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

Eugene Paul Wigner (1902–1995)

Based on:

-J.A. Aguilar-Saavedra, J.B., PRD 93(2016)011301, arXiv:1508.04592 [hep-ph]
-JAAS, JB, V. Mitsou, A. Segarra, EPJ C77(2017)234, arXiv:1701.03115 [hep-ph]

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OUTLINE

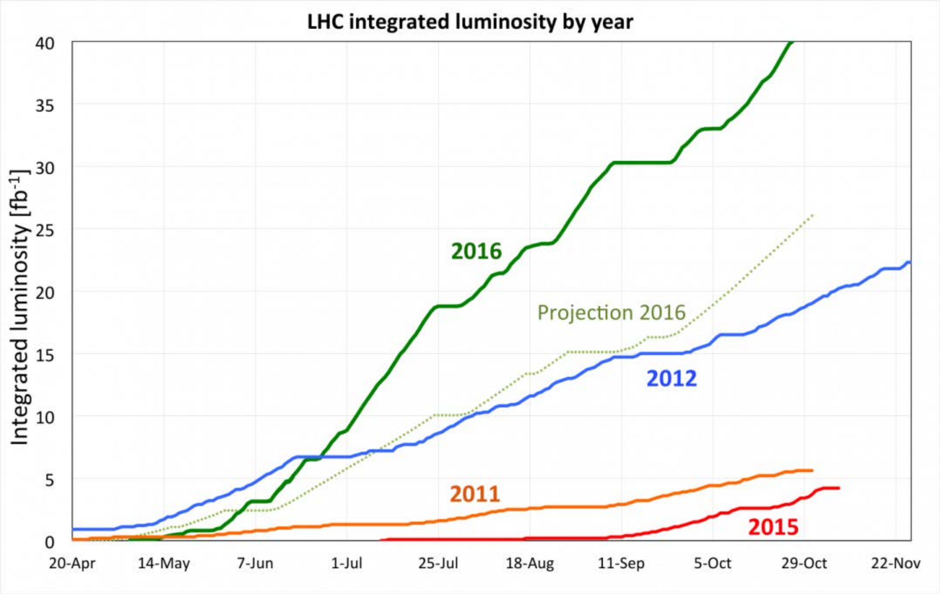
- Beyond "EXCESS OF EVENTS" → W, Z Spin Observables as Messengers

  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

SPIN DENSITY MATRIX

- Quantum mixed state for Spin 1 has 8 independent Spin Observables:

MULTIPOLE PARAMETERS t(L,M) → 3 L=1 Polarisations
5 L=2 Alignments

- Spin Density Matrix

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

- Spherical basis of Spin Operators and Rank 2 Irreducible Tensors →
OBSERVABLE Expectation Values.

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

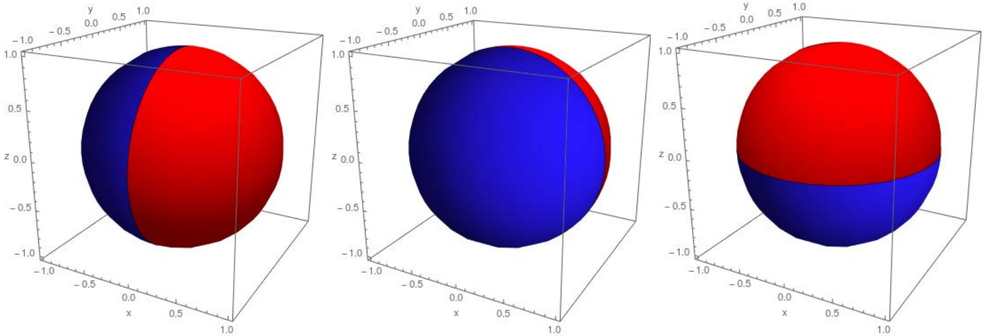
$$\mathrm{Tr}\,[\, M_{\lambda_1, \lambda_2; m}\, \rho_{mm'}\, M^*_{m'; \lambda_1, \lambda_2}\,] \quad ; \quad \mathcal{M}_{m\lambda_1\lambda_2} = b_{\lambda_1\lambda_2} D^{1*}_{m\lambda}(\phi^*, \theta^*, 0)$$

with D^1 the **Wigner D functions** for J=1; λ_1,λ_2 are the helicities of the two lepton decay products and $\lambda = \lambda_1 - \lambda_2$

