MET + bb and its backgrounds

Brda Workshop 2024

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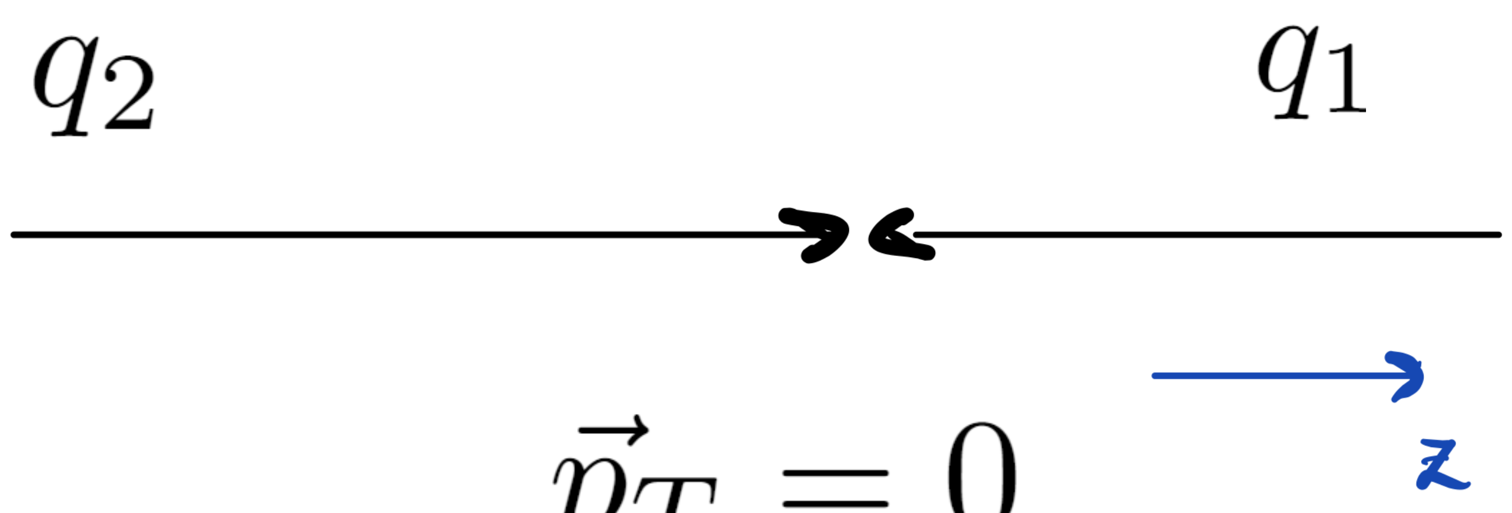
4.10.2024

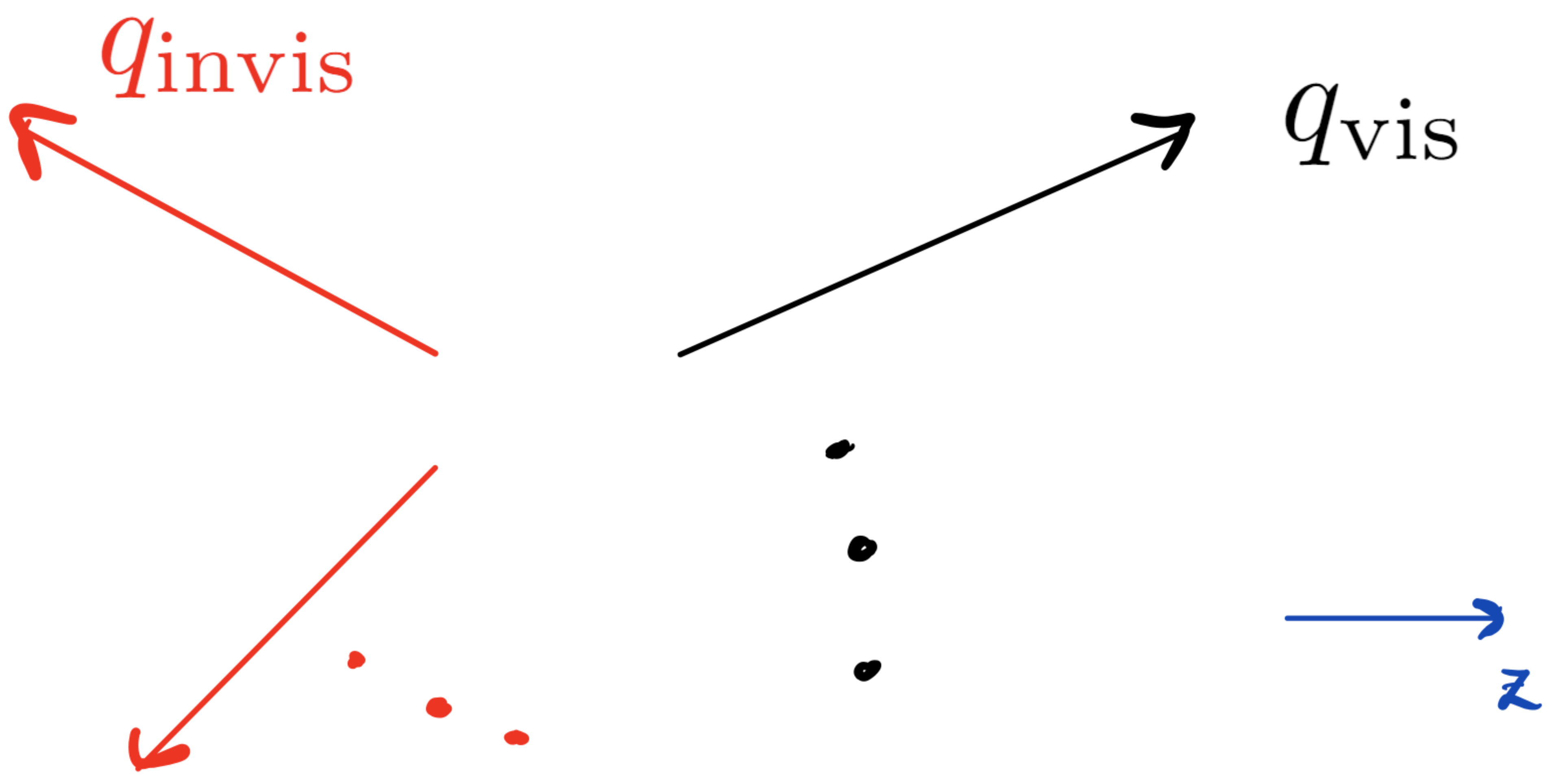
Outline

- MET + bb signature outside of and in SM
- Relevant SM backgrounds (Z, W, tt)
- Selection cuts
- Training BDTs for optimizing the search
- Conclusions

The basics



$$\vec{p}_T = 0$$



$$\vec{p}_T^{\,\text{vis}} + \vec{p}_T^{\,\text{miss}} = 0 \implies \vec{p}_T^{\,\text{miss}} = -\vec{p}_T^{\,\text{vis}}$$

Imbalance in the transverse momentum

MET = **Missing Transverse Energy**

MET E_T^{miss} and $p_T^{\text{miss}} = |\vec{p}_T^{\,\text{miss}}|$ are related:

$$E_T^{\text{miss}} = \sqrt{(p_T^{\text{miss}})^2 + m^2}$$

T Han (2005)

What causes non-zero MET?

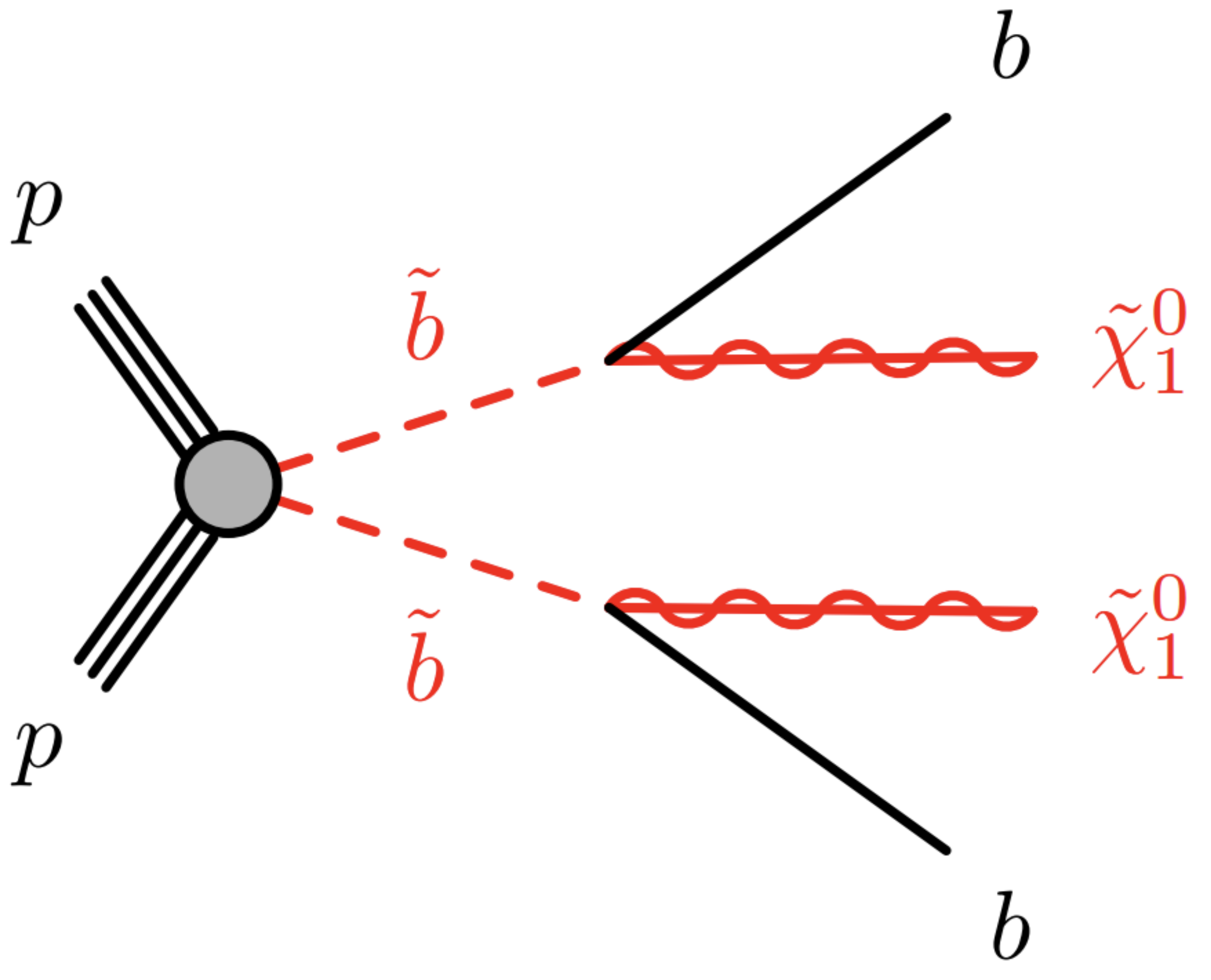
- Things that fly out/do not interact with the detector components
- Neutrinos
- Dark Matter (DM) candidates
- Soft objects (calorimeter energy deposits or tracks, not associated to physics objects)

