Z' Bosons On and Off the Resonance Peak
(and at low energy)

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

Outline

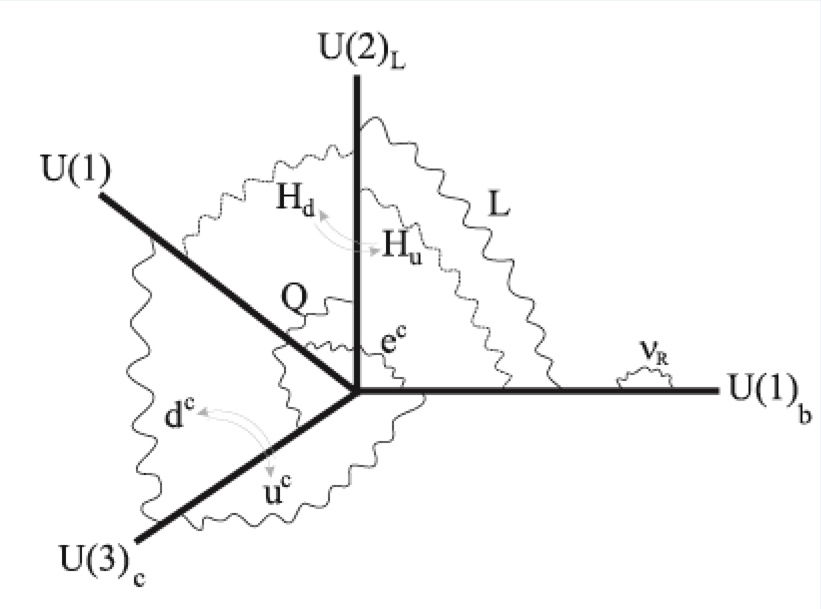
- What is a Z'? How do we see it?
- Why do we care?
- A reasonably general model template: couplings to SM particles—discriminates without reference to a particular model!
- First stab: forming effective couplings from on-peak measurements
- Second stab: measuring Z' interference off-peak
- Finally: adding next-generation low-energy experiments

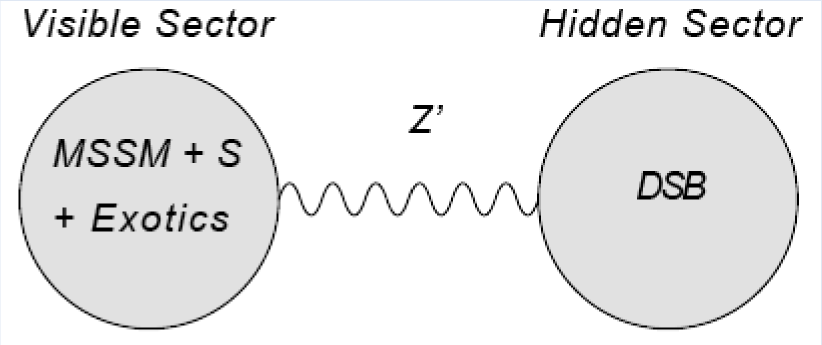
What is a Z'?

- A new Drell-Yan resonance ($pp \rightarrow l^+l^-$)
- 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?

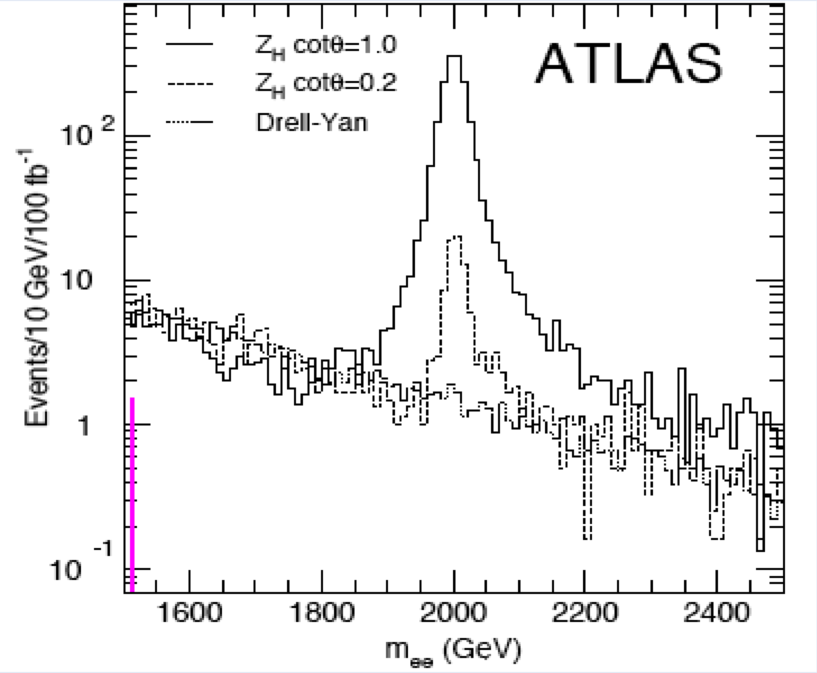
- Ubiquitous in extensions to SM
- Clean signature at LHC; very small dilepton background
- Good discovery reach

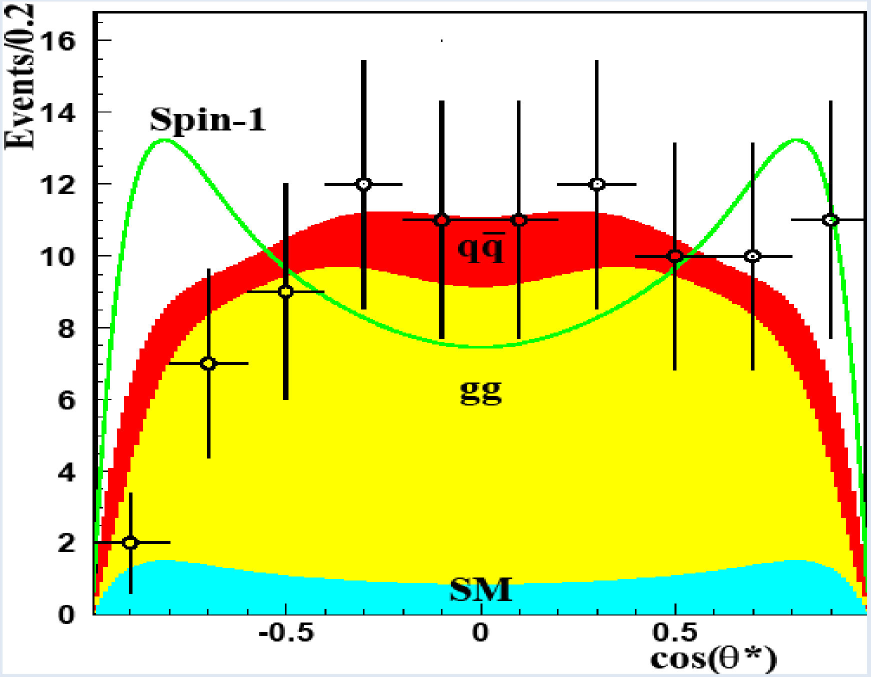




We find one! What now?

