Title: Determining Z' couplings using LHC data and low energy measurements

Date: Oct 30, 2009 09:45 AM

URL: http://pirsa.org/09100158

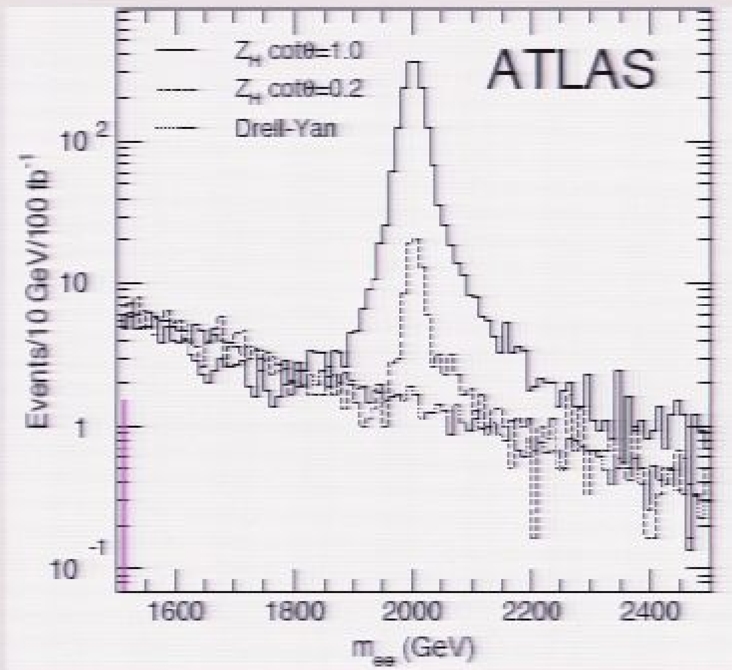
Abstract: TBA

Outline

- What is a Z' and what tools do we have to study one?
- How well can we measure its couplings, and what couplings can be determined with expected data (LHC and other)? What is best way to compare data with theory?
- Analysis strategy for investigating a Z'
  (based on FP, S. Quackenbush arXiv:0801.4389; Y. Li, FP, S. Quackenbush arXiv:0906.4132)
  - On-peak LHC data: convenient coupling basis for determining high-scale theory
  - q×e measurements with off-peak data and QWEAK
  - Breaking the final coupling degeneracy with Møller scattering

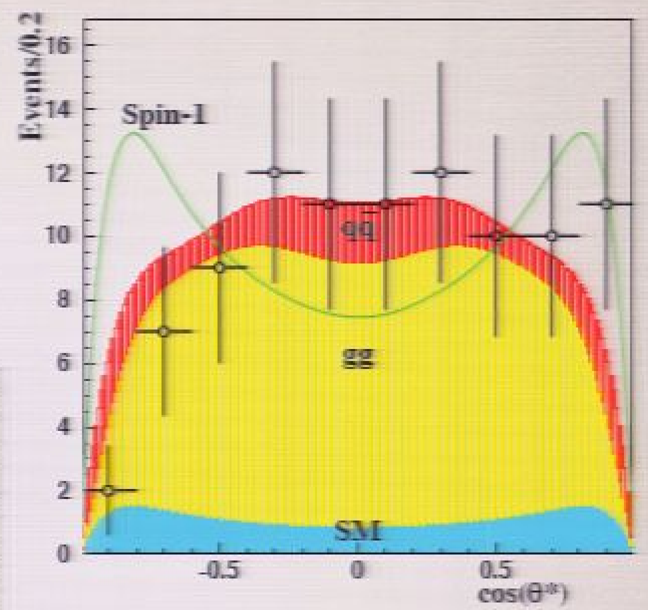
What is a Z'?

- Experimental definition: resonance observed in Drell-Yan: pp→l+l-+X; clean signature, low systematics



What spin does it have?

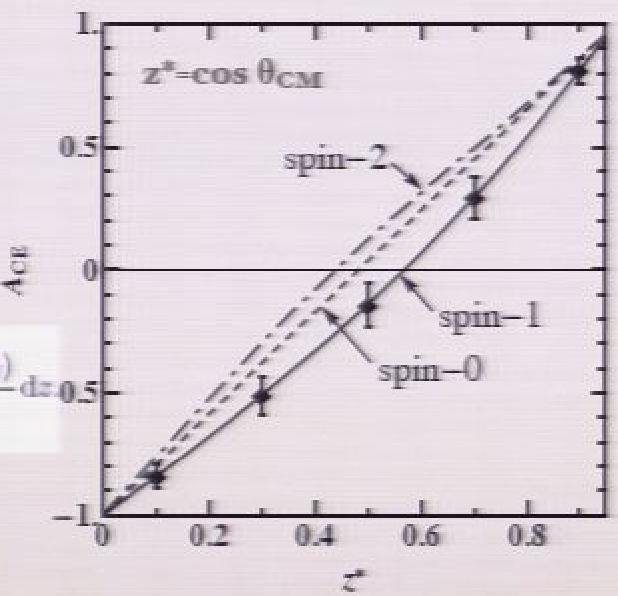
- Spin Possibilities:
  - 0: R-parity violating sneutrino
  - 1: New gauge boson
  - 2: Kaluza-Klein graviton



B. Allanach et al., hep-ph/0006114

$$A_{CE}(M_R) = \frac{\sigma_{CE}(R_{ll})}{\sigma(R_{ll})}$$

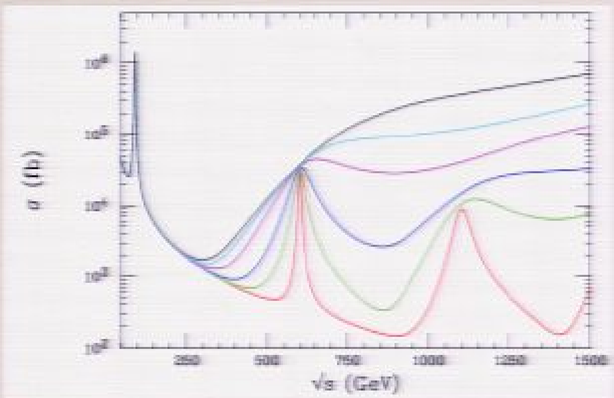
$$\sigma_{CE}(R_{ll}) \equiv \left[\int_{-z^*}^{z^*} - \left(\int_{-z_{cut}}^{-z^*} + \int_{z^*}^{z_{cut}}\right)\right] \frac{d\sigma(R_{ll})}{dz} dz$$



