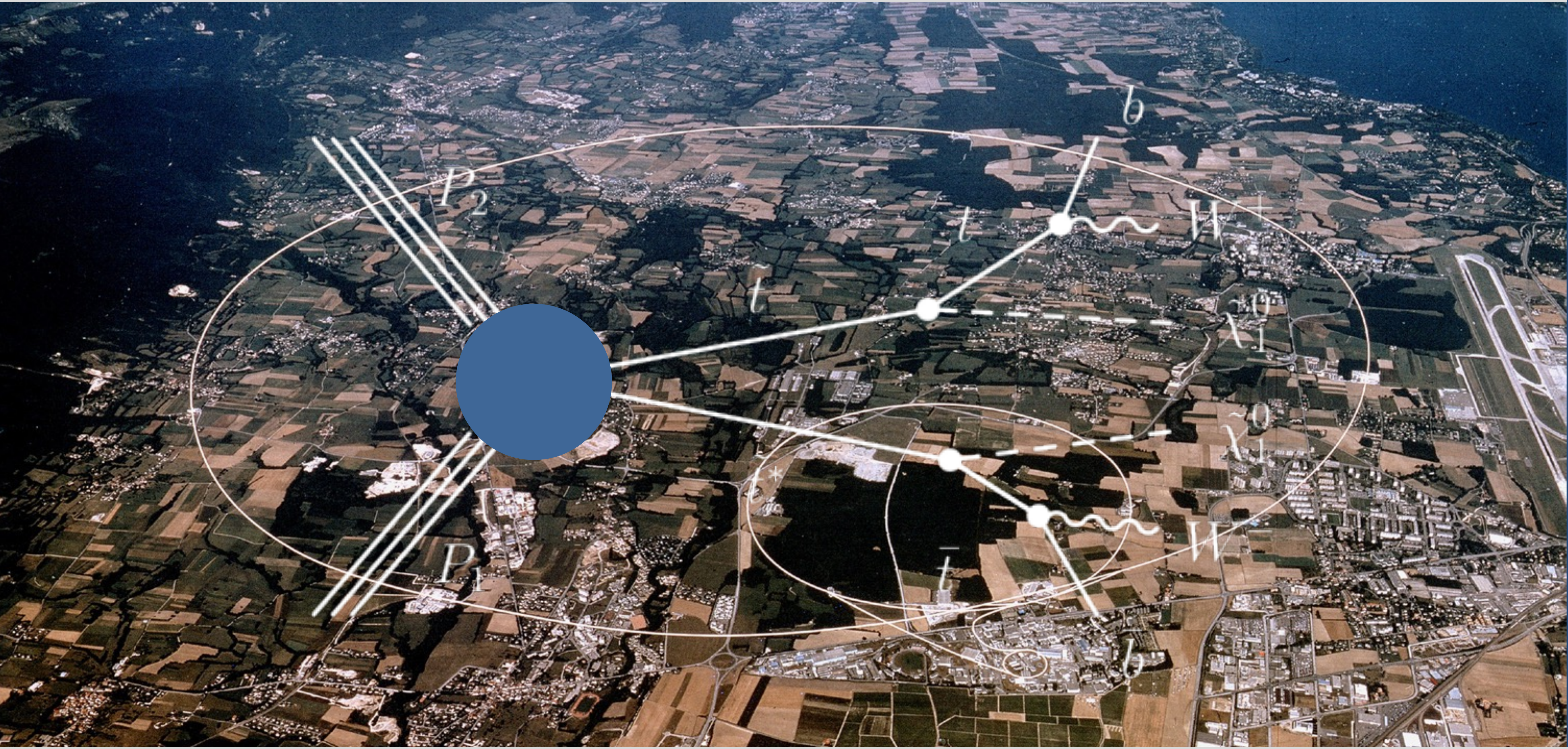
Supersymmetry in LHC Run 2 and Beyond

Jeffrey D. Richman
CMS Experiment
University of California, Santa Barbara



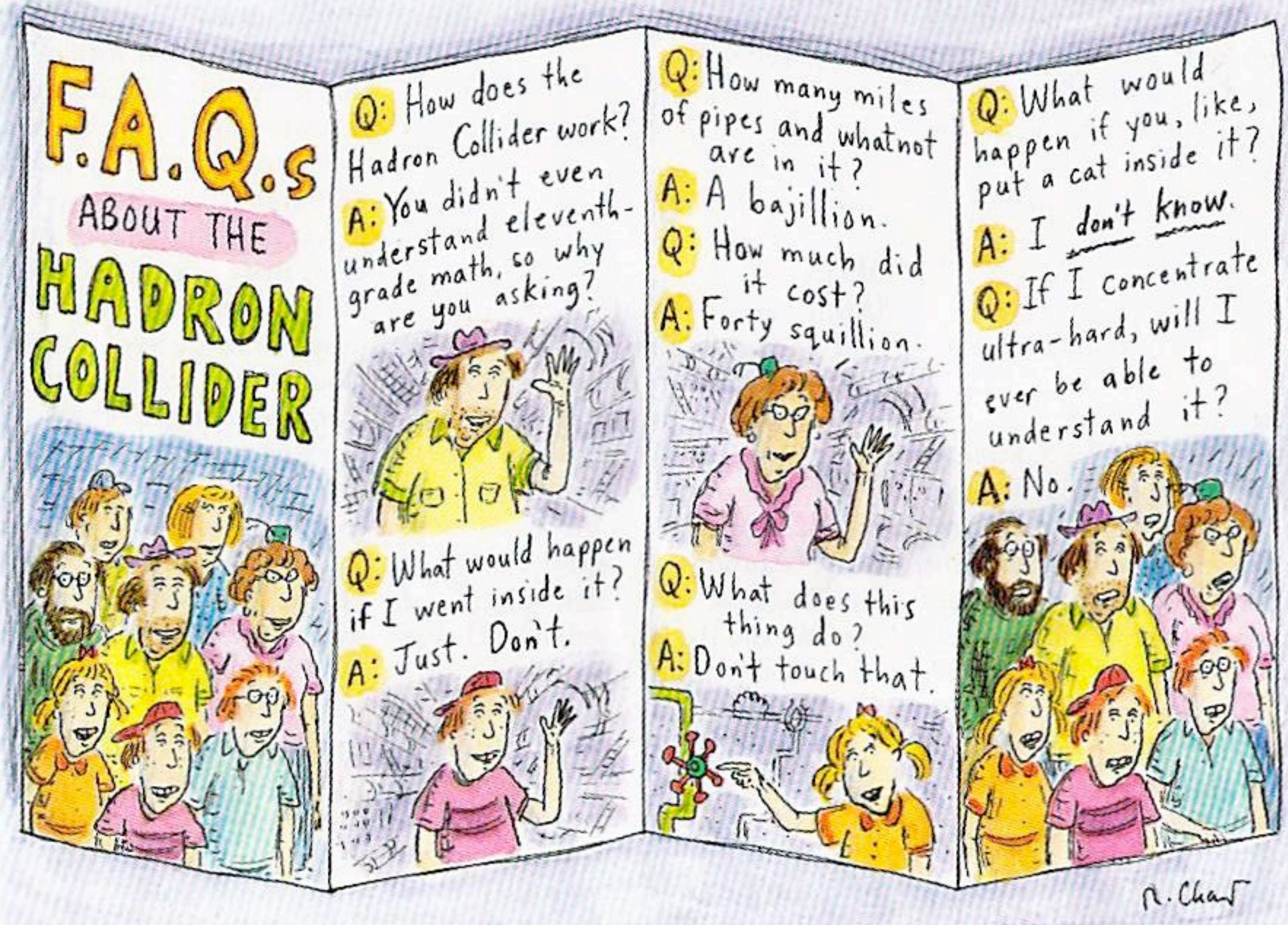
Seminar, Texas A&M University
March 31, 2016

Outline

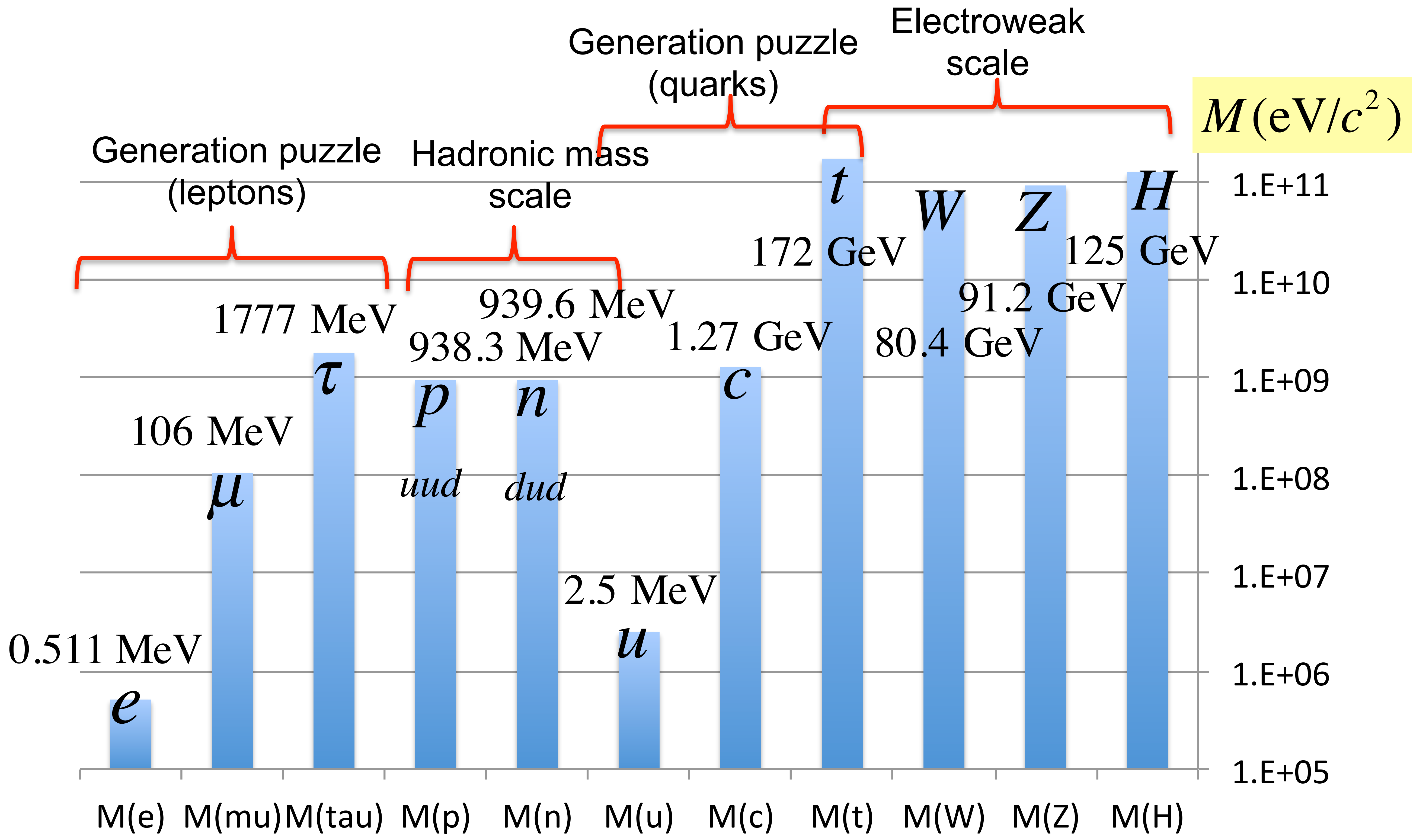
- Introduction: mass scales, symmetries, naturalness and SUSY
- Searching for SUSY: a primer
- An early 13 TeV SUSY search: Jets + 1 lepton + $\vec{p}_T^{\,\mathrm{miss}}$ with ~2 fb^{-1} (one of many presented at CERN Physics Jamboree and at Moriond)
- A brief look at prospects for SUSY with 300 fb^{-1} (Runs 2-3) and 3000 fb^{-1} (HL-LHC)

Drawing courtesy Sergio Cittolin, CMS

A new era in particle physics



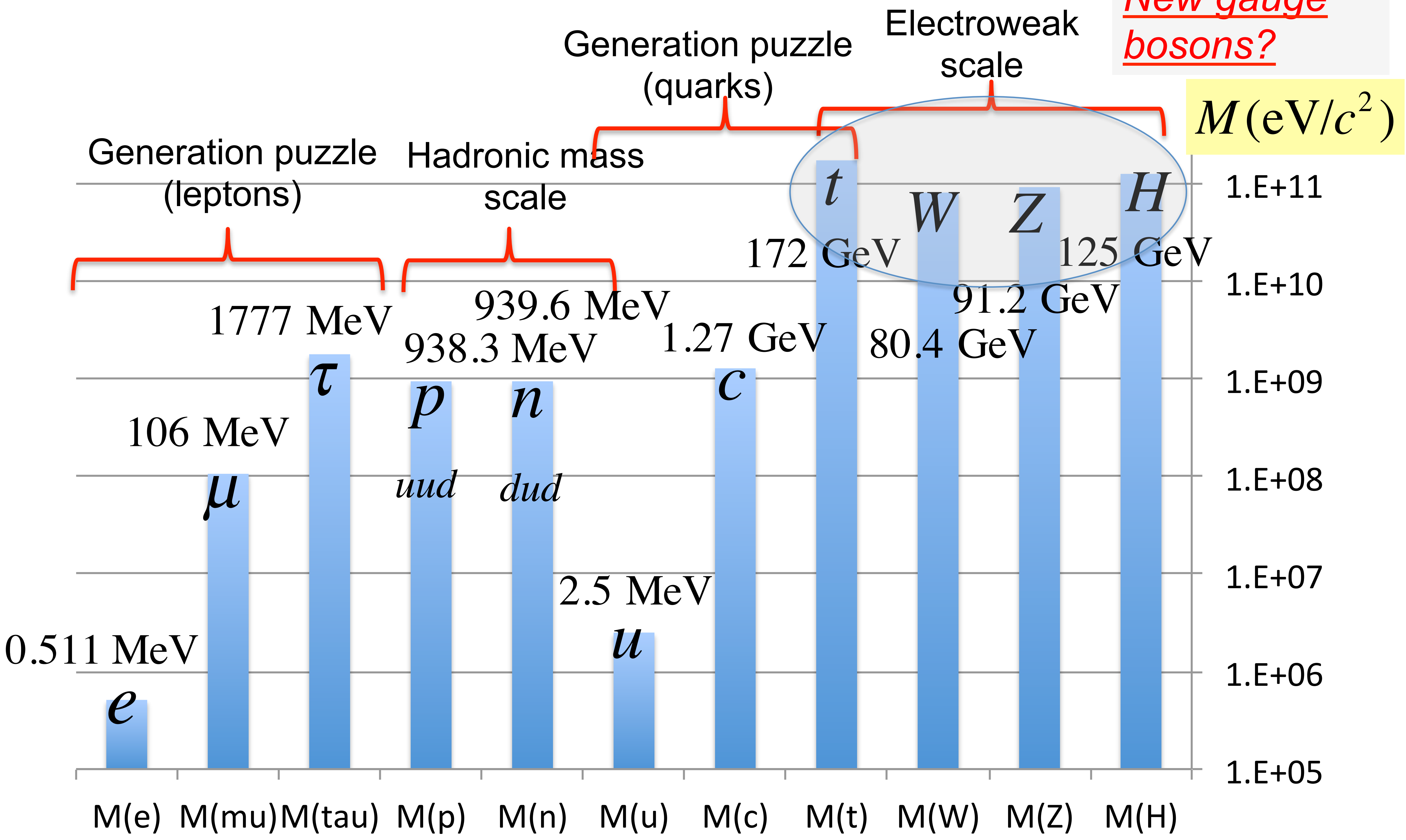
Mass scales in particle physics and the TeV scale



Si band gap: $\simeq 1.1\ \mathrm{eV}$ $m(\nu) \sim 0.1\ \mathrm{eV}?$ $m(\tilde{g}) \sim 2\ \mathrm{TeV}?$ $M_{Planck} \approx 10^{18}\ \mathrm{GeV}$

Mass scales in particle physics

SUSY?, Dark matter ? New gauge bosons? ↗



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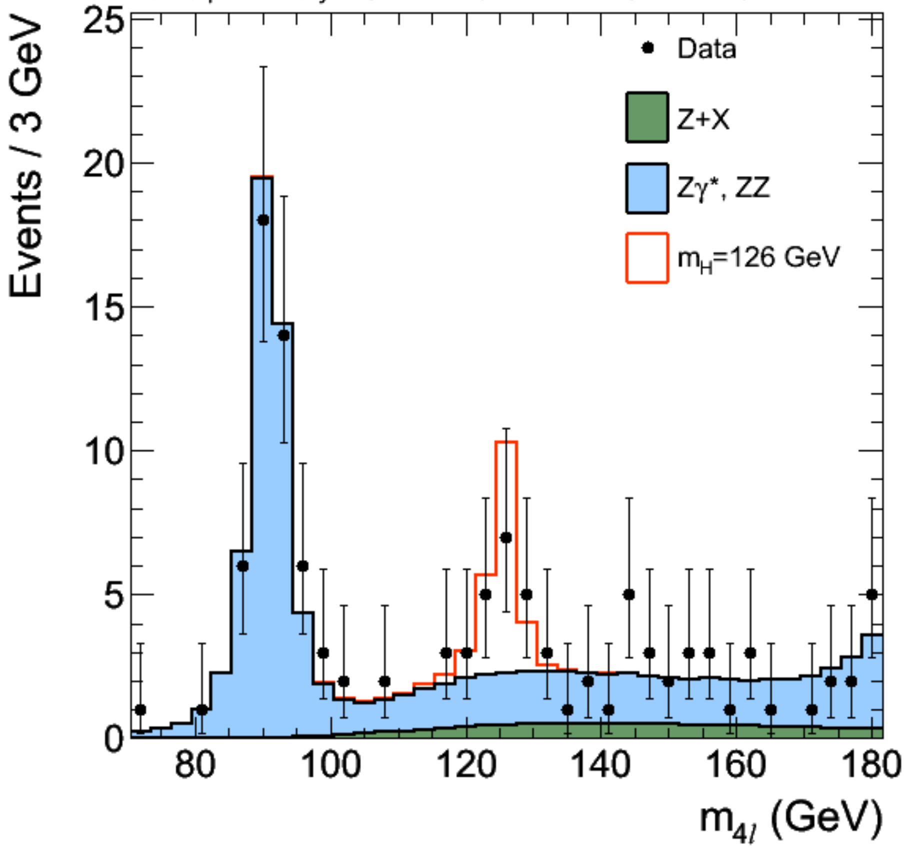
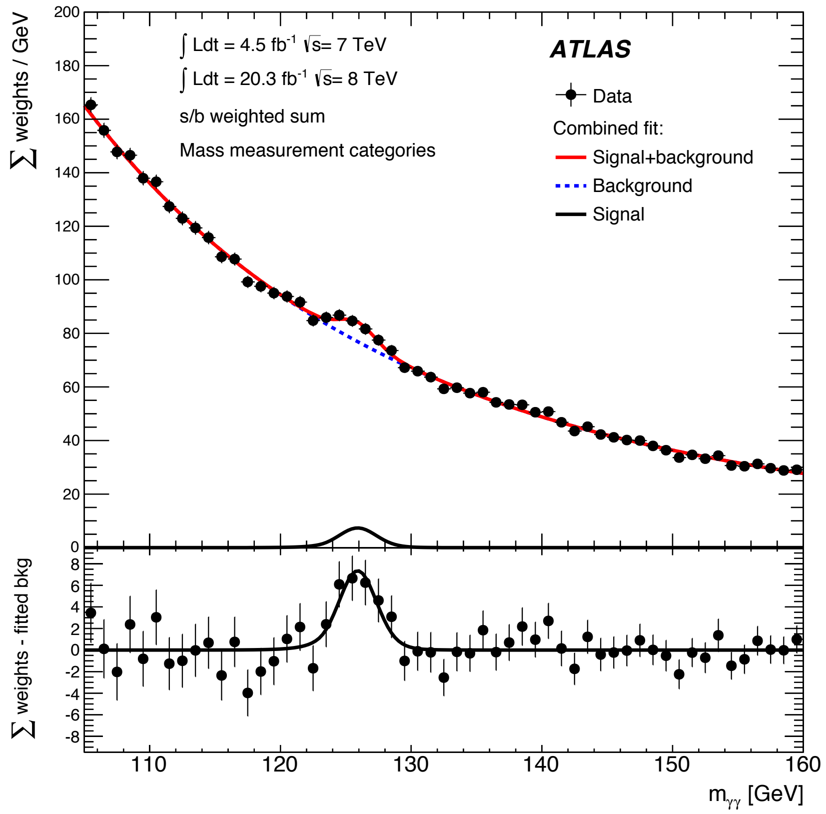
Perspective from Run 1

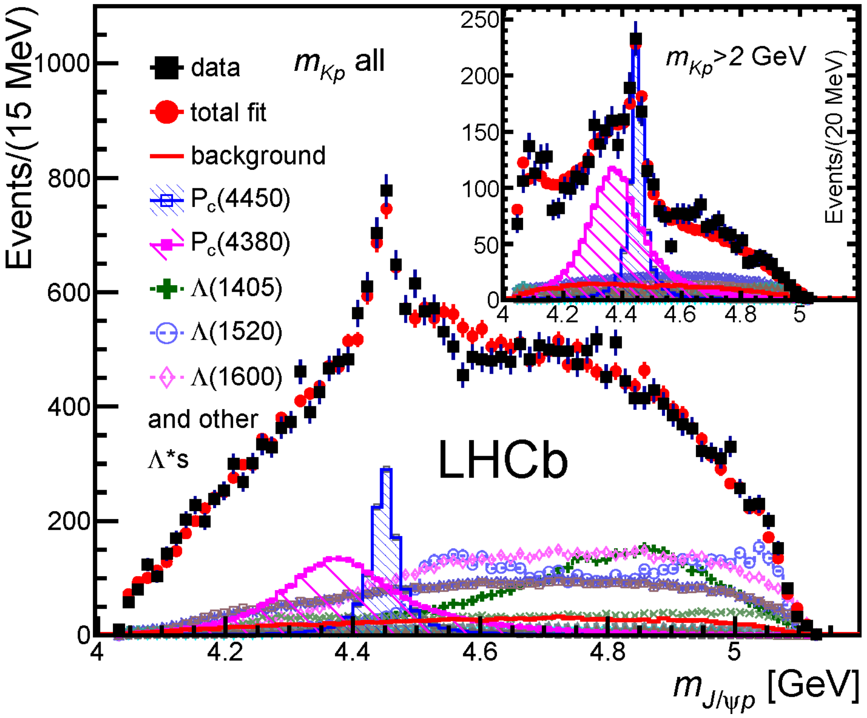
$H \rightarrow ZZ^*$



$H \rightarrow \gamma\gamma$



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

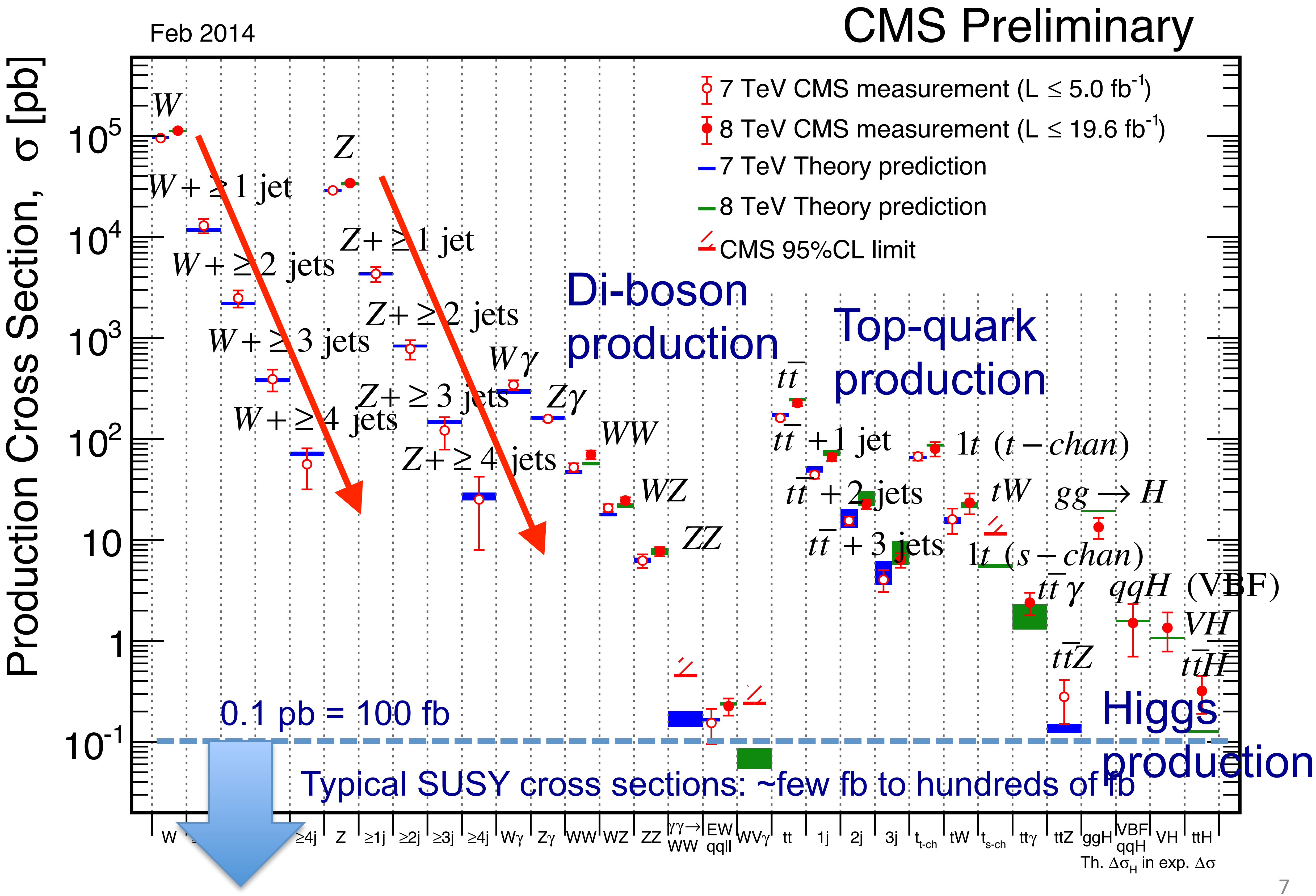


Phys. Rev. Lett. 115 (2015) 072001

Rapid interpretation of these discoveries!

- 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: 2 charmonium-pentaquark states → **Still a lot to learn about the hadronic (~1 GeV) mass scale, 80 years after the discovery of the pion.**
- **A guess: it will take at least as long to understand the physics of the EW scale.**

Mapping the standard model: the foundation of searches



Di-boson production

Top-quark production

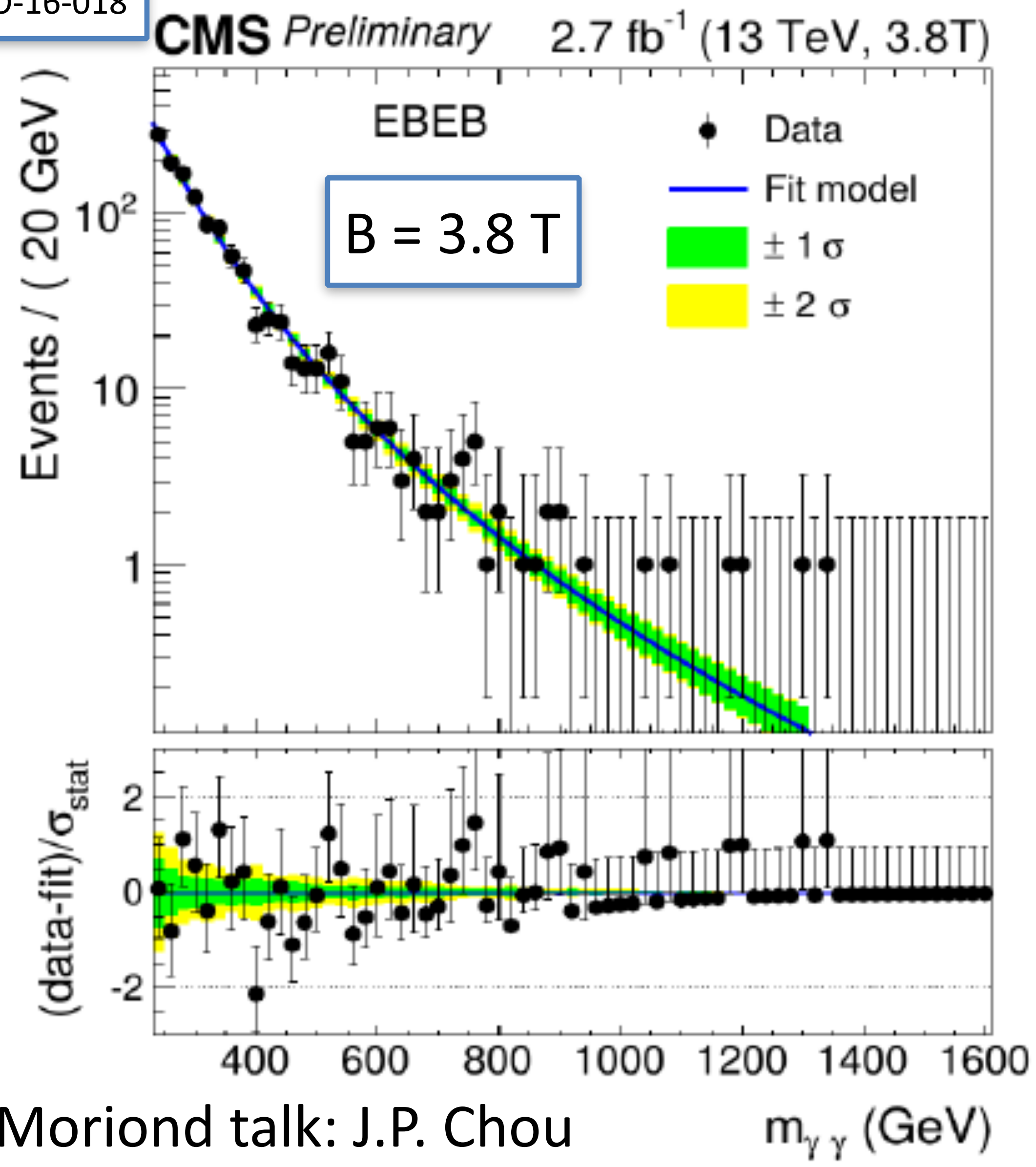
Higgs production

0.1 pb = 100 fb

Typical SUSY cross sections: ~few fb to hundreds of fb

If you were wondering about the γγ excess…

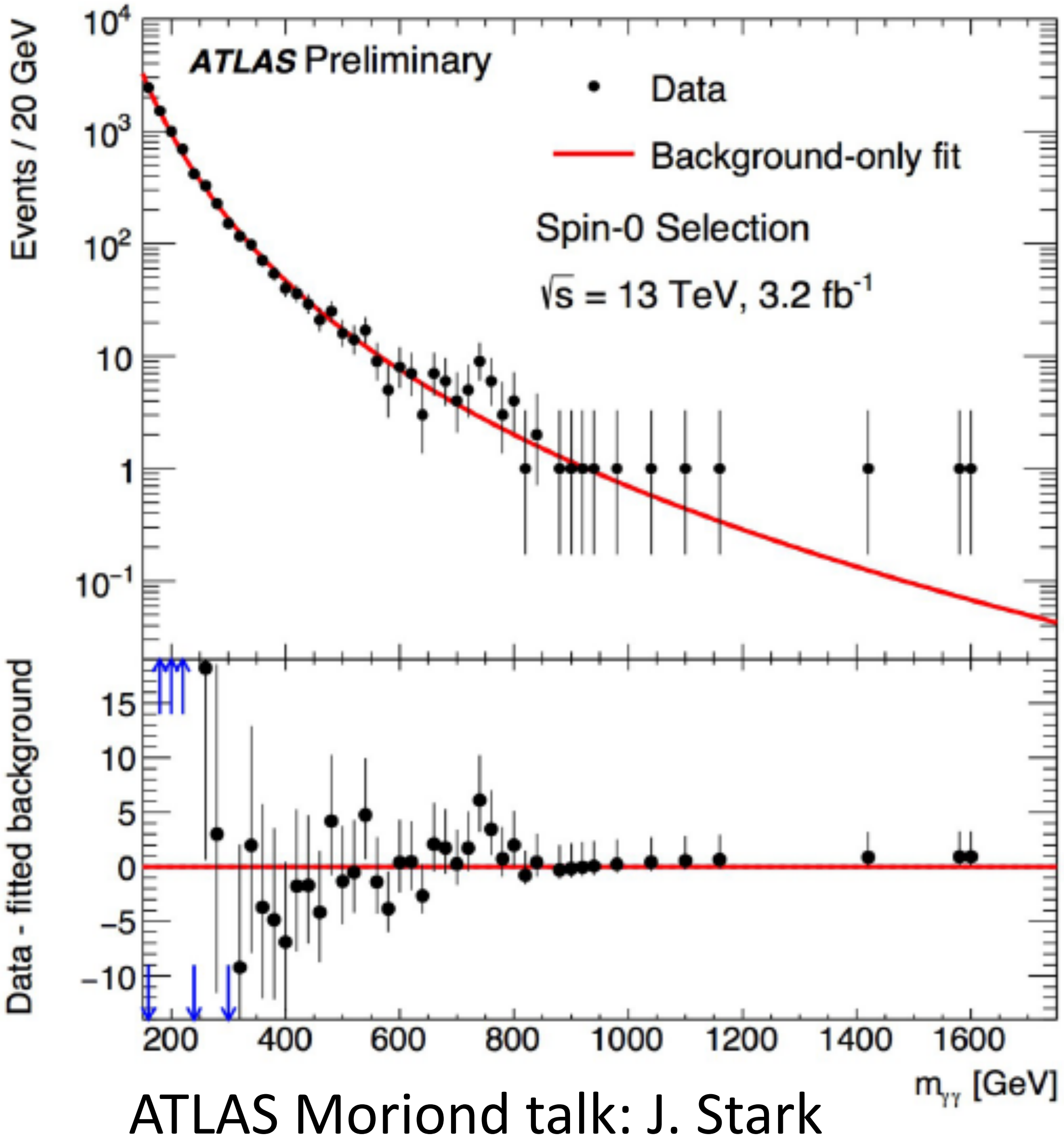
CMS EXO-16-018



CMS Moriond talk: J.P. Chou

http://moriond.in2p3.fr/QCD/2016/SundayMorning/Chou.pdf

ATLAS-CONF-2016-xxx



ATLAS Moriond talk: J. Stark

http://moriond.in2p3.fr/QCD/2016/SundayMorning/Stark.pdf,

- CMS: 13 TeV data: local signif.: 2.8 - 2.9σ, Global signif. < 1σ
- ATLAS: 13 TeV data: local signif.: 3.9σ, Global signif., 2.0σ (J=0)
- “Today it could be everything, including nothing.” — A. Strumia

http://moriond.in2p3.fr/QCD/2016/SundayMorning/Strumia.pdf

Profound questions at the TeV scale

Hierarchy problem

~10^{18} GeV

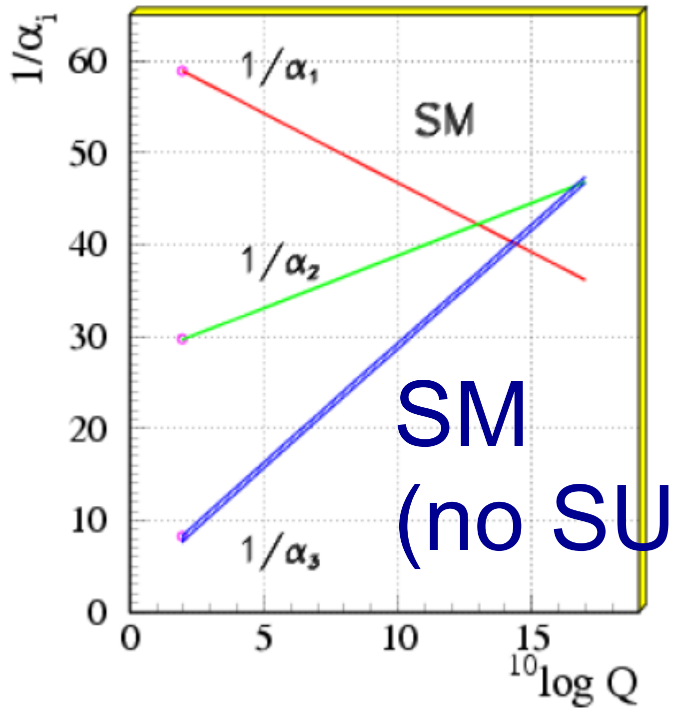
Planck scale
(quantum gravity)

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

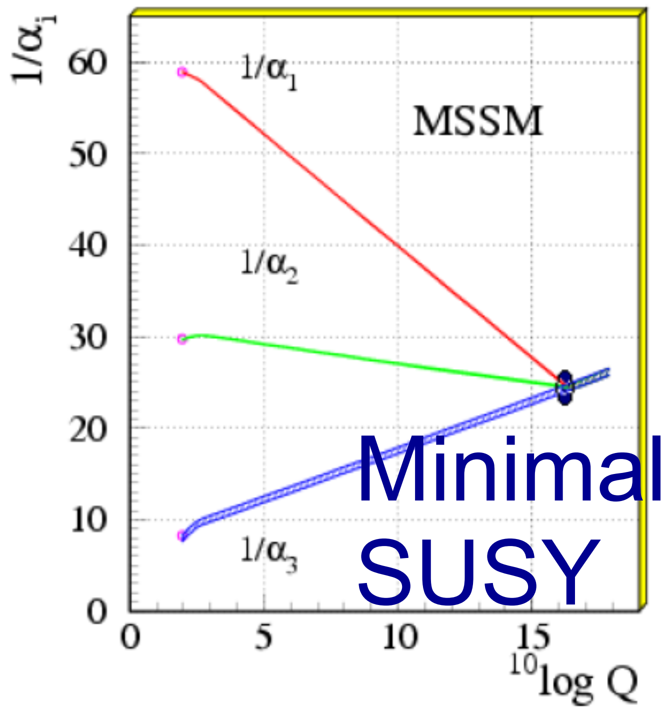
~10^2 -10^3 GeV

Electroweak scale
(unstable in SM)

Unification of couplings



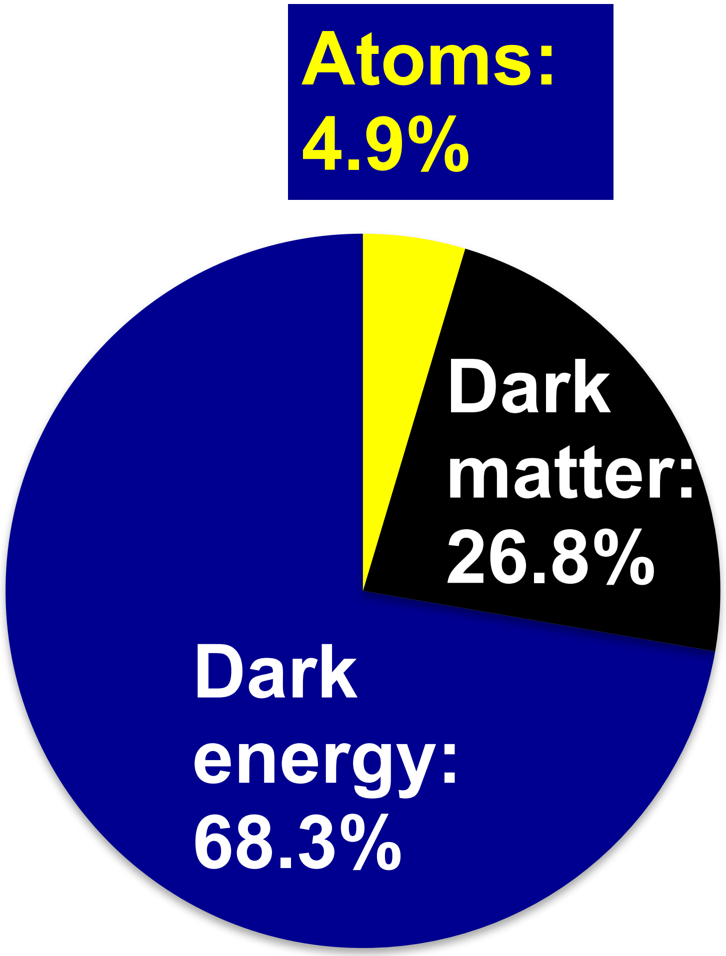
SM
(no SUSY)



Minimal
SUSY

S. Raby, Particle Data Book.

Dark matter

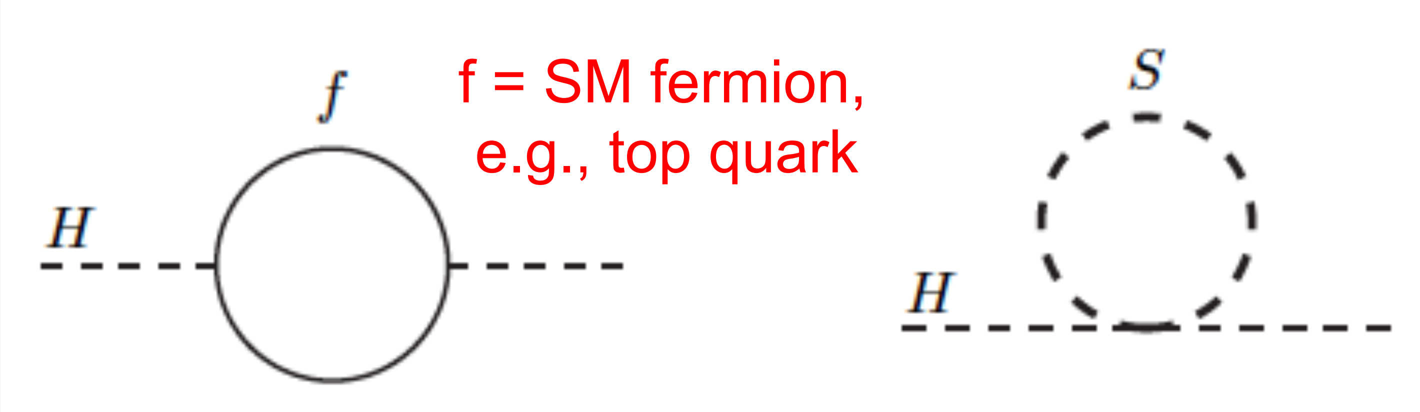


WIMP Miracle → TeV scale

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

The gauge hierarchy problem and SUSY

- Evidence is very strong that the new particle discovered at $m \approx 125$ GeV is a/the Higgs boson, with quantum numbers $J^{PC} = 0^{++}$ (scalar).
- Assuming that it is an elementary scalar particle, the Higgs mass is subject to enormous shifts from short-distance 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. Requires extraordinary fine tuning if no NP.
- SUSY can tame these corrections (as can other NP theories).



f = SM fermion, e.g., top quark

S = SUSY scalar partner, e.g., top squark

Supersymmetry basics

- The symmetry operation in SUSY is a mapping between fermionic and bosonic degrees of freedom.
- SUSY preserves the SM couplings (charges) of particles.
- Fermions: the SM is a chiral theory, and the L-handed and R-handed fermions have different EW charges!
  - L-handed fermions are $SU(2)_L$ doublets
  - R-handed fermions are $SU(2)_L$ singlets

$$\begin{bmatrix} u_L \\ d_L \end{bmatrix} \qquad u_R\,,\ d_R$$

- Each chiral projection of an SM fermion has a J = 0 SUSY partner, preserving degrees of freedom.

$$\begin{tikzcd}
 & e_L^- \arrow[r, leftrightarrow] & \tilde{e}_L^- \\
e^- \arrow[ur] \arrow[dr] & & \\
 & e_R^- \arrow[r, leftrightarrow] & \tilde{e}_R^-
\end{tikzcd}
\qquad
\begin{tikzcd}
 & t_L \arrow[r, leftrightarrow] & \tilde{t}_L \\
t \arrow[ur] \arrow[dr] & & \\
 & t_R \arrow[r, leftrightarrow] & \tilde{t}_R
\end{tikzcd}$$

↑ partner of R-handed electron; has J = 0 !

SUSY partners of gauge and higgs bosons

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

Gaugino/Higgino basis

Particle	*J*	Degrees of freedom
$\tilde{W}^+$	1/2	2
$\tilde{W}^-$	1/2	2
$\tilde{Z} \,\vert\, \tilde{W}^0$	1/2	2
$\tilde{\gamma} \,\vert\, \tilde{B}$	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

Chargino/Neutralino basis

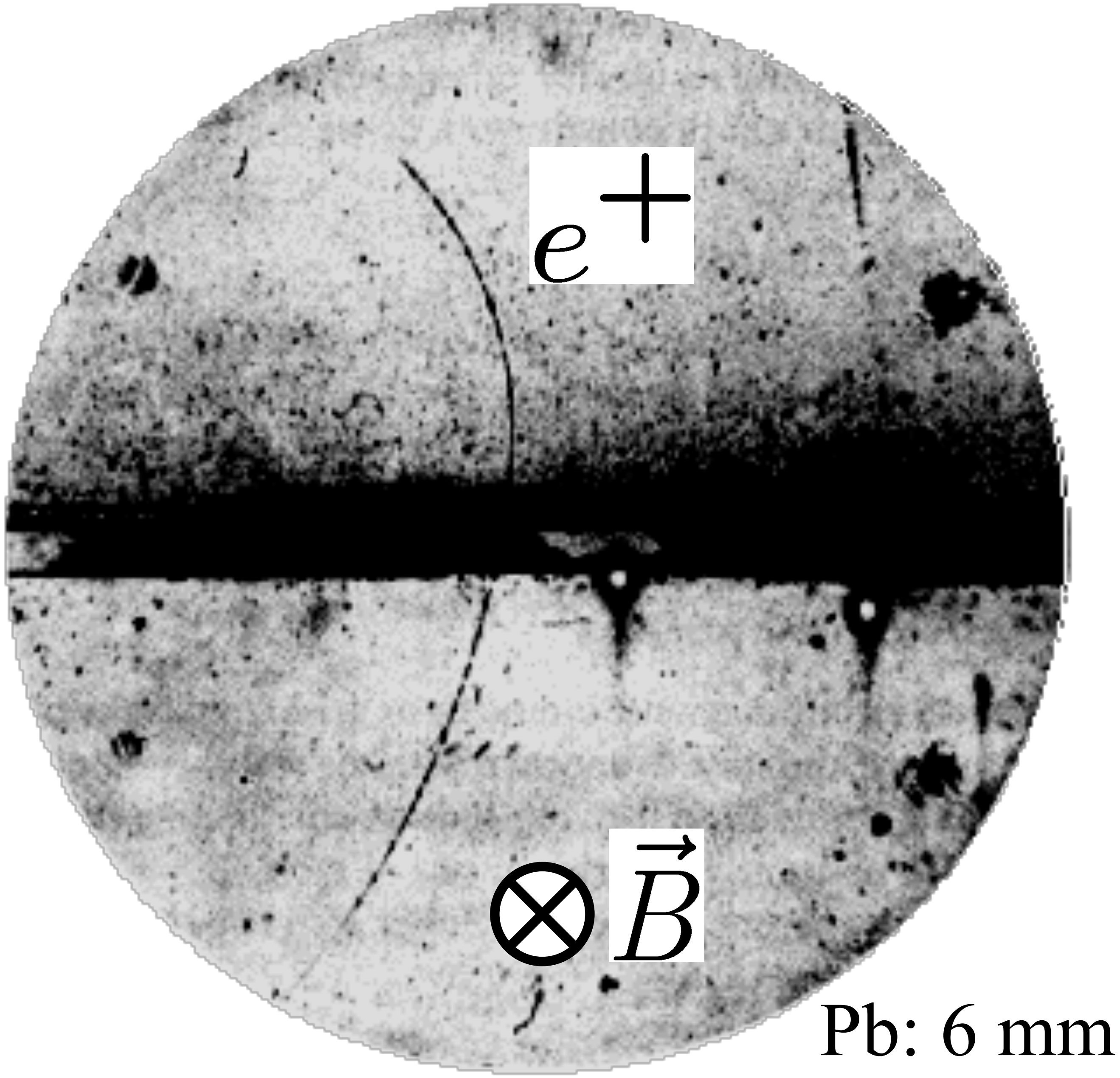
Particle	J	Degrees of freedom
$\tilde{\chi}_1^+$	1/2	2
$\tilde{\chi}_1^-$	1/2	2
$\tilde{\chi}_2^+$	1/2	2
$\tilde{\chi}_2^-$	1/2	2
$\tilde{\chi}_1^0$	1/2	2
$\tilde{\chi}_2^0$	1/2	2
$\tilde{\chi}_3^0$	1/2	2
$\tilde{\chi}_4^0$	1/2	2
Total		16

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

Generic term for all of the above “Electroweakinos” (EWKinos)

CPT symmetry and the positron

- Dirac relativistic wave equation (1928): extra, “negative-energy” solutions.
- Positron interpretation confirmed by C.D. Anderson (cosmic ray experiment) at Caltech.



