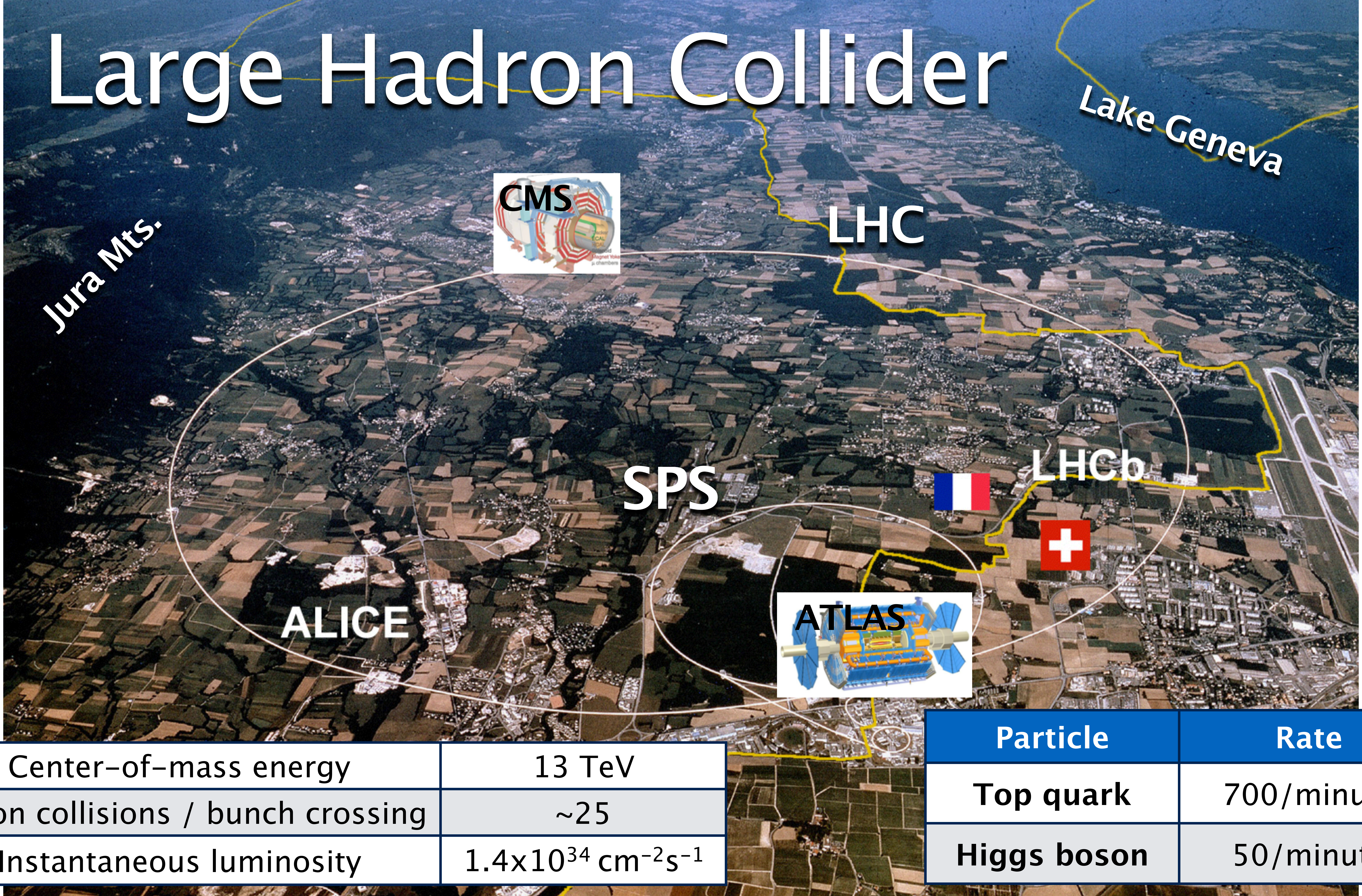
# CMS Winter Results

Jim Hirschauer
Fermilab

on behalf of the CMS collaboration

Fermilab Wine & Cheese Seminar
April 21, 2017

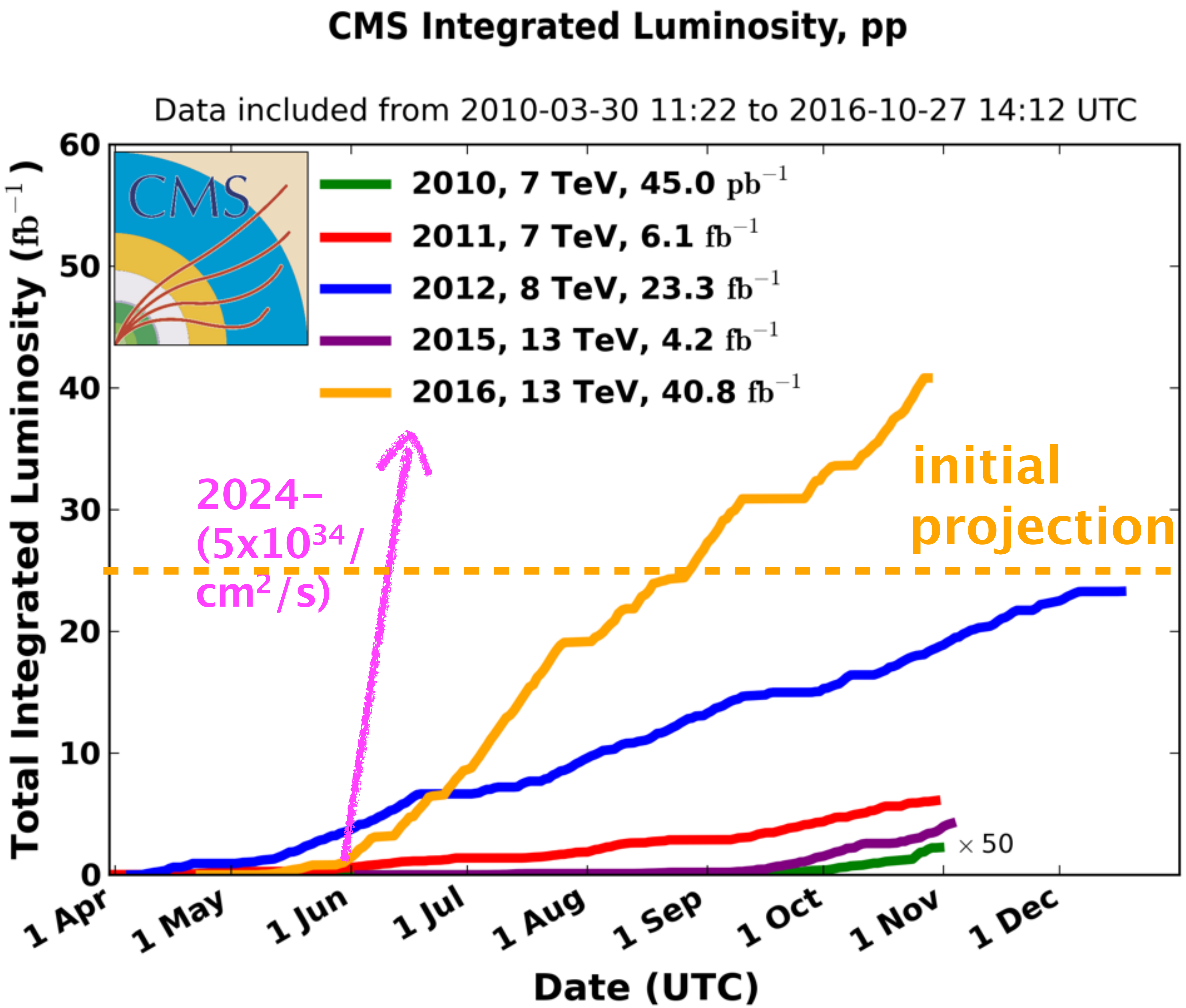
# Large Hadron Collider

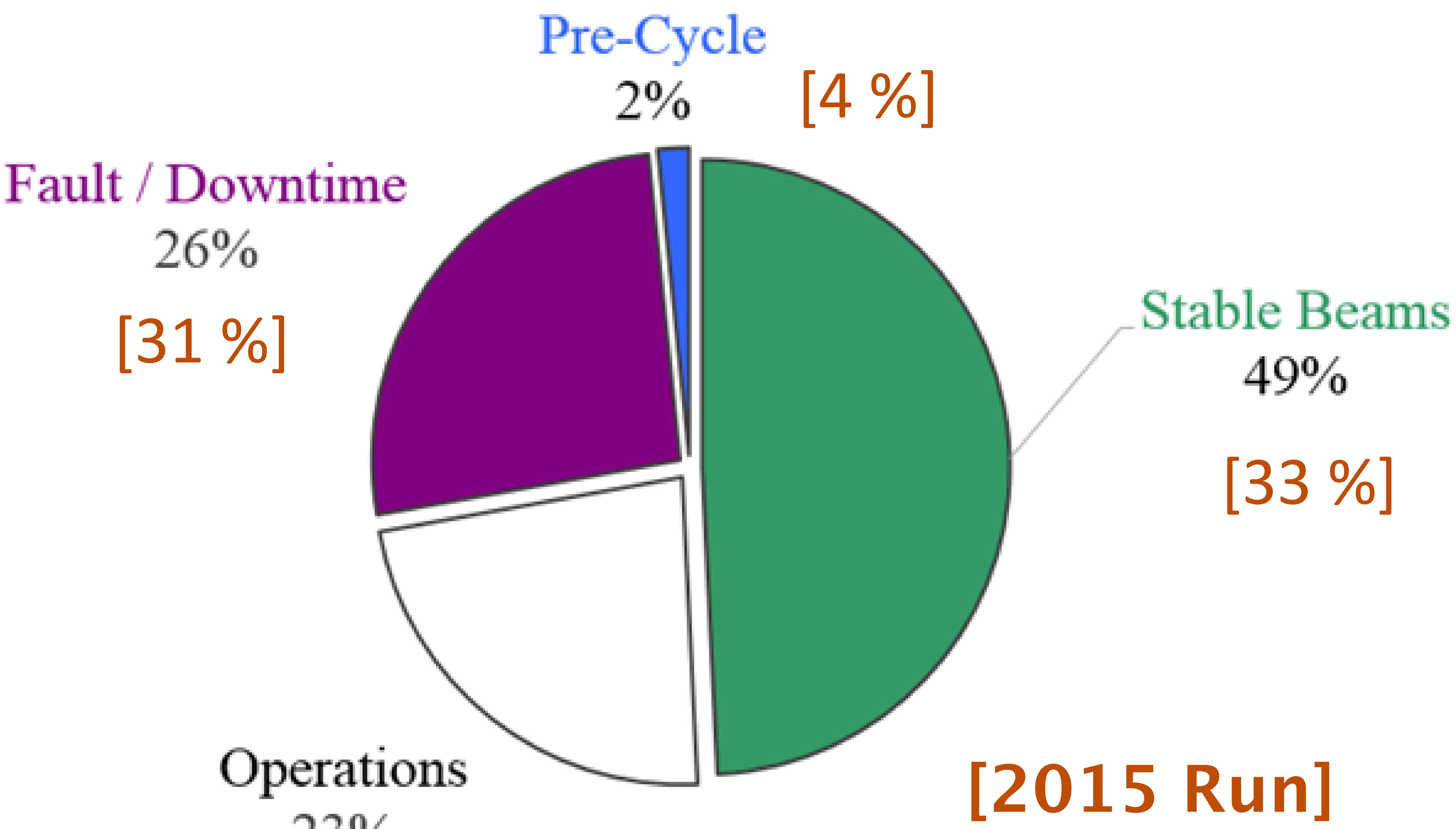



| | |
|---|---|
| Center-of-mass energy | 13 TeV |
| Proton collisions / bunch crossing | ~25 |
| Instantaneous luminosity | $1.4\text{x}10^{34}\ cm^{-2}s^{-1}$ |

| Particle | Rate |
|---|---|
| **Top quark** | 700/minute |
| **Higgs boson** | 50/minute |

# Incredible LHC!




Apollonia
Chamonix 2017

# CMS Detector

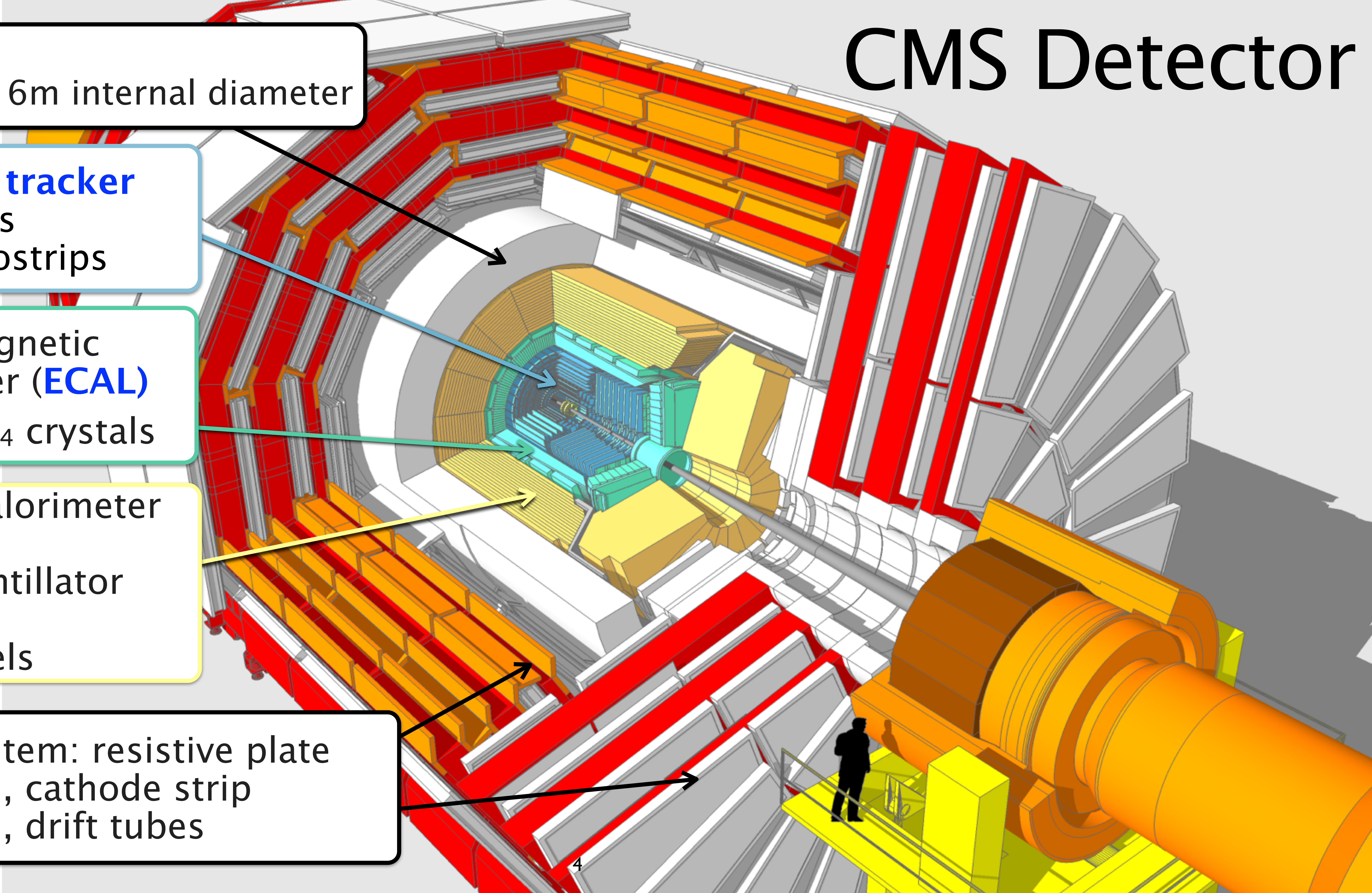
**Solenoid**
3.8T field, 6m internal diameter

All silicon **tracker**
66M pixels
10M microstrips

Electromagnetic calorimeter (**ECAL)**
76k $PbWO_4$ crystals

Hadron calorimeter (**HCAL**)
brass-scintillator sampling
7k channels

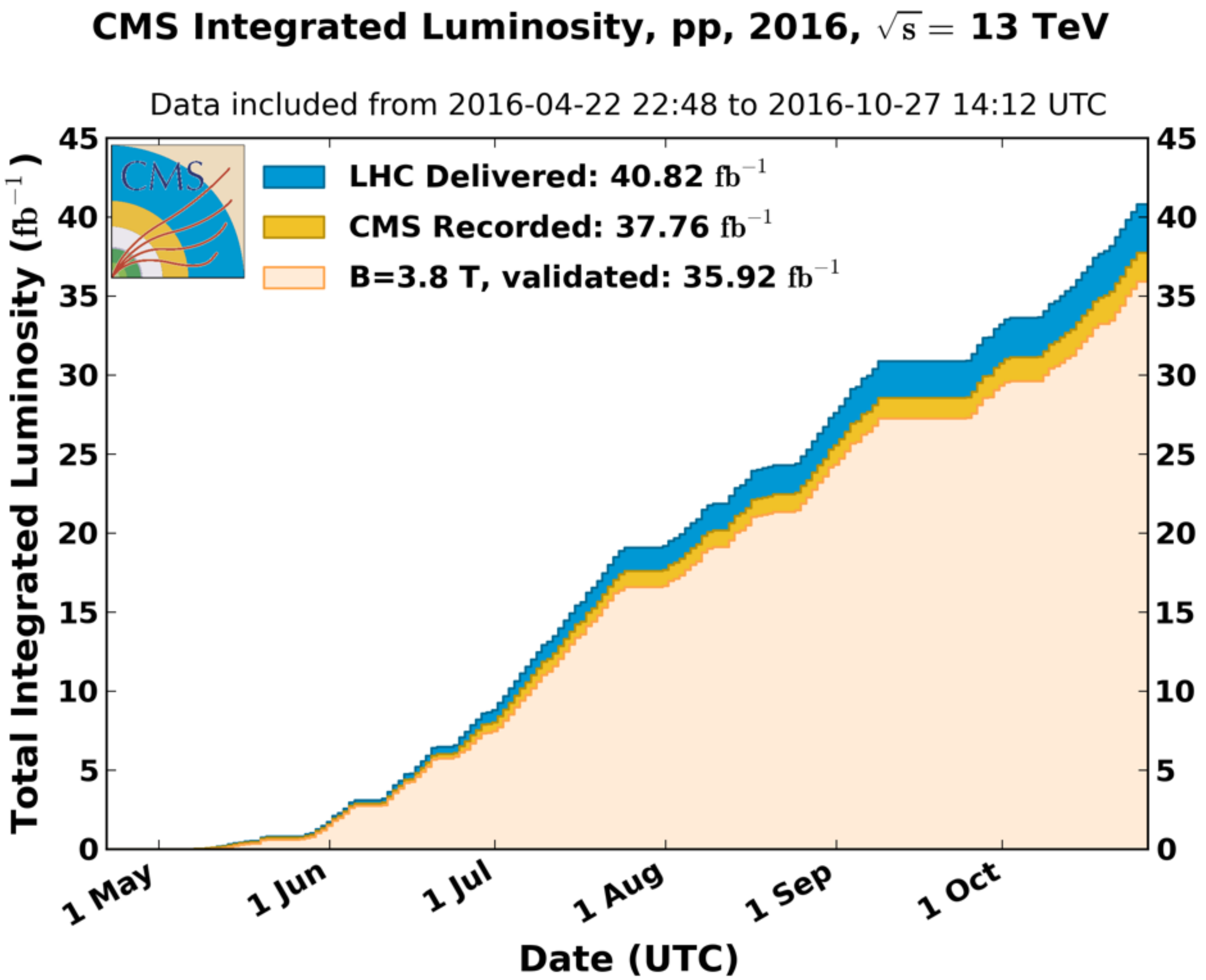
**Muon** system: resistive plate chambers, cathode strip chambers, drift tubes



# 2016 excellent detector performance

- Data taking efficiency ~ 93%
- Data certification efficiency ~ 95%

| CMS preliminary results: April 22nd - October 27th 2016 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Tracker** | | **Calorimeters** | | | **Muon Spectrometer** | | | **Operational Issue** |
| Pixel | SST | ECAL | ES | HCAL | CSC | DT | RPC | Tracker HV ramp |
| 99.9 | 99.1 | 99.3 | 99.7 | 99.6 | 99.9 | 99.9 | 99.6 | 99.5 |
| **All good for physics: 96%** | | | | | | | | |



# Eager analysts

http://cms-results.web.cern.ch/cms-results/public-results/publications/

**45 new results** based on full dataset for Moriond 2017 on diverse topics:

- 9 Higgs
- 12 SUSY
- 4 Exotica
- 5 B2G
- 7 Heavy ion
- 9 SM

| | |
|---|---|
| CMS-PAS-SMP-16-014 | Measurements of inclusive 2-jet, 3-jet and 4-jet azimuthal correlations in pp collisions at $\sqrt{s}$ = 13 TeV |
| CMS-PAS-SMP-16-017 | Measurement of the $pp \rightarrow ZZ$ production cross section, $Z \rightarrow 4\ell$ branching fraction and constraints on anomalous triple gauge couplings at $\sqrt{s}$ = 13 TeV |
| CMS-PAS-SMP-16-008 | Determination of the strong coupling constant from the measurement of inclusive multijet event cross sections in pp collisions at $\sqrt{s}$ = 8 TeV |
| CMS-PAS-EXO-16-056 | Searches for dijet resonances in pp collisions at $\sqrt{s}$ = 13 TeV using data collected in 2016 |
| CMS-PAS-EXO-17-006 | Search for evidence of Type-III seesaw mechanism in multilepton final states in pp collisions at $\sqrt{s}$ = 13 TeV |
| CMS-PAS-EXO-16-003 | Inclusive search for new particles decaying to displaced jets at $\sqrt{s}$ = 13 TeV |
| CMS-PAS-EXO-14-016 | MUSiC, a Model Unspecific Search for New Physics, in pp Collisions at $\sqrt{s}$ = 8 TeV |
| CMS-PAS-HIN-16-017 | Charge asymmetry dependence of elliptic and triangular flow in pPb and PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV |
| CMS-PAS-HIN-16-023 | Measurement of nuclear modification factors of $\Upsilon(nS)$ mesons in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV |
| CMS-PAS-HIN-16-022 | Correlations of azimuthal anisotropy harmonics in pp, pPb, and PbPb collisions at the LHC |
| CMS-PAS-HIN-16-020 | Jet properties in PbPb and pp collisions at $\sqrt{s_{NN}}$ = 5.02 TeV |
| CMS-PAS-HIN-16-019 | Measurement of the skewness of elliptic flow fluctuations in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV |
| CMS-PAS-HIN-16-018 | Measurement of mixed higher order flow harmonics in PbPb collisions |
| CMS-PAS-HIN-16-015 | Measurement of $\psi(2S)$ production in proton-lead and proton-proton collisions at $\sqrt{s_{NN}}$ = 5.02 TeV |

| | |
|---|---|
| CMS-PAS-SUS-16-036 | Search for new physics in the all-hadronic final state with the $M_{T2}$ variable |
| CMS-PAS-SUS-16-047 | Search for supersymmetry in events with at least one photon, missing transverse momentum, and large transverse event activity in proton-proton collisions at 13 TeV |
| CMS-PAS-SUS-16-035 | Search for beyond the standard model physics in events with two leptons of the same sign, missing transverse momentum, and jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV |
| CMS-PAS-SUS-16-046 | Search for GMSB supersymmetry in events with at least one photon and missing transverse momentum in pp collisions at $\sqrt{s}$ = 13 TeV |
| CMS-PAS-SUS-17-001 | Search for direct stop pair production in the dilepton final state at $\sqrt{s}$ = 13 TeV |
| CMS-PAS-SUS-16-037 | Search for supersymmetry in pp collisions at $\sqrt{s}$ = 13 TeV in the single-lepton final state using the sum of masses of large-radius jets |
| CMS-PAS-SUS-16-044 | Search for the pair production of Higgsinos in pp collisions at $\sqrt{s}$ = 13 TeV in final states with Higgs bosons and large missing transverse momentum |
| CMS-PAS-SUS-16-049 | Search for direct top squark pair production in the all-hadronic final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV |
| CMS-PAS-SUS-16-045 | Search for supersymmetry with Higgs to diphoton decays using the razor variables at $\sqrt{s}$ = 13 TeV |
| CMS-PAS-HIG-17-015 | Measurement of differential fiducial cross sections for Higgs boson production in the diphoton decay channel in pp collisions at $\sqrt{s}$ = 13 TeV |
| CMS-PAS-HIG-17-006 | Search for resonant and non-resonant Higgs boson pair production in the $b\bar{b}\ell\nu\ell\nu$ final state at $\sqrt{s}$ = 13 TeV |
| CMS-PAS-HIG-17-003 | Search for the associated production of a Higgs boson with a top quark pair in final states with a $\tau$ lepton at $\sqrt{s}$ = 13 TeV |
| CMS-PAS-HIG-16-041 | Measurements of properties of the Higgs boson in the four-lepton final state at $\sqrt{s}$ = 13 TeV |
| CMS-PAS-HIG-17-004 | Search for Higgs boson production in association with top quarks in multilepton final states at $\sqrt{s}$ = 13 TeV |
| CMS-PAS-HIG-17-011 | Constraints on anomalous Higgs boson couplings in production and decay $H \rightarrow 4\ell$ |
| CMS-PAS-HIG-17-002 | Search for pair production of Higgs bosons in the two tau leptons and two bottom quarks final state using proton-proton collisions at $\sqrt{s}$ = 13 TeV |
| CMS-PAS-HIG-16-034 | Search for new diboson resonances in the dilepton+jets final state at $\sqrt{s}$ = 13 TeV with 2016 data |
| CMS-PAS-HIG-16-036 | A search for doubly-charged Higgs boson production in three and four lepton final states at $\sqrt{s}$ = 13 TeV |


| | |
|---|---|
| CMS-PAS-EXO-16-056 | Searches for dijet resonances in pp collisions at $\sqrt{s}$ = 13 TeV using data collected in 2016 |
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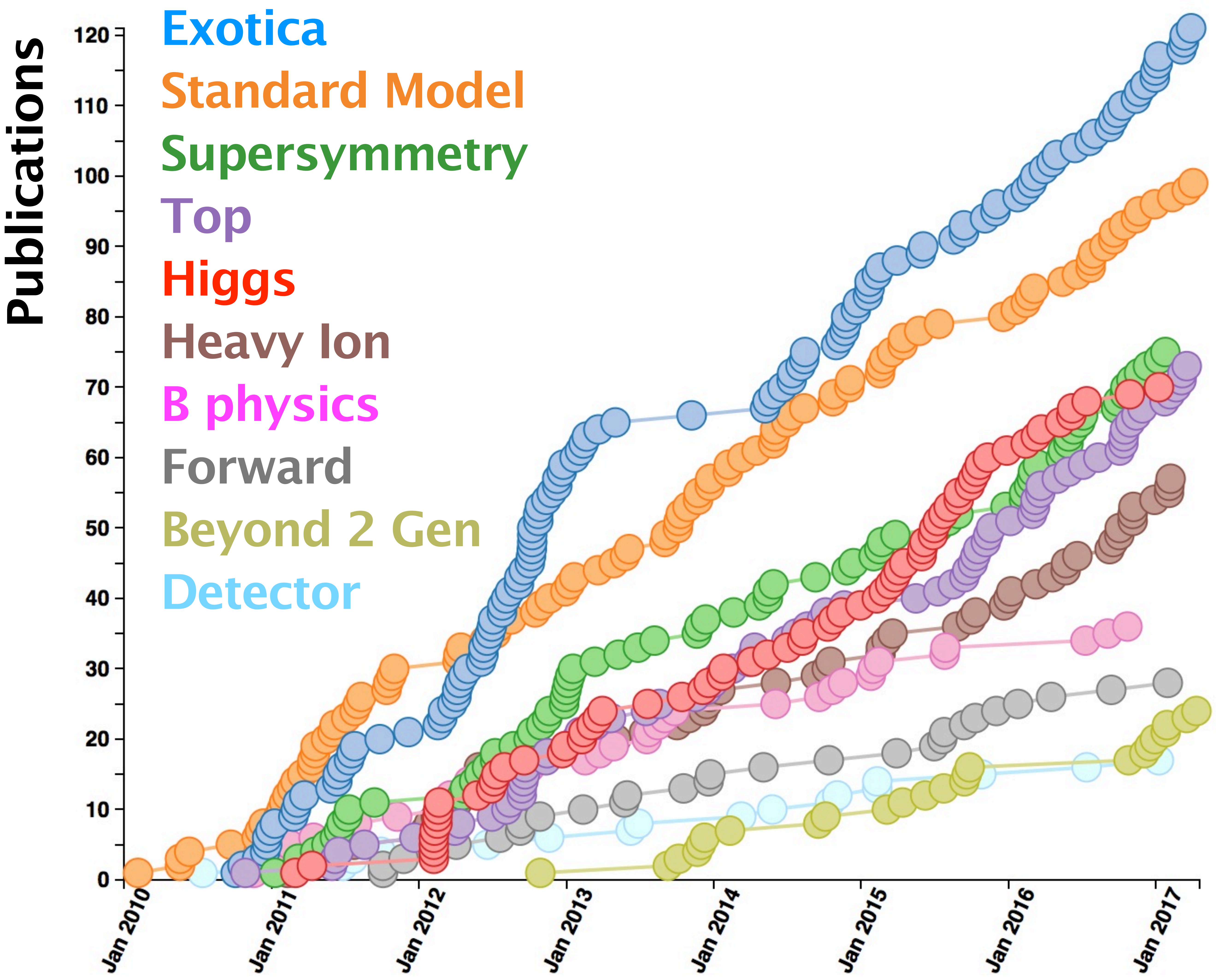
| | |
|---|---|
| CMS-PAS-TOP-16-023 | Measurement of the inclusive $t\bar{t}$ cross section at $\sqrt{s}$ = 5.02 TeV |
| CMS-PAS-TOP-16-022 | Measurement of the top quark mass with muon+jets final states in pp collisions at $\sqrt{s}$ = 13 TeV |

