Searching for Supersymmetry at the LHC

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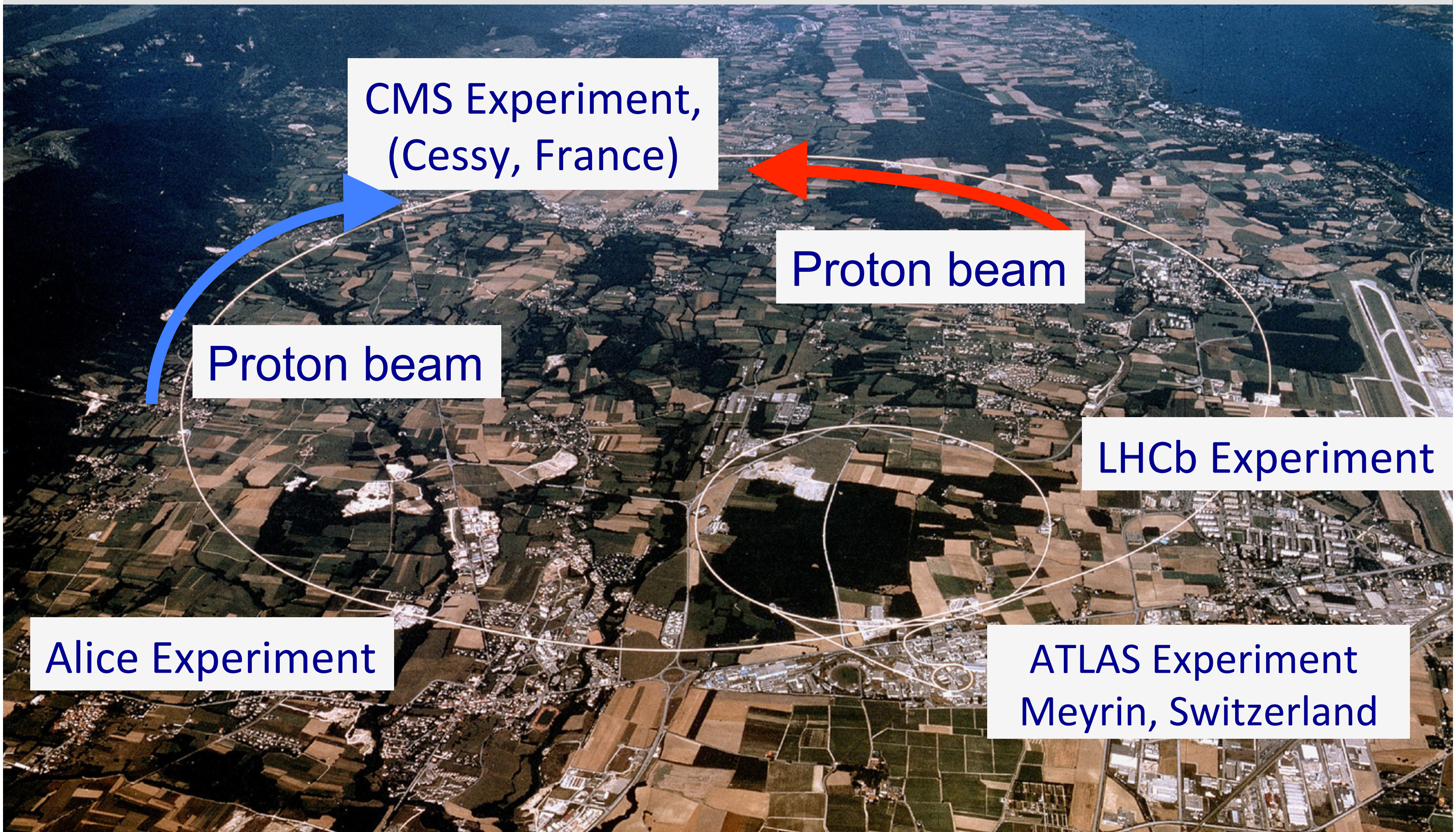
Albuquerque, November 6, 2014

LHC ring: 2 separate magnetic “highways”



- 9300 magnets, including 1232 15-meter dipoles.
- Radio-frequency EM cavity devices to accelerate beams (8/beam; 40 MHz)

Outline

- Basics of supersymmetry
- The Higgs, SUSY, and "naturalness"
- Overview of SUSY search strategies.
- Examples: Searching for gluinos, EWKinos, scalar quarks, dark matter,...
- Prospects for Run 2
- Conclusions

Drawing courtesy Sergio Cittolin

CMS PUBLIC SUSY RESULTS
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Most results use 19.5 fb^{-1} ($\sqrt{s}$ =8 TeV).

Supersymmetry transformations

- SUSY xf's map *fermionic and bosonic* degrees of freedom onto each other.
- *Q* = generator of SUSY transformation

$$\underbrace{Q|s\rangle}_{\text{boson (J=0 or J=1)}} = \underbrace{|f\rangle}_{\text{fermion (J=1/2)}}$$

Q must be fermionic in character!

- The charges (interaction couplings) are <u>unchanged</u>.
- Doubles the numbers of degrees of freedom in the particle spectrum (but CPT did that too!)
- Unlike CPT, don't see SUSY partners with same masses as SM → *if SUSY exists, it must be broken*.

Particle content of the SM

Quarks: spin-1/2

u up	c charm	t top
d down	s strange	b bottom

Leptons: spin-1/2

e^- electron	μ^- muon	τ^- tau
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino

Gauge bosons: spin-1

Strong force	EM force	Weak force		
g	γ	Z^0	W^+	W^-
gluon (8)	photon	Z boson	W bosons	

Higgs boson: spin-0

and field vacuum expectation value

H

Higgs boson

Simple (naïve) SUSY spectrum

scalar quark

squarks: spin-0

$\tilde{u}$ *up squark*	$\tilde{c}$ *charm squark*	$\tilde{t}$ *top squark*
$\tilde{d}$ *down squark*	$\tilde{s}$ *strange squark*	$\tilde{b}$ *bottom squark*

scalar lepton

sleptons: spin-0

$\tilde{e}^-$ *selectron*	$\tilde{\mu}^-$ *smuon*	$\tilde{\tau}^-$ *stau*
$\tilde{\nu}_e$ *electron sneutrino*	$\tilde{\nu}_\mu$ *muon sneutrino*	$\tilde{\nu}_\tau$ *tau sneutrino*

Gauginos: spin-1/2 "-ino" → J=1/2 Higgsino: spin-1/2

Strong force	EM force	Weak force		
$\tilde{g}$	$\tilde{\gamma}$	$\tilde{Z}^0$	$\tilde{W}^+$	$\tilde{W}^-$
gluino (8)	*photino*	*Zino*	*Wino*	

$\tilde{H}$

Higgsino

Scalar SUSY particles and chiral multiplets

- The SM is a chiral theory: the L and R chiral projections of the fermion fields have different EW interaction quantum numbers.
  - L projections are $SU(2)_L$ doublets
  - R projections are $SU(2)_L$ singlets

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad u_R, \quad d_R$$

- Each chiral projection of a SM fermion has SUSY scalar partner (preserving degrees of freedom).

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

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

partner of the R-handed e^-; has J=0

SUSY spectrum in EW sector (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

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 →

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.

Gauginos = SUSY partners of SM gauge bosons
Higgsinos = SUSY partners of higgs bosons
Neutralinos = mix of neutral gauginos and higgsinos
Charginos = mix of charged gauginos and higgsinos
EWKinos = term that denotes neutralinos or charginos

The gluino ($\tilde{g}$) is special: because of color, it cannot mix with any other particles.

Why are we still looking for SUSY?

Hierarchy problem

~10^{18} GeV

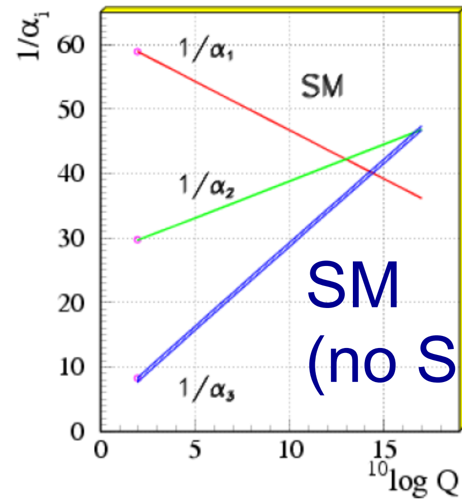
Planck scale
(quantum gravity)

Separation of scales
is stabilized by SUSY.

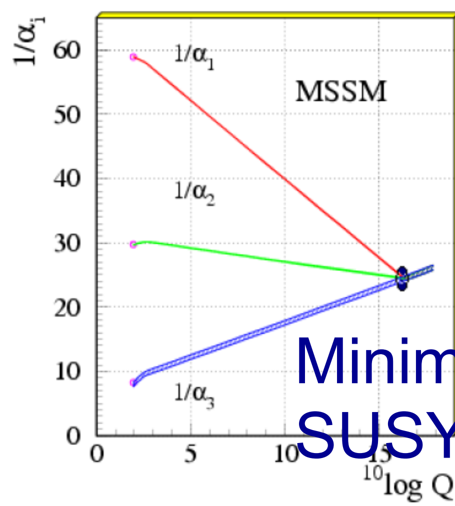
~10^{2} GeV

Electroweak scale
(unstable in SM)

Unification of couplings

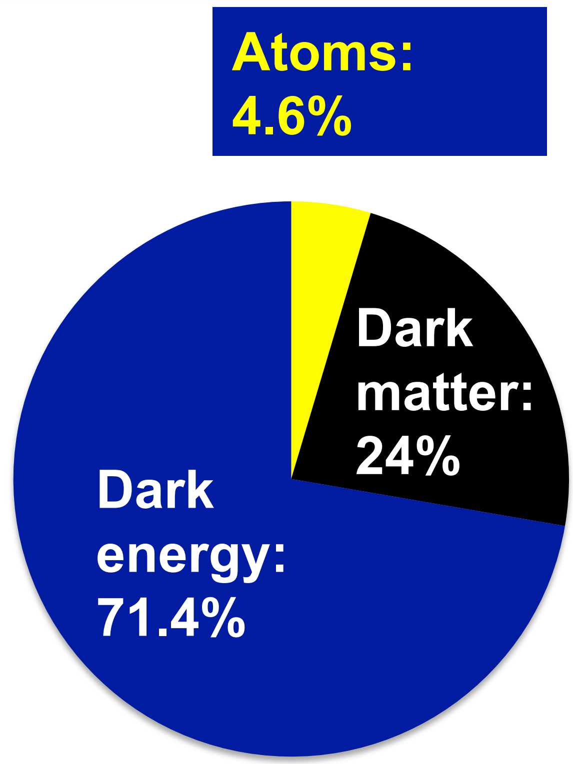


SM
(no SUSY)



Minimal
SUSY

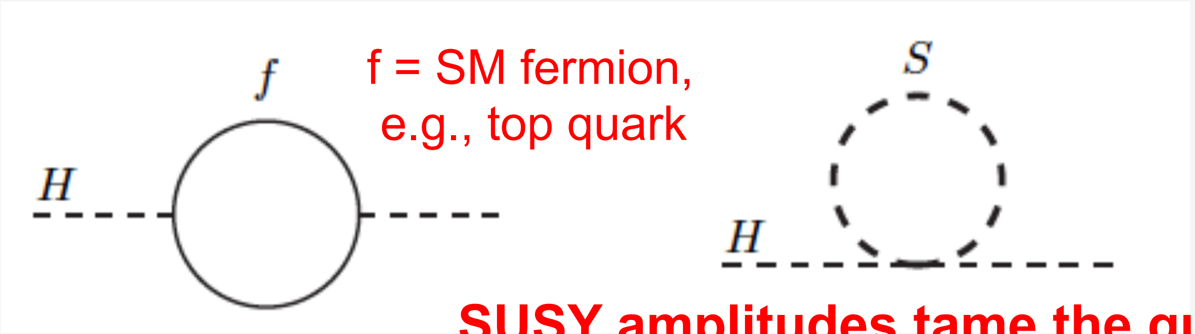
Dark matter



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

The Higgs and the Gauge Hierarchy Problem

- Evidence is very strong that the new particle discovered at m ≈ 125 GeV is a/the Higgs boson, with the quantum numbers $J^{PC} = 0^{++}$ (scalar).
- Assuming that it is an *elementary scalar* particle, the Higgs mass is subject to enormous shifts due to short distance quantum corrections.
- These corrections pull the Higgs mass up to a high physical scale, e.g., the Planck scale!



SUSY amplitudes tame the quantum corrections!

Scalar particles and fine tuning

- Fundamental scalar fields have the problem of quadratic divergences to the scalar mass squared. These arise from loop-corrections to the mass, which are generically for spin 0:

$$\delta m^2 = \lambda \int^{\Lambda} \frac{d^4 k}{(2\pi)^4} \frac{1}{k^2} \sim \frac{\lambda}{16\pi^2} \int^{\Lambda} dk^2$$

$$m^2 = m_0^2 + \alpha\lambda \frac{\Lambda^2}{16\pi^2}$$

dominant at low m_t

$$\lambda \sim m_h^2 / v^2$$

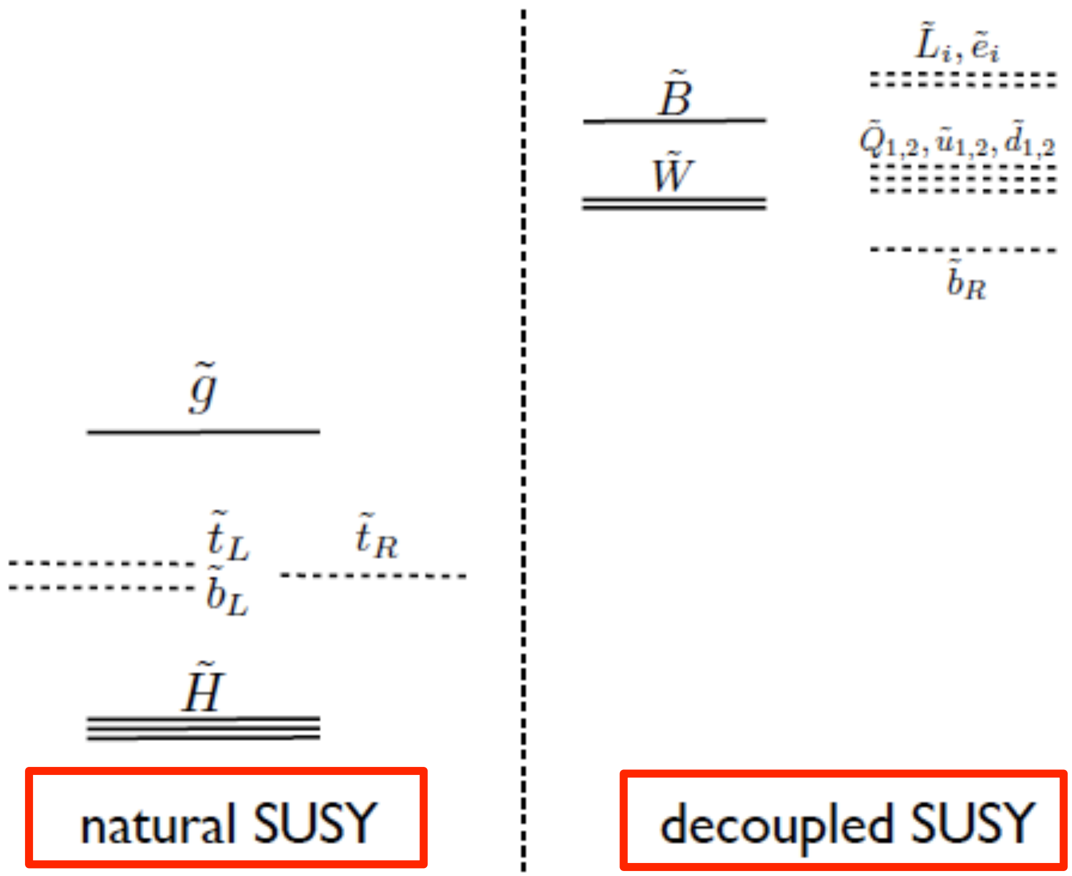
In the Standard Model:

$$\delta m_h^2 = \frac{3\Lambda^2}{8\pi^2 v^2} \left[\left(4m_t^2 - 2M_W^2 - M_Z^2 - m_h^2 \right) + O\left(\log \frac{\Lambda}{\mu} \right) \right]$$

“Natural SUSY endures”: the current fashion

Only part of the SUSY spectrum an be constrained by naturalness considerations.

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



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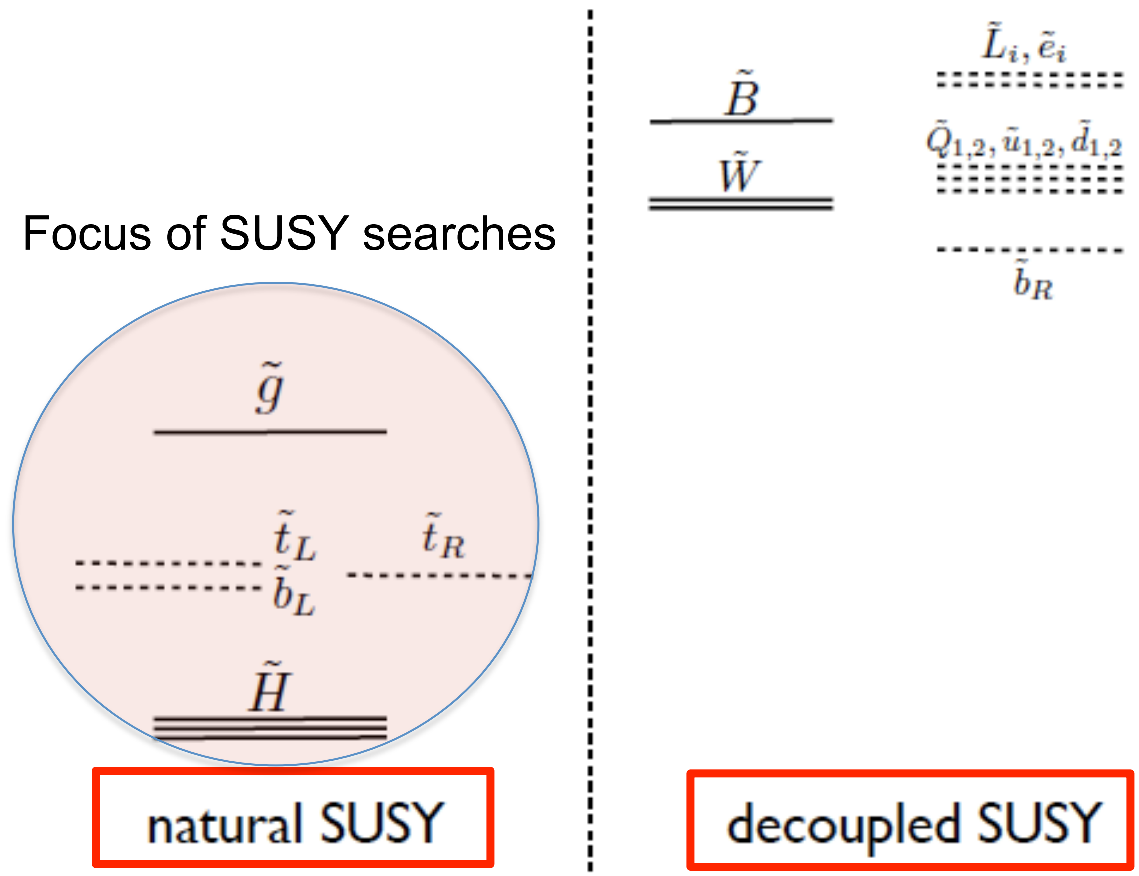
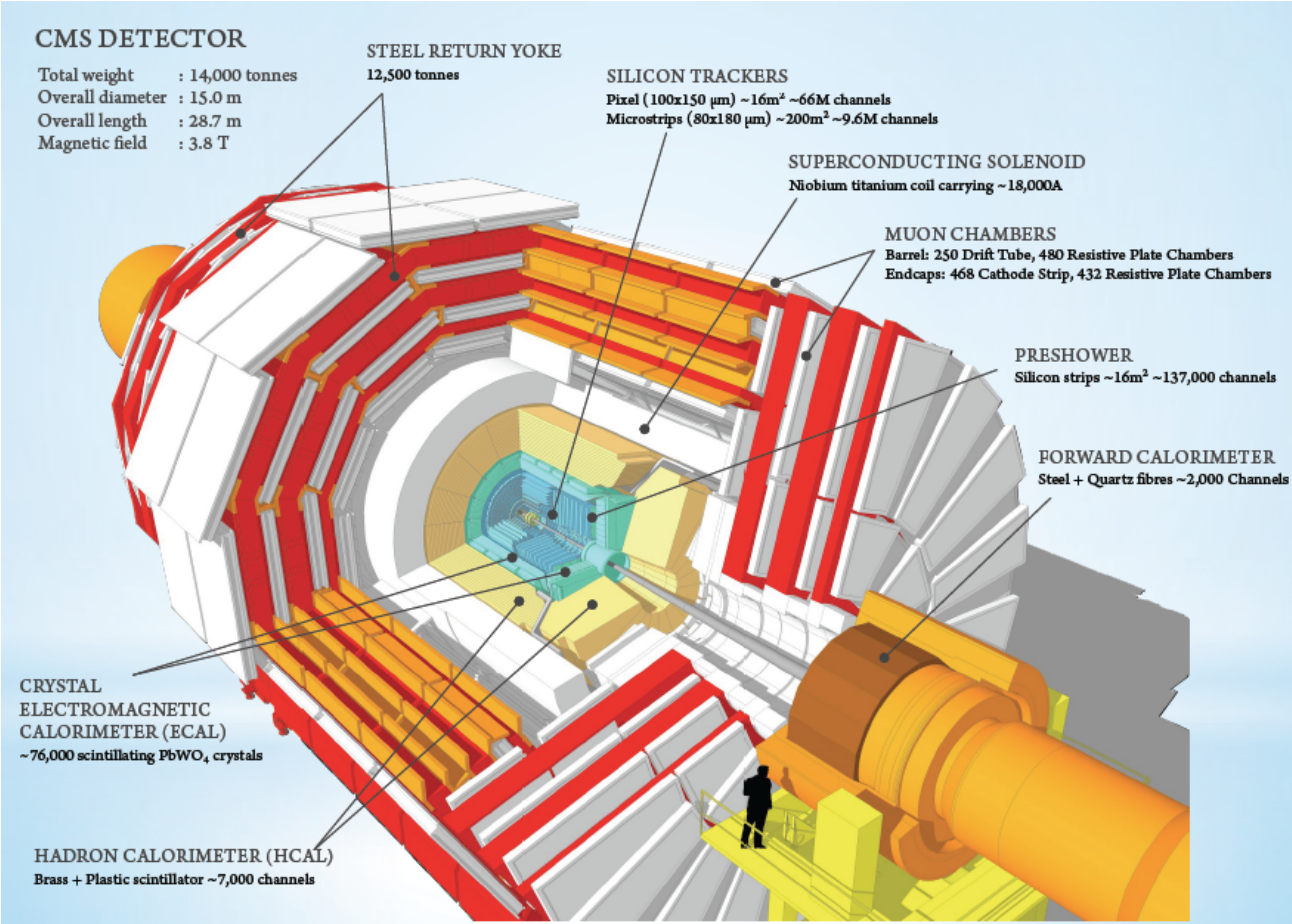


SUSY breaking

- SUSY, if it exists, is clearly a broken symmetry because partners with masses equal to the SM particles would already have been found.
- SUSY breaking is an complex subject with various scenarios; occurs in "hidden sector"; transmitted to MSSM particles via...
  - gravity mediation→ heavy gravitino ($\tilde{G}$), couplings ≈gravity
  - gauge mediation→ very light gravitino (eV range); is LSP!
- Whatever the breaking mechanism, SUSY particles still have the same SM gauge couplings as their ordinary SM partners. <u>Key point when thinking about decay modes. Your intuition for the SUSY Particle Date Book is good!</u>

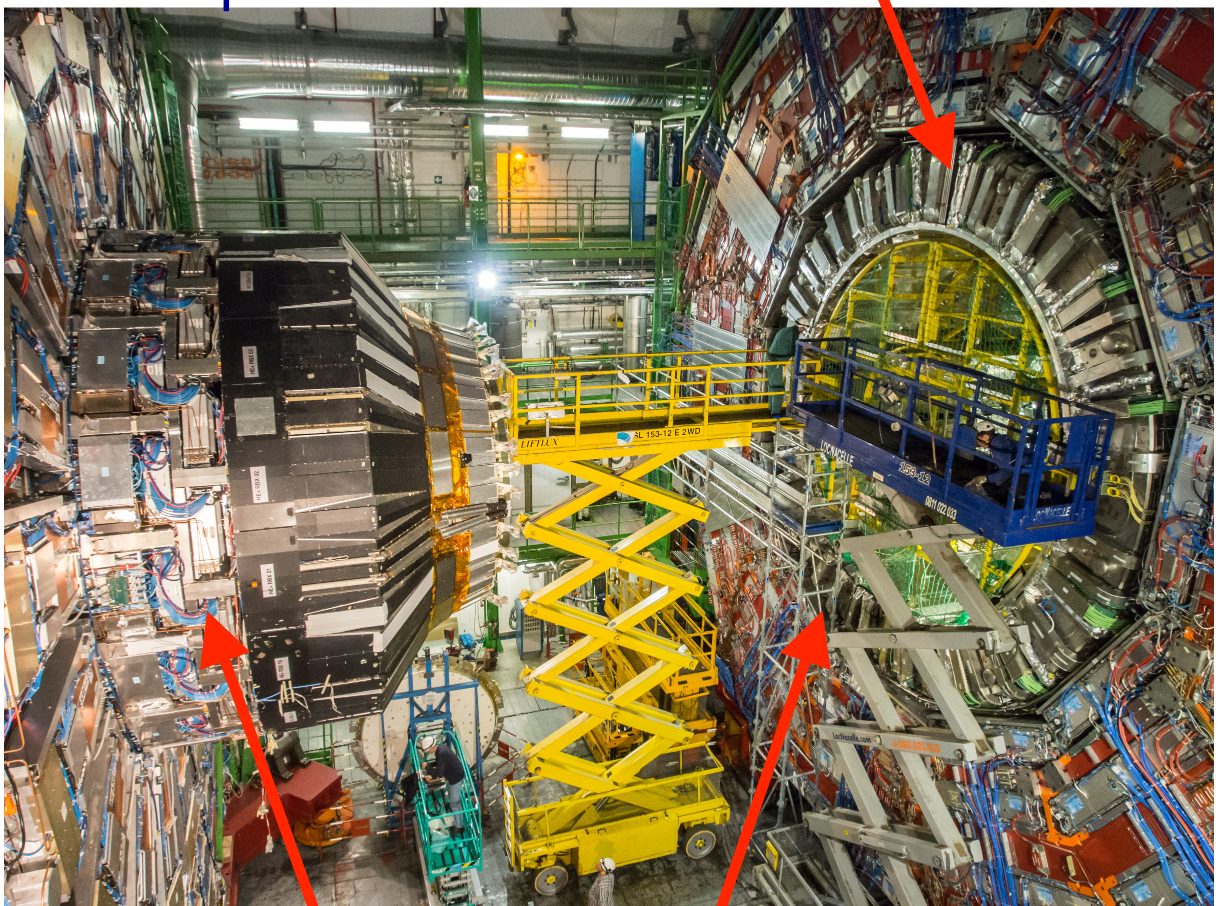


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~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 $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