The basics

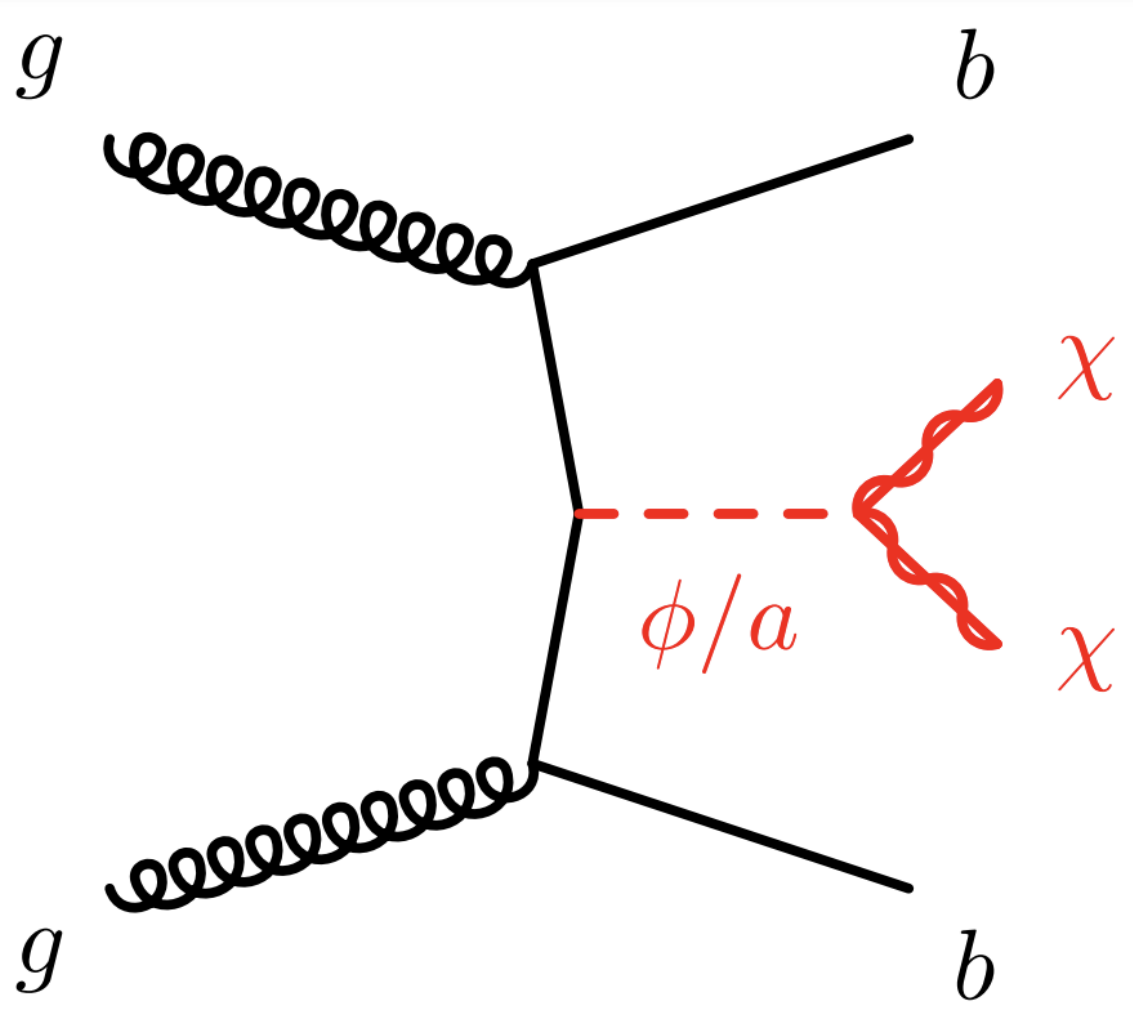
b-jets

- Requiring b-jets from a flavor-physics point of view:
  - Realization of couplings in SM-like fashion for NP
  - Flavor scenarios e.g. U(2)
  - Avoiding stringent bounds for light-quark families

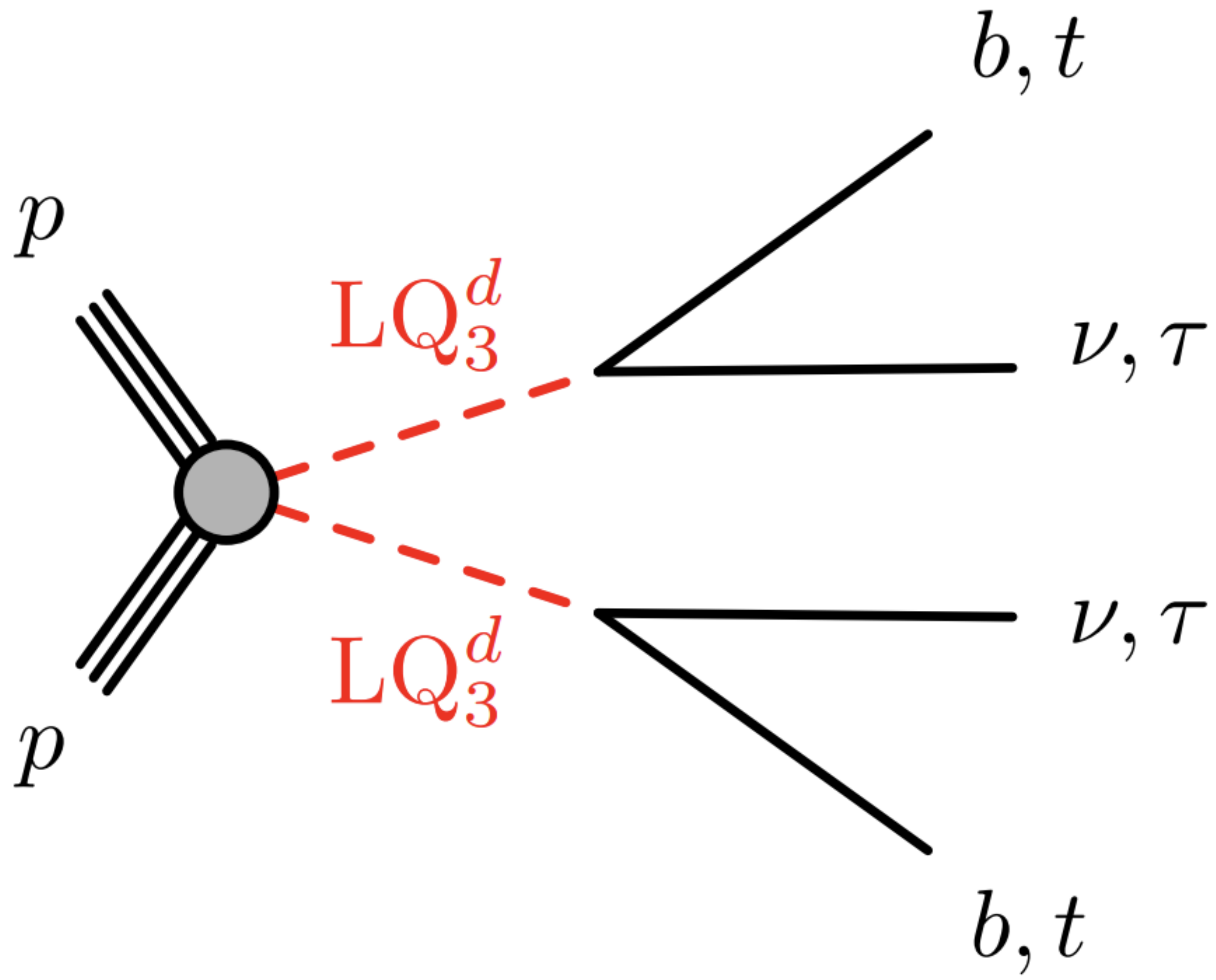
MET + bb outside of SM



- Semi-invisible decays (SUSY)



