Electroweak-Scale Objects at a 100 TeV Collider

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* Including work in progress with J Chen, T Han, and R Ruiz
How EW-Scale Objects are Made

At the hard process scale
More beam energy $\Rightarrow$ more parton lumi

Hierarchically below the hard process scale...EW parton shower
More beam energy $\Rightarrow$ easier access to extreme event kinematics
How EW-Scale Objects are Made

At the hard process scale
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Hierarchically below the hard process scale...EW parton shower
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Why Think About EW Parton Showering?

- **No choice**
  - impacts almost all physics at $E > \text{TeV}$
- **New regime to measure couplings of full EW/Higgs theory**
  - different systematics
  - different (smaller?) backgrounds
- **New leverage against new physics**
  - opportunities for new “light” particle states associated with EWPT?
Example: WZ+Jet @ 100 TeV

\[ p_T(j) > 3300 \text{ GeV} \]

* using lumi = 1 ab\(^{-1} \)
Example: WZ+Jet @ 100 TeV
Virtual weak corrections to exclusive dijets at LHC14

LO rate minus real W/Z emission events
Novelties wrt QCD/QED
Parton Showering

- Perturbative cutoff via SSB
  - physically-measurable soft/collinear emissions
- Longitudinals/scalars
- Chirality
- Yukawa showers
- Neutral boson interference
  - correct basis is $W^0/B^0$, not $\gamma/Z$
- Weak isospin self-averaging
  - $u(x) > d(x) \rightarrow u_R(x) > Q_L(x) > d_R(x)$
Electroweak Splittings

$W^\pm, W^0, B^0$

$W \rightarrow W W$
Electroweak Splittings

+ 1→3 splittings
Electroweak Splittings

\[ \frac{dP}{dz \, d \log Q^2} \propto \frac{1}{8\pi^2} \left( \frac{1 + z^2}{z} \right) \]

\[ \frac{1}{8\pi^2} \left( \frac{1-z^2}{z} \right) \]

\[ \frac{1}{8\pi^2} \left( \frac{z^2 + \bar{z}^2}{2} \right) \]

E

\( z \, E \equiv (1-z)E \)

\[ \frac{1}{8\pi^2} \left( \frac{2 \bar{z}}{z} \right) \]

\[ \frac{1}{8\pi^2} \left( \frac{\bar{z}}{2} \right) \]

\[ \frac{1}{8\pi^2} \left( \frac{z}{2} \right) \]

+ 1→3 splittings
Massive Splitting Functions

\[ d\mathcal{P}(a \rightarrow bc) \propto \frac{1}{16\pi^2} \frac{z_b z_c}{(k_T^2 + z_c m_b^2 + z_b m_c^2 - z_b z_c m_a^2)^2} |\mathcal{M}(a \rightarrow bc)|^2 \]

shower shuts off at \( k_T \sim m \) ("dead cone")

**W-boson FSR within 10 TeV quark-jet**

**Longitudinal:**
\[ d\mathcal{P}_L \propto \frac{m_W^2}{E^2} \frac{dz}{z^3} \frac{d\theta}{\theta^3} \Rightarrow \mathcal{P}_L \propto \log \left( \frac{E}{m_W} \right) \]

**Transverse:**
\[ d\mathcal{P}_T \propto \frac{dz}{z} \frac{d\theta}{\theta} \Rightarrow \mathcal{P}_T \propto \log^2 \left( \frac{E}{m_W} \right) \]

* E.g., ISR \( \Rightarrow \) polarized W/Z PDFs: Kane, Repko, Rolnik (1984), Dawson (1985)
Light Quark
Total Splitting Rates

Averaged over flavors & helicities, summed over W & Z

\[ \mathcal{P}(q \rightarrow V_T q) \simeq \left( 3 \times 10^{-3} \right) \left[ \log \frac{E}{m_{EW}} \right]^2 \Rightarrow \mathcal{P}(1 \text{ TeV}) \simeq 1.7\%, \quad \mathcal{P}(10 \text{ TeV}) \simeq 7\% \]

\[ \mathcal{P}(q \rightarrow V_L q) \simeq \left( 2 \times 10^{-3} \right) \log \frac{E}{m_{EW}} \Rightarrow \mathcal{P}(1 \text{ TeV}) \simeq 0.5\%, \quad \mathcal{P}(10 \text{ TeV}) \simeq 1\% \]
Parton Lumis at 100 TeV Collider

