Extracting Z' Couplings from the LHC and Low-energy Measurements

Seth Quackenbush
University of Wisconsin-Madison

arXiv:0801.4389 [hep-ph] (F. Petriello, SQ)
WIP (Y. Li, F. Petriello, SQ)

Outline

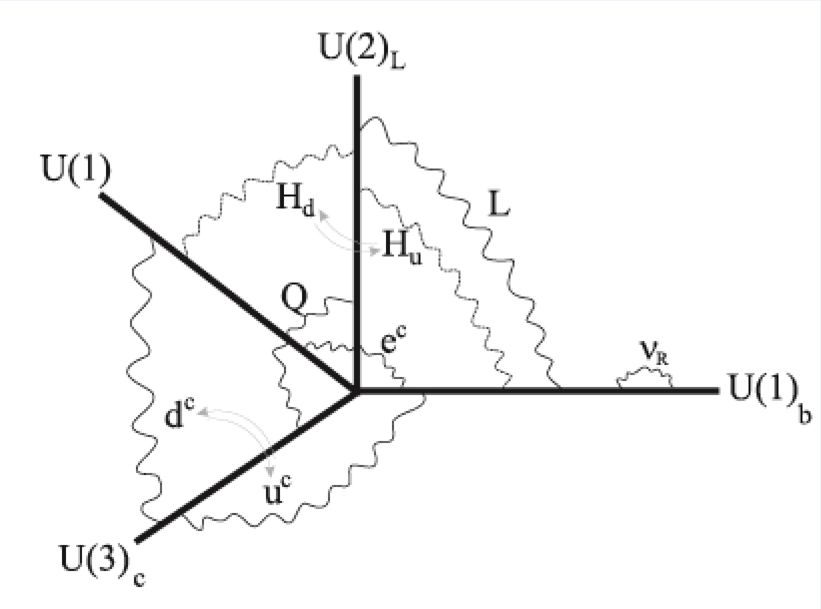
- What is a Z'? How do we see it?
- Why do we care?
- A reasonably general model template: couplings to SM particles—discriminates without reference to a particular model!
- Using LHC measurements on and off the resonance peak
- Getting at more parameters with low-energy experiments

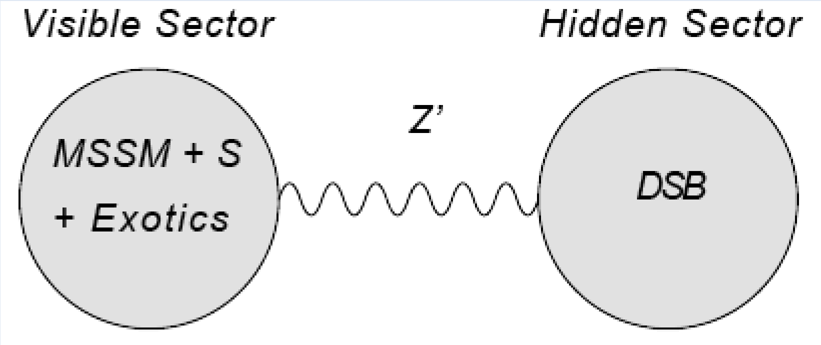
What is a Z'?

- A new Drell-Yan resonance ($pp \to l^+l^-$)
- Neutral, colorless
- Boson, pick your spin:
  0 (e.g. RP-violating sneutrino)
  1 (e.g. gauge boson)
  2 (e.g. KK graviton)

Why do we care?

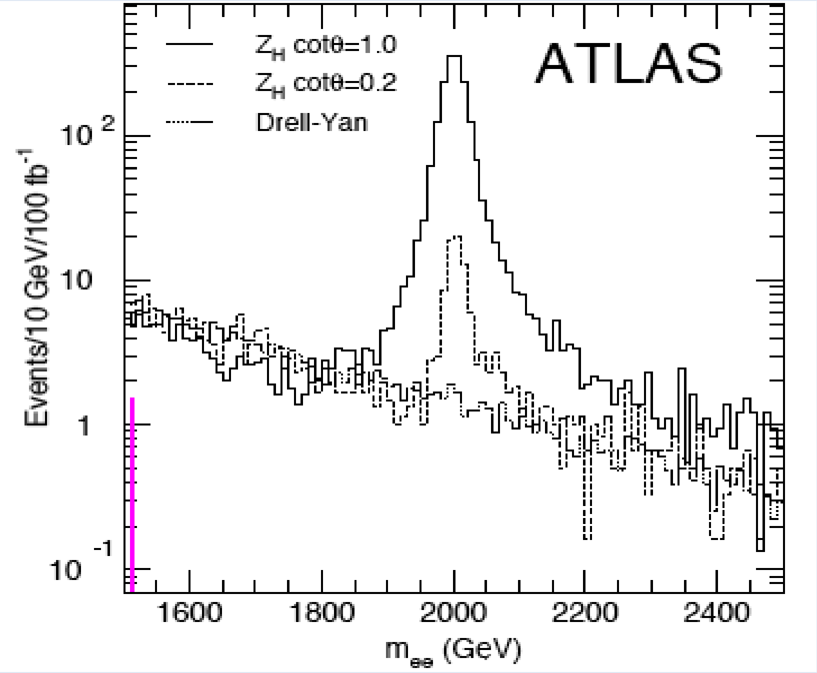
- Ubiquitous in extensions to SM
- Clean signature at LHC; very small dilepton background
- Good discovery reach

