Searching for Supersymmetry at the LHC

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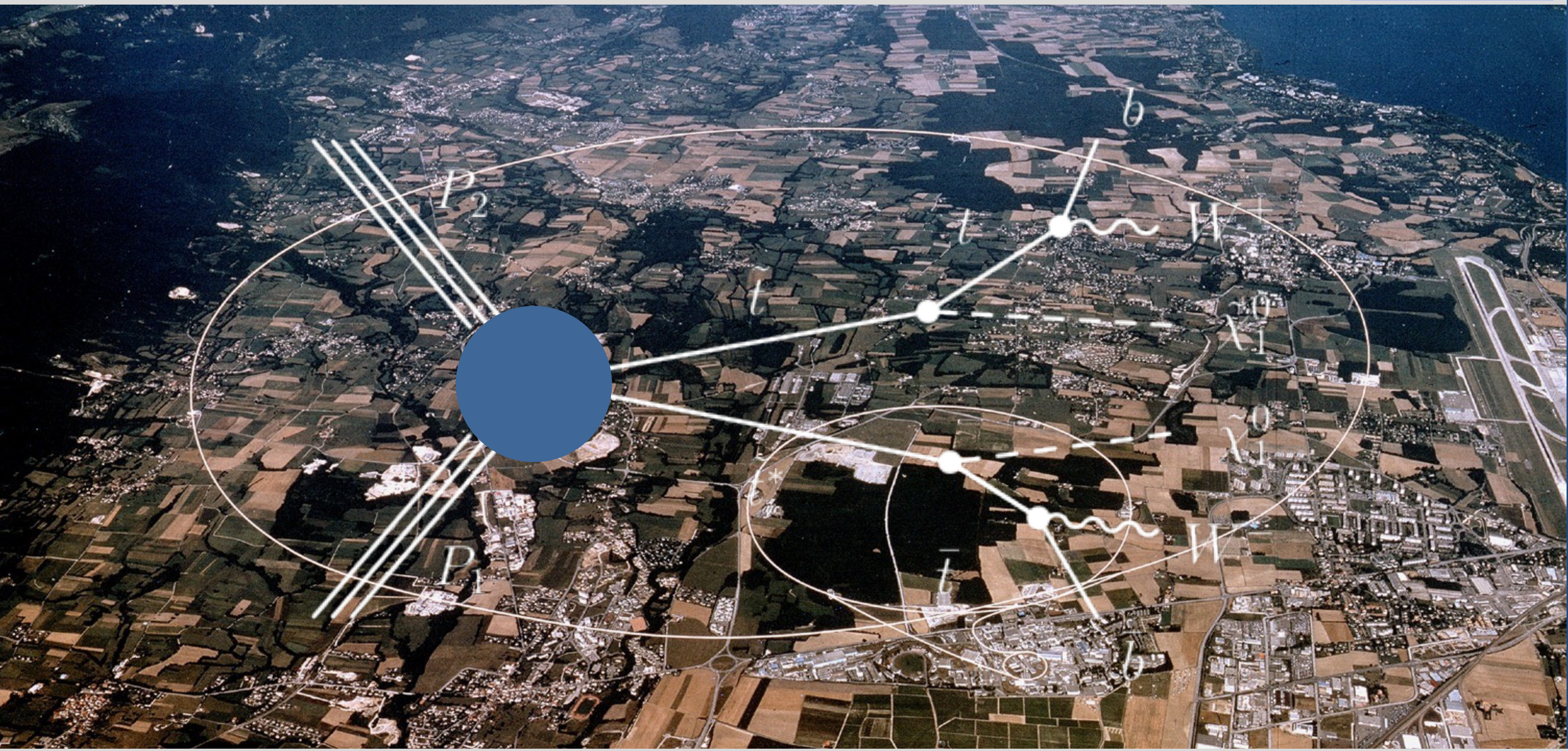


Seminar, KIT, Karlsruhe, Germany
June 29, 2017

Outline

- Introduction
- SUSY basics
- Interpreting SUSY searches
- Challenges of SUSY searches
- Examples of searches
  - All-hadronic Jets + p_T^{miss}
  - 1-lepton + (b)-jets + p_T^{miss}
  - HH + p_T^{miss}
- Conclusions and prospects

Drawing courtesy Sergio Cittolin, CMS

Some references (I)

- ATLAS public SUSY results:

  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
- CMS public SUSY results:

  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
- S.P. Martin, *A Supersymmetry Primer*

  https://arxiv.org/abs/hep-ph/9709356
- Particle Data Group reviews

  Supersymmetry, Part I (Theory) http://pdg.lbl.gov/2017/reviews/rpp2016-rev-susy-1-theory.pdf

  Supersymmetry, Part II (Experiment) http://pdg.lbl.gov/2017/reviews/rpp2016-rev-susy-2-experiment.pdf
- P. Binétruy, *Supersymmetry: Theory, Experiment, and Cosmology*, Oxford, 2006.
- I. Aitchison, *Supersymmetry in Particle Physics: An Elementary Introduction*, Oxford, 2007; see also https://arxiv.org/pdf/hep-ph/0505105.pdf

Some references (II)

- H. Baer and X. Tata, Weak Scale Supersymmetry: From Superfields to Scattering Events, Cambridge, 2006.
- M. Papucci, J. Ruderman, A. Weiler, *Natural SUSY Endures*, https://arxiv.org/abs/1110.6926
- N. Craig, *The State of Supersymmetry after Run I of the LHC*, https://arxiv.org/pdf/1309.0528.pdf
- J. Feng, *Naturalness and the State of Supersymmetry*, https://arxiv.org/abs/1302.6587
- D. Alves et al., *Simplified Models for LHC New Physics Searches*, https://arxiv.org/abs/1105.2838
- J. Richman, *Searches for New Physics at the Large Hadron Collider*, in *LHC Phenomenology,* ed. by E. Gardi, N. Glover, and A. Robson, https://link.springer.com/book/10.1007%2F978-3-319-05362-2
- ATLAS Collab., *Summary of the ATLAS experiment's sensitivity to supersymmetry after LHC Run 1 — interpreted in the phenomenological MSSM,* https://arxiv.org/abs/1508.06608

Searches for SUSY have been performed at the CERN $Sp\bar{p}S$, LEP, and the Tevatron…

The New York Times, January 5, 1993

January 5, 1993

315 Physicists Report Failure In Search for Supersymmetry

By MALCOLM W. BROWNE

Three hundred and fifteen physicists worked on the experiment.

Their apparatus included the Tevatron, the world's most powerful particle accelerator, as well as a $6 million detector weighing as much as a warship, an advanced new computing system and a host of other innovative gadgets.

But despite this arsenal of brains and technological brawn assembled at the Fermilab accelerator laboratory, the participants have failed to find their quarry, a disagreeable reminder that as science gets harder, even Herculean efforts do not guarantee success.

In trying to ferret out ever deeper layers of nature's secrets, scientists are being forced to accept a markedly slower pace of discovery in many fields of research, and the consequent rising cost of experiments has prompted public and political criticism.

…ouch.

A few questions…

- What is SUSY?
- Why is SUSY such a prominent theoretical framework for new physics?
- How do you search for SUSY?
- How are the results of SUSY searches interpreted?
- Why are SUSY searches so complex and difficult?
- How do we predict the SM backgrounds?
- What have we learned so far?
- If you saw a signal, would you believe it?
- If you saw a signal, would you know that it is SUSY?
- Is SUSY…dead?

Profound questions at the TeV scale

Hierarchy problem

~10^{18} GeV

Planck scale
(quantum gravity)

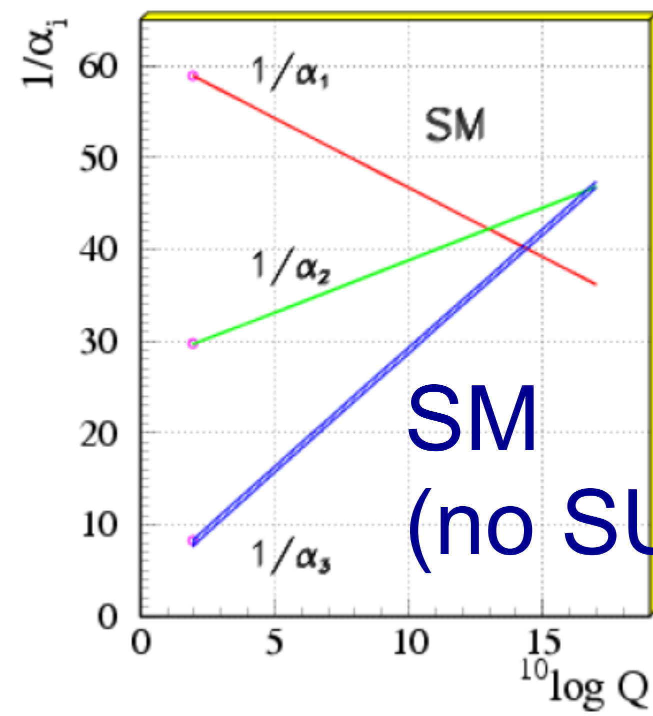
~10^{16}

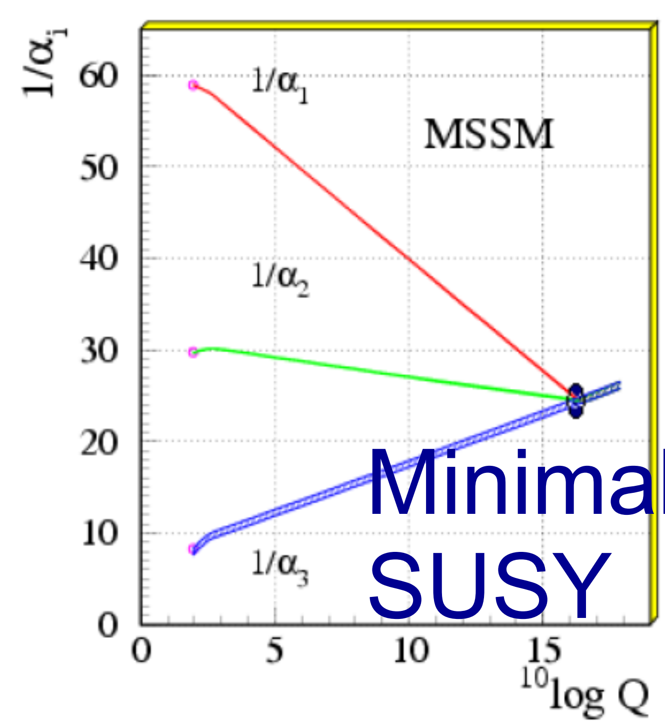
Separation of scales can be stabilized by SUSY, extra dim's,…

~10^{2} -10^{3} GeV

Electroweak scale
(unstable in SM)

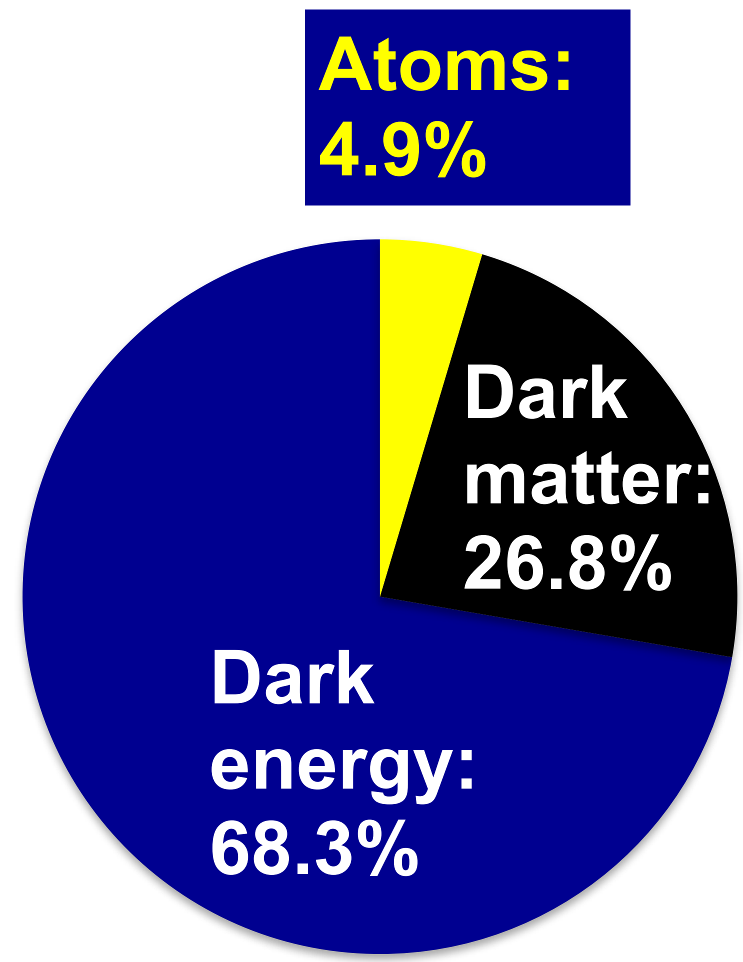
Unification of couplings





S. Raby, Particle Data Book.

Dark matter

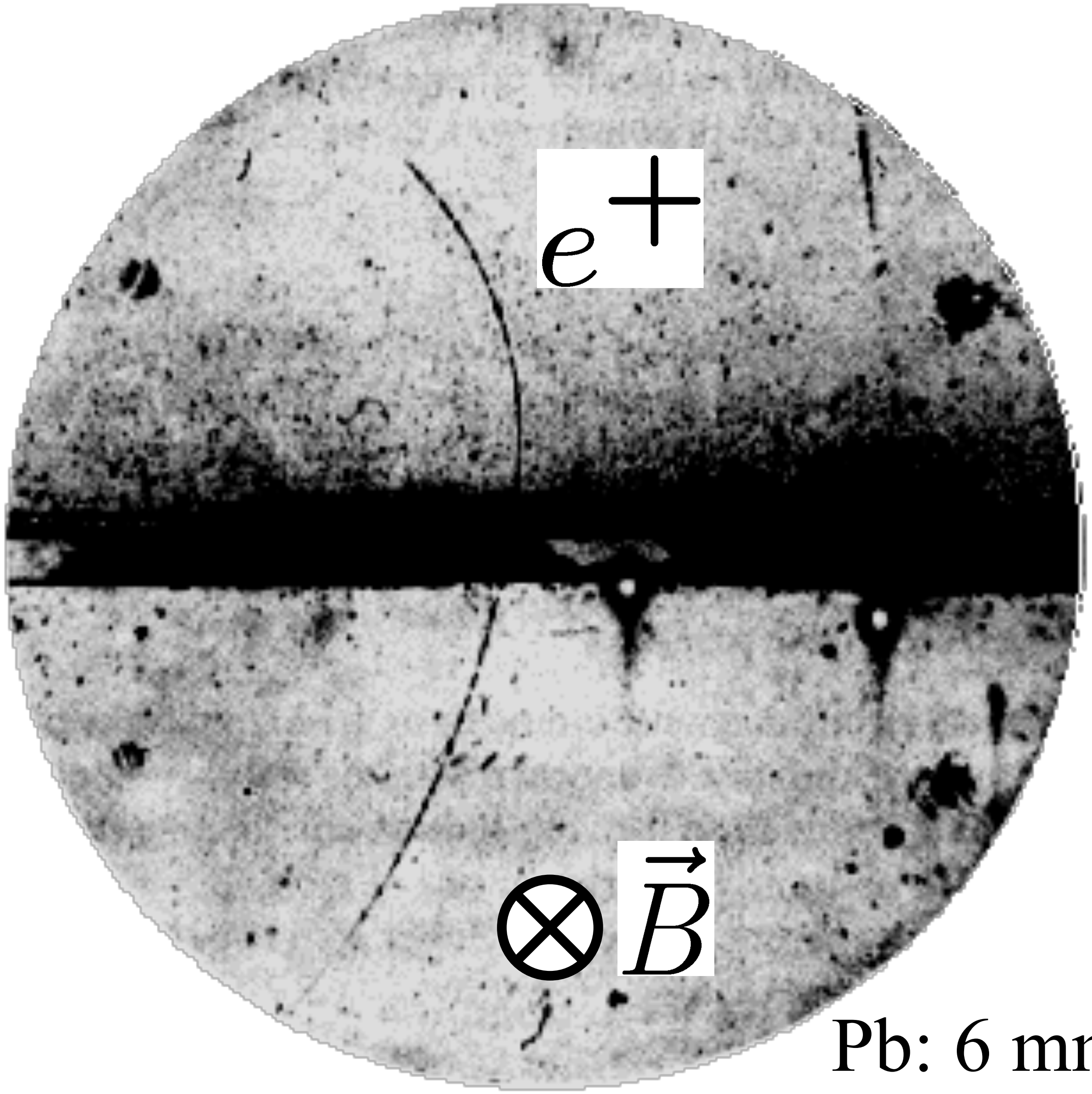


WIMP Miracle → TeV scale

SUSY provides dark matter candidate particle (Lightest Supersymmetric Particle); in MSSM this is neutralino.

Discovery of the positron…and of a symmetry

- 1928: Dirac equation.
- Struggle to interpret negative energy solution in the context of a single-particle wave equation.
- 1932: Positron interpretation confirmed by C.D. Anderson's observation of the positron in cosmic-ray events.
- Symmetry → doubled the particle spectrum!



Pb: 6 mm thick

$$a \rightarrow \bar{a}: \quad q_a = -q_{\bar{a}} \quad m_a = m_{\bar{a}} \quad \tau_a = \tau_{\bar{a}} \quad (CPT)$$

P.A.M. Dirac, Proc. Roy. Soc. (London), **A117**, 610 (1928); ibid., **A118**, 351 (1928).
C.D. Anderson, Phys. Rev. **43**, 491 (1933).

Discovery of the positron…and of a symmetry

Author lists were shorter back in 1933...

MARCH 15, 1933 PHYSICAL REVIEW VOLUME 43

The Positive Electron

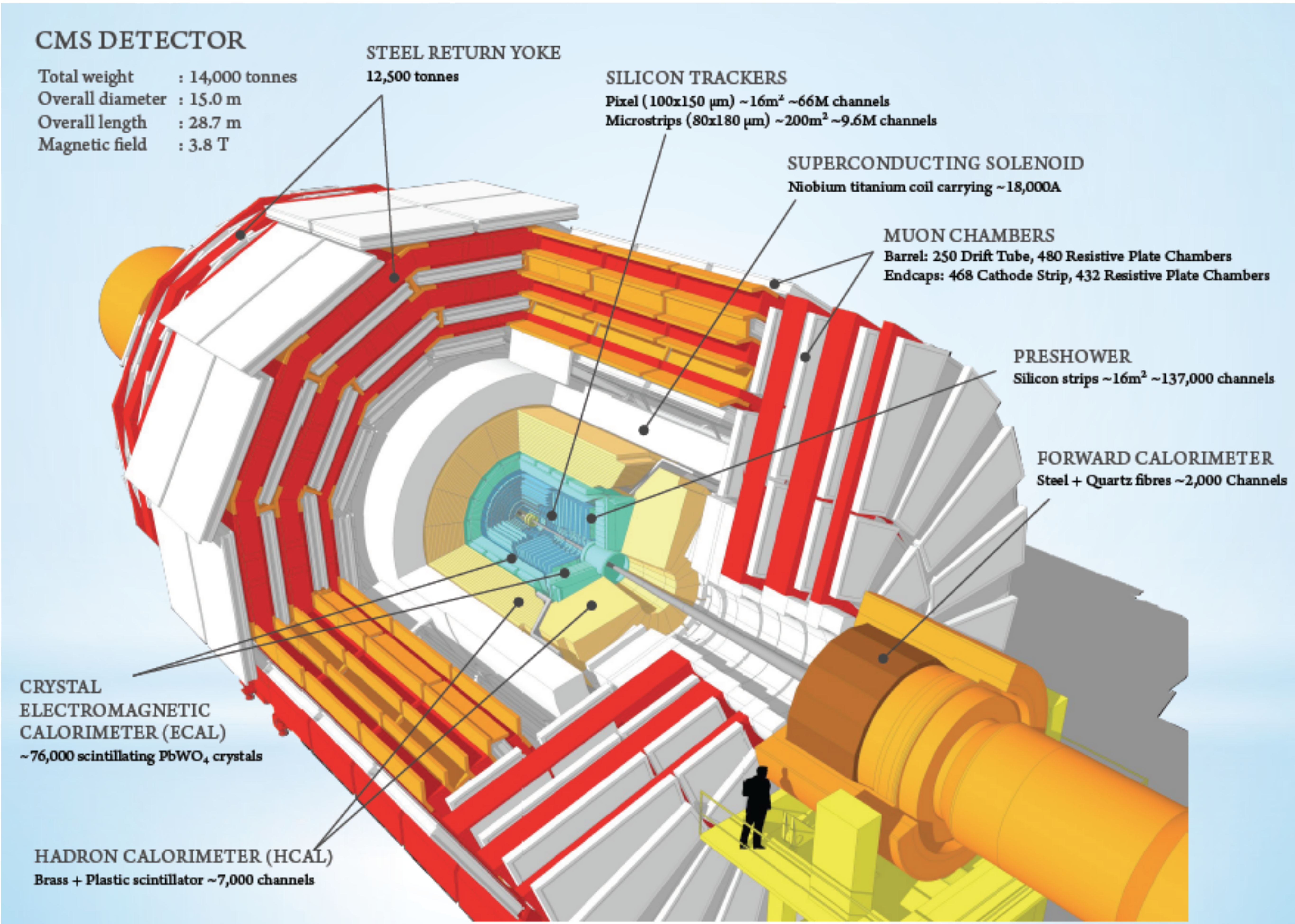
CARL D. ANDERSON, *California Institute of Technology, Pasadena, California*

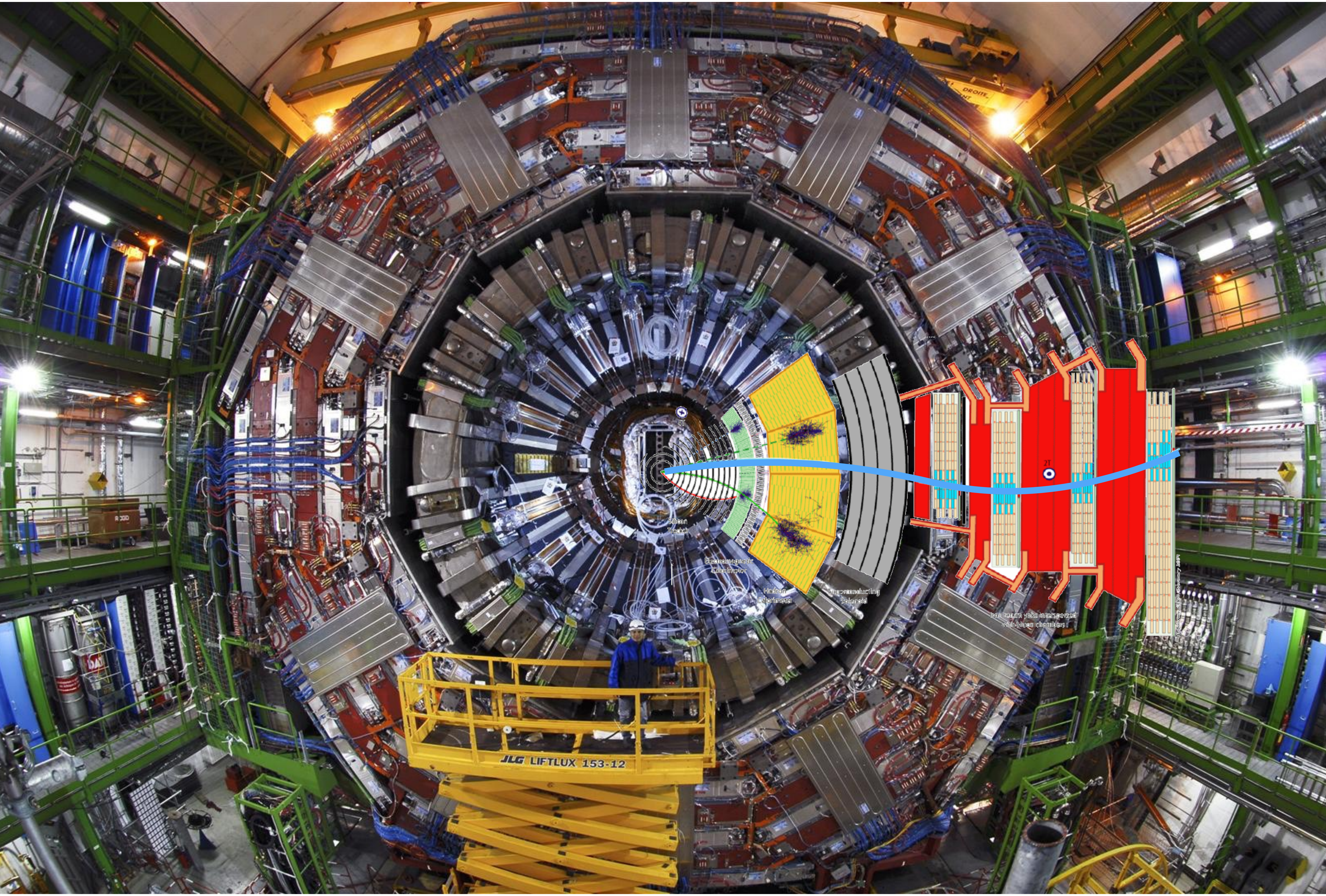
(Received February 28, 1933)

Out of a group of 1300 photographs of cosmic-ray tracks in a vertical Wilson chamber 15 tracks were of positive particles which could not have a mass as great as that of the proton. From an examination of the energy-loss and ionization produced it is concluded that the charge is less than twice, and is probably exactly equal to, that of the proton. If these particles carry unit positive charge the curvatures and ionizations produced require the mass to be less than twenty times the electron mass. These particles will be called positrons. Because they occur in groups associated with other tracks it is concluded that they must be secondary particles ejected from atomic nuclei.

Editor

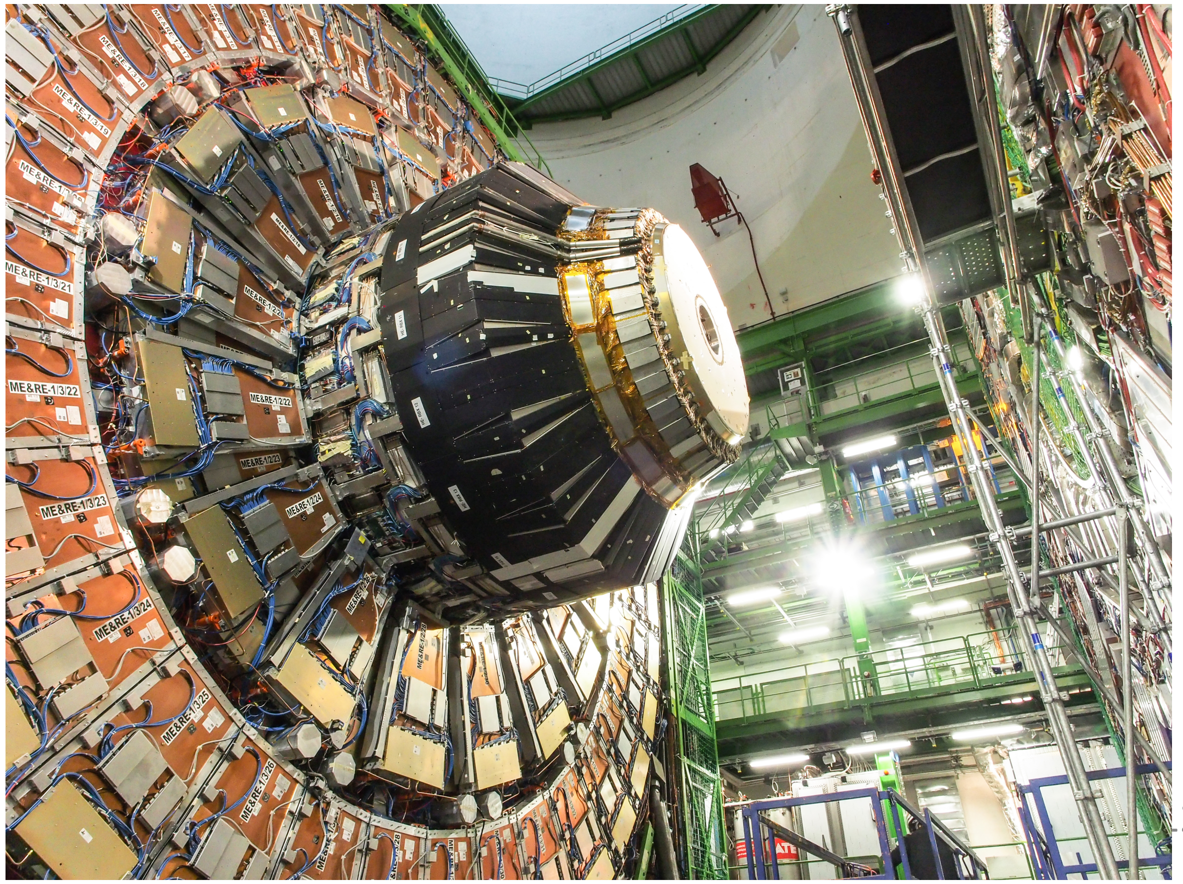
ON August 2, 1932, during the course of photographing cosmic-ray tracks produced in a vertical Wilson chamber (magnetic field of 15,000 gauss) designed in the summer of 1930 by Professor R. A. Millikan and the writer, the tracks shown in Fig. 1 were obtained, which seemed to be interpretable only on the basis of the existence in this case of a particle carrying a electrons happened to produce two tracks so placed as to give the impression of a single particle shooting through the lead plate. This assumption was dismissed on a probability basis, since a sharp track of this order of curvature under the experimental conditions prevailing occurred in the chamber only once in some 500 exposures, and since there was practically no


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

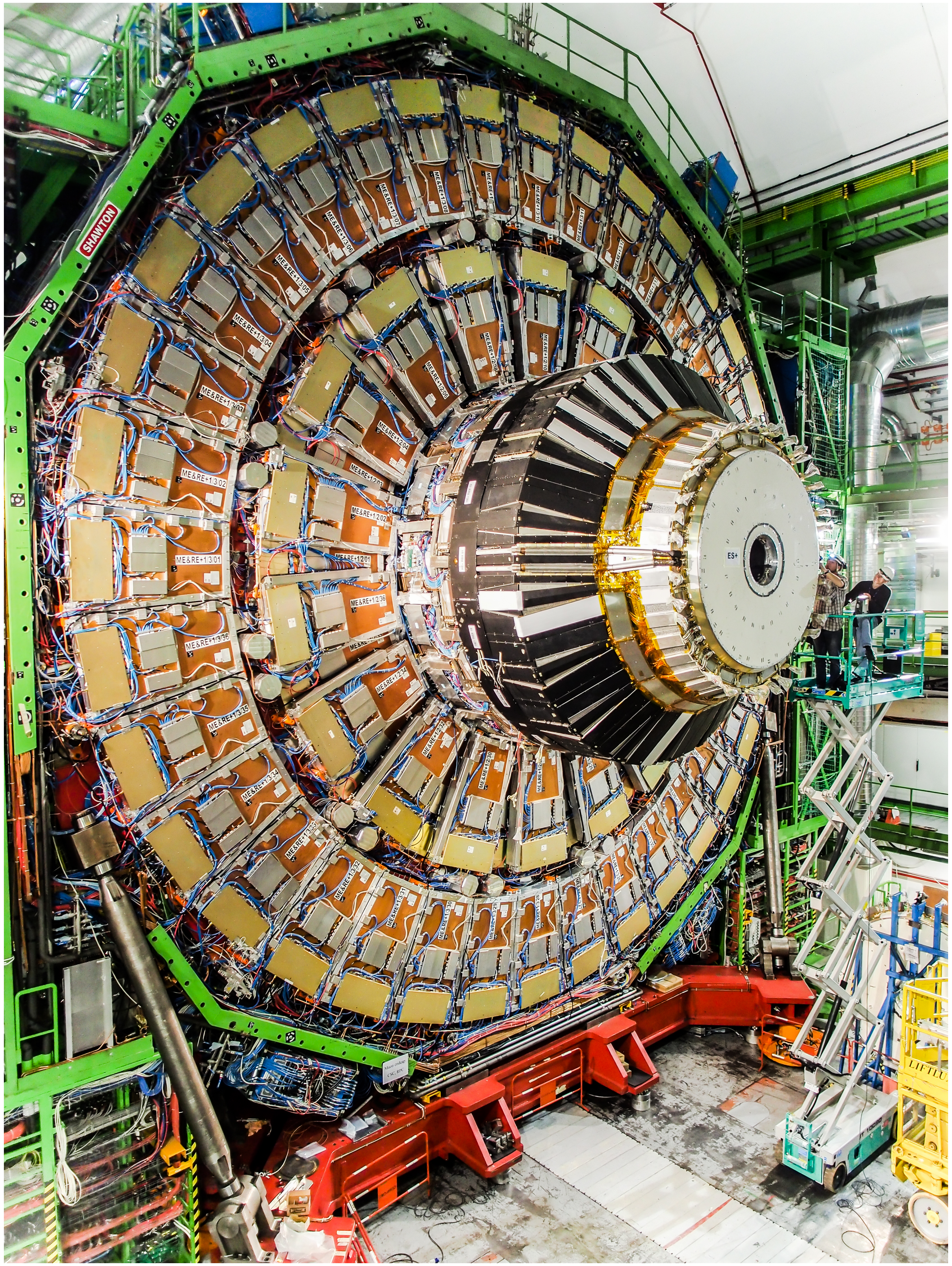


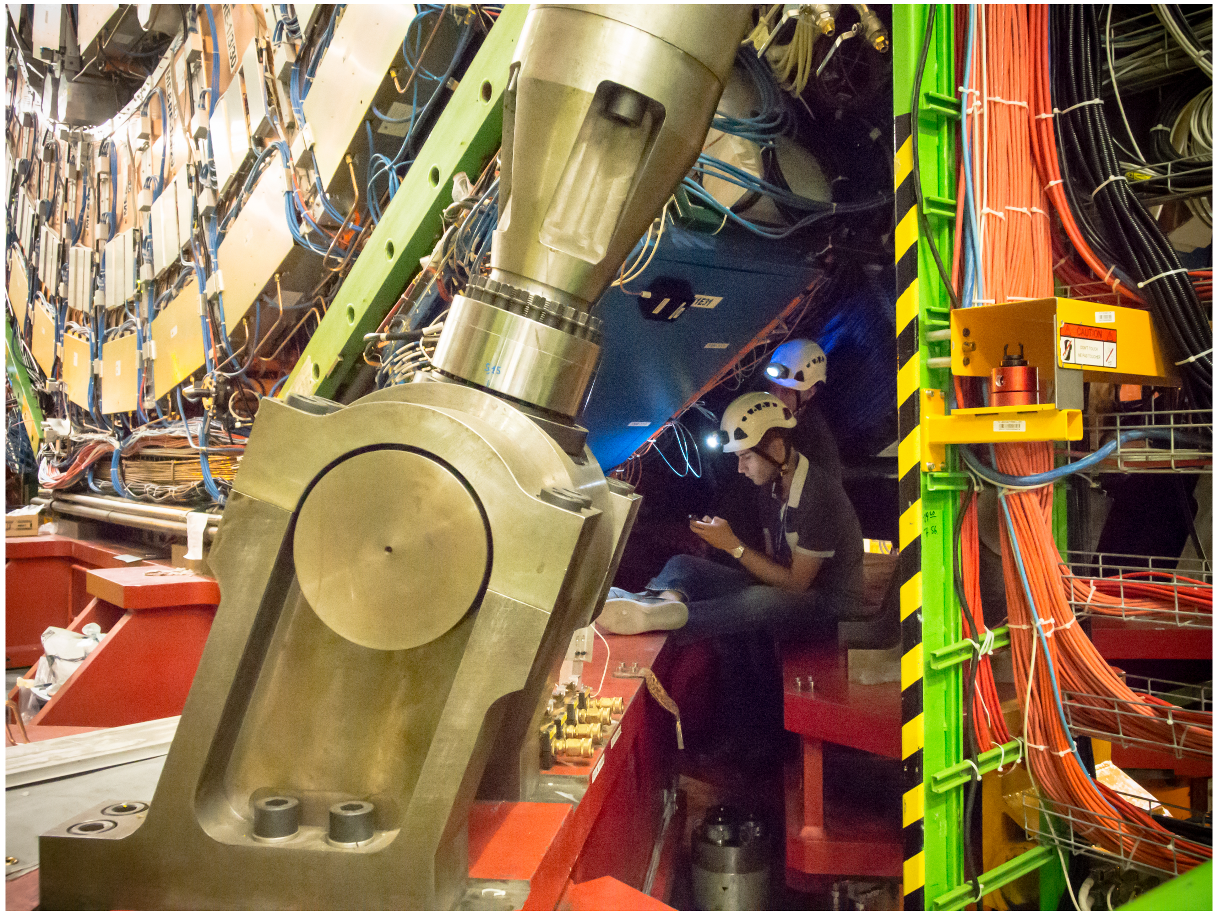
CMS Detector: barrel region

Working on the CMS detector



Working on the CMS detector



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Supersymmetry basics

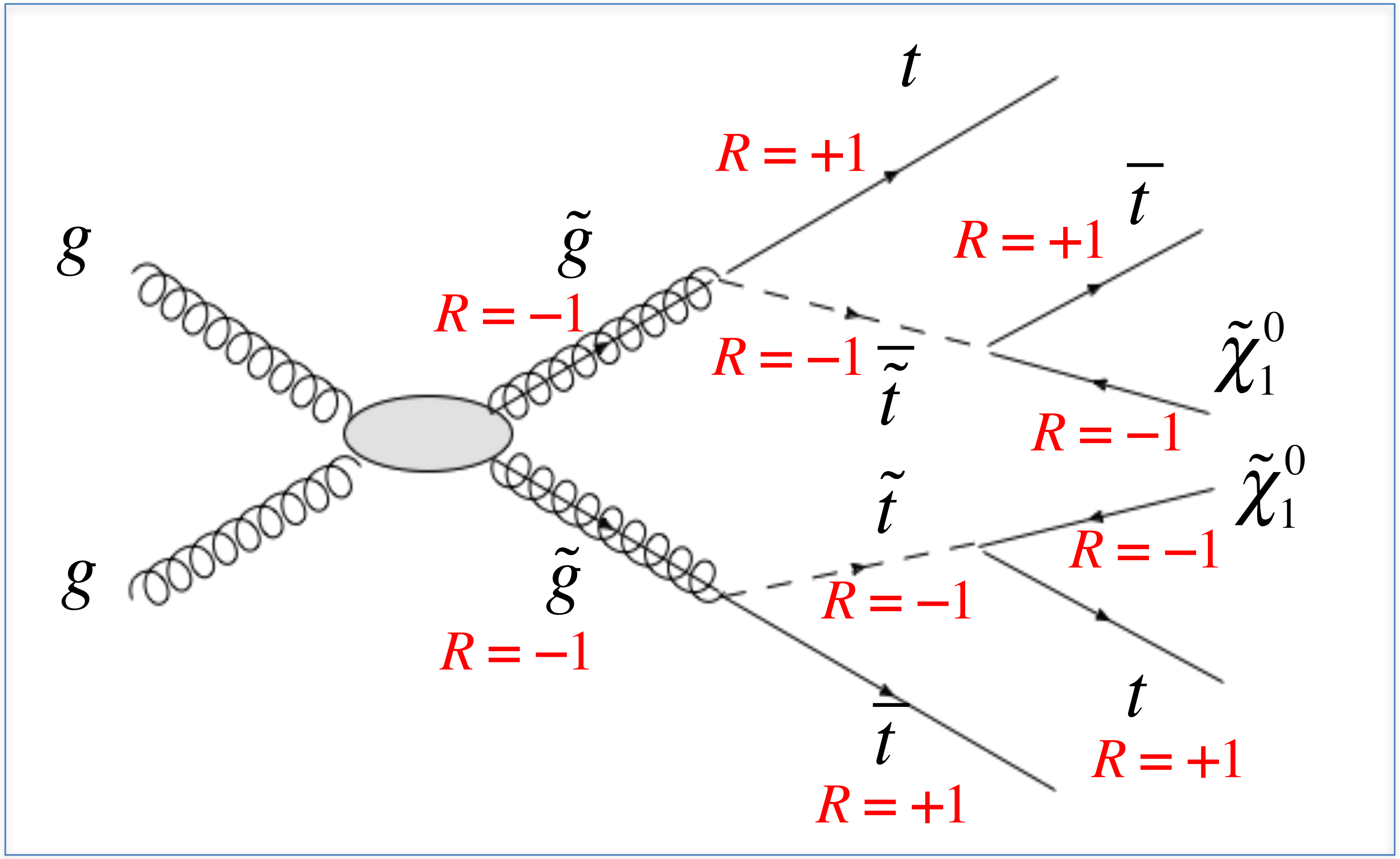
- The symmetry operation in SUSY is a mapping between fermionic and bosonic degrees of freedom.
  - "For every SM particle, there is a SUSY particle." (Well, sort of.)
  - Must be a broken symmetry: we don't observe SUSY partners with SM mass values. SUSY breaking → phenomenology
  - SUSY preserves the SM couplings (charges) of particles.
- R-parity: multiplicative quantum number that is conserved in many, but not all SUSY scenarios.

$$R = (-1)^{3(B-L)+2S}$$

	quark	lepton	gauge boson	Higgs boson	squark	slepton	gaugino/ Higgsino
3(B-L)+2S	3(1/3 - 0) +2(1/2) = 2	3(0 - 1) +2(1/2) = -2	3(0 – 0) +2 (1) = 2	3(0 – 0) +2(0) = 0	3(1/3 - 0) +2(0) = 1	3(0 – 1) +2(0) = -3	3(0 – 0) +2(1/2) = 1
R	1	1	1	1	-1	-1	-1

Supersymmetry basics

- "Curse of many parameters": MSSM has 124 (including SM).
- If R-parity is conserved, SUSY particles must be produced in pairs.
- The decay chain of each SUSY particle ends with the lightest SUSY partner (LSP), which is stable.
- If the LSP is only weakly interacting, it is a dark matter candidate.



SUSY partners of SM fermions

- SM fermions are mapped to spin-0 particles

  → proliferation of scalar (J=0) particles: squarks & sleptons

- The SM is a chiral theory, and the L-handed and R-handed fermions have different EW charges.
  - L-handed fermions transform as $SU(2)_L$ doublets
  - R-handed fermions transform as $SU(2)_L$ singlets
- Each chiral projection of an SM fermion has a J = 0 SUSY partner, preserving degrees of freedom.

$$e^- \nearrow e_L^- \leftrightarrow \tilde{e}_L^- \qquad e^- \searrow e_R^- \leftrightarrow \tilde{e}_R^-$$

$$t \nearrow t_L \leftrightarrow \tilde{t}_L \qquad t \searrow t_R \leftrightarrow \tilde{t}_R$$

Expect mixing:

$\tilde{t}_1, \tilde{t}_2$

(mass eigenstates)

SUSY partners: electroweak gauge and higgs bosons

EWK Gauge/Higgs sector of MSSM

Particle	*J*	Degrees of freedom
W^+	1	3
W^-	1	3
Z	1	3
γ	1	2
H	0	1
h	0	1
H^+	0	1
H^-	0	1
A	0	1
Total		16

EWK Gaugino/Higgino basis

Particle	*J*	Degrees of freedom
$\tilde{W}^+$	1/2	2
$\tilde{W}^-$	1/2	2
$\tilde{Z}$ | $\tilde{W}^0$	1/2	2
$\tilde{\gamma}$ | $\tilde{B}$	1/2	2
$\tilde{H}$	1/2	2
$\tilde{h}$	1/2	2
$\tilde{H}^+$	1/2	2
$\tilde{H}^-$	1/2	2
Total		16

Mixing →

EWK Chargino/Neutralino basis

Particle	J	Degrees of freedom
$\tilde{\chi}_1^+$	1/2	2
$\tilde{\chi}_1^-$	1/2	2
$\tilde{\chi}_2^+$	1/2	2
$\tilde{\chi}_2^-$	1/2	2
$\tilde{\chi}_1^0$	1/2	2
$\tilde{\chi}_2^0$	1/2	2
$\tilde{\chi}_3^0$	1/2	2
$\tilde{\chi}_4^0$	1/2	2
Total		16

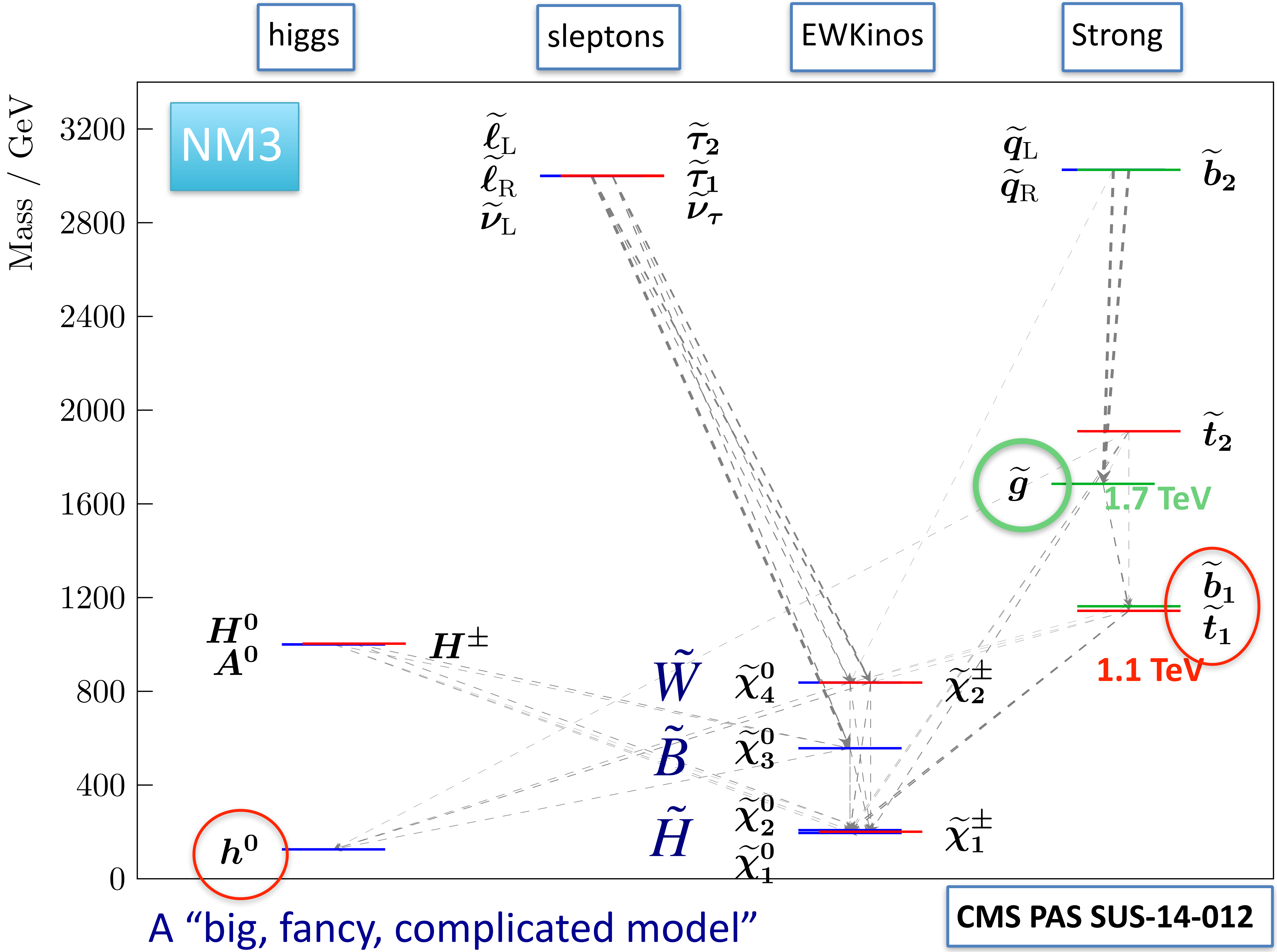
If lightest neutralino is LSP, then can be dark matter candidate.

