Z' bosons and light hidden sectors at the LHC

Frank Petriello
University of Wisconsin, Madison

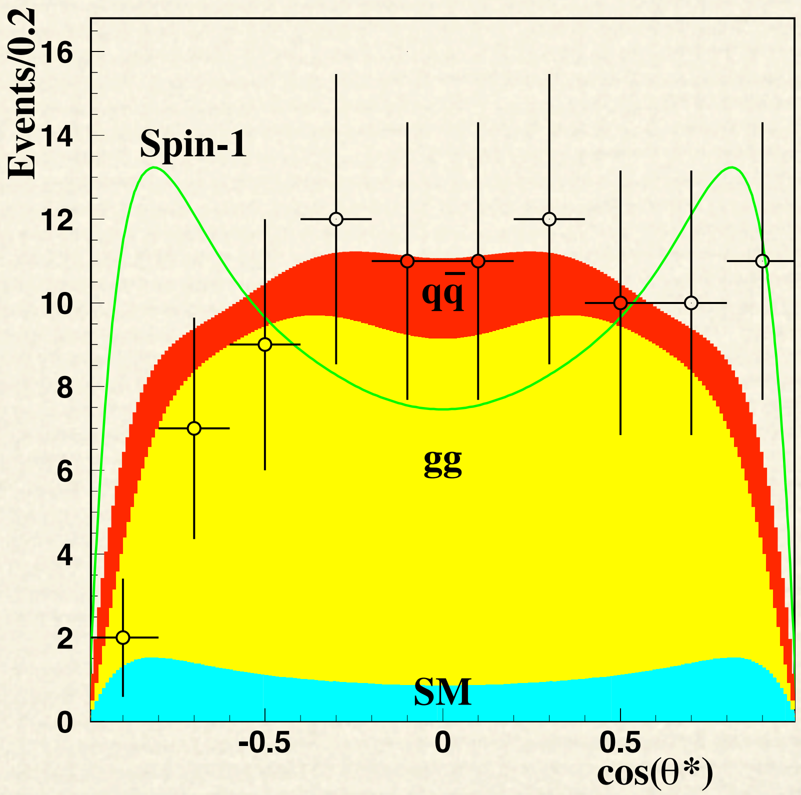
FP, Seth Quackenbush arXiv:0801.4389
FP, SQ, Kathryn Zurek arXiv:0803.4005
Yuri Gershtein, FP, SQ, KZ, in progress

Outline

- What can we learn from a Z' discovery?
- Some Z' basics and motivations Langacker, Leike, Rizzo
- How well can we determine its couplings?
  - NLO QCD, PDF+scale+statistical errors, model-independent parametrization, simple and complete analysis procedure
- Is the Z' a messenger to a hidden sector?
  - Invisible Z' decays using $ZZ', \gamma Z'$

What is a Z'

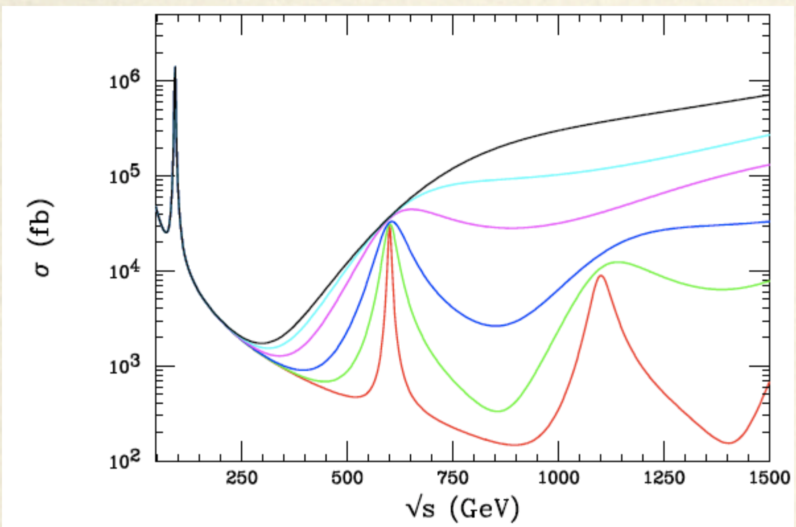
- Experimental definition: resonance observed in Drell-Yan, $pp(p\bar{p}) \to l^+l^- + X$



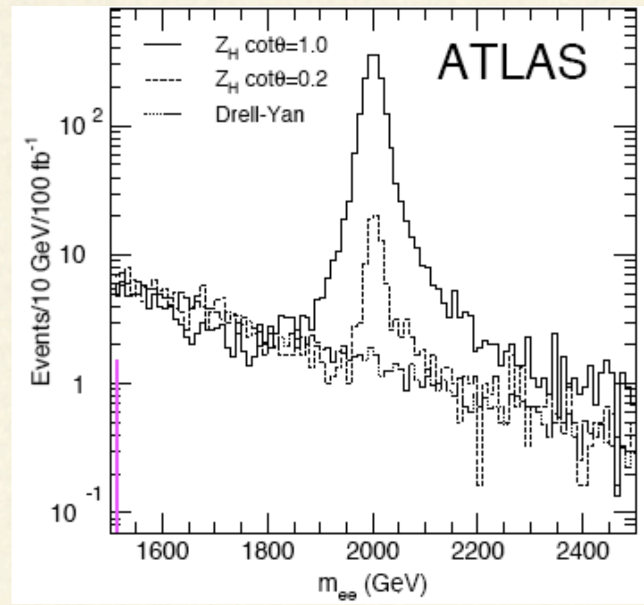
B. Allanach et al.

- Can distinguish spin-1 from spins-0,2 with a few hundred events Allanach; Orland; Rizzo; et al.

