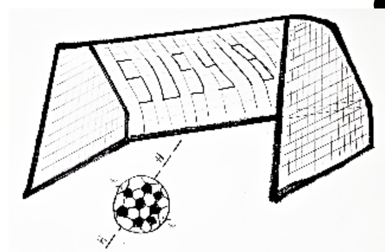
Bottom-quark Fusion Processes at the LHC for Probing Z' Models and B-meson Decay Anomalies



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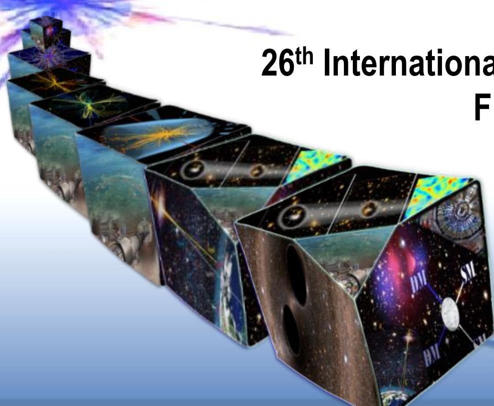

26th International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY2018)
23rd - 27th July, Barcelona, Spain

[Credits]
- Images of Baryon Acoustic Bscillations with Cosmic Microwave Background by E.M. Huff, the SDSS-III team, and the South Pole Telescope team. Graphic by Zosia Rostomian (Lawrence Berkeley National Laboratory)
- Image of Neutrino Astrophysics, taken from https://astro.desy.de/
- Image of the LHC by CERN Photo
- Image of Bullet Cluster by NASA/ Chandra X-ray Center

Prologue

4 sigma tension in flavor physics?

Nature of flavor physics?

@ Corpus Christi, Texas, USA

Phenomenology study: MADGRAPH5 v.2.5.4
PYTHIA 8.2
DELPHES 3.4

Bottom-quark fusion processes at the LHC for probing Z' models and B-meson decay anomalies

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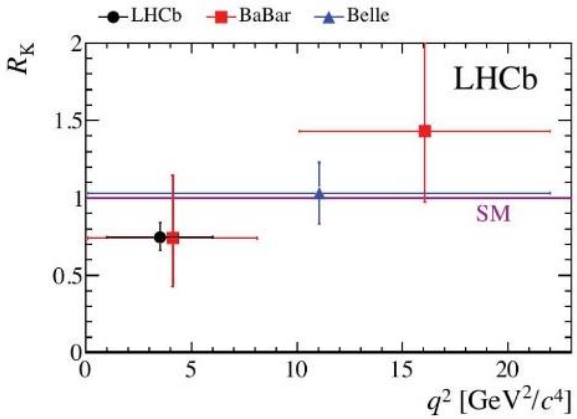
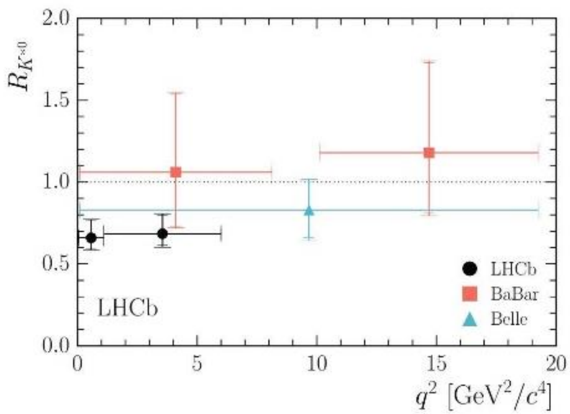
arXiv:1707.07016, Phys. Rev. D 97 (2018) 075035

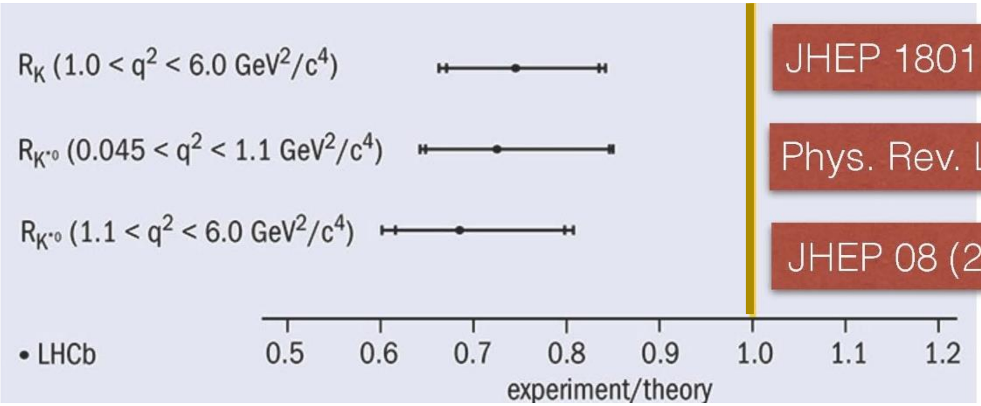
IMAGES OF BARYON ACOUSTIC BSCILLATIONS WITH COSMIC MICROWAVE BACKGROUND BY E.M. HUFF, THE SDSS-III TEAM, AND THE SOUTH POLE TELESCOPE TEAM. GRAPHIC BY ZOSIA ROSMIAN (LAWRENCE BERKELEY NATIONAL LABORATORY) IMAGE OF NEUTRINO ASTROPHYSICS, TAKEN FROM HTTPS://ASTRO.DESY.DE/IMAGE OF THE LHC BY CERN PHOTO IMAGE OF BULLET CLUSTER BY NASA/ CHANDRA X-RAY CENTERIMAGE OF THE MERGING BLACK HOLE BINARY SYSTEM INTO ONE BY SXS, THE SIMULATING EXTREME SPACETIMES (SXS) PROJECT

