VBS/VBF (without photons) at CMS

Matteo Presilla (INFN PG), on behalf of the CMS Collaboration.
THE STANDARD MODEL IN CMS

SM keeps resisting with reasonable agreement across 10 orders of magnitudes of cross-sections!

LHC was proven to be a powerful precision machine: diagrams in which two Vector Boson interacts, giving either one or two Vector Bosons in the final state, are among the rarest processed measured. 

May 2021

CMS Preliminary

All results at: http://cern.ch/go/pNj7
• At the heart of EWSB, probing non-abelian structure of the SM: triple and quartic gauge couplings
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Studies of gauge invariance of the SM: this process is gauge invariant thanks to very delicate cancellations between diagrams
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Studies of gauge invariance of the SM: this process is gauge invariant thanks to very delicate cancellations between diagrams.

Unitarity of the SM: VBS amplitude explodes with energy, without H mediation!

Undergrad typical QFT exercise:

**SCATTERING** $Z_L Z_L \leftrightarrow W^+_L W^-_L$

Higgs exchange cancels high-energy growth if its couplings are **SM-like**, matrix element is unitary for $m_H \leq 1$TeV (Lee, Quigg, Thacker bound)
• Powerful portal to access BSM in a model-independent approach, usually parametrizing deviations from SM as Effective Field Theory (EFT) expansion
**PHYSICS OF VBS/F PROCESSES**

- **Powerful portal to access BSM** in a model-independent approach, usually parametrizing deviations from SM as Effective Field Theory (EFT) expansion

\[
\mathcal{L}_{BSM} \rightarrow \mathcal{L}_{\text{eft}} \approx \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \cdots
\]

Bottom-up approach:

\[
\sum c_i \frac{\mathcal{O}_i}{\Lambda^2}
\]

New BSM couplings (Wilson coefficients)
HOW VBS LOOKS LIKE

THEORY PERSPECTIVE

exemplary case of ssWWjj

\[ \mathcal{O}(\alpha_{ew}^6) \]
HOW VBS LOOKS LIKE

THERORY PERSPECTIVE

exemplary case of ssWWjj

Gauge invariance complicates the picture...
set of LO electroweak VVjj diagrams $\mathcal{O}(\alpha_{ew}^6)$

https://arxiv.org/pdf/
**HOW VBS LOOKS LIKE**

**THEORY PERSPECTIVE**

Gauge invariance complicates the picture...

set of LO electroweak VVjj diagrams $\mathcal{O}(\alpha_{ew}^6)$

+ QCD induced processes $\mathcal{O}(\alpha_s^2\alpha_{ew}^4)$...

exemplary case of ssWWjj
HOW VBS LOOKS LIKE

**THEORY PERSPECTIVE**

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set of LO electroweak VVjj diagrams $\mathcal{O}(\alpha_{ew}^6)$

exemplary case of ssWWjj

+ QCD induced processes $\mathcal{O}(\alpha_s^2\alpha_{ew}^4)$...

**CMS PERSPECTIVE**

- Vector Bosons produced in the central part of the detector
- VBS “tag-jets” in forward detector region: highest invariant-mass in the event
- Large pseudorapidity separation between the VBS-jets - for the low QCD activity btw partons (no color flow at LO arXiv. 1805.09335)
# CMS Recent VBS/F Results

<table>
<thead>
<tr>
<th>Process</th>
<th>Lumi [fb⁻¹]</th>
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<td>W_L W_L measurement</td>
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<td>VBS ZZ</td>
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<tr>
<td>VBS WW</td>
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<td>PLB 811 (2020) 135988</td>
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*+VBS/F with photons covered in Ben’s presentation.
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\[ \sigma_{EW}(Wjj) = 6.23 \pm 0.12 \text{ (stat)} \pm 0.61 \text{ (syst) pb} \]

\[ \sigma_{EW}(\ell\ell jj) = 552 \pm 19 \text{ (stat)} \pm 55 \text{ (syst) fb} \]
# CMS Recent VBS/F Results

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*+VBS/F with photons covered in Ben’s presentation.