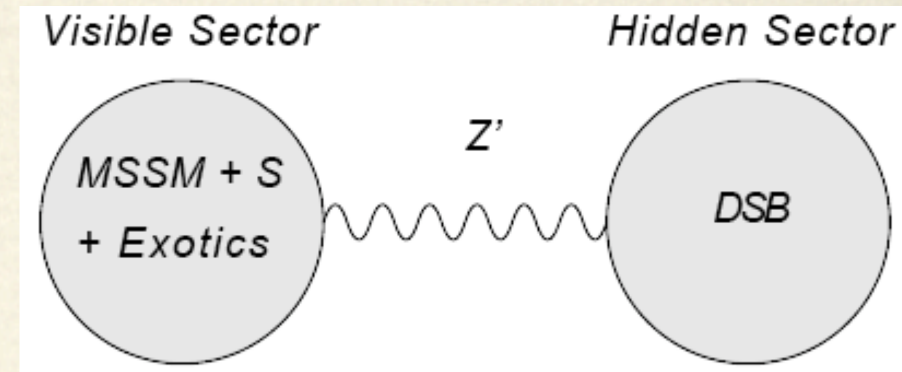
The Z' zoo



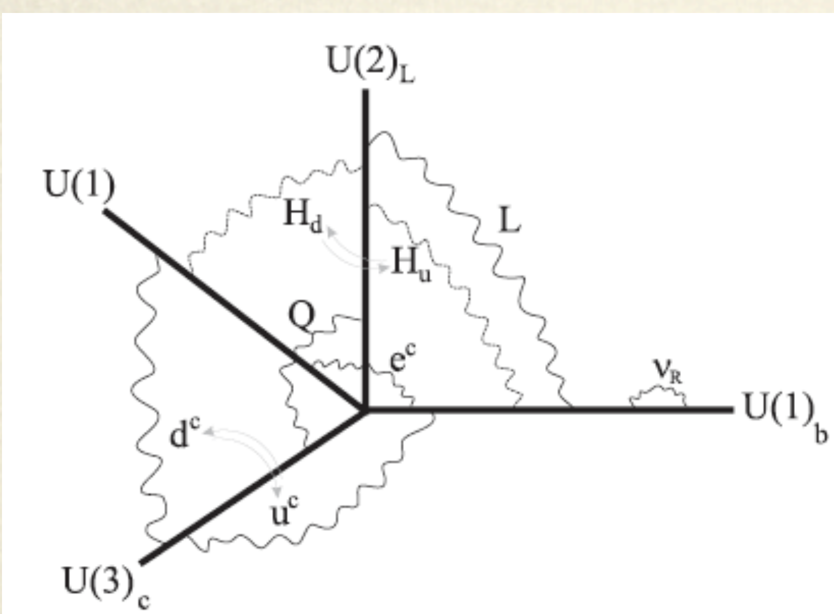
KK modes



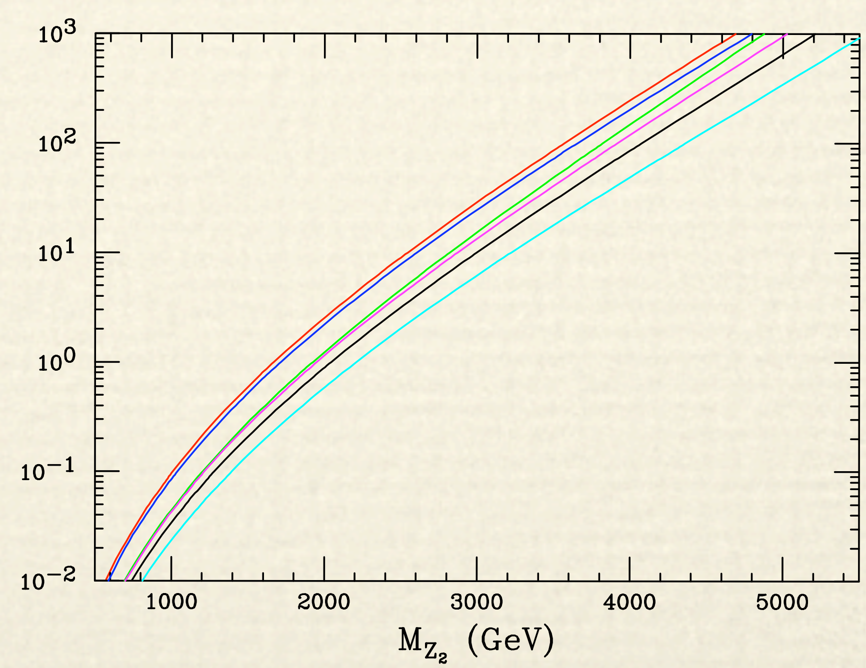
Little Higgs



Messengers



String models



T. Rizzo

Reach:

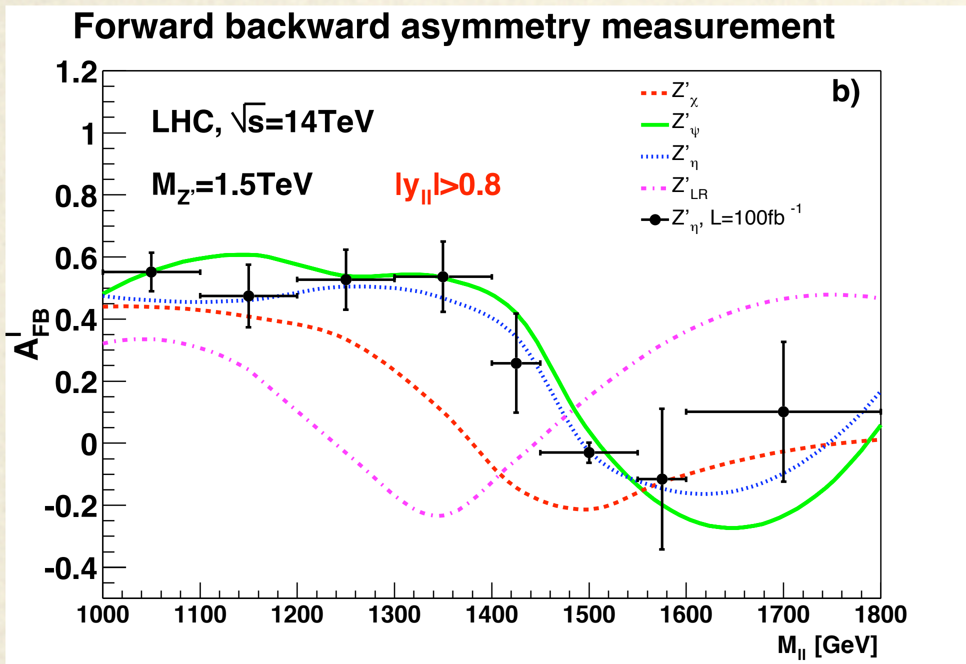
LHC: > 5 TeV

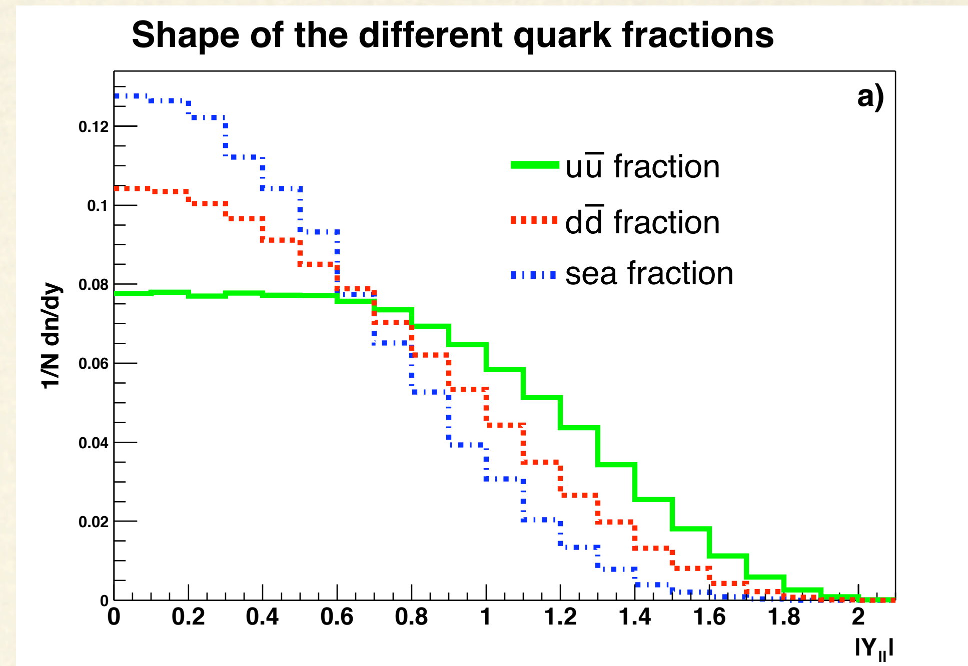
1 TeV for SSM at Tevatron

What can we measure?