- 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

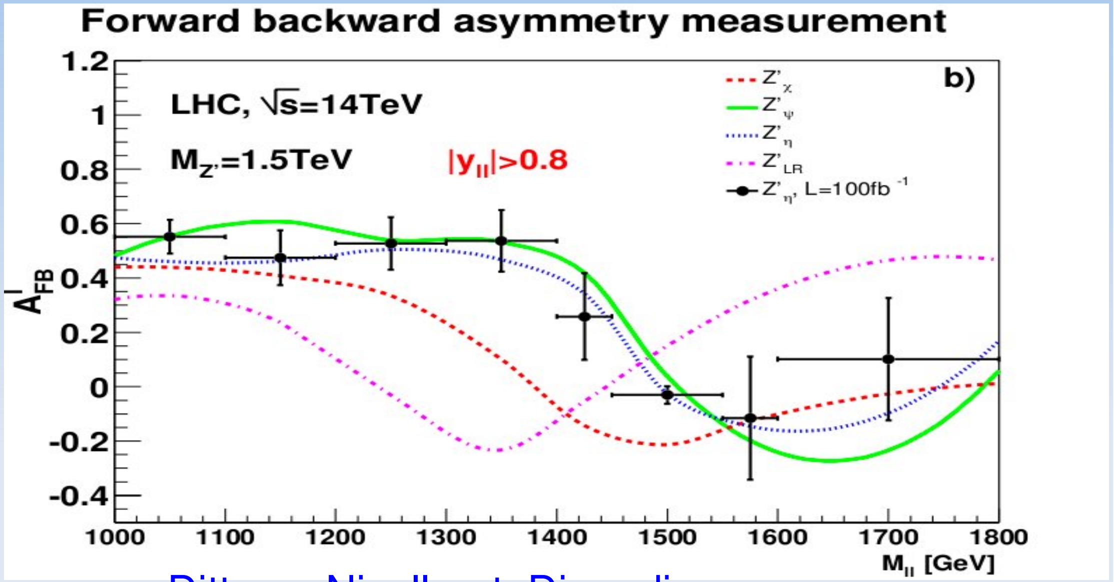
- Most likely candidates for parameter reduction:
- 1. Make couplings generation-independent (no FCNC)
- 2. Left-handed doublets have same coupling (avoids generating Z-Z' mass mixing)

The parameters

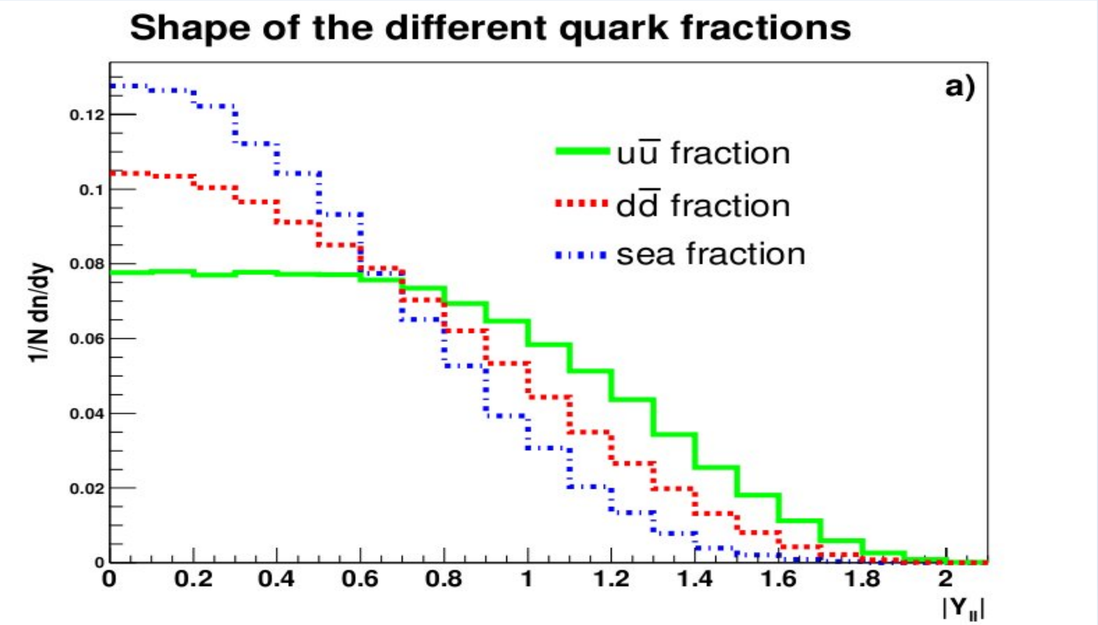
- Assume spin 1 Z' found. The cross section depends on:
- The mass, $M_{Z'}$
- Z' charges of SM particles (absorb overall coupling):
  q_L, u_R, d_R, e_L, e_R
  (couples to fermions as $g_L(1-\gamma_5)/2 + g_R(1+\gamma_5)/2$)
- The width, $\Gamma_{Z'}$

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)



