THE W AND Z BOSON SPIN OBSERVABLES AS MESSENGERS OF NEW PHYSICS AT LHC

Based on:


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Eugene Paul Wigner (1902–1995)
• Beyond “EXCESS OF EVENTS” → W, Z Spin Observables as Messengers of hidden Production Mechanism

• Spin Density Matrix → Why?, How?

• Correspondence Multipole Parameters ↔ Asymmetries in Angular Distribution

• Polarized Top Quark Decay t → bW

• Heavy Resonance Decay j → Z(W) j’

• Drell-Yan Z + jets production

• Z boson + MET ↔ SUSY, DM at LHC

• Outlook
Beyond "EXCESS OF EVENTS"

- With the successful operation of LHC, accumulating a wealth of data in the ATLAS and CMS experiments, at CM energies of 7, 8 and 13 TeV, and the expected increasing statistics, measurements beyond simple event counts are mandatory!

  See: Frederick Bordry
  Plenary talk EPS-HEP 2017

- Polarisation measurements, possible for particles with a short lifetime, through angular distributions of decay products

- WHY TO DO IT? Discriminating power between SM and New Physics models. W and Z most interesting -> MESSENGERS of hidden Production Mechanism
Quantum mixed state for Spin 1 has 8 independent Spin Observables: 

- **MULTIPOLE PARAMETERS** $t(L,M) \rightarrow 3 \ L=1 \ Polarisations$
- $5 \ L=2 \ Alignments$

Spin Density Matrix

$$\rho = \frac{1}{3} \mathbb{I} + \frac{1}{2} \sum_{M=-1}^{1} \langle S_M \rangle^* S_M + \sum_{M=-2}^{2} \langle T_M \rangle^* T_M$$

Spherical basis of Spin Operators and Rank 2 Irreducible Tensors $\rightarrow$ **OBSERVABLE Expectation Values**.

HOW TO MEASURE THEM? Correspondence $t(L,M)$ with the angular distribution

$$\text{Tr} \ [ M_{\lambda_1,\lambda_2; m, m'} M^{*}_{m', \lambda_1, \lambda_2} ] \ ; \ \mathcal{M}_{m, \lambda_1, \lambda_2} = b_{\lambda_1 \lambda_2} D^{1*}_{m, \lambda}(\phi^*, \theta^*, 0)$$

with $D^1$ the **Wigner D functions** for $J=1$; $\lambda_1, \lambda_2$ are the helicities of the two lepton decay products and $\lambda = \lambda_1 - \lambda_2$

$W \rightarrow$ fixed $(\lambda_1, \lambda_2)$ / $Z \rightarrow$ L&R $\rightarrow$ Polarization Analyzer 

$$\eta_l = \left[ (g_L^l)^2 - (g_R^l)^2 \right] / \left[ (g_L^l)^2 + (g_R^l)^2 \right]$$
HOW? Asymmetries $\leftrightarrow t(L,M)$

Forward-backward: $J_x, J_y, J_z$

- $t_0^1 = J_z$
- $t_1^1 = -\frac{1}{\sqrt{2}} (J_x + iJ_y)$
- $t_0^2 = T_0$
- $t_2^1 = A_1 + iA_2$
- $t_2^2 = B_1 + iB_2$

Edge-central: $T_0$

Double forward-backward: $A_1, A_2, B_1, B_2$
POLARIZED TOP QUARK DECAY

- General with L, R Vector & Tensor

\[ \langle B_1 \rangle = \langle B_2 \rangle = 0 \quad \text{since} \quad \rho_{\pm 1, \mp 1} = 0 \]

The transverse \( \langle S_{1,2} \rangle, \langle A_{1,2} \rangle \) need Top Quark Polarization

- Sensitivity to a dipole interaction described by a complex coupling \( g_R \)

