An Effective Z'

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Outline

- Adding Z' to SM, usual approach
- Adding Z' to SM, "effective" approach
- Simple UV completion
- Flavour and other (non-)issues
- DM
- One collider application
- Conclusions

Introduction

The SM has simple construction

- Renormalizable field theory
- Small gauge groups
- Chiral matter in fundamental reps.
- No anomalies, FCNC's, B or L number violation

Perhaps new physics copies SM

Focus on new $U(1)'$ gauge group

Introduction

Easy to add a new $U(1)'$

Introduce a new vector and a Higgs: Z', ϕ

Couplings to SM fields?

Flavour universal couplings: anomalies, new heavy chiral fermions, non-standard representations

Flavour non-universal couplings: complicates Yukawa textures, makes some couplings non-renormalizable, forbids CKM entries

Effective Z' approach

Leave the SM as intact as possible

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{Z',\phi} + \mathcal{L}_{\text{higher dim.}} - \lambda |H|^2 |\phi|^2$$

$$\frac{c^i_j}{M^2}(\bar{q}_i \gamma^\mu q^j)(\phi^* D_\mu \phi) \supset g' \frac{c^i_j}{M^2}(\bar{q}_i \gamma^\mu q^j)(\phi^* Z'_\mu \phi)$$

SM "effectively" charged under $U(1)'$

(Toy) UV Model

$$\mathcal{L} \supset -\mu Q Q^c - y\phi q Q^c$$

New "ϕ-kawa" coupling mixes states

$$\sin\theta = \frac{y\langle\phi\rangle}{\sqrt{\mu^2 + y^2\langle\phi\rangle^2}}$$

$$\tilde{Q} = \cos\theta Q + \sin\theta q \qquad \tilde{q} = -\sin\theta Q + \cos\theta q$$

Generates effective Z' coupling for SM quark

$$\bar{Q}\not{D}Q \supset \underbrace{g'\sin^2\theta}_{g_{eff}} Z'_\mu \bar{\tilde{q}}\gamma^\mu \tilde{q}$$

(Toy) UV Model

SM quark, 0

heavy quark, -1

$$\mathcal{L} \supset -\mu Q Q^c - y\phi q Q^c$$

breaks U(1)', +1

heavy quark, +1

New "ϕ-kawa" coupling mixes states

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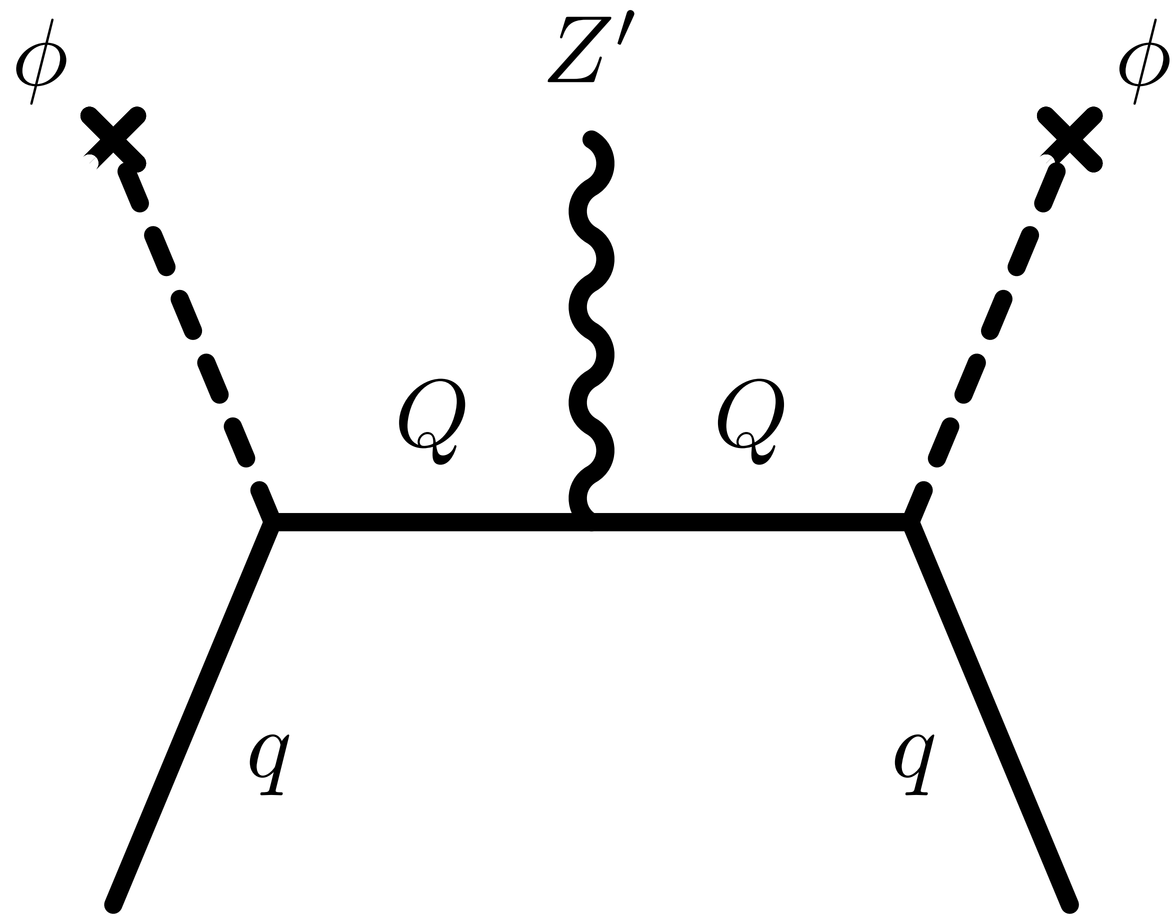
Generates effective Z' coupling for SM quark

$$\bar{Q}\not{D}Q \supset \underbrace{g' \sin^2\theta}_{g_{eff}} Z'_\mu \bar{\tilde{q}}\gamma^\mu \tilde{q}$$

Effective Z' approach

Only add vector-like matter in SM reps.
Which reps. determine which ϕ-kawa allowed



- Effective coupling $g_{eff} \leq g'$
- Only one linear combination SM quarks mix with Q. Rank of c^i_j determined by # of Q
- Heavy quarks predicted at scale $\lesssim 4\pi M_{Z'}/g_{eff}$

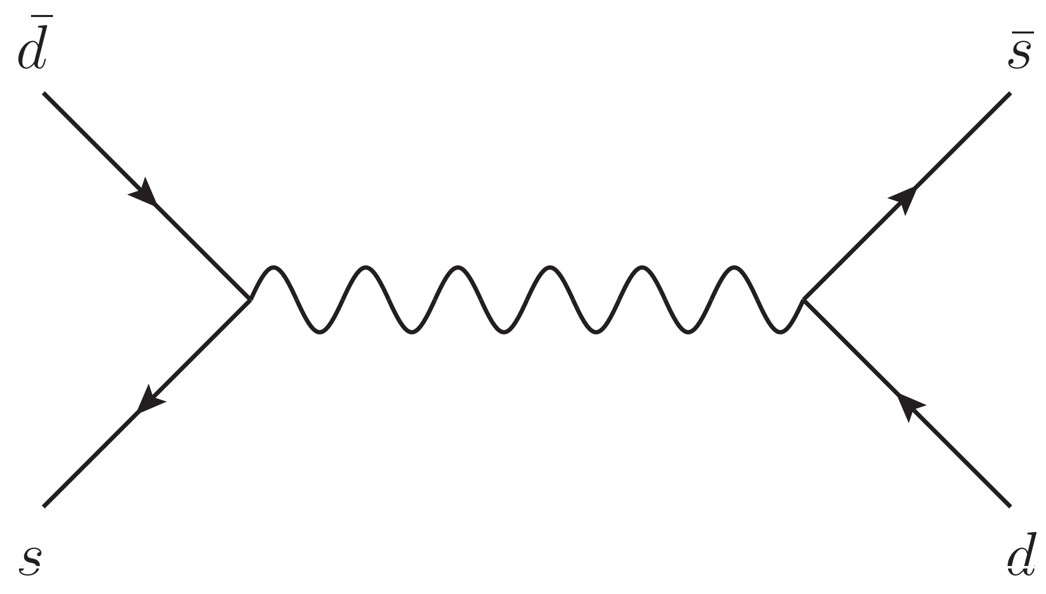
$$M_{\tilde{Q}} = \frac{\lambda/\sqrt{2}}{g' \sin\theta} M_{Z'} = \frac{\lambda/\sqrt{2}}{\sqrt{g' g_{eff}}} M_{Z'}$$

