Cornering the Top Squark with the CMS Experiment

LHC Seminar, April 27th 2021

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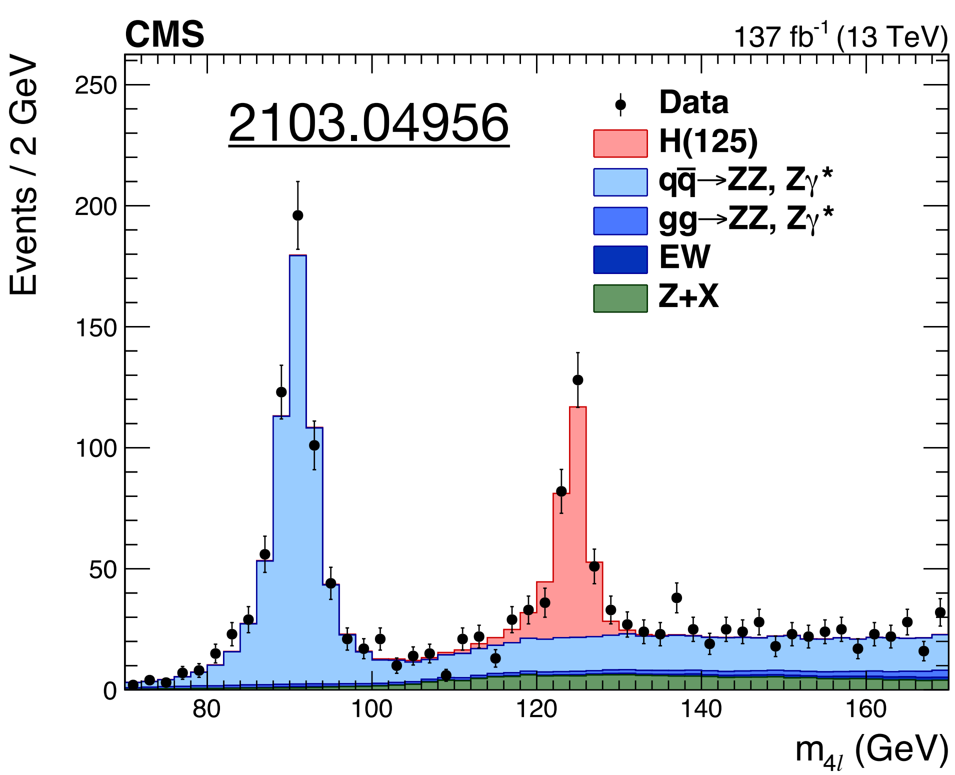
on behalf of the CMS Collaboration

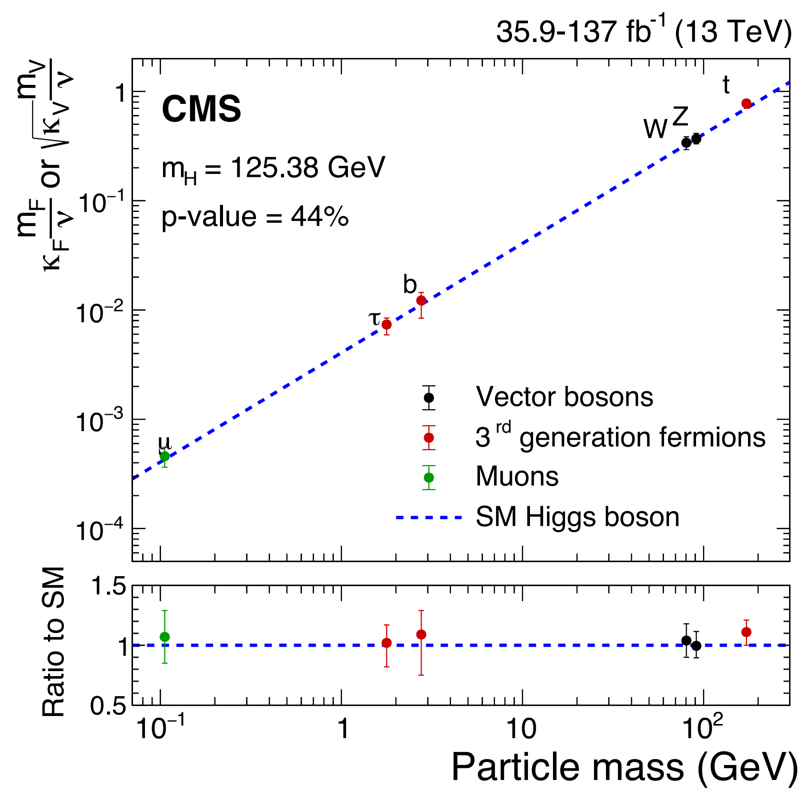
Outline

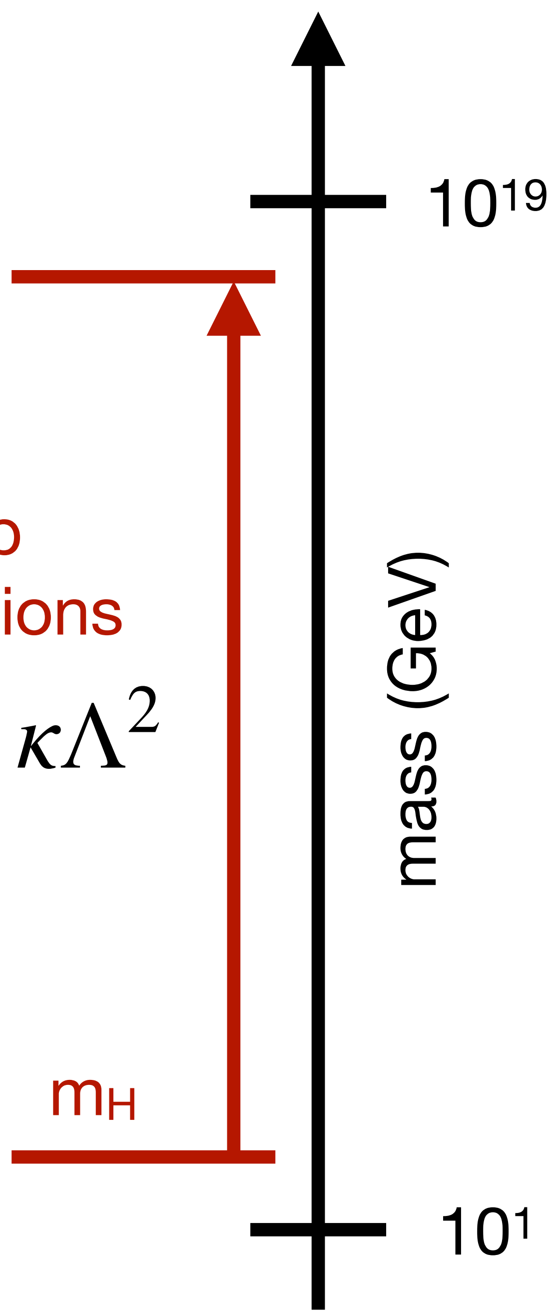
- Quick reminder of why we are interested in top squarks
- What were the constraints from Run 1?
- Novel tools that could help us find top squarks
- Results from the CMS top squark searches of LHC Run 2
- Closing some holes where the stop could be hiding

THE STATE OF THE SM

- After **Higgs discovery** and Run 1: We know that the **SM is incomplete**, but haven't found direct evidence for new physics
- Higgs boson behaves as expected - but **what stabilizes its mass?**
- **Supersymmetry (SUSY) could provide an answer**



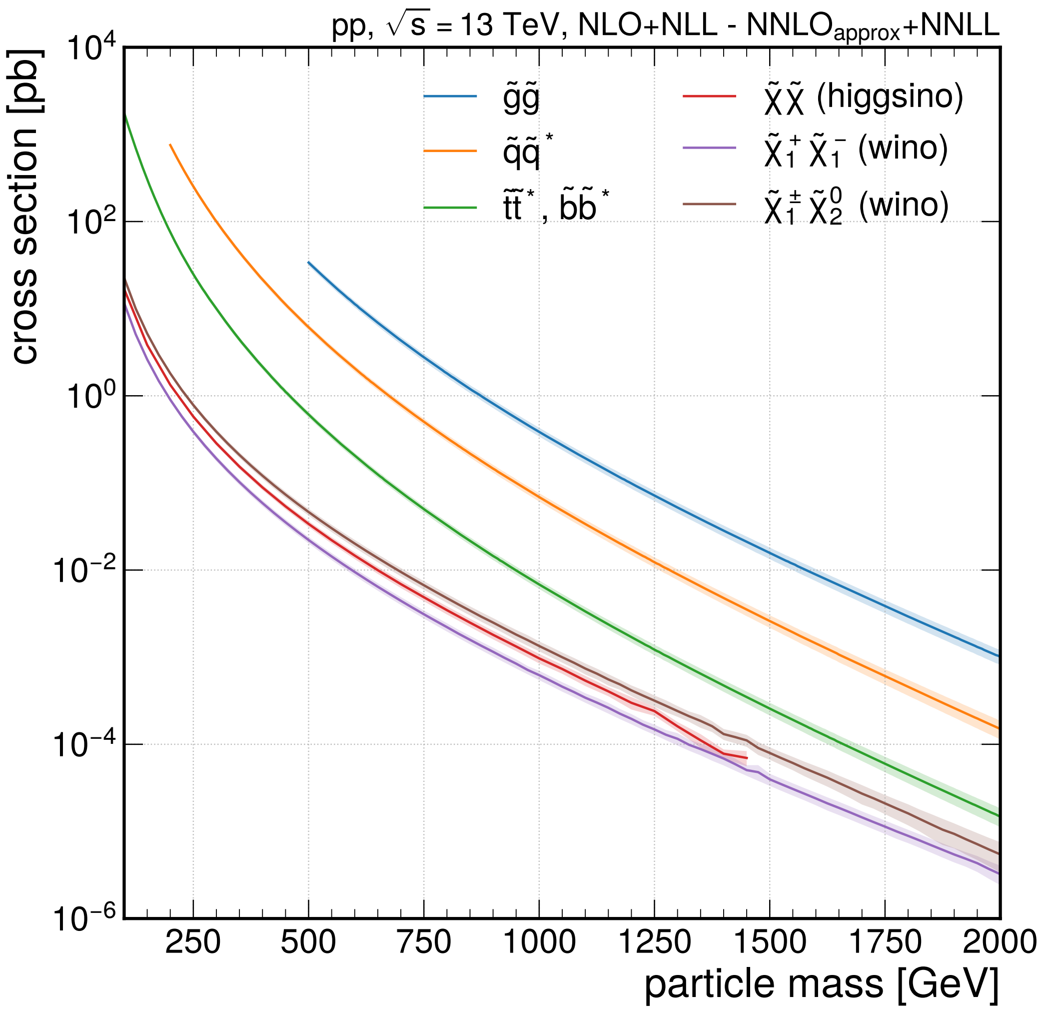




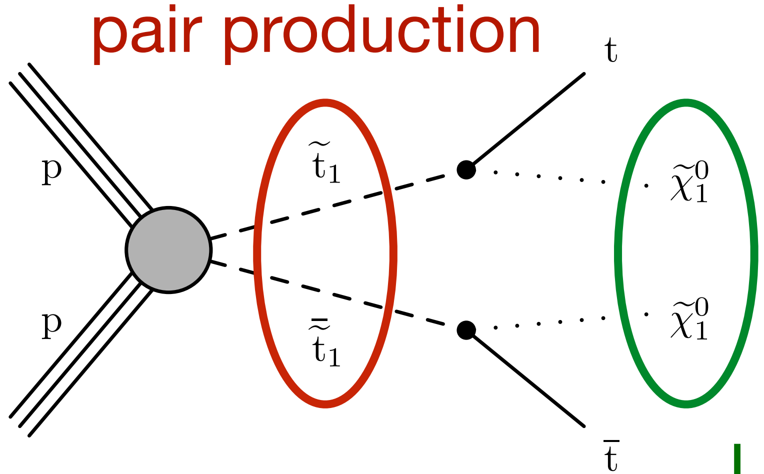
$$\delta m_H^2 = \kappa \Lambda^2$$

WHY TOP SQUARKS?

- Light top squark (stop) with mass around the TeV scale well motivated
  - Contributions of top quark to loop corrections of Higgs mass cancelled by top squark
- Top squark carries color charge → sizable x-sec at LHC
- If R-parity $R = (-1)^{3B+L+2s}$ is conserved → lightest SUSY particle (LSP) stable

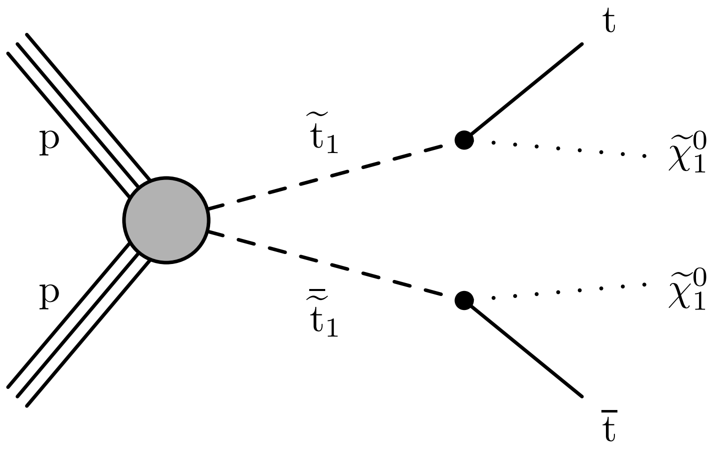


Simplified model of top squark production



Lightest neutralino: Stable, weakly interacting & massive → DM candidate

FINDING TOP SQUARKS



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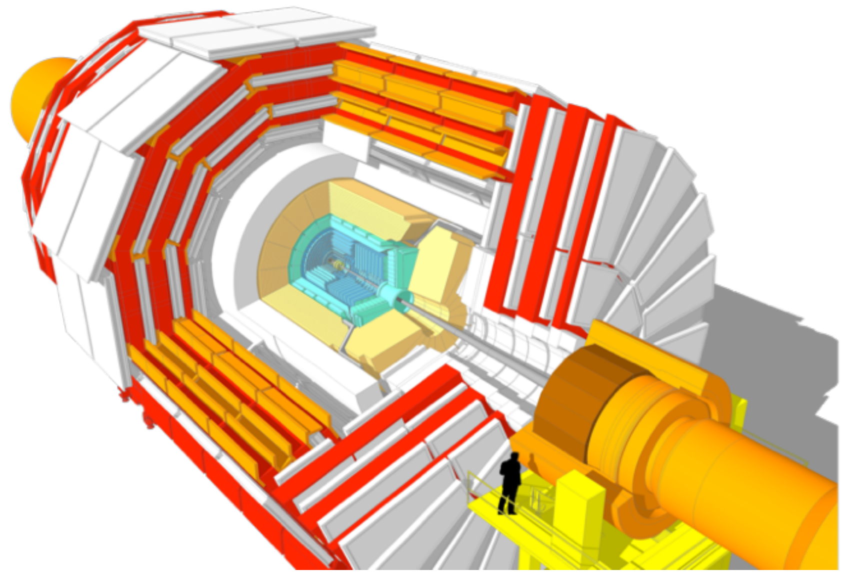

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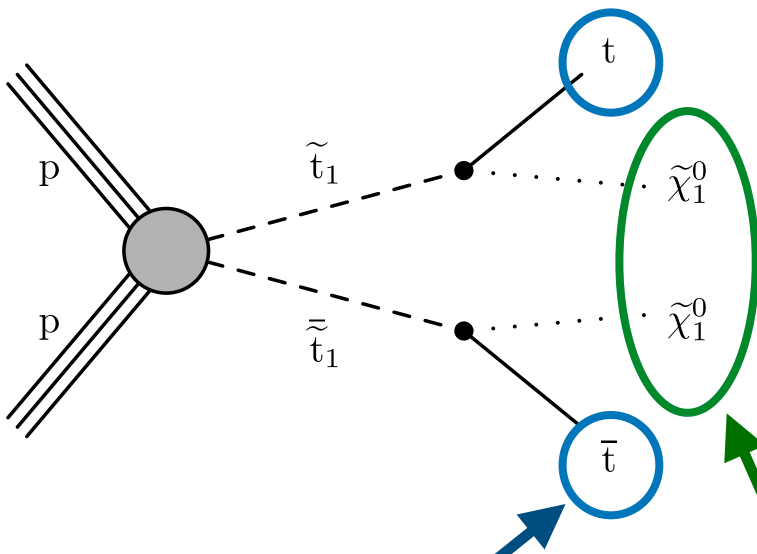
Finding Top Squarks



decay to (mostly) visible particles via t→bW

invisible to detector

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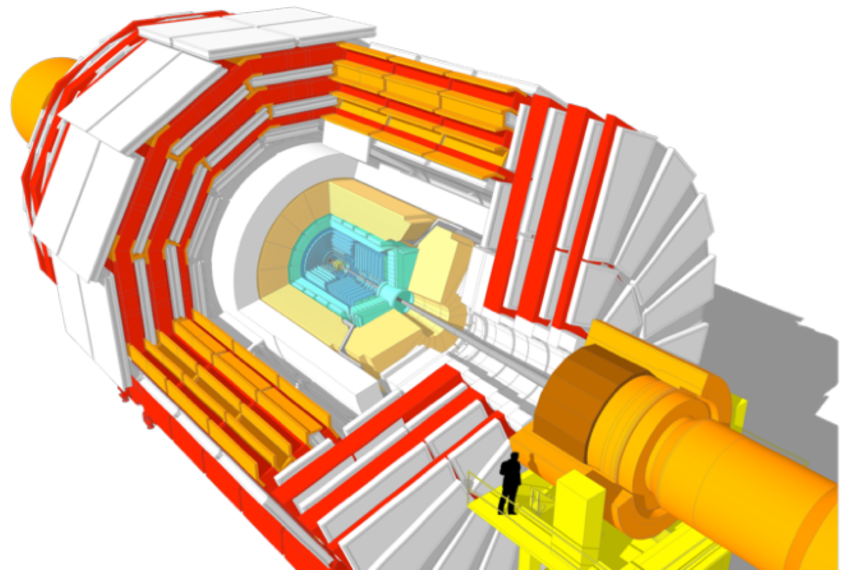

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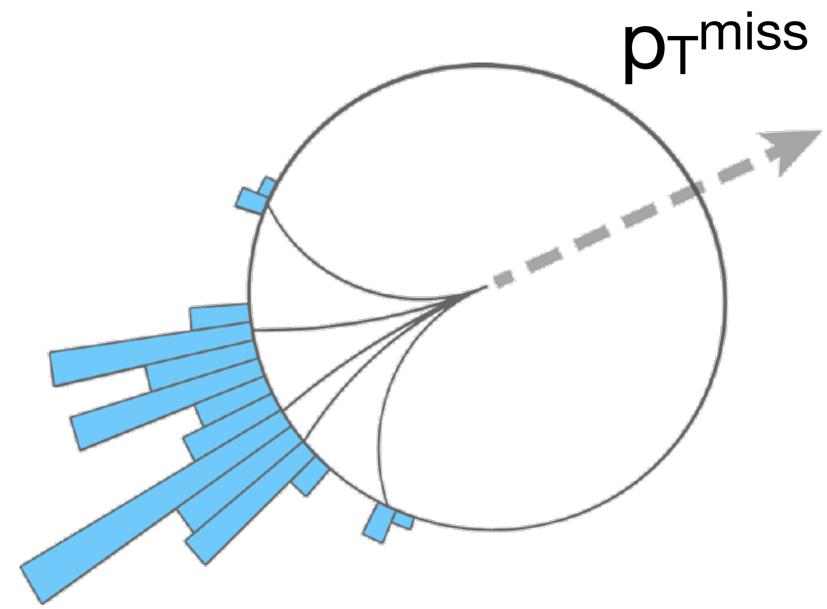
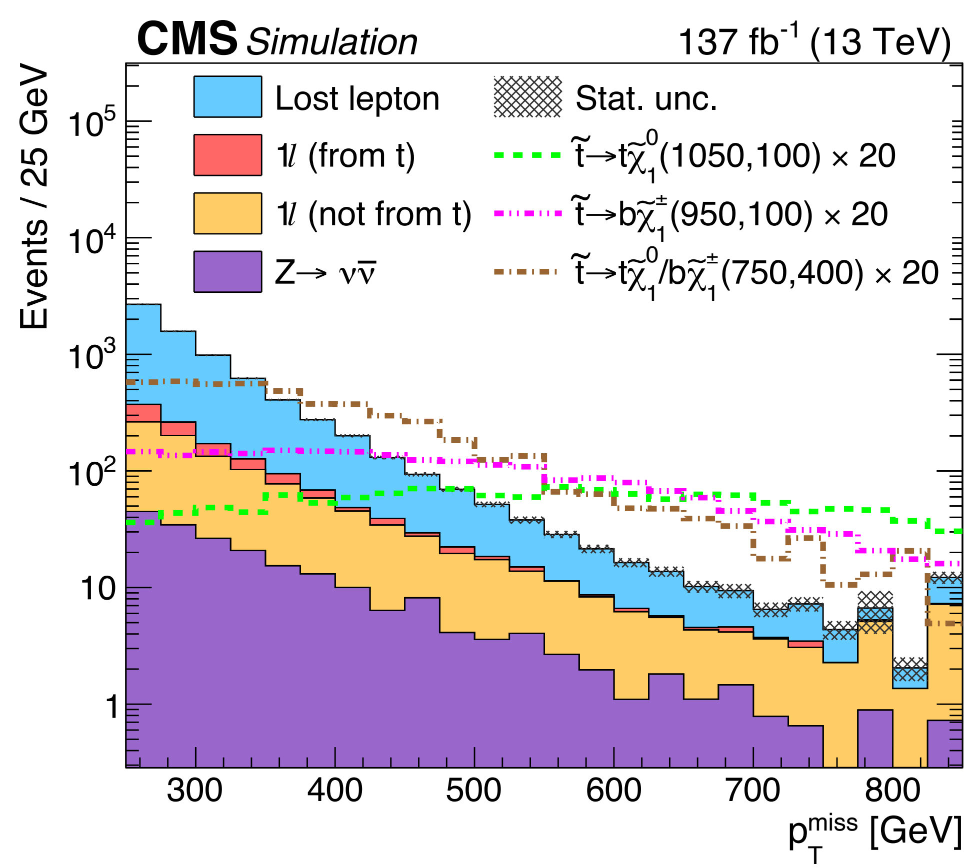
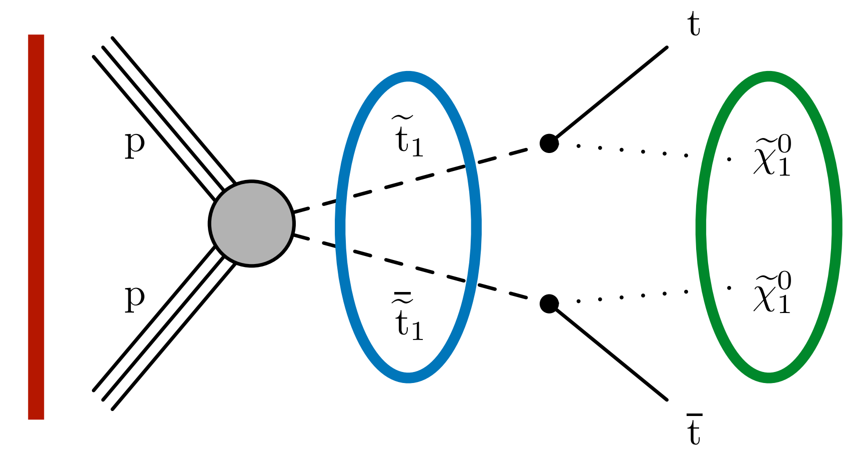
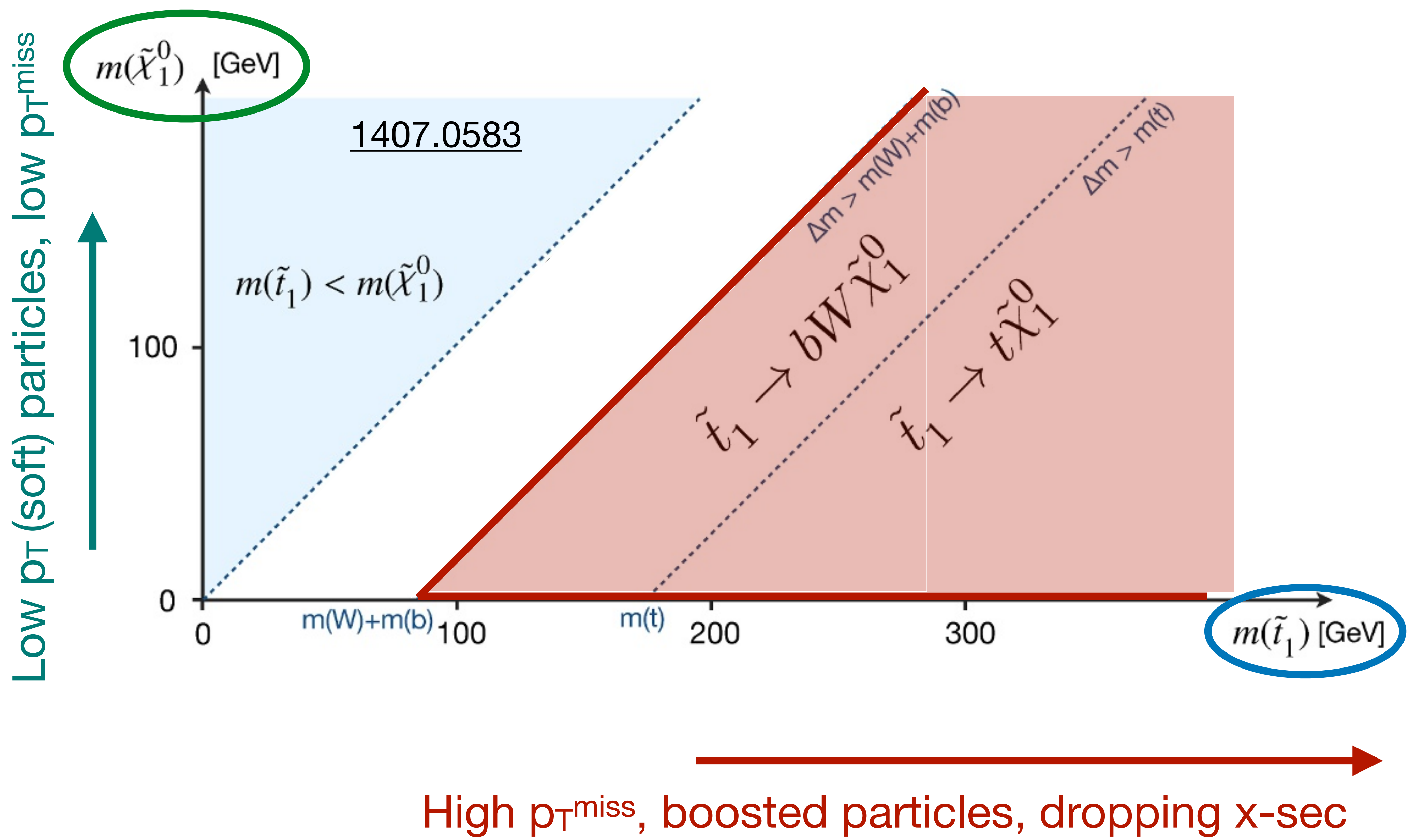




MANY CHALLENGES



- Signal kinematics highly dependent on mass splitting of top squark and LSP, $\Delta m = m(\tilde{t}_1) - m(\tilde{\chi}_1^0)$
- Larger Δm → larger p_T^{miss}



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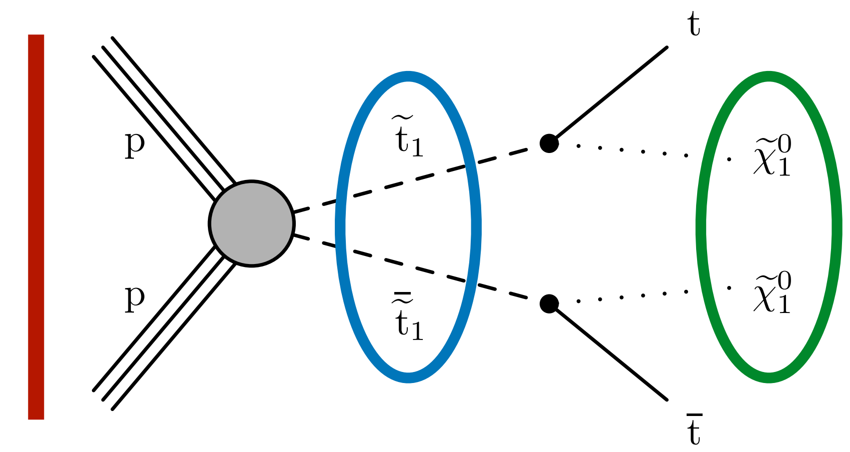

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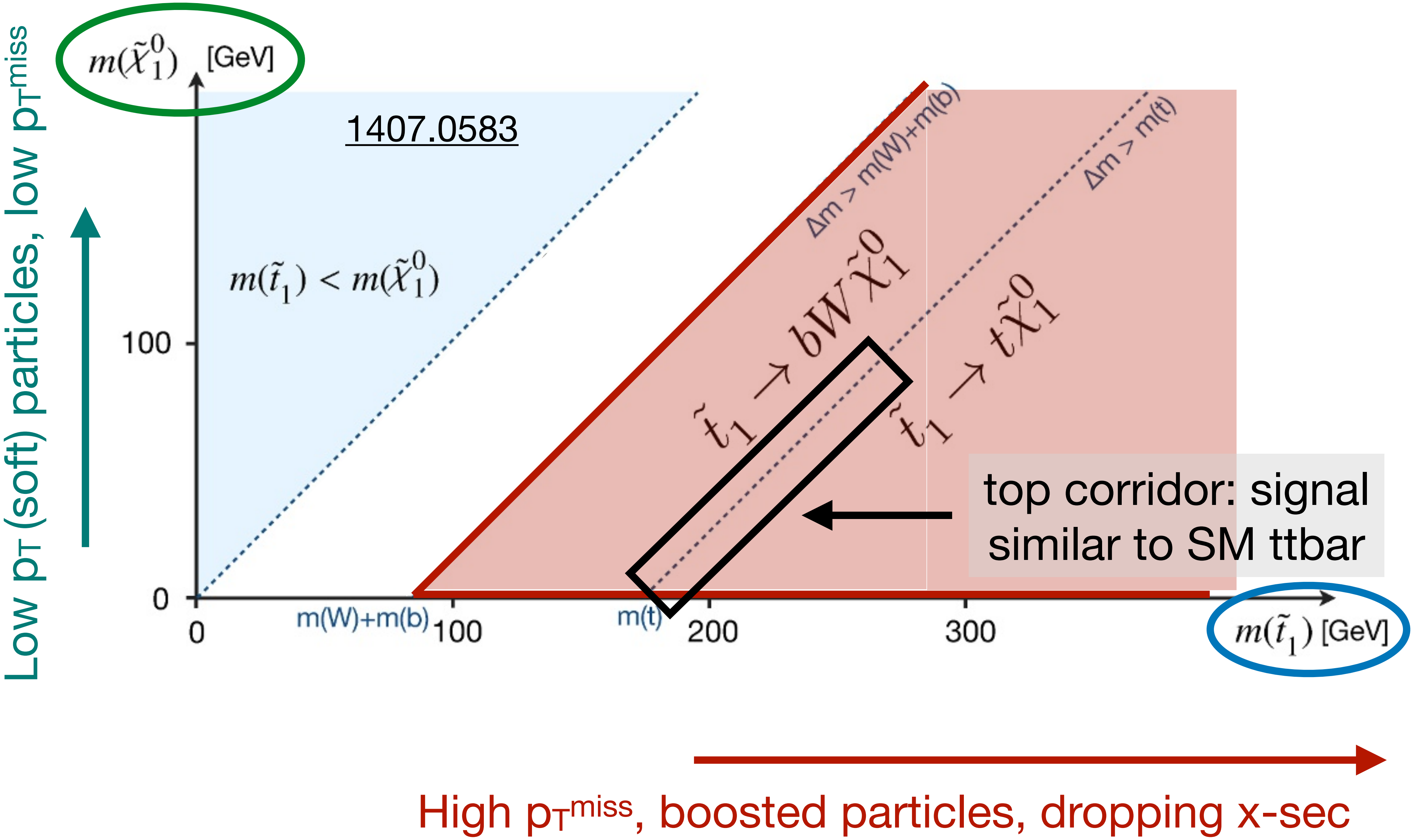

Many challenges

- Signal kinematics highly dependent on mass splitting of top squark and LSP, $\Delta m = m(\tilde{t}_1) - m(\tilde{\chi}_1^0)$
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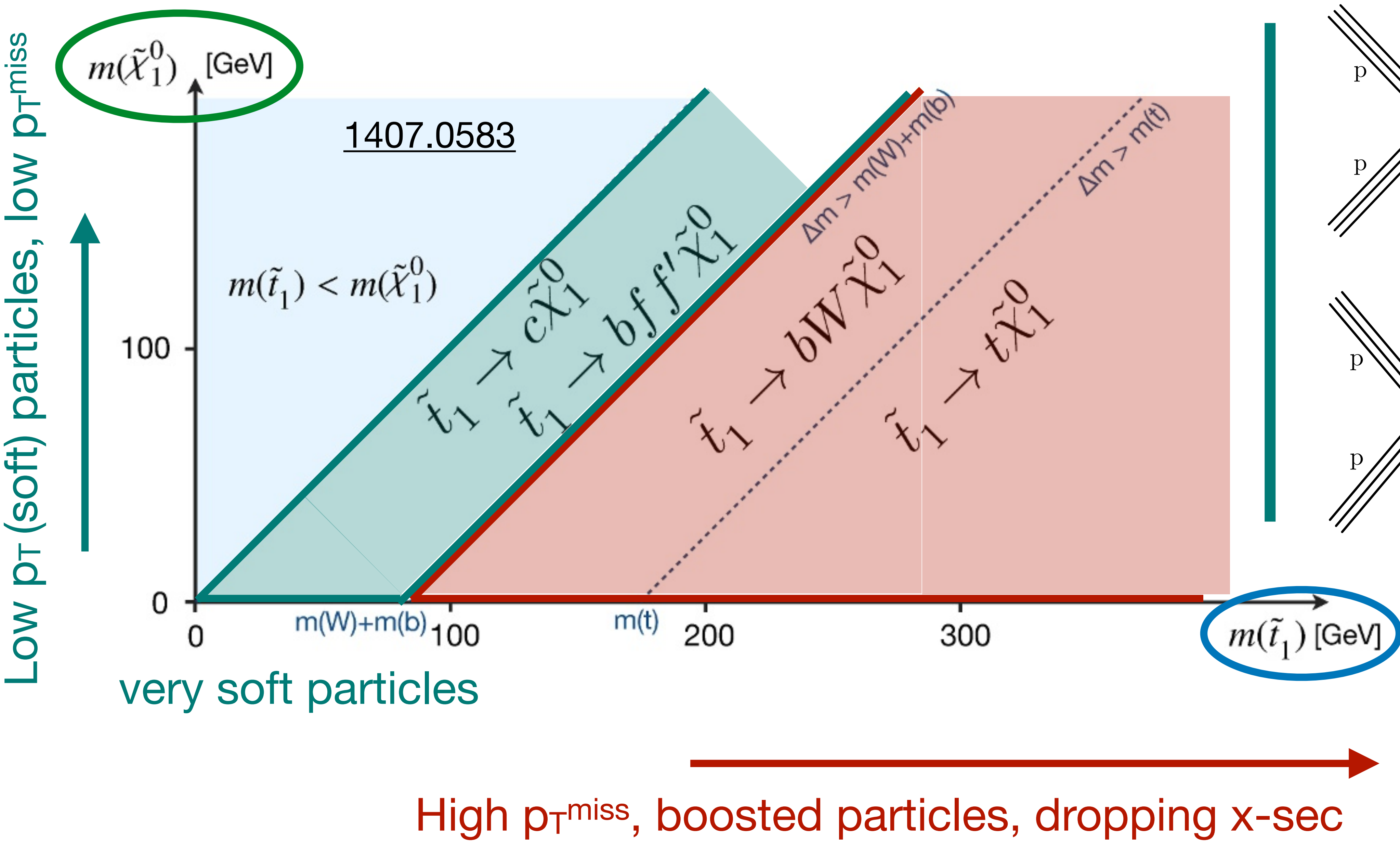
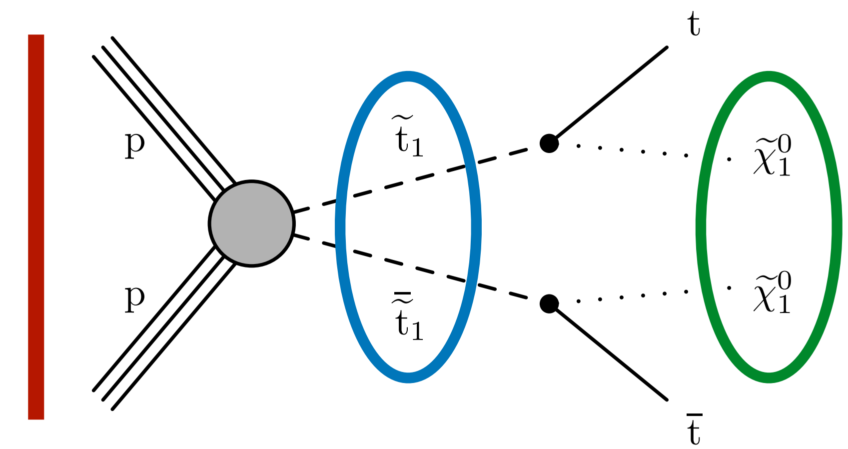
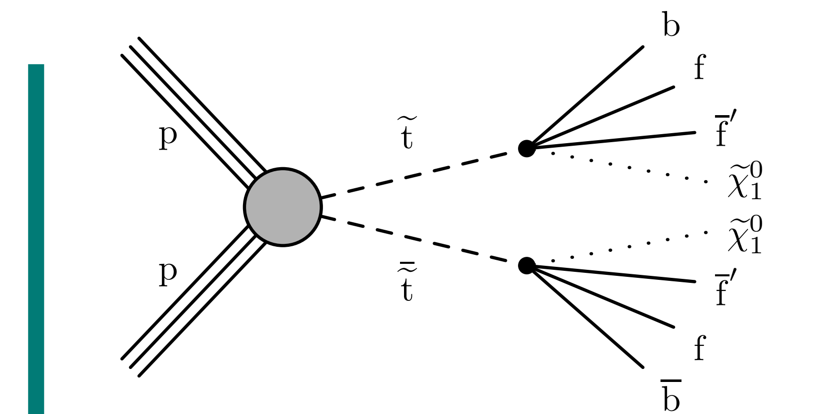
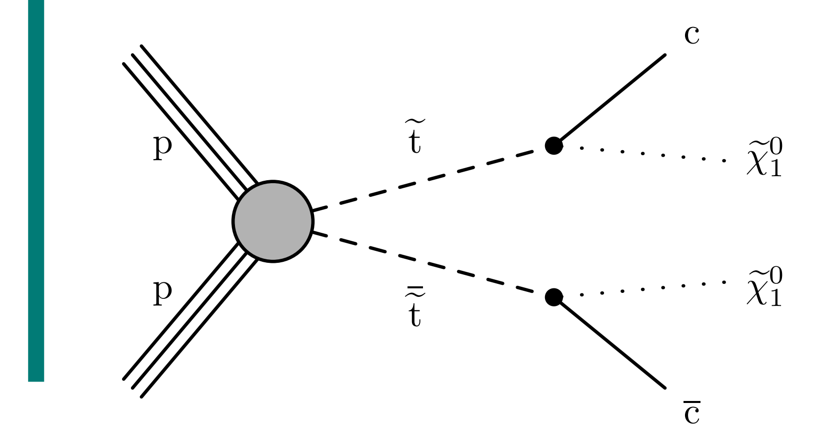
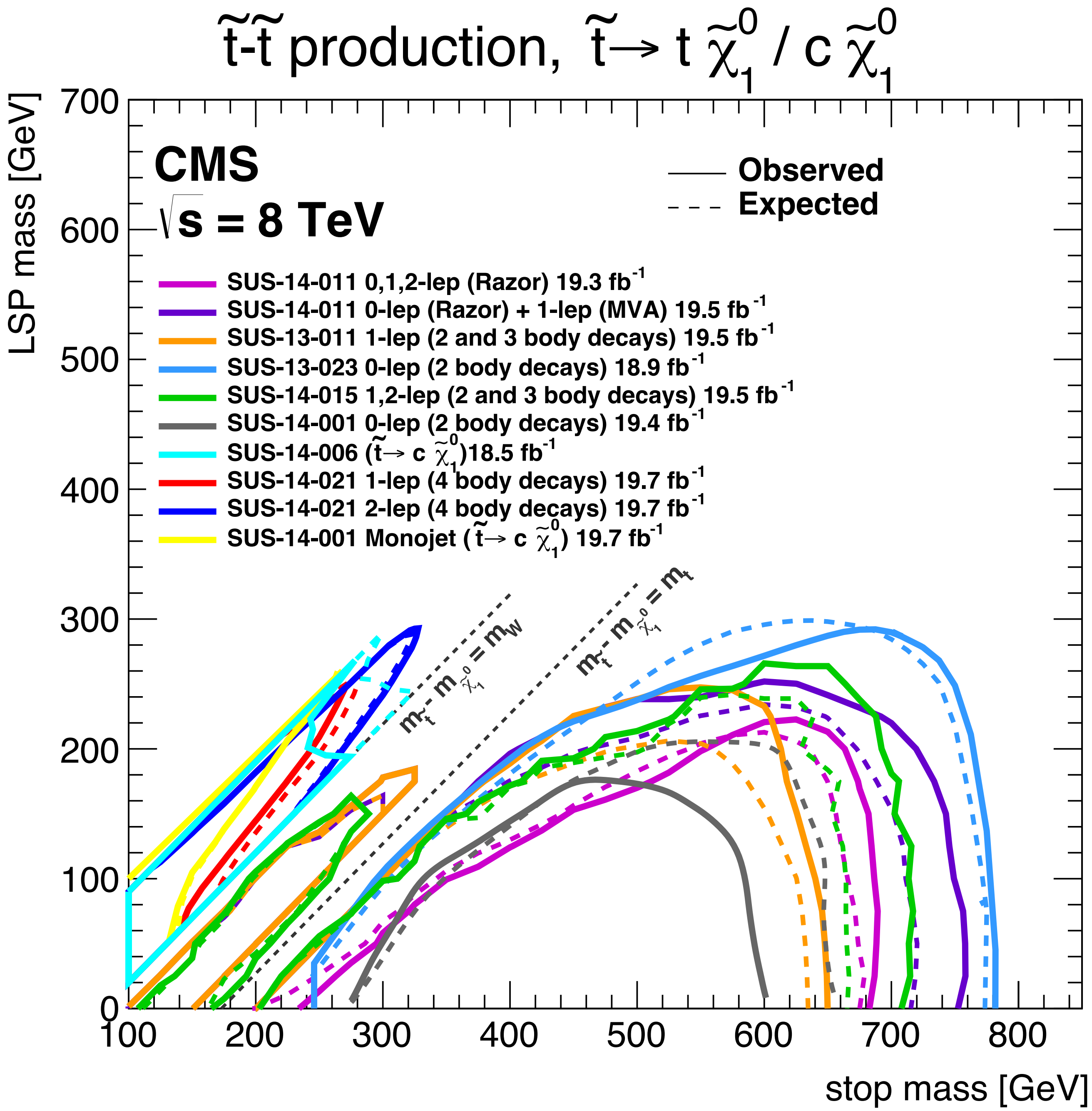






