Searches for SUSY with the CMS experiment

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for the CMS collaboration

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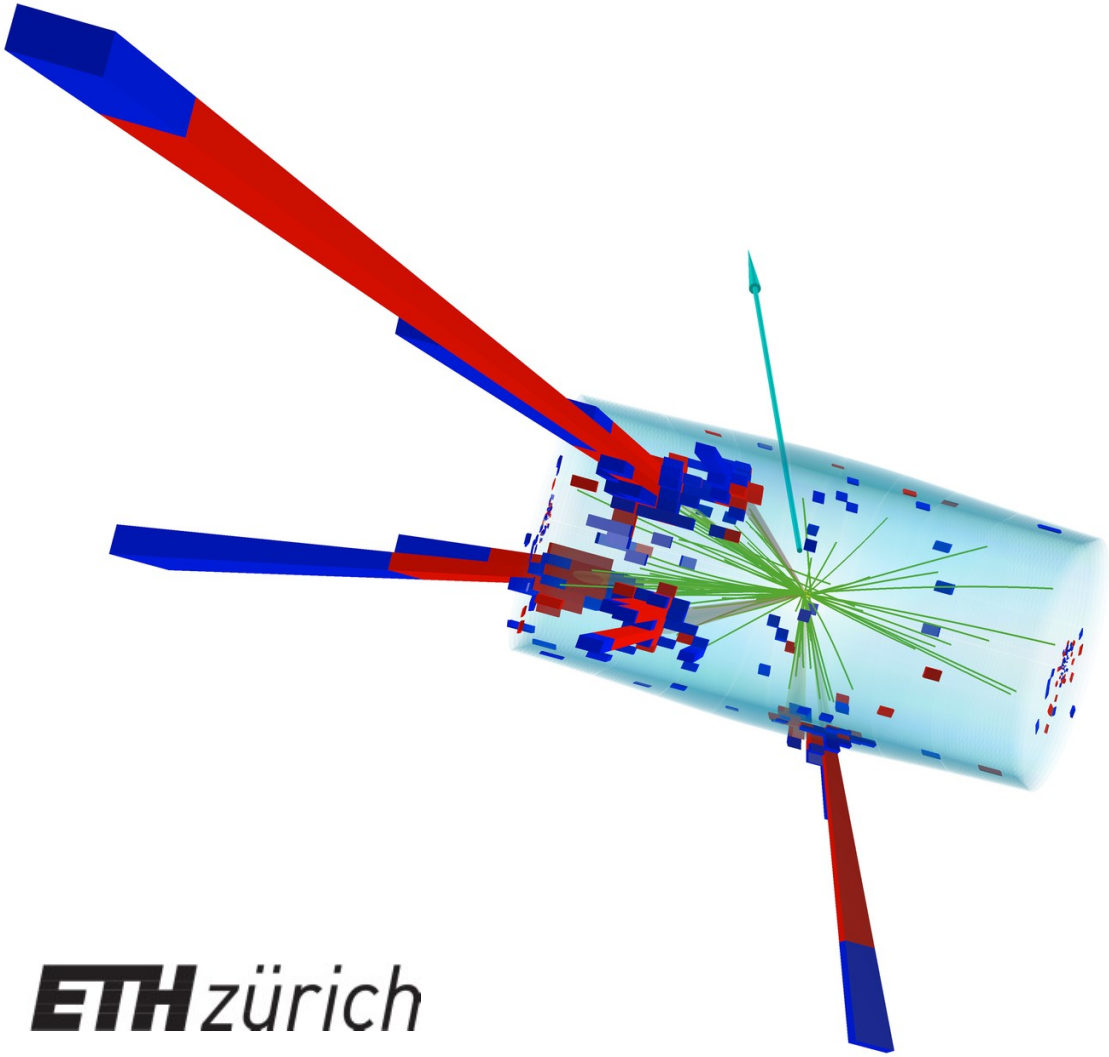
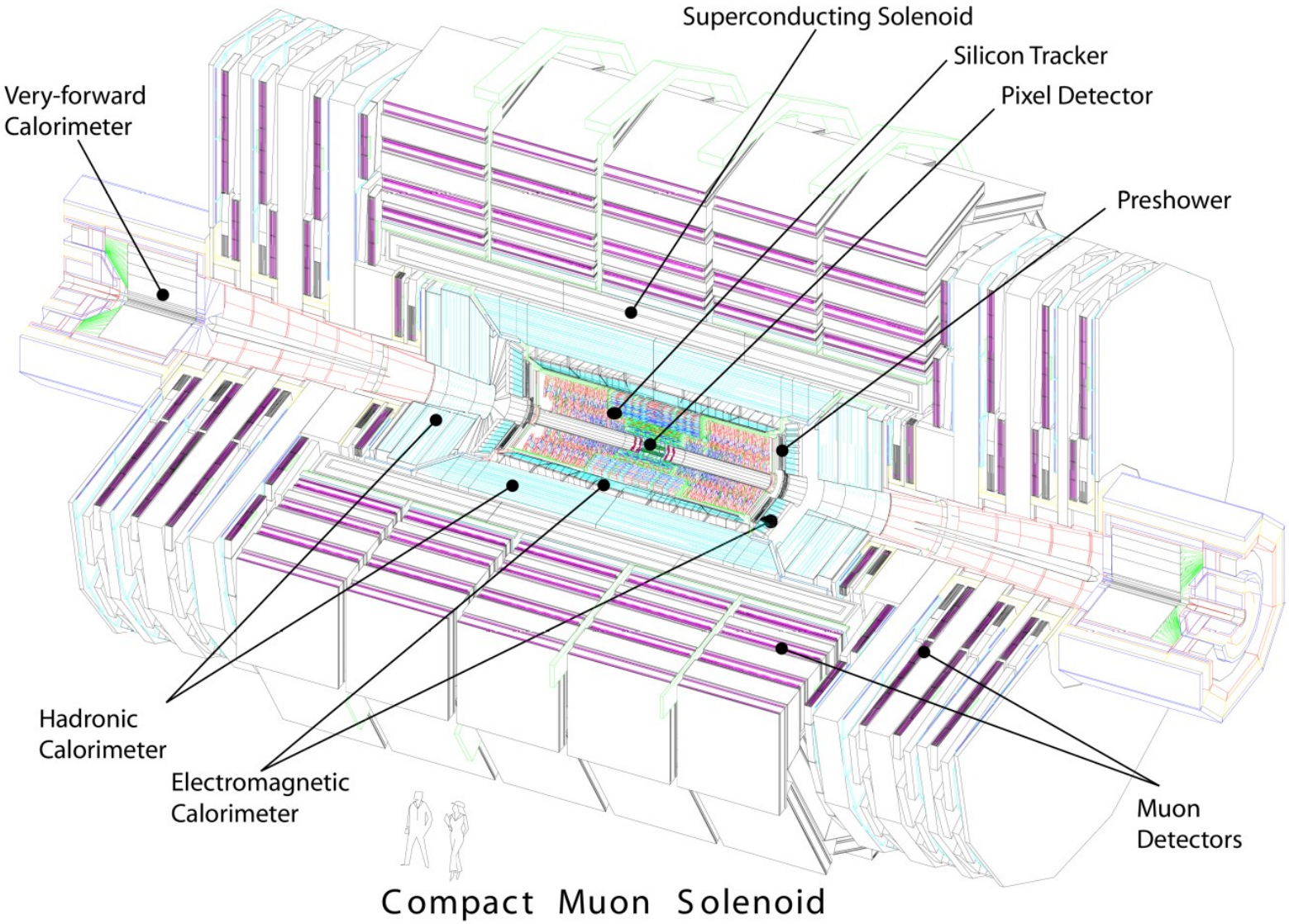
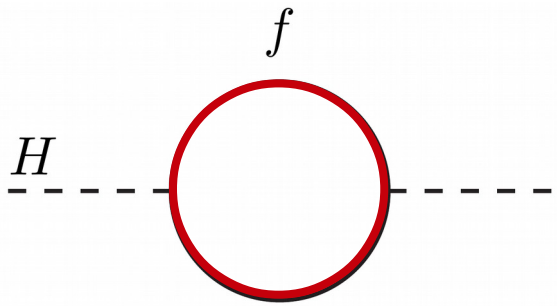


The CMS detector



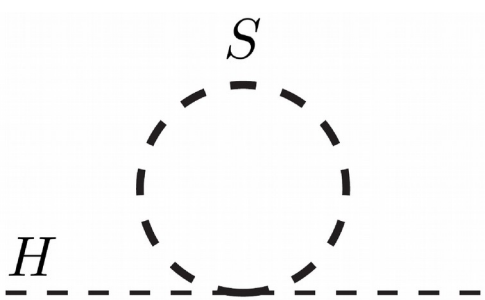
Why Supersymmetry?



Fine Tuning problem

$$(125\mathrm{GeV})^2 = {m_H}^2 = {m_{H,0}}^2 + {\Delta m_H}^2$$

$$\propto \sum_f -g_f \Lambda_{UV} \leftarrow \text{can be as large as } \Lambda_{Planck}$$



SUSY Solution:

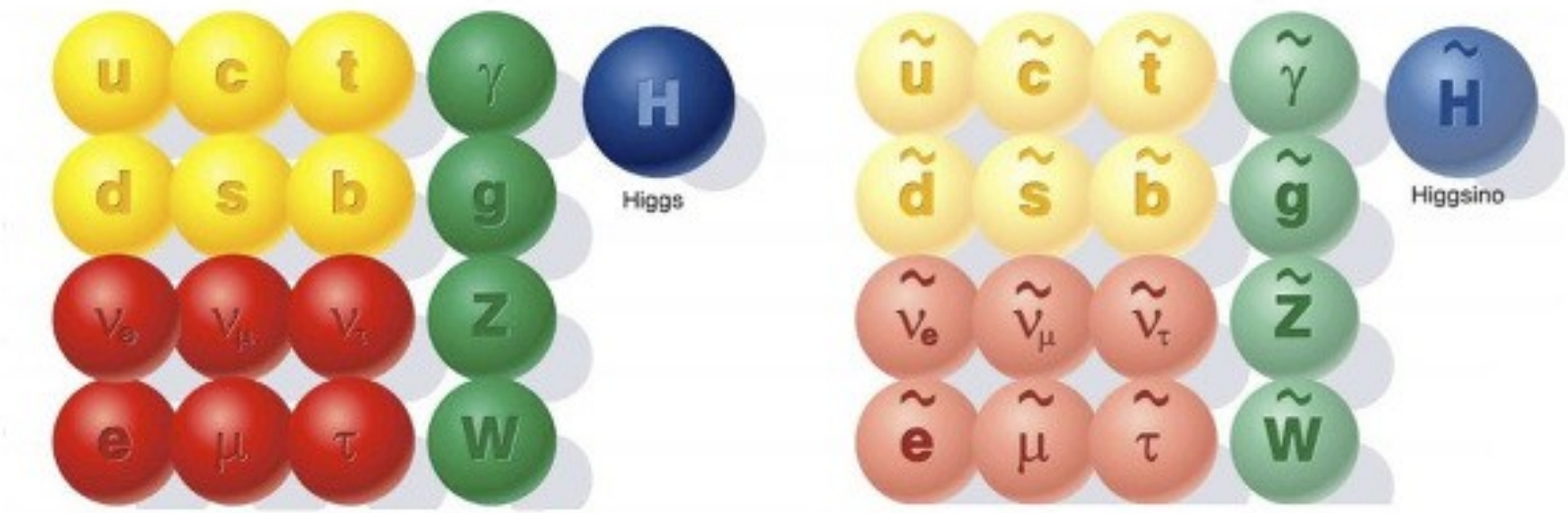
For each fermion add a diagram with a scalar to cancel ${\Delta m_H}^2$

