Sensitivity to NMSSM Signatures with Low Missing Transverse Energy at the LHC

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Theoretical Overview

Minimally Supersymmetric

- MSSM = Minimal Supersymmetric Standard Model.

- Gives solution to hierarchy problem and at low energies appears similar to SM —> so far so good.

- But has a term ***μ*** which is not very natural, involves setting *by hand* parameters which are **not** dimensionless…

$$W_{MSSM} = \text{Yukawa couplings } (q, l^+, l^- \text{ masses}) \\ + \mu H_u H_d + \ldots$$

(Almost) Minimally Supersymmetric

- **N**MSSM = **Next to** Minimal Supersymmetric Standard Model.
- **Does not** involve setting *by hand* parameters which are not dimensionless…

$$W_{NMSSM} = \text{Yukawa couplings } (q, l^+, l^- \text{ masses})$$
$$+ \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{1}{3}\kappa\hat{S}^3 + \ldots$$

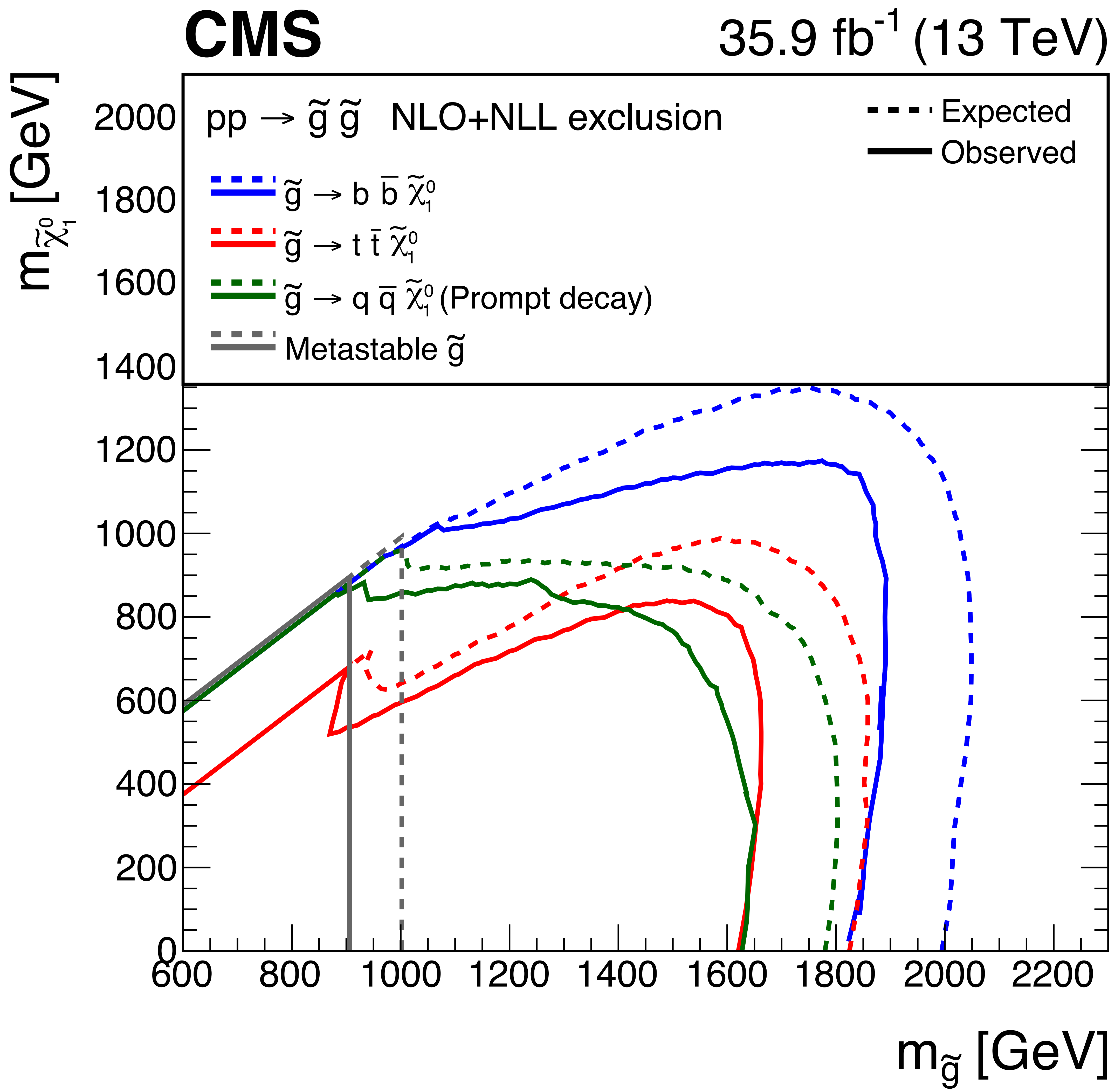
- Effective μ term given by:

$$\mu_{\text{eff}} = \lambda\langle S\rangle$$

So we want to search for this…

- Large Missing Transverse Energy (MET) searches have ruled out many areas of parameter space [1].

- How about scenario for Lightest Supersymmetric Particle (LSP) production with low MET?…



[1] CMS Collaboration, "Search for natural and split supersymmetry in proton-proton collisions at $\sqrt{s}$ = 13TeV in final states with jets and missing transverse momentum" JHEP 1805, 025 (2018)

So we want to search for this…

- Consider if LSP were a Singlino in the NMSSM (SUSY counterpart of singlet Higgs boson)

- Singlino = **Ŝ** field in NMSSM Superpotential:

$$W_{NMSSM} = \text{Yukawa couplings } (q, l^+, l^- \text{ masses}) + \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{1}{3}\kappa\hat{S}^3 + \ldots$$

- If LSP very light and NLSP-Higgs mass gap very small, MET suppressed

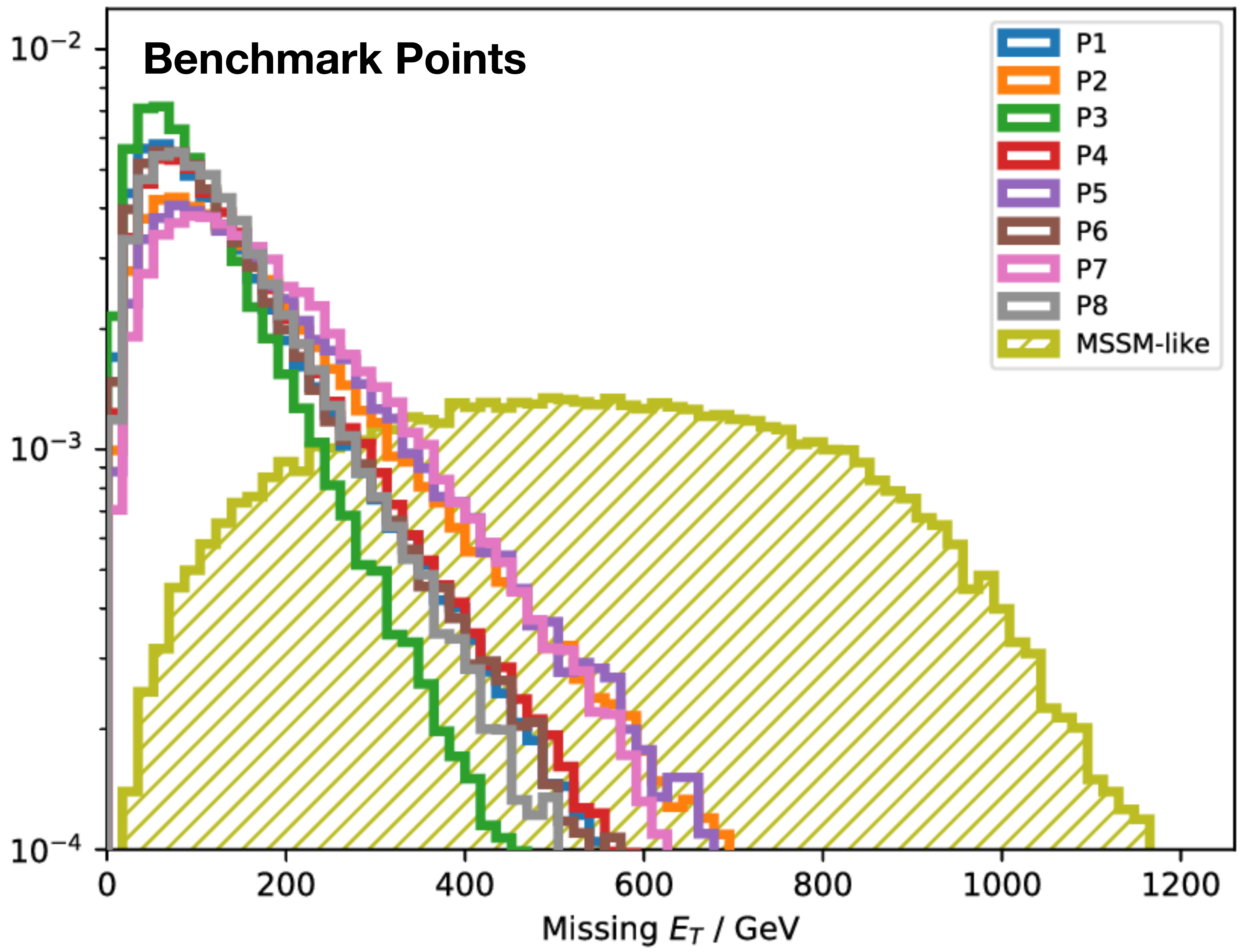
Example Decay Cascade(s)

Signal model definitions

- Start from original benchmark points P1—P8, taken from [2], which demonstrate a light-LSP low-MET scenario

- Turn these benchmark points into mass scans: M_{squark} vs M_{LSP}

- For each scan we **fix mass gaps** between squark/gluino and between NLSP/LSP, with M_H = 125 GeV also **fixed**.

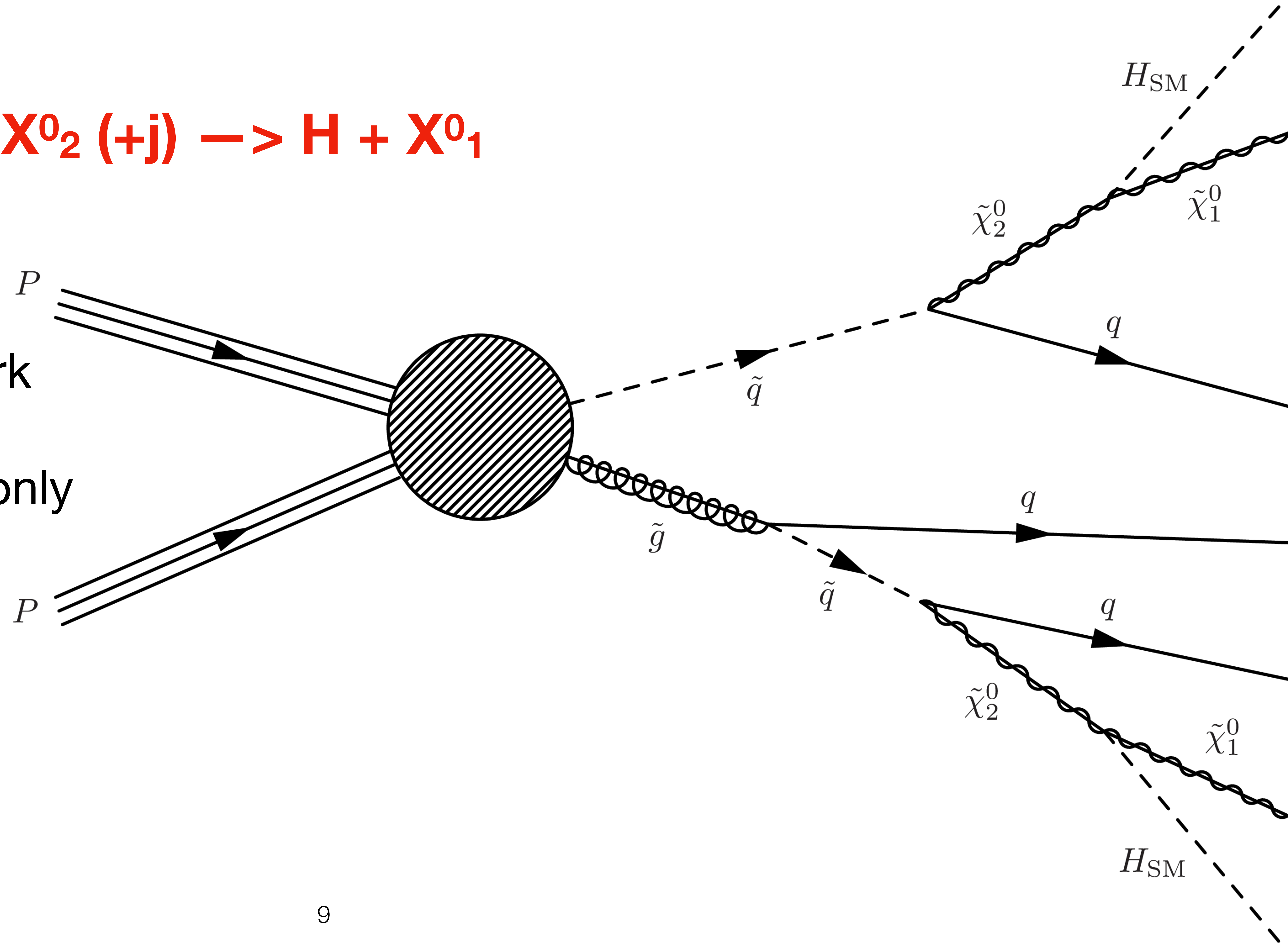


[2] U. Ellwanger and A.M. Teixeira, "Excessive Higgs pair production with little MET from squarks and gluinos in the NMSSM" JHEP 1504, 172 (2015)