Flavour

$\phi\text{-kawa}$ can lead to flavour violation

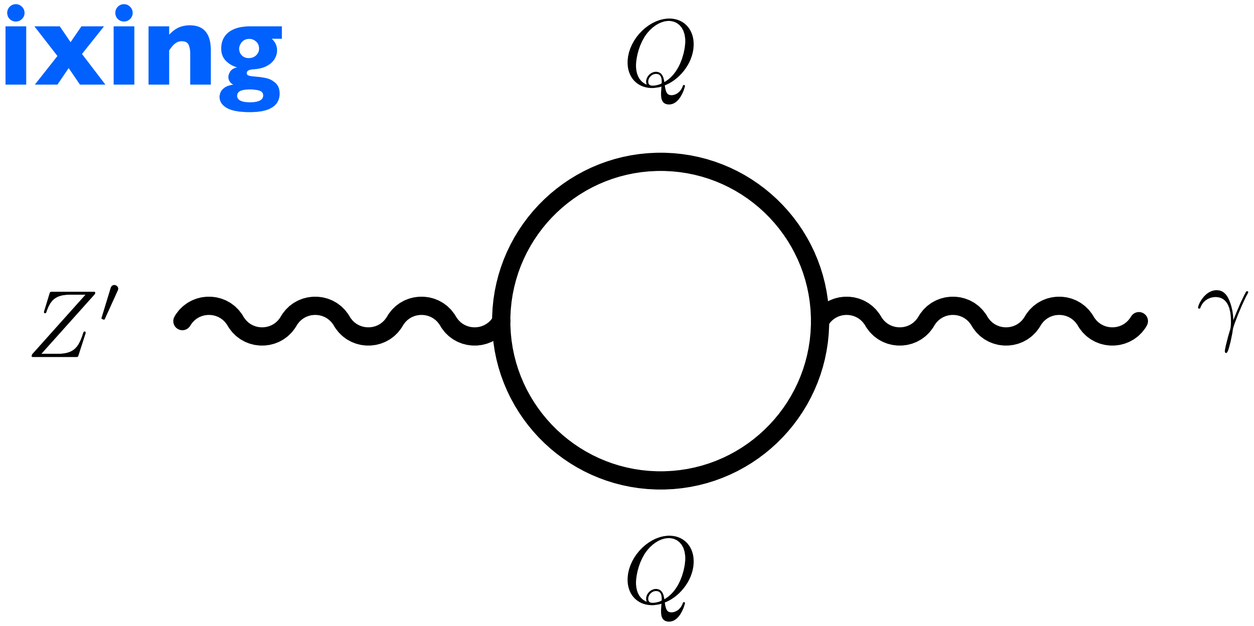
Good and bad.....

$$\bar{q}(\lambda_u\lambda_u^\dagger + \lambda_d\lambda_d^\dagger)\gamma_\mu q\phi^* D^\mu\phi \quad \Longrightarrow \quad \begin{array}{l} \frac{1}{v^2}\bar{u}_L V_{CKM} M_d^2 V_{CKM}^\dagger \gamma_\mu u_L \phi^* D^\mu \phi \\ \\ \frac{1}{v^2}\bar{d}_L V_{CKM}^\dagger M_u^2 V_{CKM} \gamma_\mu d_L \phi^* D^\mu \phi \end{array}$$



$$\propto m_c^4$$

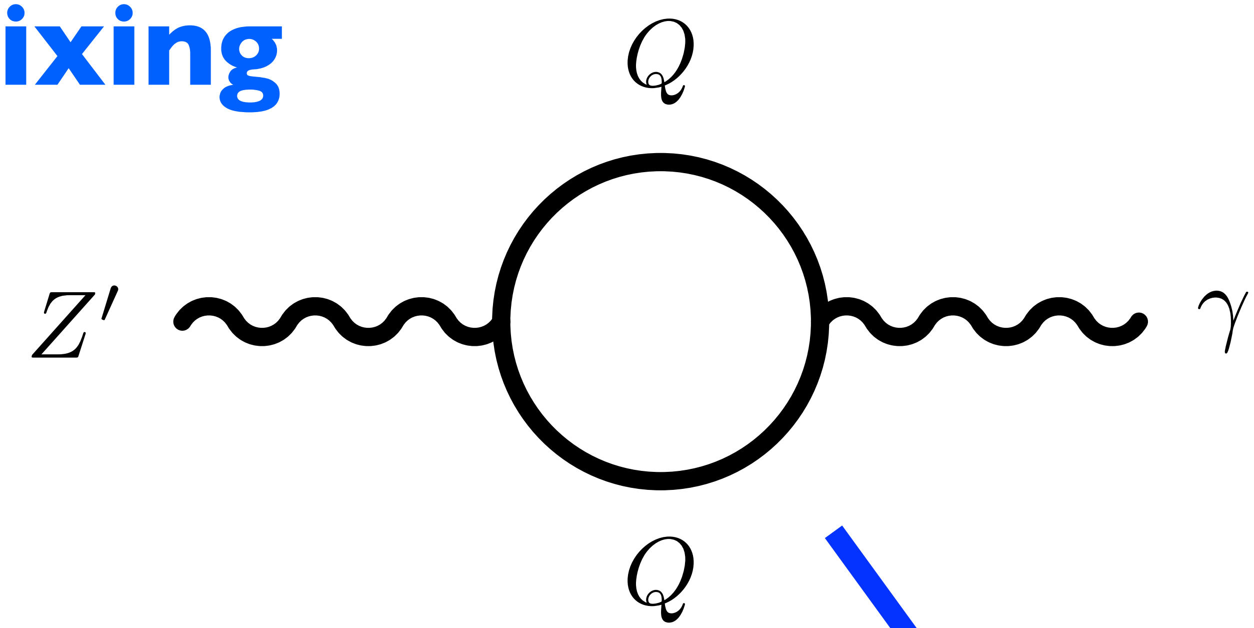
Kinetic Mixing



$$\mathcal{L} \supset -\frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{4}b_{\mu\nu}b^{\mu\nu} + \frac{\chi}{2}b_{\mu\nu}(c_w A^{\mu\nu} - s_w Z^{\mu\nu})$$
$$-\frac{1}{2}M_{Z'}^2 b_\mu b^\mu - \frac{1}{2}M_Z^2 Z_\mu Z^\mu$$

$$\chi = \frac{g_Y g'}{16\pi^2}\mathrm{tr}\, Q_Y Q' \,\log\frac{\Lambda^2}{\mu^2}$$

Kinetic Mixing



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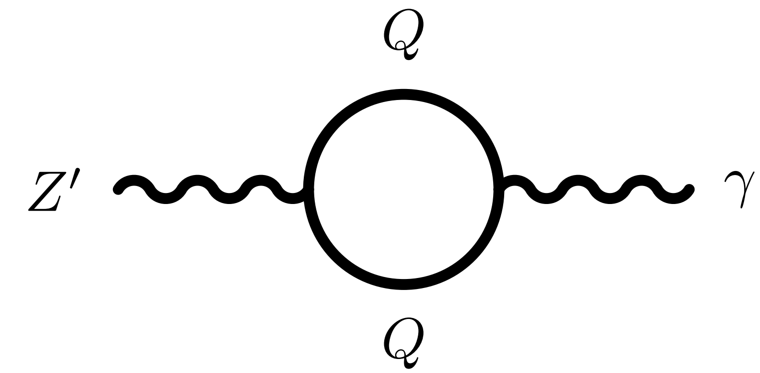
Kinetic Mixing