→ **introduce for each fermion a scalar**

(and vice versa)

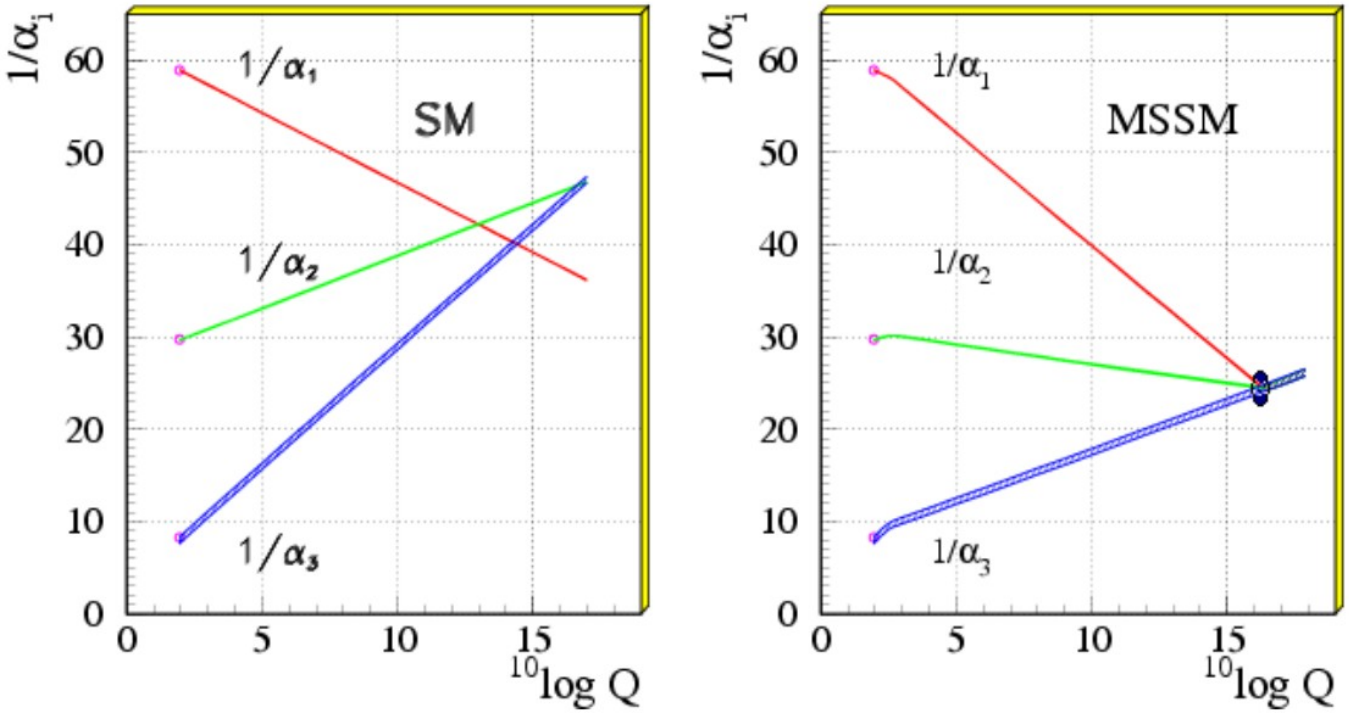
What is SUSY?

$$Q\,|\mathrm{Boson}\rangle = |\mathrm{Fermion}\rangle\,, \qquad Q\,|\mathrm{Fermion}\rangle = |\mathrm{Boson}\rangle$$



- Broken symmetry: heavier masses

Bonus I: Gauge unification



- Gauge unification of the strong, EM and weak force

Bonus II: Dark Matter Candidate

- Baryon (B) and lepton (L) quantum numbers seem intrinsically fermionic, but not nec. in SUSY

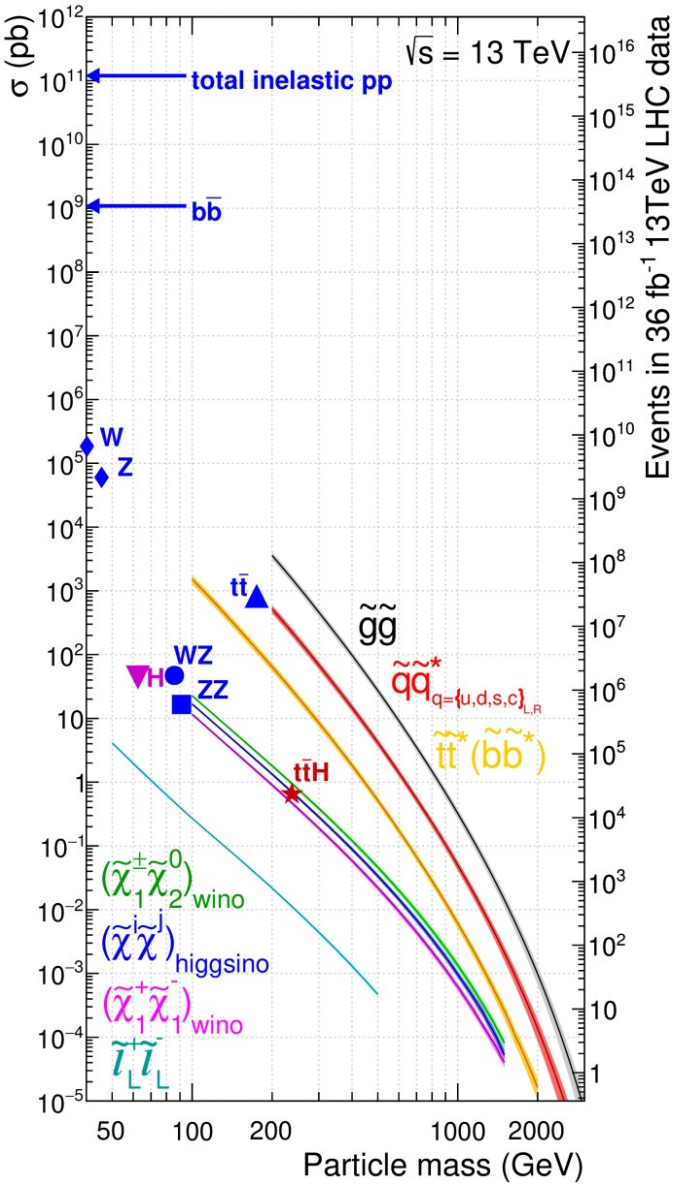
$$Q\,|\mathrm{Boson}\rangle = |\mathrm{Fermion}\rangle\,, \qquad Q\,|\mathrm{Fermion}\rangle = |\mathrm{Boson}\rangle$$

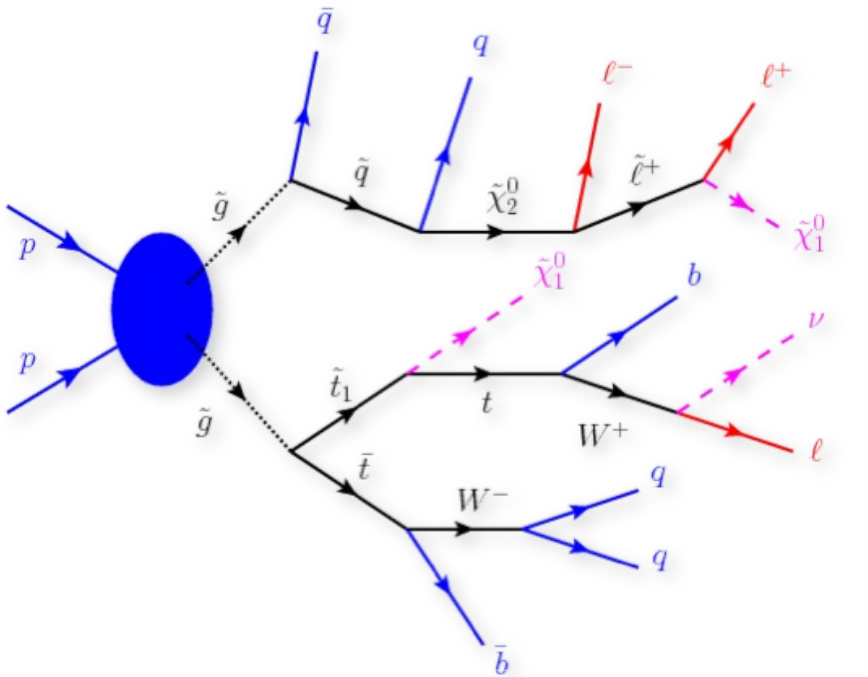
- need to forbid direct exchanges of squarks and sleptons between ordinary quarks and leptons

  → introduce a B&L for bosonic superparners

- R parity = $(-1)^R = (-1)^{2S}(-1)^{3B+L} = \begin{cases} 1 \text{ for SM particle} \\ -1 \text{ for SUSY partner} \end{cases}$
- R-parity conserved:
  - SUSY particles produced in **pairs**
  - Lightest SUSY particle (LSP) stable = **WIMP candidate**

How does SUSY compare to the SM?



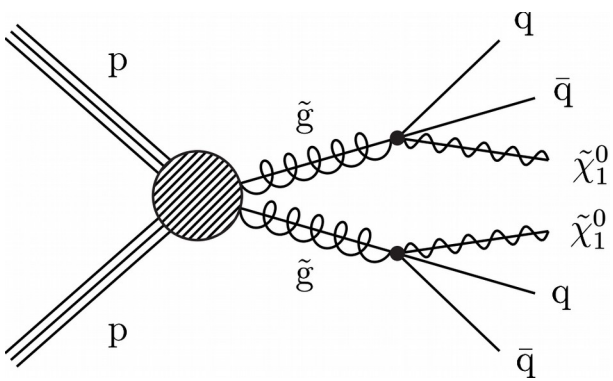


Largest cross sections for **strong production = gluinos & squarks**
→ **discovery channel at energy frontier**

Electroweak and slepton production lower cross sections, but generally cleaner signatures with leptons