Signal model definitions

BM1: g̃ —> q̃ (+j) —> X^0_2 (+j) —> H + X^0_1

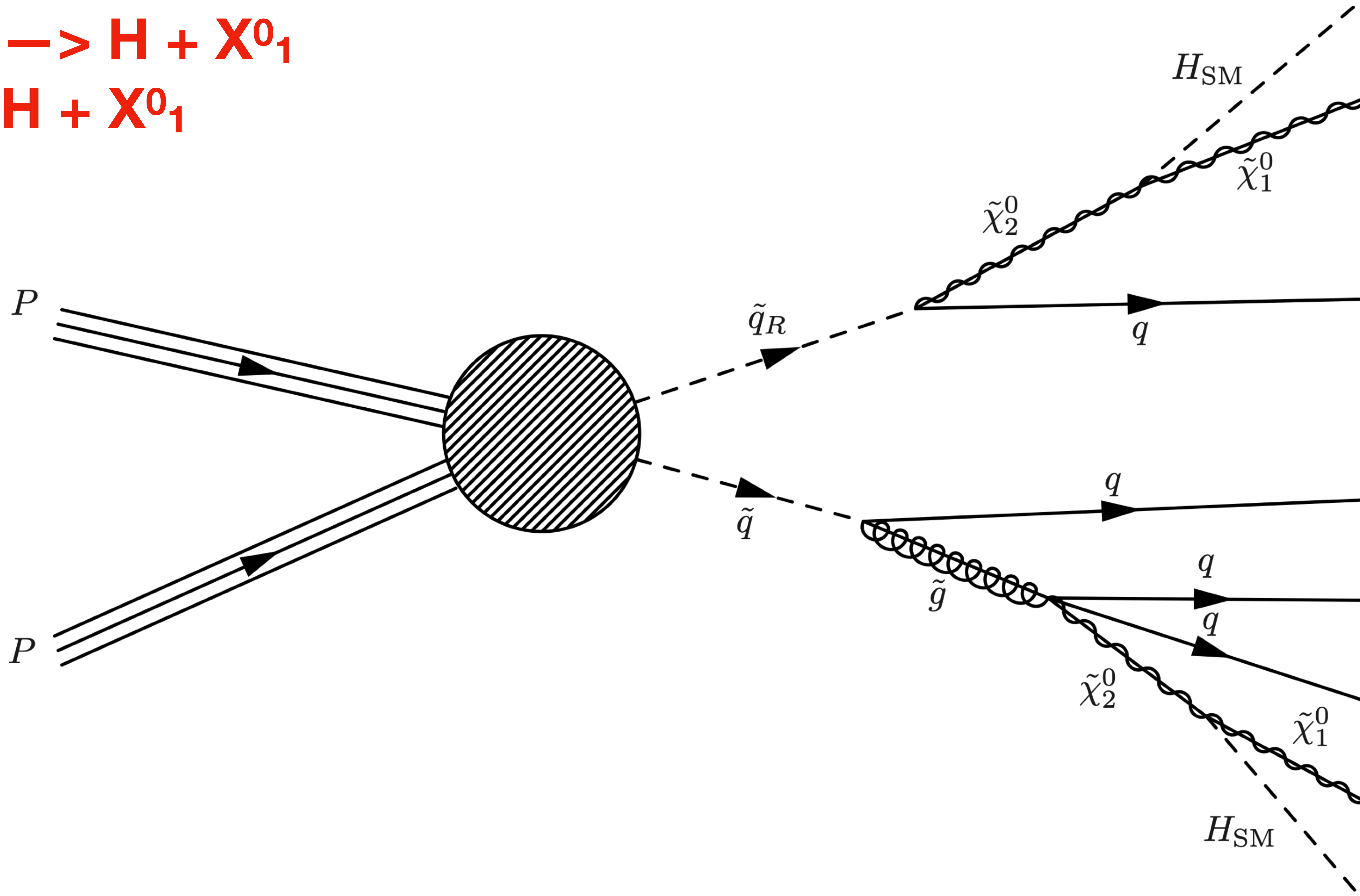
- Gluino heavier than squark
- Squark decays to NLSP only
- Simplest cascade



Signal model definitions

BM2: $\tilde{q}$ —> $\tilde{g}$ (+j) —> X^0_2 (+jj) —> H + X^0_1
or: $\tilde{q}_R$ —> X^0_2 (+j) —> H + X^0_1

- Squark heavier than gluino
- Left-handed squark decays to gluino or NLSP
- RH squark decays to NLSP
- Gluino decays to NLSP

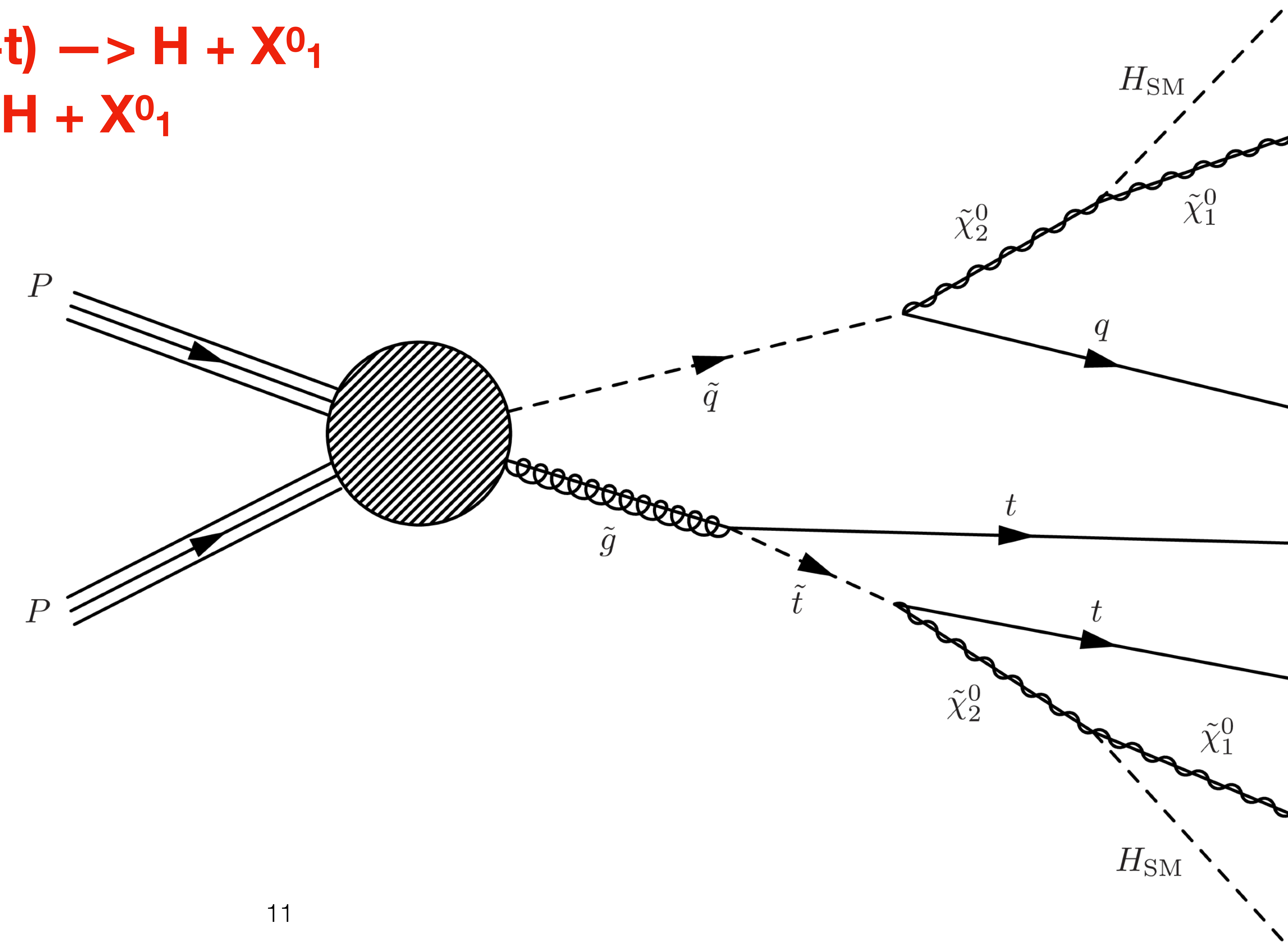


Signal model definitions

BM3: $\tilde{g} \rightarrow \tilde{t}$ (+t) $\rightarrow X^0_2$ (+t) $\rightarrow$ H + X^0_1

or: $\tilde{q} \rightarrow X^0_2$ (+j) $\rightarrow$ H + X^0_1

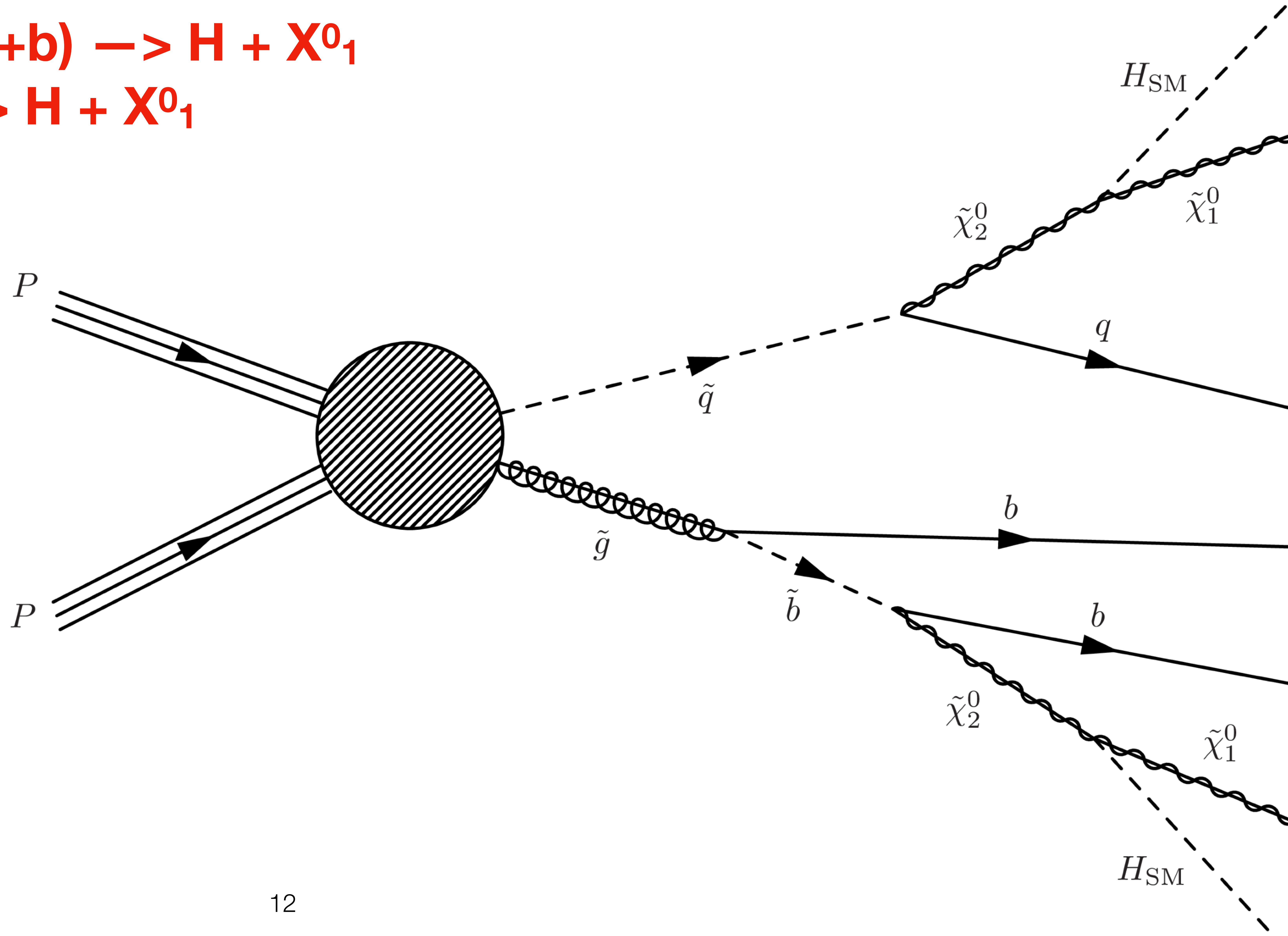
- Gluino heavier than squark
- Squark decays to NLSP
- Gluino decays to stop squark



Signal model definitions

BM4: $\tilde{g}$ —> $\tilde{b}$ (+b) —> X^0_2 (+b) —> H + X^0_1
or: $\tilde{q}$ —> X^0_2 (+j) —> H + X^0_1

- Gluino heavier than squark
- Squark decays to NLSP
- Gluino decays to sbottom squark