- **Fully-leptonic VBS (2 jets + 4 leptons)**
- **Semi-leptonic VBS (4 jets + 2 leptons)**

No fully-hadronic (all jets) VBS/F measured so far
**WW(>lνlν) same-sign lepton pair + jet events, “Golden channel” for VBS**

- Good separation
  - EW VBS vs. QCD VBS
  \[ \sigma_{\text{EW}} \approx 4-6 \sigma_{\text{QCD}} \]

- Full NLO corrections known

+ simultaneous fit the VBS $WZ(>l\nu l\nu)$

+ background control regions

---


**Fully leptonic VBS WW+WZ**

**2D fit with $m(\ell\ell)+m(jj)$ variable for sswW**

**Fit with BDT score**
WW(>lνlν) same-sign lepton pair + jet events, “Golden channel” for VBS

- Good separation
  EW VBS vs. QCD VBS
  \[ \sigma_{\text{EW}} \approx 4-6 \sigma_{\text{QCD}} \]

- Full NLO corrections known

+ simultaneous fit the VBS WZ(>lνlν)

+ background control regions

Background only hypotheses rejection > 5 \sigma
**Fully leptonic VBS WW+WZ**


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**INCLUSIVE AND DIFFERENTIAL FIDUCIAL XSEC MEASUREMENTS**

<table>
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<tr>
<th>Process</th>
<th>$\sigma B$ (fb)</th>
<th>Theoretical prediction without NLO corrections (fb)</th>
<th>Theoretical prediction with NLO corrections (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EW W$^\pm$W$^\pm$</td>
<td>$3.98 \pm 0.45$</td>
<td>$3.93 \pm 0.57$</td>
<td>$3.31 \pm 0.47$</td>
</tr>
<tr>
<td>EW+QCD W$^\pm$W$^\pm$</td>
<td>$4.42 \pm 0.47$</td>
<td>$4.34 \pm 0.69$</td>
<td>$3.72 \pm 0.59$</td>
</tr>
<tr>
<td>EW WZ</td>
<td>$1.81 \pm 0.41$</td>
<td>$1.41 \pm 0.21$</td>
<td>$1.24 \pm 0.18$</td>
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<tr>
<td>EW+QCD WZ</td>
<td>$4.97 \pm 0.46$</td>
<td>$4.54 \pm 0.90$</td>
<td>$4.36 \pm 0.88$</td>
</tr>
<tr>
<td>QCD WZ</td>
<td>$3.15 \pm 0.49$</td>
<td>$3.12 \pm 0.70$</td>
<td>$3.12 \pm 0.70$</td>
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**Measured XS for ssWW in mll**

- **Data**: Measured cross sections for $ssWW$ in $mll$.
- **Theory**: Theoretical predictions with and without NLO corrections.

---

**CMS**

- **MADGRAPH5_aMC@NLO+Pythia8 without NLO corr.**
- **MADGRAPH5_aMC@NLO+Pythia8 with NLO corr.**

---

**INFIN M. Presilla**
• **Transverse masses** show high-sensitivity to NP scenarios in EFT approach

• Good agreement with the SM predictions, limits on aQGCs:

<table>
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<tr>
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<th>Observed (W±W±) (TeV⁻⁴)</th>
<th>Expected (W±W±) (TeV⁻⁴)</th>
<th>Observed (WZ) (TeV⁻⁴)</th>
<th>Expected (WZ) (TeV⁻⁴)</th>
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<tr>
<td>f₁₀ / A²</td>
<td>[-0.28, 0.31]</td>
<td>[-0.36, 0.39]</td>
<td>[-0.62, 0.65]</td>
<td>[-0.82, 0.85]</td>
<td>[-0.25, 0.28]</td>
<td>[-0.35, 0.37]</td>
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<td>f₁₁ / A²</td>
<td>[-0.12, 0.15]</td>
<td>[-0.16, 0.19]</td>
<td>[-0.37, 0.41]</td>
<td>[-0.49, 0.55]</td>
<td>[-0.12, 0.14]</td>
<td>[-0.16, 0.19]</td>
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<tr>
<td>f₁₂ / A²</td>
<td>[-0.38, 0.50]</td>
<td>[-0.50, 0.63]</td>
<td>[-1.0, 1.3]</td>
<td>[-1.4, 1.7]</td>
<td>[-0.35, 0.48]</td>
<td>[-0.49, 0.63]</td>
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<tr>
<td>f₂₅ / A³</td>
<td>[-3.0, 3.2]</td>
<td>[-3.7, 3.8]</td>
<td>[-5.8, 5.8]</td>
<td>[-7.6, 7.6]</td>
<td>[-2.7, 2.9]</td>
<td>[-3.6, 3.7]</td>
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<tr>
<td>f₅₅ / A₄</td>
<td>[-6.7, 7.0]</td>
<td>[-8.3, 8.1]</td>
<td>[-10, 10]</td>
<td>[-14, 14]</td>
<td>[-5.7, 6.0]</td>
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Fully leptonic VBS WW+WZ, and EFT