# CMS Collaboration

~ 2000 PhDs
~ 900 students
  including
  ~ 400 LPC
  ~ 60 FNAL

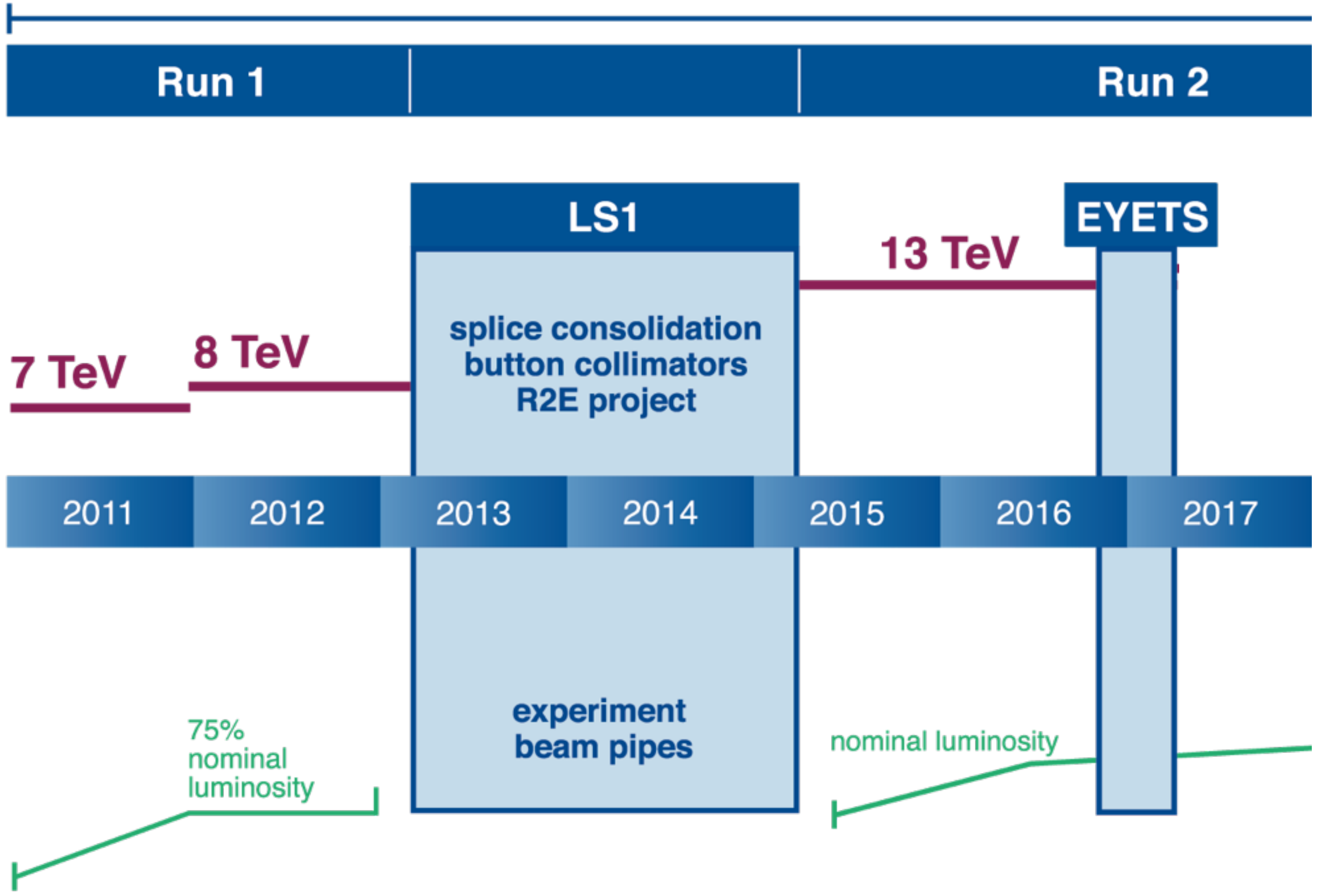
# Busy publications committee

- 599 publications since 2010
- 105 publications in 2016
- 26 publications in 2017



# Many firsts since 2010

2010 : 7 TeV results
2011 : 7 TeV results with large dataset
2012 : 8 TeV results
2015 : 13 TeV results (2/fb)




Today : First 13 TeV results with large dataset 36 $fb^{-1}$

# Selected topics for today

**Exploration for new phenomena with SUSY as guiding principle**

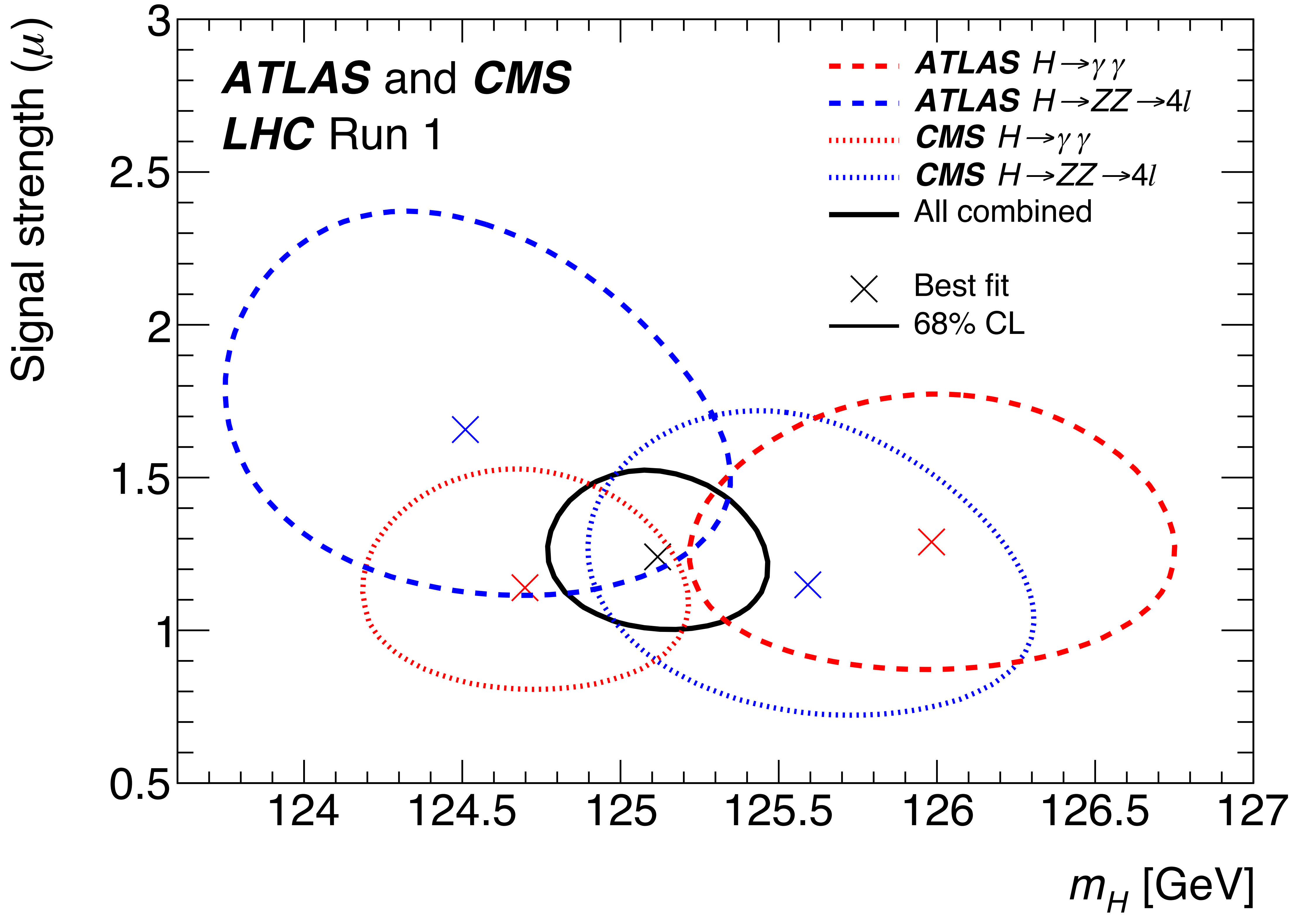
**Uncovering the Higgs**

# Uncovering the Higgs

- H → ZZ* → 4ℓ
- ttH production

# Higgs at end of Run 1

arXiv:1503.07589




$$m_H = 125.09 \pm 0.24 \;\text{GeV}$$
$$= 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.})\;\text{GeV}$$

arXiv:1606.02266

BR(H ➔ BSM) < 34% at 95% C.L.

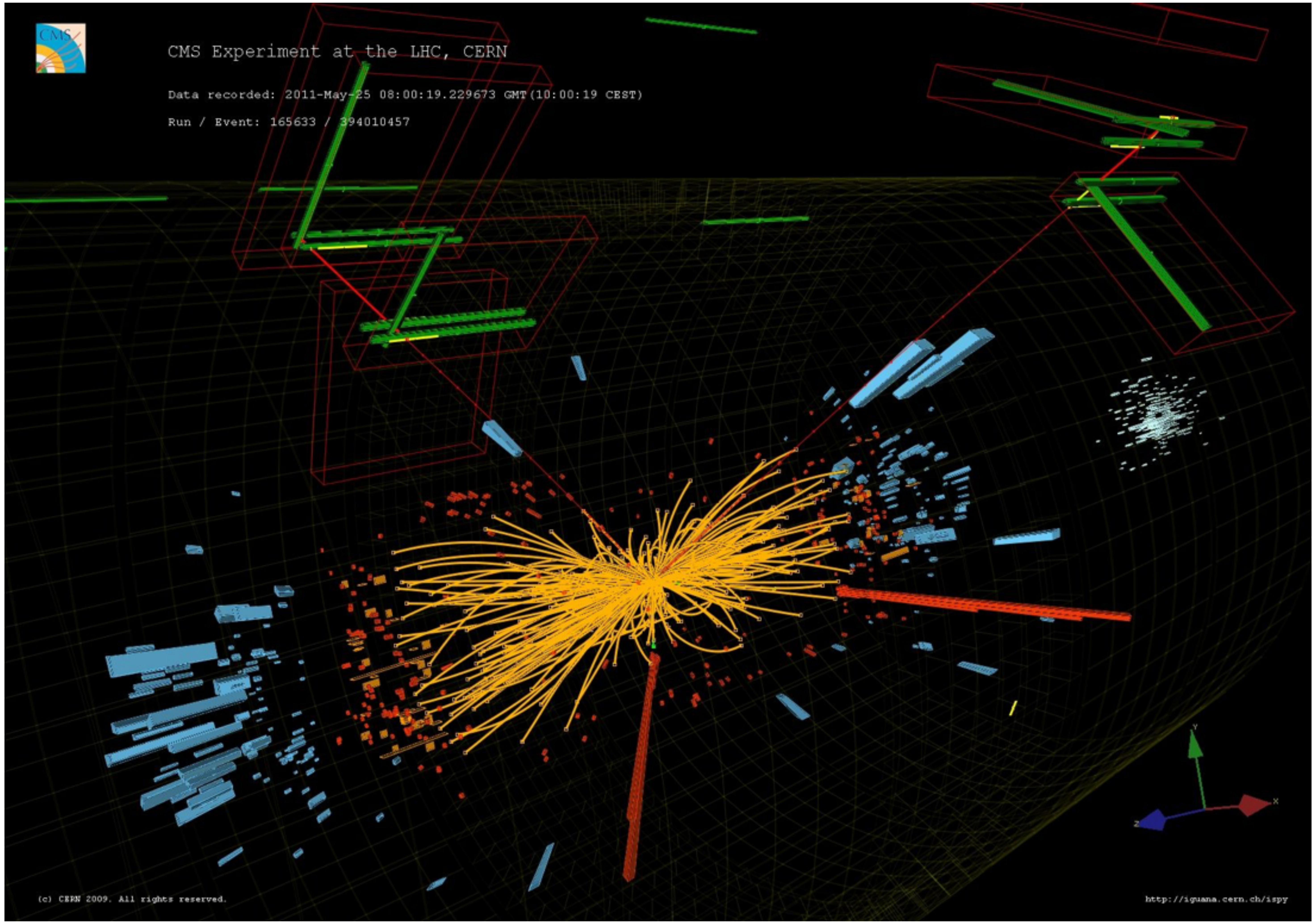
| Channel | Signal strength [$\mu$] | | Signal significance [$\sigma$] | |
|---|---|---|---|---|
| | from results in this paper (Section 5.2) | | | |
| | ATLAS | CMS | ATLAS | CMS |
| $H \to \gamma\gamma$ | $1.14\,^{+0.27}_{-0.25}$ $\left(^{+0.26}_{-0.24}\right)$ | $1.11\,^{+0.25}_{-0.23}$ $\left(^{+0.23}_{-0.21}\right)$ | 5.0 (4.6) | 5.6 (5.1) |
| $H \to ZZ$ | $1.52\,^{+0.40}_{-0.34}$ $\left(^{+0.32}_{-0.27}\right)$ | $1.04\,^{+0.32}_{-0.26}$ $\left(^{+0.30}_{-0.25}\right)$ | 7.6 (5.6) | 7.0 (6.8) |
| $H \to WW$ | $1.22\,^{+0.23}_{-0.21}$ $\left(^{+0.21}_{-0.20}\right)$ | $0.90\,^{+0.23}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$ | 6.8 (5.8) | 4.8 (5.6) |
| $H \to \tau\tau$ | $1.41\,^{+0.40}_{-0.36}$ $\left(^{+0.37}_{-0.33}\right)$ | $0.88\,^{+0.30}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$ | 4.4 (3.3) | 3.4 (3.7) |
| $H \to bb$ | $0.62\,^{+0.37}_{-0.37}$ $\left(^{+0.39}_{-0.37}\right)$ | $0.81\,^{+0.45}_{-0.43}$ $\left(^{+0.45}_{-0.43}\right)$ | 1.7 (2.7) | 2.0 (2.5) |
| $H \to \mu\mu$ | $-0.6\,^{+3.6}_{-3.6}$ $\left(^{+3.6}_{-3.6}\right)$ | $0.9\,^{+3.6}_{-3.5}$ $\left(^{+3.3}_{-3.2}\right)$ | | |
| $ttH$ production | $1.9\,^{+0.8}_{-0.7}$ $\left(^{+0.7}_{-0.7}\right)$ | $2.9\,^{+1.0}_{-0.9}$ $\left(^{+0.9}_{-0.8}\right)$ | 2.7 (1.6) | 3.6 (1.3) |

# $H \rightarrow ZZ^* \rightarrow 4\ell$

HIG-16-041

Despite $10^{-4}$ branching fraction,
$H \rightarrow 4\ell$ has large S/B

- complete reconstruction
- excellent $\ell$ momentum resolution.




**Select candidates**

- $\geq 2\ell$ w/ $p_T > 10$GeV
- $\geq 1\ell$ w/ $p_T > 20$ GeV
- $12 < m(\ell\ell) < 120$ GeV
- $m_{Z1} > 40$ GeV; Z1 is cand. w/ $m_{\ell\ell}$ near $m_Z$.
- $m(\ell^+\ell^-) > 4$ GeV for all combs
- $m(4\ell) > 70$ GeV

**Multiple candidates**

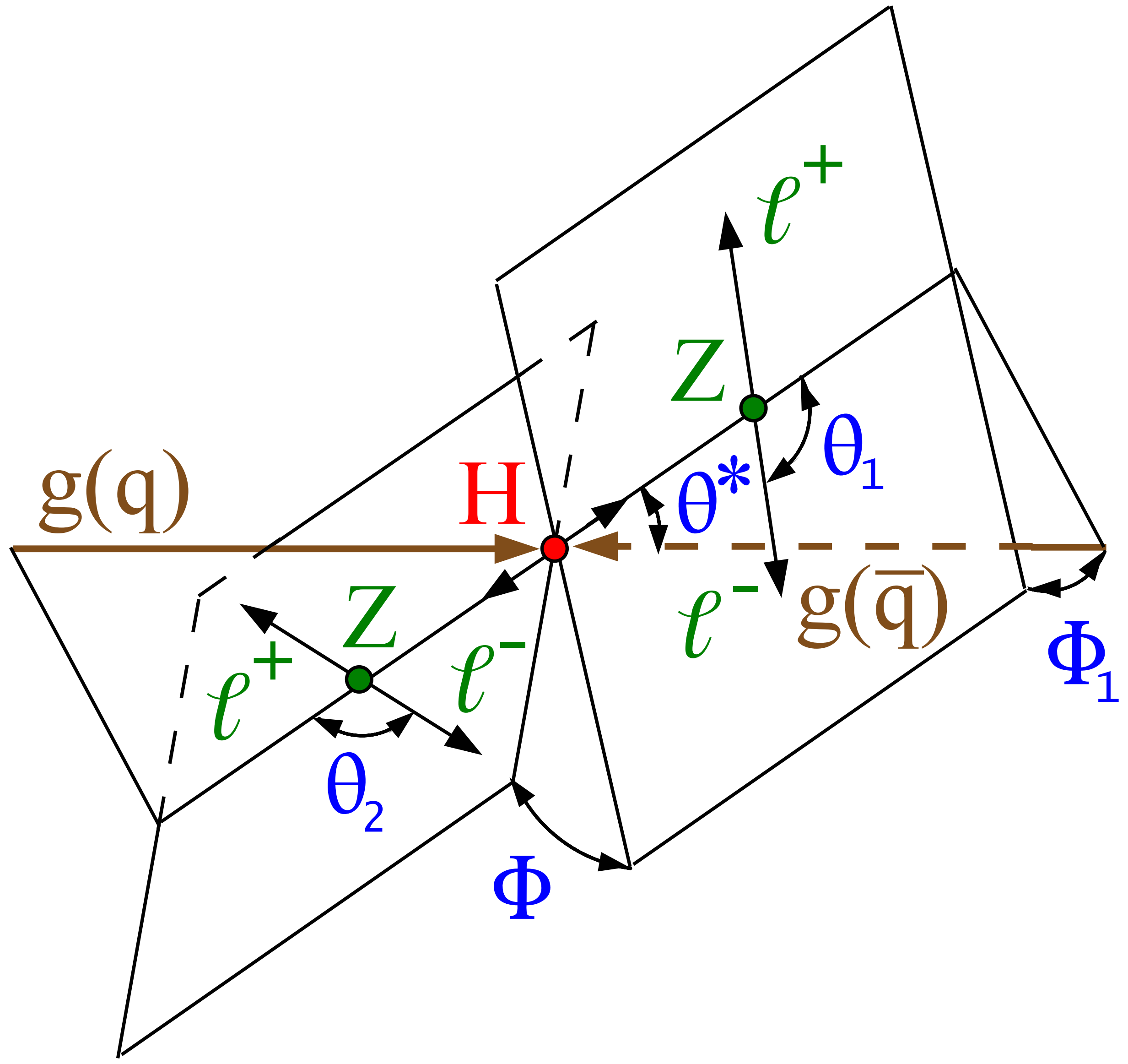
- Choose cand with highest $D_{kin}$ (next slide).
- In $4e/4\mu$, choose pairing with $m_{Z1}$ closer $m_Z$.

# H ➔ 4ℓ kinematic fits

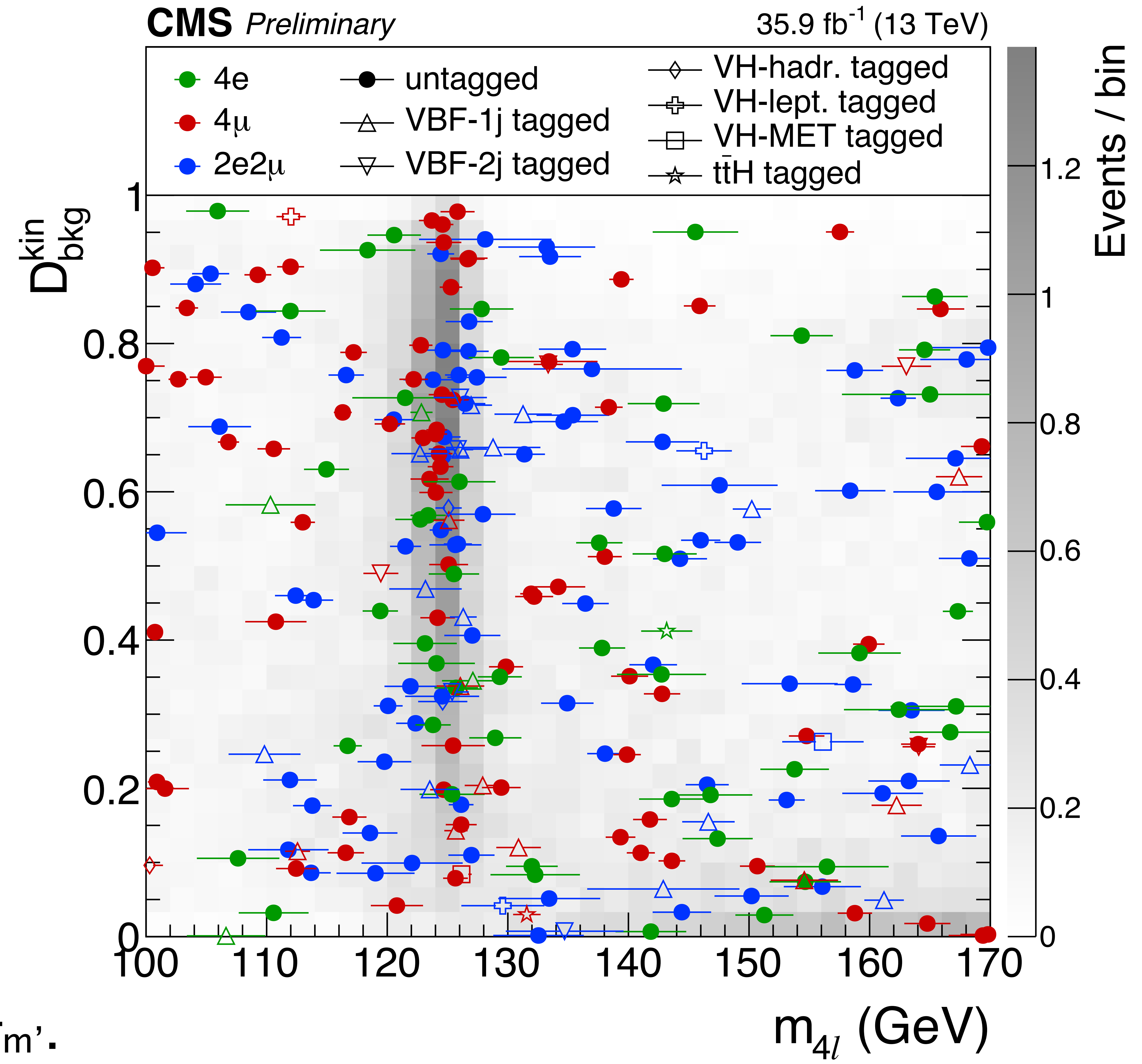
HIG-16-041

- **7 production-related categories** based on
  - number of jets (**Nj**)
  - number of b-tagged jets (**$N_b$**)
  - **N(ℓ), kinematics**

- **Discriminant** based on decay kinematics




$$D^{kin}_{bkg} = \frac{P_{sig}}{(P_{sig} + P_{bkg})}$$



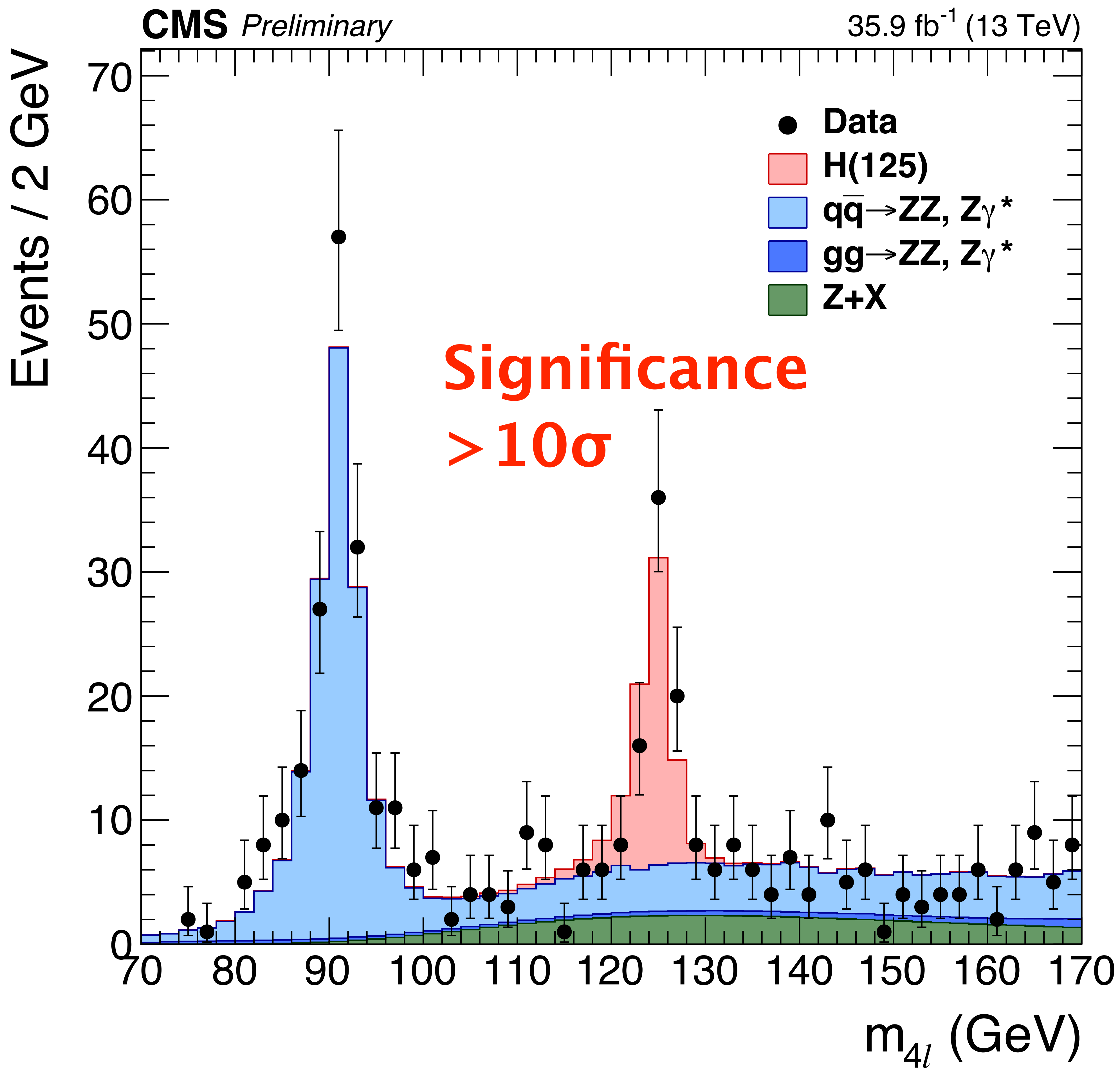

- **Rate fit:** $D^{kin}_{bkg}$ and m(4ℓ).
- **Mass fit:** Rate fit + $m_Z$ constraint on $m_{Z1}$ + $\sigma_{m'}$.