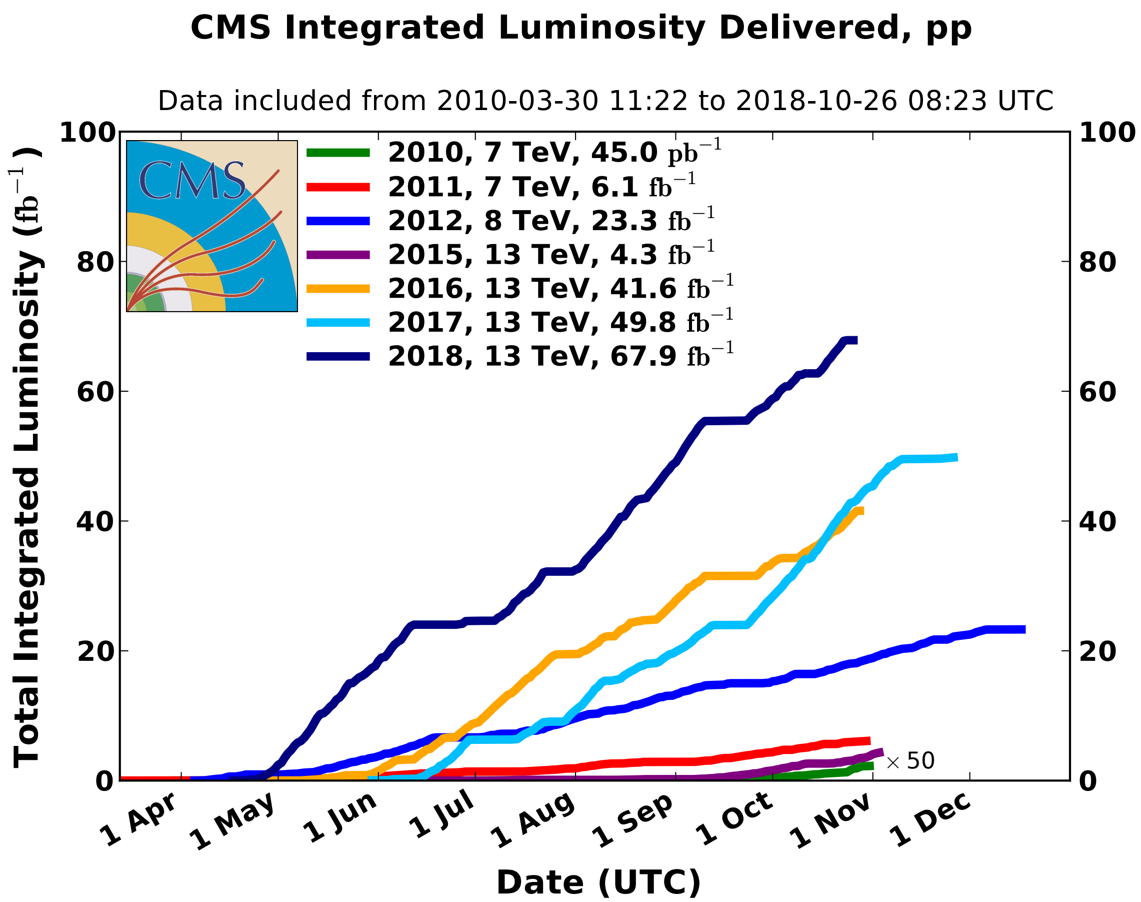


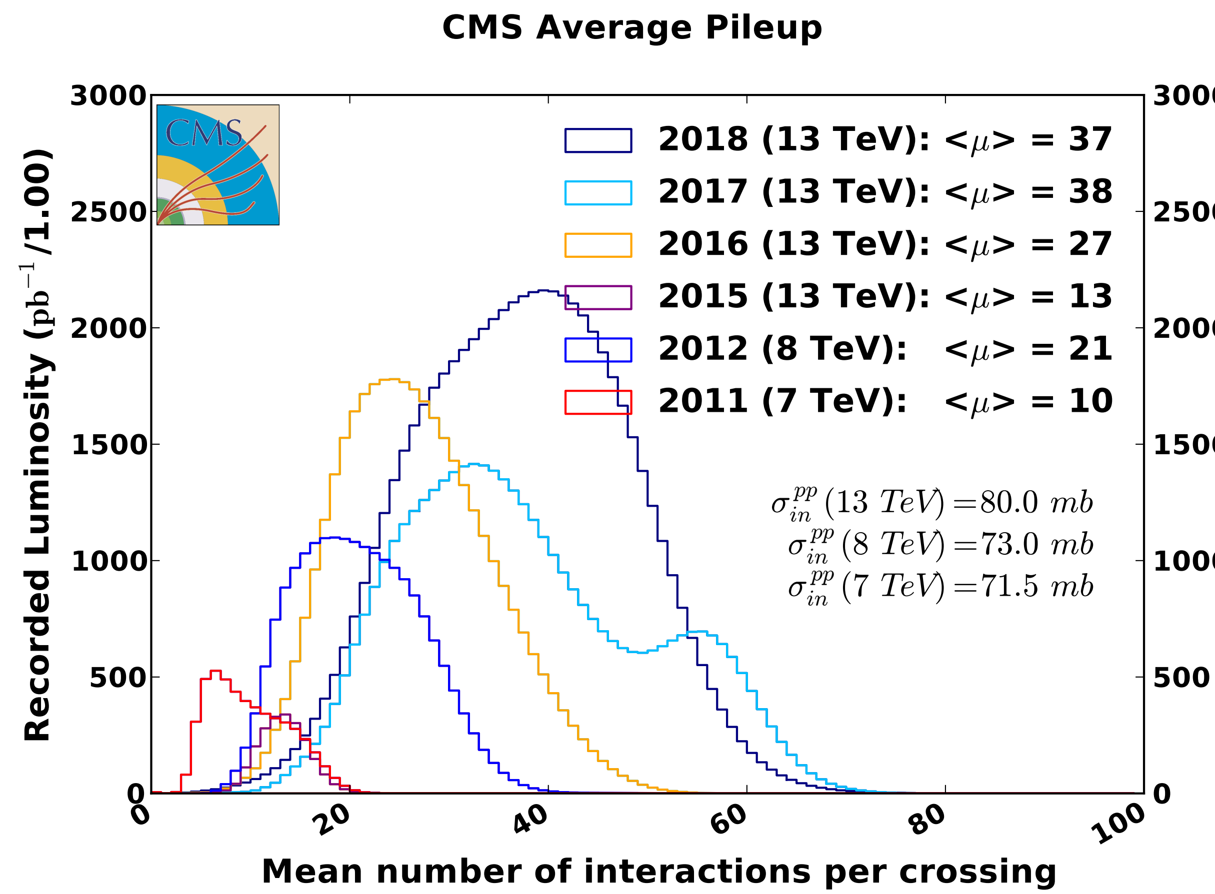
STOPS AFTER RUN 1



- Run 1 legacy from ~2015, sensitivity to top squark up to ~800 GeV
- So just collect more data at higher energy?

WHAT HAPPENED?

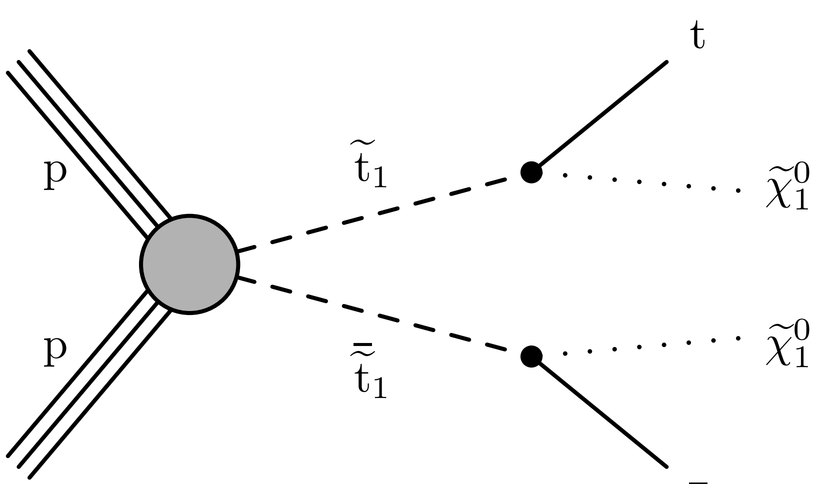




- Excellent performance of LHC and CMS during Run 2
- Collected 140/fb of proton-proton collision data that's good for physics analysis
- Challenging pileup scenario: $<\mu>$ = 13 (2015) → 27 (2016) → 38 (2017/18)

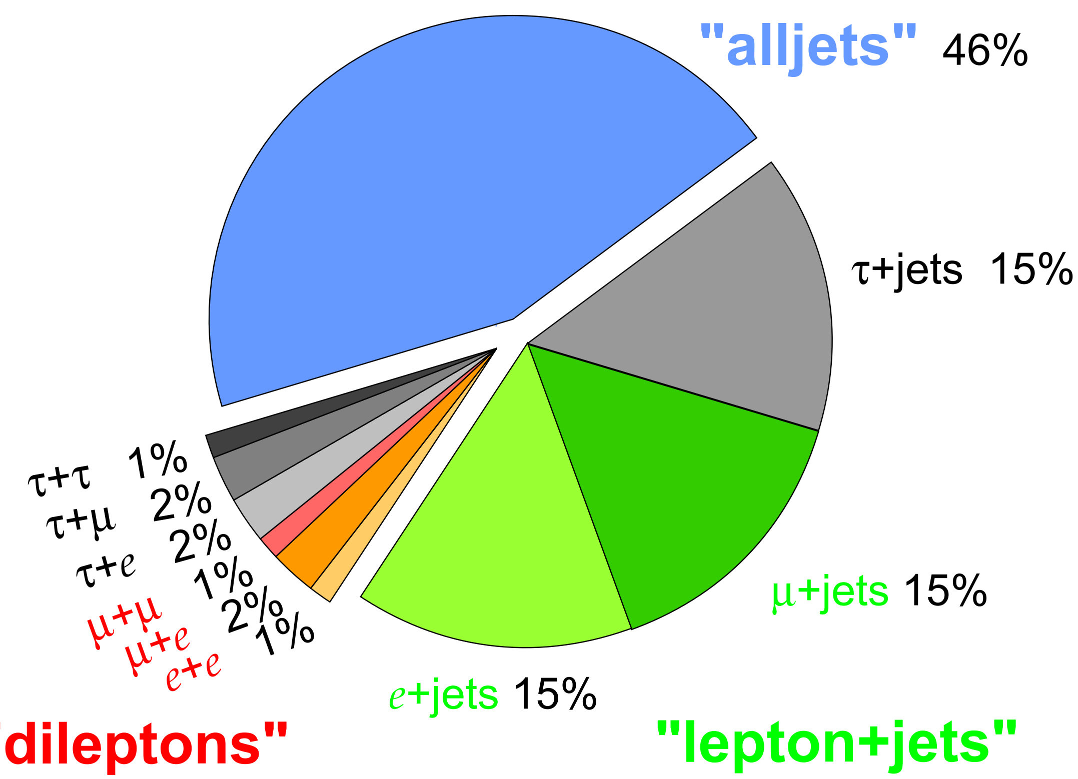
Top squark searches in CMS

- 3 independent searches in all hadronic, single lepton and dilepton channel
- Different SM backgrounds depending on channel



ttbar + p_T^{miss}

Experimental signature:
2 b-jets, 2 W bosons, p_T^{miss}



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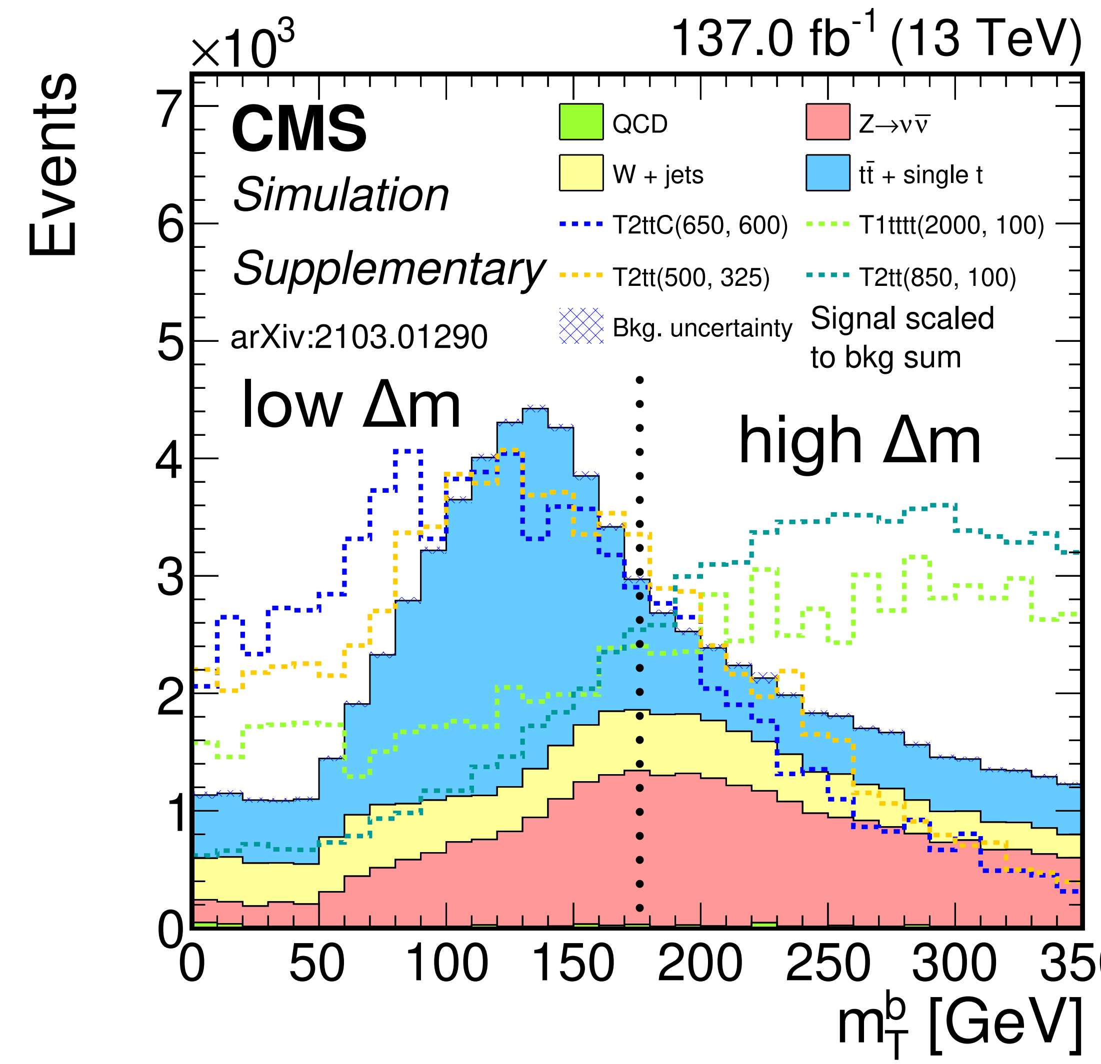
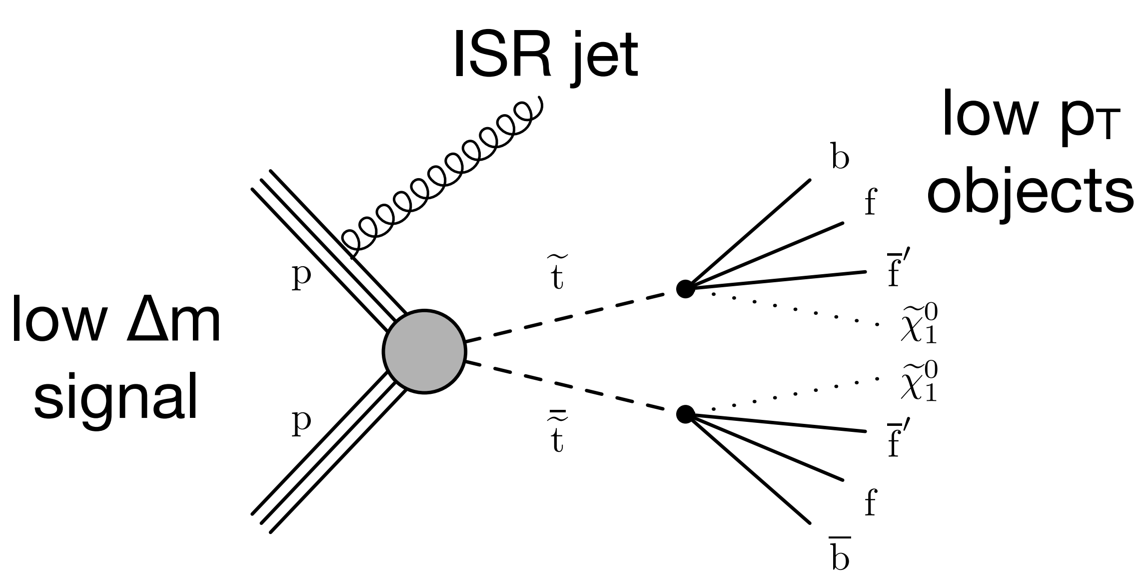
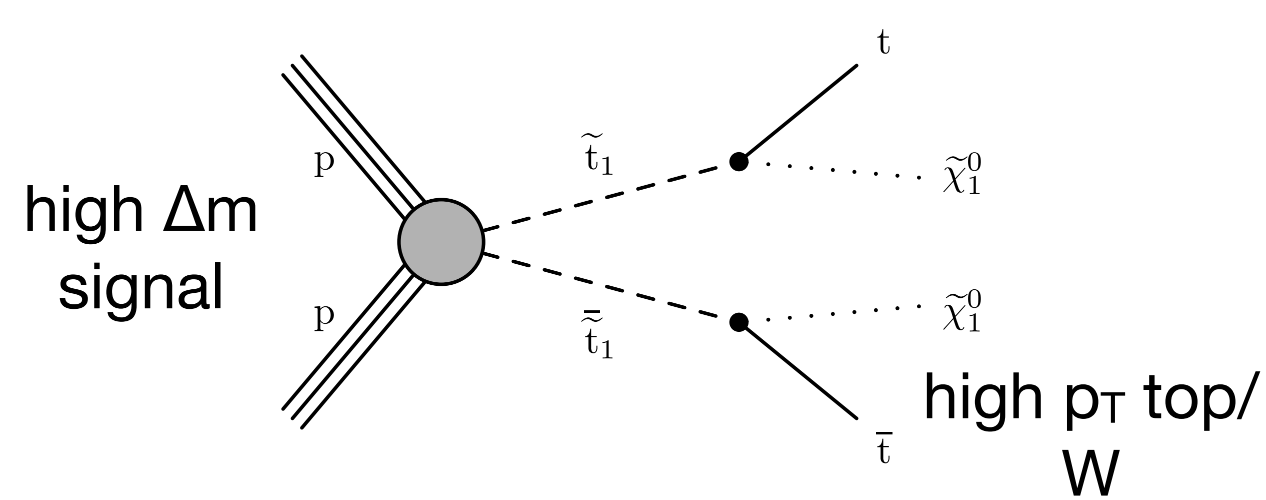
ALL HADRONIC SEARCH

- Events selected using p_T^{miss} **triggers**
- **Inclusive analysis design** for sensitivity to many signal scenarios
- Low Δm:
  - **ISR jet candidate** to boost ttbar system and increase p_T^{miss}
- High Δm:
  - **Boosted top and W quarks** → dedicated ML aided taggers

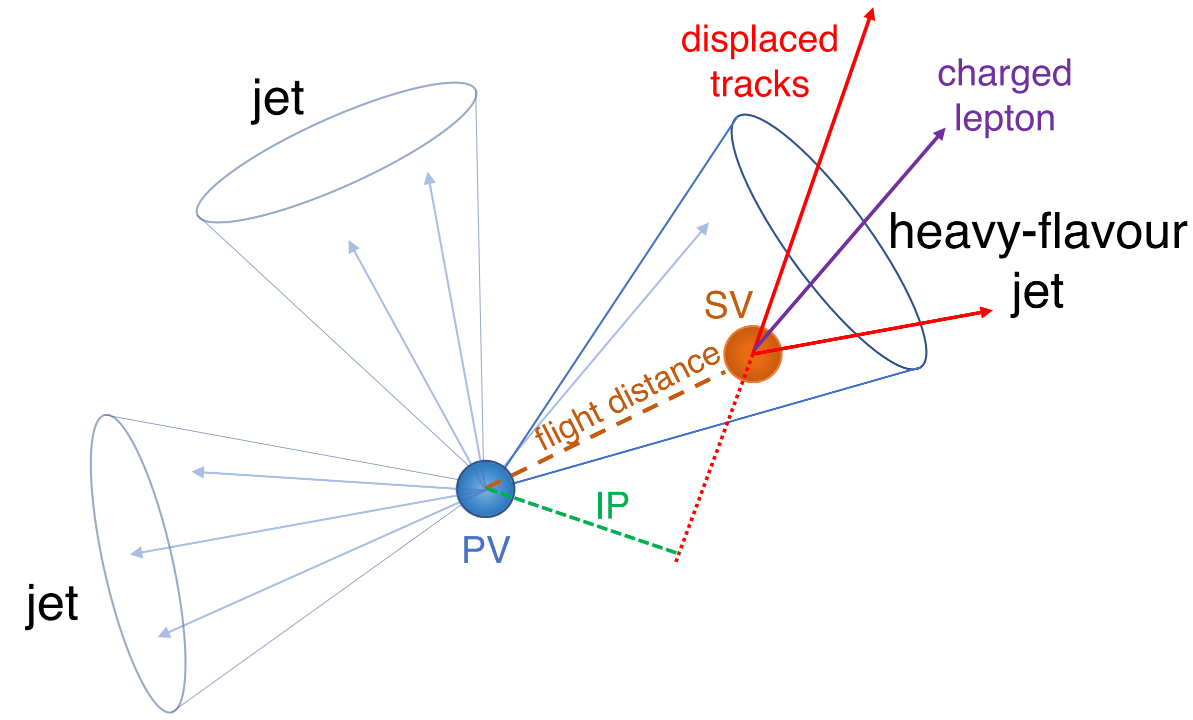


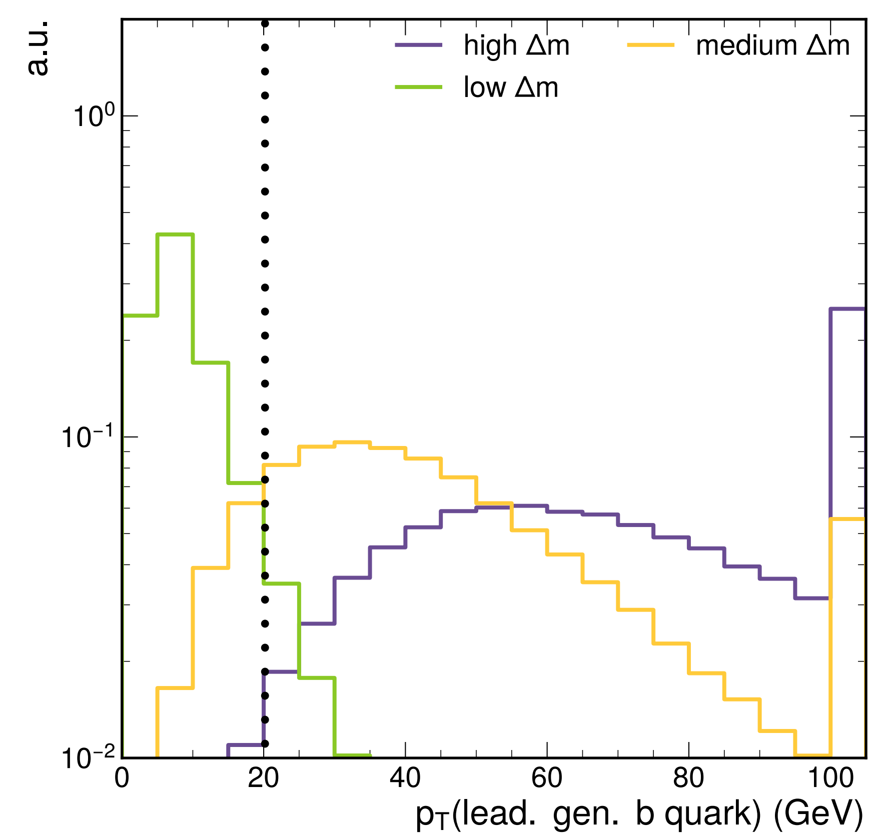




Low Δm: Soft Objects

- Usual case: **Identify jets originating from b quarks with ML based taggers → b-tagged jets**
- **Low Δm signals produce very soft b quarks**
  - Often too soft for standard b-tagging algorithms
- Directly use **secondary vertex** reconstructed with inclusive vertex finder algorithm

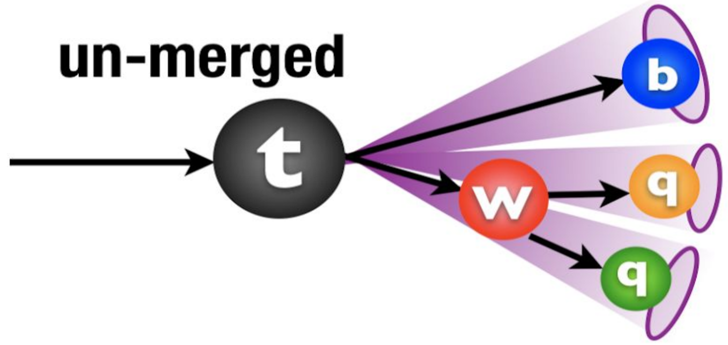




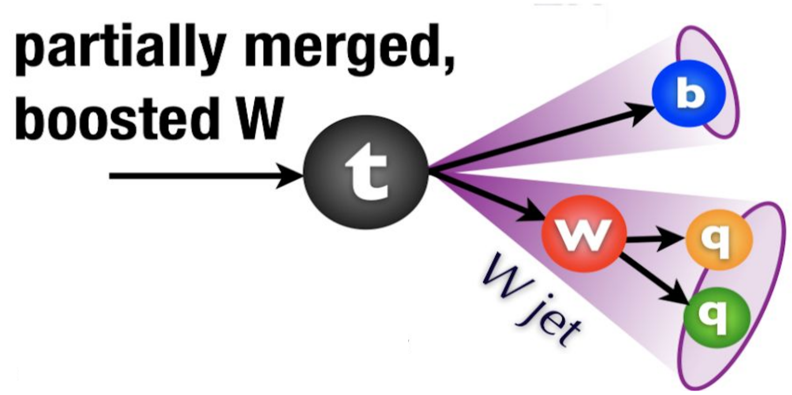
HIGH ΔM: BOOSTED OBJECTS

- Quick reminder: CMS uses anti-k_T algorithm to cluster particles (particle flow candidates) into jets with different cone sizes
  - Most commonly used: R=0.4 → AK4 jet, R=0.8 → AK8 jet
- ΔR of decay products of heavy resonance, e.g. top quark, with sizable momentum: $\Delta R \sim \dfrac{2M}{p_T}$
- Large mass splitting between top squark and LSP → boosted top quarks

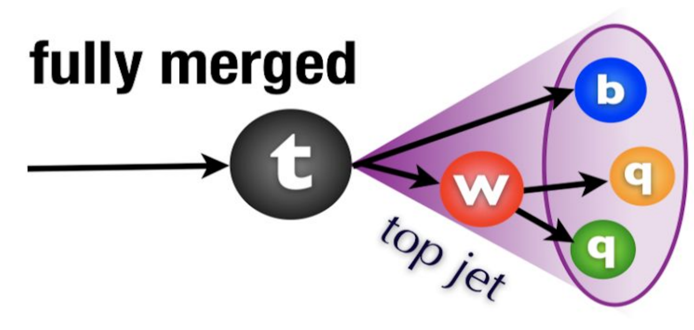
top quark with $p_T > 450$ GeV



resolved top tag
from 3 AK4 jets



merged W tag in
AK8 jet

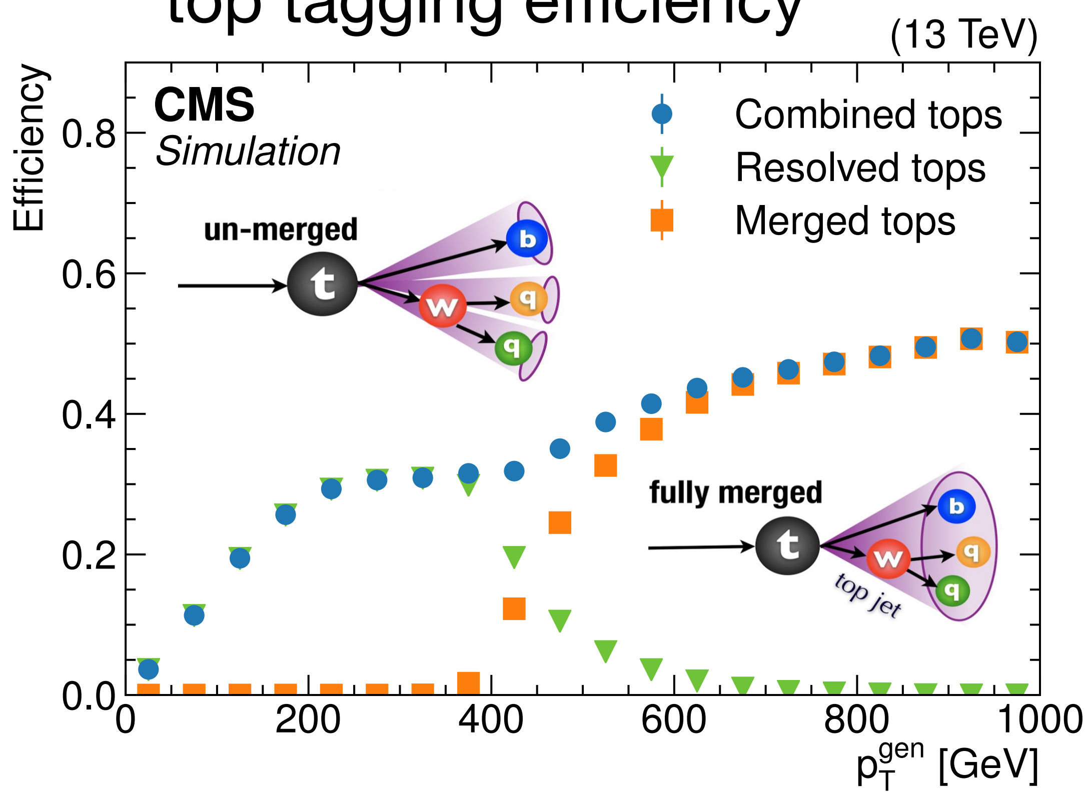


merged top tag in
AK8 jet

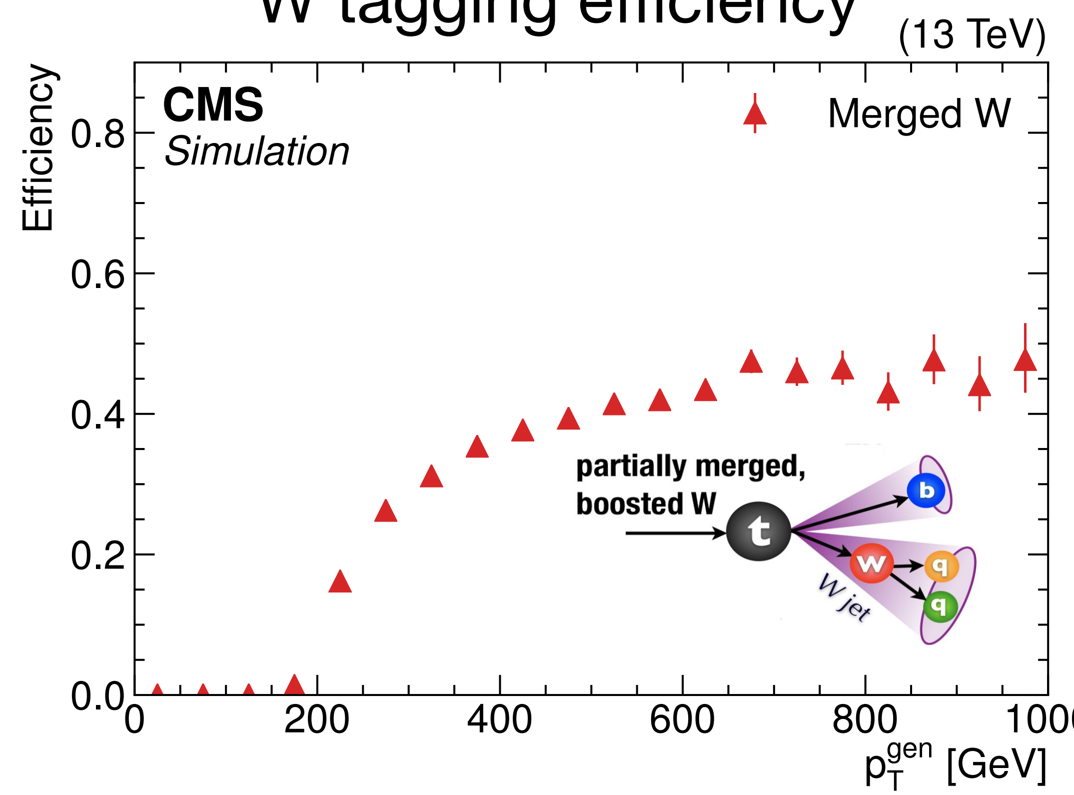
(Boosted) Object Tagging

- DNN based multi-classifier for large cone jets (AK8)
  - Takes PF candidates (42 features each) and secondary vertices (15 features) as input
  - Score for top, W, Z, Higgs, QCD jets
  - Here: Only top quark or W boson vs QCD jet tagging (merged top/W)
- Resolved top tagger: DNN tagger based on high level information of triplets of AK4 jets

top tagging efficiency



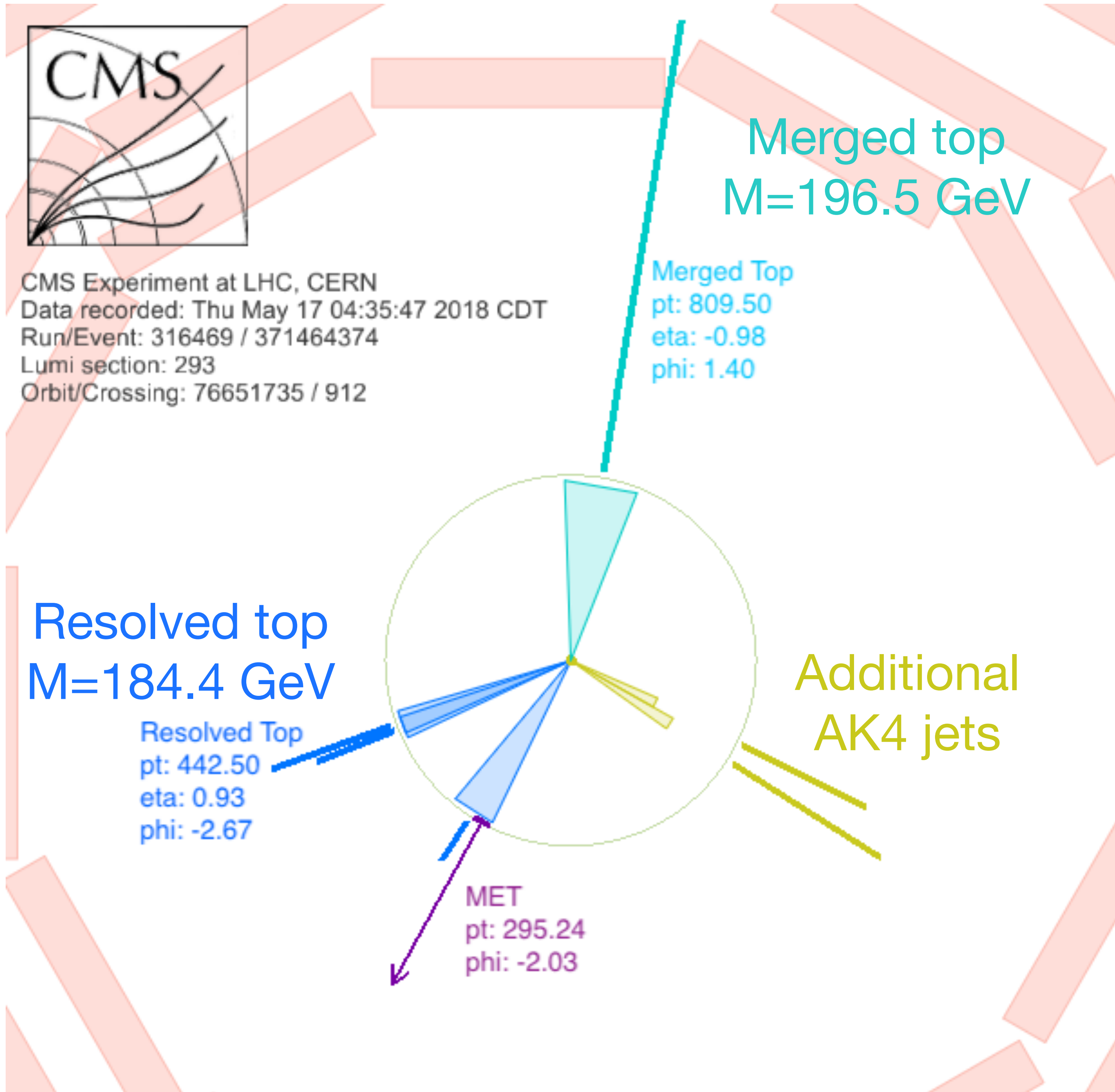
W tagging efficiency



All Hadronic Signal Regions

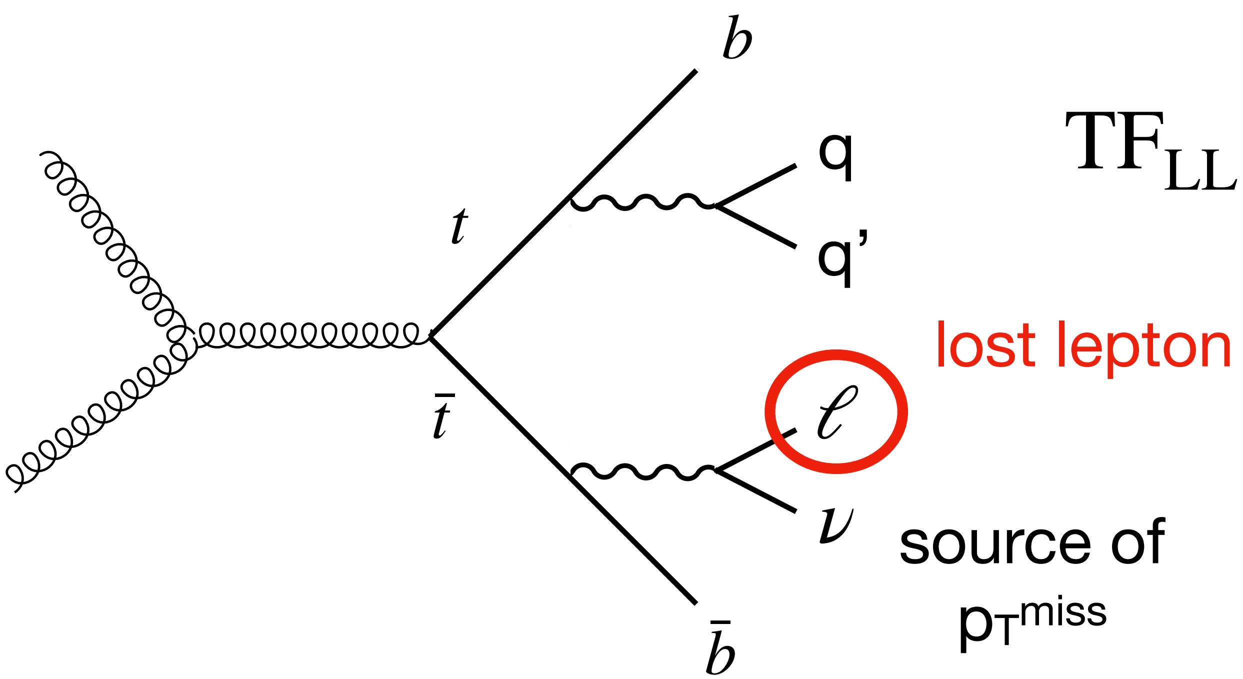
- Design 183 signal regions, optimized for different signal scenarios
- Low Δm signal regions:
  - Binned in jet multiplicity (N_{jets}), b-tagged or soft-b multiplicity (N_b, N_{SV})
  - Either inclusive in m_T^b or m_T^b<175 GeV
  - ISR jet p_T, b-jet candidate p_T, p_T^{miss}
- High Δm signal regions:
  - Binned in N_{jets}, N_b, merged top or W tag multiplicity, resolved top multiplicity
  - Hadronic activity, p_T^{miss}, m_T^b

