KCMS Lecture: SUSY

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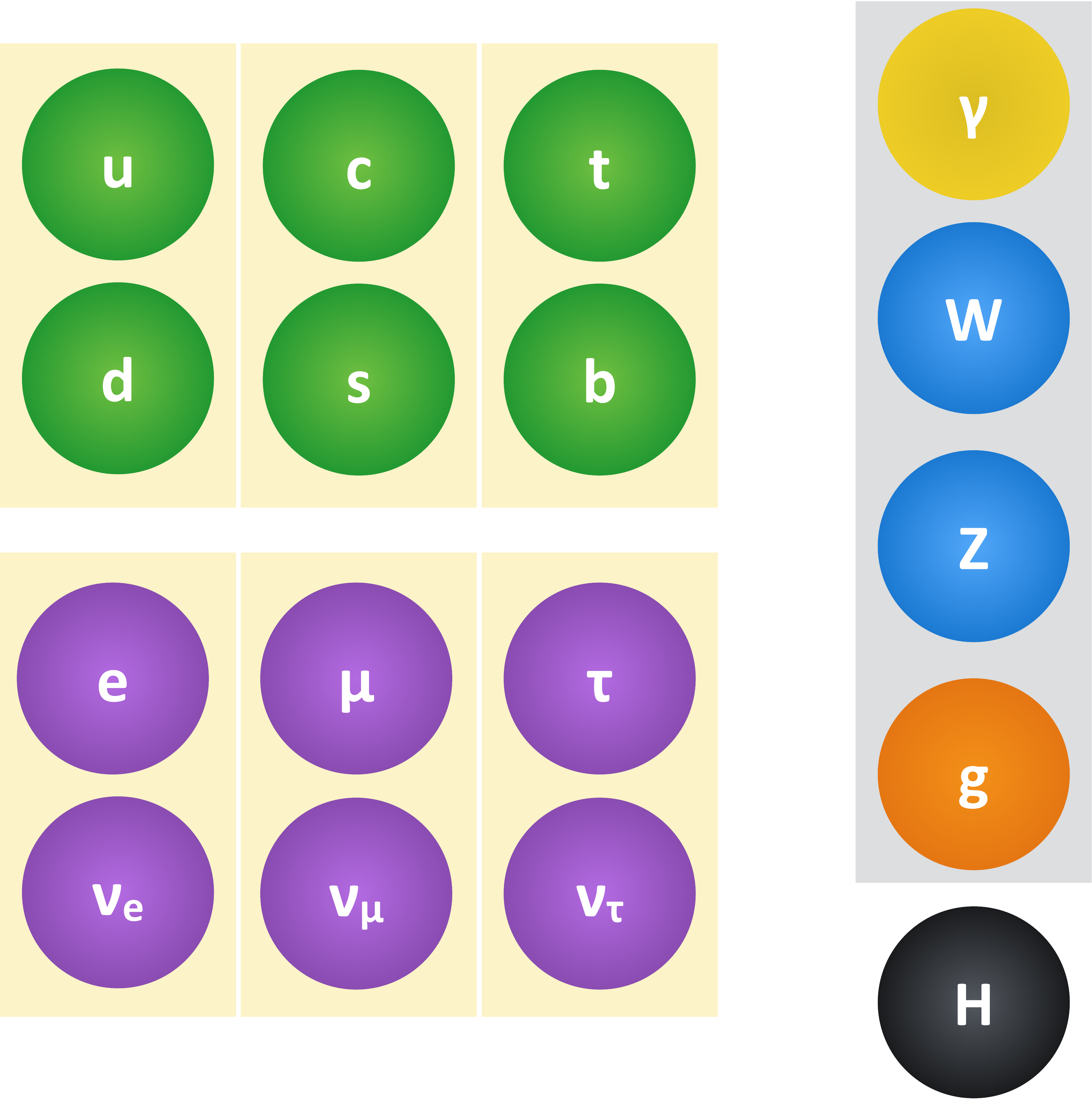
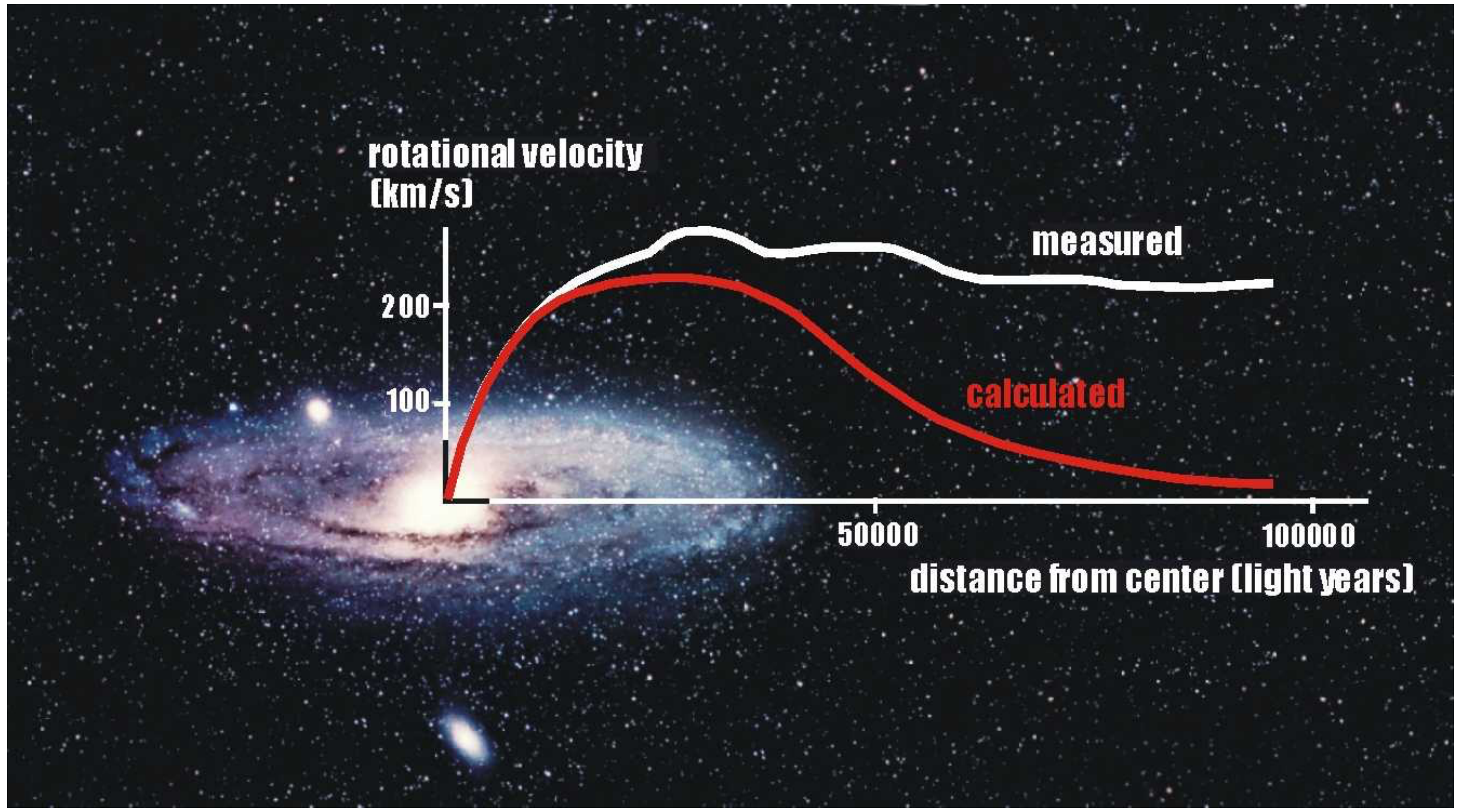
Standard Model and evidence of new physics

- Standard model of particle physics



- Evidence of physics beyond standard model (SM)
  - Non-zero neutrino mass
  - Dark Matter



Search for Supersymmetry (SUSY)

- Theoretical motivation for physics beyond SM
  - hierarchy problem, gauge coupling unification, …
- Hierarchy problem

$$m_h^2 = m_0^2 + \Delta m_h^2$$

Higgs mass	bare mass	quantum correction

Search for Supersymmetry (SUSY)

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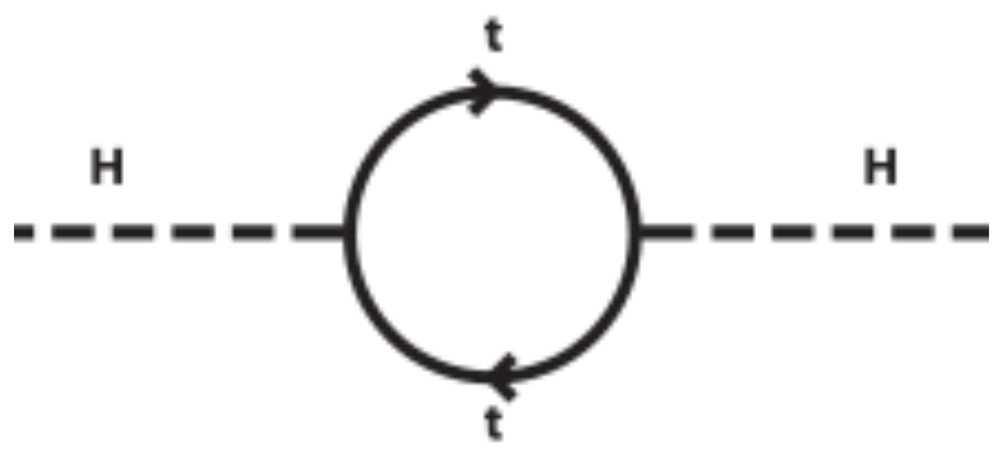
$$m_h^2 = m_0^2 + \Delta m_h^2$$

Why only top loop?

Because coupling to Higgs is proportional to fermion mass



$$-\frac{3}{8\pi^2} g_f^2 \Lambda^2$$

quadratic divergence

(Λ is scale of theory)

Search for Supersymmetry (SUSY)

- Theoretical motivation for physics beyond SM
  - hierarchy problem, gauge coupling unification, …
- Hierarchy problem

$$m_h^2 = m_0^2 + \Delta m_h^2$$

125^2 GeV^2

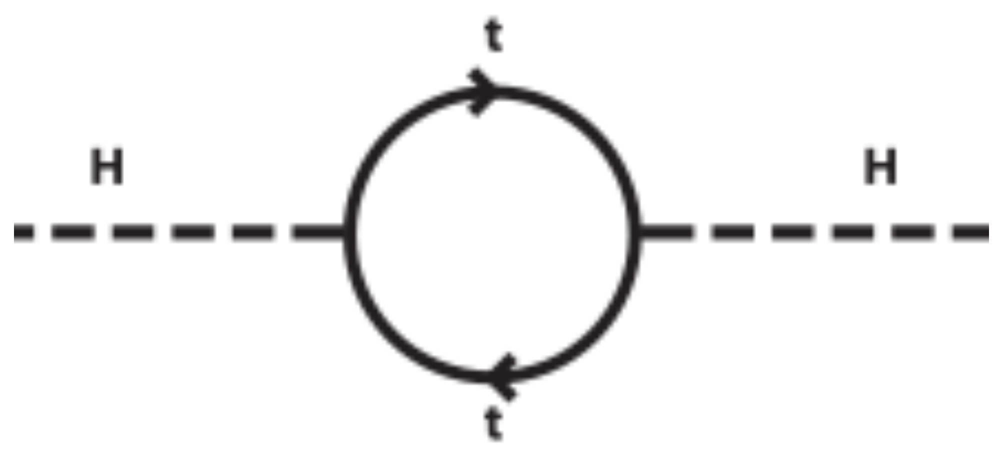
10^{34} GeV^2 at $\Lambda = M_{Planck}$

To get m_h=125 GeV,

m_0^2 = 1111 11111 11111 11111 11111 11111 15625 GeV^2

Δm_h^2 = 1111 11111 11111 11111 11111 11111 00000 GeV^2

m_0^2 should be fine-tuned to >30 orders of magnitude!

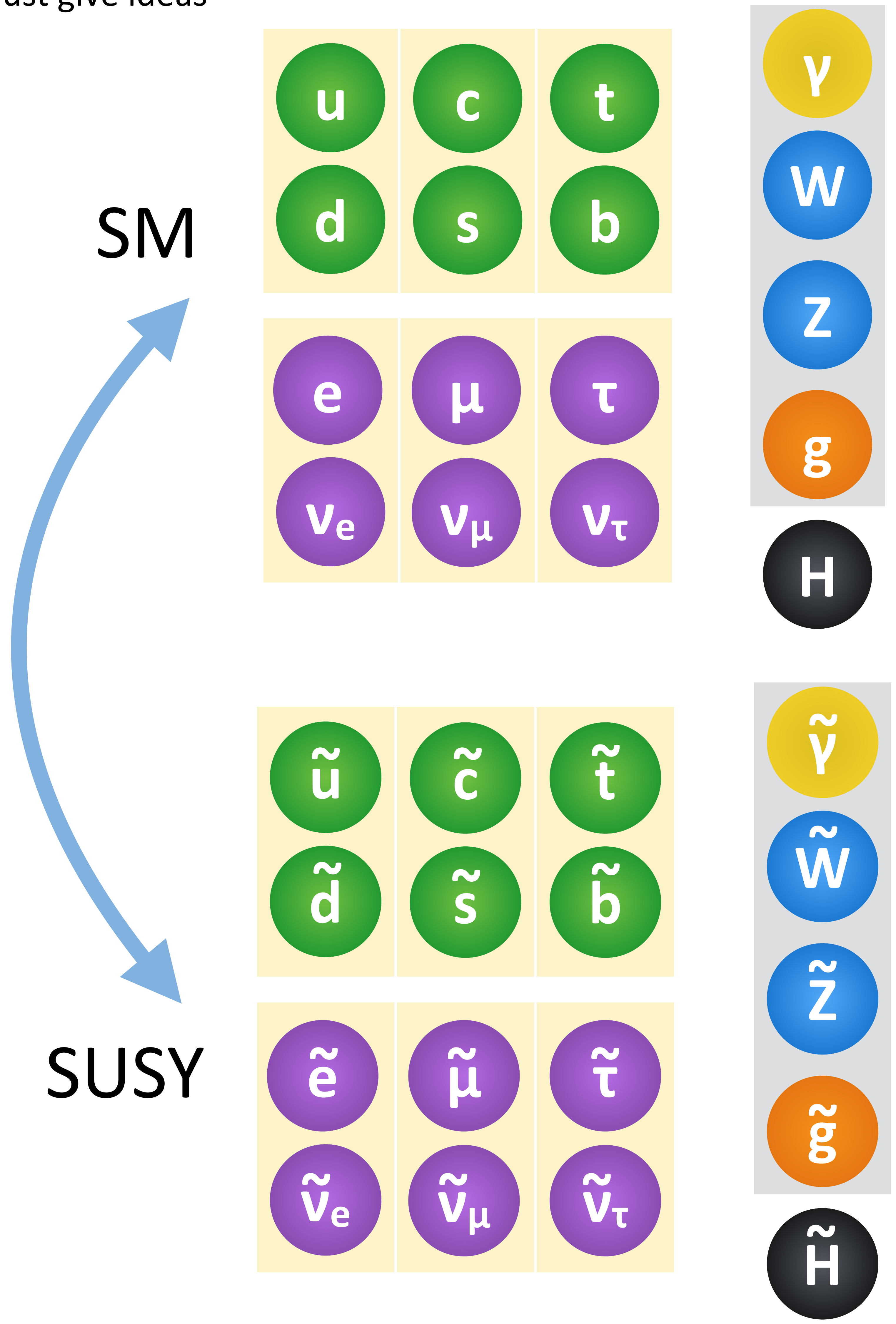


$$-\frac{3}{8\pi^2} g_f^2 \Lambda^2$$

quadratic divergence

Search for Supersymmetry (SUSY)

Cartoon not exact, just give ideas

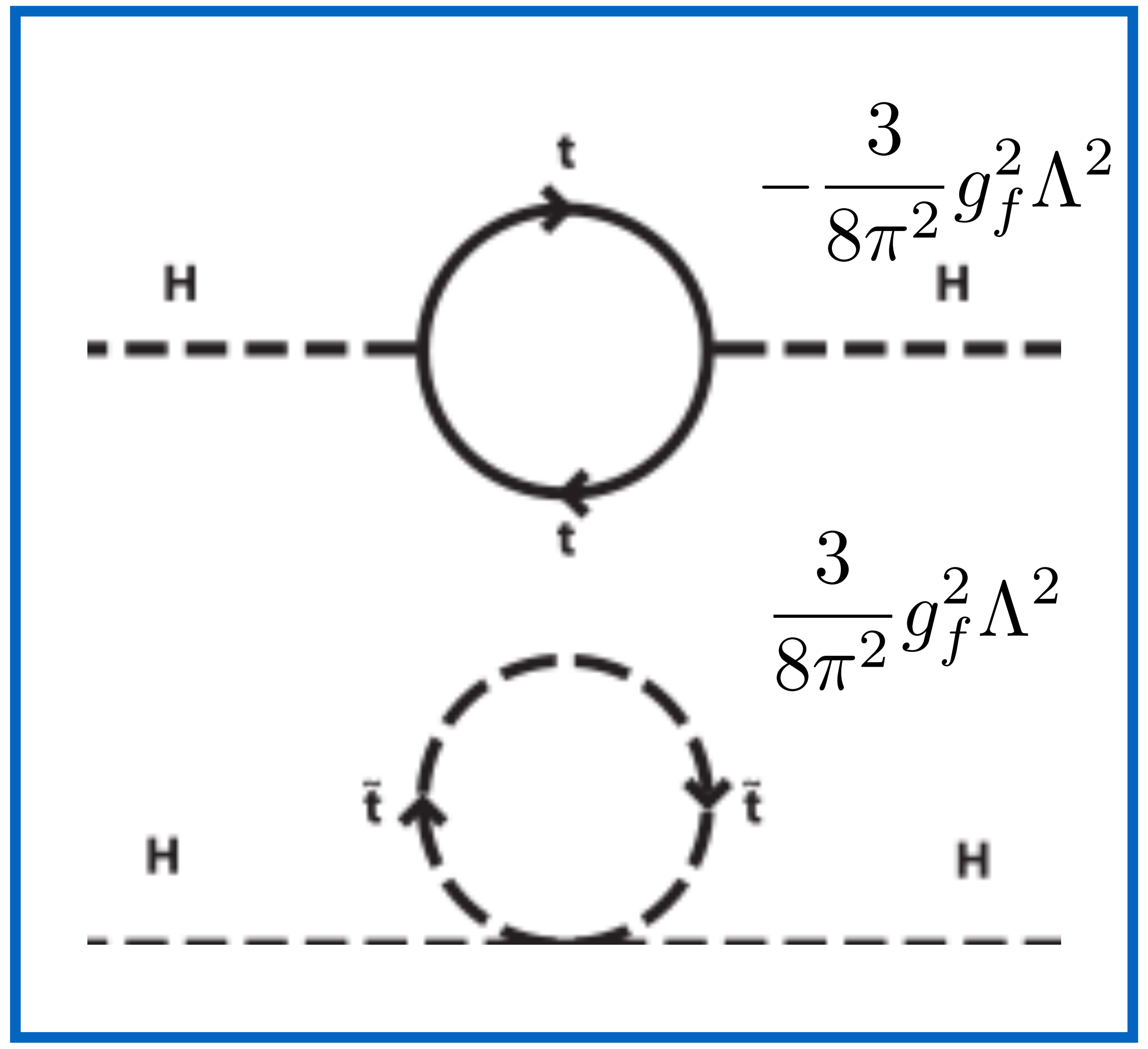


- SUSY solves this problem by introducing partners of each SM particle with spin different by 1/2
  - **fermion** → **boson partners** and **boson** → **fermion partners**
- Fermions and bosons have opposite sign in quantum correction calculation

$$m_h^2 = m_0^2 + \Delta m_h^2$$

$$-\frac{3}{8\pi^2} g_f^2 (m_{\tilde{t}}^2 - m_t^2)\log\frac{\Lambda^2}{m_{\tilde{t}}^2}$$

logarithmic divergence



quadratic divergence term gone!

SUSY is broken

- SUSY is not an exact symmetry (SM and SUSY particles have different masses) $\rightarrow$ SUSY should be broken
- No consensus on how to break SUSY (there are a few ideas)
- Major SUSY breaking mechanisms
  - Gravity-Mediated Supersymmetry Breaking: heavy $\tilde{G}$
  - Gauge-Mediated Supersymmetry Breaking (GMSB): light $\tilde{G}$ (eV scale)
  - Anomaly-Mediated Supersymmetry Breaking (AMSB)

Minimal Supersymmetric Standard Model (MSSM)

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\widetilde{G}$	(same)

- Minimal extension of the SM that realizes SUSY
  - Minimal number of new particles and interactions
- More than 100 parameters in addition to the 18 SM parameters …
- R-Parity conservation imposed
- Higgs sector requires 2 complex doublets
- Mixing between charged gauginos and charged higgsinos => charginos ($\tilde{C}_1^\pm, \tilde{C}_2^\pm$ or $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$)
- Mixing between neutral gauginos and neutral higgsinos => neutralinos ($\tilde{N}_1, \ldots$ or $\tilde{\chi}_1^0, \ldots$)

Naturalness and expected SUSY particles masses

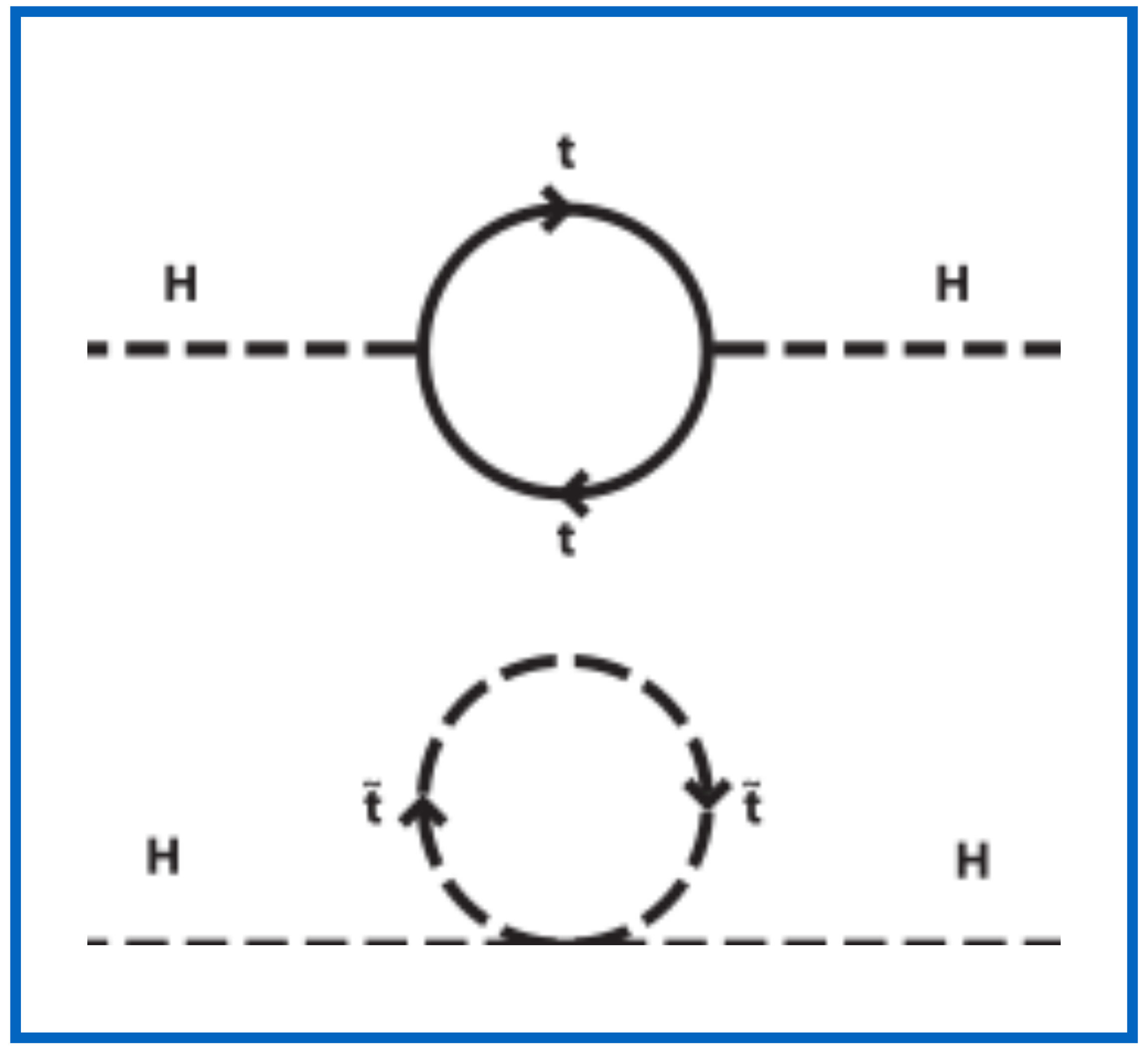
$$m_h^2 = m_0^2 + \Delta m_h^2$$

logarithmic divergence $-\frac{3}{8\pi^2} g_f^2 (m_{\tilde{t}}^2 - m_t^2) \log \frac{\Lambda^2}{m_{\tilde{t}}^2}$

Naturalness constraints

$m_{\tilde{g}} < \sim 2$ TeV

$m_{\tilde{t}} < \sim 1$ TeV

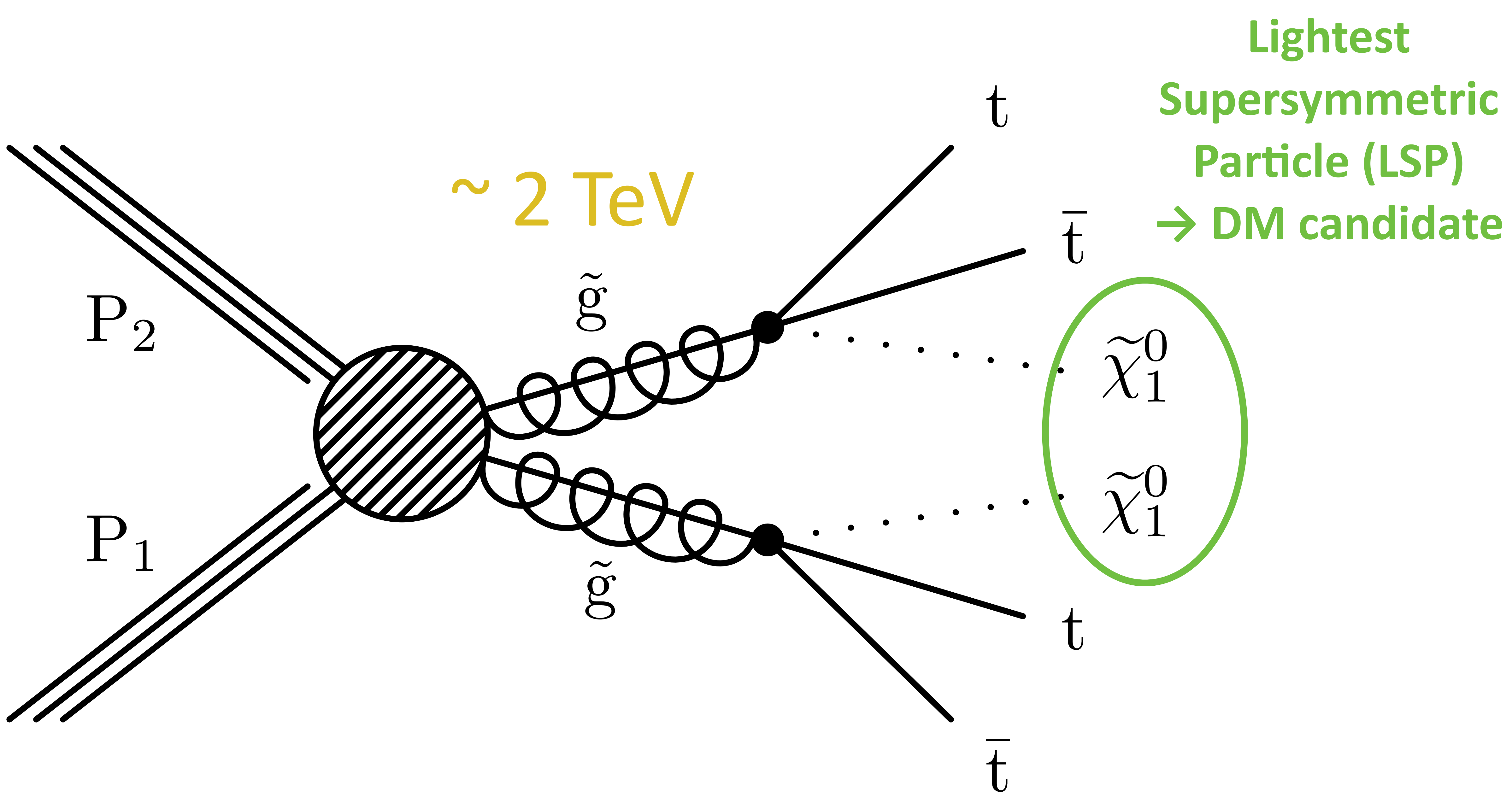


quadratic divergence term gone!

- Naturalness argument provides rough constraint on the masses of some SUSY particles
  - gluino, stop, and higgsino
- LHC SUSY searches have been focused on constraining masses of such particles

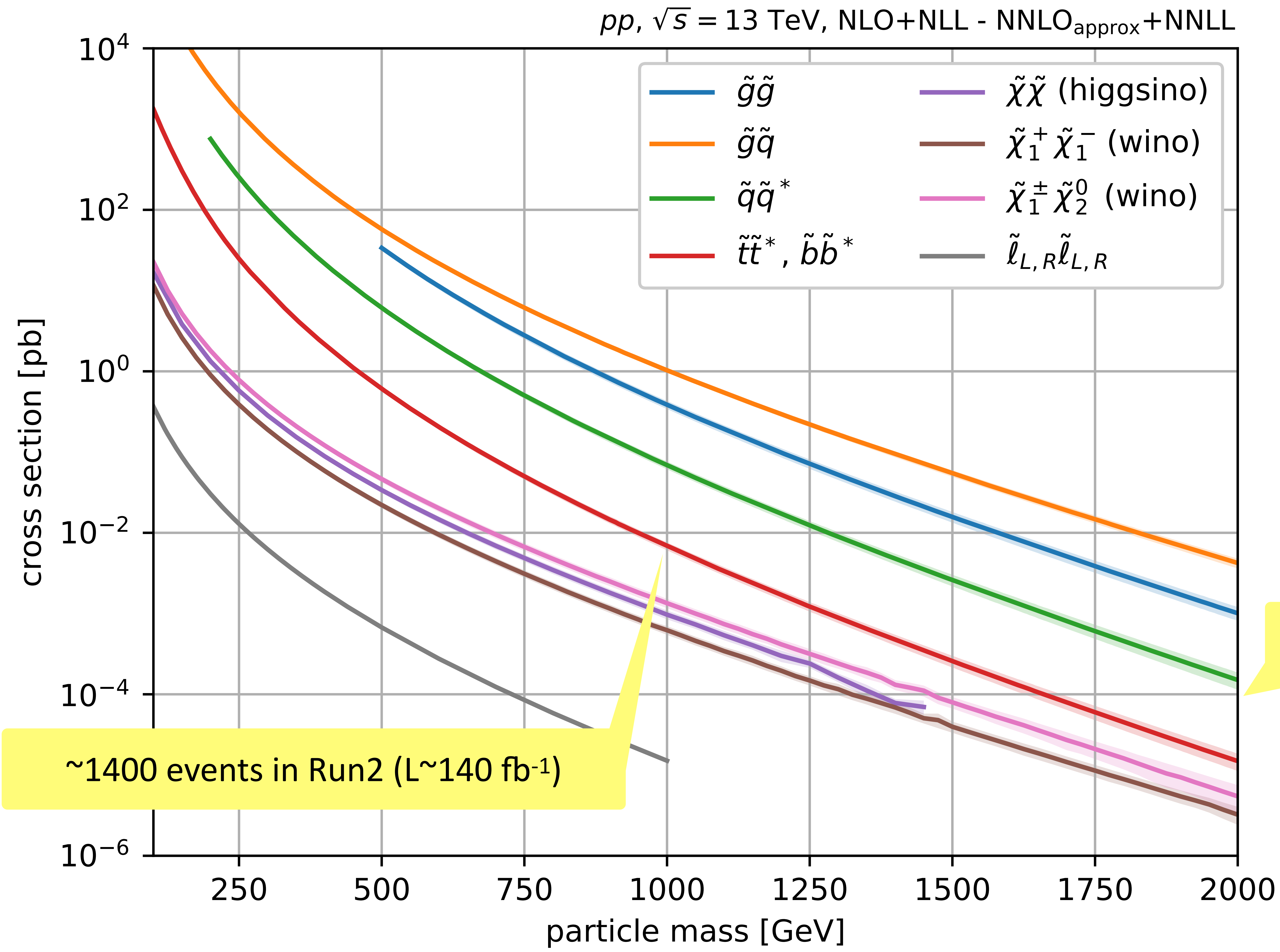
R-Parity

An example of RPC model



- R-parity = $(-1)^{3(B-L)+2S}$
  - SM particles: +1, SUSY particles: -1
  - Multiplicative quantum number
  - If conserved, SUSY particles produced in pairs at the LHC
  - Lightest SUSY Particle (LSP) is stable: if Q=0, it is a dark matter candidate
- Because R-Parity conservation provides dark matter candidate and is favored by long proton lifetime, it is a preferred assumption for SUSY searches
- Most SUSY searches target RPC models
- In RPV models, LSP allowed to decay directly to SM particles

SUSY production at LHC



- Strong and EWK productions
- At m=2000 GeV,
  $\sigma(pp \rightarrow \tilde{g}\tilde{g}) \approx 1$ fb
- Why smaller cross section for higher particle mass?