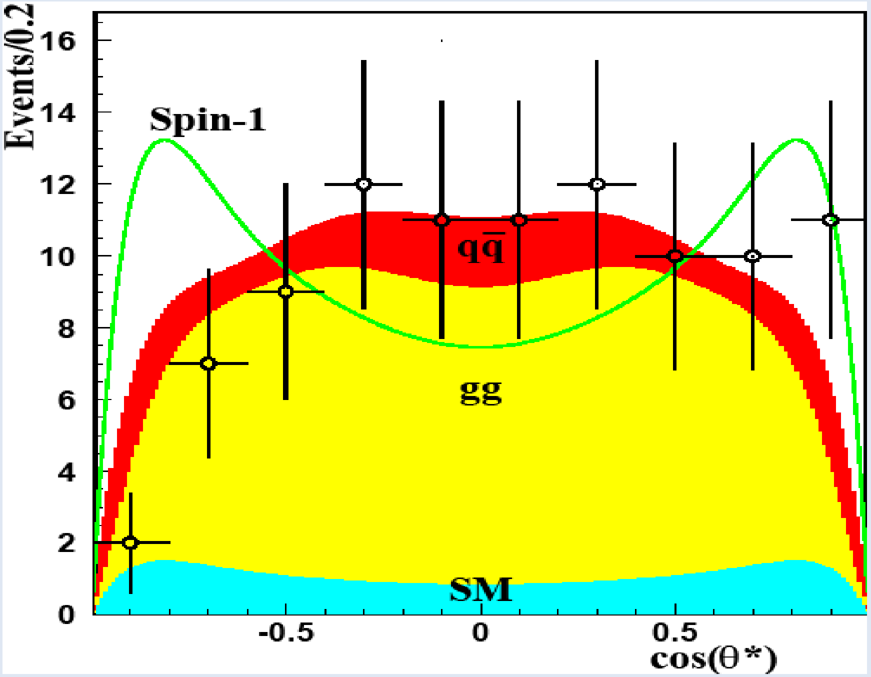




We find one! What now?

- Locate resonance peak, determine mass
- Measure spin by studying angular distribution; requires few hundred events (~ 10 fb^{-1})





Allanach, et. al

The framework

- We know the mass and spin—start with spin 1
- Goal: accommodate as many models as possible—from favorites to ones nobody's thought of
- What assumptions to make at LHC?
- Need to parametrize model space; will do this in terms of Z' couplings to SM particles
- Too many parameters!

Parameter reduction

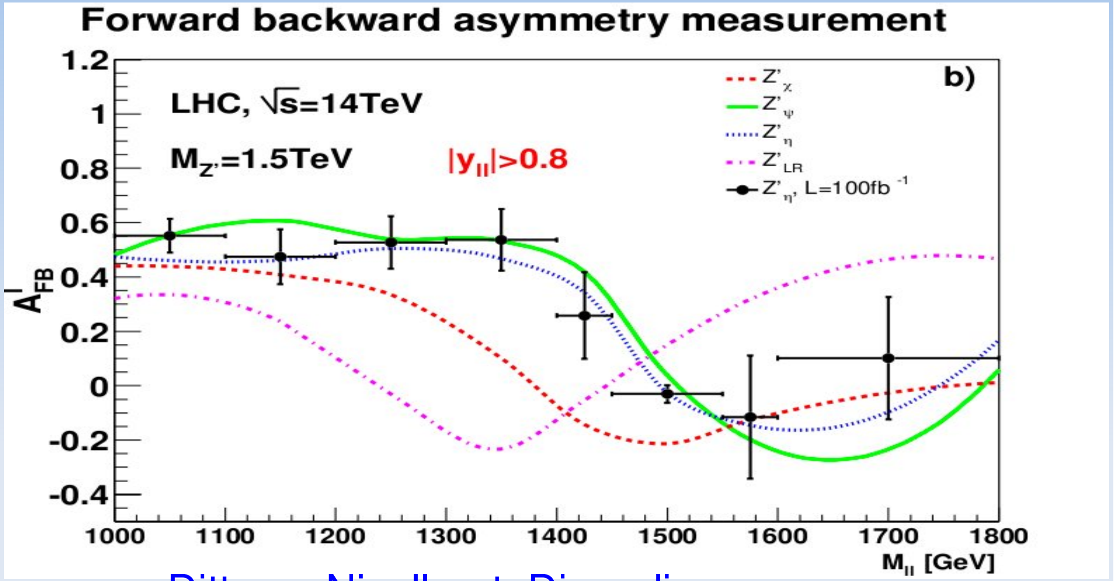
- Most likely candidates for parameter reduction:
- 1. Make couplings generation-independent (no FCNC)
- 2. Left-handed doublets have same coupling (avoids generating Z-Z' mass mixing)