Candidate Event



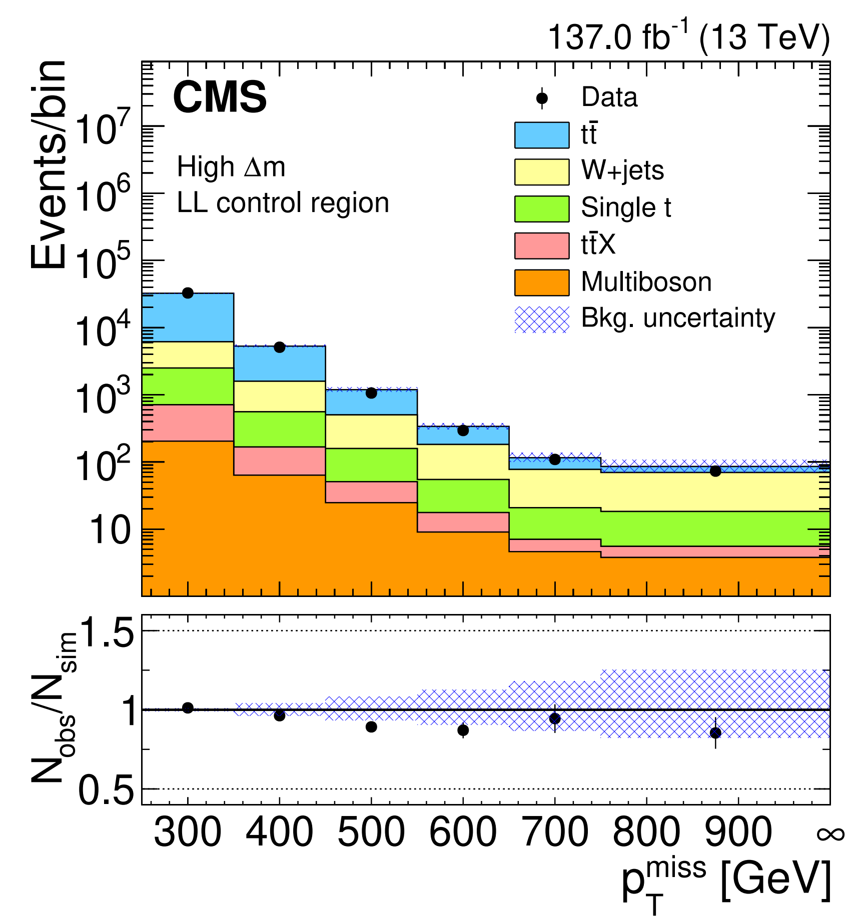
LOST LEPTON BACKGROUND

- Largest background in most signal regions: **single lepton tt+jets, single top, W+jets events with lost lepton (LL)**
- Estimate based on **measurement in single lepton data control sample**
- **Extrapolate to search region with transfer factor TF_{LL}** from simulation
- LL background greatly reduced in regions requiring merged/resolved top or W



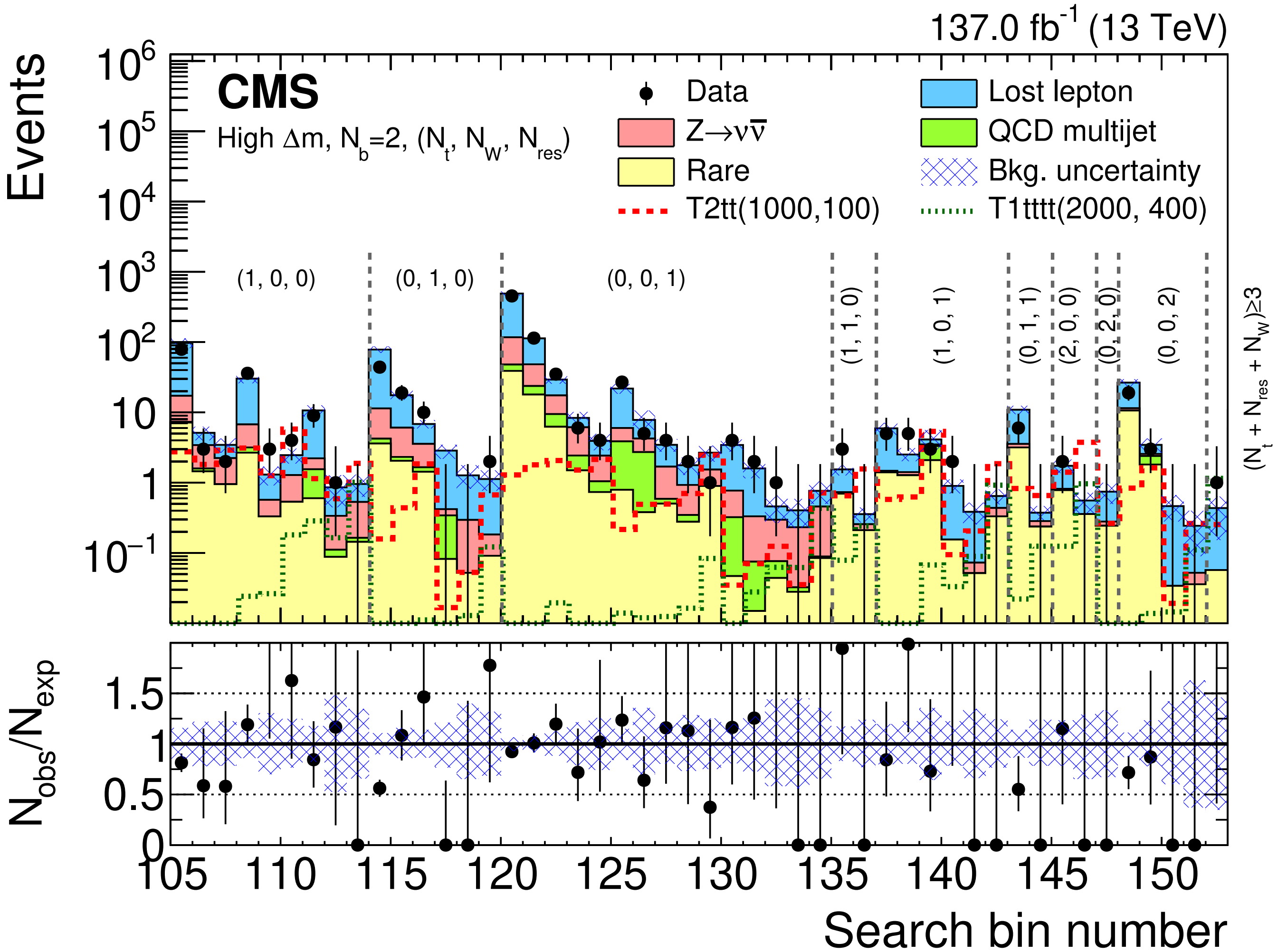
$$N_{\text{pred}}^{\text{LL}} = \text{TF}_{\text{LL}} N_{\text{data}}^{1\ell}$$

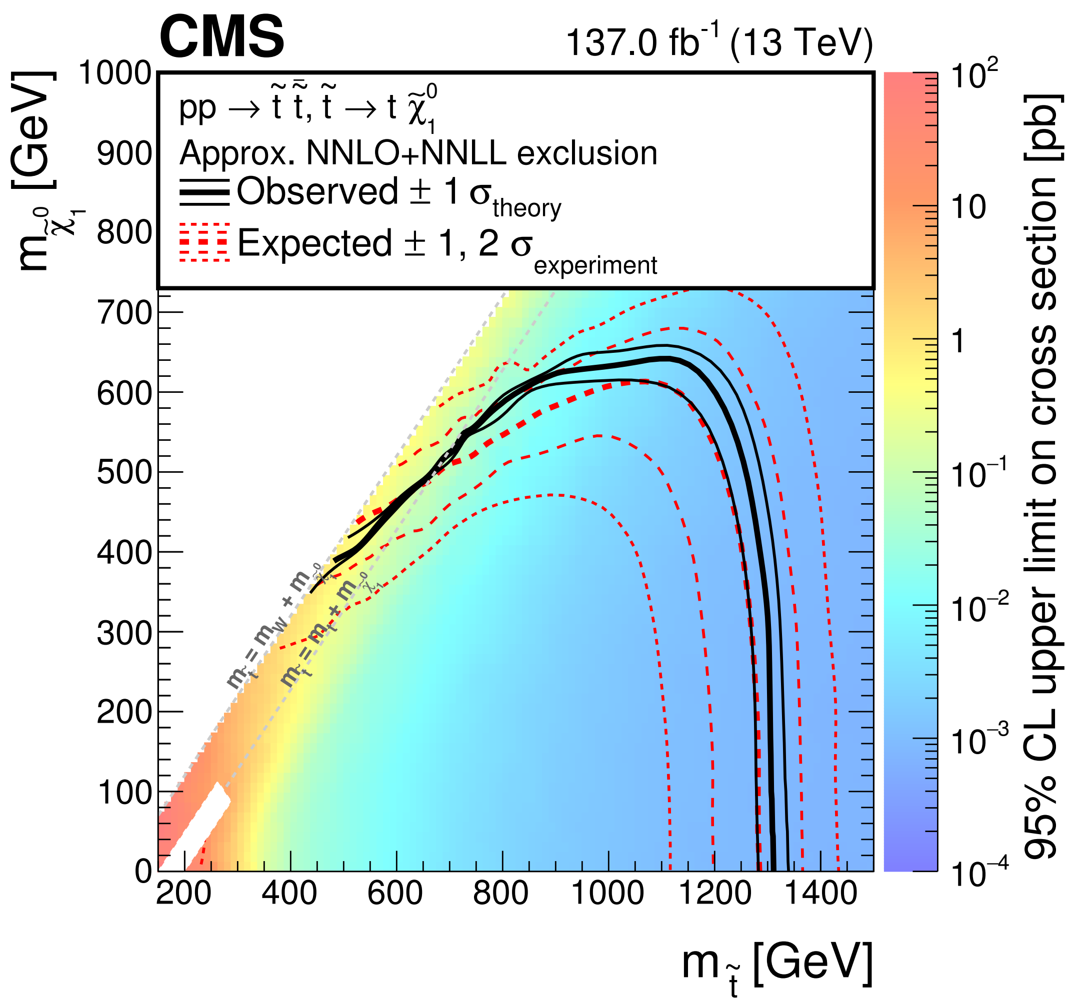
$$\text{TF}_{\text{LL}} = \frac{N_{\text{MC}}^{0\ell}}{N_{\text{MC}}^{1\ell}}$$



Results

- Showing subset of **high Δm signal regions**
  - Lost lepton background dominating in these signal regions
  - Background predictions validated in orthogonal validation regions
- **No statistically significant excess**





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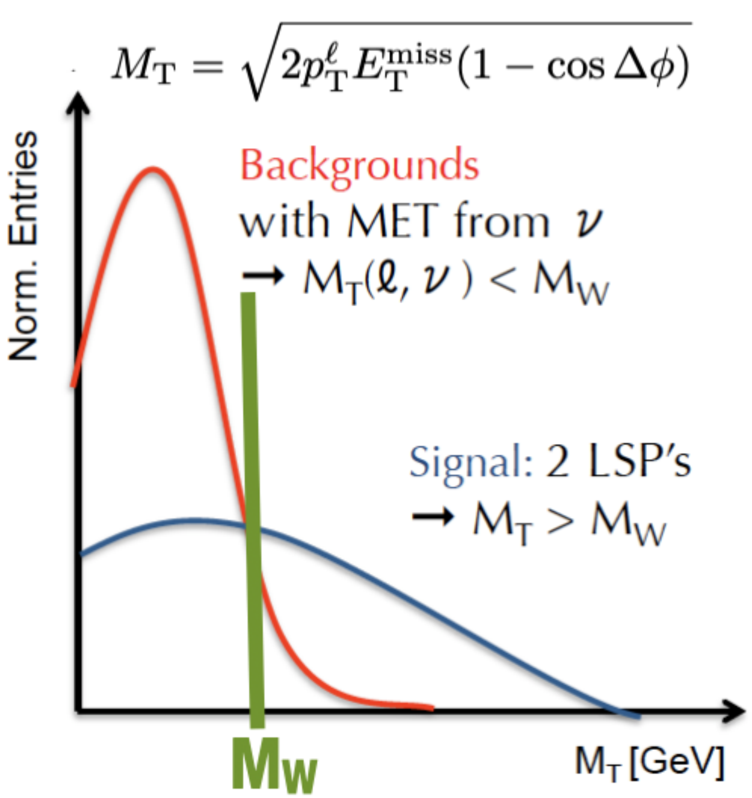
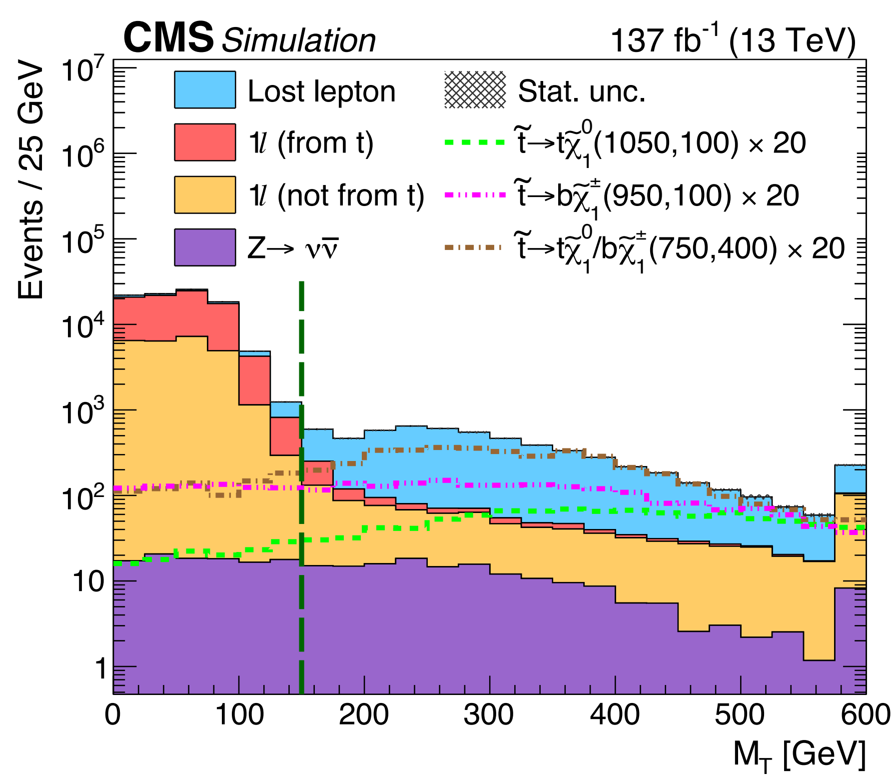
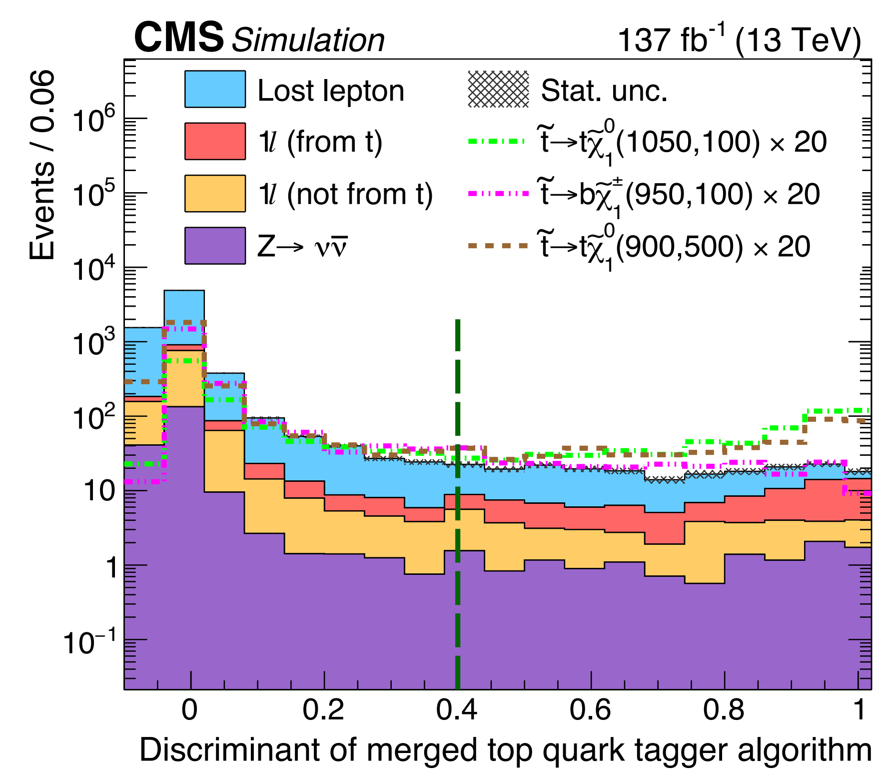
SINGLE LEPTON SEARCH

- 30% signal branching fraction, events selected with **p_T^{miss} or single lepton triggers**
- Use of **kinematic mass variables** (M_T, M_{lb}) together with **novel machine learning tools** (merged and resolved top tagger)
- Retain sensitivity to **low Δm signal points with soft b-tagger**
- Dominant background: **lost lepton** from dilepton ttbar events



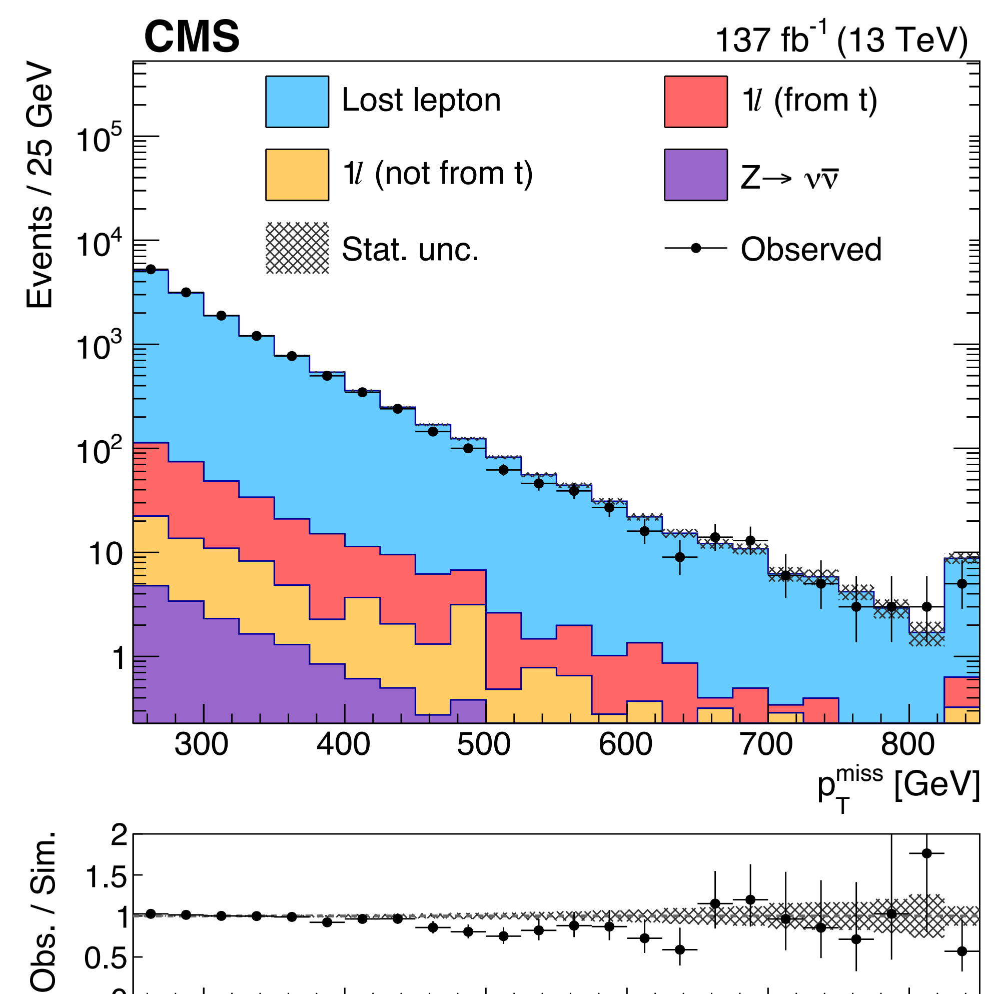




Background Estimates

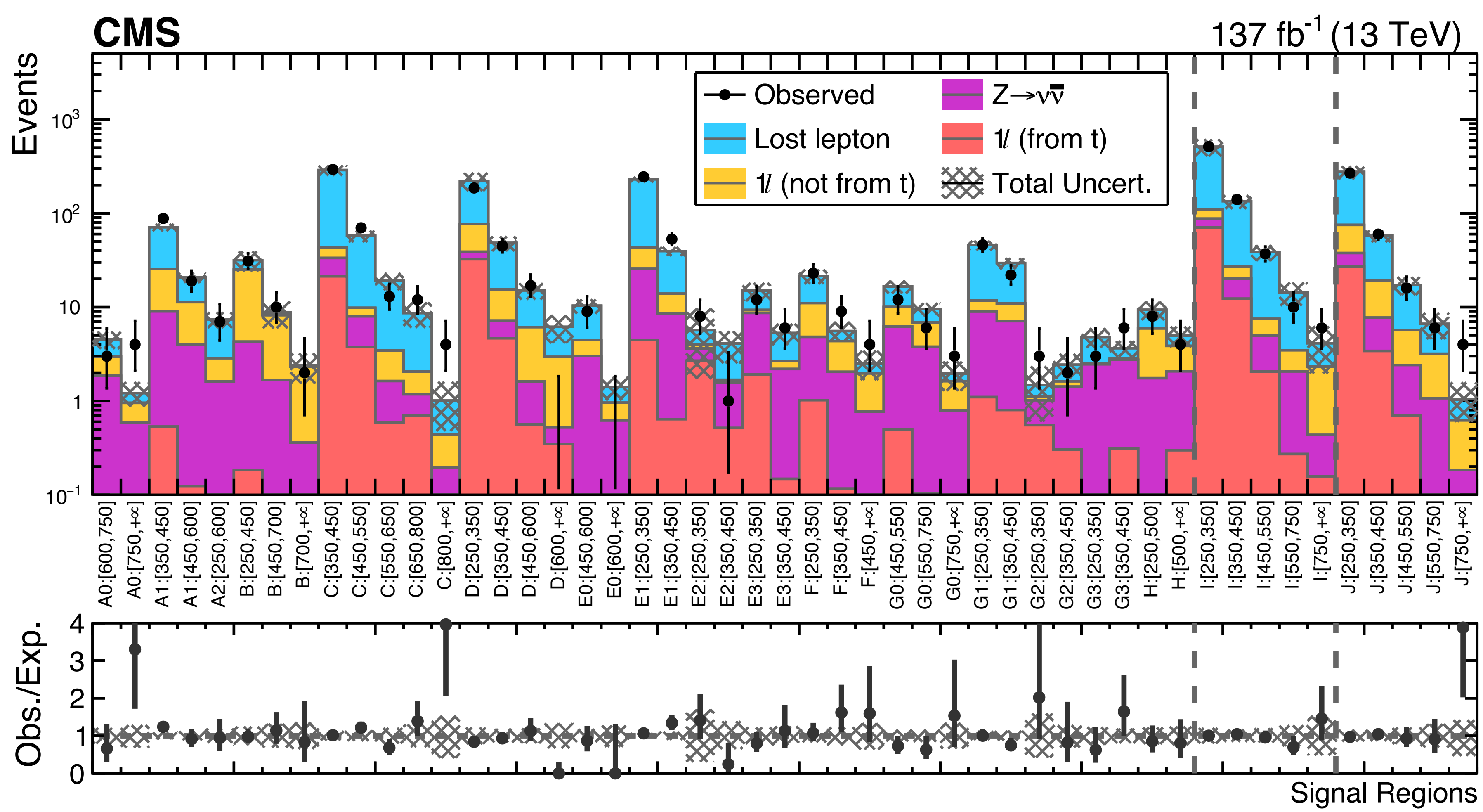
- Main backgrounds estimated using data control samples
- Lost lepton background normalization measured in dilepton sample
- W+jets background estimated from a sample vetoing b-tagged jets
- **Transfer factors** to obtain background prediction in signal regions

	1 lepton	2 leptons	3 leptons
0 b-tagged jets	W+jets dominated		WZ dominated
≥1 b-tagged jets	Signal region	$t\bar{t}/tW \rightarrow 2l$ dominated	ttZ dominated



SINGLE LEPTON RESULTS

- **Numerous signal regions** categorized in jet multiplicity, M_{lb}, modified topness, p_T^{miss}
  - Additional **untagged/resolved/merged top tag regions** for highly boosted top quarks
- **No statistically significant excess**



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

X0: Inclusive
X1: Untagged
X2: Merged t quark tag
X3: Resolved t quark tag

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

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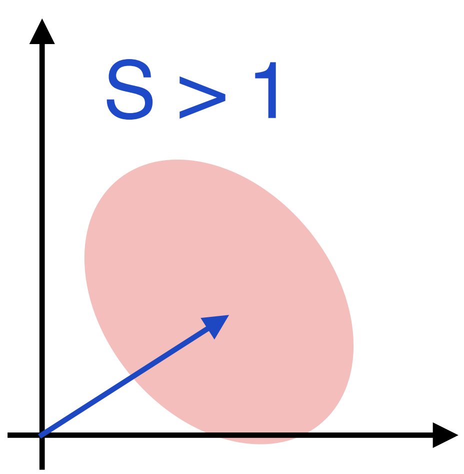
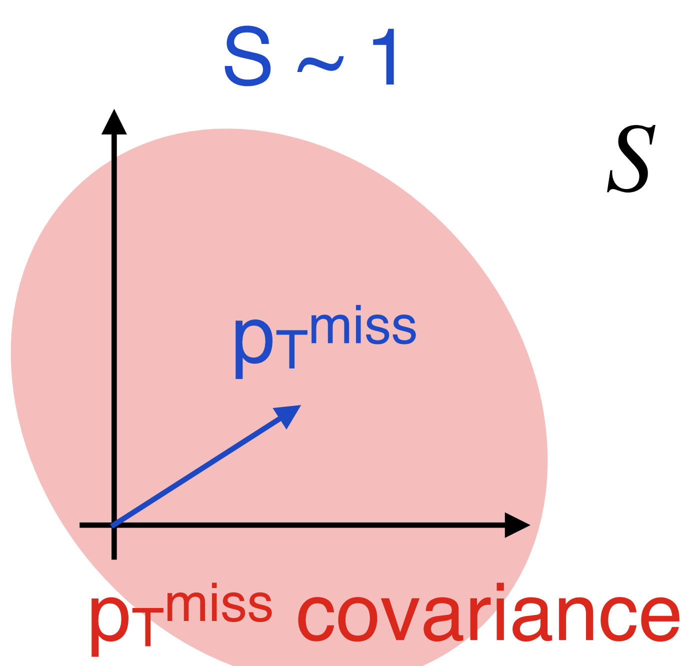
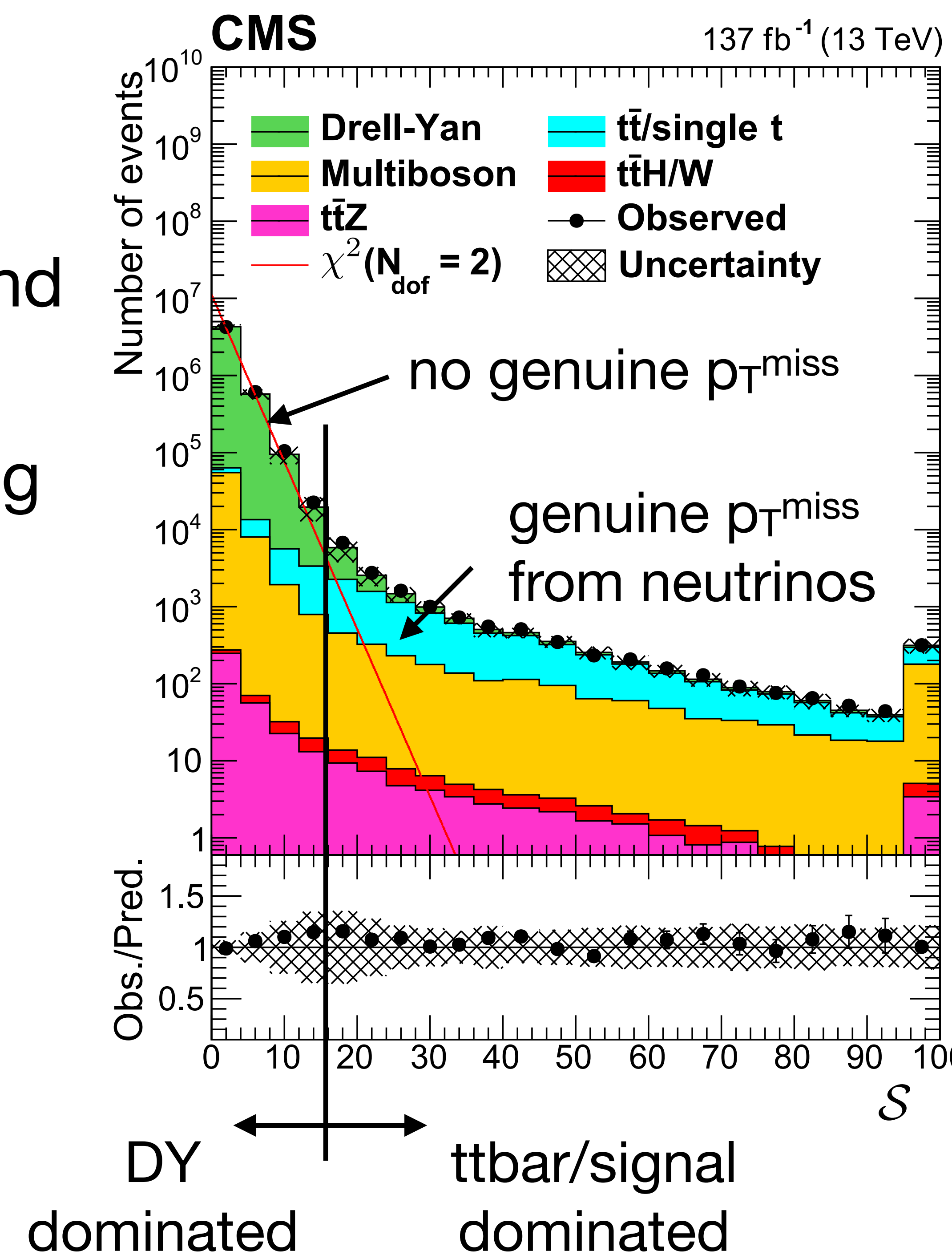
DILEPTON SEARCH

- Small signal branching fraction, but **clean dilepton final state**
- Events selected using **dilepton triggers**
- Overwhelming **Drell-Yan (Z→ll) background** reduced using p_T^{miss} **significance**
    - Proven to be **more stable under varying pileup conditions** compared to "pure" p_T^{miss}



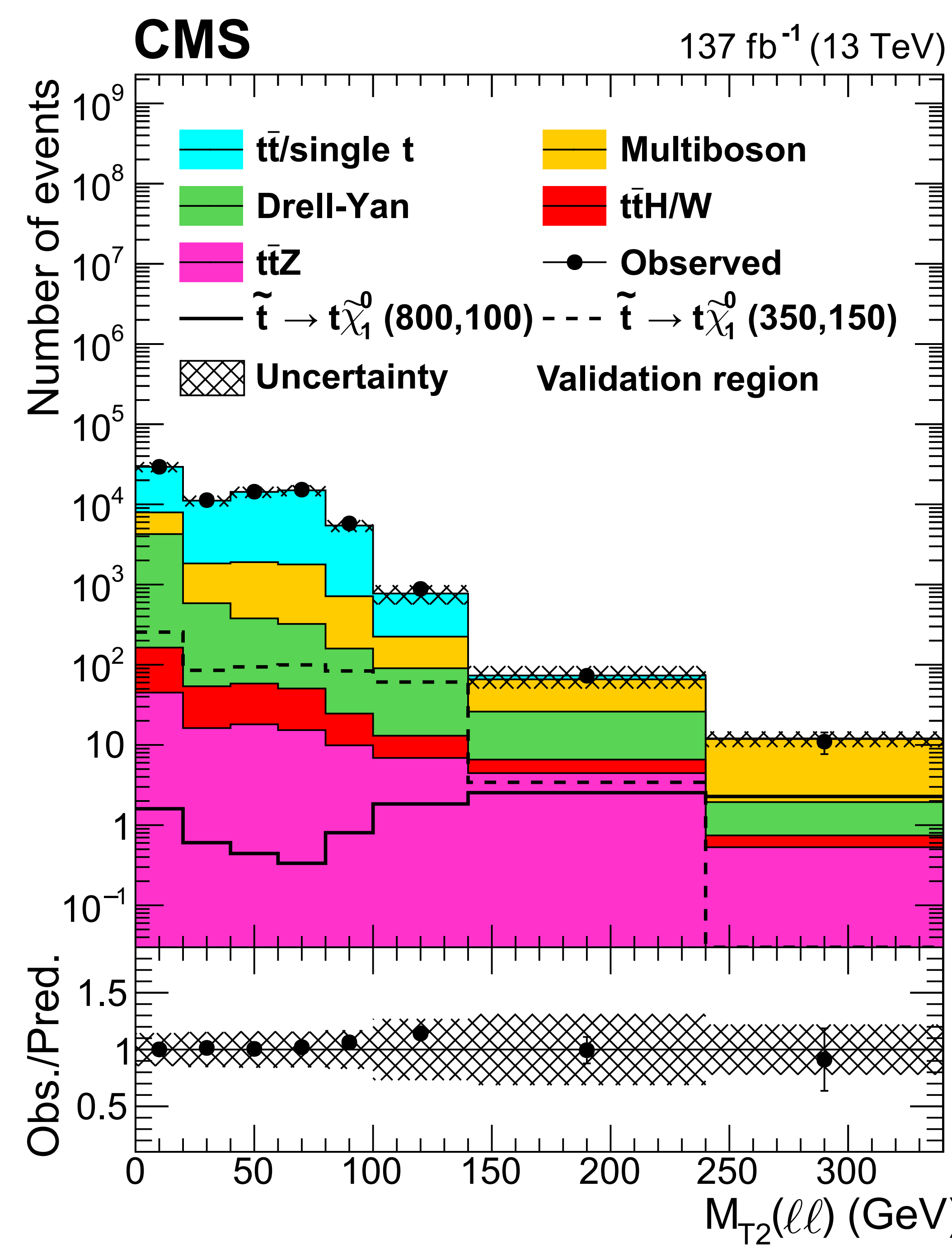


$$\mathcal{S} \sim \frac{p_T^{miss^2}}{\sigma^2_{p_T^{miss}}}$$



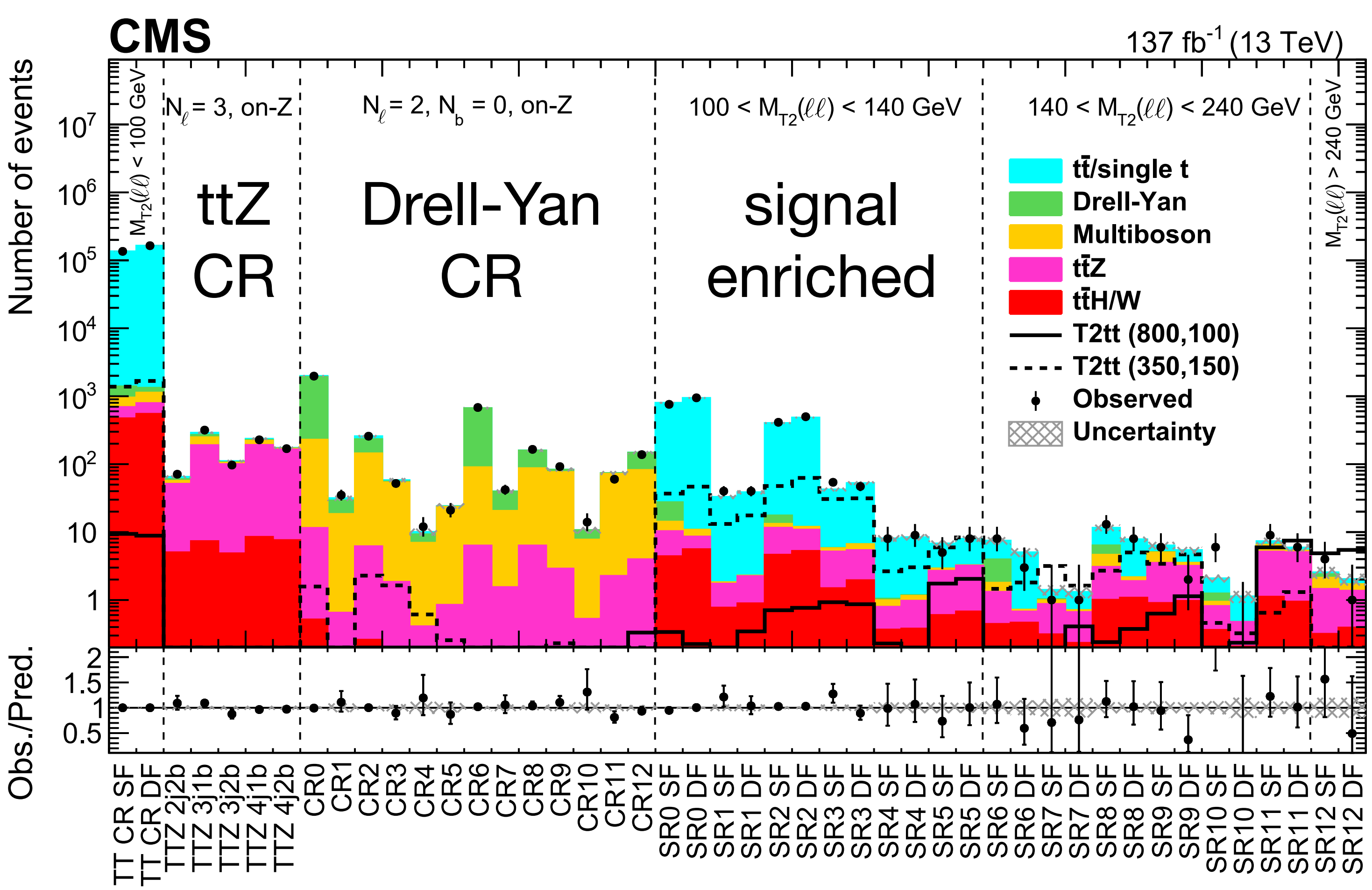
TOP QUARK BACKGROUND

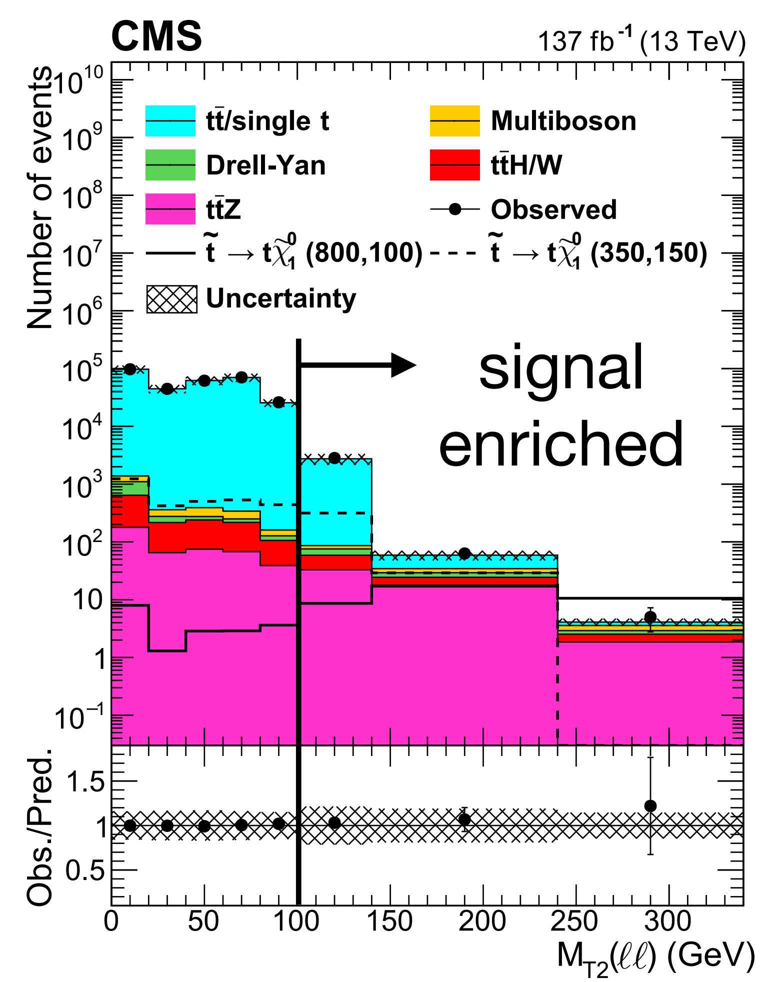
- Largest remaining **reducible background** is coming from **top quark pairs**
- Stransverse mass **M_{T2}(ll) has endpoint around W boson mass** for leptonically decaying top quark pairs
  - Not respected by events with severe **jet mismeasurements or lost and fake lepton**
  - No endpoint for some rare tt+X and diboson processes



DILEPTON RESULTS

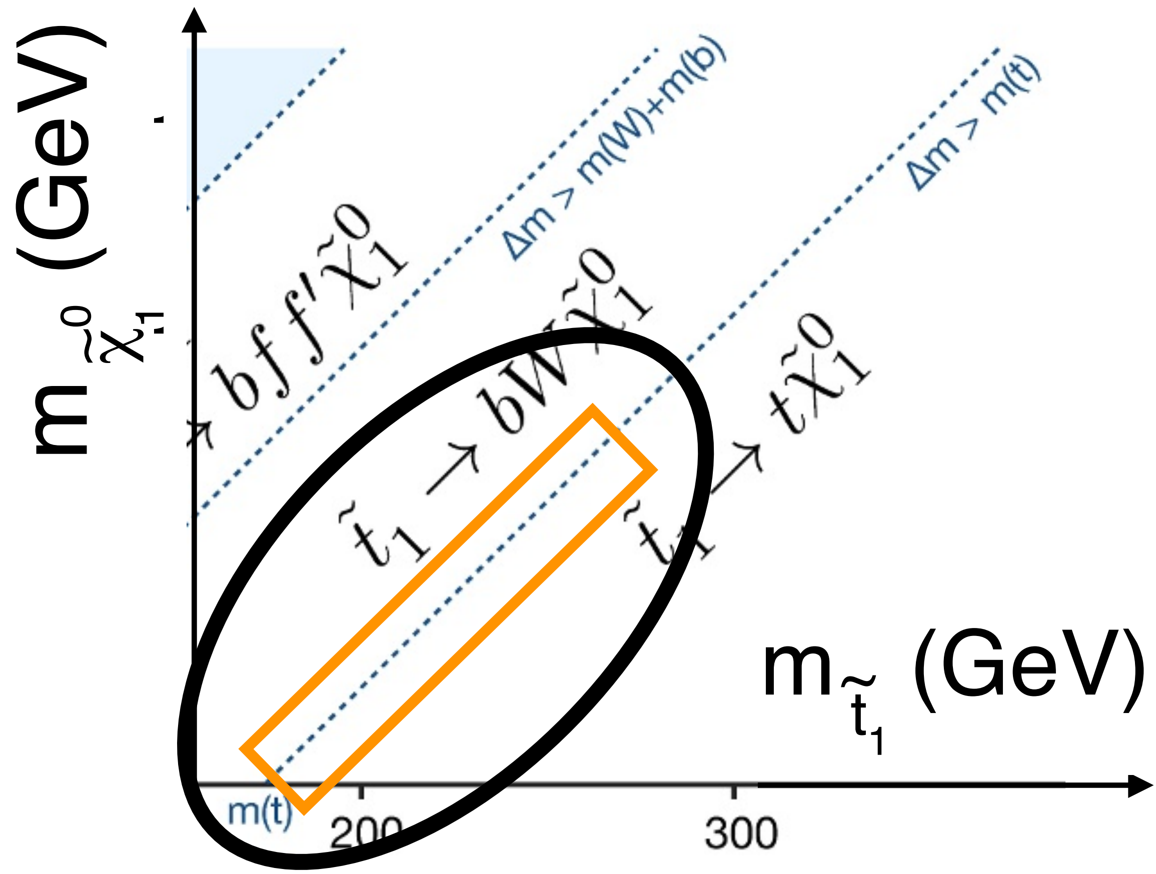
- Signal regions defined in bins of p_T^{miss} significance and stransverse mass variables
- **In-situ measurements** of the normalizations of leading backgrounds: **tt/single-t, Drell-Yan and multiboson, tt+Z**
- Very good **agreement of observation with predictions** from SM

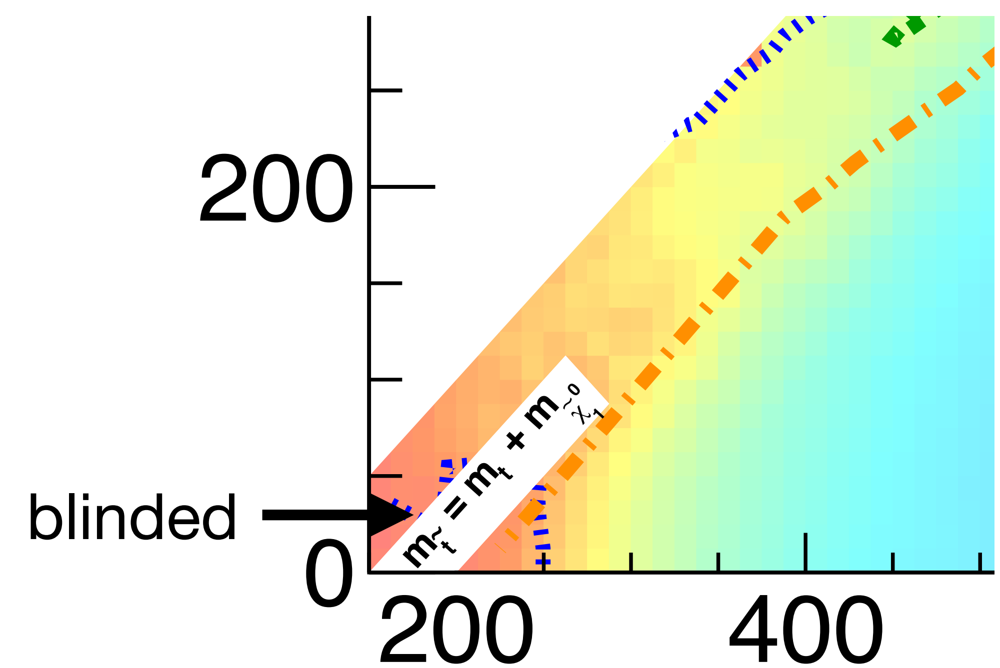




WHAT ABOUT LIGHT STOPS?

