Title: Very Light Axigluons and the Top Asymmetry

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Abstract: Both Tevatron experiments have recently reported an anomalous forward-backward asymmetry in top-antitop production. Their inclusive results are roughly 3 standard deviations larger than the standard model prediction and may be evidence of new physics that couples to the top quark. In this talk, I will present a weakly-coupled light axigluon model (< Mtop) with flavor universal couplings as a possible explanation. Surprisingly,a particle with these properties can generate a large ttbar asymmetry with model-parameters safe from dijet resonance searches, flavor changing neutral currents, and constraints from the Z pole.

# Very Light Axigluons & the Top Asymmetry

Gordan Krnjaic
(Johns Hopkins, Fermilab)

arXiv:1109.0648

Perimeter Institute
December 12, 2011

Monday, December 12, 2011

# Overview

- Motivation : “the top is special” - Everybody
- What is the forward-backward asymmetry?
- The CDF & D0 anomalies
- What kind of new physics is needed?
- Why are *very* light axigluons interesting?
- “Aren’t they ruled out?” - You, right now

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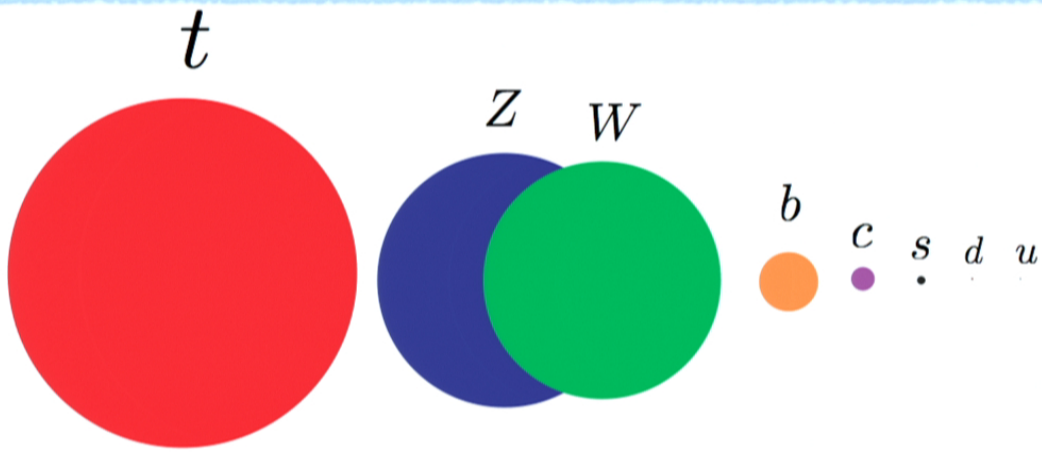
# The Top Quark




- Heaviest known particle = feels EWSB most strongly
- Relatively unknown compared to other SM particles
- Possible portal for physics beyond the SM
- Obvious target for present/future precision measurements!

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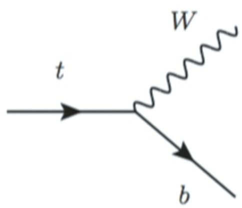
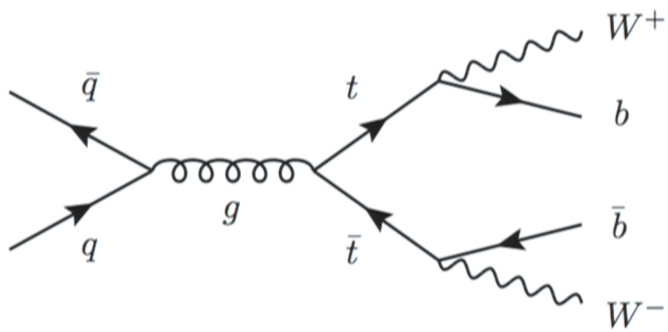



$$\Gamma_t \simeq 2\,\text{GeV} \gg \Lambda_{\text{QCD}} \sim 200\,\text{MeV}$$
$$\rightarrow \quad t_{\text{decay}} \ll t_{\text{hadronize}}$$

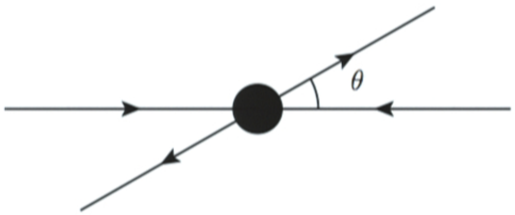
Decays *before* hadronizing, preserves parton spin info




Branching ratio to (Wb) ~ 99%, so pair production yields (6j), (2l+2v+2j), (l+v+4j) final states