Signal model definitions

BM5: $\tilde{q} \rightarrow \tilde{g}$ (+j) $\rightarrow \tilde{t}$ (+t) $\rightarrow X^0_2$ (+t) $\rightarrow$ H + X^0_1

or: $\tilde{q}_R \rightarrow X^0_2$ (+j) $\rightarrow$ H + X^0_1

- Squark heavier than gluino
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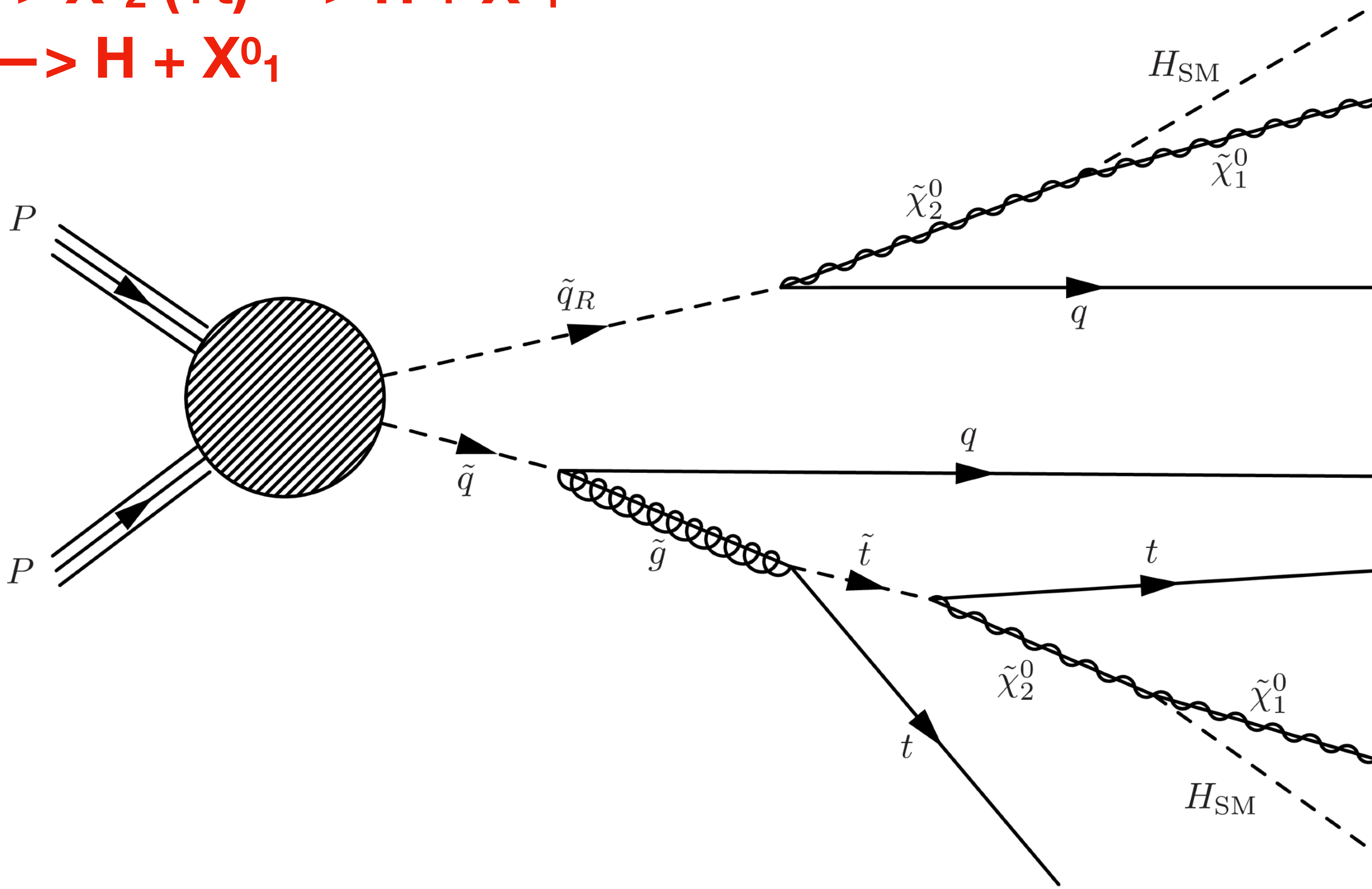

Signal model definitions

BM6: $\tilde{q}$ —> $\tilde{g}$ (+j) —> $\tilde{b}$ (+b) —> X^0_2 (+b) —> H + X^0_1
or: $\tilde{q}_R$ —> X^0_2 (+j) —> H + X^0_1

- Squark heavier than gluino
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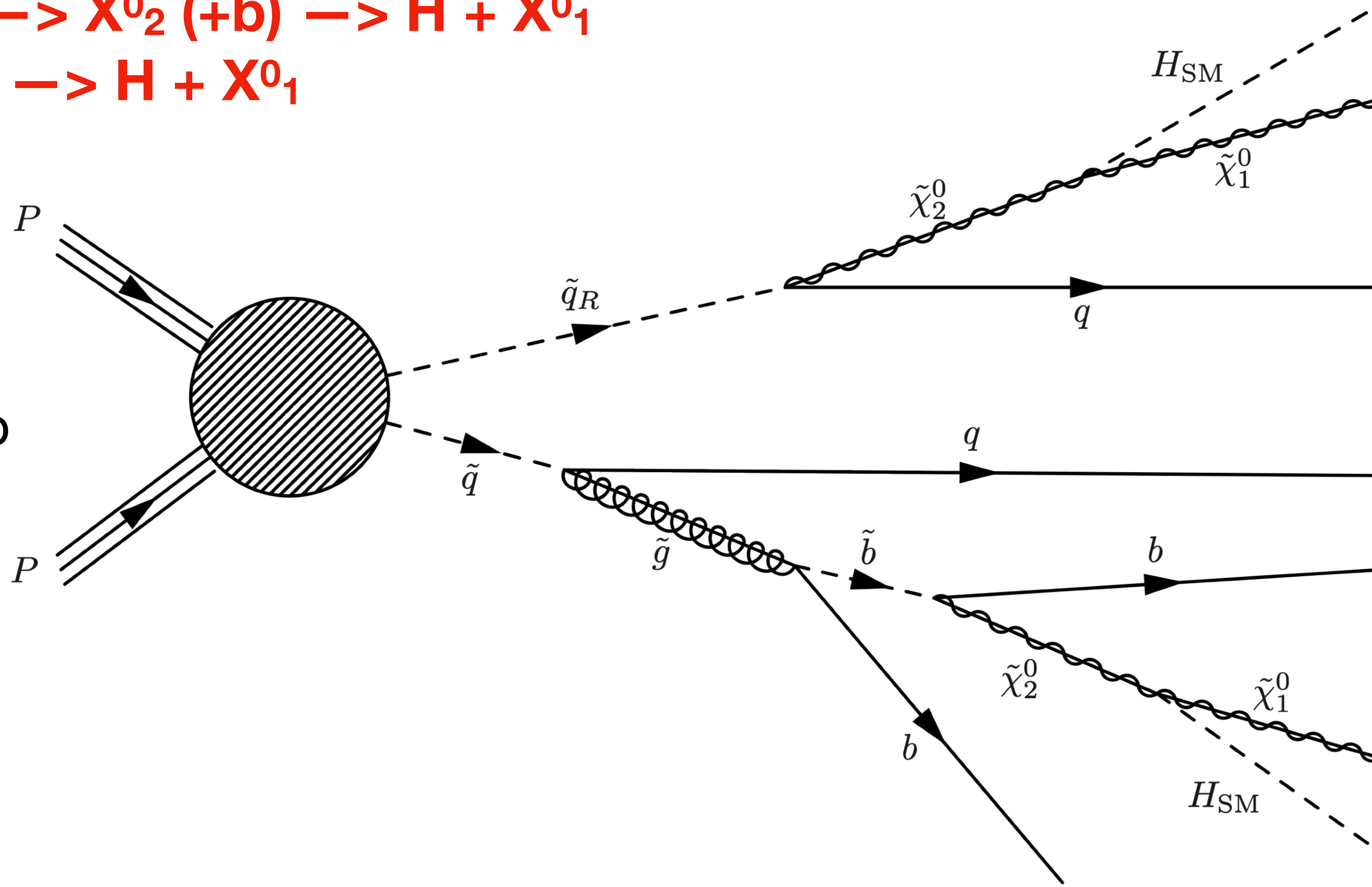
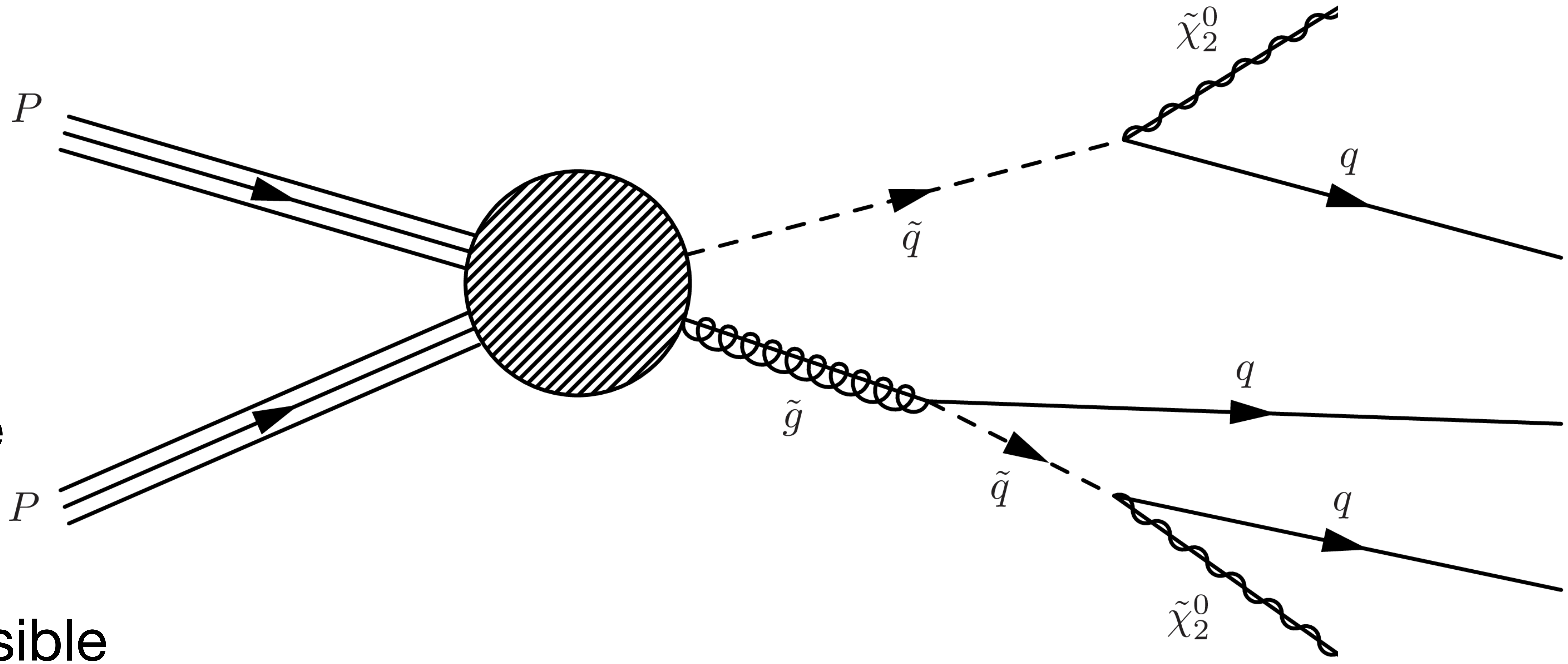