Removing kinetic mixing and going to mass basis

e.g. leptophobic at tree-level becomes:

$$\frac{e}{c_w}\chi Z'_\mu \left(c_w^2 J^\mu_{em} - \frac{M^2_{Z'}}{M^2_{Z'} - M^2_Z} J^\mu_Z \right)$$

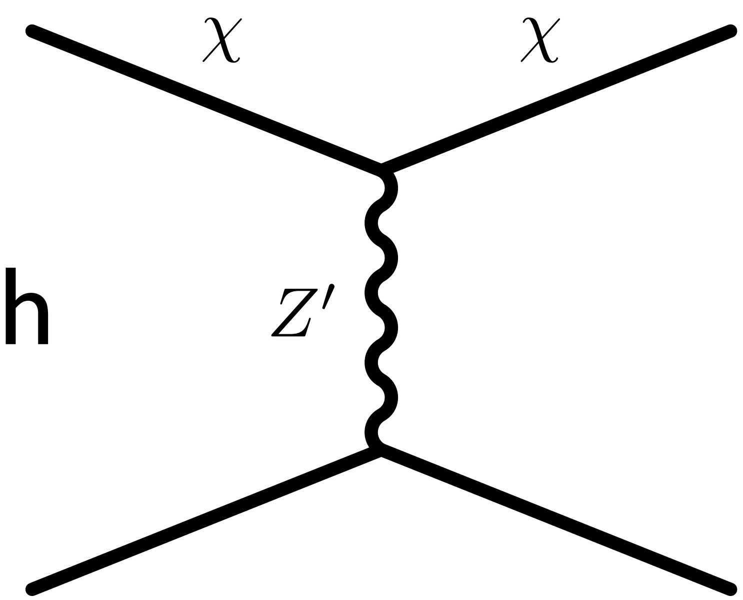
modified SM couplings

$$g'\chi \frac{s_w M^2_{Z'}}{M^2_{Z'} - M^2_Z} J^\mu_{Z'} Z_\mu$$

Can be removed by another pair of Q, non-mixing

(or non-abelian)

Dark Matter



Fewer constraints, large Z' invisible width

$$\sigma \approx \frac{16\pi\alpha_{Z'}^2 \mu_{\chi N}^2 Z_{eff}^2}{M_{Z'}^4} \sin^4\theta$$

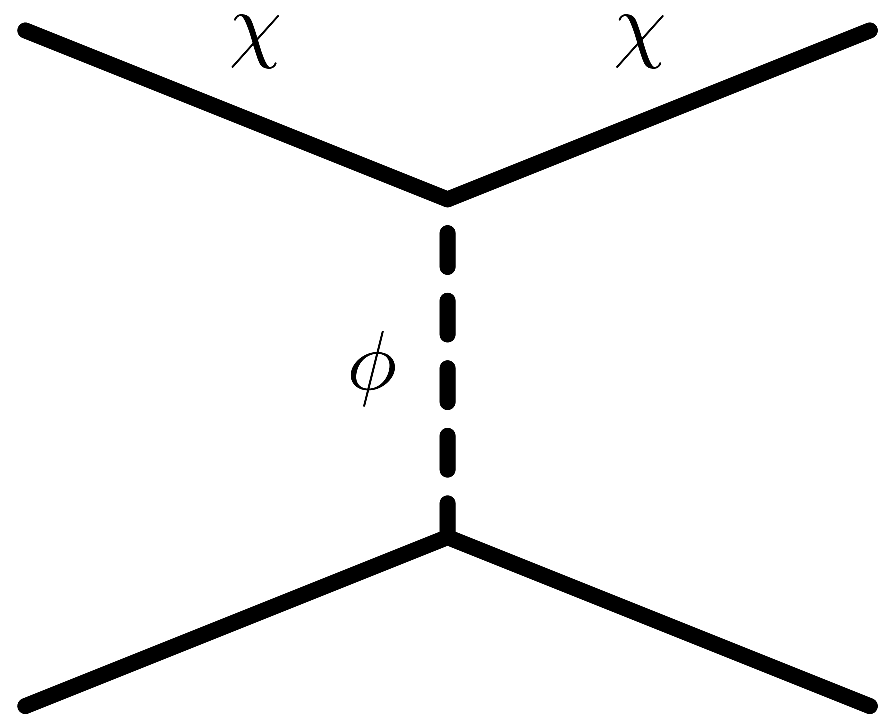
$$\sigma \approx \frac{16\pi\alpha_{Z'}^2 \mu_{\chi N}^2 Z_{eff}^2}{g^4 v^4} \frac{\lambda^4 v^4}{M^4} = \lambda^4 \frac{\mu_{\chi N}^2}{M^4} Z_{eff}^2 \pi.$$

f_p, f_n "free parameters"

$$\bar{p}\left[(2a_u + a_d)\gamma^\mu \frac{(1+\gamma_5)}{2} + 3a_q\gamma^\mu \frac{(1-\gamma_5)}{2}\right] p$$

$$\bar{n}\left[(a_u + 2a_d)\gamma^\mu \frac{(1+\gamma_5)}{2} + 3a_q\gamma^\mu \frac{(1-\gamma_5)}{2}\right] n.$$

Dark Matter



$$\sigma_\phi \approx \frac{\alpha'_{eff} M_W^2}{\alpha_W M_{Z'}^2} \frac{m_h^4}{m_\phi^4} \times \sigma_h$$