- $M_{Z'}, \Gamma_{Z'}$: Measure from resonance fit
  - Mass resolution at few % level CMS, ATLAS
  - Width accessible if $\Gamma/M \gtrsim 0.5 - 1\%$ Allanach et al.
  - g_v, g_a : From fermionic decays, window to underlying model
- Mixing induced: $Z' \to WW, ZH$
- Other rare decays, associated production

What tools do we have?





M. Dittmar et al.

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

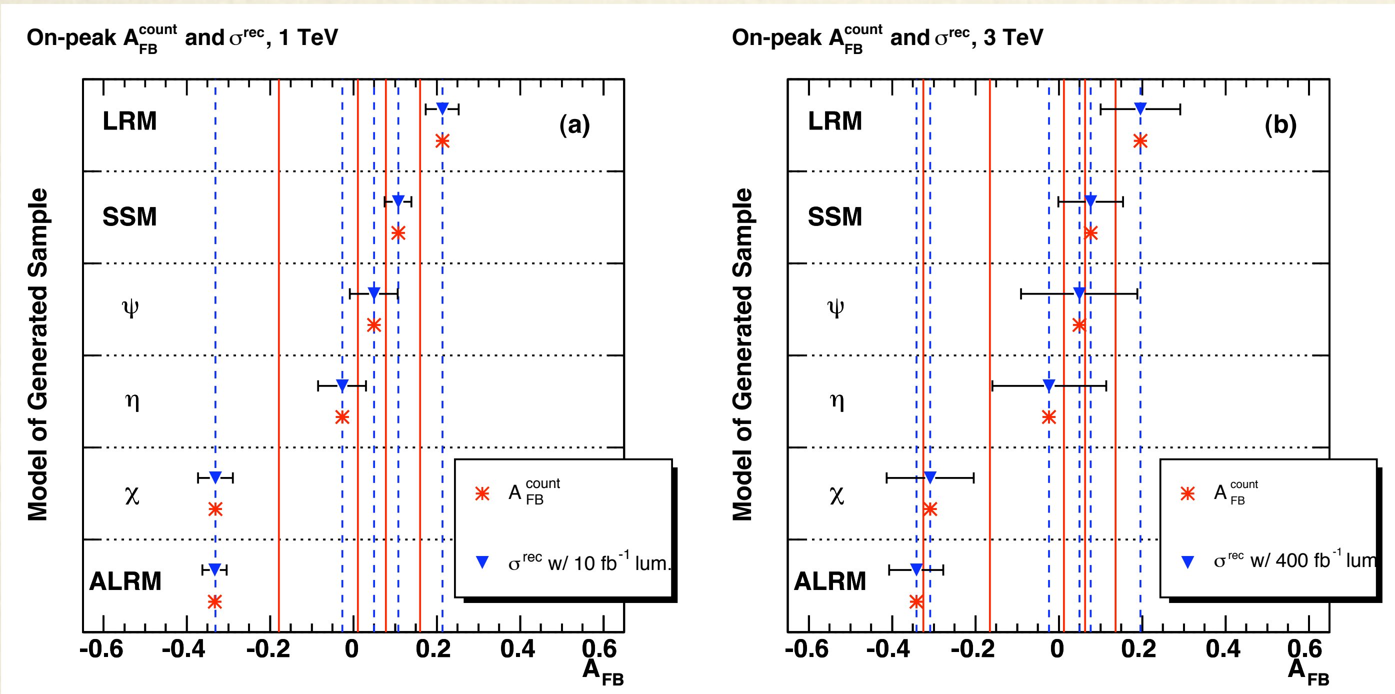
Define direction with Z' rapidity

Keep events with |Y|>0.8

Rapidity spectrum probes up/down couplings

Large component of discriminatory power comes with just 2 bins (used later)

Model discrimination studies



CMS

Results

	Generation level Fitted values (%)		Reconstruction level Fitted values (%)	
Model	Prop(Z'←dd)	Prop(Z' ←uu)	Prop(Z'←dd)	Prop(Z'←uu)
SSM	41.±10.	52.±12.	22.±16.	60.±16.
χ	62.±12.	29.±14.	79.±17.	17.±19.
η	23.±13.	75.±14.	33.±6.	67.±8.
ψ	36.±12.	61.±13.	32.±15.	62.±17.
LR	57.±4.	43.±14.	53.±13.	46.±15.

CCL: statistical power not very good… (not quite a surprise)
generation level fit result compatible with "truth"
reconstruction level compatible with generation level

ATLAS

Studies compare single observables between models

Combine for better discrimination?

Better language than specific models?

Effect of PDF, QCD errors?

What we want to improve

- NLO QCD with all acceptances, correlations
- Assess effects of statistical, PDF, and higher-order QCD uncertainties (result: statistics, PDF comparable, QCD negligible; detector systematics small $_{\text{CMS}}$)
- Simple analysis technique using all kinematics
- Parametrization both complete and convenient for theory comparison

Theoretical framework

- Assume Z' couplings generation independent
- Members of doublets have same couplings
- Five couplings to: q_L, l_L, u_R, d_R, l_R
- No Z-Z' mixing, heavy ν_R
- Example models to illustrate certain points:

$U(1)_\eta, U(1)_\chi, U(1)_\psi, LR$

Coupling parametrization

Want model-independent extraction of couplings

On peak, NLO Z' cross section takes the form:

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

(note quark/lepton degeneracy)

$a_{1,2}^{q'}$ include MEs, PDFs, cuts

Also includes the width from the Z' propagator; narrow width motivates the definitions...

Coupling parametrization

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

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

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

$a_{1,2}^q$ depend *only* on Z' mass; separate model details from QCD, cuts

Extension of Carena et al. to handle A_{FB}, etc.

Analysis strategy

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

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

- Take the following four combinations:

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

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

Analysis strategy

Matrix equation relating measurements to $c_{u,d}, e_{u,d}$

$$\vec{m} = M\vec{c} \qquad \vec{m} = (F_<, B_<, F_>, B_<) \quad \vec{c} = (c_u, c_d, e_u, e_d)$$

