Bottom Fermion Fusion initial states
Example $b\bar{b}Z' \rightarrow \mu^+\mu^-$ analysis

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The usefulness of special initial states

- Specific initial states are utilized in various ways to search for new physics:
  1. Direct dark matter production +1 jet $\rightarrow$ Monojet searches
  2. New physics + Vector Boson Fusion quark jets $\rightarrow$ VBF searches (e.g. PLB 767(2017) 126)

- These kinds of analyses utilize known physics for the initial state to suppress Standard Model backgrounds
- As a bonus, different initial states make these analyses complementary by design
- So let’s add a state to the list
Bottom Fermion Fusion

- Utilizes the only reliably identifiable jet state (bottom quarks)
- Is a handle on physics coupling to 3rd generation quarks
  \( \rightarrow +0 \) jet states suppressed in direct production by bottom PDFs
  \( \rightarrow +1 \) jet radiative diagrams suppressed by e.g. \( \frac{1}{M_{Z'}}^2 \)

- Four different channels are motivated by the B anomalies: \( Z' \rightarrow \)
  - \( b\bar{b} \) Challenging, yet unavoidable (analysis in progress with A. Delgado, R. Eusebi, A. Overton and D. Rathjens [all CMS])
  - \( t\bar{t} \) Possible, if the \( Z' \) is heavy \( \rightarrow \) non-resonant background for \( t\bar{t}H \) analyses
  - \( \tau\tau \) Coupling is possible, but not necessary. Challenging channel (analysis being considered by B. Dutta and A. Florez [Pheno only])
  - \( \mu\mu \) The cleanest possible channel. A coupling is necessary to explain the B anomalies, but might be small. **Topic of this talk.** (analysis considered by Mykhailo Dalchenko, Teruki Kamon, Hyea-Hyun Kim, Minsuk Kim, Chang-Seong Moon, Ryan Mueller [all CMS])
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Preselection

Requirements

- Two opposite sign $\mu$ to suppress SM QCD background and reduce the $t\bar{t}$ contribution
- Two jets, $p_T \geq 30$ GeV (better than a single-jet selection due to SM $Z$ production)
- $\geq 1$ of the jets must be b-tagged (BFF production mostly, but not exclusively, central)

- Preselection efficiency is $\approx 8\%$ ($t\bar{t}$), $\approx 0.2\%$ (SM $Z$), $\approx 10 - 17\%$ $Z'$ signal
SM $t\bar{t}$ is the main background ($Z^*$ drops fast with increasing mass)

Out of the two possible permutations of $b + \mu$-pairs, take the most similar one in invariant mass

Require the maximum mass of the most similar pair to be above 170

Efficient $t\bar{t}$ removal
Signal efficiency depends strongly on signal mass scenario
Efficiency after previous selections: $\approx 17\%$ ($t\bar{t}$), $\approx 41\%$ (SM $Z$), $\approx 66 - 94\%$ $Z'$ signal
normalized $E_{\text{miss}}$ requirement

- No expectation of missing energy in signal, but in $t\bar{t}$ background
- Normalize $E_{\text{miss}}$ to dimuon mass to account for resolution effects
- The aim for the phenomenological study was a general case applicable to a range of mass scenarios

- Improvements for more specific mass scenarios or a binning of an analysis is likely to decrease mass-dependency of efficiencies
- Efficiency after previous selections: $\approx 26\%$ ($t\bar{t}$), $\approx 32\%$ ($\text{SM } Z$), $\approx 72 - 94\%$ $Z'$ signal
The BFF system
\((H_T = p_T(jet\ 1) + p_T(jet\ 2))\) is most likely to yield soft jets close to selection thresholds.

Depending on the \(Z'\) mass, resulting muons are hard
\((L_T = p_T(\mu^+) + p_T(\mu^-))\)

This is the opposite expectation of SM signatures!

Background-free selections are possible, depending on the signal mass scenario.

We deliberately chose a generic requirement of \(H_T - L_T < 0\) that works for all shown \(Z'\) masses.

Efficiency after previous selections: \(\approx 27\% \ (t\bar{t}), \approx 54\% \ (SM\ Z), \approx 89 - 98\% \ Z'\ signal\)
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2 BFF $\mu^+\mu^-$ analysis strategy

3 Conclusions and expected reach
Limit setting

- Each signal and background simulated shape fit exclusively
- Shape uncertainties per fit incorporated
- Profile likelihood method

Caveats

- Delphes only study
- No pileup simulated
- No realistic systematic uncertainties

Regardless...

- This new kind of analysis allows probing 3rd generation anomalies reported by LHCb at CMS or ATLAS
- Lower selection efficiencies are traded for better background suppression → useful at intermediate masses beyond Z peak and below inclusive dimuon analysis threshold
Projected exclusion power

$M_{Z'} = 200$ GeV

$M_{Z'} = 350$ GeV

$M_{Z'} = 500$ GeV

- **Red** lines show the expected limit of the presented $b\bar{b}Z' \rightarrow \mu^+\mu^-$ analysis
- **Green** lines show the current limits of the inclusive dimuon search arXiv:1609.05391 [hep-ex]
- Even with current integrated luminosity, we expect a BFF selection to improve performance for a B-anomaly probing dimuon search
BACKUP
Suppression of $+0$ jet initial states

- Bottom states directly from the parton distribution functions are very rare.
- Having a bottom $+\text{anti-bottom}$ initial state carrying appreciable momenta is exceedingly unlikely.
Suppression of $+1$ jet initial states

- Taking a gluon from one proton solves most of the necessary momentum supply for heavy resonance production.
- But radiating e.g. a $Z'$ is suppressed by a factor of $\frac{1}{M_{Z'}^2}$ in addition to the bottom pdf.
- Having a gluon split to $b\bar{b}$ solves the radiative suppression, but adds a $g \rightarrow b\bar{b}$ branching ratio factor in addition to the bottom pdf.