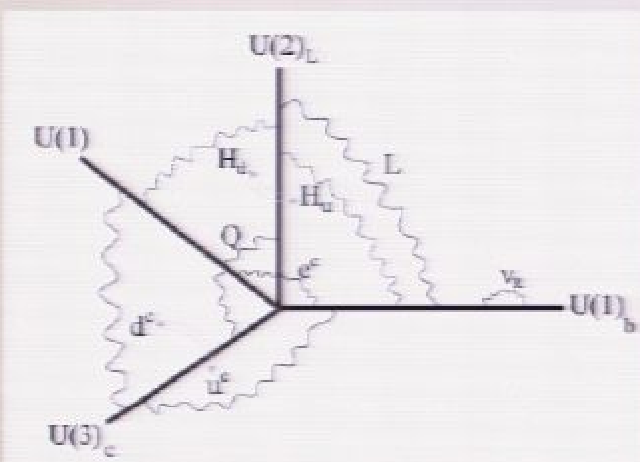
P. Osland et al., 0904.4857

☑ Can distinguish spin-1 from spins-0,2 with a few hundred events

The Z' zoo

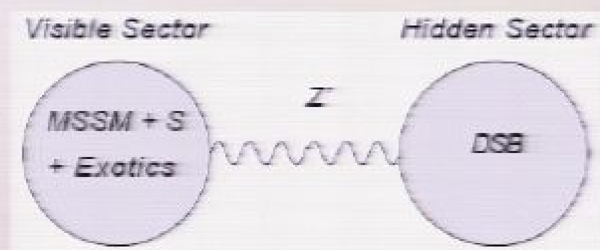


Kaluza-Klein modes



String models

- Rough numbers to remember (for E6, LR models):
  - $\sigma \times BR \sim 50$ fb (1.5 TeV)
  - $\sigma \times BR \sim 1$ fb (3 TeV)
  - $\Gamma/M \sim 0.5$–5%



Messengers

What Z's are ruled out?

- Current high energy limits near 1 TeV

CDF II preliminary $L = 2.3\ fb^{-1}$

Model	Mass Limits, 95% CL (GeV/c^2)
Z' (SM)	1030
Z' (η)	904
Z' (χ)	892
Z' (ψ)	878
Z' (N)	861
Z' (sec)	821
Z' (ι)	789

LEP limits:

Z' model	χ	ψ	η	L-R	SSM
$M_{Z'}^{limit}$ (GeV/c^2)	673	481	434	804	1787

2003 summer conferences

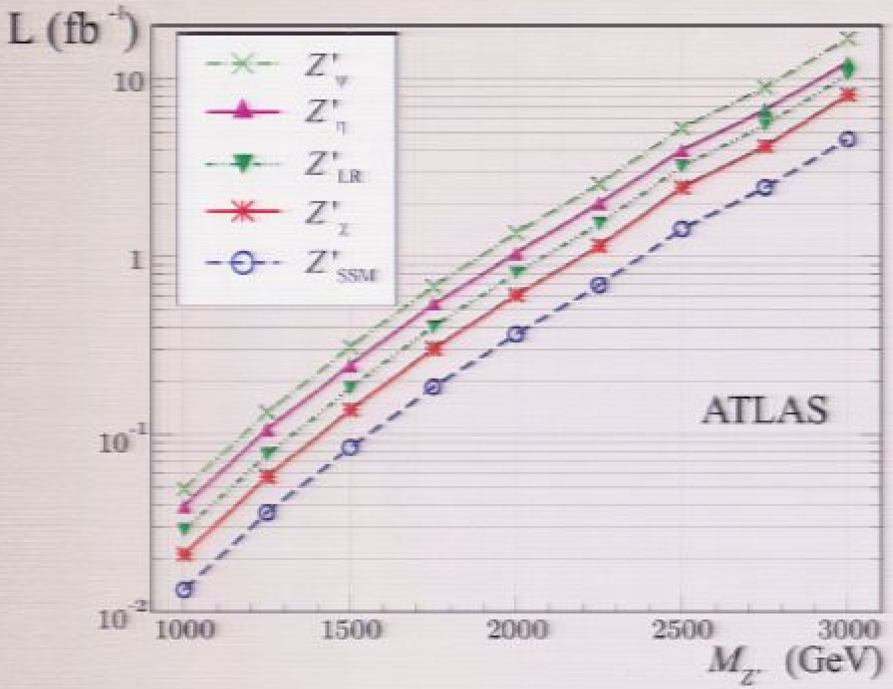
- Competitive low energy limits

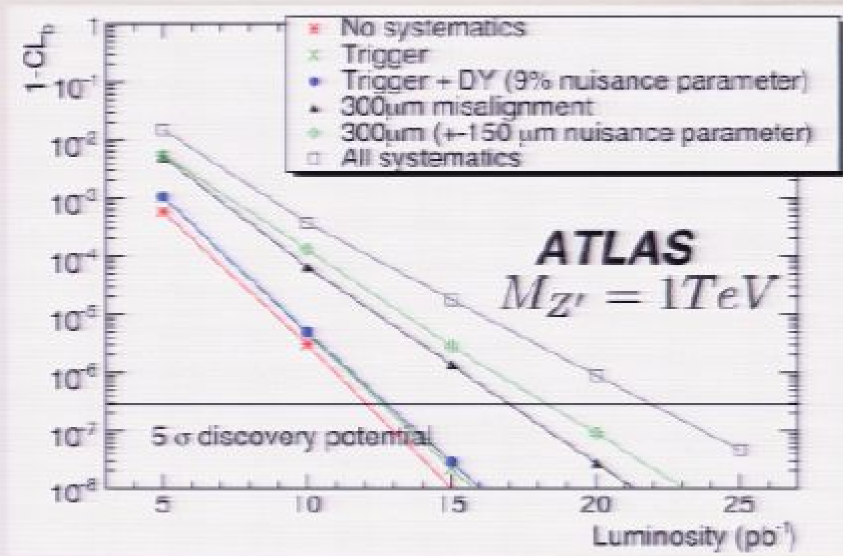
Cesium APV: $M_\chi \geq 0.89$ TeV (95% CL) (Z_ψ: $q_L + q_R = 0$)