Puzzle with Anomalies in B Decays





$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)}, \quad R_{K^*} = \frac{\mathcal{B}(B \to K^*\mu^+\mu^-)}{\mathcal{B}(B \to K^*e^+e^-)}.$$



JHEP 1801 (2018) 093

Phys. Rev. Lett. 113, 151601

JHEP 08 (2017) 055

- ❖ Deviation at 2.4σ - 2.6σ from the SM
- ❖ Compatible with other anomalies observed in $b \to s\mu\mu$ transition

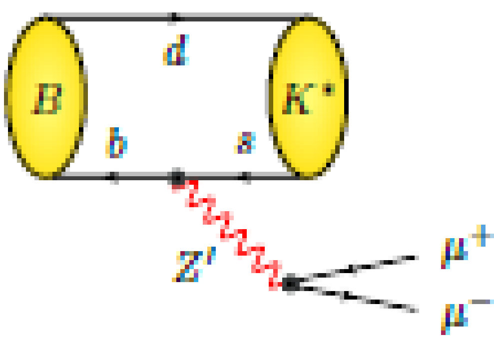
➠ ~4σ tension with SM

$$R_K^{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036\,,$$

$$R_{K^*}^{[0.045,1.1]} = 0.660^{+0.110}_{-0.070} \pm 0.024$$

$$R_{K^*}^{[1.1,6]} = 0.685^{+0.113}_{-0.069} \pm 0.047$$

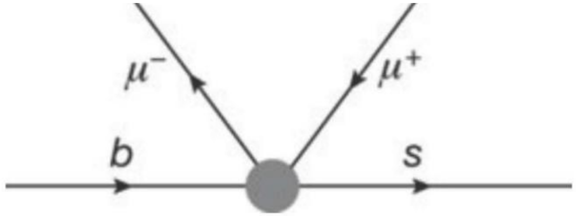
❖ New contribution?



Physics Model for B Anomalies

New physics contribution can be expressed as:

$$\mathcal{L} \supset \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} C_9 \times \underbrace{(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)}_{\mathcal{O}_9}$$



The best fit values for C_9 is: $C_9 = -1.56^{+0.46}_{-0.56}$

Z' in a minimal phenomenological setting is:

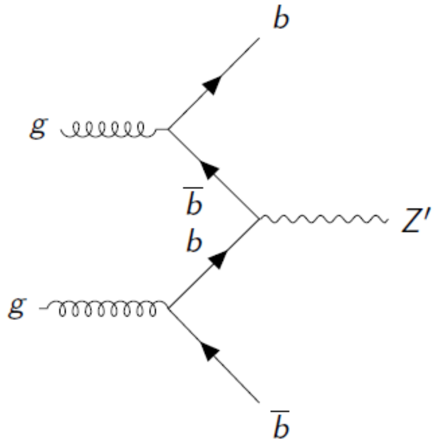
$$\boxed{L \supset Z'_\mu \left[g_\mu^V \bar{\mu}\gamma^\alpha \mu + g_\mu^V \bar{\nu}_\mu \gamma^\alpha P_L \, \nu_\mu + g_b \sum_{q=t,b} \bar{q}\gamma^\alpha P_L \, q + (g_b \, \delta_{bs}^L \bar{s}\gamma^\alpha P_L \, b + h.c.) \right]}$$

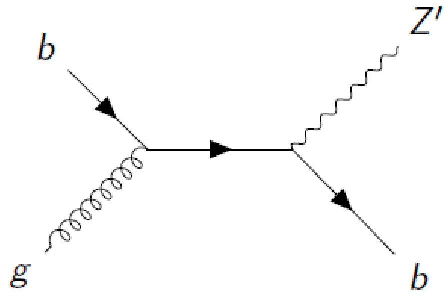
$$\frac{e^2}{16\pi^2} V_{ts}^* V_{tb} C_9 = -\frac{v^2}{2m_{Z'}^2} g_b \delta_{bs} g_\mu .$$

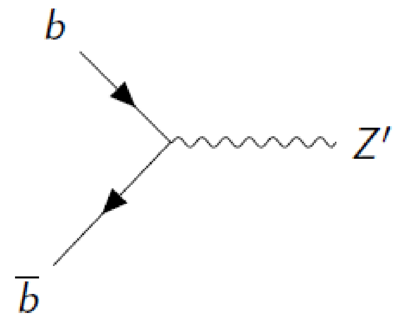
- Selective U(1) fermion charges to evade current LH and LEP constraints.
- Coupling to muons in leptonic sector and b-s in fermionic sector.
- Adding muon neutrino and top quark couplings to preserve SU(2).
- Considering tau decays

