Z′ STUDIES IN EXOTIC Z DECAYS

Felix Yu

Johannes Gutenberg University, Mainz

Work in progress with Bogdan Dobrescu (FNAL); also Lisa Michaels (JGU Mainz)

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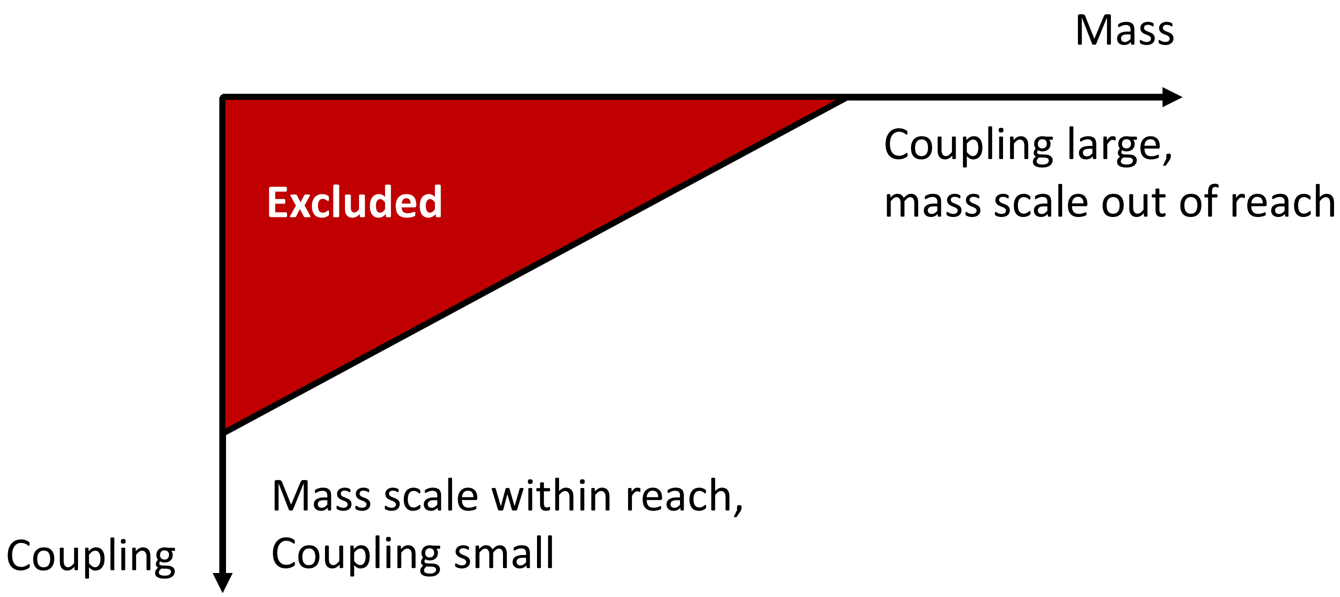
Introduction and Motivation

- Where is the new physics?
  - Coupling vs. mass plane gives a useful (but rough) schematic picture



Introduction and Motivation

- Where is the new physics?
  - Coupling vs. mass plane gives a useful (but rough) schematic picture
    - In words, can generally decouple new physics by either taking the mass scale very large or sending its coupling to be very small
  - Generally have smooth crossover between energy and intensity frontier for new physics reach
  - Canonical BSM models that exhibit “small” couplings are *portal* models

Portal couplings and sensitivity frontier

- General UV behavior of QFT motivates probing *portal* couplings to BSM sectors
  - Orthogonal to SMEFT
- Sensitivity frontier: energy and intensity crossover
  - A priori, mass scales and coupling strengths can vary over decades

$$\begin{aligned} \text{scalar Higgs portals:} &\quad \kappa_s S|H|^2 + \lambda_{hs} S^2 |H|^2 + \lambda_{hp} |\Phi|^2 |H|^2 \\ \text{neutrino portal:} &\quad y_N \bar{L} H N + \text{ h.c.} \\ \text{vector portal:} &\quad \epsilon B_{\mu\nu} K^{\mu\nu} \\ \text{axion portal:} &\quad \frac{1}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} \end{aligned}$$

Portal couplings and sensitivity frontier

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$$
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\text{vector portal:} \quad & \epsilon B_{\mu\nu} K^{\mu\nu} \\
\text{axion portal:} \quad & \frac{1}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu}
\end{aligned}
$$

Attractive NP models within direct reach of e+e– machines
e.g. J. Liu, X.-P. Wang, FY [1704.00730]

For this talk, eschew standard portal models

Instead consider *gauge* portal

Building additional gauge symmetries

- Directly augment covariant derivative of subset of SM fields
  - New gauge coupling and symmetry-breaking scale are still free parameters
- Immediate phenomenology and theory concerns
  - FCNC constraints
  - Chiral anomalies

Building additional gauge symmetries

- Want to directly charge SM fields under U(1)′
  - Flavor constraints imply U(1)′ should be subgroup of $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$
    - Otherwise, U(1)′ interactions spoil global SM flavor symmetry
- Since EW symmetry is chiral, most global symmetry choices are anomalous
    - Common exceptions: $U(1)_{B-L}$, L_μ-L_τ
  - Renormalizability in UV requires new chiral fermions

Preskill (1991)

  - Mixed anomalies force introduction of new EW-charged states $\mathcal{A}(SU(2)^2 \times U(1)_B) = \frac{3}{2}$ $\mathcal{A}(U(1)_Y^2 \times U(1)_B) = \frac{-3}{2}$

Anomaly cancellation

- Renormalizability in UV requires new chiral fermions
  - VL representations ≡ allow tree-level Dirac mass term ≡ vanishing chiral anomaly contribution
  - Chiral representations ≡ forbidden tree-level Dirac mass term ≡ nonzero chiral anomaly contribution
- Mixed anomalies force introduction of new EW-charged states

  Fileviez Perez, Wise [1002.1754]
  - Anomalons do not have to carry color
- Minimal set of anomalons (SU(2), $U(1)_Y$, $U(1)_B$)

$$L_L(2,-\frac{1}{2},-1),\ L_R(2,-\frac{1}{2},2),\quad E_L(1,-1,2),\ E_R(1,-1,-1),$$
$$N_L(1,0,2),\ N_R(1,0,-1)$$

Gauged baryon model

- Minimal set of anomalons (SU(2), $U(1)_Y$, $U(1)_B$)
  - Collider phenomenology akin to SUSY EWinos

$$L_L(2,-\frac{1}{2},-1),\ L_R(2,-\frac{1}{2},2),\quad E_L(1,-1,2),\ E_R(1,-1,-1),$$
$$N_L(1,0,2),\ N_R(1,0,-1)$$

- Introduce ϕ as baryon-number Higgs ($Q_B = 3$)

$$\mathcal{L} = -y_L \bar{L}_L \phi^* L_R - y_E \bar{E}_L \phi E_R - y_N \bar{N}_L \phi N_R + \text{ H.c.}$$

- In this construction, tree-level Z-Z′ mixing vanishes
  - Reintroduced logarithmically at anomalon mass scale
  - Can also have tree or loop-generated Higgs-ϕ mixing

Gauged baryon model vs. EW SM

- Same structure in both cases
  - Chiral fermions, spontaneous breaking, Zs and Higgses
- One underlying scale for each chiral symmetry
- Yet, $U(1)_B$ (and any new chiral U(1)') can exhibit different mass hierarchy pattern than SM
- Consider all Yukawas larger than g_B, λ_B
  - Anomalons are non-decoupling a la top quark in $h \to \gamma\gamma$, $h \to gg$

Collider phenomenology: Z′ resonance

- Canonical Z′ dijet resonance from gauged baryon number
    - [Revisited as *s*-channel simplified model of DM production]
- Lagrangian and branching fraction

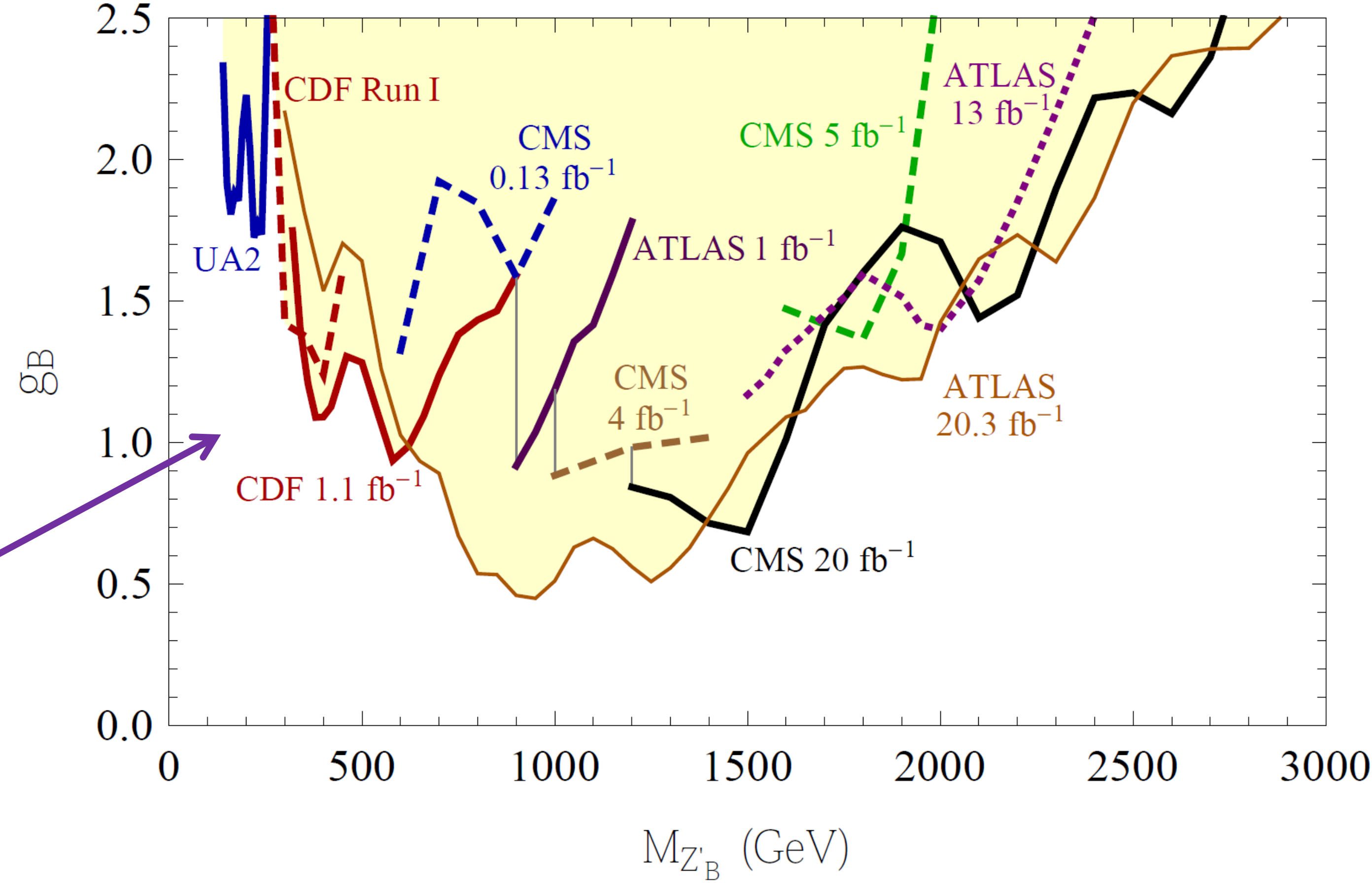
$$\mathcal{L}_q = \frac{g_B}{2} Z'_\mu \sum_q \left(\frac{1}{3}\, \bar{q}_L \gamma^\mu q_L + \frac{1}{3}\, \bar{q}_R \gamma^\mu q_R \right)$$