- W → fixed (λ_1 ,λ_2) / Z → L&R ➡ Polarization Analyzer $\eta_l = \left[\left(g_L^l\right)^2 - \left(g_R^l\right)^2\right] / \left[\left(g_L^l\right)^2 + \left(g_R^l\right)^2\right]$

HOW? Asymmetries <--> t(L,M)

Forward-backward: J_x, J_y, J_z



$$t_0^1 = J_z$$

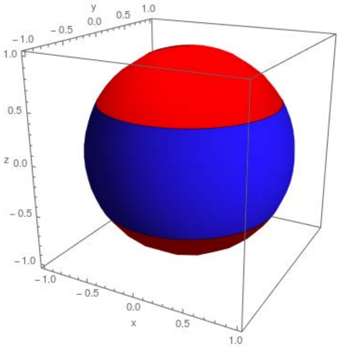
$$t_1^1 = -\frac{1}{\sqrt{2}}\left(J_x + iJ_y\right)$$

$$t_0^2 = T_0$$

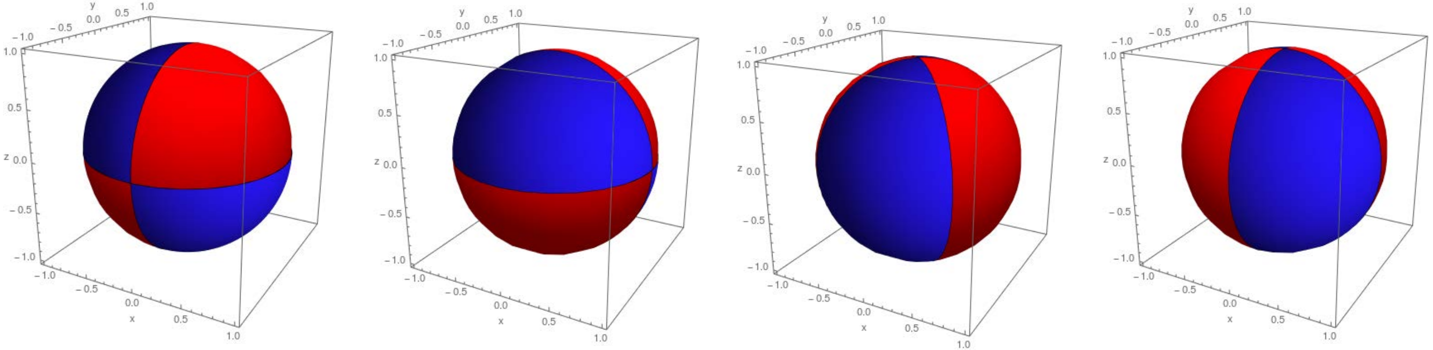
$$t_1^2 = A_1 + iA_2$$

$$t_2^2 = B_1 + iB_2$$

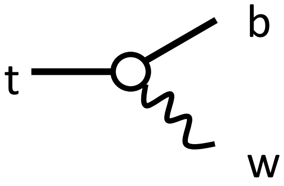
Edge-central: T_0



Double forward-backward: A_1, A_2, B_1, B_2



POLARIZED TOP QUARK DECAY

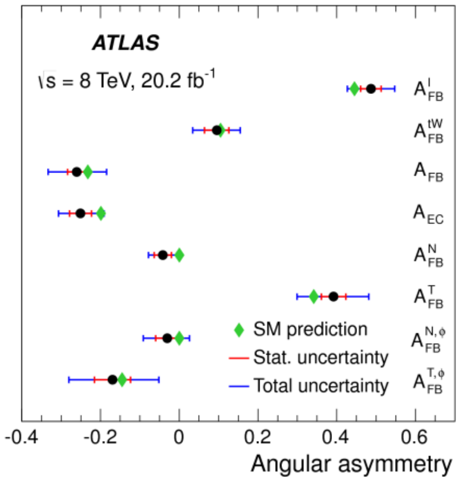
- General  with L, R Vector & Tensor

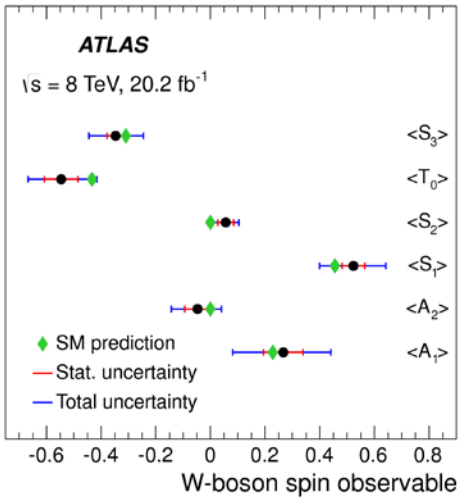
	$\langle S_1\rangle$	$\langle S_2\rangle$	$\langle S_3\rangle$	$\langle T_0\rangle$	$\langle A_1\rangle$	$\langle A_2\rangle$
SM	0.510	0	-0.302	-0.445	0.255	0