Generic term for all of the above "Electroweakinos" (EWKinos)

Strong interactions:

$g \ (J = 1,\ M = 0) \ \leftrightarrow \ \tilde{g} \ (J = \frac{1}{2})$

Example: a particle spectrum in the MSSM



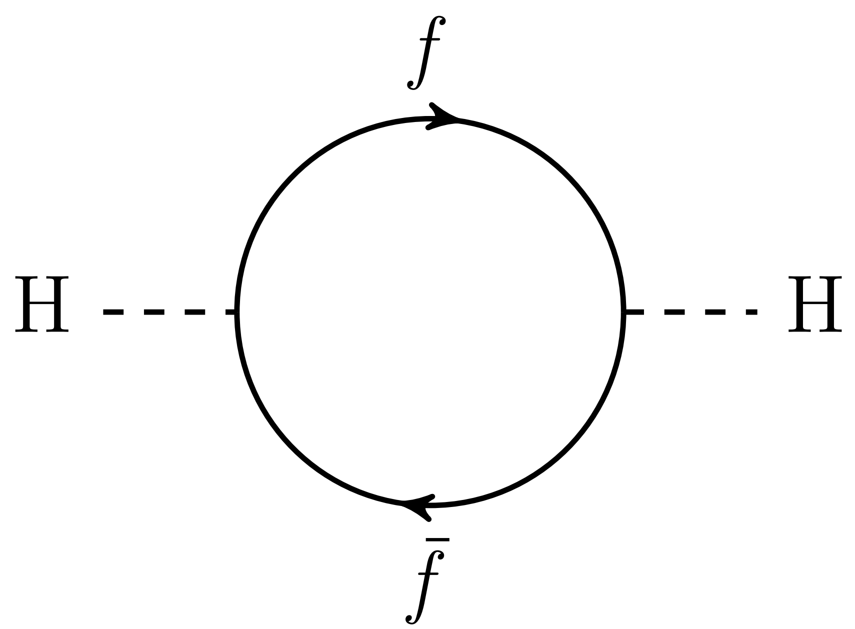
A "big, fancy, complicated model"

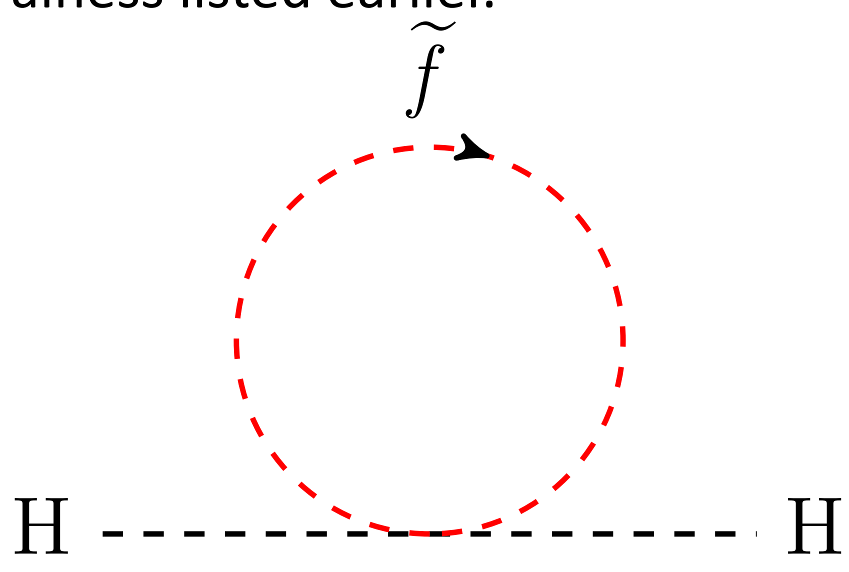
The gauge hierarchy problem and "natural" SUSY

- Evidence is very strong that the new particle discovered at $m \approx 125$ GeV is a/the Higgs boson, $J^{PC} = 0^{++}$ (scalar).
- Assuming it is an elementary scalar particle, the Higgs mass is subject to enormous shifts from quantum-loop corrections.
- These corrections can in principle pull the Higgs mass and the electroweak scale up to the cutoff scale of the SM, e.g., the Planck scale. If no new physics, requires extreme fine tuning between bare Higgs mass and the quantum corrections.
- Understanding the low mass and the stabilization of the electroweak scale is one of the great challenges of particle physics.
- BUT, "fine tuning" is not a completely well-defined concept. How much is too much?

SUSY can (in principle) address the hierarchy problem

C. Bust, A. Katz, S. Lawrence, and R. Sundrum, SUSY, the Third Generation and the LHC, https://arxiv.org/abs/1110.6670 and references on naturalness listed earlier.





$$\delta m_h^2 \approx -\frac{3\lambda_t^2}{8\pi^2}\Lambda^2 + \ldots$$

$$\delta m_h^2 \approx +\frac{3\lambda_t^2}{16\pi^2}\Lambda^2 + \ldots$$

but there are two of these…

$$m_{h_u}^2 = m_{h_u,0}^2 + \frac{3\lambda_t^2}{4\pi^2}(m_t^2 - m_{\tilde{t}}^2)\ln\left(\frac{\Lambda}{m_{\tilde{t}}}\right) + \ldots$$

SUSY particles at the TeV scale can “solve” the fine tuning problem. But current limits on the top squark and gluino masses are putting this picture under stress.

"Natural SUSY endures": still the current fashion

M. Papucci, J.T. Ruderman, and A. Weiler http://arxiv.org/abs/1110.6926

Stabilizing the EW scale in a "natural" way (without excessive fine tuning) involves only a subset of the SUSY spectrum. Which SUSY partners are constrained?

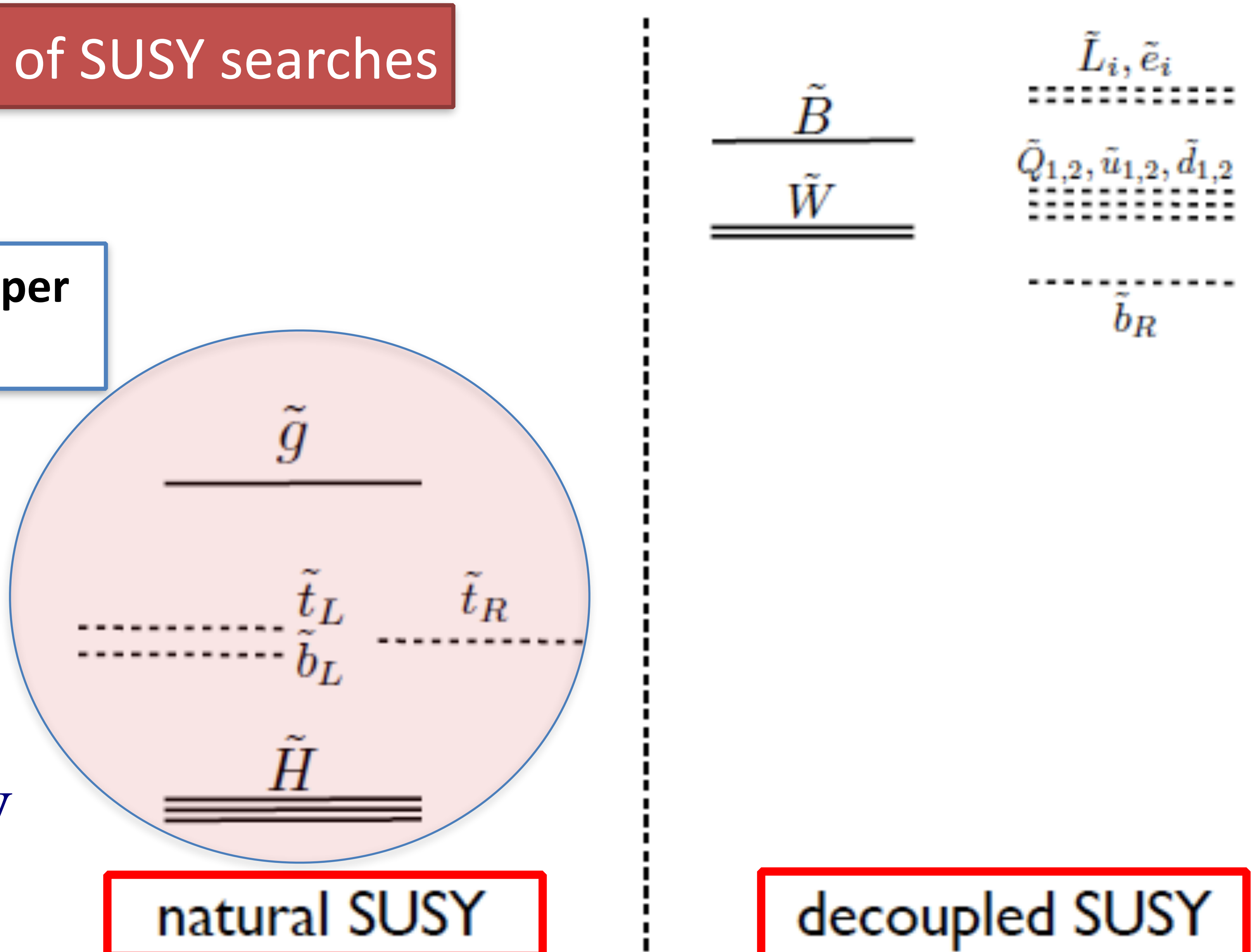
Focus of SUSY searches

Expected mass upper bound (rough):

$m_{\tilde{g}} \approx 2m_{\tilde{t}}$

$m_{\tilde{t}} \approx 400$ GeV

$m_{\tilde{H}} \approx 200$ GeV



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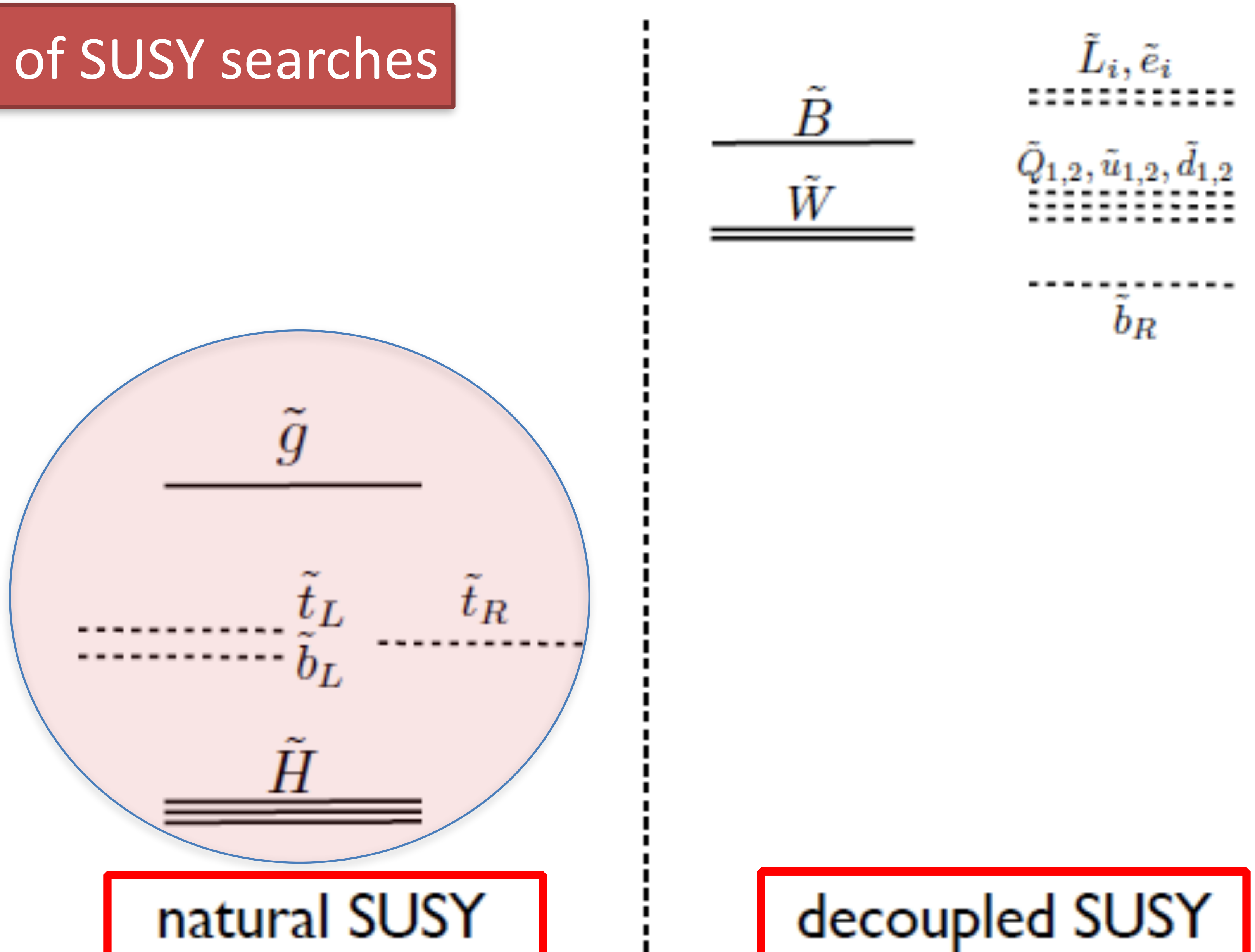
Focus of SUSY searches

The natural SUSY spectrum is well-suited to a treatment in the simplified-model framework.



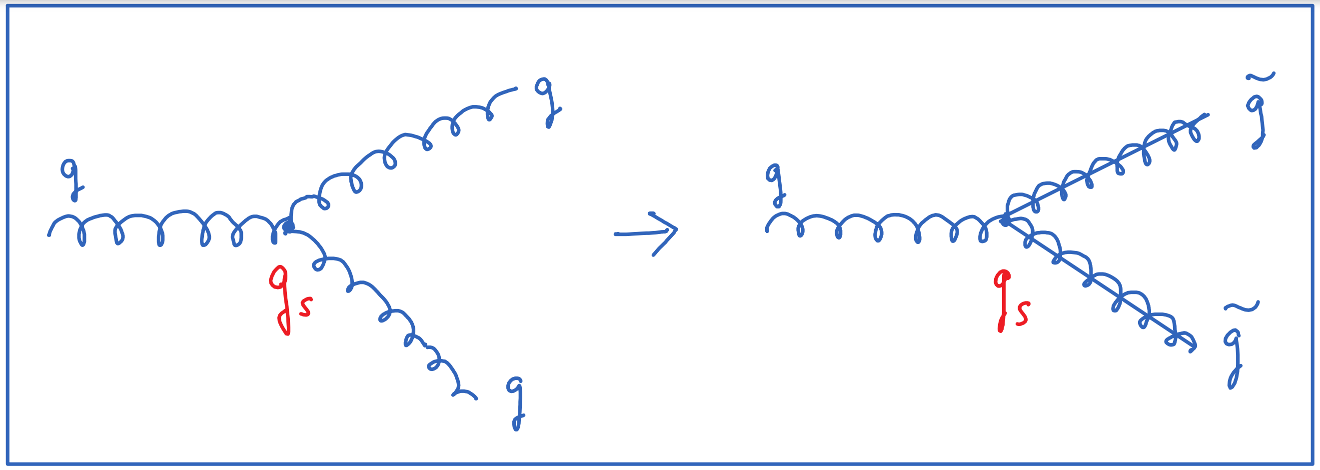
In natural model scenarios, typically assume that some or all these particles are very heavy.

While natural SUSY models are a key focus, we do not restrict ourselves to them.

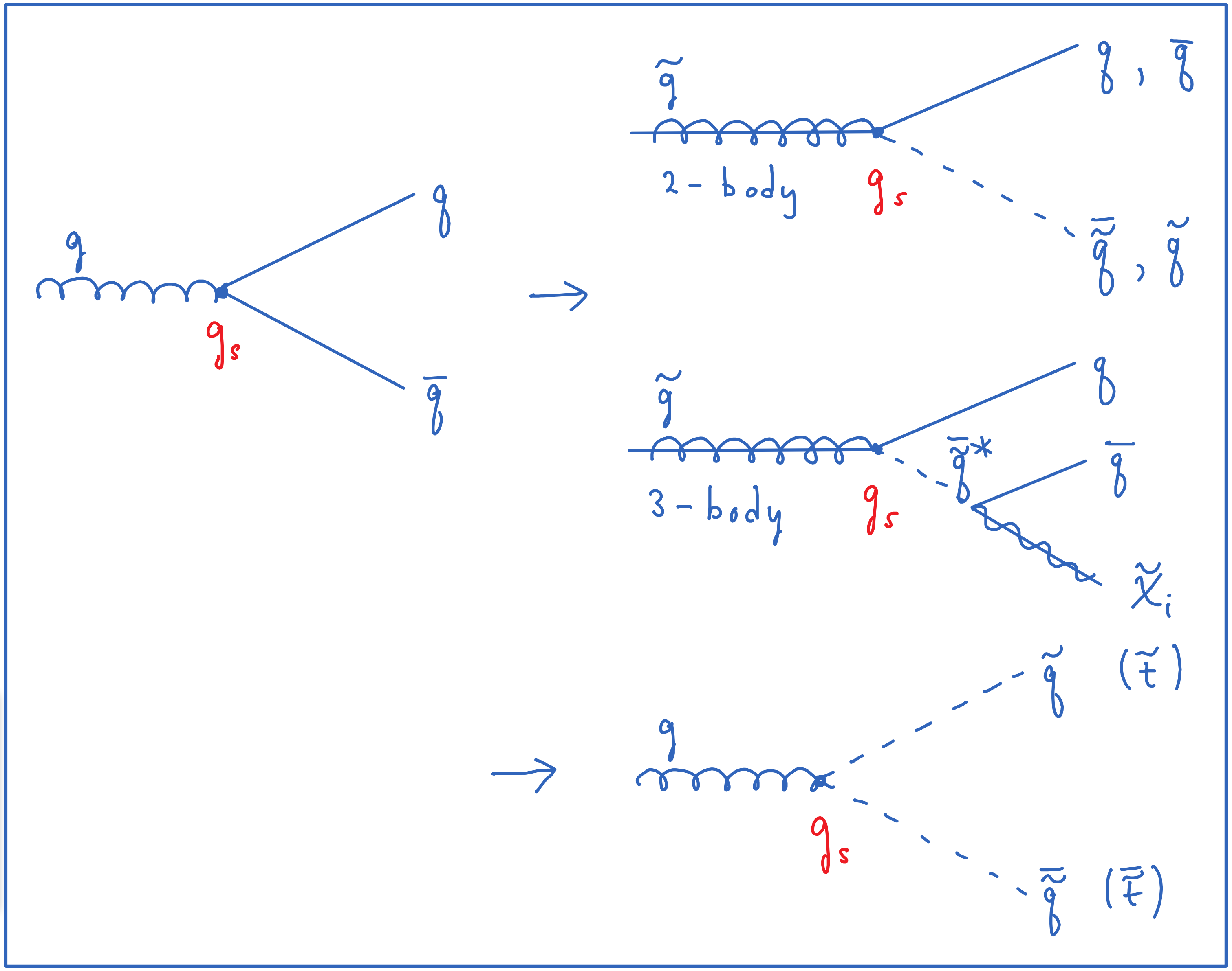
SUSY, gauge couplings, and colored-particle production

SUSY does not change the gauge couplings or gauge representations

Gluino pair production

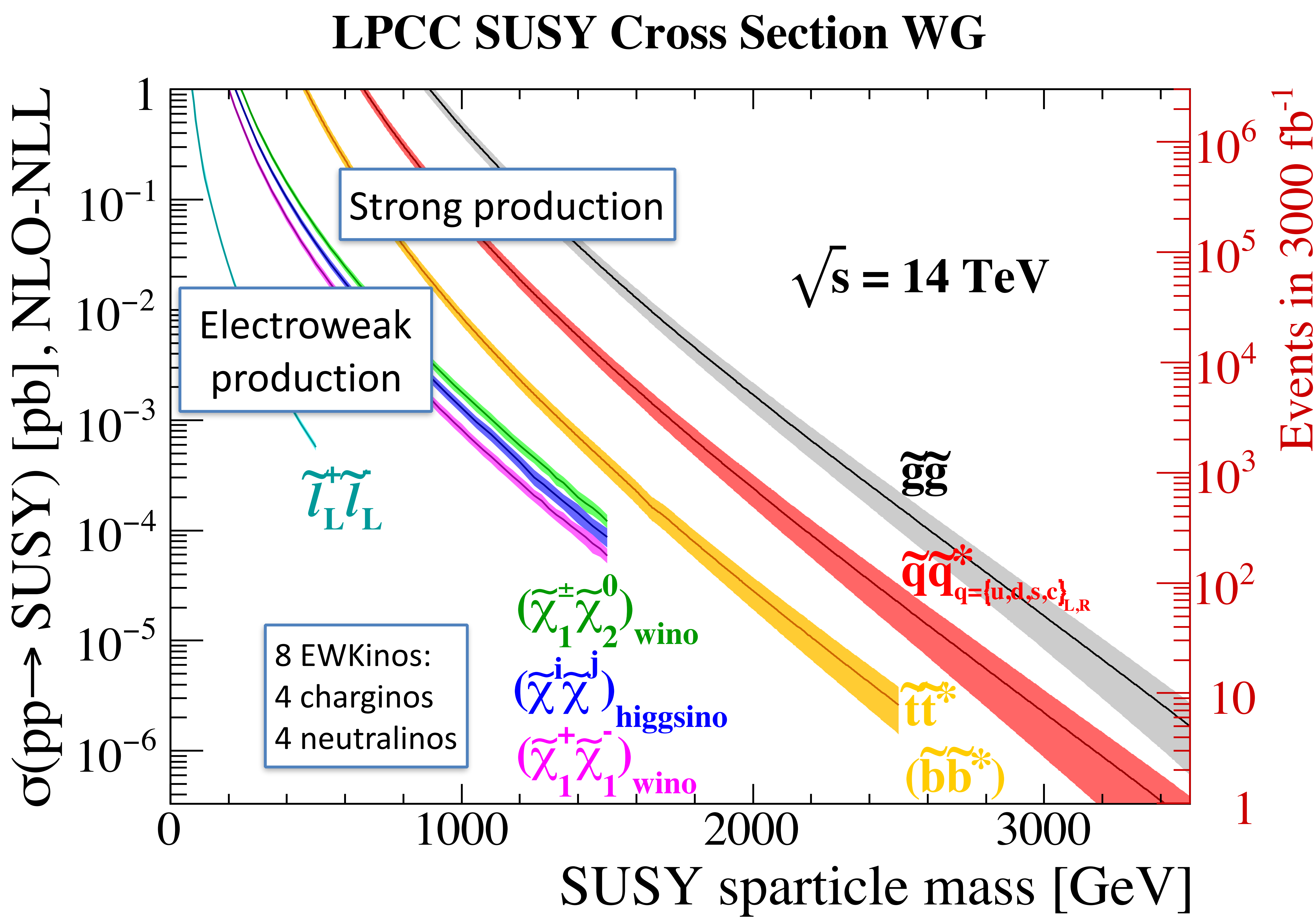


Gluino decay and squark pair production

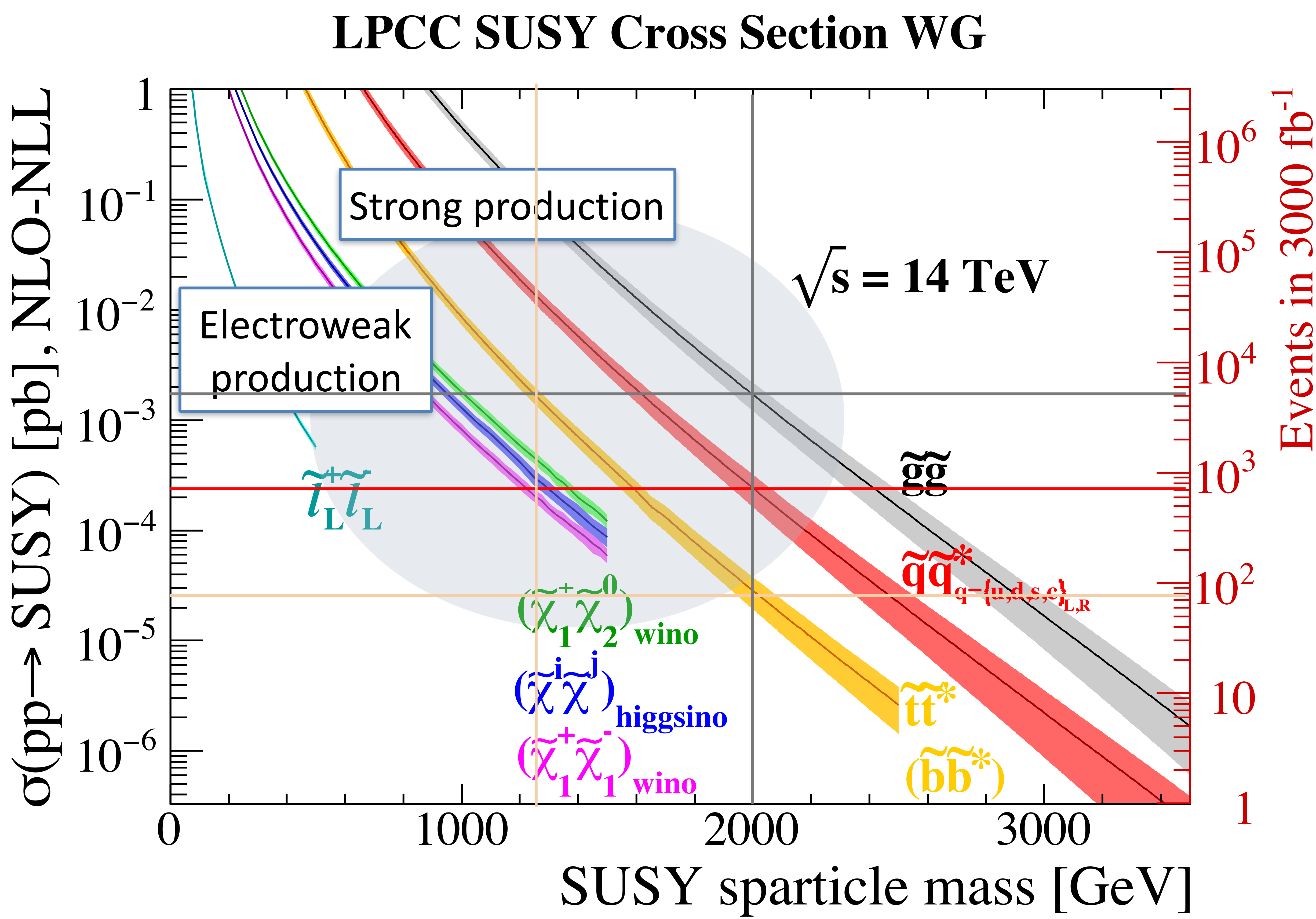


Your physics intuition from the SM mostly works,but have to be careful about spin effects! $J(\tilde{q}) = 0$

SUSY production cross sections



SUSY Production Cross Sections



https://twiki.cern.ch/twiki/bin/view/LHCPhysics arXiv:1407.5066

SUSY event rate example: gluino production

- LHC instantaneous luminosity

$$L \approx 1.5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

- 1 fb = 10^{-15} x 10^{-24} cm^2 = 10^{-39} cm^2

$$L \approx 1.5 \times 10^{-5}\ \mathrm{fb}^{-1}\mathrm{s}^{-1}$$

- 1 yr ≈ π x 10^7 s (less for an operational year)
- Gluino pair production at m($\tilde{g}$)=2 TeV: $\sigma(\tilde{g}\tilde{g}) \approx 2\ \mathrm{fb}$

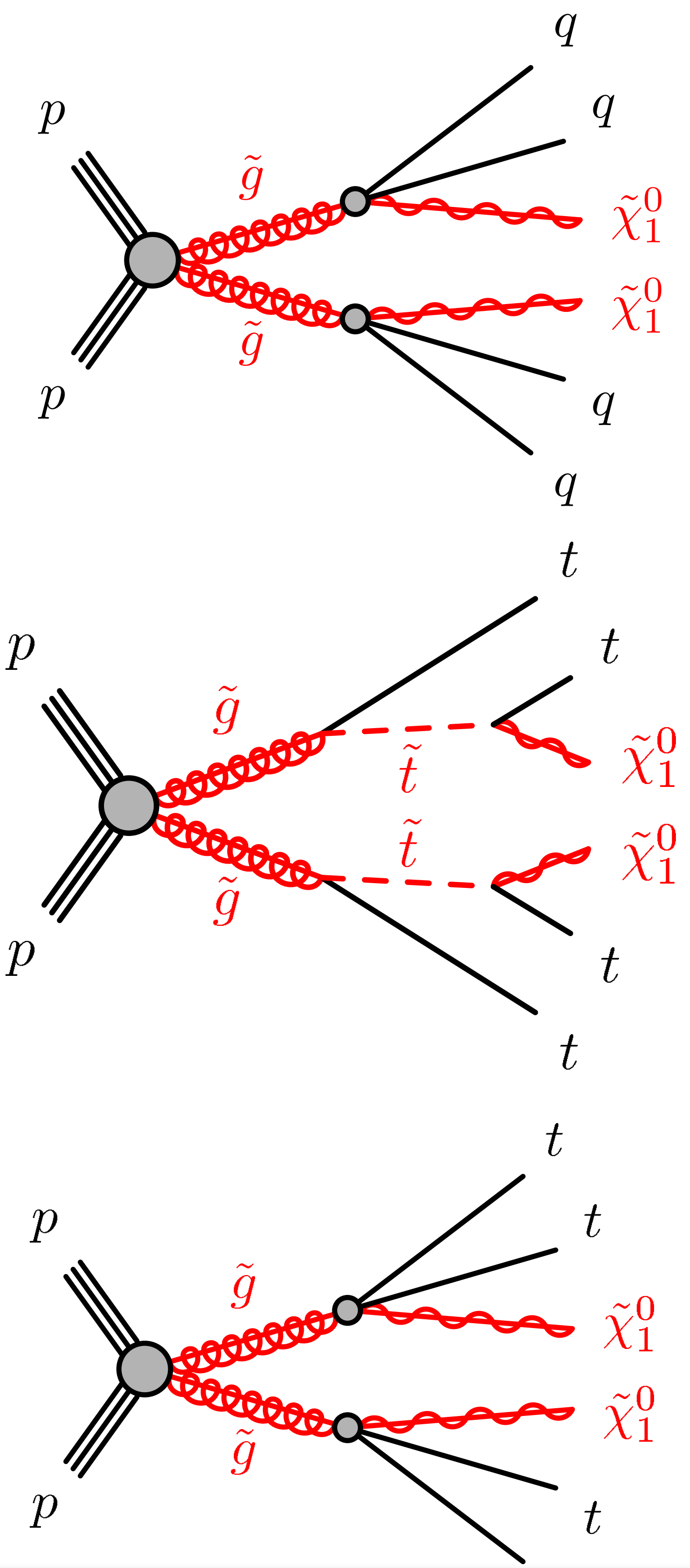
$$N_{\mathrm{evts}} \approx (1.5 \times 10^{-5}\ \mathrm{fb}^{-1}\mathrm{s}^{-1}) \times (2\ \mathrm{fb}) \times (10^{7}\ \mathrm{s}) \approx 300$$ ...produced!

- Total pp cross section: $\sigma(pp) \approx \pi r_{\mathrm{proton}}^2 \approx \pi(10^{-13}\ \mathrm{cm})^2 \approx 30\ \mathrm{mb}$

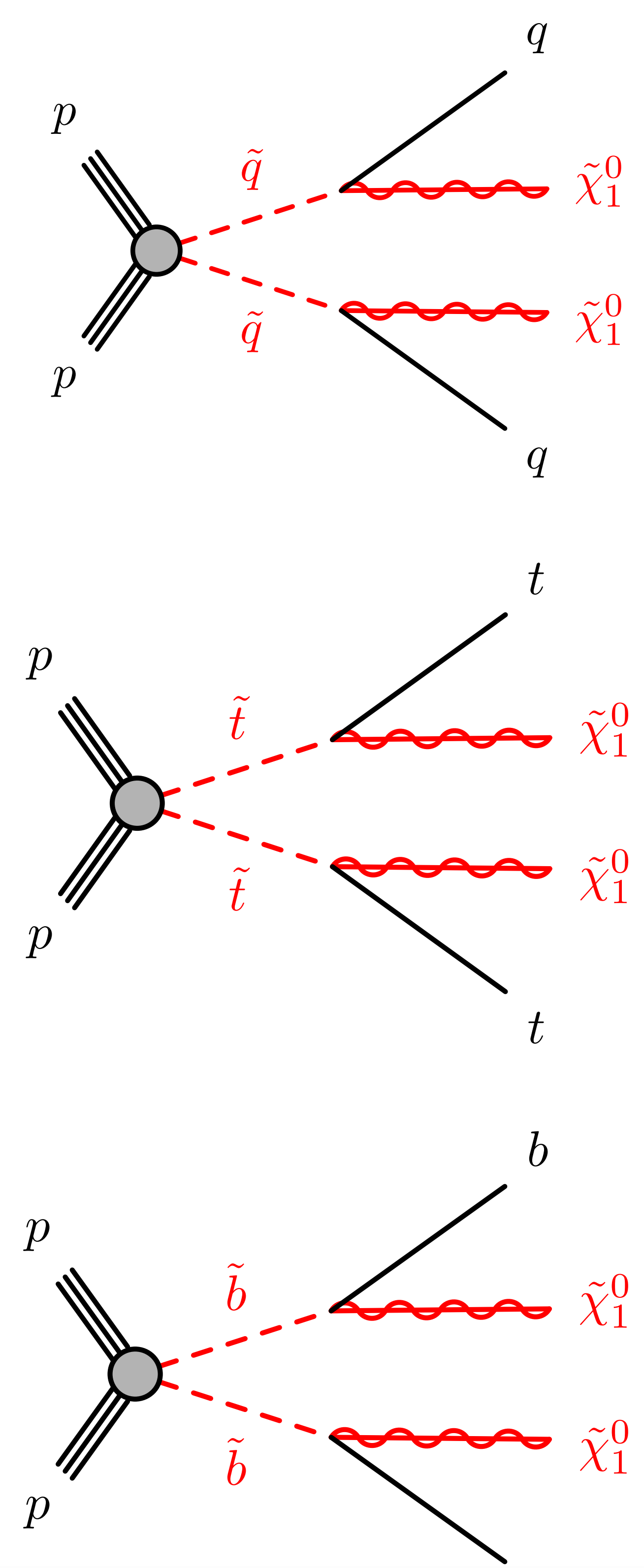
$$N_{\mathrm{evts}} \approx (1.5 \times 10^{-5}\ \mathrm{fb}^{-1}\mathrm{s}^{-1}) \times (30 \times 10^{12}\ \mathrm{fb}) \times 10^{7}\ \mathrm{s} \approx 5 \times 10^{16}$$

Interpreting searches with simplified models

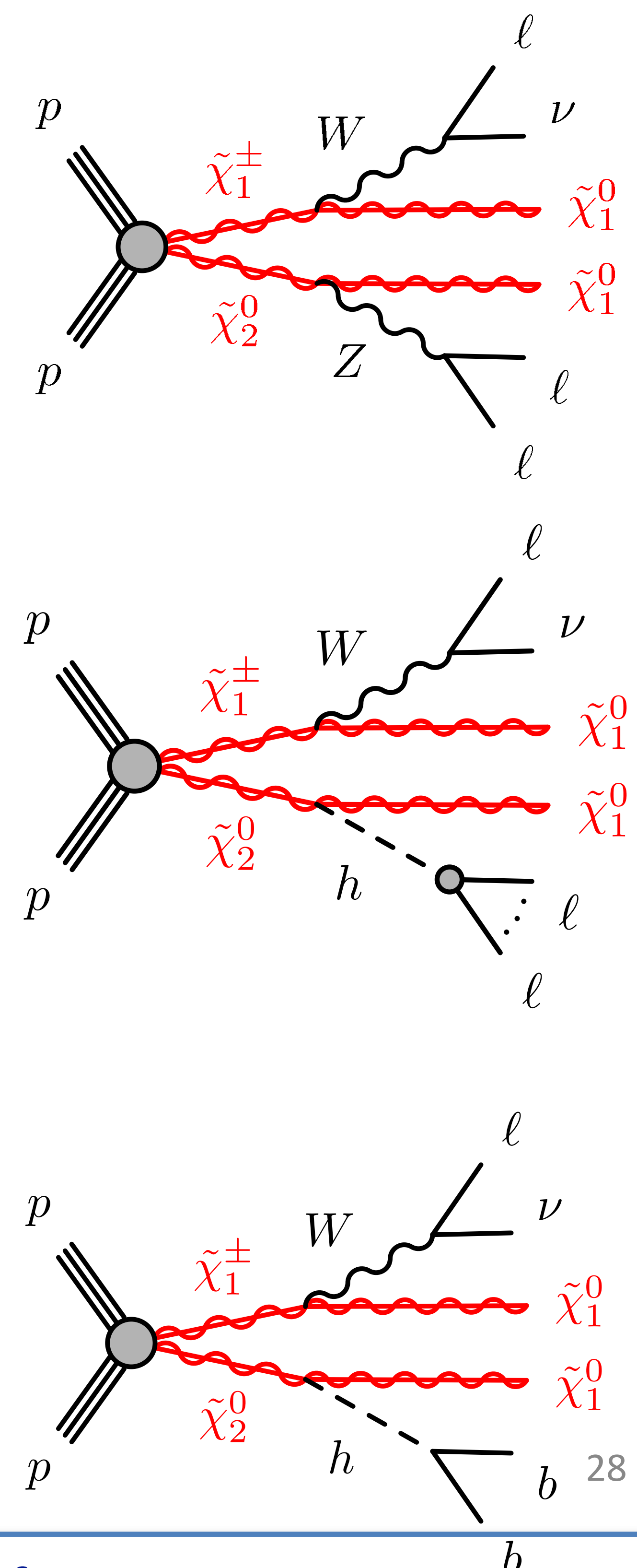
Strong production of gluinos



Strong production of squarks



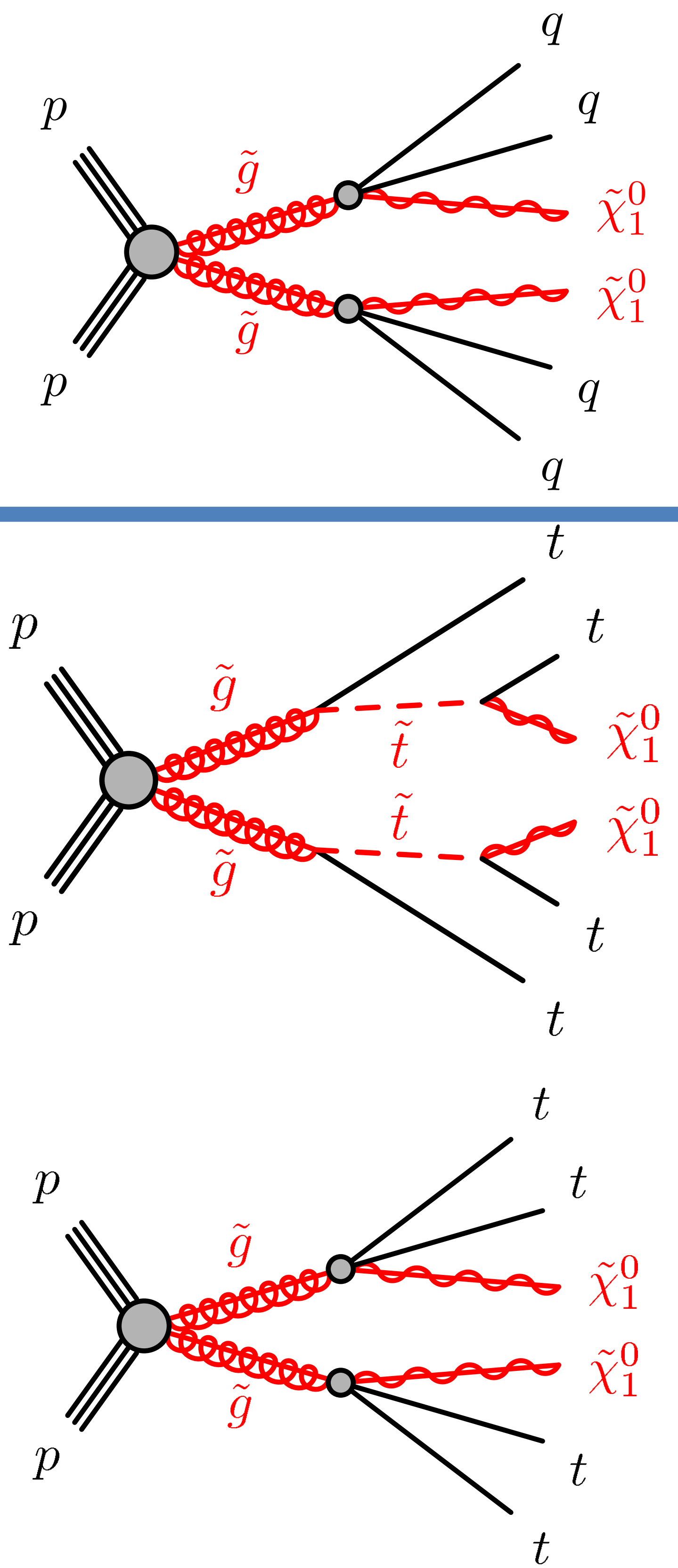
Electroweak production



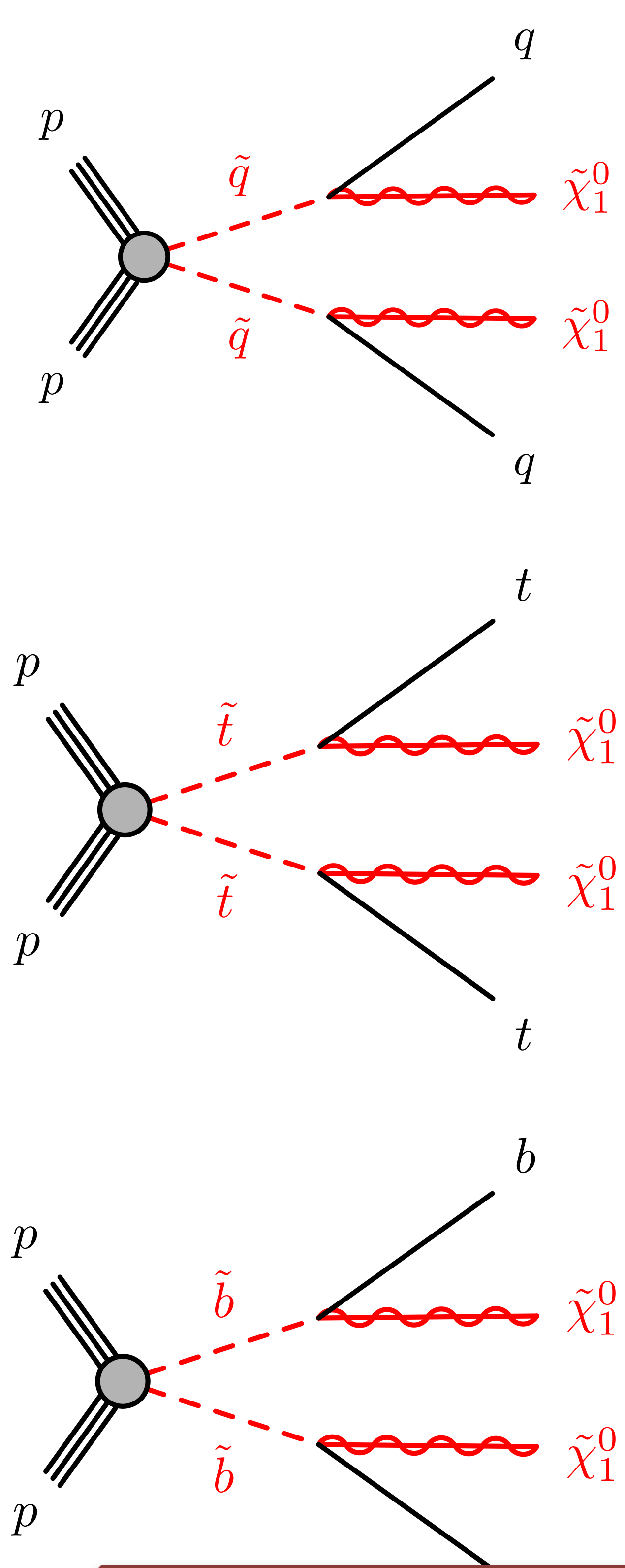
Avoids the SUSY *"curse of many parameters"*: in each case, the number of mass parameters is just 2-3.