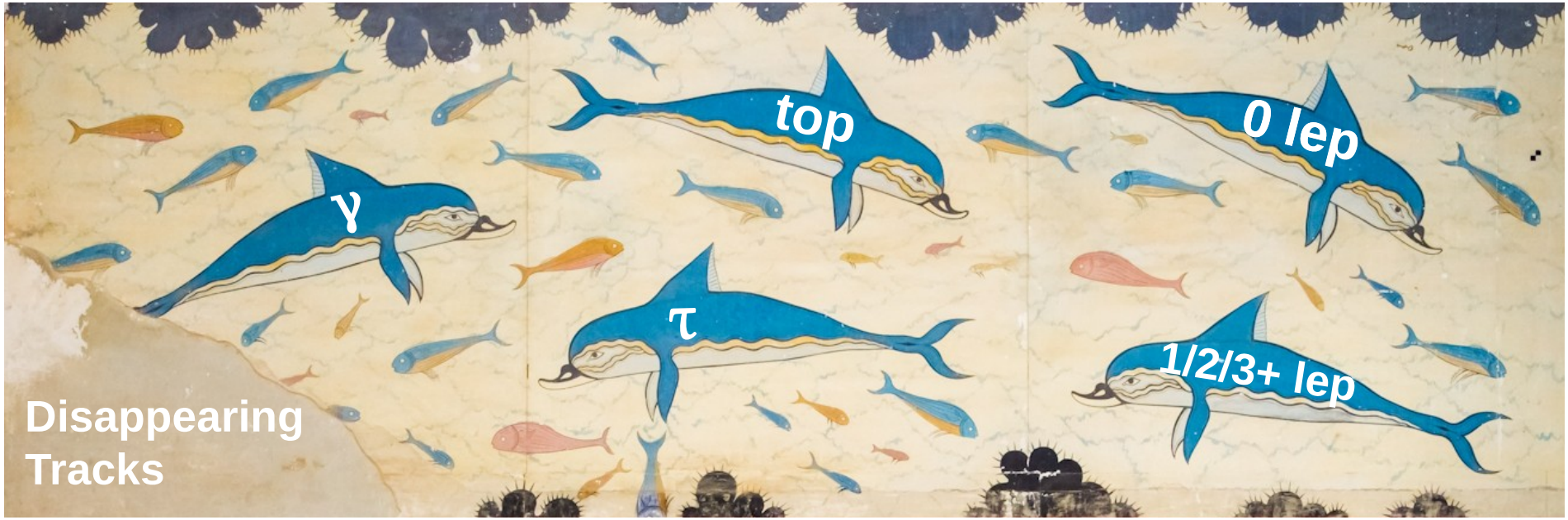
Simplified models of SUSY

- Not possible to scan the whole MSSM space
  - Huge phase space
  - many cascade decays



- Consider only simple decay chains
- Generally on only 2 parameters:
  - heavy mother particle
  - lightest supersymmetic particle (LSP) that is not directly detectable
- 100% branching ratio (unless otherwise indicated)

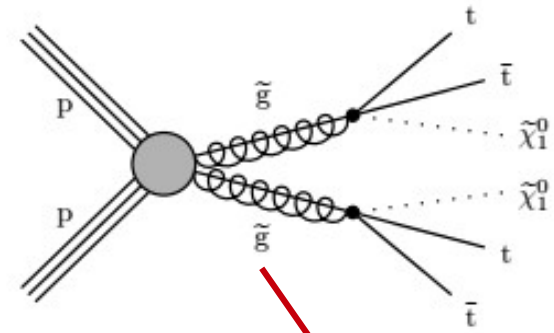
Final state menu



Diverse final states allow to target various production and decay channels

Focus of today‘s talk are the latest results with the Run2 dataset

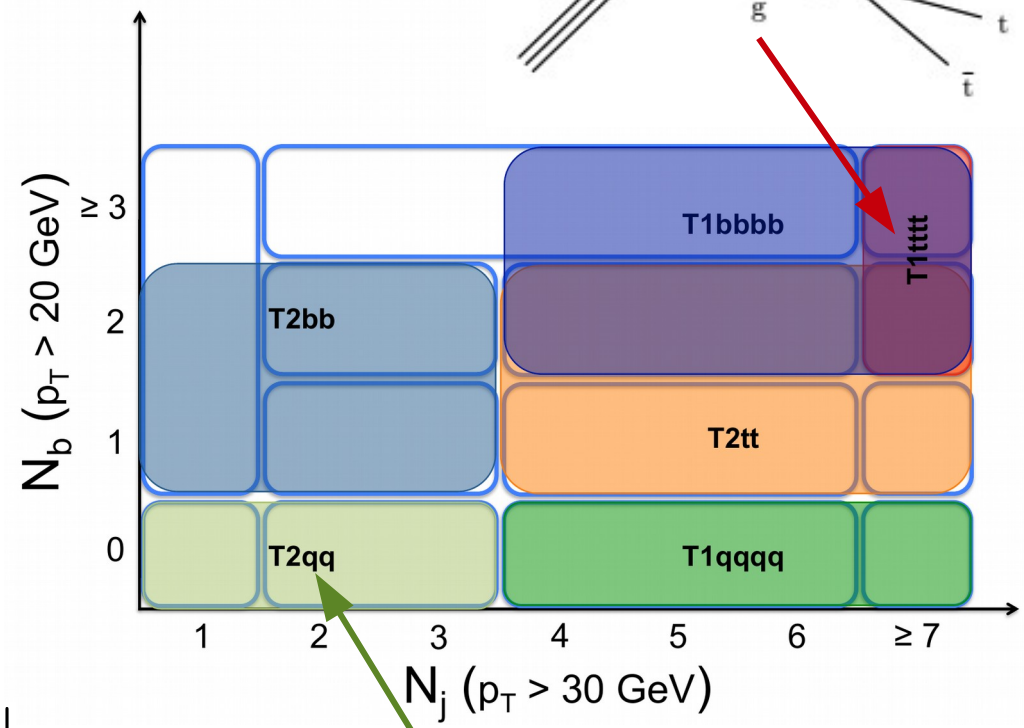
Inclusive hadronic searches: Sensitivity to a large phase space



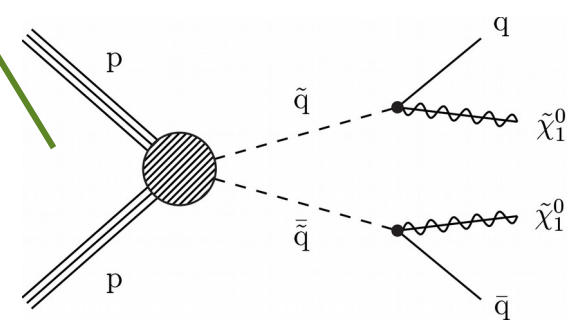
- Cover various strong production models
- Sensitivity though binning in jet & b-jet, H_T, ME_T etc..

$$\mathrm{H}_T = \sum_{jets} |\vec{p_T}|$$

$$\mathrm{H}_T^{miss} = |-\sum_{jets} \vec{p_T}|$$



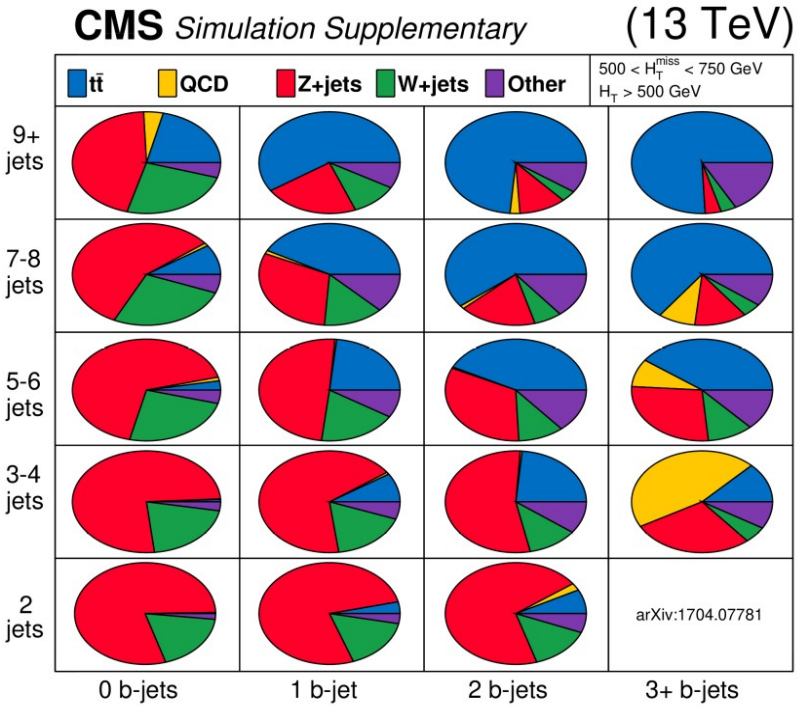
$$\mathrm{M}_{T2}(m_c) = \min_{\vec{p}_T^{\,c(1)} + \vec{p}_T^{\,c(2)} = \vec{p}_T^{\,miss}} [\max(M_T^{(1)}, M_T^{(2)})]$$



SUS-19-006 & **SUS-19-005**

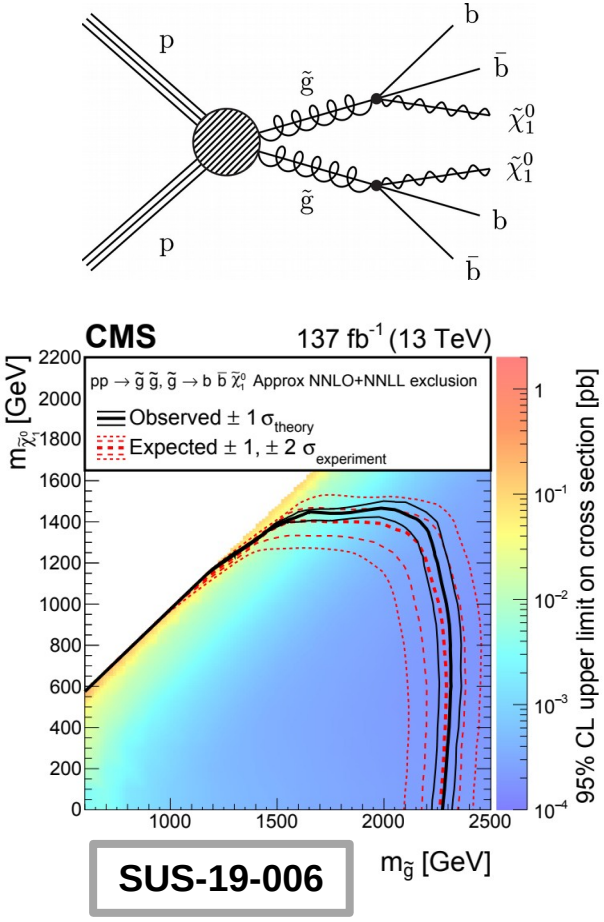
Main backgrounds

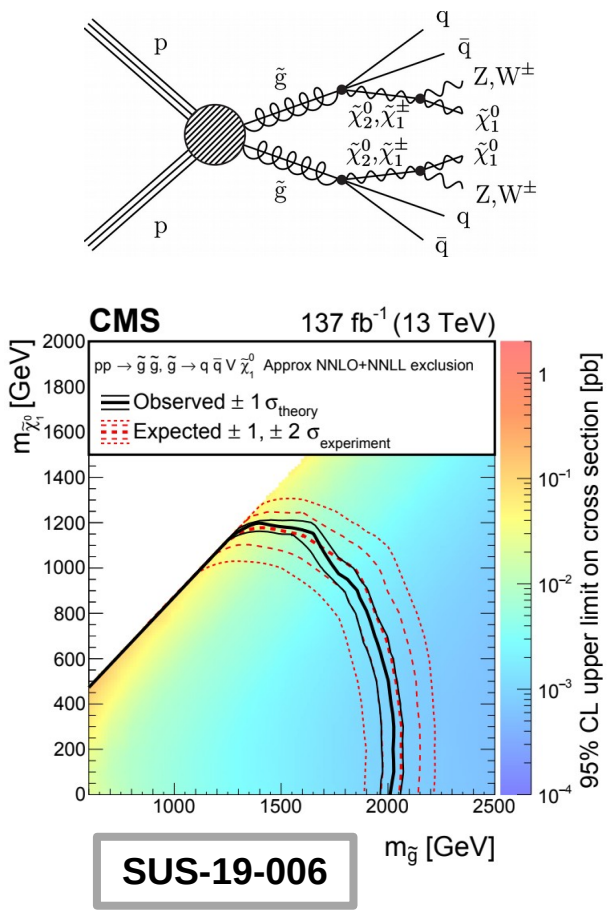
- **QCD multi-jet:**
  - Mis-measurement of a jet leads to imbalanced event
  - Estimated with rebalance & smear technique
- **W+jets & ttbar (Lost lepton):**
  - **ME_T from neutrino** from leptonic W decay
  - Charged lepton not caught by veto
  - Estimated from 1lepton data control region
- **$Z_{\nu\nu}$+jets:**
  - **ME_T from the two neutrinos**
  - Estimated from γ+jets or $Z \rightarrow ll$