# FB Asymmetry

In 2-2 scattering we define the forward-backward asymmetry as




$$A_{FB} \equiv \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$$\sigma_F = \int_0^1 \frac{d\sigma}{d\cos\theta}\, d\cos\theta \qquad \sigma_B = \int_{-1}^0 \frac{d\sigma}{d\cos\theta}\, d\cos\theta$$

- Can be sensitive to new intermediate states that interfere with SM
- Only nonzero for *odd* functions of the scattering angle
- Needs non-identical initial state to definite "forward" direction
- Used to observe first hints of Z boson in e+e- to μ+ μ- collisions

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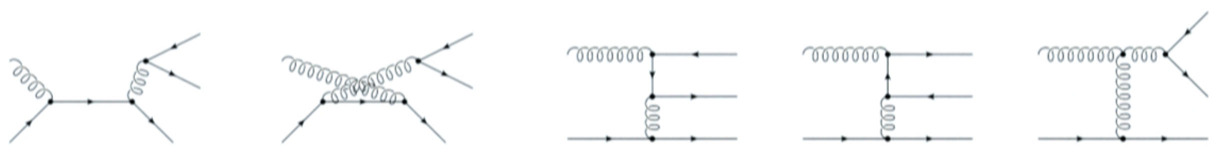
# $A_{FB}(t\bar{t})$ in the SM

Top production is a QCD process and FB symmetric at tree level.

Interference at NLO gives small asymmetry (~ 5%) from interference (Kuhn & Rodrigo arXiv:9807420)

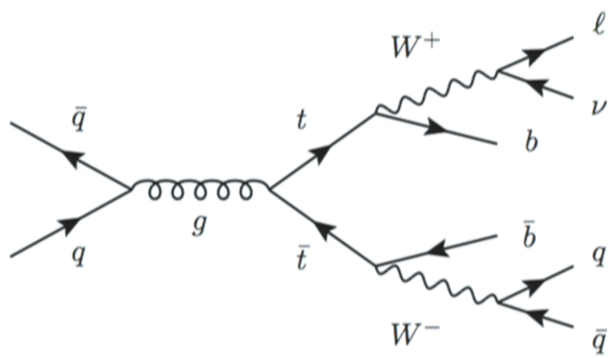

Leading contribution from $p\bar{p} \rightarrow t\bar{t}$



Also from $p\bar{p} \rightarrow t\bar{t}\,q$ and others

# CDF Lepton/Jets

Studied lepton and jets final state with 5.4 fb^-1 of data
Jan. 2011 measurement arXiv:1101.0034




$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$$\Delta y = y_t - y_{\bar{t}}$$

- They observe raw data: leptons, jets, neutrinos (“missing energy”)
- They report partonic information about top kinematics
- This requires deconvolution of detector, jet, and showering algorithms (a.k.a “unfolding”) to reconstruct top four-vectors

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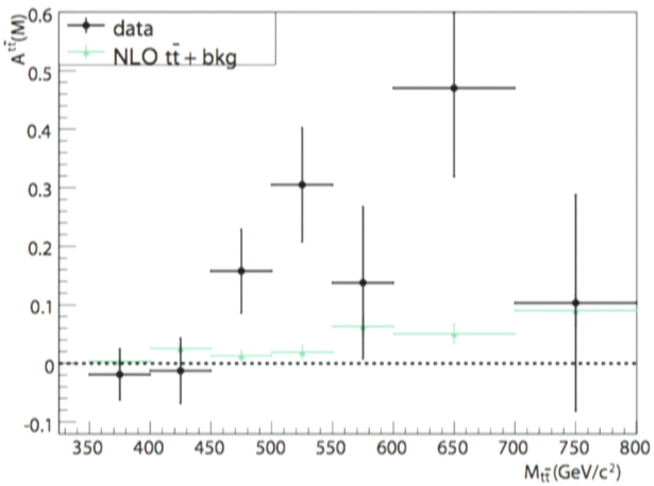
# CDF Lepton/Jets

The total ("inclusive") partonic asymmetry: somewhat high

$$A_{FB}\,(\mathrm{CDF})_{\ell j} = (15.8 \pm 7.4)\%$$




However there is a 3.4 sigma excess for invariant masses > 450 GeV

$$A_{FB}(M_{t\bar{t}} < 450\,\mathrm{GeV}) = (-11.6 \pm 14.6)\%$$
$$A_{FB}(M_{t\bar{t}} > 450\,\mathrm{GeV}) = (47.5 \pm 11.4)\%$$