The parameters

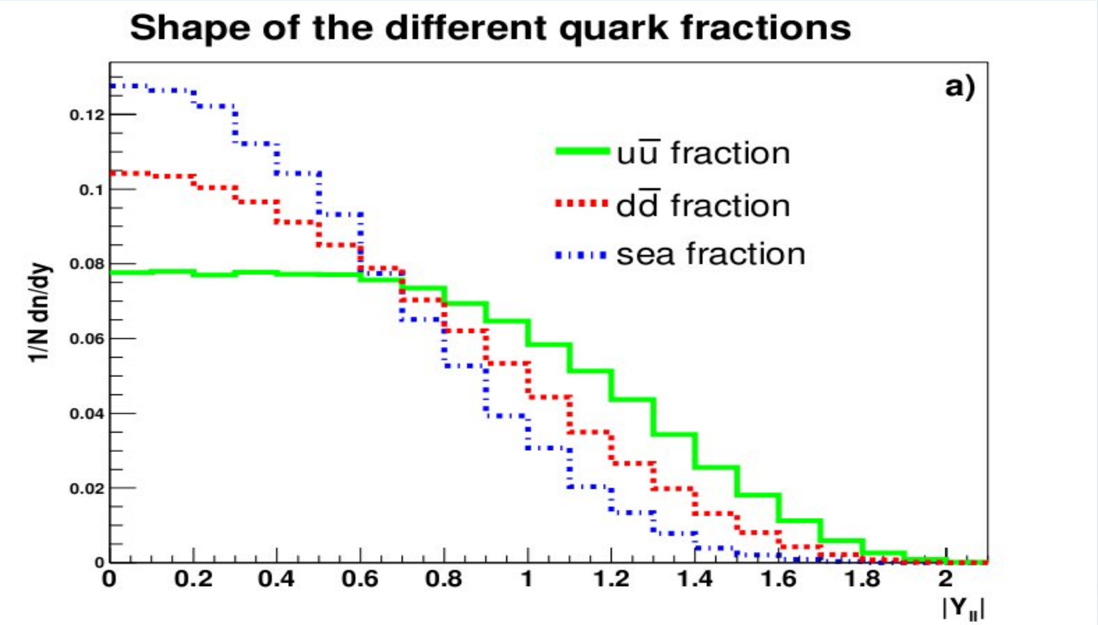
- Assume spin 1 Z' found. The cross section depends on:
- The mass, $M_{Z'}$
- Z' charges of SM particles (absorb overall coupling):
  q_L, u_R, d_R, e_L, e_R
  (couples to fermions as $g_L(1-\gamma_5)/2 + g_R(1+\gamma_5)/2$)
- The width, Γ_Z

What can we measure?

- Asymmetry (A_{FB}): does lepton scatter with quark or against?
- Z' rapidity (Y): different u/d PDFs yield different Z' rapdity distributions (more valence u at high x)



