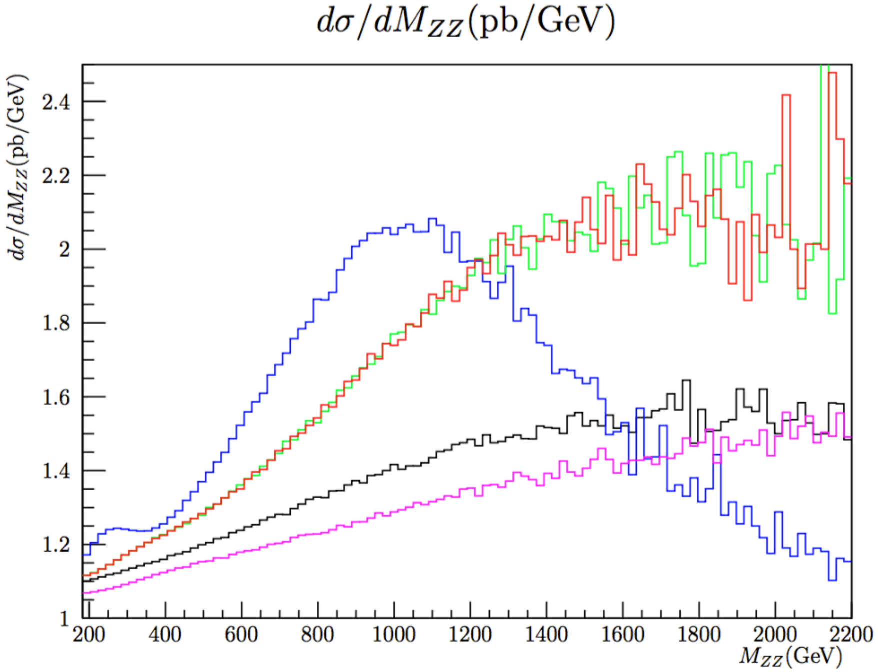
	$p_t^{\text{lepton}} > 20\text{GeV}$	$p_t^{\text{lepton}} > 20, 10, 10, 10\text{GeV}$	$\sigma_{20,10,10,10}/\sigma_{20}$	Gain
Unpol	3.26	4.36	1.34	33.67%
LL(signal)	0.27	0.31	1.14	13.65%
LT	0.62	0.79	1.28	26.79%
TL	0.62	0.79	1.28	26.75%
TT	1.71	2.39	1.39	39.38%
LT+TL+TT(bkg)	2.95	4.17	1.41	41.36%

Table 2 – Cross-section and the gain after and before changing $p_t^{\text{lepton}} > 20\text{GeV}$ to $p_t^{\text{lepton}} > 20, 10, 10, 10\text{GeV}$

- Much more increase of LT, TL and TT than for LL signal when lowering the lepton p_T, does not look interesting
- Lowering the lepton p_T does increase the overall VBS signal though

Effect of η leptons cut

Ratio of cross section $|\eta_e| < 3$ / $|\eta_e| < 2.5$



	$\|\eta_{lepton}\| < 2.5$	$\|\eta_{lepton}\| < 3.0$	$\sigma_{3.0}/\sigma_{2.5}$	Gain
Unpol	3.26	3.82	1.17	16.96%
LL(sgn)	0.27	0.34	1.27	27.03%
LT	0.62	0.76	1.21	21.57%
TL	0.62	0.76	1.21	21.56%
TT	1.71	1.95	1.14	13.68%
LT+TL+TT(bkg)	2.95	3.35	1.14	14%

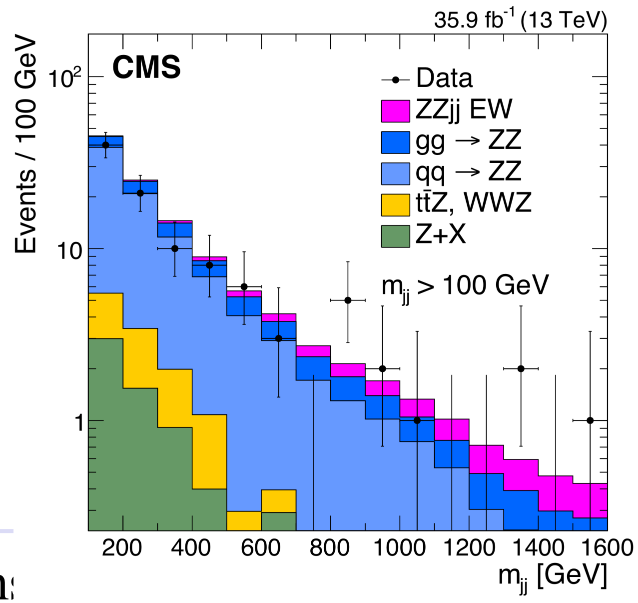
Table 3 – Cross-section in $\times 10^{-5} pb$ and gain after changing $|\eta_{lepton}| < 2.5$ to 3