$$B(Z'_B \to jj) = \left[1 + \frac{1}{5} \left(1 + \frac{2m_t^2}{M_{Z'}^2} \right) \left(1 - \frac{4m_t^2}{M_{Z'}^2} \right)^{1/2} \right]^{-1}$$

NB: This afternoon and Friday's BSM tutorial will feature an introductory lecture on collider physics and hands-on sensitivity study for Z′ resonances at future pp colliders

Direct Z'_B limits – circa 2014

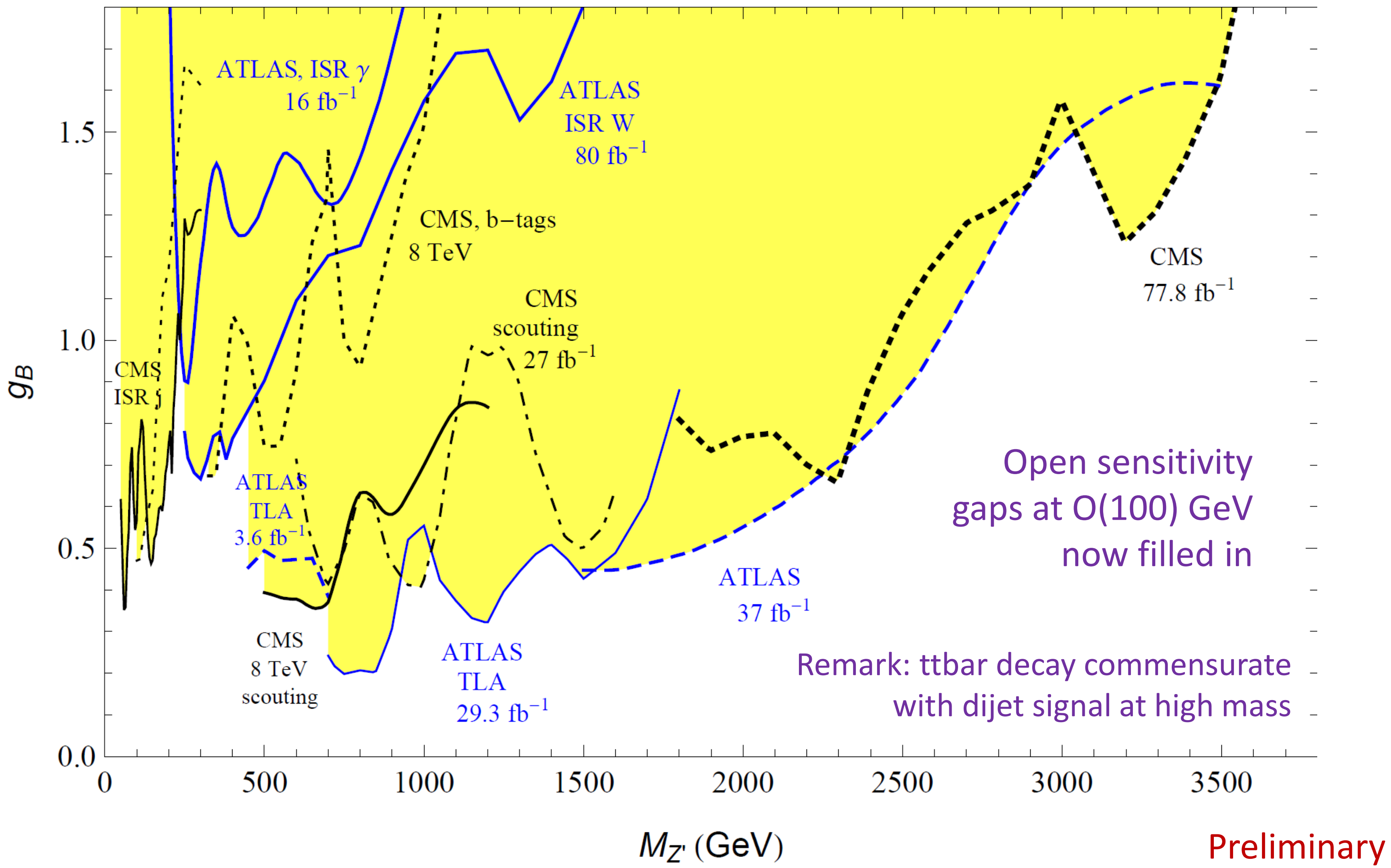
- Dijet searches parameterized by coupling and mass



Open sensitivity gaps at O(100) GeV now filled in

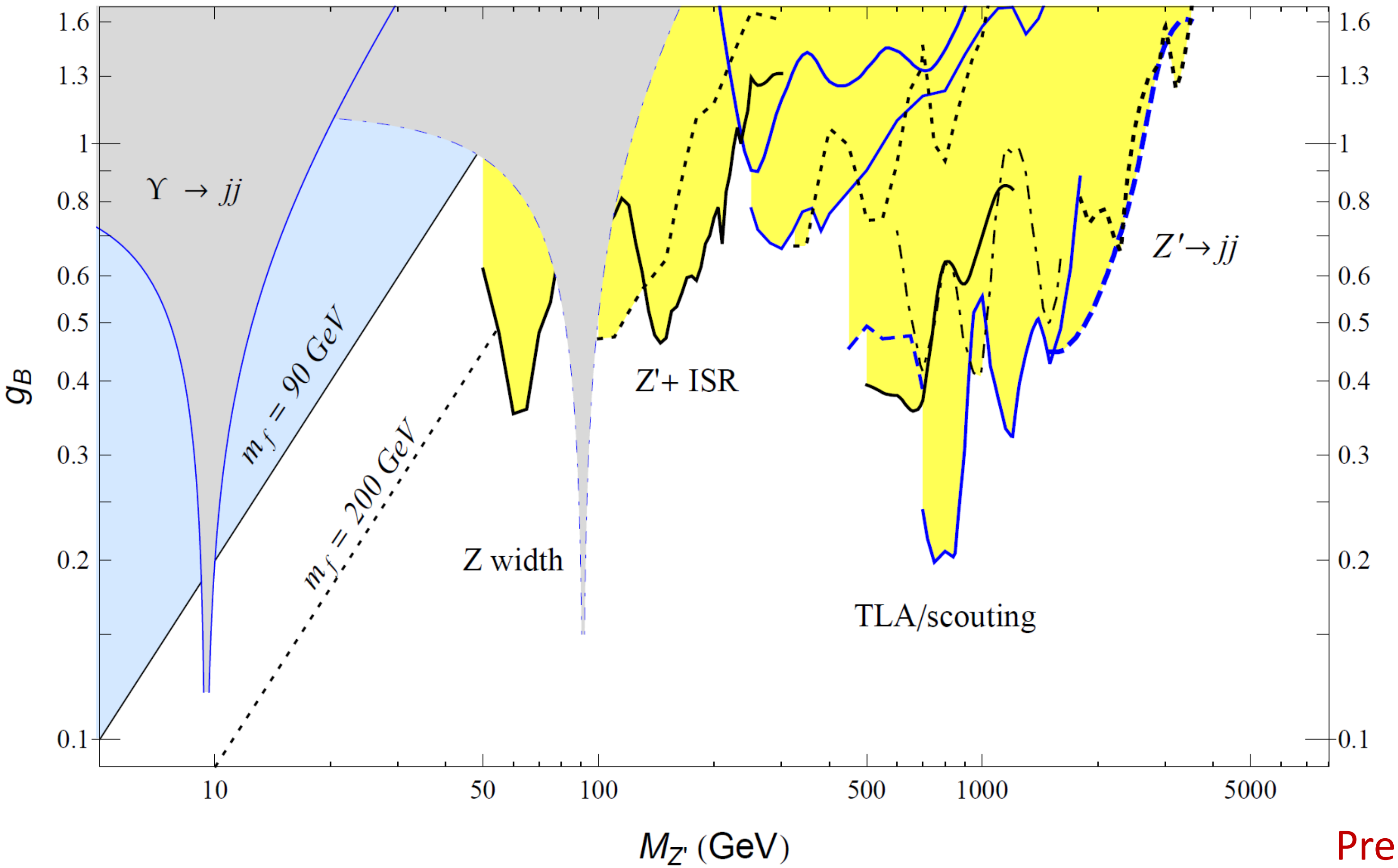
B. Dobrescu, FY [1306.2629], updated with ATLAS [1407.1376] results