Signal model definitions

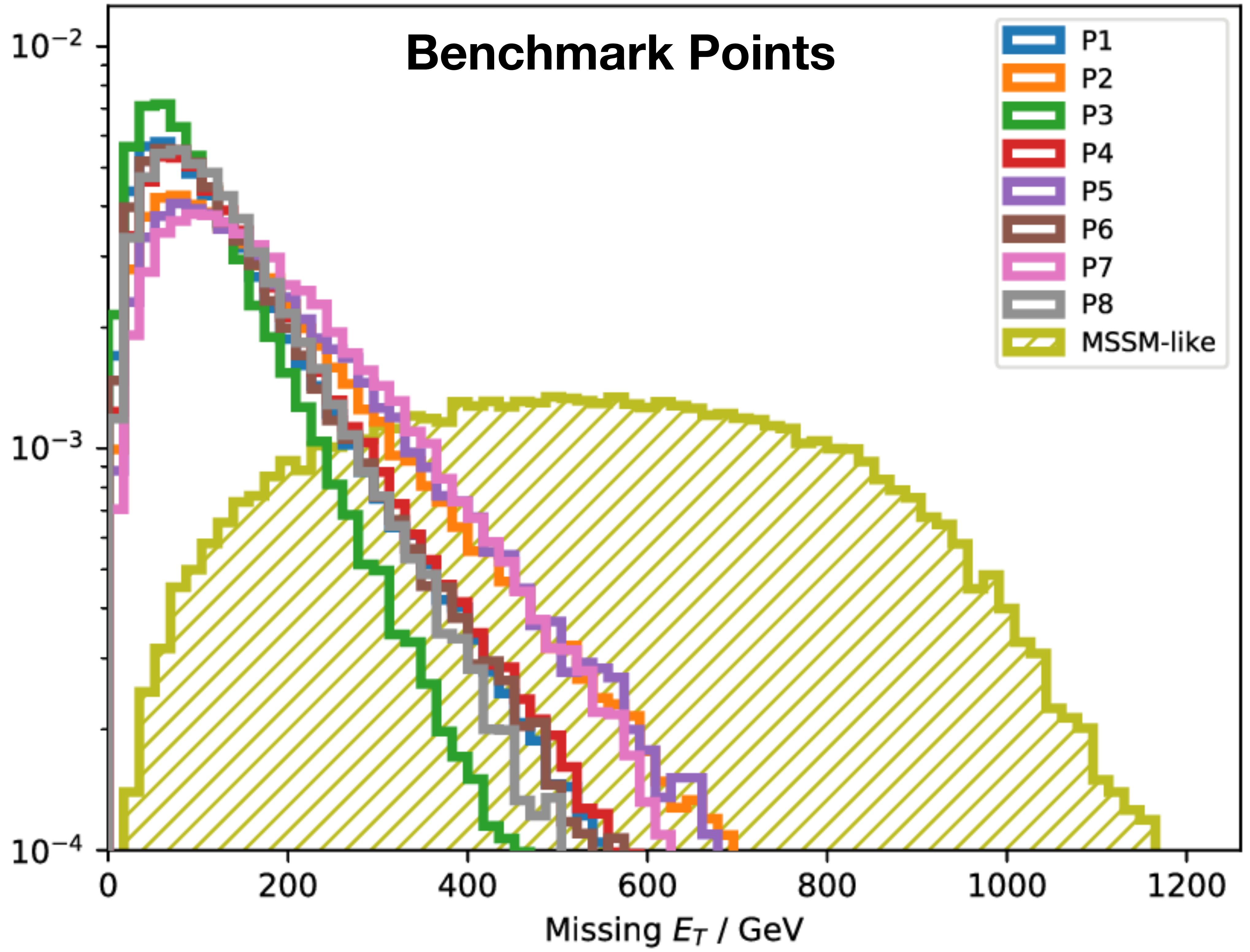
MSSM-like: BM1 with X^0_2 forced stable

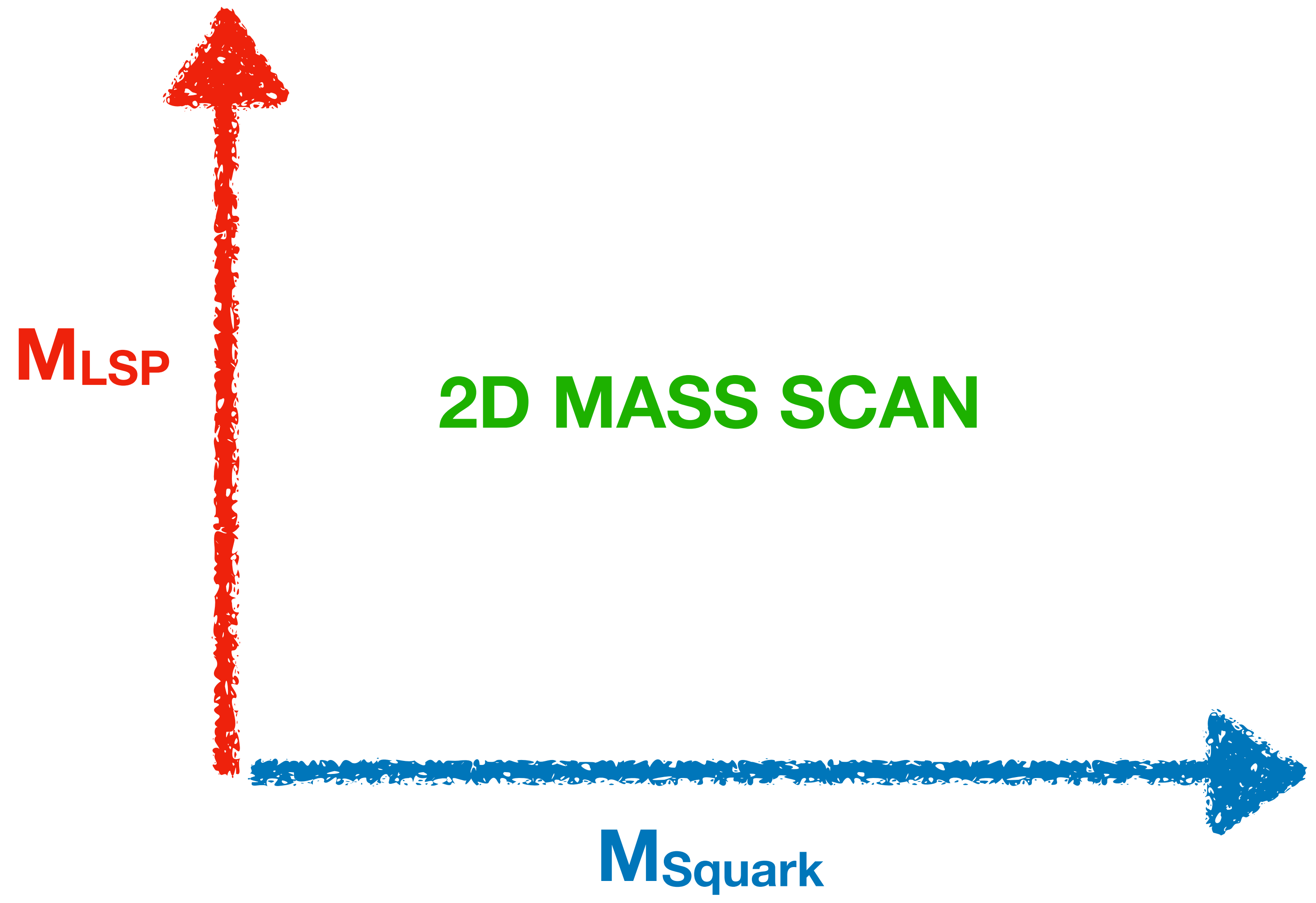


- X^0_2 stable, so acts like effective LSP
- High momentum, invisible stable particle —> MET

Signal model definitions

- All of these benchmark models have low MET, shown in figure on the right
- Turn these BMs into mass scans: M_{squark} vs M_{LSP}
- Squark-Gluino mass gap **fixed**
- NLSP-LSP mass gap **fixed**
- M_H = 125 GeV fixed

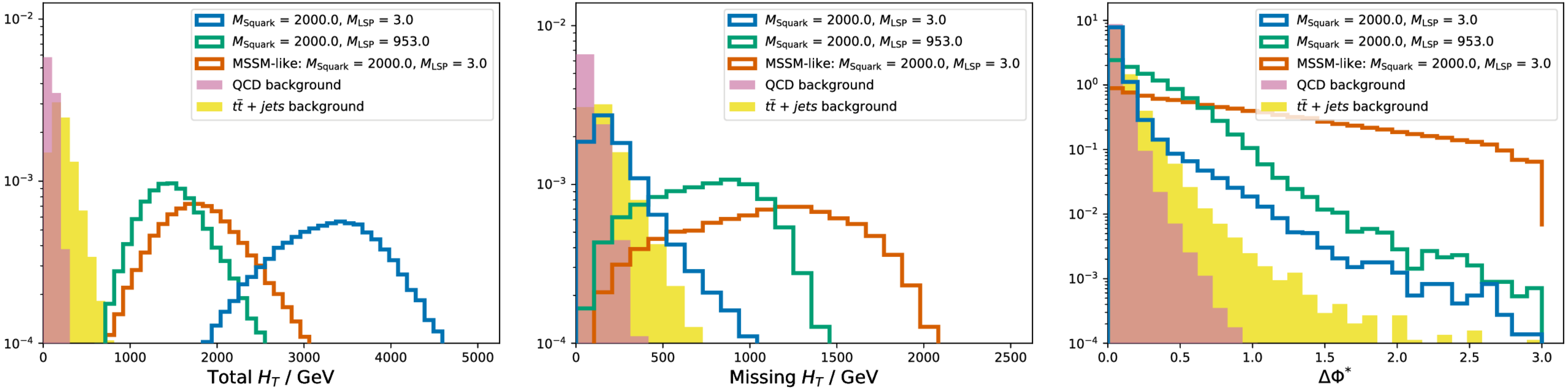




Phenomenological Interpretation

Mass Scans

- CMS analysis in [1] recast [3] to explore current sensitivity, using 35.9fb-1 data from 2016
- HT > 1200GeV; $N_{Jet} > 5$; $\Delta\phi^* > 0.5$
- $N_{b\text{-}Jet} \in \{ 2, 3, 4+ \}$
- MHT $\in$ { [200,400), [400,600), [600,900), [900,∞) } GeV

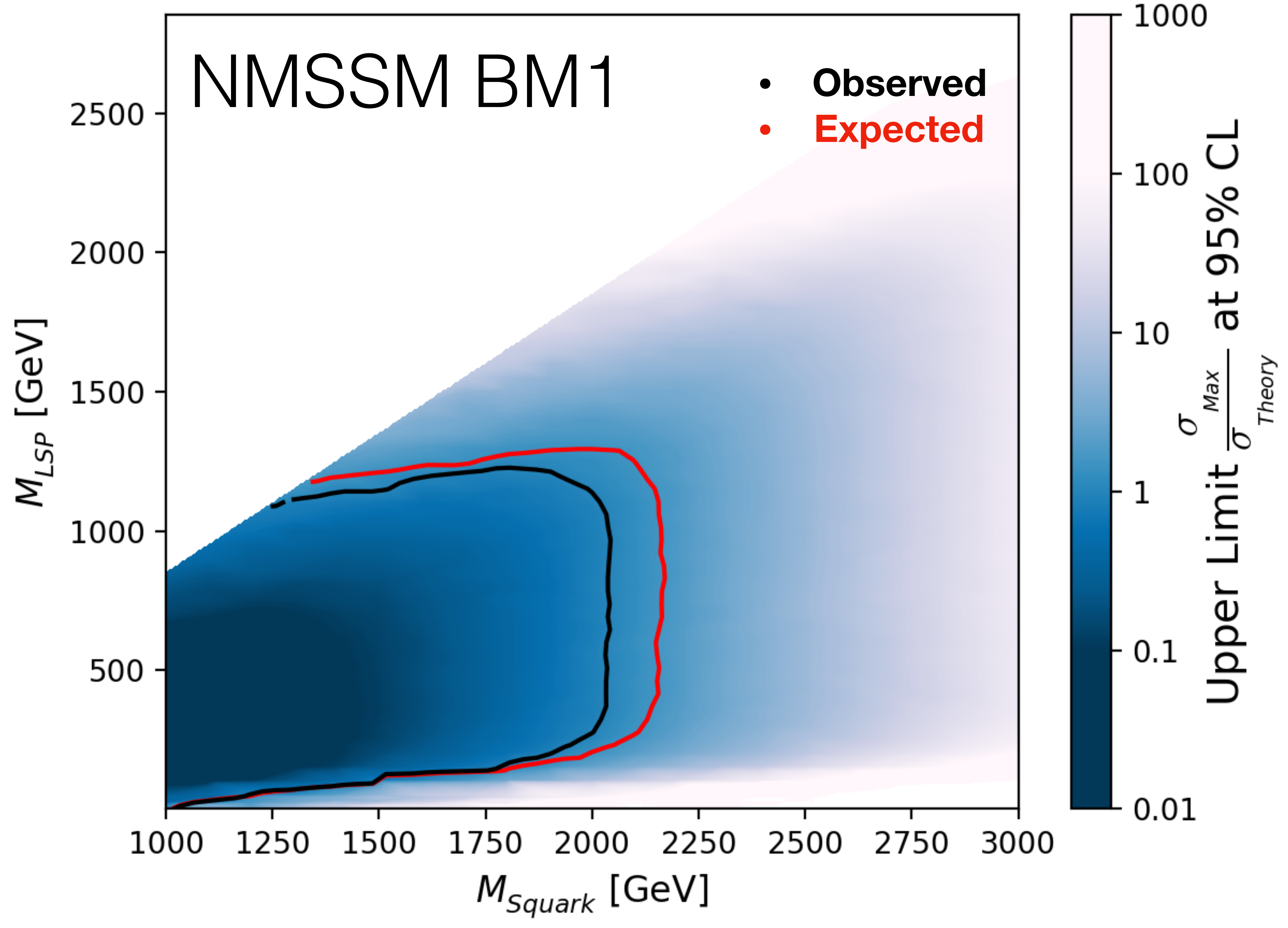


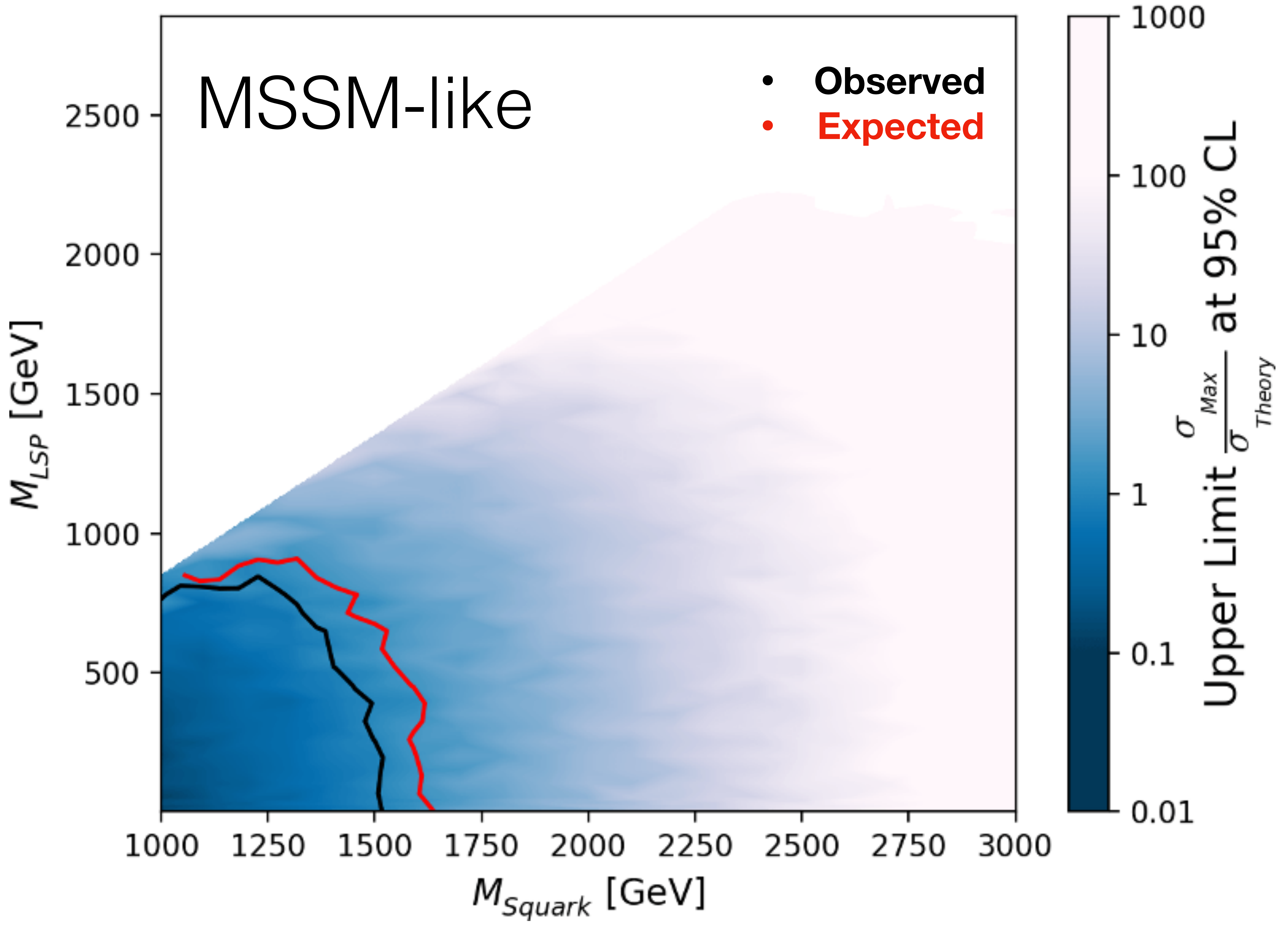
[1] CMS Collaboration "Search for natural and split supersymmetry in proton-proton collisions at √s = 13TeV in final states with jets and missing transverse momentum" JHEP 1805, 025 (2018)
[3] A Titterton et al. "Exploring Sensitivity to NMSSM Signatures with Low Missing Transverse Energy at the LHC" JHEP 1810, 064 (2018)