Suggestive of new physics

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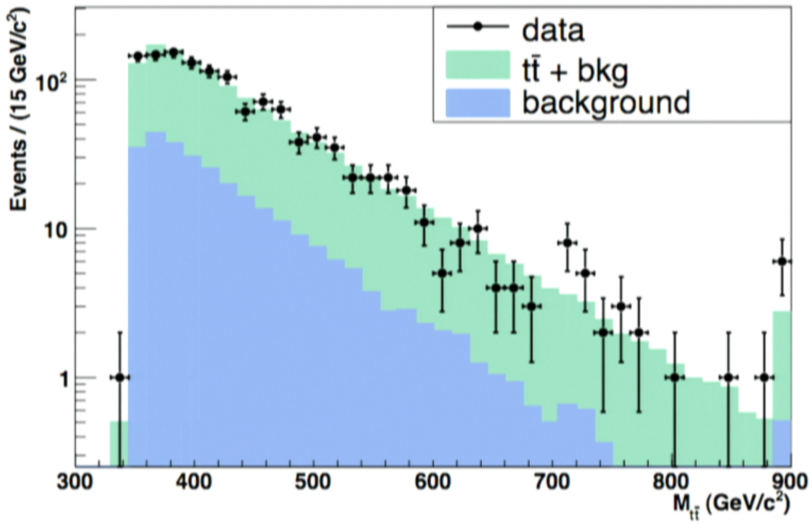
# CDF Lepton/Jets




$$\sigma_{t\bar{t}}\,(\text{obs.}) \approx 7.5\,\text{pb}$$

The same data agrees with SM ttbar production.

Difficult for "generic" new physics to increase Afb without significantly distorting this plot

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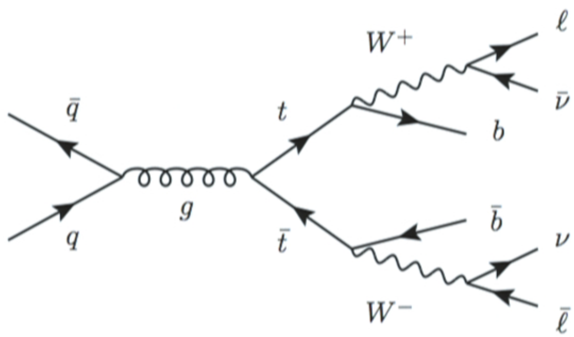
# CDF Dilepton

Preliminary measurement 5.1/fb with a 2 lepton final state
(CDF Public Note 10436)




Inclusive asymmetry even larger

$$A_{FB}(CDF)_{\ell\ell} = (42 \pm 15)\%$$

- Results also presented in terms of "unfolded" partonic data
- Consistent with the lepton + jets search at 2 sigma
- Mass dependent asymmetry is much flatter than in the lepton/jets analysis

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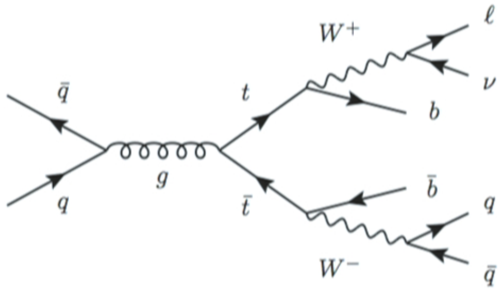
# D0 Lepton/Jets

Complementary measurement in lepton + jets channel with 5.4/fb (arXiv:1107.4995)




D0 inclusive asymmetry

$$A_{FB}\,(\mathrm{D0})_{\ell j} = (19.6 \pm 6.5)\%$$

Consistent with both CDF measurements and > 2 sigma above the SM prediction

Disagrees with the large mass-dependence in CDF's lepton/jets measurement.

D0 observes a large, flat asymmetry (and a huge *lepton* asymm.)

# Overall Verdict?

- Most aberrant single measurement (CDF mass-dependent Afb) is controversial: D0 doesn't see sharp mass dependence
- Individually, all three measurements see consistent, positive > 2 sigma deviations from the inclusive SM prediction ~ 5%
- Combined, all three *inclusive* partonic measurements give

$$A_{FB}(CDF_{\ell j} + CDF_{\ell\ell} + D0_{\ell j}) = (20.2 \pm 4.6)\%$$

- Roughly ~ 3 sigma above the SM. May be evidence of new physics

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- Roughly ~ 3 sigma above the SM. May be evidence of new physics
- All measurements based on ~ 5/fb of data -- only 1/2 of total, so more information is on the way

# Disclaimer

## FDA Warning: This could all be crap.

- The experiments themselves have not combined results, this is just an interpretation
- Some controversy over unfolding procedure. CDF and D0 don't agree on all the details -- especially the invariant-mass dependence
- Both experiments have similar detectors, so it could be a subtle systematic problem
- Higher order QCD calculations may give a much bigger SM asymmetry

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**Working Strategy:** Interpret the combined, *inclusive* result as new physics and wait for more data/calculations to resolve disputes

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# What's Needed?