Applications

- D0 dimuon asymmetry
- CDF Wjj excess
- CDF top forward-backward asymmetry

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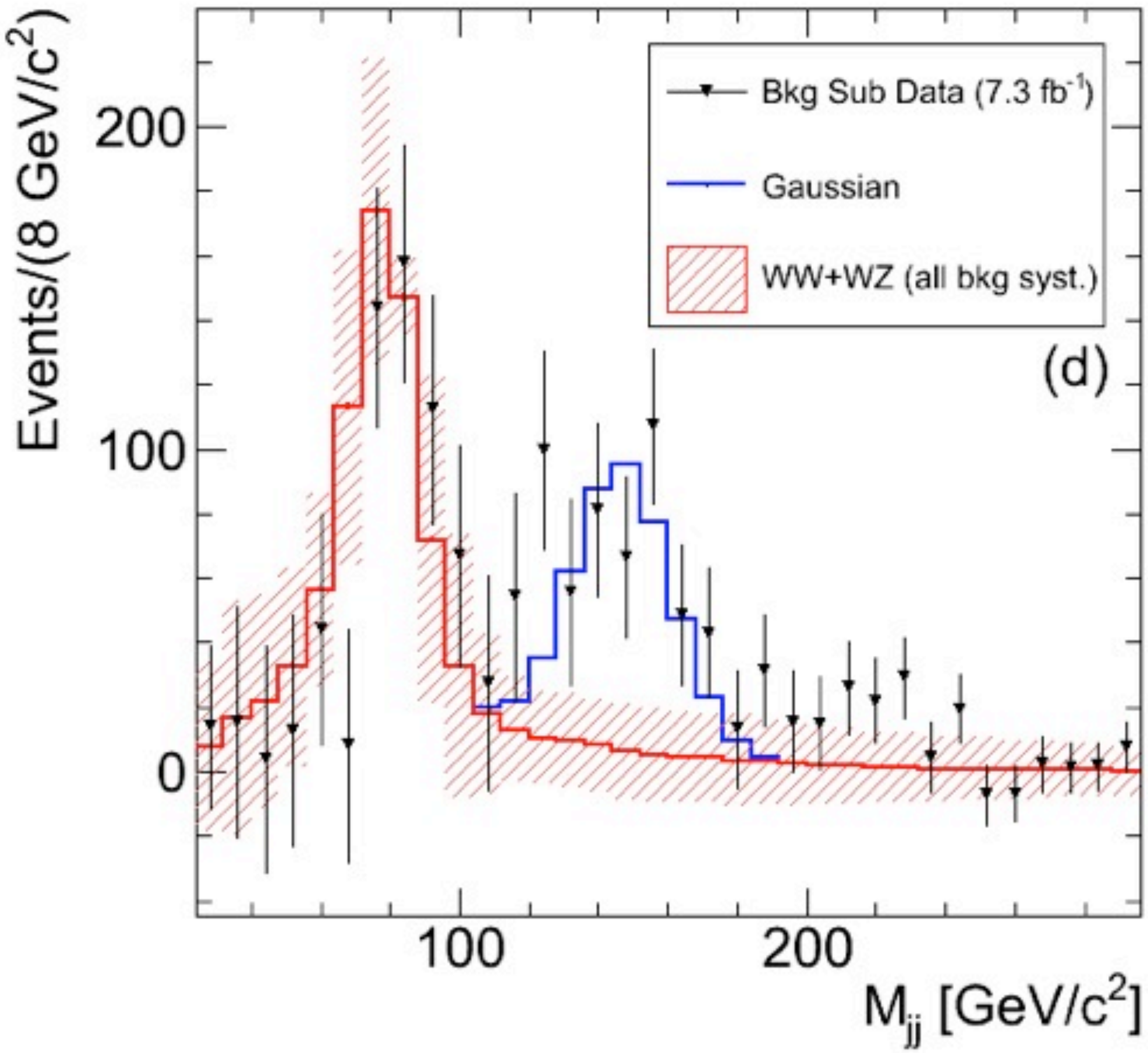
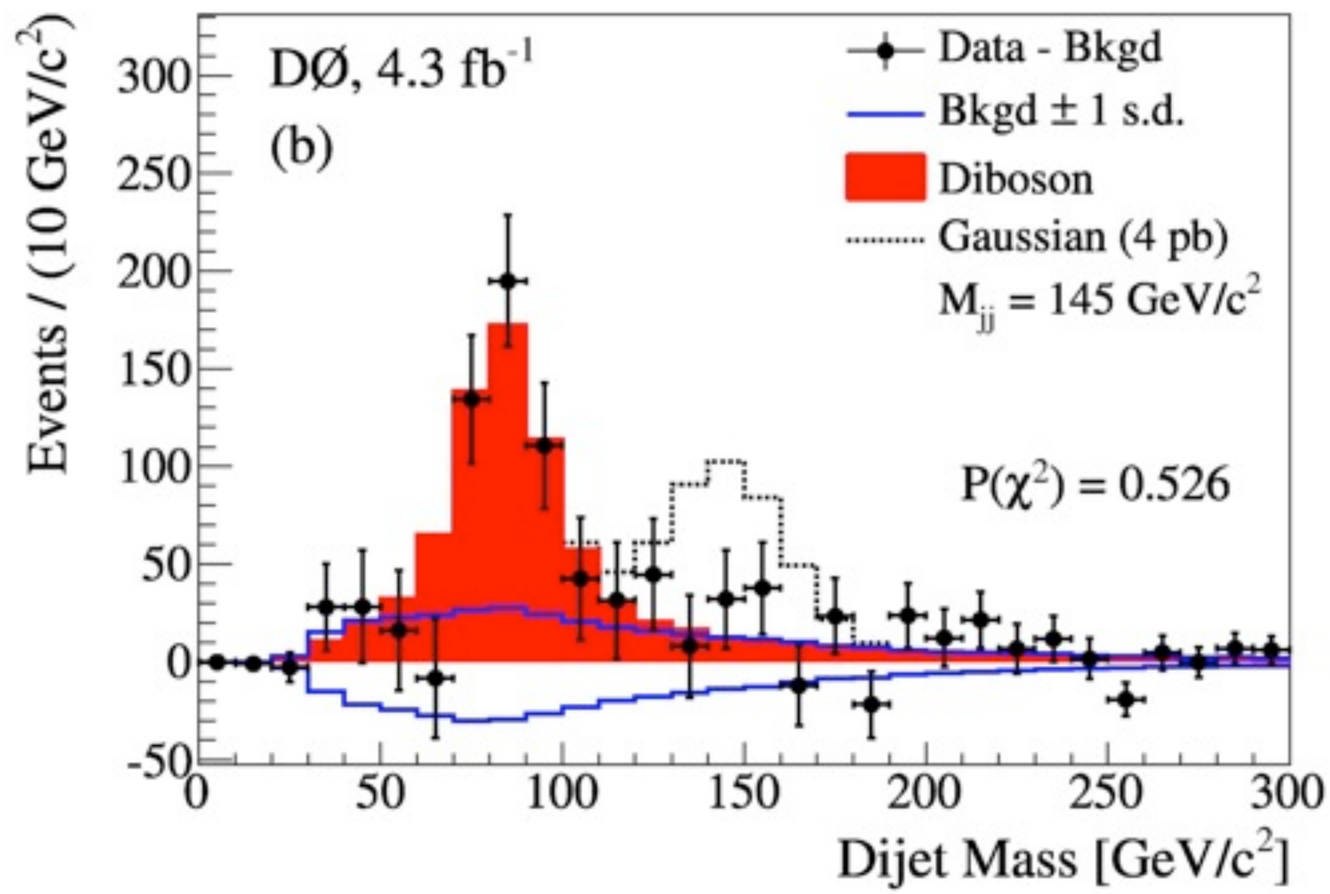
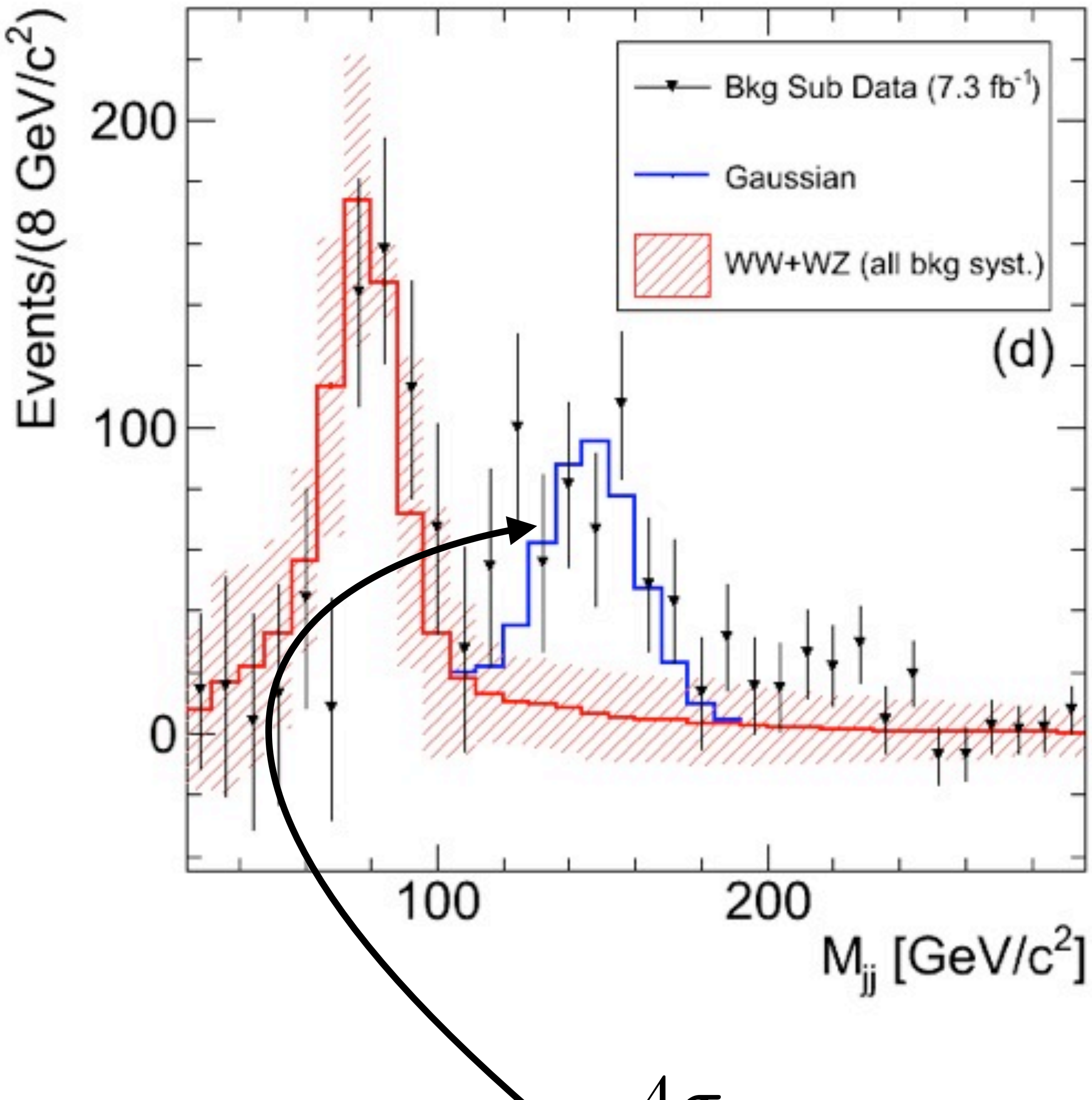
Wjj