Direct Z'_B limits



Direct Z'_B limits

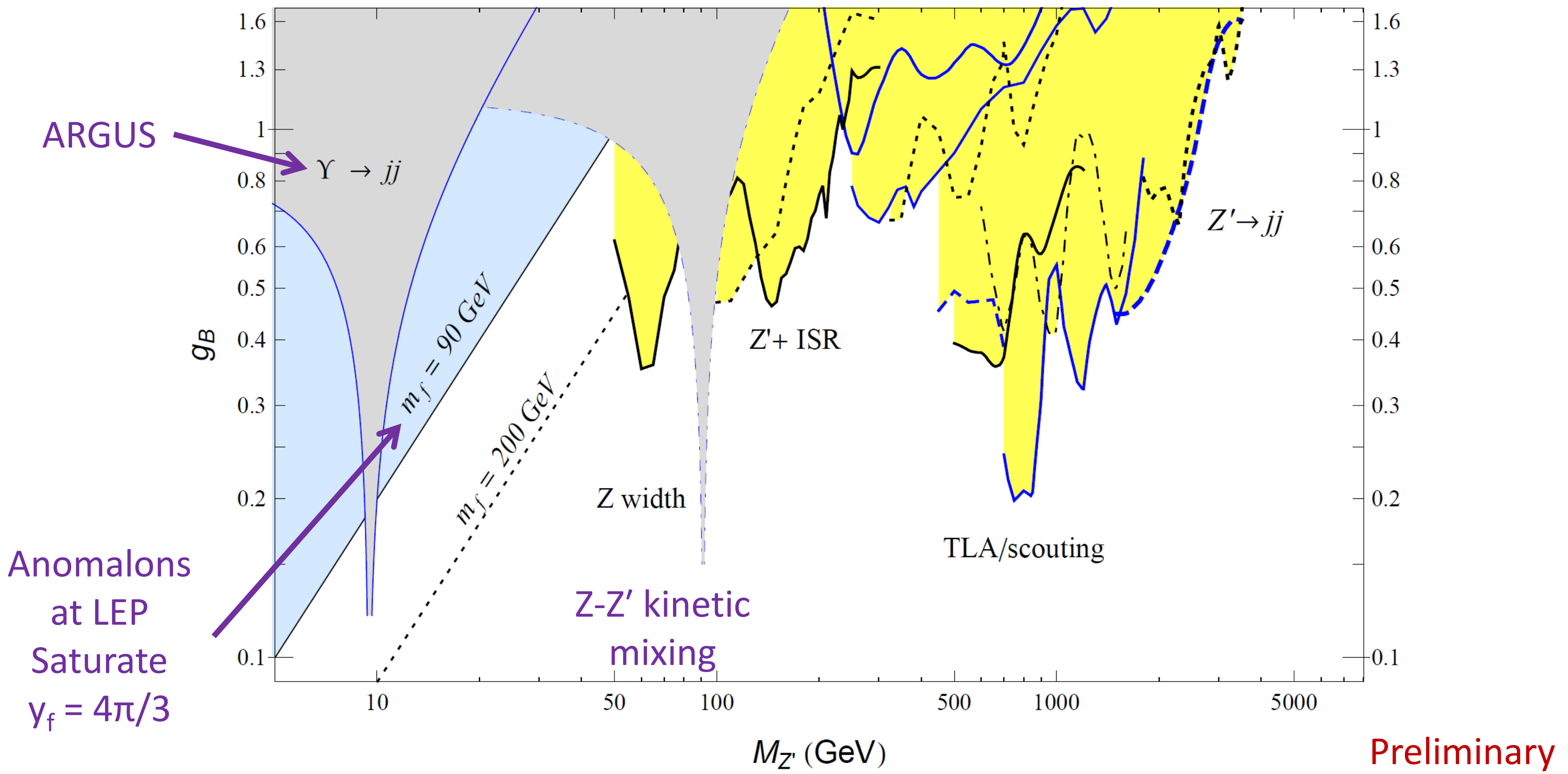
- Extend to lighter masses



Preliminary

Direct Z'_B limits

- Coupling and mass determine vev of U(1)′ breaking



Gauge anomalies and EFT

- After EWSB (and $U(1)_B$) breaking, generate an effective Z-Z′-γ vertex
  – Non-decoupling of anomalons in vertex matches with Wess-Zumino term in anomalous U(1) EFT
- Calculate exotic Z decay width

WIP with L. Michaels

  – Inherent ambiguity in evaluation of triangle loop is entire motivation for ABJ chiral anomaly

Gauge anomalies and EFT

- Anomalons *are* basically copies of SM leptons, except allow chiral mass under EW symmetry and chiral mass under $U(1)_B$

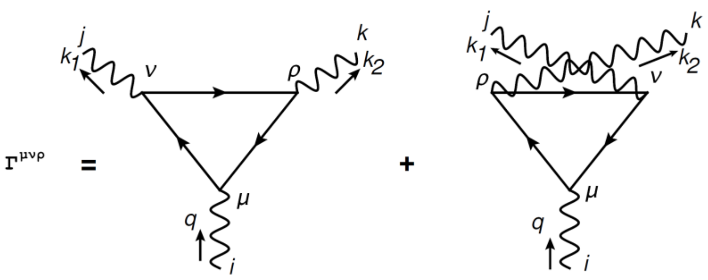
$$L_L(2, -\frac{1}{2}, -1),\ L_R(2, -\frac{1}{2}, 2), \quad E_L(1, -1, 2),\ E_R(1, -1, -1),$$
$$N_L(1, 0, 2),\ N_R(1, 0, -1)$$

  - Field content admits SM-like Yukawas as well as ϕ-coupled Yukawas
  - With both Yukawa terms, would have triangle diagrams with FCNC fermions

$$\mathcal{L} = -y_L \bar{L}_L \phi^* L_R - y_E \bar{E}_L \phi E_R - y_N \bar{N}_L \phi N_R + \text{ H.c.}$$
$$- y_1 \bar{L}_L H E_R - y_2 \bar{L}_R \tilde{H} E_L + \text{ H.c.}$$

Gauge anomalies and EFT

- Triple gauge vertex has two undetermined parameters generally requiring physicality condition (conservation of charge/Ward identity)
  - Massive Z, Z′ vectors also introduce Goldstone equivalence in Ward identity contribution

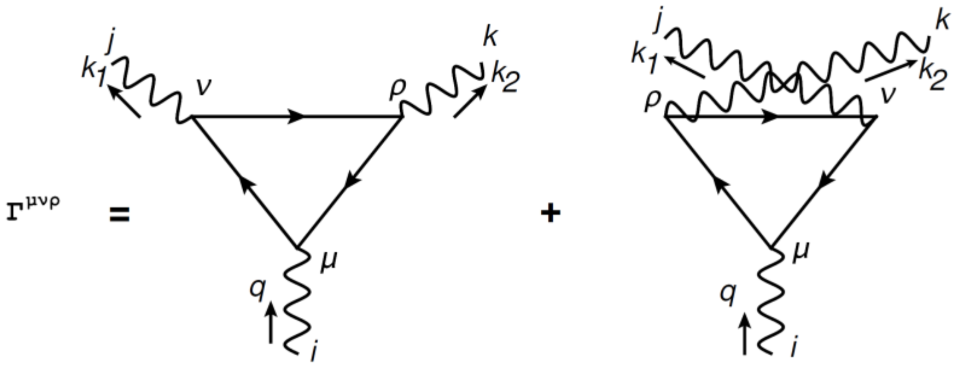


$$\Gamma^{\mu\nu\rho}(k_1, k_2; w, z) = \Big[A_1(k_1, k_2; w)\, \varepsilon^{\mu\nu\rho\sigma}\, k_{2\sigma} + A_2(k_1, k_2; z)\, \varepsilon^{\mu\nu\rho\sigma}\, k_{1\sigma} + A_3(k_1, k_2)\, \varepsilon^{\mu\rho\beta\delta}\, k_2^\nu\, k_{1\beta}\, k_{2\delta} + A_4(k_1, k_2)\, \varepsilon^{\mu\rho\beta\delta}\, k_1^\nu\, k_{1\beta}\, k_{2\delta} + A_5(k_1, k_2)\, \varepsilon^{\mu\nu\beta\delta}\, k_2^\rho\, k_{1\beta}\, k_{2\delta} + A_6(k_1, k_2)\, \varepsilon^{\mu\nu\beta\delta}\, k_1^\rho\, k_{1\beta}\, k_{2\delta} \Big] .$$

Dedes, Suxho [1202.4940]

Gauge anomalies and EFT

- Calculating the triple gauge vertex
  - Using gauge eigenstates equivalent to mass eigenstates since coupling-mass degeneracy holds
  - Shifts which vertex has vector vs. axial-vector couplings



Dedes, Suxho [1202.4940]

Exotic Z decay – complete result

- Full calculation of decay rate shows non-trivial decoupling of anomalons
  - EFT cannot know about UV completion
  - Anomalons must cancel their own anomaly

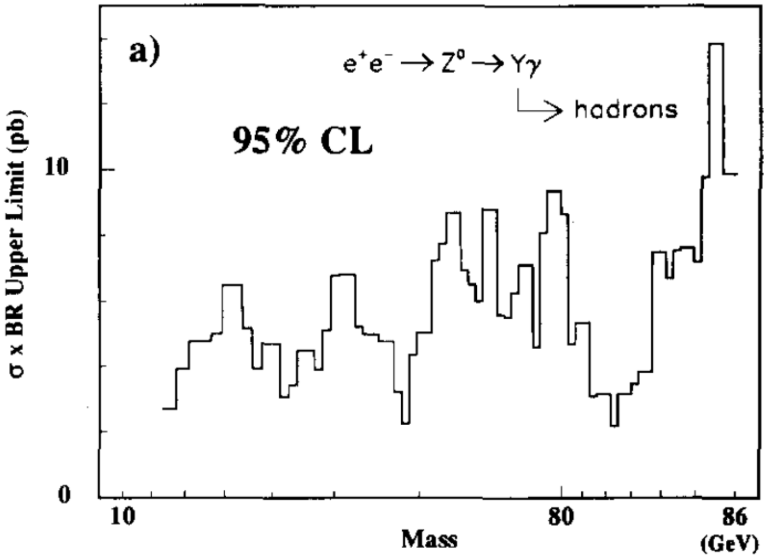
$$\Gamma(Z \to Z'\gamma) = \frac{g_B^2 g^2 e^2 m_{Z'}^2 (1 - (m_{Z'}^4/m_Z^4))}{221184\pi^5 c_W^2 m_Z} \times$$
$$\left(9 + 7\frac{m_Z^2}{m_Z^2 - m_{Z'}^2}\log(m_{Z'}^2/m_Z^2) + 4m_t^2 C_0(0, m_Z^2, m_{Z'}^2, m_t, m_t, m_t)\right.$$
$$\left. + 2\frac{m_Z^2}{m_Z^2 - m_{Z'}^2}(B_0(m_Z^2, m_t, m_t) - B_0(m_{Z'}^2, m_t, m_t))\right)^2$$