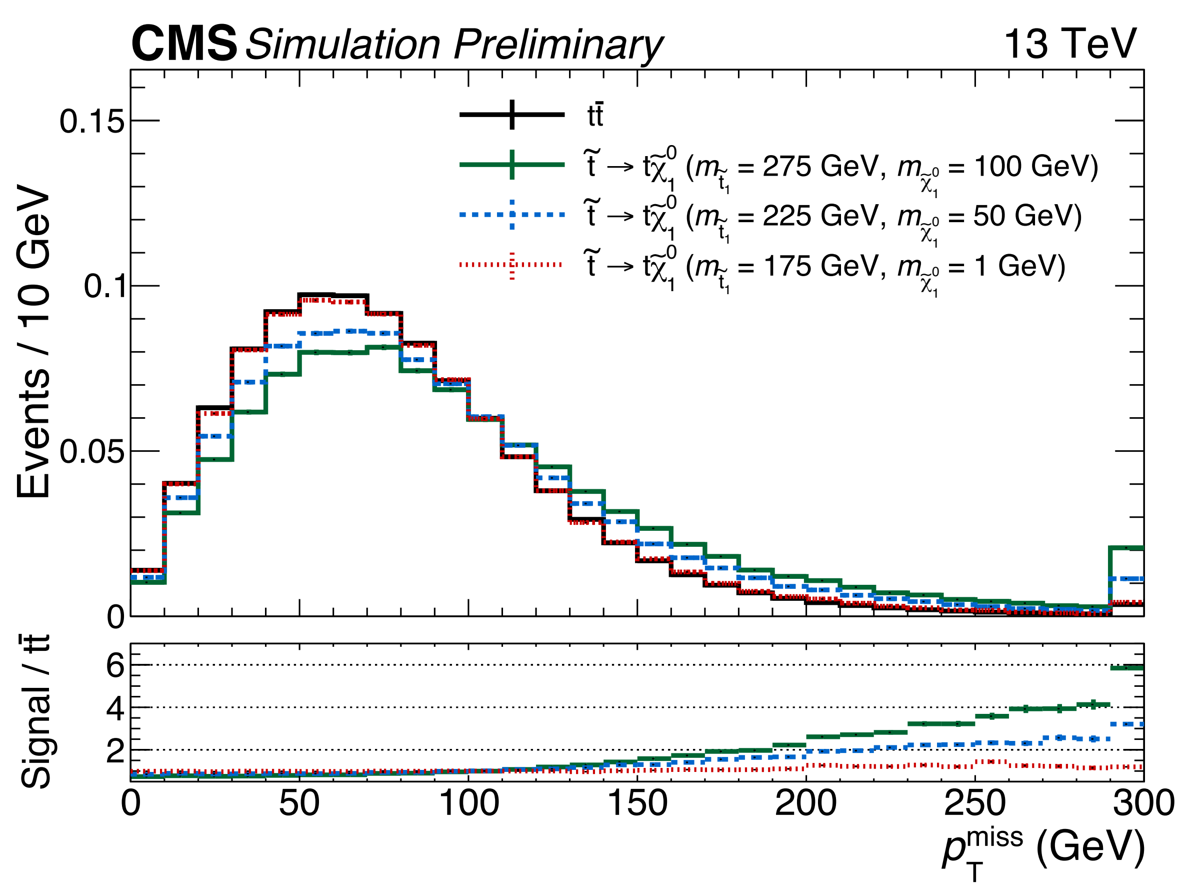
- If Δm between top squark and LSP is **close to top quark mass** → kinematics of signal and ttbar background very similar
  - Take special care of top corridor!
  - Standard background estimation techniques break down
  - Large SUSY scan uses **fast detector simulation for feasibility to generate O(100M) events** per signal model and year
  - CMS kept **top corridor blinded** in previous top squark publications
- A **dedicated search in the dilepton channel** was designed to only target this region

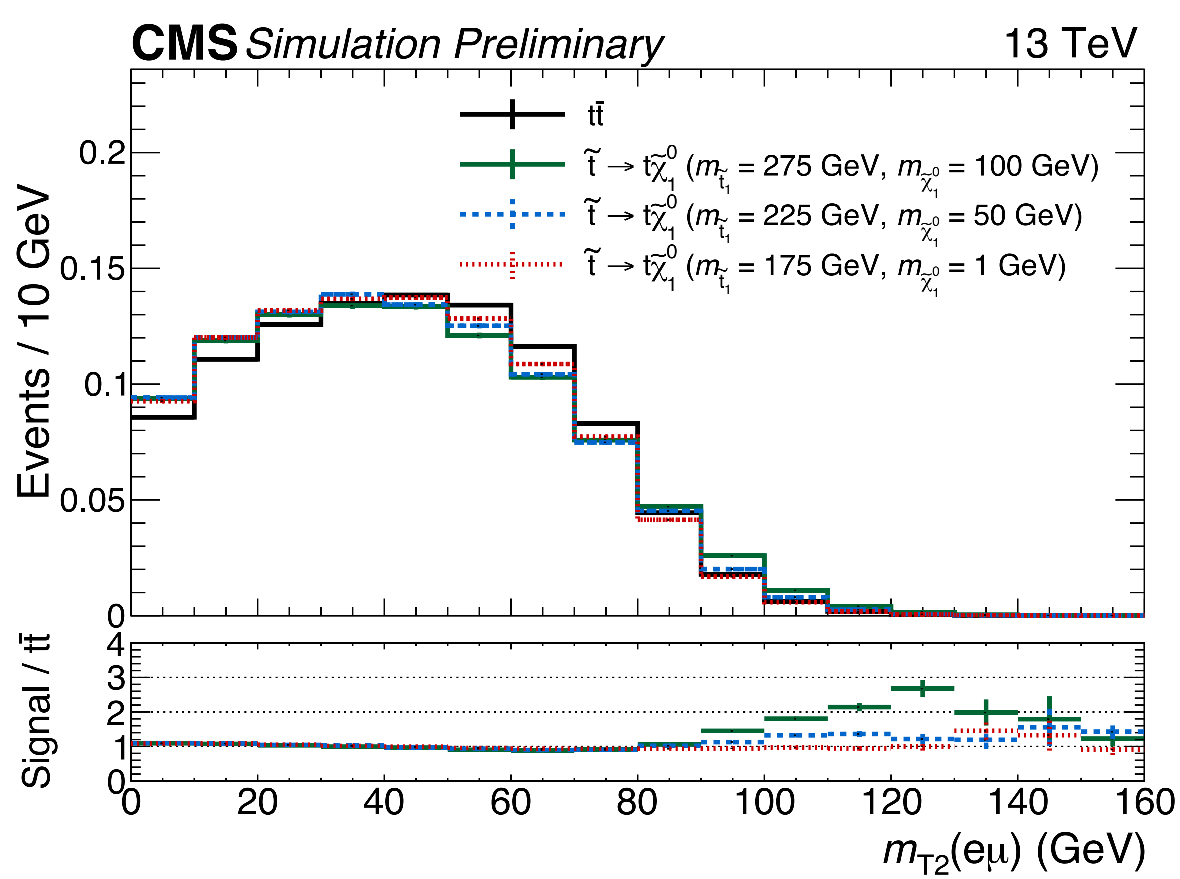




KINEMATICS

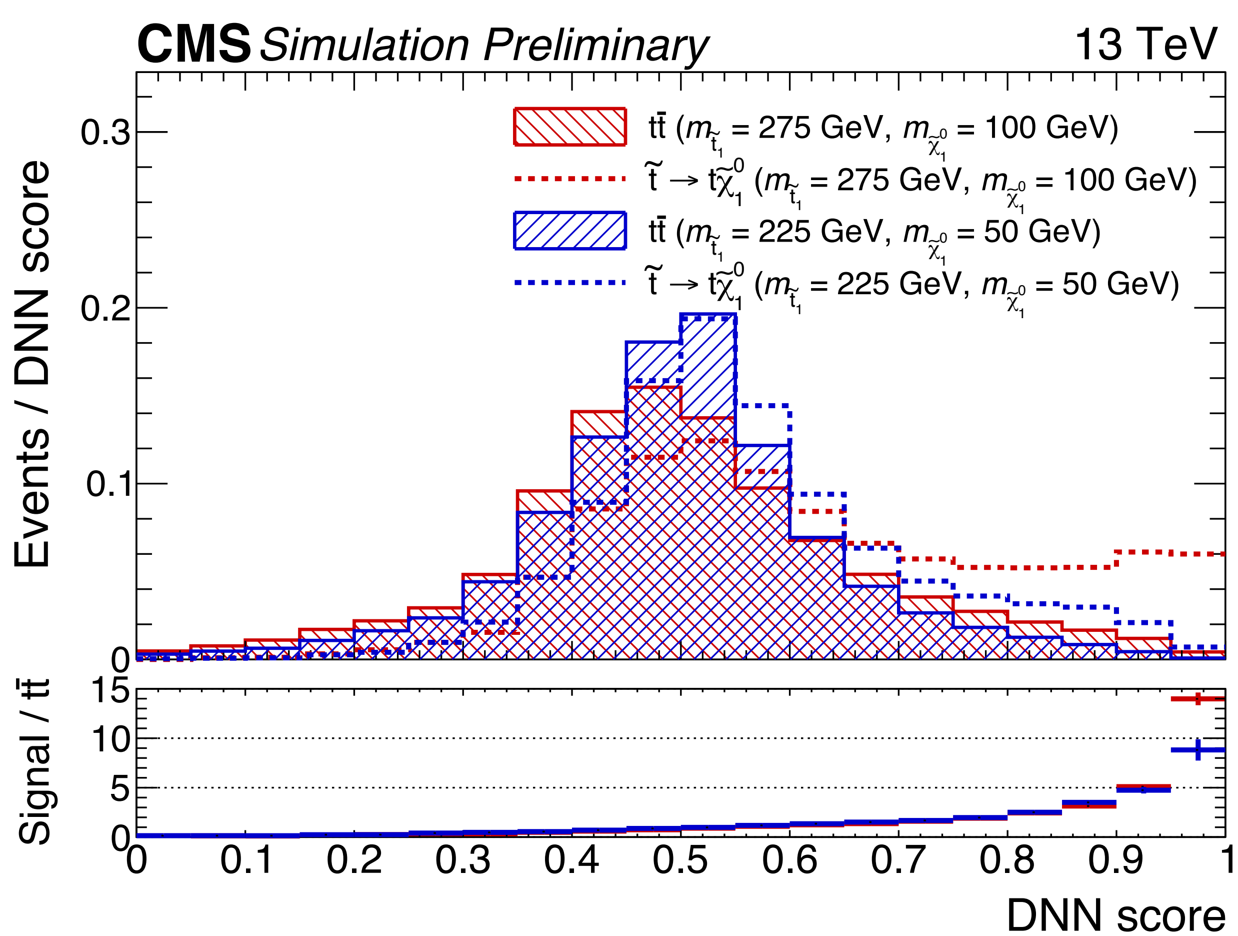
- Degenerate case with m(stop) = 175 GeV, m(LSP) = 1GeV maximally similar to SM
  - Sensitivity only through measurement of the ttbar x-sec
- Small kinematic differences for other points, e.g. p_T^{miss}, M_{T2}(ll)
  - Fully exploited by using parametric DNN: stop and LSP mass are fed to NN → optimized model for each signal mass point

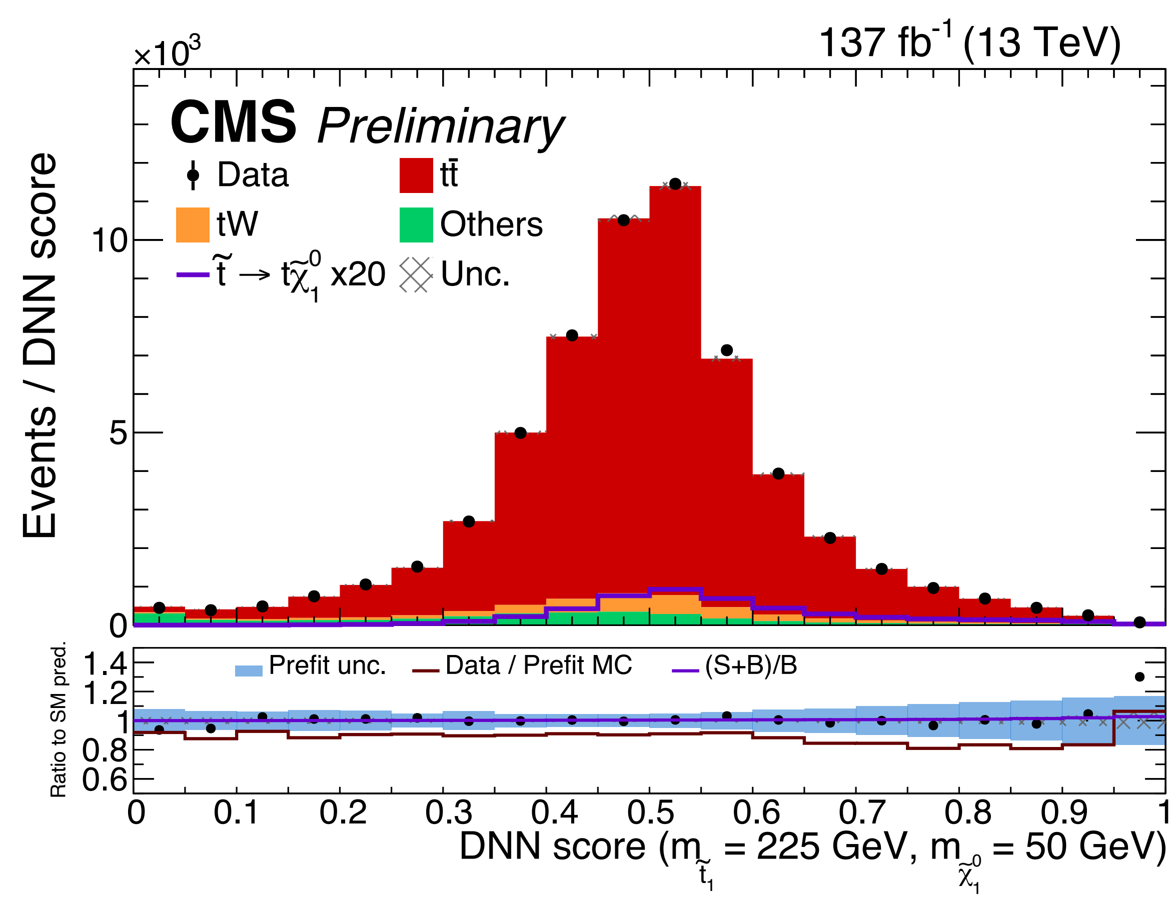




Parametric DNN Results

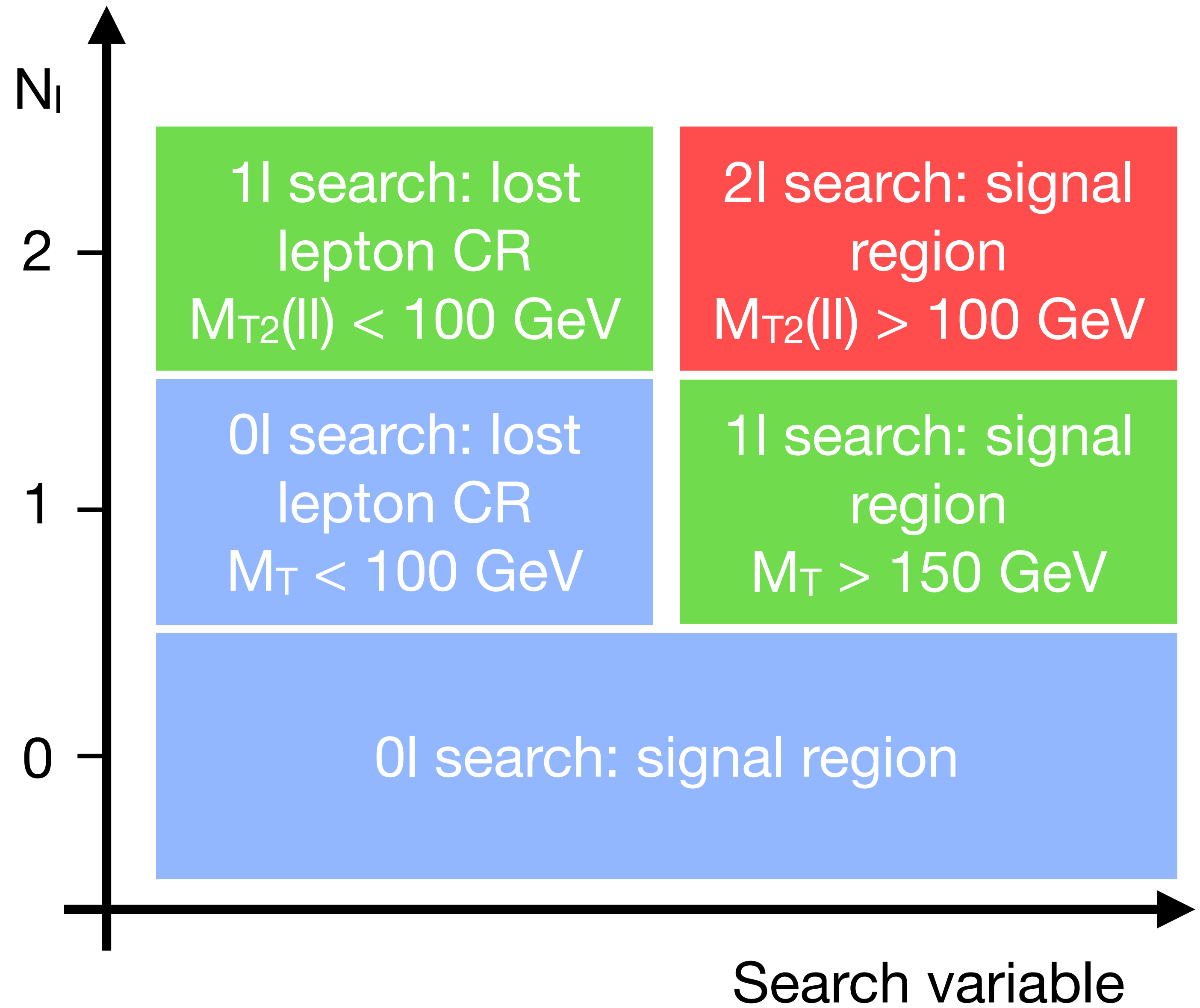
- 11 variables used as inputs additional to the stop and LSP mass
- Parametric DNN leads to **mass-point dependent background shapes**
- Good discriminating power of the DNN over the full range of signal models
- No significant excess observed



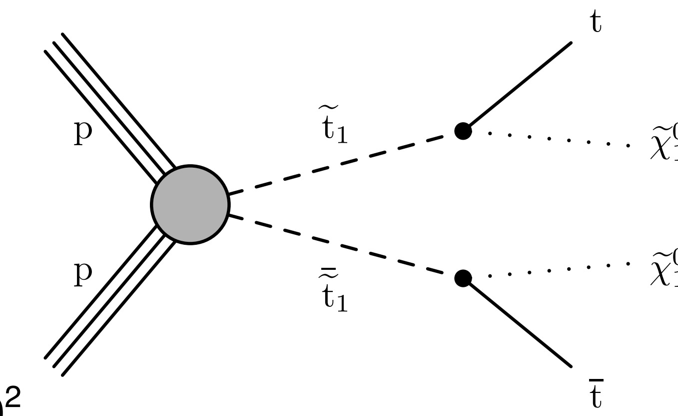


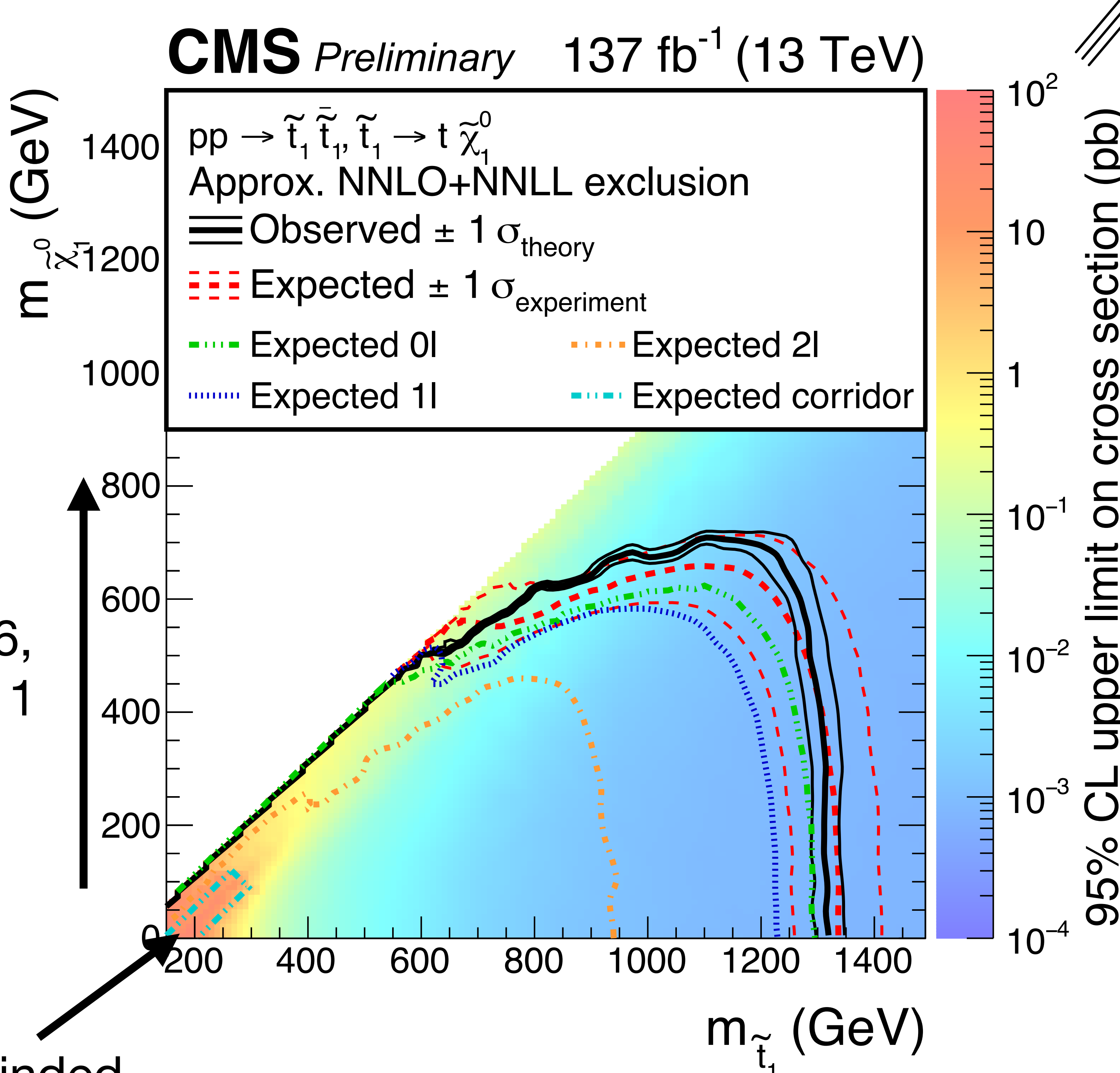
Putting the Pieces Together

- Right from the beginning of legacy Run 2 stop searches: Coordinate the different searches to **avoid overlap of signal and control regions**
- Individual searches rely on **orthogonal control samples to estimate backgrounds**, e.g. lost lepton
- **Carefully examine correlation patterns** of all systematic uncertainties



COMBINED RESULTS





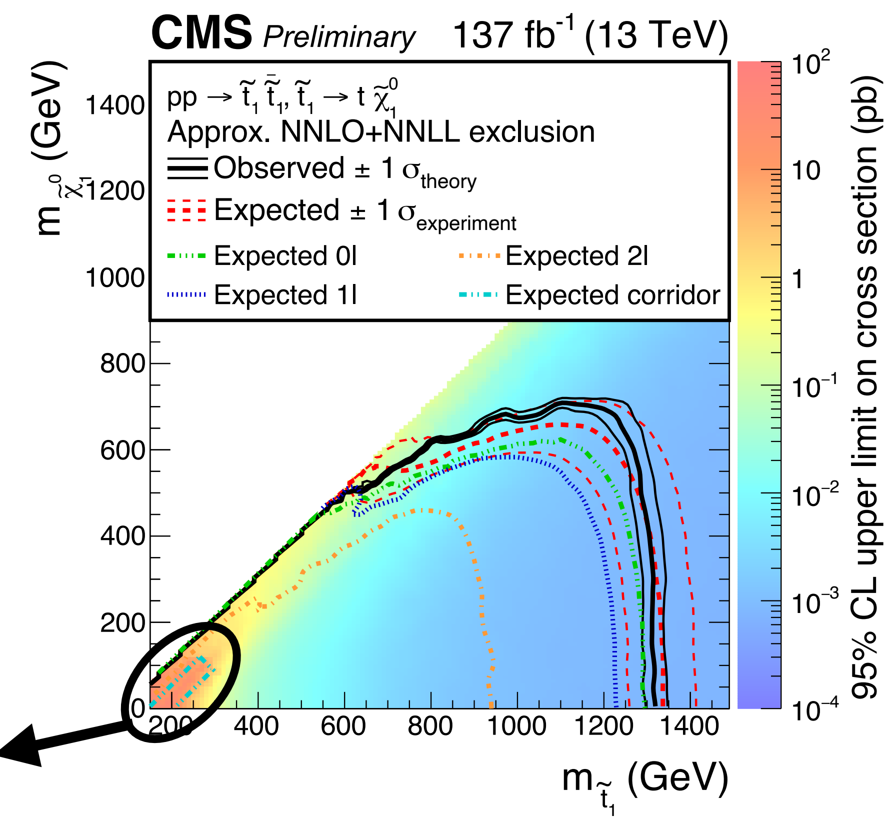
improvement by ~200 GeV wrt 2016, ~400 GeV wrt Run 1

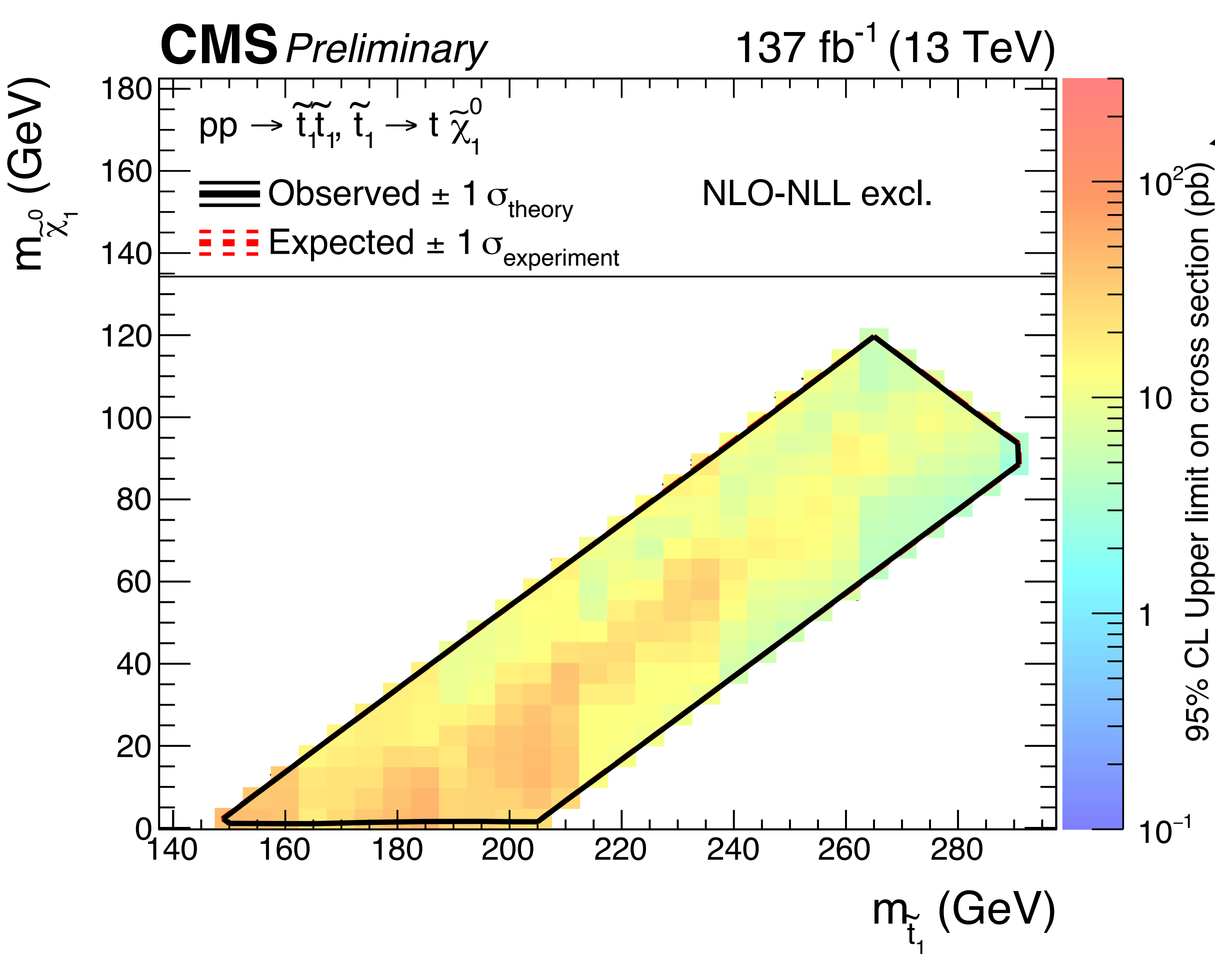
top corridor unblinded & fully excluded at 95% CL

pushed limits by ~300 GeV wrt 2016, ~500 GeV wrt Run 1

Combined Results: Corridor

- Corridor not fully excluded in previous dedicated searches

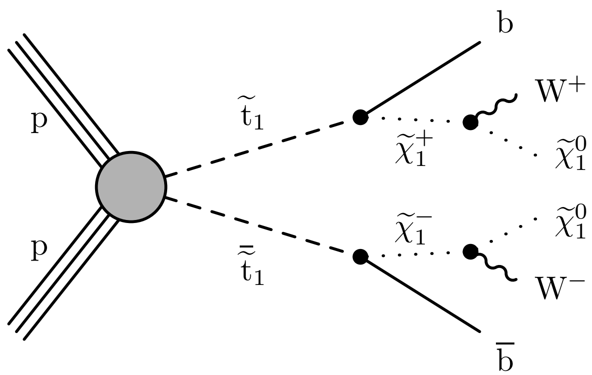


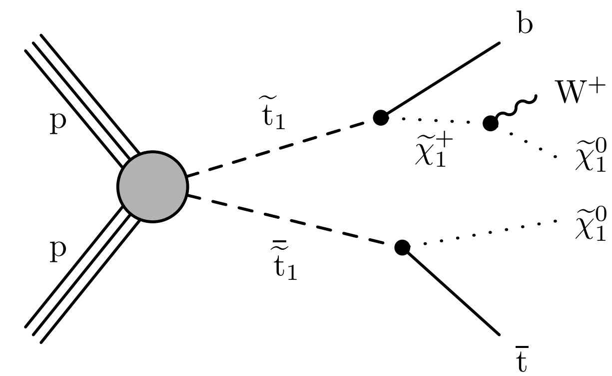


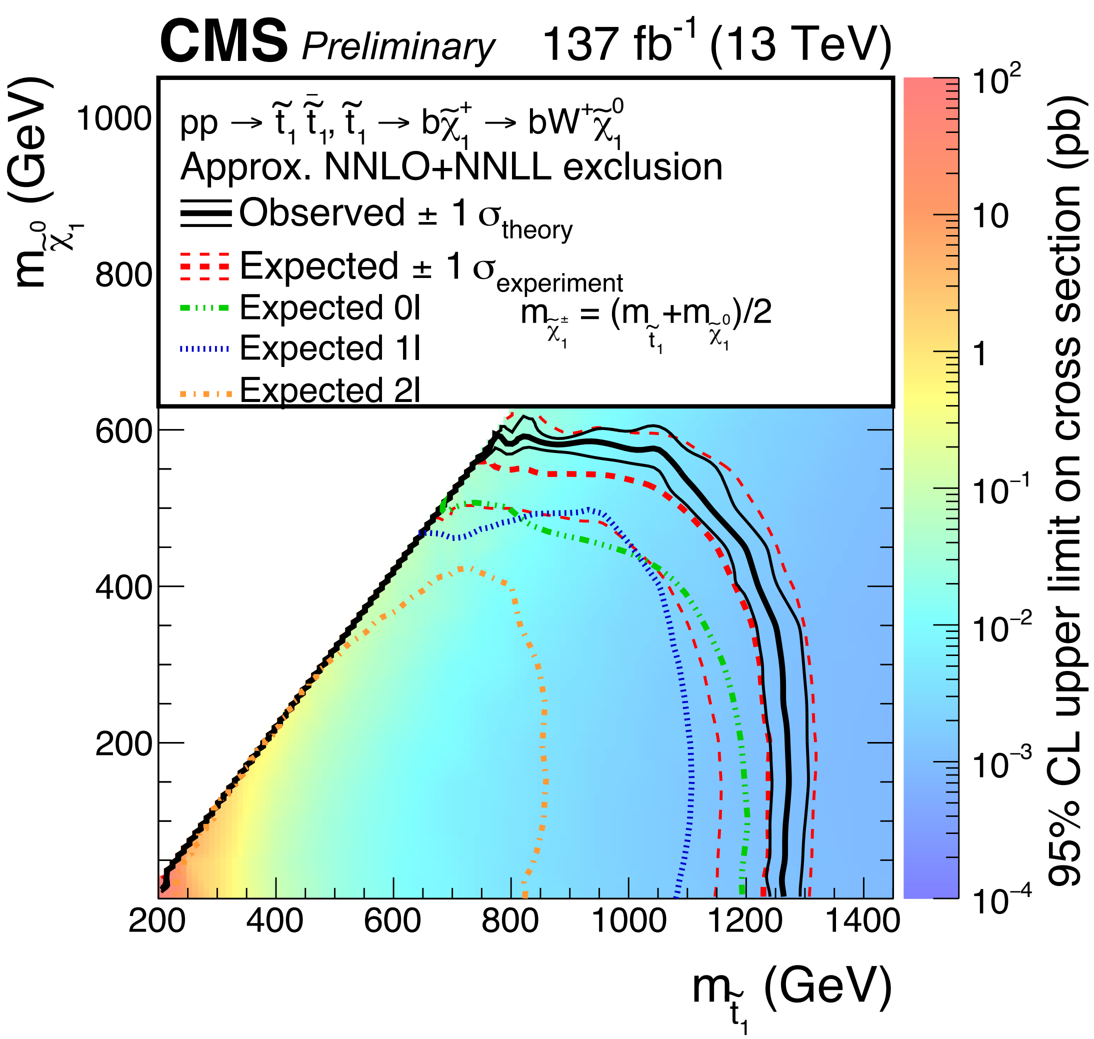
- **Numerous improvements**, way beyond the larger data sets, have led to **ever tighter constraints on top squark pair production**