Observed and Expected Limits

Observed and Expected Limits

- Compare: NMSSM mass scan compared with MSSM model approximated by forcing the NLSP stable
- NMSSM low-MET scenario (left) has **lowest** sensitivity for light LSP
- Simplified MSSM scenario has **strongest** sensitivity in this region

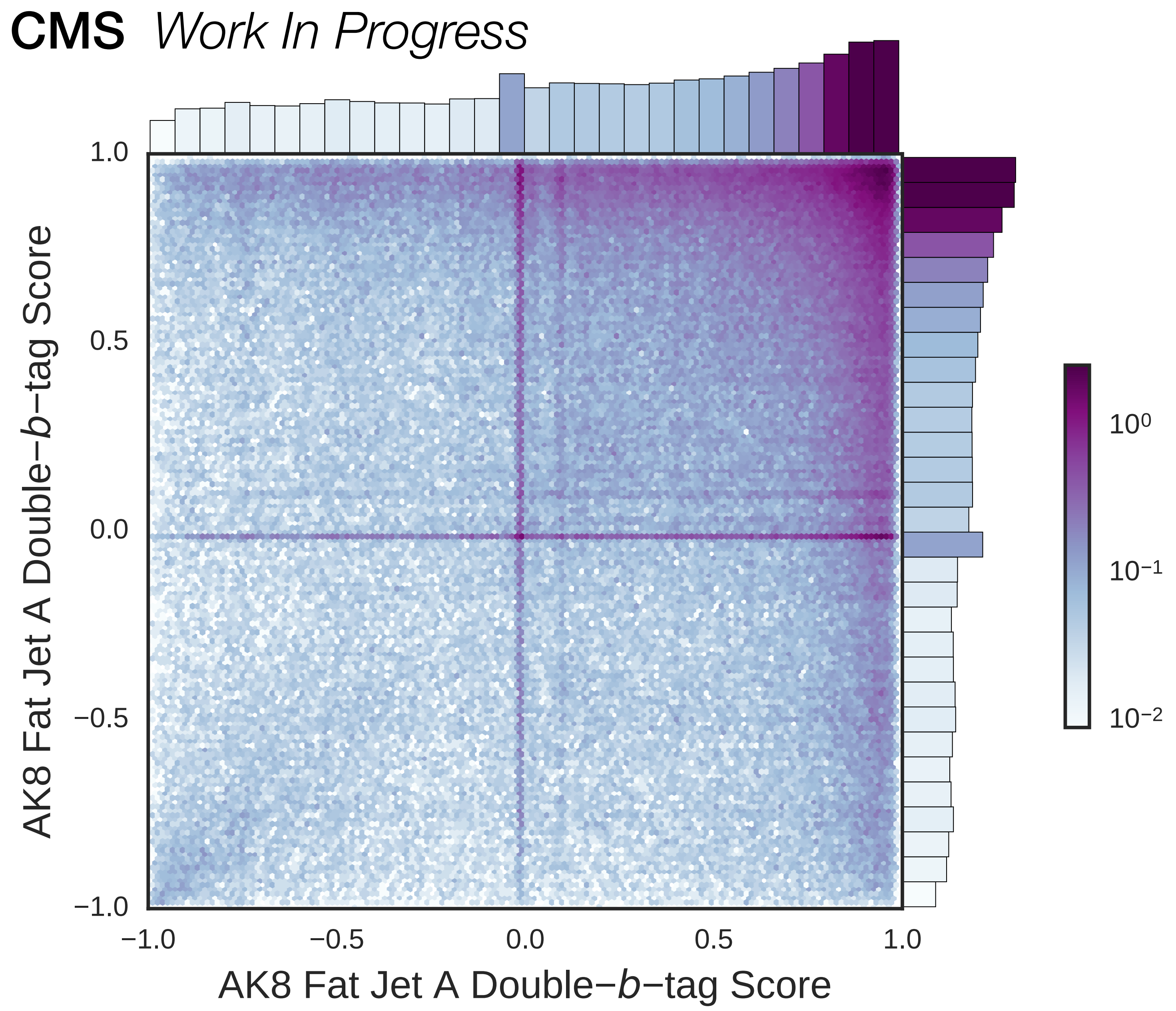


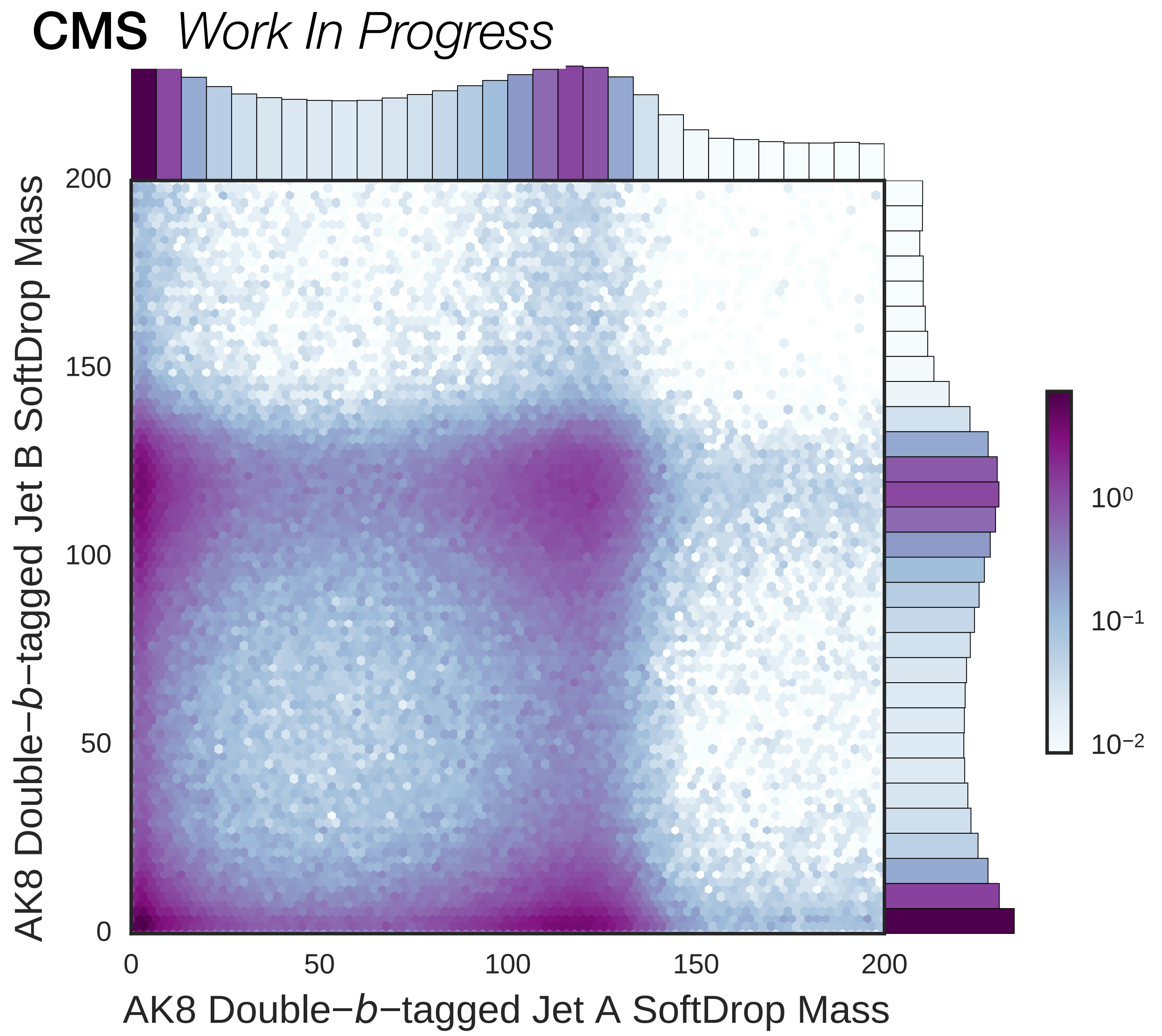


Experimental Analysis

Experimental Analysis Interpretations

- Each (2) boosted Higgs boson decays to bb pair —> b jets not separated enough to resolve!
- Solution: Look at “fat” jets (double cone radius of “slim” jets), look for two displaced vertices
- Build analysis around two **double-*b*-tagged “fat” jets** (more details in Joe Taylor’s talk)
- HT ∈ { [1500,2500), [2500,3500), [3500,∞) } GeV
- Bin in fat jet mass —> interested in bins around 125 GeV
- No MET requirement





Experimental Analysis Interpretations

- Shows dramatically increased sensitivity to these scenarios for lightest LSP (~1GeV, R=0.99) compared with phenomenological limits shown in phenomenological work

- Sensitivity drops as LSP mass increases towards 200GeV, the heaviest considered here

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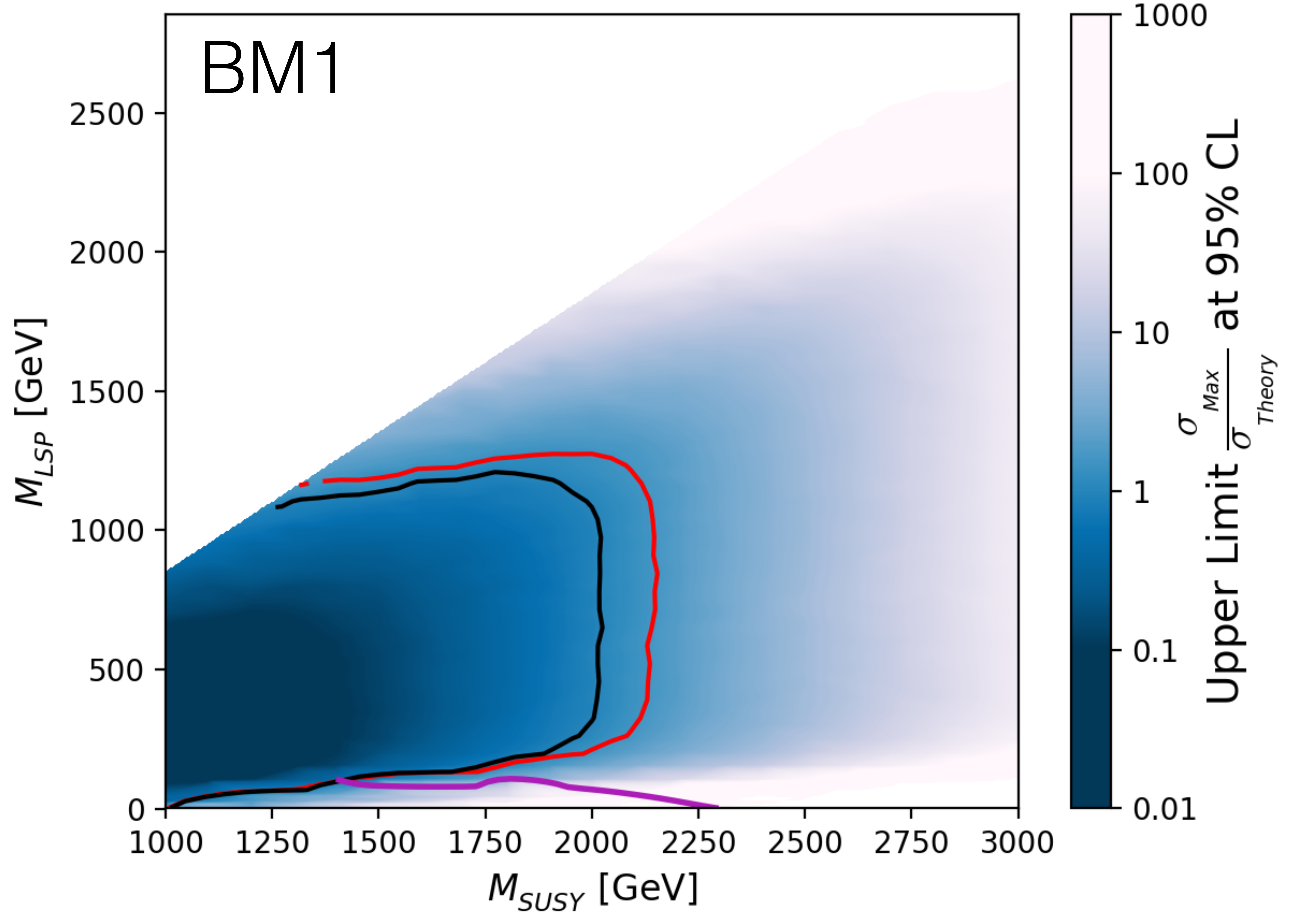
Results

- 2D expected limit (**purple**) from this analysis for LSP mass between 1-200GeV, on top of phenomenological limits (**red**=**expected**, **black**=**observed**) from [3]

- Strong sensitivity to light LSP, but this drops off quickly as the LSP becomes heavier

- For LSP mass between around 100-200GeV both analyses lose sensitivity, which we would like to address.



