Search for Top Squarks via All-hadronic Decay Channels with Heavy Object Tagging

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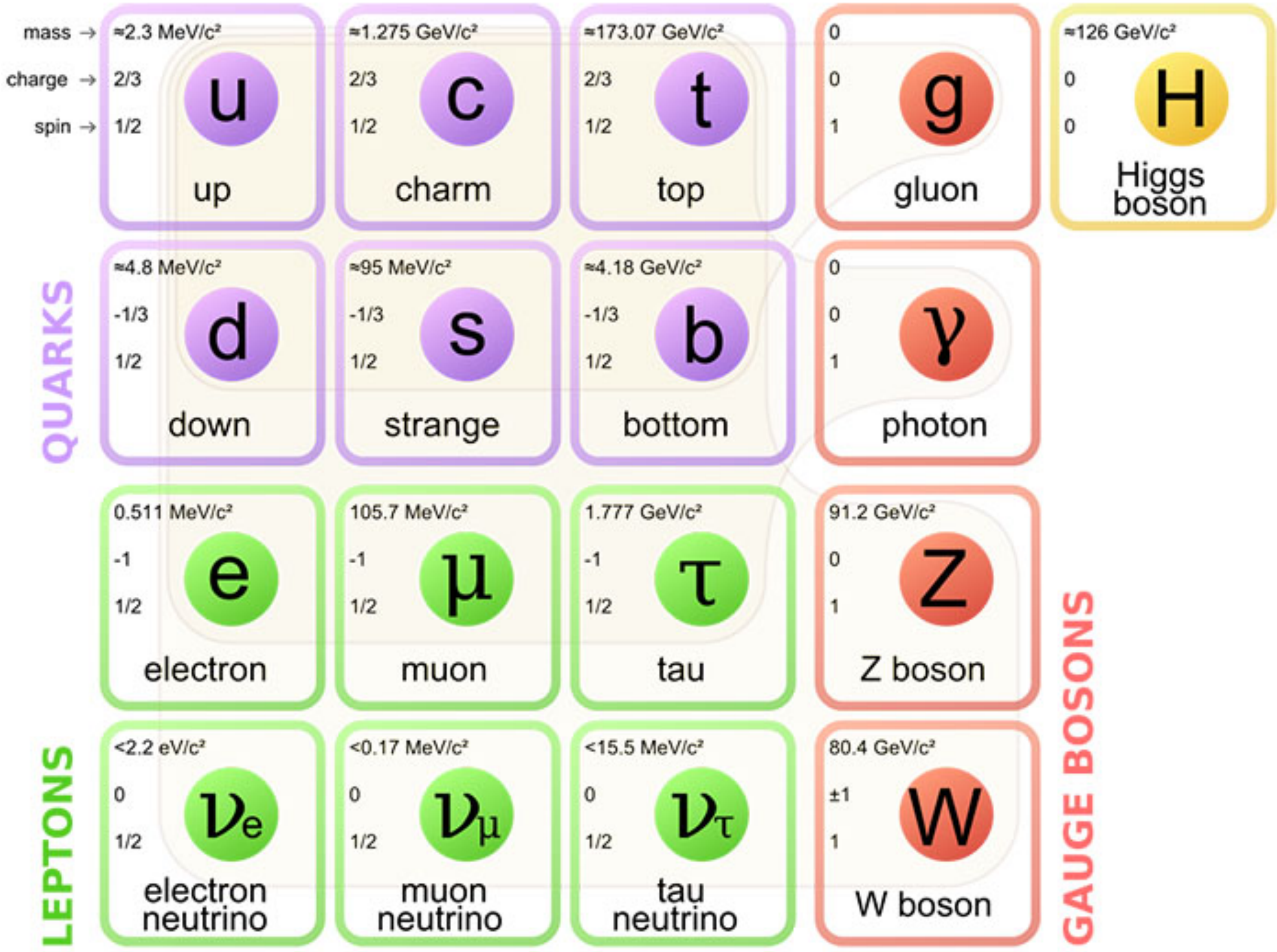
Outline

Standard Model
- **What is it?**
- **Dark Matter**
- **Why SUSY?**

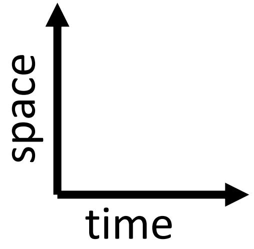
Compact Muon Solenoid
- Different methods of detection

All-hadronic Top Squark Search
- Kinematic Variables
- Search region design
- Background estimation

Standard Model

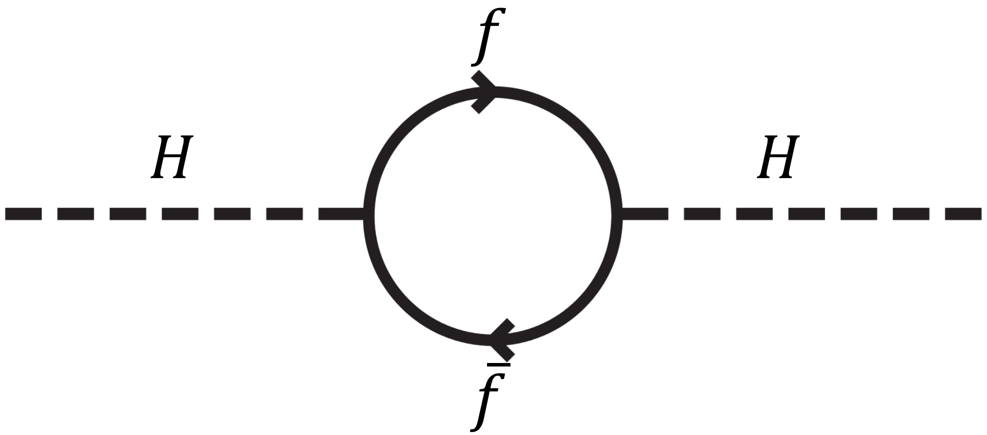


Hierarchy Problem



Hierarchy Problem

- Higgs mass divergence from fermionic loop corrections
  - Direct contradiction to observed mass of 125.18 GeV
- $\Delta m_H^2 = -\frac{\left|\lambda_f\right|^2}{8\pi^2}\Lambda_{UV}^2 + \cdots$
- Solution within Standard Model
  - Fine tuning, but is not natural
  - Ultraviolet cutoff $\Lambda_{UV} \sim m_P$

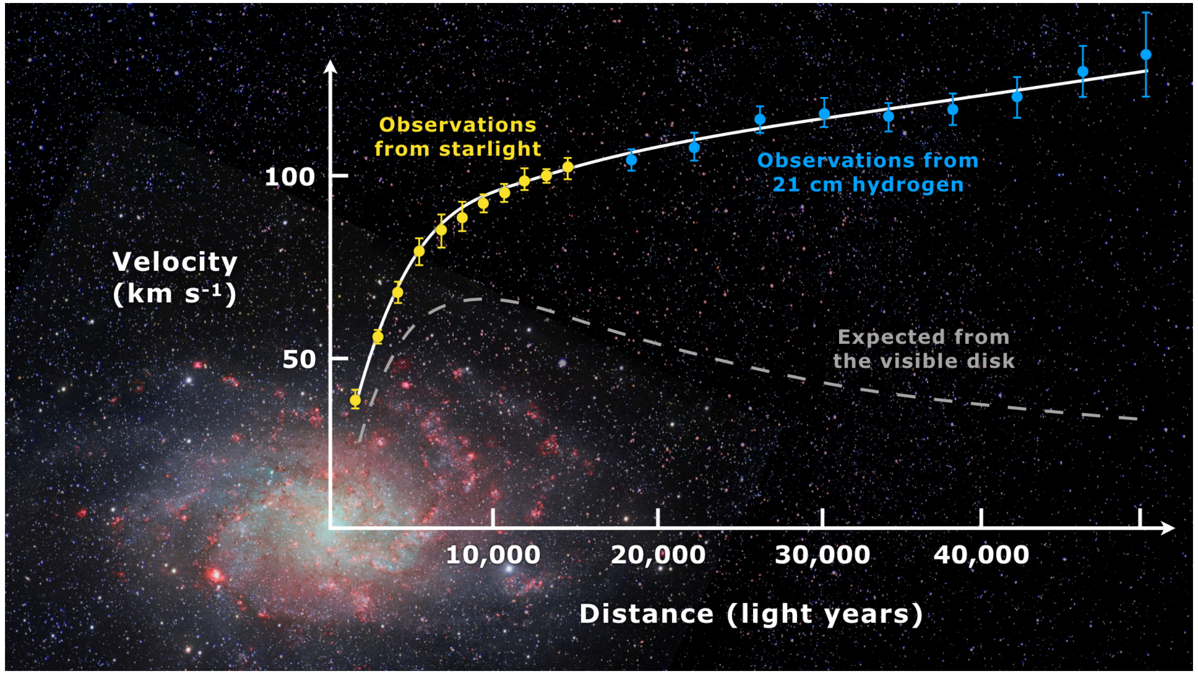


arXiv: hep-ph/9709356

Dark Matter

Galactic Velocity Curves (Messier 33)

- Radial velocity of galaxies is large
- Not explainable with visible matter and current gravitational theories
- Either:
  - Modified Newtonian Dynamics
  - "Dark matter" interacting gravitationally



arXiv:astro-ph/9909252
doi:10.1086/158003.

Gravitational Lensing

- Mass curves spacetime
- Deforms galaxies that move through
- Use a gravitational lens methods to find total amount of matter
- Disagrees with amount of visible matter

Dark Matter

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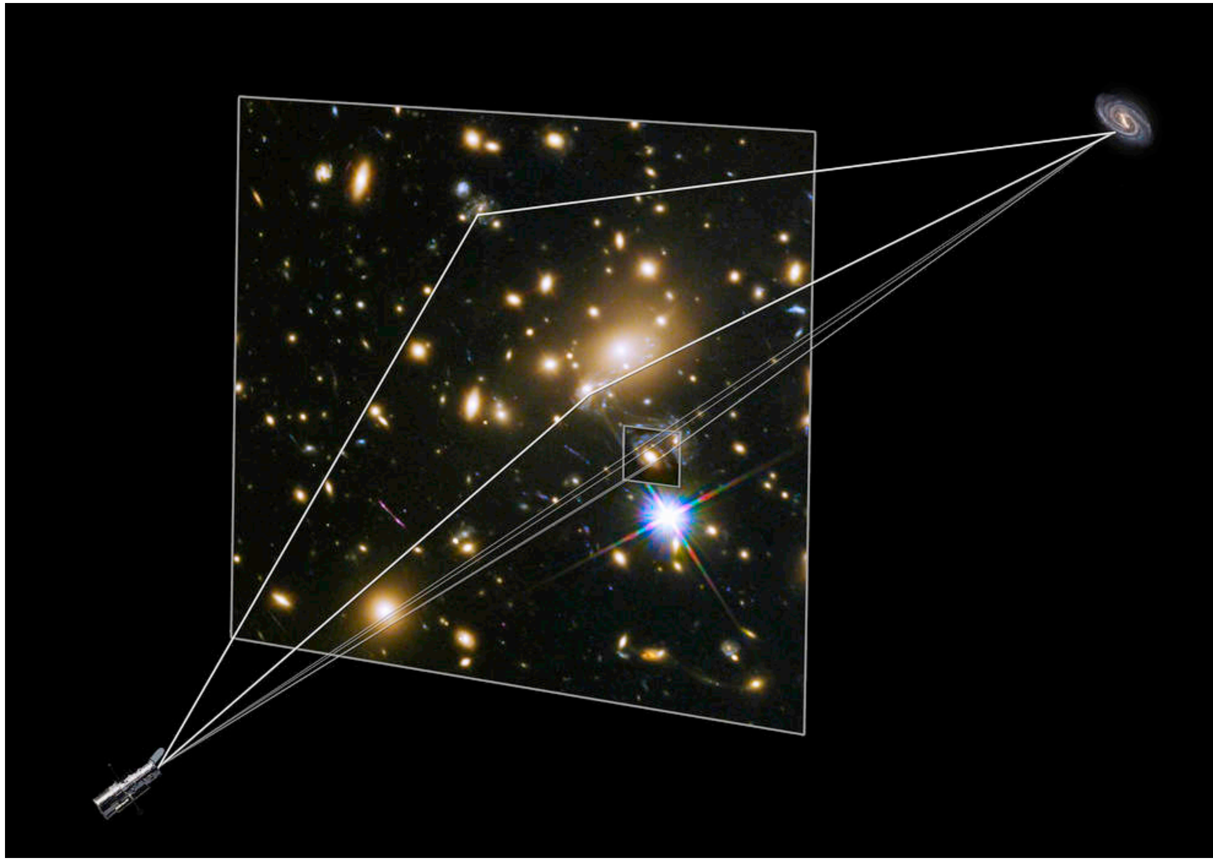
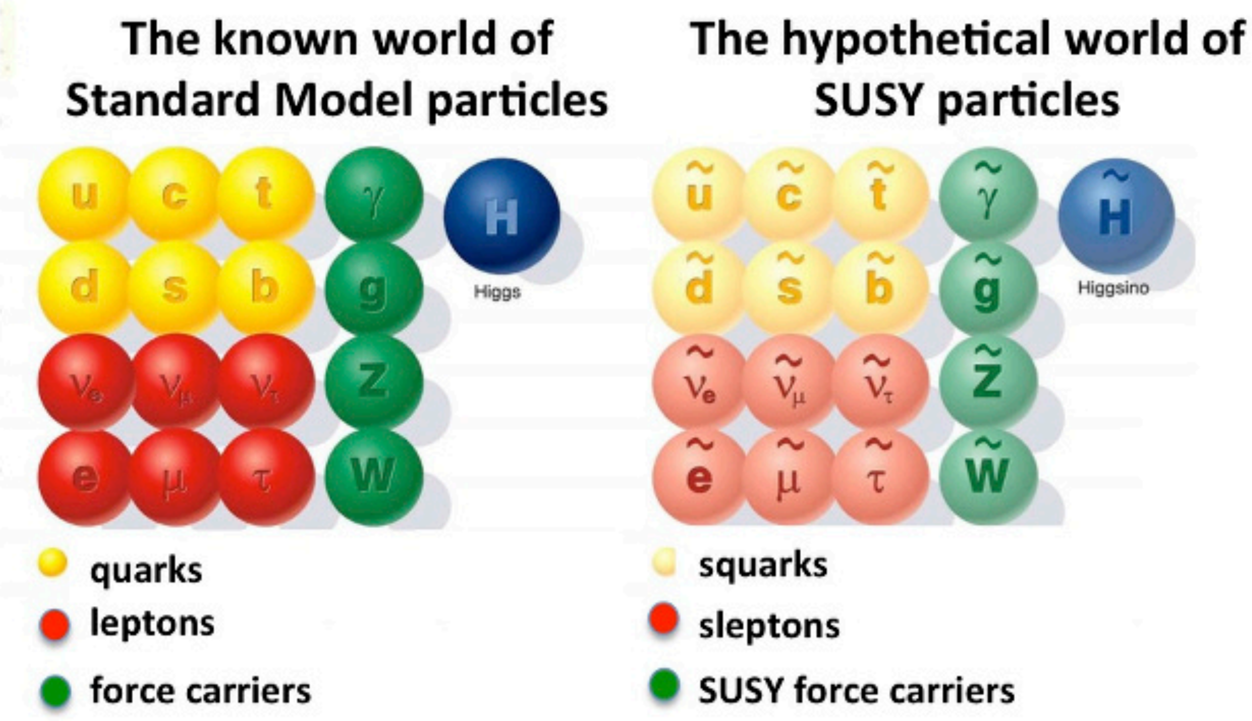
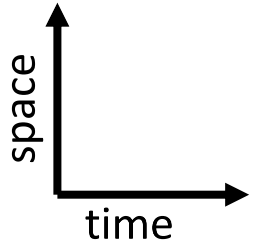


What does Supersymmetry potentially solve?

What is Supersymmetry?

- Fermion-bosonic partnership
  - For every fermion there is a boson partner, and vice-versa
  - Exact same quantum numbers except spin
  - Naming:
    - “s” in front of name, meaning scalar partner
    - “ino” at end of name, meaning fermionic partner
- Where are all of these particles?
  - Supersymmetry must be broken!
- How does this solve the previous questions?
- What should we search for?

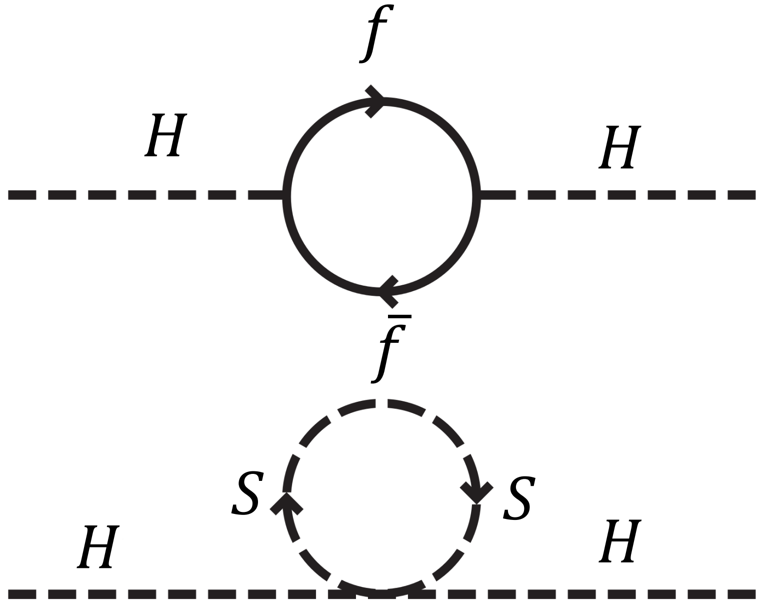




Hierarchy Solution

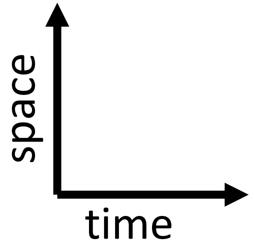
Higgs Interactions

- Higgs mass has fermionic, bosonic, and scalar contributions
- Scalar boson cancels contribution to fermion loops
- Changes quadratic divergence to logarithmic
  - Renormalizable without fine tuning
- $$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 + \cdots + \frac{\lambda_S}{16\pi^2}\left[\Lambda_{UV}^2 - 2m_S^2 \ln\left(\frac{\Lambda_{UV}}{m_S}\right) + \cdots\right]$$



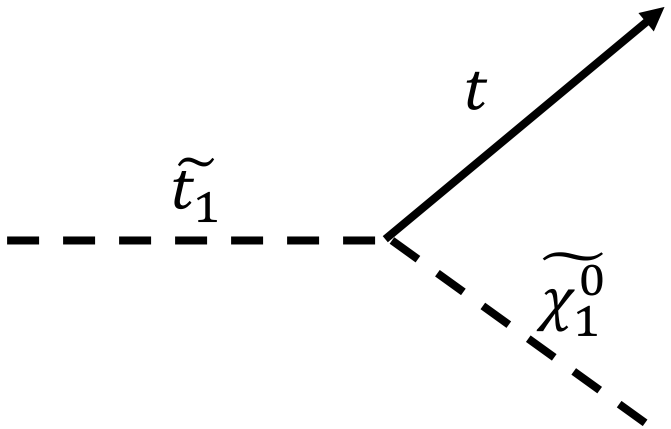
arXiv: hep-ph/9709356

Dark Matter Candidate



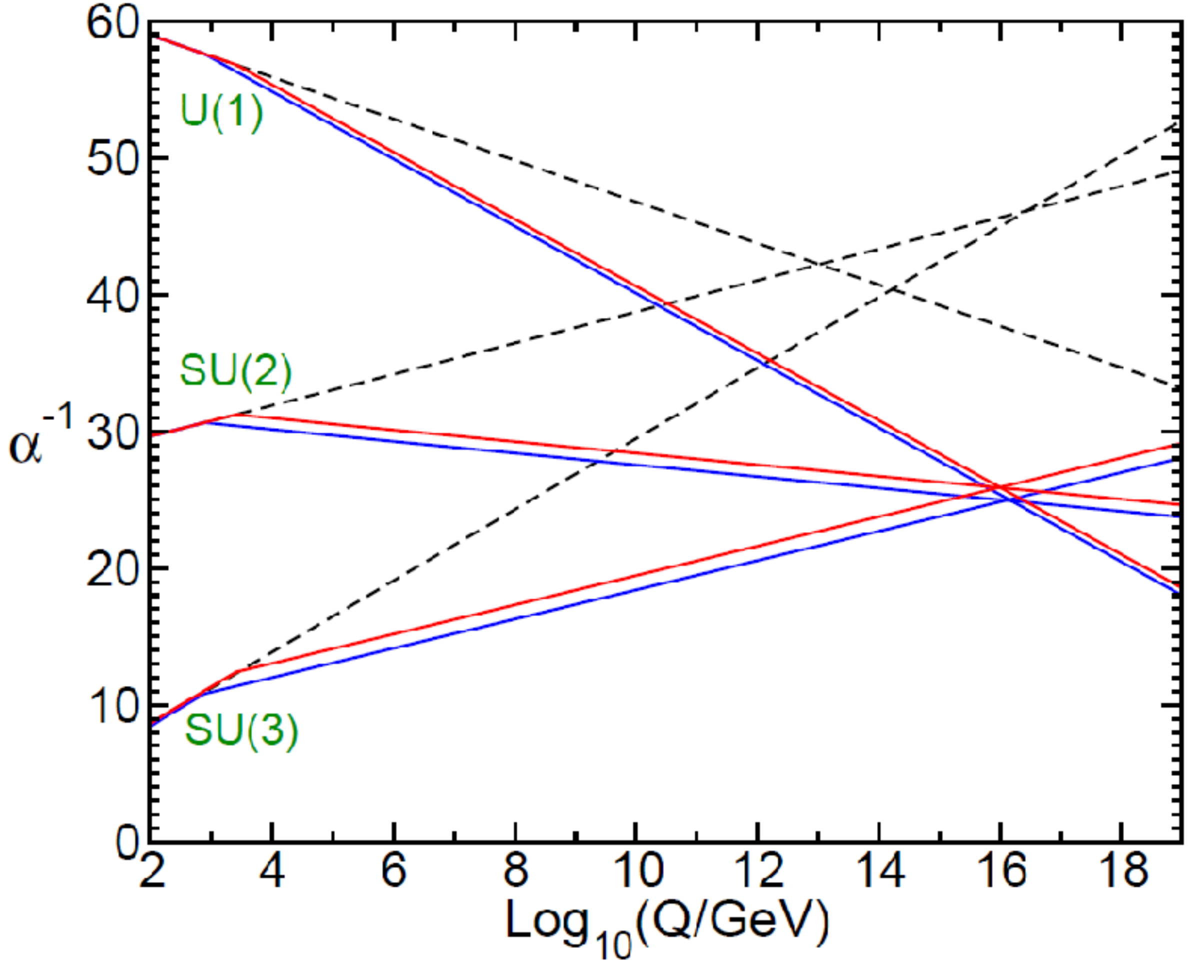
R-Parity Conservation

- Simplified SUSY models assume conservation
  - $P_R = +1$ for particles, $P_R = -1$ for sparticles
- Must have a stable SUSY particle, Lightest Supersymmetric Particle (LSP)
  - Top squark decays to LSP + SM Particles
  - Neutralino $\widetilde{\chi}_1^0$ as candidate LSP



Grand Unified Theory

Supersymmetry allows for unification at large energy scales



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- **Different methods of detection**

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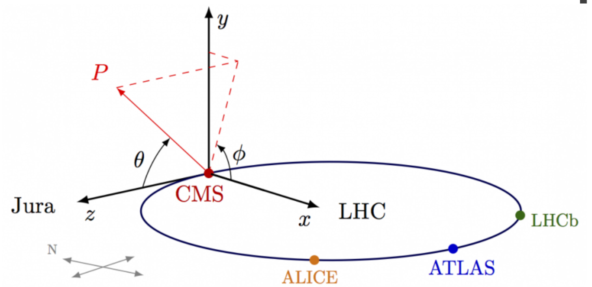
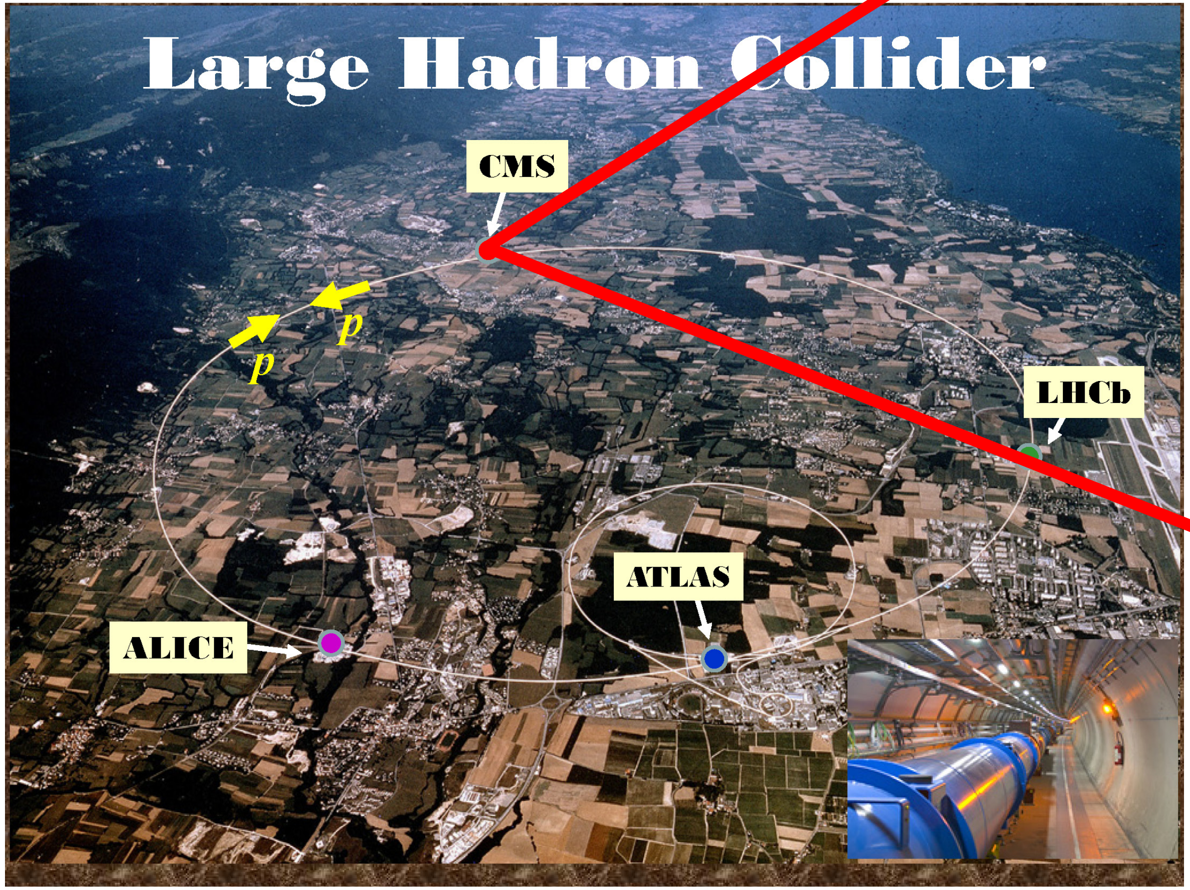
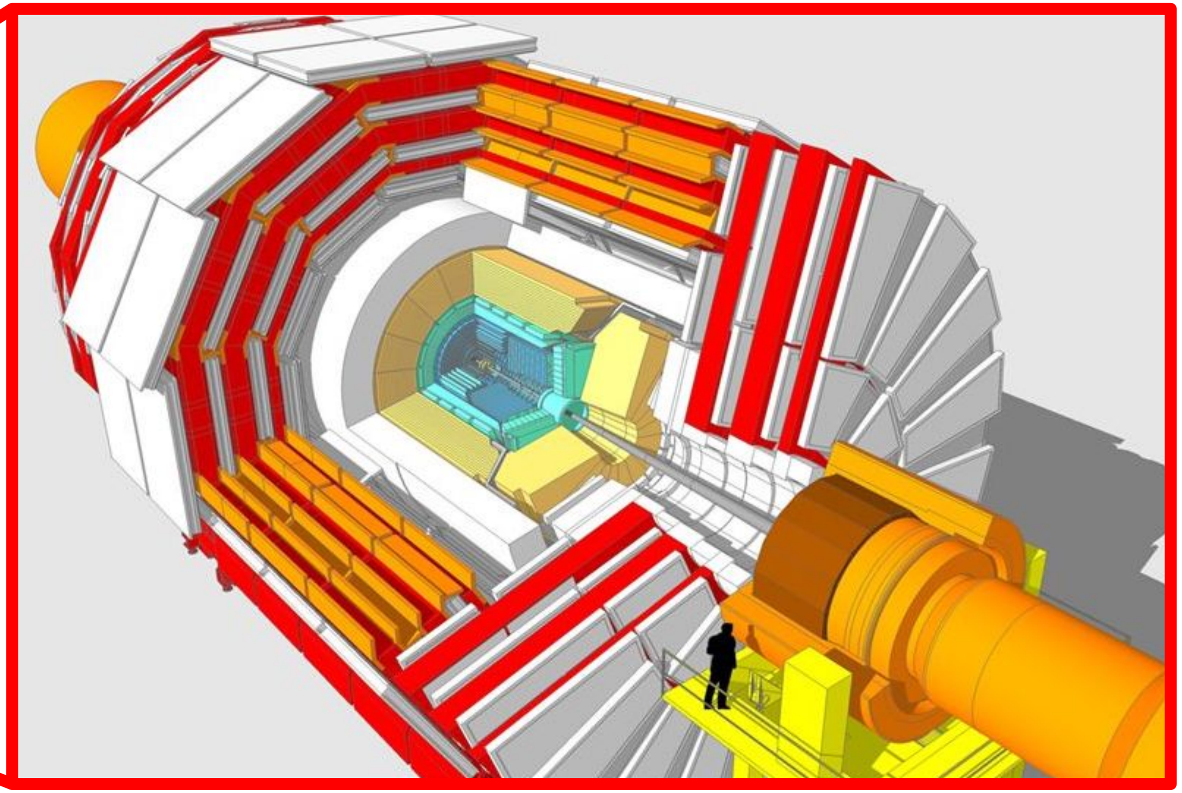
Compact Muon Solenoid (CMS)



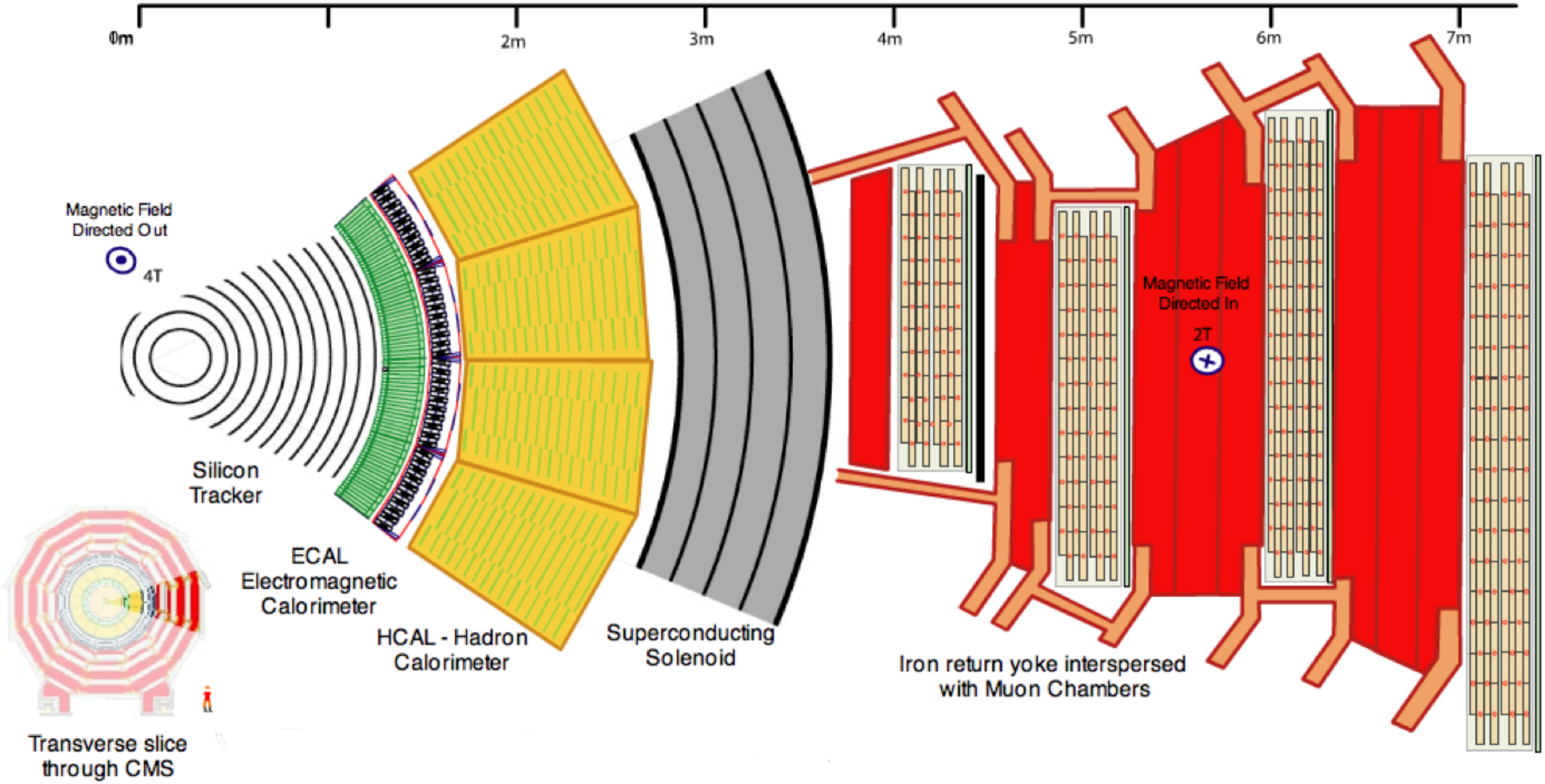




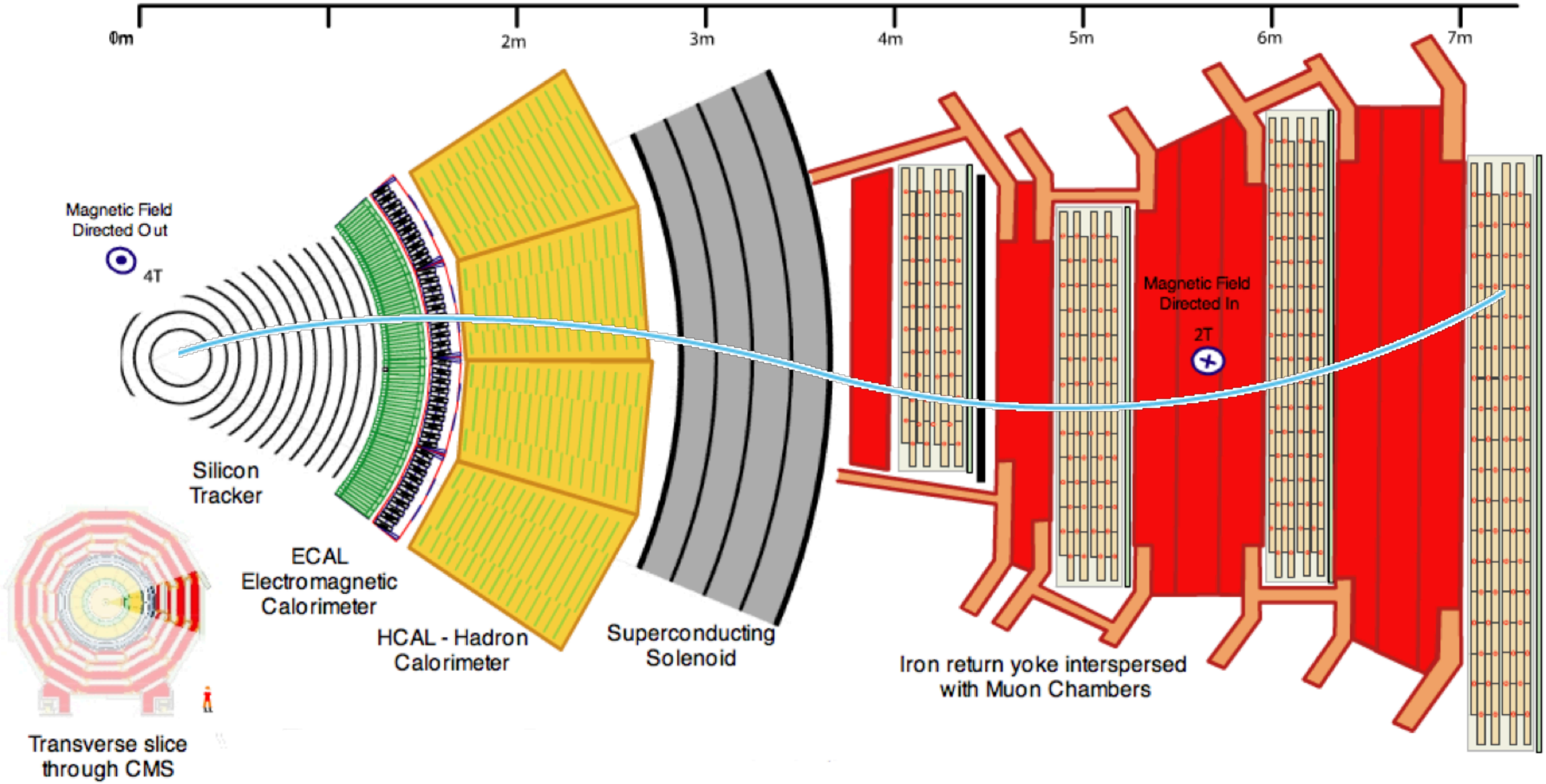
LHC

- $\sqrt{s}$ =13 TeV p-p collisions
- Design Luminosity: $2{\times}10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