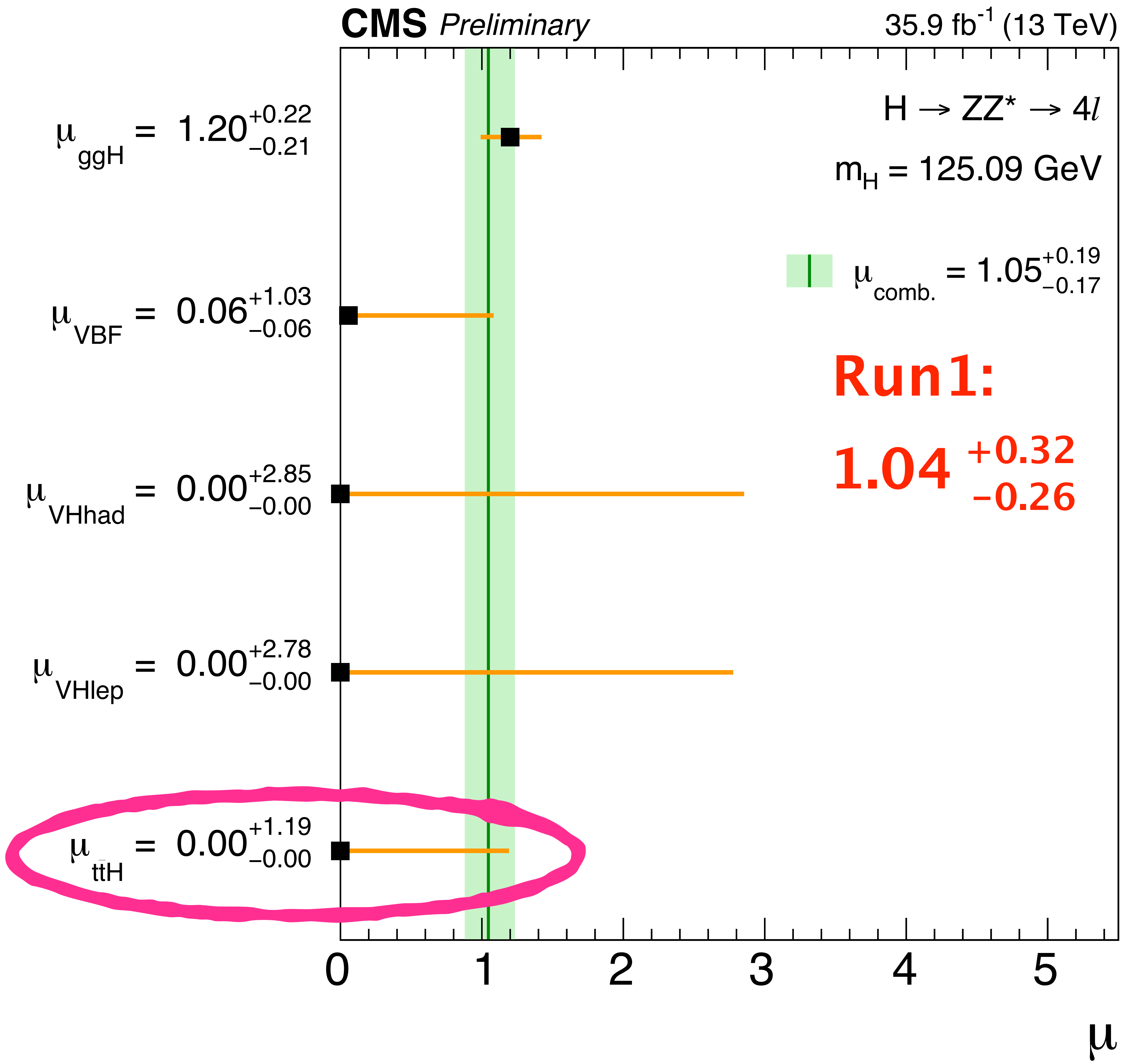
# H → 4ℓ mass and signal strength

HIG-16-041

$$m_{\mathrm{H}} = 125.26 \pm 0.20(\mathrm{stat.}) \pm 0.08(\mathrm{sys.})\ \mathrm{GeV}$$

**More precise than Run 1 combination of H→γγ and H→4ℓ !**



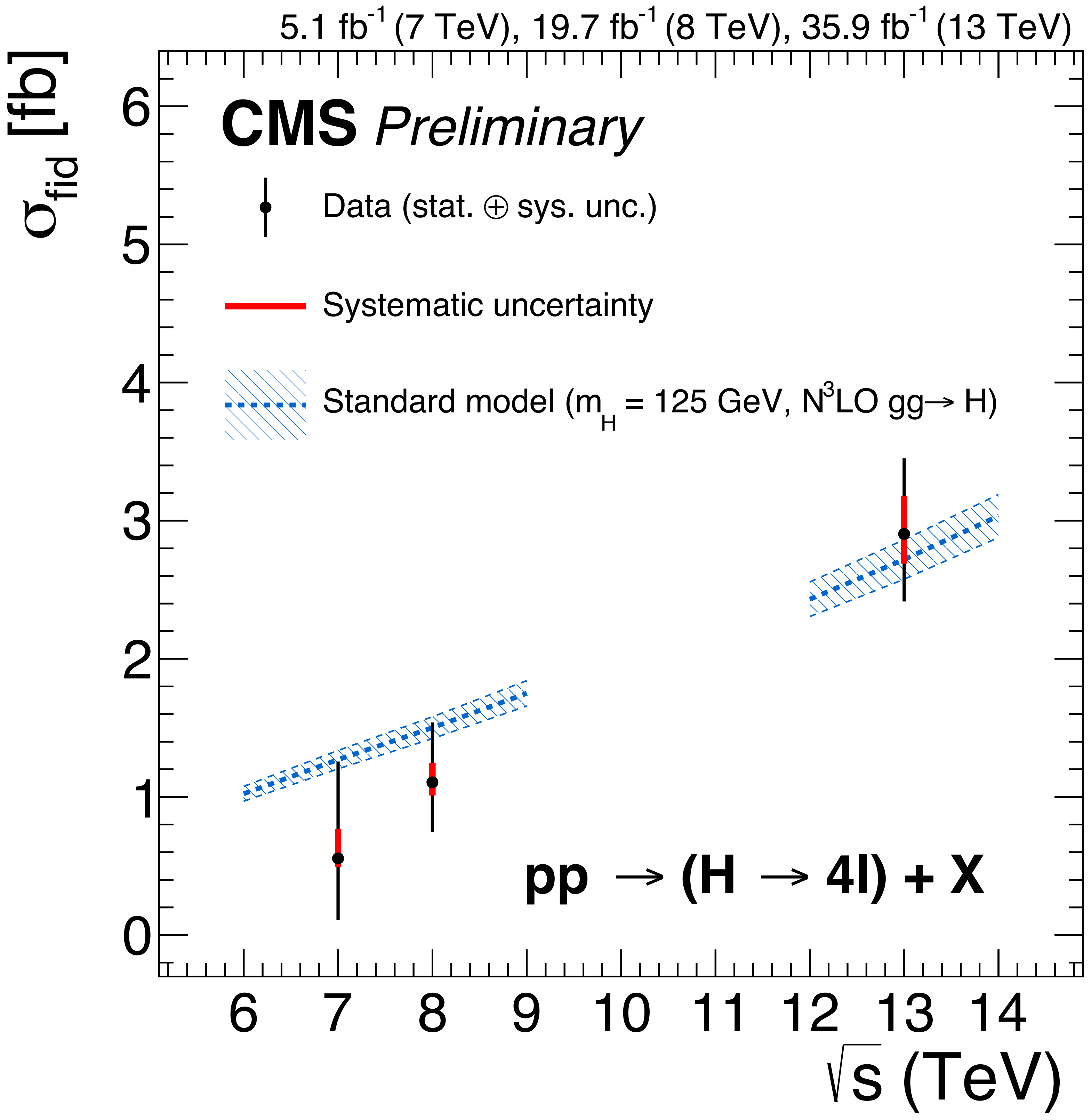



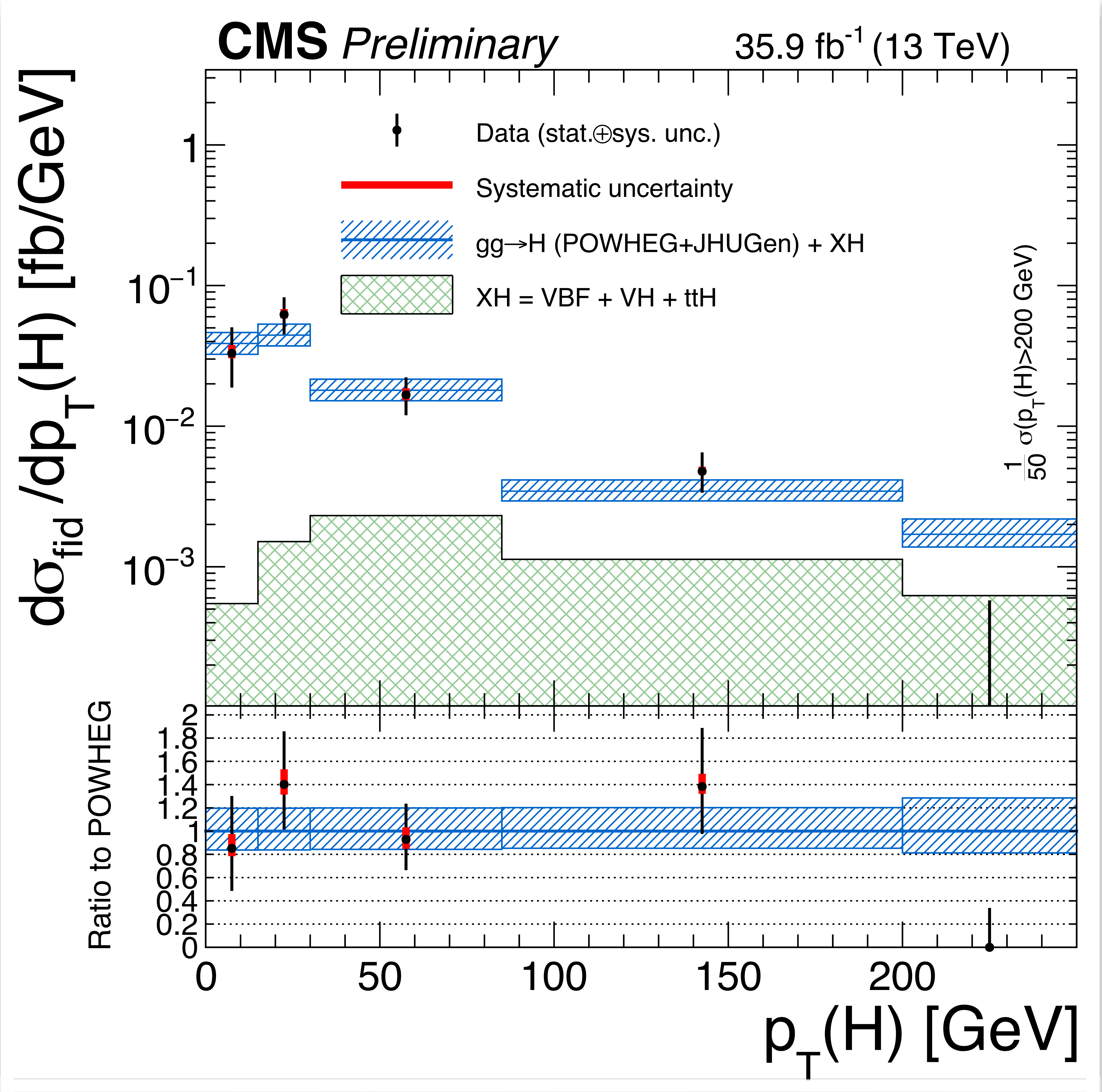
# H → 4ℓ fiducial cross section

HIG-16-041

- **Fiducial phase space** based on $p_T(\ell)$, $\eta(\ell)$, $m(\ell\ell)$, $m(4\ell)$, and more (in backup).

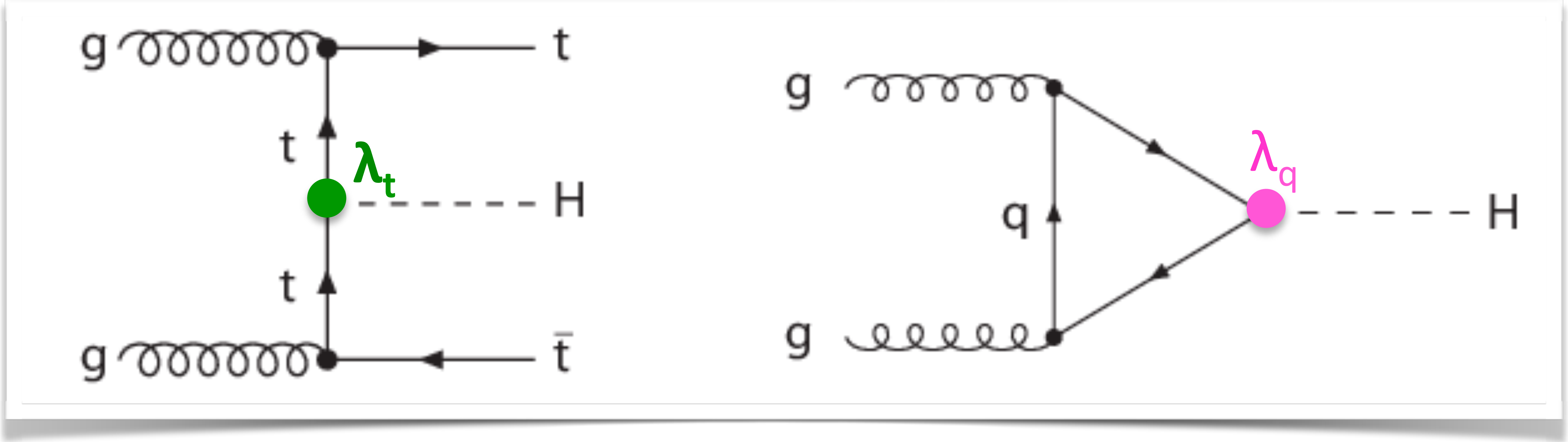
$$\sigma = 2.90\ ^{+0.48}_{-0.44}(\text{stat})\ ^{+0.27}_{-0.22}(\text{syst})\ \text{fb}$$



# Search for ttH

- **Important**: Direct probe of top / Higgs coupling.




- **Challenging**: σ(ttH) = ~1% of σ(ggH) = 500 fb

- **Potentially anomalous:**

**$t\bar{t}H^0$ Production**

Signal strengh relative to the Standard Model cross section.

| *VALUE* | *CL%* | *DOCUMENT ID* | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **$2.3^{+0.7}_{-0.6}$** | | [1,2] AAD 16J | LHC | *pp*, 7, 8 TeV |

# H decay modes for ttH search

good mix of yield and purity

**Hadronic**

$H \rightarrow bb$, $H \rightarrow \tau_h \tau_h$

**Leptonic**

$H \rightarrow WW$, $H \rightarrow \tau_\ell \tau_{any}$

**Bosonic:**

$H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4\ell$

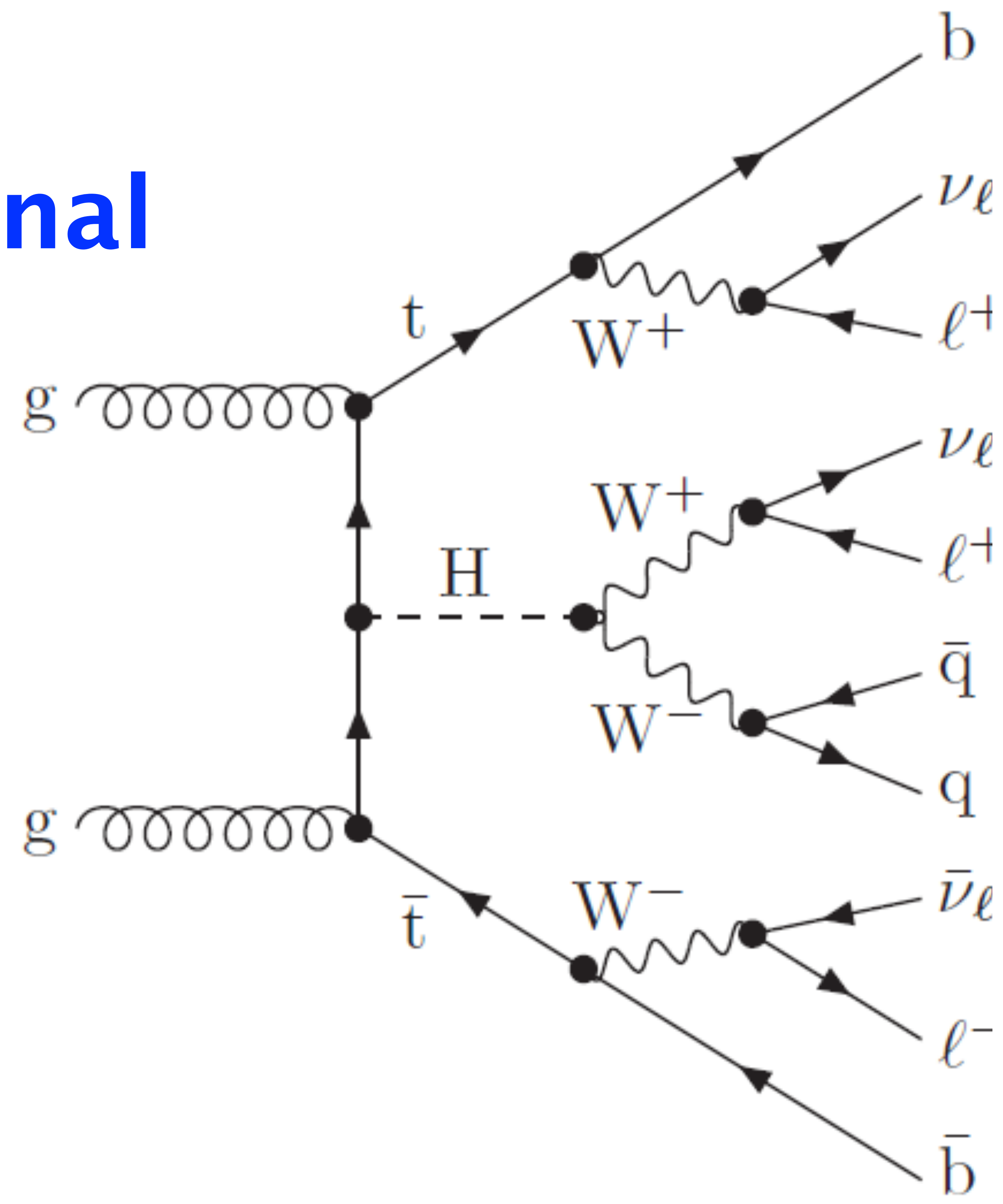
higher yield

higher purity

$\sigma \times BR < 1fb$

G. Petrucciani
Moriond 2017

## $3\ell$ signal




## Backgrounds

- tt + W/Z/$\gamma^*$
- tt + jets

# ttH multilepton search

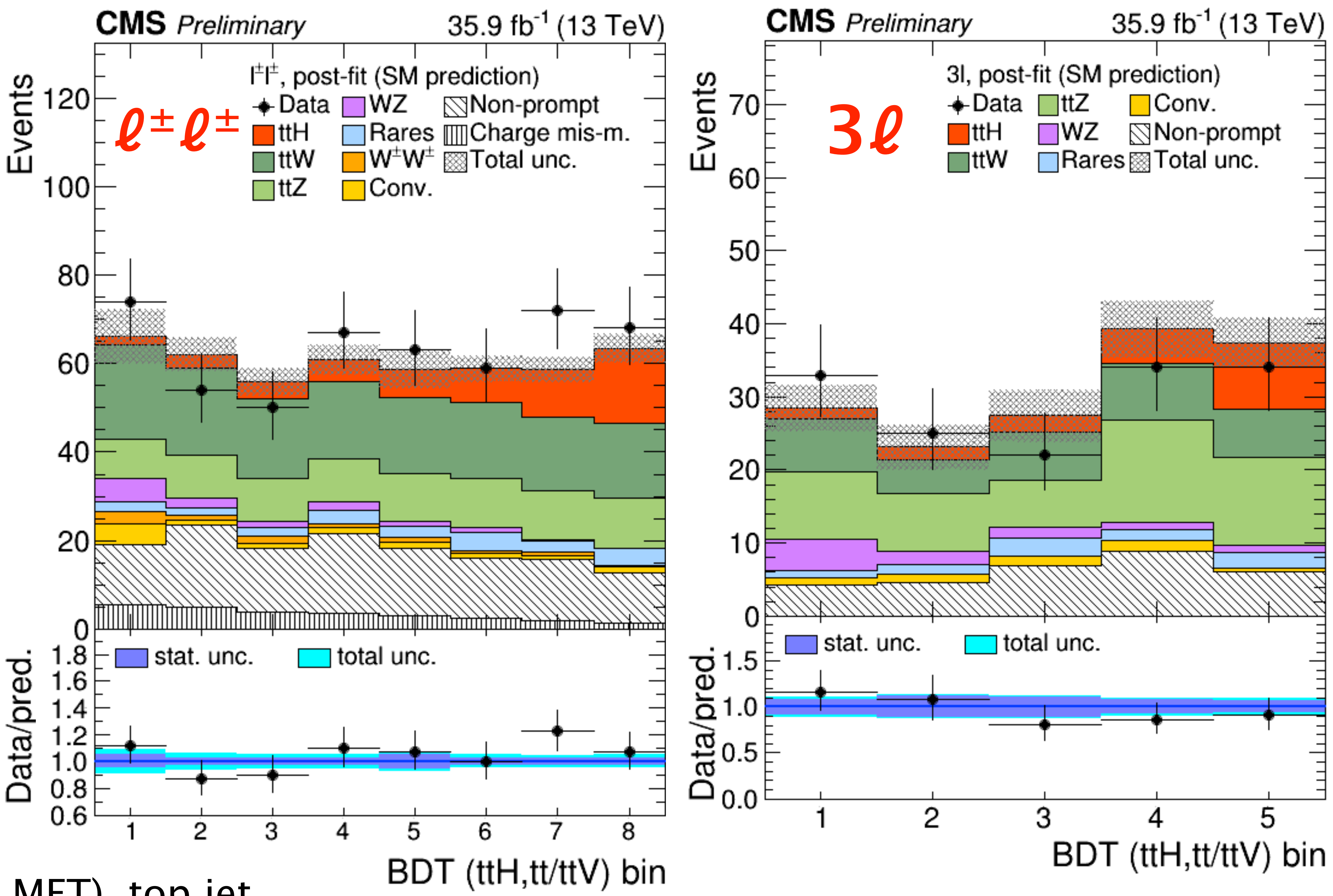
HIG-17-004

## Categories

- $\ell^{\pm}\ell^{\pm}$ , Nj≥4, $N_b$≥1
  - ee/eμ/μμ and ++/—
  - loose/tight b-tagging
- $3\ell$ , Nj≥2, $N_b$≥1
  - loose/tight b-tagging
- $4\ell$ , Nj≥2, $N_b$≥1
  - veto H→ $4\ell$

## Methods

- $2\ell$ + $3\ell$: 2-dimensional boosted decision tree (BDT)*
- $4\ell$: counting experiment

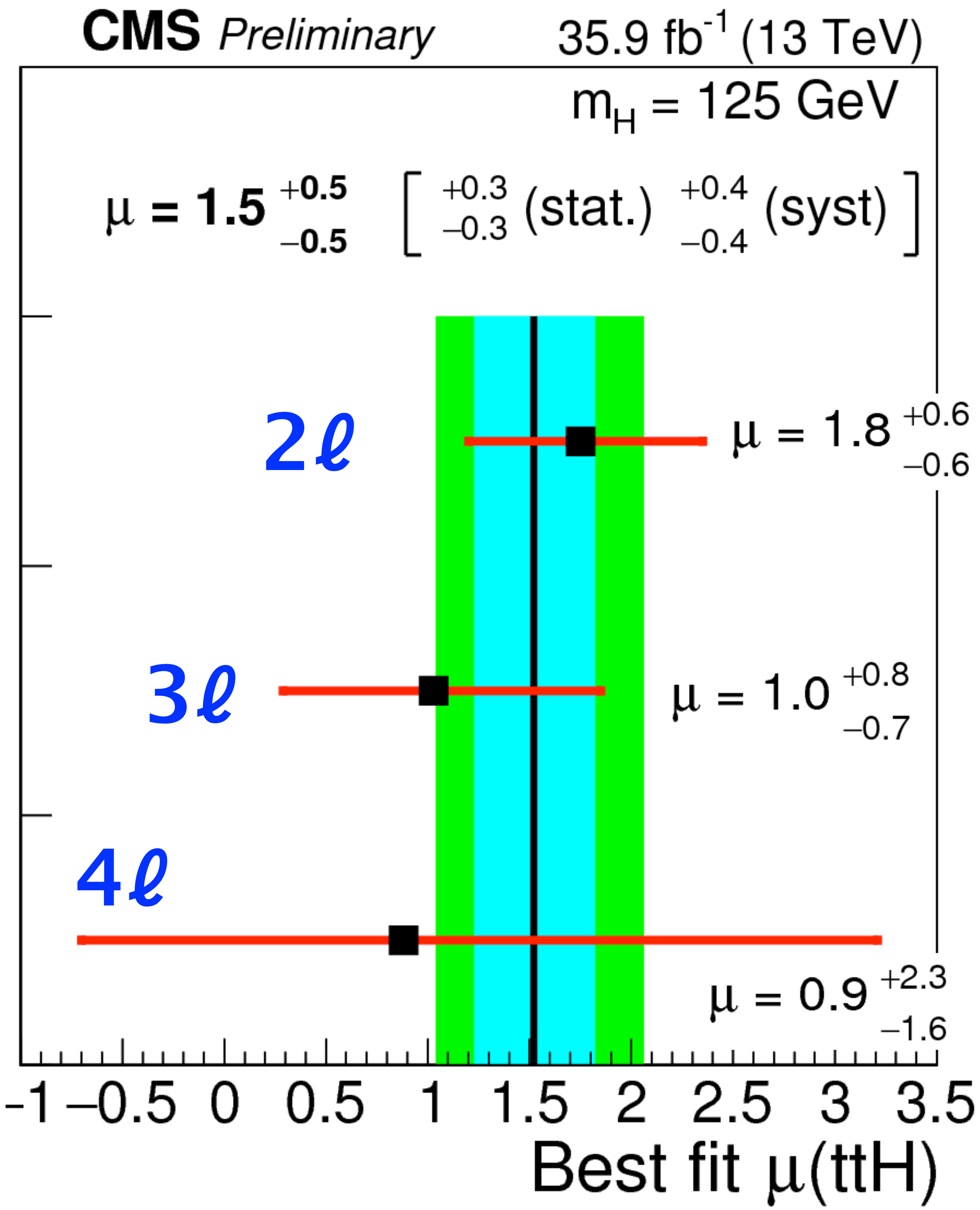



**BDT** based on $\ell$ kinematics, Nj, $m_T(\ell_1, MET)$, top jet tagger, H jet tagger, ttH and ttV ME weights.

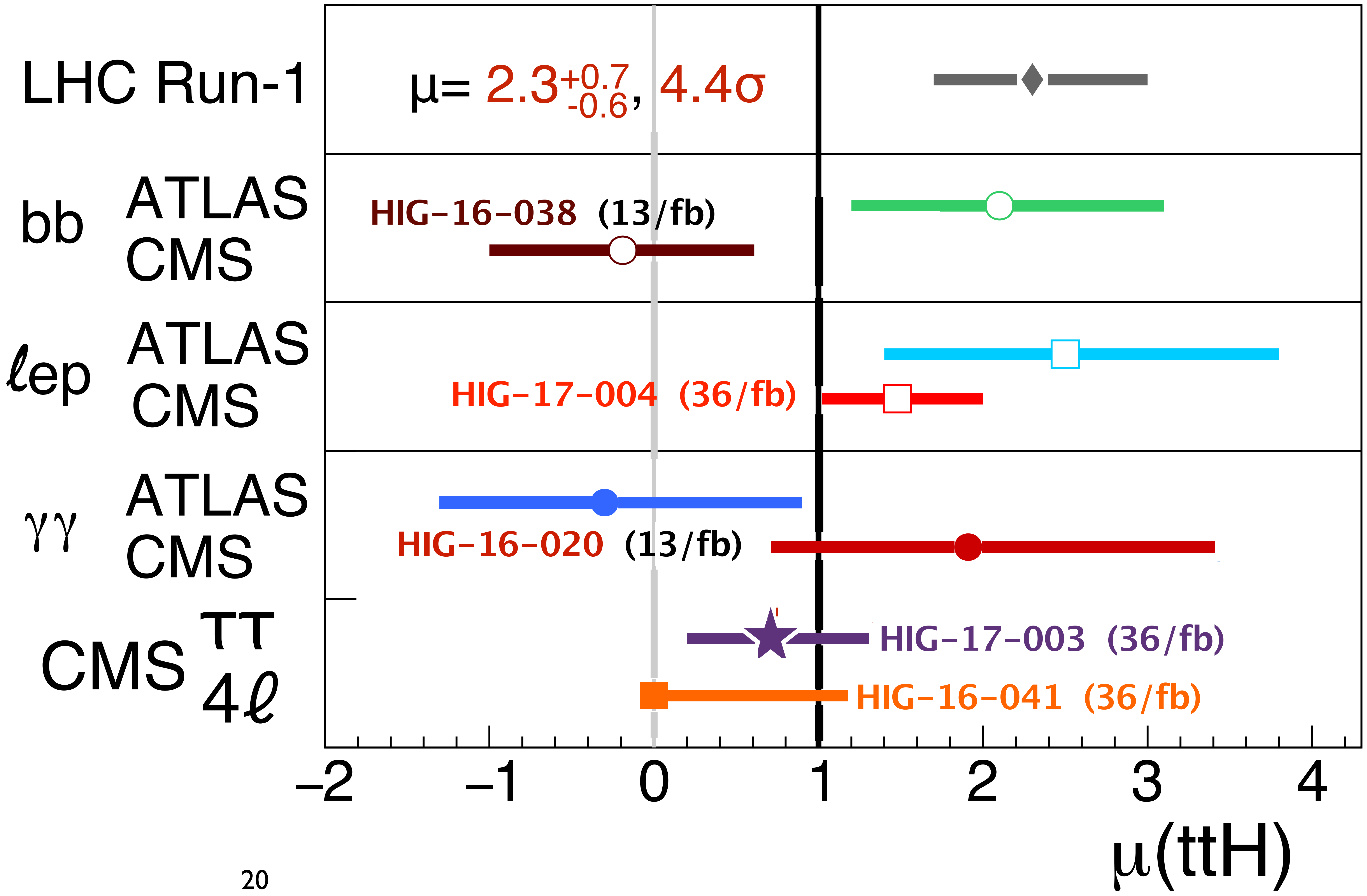
*post-fit plots with μ(ttH) constrained to SM predictions*