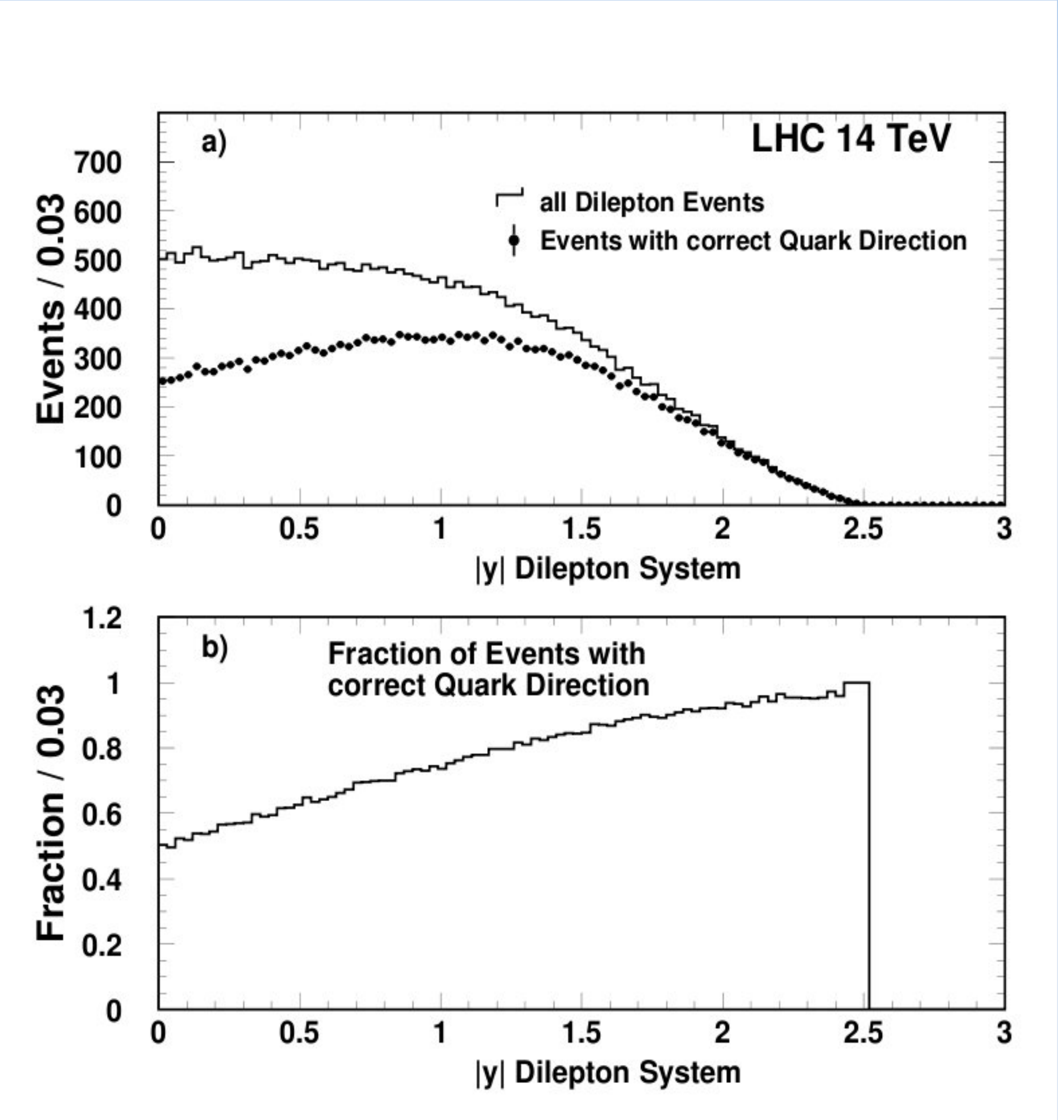
Dittmar, Nicollerat, Djouadi



Asymmetry

$$A_{FB}=\frac{F-B}{F+B}$$

- LHC is pp collider—which direction is the quark direction?
- High rapidity Z's tend to come from valence quark (high x) and sea antiquark (low x)
- Higher rapidity, better odds you guess correct quark direction



M. Dittmar

Putting them together

- Z' Rapidity discriminates relative amount of u vs. d
- Asymmetry gives us parity-symmetric vs. antisymmetric information in couplings, but quark direction correlation depends on rapidity

Structure of Z' cross section

- Can we use these observables to extract coupling information?

$$\frac{d^2\sigma}{dY\,d\cos\theta} = \sum_{q=u,d} [a_1^q{}'(q_R^2+q_L^2)(e_R^2+e_L^2)+a_2^q{}'(q_R^2-q_L^2)(e_R^2-e_L^2)$$
$$+b_1 q_L e_L + b_2 q_L e_R + b_3^q q_R e_L + b_4^q q_R e_R] + c$$

- Mass dependence, PDFs, kinematics in a, b, c coefficients of model parameters
- a terms are Z'-only pieces
- b terms are Z' interference with Z, photon
- c is SM background (Z, photon, their interference)

Measurement Strategy

- a,b,c can be integrated in any measurement bin once mass known; now fit model parameters (couplings) from measurements
- Bin in invariant mass to distinguish on vs off peak (a terms vs b terms)
- Bin in Z' rapidity to distinguish u terms vs d terms
- Bin F/B measurements to give R vs L information

Previous study: On-peak only

- b, c not important on-peak
- Width dependence of a's known on-peak (NWA): absorb into effective couplings

