Z-primes at the Tevatron & LHC

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Outline

- Introduction: Why Z's ?
- What We Know Today
  - Theoretical Framework
  - LEP II bounds
- What We Hope To Find Tomorrow
  - Model Independent Studies
  - Bridges between Modelers & Experiment
- Outlook

Introduction: Why Z'?

- The SM is based on local gauge invariance under: $SU(3)_C \times SU(2)_W \times U(1)_Y$.
- It is natural to ask: are these all of the fundamental interactions of nature? What are the limits on more?
  - How well has LEP already explored them?
  - How do hadron machines increase our knowledge?
- Good theoretical reasons point to extra gauge bosons.
  - **GUT**s with "large" gauge groups ($S0(10)$, E_6, …)
  - **Extra dimensions** with gauge fields in the bulk have copies of γ, Z, which are massive, neutral vector particles.
  - Theories like Topcolor use them to drive **EWSB**.
  - The **little Higgs** theories use massive vector particles to cancel quadratic divergences in the Higgs mass induced by W and Z.
  - New **SUSY** theories use them to survive the LEP II bound on $\mathbf{m_h}$.

Theory Framework

- We extend the SM: $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_Z$.
  - There are Z's coming from larger groups like *SU(2).* We can usually describe their properties with a ***U(1)***, though we don't capture all of the physics.
- Each SM fermion ψ (and the usual Higgs) is assigned a charge z_ψ under $U(1)_Z$. The Z-ψ-ψ coupling is: $g_Z\, z_\psi$.
- A new scalar Φ is charged under $U(1)_Z$, ($z_\Phi = 1$). Its VEV **u** determines the **Z'** mass: $M_{Z'} = g_Z\, z_\psi\, u$.
  - Φ is neutral under the SM.
- Theory can further relate the z_ψ to each other:
  - $SU(2)_W$ invariance: $z_{uL} = z_{dL}$.
  - Yukawa interactions: $z_{uL} + z_{uR} + z_H = 0$.
  - Anomaly cancellation.
  - FCNCs and family universality: $z_{dL} = z_{sL} = z_{bL}$.

Yukawas from higher dimensional operators?

New Fermions?

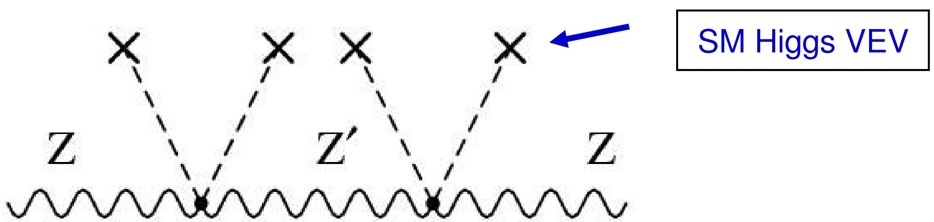
Specific "Model-lines"

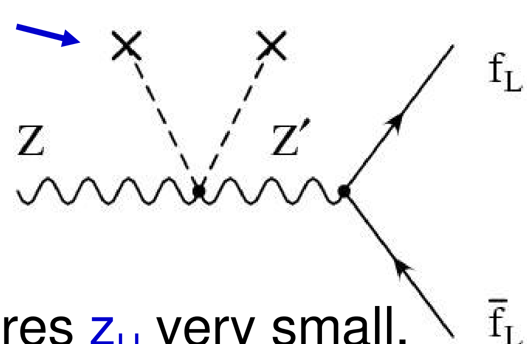
	$B-xL$	$Q+xu$	$10+x\bar{5}$	$d-xu$
$q_L=(u_L,d_L)$	+1/3	+1/3	+1/3	0
u_R	+1/3	$+x/3$	-1/3	$-x/3$
d_R	+1/3	$(2-x)/3$	$-x/3$	+1/3
$l_L=(e_L,\nu_L)$	$-x$	-1	$+x/3$	$(x-1)/3$
e_R	$-x$	$-(2+x)/3$	-1/3	$+x/3$

- Subject to theoretical motivations, we find a set of 4 "model lines".
- Each has a free parameter, ***x***, specifying all of the couplings of the Z'.
- The $\mathbf{E_6}$ Z's are certain values of ***x*** for certain model lines.

e^+e^- Limits: Z-Z' Mixing

- e^+e^- colliders constrain Z's in two important ways.
- Precision measurements of Z physics
  - SM predictions in agreement at roughly few per mil level.
  - A Z' which mixed with Z would distort these predictions.