# ttH signal strength

## CMS multilepton




## Run 2 ttH summary



# Exploration for new phenomena

*with supersymmetry as guiding principle*

- **General** search — with SUSY gluino interpretation
- Targeted **top squark** search
- Targeted **electroweakino** search

# Supersymmetry (SUSY)

Spacetime symmetry that turns bosonic states into fermionic states and vice versa:

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle, \qquad Q|\text{Fermion}\rangle = |\text{Boson}\rangle$$

SM particles

| | | | | |
|---|---|---|---|---|
| SM fermions | u | d | e | $\nu_e$ |
| | c | s | $\mu$ | $\nu_\mu$ |
| | t | b | $\tau$ | $\nu_\tau$ |
| SM bosons | h | A | $H^0$ | $H^\pm$ |
| | $\gamma$ | $Z^0$ | $W^\pm$ | g |

SUSY partners

| | | | |
|---|---|---|---|
| $\tilde{u}$ | $\tilde{d}$ | $\tilde{e}$ | $\tilde{\nu}_e$ |
| $\tilde{c}$ | $\tilde{s}$ | $\tilde{\mu}$ | $\tilde{\nu}_\mu$ |
| $\tilde{t}$ | $\tilde{b}$ | $\tilde{\tau}$ | $\tilde{\nu}_\tau$ |
| $\tilde{\chi}^0_1$ | $\tilde{\chi}^0_2$ | $\tilde{\chi}^0_3$ | $\tilde{\chi}^0_4$ |
| $\tilde{\chi}^\pm_1$ | $\tilde{\chi}^\pm_2$ | | $\tilde{g}$ |

**Why SUSY?**

- ☐ Explains dark matter
  - **Lightest SUSY particle = LSP**
- ☐ Explains Higgs mass
- ☐ Unifies forces

Special particles

- gluino
- stop
- higgsinos

Higgs and gauge boson spartners mix forming neutralinos and charginos or **“EWKinos”**

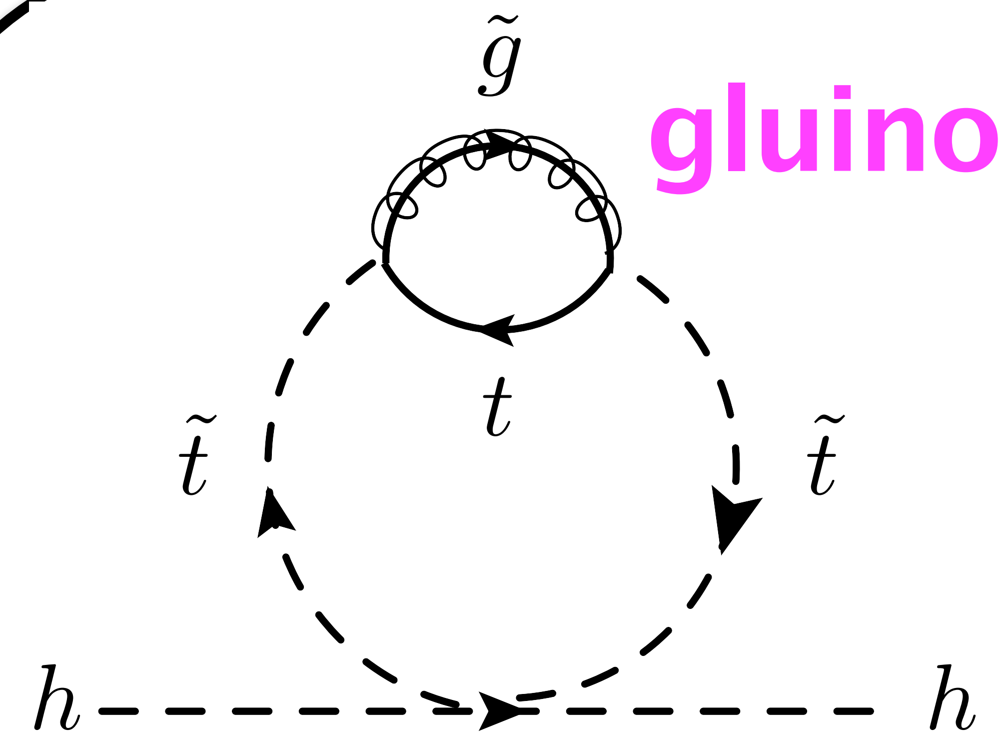
# “Natural” SUSY spectrum

$$m_H^2 = (m_H^2)_0 + \delta m_H^2$$

- We measure $|m_H^2|$~100GeV.
- In standard model (SM), $\delta m_H^2 \sim 10^{30}$ GeV.
- In SUSY, $\delta m_H^2$ can be small, but depends on sparticle masses.
- Define “natural” spectrum as giving $\delta m_H^2$ not $\gg m_H^2$.
- Traditional metric: $\Delta \equiv \frac{2|\delta m_H^2|}{m_h^2}$

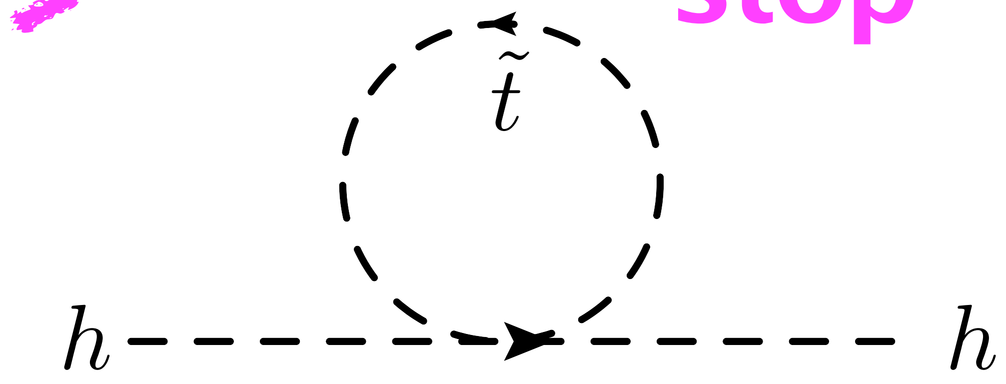
D. Shih

gluino



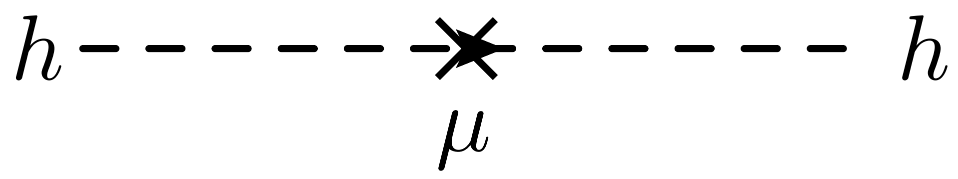

$$\delta m_H^2 \sim -\frac{y_t^2}{\pi^2}\frac{g_3^2}{4\pi^2}M_3^2\left(\log\frac{\Lambda}{Q}\right)^2$$

stop




$$\delta m_H^2 \sim -\frac{3}{8\pi^2}y_t^2(m_{Q_3}^2 + m_{U_3}^2)\log\frac{\Lambda}{Q}$$

higgsino

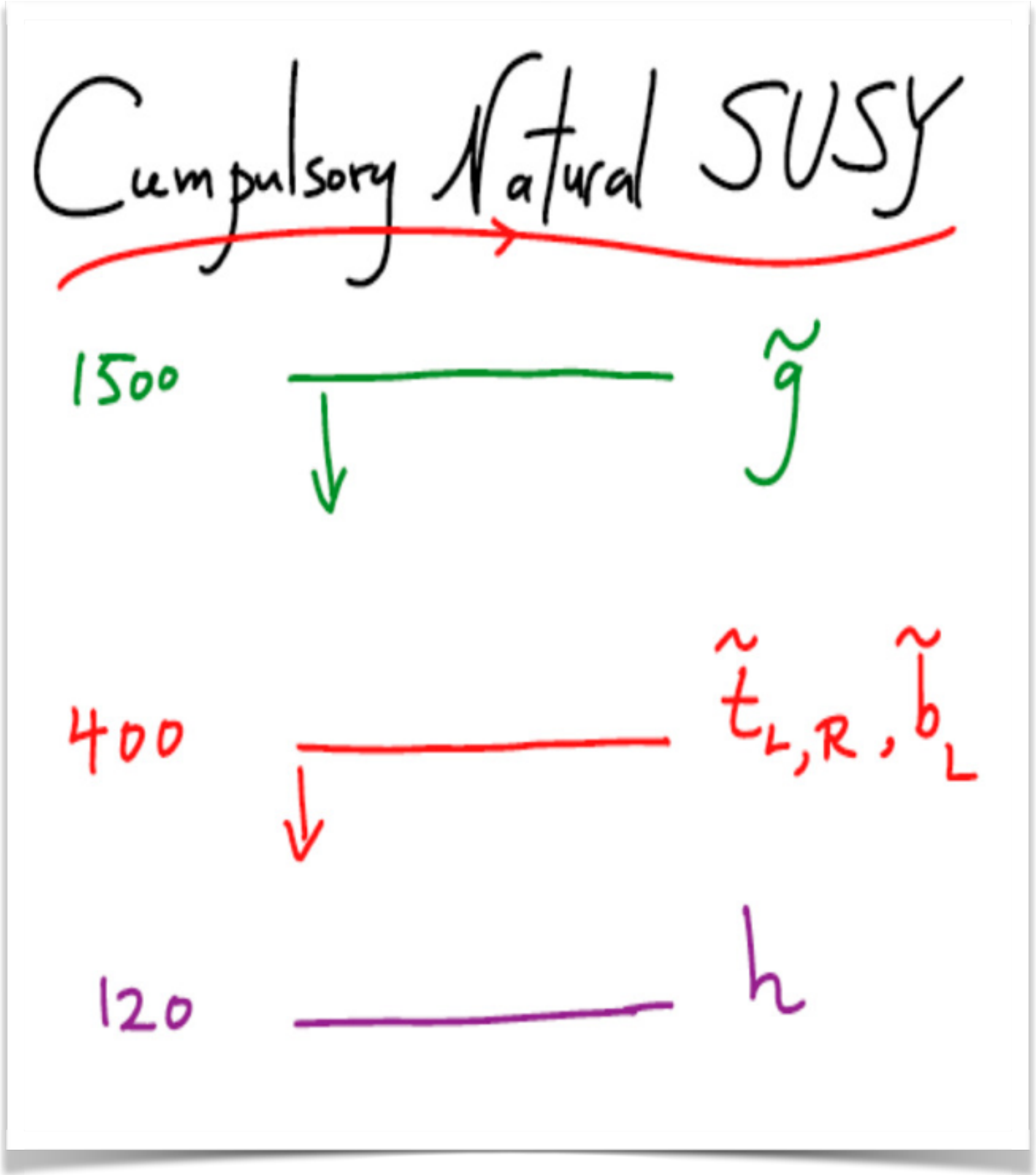


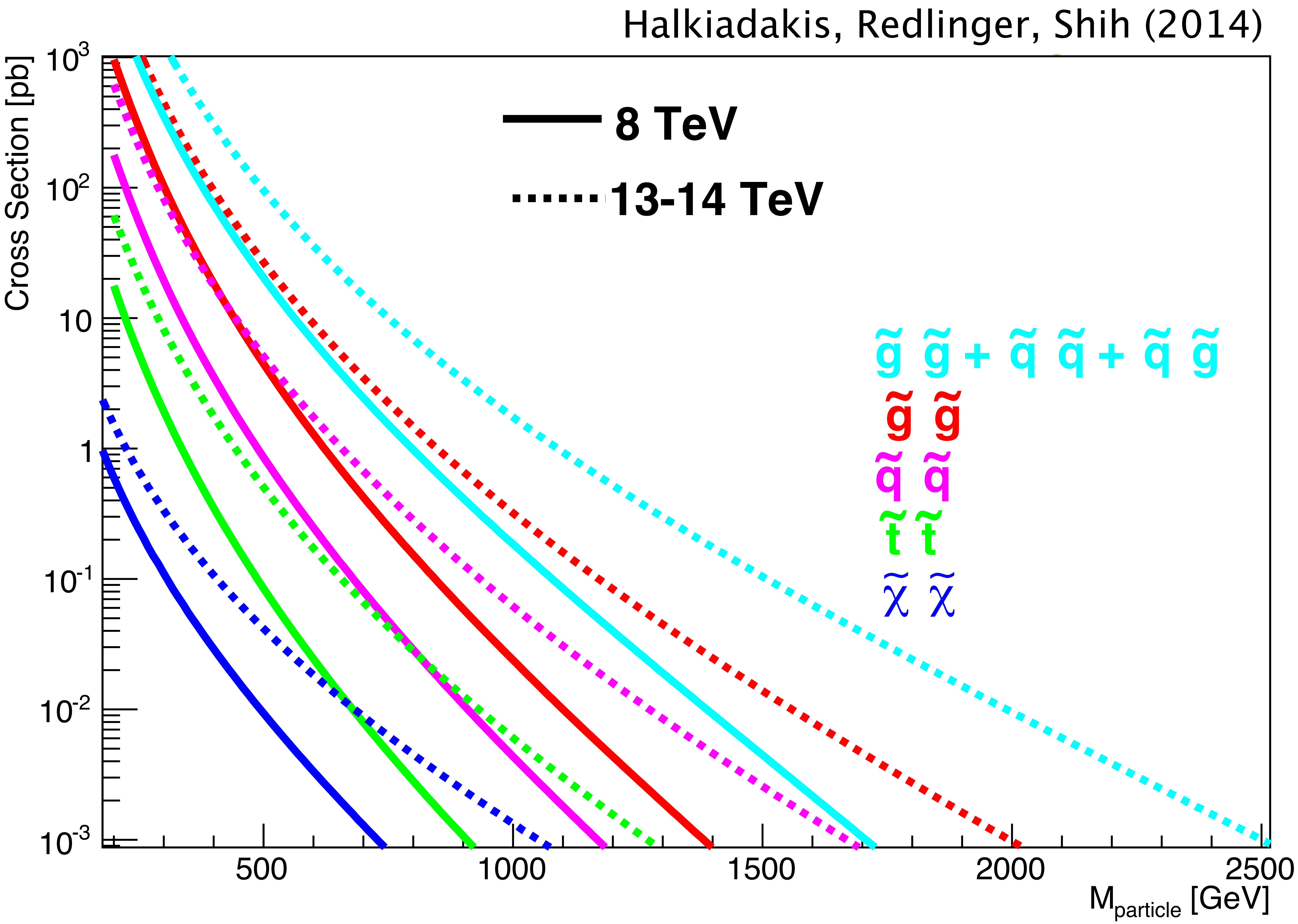

$$\delta m_H^2 \sim |\mu|^2$$

$\Lambda$ = UV cutoff scale
Q = IR scale appropriate to process

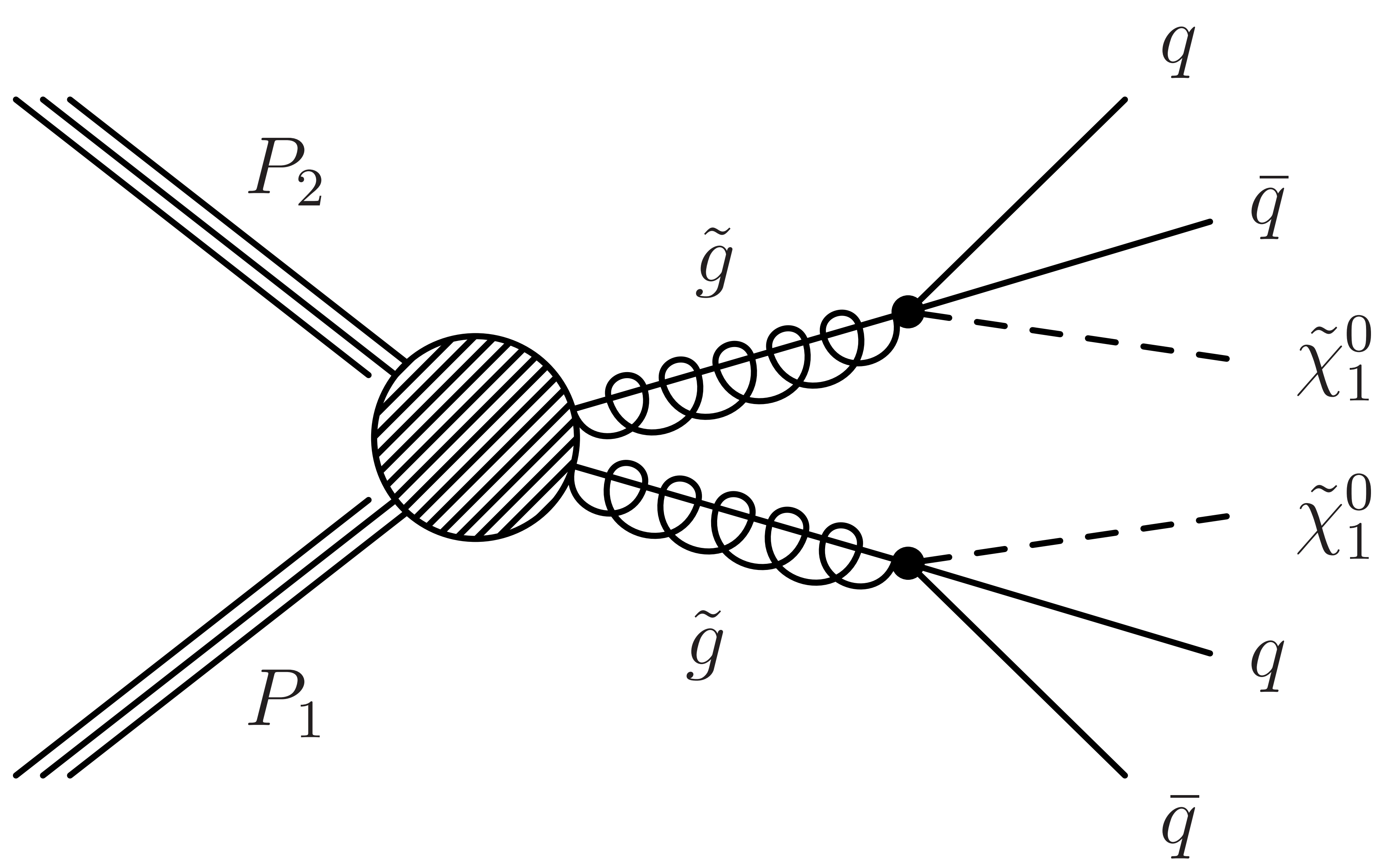
Papucci, Ruderman, Weiler, arXiv:1110.6926
Barbieri, Giudice (1988)
Martin arXiv:hep-ph/9709356

# “Natural” SUSY spectrum



# General search in hadronic final state
## (with gluino interpretation)

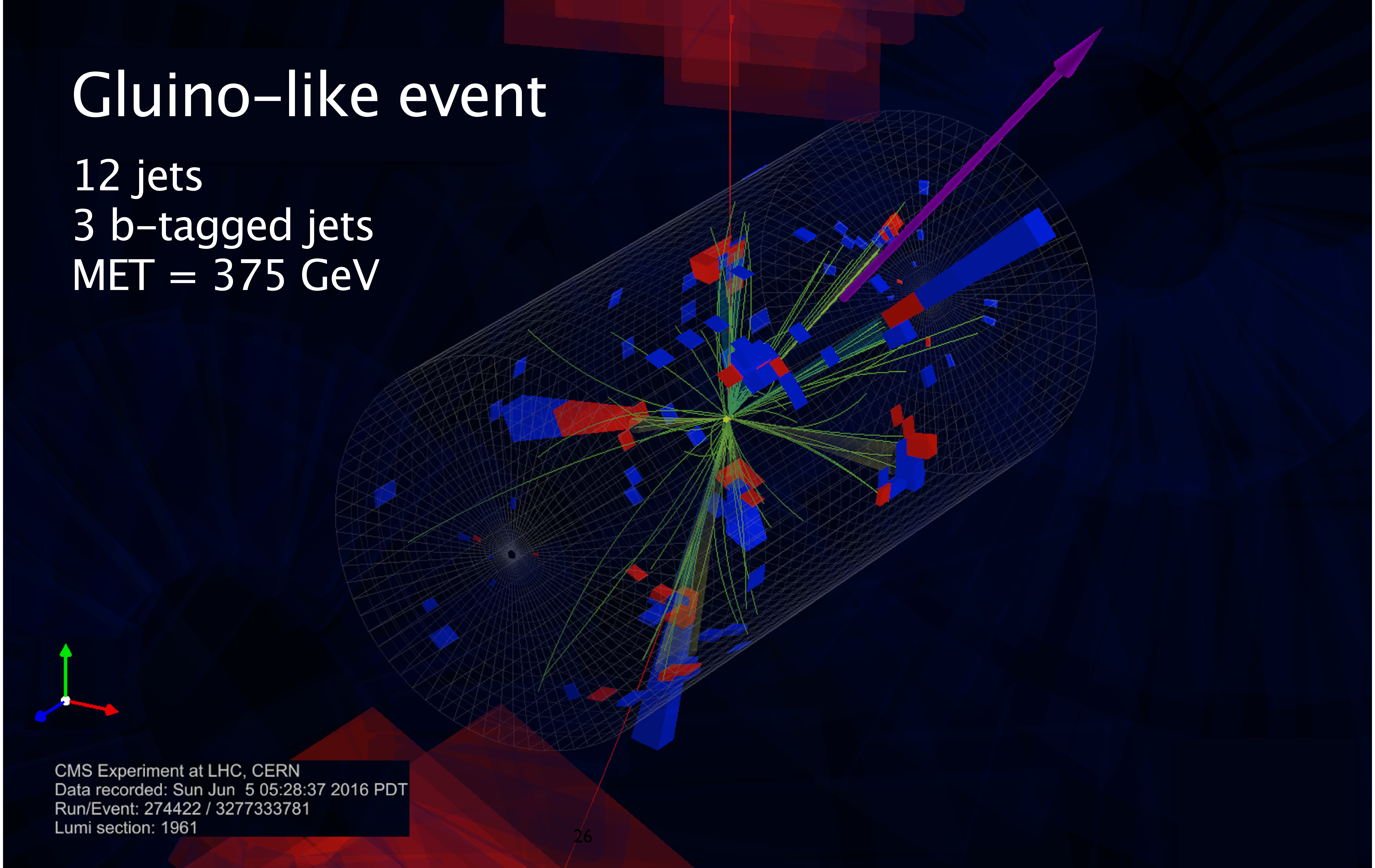



→ hadronic jets + missing transverse energy (MET)

| | gg → 4q + MET | gg → 4b + MET | gg → 4t + MET |
|---|---|---|---|
| Nj | 4 | 4 | 12 |
| Nb | 0 | 4 | 4 |
| hadronic BR | 100% | 100% | 21% |

# Gluino-like event

12 jets
3 b-tagged jets
MET = 375 GeV

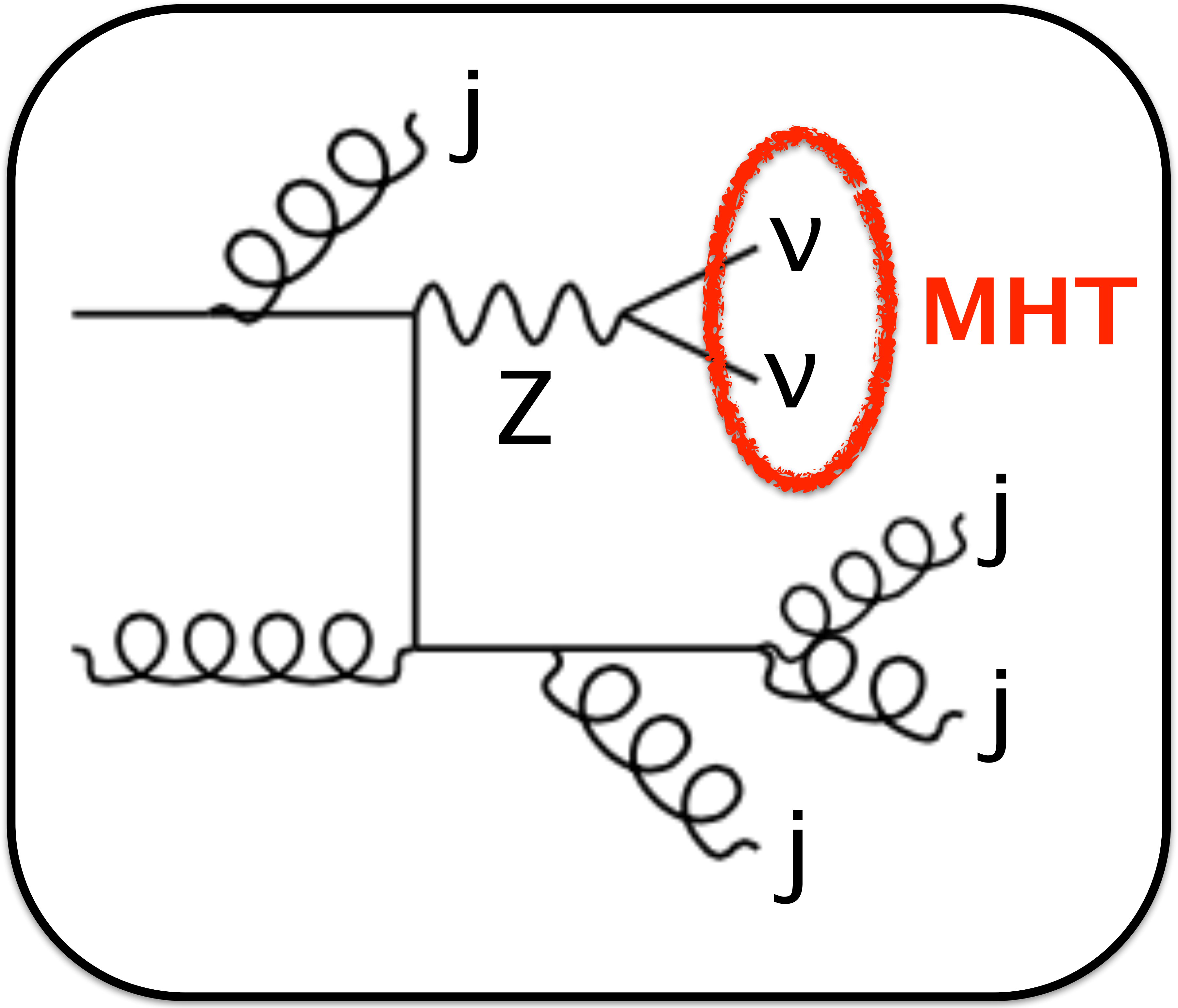


# Basic event selection

| requirement | definition | related new phenomena characteristic |
|---|---|---|
| HT>500 GeV | $H_{\mathrm{T}} = \sum_{\mathrm{jets}} \lvert p_{\mathrm{T}} \rvert$ | large overall **energy scale** of event |
| MHT>200 GeV | $MH_{\mathrm{T}} = \lvert \sum_{\mathrm{jets}} -\vec{p}_{\mathrm{T}} \rvert$ | **missing energy** from undetected particles |
| Nj ≥4 | number of jets | **many hadronic jets** |
| $N_b \geq 0$ | # of b-tagged jets | some models characterized by **b quarks** |
| $N_e = N_\mu = 0$ ($p_T >$ 10 GeV) | # of electrons & muons | remove leptonic backgrounds (top, V+jets) |

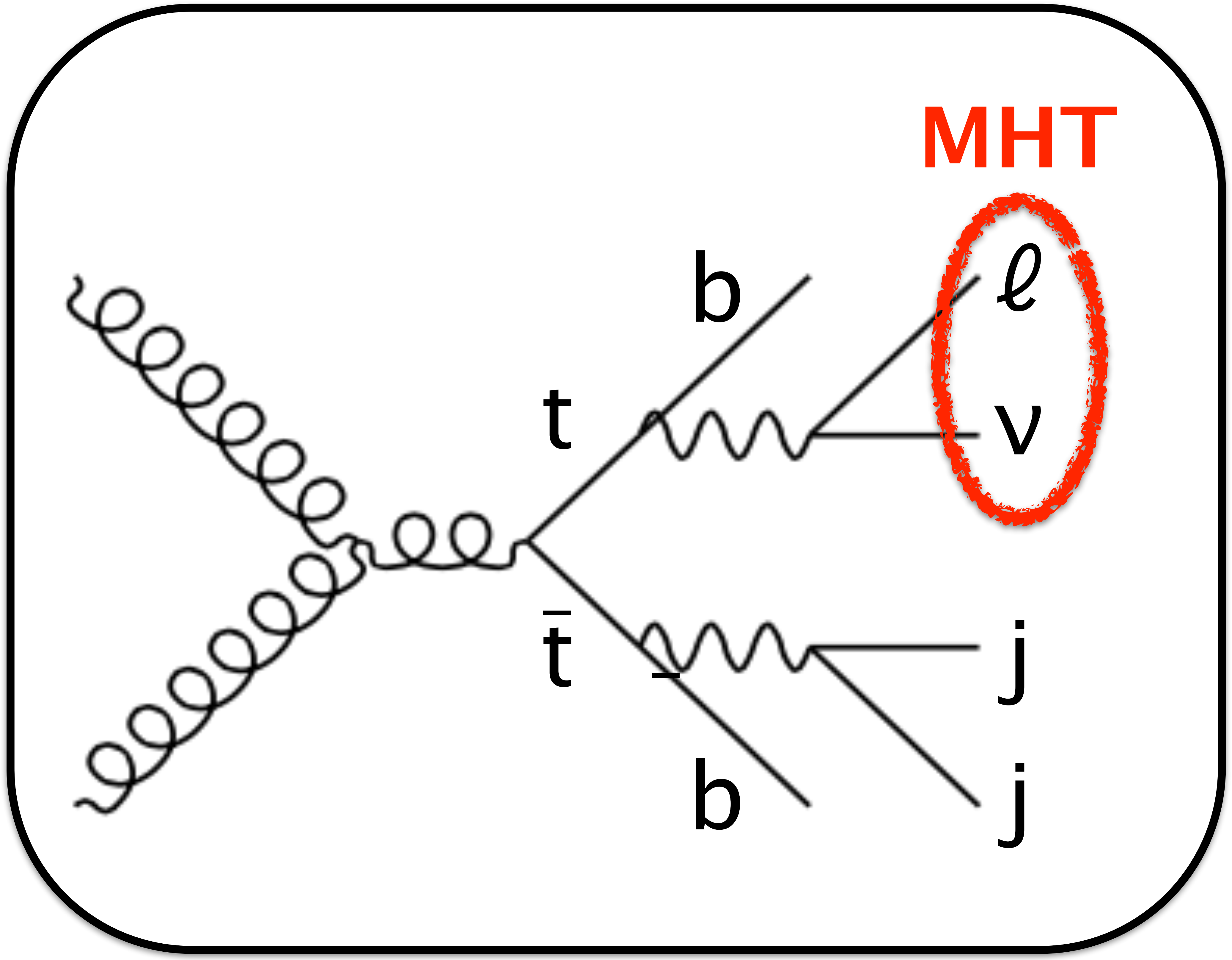
- Basic selection is >95% efficient for high mass gluinos.

