The CDF Dijet Excess & Weak Triplet, Color Octet Scalars

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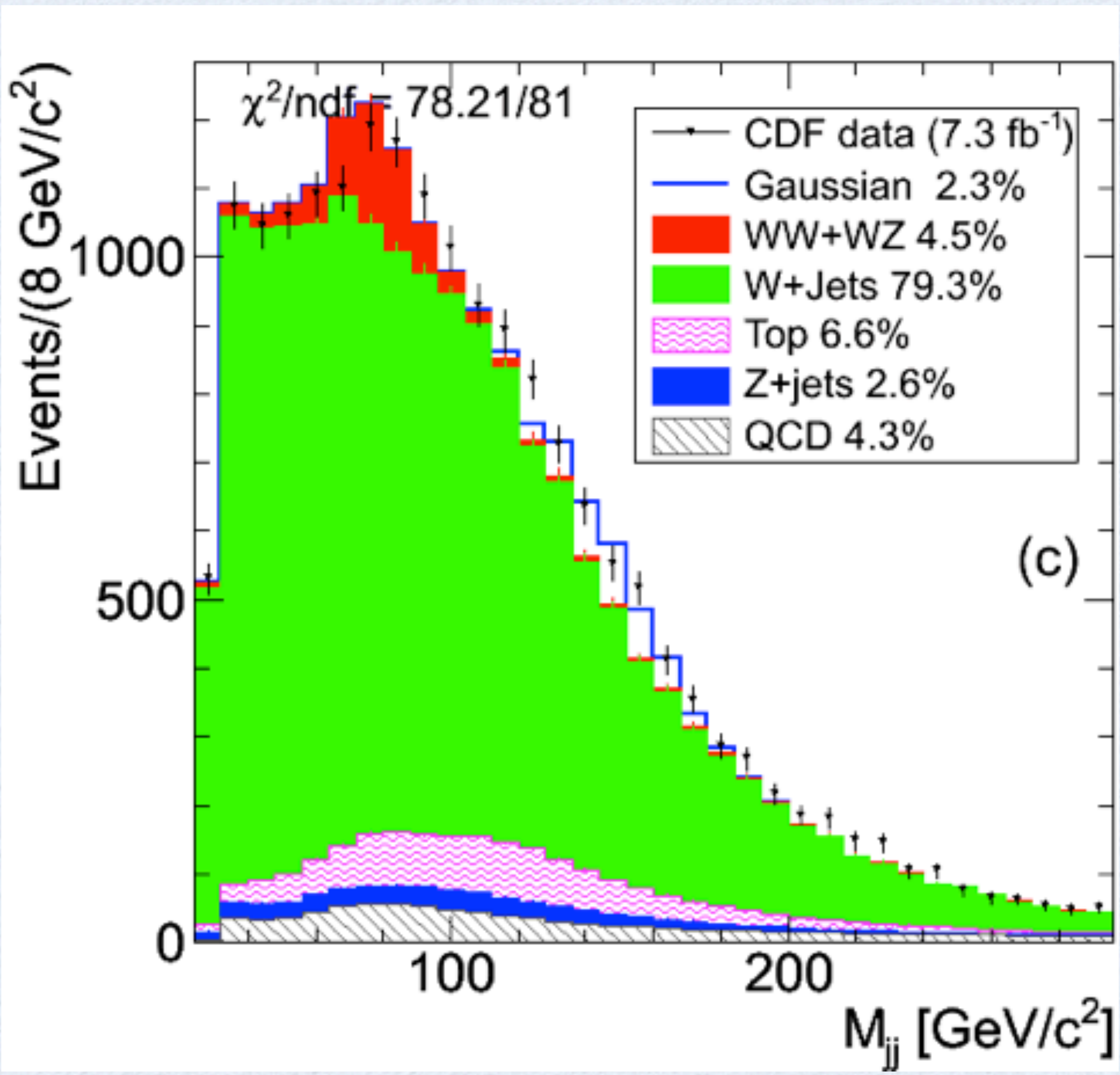
Preview

- CDF/D0 Wjj Results
- Generic W.T.C.O.S
- Extended Model(s)
- Fitting Wjj data
- Resonant Production
- B-Meson Mixing
- Concluding Remarks

CDF Sees a Bump!



- Originally a measurement of WW/WZ production (one leptonic, one hadronic decay)
- Search requires :

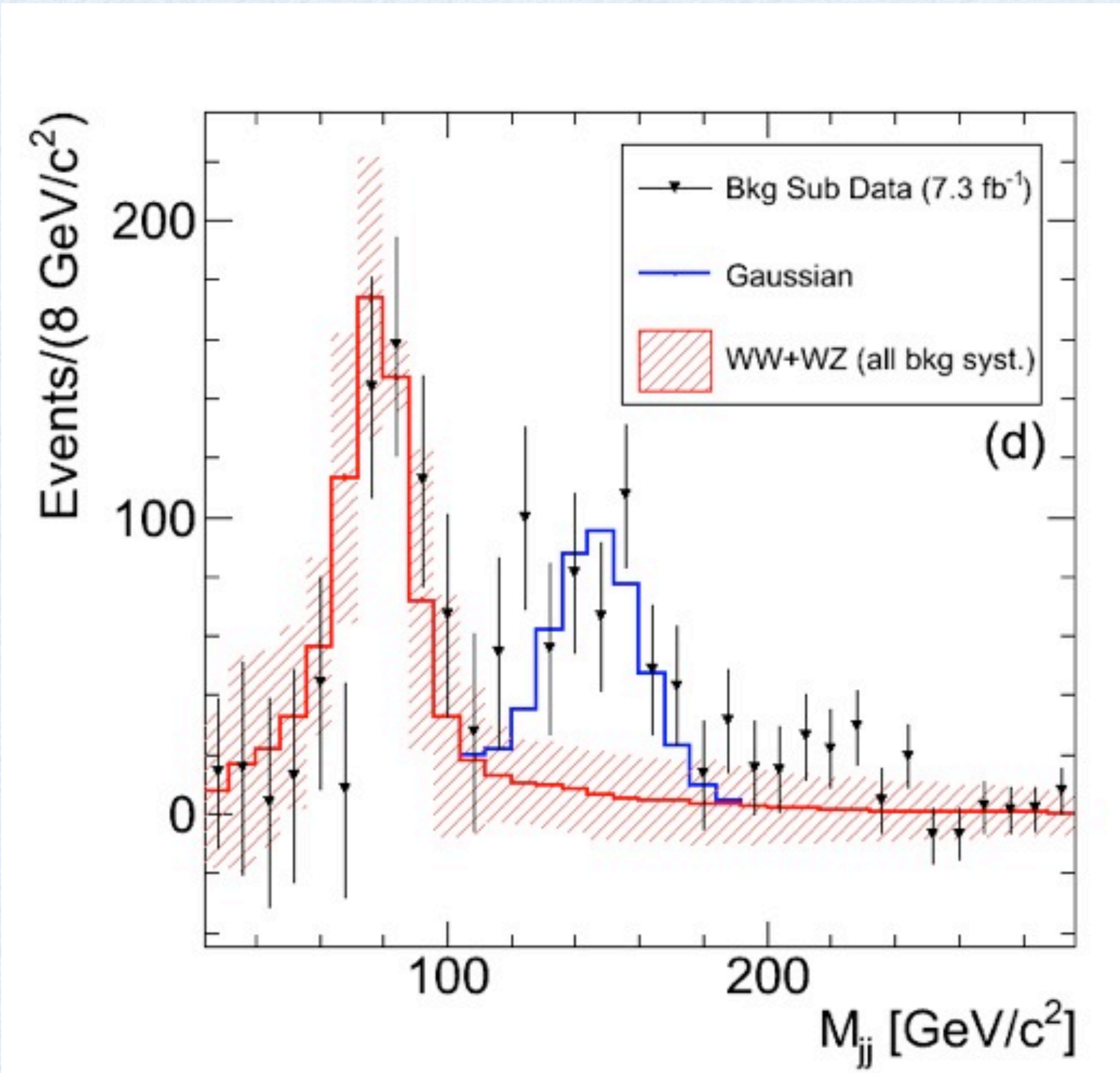
  One leptonically decaying W (Isolated lepton + missing ET)

  Exactly 2 jets PT > 30 GeV

  PT of dijet system > 40 GeV

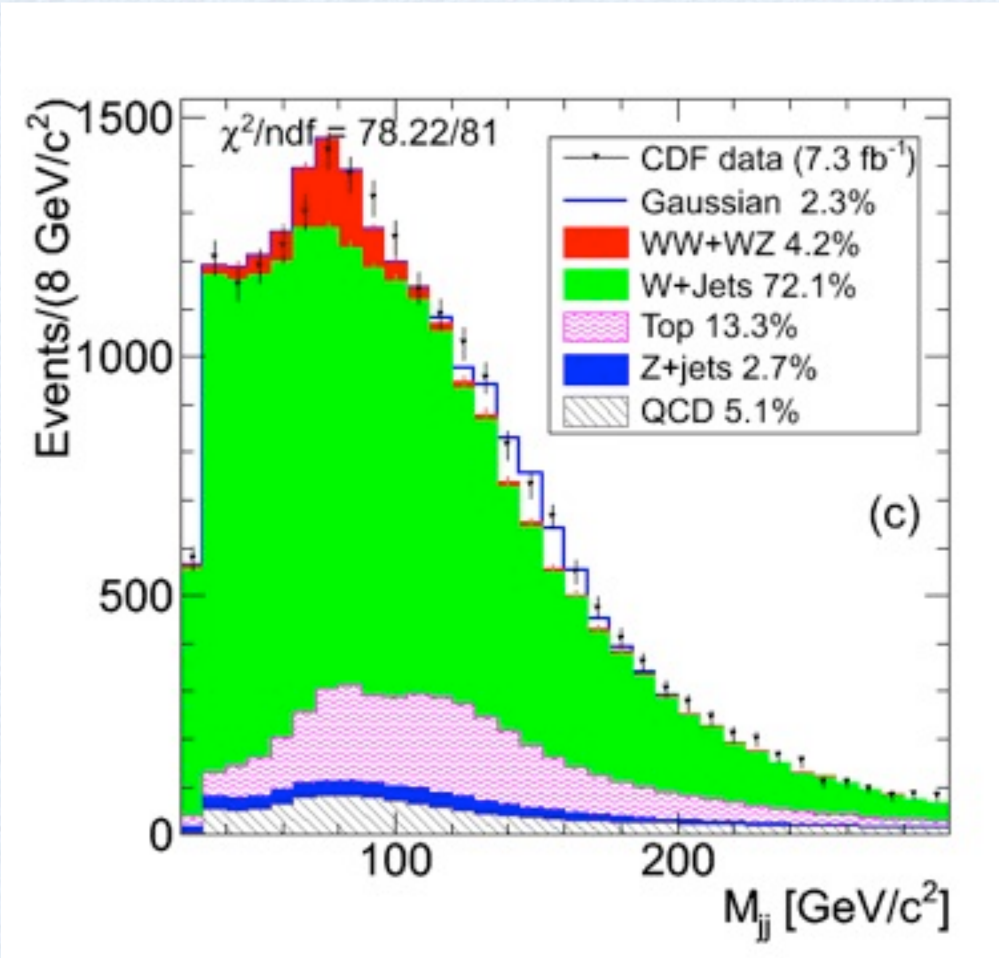
- Initial publication (4.3/fb) claims > 3σ deviation from SM background