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

Only dependence on model through mass

Measure $\vec{m}$, extract $\vec{c}$ without model assumption

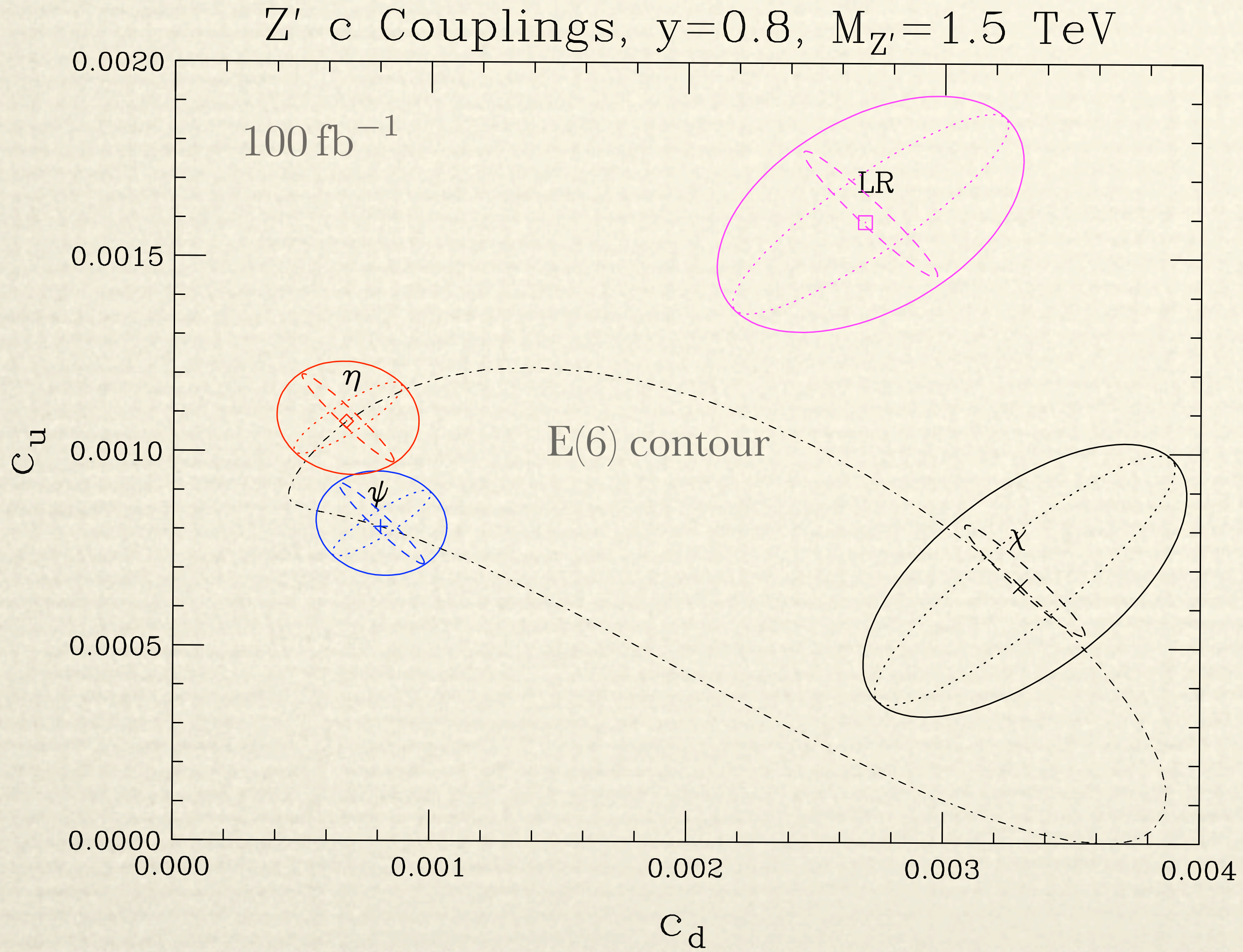
All details of QCD, acceptances, absorbed into $a_{1,2}^q$