$$c_q = \frac{M_{Z'}}{24\pi\Gamma_{Z'}}(q_R^2+q_L^2)(e_R^2+e_L^2)$$

- Carena, Daleo, Dobrescu, Tait

$$e_q = \frac{M_{Z'}}{24\pi\Gamma_{Z'}}(q_R^2-q_L^2)(e_R^2-e_L^2)$$

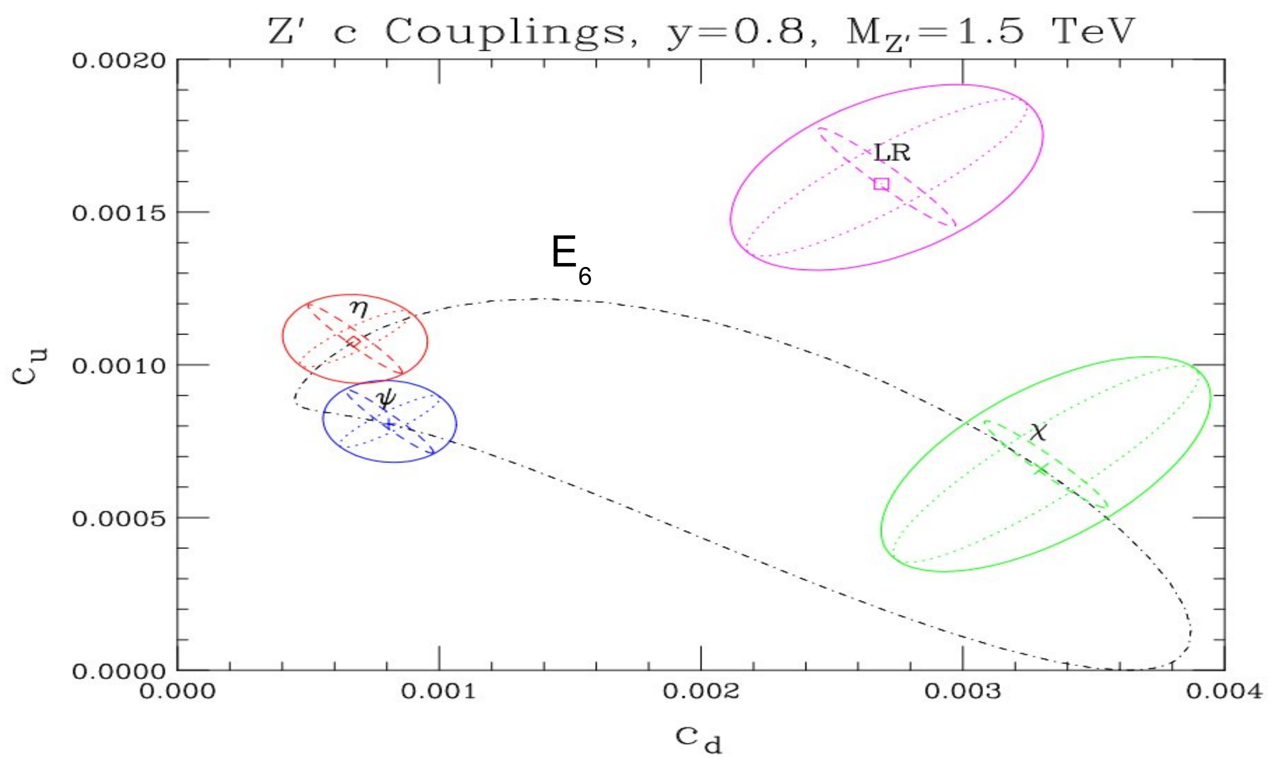
$$\frac{d^2\sigma}{dY\,d\cos\theta} = \sum_{q=u,d}[a_1^q c_q + a_2^q e_q]$$

- Four parameters (c_u, c_d, e_u, e_d); need four bins (simple linear inverse)

Model test cases

- Three from E_6 -> $SO(10) \times U(1)_\psi$ -> $SU(5) \times U(1)_\psi \times U(1)_\chi$: ψ, χ, and a mixture η
- For illustration, overall coupling taken to retain GUT relations to EM coupling
- Also, a left-right symmetric model with gauge group $SU(2)_R$, $g_R = g_L$
- Width chosen to be decay to SM particles; only matters through statistics

c_u/c_d Results, 1.5 TeV, 100 fb^{-1}



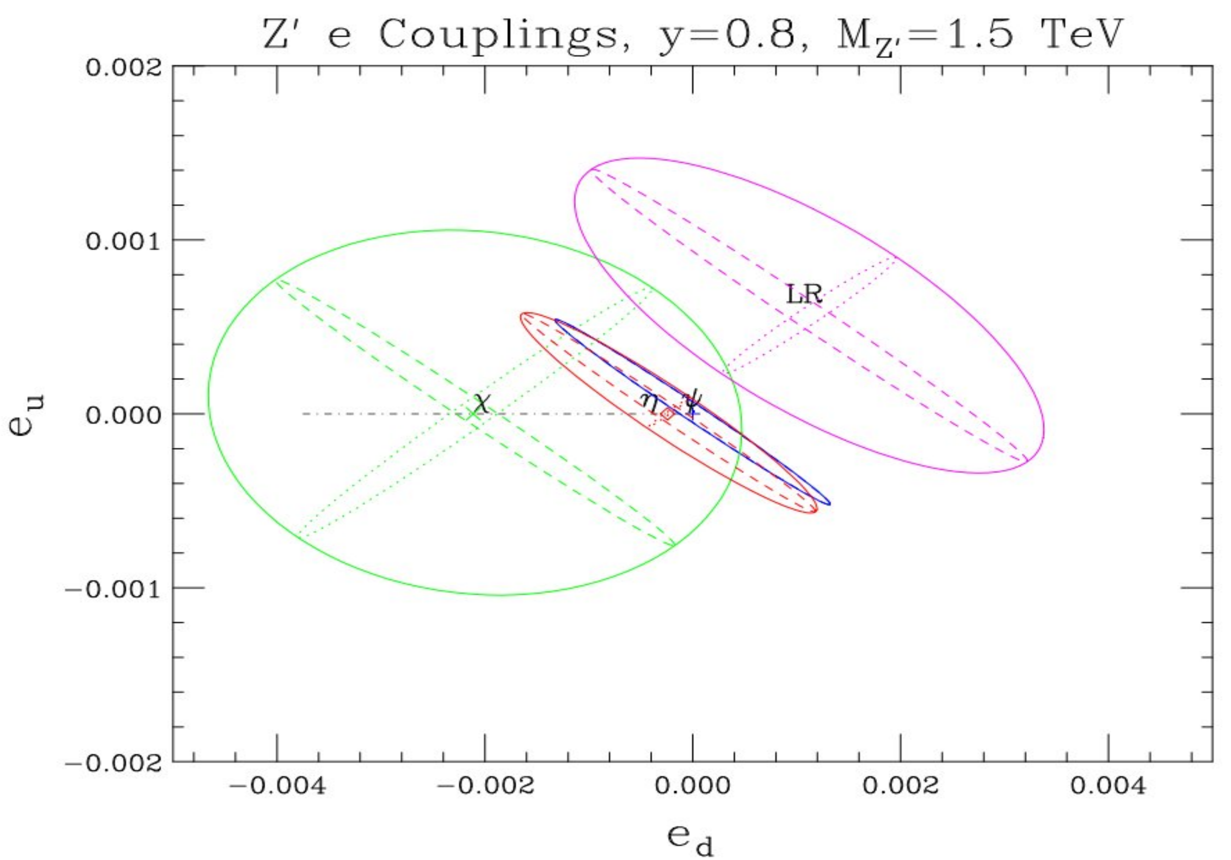
Dot: PDF error
Dash: Statistical error
Solid: Total error
Dot-dash: E_6 family