=> Extending the lepton acceptance up to $|\eta| = 3$: LL signal increases by 1.27, overall LT+TT background increases by 1.14

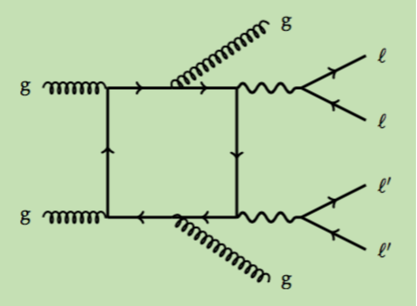
=> Need of extended acceptance increases with increasing m_{ZZ}

Mixed EW-QCD backgrounds

- Dominant background to VBS ZZ is from pp→ZZjj with two QCD vertices ($a_s^2a^4$, qq→ZZ on the plot)
- MadGraph aMC@NLO with FxFx merging used
- uncertainty from QCD scales sizeable, though not dominant (~10%)



- Second leading background is from gg→ZZjj box diagrams
- Up to now simulated with MCFM + PS
  - First results from Madgraph shown reasonable agreement once default shower settings are used
  - However technical difficulties in simulating this process at ME
- Resulted in a 40% uncertainty on MCFM gg→ZZjj yield



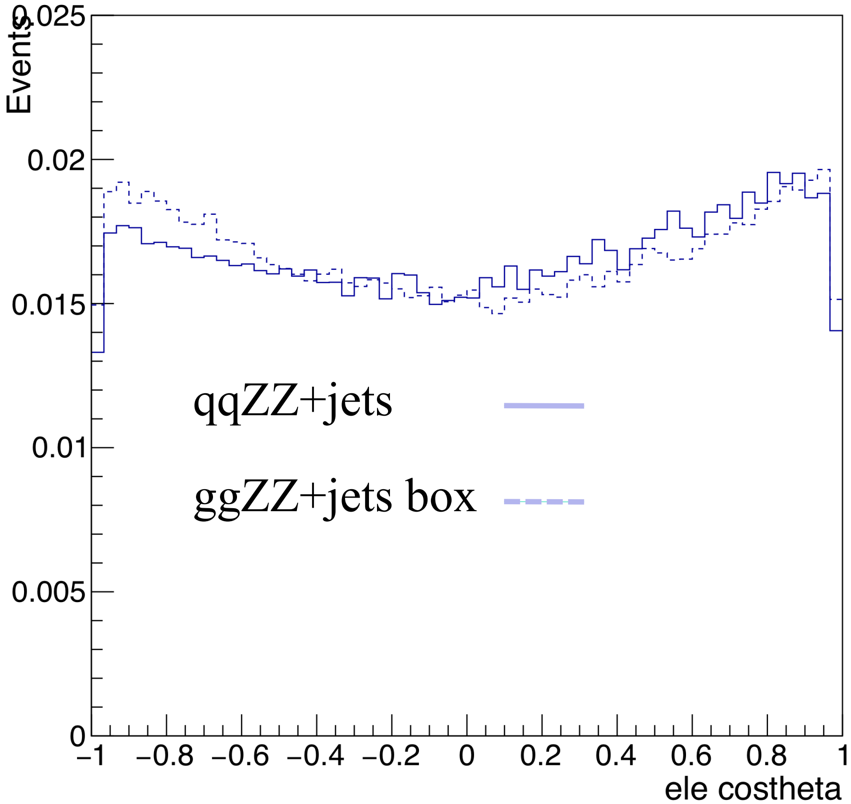
=> ME simulation of loop-induced gg→ZZjj highly needed

First look at background polarization

- In order to extract VBS signal polarization, we also need to look at the backgrounds for the most discriminant distributions
- First look here at costheta

- Simulation setup:
  - qqZZ: MadGraph aMC@NLO ZZ+2jets, FxFx merging
  - ggZZ box: MCFM + PS (Pythia8)
  - $\sqrt{s}$ =13 TeV
  - Jet p_T>25 GeV, $|\eta|$<4.7, m_{jj}>100 GeV
  - Electron(muon) p_T>20,10,7(5),7(5) GeV, $|\eta|$<2.5
- Gen level results

First look at background polarization



- Background more transverse-like as could be expected
- Both backgrounds show rather similar behaviour
- qqZZjj: slightly more left-like
- note that qqZZ actualy corresponds to many diagrams, including gluons in the initial state
- ggZZjj box: can we trust MCFM+PS here?

Conclusions

- VBS $Z_L Z_L$ in fully leptonic final state investigated using recent tools
- Cross section small, but full reconstruction of the final state
- Costheta is the main discriminant distribution
- Production also characterized by softest and more forward Zs
- Forward region is important for $V_L V_L$!