<table>
<thead>
<tr>
<th></th>
<th>( \langle S_1 \rangle )</th>
<th>( \langle S_2 \rangle )</th>
<th>( \langle S_3 \rangle )</th>
<th>( \langle T_0 \rangle )</th>
<th>( \langle A_1 \rangle )</th>
<th>( \langle A_2 \rangle )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>0.510</td>
<td>0</td>
<td>-0.302</td>
<td>-0.445</td>
<td>0.255</td>
<td>0</td>
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<tr>
<td>( g_R = 0.03 )</td>
<td>0.500</td>
<td>0</td>
<td>-0.278</td>
<td>-0.472</td>
<td>0.249</td>
<td>0</td>
</tr>
<tr>
<td>( g_R = 0.10i )</td>
<td>0.507</td>
<td>-0.084</td>
<td>-0.284</td>
<td>-0.434</td>
<td>0.253</td>
<td>-0.042</td>
</tr>
</tbody>
</table>

**ATLAS**

- \( \ell s = 8 \text{ TeV}, 20.2 \text{ fb}^{-1} \)

- \( \langle S_r \rangle \) vs Angular asymmetry
- \( \langle A_r \rangle \) vs W-boson spin observable
HEAVY PARTICLE DECAYS

- $j = 1/2 \rightarrow Z + j' = \frac{1}{2}$ \quad \text{similar analysis to } t \rightarrow Wb

- $j = 0 \rightarrow Z + j' = 0$ \quad \text{Particularly interesting} \quad \text{FULL LONGITUDINAL Z} \quad \lambda = 0 \quad \text{P-wave} L = 1
  
  \begin{itemize}
    \item The only non-zero $\rho_{00} = 1 \quad \Rightarrow \quad \langle T_0 \rangle = -\frac{2}{\sqrt{6}} \quad A(0^-) \rightarrow Z + h (0^+)$
  \end{itemize}

- $j = 0 \rightarrow Z + j' = 1$ \quad \text{Spin Density Matrix diagonal}
  
  \begin{itemize}
    \item The diagonal Spin Observables Di-Boson Resonance
    \[ \langle S_3 \rangle = \left[ |a_{1,1}|^2 - |a_{-1,-1}|^2 \right] / N \]
    \[ \langle T_0 \rangle = \frac{1}{\sqrt{6}} \left[ 1 - 3|a_{00}|^2 / N \right] \]
  \end{itemize}
DRELL–YAN $Z + \text{ jets}$

- Polarization Terms $<S_K>$ affected by small Polarization Analyzer
- Experimental Analysis in bins of rapidity & transverse momentum made at Tevatron, CMS & ATLAS → Interest in separating Z-spin observables, Some Tension

$A_2 \leftrightarrow <B_1> \text{ M}=\pm 2 \text{ Alignment}$
**Z boson + MET**

- Search for LHC SUSY signals & Dark Matter production
- Angular distribution of $l$ in $Z \rightarrow l l$ as function of final MET
- Leading SM

  ![Diagram of Z boson decaying to leptons](image)

  - $l'$ undetected (small $p_{\perp}$, large rapidity)

- Simulation at 13 TeV CM, with Z-direction as unique reference

  ![Graph showing dependence on MET cut above 100 GeV](image)

- Access to $\langle S_3 \rangle$, $\langle T_0 \rangle$ with very interesting dependence on MET cut above 100 GeV

- SUSY Dark Matter Model

  ![Diagram showing SUSY particles](image)

  - $j = \frac{1}{2} \rightarrow Z +j' = 3/2 \leftrightarrow \langle T_0 \rangle = 1/\sqrt{6}$
OUTLOOK

- Wealth of LHC collision data → Separate W, Z boson spin observables.
  **How?** : Definite Asymmetries in the Angular Distribution of leptons.

- **Why?** → **Discriminating Power of hidden Production Mechanism,** either SM or New Physics scenarios.

- W boson Spin properties in t → W b decay clearly distinguish SM from a dipole vertex.
- Two-body Decay of Heavy Particles involving W or Z boson → Different Spin assignments lead to specific zeros and values of the W or Z Spin observables.
- Drell-Yan Z production → Tension in the identified Transverse M= ± 2 Alignment at large $p_{\perp}$
- Z boson + MET → - Interesting rapid variation of $< S_3 >$ and $< T_0 >$ in SM above 100 GeV of MET, characteristic of SM.
  - Different and constant values for a $\tilde{X}_1^0$ decay to $Z + \tilde{G}$ model.

- Looking for New Physics ↔
  Invaluable interesting methodology by means of these Spin Observables