Results

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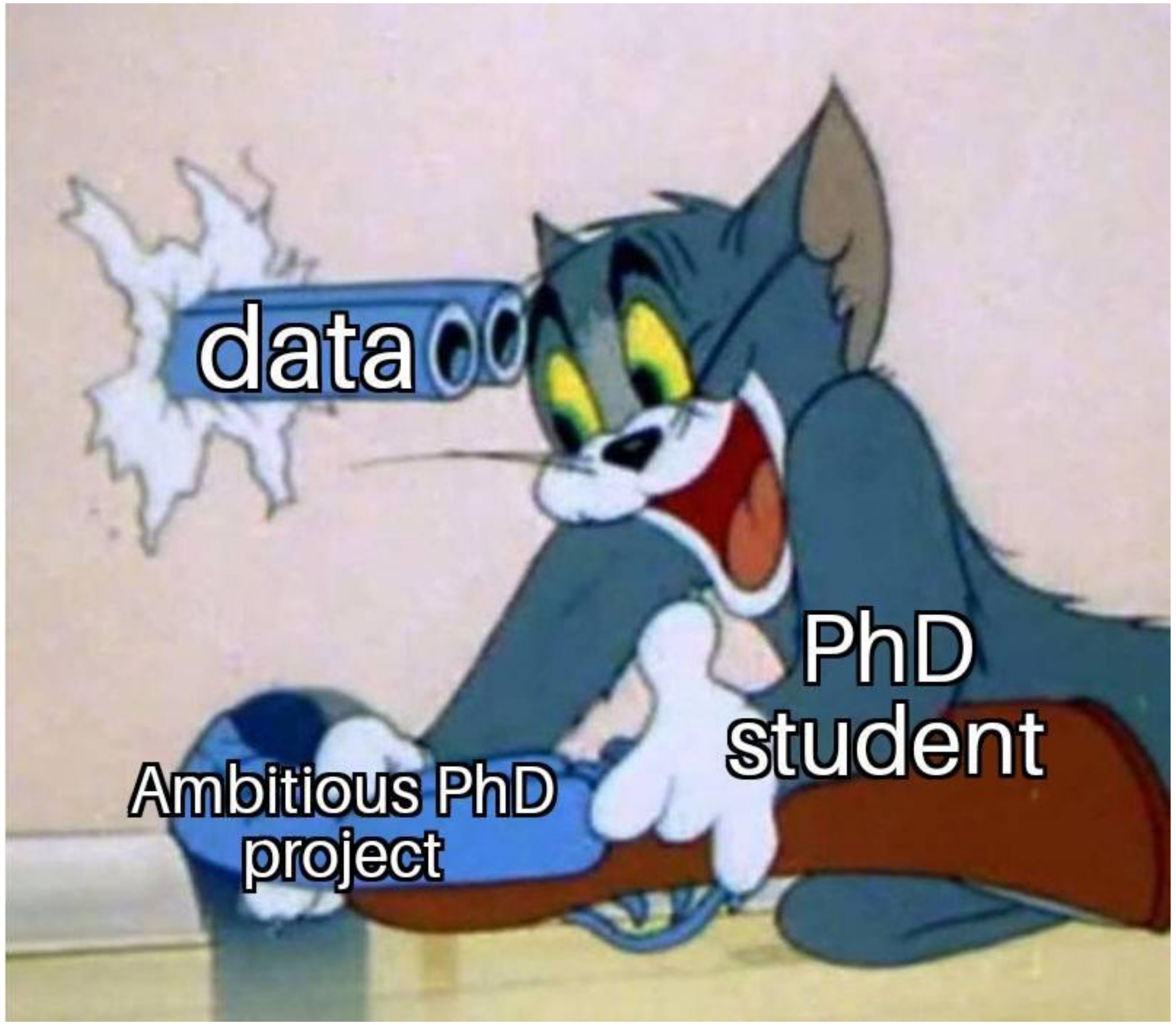
Extensions to Experimental Analysis:

- As LSP mass increases, so does MHT
- Add MHT bins: Split samples into MHT $\in$ { [0,200), [200,∞) } GeV
- Add lepton veto in higher MHT bin to suppress tt background
- Preliminary studies show this should greatly improve sensitivity in regions not currently accessible by either analysis

Conclusions

- Phenomenological work combined with experimental analysis almost covers whole mass plane.
- Analysis work with Joe Taylor close to unblinding
- Missing-HT extension work undergoing final checks for thesis
- Extension should give full coverage of the 2D mass plane

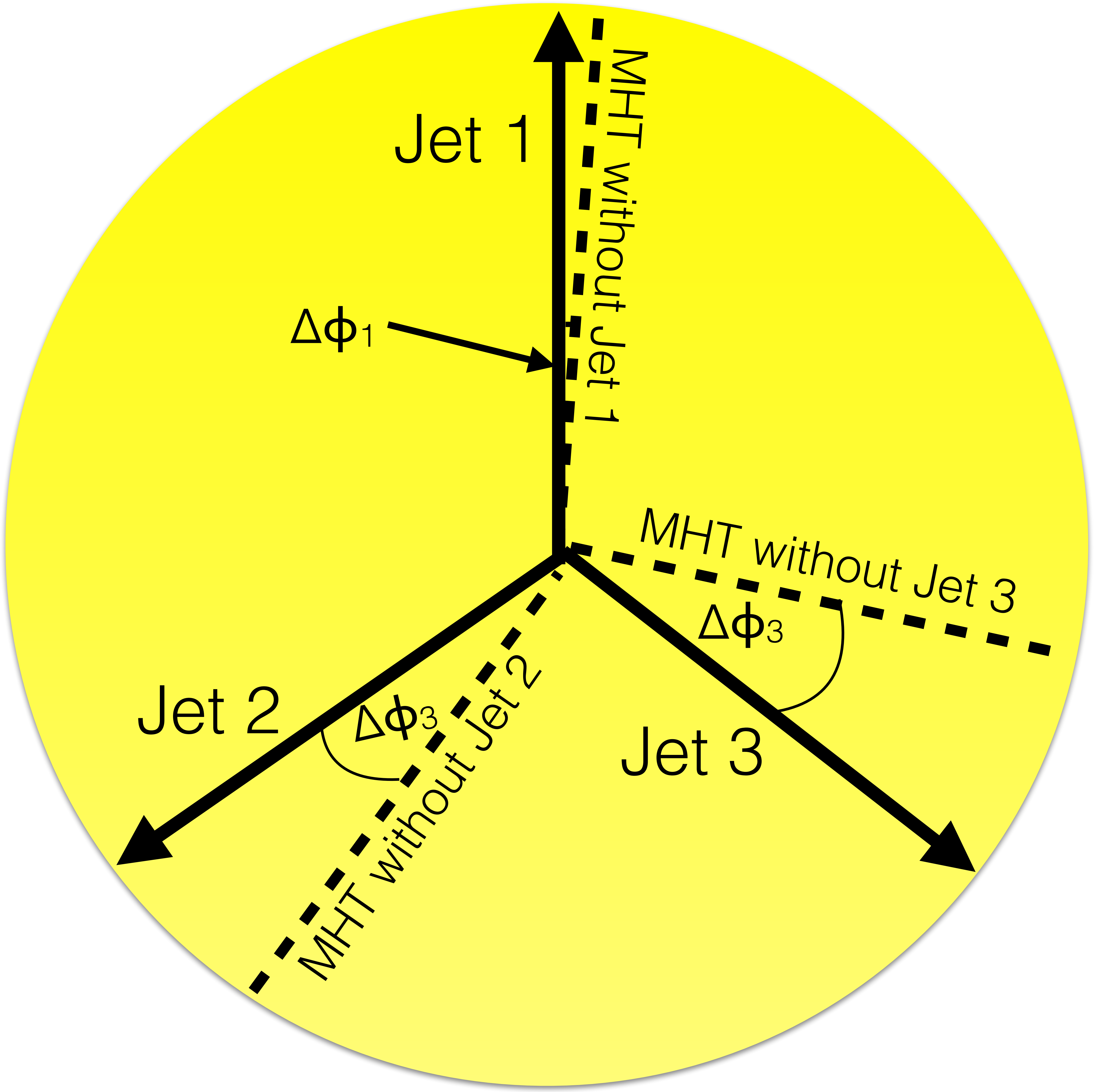


Backup

Signal Properties: min $\Delta\phi^*$

Examples with BP1 vs QCD and tt background processes

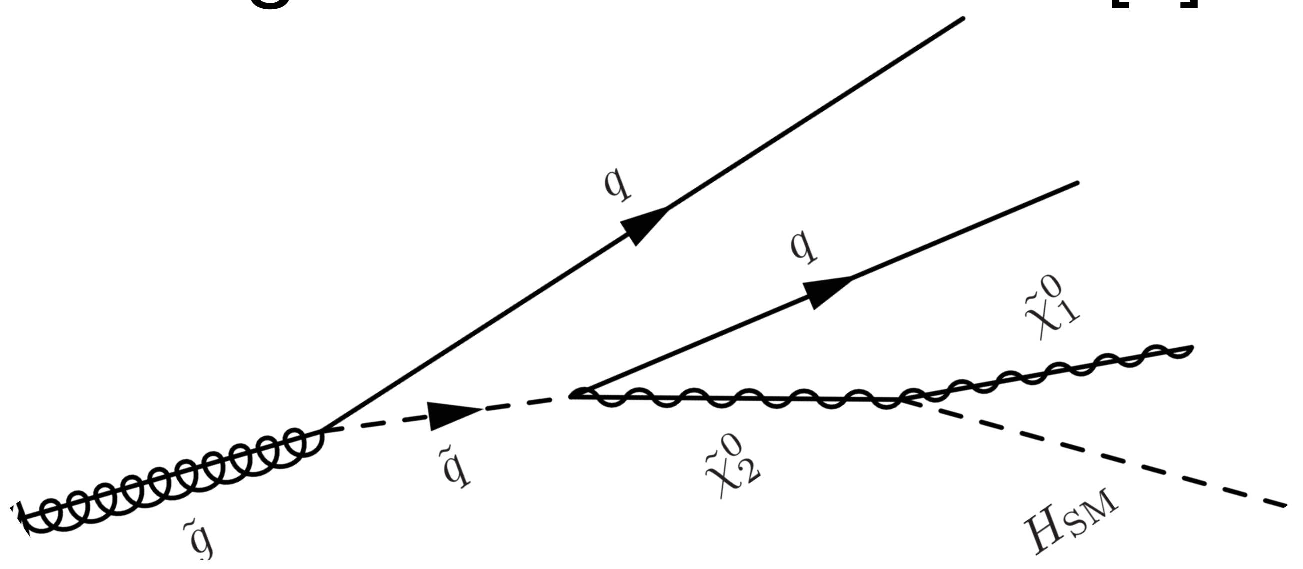
- Variable designed to reduce QCD background by identifying events with spurious MET from e.g. jet mis-measurement
- Take the difference in ϕ between a jet and the Missing-H_T without that jet
- Define "min $\Delta\phi^*$" as the minimum value over all jets in the event —> Should be the jet most likely to correspond to any mismeasurement
- Therefore if min $\Delta\phi^*$ is still large (> 0.5) then this suggests real MET