- **Transverse masses** show high-sensitivity to NP scenarios in EFT approach
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Same limits, but cutting on unitarity violating phase space

Events violating unitarity are rejected ~ 80% (WW) & 50% (WZ)
ssWW VBS Polarization


- Possibility to access different polarization states in ssWW VBS
  - Measurement of WLWL, WLWT and WTWT processes (reference-frame-dependent: parton-parton and WW CoM reference frames)
  - Similar analysis strategy of the previous search, but slightly different fitting procedure
  - Different variables discriminate the polarization components
  - Definition of two BDTs:
    - inclusive BDT to extract WW same-sign signal from non-VBS events
    - specific signal BDT for (WLWL vs WXWT) and (WTWT vs WXWL) and separate likelihood fits
  + mjj fit in the control regions

High-sensitivity of angular variables to polarization components

CMS Simulation (13 TeV)

CMS Preliminary

Data/SM

Events/bin
ssWW VBS Polarization results

- Measurements agree with SM predictions using full Run-2 dataset
- 95% CL upper limits on polarization combination XSs
- Not yet an evidence for a single-boson polarization state, but background only rejection up to 2.3$\sigma$ for WLWX
  - Observed (expected) significance of 2.3 (3.1) sigma for WLWX production
  - Observed (expected) limit of 1.17 (0.88) fb for WLWL production
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<td>WW±WW±</td>
<td>0.32±0.42</td>
<td>0.44 ± 0.05</td>
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<tr>
<td>WW±WX</td>
<td>3.06±0.48</td>
<td>3.13 ± 0.35</td>
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<tr>
<td>WW±WX</td>
<td>1.20±0.56</td>
<td>1.63 ± 0.18</td>
</tr>
<tr>
<td>WW±WT</td>
<td>2.11±0.49</td>
<td>1.94 ± 0.21</td>
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### Parton-parton CoM frame

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<td>WW±WW±</td>
<td>0.24±0.40</td>
<td>0.28 ± 0.03</td>
</tr>
<tr>
<td>WW±WX</td>
<td>3.25±0.50</td>
<td>3.32 ± 0.37</td>
</tr>
<tr>
<td>WW±WX</td>
<td>1.40±0.60</td>
<td>1.71 ± 0.19</td>
</tr>
<tr>
<td>WW±WT</td>
<td>2.03±0.51</td>
<td>1.89 ± 0.21</td>
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- Fiducial XS for all the polarizations
- Results comparable in both frames
**ZZ→4l VBS**


- One of the rarest SM processes observed to date,
  4l+jj channel: 2 pairs of opposite sign, same flavour charged leptons
  - Clean channel with small experimental background
  - Theory progress: NLO corrections available

- Evidence of EW ZZjj production at 4.0σ (3.5σ expected) using matrix element discriminant $K_D$ to separate signal from the main background (QCD ZZ)

**Built from analytical matrix elements**
ZZ → 4l VBS


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<th>Measured σ (fb)</th>
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<td></td>
<td></td>
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<td>EW LO</td>
<td>0.275 ± 0.021</td>
<td>0.33 ± 0.11 (stat) + 0.04 (syst)</td>
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<tr>
<td>EW NLO QCD</td>
<td>0.278 ± 0.017</td>
<td></td>
<td></td>
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<tr>
<td>EW+QCD</td>
<td>5.35 ± 0.51</td>
<td>5.29 ± 0.31 (stat) ± 0.46 (syst)</td>
<td></td>
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<td>VBS-enriched (loose)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>EW LO</td>
<td>0.186 ± 0.015</td>
<td>0.200 ± 0.078 (stat) + 0.023 (syst)</td>
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<td>0.197 ± 0.013</td>
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<tr>
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<td>0.108 ± 0.007</td>
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<td>0.221 ± 0.014</td>
<td>0.20 ± 0.05 (stat) ± 0.02 (syst)</td>
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EW and EW+QCD measurements in agreement with SM predictions