**TABLE I:** An illustrative set of approximate total electroweak splitting rates in final-state showers [11].

<table>
<thead>
<tr>
<th>Process</th>
<th>Approximate Rate</th>
<th>Log Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_T \rightarrow V_T V_T$</td>
<td>$(0.01)$</td>
<td>$\log p_T m_{EW}$</td>
</tr>
<tr>
<td>$V_T \rightarrow V_L V_T$</td>
<td>$(0.01)$</td>
<td>$\log p_T m_{EW}$</td>
</tr>
<tr>
<td>$V_T \rightarrow f \bar{f}$</td>
<td>$(0.02)$</td>
<td>$\log p_T m_{EW}$</td>
</tr>
<tr>
<td>$V_T \rightarrow V_L h$</td>
<td>$(4 \times 10^{-4})$</td>
<td>$\log p_T m_{EW}$</td>
</tr>
<tr>
<td>$V_L \rightarrow V_T h$</td>
<td>$(2 \times 10^{-3})$</td>
<td>$\log p_T m_{EW}$</td>
</tr>
</tbody>
</table>

**FIG. 1:** Partonic luminosities at the 100 TeV SPPC, illustrating the relative contributions from weak bosons when treated as partons in the PDFs [11]. Processes with prompt transverse boson production such as $W/Z/\gamma +$jets, and especially on multiboson production including transverse boson scatter. Generally, it is important to appreciate that any particle in an event, whether initial-state or final-state, or even itself produced inside of a parton shower, can act as a potential electroweak radiator. Consequently, the total rate for finding one or more electroweak splittings within a given event must be compounded, and can sometimes add up to $O(1)$. Fig 1 summarizes the parton luminosities when electroweak bosons are included in the
"Broken" Showering at $O(v)$
“Broken” Showering at $O(v)$

$\Rightarrow \log(E/m)$

$\Rightarrow \text{constant}^*$

$\Rightarrow \text{constant}^*$

$\Rightarrow \text{constant}^*$ (~0.001)

* All beamed into a cone of size $\sim m/E$
Gauging to Manifest Goldstone Equivalence

(rotating) lightcone gauge condition

\[ n(k) \cdot A(k) = 0 \]
\[ n^0(k) \equiv 1, \quad \vec{n}(k) \equiv -\frac{k^0}{|k^0|} \]
long. polarization \( e_\phi^\mu(k) \equiv \frac{\sqrt{|k^2|}}{n(k) \cdot k} n^\mu(k) \)

\[ \langle A_T(k)A_T(-k) \rangle = \frac{i}{k^2 - m^2} \]
\[ \langle A_\phi(k)A_\phi(-k) \rangle = \frac{i}{k^2 - m^2} \text{sign}(k^2) \]
\[ \langle \phi(k)\phi(-k) \rangle = \frac{i}{k^2 - m^2} \]
\[ \langle A_\phi(k)\phi(-k) \rangle = \frac{i}{k^2 - m^2} \frac{-im}{\sqrt{|k^2|}}. \]

- Delete (sometimes) problematic \( k^\mu/m \) part of longitudinal polarization
  - replaced by on- & off-shell in Feynman rules by Goldstone
  - amplitude to create on-shell longitudinal from \( A^\mu \sim m/E \)

- Keep mixed field basis

- Unlike \( R_\xi \), Goldstone field interpolates physical longitudinal bosons (amplitude \( \sim i \))