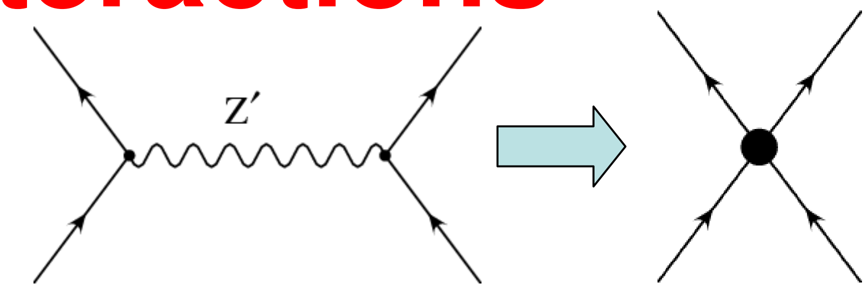


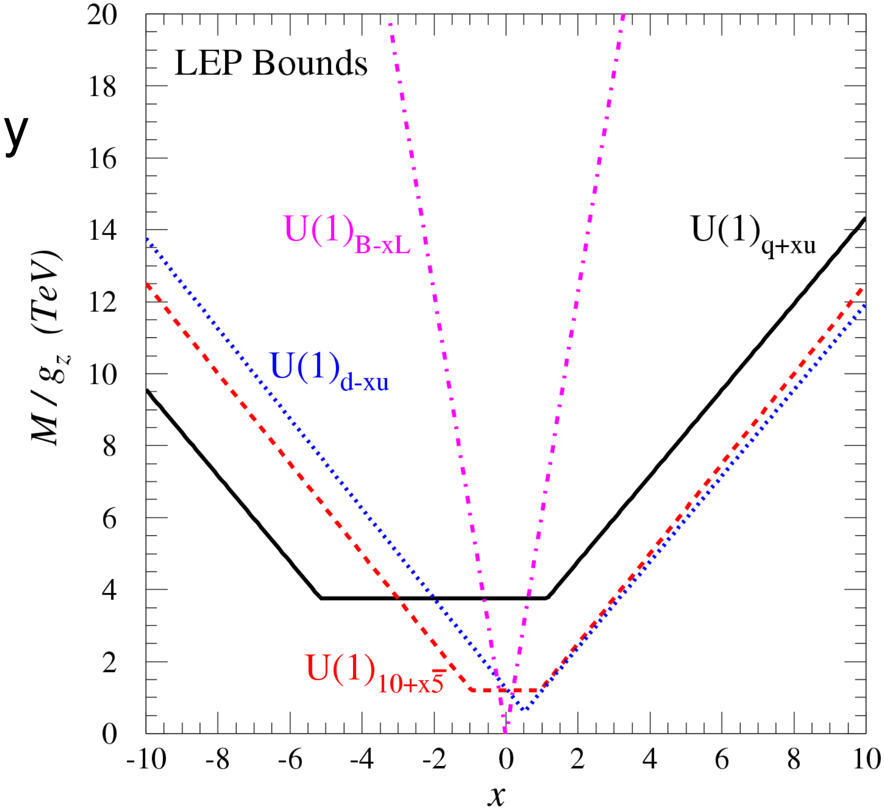
  - If there is a single (SM) Higgs, this requires z_H very small.
  - For **multiple Higgses**, one can cancel the mixing, by fine-tuning the Higgs potential against the z_Hs (to the sub-% level).
  - This is how the famous $\mathbf{E_6}$ models survive LEP-II limits.
  - I will fix $z_H = 0$.