# Z➔νν+jets background



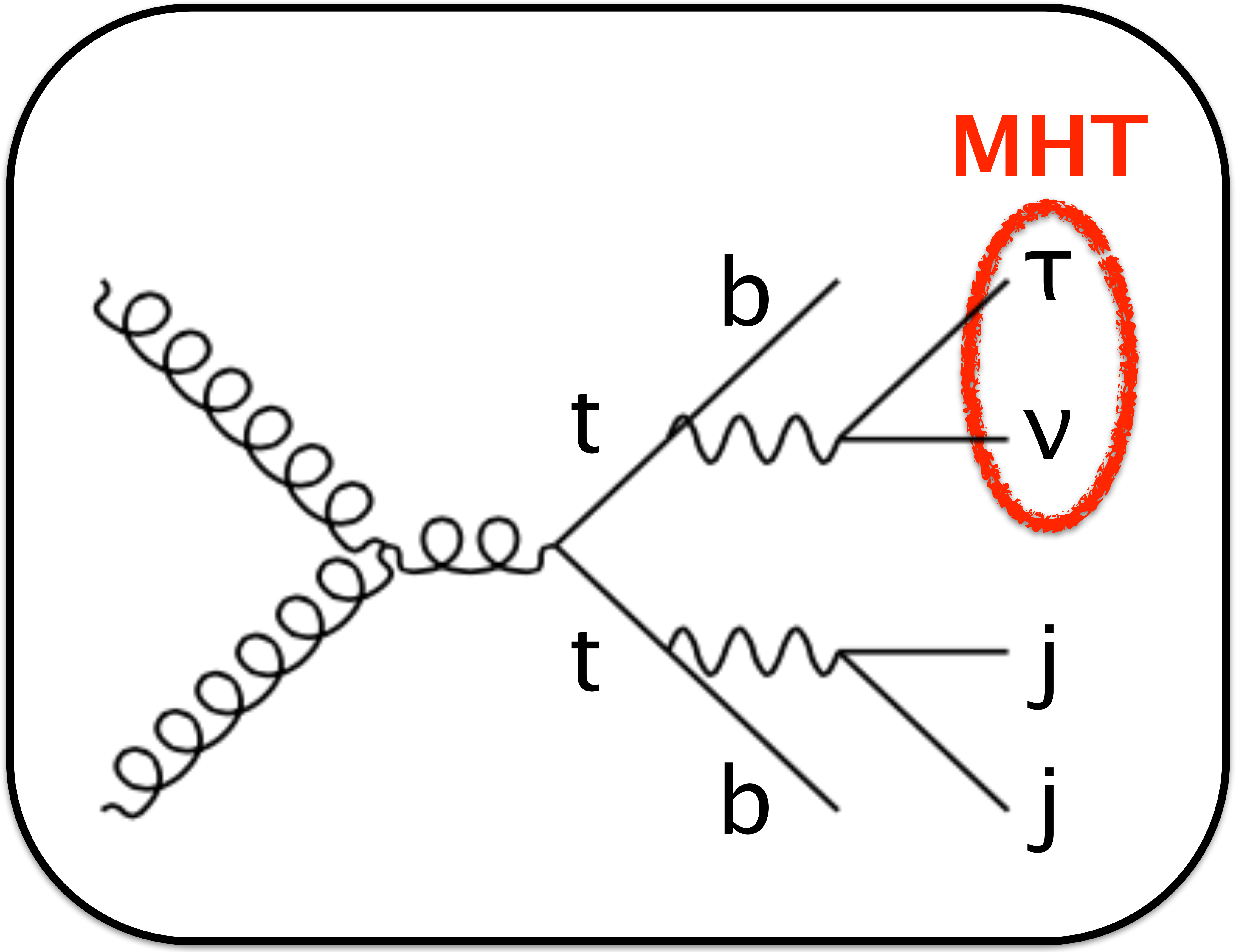

- **Irreducible** background for jets + MET.
- Estimate from data and simulation with **$Z \rightarrow \ell^+\ell^-$+jets** and **γ+jets** control samples
    - use γ or $Z \rightarrow \ell\ell$ as proxy for MHT.
- Signature: few b-jets, few jets, high MET.

# Lost lepton background



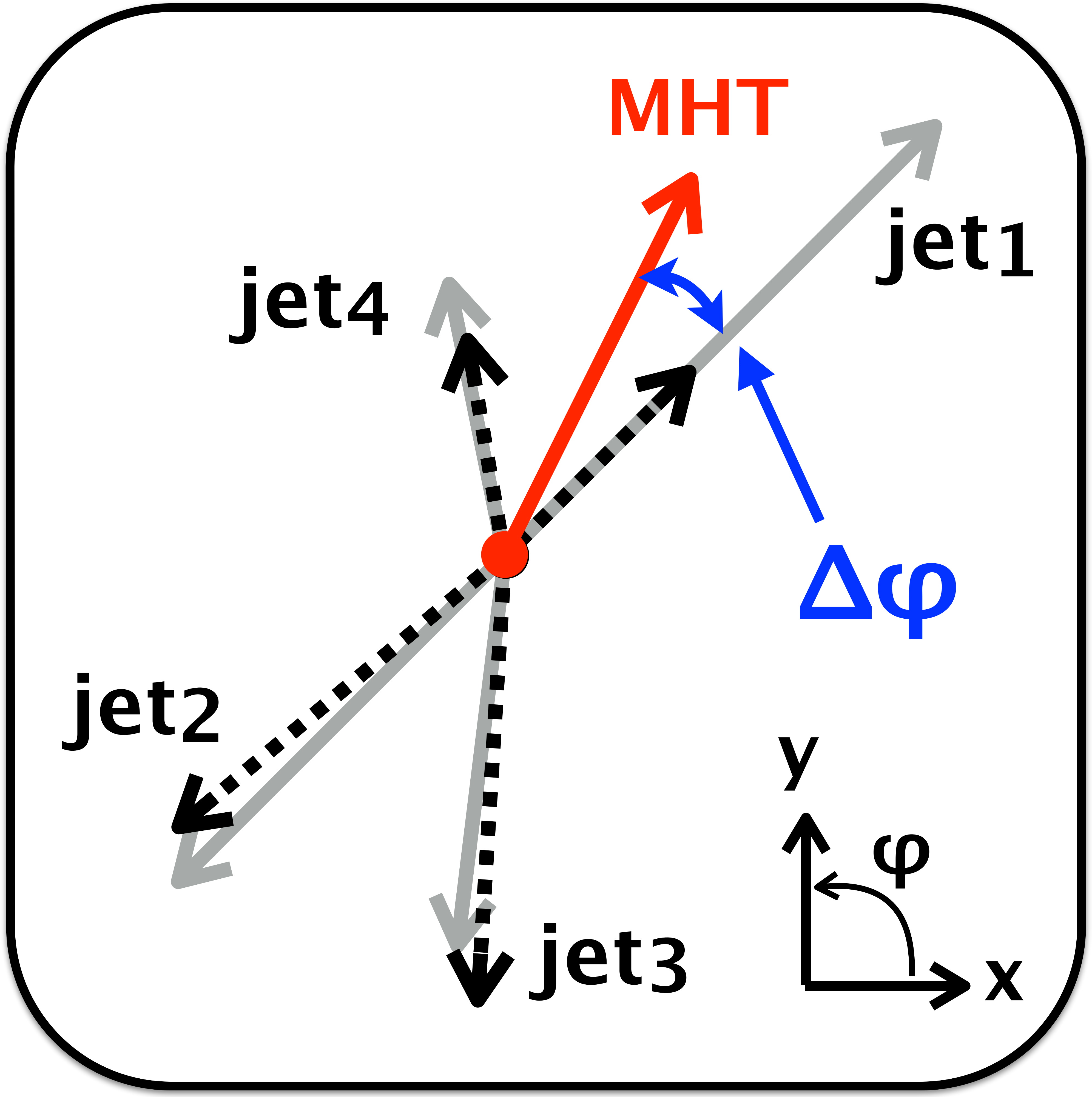

- $t\bar{t}$+jets and W+jets decaying to $e^{\pm}$ or $\mu^{\pm}$
  - **Un-reconstructed $\ell^{\pm}$ ➔ MHT**.
- **Reduce** by vetoing events with isolated tracks ($p_T$ > 5 GeV) consistent with leptons.
- **Estimate** from 1$\ell$ control sample
  - efficiency measured in data
  - acceptance measured in simulation
- **Signature**: several $N_{jets}$, $N_{bjets}$>0

# Hadronic tau decay background




- tt+jets and W+jets decaying to $\tau^{\pm}$
  - **hadronically decaying $\tau^{\pm}$ ➔ MHT**.
- **Reduce** by vetoing events with isolated tracks ($p_T$>10 GeV) consistent with hadron.
- **Estimate** from 1μ control sample
  - adjust μ response to mimic τ response using template from simulation.
- **Signature**: several $N_{jets}$, $N_{bjets}$>0

# Mismeasured jet background



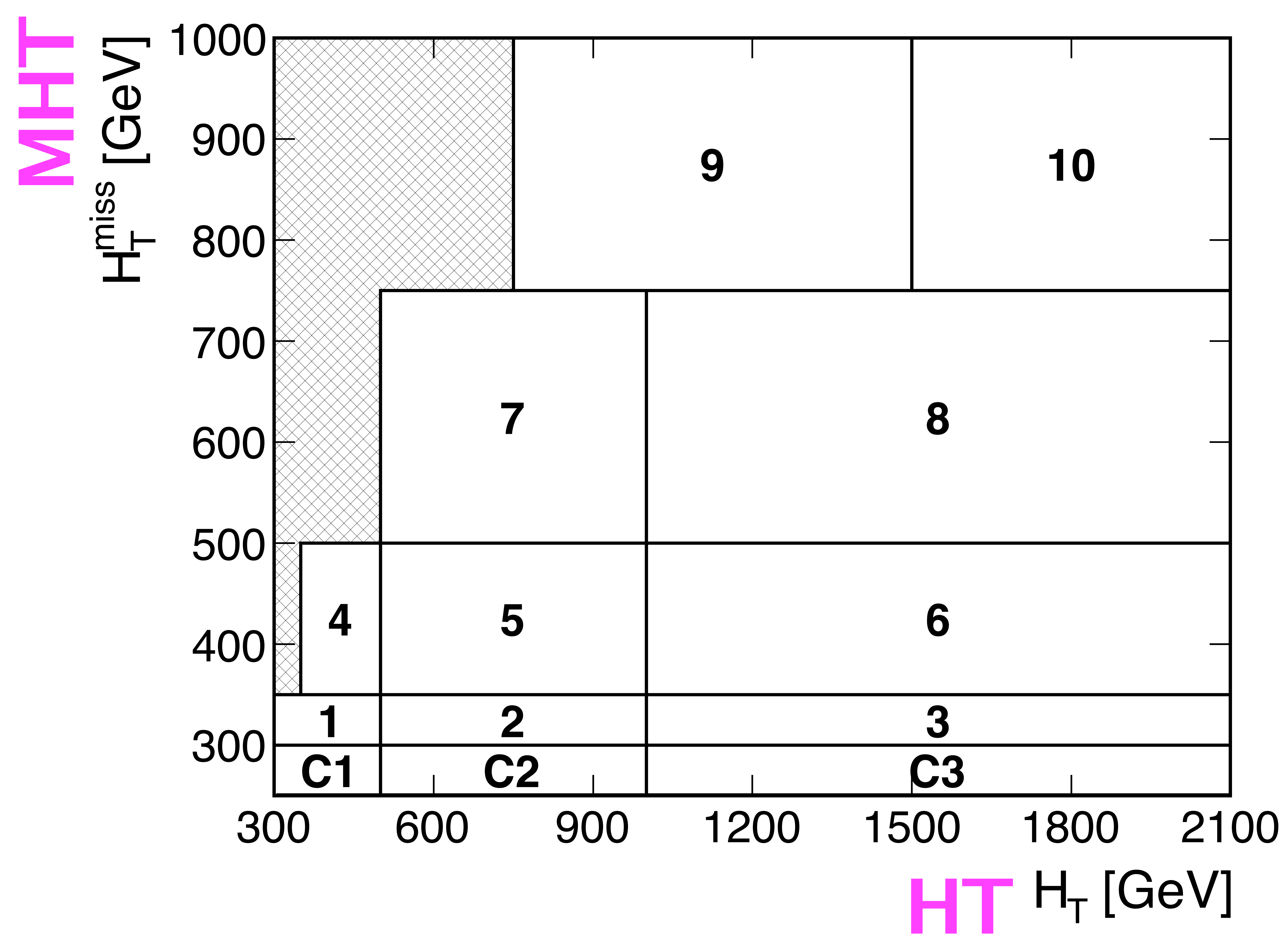

- QCD multijet events
  - **Mismeasurement of jet $p_T$** ➔ MHT
- **Reduce** by requiring $\Delta\varphi(jet_i, MH_T) > 0.5$.
  - MHT is aligned with mismeasured jet.
- **Estimate** with two independent methods
  - low $\Delta\varphi$ control sample
  - "Rebalance & smear"
- **Signature**: few $N_{jets}$, few $N_{bjets}$

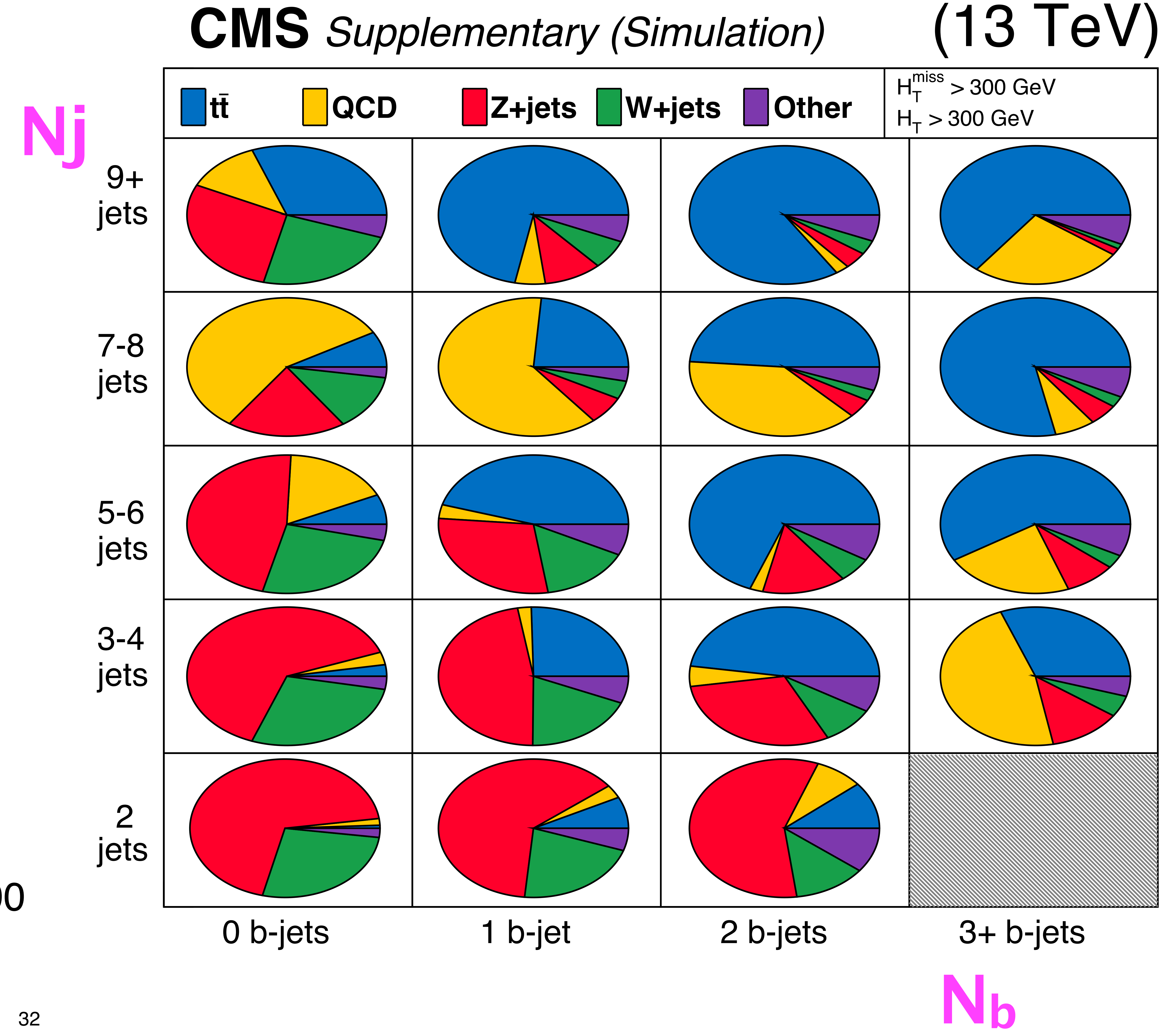
# Event categorization

SUS-16-033

**174** categories based on

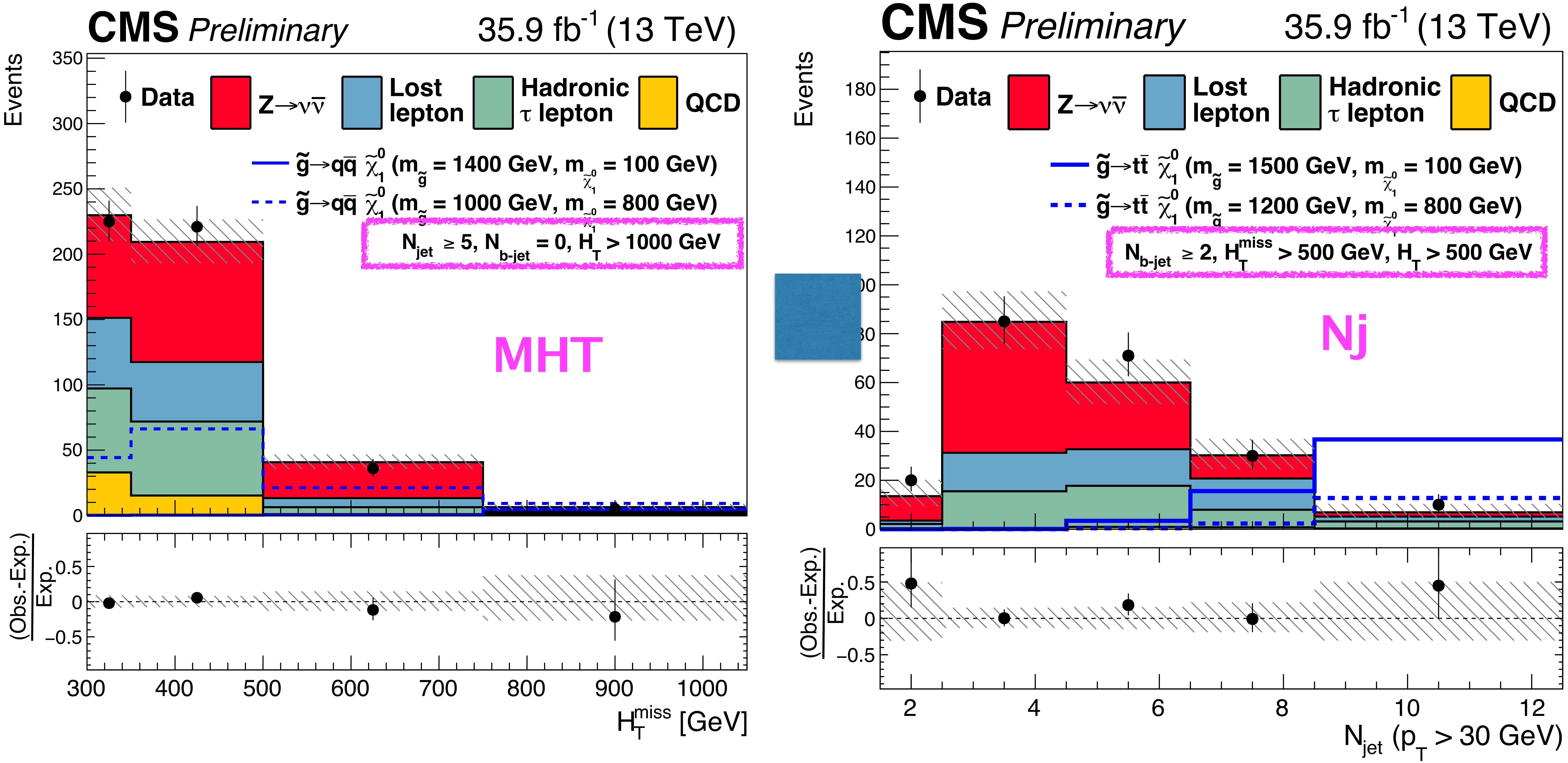
**Nj, Nb, MHT, HT**



# Kinematic distributions

SUS-16-033

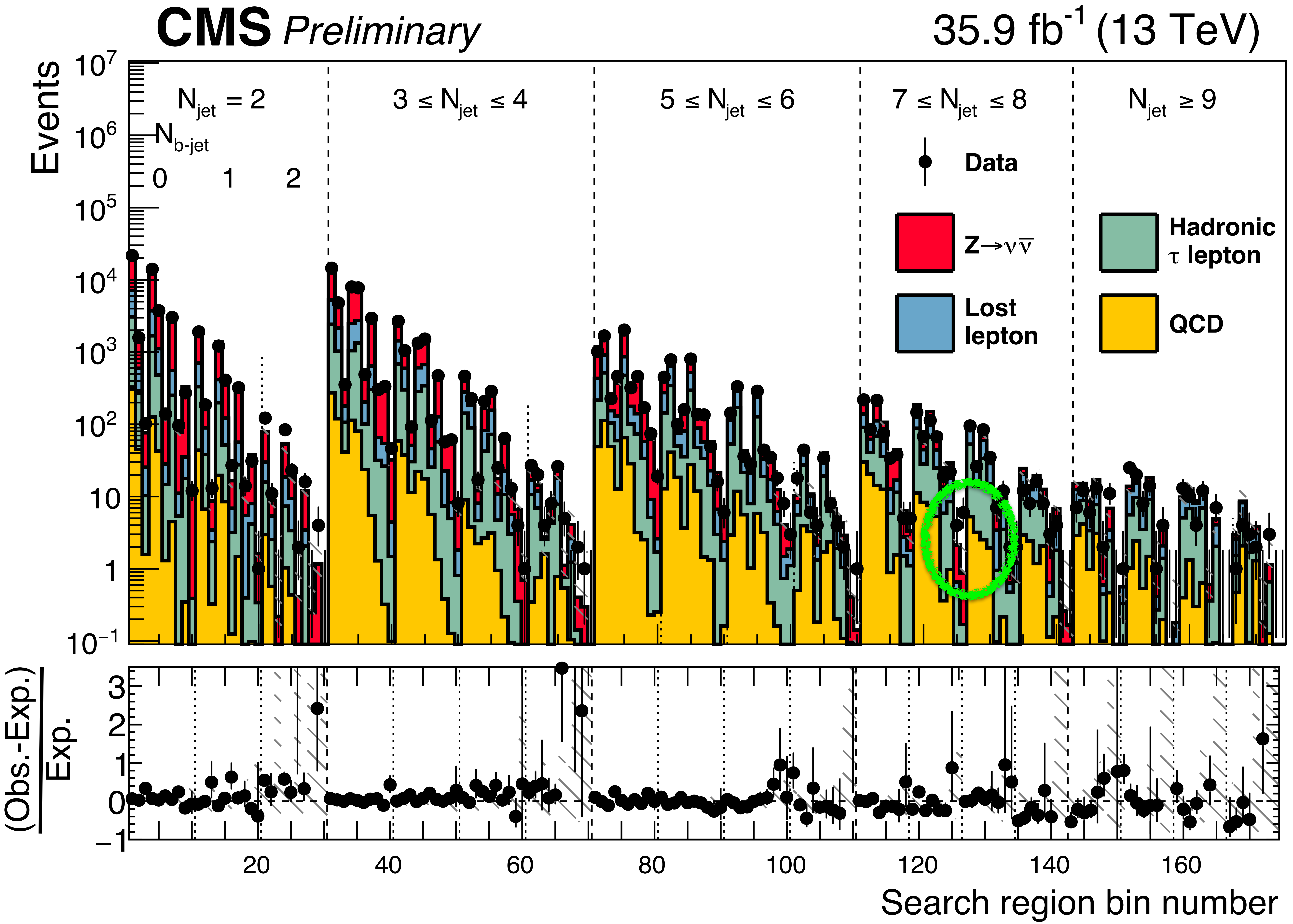


# Results

**SUS-16-033**

Largest excess is ~3σ in bin 126

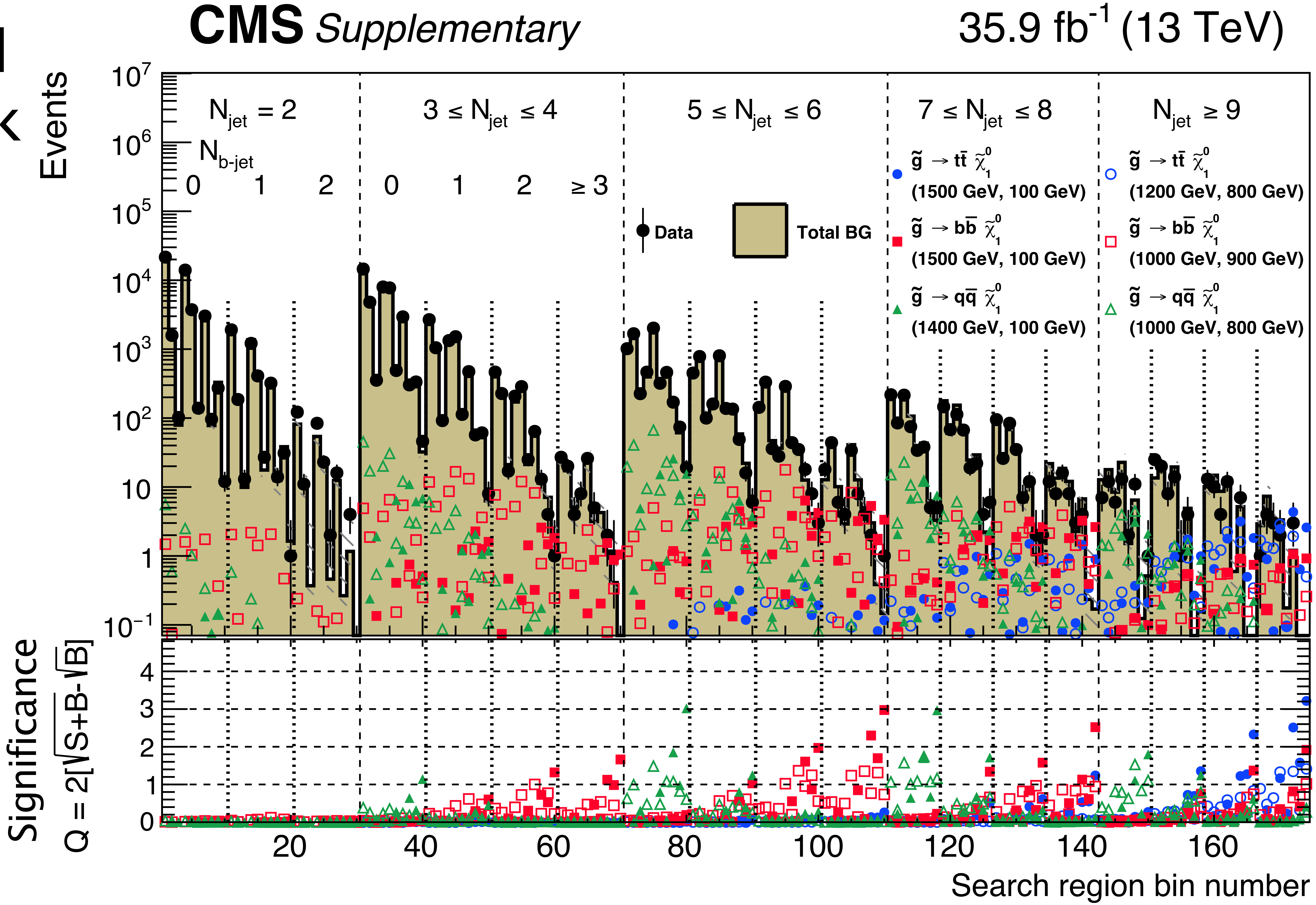
- MHT>750 GeV
- HT>1500 GeV
- Nj = 7-8
- Nb = 1