Installing muon readout electronics

Superconducting solenoid:
B-field parallel to beam axis

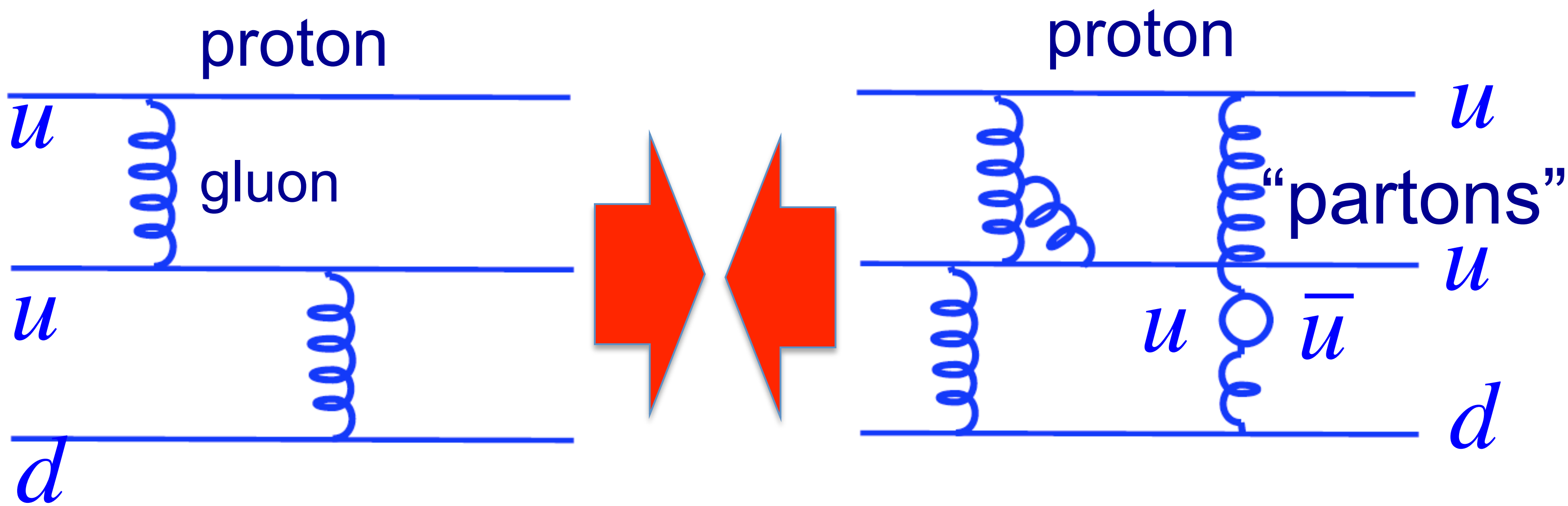
Spring – summer 2014



Endcap detectors

Central barrel detectors

Proton-proton collisions



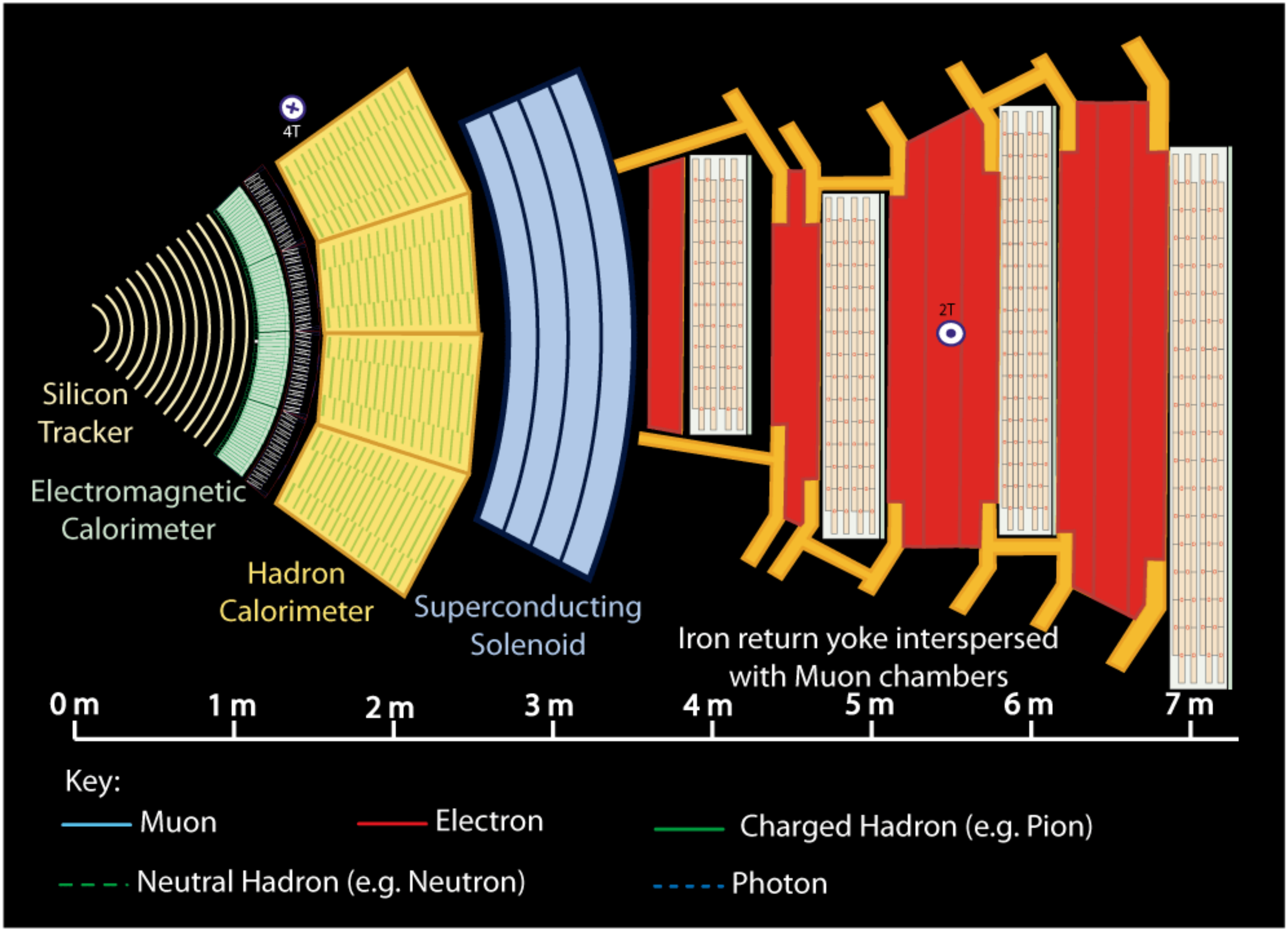
- Parton momentum transverse to the beam is negligible.
- Parton momentum along the beam direction (z) is large and unknown, except on a statistical basis.

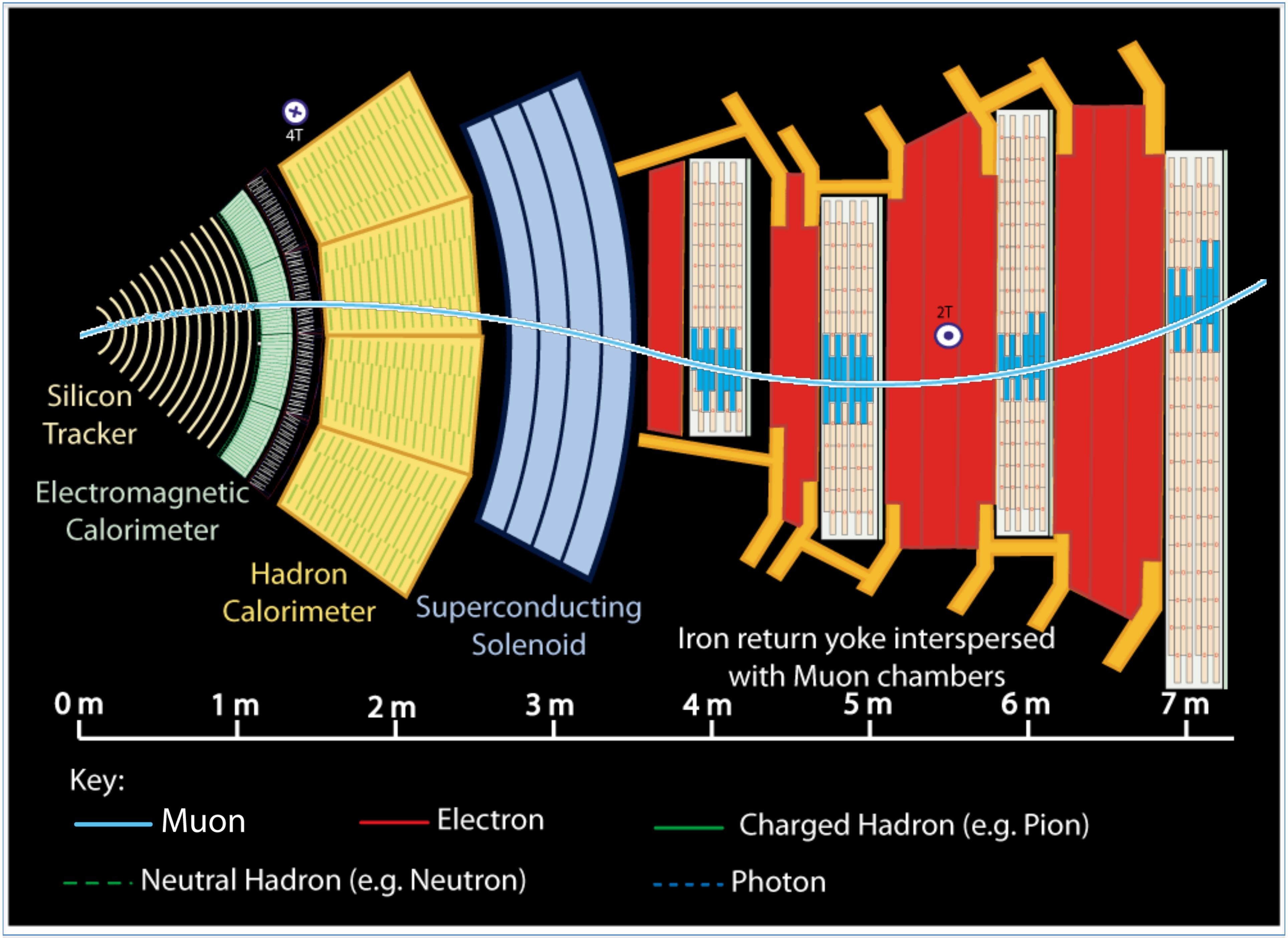
$$\sum_{i=colliding\ partons} p_x^i \simeq 0$$

$$\sum_{i=colliding\ partons} p_y^i \simeq 0$$

momentum transverse to beam is zero

$$\sum_{i=colliding\ partons} p_z^i \neq 0$$


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon



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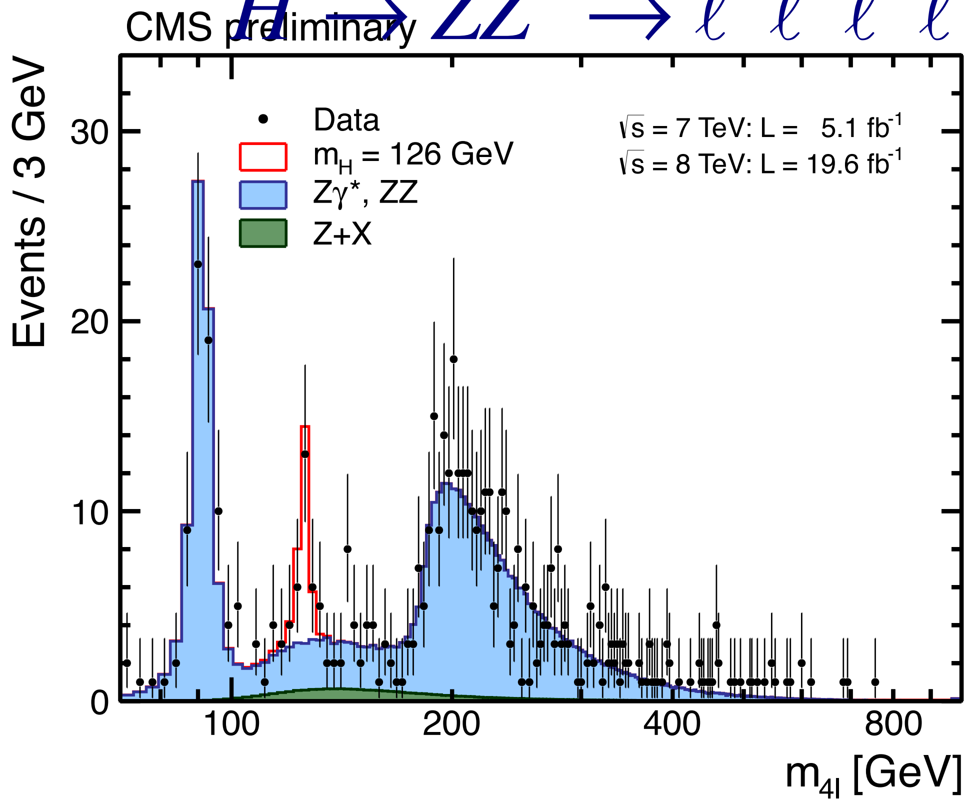
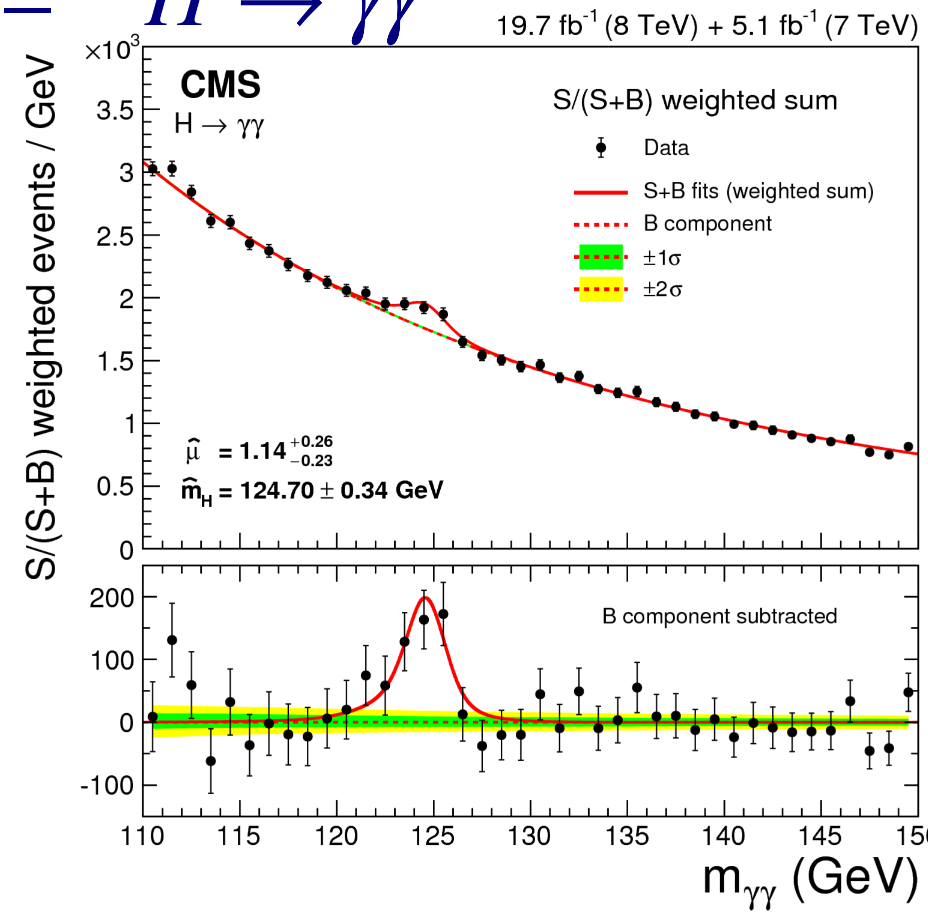
Higgs boson mass peaks

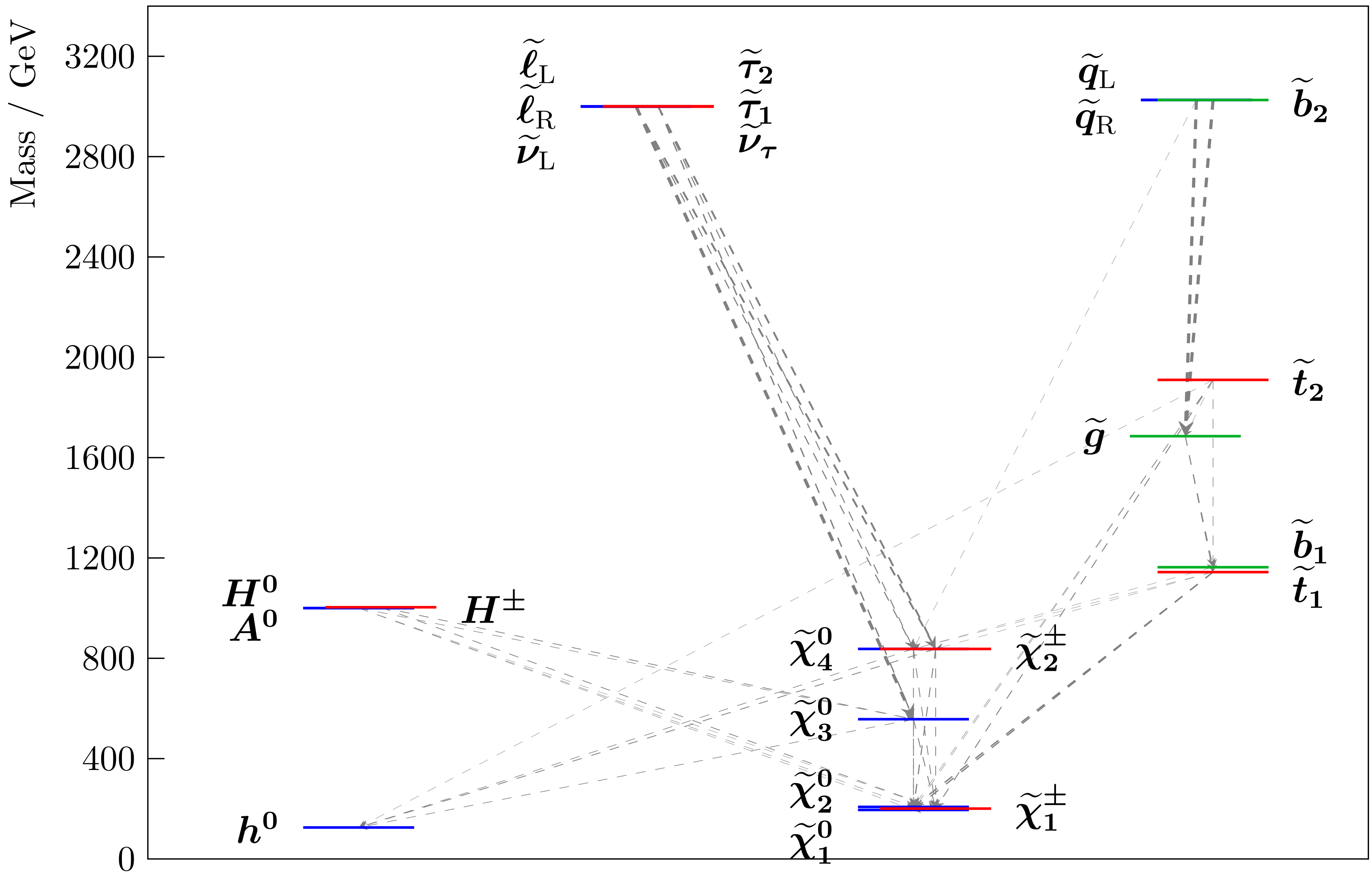
$H \to ZZ^* \to \ell^+\ell^-\ell^+\ell-$ $\quad$ $H \to \gamma\gamma$





- Discovery was based on searches for narrow peaks at a consistent mass in multiple search channels.
- The determination of the event yield is greatly simplified.
- The masses are Lorentz-invariant quantities. Any reference frame is OK!

An example of a "natural" SUSY model ("NM3")



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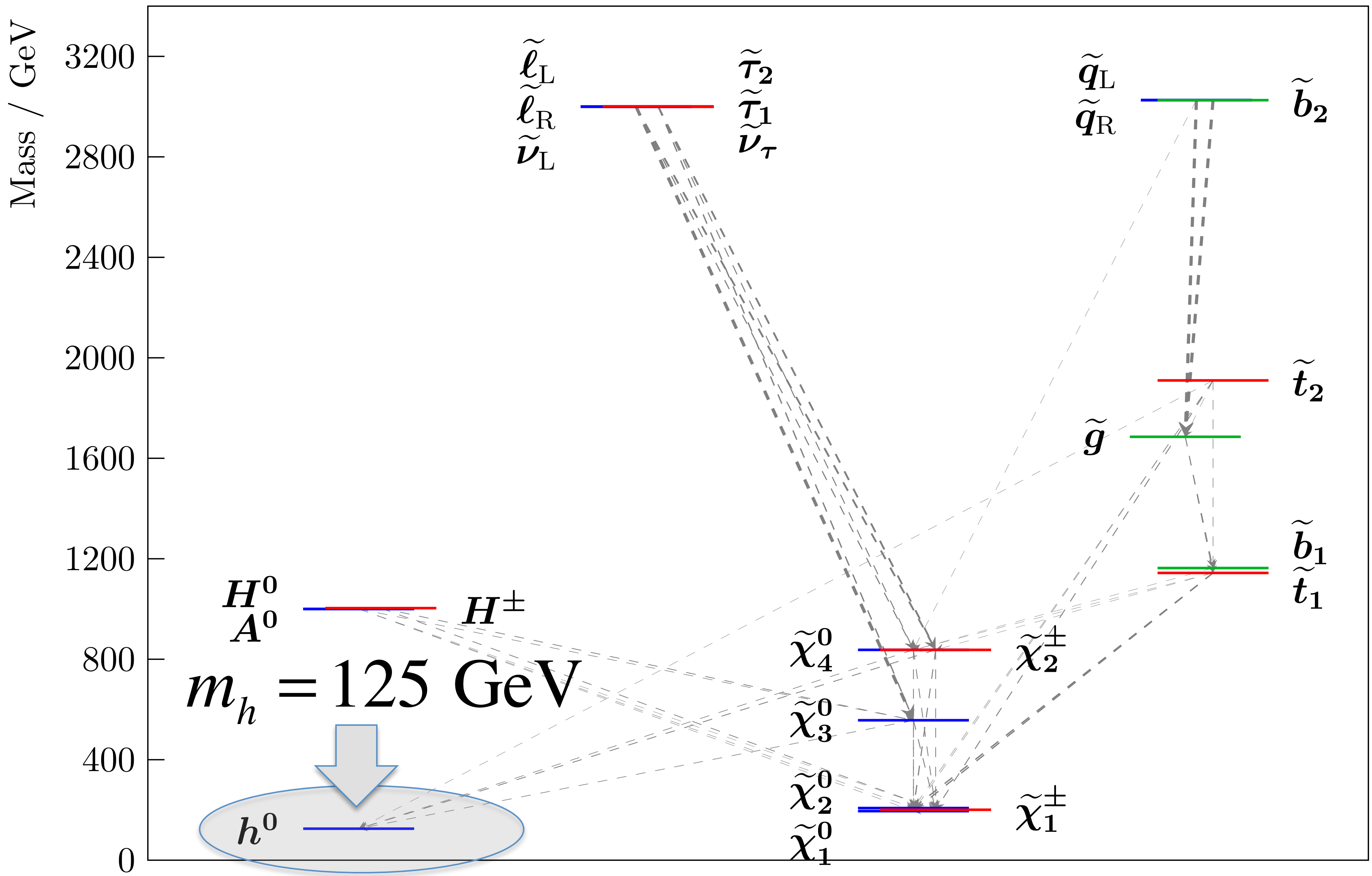