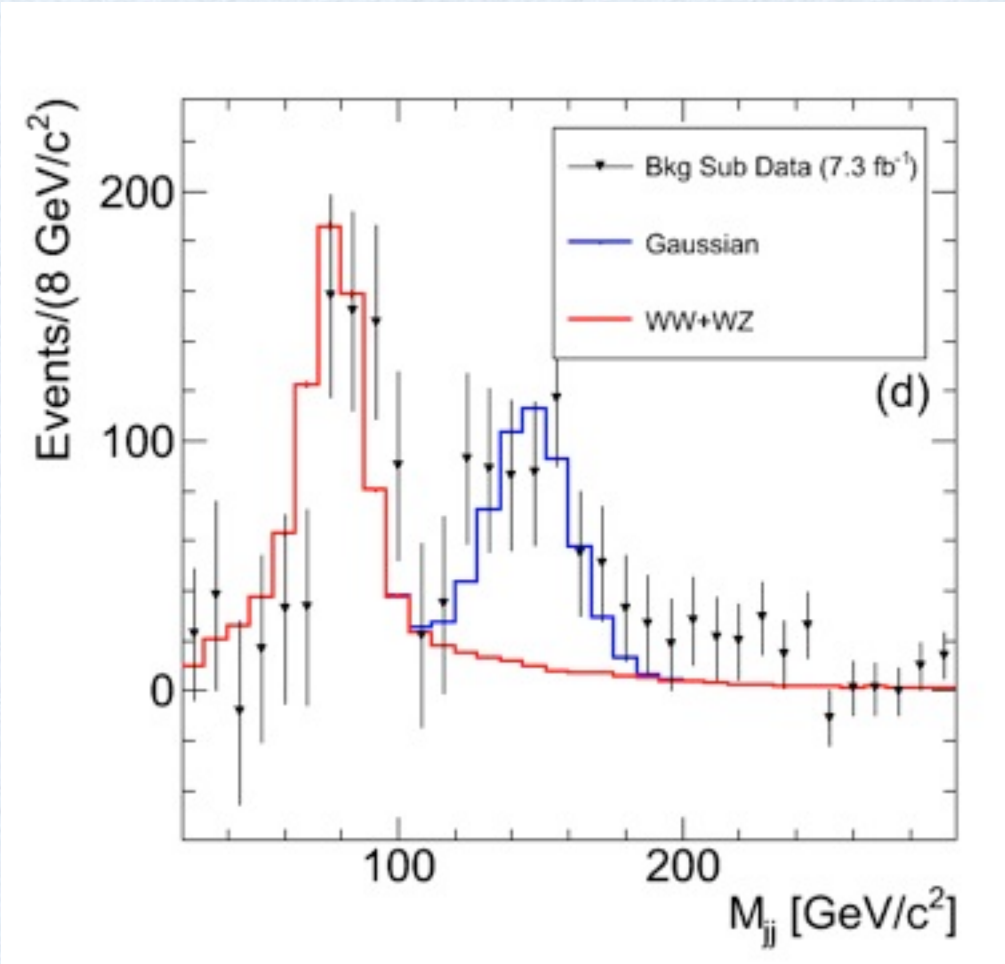
CDF Sees a Bump!



- Updated 7.3 / fb analysis finds a 4.1 σ deviation from SM
- Observes large excess near $M_{jj} \approx$ 150 GeV with ~ 400 events
- Background (except diboson peak) normalized assuming gaussian signal present
- Good fit with σ x Br ≈ 4 pb and a central value near Mjj ≈ 150 GeV
- Interesting tail in high Mjj region

Inclusive (2+ jet) Distributions



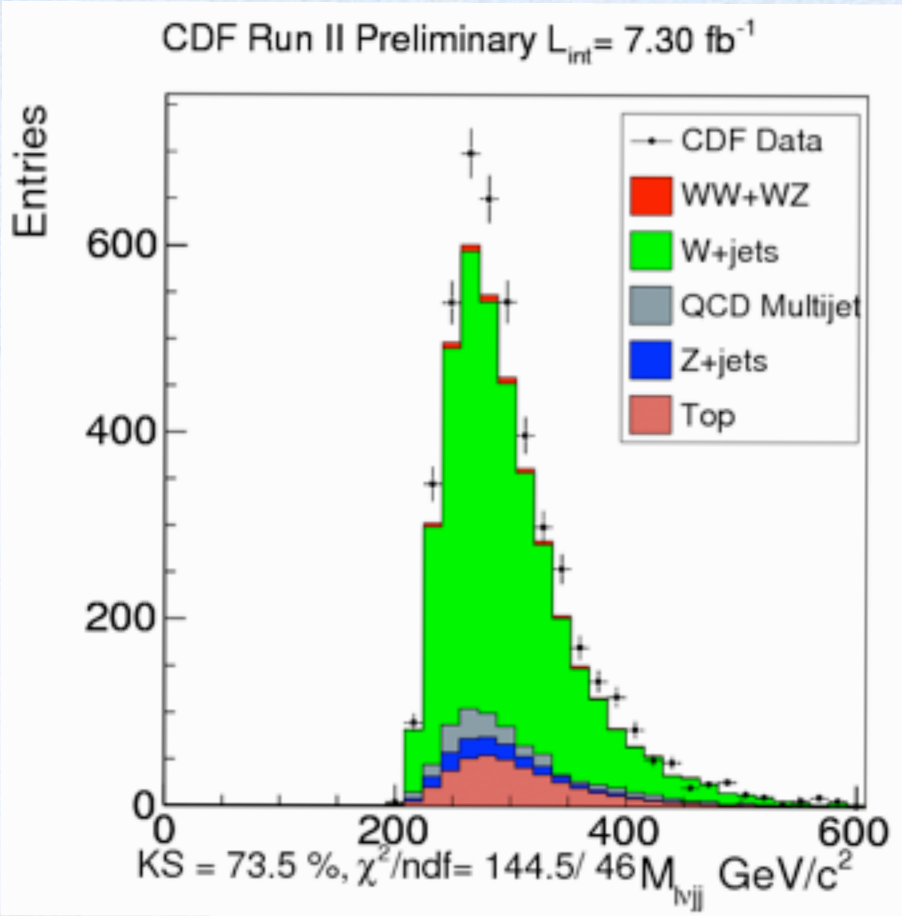


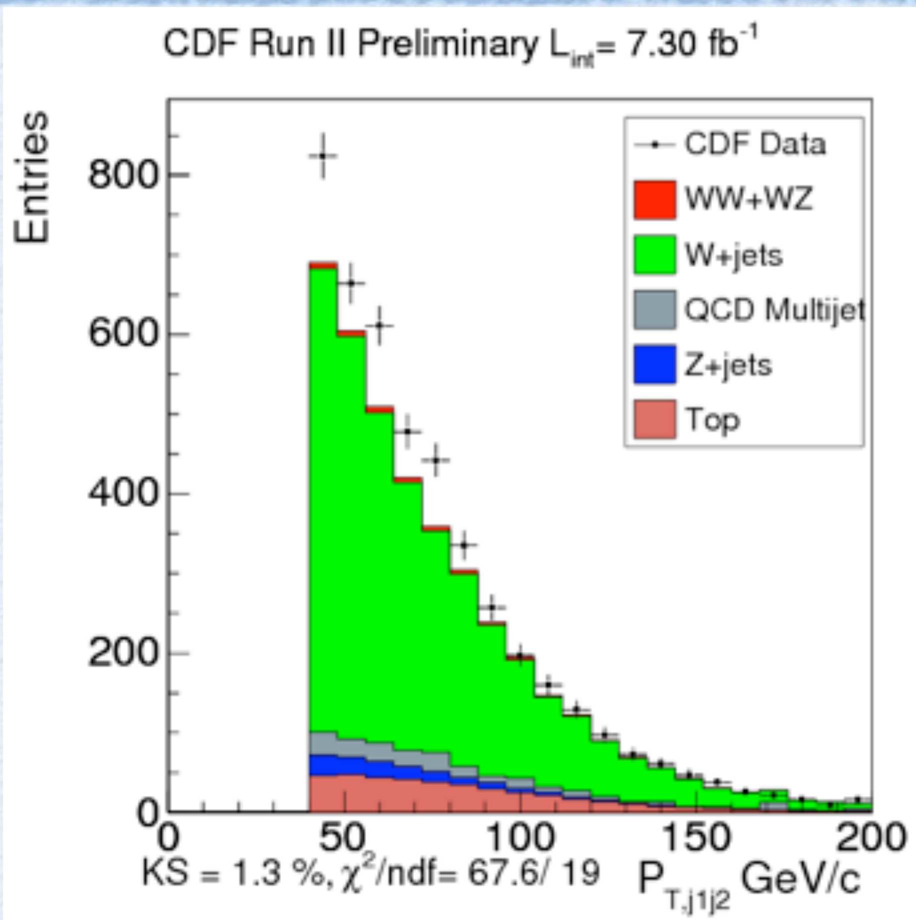
Excesses grows to 4.8 σ, almost certainly not statistical fluke

Background better modeled without vetoing 3+ jet events

Similar increases in statistical significance (V. Cavaliere, CDF Thesis, 2010) when cuts are varied.