Interpreting searches with simplified models

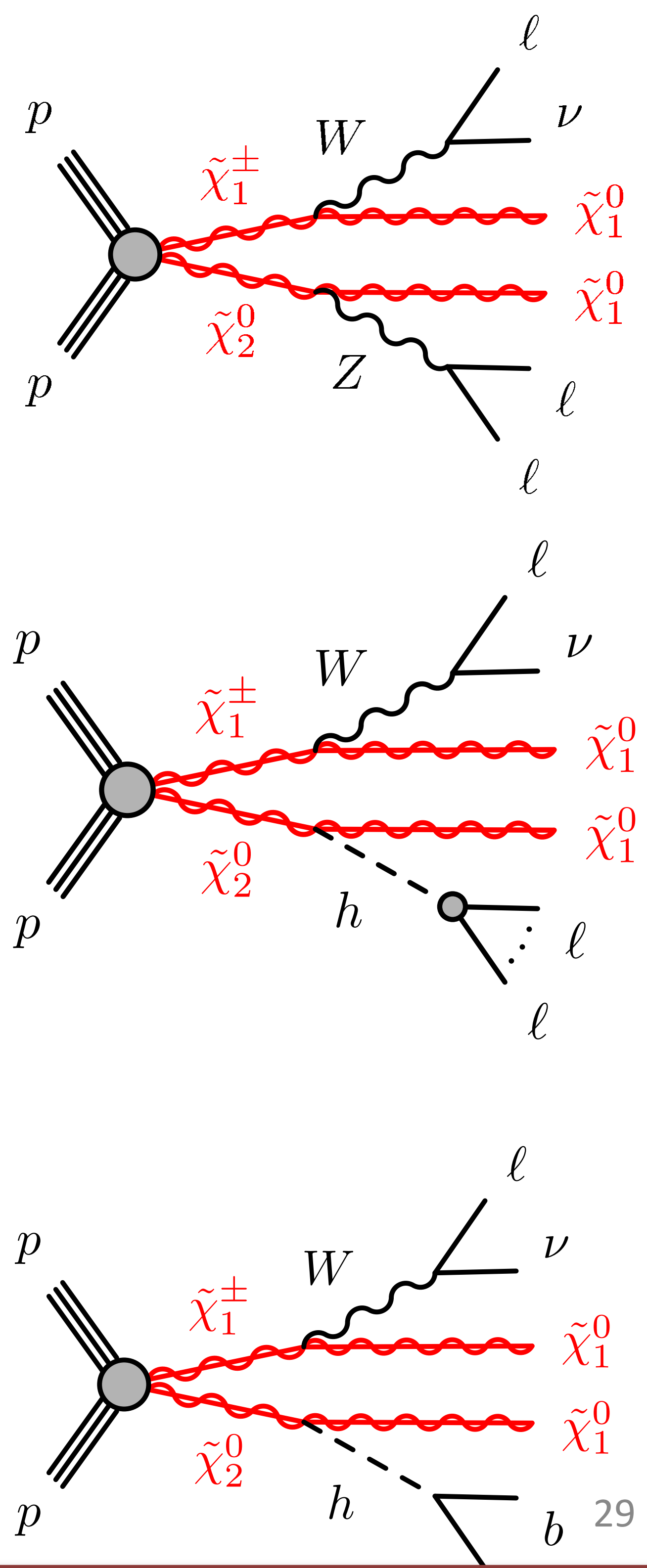
Strong production of gluinos



Strong production of squarks

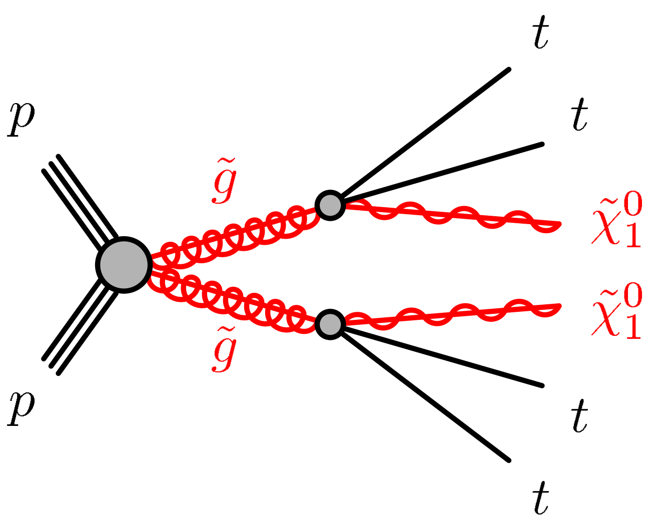


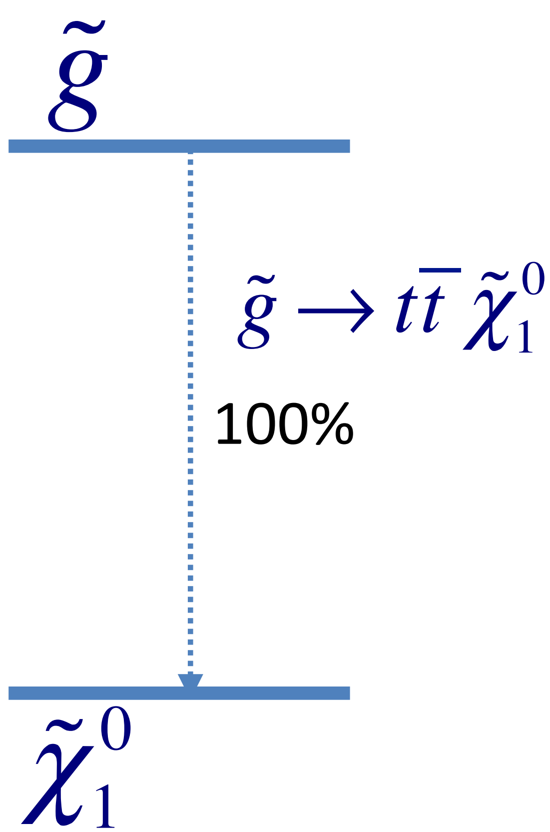
Electroweak Production

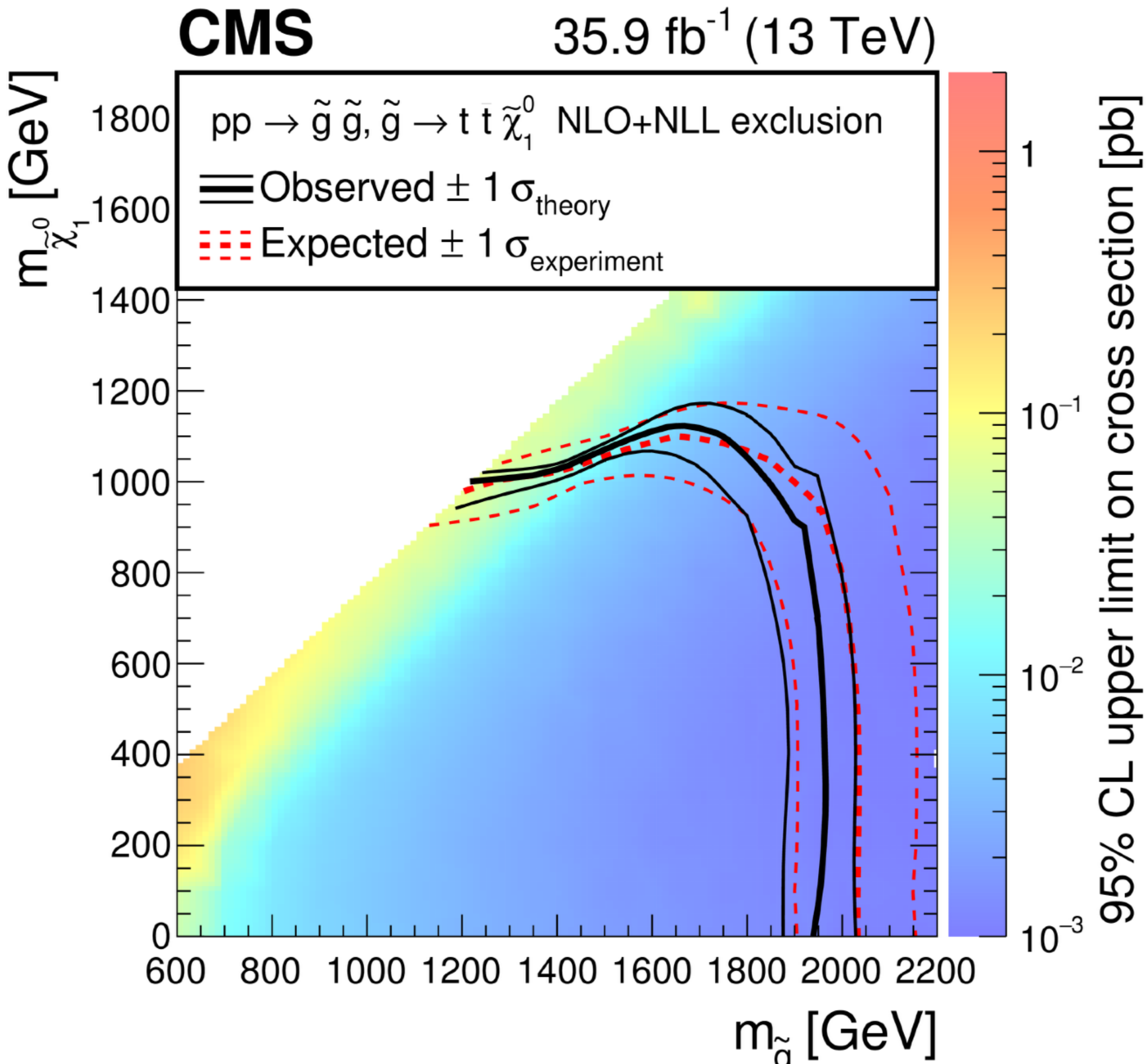


Signature: Large p_T^{miss}, high jet multiplicity, leptons, b-jets

How to read a simplified model exclusion plot

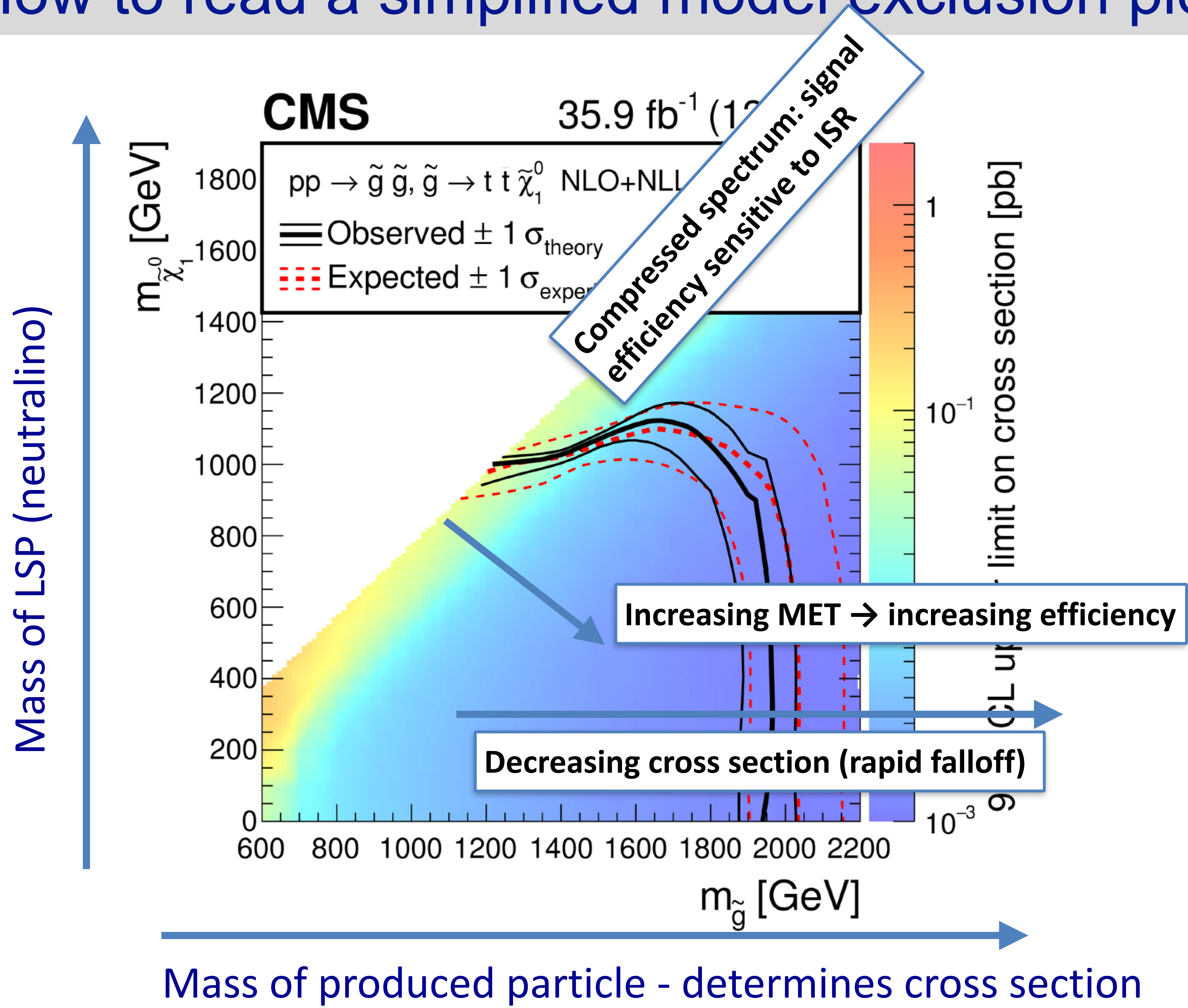




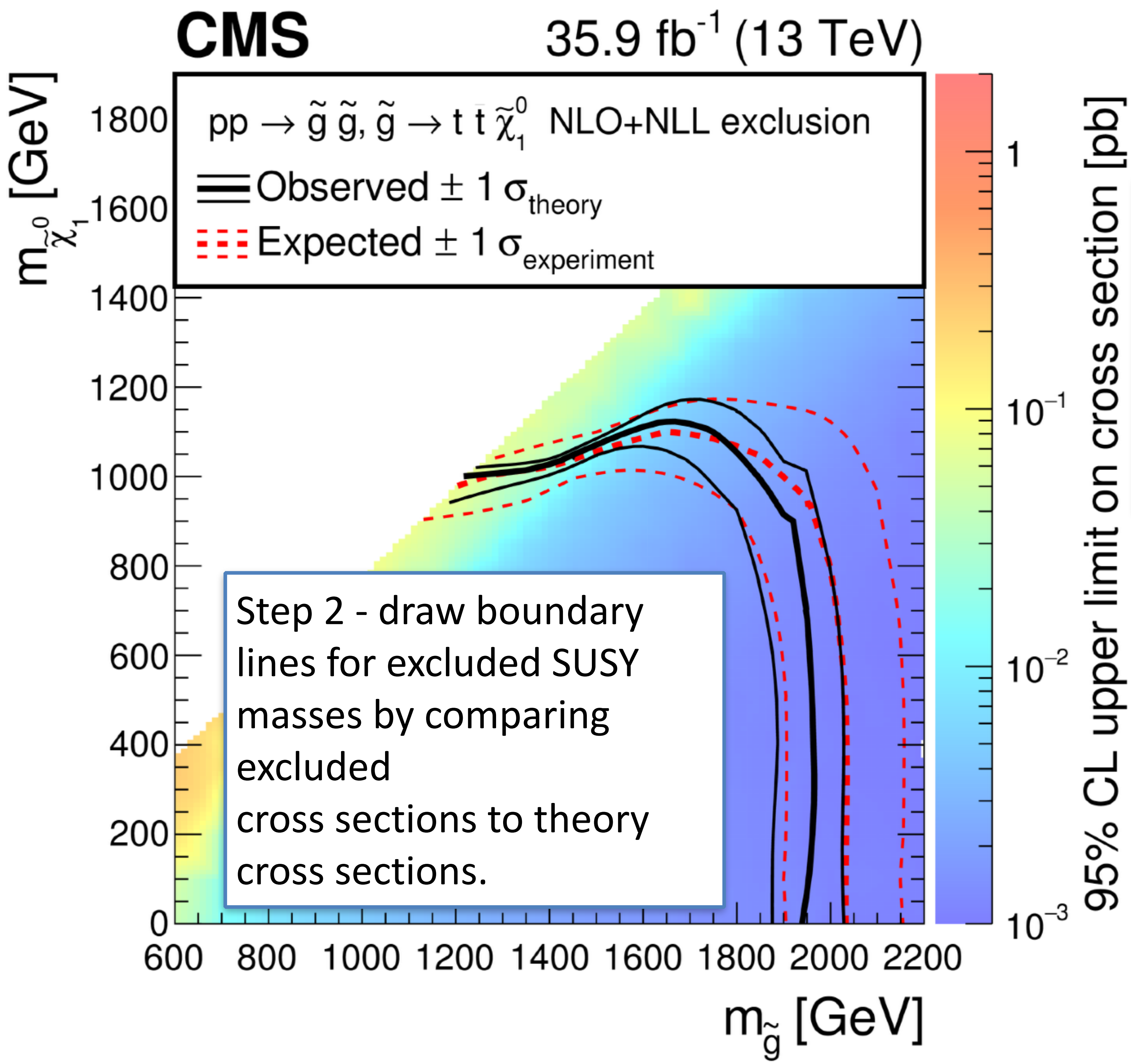


The neutralino produces missing transverse momentum (p_T^{miss} in the event).

How to read a simplified model exclusion plot



How to read a simplified model exclusion plot



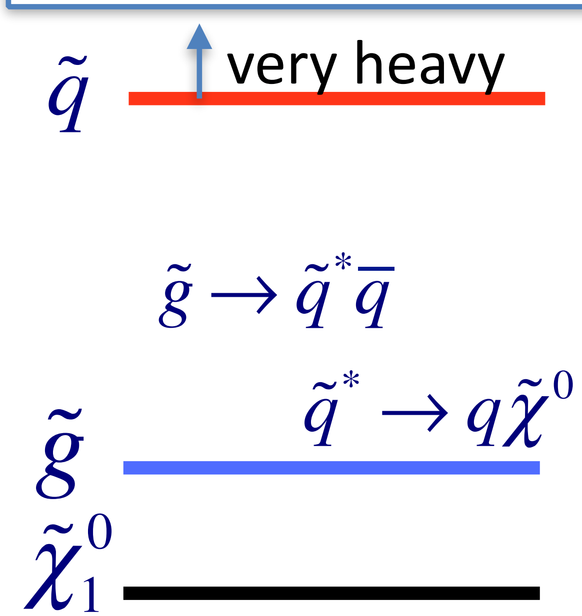
Step 1 - compute upper limit on the signal cross section for each point in SUSY model space.

Step 2 - draw boundary lines for excluded SUSY masses by comparing excluded cross sections to theory cross sections.

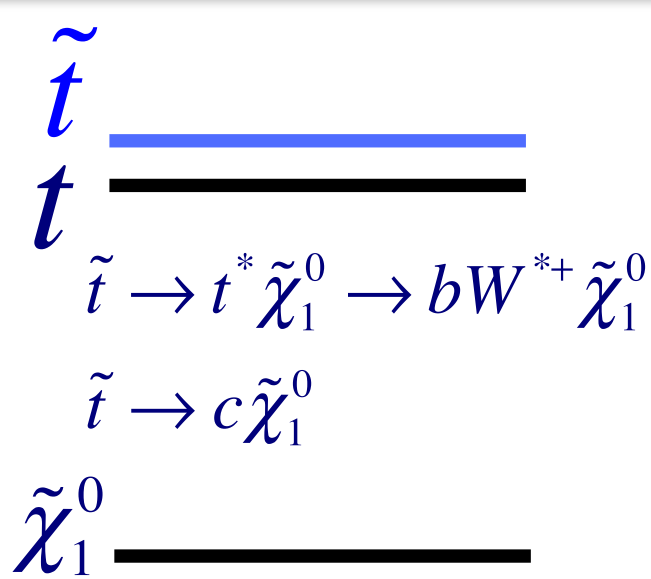
Challenges of SUSY searches at the LHC (I)

1. The SUSY parameter space is enormous. MSSM: 124 parameters.
   - Many scenarios, with diverse mass spectra and kinematics
   - Complicates analysis design & interpretation
2. Experimental signatures are usually “weak” (no mass peaks) and involve studies of the extreme tails of SM distributions, such as p_T^{miss} (formerly known as MET).
3. Cross sections are small relative to those of the SM backgrounds.

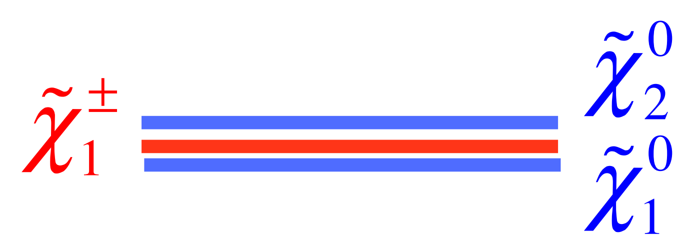
“split SUSY” spectrum



difficult top squark decay scenarios



degenerate Higgsinos in natural SUSY



- Low electroweak prod. cross section
- Very soft decay products & low p_T^{miss}

A Holy Grail search

Challenges of SUSY searches at the LHC (II)

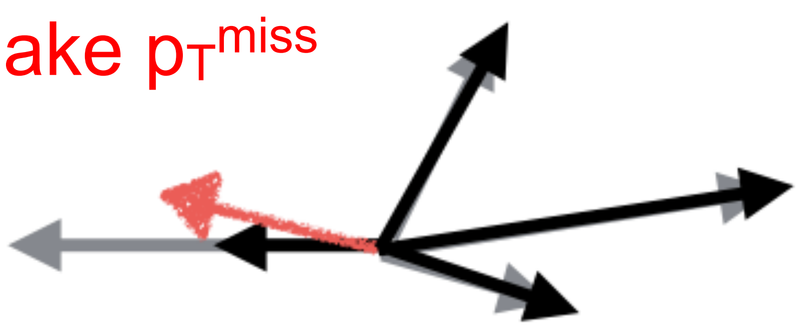
4. Monte Carlo simulations for SM backgrounds are amazingly good but cannot in general be trusted to correctly model extreme tails of kinematic distributions.
5. Need to determine uncertainties on background estimates.
6. Detector problems → fake p_T^{miss}, fake leptons, fake b-jets,…
7. SM backgrounds can produce events with large, genuine p_T^{mis}

Jet mis-measurement can produce fake p_T^{miss}, so QCD multijets events can be important background.

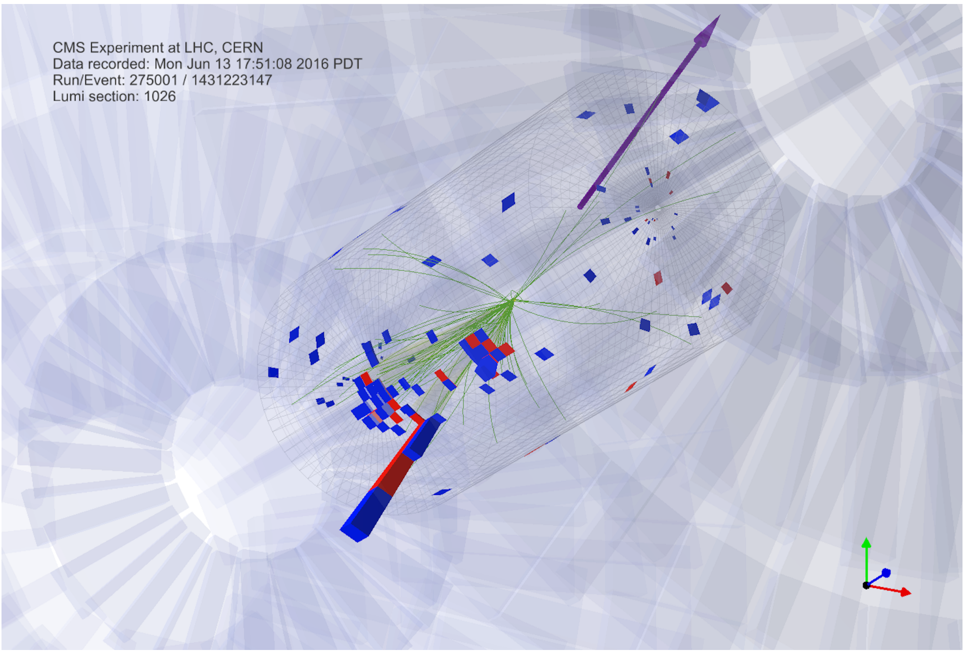
Neutrinos from $Z \rightarrow \nu\bar{\nu}$ + additional jets from ISR

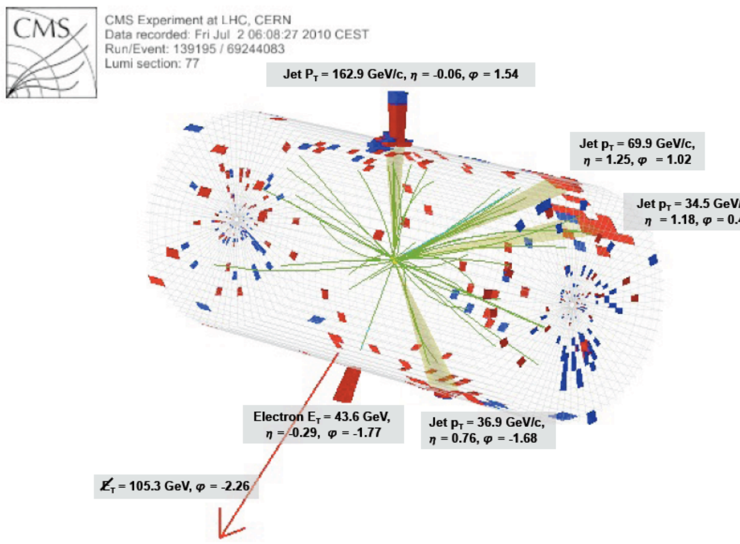
ttbar and W+jet events have p_T^{miss} from neutrinos

Fake p_T^{miss}

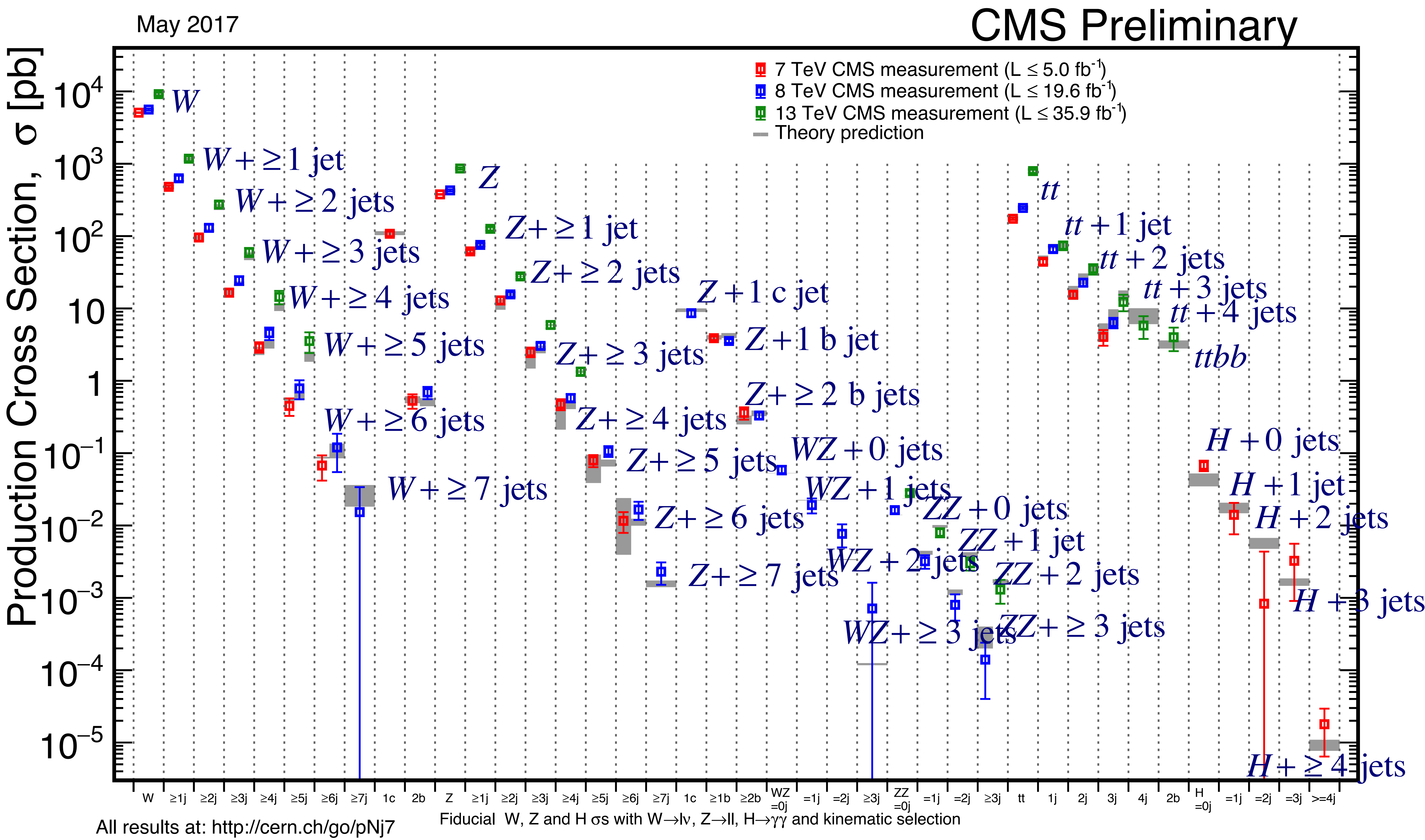


Gray: true jet p_T, **Black: meas. p_T**

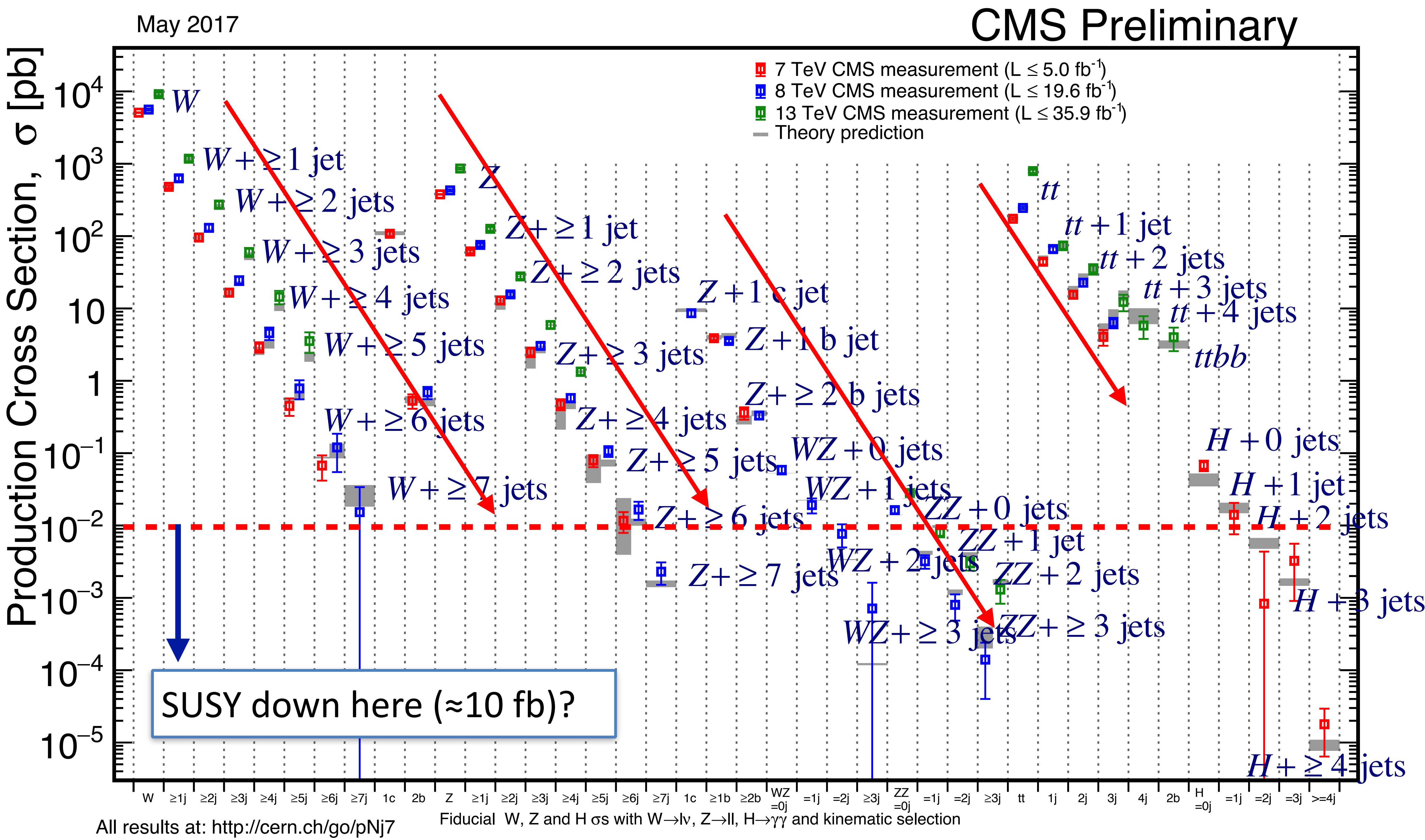




Mapping the standard model: the foundation of searches



Mapping the standard model: the foundation of searches

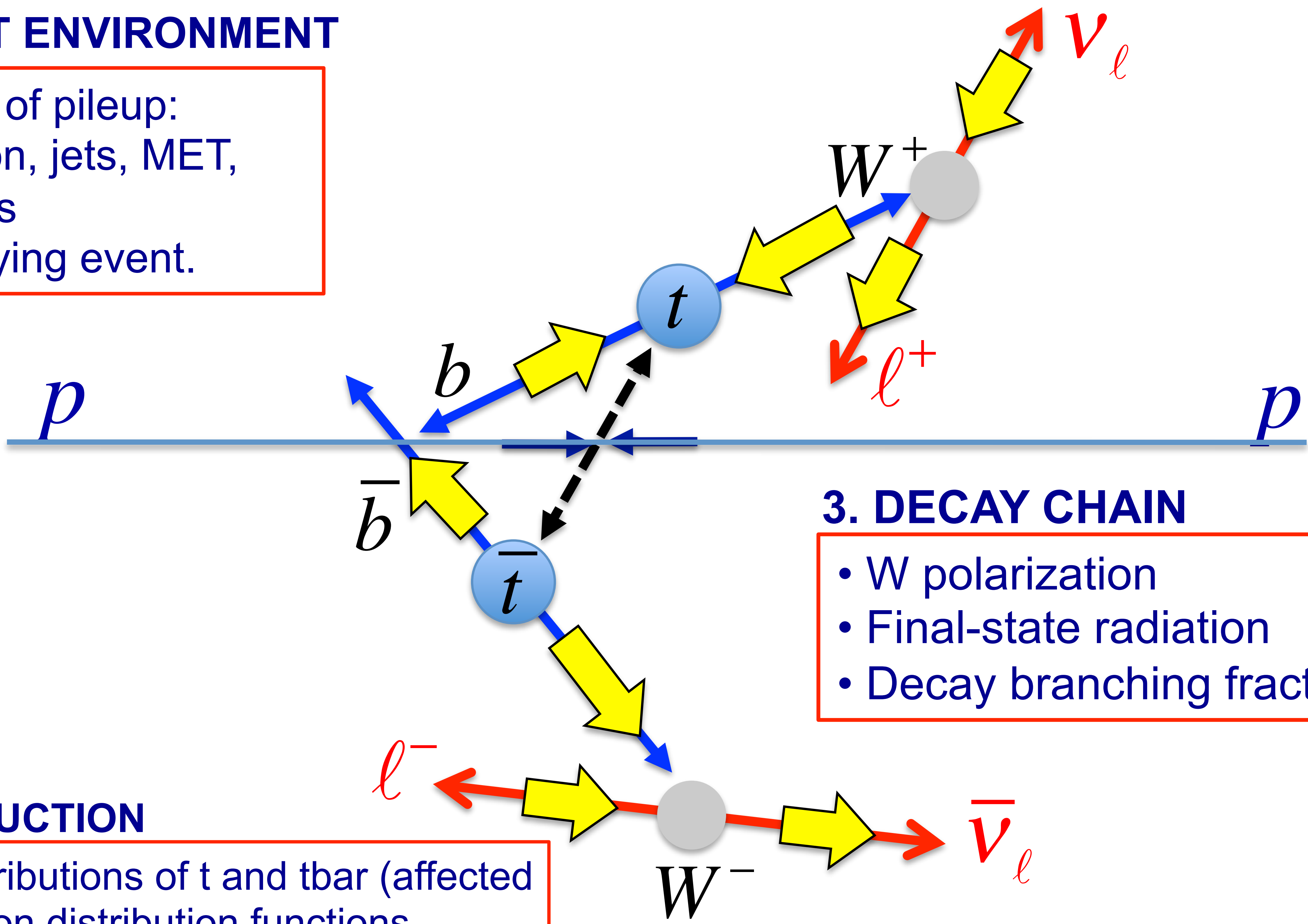


Foundations of a SUSY search: (1) understand your detector and (2) understand your backgrounds

The most SUSY-like SM background: ttbar

1. EVENT ENVIRONMENT

- Effects of pileup: isolation, jets, MET, vertices
- Underlying event.



3. DECAY CHAIN

- W polarization
- Final-state radiation
- Decay branching fractions

2. PRODUCTION

- pT distributions of t and tbar (affected by parton distribution functions, QCD renorm & factorization scales)
- Effect of initial-state radiation
- Spin correlations of t and tbar

Challenges of SUSY searches at the LHC (III)

8. If you didn't trigger on it, it didn't happen."

- Early step of any analysis: do you have triggers for your signal? Can you measure your trigger efficiency?
- Why it matters: the harsh reality of life at a hadron collider.

  pp interaction rate (hundreds of MHz)

  L1 trigger rate (100 kHZ)

  HLT rate - recorded (1 kHZ)

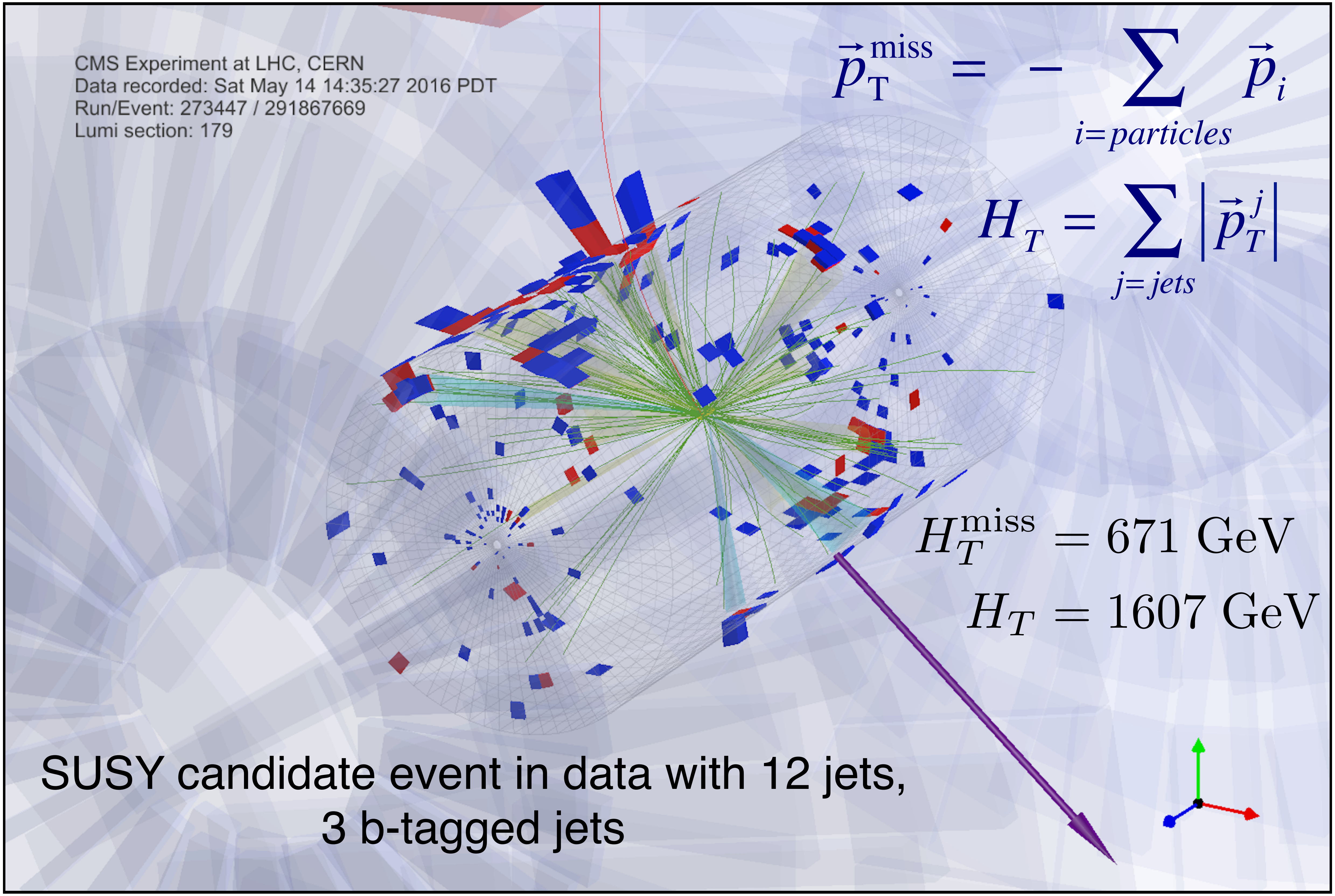
- Tough, macho experimentalist's attitude: "SUSY is mainly useful to me because it provides a lot of ideas for signatures. SUSY is a 'signature generator' to help me think of triggers for signatures that might be useful."

Quick look at three example SUSY searches

Signature	Scenarios	Dominant backgrounds	Background determination
All hadronic: Jets + p_T^{miss} Inclusive, heavily binned, search targets broad range of strongly produced SUSY	**More inclusive: addresses wider range of SUSY scenarios.**	**More inclusive: wider range of backgrounds to understand.**	**More inclusive: search regions span broader range → more reliance on MC for background estimation.**
1 lepton + (b)-Jets + p_T^{miss} Targets strongly produced natural SUSY with higher jet multiplicity			
HH + p_T^{miss}; H→ bb Targets electroweak production of higginos in gauge-mediated SUSY breaking models	**More specific: better sensitivity to targeted process.**	**More specific: limited set of backgrounds.**	**More specific: less dependence on MC for background estimation.**

More control samples → more ways to find problems that you didn't even think of!