- **Any new process must preserve the total production cross section**
  - Difficult because new s-channel diagrams induce resonances in the the $M_{tt}$ distribution. One possibility: neutral t-channel exchange?
- **Also needs to interfere with SM gluon-exchange diagrams**
  - Without interference, the rate needed to explain Afb is too large
- **To interfere, new particle needs to be a color octet (if s-channel) or color-singlet (if t-channel)**
  - Natural candidates : massive "gluon" or Z′ boson (plus exotics ... )

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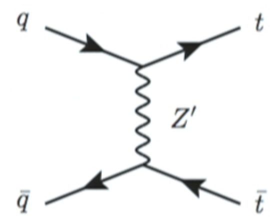
# Case Study 1 : Z′

Consider a flavor violating Z prime (Cao et. al. 1003.3461)

$$\mathcal{L} = e\bar{u}\gamma^{\mu}(f_L P_L + f_R P_R) t Z'_{\mu}$$




t-channel kinematics can generate an asymmetry through interference

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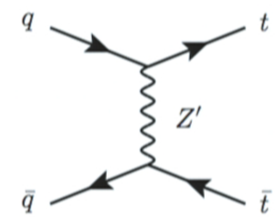


t-channel kinematics can generate an asymmetry through interference

Must be leptophobic to avoid lepton collider bounds

Predicts lots of single-top events at the LHC - tight constraints

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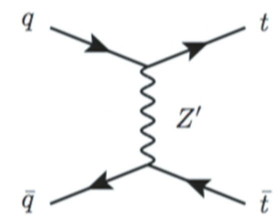


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Must be leptophobic to avoid lepton collider bounds

Predicts lots of single-top events at the LHC - tight constraints

Strong bounds from FCNCs $f_L < 3.5 \times 10^{-4} \left(\frac{M_{Z'}}{100 \text{ GeV}}\right)$

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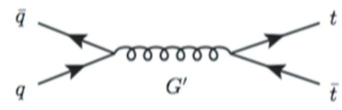
# Case Study 2: G′

Heavy (~TeV), spin-1 color-octet with flavor violating couplings (Cao et. al.)

$$G' q\bar{q} \; : \; i g_s t^A \gamma^\mu \left( f_L P_L + f_R P_R \right)$$

$$G' t\bar{t} \; : \; i g_s t^A \gamma^\mu \left( g_L P_L + g_R P_R \right)$$




Partonic cross section $$\frac{d\hat{\sigma}(G')}{d\cos\theta} = \mathcal{A}_{SM} + \mathcal{A}_{INT}^{G'} + \mathcal{A}_{NPS}^{G'}$$

$$\mathcal{A}_{INT}^{G'} = \frac{\pi\beta\alpha_s^2}{18\hat{s}} \frac{\hat{s}\left(\hat{s} - m_{G'}^2\right)}{\left(\hat{s} - m_{G'}^2\right)^2 + m_{G'}^2\Gamma_{G'}^2} \left(f_L + f_R\right)\left(g_L + g_R\right)$$
$$\times \left\{ \left(2 - \beta^2\right) + 2\frac{\left(f_L - f_R\right)\left(g_L - g_R\right)}{\left(f_L + f_R\right)\left(g_L + g_R\right)} \beta\cos\theta + \left(\beta\cos\theta\right)^2 \right\}$$

Needs opposite-sign couplings to 1st/3rd generations for correct Afb

$$(f_L + f_R)(g_L + g_R) < 0$$

Problems with dijet bounds and ttbar cross section

# "Very Light" Axigluon

Consider a similar idea with a twist

Enlarge the strong sector in the UV and break it down to SM QCD

$$G \supset SU(3)_c$$

The IR Lagrangian contains the flavor diagonal operator

$$\mathcal{L} \supset g' G'^a_\mu \bar{Q} T^a \gamma^\mu \gamma^5 Q \qquad g' \equiv \lambda g_s\ ,\ \lambda < 1$$

And an octet of massive, axially coupled "axigluons" with masses we choose to be light

$$m_{G'} \ll 2m_t$$

What does this accomplish?