J Hewett, T Rizzo, **Phys.Rept.183, 193 (1989)**

Contact Interactions

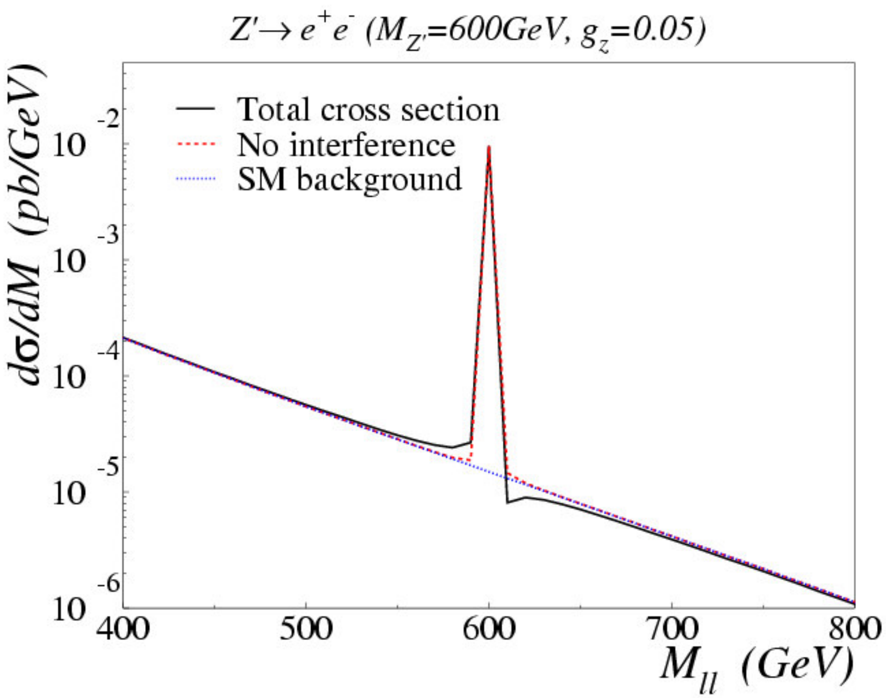
- Searching for evidence of physics beyond the SM in $e^+e^-\psi\bar{\psi}$ contact interactions.
  - At **E<< $m_{Z'}$**, the Z' effects look like four fermion interactions:
  - These depend quite sensitively on how Z' couples to e, and also to other fermions.
- LEP-II has searched for evidence of contact interactions in almost all conceivable channels.
- Bounds vary from channel to channel, complicating the analysis.