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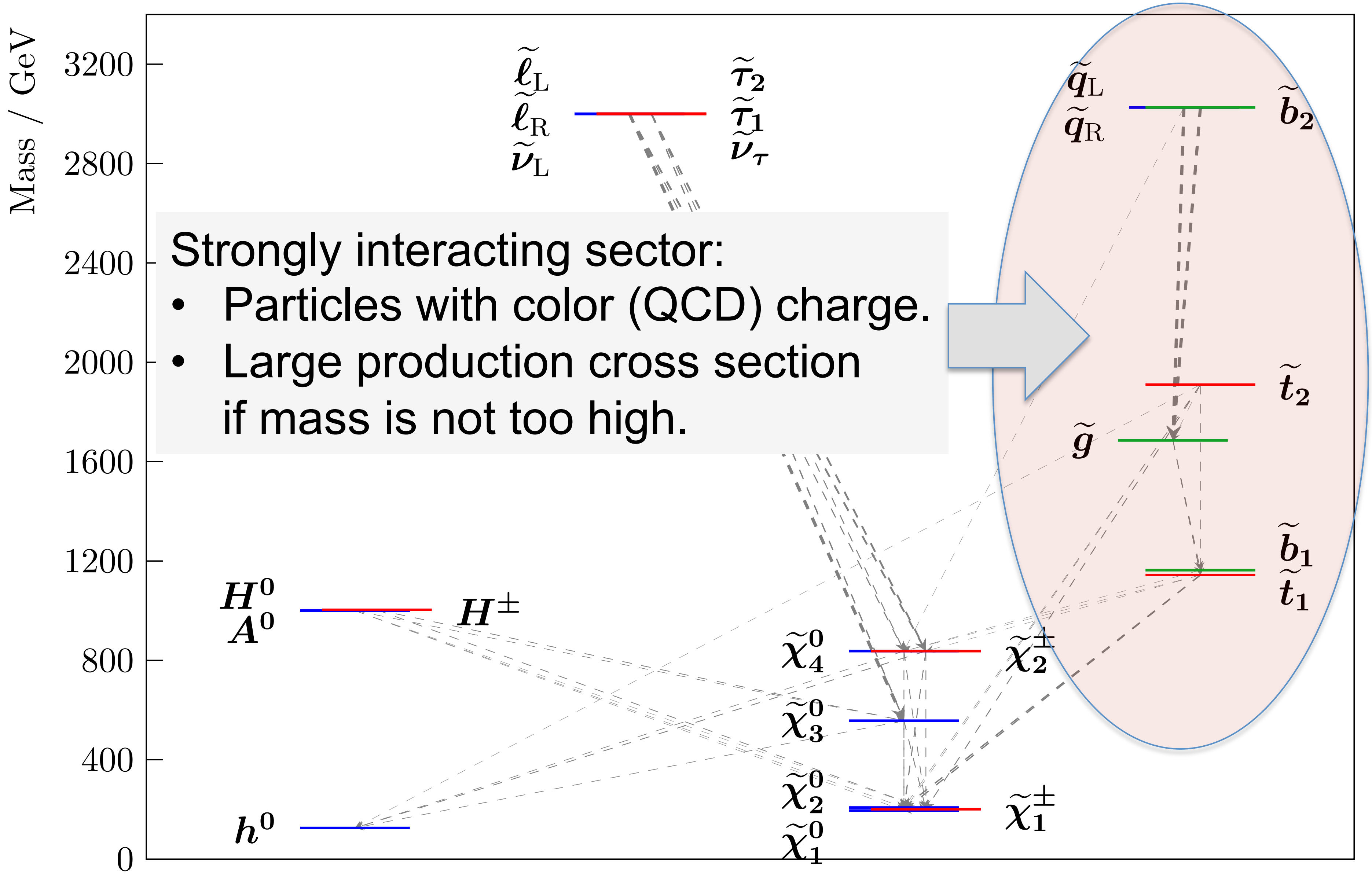
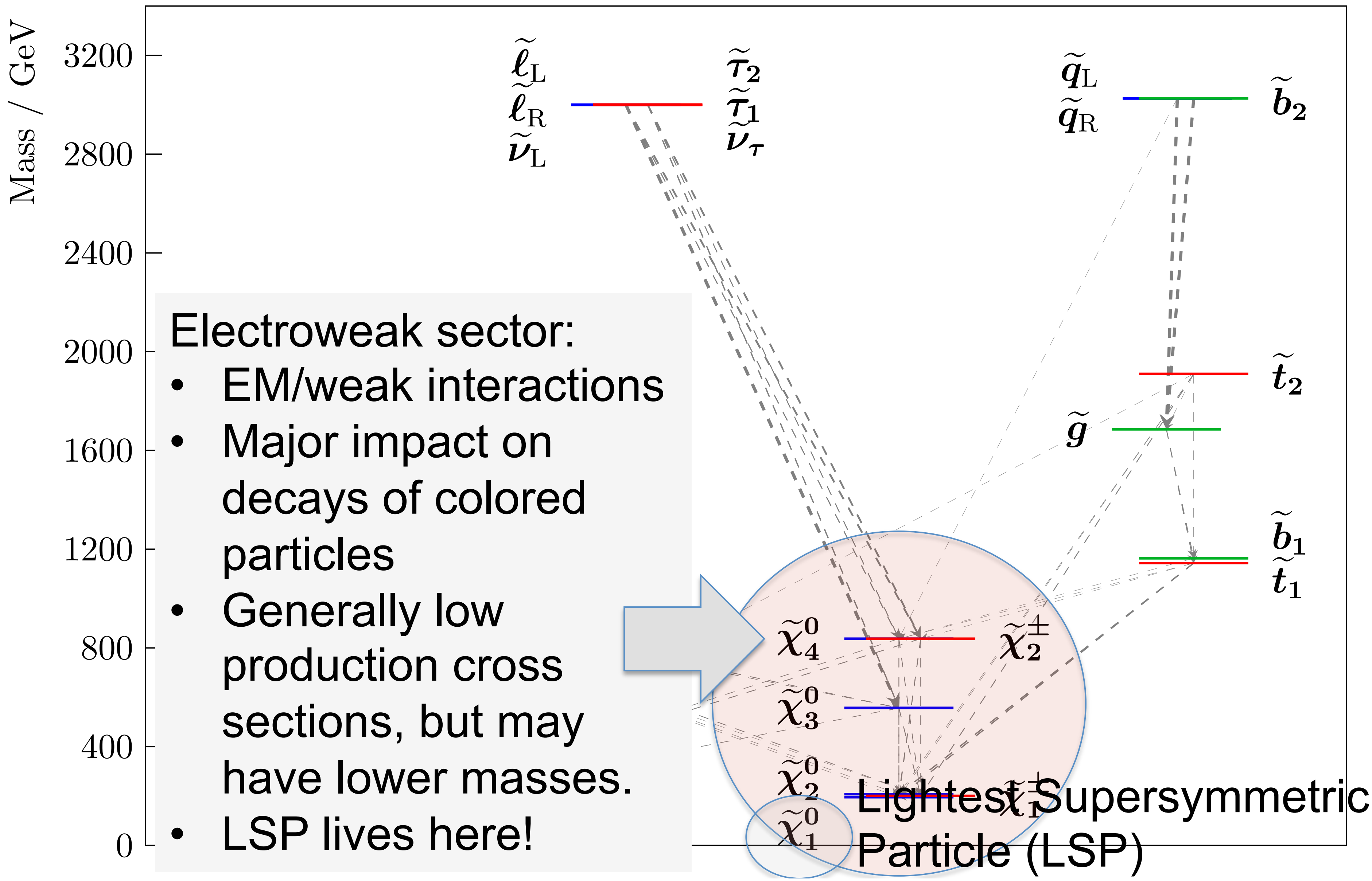


Strongly interacting sector:

- Particles with color (QCD) charge.
- Large production cross section if mass is not too high.

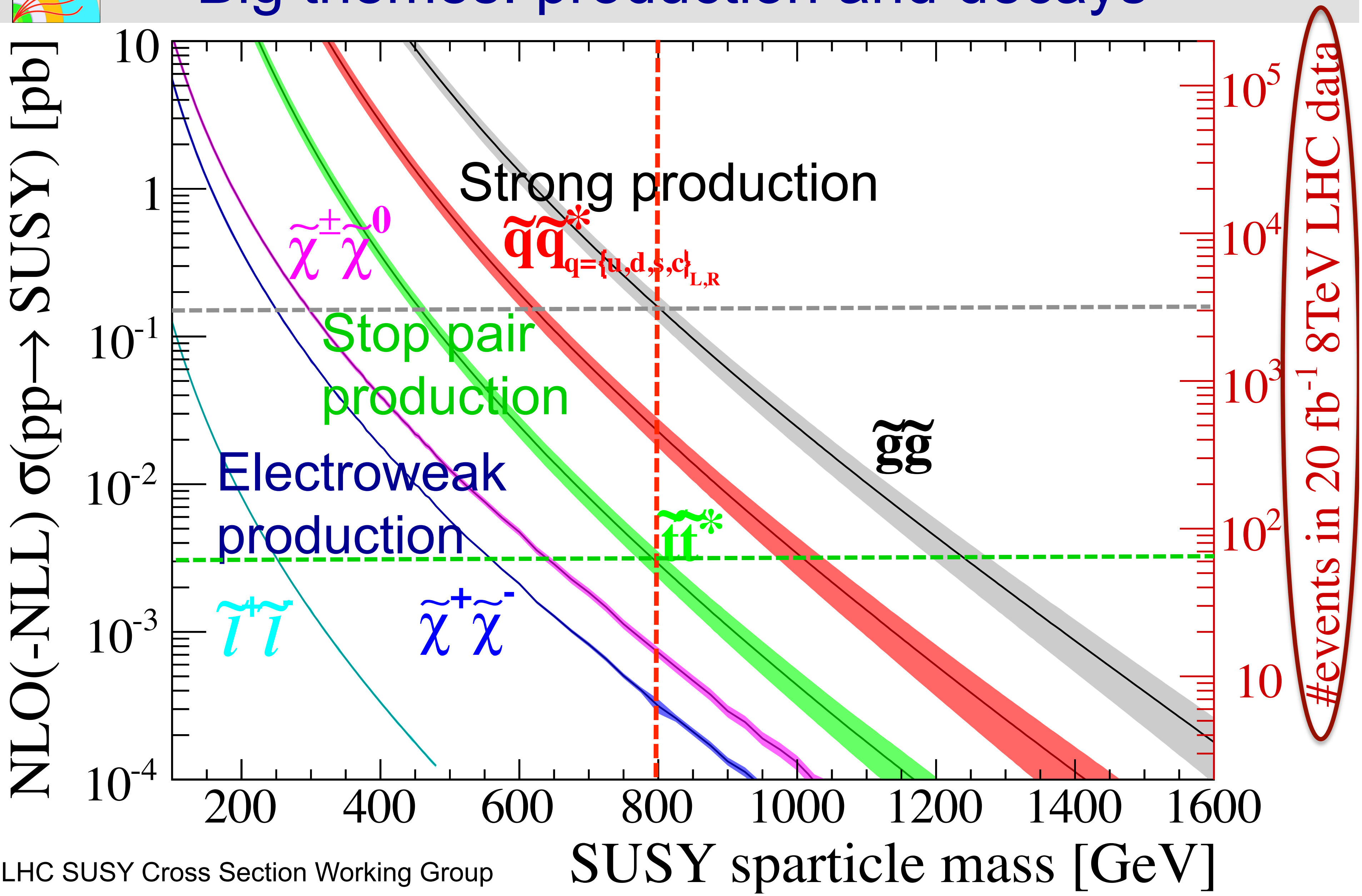
An example of a "natural" SUSY model ("NM3")



Electroweak sector:

- EM/weak interactions
- Major impact on decays of colored particles
- Generally low production cross sections, but may have lower masses.
- LSP lives here!

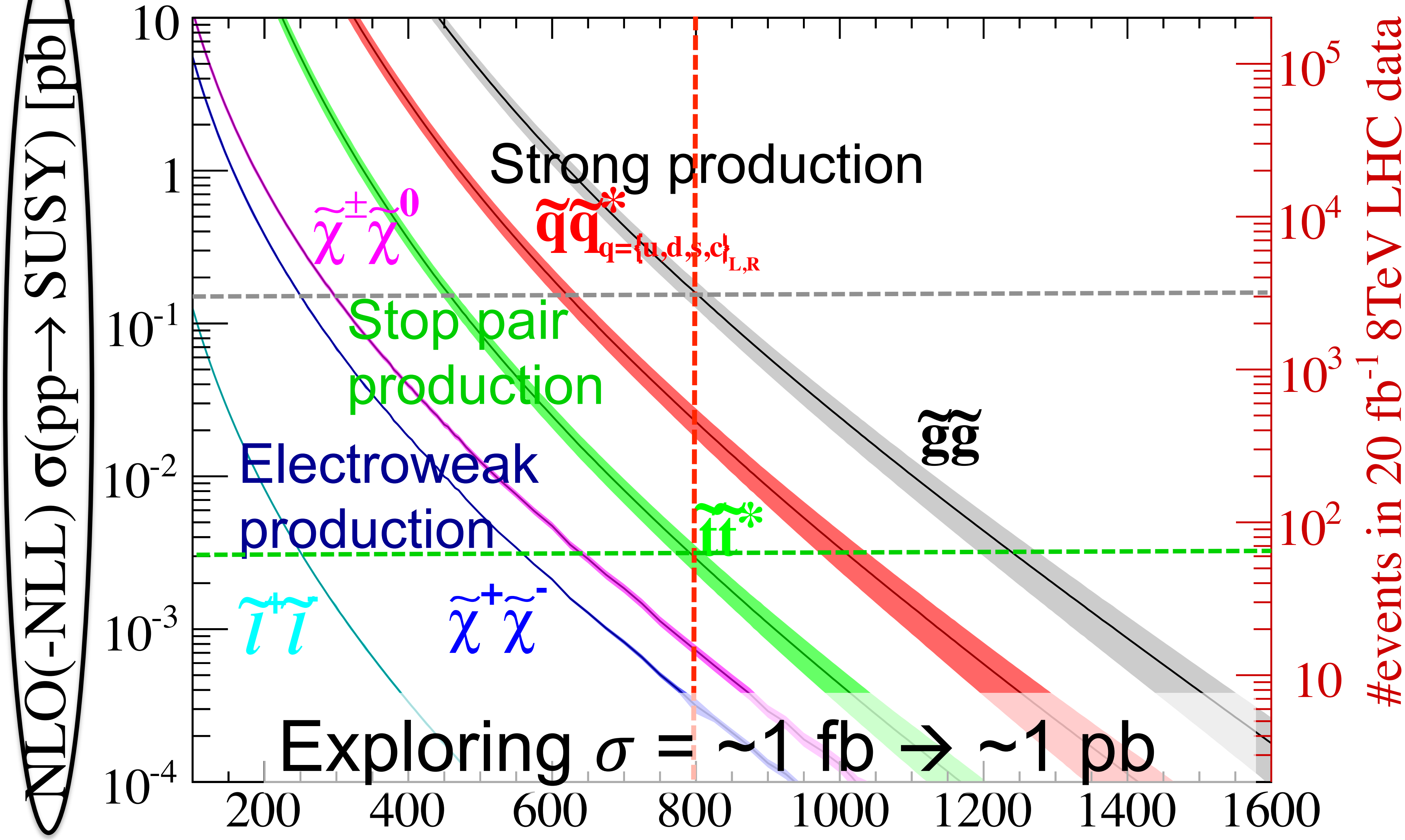
Big themes: production and decays



LHC SUSY Cross Section Working Group

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

Big themes: production and decays

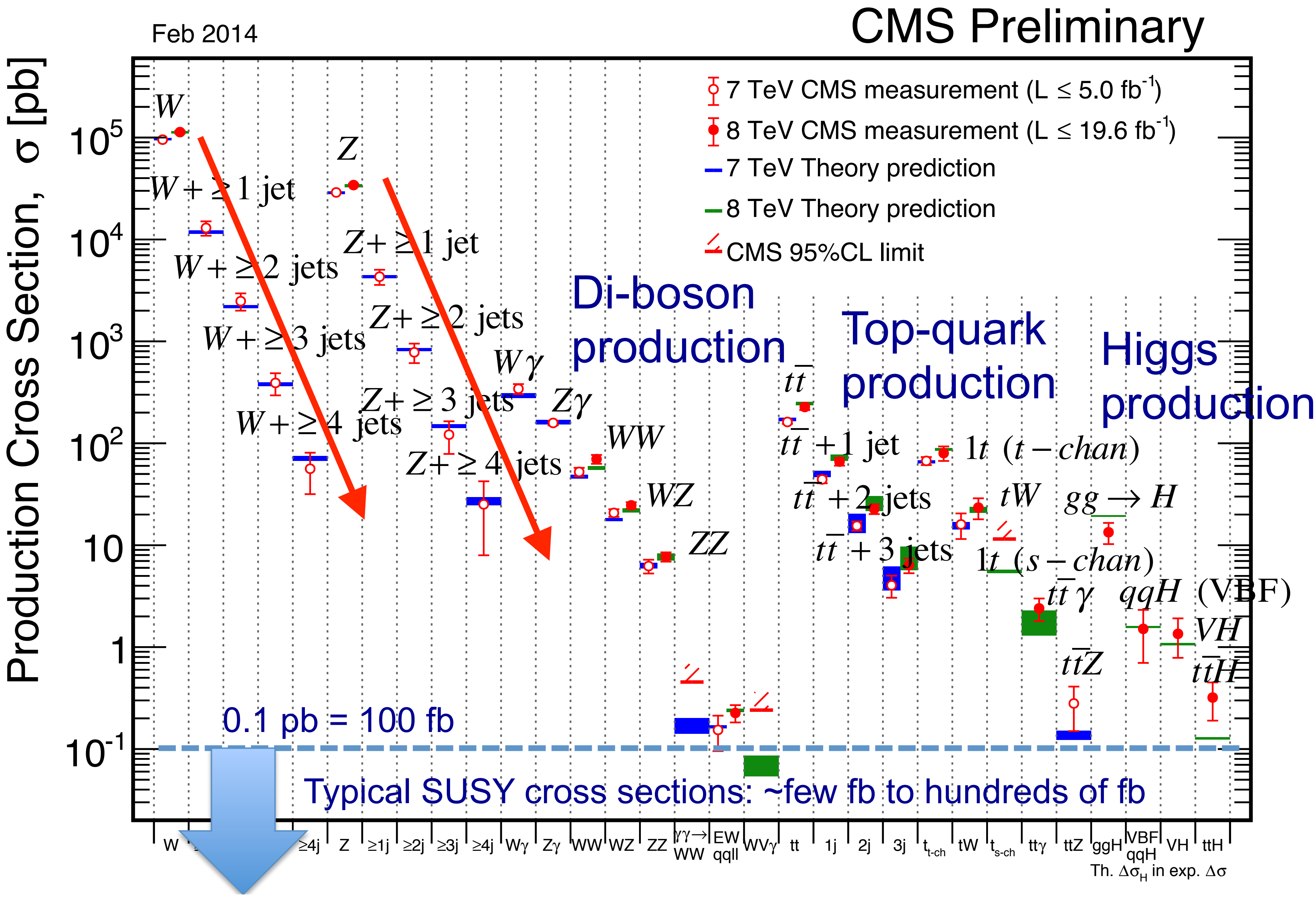


LHC SUSY Cross Section Working Group

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

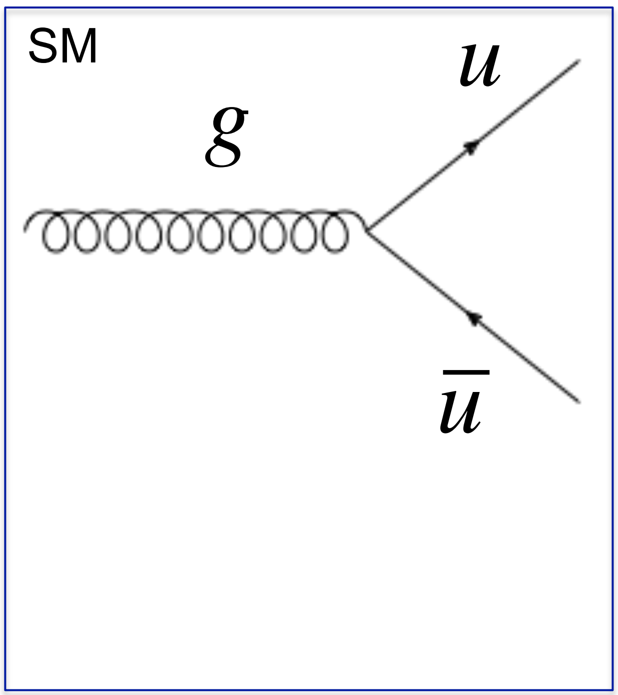
arXiv:1206.2892

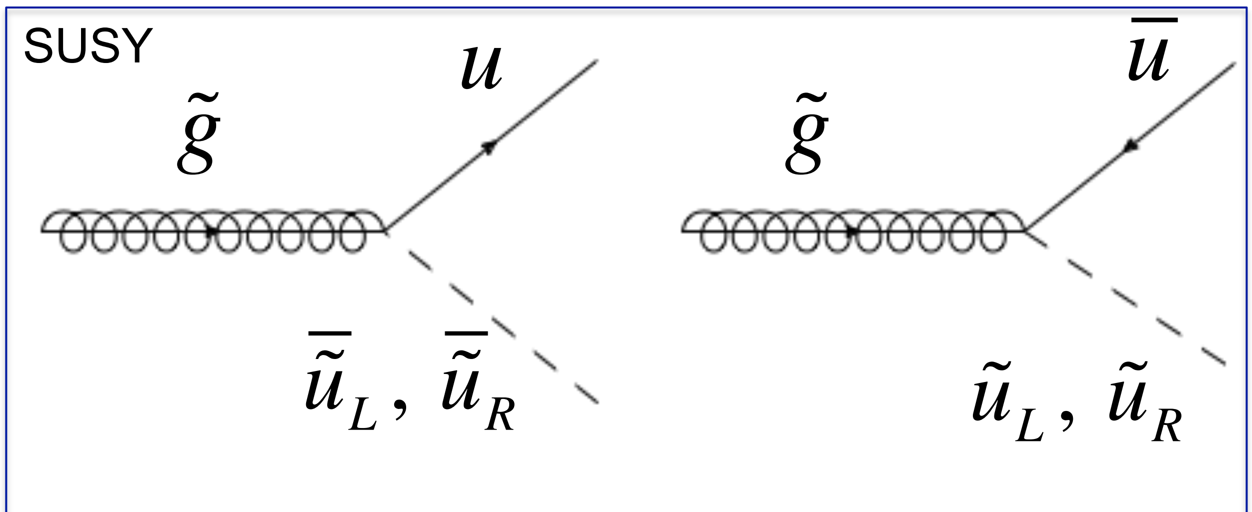
Measurements of SM processes in CMS



Gluino decay

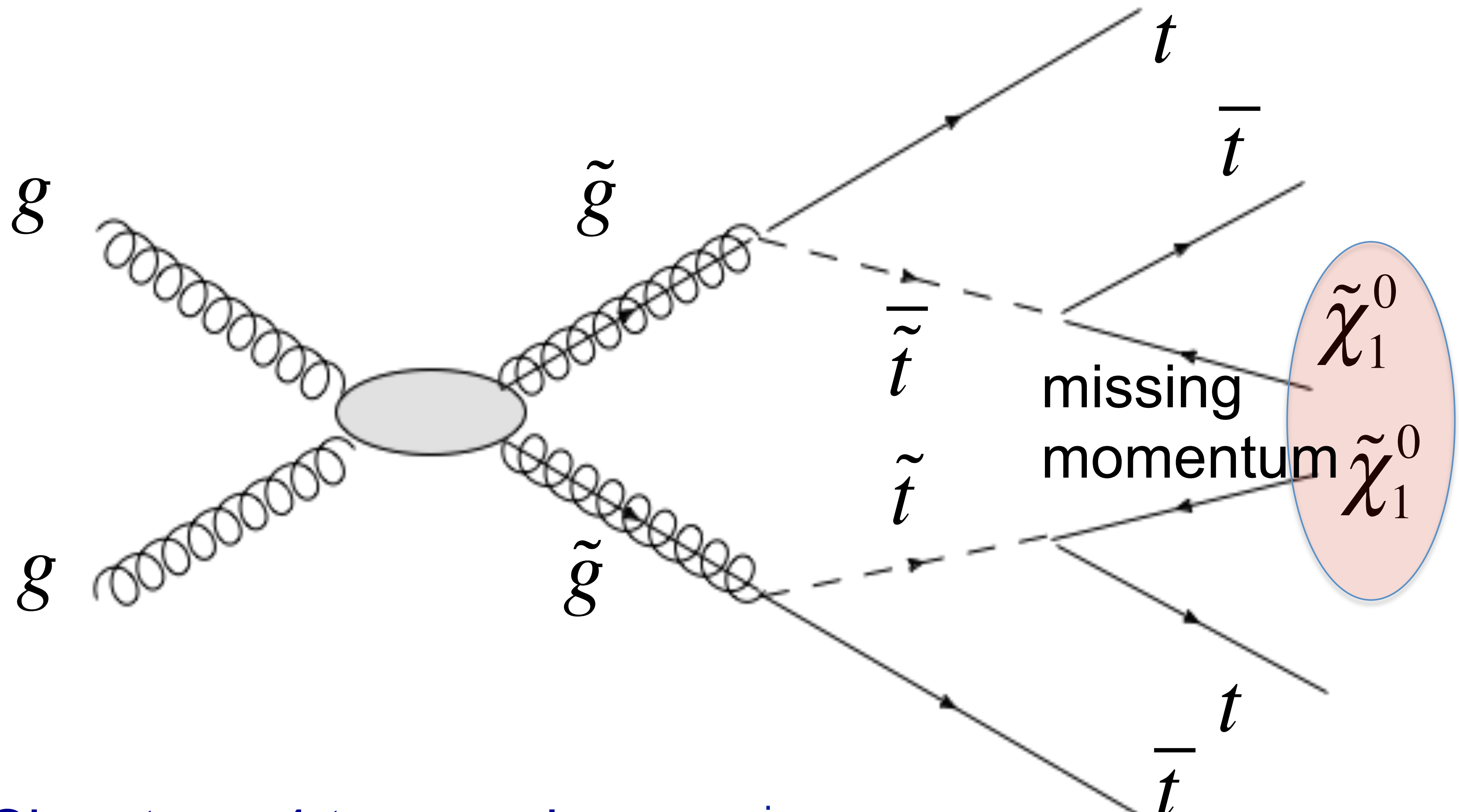
- SUSY preserves the gauge symmetries, so the SUSY partners of the gluons must also transform according to the 8-dimensional representation of $SU(3)_C$.
- Fundamental vertex for $g \to \tilde{q}_{L,R} + \bar{q}$ has same coupling strength as that for $g \to q + \bar{q}$.





$$\tilde{g} \to u + \bar{\tilde{u}}_L ,\ \bar{u} + \tilde{u}_L ,\ u + \bar{\tilde{u}}_R ,\ \bar{u} + \tilde{u}_R$$

Gluino pair production and decay to stop

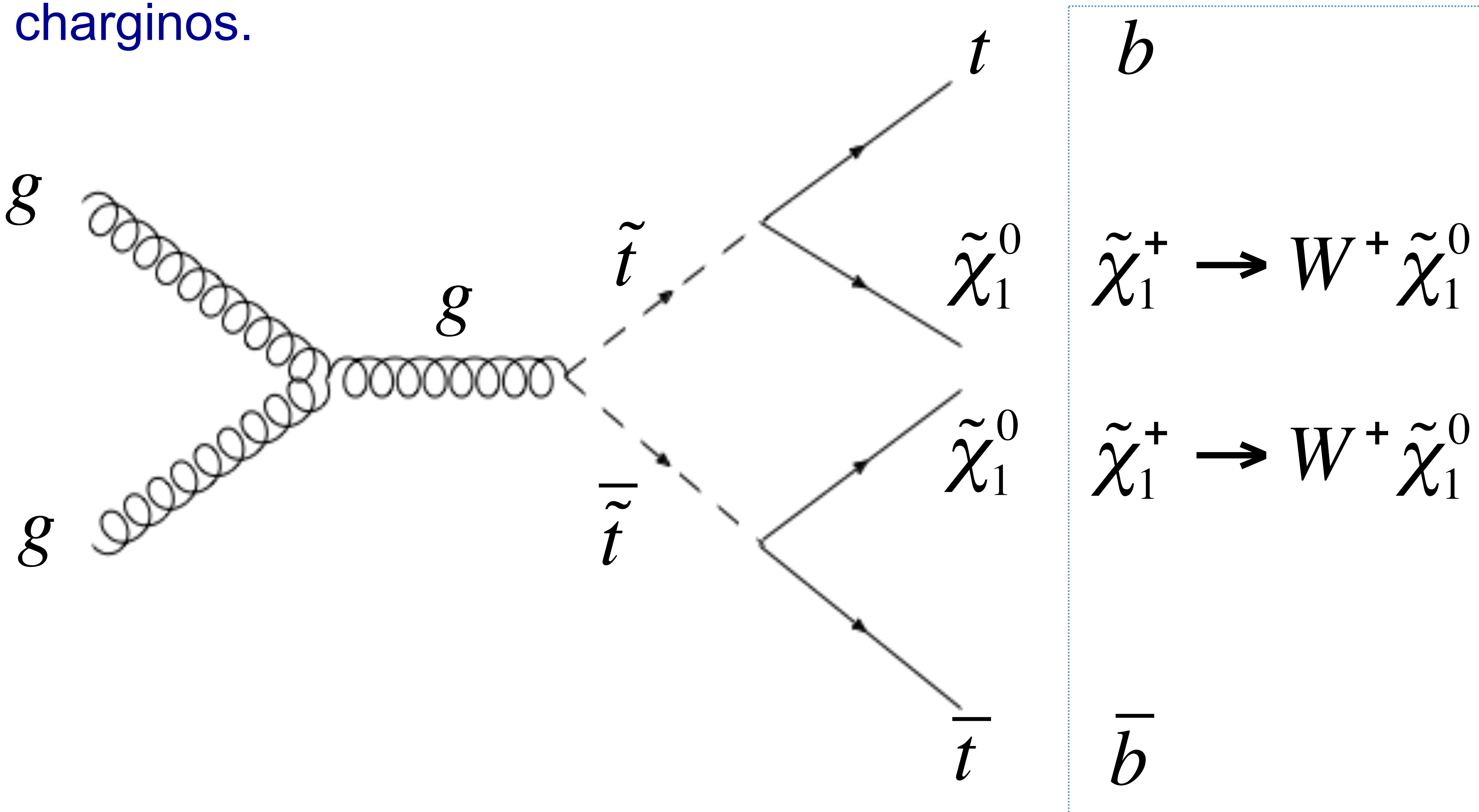


Signature: 4 top quarks + p_T^{miss}

LSPs are unobserved: cannot reconstruct mass peaks!

