ONCE upon a Z' …

Story by

POUYA Asadi, DOROTHEA vom Bruch, ALLISON Reinsvold Hall, ABIGAIL O'Rourke, LUIGI Marchese, CHRISTIAN Weber

Imagine we have discovered a 3.5 TeV Z'...

- In the dilepton channel at the LHC ($Z' \rightarrow e^+e^-$, $Z' \rightarrow \mu^+\mu^-$)
- Cross section of 0.5 fb in dilepton channel.
- First we need to look at what it could be - different models
- Study it at the HL-LHC with ~3 ab^{-1} of data

N_{events} = 0.5 x 3000 = 1500 ± 39 Z' events (*assuming 100% efficiency & acceptance - unrealistic*)

Questions to answer:

- Can we tell which model the Z' belongs to?
- How would we measure the couplings? What are the errors?
- What non-hadron collider measurements could be made to provide more info?

What is a Z'?

this guy →

- Massive, neutral, gauge boson
- Simplest gauge group is a U(1) extension of the SM
- U(1) could come from a larger, spontaneously broken symmetry such as E_6
- Values for the charges of SM particles under the Z' motivated by different theories, e.g.:
  - GUTs
  - B-L conservation models

Which Z' is it?

- Which models predict a 3.5 TeV Z' that hasn't been excluded?
- Which models predict a cross-section ~0.5 fb?
- Does the model have Z/Z' mixing? → interference effects show in invariant mass distribution
- Differentiate between models by measuring couplings...

Example 1: E6 Gauge Group

- Motivated by different String Theories or other GUTs
- The E6 gauge symmetry breaking pattern:

$$E_6 \rightarrow SO(10) \times U(1)_\psi \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi \rightarrow SM \times U(1)_\beta$$

- Different models can be defined with different mixing of U(1) gauges

$$Q(\theta_{E_6}) = \cos(\theta_{E_6})Q_\chi + \sin(\theta_{E_6})Q_\psi \qquad 0 \leqslant \theta_{E_6} \leqslant \pi$$

	Q_χ	Q_ψ	Q_I	Q_N	Q_S	Q_η
θ_{E6}	0	0.5 π	0.21 π	0.42 π	0.13 π	0.71 π

Inert Model (Q_I)

Neutral Model (Q_N)

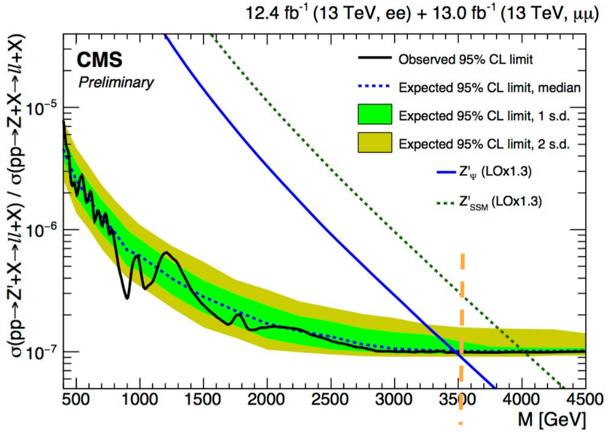
Secluded Sector Model (Q_S)

eta Model (Q_η)

Example 2: Sequential Standard Model

- SSM is a standard benchmark for Z' models
  - Z' has same couplings as SM Z

CMS PAS EXO-16-031

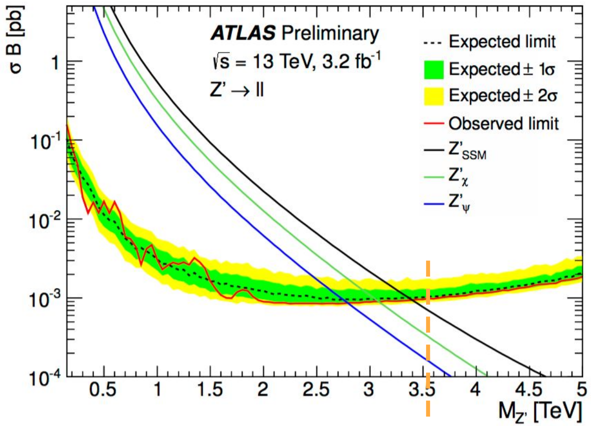


Other models...