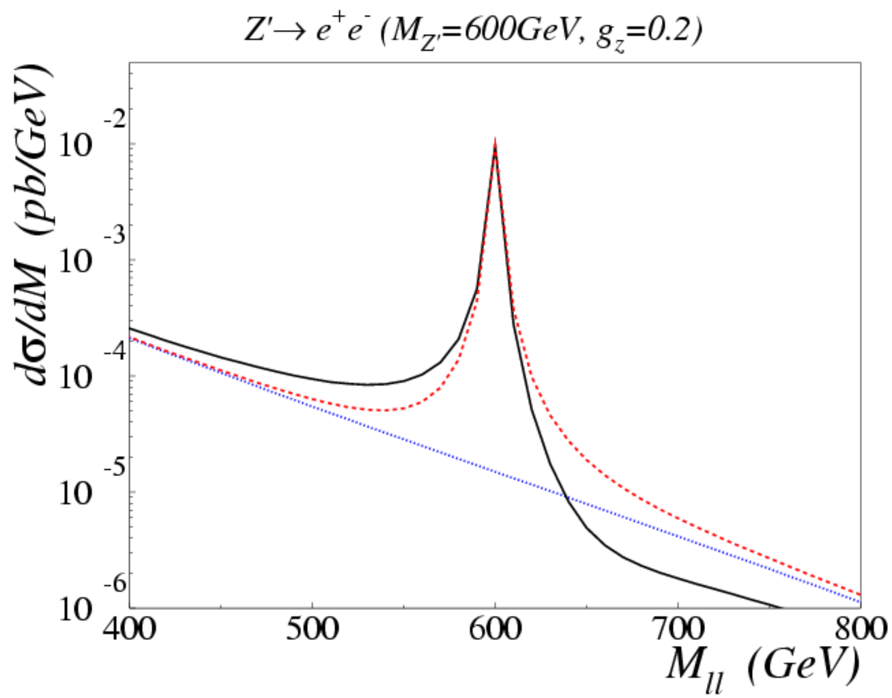




Hadron Colliders

- Hadron colliders look for Z's most effectively in the decay into charged leptons (**e±, μ±, τ±**).
- Unlike LEP, hadron colliders are sensitive to Z's which do not couple to **e±** : unexplored territory!
- The signal appears as a resonance above the (smooth) lepton pair backgrounds. Interference effects are tiny.





Common Ground

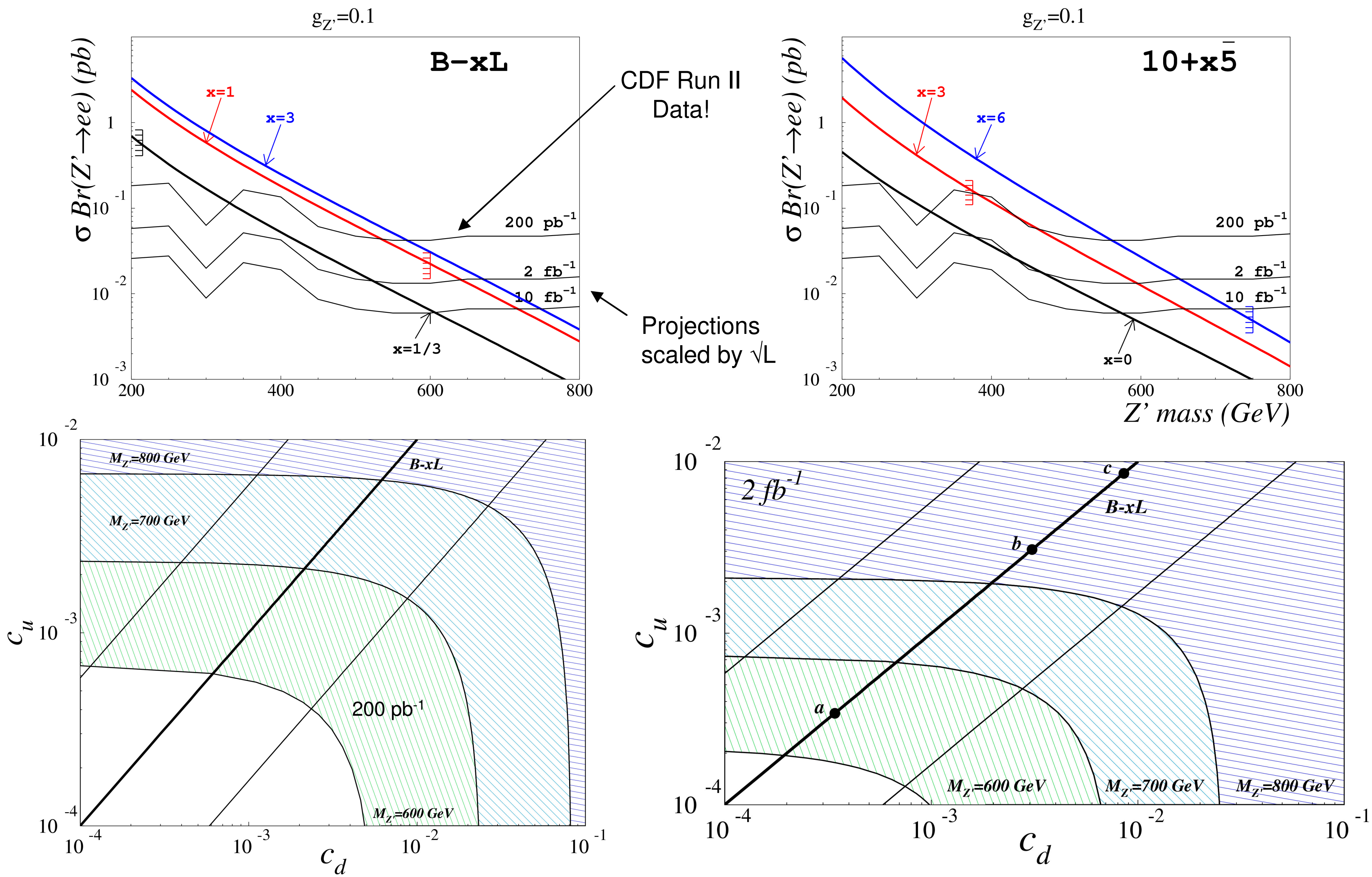
- Run I and existing Run II analyses have presented limits on σ x BR. Specific **E_6** models are usually overlaid to illustrate the results.
  - This is good because σ x BR is fairly model-independent: results can in principle be applied to other theories with Z's.
  - However, it is inconvenient because computing a hadronic cross section is not a completely trivial task : one has to know about QCD, PDFs, etc..
  - These are important for σ, but don't have anything to do with Z's.
- An alternate approach tries to factor out the universal QCD dependence, and bound only the Z' quantities themselves.
  - This works perfectly at LO and NLO in QCD; at NNLO there is some (very) small model-dependence.
  - Dominant NLO EW corrections are model-independent (and probably important at the few % level).