E-158 Møller: $M_\chi \geq 0.67$ TeV (95% CL) (Z_ψ: $e_L + e_R = 0$)

J. Erler, LoopFest 2009 conference

What Z's can we discover?





B. Mellado, ANL Analysis Jamboree
20 May 2009

- Eventual reach - 5 TeV for most models
- Can extend Tevatron reach with 10s of pb^{-1}

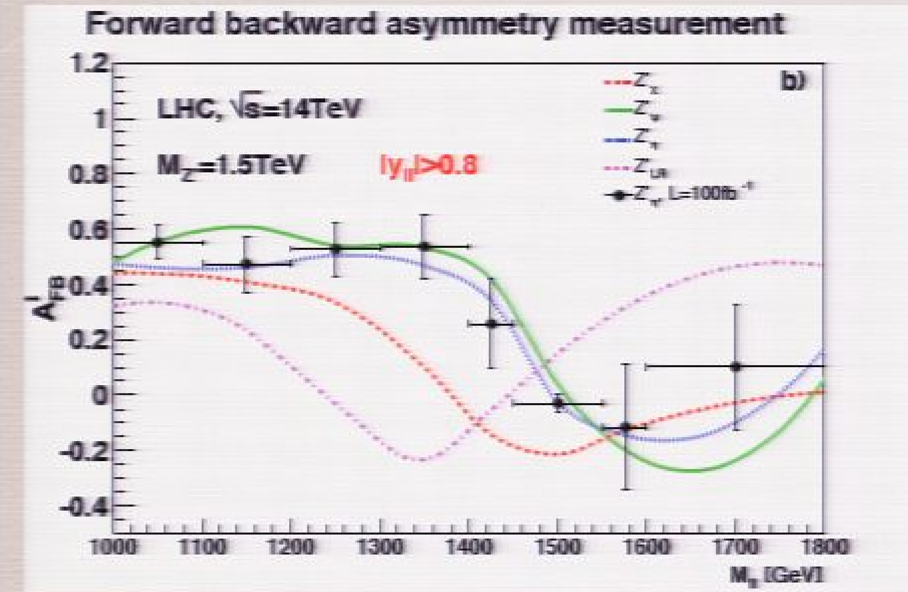
What can we measure?

- $M_{Z'}$, $\Gamma_{Z'}$ from scan of resonance peak
  - $\Delta M/M$ ~ 0.03-0.05% for $M_{Z'}$=1.5 TeV, 0.3-0.5% for $M_{Z'}$=4 TeV
  - $\Delta\Gamma/\Gamma$ ~ 5-10% for $M_{Z'}$=1.5 TeV, 10-35% for $M_{Z'}$=4 TeV

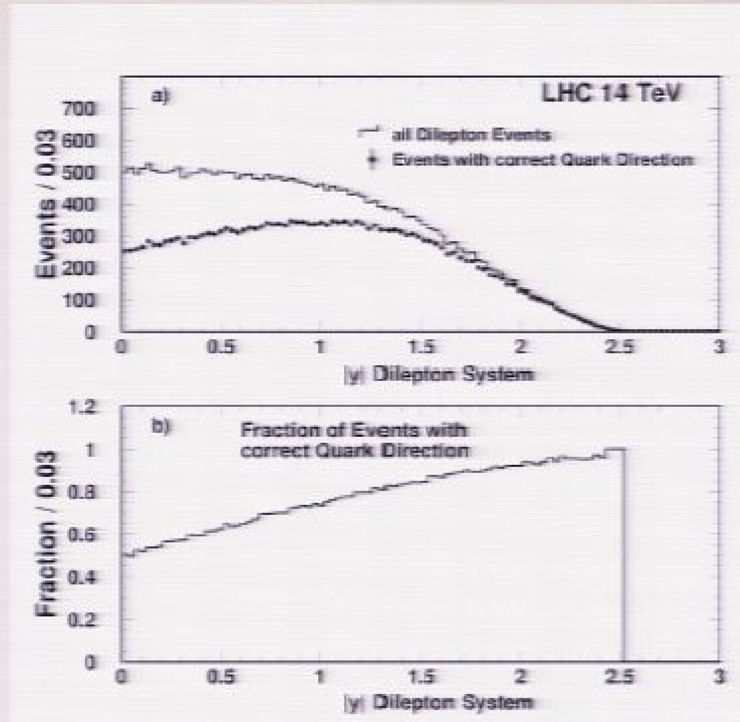
Schäfer, Ledroit, Trocmé, ATLAS-PHYS-PUB-2005-010

- g_v, g_a from $Z' \to f\bar{f}$ decays: window to underlying models
- Invisible decays, if Z' is messenger to hidden sector
- Mixing-induced Z'→WW, ZH decays, Z'γ,Z associated production

What tools do we have?