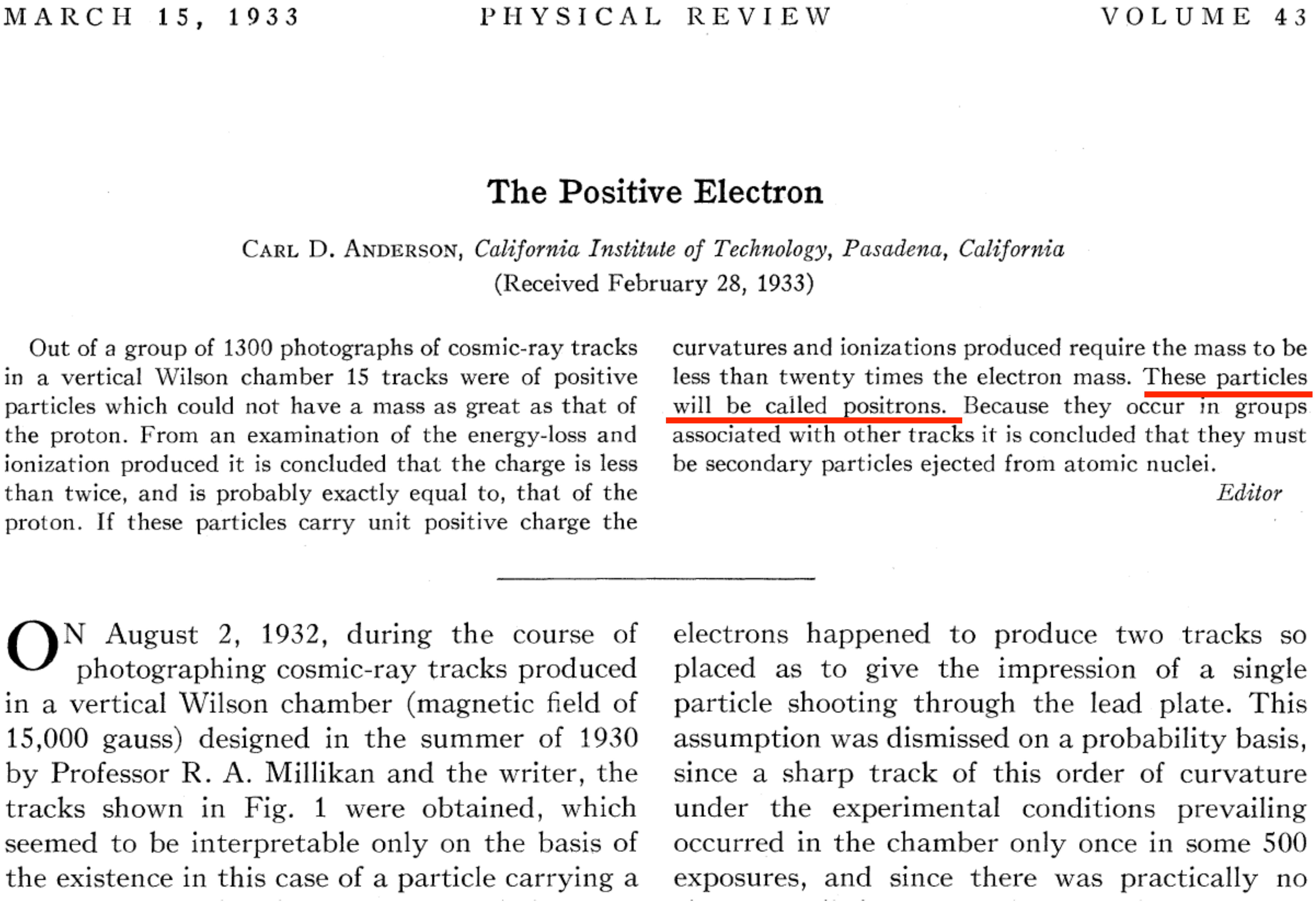
Pb: 6 mm thick

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

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

CPT symmetry and the positron

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)

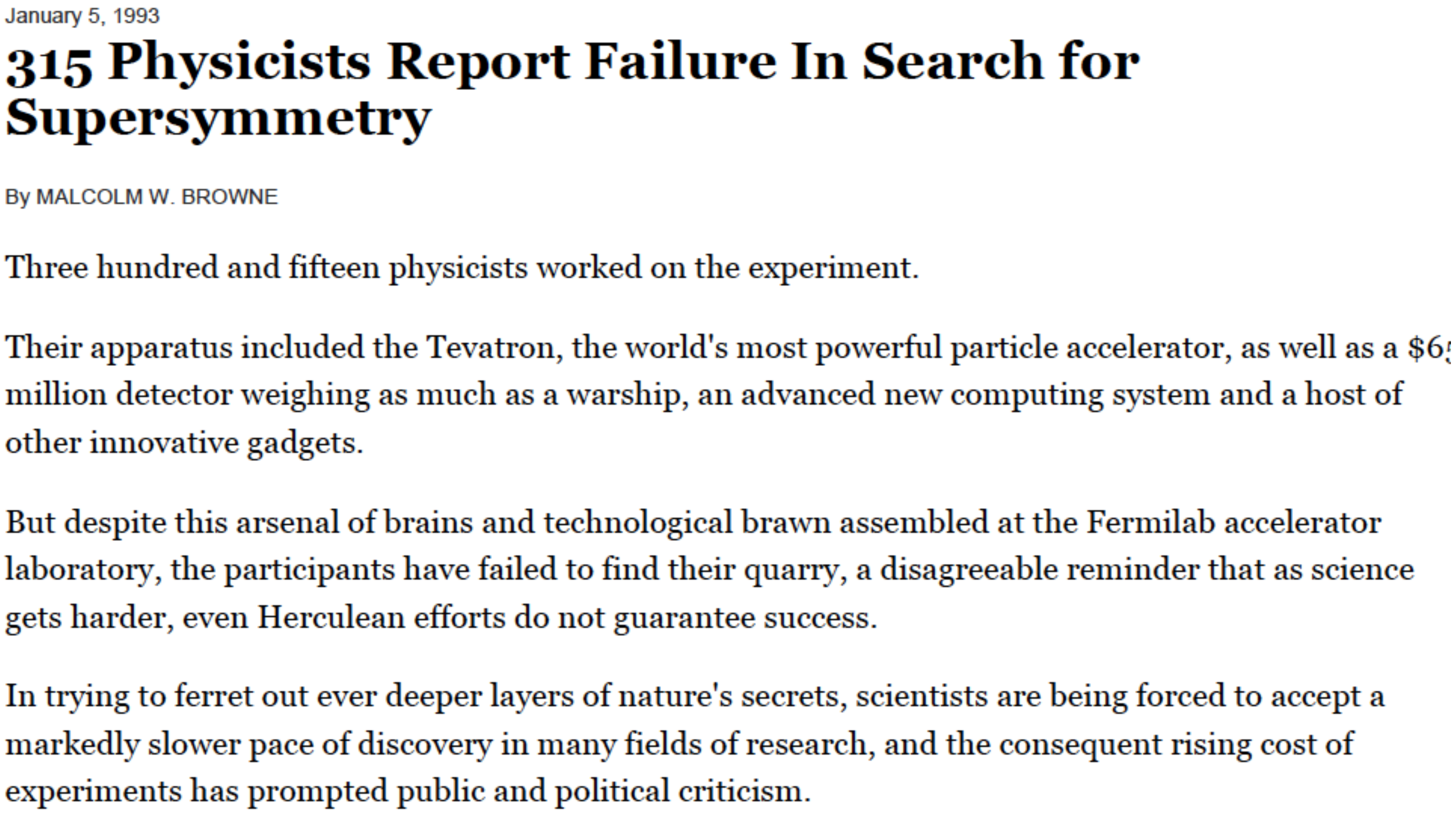
Out of a group of 1300 photographs of cosmic-ray tracks in a vertical Wilson chamber 15 tracks were of positive particles which could not have a mass as great as that of the proton. From an examination of the energy-loss and ionization produced it is concluded that the charge is less than twice, and 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

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.

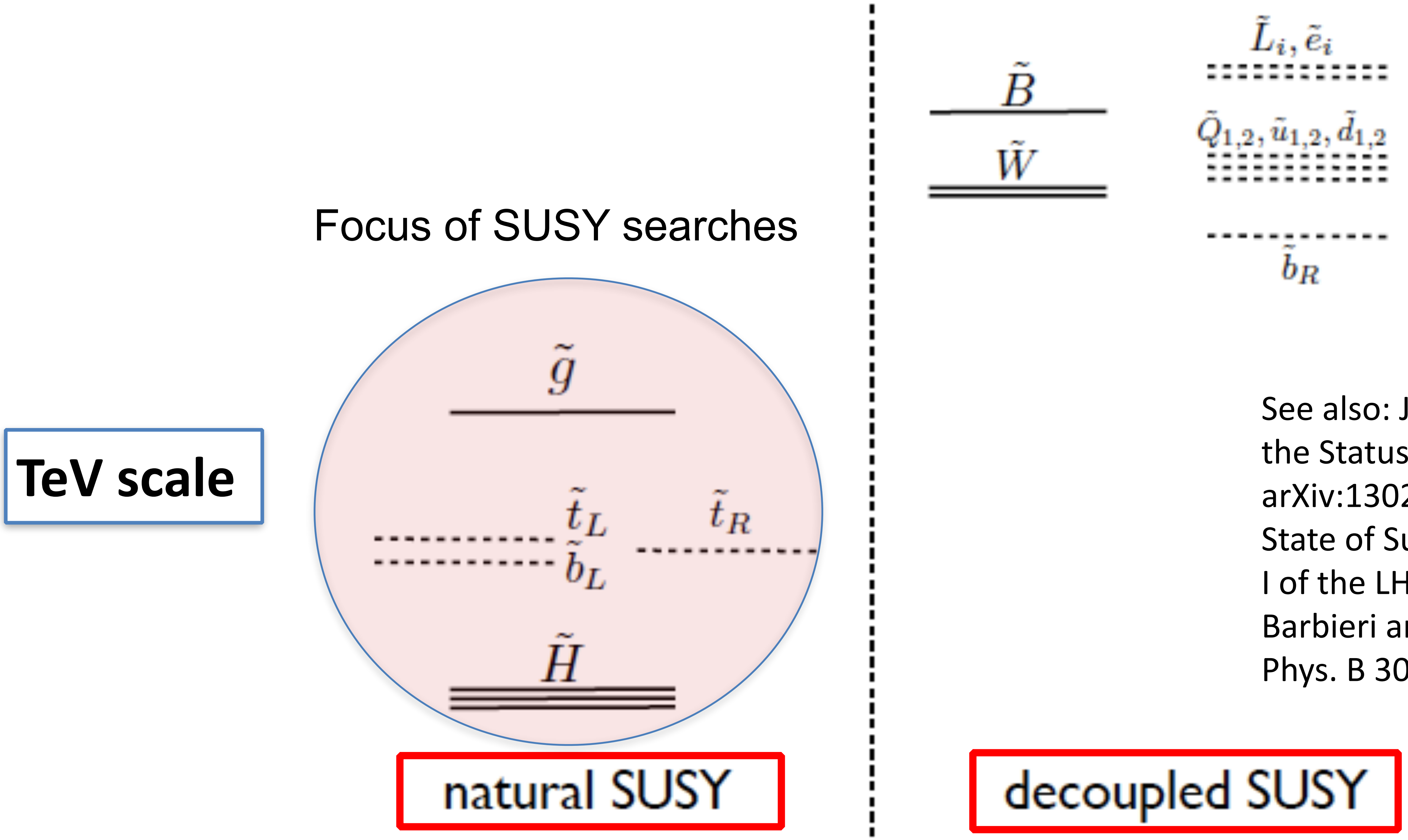
In trying to ferret out ever deeper layers of nature's secrets, scientists are being forced to accept a markedly slower pace of discovery in many fields of research, and the consequent rising cost of experiments has prompted public and political criticism.

...ouch.

“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?



See also: J. Feng, Naturalness and the Status of Supersymmetry, arXiv:1302.6587; N. Craig, The State of Supersymmetry after Run I of the LHC, arXiv:1309.0528; R. Barbieri and G.F. Giudice, Nucl. Phys. B 306, 63 (1988).

“Natural SUSY endures”: still the current fashion

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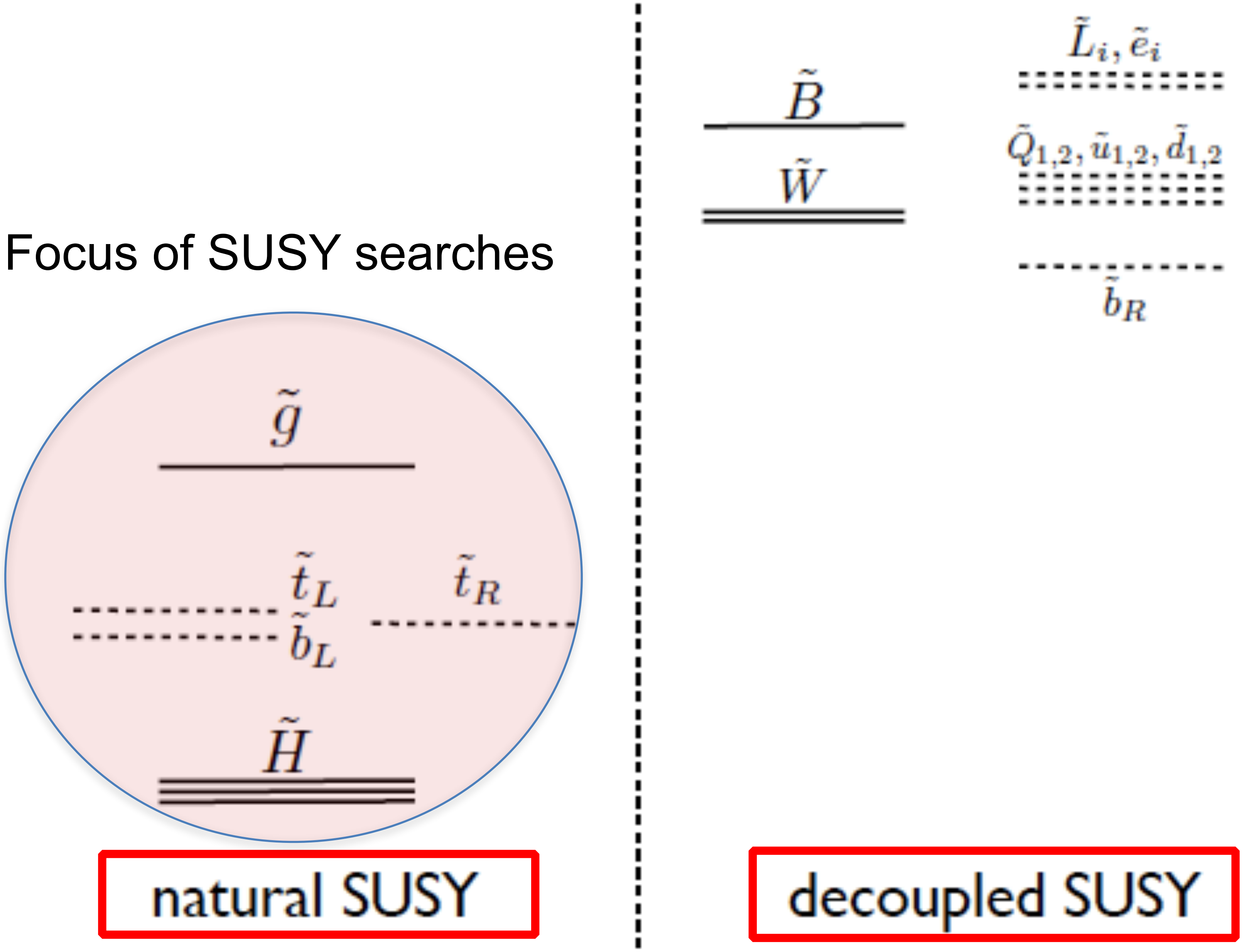
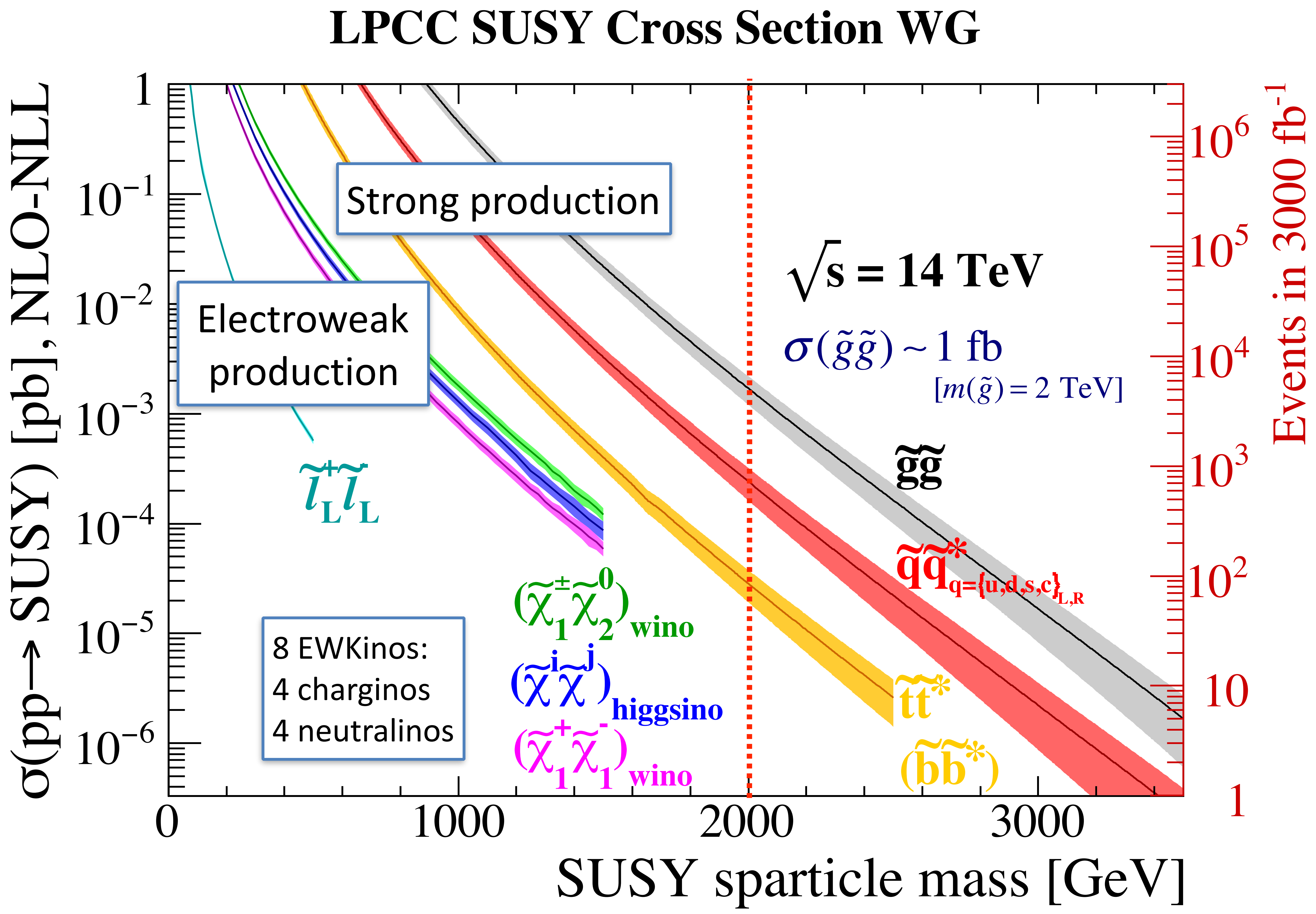
The natural SUSY spectrum is well-suited to a treatment in the simplified-model framework.


Focus of SUSY searches

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.

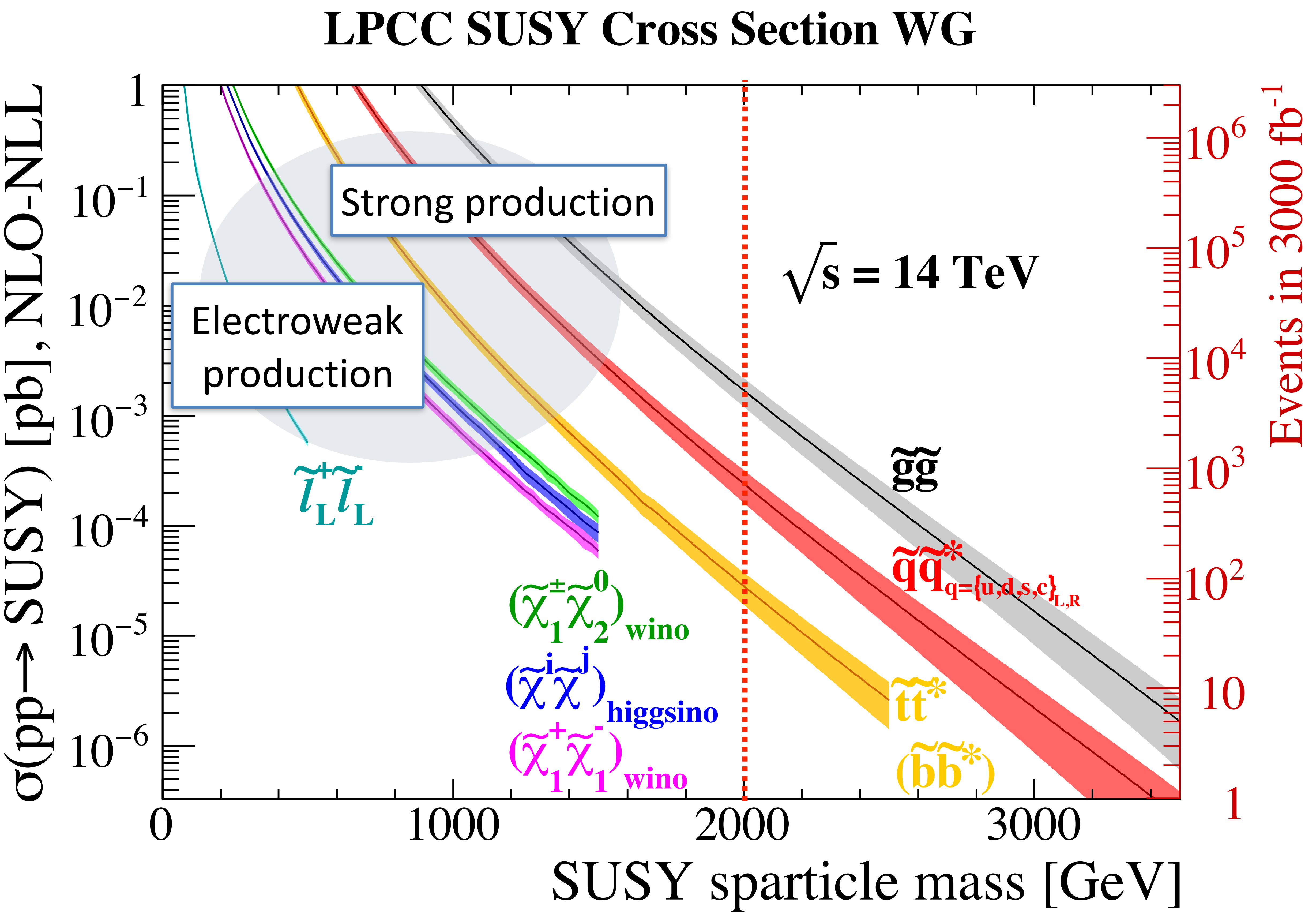
SUSY Production Cross Sections



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

arXiv:1407.5066

SUSY Production Cross Sections



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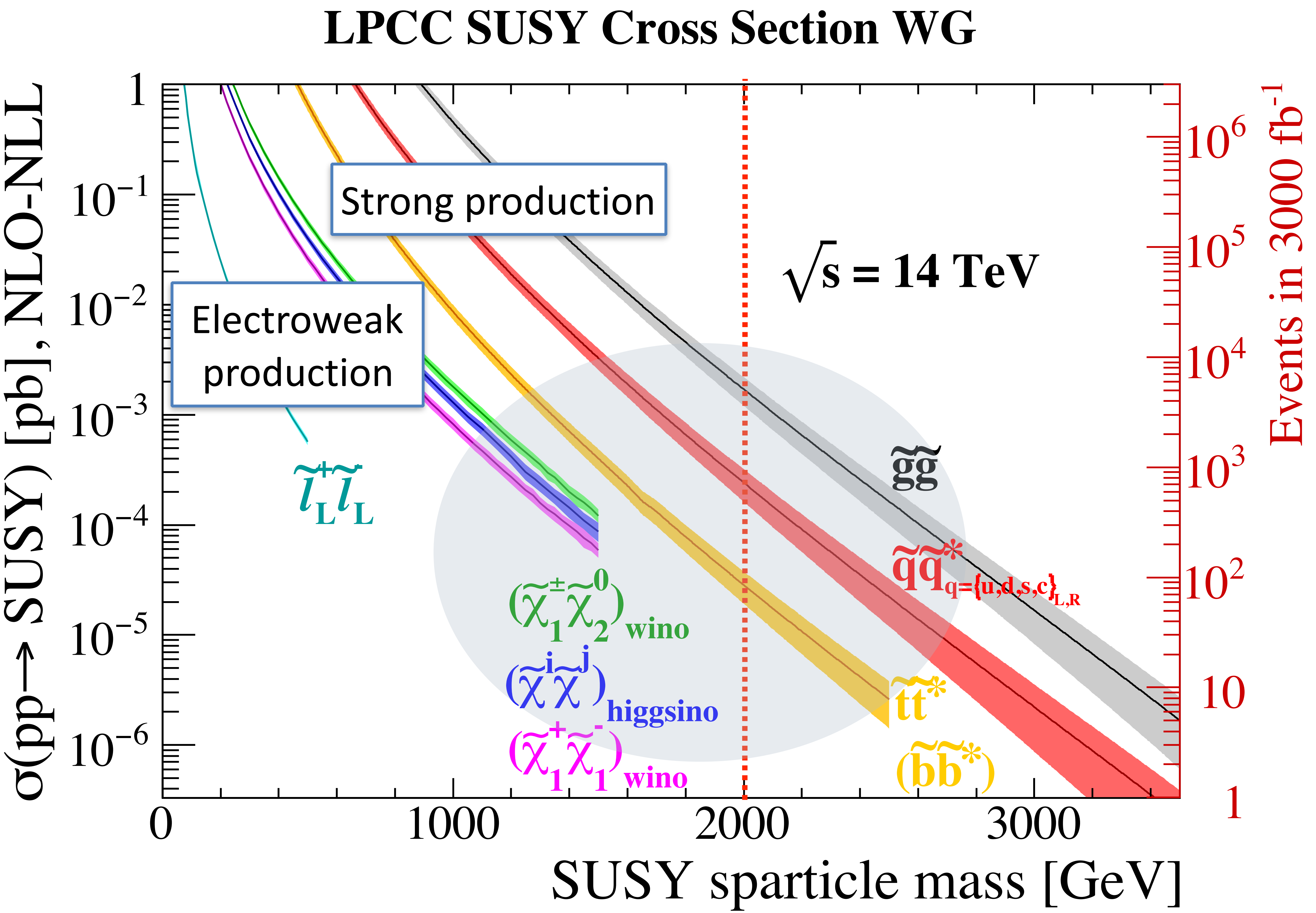
SUSY Production Cross Sections



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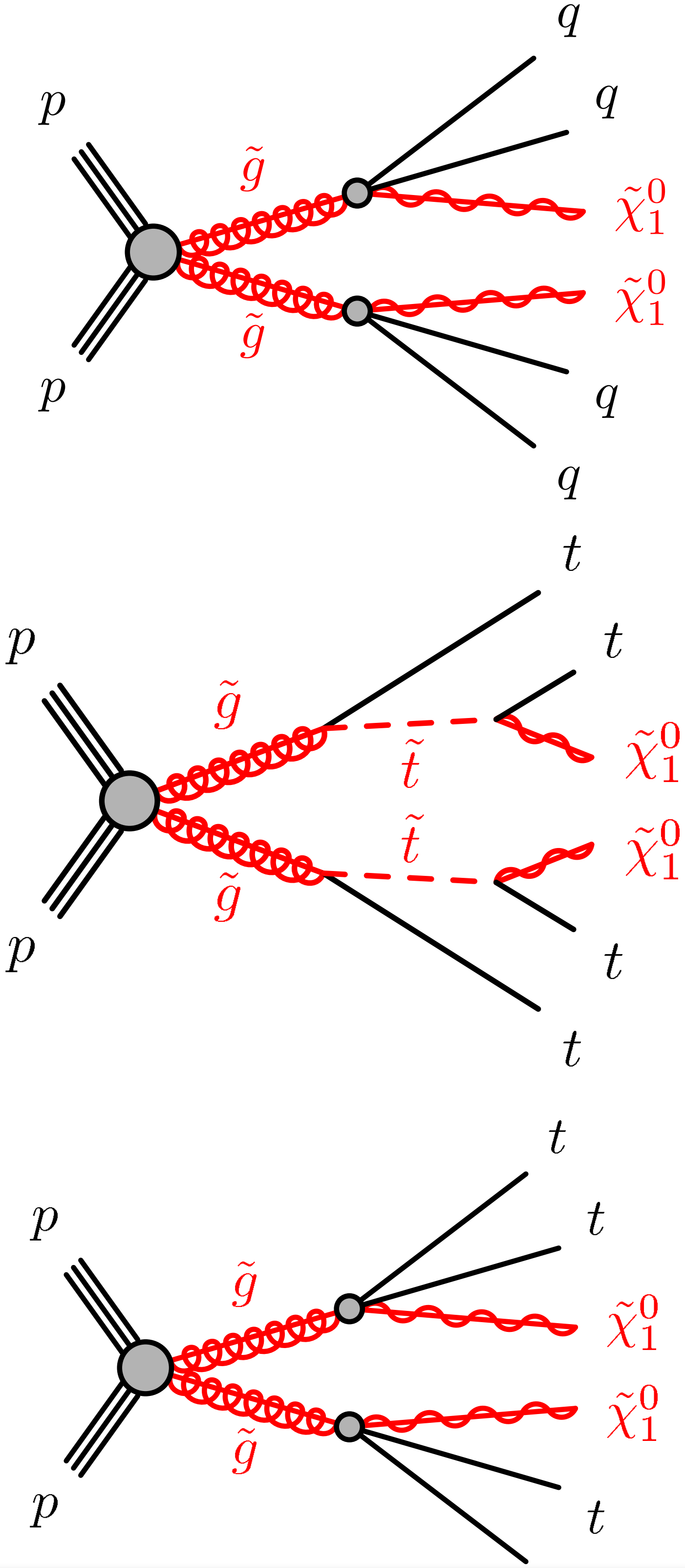
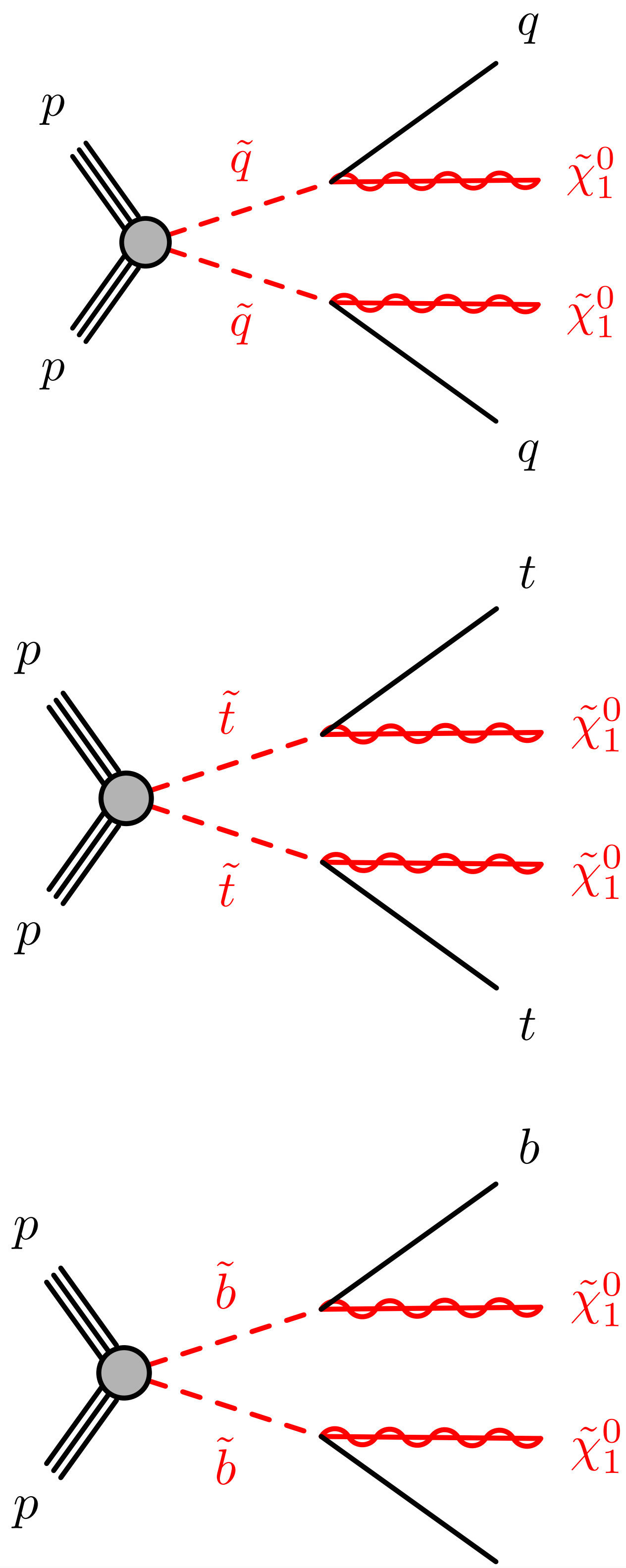
Simplified models for interpretation of search results

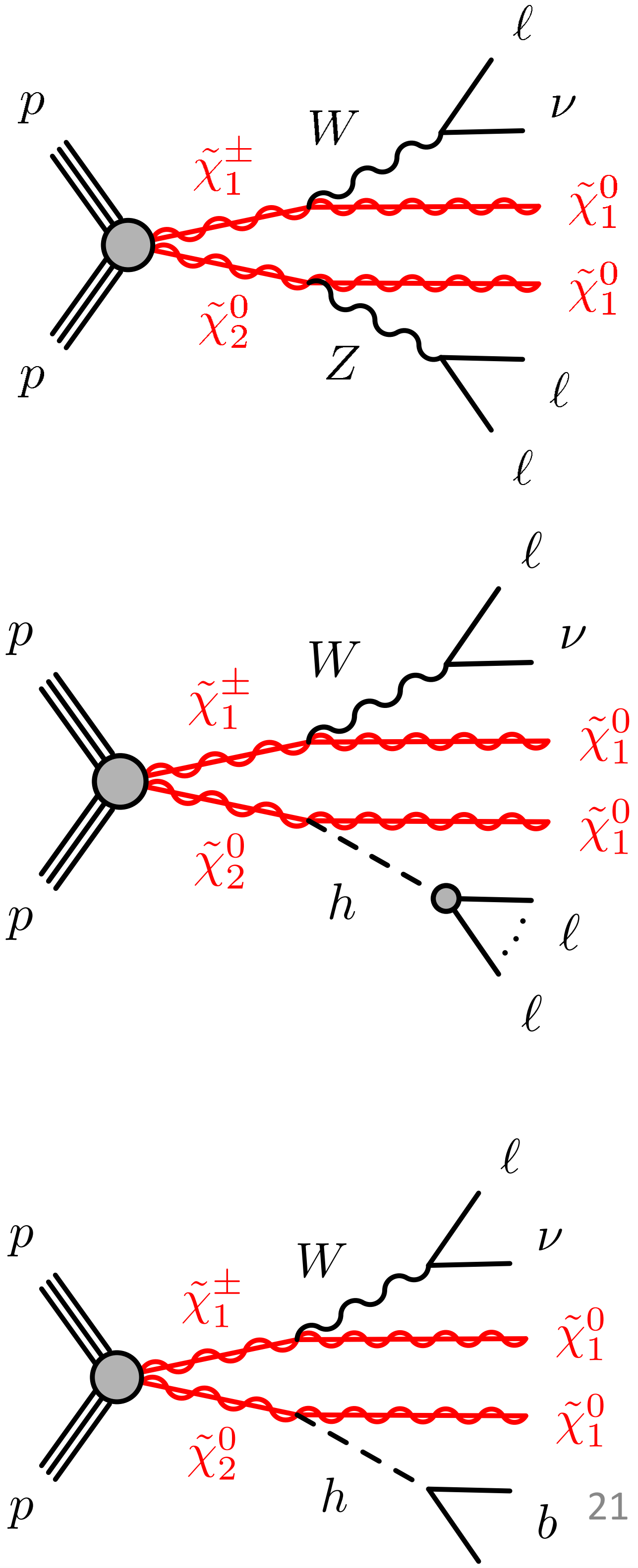
Strong production of gluinos



Strong production of squarks



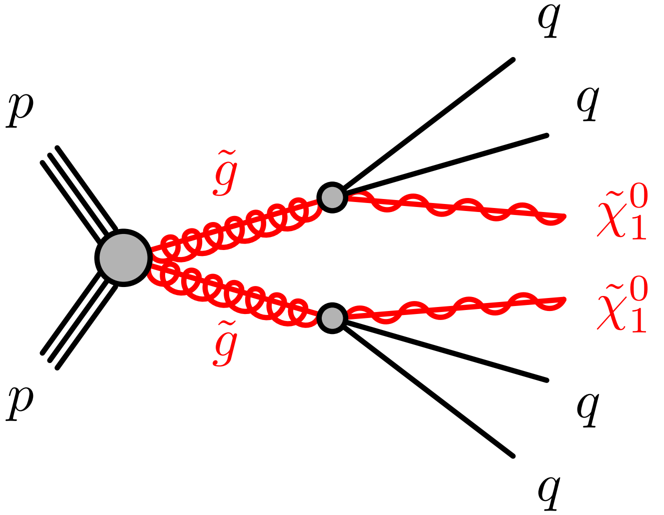
Electroweak Production

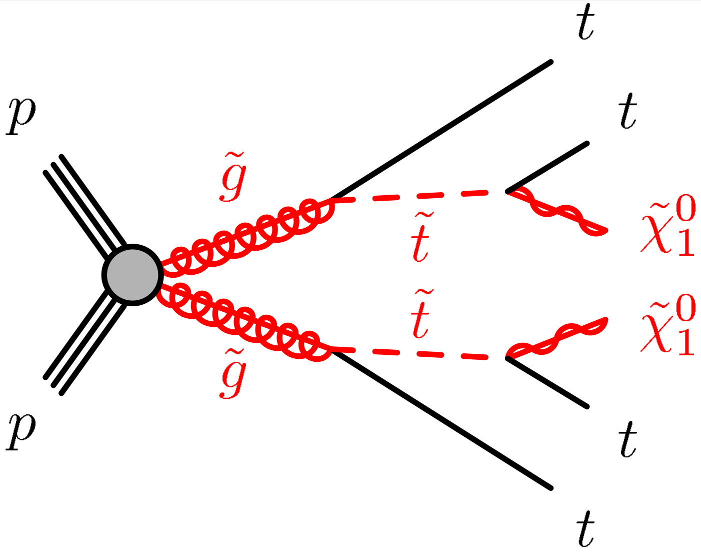


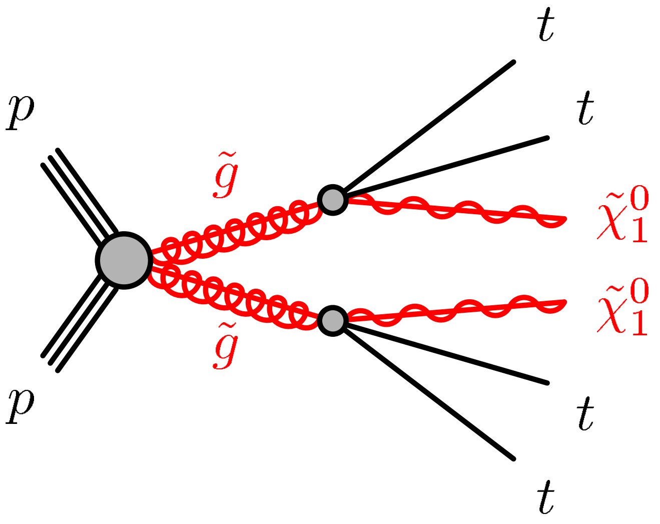
Avoids the SUSY *"curse of many parameters"*: in each case, the number of mass parameters is just 2-3.