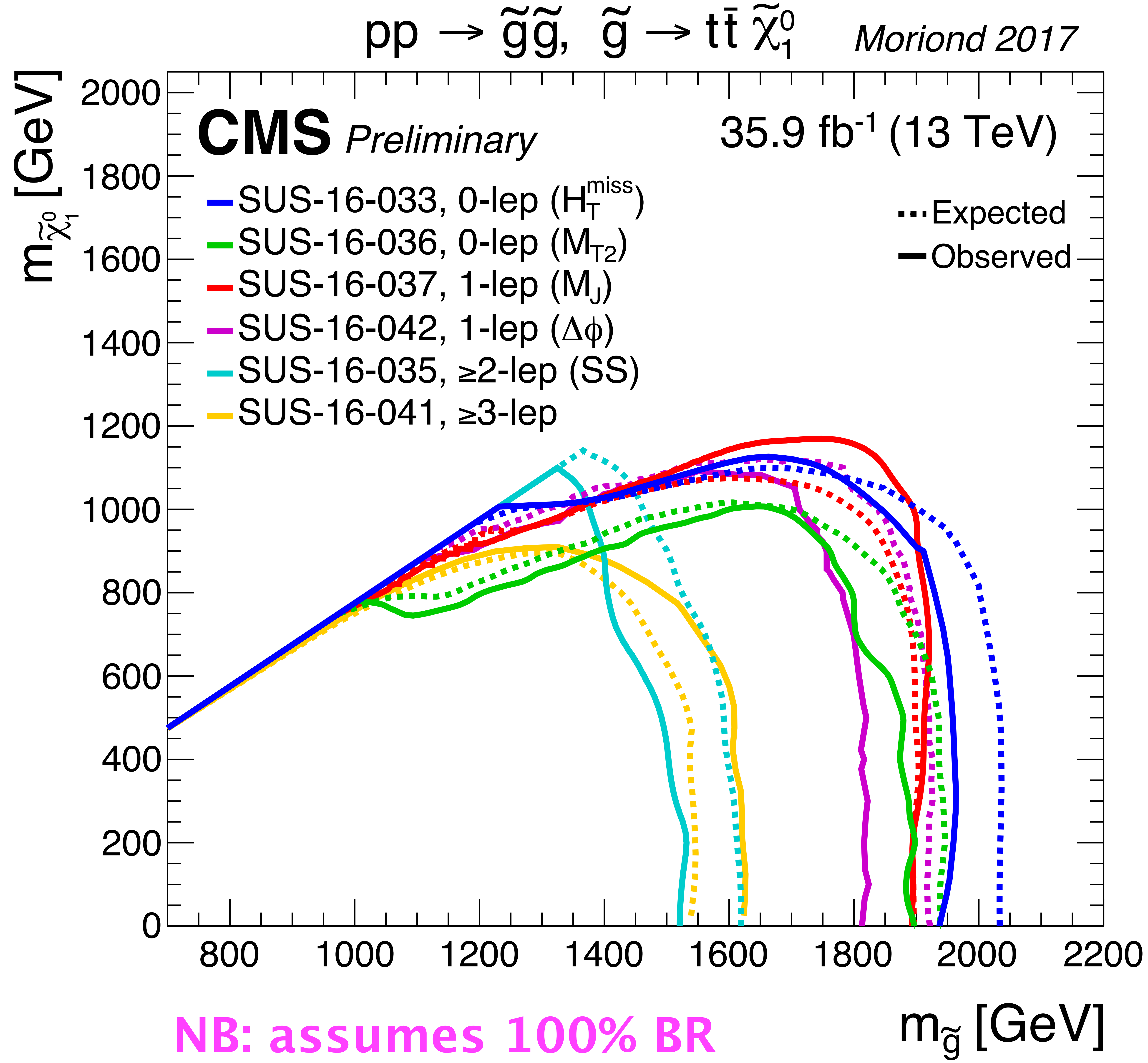
# What would a signal look like?

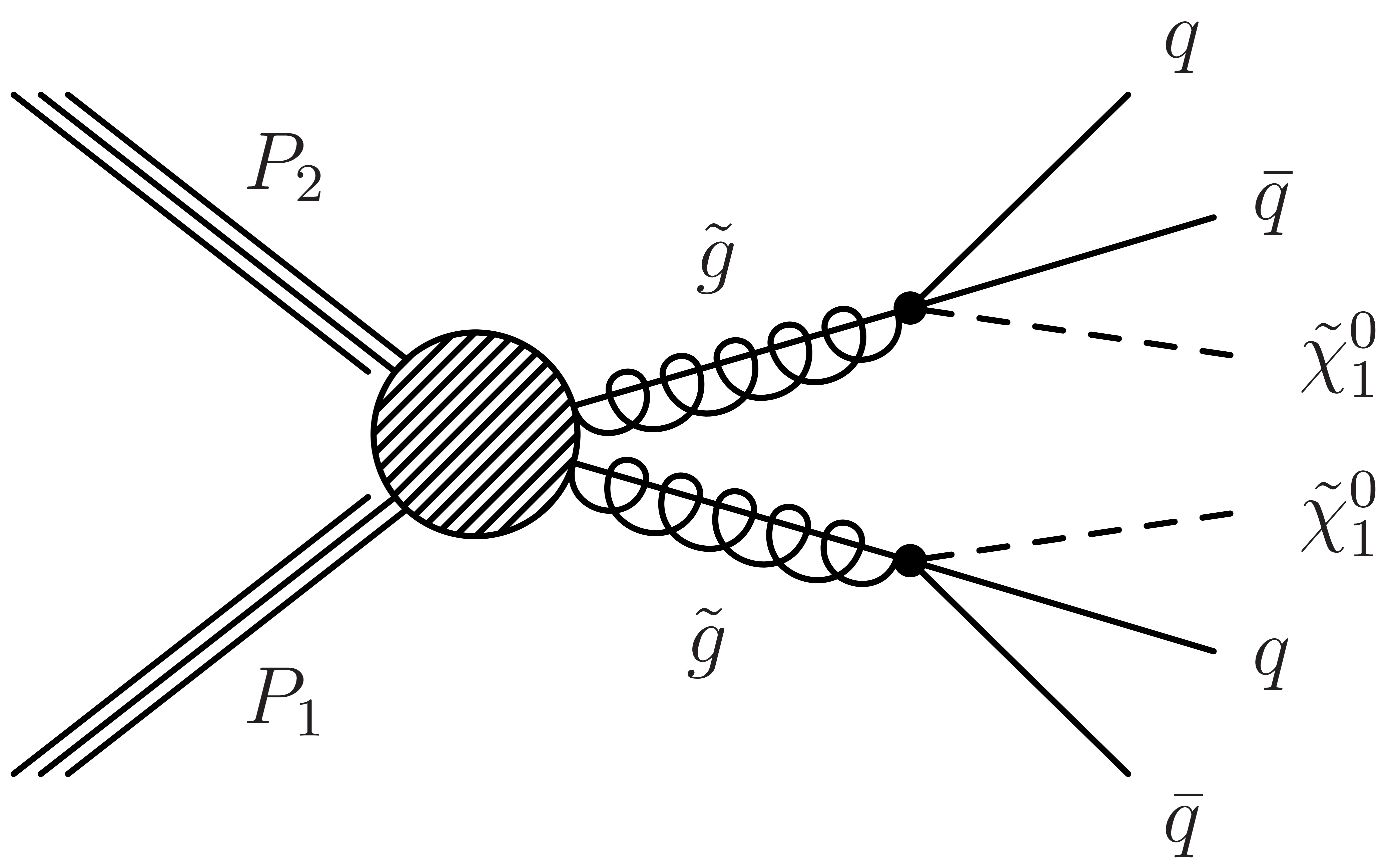
**SUS-16-033**

Expect correlated excesses for real signal.



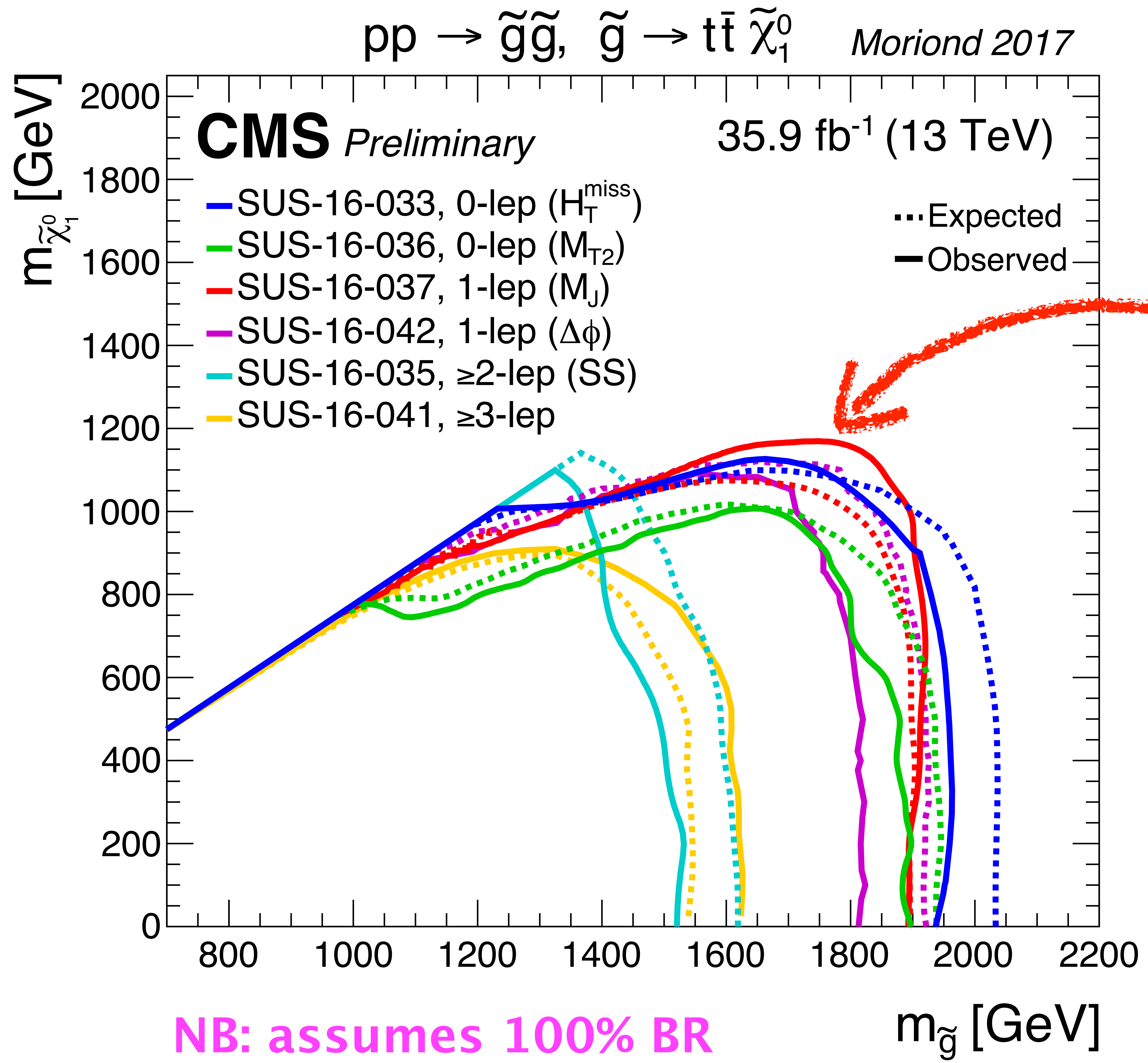
# Gluino sensitivity

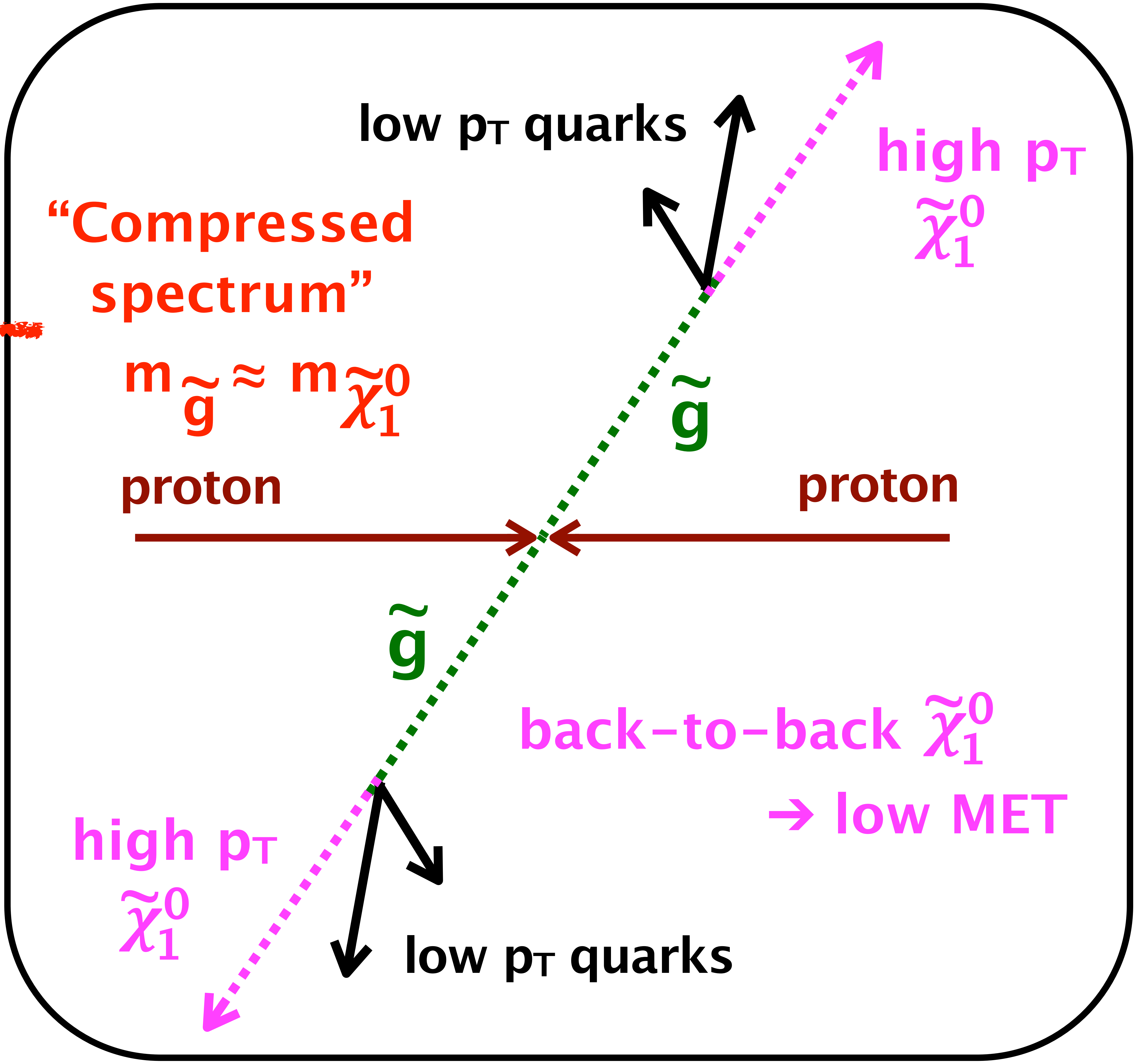



NB: assumes 100% BR

# Gluino sensitivity

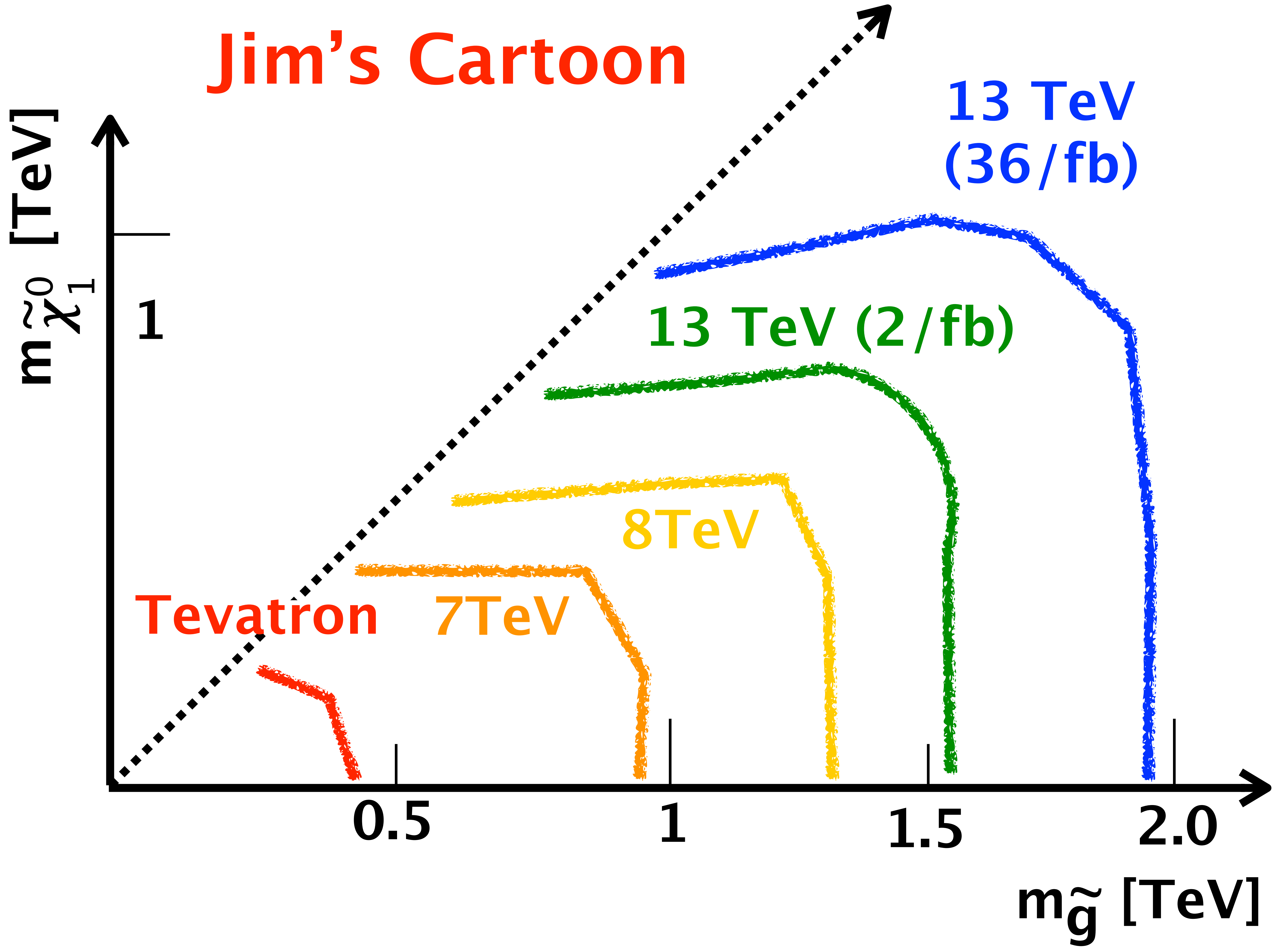


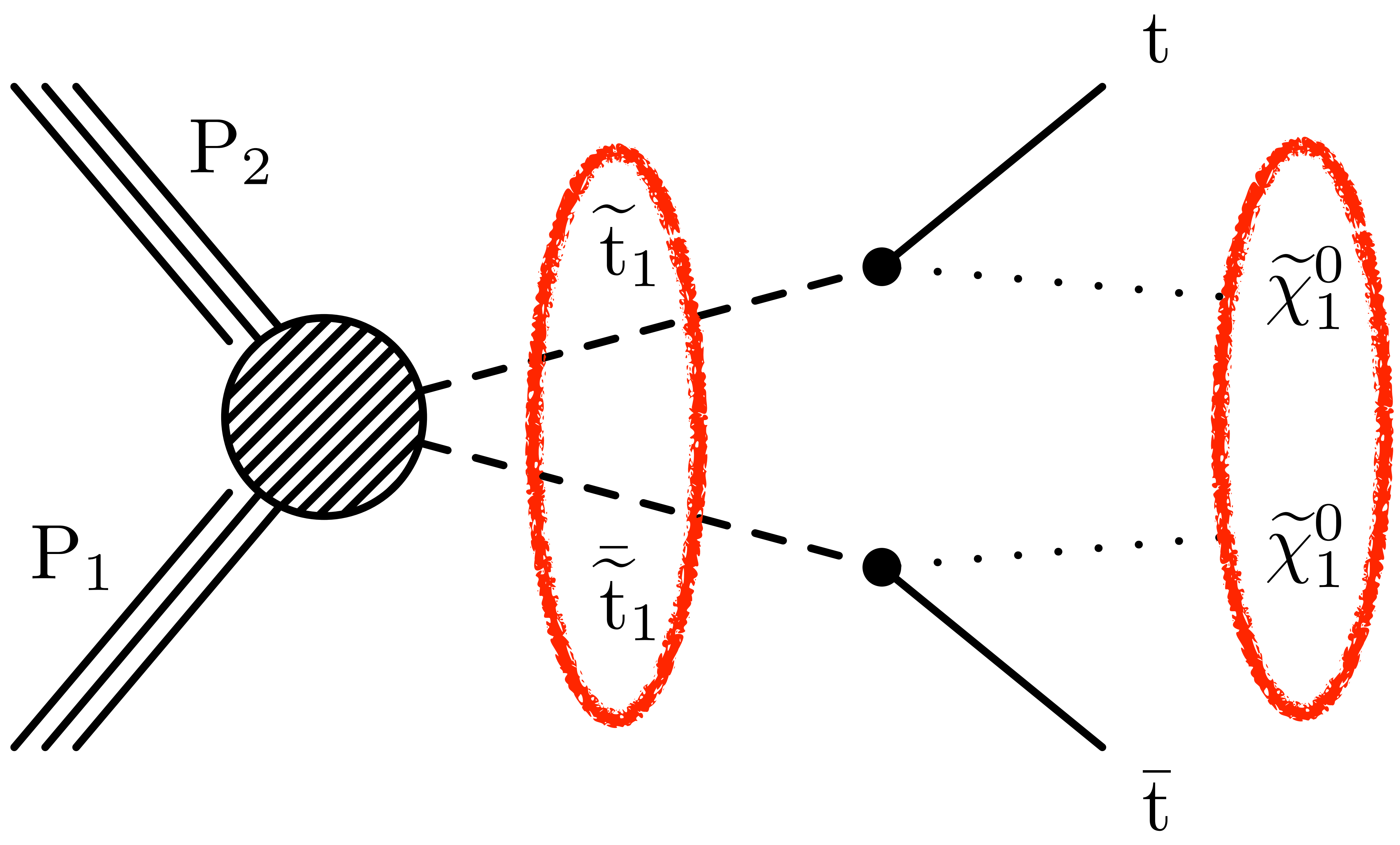

NB: assumes 100% BR

# Gluino sensitivity

Although very disappointing (so far), null gluino results clearly demonstrate the **vast reach of the LHC**.



# Targeted search for top squark in fully hadronic final state




In addition to general searches, we target specific topologies.