- Separation of longitudinal component will rely also on precise prediction for the mixed EW-QCD backgrounds
- Better predictions for jet kinematics needed for the ggZZjj box background
- Predictions for polarized distributions also needed for main backgrounds

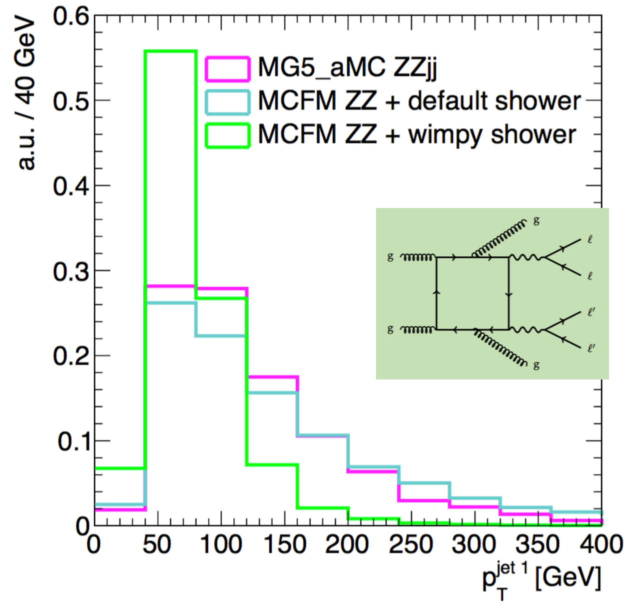
Backup

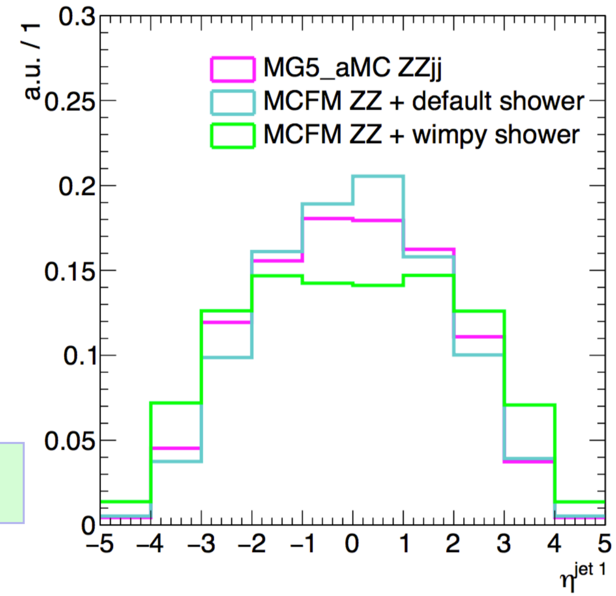
ggZZ loop-induced background

- Challenging territory, gg→ZZ part of NNLO contribution to ZZ production
- Contributes to ~10% of inclusive yields but up to ~30% in most signal-like region
- Currently simulated with MCFM => jets from PS

- What we need is loop-induced gg→ZZjj from ME ($\alpha_s^4\alpha_{EW}^2$)
- First results from Madgraph shown reasonable agreement once default shower settings are used
- Technical implementation challenging, on-shell bosons decayed without mass smearing nor spin correlations in Madspin, O(10min/event)

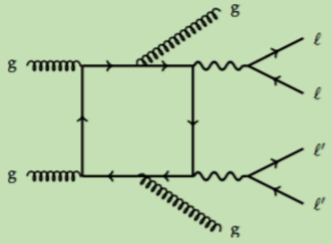
=> Resulted in a 40% uncertainty on MCFM gg→ZZjj yield





ME prediction of gg box ZZjj

What we want:
Loop-induced ZZjj ($\alpha^4\alpha_{EW}^4$) from matrix element



+ many more

Based on discussion with V. Hirschi on MG forum:

There are three types of amplitudes:

Tree diagrams | Loop-corrections to tree | Loop-induced diagrams

We want the finite contribution coming from Loop-induced diagrams x Loop-induced diagrams

In MG5_aMC, `noborn=QCD` syntax removes Tree diagrams

but includes terms from Loop-corrections to tree x Loop-induced diagrams

which are divergent (need double real-emission contributions to cancel)

ME prediction of gg box ZZjj

Solutions:

A. Exclude quark initial+final states (g g > z z g g), misses q→qg splittings
B. Better: remove diagrams that are loop-corrections of the tree amplitude

1. Specify process:

```
Process card:
generate p p > z z j j QED=2 QCD=99 [noborn=QCD]
```

2. Remove loop-corrections, i.e., diagrams where no Z boson is attached to the loop:

```
[<MG_ROOT>/madgraph/loop/loop_diagram_generation.py]
...
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)):
   valid_diag = False
...
```

3. Decay on-shell bosons. Caveat: no mass smearing nor spin correlations in MadSpin. Pythia won't consider branching ratios when restricting decays.