Simplified models for interpretation of search results

Strong production of gluinos







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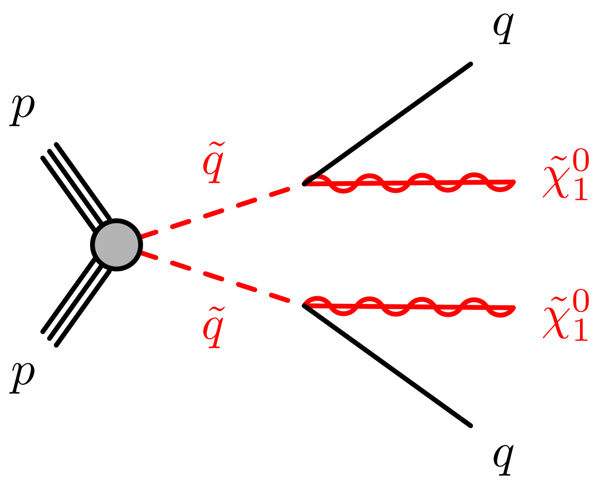
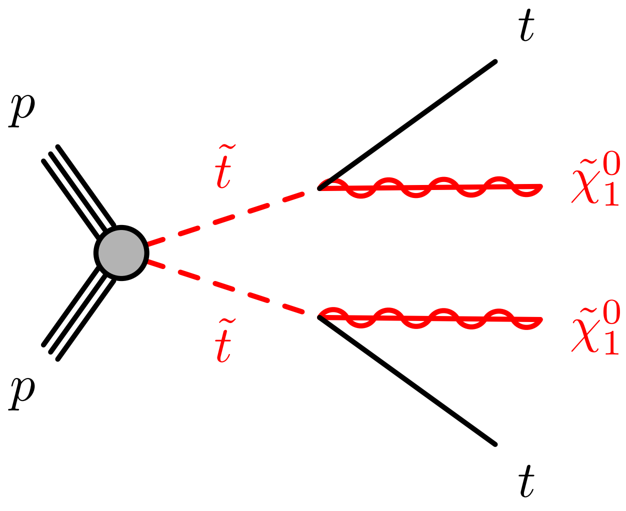
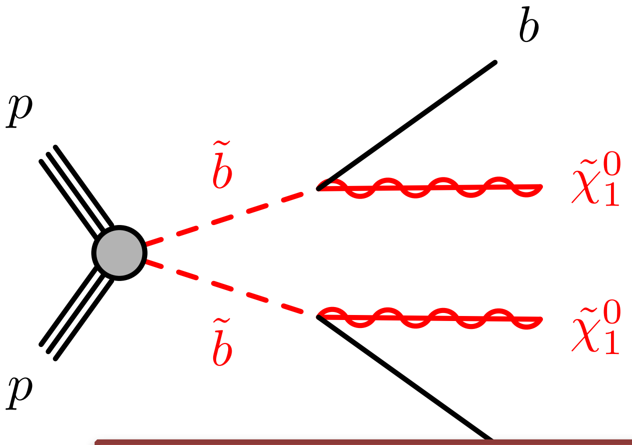
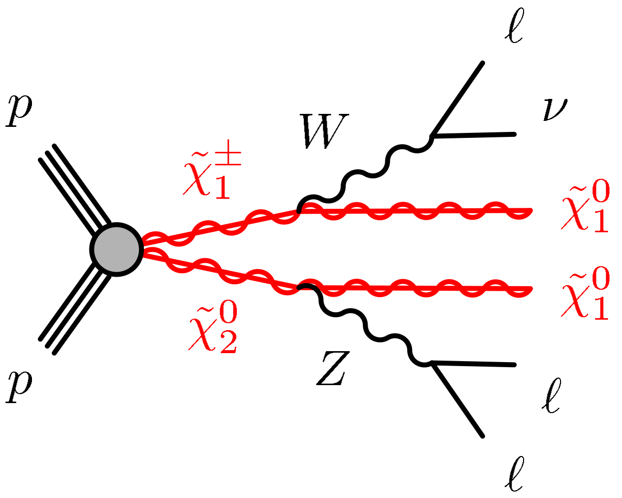
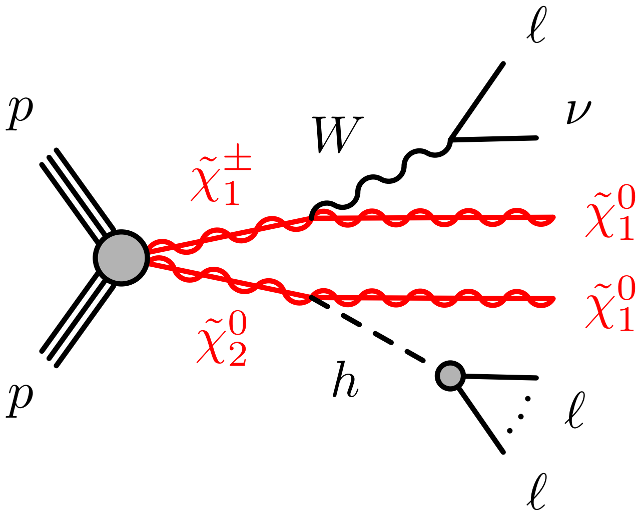


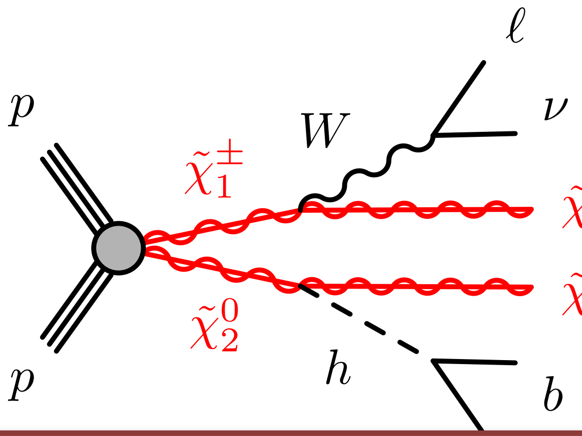




Electroweak Production







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

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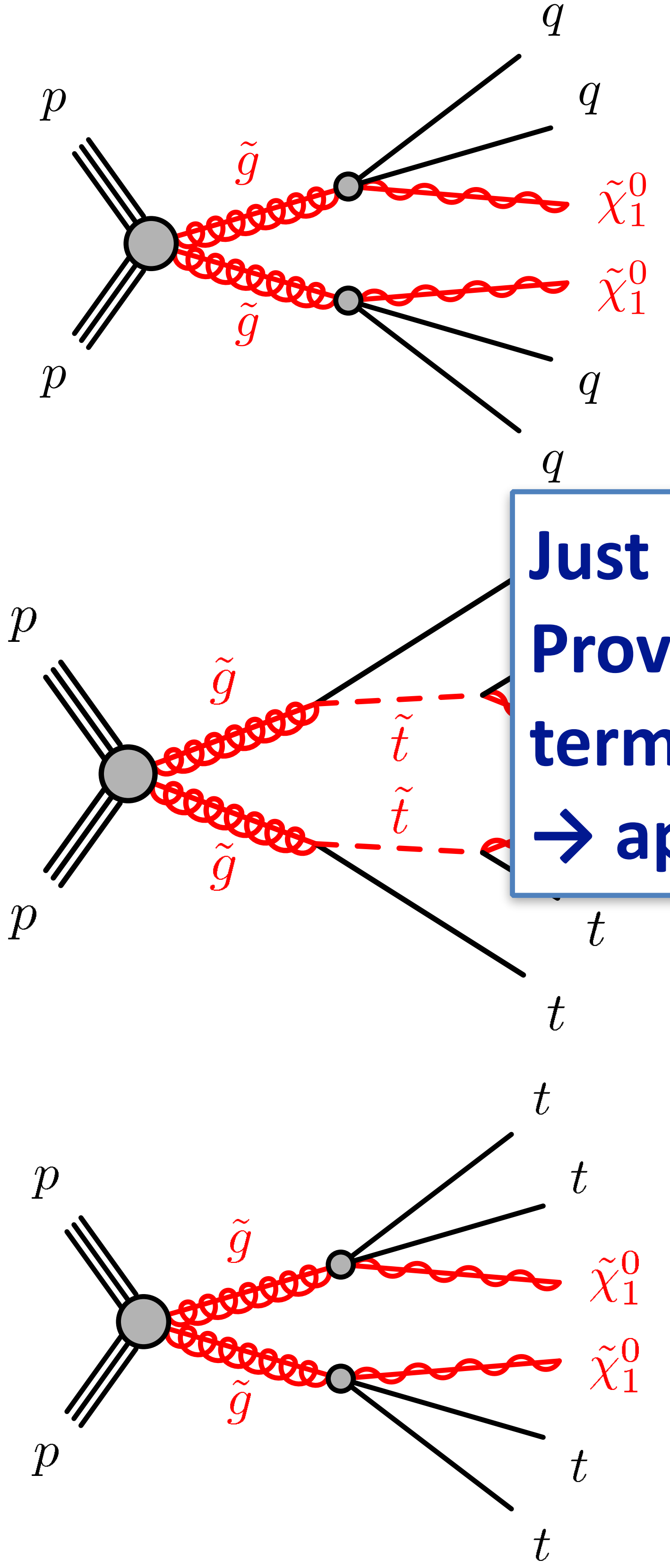

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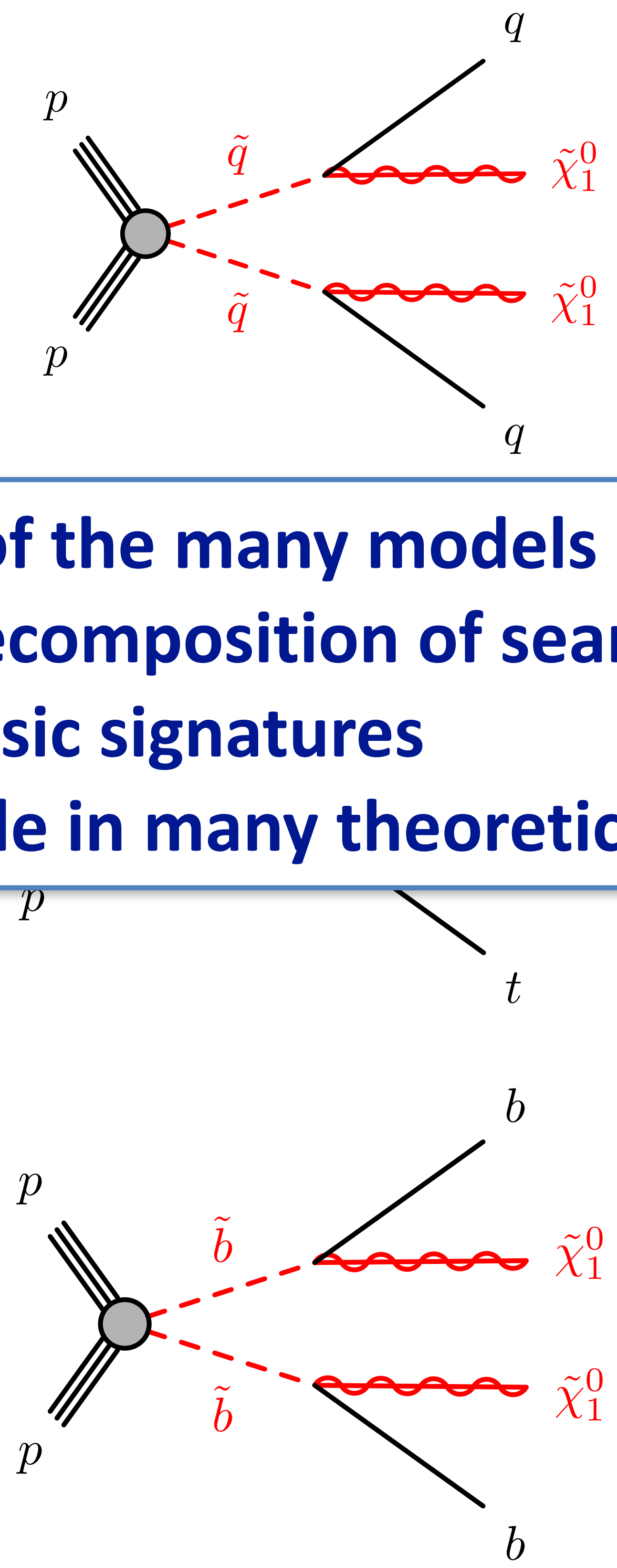
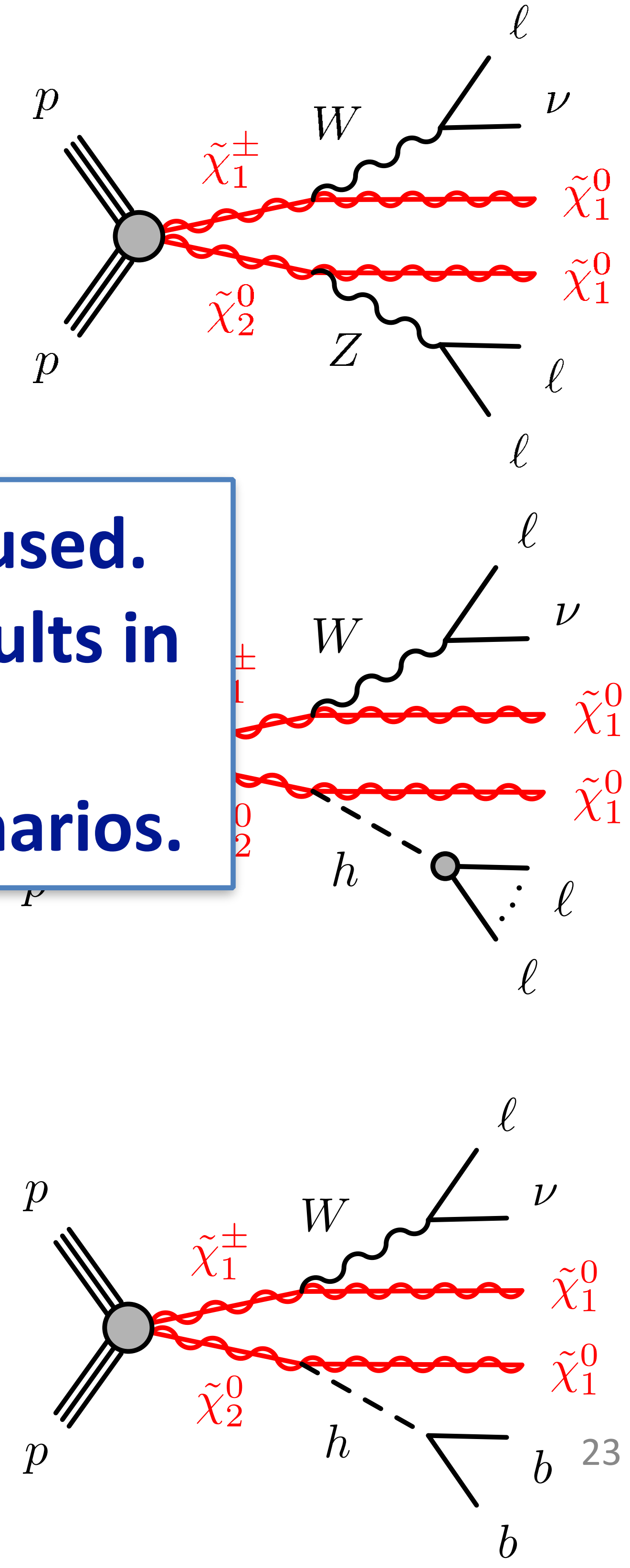


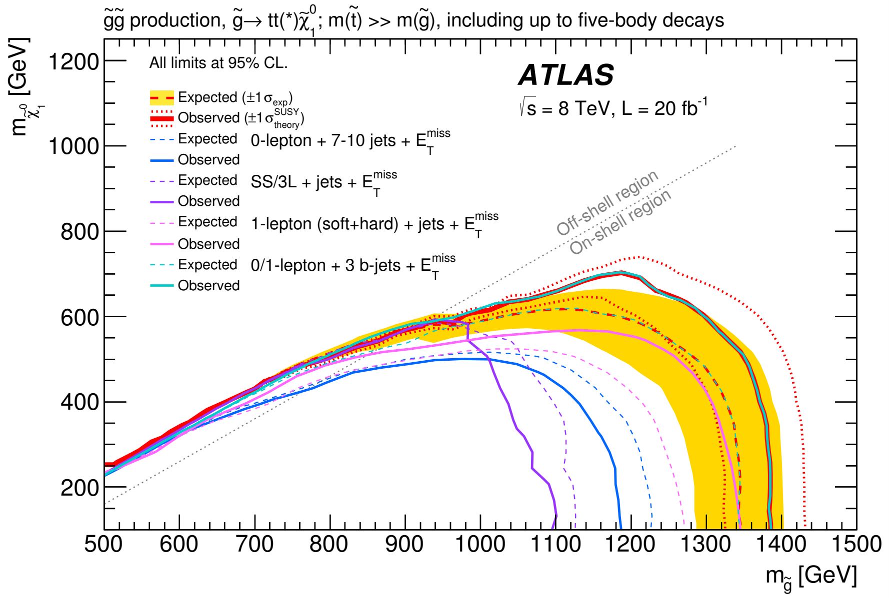
Electroweak Production



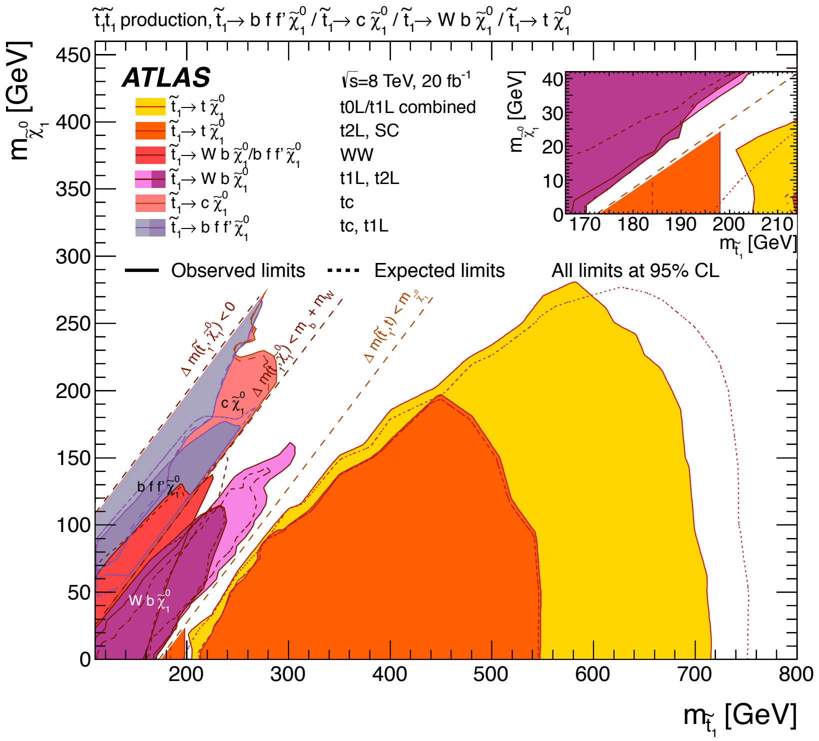
Just a few of the many models being used.
Provides decomposition of search results in terms of basic signatures
→ applicable in many theoretical scenarios.

SUSY searches at the end of Run 1

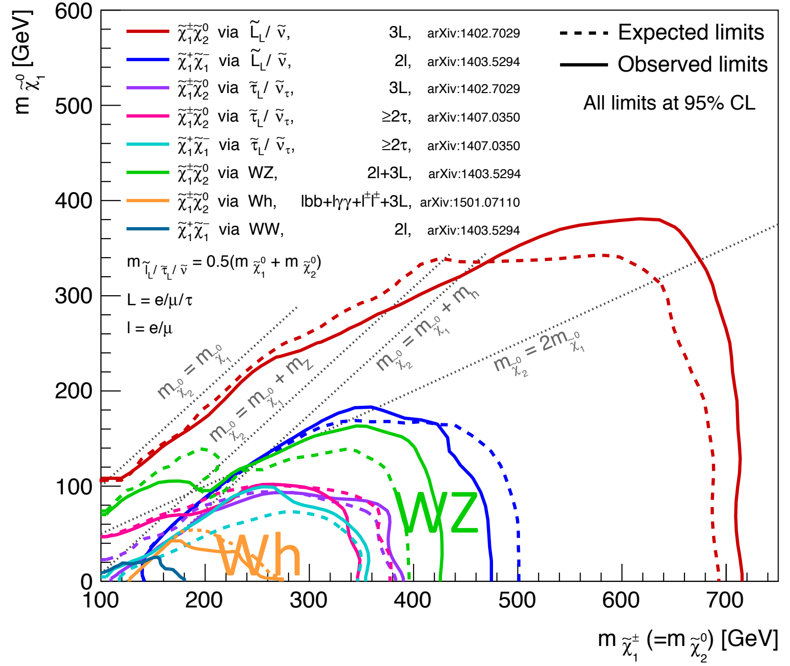
$M(\tilde{g}) > 1.35$ TeV
for $\tilde{g} \to \tilde{t}\bar{t}$; $B(\tilde{t} \to t\tilde{\chi}_1^0) = 1$
and small $M(\tilde{\chi}_1^0)$

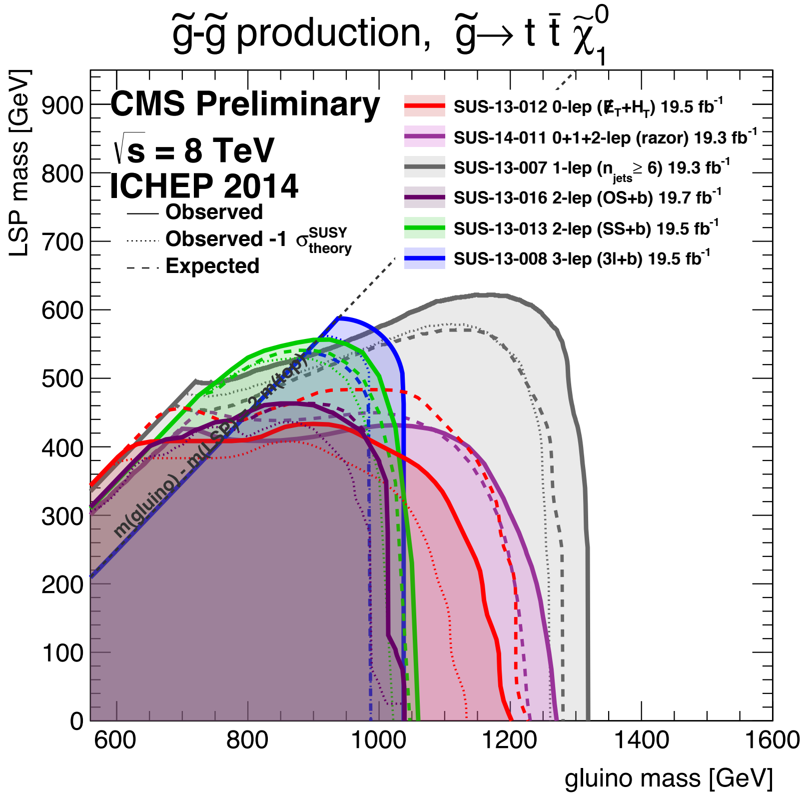


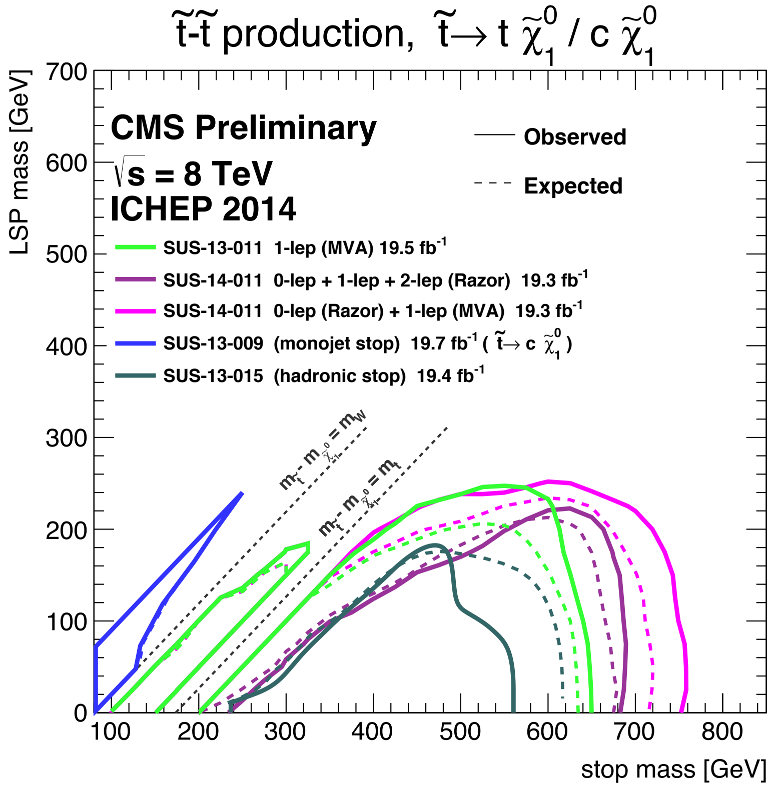
$M(\tilde{t}) > 750$ GeV
for B$(\tilde{t} \to t\tilde{\chi}_1^0) = 1$
and small $M(\tilde{\chi}_1^0)$

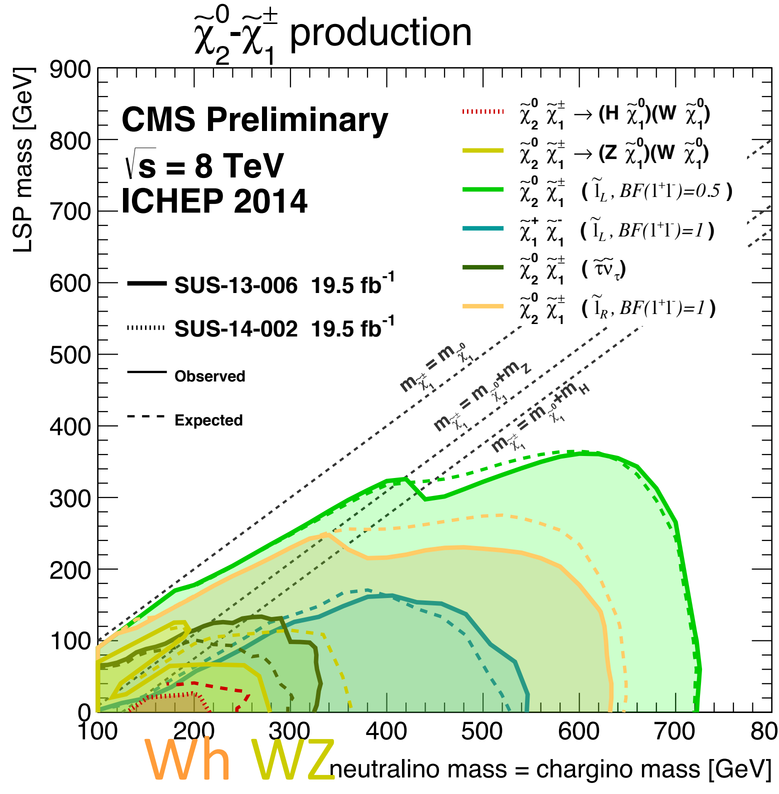


$M(\tilde{\chi}_1^\pm) = M(\tilde{\chi}_2^0) > 420$ GeV
$\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0$
$M(\tilde{\chi}_1^\pm) = M(\tilde{\chi}_2^0) > 250$ GeV
$\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0$

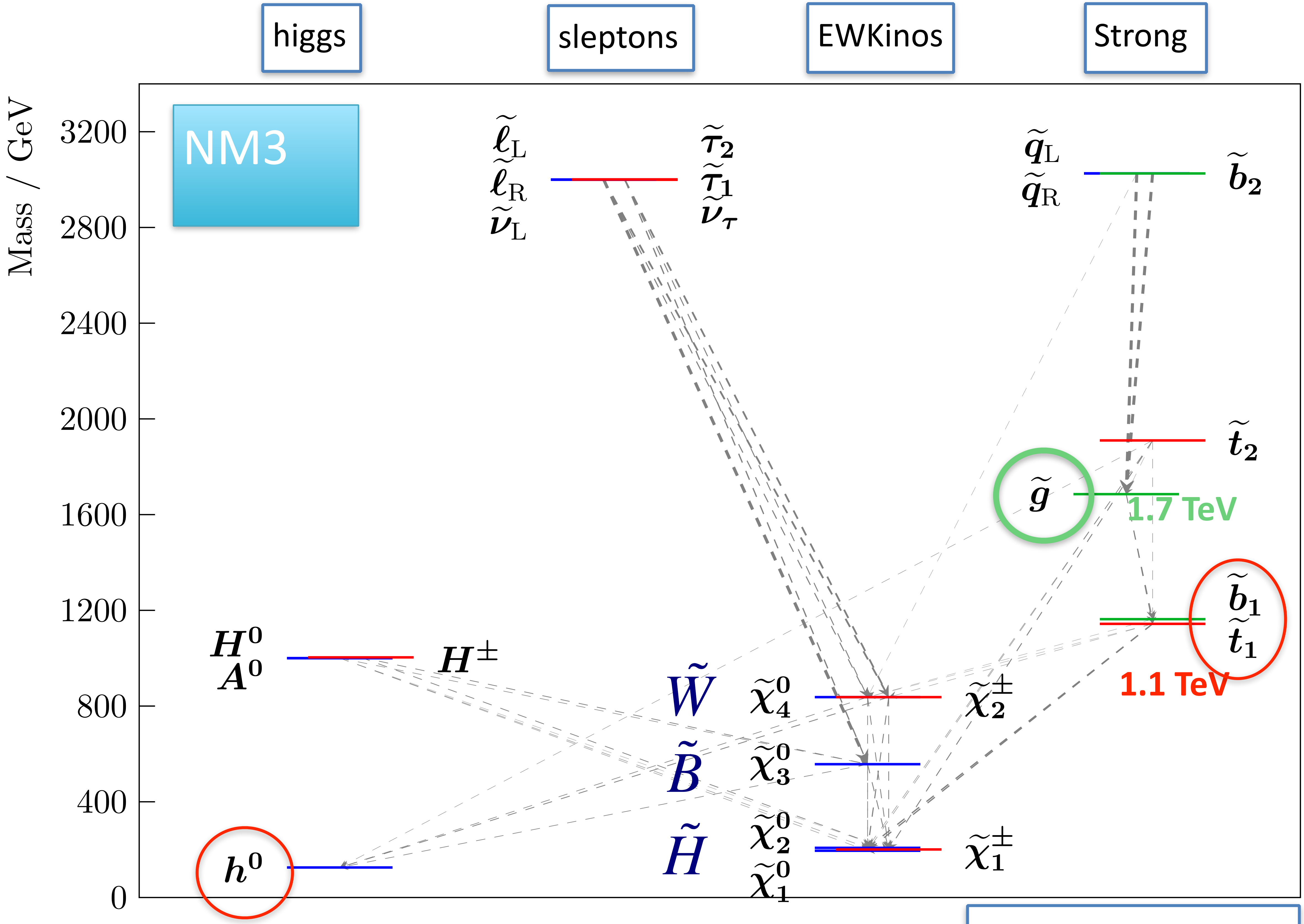






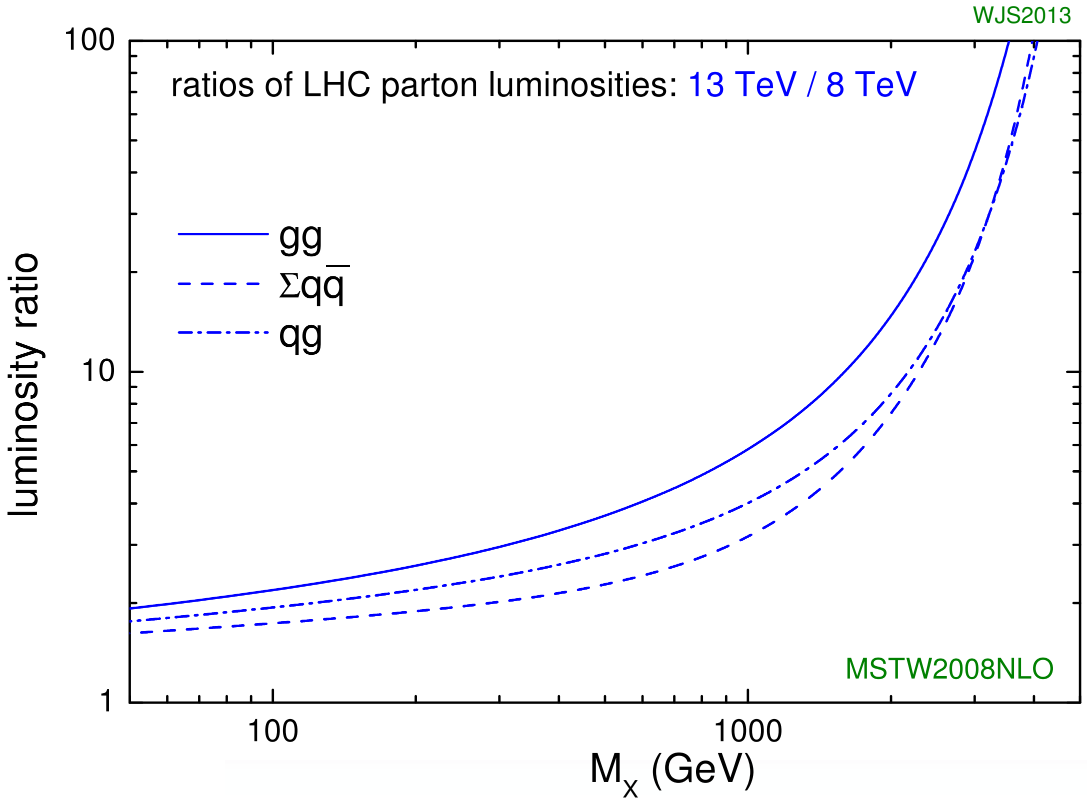


A full-spectrum SUSY model

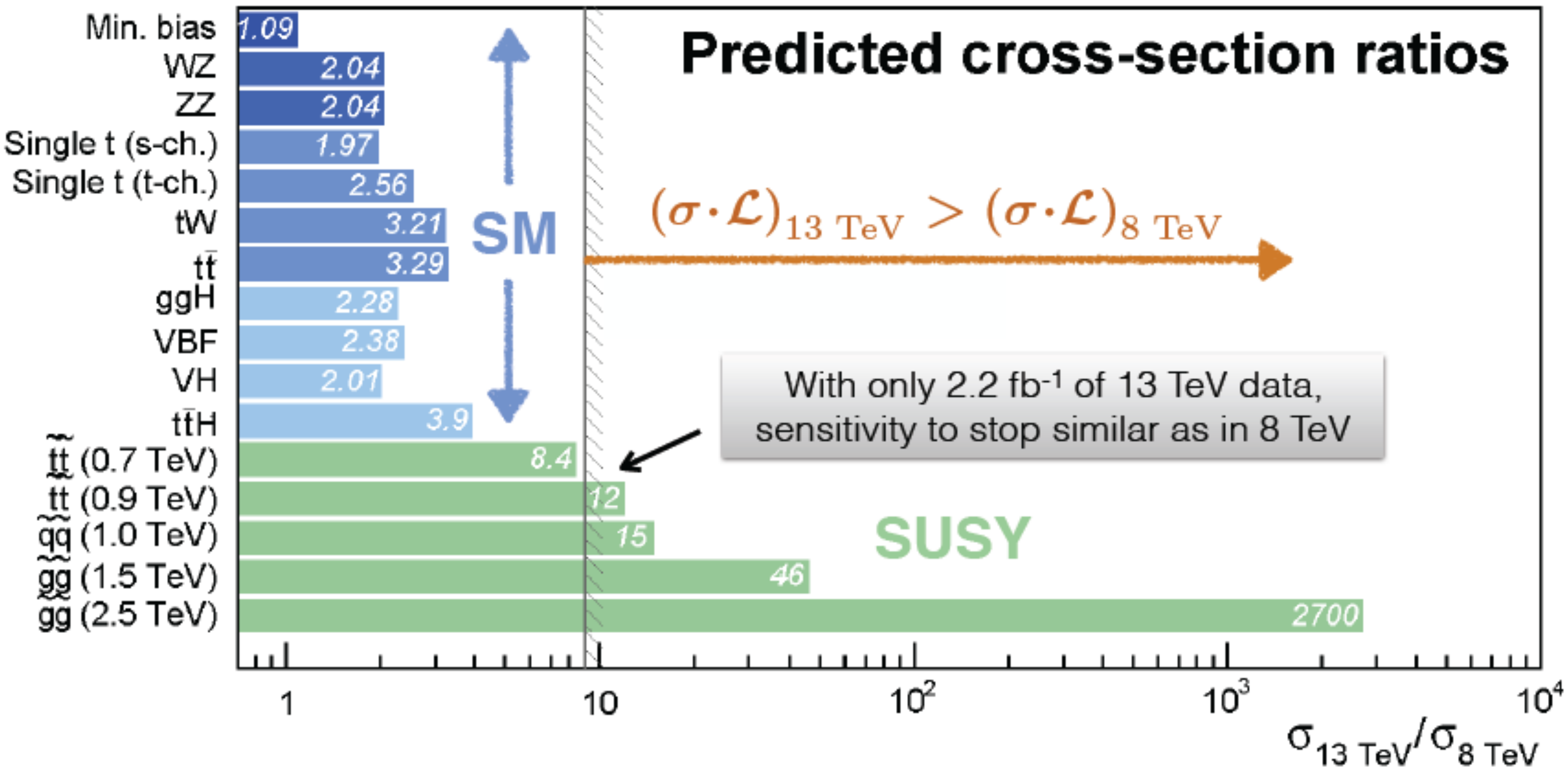


CMS PAS SUS-14-012

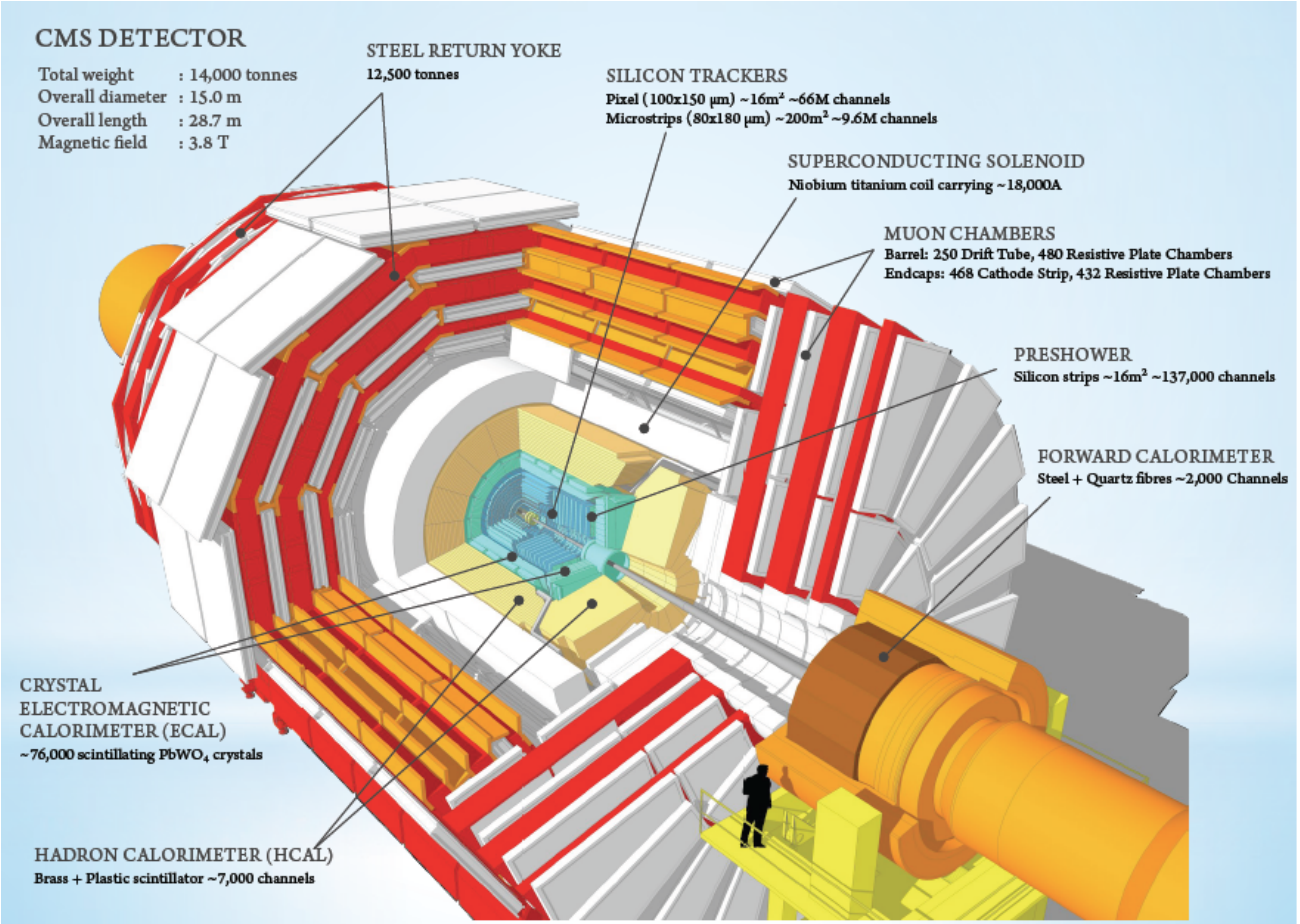
From 8 TeV to 13 TeV: 2 fb^{-1} goes a long way!



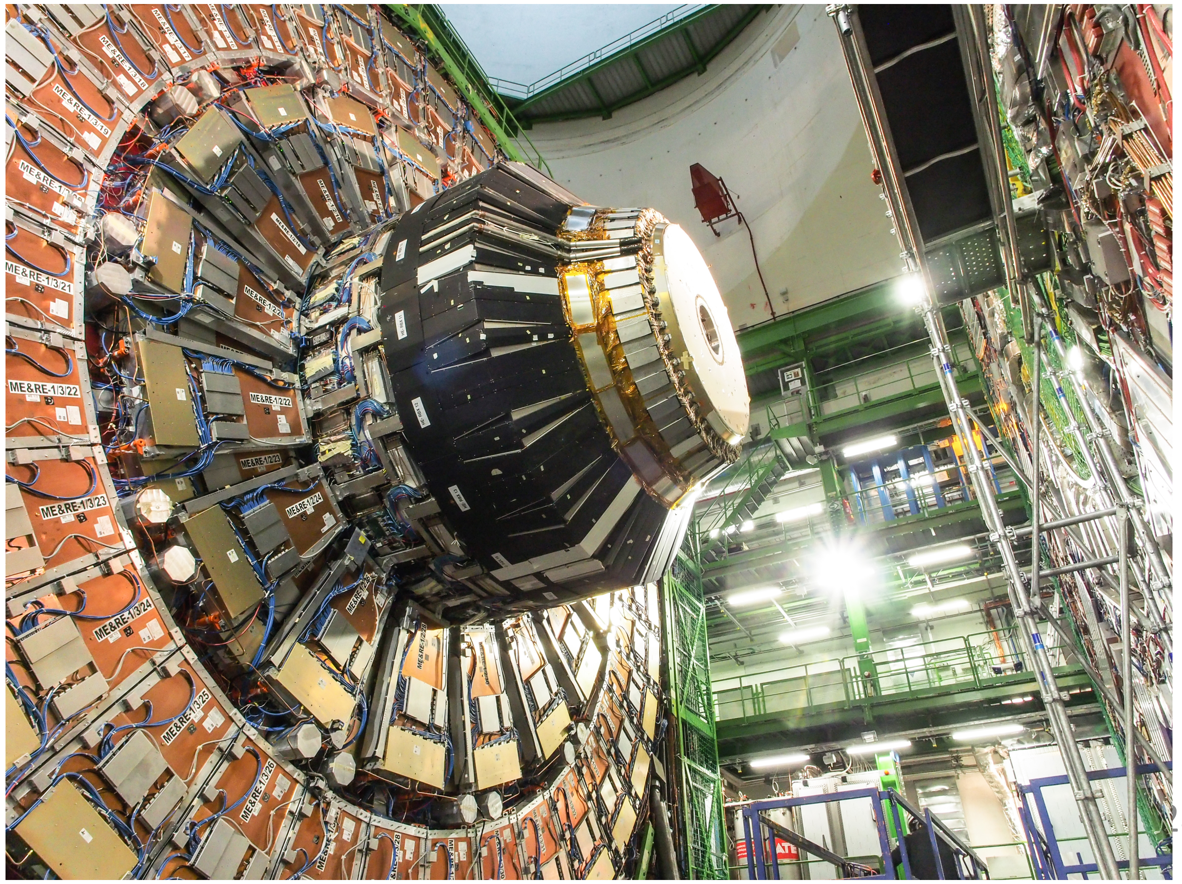
- The 13 TeV data sample has only ~1/10 the luminosity of the 8 TeV data sample.
- But sensitivity for this search still surpasses that at 8 TeV!



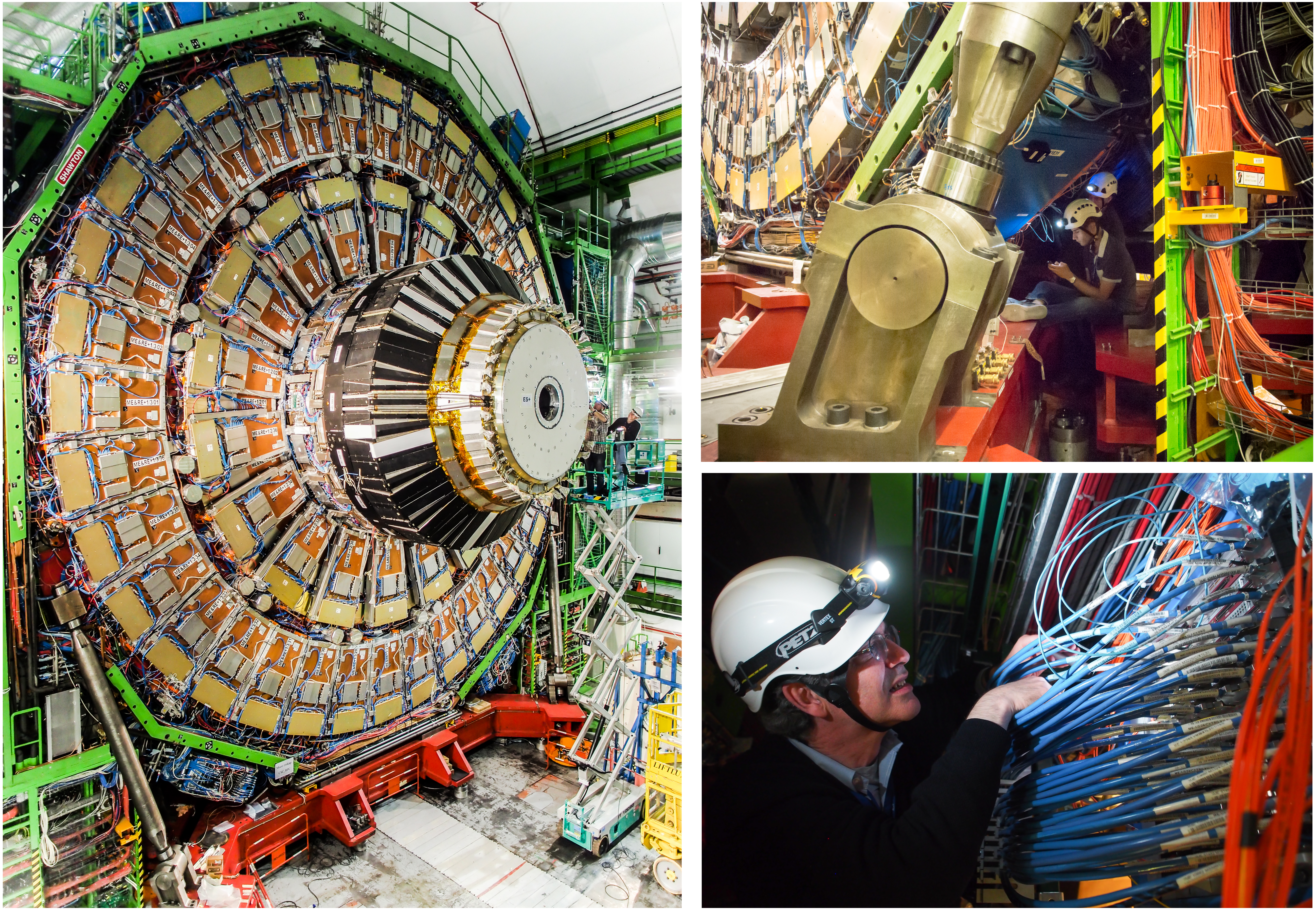
With only 2.2 fb^{-1} of 13 TeV data, sensitivity to stop similar as in 8 TeV


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

Working on the CMS detector



Working on the CMS detector




153-12
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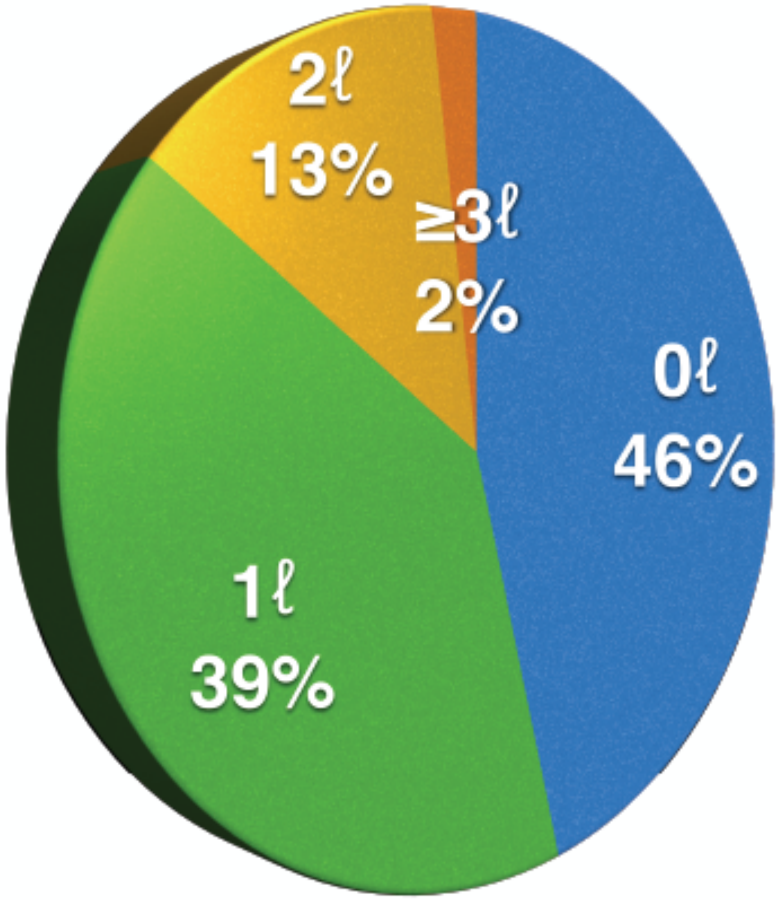
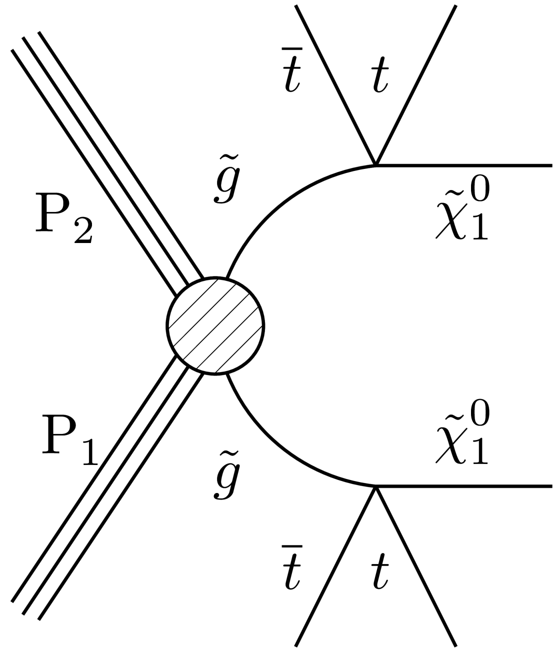
A single-lepton SUSY search (CMS SUS-15-007)

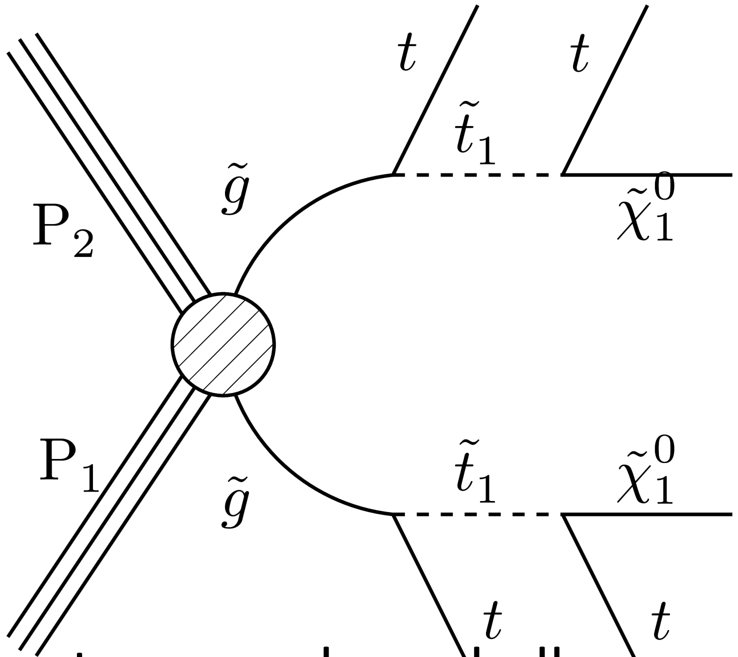
- Designed for a high jet multiplicity signal, with 1 isolated lepton, large p_T^{miss}, and at least one b-jet.
- Strong production process already has sensitivity gain from increase in CM energy.
- Probes gluino decay to on-shell or off-shell top squark + top quark.