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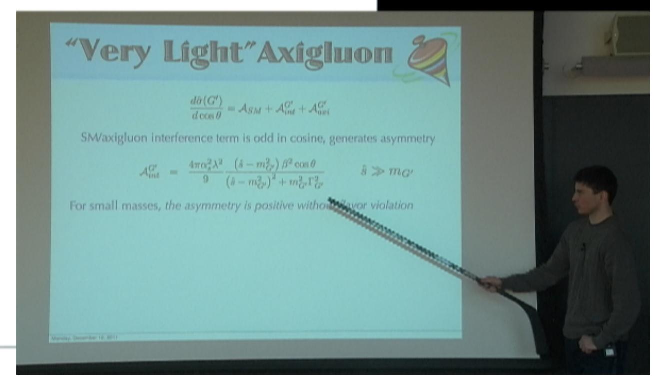
# "Very Light" Axigluon

$$\frac{d\hat{\sigma}(G')}{d\cos\theta} = \mathcal{A}_{SM} + \mathcal{A}_{int}^{G'} + \mathcal{A}_{axi}^{G'}$$

SM/axigluon interference term is odd in cosine, generates asymmetry

$$\mathcal{A}_{int}^{G'} = \frac{4\pi\alpha_s^2\lambda^2}{9}\frac{\left(\hat{s}-m_{G'}^2\right)\beta^2\cos\theta}{\left(\hat{s}-m_{G'}^2\right)^2 + m_{G'}^2\Gamma_{G'}^2} \qquad \hat{s} \gg m_{G'}$$

For small masses, *the asymmetry is positive without flavor violation*



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For small masses, *the asymmetry is positive without flavor violation*

Odd function of cosine does not add to the total cross section

$$\mathcal{A}_{axi}^{G'} = \frac{\pi\alpha_s^2\lambda^4}{9}\frac{\hat{s}\,\beta^3(1+\cos^2\theta)}{\left(\hat{s} - m_{G'}^2\right)^2 + m_{G'}^2\Gamma_{G'}^2}$$

New-physics squared term is $\mathcal{O}(\lambda^4)$ so the correction to $\sigma_{t\bar{t}}$ is tiny

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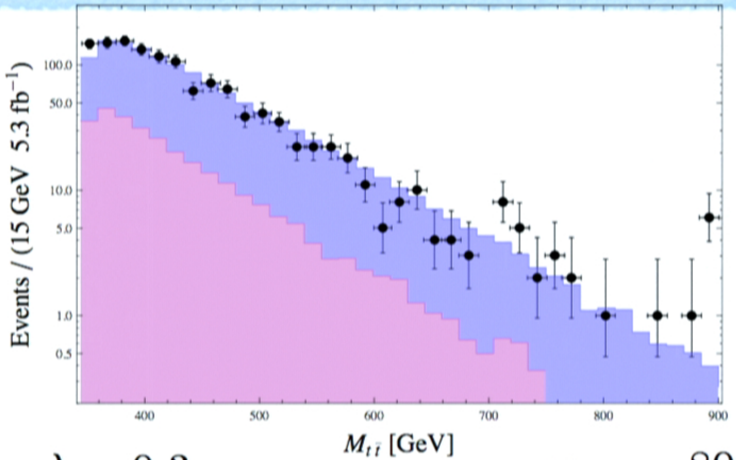
# "Very Light" Axigluon




$\lambda = 0.3$ $\qquad$ $m_{G'} = 80\,\mathrm{GeV}$

top anti-top Invariant mass distribution (FeynRules, Madgraph, Pythia, PGS )

- Pink (lower histograms) SM background taken from CDF lepton/jets paper
- Purple (upper histograms) BG + ttbar (SM) + ttbar (axigluon)
- Axigluon mass is below top threshold, so no bumps in the distribution -- just like with SM gluons

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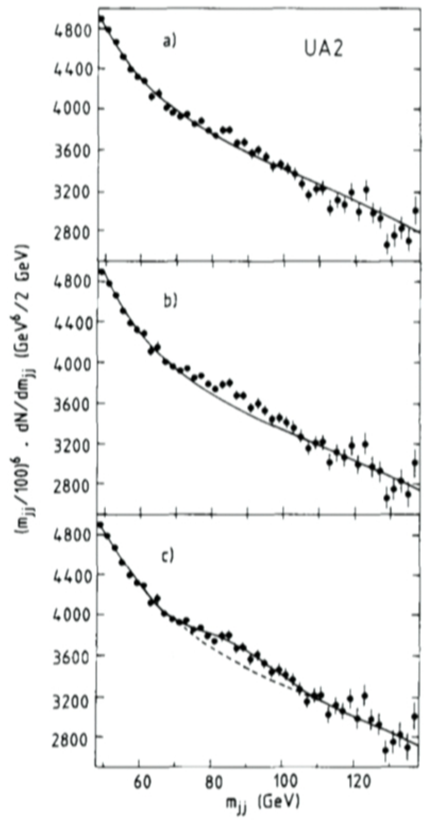
# Dijet Searches