Models

- **Simplified models (`/SMS-T1tttt_…`)**
  - Less dependent on fundamental assumptions
  - Enable comprehensive studies of individual SUSY topologies
  - Well-defined cross section
  - 100% BR for the interested decay chain
    - Limit can be weakened in full theory (BR != 100%)
- **phenomenological-MSSM (pMSSM)**
  - Eliminate parameters that are free in principle but have already been highly constrained by measurements
  - 19 more parameters in addition to SM → More realistic than Simplified Models

Ingredients for new physics search

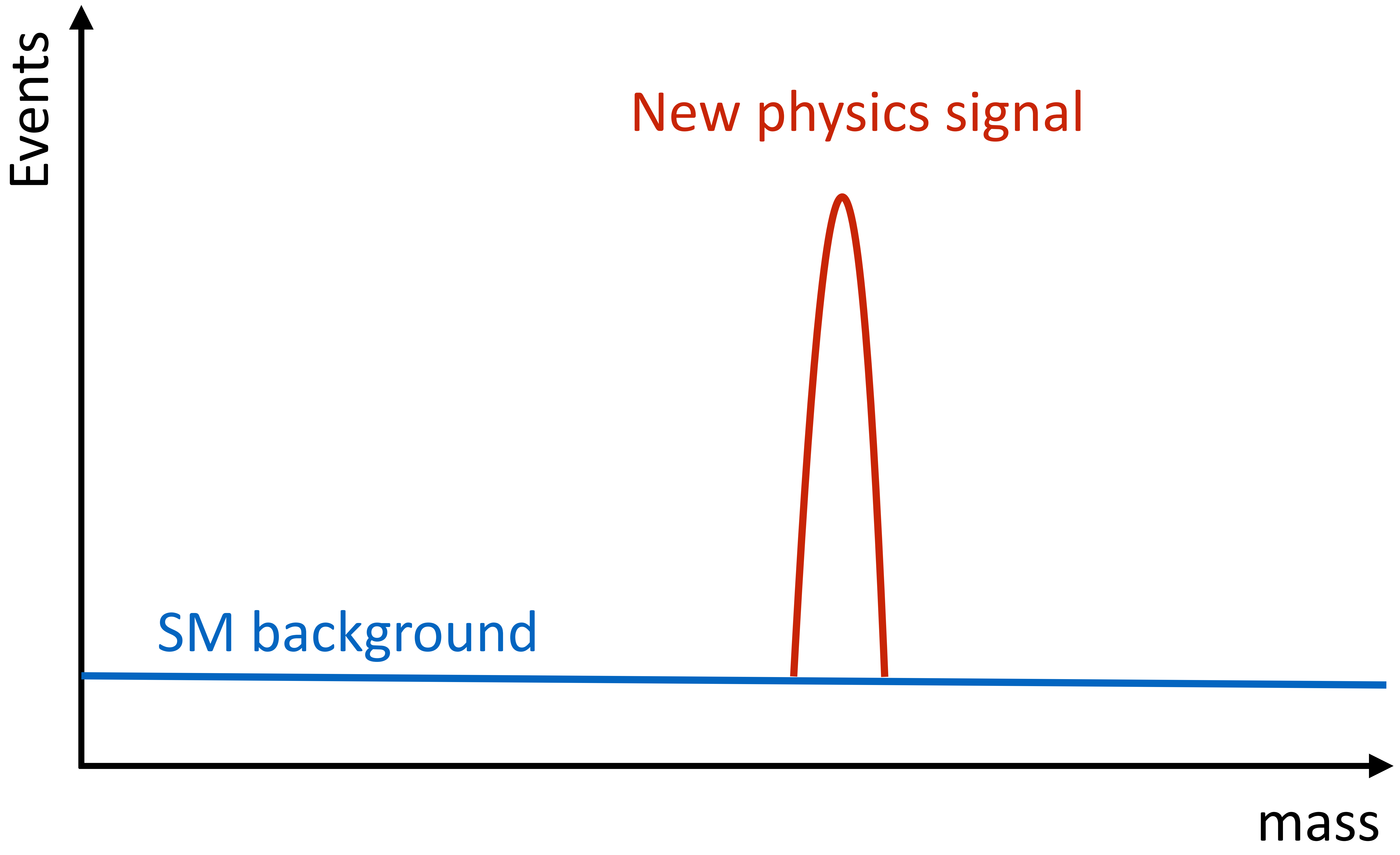
- Detector & collider
- Define what you want to look for
  - Target model (physics motivation) or interested phase space (signature)
- Design trigger(s): this is the starting point of your analysis
- Define analysis strategy: selection, binning, …
- Estimate backgrounds: new physics search $\approx$ understanding backgrounds
  - Background = SM + instrumental

What lessons can we learn from these (and many other) examples in our field? First of all, searches are difficult! Here is a list of some common mistakes or situations that occur. Do any of these affect your analysis?

- The detector may not be correctly calibrated or aligned, leading to mismeasured objects in events.
- Limitations in the detector design or technology can produce spectacular mismeasurements such as E_T^{miss} or lepton isolation in rare circumstances. Event displays can be useful for identifying unusual problems, but they can also be used in a problematic way to reject events without a well-defined procedure.
- Trigger efficiencies (including their kinematic dependence) may not be fully accounted for and can bias yields in the signal or control regions.
- Changes in the experimental conditions or calibrations may not be fully taken into account. For example, at the LHC, the presence of multiple pp collisions within a single beam crossing leads to multiple vertices and can affect many reconstructed quantities. This effect is luminosity dependent.
- A prescription for a "standard" analysis method or reconstructed object (b-tagged jets, leptons, etc.) may not give the correct result when applied in the sample of events used in your analysis. Was the standard recipe validated in an event sample in which the relevant properties are similar to yours?
- Monte Carlo event samples may not have been generated correctly.
- Monte Carlo event samples may not have correctly modeled the true physics. For example, the number of extra jets from initial- or final-state radiation may not be correct. The simulation may not model all of the kinematic correlations in the signal, leading to an incorrectly estimated signal efficiency.
- The yield in signal region can be biased by tuning selection requirements on the signal region in the data.
- The yield in the signal region can be biased by tuning selection requirements on the region used to determine the background to be subtracted.
- The background shape or normalization may be estimated incorrectly. Background estimates are especially tricky if there are contributions from many sources or if control samples are obtained with different triggers.
- Understanding the background in one kinematic region does not necessarily mean that you understand it in another region. The background composition may vary substantially from a control sample to a signal region, and the kinematic distributions may also vary between these regions.
- The shapes used in a fit may not be adequate to describe the data, which can easily produce a bias in the extracted signal yield. This effect is especially worrisome in multidimensional fits, where the shapes may not fully track the correlations among kinematic variables.
- Theoretical assumptions used to determine the backgrounds or their uncertainties may be incorrect. Consultation with theorists can be valuable in such cases.
- Systematic uncertainties may be underestimated or incomplete.
- Correlations may not be taken into account correctly. Correlations can arise from many different mechanisms. Two kinematic quantities can become correlated not only analytically, within a given sample of events, but also through a variation in the sample composition as one variable is changed.
- Backgrounds peaking under the signal may not be fully taken into account.
- The signal efficiency may be incorrectly determined.
- The signal significance may not be be estimated correctly.
- The look-elsewhere effect may not have been taken into account in assessing the statistical significance.
- A signal can be created artificially as a "reflection" of a background process that produces a peak or other structure in a related kinematic variable.
- Averaging multiple measurements can be tricky; all uncertainties and their correlations must be understood.
- Bug in your program. Bug in someone else's program. Bug in ROOT.
- Advisor is in a hurry! Need to finish thesis! No time to look for more problems!
- People sometimes stop looking for mistakes or declare a result ready to be presented publically when they obtain a "desirable" result. In precision measurements, people sometimes prefer to obtain agreement with previous results, leading to a clustering of measurements that is better than the uncertainties should typically allow.
- A superposition of several of the above effects.

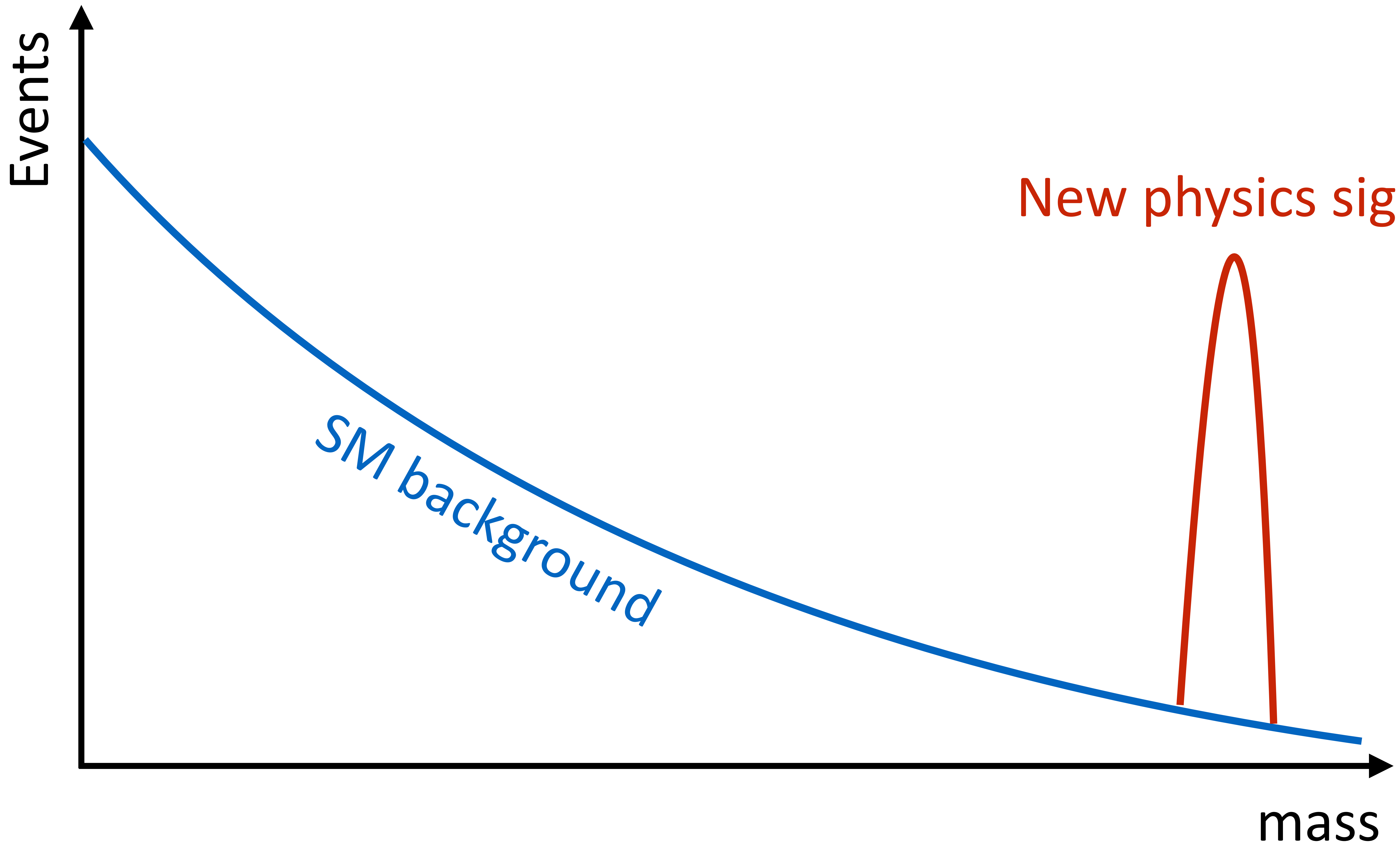
Jeff Richman (UCSB)

How do we know there's something other than SM?



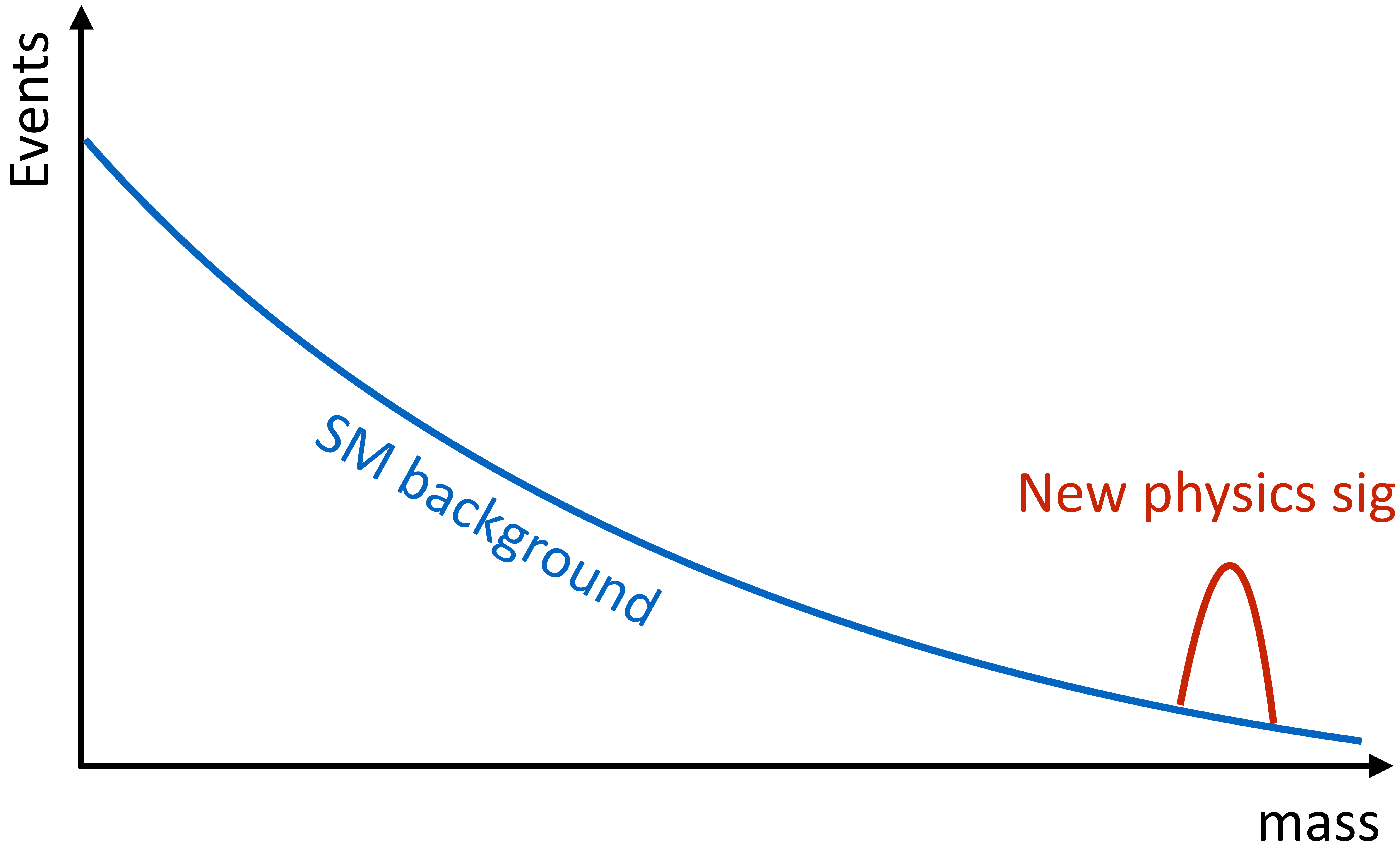
Difficulty level:
1

How do we know there's something other than SM?



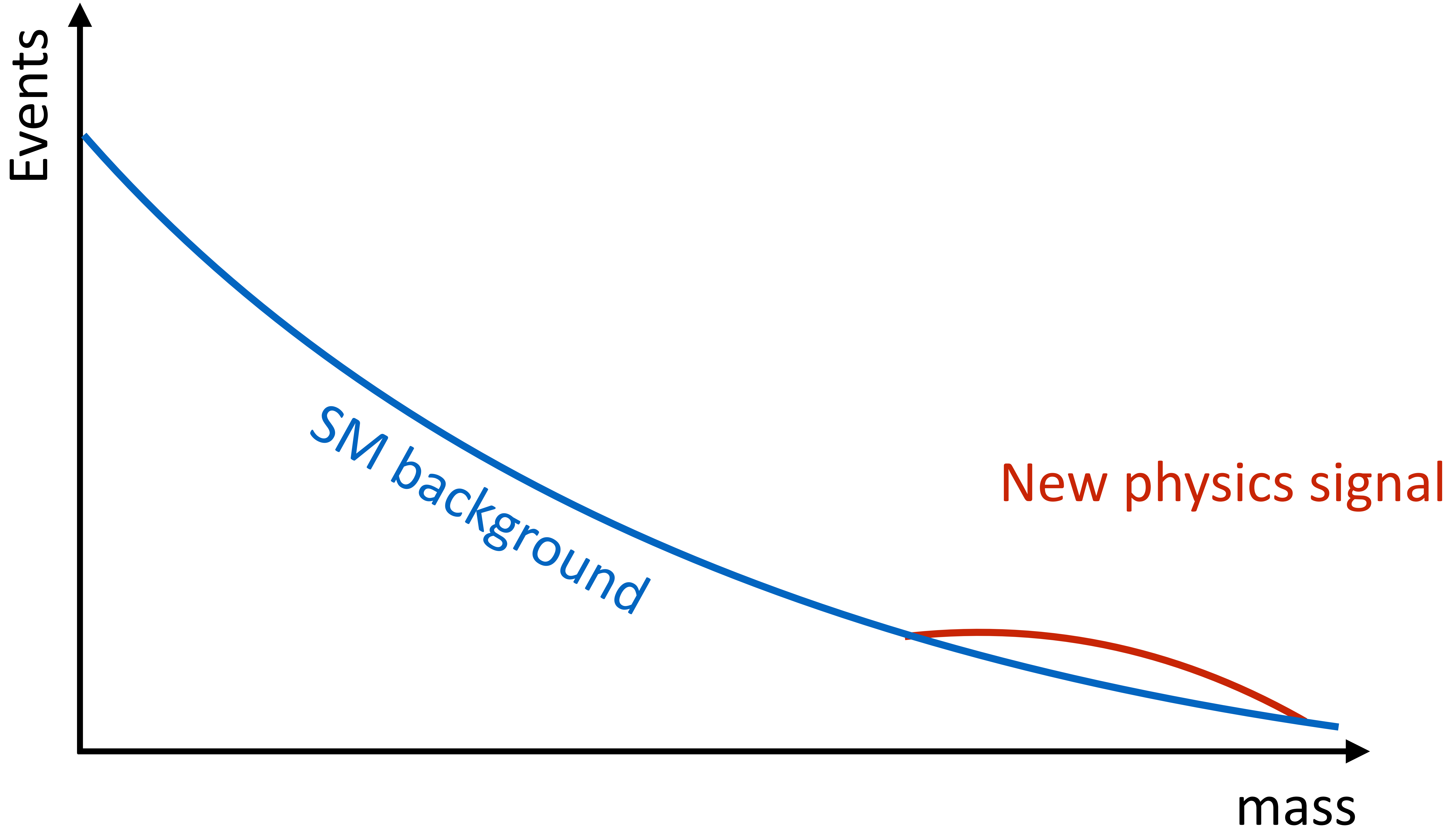
Difficulty level:
2

How do we know there's something other than SM?



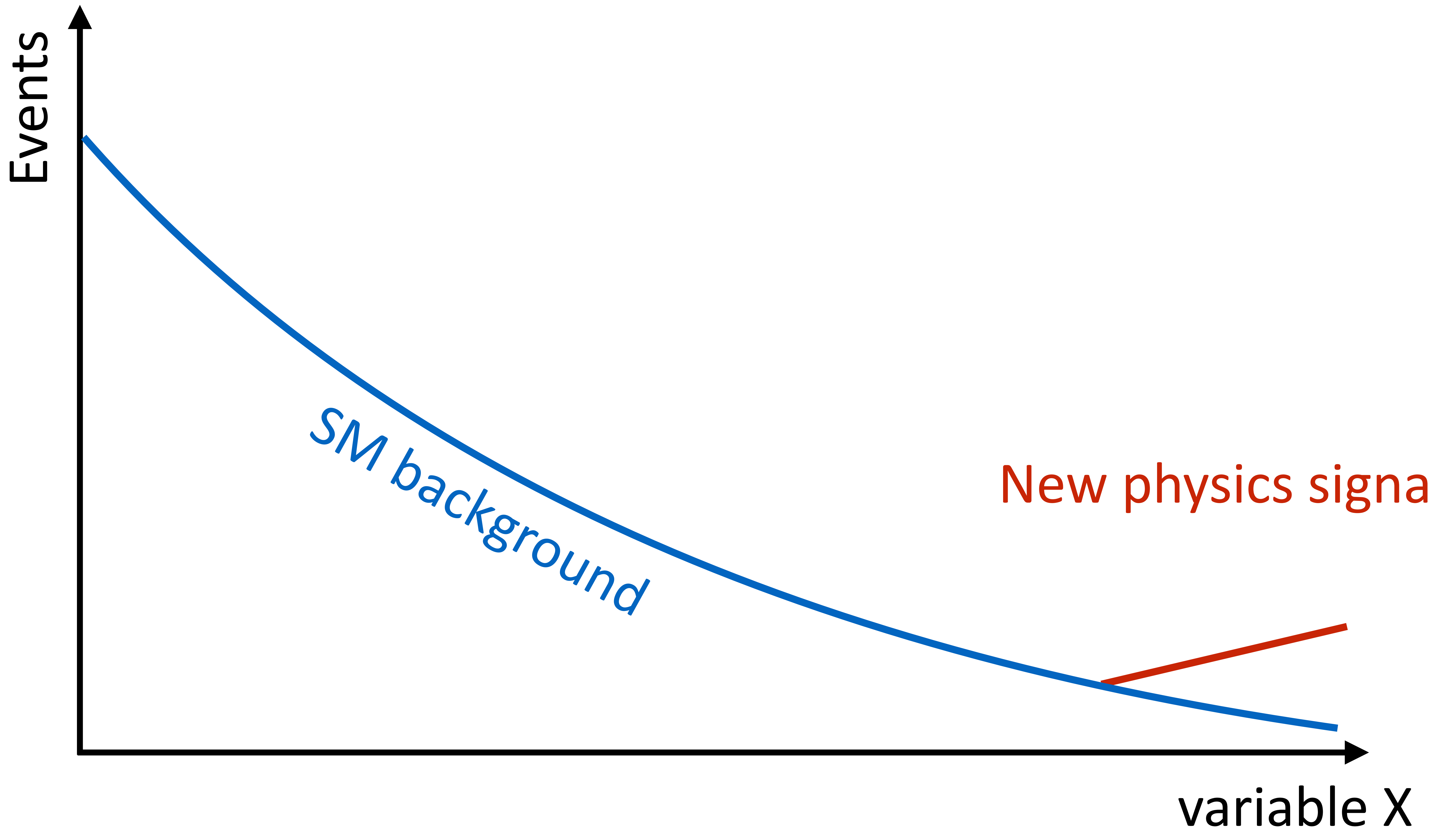
Difficulty level:
4

How do we know there's something other than SM?



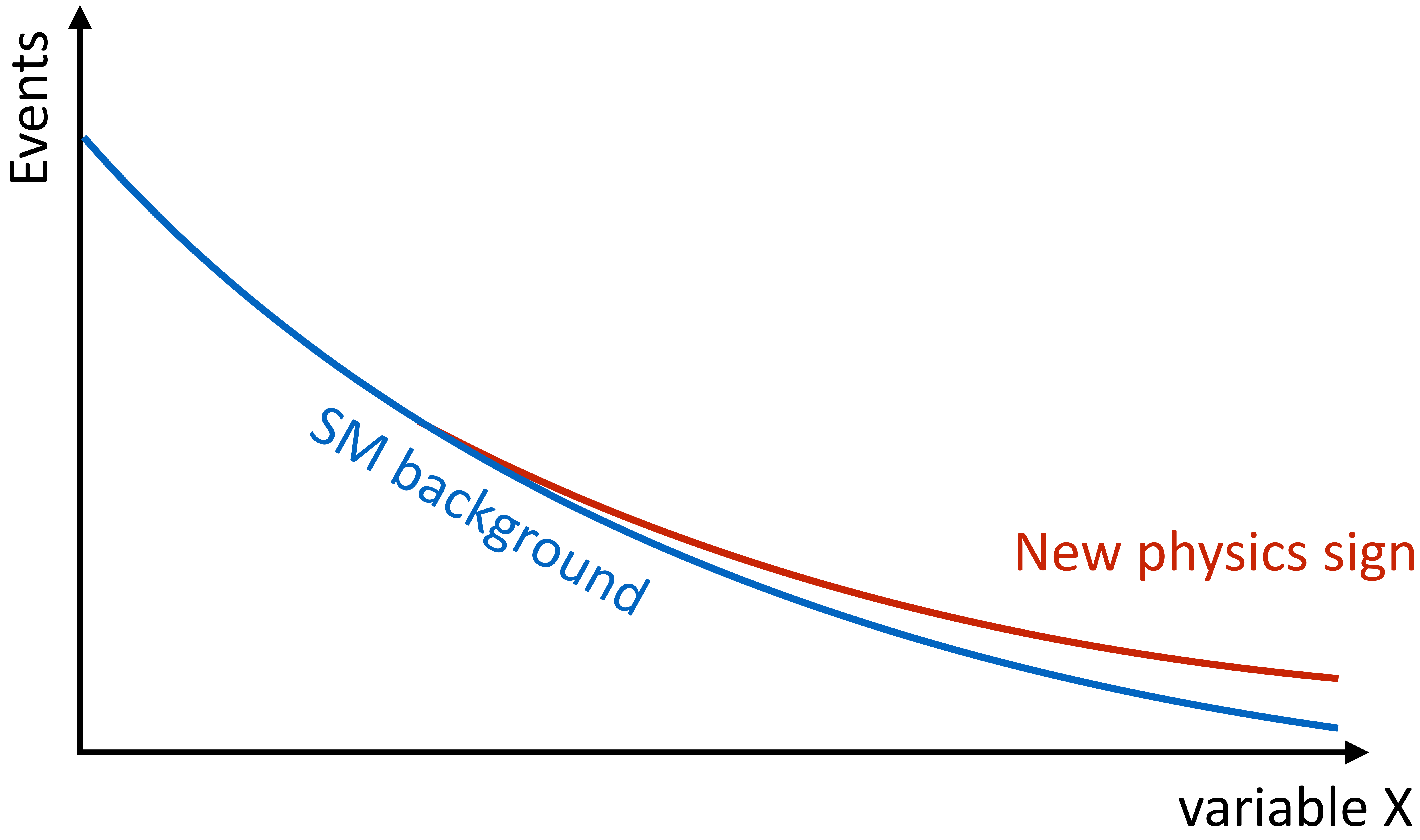
Difficulty level:
6

How do we know there's something other than SM?



Difficulty level:
7

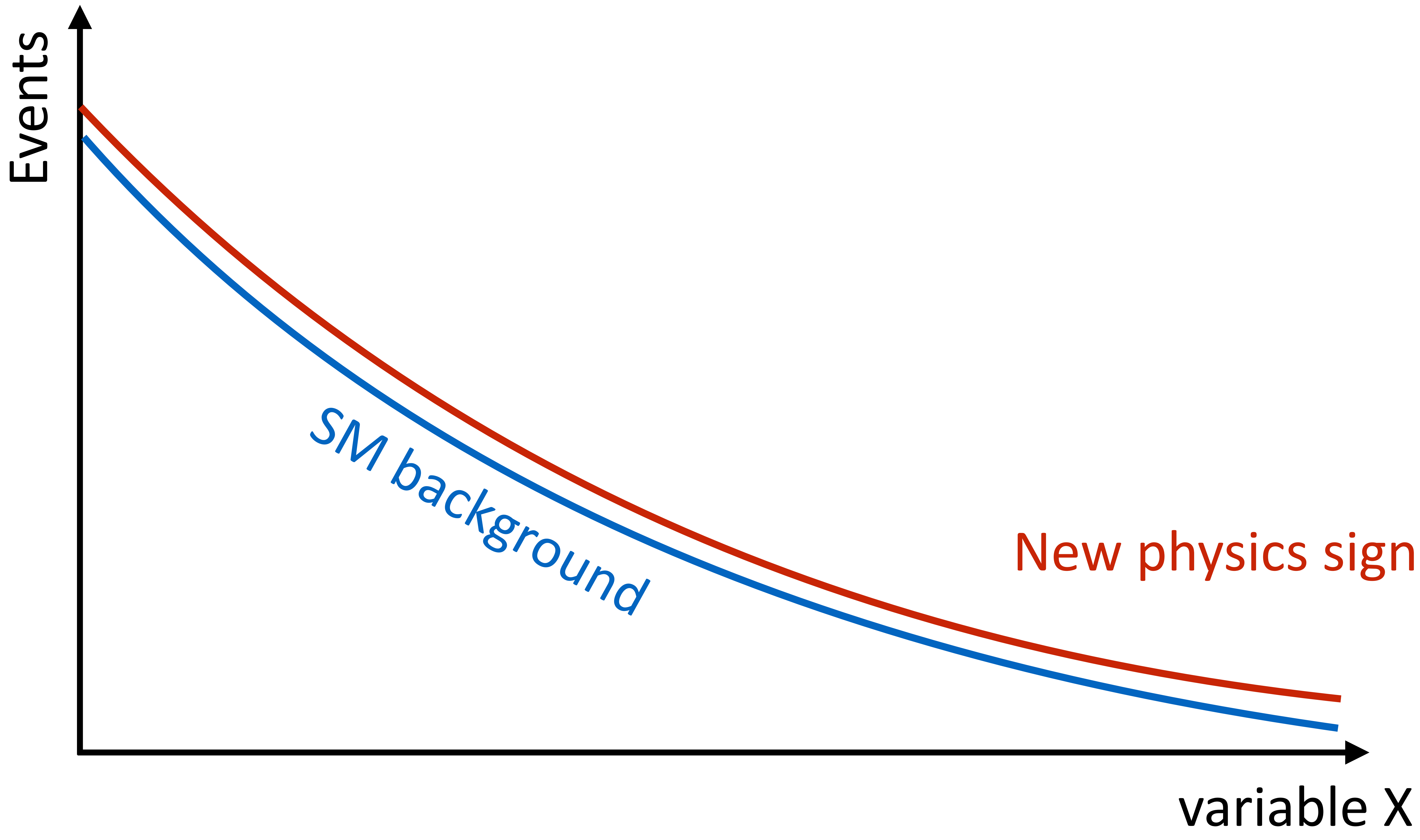
How do we know there's something other than SM?



Difficulty level:
9

This is what most SUSY searches do; look at broad excess in the spectrum of variable X (and Y, Z, …)

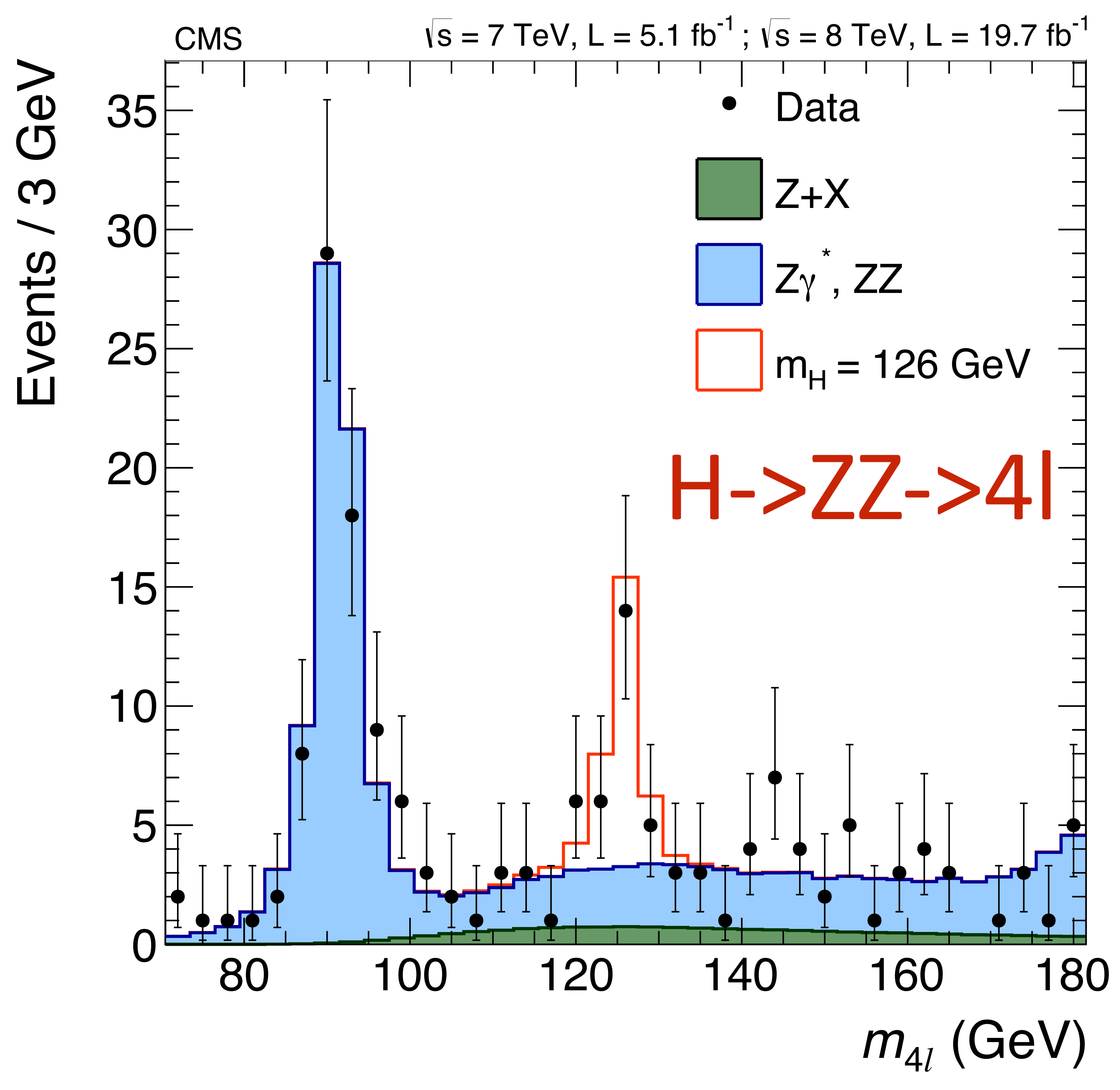
How do we know there's something other than SM?