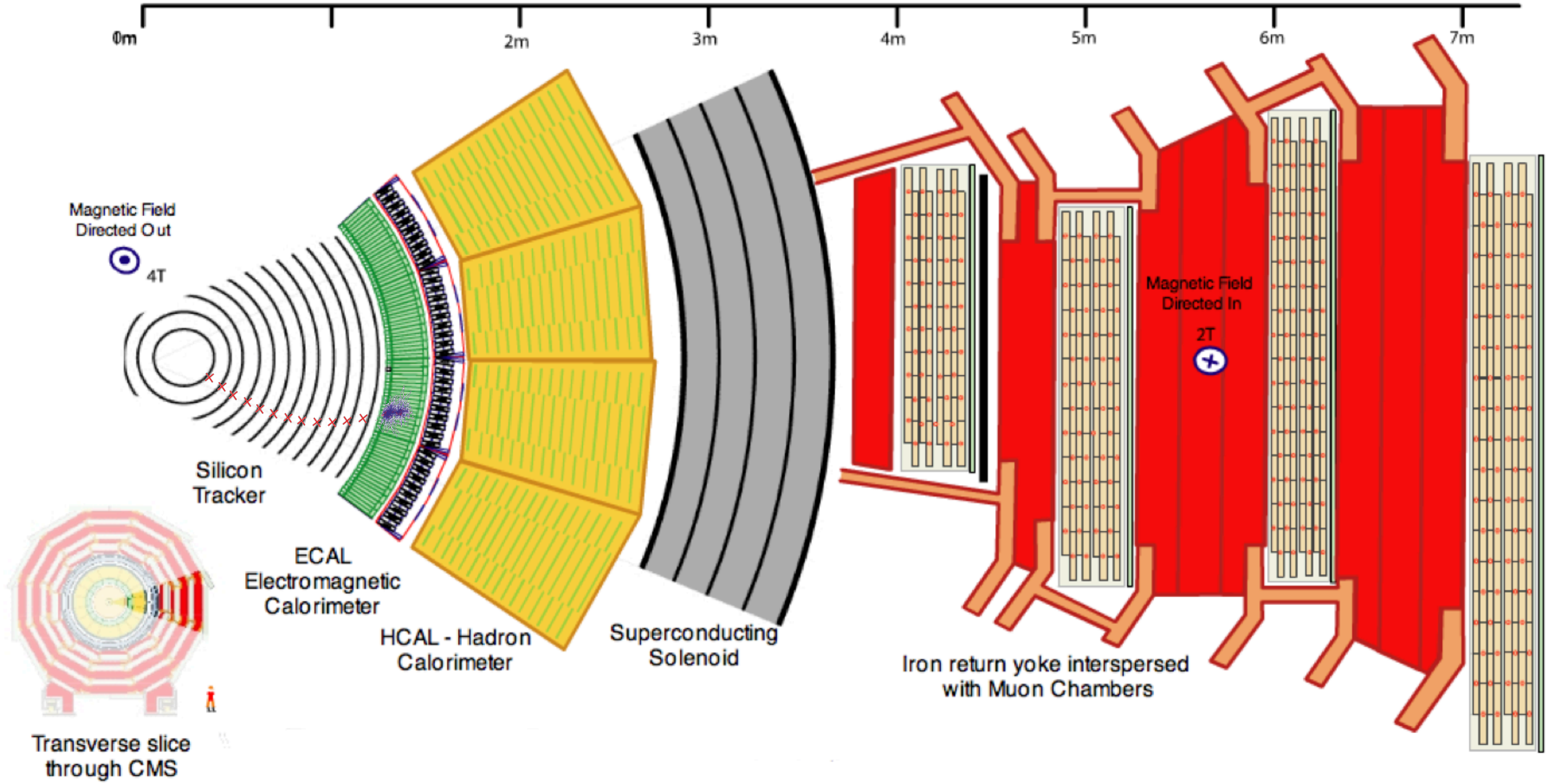
CMS Detector



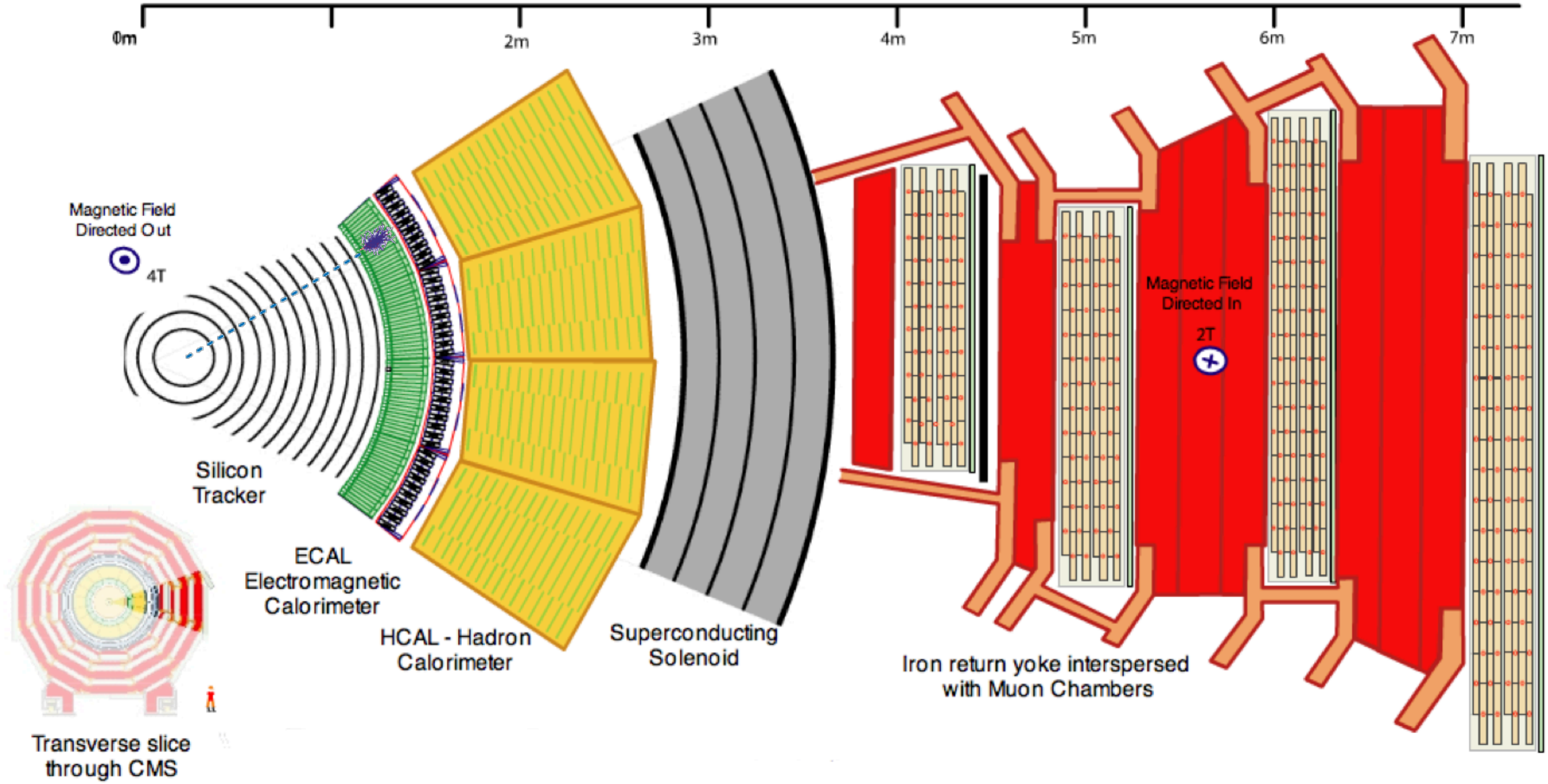
Muon Interaction



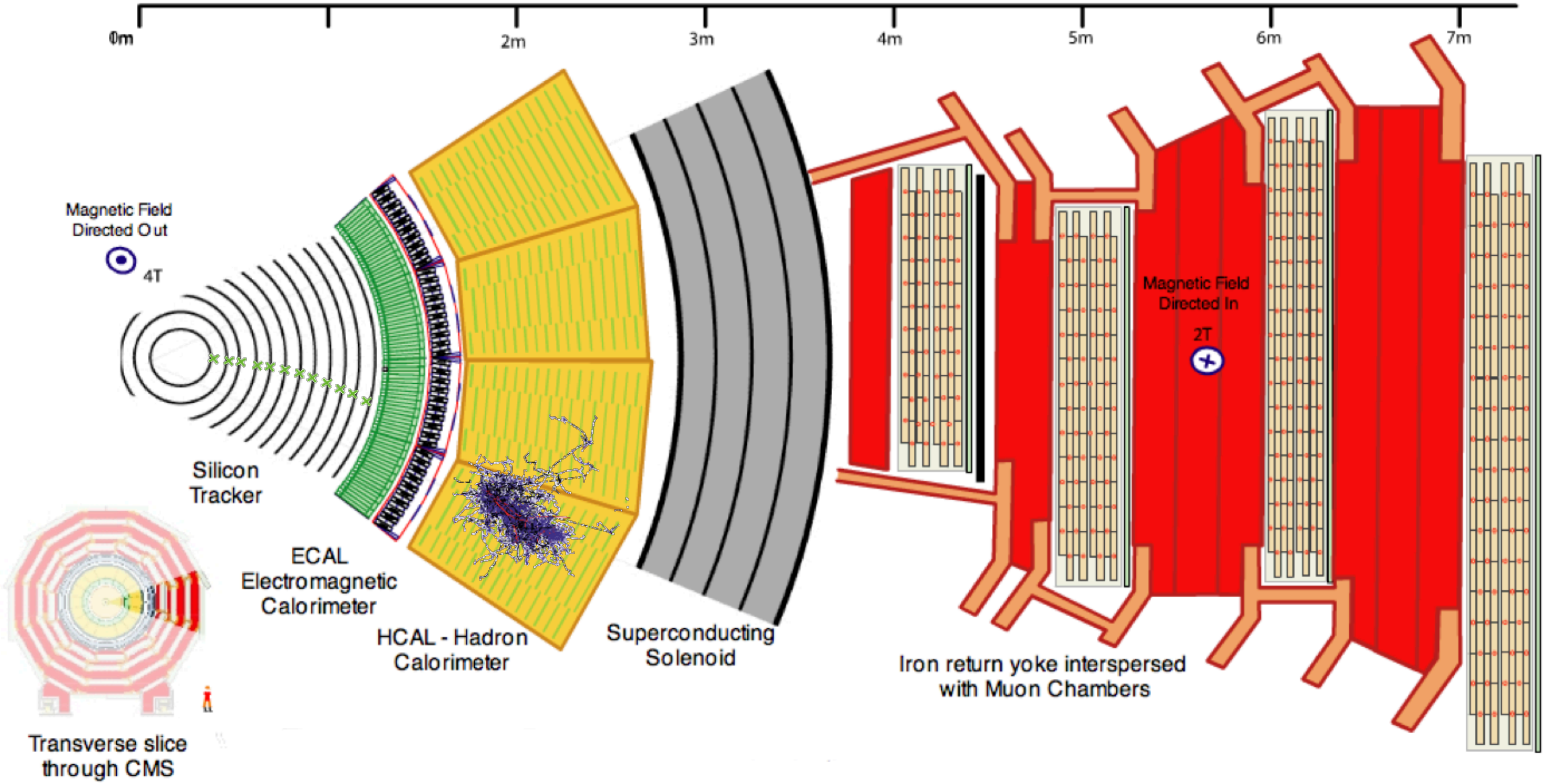
Electron Interaction



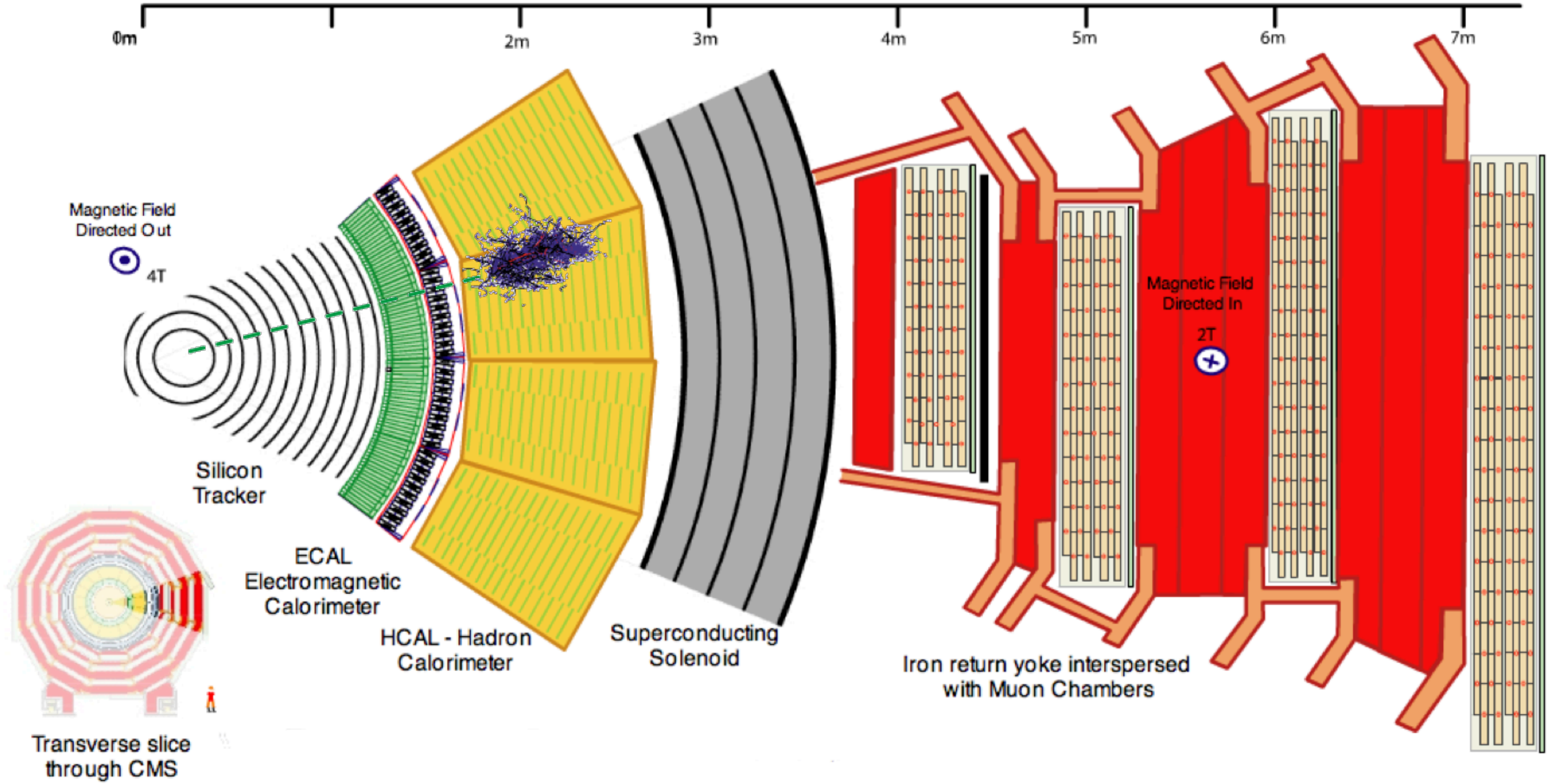
Photon Interaction



Charged Hadron Interaction



Neutral Hadron Interaction



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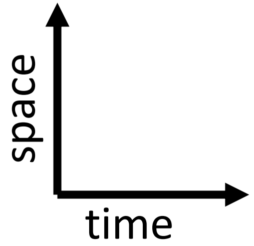
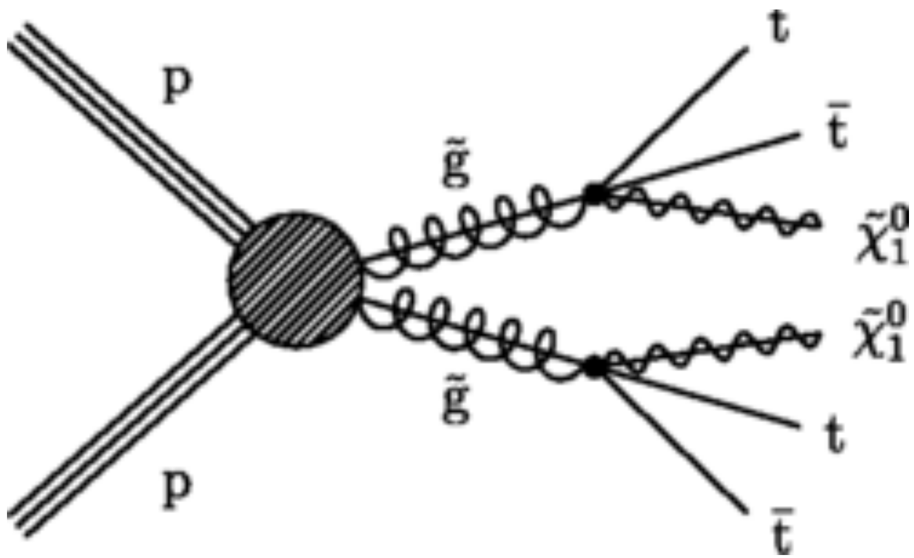
Simplified SUSY Models

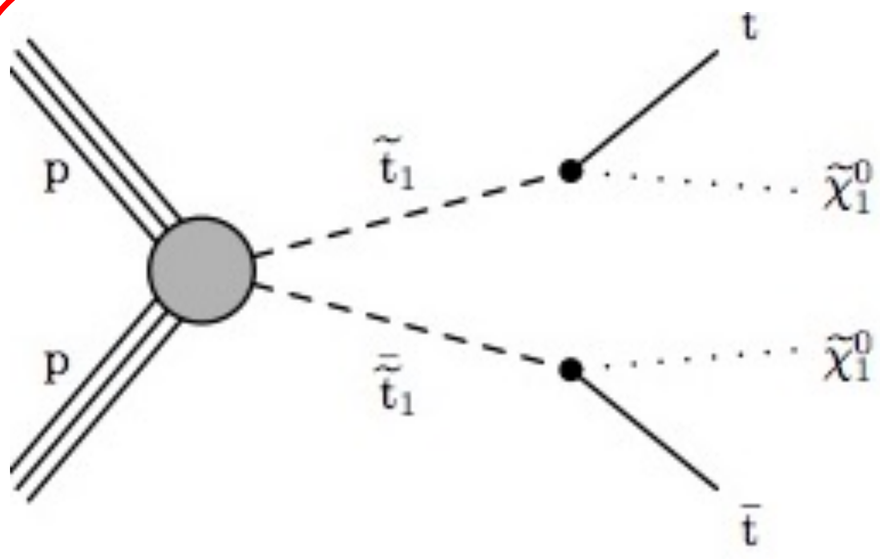


- Looking at inclusive models for a most general stop search
- Lightest Squark is the top Squark
- Baseline Selection: $N_j \geq 2,\ p_T^{miss} > 250$ GeV
- Main Backgrounds: Lost Lepton, QCD Multi-jet, $Z \rightarrow \nu\bar{\nu}$, and Rare (ttZ, WW, WZ, ZZ)

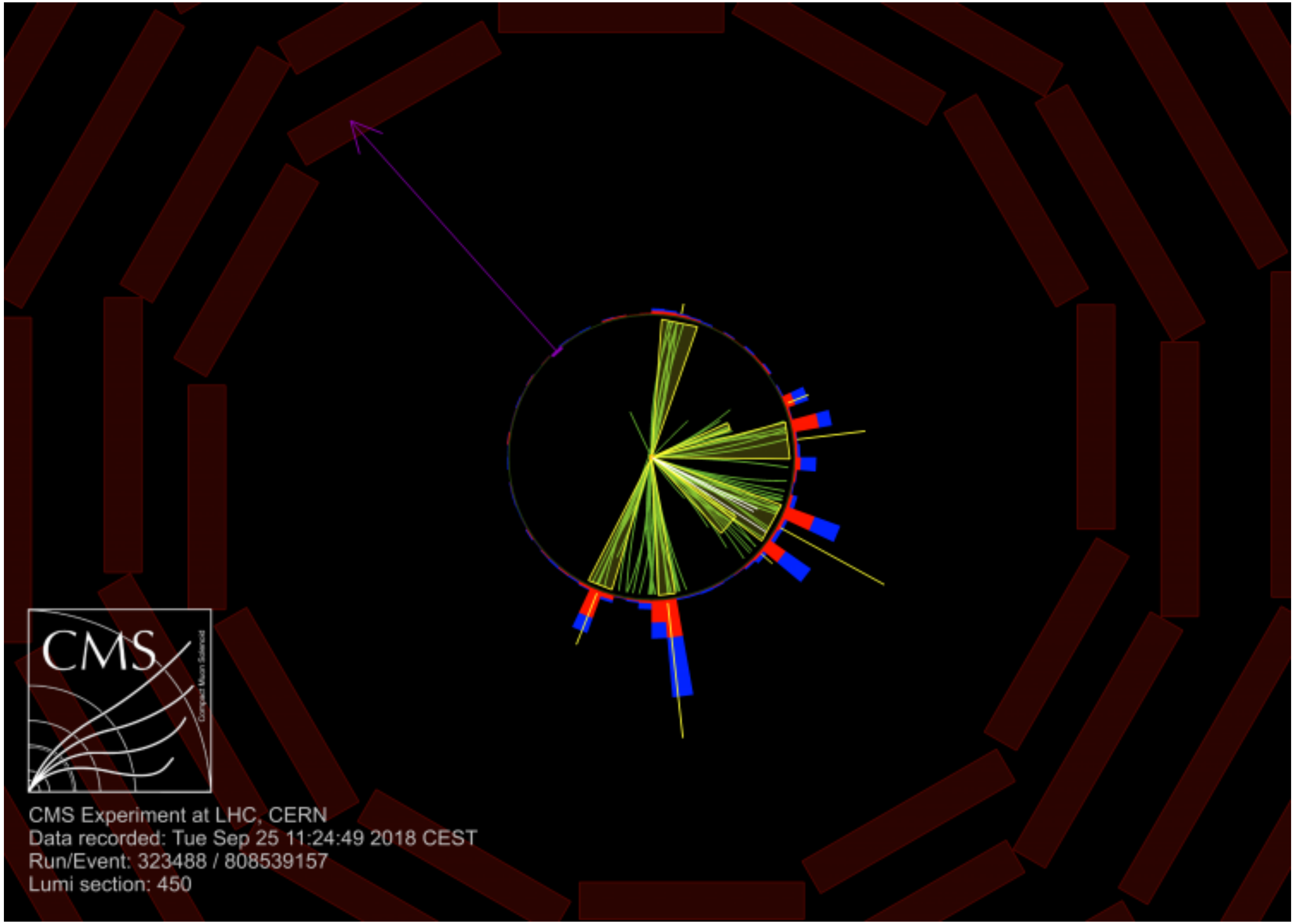
Gluino Mediated Stop Production



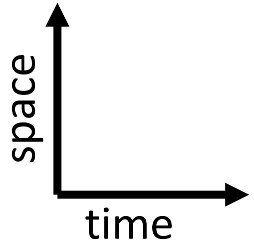
Direct Stop Production



Example Event Signature



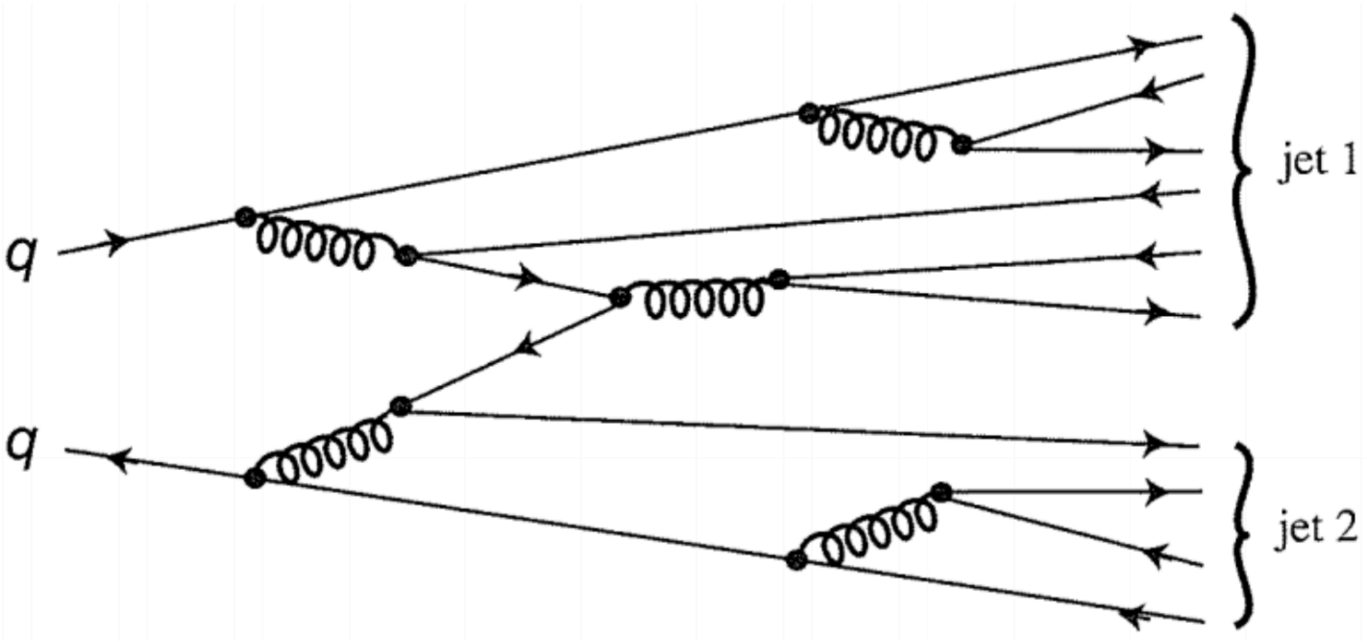
CMS-PAS-SUS-19-005



Jet Reconstruction

Hadronization

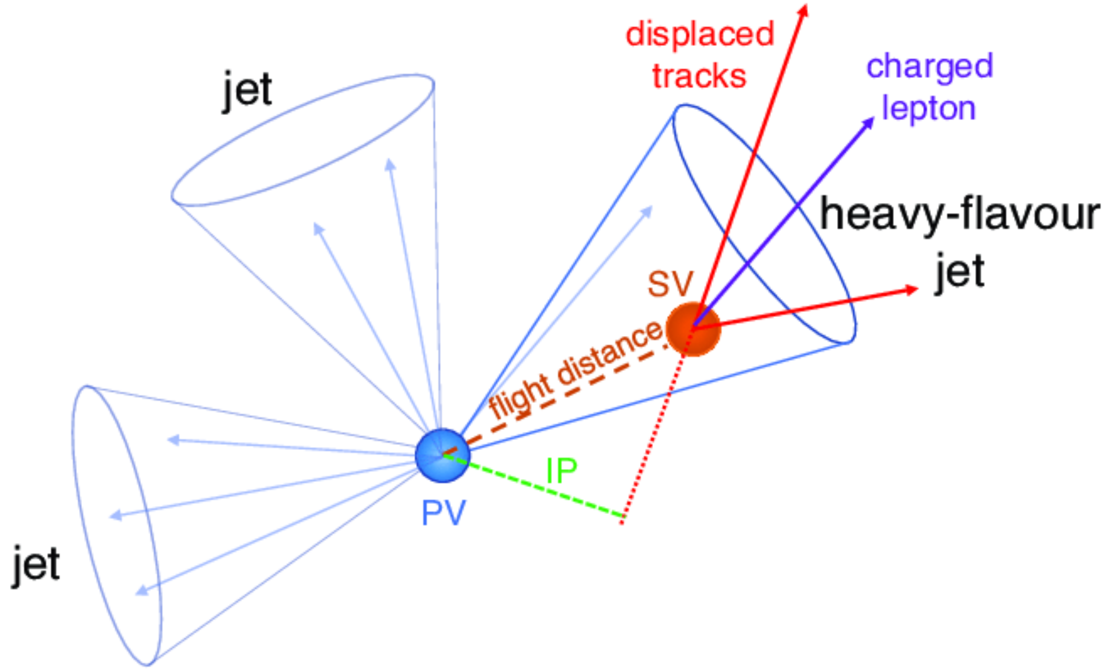
- Radiation of gluons and pair production of $q\bar{q}$
- Many algorithms for attributing particles for a particular jet
- Reconstruct jets with radius $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$



B Tagging

How to Identify b quarks?

- Mean lifetime: $\tau \approx 10^{-12}$ sec
- Moves significant distance away from PV
- Momentum dependent methods
  - High $p_T \geq 20$ GeV
    - Deep Neural network inputs: tracks, SV, IP significance
  - Low $p_T < 20$ GeV
    - IP and significance, Pointing angle, and tracks

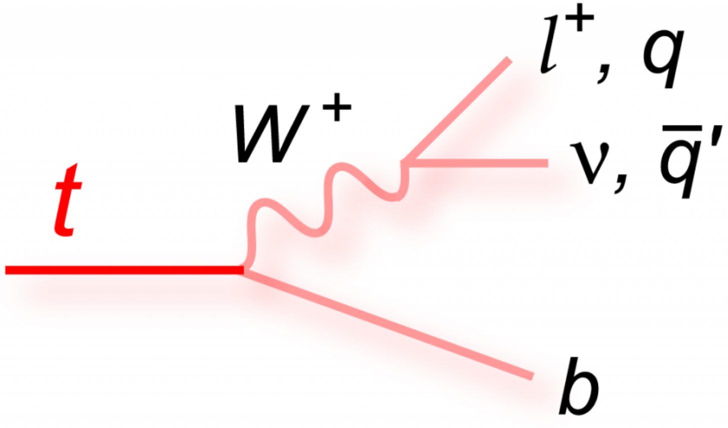


arXiv:1712.07158

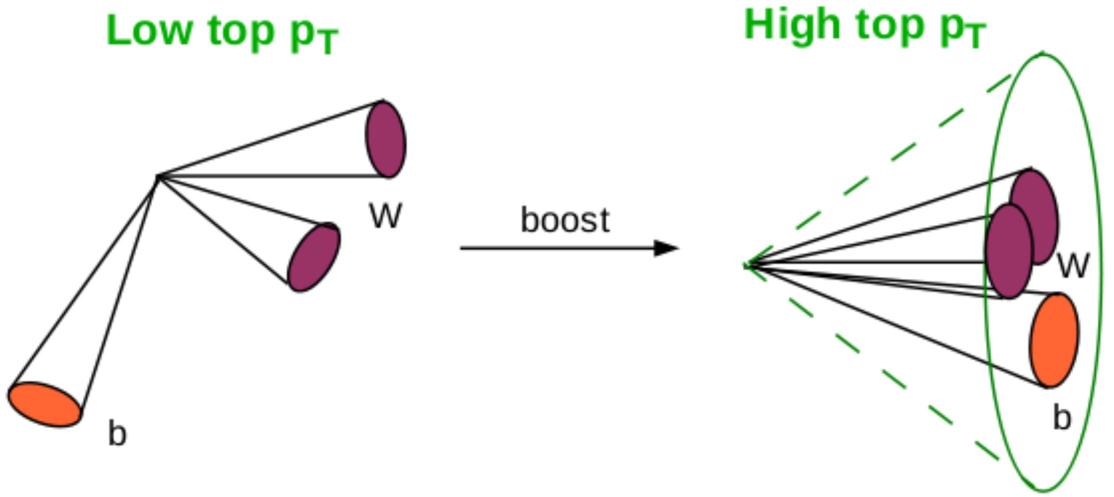
Heavy Object Tagging

Different Types of Top Reconstruction

- Merged top/W
  - Boosted jets
  - $\Delta R = 0.8, p_T > 300\ (200)$ GeV
  - $105 < m_t < 210$ GeV
  - $65 < m_W < 105$ GeV



- Resolved tops
  - Can distinguish each individual jet of the top decay
    - Three jets with invariant mass of 100-250 GeV

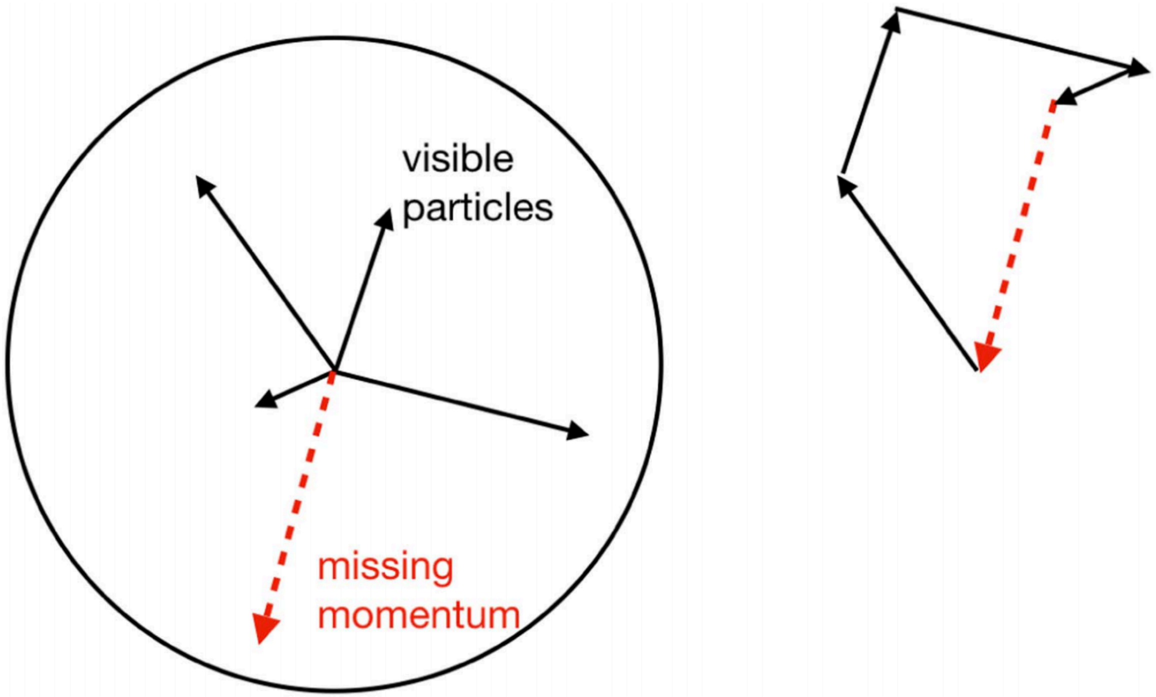


arXiv:1409.7495
JHEP v. 2014 p. 146, May 2014

Missing Transverse Momentum

Vector sum of total momentum measured in the detector

- $\vec{p}_T^{miss} = -\sum_{i \in vis} \vec{p}_{i,T}$
- SUSY: Models predict large missing momentum
- SM: Neutrinos also escape detection

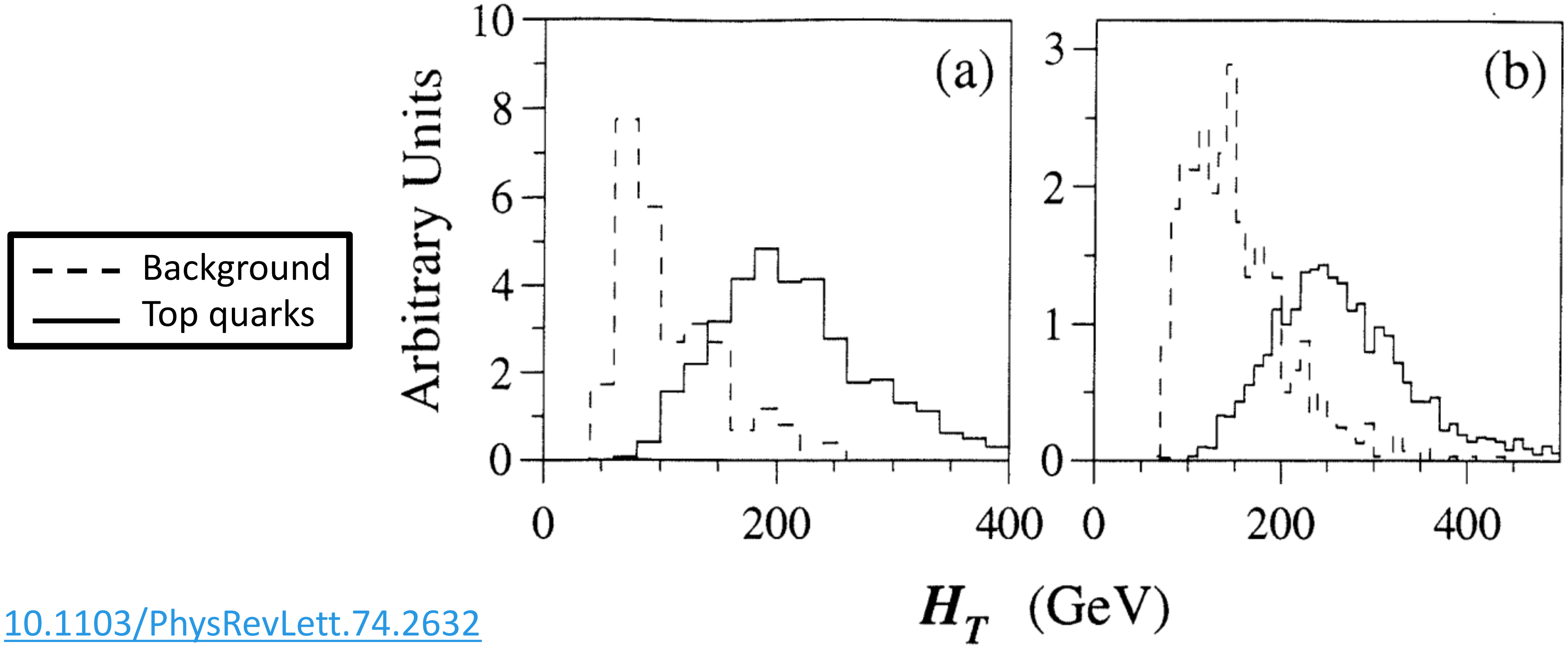


Phys. G: Nuclear and Particle Physics v.45 p. 063001

H_T

Scalar sum of total jet momentum

- $H_T = \sum_{i \in jets} p_{i,T}$
- Selection for massive particle decays

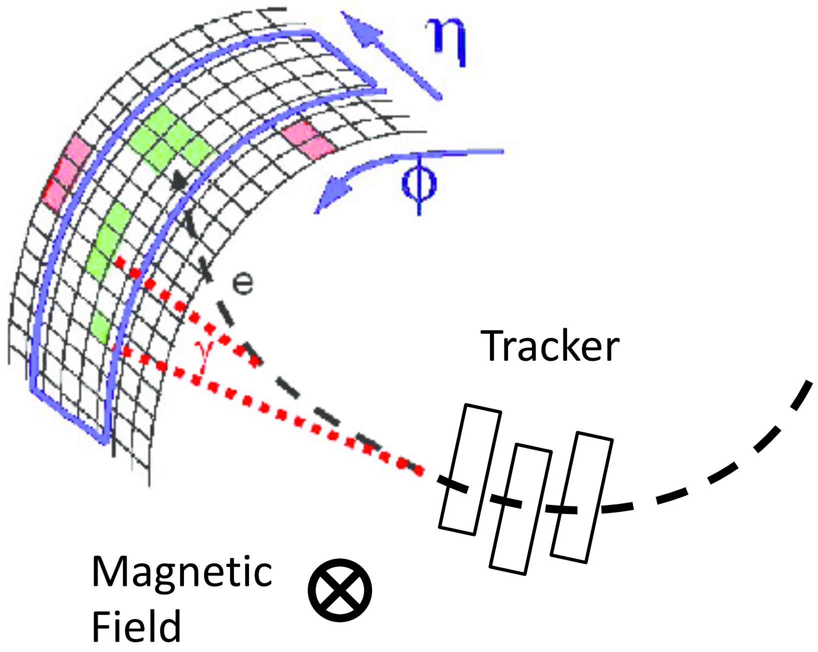


DOI: [10.1103/PhysRevLett.74.2632](https://doi.org/10.1103/PhysRevLett.74.2632)

Electron and Muon Identification

Match Track and energy in ECAL (Muon Chambers)

- Charged particles leave tracks in the Tracker
- Electrons
  - Look at energy deposits
- Muons
  - Tracker muons are built “inside out”
  - Global muons are built “outside in”
- Hadronic Tau Tagging
  - Isolated tracks with charged hadrons
  - Neural Network developed by Tau Physics Group

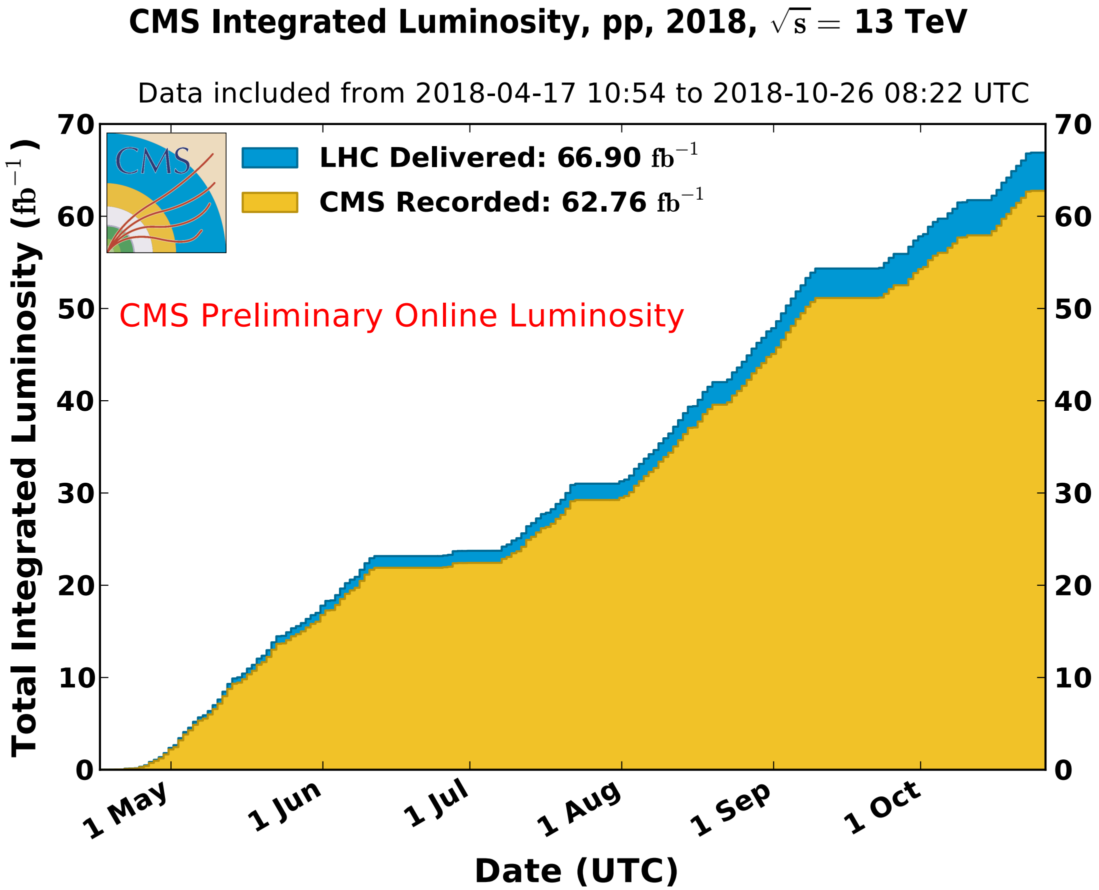


JINST 10 (2015) P06005
JINST 13 (2018) P06015
JINST 13 (2018) P10005
arXiv:1401.8155

Data Methods

Using data from all of Run 2 (2016/2017/2018) at CMS

- $136.7\ \mathrm{fb}^{-1} \approx 136.7\times10^{12}$ events
- Differences between years
- Need to combine!