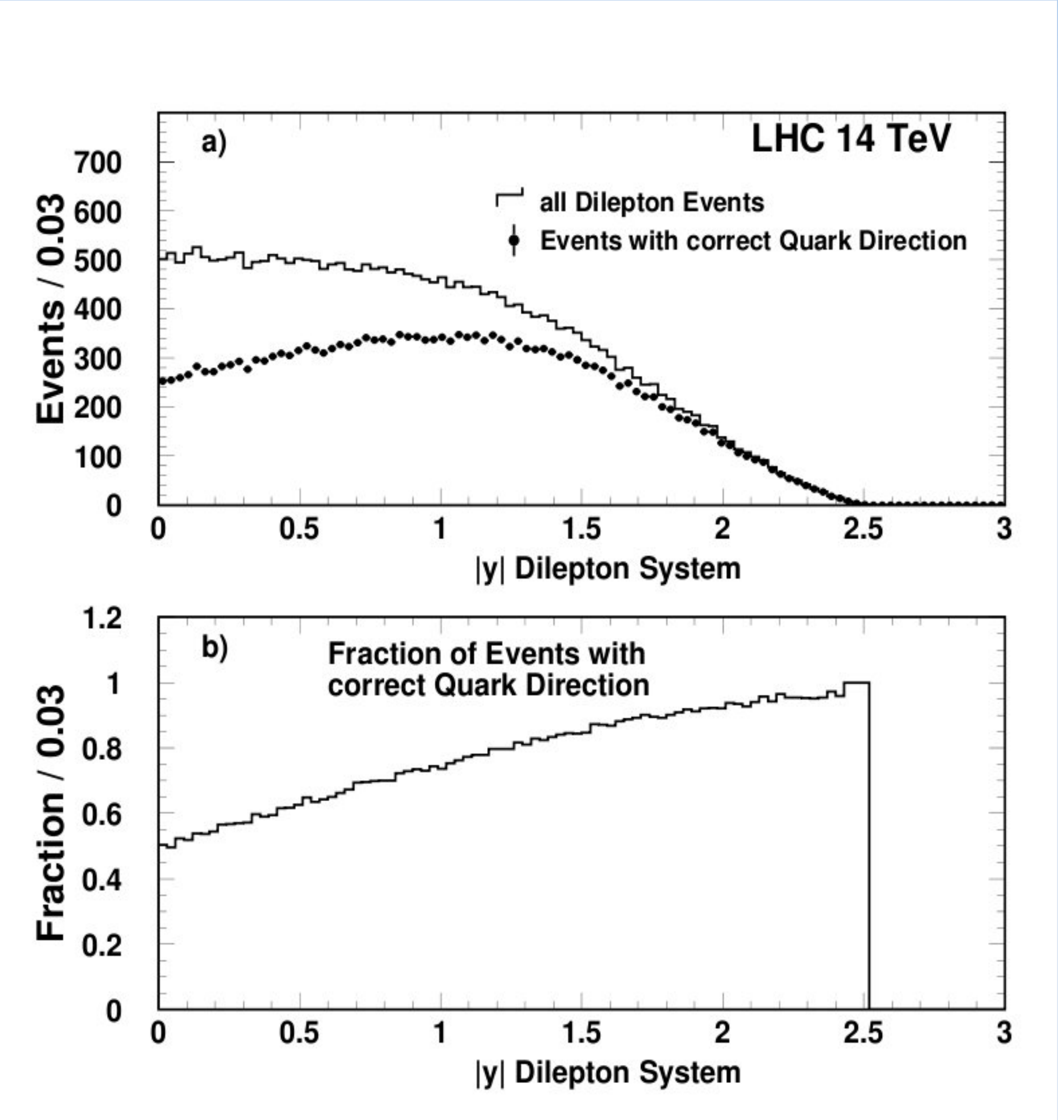
Dittmar, Nicollerat, Djouadi



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

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- “You got chocolate in my peanut butter!” “You got peanut butter in my chocolate!”

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)

First stab: On-peak

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

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

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

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

Four measurements

- Four model parameters: c_u, c_d, e_u, e_d
- c_q defined and bounded in Tevatron study
  Carena, Daleo, Dobrescu, Tait
- e_q parity antisymmetric: need F/B asymmetry!
- Four measurements for four parameters
  Define:

$$F(Y)=\int_0^1 d\cos\theta \frac{d^2\sigma}{dY\, d\cos\theta} \qquad B(Y)=\int_{-1}^0 d\cos\theta \frac{d^2\sigma}{dY\, d\cos\theta}$$

$$F_> = \left[\int_{Y_1}^{Y_{max}} + \int_{-Y_{max}}^{-Y_1}\right] F(Y)\, dY \qquad B_> = \left[\int_{Y_1}^{Y_{max}} + \int_{-Y_{max}}^{-Y_1}\right] B(Y)\, dY$$

$$F_< = \int_{-Y_1}^{Y_1} F(Y)\, dY \qquad B_< = \int_{-Y_1}^{Y_1} B(Y)\, dY$$

Extracting the couplings

- Four measurements related to four parameters linearly:

$$\begin{pmatrix} F_< \\ B_< \\ F_> \\ B_> \end{pmatrix} = \begin{pmatrix} \int_{F_<} a_1^u & \int_{F_<} a_1^d & \int_{F_<} a_2^u & \int_{F_<} a_2^d \\ \int_{B_<} a_1^u & \int_{B_<} a_1^d & \int_{B_<} a_2^u & \int_{B_<} a_2^d \\ \int_{F_>} a_1^u & \int_{F_>} a_1^d & \int_{F_>} a_2^u & \int_{F_>} a_2^d \\ \int_{B_>} a_1^u & \int_{B_>} a_1^d & \int_{B_>} a_2^u & \int_{B_>} a_2^d \end{pmatrix} \begin{pmatrix} c_u \\ c_d \\ e_u \\ e_d \end{pmatrix}$$

$$\vec{m} = M\vec{c}$$

$$\vec{c} = M^{-1}\vec{m}$$

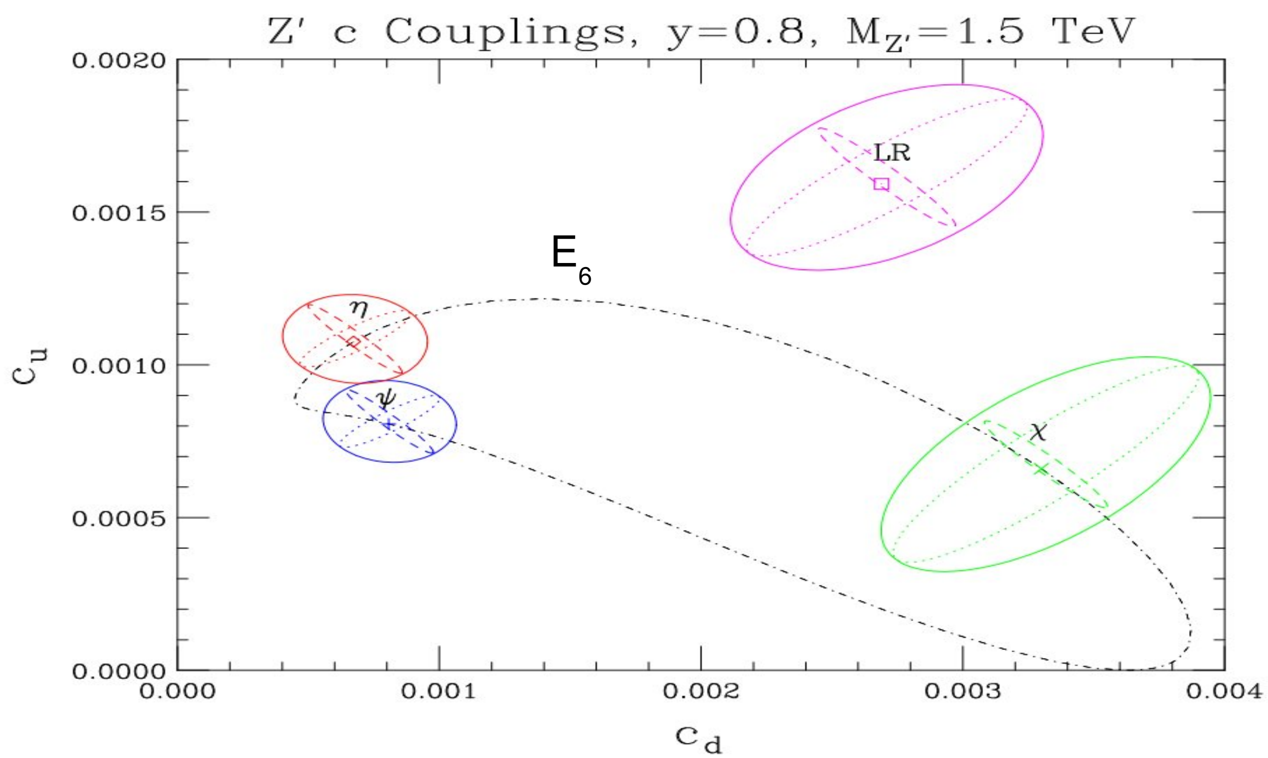
Analysis

- Evaluate entries of matrix M at NLO in QCD (corrections important)
- Generate measurements for test models with full Drell-Yan (+ interference, SM)
- Code includes basic detector cuts ($|\eta| < 2.5$, $p_T > 20$ GeV)
- Include statistical and PDF errors; add in quadrature and diagonalize errors in couplings
- How well are couplings determined if we “find” a particular model?