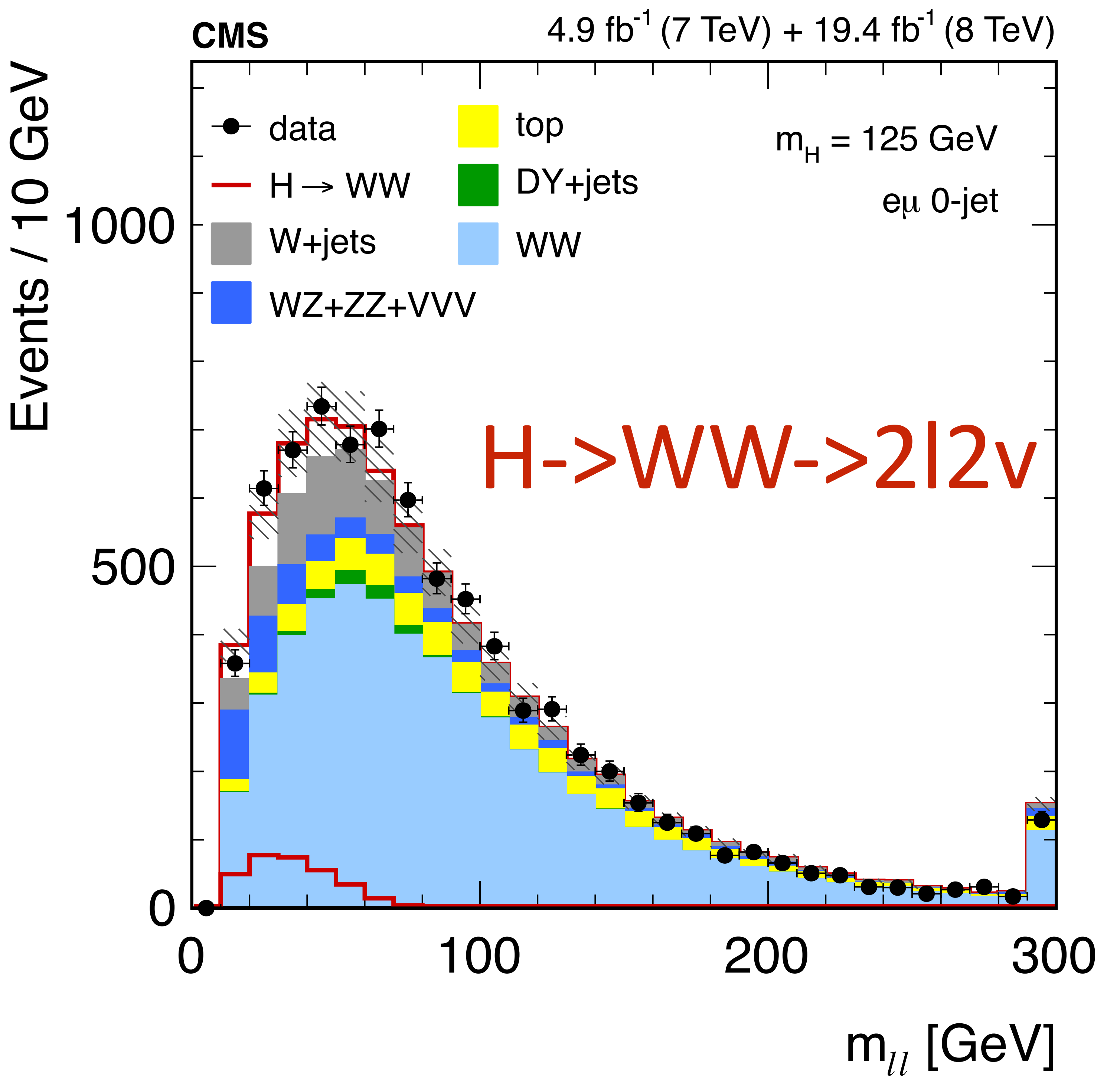


Difficulty level:
10

Example

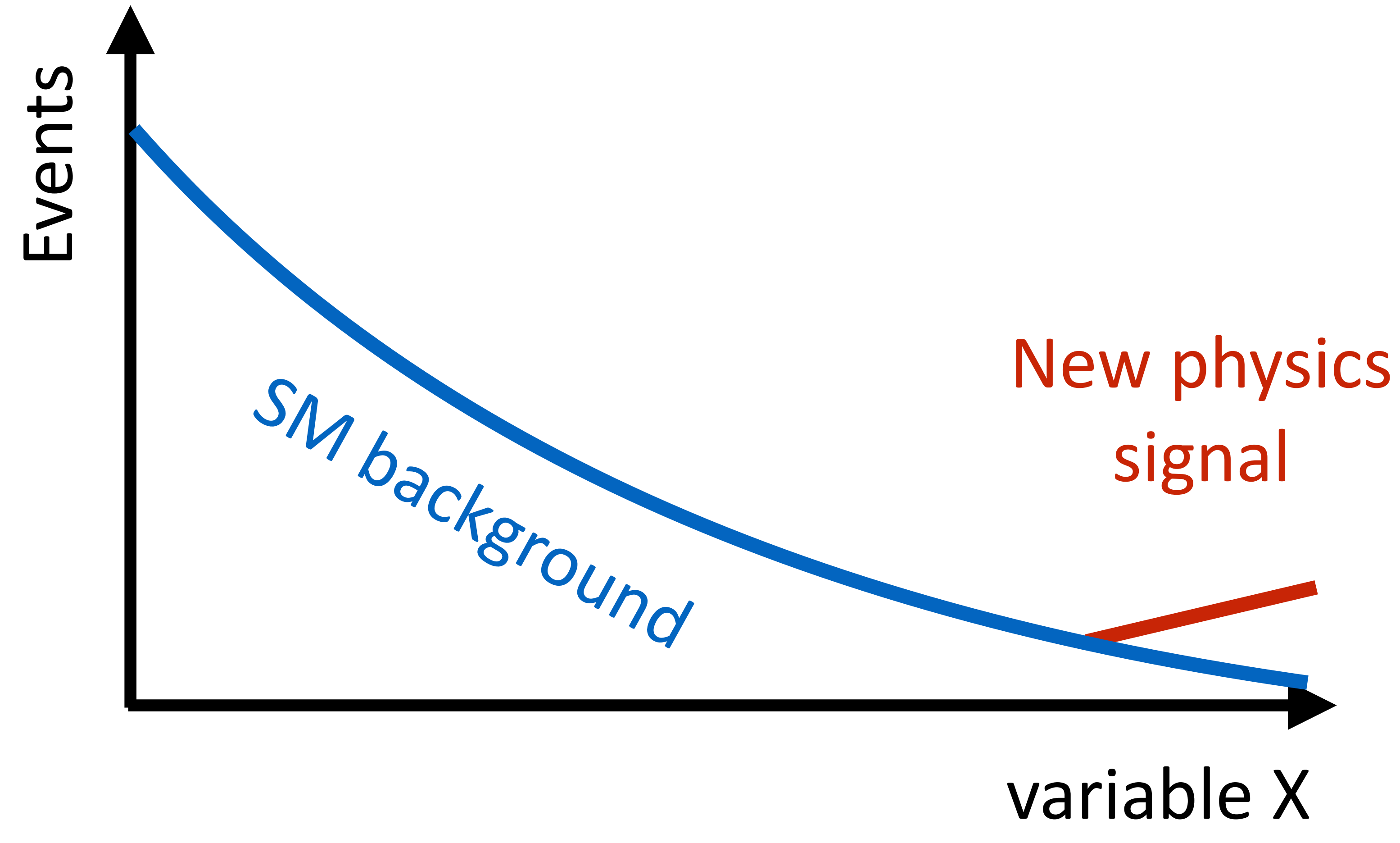
- Search for Higgs boson: there were 3 main decay modes
  - H->ZZ->4l, H->gg and H->WW->2l2v
- H->ZZ->4l and H->gg have mass peak while H->WW->2l2v does not

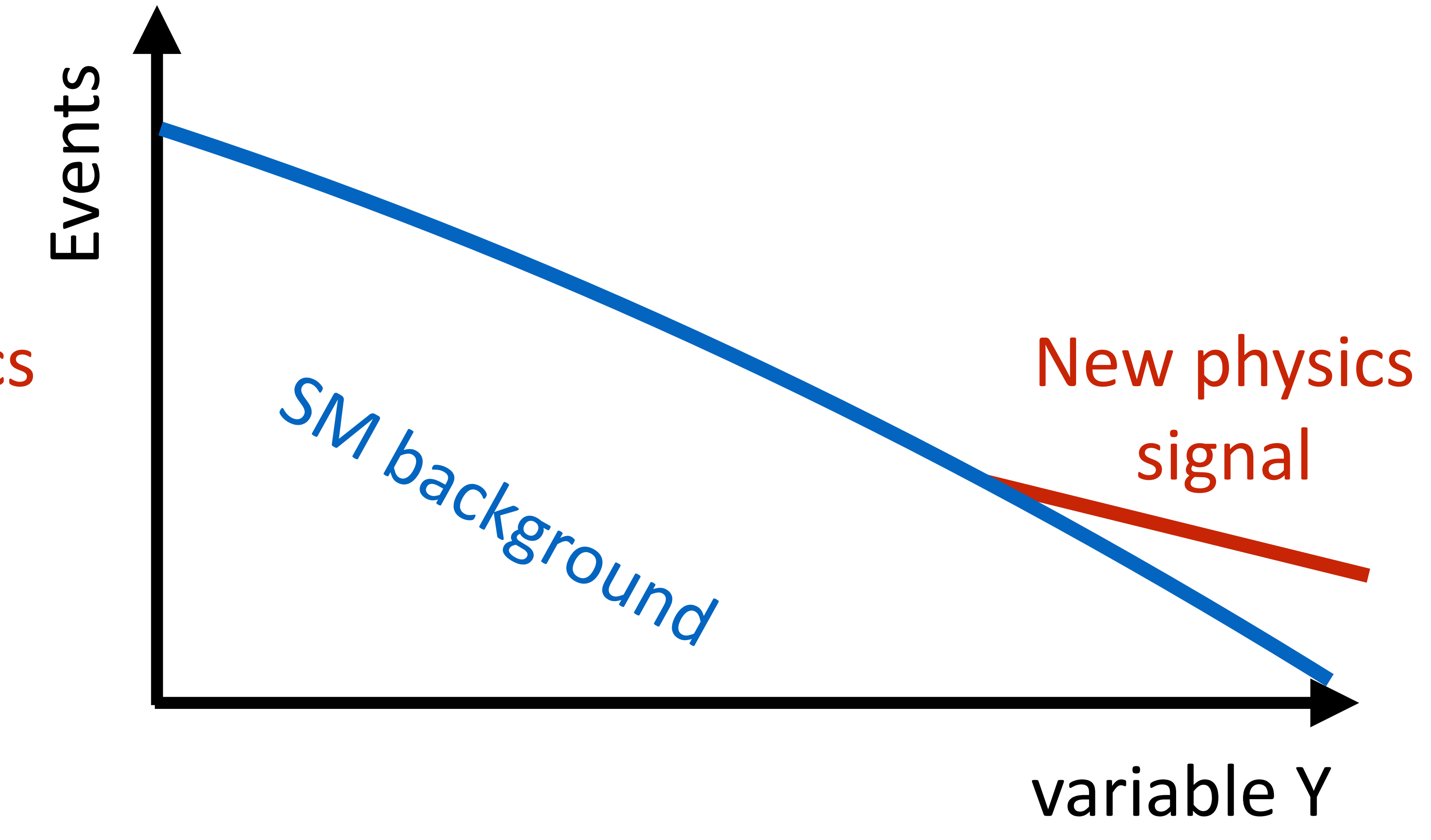


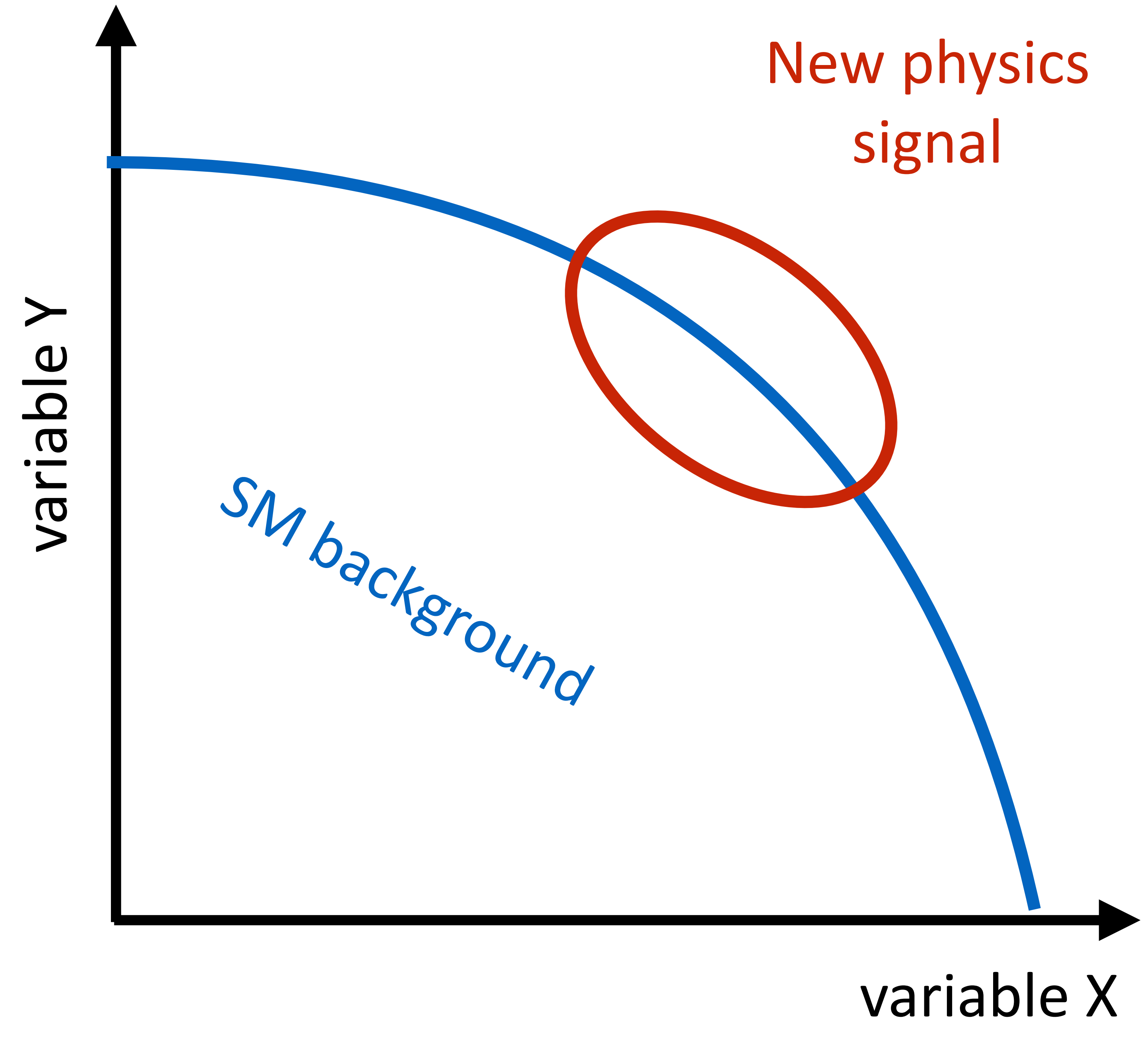


Look at the tail of distributions

- Search is possible only if S/B (signal/background) is large
  - For B to be small, we should go to the tail of distribution of a variable
  - For S to be large, cross section shouldn't be small
- There are usually more than one variable



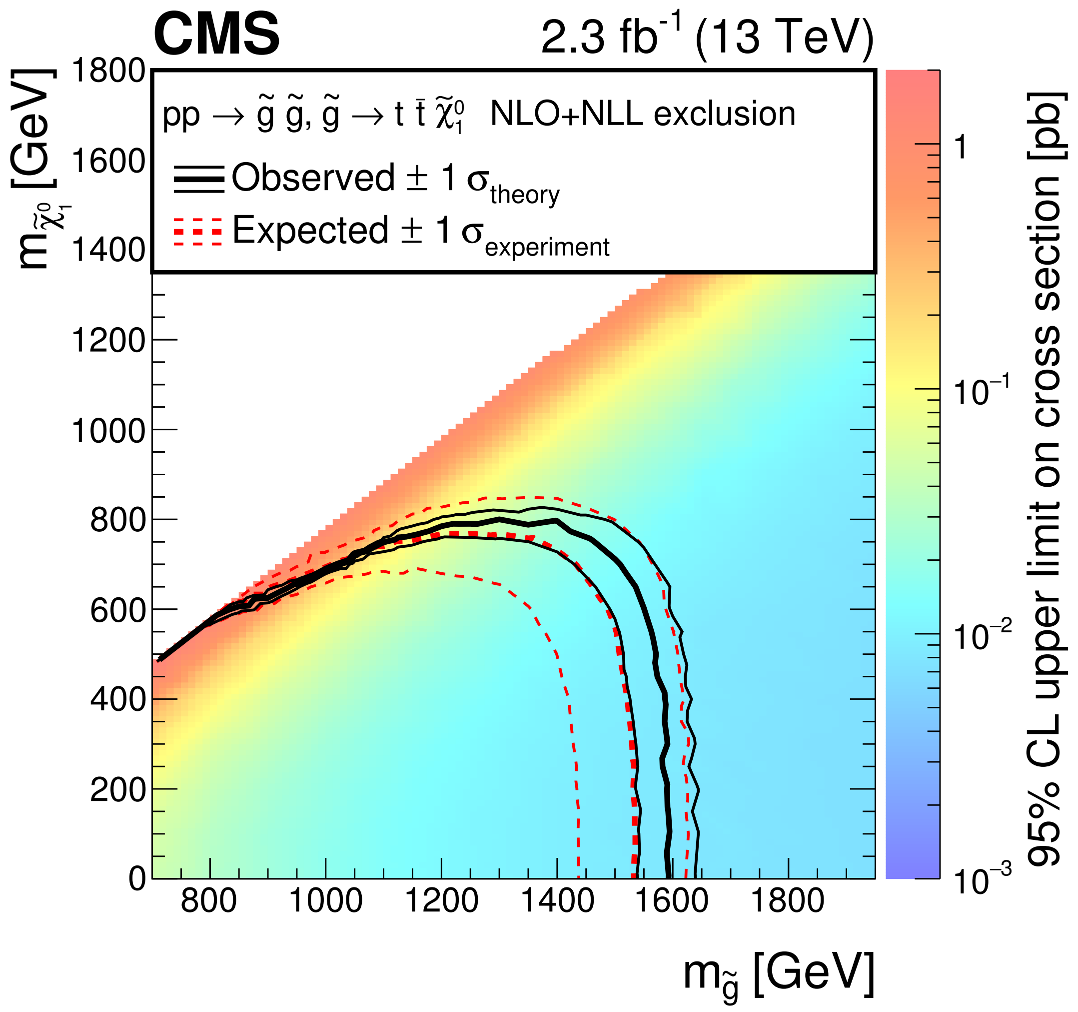


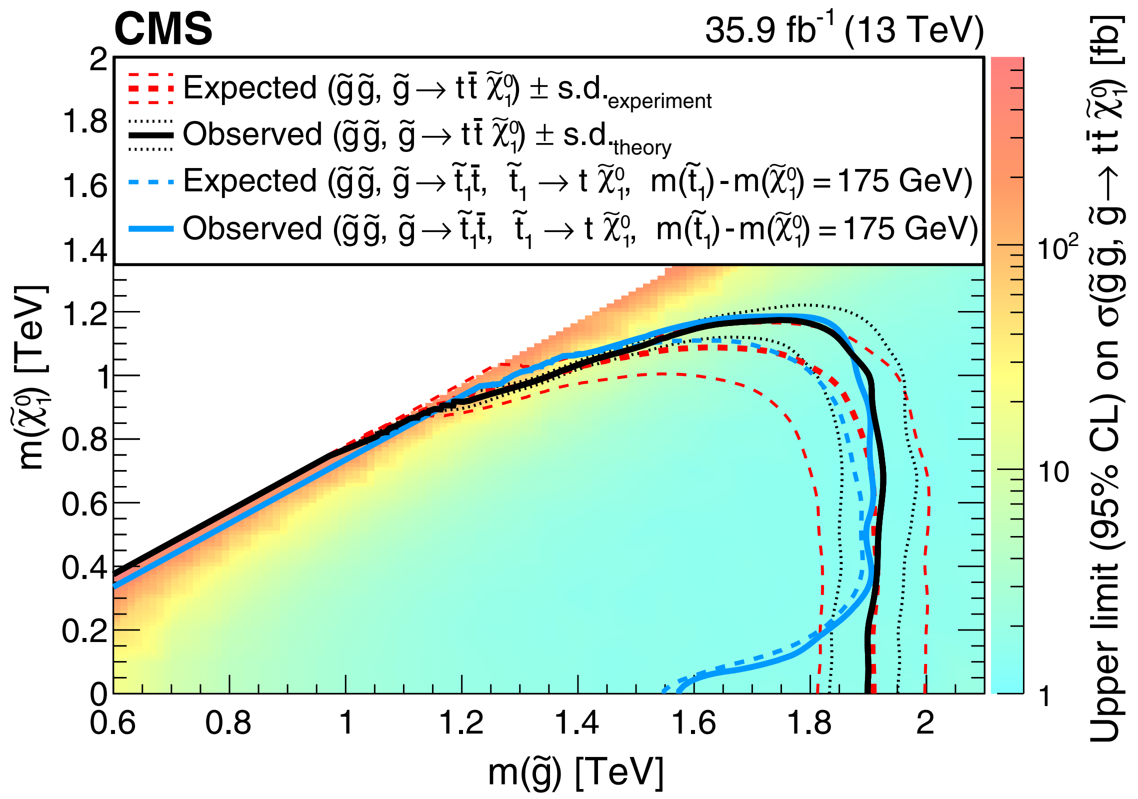


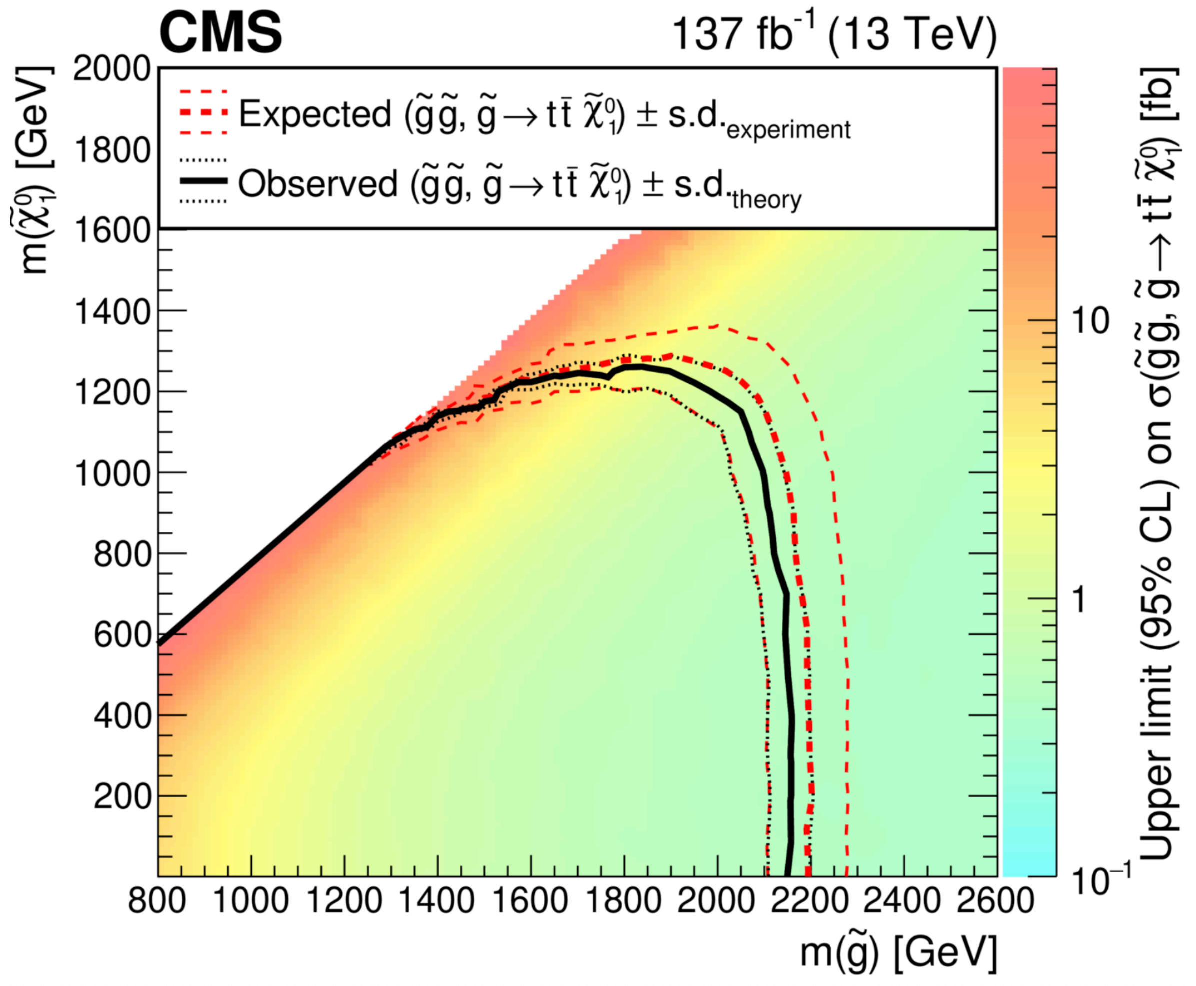
Case study

- Don’t want to show you all SUSY analyses in CMS …
- Maybe more helpful to take one analysis and learn as much about SUSY search as possible

1L SUSY search

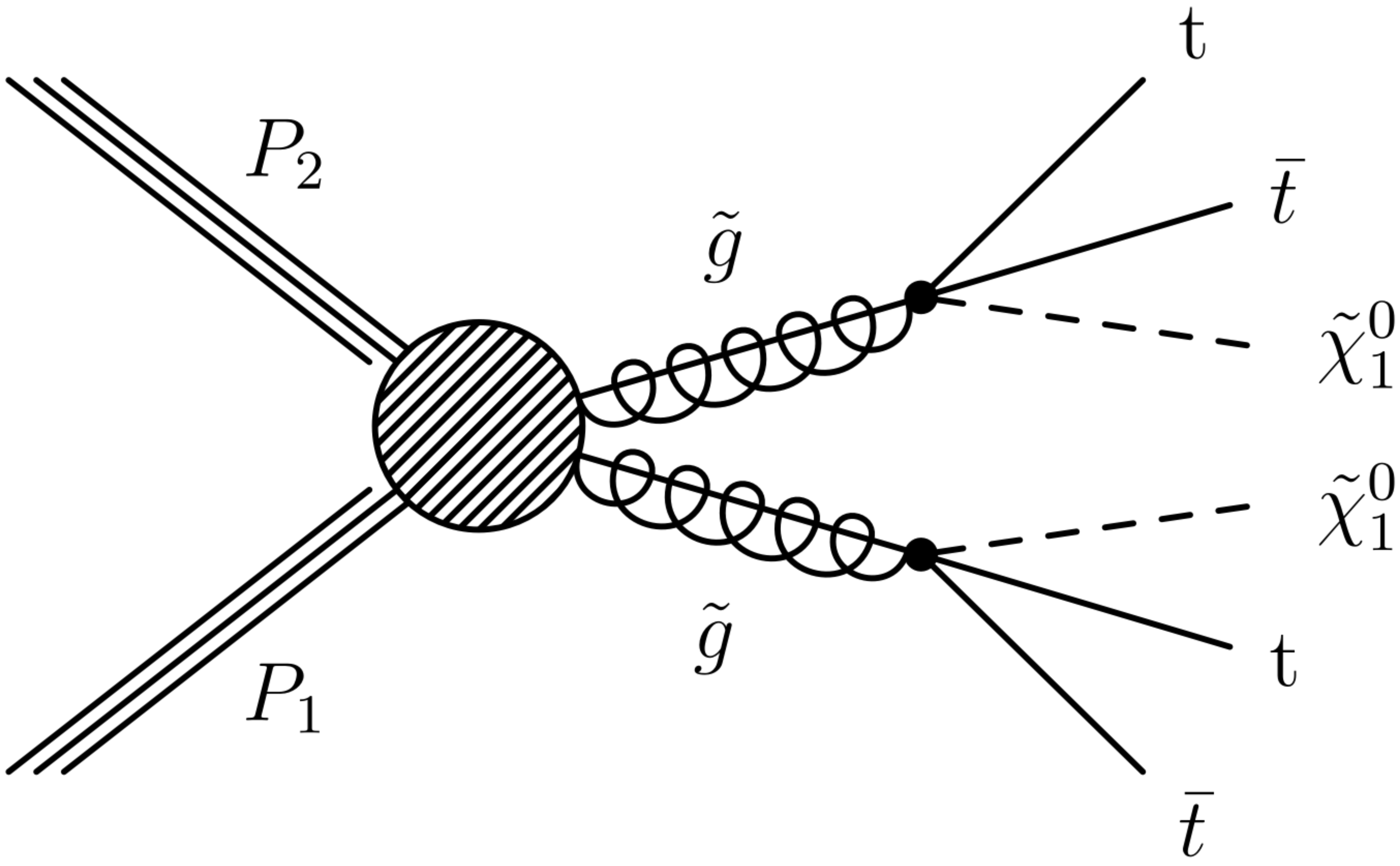






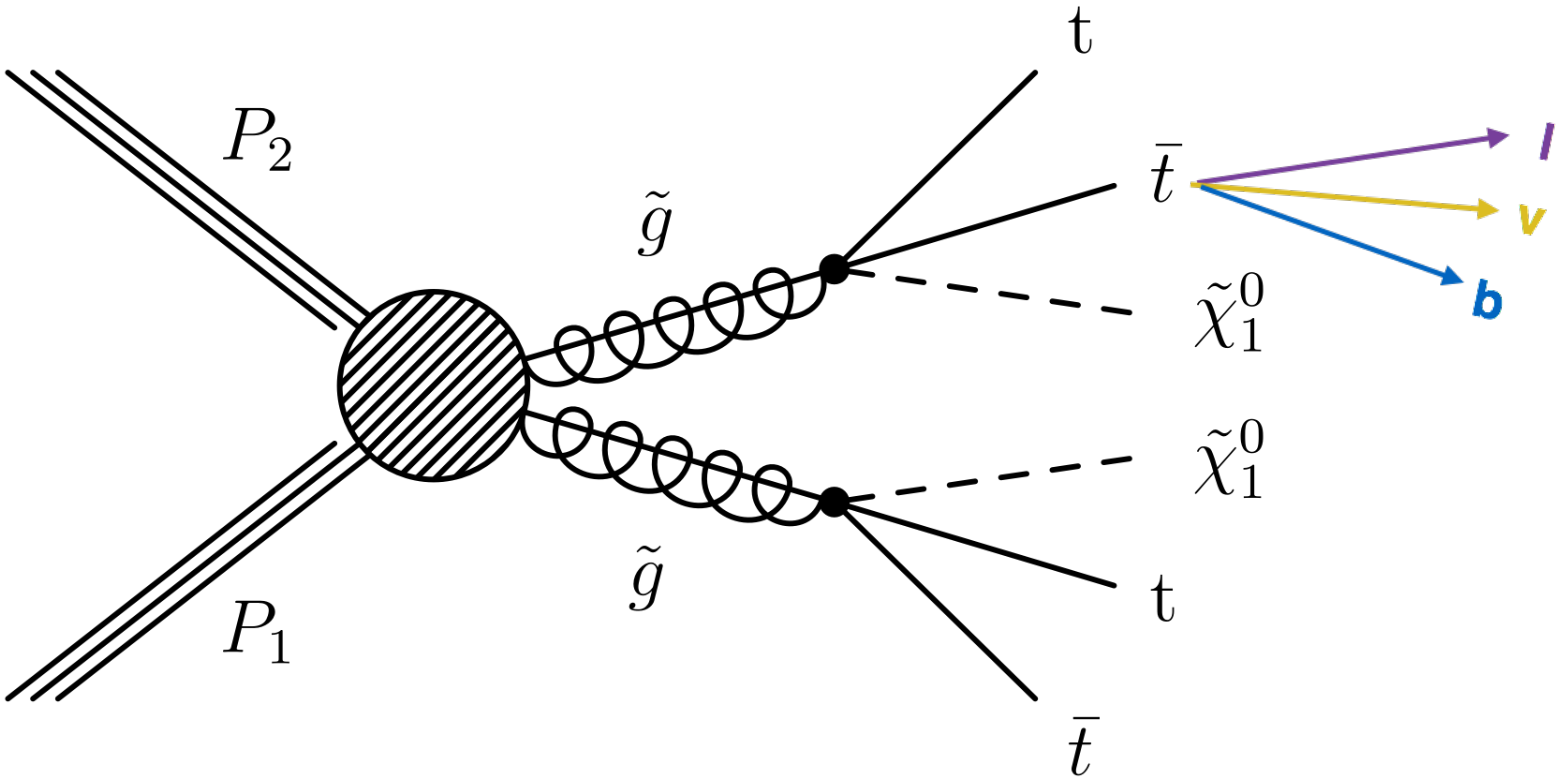
- 1-lepton SUSY analysis using MJ
  - First studied in 2014 when machine was not running
- 3 papers using Run2 data
  - First results with 2015 data (~2.3 fb^{-1})
  - Updates with 35.9 and 137 fb^{-1}