- Errors perpendicular!
- $c_u + c_d$ PDF-limited
- $c_u - c_d$ statistics limited
- Test models discriminated

e_u/e_d Results, 1.5 TeV, 100 fb^{-1}

- Statistics more difficult with e's, but still get something

Dot: PDF error
Dash: Statistical error
Solid: Total error
Dot-dash: E_6 family



Can we do better?

- We lost information: measured parameters go like q^2 e^2
- Look at cross section again:

$$\frac{d^2\sigma}{dY\,d\cos\theta}=\sum_{q=u,d}[a_1^q{}'(q_R^2+q_L^2)(e_R^2+e_L^2)+a_2^q{}'(q_R^2-q_L^2)(e_R^2-e_L^2)$$
$$+\boxed{b_1 q_L e_L+b_2 q_L e_R+b_3^q q_R e_L+b_4^q q_R e_R]}+c$$

- There's sign information! We should probe a region where this has an effect

New parameters

- Still have q X e degeneracy
- This leaves $q_L e_L$, $q_L e_R$, $u_R e_L$, $d_R e_L$
- Other two combinations are dependent on these four:

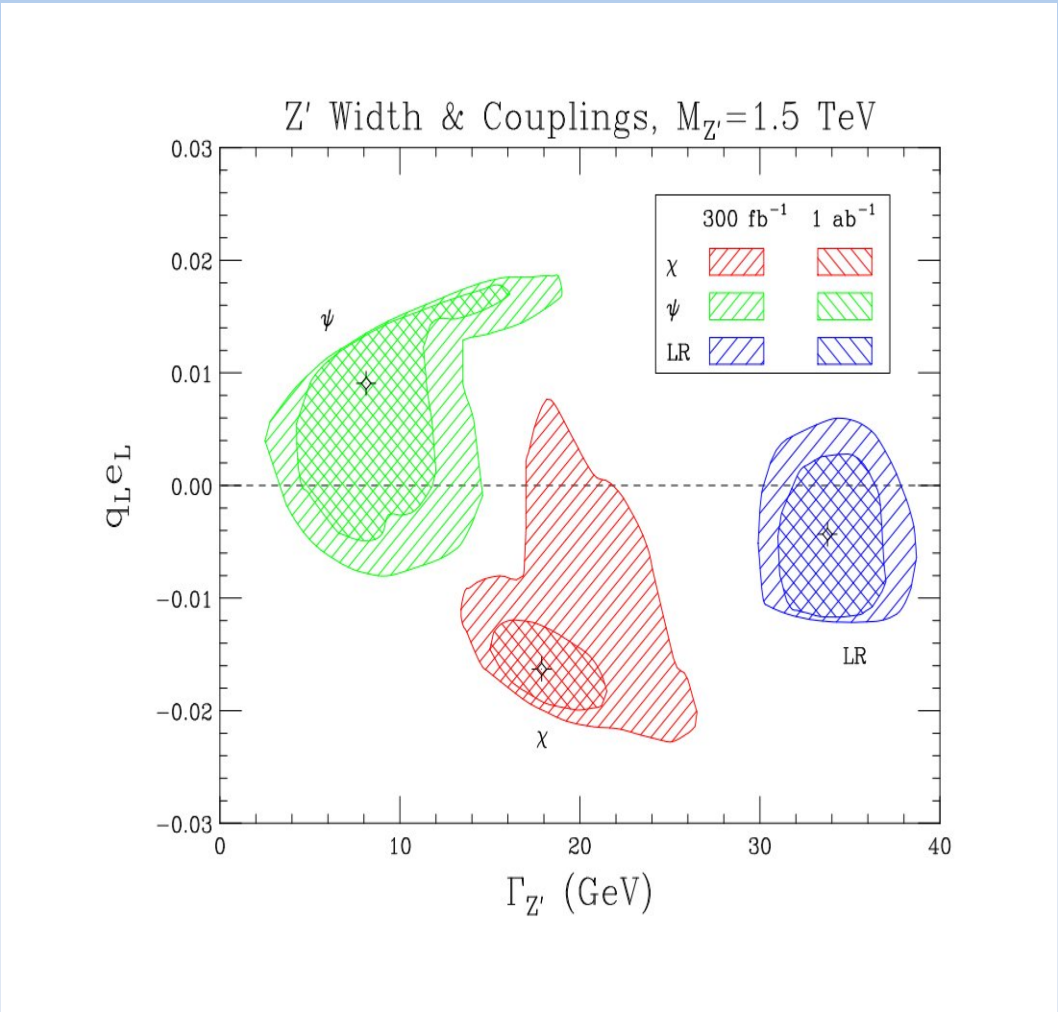
$$\frac{q_L e_L}{q_L e_R} = \frac{u_R e_L}{u_R e_R} = \frac{d_R e_L}{d_R e_R}$$