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

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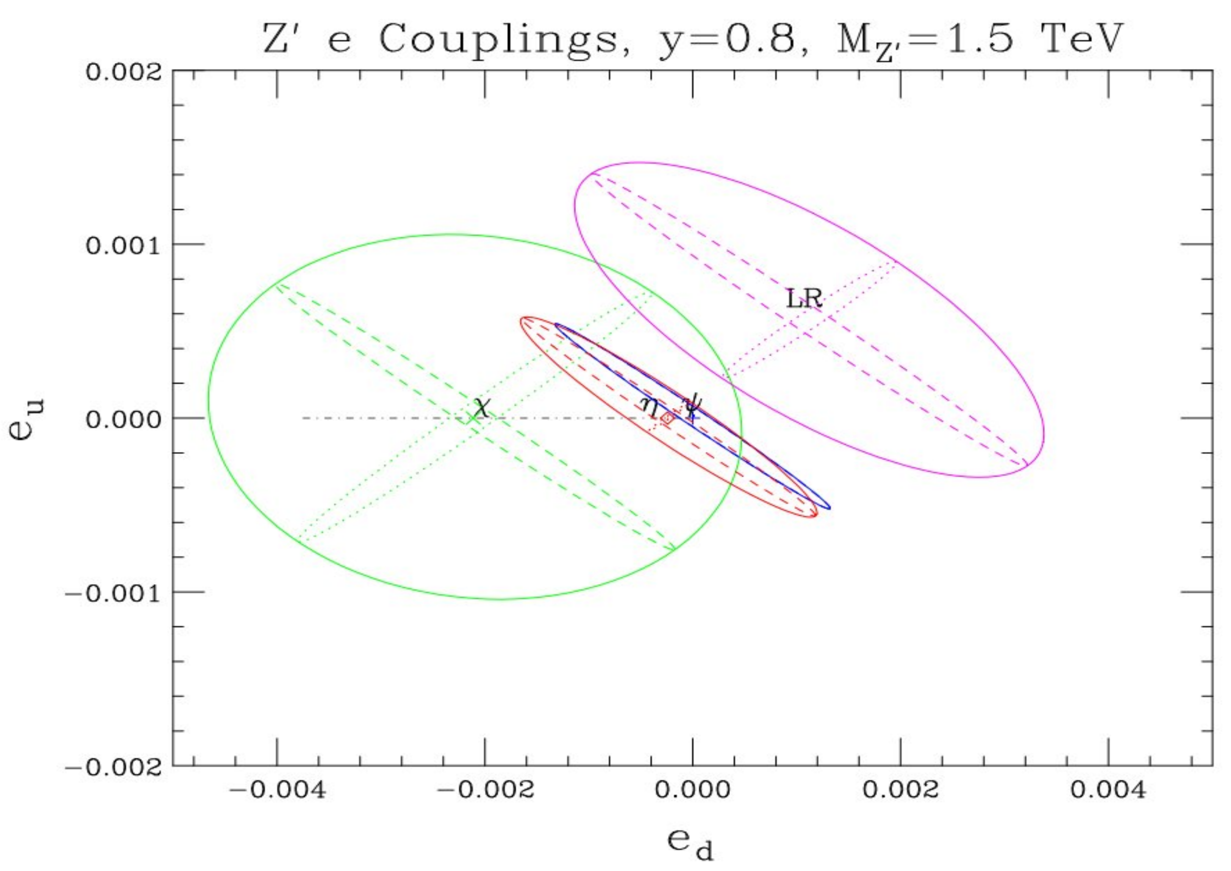
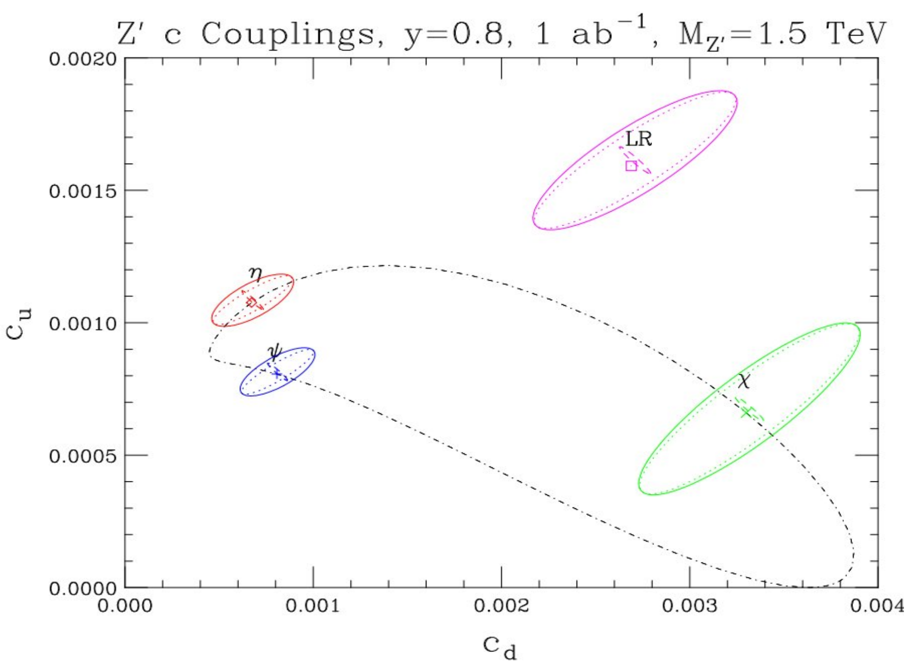