Target model: $\tilde{g} \to \tilde{t}\bar{t}(\tilde{t} \to t\tilde{\chi}_1^0)$ (T1tttt)

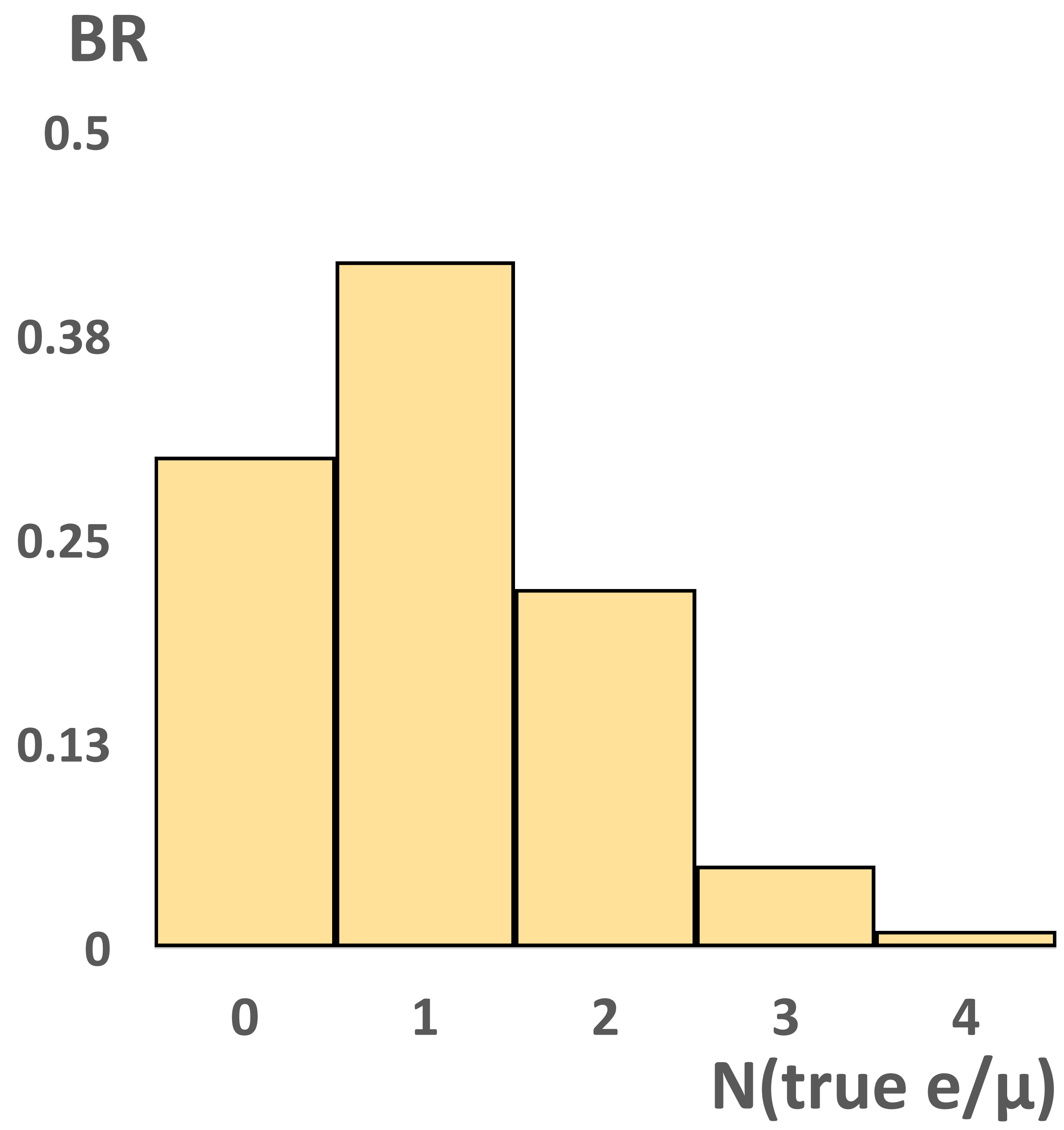


- Relevant in the context of natural SUSY models
  - Not too heavy gluino, light stop, sbottom, and Higgsinos
- Can a gluino decay to $t\bar{t}\tilde{\chi}_1^0$?
  - Actual decay chain is $\tilde{g} \to t\tilde{t} \to t\bar{t}\tilde{\chi}_1^0$
  - $\tilde{t}$ is assumed to be very heavy
- 4 tops and 2 LSPs
- Assume off-shell stop
  - 3-body gluino decay

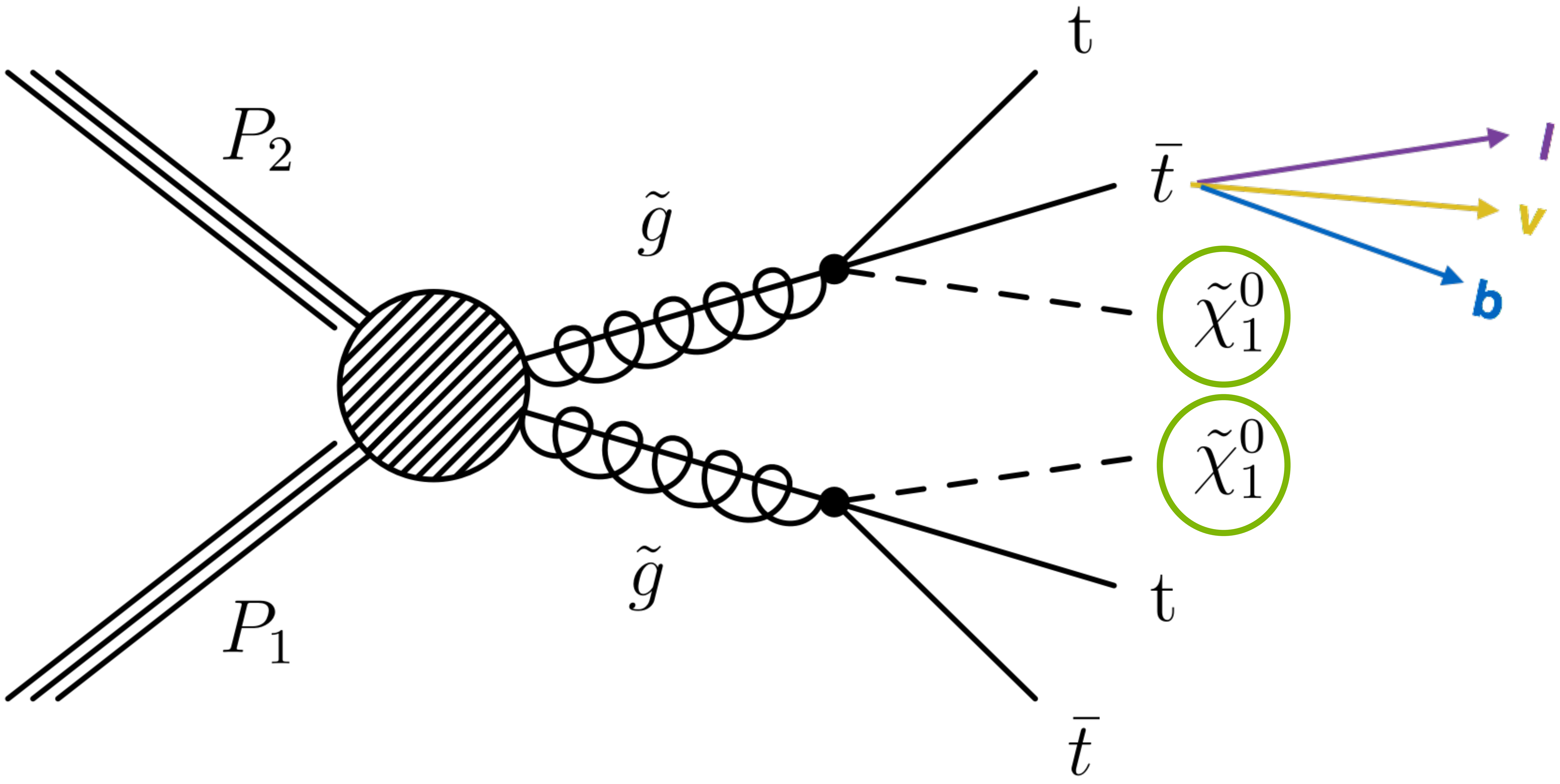
Target model: $\tilde{g} \rightarrow \widetilde{t}\bar{t}(\widetilde{t} \rightarrow t\tilde{\chi}_1^0)$ (T1tttt)



Single lepton final state:
Highest BR for e/μ

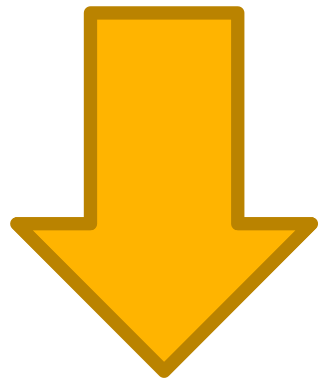


Target model: $\tilde{g} \to \widetilde{t}\bar{t}(\widetilde{t} \to t\tilde{\chi}_1^0)$ (T1tttt)



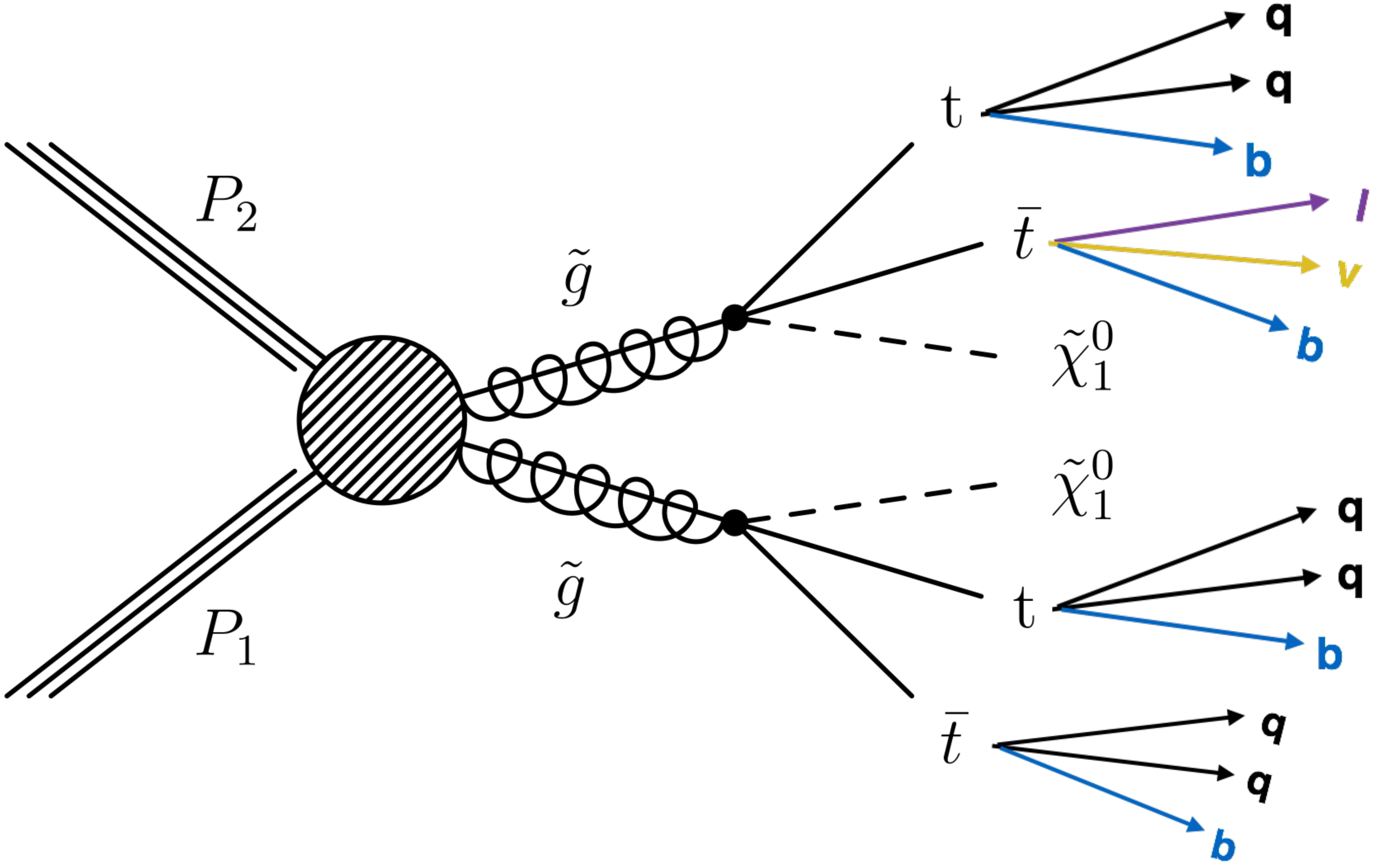
Single lepton final state:
Highest BR for e/μ

Two LSPs and
one neutrino



Signature:
large missing transverse momentum (MET)

Target model: $\tilde{g} \to \widetilde{t}\bar{t}(\widetilde{t} \to t\tilde{\chi}_1^0)$ (T1tttt)

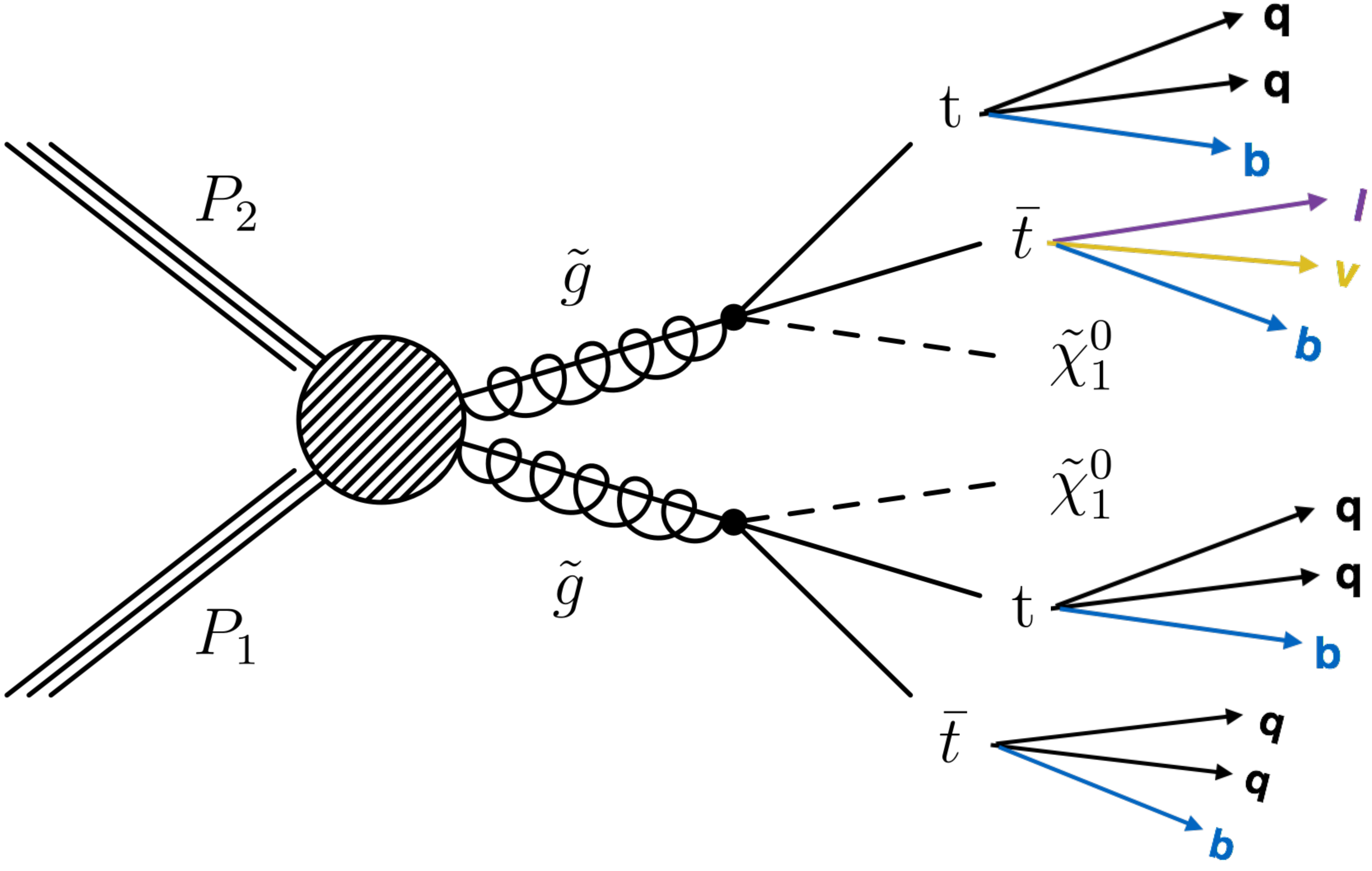


Single lepton final state:
Highest BR for e/μ

There are 10 quarks
4 are b quarks

Signature:
high jet multiplicity and b-jets

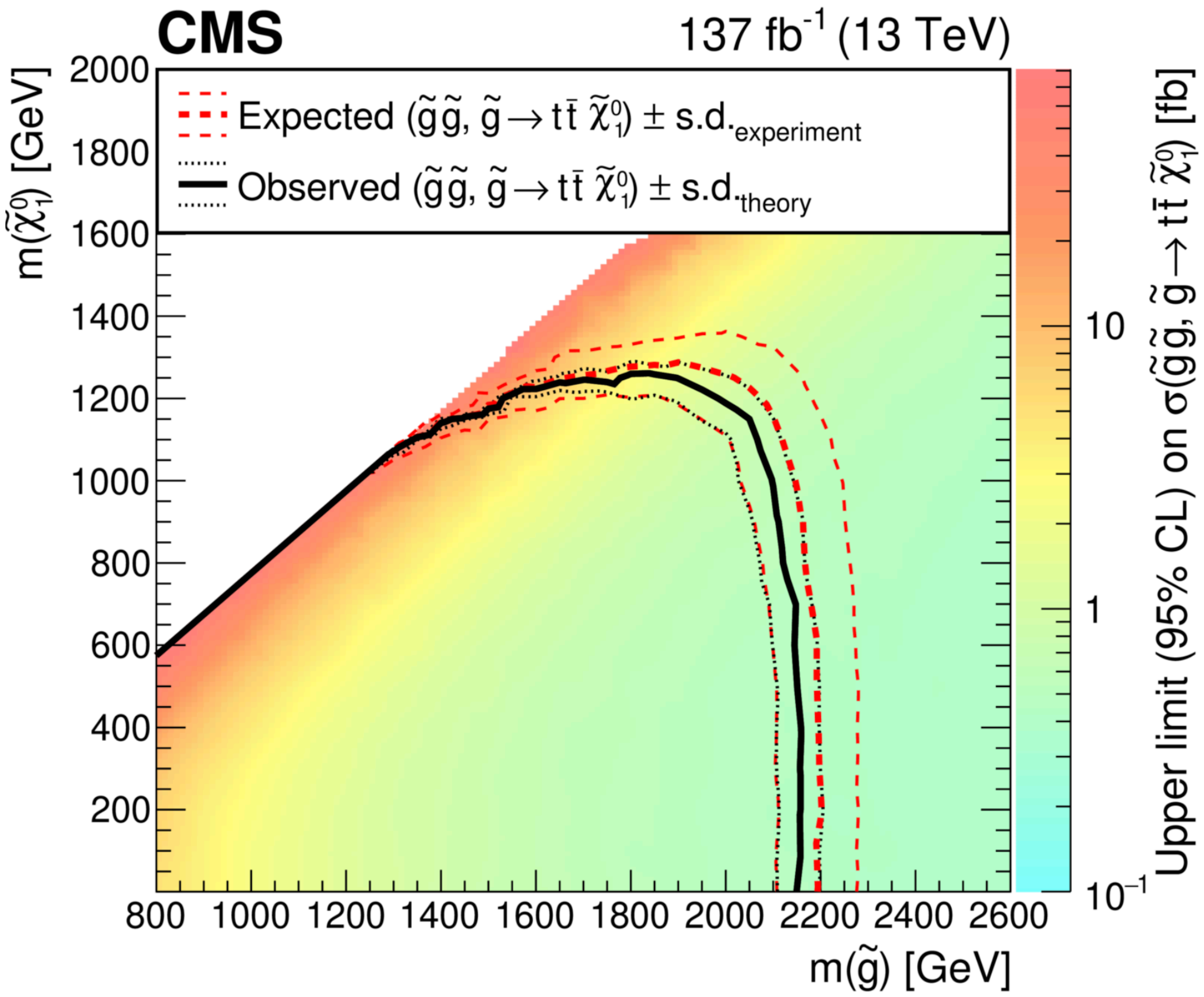
Target model: $\tilde{g} \to \widetilde{t}\bar{t}(\widetilde{t} \to t\tilde{\chi}_1^0)$ (T1tttt)

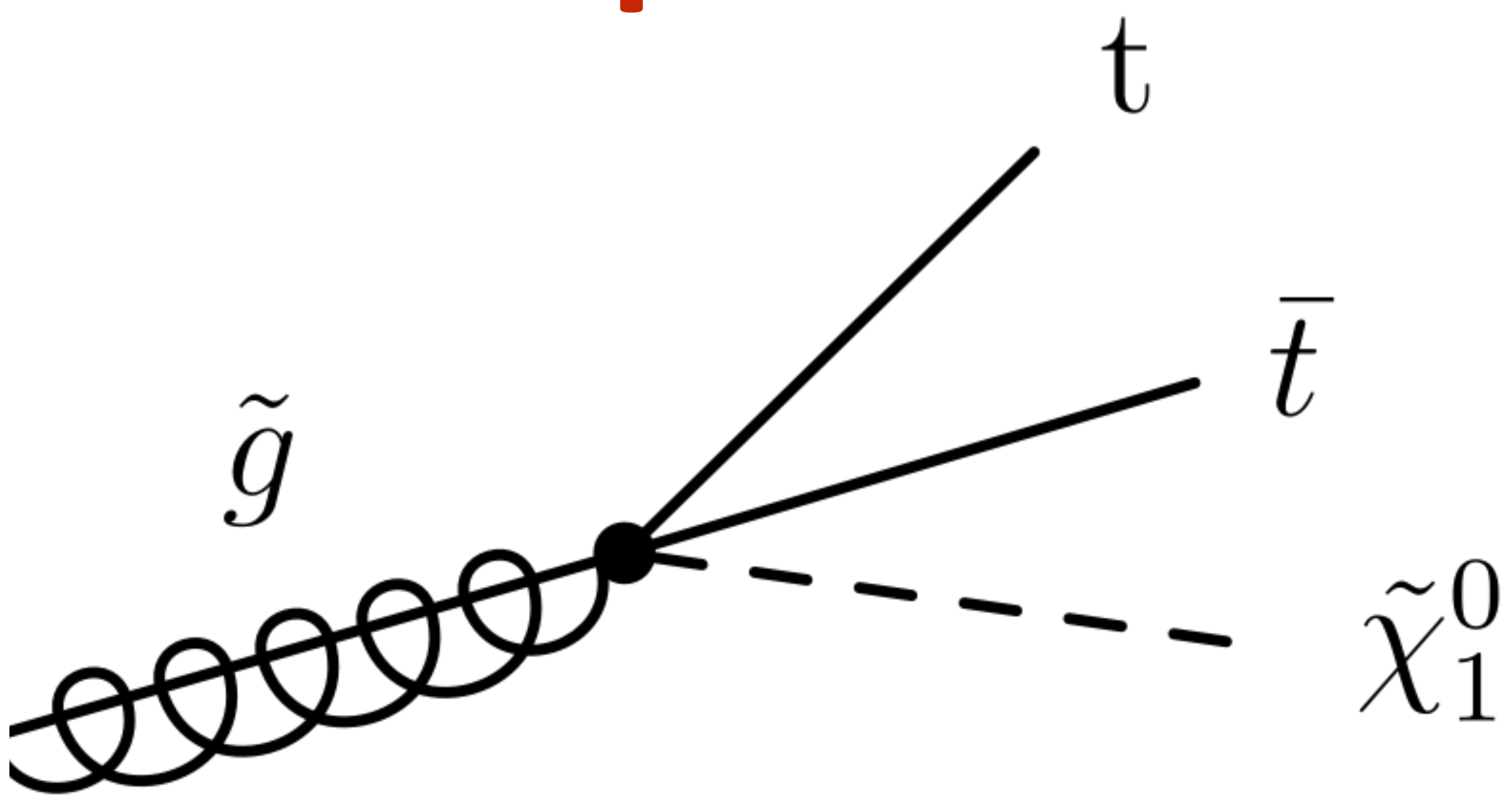


Signature:

- one lepton (e or μ)
- large MET
- large jet multiplicity
- large b-jet multiplicity

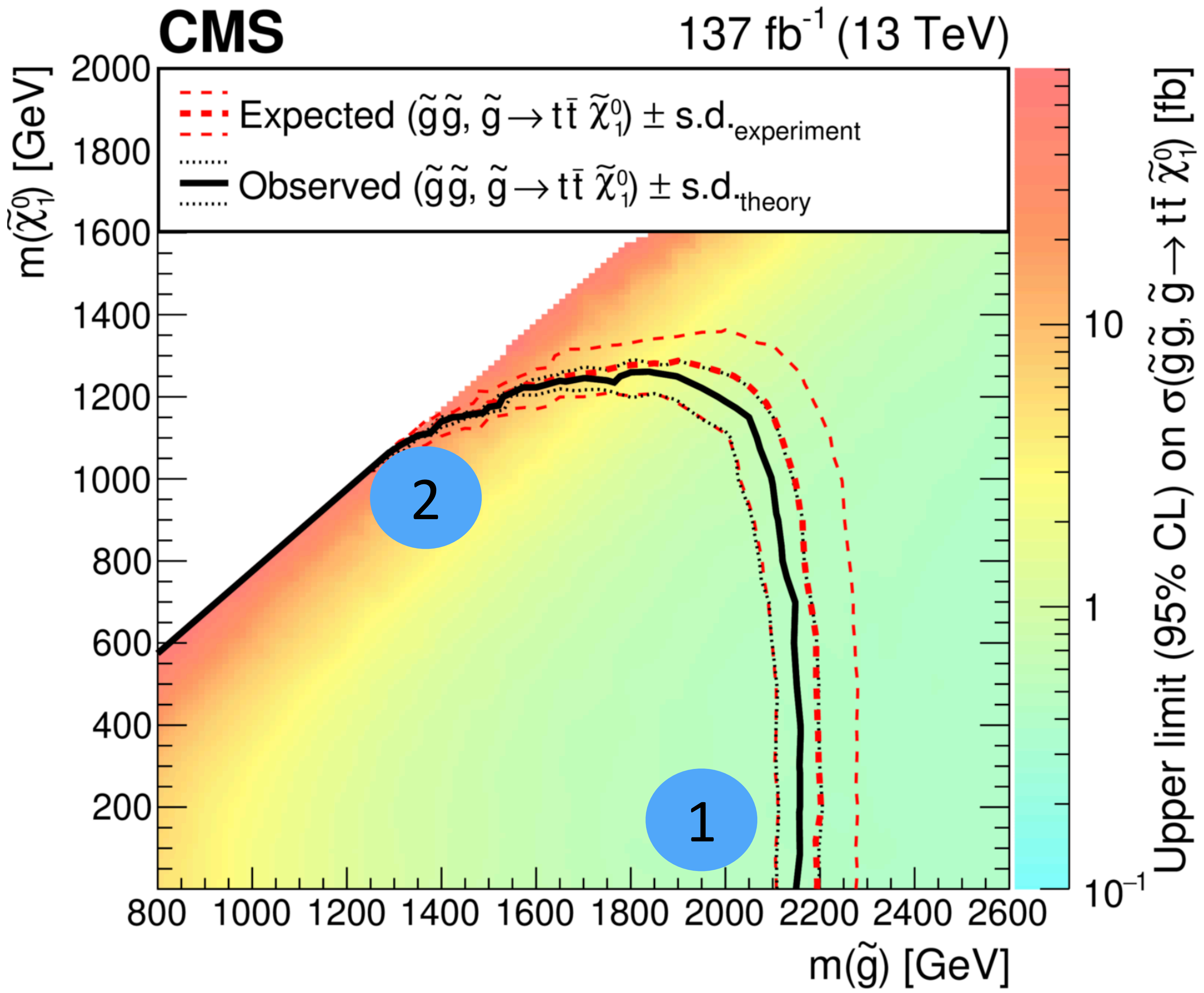
Compressed vs non-compressed

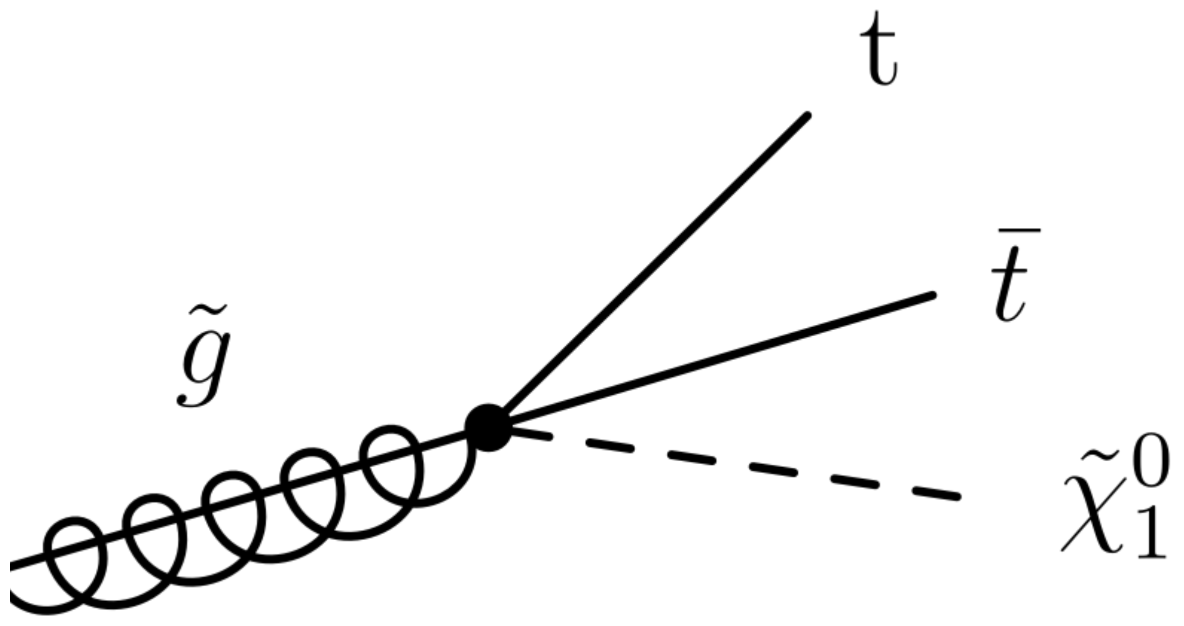




- Event kinematics changes (significantly) by mass difference (Δm) btw gluino ($\tilde{g}$) and the LSP ($\tilde{\chi}^0_1$)