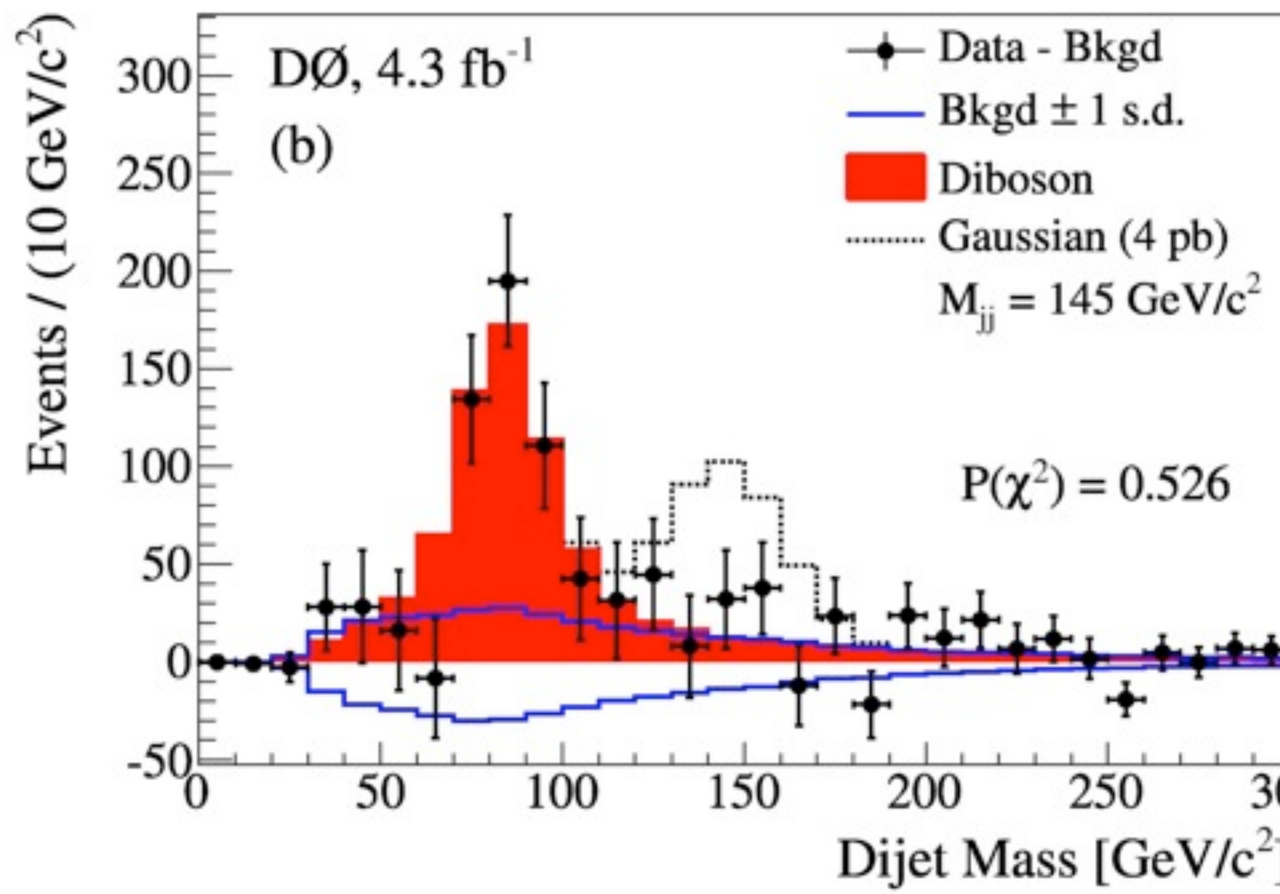


Many proposed explanations: technicolor, Z', RPV SUSY, new scalars, colour octets, octo-triplets,......

Wjj



$\sim 4\sigma$

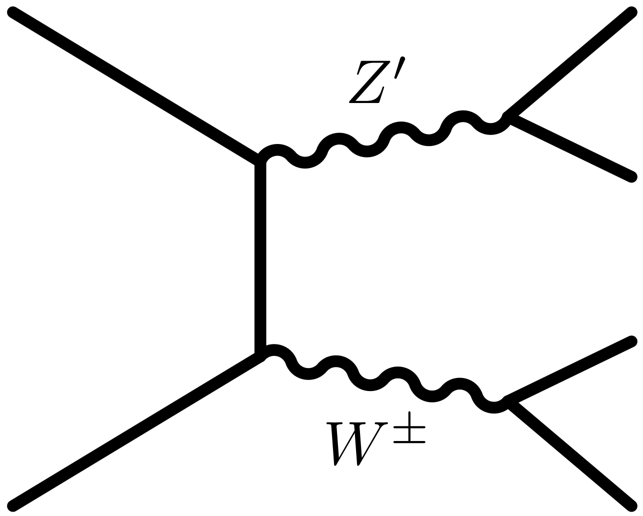


Many proposed explanations: technicolor, Z’, RPV SUSY, new scalars, colour octets, octo-triplets,......

Wjj & effective Z’

$$\frac{c^i_j}{M^2}(\bar{q}_i\gamma^\mu q^j)(\phi^* D_\mu \phi)$$

$$q \to q_L$$



Flavour constraints imply $c^i_j \propto \delta^i_j$

UV model respects flavour SU(3)

$$\mathcal{L} \supset -(\mu Q^c_i Q_i + \lambda Q^c_i q_i \phi)$$

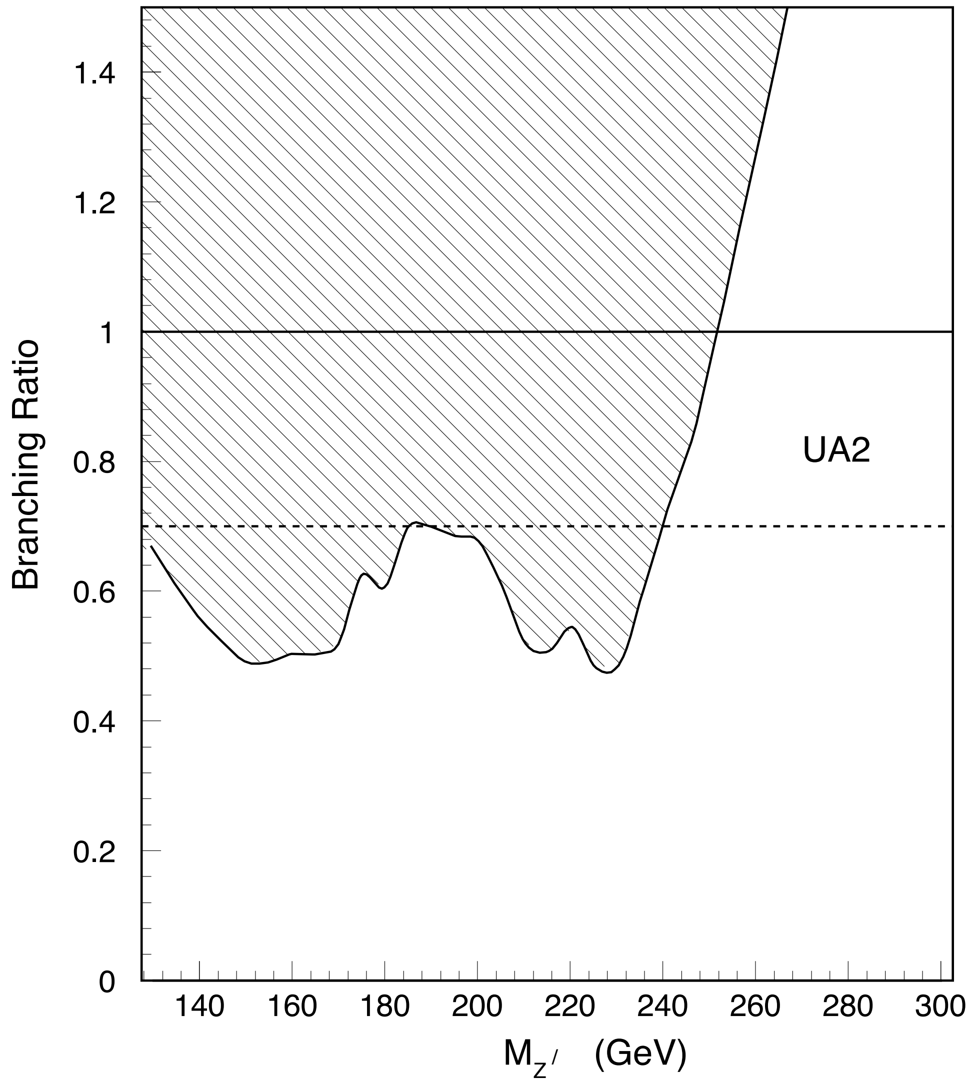
$g_{eff} \ = \ g' \sin^2\theta \ \sim \ 0.37$ for 4 pb x-sec