M. Dittmar et al., hep-ph/0307020



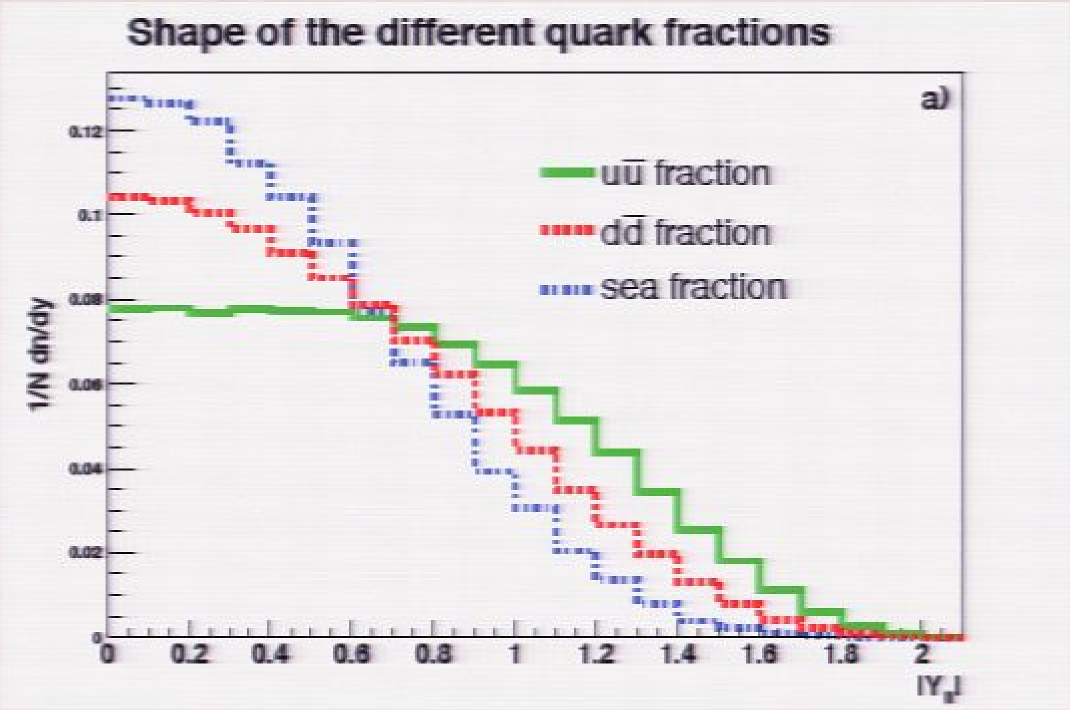
M. Dittmar, hep-ex/9606002

$$\frac{d\sigma}{d\cos\theta} \sim \frac{3}{8}(1+\cos^2\theta) + A_{FB}\cos\theta$$

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

LHC is pp collider; define 'forward' by Z' rapidity (high Y typically from valence quark)

What tools do we have?



M. Dittmar et al., hep-ph/0307020

- Rapidity spectrum probes up/down couplings
- More up-type quarks at high Y

Combined analysis

- Z' rapidity determines relative couplings to u and d quarks
- Asymmetry determines vector versus axial couplings; at LHC, depends on Z' rapidity
- Want a simple analysis technique to combine all kinematic information and extract couplings

Theoretical framework

- Assume Z' couplings generation independent ⇒ for 1st, 2nd generation, strongly constrained by FCNC; check for 3rd by measurement in τ, b, t
- Members of doublets have same couplings ⇒ strongly constrained by LEP measurements
- Five couplings to: q_L, u_R, d_R, e_L, e_R
- Z' described by seven parameters: q_L, u_R, d_R, e_L, e_R, $M_{Z'}$, Γ
- Example models *only* to illustrate certain points: $U(1)_\eta$, $U(1)_\chi$, $U(1)_\psi$, left-right

Structure of Z' cross section

Z' amplitude squared

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

Interference with γ, Z

Background

- $a_{1,2}$ contain PDFs, matrix elements, cuts
- On-peak in the narrow-width limit: $a_{1,2} \sim 1/\Gamma$
- Six coupling combinations appear: $q_L e_R$, $q_L e_L$, $u_R e_R$, $u_R e_L$, $d_R e_R$, $d_R e_L$; only four independent
- Only $a_{1,2}$ important on-peak

On-peak measurements

- Define the following combinations of couplings

Carena et al., hep-ph/0408098

$$c_q = \frac{M_{Z'}}{24\pi\Gamma}(q_R^2 + q_L^2)(e_R^2 + e_L^2) = (q_R^2 + q_L^2) Br(Z' \to e^+e^-)$$

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

$$\Rightarrow \frac{d\sigma}{dY\, d\cos\theta^* dM^2} = \sum_{q=u,d} \left[a_1^{q'}(M_{Z'})c_q + a_2^{q'}(M_{Z'})e_q\right]$$

- All details of model in c_u, c_d, e_u, e_d;
- c_q probes parity-conserving couplings, e_q parity violating

Analysis strategy

- Four quantities to measure: $c_{u,d}$, $e_{u,d}$
- Use all differential information to extract
- Define usual forward, backward regions:

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

- Take the following four combinations (y_1 an arbitrary parameter separating forward and central rapidity):

$$F_< = \int_{-Y_1}^{Y_1} dY\, F(Y) \qquad F_> = \left\{ \int_{y_1}^{y_{max}} + \int_{-y_{max}}^{y_1} \right\} dY\, F(Y)$$

$$B_< = \int_{-Y_1}^{Y_1} dY\, B(Y) \qquad B_> = \left\{ \int_{y_1}^{y_{max}} + \int_{-y_{max}}^{y_1} \right\} dY\, B(Y)$$

Analysis strategy

- Matrix equation relating four couplings to measurements: $m = M \times c$, $m = (F_<, B_<, F_>, B_>)$, $c = (c_u, c_d, e_u, e_d)$

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

- M depends only on Z' mass: measure m, calculate M without model assumption, extract c
- All details of QCD, cuts, in $a_{1,2}$
- Don't need χ^2 comparison between model assumptions
- Lose very little discriminatory power from coarse binning