**Top quark decay kinematics depend strongly on**

$$\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$$

# Top quark decay kinematics

# Identifying top quarks SUS-16-049

**1.** select candidate **merged tops** (W bosons):

- $M_{jet}$ >110 GeV (50–110 GeV), $p_T$>400 GeV (200 GeV)

**2.** identify merged tops (Ws) with **boosted decision tree** (BDT)

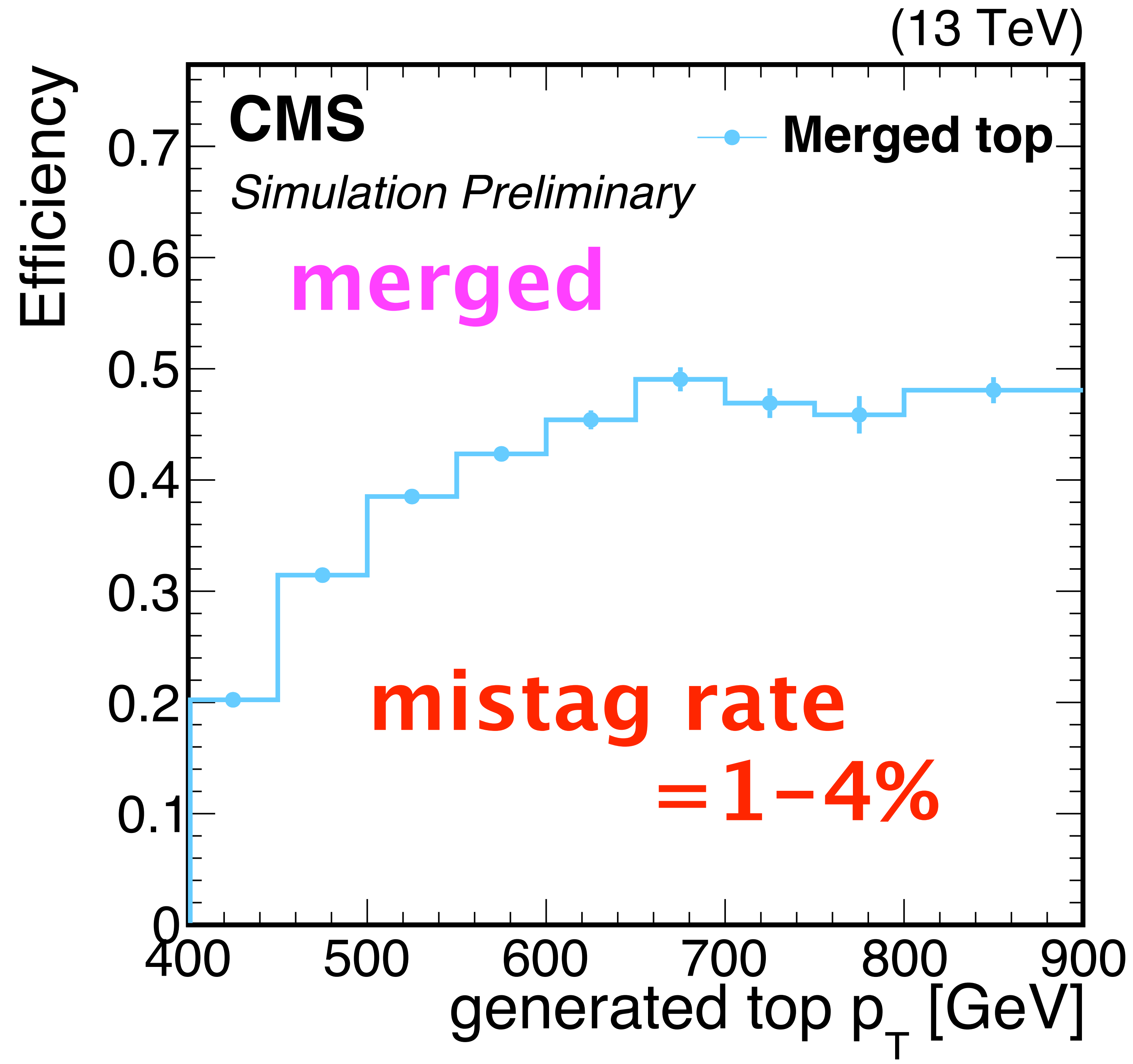
- jet mass corrected for soft radiation effects (soft-drop)
- sub-jet consistency and kinematics (N-subjettiness)
- b-tagging discriminant

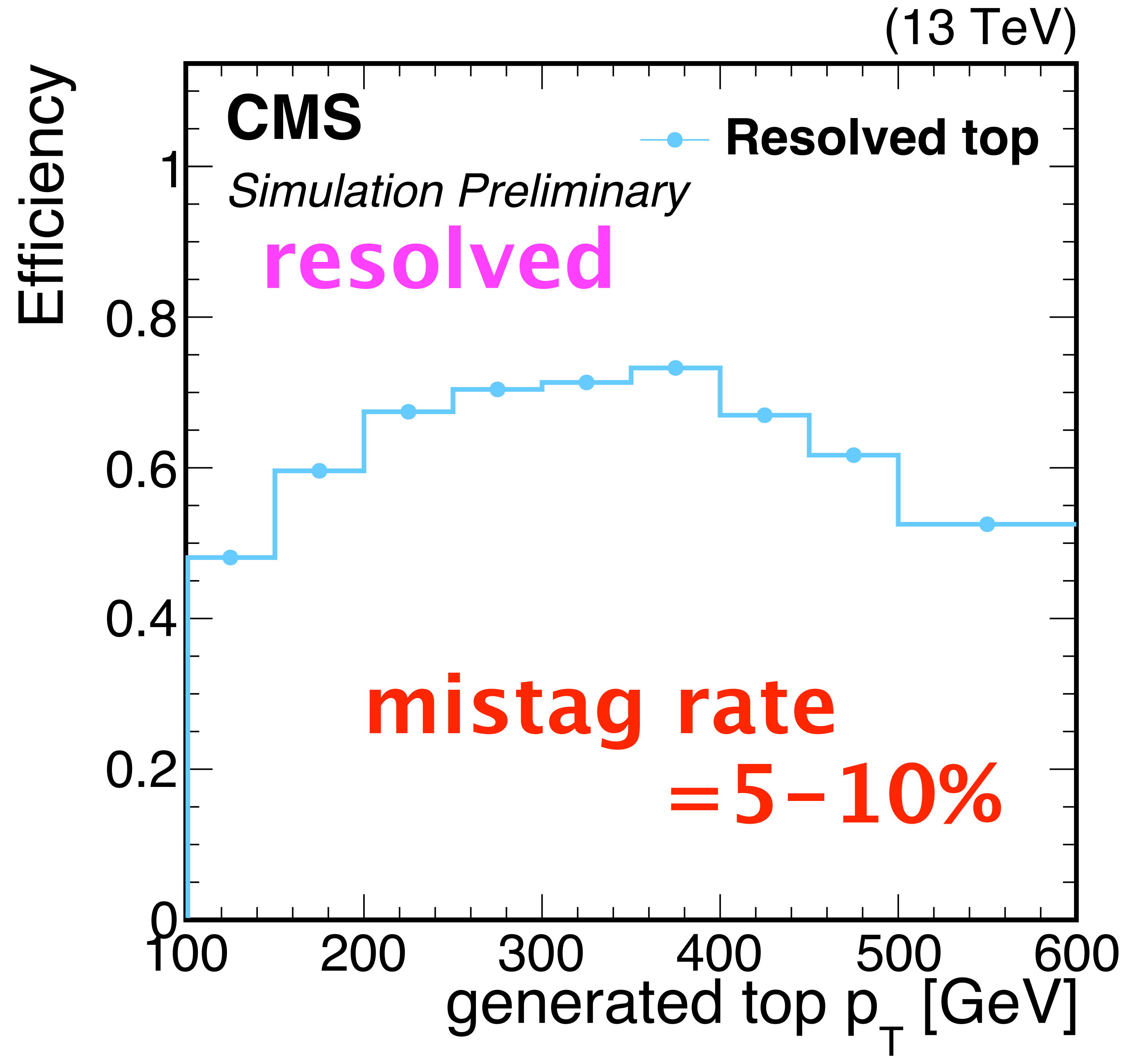
**3.** select candidate **resolved tops** from remaining jets

- Mass consistent with top

**4.** identify resolved tops with **BDT** based on jet 4-vectors and b-tagging discriminant.

- Both **BDTs discriminate between** truth-matched and non-matched tops in tt simulation.



# Δm>mW selection

SUS-16-049

**Basic selection**

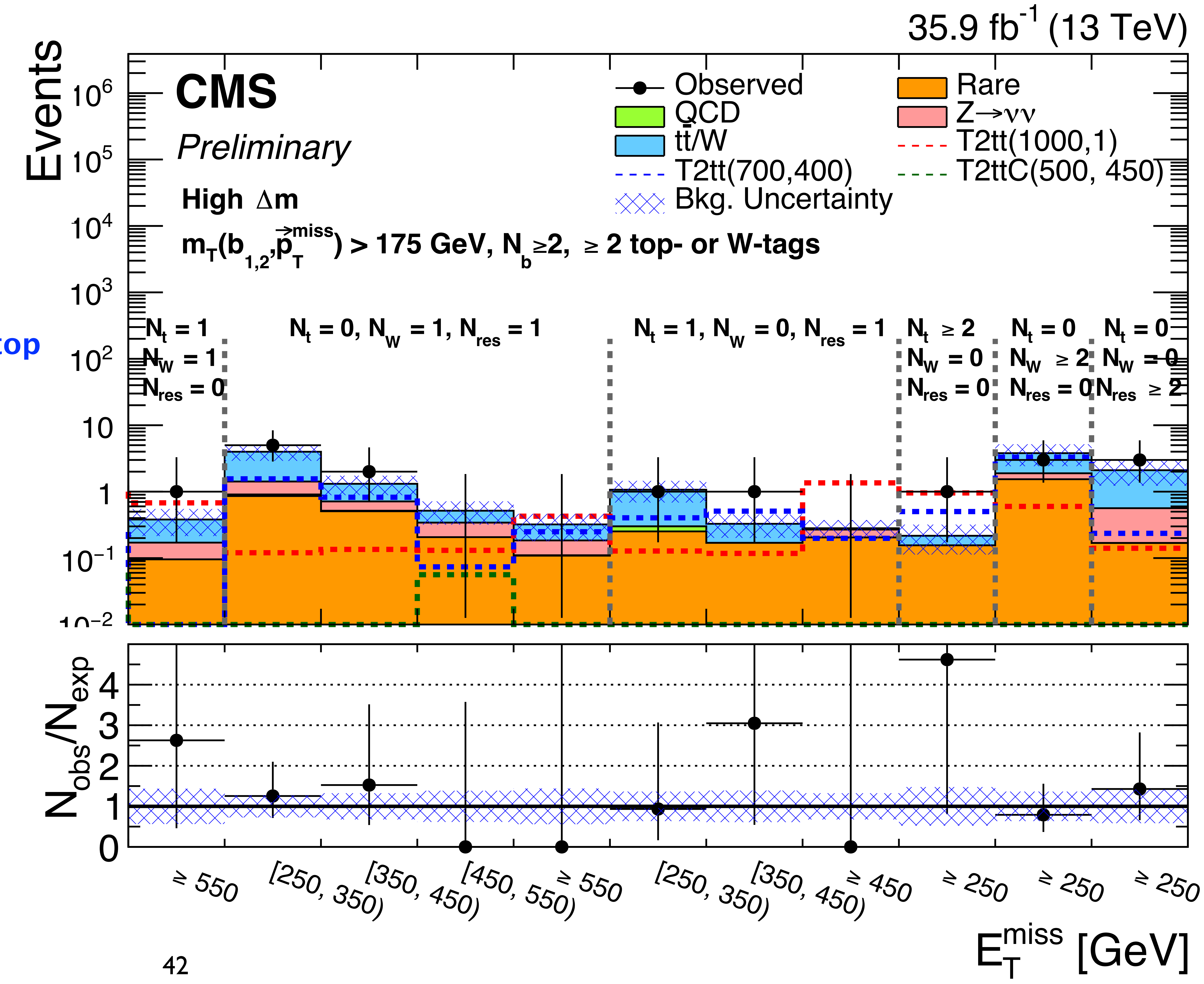
- $N_b \geq 1$, $N_{jets} \geq 5$
- Δφ(jets, MET)>0.5
- MET> 250 GeV

Sample with minimum $m_T^*(b,MET) < m_{top}$ is top enriched so also requires

- $N_{jets} \geq 7$
- $N_{resolved} \geq 1$

**Classify** according to:

- $N_{merged-top}$, $N_{resolved-top}$, $N_W$, Nj, $N_b$



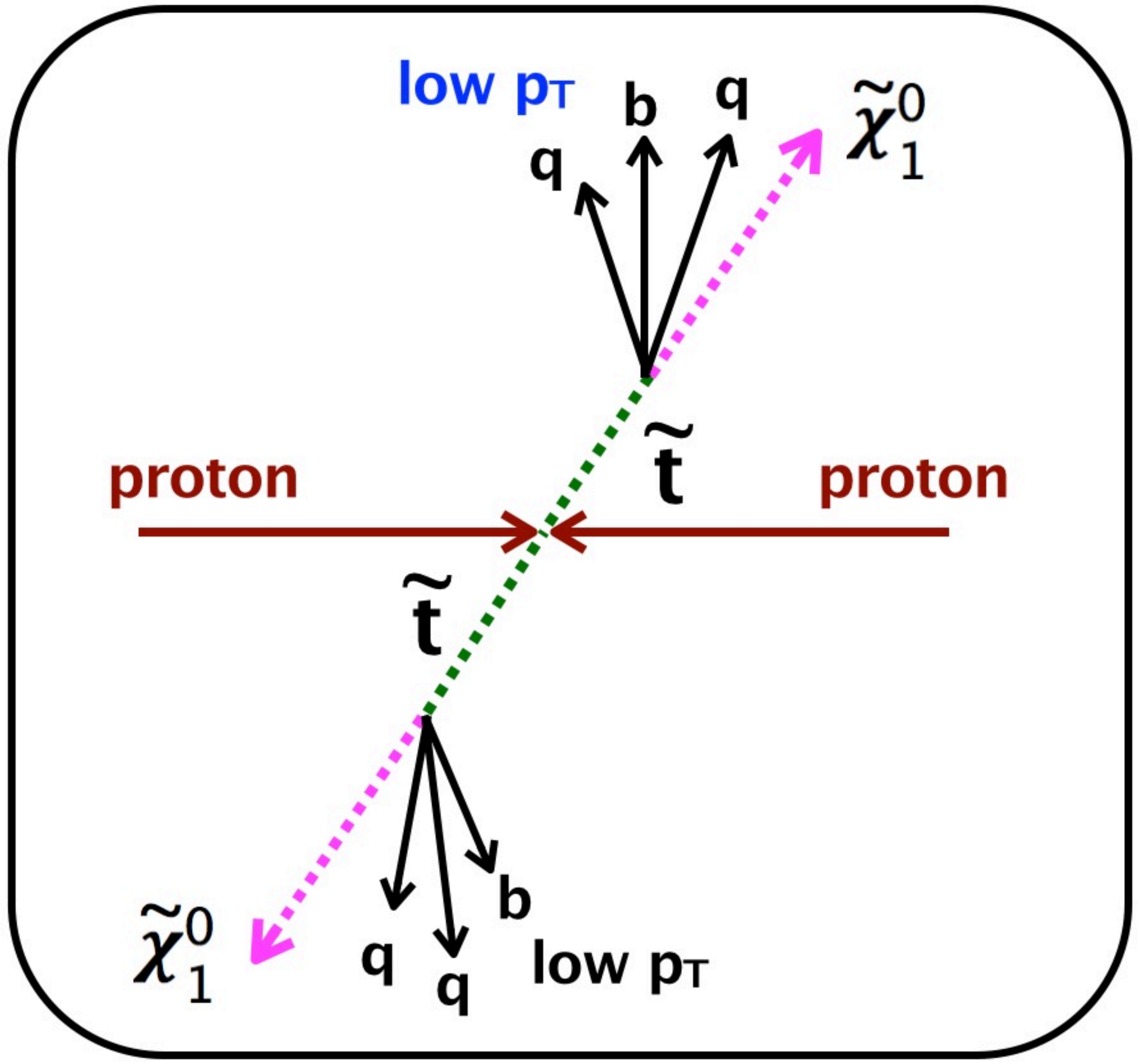

* $m_T(q_1, q_2) = 2p_{T1}p_{T2}(1 - \cos\Delta\varphi)$

$m_T(q_1, q_2) \leq (q_1+q_2)^2$

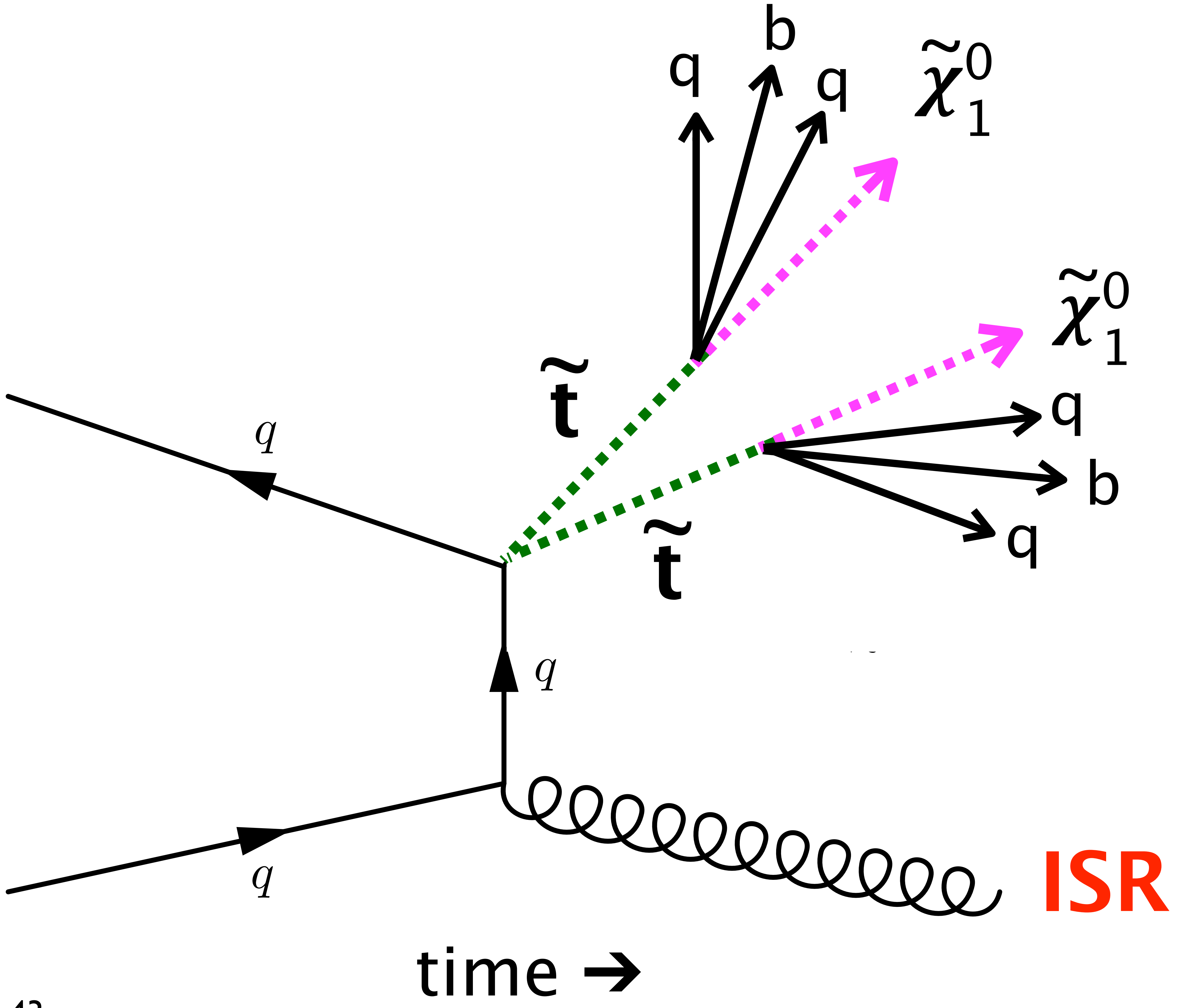
# Triggering on low MET with ISR

- When $\Delta m \rightarrow 0$
  - **low MET** from back-to-back $\tilde{\chi}_1^0$.
  - **low jet $p_T$** from soft quarks.

- **Challenge**: **How do we trigger?**




- **Solution**: **Initial state radiation** boosts $\tilde{t}\tilde{t}$ system so that $\tilde{\chi}_1^0$ are not back-to-back yielding in high MET.

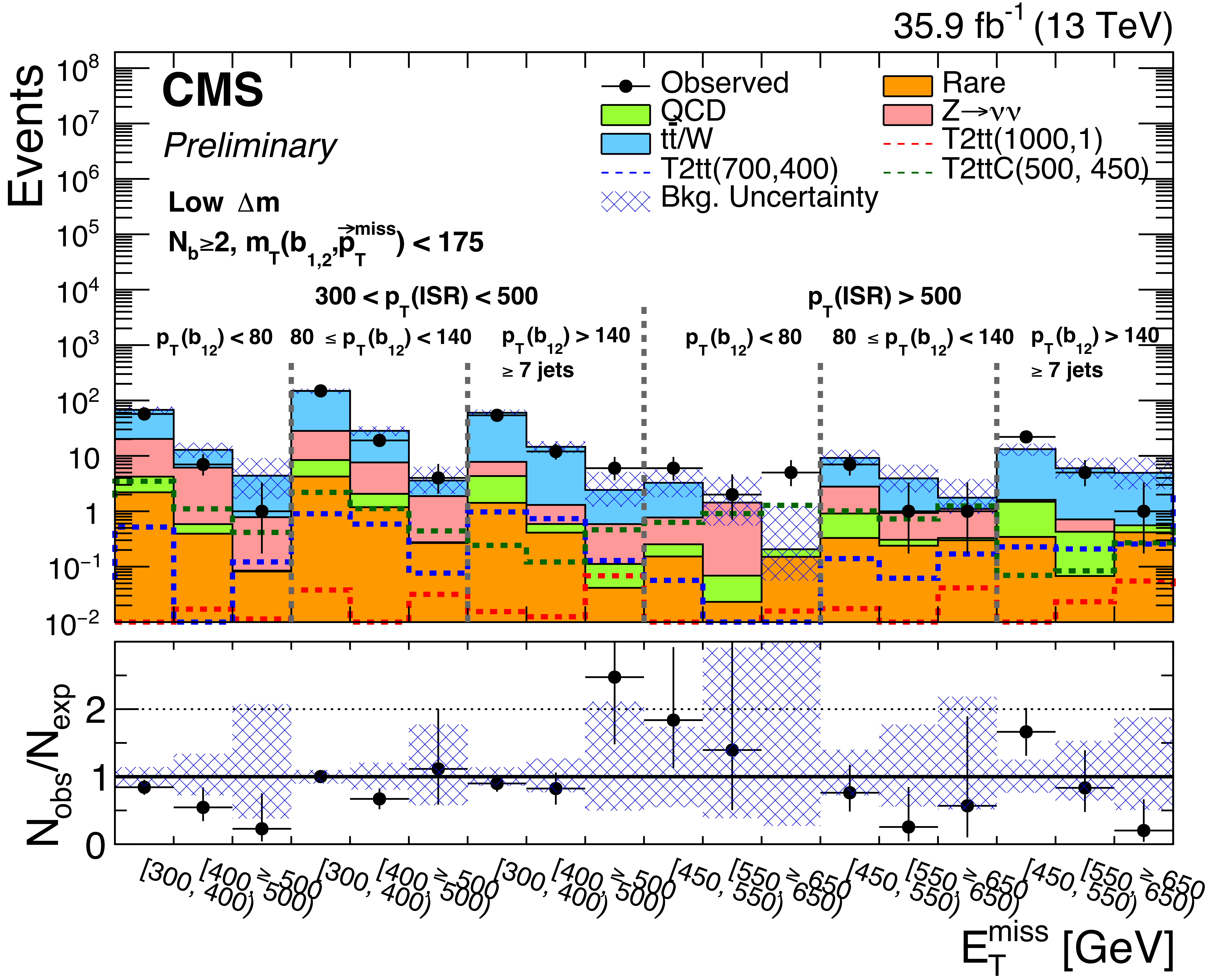


# $\Delta m < m_W$ selection

SUS-16-049

### Basic selection

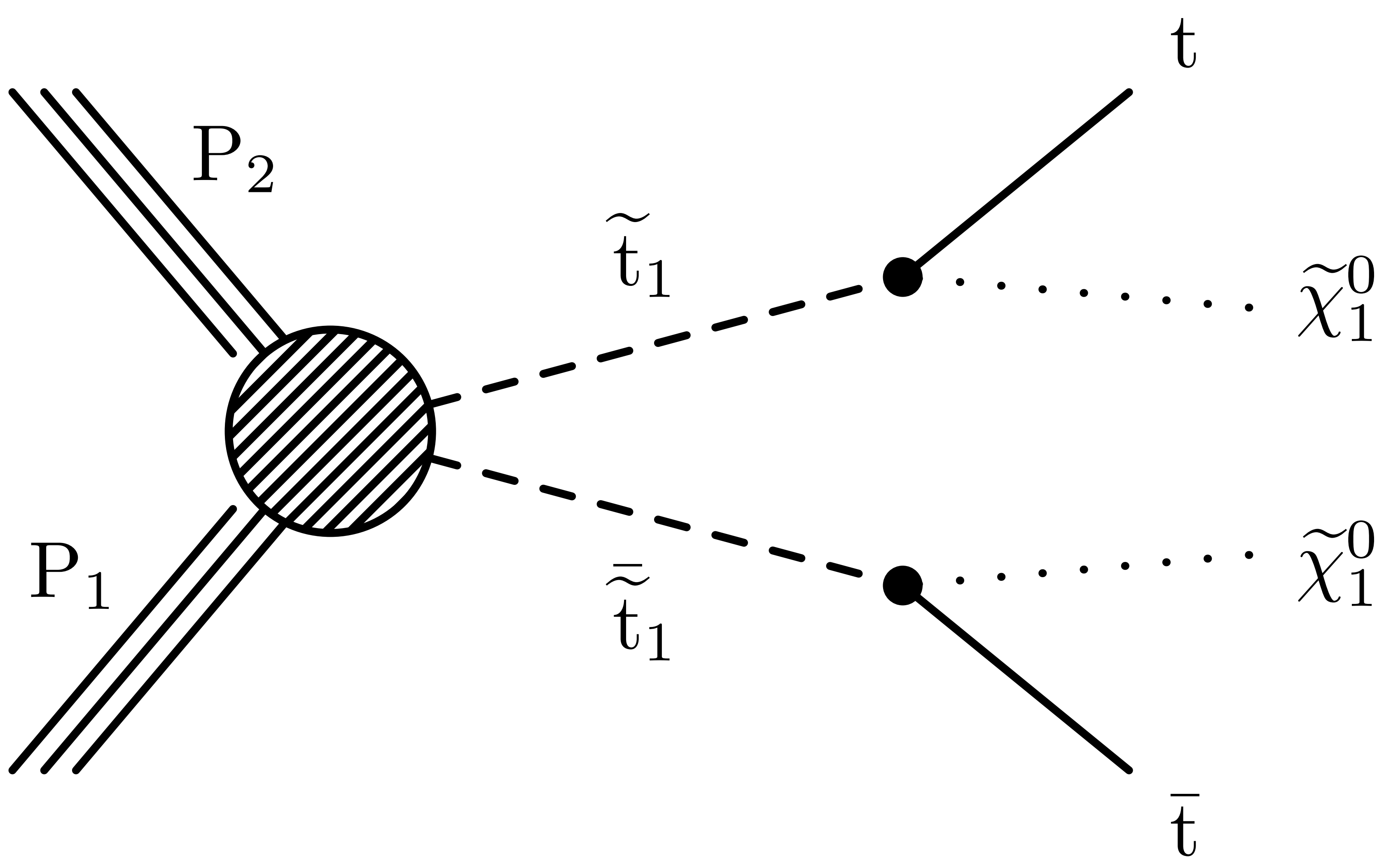
- $N(\ell) = 0$, $N_j \geq 2$,
- $N_{merged-top} = N_{resolved-top} = N_W = 0$
- MET > 250 GeV
- ISR jet with $p_T$ > 200 GeV
- MET significance > 10 $GeV^{1/2}$
- minimum $m_T$(b,MET)<175 GeV (for orthogonality with high $\Delta m$)