Jets + p_T^{miss} search: candidate event



$$\vec{p}_T^{\text{miss}} = -\sum_{i=particles} \vec{p}_i$$

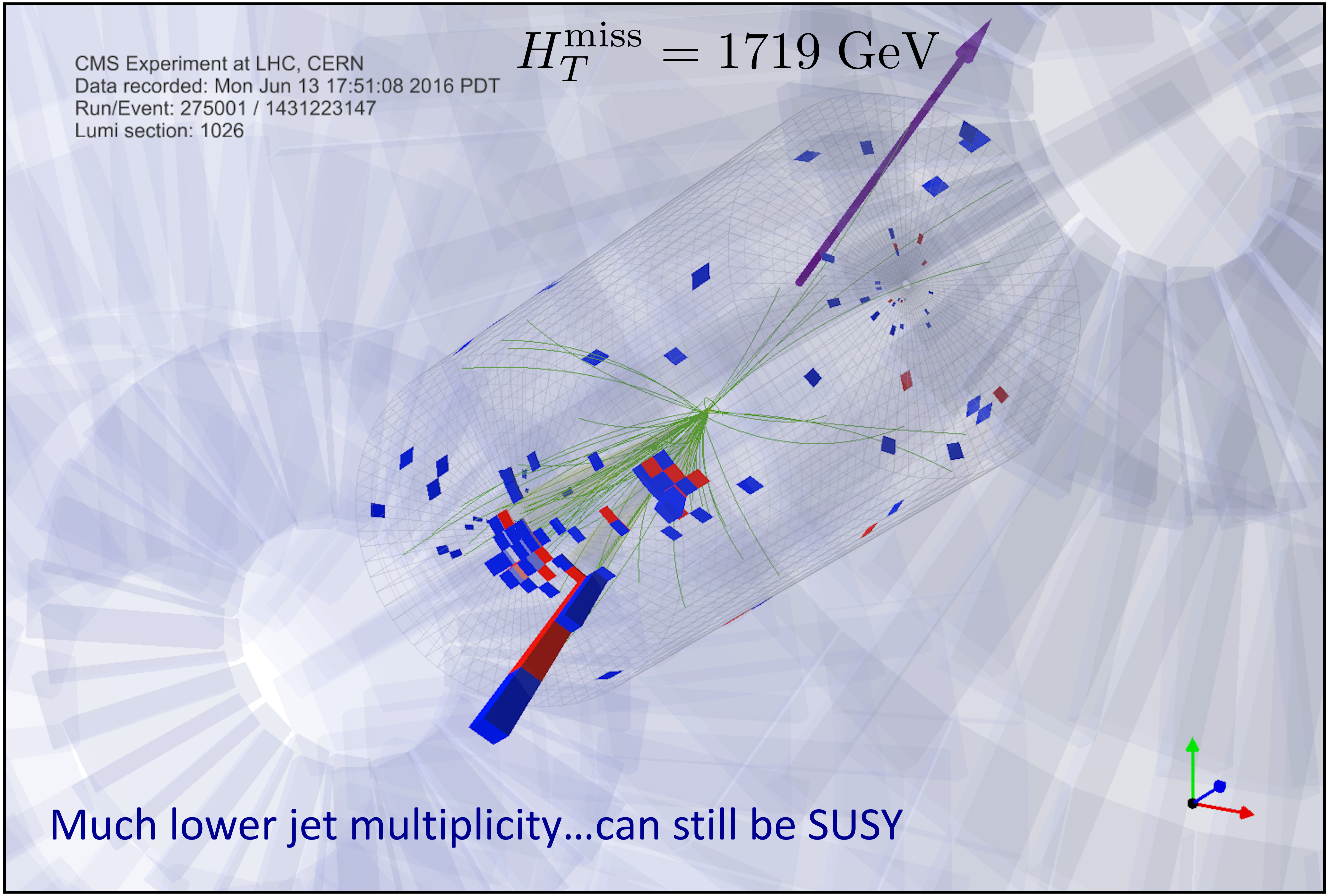
$$H_T = \sum_{j=jets} \left|\vec{p}_T^{\,j}\right|$$

$$H_T^{\text{miss}} = 671 \text{ GeV}$$

$$H_T = 1607 \text{ GeV}$$

SUSY candidate event in data with 12 jets,
3 b-tagged jets

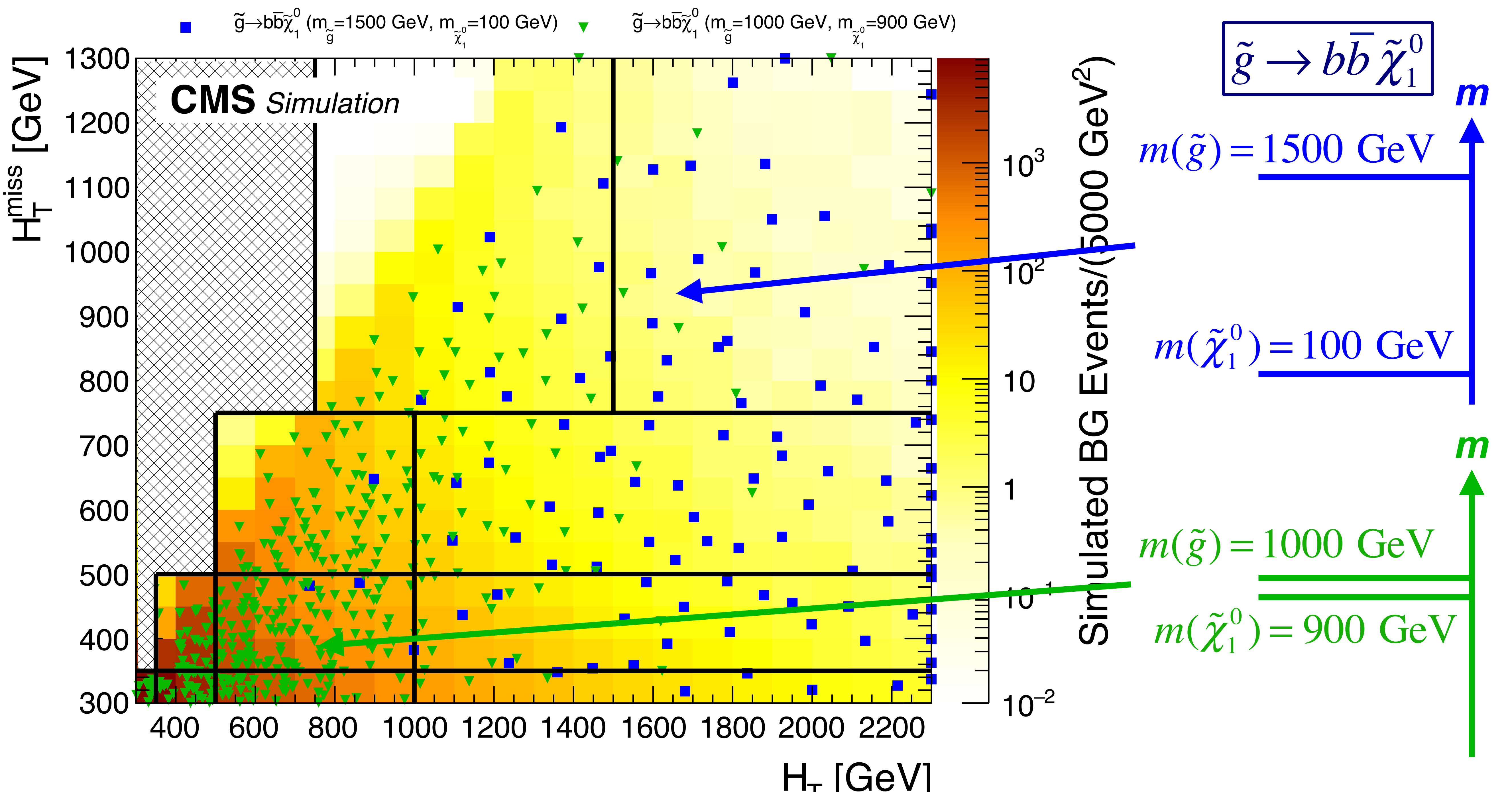
Jets + p_T^{miss} search: candidate event



Jets + p_T^{miss} search: Many analysis regions

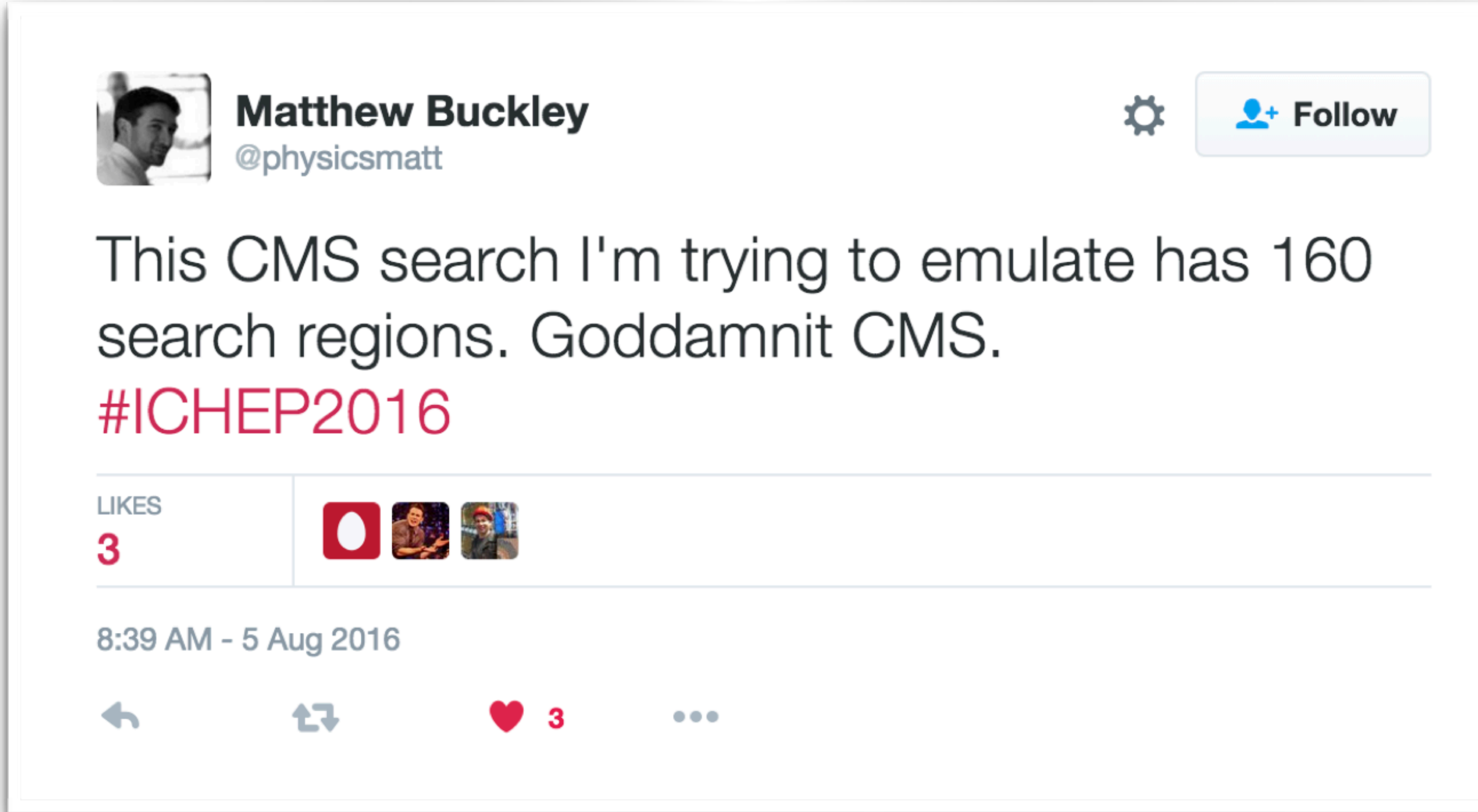
https://arxiv.org/abs/1704.07781

1. Require $N_{jets} \geq 2$ ($p_T > 30$ GeV)
2. Bin the data in four variables: N_{jets}, $N_{b\text{-jets}}$, H_T, H_T^{miss}



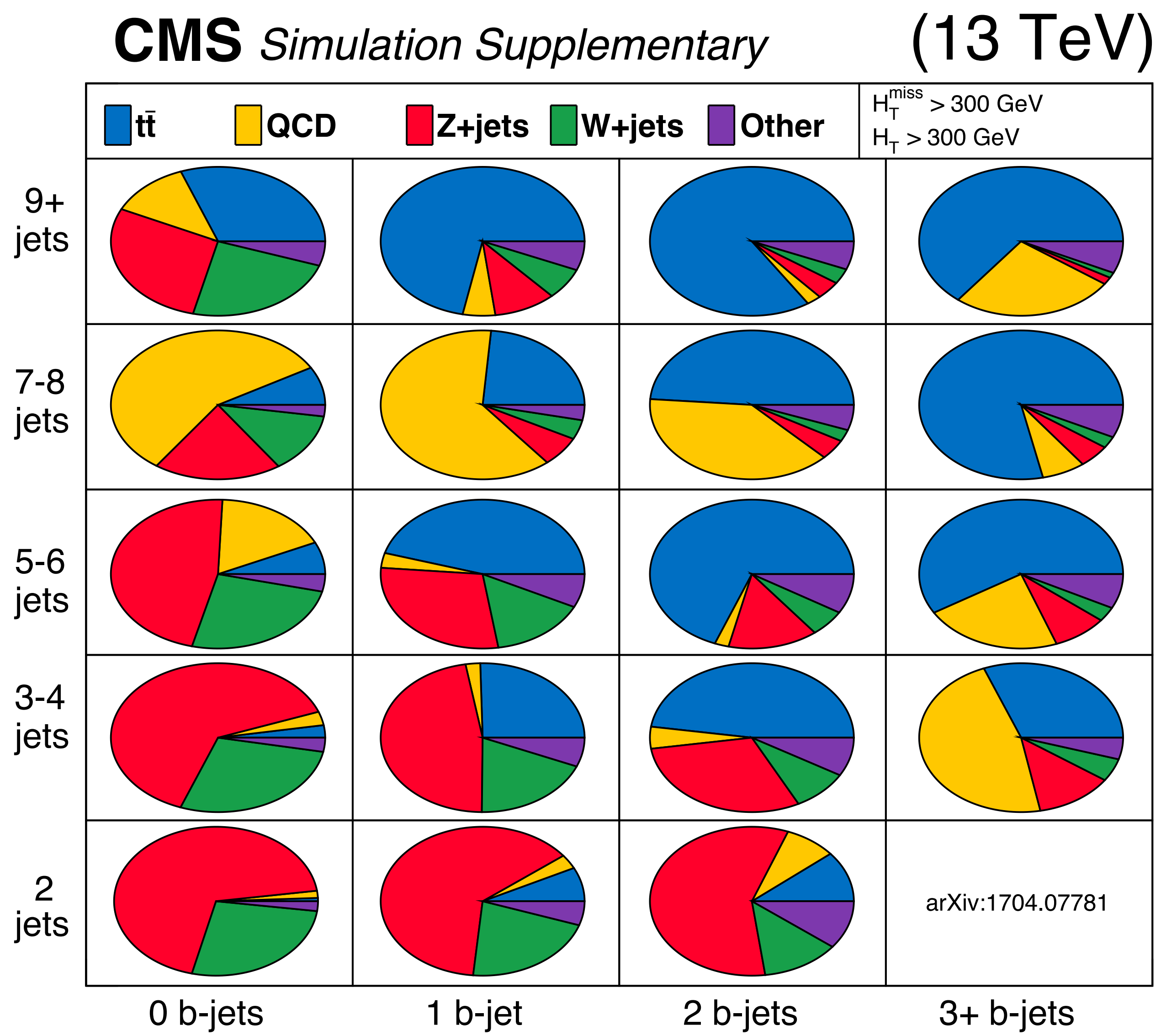
$4(N_{\text{jet}}\text{ bins}) \times 4(N_{\text{b-jet}}\text{ bins}) \times 10(H_T,\ H_T^{\text{miss}}\text{ bins}) = 160$ independent search regions

Jets + p_T^{miss} search: commentary from a theorist

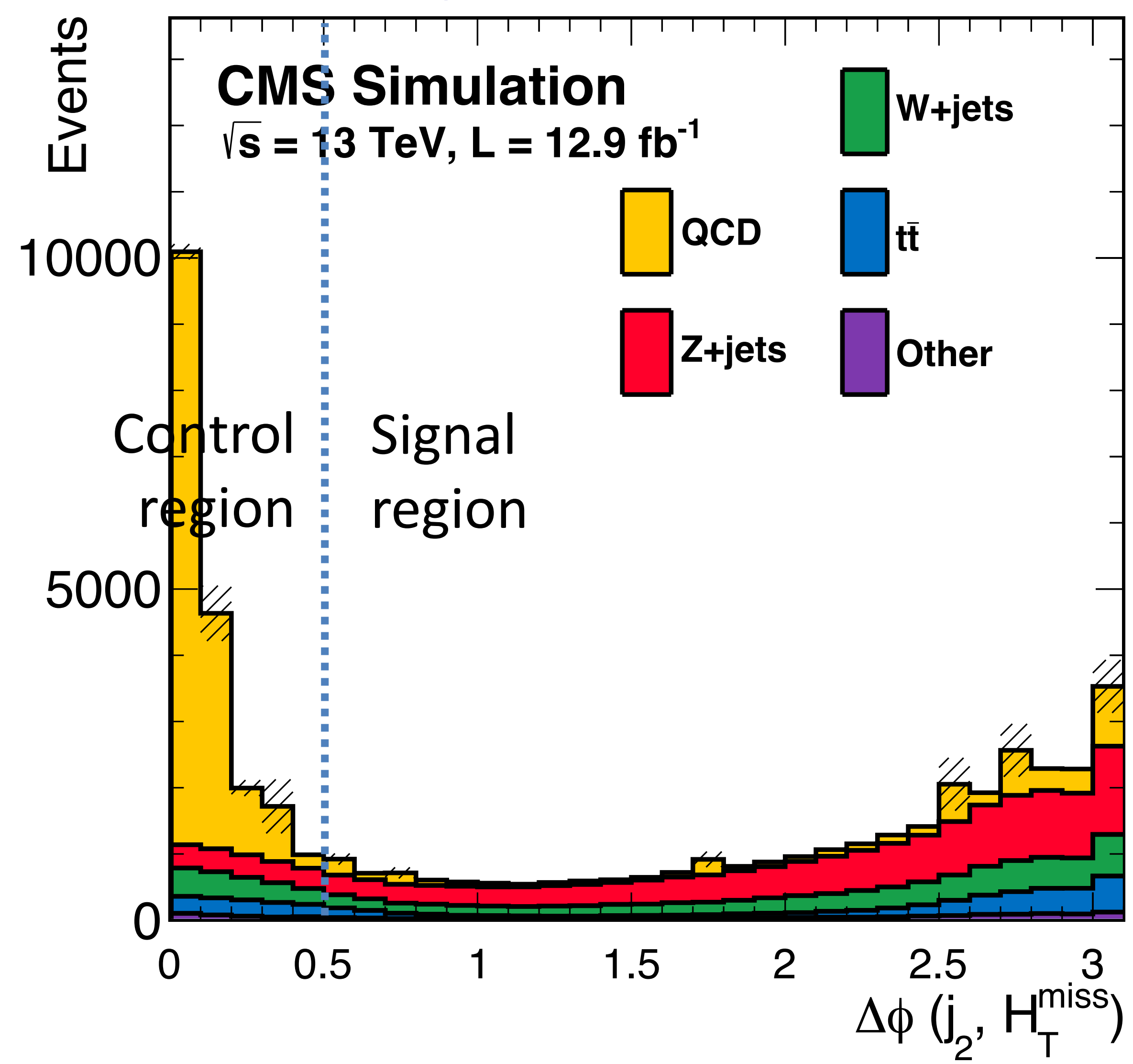


Our answer: you will find results for “aggregated search regions” (12 bins) in the paper!

Jets + p_T^{miss} search: background composition



QCD background estimation method



Background composition varies significantly across the analysis bins:

- High jet and b-jet multiplicity → ttbar
- Lower jet and b-jet multiplicity→ Z + jets

Veto events if any of the four highest p_T jets is aligned with the p_T^{miss} vector:

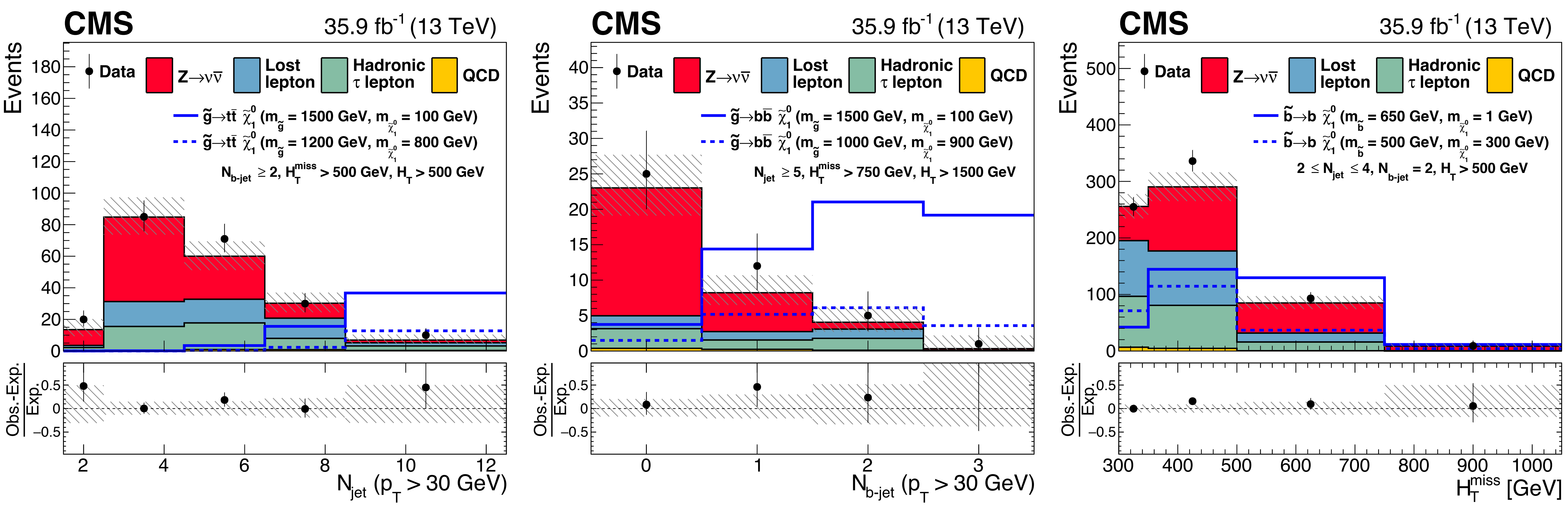
Veto if $$\Delta\varphi(J_{1,2}, p_T^{miss}) < 0.5$$

$$\Delta\varphi(J_{3,4}, p_T^{miss}) < 0.3$$

Jets + p_T^{miss} search: some projections of the data

Background estimation: control samples x scale factors:

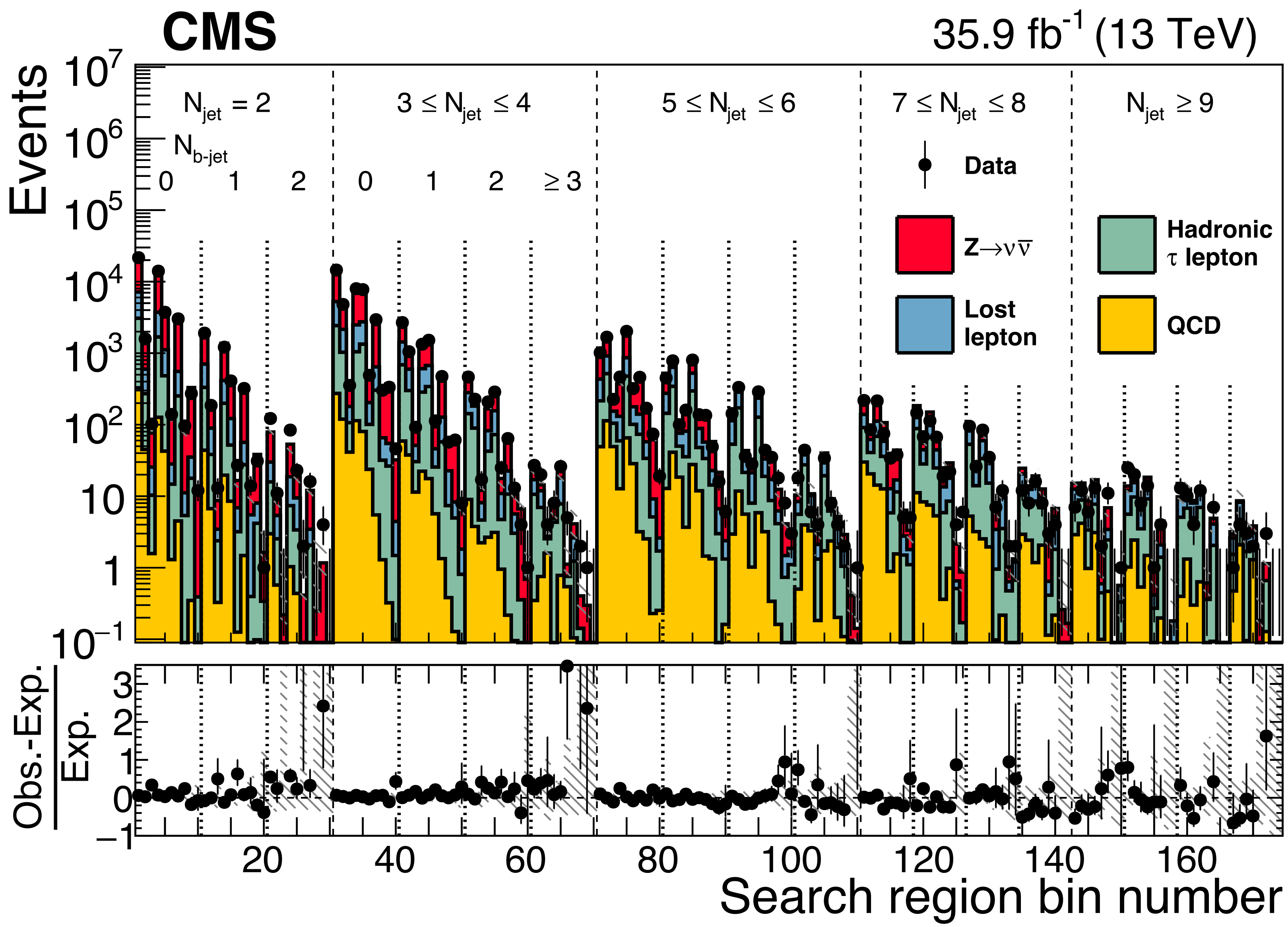
- QCD background - from "inverted $\Delta\varphi$" control samples
- Z→ νν + jets - from Z⟶ $\ell^+\ell^-$ + jets and γ +jets conrol samples
- "Lost lepton": ttbar W→ (e, μ)ν and W → ℓν + jets - from 1-lepton control samples
- ttbar W→ τν→ hadrons + ν - from 1-lepton control samples

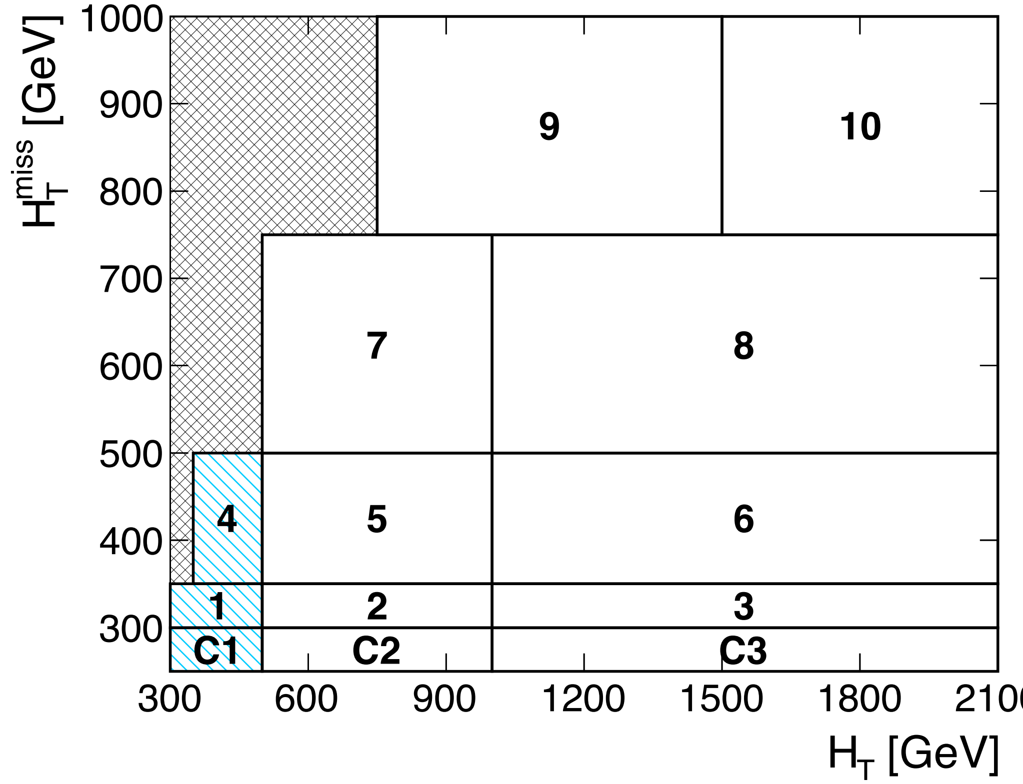


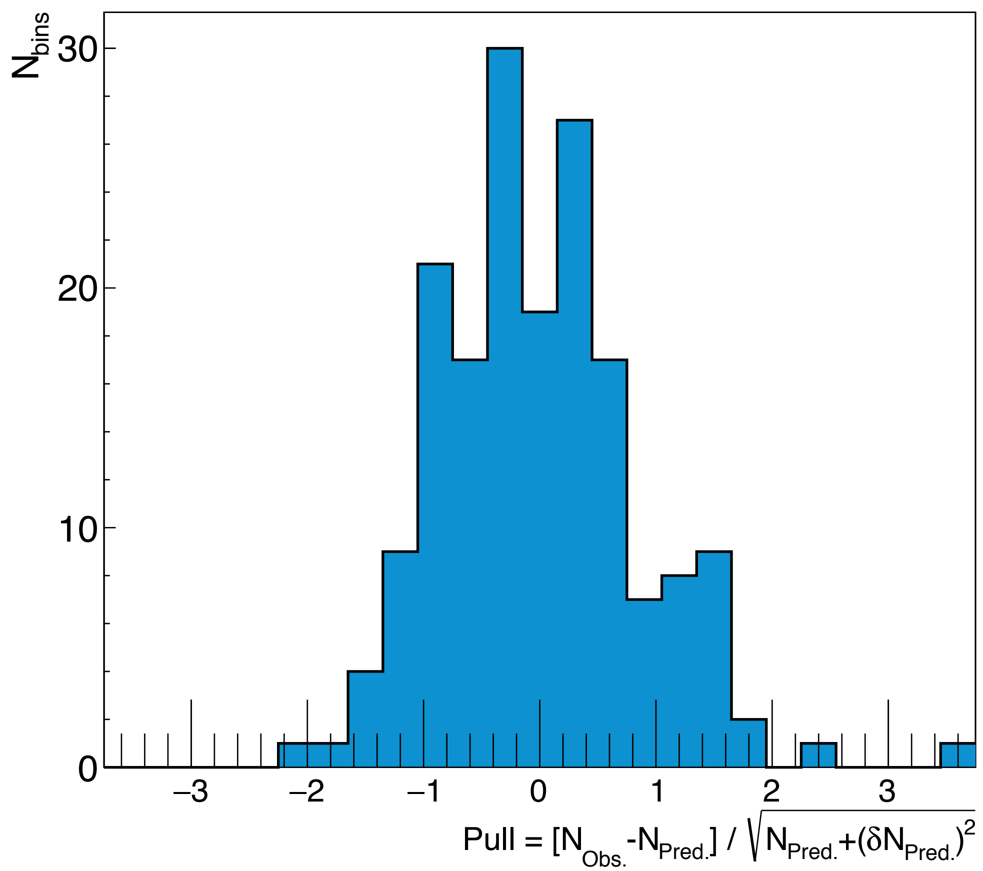
No evidence for a large/significant excess event yield above the SM background prediction.

Jets + p_T^{miss} search: observed yields in signal regions

Bin numbering: increasing: Njets, Nbjets, HT & HTmiss (order according to plot at right)

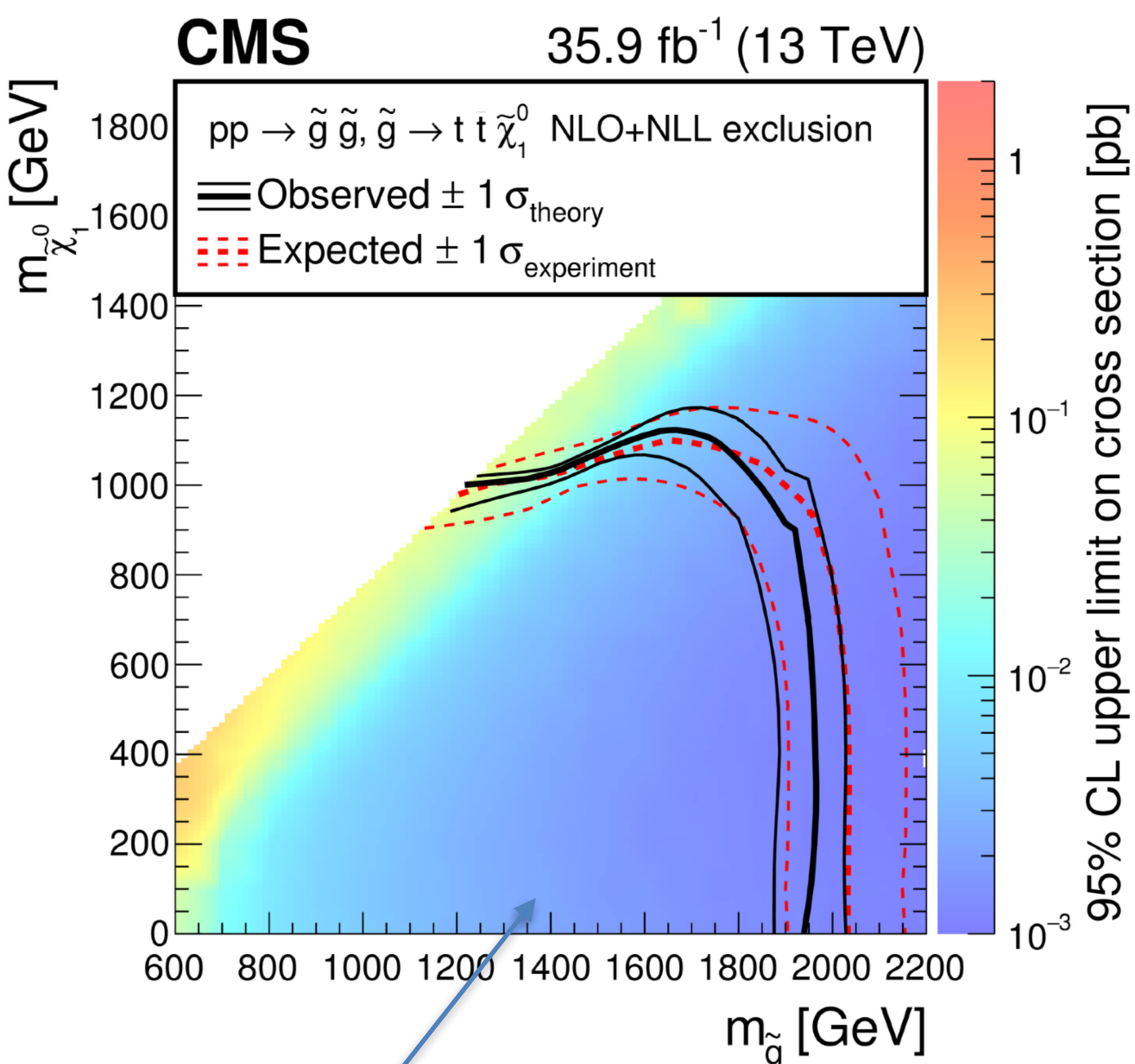


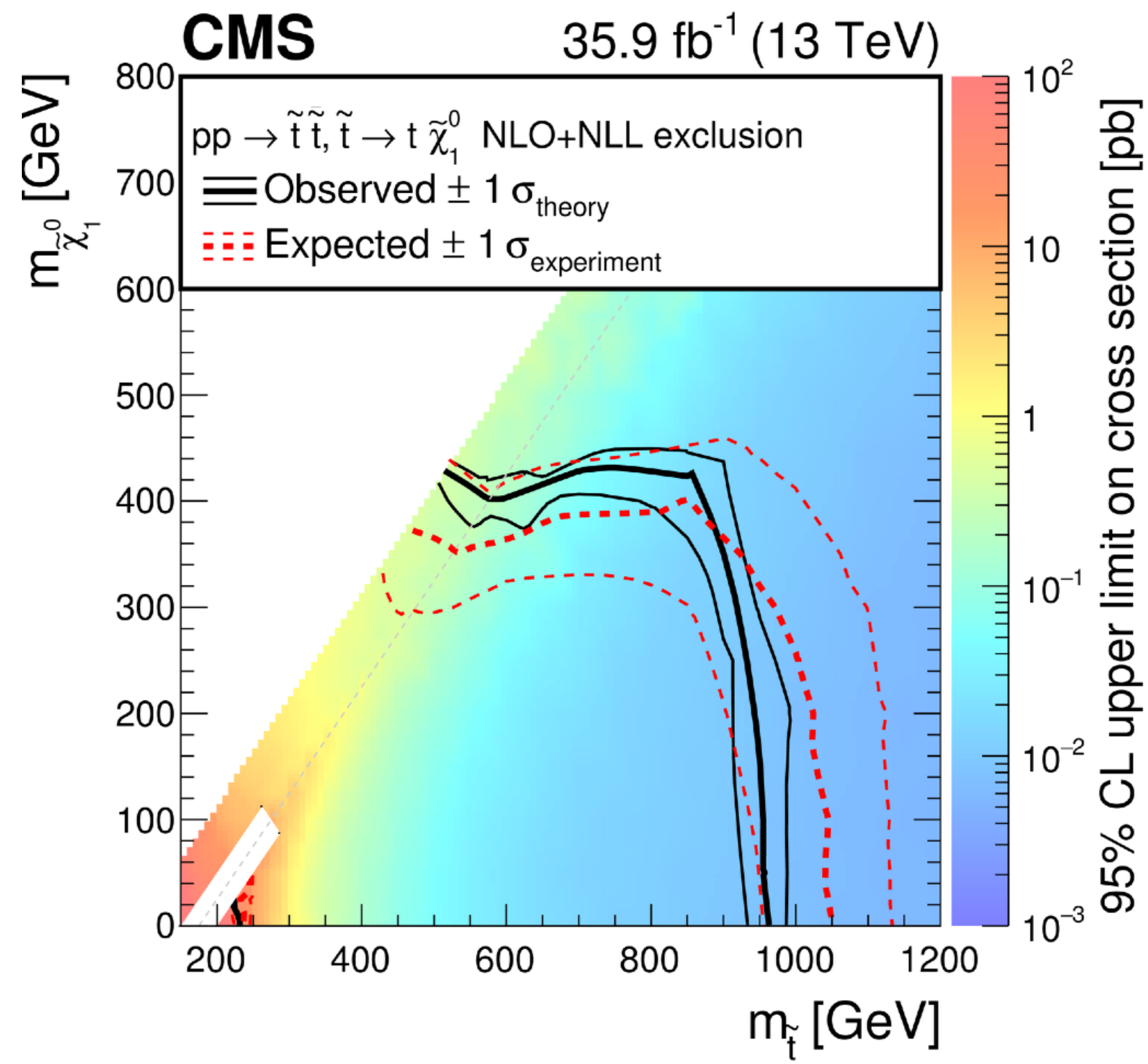




In each bin, each main background is predicted separately from control sample(s) in the data that is (are) dominated by that background.

Jets + p_T^{miss} search: example interpretations





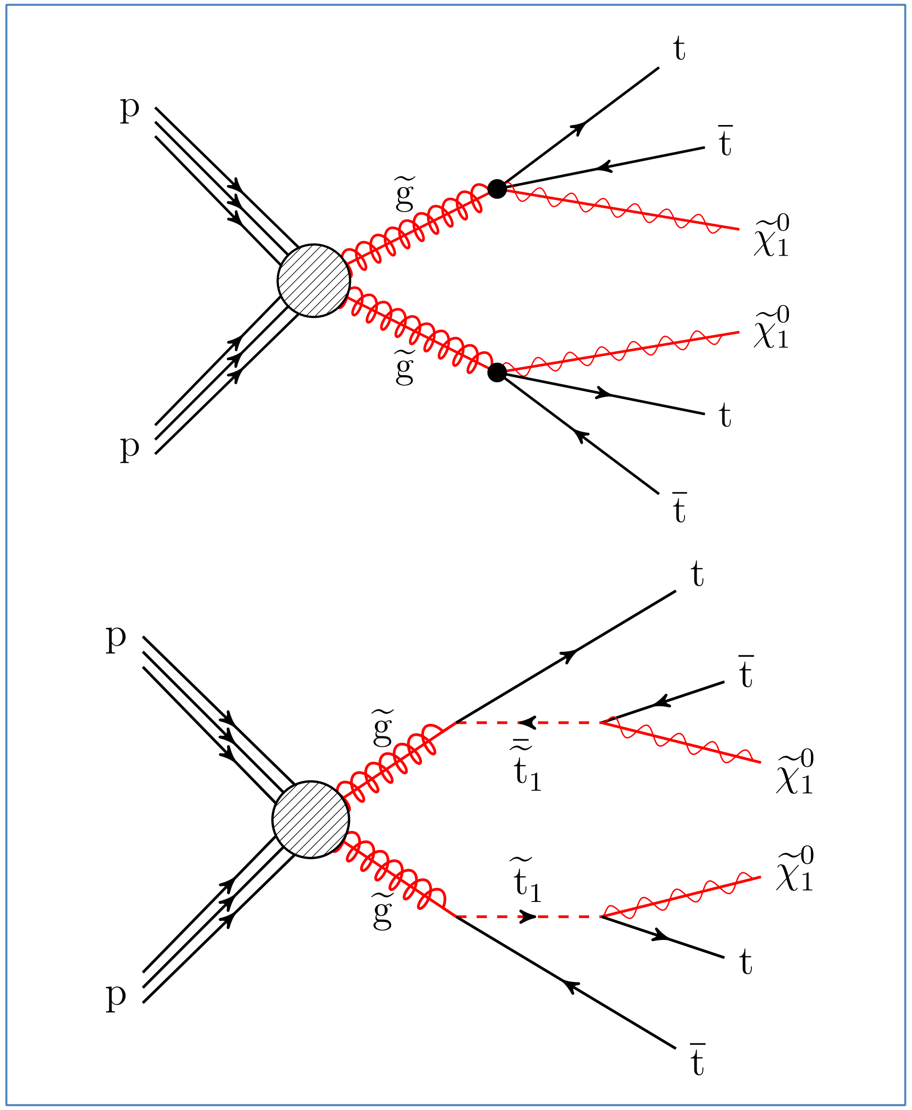
Color map shows the excluded cross section (95% CL)
Comparison of this cross section with a theoretical reference cross section for the signal gives the boundary of the excluded model points.

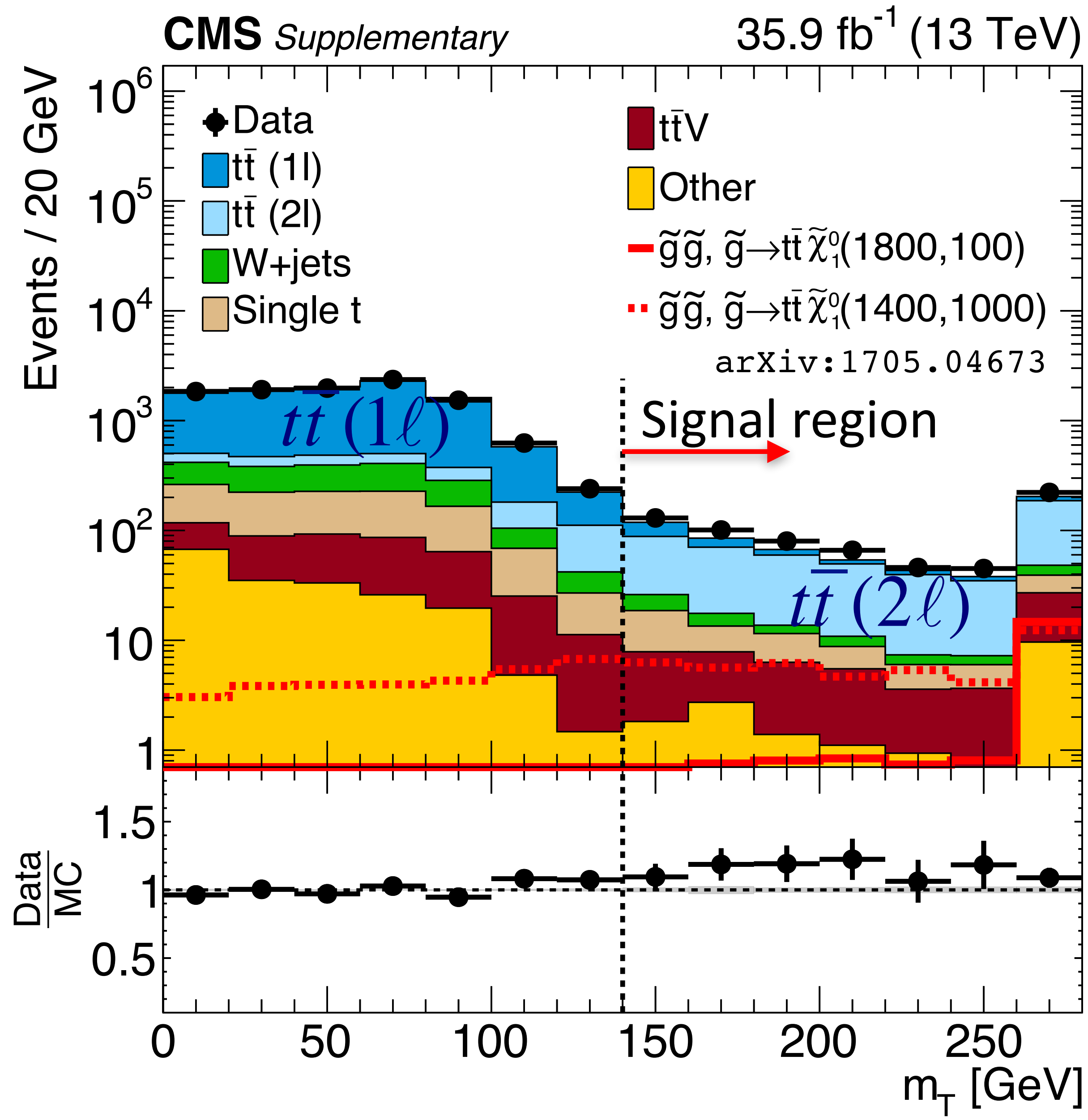
Many more interpretations available at
http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS-16-033/index.html

Single-lepton + (b)-jets + p_T^{miss} search

Search targets processes prominent in natural SUSY models.

$$m_T = \sqrt{2 p_T^{\ell} p_T^{miss} \left[1 - \cos(\varphi_\ell - \varphi_{p_T miss})\right]}$$





https://arxiv.org/abs/1705.04673

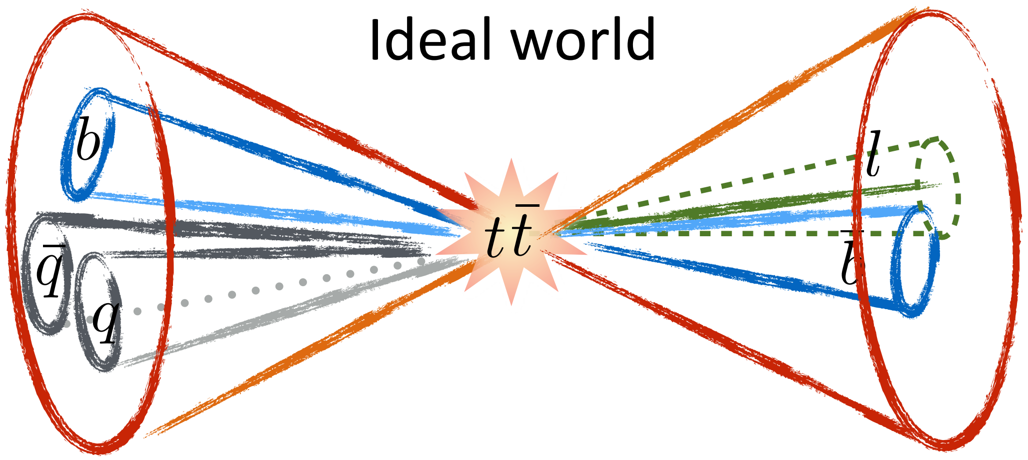
- Single-lepton events capture ~40% of the signal.
- Can strongly suppress 1-lepton ttbar and W+jets with cut on transverse mass of lepton-pTmiss system.
- High jet multiplicity suppresses 2-lepton ttbar; but is still background with ISR!