- Numerous other theoretically-motivated models
  - Large Extra Dimensions
  - Little Higgs Models
  - ...
  - Left/Right Symmetric Models

- Differ by coupling strengths to (SM) particles

ATLAS-CONF-2015-070



Other models

- Some U(1) models and corresponding charges:

fermion	$U(1)_{B-xL}$	$U(1)_{10+x\bar{5}}$	$U(1)_{d-xu}$	$U(1)_{q+xu}$
(u_L, d_L)	$1/3$	$1/3$	0	$1/3$
u_R	$1/3$	$-1/3$	$-x/3$	$x/3$
d_R	$1/3$	$-x/3$	$1/3$	$(2-x)/3$
(ν_L, e_L)	$-x$	$x/3$	$(-1+x)/3$	-1
e_R	$-x$	$-1/3$	$x/3$	$-(2+x)/3$

PDG review

	χ	ψ	η	LR
q_L	$\frac{-1}{2\sqrt{6}}$	$\frac{\sqrt{10}}{12}$	$1/3$	$\frac{-1}{6\alpha_{LR}}$
u_R	$\frac{1}{2\sqrt{6}}$	$\frac{-\sqrt{10}}{12}$	$-1/3$	$\frac{-1}{6\alpha_{LR}} + \frac{\alpha_{LR}}{2}$
d_R	$\frac{-3}{2\sqrt{6}}$	$\frac{-\sqrt{10}}{12}$	$1/6$	$\frac{-1}{6\alpha_{LR}} - \frac{\alpha_{LR}}{2}$
l_L	$\frac{3}{2\sqrt{6}}$	$\frac{\sqrt{10}}{12}$	$-1/6$	$\frac{1}{2\alpha_{LR}}$
e_R	$\frac{1}{2\sqrt{6}}$	$\frac{-\sqrt{10}}{12}$	$-1/3$	$\frac{1}{2\alpha_{LR}} - \frac{\alpha_{LR}}{2}$

arxiv:0801.4389

- Effectively, new U(1) gauge that may/may not mix with SM neutral gauge bosons
- Differentiate between models: **determine the gauge coupling and charges of SM fields under the new gauge**

Measure the couplings

Directly measure couplings to distinguish between models

Decays:

- Measure the decays in each channel: dilepton, hadronic
- Z' → dileptons has been measured
- For Z' → hadrons, can look at Z → ttbar and Z → bbar

Observables:

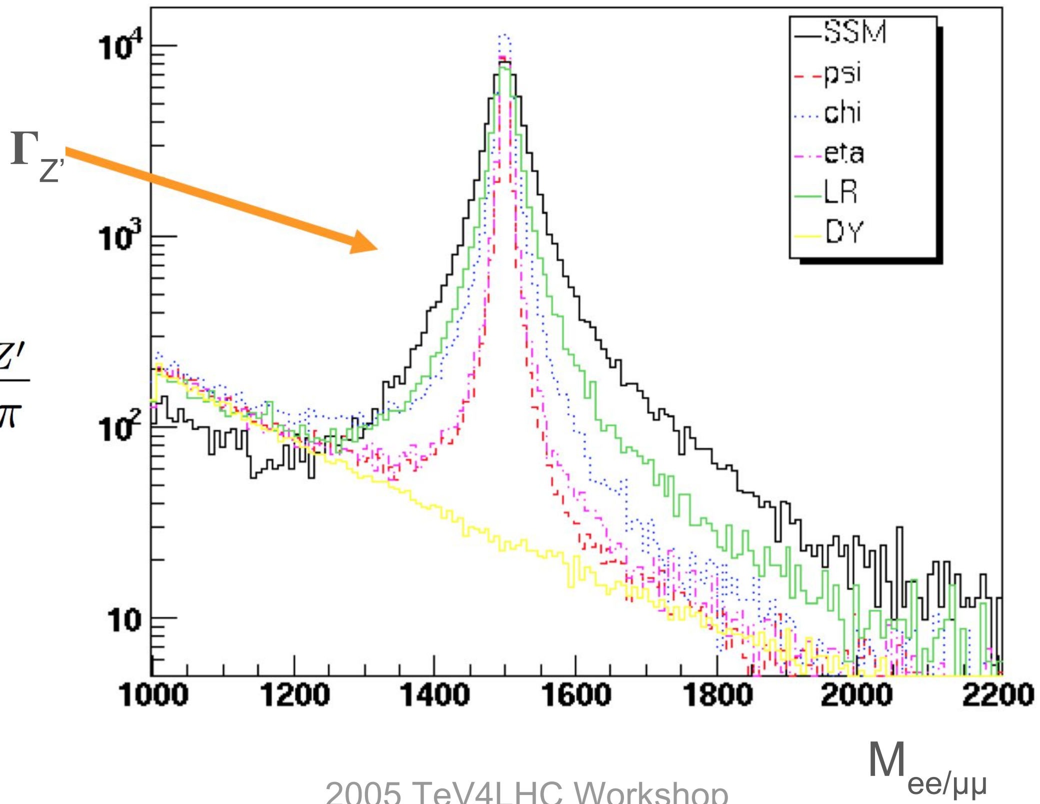
- Decay Width Γ: sensitive to couplings to all final states
- A_{FB}: sensitive to parity-violating couplings - on- (A_{FB}^{on}) and off-peak (A_{FB}^{off})
- Rapidity ratio, R: distinguish between the couplings to up and down quarks using a fit