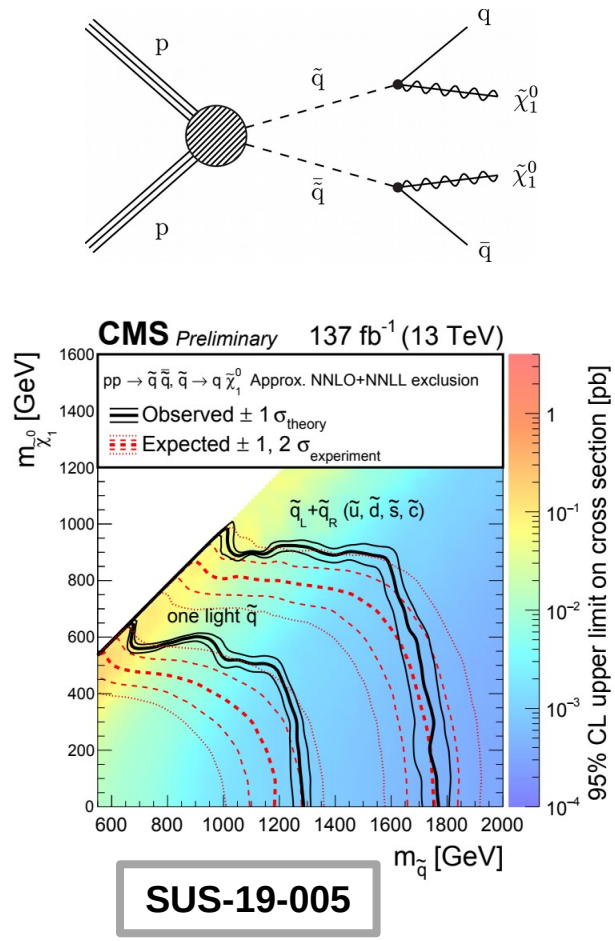


SUS-16-33

Interpretation in gluino & squark production

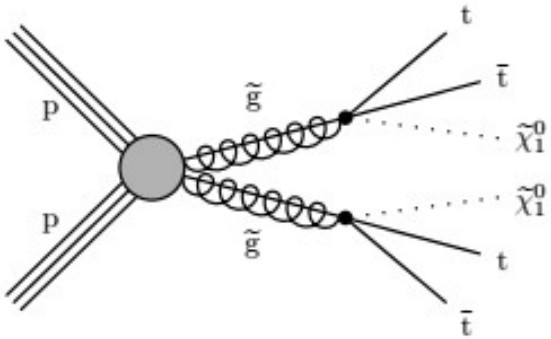






- Full Run2 dataset analyzed
- Reach masses of over 2 TeV

Single lepton search

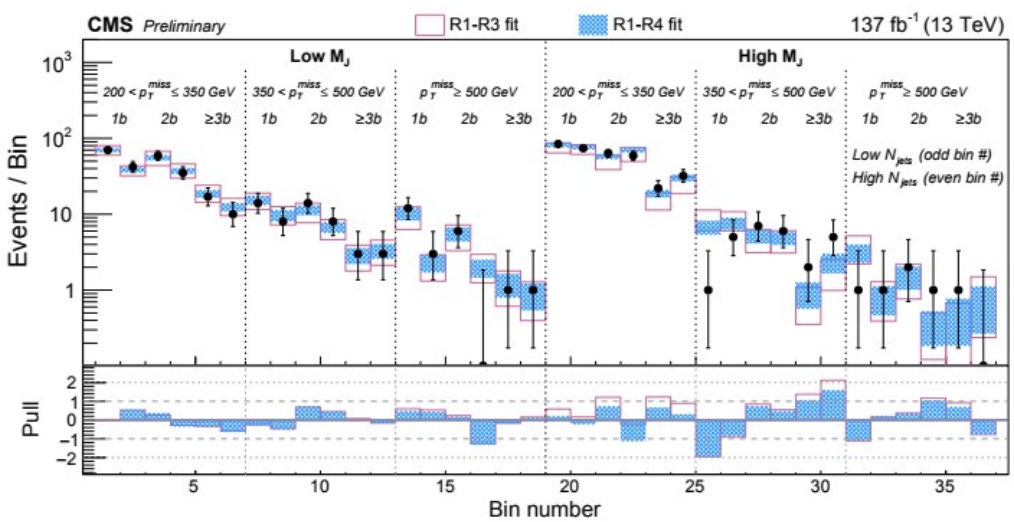


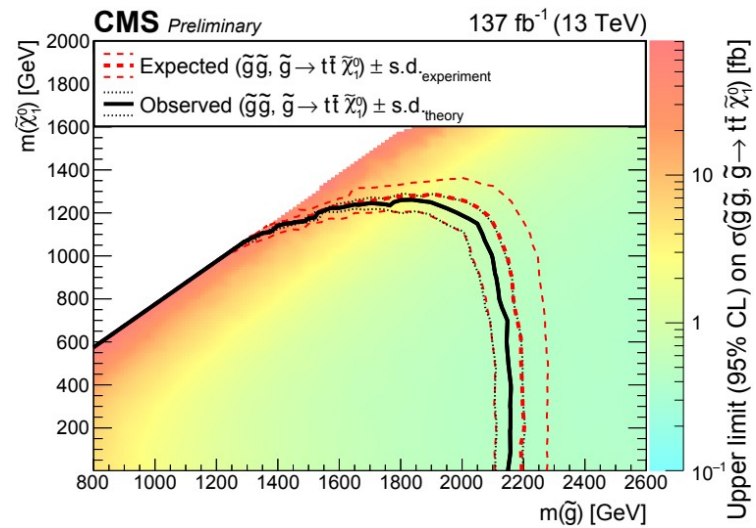
- 1 lepton p_T^{miss}, S_T, N_j, N_b, M_J

$$M_J = \sum_{J_i = \text{large-}R\text{ jets}} m(J_i)$$

$$m_T = \sqrt{2 p_T^{\ell} p_T^{miss} [1 - \cos(\Delta\phi_{\ell, \vec{p}_T^{miss}})]}$$

- Main background from leptonic decays of $t\bar{t}$ estimated with ABCD in M_J and m_T plane

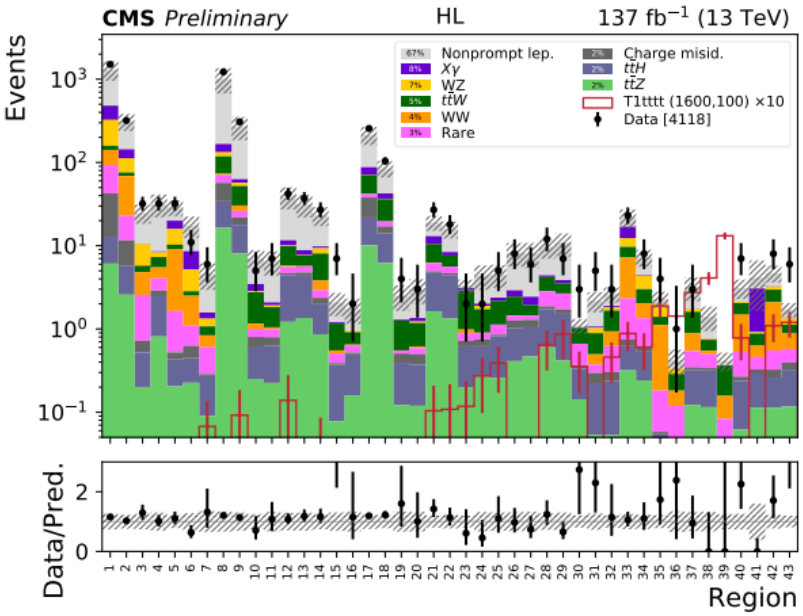


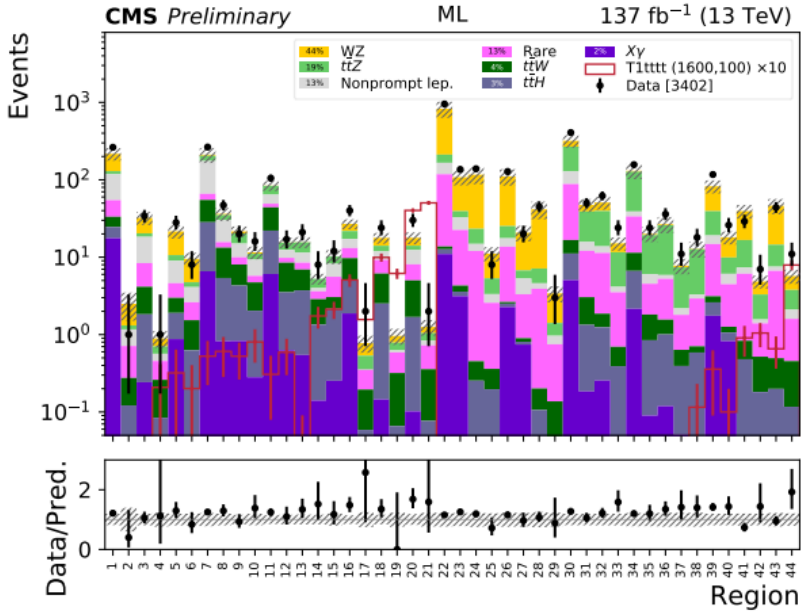


SUS-19-007

2 same sign leptons & multilepton search

- Signal regions by number of leptons and their p_T, H_T, p_T^{miss}, m_T, N_j, N_b
- Main backgrounds:
  - Non-prompt leptons from W+jets & QCD
  - Rare SM: ttV, WW, WZ
- Low thresholds for the leptons (15/10 for e/μ) give sensitivity to small mass splittings