Analysis strategy

- Four quantities to measure: $c_{u,d}$, $e_{u,d}$
- Use all differential information to extract
- Define usual forward, backward regions:

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

- Take the following four combinations (y_1 an arbitrary parameter separating forward and central rapidity):

$$F_< = \int_{-Y_1}^{Y_1} dY\, F(Y) \qquad F_> = \left\{ \int_{y_1}^{y_{max}} + \int_{-y_{max}}^{y_1} \right\} dY\, F(Y)$$

$$B_< = \int_{-Y_1}^{Y_1} dY\, B(Y) \qquad B_> = \left\{ \int_{y_1}^{y_{max}} + \int_{-y_{max}}^{y_1} \right\} dY\, B(Y)$$

Analysis strategy

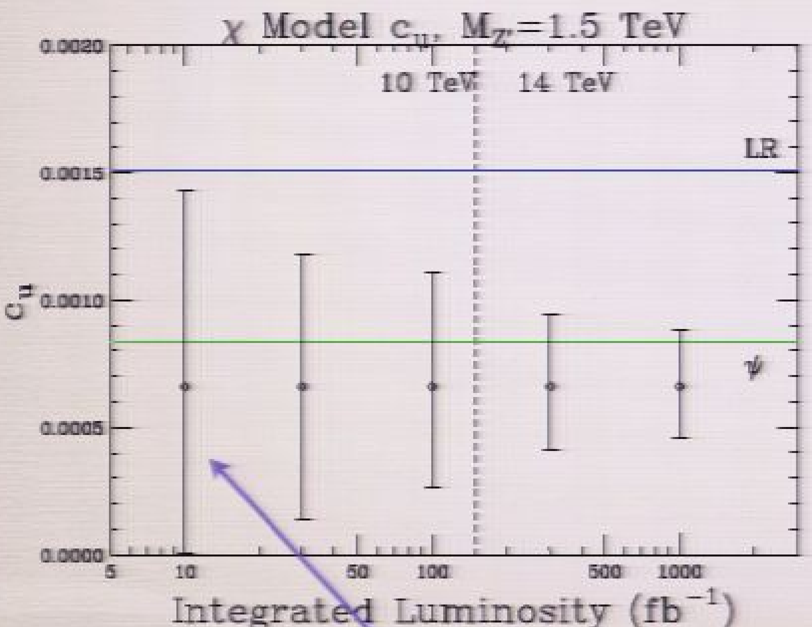
- Matrix equation relating four couplings to measurements: $m=M\times c$, $m=(F_<, B_<, F_>, B_>)$, $c=(c_u, c_d, e_u, e_d)$

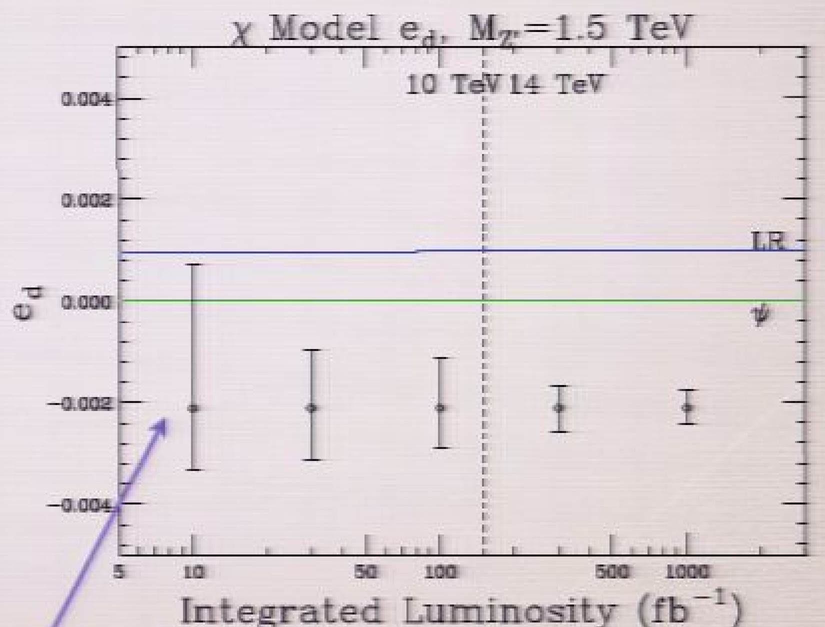
$$M = \begin{pmatrix} \int_{F_<} a_1^u & \int_{F_<} a_1^d & \int_{F_<} a_2^u & \int_{F_<} a_2^d \\ \int_{B_<} a_1^u & \int_{B_<} a_1^d & \int_{B_<} a_2^u & \int_{B_<} a_2^d \\ \int_{F_>} a_1^u & \int_{F_>} a_1^d & \int_{F_>} a_2^u & \int_{F_>} a_2^d \\ \int_{B_>} a_1^u & \int_{B_>} a_1^d & \int_{B_>}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

- M depends only on Z' mass: measure m, calculate M without model assumption, extract c
- All details of QCD, cuts, in $a_{1,2}$
- Don't need χ^2 comparison between model assumptions
- Lose very little discriminatory power from coarse binning

LHC: low luminosity

- Off-peak bins very small at low luminosity; follow this strategy
- Assume Z' observation, propagate through theory, statistical and PDF errors to see how well c, e measured (statistical+PDF dominant; expected systematics small CMS note 2006-083)