Preliminary

– C_0 and B_0 are usual three-pt., two-pt. scalar integrals
  - Top quark effectively acts as an anomalon

Exotic Z decay

- Rate too small for LEP
  - – L3 probed $Z \rightarrow (jj)\gamma$ for $Br(O(10^{-4}))$



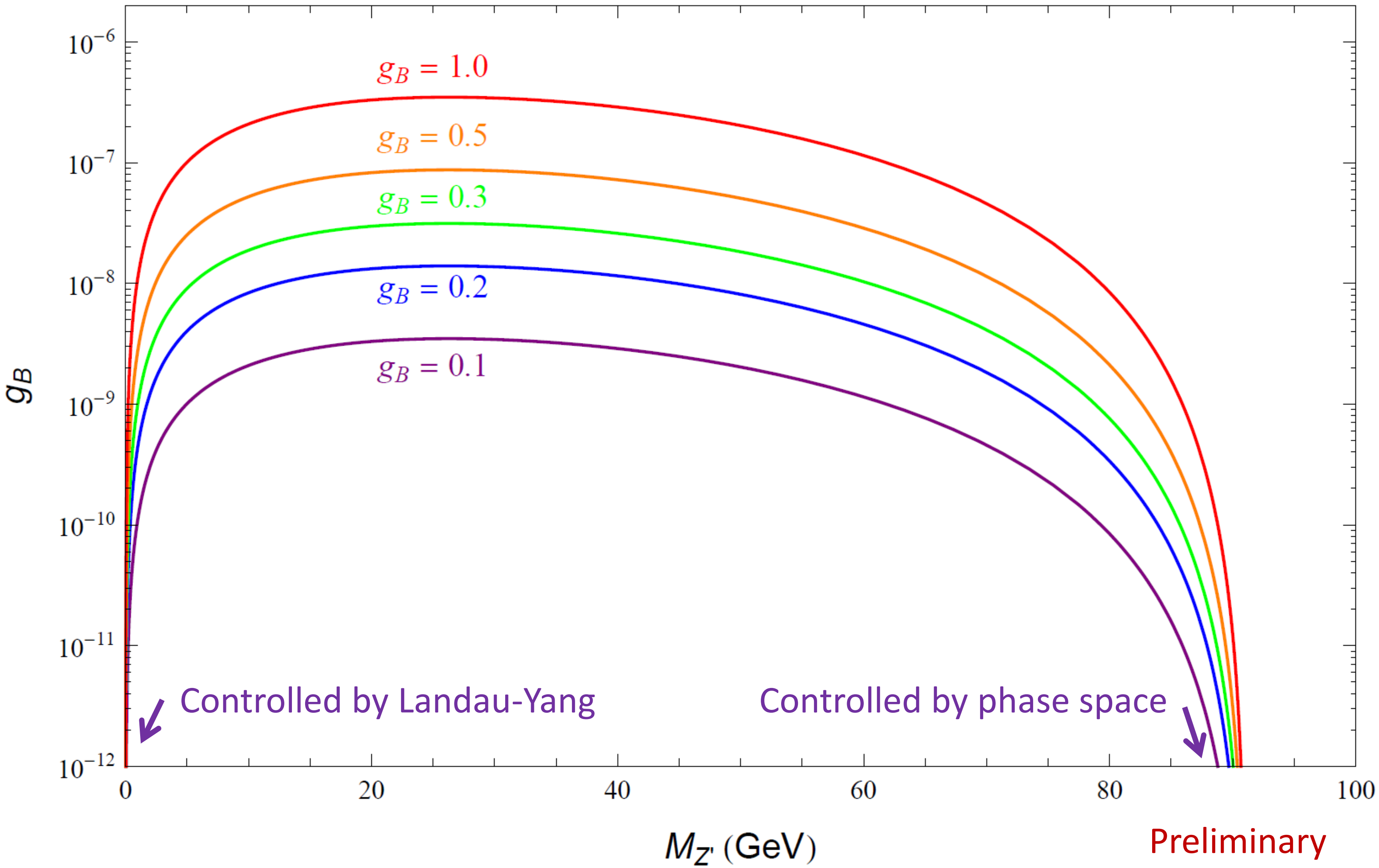
L3, PLB 292 (1992) 472

Preliminary

$$B(Z \to Z'\gamma) = \frac{49 g_B^2 g^2 e^2 m_{Z'}^2 (1 - (m_{Z'}^4/m_Z^4))}{221184\pi^5 c_W^2 m_Z \Gamma_Z} \left(1 + \frac{m_Z^2}{m_Z^2 - m_{Z'}^2} \log(m_{Z'}^2/m_Z^2)\right)^2$$

$$\approx 1.52 \times 10^{-7} \frac{m_{Z'}^2}{m_Z (10 \ \text{GeV})} (1 - m_{Z'}^4/m_Z^4) \left(1 + \frac{m_Z^2}{m_Z^2 - m_{Z'}^2} \log(m_{Z'}^2/m_Z^2)\right)^2$$

Exotic Z decay



Preliminary

Exotic Z decay

- Rate too small for LEP
  - L3 probed Z → (jj)γ for Br(O(10^{-4}))
  - Possible for GigaZ or TeraZ future collider, even HL-LHC?
    - For TeraZ, naïve rescaling from LEP gives Br(O(10^{-7})) sensitivity – currently under study
    - Also interesting to consider Z → (ll)γ to improve on LEP bounds

$$B(Z \to Z'\gamma) = \frac{49 g_B^2 g^2 e^2 m_{Z'}^2 (1 - (m_{Z'}^4/m_Z^4))}{221184 \pi^5 c_W^2 m_Z \Gamma_Z} \left(1 + \frac{m_Z^2}{m_Z^2 - m_{Z'}^2} \log(m_{Z'}^2/m_Z^2)\right)^2$$

$$\approx 1.52\, g_B^2 \times 10^{-7} \frac{m_{Z'}^2}{m_Z (10 \ \ \text{GeV})} (1 - m_{Z'}^4/m_Z^4) \left(1 + \frac{m_Z^2}{m_Z^2 - m_{Z'}^2} \log(m_{Z'}^2/m_Z^2)\right)$$

Preliminary

Exotic Z decay

- Another study considered another set of exotic Z decays, mainly focusing on MET signals (but also include 4j and 3γ)