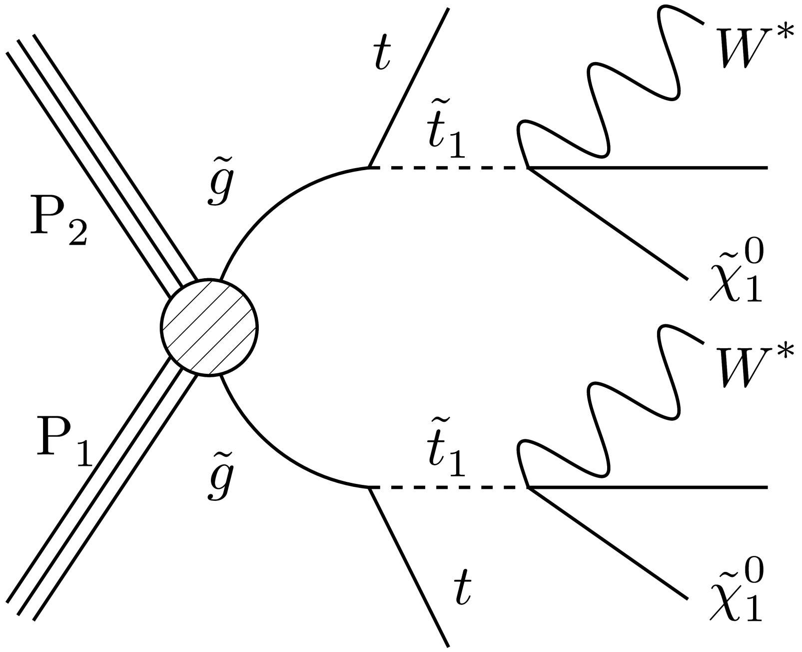
Final states for T1tttt



“T1tttt” simplified model



top squark on shell



SUS-15-007: Baseline event selection

- **Trigger**: p_T (e,μ) > 15 GeV with v. loose isolation, H_T > 350 GeV (ϵ_{trig} = 95% for offline selection, measured with E_T^{miss} > 170 GeV trigger sample).
- **Baseline selection**: exactly 1 isolated e or μ, p_T (e,μ) > 20 GeV, H_T > 500 GeV, E_T^{miss} > 200 GeV, N(jets) ≥ 6, N(b-jets) ≥ 1.

SUSY benchmarks

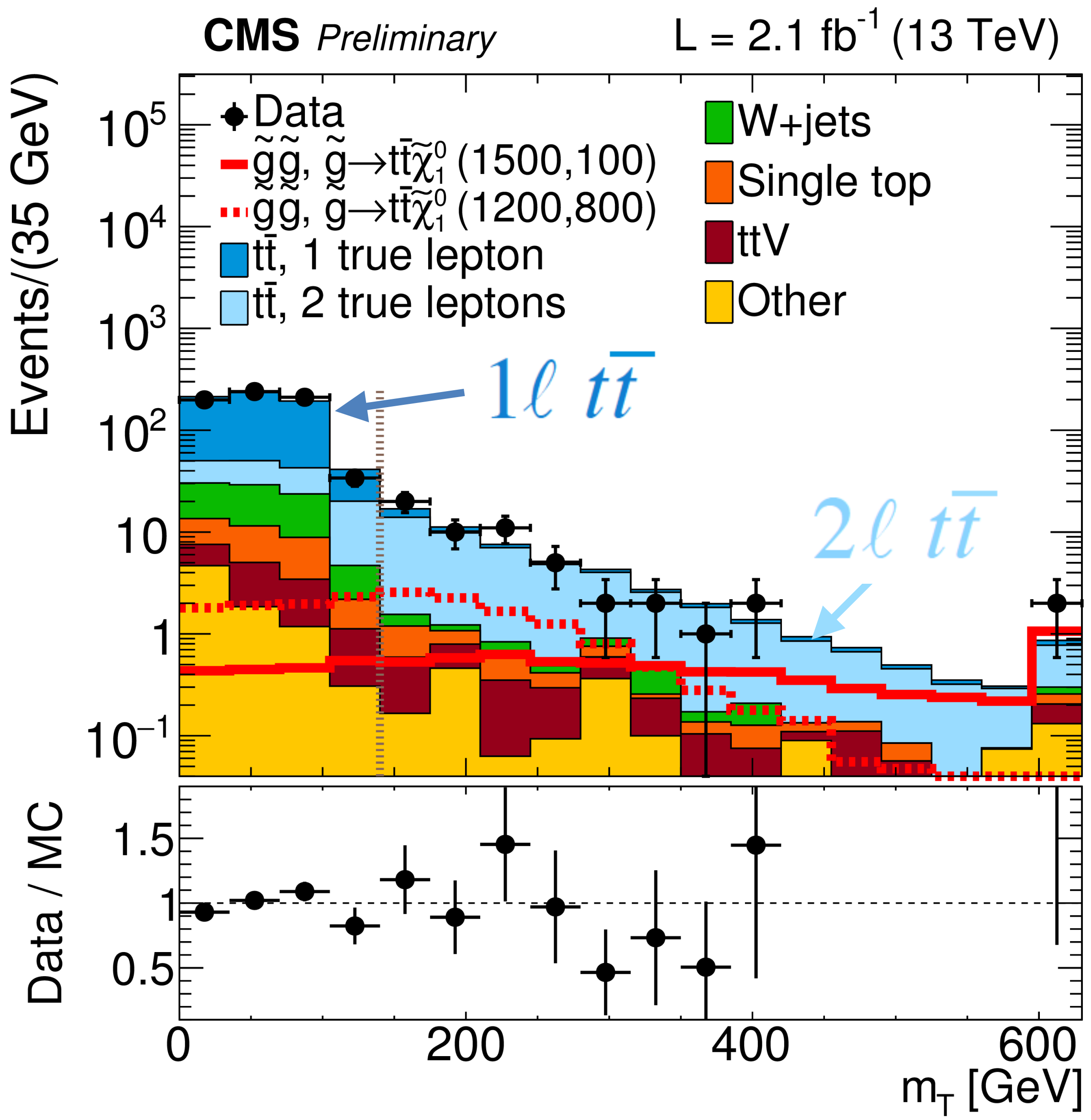
$m(\tilde{g}), m(\tilde{\chi}_1^0)$

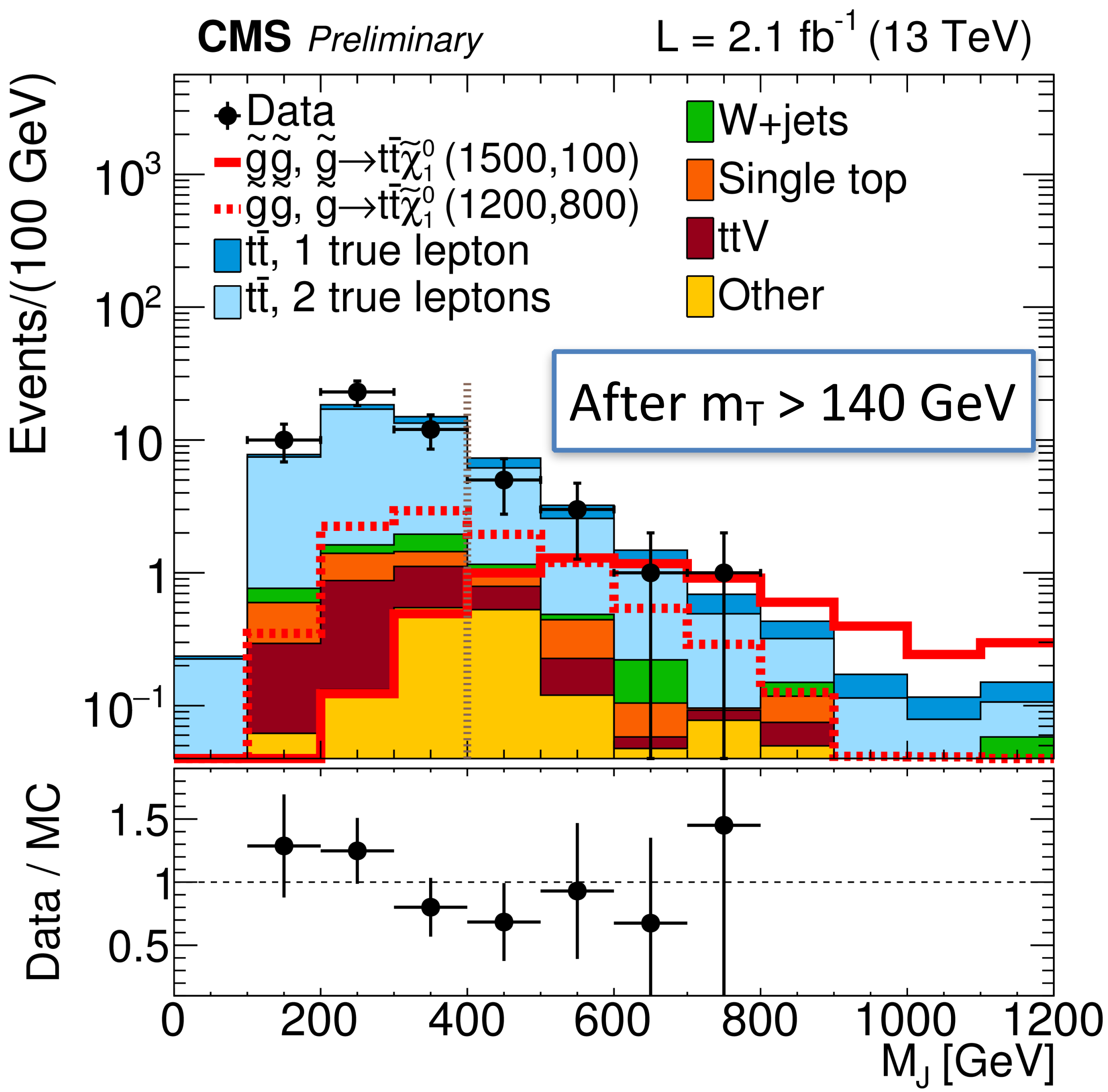
Event yields: Selection/ MC sample	*DY, VV tttt, ttH*	*QCD incl. tt→had*	*ttV*	*Single t*	*W + jets*	*ttbar 1 lep*	*ttbar 2 lep*	*Total SM*	*T1tttt 1500, 100 (~14 fb)*	*T1tttt 1200,800*
1 iso lepton, HT>500	3850	29240	660	2690	29290	25690	3170	94620	11	*42*
BASELINE	9	2.4	28	59	61	600	135	890	8.4	17.7
BASELINE + M_J > 250 and M_T > 140	0.7	1.3	3.0	3.5	1.2	5.4	32	47	6.8	9.0

S/B ≈ 1%

99% 1-lep rejected

Beyond the baseline selection: M_T and M_J





$$m_\mathrm{T} = \sqrt{2 p_\mathrm{T}^\ell E_\mathrm{T}^\mathrm{miss} [1 - \cos(\varphi_\ell - \varphi_\mathrm{MET})}$$

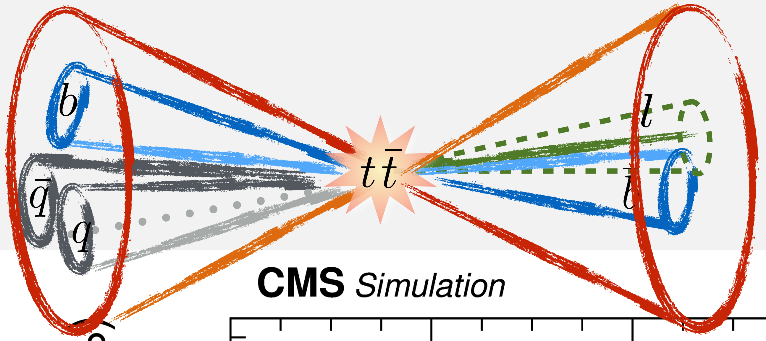
$$M_J = \sum_{\text{Large-}R\text{ jets}} m(J_i) \qquad R = 1.2$$

- The cut m_T > 140 GeV suppresses most single-lepton ttbar evts.
- Large-R jets formed by clustering standard AK4 jets; highly robust

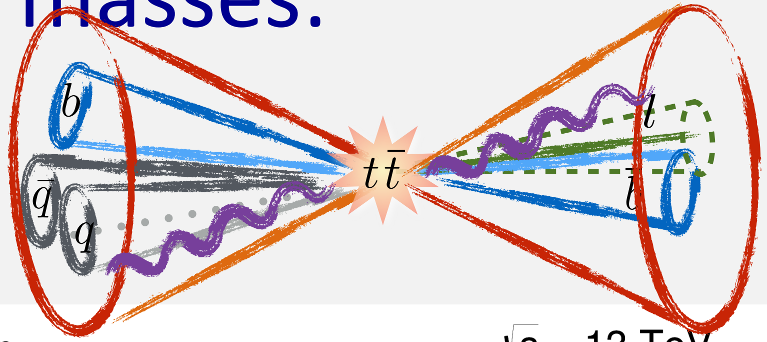
Masses of large-R jets, MJ, & initial-state radiation

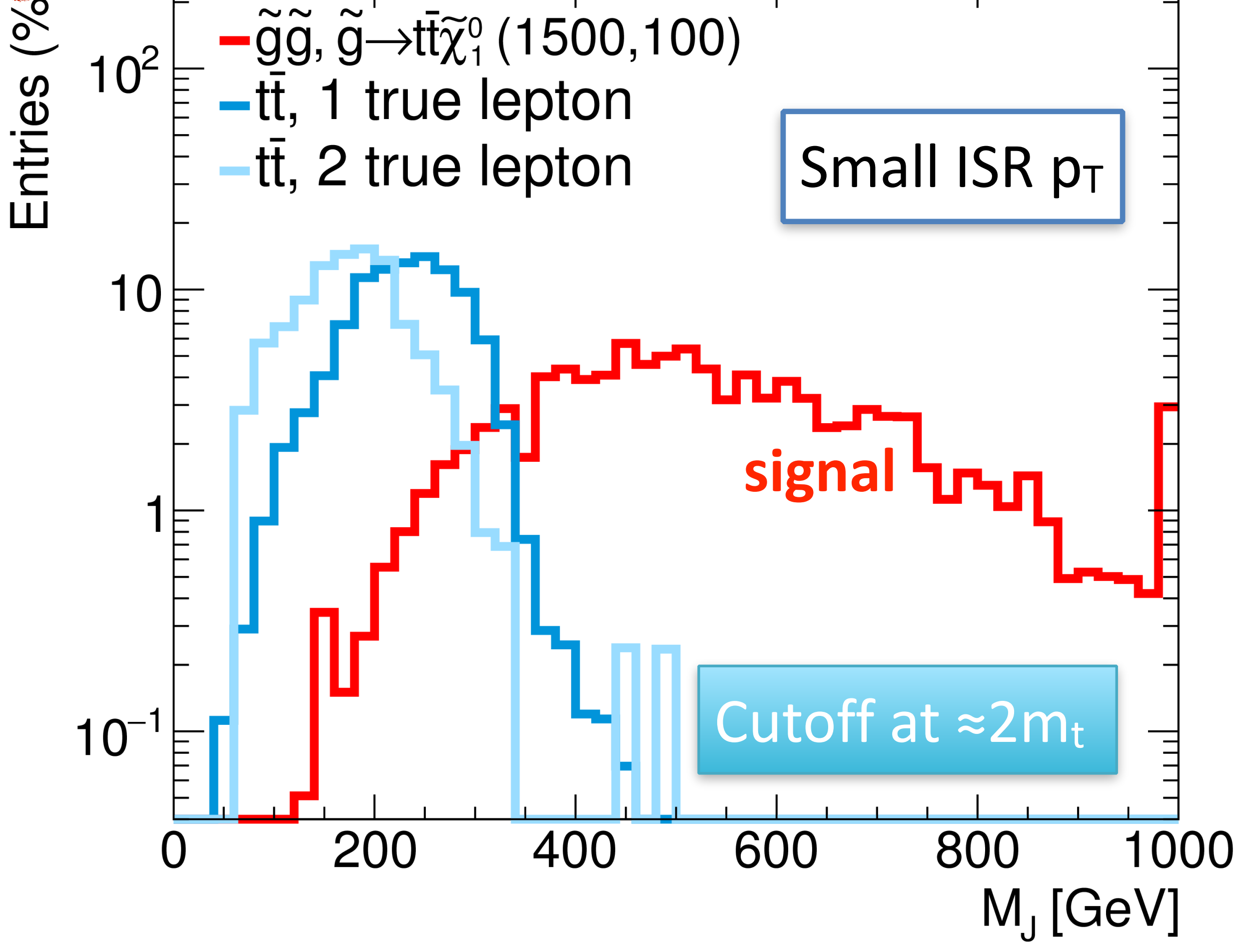
Starting from standard anti-kT jets (R = 0.4), we build large radius, or “fat” jets by further combining these AK4 jets using the anti-kT algorithm with cone size R = 1.4.

Define M_J to be the scalar sum of these fat jet masses:



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



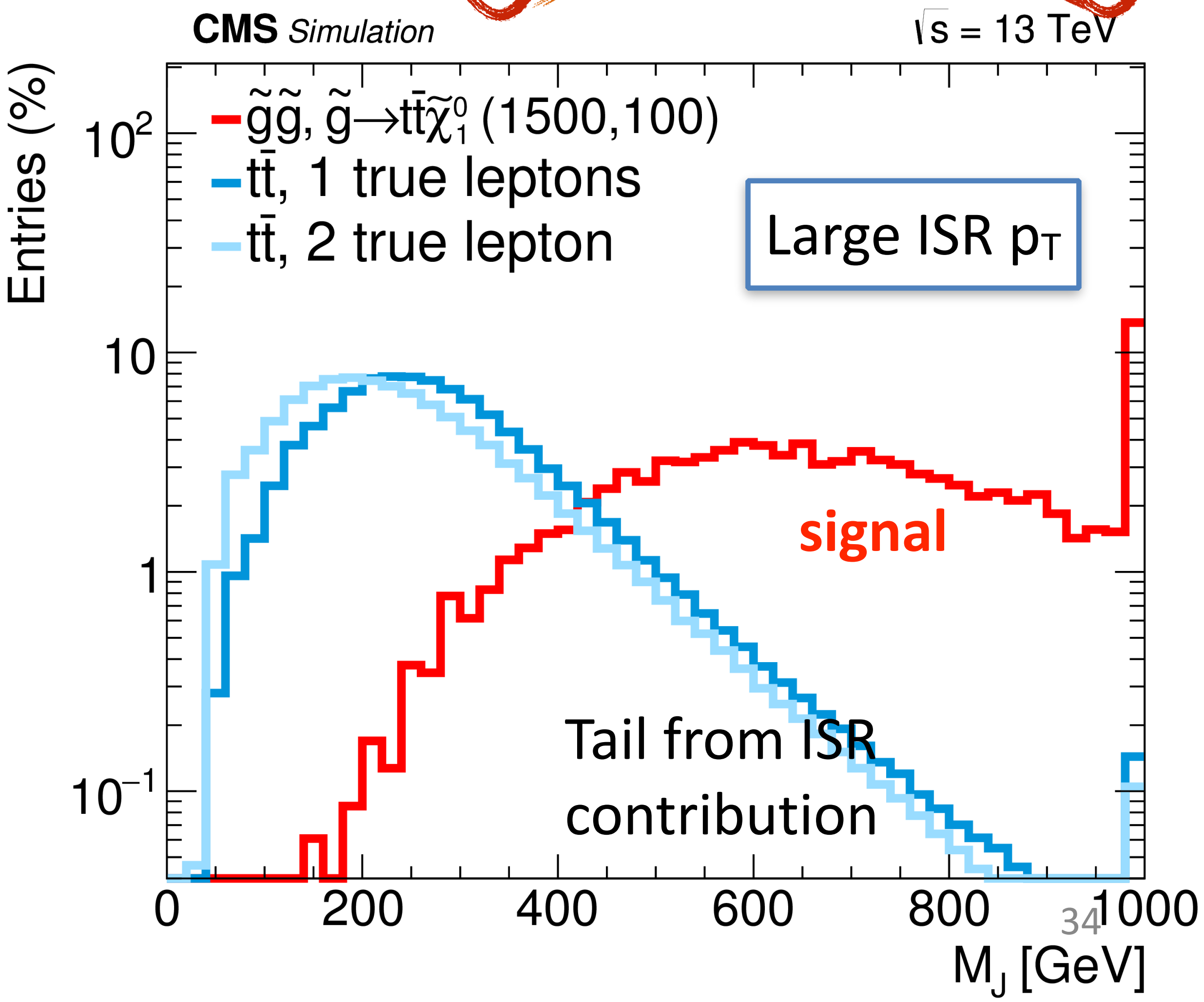


Small ISR p_T

signal

Cutoff at ≈$2m_t$

1



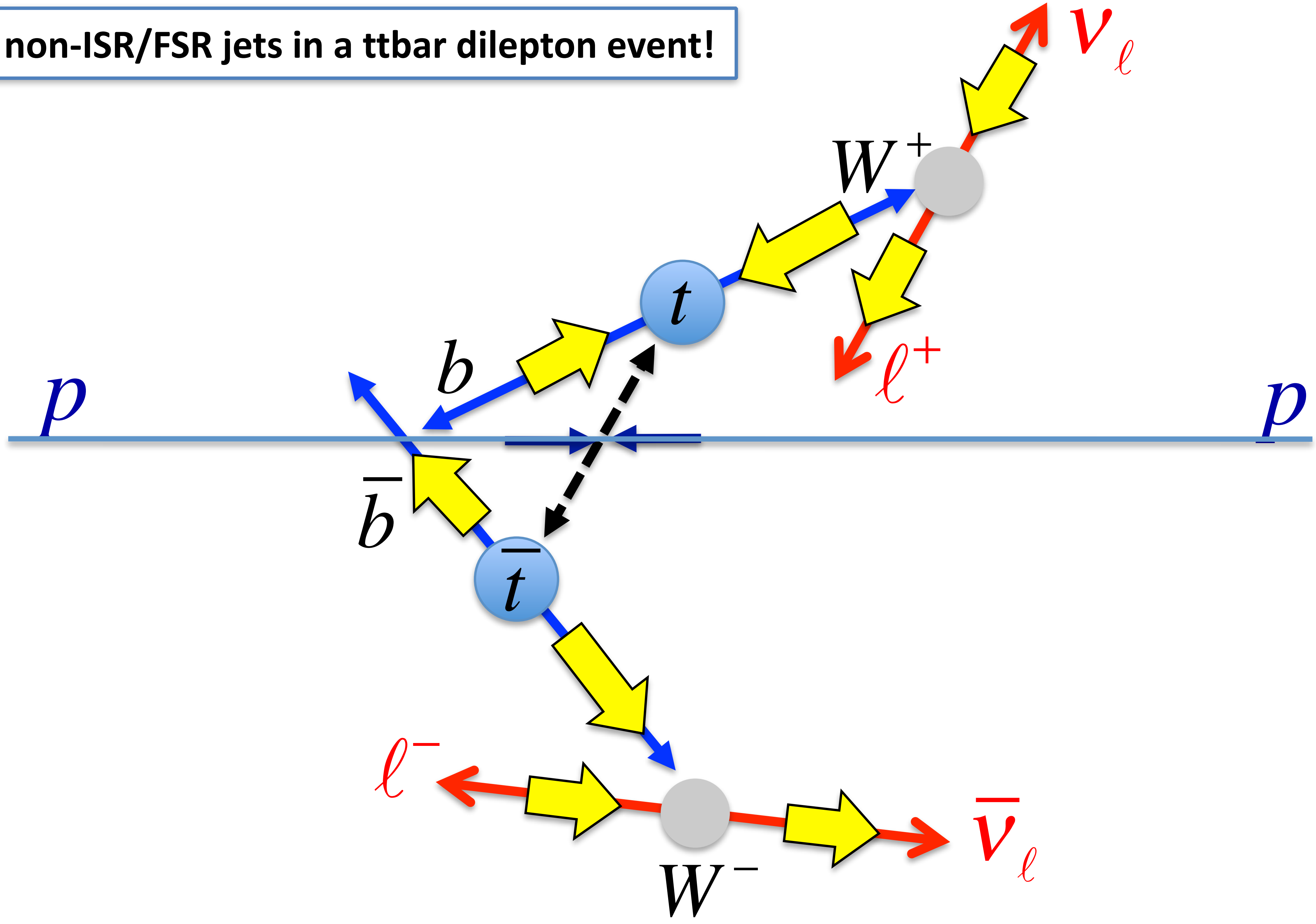
Large ISR p_T

signal

Tail from ISR contribution

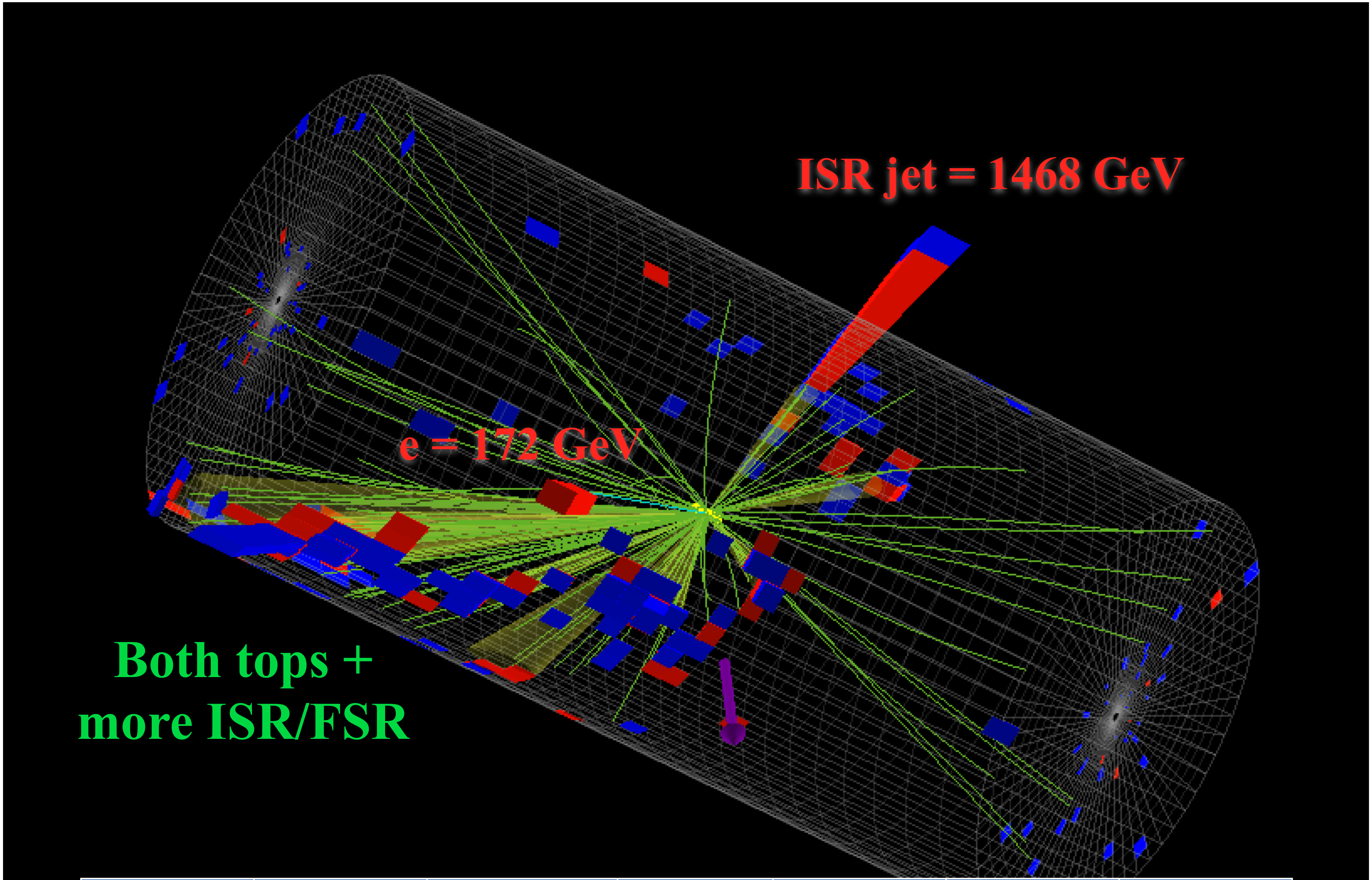
Anatomy of the ttbar→ 2 lepton background

ONLY 2 non-ISR/FSR jets in a ttbar dilepton event!



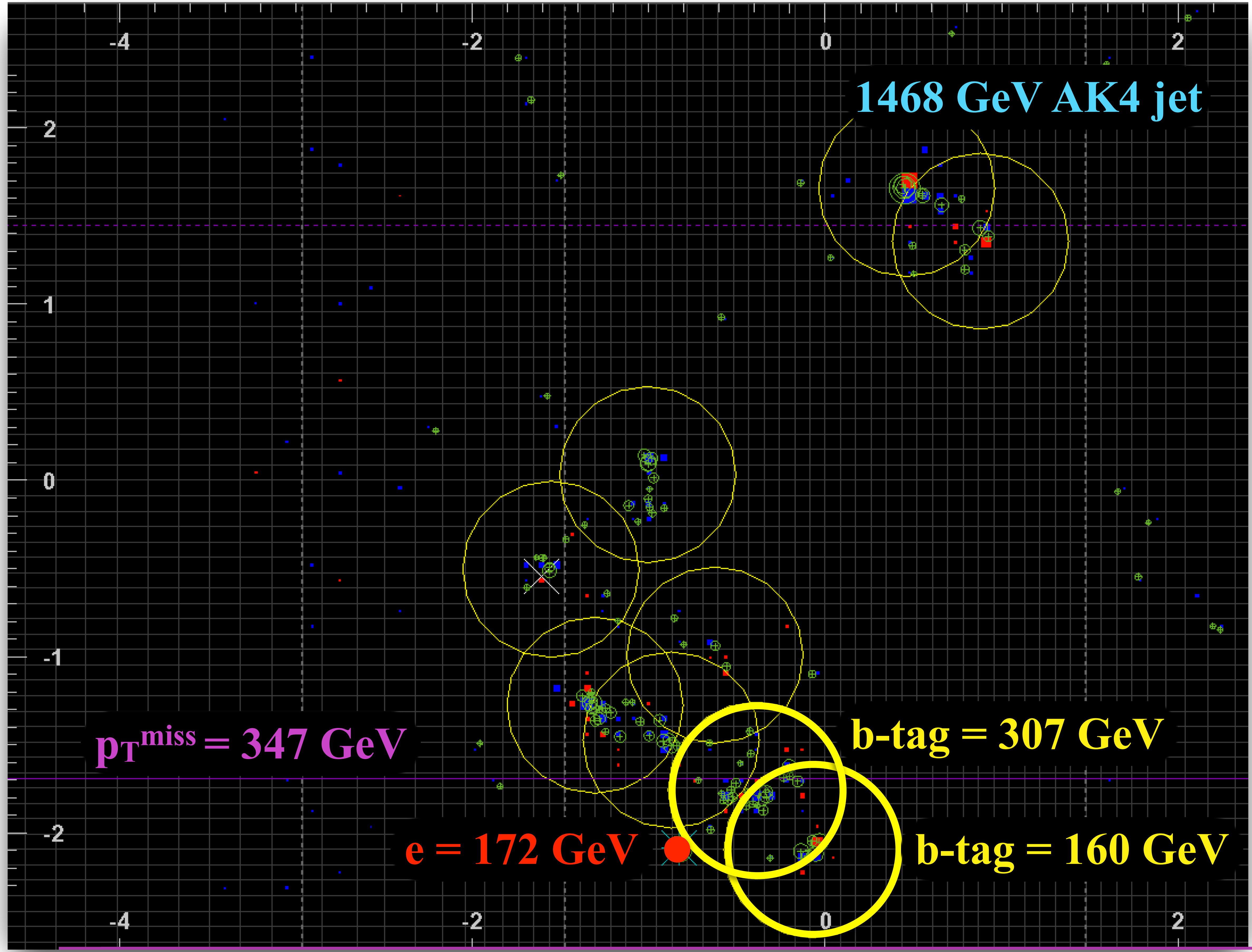
Our analysis requires at least 6 standard jets → rest come from ISR !

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

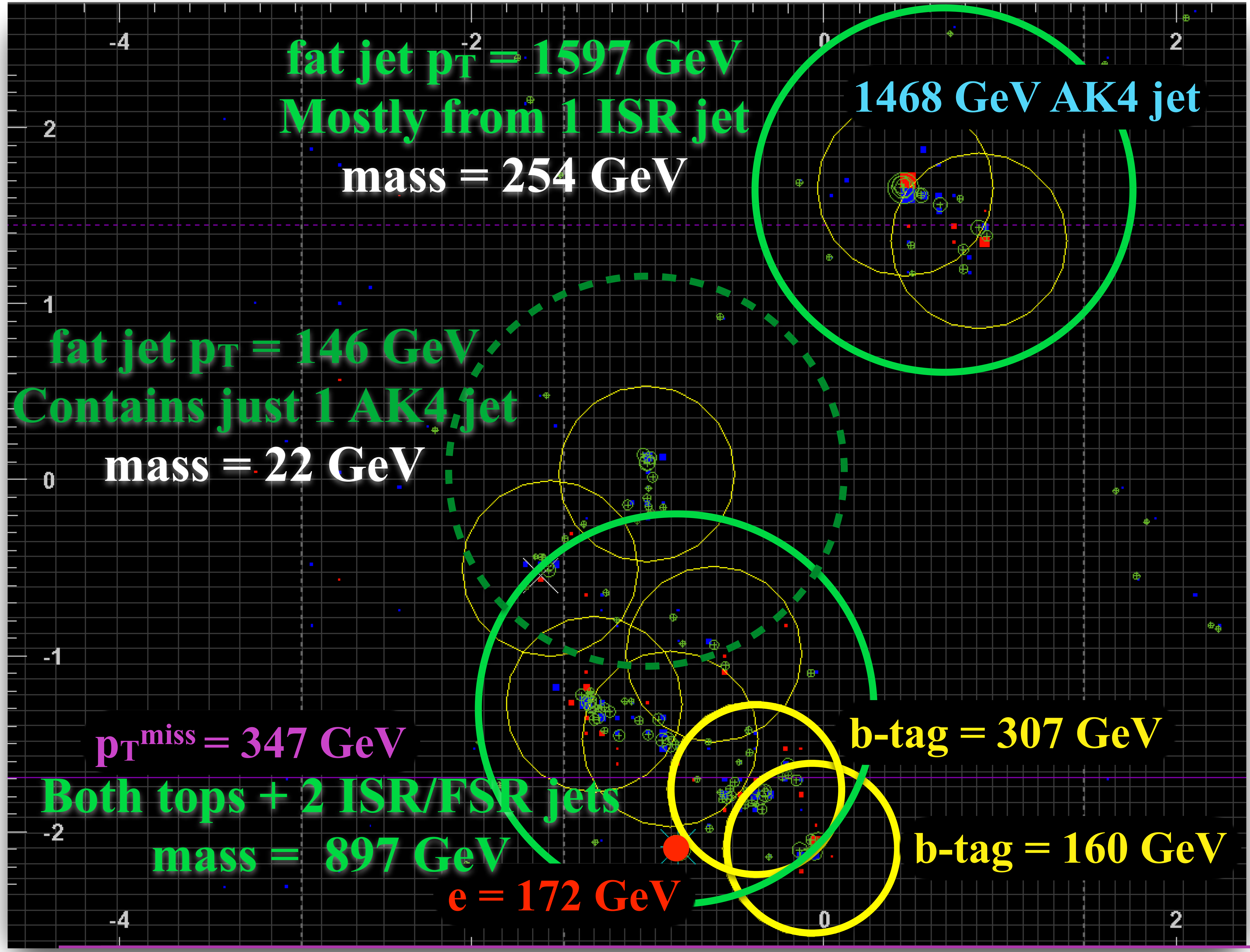


H_T (GeV)	M_J (GeV)	p_T^{miss} (GeV)	m_T (GeV)	N_{jets}	N_b	lep, p_T
2903	1173	347	91	9	2	e, 172

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



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



fat jet p_T = 1597 GeV
Mostly from 1 ISR jet
mass = 254 GeV

1468 GeV AK4 jet

fat jet p_T = 146 GeV
Contains just 1 AK4 jet
mass = 22 GeV

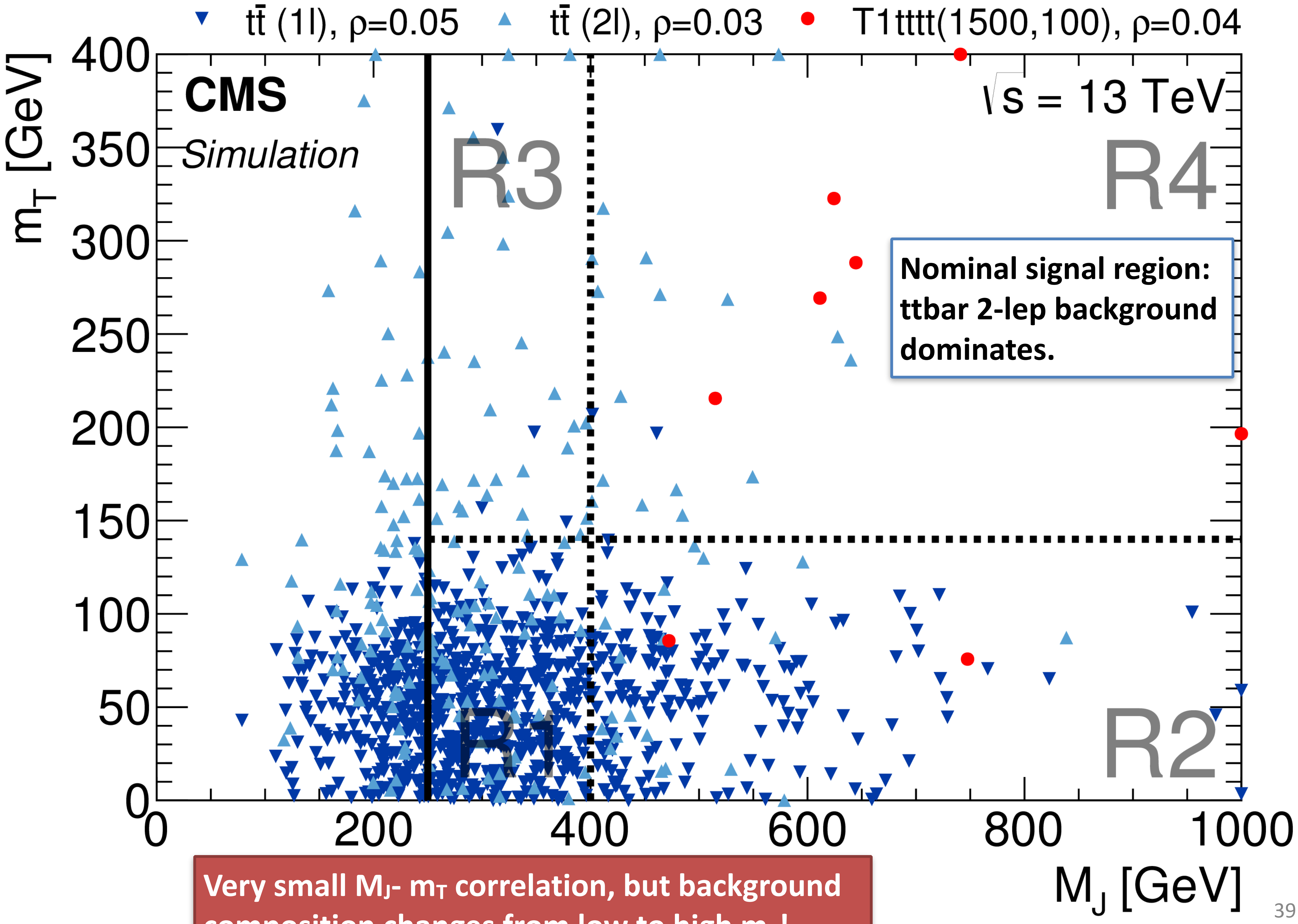
p_T^{miss} = 347 GeV
Both tops + 2 ISR/FSR jets
mass = 897 GeV

e = 172 GeV

b-tag = 307 GeV

b-tag = 160 GeV

Beyond the baseline selection: M_T and M_J



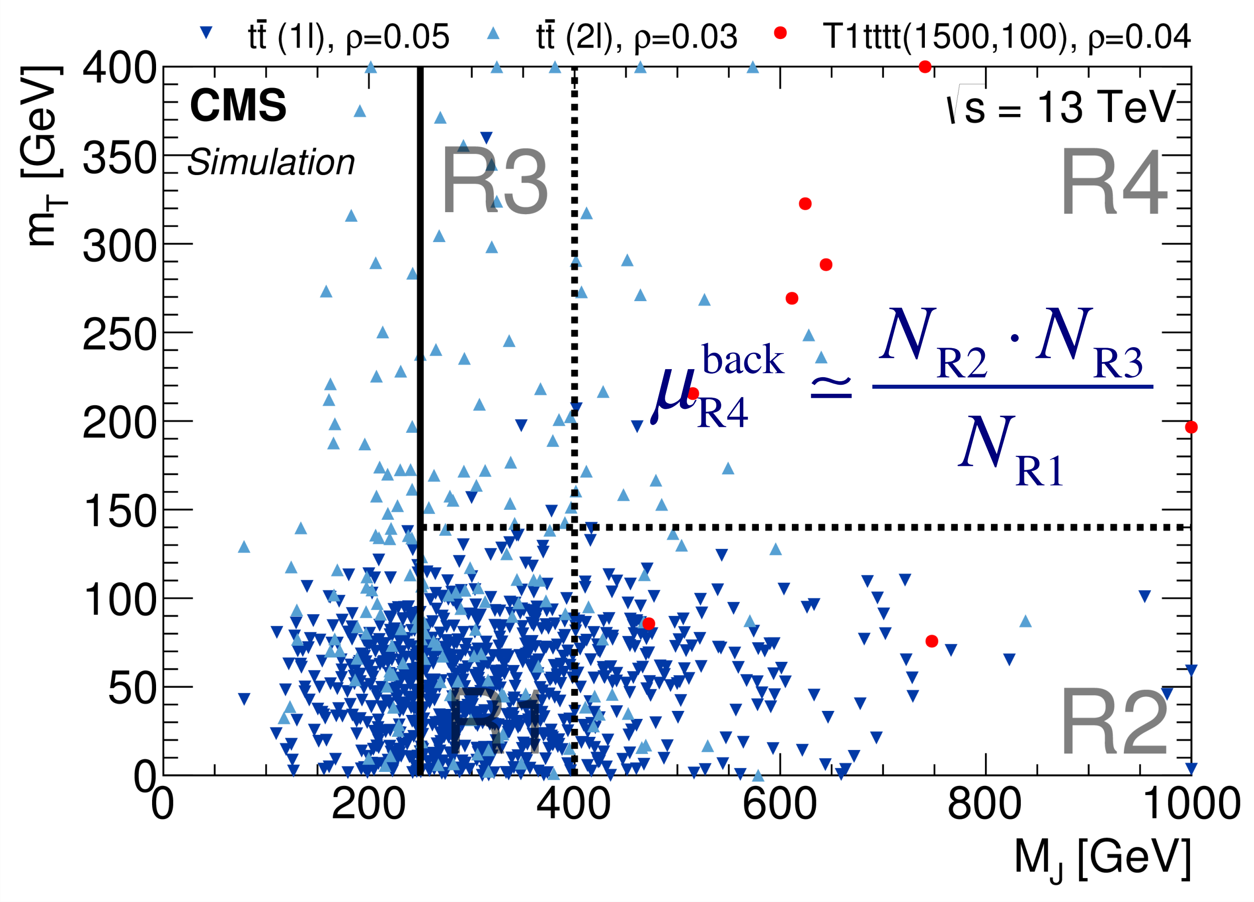
Nominal signal region: ttbar 2-lep background dominates.

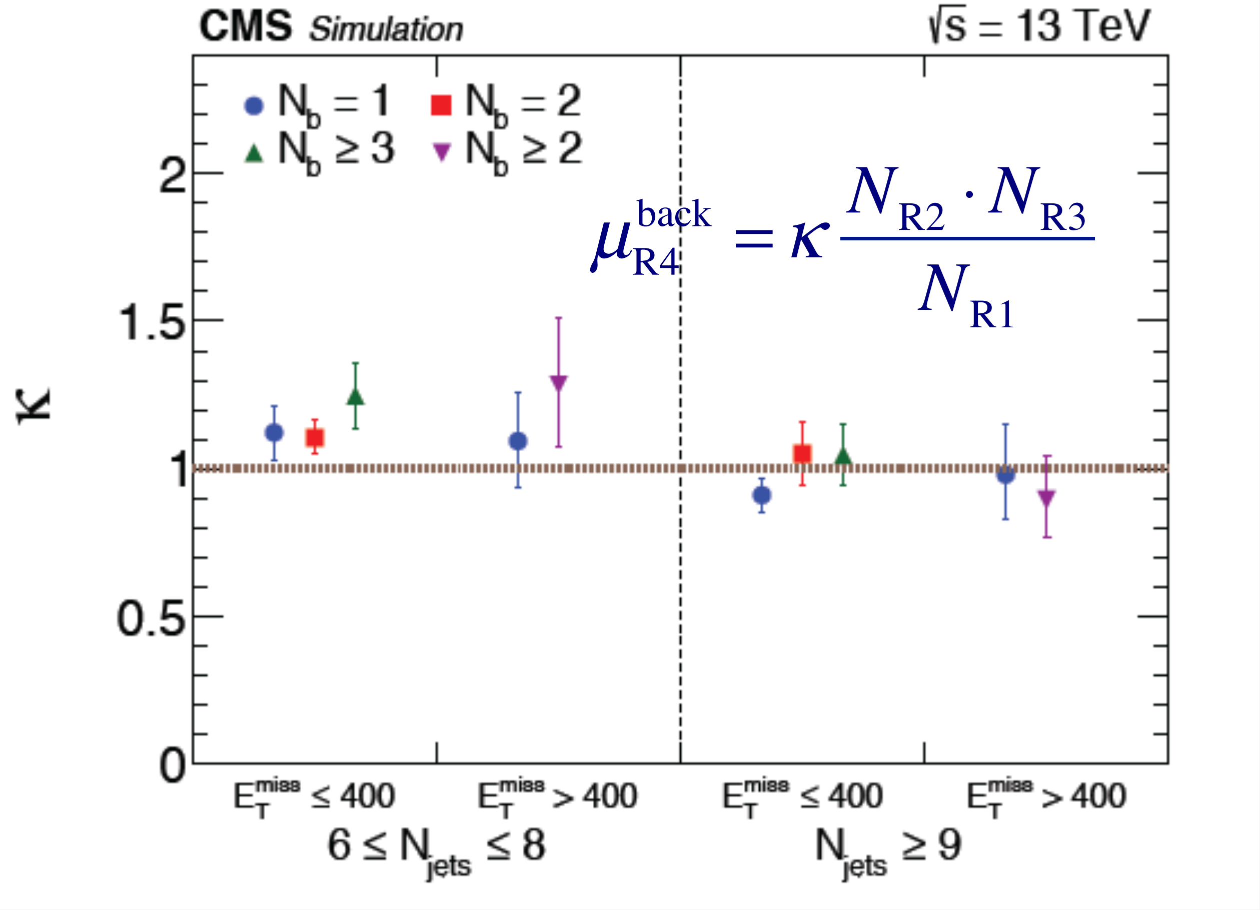
Very small M_J- m_T correlation, but background composition changes from low to high m_T!

Background estimation method

- Do we understand the M_J distribution for these backgrounds, given the large role of ISR?