Single-lepton search: large-R jets and Initial State Radiation

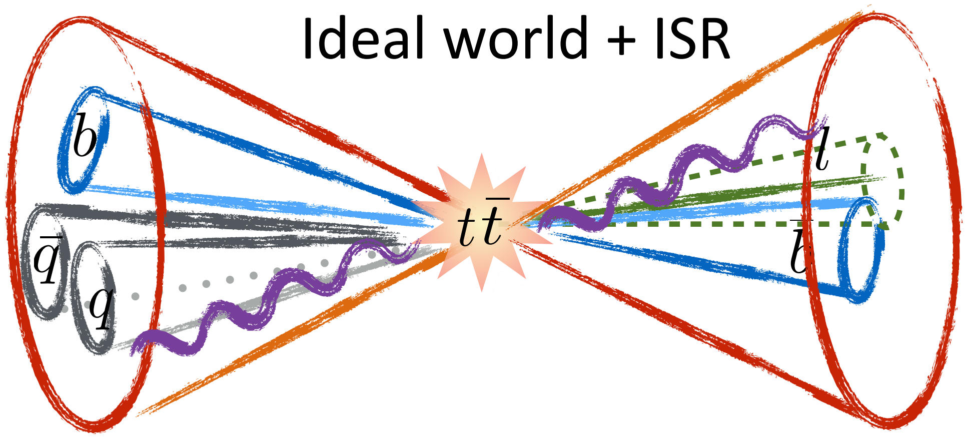
- Reconstruct large-radius jets J with R=1.2 rather than the usual R=0.4.
- Start from standard jets and apply clustering algorithm to them.

$$M_J = \sum_{\text{Large-}R\text{ jets}} m(J_i) \qquad R = 1.2$$

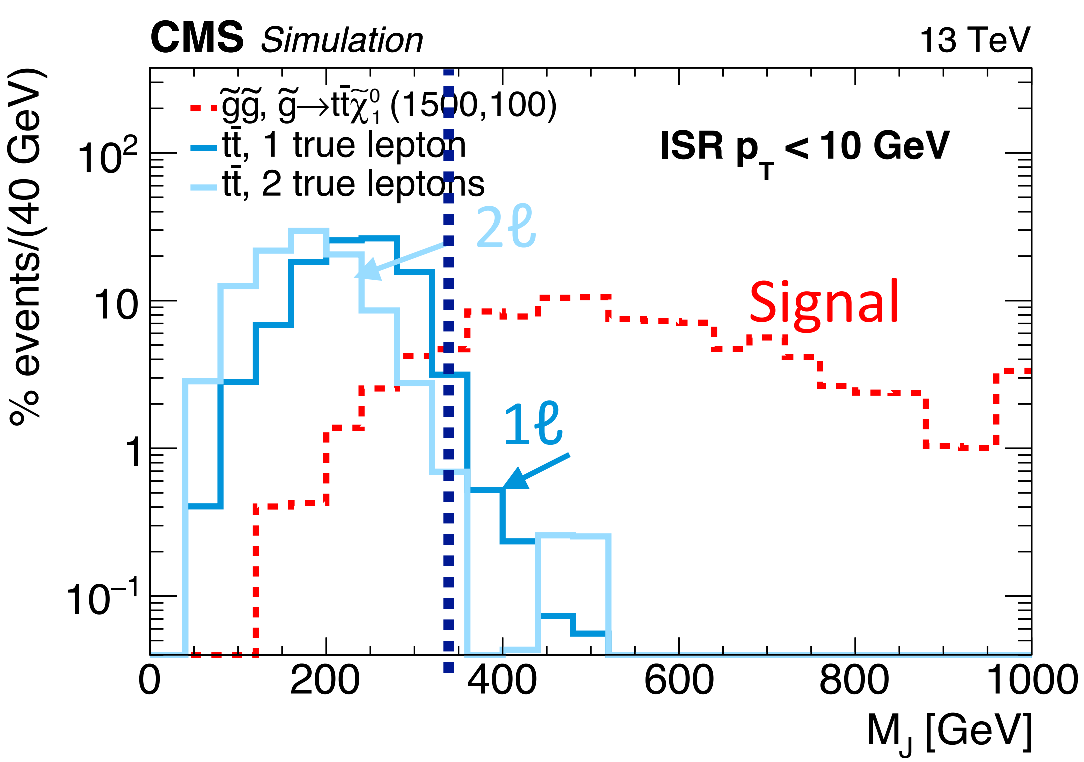
Ideal world



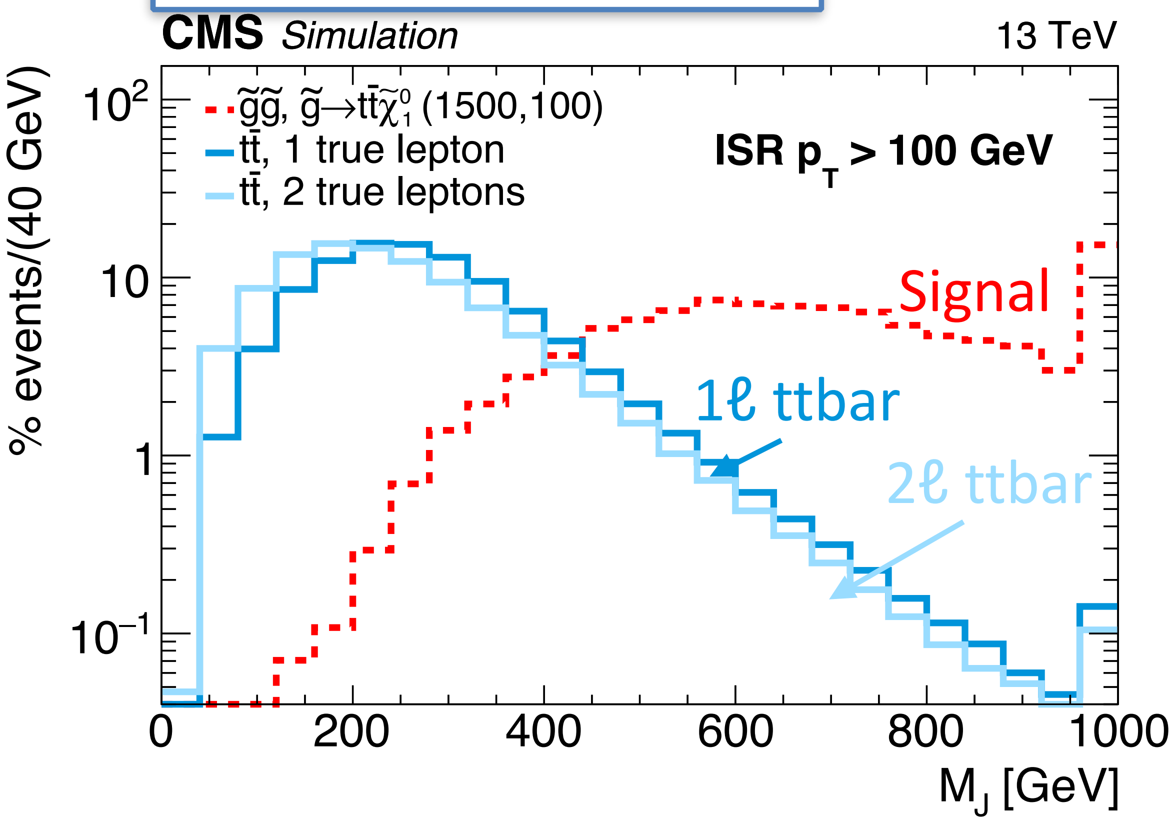
Ideal world + ISR



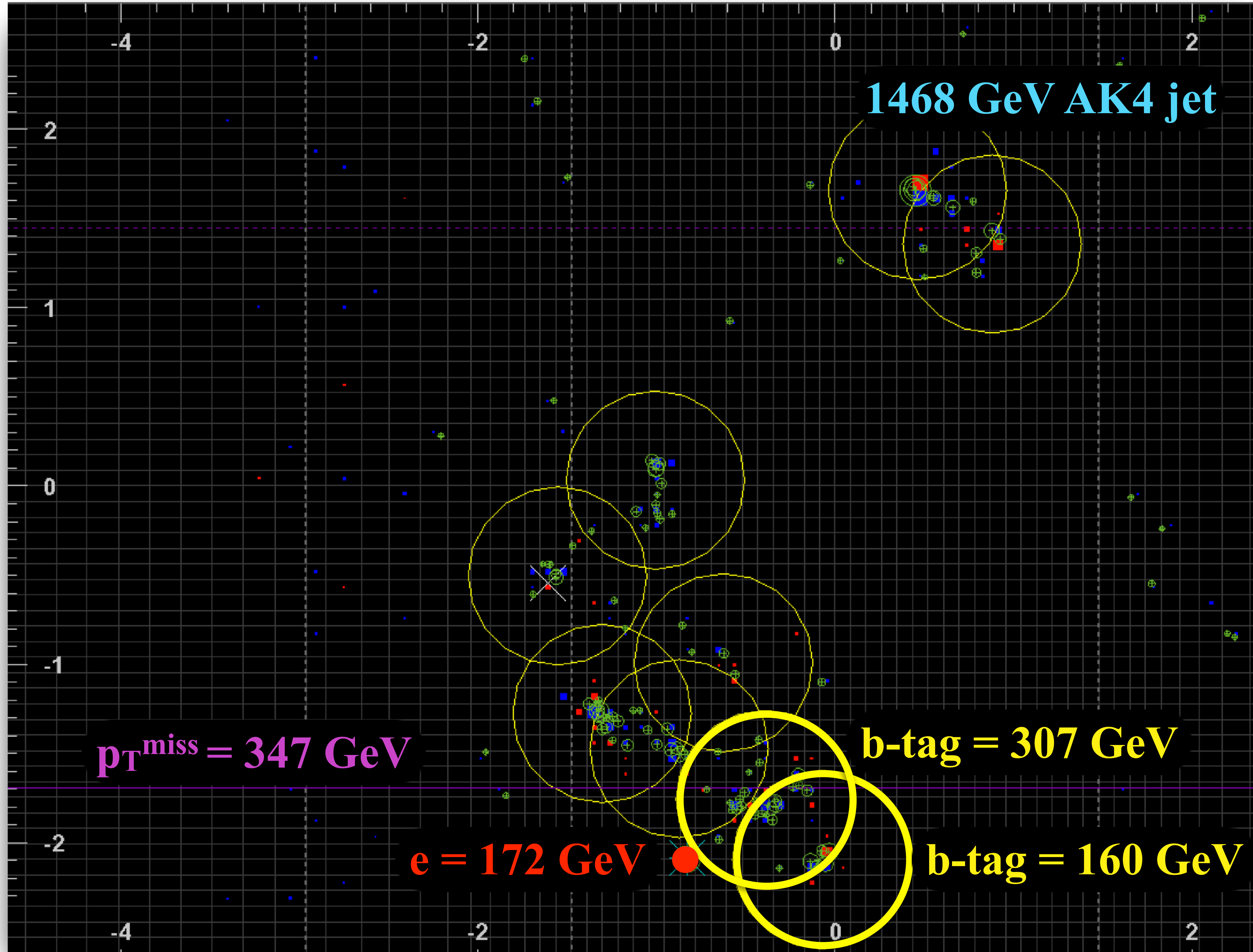
Low ISR: $p_T < 10$



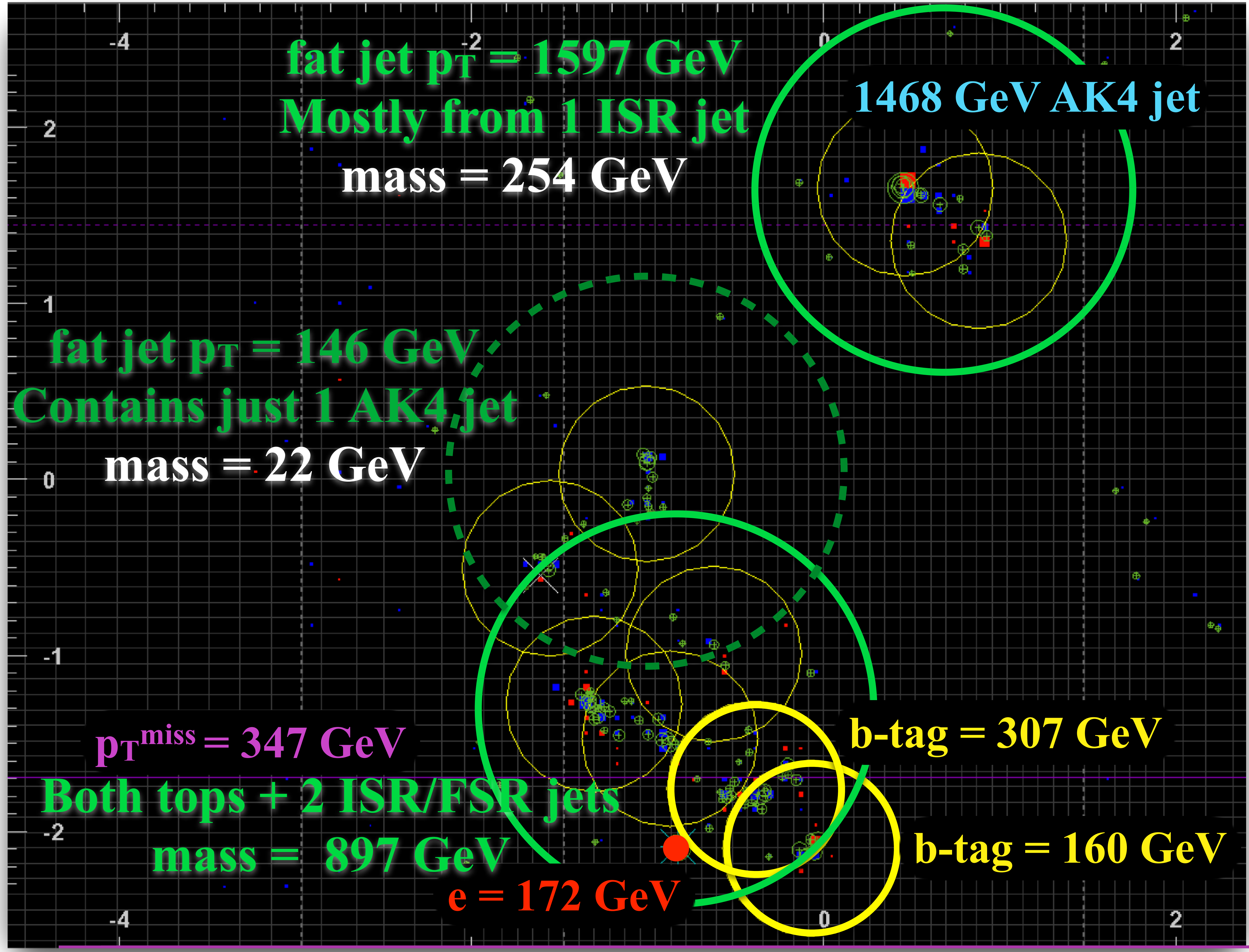
High ISR: p_T > 100 GeV



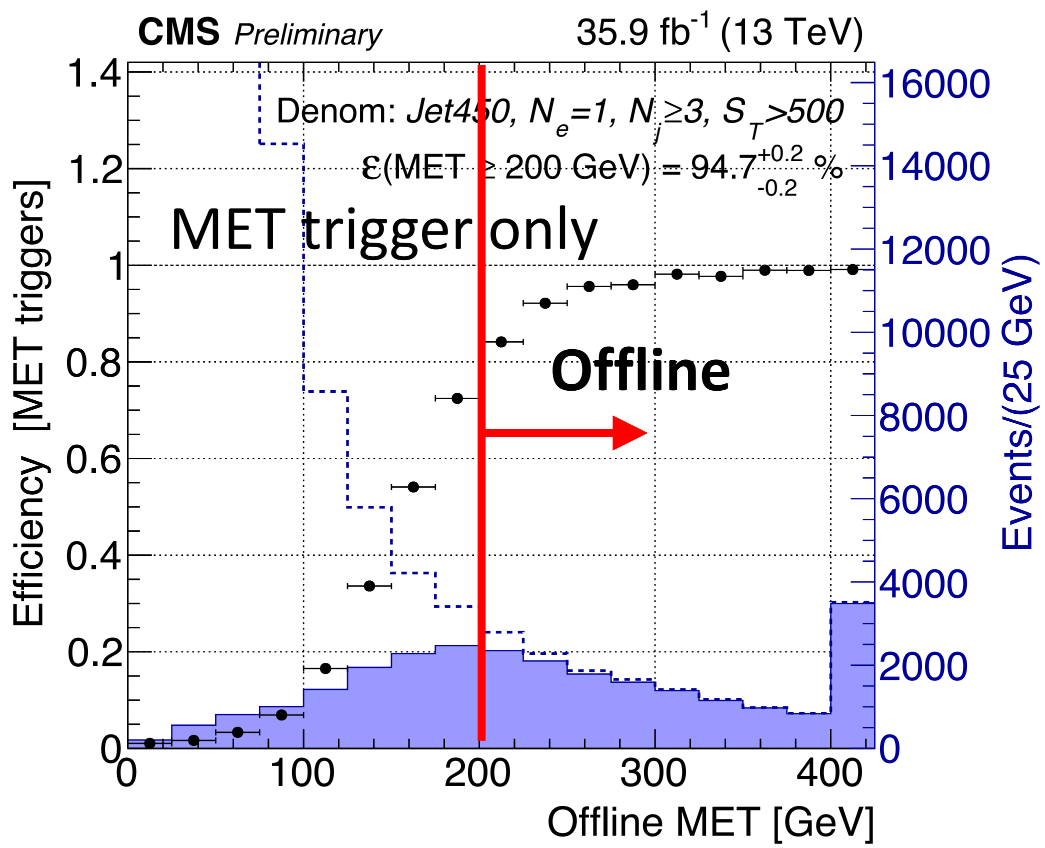
Event with 9 jets, 1 isolated electron, M_J = 1173 GeV

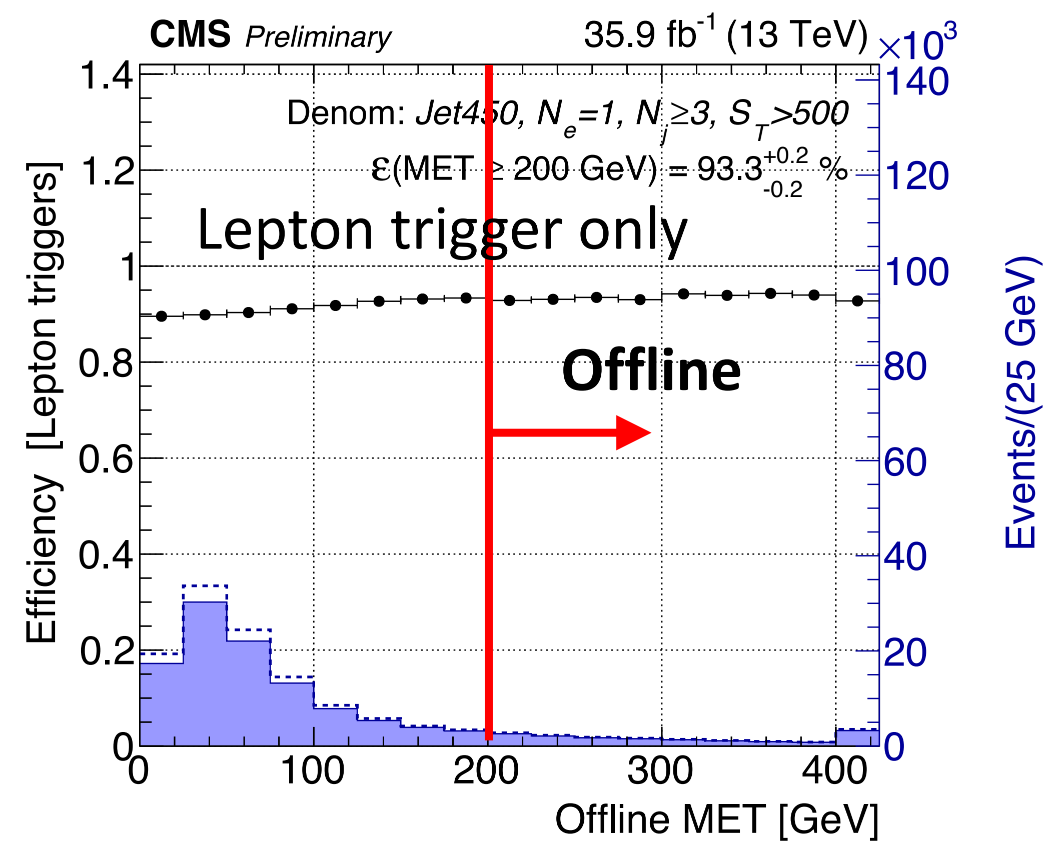


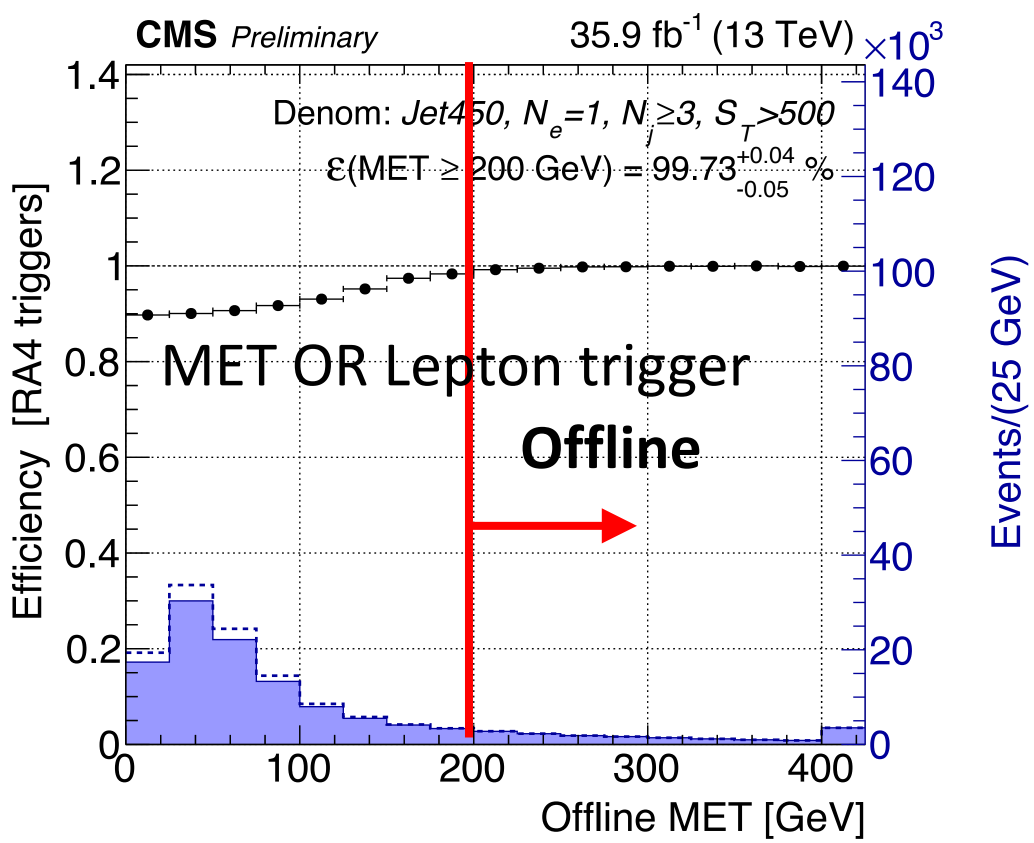
Event with 9 jets, 1 isolated electron, M_J = 1173 GeV

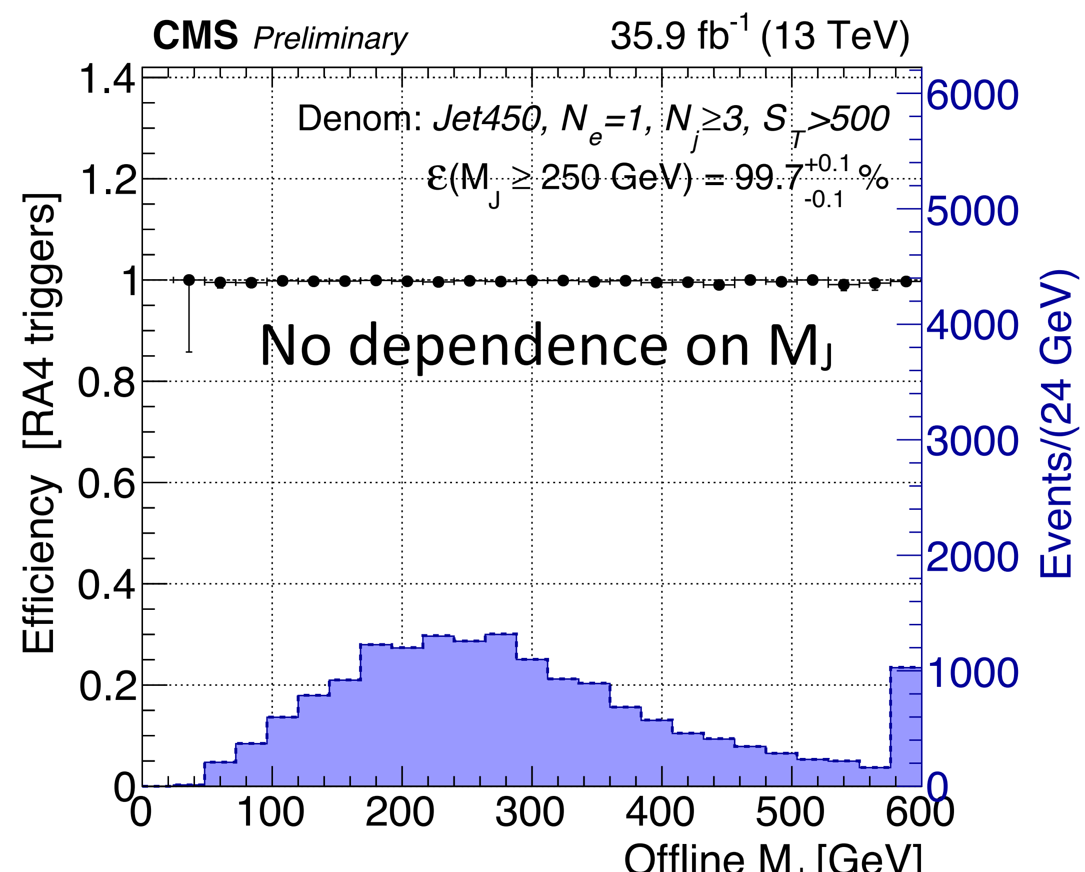


1 lepton + (b)-Jets + p_T^{miss}: trigger considerations







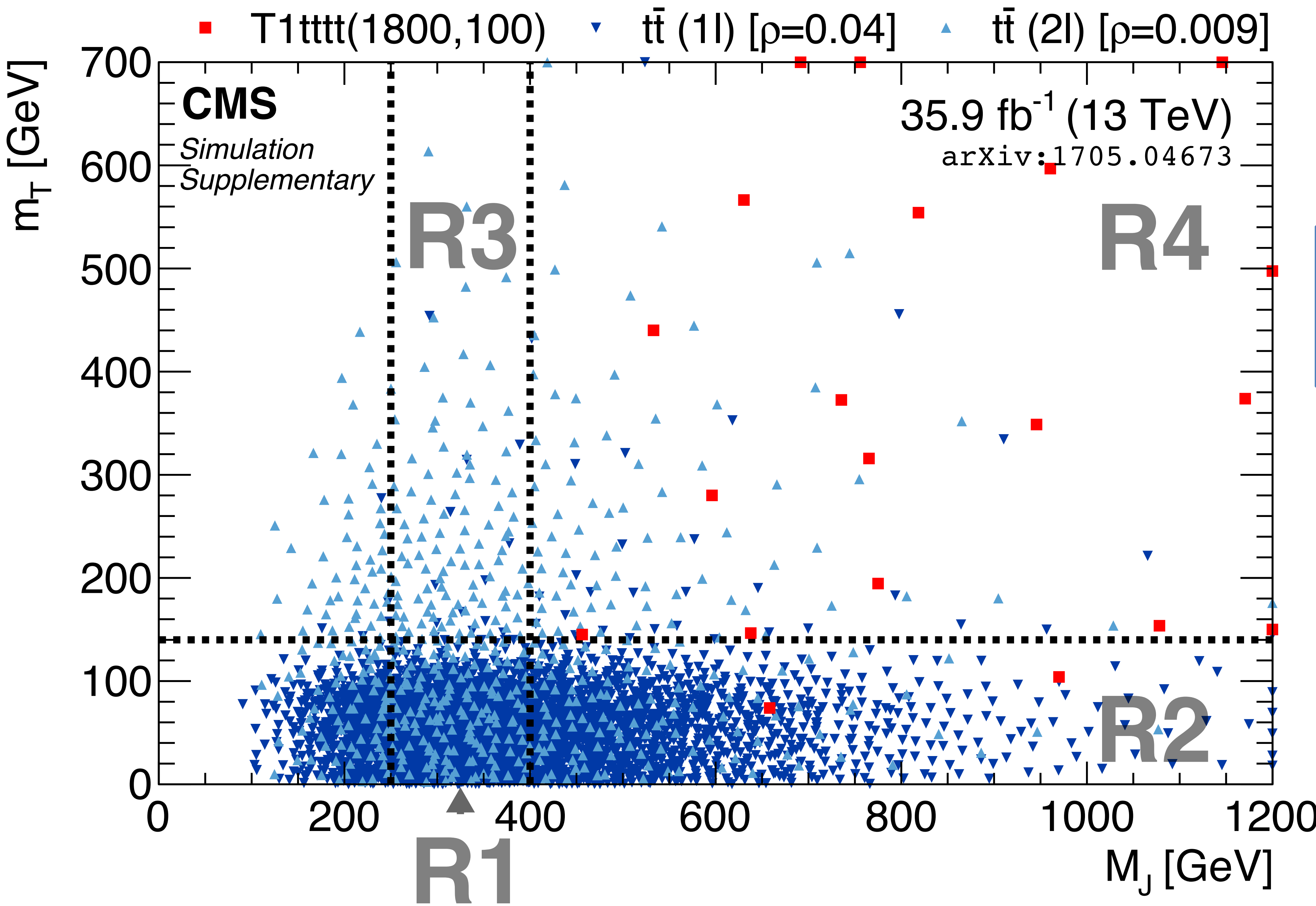


Single-lepton + (b)-jets + p_T^{miss} search

Baseline selection:

1 lepton (e or μ), pTmiss > 200 GeV, Njets ≥ 6, S_T > 500 GeV, $N_{veto\ leptons}$ =0

→ 80% of background is ttbar



Basic idea for background estimation

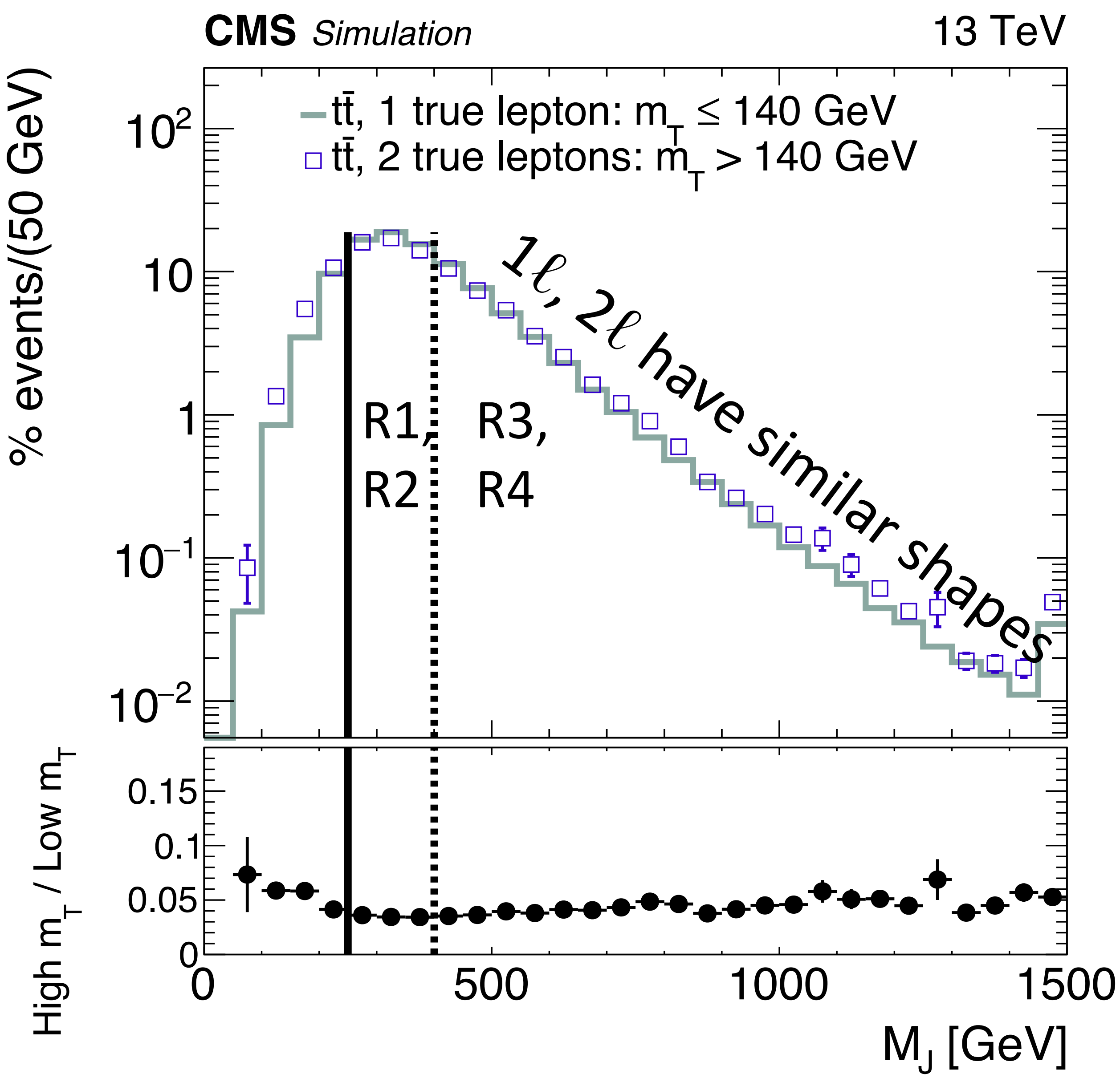
$$\mu_{R4}^{back} \simeq N_{R3} \cdot \frac{N_{R2}}{N_{R1}}$$

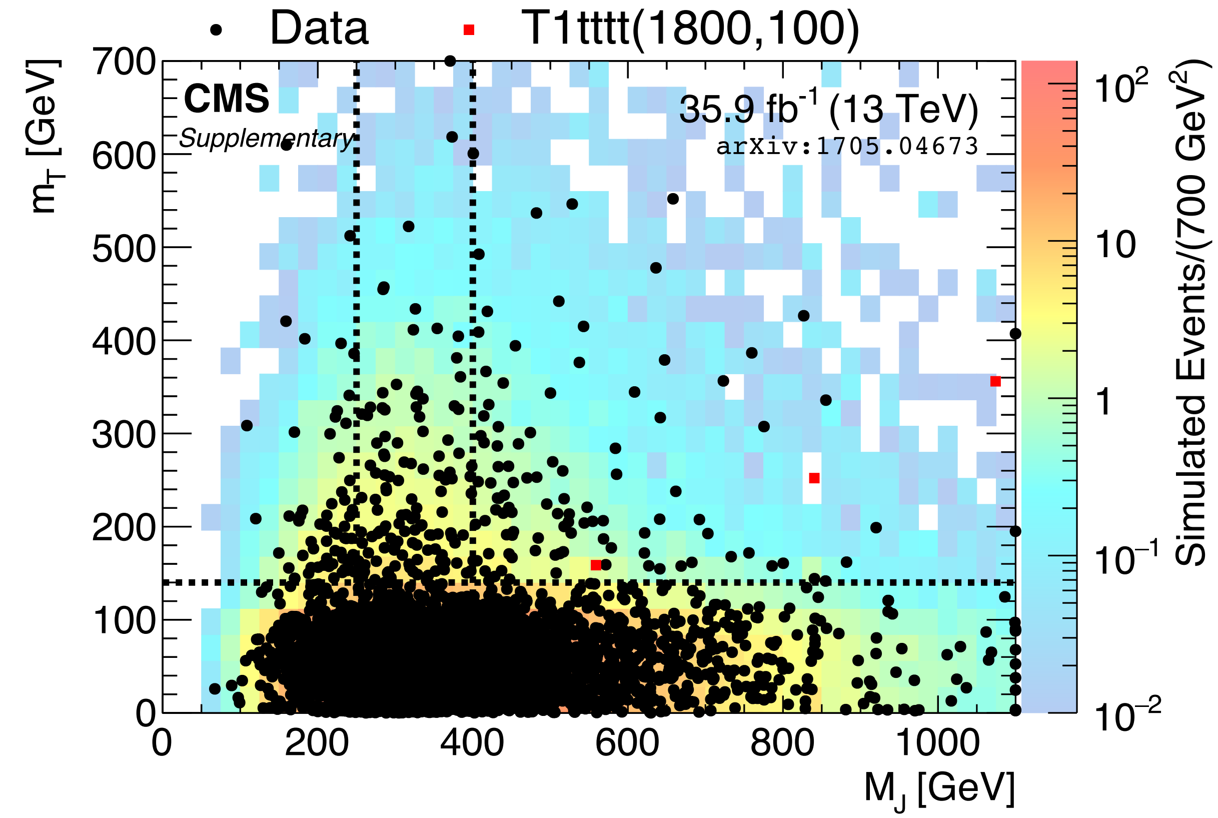
In practice,

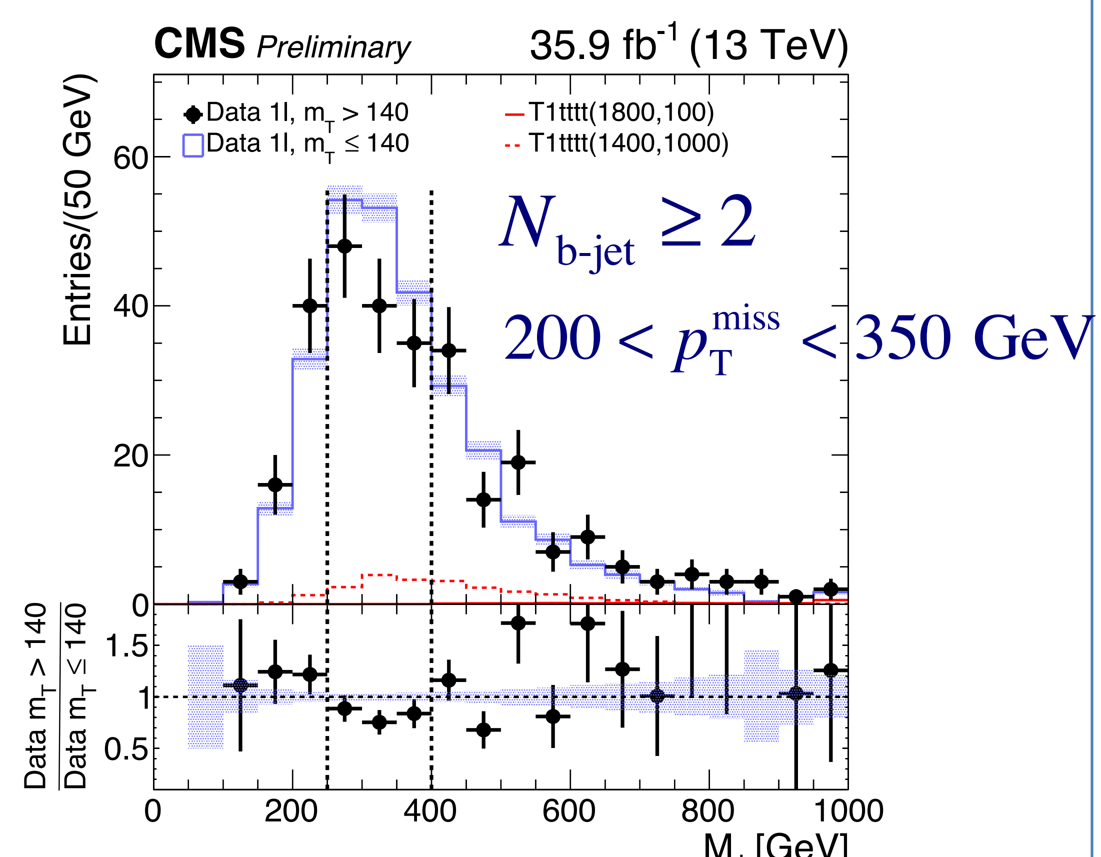
- Incorporate this into a fit that allows for signal contamination in R1, R2, and R3.
- Apply MC correction to account for small residual correlation.

Single-lepton + (b)-Jets + p_T^{miss} search

Comparison of MJ shapes in simulation: ttbar 1ℓ with low m_T vs. ttbar 2ℓ at high m_T. Shapes are very similar.





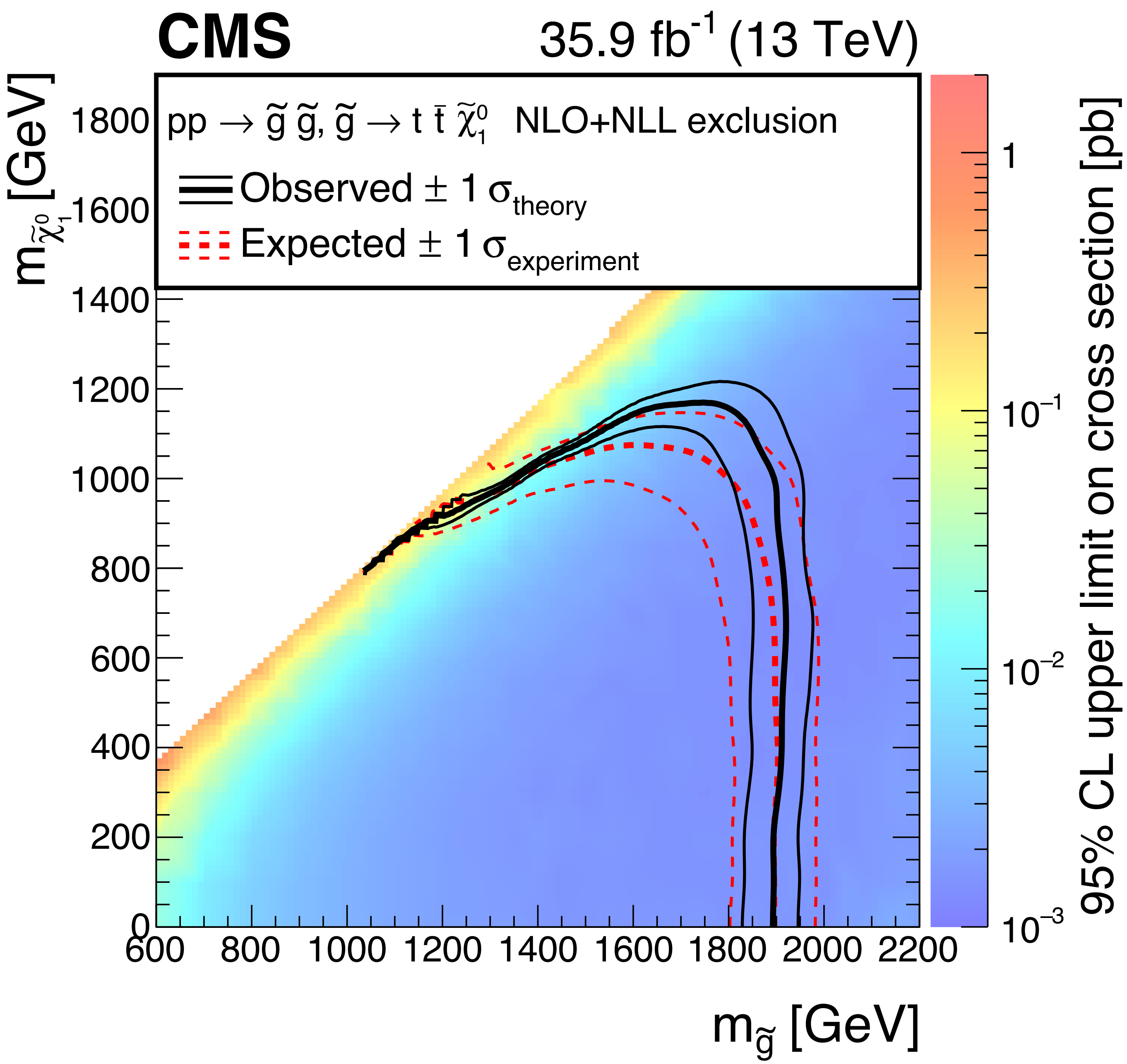


To improve the sensitivity, analysis is binned in Njets, Nbjets, and pTmiss.

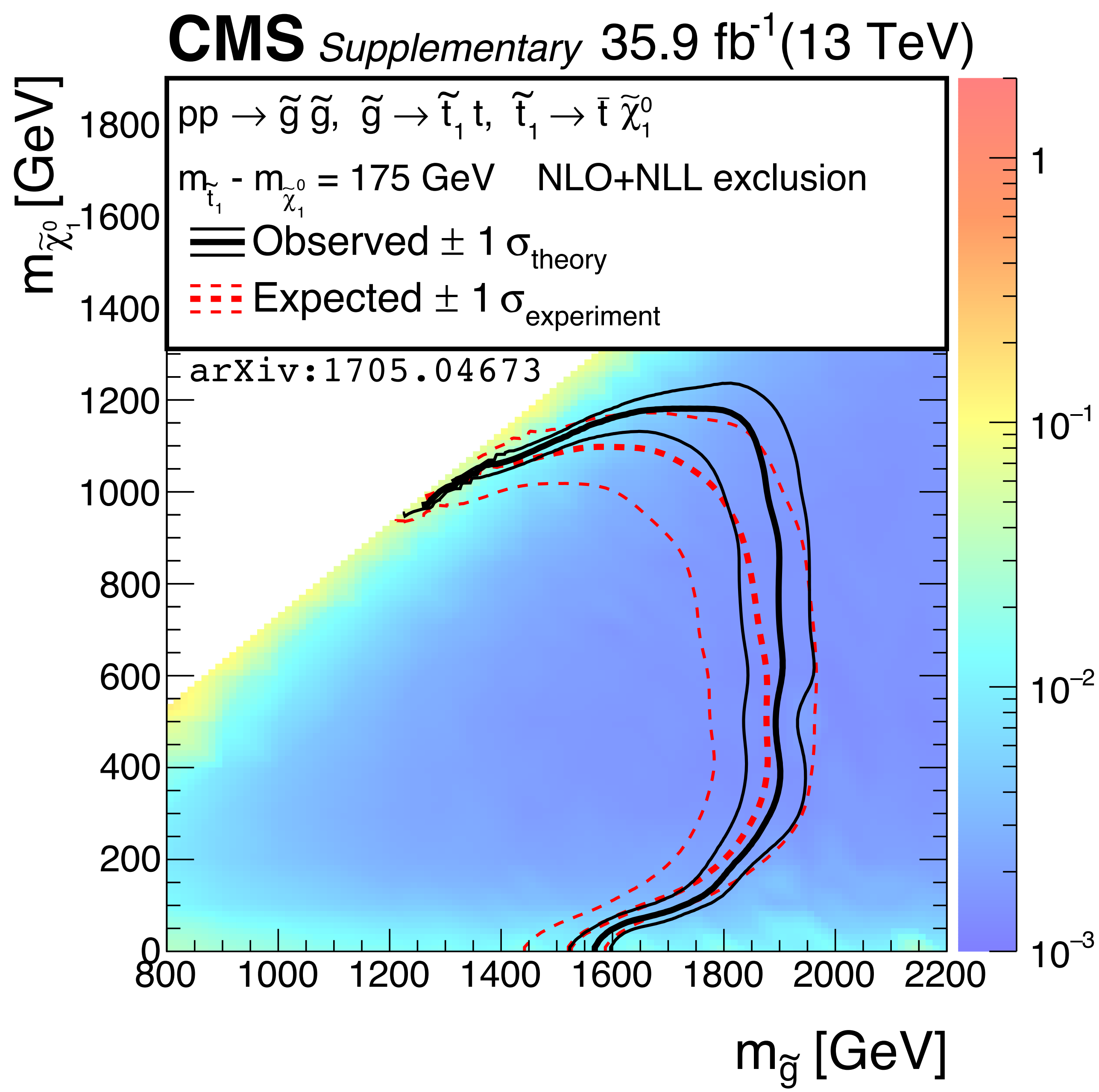
Single-lepton + (b)-Jets + p_T^{miss} search

No significant excess is observed in data → set limits on gluino pair production with decays to top squarks.