Decay width

- Decay width $\Gamma_{Z'}$ can be a strong discriminant between models
- Width is sensitive to all Z' couplings, including invisible decay modes

$$\Gamma\left(Z' \to e^+e^-\right) \simeq \left[\left(g_e^L\right)^2 + \left(g_e^R\right)^2\right] \frac{M_{Z'}}{24\pi}$$

- Total width given by sum of partial widths from all decay modes
- Can derive total cross section from Γ and partial cross section

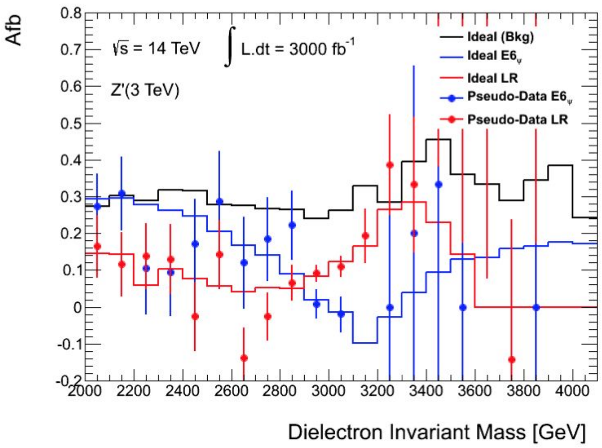


2005 TeV4LHC Workshop

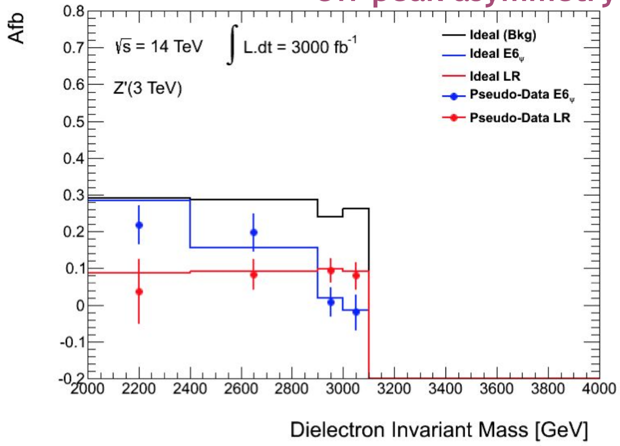
Forward-backward asymmetry (A_{FB})

- A_{FB} is a measure of how many Z' are produced in the forward vs. backward direction
  - "forward" is the original quark direction
- Sensitive to parity-violating couplings in the model
- Statistical uncertainty Sqrt($(1 - A_{FB}^2) / N$)
- Ratio of differential cross-sections: reduces systematic uncertainties
- A_{FB} vs. $M_{ee/\mu\mu}$ distributions vary by model, particularly below the mass peak → useful tool

On-peak asymmetry



Off-peak asymmetry



arxiv:1308.5874

Extract couplings from observables (1)

Coupling independent factors (PDF, phase space, etc.)

$$e_q = (q_R^2 - q_L^2)(e_R^2 - e_L^2)$$

Parity-violating couplings

Differential cross section:

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

Parity-symmetric couplings

$$c_q = (q_R^2 + q_L^2)(e_R^2 + e_L^2)$$

Extract couplings from observables (2)

on-peak/off-peak forward-backward asymmetry

Combinations of observables σ, A_{FB}^{on}, A_{FB}^{off}, R related to differential cross-sections:

cross section — central/forward rapidity ratio

$$F_< = \frac{\sigma}{2}\left(1 + A_{FB}^{\mathrm{off}} - \frac{1 + A_{FB}^{\mathrm{on}}}{R+1}\right); \qquad F_> = \frac{\sigma}{2}\frac{1 + A_{FB}^{\mathrm{on}}}{R+1}$$

$$B_< = \frac{\sigma}{2}\left(1 - A_{FB}^{\mathrm{off}} - \frac{1 - A_{FB}^{\mathrm{on}}}{R+1}\right); \qquad B_> = \frac{\sigma}{2}\frac{1 - A_{FB}^{\mathrm{on}}}{R+1}$$

calculate

$$\begin{pmatrix} F_< \\ B_< \\ F_> \\ B_> \end{pmatrix} = \begin{pmatrix} \int_{F_<} a_1^u & \int_{F_<} a_1^d & \int_{F_<} a_2^u & \int_{F_<} a_2^d \\ \int_{B_<} a_1^u & \int_{B_<} a_1^d & \int_{B_<} a_2^u & \int_{B_<} a_2^d \\ \int_{F_>} a_1^u & \int_{F_>} a_1^d & \int_{F_>} a_2^u & \int_{F_>} a_2^d \\ \int_{B_>} a_1^u & \int_{B_>} a_1^d & \int_{B_>} a_2^u & \int_{B_>} a_2^d \end{pmatrix} \begin{pmatrix} c^u \\ c^d \\ e^u \\ e^d \end{pmatrix}$$

measure — solve for

$$c_q = (q_R^2 + q_L^2)(e_R^2 + e_L^2) \qquad e_q = (q_R^2 - q_L^2)(e_R^2 - e_L^2)$$