Compressed vs non-compressed

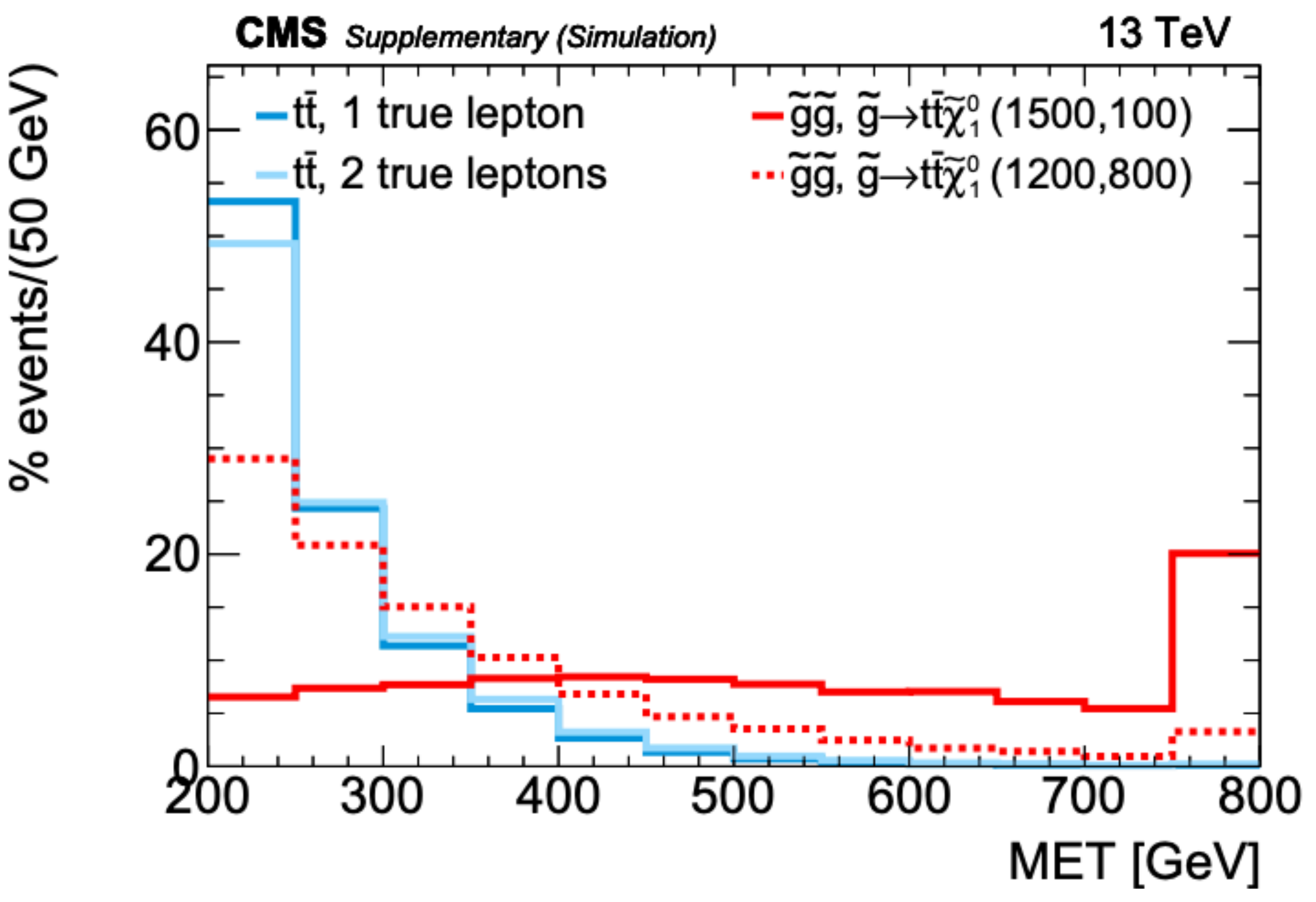


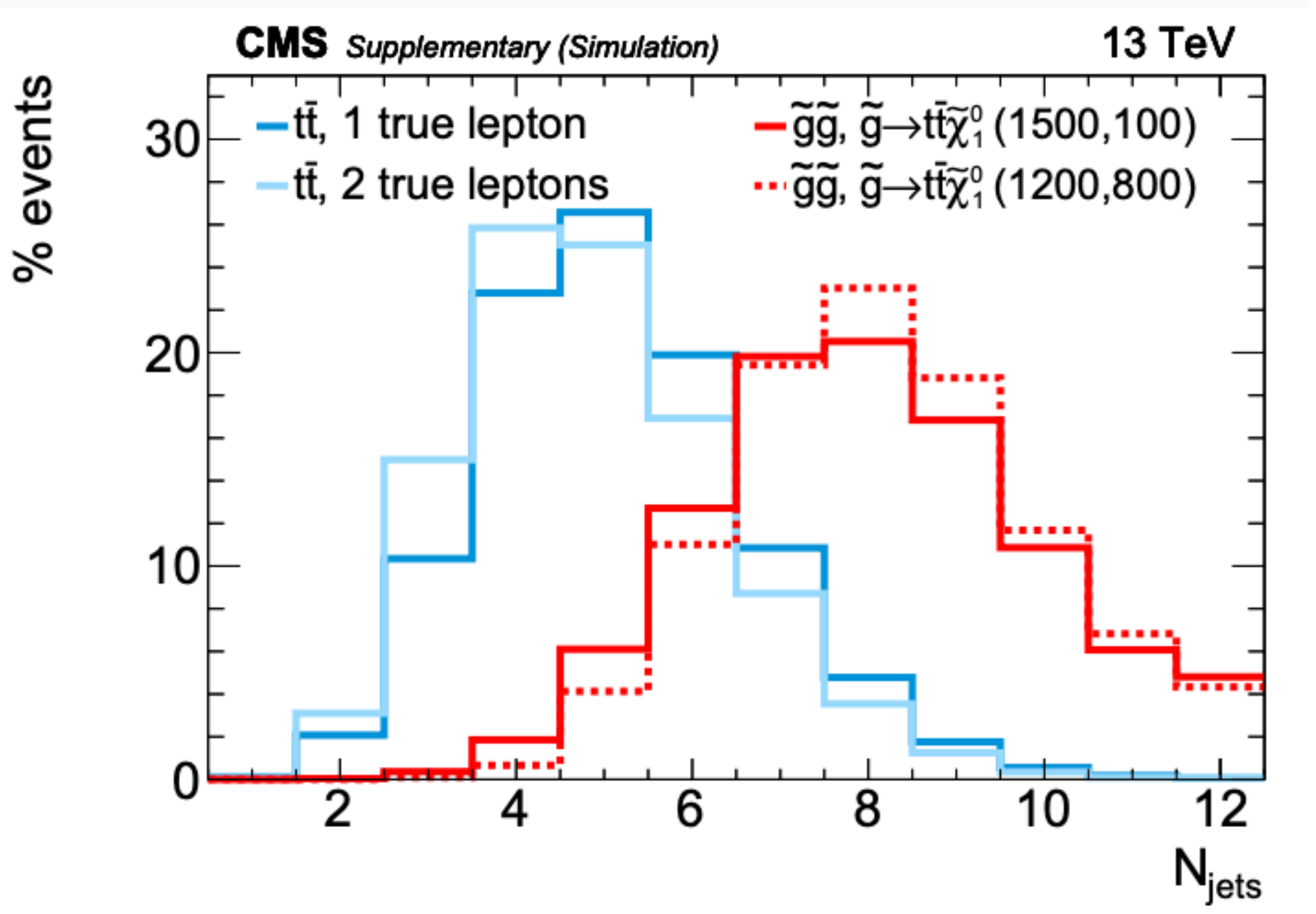


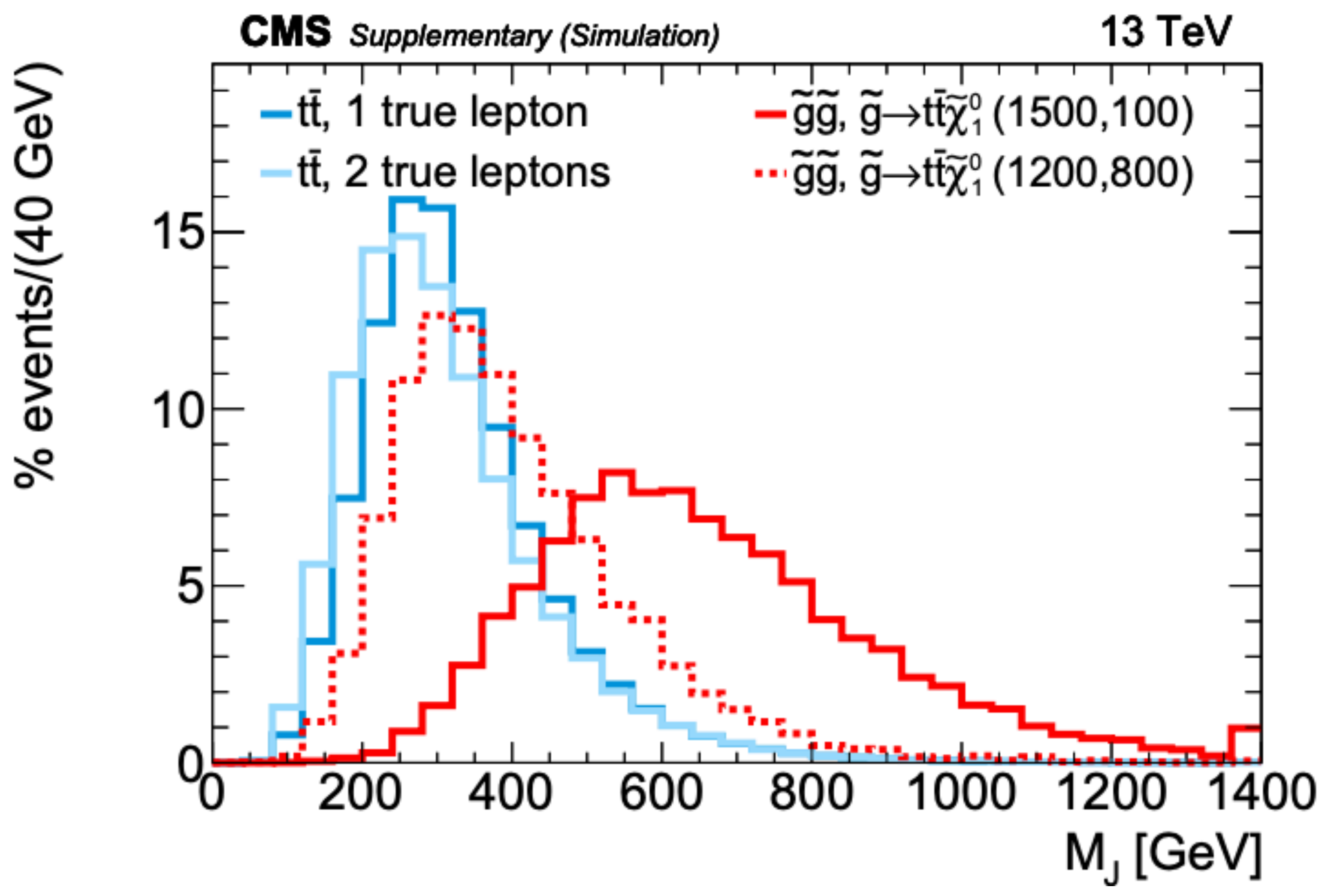
1

2

Compressed vs non-compressed







Many signal regions

Why Many Signal Regions (SR)

- Comprehensive coverage of unknown signals
- Improved sensitivity also for a particular signal
  - Shape analysis vs. counting experiment
- Searches become almost ”signature based”
  - Can be used to constrain (or discover!) something that you were not necessarily looking for
- There ”better motivated” targets where a very focused search makes sense
  - But even then, many SR help

Claudio
Campagnari
(UCSB)

9

N_b	m_T^{min}	p_T^{miss}	N_{jets}	$H_T < 300$	$H_T \in [300, 1125]$	$H_T \in [1125, 1300]$	$H_T \in [1300, 1600]$	$H_T > 1600$
0	<120	50–200	2–4	SR1	SR2	SR54 $N_{jets} < 5$	SR55 $N_{jets} < 5$	SR56 $N_{jets} < 5$
			≥5	SR3	SR4			
		200–300	2–4		SR5 (++) / SR6 (- -)			
			≥5		SR7			
	>120	50–200	2–4		SR8 (++) / SR9 (- -)			
			≥5		SR10			
		200–300	2–4					
			≥5					
1	<120	50–200	2–4	SR11	SR12	SR57 $N_{jets} = 5$ or 6	SR58 $N_{jets} = 5$ or 6	SR59 $N_{jets} = 5$ or 6
			≥5	SR13 (++) / SR14 (- -)	SR15 (++) / SR16 (- -)			
		200–300	2–4		SR17 (++) / SR18 (- -)			
			≥5		SR19			
	>120	50–200	2–4		SR20 (++) / SR21 (- -)			
			≥5		SR22			
		200–300	2–4					
			≥5					
2	<120	50–200	2–4	SR23	SR24	SR60 $N_{jets} > 6$	SR61 $N_{jets} > 6$	SR62 $N_{jets} > 6$
			≥5	SR25 (++) / SR26 (- -)	SR27 (++) / SR28 (- -)			
		200–300	2–4		SR29 (++) / SR30 (- -)			
			≥5		SR31			
	>120	50–200	2–4		SR32 (++) / SR33 (- -)			
			≥5		SR34			
		200–300	2–4					
			≥5					
≥3	<120	50–200	2–4	SR35 (++) / SR36 (- -)	SR37 (++) / SR38 (- -)			
			≥5		SR39 (++) / SR40 (- -)			
		200–300	2–4		SR37 (++) / SR38 (- -)			
			≥5		SR39 (++) / SR40 (- -)			
	>120	50–300	2–4	SR41	SR42 (++) / SR43 (- -)			
			≥5		SR44 (++) / SR45 (- -)			
Inclusive	Inclusive	300–500	2–4	—	SR46 (++) / SR47 (- -)			
		>500			SR48 (++) / SR49 (- -)			
		300–500	≥5		SR50 (++) / SR51 (- -)			
		>500			SR52 (++) / SR53 (- -)			

N_b	m_T^{min}	p_T^{miss}	N_{jets}	$H_T < 300$	$H_T \in [300, 1125]$	$H_T \in [1125, 1300]$	$H_T > 1300$
0	<120	50–200	2–4	SR1	SR2	SR40 (++) / SR41 (- -)	SR42 (++) / SR43 (- -)
			≥5	SR3	SR4		
		200–300	2–4		SR5 (++) / SR6 (- -)		
			≥5		SR7		
1	<120	50–200	2–4	SR8	SR9		
			≥5	SR10 (++) / SR11 (- -)	SR12 (++) / SR13 (- -)		
		200–300	2–4		SR14		
			≥5		SR15 (++) / SR16 (- -)		
2	<120	50–200	2–4	SR17	SR18		
			≥5	SR19 (++) / SR20 (- -)	SR21 (++) / SR22 (- -)		
		200–300	2–4		SR23 (++) / SR24 (- -)		
			≥5		SR25		
≥3	<120	50–200	≥2	SR26 (++) / SR27 (- -)	SR28 (++) / SR29 (- -)		
		200–300			SR30		
Inclusive	>120	50–300	≥2	SR31	SR32		
Inclusive	Inclusive	300–500	2–4	—	SR33 (++) / SR34 (- -)		
		>500			SR35 (++) / SR36 (- -)		
		300–500	≥5		SR37 (++) / SR38 (- -)		
		>500			SR39		

off-Z				
N_b	H_T	$p_T^{miss} \in [50, 150]$	$p_T^{miss} \in [150, 300]$	$p_T^{miss} \geq 300$
0	<400	SR1/SR2†	SR3/SR4†	SR20/SR21†
	400–600	SR5	SR6	
1	<400	SR7	SR8	
	400–600	SR9	SR10	
2	<400	SR11	SR12	
	400–600	SR13	SR14	
≥3	<600	SR15		
Inclusive	≥600	SR16/SR17†	SR18/SR19†	

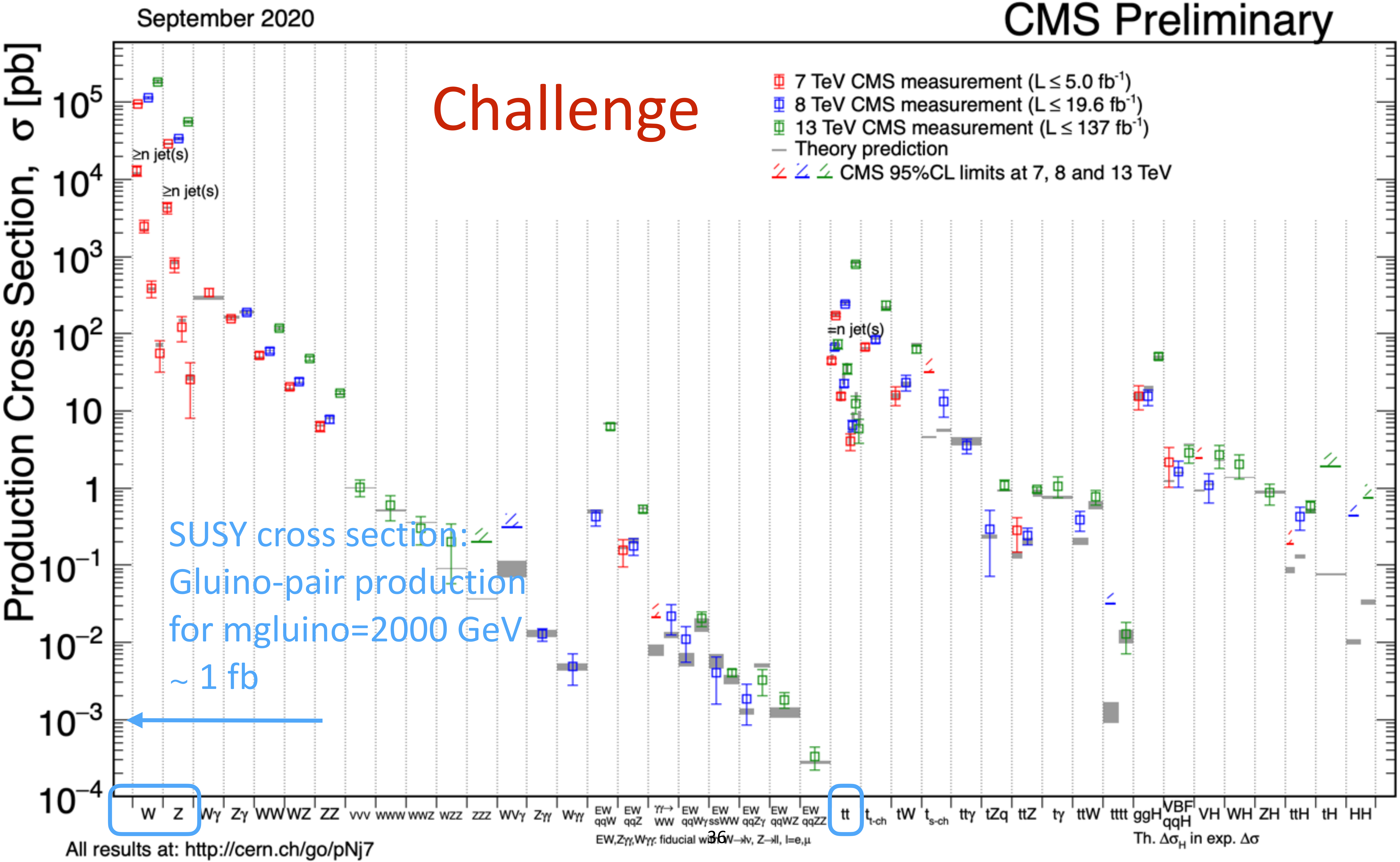
on-Z				
N_b	H_T	$p_T^{miss} \in [50, 150]$	$p_T^{miss} \in [150, 300]$	$p_T^{miss} \geq 300$
0	<400	SR22/SR23†	SR24/SR25†	SR43/SR44†
	400–600	SR26/SR27†	SR28/SR29†	
1	<400	SR30	SR31	
	400–600	SR32	SR33	
2	<400	SR34	SR35	
	400–600	SR36	SR37	
≥3	<600	SR38		
Inclusive	≥600	SR39/SR40†	SR41/SR42†	

N_b	N_{jets}	$H_T \in [300, 1125]$	$H_T \in [1125, 1300]$	$H_T > 1300$
0	2–4	SR1	SR8 ($N_{jets} < 5$)	SR10 ($N_{jets} < 5$)
	≥5	SR2		
1	2–4	SR3		
	≥5	SR4	SR9 ($N_{jets} \geq 5$)	SR11 ($N_{jets} \geq 5$)
2	2–4	SR5		
	≥5	SR6		
≥3	≥2	SR7		

N_b	m_T^{min}	H_T	$p_T^{miss} \in [50, 200]$	$p_T^{miss} > 200$
0	<120	>400	SR1	SR2
1			SR3	SR4
2			SR5	SR6
≥3			SR7	
Inclusive	>120		SR8	

CMS-SUS-19-008

Challenge



SUSY cross section:
Gluino-pair production
for mgluino=2000 GeV
~ 1 fb

Quiz: what would be the main background?

Signature:

- one lepton (e or μ)
- large MET
- large jet multiplicity
- large b-jet multiplicity

ttbar

Design an analysis

- How to separate signal from backgrounds?

Methods

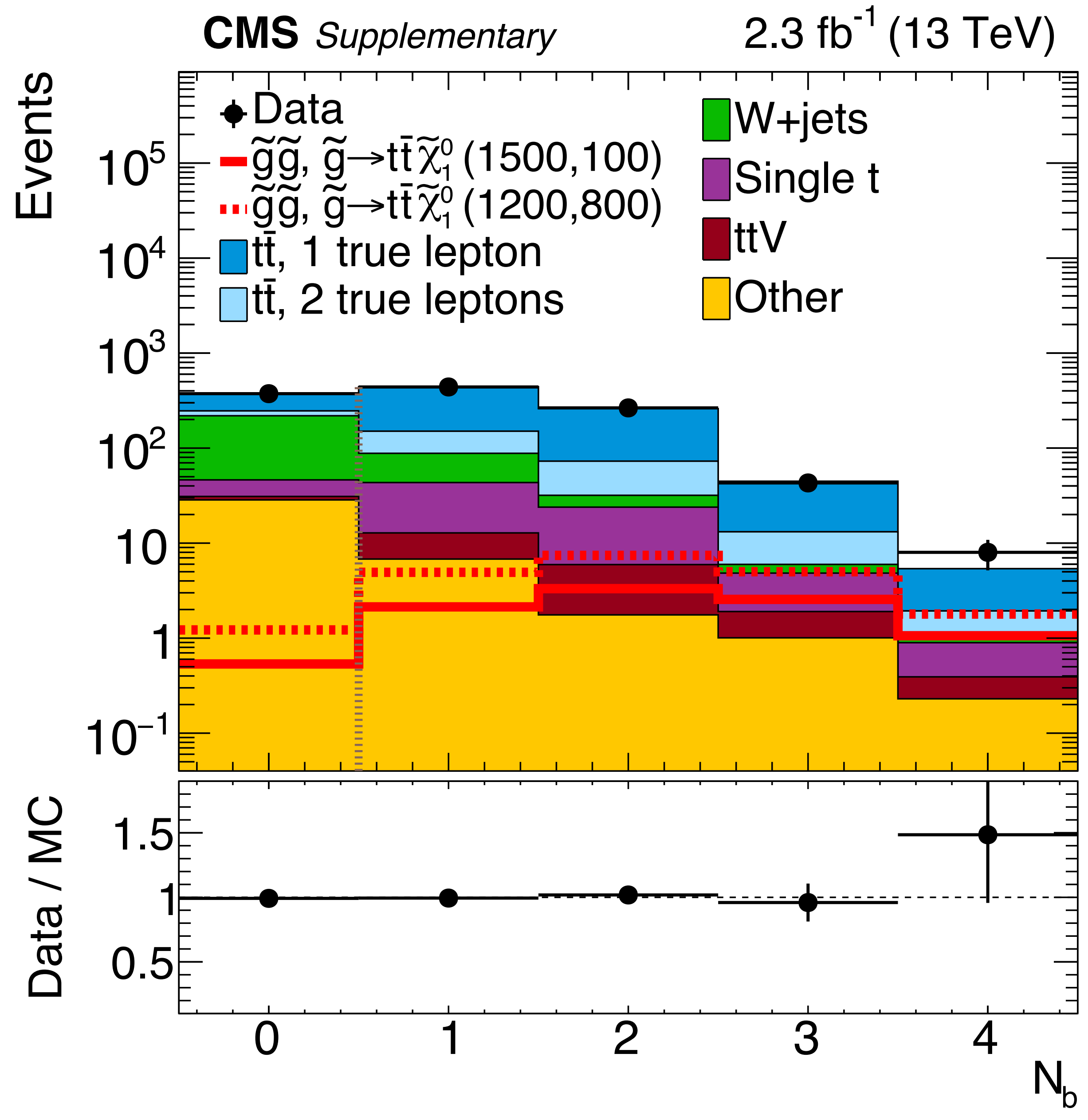
- Cut-and-count: C&C
- Shape fit
- ML technique
- …

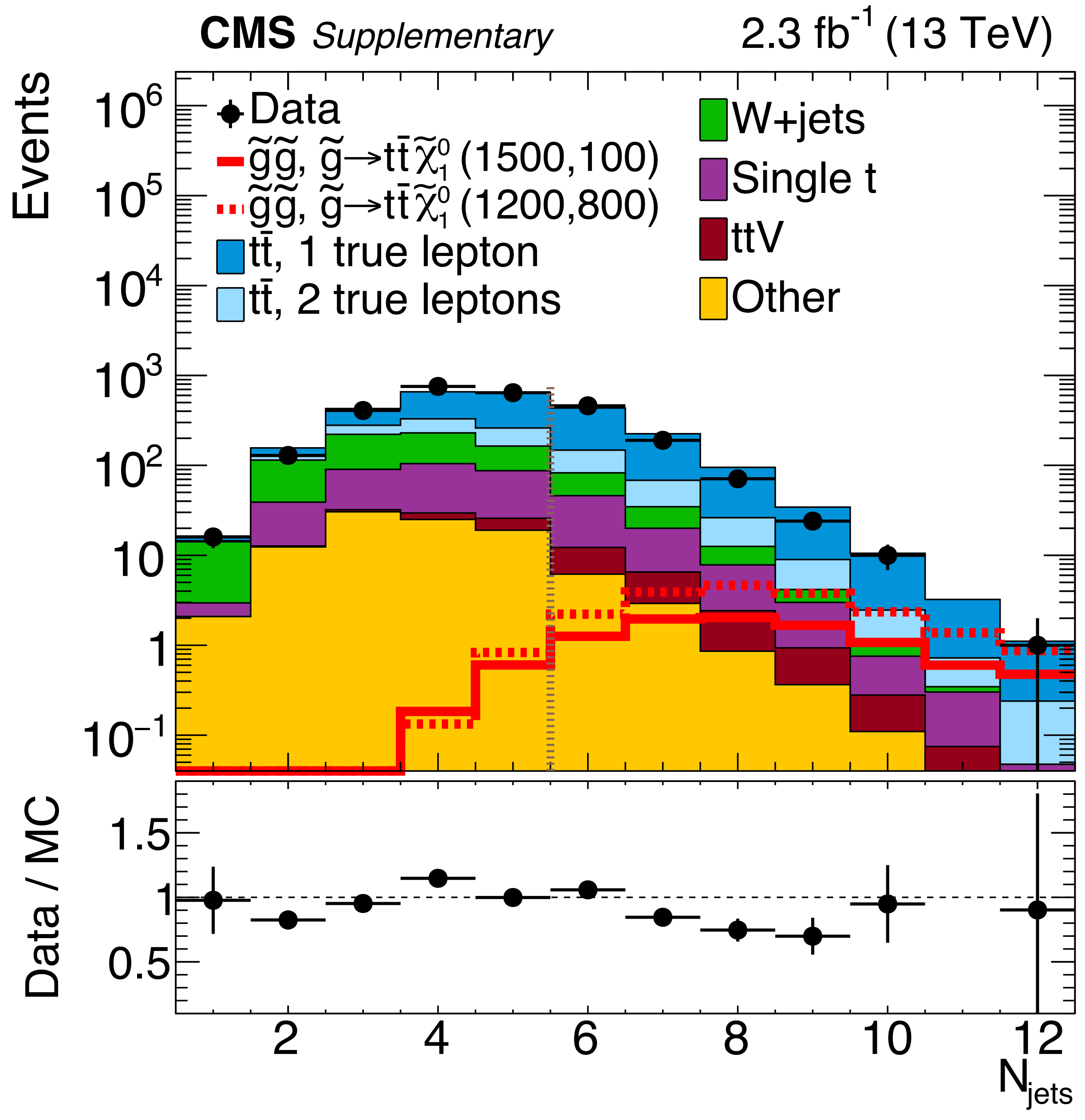
Kinematic variables

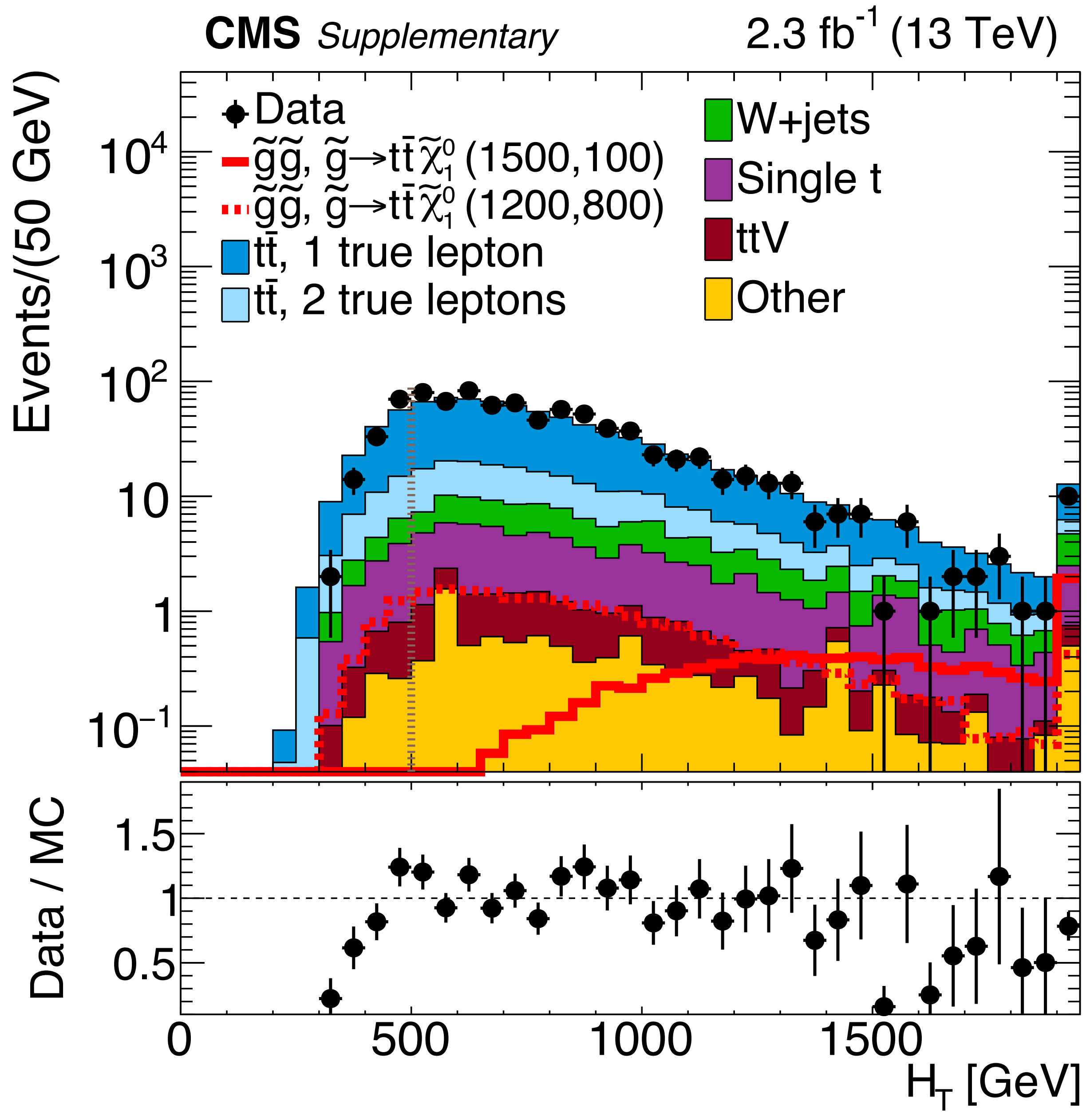
- Good signal vs background separation
- Robust modeling (if MC is used at all)
- Cut variable vs binning variable