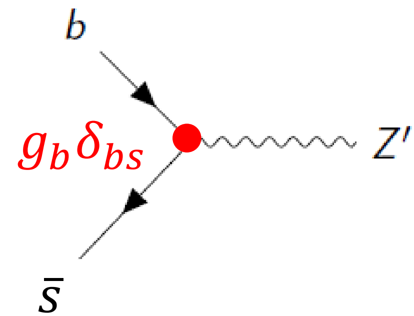
Z' Production via B-Fusion at LHC

$$L \supset Z'_{\mu}\,[g_{\mu}^{V}\bar{\mu}\gamma^{\alpha}\mu + g_{\mu}^{V}\bar{\nu}_{\mu}\gamma^{\alpha}P_L\,\nu_{\mu} + g_b \sum_{q=t,b} \bar{q}\gamma^{\alpha}P_L\,q + (g_b\,\delta_{bs}^{L}\bar{s}\gamma^{\alpha}P_L\,b + h.c.)\,]$$









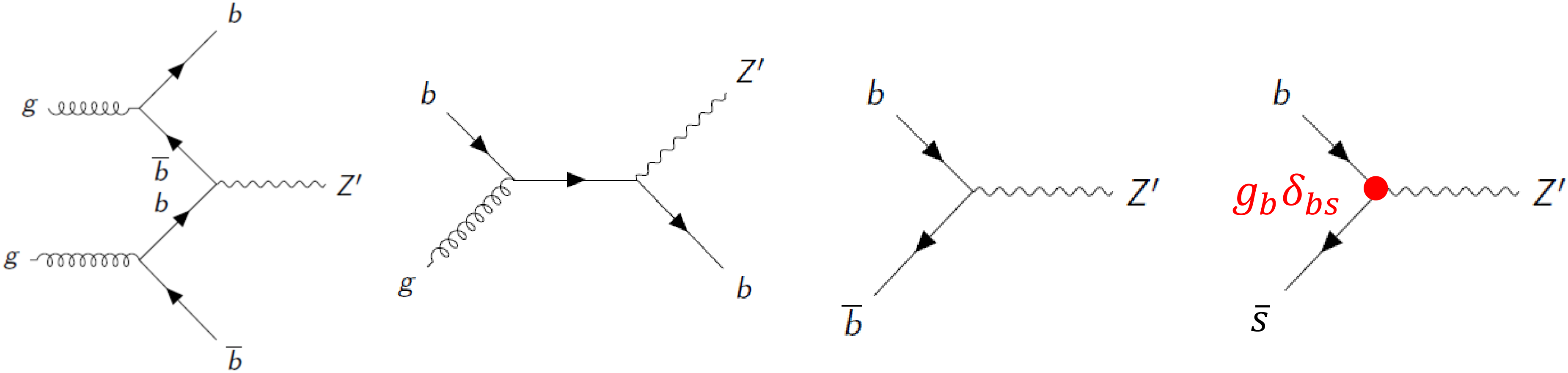
Bottom Fermion Fusion (BFF)

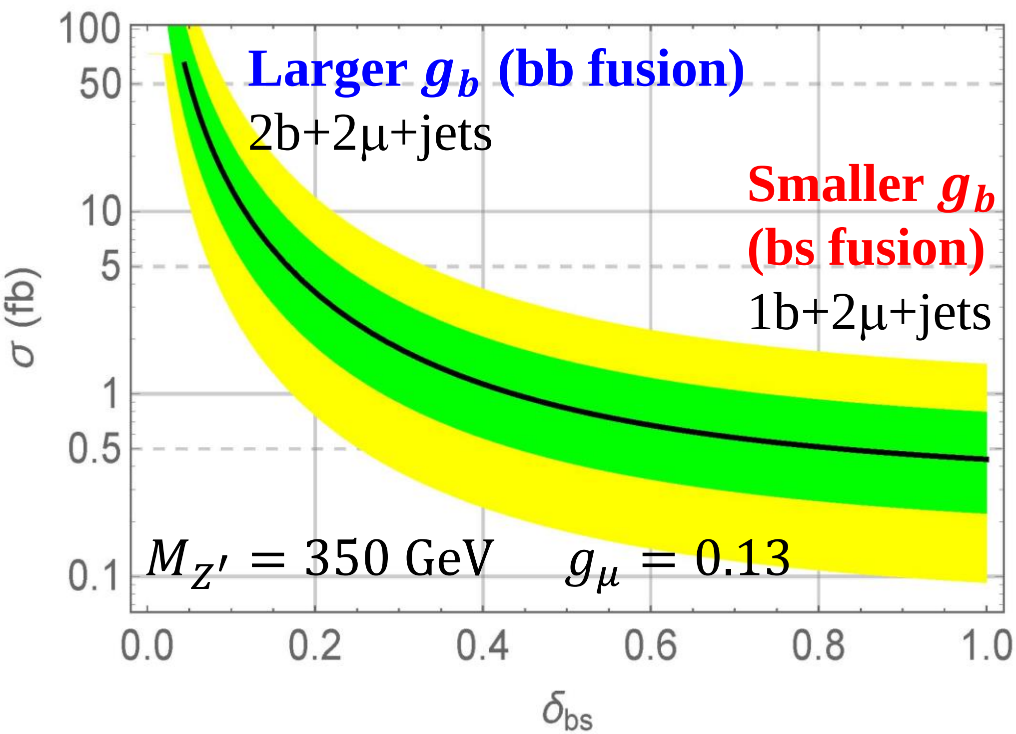
Similarly, one can consider bottom-strange quark fusion

$$\sigma(pp \to Z' \to \mu\,\mu) \propto 2\,g_b^2(1+k\delta_{bs}^2)\,g_{\mu}{}^2$$

$$\sigma(pp \to Z' \to b\,\bar{b}) \propto 3\,g_b^4(1+k\delta_{bs}^2)$$

Production Cross Section at LHC





Z' production cross section to be consistent with anomalies in B meson decays depends on g_b for larger g_b or $g_b\delta_{bs}$ for smaller g_b:

$$g_b\delta_{bs}g_\mu^V\,(100\ \text{GeV}/M_{Z'})^2$$
$$\approx 1.3 \times 10^{-5}$$