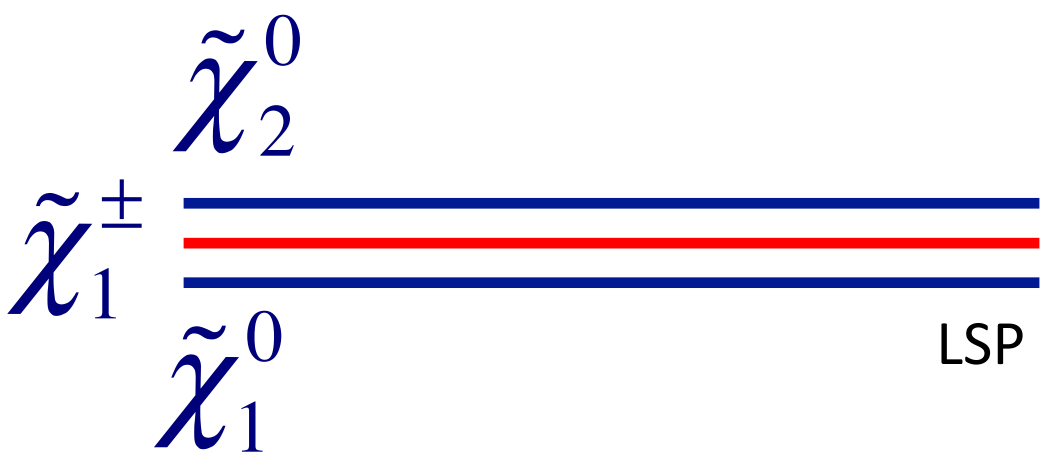
3-body gluino decays



2-body gluino decays

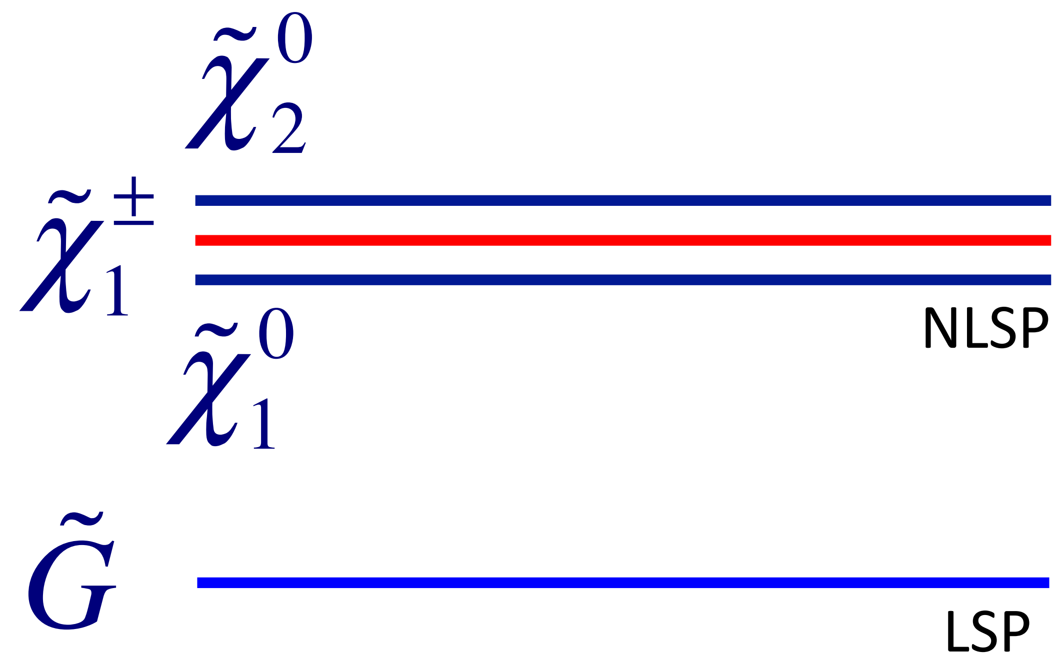


Higgsino search in GMSB SUSY models

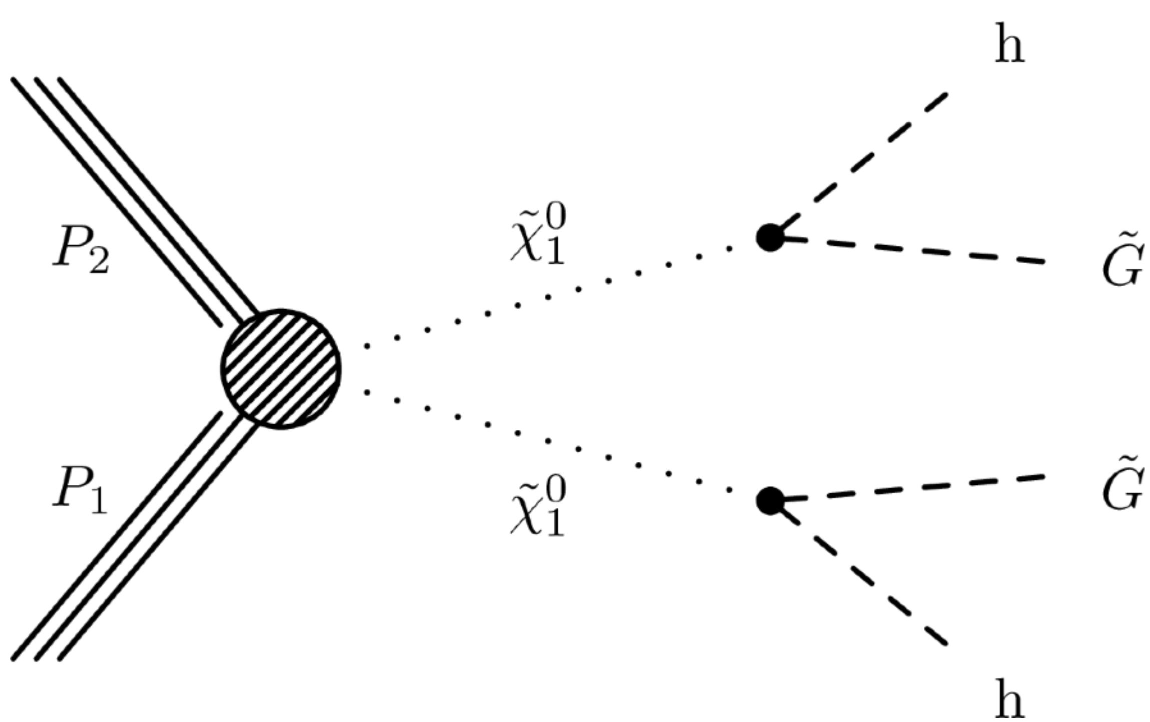


Small mass splitting implies that decay products are very soft and the LSP does not carry much p_T^{miss}

scenario in gauge-mediated SUSY breaking



gravitino/goldstino - Goldstone particle from SUSY breaking - very light in GMSB models



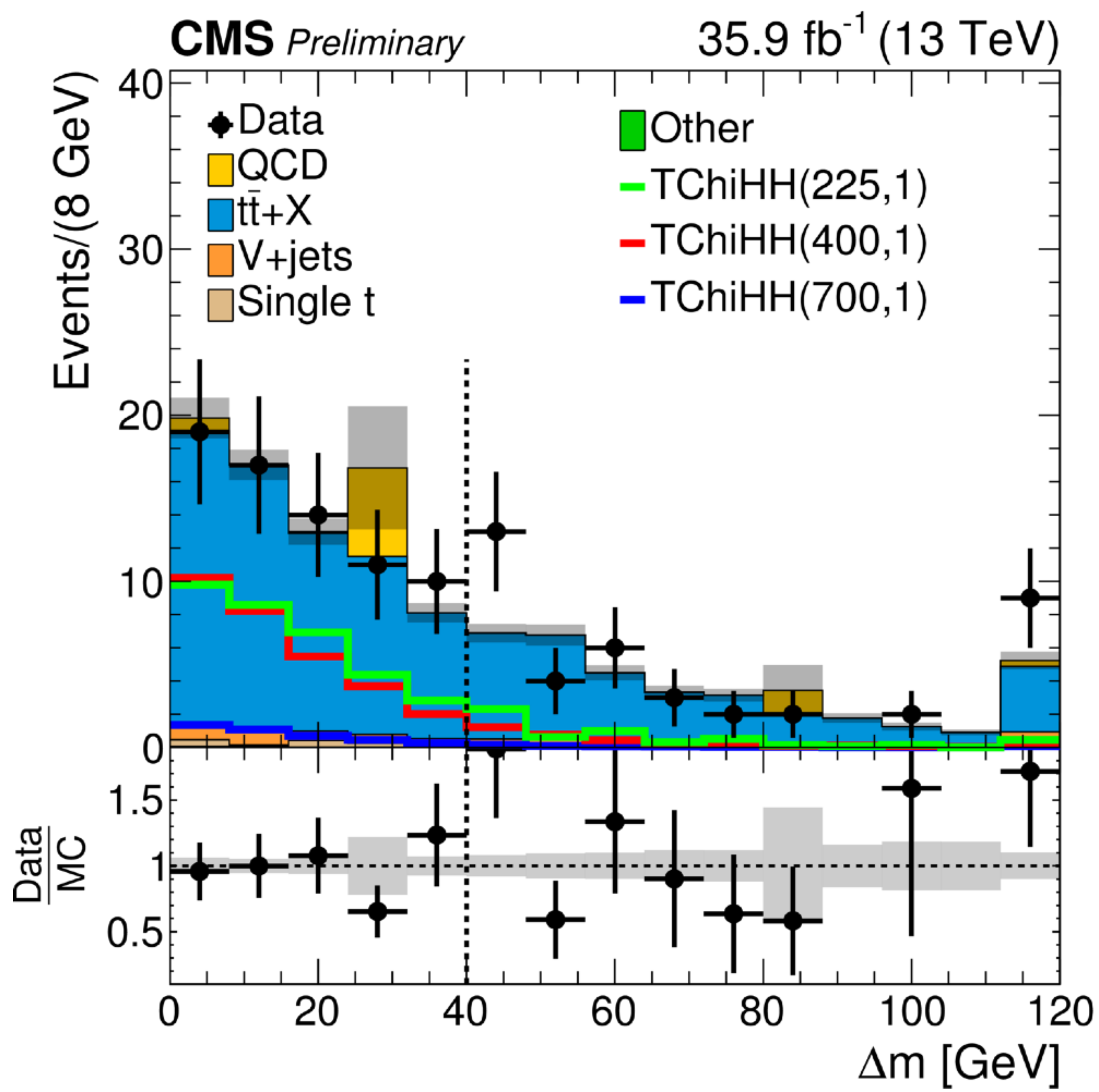
$$\tilde{\chi}_i\tilde{\chi}_j \to H\tilde{G}H\tilde{G} \to HH + p_T^{miss}$$

$$\to H(b\bar{b})H(b\bar{b}) + p_T^{miss}$$

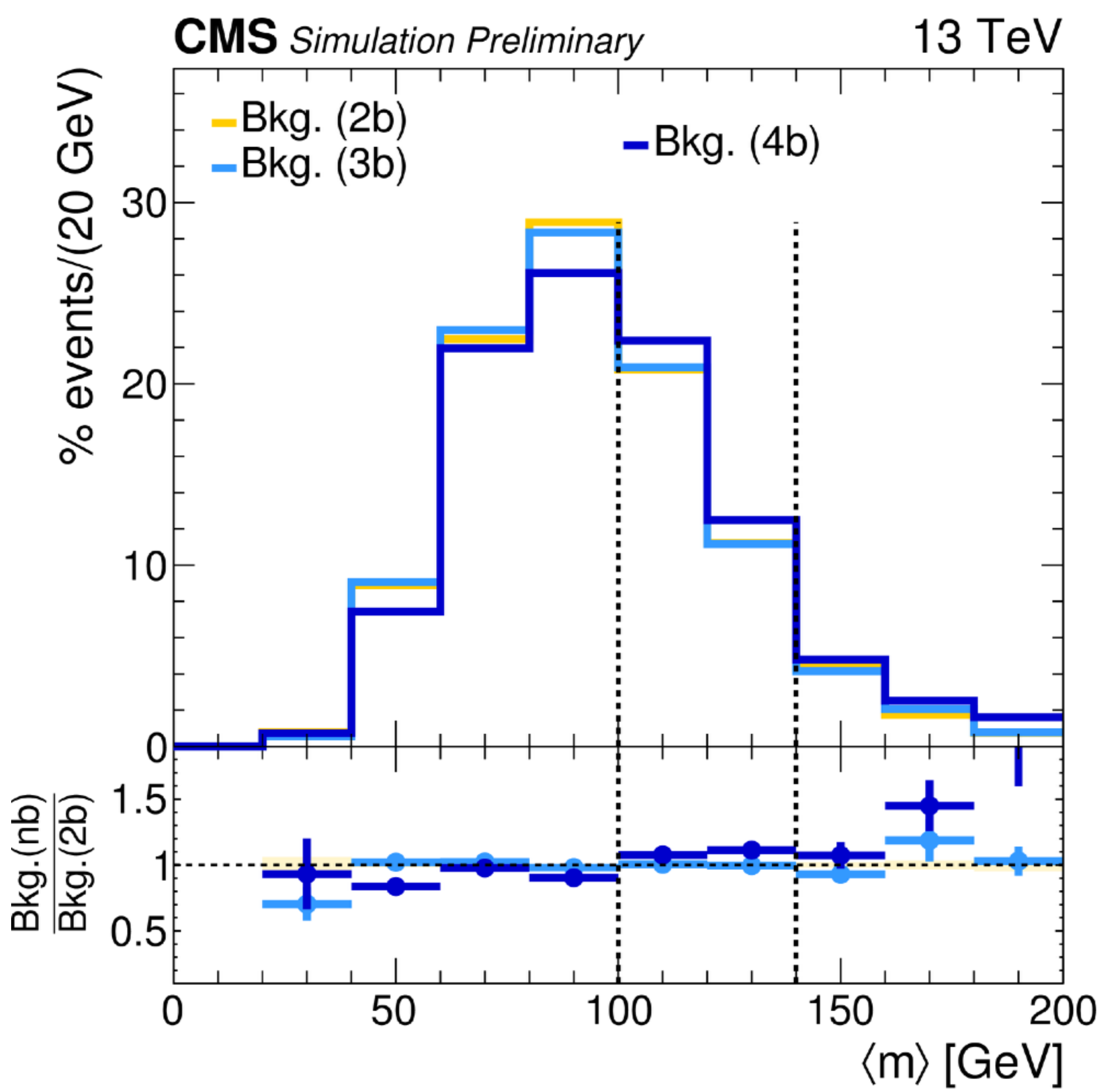
A SUSY signature with mass peaks!

Higgsino search in GMSB SUSY models

- Require 4-5 jets, ≥3 b-jets, pTmiss > 150 GeV, no leptons.
- Additional kinematic cuts to suppress ttbar.
- b-jets: find the pairs that minimize Δm between the two Higgs. candidates and require Δm < 40 GeV.

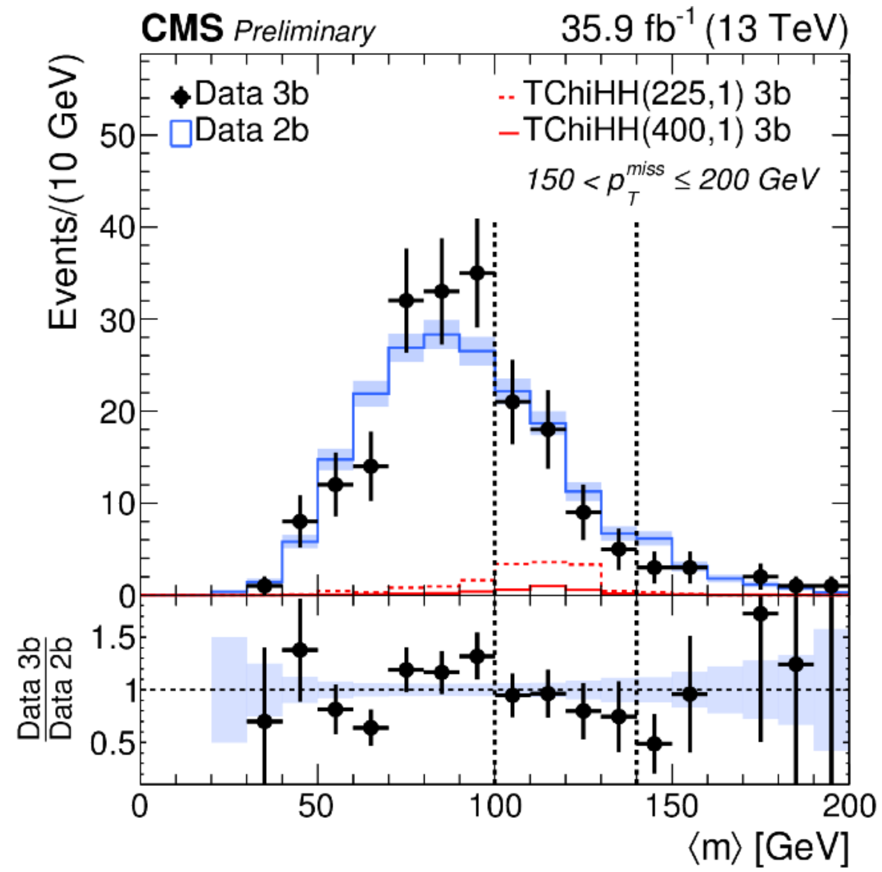


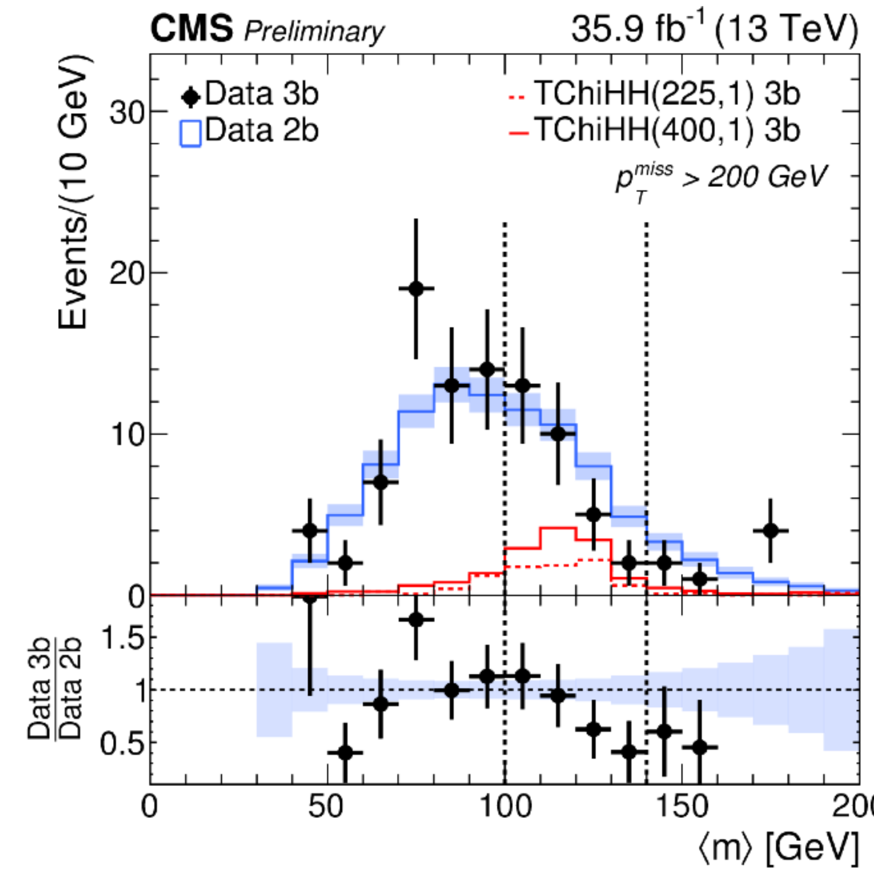
Background shape independent of N_b

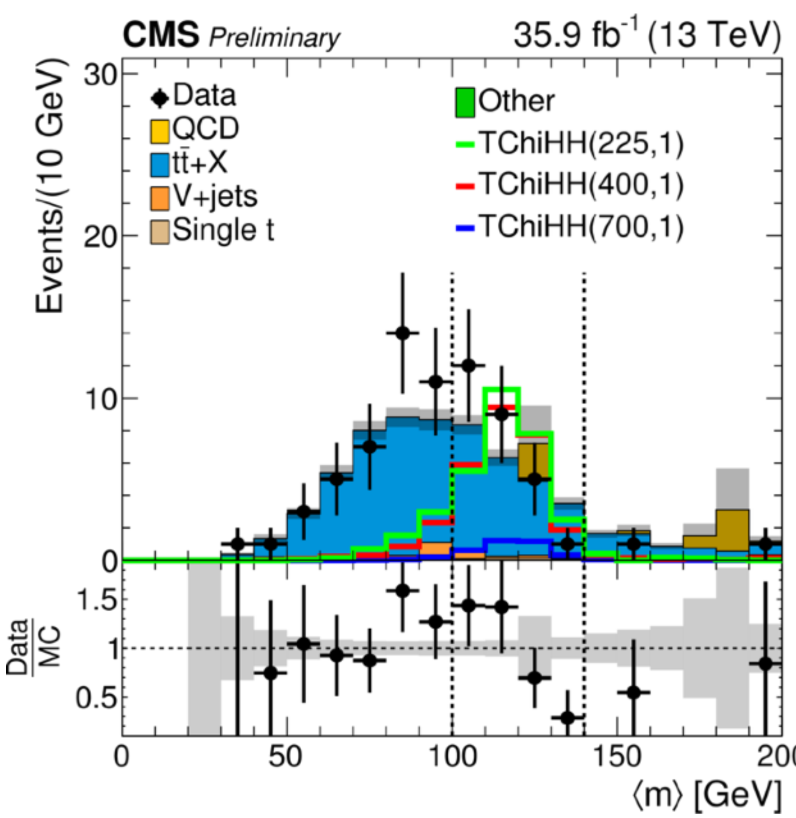


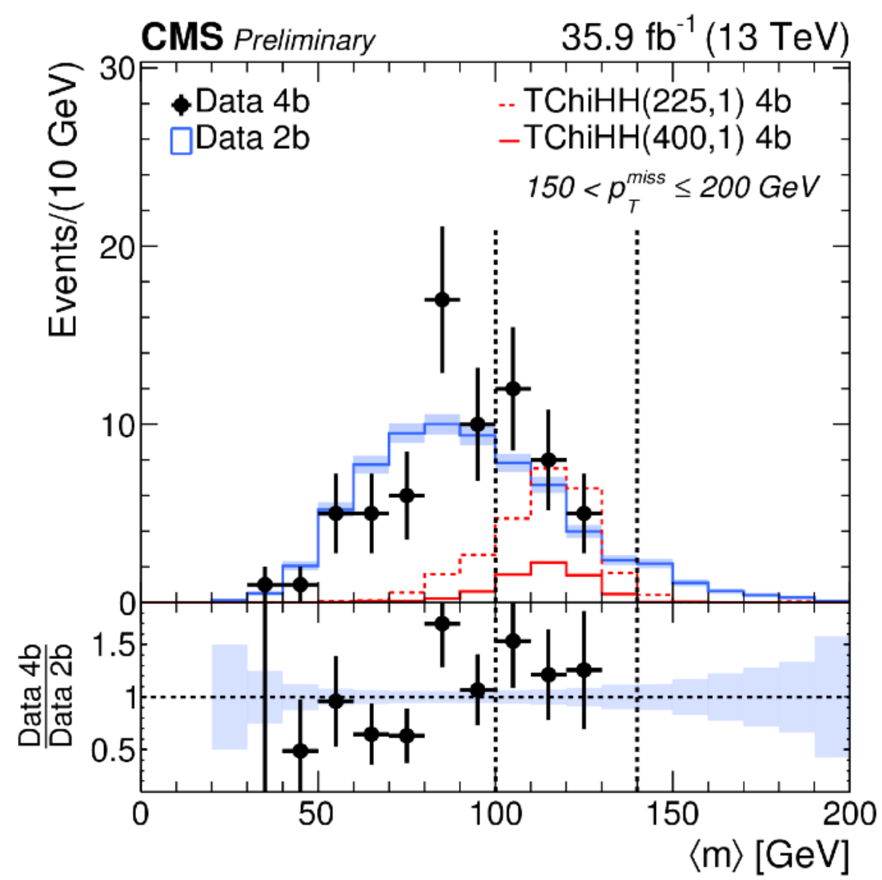
Higgsino search in GMSB SUSY models

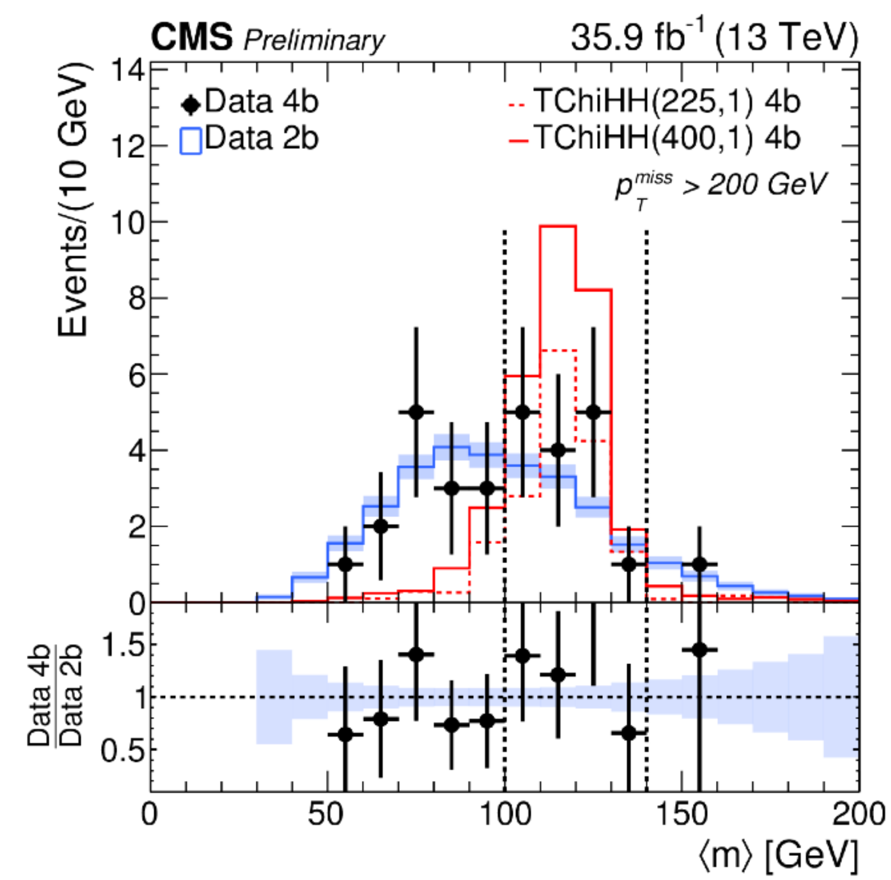
- Use 2 b-jet sample to obtain background shape.
- Normalize to m(H) sidebands in 3 b-jet and 4 b-jet samples.
- No MC correction needed.



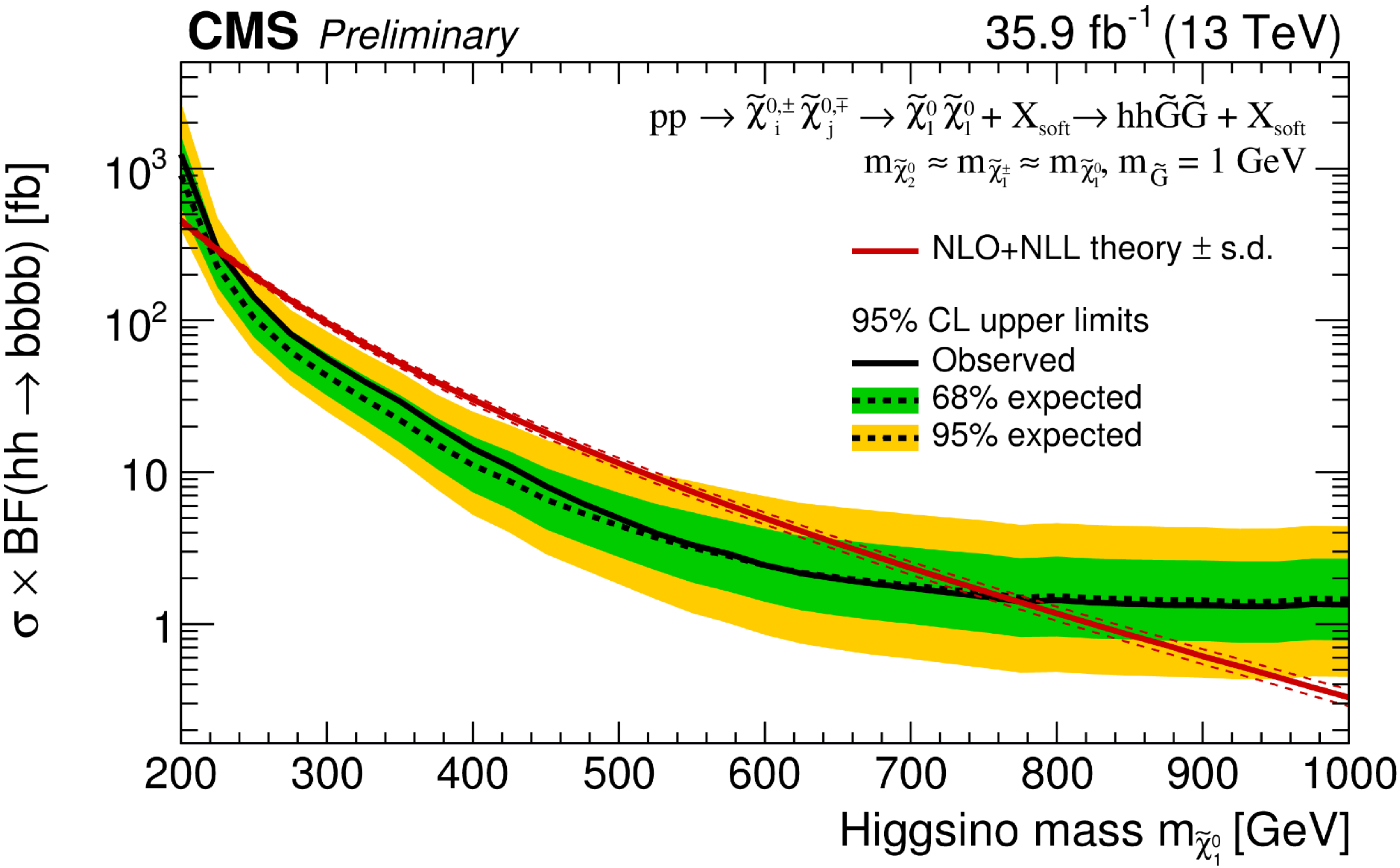






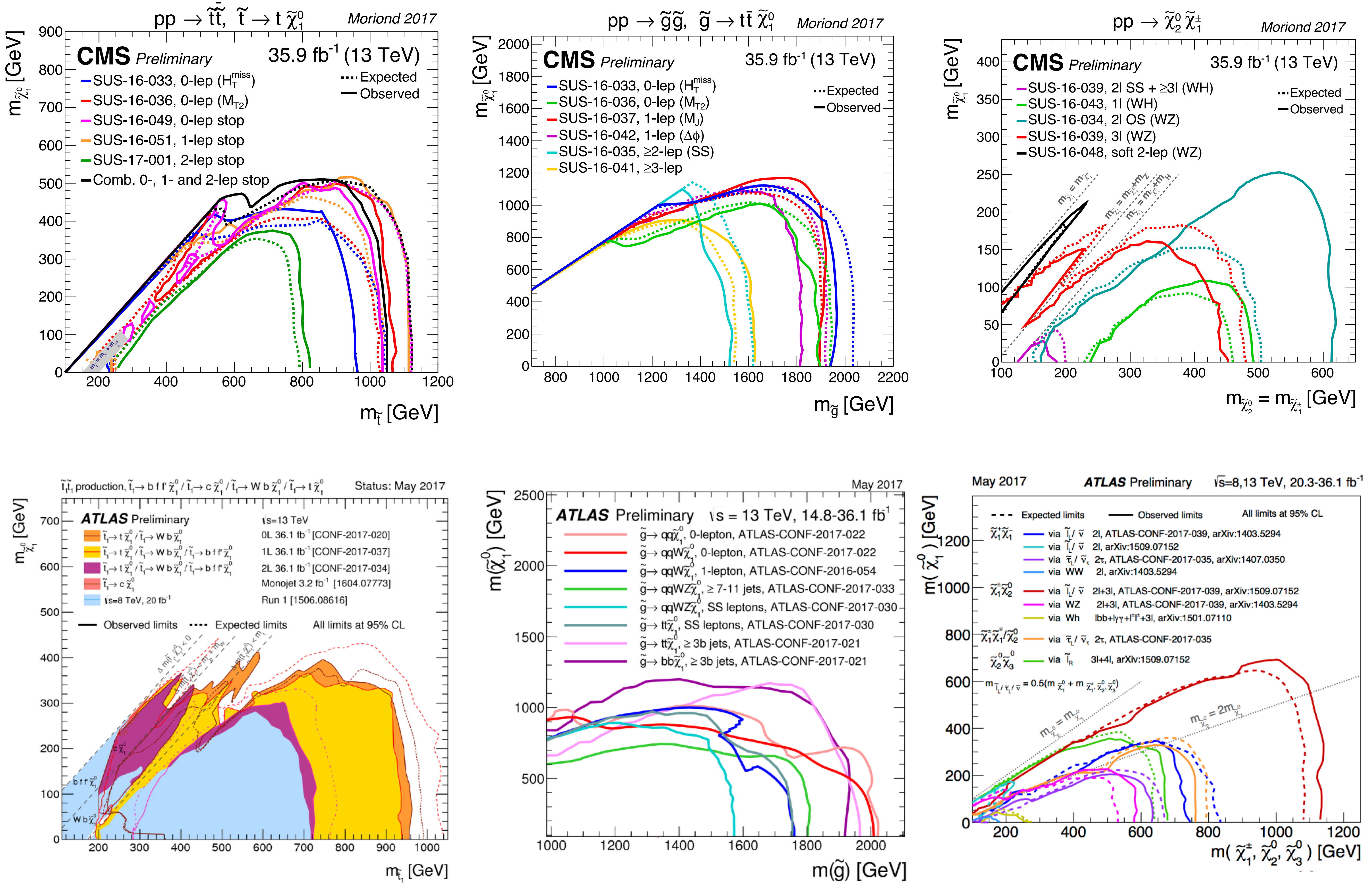


Higgsino search in GMSB SUSY models

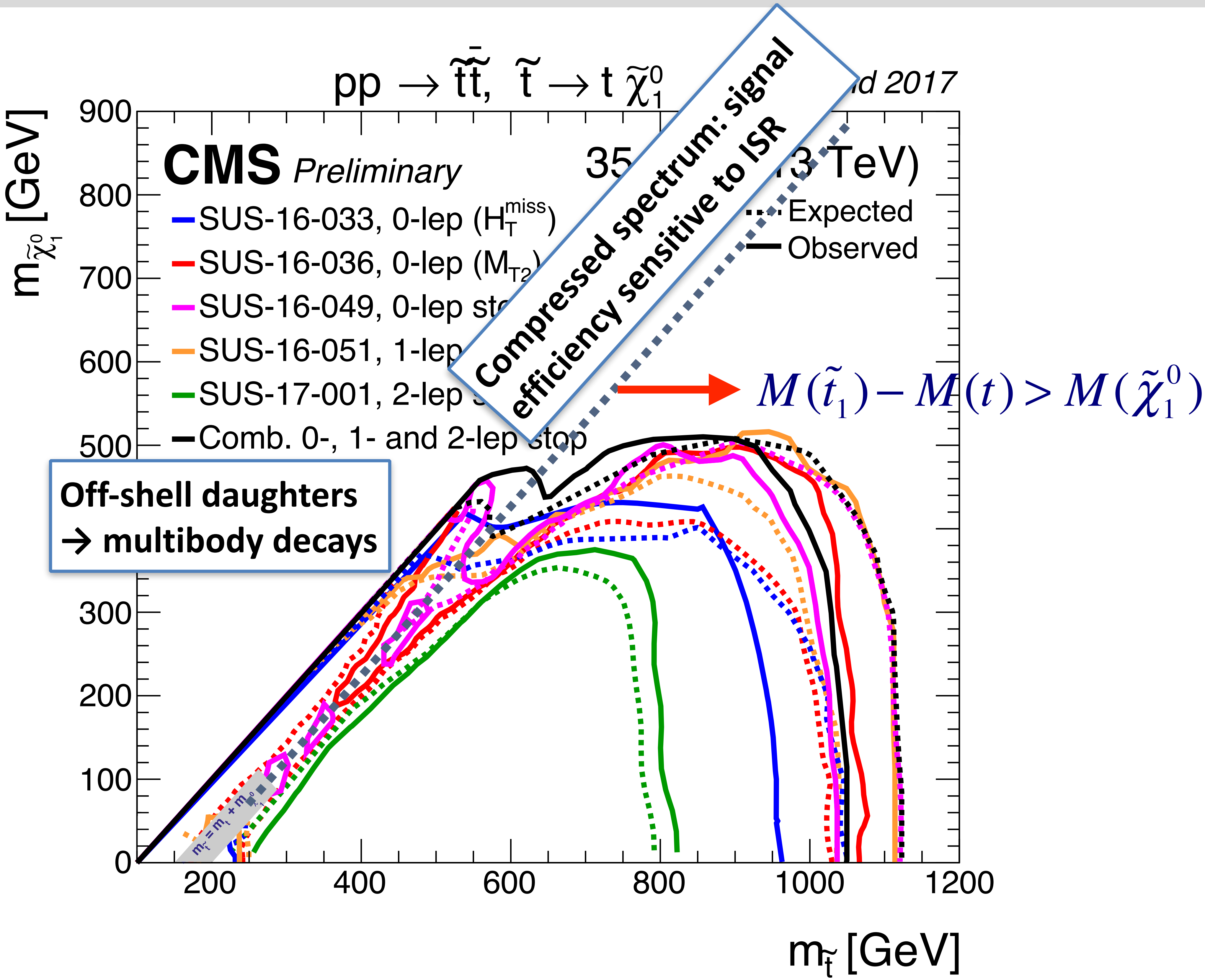


Excludes Higgsinos in mass range 230-770 GeV.

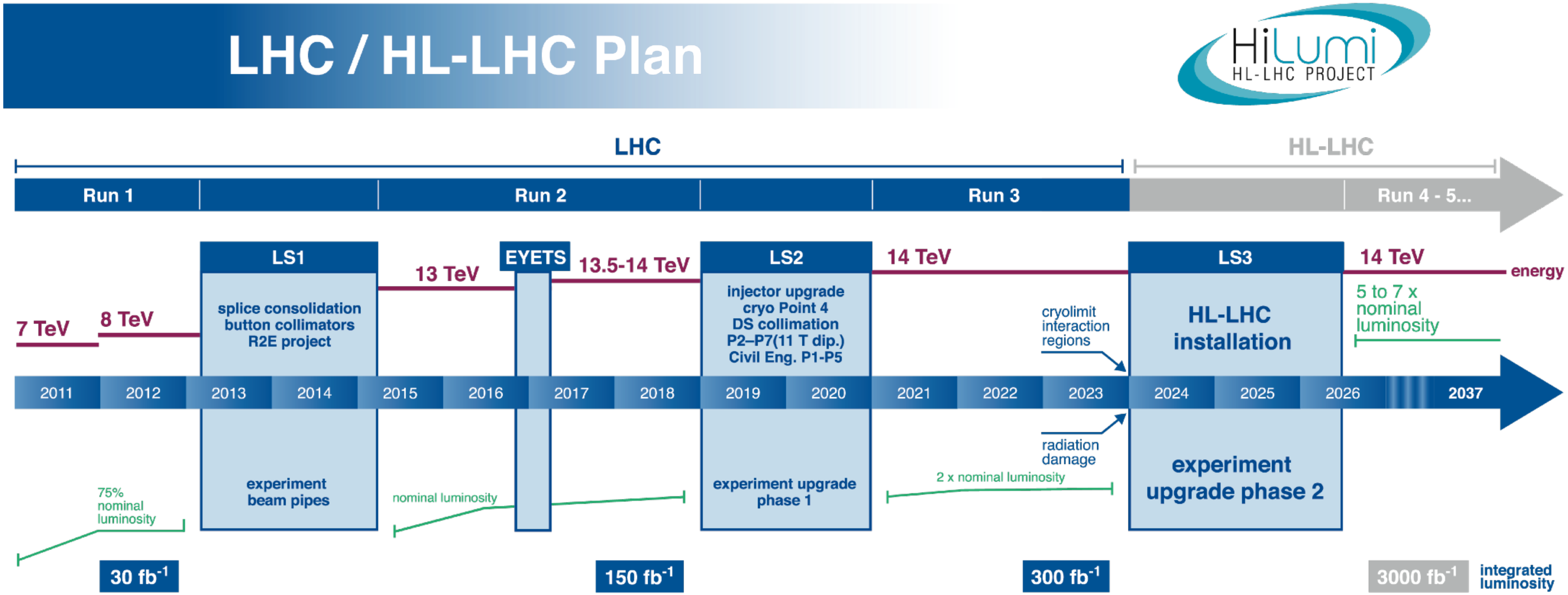
A lot of spaghetti, but no signals…



Exclusion limits on top squark pair production



LHC timeline



Conclusions and prospects

- Early Run 2 searches have already significantly extended the mass reach for strongly produced SUSY particles.
- There is now considerable pressure on natural SUSY.
- But…
  - SUSY has many ways to hide. We have to keep looking.
  - significant assumptions used in obtaining our exclusion limits.
- If no significant excess is observed with ~300 fb^{-1}, the strongest discovery possibilities may be associated with EWK processes.
- Evidence of an excess event yield over the SM with ~300 fb^{-1} will open the door to an intensive HL-LHC program to illuminate the nature of the excess.
- We are at a relatively early phase in the exploration of the TeV energy scale. It took ~10^2 years to understand the 1 GeV scale!

History and a prediction

New York Times, January 5, 1993

January 5, 1993

315 Physicists Report Failure In Search for Supersymmetry

By MALCOLM W. BROWNE

Three hundred and fifteen physicists worked on the experiment.

Their apparatus included the Tevatron, the world's most powerful particle accelerator, as well as a $65 million detector weighing as much as a warship, an advanced new computing system and a host of other innovative gadgets.

New York Times, January 5, 2024

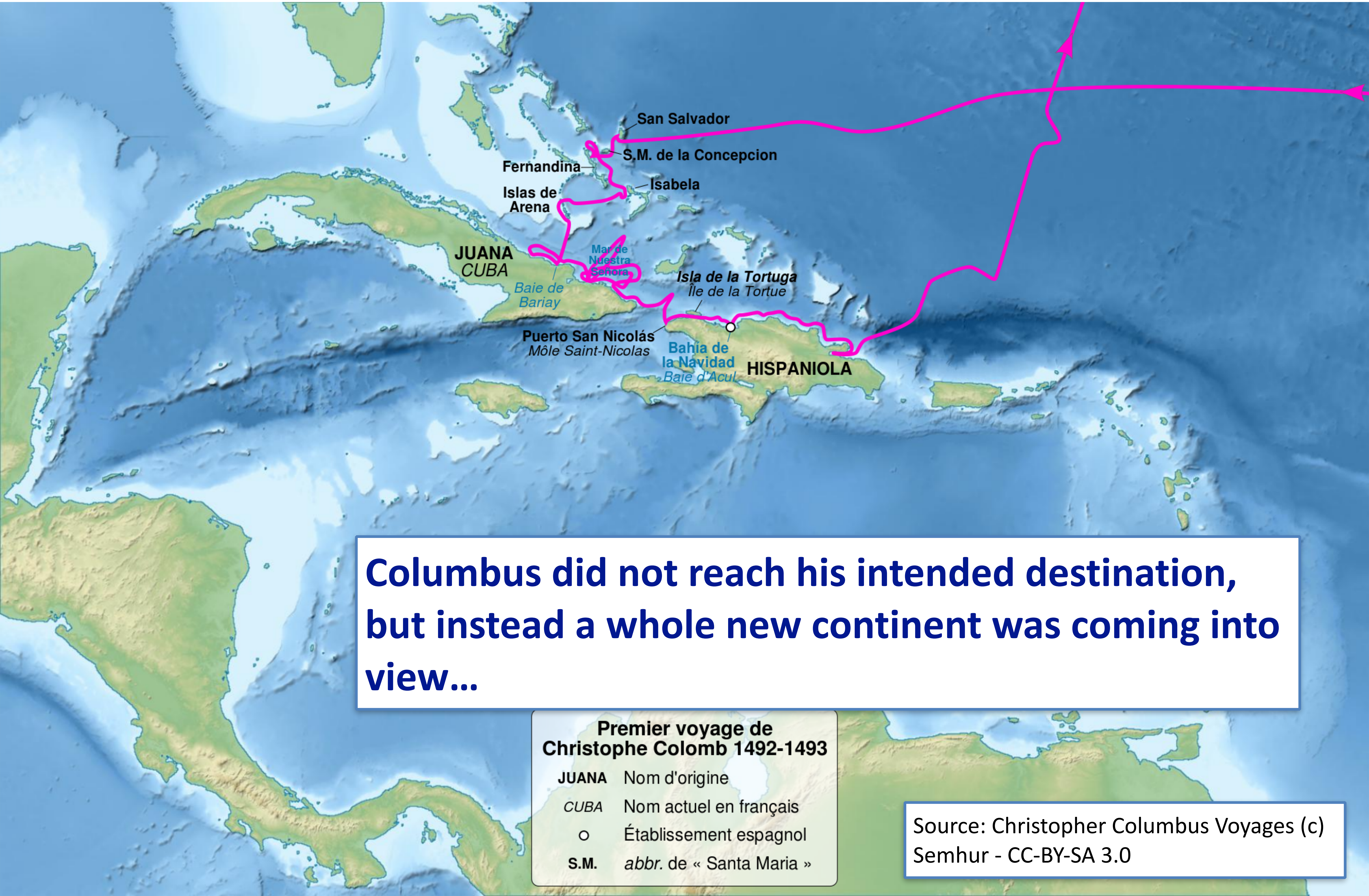
8,345 Physicists Report Discovery of Something But Aren't Exactly Sure What It Is

Eight thousand, three hundred and forty five physicists worked on two gigantic experiments, ATLAS and CMS.