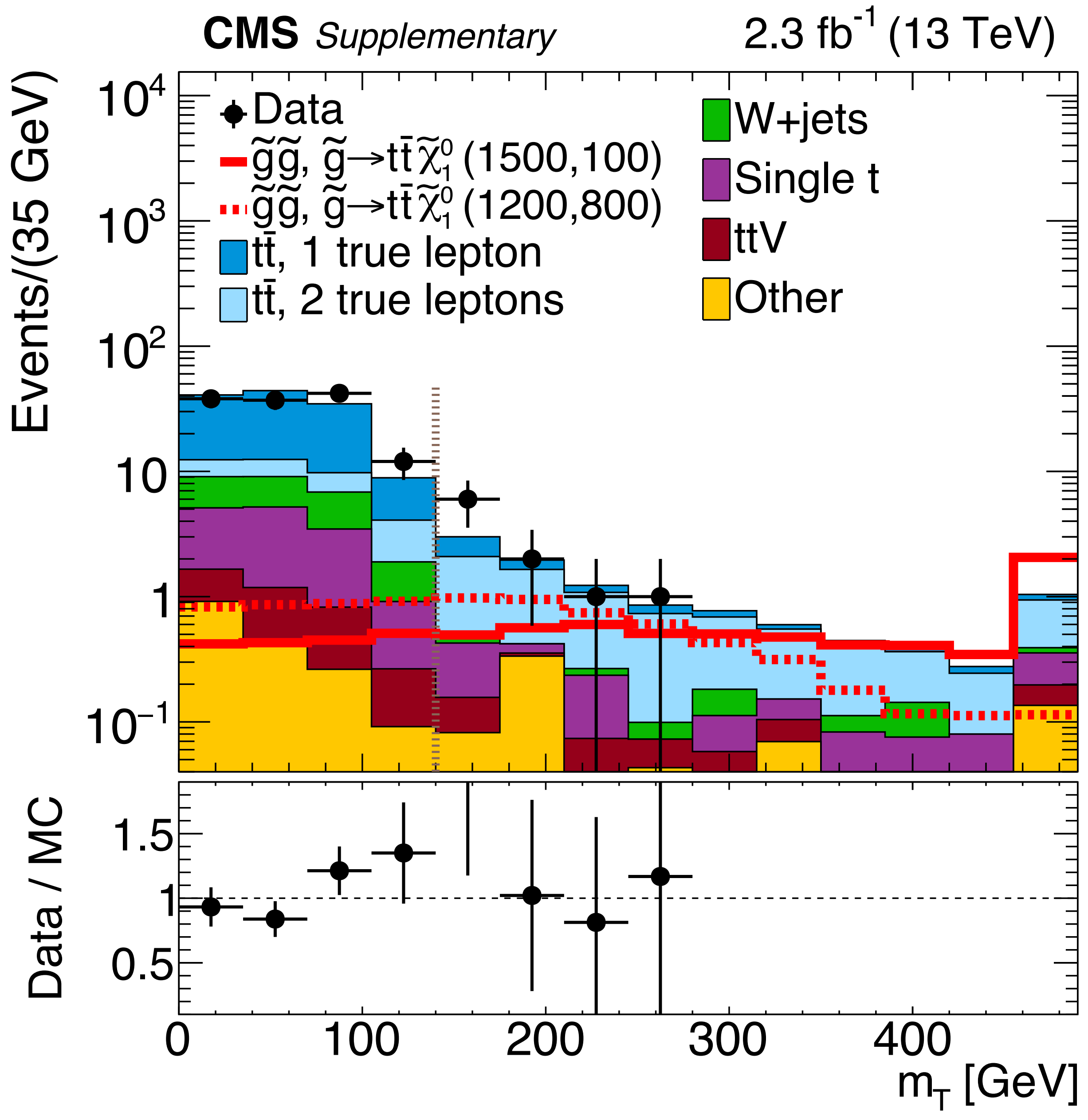
- How to estimate backgrounds?
  - MC based, data-driven, or combination of these

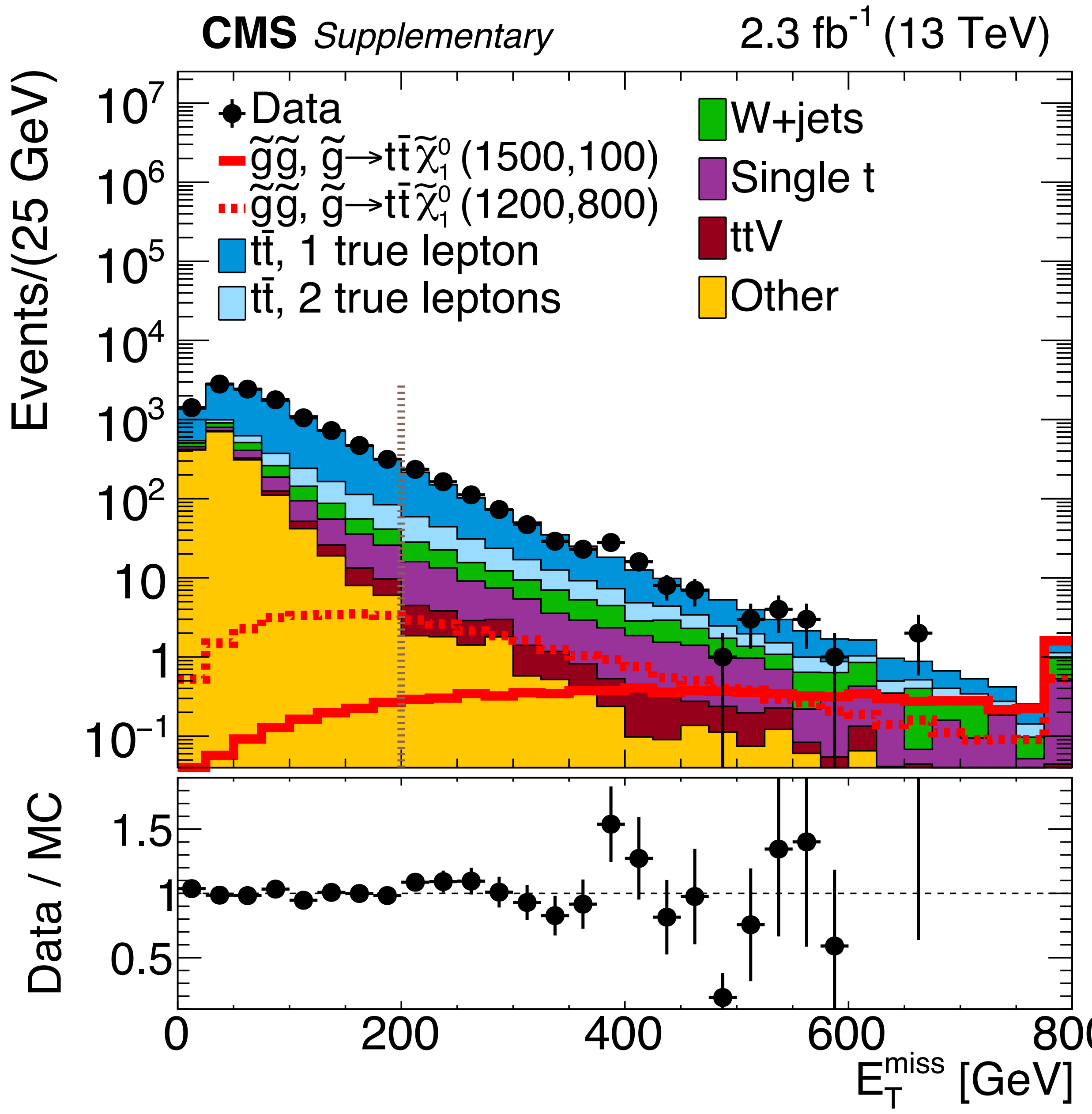
Analysis variables







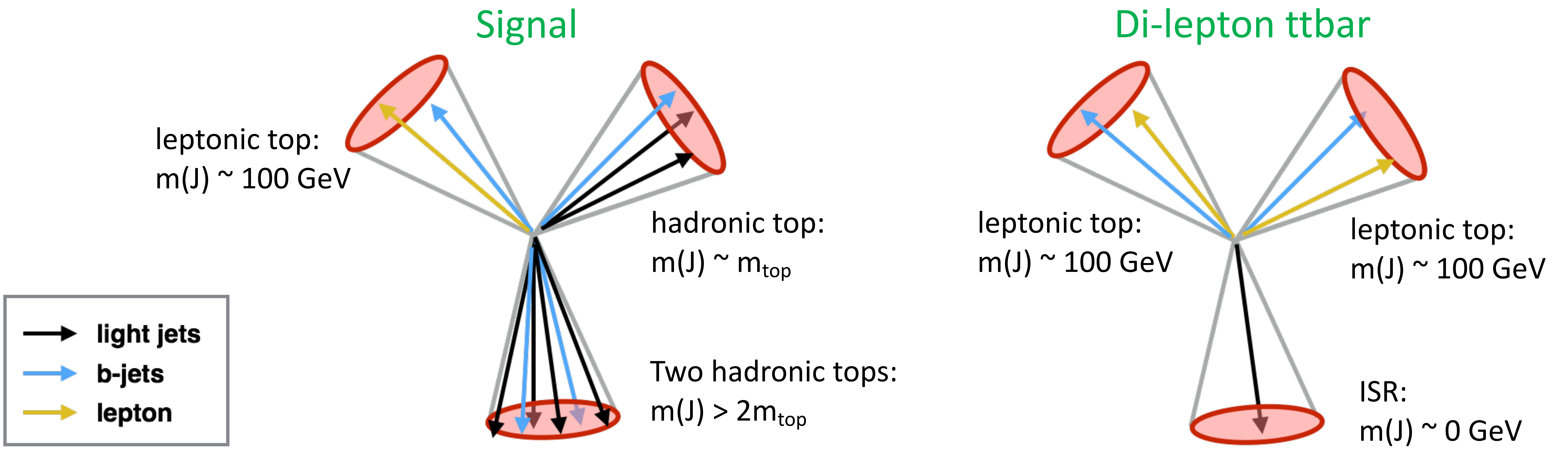




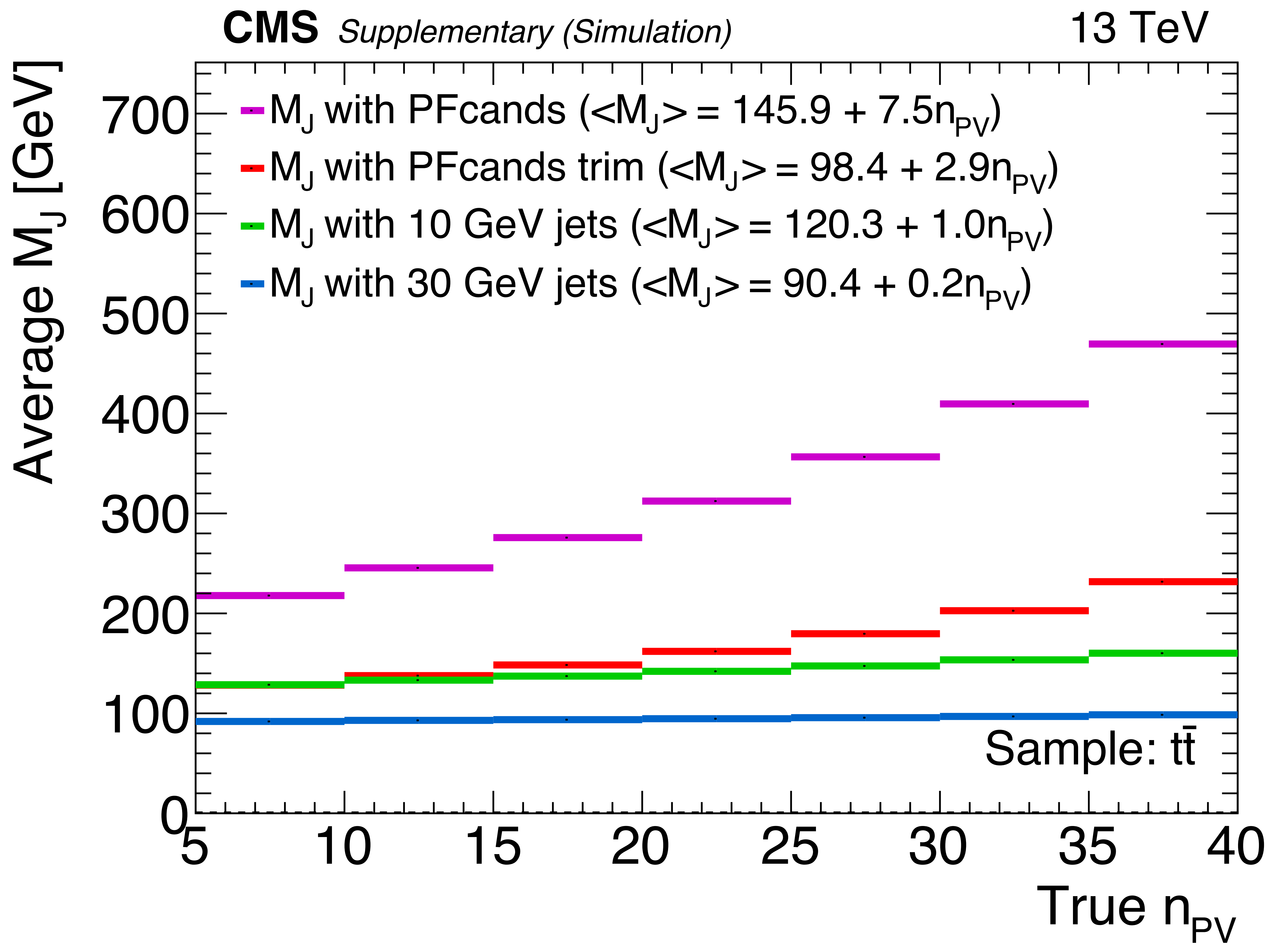
M_J variable: idea

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

- M_J is the scalar sum of masses of fat jets (m(J))
- Combines information of multiplicity (such as n_{jets}) and energy scale/mass of event (such as H_T)
  - Works well for accidentally boosted topology (random overlap of partons) or real boost objects (e.g., boosted hadronic tops)

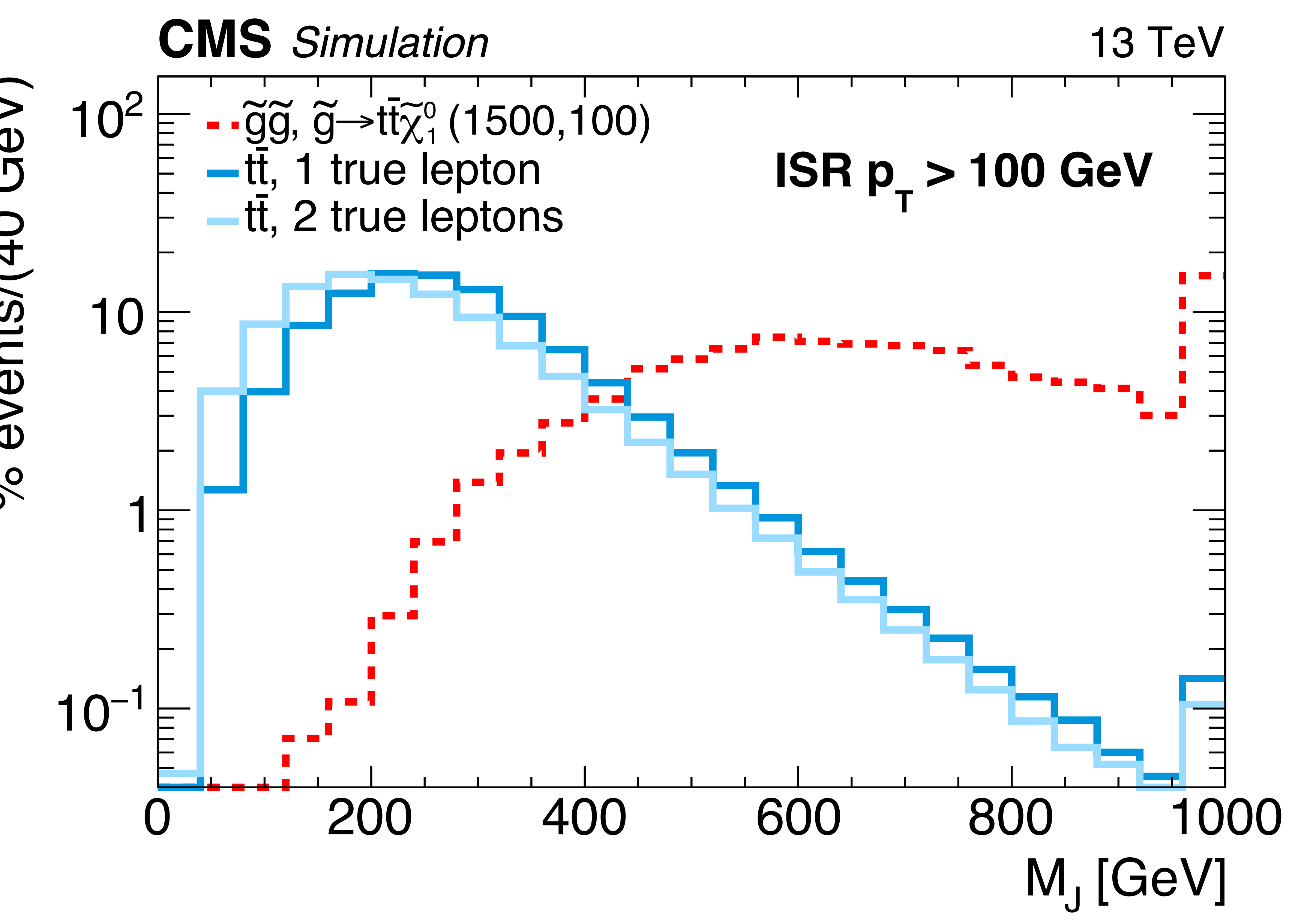


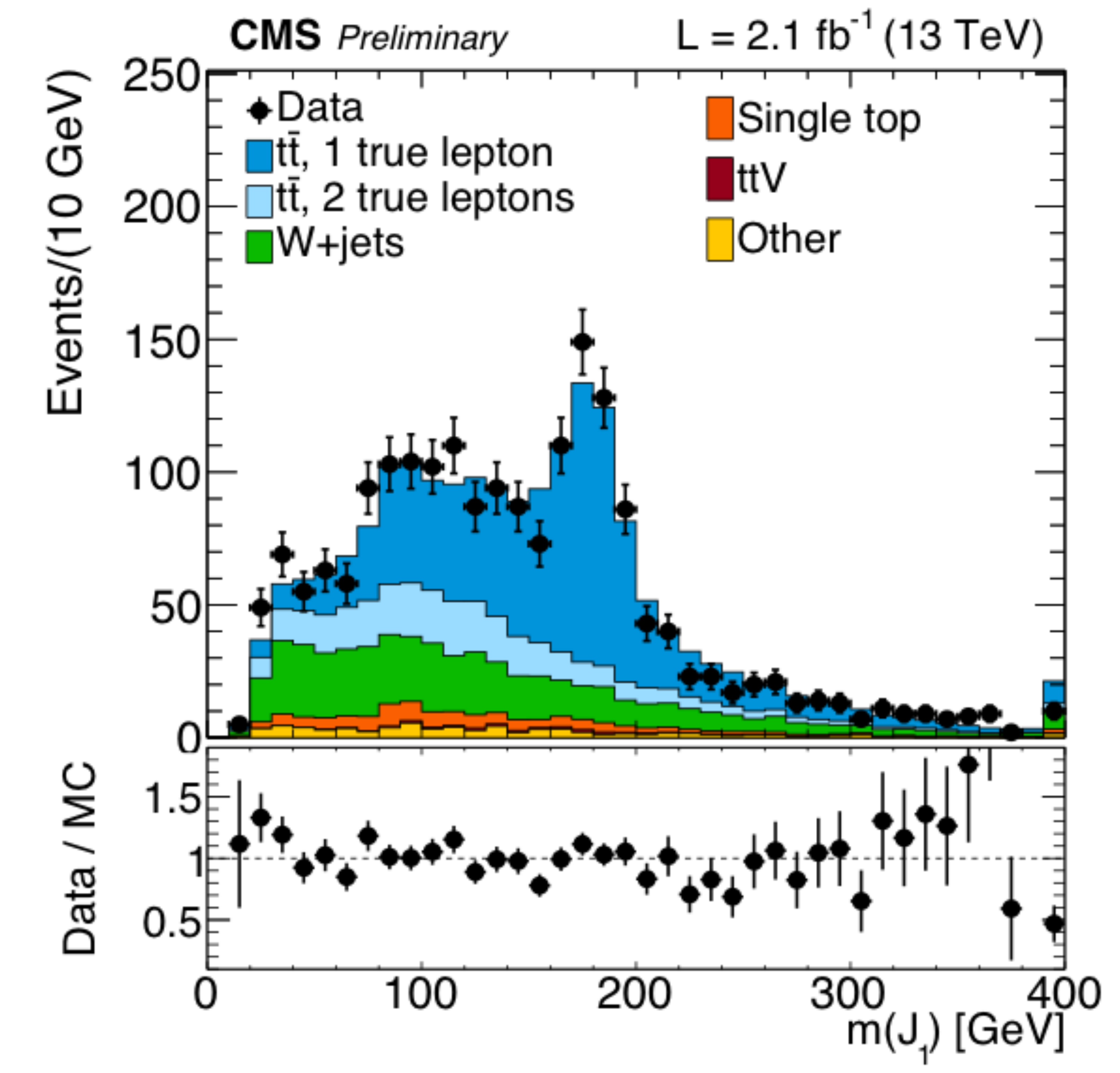
M_J variable: validation

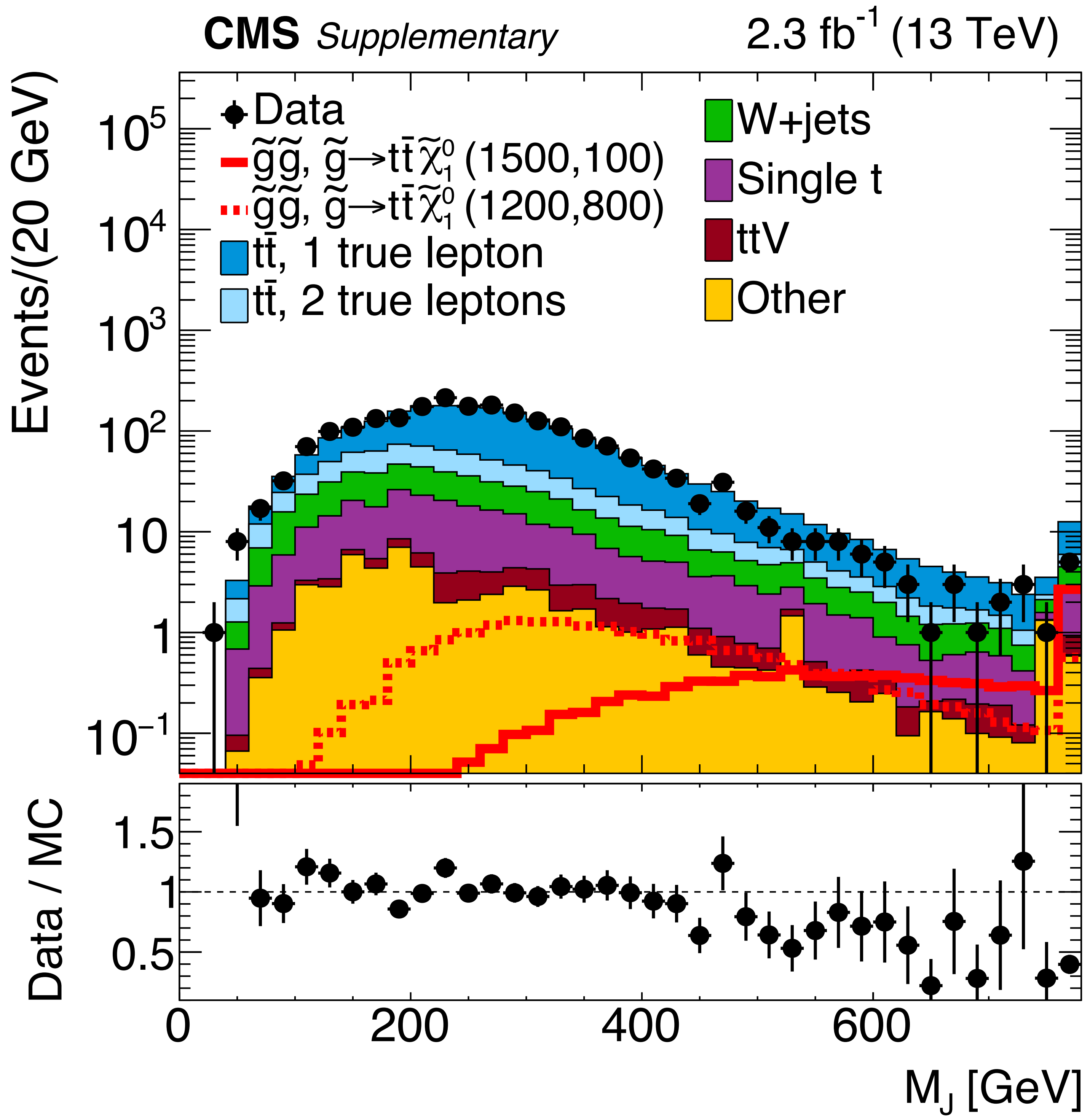


- Multiple choices for clustering : PF cands vs AK4 jets(anti-kT, R=0.4, CMS standard jets), cone size, $p_{T,}$ eta, etc
- Extensively studied for optimization
- **Fat jets (FJ) with R=1.2 are built clustering AK4 jets and leptons that pass object selection using anti-k_T algorithm**
  - Better signal vs background separation
  - Use of official calibrations including PU subtraction
- Observed stability of M_J distribution w.r.t. pileup in all MC samples studied