$Z'(\to \mu\mu)$ at ATLAS and CMS

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Fig. 3

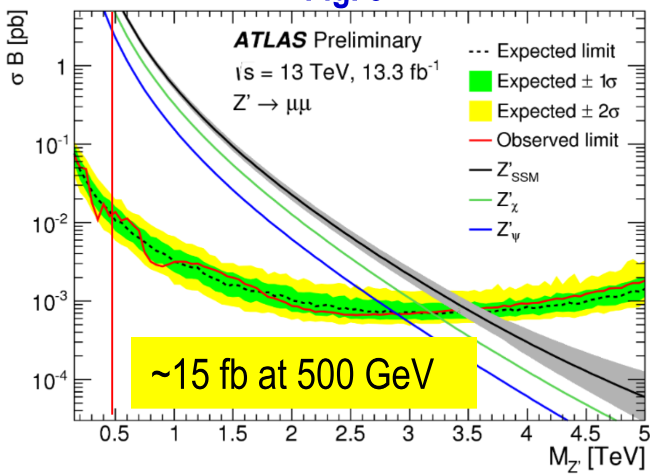
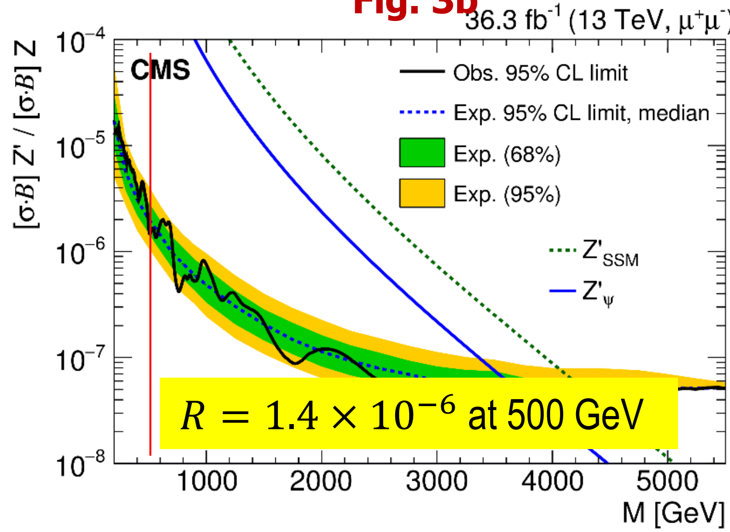


Fig. 3b



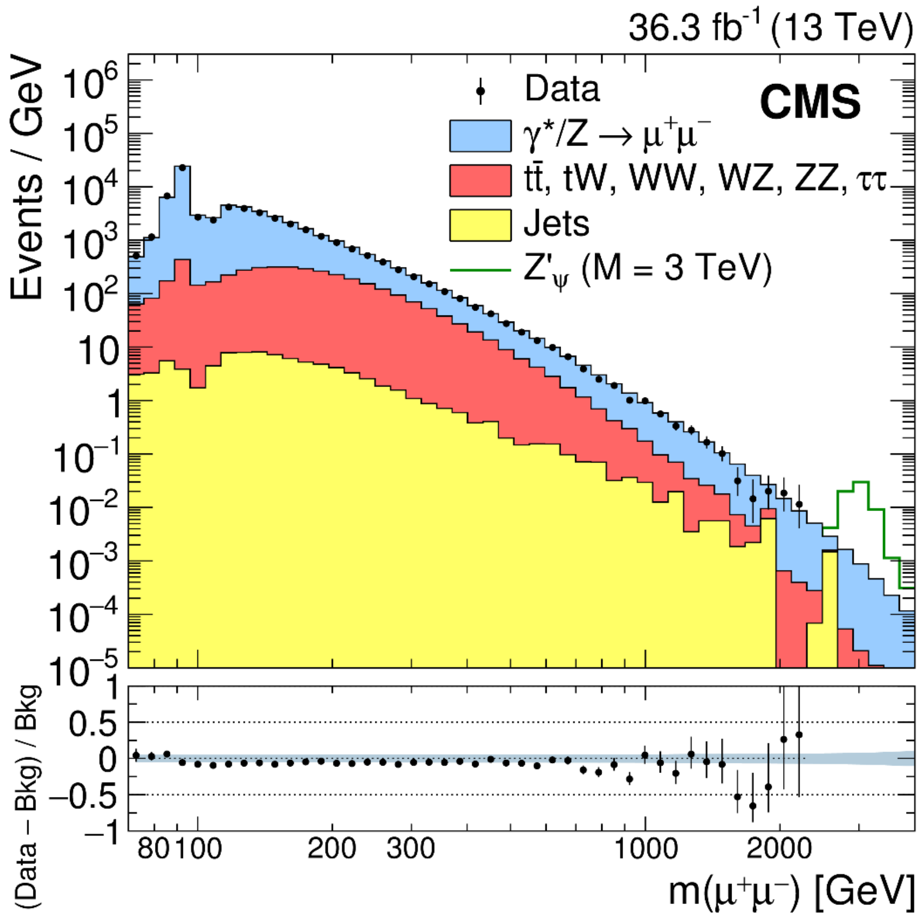
[Constraints from current inclusive di-muon resonance searches]