Suggestive Kinematics

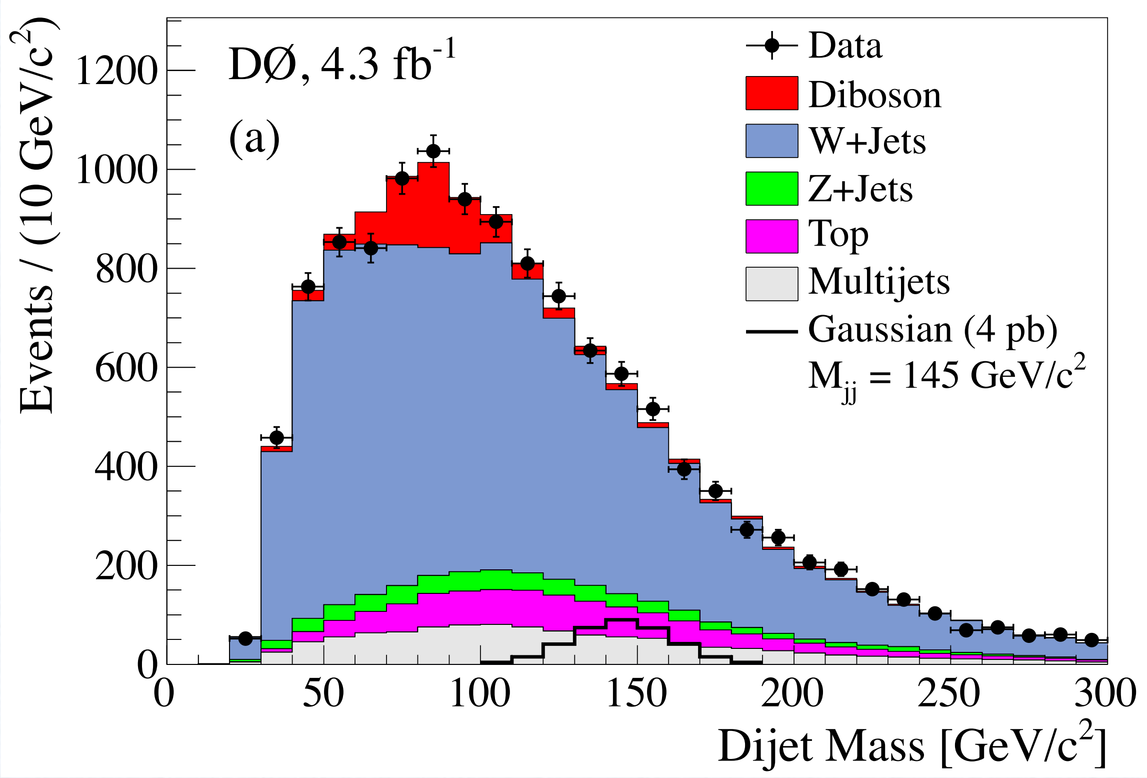


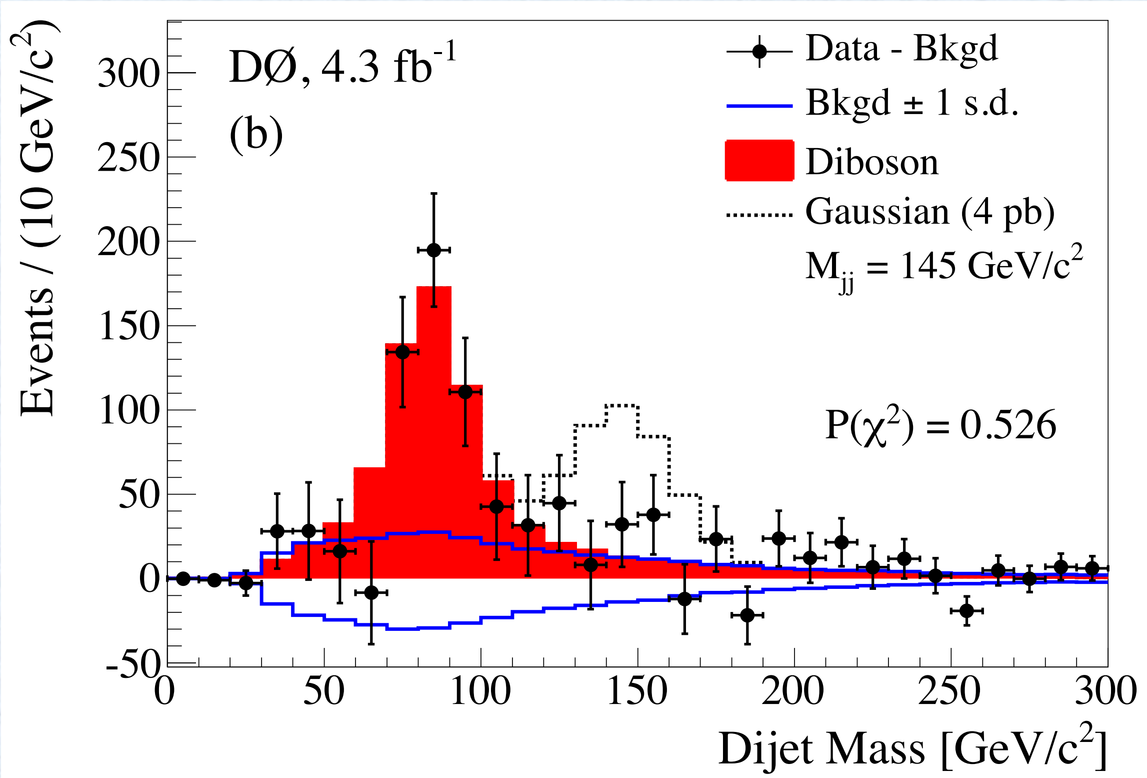


- **Data from inside signal window (115 GeV < Mjj < 175 GeV)**
- **Total mass (Mlvjj) looks highly resonant**
  pp -> X -> W + 2j with Mlvjj = Mx
- **Dijet system (PTjj) shows consistent excess**
- **Similar results for many other distributions -- no excesses in sidebands**

DO Sees "Nothing"

Complimentary Measurement





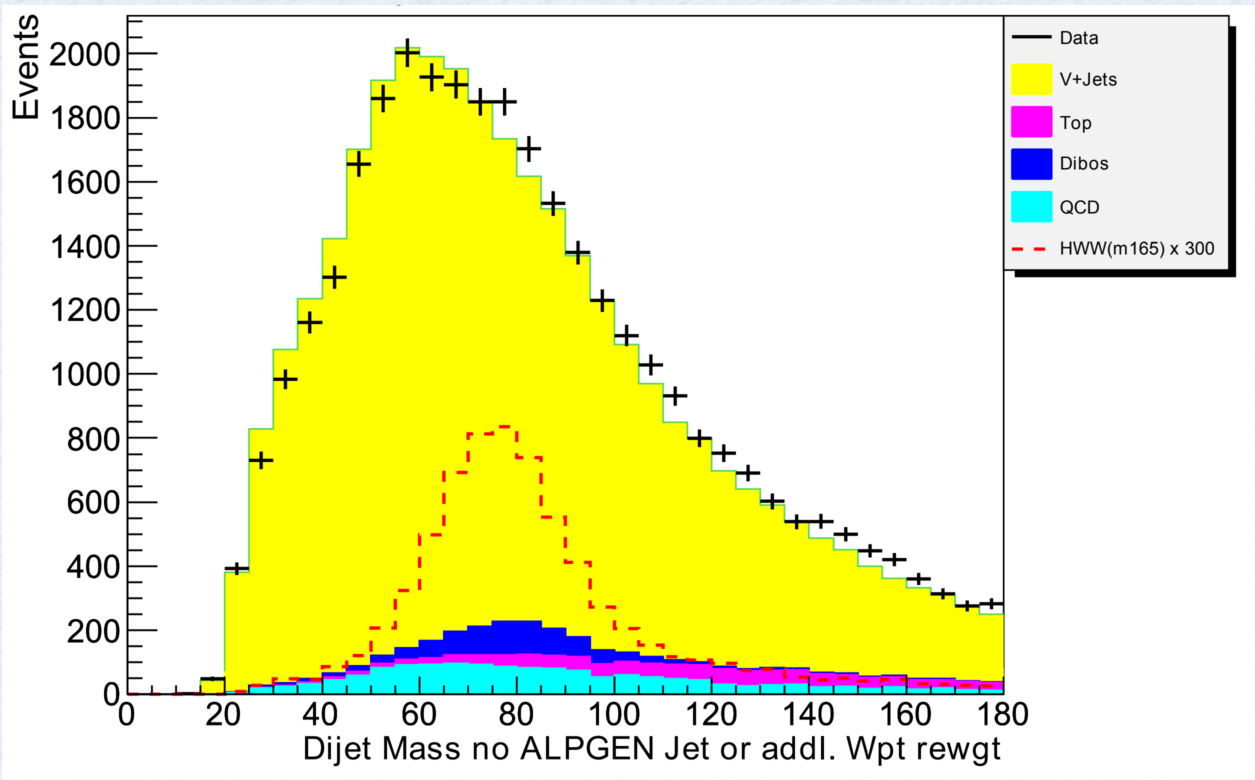
D0 imposes the same cuts and sees only a modest ~ 1.5σ excess near 150 GeV

Claims to rule out CDF's (4pb) gaussian signal with p-value 8x10^-6

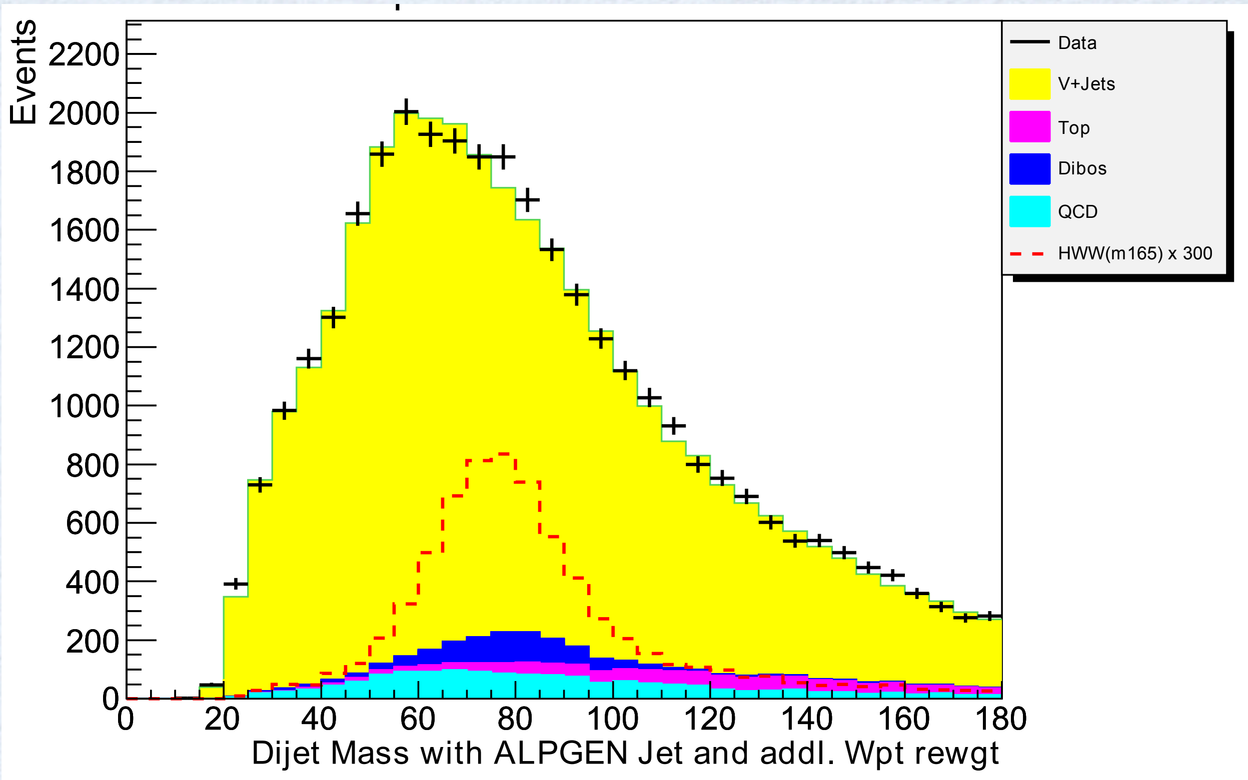
Claims to rule out smaller (1.9 pb) signal at 95% confidence