Results, 1.5 TeV, 1ab^{-1}



Dot: PDF error
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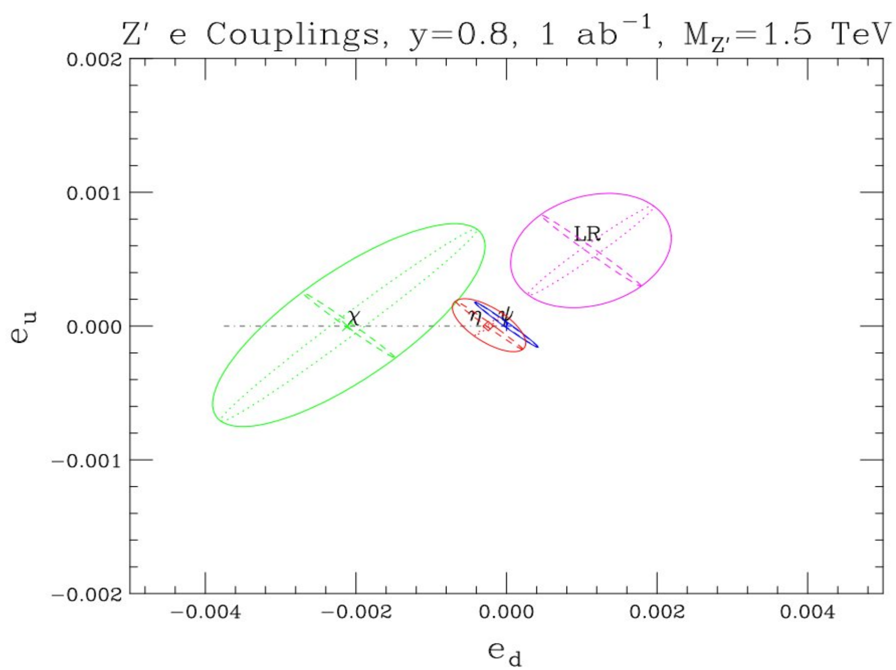
- c's PDF-limited only
- e's start to discriminate by themselves



Can we do better?

- Look at cross section again:

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

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

Second stab: Off-peak

- Bin in dilepton mass, M_{ll}; linear terms important in region between Z and Z' poles, keep on-peak bin
- No easy inversion of cross section; do a brute-force scan of parameter space
- Must fit width to compare on- and off-peak measurements!
- With simple linear relation lost, might as well use more than two Y bins (preliminary result: negligible improvement)

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

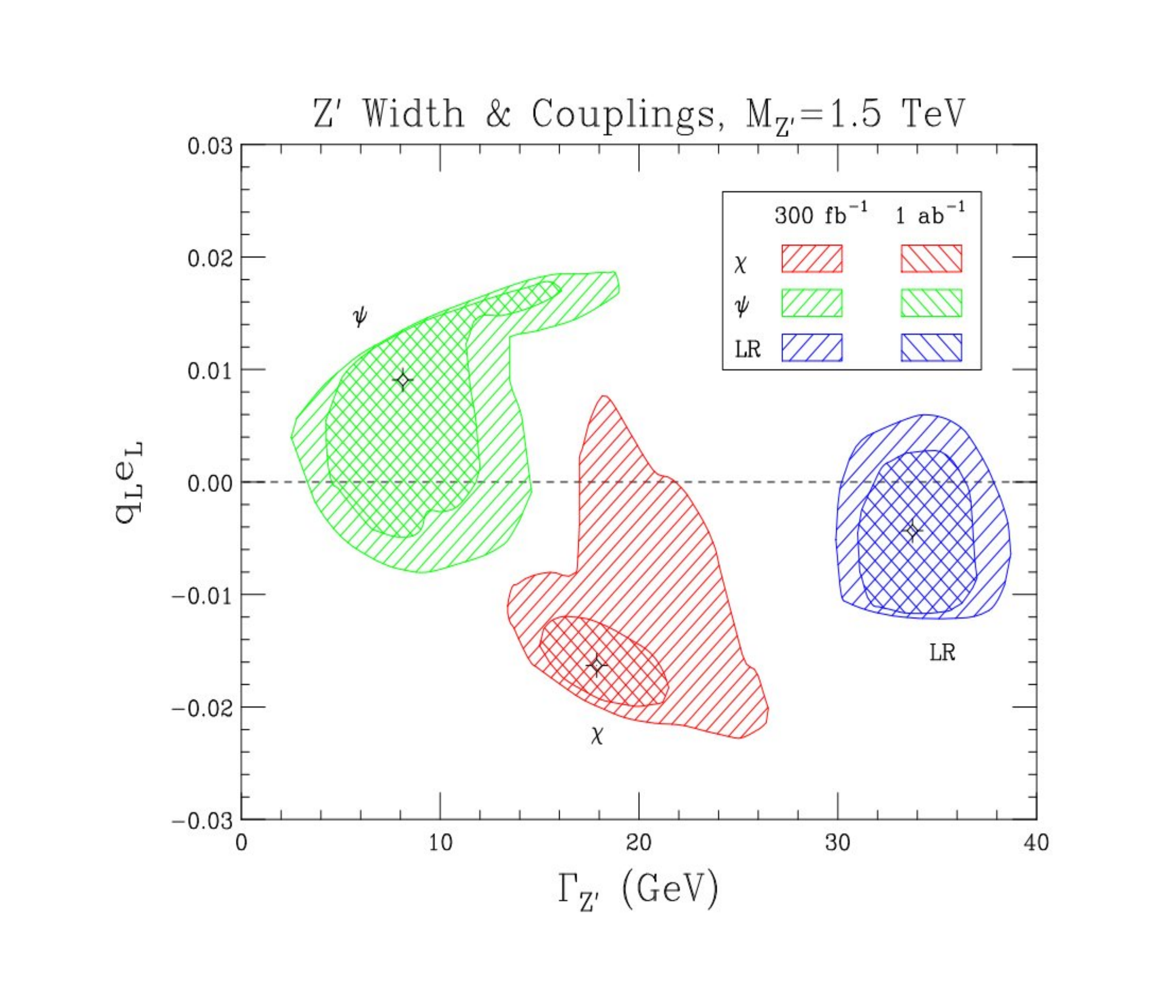
Procedure (1.5 TeV)

- Define a set of measurements to distinguish different terms in cross section
- Bin in invariant mass (different weights in linear/ quadratic terms): 800-1000 GeV, 1000-1200 GeV, 1200-1400 GeV, 1400-1600 GeV
- Bin in Y (different u/d weights): every 0.4 up to 1.2, 1.2+
- Split F/B (different parity weights): as defined previously

Procedure, continued

- Assume we find a particular test model corresponding to a set of measurements
- Determine statistical and PDF errors for the test model
- Scan 5D parameter space: for each test point, construct measurements
- Keep points where χ^2 comparison with model within 5.9 (68% CL)
- This way we see what sections of parameter space are experimentally consistent with test model (illustrated in 2D projections of 5D confidence region)