Their apparatus included the Large Hadron Collider, the world's most powerful particle accelerator, as well as…

Backup slides

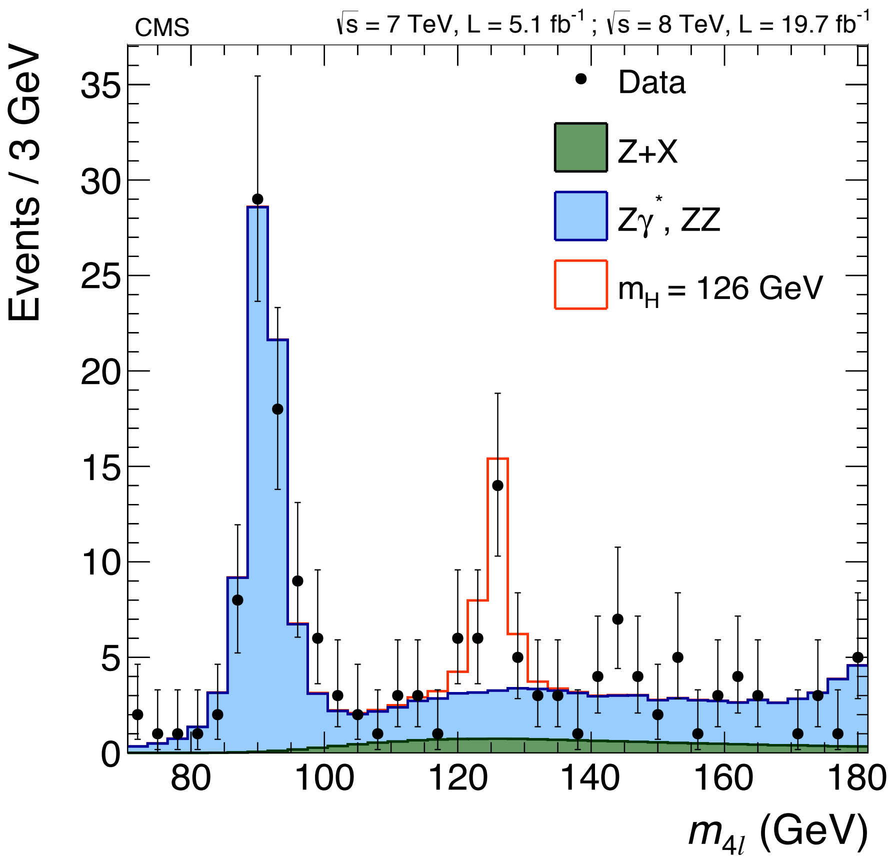
You can discover something and not know what it is



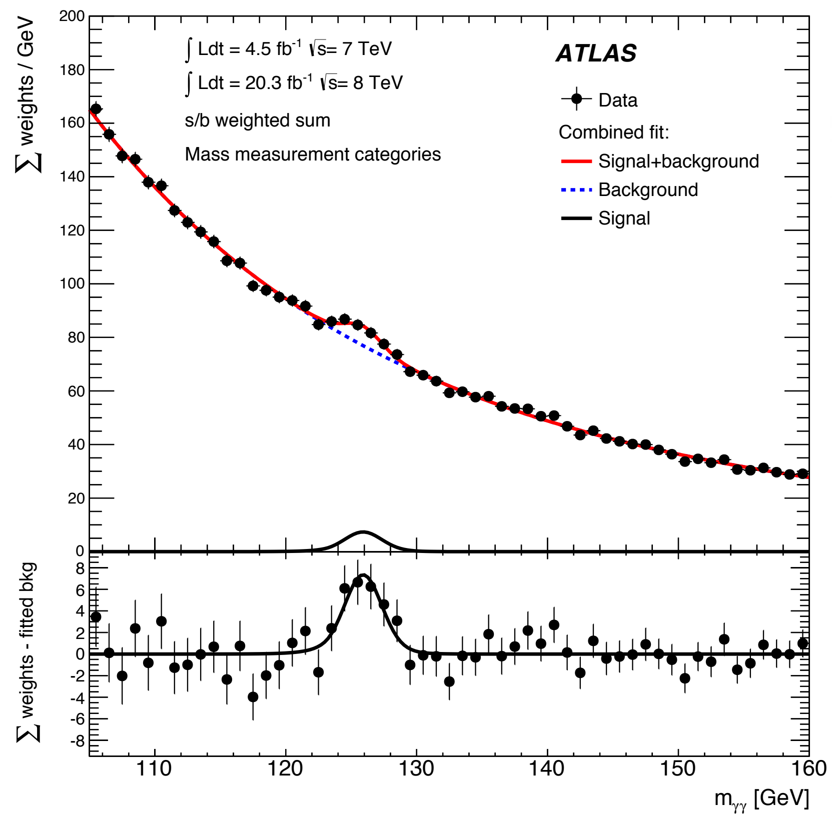
Columbus did not reach his intended destination, but instead a whole new continent was coming into view…

Perspective from Run 1

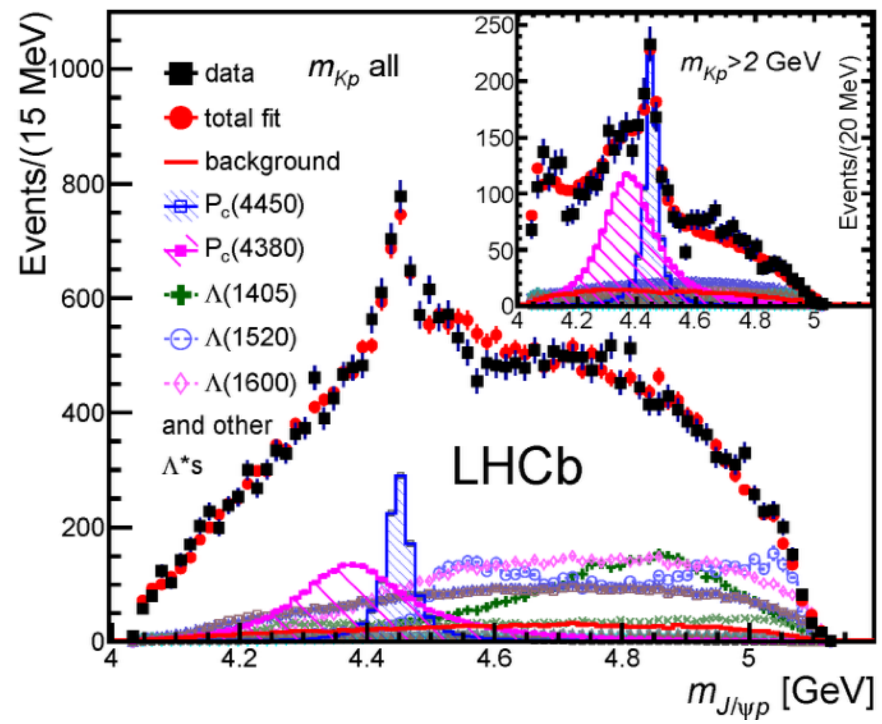
$H \to ZZ^*$



$H \to \gamma\gamma$



$\Lambda_b^0 \to K^- P_c^+(\bar{c}cuud);\ P_c^+ \to J/\psi\, p$

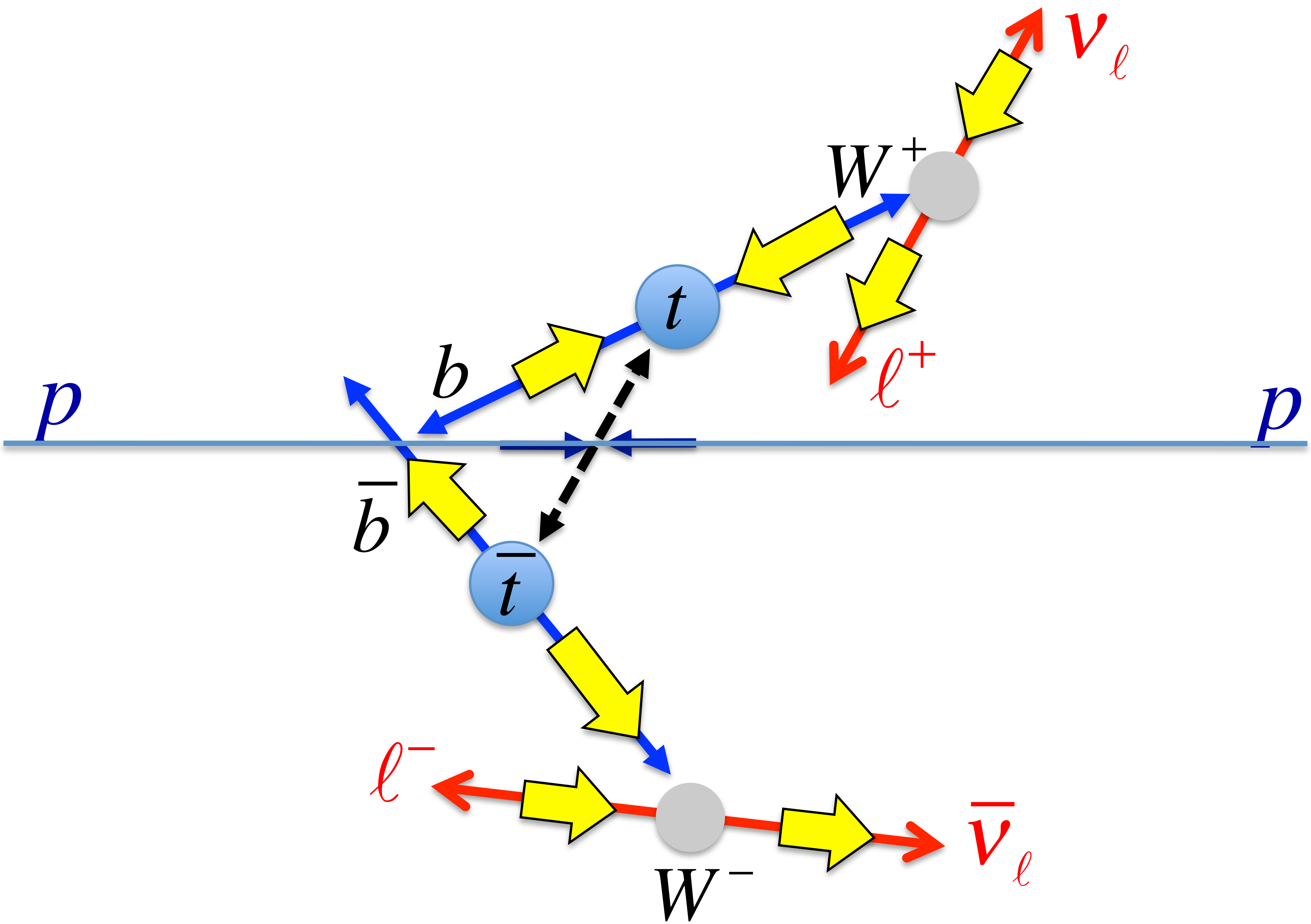


Phys. Rev. Lett. 115 (2015) 072001

Rapid interpretation of Higgs discovery!

- Higgs discovery: strong evidence for our overall picture of EW symmetry breaking. **But the question of how the EW mass scale is stabilized against short-distance quantum corrections is now even more urgent.**
- LHC-b: Two charmonium-pentaquark states → **Still a lot to learn about the hadronic (~1 GeV) mass scale, 70 years after discovery of the pion.**
- **A guess: it will take at least as long to understand the physics of the EW scale.**

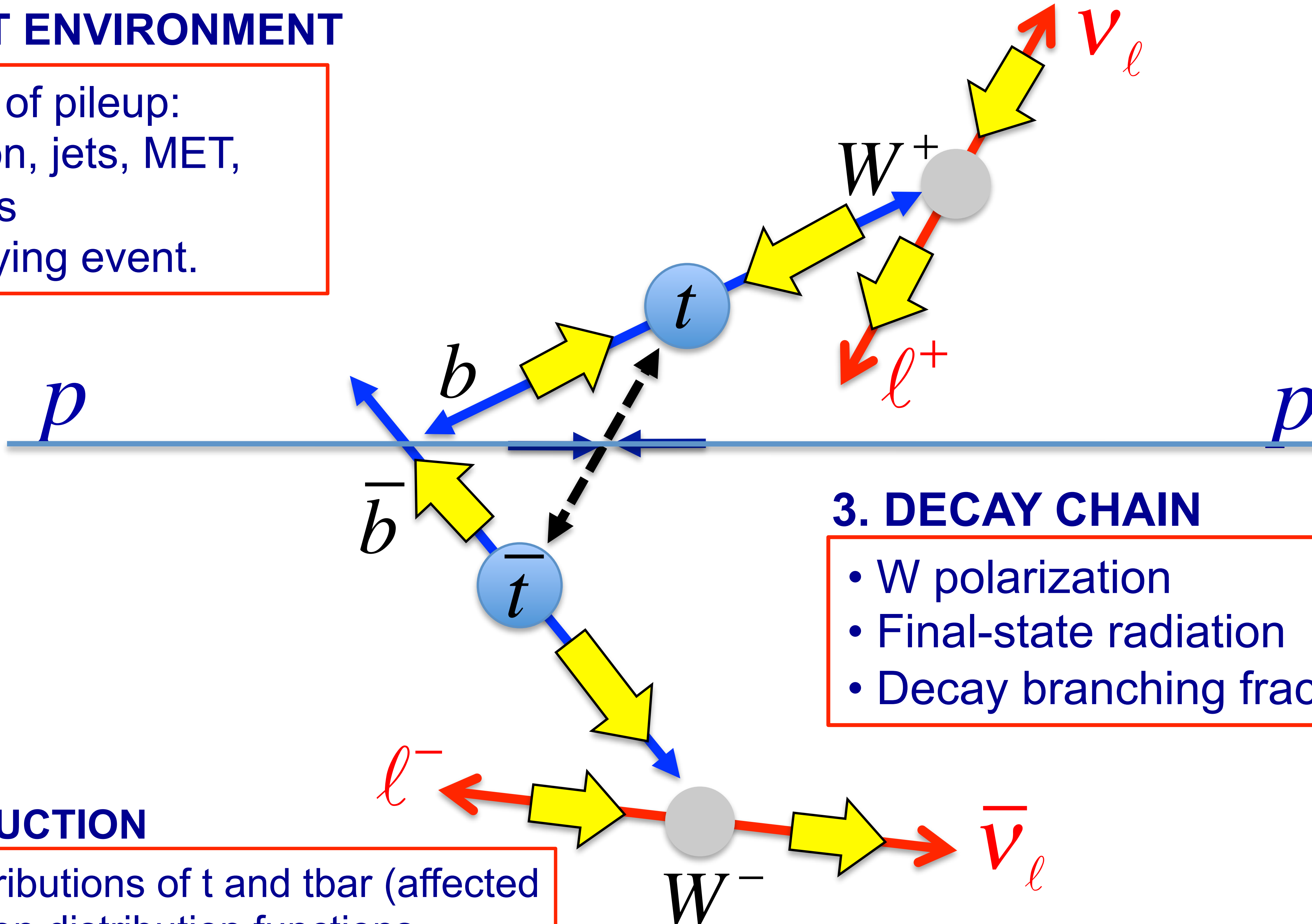
The most SUSY-like SM background: ttbar



The most SUSY-like SM background: ttbar

1. EVENT ENVIRONMENT

- Effects of pileup: isolation, jets, MET, vertices
- Underlying event.



3. DECAY CHAIN

- W polarization
- Final-state radiation
- Decay branching fractions

2. PRODUCTION

- pT distributions of t and tbar (affected by parton distribution functions, QCD renorm & factorization scales)
- Effect of initial-state radiation
- Spin correlations of t and tbar

Quick look at three example SUSY searches

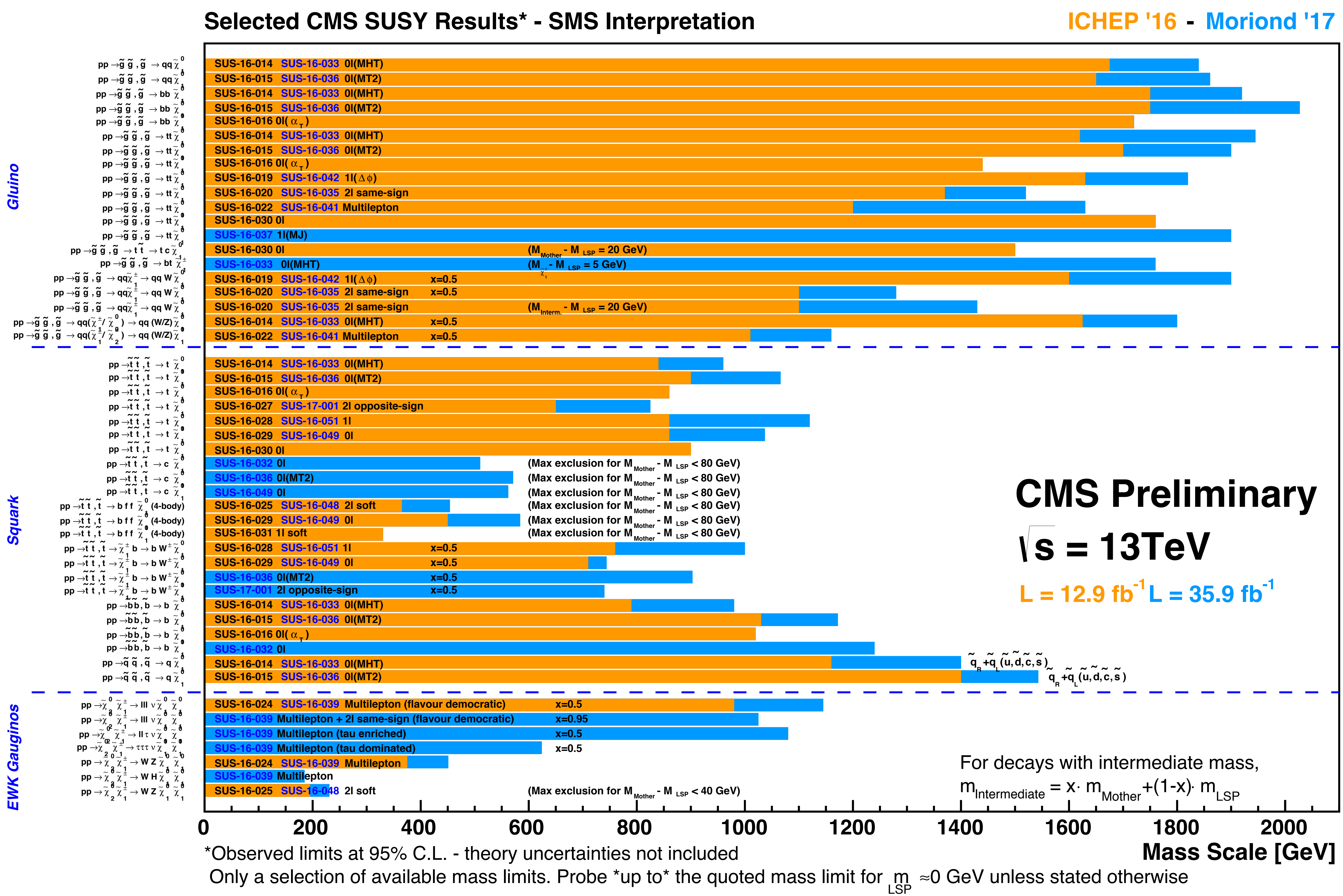
Signature	Trigger(s)	Dominant backgrounds	Background determination
All hadronic: Jets + p_T^{miss} Inclusive, heavily binned, search targets broad range of strongly produced SUSY	p_T^{miss}	ttbar 1 lepton (e, mu), ttbar $\tau\rightarrow$had, Z + jets, QCD multijet events	Control region(s) for each background; correction factors for each background/ analysis bin
1 lepton + (b)-jets + p_T^{miss} Targets strongly produced natural SUSY with higher jet multiplicity	p_T^{miss} OR single lepton	ttbar dilepton events with one “lost” lepton	ABCD method with small MC correction; systematics from additional control samples
HH + p_T^{miss}; H$\rightarrow$ bb Targets electroweak production of higginos in gauge-mediated SUSY breaking models	p_T^{miss}	ttbar 1 lepton events with lost lepton	ABCD method with no MC correction

Quick look at three example SUSY searches

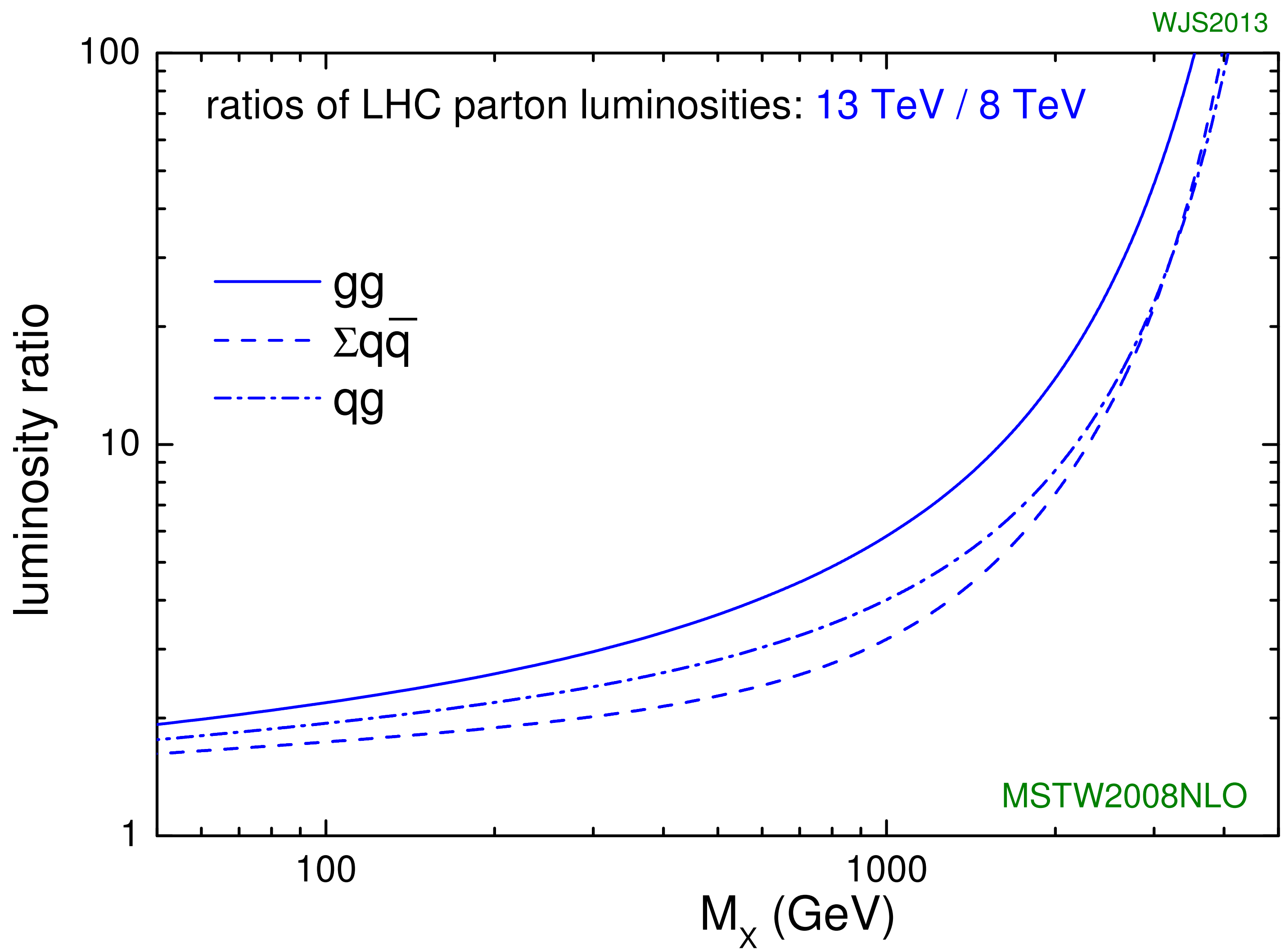
Signature	Scenarios	Dominant backgrounds	Background determination
All hadronic: Jets + p_T^{miss} Inclusive, heavily binned, search targets broad range of strongly produced SUSY	**More inclusive: addresses wider range of SUSY scenarios.**	**More inclusive: wider range of backgrounds to understand.**	**More inclusive: search regions span broader range → more reliance on MC for background estimation.**
1 lepton + (b)-Jets + p_T^{miss} Targets strongly produced natural SUSY with higher jet multiplicity			
HH + p_T^{miss}; H→ bb Targets electroweak production of higginos in gauge-mediated SUSY breaking models	**More specific: better sensitivity to targeted process.**	**More specific: limited set of backgrounds.**	**More specific: less dependence on MC for background estimation.**

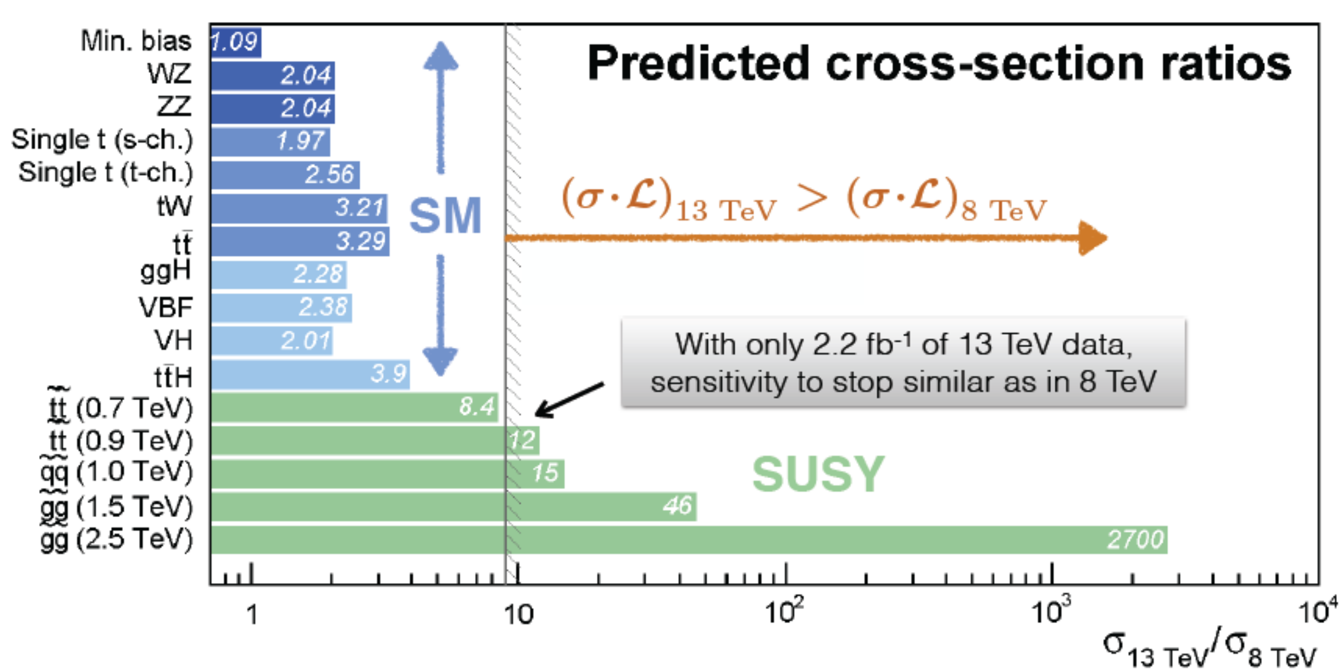
More control samples → more ways to find problems that you didn't even think of!

Searching for SUSY is a major program

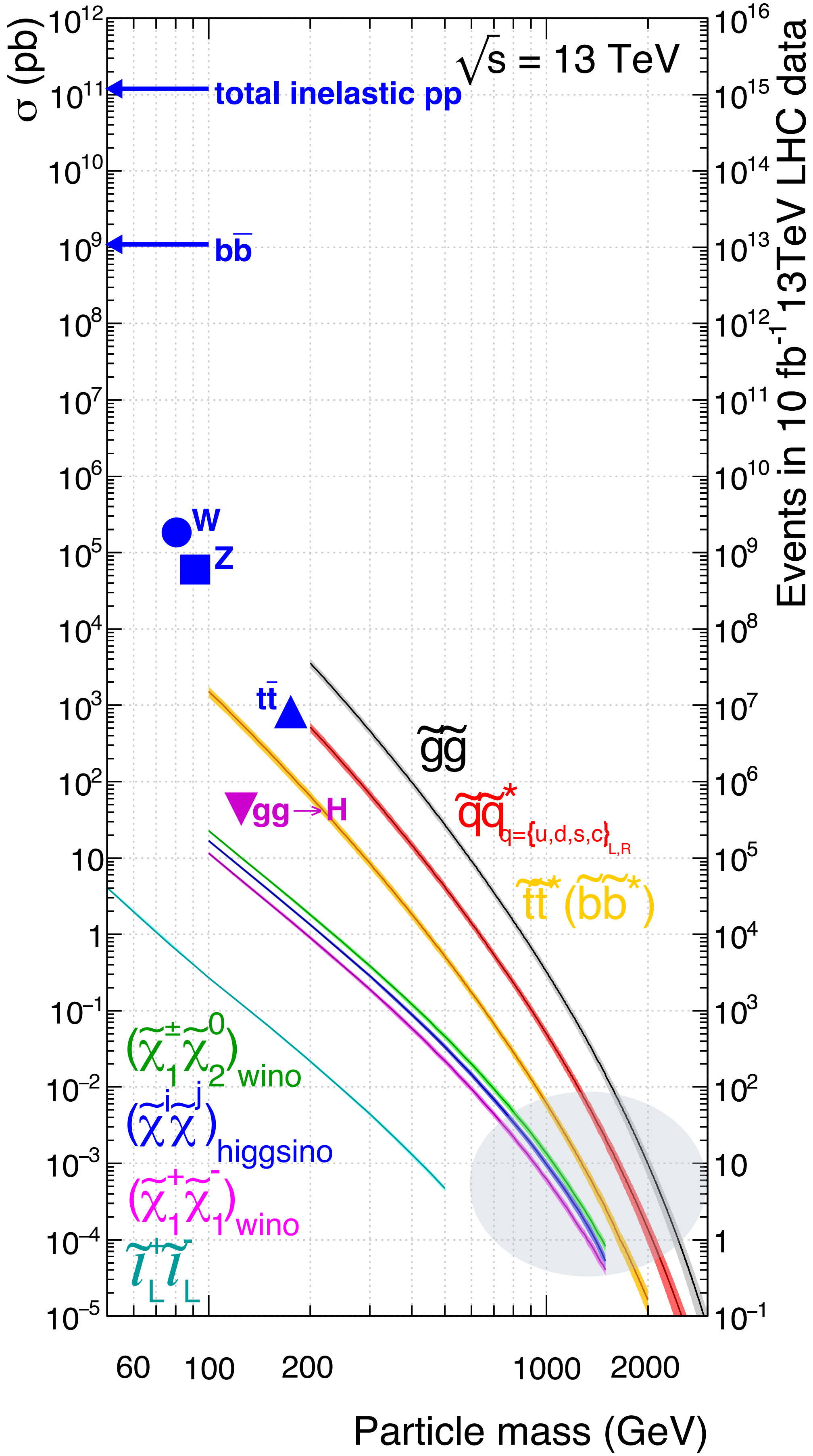


From 8 TeV to 13 TeV



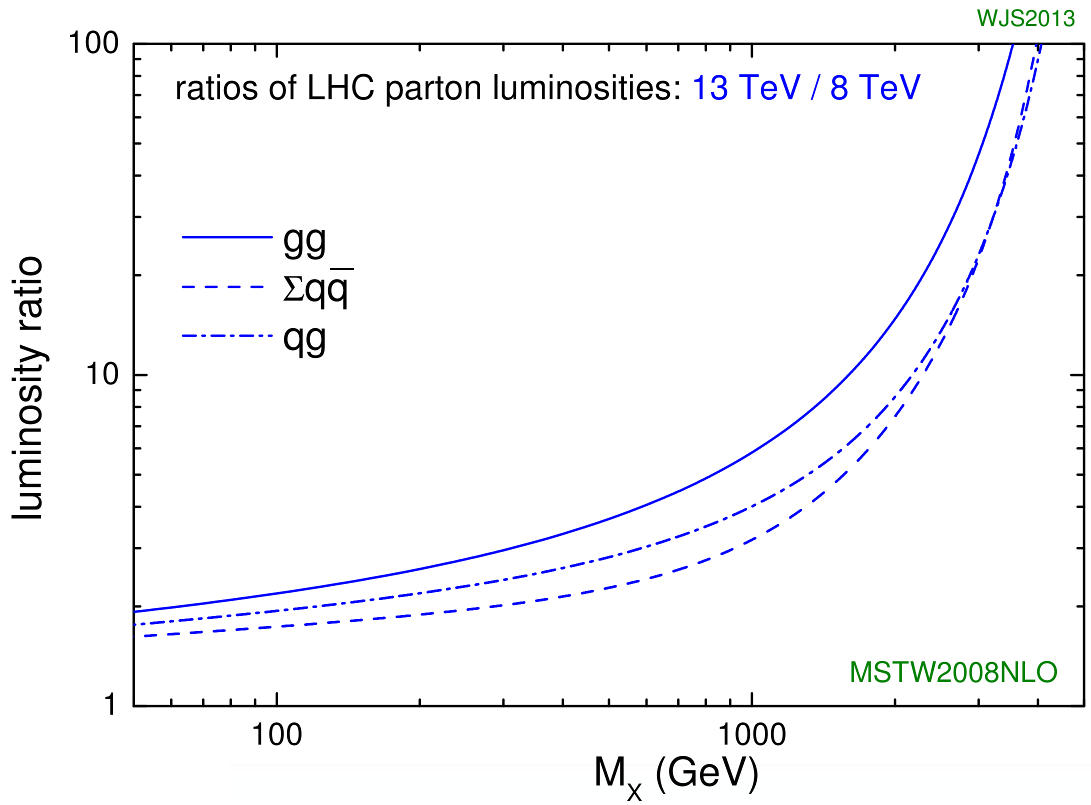


Remarks on backgrounds and methods

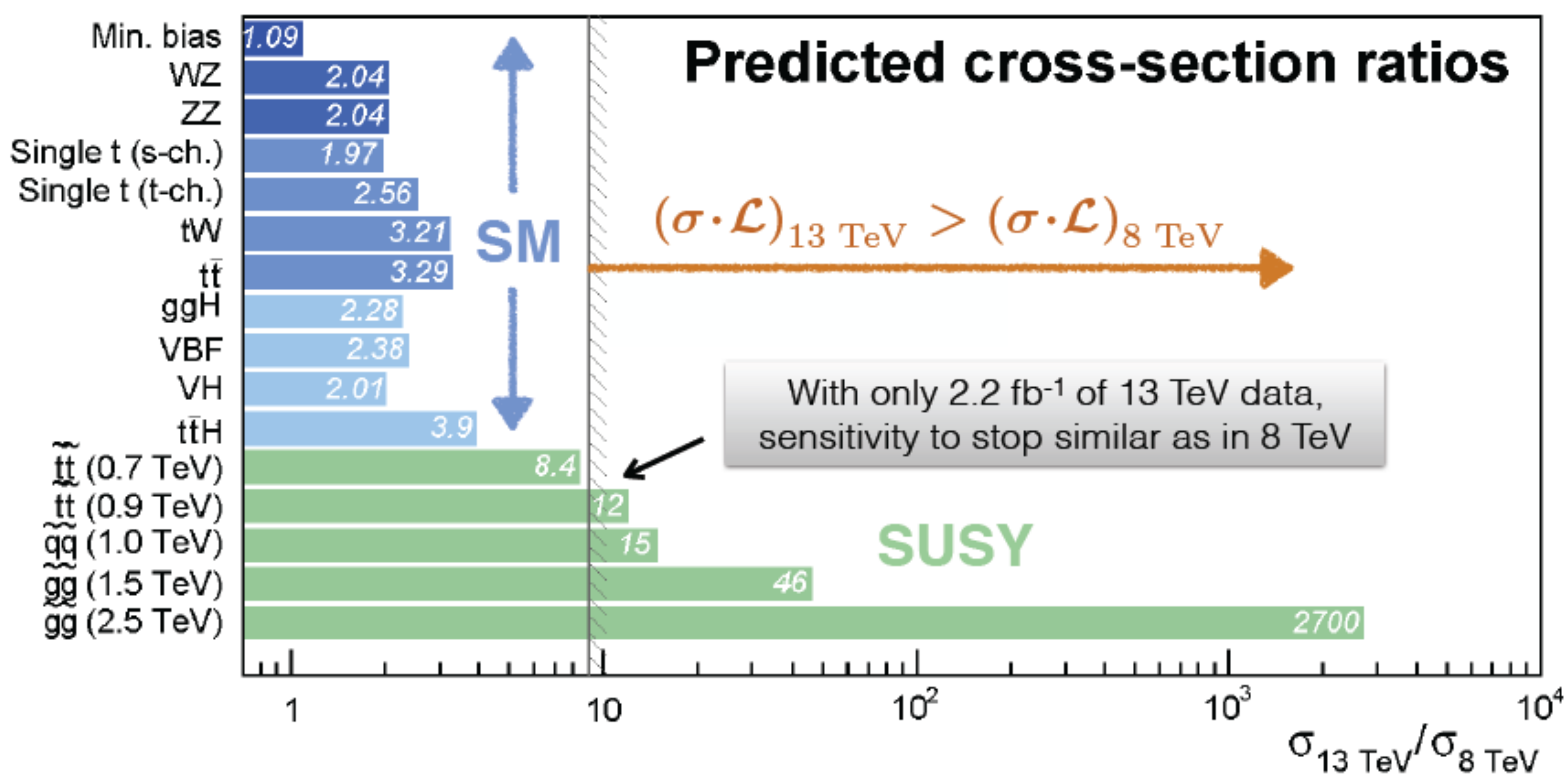


- Have entered the territory where SUSY cross sections are much less than those of the dominant SM backgrounds.
- Very tight kinematic cuts; operate on extreme tails of SM distributions such as E_T^{miss}. "Weak" signatures (no peaks).
- Need highly robust background estimation methods. Rely extensively on control samples, less on MC.

From 8 TeV to 13 TeV: 2 fb^{-1} goes a long way!

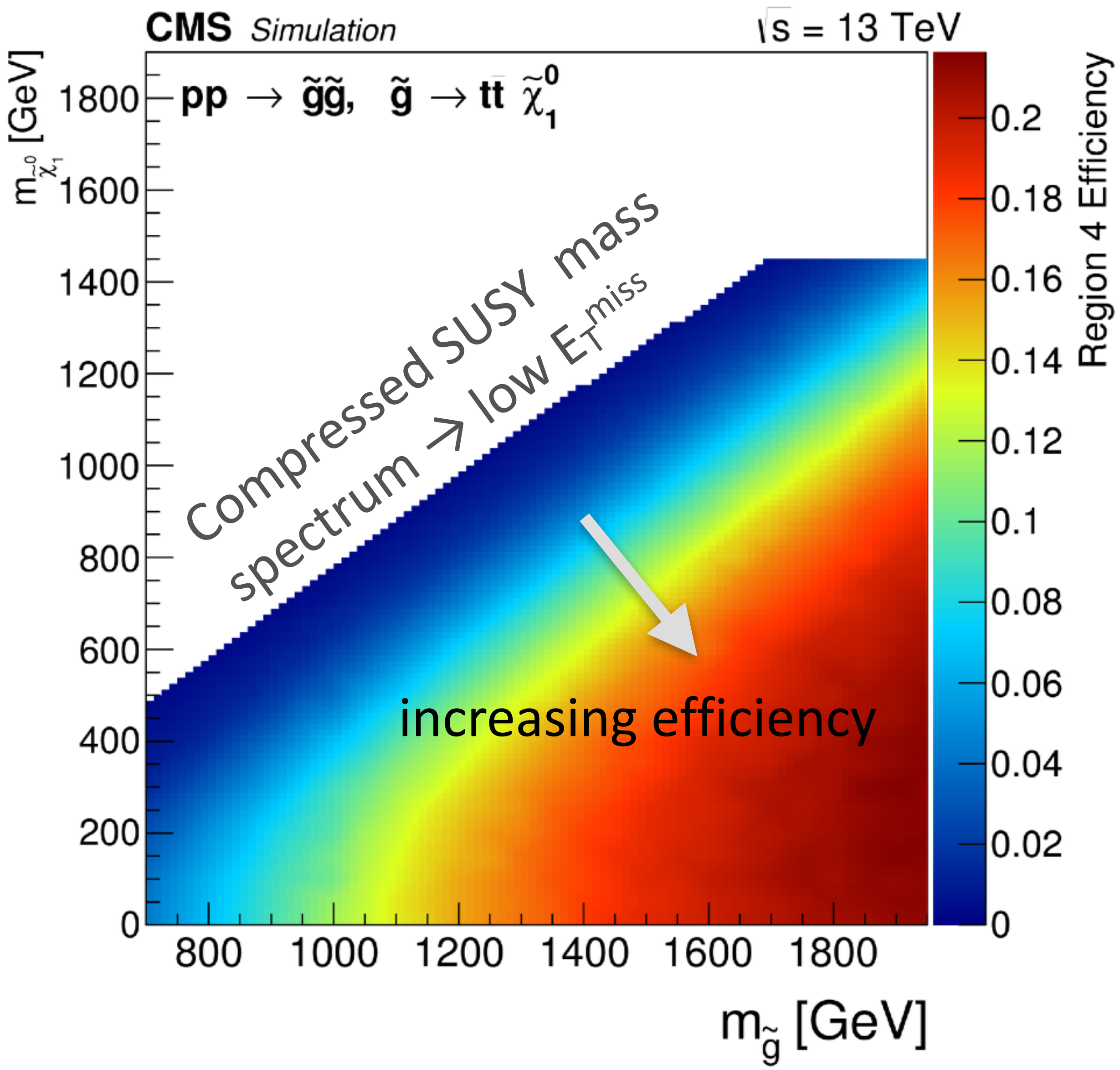


- The 13 TeV data sample has only ~1/10 the luminosity of the 8 TeV data sample.
- But sensitivity for this search still surpasses that at 8 TeV!

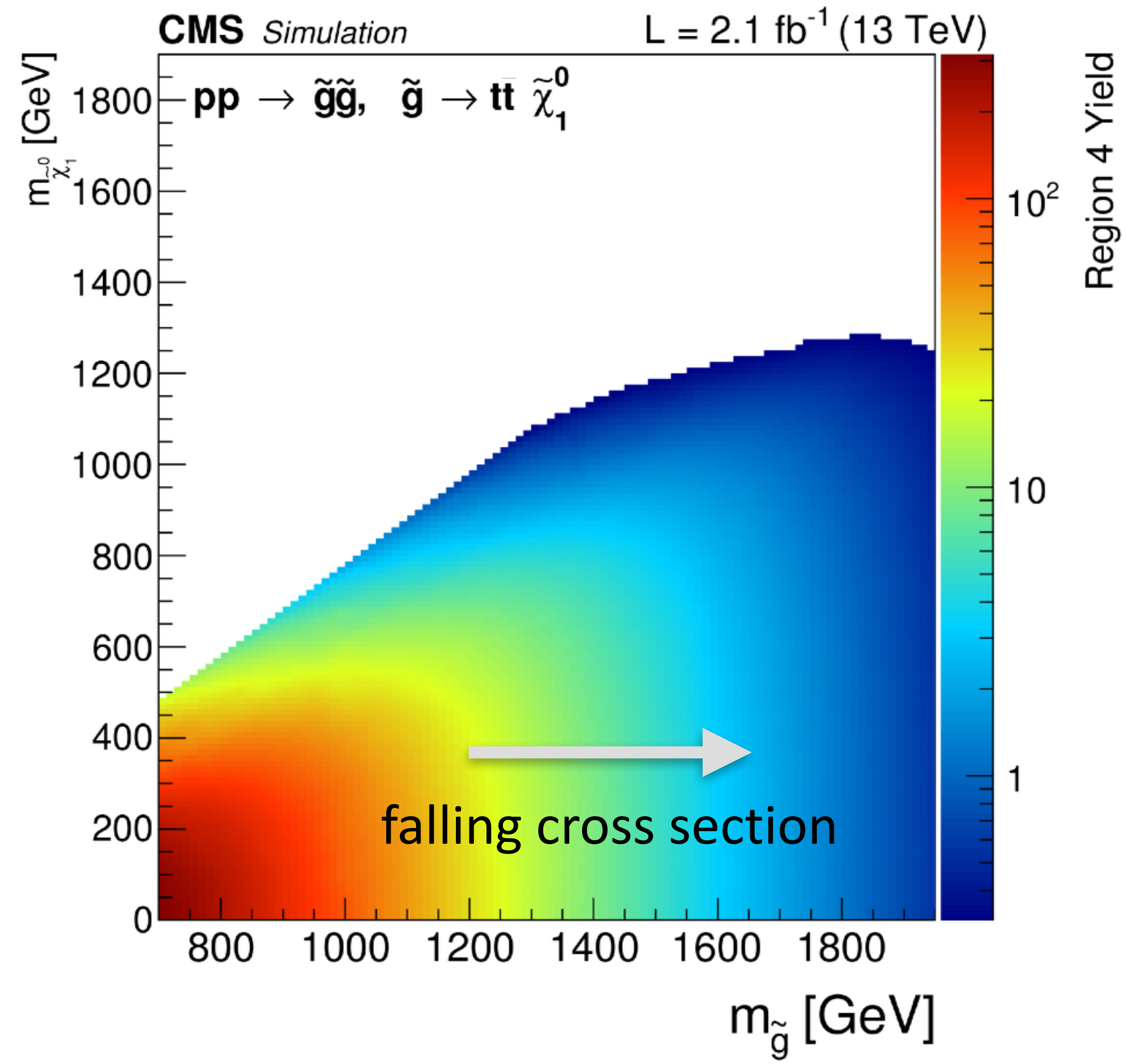


Signal efficiency and expected yields for T1tttt

Signal efficiency vs. $M(\tilde{g})$ and $M(\tilde{\chi}_1^0)$



Signal event yield vs. $M(\tilde{g})$ and $M(\tilde{\chi}_1^0)$

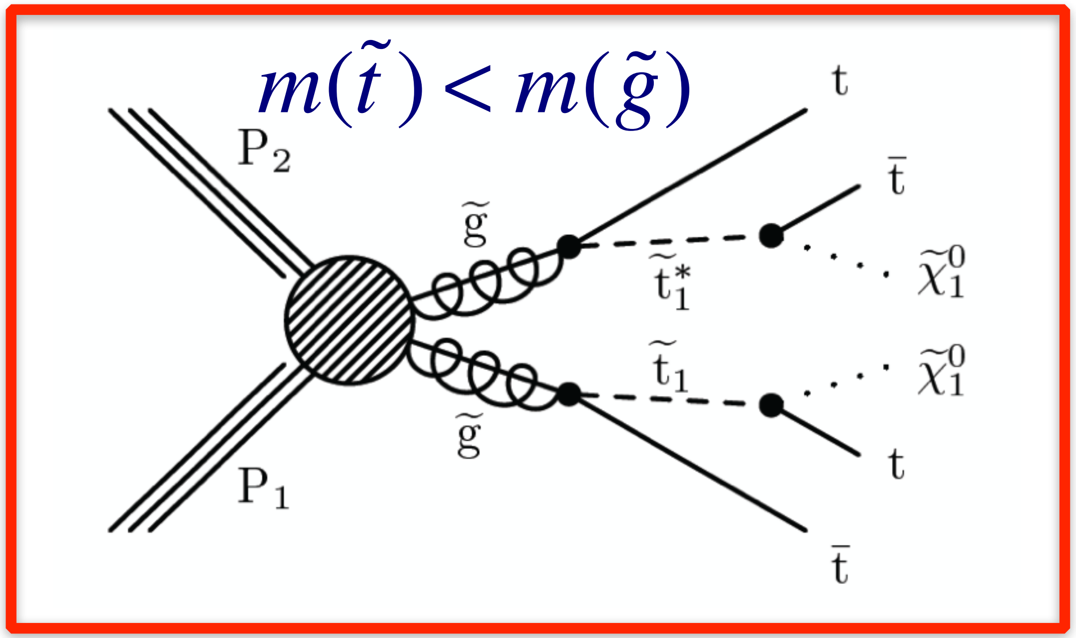


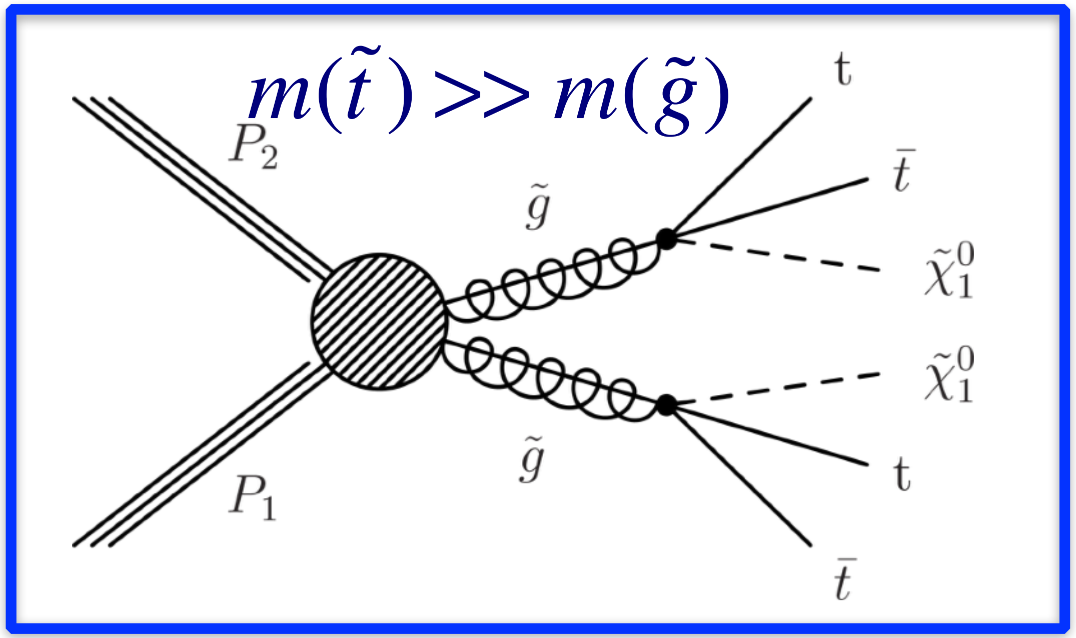
- Signal efficiency increases moving away from the diagonal, where the spectrum compresses and E_T^{miss} becomes small.
- Expected signal event yield decreases with increasing $m(\tilde{g})$.