- We will establish an “ABCD method”

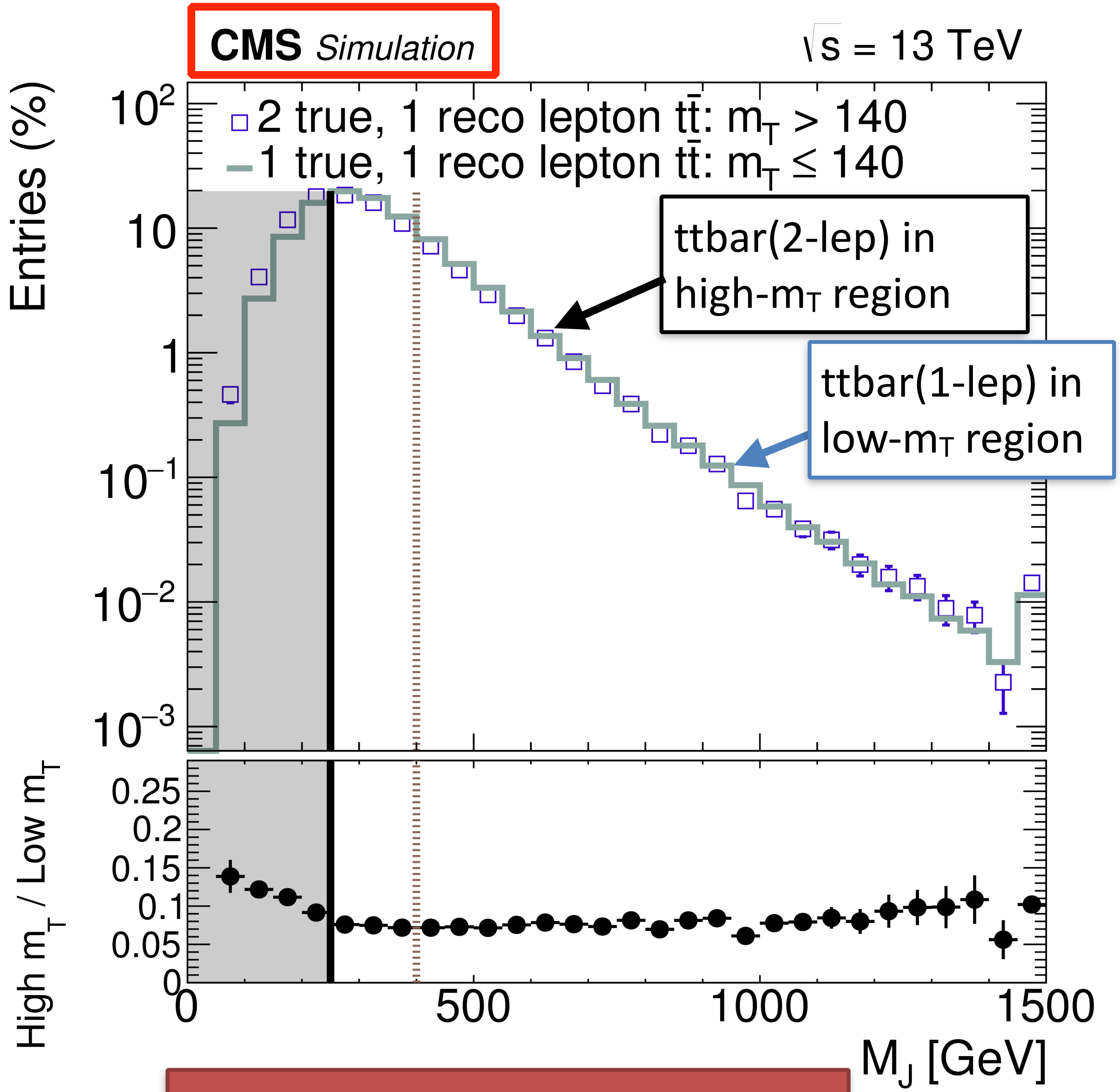




- To increase sensitivity, perform a similar background estimate for signal regions that are binned in

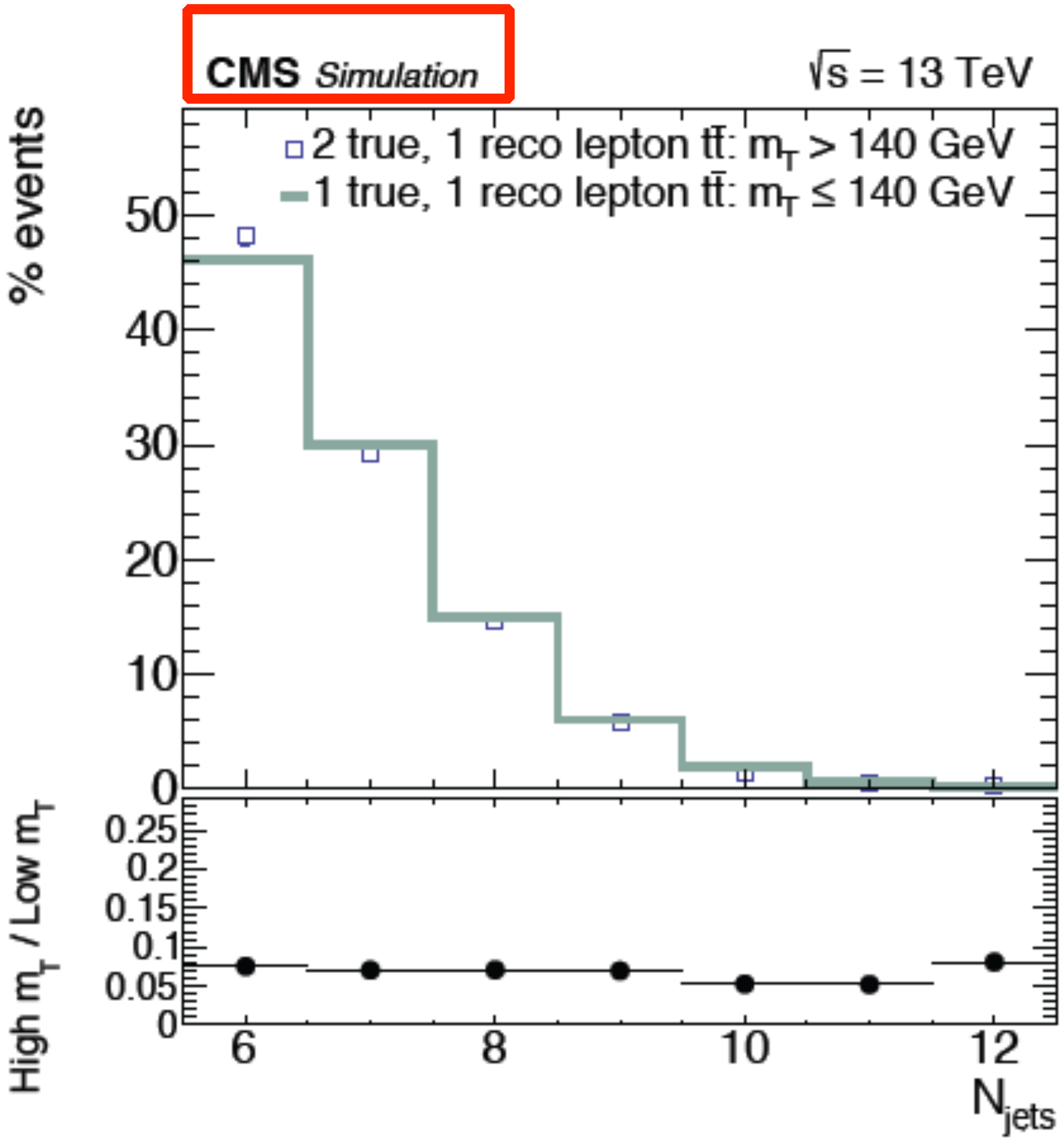
  E_T^{miss} = [200-400, >400 GeV], N_{jets} = [6-8, ≥9], and N_b = [1,2, ≥3]

M_J and N(jets) behavior for 2-true and 1-true lepton



ttbar(2-lep) in high-m_T region

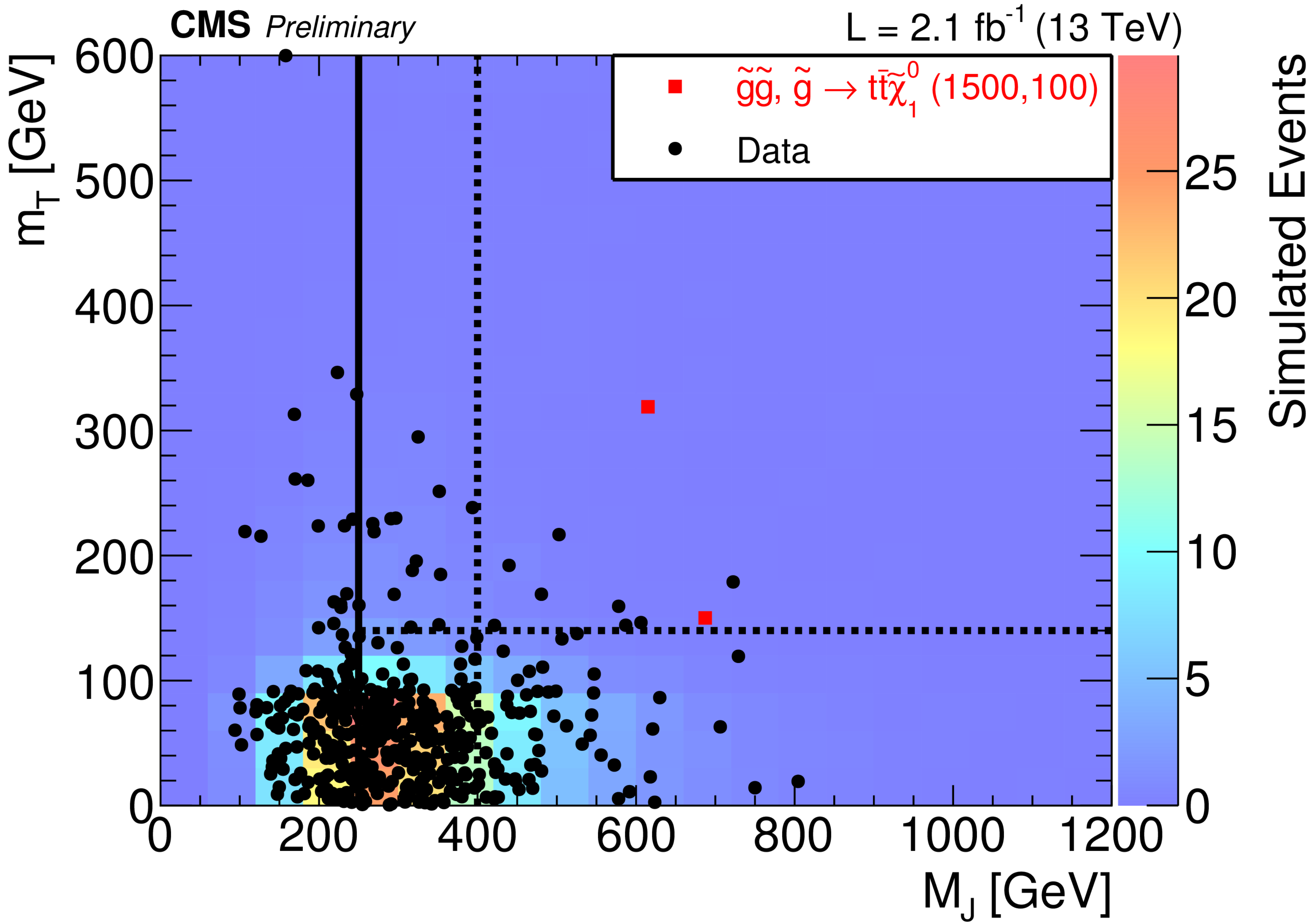
ttbar(1-lep) in low-m_T region



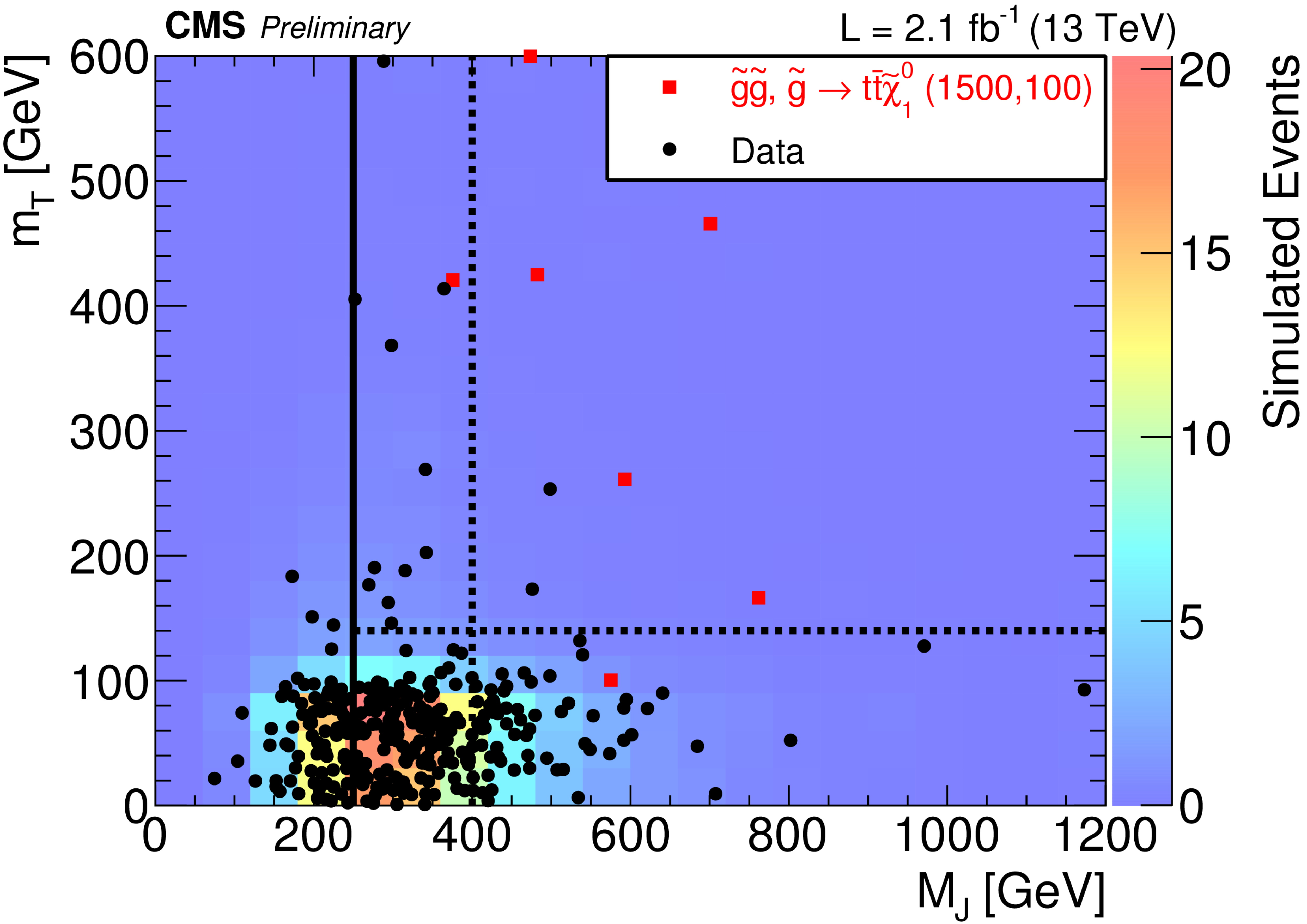
Shape of M_J distributions is very similar. Ratio of high-m_T to low-m_T yields is ~uniform across M_J bins.

Shape of N(jets) distributions is very similar. Ratio of high-m_T to low-m_T yields is ~uniform across N(jets) bins.

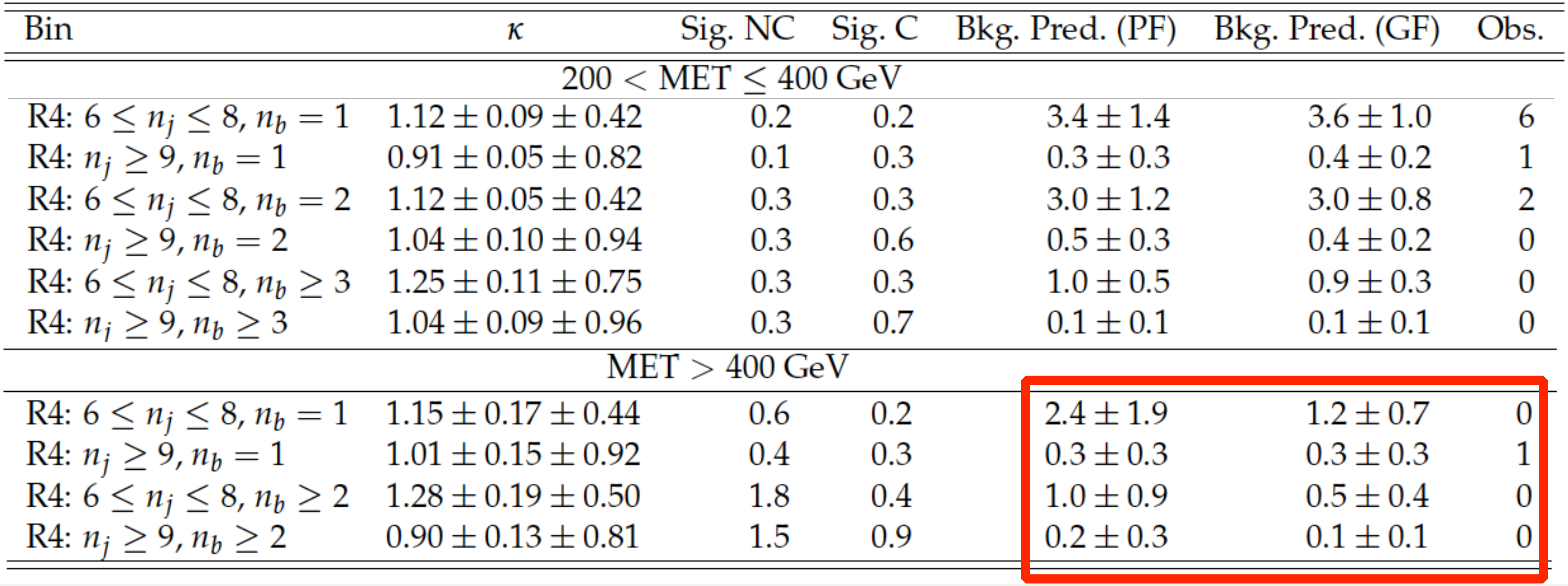
Unblinded data: $N_b = 1$ (background dominated)



Unblinded data: N_b = 2 (sensitive to signal)



Predicted and observed event yields

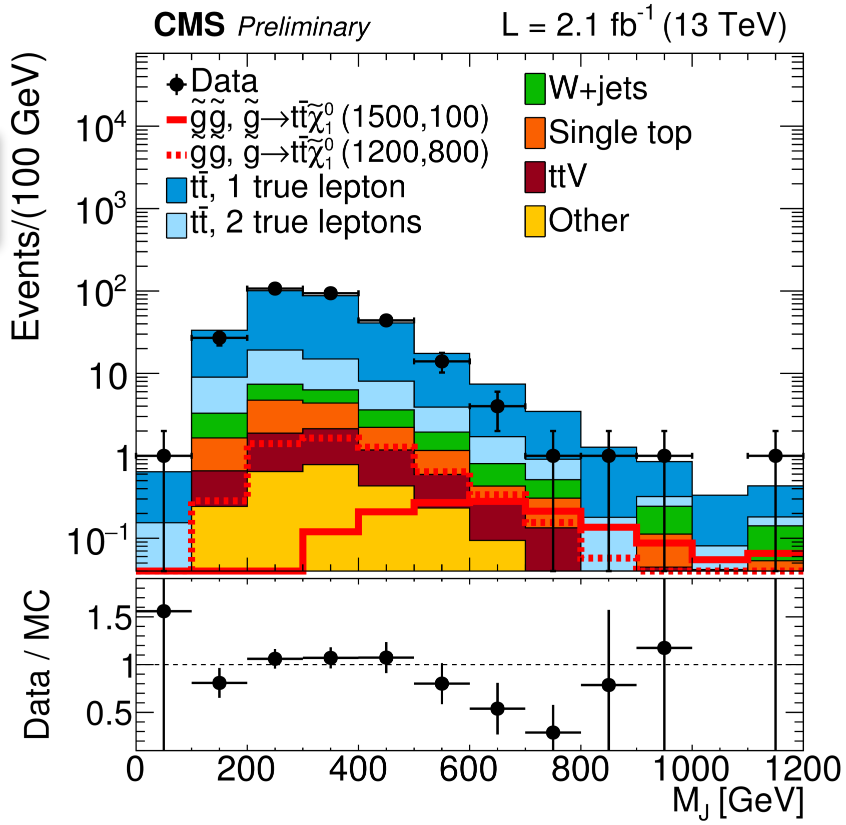


Bin	κ	Sig. NC	Sig. C	Bkg. Pred. (PF)	Bkg. Pred. (GF)	Obs.
$200 < \text{MET} \leq 400$ GeV						
R4: $6 \leq n_j \leq 8, n_b = 1$	$1.12 \pm 0.09 \pm 0.42$	0.2	0.2	3.4 ± 1.4	3.6 ± 1.0	6
R4: $n_j \geq 9, n_b = 1$	$0.91 \pm 0.05 \pm 0.82$	0.1	0.3	0.3 ± 0.3	0.4 ± 0.2	1
R4: $6 \leq n_j \leq 8, n_b = 2$	$1.12 \pm 0.05 \pm 0.42$	0.3	0.3	3.0 ± 1.2	3.0 ± 0.8	2
R4: $n_j \geq 9, n_b = 2$	$1.04 \pm 0.10 \pm 0.94$	0.3	0.6	0.5 ± 0.3	0.4 ± 0.2	0
R4: $6 \leq n_j \leq 8, n_b \geq 3$	$1.25 \pm 0.11 \pm 0.75$	0.3	0.3	1.0 ± 0.5	0.9 ± 0.3	0
R4: $n_j \geq 9, n_b \geq 3$	$1.04 \pm 0.09 \pm 0.96$	0.3	0.7	0.1 ± 0.1	0.1 ± 0.1	0
$\text{MET} > 400$ GeV						
R4: $6 \leq n_j \leq 8, n_b = 1$	$1.15 \pm 0.17 \pm 0.44$	0.6	0.2	2.4 ± 1.9	1.2 ± 0.7	0
R4: $n_j \geq 9, n_b = 1$	$1.01 \pm 0.15 \pm 0.92$	0.4	0.3	0.3 ± 0.3	0.3 ± 0.3	1
R4: $6 \leq n_j \leq 8, n_b \geq 2$	$1.28 \pm 0.19 \pm 0.50$	1.8	0.4	1.0 ± 0.9	0.5 ± 0.4	0
R4: $n_j \geq 9, n_b \geq 2$	$0.90 \pm 0.13 \pm 0.81$	1.5	0.9	0.2 ± 0.3	0.1 ± 0.1	0

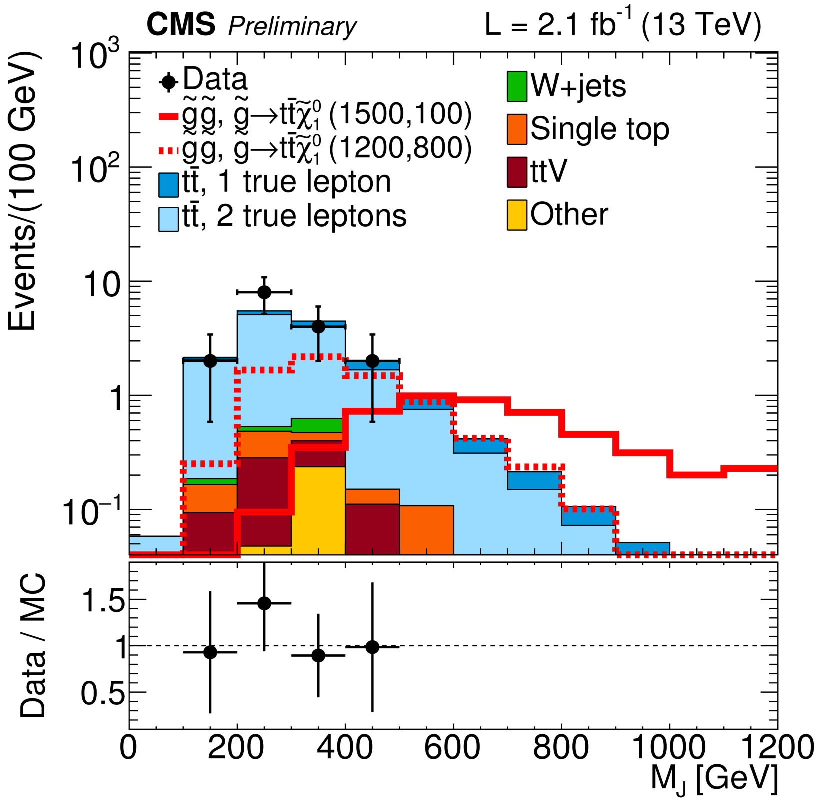
- Observed yields in data are consistent with predicted background in all bins.
- Interpret results as exclusion limits on cross sections and SUSY particle masses. Incorporate signal systematic uncertainties on efficiencies, luminosity, etc.

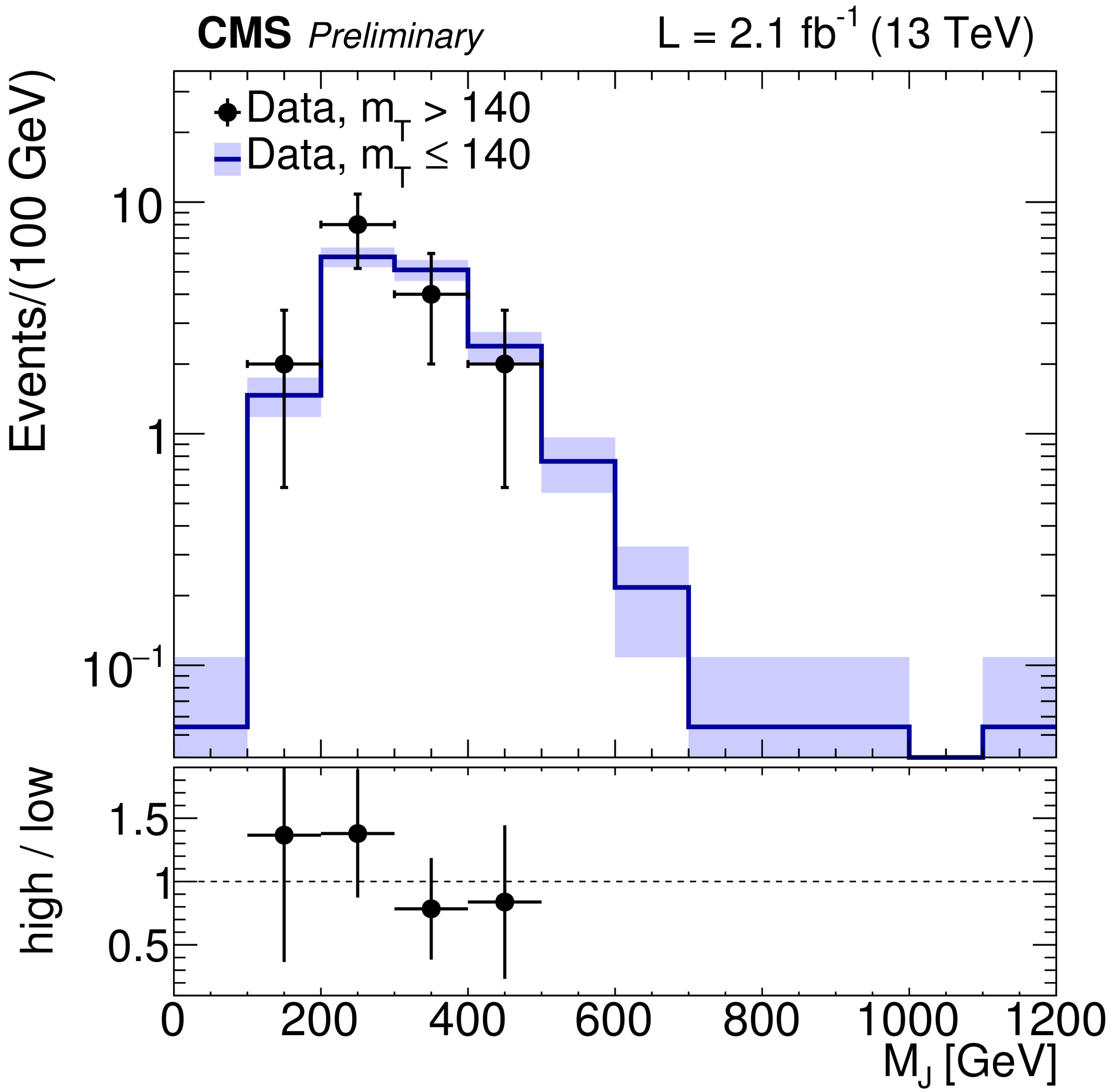
Distributions of M_J for $N_b \geq 2$ at low and high m_T

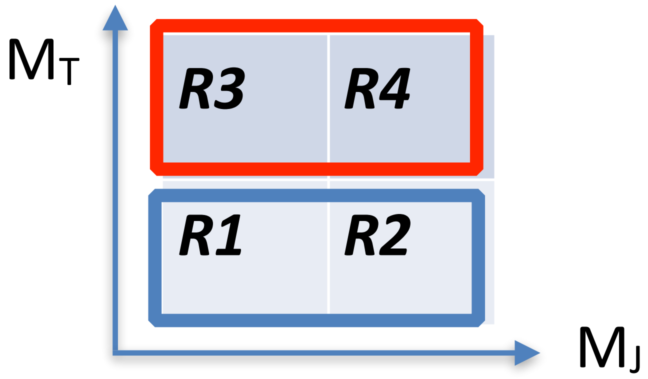
Low mT



High m_T

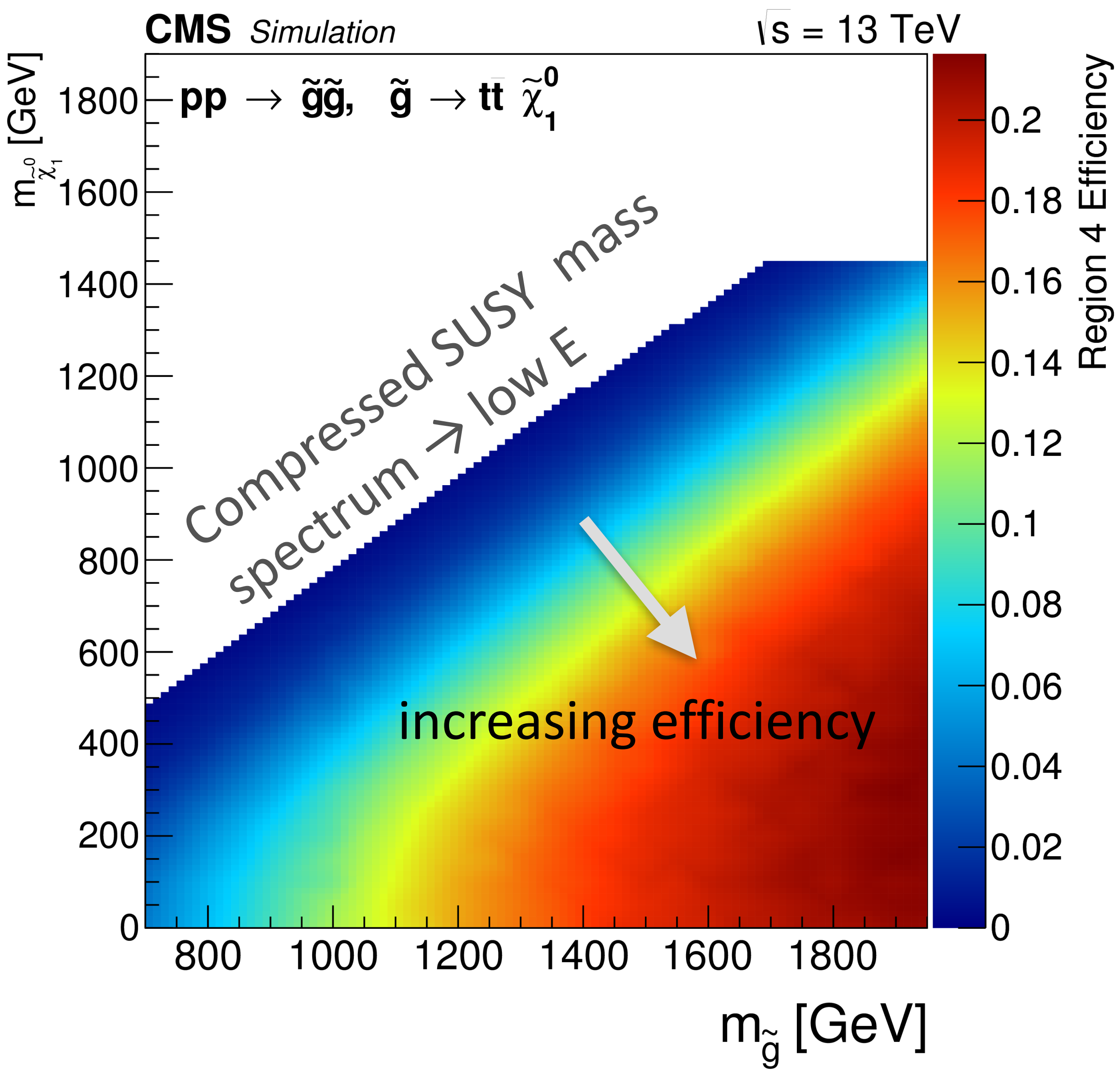




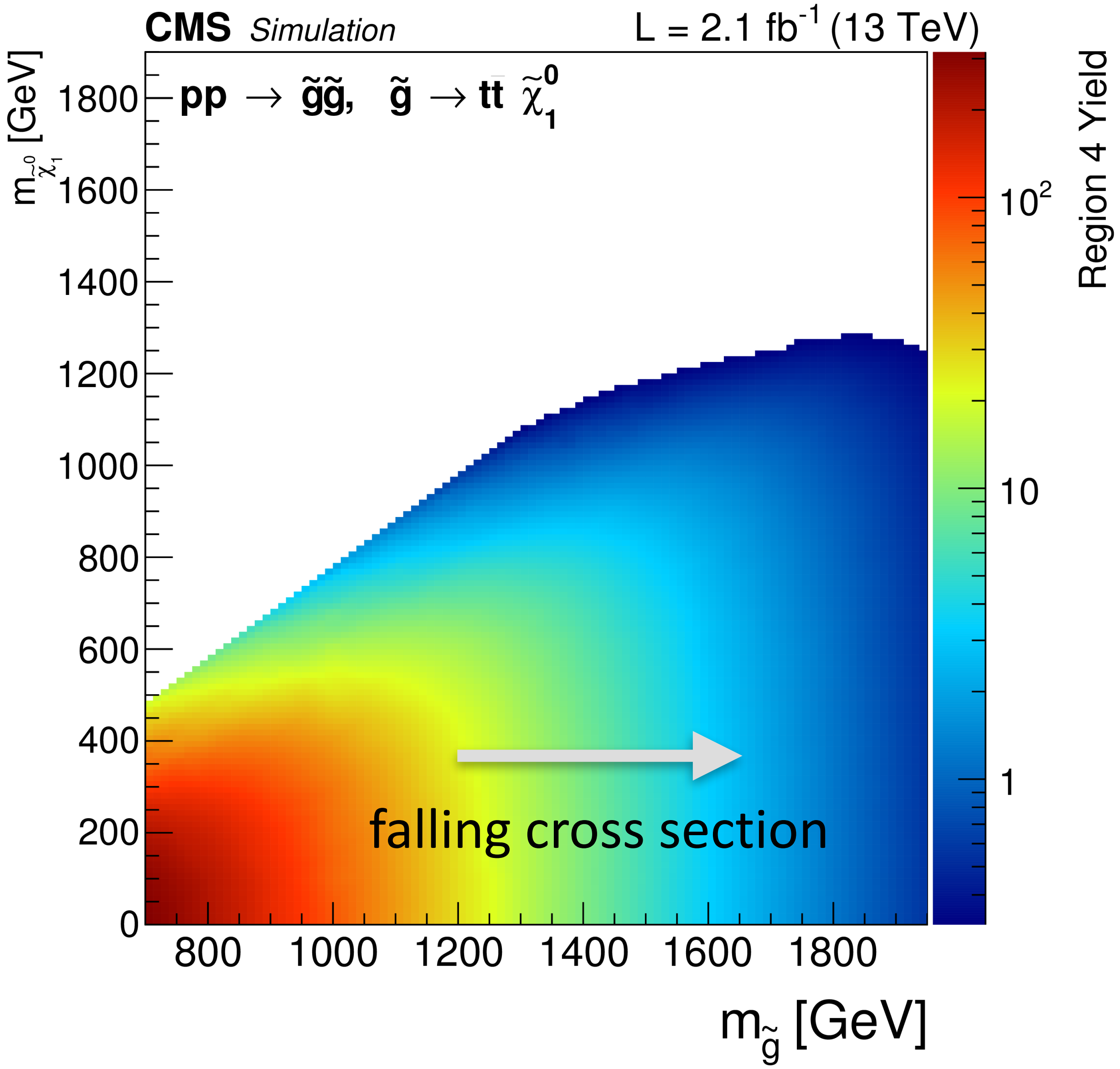


Signal efficiency and expected yields for T1tttt

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



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

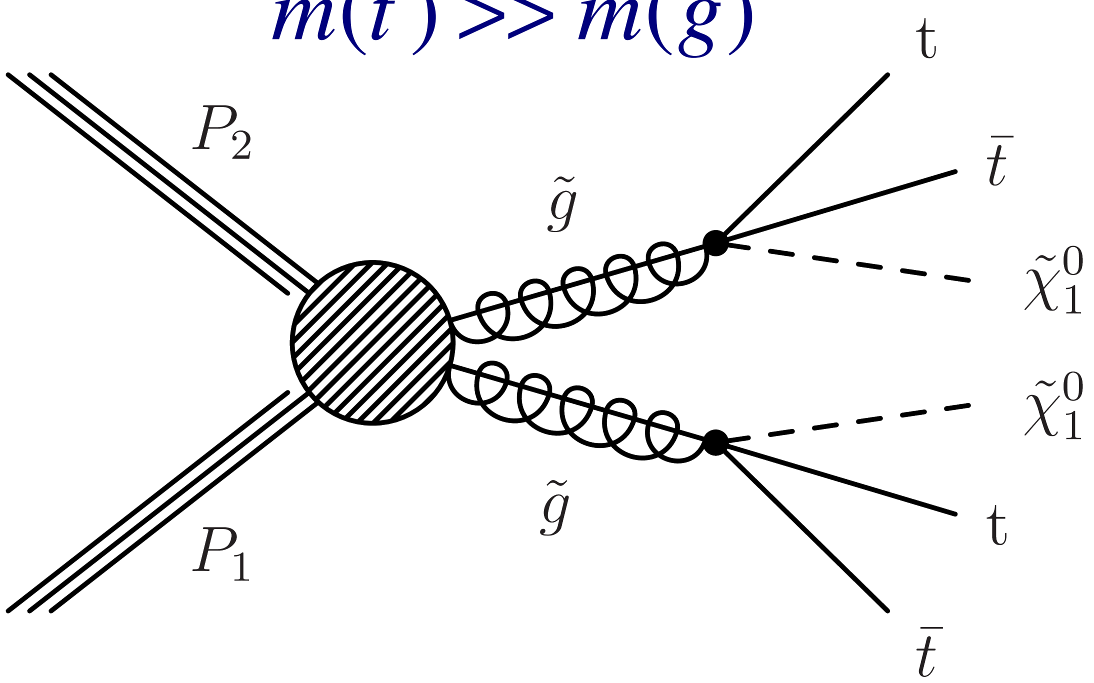


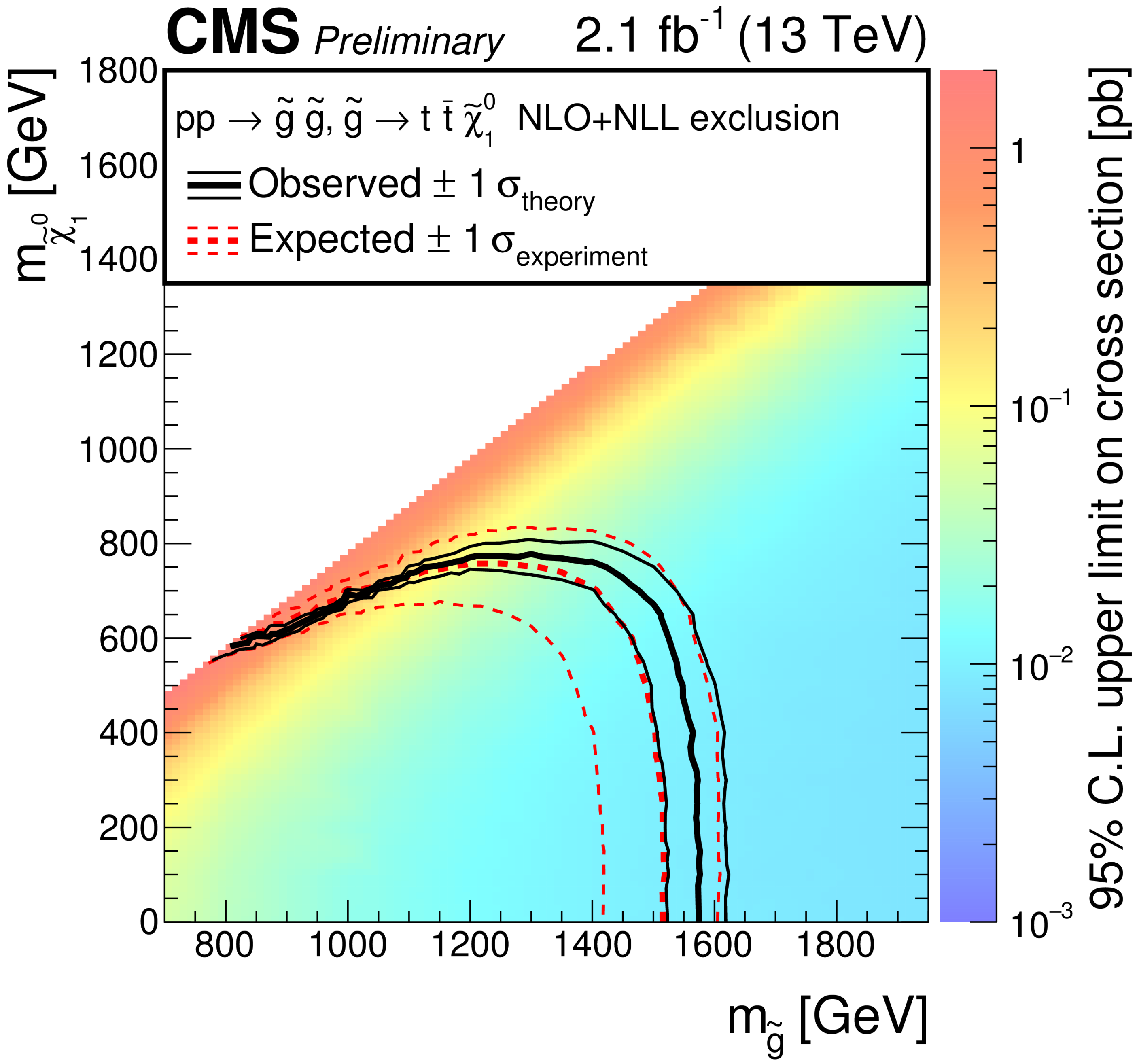
- Signal efficiency increases moving away from the diagonal, where the spectrum compresses and E_T^{miss} becomes small.
- Expected signal event yield decreases with increasing m($\tilde{g}$).

Gluino pair production with off-shell top squarks

T1tttt simplified model

$m(\tilde{t}) >> m(\tilde{g})$



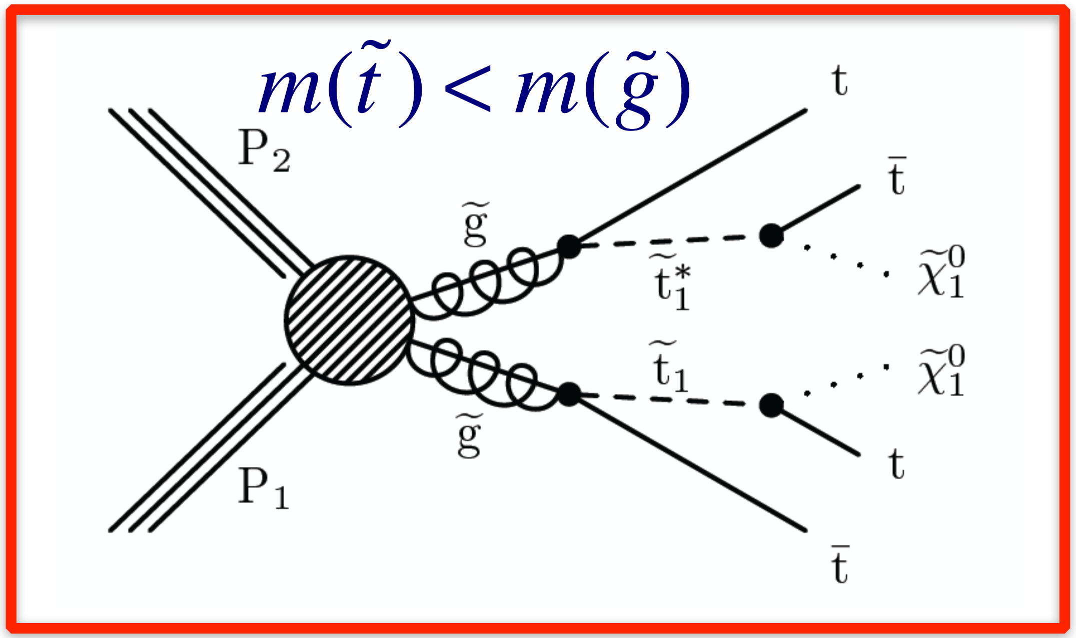


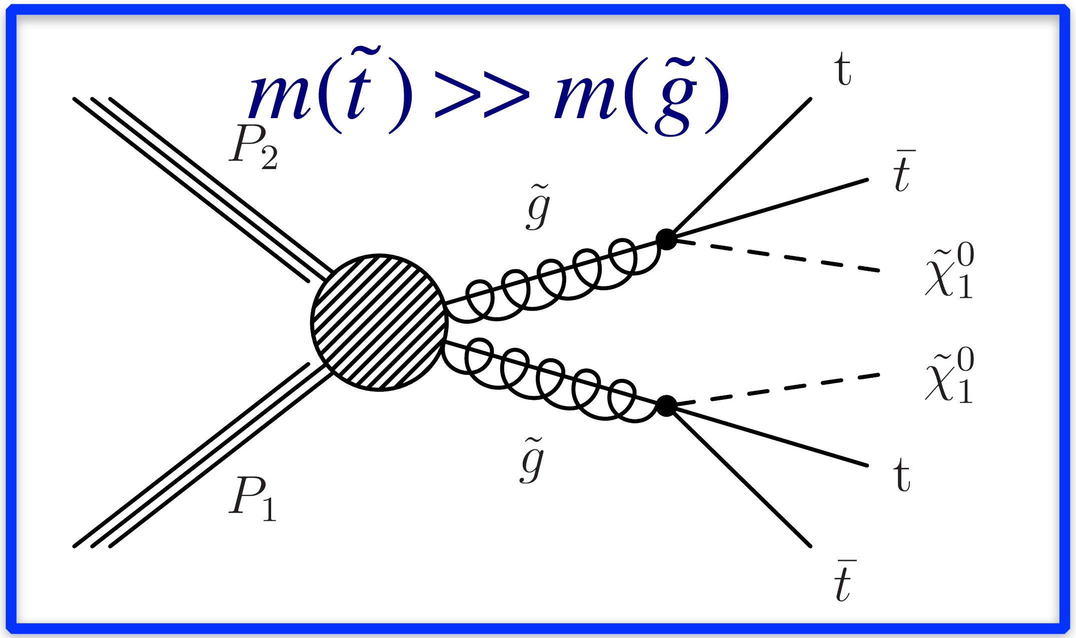
Mass limits are based on comparing cross section limits to theory assuming 100% branching fraction to the assumed decay mode. Exclude gluinos up to ~1.6 TeV. Compare to ~1.35 TeV at 8 TeV.