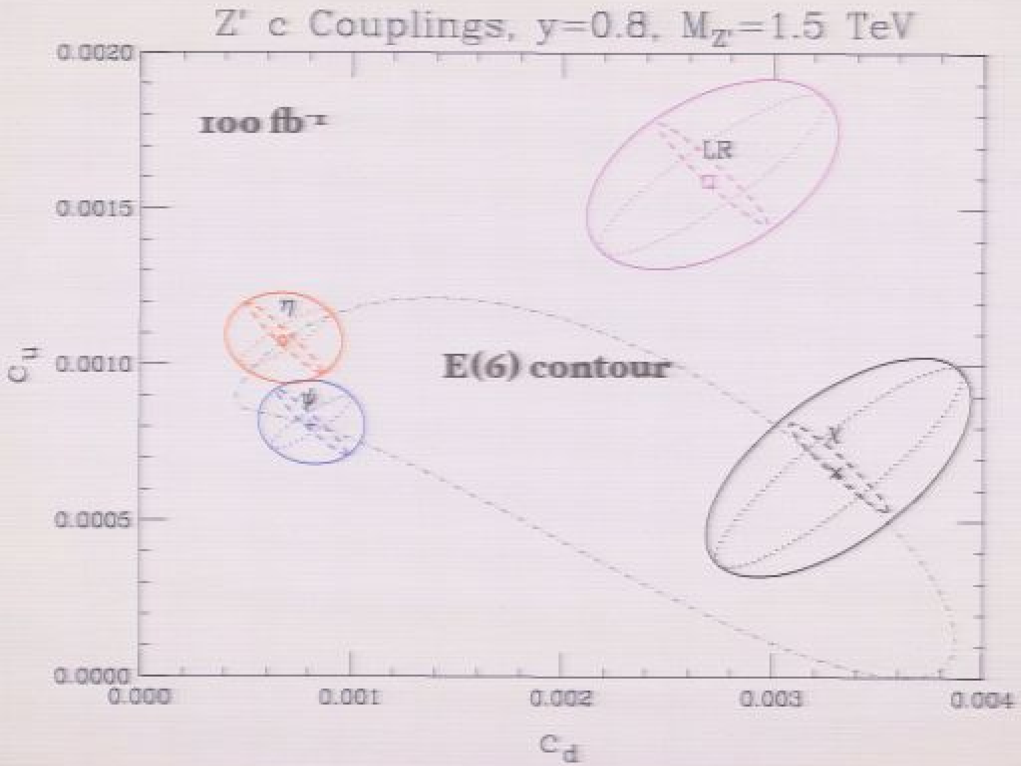




begin discriminating between models at 10 fb^{-1} for 1.5 TeV

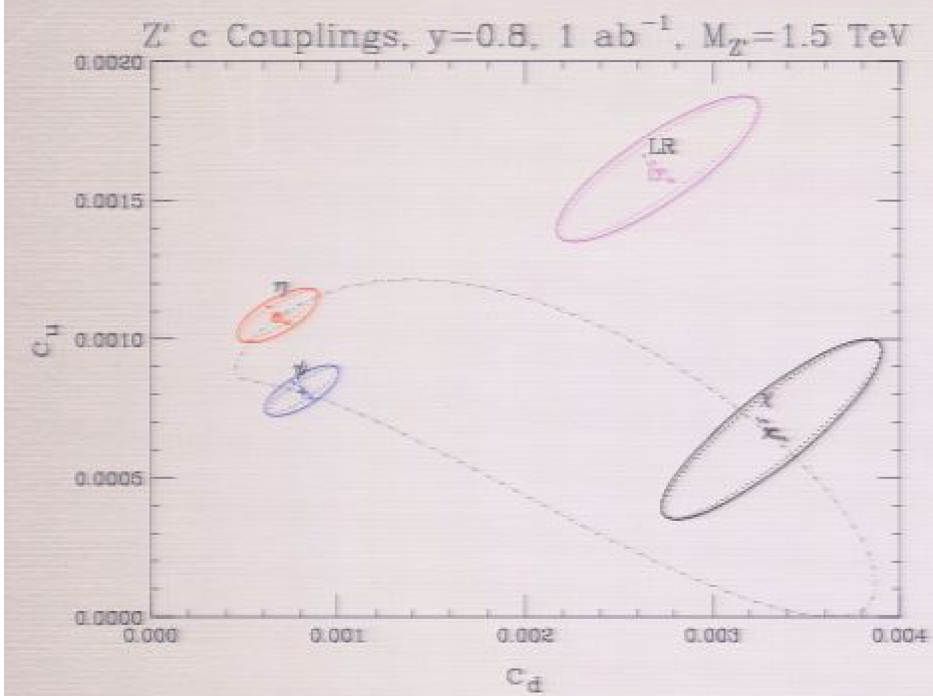
Higher luminosities and errors

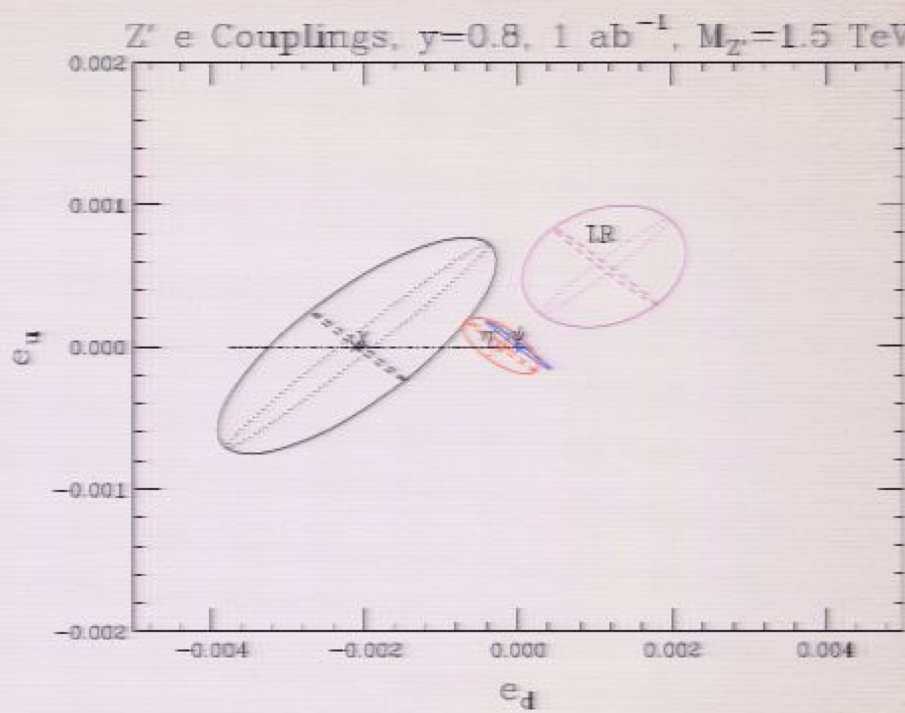
- Dominant errors become PDF; possibilities of improvement with LHC data ➪ precision measurements then possible