- DM models



- Leptoquarks

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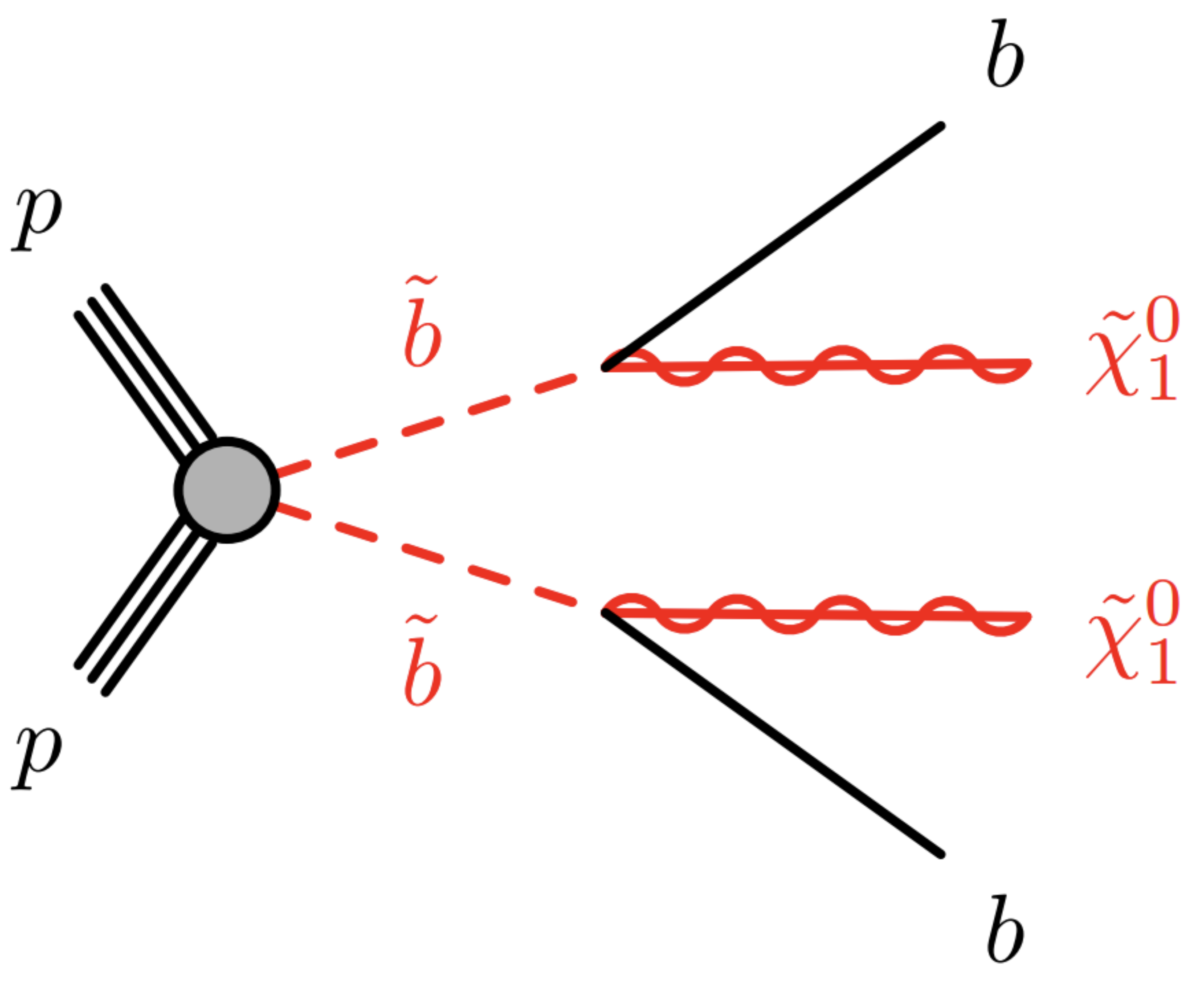
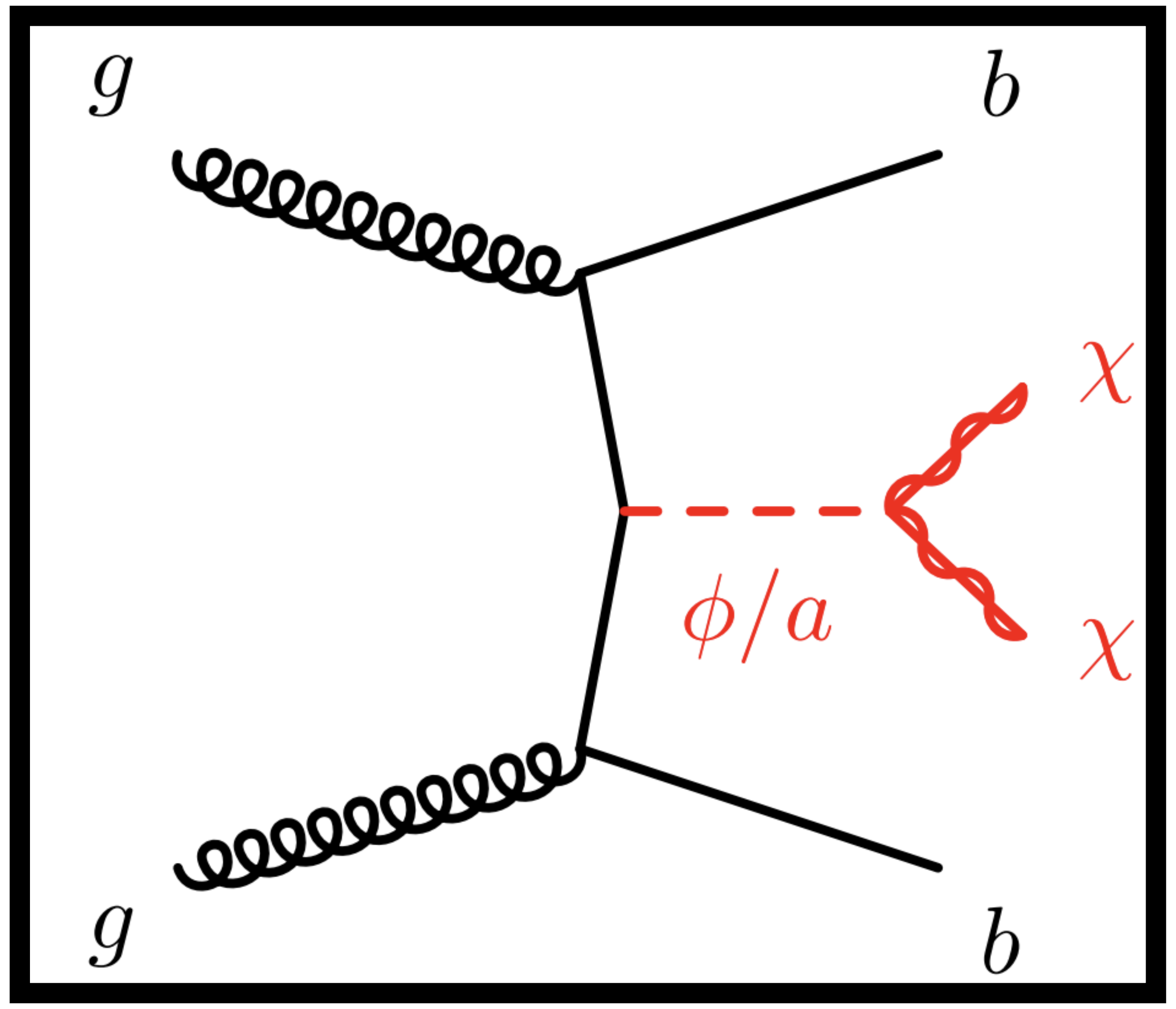
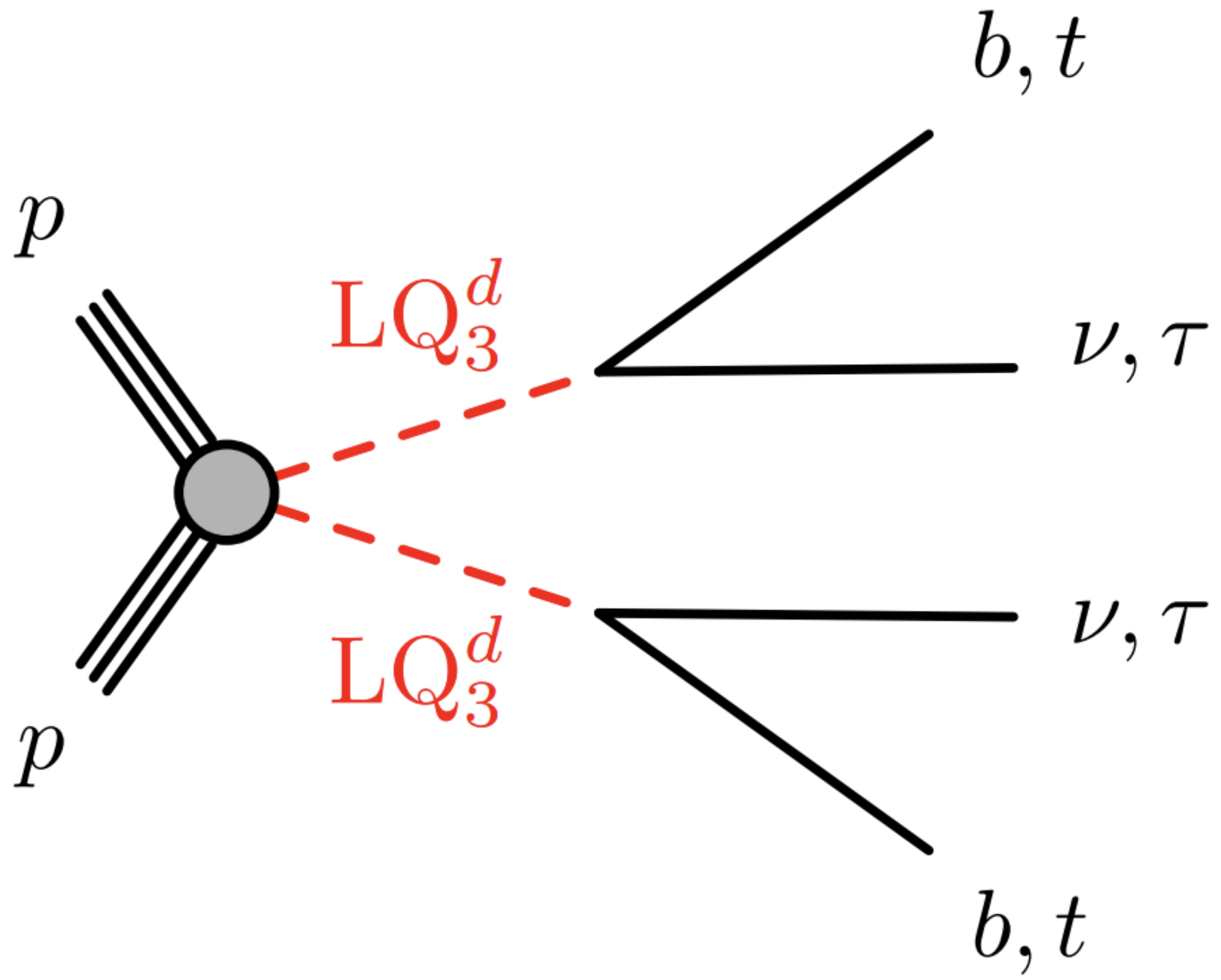
MET + bb outside of SM







- Semi-invisible decays (SUSY)
- DM models
- Leptoquarks

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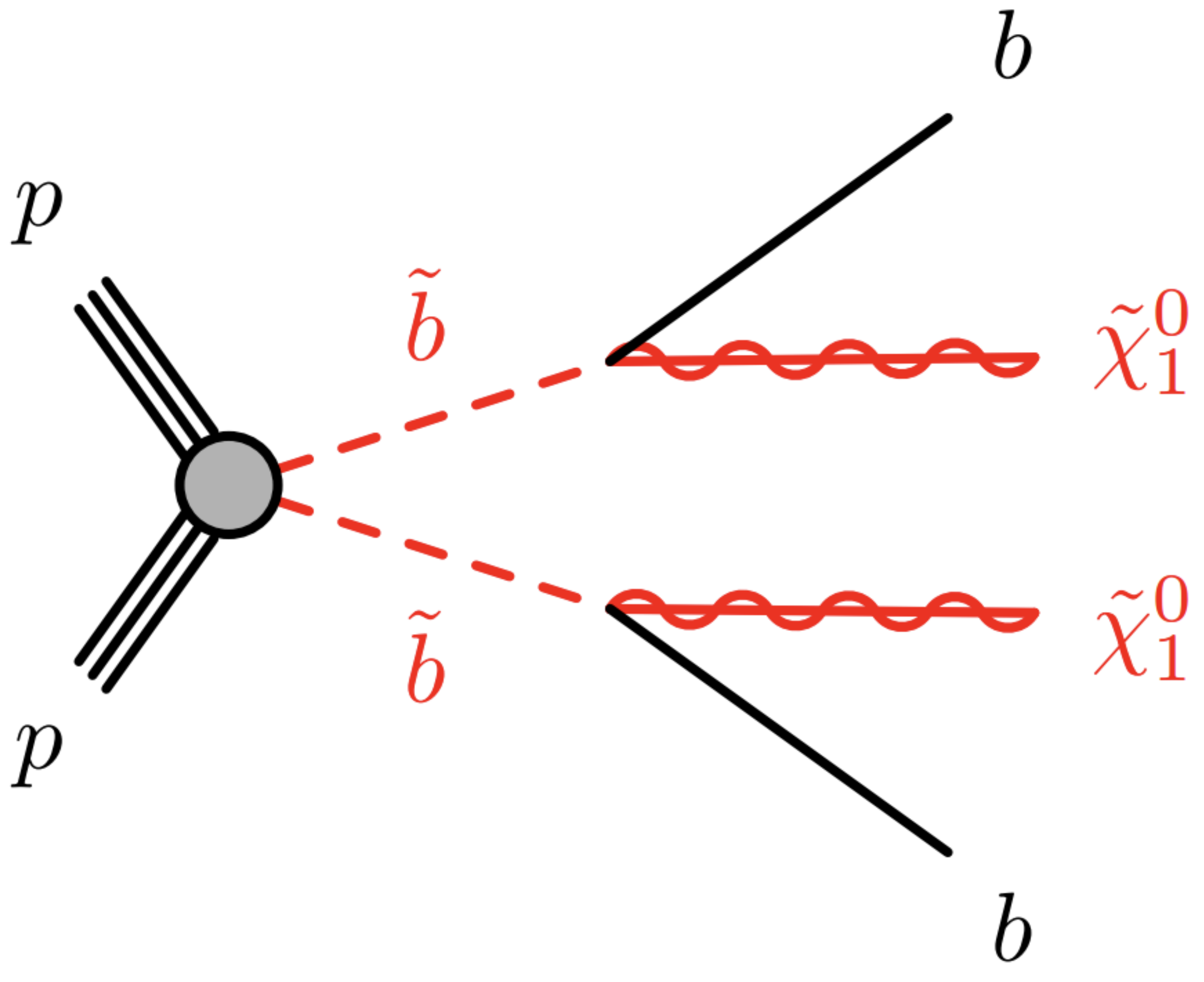
MET + bb outside of SM