- Axigluons decay only to jet pairs
- Tevatron and LHC searches sensitive to Mjj ~ 200 GeV or greater
- UA2 W/Z peak is the strongest constraint
- **... and it looks bad: only W and Z resonances appear here**
- Extracted W/Z signal almost 2 x SM

$$\sigma \cdot Br(W, Z \to jj)_{\rm obs} = 9.6 \pm 2.3\,{\rm nb}$$

$$\sigma \cdot Br(W, Z \to jj)_{\rm SM-NLO} \simeq 5.8\,{\rm nb}$$

- Normalization also deceptive S/B < 1%

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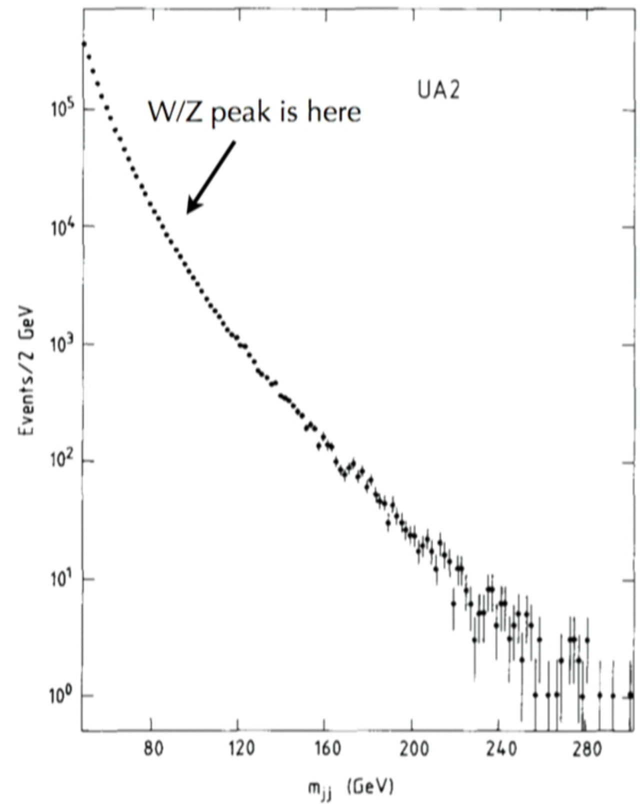
# Dijet Searches

- Same data *before* rescaling
- Unless you know that W and Z are there you cant see them
- Need a dedicated new physics search to spot an axigluon with reduced couplings
- To be conservative: use constraint from the statistical uncertainty of gaussian for best fit W/Z signal

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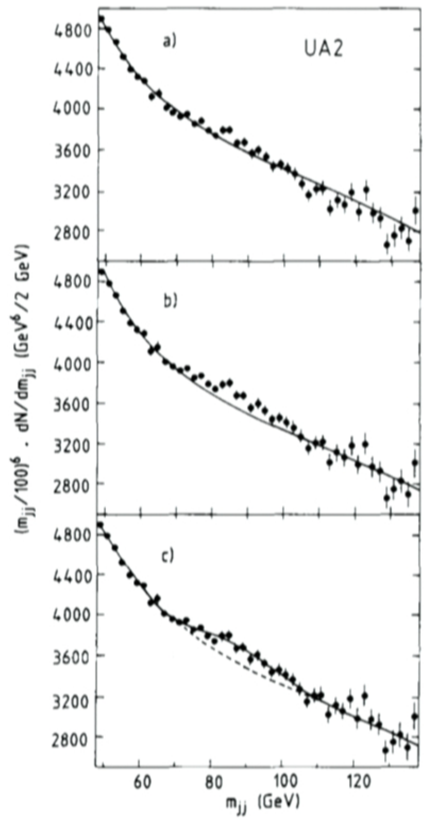


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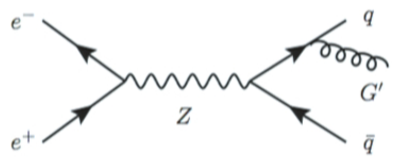
# LEP Bounds: Z-pole