Bulk of discriminatory power from two Y bins

LHC results

See how this works for example models at LHC

Propagate through PDF, statistical, scale errors to determine effect on c_q, e_q



Dashed: statistical

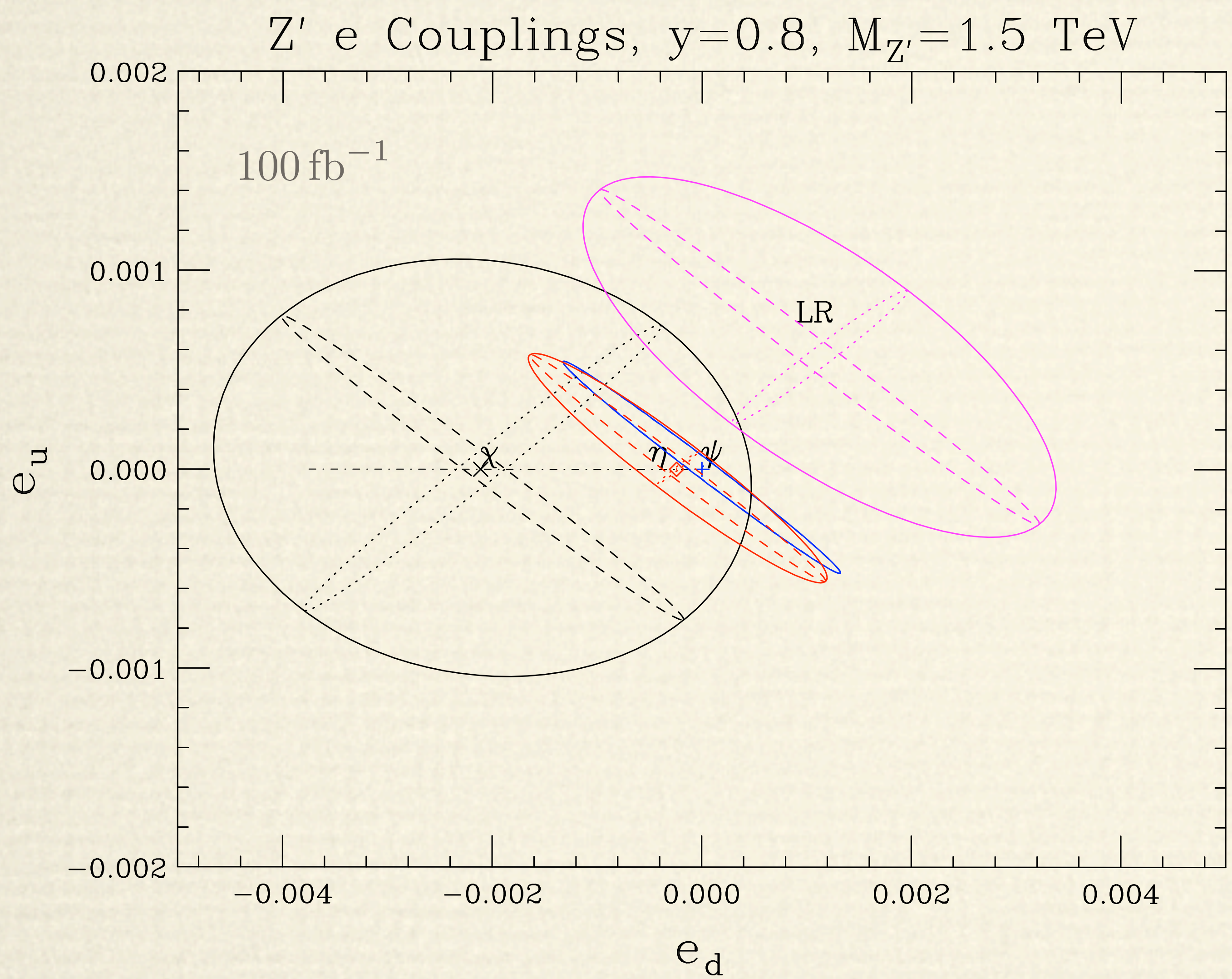
Dotted: PDF

Standard acceptance cuts

$c_u + c_d$: statistical small

$c_u - c_d$: PDF small

LHC results

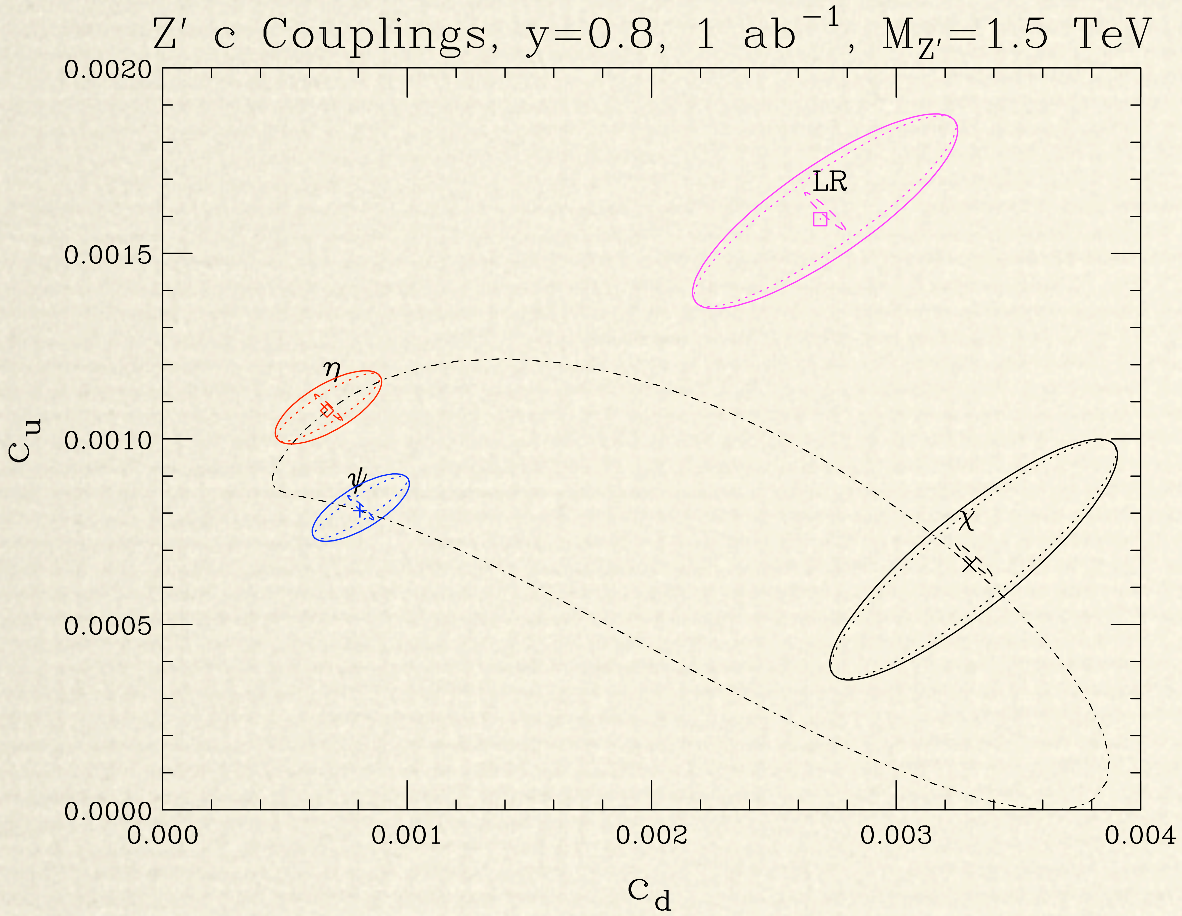


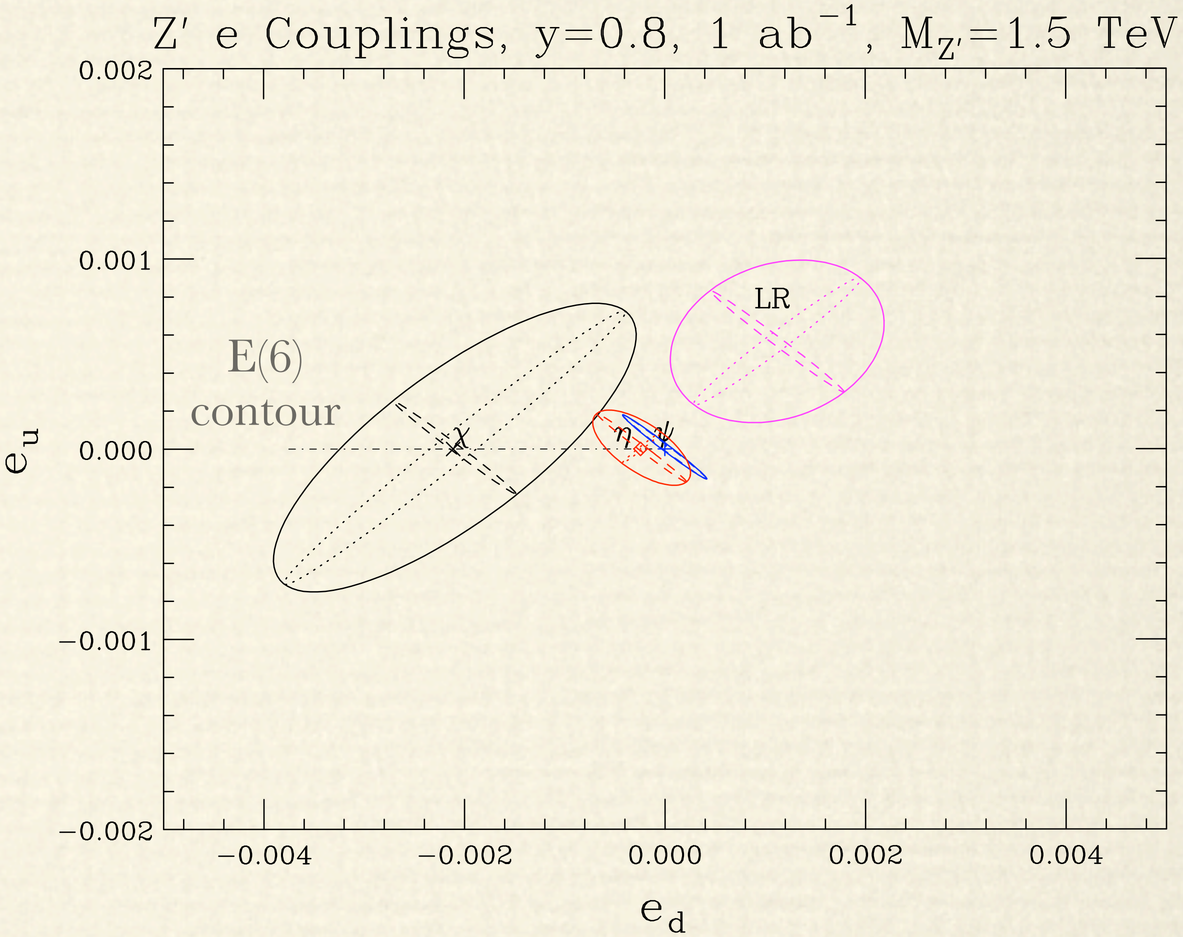
e_q measurements much tougher

Primarily statistics

How about SLHC?