$g_R = 0.03$	0.500	0	-0.278	-0.472	0.249	0
$g_R = 0.10\,i$	0.507	-0.084	-0.284	-0.434	0.253	-0.042

$\{$ $< B_1> = < B_2> = 0$ since $\rho_{\pm1,\mp1} = 0$
The transverse $< S_{1,2} >$, $< A_{1,2} >$ need Top Quark Polarization

- Sensitivity to a **dipole interaction** described by a complex coupling

g_R





HEAVY PARTICLE DECAYS

- $j = 1/2 \rightarrow Z + j' = 1/2$ ⟷ similar analysis to $t \rightarrow Wb$

- $j = 0 \rightarrow Z + j' = 0$ ⟷ Particularly interesting ⟹ FULL LONGITUDINAL Z ⟷ $\lambda = 0$ ⟷ P- wave L=1

  - The only non-zero $\rho_{00} = 1$ ⟹ $\langle T_0 \rangle = -\frac{2}{\sqrt{6}}$ $A(0^-) \rightarrow Z + h\,(0^+)$

- $j = 0 \rightarrow Z + j' = 1$ ⟷ Spin Density Matrix diagonal

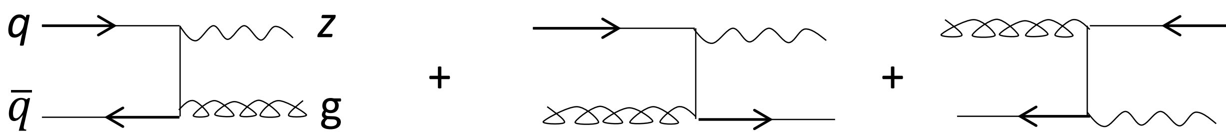
  - The diagonal Spin Observables
    Di-Boson Resonance

$$\langle S_3 \rangle = \left[\left| a_{1,1} \right|^2 - \left| a_{-1,-1} \right|^2 \right] / N$$