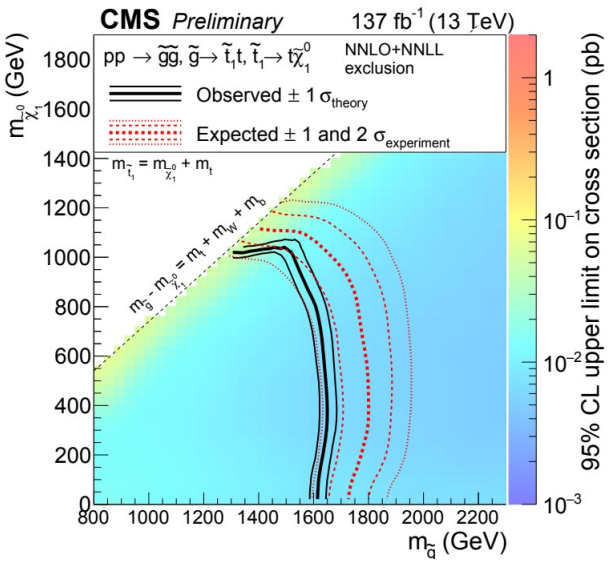


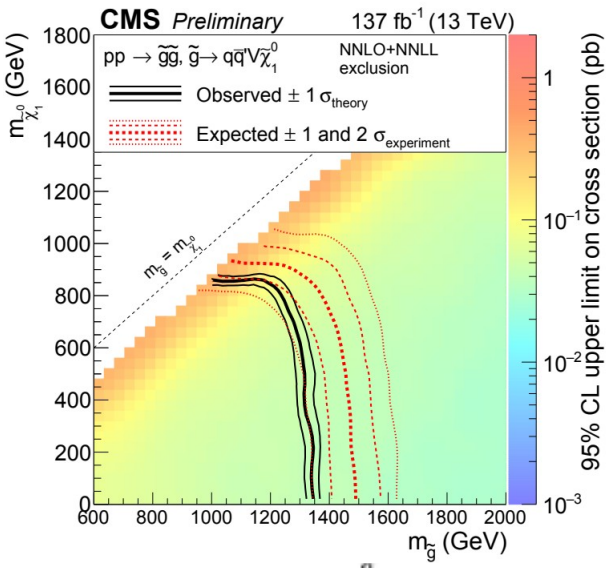
SUS-19-008

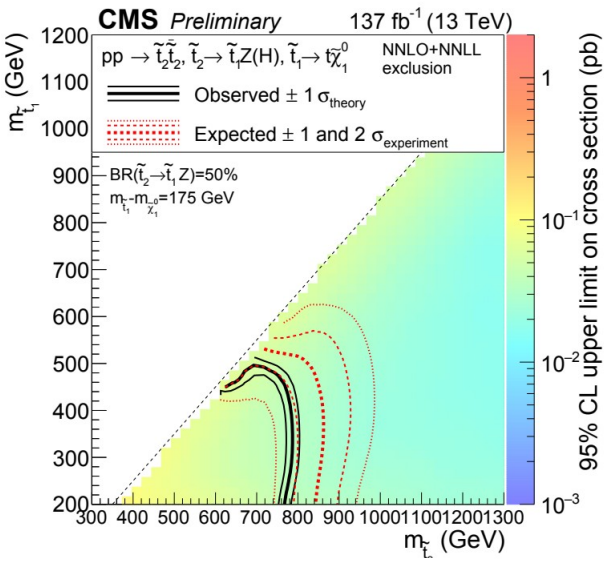
Interpretation in gluino & squark production

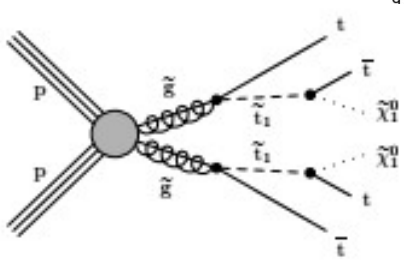
SUS-19-008

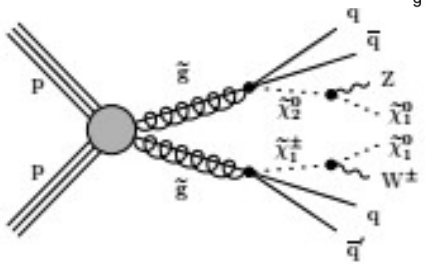
Sensitivity to leptonic decays of EW bosons produced in the decay chains

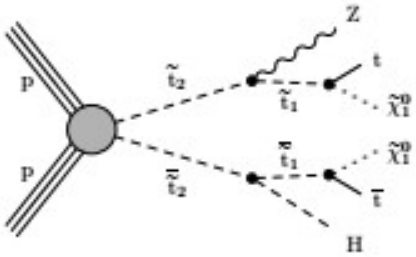








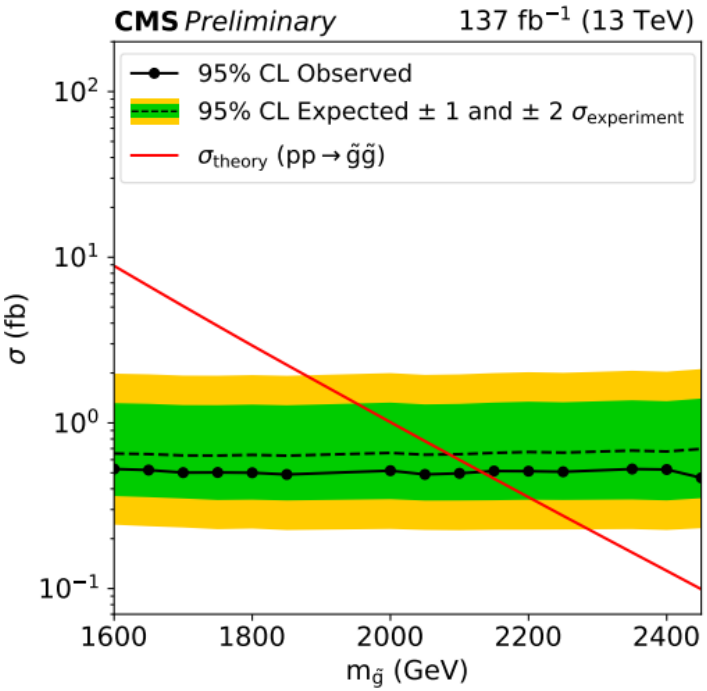


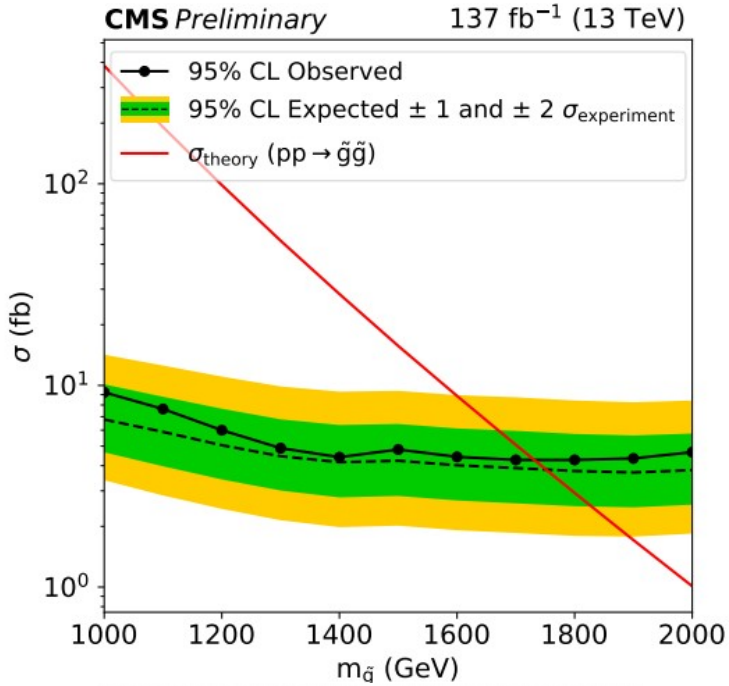


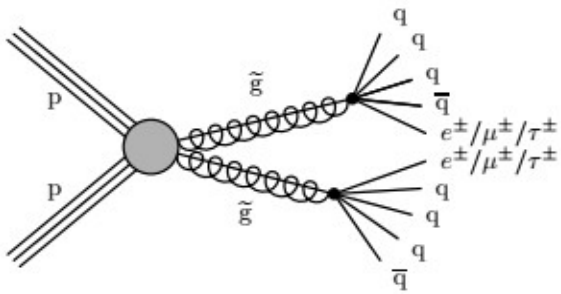
Interpretation in R-parity violating models

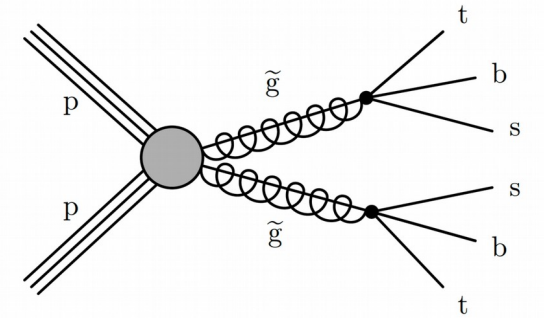
SUS-19-008

- R parity not conserved: lightest SUSY particle **not** stable
  → no LSP in the final state





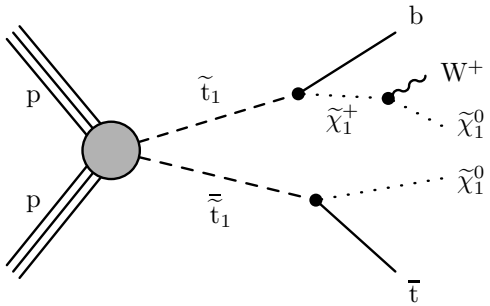


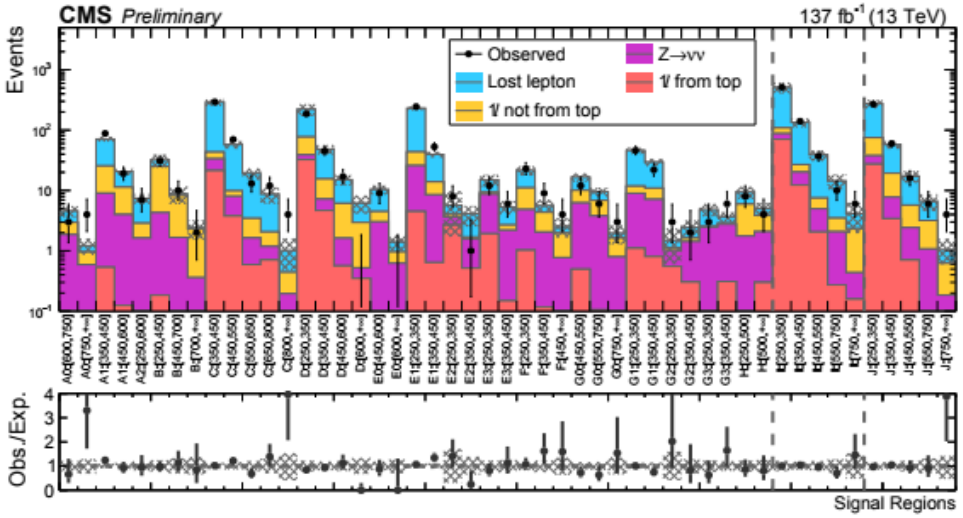


Dedicated stop search in 1 lepton final state

- Signal regions: H_T, H_T^{miss}, N_j, N_b and top-tagging (resolved and boosted)

- Main backgrounds:
  - 2-lepton events where 1-lepton is lost (ttbar+single top): estimated from 2 lepton control region in data
  - W+jets: estimated from 0b data control region