SLHC results





c_q errors only PDF; precision result with SLHC

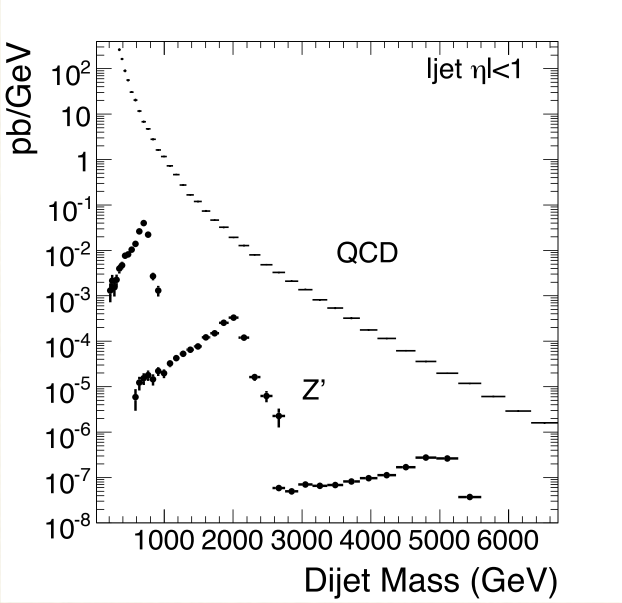
e_q : good enough result to begin discriminating models

Summary of on-peak results

- Convenient parametrization for model independent interpretation of Z' signal
- Simple analysis procedure to go from data in four kinematic regions to four observables
- Precision reaches 10% on couplings with current error estimates; PDF limited
- PDF error reduction with LHC data?

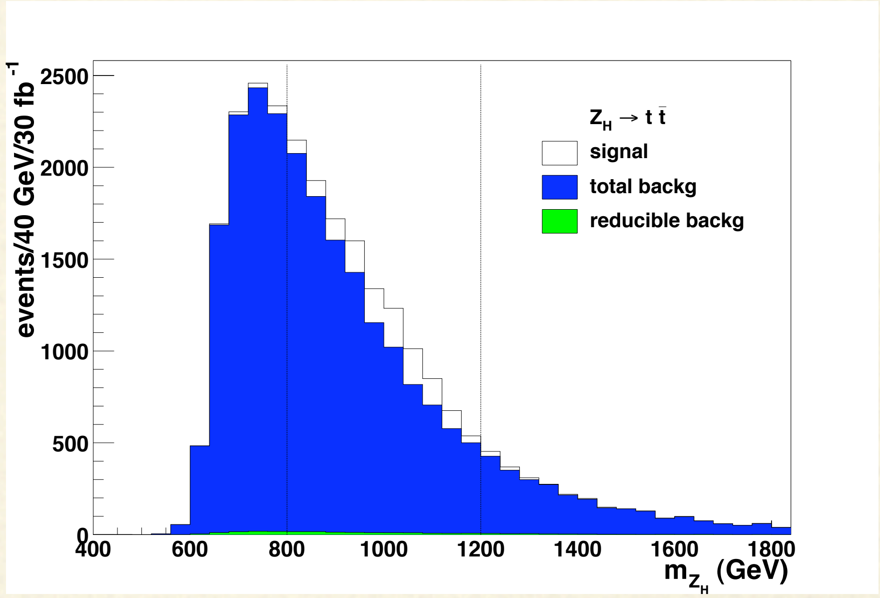
Limitations

Only 4 of 5 couplings due to quark/lepton coupling degeneracy



CMS

$pp \to Z' \to jj$ tough...



ATLAS

$t\bar{t}$ possible, but likely for limited mass range

Other experiments (ILC, low-energy Moller)

Z' invisible width

Measurement of the width breaks degeneracy

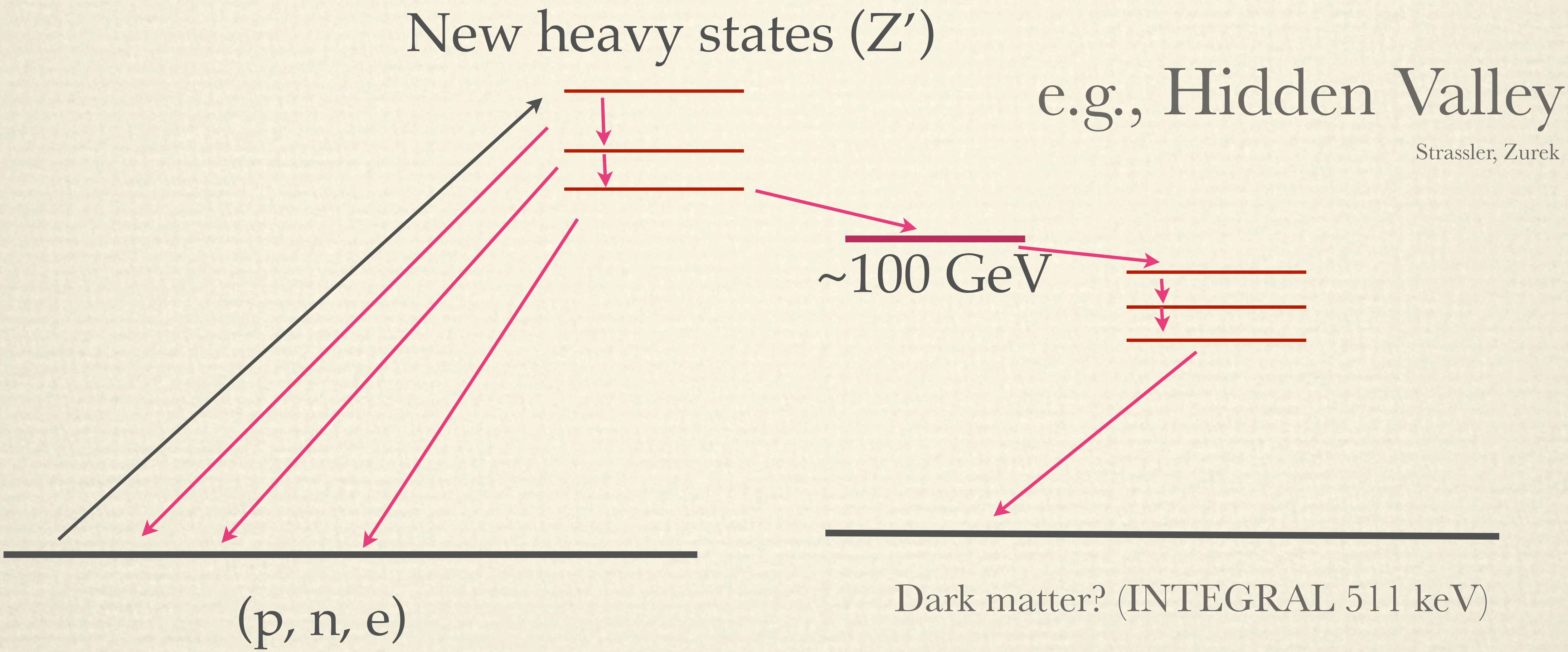
$$\Gamma = \Gamma_{inv} + \Gamma_l + \Gamma_q + \Gamma_{oth} \quad \text{while} \quad c_q \sim \Gamma_l \Gamma_q$$

If we knew invisible width was just from neutrinos and assumed SU(2), could break degeneracy up to discrete ambiguity

$$\Gamma_l \sim \frac{1}{2}\left[X \pm \sqrt{X^2 - 4Y}\right] \qquad X \sim \Gamma, Y \sim \sum_{q=u,d} c_q \Gamma^2$$

Hidden sectors

Other reasons to study invisible decays; Z' often acts as messenger field



$U(1)_\chi\ Z',\ SU(3)$ HV example: up to 90% inv. decays

Finding the invisible Z'

In what channels can we find invisible decays?