* see also Wulzer (1309.6055), Srivastava & Brodsky (hep-ph/0202141), earlier papers
Factorization for Longitudinals

\[ \text{HARD} \times \text{split} + \text{HARD} \times \text{split} + \text{HARD} \times \text{split} + \text{HARD} \times \text{split} \]
We can decompose the remaining gauge degrees of freedom as the component $A_n$ aligned with $n$ and the two $\pm x$ helicity oor $"x, y"$ transverse modes collectively. Counting for the gaugeGoldstone mixing terms the quadratic Lagrangian can be expressed as

$$L_{\text{transverse}} = \int \frac{i}{k^2 - m^2} \cdot -$$

The transverse modes develop the usual propagators $i/k^2 - m^2$ with the poles corresponding to physical quantau. The propagators for $A_n$ and $\phi$ appear to be much more complicated. To facilitate the inversion of the kinetic operators we can use a rescaled basis for $n$ and $A_n$:

$$n_k \cdot A_n = \frac{\mu}{\phi_k}$$

The above polarization basis vector is Lorentz-invariant under longitudinal boosts and is in direct correspondence with the tree-level creation-annihilation amplitudes of on-shell longitudinal gauge bosons via the operator $A \phi$. It becomes exactly $rac{-k}{m}$.

The nonttransverse Lagrangian simplifies to

$$L_{\text{nont}} = \int \frac{i}{k^2 - m^2} \cdot -$$

Inverting yields a set of propagators

$$A_{\text{transverse}} = i/k^2 - m^2$$

The expressions are compact and naively Lorentz-invariant and have the correct physical pole at $m_s$ but also have some peculiar-looking features. The apparent spurious $-k^2 = \omega$ pole in the mixed propagator is always accompanied by an $\phi$ factor in a complete diagram and is therefore never realized. However, as mentioned above, it does develop a spurious multivalued pole at $k^\omega = \omega$. The sign $-k^2$ factor in the gauge propagator is familiar from LorentzLandau gauges where the same sign flip occurs for the longitudinal gauge degree such as respectively $k_0 = 0$ or $\pi/2$. The latter can be troublesome for computing the low-momentum behavior of massive splitting functions. Temporal gauge is better-behaved in the kinematic regions of interest to us, but requires some additional Lorentz-violating awkwardness in the form of the propagators.
Transverse Vector
Total Splitting Rates

\[ \mathcal{P}(V_T \rightarrow V_T V_T) \simeq (0.01) \left[ \log \frac{E}{m_{EW}} \right]^2 \Rightarrow \mathcal{P}(1 \text{ TeV}) \simeq 6\%, \quad \mathcal{P}(10 \text{ TeV}) \simeq 22\% \]

\[ \mathcal{P}(V_T \rightarrow V_T V_L) \simeq (0.01) \log \frac{E}{m_{EW}} \Rightarrow \mathcal{P}(1 \text{ TeV}) \simeq 2\%, \quad \mathcal{P}(10 \text{ TeV}) \simeq 5\% \]

\[ \mathcal{P}(V_T \rightarrow V_L V_L) \simeq (4 \times 10^{-4}) \log \frac{E}{m_{EW}} \Rightarrow \mathcal{P}(1 \text{ TeV}) \simeq 0.1\%, \quad \mathcal{P}(10 \text{ TeV}) \simeq 0.2\% \]

\[ \mathcal{P}(V_T \rightarrow f \bar{f}) \simeq (0.02) \log \frac{E}{m_{EW}} \Rightarrow \mathcal{P}(1 \text{ TeV}) \simeq 5\%, \quad \mathcal{P}(10 \text{ TeV}) \simeq 10\% \]

\[ \mathcal{P}(V_T \rightarrow V_L h) \simeq (4 \times 10^{-4}) \log \frac{E}{m_{EW}} \Rightarrow \mathcal{P}(1 \text{ TeV}) \simeq 0.1\%, \quad \mathcal{P}(10 \text{ TeV}) \simeq 0.2\% \]

\[ \mathcal{P}(V_T \rightarrow V_T h) \simeq (3 \times 10^{-4}) \Rightarrow \mathcal{P}(1 \text{ TeV}) \simeq 0.03\%, \quad \mathcal{P}(10 \text{ TeV}) \simeq 0.03\% \]
Longitudinal Vector
Total Splitting Rates

\[ P(q \rightarrow VTq) \approx (3 \times 10^{-3}) \left( \log \frac{E}{m_{EW}} \right)^2 \Rightarrow P(1 \text{ TeV}) \approx 1\%, \quad P(10 \text{ TeV}) \approx 7\% \]