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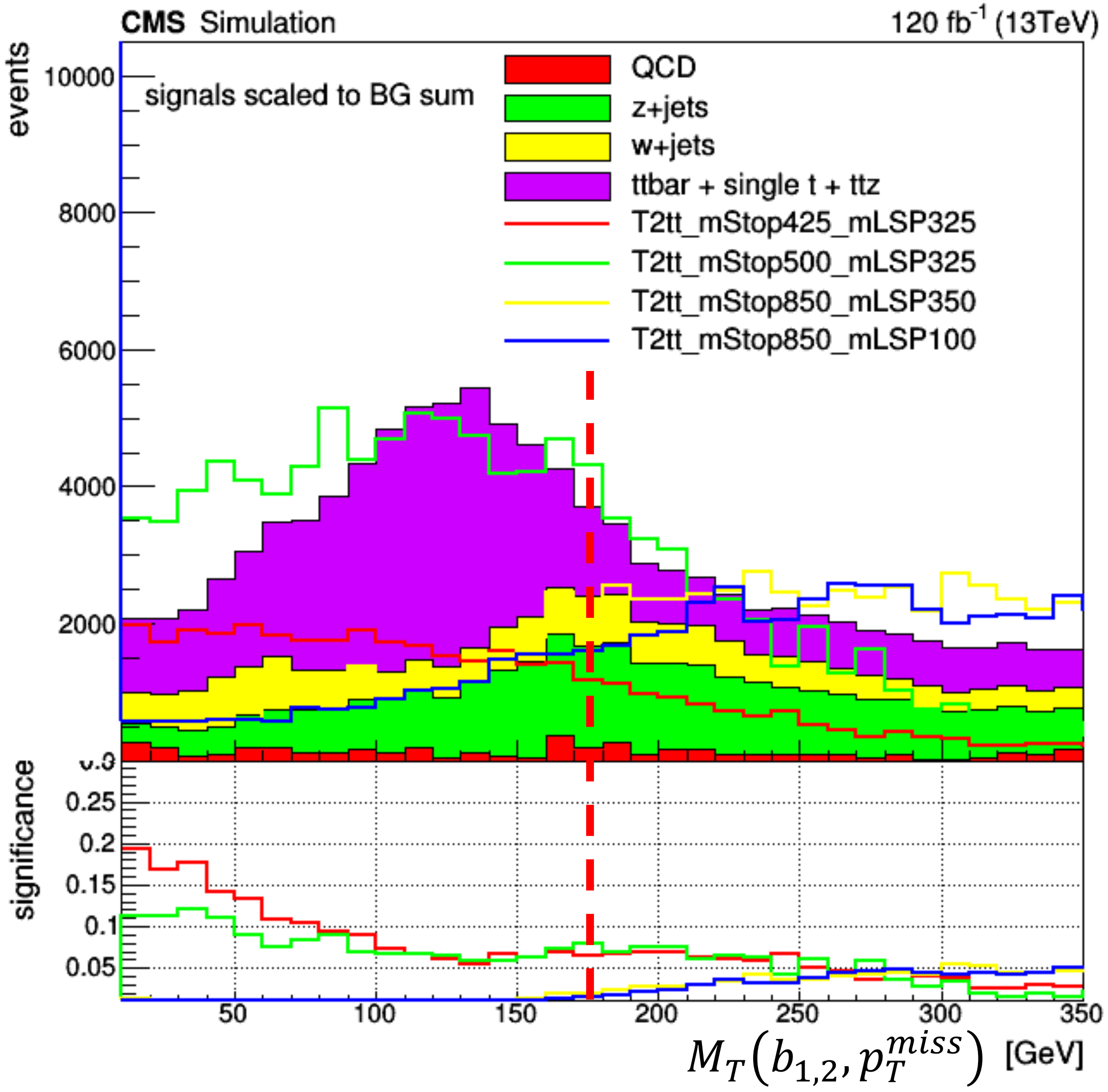
Classifying Interesting Regions

Categorize low Δm and high Δm by $M_T\left(b_{1,2}, p_T^{miss}\right)$

Low Δm
- $M_T\left(b_{1,2}, p_T^{miss}\right) < 175$ GeV

High Δm
- $M_T\left(b_{1,2}, p_T^{miss}\right) > 175$ GeV

- $M_T\left(b_{1,2}, p_T^{miss}\right) = \sqrt{2 \cdot p_T^{miss} \cdot p_T(b)(1 - \cos(\Delta\phi(p_T^{miss}, p_b))\,)}$



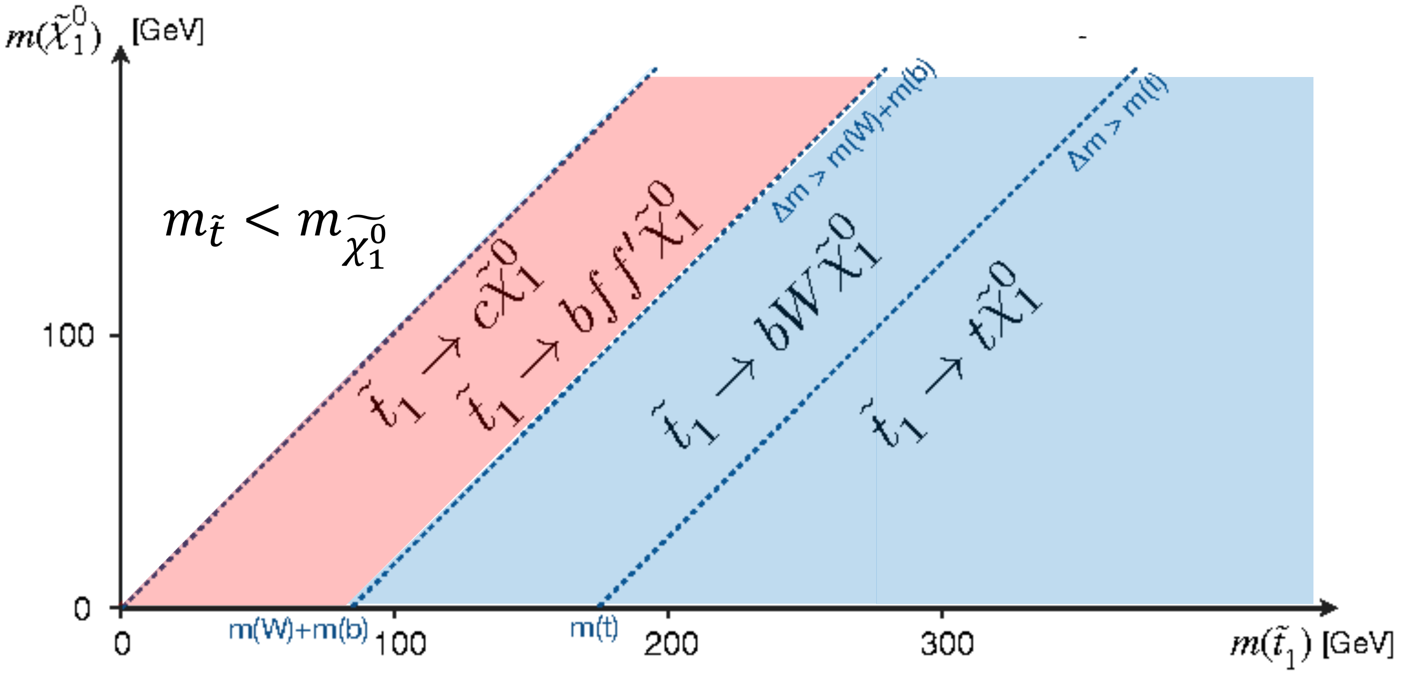
Targeted Search Regions

Looking in low and high Δm regions

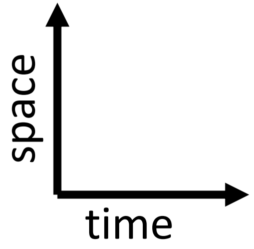
- Top Squark: $\Delta m = m_{\tilde{t}} - m_{\widetilde{\chi}_1^0}$

Search Regions

- 183 Search regions → 53 low + 130 high
- Low Δm
- High Δm

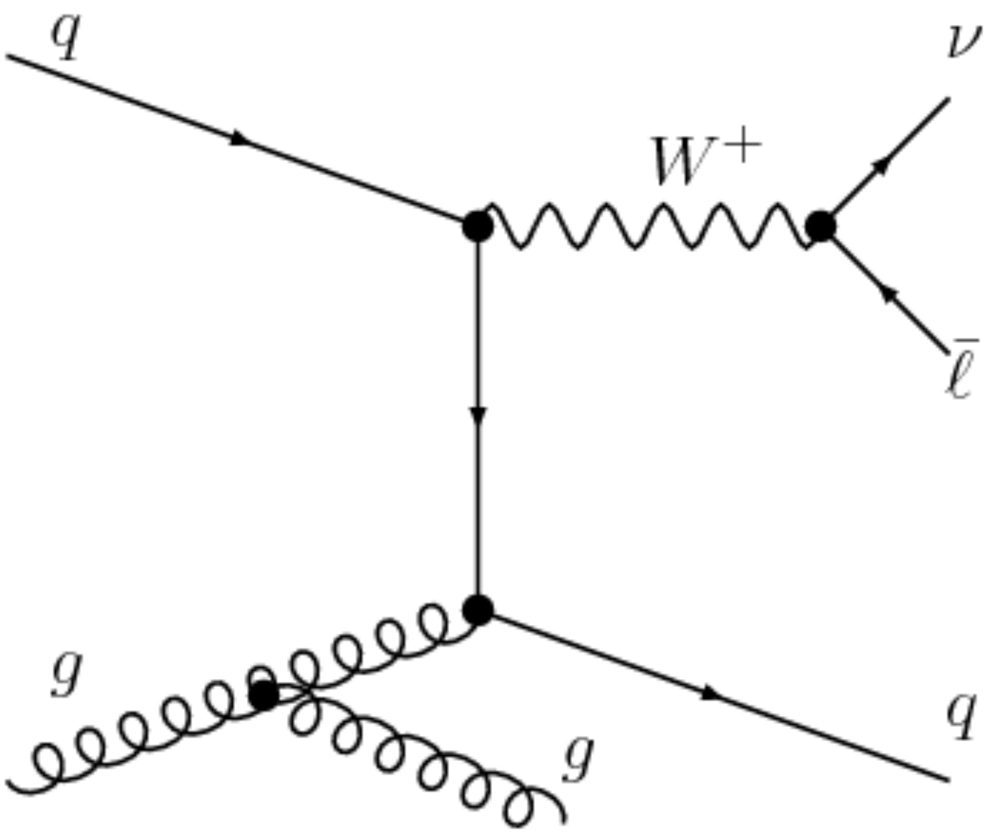


Lost Lepton Background



Standard Model Background

- $t\bar{t}, W + jets, tW, ttW$
- Causes
  - Misidentification
  - Out of detector acceptance
- How to prediction contribution for Run 2?



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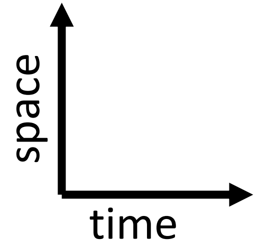

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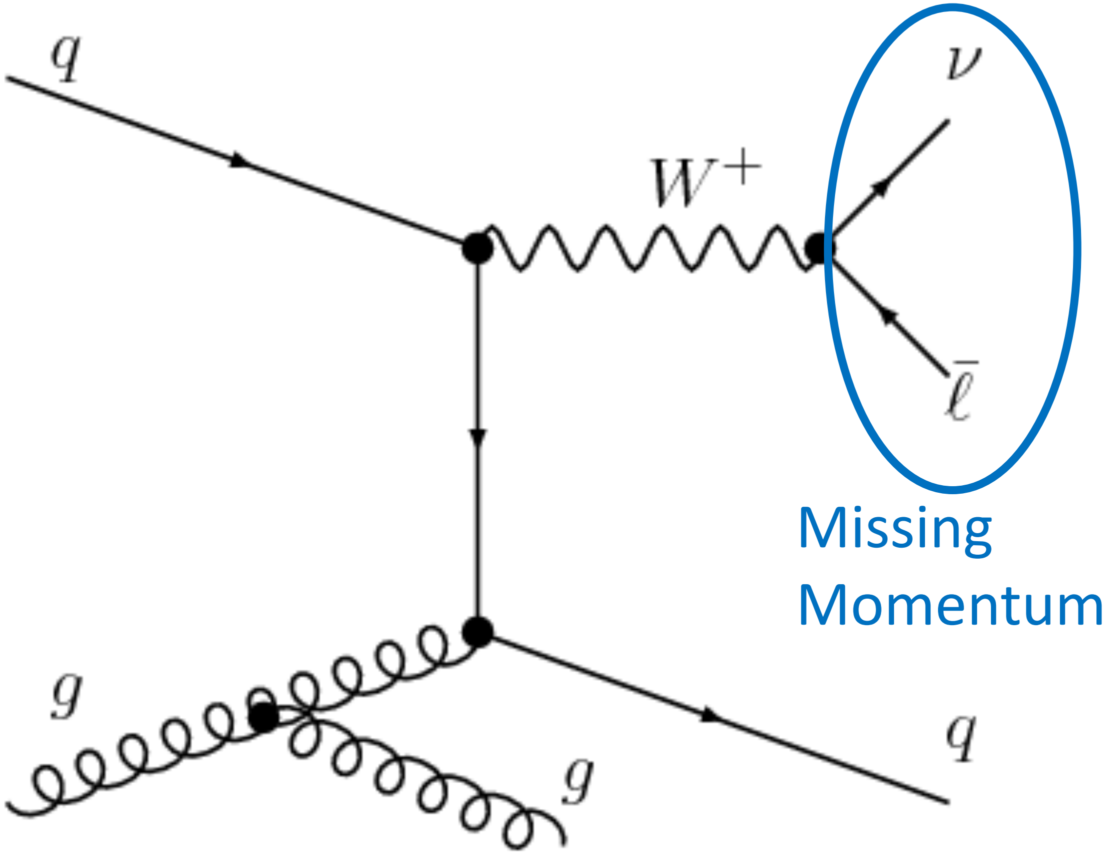

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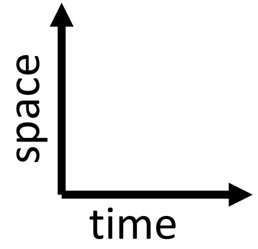

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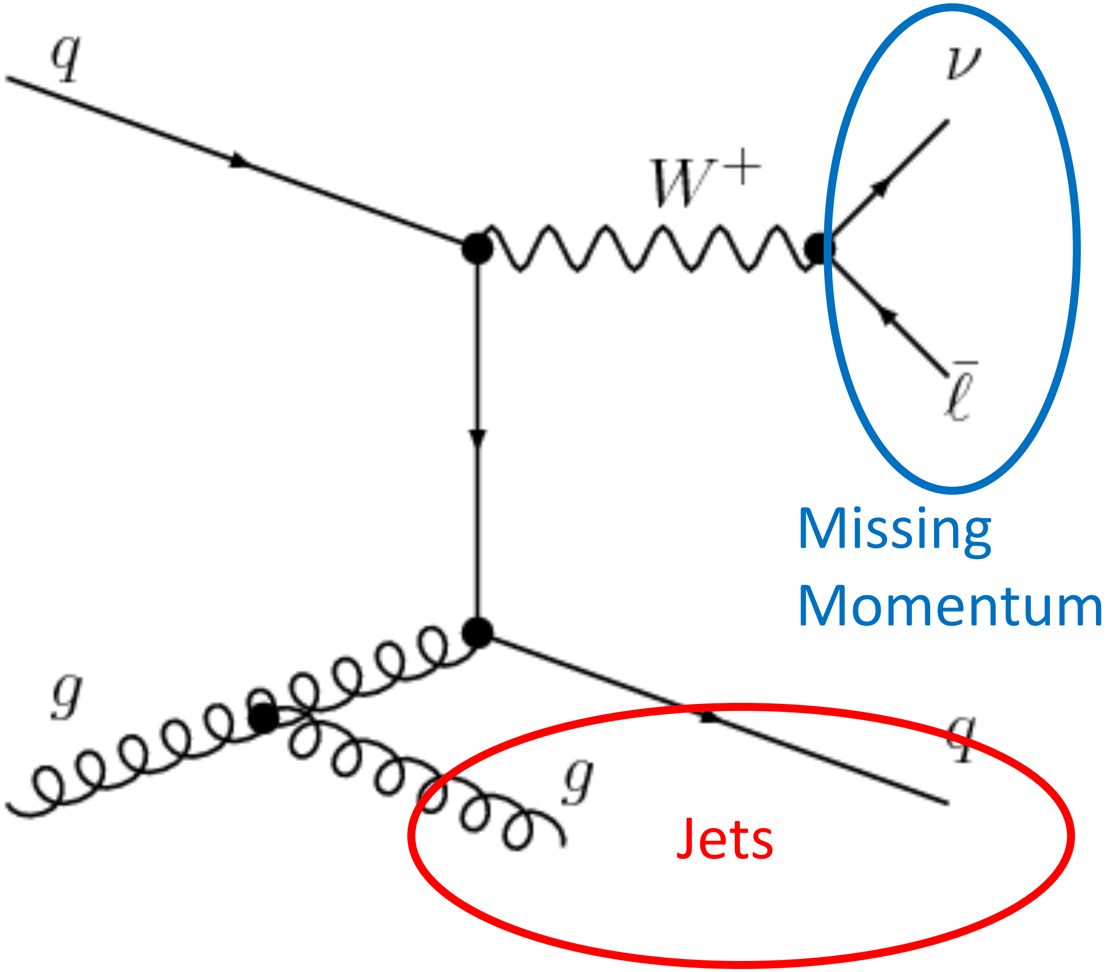
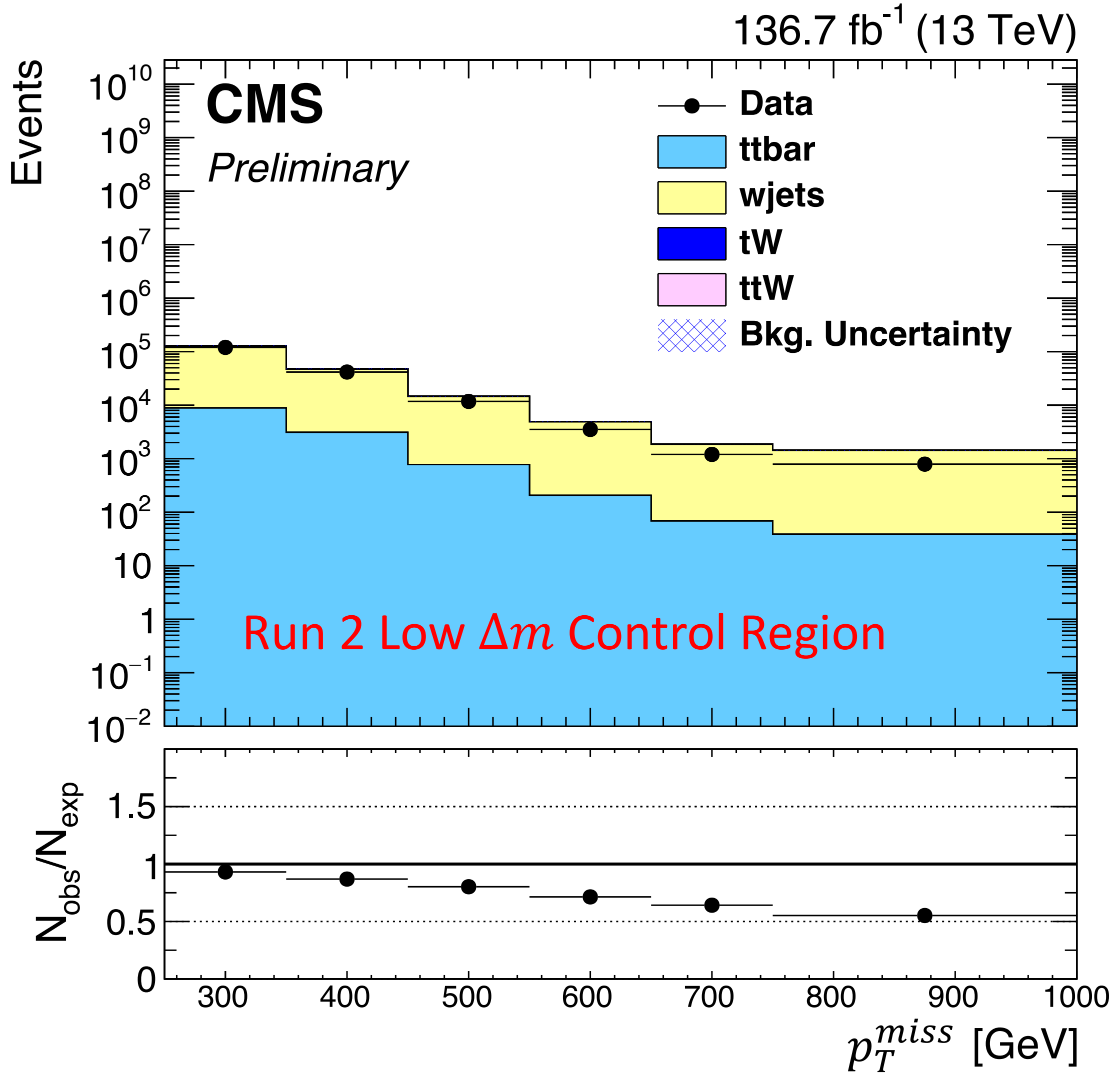
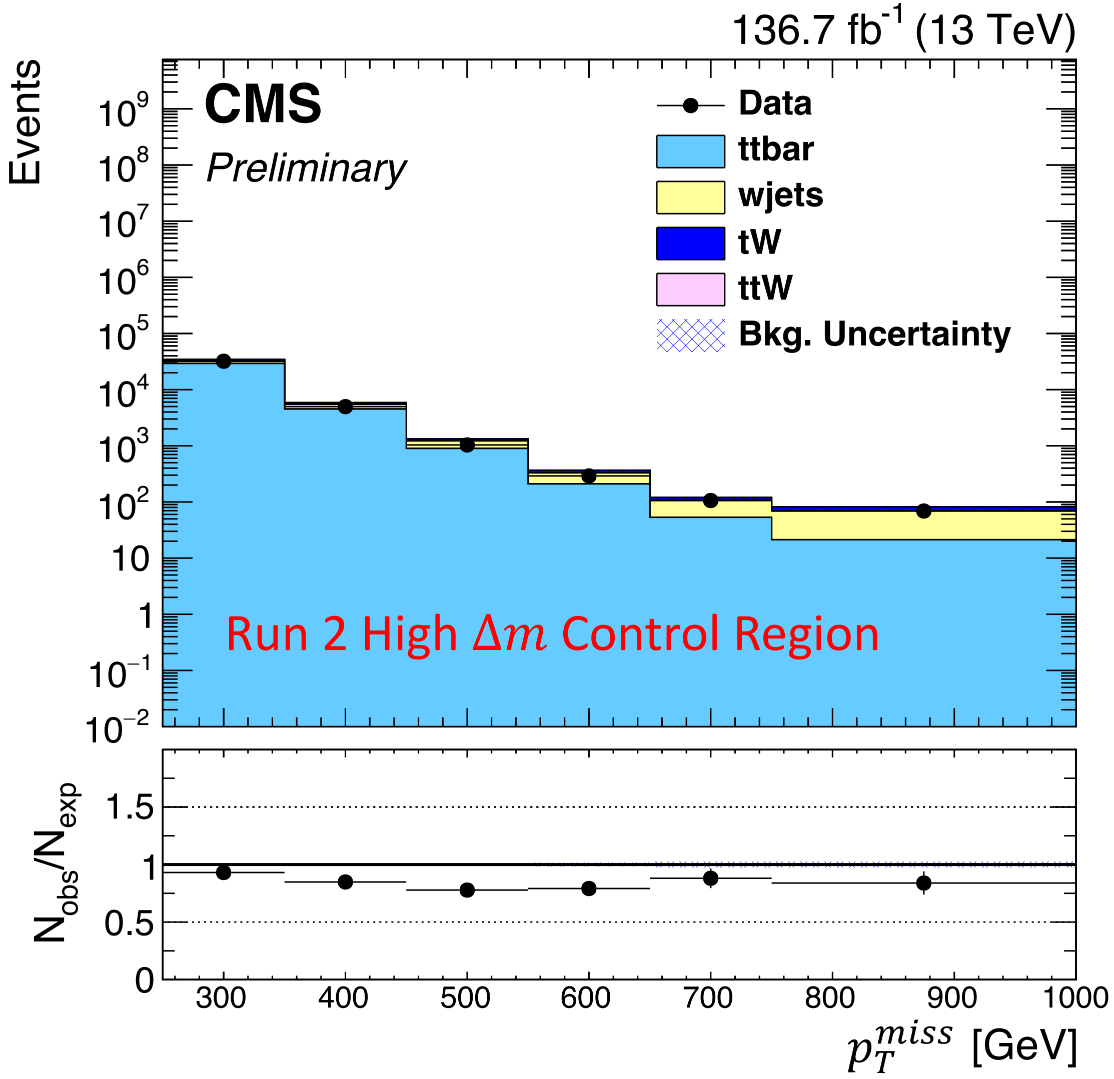


Compare Inclusive Regions

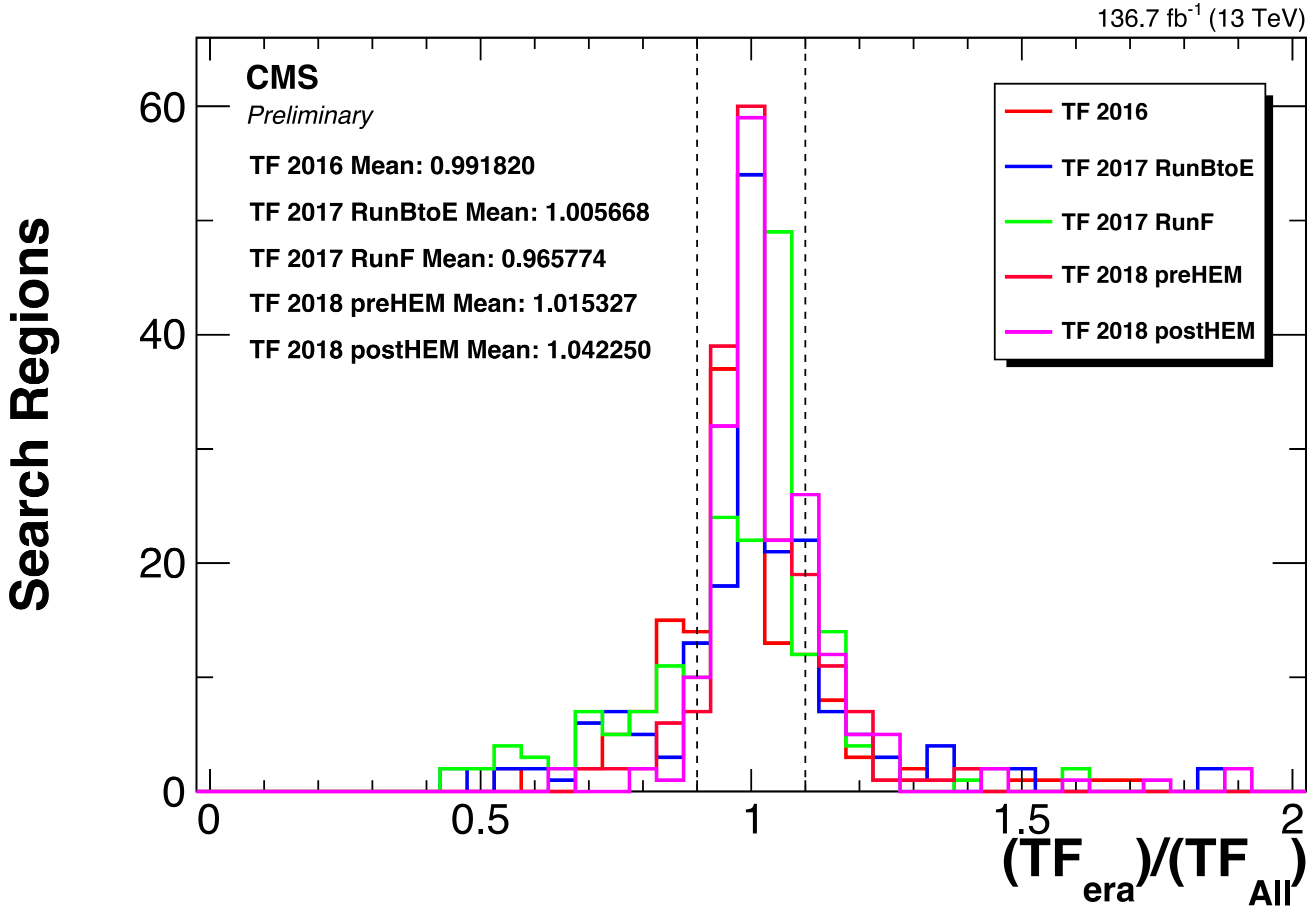




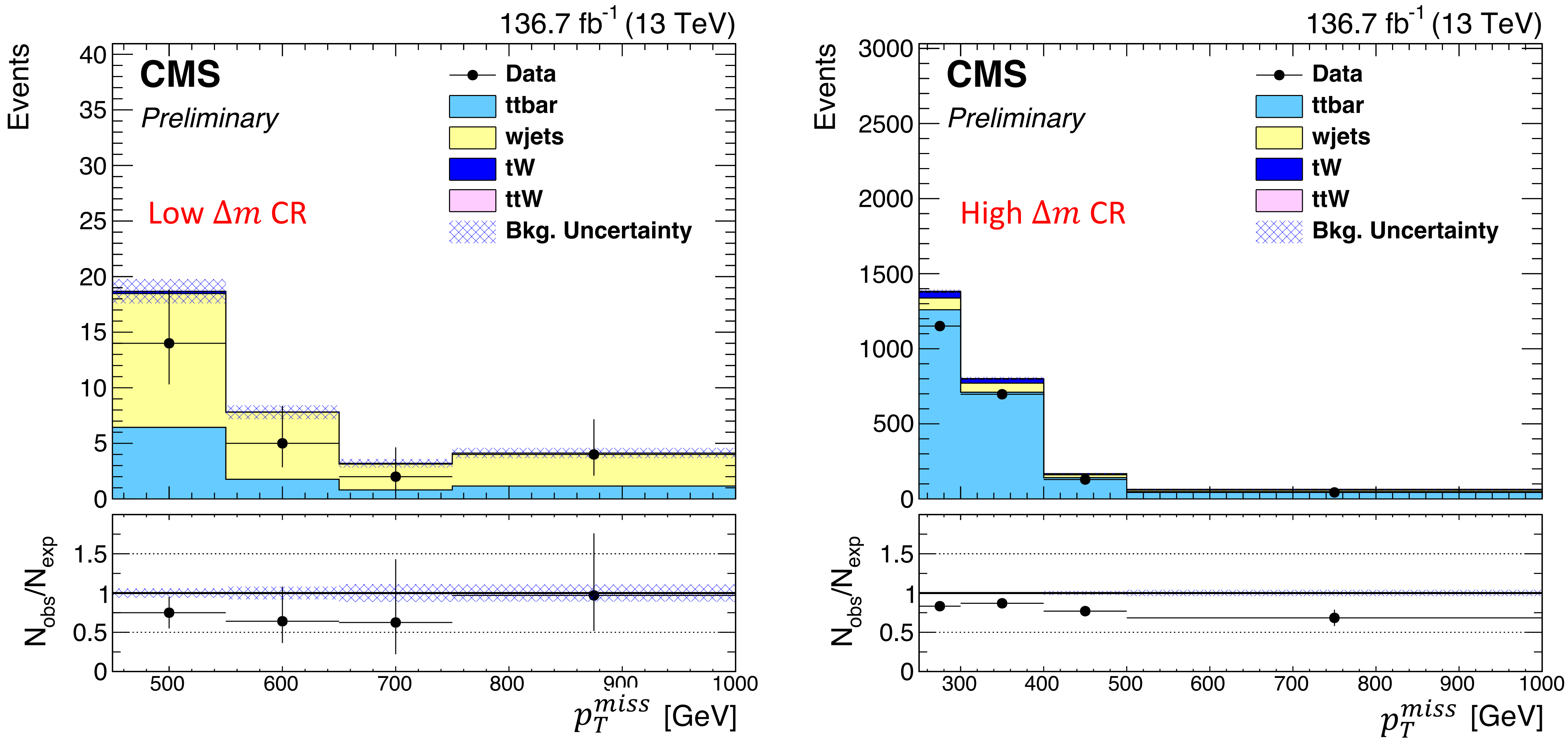
Transfer Factor Methods

LL Contribution

- Control region (CR): $N_{lep} = 1, M_T(l, p_T^{miss}) < 100$ GeV
- Search region (SR): $N_{lep} = 0$
- $N_{pred}^{LL} = \underbrace{\frac{N_{MC}(0l)}{N_{MC}(1l)}}_{\text{Transfer Factor}} \cdot N_{data}(1l)$