Z' stuff **QCD stuff**

$$\sigma\left(p\bar{p} \to Z'X \to \ell^+\ell^- X\right) = \frac{\pi}{48s}\left[c_u w_u + c_d w_d\right]$$

$$c_u = g_Z^2\left(z_q^2 + z_u^2\right)\mathrm{BR}(Z' \to \ell^+\ell^-) \quad c_d = g_Z^2\left(z_q^2 + z_d^2\right)\mathrm{BR}(Z' \to \ell^+\ell^-)$$

Bounds & Projections



TeV4LHC ?

- LHC will eventually reach into the TeV range for Z' masses.
- Equivalently, for lower masses the larger luminosity should eventually allow one to probe **smaller couplings**.

- Of course, our theoretical results for a "common ground" between experiments and model-builders are also of value at the LHC.
- Once the Z' is discovered, we will need more observables to pin down its properties.

- Tevatron inputs for high *x* PDFs will be important for Z' and all high mass search processes.
- Especially high *x* gluon PDFs are constrained by jet data, and are particularly important at LHC (LHC k-factors can be ~100%).
- Techniques such as τ ID are being developed and can be refined using real data at Tevatron.

Outlook

- Models with massive neutral bosons, Z's, are of great interest for a variety of reasons. Many different kinds of models of physics beyond the SM contain Z's.
- e+e- colliders put strong bounds, and favor a Z' which does not mix with the Z. This implies either $z_H=0$ or some kind of tuning.
- We have introduced several new "model lines" which contain popular $\mathbf{E_6}$ inspired models, but also generalizations of them.
- A new proposal is that we directly bound quantities which contain Z' physics, but none of the QCD inputs, bringing experiment and modelers together easily (for both sides!).

$$c_u = g_Z^2 \left(z_q^2 + z_u^2 \right) \mathrm{BR}(Z' \to \ell^+ \ell^-) \quad c_d = g_Z^2 \left(z_q^2 + z_d^2 \right) \mathrm{BR}(Z' \to \ell^+ \ell^-)$$

- Tevatron can provide important inputs to LHC, including high *x* PDFs and new experimental technique.
- Let's find nature's next force!