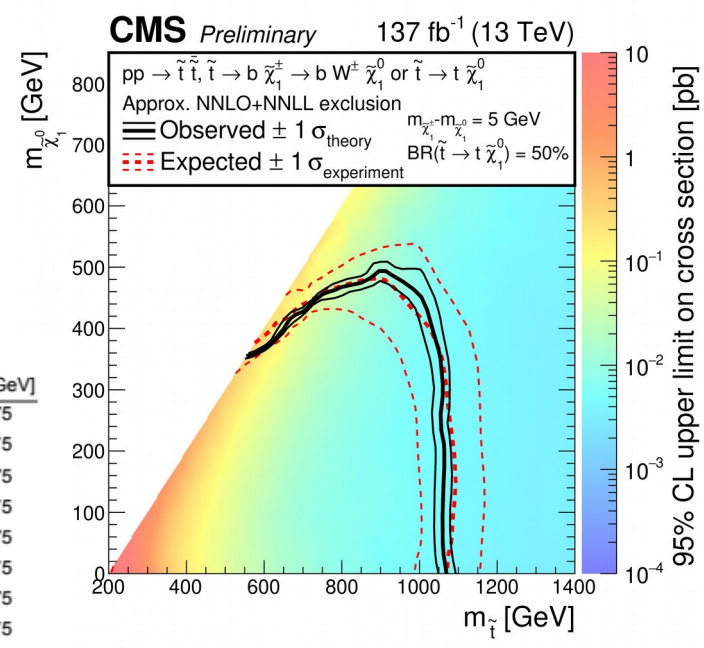




	N_J	t_{mod}	M_{lb} [GeV]
A	2–3	> 10	≤ 175
B	2–3	> 10	> 175
C	≥ 4	≤ 0	≤ 175
D	≥ 4	≤ 0	> 175
E	≥ 4	0–10	≤ 175
F	≥ 4	0–10	> 175
G	≥ 4	> 10	≤ 175
H	≥ 4	> 10	> 175

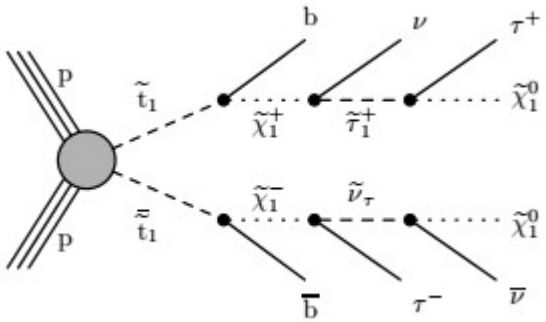
X0: Inclusive
X1: Untagged
X2: Boosted top
X3: Resolved top

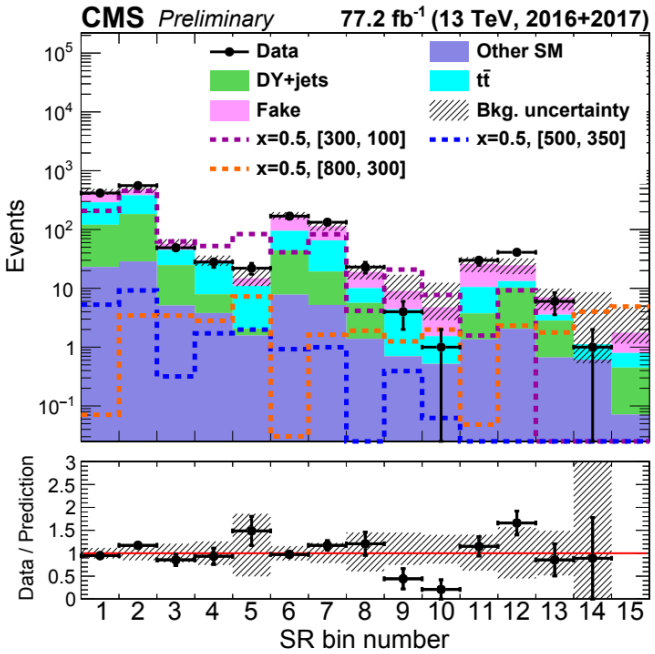
I: $N_J \geq 5$, $N_{b,med} \geq 1$
J: $N_J \geq 3$, $N_{b,soft} \geq 1$



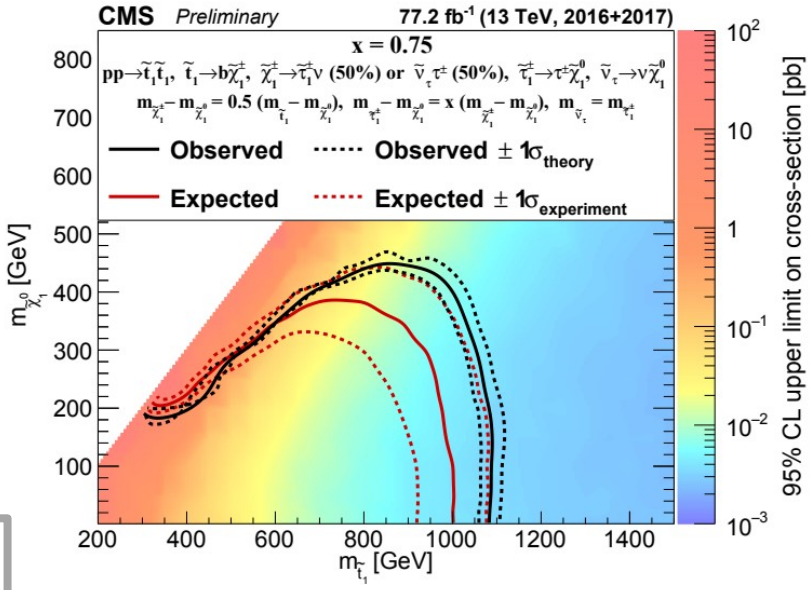
SUS-19-009

Stop → tau decays





- Signal regions: H_T, p_T^{miss}, M_{T2}
- Main backgrounds:
  - Taus from ttbar decays
  - Misidentified jet as a tau
- Sensitive to tanβ and higgsino-like scenarios



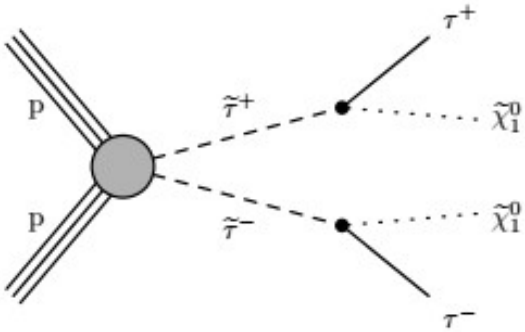
$$m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0} = x\,(m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0})$$
$$x = [0.25,\ 0.5,\ 0.75]$$

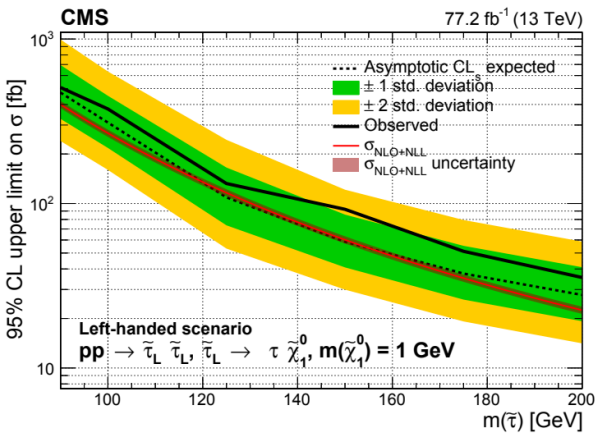
SUS-19-003

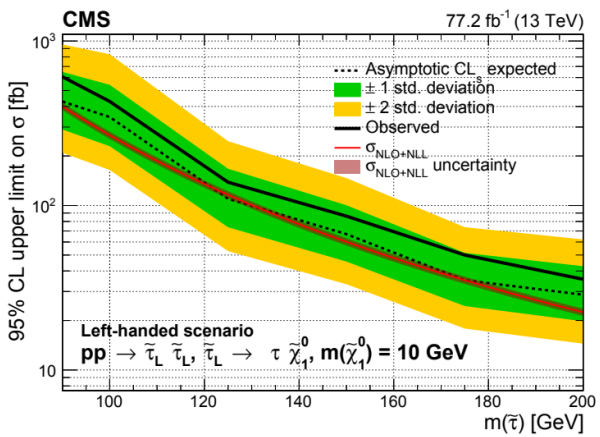
Tau slepton search

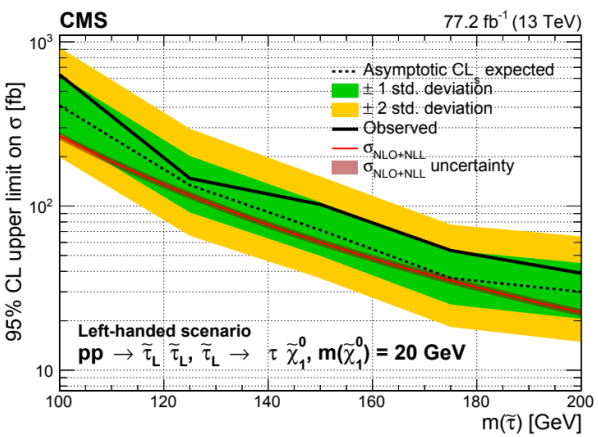
SUS-18-006

- Signal regions: $\tau_h\tau_h$ & $\ell\tau_h$ (ℓ=e,μ)
- Machine learning used to improve previous results
  - DNN for $\tau_h\tau_h$
  - Boosted decision tree for $\ell\tau_h$