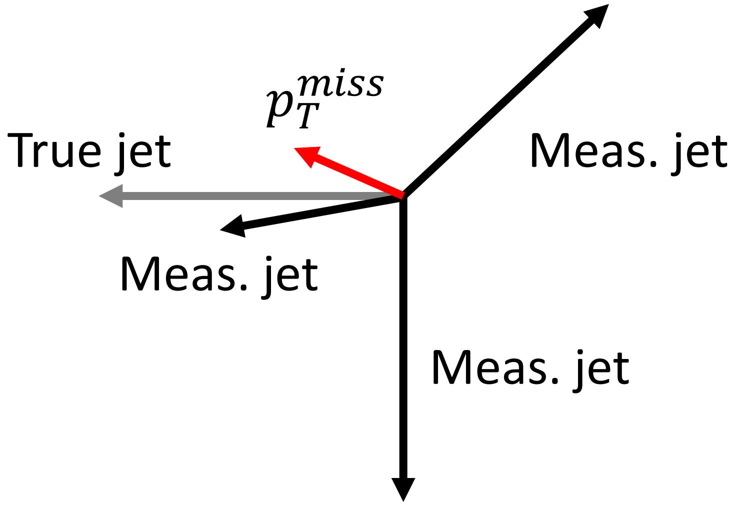
Example LL Control Region Comparison



QCD Multi-jet Background

Missing Energy from the mismeasurement of jets

- QCD Estimation used Transfer Factor method where:
  - Control Region defined by $\Delta\phi(j_{123}, \not{E}) < 0.1$
  - Transfer Factor
    - $$N_{pred}^{QCD} = \underbrace{\frac{N_{MC}^{QCD}(SR)}{N_{MC}^{QCD}(CR)}}_{\text{Transfer Factor}} \cdot (N_{data} - N_{MC}^{non-QCD})$$
  - Take MC events and do smearing (from 2 leading jets)
    - Statistical Uncertainty for the TF
    - Increasing the effective luminosity with a method called "**local smearing**"



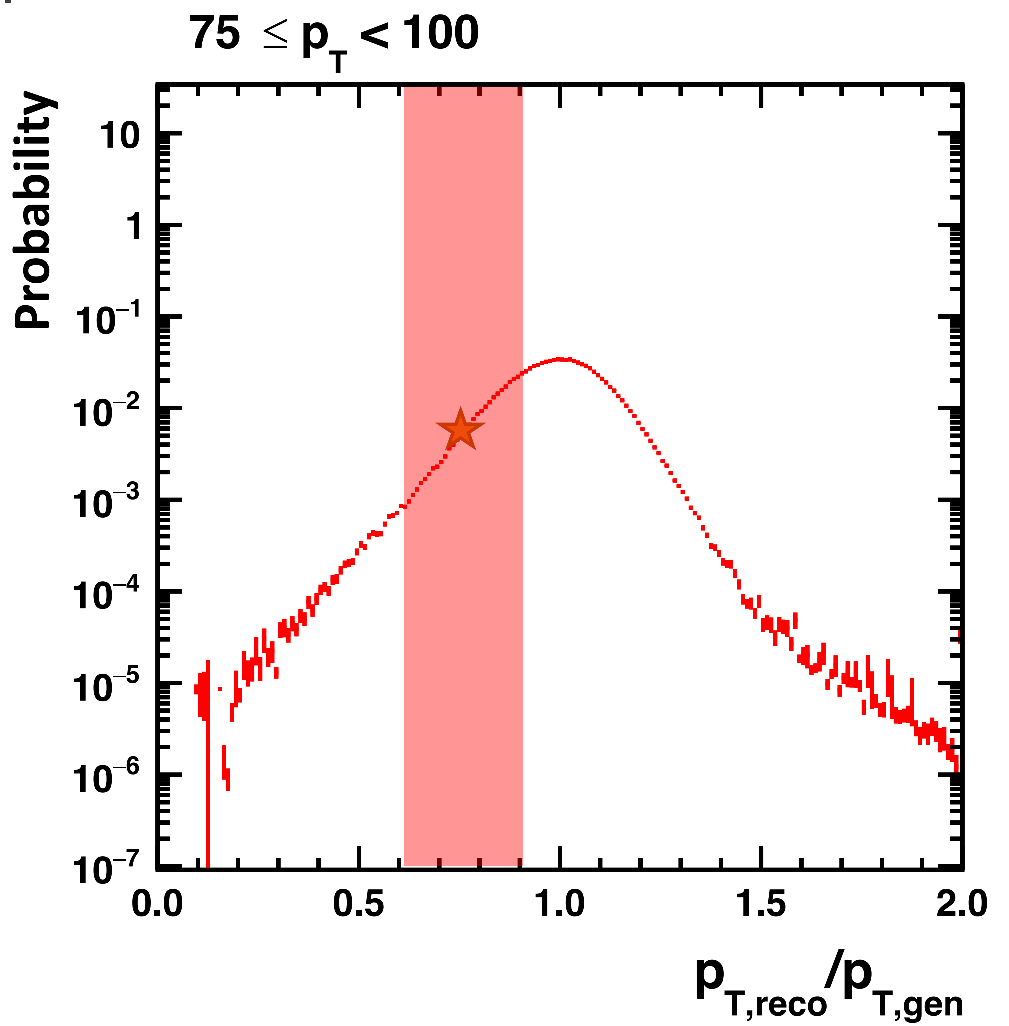
QCD Smearing Method

Methods based on the jet response (JR) function

- Parameterize jet reconstruction
- Binned in p_T and jet flavor

Local Smearing

- Consider the two leading jets
  - Start at JR for standard MC (★)
  - Sample in small window ( )
  - Recalculate variables jet$(p_T, \phi, \eta), p_T^{miss}, p_\phi^{miss}$
  - Small window → does not bias jet quantities



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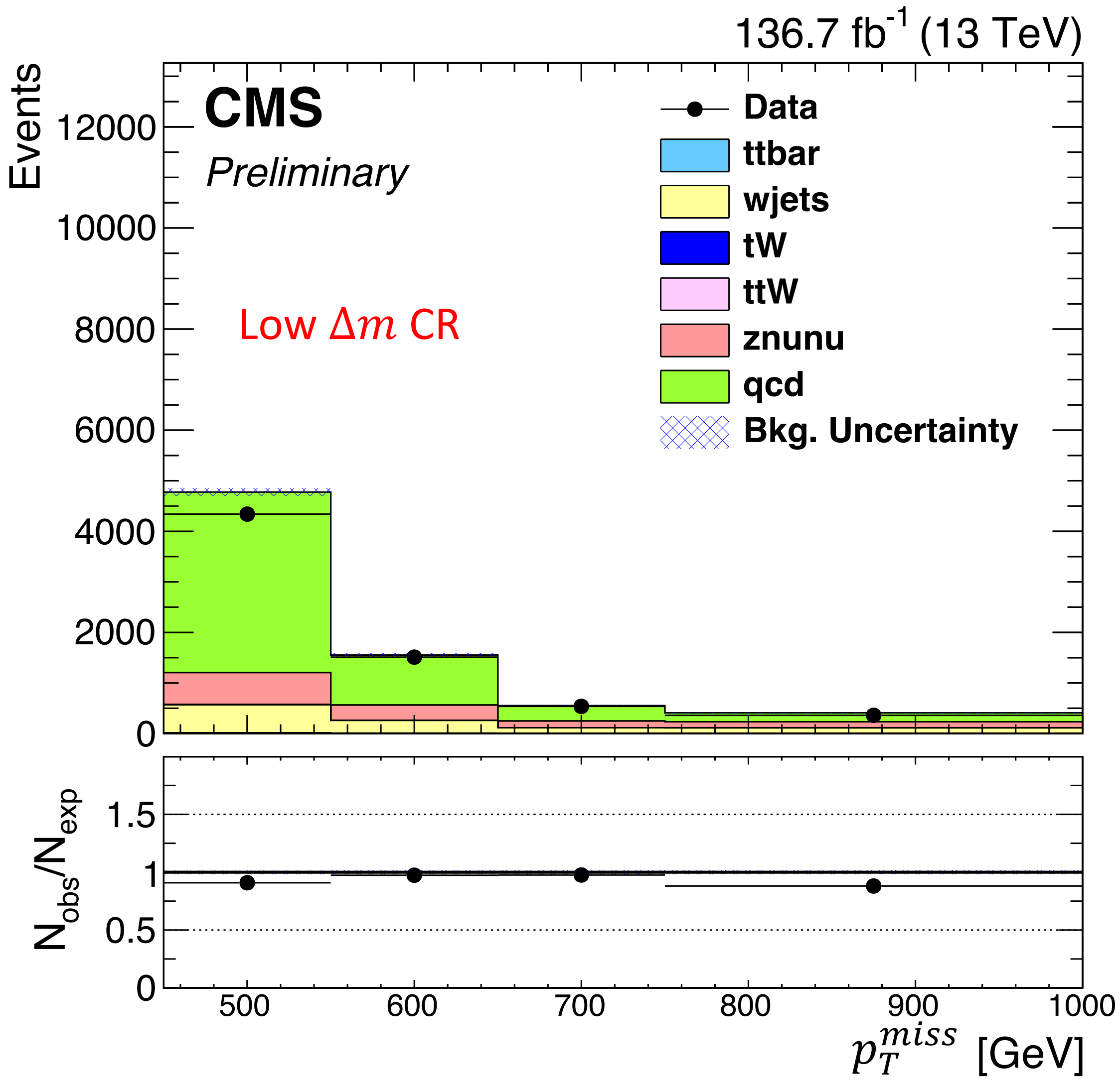
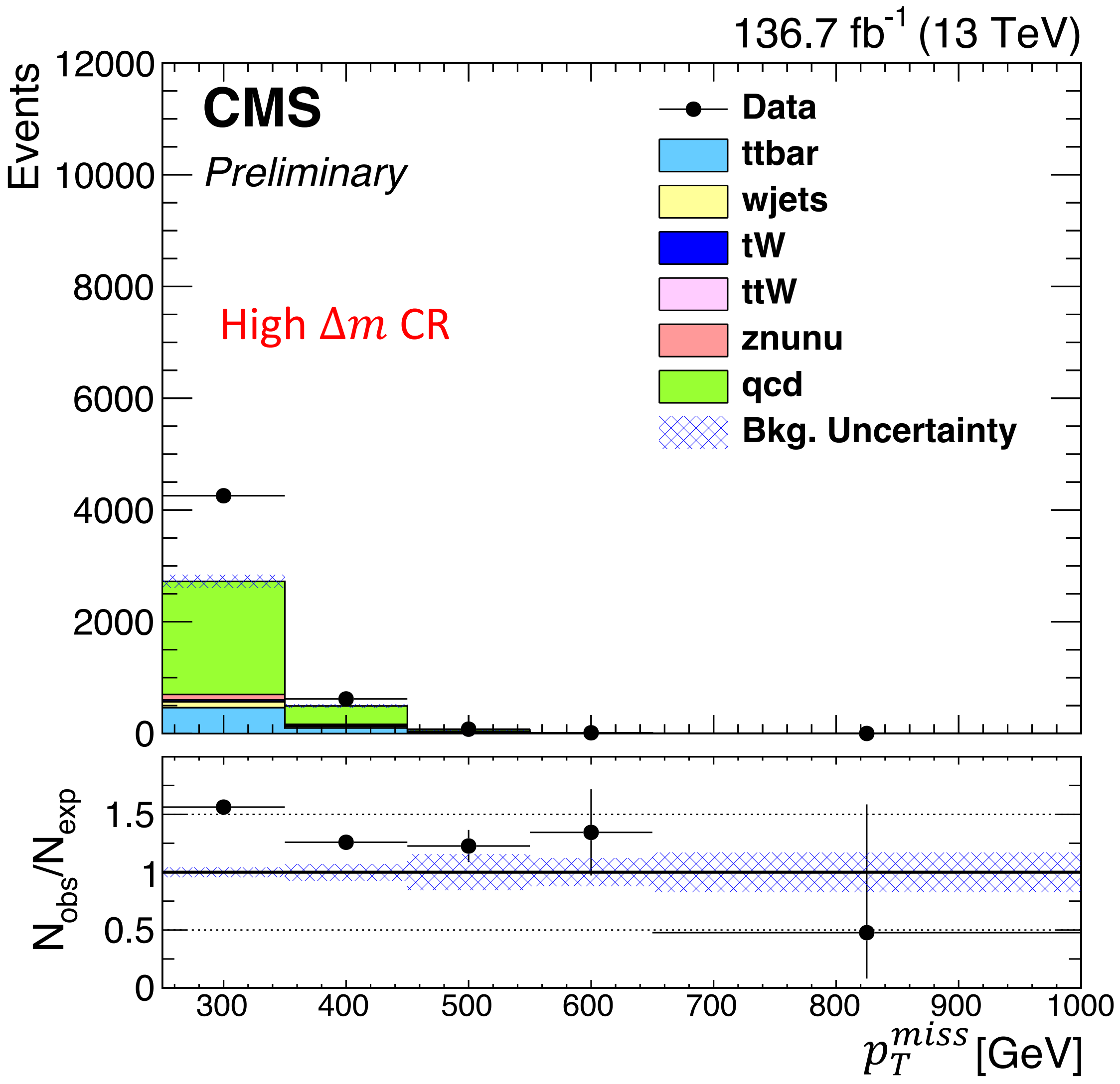
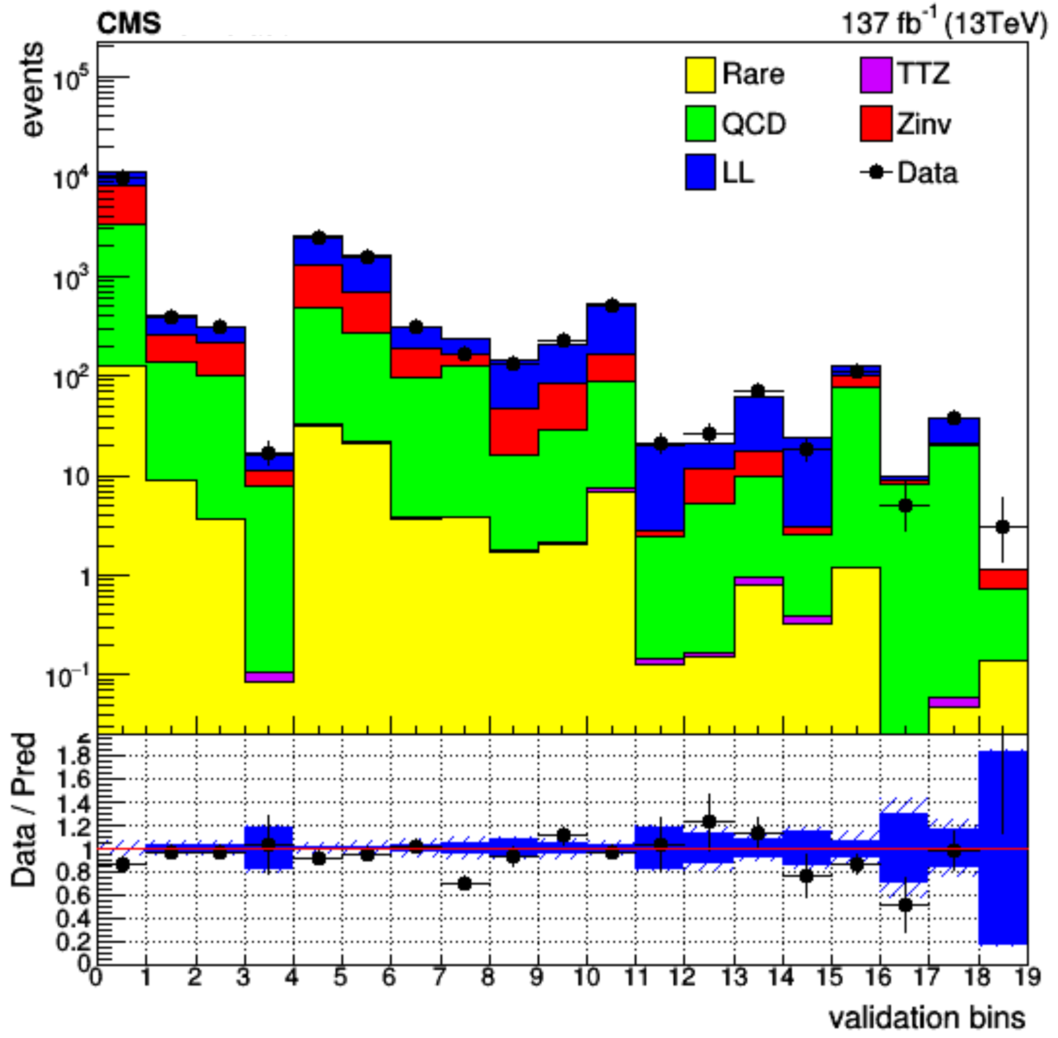




Validation Regions

Low Δm

- Validate background estimation
- $250 < p_T^{miss} < 350(400)$ GeV
- Relaxed cuts compared to search region



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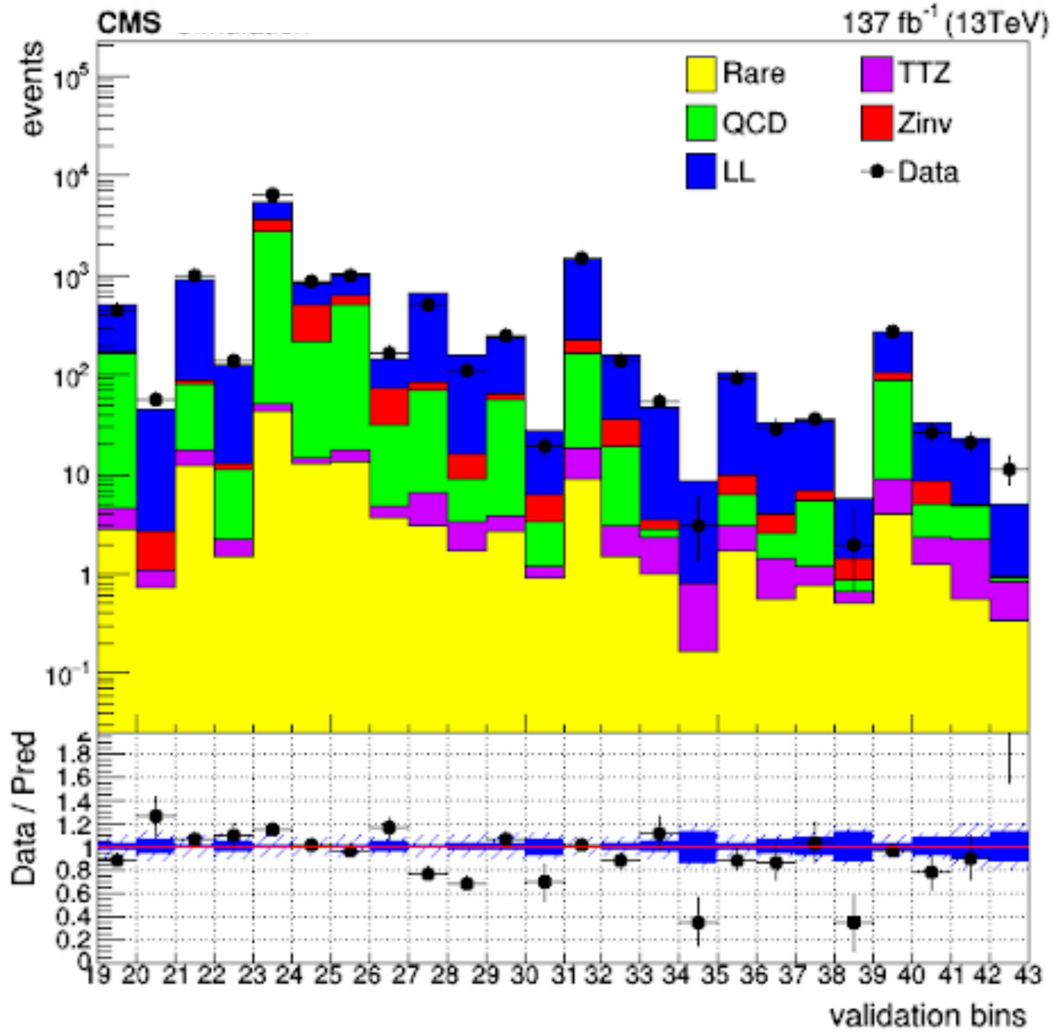
High Δm

- Validate background estimation
- $250 < p_T^{miss} < 400$ GeV
- $p_T^{miss} > 400$ GeV
- Relaxed cuts compared to search region



Higgs Combined Tool Statistics

Method for getting limits on Data, signal, and background

- Likelihood function
  - $\mathcal{L}(\mu,\theta) = \prod_i \frac{[\mu \cdot s_i(\theta)+b_i(\theta)]^{n_i}}{n_i!} e^{-[\mu \cdot s_i(\theta)+b_i(\theta)]} \prod_\kappa e^{-\frac{1}{2}\theta_\kappa^2}$
  - $\tilde{q}_\mu = -2\ln \frac{\mathcal{L}(\mu,\hat{\theta}_\mu)}{\mathcal{L}(\mu,\theta)}$
- Calculate the confidence levels for each signal region
  - $p_\mu = P\left(\tilde{q}_\mu \geq \tilde{q}_\mu^{obs} \middle| \text{signal+background}\right) = \int_{\tilde{q}_\mu^{obs}}^{\infty} f\left(\tilde{q}_\mu \middle| \mu, \hat{\theta}_\mu^{obs}\right) d\tilde{q}_\mu$
  - $1 - p_\mu = P\left(\tilde{q}_\mu \geq \tilde{q}_\mu^{obs} \middle| \text{background−only}\right) = \int_{\tilde{q}_\mu^{obs}}^{\infty} f\left(\tilde{q}_\mu \middle| 0, \hat{\theta}_0^{obs}\right) d\tilde{q}_\mu$
  - $CL_s(\mu) = \frac{p_\mu}{1-p_b}$
  - Look for $CL_s = 0.05$

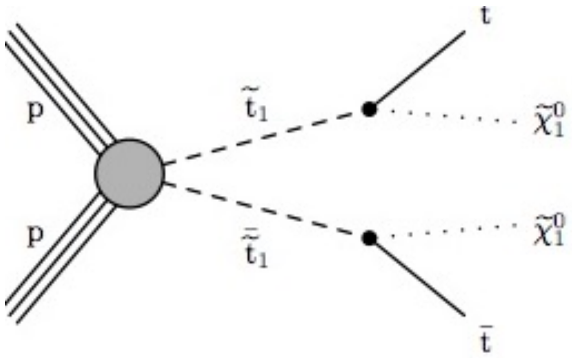
Systematics

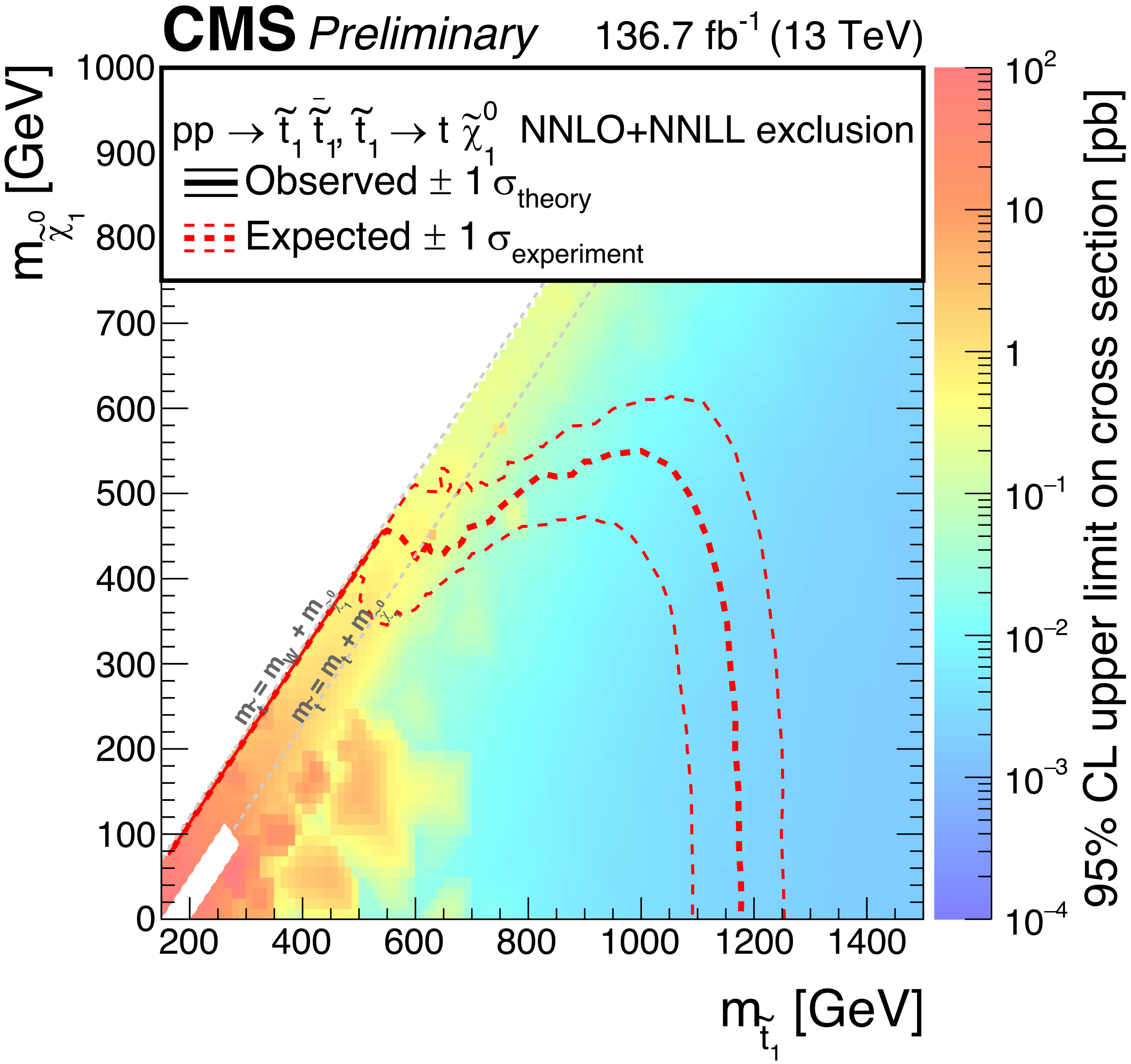
Systematic	Signal	Lost Lepton	QCD Multijet	$Z \rightarrow \nu\bar{\nu}$	Rare
Initial State Radiation	~15-30%	~1-5%	----	----	----
Jet Energy Correction	~2-4%	~1-3%	~4-7%	~2-14%	~4-20%
Pileup	~1-5%	~1-5%	~1-3%	~1-3%	~2-7%
B tagging	~2-8%	~1-7%	~3-5%	~1-10%	~1-8%
Soft b-tagging	~1-4%	~1%	~1-4%	~1-5%	~1-4%
Resolved Tops	~1-7%	~1-9%	~1-25%	~8-16%	~5-12%
Merged Tops	~1-8%	~1-7%	~1-10%	~4-9%	~1-10%
Merged W	~1-10%	~1-8%	~1-5%	~1-14%	`1-8%

Log Normal Distribution

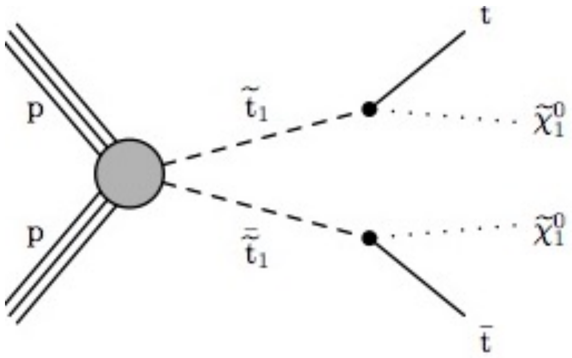
$$\rho(\theta) = \frac{1}{\sqrt{2\pi}\ln(\kappa)}\exp\left(-\frac{(\ln(\theta/\widetilde{\theta}))^2}{2(\ln\kappa)^2}\right)\frac{1}{\theta}$$