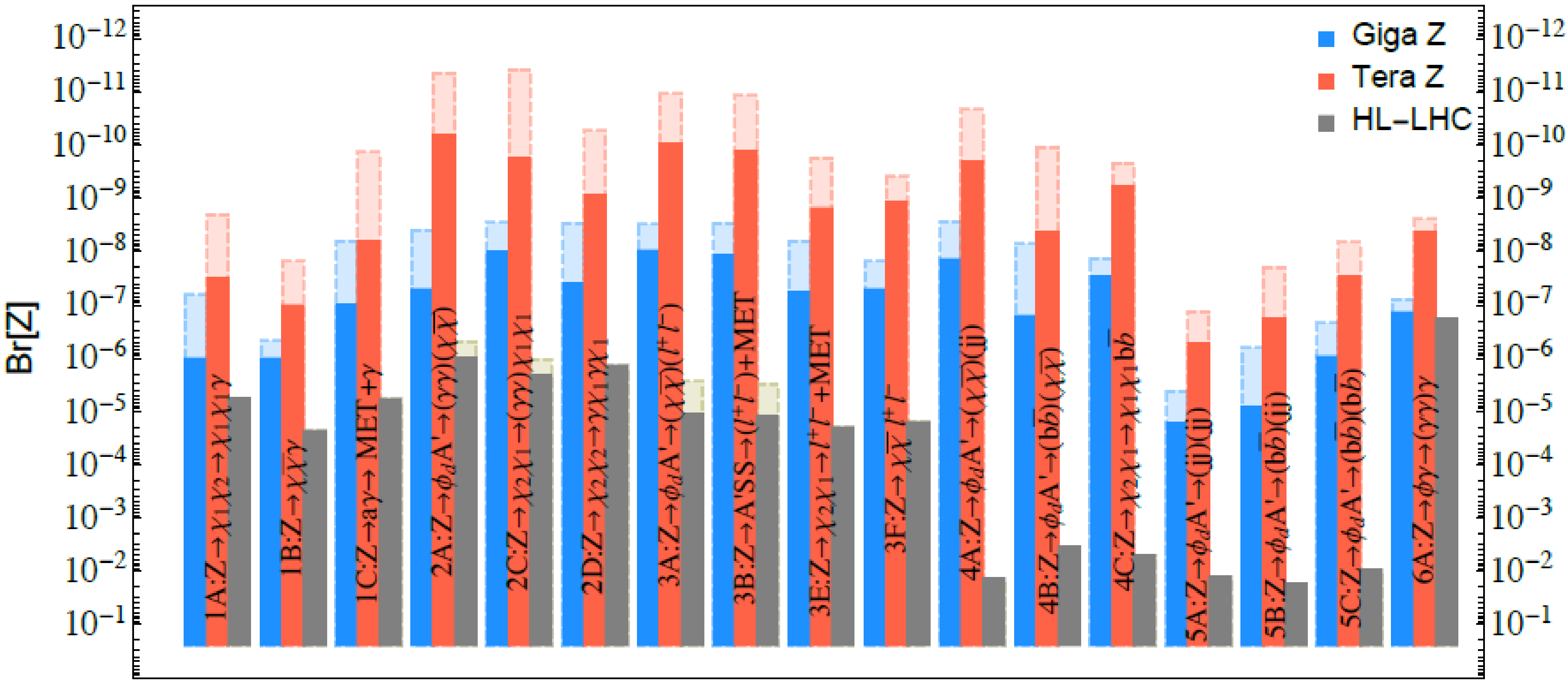
exotic decays	topologies	n_{res}	models
$Z \to \not{E} + \gamma$	$Z \to \chi_1\chi_2, \chi_2 \to \chi_1\gamma$	0	1A: $\frac{1}{\Lambda_{1A}}\bar{\chi}_2\sigma^{\mu\nu}\chi_1 B_{\mu\nu}$ (MIDM)
	$Z \to \chi\bar{\chi}\gamma$	0	1B: $\frac{1}{\Lambda_{1B}^3}\bar{\chi}\chi B_{\mu\nu}B^{\mu\nu}$ (RayDM)
	$Z \to a\gamma \to (\not{E})\gamma$	1	1C: $\frac{1}{4\Lambda_{1C}}aB_{\mu\nu}\tilde{B}^{\mu\nu}$ (long-lived ALP)
	$Z \to A'\gamma \to (\bar{\chi}\chi)\gamma$	1	1D: $\epsilon^{\mu\nu\rho\sigma}A'_\mu B_\nu \partial_\rho B_\sigma$ (WZ terms)
$Z \to \not{E} + \gamma\gamma$	$Z \to \phi_d A', \phi_d \to (\gamma\gamma), A' \to (\bar{\chi}\chi)$	2	2A: Vector portal
	$Z \to \phi_H\phi_A$, $\phi_H \to (\gamma\gamma)$, $\phi_A \to (\bar{\chi}\chi)$	2	2B: 2HDM extension
	$Z \to \chi_2\chi_1$, $\chi_2 \to \chi_1\phi$, $\phi \to (\gamma\gamma)$	1	2C: Inelastic DM
	$Z \to \chi_2\chi_2$, $\chi_2 \to \gamma\chi_1$	0	2D: MIDM
$Z \to \not{E} + \ell^+\ell^-$	$Z \to \phi_d A'$, $A' \to (\ell^+\ell^-)$, $\phi_d \to (\bar{\chi}\chi)$	2	3A: Vector portal
	$Z \to A'SS \to (\ell\ell)SS$	1	3B: Vector portal
	$Z \to \phi(Z^*/\gamma^*) \to \phi\ell^+\ell^-$	1	3C: Long-lived ALP, Higgs portal
	$Z \to \chi_2\chi_1 \to \chi_1 A'\chi_1 \to (\ell^+\ell^-)\not{E}$	1	3D: Vector portal and Inelastic DM
	$Z \to \chi_2\chi_1$, $\chi_2 \to \chi_1\ell^+\ell^-$	0	3E: MIDM, SUSY
	$Z \to \bar{\chi}\chi\ell^+\ell^-$	0	3F: RayDM, slepton, heavy lepton mixing
$Z \to \not{E} + JJ$	$Z \to \phi_d A' \to (\bar{\chi}\chi)(jj)$	2	4A: Vector portal
	$Z \to \phi_d A' \to (bb)(\bar{\chi}\chi)$	2	4B: Vector portal + Higgs portal
	$Z \to \chi_2\chi_1 \to bb\chi_1 + \chi_1 \to bb\not{E}$	0	4C: MIDM
$Z \to (JJ)(JJ)$	$Z \to \phi_d A', \phi_d \to jj, A' \to jj$	2	5A: Vector portal + Higgs portal
	$Z \to \phi_d A', \phi_d \to b\bar{b}, A' \to jj$	2	5B: vector portal + Higgs portal
	$Z \to \phi_d A', \phi_d \to b\bar{b}, A' \to b\bar{b}$	2	5C: vector portal + Higgs portal
$Z \to \gamma\gamma\gamma$	$Z \to \phi\gamma \to (\gamma\gamma)\gamma$	1	6A: ALP, Higgs portal

Table I. Classification of exotic Z decay channels by particles in final states and number of resonances (n_{res}). The χ and χ_1 are fermionic DM, χ_2 is an excited state of DM, and S denotes scalar DM. The final state J represents either light flavor jet j or heavy flavor jet b. A' is the dark photon, and the ϕ is intermediate scalars. The parentheses () indicates a resonance in the final states. The details of these models are discussed in the text.

Liu, Wang, Wang, Xue [1712.07237]

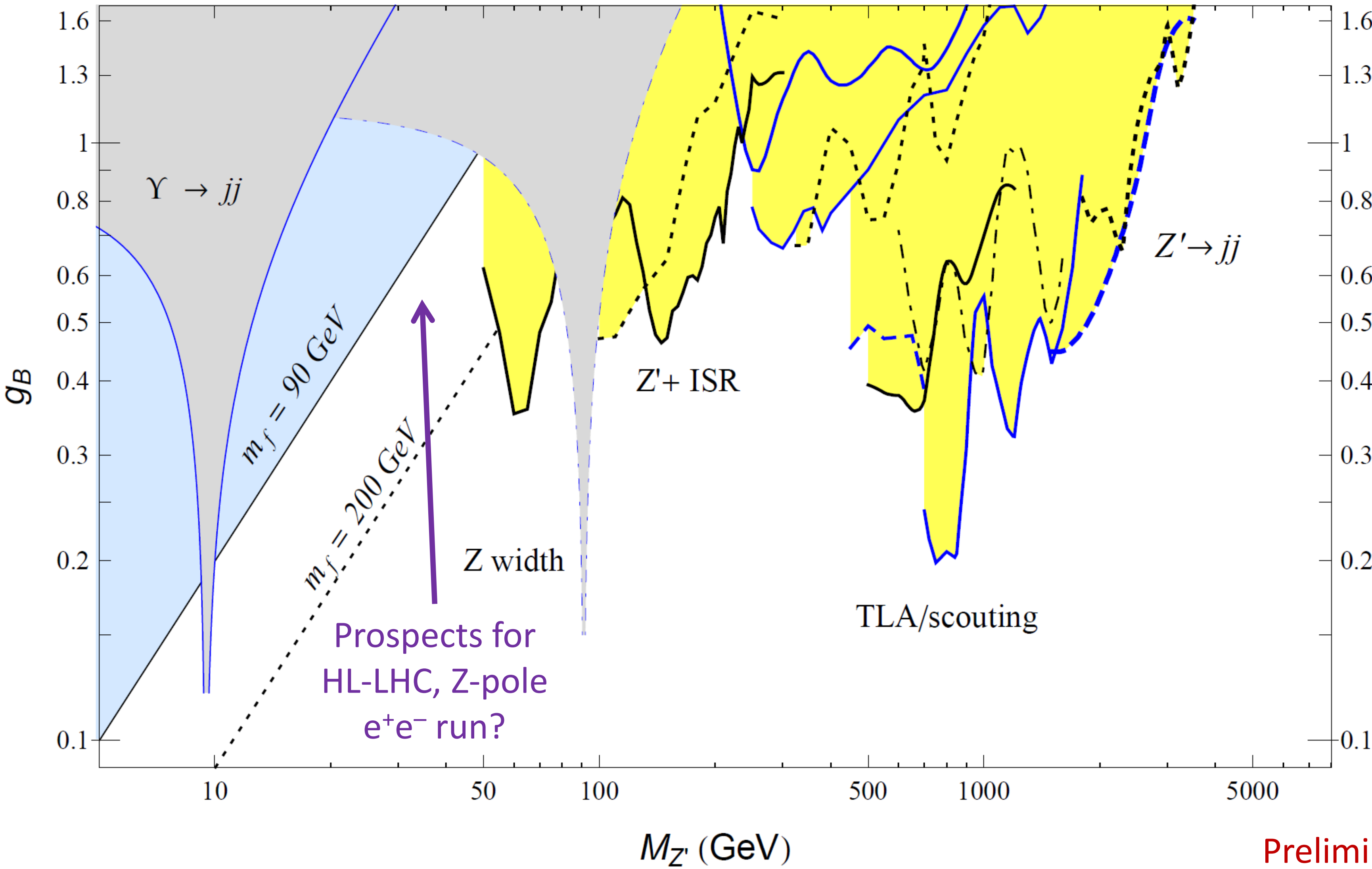
Exotic Z decay

- Model parameters determine precise Br reach



Liu, Wang, Wang, Xue [1712.07237]