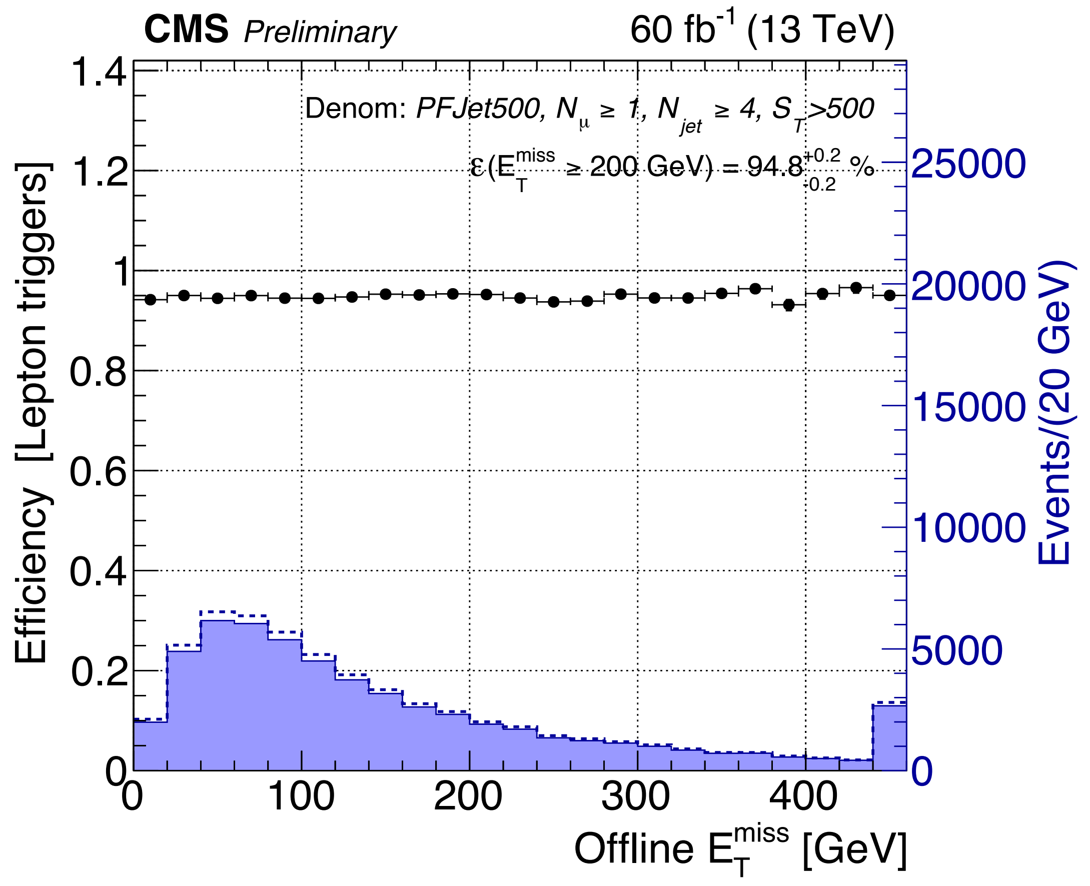
M_J variable: validation

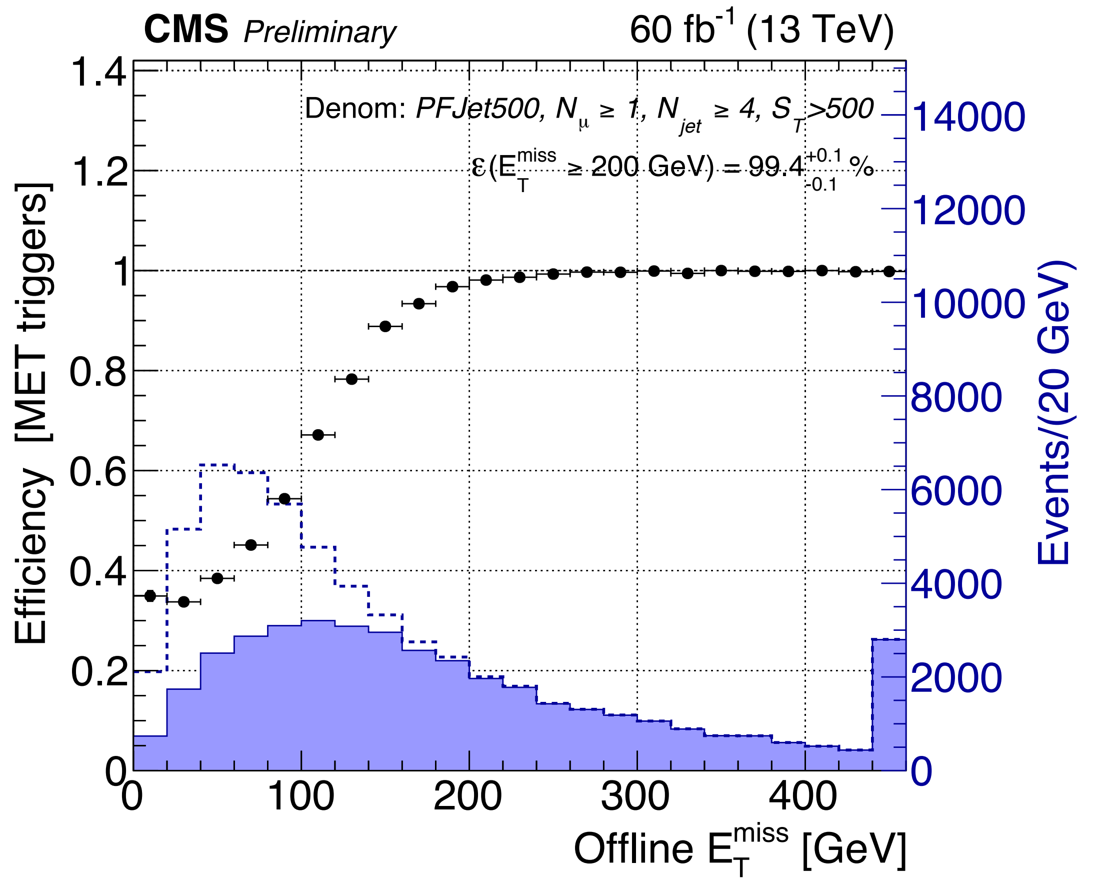


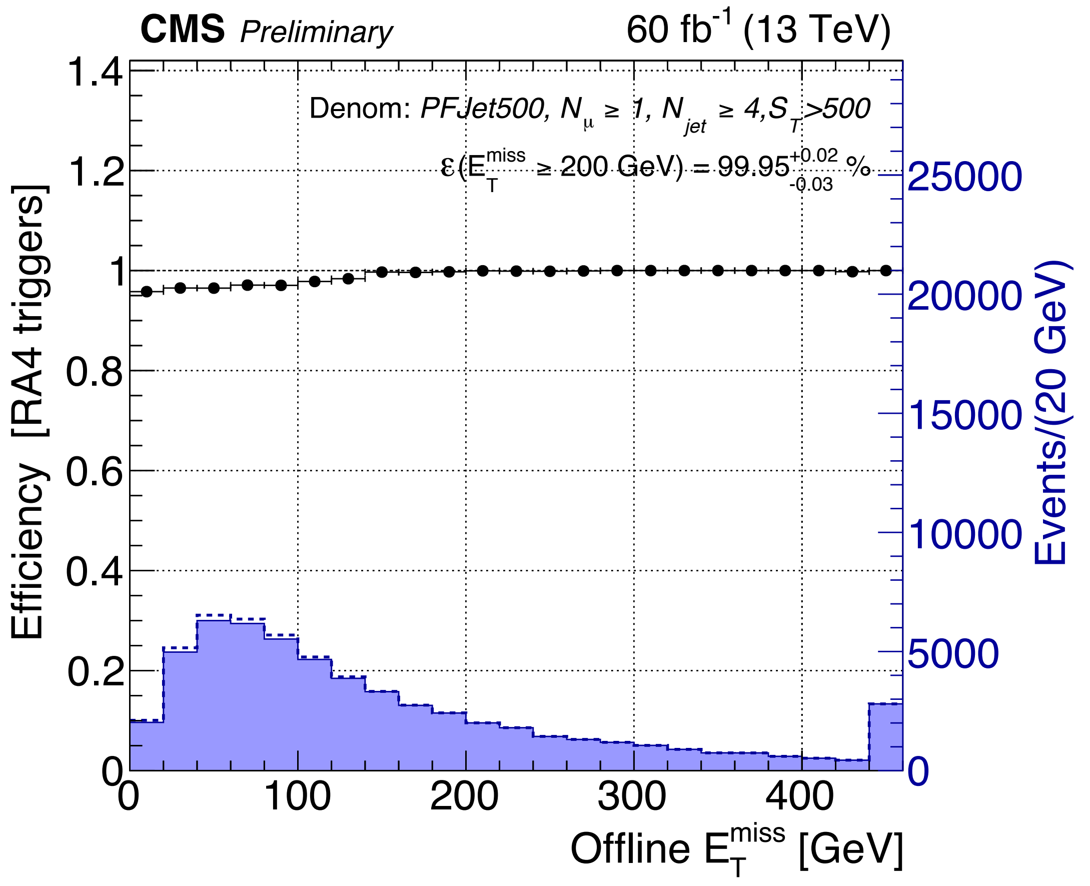


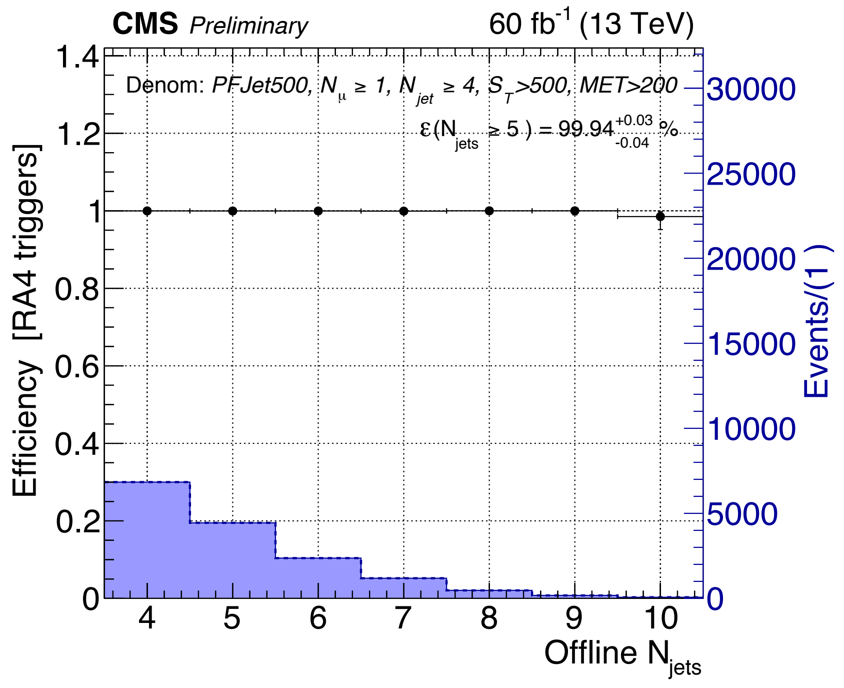


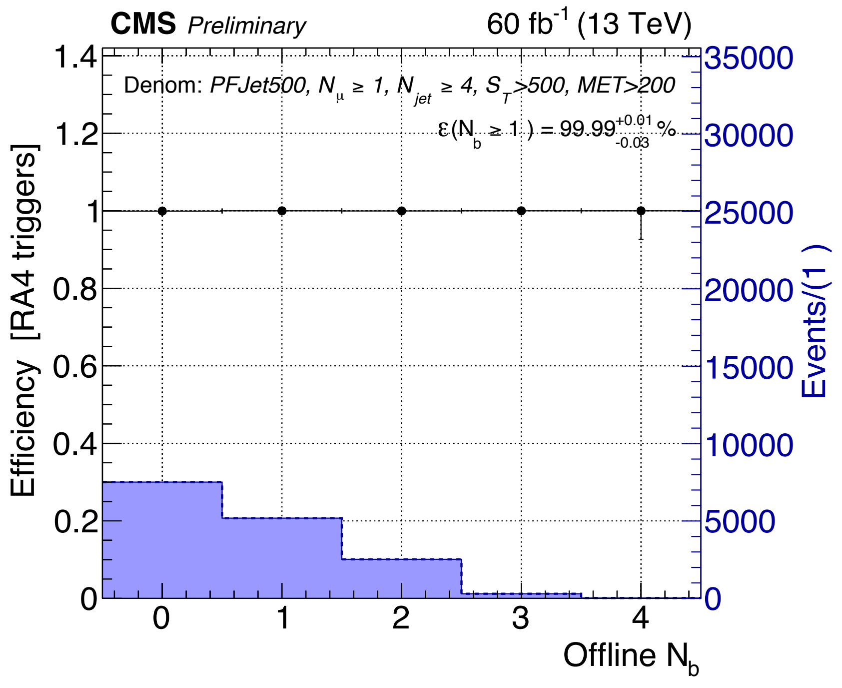
Trigger and objects

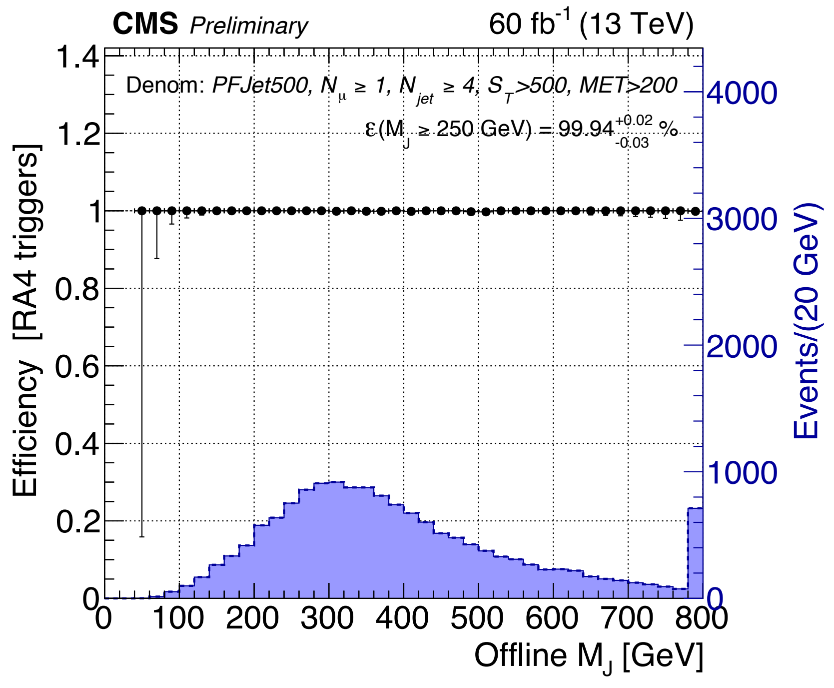


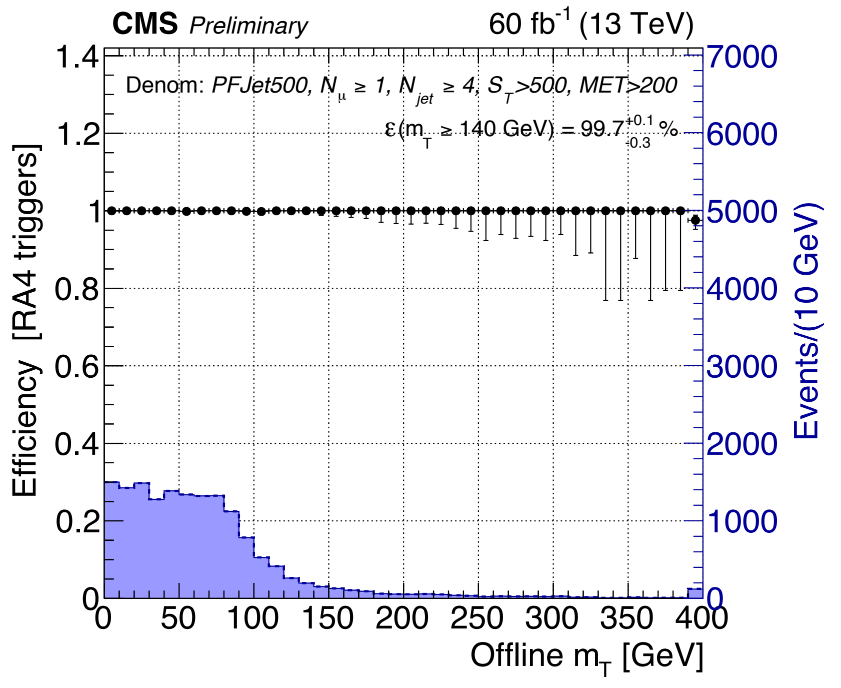








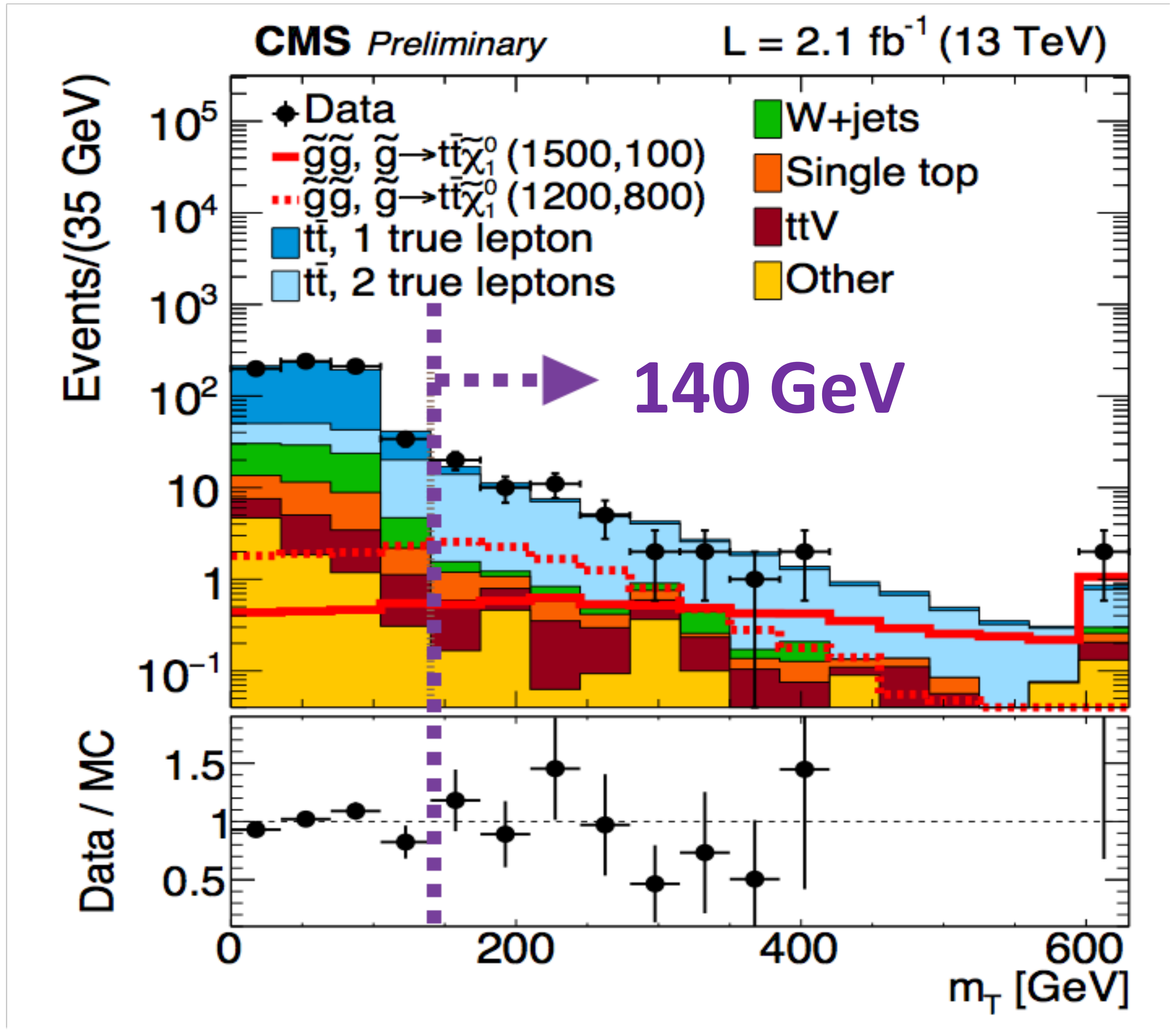




- Trigger (online requirement)
  - **Lepton**(p_T>15 GeV, very very loose isolation) + $\mathbf{H_T}$ (>350 GeV)
- Trigger efficiency not 100%
  - need to estimate it
- Use data sample collected by trigger(s) independent to the analysis triggers

$$\epsilon_{trig} = \frac{\text{Number of events that passed denominator + trigger(s) to be tested}}{\text{Number of events that passed independent trigger(s)}}$$

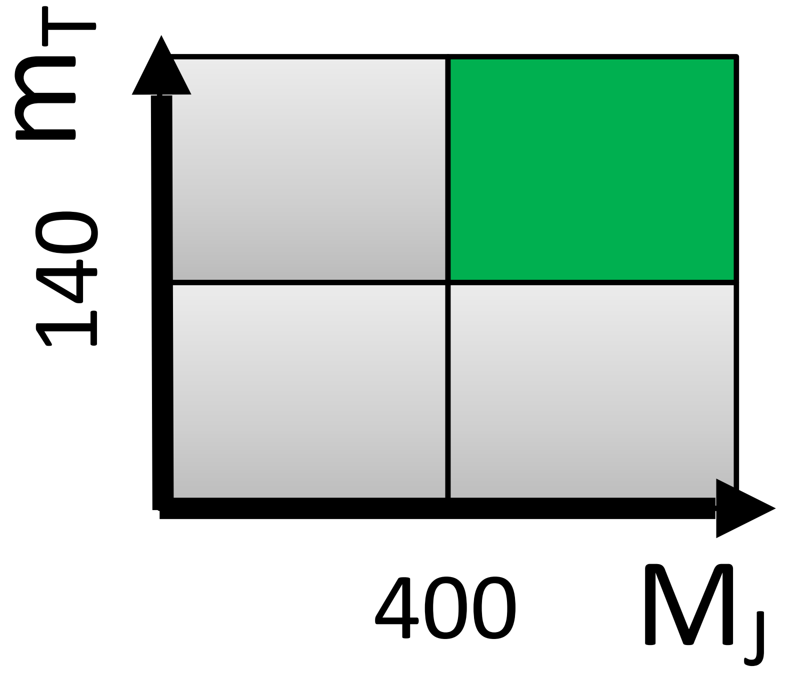
m_T: suppress single-lepton ttbar



$$m_T = \sqrt{2p_T^l\, MET\,(1-\cos(\phi_l - \phi_{MET}))}$$

L=2.1 fb-1	ttbar (1l)	ttbar (2l)	All others	All bkg.	T1tttt NC	T1tttt C
Baseline MJ>250 GeV nb≥2	194.1	39.4	37.0	270.5	6.4	11.5
m_T>140 GeV	2.5	14.7	3.9	21.1	5.0	6.4

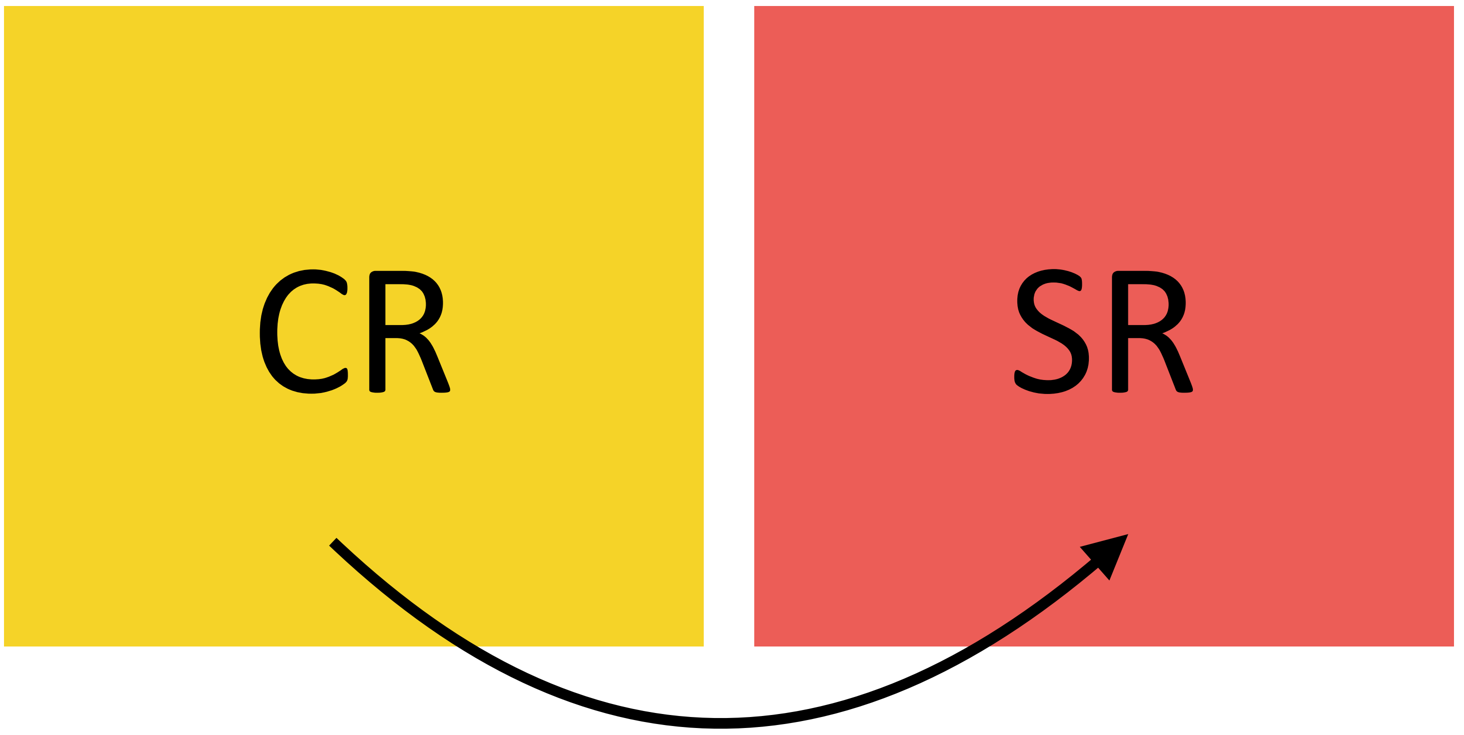
After m_T>140 GeV, background dominated by di-lepton ttbar (~70%)



Signal region: high MJ, high mT

Background estimation

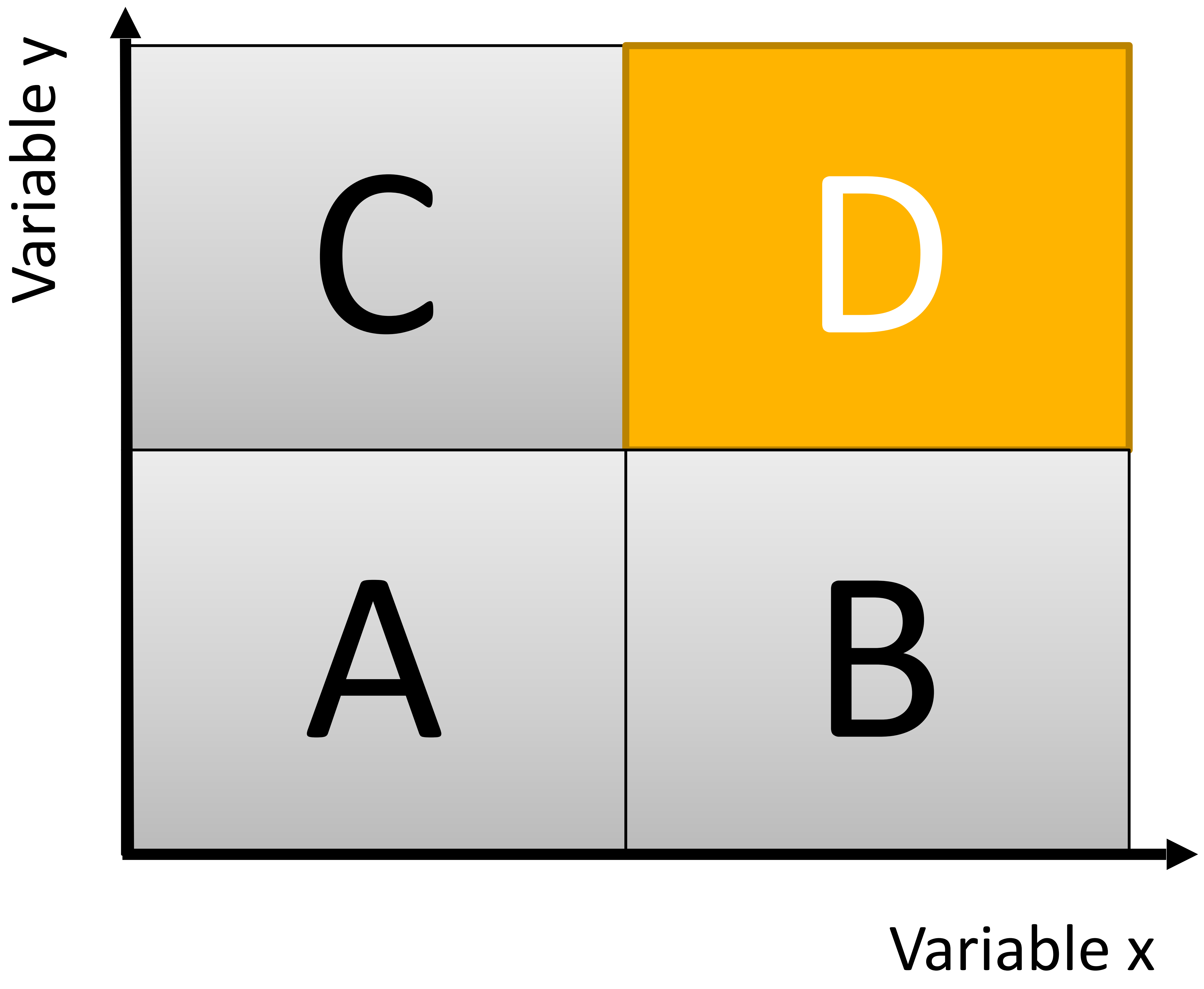
- Search is understanding background (correct background prediction)
  - Both amount and uncertainty
- Underestimated background interpreted as excess in data
- Overestimated background can hide signal
- MC-based vs data-driven
  - Out of the box MC: e.g., rare MC processes
  - Extrapolate using MC: transfer factor from MC
  - Extrapolate using data: transfer factor from data sample



Transfer factor f

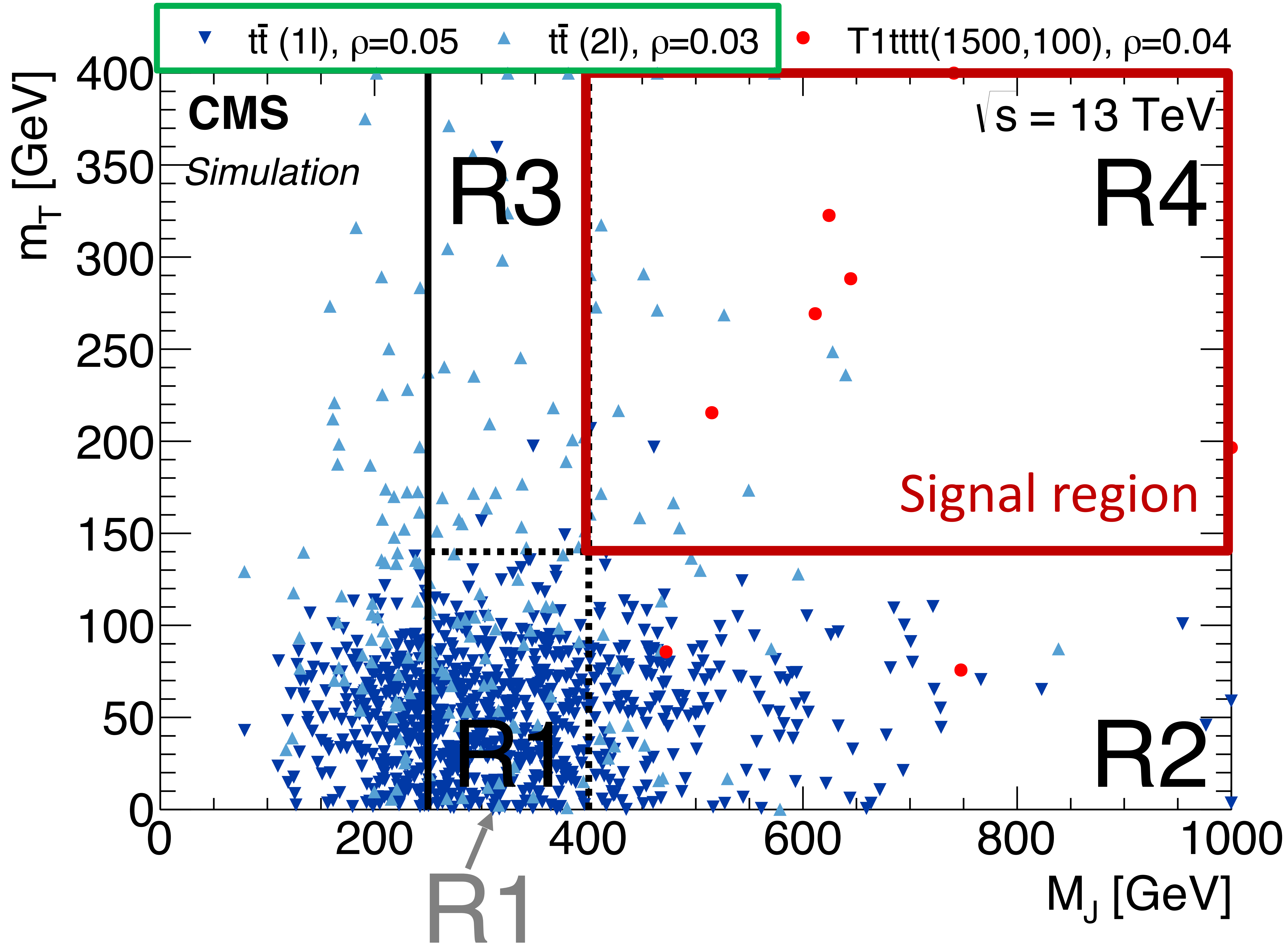
$$N_{SR}^{pred} = N_{CR} \times f$$

Background estimation: ABCD method



- If variable x and y are not correlated, A:B=C:D
- If we know
  - x and y are not correlated
  - A,B and C
- We can predict D
  - D=BC/A
- Putting differently
  - Measure shape of x in A and B, and do extrapolation from C
  - Transfer factor = B/A

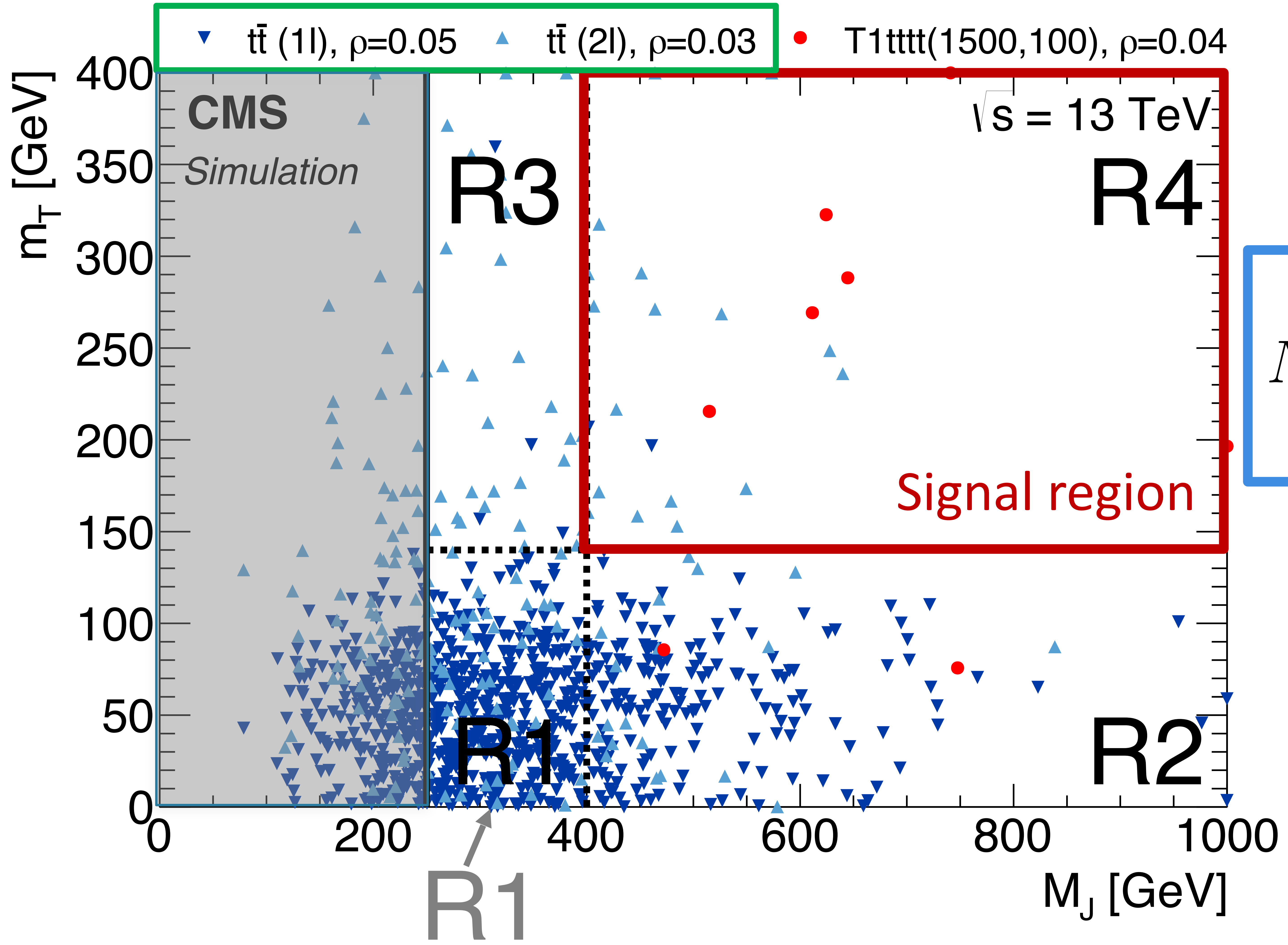
Background estimation : ABCD with m_T and M_J



- m_T and M_J are largely uncorrelated
- ABCD regions: R1-4
- Perform ABCD prediction for R4 (high M_J, high m_T)

$$N_{R4}^{prediction} = \left(\frac{N_{R2} \times N_{R3}}{N_{R1}}\right)_{data}$$

Background estimation : ABCD with m_T and M_J



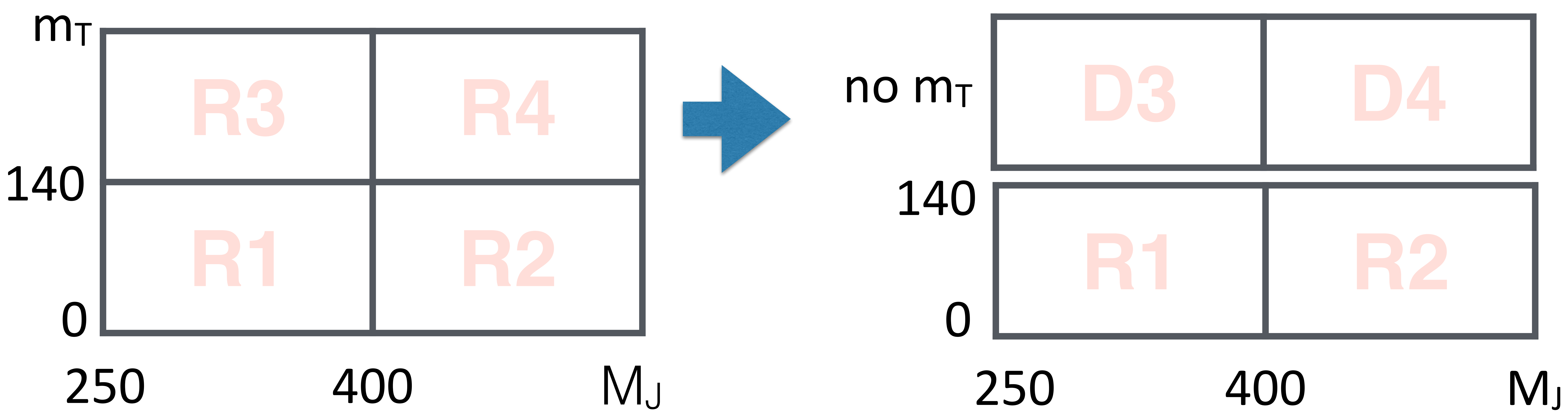
$$N_{R4}^{prediction} = \left(\frac{N_{R2} \times N_{R3}}{N_{R1}}\right)_{data} \times \kappa$$

$$\kappa = \left(\frac{N_{R4}/N_{R2}}{N_{R3}/N_{R1}}\right)_{MC}$$

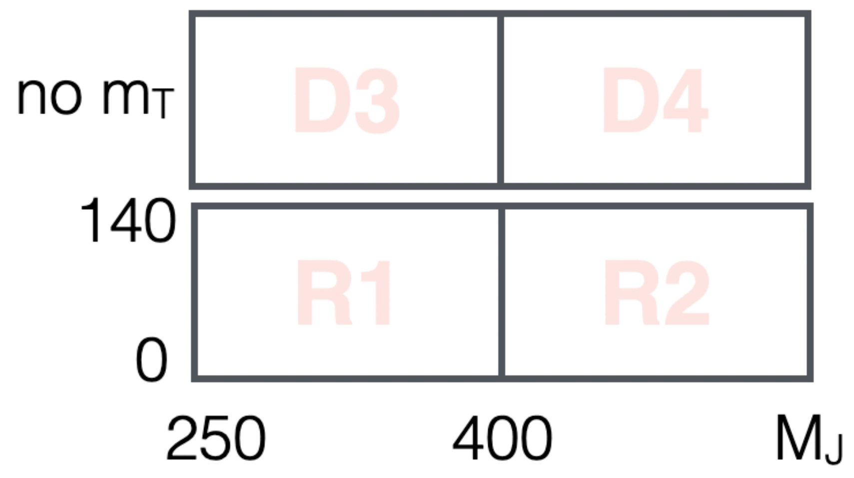
Small correlation between m_T and M_J corrected by κ derived from MC: Small correction → κ=1