Direct pair production of top squarks

Example: direct stop production with decay to neutralinos or charginos.

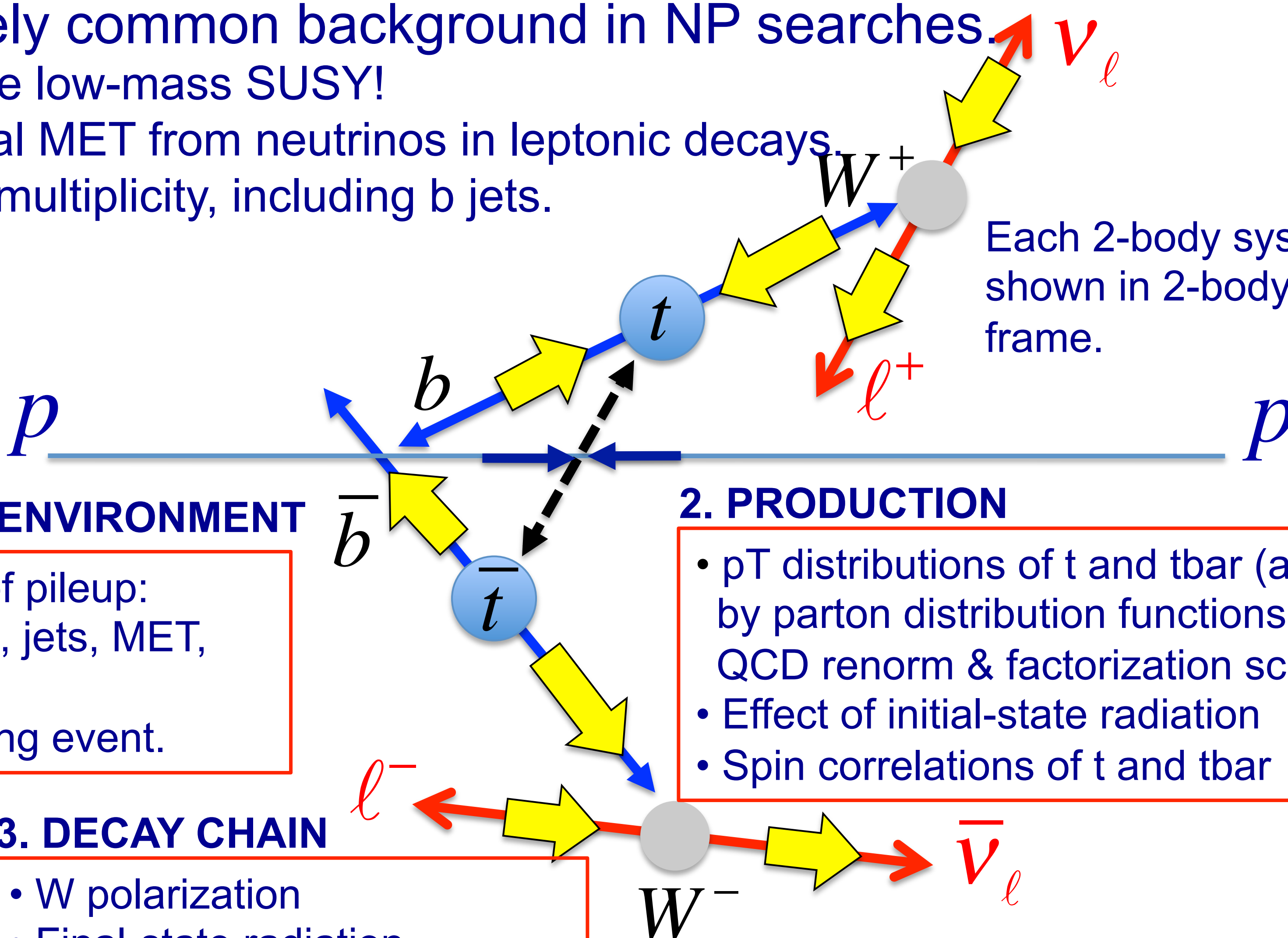


Sensitivity of the searches will depend strongly on the neutralino mass.
The channel with $\tilde{t} \rightarrow b\tilde{\chi}_1^+$ has sensitivity to lower stop mass.

Anatomy of a background: ttbar

Extremely common background in NP searches.

- looks like low-mass SUSY!
- large real MET from neutrinos in leptonic decays.
- high jet multiplicity, including b jets.



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

1. EVENT ENVIRONMENT

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

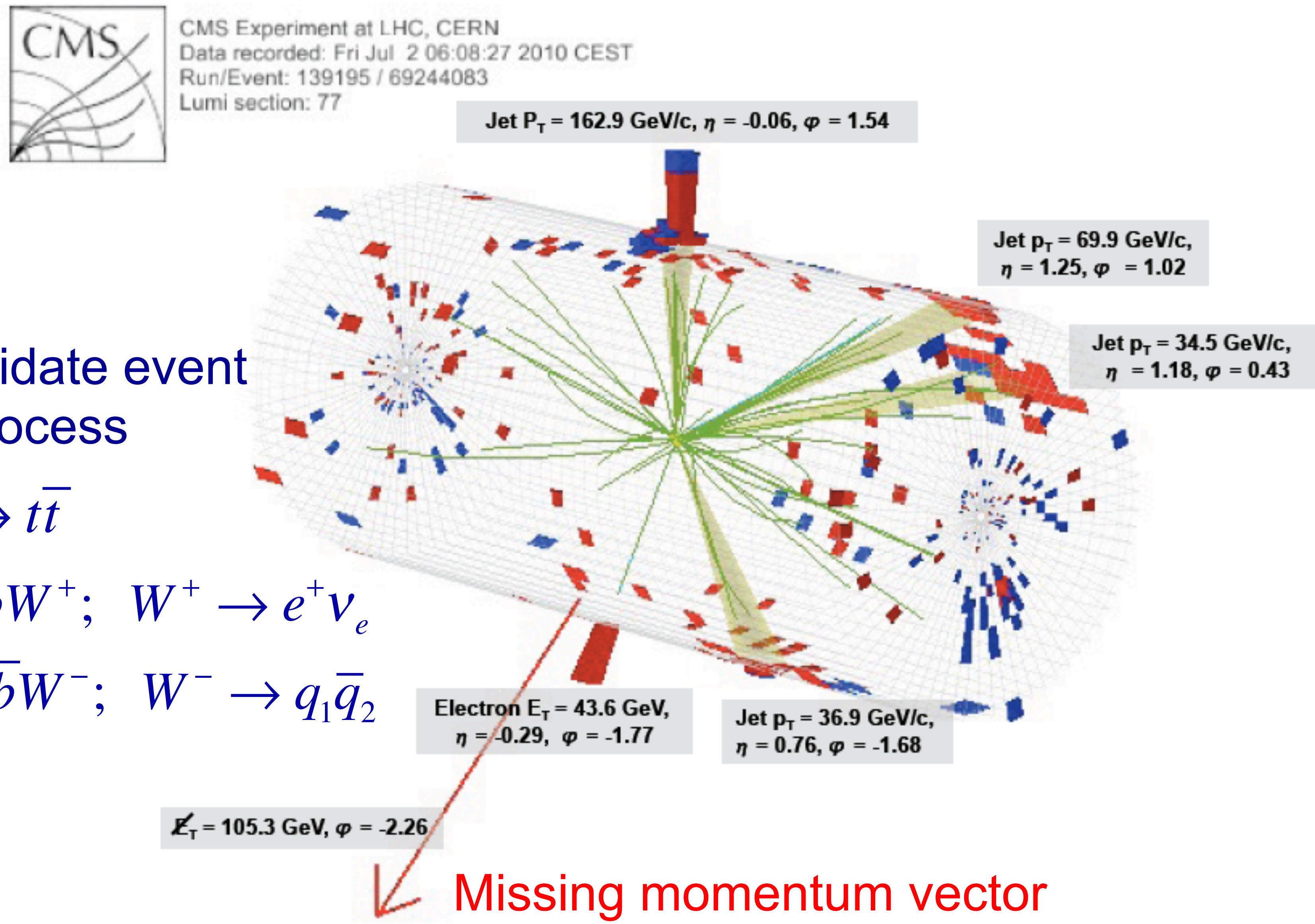
2. PRODUCTION

- 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

Most "SUSY-like" process in SM: $pp \rightarrow t\bar{t}$



Candidate event for process

$$pp \rightarrow t\bar{t}$$

$$t \rightarrow bW^+; \quad W^+ \rightarrow e^+\nu_e$$

$$\bar{t} \rightarrow \bar{b}W^-; \quad W^- \rightarrow q_1\bar{q}_2$$

Missing momentum vector from neutrino

Data analysis for SUSY searches

SIGNAL: Characterize kinematic distributions using simulated (MC) samples.

BACKGROUND: Characterize kinematic distributions using simulated (MC) samples; validate simulation using control samples in data.

DEFINE SIGNAL REGIONS (without looking at this neighborhood of the event sample).
Use SIGNAL MC to determine SELECTION EFFICIENCY

PREDICT BACKGROUND contribution in SIGNAL regions, ideally using CONTROL REGIONS. Extrapolation factors from MC, with uncertainties determined from agreement in other control regions.

What could possibly go wrong?

SUSY Search Challenges

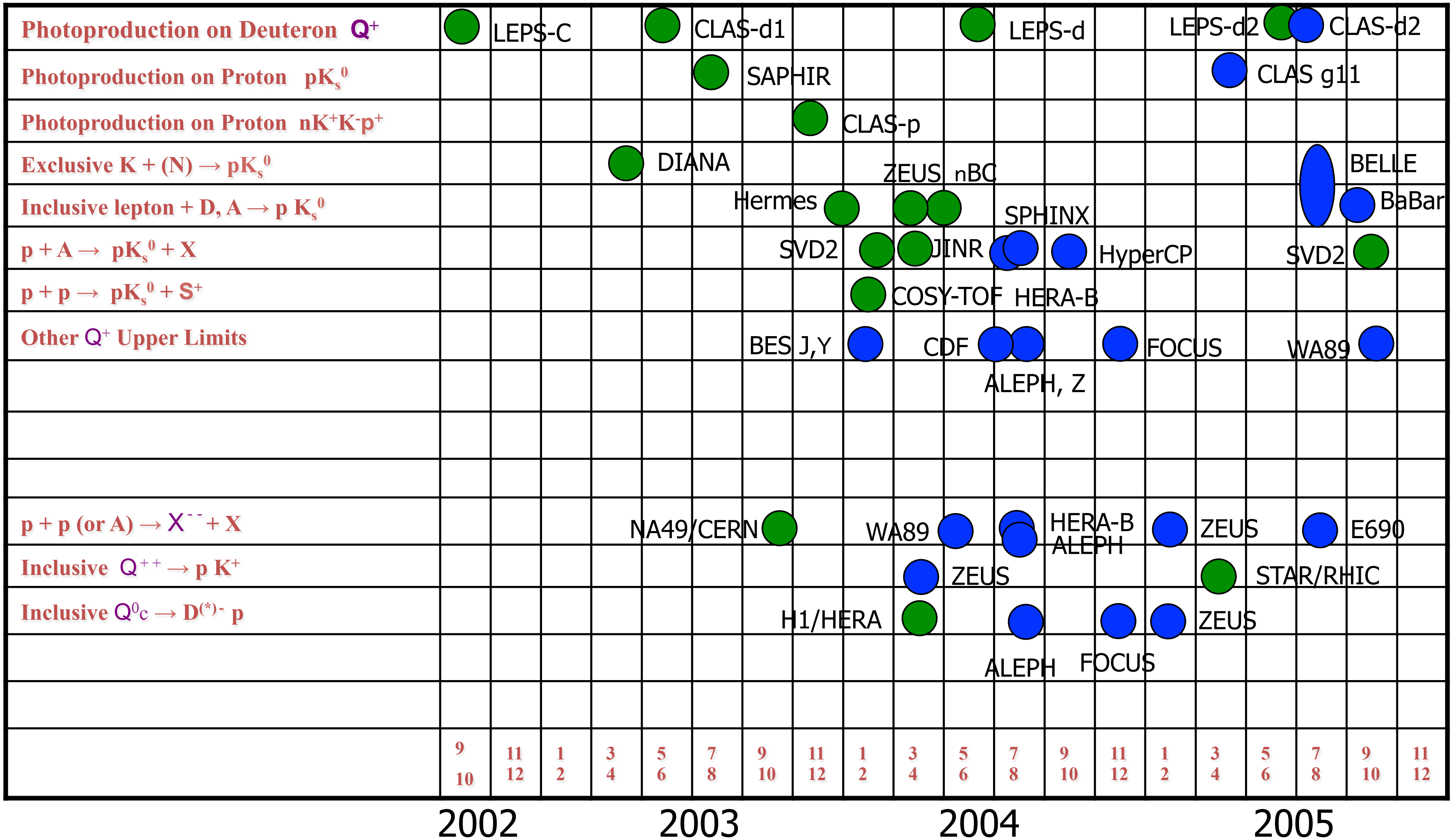
1. Presence of LSP in each SUSY decay chain (R-parity conserving models)→ no observable mass peak for parent particle.
2. Looking for excess yields in the tails of distributions of kinematic variables, such as missing transverse momentum.
3. The background determination is much more complicated, since one cannot simply use mass sidebands.
4. Many potential problems. Robust and complementary approaches to background determinations are extremely valuable.

What can possibly go wrong?

- Yield in signal region can be biased by tuning selection cuts on the data.
- People often stop looking for mistakes when they obtain a “desirable” result.
- Background shape or normalization can be estimated incorrectly.
- Understanding the background in one kinematic region does not necessarily mean that you understand it in another region.
- Shapes used in fit may not adequate to describe the data. (Especially worrisome in multidimensional fits!)
- Trigger efficiencies may not be acccounted for & can bias sig. or backgrounds.
- Systematic errors may be underestimated or incomplete. Assumptions may be wrong!
- Correlations may not taken into account.
- Backgrounds peaking under signal may not correctly determined.
- Signal significance may not be estimated correctly.
- Signal can created artificially as “reflection” of another peaking process.
- Changes in experimental conditions may not fully taken into account.
- Average of many bad measurements might not give a good measurement.
- Bugs in the program!
- Advisor in a hurry. Need to finish thesis! No time to look for more problems.
- A superposition of several of the above effects!

The penta-quark phenomenon: 2002-2005

Slide courtesy of R. Schumacher

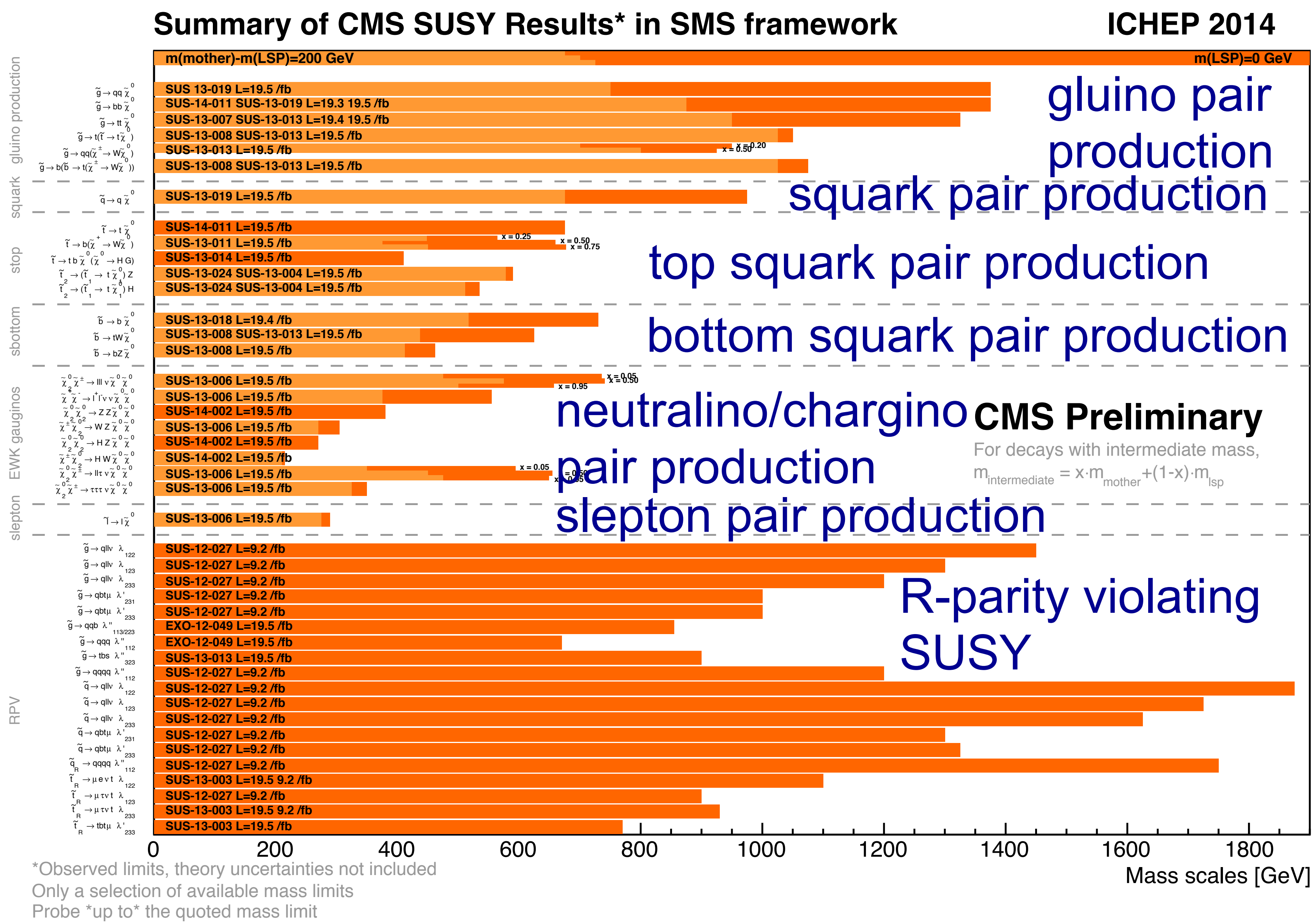


From Particles and Nuclei International Conference, Santa Fe, 2005

SUSY Search Strategies

1. Large missing momentum transverse to the beam axis.
2. High mass scales (but difficult to isolate decay products of a specific SUSY parent particle)
3. Long decay chains → large number of jets and isolated leptons. But mass splittings are unknown, so don't know energy distributions of these objects.
4. Natural SUSY → 3rd generation quarks (t, b) → b-jet tagging is extremely important.
5. In models with Gauge Mediated SUSY breaking, can have high pT photons.
6. In some scenarios, can have Higgs bosons produced in the decay chains.

CMS SUSY Results (ICHEP 2014)



Generic hadronic SUSY search using MHT

SUS-13-012 https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS13012

- Signature: Jets + MHT; events with leptons are vetoed
  - Jets: ≥3 jets with $p_T > 50$ GeV, no b-tagging.
  - Veto event if MHT vector is ≈aligned with any of 3 leading jets.
- Bin data in
  - HT
  - missing HT (MHT)
  - Jet multiplicity (3—5, 6—7, ≥8 jets)

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

$$\not{H}_T = \left|\vec{\not{H}}_T\right| = \left|-\sum_{j=jets} \vec{p}_T^{\,j}\right|$$

- Background estimation: largely data driven.

- ttbar with $W \to l\,\nu$
- $W \to l\,\nu$ + jets
- ttbar with $W \to \tau\,(\to h)\,\nu$
- $W \to \tau\,(\to h)\,\nu$ + jets

Control sample: Single-lepton + jets + MHT

- $Z \to \nu\nu$ + jets

Control samples:
γ + jets,
$Z(\mu\mu)$+jets

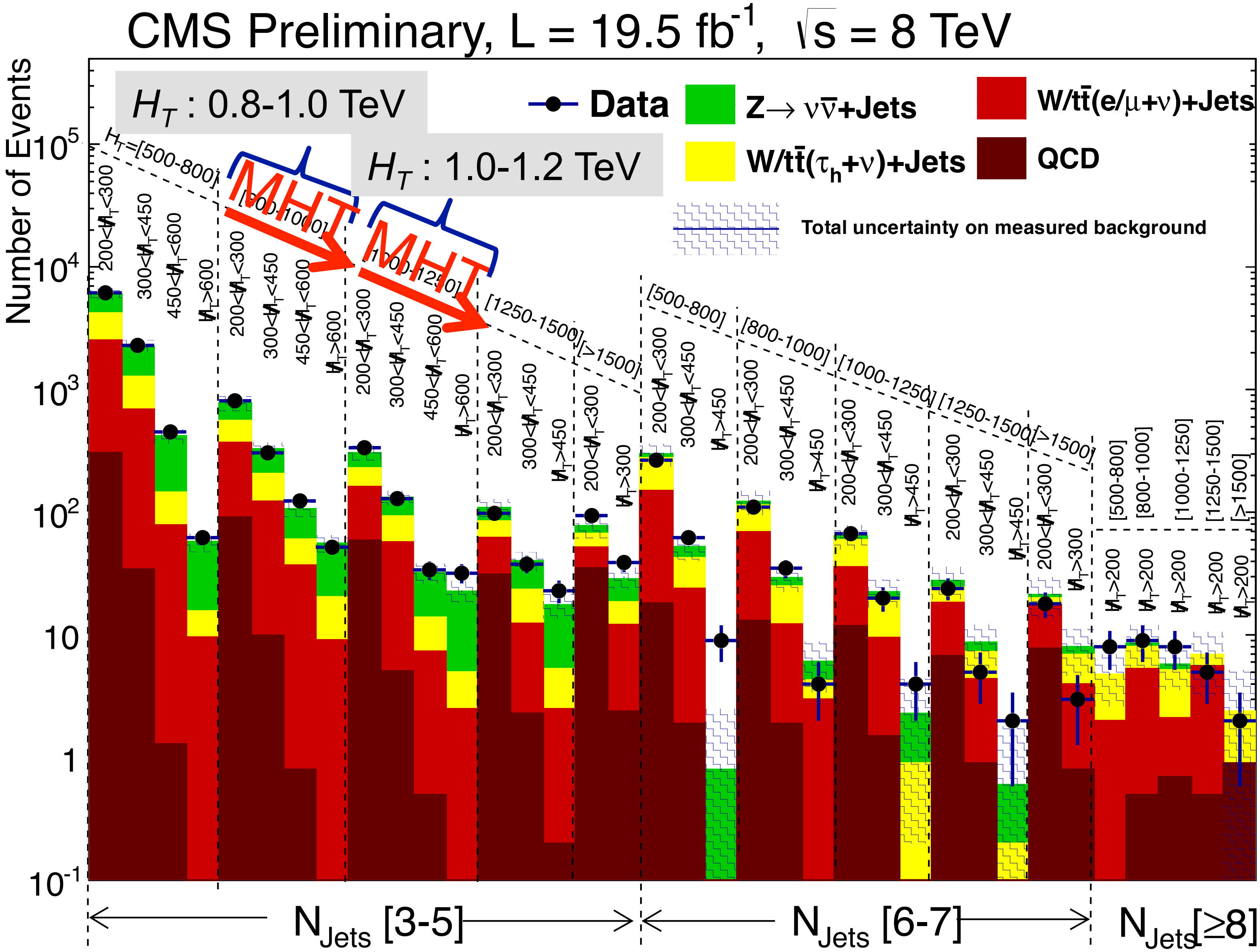
- QCD multijet events

MHT ~ aligned with high pT jet.