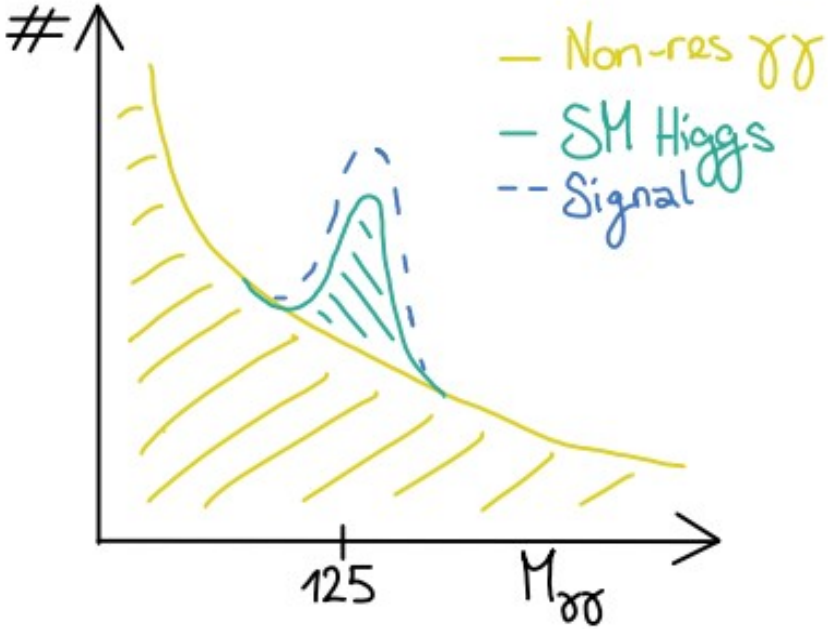




χ^0_1 mass

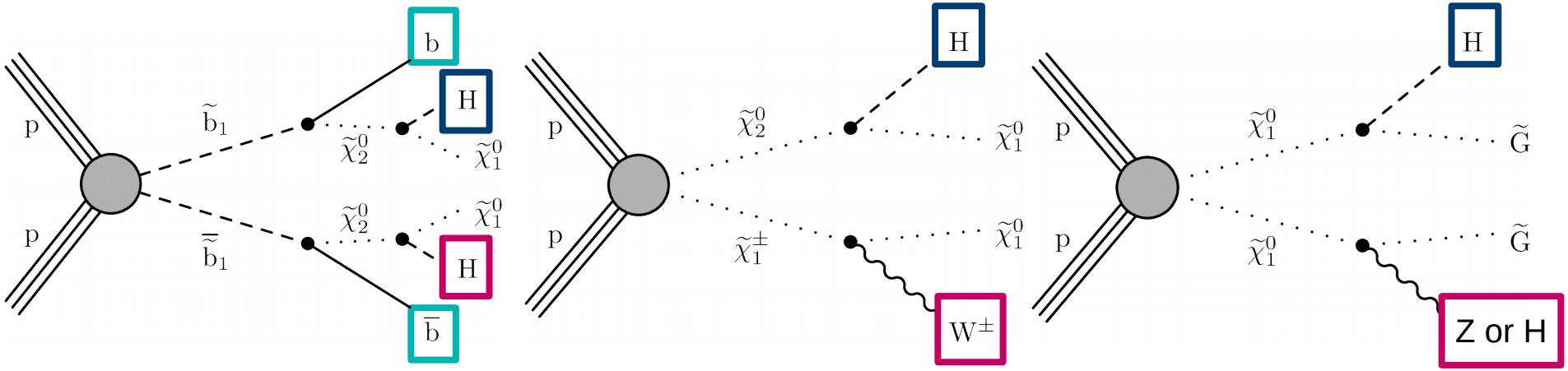
Search with H → $\gamma\gamma$ in the cascade

- Search for excess on Higgs peak
- **Non resonant background** from fit to data
- **SM Higgs** and **Signal** shapes from simulation
- Simultaneous fit of signal & background



SUS-18-007

Target Signals



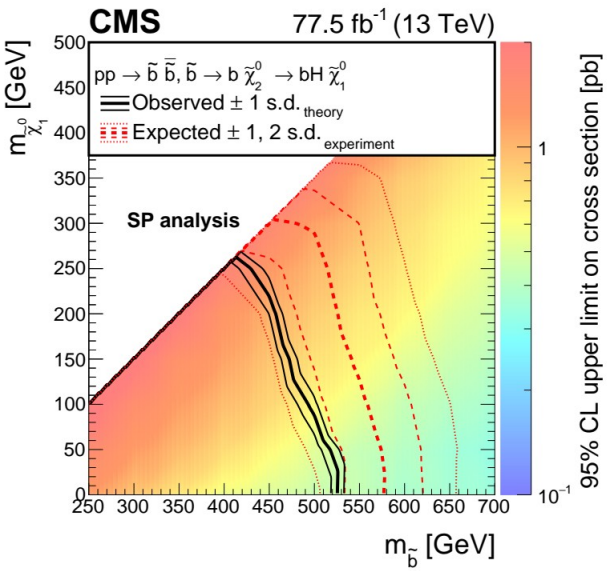
One boson per cascade produced

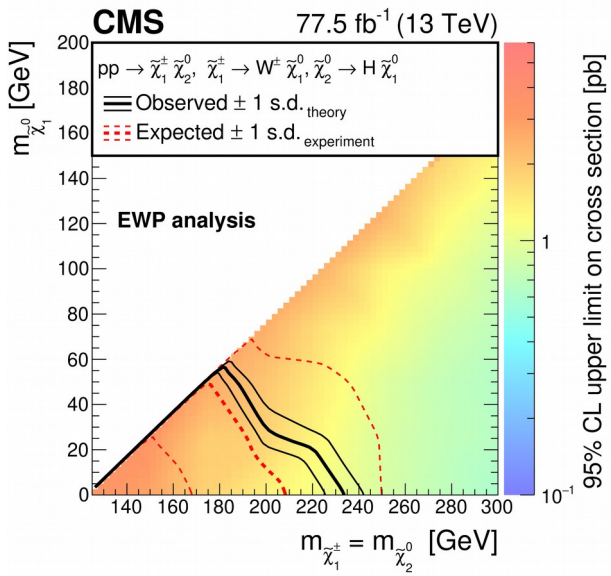
- At least one **H → γγ**
- Use **other boson** as additional discriminant against SM: H → bb, Z → bb, Z → ll, W → eν, W → μν
- **Additional b jets** for sbottom quark model

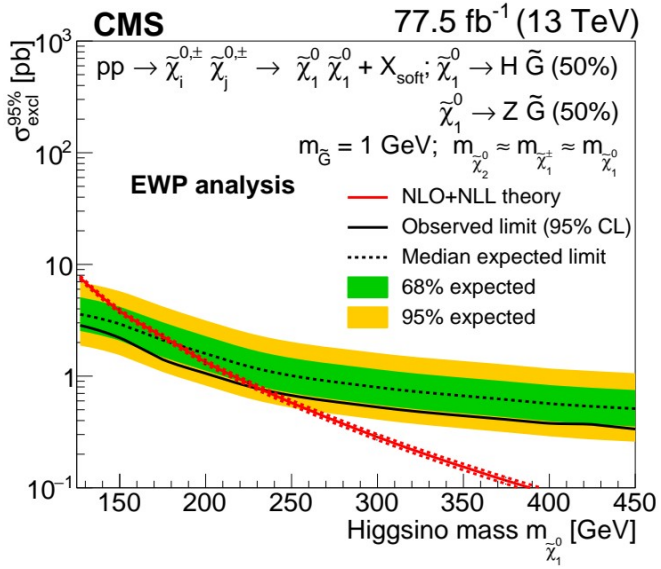
Search with H → $\gamma\gamma$ in the cascade

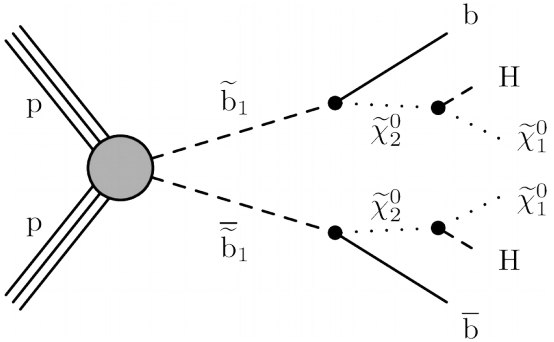
SUS-18-007

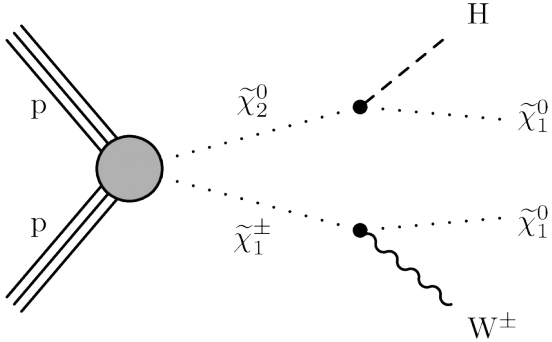
- Two approaches targeting strong (SP) and electroweak (EWP) production models

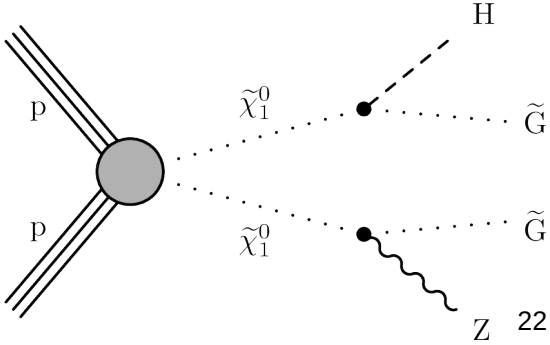




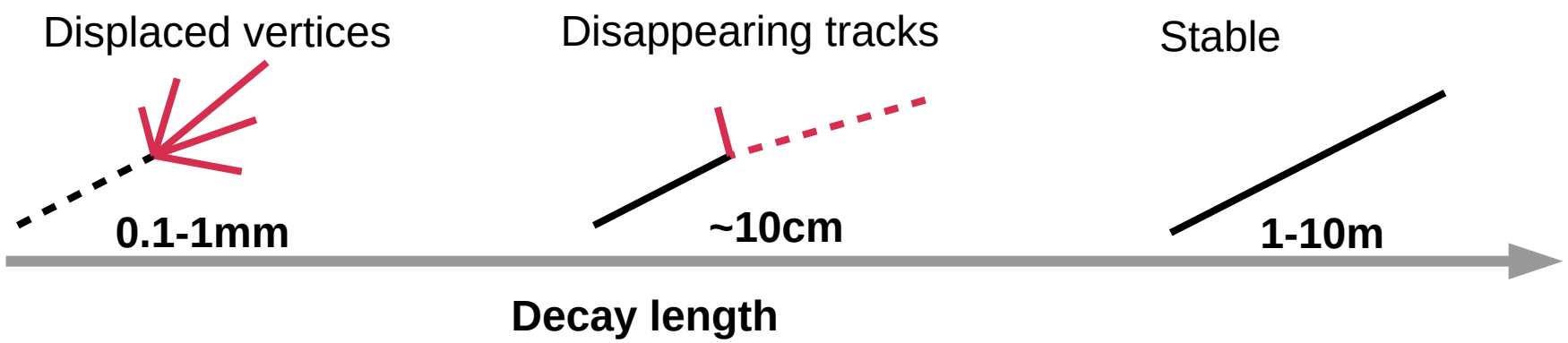




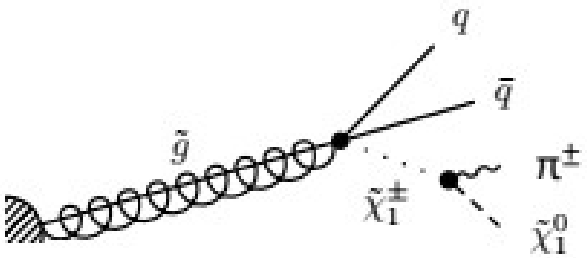




Long-lived SUSY particles



Long-lived particles: Disappearing tacks

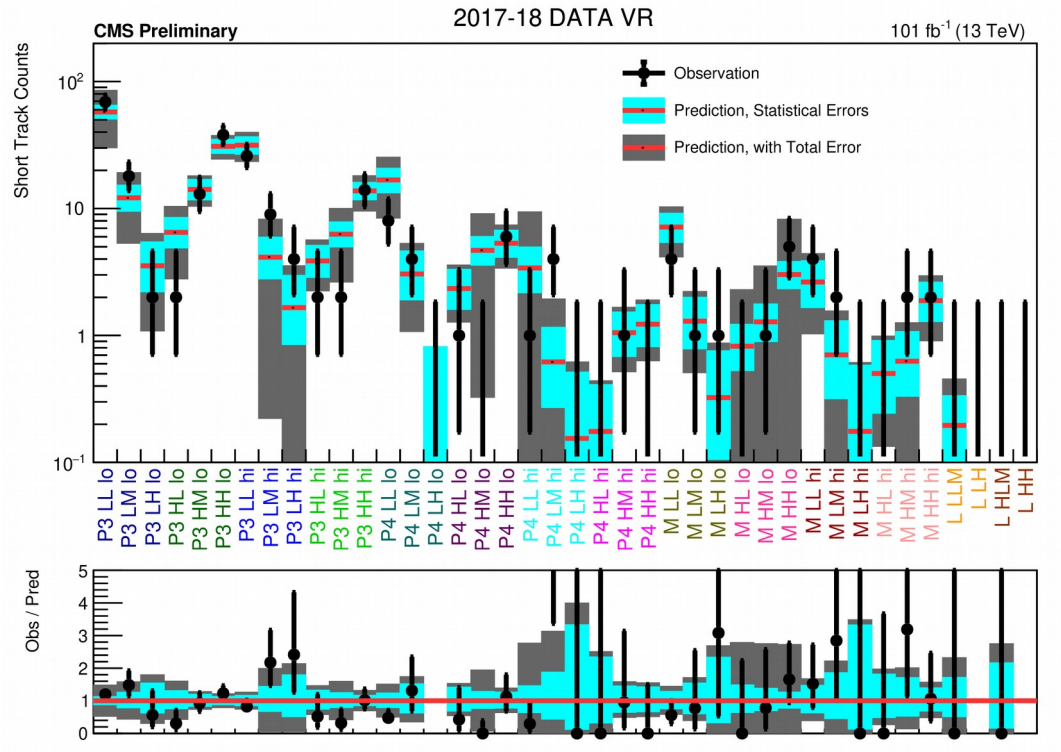


- Extension of the fully hadronic M_{T2} analysis
- Categorizing in length of the track:
  Short (pixel only), medium (<7 hits), long (>7 hits)
  & track p_T