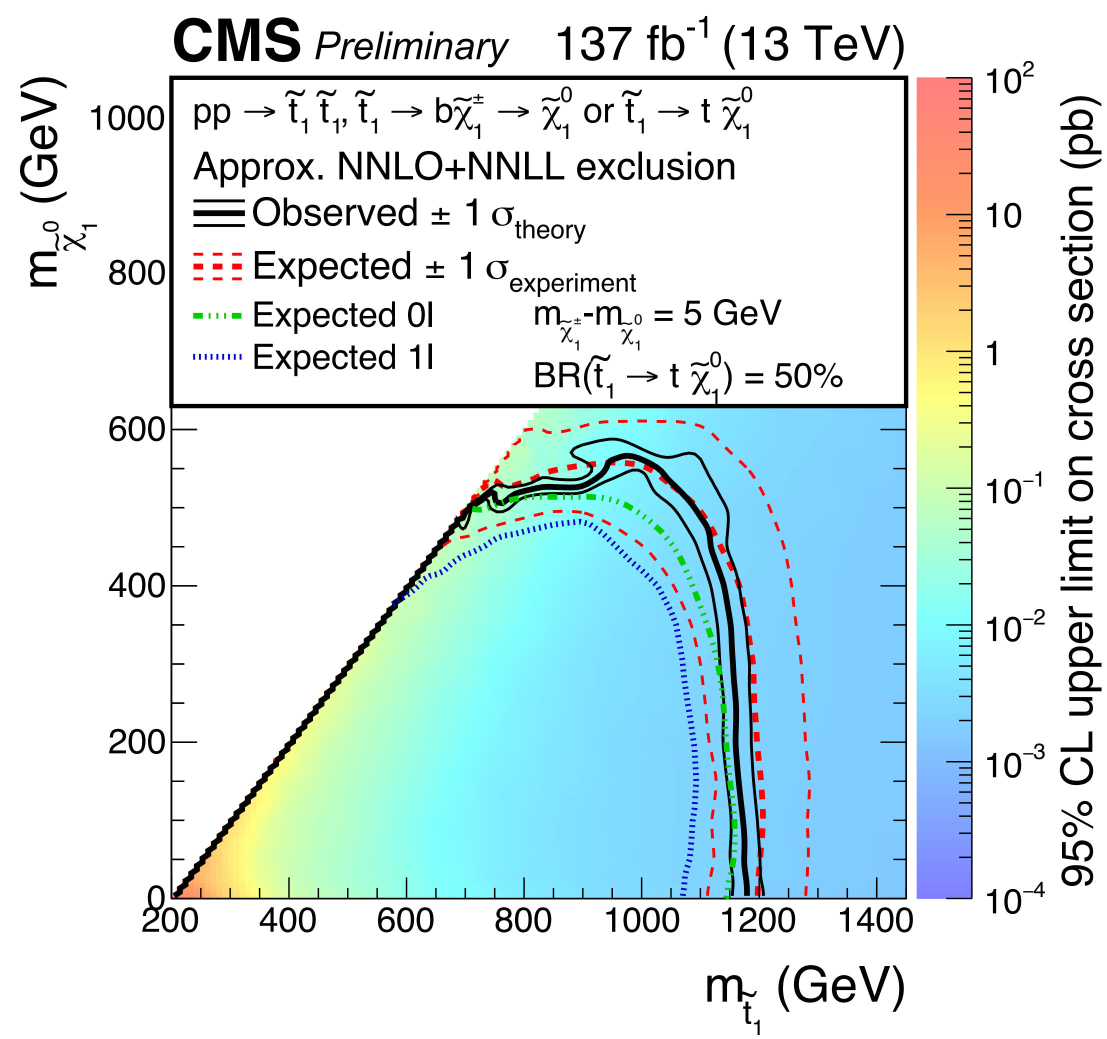
ADDITIONAL SIGNAL MODELS

- Models with intermediate chargino in top squark decay chain



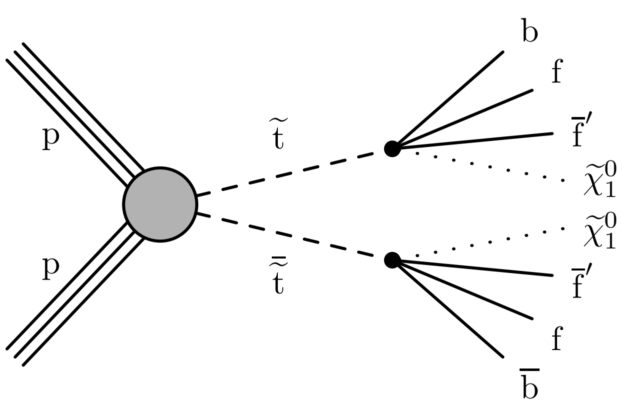


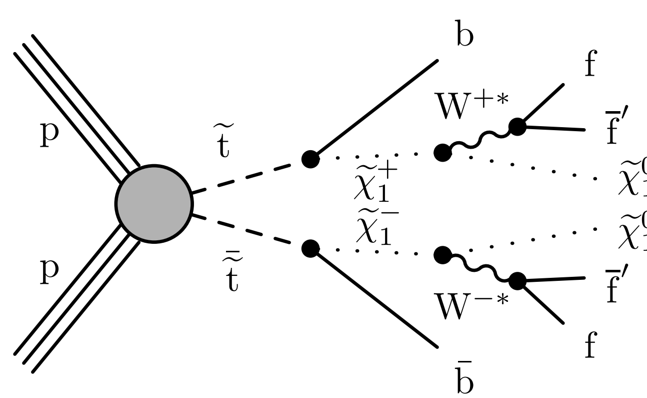


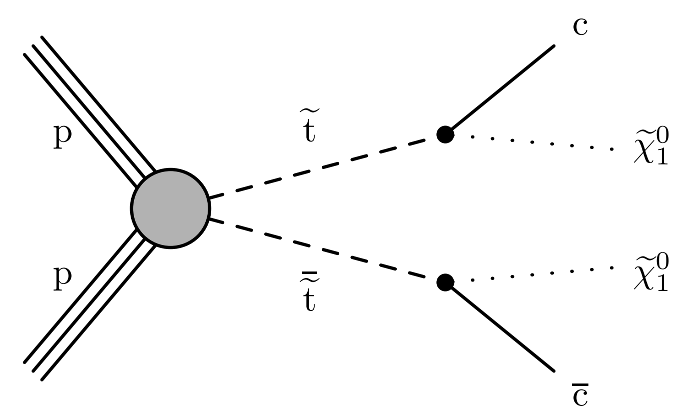


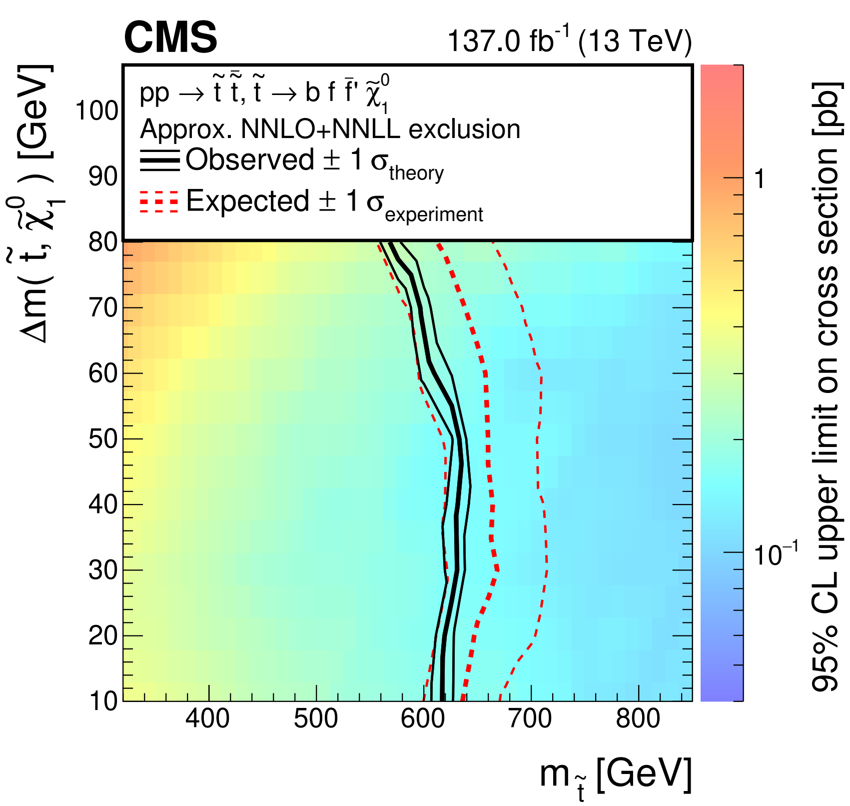
ADDITIONAL SIGNAL MODELS

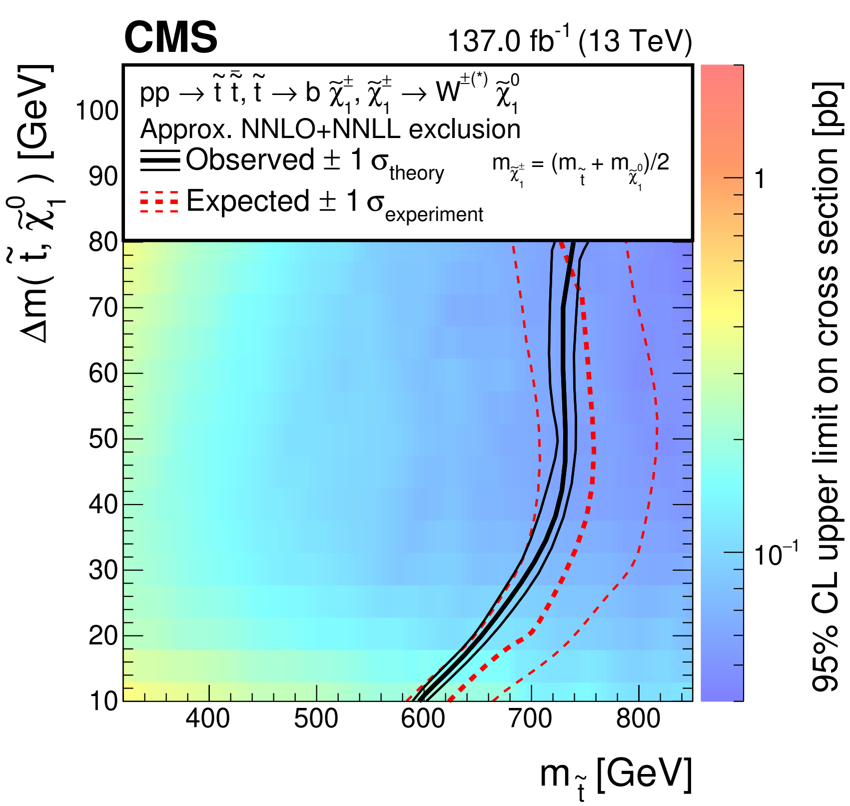
- Signal models with $\Delta m < m_W$
  - Decays of top squarks via off-shell top quarks or W bosons

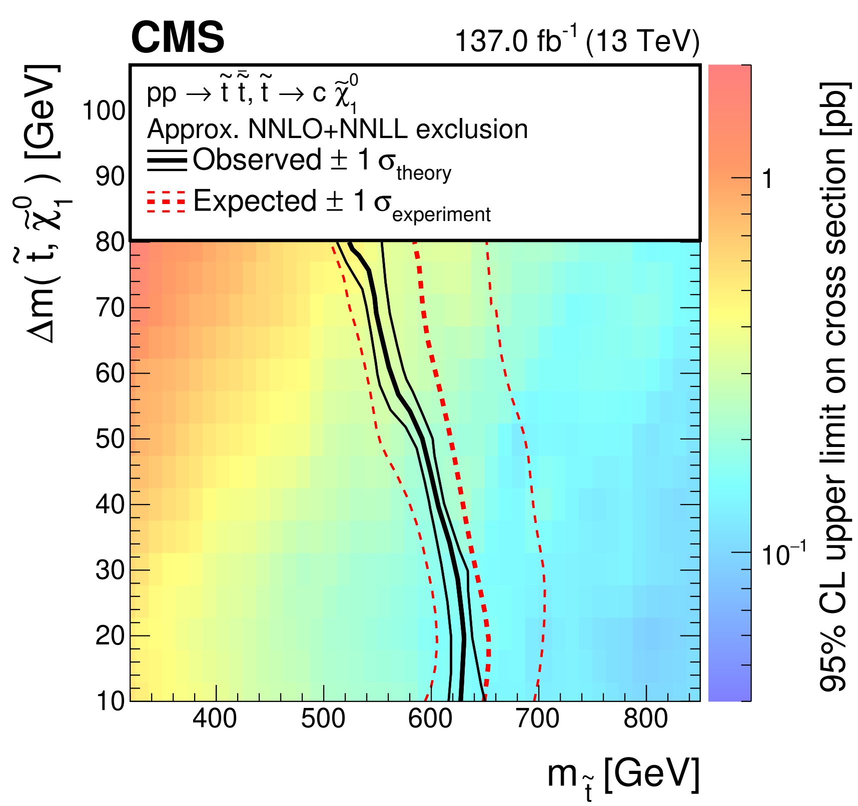






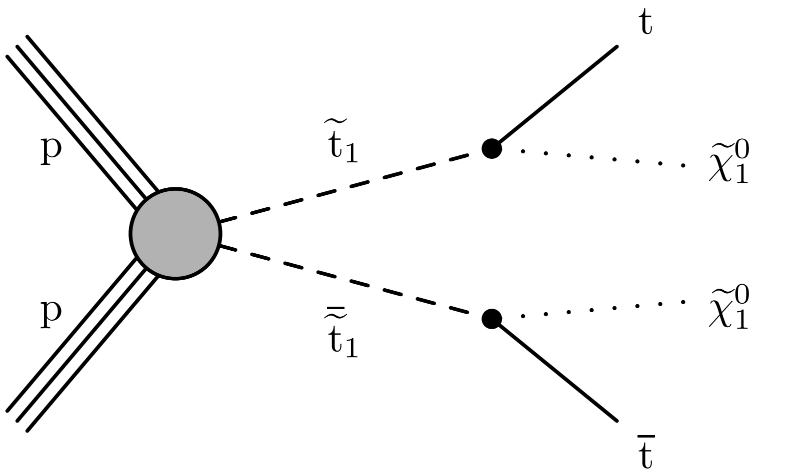




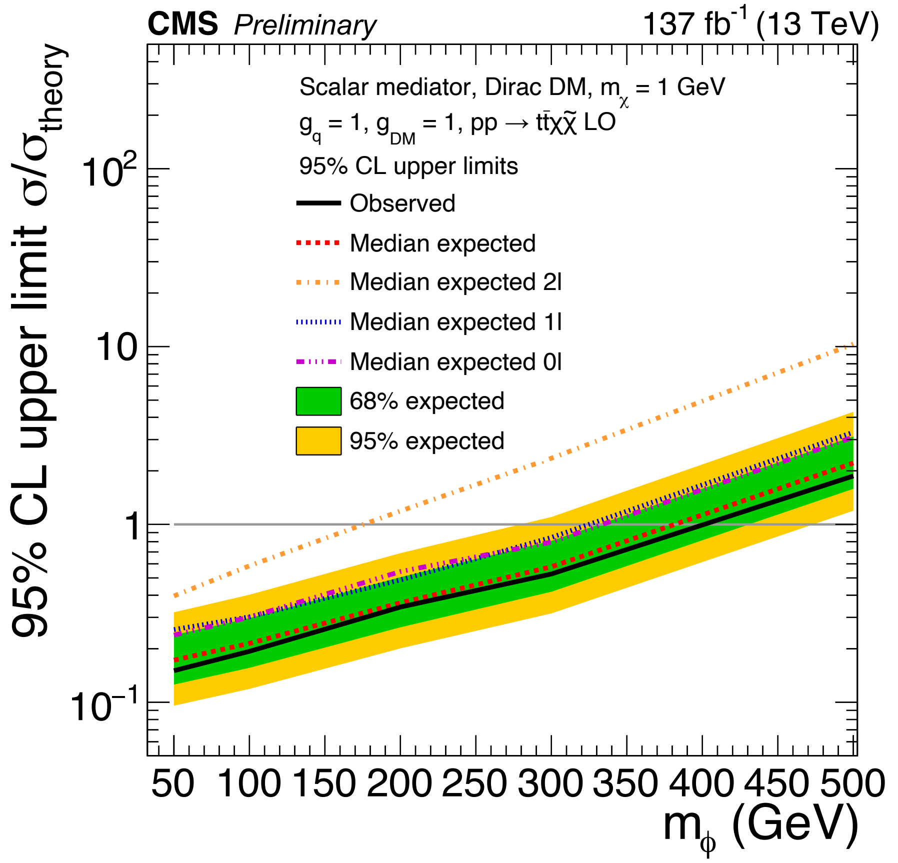


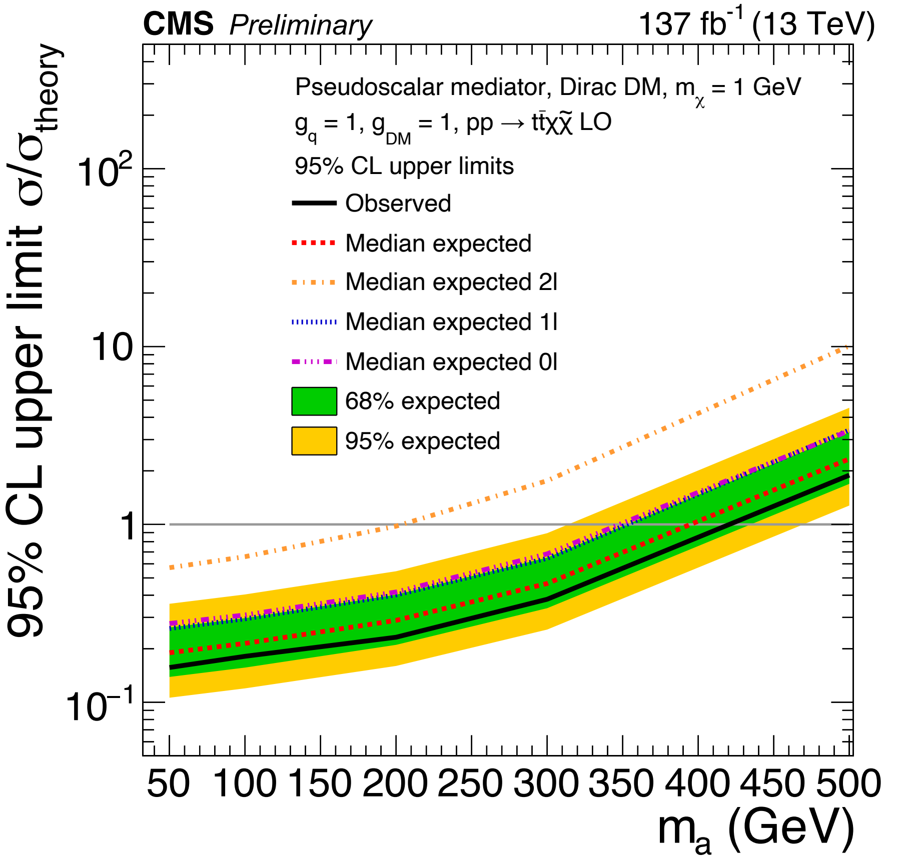
INCLUSIVE SEARCHES

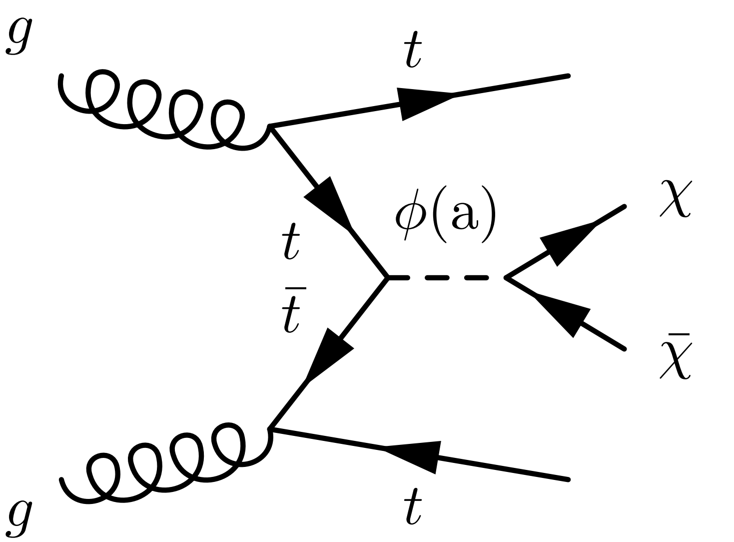
- **Searches are designed to be inclusive**
- Other signal models produce **similar final states**, e.g. mediated dark matter production in association with ttbar: pp→ttχχ
- Assumes scalar/pseudoscalar mediator with couplings similar to SM Higgs boson
    - Currently best limits for this model



ttbar + p_T^{miss}



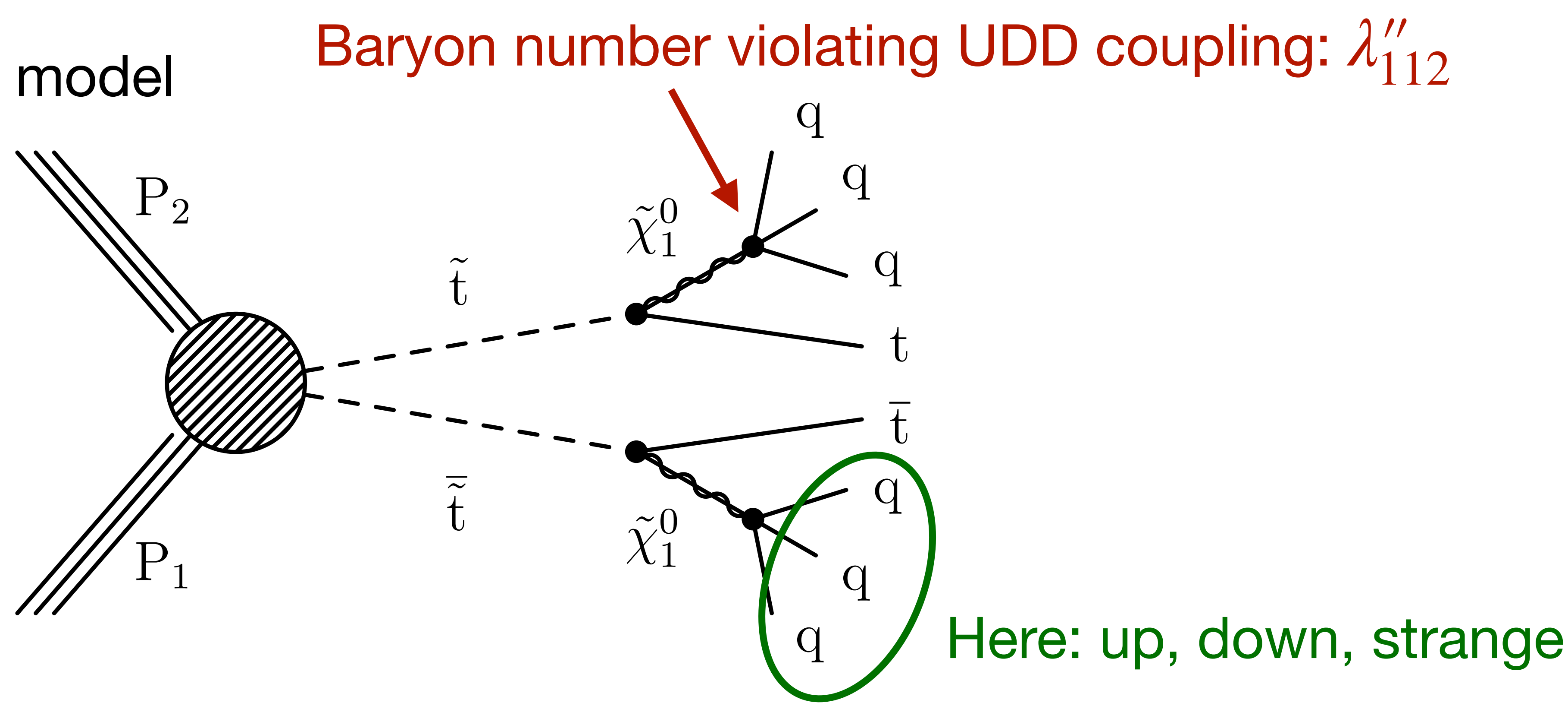




What if …?

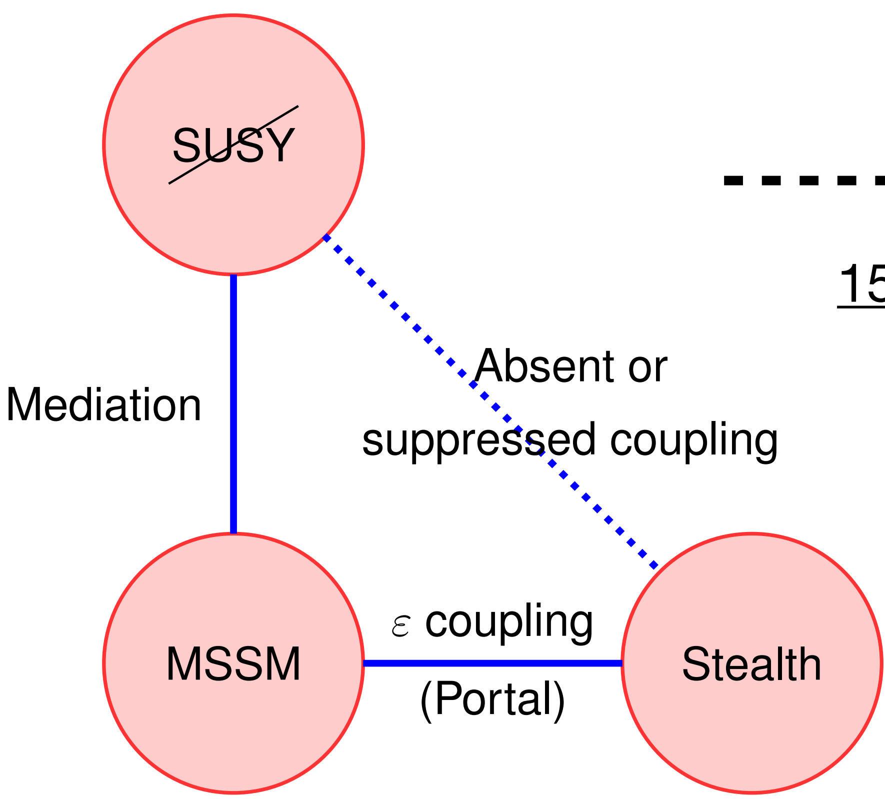
- What if R-parity is violated (RPV SUSY)?
- Searches are inclusive but **rely on p_T^{miss} → not present if LSP decays back into stable SM particles**
  - E.g. through **interaction terms that do not conserve B or L**, decay via off-shell squark
  - **Couplings: λ''_{ijk} with i, j, k corresponding to generation of quarks**

Simplified RPV model

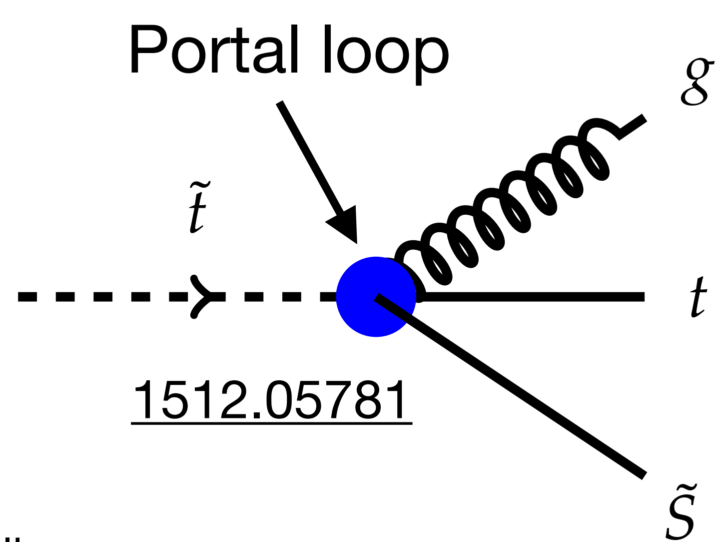


WHAT IF ...?

- **Several ways to end up with low p_T^{miss}**, not just previous RPV model
- Another example: **R-parity conserving SUSY with Stealth sector, coupled to MSSM via portal**
- **Small mass splitting** between superpartners in **stealth sector**



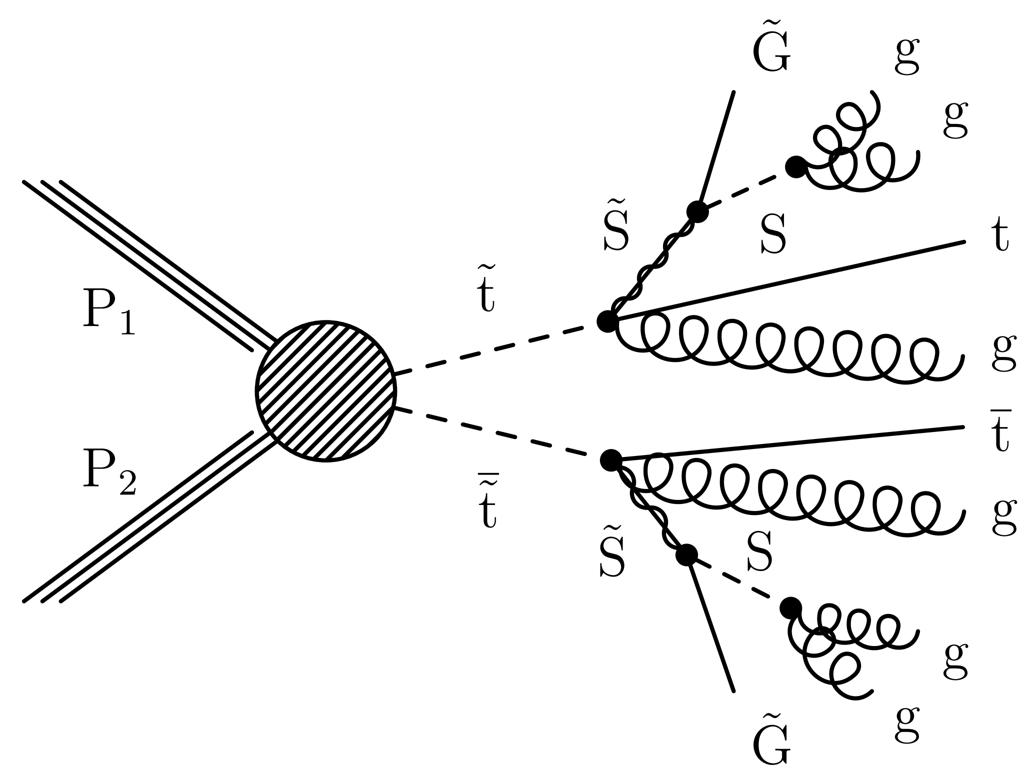
1201.4875



$M_{\mathrm{SUSY}} \sim M_{\mathrm{EWK}}$

$M_{\not{SUSY}} \sim \varepsilon M_{\mathrm{EWK}}$

Stop SYY simplified model

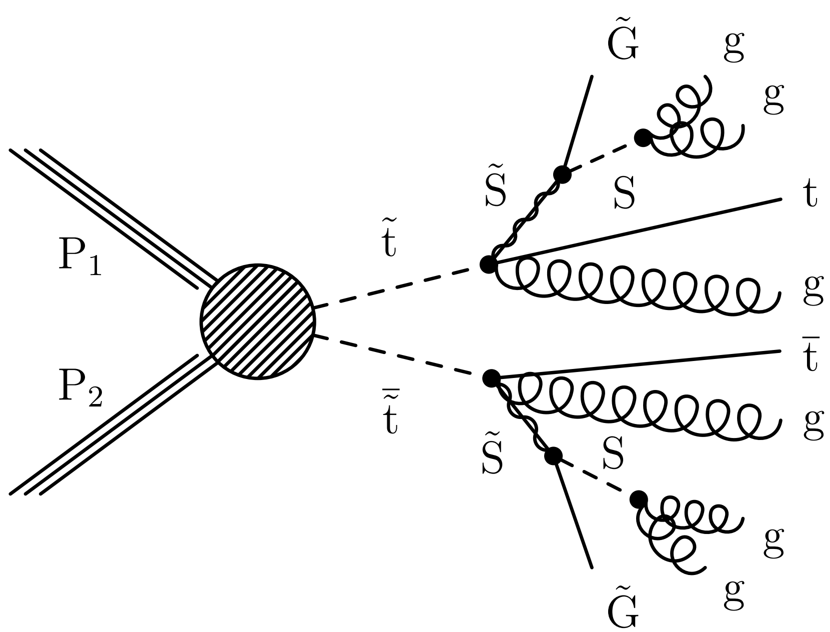


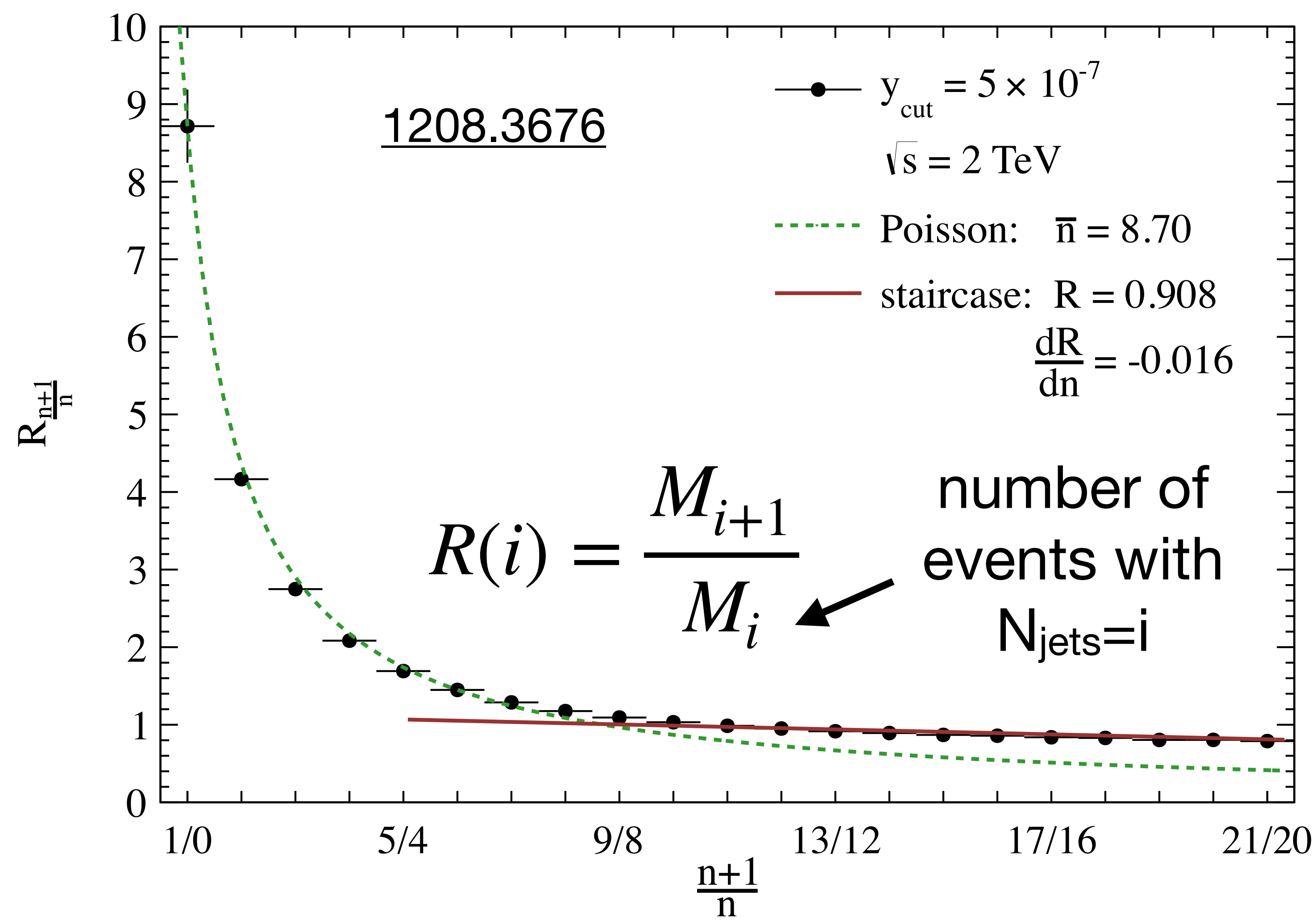
Gravitino carries little momentum

SEARCH FOR RPV/STEALTH STOPS

- Final state: tt+jets
  - Select events with single lepton to suppress QCD multijet production
- Most distinct feature: **jet multiplicity N_{jets} → difficult to model**
- Parametrize N_{jets} with **jet scaling function R(i)** which can be well modeled by **functional form**

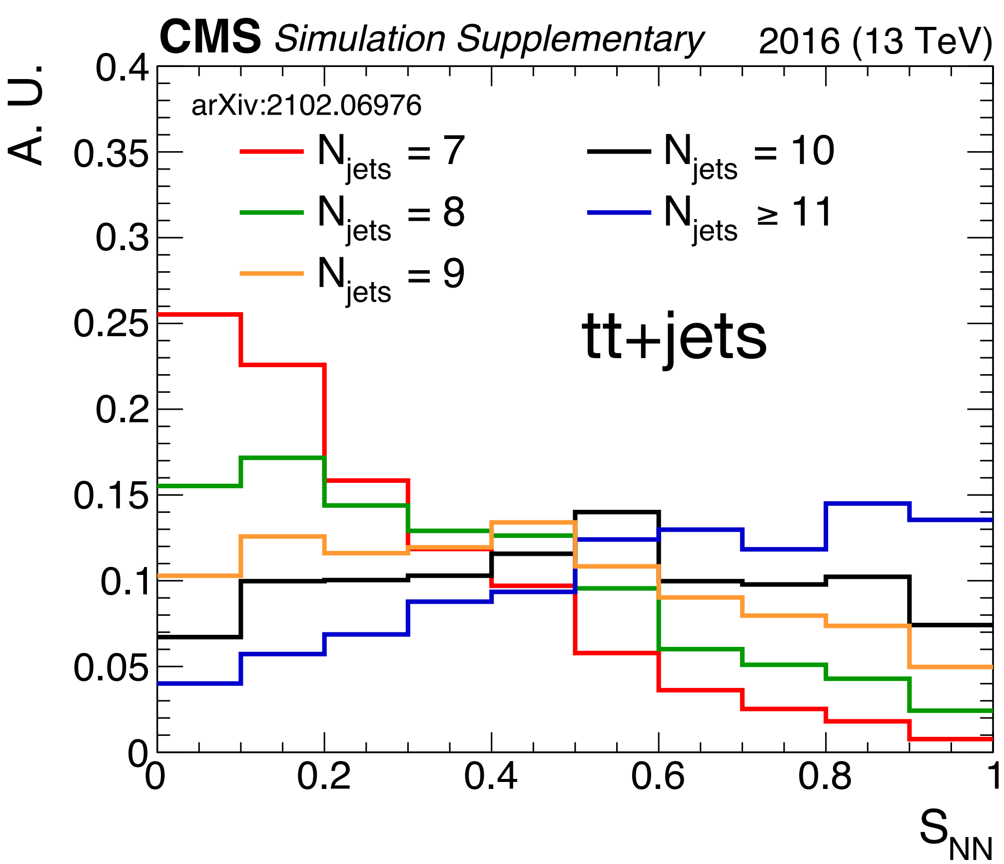
ttbar with many additional light flavor jets



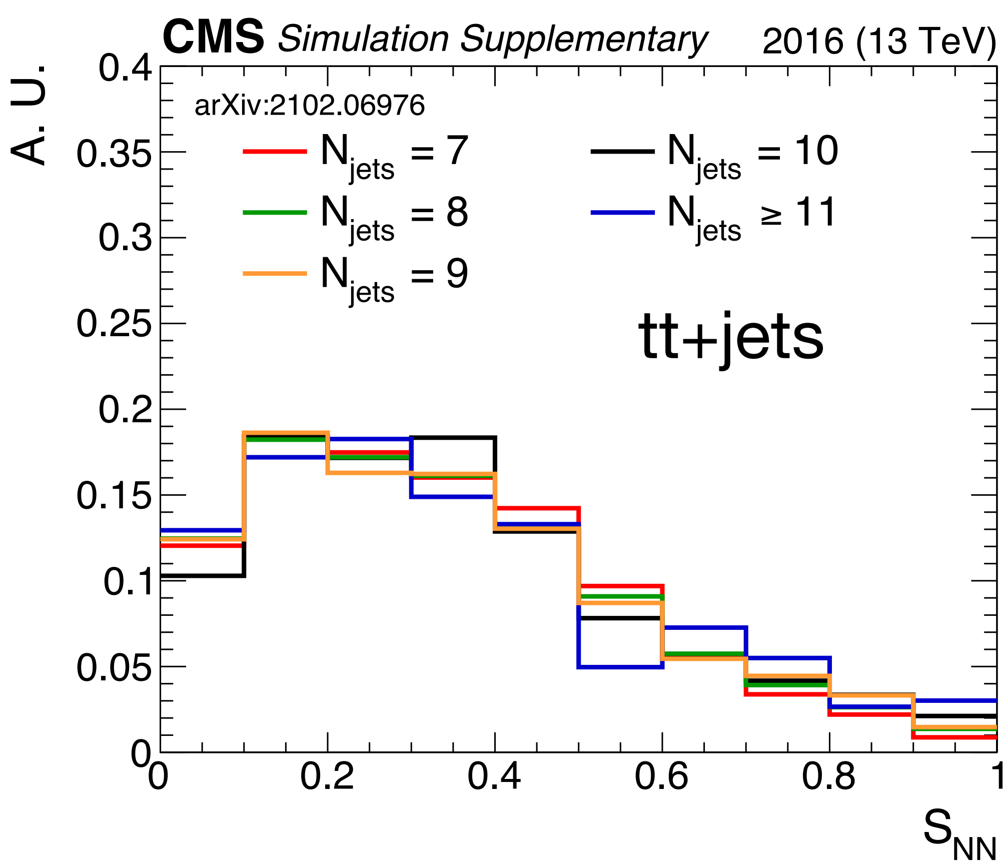


NEURAL NETWORK VS SM TT+JETS

- Event shape and kinematic variables used in a NN, score S_{NN}
  - S_{NN} correlated with N_{jets}
- Gradient reversal is used to decorrelate S_{NN} and N_{jets}
- Allows to use N_{jets} spectrum in the signal extraction fit in 4 bins of S_{NN}