\[ P(q \rightarrow VLq) \approx (2 \times 10^{-3}) \left( \log \frac{E}{m_{EW}} \right)^2 \Rightarrow P(1 \text{ TeV}) \approx 0.5\%, \quad P(10 \text{ TeV}) \approx 1\% \]

\[ P(VT \rightarrow VTVT) \approx (0.01) \left( \log \frac{E}{m_{EW}} \right)^2 \Rightarrow P(1 \text{ TeV}) \approx 6\%, \quad P(10 \text{ TeV}) \approx 22\% \]

\[ P(VT \rightarrow VTVL) \approx (2 \times 10^{-3}) \left( \log \frac{E}{m_{EW}} \right)^2 \Rightarrow P(1 \text{ TeV}) \approx 2\%, \quad P(10 \text{ TeV}) \approx 5\% \]

\[ P(VT \rightarrow VLVL) \approx (4 \times 10^{-4}) \left( \log \frac{E}{m_{EW}} \right)^2 \Rightarrow P(1 \text{ TeV}) \approx 0.1\%, \quad P(10 \text{ TeV}) \approx 0.2\% \]

\[ P(VT \rightarrow VTf) \approx (0.02) \left( \log \frac{E}{m_{EW}} \right)^2 \Rightarrow P(1 \text{ TeV}) \approx 5\%, \quad P(10 \text{ TeV}) \approx 10\% \]

\[ P(VT \rightarrow VTh) \approx (2 \times 10^{-3}) \left( \log \frac{E}{m_{EW}} \right)^2 \Rightarrow P(1 \text{ TeV}) \approx 1\%, \quad P(10 \text{ TeV}) \approx 4\% \]

\[ P(VL \rightarrow VT) \sim (2 \times 10^{-3}) \left( \log \frac{E}{m_{EW}} \right)^2 \Rightarrow P(1 \text{ TeV}) \sim 1\%, \quad P(10 \text{ TeV}) \sim 4\% \]

\[ P(VL \rightarrow VTh) \sim (2 \times 10^{-3}) \left( \log \frac{E}{m_{EW}} \right)^2 \Rightarrow P(1 \text{ TeV}) \sim 1\%, \quad P(10 \text{ TeV}) \sim 4\% \]

Plus many others.....
Our Shower Program

- Currently PYTHIA6-like virtuality-ordered
  - collinear approximation, no coherence between dipoles
- Polarized splittings
- Massive splitting functions
  - amplitudes and phase space
- Reweighting of secondary splittings
- Interleaved with QCD
- Only FSR (so far)
- Built in C++…ideally adapt to run within PYTHIA 8 framework
WZ+Jet Revisited

MadGraph

Pythia8 W/Z+jet + EW-Shower
WZ+Jet Revisited

MadGraph

Pythia8 W/Z+jet + EW-Shower

~10% loss from further showering
Measurement of Weakstrahlung Rate (LHC)

Krauss, Petrov, Schönherr, Spannowsky (1403.4788)
Effect on Top-Tagging
(Any $p_T > \text{TeV}$)

Leptonic top-jets:
main background ($\sim 10^{-3}$ quark-mistag)

Hadronic top-jets:
5-10% perturbation to quark mistag

Rehermann & Tweedie (1007.2221)

with Z Han & M Son
As a Handle on Heavy New Physics

Hook & Katz (1407.2607) also Rizzo (1403.5465)

Figure 2. On the LHS we plot the difference between our “guess” about the energy of the neutrino and the actual neutrino energy. The “guess” for the neutrino energy comes from assuming that the neutrino is perfectly collinear with the leptonic Z. The reconstructed Z is required to have $|\eta| < 2.5$ and $\Delta \phi_{Z/E_T} < 0.5$. The reconstructed neutrino allows one to guess the real missing energy in an event as well as reconstruct the full mass peak of a W’ particle on the RHS. The mass resolution is smeared since the Z is not always collinear with the neutrino, but there is a very clear peak at the W’ mass of 5 TeV.

The additional Z in these events can come from ISR radiation off of the W’ and FSR from both the lepton and neutrino. The last is of course especially interesting for us as we are interested in genuine three-body decays where the Z is expected to be roughly collinear with the neutrino or lepton. To show the effect of the collinear enhancement we plot in Fig. 1 the distribution of $\Delta R$ and $\Delta \phi$ between the reconstructed Z and the neutrino. The collinear enhancement is seen very clearly. The Z has larger couplings to the neutrino than to the leptons as can also be seen in the plot as the lepton and neutrino are roughly back to back.