- ✓ The ATLAS limit for 500-GeV Z' is ~15 fb from Fig. 3. The leptonic production for the SM Z is 1.981 nb from the ATLAS paper (cf. 1.89 nb at DYNNLO). Thus the ATLAS limit on the cross section ratio R = 15 fb / 1.9 nb = **7.9x10^-6**.
- ✓ The corresponding CMS limit on R is **1.4x10^-6** from Fig. 3b (CMS-EXO-16-047, CERN-EP-2018-027), which is stringent compared to the ATLAS result.

- SM background becomes dominant for $M_{Z'}$ < 500 GeV.
- Di-jet, $t\bar{t}$ resonance searches produce weaker limits.
- Below 500 GeV, di-muon resonance + ≥1 b tagged jet.

Final States at LHC

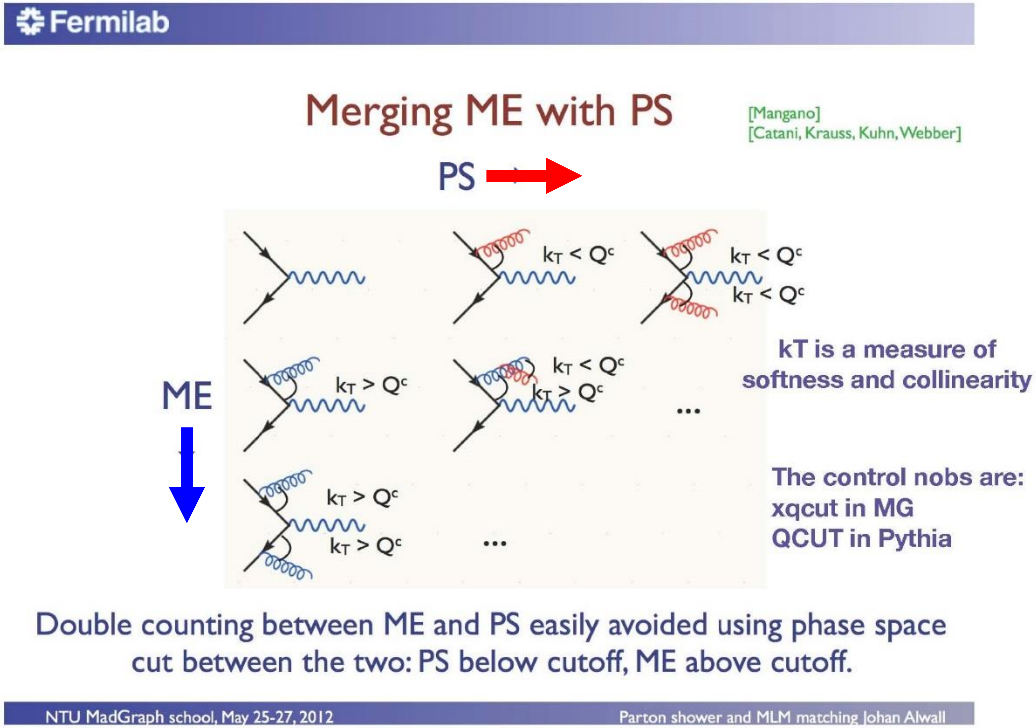
- Two main backgrounds: (i) SM DY γ^*/Z + jets, (ii) top quark production.
- Use ISR jets to reduce the SM background



Final States at LHC

- Two main backgrounds: (i) SM DY γ^*/Z + jets, (ii) top quark production.
- Use ISR jets to reduce the SM background

# ISR jets	process	description
0	*b-b fusion*	both *b* from sea quarks
0	*b-s fusion*	*b* and *s* from sea quarks
1	*b-b fusion*	one *b* from gluon splitting and one *b* from sea quarks
1	*b-s fusion*	one *b* from gluon splitting and one *s* from sea quarks
2	*b-b fusion*	both *b* from gluon splitting 6
2	*b-s fusion*	both *b* and *s* from gluon splitting



MLM matching with xqcut = 30 and qcut = 60 for smooth DJR and being insensitive to physical observables (e.g., cross section, kinematical distributions)

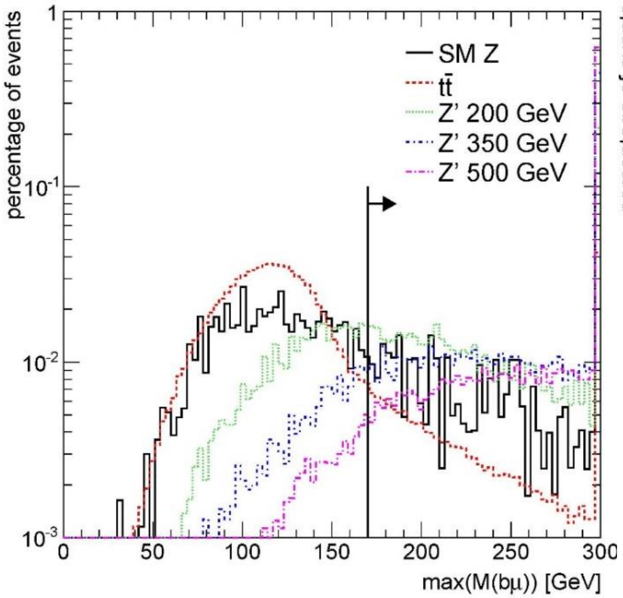
OS di-muon resonance + ≥ 1 b tagged jet (at least 2jets)