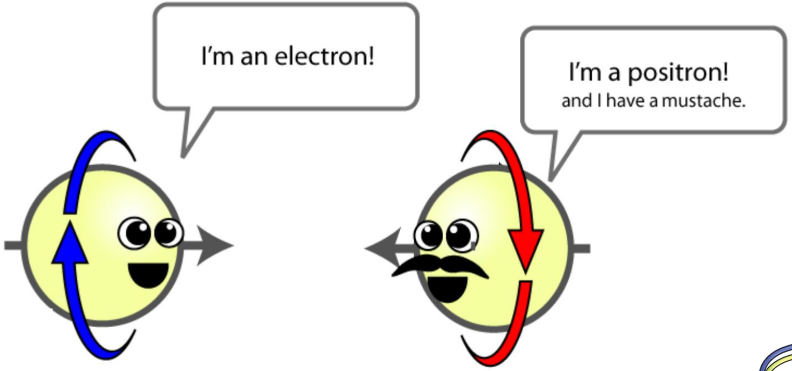
Z′ couplings to leptons: e^+e^- measurements

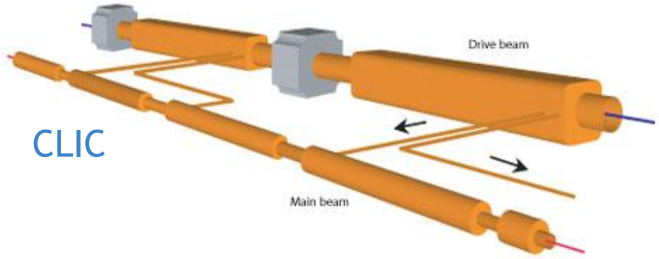
Dominant uncertainty arises from PDFs: need an e^+e^- collider to study further

Let's assume two possible scenarios:

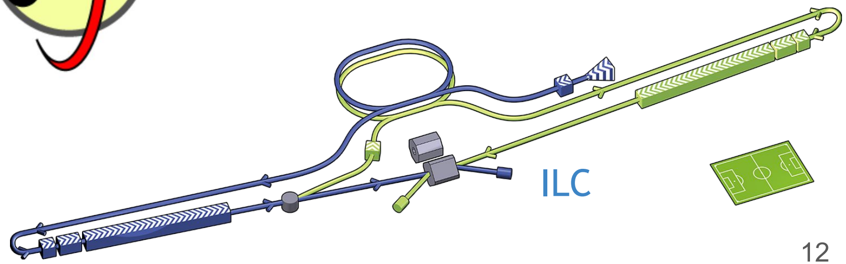
A. $\sqrt{s} < m_{Z'}$

B. $\sqrt{s} \approx m_{Z'}$





CLIC



ILC

Z′ couplings to leptons: e^+e^- measurements

1) Assuming lepton universality Z' couplings to the initial and final state are equal.

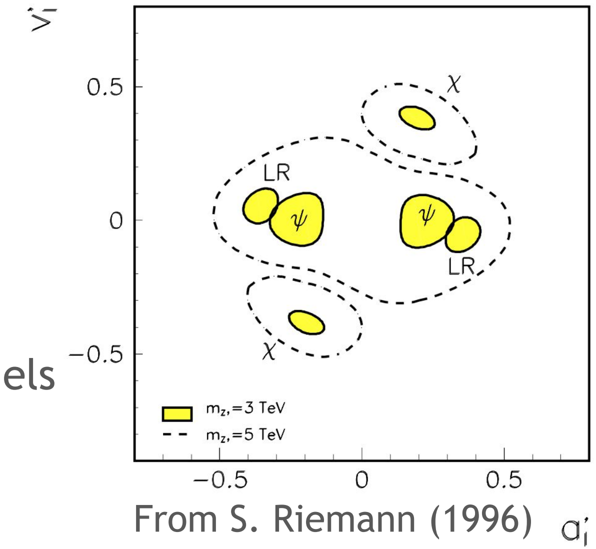
Good accuracy in the measurement for $m_{Z'} \geq \sqrt{s}$

v: vector coupling; a: axial-vector coupling

2) Systematic uncertainty of 0.5% for all leptonic observables

Efficiency of lepton identification of 95% for leptonic channels

Ambiguity in the signs of couplings persists.