- Must fit width, Γ
- Total: 5

Procedure

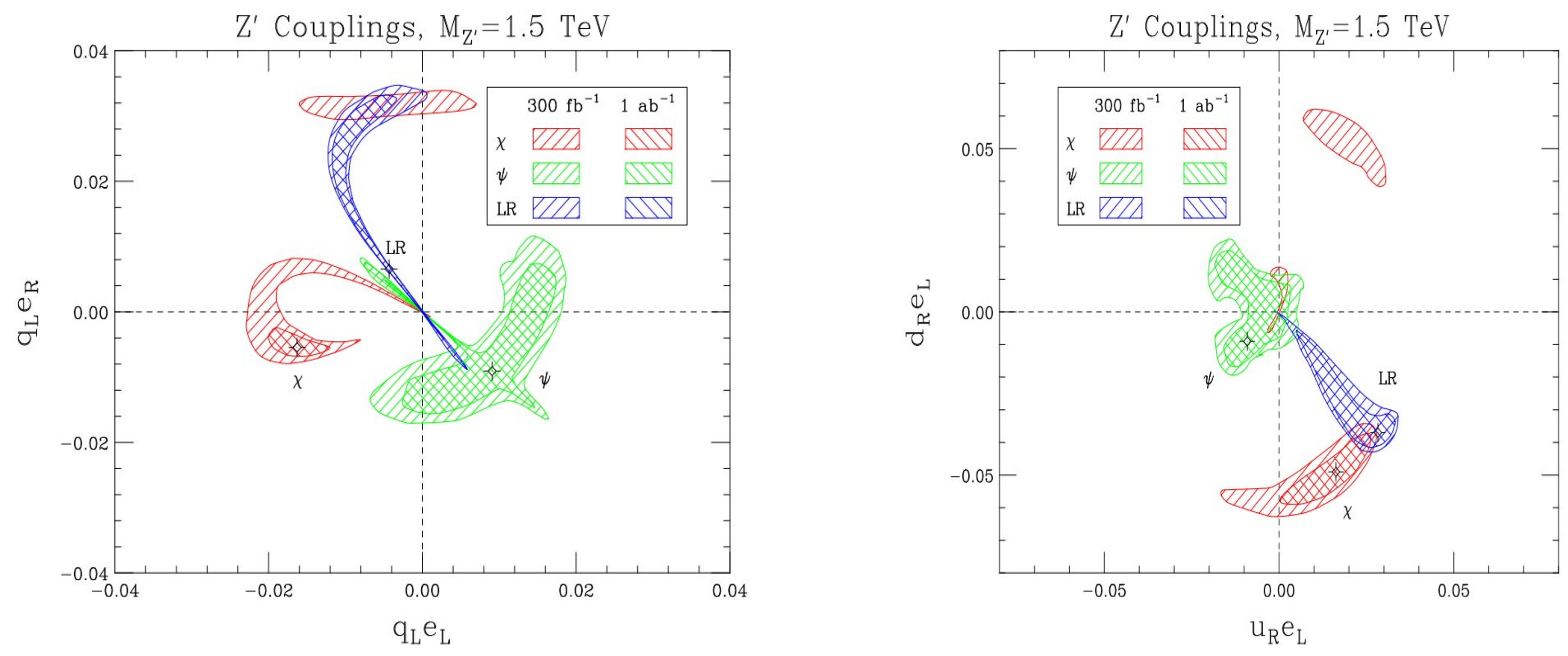
- Assume we find a particular test model corresponding to a set of measurements
- Scan 5D parameter space: for each test point, construct measurements (32 bins)
- Keep points where χ^2 comparison (from statistical, PDF, and theory error) with model within 5.9 (68% CL)
- Project 5D confidence region to 2D graphs

Fitting the width



- Width determined to a few GeV by comparison of on- and off-peak alone!
- Probably better than experimental resolution of resonance shape
- Tends to correlate with larger coupling