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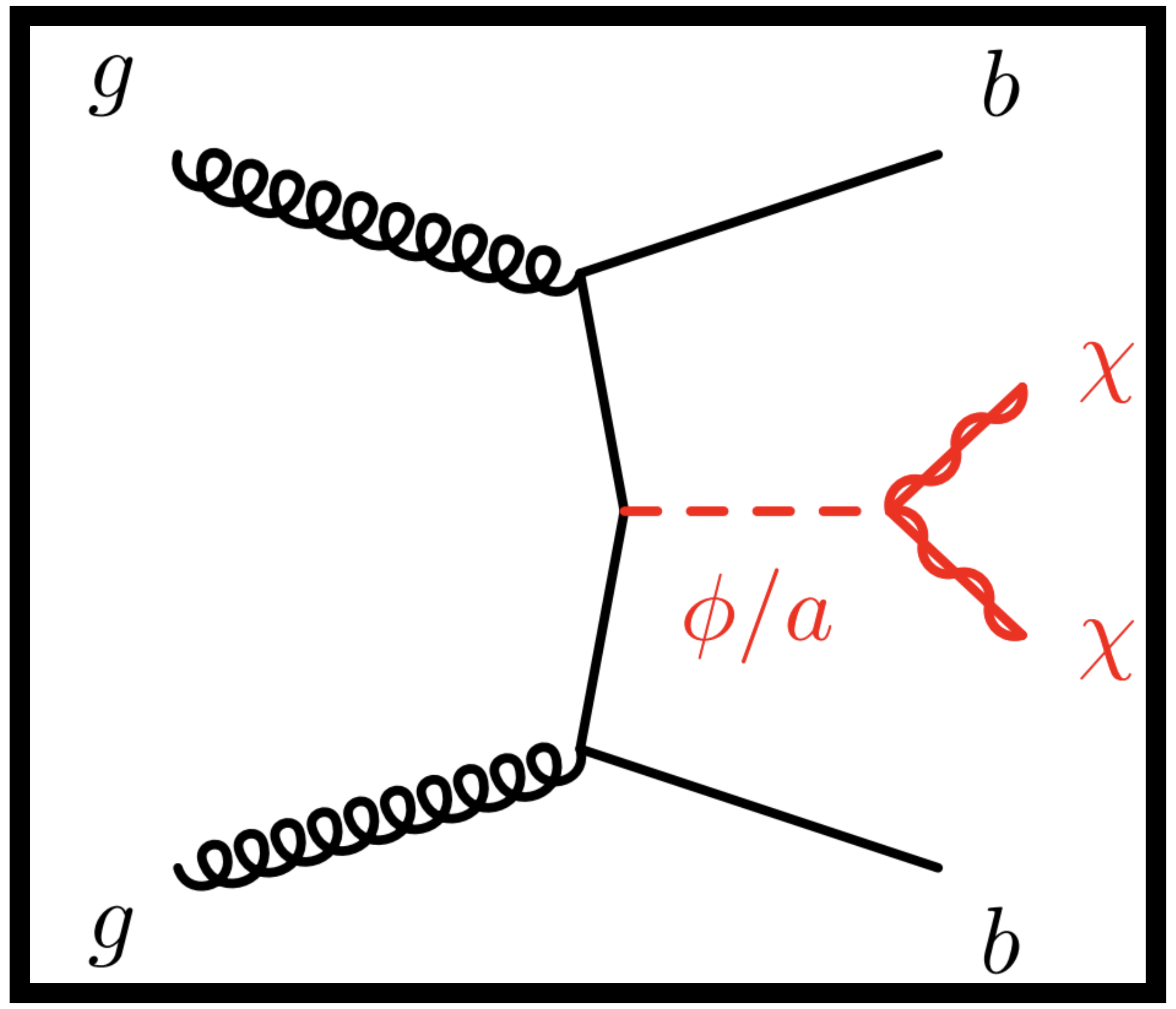

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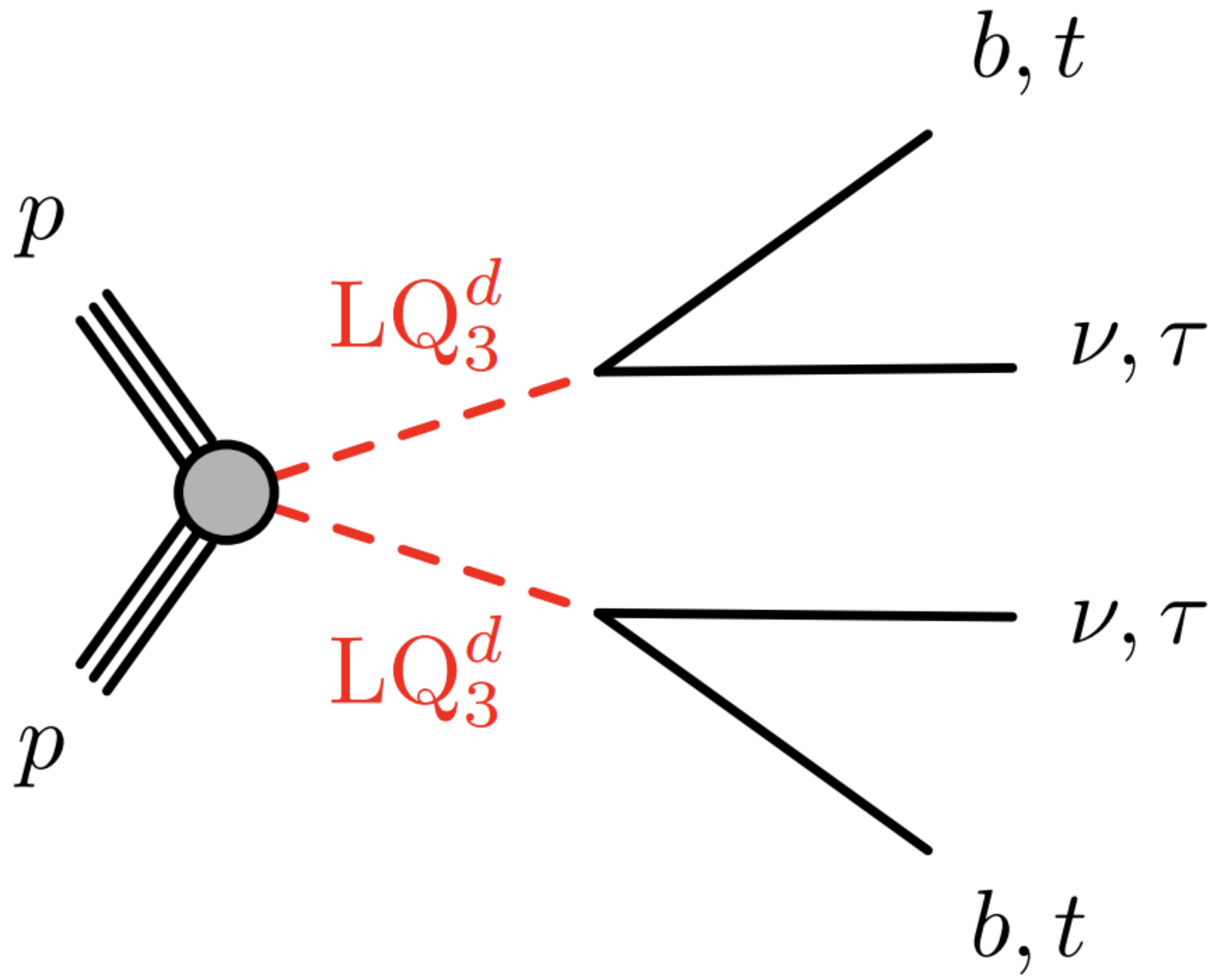

- Leptoquarks

$$\mathcal{L}_\phi \supset \bar{\chi}(g^S_\chi + i g^P_\chi \gamma_5)\chi\phi + \sum_q \bar{q}\frac{y_q}{\sqrt{2}}\left(g^S_q + i g^P_q \gamma_5\right) q\phi$$

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Assume Yukawa couplings are SM-like