Fitting the width

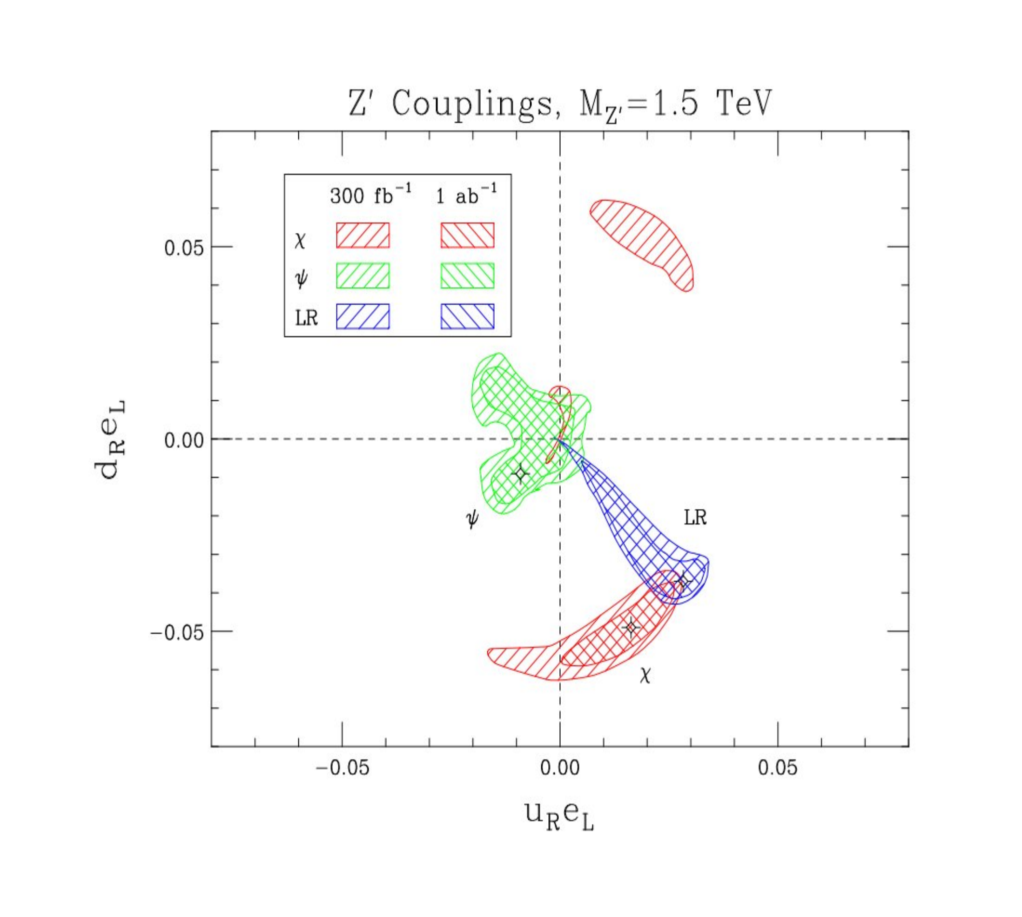


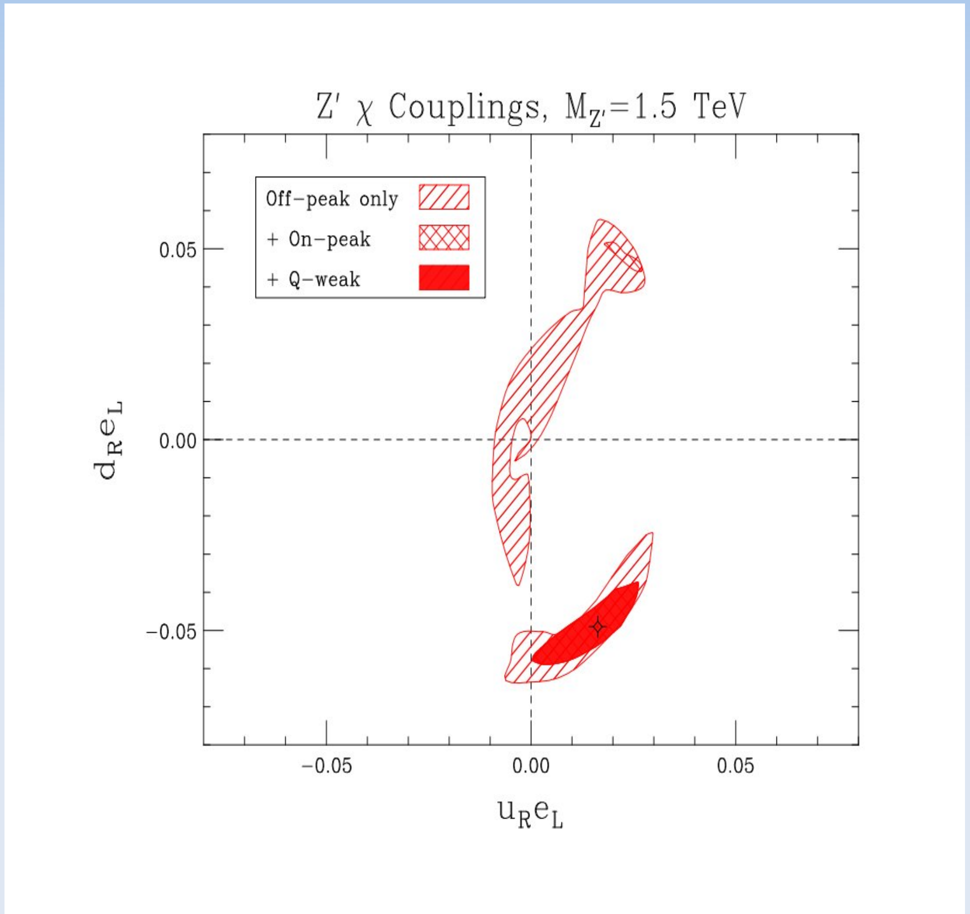
Width determined to a few GeV by comparison of on- and off-peak alone!

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

Anything more?