Di-lepton systematics: concept

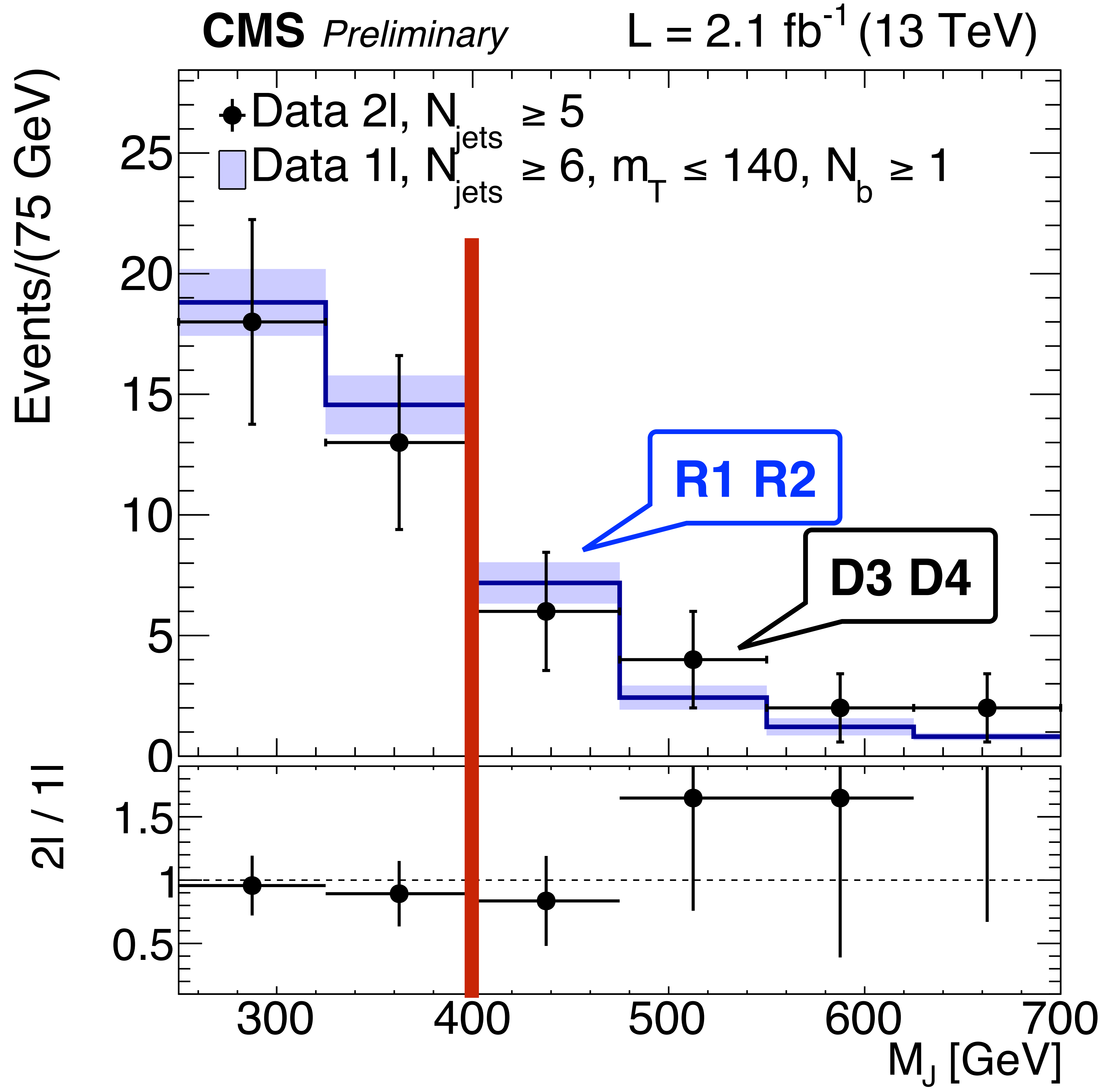
- Validate the background estimation method using ttbar events with two reconstructed leptons
- Replace R3 and R4 (dominated by di-lepton ttbar with one lepton lost) by D3 and D4

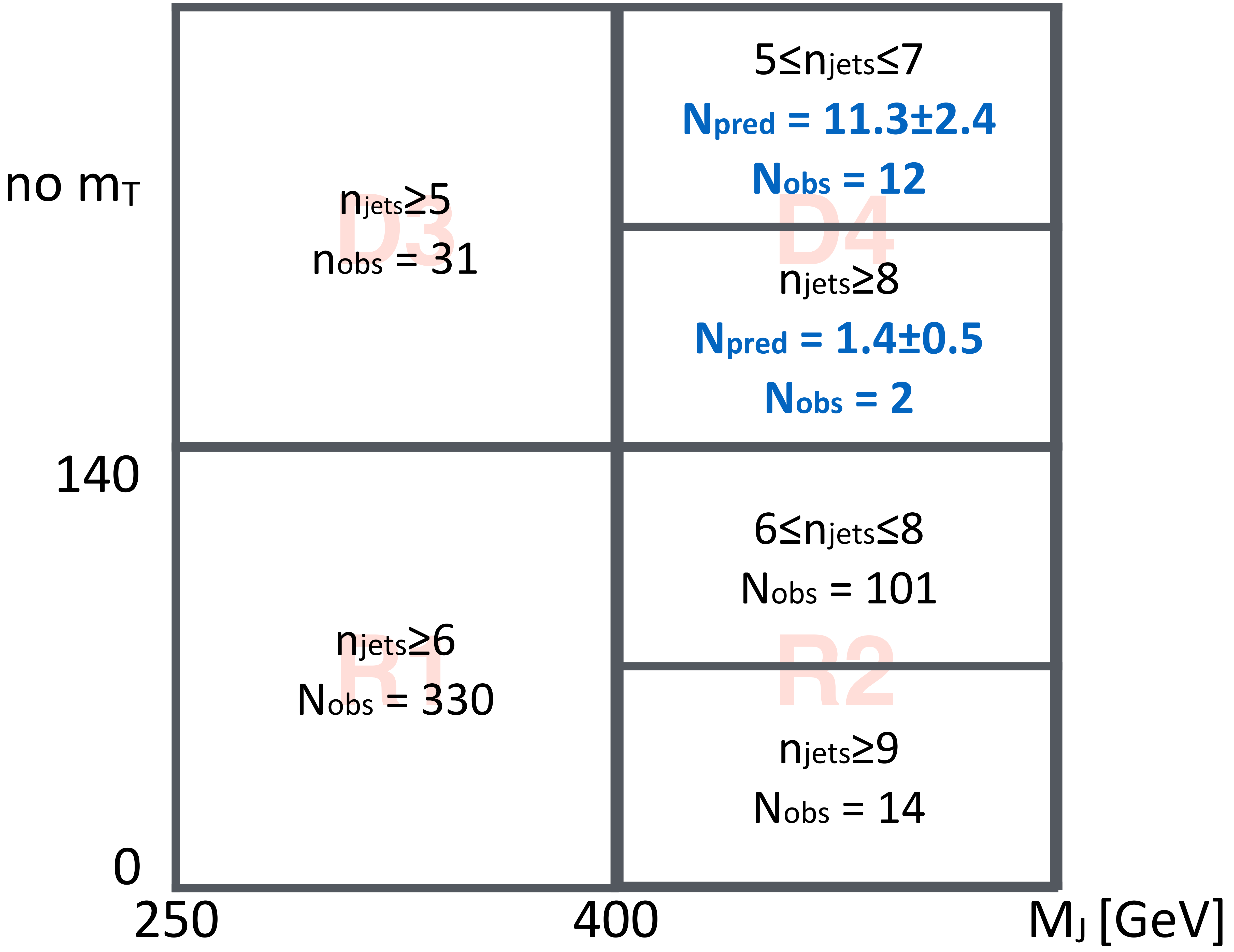


- MET<400 GeV and n_b≤2 to alleviate signal contamination
- n_{jets} requirement loosened by 1 in order to have same number of objects in fat jet clustering
- Test done in two n_{jets} bins : 6-8 and ≥9 for R2 / 5-7 and ≥8 for D4

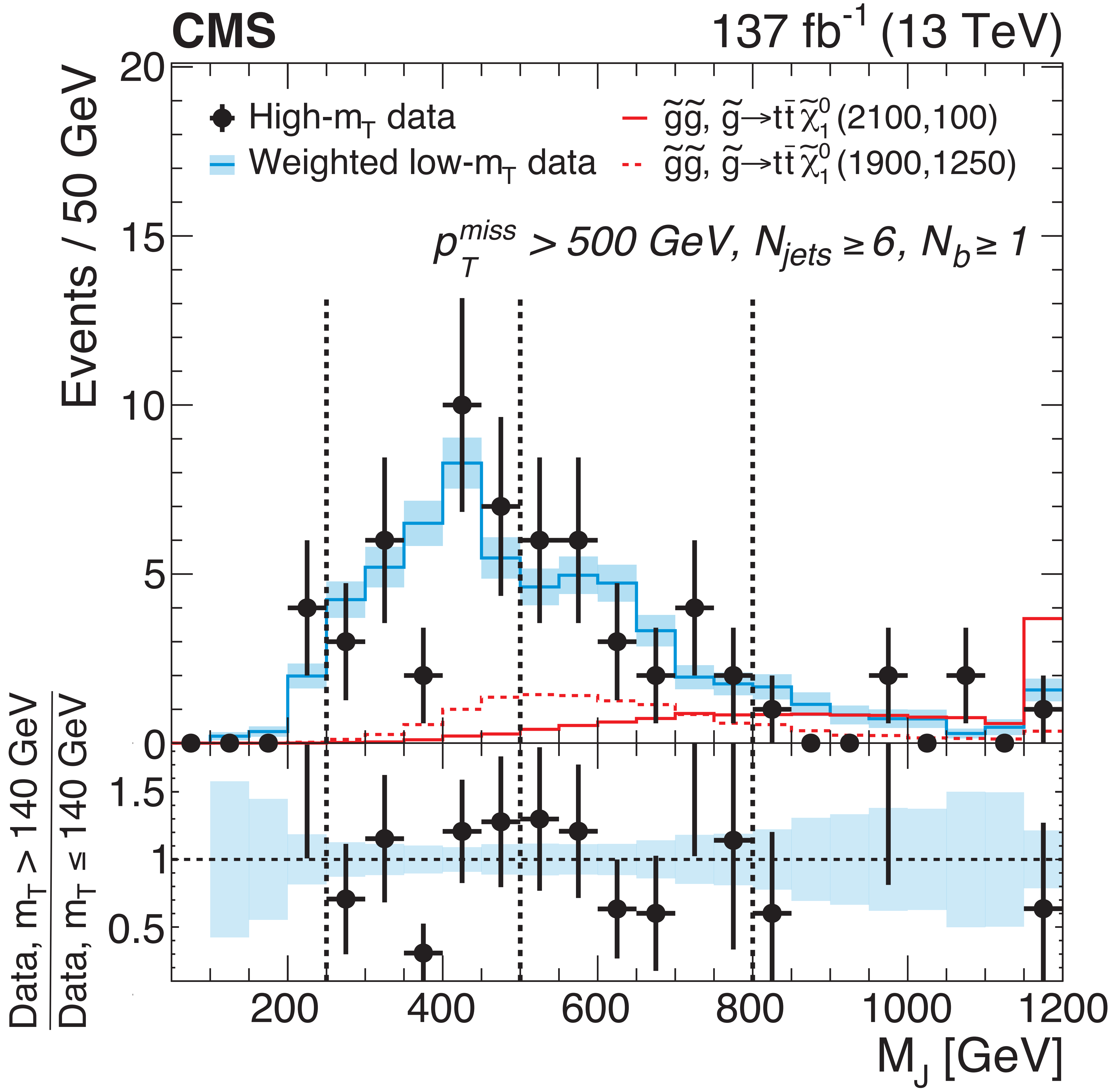


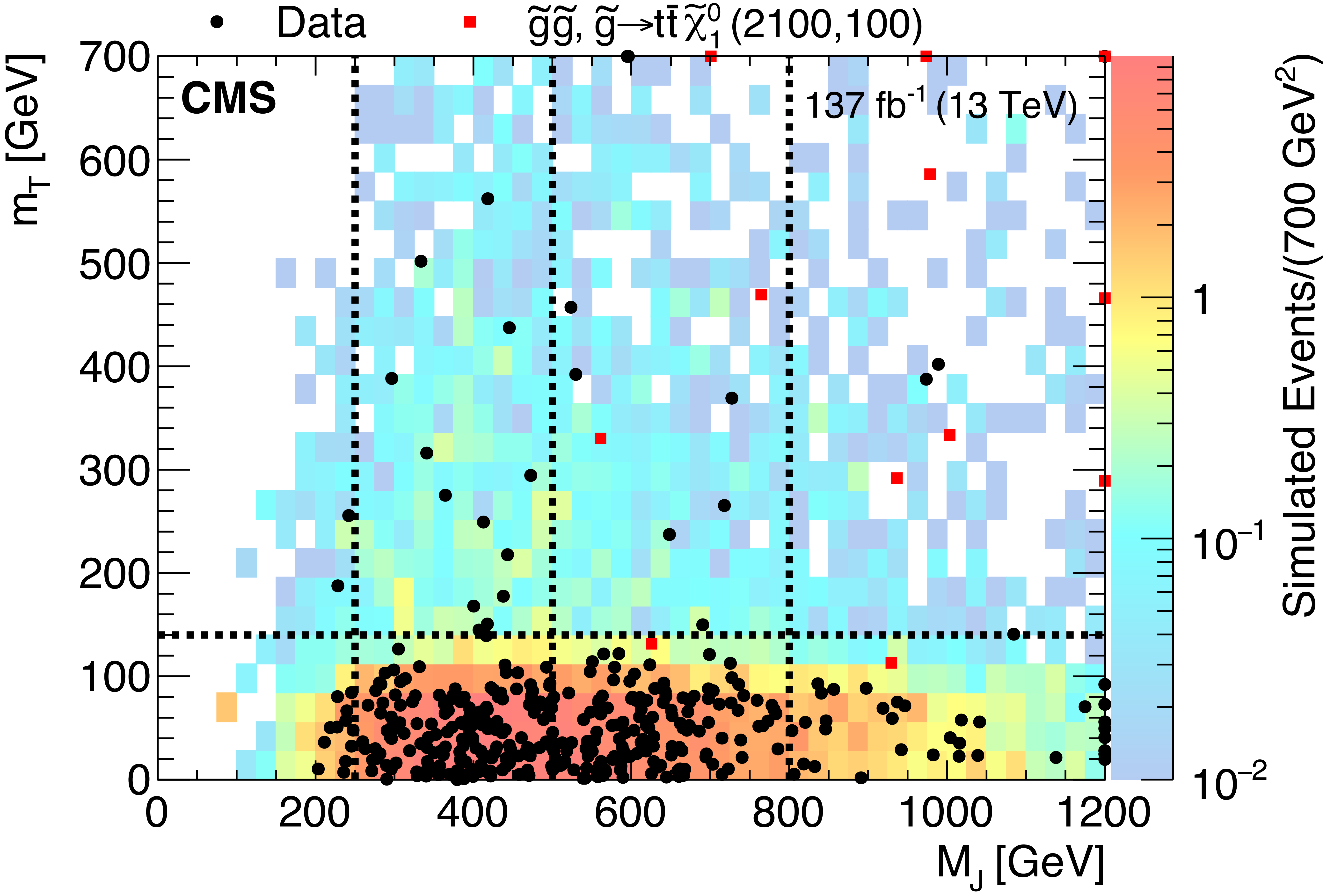
Di-lepton systematics: result





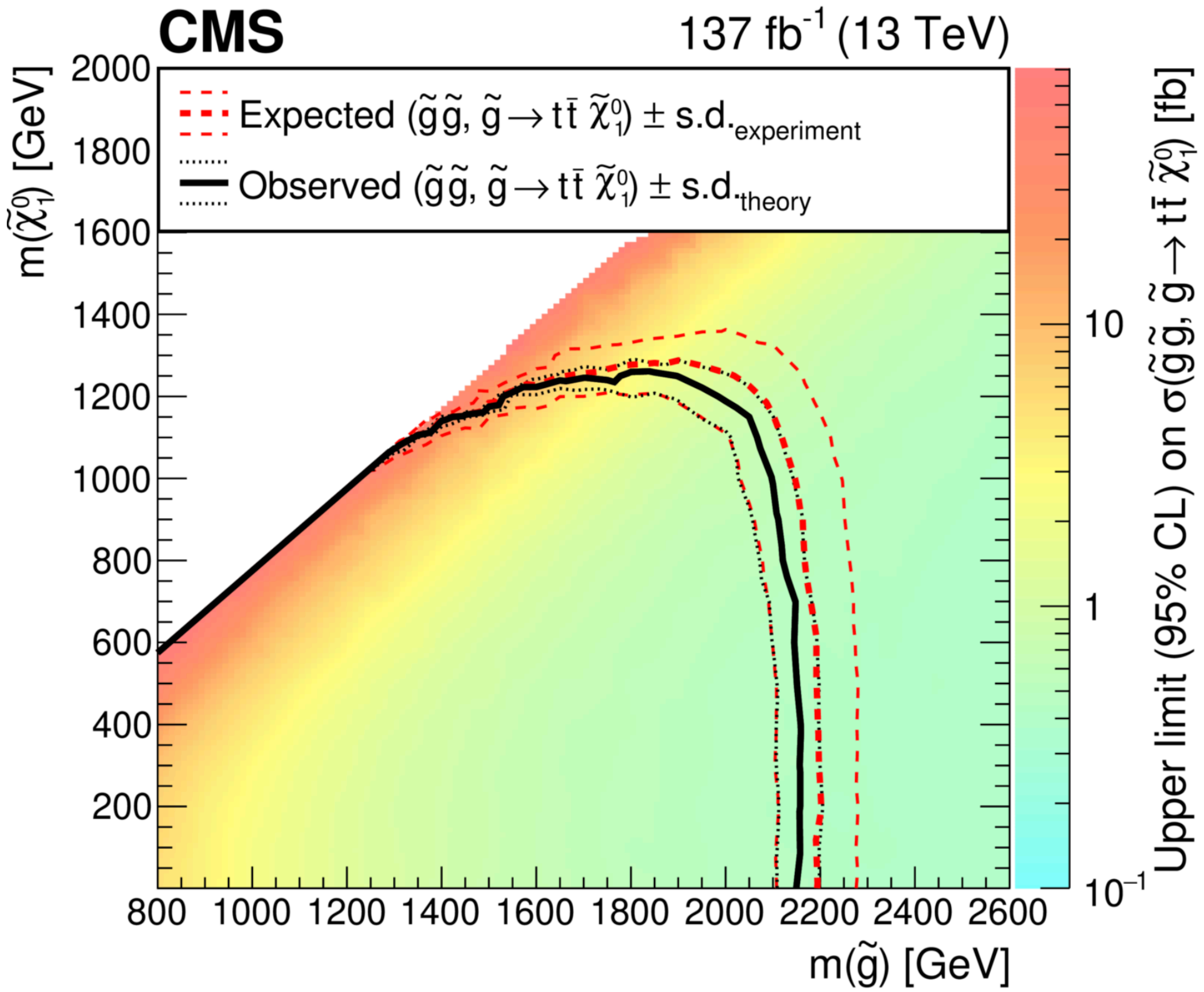
Results


CMS
137 fb-1 (13 TeV)
High-mT data
Weighted low-mT data
g̃g̃, g̃→tt̄χ̃⁰₁ (2100,100)
g̃g̃, g̃→tt̄χ̃⁰₁ (1900,1250)
pT miss > 500 GeV, Njets ≥ 6, Nb ≥ 1
Events / 50 GeV
Data, mT > 140 GeV / Data, mT ≤ 140 GeV
MJ [GeV]


Data
g̃g̃, g̃→tt̄χ̃⁰₁ (2100,100)
CMS
137 fb-1 (13 TeV)
mT [GeV]
MJ [GeV]
Simulated Events/(700 GeV2)

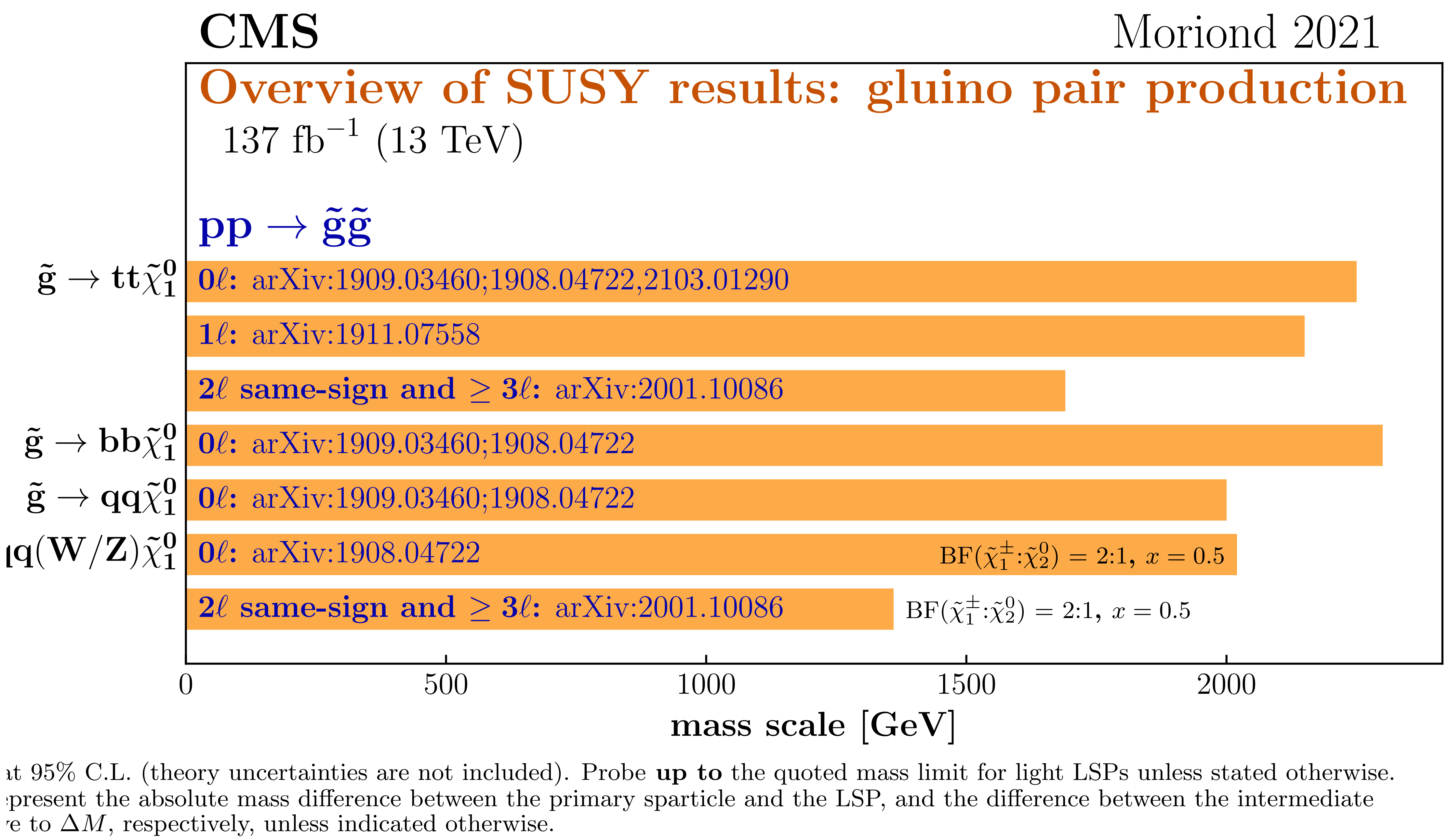
CMS
R1-R3 fit
R1-R4 fit
137 fb^-1 (13 TeV)
Low M_J
High M_J
200 < p_T^miss ≤ 350 GeV
350 < p_T^miss ≤ 500 GeV
p_T^miss ≥ 500 GeV
1b
2b
≥3b
Low N_jets (odd bin #)
High N_jets (even bin #)
Events / Bin
Pull
Bin number

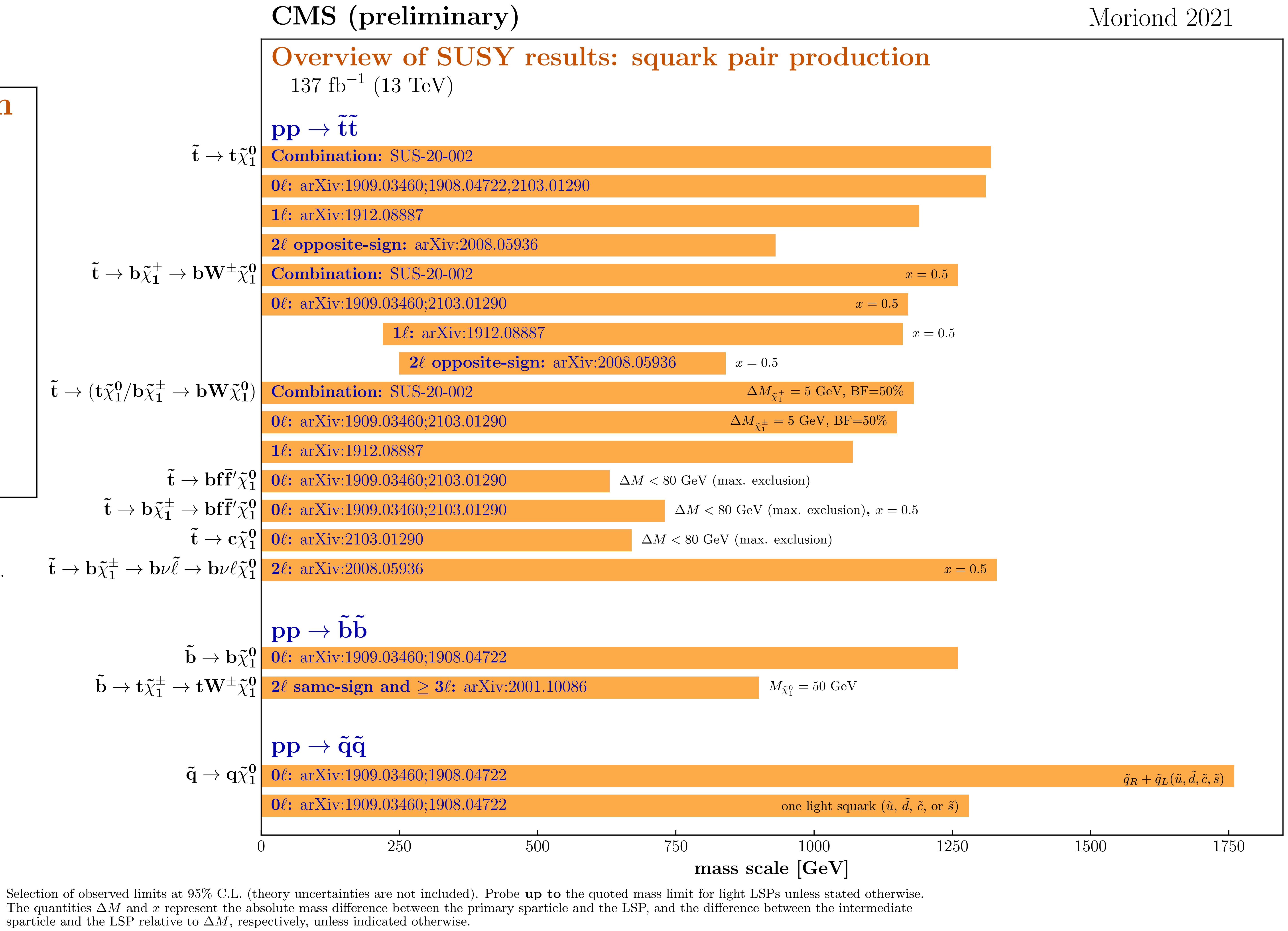
What does a limit plot tell us?



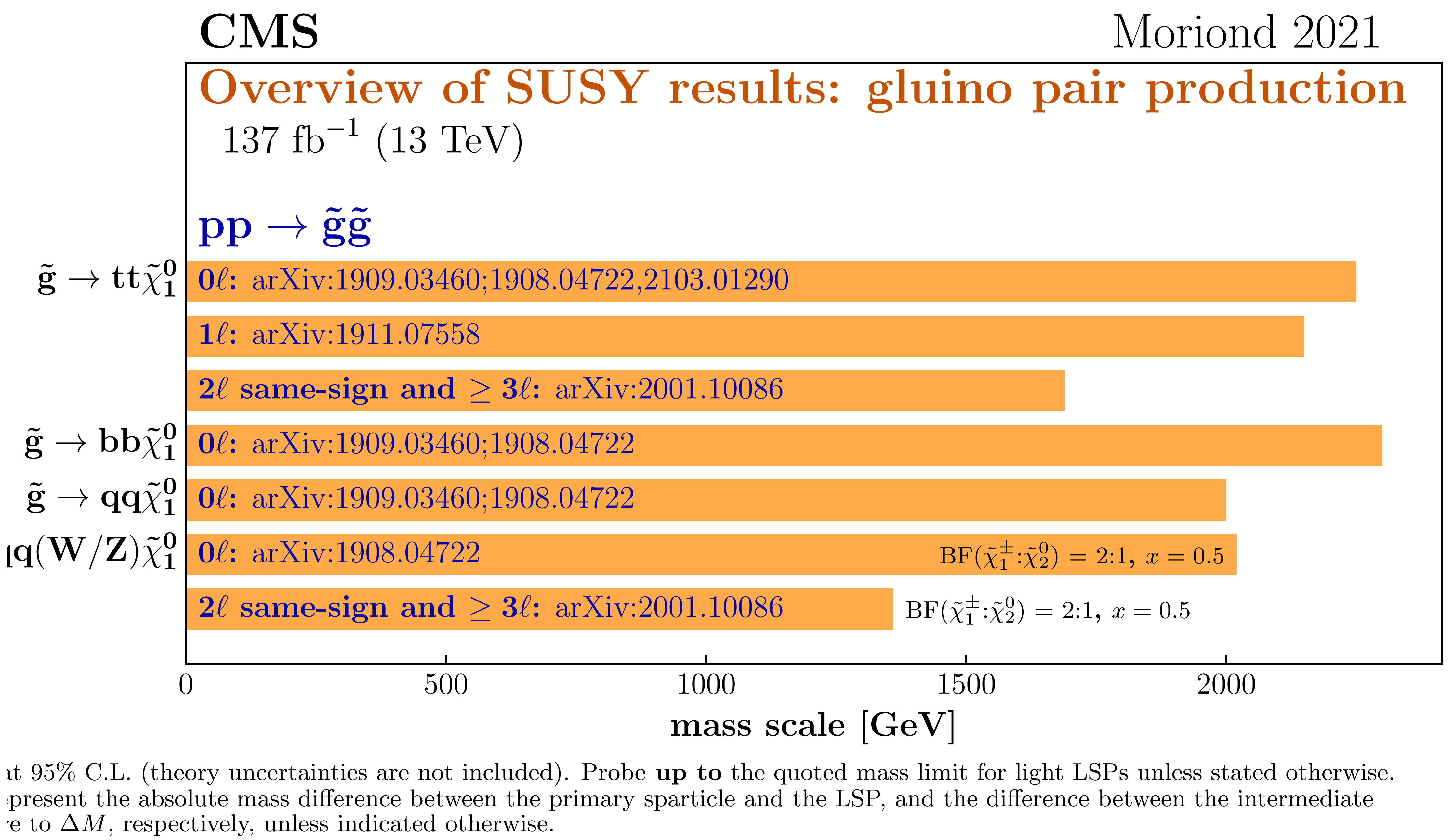
- Color map
  - cross section upper limit in fb
- Region left to the red line is expected to be excluded if data is equal to background prediction
- Region left to the black line (observed) is excluded assuming theoretical cross section of the model
- Worse limit in compressed region WHY?
  - Event kinematics is different
- Why is observed limit worse than expected limit?
  - Excess in data (or underestimation of background)

Where do we stand?





Where do we stand?



- Natural SUSY seriously challenged …
- Era of cross section/luminosity jump has ended
- EWKino production is less constrained due to smaller cross sections than strong production
- Should think if we have missed any phase space/signatures (leave no stones unturned)
    - RPV, LLP, …

References

- https://pdg.lbl.gov/2019/reviews/rpp2018-rev-susy-2-experiment.pdf
- https://pdg.lbl.gov/2019/reviews/rpp2019-rev-susy-1-theory.pdf
- https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections
- http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS-15-007/index.html
- http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS-16-037/index.html
- http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS-19-007/index.html
- http://hep.ucsb.edu/people/richman/Richman_SUSSP69_Lectures.pdf
- http://hep.ucsb.edu/people/claudio/talks/SUSY_Bangalore.pdf