When the $\Delta R$ between the neutrino and the Z is small, then the direction of the Z approximately corresponds to the spatial direction of the neutrino, thus allowing the full reconstruction of the latter. To establish that the leptonic Z was Sudakov radiated off of the neutrino rather than the lepton, we put a $\Delta \phi_{Z/l/E_T} < 0.5$ cut between the reconstructed Z and the missing energy. Z semi-timed from ISR which happen at point in the same \phi direction as the missing energy can be effectively removed by requiring that the reconstructed Z boson has $|\eta| < 2.5$ to not be confused with acceptance cuts that we put on the leptons themselves.

We work at parton level assuming that the leptons and missing energy are measured perfectly. Madgraph5 [11–13] was used to generate the events. In this very preliminary analysis, alongside with the standard acceptance criteria, we apply following cuts:

Radiated Z-boson traces neutrino’s 3-vector direction (and probes W’ chirality)
Some Other Back-of-the-Envelope Applications

- $W_T W_T$ production at $O(10 \text{ TeV})$
  - $W_T W_T \rightarrow W_T W_T$ scattering: potentially $O(1)$ showering probability
  - KK graviton: corrections up to $O(50\%)$
- $W_L W_L$ production at $O(10 \text{ TeV})$
  - $W_L W_L \rightarrow W_L W_L / h h, Z' \rightarrow Z_L h, W' \rightarrow W_L h / W_L Z_L$: $O(10\%)$ showering probability
“New” Higgs Production Modes

Are they good for something? Reduced systematics? Complementary information?

*slide from Mangano (HXSWG meeting, July)

