Flavor Anomalies and a Weak-scale Z-prime at the LHC

Ian Low
Argonne/Northwestern/CERN
Based on collaboration with P. Fox and Y. Zhang in 1801.03505

Seventh Workshop on Theory, Experiments and Phenomenology of Flavor Physics

The subtlety of hiding a Weak Scale Z-prime at the LHC

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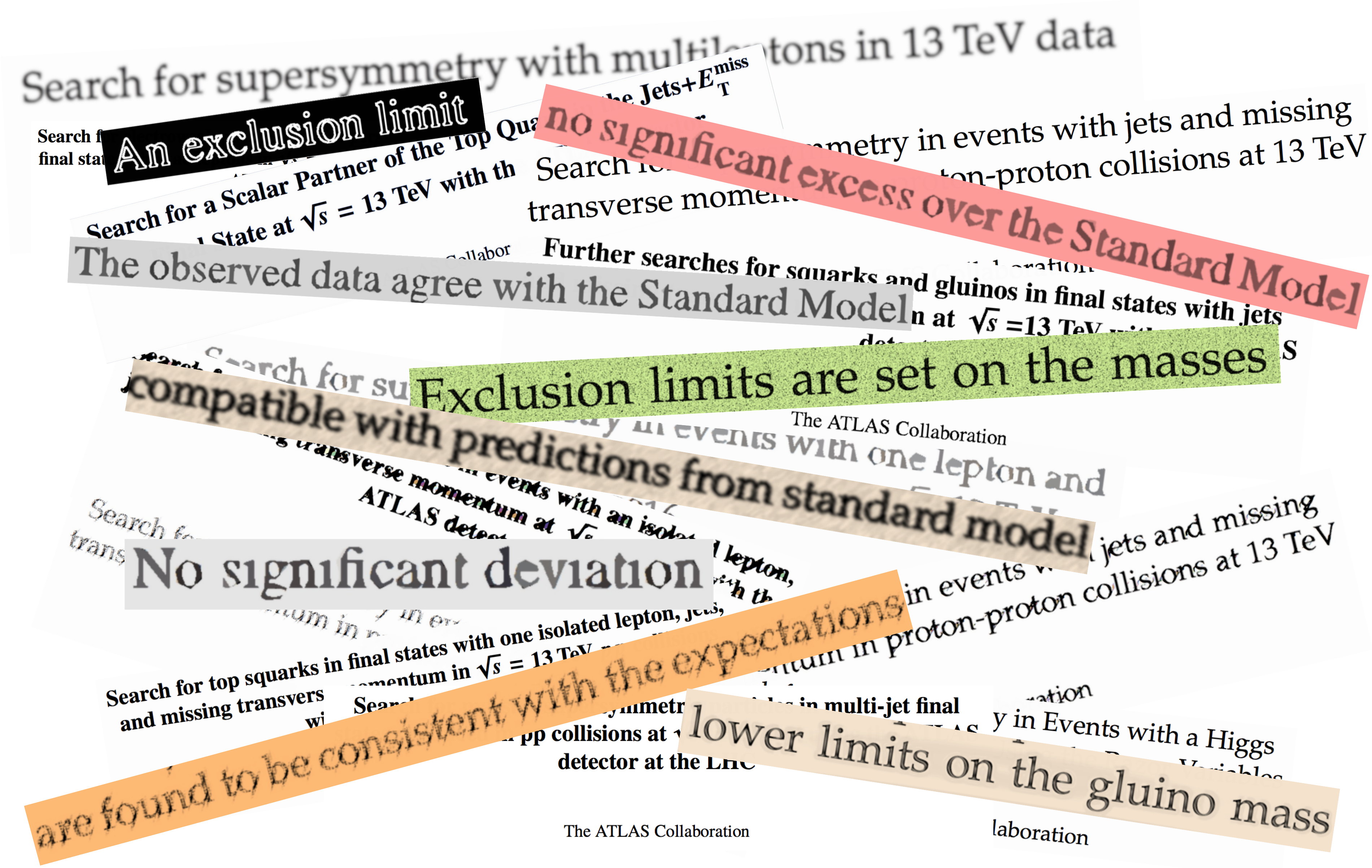
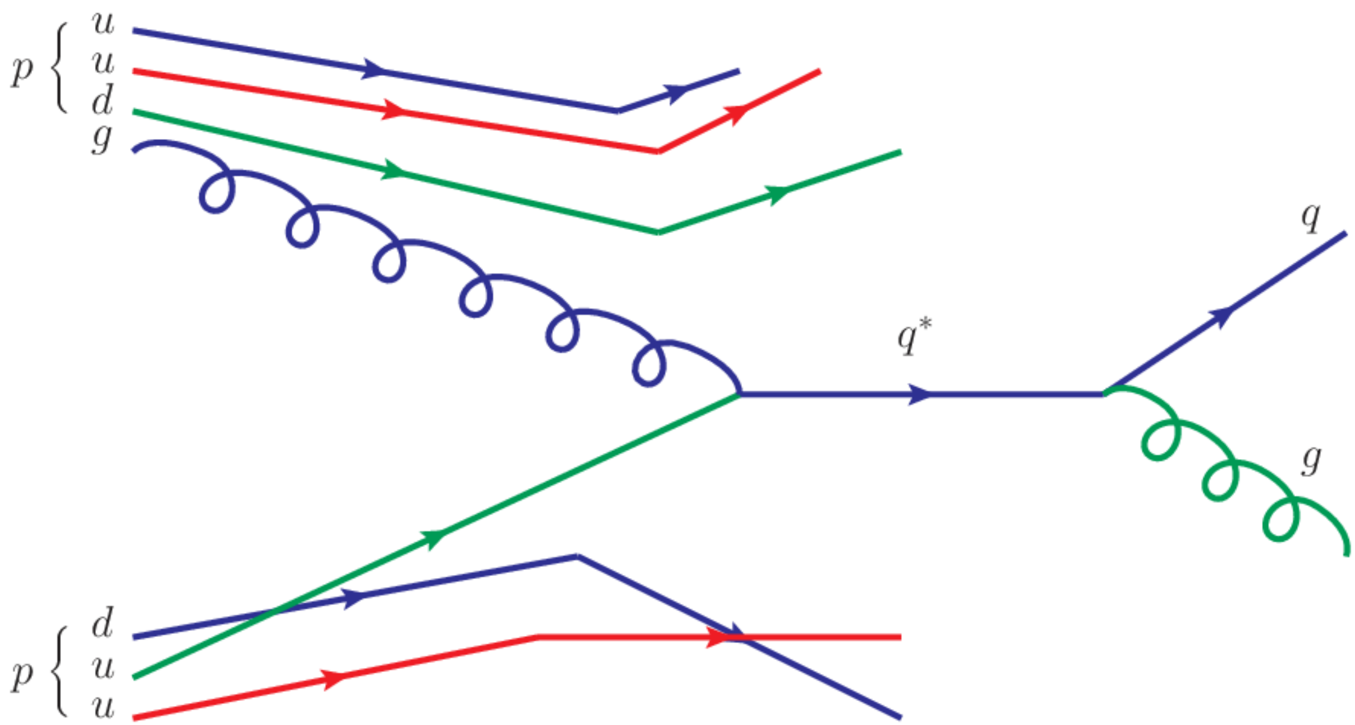
Motivation 1: Where is new physics at the LHC?