- Dotted: PDF
- Dashed: statistics

SLHC results





Off-peak extension

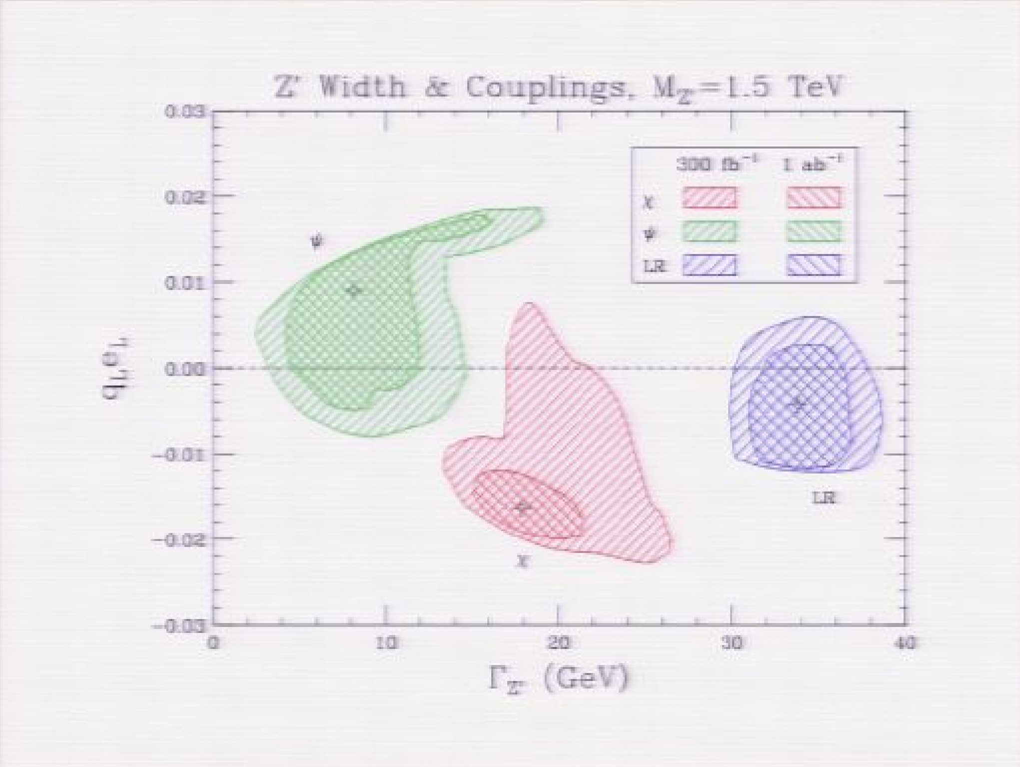
- Only measure $(q \times e)^2$ on-peak; width is lumped into c_q, e_q
- Off-peak bins become useable at higher luminosities

on-peak LHC:	$M_{Z'}, c_u, c_d, e_u, e_d$
on-peak+off-peak LHC:	$M_{Z'}, \Gamma_{Z'}, q_L e_L, q_L e_R, u_R e_L, d_R e_L$

separate width, measure linear $q \times e$

- Assume discovery of Z', bin cross section in Y, $\cos\theta_{CM}$, M^2 and determine how well couplings can be measured (NB: this is also how we check that that course on-peak binning doesn't reduce discrimination)

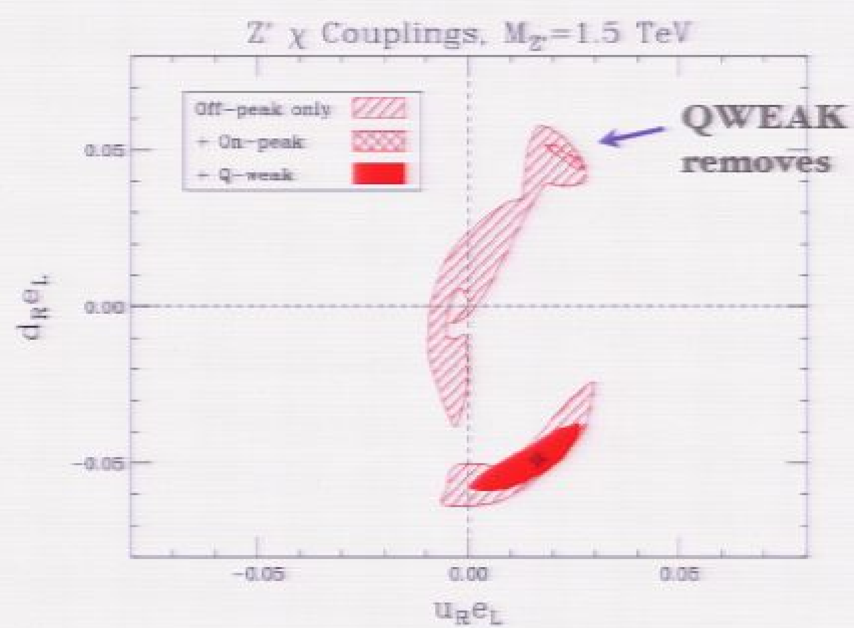
Fitting the width



- Can determine width to few GeV from comparison of on- and off-peak data alone
- Competitive with resonance-peak scan at 100-300 fb^{-1}, different systematics Schäfer, Ledroit, Trocmé, ATLAS-PHYS-PUB-2005-010

