## Electroweak Precision Tests at High Energy

## Josh Ruderman (NYU) @Aspen, 3/20/2017

- Farina, Panico, Pappadopulo, JTR, Torre, Wulzer 1609.08157
- Alioli, Farina, Pappadopulo, JTR, to appear


## lepton vs. hadron colliders


pp

precision tests

direct production

## precision tests at the LHC?

Standard Model Production Cross Section Measurements
Status: August 2016


## plan

1. oblique parameters
2. electroweak tests from Drell-Yan
3. oblique parameters from jets

## 1. oblique parameters

$$
V_{i} \text { MMn ? MOM } V_{j}
$$

## Oblique Parameters

$$
V_{i} \leadsto \sim \text { мั~ } V_{j} \quad V=\gamma, Z, W^{ \pm}
$$

$\Pi_{V_{i} V_{j}}\left(q^{2}\right)=\Pi_{V_{i} V_{j}}(0)+q^{2} \Pi_{V_{i} V_{j}}^{\prime}(0)+\frac{1}{2} q^{4} \Pi_{V_{i} V_{j}}^{\prime \prime}(0)+\ldots$
form factor operator parameter

| $\Pi_{W_{3} B}^{\prime}(0)$ | $\frac{1}{\Lambda_{S}^{2}} H^{\dagger} W_{\mu \nu} H B_{\mu \nu}$ | $S=\frac{8 \sin \left(2 \theta_{W}\right)}{g^{2} \alpha} \frac{m_{W}^{2}}{\Lambda_{S}^{2}}$ |
| :---: | :---: | :---: |
| $\Pi_{W_{3} W_{3}}(0)-\Pi_{W+W}(0)$ | $\frac{1}{\Lambda_{T}^{2}}\left\|H^{\dagger} D_{\mu} H\right\|^{2}$ | $T=-\frac{2}{g^{2} \alpha} \frac{m_{W}^{2}}{\Lambda_{T}^{2}}$ |
| $\Pi_{W_{3} W_{3}}^{\prime \prime}(0)$ | $\frac{1}{\Lambda_{W}^{2}}\left(D_{\rho} W_{\mu \nu}^{a}\right)^{2}$ | $W=-4 \frac{m_{W}^{2}}{\Lambda_{W}^{2}}$ |
| $\Pi_{B B}^{\prime \prime}(0)$ | $\frac{1}{\Lambda_{Y}^{2}}\left(\partial_{\rho} B_{\mu \nu}\right)^{2}$ | $Y=-4 \frac{m_{W}^{2}}{\Lambda_{Y}^{2}}$ |

- Peskin, Takeuchi 1990
- Barbieri, Pomarol, Rattazzi, Strumia hep-ph/0405040


## Drell-Yan with Oblique Parameters

$$
\mathcal{L} \supset \frac{1}{\Lambda_{S}^{2}} H^{\dagger} W_{\mu \nu} H B_{\mu \nu}+\frac{1}{\Lambda_{T}^{2}}\left|H^{\dagger} D_{\mu} H\right|^{2}+\frac{1}{\Lambda_{W}^{2}}\left(D_{\rho} W_{\mu \nu}^{a}\right)^{2}+\frac{1}{\Lambda_{Y}^{2}}\left(\partial_{\rho} B_{\mu \nu}\right)^{2}
$$

2. electroweak tests from Drell-Yan


- Farina, Panico, Pappadopulo, JTR, Torre, Wulzer 1609.08157


## High Mass Drell-Yan Probes W/Y

- neutral current:
 $M_{l^{+} l^{-}}(W, Y)$
- charged current:



## Theory vs. Drell-Yan Data


we include:

- experimental uncertainties (with correlations)
- NNLO scale uncertainty (from FEWZ)
- PDF uncertainty
(NNPDF, with correlations)


## LHC8 Limits


$\Lambda_{Y} \gtrsim 4 \mathrm{TeV}$
$\Lambda_{W} \gtrsim 8 \mathrm{TeV}$
experimental uncertainty:

$$
\begin{aligned}
& \delta_{\text {cor }}=5 \% \\
& \delta_{\text {unc }}=5 \%
\end{aligned}
$$

LEP bound: • Falkowski, Mimouni 1511.07434

## Future W/Y Reach



## EFT Validity



## application: Heavy Vector Triplet

$$
\begin{aligned}
& \frac{m_{V}^{2}}{2} V^{2}+g_{V} V_{\mu}^{a} \sum_{i} \bar{\psi}_{i} \gamma^{\mu} \tau^{a} \psi_{i} \\
& W=\frac{g_{V}^{2}}{g^{2}} \frac{m_{W}^{2}}{m_{V}^{2}}
\end{aligned}
$$

## application: Heavy Vector Triplet



## 3. oblique parameters from jets



- Alioli, Farina, Pappadopulo, JTR, to appear


## Z

$$
\frac{1}{\Lambda_{Z}^{2}}\left(D_{\rho} G_{\mu \nu}^{a}\right)^{2} \quad Z=-\frac{4 m_{W}^{2}}{\Lambda_{Z}^{2}}
$$


earlier bounds:

- Cho, Simmons hep-ph/9307345
- Domenech, Pomarol, Serra 1201.6510


## LHC vs Z

CMS dijet


ATLAS inclusive jet


$$
\Lambda_{Z} \gtrsim 7 \mathrm{TeV}
$$

*13 TeV projections in progress

## take away

$$
\mathcal{L}_{\text {eff }} \supset \frac{1}{\Lambda_{Y}^{2}}\left(\partial_{\rho} B_{\mu \nu}\right)^{2}+\frac{1}{\Lambda_{W}^{2}}\left(D_{\rho} W_{\mu \nu}^{a}\right)^{2}+\frac{1}{\Lambda_{Z}^{2}}\left(D_{\rho} G_{\mu \nu}^{a}\right)^{2}
$$

- high mass neutral/charged Drell-Yan probes oblique parameters W,Y (LHC is about to beat LEP!)
- LHC jets constrain Z
- motivates effort to minimize exp/theory systematics in high energy tails