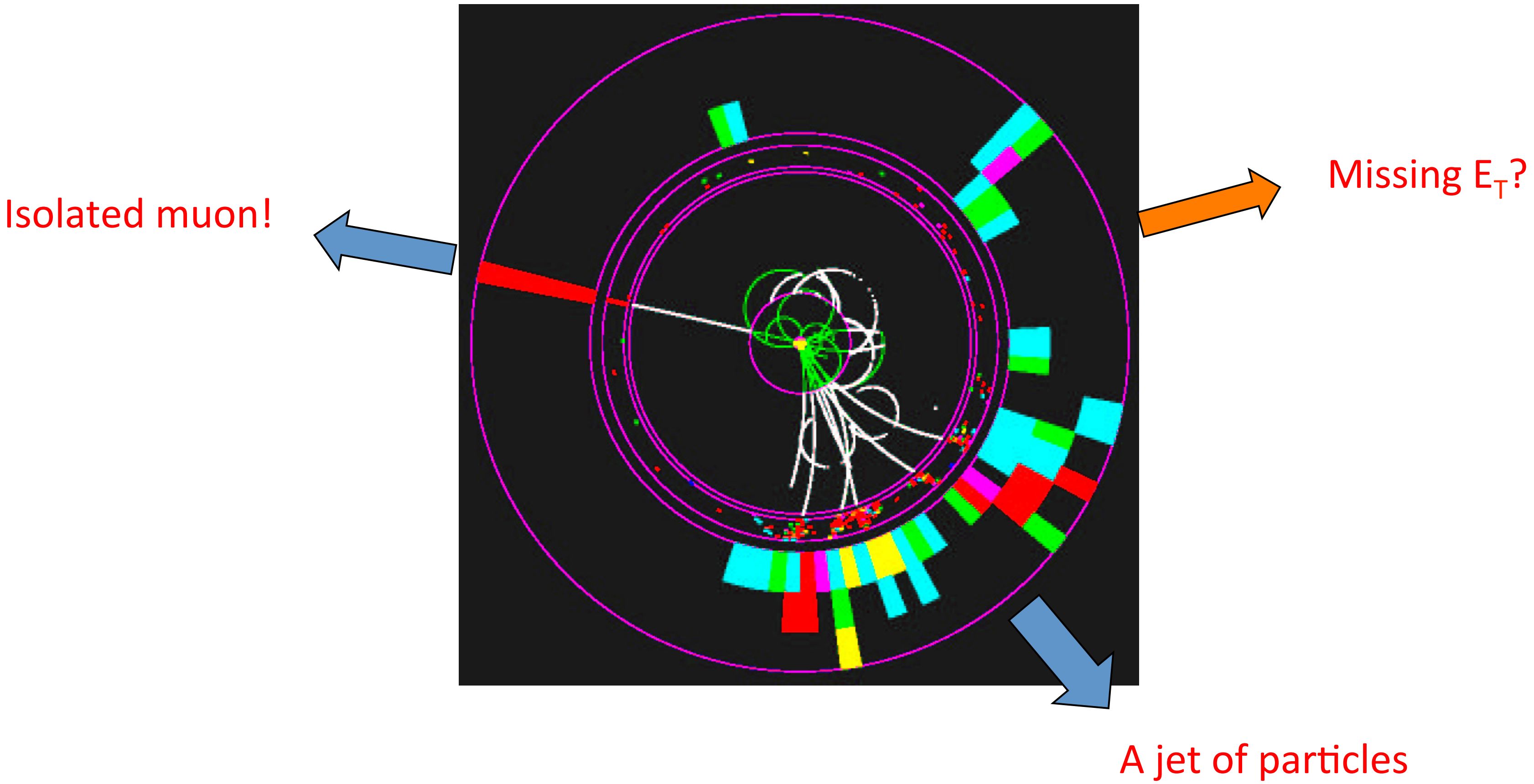


Most searches at the LHC rely on two essential assumptions:

1. New physics has significant couplings to partons inside the proton:



2. New physics decays to high P_T objects, whether visible or invisible:



These considerations point to two possibilities:

- New physics mostly decays to soft particles or outside of detector.
  Motivated many "dark sector models."

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- New physics mostly decays to soft particles or outside of detector.
  Motivated many “dark sector models.”

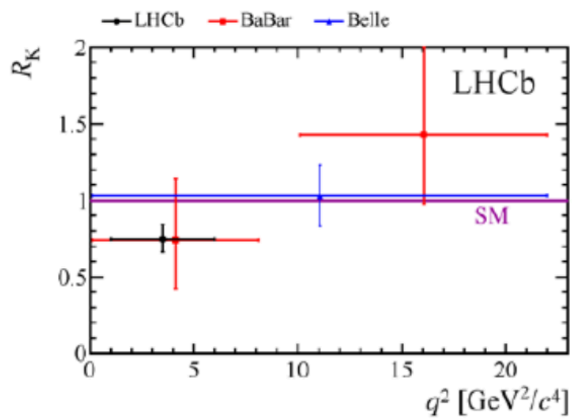
- New physics has diminished couplings to light-flavor quarks and gluons.
  Need to consider new production channels that are either loop-induced or in association with heavy flavors.

  → the focus on my talk today.
  → Use a top-philic Z-prime to make my point.

Motivation 2: flavor anomalies in B decays

Lepton flavour universality in $B^+ \to K^+\ell^+\ell^-$

- June 2014 (3 fb^{-1}): measurement of R_K in the [1-6] GeV^2 bin (PRL 113, 151601 (2014)): **2.6σ** tension in [1-6] GeV^2 bin
- SM prediction very accurate (leading corrections from QED, giving rise to large logarithms involving the ratio $m_B/m_{\mu,e}$)



BaBar, PRD 86 (2012) 032012; Belle, PRL 103 (2009) 171801

$$R_K = BR(B^+ \to K^+\mu^+\mu^-)/BR(B^+ \to K^+e^+e^-)$$

$$R_K^{\rm exp} = 0.745^{+0.090}_{-0.074}({\rm stat}) \pm 0.036({\rm syst})$$

$$R_K^{\rm SM} = 1.0006 \pm 0.0004$$

Bordone, Isidori, Pattori, arXiv:1605.07633

Would be a spectacular fall of the SM !

Slides from Tobias' talk yesterday

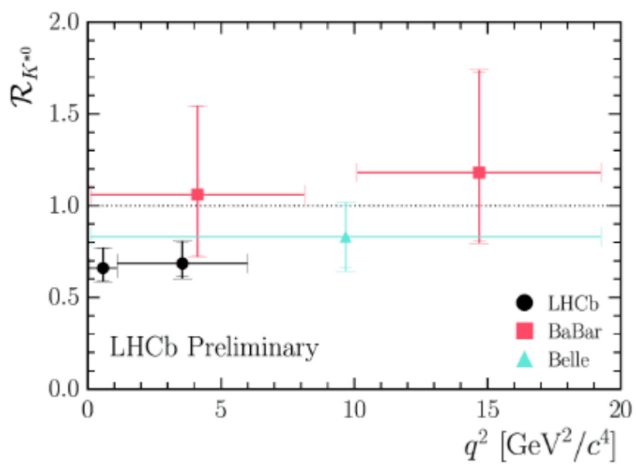
Motivation 2: flavor anomalies in B decays

Lepton flavour universality in $B^0 \to K^{*0}\ell^+\ell^-$

- LHCb measurement (April 2017): JHEP 08 (2017) 055

$$R_{K^*} = BR(B^0 \to K^{*0}\mu^+\mu^-)/BR(B^0 \to K^{*0}e^+e^-)$$

- Two q^2 regions: [0.045-1.1] and [1.1-6.0] GeV^2



BaBar, PRD 86 (2012) 032012; Belle, PRL 103 (2009) 171801

$$R_{K^*}^{\text{exp,bin1}} = 0.660^{+0.110}_{-0.070}(\text{stat}) \pm 0.024(\text{syst})$$

$$R_{K^*}^{\text{exp,bin2}} = 0.685^{+0.113}_{-0.069}(\text{stat}) \pm 0.047(\text{syst})$$

$$R_{K^*}^{\text{SM,bin1}} = 0.906 \pm 0.020_{\text{QED}} \pm 0.020_{\text{FF}}$$