From S. Riemann (1996)

Discrimination among models based on 95% CL contours for $(a_l)'$ and $(v_l)'$

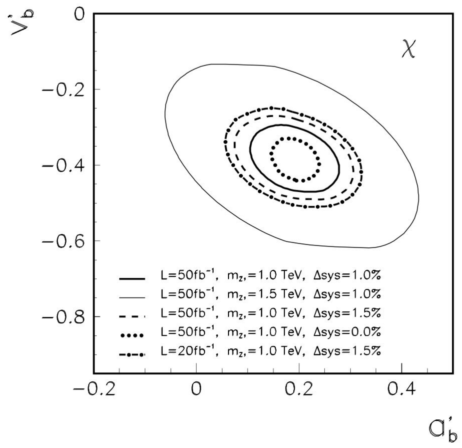
Weak influence of the systematic uncertainties for leptonic observables

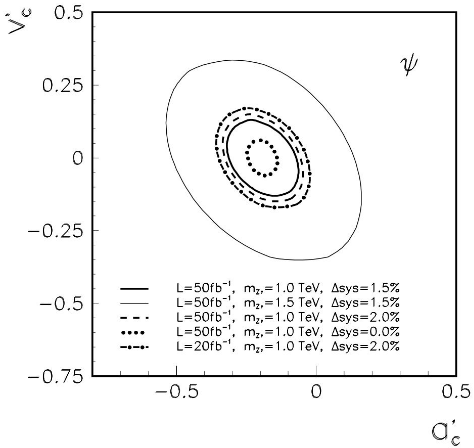
Z' couplings to quarks: experimental measurements

Quark flavour identification is more complex than lepton identification

Although the ILC vertex detectors should achieve efficiencies of 60% in b-tagging and a purity of 60%, a systematic uncertainty of no less than 1% is expected

The systematic uncertainty can limit the accuracy of $(a_q)'$ and $(v_q)'$ measurements.



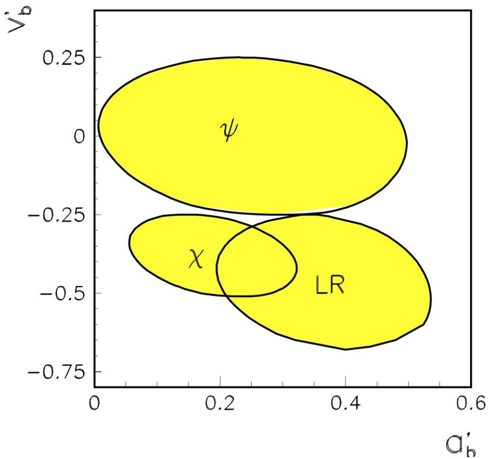


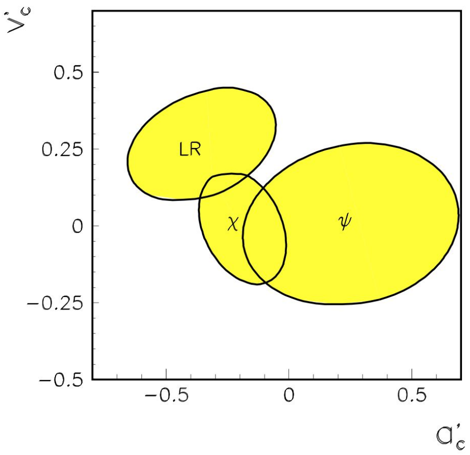
Assuming 500 GeV cm energy, 50 fb^{-1}

From S. Riemann (1996)

Z′ couplings to quarks: experimental measurements

Assuming a syst. unc. of 1% for bb observables and 1.5% cc observables, the following model separation is possible





Assuming 1.5 TeV cm energy, 100 fb^{-1}

From S. Riemann (1996)

$$R = m_{Z'}/\sqrt{s}$$

R > 2 the model separation using the quark channel is impossible.

Ideally we would build an e^+e^- collider with sqrt(s) = 3.5 TeV

Further measurements

- Electroweak observables can be used to extract further information about the couplings to fermions and Higgs
- Neutrino-nucleus coherent scattering with ultra-low energy threshold Si and Ge detectors (~10 eV): sensitive to coupling to u/d quarks by using different atomic number detector material
- If we assume non-universal charges: test couplings to the different charges with μ-e conversion, $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, $ee \rightarrow \mu\tau$, $ee \rightarrow \mu\mu$, muon anomalous magnetic moment
- Electron electric dipole moment measurements, infer amount of CP violating phase

fine-structure constant

$$M_{Z'}^2 \sim e\left(\frac{m_e}{d_e}\right)\frac{\alpha}{4\pi}\sin(\phi_{CP})$$

electron dipole moment

CP-violating phase

Conclusions

- Yeah, we found a Z´ :-)
- Need further measurements to uniquely identify which model it belongs to
- We propose an e^+e^- collider with sqrt(s) = 3.5 TeV for further studies
  - Make use of precise knowledge of colliding beam energies
  - Polarized beam for more angular studies (forward-backward asymmetry)
- Use low-energy experimental data for further constraints