Axigluons can increase hadronic Z width at LEP




$$\Gamma(Z \to \text{hadrons})_{\text{obs.}} = 1.744 \pm 0.002\,\text{GeV}$$

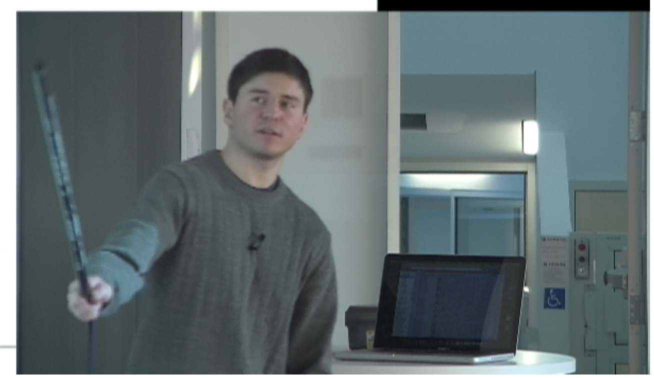
Agrees with SM -- 0.1% error bars (PDG)

Adds factor proportional to

$$1 + \frac{\alpha_s(m_Z)}{\pi} f(m_z/m_{G'}) + \mathcal{O}(\alpha_s^2)$$

At 95 % confidence, fractional correction satisfies

$$\frac{\delta\Gamma}{\Gamma} \leq 2.3 \times 10^{-3}$$



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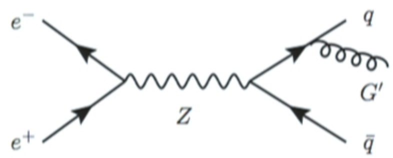


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Axigluons also decrease value of alpha strong at Z-pole RG running, by few %

$$\alpha_s(m_Z)_{SM} = 0.1184 \pm 0.0007$$

Decreases SM width prediction, opens up more room for new physics

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# Other Bounds

- **Tevatron 3b-jet search**
  - Designed for MSSM higgs, looks for dijet resonances in 3b events
  - Search starts at axigluons with M > 100 GeV
  - Safe for smaller dijet masses

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- **LEP event shapes (Kaplan, Schwartz 0804.2477)**
  - Analyzed jet observables to constrain strongly-interacting states
  - Found lower-bound of ~ 50 GeV for Gluino-like particles (no quark couplings)
  - Model dependent. Quark couplings can affect limits. They may become more constraining if they are included.

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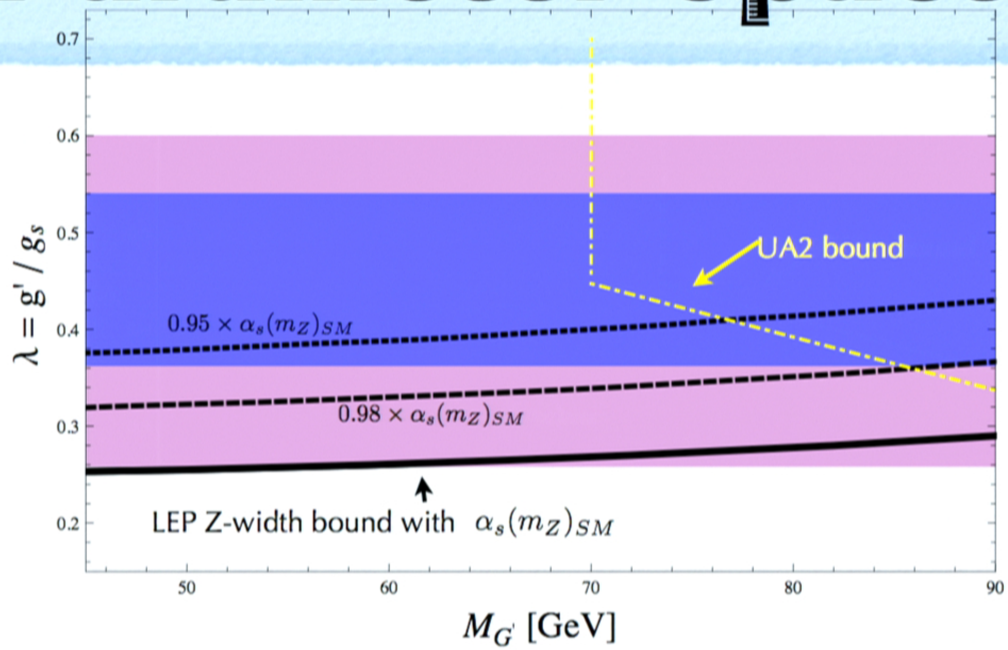
# Parameter Space




Blue and purple bands: 1 and 2 sigma favored regions for Afb (CDF+D0)

- Region below all lines completely allowed
- Light axigluon generically decreases $\alpha_s(m_Z)$
- Bound *very* sensitive to new physics extraction