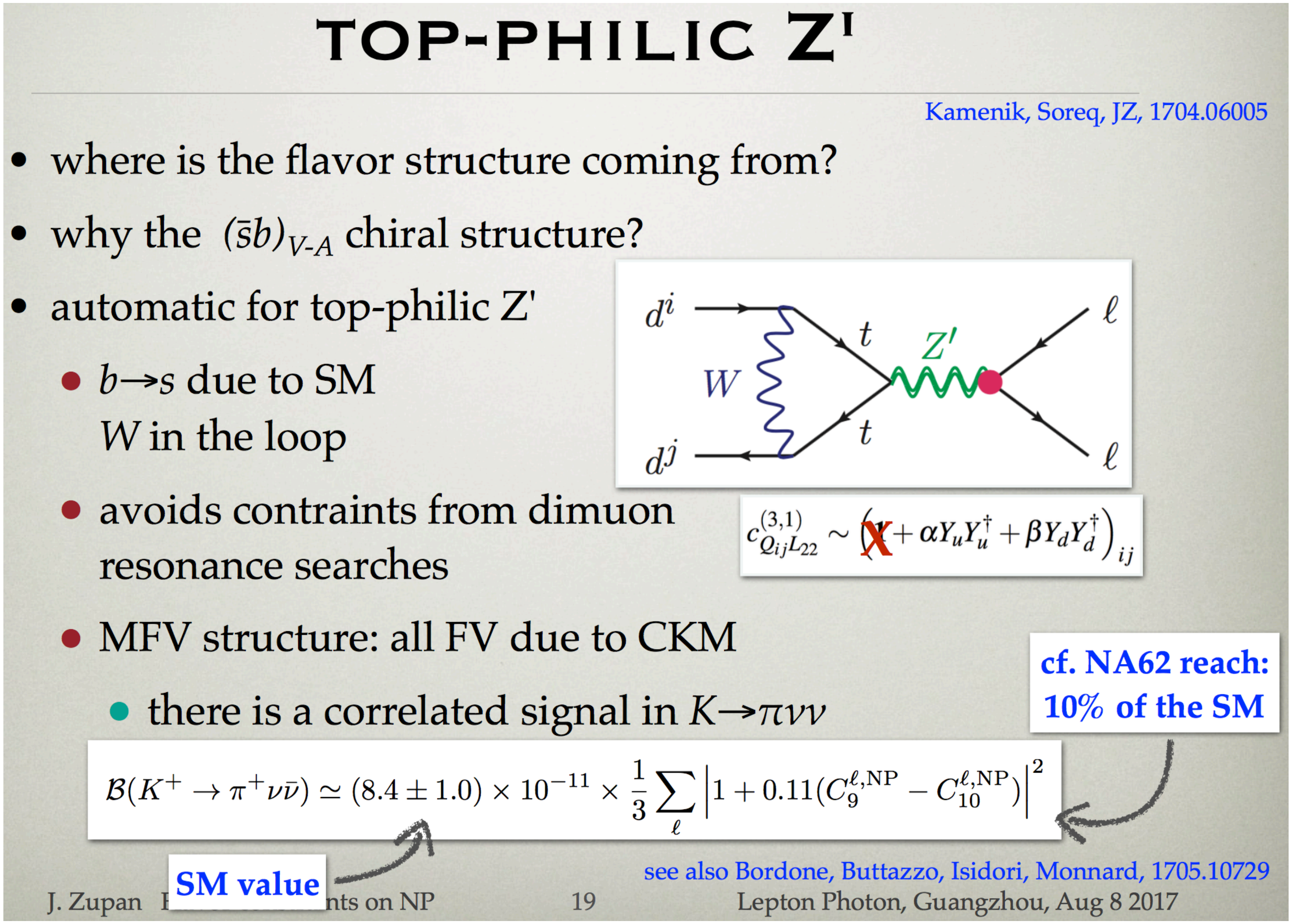
$$R_{K^*}^{\text{SM,bin2}} = 1.000 \pm 0.010_{\text{QED}}$$

Bordone, Isidori, Pattori, arXiv:1605.07633

2.2-2.5σ tension with the SM predictions in each bin

Slides from Tobias' talk yesterday

Motivation 2: flavor anomalies in B decays



Slides from J. Zupan at 2017 Lepton-Photon

First, an effective field theorist's perspective.

Let's start with the following simplified model for a top-philic Z-prime:

$$\mathcal{L}_{eff} = \mathcal{L}_{\rm SM} - \frac{1}{4} Z'_{\mu\nu} Z'^{\,\mu\nu} + \frac{1}{2} M^2_{Z'} Z'^{\mu} Z'_{\mu} \\ + Z'_{\mu}\, \bar{t}\gamma^{\mu}(c_{t_L} P_L + c_{t_R} P_R) t + \sum_{i=e,\mu,\tau} Z'_{\mu}\, \bar{\ell}_i \gamma^{\mu}(c_{\ell_i\, L} P_L + c_{\ell_i\, R} P_R)\ell_i$$

An EFT with a Z-prime is usually considered as descending from an abelian U(1)' gauge theory in the Higgs phase, by introducing a complex scalar charged under the U(1)', whose VEV breaks U(1)' spontaneously.

$$\mathcal{L}_{eff} = \mathcal{L}_{\rm SM} - \frac{1}{4} Z'_{\mu\nu} Z'^{\,\mu\nu} + \frac{1}{2} M_{Z'}^2 Z'^{\mu} Z'_{\mu}$$
$$+ Z'_{\mu}\, \bar{t}\gamma^{\mu}(c_{t_L} P_L + c_{t_R} P_R) t + \sum_{i=e,\mu,\tau} Z'_{\mu}\, \bar{\ell}_i \gamma^{\mu}(c_{\ell_i\,L} P_L + c_{\ell_i\,R} P_R)\ell_i$$

The simplified model has a more subtle issue, having to do with the U(1)' anomaly unless the Z' coupling is vector-like:

$$c_{\bullet L} = c_{\bullet R}$$

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As an EFT, the non-conservation of the U(1)' current is not necessarily pathological –

The EFT could still be quantized consistently, albeit with a cutoff

$$\Lambda \sim \frac{64\pi^3 m'_Z}{\left| g' \sum_i Q_i^3 \right|}$$

J. Preskill, 1991

In the UV theory, the anomaly can be cancelled by introducing additional "spectator fermions".

These spectator fermions can have a heavy mass and integrated out of the low-energy EFT, thereby justifying the simplified model.

(Of course, these spectator fermions could also be light and detected at the LHC.)

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The typical course of action is then to plug the EFT for the top-philic Z' into the softwares and starting generating events:

FeynRules → FeynArts/FormCalc or MG5_mc@nlo → Plots

(This was done in the literature.)

While anomaly cancellation is often brushed aside as a “UV” issue, the case of an anomalous, top-philic Z’ requires special attention due to a number of subtleties.

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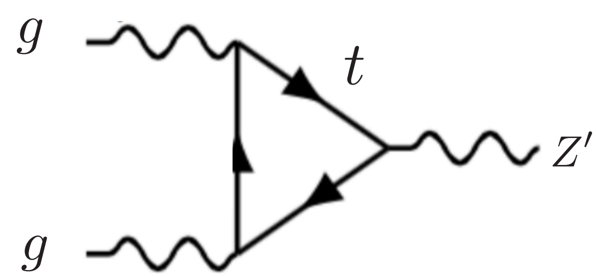
The top-philic Z' cannot be produced through the usual Drell-Yan channel, so it must go through either the tt+Z' or the loop-induced glue-glue fusion:



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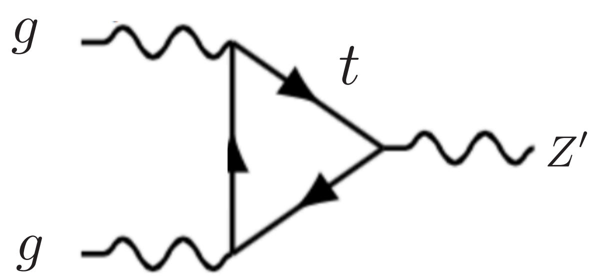

But we are saved by the Landau-Yang theorem from having to do this calculation!