EW and EW+QCD measurements in agreement with SM predictions

3 regions for fiducial XS:
**ZZ→4l VBS, and EFT**

- Access to **quartic gauge couplings** → EFT interpretation dimension-8 (transverse) operators
- Particularly constraining T8, T9 operators, involving only neutral current fields
- Statistical uncertainty is the dominant source here

**ZZ IN Variant Mass in the Most Inclusive Region**

**Coupling** | **Exp. lower** | **Exp. upper** | **Obs. lower** | **Obs. upper** | **Unitarity bound**
---|---|---|---|---|---
\(f_{T0}/Λ^4\) | -0.37 | 0.35 | -0.24 | 0.22 | 2.4
\(f_{T1}/Λ^4\) | -0.49 | 0.49 | -0.31 | 0.31 | 2.6
\(f_{T2}/Λ^4\) | -0.98 | 0.95 | -0.63 | 0.59 | 2.5
\(f_{T8}/Λ^4\) | -0.68 | 0.68 | -0.43 | 0.43 | 1.8
\(f_{T9}/Λ^4\) | -1.5 | 1.5 | -0.92 | 0.92 | 1.8

**Data**

- [ZZINVARIANTMASSINTHEMOSTINCLUSIVEREGION](#)
- [Most stringent constraint on T8 operator](#)
- [aQGC observed strength That would result in unitarity-violating amplitude (VBFNLO estimation)](#)
SEMI-LEPTONIC VBS

• Looking for hadronic W, Z decays, good balance between:
  ✓ Large hadronic branching fraction of W or Z boson
  ★ Large irreducible backgrounds
SEMI-LEPTONIC VBS


- Looking for hadronic $W$, $Z$ decays, good balance between:
  - Large hadronic branching fraction of $W$ or $Z$ boson
  - Large irreducible backgrounds
- Sensitivity to SM VBS negligible with $36/fb$, focus on aQGCs looking for dim-8 operators deviations:

\[
\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{i=WWW,WW,BB,WWBB} \frac{c_i}{\Lambda^2} \phi_i + \sum_{j=1,2} \frac{f_{S,j}}{\Lambda^4} \phi_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4} \phi_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4} \phi_{M,j}
\]

<table>
<thead>
<tr>
<th>Final state</th>
<th>$WV$</th>
<th>$ZV$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>347</td>
<td>47</td>
</tr>
<tr>
<td>$V+$jets</td>
<td>$196 \pm 14$</td>
<td>$42.6 \pm 6.1$</td>
</tr>
<tr>
<td>Top quark</td>
<td>$113 \pm 15$</td>
<td>$0.14 \pm 0.04$</td>
</tr>
<tr>
<td>QCD $VV$</td>
<td>$27 \pm 8$</td>
<td>$5.5 \pm 1.9$</td>
</tr>
<tr>
<td>SM EW $VV$</td>
<td>$16 \pm 2$</td>
<td>$2.0 \pm 0.4$</td>
</tr>
<tr>
<td>Total bkg.</td>
<td>$352 \pm 19$</td>
<td>$50.3 \pm 5.8$</td>
</tr>
<tr>
<td>$f_{T2}/\Lambda^4$</td>
<td>$-0.5, -2.5 \text{ TeV}^{-4}$</td>
<td>$19 \pm 1$</td>
</tr>
<tr>
<td>$m_{H_5} = 500 \text{ GeV}, s_H = 0.5$</td>
<td>$38 \pm 1$</td>
<td>$4.1 \pm 0.1$</td>
</tr>
</tbody>
</table>
**SEMI-LEPTONIC VBS**


- Looking for hadronic W, Z decays, good balance between:
  - ✓ Large hadronic branching fraction of W or Z boson
  - ✴ Large irreducible backgrounds

- Sensitivity to SM VBS negligible with 36/fb, focus on aQGCs looking for **dim-8 operators** deviations:

\[
\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{i=WWWW,WW,B,WW,WW} \frac{c_i}{\Lambda^2} \mathcal{O}_i + \sum_{j=1,2} \frac{f_{S,j}}{\Lambda^4} \mathcal{O}_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4} \mathcal{O}_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4} \mathcal{O}_{M,j}
\]