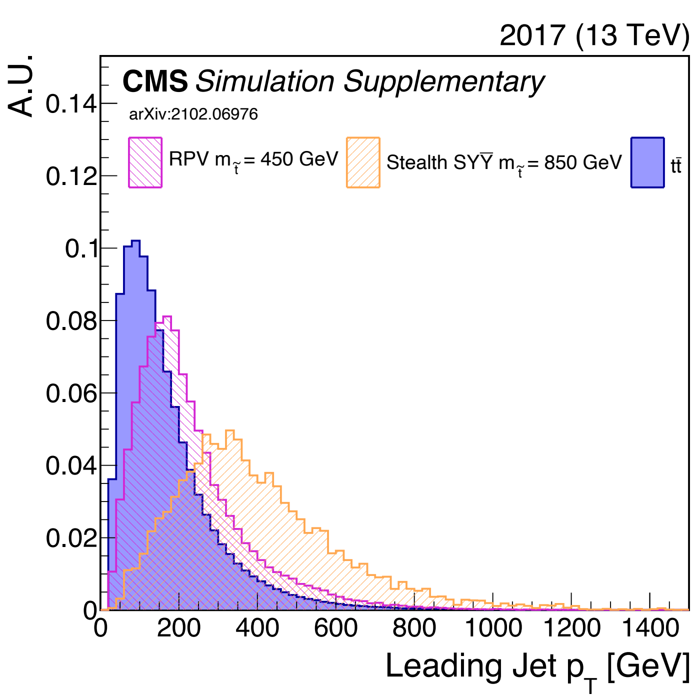


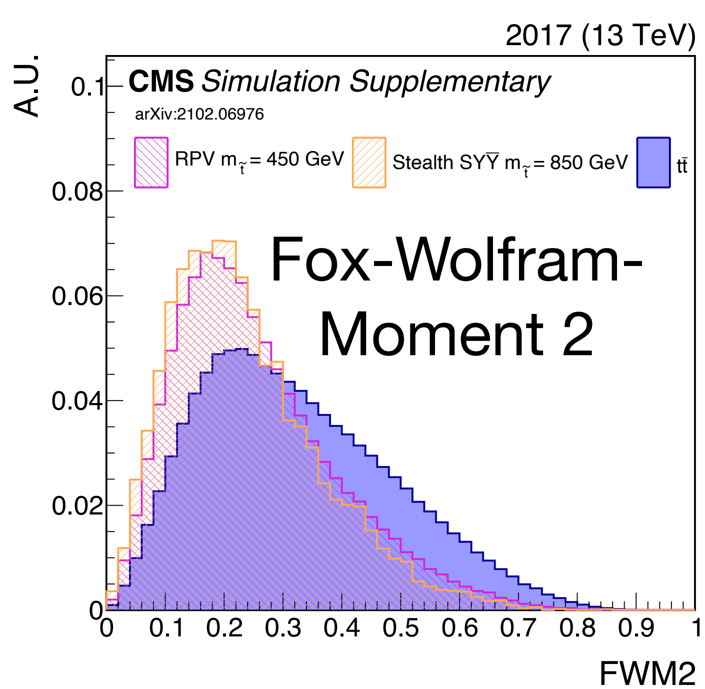
gradient reversal

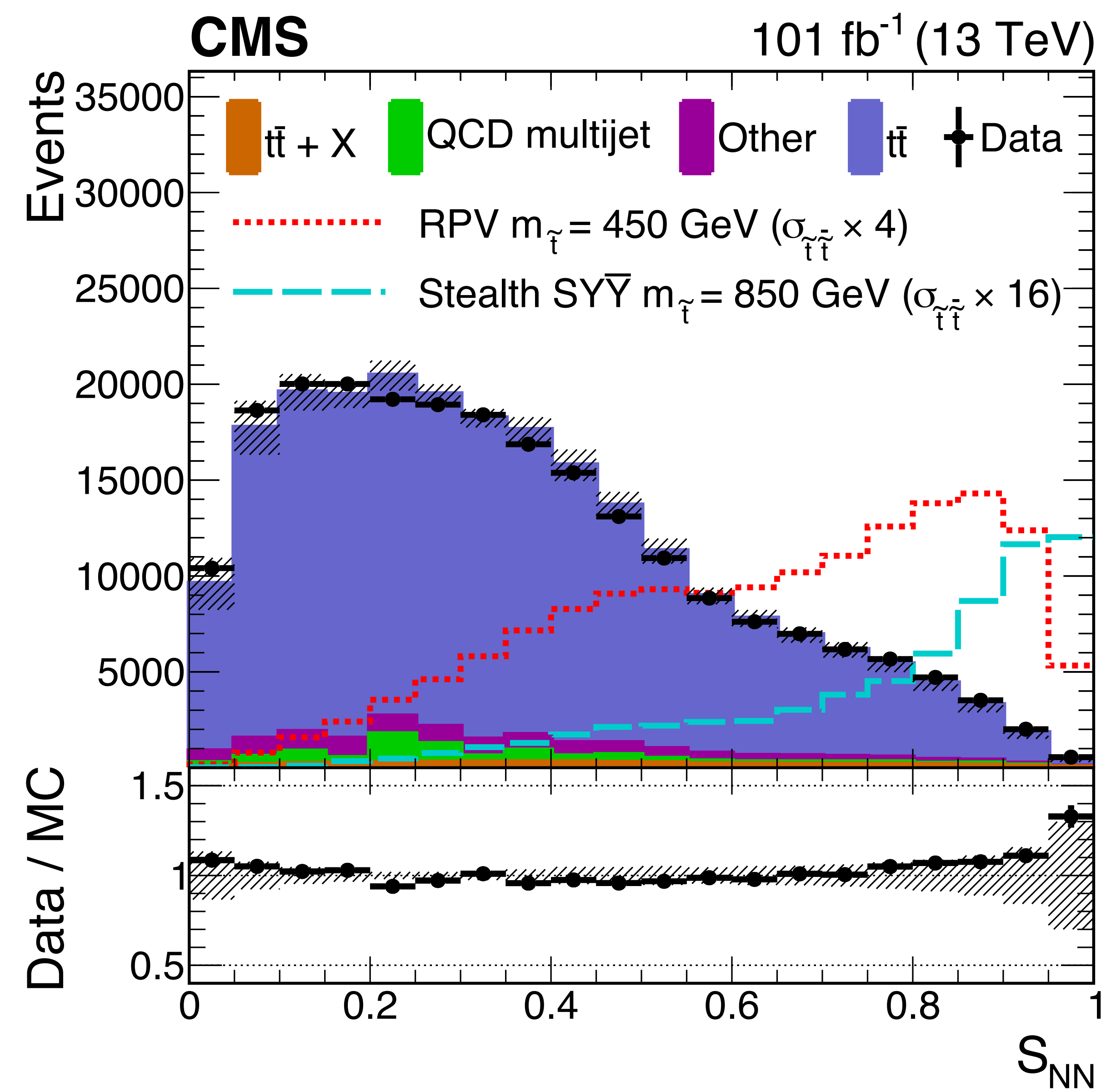


DNN Training and Response

- NN training done on mix of signal models with m(stop) 350-850 GeV
- Agreement of data and simulation within uncertainty

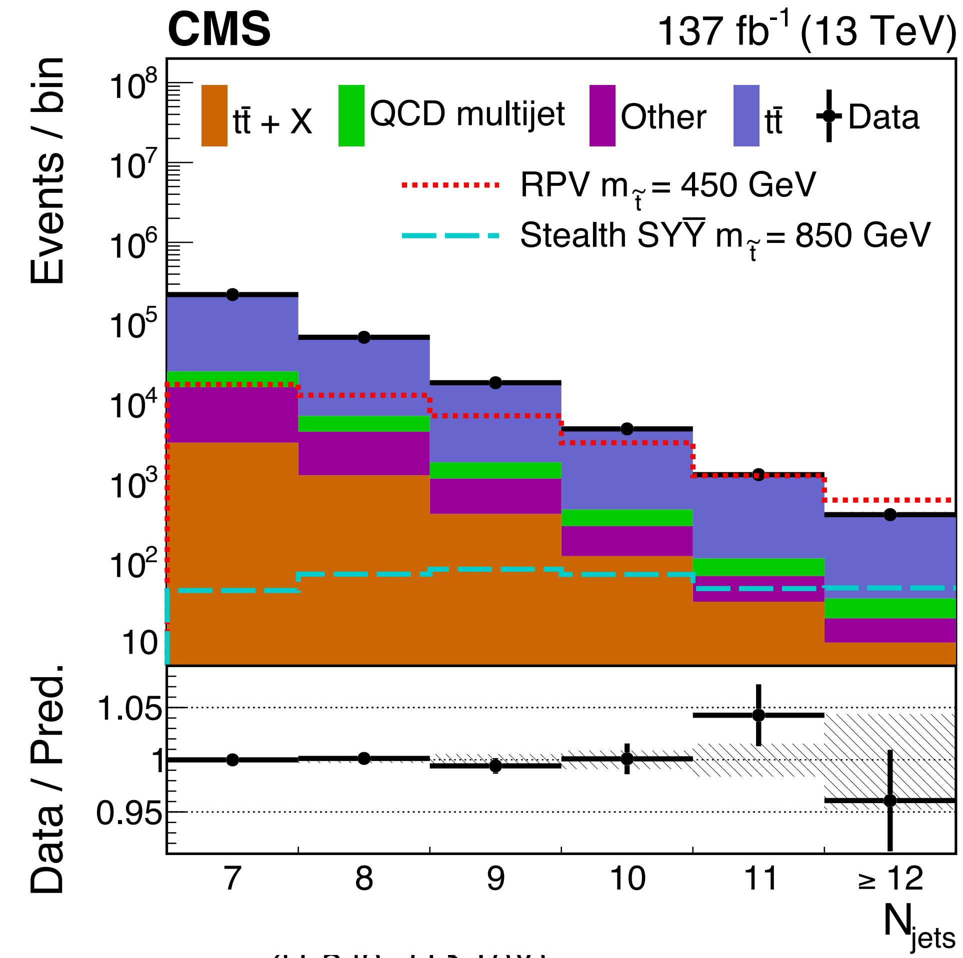


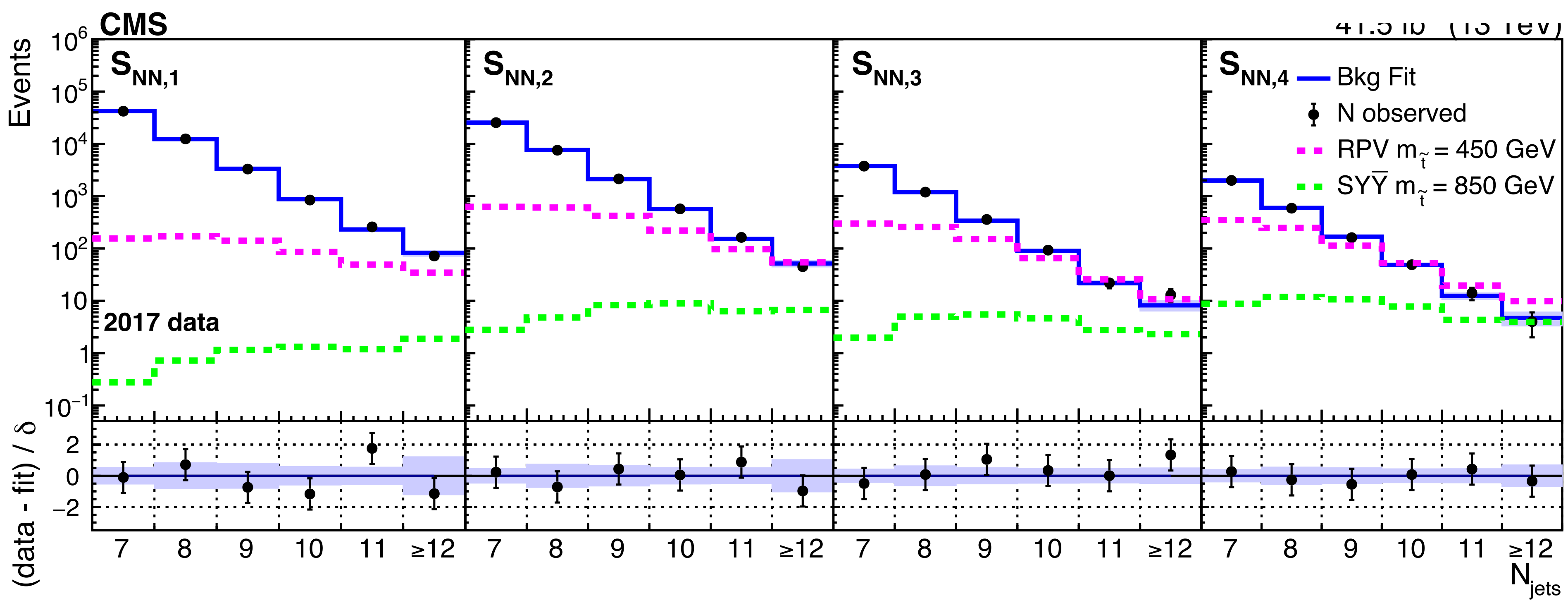




RESULTS

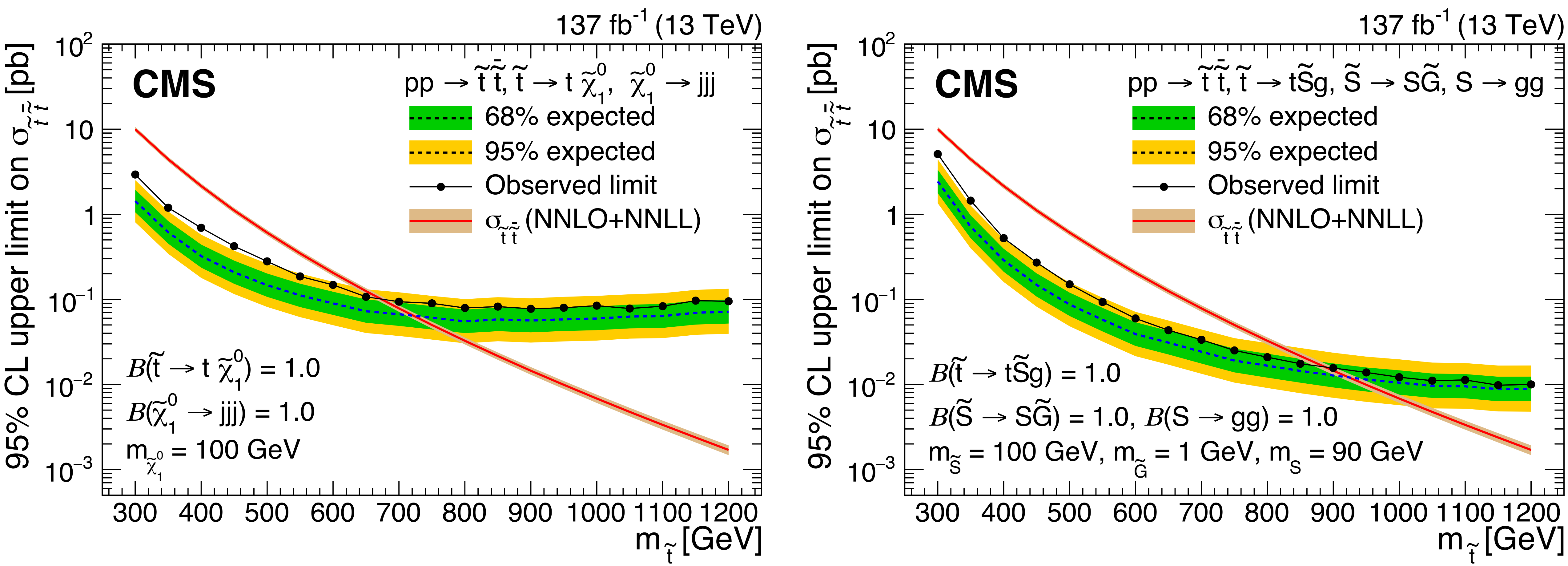
- Fits of functional form describing N_{jets} to data
  - Using 4 S_{NN} bins in 4 data taking eras
- Agreement of background only fit in combined S_{NN} bins and years
- Similar agreement in individual regions / eras





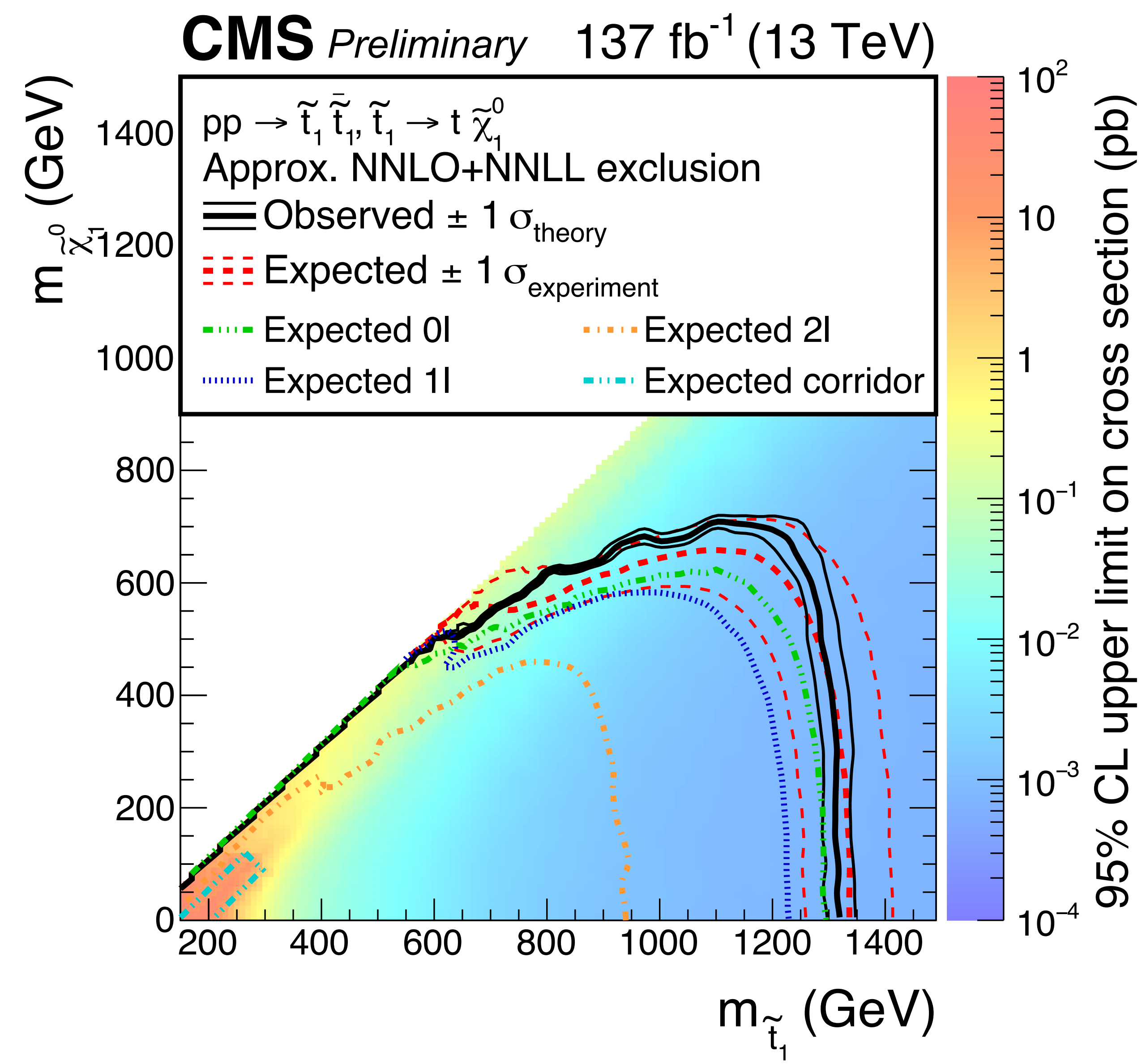
INTERPRETATIONS

- Results interpreted in RPV and stealth SUSY model as function of m(stop)
- Largest local significances of 2.8σ for RPV model with m(stop) = 400 GeV, 2.5σ for stealth SUSY with m(stop) = 350 GeV



CONCLUSIONS

- New developments in search strategies and tools have **greatly improved the constraints on top squarks**
  - Boosted object tagging, soft b-tagging, p_T^{miss} significance, …
  - Dedicated top corridor search allows to also constrain very particular region of parameter space
  - **From 800 GeV in m(stop) in Run 1 to above 1300 GeV**
- Novel search for **RPV and stealth top squarks** exhibits excellent sensitivity to **previously uncovered signal scenarios**



BACKUP

Bibliography

CMS has conducted various searches for top squarks during Run 2 of the LHC (2015 - 2018):

Search for top squark production in fully-hadronic final states, submitted to PRD

Search for direct top squark pair production in events with one lepton, jets, and missing transverse momentum, JHEP 05 (2020) 032

Search for top squark pair production using dilepton final states, Eur.Phys.J.C 81 (2021)

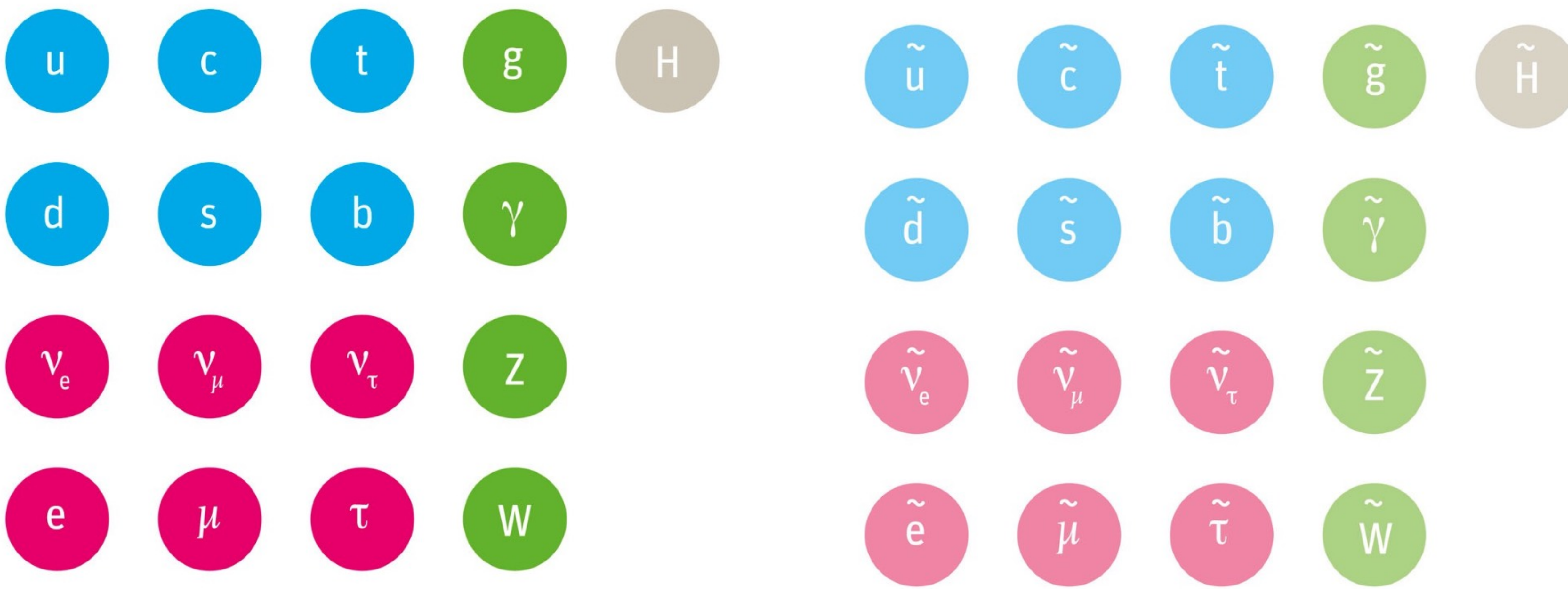
Combined searches for the production of supersymmetric top quark partners, CMS-SUS-20-002

Search for top squarks in final states with two top quarks and several light-flavor jets, submitted to PRD

SUPERSYMMETRY

Standard model — **Supersymmetric partners**

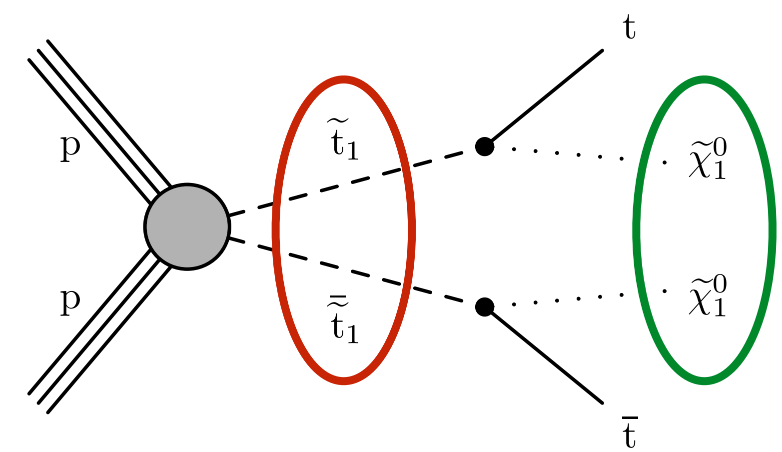
Fermions | Bosons | Bosons | Fermions



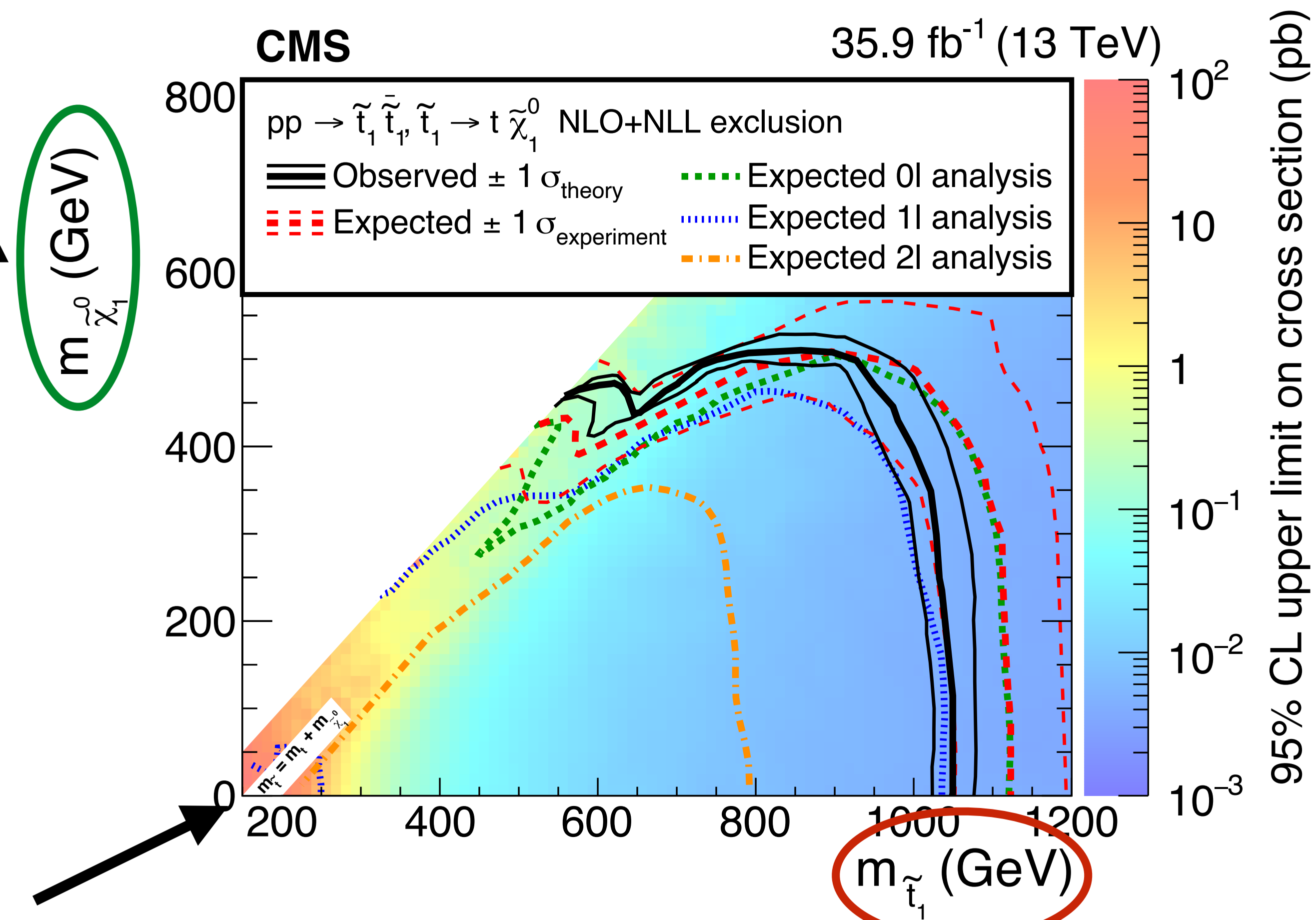
"light" ← soft SUSY breaking → "heavy"

STOPS AT THE BEGINNING OF RUN 2

- Simplified model assuming R parity conservation: **top squark pair production**, prompt decay to a top quark and the **stable lightest neutralino (LSP)** → two parameters to scan
- Different **challenges depending on Δm** between the particles



Soft b-tagging, ISR jets



top corridor:
signal similar to ttbar

High p_T^{miss}, boosted objects

SIGNAL REGIONS ALL HADRONIC

$m_{\mathrm{T}}^{\mathrm{b}}$ [GeV]	N_{j}	N_{b}	N_{t}	N_{W}	N_{res}	H_{T} [GeV]	$p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	Bin number
<175	≥ 7	1	≥ 0	≥ 0	≥ 1	>300	$[250, 300, 400, 500, \infty]$	53–56
<175	≥ 7	≥ 2	≥ 0	≥ 0	≥ 1	>300	$[250, 300, 400, 500, \infty]$	57–60
>175	≥ 5	1	0	0	0	>1000	$[250, 350, 450, 550, \infty]$	61–64
>175	≥ 5	≥ 2	0	0	0	>1000	$[250, 350, 450, 550, \infty]$	65–68
>175	≥ 5	1	≥ 1	0	0	300–1000	$[250, 550, 650, \infty]$	69–71
>175	≥ 5	1	≥ 1	0	0	1000–1500	$[250, 550, 650, \infty]$	72–74
>175	≥ 5	1	≥ 1	0	0	>1500	$[250, 550, 650, \infty]$	75–77
>175	≥ 5	1	0	≥ 1	0	300–1300	$[250, 350, 450, \infty]$	78–80
>175	≥ 5	1	0	≥ 1	0	>1300	$[250, 350, 450, \infty]$	81–83
>175	≥ 5	1	0	0	≥ 1	300–1000	$[250, 350, 450, 550, 650, \infty]$	84–88
>175	≥ 5	1	0	0	≥ 1	1000–1500	$[250, 350, 450, 550, 650, \infty]$	89–93
>175	≥ 5	1	0	0	≥ 1	>1500	$[250, 350, 450, 550, 650, \infty]$	94–98
>175	≥ 5	1	≥ 1	≥ 1	0	>300	$[250, 550, \infty]$	99–100
>175	≥ 5	1	≥ 1	0	≥ 1	>300	$[250, 550, \infty]$	101–102
>175	≥ 5	1	0	≥ 1	≥ 1	>300	$[250, 550, \infty]$	103–104
>175	≥ 5	2	1	0	0	300–1000	$[250, 550, 650, \infty]$	105–107
>175	≥ 5	2	1	0	0	1000–1500	$[250, 550, 650, \infty]$	108–110
>175	≥ 5	2	1	0	0	>1500	$[250, 550, 650, \infty]$	111–113
>175	≥ 5	2	0	1	0	300–1300	$[250, 350, 450, \infty]$	114–116
>175	≥ 5	2	0	1	0	>1300	$[250, 350, 450, \infty]$	117–119
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>175	≥ 5	2	0	0	1	>1500	$[250, 350, 450, 550, 650, \infty]$	130–134
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>175	≥ 5	2	1	0	1	300–1300	$[250, 350, 450, \infty]$	137–139
>175	≥ 5	2	1	0	1	>1300	$[250, 350, 450, \infty]$	140–142
>175	≥ 5	2	0	1	1	>300	$[250, 550, \infty]$	143–144
>175	≥ 5	2	2	0	0	>300	$[250, 450, \infty]$	145–146
>175	≥ 5	2	0	2	0	>300	>250	147
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>175	≥ 5	2	$N_{\mathrm{t}} + N_{\mathrm{W}} + N_{\mathrm{res}} \geq 3$			>300	>250	152
>175	≥ 5	≥ 3	1	0	0	300–1000	$[250, 350, 550, \infty]$	153–155
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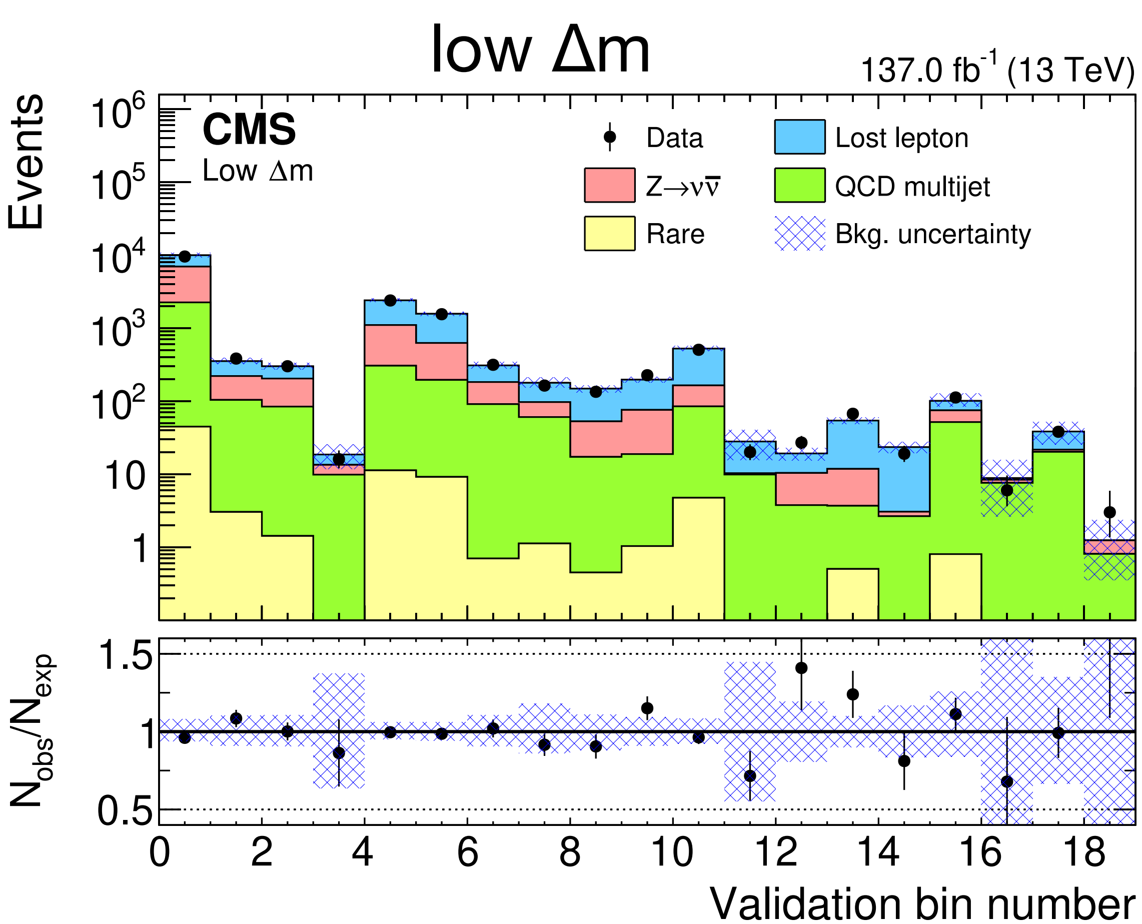
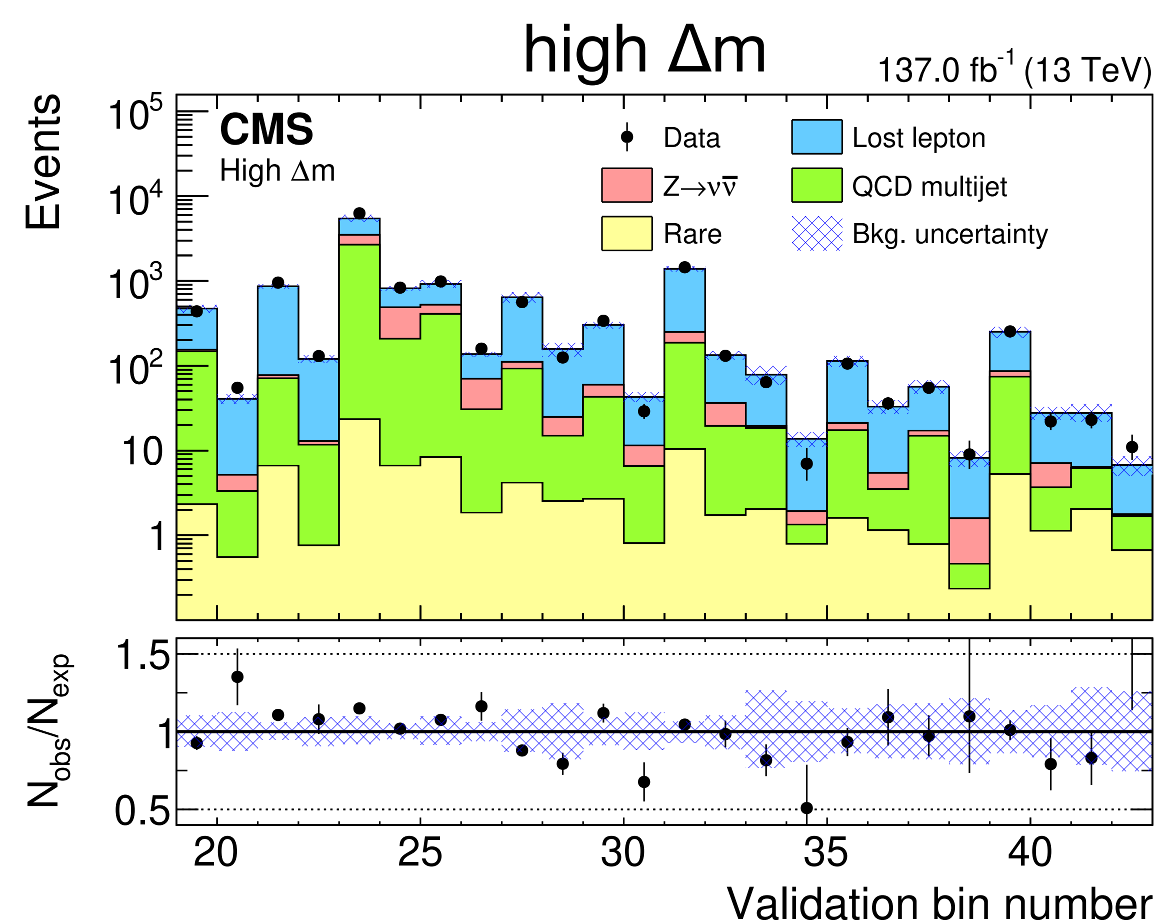
>175	≥ 5	≥ 3	2	0	0	>300	>250	178
>175	≥ 5	≥ 3	0	2	0	>300	>250	179
>175	≥ 5	≥ 3	0	0	2	>300	$[250, 350, \infty]$	180–181
>175	≥ 5	≥ 3	$N_{\mathrm{t}} + N_{\mathrm{W}} + N_{\mathrm{res}} \geq 3$			>300	>250	182

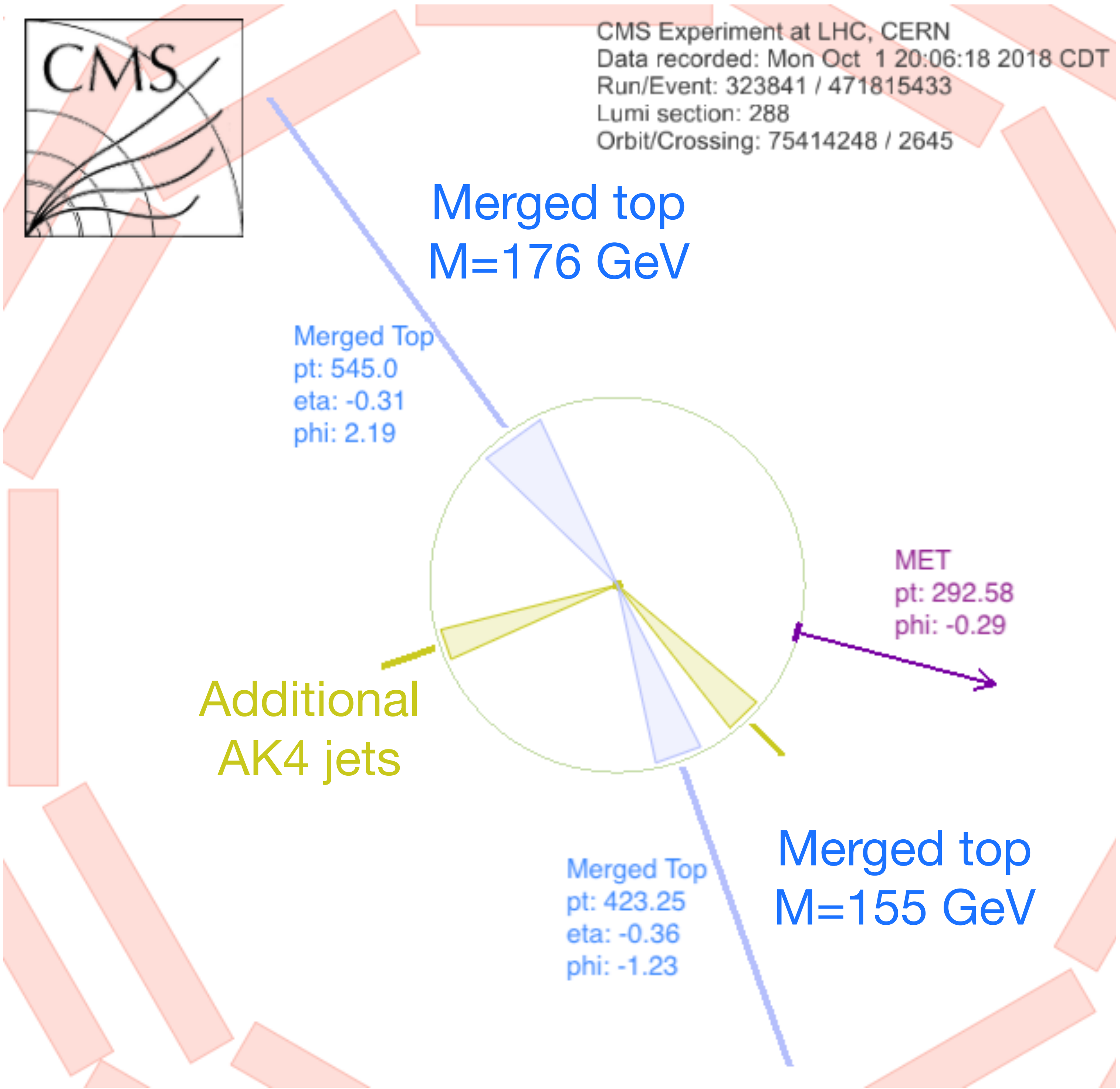
VALIDATION

- Background estimates **validated in dedicated signal depleted samples** orthogonal to signal regions
  - Kinematically similar to signal regions
- **Inverting separation requirement of jets and p_T^{miss}**