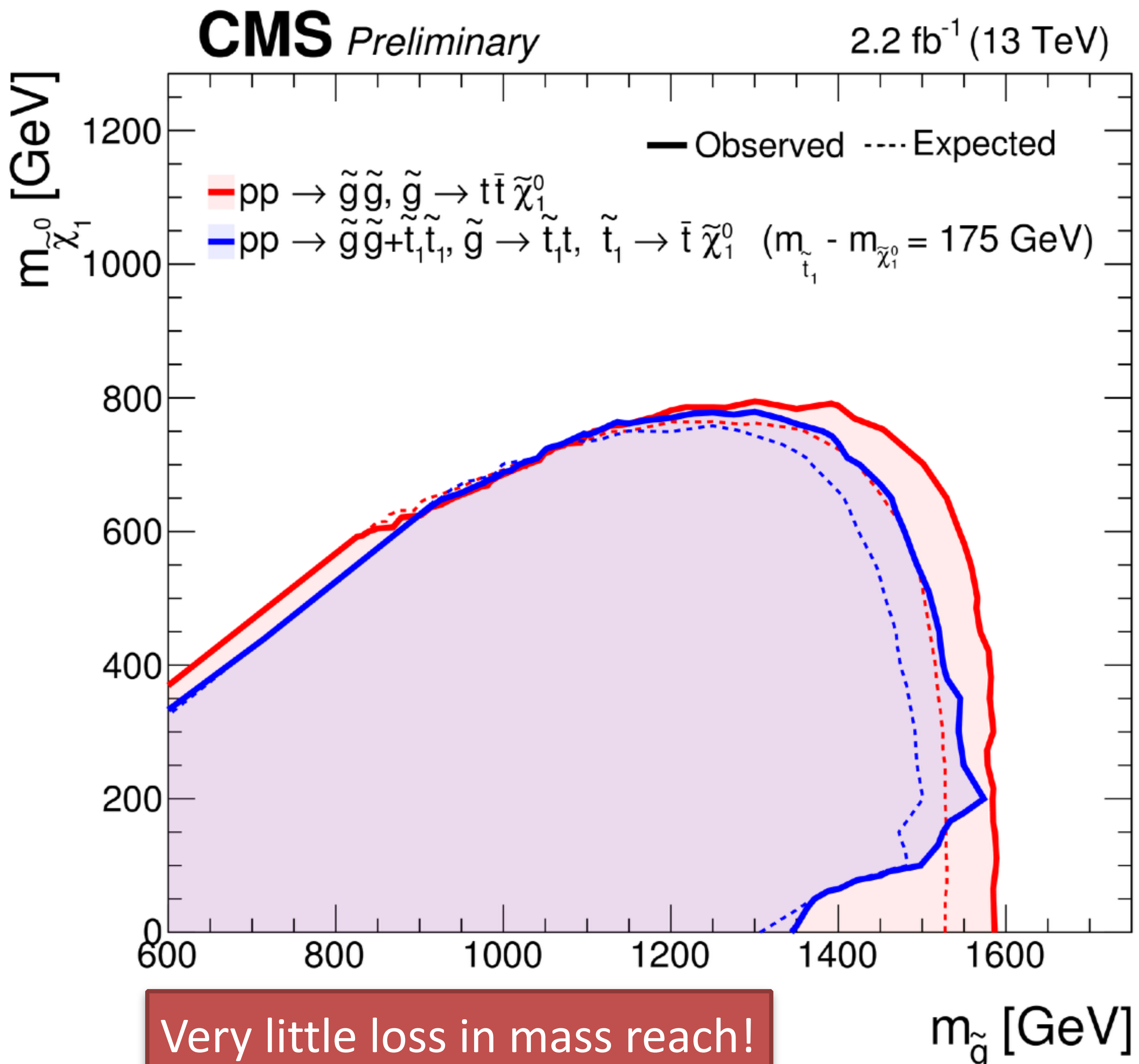
Excluded region for on-shell top squarks

How would intermediate-state, on-shell top squarks in gluino decay affect the limits?

Most difficult case (lowest efficiency) corresponds to the smallest allowed top squark mass for a given LSP mass: $m(\tilde{t}) = m(\tilde{\chi}_1^0) + m(t) \simeq m(\tilde{\chi}_1^0) + 175\ \text{GeV}$



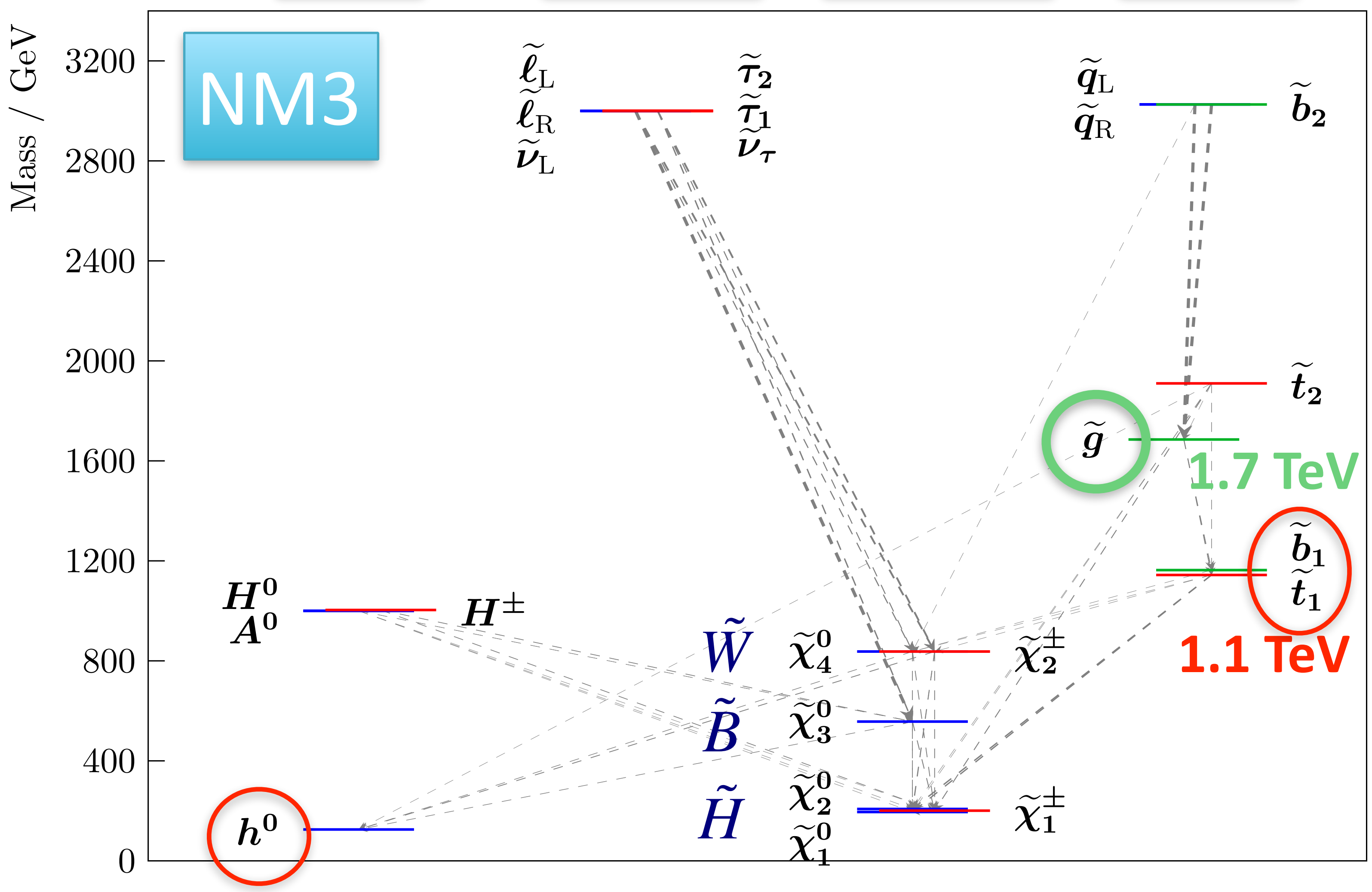




Very little loss in mass reach!

Discovery scenarios with full-spectrum models

CMS PAS SUS-14-012



The nature of the EWKino sector has a large influence on the decays of the top squark.

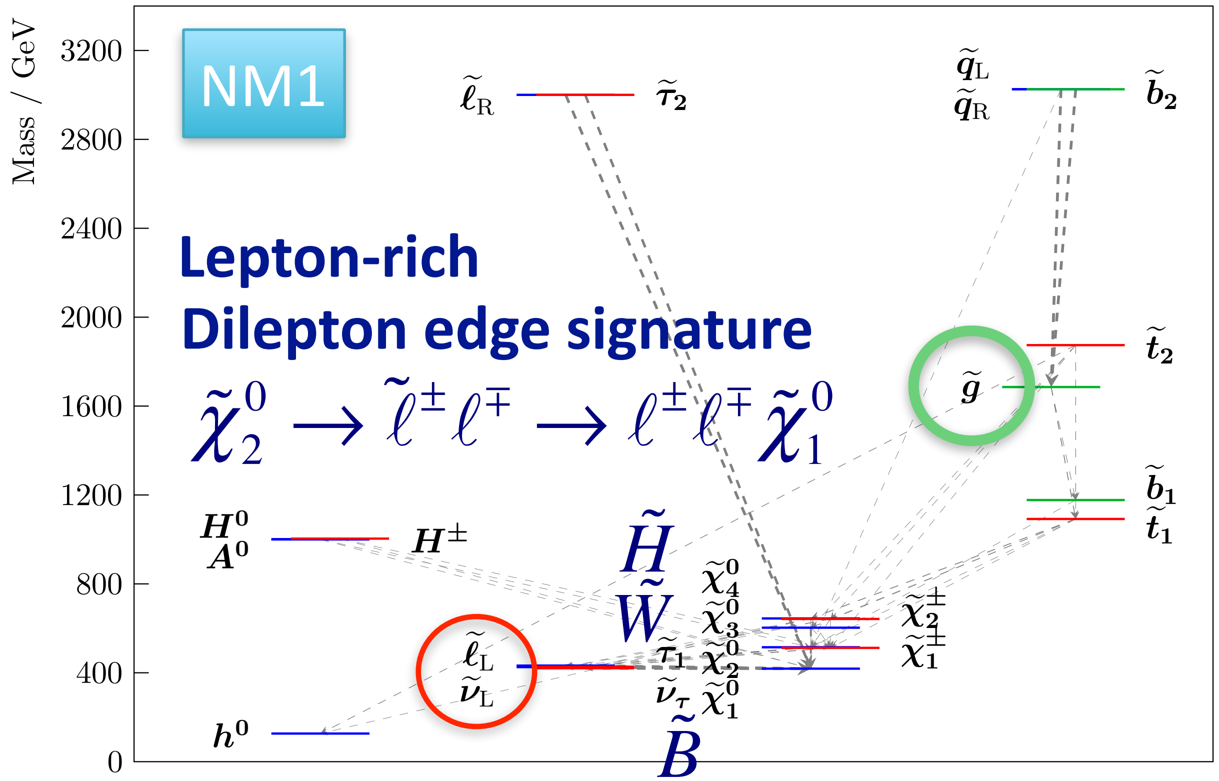
	NM1	NM2	NM3
$B(\tilde{t} \to t\tilde{\chi}_1^0)$	0.6%	1.5%	39%

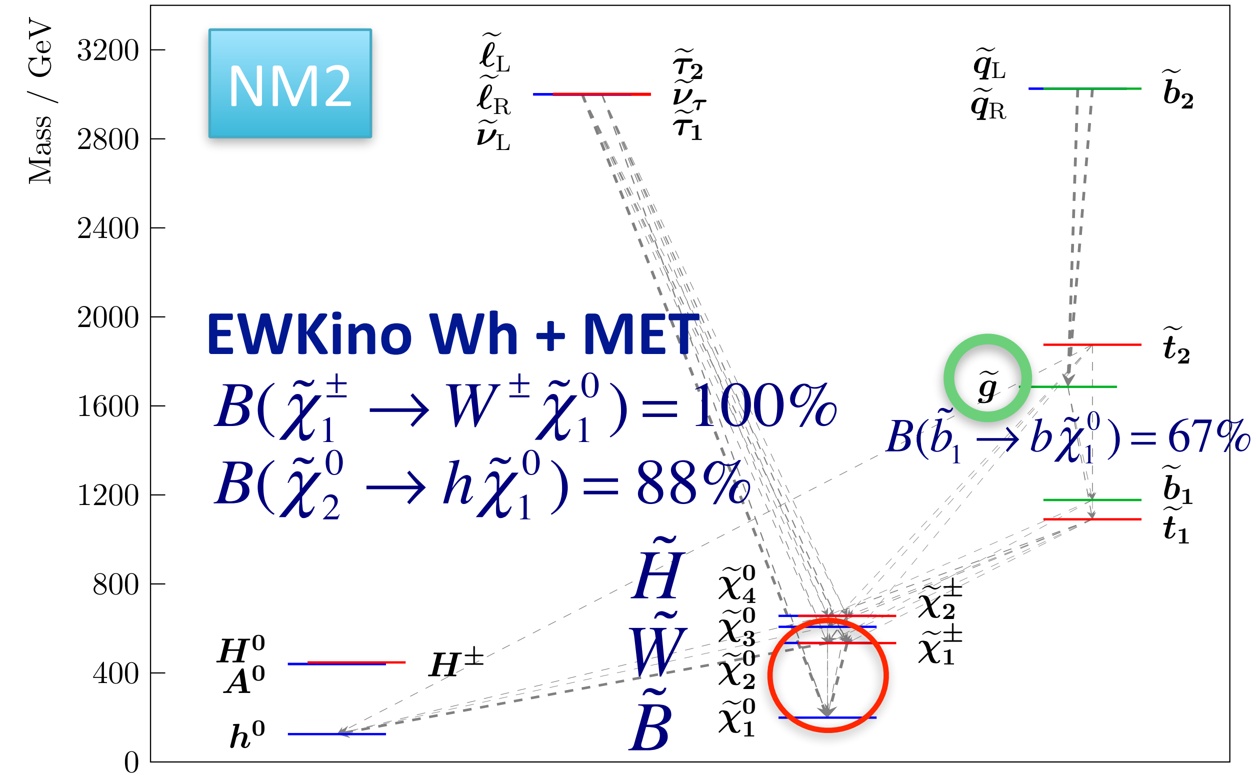
- **Studied 5 full-spectrum SUSY models.**
- **9 analyses performed in parallel.**
- m_H = 125 GeV
- **NM 1,2,3** ="Natural" Model 1, 2, 3

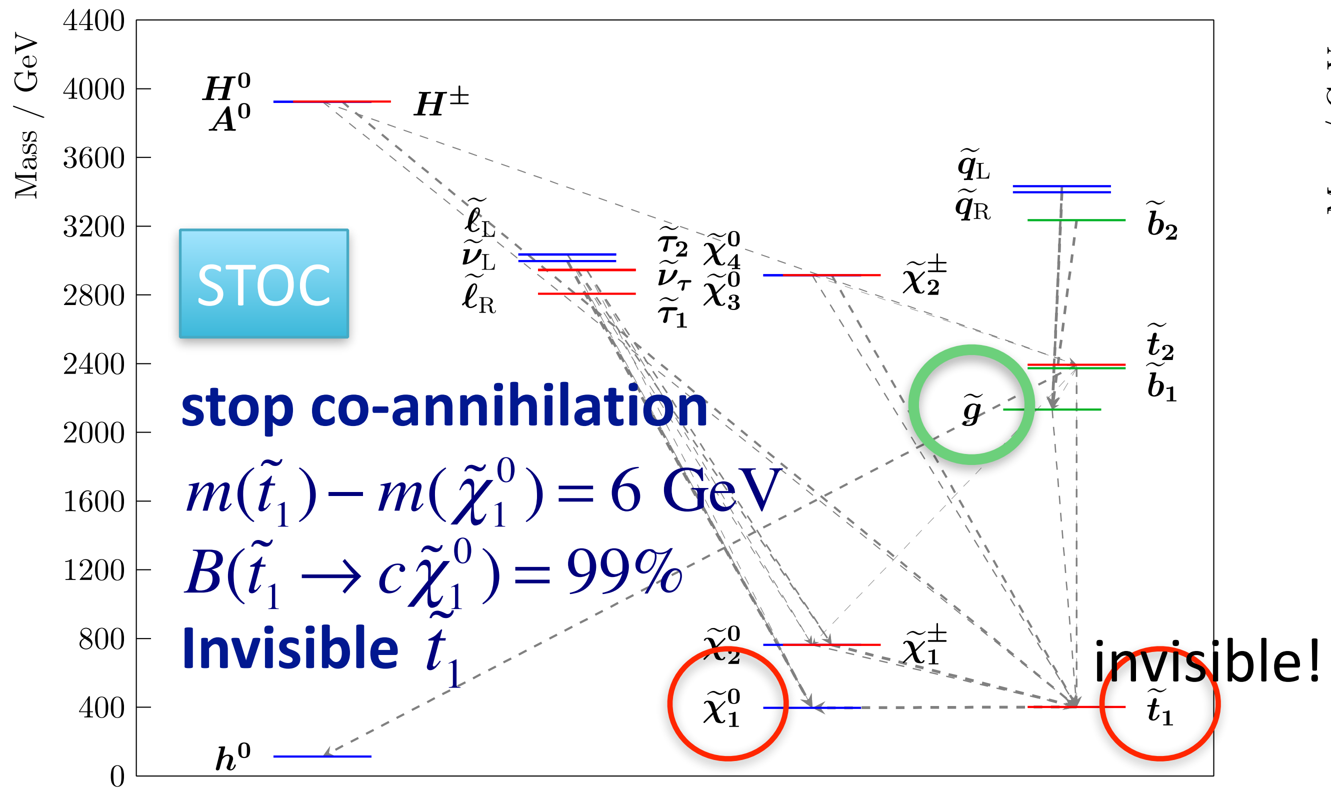
  $m(\tilde{g})$=1.7 TeV, $m(\tilde{t})$=1.1 TeV
- **STC** -Stau co-annihilation $m(\tilde{\tau}_1) \approx m(\tilde{\chi}_1^0) \approx 190$ GeV
- **STOC**-Stop co-annihilation $m(\tilde{t}_1) \approx m(\tilde{\chi}_1^0) \approx 400$ GeV

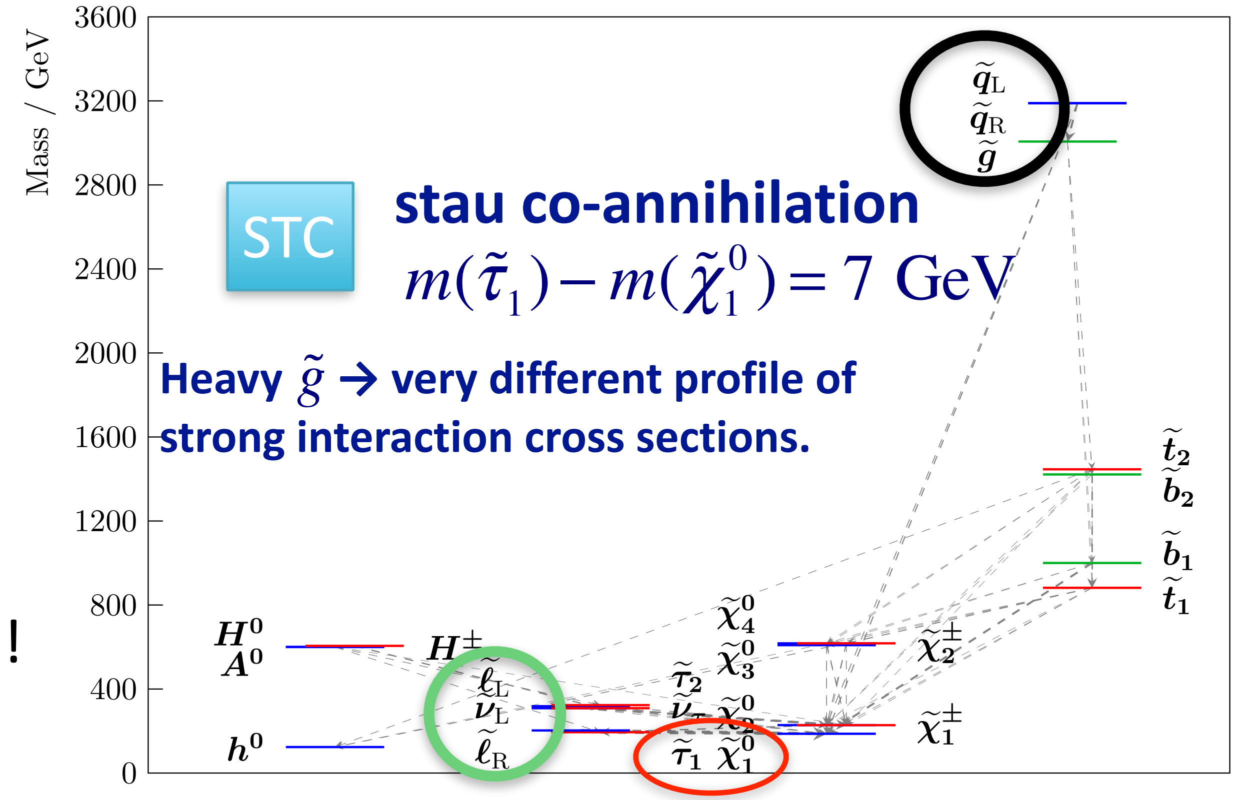
Discovery scenarios with full-spectrum models

CMS PAS SUS-14-012









SUSY models & multi-signature fingerprints

SUSY Model →

Experimental signature ↓

Analysis	Luminosity (fb^{-1})	Model				
		NM1	NM2	NM3	STC	STOC
all-hadronic (H_T-H_T^{miss}) search	300				$< 3\sigma$	$3-5\sigma$
	3000				$3-5\sigma$	$> 5\sigma$
all-hadronic (M_{T2}) search	300	$3-5\sigma$	$> 5\sigma$	$> 5\sigma$		
	3000	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$		
all-hadronic $\tilde{b}_1$ search	300	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$	$3-5\sigma$	$< 3\sigma$
	3000	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$	$> 5\sigma$	$< 3\sigma$
1-lepton $\tilde{t}_1$ search	300	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$3-5\sigma$	$< 3\sigma$
	3000	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$
monojet $\tilde{t}_1$ search	300					$3-5\sigma$
	3000					$3-5\sigma$
$m_{\ell^+\ell^-}$ kinematic edge	300	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$		
	3000	$> 5\sigma$	$< 3\sigma$	$< 3\sigma$		
multilepton + b-tag search	300	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$3-5\sigma$	
	3000	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	
multilepton search	300	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$	
	3000	$3-5\sigma$	$3-5\sigma$	$< 3\sigma$	$3-5\sigma$	
ewkino WH search	300		$< 3\sigma$			
	3000		$3-5\sigma$			

$< 3\sigma$ | $3-5\sigma$ | $> 5\sigma$

No mass peaks! Interpretation will be very complex. Is it even SUSY?
Different signatures can require very different amounts of data to detect!

SUSY models & multi-signature fingerprints

SUSY Model

Experimental signature

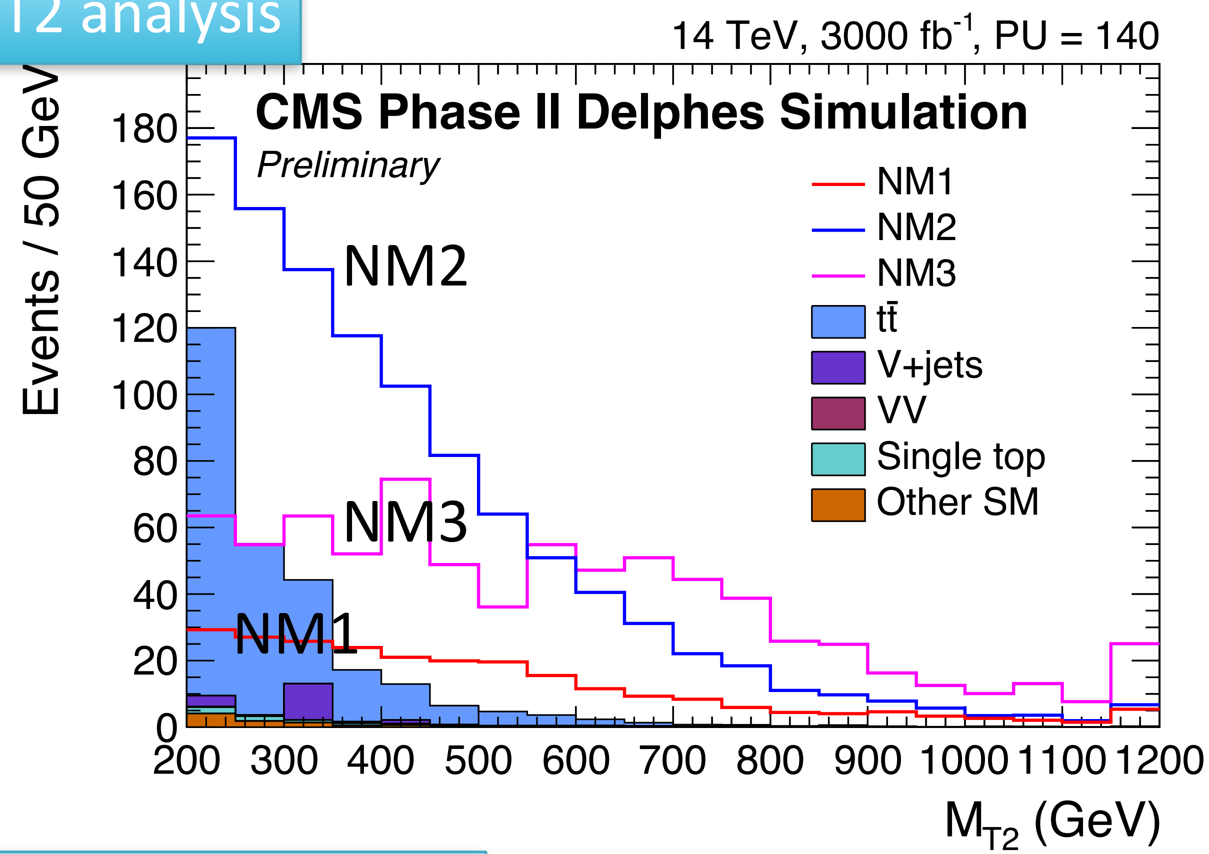
Analysis	Luminosity (fb^{-1})	Model				
		NM1	NM2	NM3	STC	STOC
all-hadronic (H_T-H_T^{miss}) search	300					
	3000					
all-hadronic (M_{T2}) search	300					

- **Powerful approach, but in reality, there are an infinite number of possible theories (not 5), so the challenge is very significant.**
- **Multi-signature fingerprint will require large data samples to acquire.**
- **Different search channels can produce significant signals at very different times.**
- **Interpretation of a significant excess is likely to be much slower than for the Higgs discovery.**
- **"Discovery" could take place with multiple 3-4 σ excesses, rather than a single 5σ excess.**

$< 3\sigma$	$3-5\sigma$	$> 5\sigma$

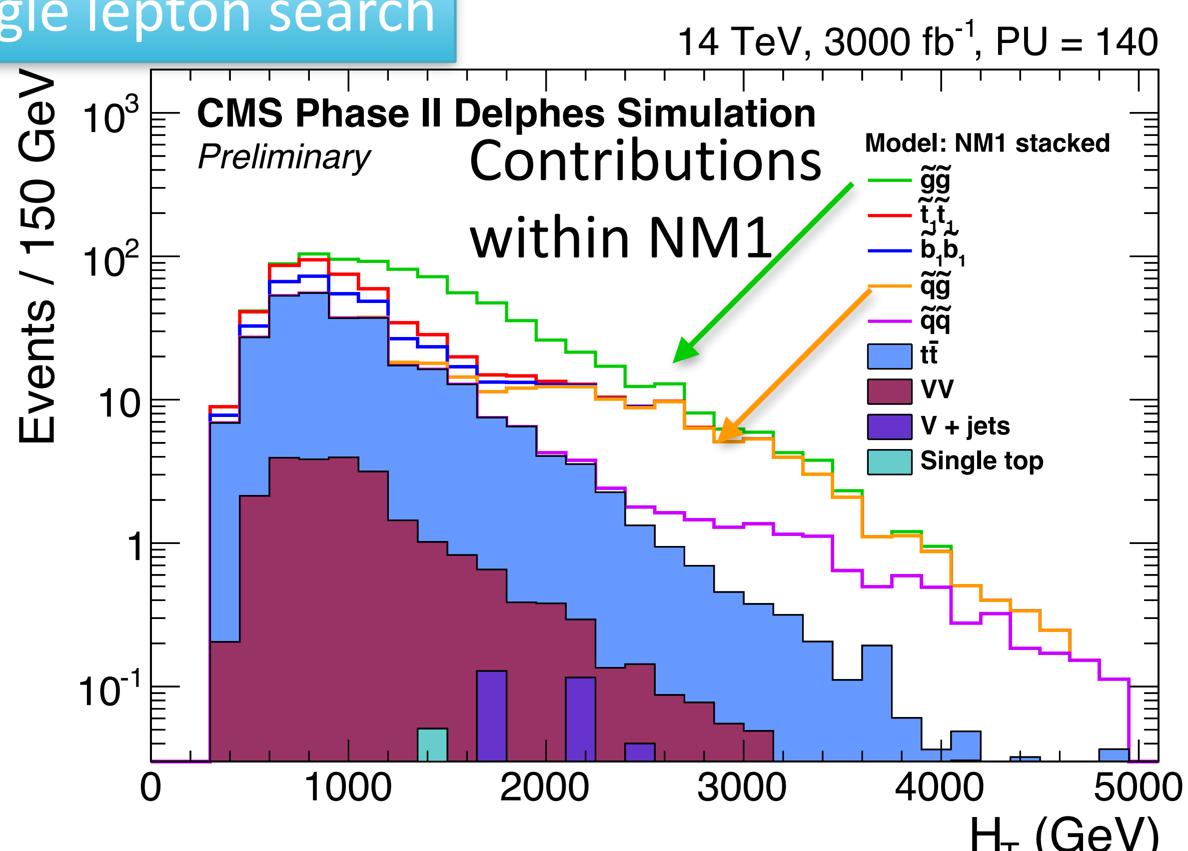
CMS: lessons from full-spectrum SUSY studies

MT2 analysis



- Search for all-hadronic jets + MET.
- MT2 can provide valuable information on the kinematics/ mass splittings of the signal processes
- NM1: more leptons → few events in hadronic channel.

Single lepton search



- Designed as 1-lepton search for top-squark pair production.
- Show stacked contributions from NM1 model. Target process does not dominate the observed yield!
- **“Discovery” does not mean you found what you were looking for!**

PDG for CMS full-spectrum SUSY models

CMS PAS SUS-14-012

Process	Cross section (fb)				
	NM1	NM2	NM3	STC	STOC
$\widetilde{g}\widetilde{g}$	5.4	5.4	5.4	0.007	0.53
$\widetilde{q}\widetilde{g}$	2.0	2.0	2.0	0.05	0.30
$\widetilde{q}\widetilde{q}$, $\widetilde{q}\widetilde{q}^*$	0.14	0.14	0.14	0.07	0.03
$\widetilde{b}_1\widetilde{b}_1^*$	2.6	2.6	2.8	8.3	-
$\widetilde{t}_1\widetilde{t}_1^*$	4.4	4.4	3.1	19	2110
$\widetilde{\chi}_1^{\pm}\widetilde{\chi}_1^0$	1.1	0.2	520	11	-
$\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$	29	22	460	1104	5.5
$\widetilde{\chi}_1^0\widetilde{\chi}_2^0$	-	-	258	0.02	-
$\widetilde{\chi}_1^+\widetilde{\chi}_1^-$	15	11	278	553	2.6
$\widetilde{\ell}^+\widetilde{\ell}^-$	3.3	-	-	34	-
$\widetilde{\ell}^+\widetilde{\nu}, \widetilde{\ell}^-\widetilde{\nu}^*$	12	-	-	32	-
$\widetilde{\nu}\widetilde{\nu}^*$	3.3	-	-	13	-

Decay	Branching fraction				
	NM1	NM2	NM3	STC	STOC
$\widetilde{g} \to \widetilde{t}_1\bar{t}, \widetilde{t}_1^*t$	59%	60%	53%	28%	50%
$\widetilde{g} \to \widetilde{b}_1\bar{b}, \widetilde{b}_1^*b$	41%	40%	47%	28%	50%
$\widetilde{g} \to t_2\bar{t}, t_2^*t$	-	-	-	22%	-
$\widetilde{g} \to \widetilde{b}_2\bar{b}, \widetilde{b}_2^*b$	-	-	-	21%	-
$\widetilde{t}_1 \to t\widetilde{\chi}_1^0$	0.6%	1.5%	39%	20%	-
$\widetilde{t}_1 \to t\widetilde{\chi}_2^0$	13%	13%	41%	5.4%	-
$\widetilde{t}_1 \to t\widetilde{\chi}_3^0$	22%	23%	1.3%	20%	-
$\widetilde{t}_1 \to t\widetilde{\chi}_4^0$	30%	30%	5.5%	9.2%	-
$\widetilde{t}_1 \to b\widetilde{\chi}_1^+$	16%	12%	2.1%	12%	-
$\widetilde{t}_1 \to b\widetilde{\chi}_2^+$	18%	21%	11%	34%	-
$\widetilde{t}_1 \to c\widetilde{\chi}_1^0$	-	-	-	-	99%
$\widetilde{b}_1 \to b\widetilde{\chi}_1^0$	1.5%	1.0%	1.3%	67%	-
$\widetilde{b}_1 \to b\widetilde{\chi}_2^0$	11%	10%	1.0%	2.2%	5.7%
$\widetilde{b}_1 \to b\widetilde{\chi}_3^0$	0.6%	0.6%	0.4%	8.2%	-
$\widetilde{b}_1 \to b\widetilde{\chi}_4^0$	4.5%	5.7%	5.7%	7.6%	-
$\widetilde{b}_1 \to t\widetilde{\chi}_1^-$	32%	34%	80%	3.4%	11%
$\widetilde{b}_1 \to t\widetilde{\chi}_2^-$	49%	48%	12%	12%	-
$\widetilde{b}_1 \to W^-\widetilde{t}_1$	0.4%	0.7%	-	$< 0.1\%$	65%
$\widetilde{b}_1 \to b\widetilde{g}$	-	-	-	-	18%
$\widetilde{\chi}_1^+ \to \ell^+\widetilde{\nu}$	56%	-	-	-	-
$\widetilde{\chi}_1^+ \to \nu\widetilde{\ell}^+$	43%	-	-	100% (only $\nu_\tau\widetilde{\tau}_1^+$)	-
$\widetilde{\chi}_1^+ \to W^+\widetilde{\chi}_1^0$	1.8%	100%	-	-	-
$\widetilde{\chi}_1^+ \to q\bar{q}'\widetilde{\chi}_1^0$	-	-	70%	-	-
$\widetilde{\chi}_1^+ \to \ell^+\nu\widetilde{\chi}_1^0$	-	-	30%	-	-
$\widetilde{\chi}_1^+ \to \widetilde{t}_1\bar{b}$	-	-	-	-	100%
$\widetilde{\chi}_2^0 \to \ell^+\ell^-, \ell^-\ell^+$	59%	-	-	100%	-
$\widetilde{\chi}_2^0 \to \widetilde{\nu}\bar{\nu}, \widetilde{\nu}^*\nu$	41%	-	-	-	-
$\widetilde{\chi}_2^0 \to Z\widetilde{\chi}_1^0$	$< 0.1\%$	12%	-	-	-
$\widetilde{\chi}_2^0 \to H\widetilde{\chi}_1^0$	-	88%	-	-	-
$\widetilde{\chi}_2^0 \to q\bar{q}\widetilde{\chi}_1^0$	-	-	56%	-	-
$\widetilde{\chi}_2^0 \to \ell^+\ell^-\widetilde{\chi}_1^0$	-	-	10%	-	-
$\widetilde{\chi}_2^0 \to \nu\bar{\nu}\widetilde{\chi}_1^0$	-	-	21%	-	-
$\widetilde{\chi}_2^0 \to q\bar{q}'\widetilde{\chi}_1^{\pm}$	-	-	8.8%	-	-
$\widetilde{\chi}_2^0 \to \ell^+\nu\widetilde{\chi}_1^-, \ell^-\bar{\nu}\widetilde{\chi}_1^+$	-	-	4.0%	-	-
$\widetilde{\chi}_2^0 \to \widetilde{t}_1\bar{t}, \widetilde{t}_1^*t$	-	-	-	-	100%

gluino: $\tilde{t}\bar{\tilde{t}} + \tilde{b}\bar{\tilde{b}}$

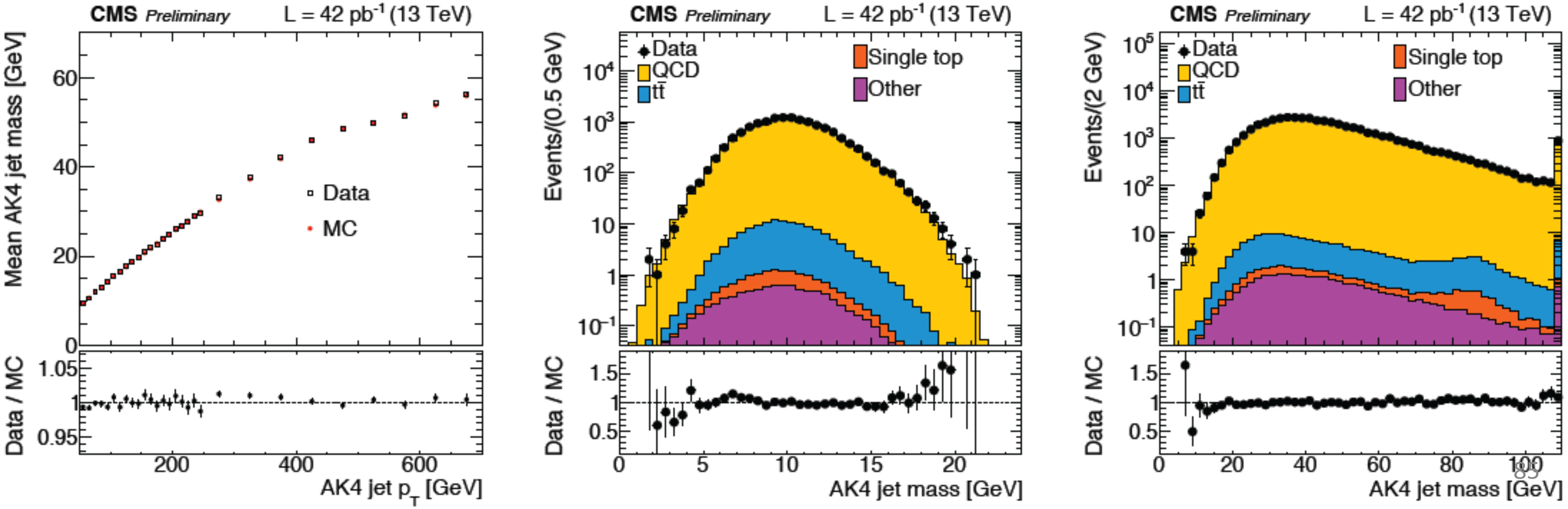
Object reconstruction

Reconstruction object	*Method/criteria*	*Performance/Comments*
Jets **Large-R jets**	**$p_T > 30$ GeV, $\|\eta\| < 2.4$** **Cluster particle-flow objects using anti-kT with R = 0.4** **Rejected if jet contains isolated lepton, as defined below.** **Cluster standard jets with anti-kT and**	
b - tagged jets	**N(b-tag) ≥ 1, $p_T > 30$ GeV, $\|\eta\| < 2.4$** **Combined secondary vertex algorithm**	**ϵ(b) = 60 - 70%, increasing with pT** **ϵ(c) ≈ 10 - 15% [mistag rate]** **ϵ(light quark) ≈ 1 - 2% [mistag rate]**
electrons	**$p_T > 20$ GeV, $\|\eta\| < 2.5$** **Isolation: $I^{rel} = \Sigma_{i \text{ in cone}}\, p_{T,i} / p_{T,e} < 0.1$** **with p_T-dependent cone size ($\sim 1/p_{T,e}$)**	**ϵ(e) = 50-80%, increasing with pT** **[includes isolation efficiency]** **$\sigma(p_T)$ = 1-3% (p_T = 5 - 100 GeV)**
muons	**$p_T > 20$ GeV, $\|\eta\| < 2.4$** **Isolation: $I^{rel} = \Sigma_{i \text{ in cone}}\, p_{T,i} / p_{T,e} < 0.2$** **with p_T-dependent cone size ($\sim 1/p_{T,e}$)**	**ϵ(e) =70-95%, increasing with pT** **[includes isolation efficiency]**
p_T^{miss} and $E_T^{miss} = \|p_T^{miss}\|$	**$p_T^{miss} = -\Sigma_{\text{Particle-flow objects } i}\, p_{T,i}$** **with PF candidates in jet replaced by calibrated jet p_T**	

Validation of M_J modeling using data

Before using MJ, we performed an extensive set of studies in data and Monte Carlo.

- By clustering AK4 PF jets (pT>30 GeV, |η|<2.4), we are robust against pile-up effects because standard jets are already corrected for pile-up.
- Simulation of M_J distributions tested in QCD, ttbar, Z+jets, W+jets dominated samples in 8 TeV data.



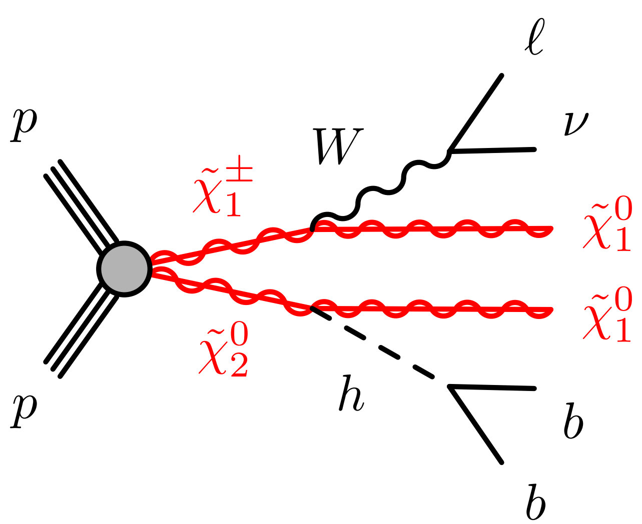
CMS: $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ with $\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \to h \tilde{\chi}_1^0$

Search for Wh(bb) + E_T^{miss}

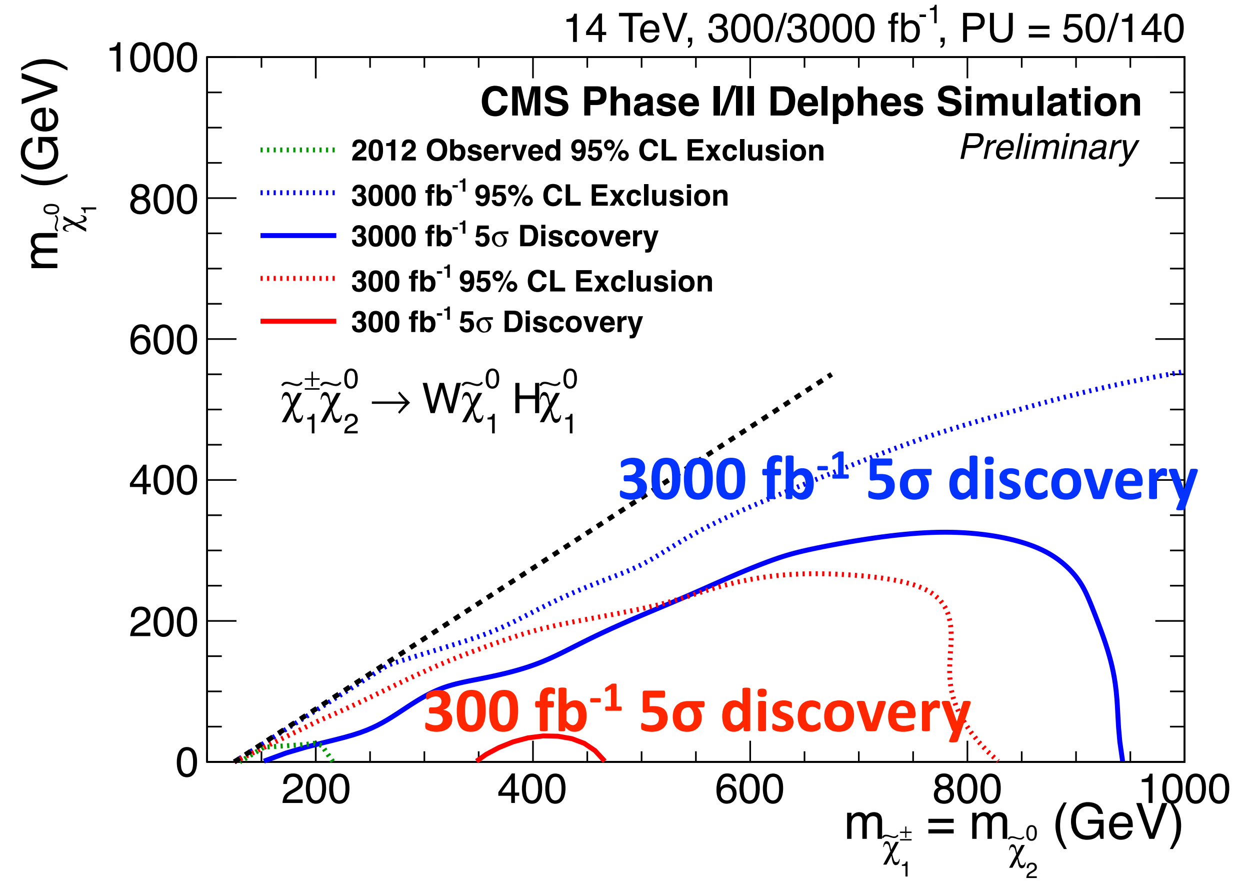
1 lepton + m(bb) + E_T^{miss} + mT cut + mCT

Dominant SM background: ttbar production

CMS-PAS-SUS-14-012



Discovery sensitivity: up to ~950 GeV.



Effect of aged Run 1 detector performance on search for Wh(bb) + E_T^{miss}

Study based on full simulation.

- Emulated aged detector with worse E_T^{miss} resolution (→impact MT), b-tagging efficiency, e/μ efficiency.
- Discovery sensitivity substantially reduced with aged detector.