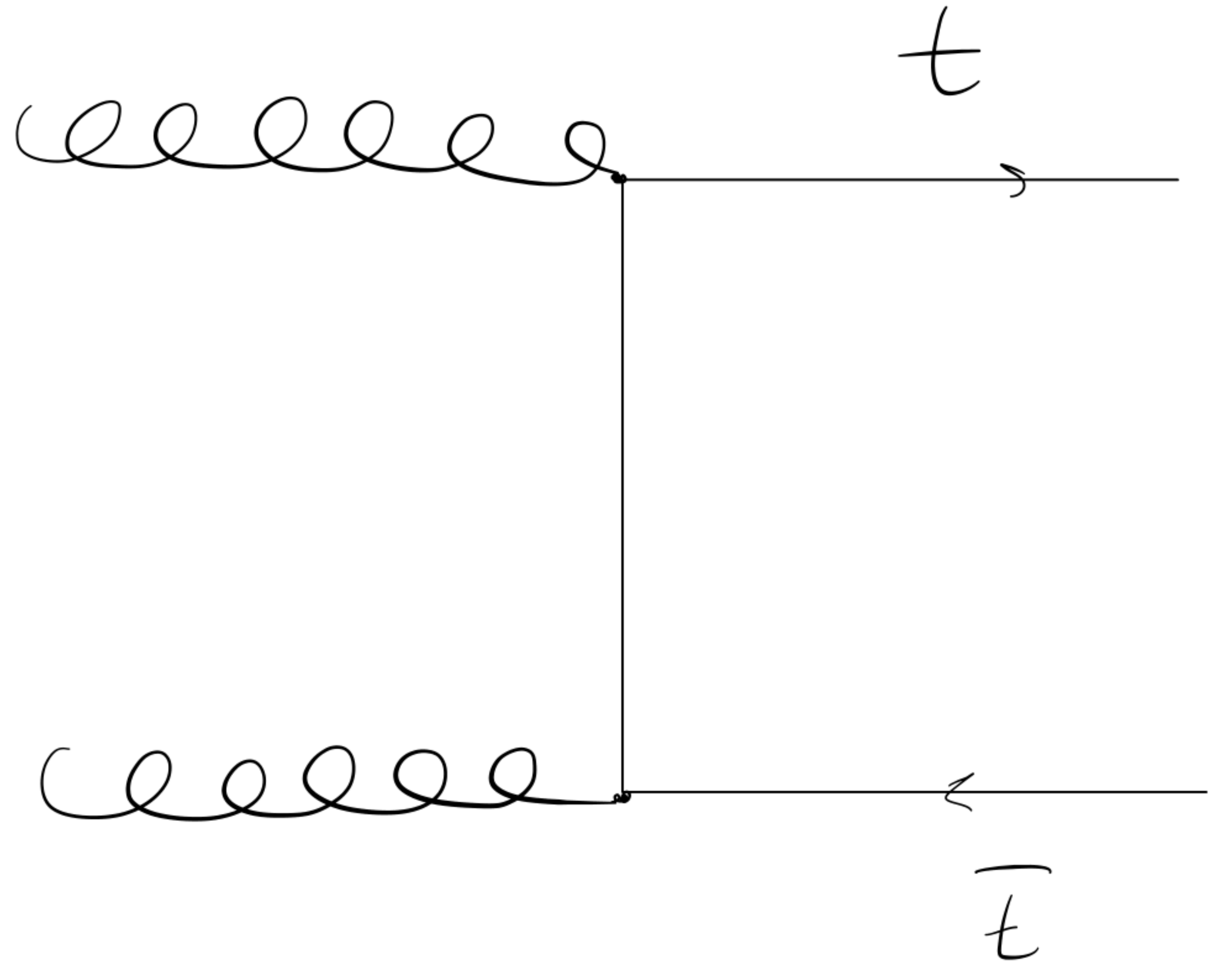
MET + bb in SM

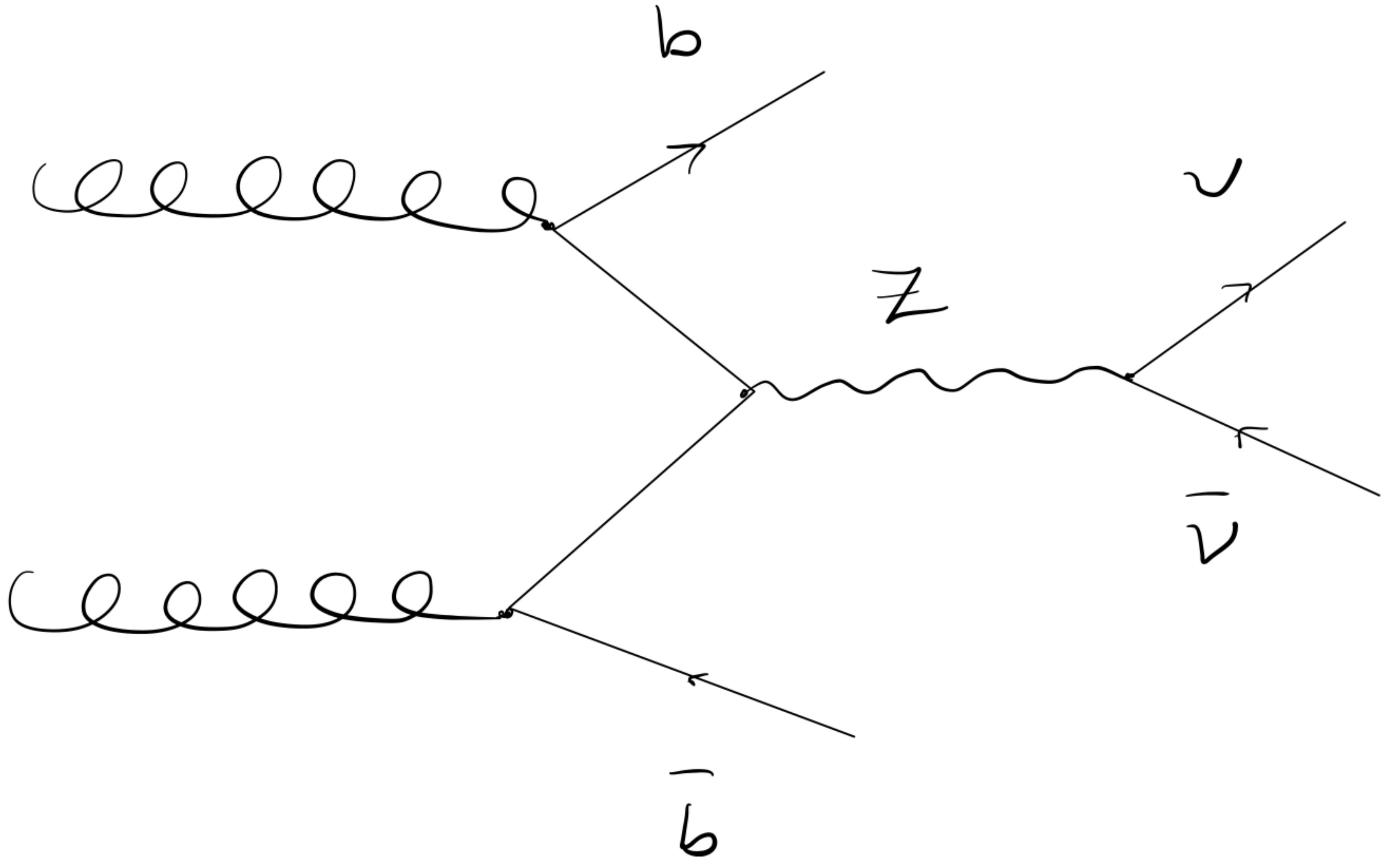
- Some of the SM processes that produce the same signature, which are the main sources of background:

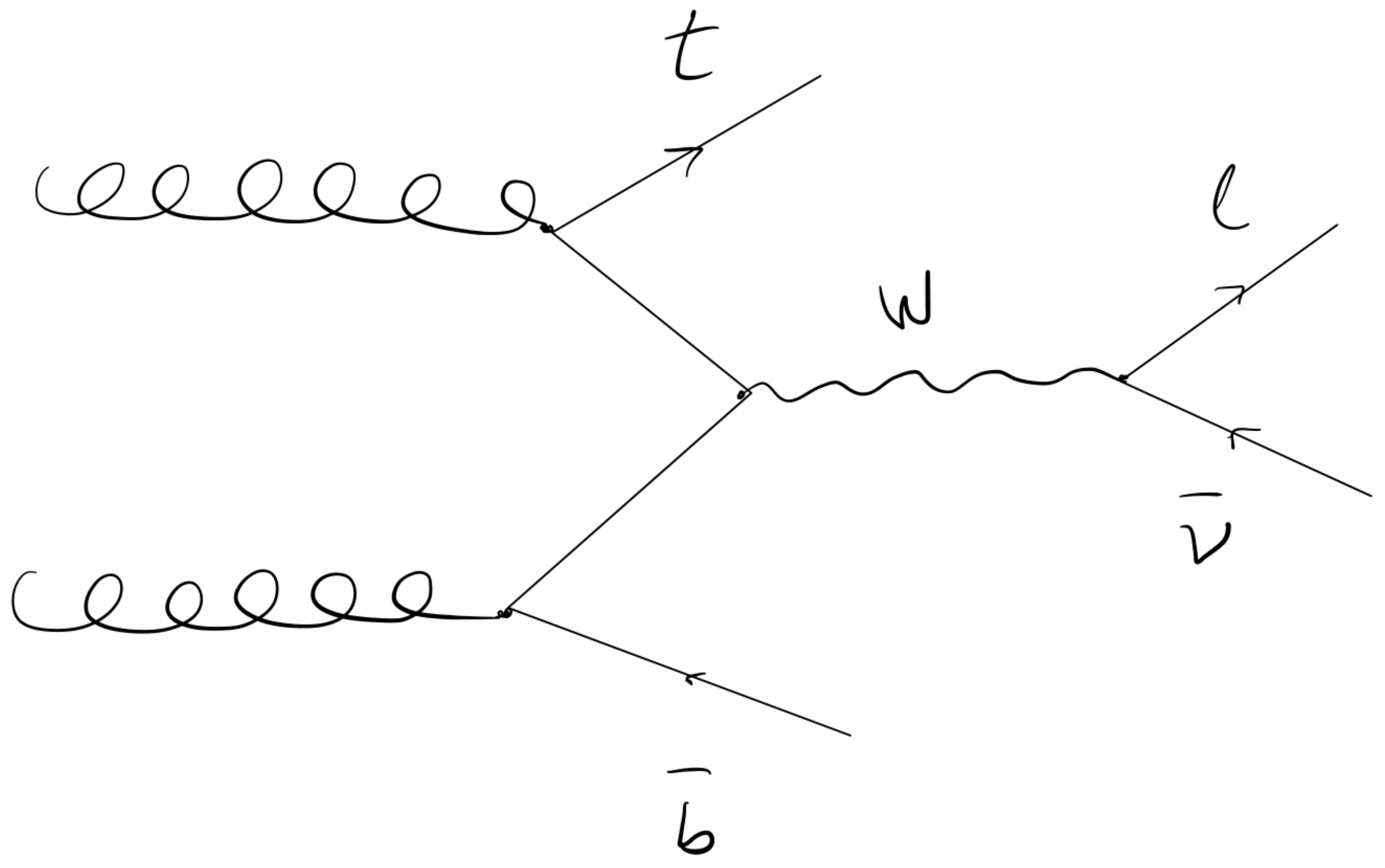
$$Z(\to \nu\bar{\nu}) + \text{jets}$$

$$W(\to \ell\nu) + \text{jets}$$

$$t\bar{t}, t \to Wb \to \ell\nu b$$







Extracting the relevant signal events

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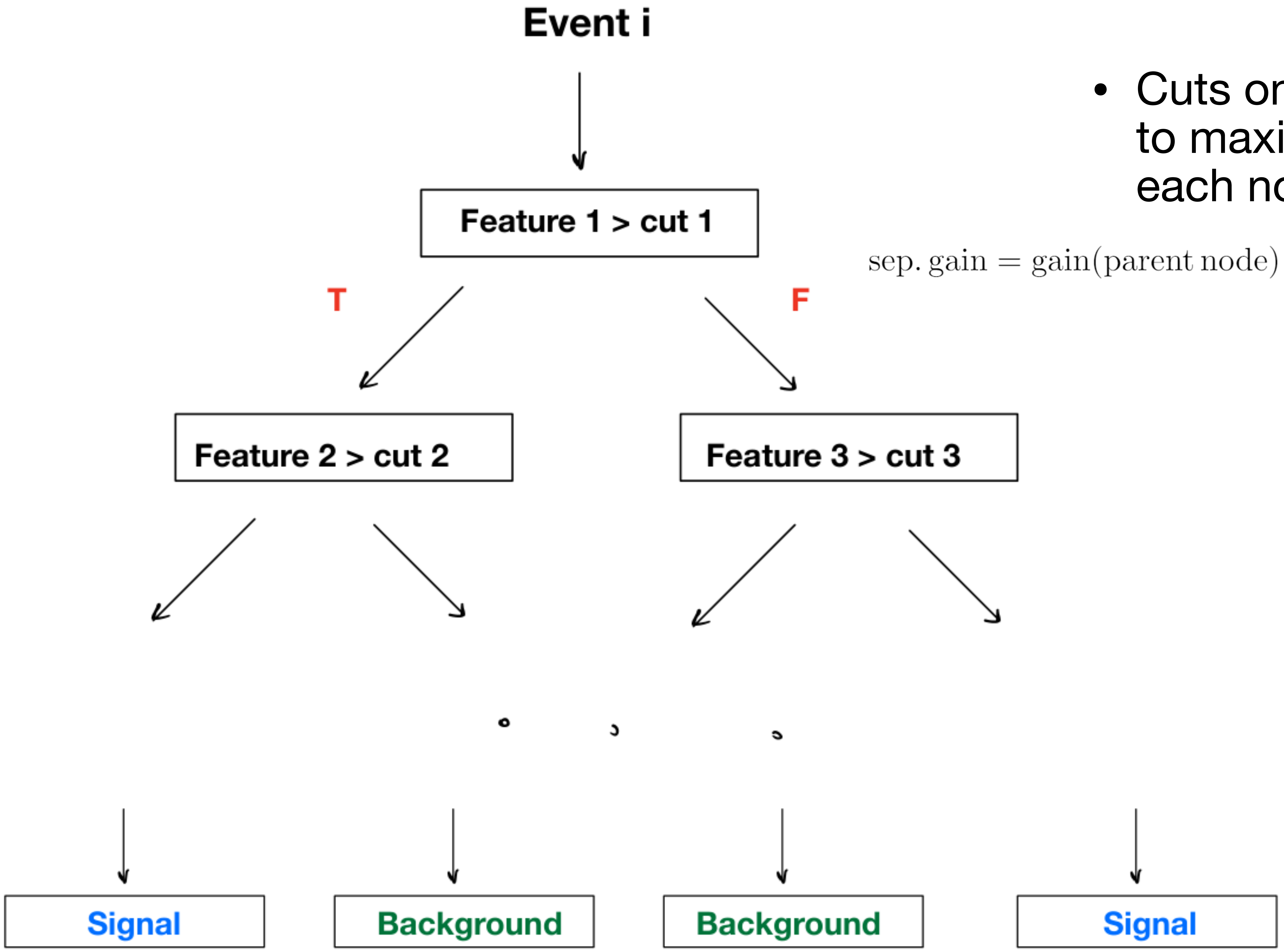
Number of baseline leptons	0
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 180 GeV
N_{jets}	2–3
$N_{b\text{-jets}}$	≥ 2
$p_{\mathrm{T}}(j_1)$	> 100 GeV
$p_{\mathrm{T}}(j_2)$	> 50 GeV
$\min[\Delta\phi(\mathbf{p}_{1-3}^{\mathrm{jet}}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})]$	> 0.4
$\mathcal{S}$	> 7
$p_{\mathrm{T}}(j_1)/H_{\mathrm{T}}$	> 0.7

Extracting the relevant signal events

ATLAS 2101.12527

Number of baseline leptons	0	→ Reducing W, top bckg
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 180 GeV	→ Reducing soft physics
N_{jets}	2–3	→ Reducing tt bckg
$N_{b\text{-jets}}$	≥ 2	
$p_{\mathrm{T}}(j_1)$	> 100 GeV	
$p_{\mathrm{T}}(j_2)$	> 50 GeV	
$\min[\Delta\phi(\mathbf{p}_{1-3}^{\mathrm{jet}}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})]$	> 0.4	} QCD suppression
$\mathcal{S}$	> 7	} QCD suppression
$p_{\mathrm{T}}(j_1)/H_{\mathrm{T}}$	> 0.7	} QCD suppression

Training a Boosted Decision Tree (BDT)



- Cuts on the decision tree are chosen to maximize the separation gain of each node

$$\text{sep. gain} = \text{gain}(\text{parent node}) - \text{gain}(\text{daughter node1}) - \text{gain}(\text{daughter node2})$$

$$\text{gain}(\text{node}) = p(1-p)$$

$$p = S/B$$

Training a Boosted Decision Tree (BDT)

- Initialize *N* trees
- Calculate the error for each tree j (j = 1,...,*N*):

$$\varepsilon_j = \frac{\sum_{y_i \neq h_j(\mathbf{x}_i)} w_i^{(j)}}{\sum_{i=1}^{n} w_i^{(j)}}$$

weight sum of misidentified events

sum of all weights

- Update (boost) the weights of the trees:

$$w_i^{(j+1)} = w_i^{(j)} e^{\alpha_j}$$

- where α_j is the BDT output score:

$$\alpha_j = \beta \ln \frac{1-\varepsilon_j}{\varepsilon_j}$$

- The final decision output value (> 0.5 if signal, <0.5 if bckg) for the event i is given as:

$$h_{fin}(\mathbf{x}_i) = \frac{1}{N_{\text{trees}}} \sum_{j=1}^{N_{\text{trees}}} \alpha_j h_j(\mathbf{x}_i)$$

Training a Boosted Decision Tree (BDT)

- Variables chosen such that they do not correlate too much with each other (provide relevant information to the BDT)

- For different backgrounds, train different BDTs (i.e. one BDT for each background source)

- Variables that the BDTs were trained on include:

$$p_T(j_2), p_T(j_3), p_T(b_1), E_T^{\rm miss}, S\,,\ \delta^-, \delta^+, p_T(j_1)/H_T$$

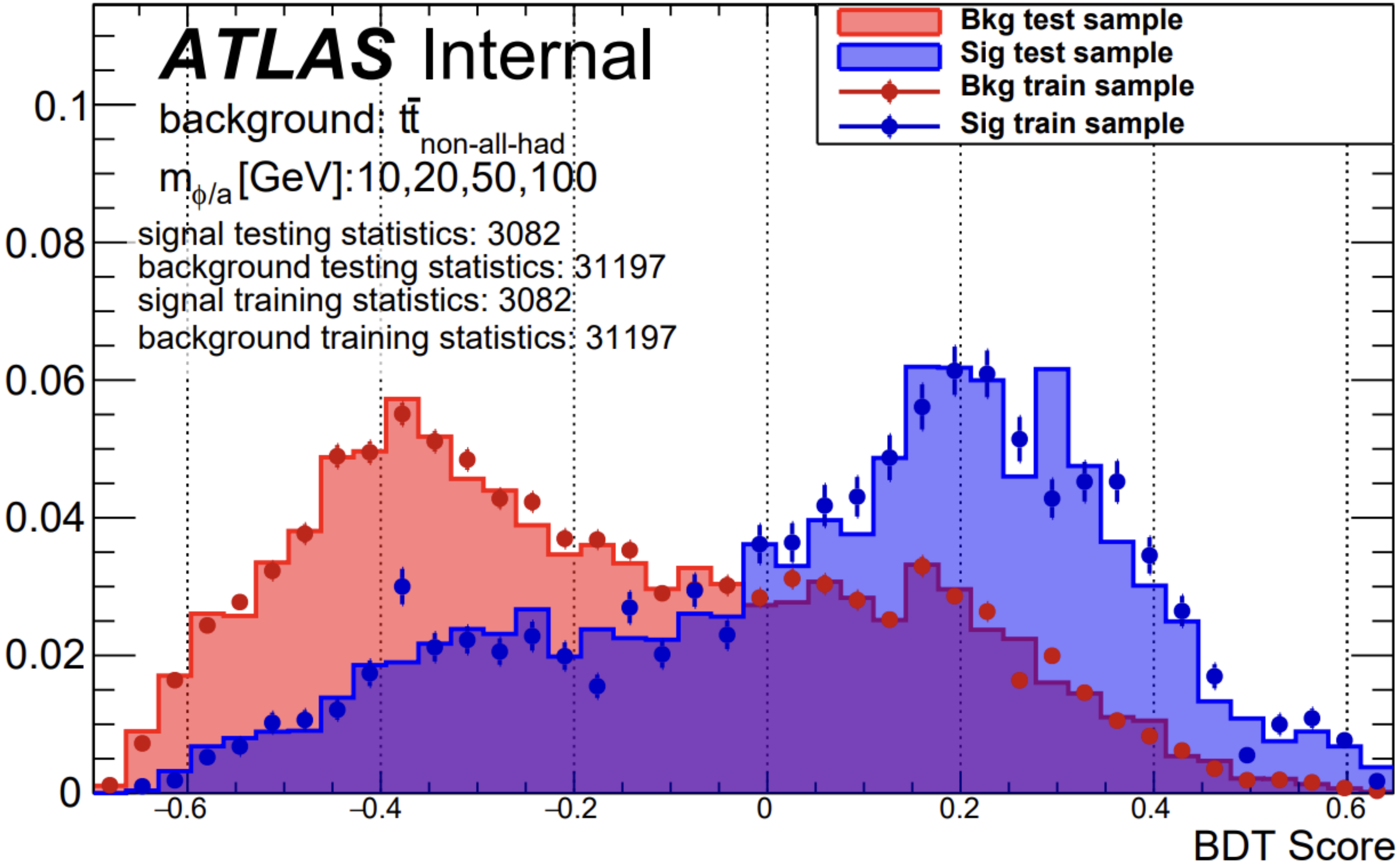
$$\min\left[\Delta\phi(\vec{p}_T^{\,\rm miss}, \vec{p}_{T,j}^{\,1,2,3})\right], \left|\Delta\phi_{bb}\right|, m_{\rm CT}^{j_1 j_2}, H_T$$

- Finally, choose cuts on the BDT output scores to successfully enhance the S/B ratio

E. J. Thorpe - PhD Thesis

Training a Boosted Decision Tree (BDT)

- Results from ATLAS for the separation from the ttbar background:



E. J. Thorpe - PhD Thesis

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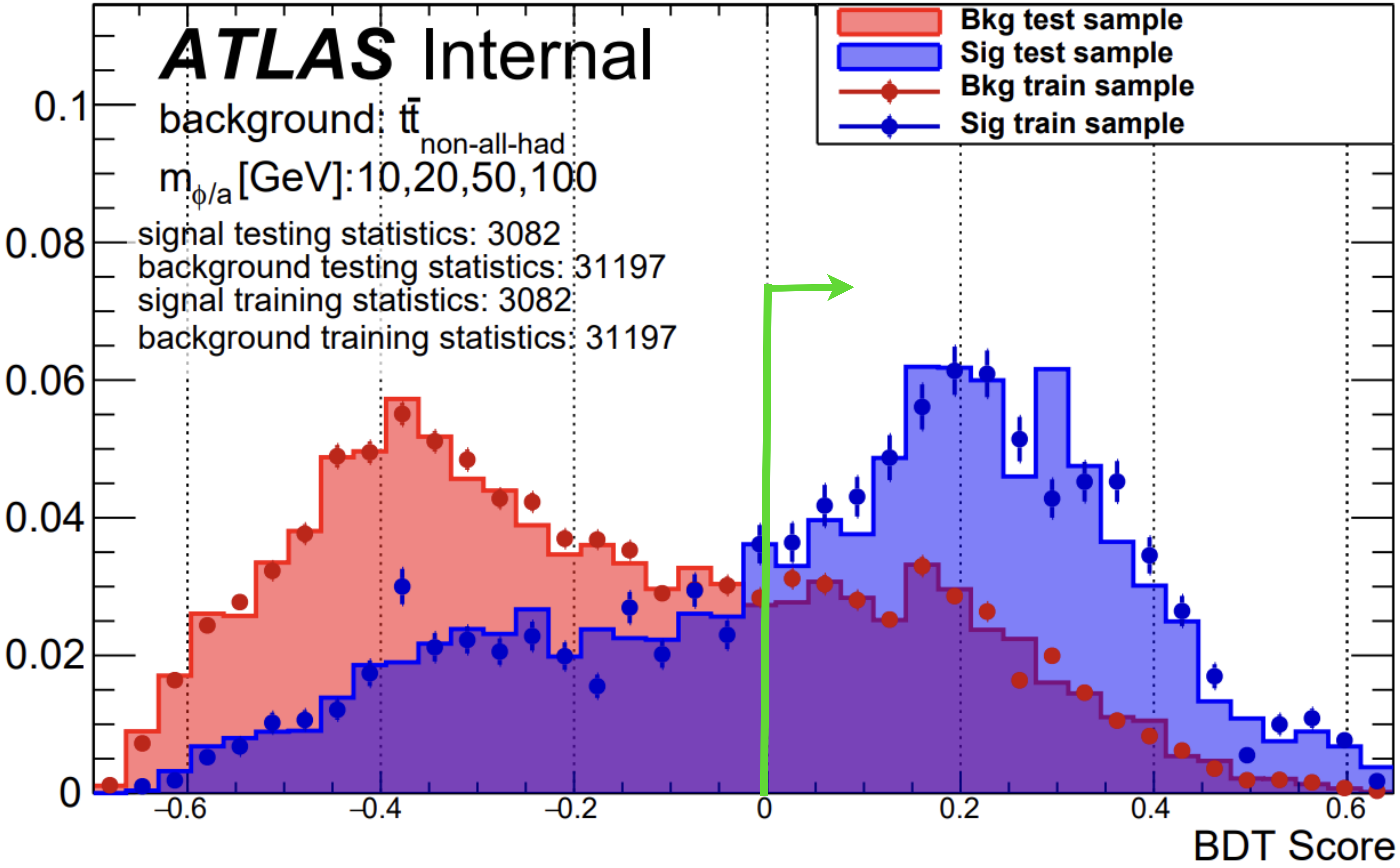


E. J. Thorpe - PhD Thesis

Training a Boosted Decision Tree (BDT)

- The variable with the highest feature importance are

$$\min\left[\Delta\phi(\vec{p}_T^{\,\text{miss}}, \vec{p}_{T,j}^{\,1,2,3})\right], p_T(b_1), m_{\text{CT}}^{j_1 j_2}, S$$

- where:

$$S = E_T^{\text{miss}}/\sigma_{\text{MET}}$$

- For practical purposes, in ATLAS:

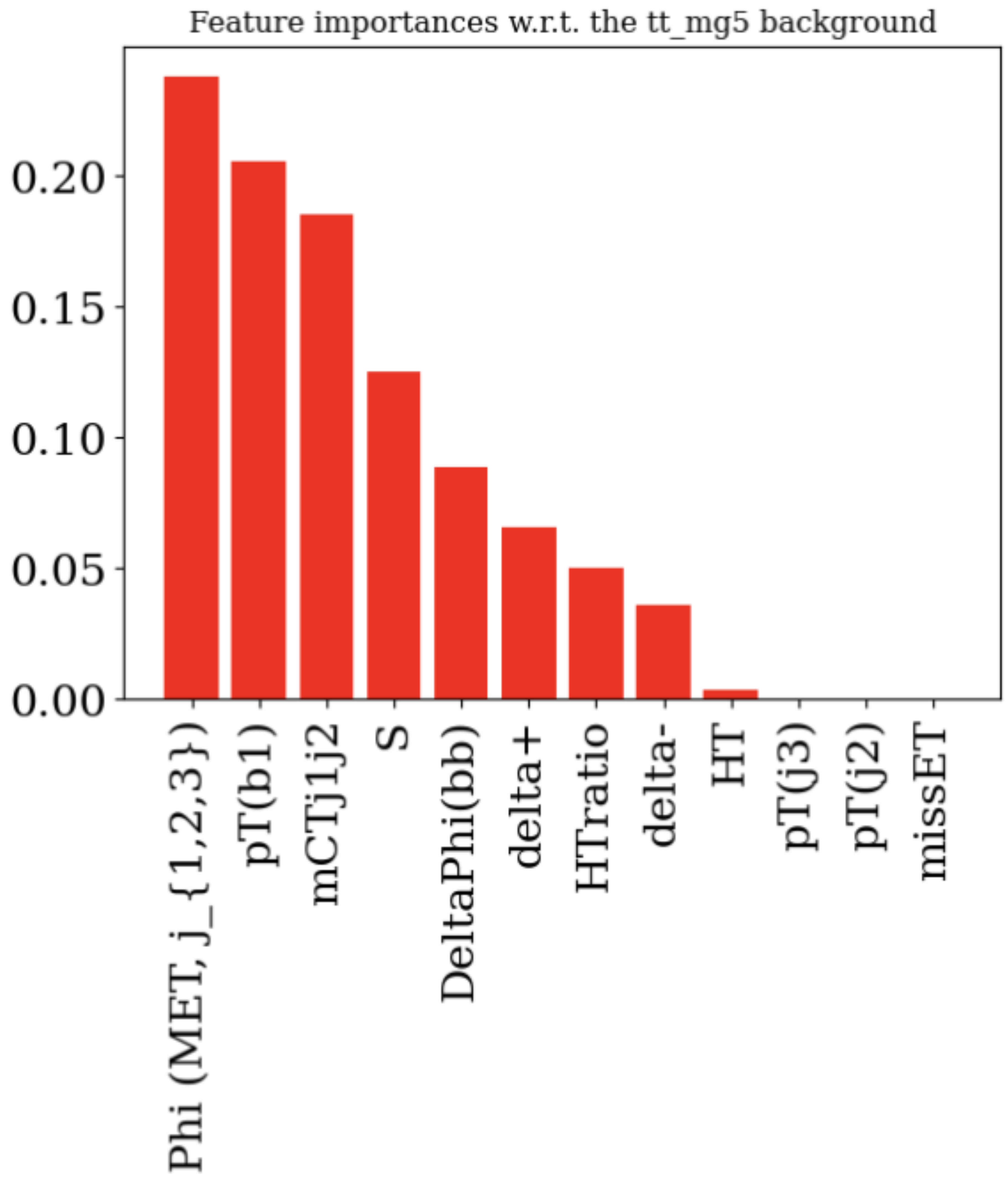
$$S = E_T^{\text{miss}}/\sqrt{\sum E_T}$$

ATLAS Collab., 1609.09324
1802.08168
2402.05858

- The contransverse mass is given as:

$$m_{\text{CT}}^2(v_1,\ v_2) = [E_{\text{T}}(v_1) + E_{\text{T}}(v_2)]^2 - [\mathbf{p}_{\text{T}}(v_1) - \mathbf{p}_{\text{T}}(v_2)]^2$$

$$m_{\text{CT}}^{\text{max}} = (m_I^2 - m_X^2)/m_I \qquad I = t, X = W$$



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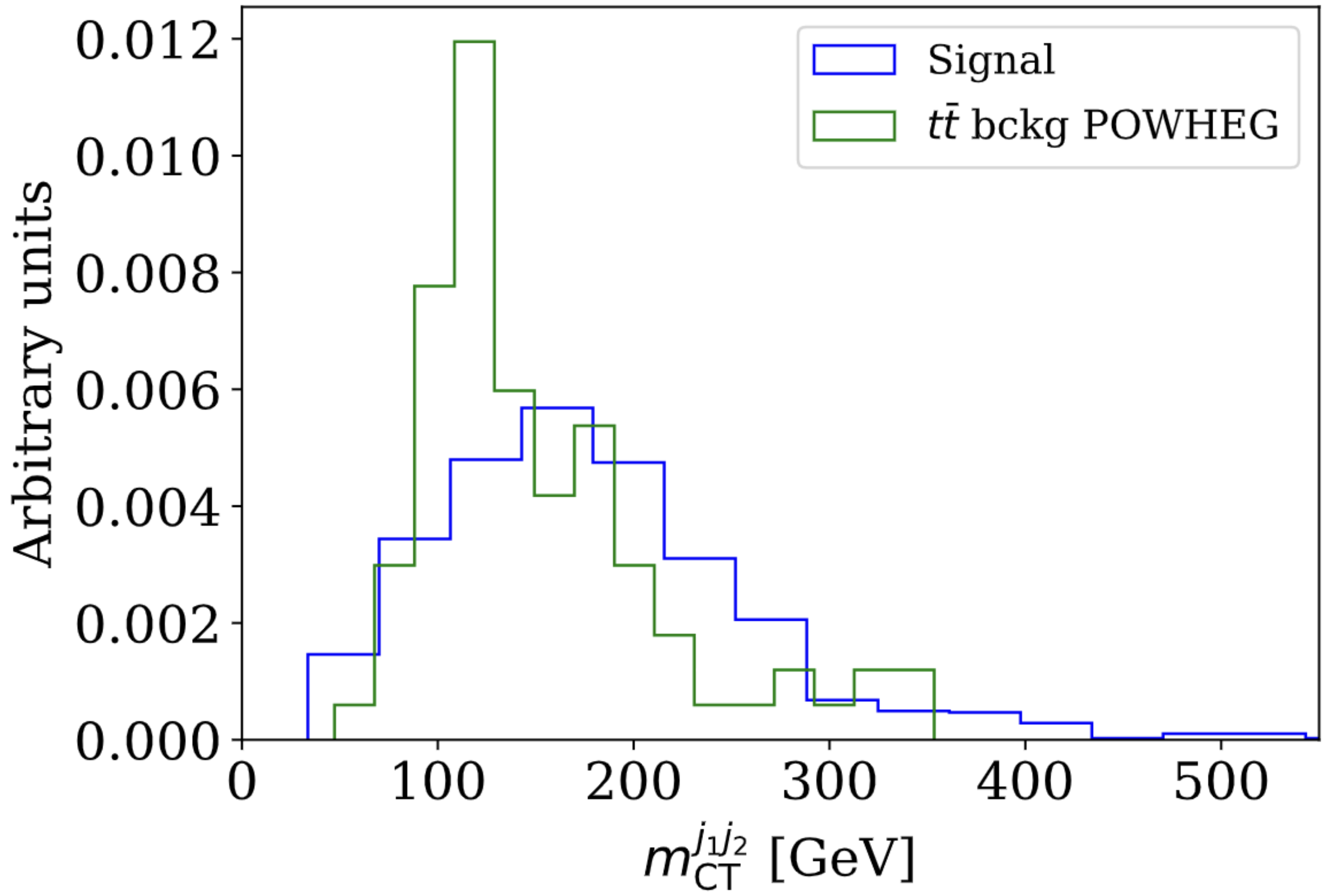

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$$\boxed{m_{\text{CT}}^{\text{max}} = (m_I^2 - m_X^2)/m_I} \qquad I = t, X = W$$

$$m_{\text{CT}}^{\text{max},t\bar{t}} \sim 135\,\text{GeV}$$

Can we perform such an analysis home?