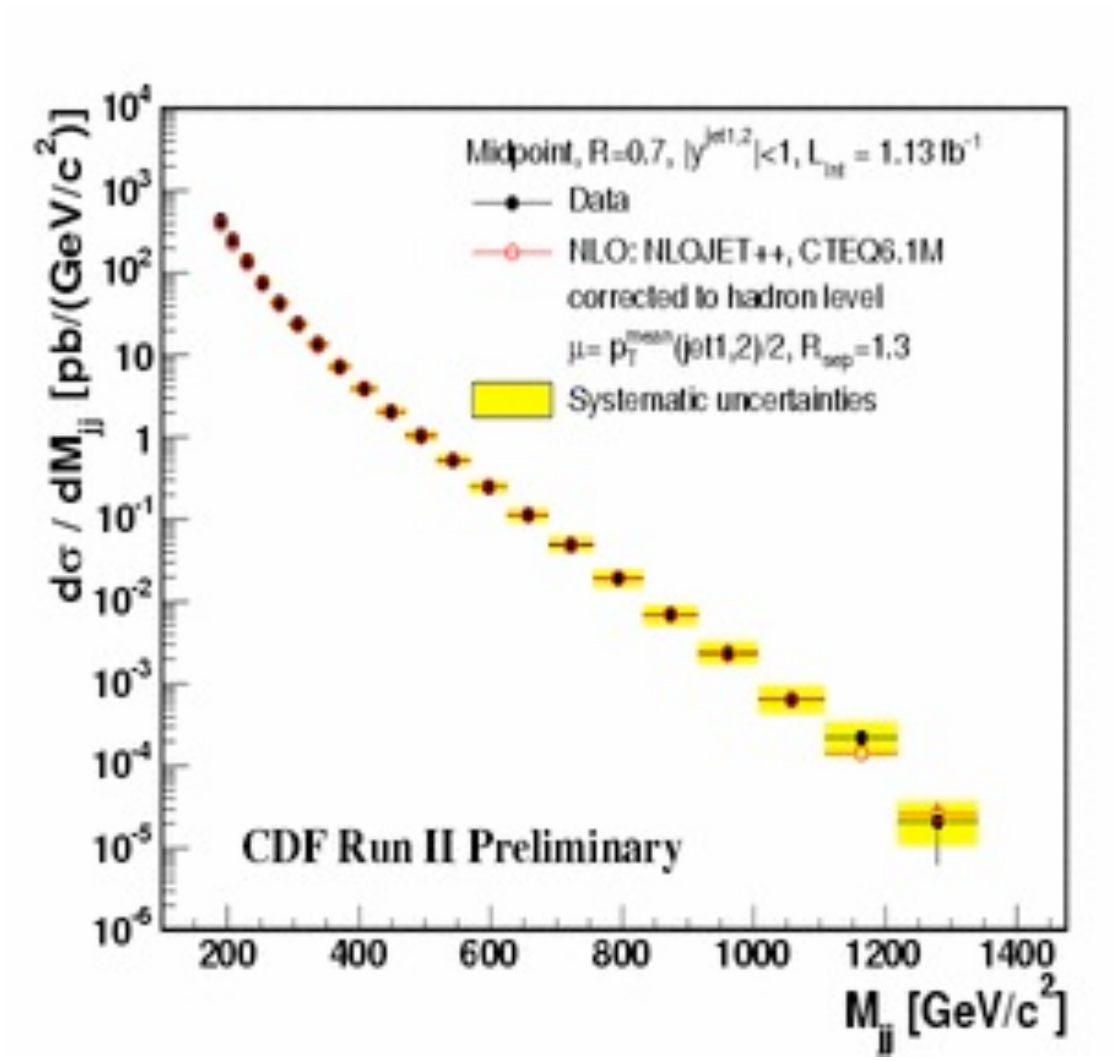
(~2 pb fits)

Wjj & effective Z'

Existing constraints:

- couplings to leptons?
- dijet rate?





Wjj & effective Z'

Existing constraints:

- couplings to leptons?
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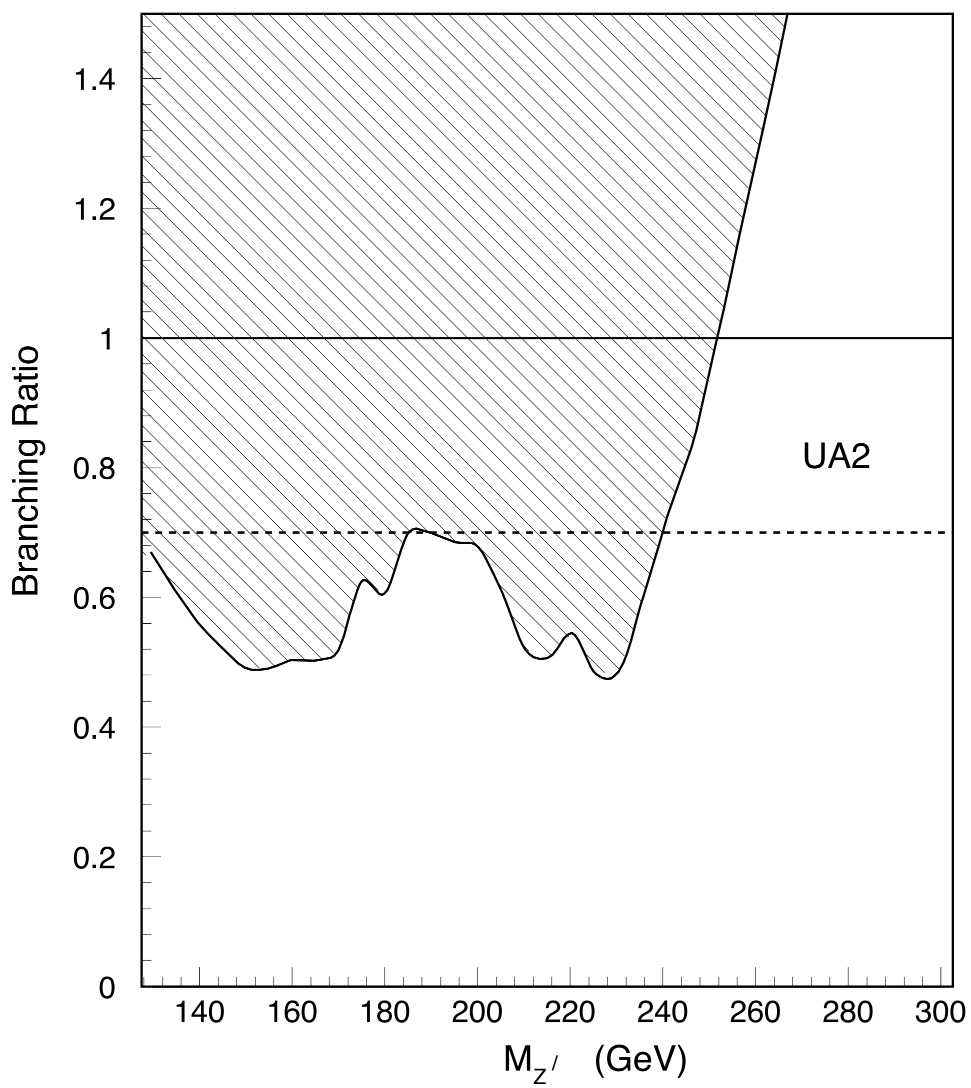
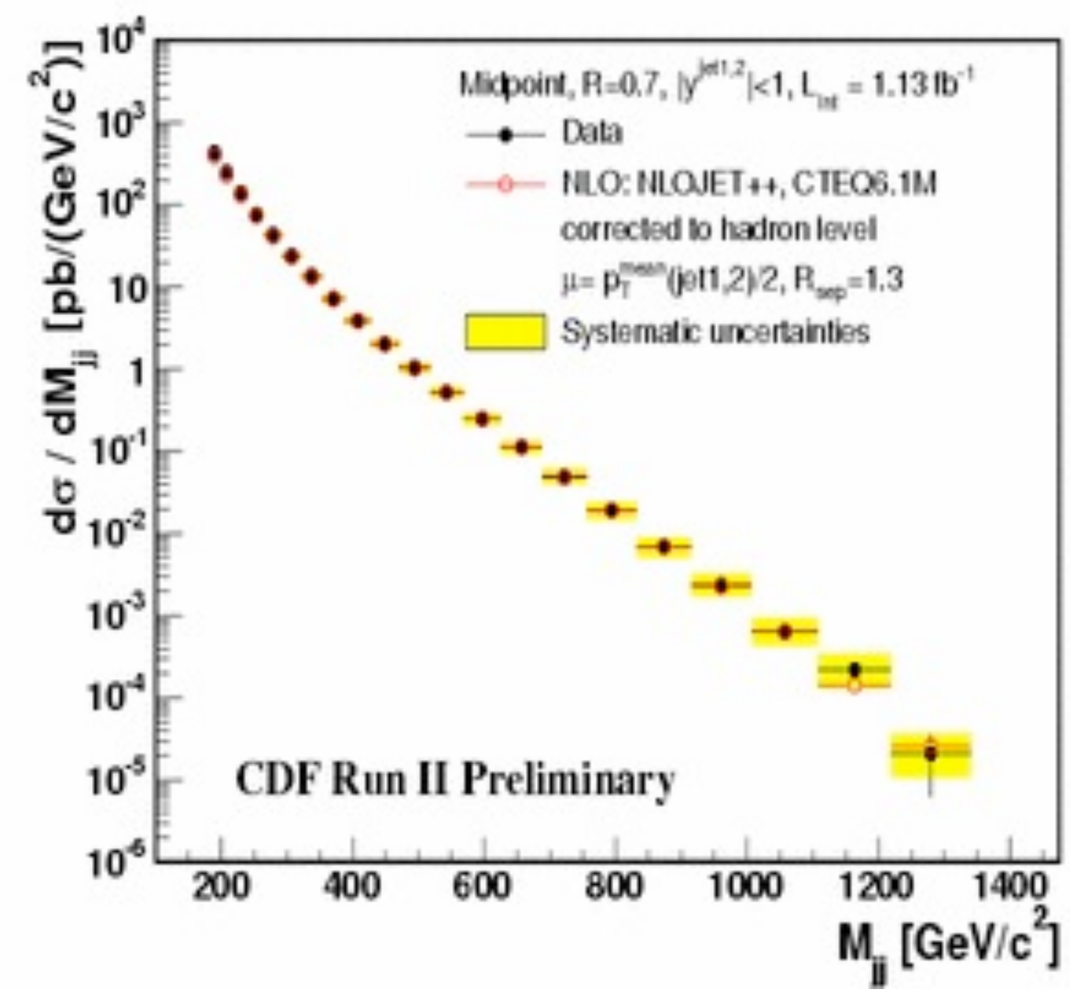
No vectorlike leptons