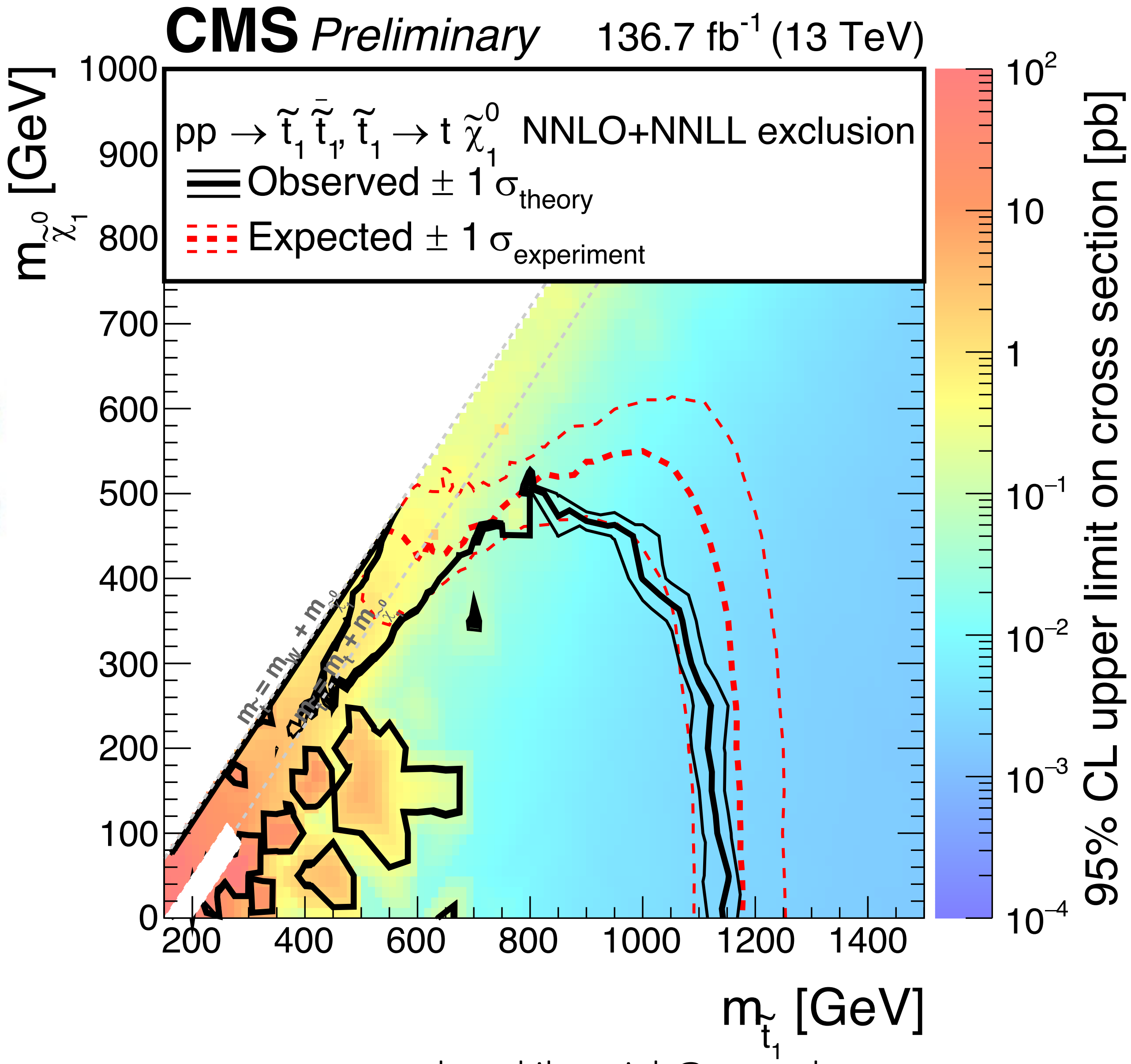
Expected Limits



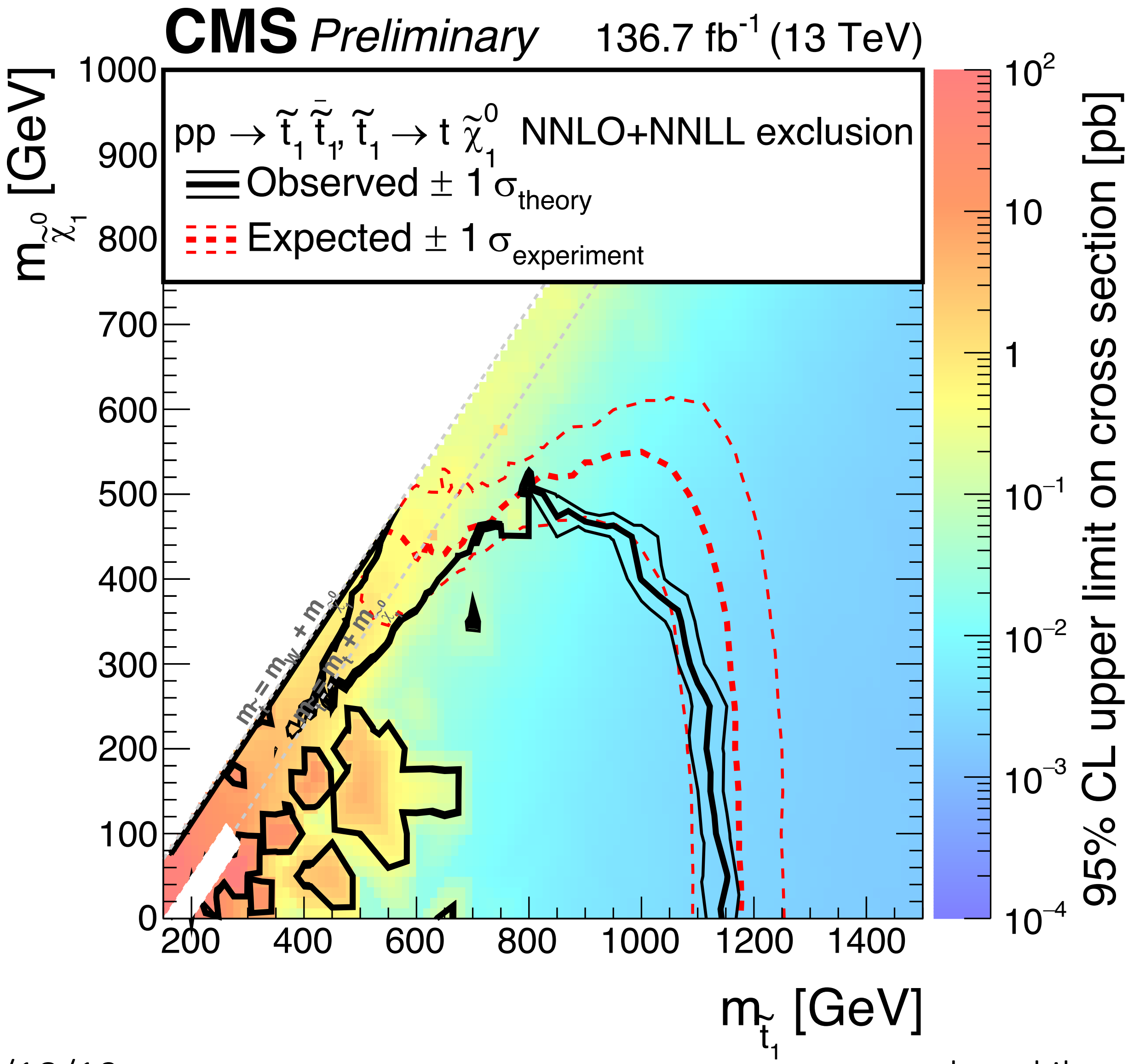


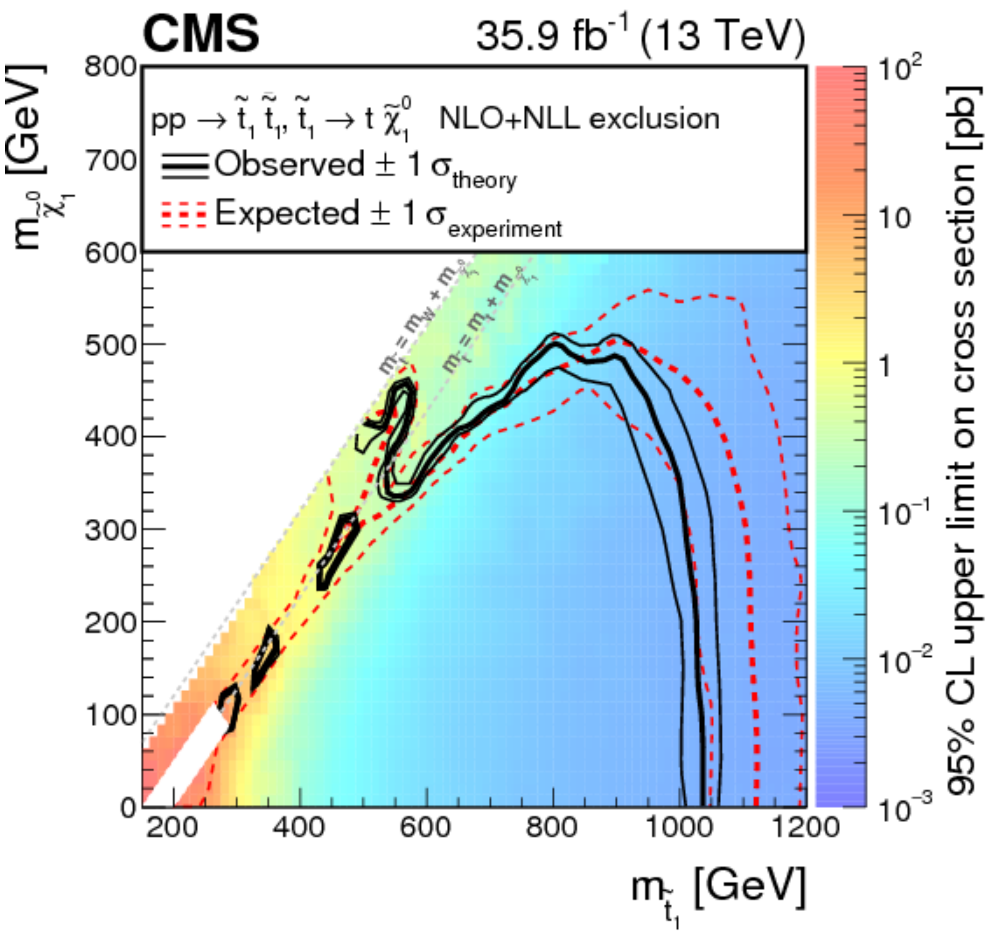
Observed Limits



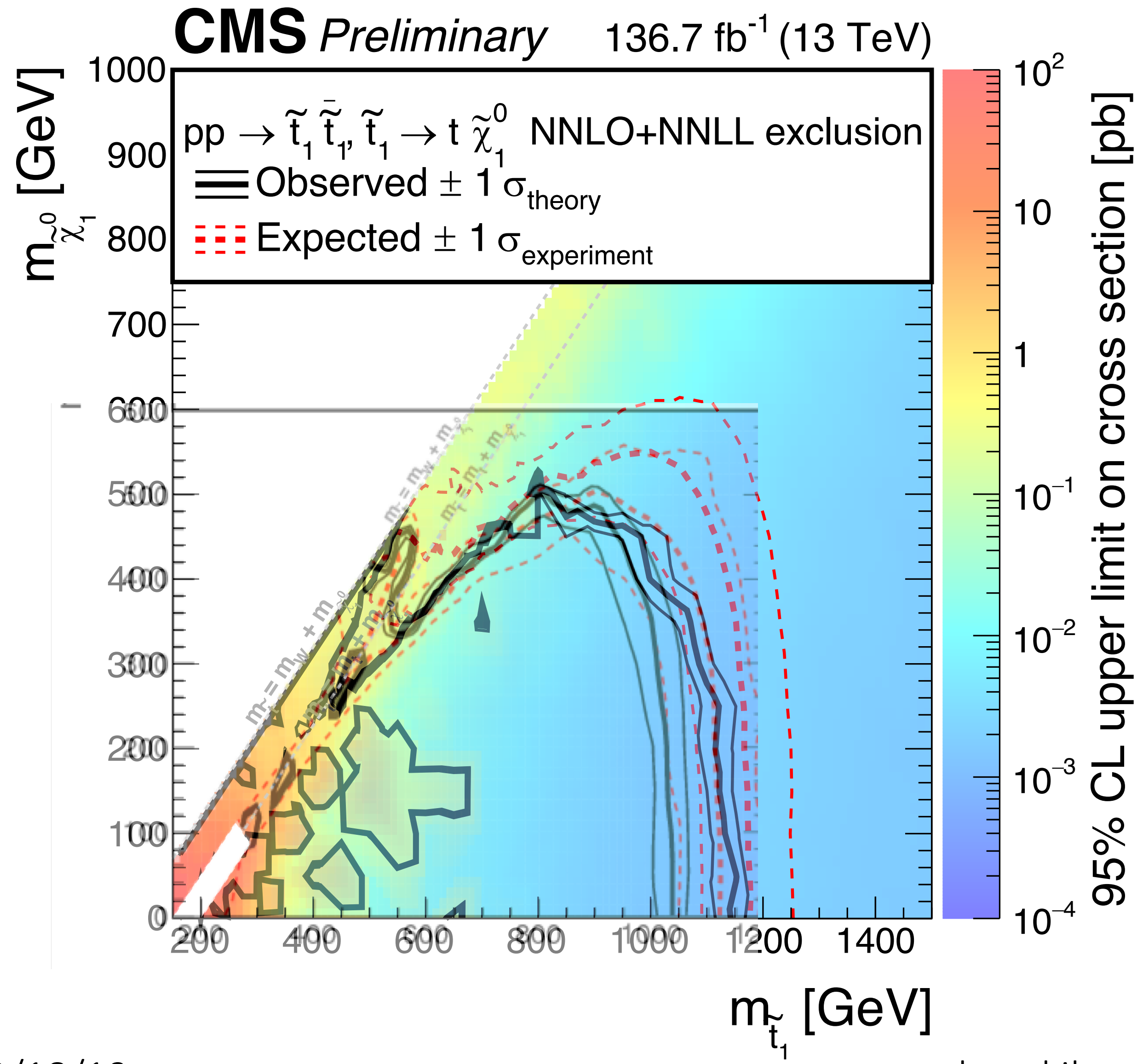


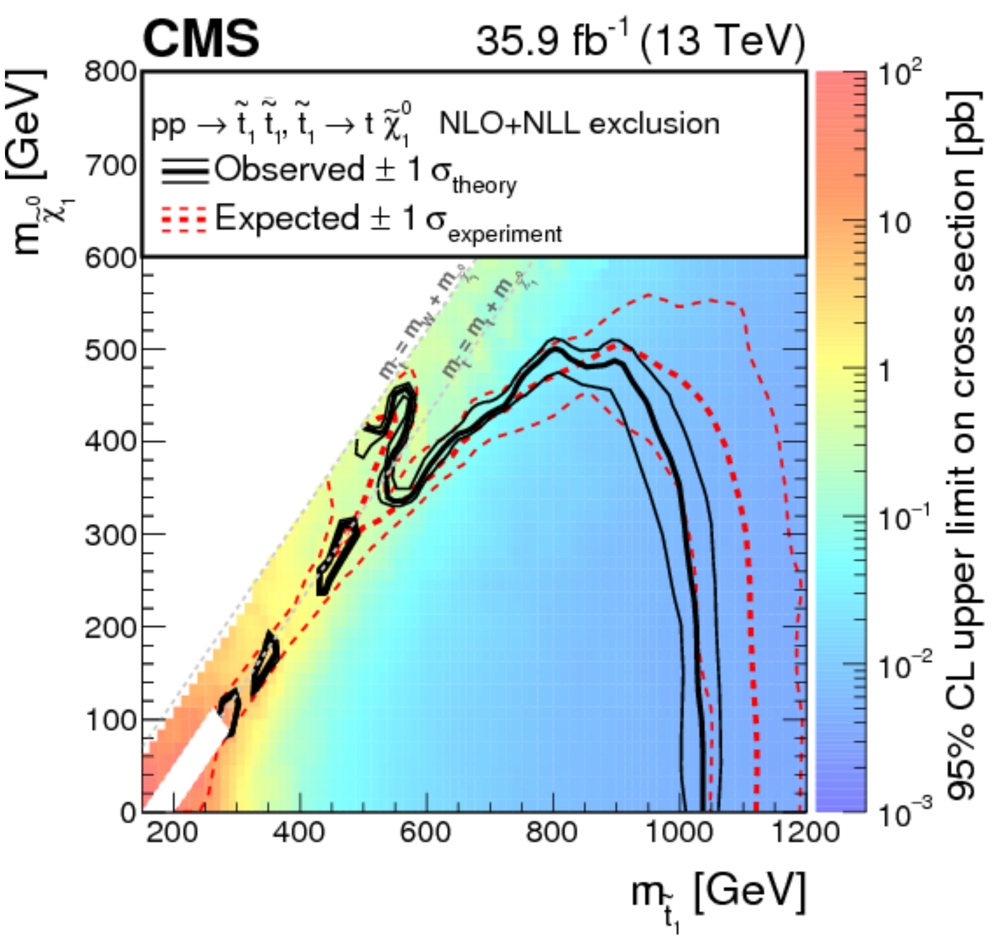
Comparing with Previous Analysis



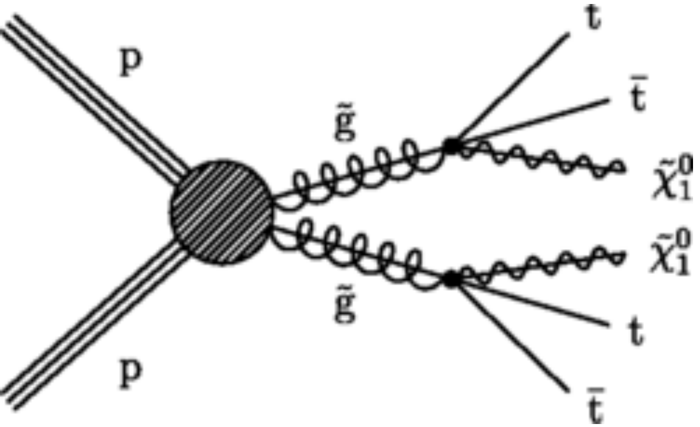


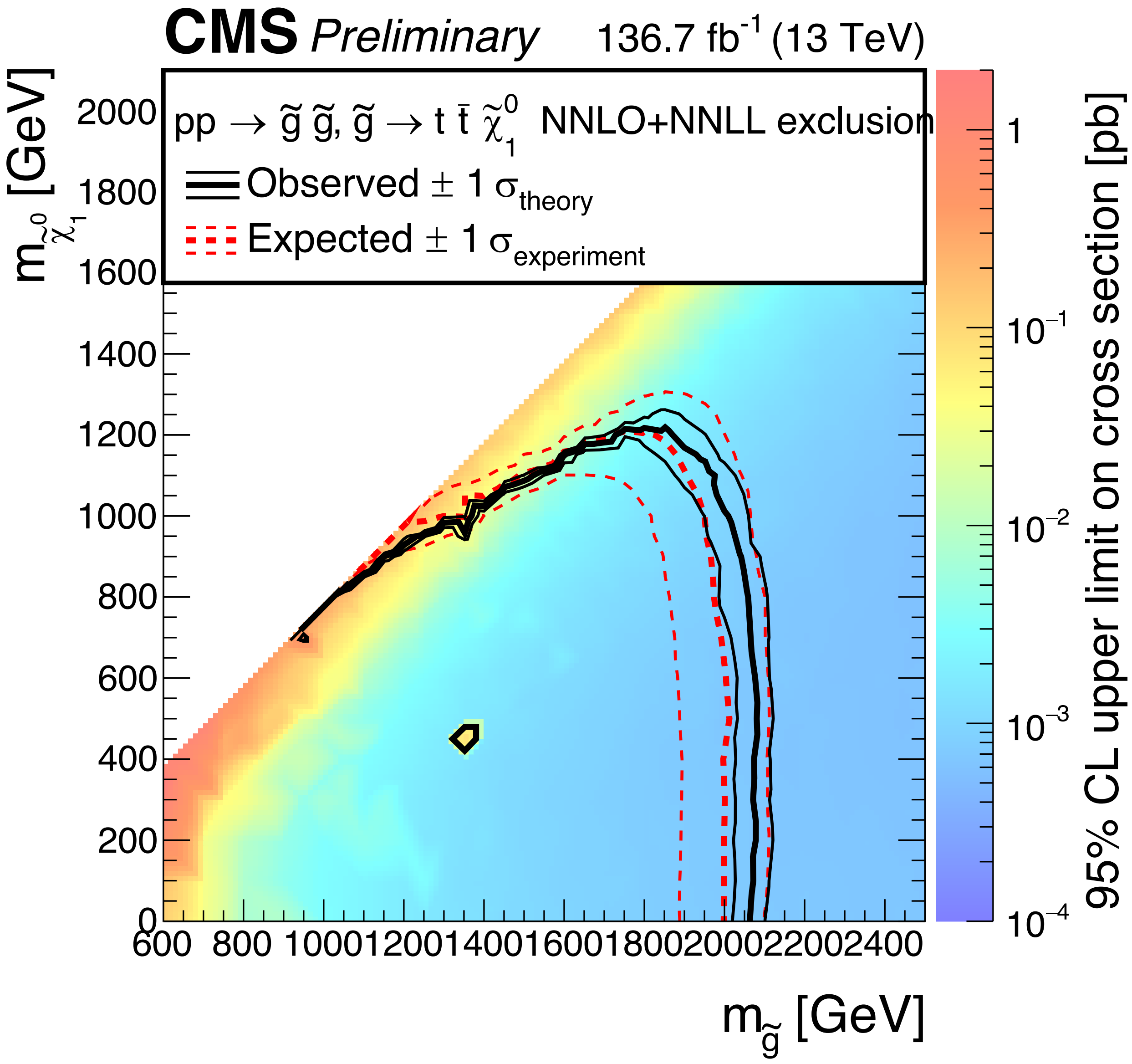
Comparing with Previous Analysis



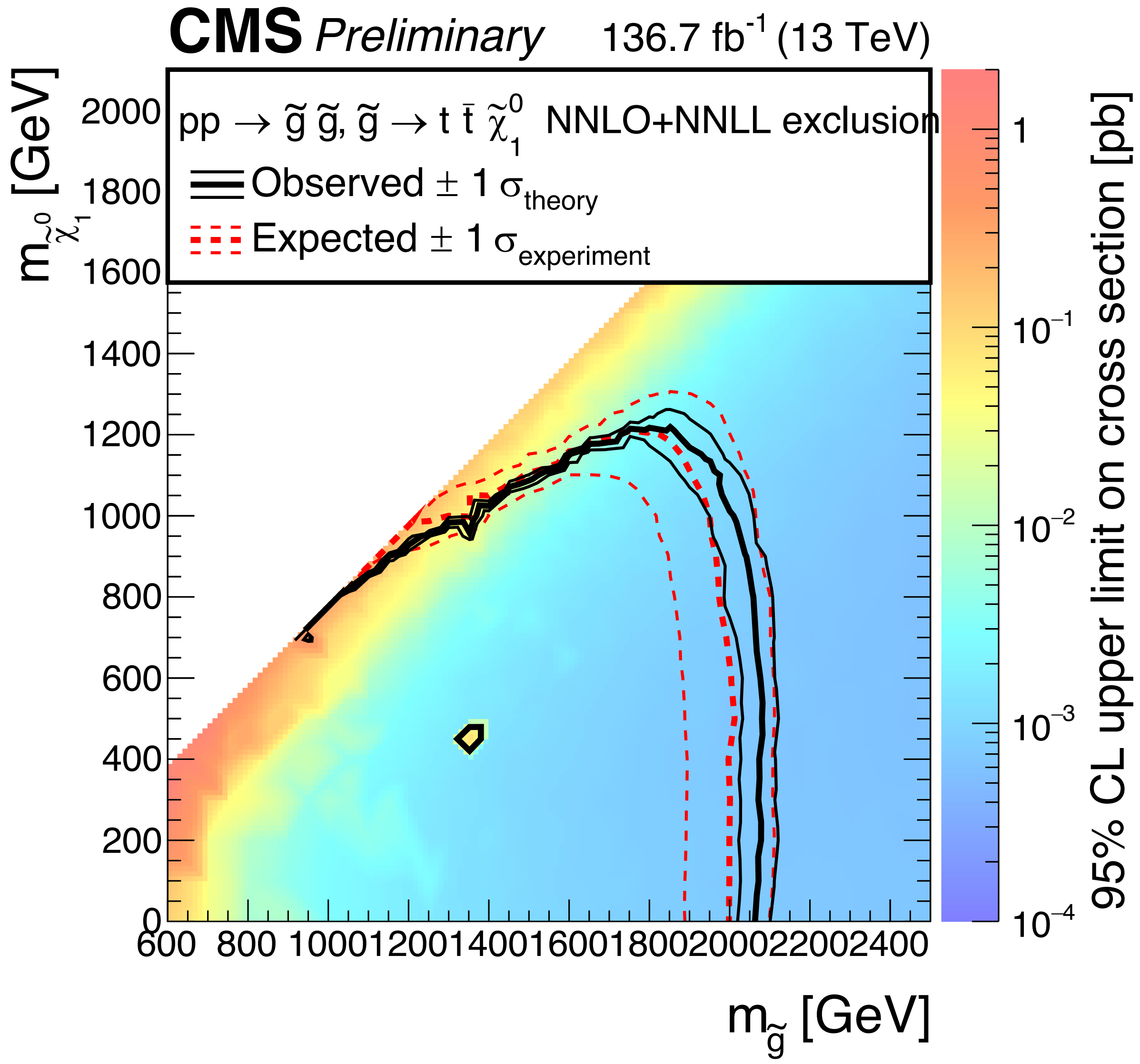


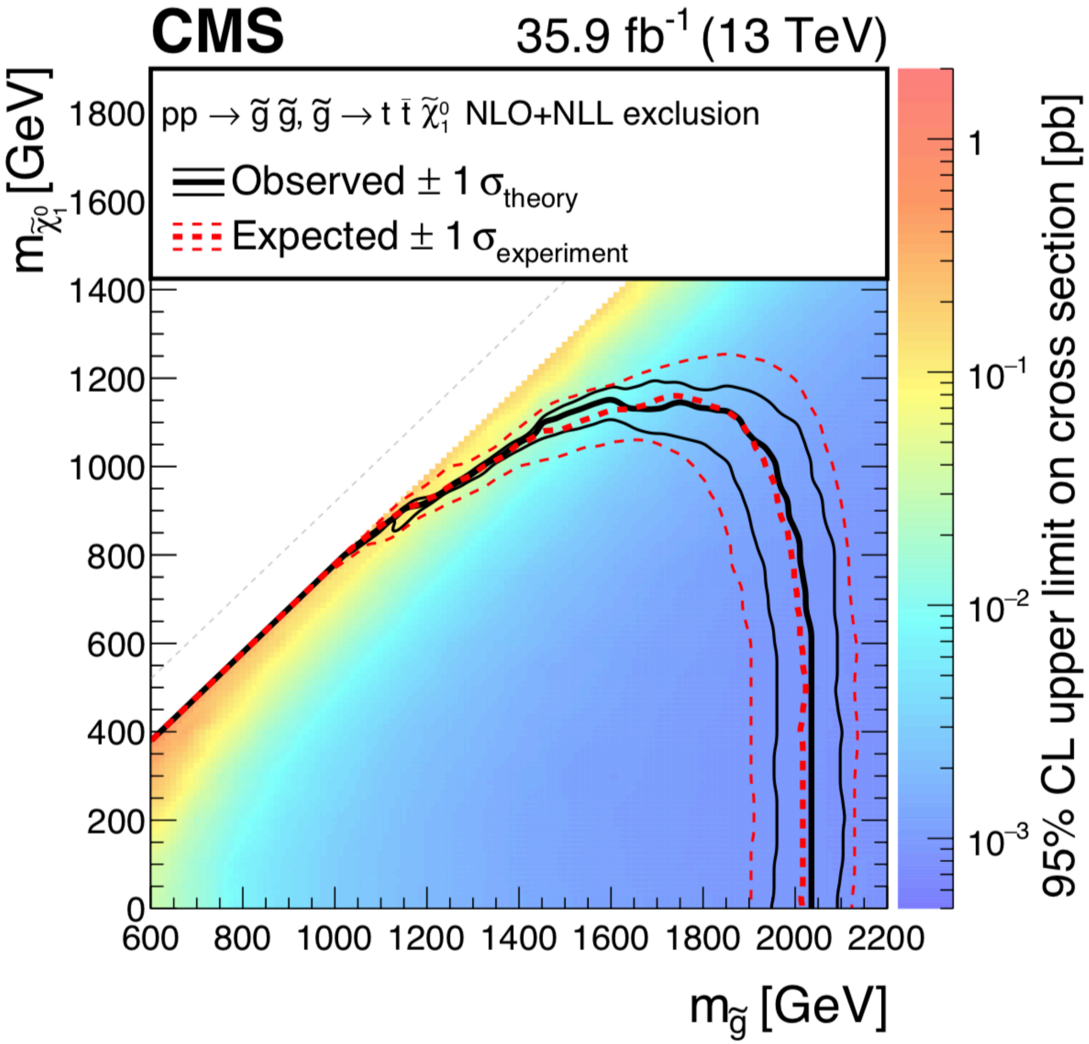
Observed Limits



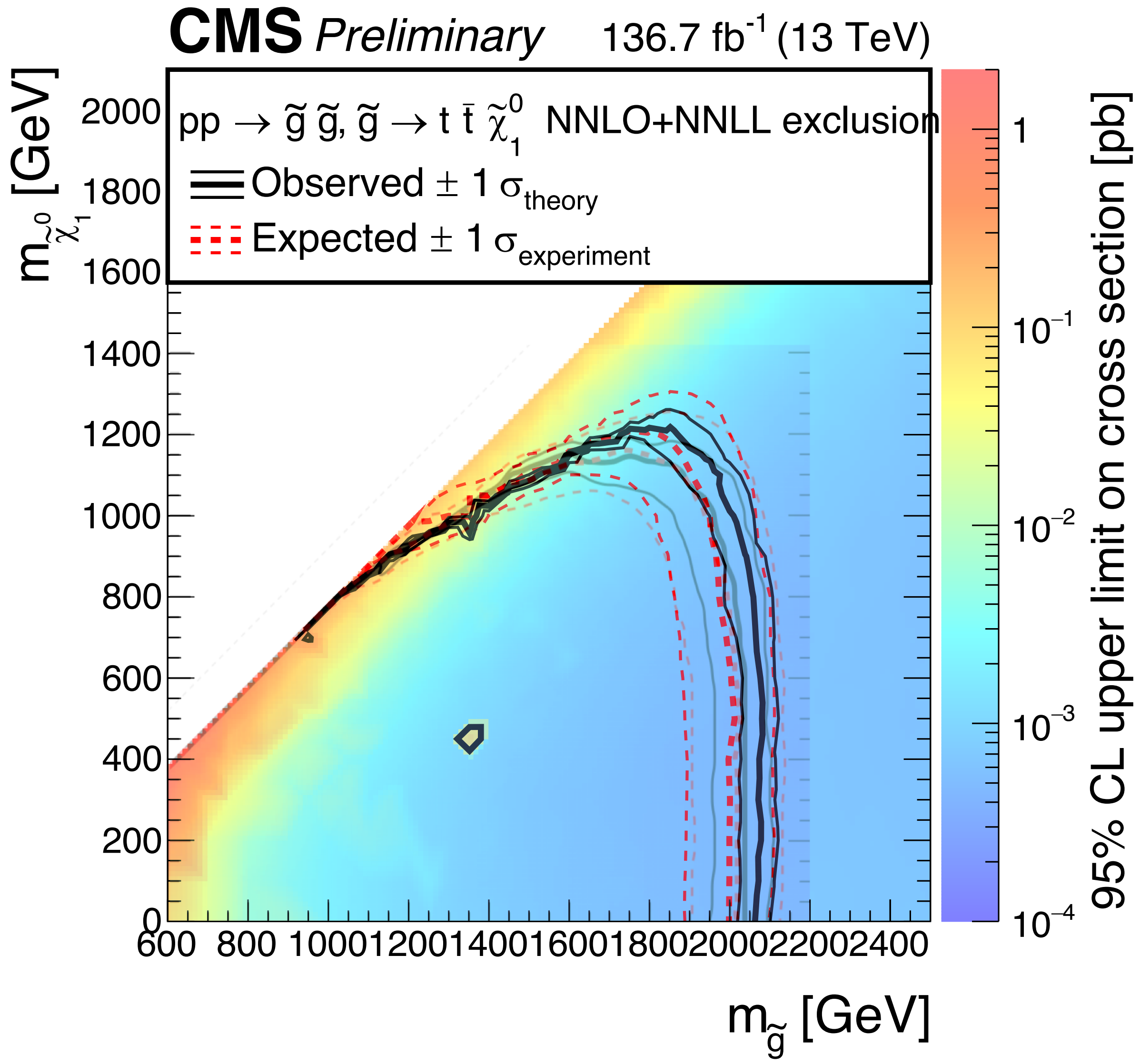


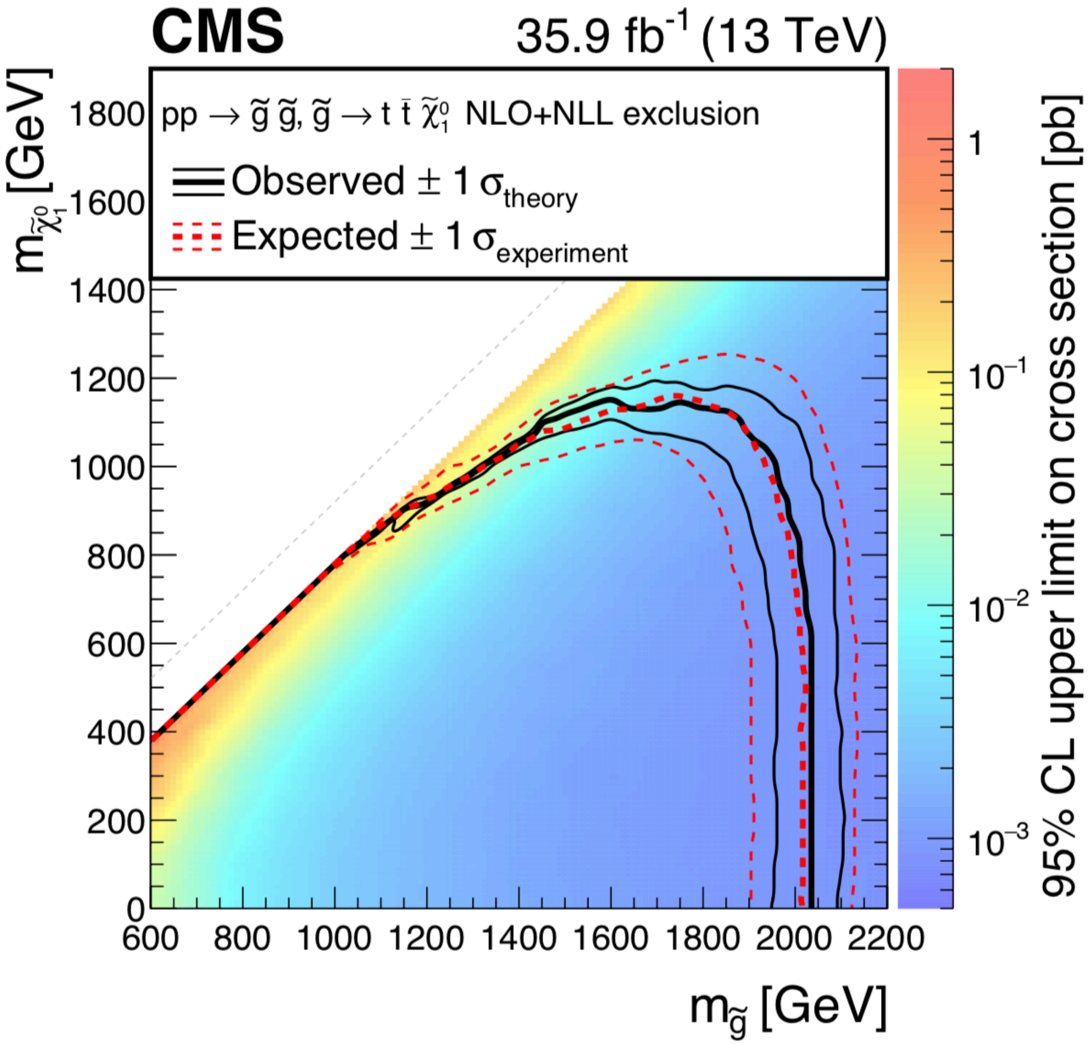
Observed Limits





Observed Limits





Summary

Completed analysis on $\tilde{t} \rightarrow t + \tilde{\chi}_1^0$ and $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$

- 137 /fb of data from Run 2 of the LHC
- Comprehensive search for top squark and SUSY
- Improved limits from previous studies
  - $\tilde{t} \rightarrow t + \tilde{\chi}_1^0$: $\mathrm{m}_{\tilde{t}} = 1175$ GeV at minimal neutralino mass
  - $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$: $m_{\tilde{g}} = 2000$ GeV at minimal neutralino mass
- Sensitive to low mass spectra

Acknowledgements

Advisor: Karl Ecklund

Committee Members: Paul Padley and David Scott

Rice Bonner Lab:

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- James Zabel
- Jamal Rorie
- Wei Shi
- Sven Dildick
- Matthew Decaro

CMS Collaboration

Thanks Friends and Family

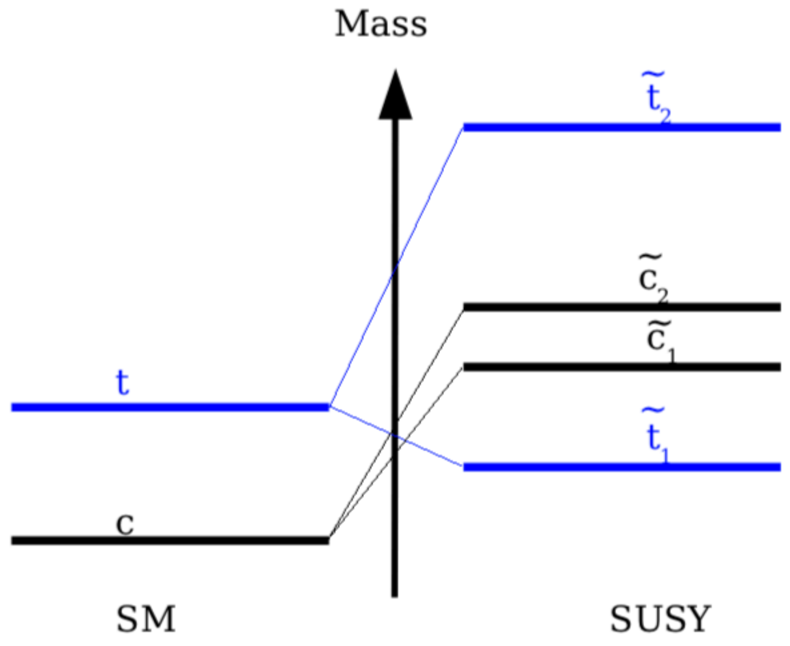
Backup

$\tilde{t}_1$: Dynamic Reason to be at bottom of sParticles

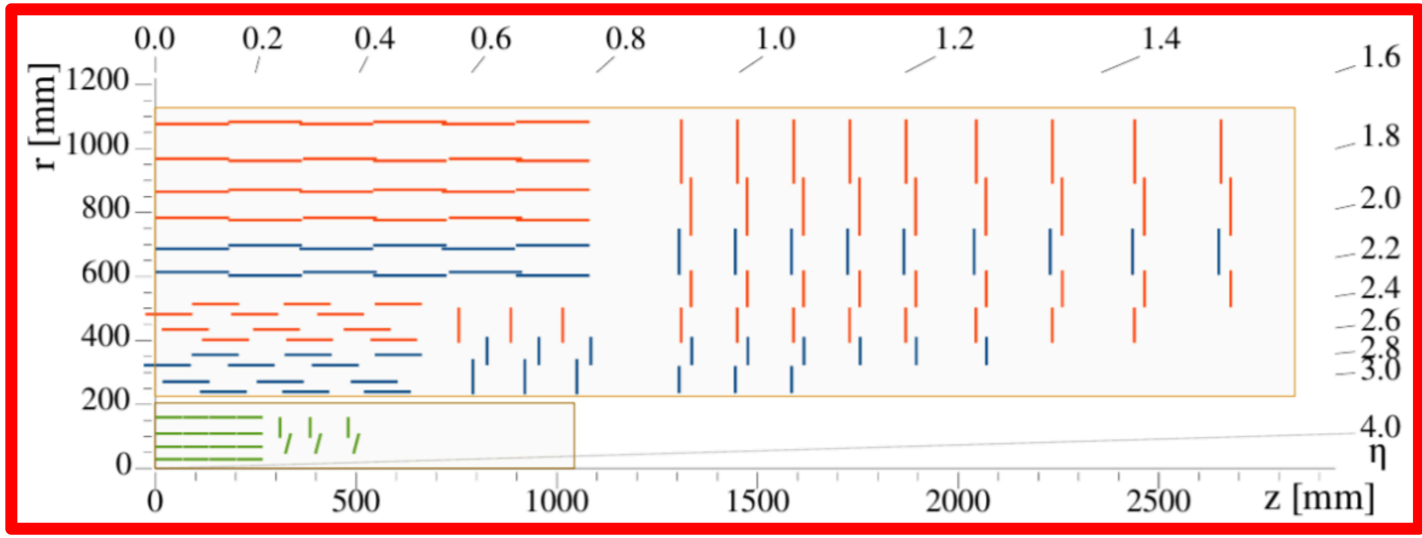
Quark left and right superpartners can strongly mix to form mass eigenstates

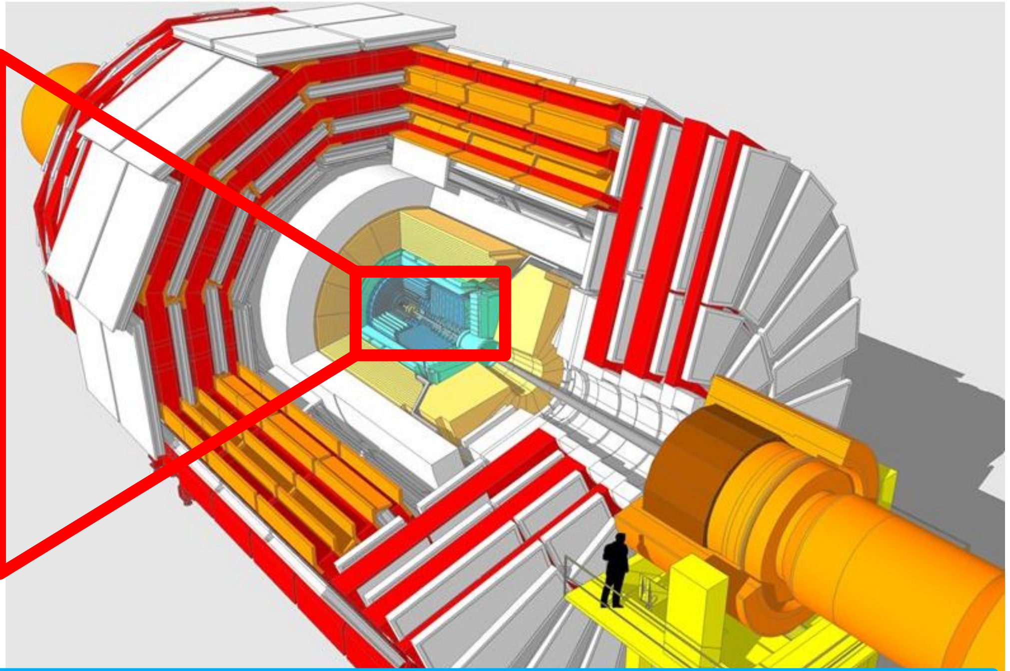
- $M^2_{\tilde{t}_1} = \begin{pmatrix} \widetilde{M}^2_{Q_3} + M_t^2 + M_Z^2\left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right)cos2\beta & v(a_t^* sin\beta - \mu y_t cos\beta) \\ v(a_T^* sin\beta - \mu y_t cos\beta) & \widetilde{M}^2_{\tilde{u}_3} + M_t^2 + \frac{2}{3}M_Z^2\sin^2\theta_W cos2\beta \end{pmatrix}$

- Strong mixing in the stop sector
- Could lead to $\tilde{t}_1$ being the lightest squark



The Tracker Detector





Outer Tracker

- Active area: 200 m^2, 15148 modules
- 10 layers in barrel region
- 9 + 3 in inner disks and endcaps
- Analog readout

Phase 1 Pixel Tracker

- 4 barrel layers
- 3 endcap disks on each side
- 124 million pixel channels
- Digital Readout

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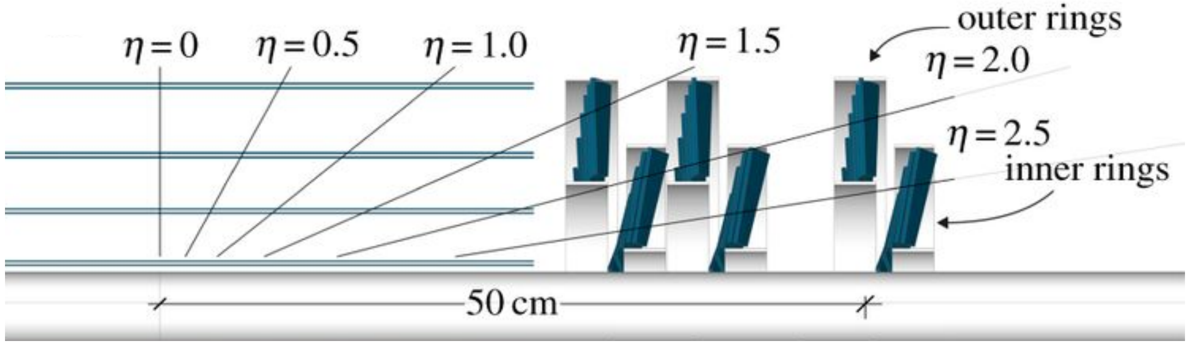
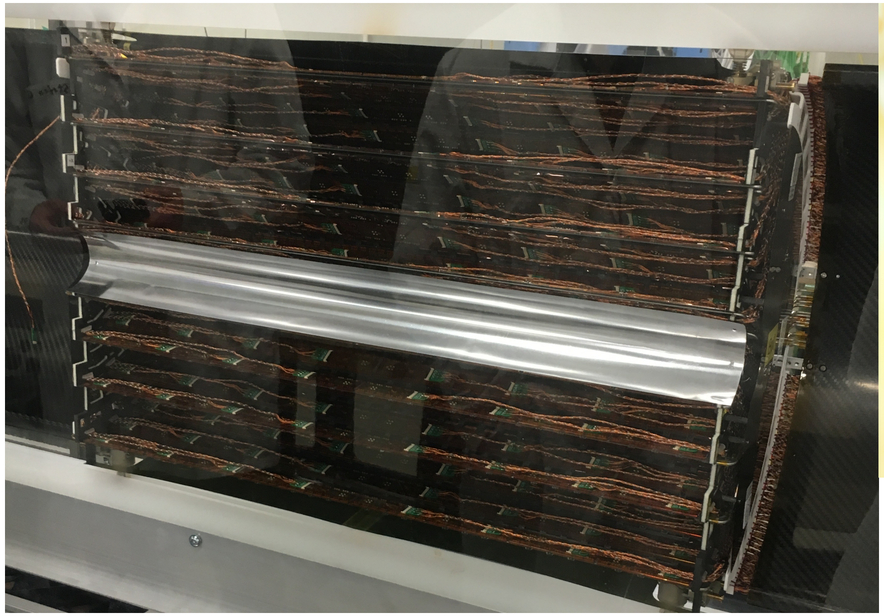
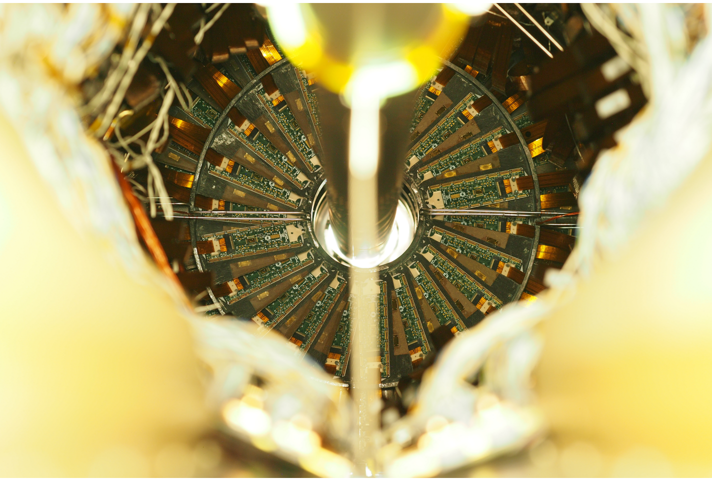
Phase 1 Pixels

Replaced in winter 2016/2017

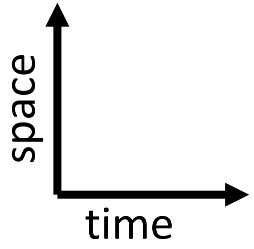
- Approximately 1 m long
- Designed for peak luminosity of $2.5 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ with 50 ns bunch crossings
- Analog → digital
  - New data acquisition (DAQ)
- DCDC powering
- CO_2 cooling
  - Light weight
  - Cost effective
- Layer 1 closer to beam line
  - 43 mm to 30 mm
- Layer 4 extends to 160 mm