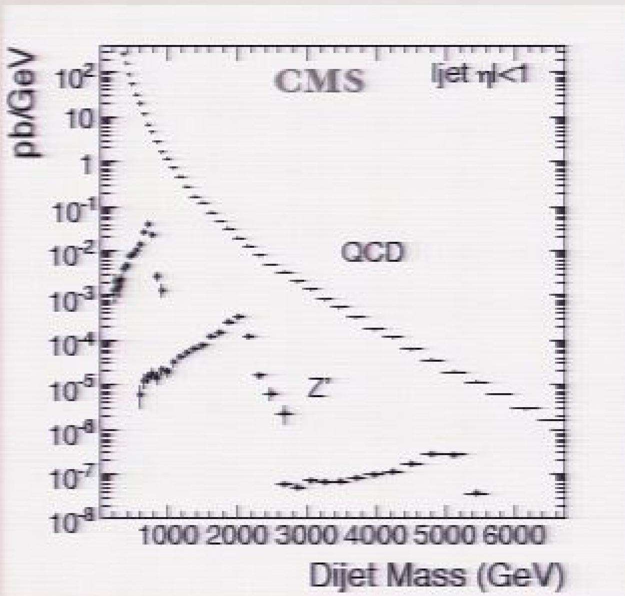
Fitting the couplings and Qweak

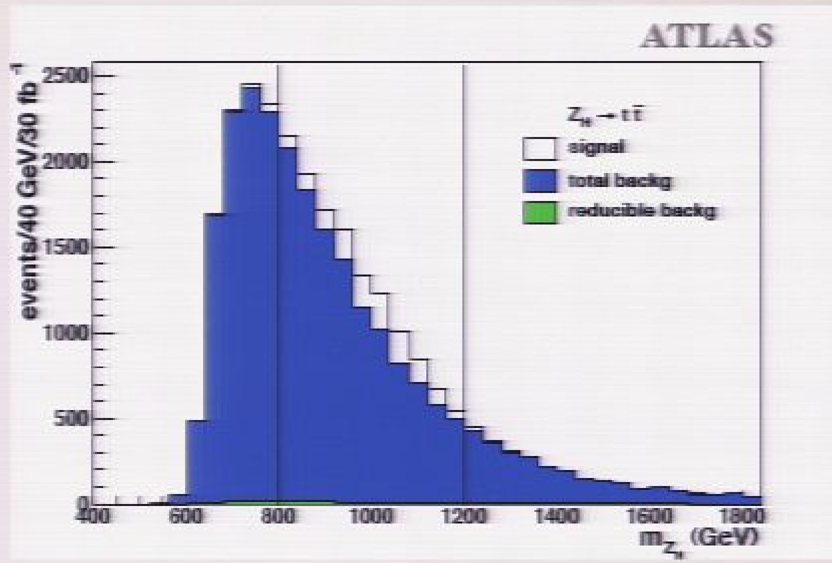
- Qweak: 4% measurement of the proton's weak charge, proposed for Jefferson Lab: $\Delta Q^p \sim (3q_L+2u_R+d_R)(e_R-e_L)$
- Off-peak data, Qweak help remove degeneracies between couplings



q×e degeneracy

- Still have q×e coupling degeneracy; can we break with LHC?





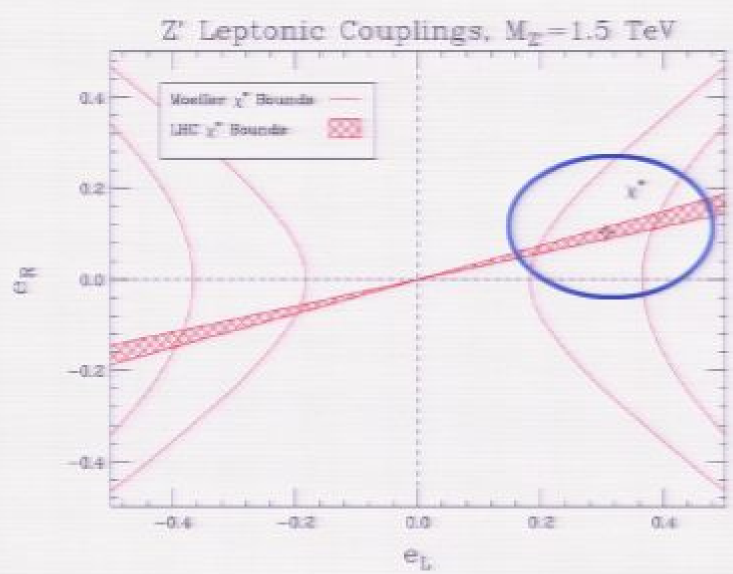
- Observation of di-jet decay likely very tough
- tt possible: likely for limited mass range due to backgrounds
  (see S. Godfrey, T. Martin 0807.1080)

Møller scattering

- Planned J-lab upgrade: proposed improved measurement of parity violation in e^-e^- scattering (recall that E158 already constrains Z')
- $\Delta A_{exp} = 0.6$ ppb; measures $e_V e_A = e_R^2 - e_L^2$ (hyperbola)

$$\text{Note}: \frac{e_L}{\sqrt{e_L^2 + e_R^2}} = \frac{|q| e_L}{\sqrt{q^2 e_L^2 + q^2 e_R^2}}$$

⇒LHC measures wedge in e_R–e_L plane



☑ Combined analysis removes last degeneracy; allows separate q, e coupling extraction

Summary: Z' analysis strategy

- TeV-scale Z' bosons ubiquitous in TeV-scale Standard Model extensions; ~5 TeV reach at LHC, possibility of early discovery
- Convenient basis to describe on-peak data: c_q, e_q $\Rightarrow$ complete model-independent extraction of couplings
- Can begin discriminating models with $\leq 10\ fb^{-1}$
- Off-peak data+Qweak breaks degeneracies and provides width measurement
- Møller scattering can break remaining q×e degeneracy $\Rightarrow$ then extract individual charges