An interesting twist is that the off-shell production of a single Z' is allowed:

$$gg \to Z'^{*} \to t\bar{t}$$

In this case, one need to treat the width of Z' with care, by consistently adopting the complex mass scheme:

$$M_{Z'}^2 \to M_{Z'}^2 - i\Gamma_{Z'} M_Z$$

Artoisenet et. al.:1306.6464

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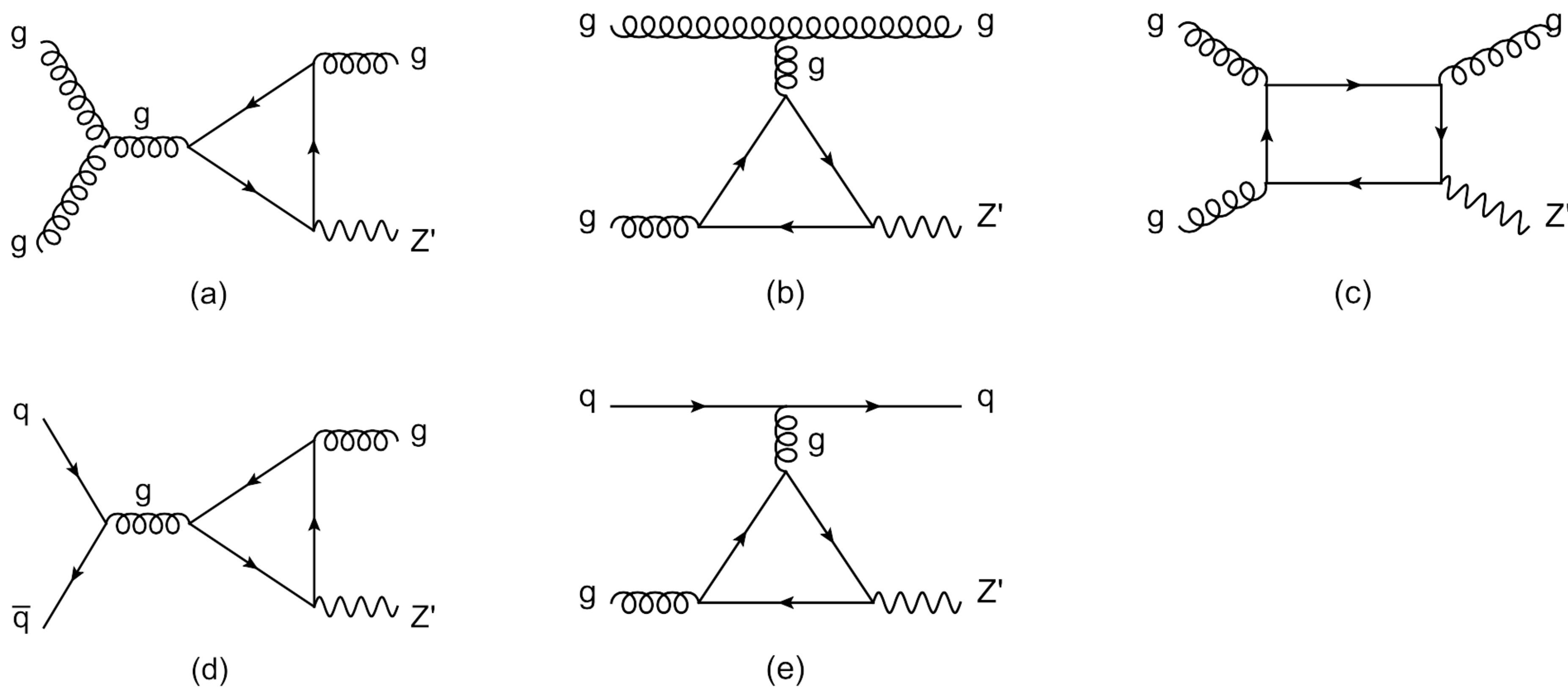
Artoisenet et. al.:1306.6464

Otherwise, artificial features in the invariant mass spectrum of the final states would appear, while there should not none.

When done properly, this contributes to the continuum production of ttbar, and is expected to be subdominant to what we will discuss in the following.

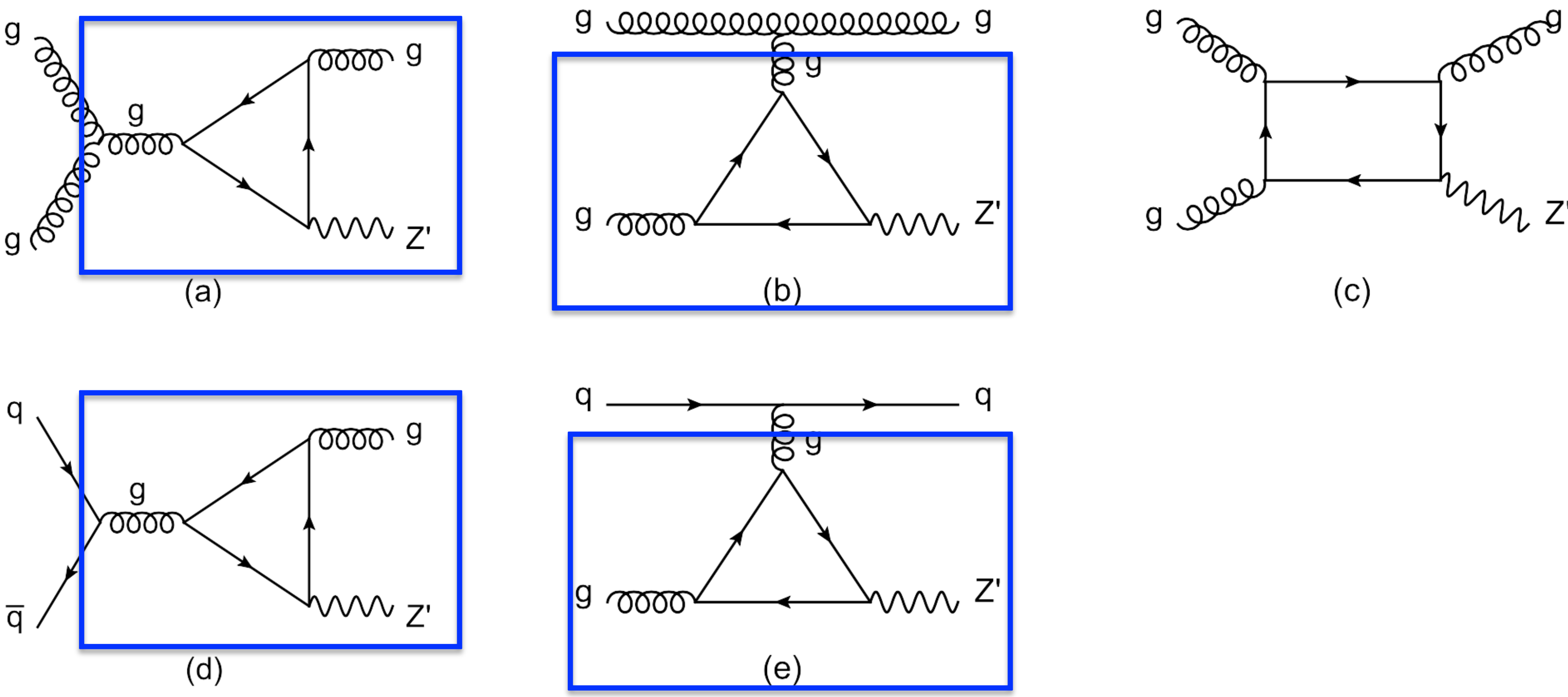
Coming back to Z' production, it turns out that one can look at the loop-induced:

$$pp \to Z' + j$$

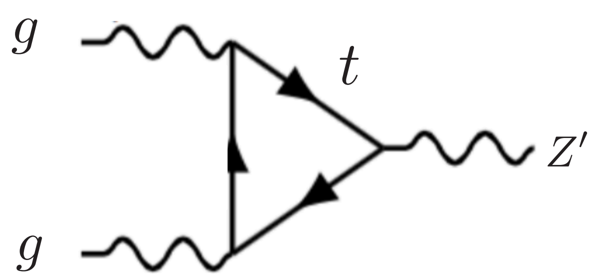


So you can run from the anomaly, but you can't hide from it!