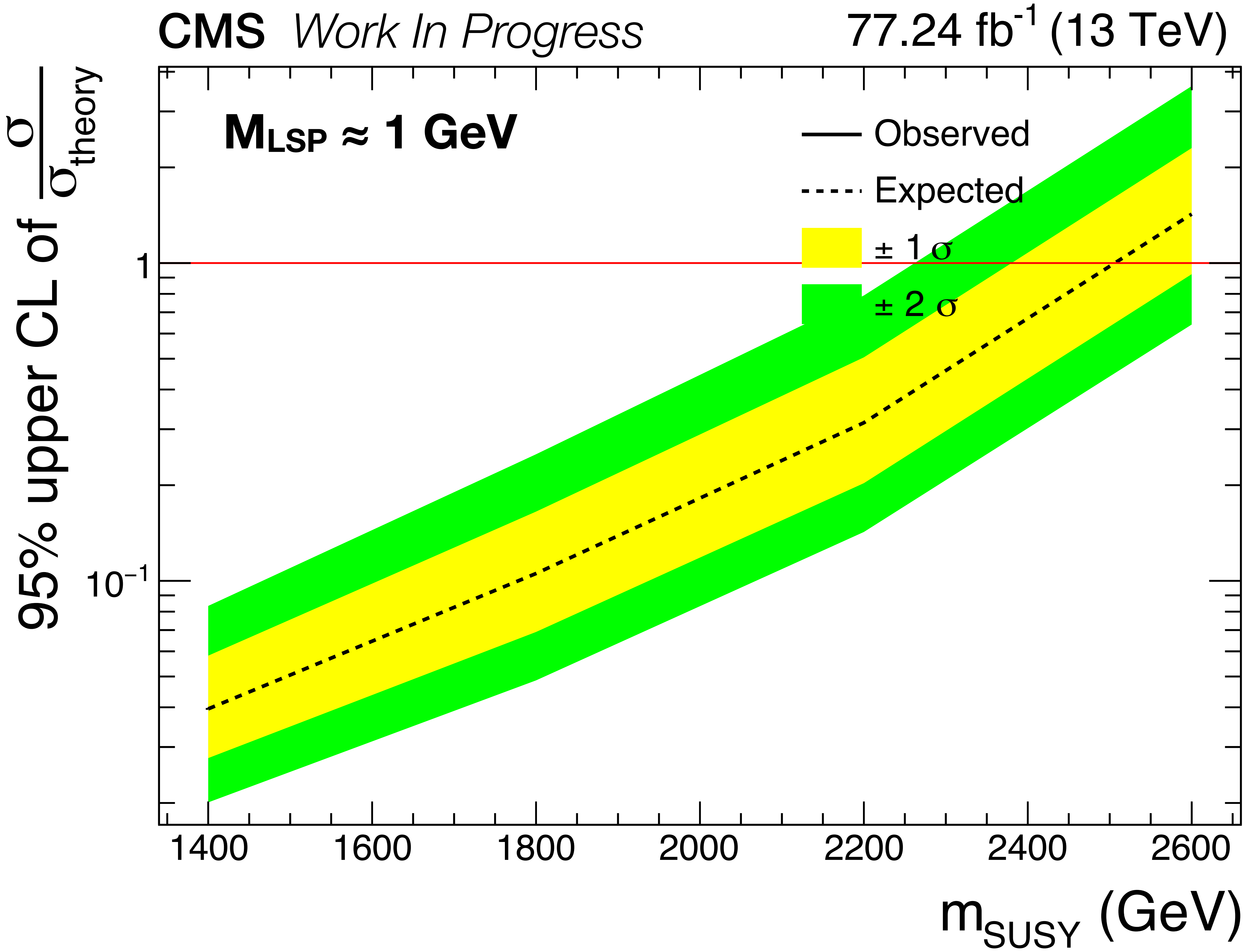


Results

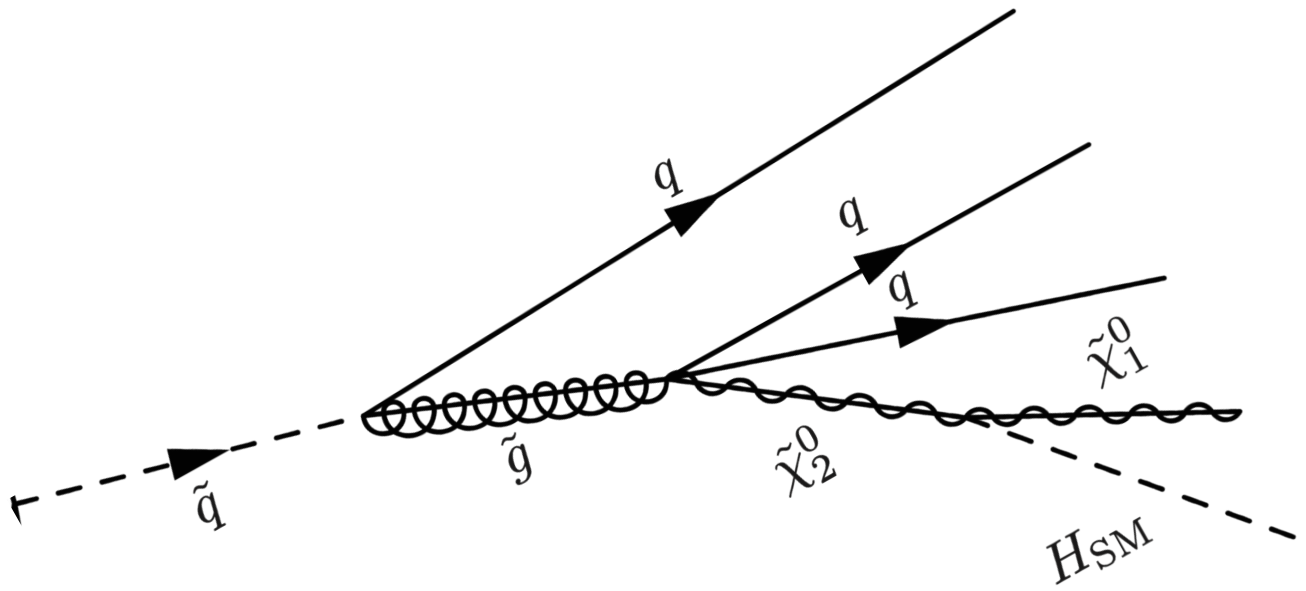
- 1D expected limit plots for lightest LSP (~1GeV, R=0.99)
- Shows dramatically increased sensitivity to these scenarios compared with phenomenological limits from recasting CMS-SUS-16-038 [2]