Control sample:
Multijets with re-balance and smear procedure

Distribution in bins of N(jets), H_T, and $\not{H}_T$

CMS SUS-13-012



Statistical interlude

See CMS PAS SUS-13-012, Table 1, p. 10

Njets: 6-7
HT: 500-800 GeV
MHT>450 GeV

- Consider the bin with
  - N(observed) = 9 events
  - N(background) = 0.8 ± 1.7 events
- First, let's ignore the uncertainty on the background. What is the probability for a Poisson with μ=0.8 to fluctuate to at least 9 events?
  - Prob($n \geq 9 \mid \mu = 0.8$) = 1.8×10^{-7}

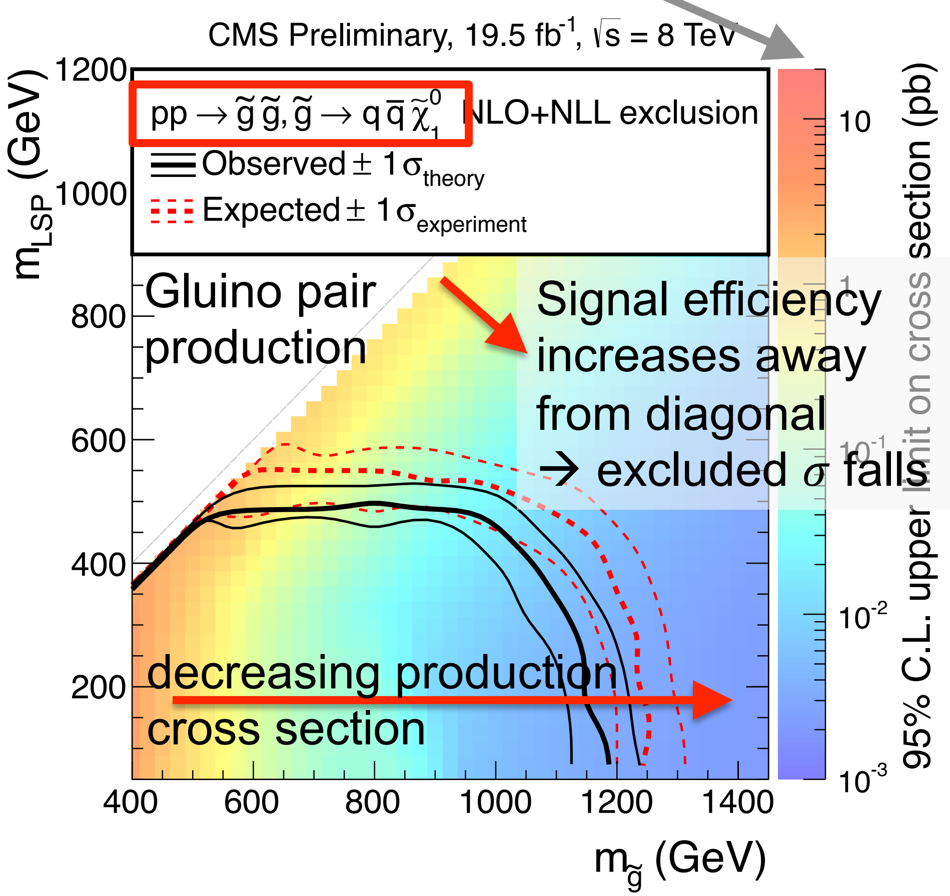
  Have we discovered new physics?
- NO! The uncertainty is crucial!
  - Prob($n \geq 9 \mid \mu = 0.8 \pm 1.7$) ≈ 0.15
- This example highlights the importance of <u>quantifying the uncertainties on the SM backgrounds.</u>

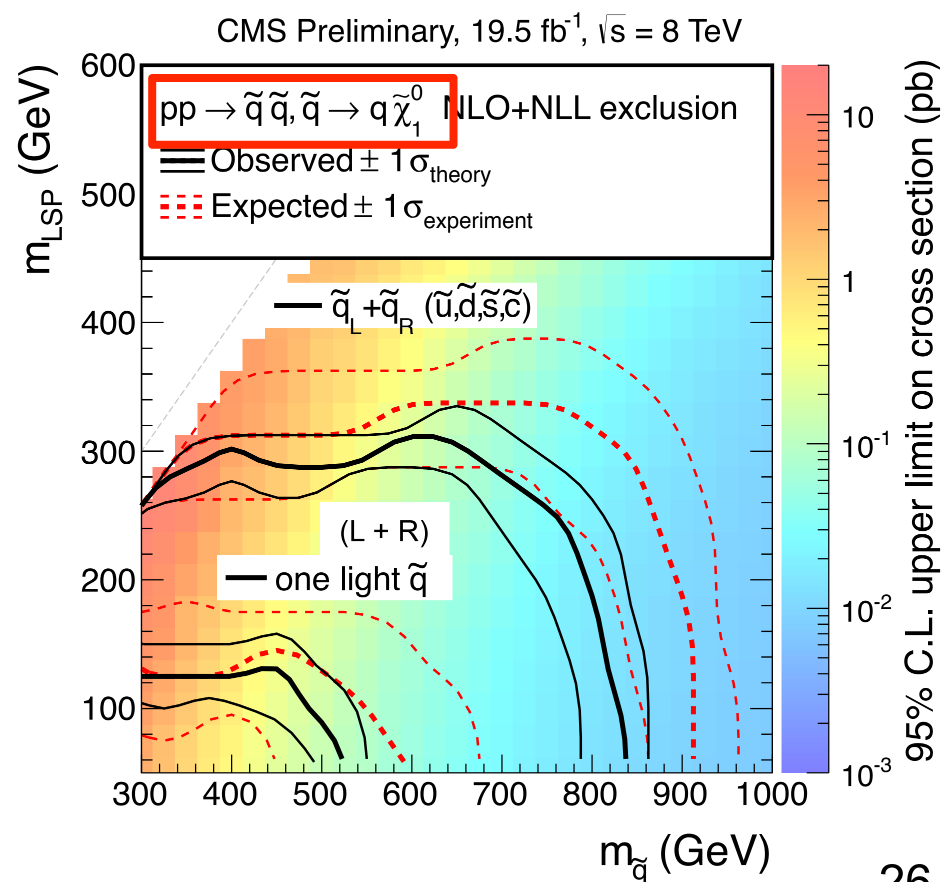
Search for generic jets and MET: results

- Simplified model exclusion plots

CMS SUS-13-012

1. Compute excluded cross section for each model in param space
2. Compare to reference cross section to see if model excluded
   - Assume 100% branching fraction for stated process!





Search for generic jets and MET: results

- Simplified model exclusion plots

CMS PAS SUS-13-012

1. Compute excluded cross section for each model in param space
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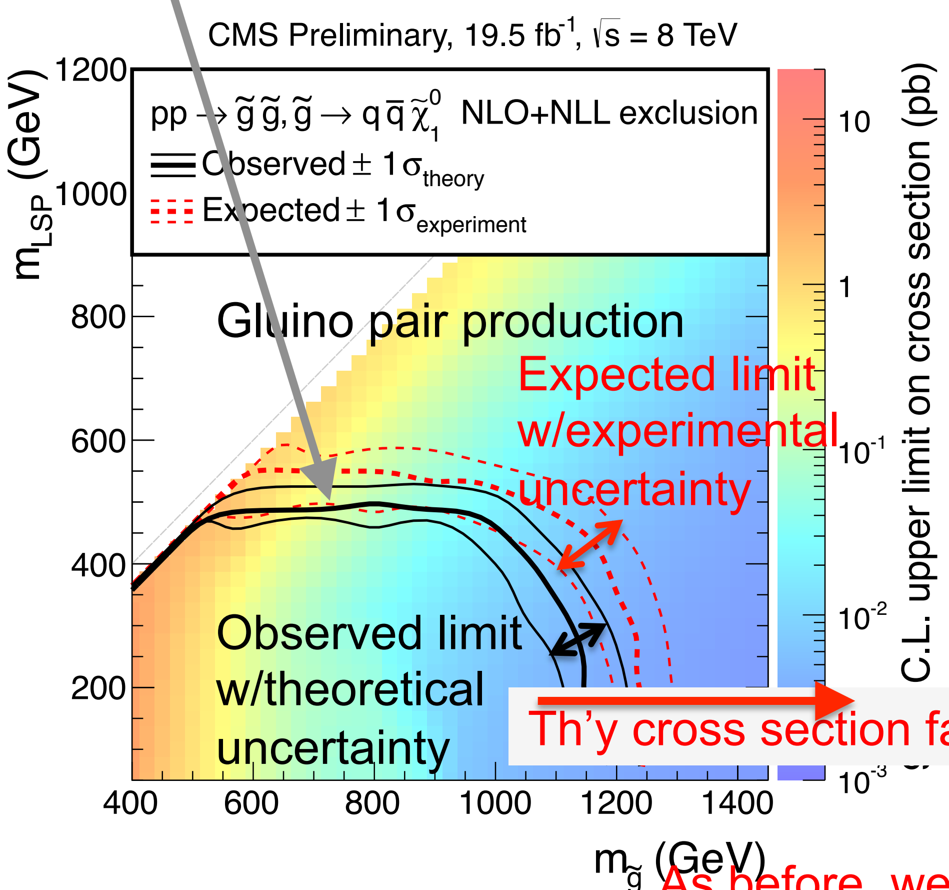
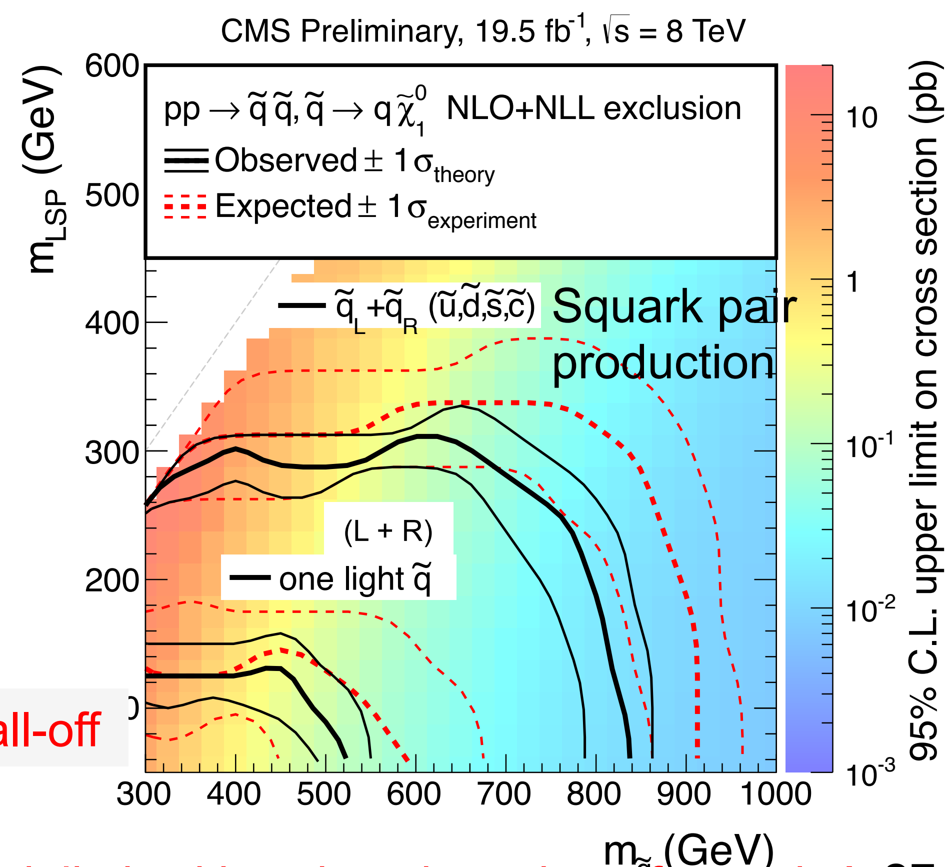




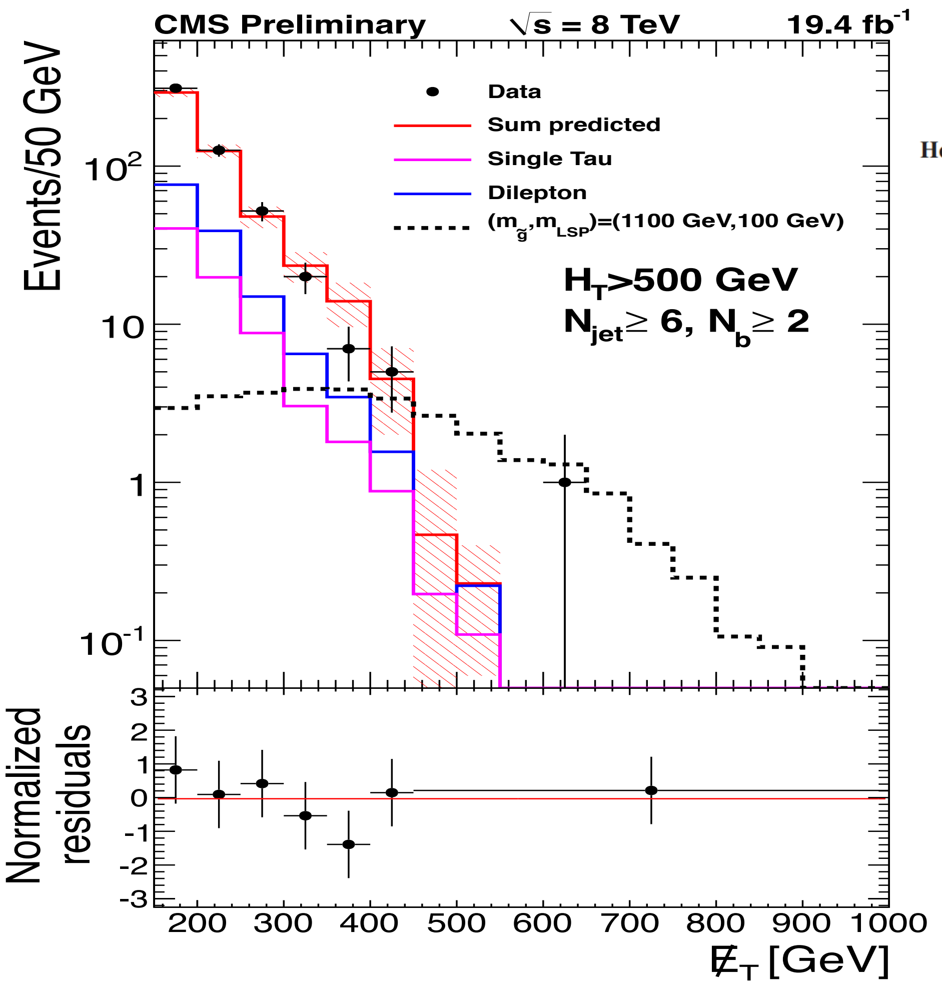
As before, weak limit with reduced number of squarks!

SUSY search for b-jets, 1 lepton, and MET

CMS PAS SUS-13-007

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS13007

Lepton spectrum method: for leptons produced in W decay, the lepton spectrum can be used to measure the ν spectrum.



Makes use of W helicity fractions in t→bW

PHYSICAL REVIEW D **81,** 111503(R) (2010)

Helicity fractions of *W* bosons from top quark decays at next-to-next-to-leading order in QCD

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(Received 13 May 2010; published 18 June 2010)

Decay rates of unpolarized top quarks into longitudinally and transversally polarized W bosons are calculated to second order in the strong coupling constant α_s. Including the finite bottom quark mass and electroweak effects, the standard model predictions for the W-boson helicity fractions are $\mathcal{F}_L = 0.687(5)$, $\mathcal{F}_+ = 0.0017(1)$, and $\mathcal{F}_- = 0.311(5)$.

...and W helicity fractions in W+jets

PHYSICAL REVIEW D **84,** 034008 (2011)

Left-handed *W* bosons at the LHC

Z. Bern,[1] G. Diana,[2] L. J. Dixon,[3,4] F. Febres Cordero,[5] D. Forde,[3,6] T. Gleisberg,[4] S. Höche,[4] H. Ita,[1] D. A. Kosower,[2] D. Maître,[3,7] and K. Ozeren[1]

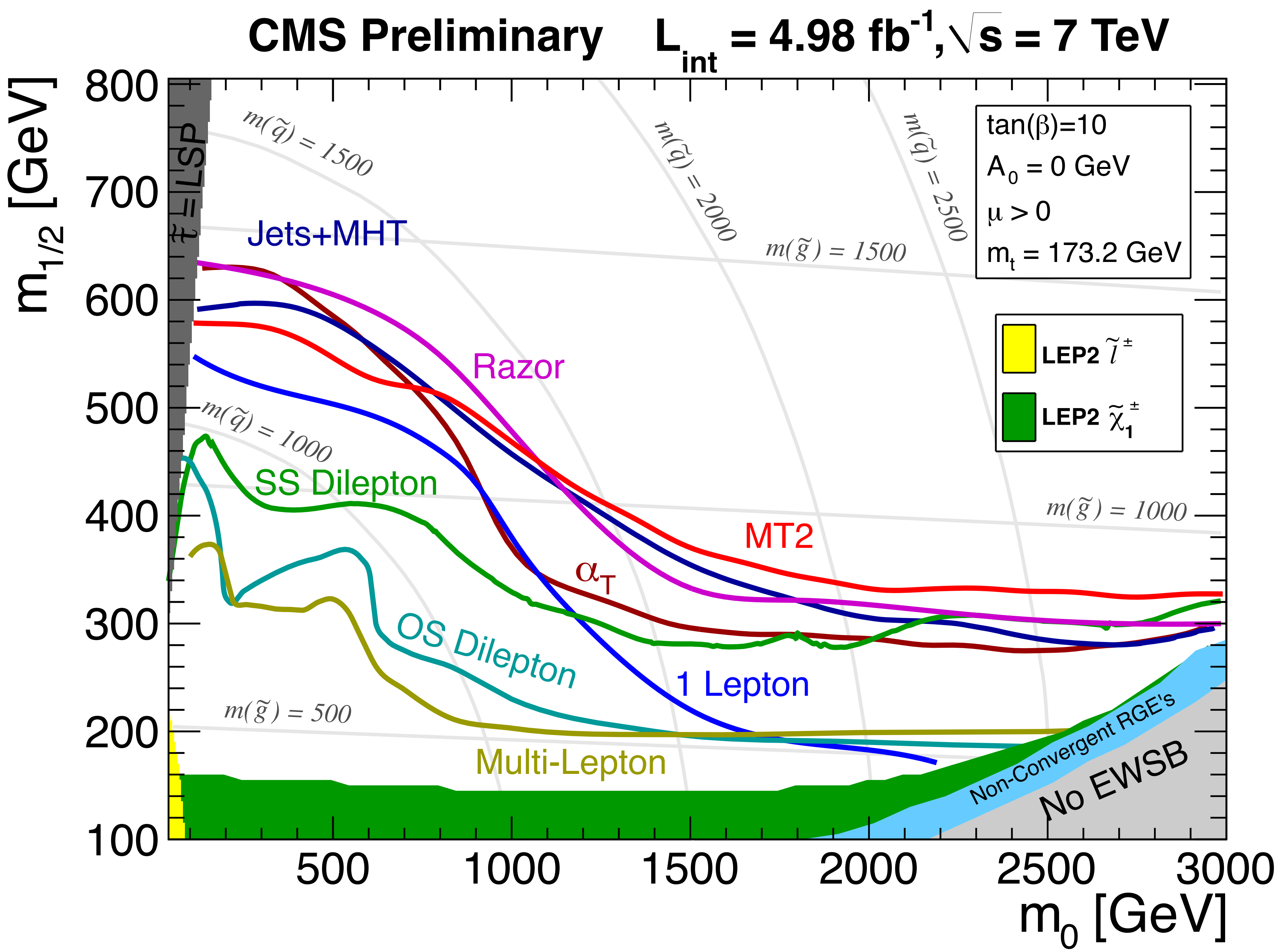
The production of W bosons in association with jets is an important background to new physics at the LHC. Events in which the W carries large transverse momentum and decays leptonically lead to large missing energy and are of particular importance. We show that the left-handed nature of the W coupling, combined with valence quark domination at a pp machine, leads to a large left-handed polarization for both W^+ and W^- bosons at large transverse momenta. The polarization fractions are very stable with

MSSM parameter count

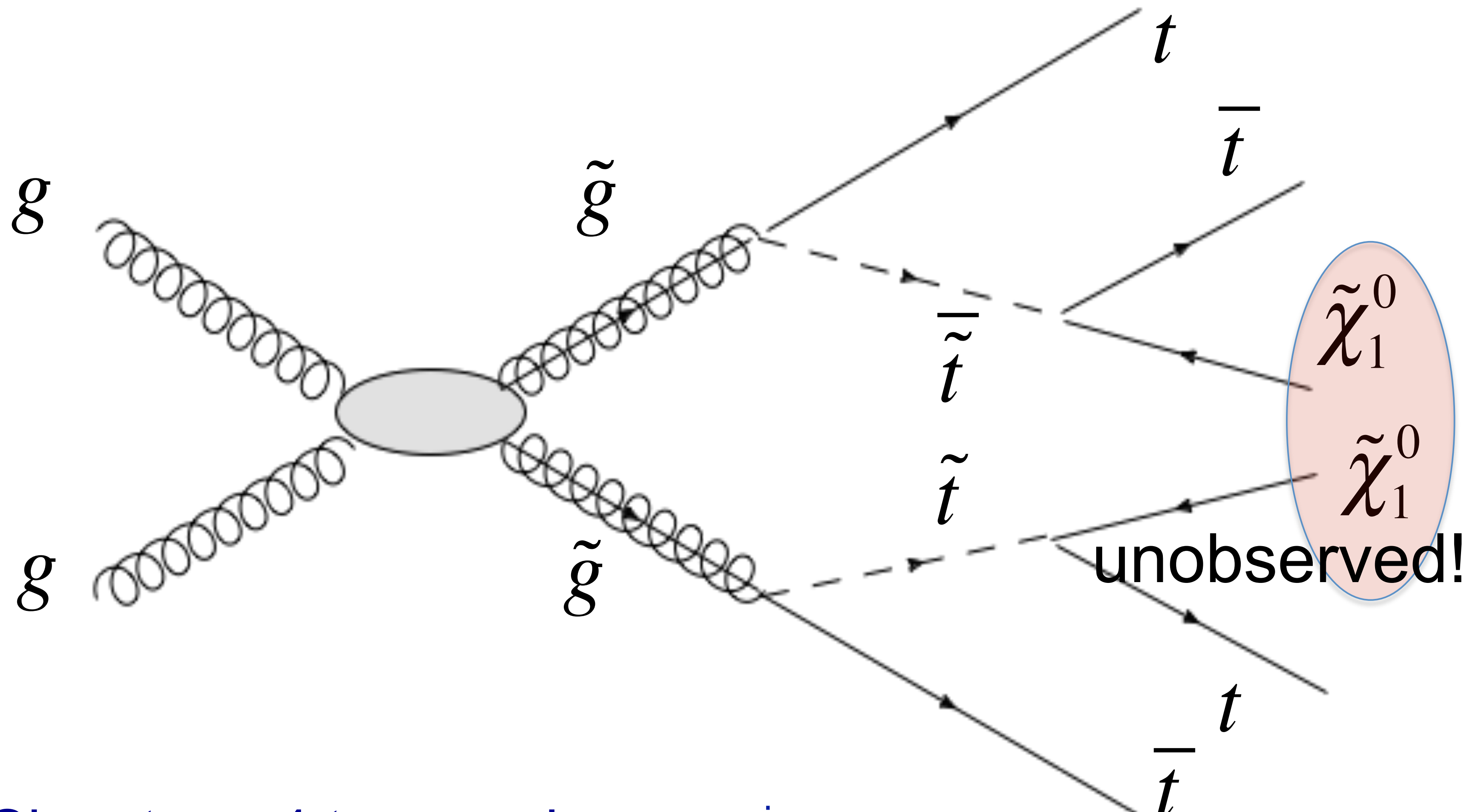
Sector of MSSM	Number of parameters
Standard Model parameters	18
1 Higgs parameter, analogous to Higgs mass in SM	1
Gaugino/higgsino sector	5
Gaugino/higgsino sector – CP violating phases	3
Squark and slepton masses	21
Mixing angles to define squark and slepton mass eigenstates	36
CP violating phases	40
Total	124

In cMSSM, SUSY is described by just 4 continuous real params + 1 sign.

Formulating SUSY – a short history



Gluino pair production and decay to stop



Signature: 4 top quarks + p_T^{miss}

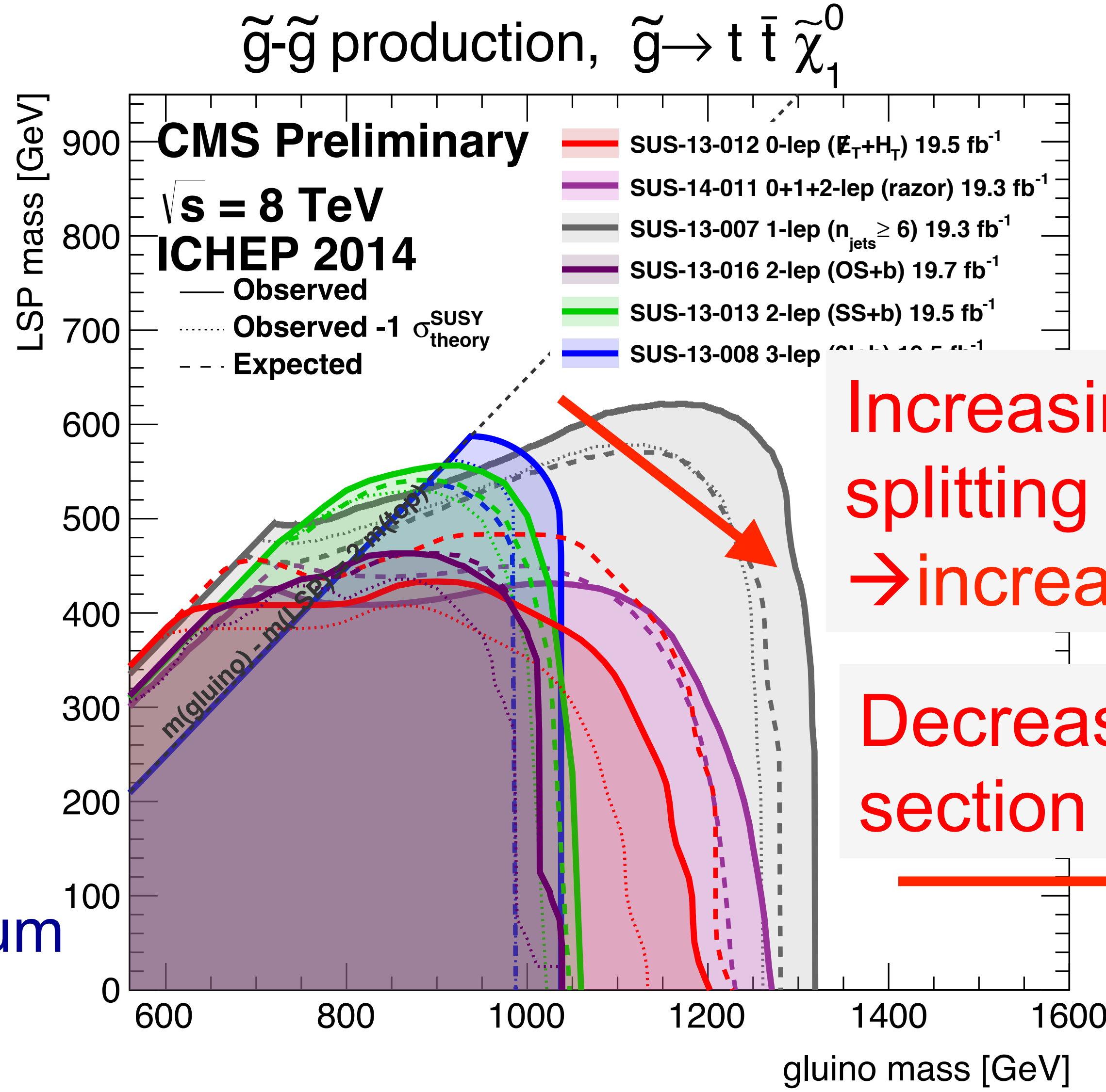
LSPs are unobserved: cannot reconstruct mass peaks!