Candidate Events



Z→INV BACKGROUND

- Z→νν events have large genuine p_T^{miss}
- Two data control samples used to estimate Z→νν background
  - Z→ll to extract normalization factor R_Z
  - γ+jets for shape correction factor S_γ

$$N_{\text{pred}}^{Z(\nu\overline{\nu})+\text{jets}} = R_Z S_\gamma N_{\text{MC}}^{Z(\nu\overline{\nu})+\text{jets}}$$

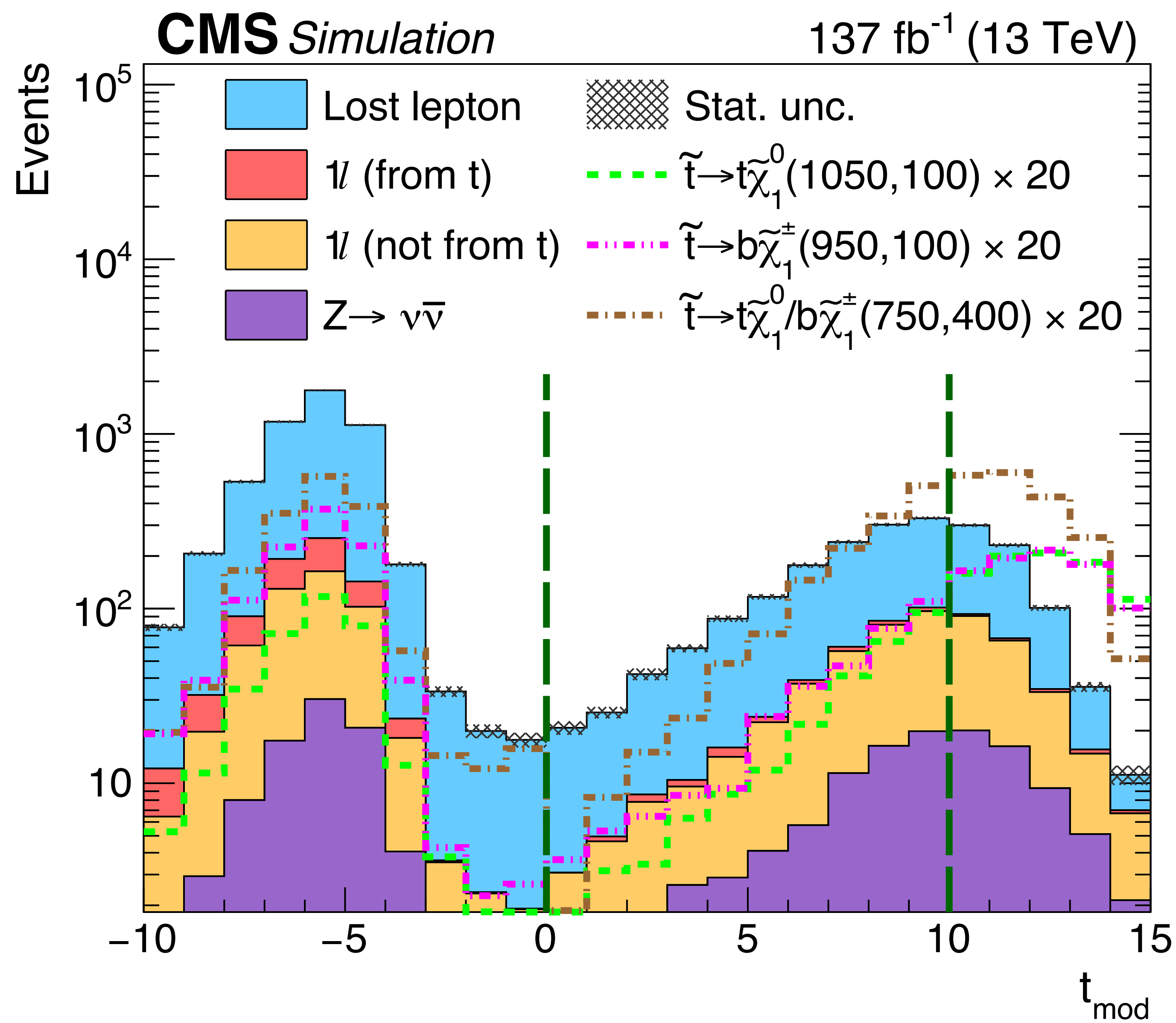
Single Lepton Search

Label	N_j	t_{mod}	$M_{\ell b}$ [GeV]	ttagging category	p_T^{miss} bins [GeV]
A0				—	[600, 750, +∞]
A1	2–3	>10	≤175	U	[350, 450, 600]
A2				M	[250, 600]
B	2–3	>10	>175	—	[250, 450, 700, +∞]
C	≥4	≤0	≤175	—	[350, 450, 550, 650, 800, +∞]
D	≥4	≤0	>175	—	[250, 350, 450, 600, +∞]
E0				—	[450, 600, +∞]
E1	≥4	0–10	≤175	U	[250, 350, 450]
E2				M	[250, 350, 450]
E3				R	[250, 350, 450]
F	≥4	0–10	>175	—	[250, 350, 450, +∞]
G0				—	[450, 550, 750, +∞]
G1	≥4	>10	≤175	U	[250, 350, 450]
G2				M	[250, 350, 450]
G3				R	[250, 350, 450]
H	≥4	>10	>175	—	[250, 500, +∞]

Single Lepton Search

Source	Signal	Lost lepton	1ℓ (not from t)	$Z \to \nu\bar{\nu}$
Data statistical uncertainty	—	5–50%	4–30%	—
Simulation statistical uncertainty	6–36%	3–68%	5–70%	4–41%
$t\bar{t}$ p_T^{miss} modeling	—	3–50%	—	—
Signal p_T^{miss} modeling	1–25%	—	—	—
QCD scales	1–5%	0–3%	2–5%	1–40%
Parton distribution	—	0–4%	1–8%	1–12%
Pileup	1–5%	1–8%	0–5%	0–7%
Luminosity	2.3–2.5%	—	—	2.3–2.5%
$W + b(\bar{b})$ cross section	—	—	20–40%	—
$t\bar{t}Z$ cross section	—	—	—	5–10%
System recoil (ISR)	1–13%	0–3%	—	—
Jet energy scale	2–24%	1–16%	1–34%	1–28%
p_T^{miss} resolution	—	1–10%	1–5%	—
Trigger	2–3%	1–3%	—	2–3%
Lepton efficiency	3–4%	2–12%	—	1–2%
Merged t tagging efficiency	3–6%	—	—	5–10%
Resolved t tagging efficiency	5–6%	—	—	3–5%
b tagging efficiency	0–2%	0–1%	1–7%	1–10%
Soft b tagging efficiency	2–3%	0–1%	0–1%	0–5%

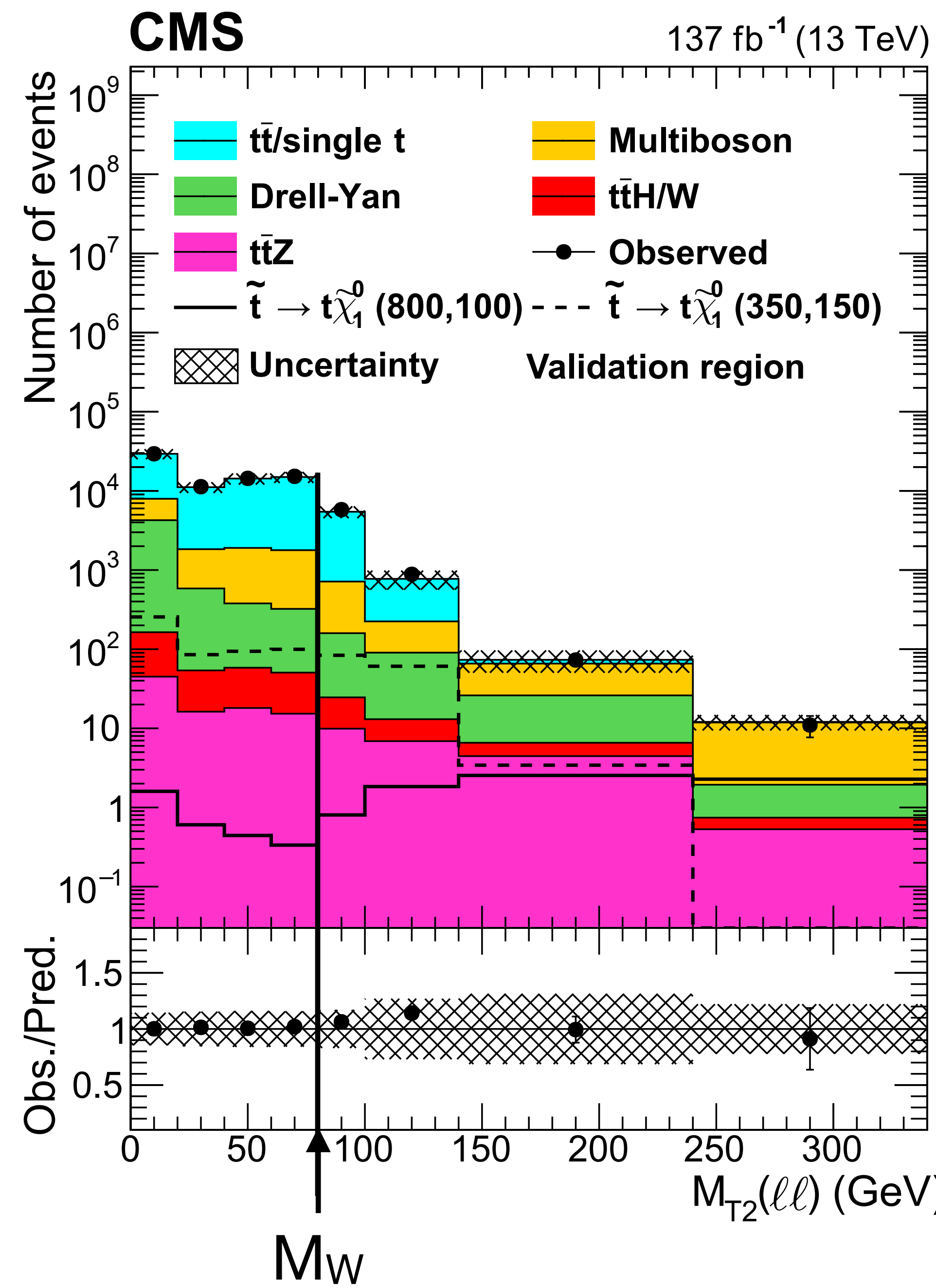
Modified Topness



$$t_{\mathrm{mod}} = \ln(\min S), \text{ with } S = \frac{\left(m_{\mathrm{W}}^2 - (p_\nu + p_\ell)^2\right)^2}{a_{\mathrm{W}}^4} + \frac{\left(m_{\mathrm{t}}^2 - (p_{\mathrm{b}} + p_{\mathrm{W}})^2\right)^2}{a_{\mathrm{t}}^4},$$

Stop search in Dileptons

- Top quark pair production (ttbar) can result in final state with two leptons and two neutrinos → genuine p_T^{miss}
- Exploit fact that leptons and neutrinos come from W bosons
  - Transverse mass $M_{T2}(ll)$
- In a perfect world, ttbar events contained in $M_{T2}(ll)<M_W$ region
- Several detector effects can promote events over this threshold
  - Extensive studies conducted



$$M_{T2}(\ell\ell) = \min_{\vec{p}_T^{miss1}+\vec{p}_T^{miss2}=\vec{p}_T^{miss}} \left(\max \left[M_T(\vec{p}_T^{vis1}, \vec{p}_T^{miss1}), M_T(\vec{p}_T^{vis2}, \vec{p}_T^{miss2}) \right] \right)$$

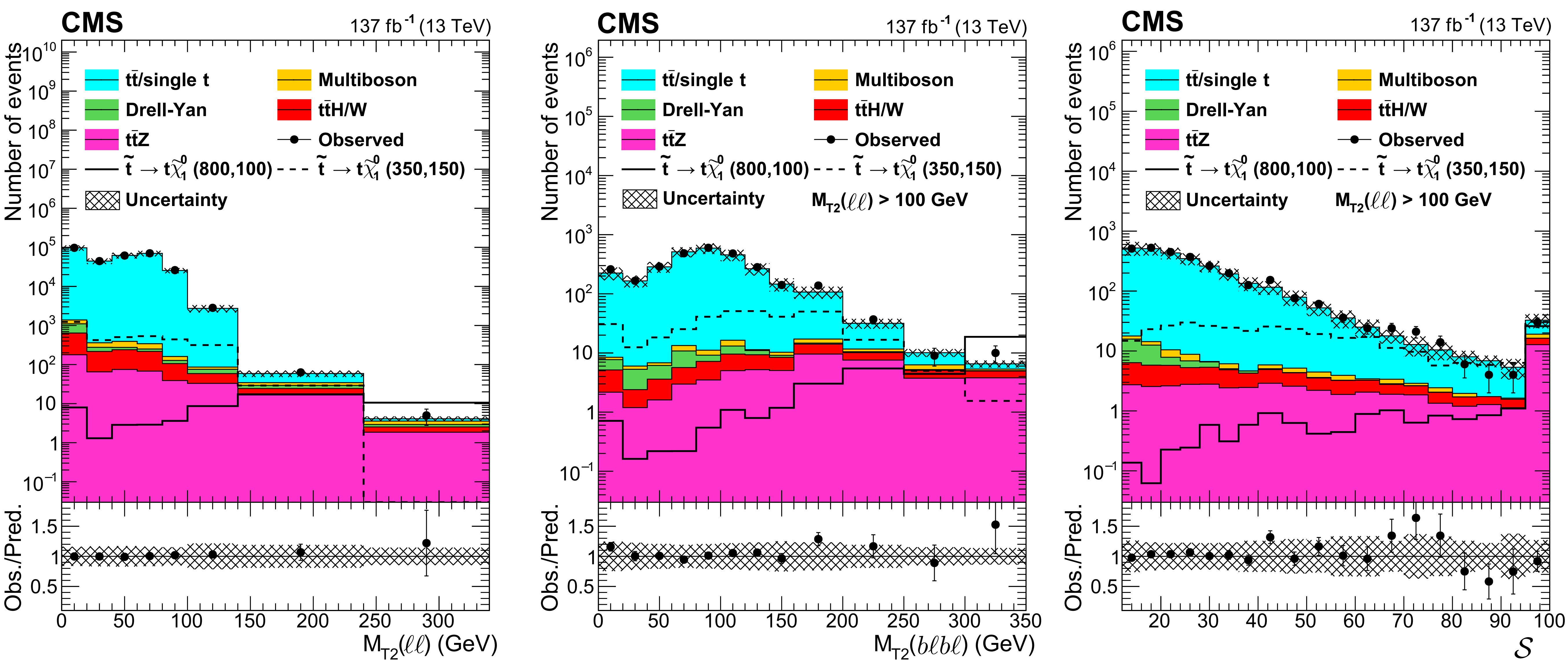
DILEPTON SEARCH

Systematic uncertainty	Typical (%)	Max (%)
Integrated luminosity	2	2
Pileup modeling	5	7
Jet energy scale	4	20
Jet energy resolution	3	4
btagging efficiency	2	3
btagging mistag rate	1	7
Trigger efficiency	1	2
Lepton identification efficiency	3	5
Modeling of unclustered energy	3	7
Non-Gaussian jet mismeasurements	6	6
Misidentified or nonprompt leptons	5	5
$t\bar{t}$ normalization	9	9
$t\bar{t}Z$ normalization	10	14
Multiboson background normalization	4	8
$t\bar{t}H/W$background normalization	5	8
Drell–Yan normalization	3	8
Parton distribution functions	2	4
μ_R and μ_F choice	7	11

Name	Definition	
TTCRSF	$M_{T2}(\ell\ell) < 100\,\text{GeV}$, SF leptons, $\|m(\ell\ell) - m_Z\| > 15\,\text{GeV}$	
TTCRDF	$M_{T2}(\ell\ell) < 100\,\text{GeV}$, DF leptons	
TTZ2j2b		$N_{jets} = 2$, $N_b \geq 2$
TTZ3j1b	$N_\ell = 3$, $\mathcal{S} \geq 0$, ≥ 1 SF lepton pair	$N_{jets} = 3$, $N_b = 1$
TTZ3j2b	with $\|m(\ell\ell) - m_Z\| < 10\,\text{GeV}$	$N_{jets} = 3$, $N_b \geq 2$
TTZ4j1b		$N_{jets} \geq 4$, $N_b = 1$
TTZ4j2b		$N_{jets} \geq 4$, $N_b \geq 2$
CR0-CR12	Same as SR0-SR12 in Table **??**, but SF leptons, $\|m(\ell\ell) - m_Z\| < 15\,\text{GeV}$ and $N_b = 0$	

$M_{T2}(b\ell b\ell)$ (GeV)	$\mathcal{S}$	$100 < M_{T2}(\ell\ell) < 140\,\text{GeV}$	$140 < M_{T2}(\ell\ell) < 240\,\text{GeV}$	$M_{T2}(\ell\ell) > 240\,\text{GeV}$
0–100	12–50	SR0	SR6	SR12
	>50	SR1	SR7	
100–200	12–50	SR2	SR8	
	>50	SR3	SR9	
>200	12–50	SR4	SR10	
	>50	SR5	SR11	

DILEPTON SEARCH



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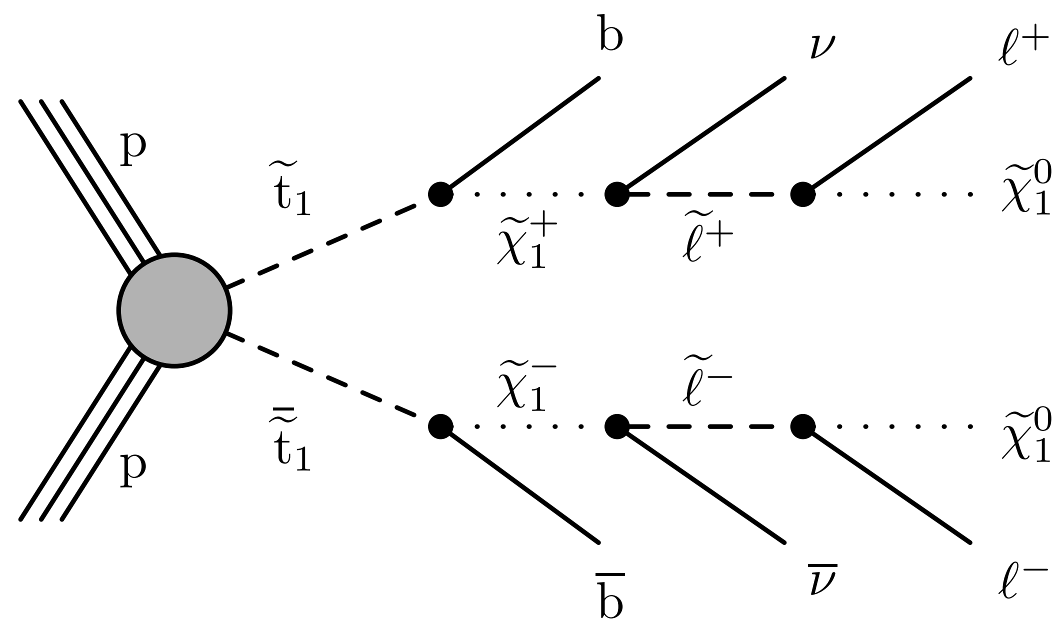
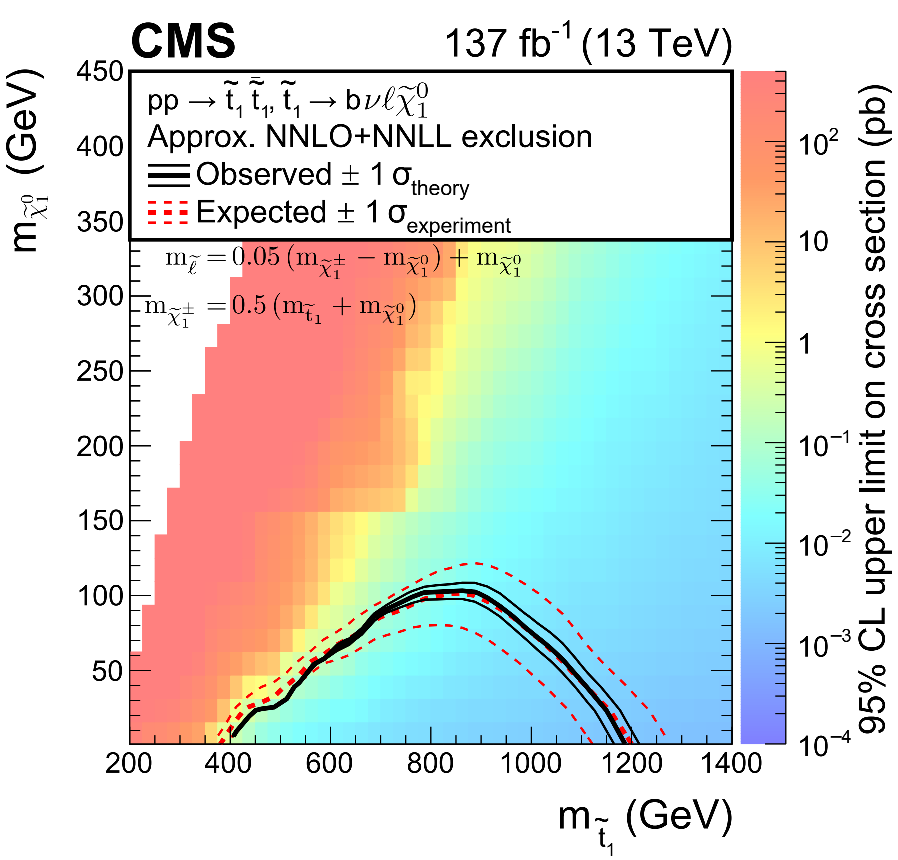
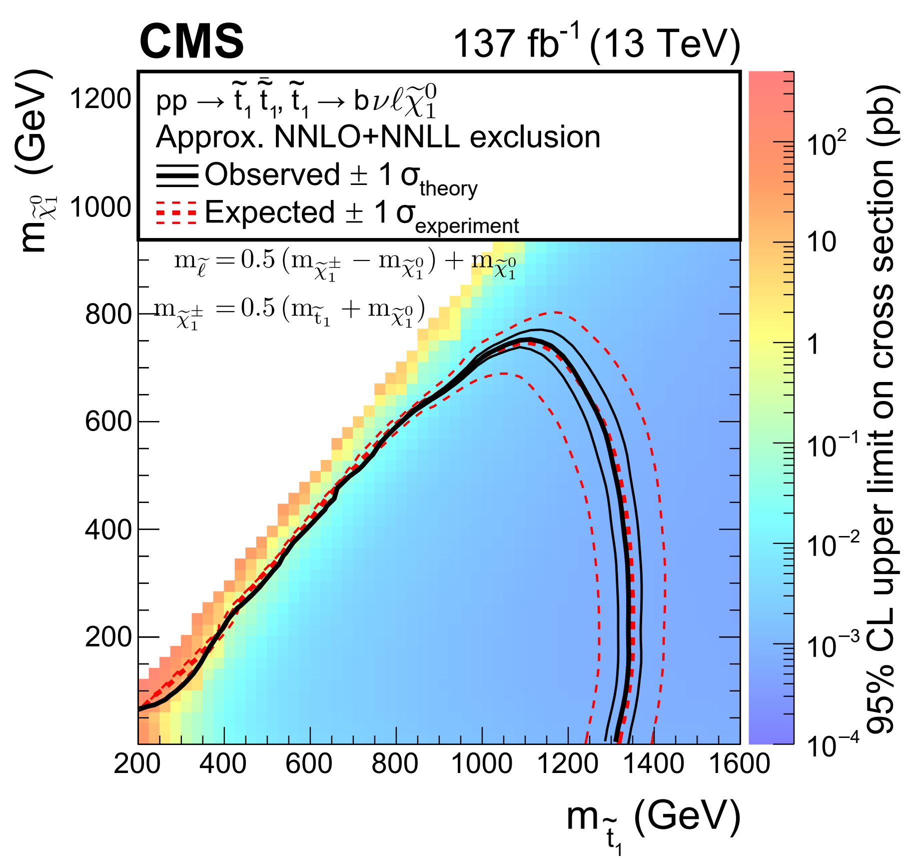


p
p
b
ν
ℓ+
χ̃⁰₁
b̄
ν̄
ℓ−



CMS
137 fb-1 (13 TeV)
Approx. NNLO+NNLL exclusion
Observed ± 1 σtheory
Expected ± 1 σexperiment
95% CL upper limit on cross section (pb)



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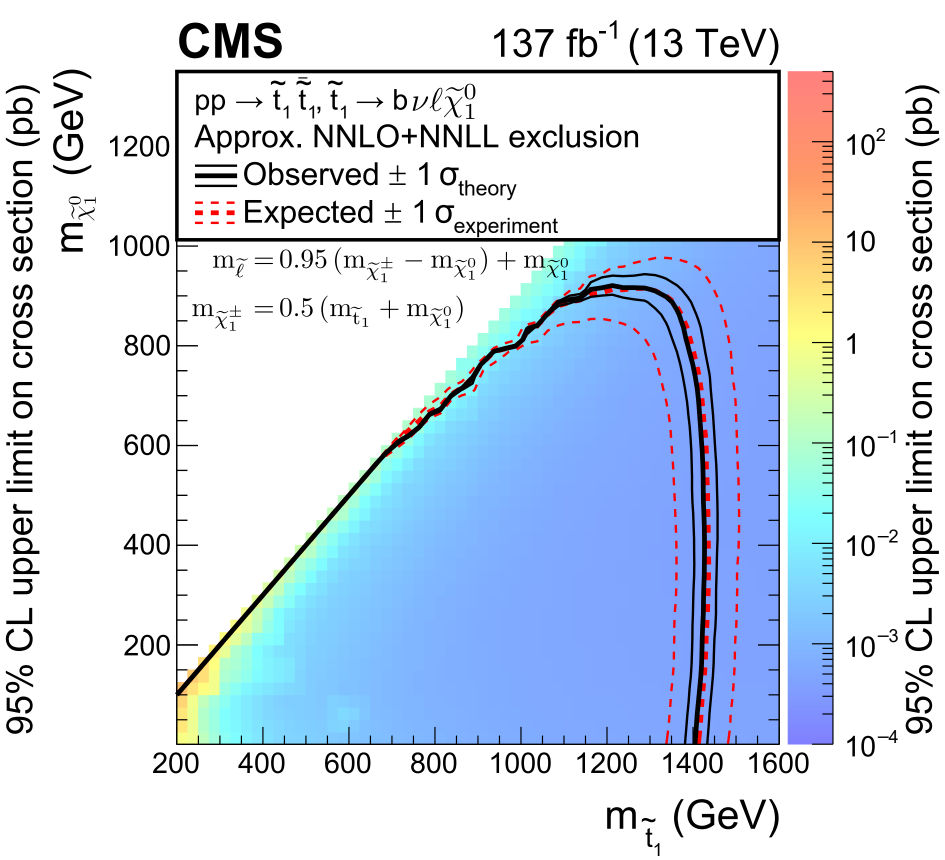
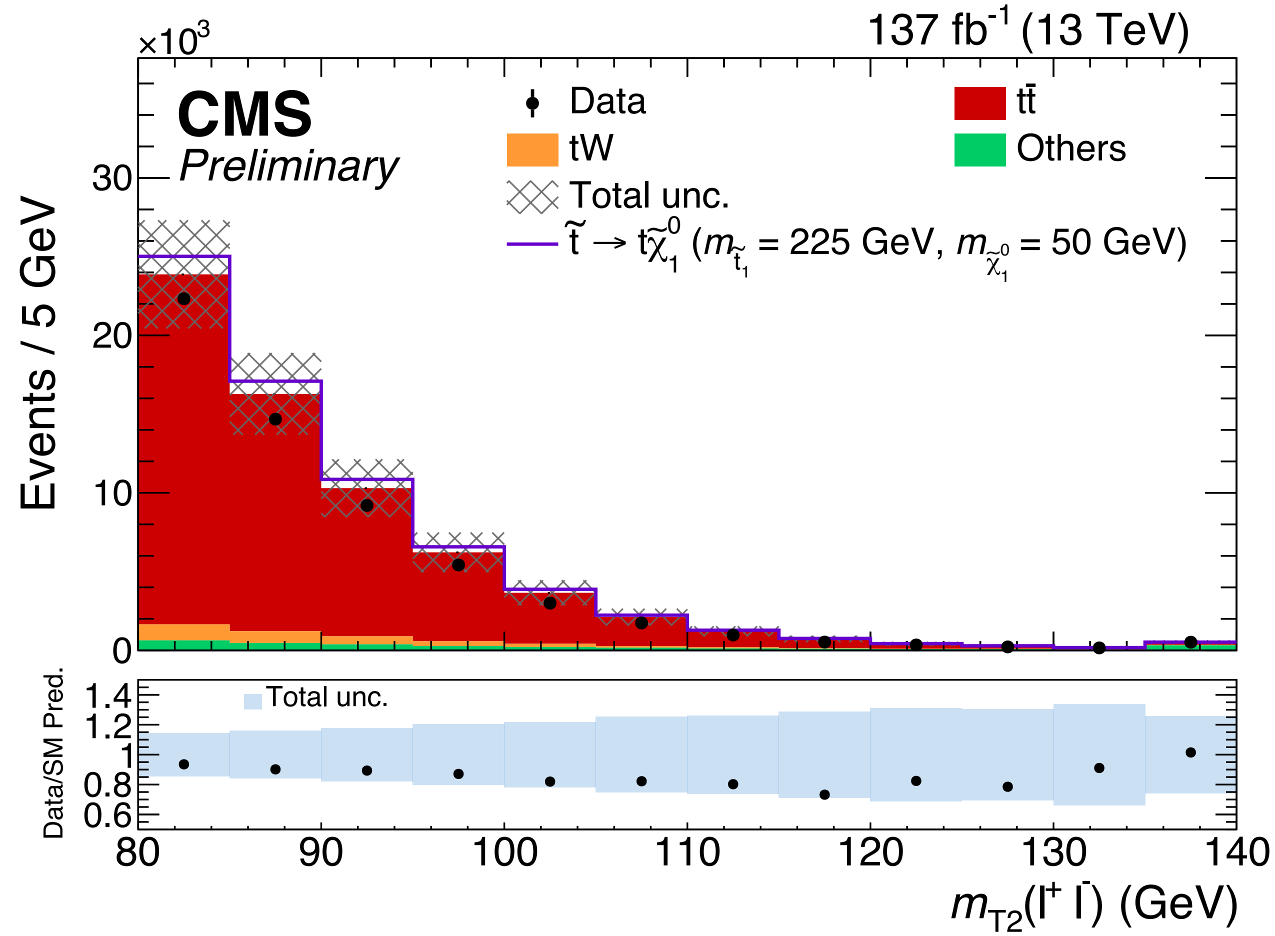


CMS
137 fb-1 (13 TeV)
Approx. NNLO+NNLL exclusion
Observed ± 1 σtheory
Expected ± 1 σexperiment
95% CL upper limit on cross section (pb)

Corridor Search

Source	Uncertainties (%) $t\bar{t}$	signal
Muon efficiencies	0.5	
Electron efficiencies	1.5	
Trigger modeling	1.2	
Muon energy scale	1.4	
b-tagging efficiency	3	
Jet energy resolution	16	7.0
Jet energy scale	7.5	5.7
Unclustered energy	4.2	5.0
Pileup modeling	3.2	1.5
Size of the MC sample	3	25



Source	Average for $t\bar{t}$ (%)
PDFs and α_S (acceptance)	1.0
μ_F, μ_R scales (acceptance)	3.8
Initial-state radiation	0.6
Final-state radiation	3.4
Top p_T	1.3
Matrix element/parton shower matching	2
Underlying event	1.5
Top mass (acceptance)	1.5

SEARCH FOR RPV/STEALTH STOPS

- Final state: tt+jets
  - Select events with single lepton to suppress QCD
- Most distinct feature: jet multiplicity N_{jets} → difficult to model
- Parametrize N_{jets} with jet scaling function R(i)
- Ratio can be well modeled by functional form

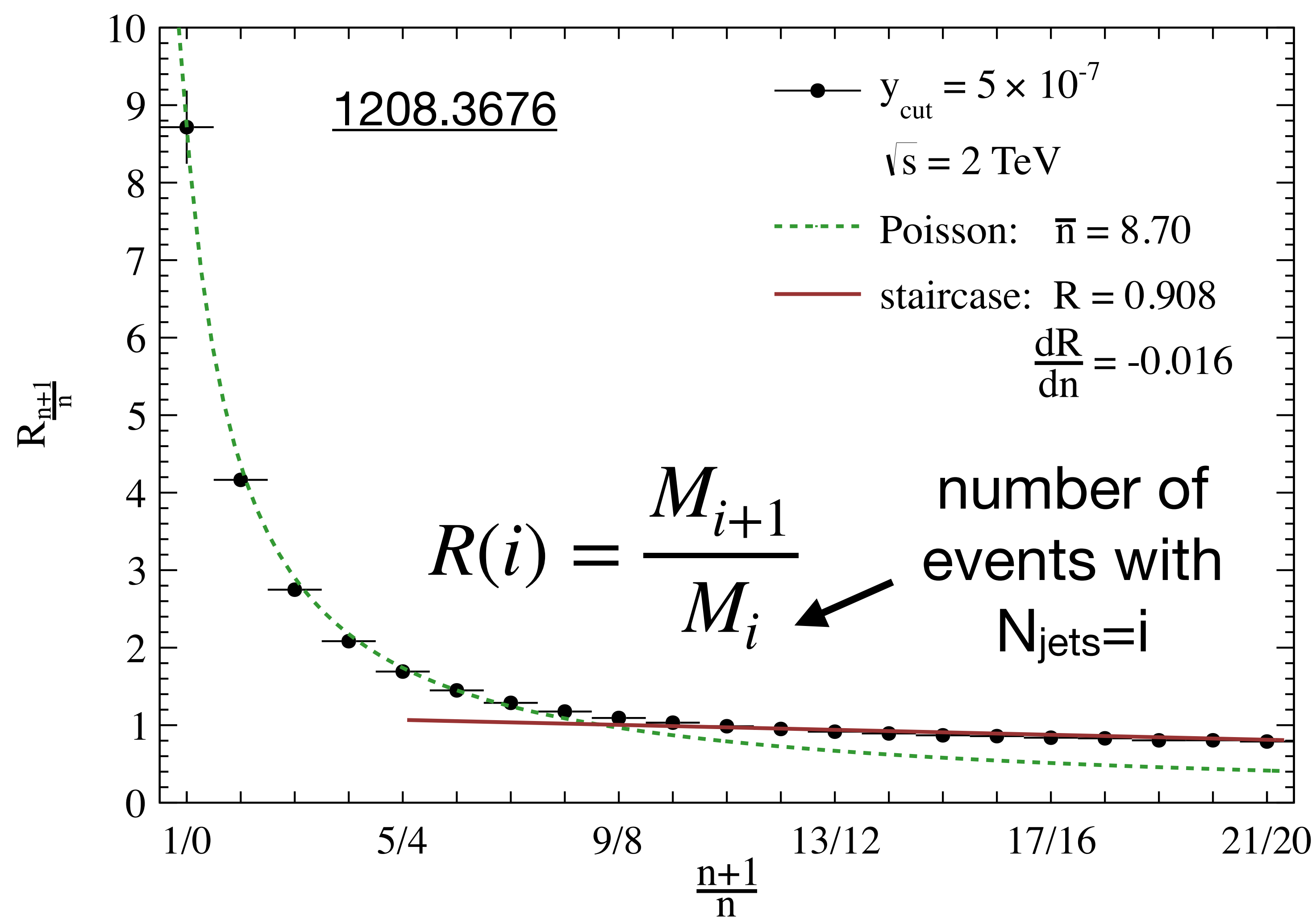
$$f(i) = a_2 + \left[\frac{(a_1 - a_2)^{i-7}}{(a_0 - a_2)^{i-9}}\right]^{1/2}$$

with

$$a_0 = f(7),\ a_1 = f(9),\ a_2 = \lim_{i\to\infty} f(i)$$

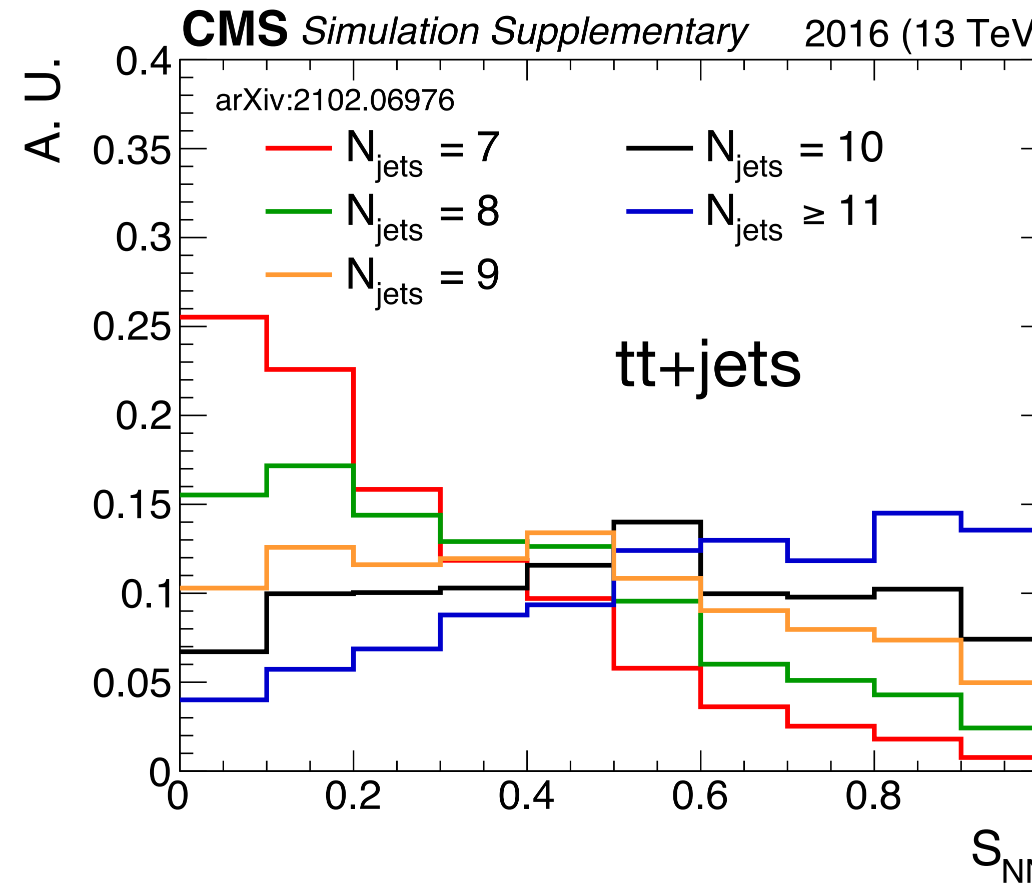
Njets distribution in each $S_{NN,j}$ bin given by recursive expression, with free parameter Y_7^j

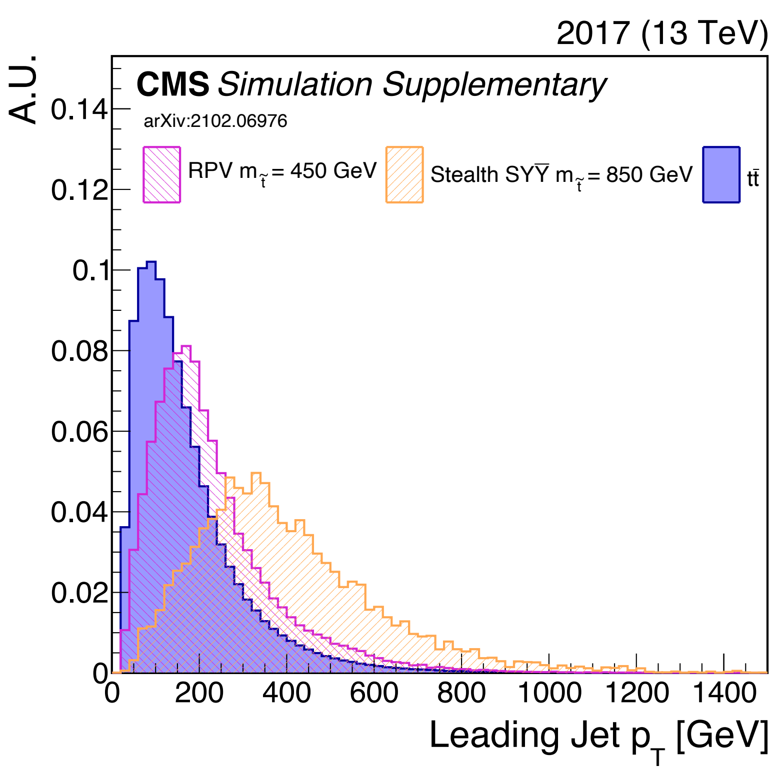
$$M_i^j = Y_7^j \Pi_{k=7}^{i-1} f(k)$$

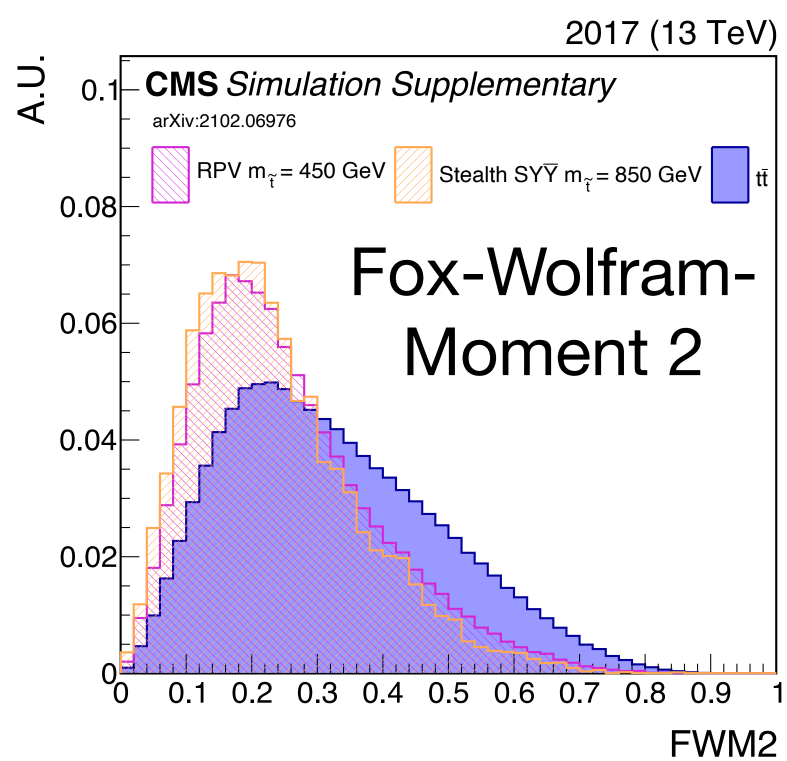


NEURAL NETWORK VS SM TT+JETS

- Feed event shape and kinematic variables into a NN producing score S_{NN}
- Problem: S_{NN} correlated with N_{jets}
- S_{NN} of tt+jets with high N_{jets} more signal lik
- Gradient reversal is used to decorrelate DNN response S_{NN} and N_{jets}
- Allows to use N_{jets} spectrum in the signal extraction fit in 4 bins of S_{NN}