Both claims assume SM Higgs acceptances

However,



unreweighted



reweighted

Comparable Higgs analysis (S. Zellich, D0 thesis, 2010) suggests similar excess in unreweigted sample, but then goes away

Analysis based on 5.4/fb of data

No comment on possible excess

Controversy

- CDF data consistently suggest a new physics.
- D0 jet definition $\Delta R < 0.5$ ==> may veto some signals (CDF: $\Delta R < 0.4$)
- D0 corrects out-of-cone radiation ==> more high-energy jets, more likely to veto events (Buckley, Hooper, Kopp, Martin, Neil hep-ph/1107.5799)
- How does D0 signal change with different cuts? CDF's significance varies considerably.
- Will we see full ~ 10/fb D0 analysis? Inclusive?
- Task Force and/or LHC will ultimately settle discrepancy
- Our strategy: Interpret CDF signal as new physics




OCTO-TRIPLETS

$$\Theta^{a\alpha} : (8, 3, 0)$$

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$




Most General Renormalizable Lagrangian

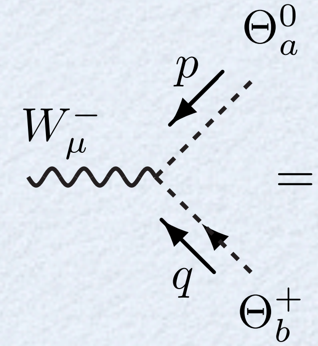
$$\mathcal{L}_\Theta = \frac{1}{2} D^\mu \Theta^{a\alpha} D_\mu \Theta^{a\alpha} - \frac{1}{2} M_\Theta^2 \Theta^{a\alpha}\Theta^{a\alpha} - V(\Theta, H)$$

$$D_\mu \Theta^{a\alpha} = \partial_\mu \Theta^{a\alpha} + g_s f^{abc} G_\mu^b \Theta^{c\alpha} + + g\epsilon^{\alpha\beta\gamma} W_\mu^\beta \Theta^{a\gamma}$$

Charge Eigenstates : $\Theta^{a\pm} \equiv \frac{1}{\sqrt{2}}(\Theta^{a1} \mp i\Theta^{a2})$ $\quad \Theta^{a0} \equiv \Theta^{a3}$

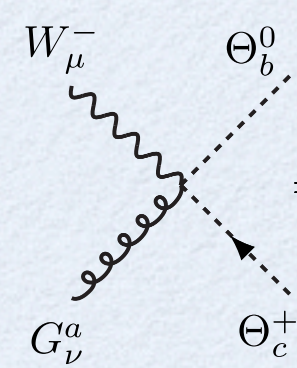
(Some) Gauge Interactions :

$$-igW_\mu^- \left[(\partial_\mu \Theta^{a+})\Theta^{a0} - \Theta^{a+}\partial_\mu\Theta^{a0}\right]$$



$= ig\,\delta^{ab}(p-q)_\mu$

$$2igg_s f^{abc} G^{\mu a}\left(W_\mu^+ \Theta^{b-} - W_\mu^- \Theta^{b+}\right)\Theta^{c0}$$



$= -2g_s g f^{abc} g_{\mu\nu}$

Similar couplings to (WW), (ZZ), (Zg), (gg), (γγ)...

Octo-triplet Masses

Mass term gets "democratic"
SM Higgs correction

$$-\frac{1}{2}\left(M_\Theta^2 - \lambda_H H^\dagger H\right)\Theta^{a\alpha}\Theta^{a\alpha}$$

Other Higgs bilinears are equivalent to above or vanish.

$$(H^\dagger \sigma^\alpha \sigma^\beta H)\Theta^{a\alpha}\Theta^{a\beta}$$

All Θs get same positive mass. Must not acquire VEV to preserve SU(3)c.

$$M_\Theta \to \sqrt{M_\Theta^2 - \lambda_H v_H^2}$$

Small O(100MeV) charged/neutral mass splitting from EW loops

$$\delta M \equiv M_{\Theta^+} - M_{\Theta^0} \simeq \frac{1-\cos\theta_W}{2\sin^2\theta_W}\alpha M_W$$

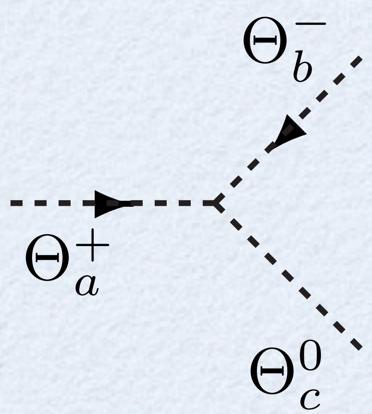
Scalar Potential

$$V(\Theta) \supset \mu_\Theta f^{abc} \epsilon^{\alpha\beta\gamma} \Theta^{a\alpha} \Theta^{b\beta} \Theta^{c\gamma} - \lambda_\Theta \left(\Theta^{a\alpha}\Theta^{a\alpha}\right)^2 + \cdots$$

Other quartics also allowed, but not important for us.

Without cubic term, all scalars are stable -- all operators feature pairwise couplings.

Generic to all nonzero hypercharge assignments .



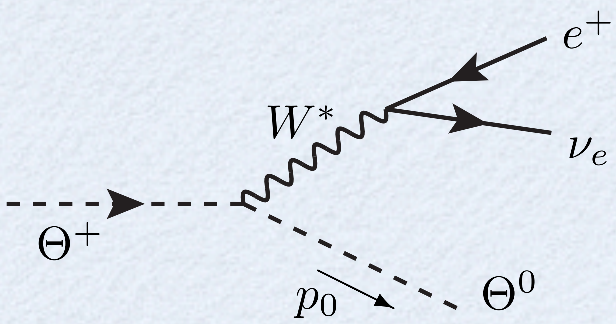
$$= 2\mu_\Theta f^{abc}$$

In charge eigenbasis cubic term is

$$2i\mu_\Theta f^{abc} \Theta^{a+} \Theta^{b-} \Theta^{c0}$$

Charged Decays

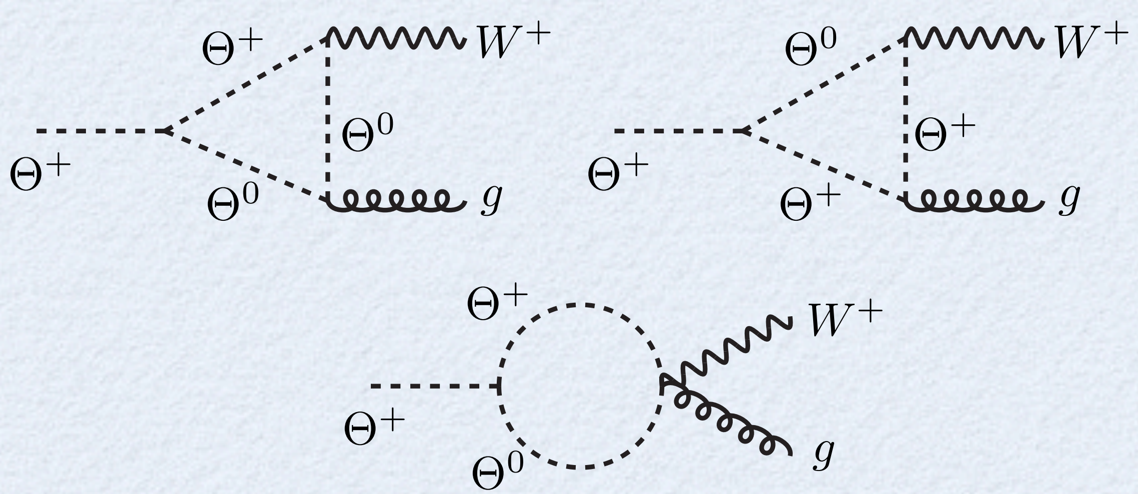
Extremely tiny tree-level width



$$\Gamma\left(\Theta^{\pm}\to\Theta^0 e^{\pm}\nu\right) \simeq \frac{\alpha^2}{15\pi\sin^4\theta_W}\frac{(\delta M)^5}{M_W^4} = 1.6\times 10^{-16}\,\mathrm{GeV}$$

Loop decays easily dominate for nonzero cubic term

$$\Gamma\left(\Theta^{\pm}\to W^{\pm}g\right) \simeq \frac{\alpha\alpha_s\mu_\Theta^2}{\pi^3\sin^2\theta_W M_\Theta} f(M_W/M_\Theta) \sim 10^{-7}\frac{\mu_\Theta^2}{M_\Theta}$$



Similar diagrams for Neutral scalar decay
(replace W --> Z,γ)

Dijet decays forbidden by gauge invariance
(even at one-loop)

Accidental Suppression

Function "f" arises from integration over Feynman parameters First define:

$$\mathcal{C} = \int_0^1 dx \int_0^{1-x} dy \, \frac{-3(1-R^2)\, xy}{1 - xy - R^2\, x\,(1-x-y)} \qquad R \equiv M_V / M_\Theta$$

Computing the width diagrams and expanding in R gives

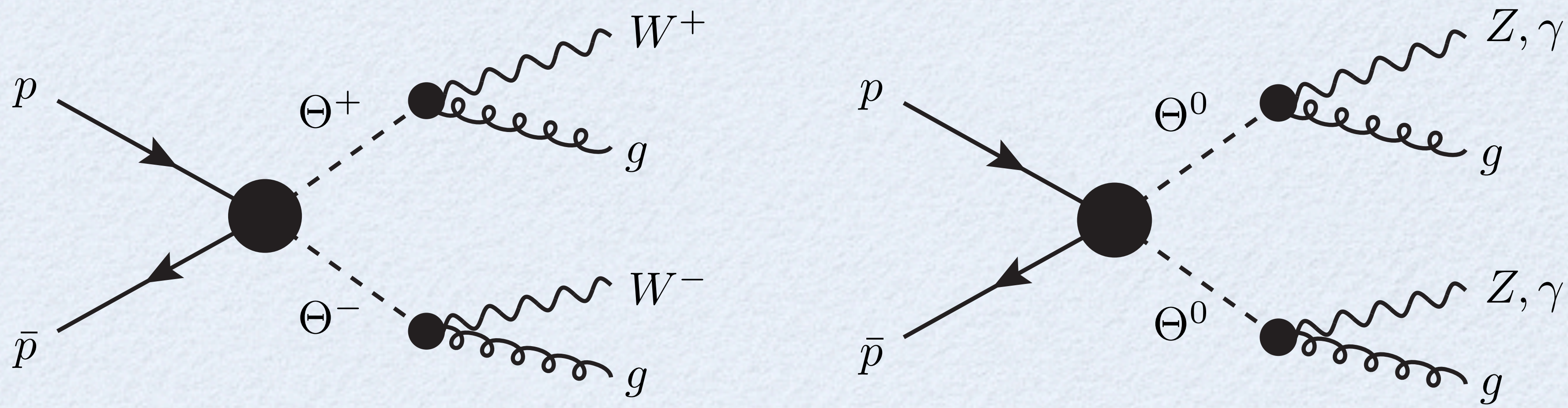
$$f(R) = \frac{1}{2}\mathcal{C}^2(1-R^2) = f(0) + f_1 R^2 + f_2 R^4 + \mathcal{O}(R^6)$$

Where the coefficients are all O(10^-2)

$$f(0) = \frac{9}{8}\left(\frac{\pi^2}{9} - 1\right)^2 \simeq 1.05 \times 10^{-2} \qquad f_1 = f(0) + \frac{9}{4}\left(\frac{\pi^2}{9} - 1\right)\left(\frac{\pi}{\sqrt{3}} - 2\right) \simeq -3.00 \times 10^{-2}$$

$$f_2 = \frac{9}{8}\left(\frac{\pi^2}{9} + \frac{\pi}{\sqrt{3}} - 3\right)^2 + \frac{3}{16}\left(\frac{\pi^2}{9} - 1\right) \simeq 2.71 \times 10^{-2}$$

Collider Signals



Charged pair resonances : (Wj)(Wj)

Neutral pairs : (Zj)(Zj), (γj)(γj), (Zj)(γj)

Charged/Neutral EW production : (Wj)(Zj), (Wj)(γj)

Recall that these widths are extremely small.
Can higher dimension operators compete for variety?