Search for BFF Z' at LHC

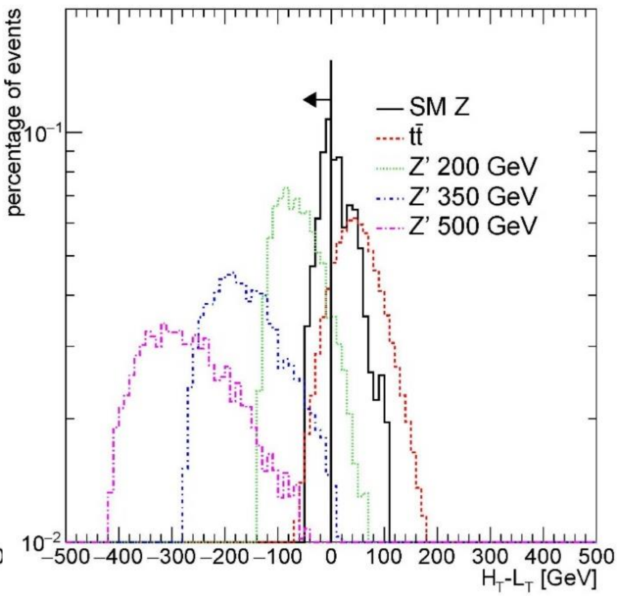
[Preselection] OS di-muon + ≥ 1 b tagged jet (at least 2jets)

MADGRAPH5 v.2.5.4
PYTHIA 8.2
DELPHES 3.4 (CMS card)

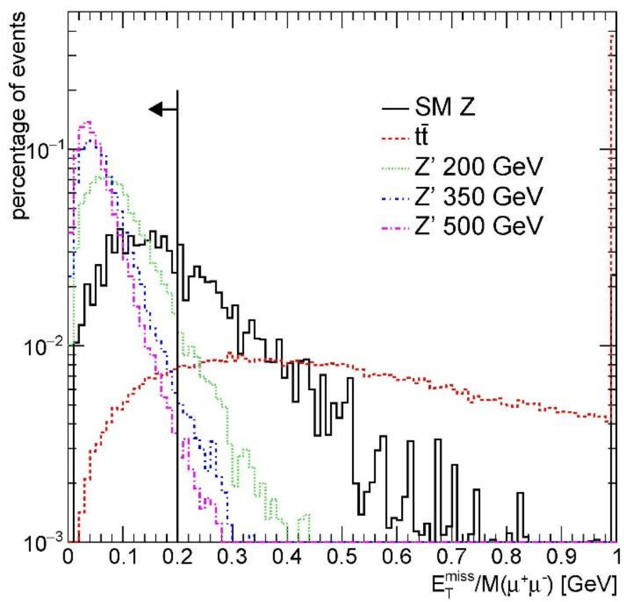
	Preselection	$M_{\mu b}$	$H_T - L_T$	$E_T^{miss}/M(\mu^+\mu^-)$
$t\bar{t}$	8%	17%	26%	27%
SM Z	0.2%	41%	32%	54%
Z' 200	7%	60%	74%	89%
Z' 350	10%	82%	90%	97%
Z' 500	13%	90%	94%	98%



$M_{b\mu}$ or $M_{\mu j} > 170$ GeV (top mass bound)



$H_T - L_T < 0$ (hadronic vs. leptonic activity)