Summary of collider constraints



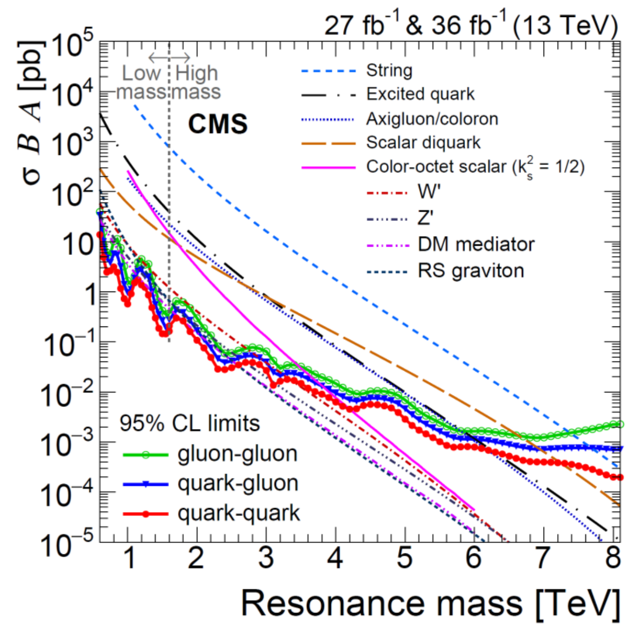
Preliminary

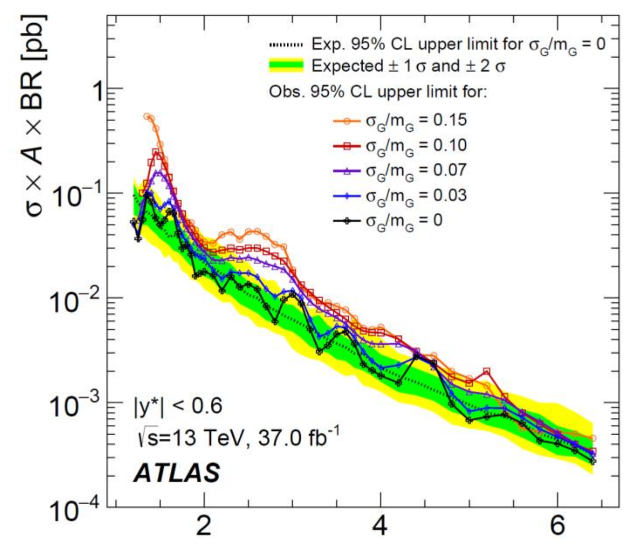
Conclusions

- New BSM sectors built from a simple principle, gauging an anomalous global symmetry of the SM, has many rich phenomenological features
  - – Built from *gauge portal*
- Natural and irreducible signals arise from familiar themes in EW physics
    - Non-decoupling fermions in Wess-Zumino terms (and diphoton decay of ϕ)
- Transition to sensitivity frontier of NP searches
  - – Crossover between energy and intensity reach

Dijet resonances at LHC

- Generally, any *s*-channel resonance decays as a dijet resonance
    - Practical counterexample: SM Higgs
  - Experimental treatment distinguishes parton content, mass and width
    - Historically, emphasis has been high mass reach
    - Many recent developments on low mass probes

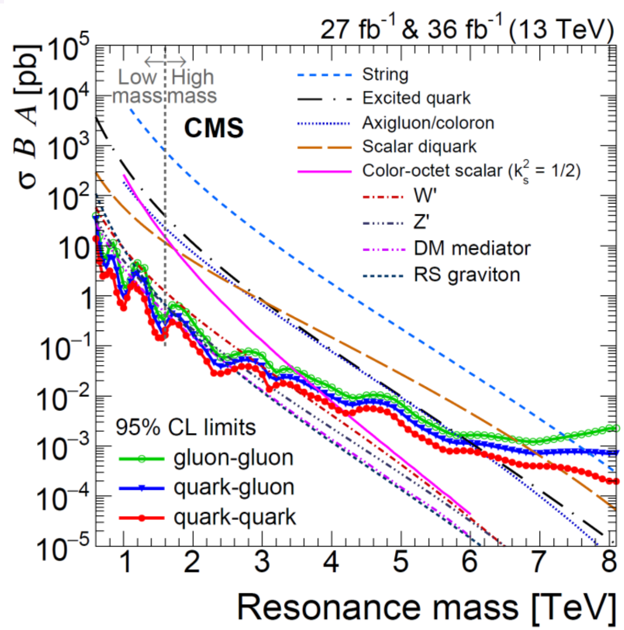


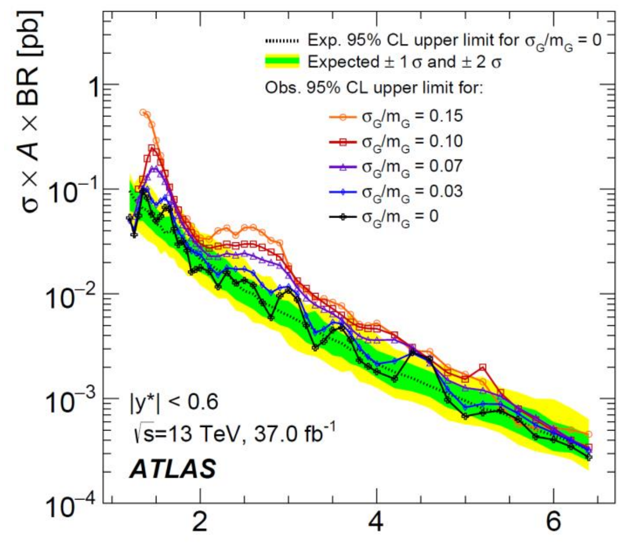


CMS [1806.00843], ATLAS [1703.09127]

Dijet resonances at LHC

- Parton content
  - Affects expected resonance shape reconstruction
- Mass and width
  - Drives expected background
- Low mass vs. high mass
  - Orders of magnitude change in QCD rates

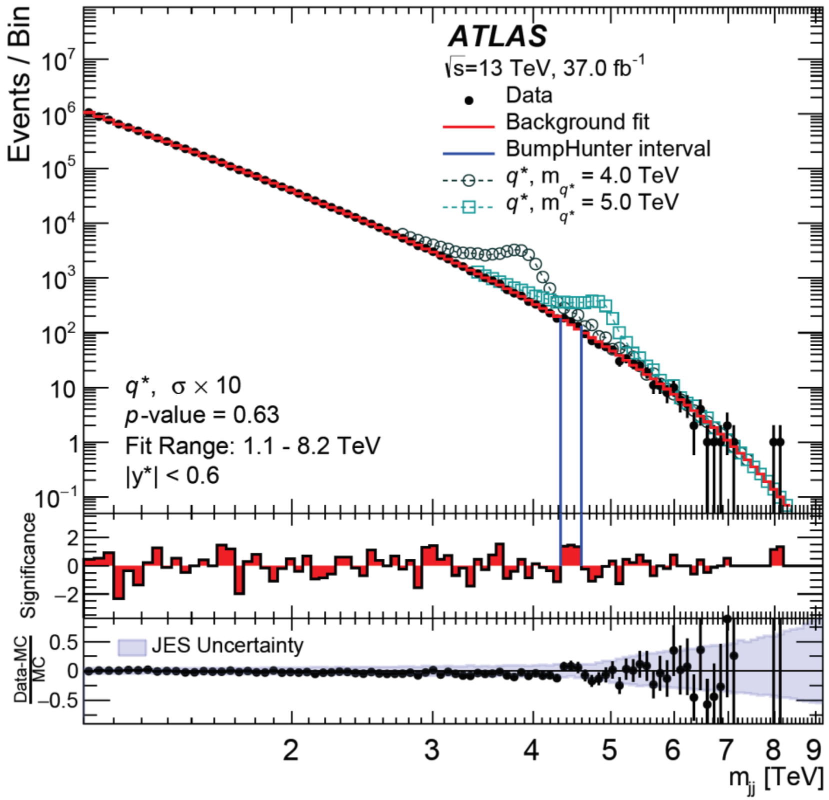




CMS [1806.00843], ATLAS [1703.09127]

Dijet resonances at LHC

- Parton content
  - Affects expected resonance shape reconstruction
- Mass and width
  - Drives expected background
- Low mass vs. high mass
  - Orders of magnitude change in QCD rates
  - Essentially, straightforward bump hunting

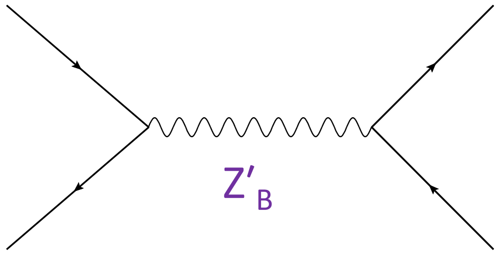


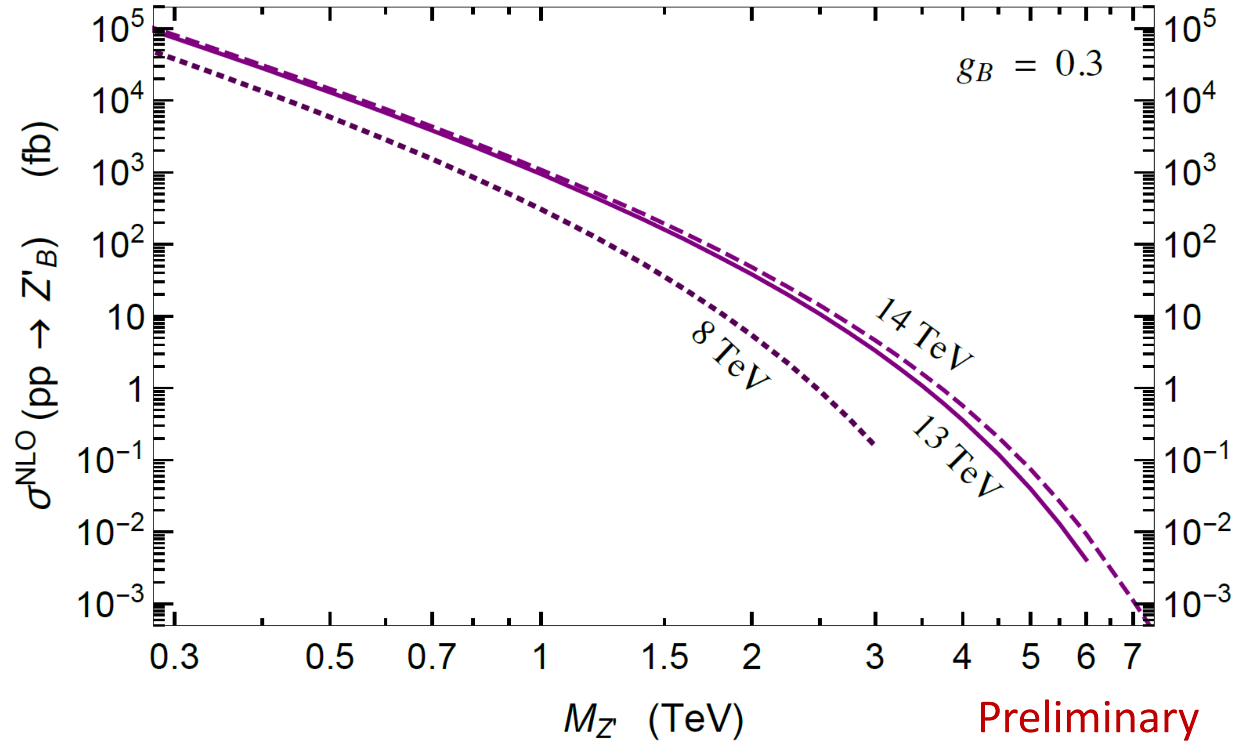
(a) $|y^*| < 0.6$ selection

ATLAS [1703.09127]