- Focus on boosted-topology
SEMI-LEPTONIC VBS

- Tight VBS selection: $mjj > 800$ GeV, $|\Delta \eta| > 4.0$
- Large backgrounds from V+jets processes, estimated from data distributions in a sideband region
- Invariant mass of the di-boson system used in the statistical analysis
- WV significantly more sensitive compared to ZV

Most stringent limits on Wilson coefficients obtained from semi-leptonic channels
(in some cases limits from 3 to 5 times better than leptonic final state, with one-fourth of data!)
SUMMARY

• Highlights from CMS measurements in VBS/F: consistency tests of the EW sector of SM at the LHC

• Many new analyses under implementation
  • Leptonic decays of V bosons involved much powerful tool for SM EW measurements
  • Semi-leptonic targeted mostly to BSM

• VBS/VBF powerful enough to infer on the presence of new physics in a “UV-agnostic” way

• Huge theoretical & experimental progress behind all these measurements
  • Fine control of background sources in control regions
  • Exploit machine learning techniques
  • Importance of NLO calculations (up to ~15% effect on XS!)

• Run3/4 are ahead, but please stay tuned for many interesting results from Run 2 are yet to come!
THANK YOU FOR LISTENING!

Backup.
Fully leptonic VBS WW+WZ

Fully leptonic VBS WW+WZ

- **EWK WW (Signal) Region:** 8 X 4 = 32 bins
  - $m_{jj}$: [500, 650, 800, 1000, 1200, 1500, 1800, 2300, $\infty$] GeV
  - $m_{ll}$: [20, 80, 140, 240, $\infty$] GeV

- **EWK WZ (Signal) Region:** 8 bins
  - BDT: [-1,-0.28,0.00,0.23,0.43,0.60,0.74,0.86,1]

- **Nonprompt (Control) Region:** 4 bins
  - Inverted b-tagging requirements
  - $m_{jj}$: [500, 800, 1200, 1800, $\infty$] GeV

- **ZZ (Control) Region:** 4 bins
  - Select ZZ $\rightarrow$ 4l candidates with the same VBS-like selection as in the SR
    - Exactly four selected leptons ($p_T > 25/20/10/10$ GeV) paired up with each other
  - $m_{jj}$: [500, 800, 1200, 1800, $\infty$] GeV

- **WZb(tZq) (Control) Region:** 4 bins
  - Same as WZ SR with Inverted b-tagging requirements
  - $m_{jj}$: [500, 800, 1200, 1800, $\infty$] GeV
ssWW VBS Polarization

- Same sign unpolarized WW is the only diboson process with full NLO computation

<table>
<thead>
<tr>
<th>Order</th>
<th>$\mathcal{O}(\alpha^7)$</th>
<th>$\mathcal{O}(\alpha_s\alpha^6)$</th>
<th>$\mathcal{O}(\alpha_s^2\alpha^5)$</th>
<th>$\mathcal{O}(\alpha_s^3\alpha^4)$</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta\sigma_{NLO}$ [fb]</td>
<td>-0.2169(3)</td>
<td>-0.0568(5)</td>
<td>-0.00032(13)</td>
<td>-0.0063(4)</td>
<td>-0.2804(7)</td>
</tr>
<tr>
<td>$\delta\sigma_{NLO}/\sigma_{LO}$ [%]</td>
<td>-13.2</td>
<td>-3.5</td>
<td>0.0</td>
<td>-0.4</td>
<td>-17.1</td>
</tr>
</tbody>
</table>

- EW corrections are large and negative (~-15%) in the fiducial region and increasing with dijet and dilepton masses

- NLO corrections for the polarized samples are not known (alpha_s corrections expected to be the same for the 3 modes. alpha corrections expected to be small for the longitudinal modes). Recommendation by M. Pellen:
  - Apply alpha_s corrections on LL, LT, and TT
  - Apply alpha corrections for TT
  - Take the size of alpha corrections as uncertainty for LL and LT

B. Biedermann, A. Denner, and M. Pellen
Discussed during ARC-author meeting

A. Apyan