- Do we need an ILC to get any further?
- What about the q X e degeneracy?
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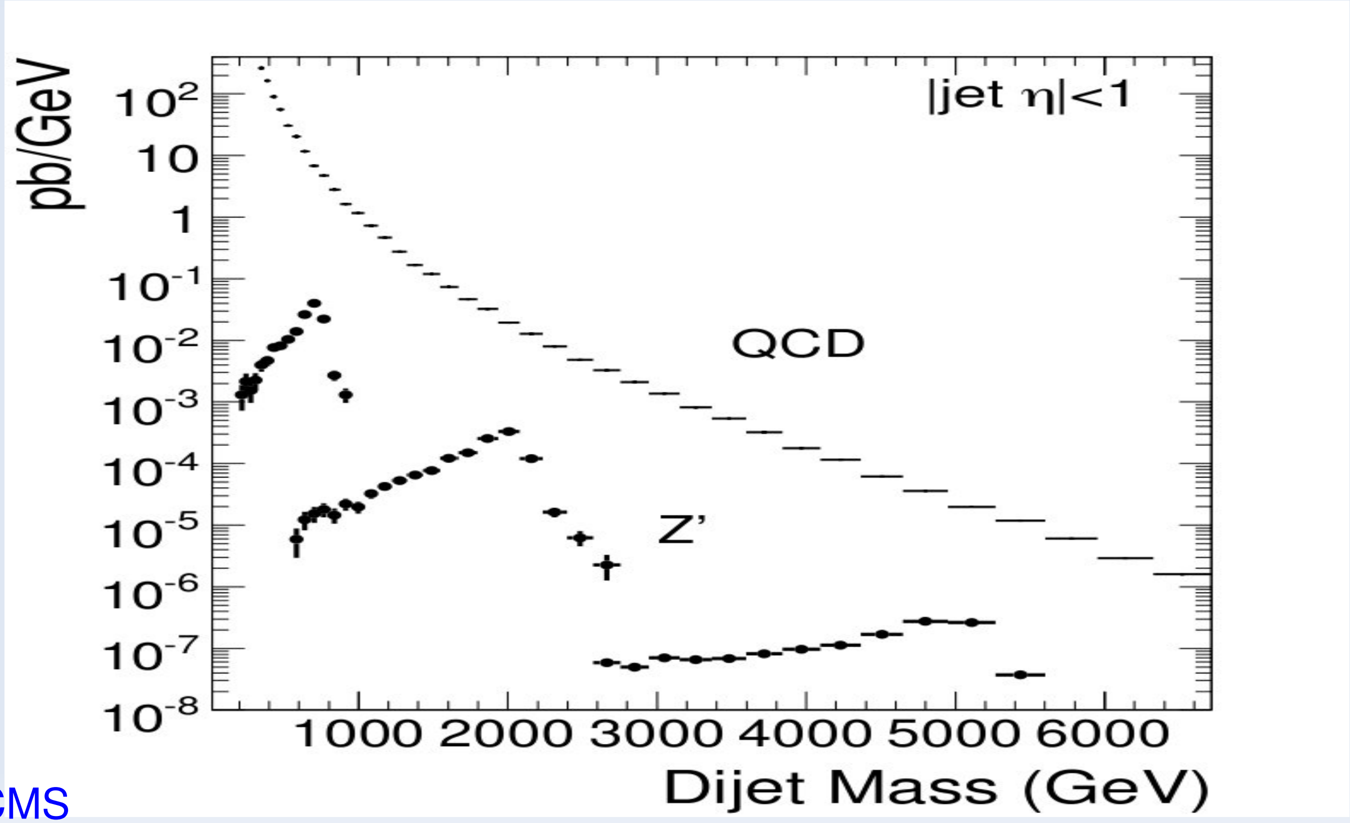
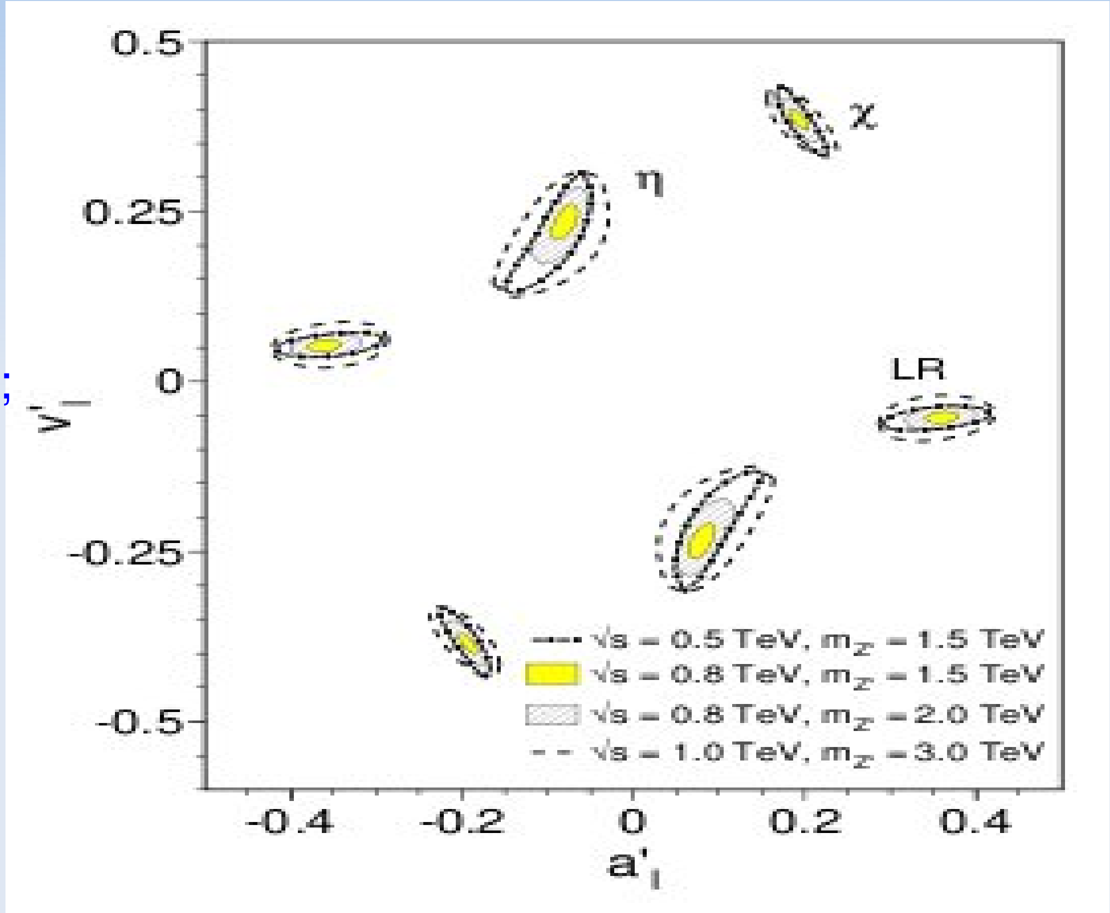


CMS

Probably not...

ILC, anyone?

- ILC *would* be great for e X e
- t t-bar another possibility Barger, Han, Walker; Godfrey, Martin