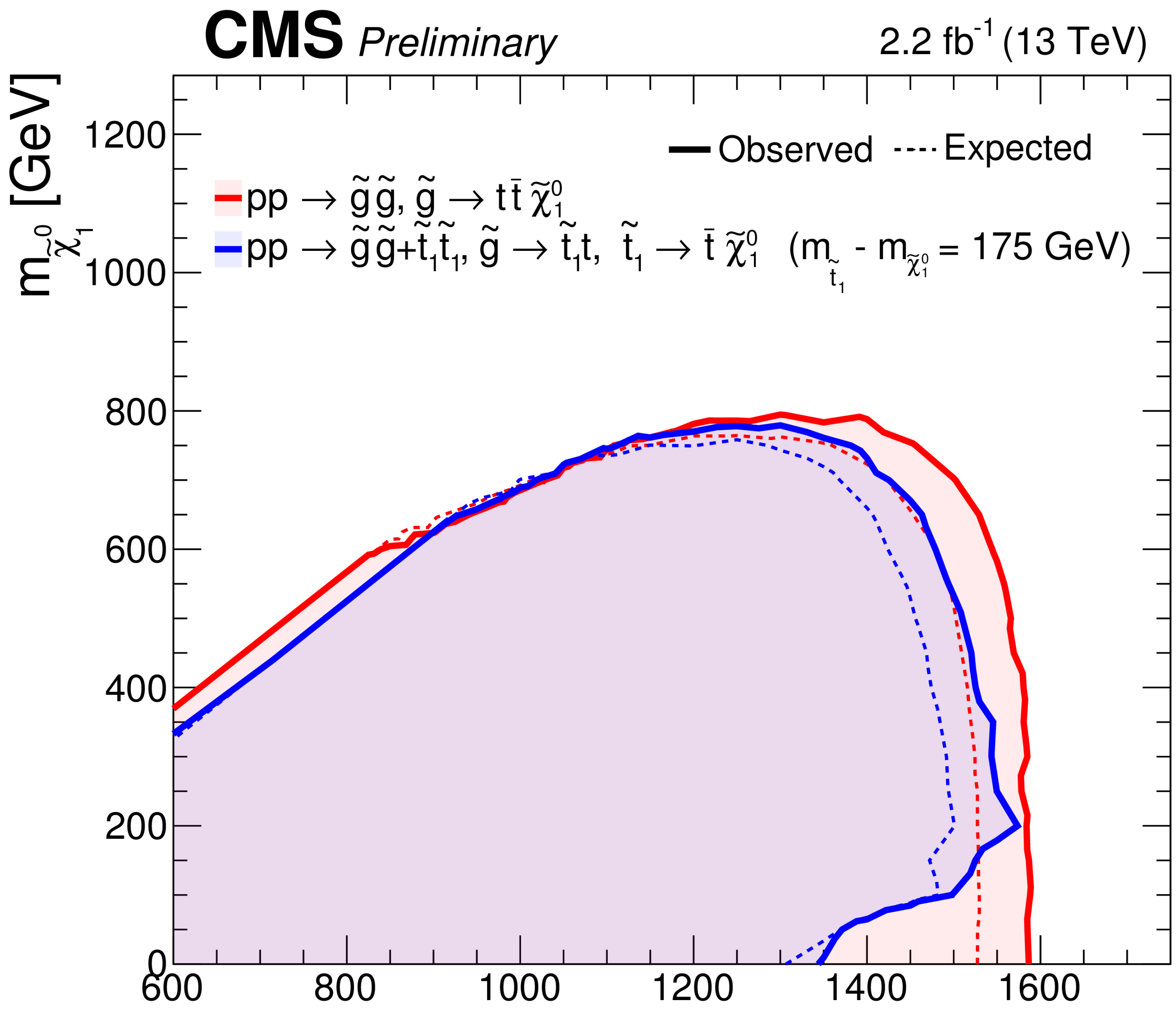
Excluded region for on-shell top squarks

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: $m(\tilde{t}) = m(\tilde{\chi}_1^0) + m(t) \simeq m(\tilde{\chi}_1^0) + 175\ \text{GeV}$



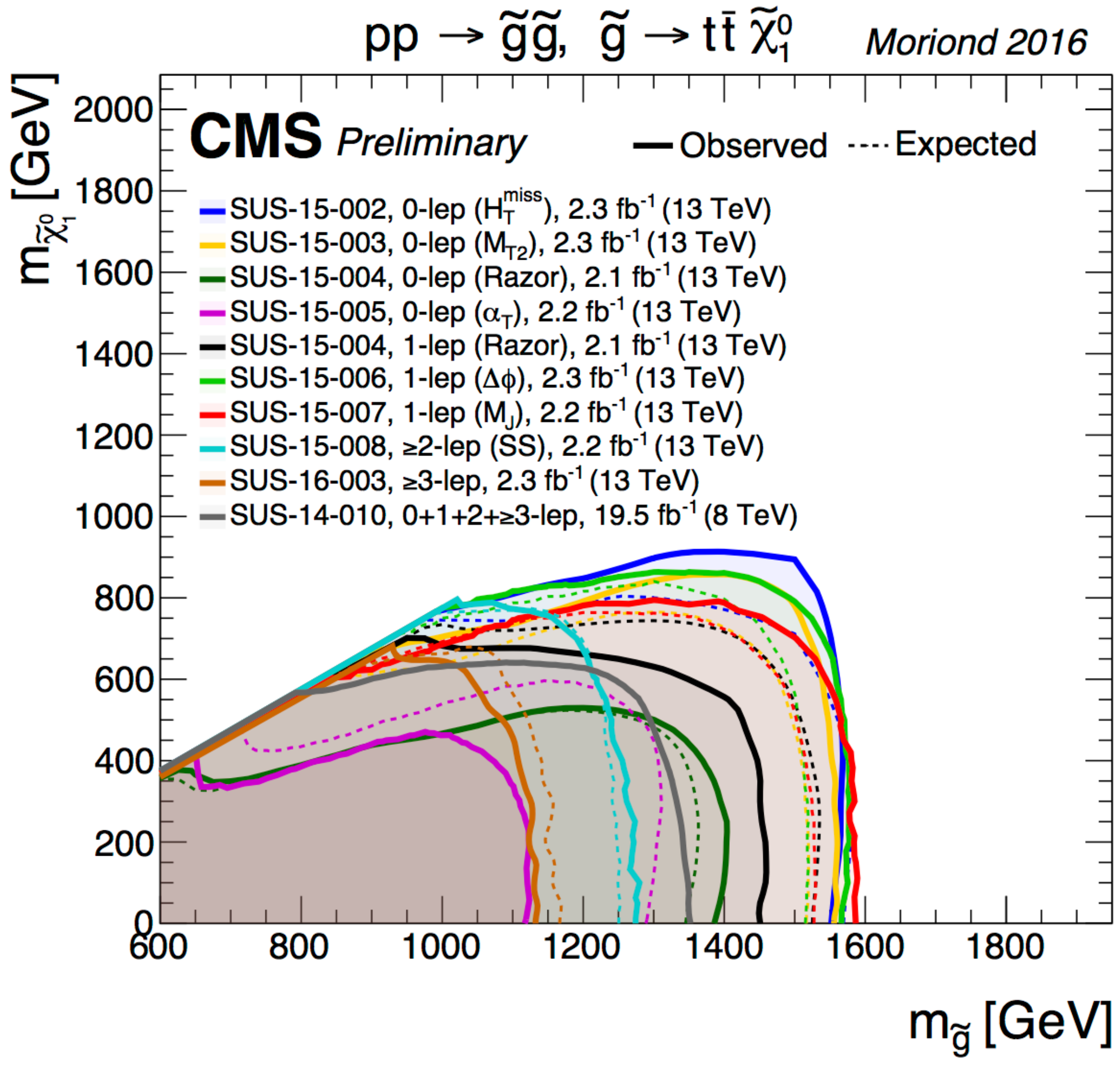


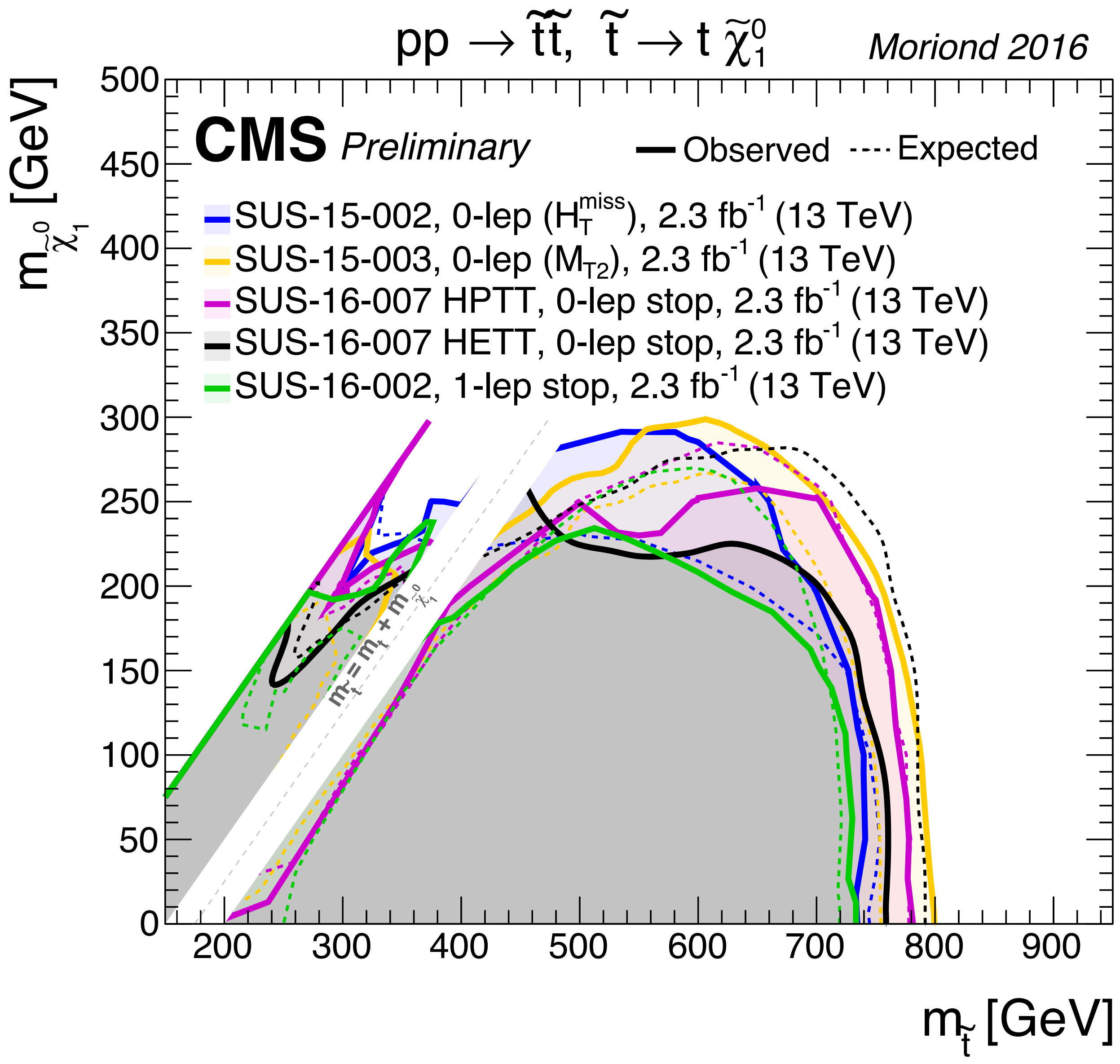


Very little loss in mass reach!

CMS searches: gluino and stop pair production

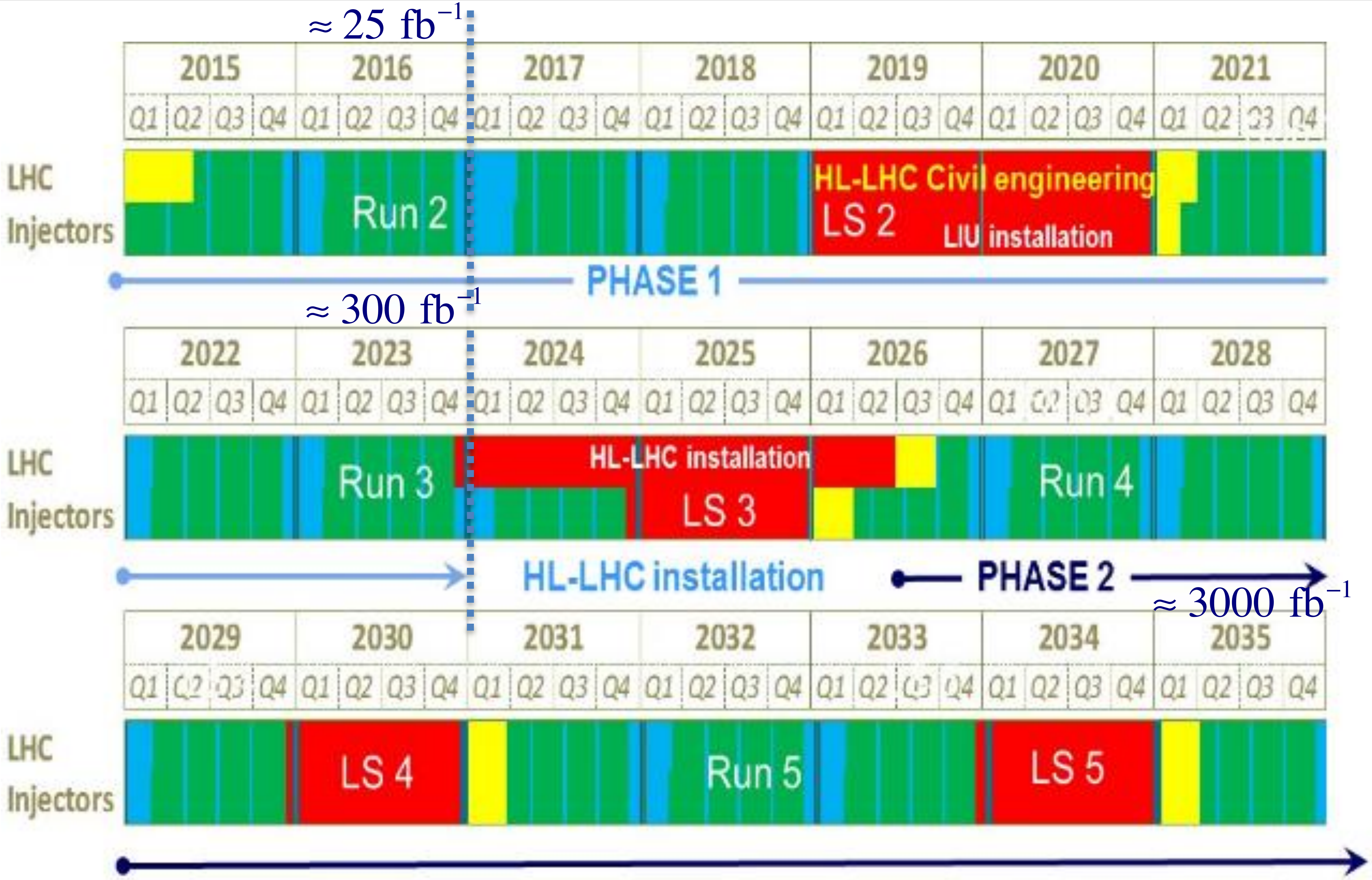
Presented either at the CERN physics jamorboo (Dec 2015) or at Moriond 2016,



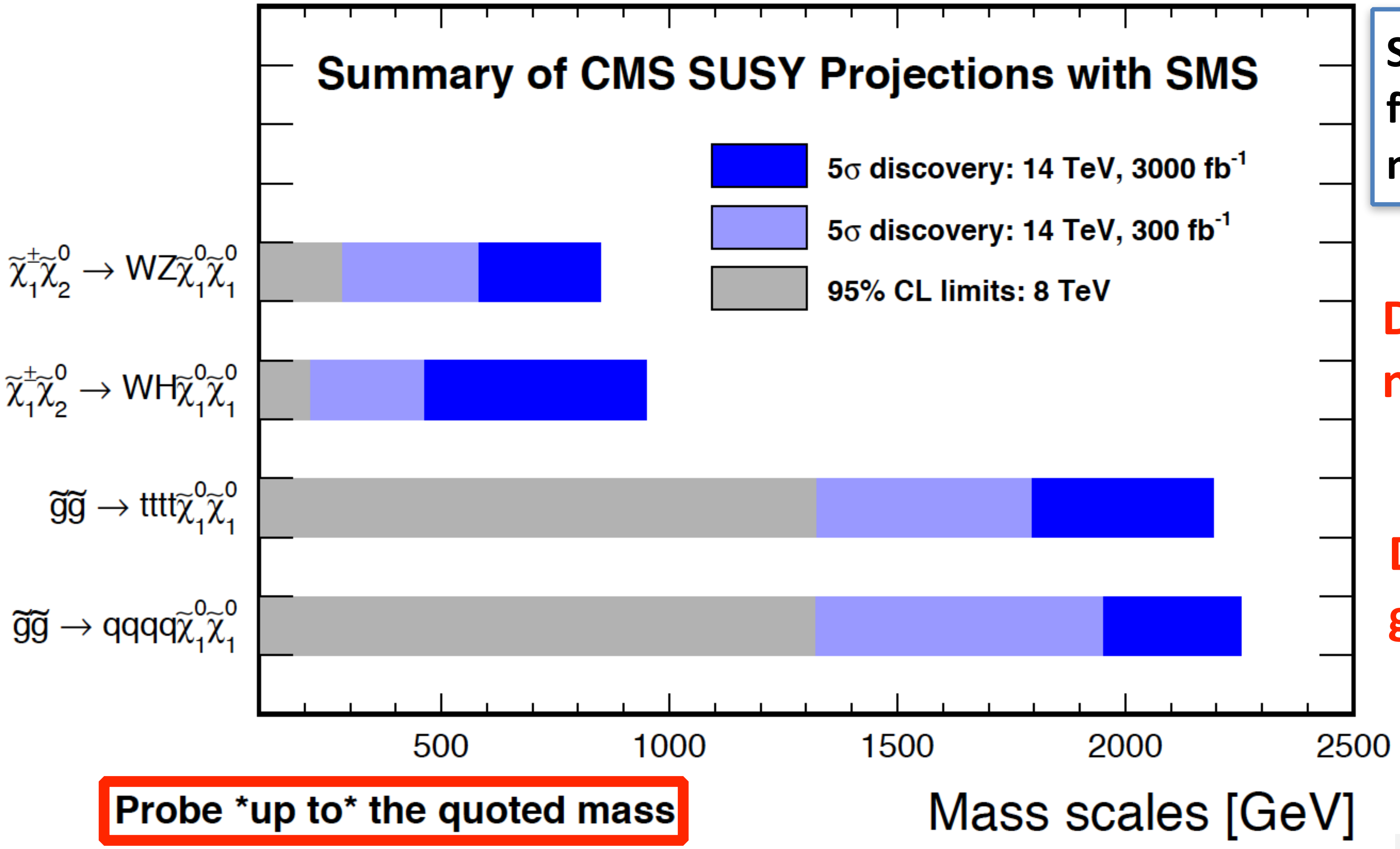


- The sensitivity of this analysis for T1tttt is typical of most 0-lepton and 1-lepton searches with the early 13 TeV data.

Long-term LHC schedule



CMS: discovery reach at 300 fb^{-1} & 3000 fb^{-1}



Probe *up to* the quoted mass

Simplified model framework: single decay mode dominates.

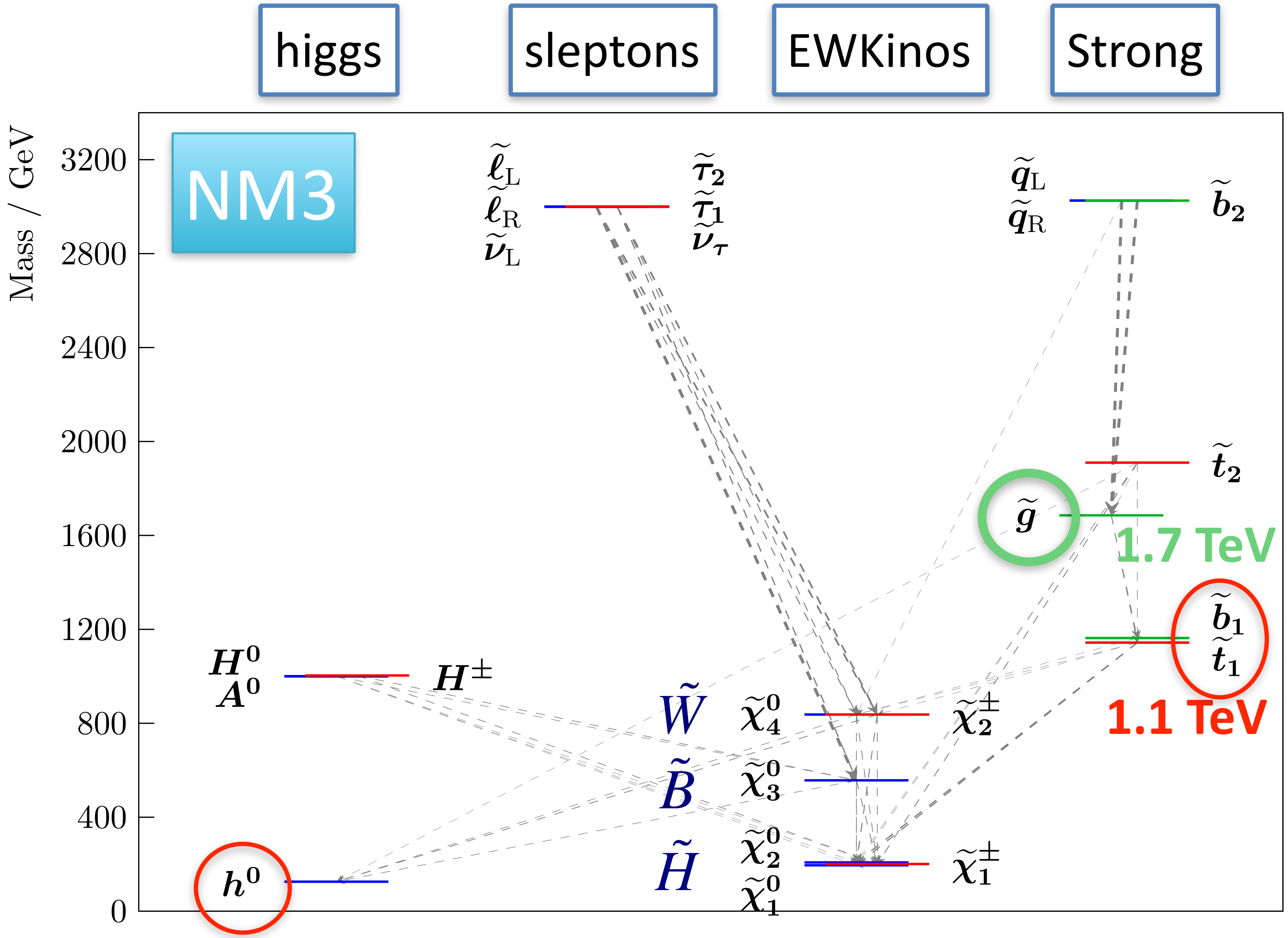
Discovery sensitivity: neutralinos up to ~1 TeV

Discovery sensitivity: gluinos up to ~2.2 TeV

- **Largest increase in discovery sensitivity with HL-LHC is for direct production of electroweak SUSY partners (EWKinos). Small cross section!**
- Up to 500 GeV increase in discovery reach with HL-LHC for chargino-neutralino pair production (Wh mode).
- **If strongly interacting SUSY partners are too heavy to be produced, EWKinos may be our best window to SUSY at the HL-LHC. Searches for ~degenerate Higgsinos are extremely difficult but highly motivated by naturalness.**

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.

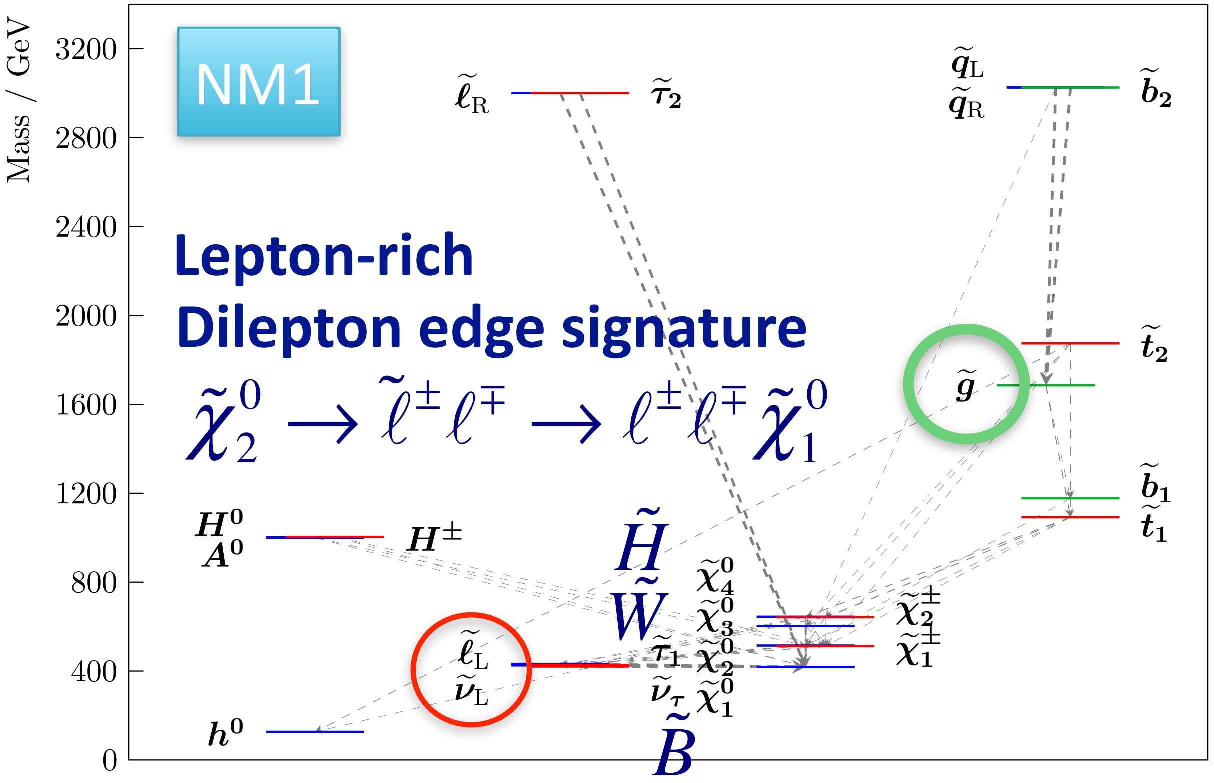
	NM1	NM2	NM3
$B(\tilde{t} \to t\tilde{\chi}_1^0)$	**0.6%**	**1.5%**	**39%**

- **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 $m(\tilde{\tau}_1) \approx m(\tilde{\chi}_1^0) \approx 190 \text{ GeV}$
- **STOC**-Stop co-annihilation $m(\tilde{t}_1) \approx m(\tilde{\chi}_1^0) \approx 400 \text{ GeV}$

Discovery scenarios with full-spectrum models

CMS PAS SUS-14-012



NM1

Lepton-rich

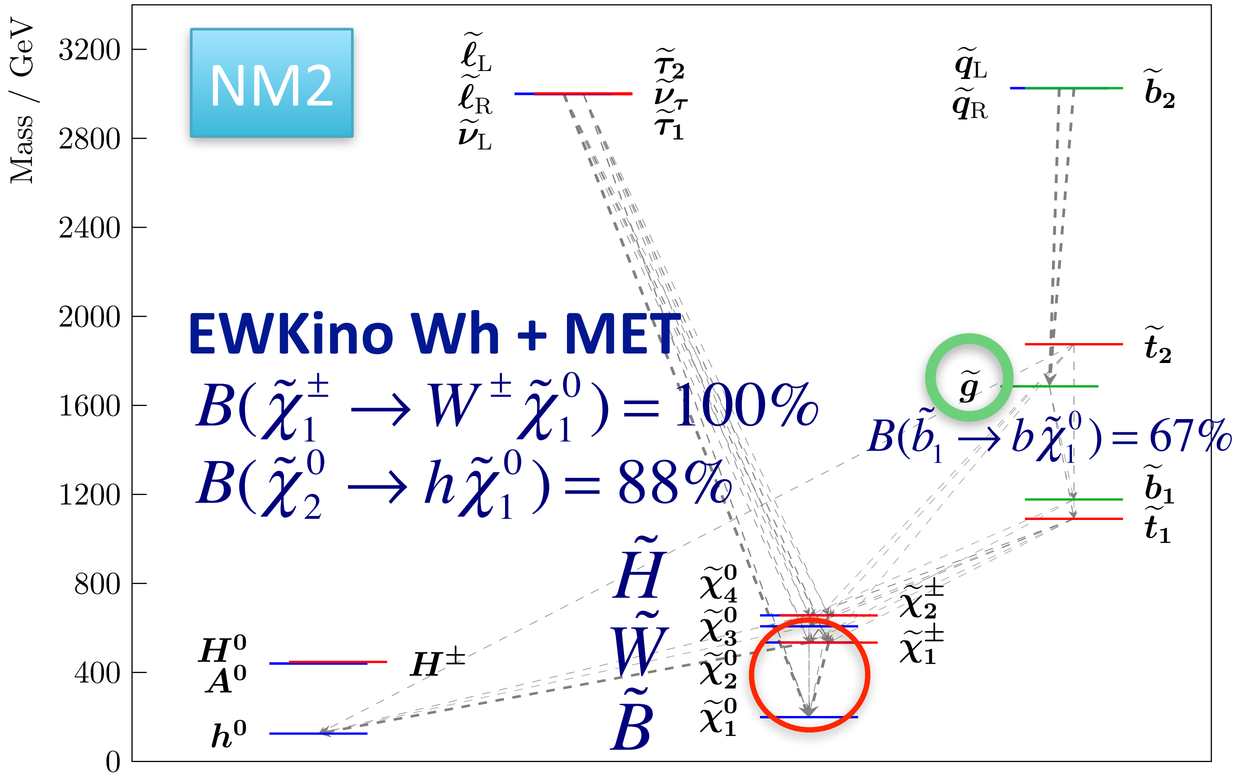
Dilepton edge signature

$$\tilde{\chi}_2^0 \to \tilde{\ell}^{\pm}\ell^{\mp} \to \ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$$

$\tilde{H}$

$\tilde{W}$

$\tilde{B}$



NM2

EWKino Wh + MET

$B(\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0) = 100\%$

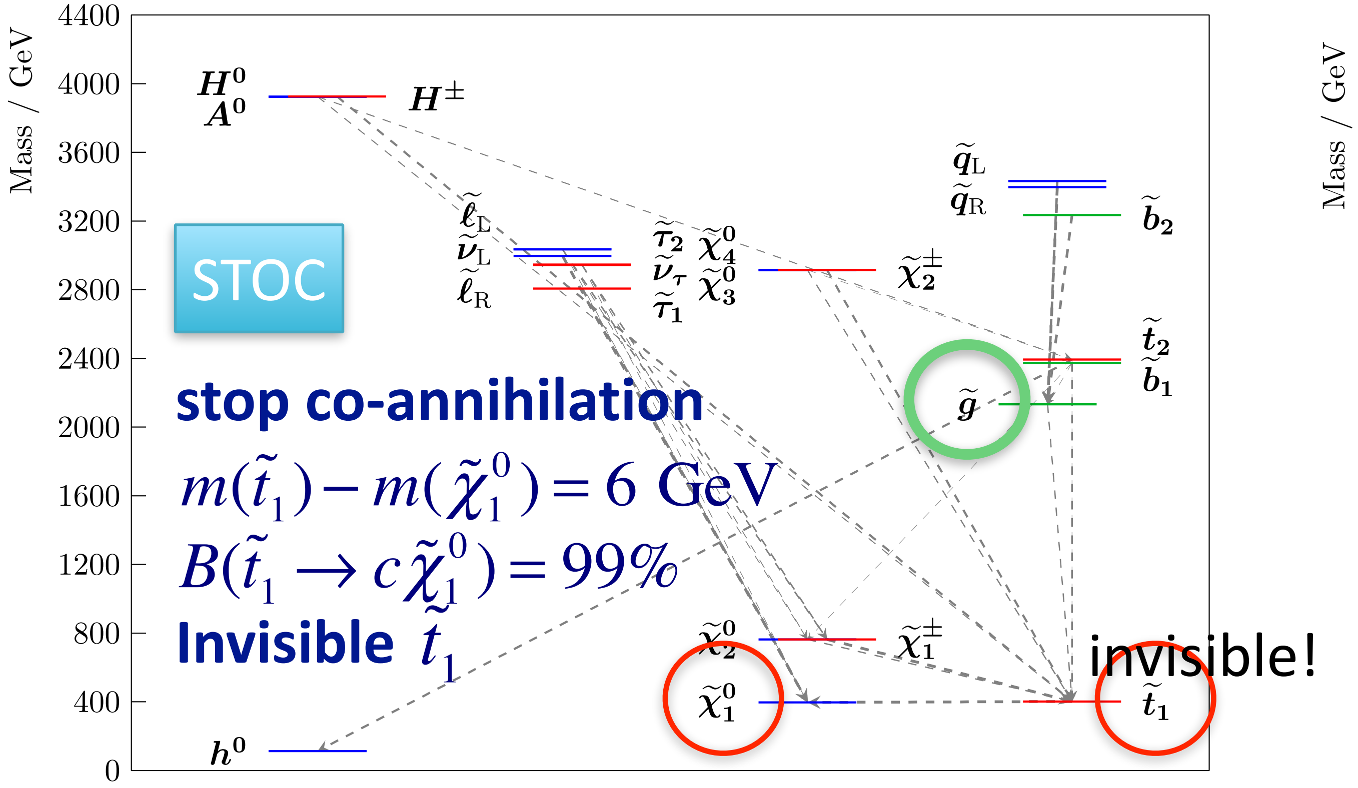
$B(\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0) = 88\%$

$B(\tilde{b}_1 \to b\tilde{\chi}_1^0) = 67\%$

$\tilde{H}$

$\tilde{W}$

$\tilde{B}$



STOC

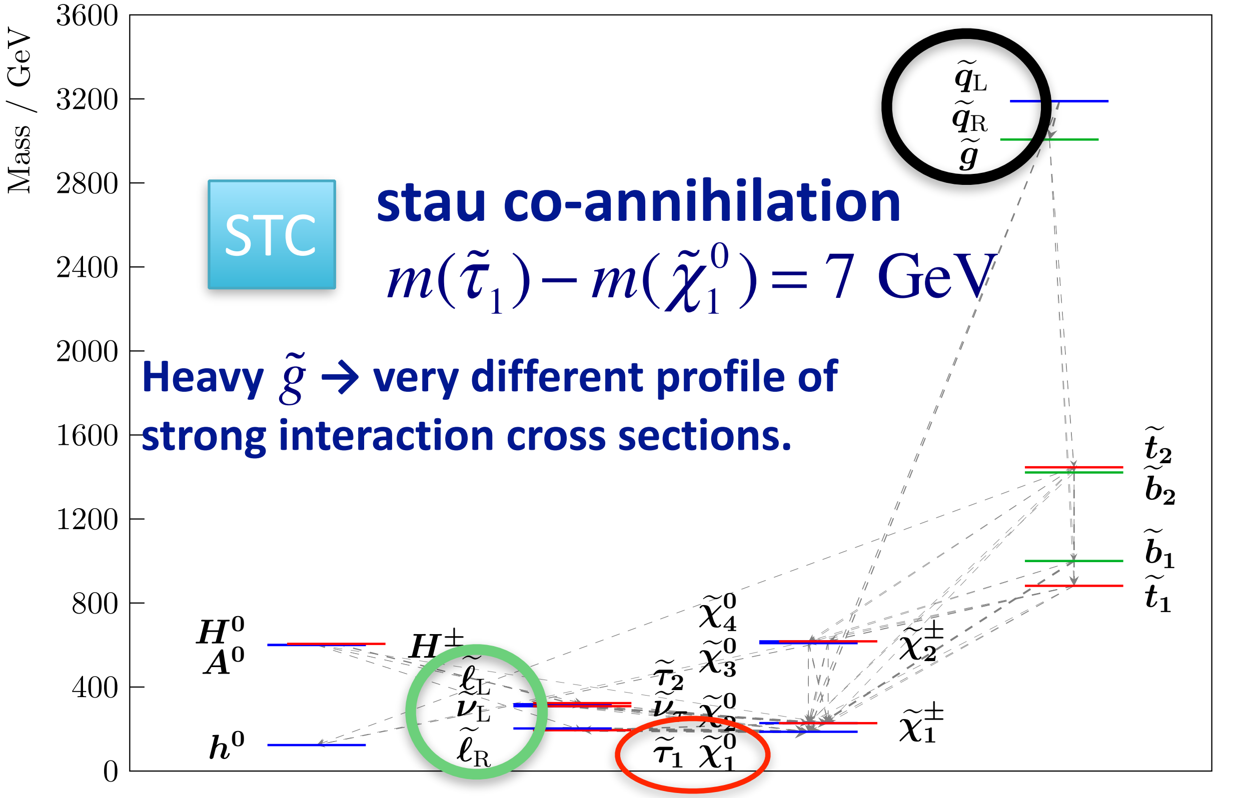
stop co-annihilation

$m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 6$ GeV

$B(\tilde{t}_1 \to c\tilde{\chi}_1^0) = 99\%$

Invisible $\tilde{t}_1$

invisible!



STC

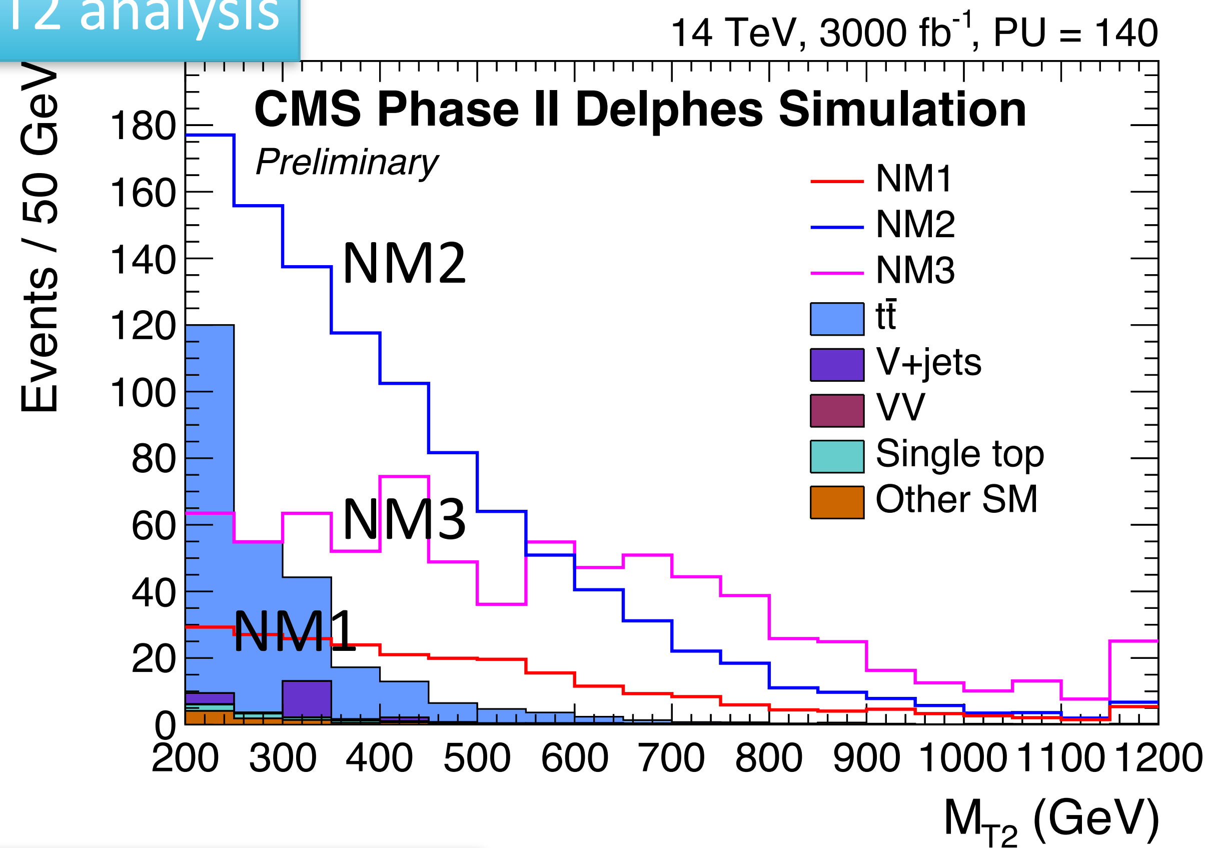
stau co-annihilation

$m(\tilde{\tau}_1) - m(\tilde{\chi}_1^0) = 7$ GeV

Heavy $\tilde{g}$ → very different profile of strong interaction cross sections.