Resources

B. Trocme, “Distinguishing Z’ Models at ATLAS”, TeV4LHC Workshop
http://indico.cern.ch/event/422441/

Daniel Hayden, Raymond Brock, Christopher Willis, “Z Prime: A Story”, arXiv:1308.5874v1

F. Petriello, S. Quackenbush, “Measuring Z’ Couplings at the LHC”, arXiv:0801.4389v2

G. Cacciapaglia, C. Csáki, G. Marandella, A. Strumia, “The Minimal Set of Electroweak Precision Parameters”, arXiv : hep-ph/0604111

S. Riemann: “Study of Z’ Couplings to Leptons and Quarks at NLC”, hep-ph/9610513

P. Langacker, “The Physics of Heavy Z’ Gauge Bosons”, arXiv: 0801.1345v3

J. L. Hewett, T. G. Rizzo, 1989, Phys. Rept. 183, 193

Story by

POUYA Asadi, DOROTHEA vom Bruch, ALLISON Reinsvold Hall, ABIGAIL O'Rourke, LUIGI Marchese, CHRISTIAN Weber

BACKUP

Question Statement

- Imagine that a new Z' boson is discovered at the LHC in the dilepton channel with a mass of 3.5 TeV & with a cross section of 0.5 fb. Many theories predict such states & the HL-LHC will eventually provide integrated luminosities of ~3 ab^{-1} that can be used to learn about it. To determine which, if any, of these theories is correct we need to measure the many couplings of this Z'.
- Search the literature & survey the set of such Z' models.
- Which measurements would you make to do this and roughly what would you expect for the measurement errors?
- Can these results tell us the Z' identity uniquely among the models you've surveyed?
- What non--hadron collider measurements in the future, if any, could provide additional information?

A_{FB} Definition

Petriello et al, 2008

A_{FB} is defined as

$$A_{FB}^{y_1} = \frac{[\int_{y_1}^{y_{max}} - \int_{-y_{max}}^{-y_1}][F(y) - B(y)]dy}{[\int_{y_1}^{y_{max}} + \int_{-y_{max}}^{-y_1}][F(y) + B(y)]dy}$$

where y is the Z' rapidity, considered from y_1 to y_{max}, and *F(y)* and *B(y)* are given by

$$B(y) = \int_{-1}^{0} d\cos\theta \frac{d^2\sigma}{dy\, d\cos\theta}$$

$$F(y) = \int_{0}^{1} d\cos\theta \frac{d^2\sigma}{dy\, d\cos\theta}$$

and θ is the angle between the quark and electron in the Collins-Soper frame

Choose the quark direction to be the same as the Z'

EW observables @ e^+e^- colliders

- Some of the most precise ***EW observables are***:

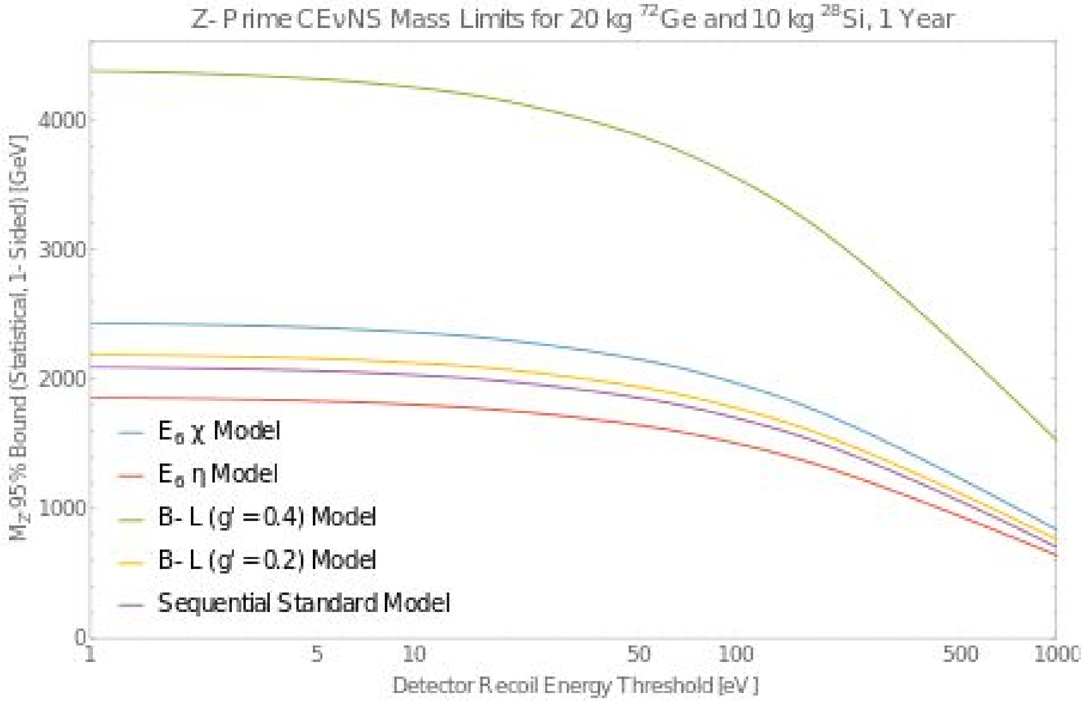
$$\alpha_{\rm em},\ \Gamma(\mu),\ M_Z,\ M_W,\ \Gamma(Z\to\ell\bar{\ell}),\ A^{\ell}_{FB},\ A^{\ell}_{LR},\ A^{\tau}_{\rm pol}$$