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma_{\text{NLO}}$(8 TeV) [fb]</th>
<th>$\sigma_{\text{NLO}}$(100 TeV) [fb]</th>
<th>$\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \to H (m_H,m_{H'})$</td>
<td>$1.44 \cdot 10^4$ +20% +1% -16% -2%</td>
<td>$5.46 \cdot 10^5$ +28% +2% -27% -2%</td>
<td>38</td>
</tr>
<tr>
<td>$pp \to Hjj$ (VBF)</td>
<td>$1.61 \cdot 10^3$ +1% +2% -0% -2%</td>
<td>$7.40 \cdot 10^4$ +3% +2% -3% -1%</td>
<td>46</td>
</tr>
<tr>
<td>$pp \to Htt$</td>
<td>$1.21 \cdot 10^2$ +5% +3% -9% -3%</td>
<td>$3.25 \cdot 10^4$ +7% +1% -8% -1%</td>
<td>269</td>
</tr>
<tr>
<td>$pp \to Hbb$ (4FS)</td>
<td>$2.37 \cdot 10^2$ +9% +2% -9% -2%</td>
<td>$1.21 \cdot 10^4$ +3% +2% -10% -2%</td>
<td>51</td>
</tr>
<tr>
<td>$pp \to Htj$</td>
<td>$2.07 \cdot 10^1$ +2% +2% -1% -2%</td>
<td>$5.21 \cdot 10^3$ +3% +1% -5% -1%</td>
<td>252</td>
</tr>
<tr>
<td>$pp \to HW^\pm$</td>
<td>$7.31 \cdot 10^2$ +2% +2% -1% -2%</td>
<td>$1.54 \cdot 10^4$ +5% +2% -8% -3%</td>
<td>21</td>
</tr>
<tr>
<td>$pp \to HZ$</td>
<td>$3.87 \cdot 10^2$ +2% +2% -1% -2%</td>
<td>$8.82 \cdot 10^3$ +4% +2% -8% -2%</td>
<td>23</td>
</tr>
<tr>
<td>$pp \to HW^+W^-$ (4FS)</td>
<td>$4.62 \cdot 10^0$ +3% +2% -2% -2%</td>
<td>$1.68 \cdot 10^2$ +5% +2% -6% -1%</td>
<td>36</td>
</tr>
<tr>
<td>$pp \to HZW^\pm$</td>
<td>$2.17 \cdot 10^0$ +4% +2% -4% -2%</td>
<td>$9.94 \cdot 10^1$ +6% +2% -7% -1%</td>
<td>46</td>
</tr>
<tr>
<td>$pp \to HW^\pm\gamma$</td>
<td>$2.36 \cdot 10^0$ +3% +2% -3% -2%</td>
<td>$7.75 \cdot 10^1$ +7% +2% -8% -1%</td>
<td>33</td>
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<tr>
<td>$pp \to HZ\gamma$</td>
<td>$1.54 \cdot 10^0$ +3% +2% -2% -2%</td>
<td>$4.29 \cdot 10^1$ +5% +3% -7% -2%</td>
<td>28</td>
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<tr>
<td>$pp \to HZZ$</td>
<td>$1.10 \cdot 10^0$ +3% +2% -2% -2%</td>
<td>$4.20 \cdot 10^1$ +4% +3% -6% -1%</td>
<td>38</td>
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<tr>
<td>$pp \to HW^\pm j$</td>
<td>$3.18 \cdot 10^2$ +4% +2% -4% -1%</td>
<td>$1.07 \cdot 10^4$ +2% +2% -7% -1%</td>
<td>34</td>
</tr>
<tr>
<td>$pp \to HW^\pm jj$</td>
<td>$6.06 \cdot 10^1$ +6% +1% -8% -1%</td>
<td>$4.90 \cdot 10^3$ +2% +1% -6% -1%</td>
<td>81</td>
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<tr>
<td>$pp \to HZ j$</td>
<td>$1.71 \cdot 10^2$ +4% +1% -4% -1%</td>
<td>$6.31 \cdot 10^3$ +2% +2% -7% -1%</td>
<td>37</td>
</tr>
<tr>
<td>$pp \to HZ jj$</td>
<td>$3.50 \cdot 10^1$ +7% +1% -10% -1%</td>
<td>$2.81 \cdot 10^3$ +2% +1% -5% -1%</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 1: Production of a single Higgs boson at the LHC and at a 100 TeV FCC-hh. The rightmost column reports the ratio $\rho$ of the FCC-hh to the LHC cross sections. Theoretical uncertainties are due to scale and PDF variations, respectively. Monte-Carlo-integration error is always smaller than theoretical uncertainties, and is not shown. For $pp \to HVjj$, on top of the transverse-momentum cut of section 2 I require $m(j_1,j_2) > 100$ GeV, $j_1$ and $j_2$ being the hardest and next-to-hardest jets, respectively. Processes $pp \to Htj$ and $pp \to Hjj$ (VBF) do not feature jet cuts.

P.Torrielli, arXiv:1407.1623
Example Topologies

Balance of “clean” high-$p_T$ topologies vs small high-$p_T$ rates not a priori obvious
Semi-Boosted Measurement of Top Yukawa

Mangano, et al (1507.08169)

\[ \Delta y \sim \% \text{ with } 20 \text{ ab}^{-1} \]

PDF uncertainties cancel
Summary

• 100 TeV collider opens up new kinematic regimes for interactions of EW-scale particles
  – hopefully this at least served as a reminder
• EW splitting processes quickly grow/asymptote in rate
  – range from totally negligible to $O(1)$, depending on what you’re looking at
• We’re working on a multipurpose EW shower program
  – “quick and dirty” way to capture universal collinear physics
  – main addition is $W \rightarrow WW$, lots of other Higgs and Goldstone-equivalent processes
• Opportunities for precision-supplementary coupling measurements in/near these kinematic regions
• Sensitivity to new “light” states?
More...
“Shower” Vs “Prompt” Diboson

\[ p_T(\text{leading V}) \]

\[ p_T(\text{subleading V}) \]

diboson
VBF
showered V+jet
showered dijet

\[ H_T(\text{jets + V’s}) \]
Multiple Weak Emissions Inside One Jet

\[ u_L(10 \text{ TeV}) \rightarrow d_L W^+ Z \]

\[ \Delta R(Z, \text{rest of jet}) \]

\[ p_T(W) / p_T(j) \]

* R=1.0 anti-kT jet, W/Z as partons
Isospin Self-Averaged PDFs