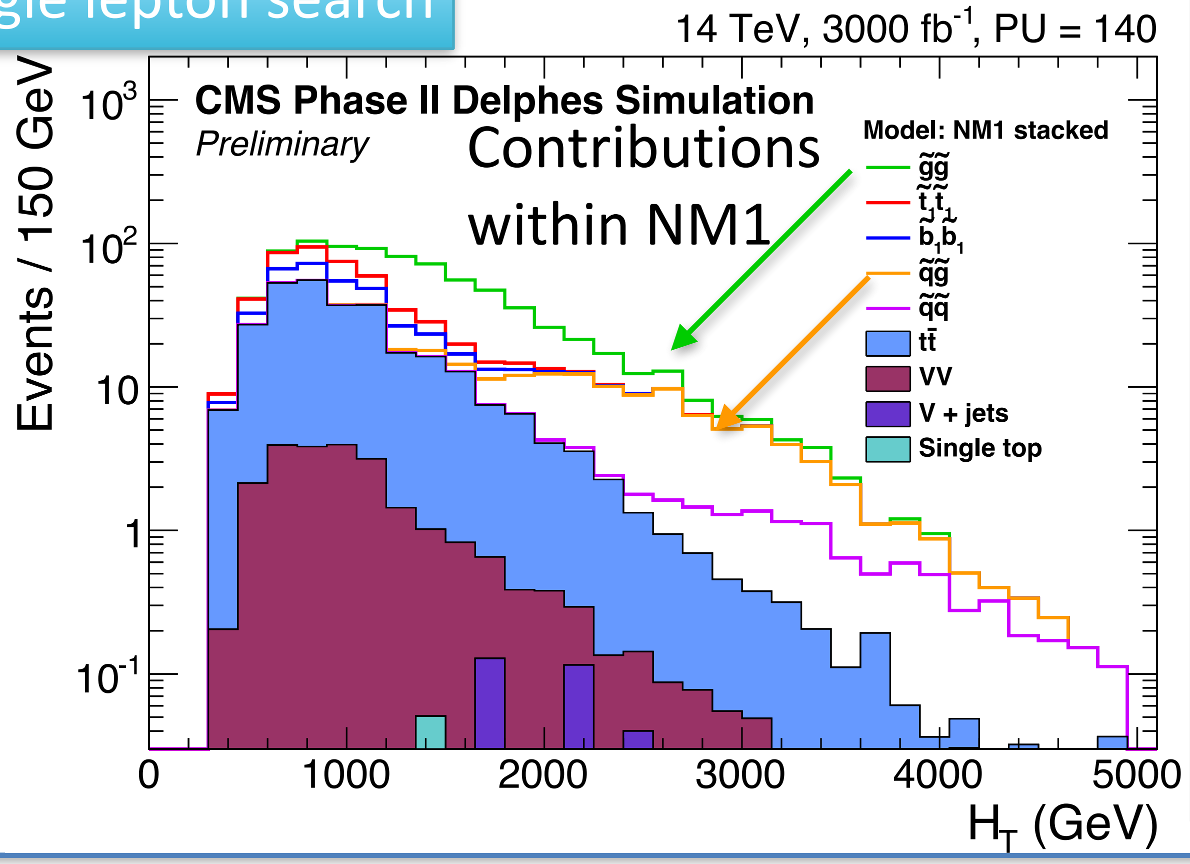
CMS: lessons from full-spectrum SUSY studies

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

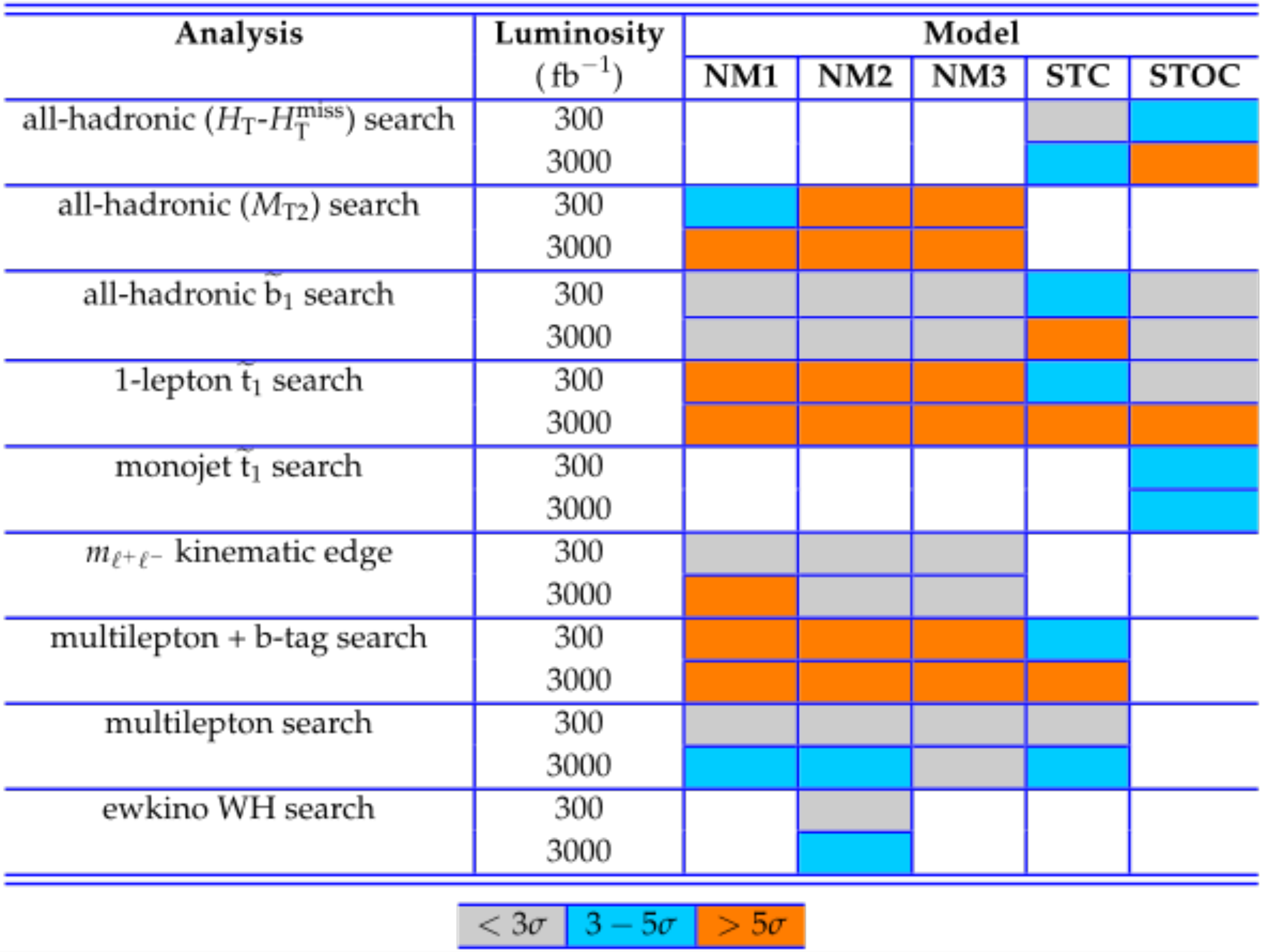


- Designed as 1-lepton search for top-squark pair production.
- Show stacked contributions from NM1 model. Target process does not dominate the observed yield!
- **“Discovery” does not mean you found what you were looking for!**

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	🟦	🟧	🟧		
	3000	🟧	🟧	🟧		
all-hadronic $\tilde{b}_1$ search	300	▨	▨	▨	🟦	▨
	3000	▨	▨	▨	🟧	▨
1-lepton $\tilde{t}_1$ search	300	🟧	🟧	🟧	🟦	▨
	3000	🟧	🟧	🟧	🟧	🟧
monojet $\tilde{t}_1$ search	300					🟦
	3000					🟦
$m_{\ell^+\ell^-}$ kinematic edge	300	▨	▨	▨		
	3000	🟧	▨	▨		
multilepton + b-tag search	300	🟧	🟧	🟧	🟦	
	3000	🟧	🟧	🟧	🟧	
multilepton search	300	▨	▨	▨	▨	
	3000	🟦	🟦	▨	🟦	
ewkino WH search	300		▨			
	3000		🟦			

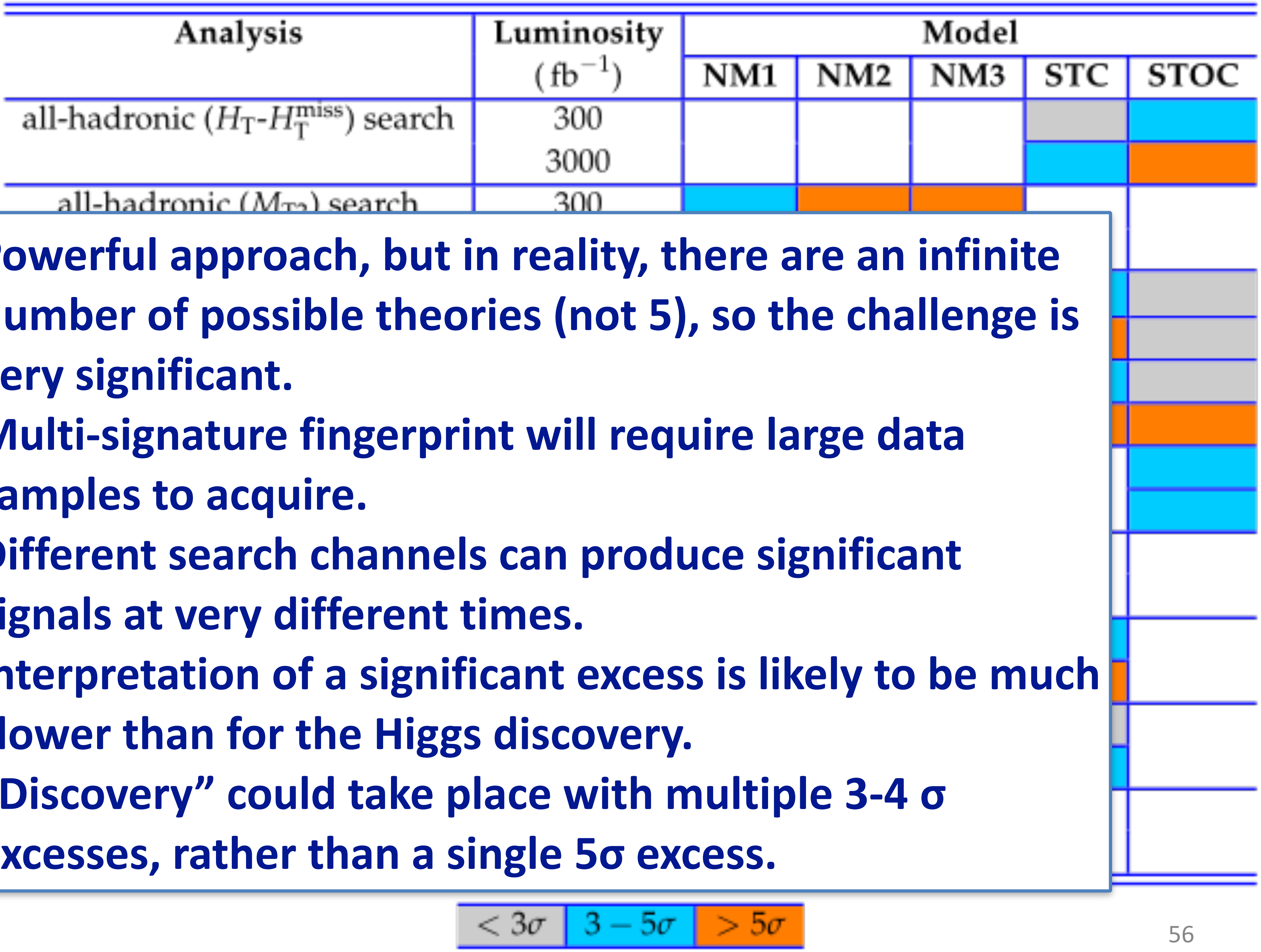
▨ $< 3\sigma$ 🟦 $3 - 5\sigma$ 🟧 $> 5\sigma$

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



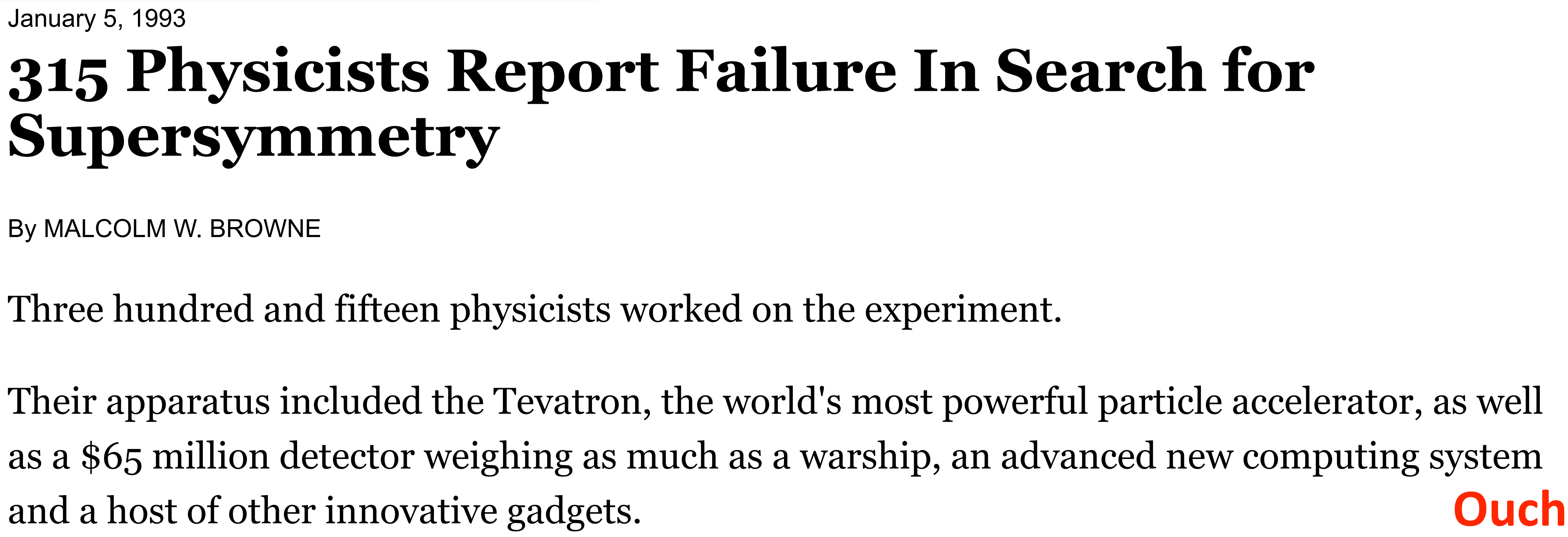
Analysis	Luminosity (fb^{-1})	NM1	NM2	NM3	STC	STOC
all-hadronic (H_T-H_T^{miss}) search	300				▨	🟦
	3000				🟦	🟧
all-hadronic (M_{T2}) search	300	🟦	🟧	🟧		

▨ $< 3\sigma$ 🟦 $3-5\sigma$ 🟧 $> 5\sigma$

- **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.**

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.

Ouch…

New York Times, January 5, 2022

I hope….

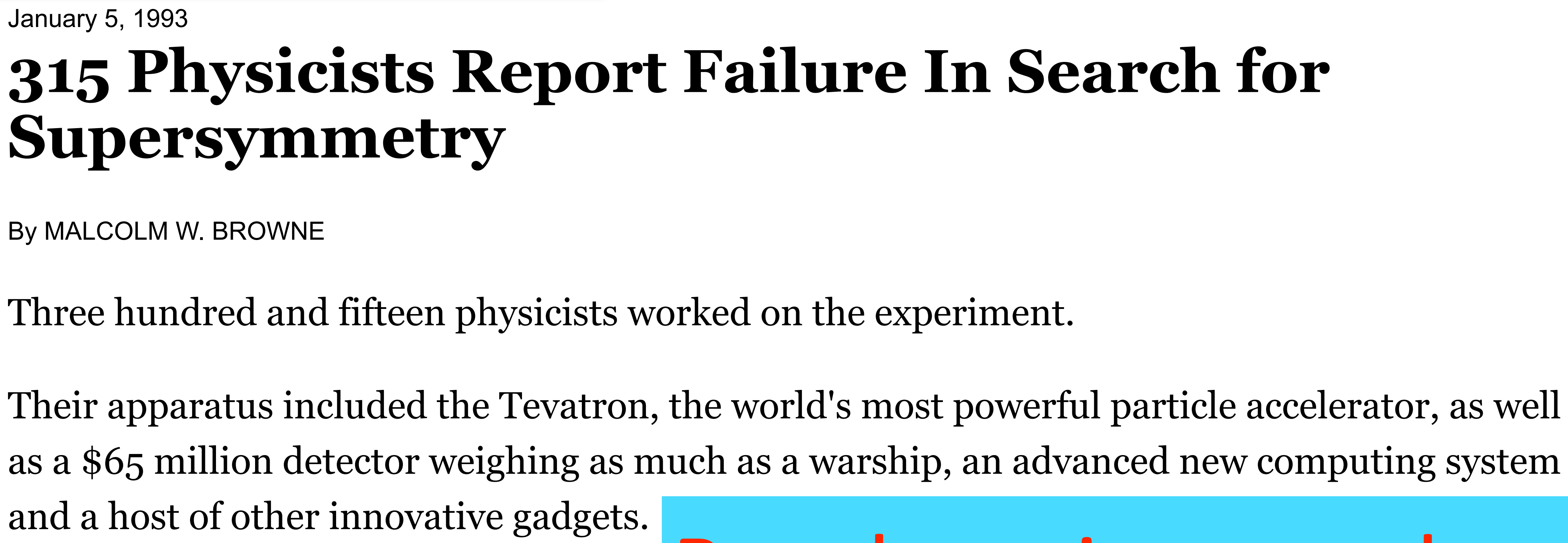
8,345 Physicists Report Discovery of Something But Aren’t Exactly Sure What It Is

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…

History and a prediction

New York Times, January 5, 1993



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But there is precedent!

(and this is a problem we want to have)

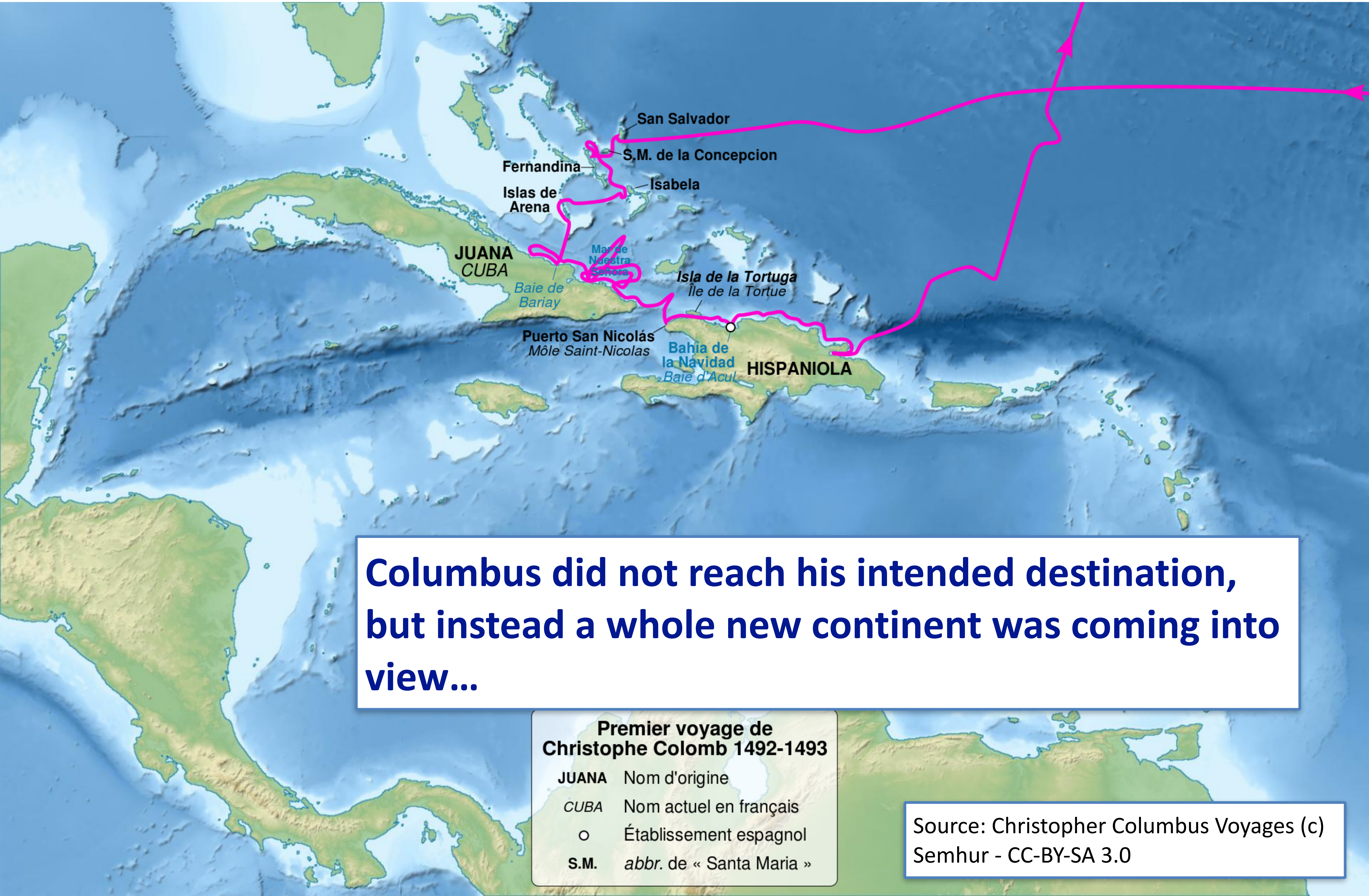
New York Times, January 5, 2022

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…

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…

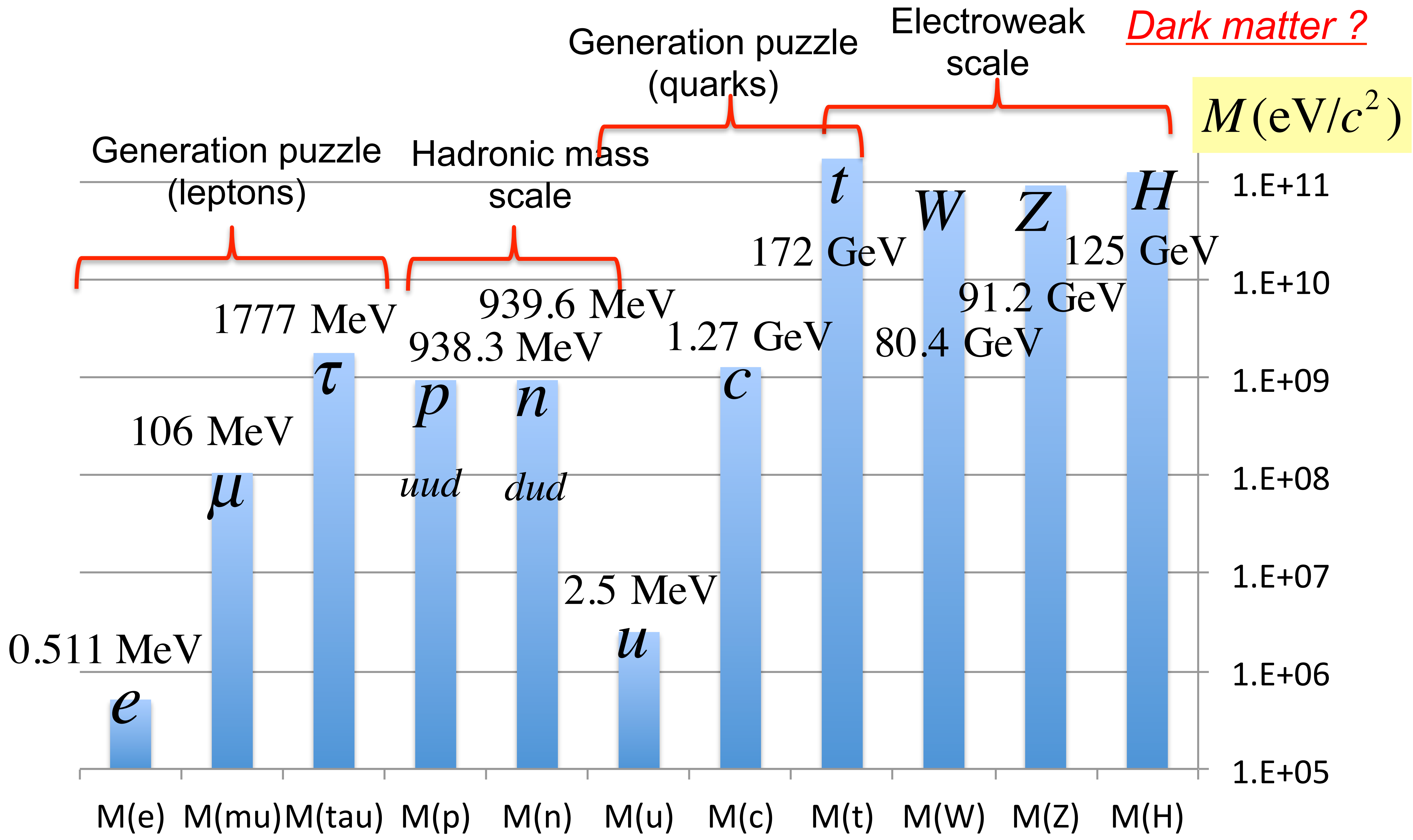
Source: Christopher Columbus Voyages (c) Semhur - CC-BY-SA 3.0

Summary/Observations

- Early Run 2 searches have already significantly extended the mass reach for strongly produced SUSY particles.
- Expect ~10 X more data in 2016 running → another jump in sensitivity.
- If no significant excess is observed with ~300 fb^{-1}, the strongest discovery possibilities may be associated with EWK processes.
- Evidence or discovery 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.
- **A compelling discovery scenario may arise with several 3-4 σ effects, rather than a single 5σ effect.** Life could be quite complicated (e.g., look-elsewhere effects).
- Interpretation of any observed excess will be complex and will require a full fingerprint from multiple searches.

Backup slides

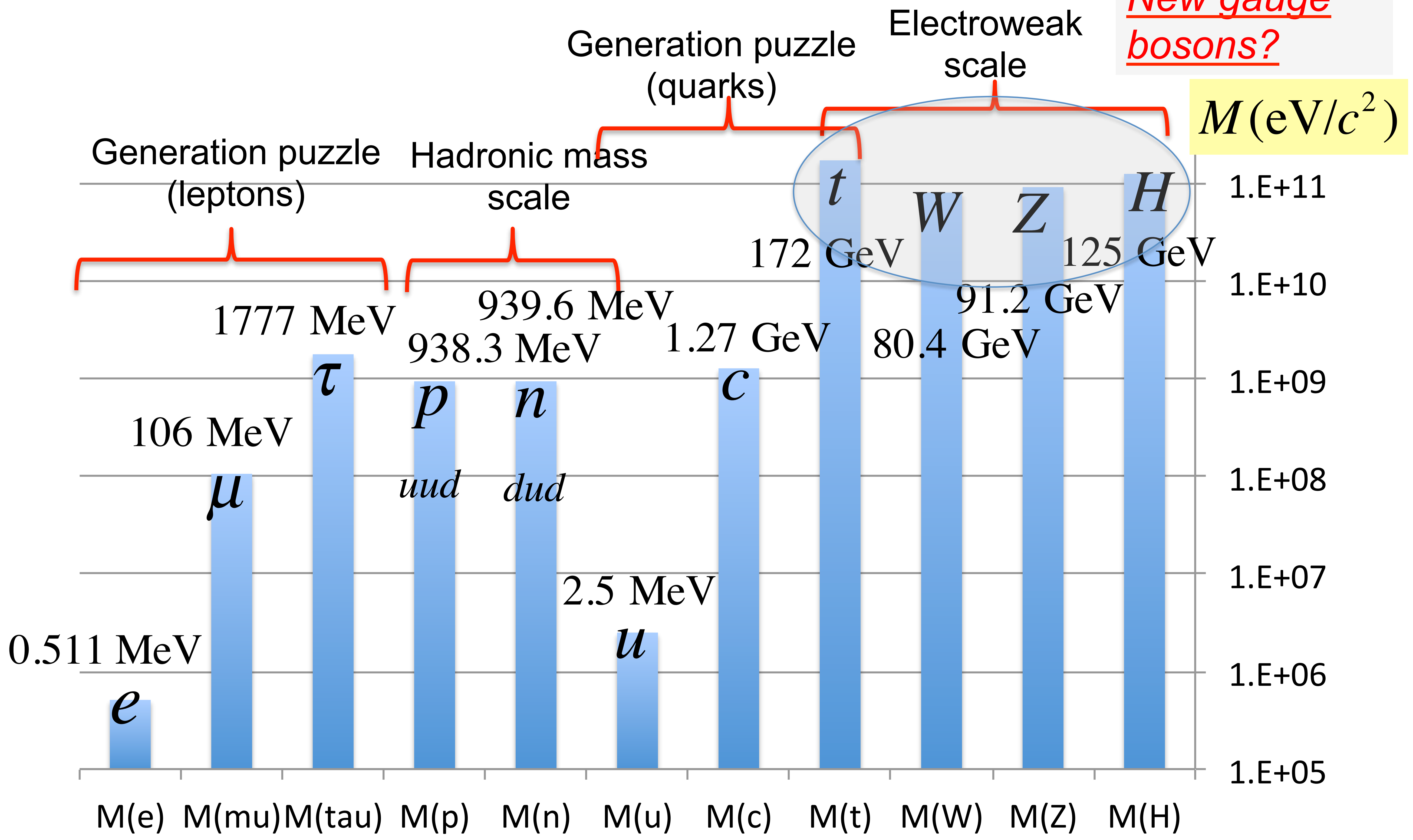
Mass scales in particle physics



Si band gap: $\simeq 1.1\ \mathrm{eV}$ $m(\nu) \sim 0.1\ \mathrm{eV}?$ $m(\tilde{g}) \sim 2\ \mathrm{TeV}?$ $M_{Planck} \approx 10^{18}\ \mathrm{GeV}$

Mass scales in particle physics

SUSY?,
Dark matter ?
New gauge bosons?



Si band gap: $\simeq 1.1$ eV $\quad m(\nu) \sim 0.1$ eV? $\quad m(\tilde{g}) \sim 2$ TeV? $\quad M_{Planck} \approx 10^{18}$ GeV

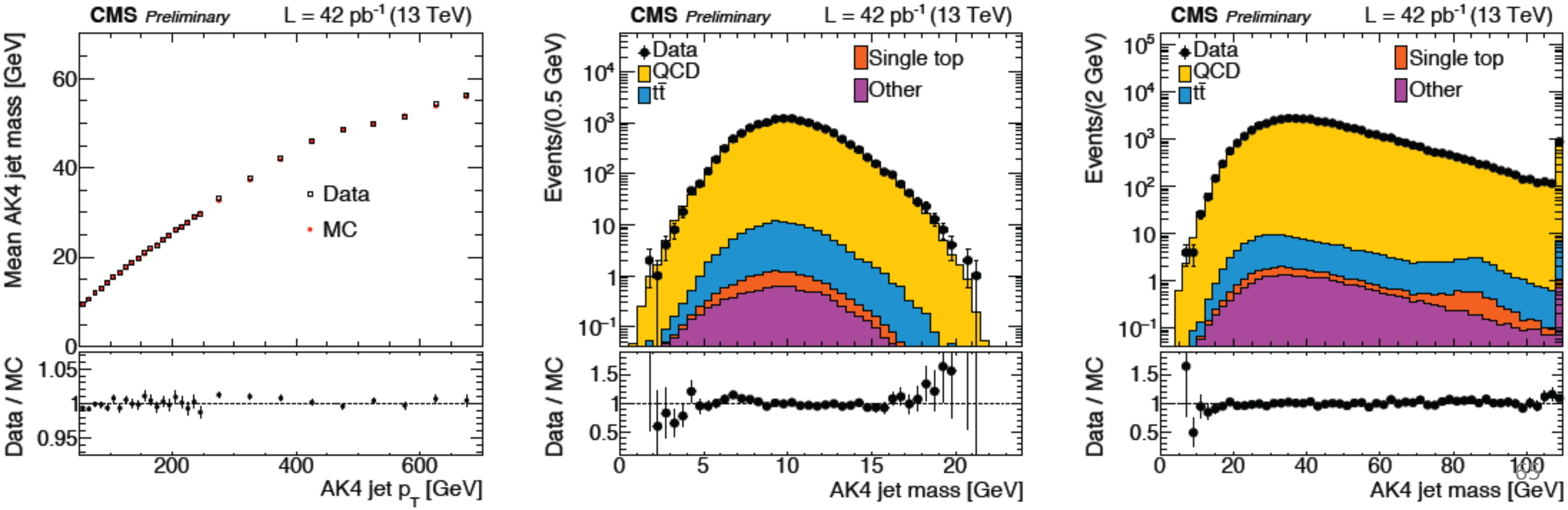
Object reconstruction

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.

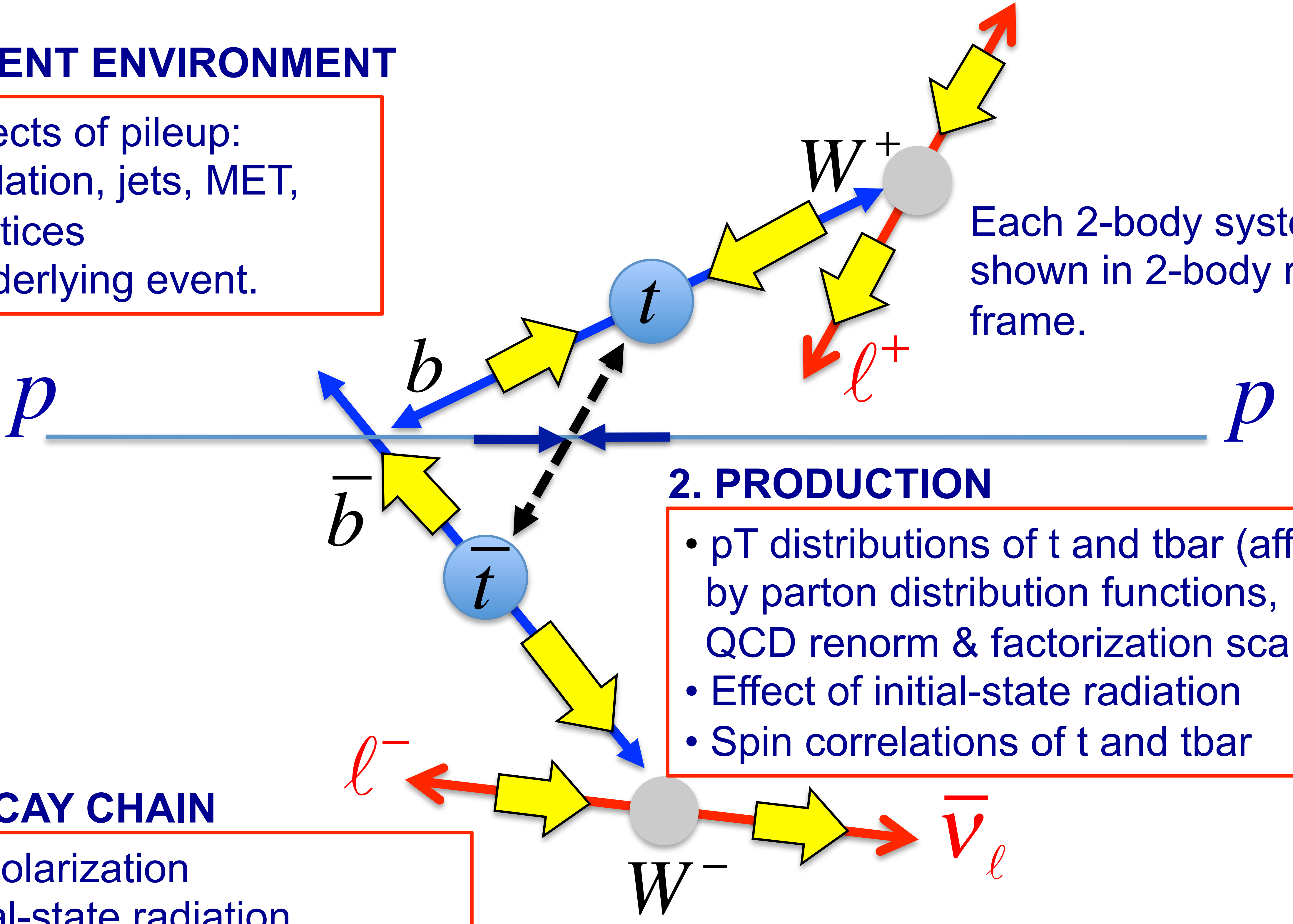
- By clustering AK4 PF jets (pT>30 GeV, |η|<2.4), we are robust against pile-up effects because standard jets are already corrected for pile-up.
- Simulation of M_J distributions tested in QCD, ttbar, Z+jets, W+jets dominated samples in 8 TeV data.



Anatomy of the ttbar→ 2 lepton background

1. EVENT ENVIRONMENT

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



Each 2-body system shown in 2-body rest frame.

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

3. DECAY CHAIN

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

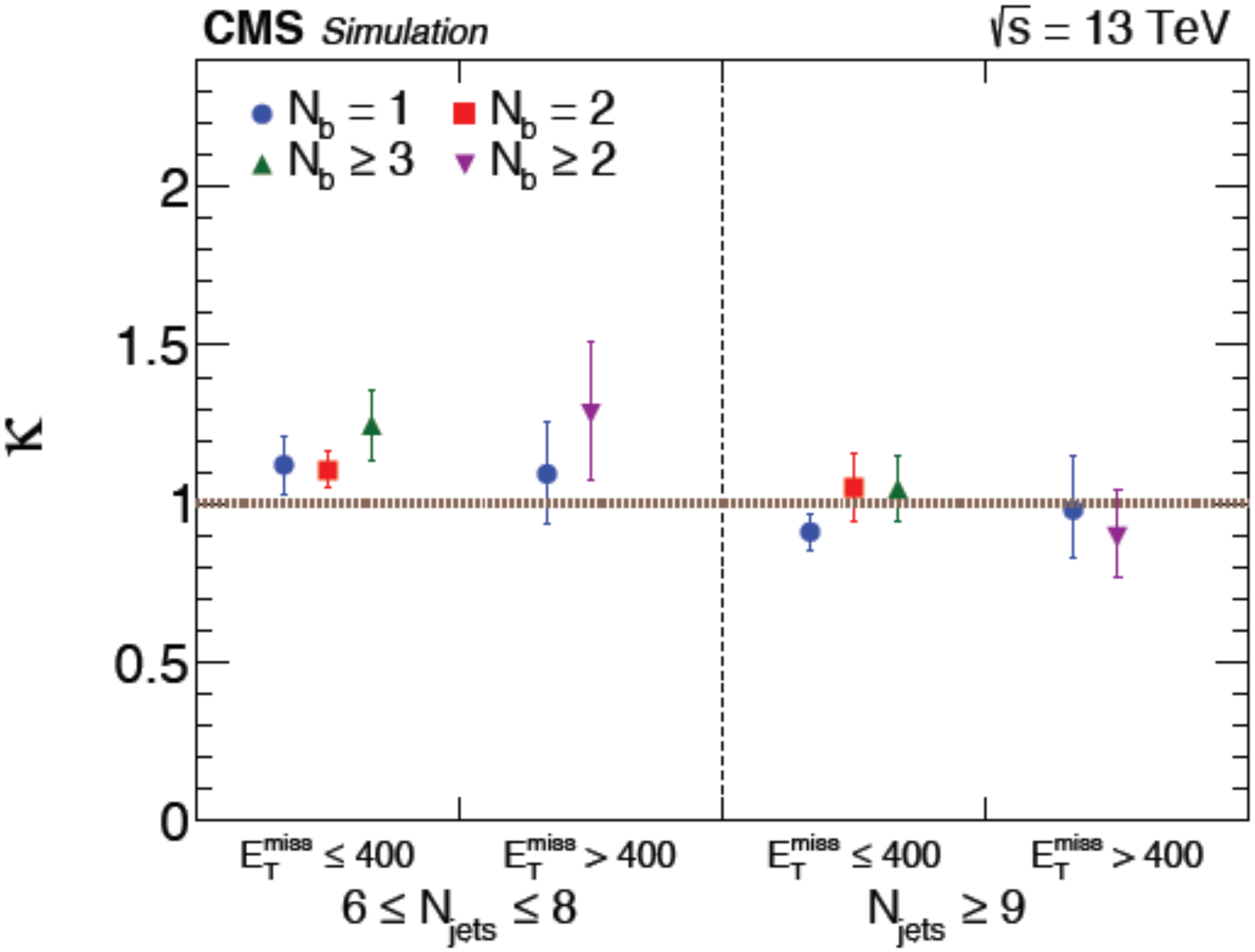
ONLY 2 non-ISR jets in a ttbar dilepton event!

Studying the validity of ABCD in simulation

- Standard ABCD method

  Estimated background: $\mu_{R4} = N_{R2} \times N_{R3}/N_{R1}$

- Apply correction factor κ (≈1) from MC: $\kappa = N_{R4}\,N_{R1}/N_{R2}N_{R3}$ (MC)
- Perform calculation in 10 signal bins of E^T_{miss}, N_{jets}, and N_b

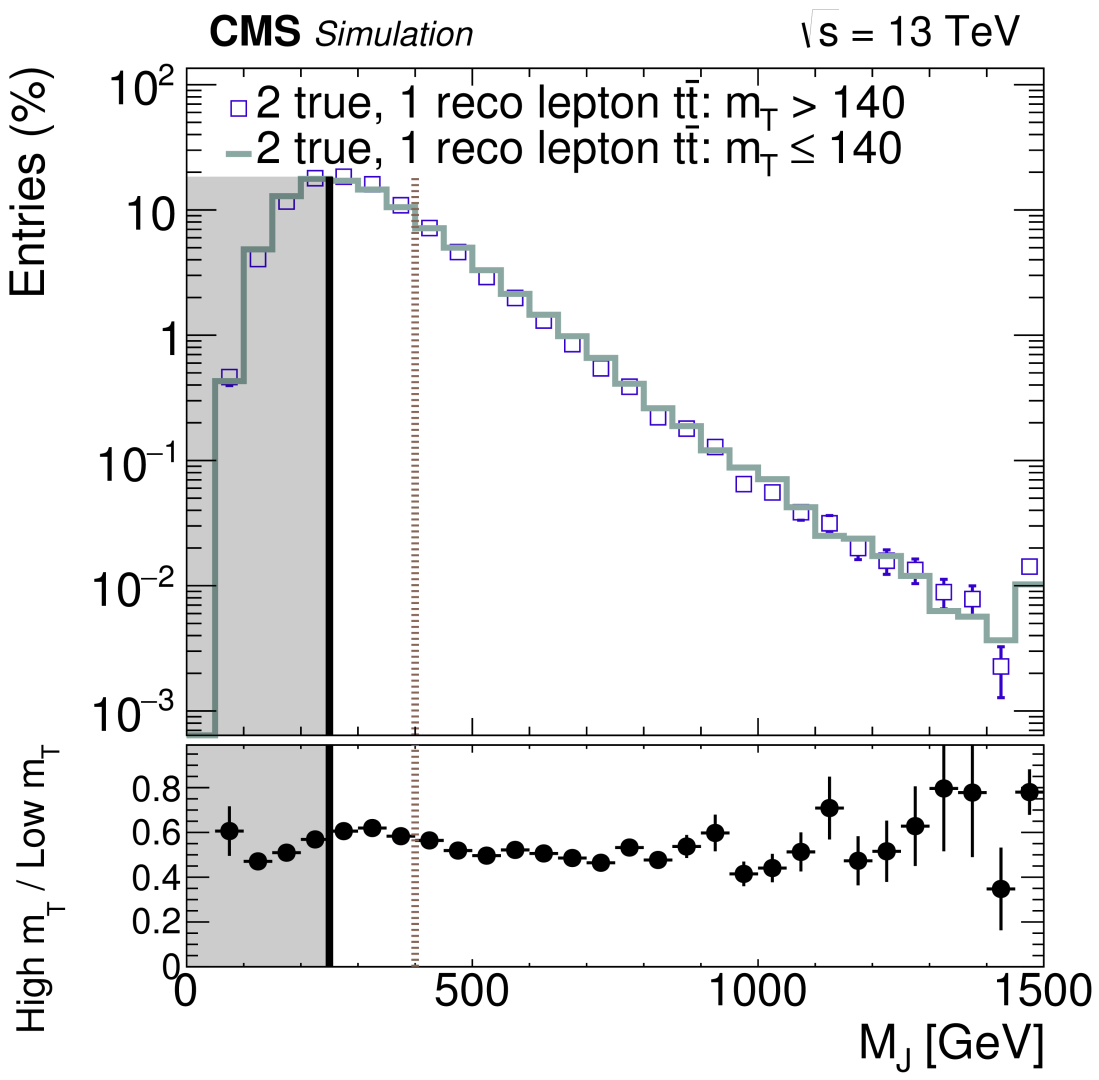


Values computed for the full simulated background.

Uncertainties shown are statistical, from MC.

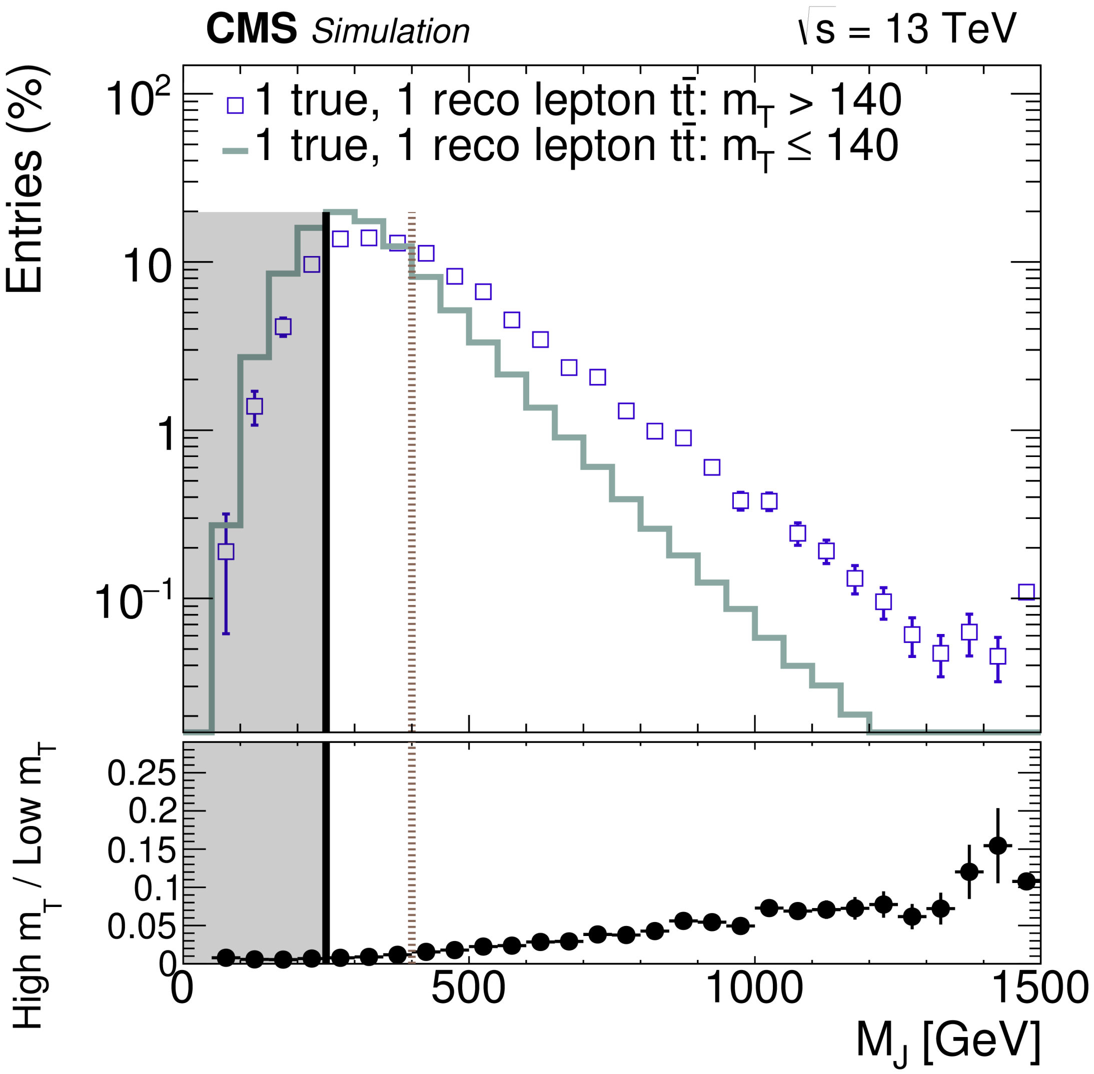
We perform extensive studies in data to establish systematic uncertainties on these correction factors.

M_J for 2-true and 1-true lepton at high/low m_T



Shape of M_J distributions is very similar for all dilepton events reconstructed with 1 lepton, independent of low or high m_T.

→ 2-lep ttbar "contamination" at LOW m_T is not a problem.

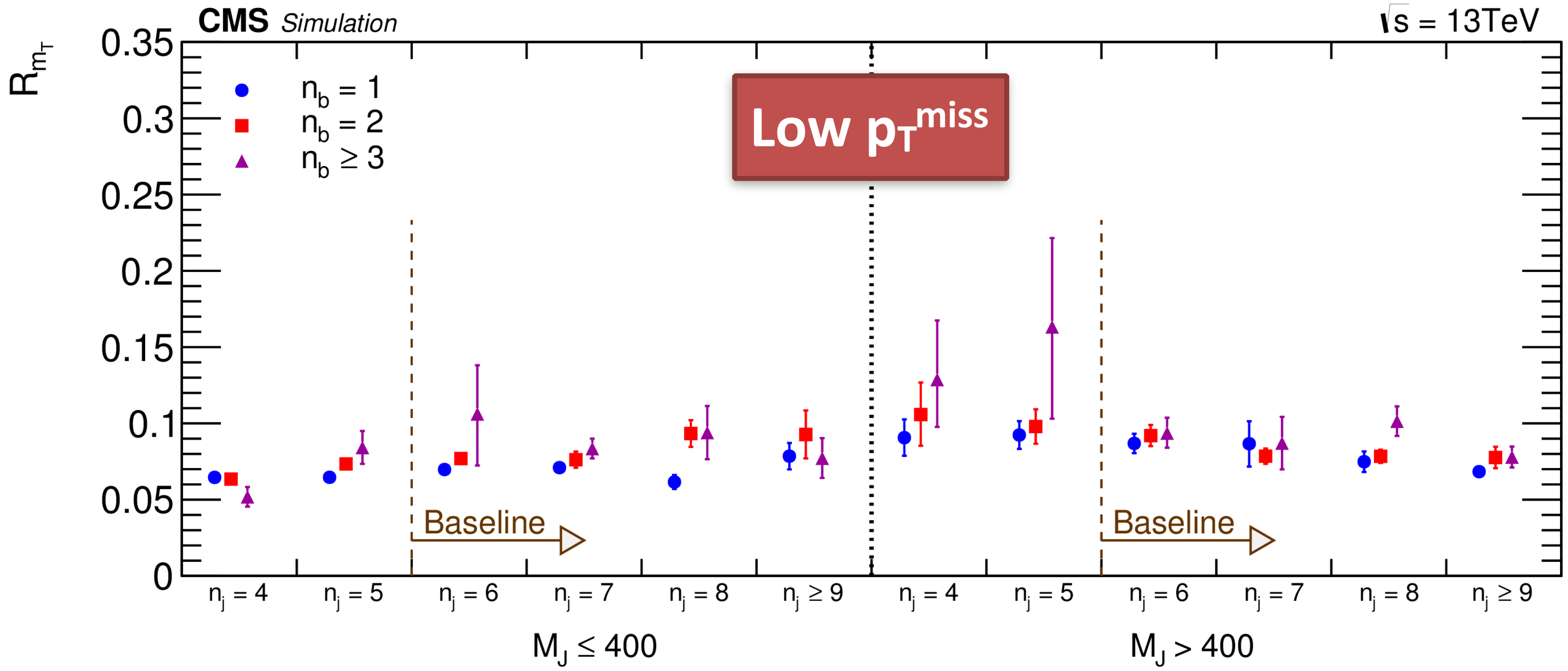


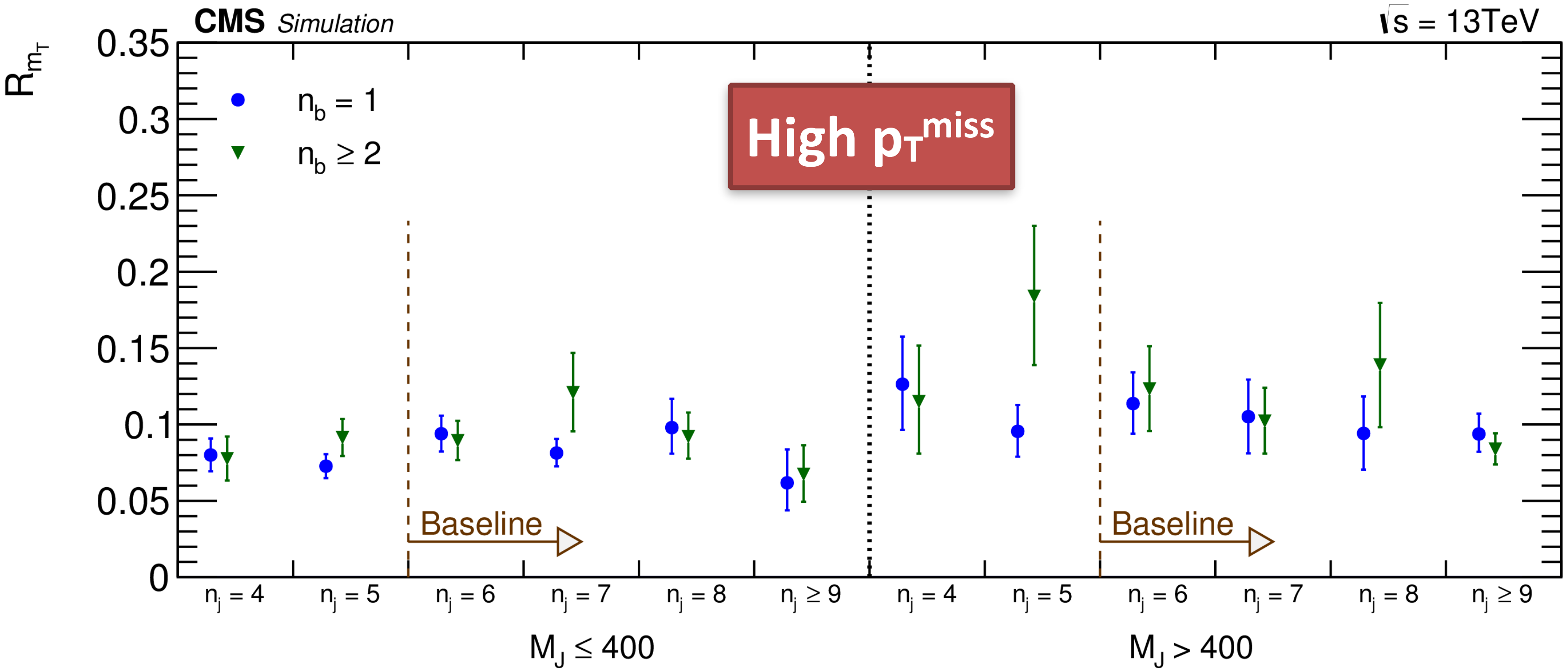
Shape of M_J distributions is NOT similar for all 1-lepton events, independent of low or high m_T.