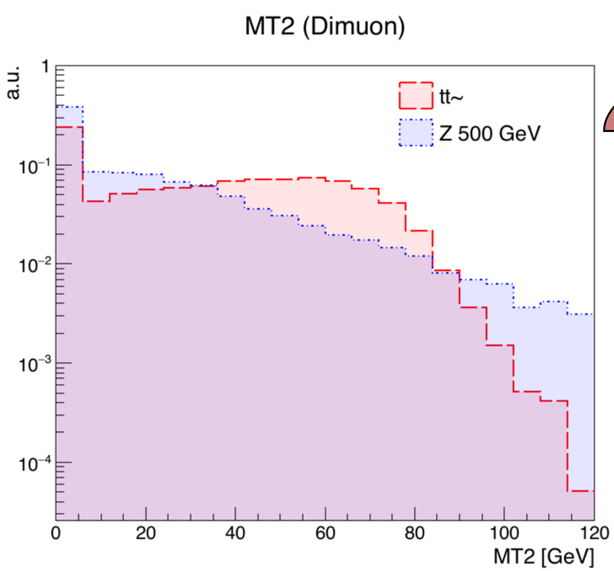
$E_T^{miss}/M_{\mu\mu} < 0.2$

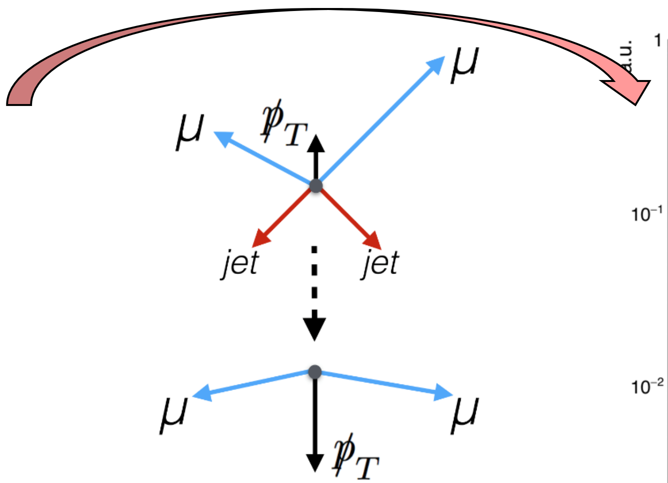
"Unboosted" m_{T2} - I am Number Four

$$m_{T2}^2(\mu_N) \equiv \min_{\mathbf{p}_T^1+\mathbf{p}_T^2=\not{\mathbf{p}}_T} \left[\max\{m_T^2(\mathbf{p}_T^1,\, \mathbf{p}_T^a;\, \mu_N),\, m_T^2(\mathbf{p}_T^2,\, \mathbf{p}_T^b;\, \mu_N)\}\right]$$

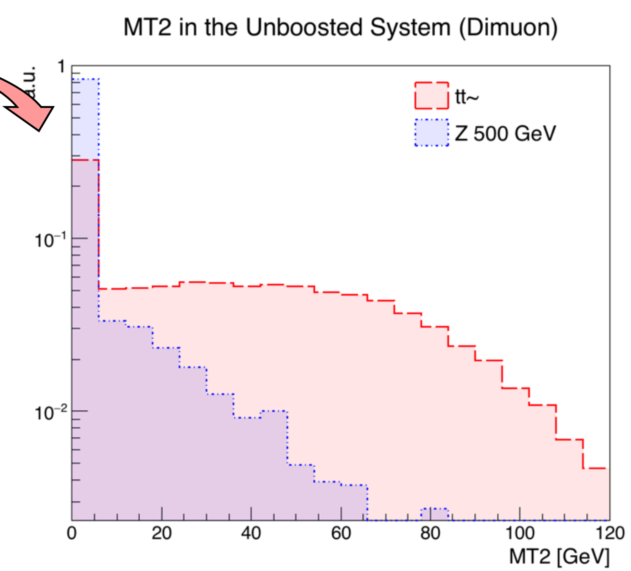
arXiv:0810.5178v2 [hep-ph]

m_{T2}





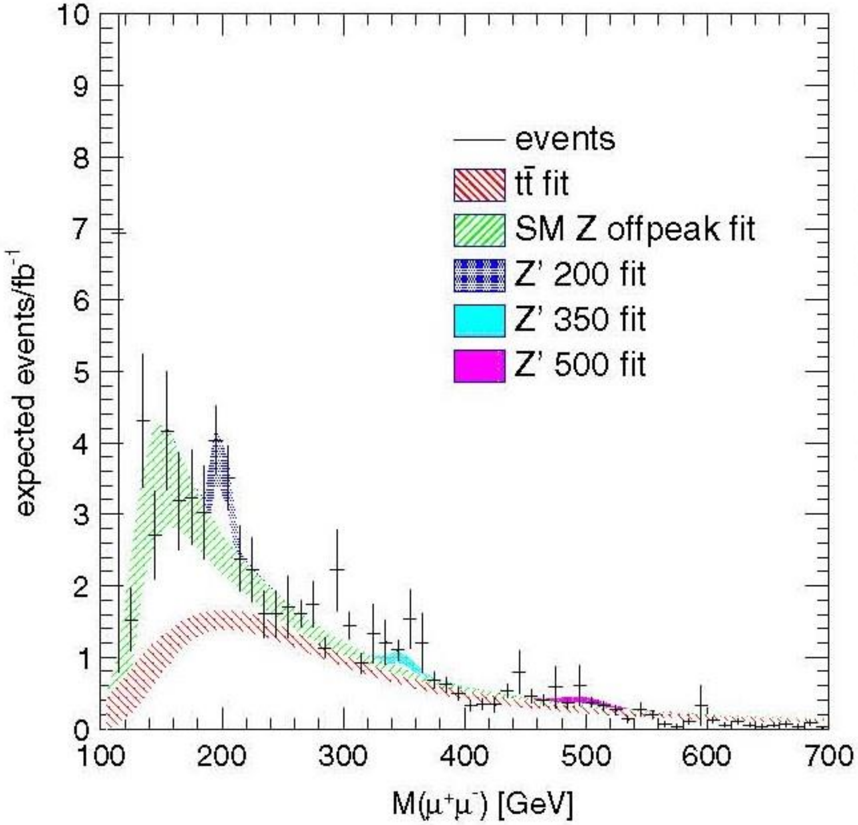
unboosted m_{T2}



We didn't use the 4th requirement (unboosted m_{T2}), which provides a good discrimination, but does not improve its sensitivity.

Limit Extraction

- $g_\mu = 1$ for calculating Z′ decay width
- The significance increases for smaller g_μ.