Dimension 5 operators

Mass scale set by some heavy field (Mψ >> MΘ) integrated out

$$\frac{c_{ij}}{m_\psi}\,\Theta^{a\alpha}\,\overline{Q}_L^{\,i}\,T^a\,\frac{\sigma^\alpha}{2}\gamma^\mu D_\mu Q_L^j + \text{H.c.}$$

Coefficients C, C′, C″ related by SM fermion Eqs. of Motion

$$\Theta^{a\alpha}\,\overline{Q}_L^{\,i} T^a \frac{\sigma^\alpha}{2}\left(\frac{c'_{ij}}{m_\psi}\widetilde{H} u_R^j + \frac{c''_{ij}}{m_\psi} H d_R^j\right)$$

Can trade derivative operator for quark masses upon Higgs insertion

$$\tilde{H} \equiv i\sigma^2 H^\dagger$$

UV completion for operators can be a heavy vector-like quark

ψ : (3, 2, 1/6) under SU(3) c x SU(2) L x U(1)Y

Vector-like Quark (ψ)

Including the most general octo-triplet interactions

$$\mathcal{L}_{\Theta\Psi} = \Theta^{a\alpha}\,\overline{\Psi}_R\,T^a\,\frac{\sigma^\alpha}{2}\left(\eta_i Q_L^i + \eta_\psi \Psi_L\right) + \text{H.c.}$$

and mass terms

$$-m_\psi \overline{\Psi}_L \Psi_R - \mu_i \overline{Q}_L^i \Psi_R + \text{H.c.}$$

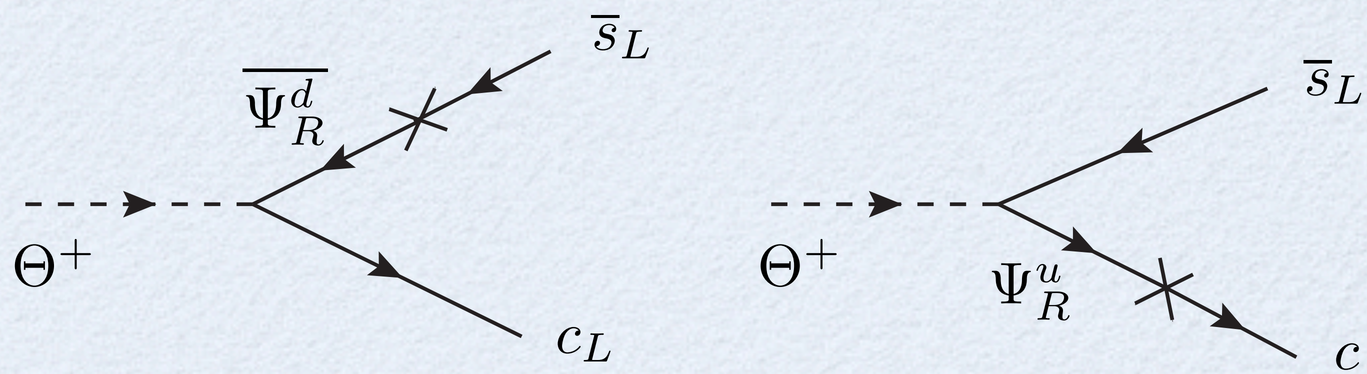
integrate out ψ, use EOM, work in quark mass-eigenbasis

$$\frac{-i}{\sqrt{2}m_\psi}\,\Theta^{a+}\,\overline{U}^i T^a\Big[(C\,V_{\text{KM}})_{ij}\,m_{d_j}P_R - m_{u_i}\left(C^\dagger\,V_{\text{KM}}\right)_{ij}P_L\Big]\,D^j + \text{H.c.}$$

C is now a matrix in flavor space and depends on Lagrangian parameters μ η, and m_ψ

New Dijet Decay Modes

Now octo-triplets can decay to jet pairs



$$\Gamma(\Theta^+ \to c\,\bar{s}) \simeq \frac{m_c^2 + m_s^2}{64\,\pi\,m_\psi^2}\,|C_{22}|^2 M_\Theta = 1.3\times 10^{-6}\,\mathrm{GeV}\,|C_{22}|^2 \left(\frac{M_\Theta}{150\,\mathrm{GeV}}\right)\left(\frac{1\,\mathrm{TeV}}{m_\psi}\right)^2$$

Decays with mixed generation jets scale with different C's

$$\frac{\Gamma(\Theta^+ \to c\,\bar{b})}{\Gamma(\Theta^+ \to c\,\bar{s})} \simeq \frac{1}{|C_{22}|^2}\left(\frac{m_b^2}{m_c^2}\,|C_{23}|^2 + |C_{32}|^2\right),$$

3d generation dominates w/ top-mass enhancement, but kinematically forbidden if $M_\Theta < m_t + m_b$

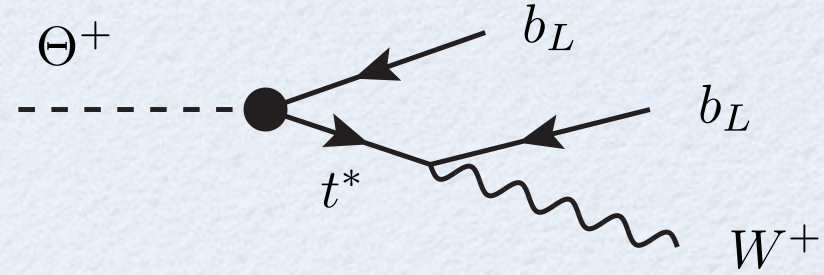
Virtual Top Decays

If allowed, the dominant width is

$$\Gamma(\Theta^+ \to t\bar{b}) \simeq 2.2 \times 10^{-2}\,\mathrm{GeV}\,|C_{33}|^2 \left(1 - \frac{m_t^2}{M_\Theta^2}\right)^2 \left(\frac{M_\Theta}{150\,\mathrm{GeV}}\right) \left(\frac{1\,\mathrm{TeV}}{m_\psi}\right)^2$$

However, for $M_\Theta \approx 150$ GeV, there is a 3-body off-shell decay with much smaller (but still relatively large) width

$$\Gamma(\Theta^+ \to W^+ b\bar{b}) = \frac{\alpha\,|C_{33}|^2\, m_t^4}{64\pi^2 \sin^2\theta_W\, m_\psi^2} \mathcal{F}(M_\Theta)$$



With a dimensionful function arises from the phase-space integral

$$\mathcal{F}(M_\Theta) = \int_0^{E_0} d\overline{E}_{\bar{b}} \int_{E_0 - \overline{E}_{\bar{b}}}^{E_b^{\max}} dE_b\, \frac{E_b + (E_0 - \overline{E}_{\bar{b}})\left[\frac{2M_\Theta}{M_W^2}(E_0 - E_b) - 1\right]}{(M_\Theta^2 - 2M_\Theta \overline{E}_{\bar{b}} - m_t^2 + m_b^2)^2 + m_t^2 \Gamma_t^2}$$

$$E_0 = \frac{M_\Theta^2 - M_W^2}{2M_\Theta} \qquad E_b^{\max} = \frac{E_0 - \overline{E}_{\bar{b}}}{1 - 2\overline{E}_{\bar{b}}/M_\Theta}$$

Competition

Numerically we find

$$\Gamma(\Theta^+ \to W^+ b\bar{b}) \simeq 2.9 \times 10^{-6}\,\text{GeV}\,|C_{33}|^2 \frac{\mathcal{F}(M_\Theta)}{\mathcal{F}(150\text{ GeV})}\left(\frac{1\,\text{TeV}}{m_\psi}\right)^2$$

Recall that the 2 body dijet width is

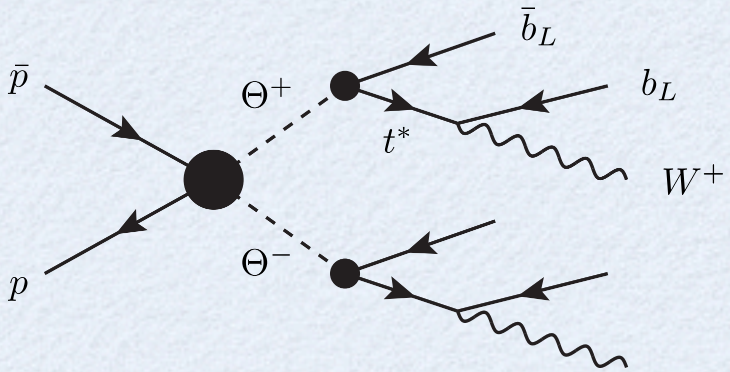
$$\Gamma(\Theta^+ \to c\,\bar{s}) \simeq 1.3 \times 10^{-6}\,\text{GeV}\,|C_{22}|^2 \left(\frac{M_\Theta}{150\,\text{GeV}}\right)\left(\frac{1\,\text{TeV}}{m_\psi}\right)^2$$

For natural Lagrangian parameters, processes are automatically in competition w/ comparable branching fractions

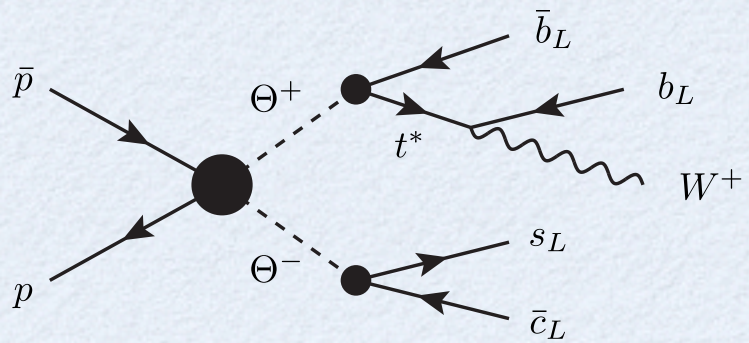
Both also dominate over loop-induced diboson and tree-level (virtual W) decays.