→1-lep ttbar "contamination" at HIGH m_T is a potential problem. But this contamination is very small.

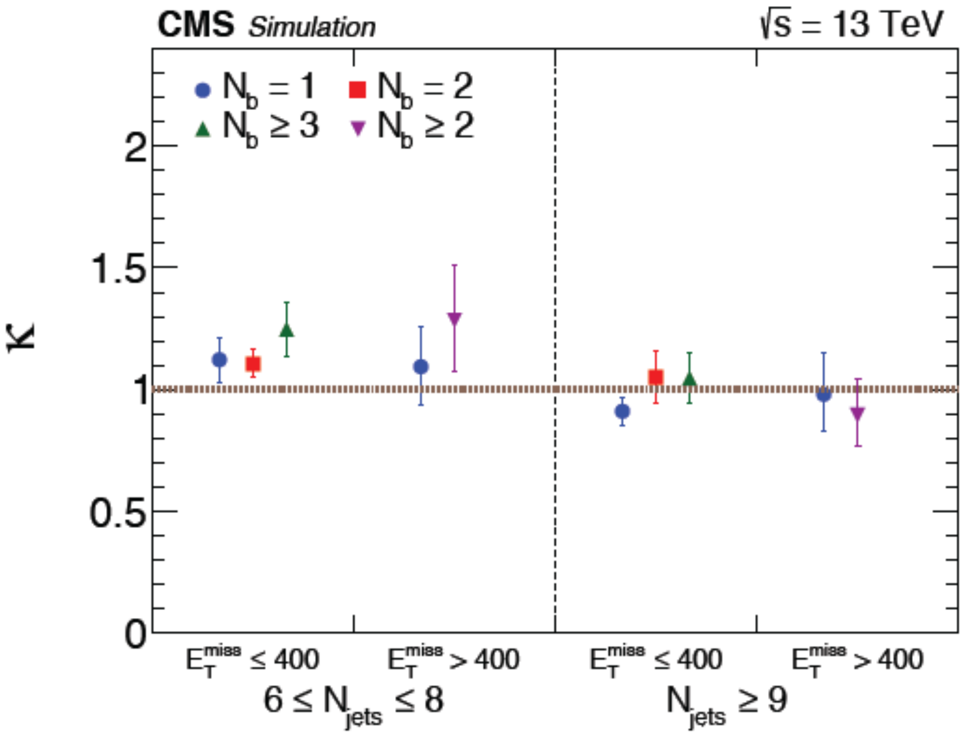
Studying the validity of ABCD in simulation

$$R_{m_T} = \frac{N(m_T > 140)}{N(m_T \leq 140)}$$





$$\kappa = \frac{R_{m_T}(M_J > 400)}{R_{m_T}(M_J \leq 400)}$$



κ for each of the 10 signal bins

Predicted and observed event yields

- Perform two types maximum likelihood fits:
  - "Predictive fit": uses yields in R1, R2, and R3 *only* to predict R4 (convenient way to implement ABCD method while propagate uncertainties). Assumes no signal contamination of R1-R3. Test of null hypothesis.
  - "Global fit": uses yields in R1, R2, R3, and R4 in each of 6 analysis bins. Allows for signal events in all regions, in relative proportion set by signal models.

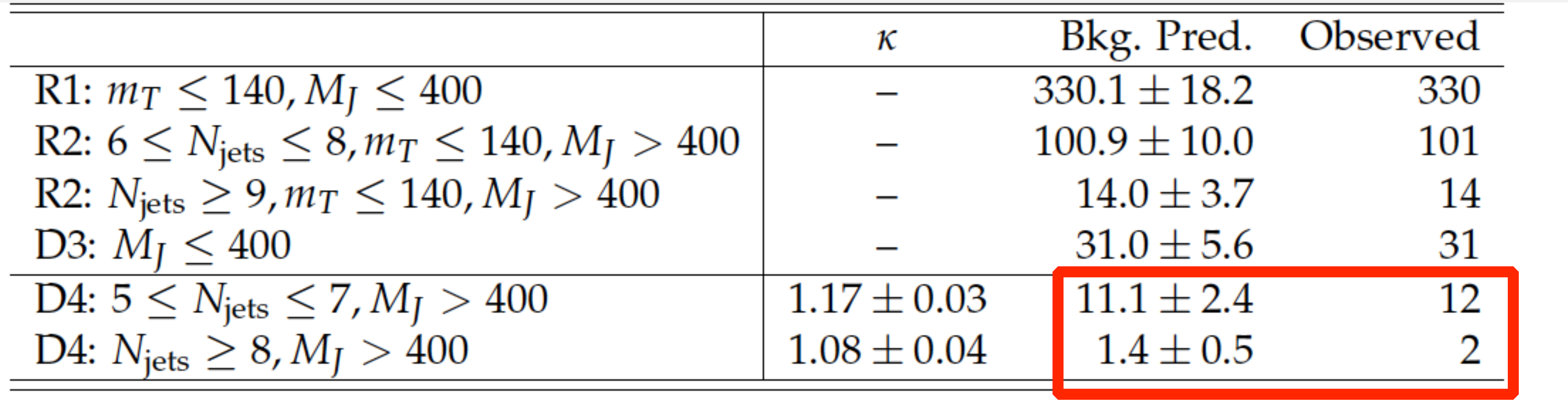
$$\mu_{\mathrm{R}1}^{\mathrm{bkg}} = \mu \qquad \mu_{\mathrm{R}2}^{\mathrm{bkg}} = \mu \cdot R(M_J)$$

$$\mu_{\mathrm{R}3}^{\mathrm{bkg}} = \mu \cdot R(m_{\mathrm{T}}) \qquad \mu_{\mathrm{R}4}^{\mathrm{bkg}} = \kappa \cdot \mu \cdot R(M_J) \cdot R(m_{\mathrm{T}})$$

$$L^{\mathrm{data}} = \prod_{i=1}^{4} \prod_{k=1}^{N_{\mathrm{bins}}(\mathrm{R}i)} \mathrm{Poisson}(N_{\mathrm{Ri},k}^{\mathrm{data}} \,|\, \mu_{\mathrm{Ri},k}^{\mathrm{bkg}} + r \cdot \mu_{\mathrm{Ri},k}^{\mathrm{MC\ sig}})$$

Systematic uncertainties on the background

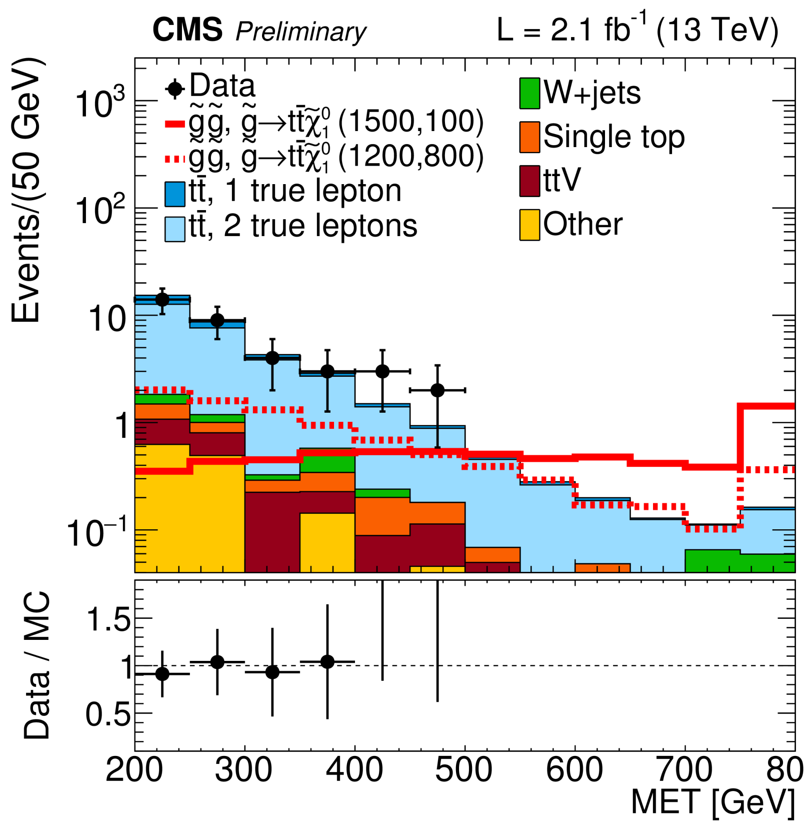
- Incorporated as uncertainty on κ.
- Dominant background: 2-lep ttbar → use 2-lep control sample to measure an uncertainty. Replace R3, R4 with corresponding 2-lep control regions D3, D4

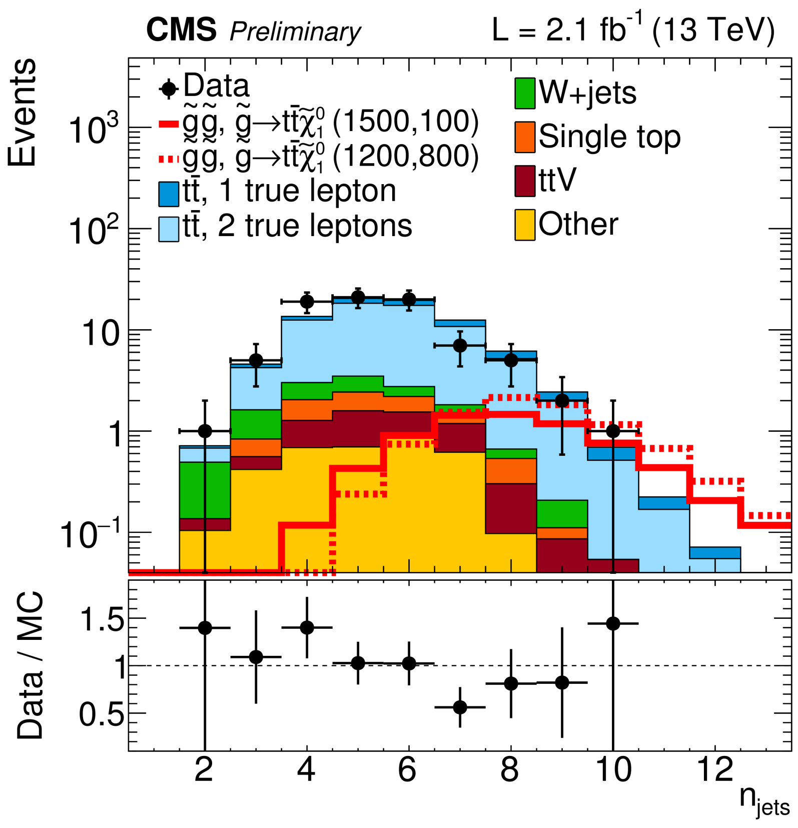


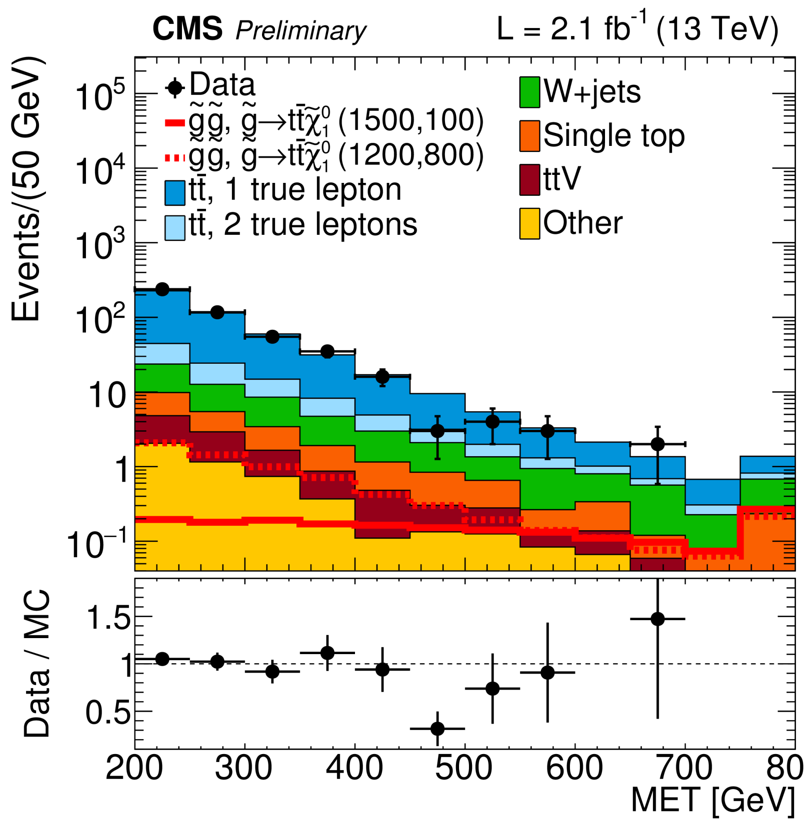
	κ	Bkg. Pred.	Observed
R1: $m_T \leq 140, M_J \leq 400$	–	330.1 ± 18.2	330
R2: $6 \leq N_{\text{jets}} \leq 8, m_T \leq 140, M_J > 400$	–	100.9 ± 10.0	101
R2: $N_{\text{jets}} \geq 9, m_T \leq 140, M_J > 400$	–	14.0 ± 3.7	14
D3: $M_J \leq 400$	–	31.0 ± 5.6	31
D4: $5 \leq N_{\text{jets}} \leq 7, M_J > 400$	1.17 ± 0.03	11.1 ± 2.4	12
D4: $N_{\text{jets}} \geq 8, M_J > 400$	1.08 ± 0.04	1.4 ± 0.5	2

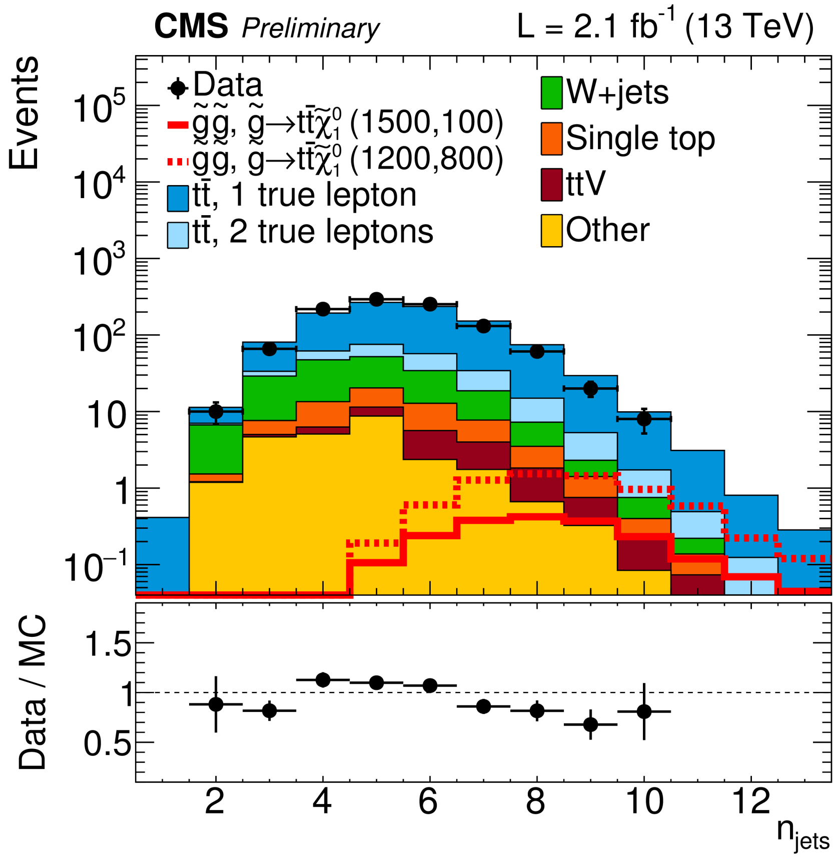
- Additional systematic uncertainties (all < 11%)
  - 1-lep ttbar events at high mT (due to jet energy mismeasurementd), effect of jet energy resolution and corrections, ISR and top pT modeling, non- ttbar background

Key kinematic distributions in data and simulation

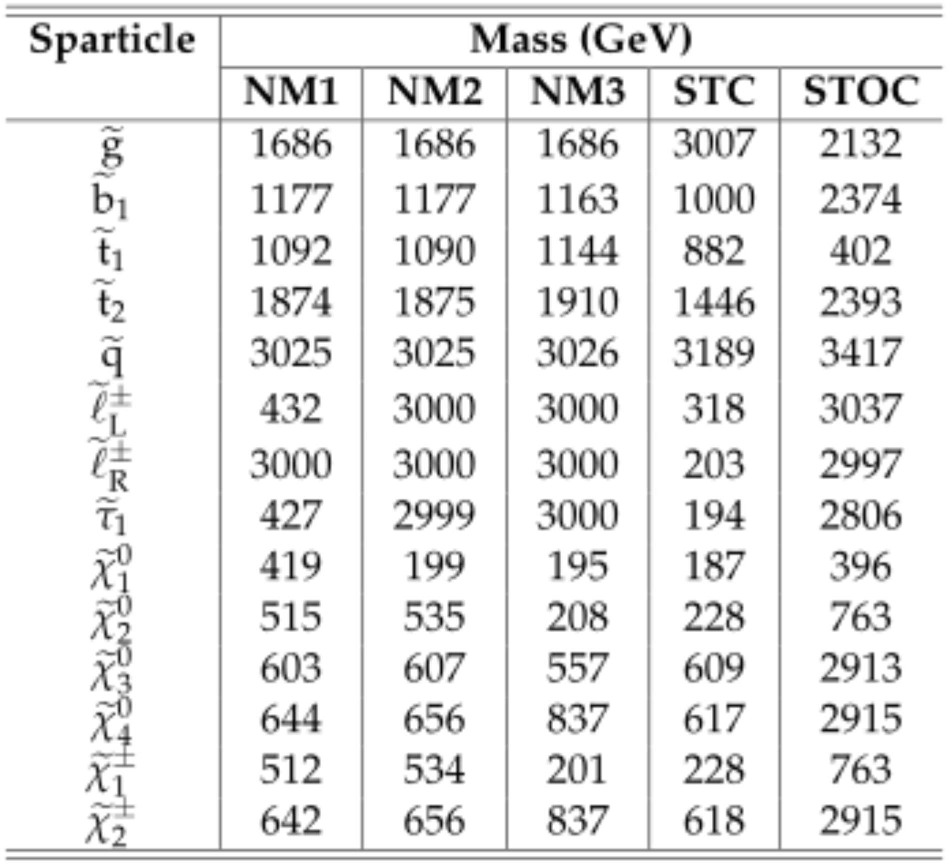




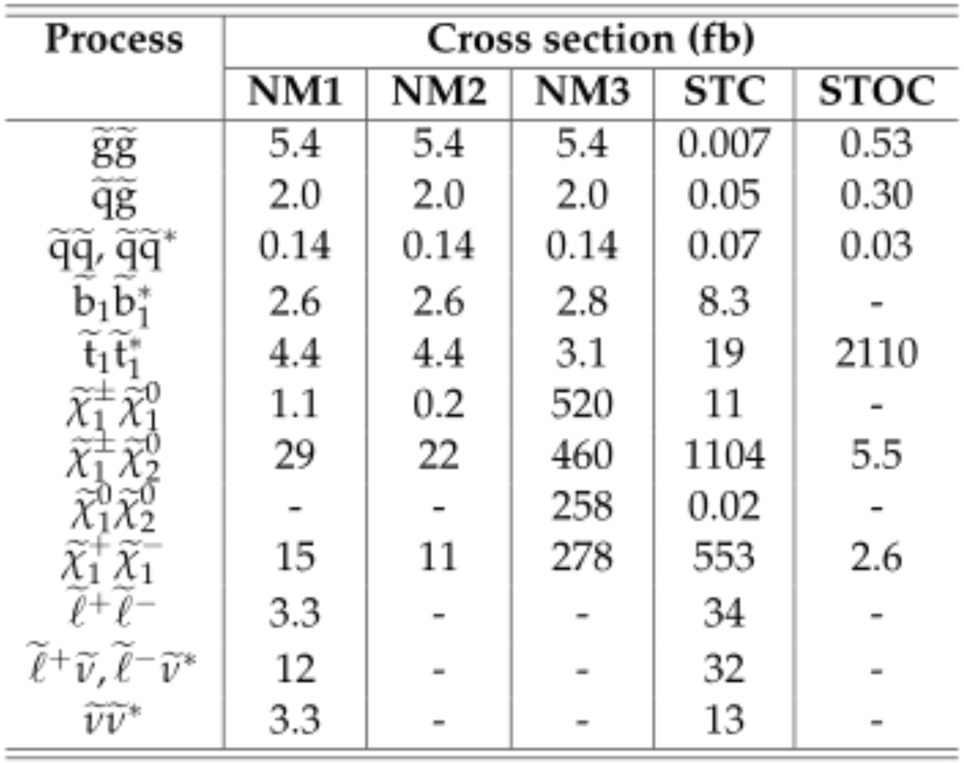




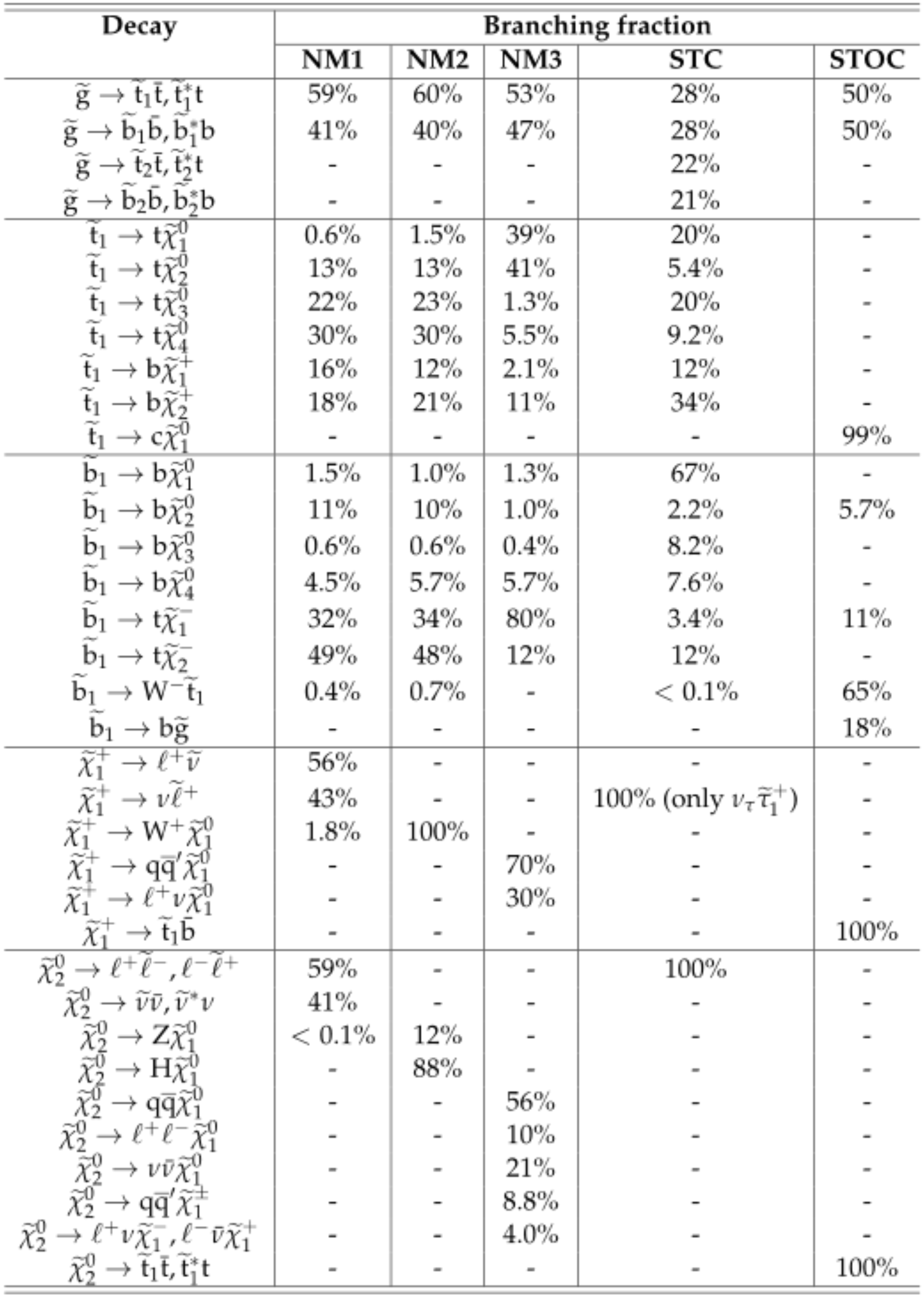
CMS full-spectrum SUSY models



Sparticle	Mass (GeV)				
	NM1	**NM2**	**NM3**	**STC**	**STOC**
$\widetilde{g}$	1686	1686	1686	3007	2132
$\widetilde{b}_1$	1177	1177	1163	1000	2374
$\widetilde{t}_1$	1092	1090	1144	882	402
$\widetilde{t}_2$	1874	1875	1910	1446	2393
$\widetilde{q}$	3025	3025	3026	3189	3417
$\widetilde{\ell}_L^\pm$	432	3000	3000	318	3037
$\widetilde{\ell}_R^\pm$	3000	3000	3000	203	2997
$\widetilde{\tau}_1$	427	2999	3000	194	2806
$\widetilde{\chi}_1^0$	419	199	195	187	396
$\widetilde{\chi}_2^0$	515	535	208	228	763
$\widetilde{\chi}_3^0$	603	607	557	609	2913
$\widetilde{\chi}_4^0$	644	656	837	617	2915
$\widetilde{\chi}_1^\pm$	512	534	201	228	763
$\widetilde{\chi}_2^\pm$	642	656	837	618	2915



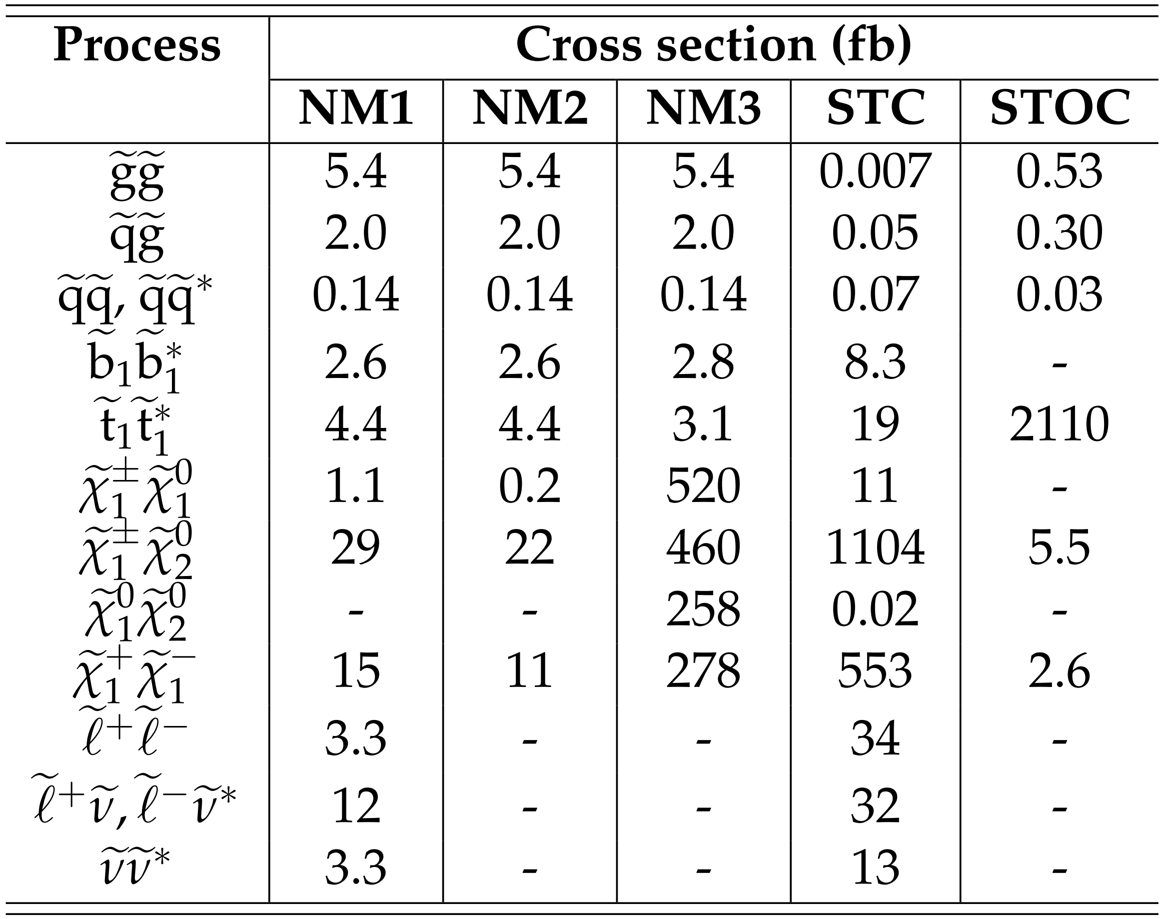
Process	Cross section (fb)				
	NM1	**NM2**	**NM3**	**STC**	**STOC**
$\widetilde{g}\widetilde{g}$	5.4	5.4	5.4	0.007	0.53
$\widetilde{q}\widetilde{g}$	2.0	2.0	2.0	0.05	0.30
$\widetilde{q}\widetilde{q}, \widetilde{q}\widetilde{q}^*$	0.14	0.14	0.14	0.07	0.03
$\widetilde{b}_1\widetilde{b}_1^*$	2.6	2.6	2.8	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	-



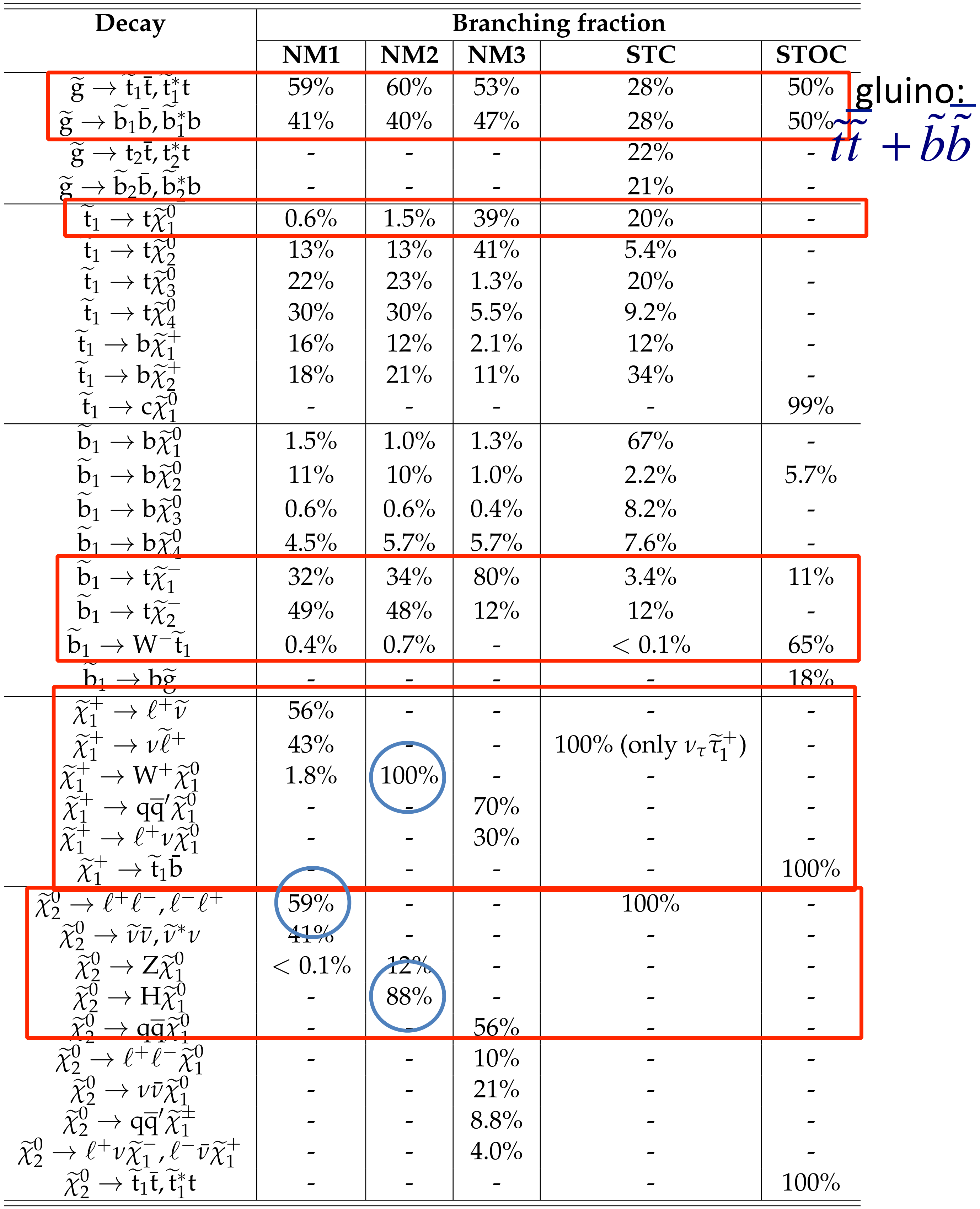
Decay	Branching fraction				
	NM1	**NM2**	**NM3**	**STC**	**STOC**
$\widetilde{g} \to \widetilde{t}_1\bar{t}, \widetilde{t}_1^*t$	59%	60%	53%	28%	50%
$\widetilde{g} \to \widetilde{b}_1\bar{b}, \widetilde{b}_1^*b$	41%	40%	47%	28%	50%
$\widetilde{g} \to \widetilde{t}_2\bar{t}, \widetilde{t}_2^*t$	-	-	-	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%
$\widetilde{\chi}_2^0 \to \ell^+\widetilde{\ell}^-, \ell^-\widetilde{\ell}^+$	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%

PDG for CMS full-spectrum SUSY models

CMS PAS SUS-14-012



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



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

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

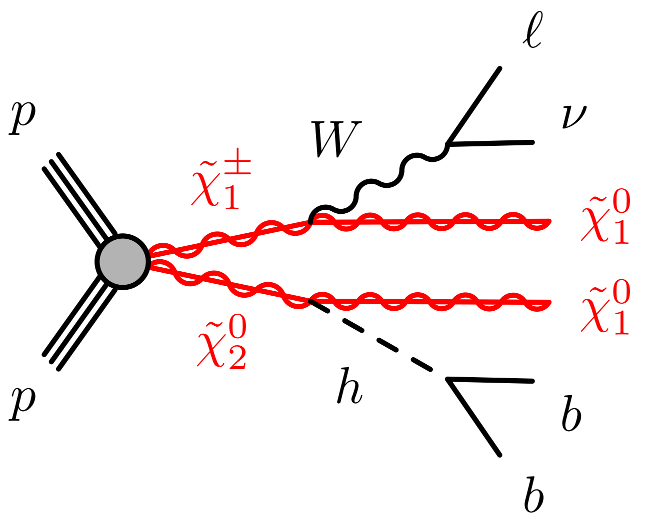
CMS: $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ with $\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$

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

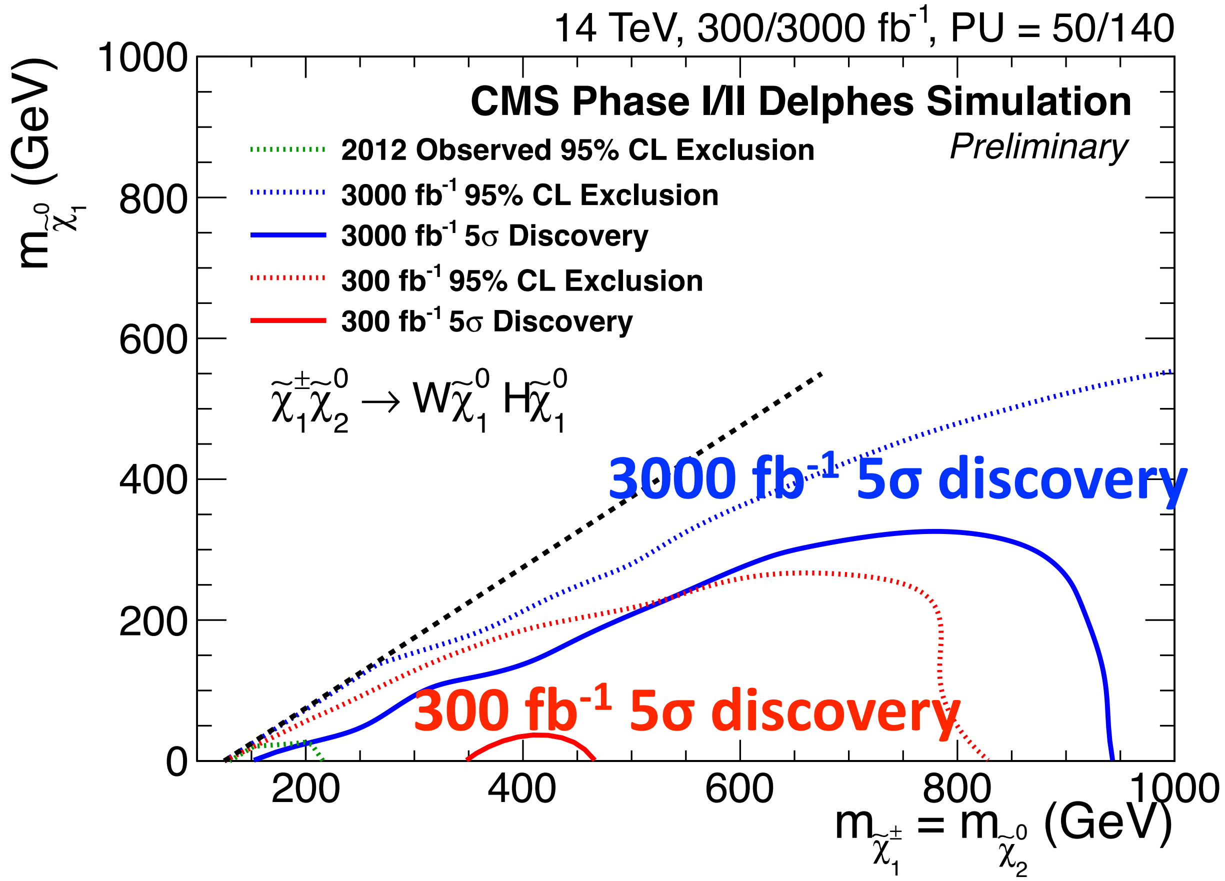
1 lepton + m(bb) + E_T^{miss} + mT cut + mCT

Dominant SM background: ttbar production

CMS-PAS-SUS-14-012



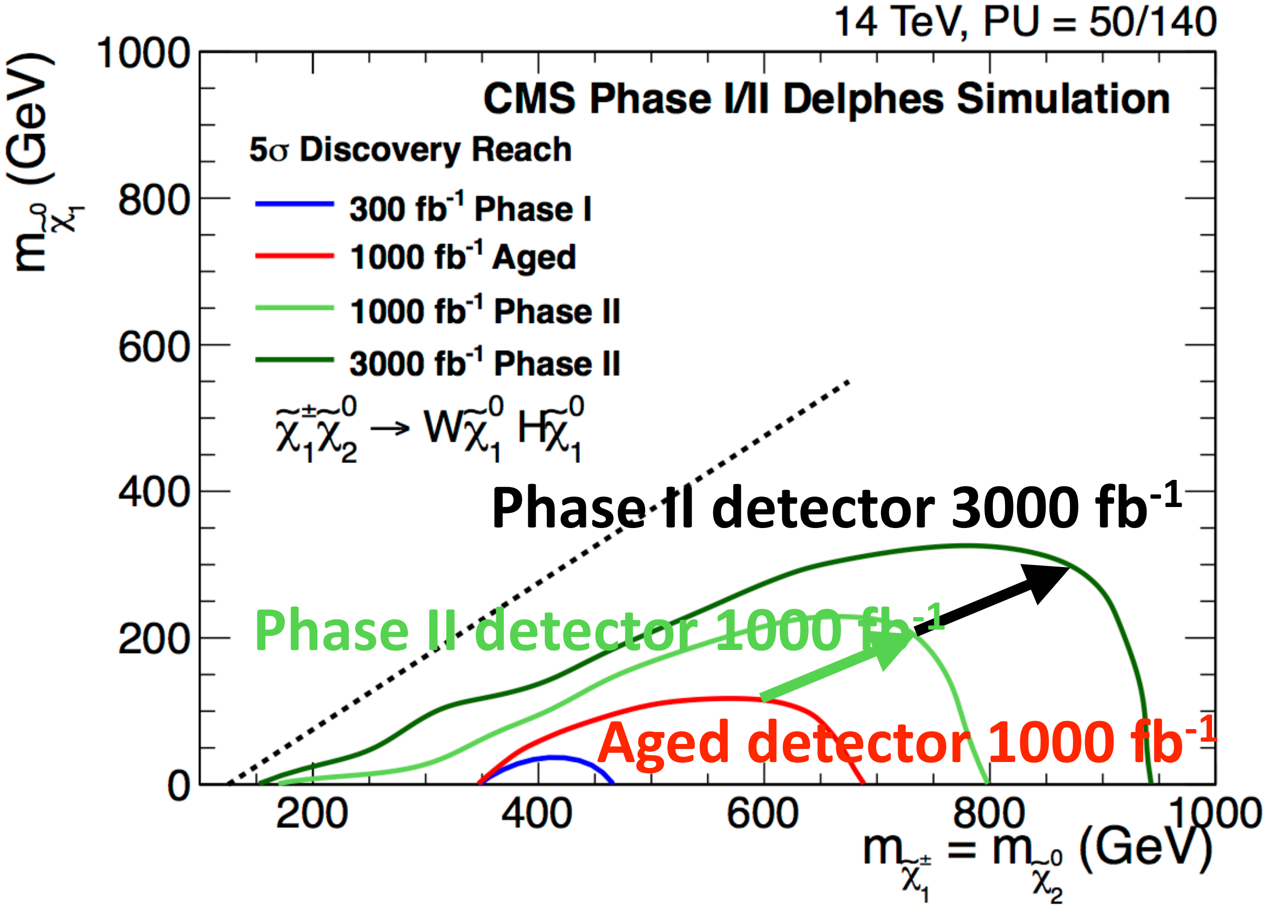
Discovery sensitivity: up to ~950 GeV.



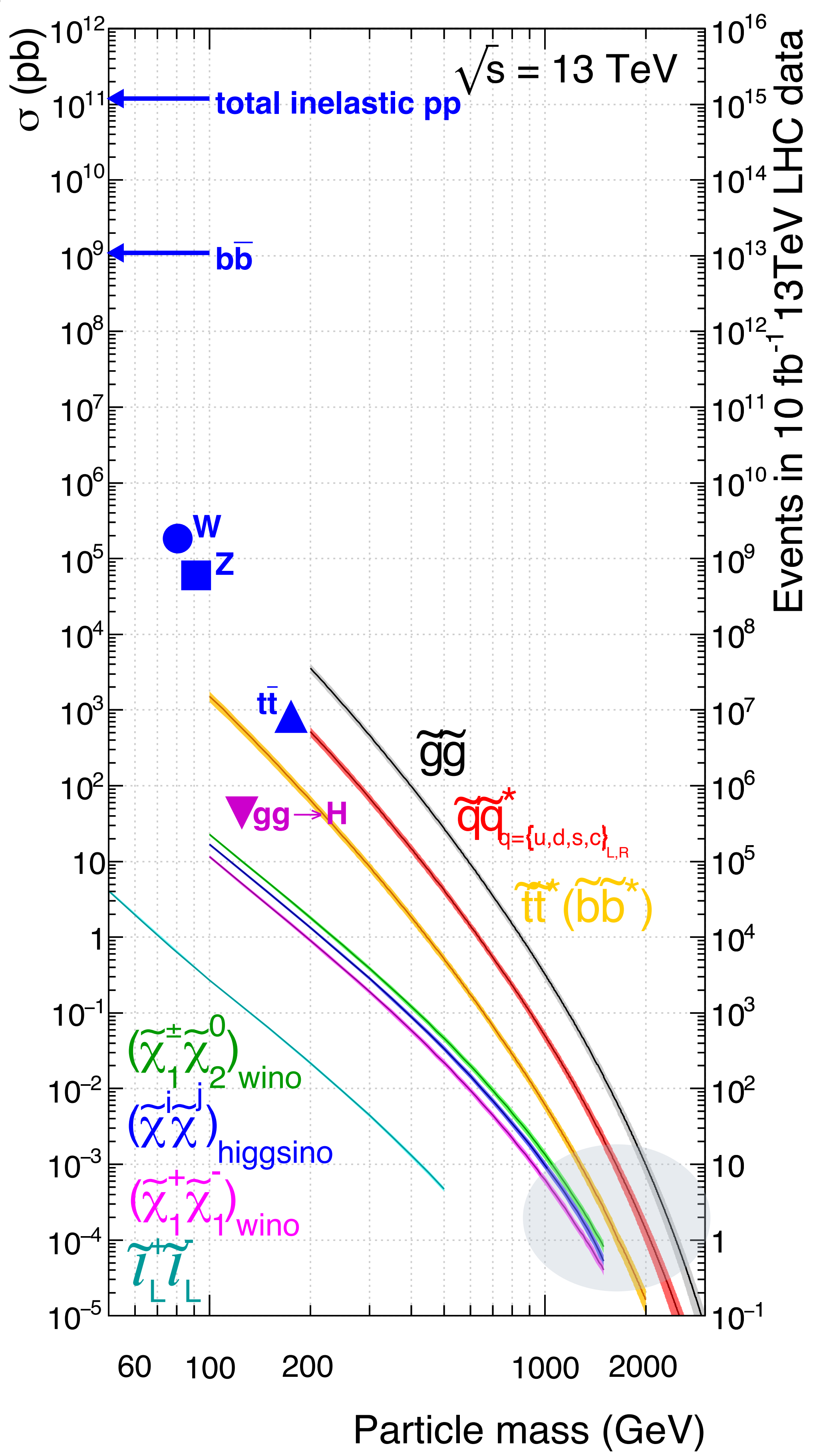
Effect of aged Run 1 detector performance on search for Wh(bb) + E_T^{miss}

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.



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).
- Most HL-LHC simulations use parametrized MC with background uncertainties either guessed (based on actual measurements with 8 TeV data), or simply assumed.
- Studies generally use simple methods; best to regard the results as *indicative*.
- Compare reach for 300 fb^{-1} & 3000 fb^{-1}.

Documents and References

Continued in the backup slides.

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- **Supersymmetry discovery potential in future LHC and HL-LHC running with the CMS detector,** CMS-PAS-SUS-14-012.
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- **Natural SUSY Endures**, M. Papucci et al., arXiv:1110.6926.
- **Naturalness and the Status of Supersymmetry**, J.L. Feng, arXiv:1302.6587.
- **The State of Supersymmetry after Run I of the LHC**, N. Craig, arXiv:1309.0528.
- **Hunting Quasi-Degenerate Higgsinos**, Z.Han et al., arXiv 1401.1235.
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- **The Physics of Heavy Z’ Gauge Bosons**, P. Langacker, arXiv:0801.1345.

CMS studies of discovery scenarios