Results for gluino pair production with $\tilde{g} \rightarrow t\bar{t}\,\tilde{\chi}_1^0$

$M(\tilde{\chi}_1^0)$

Mass of LSP

Maximum gluino mass limit at minimum LSP mass.

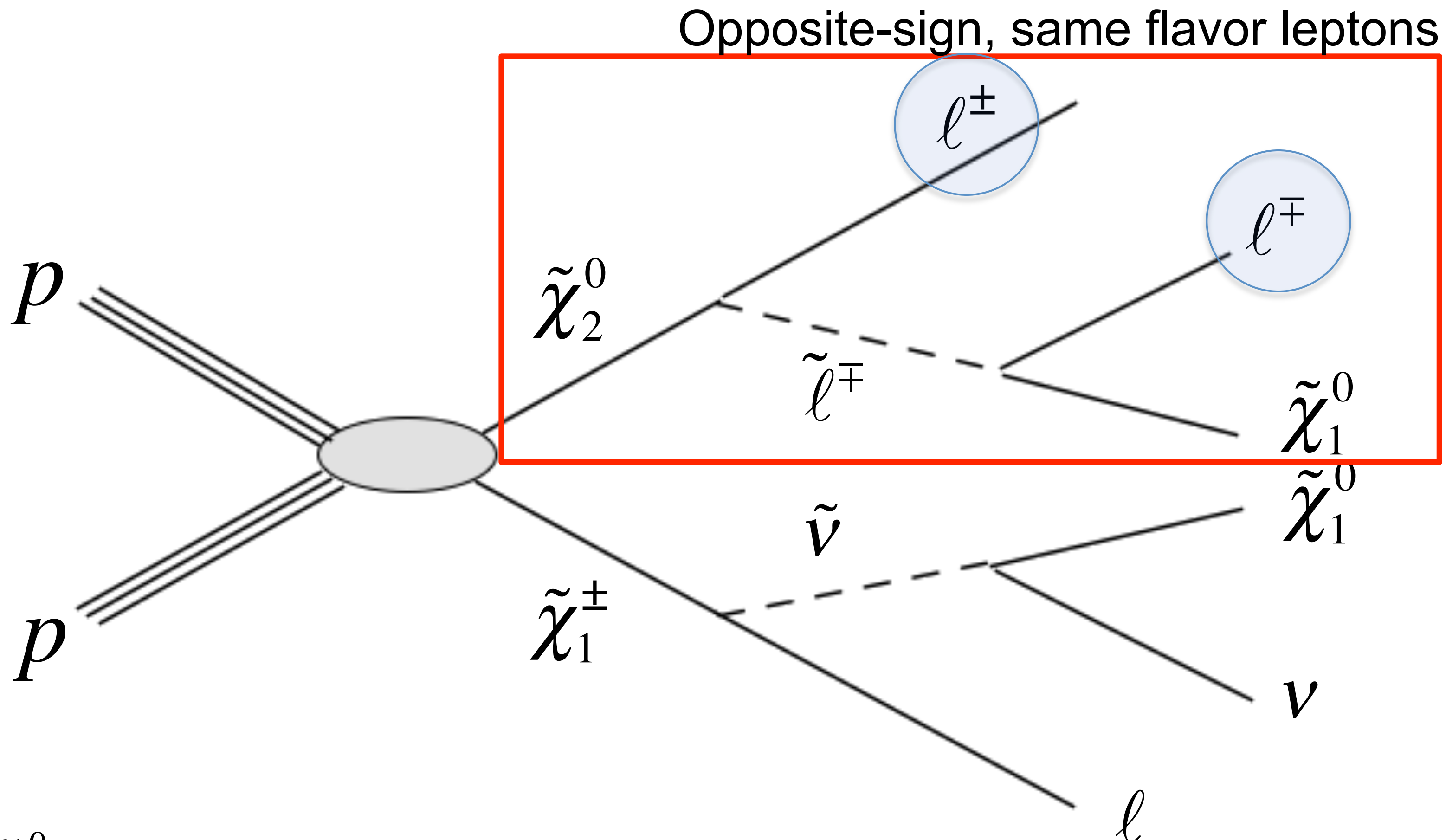


Increasing mass splitting →increasing MET

Decreasing cross section

Mass of pair-produced particle $M(\tilde{g})$

The famous neutralino dilepton cascade

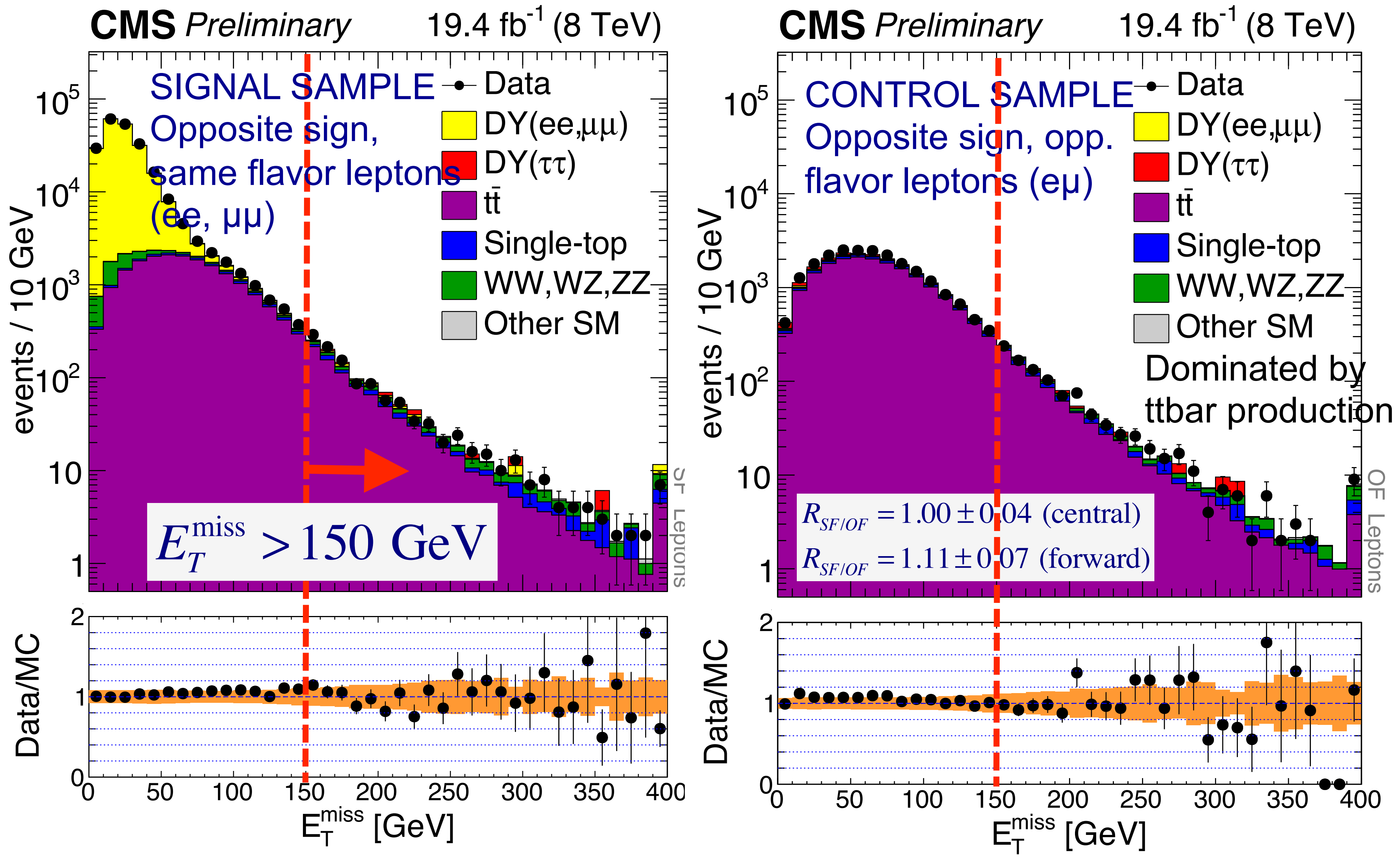


The $\tilde{\chi}_2^0$ can be produced in any process, not just direct EW production.

$$m_{\ell^+\ell^-}(\max) = \sqrt{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2)} / m_{\tilde{\ell}}$$

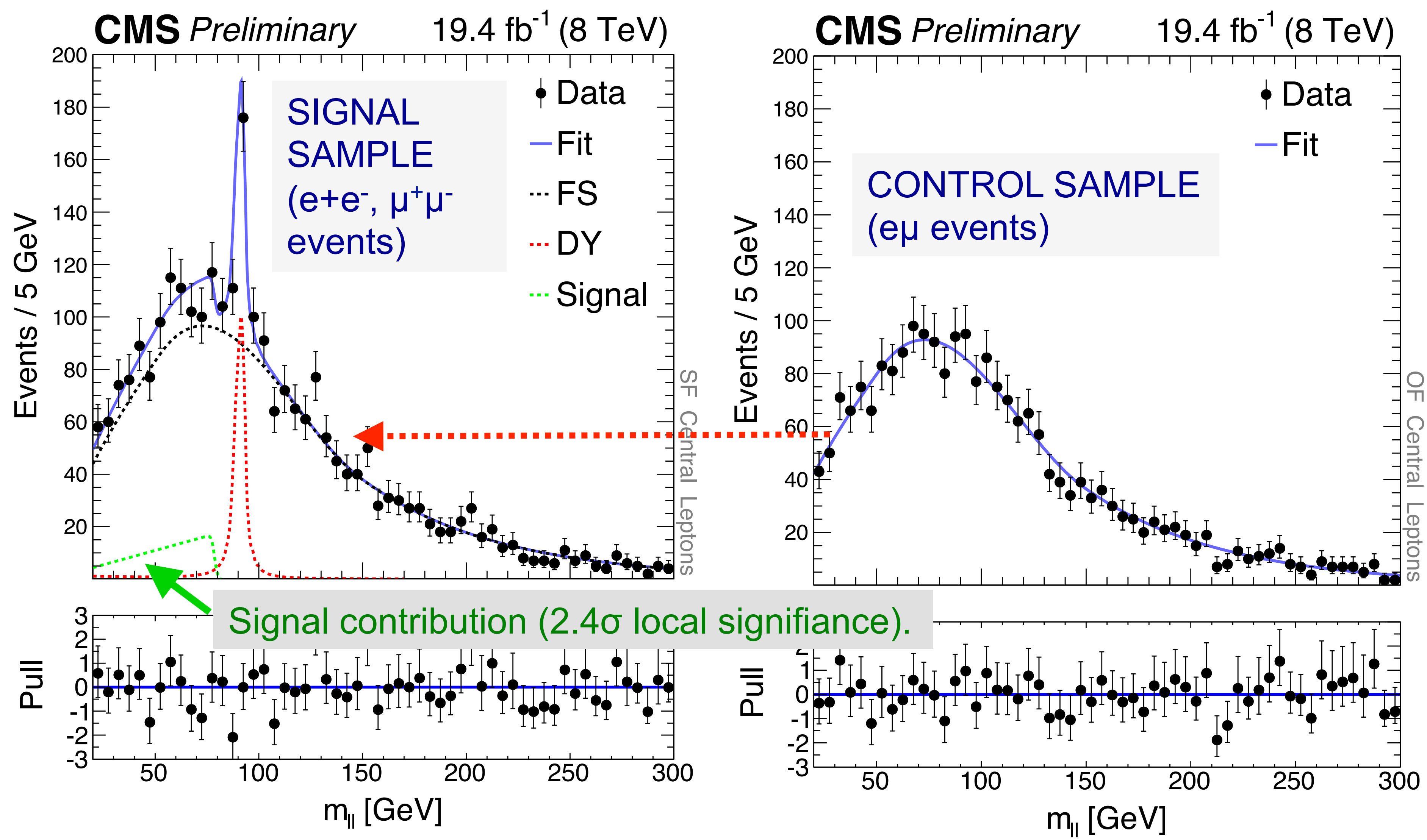
Search for SUSY in opposite sign dileptons

$$m_{\ell^+\ell^-} > 20\ \text{GeV},\ \ N(\text{jets}) \geq 2\ \ (p_T > 40\ \text{GeV})$$

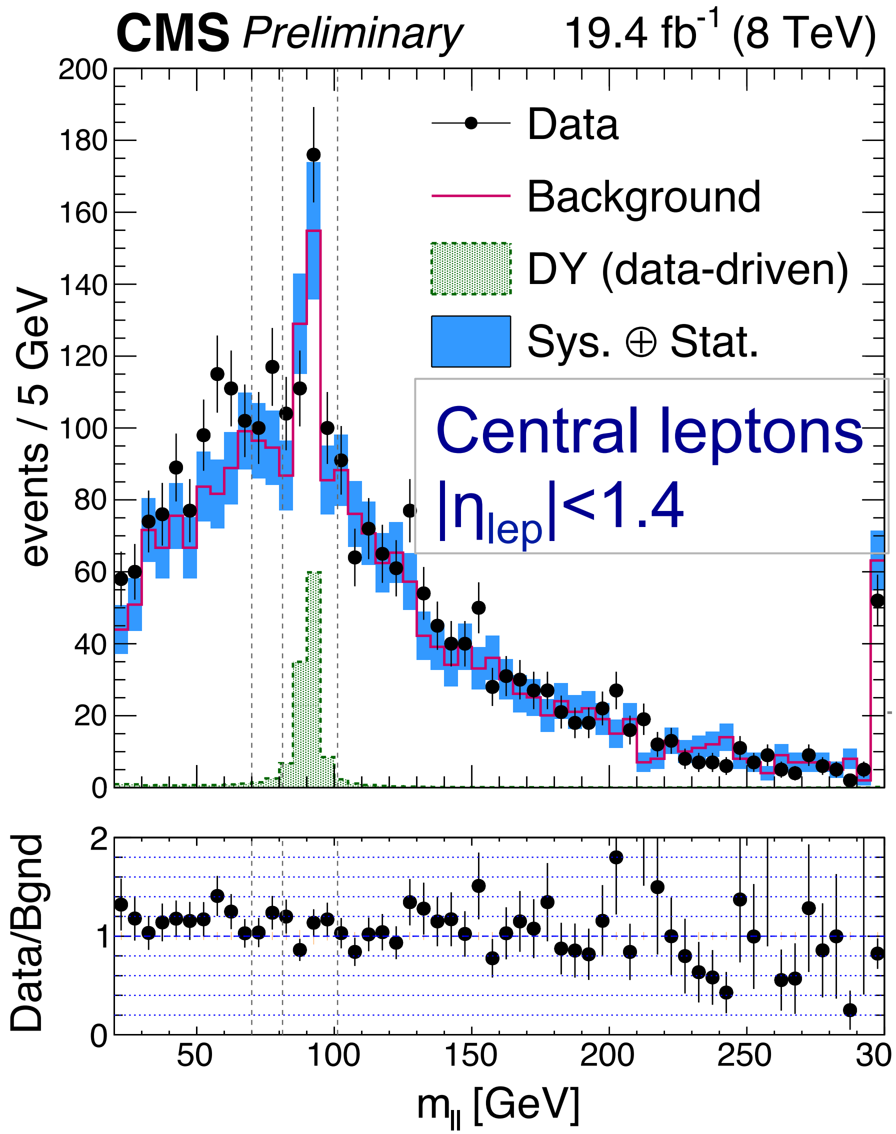


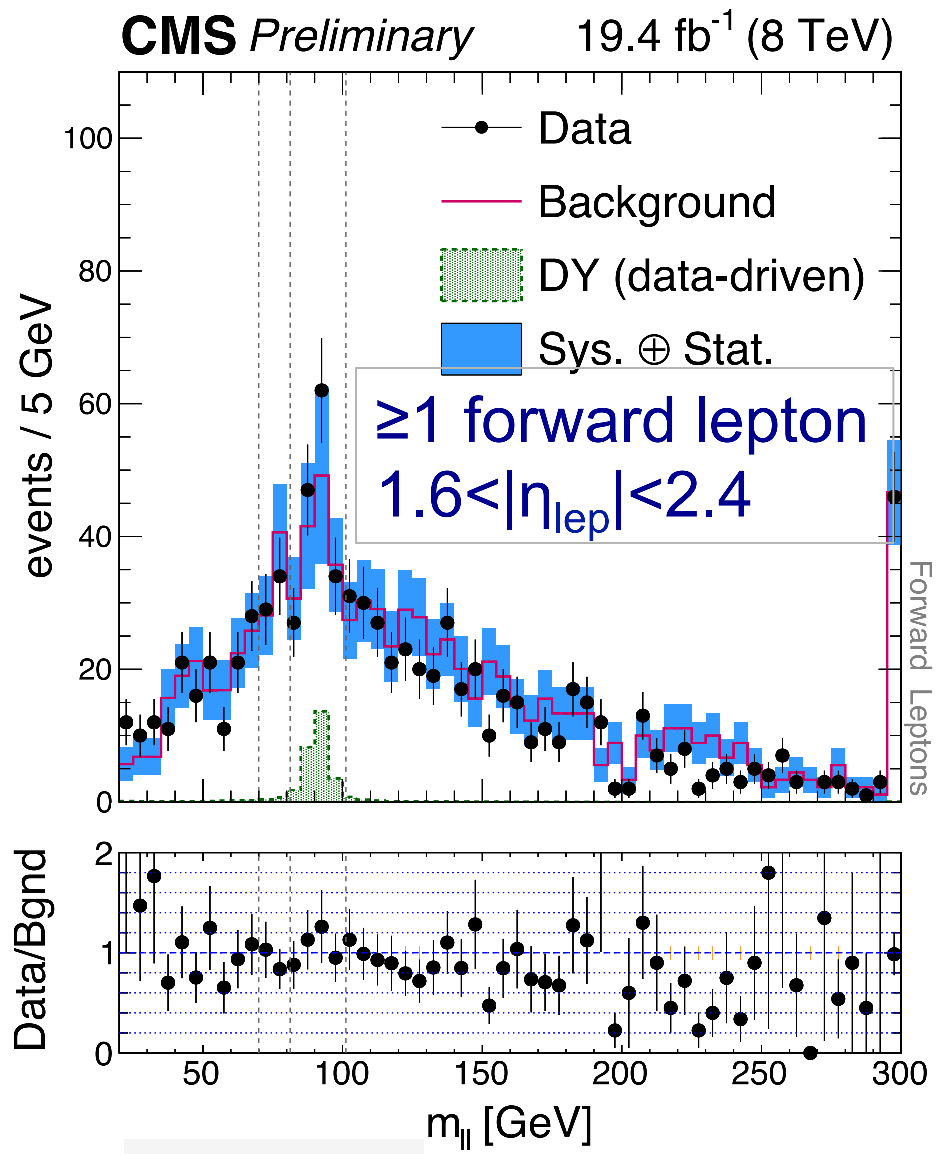
Search for SUSY in opposite sign dileptons

Fit opposite sign dilepton mass distribution to shapes from (1) Flavor Symmetric (FS) background, Drell Yan, and signal.



Search for SUSY in opposite-sign dileptons

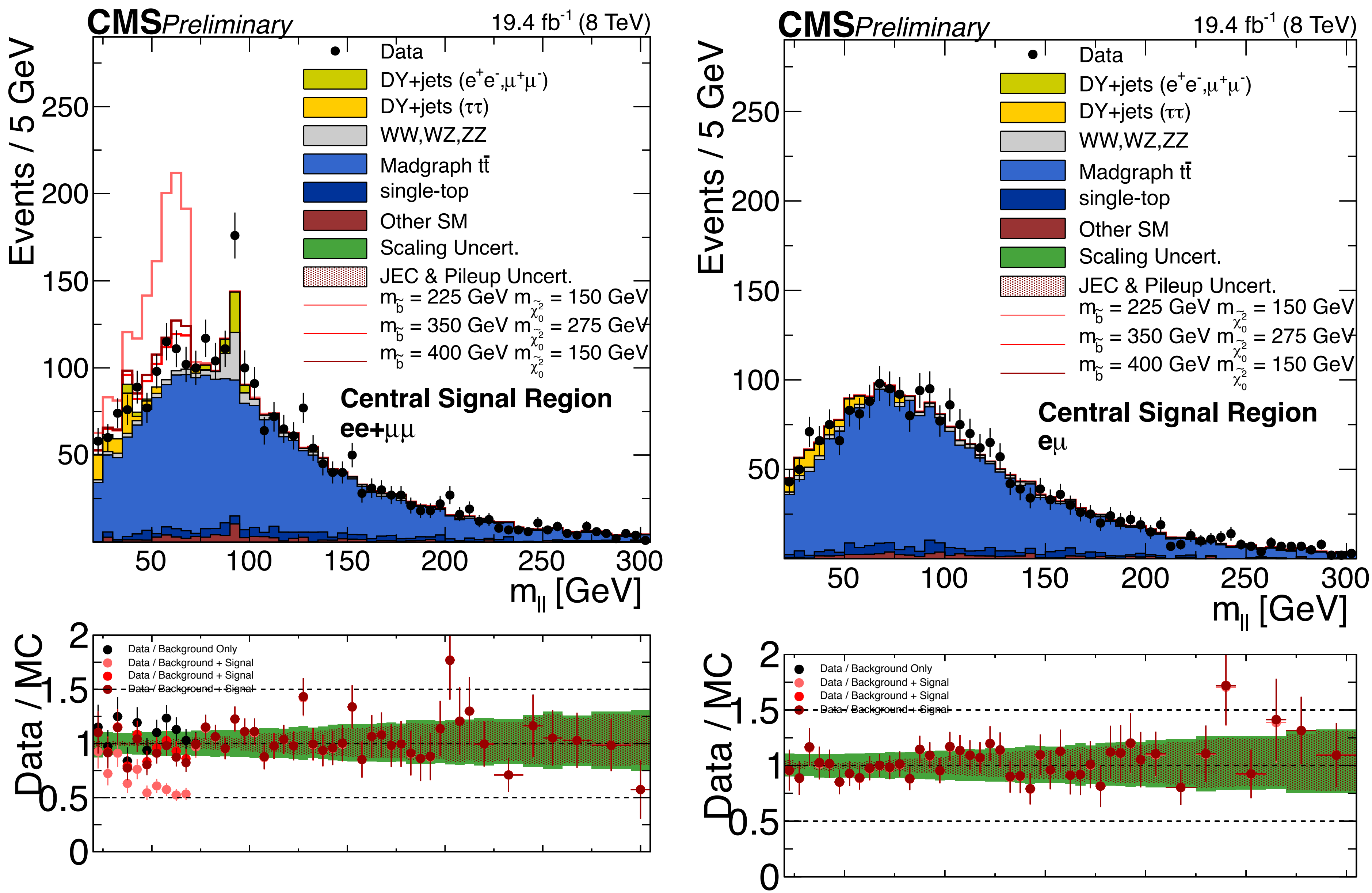




2.6σ excess (not significant)

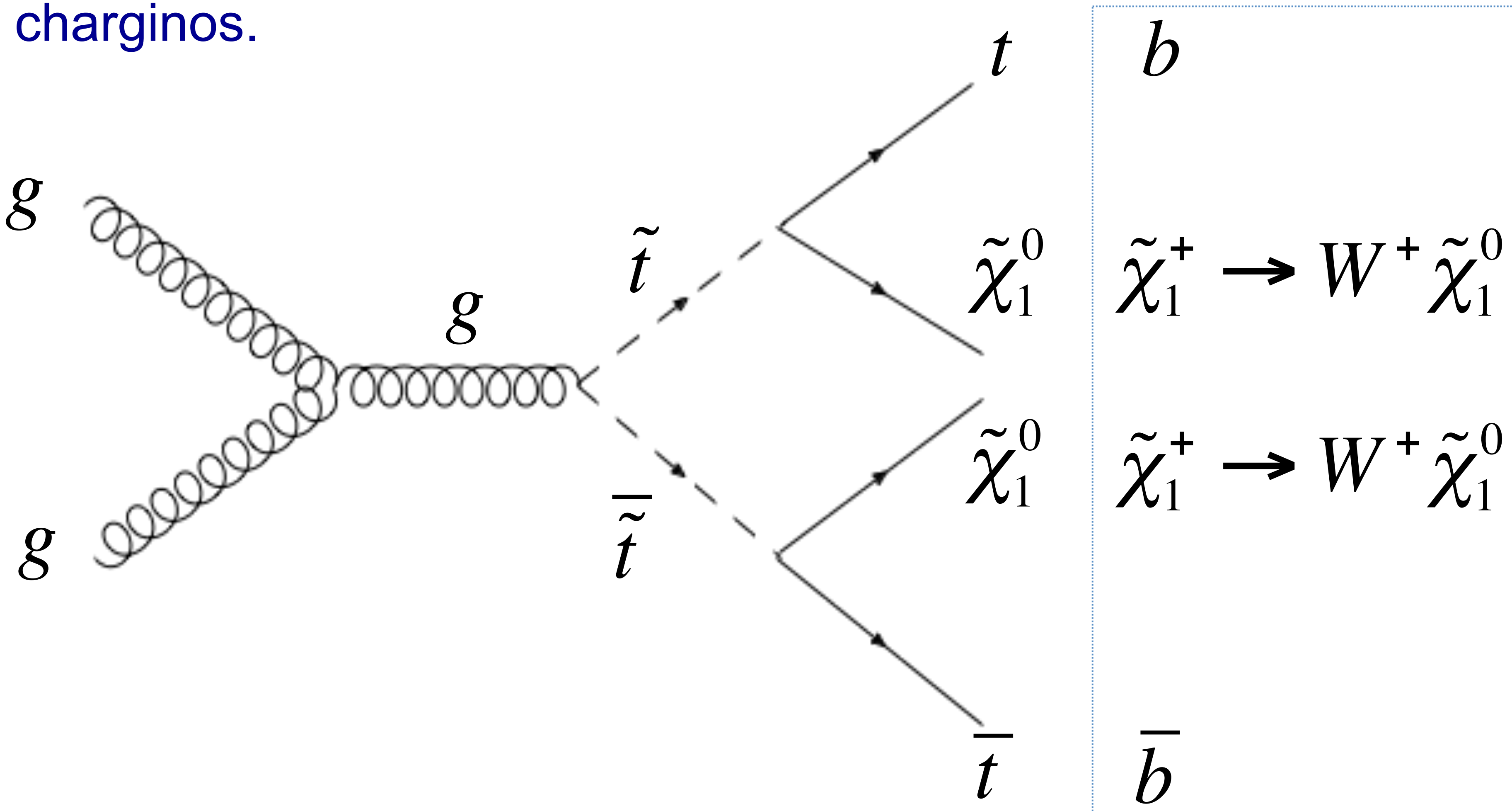
0.3σ excess

Search for SUSY in opposite sign dileptons



“Direct” pair production of light stops

Example: direct stop production with decay to neutralinos or charginos.