- Once measured, could be related to the following quantities:
  - Determine the charges in generation-universal model as below
  - Determine the **gauge coupling**

$$\begin{aligned} Y &= \frac{M_W^2 g_{Z'}^2}{g'^2 M_{Z'}^2} Z_E^2\,,\\ V &= \frac{M_W^2 g_{Z'}^2}{g^2 M_{Z'}^2}(Z_E+2Z_L)^2\,,\\ X &= -\frac{M_W^2 g_{Z'}^2}{g g' M_{Z'}^2} Z_E(Z_E+2Z_L)\,, \end{aligned}$$

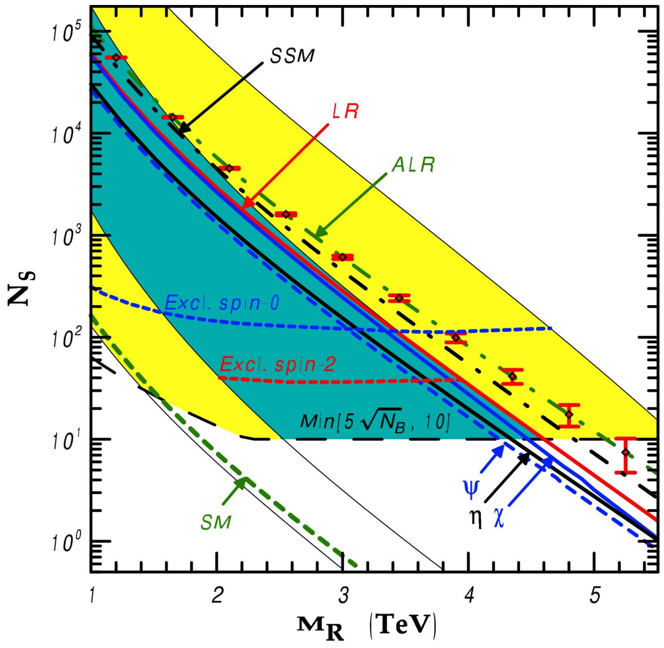
$$\begin{aligned} \hat{S} &= \frac{2M_W^2 g_{Z'}^2}{g^2 g'^2 M_{Z'}^2}(Z_E-Z_H+Z_L)(g^2 Z_E+g'^2(Z_E+2Z_L))\,,\\ \hat{T} &= \frac{4M_W^2 g_{Z'}^2}{g^2 M_{Z'}^2}(Z_E-Z_H+Z_L)^2\,,\\ \hat{U} &= \frac{4M_W^2 g_{Z'}^2}{g^2 M_{Z'}^2}(Z_E-Z_H+Z_L)(Z_E+2Z_L)\,,\\ W &= \frac{M_W^2 g_{Z'}^2}{g^2 M_{Z'}^2}(Z_E+2Z_L)^2\,, \end{aligned}$$

Sensitivity to Z' with neutrino-nucleus coherent scattering



From B. Dutta et al (2016)

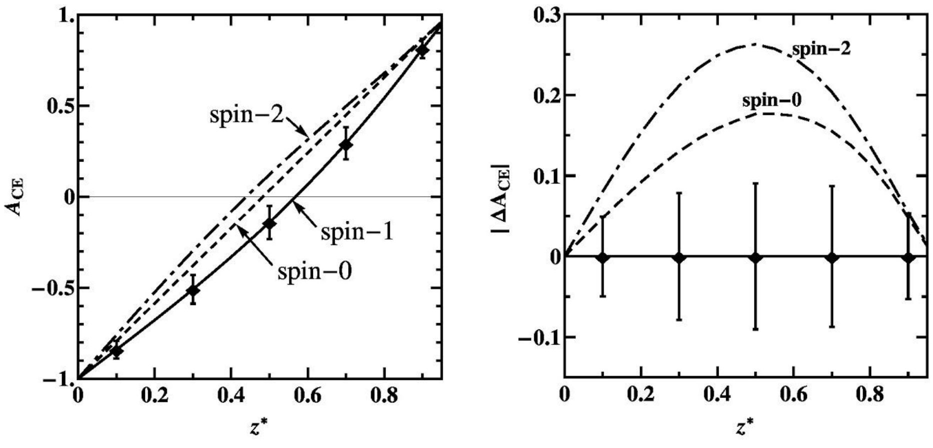
Distinguish between models by using # signal events



From P. Osland et al (2009)

Number of resonance signal events as a function of Z' mass at the LHC with integrated luminosity of 100 fb-1 for dilepton channel. Minimum number of signal events needed to detect the resonance (5 sigma level) above the bkgrd are shown.