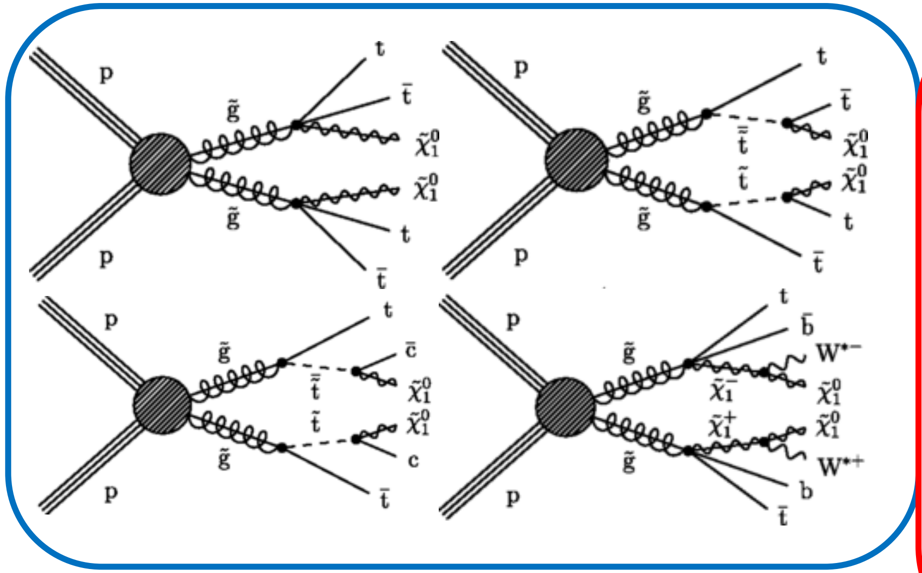


Simplified SUSY Models

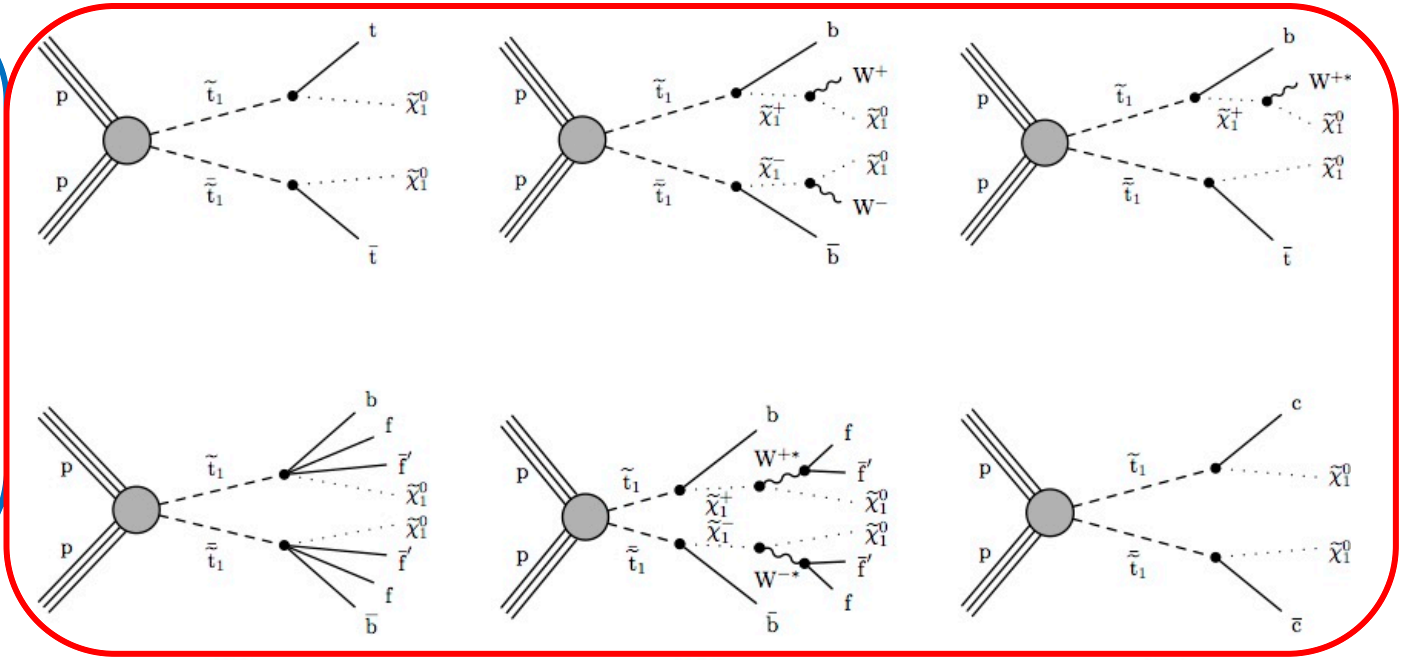


- Looking at inclusive models for a most general stop search

Gluino Mediated Stop Production

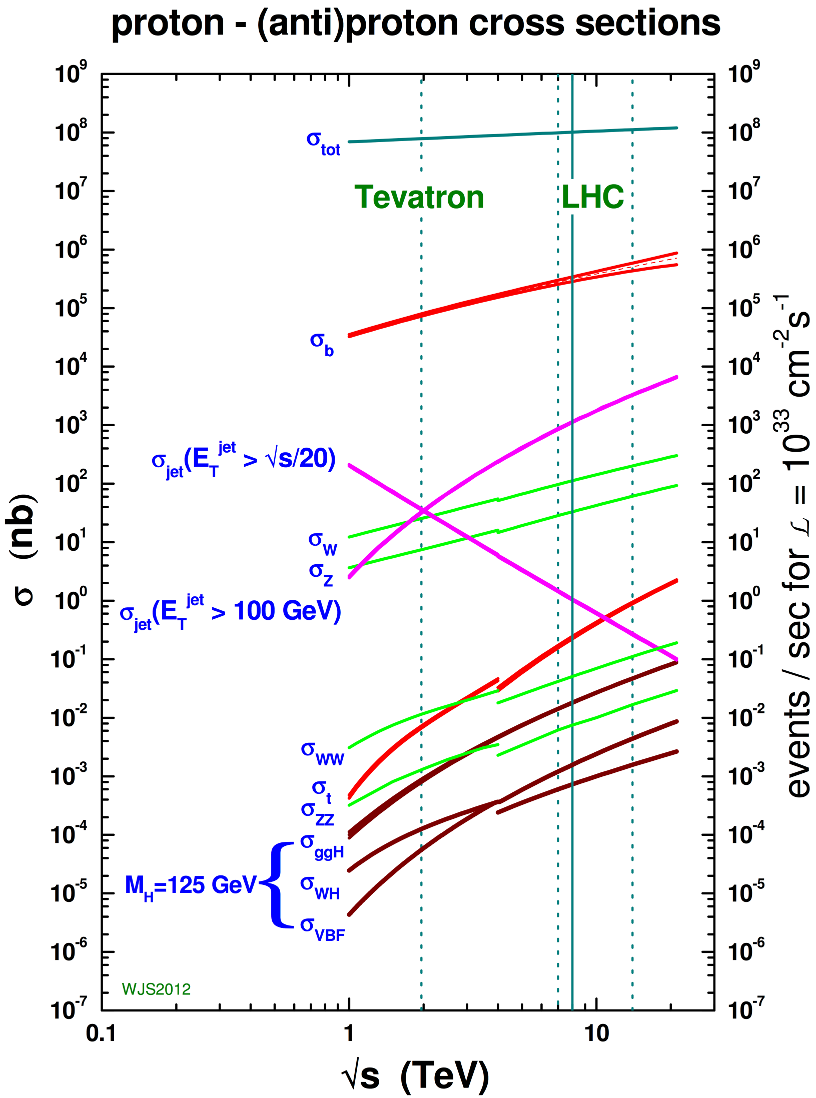


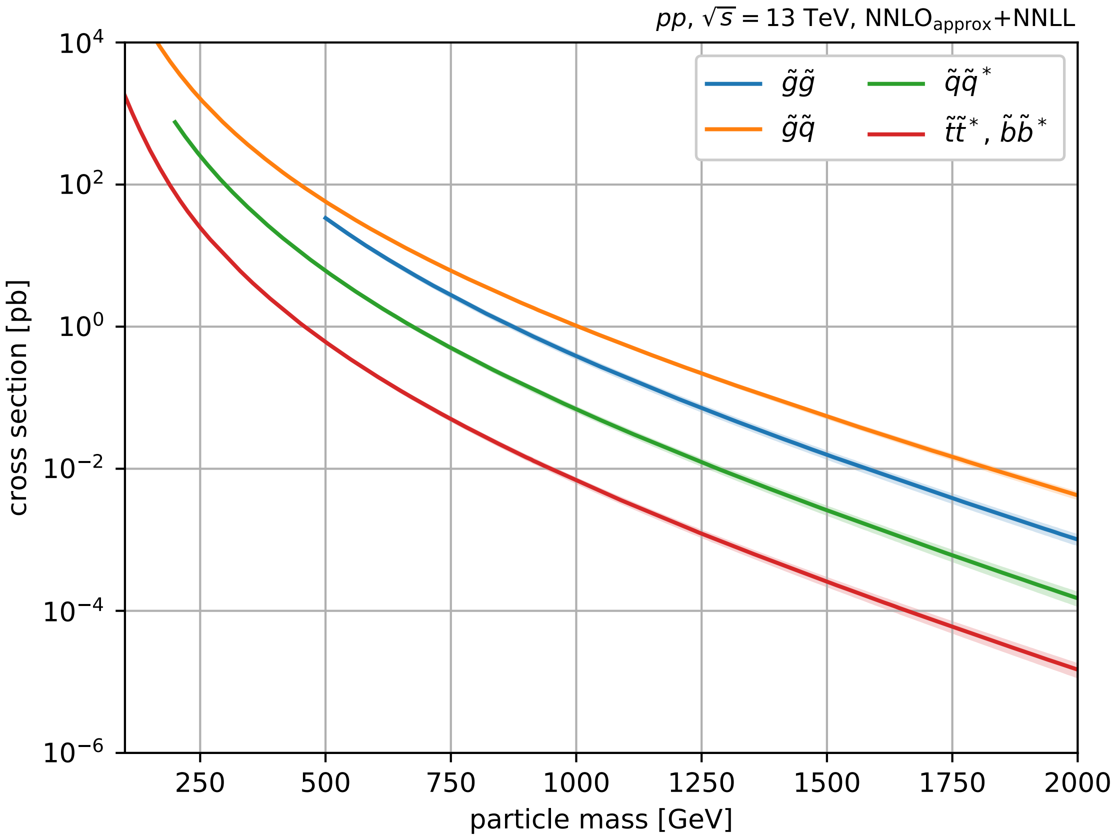
Direct Stop Production



Stop Cross Section

Cross section-probability that two particles will collide and react a certain way





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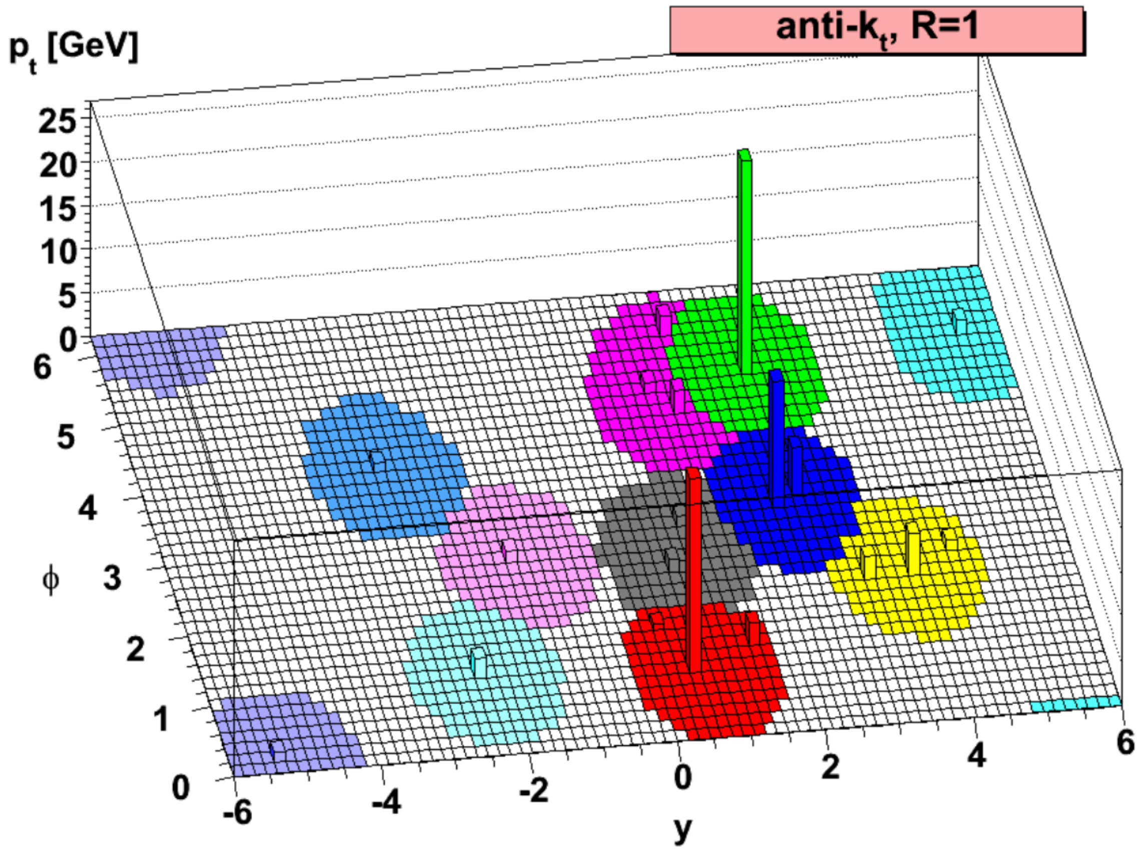
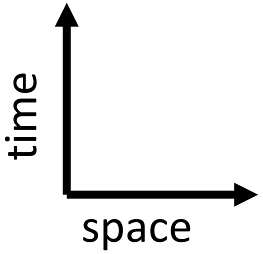
Anti-kT Algorithm

Distance calculation

- $d_{ij} = \min(k_{Ti}^{-2}, k_{Tj}^{-2}) \frac{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}{R^2}$
- $d_{iB} = k_{Ti}^{-2}$
- Infrared safe
- Circular jet area

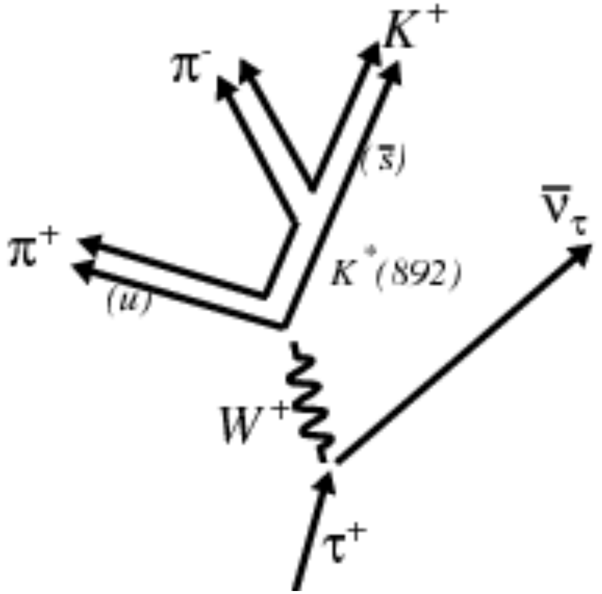


Tau Identification



Tau Decays are Interesting

- 17% of decays to leptons
- 51% is 1 prong hadronic decays
- 15% is 3 prong hadronic decays
- Identify taus
  - Isolated tracks using charged hadrons
  - TauPOG Neural Network



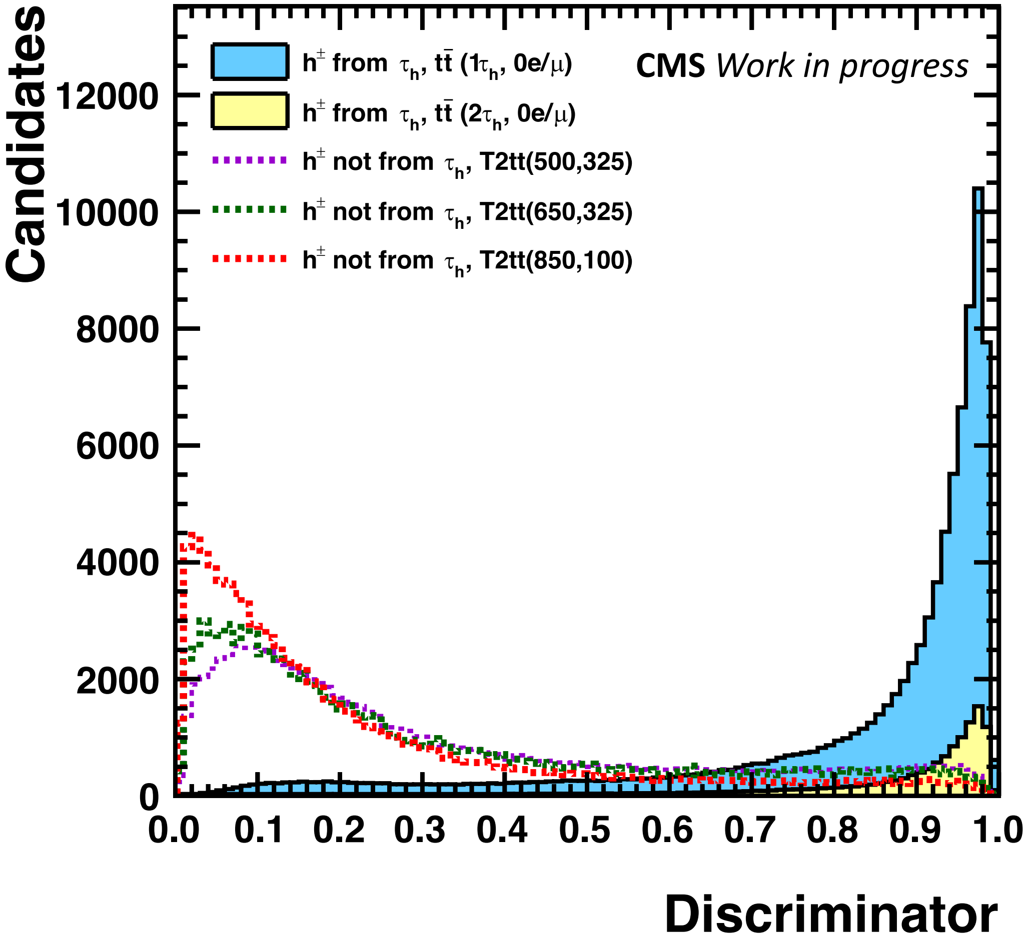
Identification of Leptons

Isolation Methods

- Electrons and muons are isolated
  - Measurements in Electromagnet Calorimeter and Muon Chambers, respectively
- Using recommendations by CMS

Hadronic Taus

- Looking at isolated charged hadrons
- Boosted Decision Trees (BDT)
- Training is matched gen level taus from 2017 TTbar simulation
- Good discrimination between taus and other particles



Tau MVA

Comparison of three hadronically decaying tau tagging methods

- Custom MVA identifying charged hadron candidates
  - Custom BDT trained on ttbar 2017 samples to identify hadronically decaying taus
- Isotrack using cut-based methods
- Isotrack+tauPOG identification
- Veto percent $= 1 - \frac{N_{\tau=0}}{N_{\tau\geq 0}}$
- Efficiency $= \frac{(N_{\tau>0}\ \&\&\ N^{gen}_{\tau>0})}{N^{gen}_{\tau>0}}$

	ttbar 1-lep Background		T2tt(850, 100)		T2tt(500, 325)	
Methods	Veto Percentage	Veto Efficiency	Veto Percentage	Veto Efficiency	Veto Percentage	Veto Efficiency
Custom MVA	32.2%	57.7%	6.5%	10.9%	27.6%	39.4%
IsoTrack	21.3%	37.9%	2.6%	6.6%	8.9%	22.6%
IsoTrack + TauPOG	29.0%	49.1%	7.2%	22.6%	14.6%	37.3%

Baseline Selection

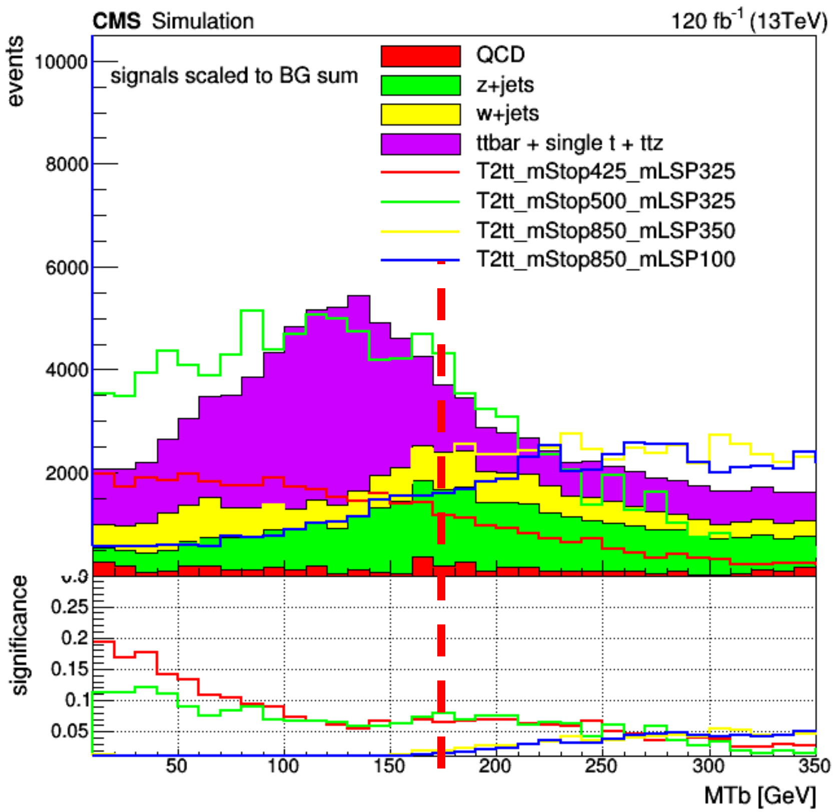
- Lepton Selection
  - Veto ID electron: $p_T > 5$ GeV, $|\eta| < 2.5$
  - Loose muon: $p_T > 5$ GeV, $|\eta| < 2.5$
  - IsoTrack: cut based charged PF candidate
  - TauPOG: $p_T > 20$ GeV, $|\eta| < 2.4$, medium working point
- $N_j(p_T > 20\text{ GeV}) \geq 2, |\eta| < 2.4$
- $\Delta\phi\left(j_1, p_T^{miss}\right) > 0.5, \Delta\phi\left(j_{23}, p_T^{miss}\right) > 0.15$
- $p_T^{miss} > 250$ GeV
- $H_T > 300$ GeV
- HEM Veto: $\eta[-3, -1.4], \phi[-1.57, -0.87], p_T > 20$ GeV applied to jets, electrons, and photons
- Bjets: DeepCSV medium working point
- W/Top: deepAK8 tight working point
- Deep Resolved Top: tight working point
- Scale Factors: PUWeights, BtagWeights, resTop/Top/W, soft btaggin, ISRWeights (2016), PrefireWeights (2016/2017) for all backgrounds

Search Strategy

Categorize low Δm and high Δm by $M_T(b_{1,2}, p_T^{miss})$

Low Δm

- $M_T(b_{1,2}, p_T^{miss}) < 175$ GeV
- Veto Tops and W
- ISR Tagging
- Soft-b tagging
- $N_j \geq 2$
- $\Delta\phi(j_1, p_T^{miss}) > 0.5$, $\Delta\phi(j_{23}, p_T^{miss}) > 0.15$
- $\frac{p_T^{miss}}{\sqrt{H_T}} > 10$



High Δm

- $M_T(b_{1,2}, p_T^{miss}) > 175$ GeV
- Top and W tagging
- $N_j \geq 5, N_b \geq 1$
- $\Delta\phi(j_{1234}, p_T^{miss}) > 0.5$

Low Mass Region

Table 4.5 : Summary of the 53 disjoint search regions that mainly target low Δm signal models. The low Δm baseline selection is again $N_j \geq 2$, $p_T^{miss} > 250$ GeV, $N_t = N_W = N_{\mathrm{res}} = 0$, $N_b \geq 0$, $M_T(b_{1,2}, p_T^{miss}) < 175$ GeV (when applicable), $|\Delta\phi(\mathrm{j}_1, p_T^{miss})| > 0.5$, $|\Delta\phi(\mathrm{j}_{2,3}, p_T^{miss})| > 0.15$, $p_T(\mathrm{ISR}) > 200$ GeV, $|\eta(\mathrm{ISR})| < 2.4$, $|\Delta\phi(j_{\mathrm{ISR}}, p_T^{miss})| > 2$, and $S_{p_T^{miss}} > 10$.

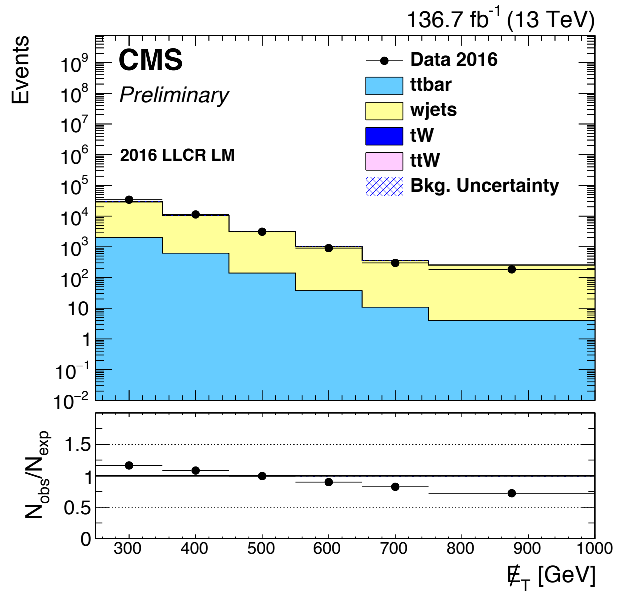
N_j	N_b	N_{SV}	$p_T(ISR)$ [GeV]	$p_T(b)$ [GeV]	p_T^{miss} [GeV]
$2-5$	0	0	> 500	-	$450-550$, $550-650$, $650-750$, > 750
≥ 6	0	0	> 500	-	$450-550$, $550-650$, $650-750$, > 750
$2-5$	0	≥ 1	> 500	-	$450-550$, $550-650$, $650-750$, > 750
≥ 6	0	≥ 1	> 500	-	$450-550$, $550-650$, $650-750$, > 750
≥ 2	1	0	$300-500$	$20-40$	$300-400$, $400-500$, $500-600$, > 600
≥ 2	1	0	$300-500$	$40-70$	$300-400$, $400-500$, $500-600$, > 600
≥ 2	1	0	> 500	$20-40$	$450-550$, $550-650$, $650-750$, > 750
≥ 2	1	0	> 500	$40-70$	$450-550$, $550-650$, $650-750$, > 750
≥ 2	1	≥ 1	> 300	$20-40$	$300-400$, $400-500$, > 500
≥ 2	≥ 2	≥ 0	$300-500$	$40-80$	$300-400$, $400-500$, > 500
≥ 2	≥ 2	≥ 0	$300-500$	$80-140$	$300-400$, $400-500$, > 500
≥ 7	≥ 2	≥ 0	$300-500$	> 140	$300-400$, $400-500$, > 500
≥ 2	≥ 2	≥ 0	> 500	$40-80$	$450-550$, $550-650$, > 650
≥ 2	≥ 2	≥ 0	> 500	$80-140$	$450-550$, $550-650$, > 650
≥ 7	≥ 2	≥ 0	> 300	> 140	$450-550$, $550-650$, > 650

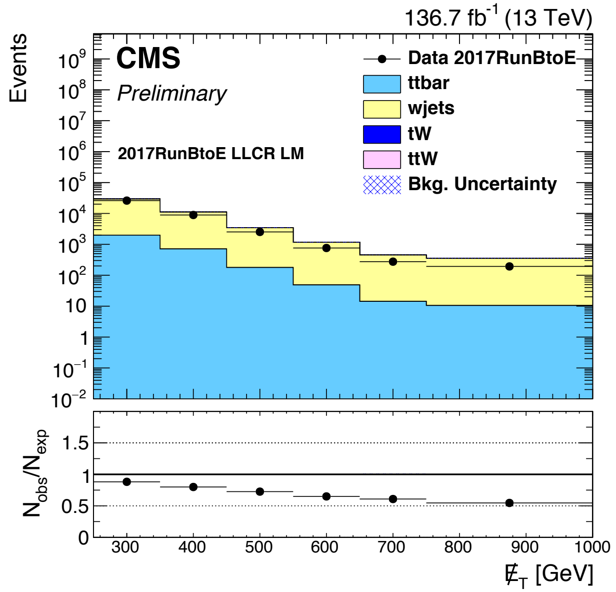
High Mass Region

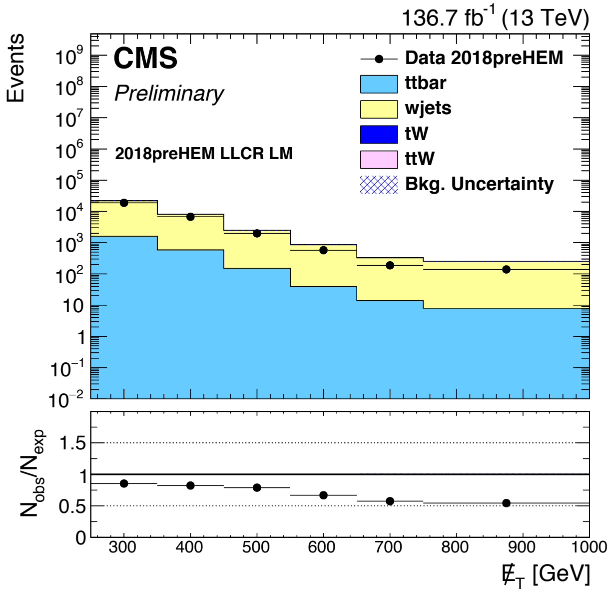
Table 4.4 : Summary of the 130 disjoint search regions that mainly target high Δm signal models. The high Δm baseline selection is again $N_j \geq 5$, $p_T^{miss} > 250$ GeV, $N_b \geq 1$, and $\Delta\phi_{1234} > 0.5$.

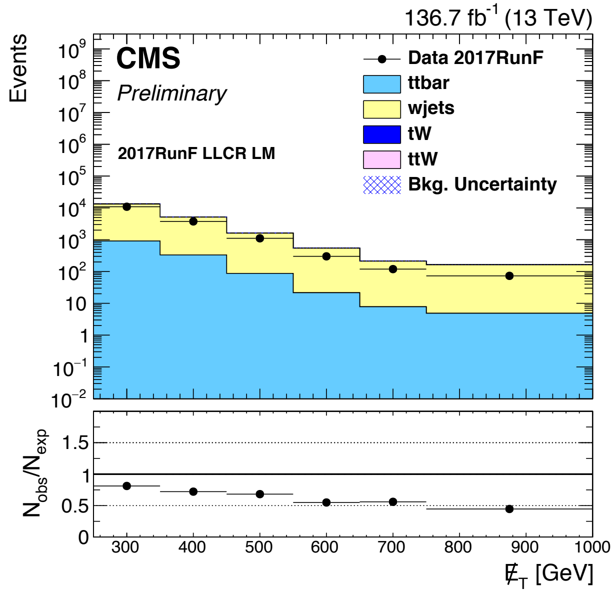
$M_T(b_{1,2}, p_T^{miss}) < 175$ GeV						
N_j	N_b	N_t	N_W	N_{res}	H_T [GeV]	p_T^{miss} [GeV]
≥ 7	$1, \geq 2$	≥ 0	≥ 0	≥ 1	≥ 300	$250-300,\ 300-400,\ 400-500,\ \geq 500$
$M_T(b_{1,2}, p_T^{miss}) \geq 175$ GeV						
N_j	N_b	N_t	N_W	N_{res}	H_T [GeV]	p_T^{miss} [GeV]
≥ 5	$1, \geq 2$	0	0	0	≥ 1000	$250-350,\ 350-450,\ 450-550,\ \geq 550$
≥ 5	1	≥ 1	0	0	$300-1000,\ 1000-1500,\ \geq 1500$	$250-550,\ 550-650,\ \geq 650$
		0	≥ 1	0	$300-1300,\ \geq 1300$	$250-350,\ 350-450,\ \geq 450$
		0	0	≥ 1	$300-1000,\ 1000-1500,\ \geq 1500$	$250-350,\ 350-450,\ 450-550,\ 550-650,\ \geq 650$
		≥ 1	≥ 1	0	≥ 300	$250-550,\ \geq 550$
		≥ 1	0	≥ 1	≥ 300	$250-550,\ \geq 550$
		0	≥ 1	≥ 1	≥ 300	$250-550,\ \geq 550$
≥ 5	2	1	0	0	$300-1000,\ 1000-1500,\ \geq 1500$	$250-550,\ 550-650,\ \geq 650$
		0	1	0	$300-1300,\ \geq 1300$	$250-350,\ 350-450,\ \geq 450$
		0	0	1	$300-1000,\ 1000-1500,\ \geq 1500$	$250-350,\ 350-450,\ 450-550,\ 550-650,\ \geq 650$
		1	1	0	≥ 300	$250-550,\ \geq 550$
		1	0	1	$300-1300,\ \geq 1300$	$250-350,\ 350-450,\ \geq 450$
		0	1	1	≥ 300	$250-550,\ \geq 550$
		2	0	0	≥ 300	$250-450,\ \geq 450$
		0	2	0	≥ 300	≥ 250
		0	0	2	$300-1300,\ \geq 1300$	$250-450,\ \geq 450$
		$N_t + N_W + N_{res} \geq 3$			≥ 300	≥ 250
≥ 5	≥ 3	1	0	0	$300-1000,\ 1000-1500,\ \geq 1500$	$250-350,\ 350-550,\ \geq 550$
		0	1	0	≥ 300	$250-350,\ 350-550,\ \geq 550$
		0	0	1	$300-1000,\ 1000-1500,\ \geq 1500$	$250-350,\ 350-550,\ \geq 550$
		1	1	0	≥ 300	≥ 250
		1	0	1	≥ 300	$250-350,\ \geq 350$
		0	1	1	≥ 300	≥ 250
		2	0	0	≥ 300	≥ 250
		0	2	0	≥ 300	≥ 250
		0	0	2	≥ 300	$250-350,\ \geq 350$
		$N_t + N_W + N_{res} \geq 3$			≥ 300	≥ 250