For simplicity, we will ignore other decay modes for main results

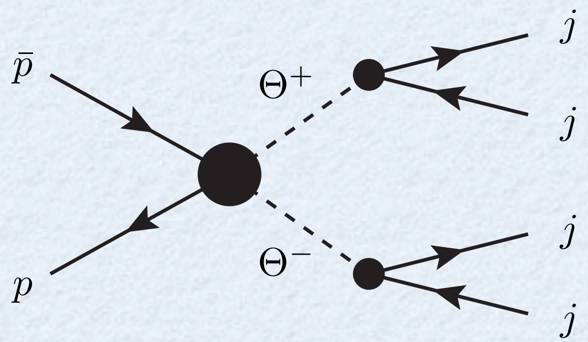
Collider Signals Revisited



W+W- + 4jets signal. Leptonic W decays looks like dilepton top signal. With branching fractions the contribution is negligible for MΘ ≈ 150 GeV

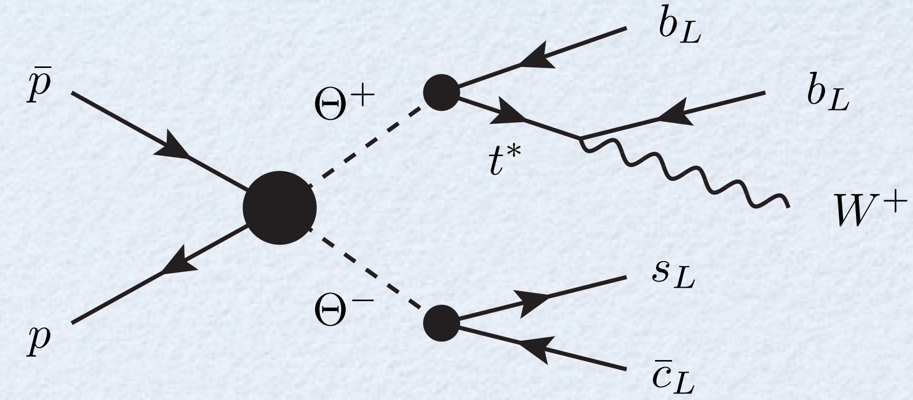


(Wbb)(jj) signal relevant for CDF Result. Can contribute to W + 2 jet events with large jet Pt cuts

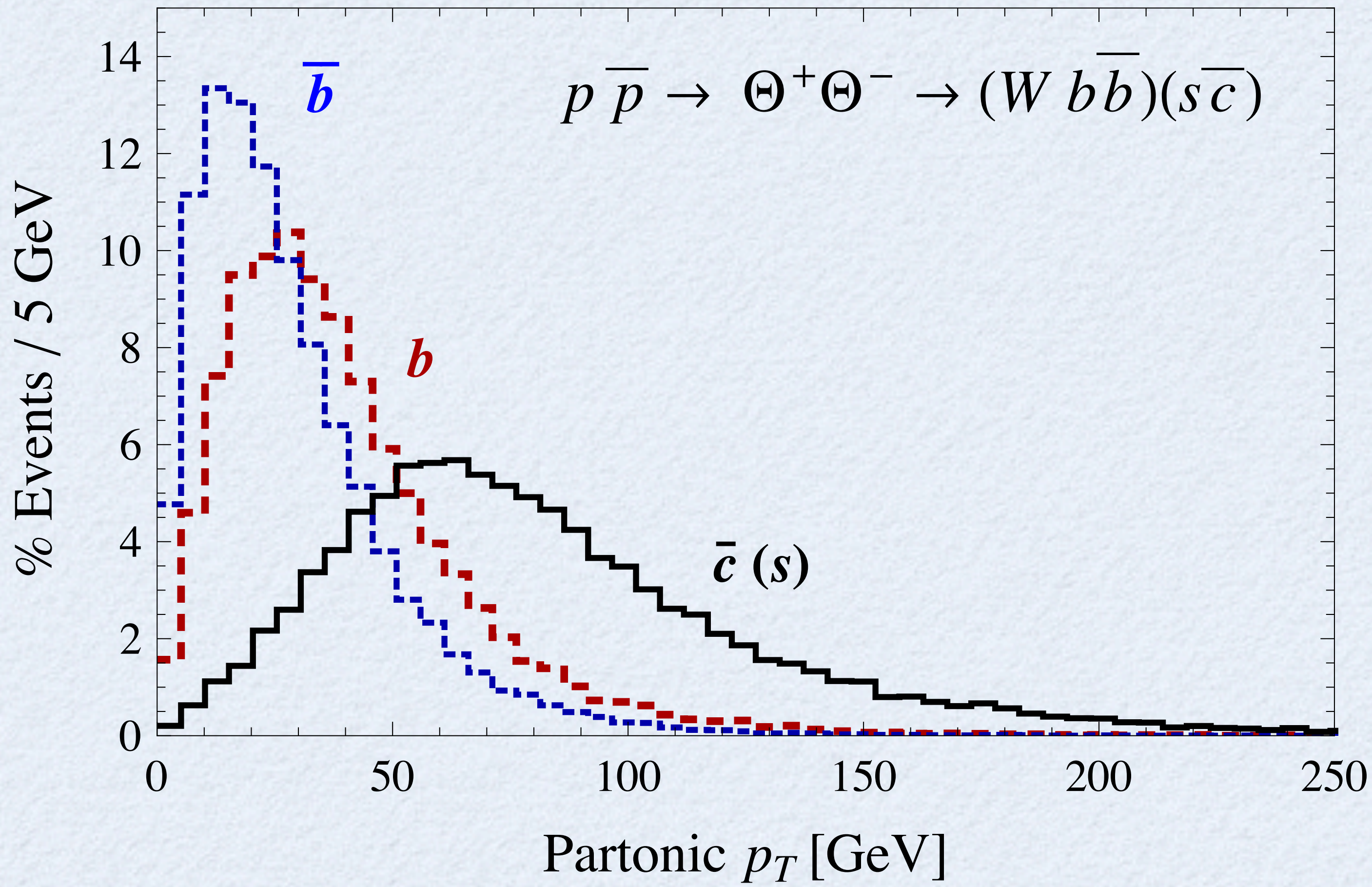


4jet final state. Also dominant channel for neutral pair-produced scalars. May explain CDF 3b anomaly.

Looks can be deceiving



Naively a W + 4 jet event, but the b-jets are very soft



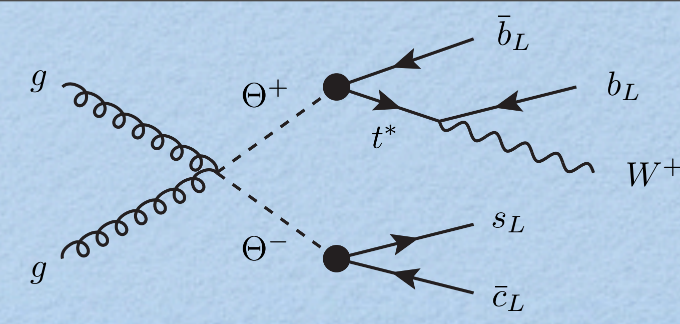
Partonic simulation using MadGraph5 at $\sqrt{s}$ = 1.96TeV

Interactions generated in FeynRules

For sufficient cuts, the b-jets will be vetoed to give effective W+2 jets event

***Similar result with gluon from loop decays (θ-> Wg)**

CDF Mjj spectrum



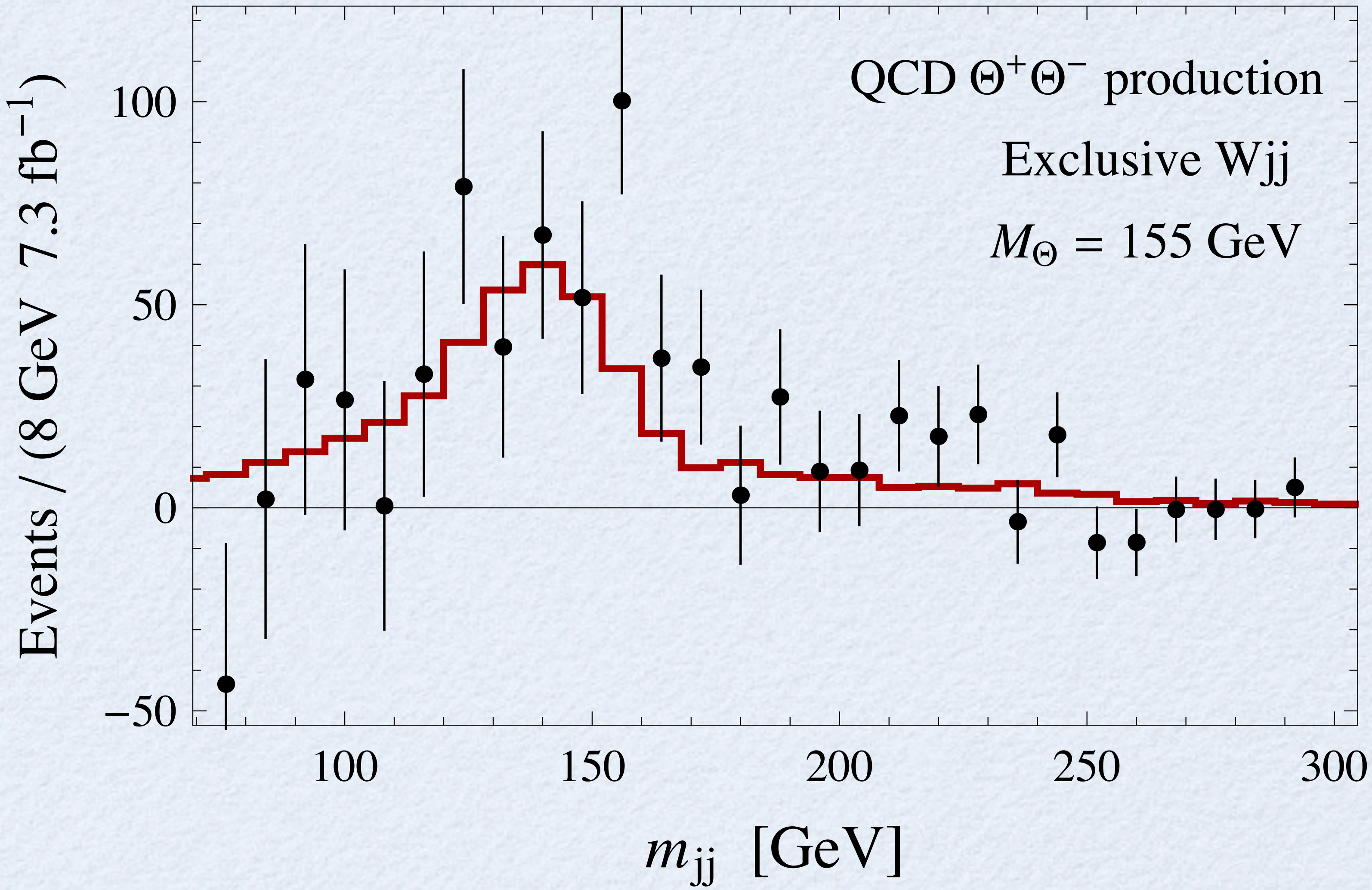
Exclusive dijet mass spectrum for θθ ->(jj)(Wbb)->(lνbb)(jj) at √s = 1.96 TeV