Fitting the couplings



- Sign degeneracy from on-peak mostly broken
- Needs both on + off peak to work!
  Degeneracies remain with off-peak only

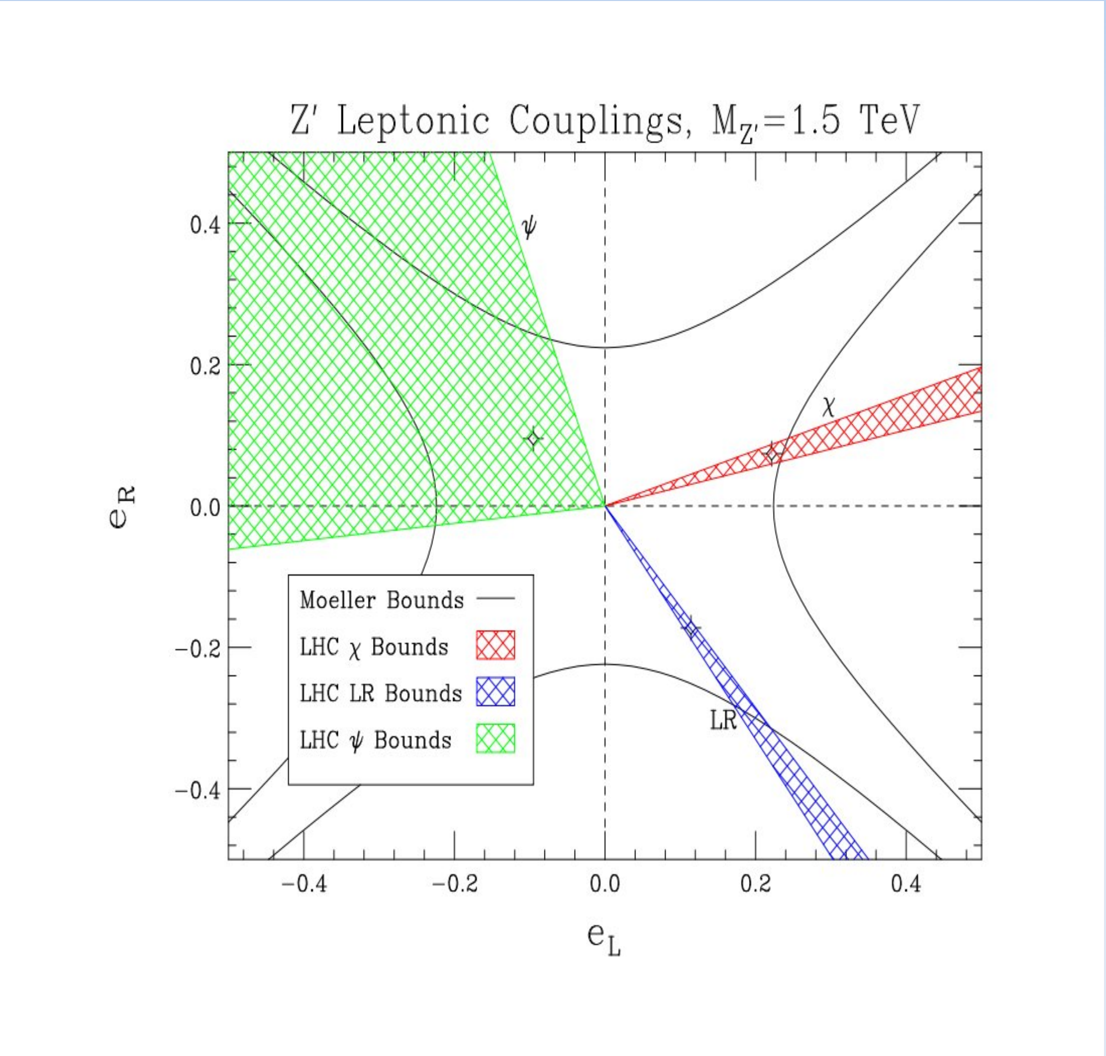
Moeller scattering

- Still have q X e degeneracy; need to probe one or the other
- New Jlab Moeller experiment measures asymmetry to very high precision, δA ~0.6 ppb
- Z' deviation from SM goes like $(e_R^2 - e_L^2)/M_{Z'}^2$— hyperbolic bound in e_L-e_R plane
- Large enough deviation leads to measurement
- We should know e_L/e_R from on-/off-peak analysis— angle in e_L-e_R plane

$$\frac{q_L e_L}{q_L e_R} = \frac{e_L}{e_R}$$

Moeller scattering, continued

- Intersection of hyperbolas and lines from other data give us e_L and e_R! Breaks degeneracy!
- At 1.5 TeV, test models consistent with Standard Model—we still limit size of e couplings



Summary: Z' analysis strategy

- Mostly model-independent procedure
- Simple choice of bins yields a lot of coupling information
- LHC measurements determine q X e couplings with fair precision; strong reduction of parameter space
- Moeller scattering could break last parameter degeneracy, give us all SM couplings
- Can select high scale theory with these parameters if known well enough