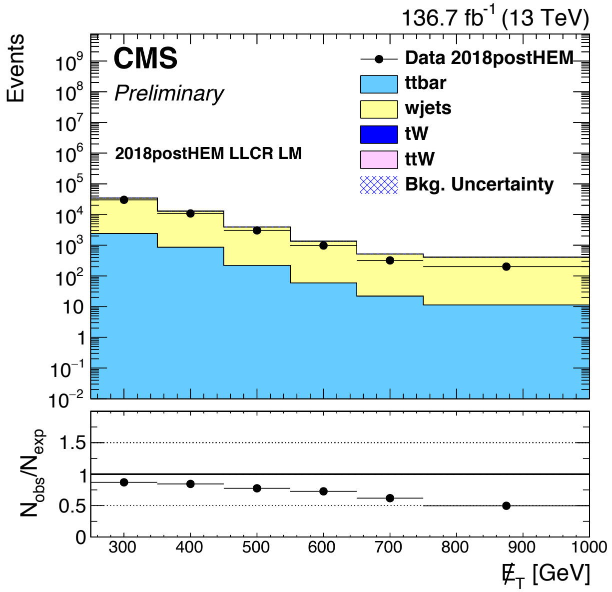
Lost Lepton Inclusive Low DM



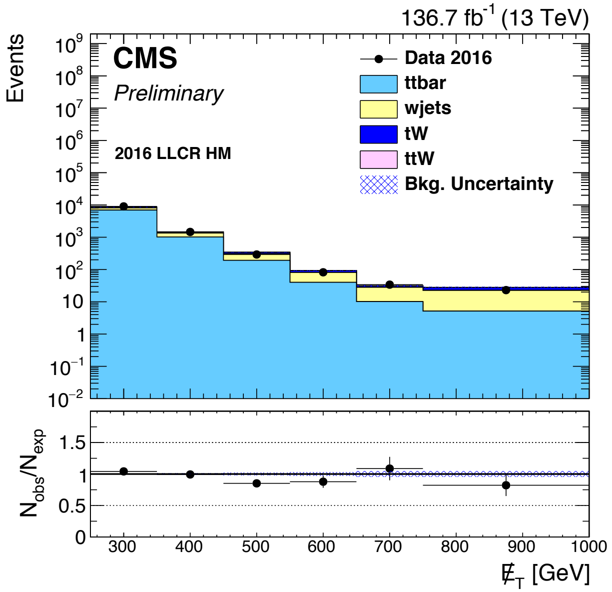


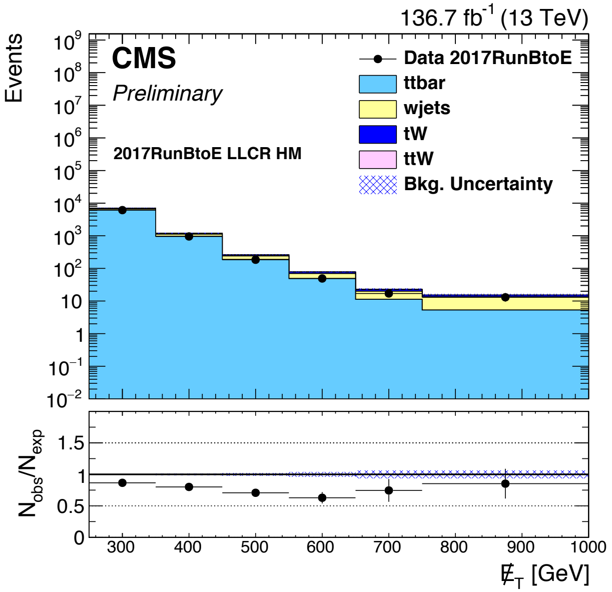


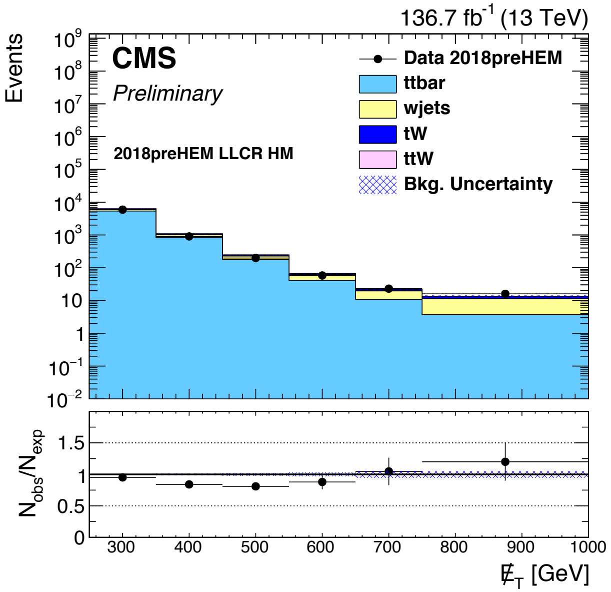


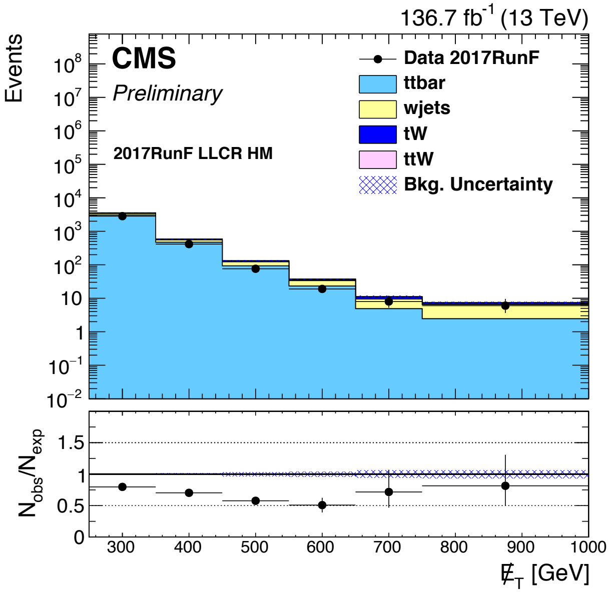


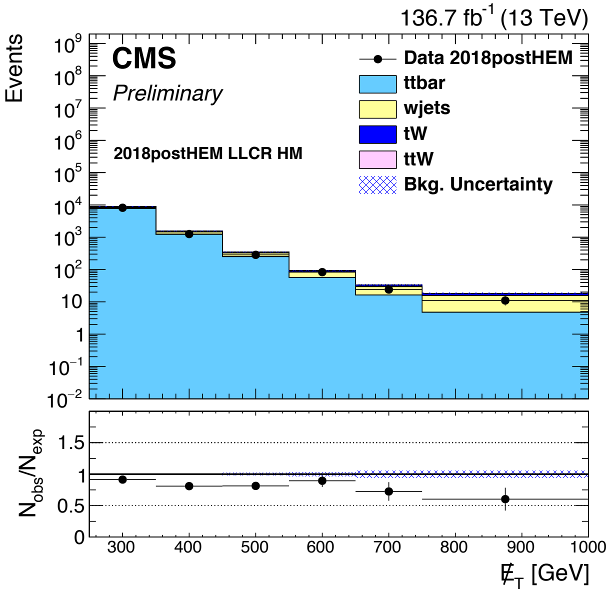
Lost Lepton Inclusive High DM



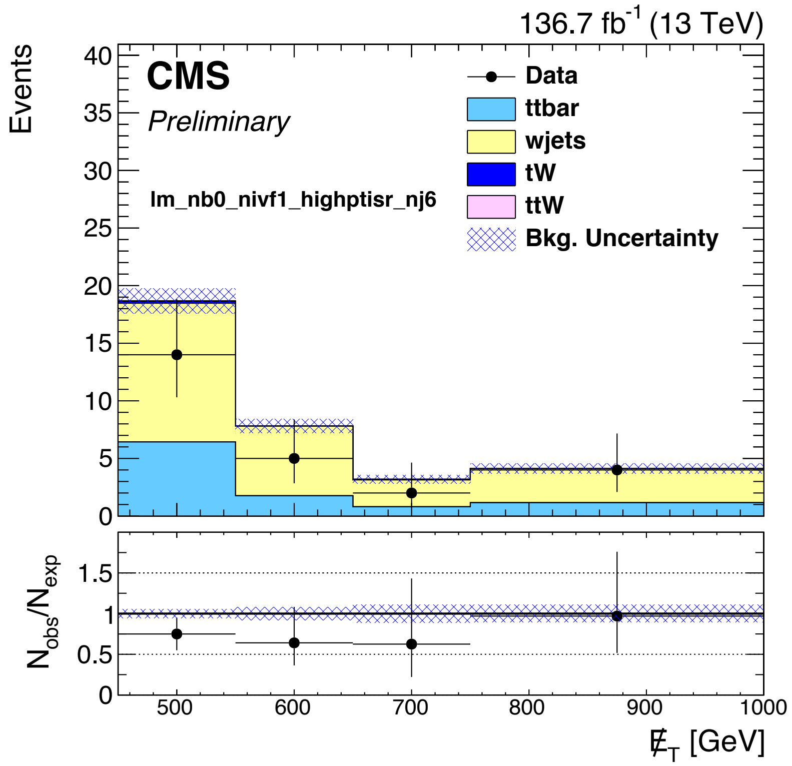


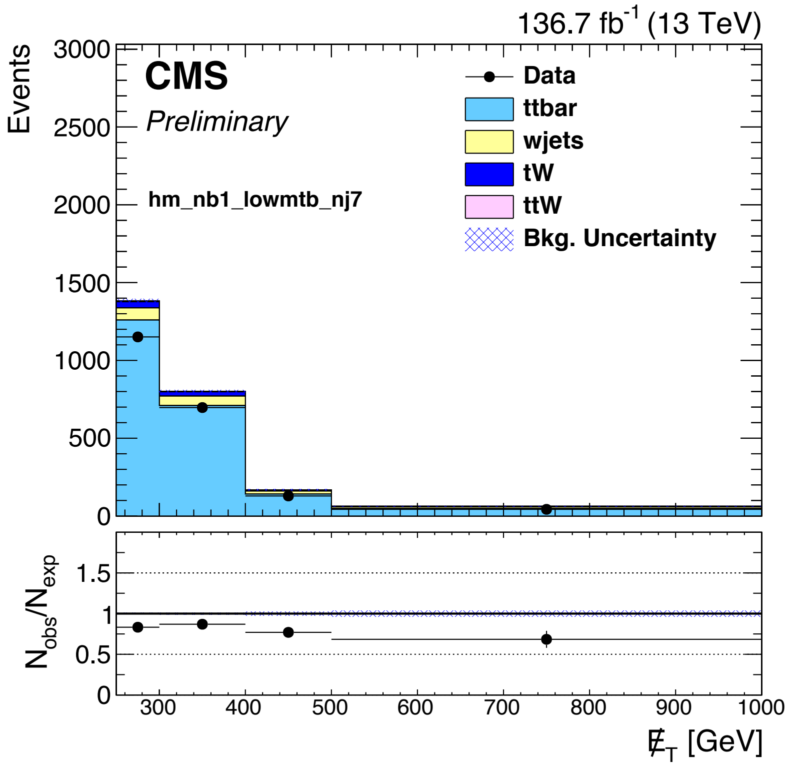






Example LL Prediction





Search Region	p_T^{miss}[GeV]	$N_{\rm data}(1l)$	TF_{LL}	$N^{\rm LL}_{\rm pred}$
low Δm, $N_b = 0$, $N_{SV} \geq 1$, $p_T(ISR) \geq 500$ GeV, $N_j \geq 6$				
12	450−550	14	0.357±0.042	4.99±1.46
13	550−650	5	0.418±0.069	2.09±1.00
14	650−750	2	0.486±0.085	0.97±0.71
15	$\geq$ 750	4	0.332±0.076	1.33±0.73

Search Region	p_T^{miss}[GeV]	$N_{\rm data}(1l)$	TF_{LL}	$TF_{LL}^{\rm CR\text{-}SR}$	$TF_{LL}^{\rm SR\text{-}extrap}$	$N^{\rm LL}_{\rm pred}$
high Δm, $N_b = 1$, $M_T(b_{1,2}, p_T^{miss}) < 175$ GeV, $N_j \geq 7$, $N_{\rm res} \geq 1$						
53	250−300	1151	0.196±0.004	0.519	0.378	225.43±8.24
54	300−400	697	0.187±0.005	0.550	0.340	130.35±6.21
55	400−500	129	0.180±0.011	0.577	0.313	23.26±2.53
56	$\geq$ 500	43	0.157±0.016	0.598	0.263	6.77±1.25

Z to Invisible

Events with jets and a Z decaying to two neutrinos

- Large H_T and p_T^{miss}, similar to signal
- Control Region
  - $Z \rightarrow ll +$ jets: R_Z(Z Normalization factor)
    - Use in low mass N_b and N_{SV}
    - Calculate $t\bar{t}$ normalization R_t
  - Photon + jets: $S_\gamma(p_T^{miss}$ shape weight)
    - Use in low mass N_b and N_j
- Reconstructed Z or γ is added to p_T^{miss} for $Z \rightarrow \nu\bar{\nu}$

$$N_{pred}^{Z\rightarrow\nu\bar{\nu}} = N_{MC}^{Z\rightarrow\nu\bar{\nu}} \cdot R_Z \cdot S_\gamma$$

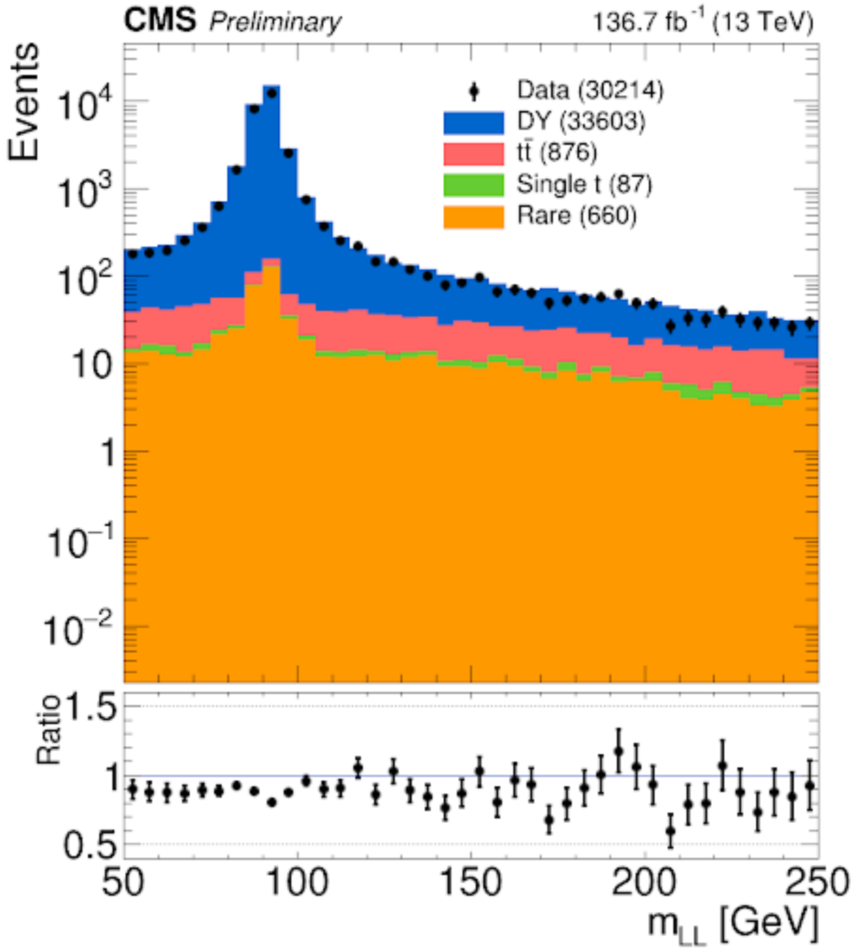
Z to Invisible: Normalization (R_Z)

Normalization R_Z is calculated in the $Z \to ll$ control region

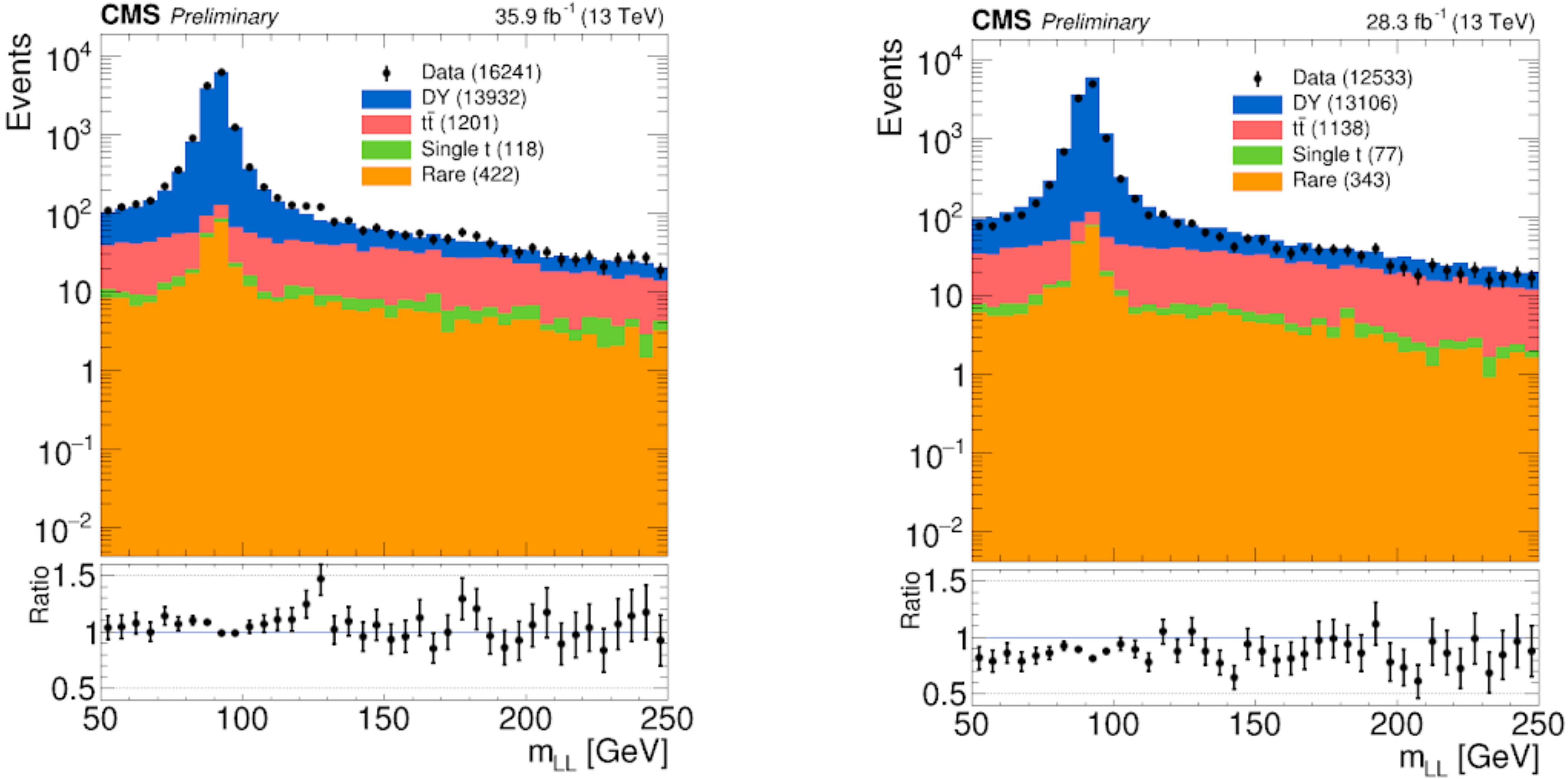
- Calculated for electrons and muons separately
- Weighted average is combined

How to calculate?

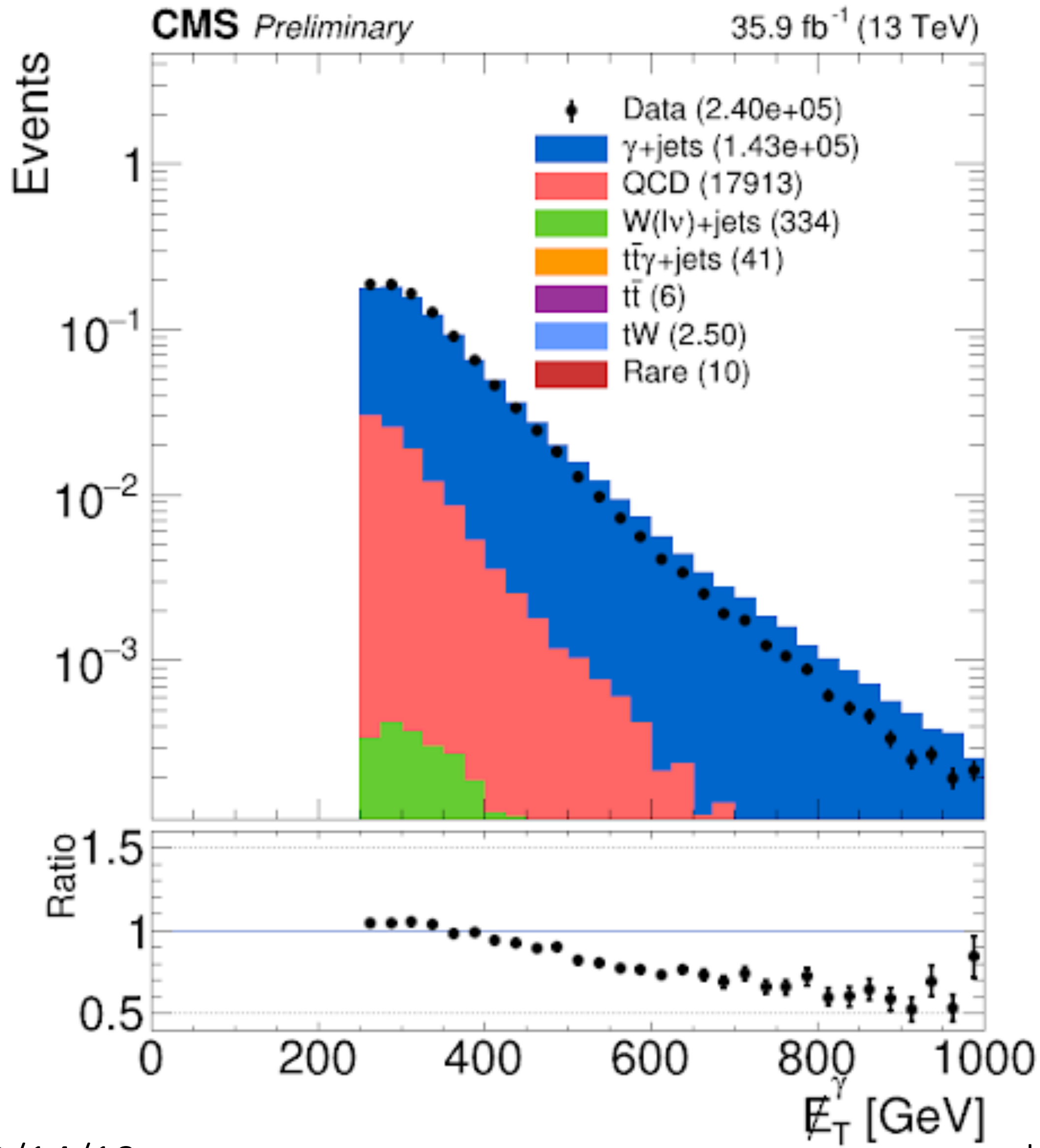
- Reconstruct Z from leptons
- Two regions
  - On Z mass: $81 < m_{ll} < 101$ GeV
  - Off Z mass: $50 < m_{ll} < 81$ GeV and $m_{ll} > 101$ GeV
- $\begin{bmatrix} Data_{on-Z} \\ Data_{off-Z} \end{bmatrix} = \begin{bmatrix} MC_{on-Z}(Z \to ll) & MC_{on-Z}(t\bar{t}) \\ MC_{off-Z}(Z \to ll) & MC_{off-Z}(t\bar{t}) \end{bmatrix} \cdot \begin{bmatrix} R_Z \\ R_T \end{bmatrix}$

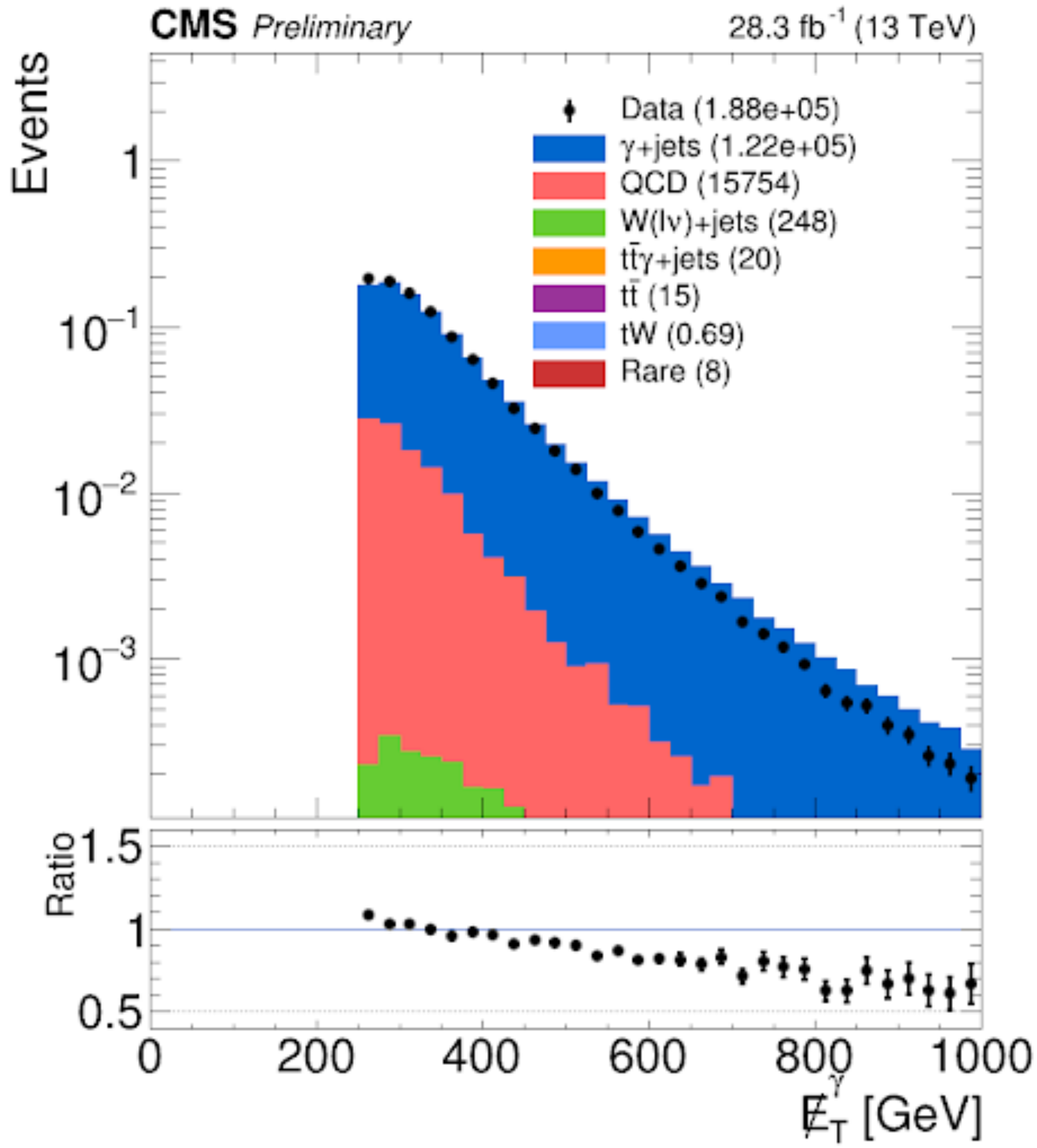


Comparison of Z Normalization for Muons

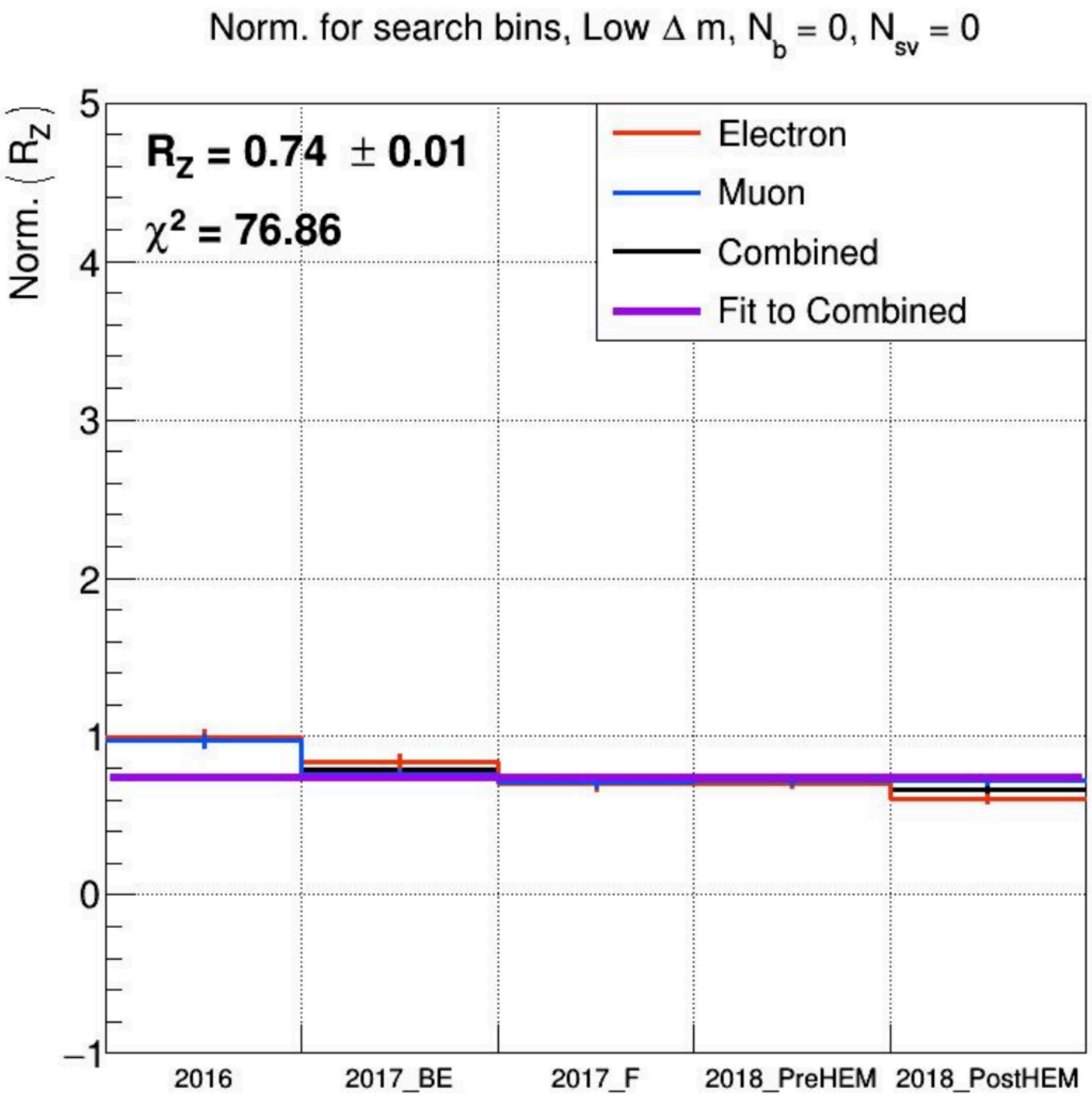


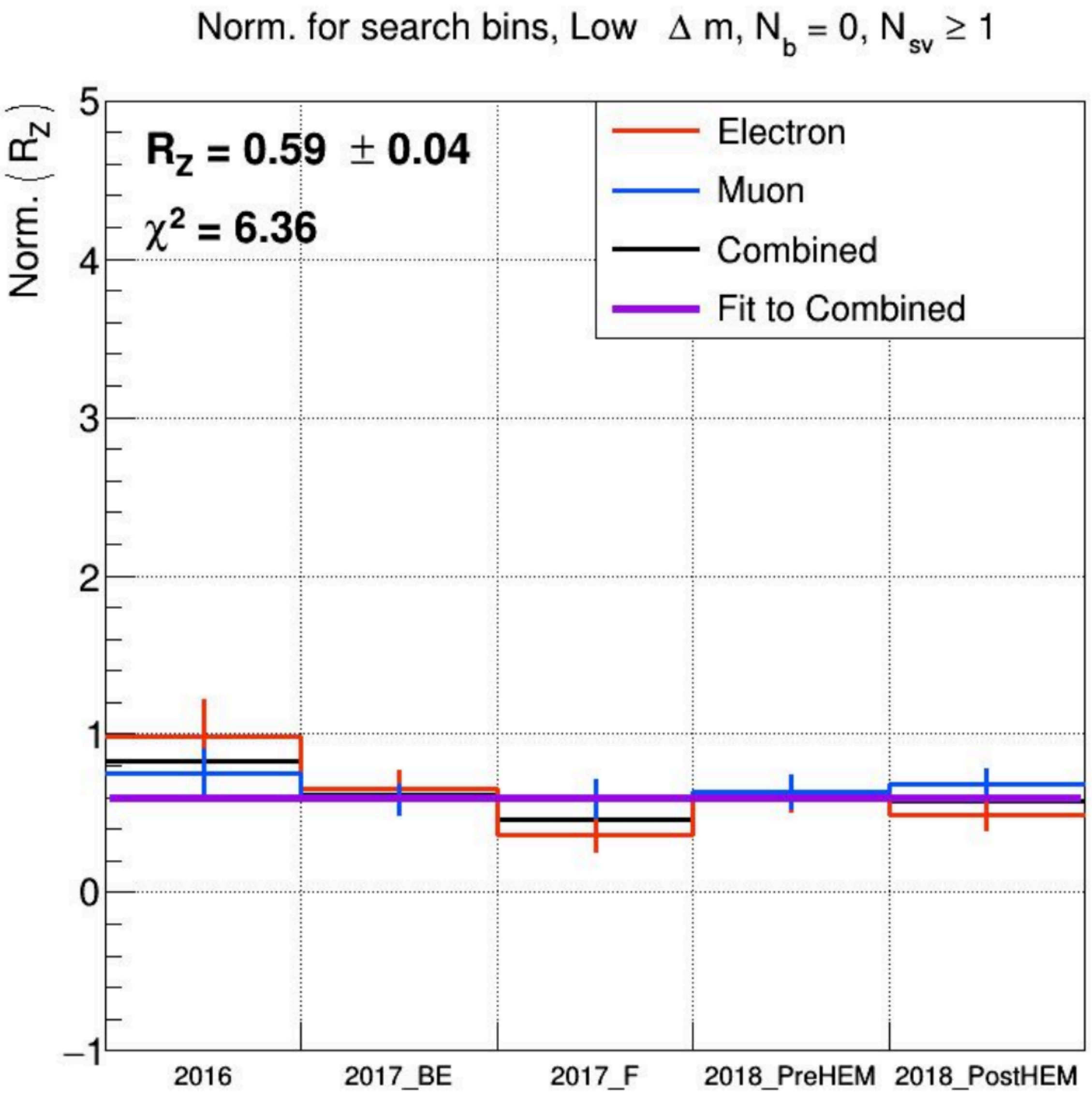
Photon Shape Corrections



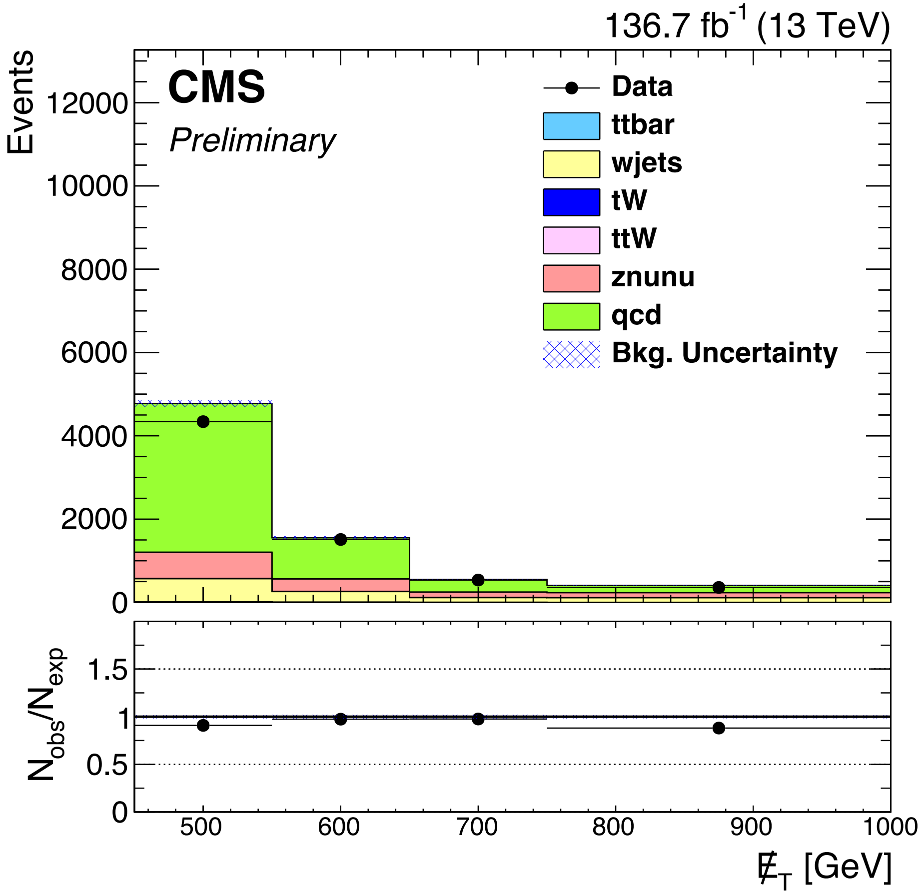


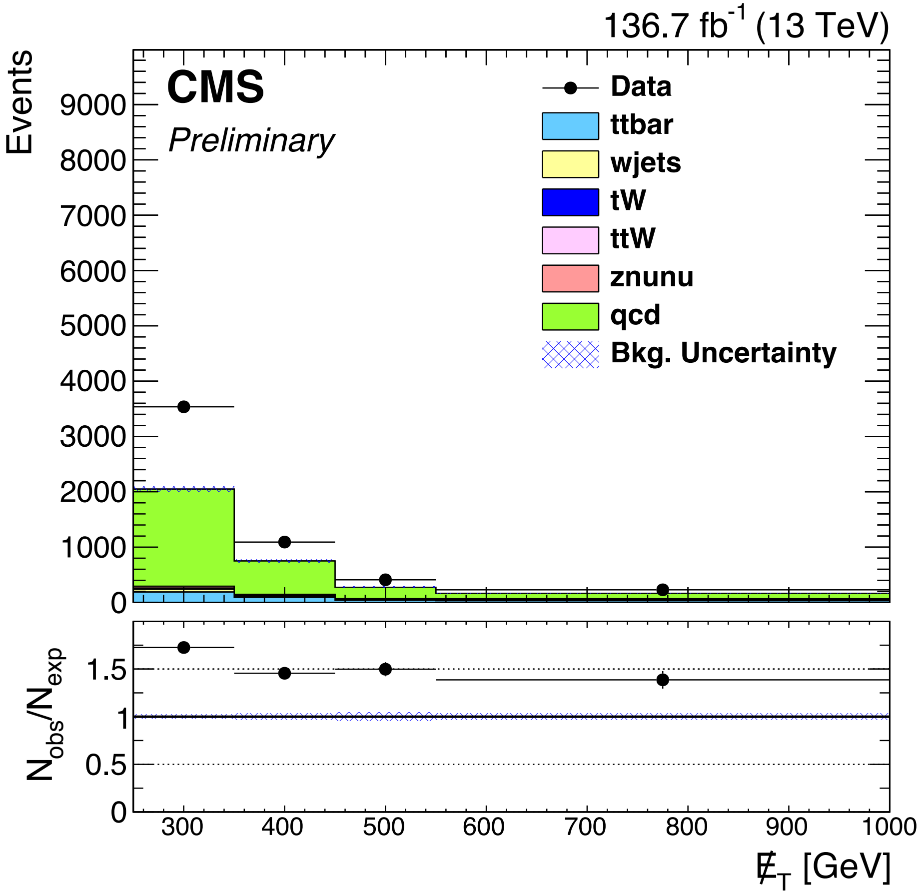
Comparison of Normalization





QCD Control Region Comparison





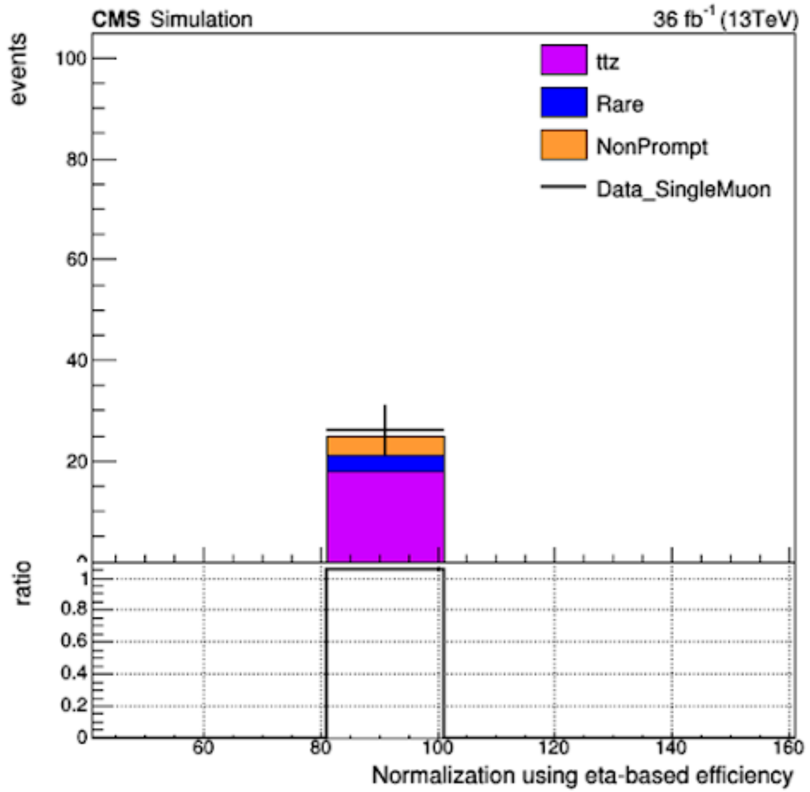
Search Region	p_T^{miss}[GeV]	$N_{\text{data}}(1l)$	TF_{QCD}	$N^{\text{LL}}_{\text{pred}}$
low Δm, $N_b = 0$, $N_{SV} = 0$, $p_T(ISR) \geq 500$ GeV, $2 \leq N_j \leq 5$				
0	450−550	4340	0.029±0.003	123.96±12.42
1	550−650	1511	0.010±0.001	14.69±2.10
2	650−750	537	0.006±0.002	3.23±1.02
3	≥ 750	360	0.006±0.002	2.16±0.59

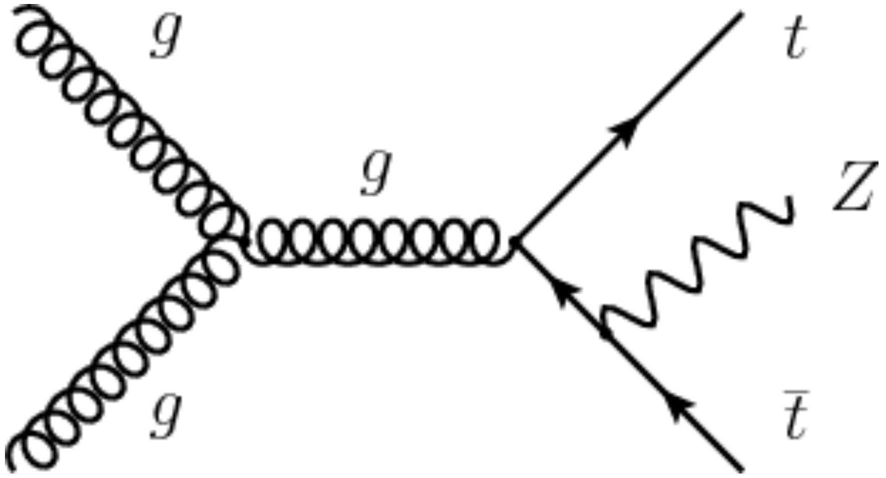
Search Region	p_T^{miss}[GeV]	$N_{\text{data}}(1l)$	TF_{QCD}	$TF_{QCD}^{\text{CR-SR}}$	$TF_{QCD}^{\text{SR-extrap}}$	$N^{\text{LL}}_{\text{pred}}$
high Δm, $N_b = 1$, $M_T(b_{1,2}, p_T^{miss}) < 175$ GeV, $N_j \geq 7$, $N_{\text{res}} \geq 1$						
53	250−300	1440	0.006±0.006	0.263	0.024	9.18±8.23
54	300−400	798	0.014±0.010	0.270	0.052	11.28±8.05
55	400−500	179	0.009±0.006	0.174	0.049	1.53±1.14
56	≥ 500	74	0.000±0.000	0.053	0.000	0.00±0.00

Rare Background

3 lepton channels to validate ttZ contribution

- Also contribution from diboson (WW, WZ, and ZZ)





Low DM Validation Region

Table 6.1 : Summary of the 19 disjoint validation regions that mainly target low Δm signal models. The low Δm baseline selection is again $N_j \geq 2$, $p_T^{miss} > 250\ GeV$, $N_t = N_W = N_{\mathrm{res}} = 0$, $N_b \geq 0$, $M_T(b_{1,2}, p_T^{miss}) < 175\ GeV$ (when applicable), $p_T(ISR) > 200$ GeV, $|\eta(ISR)| < 2.4$, $|\Delta\phi(j_{\mathrm{ISR}}, p_T^{miss})| > 2$, and $S_{p_T^{miss}} > 10$.