- We generate the signal samples (pp to chi chi bb) with the DMSimp FeynRules UFO model, using MG5 + Pythia8 + Delphes

- We employ the same tools for the background, the $t\bar{t}$ samples have also been generated with POWHEG and the **hvq** model

- Create custom analysis using upROOT

- Utilize ATLAS OpenData for analysis frameworks, generated background events and codes

Y. Afik, F. Maltoni et al (2018)

S. Frixione, P. Nason, G. Ridolfi (2009)

https://opendata.atlas.cern/

https://github.com/atlas-outreach-data-tools/notebooks-collection-opendata/

Can we perform such an analysis home?

Initial			95270		
No leptons and $E_T^{miss} > 180$ GeV			897		
Number of jets ($p_T > 35$ GeV)			495		
Number of b-jets			76		
$\min[\Delta\phi(\text{jet}_{1-3}, \mathbf{p}_T^{miss})]$			67		
$\mathcal{S}$			64		
$\frac{p_T(j_1)}{H_T}$			31		
BDT selections			5.6		
$\cos\theta^*_{bb}$	bin0	bin1	bin2	bin3	bin4
	0.6	0.8	1.1	1.2	1.9

Another useful variable - for (pseudo-)scalars, does not suffer from cuts in transverse plane

ATLAS 2101.12527

M. R. Buckley and D. Goncalves (2016)
U. Haisch, P. Pani and G. Polesello (2017)

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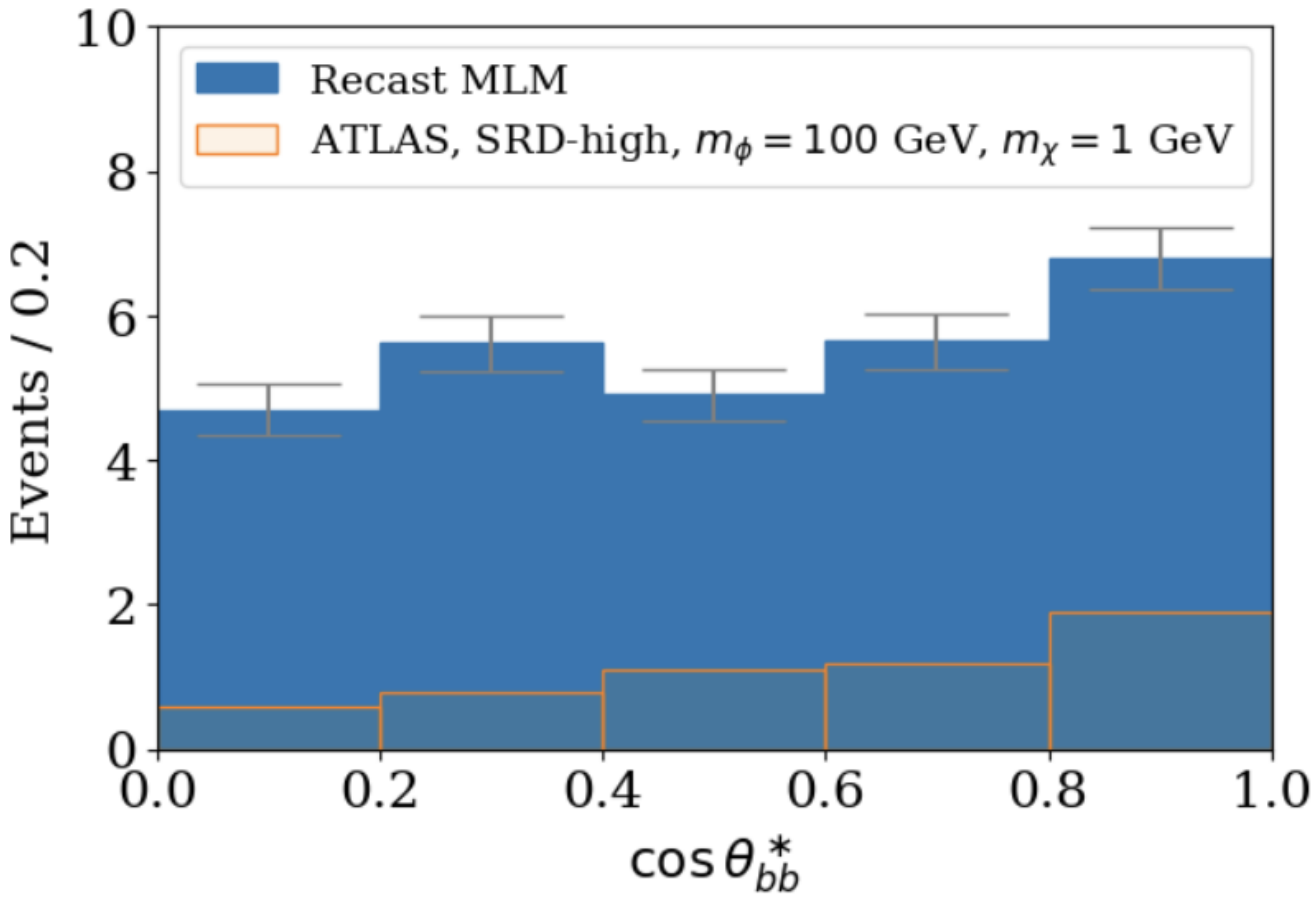


After we do this...

- Test different models with invisible decays (see Patrick Bolton's talk)
- Not necessarily rely on MET + bb signature. E.g. recasts and bounds on NP from MET + jet(s) exist already, or MET + top(s).

Hiller, Wendler, 2403.17063

- Not necessarily rely on scalar and pseudoscalar mediators (e.g. vector mediators could also be tested)
- Combine with low-energy observables

Thank you for your attention!

Backup

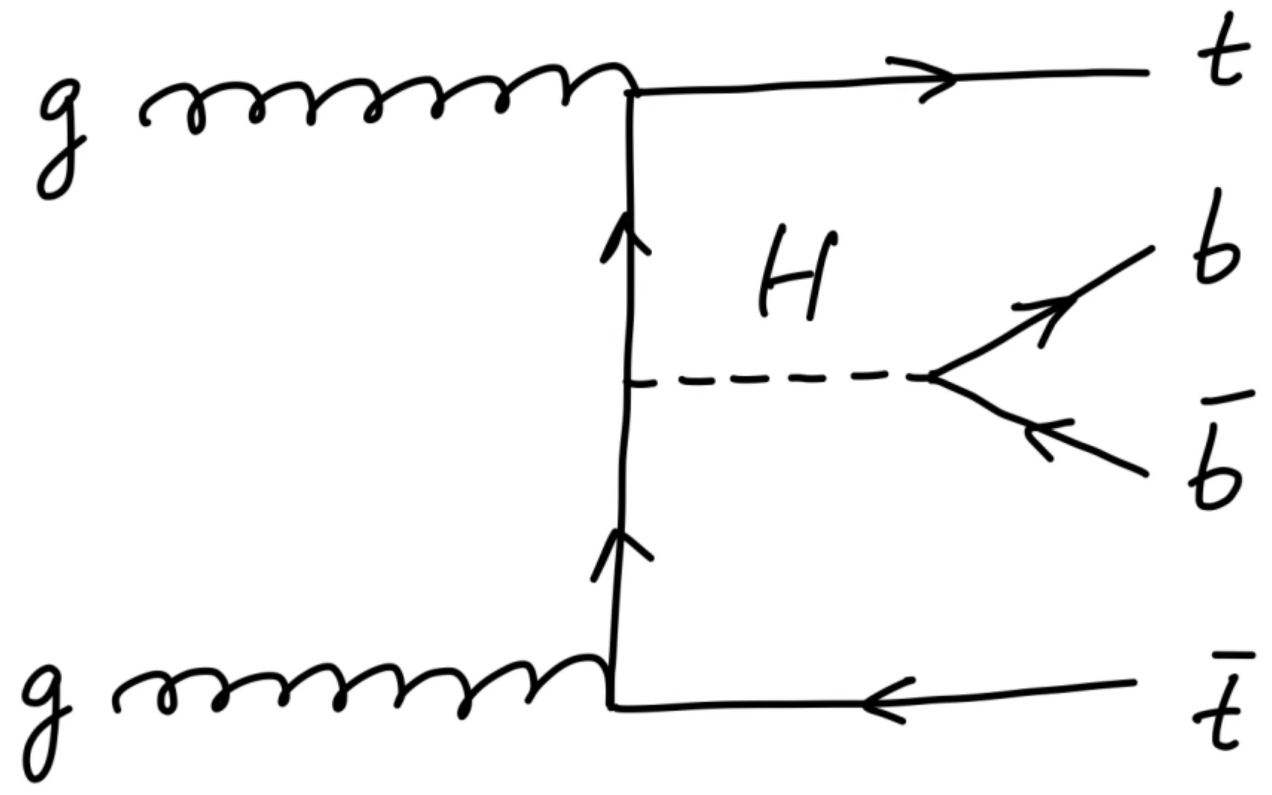
4FS vs 5FS

- 4FS calculations are the most precise at fixed order (i.e. w/o a parton shower)
  - b-quark mass effects taken into account
  - The processes can be generated down to any energies
- Calculation with a certain number of jets at fixed order is reliable only if there are no scale hierarchies

Bredenstein, Denner, Dittmaier, Pozzorini (2008)
Bredenstein, Denner, Dittmaier, Pozzorini (2009)
Bevilacqua, Czakon, Papadopoulos, Pittau, Worek (2009)
Buccioni, Kallweit, Pozzorini, Zoller (2019)
Bredenstein, Denner, Dittmaier, Pozzorini (2010)
Denner, Lang, Pellen (2021)
Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek (2021)
Bevilacqua, Bi, Hartanto, Kraus, Lupattelli, Worek (2023)

4FS

- For example, *ttbb* production is a multi-scale process
  - Large mass difference between the top and bottom-quarks -> large logarithms log^n (m_b / \sqrt{s})
  - Difficult to choose optimal renormalisation and factorisation scales
  - Need a very small muR and muF != muR



see discussion in the LHC Higgs Xsec WG report arXiv:1610.07922

4FS

- Challenges arise when matching to a parton shower
  - PS radiation can produce additional b-quarks
  - Jets generated by the shower can be harder than the ME-level bottom quarks
  - Need only the subleading b-quarks to come from the PS but not the leading ones
  - Poorly understood how the PS radiation should be constraint

Cascioli, Maierhöfer, Moretti, Pozzorini, Siegert (2014)
Ježo, Lindert, Moretti, Pozzorini (2018)

5FS

- In 5FS one has to generate an inclusive DM DMbar + jets sample
  - b-jets are selected only after parton showering

Frixione, Nason, Webber (2003)
Frixione, Nason, Ridolfi (2007)
Hoeche, Krauss, Maierhoefer, Pozzorini, Schonherr, Siegert (2015)
Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi (2022)

- 5FS: massless b-quarks
  - Large logarithms do not arise in the ME
  - Large scale hierarchies between the top quarks and the jets can be resummed by a multi-jet merging
- Multi-jet merging: combination of events with different jet multiplicities
  - For example, FxFx merging in MadGraph5_aMC@NLO