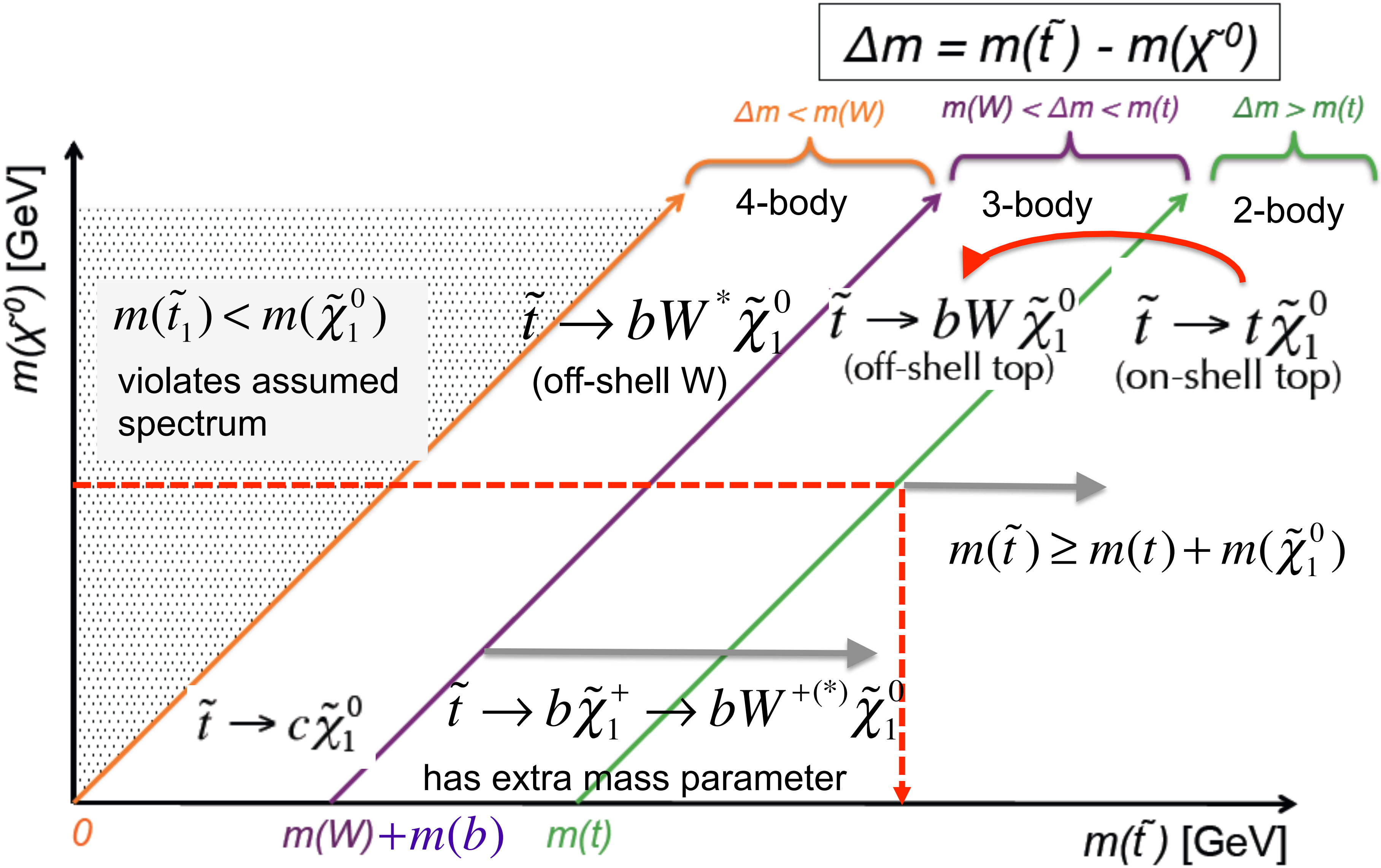
Sensitivity of the searches will depend strongly on the neutralino mass.

The channel with $\tilde{t} \rightarrow b\tilde{\chi}_1^+$ has sensitivity to lower stop mass.

Search for direct stop production: $pp \rightarrow \tilde{t}_1 \bar{\tilde{t}}_1$

SUS-13-011

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS13011 http://arxiv.org/abs/1308.1586



Search for direct stop production: $pp \to \tilde{t}_1 \bar{\tilde{t}}_1$

SUS-13-011

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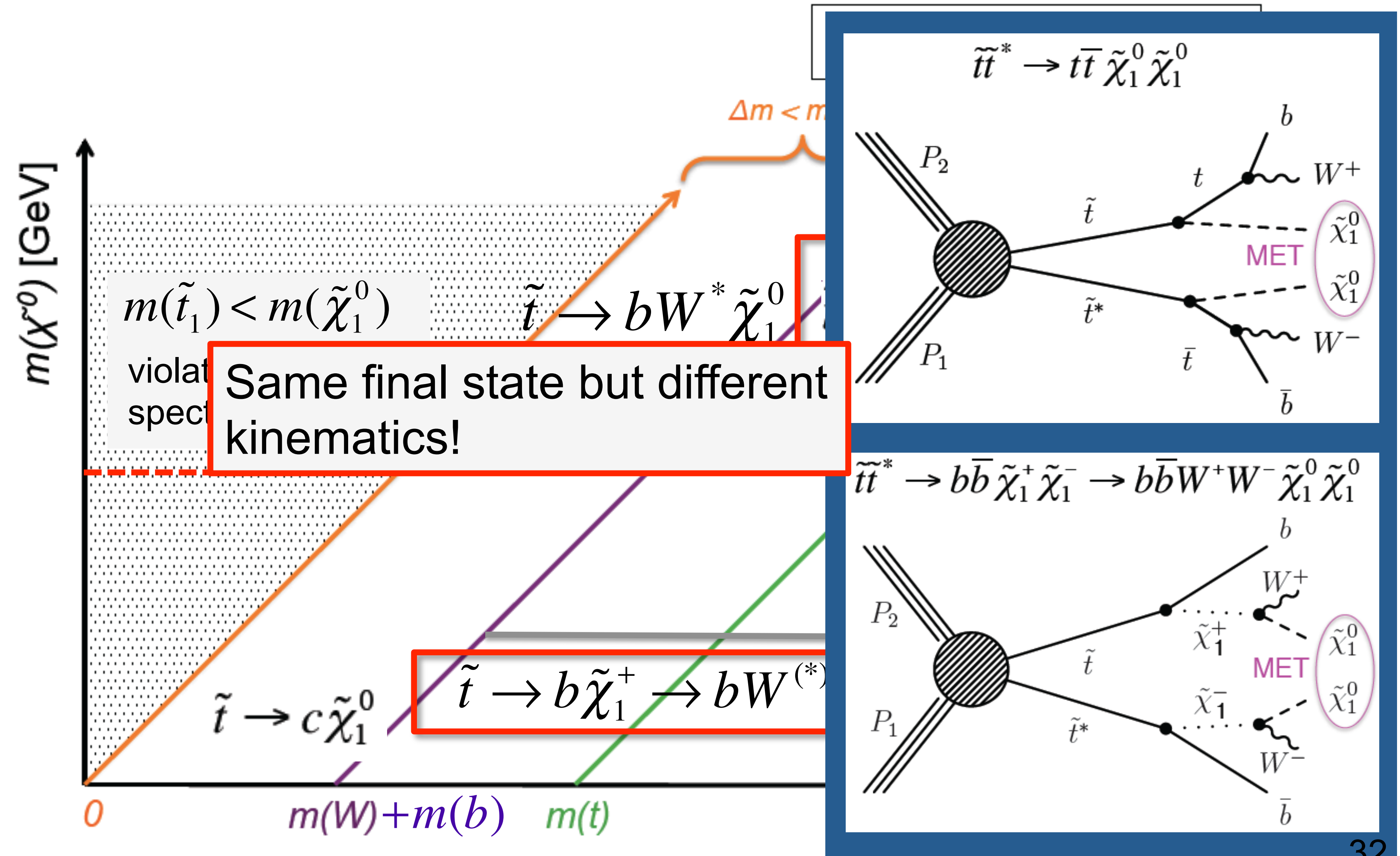

Search for direct stop production: $pp \to \tilde{t}_1 \bar{\tilde{t}}_1$

SUS-13-011

https://twiki.cern.ch/twiki/bin/vie\

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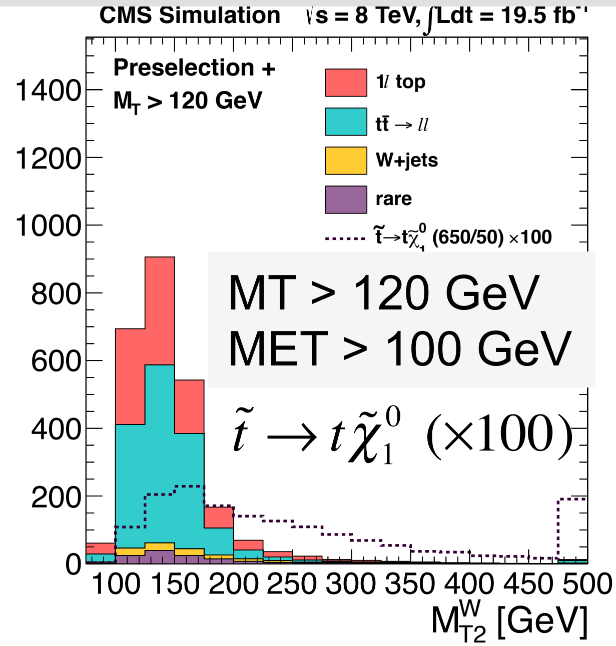
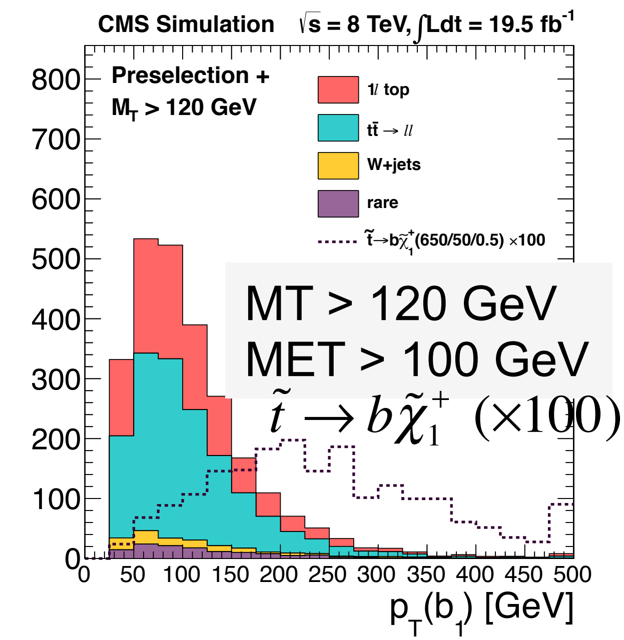
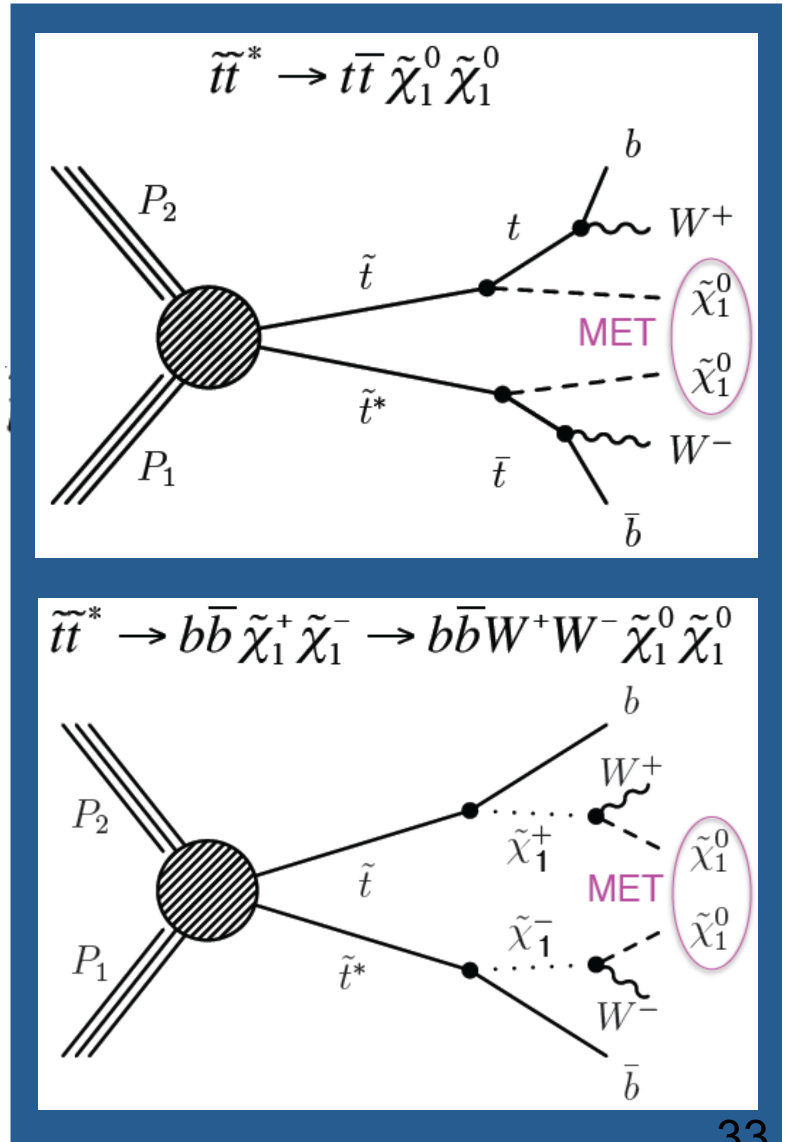
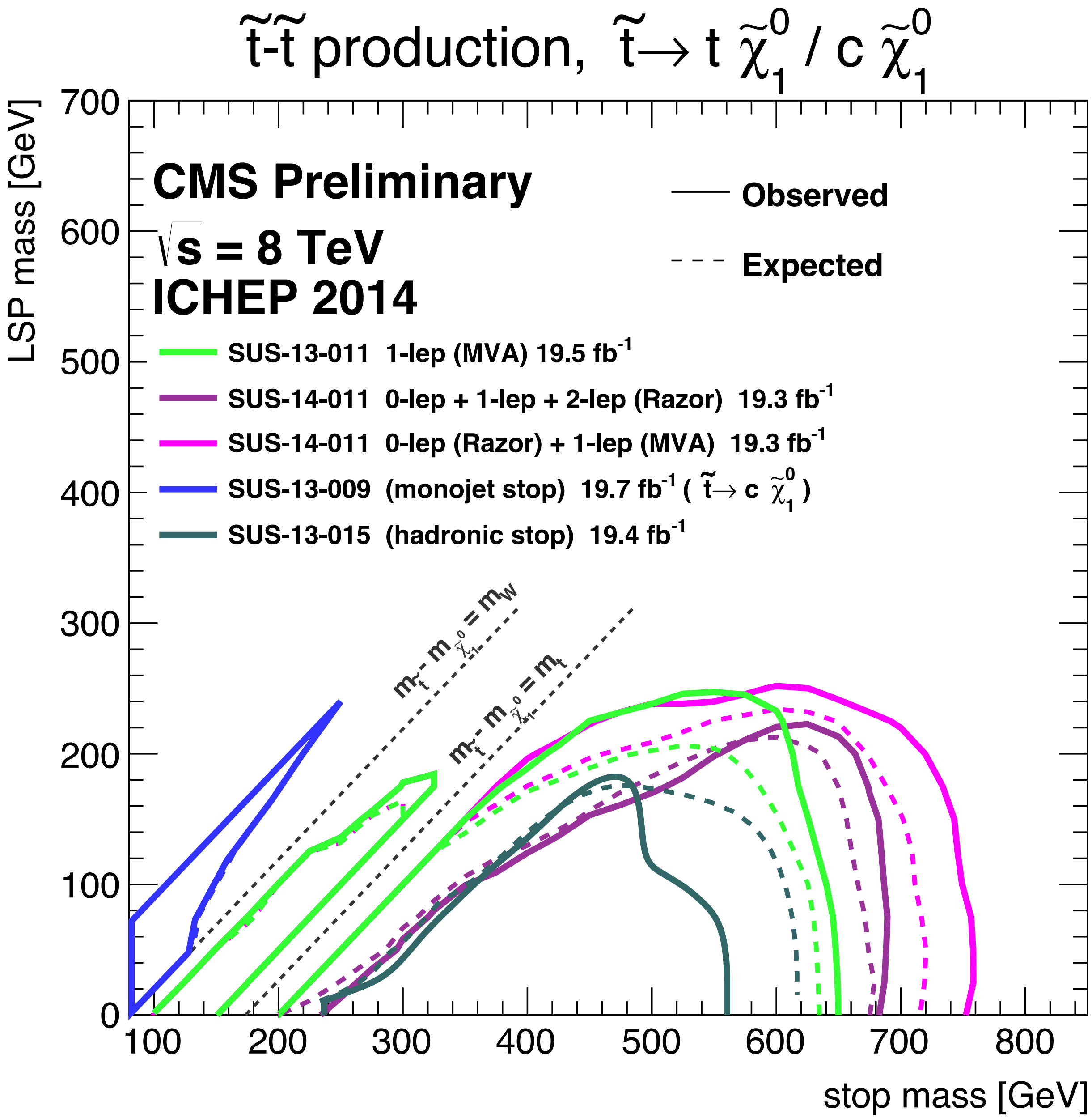




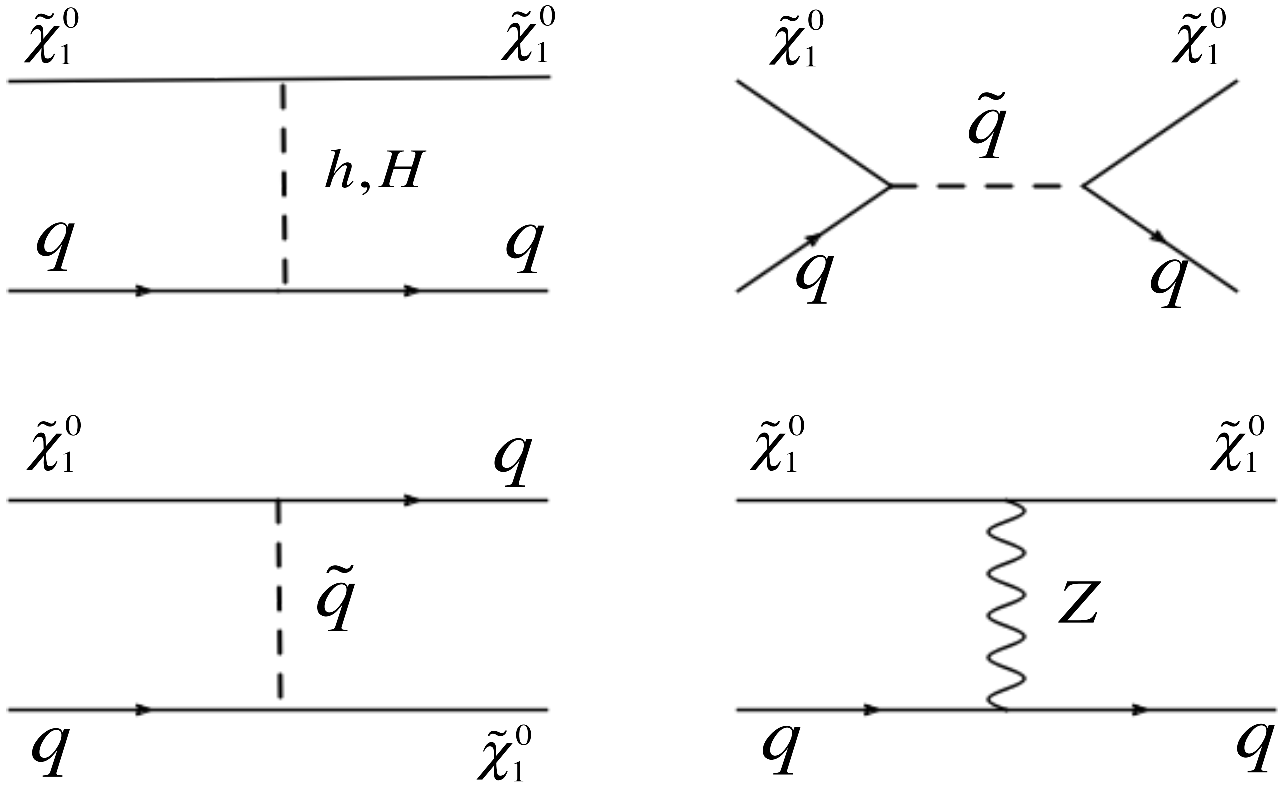


Use BDTs for separate modes & regions.

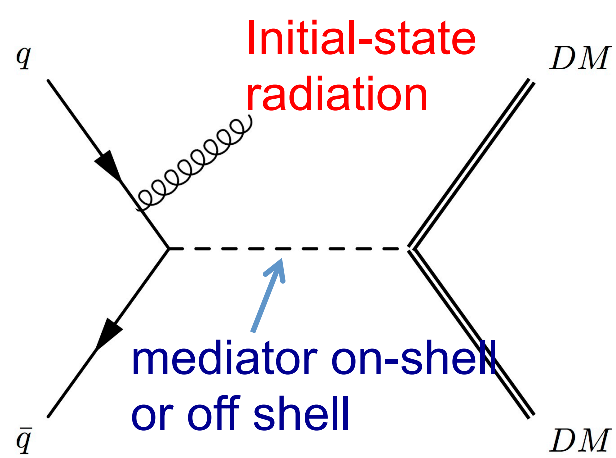
Results from searches for top squarks



Search for dark matter at the LHC

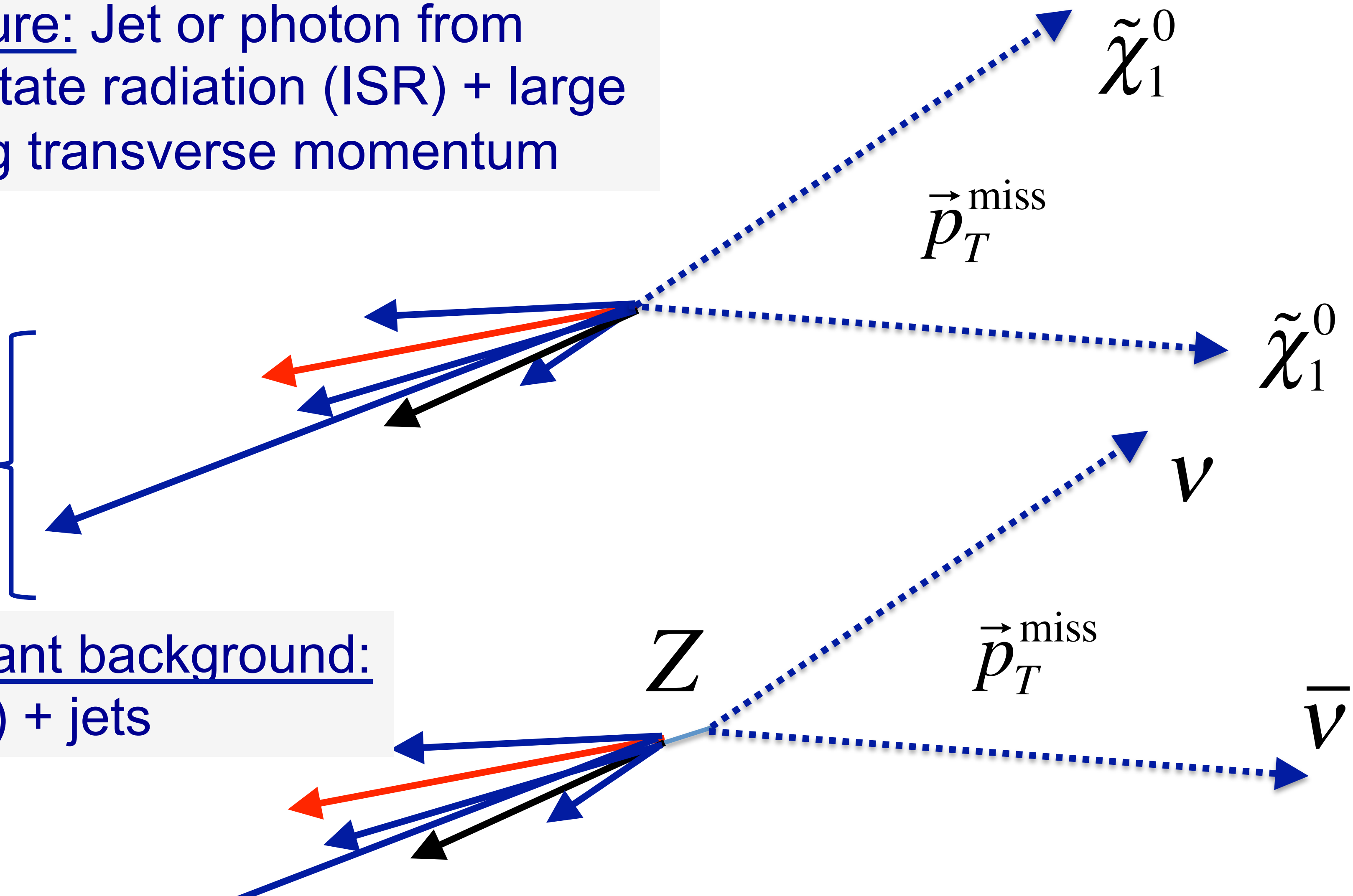


- Above: direct dark matter detection processes: doesn't have to be SUSY!
- Use crossing to get $q+\overline{q} \rightarrow \tilde{\chi}_1^0 + \tilde{\chi}_1^0$
- How to see $q+\overline{q} \rightarrow$ invisible?