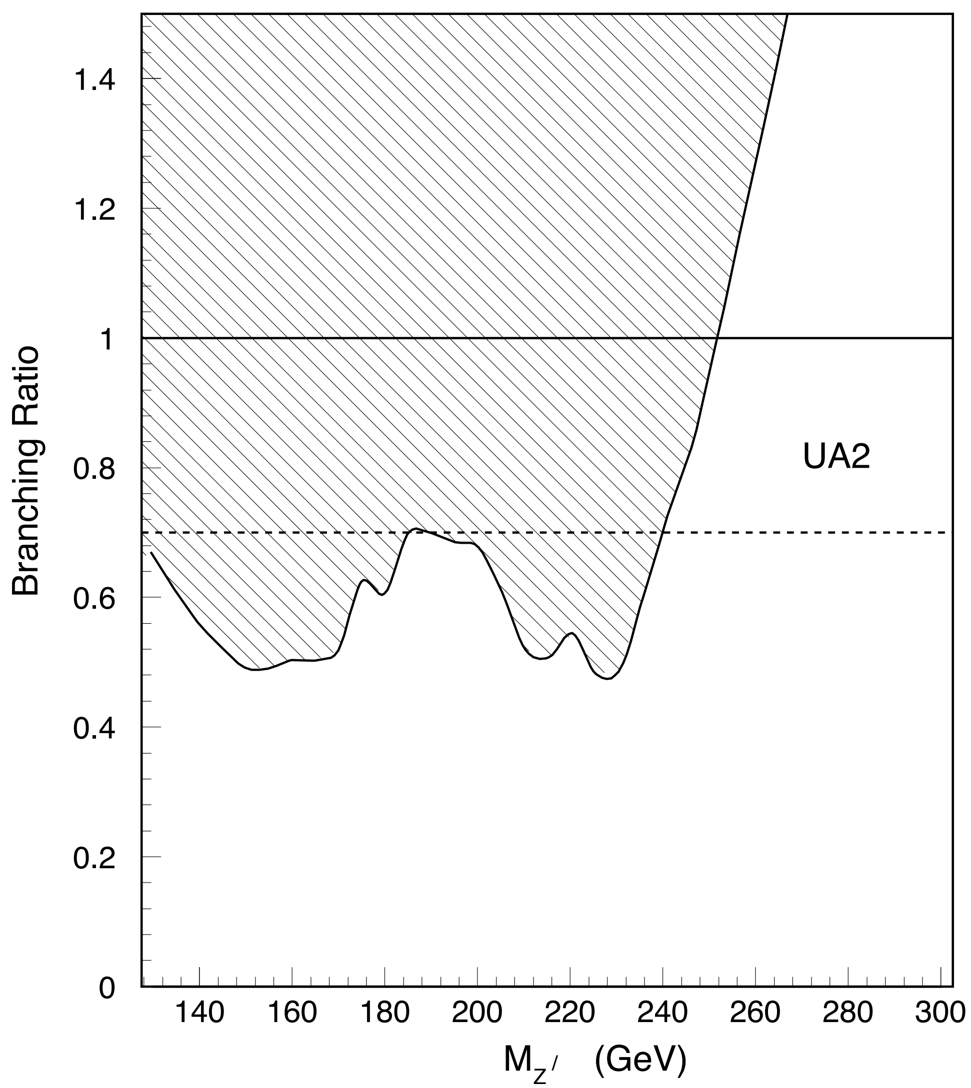


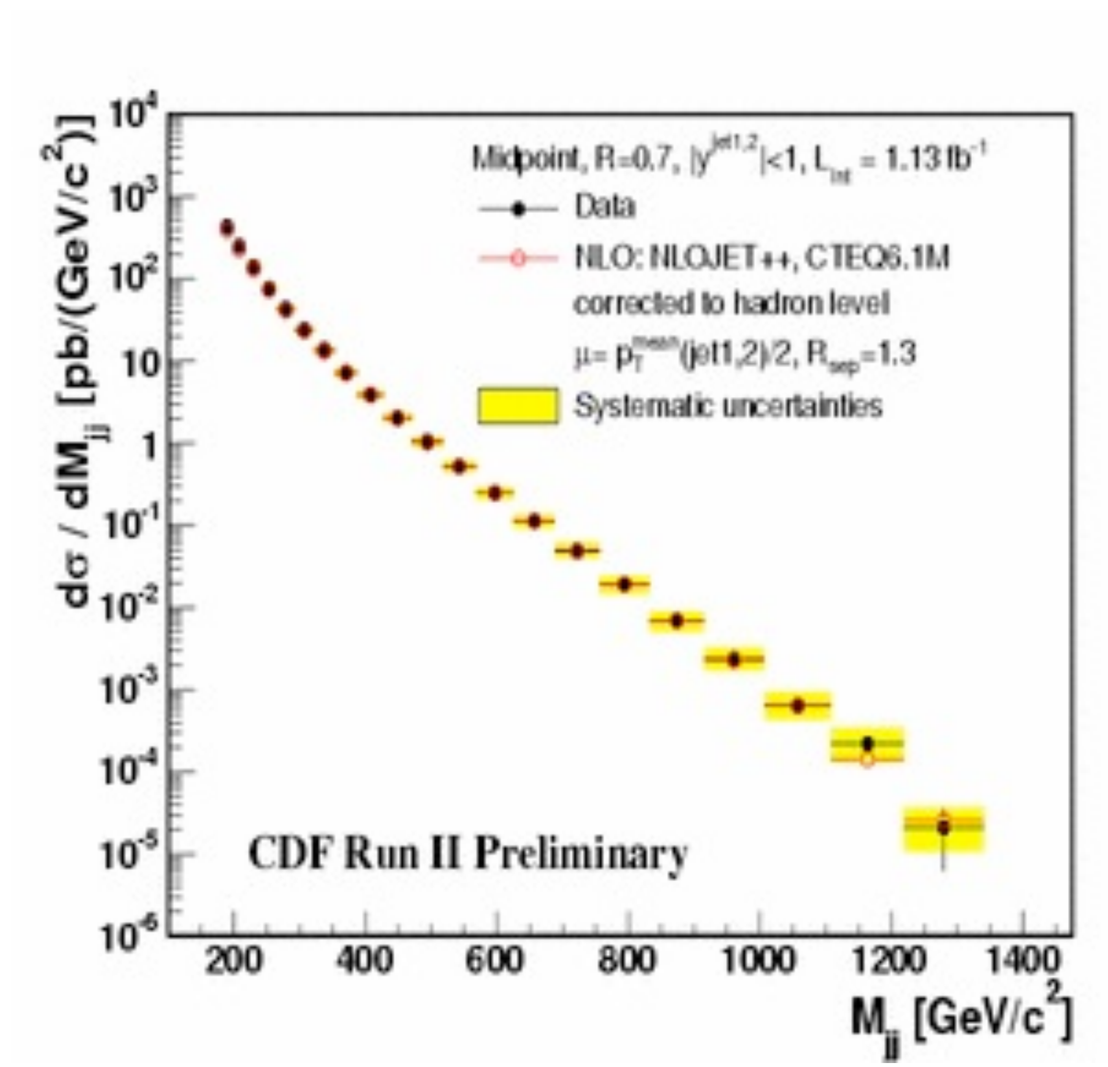


Wjj & effective Z'

Existing constraints:

- couplings to leptons? No vectorlike leptons
- dijet rate? → $g_{eff} \lesssim 0.23$

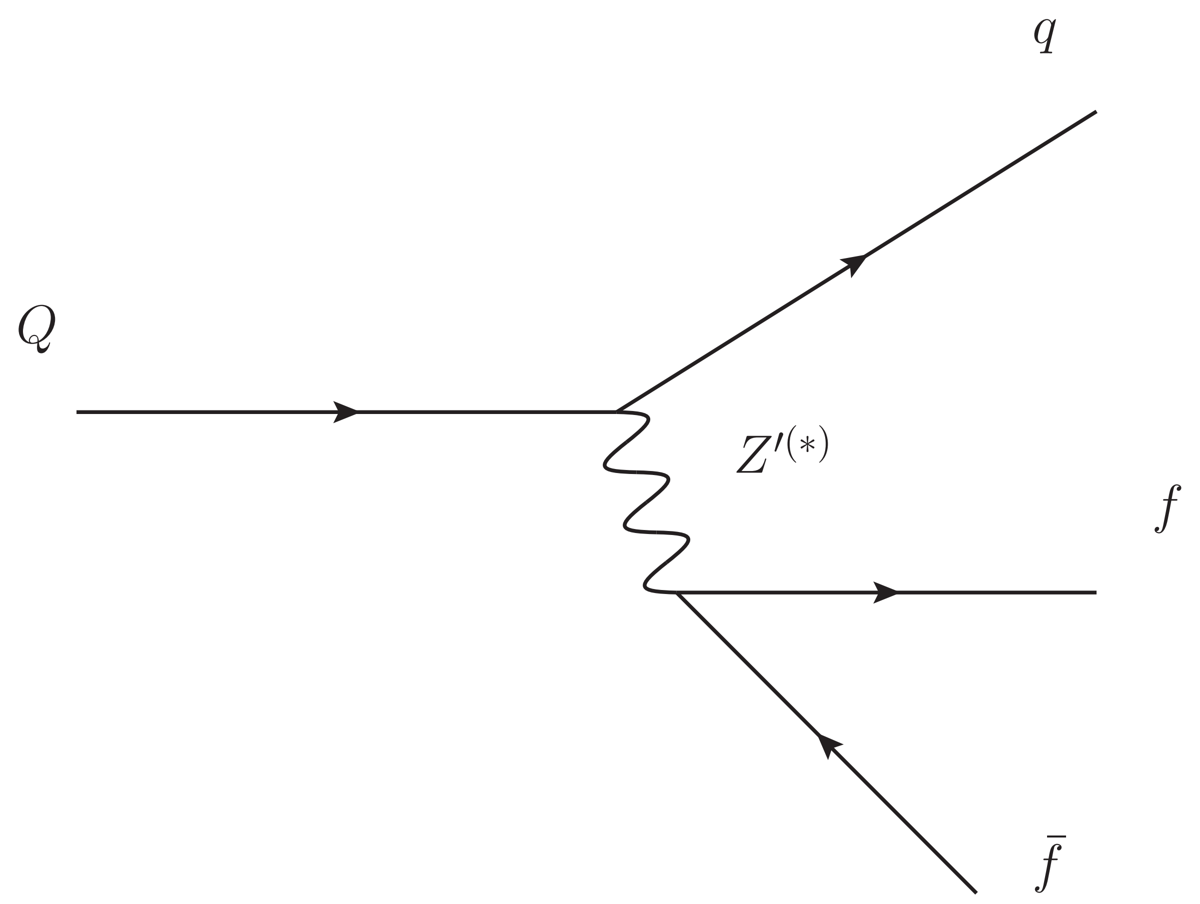




Wjj & effective Z'

Q around the corner?

$$M_{\tilde{Q}} = \frac{\lambda/\sqrt{2}}{g' \sin\theta} M_{Z'} = \frac{\lambda/\sqrt{2}}{\sqrt{g' g_{eff}}} M_{Z'}$$



3 body resonances, potentially with sub-resonances

Conclusions

- Z' very natural extension of SM, but adding one often feels very unnatural
    - removes many nice SM features
    - introduces weird matter content
- Keep nice features of SM, add Z' through effective operators
- UV completion is simple, vectorlike matter in SM reps. mixes with SM states
- Tree-level couplings determined by vectorlike content
- New states to see at colliders