FeynRules (model file)
MadGraph5 (parton events)

Pythia (parton shower)

PGS (detector simulation)

Data w/ diboson tail subtracted



2 σ x Br(Wbb) x Br(jj) = 3.2 pb

Br(Wbb) = 40 %   Br(jj) = 60 %

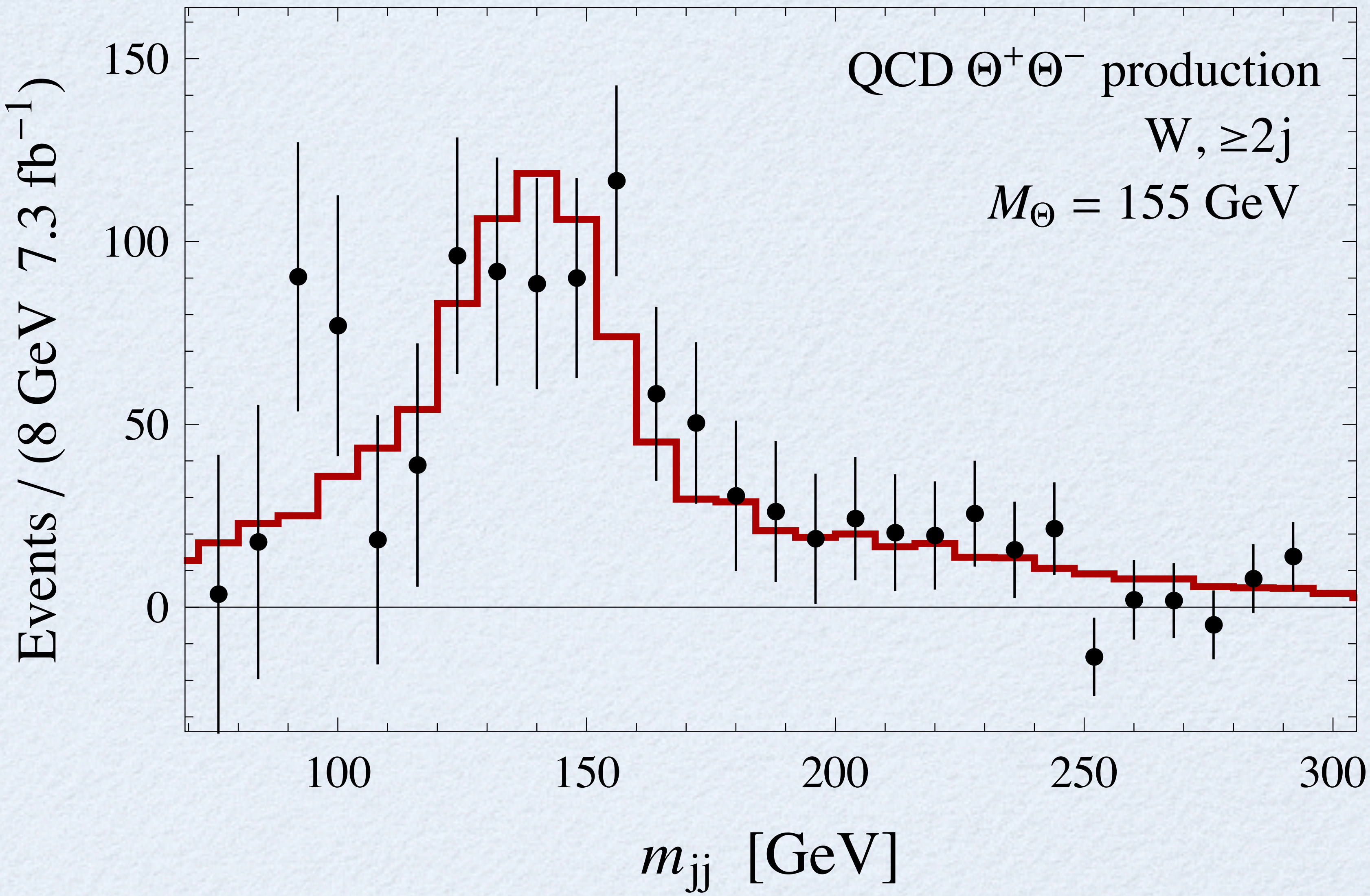
Inclusive dijet spectrum (QCD production)

Same inputs as exclusive sample

High tail arises when hardest jets are from different octo-triplets

Excellent agreement, even captures the tail

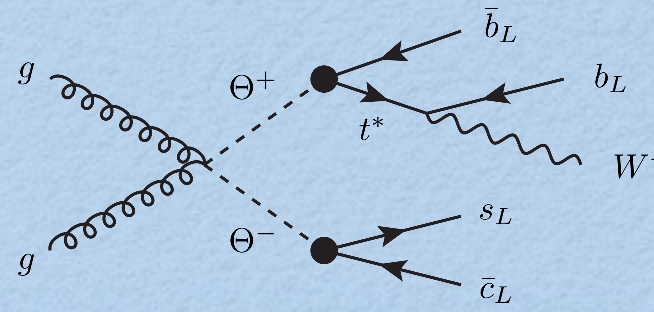
Br(Wbb) = 40 %
Br(jj) = 60 %



$2\sigma \times$ Br(Wbb) x Br(jj) = 3.2 pb

before cuts, without W branching fraction

Comments



The agreement is quite good, but the exclusive spectrum is a little low.

Neither curve includes a K factor, which would improve agreement.

Note tail for large Mjj in both data and curve. Arises when hardest jets come from different octo-triplets

CDF BG normalization assumes gaussian signal, so proper subtraction may improve agreement

Recall: CDF data seem to favor resonant (s-channel) production. How does this (QCD) production mechanism model compare to alternatives?

Resonant Production

Embed color sector into extended SU(3)xSU(3) gauge group

Adapt simple "Renormalizable Coloron Model" (Bai, Dobrescu hep-ph/1012.5814)

Charge the scalar responsible for SU(3)xSU(3) -> SU(3)c breaking

IR spectrum features 8 massive spin 1 "colorons" and three color octet scalars (two charged, one neutral)

Coloron couples to both quarks and scalars and induces qq -> G′ -> $\theta\theta$ production through an s-channel resonance

Coloron Features

New interaction with coloron G′

$$g_s \frac{1-\tan^2\phi}{2\tan\phi} f^{abc} G'^{a}_{\mu} \left[\left(\Theta^{b+}\partial^\mu\Theta^{c-} + \text{H.c.}\right) + \Theta^{b0}\partial^\mu\Theta^{c0}\right]$$

Single coloron production proceeds only from qq initial states

Decays mostly to scalar pairs

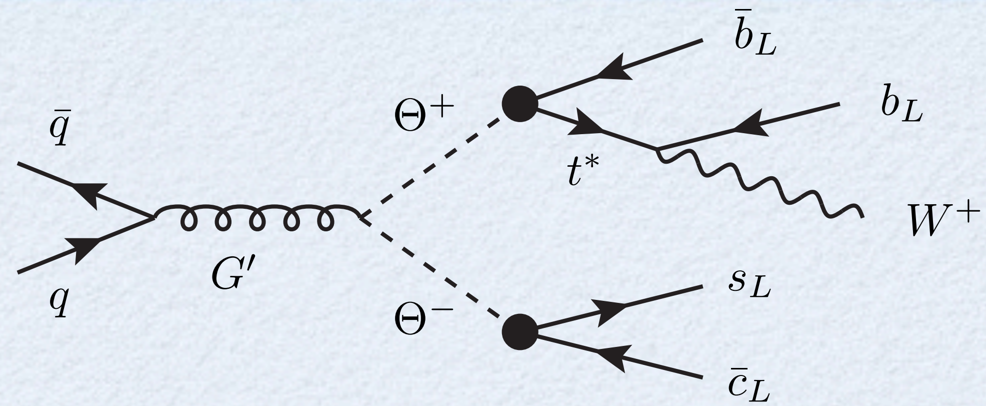
$$\Gamma(G' \to \Theta^+\Theta^-) = \frac{\alpha_s M_{G'}}{16\tan^2 2\phi}\left(1 - \frac{4M_\Theta^2}{M_{G'}^2}\right)^{3/2}$$

Quark couplings suppressed $\qquad g' = g_s \tan\phi \ll g_s$

$$\Gamma(G' \to q\bar{q}) = \frac{\alpha_s}{6}\tan^2\phi\, M_{G'}\left(1 - \frac{4M_q^2}{M_{G'}^2}\right)^{3/2}$$

for tan ϕ ≈ 0.1 model is completely safe from dijet searches.
Total width typically few GeV

Resonant Octo-triplet Production



Nonresonant QCD production of octo-triplets still present
Goal: decrease QCD, enhance Coloron

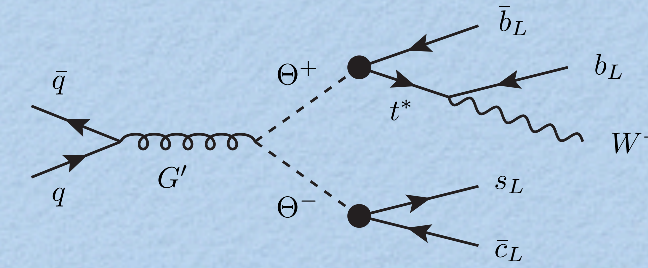
Strategy:

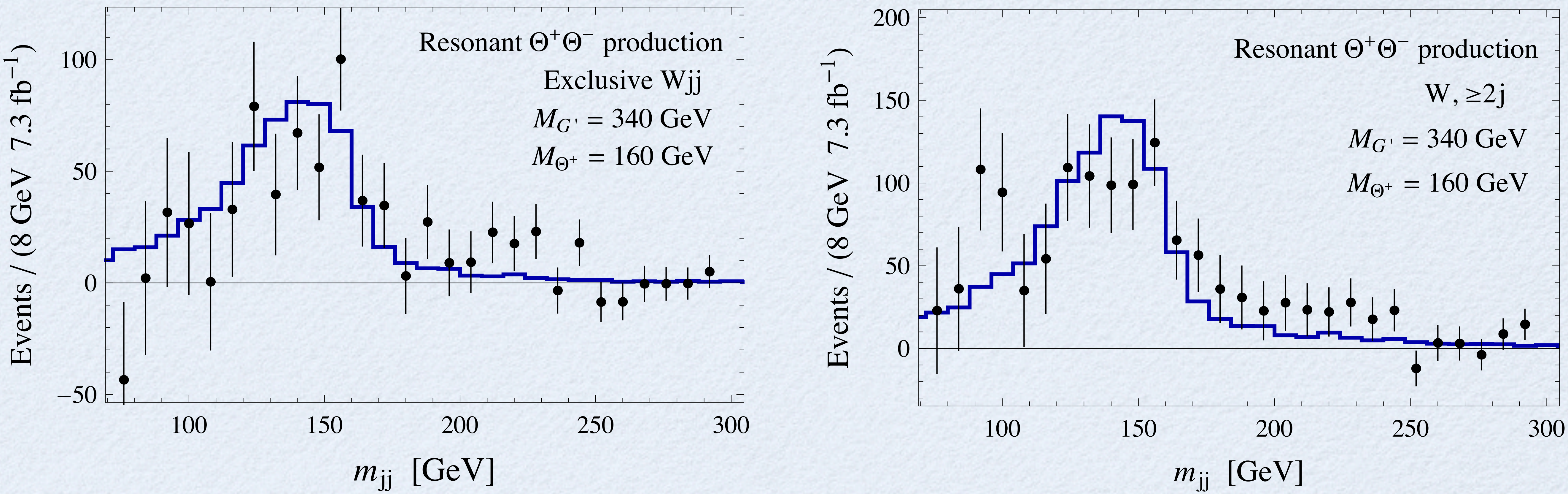
1. Decrease Br(Wbb) from 40% to 4% => Kills QCD signal (4jet events dominate)

2. Total Coloron section very sensitive to width.
Pick tanϕ to modify coupling and width to get large coloron signal.

Simulations for this model include both QCD and Coloron diagrams and their interference

CDF Dijet excess revisited





Br(Wbb) = 4 %, Γ = 6.5 GeV, tanϕ = 0.15, σ x Br = 3.8 pb

Very good fit, but unlike QCD production, misses the tail.

Same simulation method (FeynRules, MG5, Pythia, PGS)

So far, no clear winner, but ...

LHC Cross Sections

Benchmark QCD and production rates (not including acceptances)

$$\sigma\big(pp \to \Theta^+\Theta^- \to (jj)(\ell\nu b\bar{b})\big) \simeq 52 \text{ pb}$$

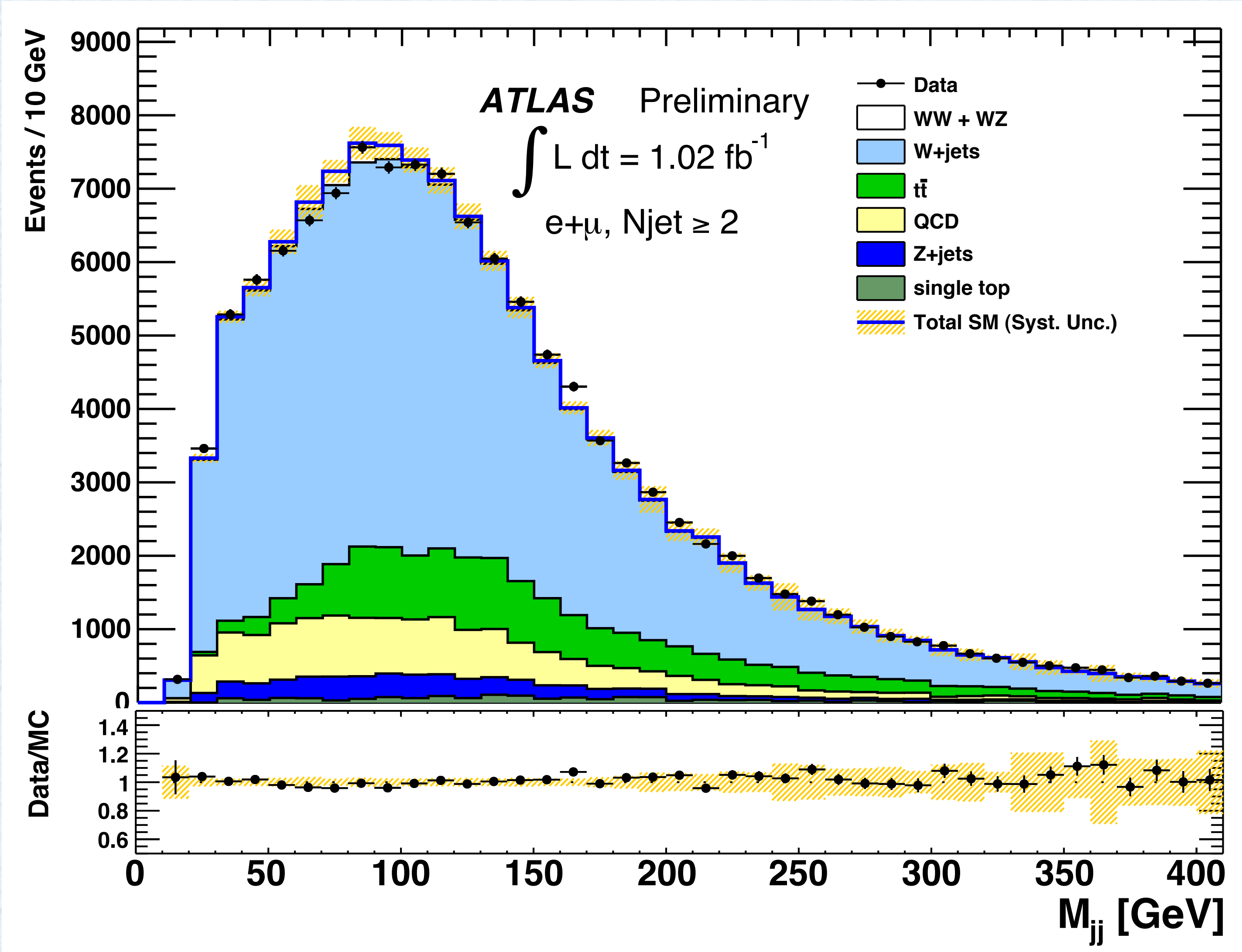
$$\sigma\big(pp \to G' \to \Theta^+\Theta^- \to (jj)(\ell\nu b\bar{b})\big) \simeq 10 \text{ pb}$$

Naive estimate: assume same acceptances as CDF (few %) both models predict a few hundred total events at LHC so far.

Coloron cross section smaller because of relatively smaller quark luminosities at the LHC. Resonant production is boosted at the Tevatron where CM energy is closer to threshold.

Current results may be borderline for QCD production, but Coloron induced events are invisible at current luminosity

Preliminary ATLAS Spectrum

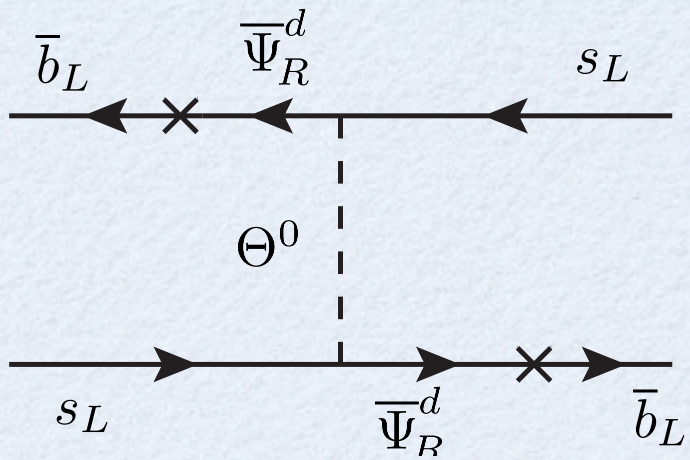


Possibly a small excess near 160-170 GeV. Too soon to tell

Uncertainties near 150 GeV O(few 100) events for each bin

Diboson peak (white) not yet visible

Bonus: B Mixing



$$\mathcal{L}_{B_s-\overline{B}_s} = \left(\frac{C_{23}\, m_b}{2M_\Theta m_\psi}\right)^2 (\bar{b}_R\, T^a s_L)^2 + \text{H.c.}$$

Exchange induces mixing in the B meson system.
Complex coefficients provide a new source of CP violation

New physics contribution to Hamiltonian matrix element is

$$\langle \overline{B}_s | \mathcal{H}_\Theta | B_s \rangle \simeq \left(\frac{C_{23}}{M_\Theta m_\psi}\right)^2 M_{B_s}^4 f_{B_s}^2 \eta_{\text{QCD}} \frac{5B_2 + 3B_3}{288}$$

Parametrize new physics matrix element

$$\frac{\langle \overline{B}_s | \mathcal{H}_{\text{SM}} + \mathcal{H}_\Theta | B_s \rangle}{\langle \overline{B}_s | \mathcal{H}_{\text{SM}} | B_s \rangle} \equiv C_{B_s} e^{-i\phi_s}$$

Bonus: B Mixing

Using the SM contribution and the known B mass difference

$$\langle \overline{B}_s | \mathcal{H}_{\rm SM} | B_s \rangle \approx \left(8.0 \times 10^{-6}\,{\rm GeV}\right)^2 (1 \pm 0.15)\ . \qquad C_{B_s} \approx 0.98 \pm 0.15.$$

Mass needed to produce a given CPV phase

$$m_\psi = 1.1\,{\rm TeV} \times |C_{23}| \left(\frac{150\,{\rm GeV}}{M_\Theta}\right) \left(C_{B_s}^2 + 1 - 2 C_{B_s} \cos\phi_s\right)^{-1/4}$$

For large phases ~ π/4, this requires Mψ ~ 300 GeV, which is not ruled out.
Only decay process is ψ --> Θ q --> 3j.

Pair production yields 6 jet events with pairs of 3j resonances. Still allowed above ~ 200 GeV

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Nonzero phases can contribute to like sign dimuon asymmetry (D0 sees ~ 4σ excess)

For large phases ~ π /4, this requires M_ψ ~ 300 GeV, which is not ruled out. Only decay process

$$\psi \to \Theta q \to 3j$$

Pair production we get 6 jet events with 3j resonances. Not ruled out by 3j searches above ~ 250 GeV

Conclusion

- CDF and D0 discrepancy is not yet resolved. Not clear yet whether D0 actually disagrees
- Octo-triplet scalars give a good fit to the CDF data
- Minimal model features small widths, loop decays, and diboson resonances
- Higher dimension operators allow (jj)(Wjj) decays that give right topology
- Resonant production through s-channel coloron can modify kinematics
- Production through coloron gives better fit to other kinematic plots
- Extended model w/ vectorlike quark can also induce CPV in B meson mixing
- Dont take my word for it, play with the model files http://theory.fnal.gov/people/dobrescu/octet/