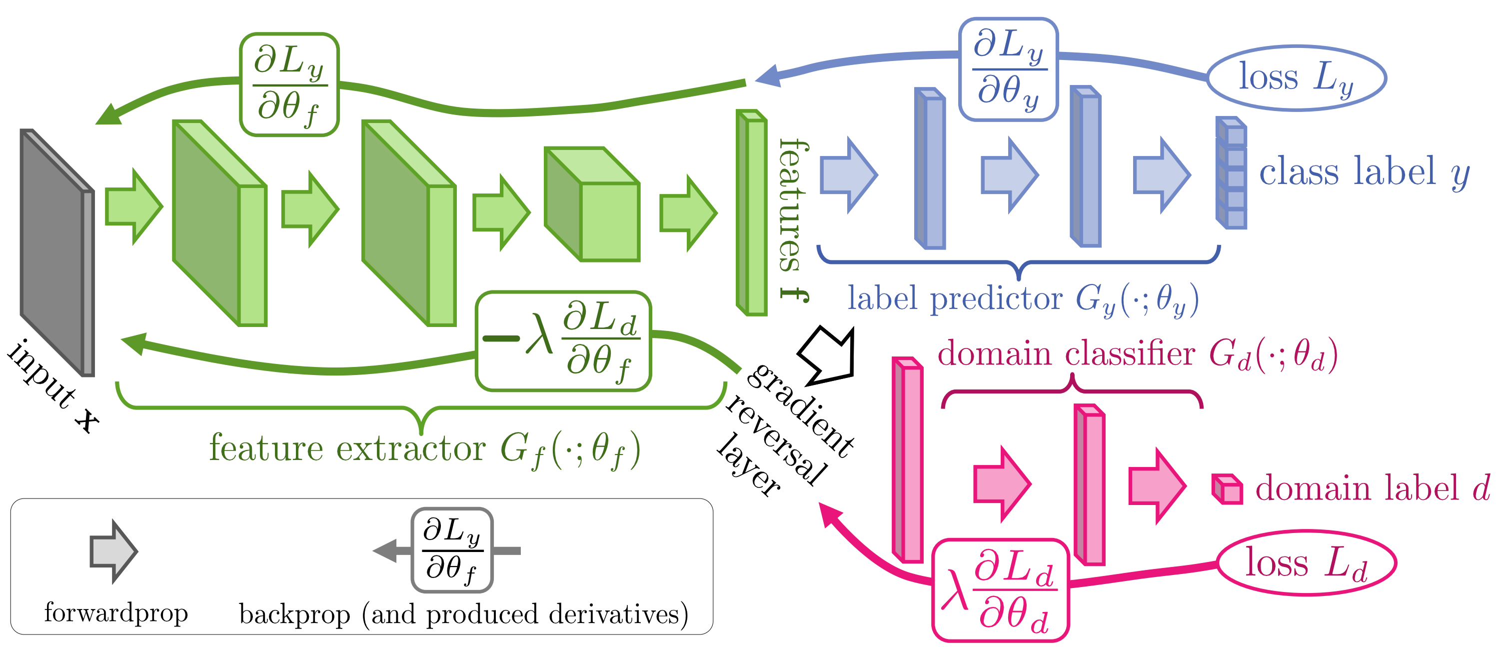


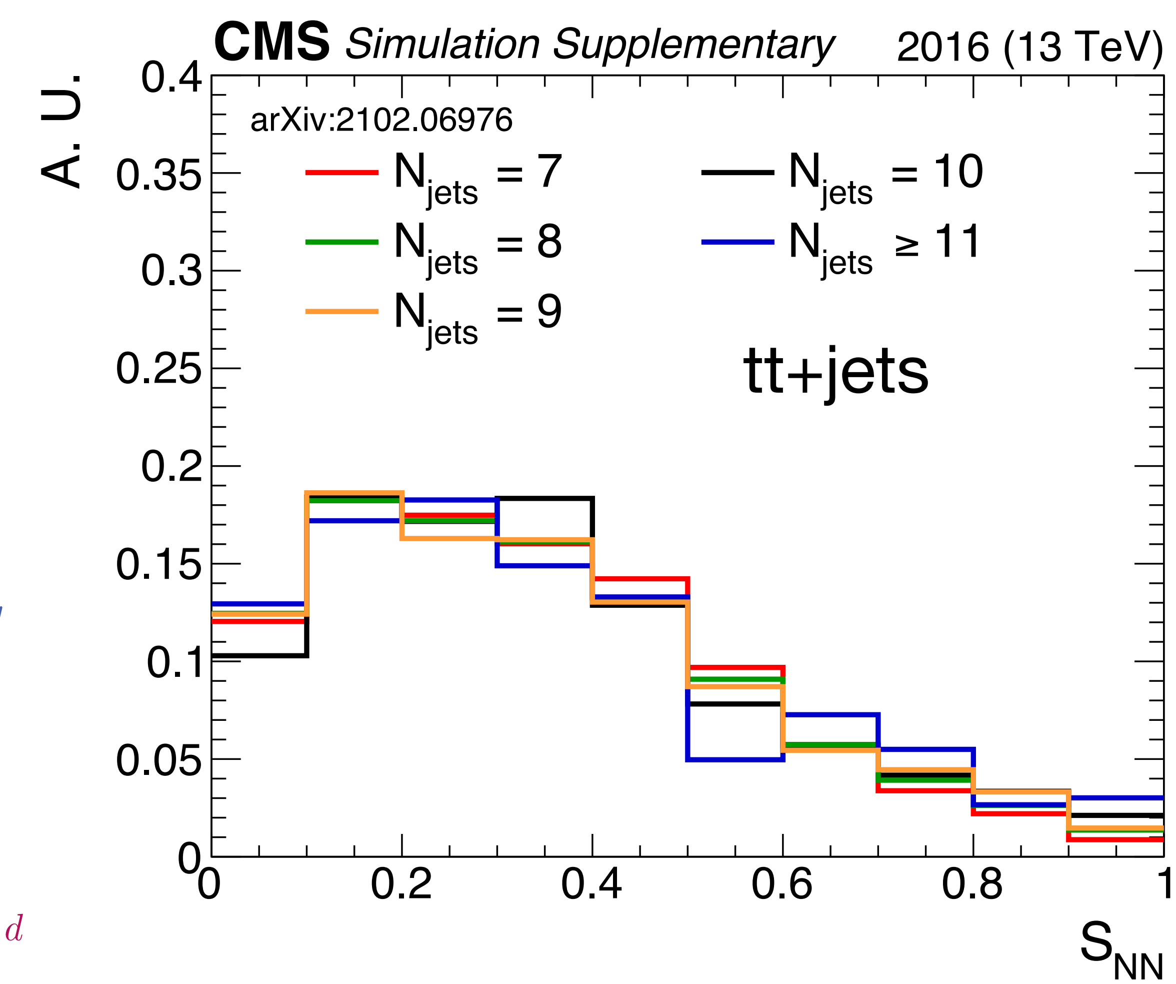




DECOUPLING DNN FROM N_{JETS}

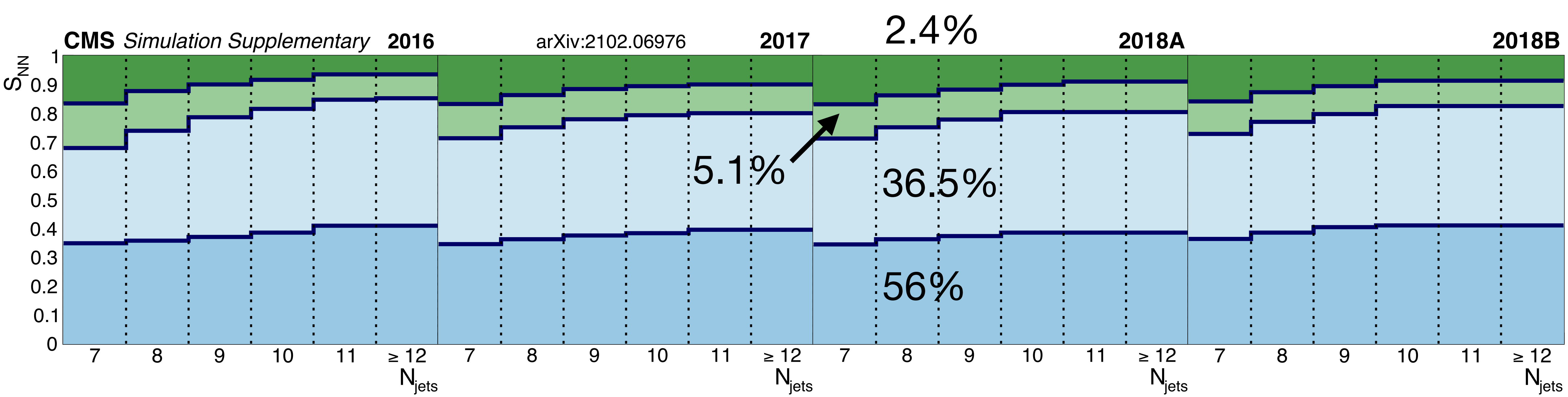
- S_{NN} of tt+jets with high N_{jets} more signal like
- Gradient reversal is used to decorrelate DNN response S_{NN} and N_{jets}
- Allows to use N_{jets} spectrum in the signal extraction fit in 4 bins of S_{NN}



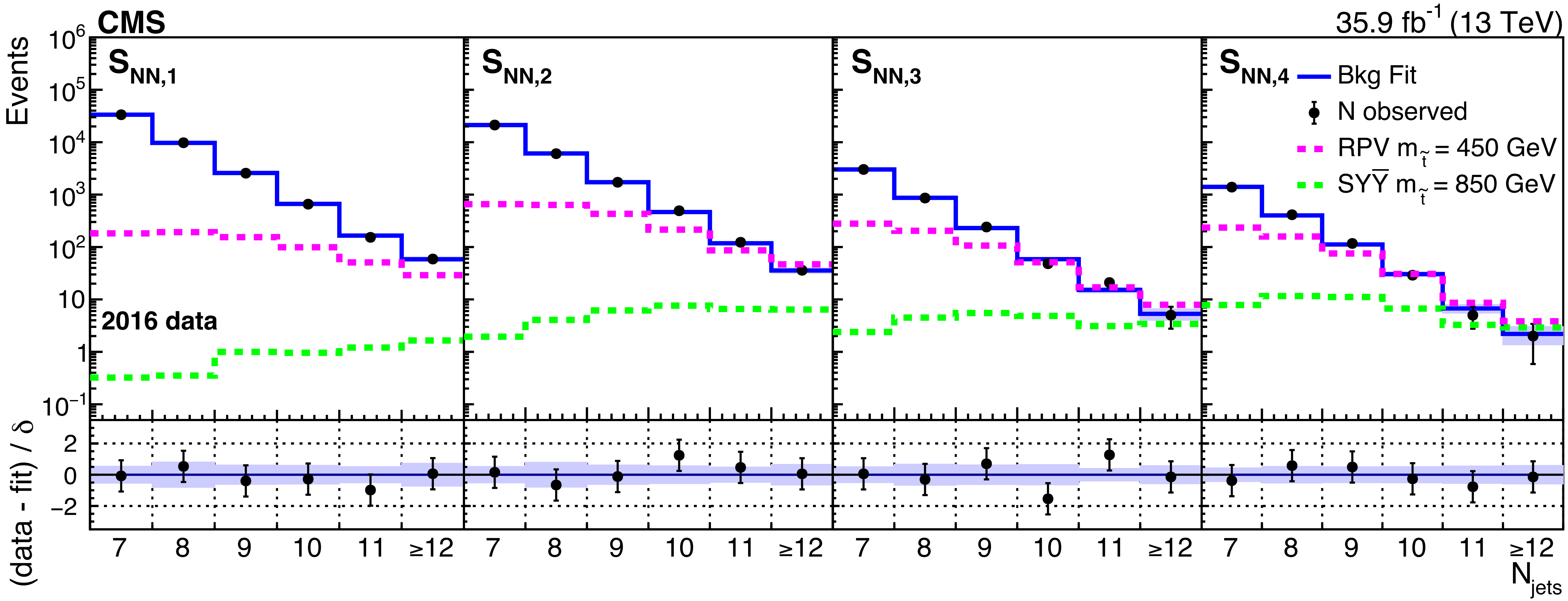


N_{JETS} VS S_{NN} BINNING

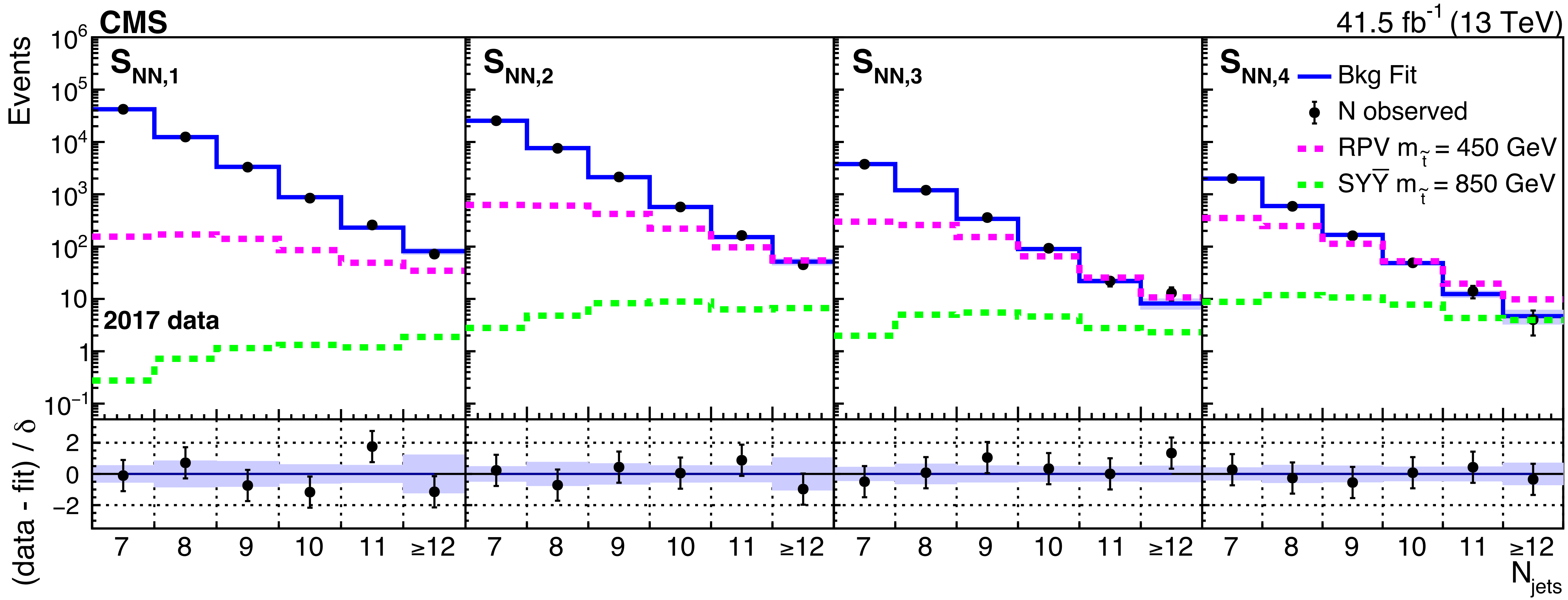
- SNN bin boundaries chosen to maximize expected significance for RPV model with m(stop) = 550 GeV
  - Constraint: fraction of simulated tt+jets events in each S_{NN} bin is same, e.g. 56% in $S_{NN,1}$
  - Removes residual dependency of N_{jets} on S_{NN}
- Source of systematic uncertainty: Is this binning assumption also applicable in data?



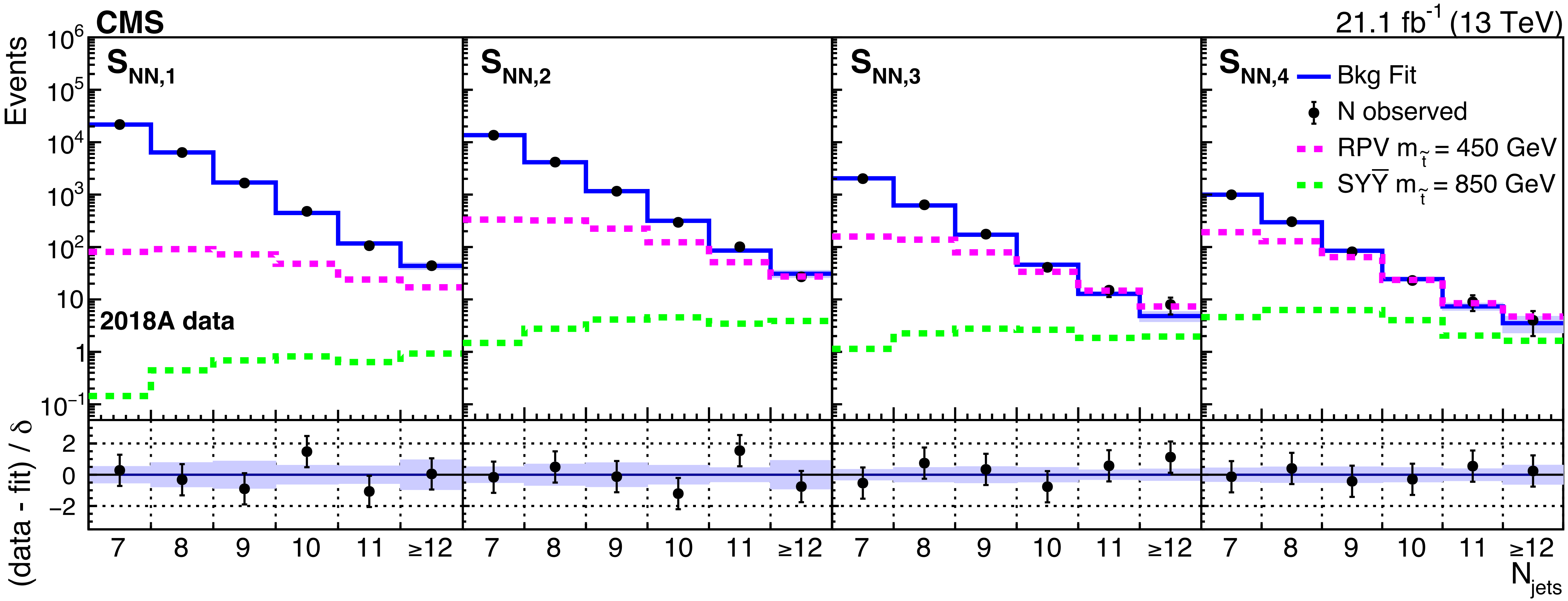
RPV/Stealth 2016



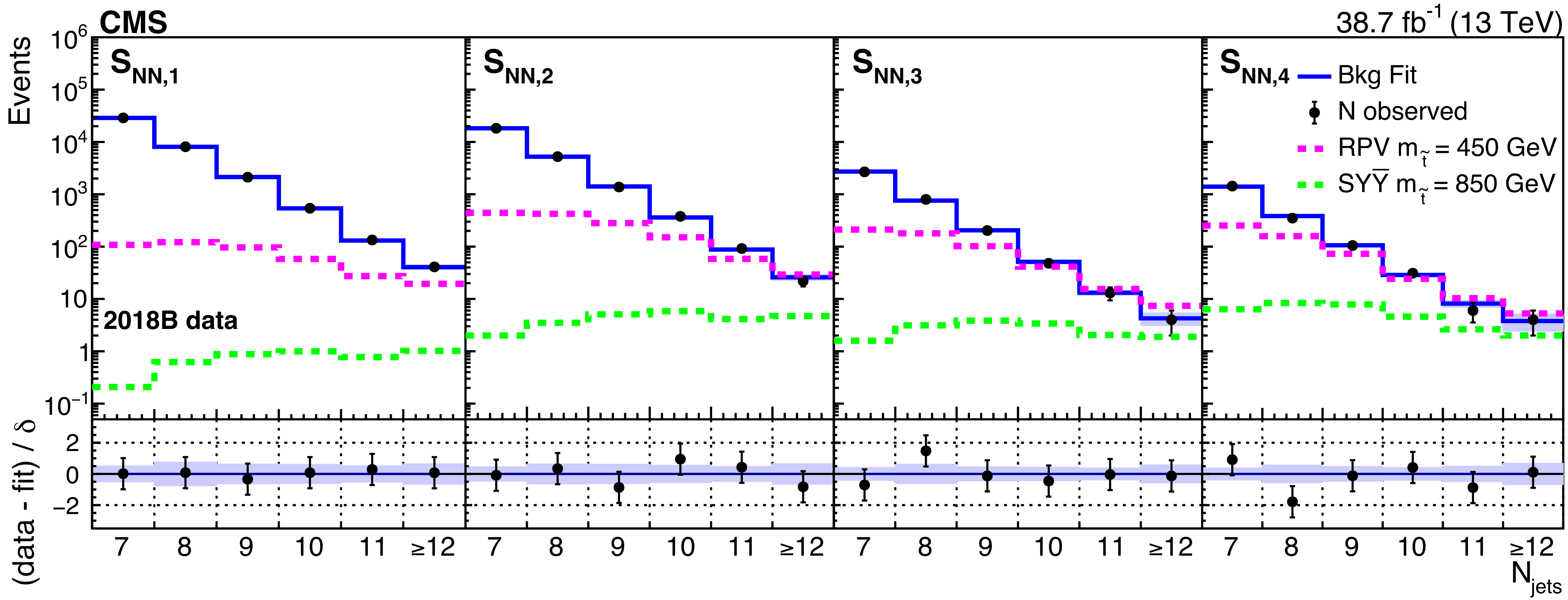
RPV/Stealth 2017



RPV/Stealth 2018A



RPV/STEALTH 2018B

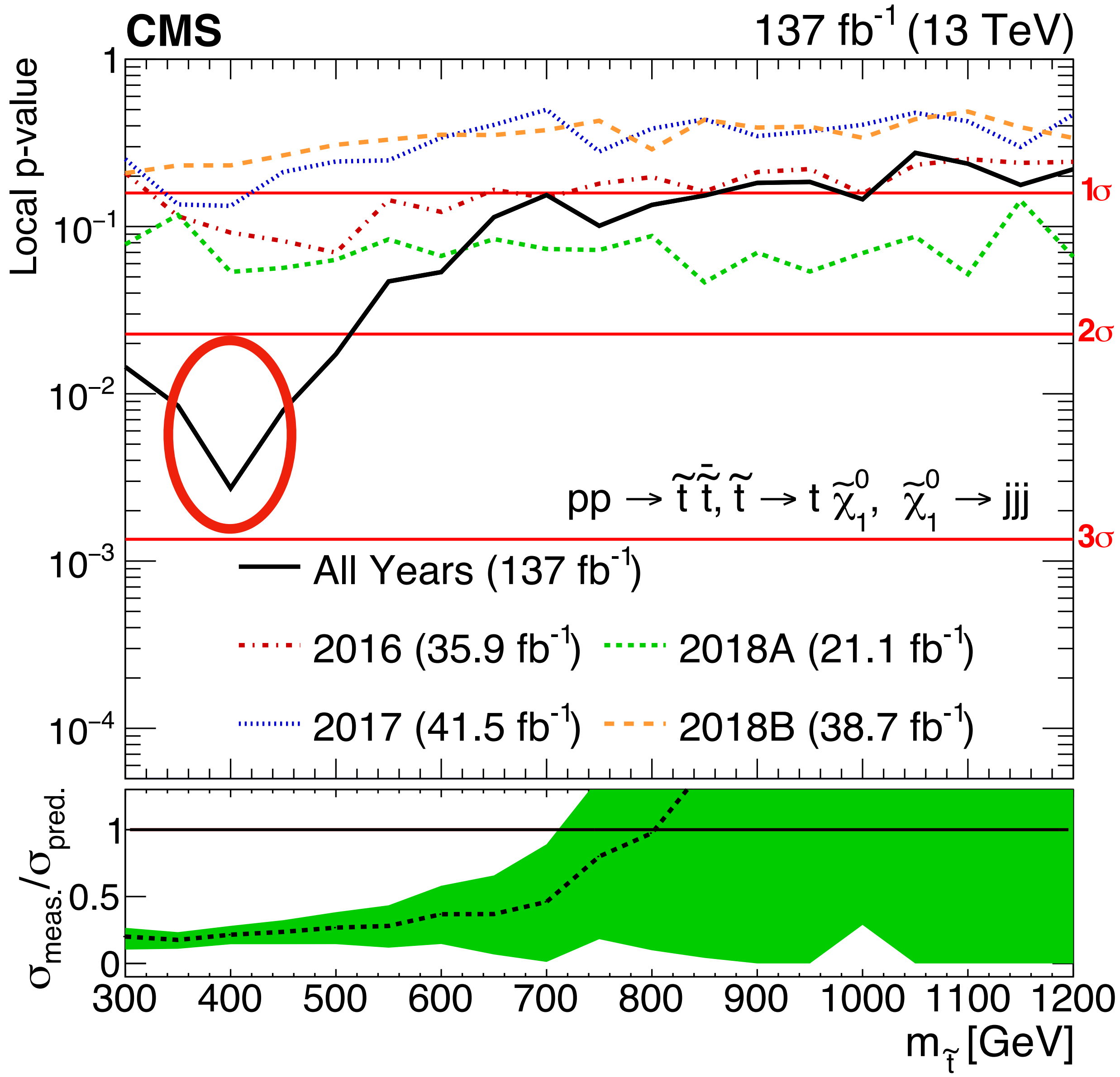


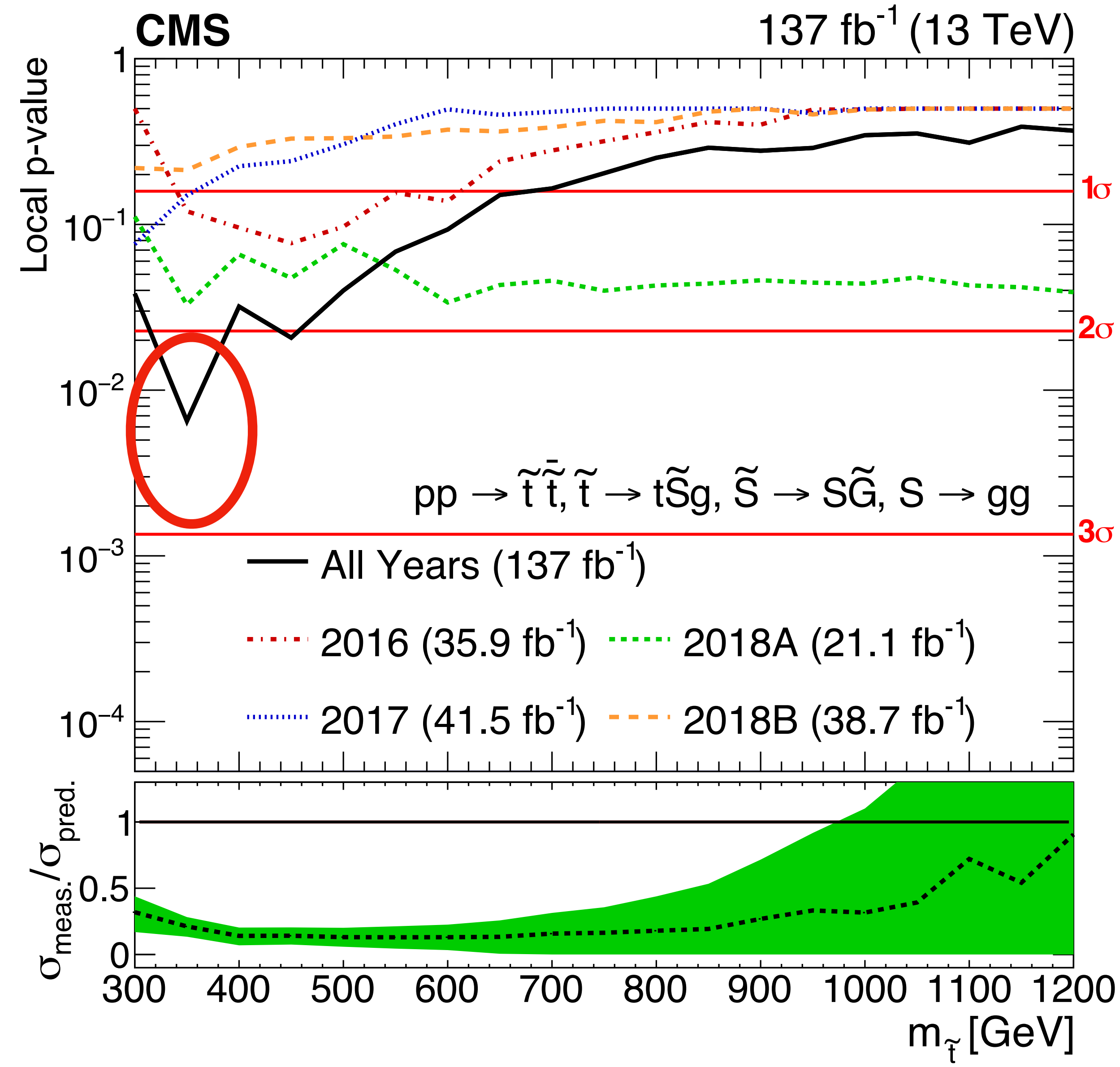
RPV/Stealth Systematics

Source of uncertainty	$t\bar{t}$ background	Minor background	RPV signal
PDFs	0–1 (2)	0–1 (8)	0–2 (7)
(μ_R, μ_F) scales	0–2 (5)	1–8 (18)	0–3 (4)
ISR	0–4 (15)	—	—
FSR	0–8 (27)	—	—
Color reconnection	0–10 (44)	—	—
ME-PS	0–14 (82)	—	—
UE tune	0–7 (100)	—	—
Pileup	0–2 (7)	0–7 (28)	0–2 (4)
JES	0–4 (18)	5–21 (100)	1–11 (31)
JER	0–2 (10)	1–15 (100)	0–6 (14)
btagging	0–1 (3)	0–2 (12)	0–2 (2)
Lepton efficiencies	0–1 (1)	3–5 (5)	3–4 (4)
H_T primary	0–5 (17)	—	—
H_T validation	0–1 (4)	0–6 (10)	—
H_T H_T-parameterization	0–2 (9)	—	—
H_T N_{jets}-parameterization	0–7 (27)	—	—
Jet p_T	0–4 (15)	—	—
Jet mass	0–4 (15)	—	—
N_{jets} shape invariance	0–12 (37)	—	—
Integrated luminosity	—	2.3–2.5	2.3–2.5
Theoretical cross section	—	30	—

Local Significance

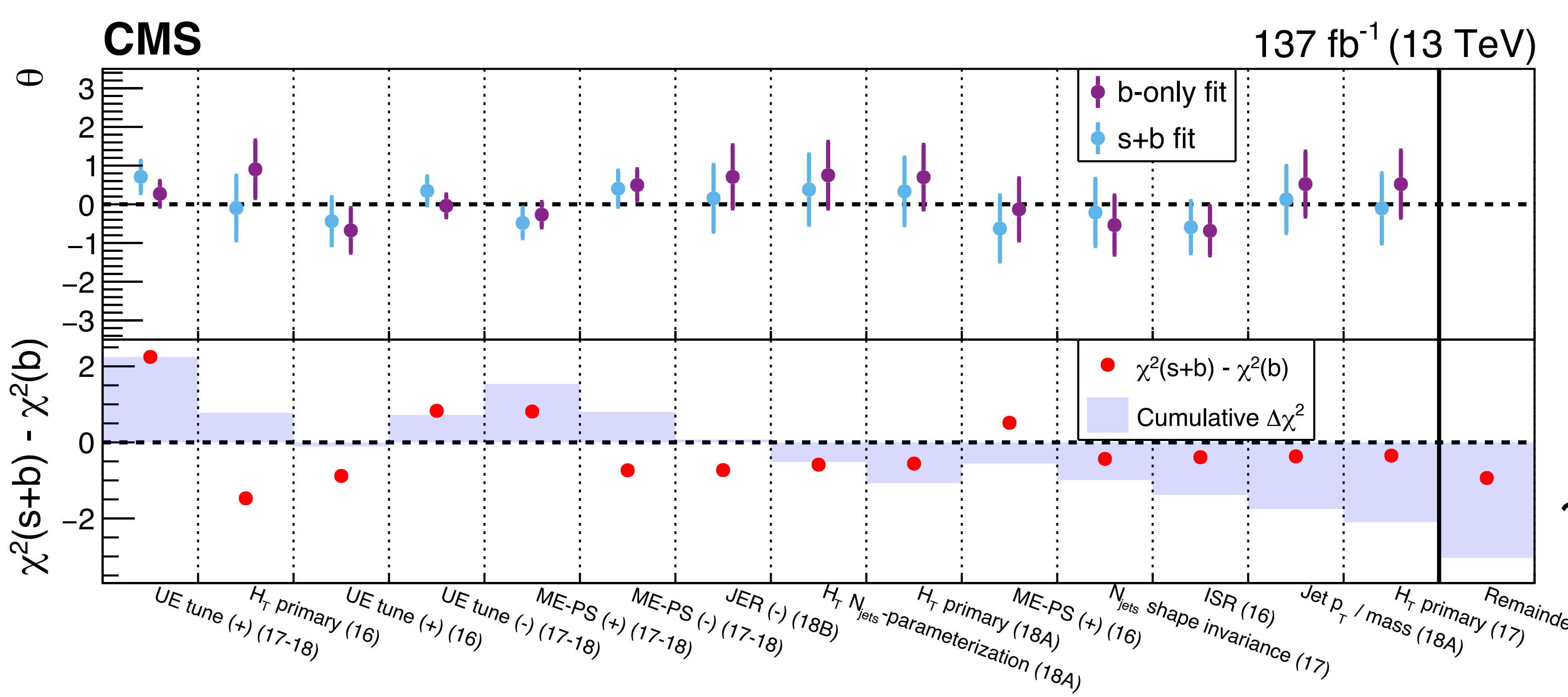
- Local significance of excess 2.8σ for RPV model with m(stop) = 400 GeV, 2.5σ for stealth SUSY with m(stop) = 350 GeV
- Significance not visible in individual years
- Best fit signal strength 0.21±0.07





SOURCE OF LOCAL SIGNIFCANCE

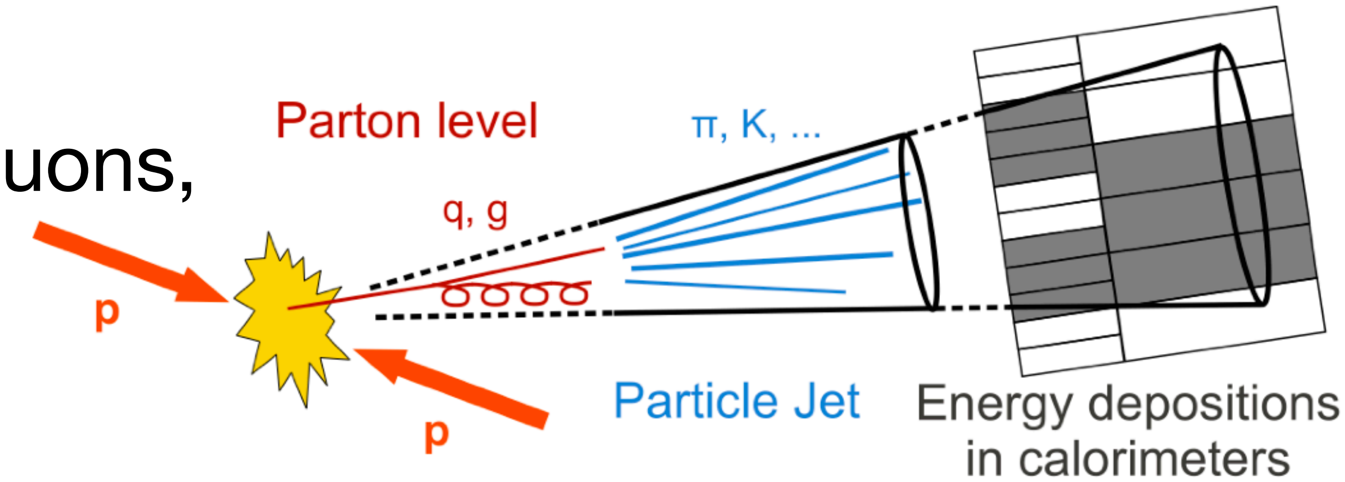
- No significant excess of observation over background only fit observed, so where does the significance come from?
  - Agreement improves when fitting S+B model, accounting for ~1.1σ
  - Significantly smaller pulls for S+B fit wrt background only fit

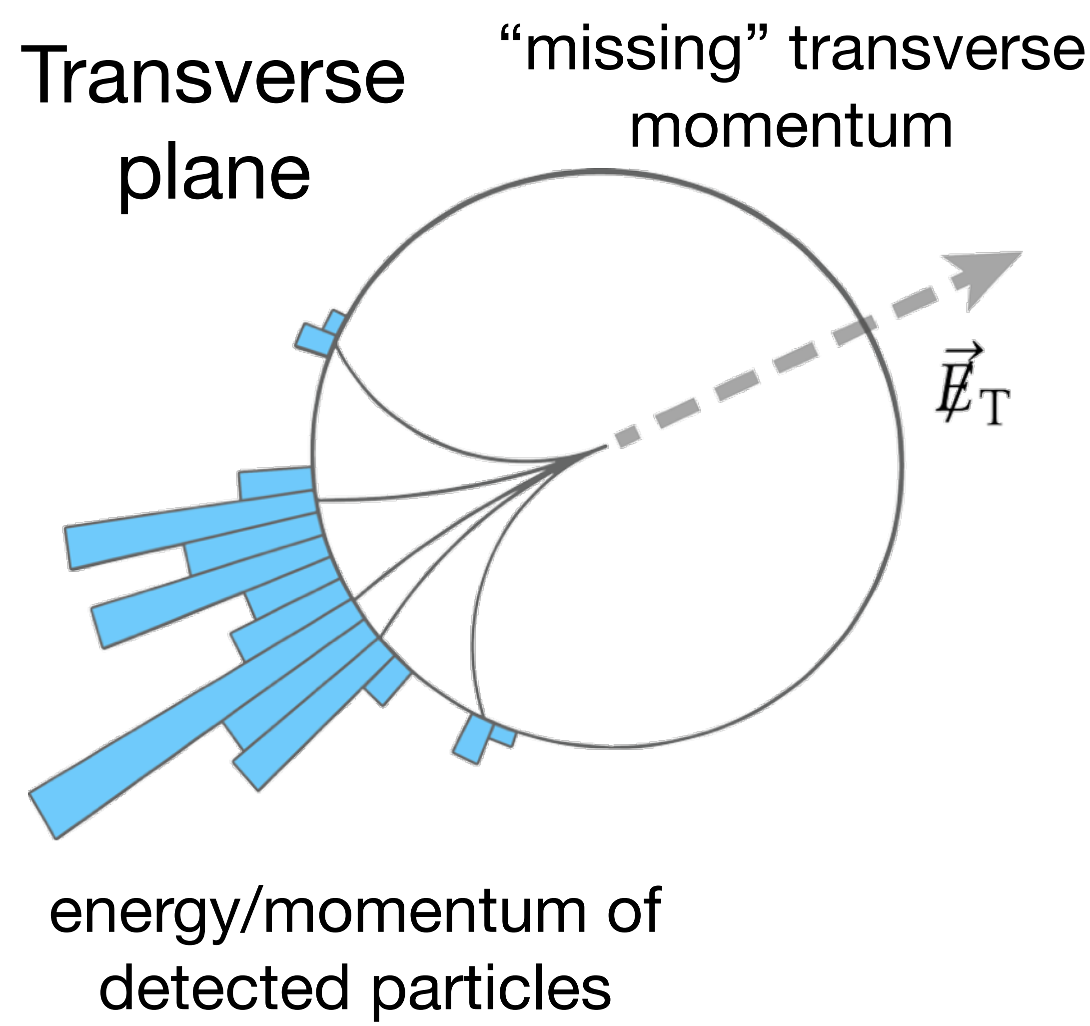


~1.7σ

SEEING THE INVISIBLE

- **Direct detection** of electrons, muons, photons and jets (experimental signature of quarks und gluons)
- **Indirect detection** of weakly interacting particles like neutrinos
  - Sum of particle momenta in transverse plane has to be conserved
  - Non-zero sum → undetected particles: neutrinos (or WIMPs?)
  - Highly dependent on performance and precision of all subdetectors





CMS Detector