Exptl. innovations in dijet searches

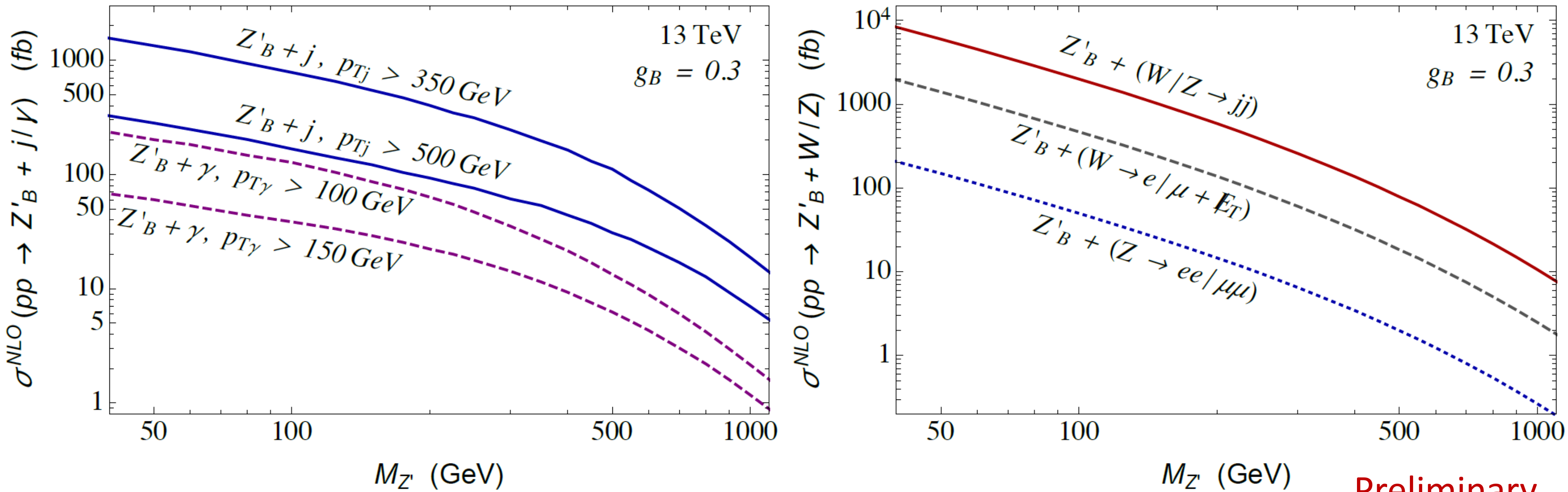
- Recall orders of magnitude variation in QCD bkgd
  - Trigger rate saturates
    - Reduce data volume (TLA/scouting) or set aside events (parking)





Z'_B Collider Phenomenology

- Alternate trigger paths
  - Use ISR jets, photons, leptons
    - No new model dependence

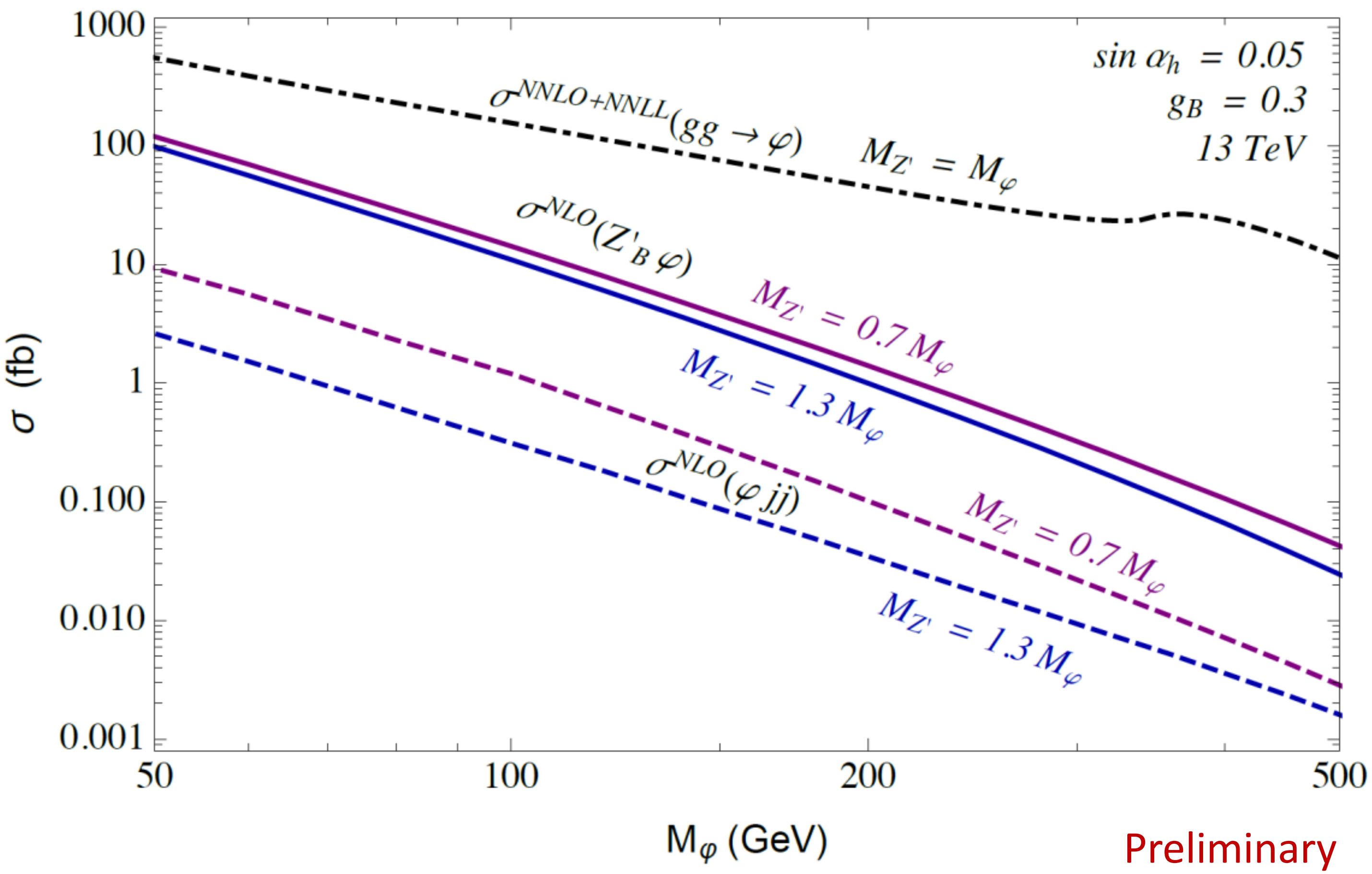


Preliminary

Reminiscent Higgs-like behavior

- ϕ production at LHC: Higgs-strahlung and VBF irreducible

gg→ ϕ is mixing angle-suppressed



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Reminiscent SSB behavior

- ϕ decay: $Z'Z'^{\{*\}}$ is tree-level
  - Essential: perturbative unitarization of Z'Z' scattering

$$\Gamma(\varphi \to Z' Z'^{\{*\}}) = \begin{cases} \dfrac{M_\varphi^3 \cos^2\alpha_h}{32\pi v_\phi^2} \left(1 - 4\dfrac{M_{Z'}^2}{M_\varphi^2} + 12\dfrac{M_{Z'}^4}{M_\varphi^4}\right) \sqrt{1 - 4\dfrac{M_{Z'}^2}{M_\varphi^2}} \quad , \quad \text{for} \;\; M_\varphi > 2M_{Z'} \\ \dfrac{5M_{Z'}^4 \cos^2\alpha_h}{6144\pi^3 \, z_\phi^2 v_\phi^4} M_\varphi \, R_T\left(M_{Z'}^2/M_\varphi^2\right) \quad , \quad \text{for} \;\; 2M_{Z'} > M_\varphi > M_{Z'} \quad , \end{cases}$$

$$R_T(x) = 3\,\frac{1 - 8x + 20x^2}{\sqrt{4x-1}} \arccos\left(\frac{3x-1}{2x^{3/2}}\right) - \frac{1-x}{2x}(2 - 13x + 47x^2) - \frac{3}{2}(1 - 6x + 4x^2)\log x$$

Preliminary

Reminiscent non-decoupling behavior

- ϕ decay: $Z'Z'^{\{*\}}$ is tree-level
  - At one-loop: ZZ′, Zγ, Z′γ, and γγ are irreducible and non-decoupling

$$\Gamma(\varphi \to \gamma\gamma) = \frac{\alpha^2 M_\varphi^3}{256\pi^3} \left| \frac{\sin\alpha_h}{v_h} F_V\left(\frac{M_\varphi^2}{4M_W^2}\right) + \frac{4\sin\alpha_h}{3v_h} F_1\left(\frac{M_\varphi^2}{4M_t^2}\right) + \frac{\cos\alpha_h}{v_\varphi} \sum_f Q_f^2 F_1\left(\frac{M_\varphi^2}{4M_f^2}\right) \right|^2$$