$$\langle T_0 \rangle = \frac{1}{\sqrt{6}} \left[1 - 3 |a_{00}|^2 / N \right]$$

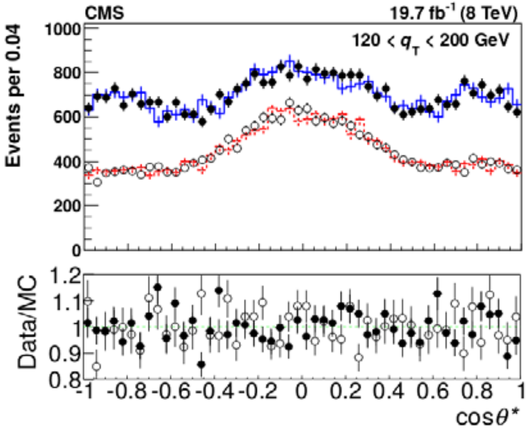
DRELL–YAN Z + jets

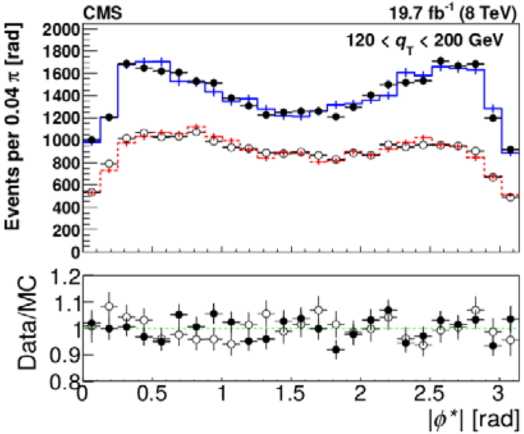
SM

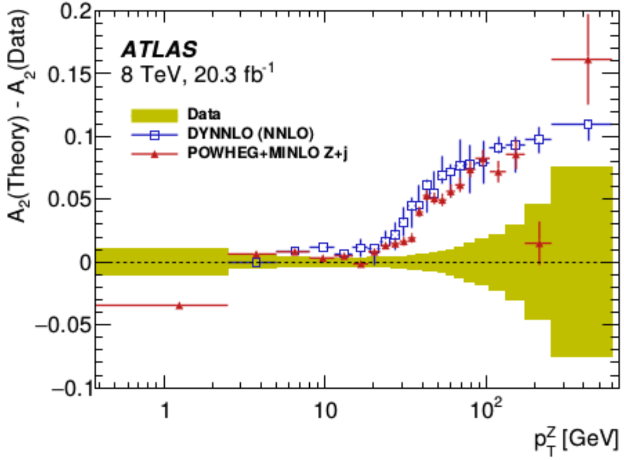


NNLO

- Polarization Terms $\langle S_K \rangle$ 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**



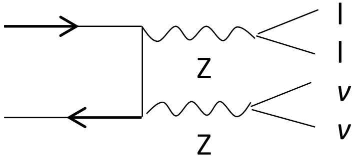


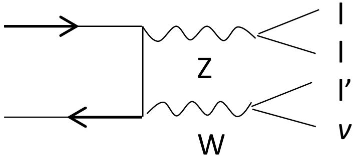


$A_2^{ATLAS} \leftrightarrow \langle B_1 \rangle$ M= ±2 Alignment

Z boson + MET

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



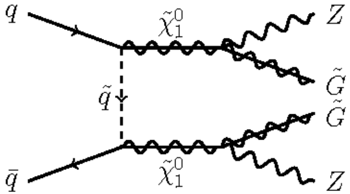


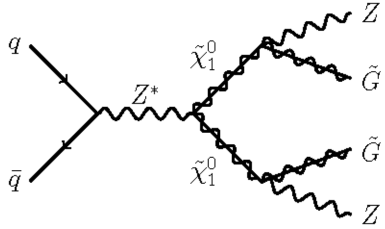
l' undetected
(small $p_\perp$, large rapidity)

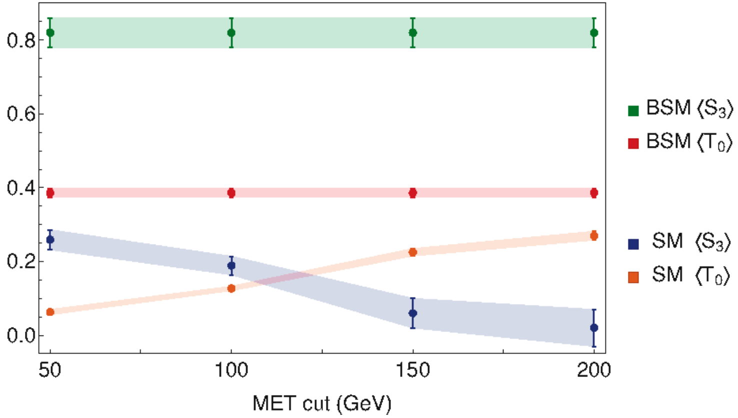
- Simulation at 13 TeV CM, with Z-direction as unique reference

➡ Access to $<S_3>$, $<T_0>$ with very interesting dependence on MET cut above 100 GeV

- ➢ SUSY Dark Matter Model
  - Gravitino $\tilde{G}$ LSP
  - Neutralino $\tilde{\chi}_1^0$ NLSP







j = ½ → Z +j' = 3/2 ↔ $<T_0> = 1/\sqrt{6}$

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