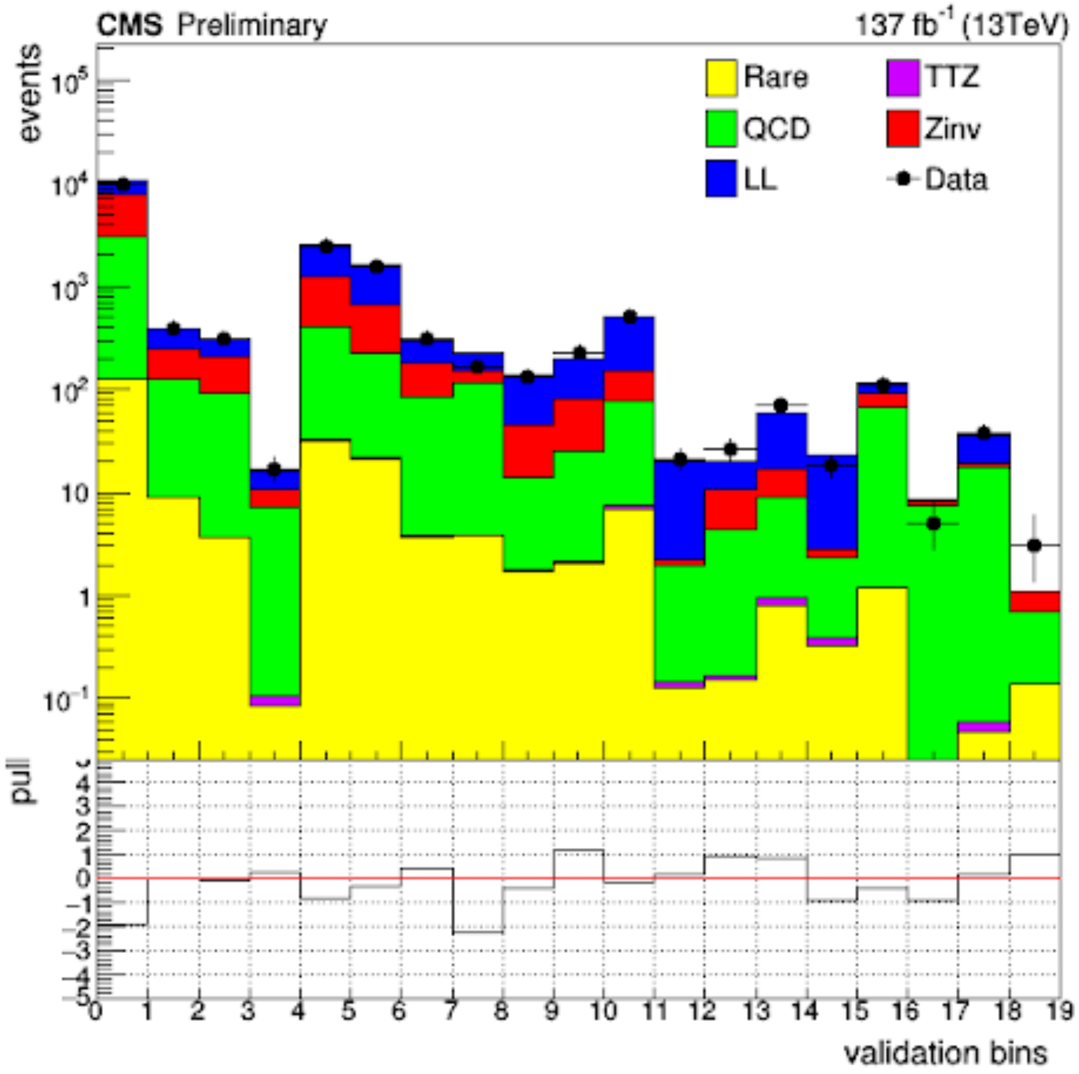
N_j	N_b	N_{SV}	$p_T(ISR)$ [GeV]	$p_T(b)$ [GeV]	p_T^{miss} [GeV]
$\lvert\Delta\phi(j_1, p_T^{miss})\rvert \geq 0.5$, $\lvert\Delta\phi(j_{2,3}, p_T^{miss})\rvert \geq 0.15$					
$2-5$	0	0	≥ 500	-	$250-400$
≥ 6		0			$250-400$
$2-5$		≥ 1			$250-400$
≥ 6		≥ 1			$250-400$
≥ 2	1	0	$300-500$	$20-40$	$250-300$
		0	$300-500$	$40-70$	$250-300$
		0	≥ 500	$20-40$	$250-400$
		0	≥ 500	$40-70$	$250-400$
		≥ 1	≥ 300	$20-40$	$250-300$
≥ 2	≥ 2	≥ 0	$300-500$	$40-80$	$250-300$
≥ 2			$300-500$	$80-140$	$250-300$
≥ 7			$300-500$	≥ 140	$250-300$
≥ 2			≥ 500	$40-80$	$250-400$
≥ 2			≥ 500	$80-140$	$250-400$
≥ 7			≥ 300	≥ 140	$250-400$
$0.15 \leq \Delta\phi(j_1, p_T^{miss}) \leq 0.5$, $\lvert\Delta\phi(j_{2,3}, p_T^{miss})\rvert \geq 0.15$					
≥ 2	0	0	≥ 200	≥ 20	≥ 250
≥ 2	0	1	≥ 200	≥ 20	≥ 250
≥ 2	1	0	≥ 200	≥ 20	≥ 250
≥ 2	1	1	≥ 200	≥ 20	≥ 250

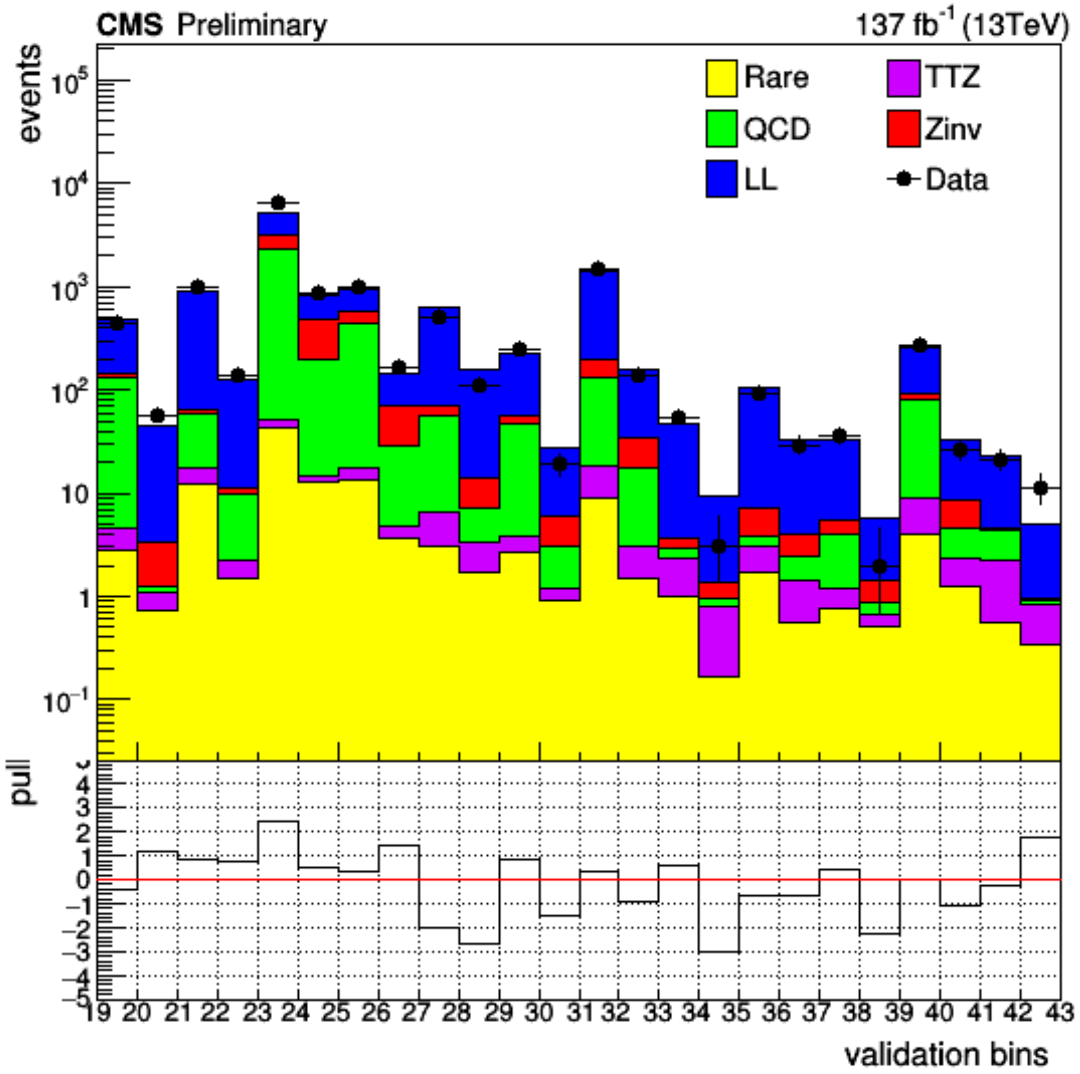
High DM Validation

Table 6.2 : Summary of the 25 disjoint validation regions that mainly target high Δm signal models. The high Δm baseline selection is again $N_j \geq 5$, $p_T^{miss} > 250\ GeV$, $N_b \geq 1$, and and $\neg\Delta\phi_{1234} < 0.5$.

<table>
<tr><td colspan="6">$M_T(b_{1,2}, p_T^{miss}) < 175$ GeV</td></tr>
<tr><td>N_j</td><td>N_b</td><td>N_t</td><td>N_W</td><td>N_{res}</td><td>p_T^{miss} [GeV]</td></tr>
<tr><td>≥ 7</td><td>$1, \geq 2$</td><td>≥ 0</td><td>≥ 0</td><td>≥ 1</td><td>$250-400, \geq 400$</td></tr>
<tr><td colspan="6">$M_T(b_{1,2}, p_T^{miss}) \geq 175$ GeV</td></tr>
<tr><td>N_j</td><td>N_b</td><td>N_t</td><td>N_W</td><td>N_{res}</td><td>p_T^{miss} [GeV]</td></tr>
<tr><td>≥ 5</td><td>$1, \geq 2$</td><td>0</td><td>0</td><td>0</td><td>$250-400, \geq 400$</td></tr>
<tr><td rowspan="4">≥ 5</td><td rowspan="4">1</td><td>1</td><td>0</td><td>0</td><td>$250-400, \geq 400$</td></tr>
<tr><td>0</td><td>1</td><td>0</td><td>$250-400, \geq 400$</td></tr>
<tr><td>0</td><td>0</td><td>1</td><td>$250-400, \geq 400$</td></tr>
<tr><td colspan="3">$N_t + N_W + N_{\mathrm{res}} \geq 3$</td><td>$\geq 400$</td></tr>
<tr><td rowspan="4">≥ 5</td><td rowspan="4">2</td><td>1</td><td>0</td><td>0</td><td>$250-400, \geq 400$</td></tr>
<tr><td>0</td><td>1</td><td>0</td><td>$250-400, \geq 400$</td></tr>
<tr><td>0</td><td>0</td><td>1</td><td>$250-400, \geq 400$</td></tr>
<tr><td colspan="3">$N_t + N_W + N_{\mathrm{res}} \geq 3$</td><td>$\geq 400$</td></tr>
</table>

Validation Pulls





Datacard Calculation

```
# Datacard produced by CombineHarvester with git status: analysis-HIG-16-006-freeze-080416-794-g1f6819a-dirty
imax    1 number of bins
jmax    5 number of processes minus 1
kmax    * number of nuisance parameters
--------------------------------------------------------------------------------
shapes * bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 FAKE
--------------------------------------------------------------------------------
bin          bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350
observation  632.8796
--------------------------------------------------------------------------------
bin                                                                                  bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350
bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350
bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350
process                                                                              signal          ttbarplusw      znunu           qcd             ttZ             diboson
process                                                                              0               1               2               3               4               5
rate                                                                                 9.14402         1               1               1               1.73918         6.63444
--------------------------------------------------------------------------------
ISR_Weight                                                                   lnN     0.745237/1.14938 1.01244/0.992847 -               1/1             -               -
JES                                                                          lnN     0.955953/1.01982 1.00457/0.997025 -               0.966463/1.06259 0.924388/1.07561 0.975366/1.02463
MET_Unc                                                                      lnN     0.754791/1.16343 -               -               -               -               -
PDF_Weight                                                                   lnN     1/1             0.997194/1.00244 -               -               0.989299/1.0107 0.956243/1.04376
PU_Weight                                                                    lnN     1.00021/0.999801 0.999705/1.00029 -               0.950886/1.04932 0.999391/1.00061 0.997822/1.00218
Prefire_Weight                                                               lnN     0.995445/1.00451 0.999747/1.00026 -               1.00014/0.999902 0.9949/1.0051   0.998006/1.00199
Scale_Unc                                                                    lnN     0.999939/1.00006 -               -               -               -               -
b                                                                            lnN     0.989096/1.00912 0.988665/1.01087 -               0.991081/1.0078 0.987071/1.01293 0.961271/1.03873
eff_e                                                                        lnN     1/1             1.05416/0.947292 -               0.999131/1.00085 1/1             1/1
eff_restop                                                                   lnN     -               1.01249/0.987828 -               1.00905/0.991108 1/1             1/1
eff_restoptag                                                                lnN     1/1             -               -               -               -               -
eff_tau                                                                      lnN     1/1             1.03345/0.966549 -               1/1             1/1             1/1
eff_toptag                                                                   lnN     1/1             1.01367/0.986692 -               1.0025/0.997513 1/1             1/1
eff_wtag                                                                     lnN     1/1             1.00316/0.996862 -               1.00108/0.998918 1/1             1/1
err_mu                                                                       lnN     1/1             1.00319/0.996816 -               0.999946/1.00005 1/1             1/1
ivfunc                                                                       lnN     1/1             1/1             -               1/1             1/1             1/1
mcstats_diboson_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350      lnN     -               -               -               -               -               1.16861
mcstats_qcd_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350          lnN     -               -               -               1.01527         -               -
mcstats_signal_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350       lnN     1.07609         -               -               -               -               -
mcstats_ttZ_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350          lnN     -               -               -               -               1.07256         -
mcstats_ttbarplusw_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350   lnN     -               1.01536         -               -               -               -
mcstats_znunu_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350        lnN     -               -               1.01241         -               -               -
metres                                                                       lnN     1.03905/0.99492 0.996265/1.00374 -               0.001/2         0.996604/1.0034 0.986278/1.01372
trigger_err                                                                  lnN     0.998229/1.00163 1.00001/0.999993 -               0.999794/1.00019 0.9982/1.0018   0.998112/1.00189
ttZ_SF                                                                       lnN     -               -               -               -               0.893554/1.10645 -
R_qcd_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350                rateParam  *        qcd        (@0*60.303522+@1*14.168854+@2*56.790391)
R_bin_qcdcr_hm_nb1_highmtb_ht1000to1300_MET_pt250to350,R_bin_qcdcr_hm_nb1_highmtb_ht1300to1500_MET_pt250to350,R_bin_qcdcr_hm_nb1_highmtb_htgt1500_MET_pt250to350
R_ttbarplusw_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350         rateParam  *        ttbarplusw (@0*159.445933+@1*45.881273+@2*57.290734)
R_bin_lepcr_hm_nb1_highmtb_ht1000to1300_MET_pt250to350,R_bin_lepcr_hm_nb1_highmtb_ht1300to1500_MET_pt250to350,R_bin_lepcr_hm_nb1_highmtb_htgt1500_MET_pt250to350
R_znunu_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350              rateParam  *        znunu      (@0*109.049678+@1*30.471561+@2*39.475517)
R_bin_phocr_hm_nb1_highmtb_ht1000to1300_MET_pt250to350,R_bin_phocr_hm_nb1_highmtb_ht1300to1500_MET_pt250to350,R_bin_phocr_hm_nb1_highmtb_htgt1500_MET_pt250to350
```

Datacard Calculation

```
# Datacard produced by CombineHarvester with git status: analysis-HIG-16-006-freeze-080416-794-g1f6819a-dirty
imax    1 number of bins
jmax    5 number of processes minus 1
kmax    * number of nuisance parameters
--------------------------------------------------------------------------------
shapes * bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 FAKE
--------------------------------------------------------------------------------
bin          bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350
observation  632.8796
--------------------------------------------------------------------------------
bin                                                                             bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350
bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350
bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350
process                                                                         signal          ttbarplusw      znunu           qcd             ttZ             diboson
process                                                                         0               1               2               3               4               5
rate                                                                            9.14402         1               1               1               1.73918         6.63444
--------------------------------------------------------------------------------
ISR_Weight                                                              lnN     0.745237/1.14938 1.01244/0.992847 -             1/1             -               -
JES                                                                     lnN     0.955953/1.01982 1.00457/0.997025 -             0.966463/1.06259 0.924388/1.07561 0.975366/1.02463
MET_Unc                                                                 lnN     0.754791/1.16343 -              -               -               -               -
PDF_Weight                                                              lnN     1/1             0.997194/1.00244 -              -               0.989299/1.0107 0.956243/1.04376
PU_Weight                                                               lnN     1.00021/0.999801 0.999705/1.00029 -             0.950886/1.04932 0.999391/1.00061 0.997822/1.00218
Prefire_Weight                                                          lnN     0.995445/1.00451 0.999747/1.00026 -             1.00014/0.999902 0.9949/1.0051  0.998006/1.00199
Scale_Unc                                                               lnN     0.999939/1.00006 -              -               -               -               -
b                                                                       lnN     0.989096/1.00912 0.988665/1.01087 -             0.991081/1.0078 0.987071/1.01293 0.961271/1.03873
eff_e                                                                   lnN     1/1             1.05416/0.947292 -              0.999131/1.00085 1/1            1/1
eff_restop                                                              lnN     -               1.01249/0.987828 -              1.00905/0.991108 1/1            1/1
eff_restoptag                                                           lnN     1/1             -               -               -               -               -
eff_tau                                                                 lnN     1/1             1.03345/0.966549 -              1/1             1/1             1/1
eff_toptag                                                              lnN     1/1             1.01367/0.986692 -              1.0025/0.997513 1/1             1/1
eff_wtag                                                                lnN     1/1             1.00316/0.996862 -              1.00108/0.998918 1/1            1/1
err_mu                                                                  lnN     1/1             1.00319/0.996816 -              0.999946/1.00005 1/1            1/1
ivfunc                                                                  lnN     1/1             1/1             -               1/1             1/1             1/1
mcstats_diboson_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350     lnN     -               -               -               -               -               1.16861
mcstats_qcd_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350         lnN     -               -               -               1.01527         -               -
mcstats_signal_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350      lnN     1.07609         -               -               -               -               -
mcstats_ttZ_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350         lnN     -               -               -               -               1.07256         -
mcstats_ttbarplusw_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 lnN     -               1.01536         -               -               -               -
mcstats_znunu_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350       lnN     -               -               1.01241         -               -               -
metres                                                                  lnN     1.03905/0.99492 0.996265/1.00374 -              0.001/2         0.996604/1.0034 0.986278/1.01372
trigger_err                                                             lnN     0.998229/1.00163 1.00001/0.999993 -             0.999794/1.00019 0.9982/1.0018  0.998112/1.00189
ttZ_SF                                                                  lnN     -               -               -               -               0.893554/1.10645 -
R_qcd_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350           rateParam  *        qcd        (@0*60.303522+@1*14.168854+@2*56.790391)
R_bin_qcdcr_hm_nb1_highmtb_ht1000to1300_MET_pt250to350,R_bin_qcdcr_hm_nb1_highmtb_ht1300to1500_MET_pt250to350,R_bin_qcdcr_hm_nb1_highmtb_htgt1500_MET_pt250to350
R_ttbarplusw_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350    rateParam  *        ttbarplusw (@0*159.445933+@1*45.881273+@2*57.290734)
R_bin_lepcr_hm_nb1_highmtb_ht1000to1300_MET_pt250to350,R_bin_lepcr_hm_nb1_highmtb_ht1300to1500_MET_pt250to350,R_bin_lepcr_hm_nb1_highmtb_htgt1500_MET_pt250to350
R_znunu_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350         rateParam  *        znunu      (@0*109.049678+@1*30.471561+@2*39.475517)
R_bin_phocr_hm_nb1_highmtb_ht1000to1300_MET_pt250to350,R_bin_phocr_hm_nb1_highmtb_ht1300to1500_MET_pt250to350,R_bin_phocr_hm_nb1_highmtb_htgt1500_MET_pt250to350
```

Datacard Calculation

```
# Datacard produced by CombineHarvester with git status: analysis-HIG-16-006-freeze-080416-794-g1f6819a-dirty
imax    1 number of bins
jmax    5 number of processes minus 1
kmax    * number of nuisance parameters
--------------------------------------------------------------------------------
shapes * bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 FAKE
--------------------------------------------------------------------------------
bin          bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350
observation  632.8796
--------------------------------------------------------------------------------
bin                                                                             bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350
bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350
bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350
process                                                                         signal          ttbarplusw      znunu           qcd             ttZ             diboson
process                                                                         0               1               2               3               4               5
rate                                                                            9.14402         1               1               1               1.73918         6.63444
--------------------------------------------------------------------------------
ISR_Weight                                                              lnN     0.745237/1.14938 1.01244/0.992847 -               1/1             -               -
JES                                                                     lnN     0.955953/1.01982 1.00457/0.997025 -               0.966463/1.06259 0.924388/1.07561 0.975366/1.02463
MET_Unc                                                                 lnN     0.754791/1.16343 -               -               -               -               -
PDF_Weight                                                              lnN     1/1             0.997194/1.00244 -               -               0.989299/1.0107 0.956243/1.04376
PU_Weight                                                               lnN     1.00021/0.999801 0.999705/1.00029 -               0.950886/1.04932 0.999391/1.00061 0.997822/1.00218
Prefire_Weight                                                          lnN     0.995445/1.00451 0.999747/1.00026 -               1.00014/0.999902 0.9949/1.0051   0.998006/1.00199
Scale_Unc                                                               lnN     0.999939/1.00006 -               -               -               -               -
b                                                                       lnN     0.989096/1.00912 0.988665/1.01087 -               0.991081/1.0078 0.987071/1.01293 0.961271/1.03873
eff_e                                                                   lnN     1/1             1.05416/0.947292 -               0.999131/1.00085 1/1             1/1
eff_restop                                                              lnN     -               1.01249/0.987828 -               1.00905/0.991108 1/1             1/1
eff_restoptag                                                           lnN     1/1             -               -               -               -               -
eff_tau                                                                 lnN     1/1             1.03345/0.966549 -               1/1             1/1             1/1
eff_toptag                                                              lnN     1/1             1.01367/0.986692 -               1.0025/0.997513 1/1             1/1
eff_wtag                                                                lnN     1/1             1.00316/0.996862 -               1.00108/0.998918 1/1             1/1
err_mu                                                                  lnN     1/1             1.00319/0.996816 -               0.999946/1.00005 1/1             1/1
ivfunc                                                                  lnN     1/1             1/1             -               1/1             1/1             1/1
mcstats_diboson_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350   lnN     -               -               -               -               -               1.16861
mcstats_qcd_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350       lnN     -               -               -               1.01527         -               -
mcstats_signal_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350    lnN     1.07609         -               -               -               -               -
mcstats_ttZ_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350       lnN     -               -               -               -               1.07256         -
mcstats_ttbarplusw_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 lnN    -               1.01536         -               -               -               -
mcstats_znunu_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350     lnN     -               -               1.01241         -               -               -
metres                                                                  lnN     1.03905/0.99492 0.996265/1.00374 -               0.001/2         0.996604/1.0034 0.986278/1.01372
trigger_err                                                             lnN     0.998229/1.00163 1.00001/0.999993 -               0.999794/1.00019 0.9982/1.0018   0.998112/1.00189
ttZ_SF                                                                  lnN     -               -               -               -               0.893554/1.10645 -
R_qcd_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350           rateParam  *        qcd        (@0*60.303522+@1*14.168854+@2*56.790391)
R_bin_qcdcr_hm_nb1_highmtb_ht1000to1300_MET_pt250to350,R_bin_qcdcr_hm_nb1_highmtb_ht1300to1500_MET_pt250to350,R_bin_qcdcr_hm_nb1_highmtb_htgt1500_MET_pt250to350
R_ttbarplusw_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350    rateParam  *        ttbarplusw (@0*159.445933+@1*45.881273+@2*57.290734)
R_bin_lepcr_hm_nb1_highmtb_ht1000to1300_MET_pt250to350,R_bin_lepcr_hm_nb1_highmtb_ht1300to1500_MET_pt250to350,R_bin_lepcr_hm_nb1_highmtb_htgt1500_MET_pt250to350
R_znunu_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350         rateParam  *        znunu      (@0*109.049678+@1*30.471561+@2*39.475517)
R_bin_phocr_hm_nb1_highmtb_ht1000to1300_MET_pt250to350,R_bin_phocr_hm_nb1_highmtb_ht1300to1500_MET_pt250to350,R_bin_phocr_hm_nb1_highmtb_htgt1500_MET_pt250to350
```

Datacard Calculation

```
# Datacard produced by CombineHarvester with git status: analysis-HIG-16-006-freeze-080416-794-g1f6819a-dirty
imax    1 number of bins
jmax    5 number of processes minus 1
kmax    * number of nuisance parameters
--------------------------------------------------------------------------------
shapes * bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 FAKE
--------------------------------------------------------------------------------
bin          bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350
observation  632.8796
--------------------------------------------------------------------------------
bin                                                                       bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350
bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350
bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350
process                                                                   signal          ttbarplusw      znunu           qcd             ttZ             diboson
process                                                                   0               1               2               3               4               5
rate                                                                      9.14402         1               1               1               1.73918         6.63444
--------------------------------------------------------------------------------
ISR_Weight                                                        lnN     0.745237/1.14938 1.01244/0.992847 -              1/1             -               -
JES                                                               lnN     0.955953/1.01982 1.00457/0.997025 -              0.966463/1.06259 0.924388/1.07561 0.975366/1.02463
MET_Unc                                                           lnN     0.754791/1.16343 -               -               -               -               -
PDF_Weight                                                        lnN     1/1             0.997194/1.00244 -               -               0.989299/1.0107 0.956243/1.04376
PU_Weight                                                         lnN     1.00021/0.999801 0.999705/1.00029 -              0.950886/1.04932 0.999391/1.00061 0.997822/1.00218
Prefire_Weight                                                    lnN     0.995445/1.00451 0.999747/1.00026 -              1.00014/0.999902 0.9949/1.0051   0.998006/1.00199
Scale_Unc                                                         lnN     0.999939/1.00006 -               -               -               -               -
b                                                                 lnN     0.989096/1.00912 0.988665/1.01087 -              0.991081/1.0078 0.987071/1.01293 0.961271/1.03873
eff_e                                                             lnN     1/1             1.05416/0.947292 -              0.999131/1.00085 1/1            1/1
eff_restop                                                        lnN     -               1.01249/0.987828 -              1.00905/0.991108 1/1            1/1
eff_restoptag                                                     lnN     1/1             -               -               -               -               -
eff_tau                                                           lnN     1/1             1.03345/0.966549 -              1/1             1/1             1/1
eff_toptag                                                        lnN     1/1             1.01367/0.986692 -              1.0025/0.997513 1/1             1/1
eff_wtag                                                          lnN     1/1             1.00316/0.996862 -              1.00108/0.998918 1/1            1/1
err_mu                                                            lnN     1/1             1.00319/0.996816 -              0.999946/1.00005 1/1            1/1
ivfunc                                                            lnN     1/1             1/1             -               1/1             1/1             1/1
mcstats_diboson_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350   lnN     -               -               -               -               -               1.16861
mcstats_qcd_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350       lnN     -               -               -               1.01527         -               -
mcstats_signal_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350    lnN     1.07609         -               -               -               -               -
mcstats_ttZ_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350       lnN     -               -               -               -               1.07256         -
mcstats_ttbarplusw_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 lnN    -               1.01536         -               -               -               -
mcstats_znunu_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350     lnN     -               -               1.01241         -               -               -
metres                                                            lnN     1.03905/0.99492 0.996265/1.00374 -              0.001/2         0.996604/1.0034 0.986278/1.01372
trigger_err                                                       lnN     0.998229/1.00163 1.00001/0.999993 -              0.999794/1.00019 0.9982/1.0018  0.998112/1.00189
ttZ_SF                                                            lnN     -               -               -               -               0.893554/1.10645 -
R_qcd_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350            rateParam  *          qcd        (@0*60.303522+@1*14.168854+@2*56.790391)
R_bin_qcdcr_hm_nb1_highmtb_ht1000to1300_MET_pt250to350,R_bin_qcdcr_hm_nb1_highmtb_ht1300to1500_MET_pt250to350,R_bin_qcdcr_hm_nb1_highmtb_htgt1500_MET_pt250to350
R_ttbarplusw_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350     rateParam  *          ttbarplusw (@0*159.445933+@1*45.881273+@2*57.290734)
R_bin_lepcr_hm_nb1_highmtb_ht1000to1300_MET_pt250to350,R_bin_lepcr_hm_nb1_highmtb_ht1300to1500_MET_pt250to350,R_bin_lepcr_hm_nb1_highmtb_htgt1500_MET_pt250to350
R_znunu_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350          rateParam  *          znunu      (@0*109.049678+@1*30.471561+@2*39.475517)
R_bin_phocr_hm_nb1_highmtb_ht1000to1300_MET_pt250to350,R_bin_phocr_hm_nb1_highmtb_ht1300to1500_MET_pt250to350,R_bin_phocr_hm_nb1_highmtb_htgt1500_MET_pt250to350
```

Datacard Calculation

```
# Datacard produced by CombineHarvester with git status: analysis-HIG-16-006-freeze-080416-794-g1f6819a-dirty
imax    1 number of bins
jmax    5 number of processes minus 1
kmax    * number of nuisance parameters
--------------------------------------------------------------------------------
shapes * bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 FAKE
--------------------------------------------------------------------------------
bin          bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350
observation  632.8796
--------------------------------------------------------------------------------
bin                                                                               bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350
bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350
bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350
process                                                                           signal          ttbarplusw      znunu           qcd             ttZ             diboson
process                                                                           0               1               2               3               4               5
rate                                                                              9.14402         1               1               1               1.73918         6.63444
--------------------------------------------------------------------------------
ISR_Weight                                                                lnN     0.745237/1.14938 1.01244/0.992847 -              1/1             -               -
JES                                                                       lnN     0.955953/1.01982 1.00457/0.997025 -              0.966463/1.06259 0.924388/1.07561 0.975366/1.02463
MET_Unc                                                                   lnN     0.754791/1.16343 -               -               -               -               -
PDF_Weight                                                                lnN     1/1             0.997194/1.00244 -               -               0.989299/1.0107 0.956243/1.04376
PU_Weight                                                                 lnN     1.00021/0.999801 0.999705/1.00029 -              0.950886/1.04932 0.999391/1.00061 0.997822/1.00218
Prefire_Weight                                                            lnN     0.995445/1.00451 0.999747/1.00026 -              1.00014/0.999902 0.9949/1.0051   0.998006/1.00199
Scale_Unc                                                                 lnN     0.999939/1.00006 -               -               -               -               -
b                                                                         lnN     0.989096/1.00912 0.988665/1.01087 -              0.991081/1.0078 0.987071/1.01293 0.961271/1.03873
eff_e                                                                     lnN     1/1             1.05416/0.947292 -               0.999131/1.00085 1/1            1/1
eff_restop                                                                lnN     -               1.01249/0.987828 -               1.00905/0.991108 1/1            1/1
eff_restoptag                                                             lnN     1/1             -               -               -               -               -
eff_tau                                                                   lnN     1/1             1.03345/0.966549 -               1/1             1/1             1/1
eff_toptag                                                                lnN     1/1             1.01367/0.986692 -               1.0025/0.997513 1/1             1/1
eff_wtag                                                                  lnN     1/1             1.00316/0.996862 -               1.00108/0.998918 1/1            1/1
err_mu                                                                    lnN     1/1             1.00319/0.996816 -               0.999946/1.00005 1/1            1/1
ivfunc                                                                    lnN     1/1             1/1             -               1/1             1/1             1/1
mcstats_diboson_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350   lnN     -               -               -               -               -               1.16861
mcstats_qcd_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350       lnN     -               -               -               1.01527         -               -
mcstats_signal_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350    lnN     1.07609         -               -               -               -               -
mcstats_ttZ_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350       lnN     -               -               -               -               1.07256         -
mcstats_ttbarplusw_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350 lnN    -               1.01536         -               -               -               -
mcstats_znunu_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350     lnN     -               -               1.01241         -               -               -
metres                                                                    lnN     1.03905/0.99492 0.996265/1.00374 -               0.001/2         0.996604/1.0034 0.986278/1.01372
trigger_err                                                               lnN     0.998229/1.00163 1.00001/0.999993 -              0.999794/1.00019 0.9982/1.0018   0.998112/1.00189
ttZ_SF                                                                    lnN     -               -               -               -               0.893554/1.10645 -
R_qcd_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350             rateParam  *           qcd        (@0*60.303522+@1*14.168854+@2*56.790391)
R_bin_qcdcr_hm_nb1_highmtb_ht1000to1300_MET_pt250to350,R_bin_qcdcr_hm_nb1_highmtb_ht1300to1500_MET_pt250to350,R_bin_qcdcr_hm_nb1_highmtb_htgt1500_MET_pt250to350
R_ttbarplusw_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350      rateParam  *           ttbarplusw (@0*159.445933+@1*45.881273+@2*57.290734)
R_bin_lepcr_hm_nb1_highmtb_ht1000to1300_MET_pt250to350,R_bin_lepcr_hm_nb1_highmtb_ht1300to1500_MET_pt250to350,R_bin_lepcr_hm_nb1_highmtb_htgt1500_MET_pt250to350
R_znunu_bin_hm_nb1_highmtb_nt0_nrt0_nw0_htgt1000_MET_pt250to350           rateParam  *           znunu      (@0*109.049678+@1*30.471561+@2*39.475517)
R_bin_phocr_hm_nb1_highmtb_ht1000to1300_MET_pt250to350,R_bin_phocr_hm_nb1_highmtb_ht1300to1500_MET_pt250to350,R_bin_phocr_hm_nb1_highmtb_htgt1500_MET_pt250to350
```

Example Calculation for Single Bin

Total yield of background

- N=3042.65(LL)+7457.98(Znunu)+690.827(QCD)+0.390779(ttZ)+196.672(Diboson)
- N=11388.52
- Stat. Uncertainty = 0.0066(LL)+0.0027(Znunu)+0.03078(QCD)+0.10877(ttZ)+0.03485(Diboson)
- Stat. Uncertainty = 68.40 (sum of weights squared)
  - $\mu = \frac{\sum w_i x_i}{\sum w_i}$ where x_i = stat uncertainty
- SimpleSyst. Uncertainty =