Determining the Spin



Study center-edge asymmetry to determine spin of new particle.
z*: a priori free value of cos theta_cm defining center and edge angular regions

From P. Osland et al (2009)

arxiv:0801.4389

Testing models

$M_{Z'}$	Mdl	χ			ψ			η			LR		
		$\chi^2_{c,e}$	χ^2_{tot}	σ	$\chi^2_{c,e}$	χ^2_{tot}	σ	$\chi^2_{c,e}$	χ^2_{tot}	σ	$\chi^2_{c,e}$	χ^2_{tot}	σ
3 TeV	χ				49	61	6.8	37	43	5.5	32	32	4.5
	ψ	15	29	4.3				1.1	2.3	0.2	4.6	26	3.9
	η	15	22	3.4	1.3	2.3	0.2				13	24	3.7
	LR	14	14	2.4	44	58	6.7	30	38	5.1			

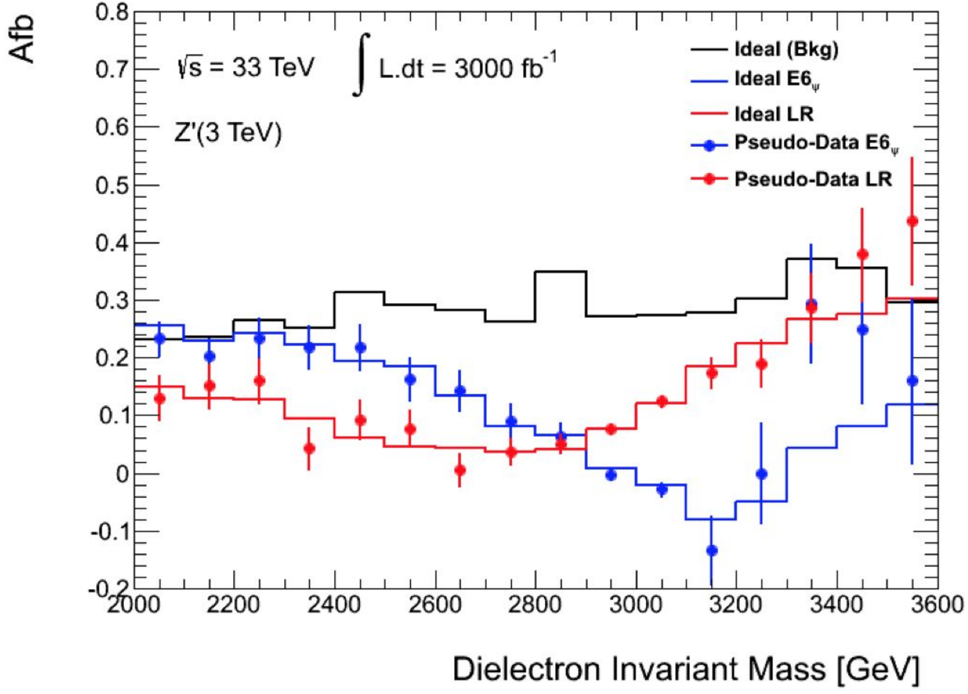
Table 7: Pairwise χ^2 for 1 ab^{-1}, $y_1 = 0.4$, and $M_{Z'} = 3$ TeV. As before, the rows are tested against the hypothesis columns.

Assume one model is correct, find of other χ^2 model as a test, using errors of first model.

Models are fairly distinguishable at this level

→ assume situation for 3.5 TeV Z' with 3 ab^{-1} might be better?

Forward-backward asymmetry at 33 TeV collider



From D. Hayden et al (2013)

Different E6 Models

- χ model: special case of the T_{3R} and B - L models, supplemented with additional exotic fields in the 10 + 1 of SO(10)
- Ψ model: has chiral exotics and requires three full 27-plets
- η model: occurs in Calabi-Yau compactifications of the heterotic string if E_6 breaks directly to a rank 5 group via the Wilson line mechanism
- Inert model: charge orthogonal to Q_η, follows from alternative E_6 breaking pattern
- Neutral model: ν has zero charge, allowing a large Majorana mass or avoiding big bang nucleosynthesis constraints for a Dirac ν; basically the same as the alternative left-right model
- Secluded sector model: four standard model singlets that are charged under a U(1)´