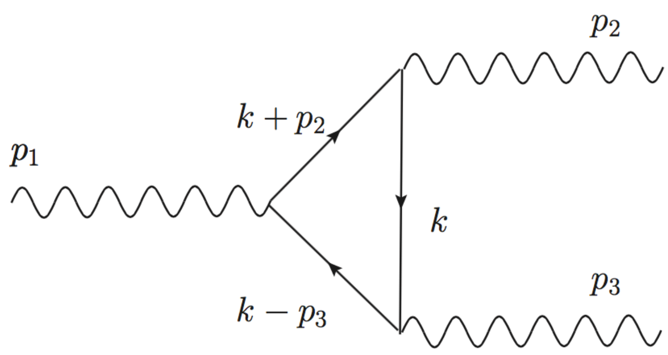
$$pp \to Z' + j$$

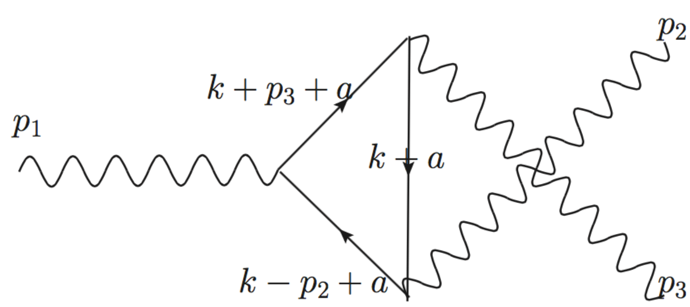


The question: how to evaluate the fermion triangle diagram in the EFT?



This diagram has been evaluated since the early days of chiral anomaly. There are really two diagrams:





In an anomaly-free theory, the momentum shift in one diagram can be different from the shift in the other diagram and the outcome remains the same.

NO LONGER TRUE in an anomalous theory.

One therefore need further physical input to choose a momentum routing in computing the diagram.

Most popular choice in the literature is that giving rise to the "consistent anomaly":

$$p_1^\rho \mathcal{M}_{\mu\nu\rho} = p_2^\rho \mathcal{M}_{\mu\rho\nu} = p_3^\rho \mathcal{M}_{\rho\mu\nu}$$

This choice symmetrizes with respect to all three external momenta.

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This choice symmetrizes with respect to all three external momenta.

Since all three currents cannot be conserved simultaneously, this implies the Ward identity for SU(3) color is NOT respected.

The remedy is to add by hand a Wess-Zumino term to the EFT:

$$c_{WZ}\ g_X g_s^2\ \epsilon^{\mu\nu\rho\sigma} Z'_\mu \left(G^a_\nu \partial_\rho G^a_\sigma + \frac{1}{3} g_s \epsilon^{abc} G^a_\nu G^b_\rho G^c_\sigma \right)$$

WZ term gives a new contribution to the three-point vertex,

$$\mathcal{M}_{\text{tot}} = \mathcal{M} + \mathcal{M}_{WZ}$$

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The "consistent anomaly" is popular, partly because it is what you get from starting with an anomaly-free UV theory and then integrating out the spectator fermions.

This is similar to integrating out the top quark in the SM, thereby generating a Wess-Zumino term. (D'Hoker and Farhi, 1984)

On the other hand, this is just one of the possibilities.

One could also choose a momentum routing to respect the SU(3) Ward identity:

$$p_1^\rho \mathcal{M}_{\mu\nu\rho} = p_2^\rho \mathcal{M}_{\mu\rho\nu} = 0$$

Then there is no need to add a WZ term in the EFT "by hand."
This is related to the "covariant anomaly" approach.

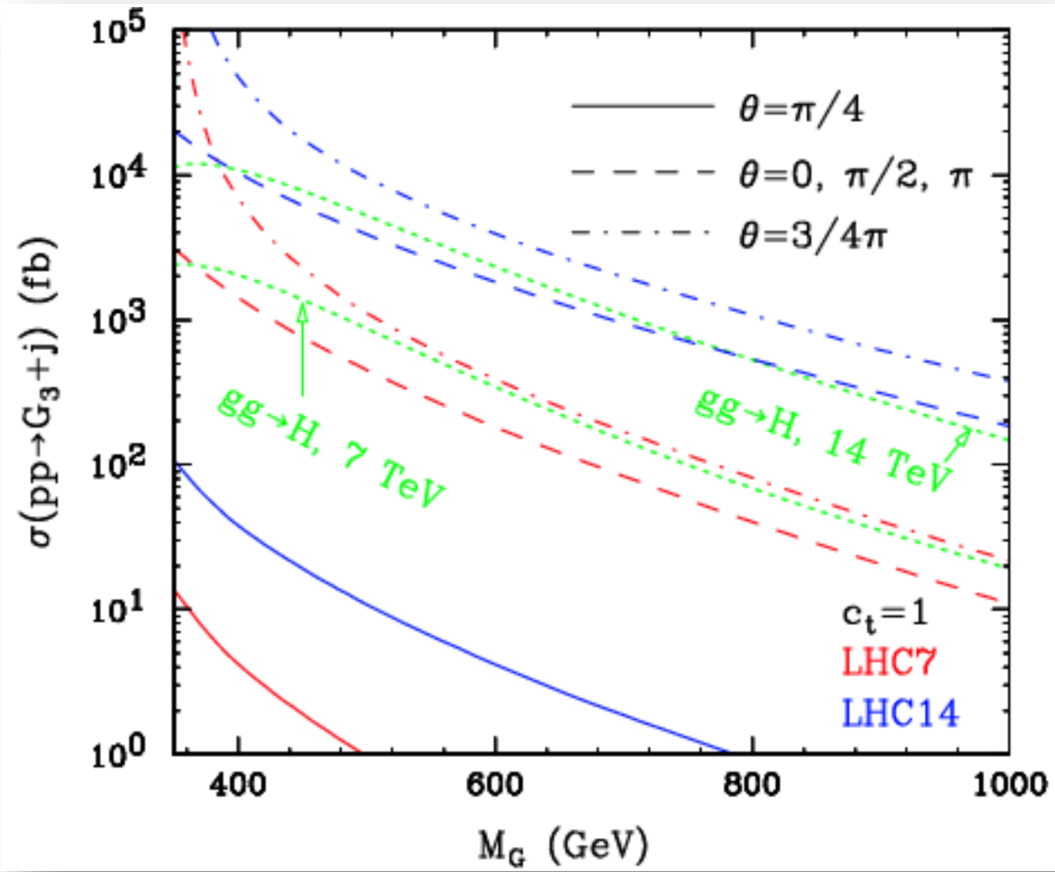
When done properly, both approaches give the same answer.

The only question is:

Which momentum routing is your software using to compute the triangle diagram?

(I am not aware of any computing code that is intelligent enough to add the Wess-Zumino term to the Lagrangian automatically.)