Riemann

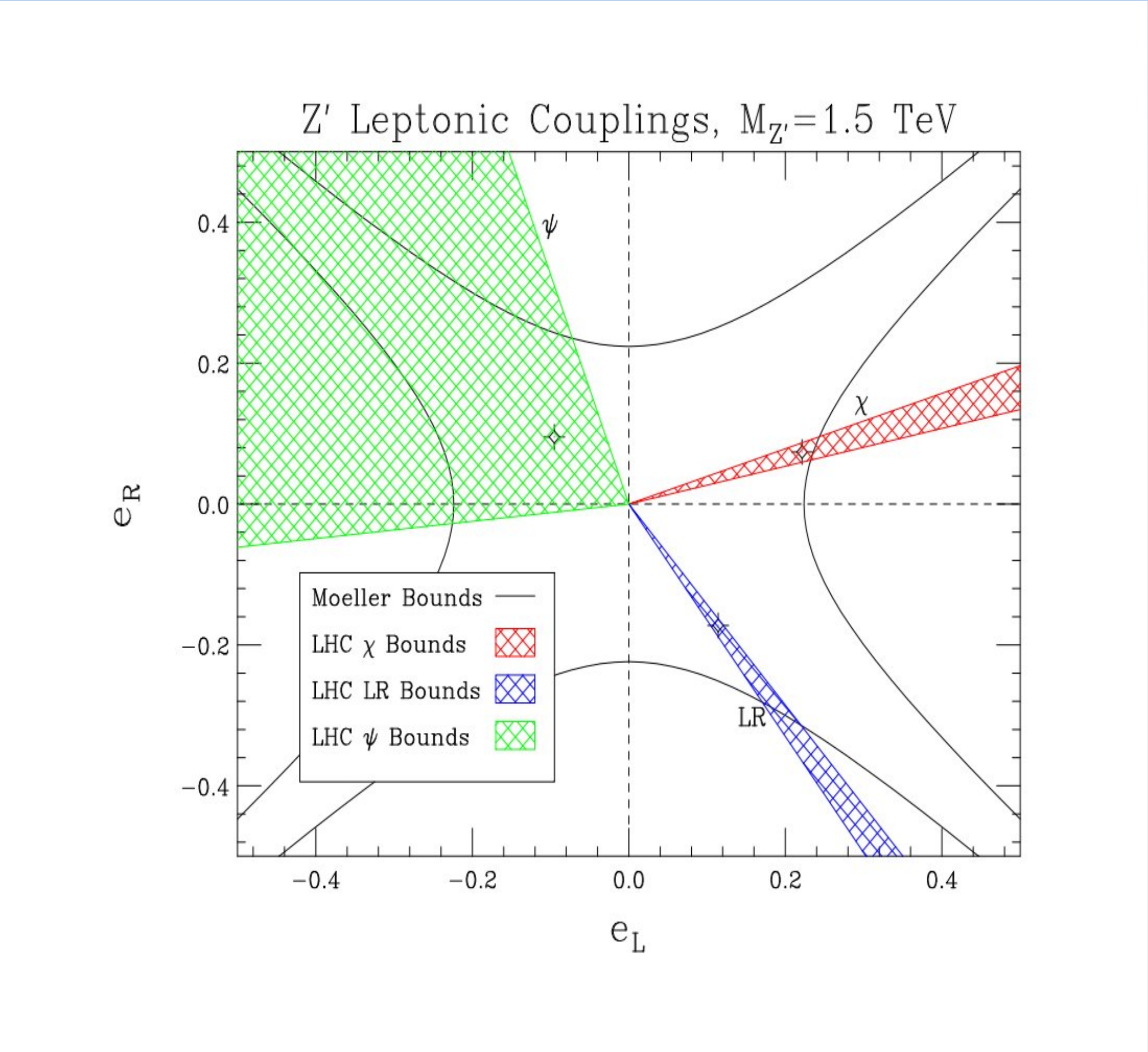
Moeller scattering

- New Jlab Moeller experiment measures asymmetry to very high precision, δA ~0.6 ppb
- Leads to error in $\sin^2\theta_W^{eff}$ of 0.00025 (0.00017 theory)
- 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

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

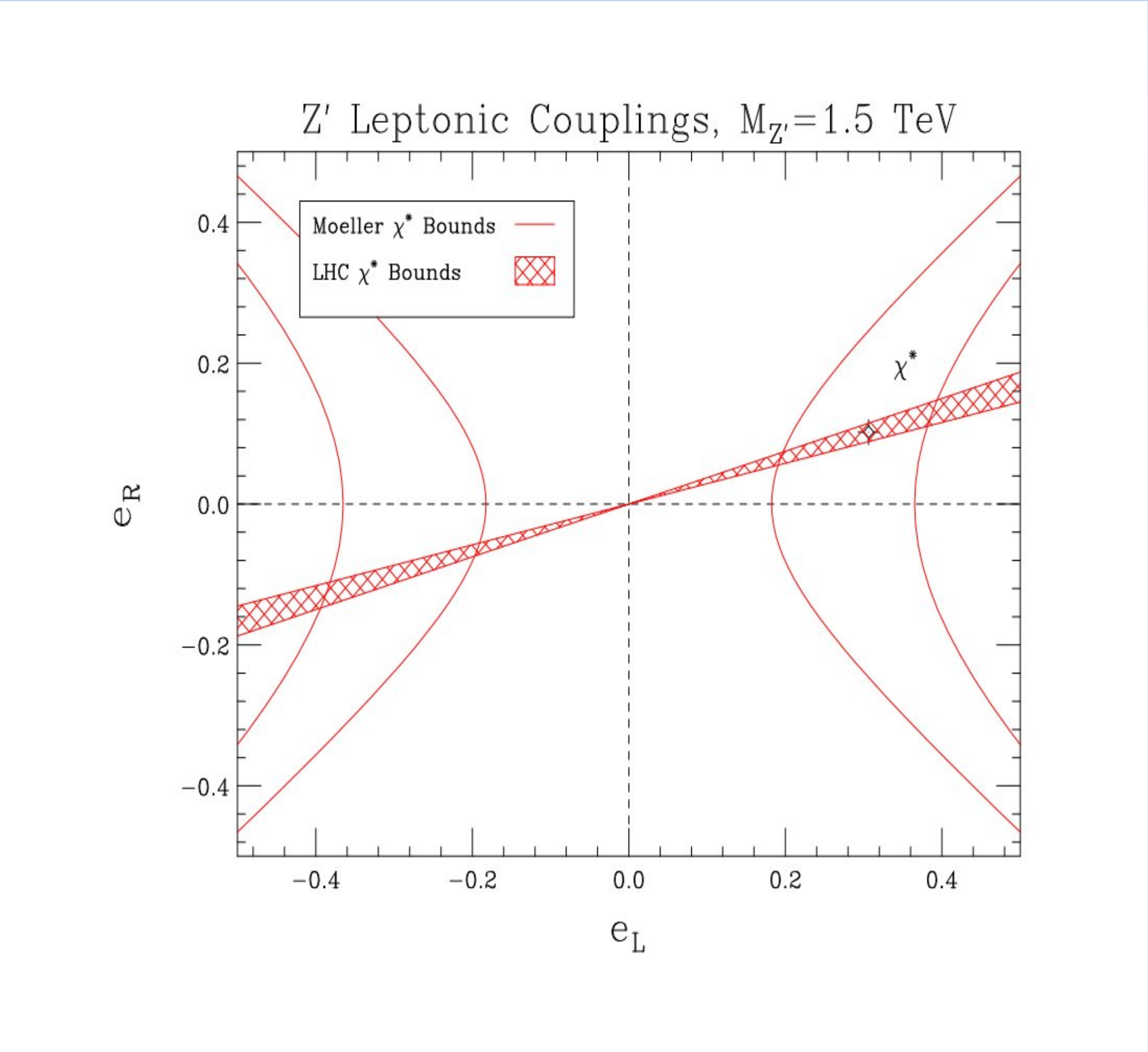
Moeller scattering, continued

- 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



Moeller scattering, continued

- Increase coupling a little: chi model, $e/\cos\theta_W \rightarrow \frac{1}{2}$
- We can see a deviation in Moeller! Now we get all SM couplings



Summary: Z' analysis strategy

- Mostly model-independent procedure
- On-peak bin gives us square couplings with good precision, only PDF limited
- Combining with off-peak bins gives signs, width if poorly measured from resonance shape
- Moeller scattering could break last parameter degeneracy, give us all SM couplings
- Can select high scale theory with these parameters if known well enough