$pp \to Z' j \to \not{E}_T j$: hard, jet energy mismeasurement

$pp \to Z' Z \to \not{E}_T l^+ l^-$: much cleaner mode

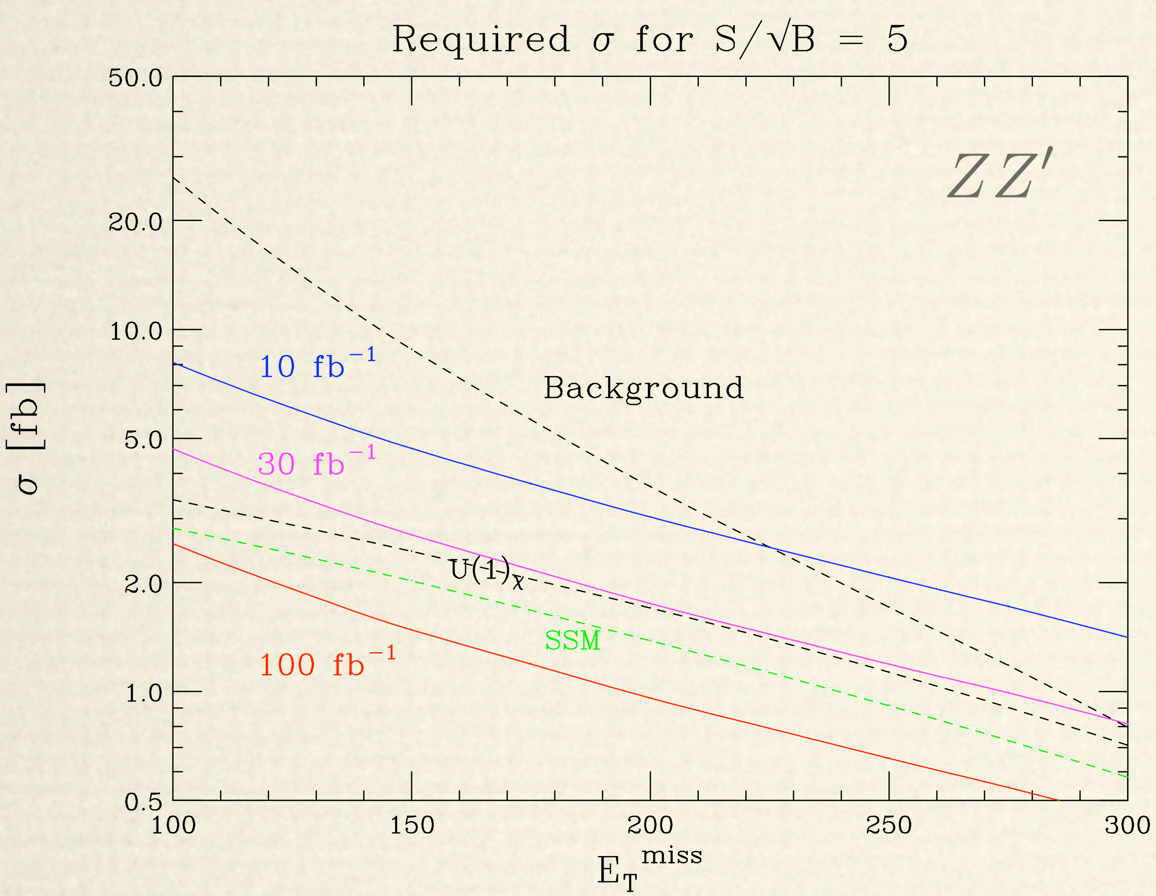
$\text{Backgrounds} : ZZ, WW, Zj$

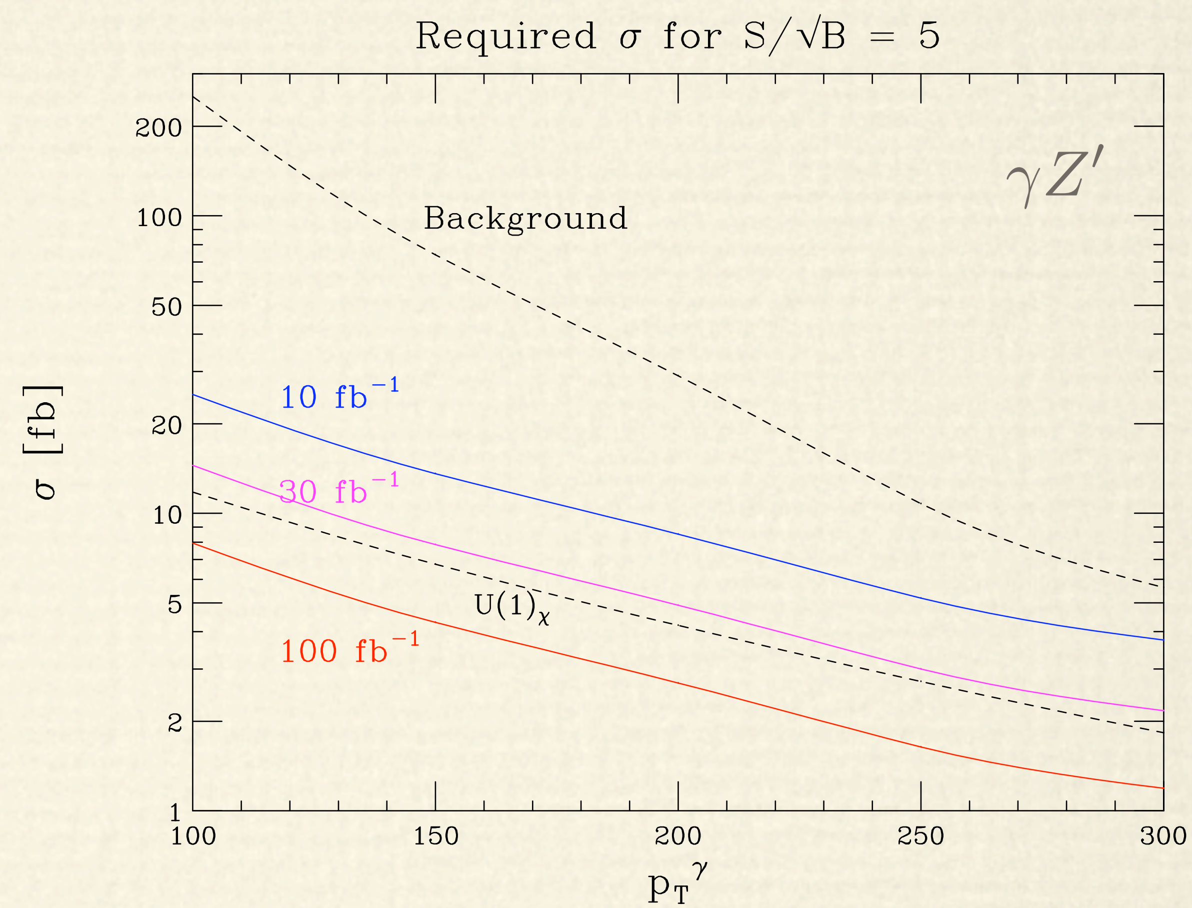
$pp \to Z' \gamma \to \not{E}_T \gamma$: also possible