Some authors obtained a large cross-section:



$$
\begin{aligned}
\mathcal{L} &= \bar{t}\,\gamma_\mu\Big(c_L P_L + c_R P_R\Big)t\,G_3^\mu\ , \\
&= c_t\,\bar{t}\,\gamma_\mu\Big(\cos\theta\,P_L + \sin\theta\,P_R\Big)t\,G_3^\mu
\end{aligned}
$$

Greiner et. al.: 1410.6099

There is a fool-proof way of dealing with this issue, by explicitly adding the anomaly-cancelling spectator fermion in the code:

$$\mathcal{L} = \bar{t}\not{Z}'(c_{t_L} P_L + c_{t_R} P_R)t + \bar{T}\not{Z}'(c_{T_L} P_L + c_{T_R} P_R)T$$

Conservation of the U(1)' current requires

$$c_{t_L} - c_{t_R} = -(c_{T_L} - c_{T_R})$$

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Conservation of the U(1)' current requires

$$c_{t_L} - c_{t_R} = -(c_{T_L} - c_{T_R})$$

which is simply the statement that the axial couplings of Z' to t and T are opposite of each other.

These parameters can be free otherwise.

In particular, if one is not interested in the collider phenomenology of the spectator fermion, M_T can be taken as large as one wishes.

It is also instructive to take a look from the UV perspective.

A top-philic Z' can be implemented in a couple of ways. At a minimum, we need

- A complex scalar that is an electroweak singlet and charged under U(1)', whose VEV gives a mass to Z'.
- A vector-like pair of $SU(2)_L$ singlet fermions charged under U(1)'.

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Then if the vector-like fermion mixes with the SM top, a top-philic Z' is generated.

The heavy fermionic mass eigenstate now plays the role of the "spectator fermion responsible for canceling the U(1)' anomaly.

There are two possible sources for the mixing with the SM top:

- Through U(1)' breaking effect.

  That is, the mixing is induced after the U(1)' scalar gets a VEV.

  In the literature this is called the "effective Z-prime model."

  (1104.4127: Fox, Liu, Tucker-Smith and Weiner.)

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- Through electroweak SU(2)xU(1) breaking effect.
  The mixing is induced after an electroweak doublet scalar gets a VEV.
  This is a 2HDM model, with only one doublet charged under U(1)'.
  SM right-handed top is directly charged under U(1)'.
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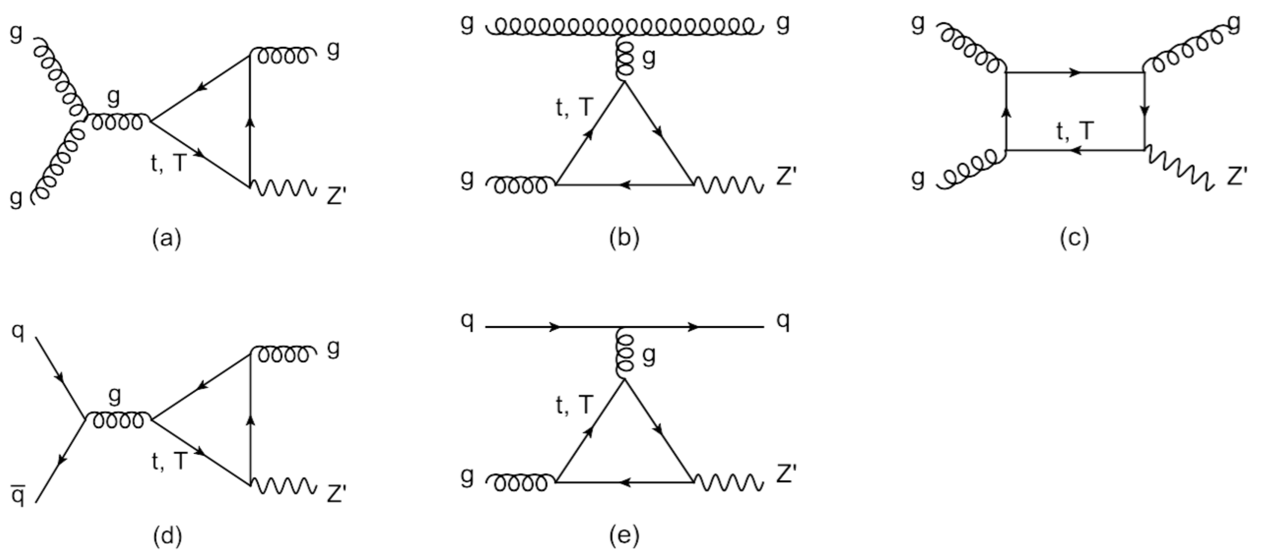
- And there is a continuous interpolation between these two cases.

Now we are ready to consider the collider phenomenology of a top-philic Z-prime. There are two dominant production channels at the LHC:

- Tree-level ttbar+Z'

- Loop-induced gg→g+Z', qqbar→g+Z', qg→q+Z', gqbar→qbar+Z':
  here it is important to introduce the anomaly-cancelling spectator fermion to ensure the triangle diagrams are evaluated properly.



Let's make a comparison:

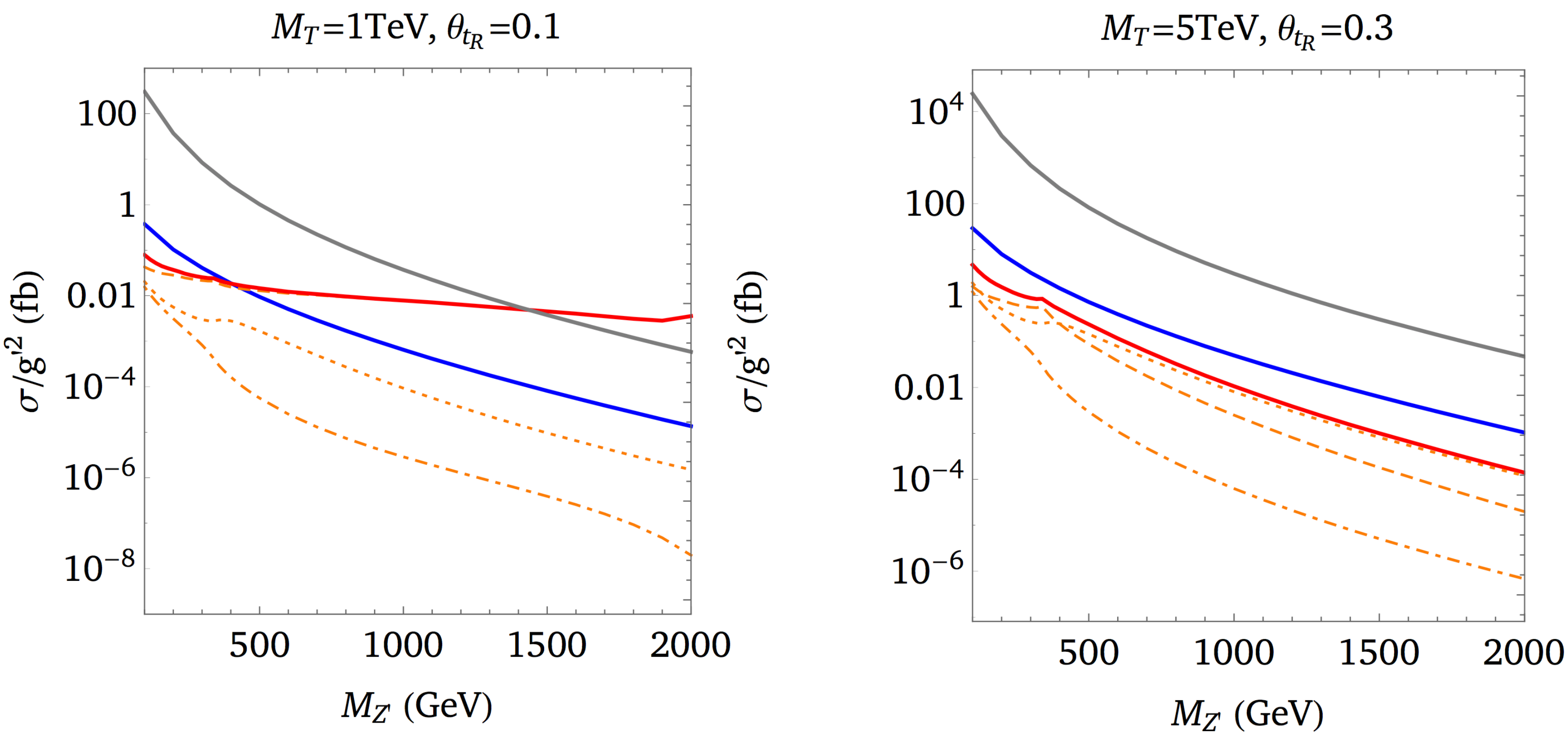


Figure 5: Z' production cross sections at 13 TeV LHC for various channels and various sets of parameters in the model we consider. Blue: tree-level $pp \to t\bar{t}Z'$; Red: sum of all loop level channels; Orange dashed: loop-level $gg \to gZ'$; Orange dot-dashed: loop-level $q\bar{q} \to gZ'$; Orange dotted: loop-level $qg \to qZ'$ and $\bar{q}g \to \bar{q}Z'$. Grey: sum of all loop level channels in the incomplete theory without T.