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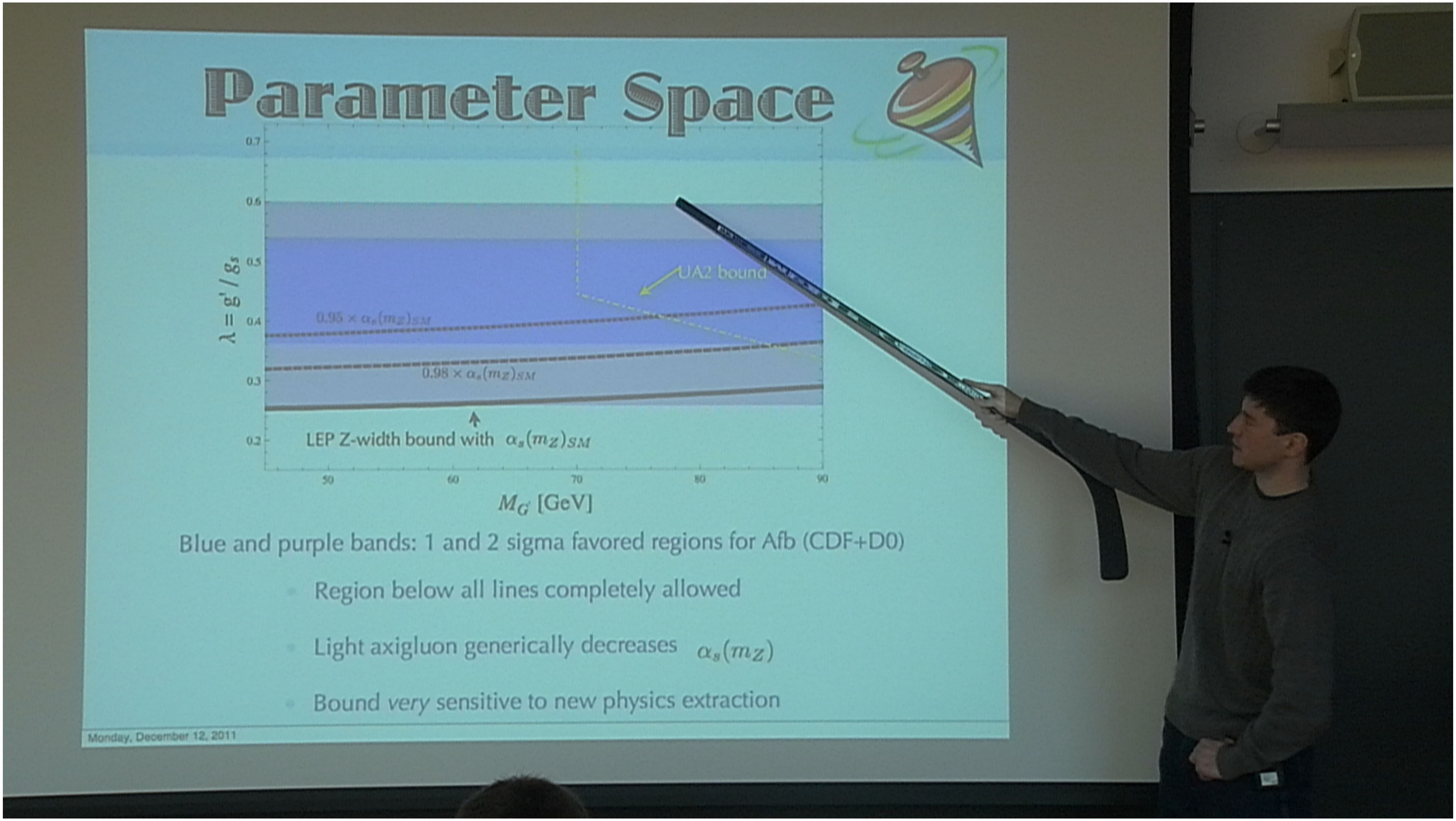

Parameter Space
$\lambda = g' / g_s$
0.7
0.6
0.5
0.4
0.3
0.2
UA2 bound
$0.95 \times \alpha_s(m_Z)_{SM}$
$0.98 \times \alpha_s(m_Z)_{SM}$
LEP Z-width bound with $\alpha_s(m_Z)_{SM}$
50
60
70
80
90
$M_G$ [GeV]
Blue and purple bands: 1 and 2 sigma favored regions for Afb (CDF+D0)
Region below all lines completely allowed
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# Conclusion

- Forward backward asymmetry may be evidence of new physics
- Most models require > few TeV masses *and* flavor violating couplings
- Flavor-universal (50 - 90 GeV) axigluons with reduced quark-couplings can yield a large asymmetry
- Contributions to top cross section suppressed
- Parameter space for Afb not that large, but very sensitive to $\alpha_s(m_Z)$

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- Parameter space for Afb not that large, but very sensitive to $\alpha_s(m_Z)$
- May be possible to revisit low Mjj region with dedicated search

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