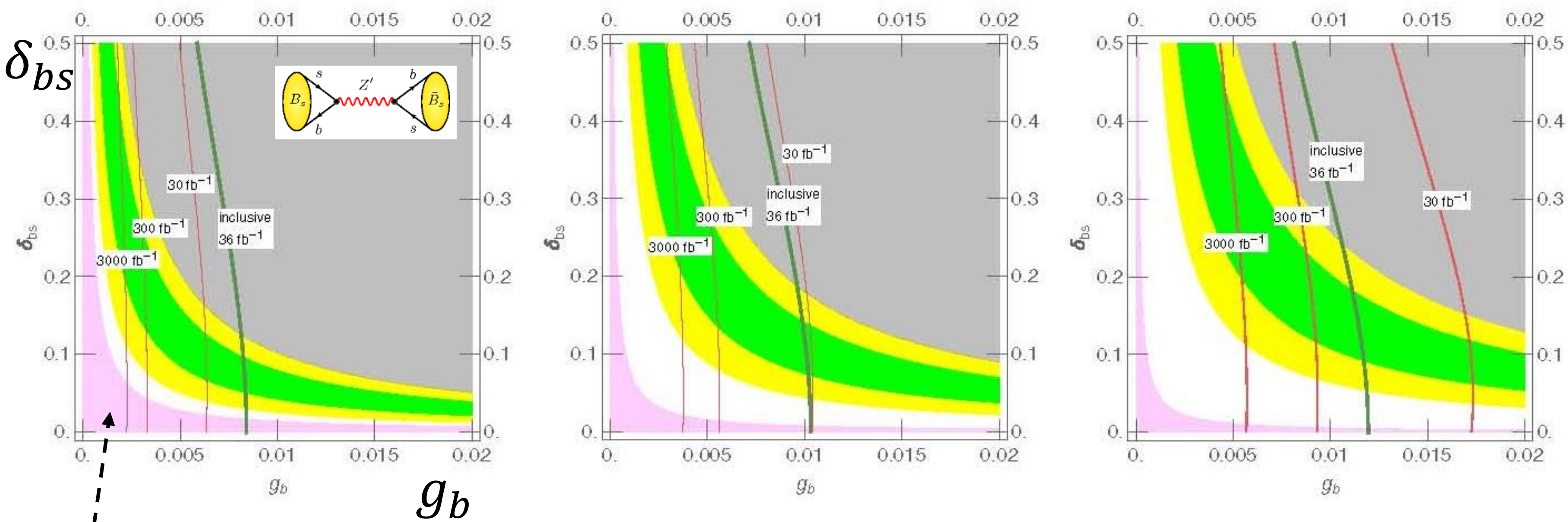


- ☑ Provide shapes for each signal and background process
- ☑ Take into account shape uncertainties
- ☑ Use Profile Likelihood estimator
- ☒ Delphes-only simulation
- ☒ Systematic uncertainties aren't accounted for
- ☒ Pile-up contribution is not accounted for

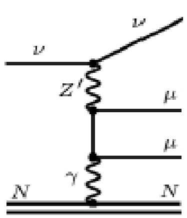
Current & Future Constraints

Allowed regions (yellow/green) in δ_{bs}-g_b

$M_{Z'} = 200$ GeV $\quad M_{Z'} = 350$ GeV $\quad M_{Z'} = 500$ GeV

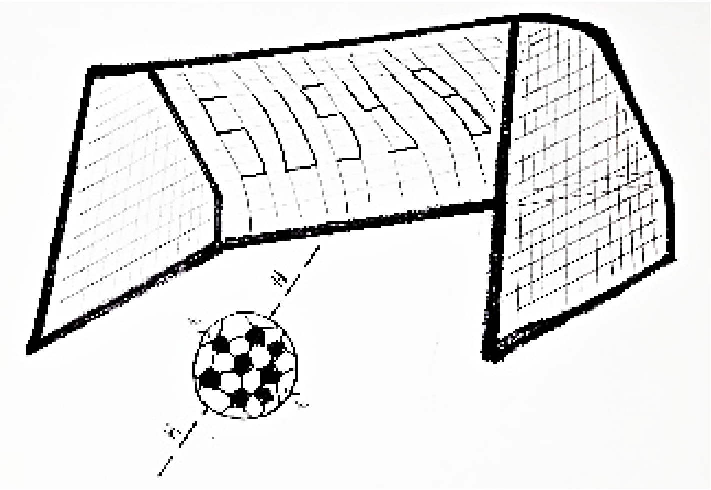


Neutrino trident constraints



- CMS inclusive analysis
- Our exclusive analysis
- 1σ band for B-anomalies
- 2σ band for B-anomalies

Summary



❖ Anomalies in B meson decays - one of hot topics

❖ Can be explained with Z' coupling to b, s and muon.

❖ [Phys. Rev. D 97 (2018) 075035] **Dedicated search for b-associated Z' is beneficial:**

- Showing that Z' couples to third generation SM particles should be probed with di-muon + ≥ 1 b events via b-fusion processes.
- Flavor violating b-s-Z' coupling introduces a minimum production cross-section.
- The limits on $\sigma \cdot B$ in the existing inclusive di-muon searches can be applied to these model parameter space. The reach can be improved by utilizing di-muon + ≥ 1 b for 350 GeV or lighter Z'.
- $pp \to Z' \to bb$ or bs and $pp \to Z' \to tt$ for further understanding of such models.