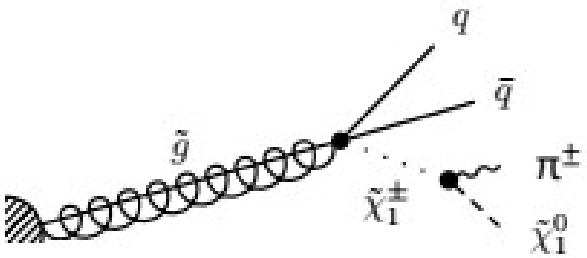
Main backgrounds from:

- charged pions & leptons that
  - significantly interact with tracker

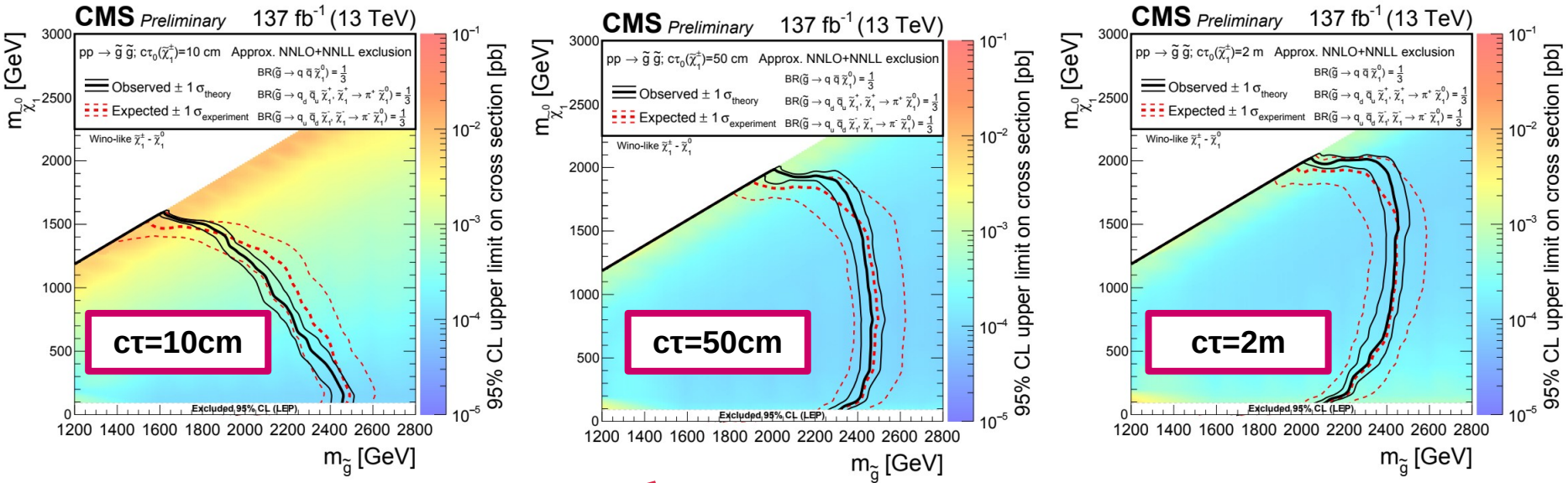
    or
  - poorly reconstructed
- Fake tracks



Long-lived particles: Disappearing tacks



- gluino branching fraction is 1/3 each for $\tilde{\chi}^0_1$, $\tilde{\chi}^+_1$ and $\tilde{\chi}^-_1$
- Mass of $\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_1$ assumed to differ by only a few hundred MeV
  → momentum of pion only a few hundred MeV



Conclusions

- Showed the latest results of SUSY searches at the CMS experiment with the Run2 dataset
  - More results to come with the full Run2 dataset!

- No significant excess over background predictions were found

  → set exclusion limits on various simplified models of SUSY

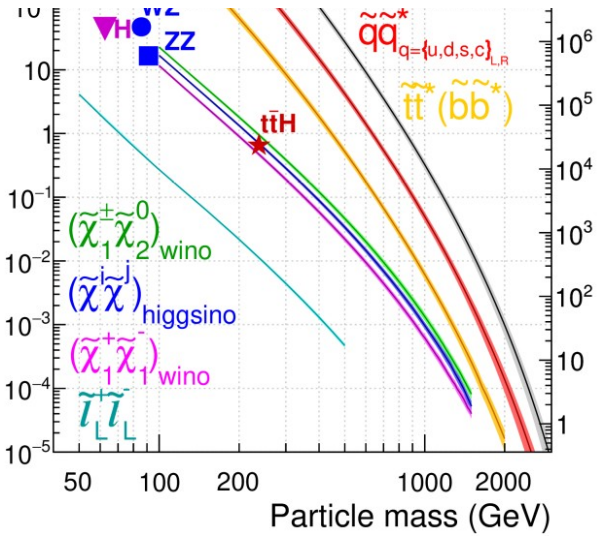
- Factor of 20 in integrated luminosity still to come with the HL-LHC

- We‘re at about 60% of the mass reach with the LHC

BACK UP

Electroweak composition

- Cross section depends on the bino/wino/higgsino composition



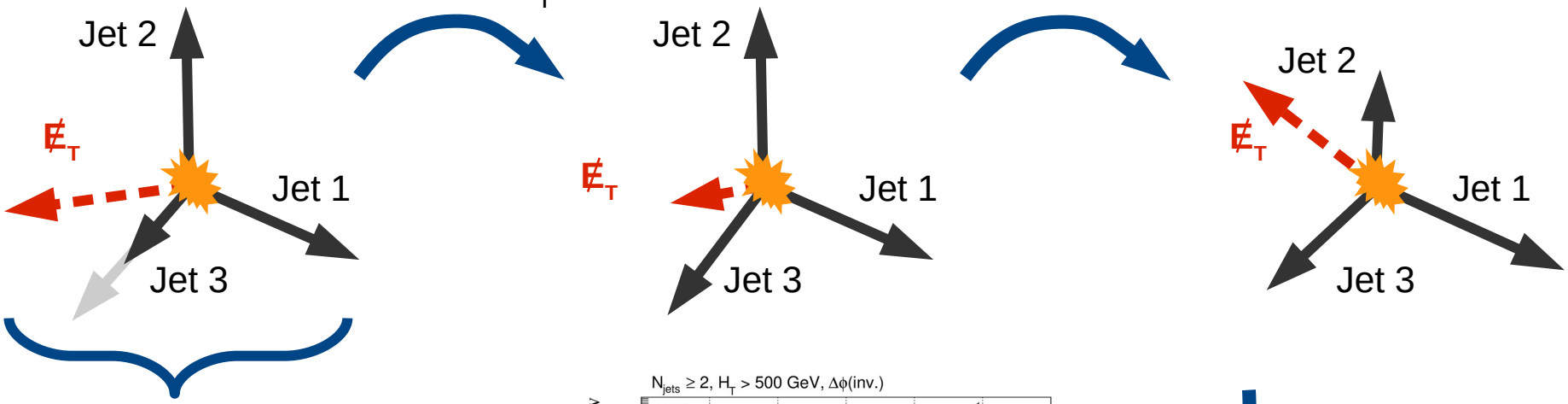
Bino			Wino			Higgsino		
$\tilde{q}_{L,R}$	—		$\tilde{q}_{L,R}$	—		$\tilde{q}_{L,R}$	—	
$\tilde{H}_{u,d}$	—	$\tilde{\chi}^0_{3,4}/\tilde{\chi}^\pm_2$	$\tilde{H}_{u,d}$	—	$\tilde{\chi}^0_{3,4}/\tilde{\chi}^\pm_2$	$\tilde{W}$	—	$\tilde{\chi}^0_4/\tilde{\chi}^\pm_2$
$\tilde{W}$	—	$\tilde{\chi}^0_2/\tilde{\chi}^\pm_1$	$\tilde{B}$	—	$\tilde{\chi}^0_2$	$\tilde{B}$	—	$\tilde{\chi}^0_3$
$\tilde{B}$	—	$\tilde{\chi}^0_1$	$\tilde{W}$	—	$\tilde{\chi}^0_1/\tilde{\chi}^\pm_1$	$\tilde{H}_{u,d}$	—	$\tilde{\chi}^0_{1,2}/\tilde{\chi}^\pm_1$

arxiv 1902.11267

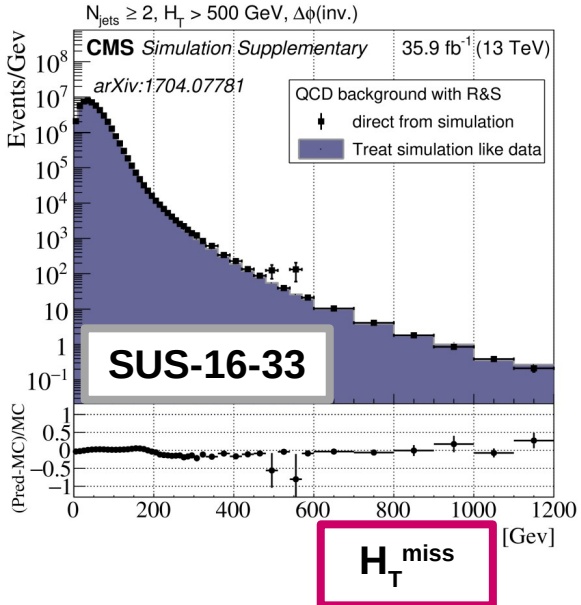
QCD Estimate: Rebalance and Smear

Rebalance jets to true hard scatter event with $ME_T \approx 0$

Smear jets according to response



QCD multi-jet events have no intrinsic ME_T, only **instrumental ME_T** due to detector response that depends on η & p_T of jets



Good agreement with out of the box simulation