$\text{Backgrounds} : Z\gamma, W\gamma, W \to e, Zj$

(jet, electron fakes photon)

Observing the invisible Z'





Discovery channel for leptophobic Z'

Possible observation with $30\,\mathrm{fb}^{-1}$

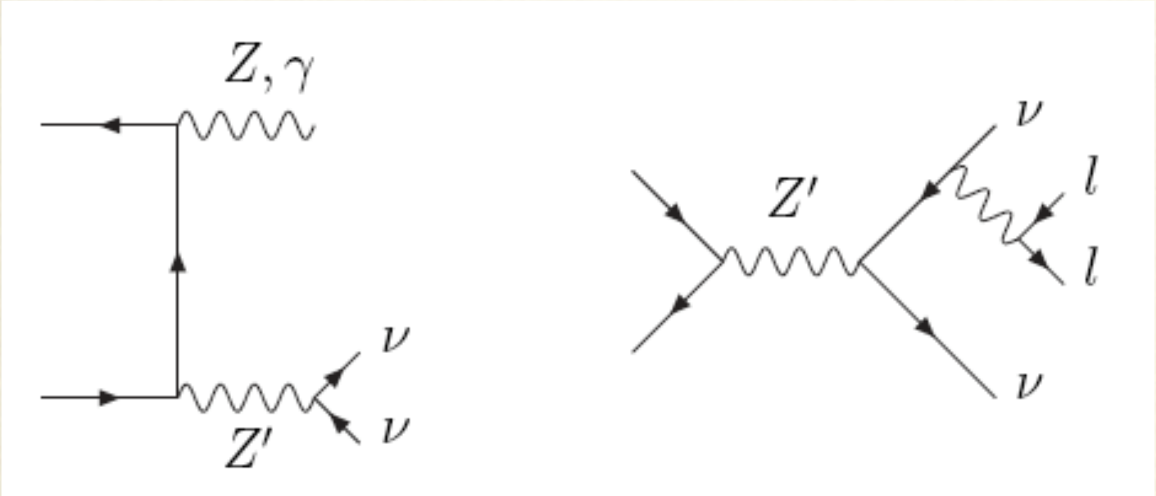
No shape fit yet; results will improve

Background normalization

- Can we control background, especially for $Z'\gamma$?
- Normalize $ZZ, WW, Z\gamma$ to Z, W for %-level prediction; removes many systematics Dittmar et al.
- Use di-photons, γj to control $Z\gamma, Zj$
- With 2% background uncertainty, roughly need 60 fb for 5σ, 35 fb without in $Z'\gamma$
- Still studying...

Interpreting the invisible Z'

How do we know we're not seeing neutrino decays?



ISR FSR

Two distinct contributions

For hidden states, $Z'\gamma$, only ISR

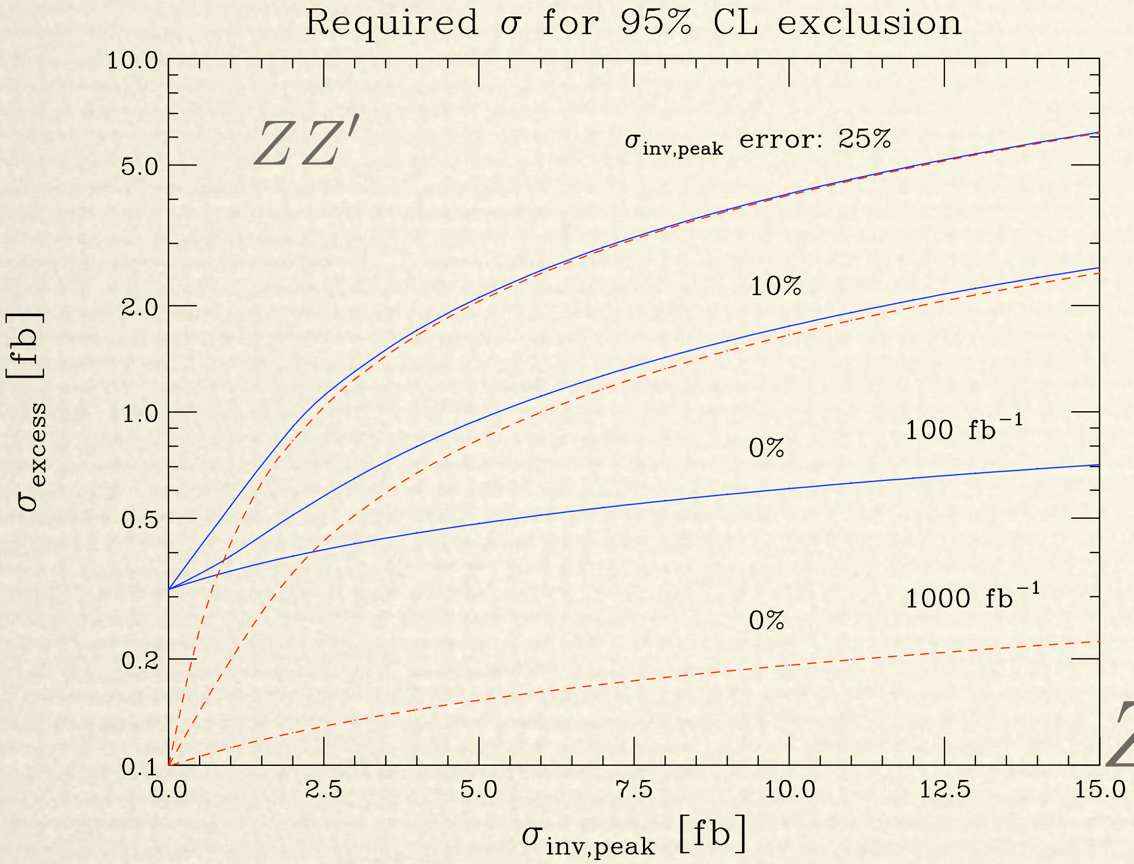
For example, $Z'\gamma$ matrix element given by charge

$$Q^q_{ISR} = (q'^2_V + q'^2_A)(Q^q_\gamma)^2 \frac{\Gamma^{inv}_{Z'}}{\Gamma_{Z'}} \Rightarrow \frac{c_q}{2} \frac{C}{C+1} (Q^q_\gamma)^2$$ if neutrinos by $SU(2)_L$

Neutrino part predicted by on-peak c_q, e_q !

Finding the hidden sector

Can we distinguish decays to hidden sector given on-peak predictions for charges?



Depends strongly on precision of on-peak extraction

Some significant restrictions for $M_{Z'} \sim 1\,\text{TeV}$

ZZ' : exclusion of 25% hidden branching fractions possible

Still working on quantifying this, $Z'\gamma$

Conclusions

- Many reasons to expect Z' bosons to be at TeV
- Many things can be learned from LHC data
- Can parametrize and extract couplings with minimal model assumptions
- Potentially reach 10% or better precision on couplings
- Can probe invisible Z' decays and test for connection to hidden sectors