(The calculation is done using FeynRule/FeynArt/FormCalc)

Another comparison:

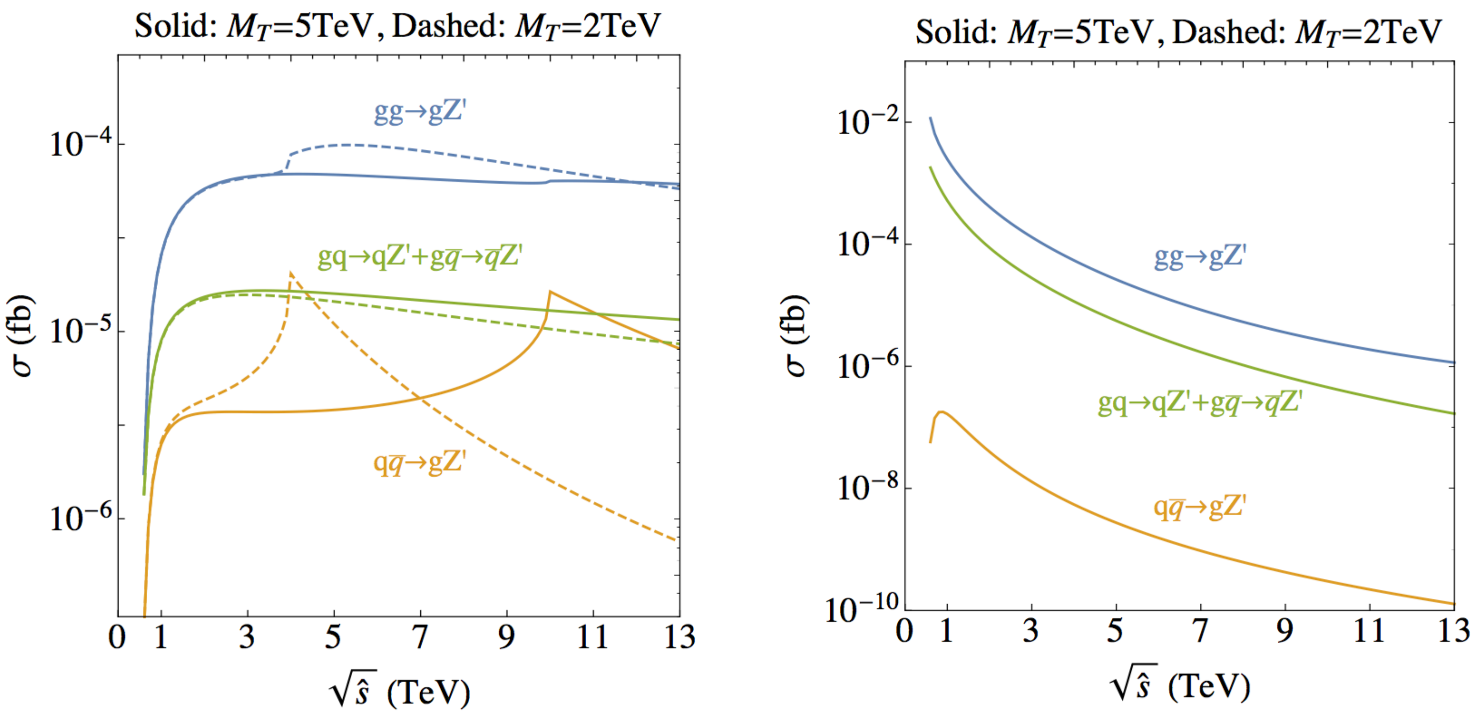


Figure 5: Left: UV complete model with $M_{Z'} = 500\,\mathrm{GeV}$, $c_{t_L} = 0$, $c_{t_R} = 0.1$, $c_{T_L} = 1$, $c_{T_R} = 0.9$ and for two values of $M_T = 5\,\mathrm{TeV}$ (solid), $2\,\mathrm{TeV}$ (dashed). Right: Incomplete model with $M_{Z'} = 500\,\mathrm{GeV}$, $c_{t_L} = 0$, $c_{t_R} = 0.1$, $c_{T_L} = 0$, $c_{T_R} = 0$.

To summarize, here's a recipe for doing the calculations properly:

- Include both the SM top quark and the vector-like top partner in the loop, making sure the anomaly cancellation condition is met:

$$\boxed{c_{t_L} - c_{t_R} = -(c_{T_L} - c_{T_R})}$$

To summarize, here's a recipe for doing the calculations properly:

- Include both the SM top quark and the vector-like top partner in the loop, making sure the anomaly cancellation condition is met:

$$\boxed{c_{t_L} - c_{t_R} = -(c_{T_L} - c_{T_R})}$$

- Calculate the loop diagrams with only the SM top quark, but ensure the Ward identity for the SU(3) color is satisfied:

$$\boxed{p_1^\rho \mathcal{M}_{\mu\nu\rho} = p_2^\rho \mathcal{M}_{\mu\rho\nu} = 0}$$

After making sure the production rate is computed properly, one can start looking at constraints.

At the LHC, the top-philic Z' is produced in

$$pp \to Z' + t\bar{t}$$
$$pp \to Z' + j$$

Possible searches include

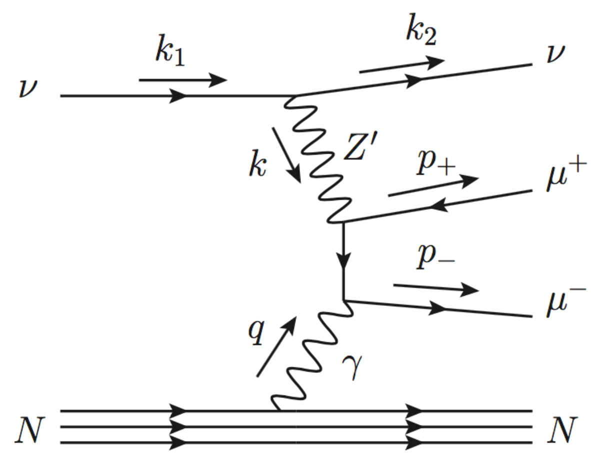
- (model dependent) inclusive dilepton searches.
- (model depednent) MET + X searches (for Z' decaying to neutrinos).
- (model independent) four top searches – multi-jet/multi-lepton + MET.

There are also constraints from "low-energy" probes of new physics:
(Mostly on Z' couplings to leptons.)

- Measurements at the Z-pole (LEP): Z-Z' mixing/Lepton-flavor universality in the Z decays.

- Muon g-2.

- Neutrino trident production seems particularly powerful:



Altmannshofer et. al.: 1406.2332

Among these constraints, the most competitive ones are

- Dilepton searches at the LHC
- LUF at LEP
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However, these constraints are all somewhat model-dependent.

The only truly model-independent constraint is the 4-top production.

→ The relevant analyses are not usually interpreted in the top-philic Z-prime model.