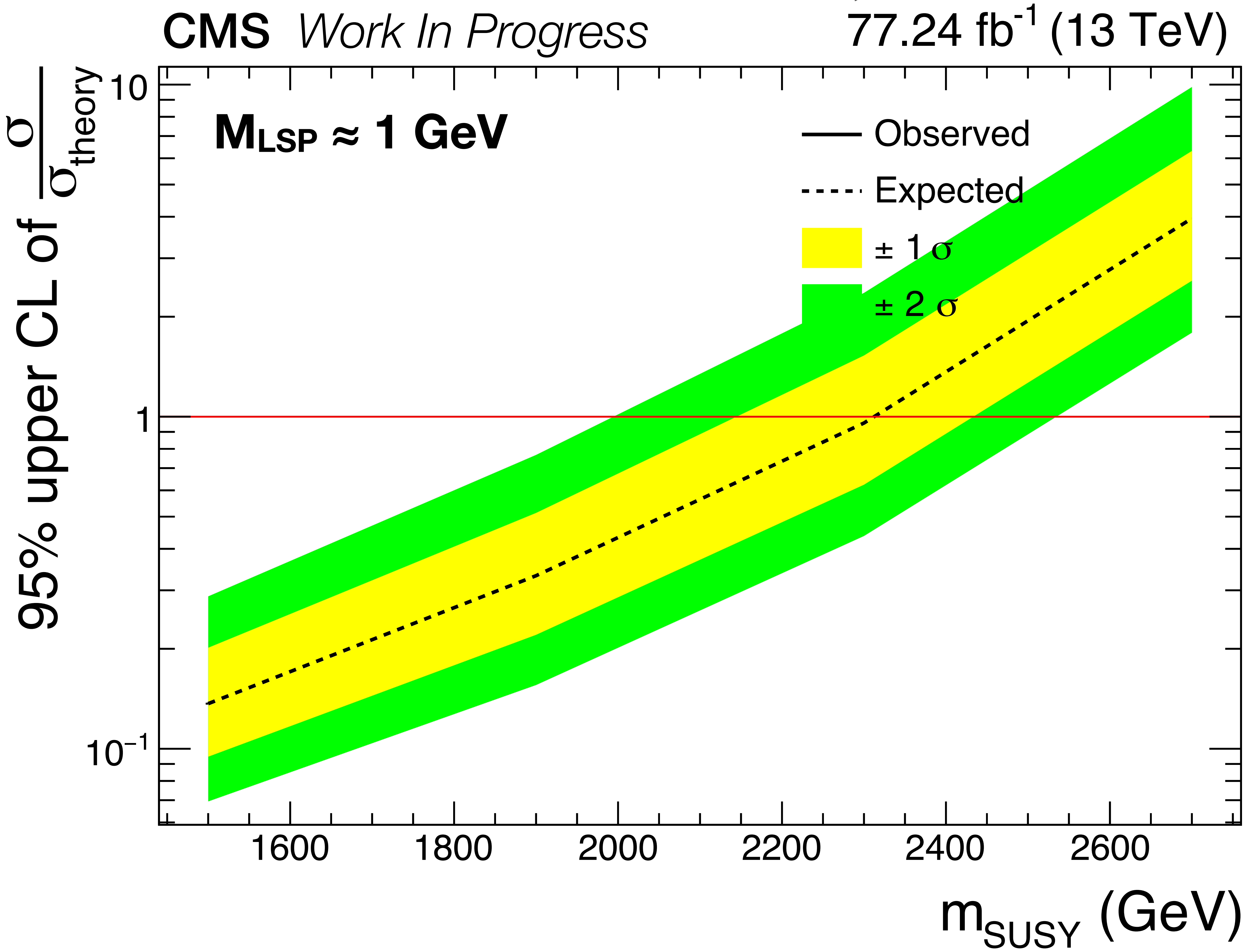
BM1





BM2





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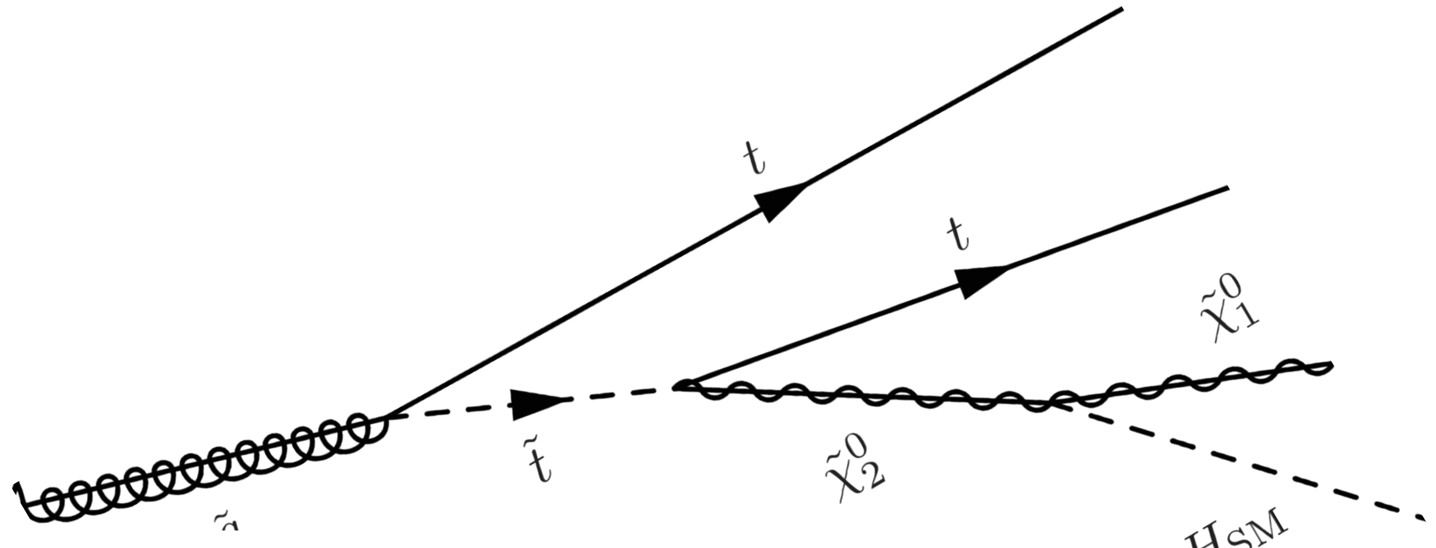
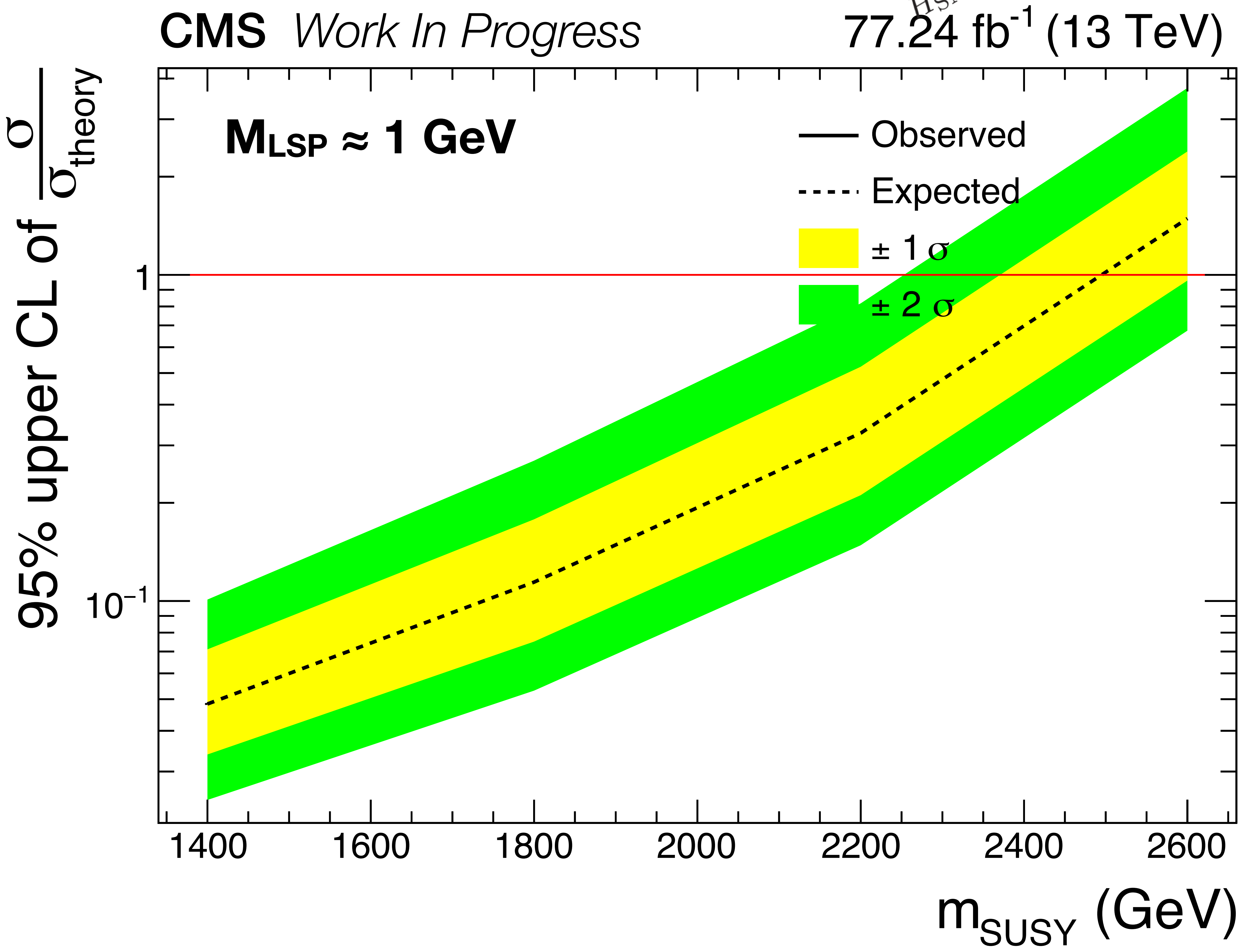
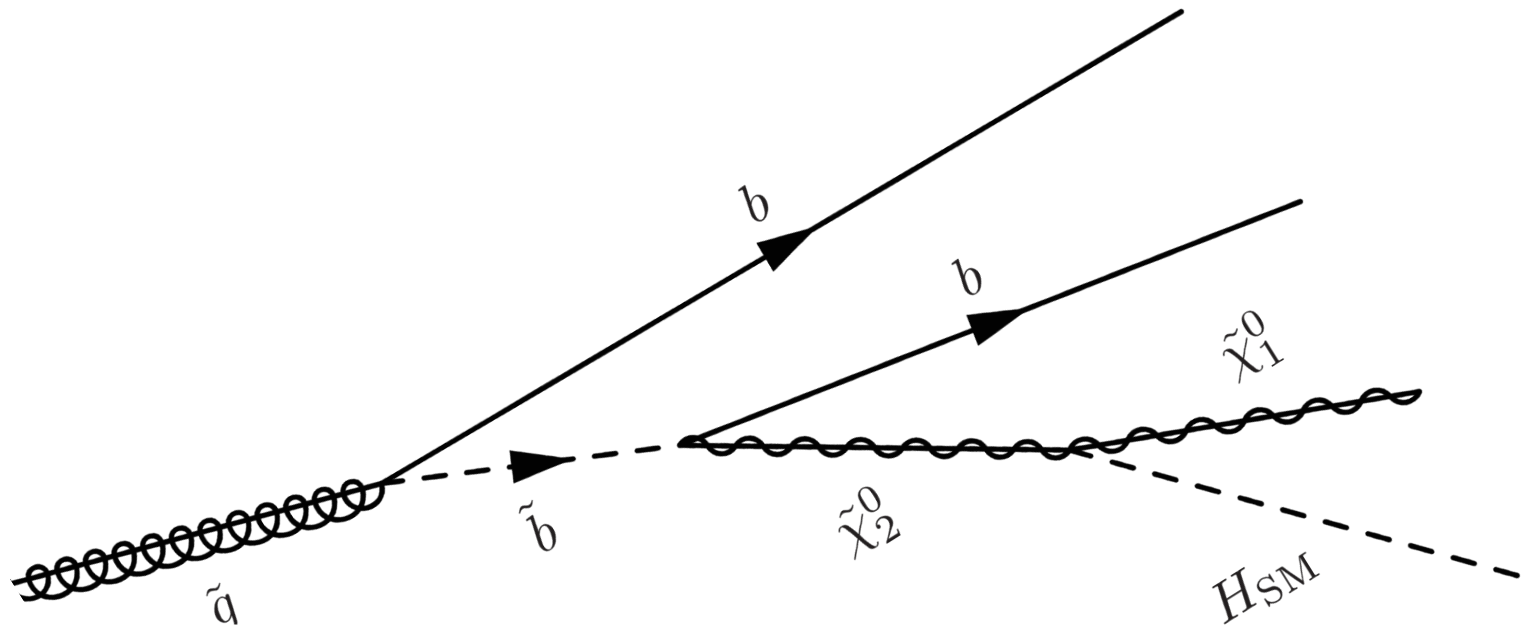
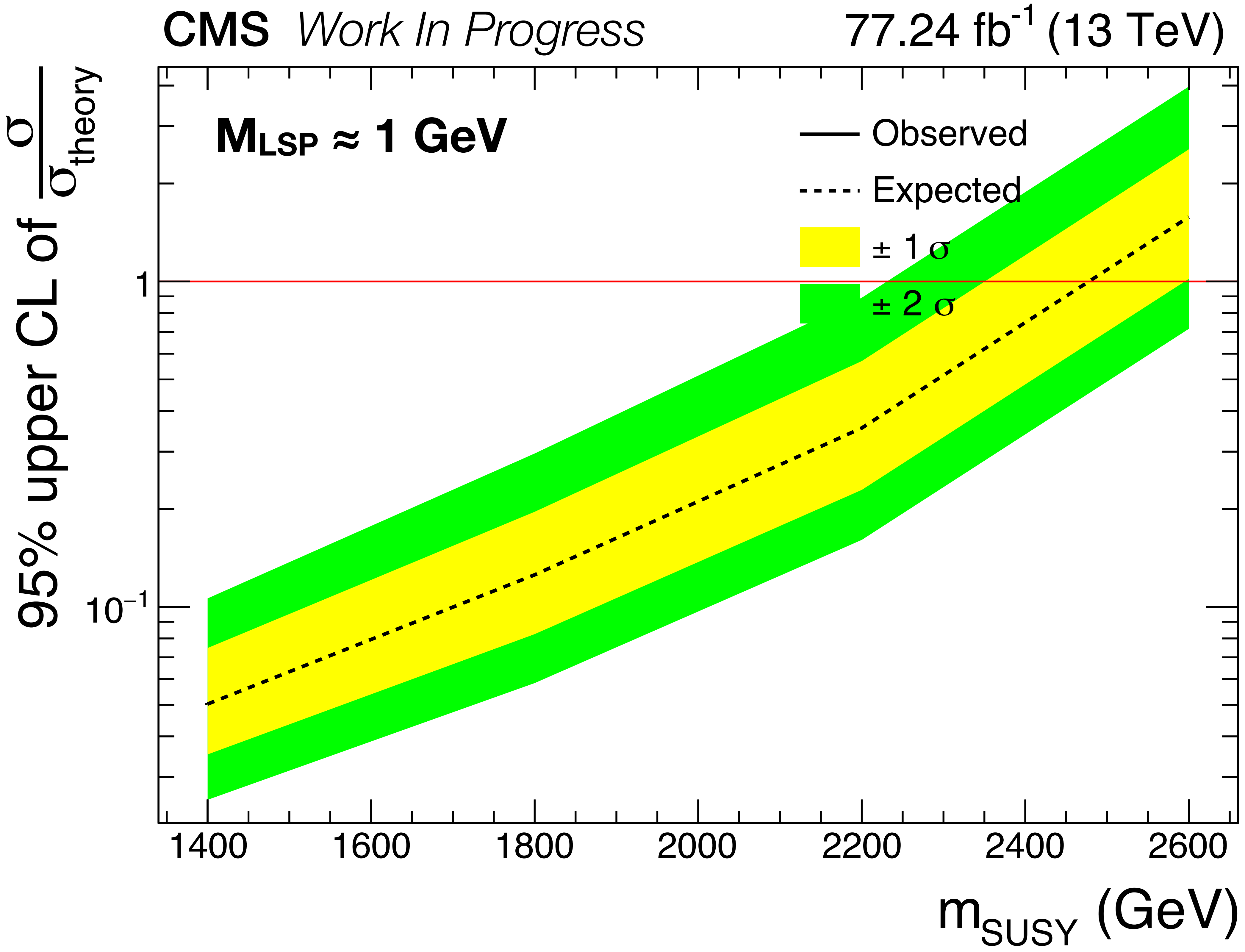
BM3





BM4





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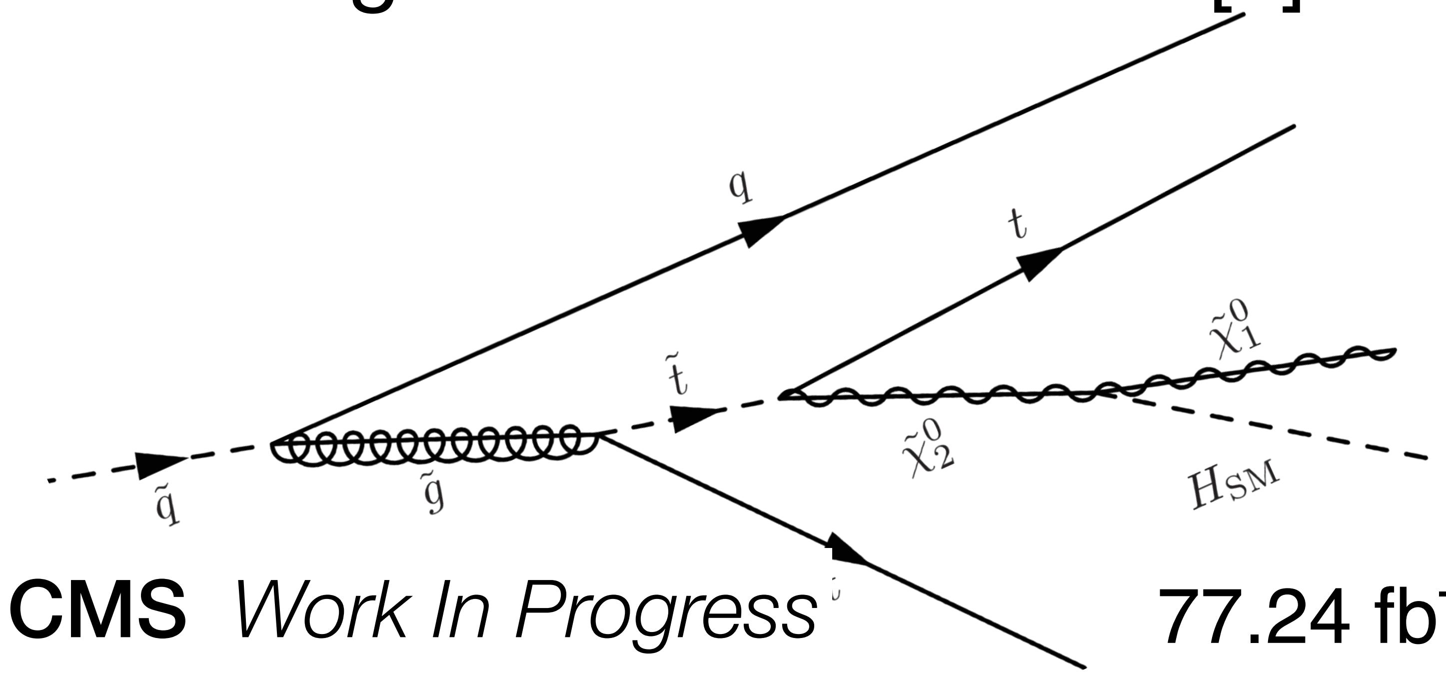
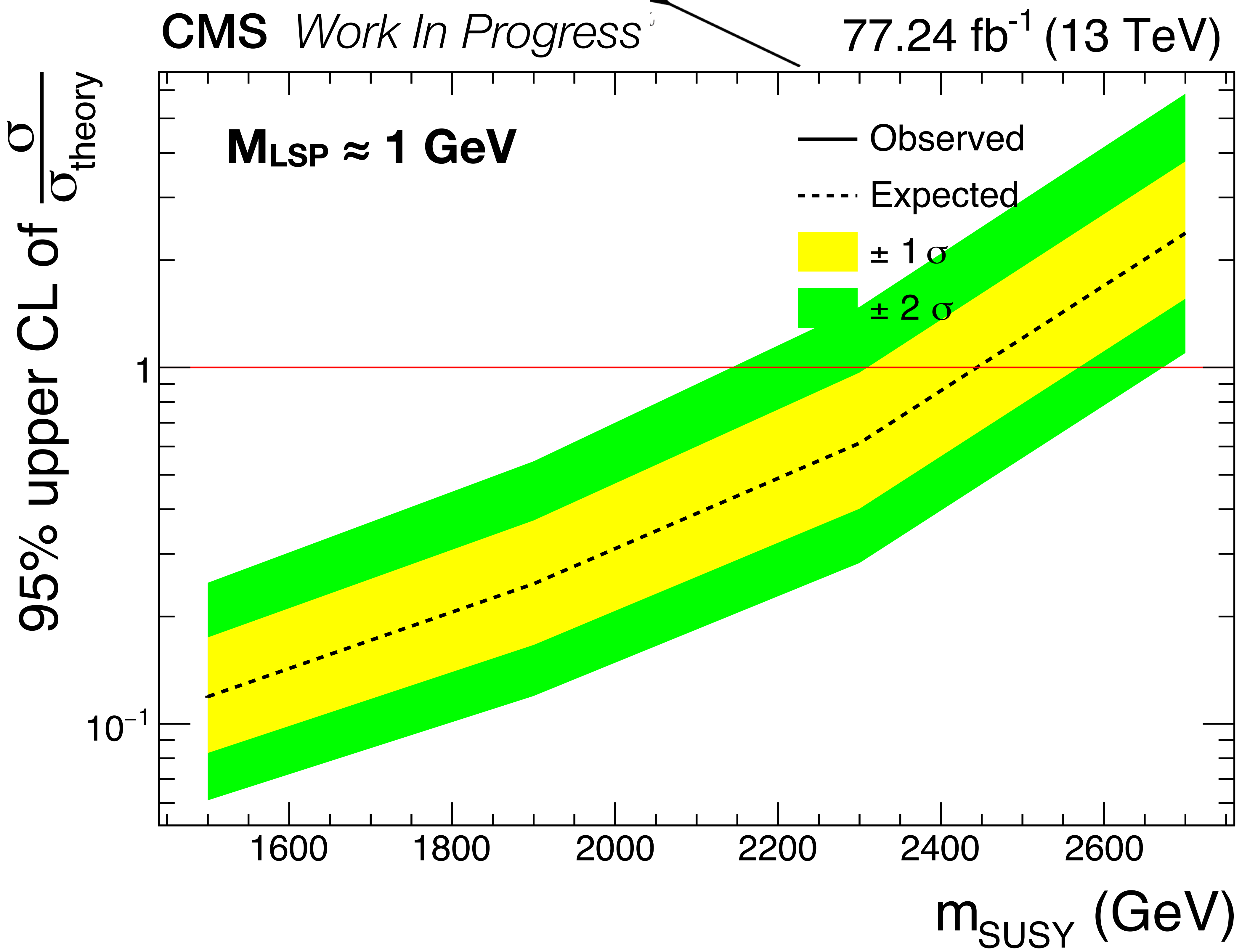
BM5





BM6