Interference from top, W, and anomalons

$$F_1(x) = \frac{2}{x^2}\left[x + (x-1)Z(x)\right] \quad ,$$

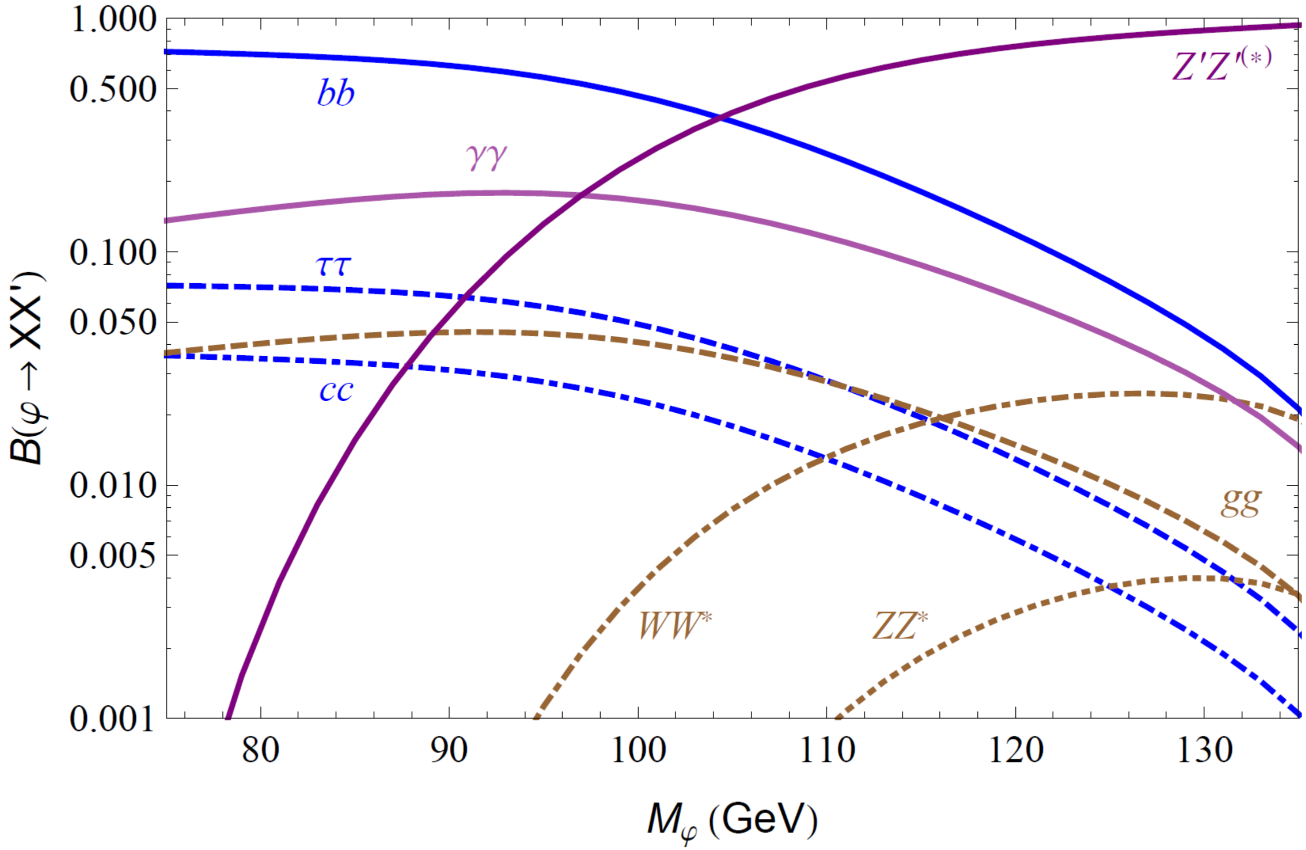
$$F_V(x) = -2 - \frac{3}{x} + \frac{3}{x^2}(1-2x)Z(x)$$

$$Z(x) = \begin{cases} \frac{-1}{4}\left[2\log\left(\sqrt{x}+\sqrt{x-1}\right) - i\pi\right]^2 & , \text{ for } x > 1 \\ \arcsin^2(\sqrt{x}) & , \text{ for } x \leq 1 \end{cases} \qquad (1)$$

Preliminary

Reminiscent Higgs-like behavior

- If ϕ→Z′Z′ decay is phase space suppressed, rich set of decays to SM states



$\sin\alpha_h = 0.05$

$g_B = 0.3$

$M_{Z'} = 70$ GeV

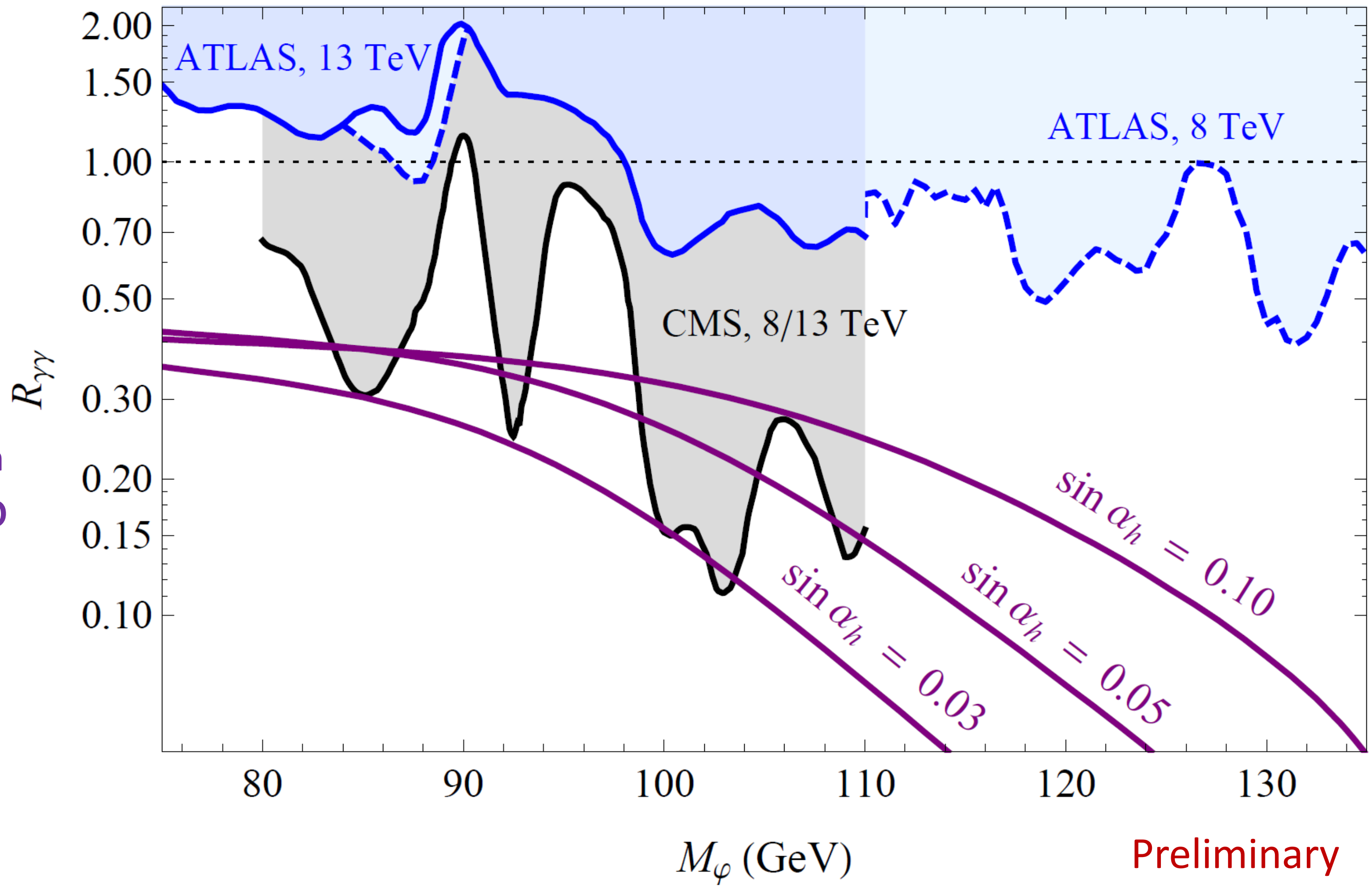
$m_L = m_E = 200$ GeV

Preliminary

Reminiscent Higgs-like behavior

- Diphoton resonance is an attractive discovery channel

Non-trivial interplay from mixing angle α_h between $gg \to \phi$ and $\phi \to \gamma\gamma$



Preliminary

Gauge anomalies and EFT

- Besides non-decoupling in Higgs physics, chiral fermions also exhibit non-decoupling in gauge interactions
  - Induce Wess-Zumino terms

$$\mathcal{L} \supset g_B g'^2 c_{BB} \epsilon^{\mu\nu\rho\sigma} Z_{B,\mu} B_\nu \partial_\rho B_\sigma$$
$$+ g_B g^2 c_{WW} \epsilon^{\mu\nu\rho\sigma} Z_{B,\mu} (W^a_\nu \partial_\rho W^a_\sigma + \frac{1}{3} g \epsilon^{abc} W^a_\nu W^b_\rho W^c_\sigma)$$

Harvey, Hill, Hill
Dror, Lasenby, Pospelov

Comparison to GBE

- Our result

$$\Gamma(Z \to Z'\gamma) = \frac{g_B^2 g^2 e^2 m_{Z'}^2 (1 - (m_{Z'}^4/m_Z^4))}{221184\pi^5 c_W^2 m_Z} \times$$
$$\left(9 + 7\frac{m_Z^2}{m_Z^2 - m_{Z'}^2}\log(m_{Z'}^2/m_Z^2) + 4m_t^2 C_0(0, m_Z^2, m_{Z'}^2, m_t, m_t, m_t)\right.$$
$$\left. +2\frac{m_Z^2}{m_Z^2 - m_{Z'}^2}(B_0(m_Z^2, m_t, m_t) - B_0(m_{Z'}^2, m_t, m_t))\right)^2$$

- Dror, et. al.: Replace Z′ by Goldstone, only consider anomaly coupling
  – Ignores poles in finite form factors that cancel anomaly

$$\mathcal{L} = \frac{\mathcal{A}}{16\pi^2}\frac{g_X\varphi}{m_X}2gg'Z_{\mu\nu}\tilde{F}^{\mu\nu}$$
$$\Gamma(Z \to X\gamma) = 1.1 \times 10^{-5}\mathcal{A}^2 g_X^2 \left(\frac{100\text{ GeV}}{m_X}\right)^2$$

Dror, Lasenby, Pospelov [1705.06726]