In the context of the flavor anomaly in LFV of B decays:

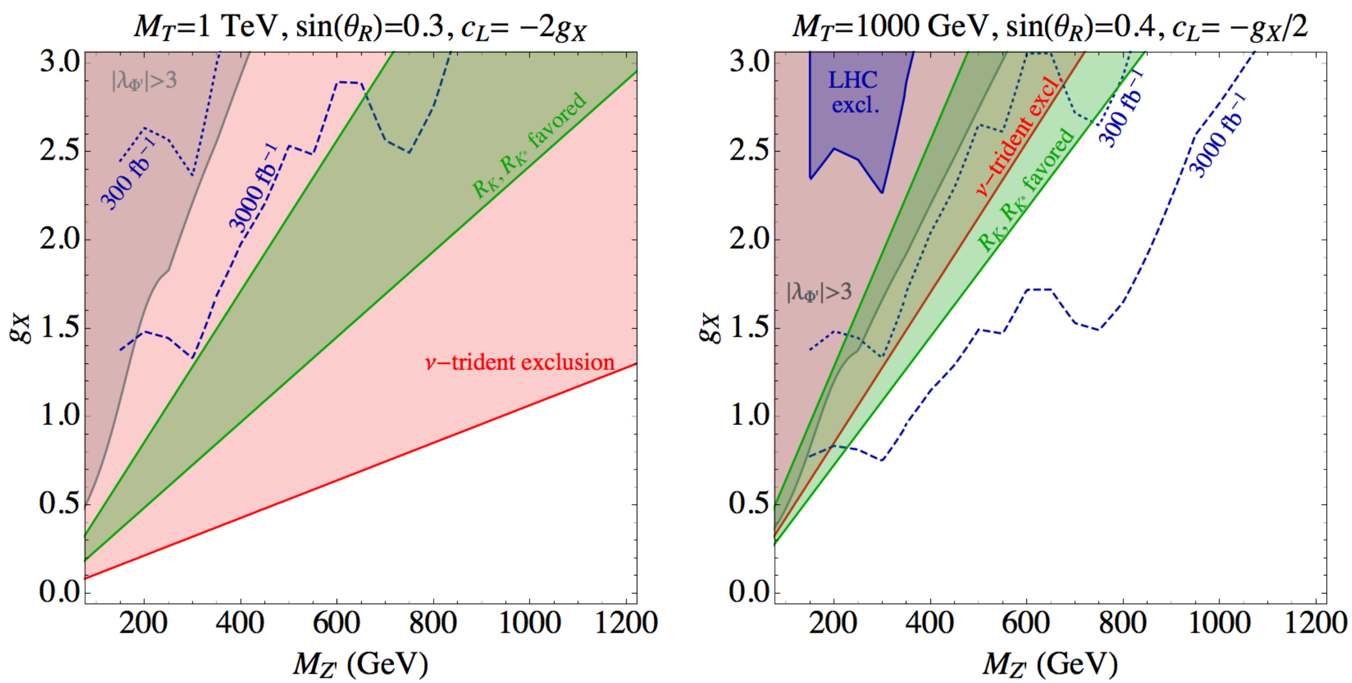
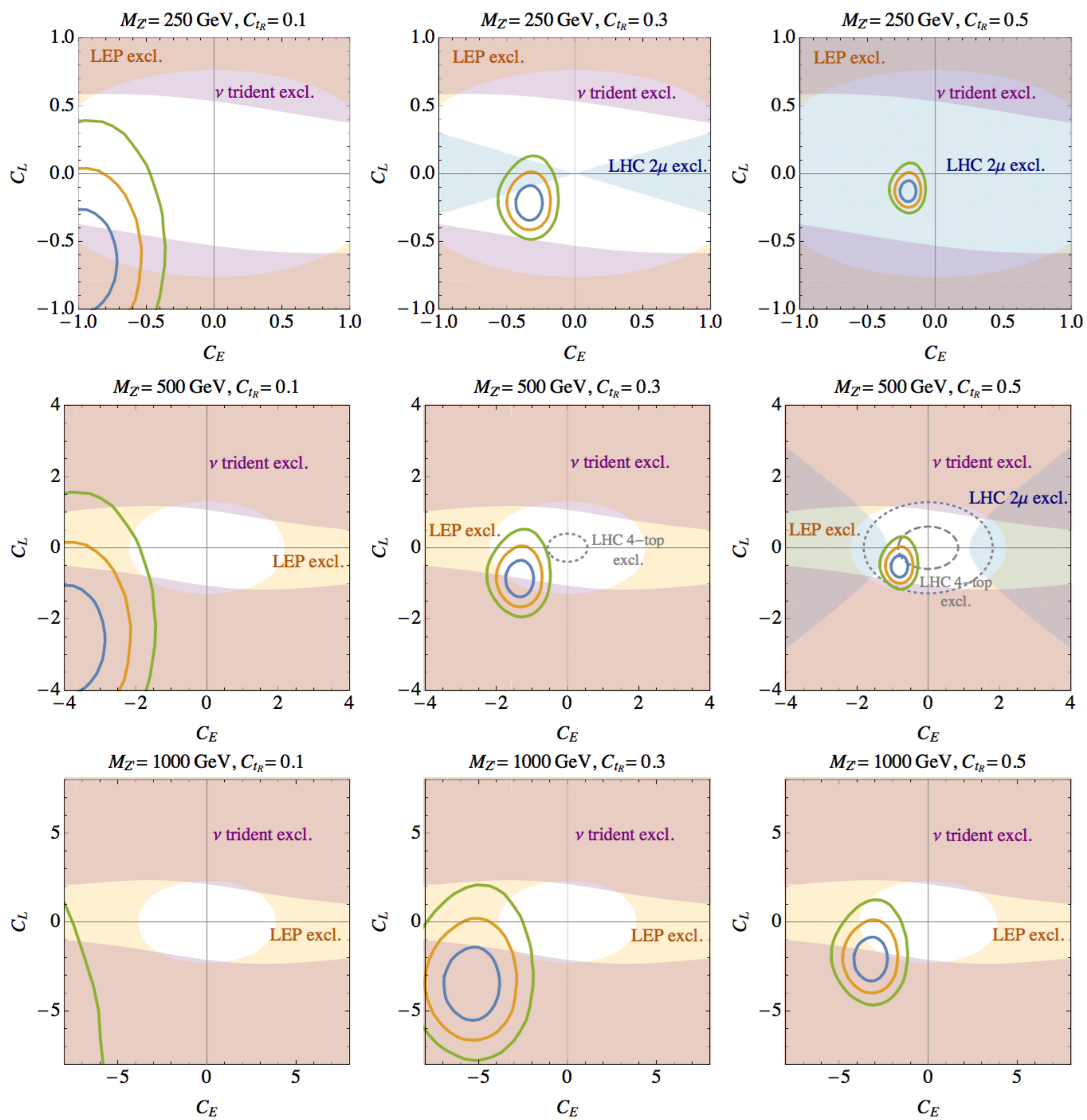


Figure 8: Favored regions and constraints on the parameter space (the g_X-$M_{Z'}$ plane) of the effective Z' model, defined in Eq. (5.1) and (5.3), with $M_T = 1\,\text{TeV}$, and $\sin\theta_R = 0.3$, $c_L = 2g_X$, $c_E = 0$ (left); $\sin\theta_R = 0.4$, $c_L = g_X/2$, $c_E = 0$ (right). The green region in each plot is favored for explaining the LHCb anomalies. The yellow shaded regions are excluded by the neutrino trident production measurement. The orange shaded region is excluded by the LHC dimuon resonance search. The dashed (dotted) orange curve corresponds to the future LHC reach with an integrated luminosity 300 (3000)/fb.

Just a glance of constraints on more general parameter space:



Concluding Remarks:

- The absence of significant deviations in LHC searches means we are on a slow march to potential discovery.
- Time is ripe to reconsider and revise our search strategies.
- There's still a lot to be done, even for such a simple subject like the Z-prime.
- It's important to think about implications of the flavor anomaly at the LHC.