Signature for dark matter at the LHC

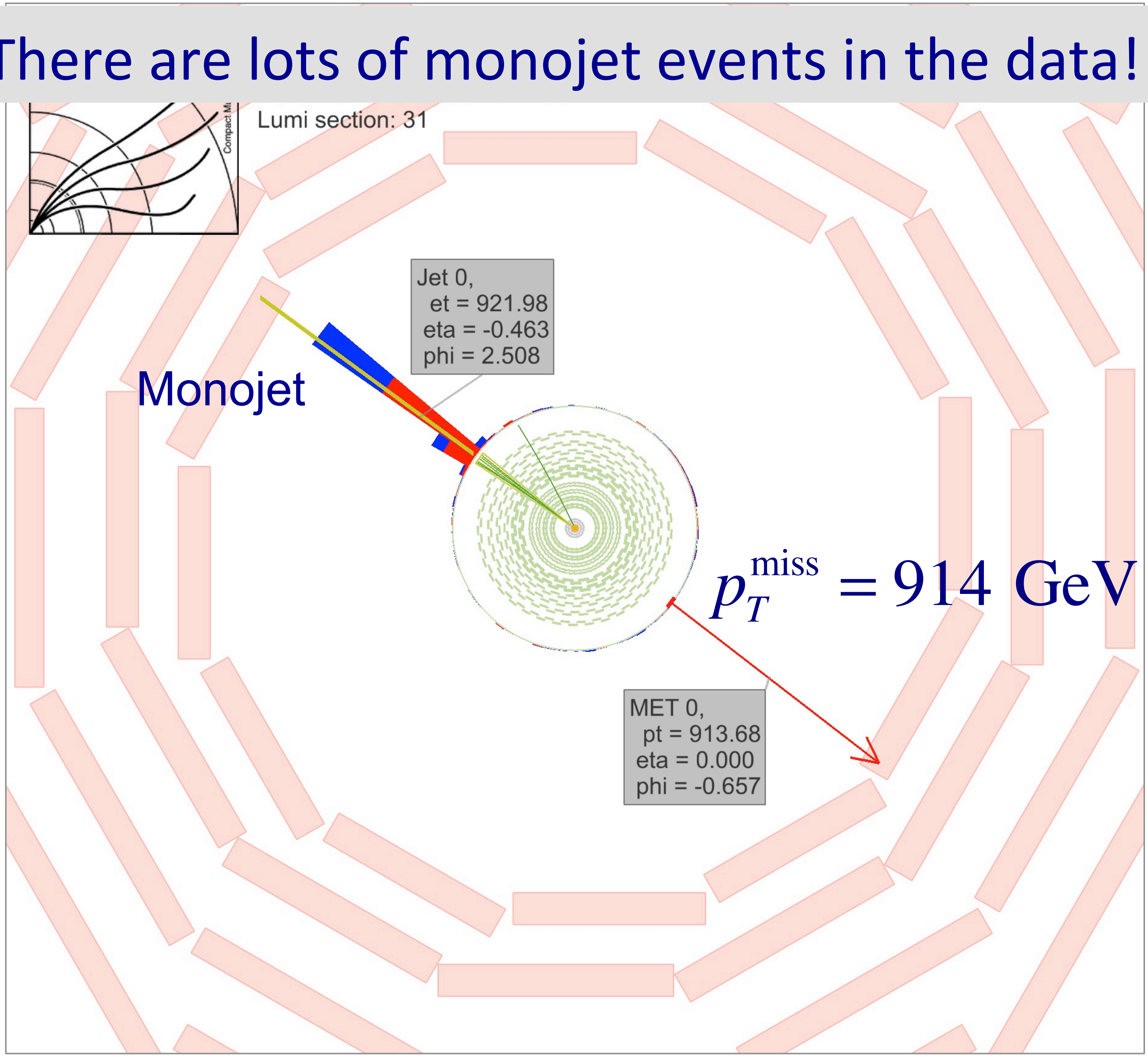
<u>Signature:</u> Jet or photon from initial-state radiation (ISR) + large missing transverse momentum



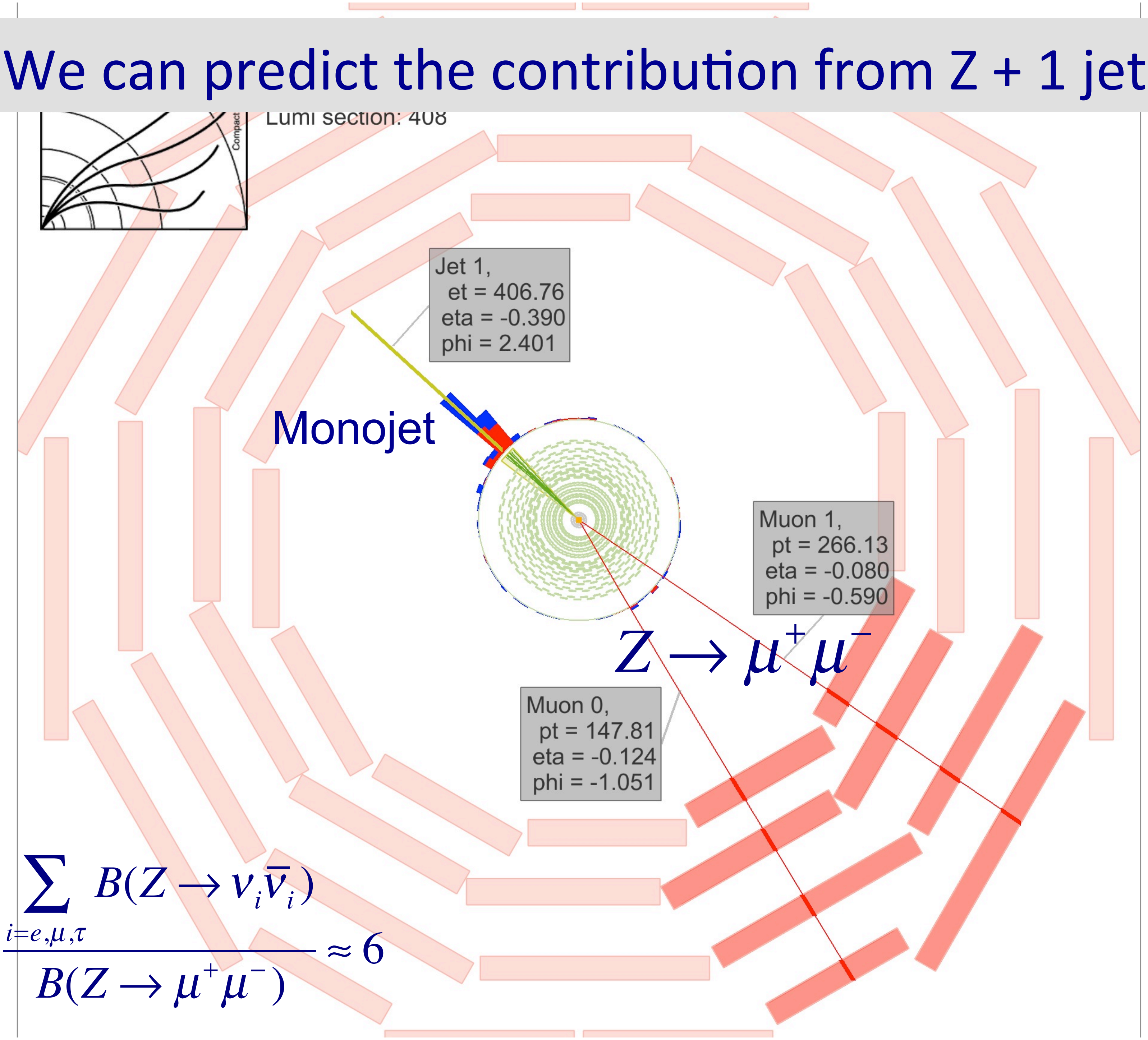
<u>Dominant background:</u>
Z(→νν) + jets

...don't want to rely on MC modeling of initial-state radiation

There are lots of monojet events in the data!

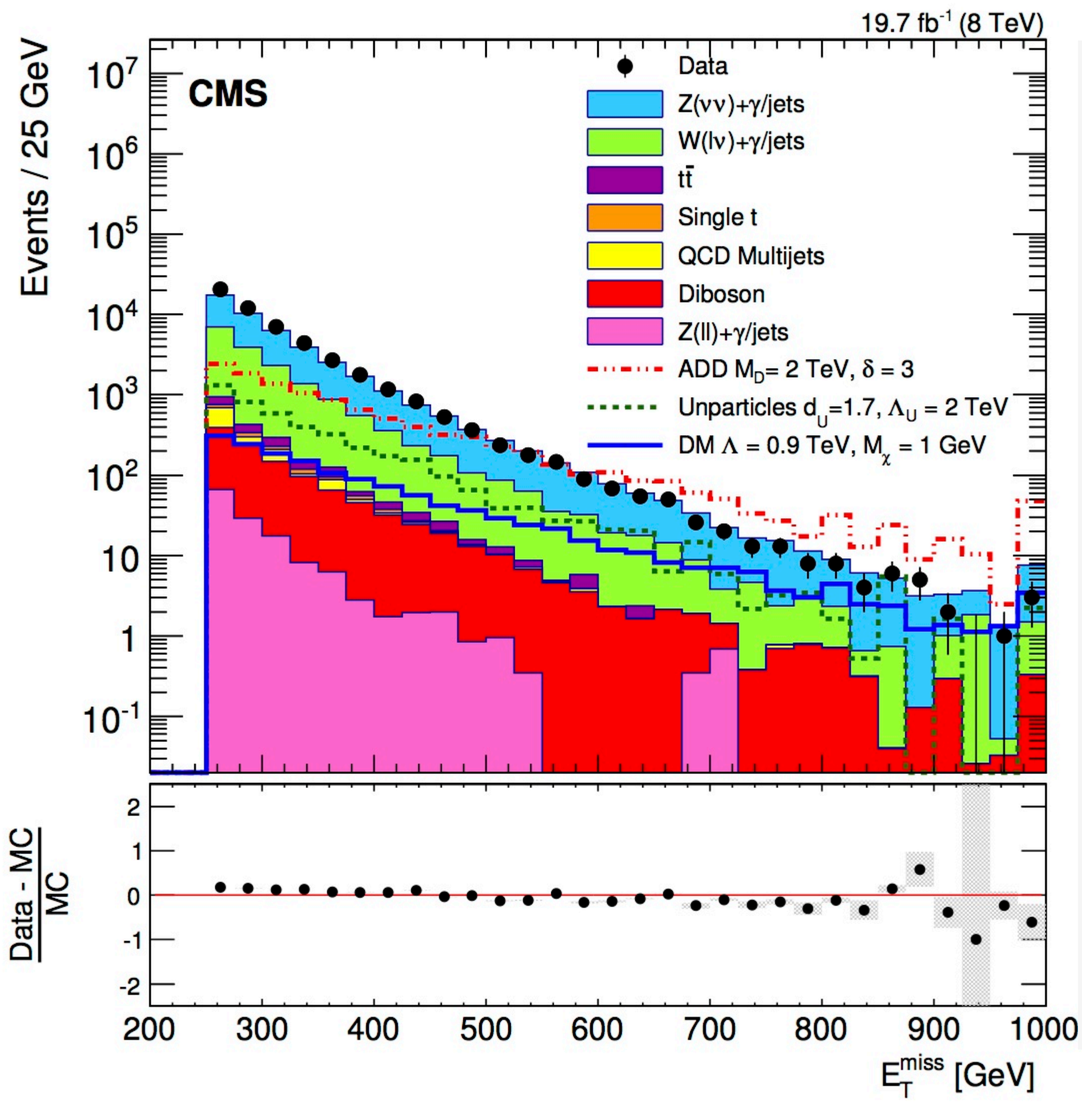


We can predict the contribution from Z + 1 jet



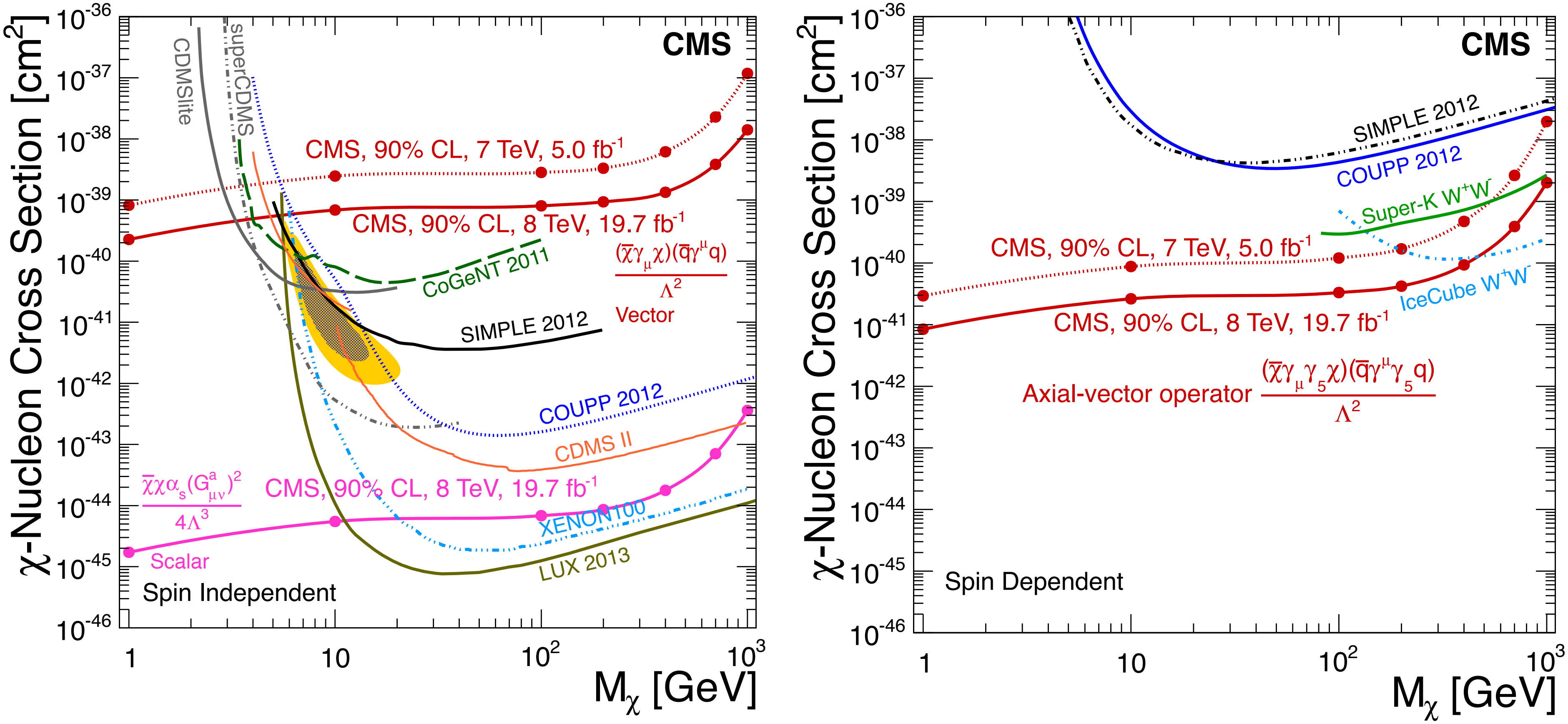
$$\frac{\sum_{i=e,\mu,\tau} B(Z \to \nu_i \bar{\nu}_i)}{B(Z \to \mu^+\mu^-)} \approx 6$$

Searching for dark matter: monojet search results

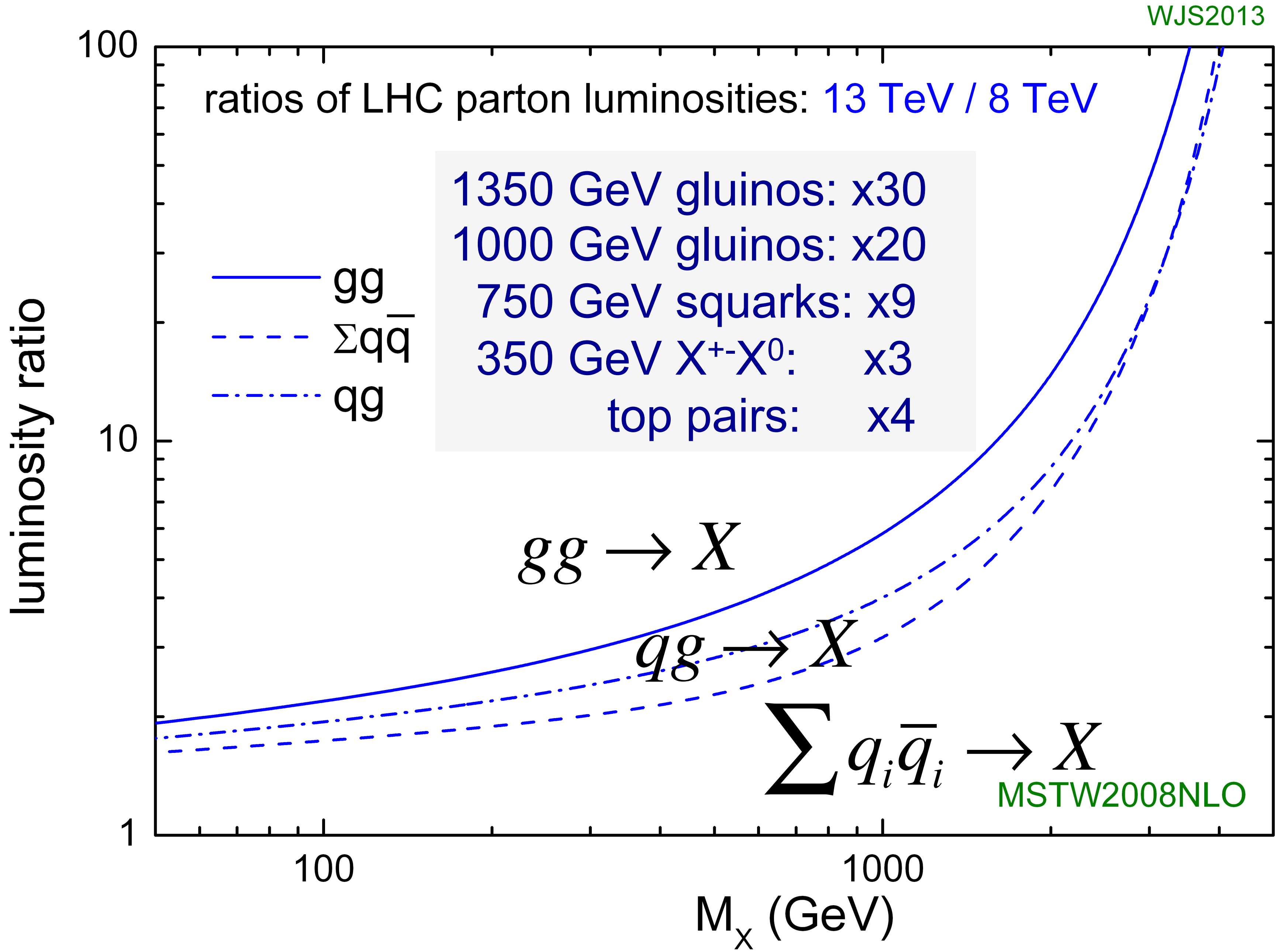


- MET > 250 GeV
- 1 central jet, pT>110 GeV.
- 2nd softer jet allowed, not back-to-back.
- Remarkable that QCD is so well controlled.
- Veto events with leptons
- Z→vv is dominant background; predict from Z→μμ control sample.

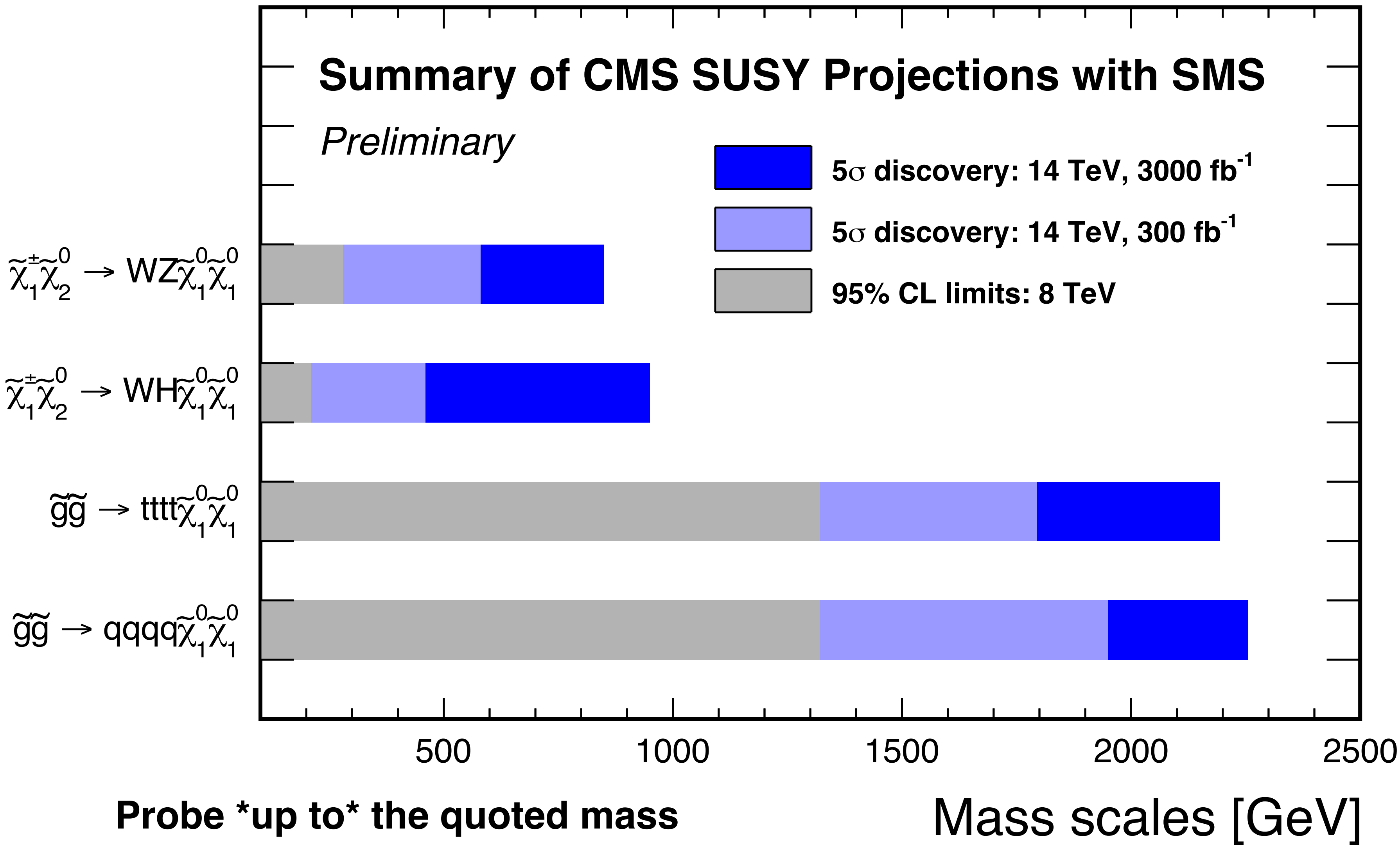
Searching for dark matter: monojet search results



Relative parton luminosities: 13 TeV vs. 8 TeV

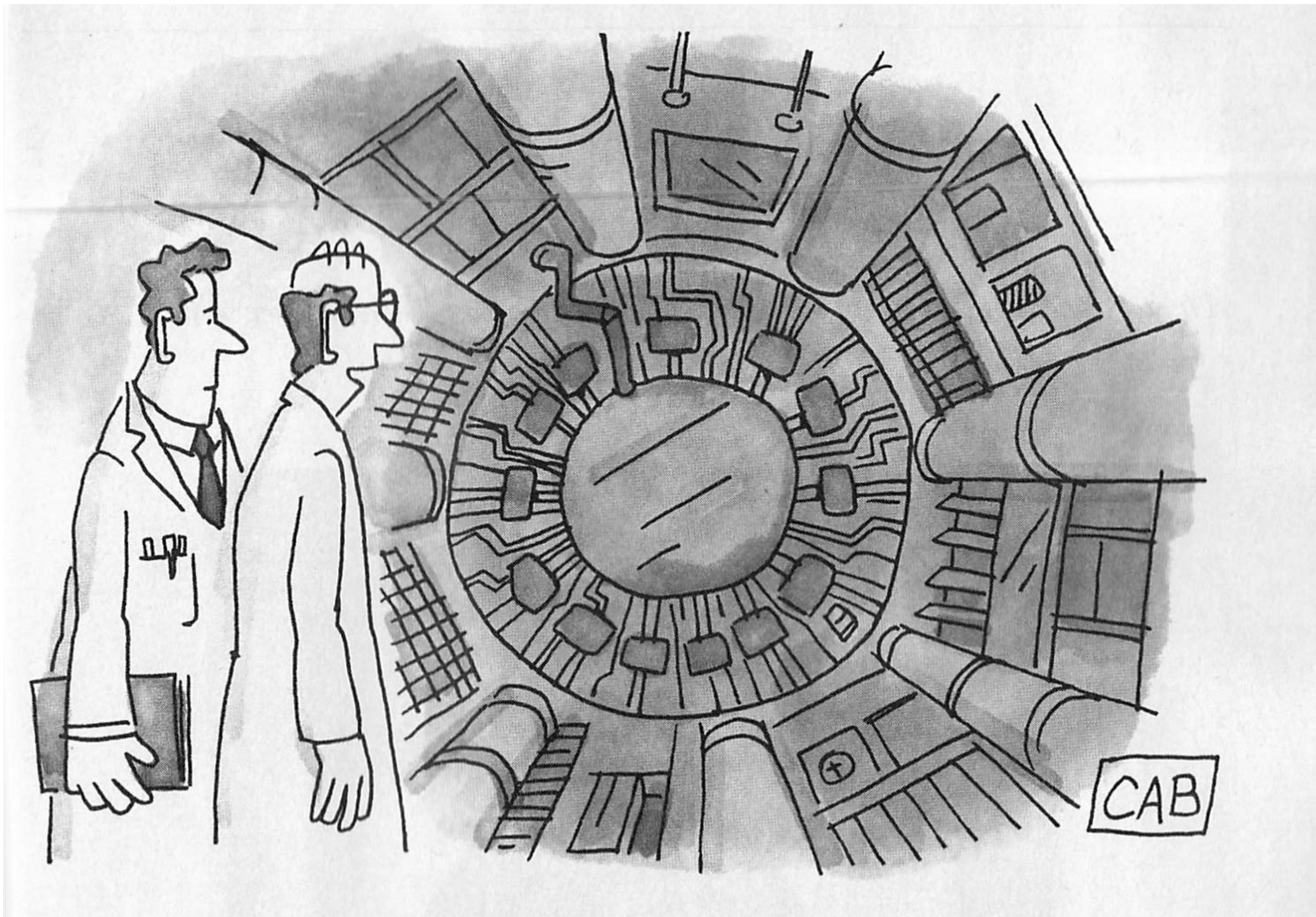


Sensitivity projections for selected searches



Probe *up to* the quoted mass

...is there a message here?



"Once you have a collider, every problem starts to look like a particle."