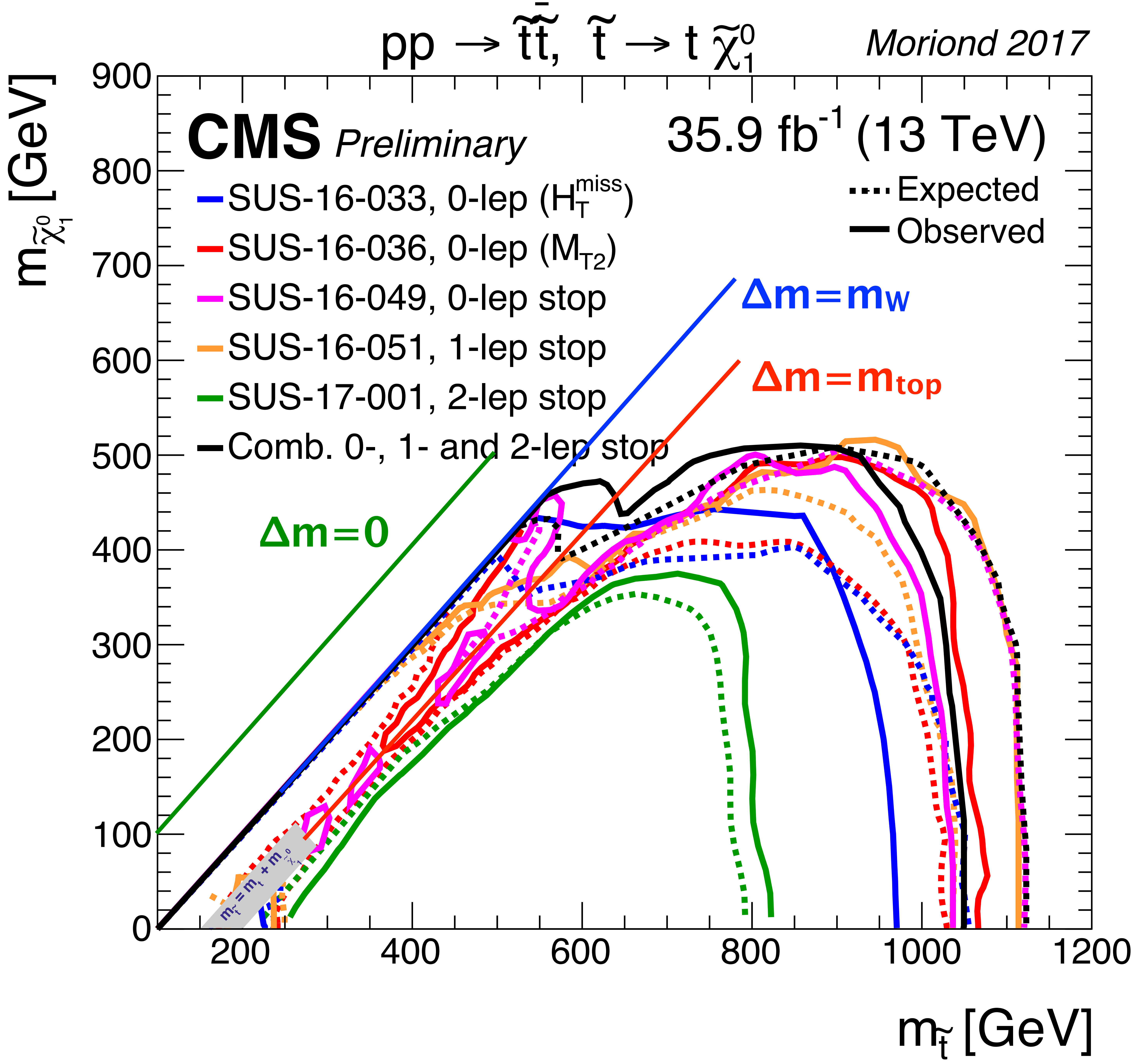



**Classify** according to:

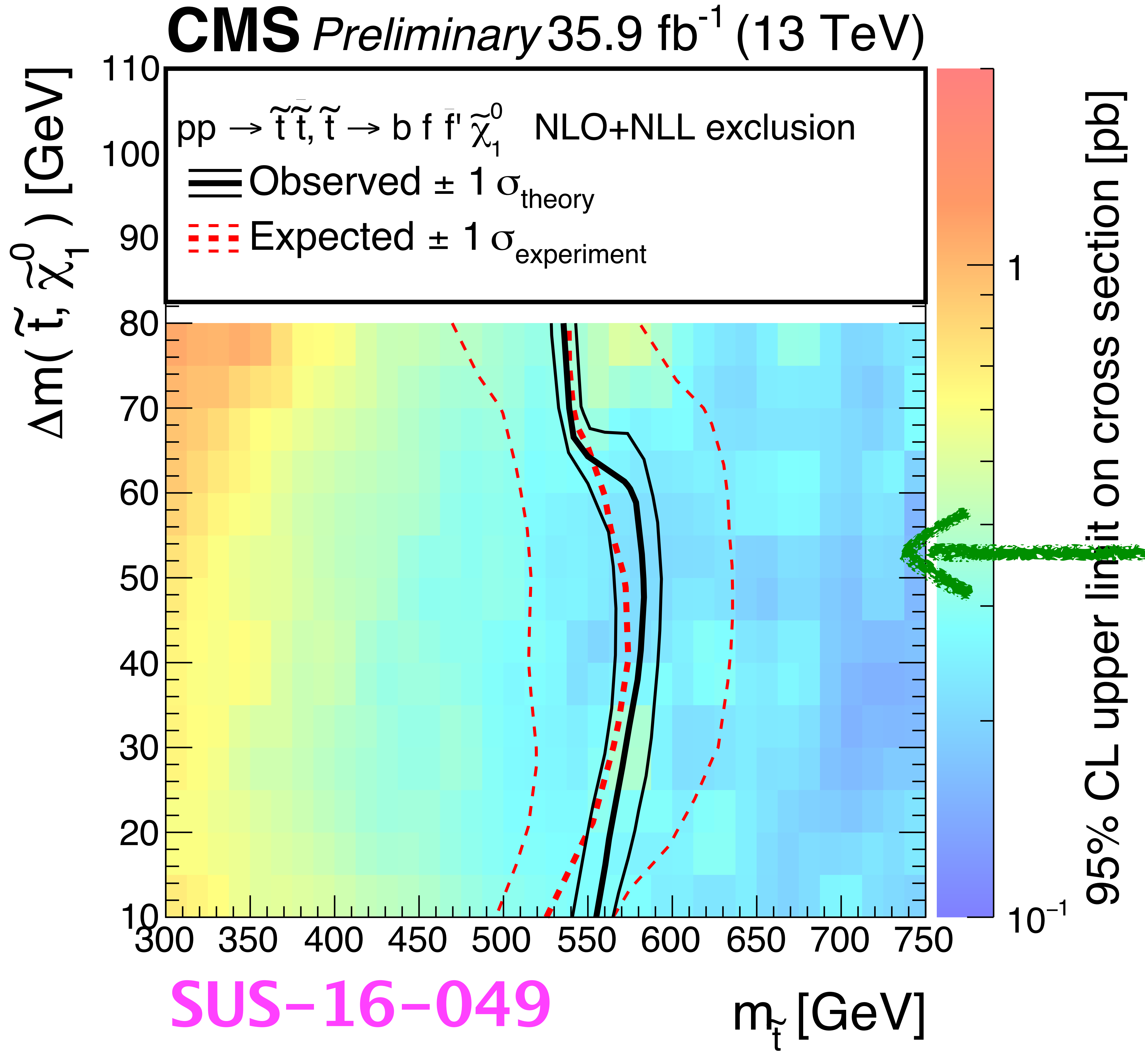
- $N_b$, Nj
- ISR jet $p_T$, bjet sum $p_T$
- number of secondary vertices

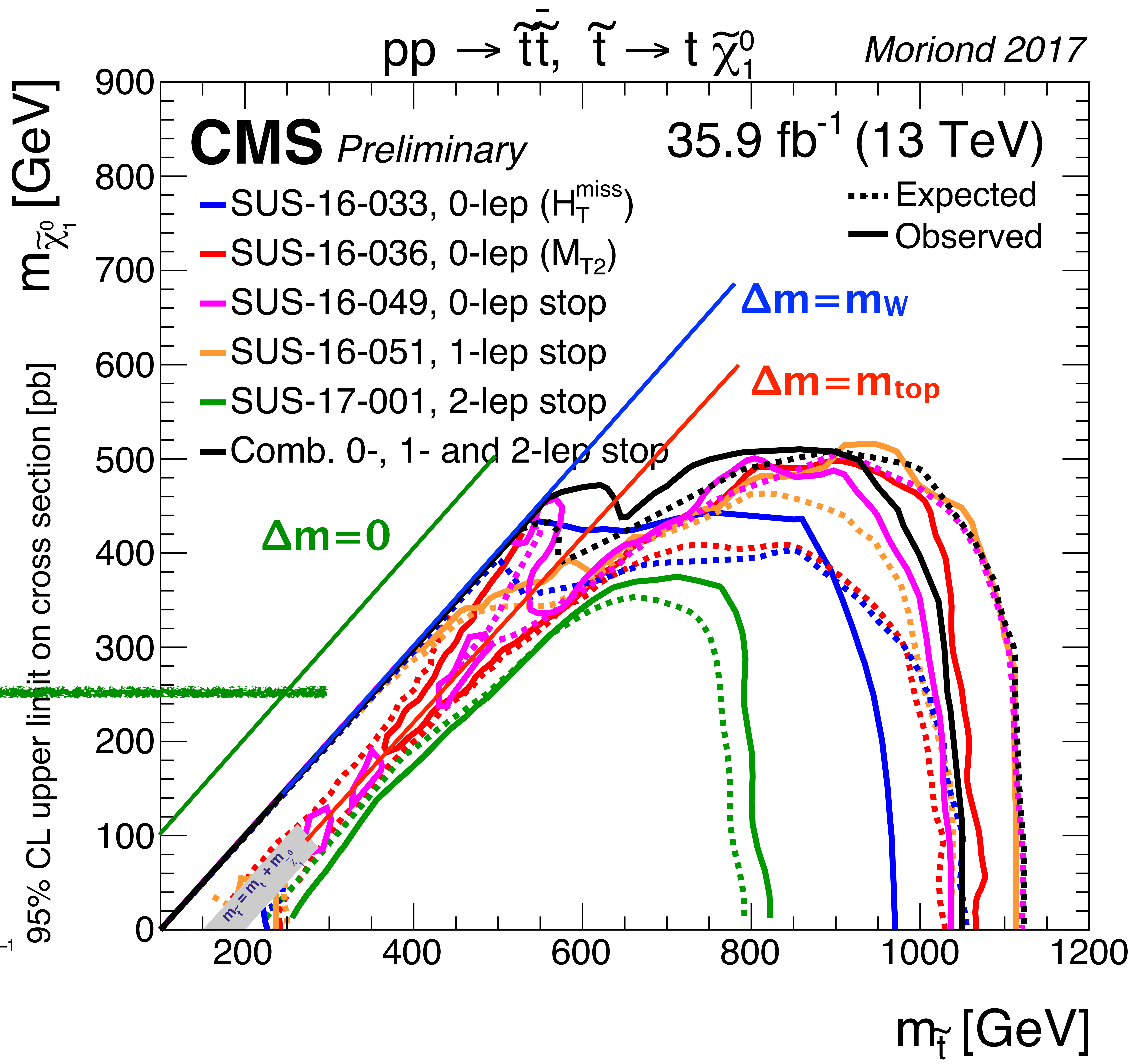
# Top squark sensitivity



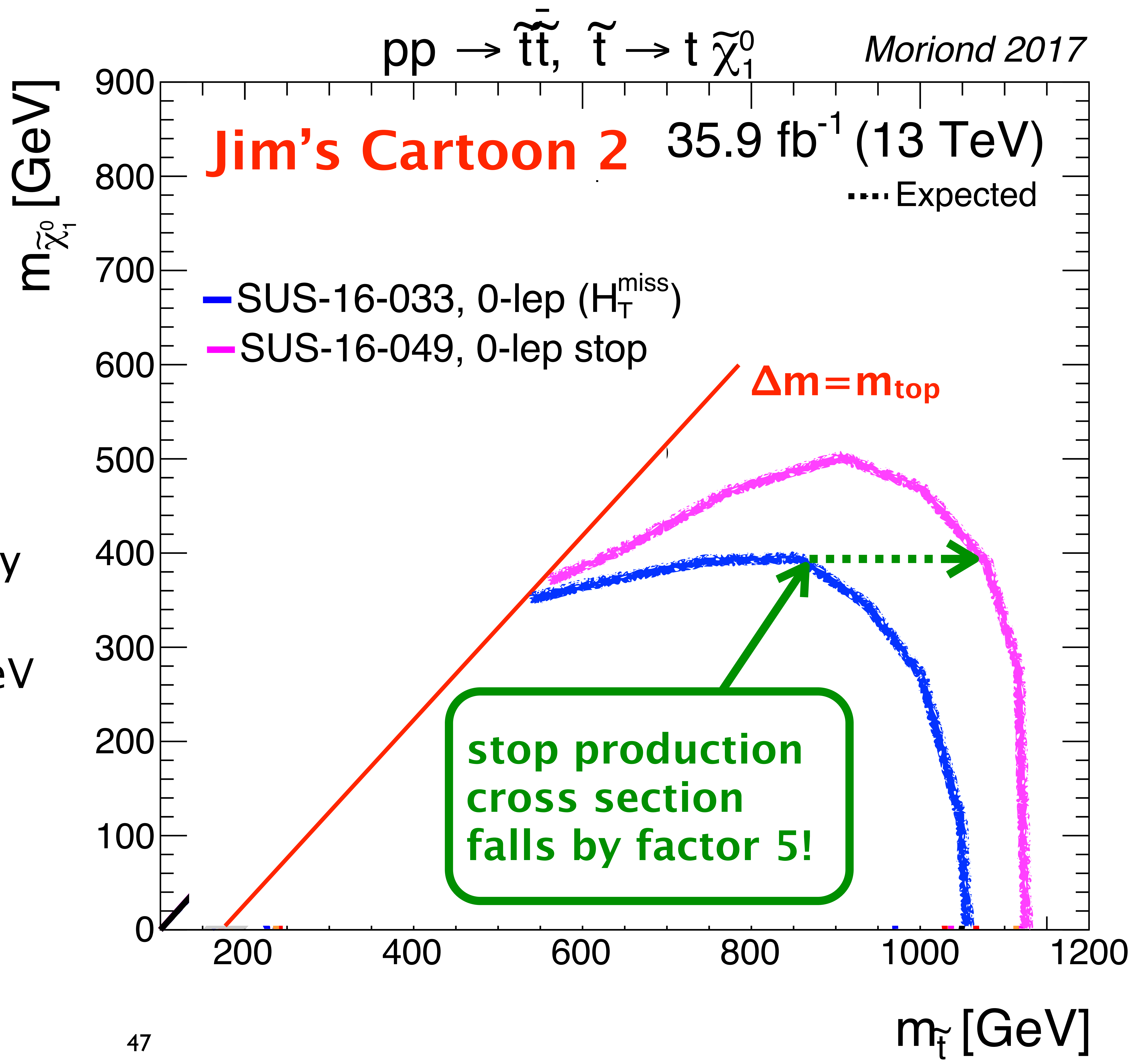
# Top squark sensitivity



# Top squark sensitivity

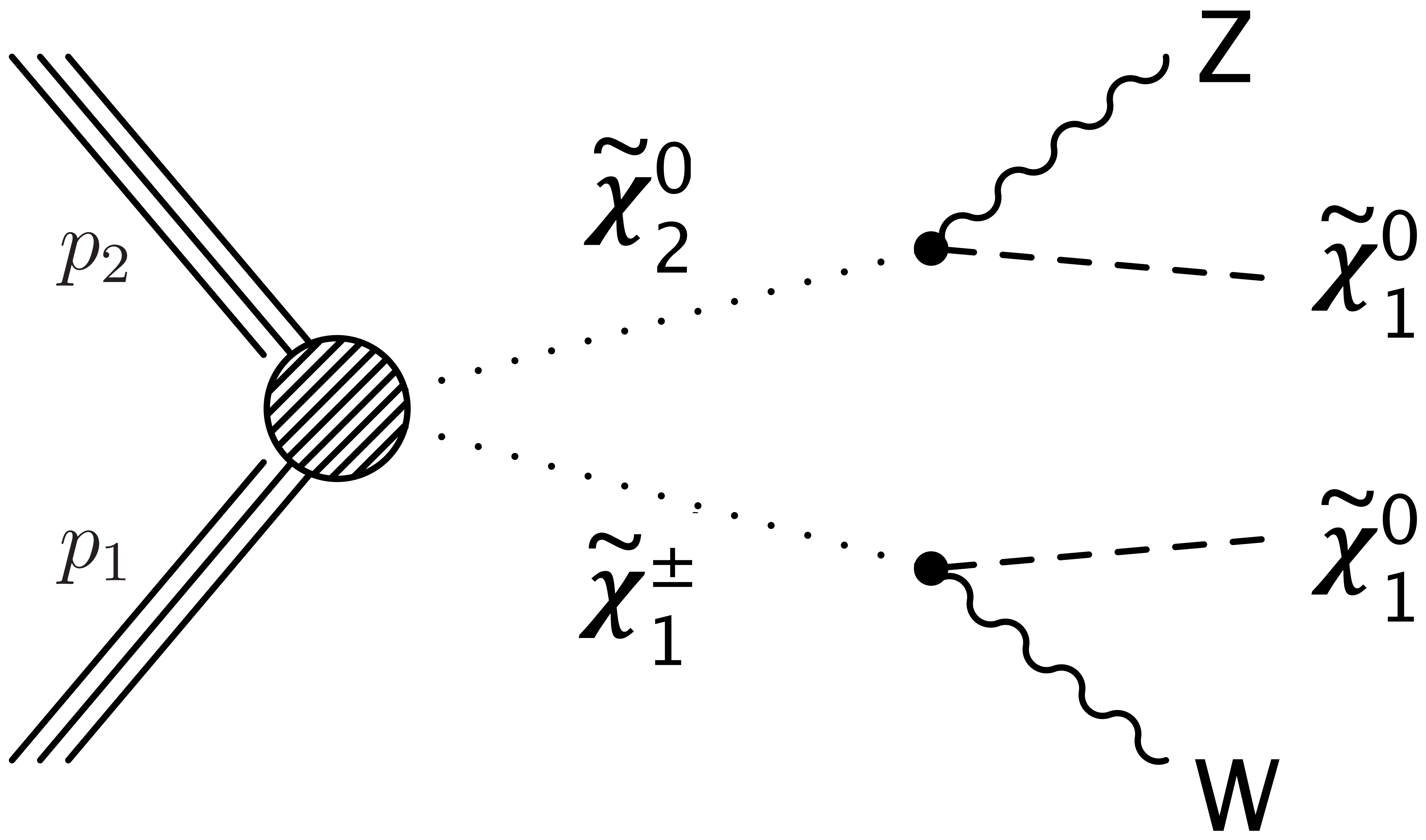
- **General searches** have good sensitivity to top squarks.
- **Targeted searches** use full decay kinematics
  - improve mass reach by 150 GeV
  - critical for potential discovery



# Weakly produced SUSY : EWKinos

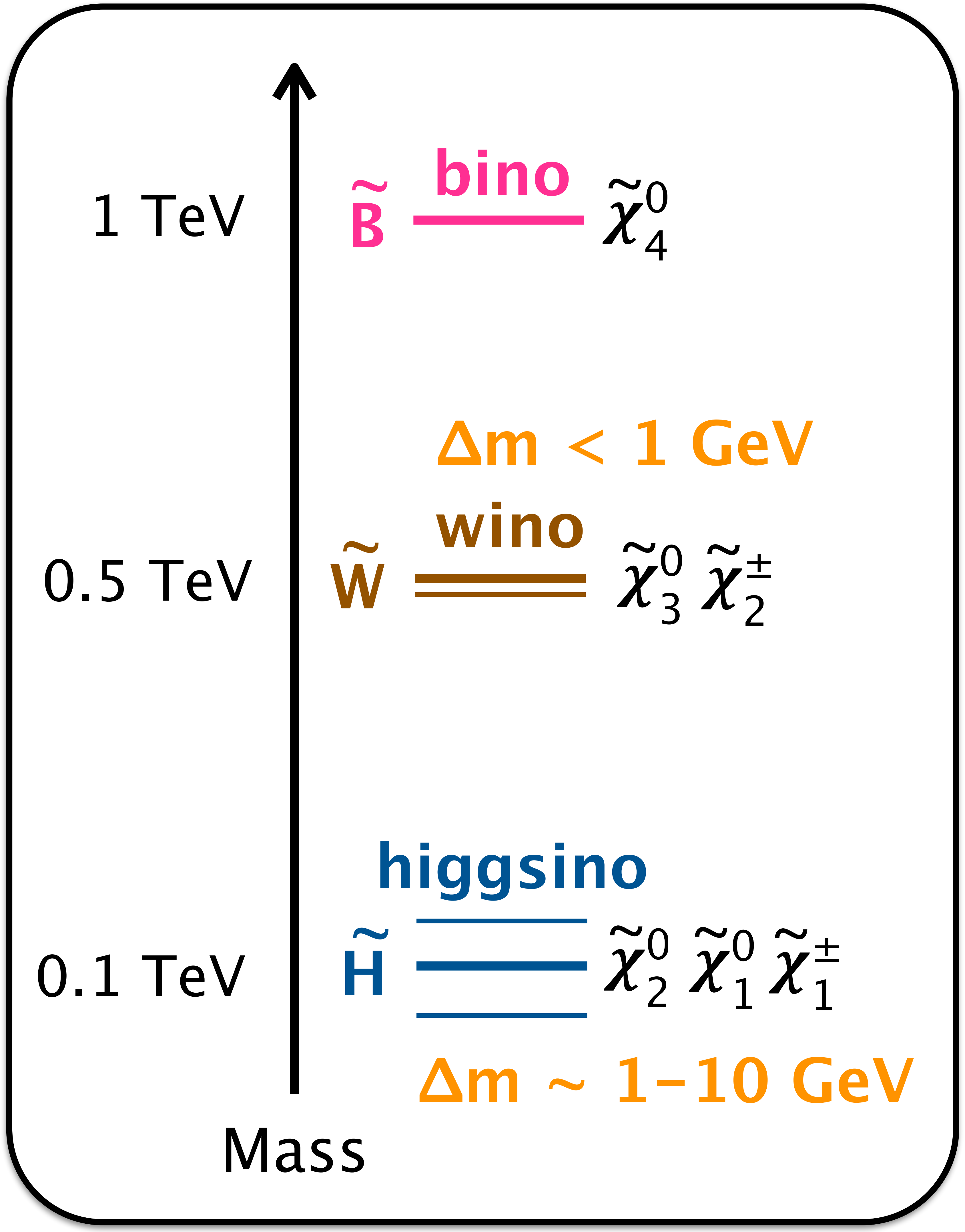
- Search for chargino and neutralino
- Cross sections depend on mixing
  - mostly wino, higgsino?
- Produce gauge bosons ➔ leptons in final state.

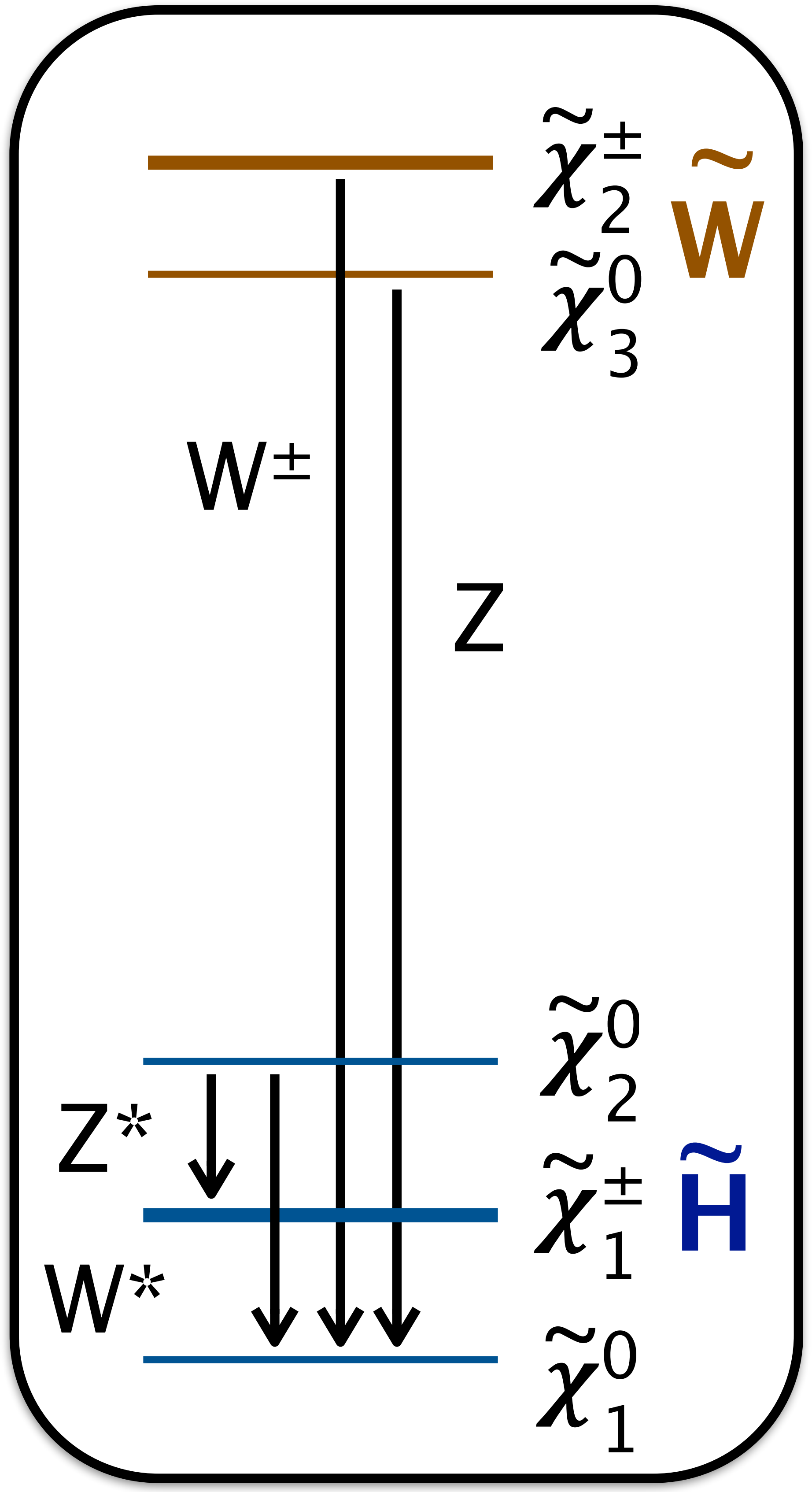
**Boson decay kinematics depend strongly on $\Delta m = m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}$**

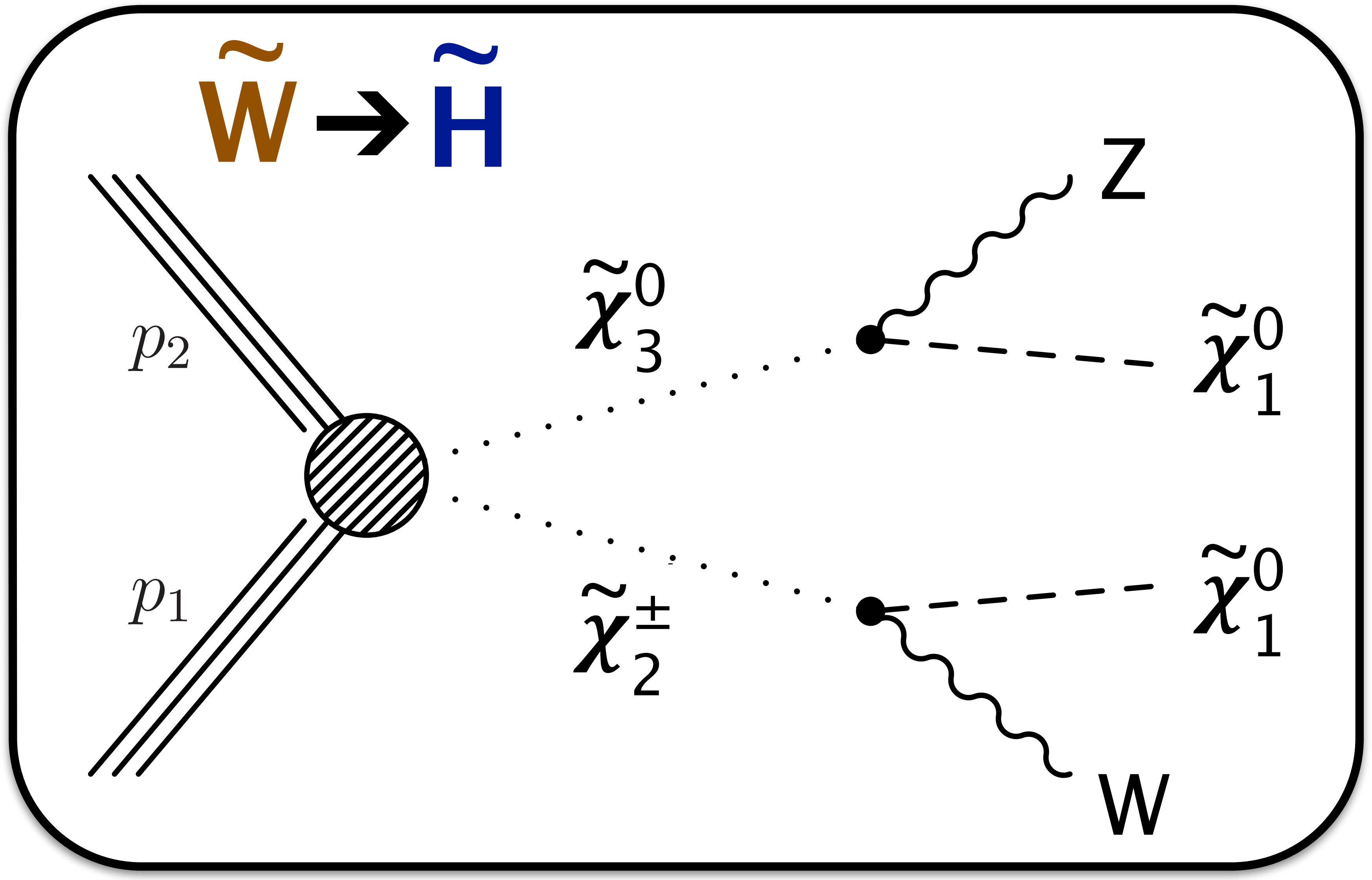


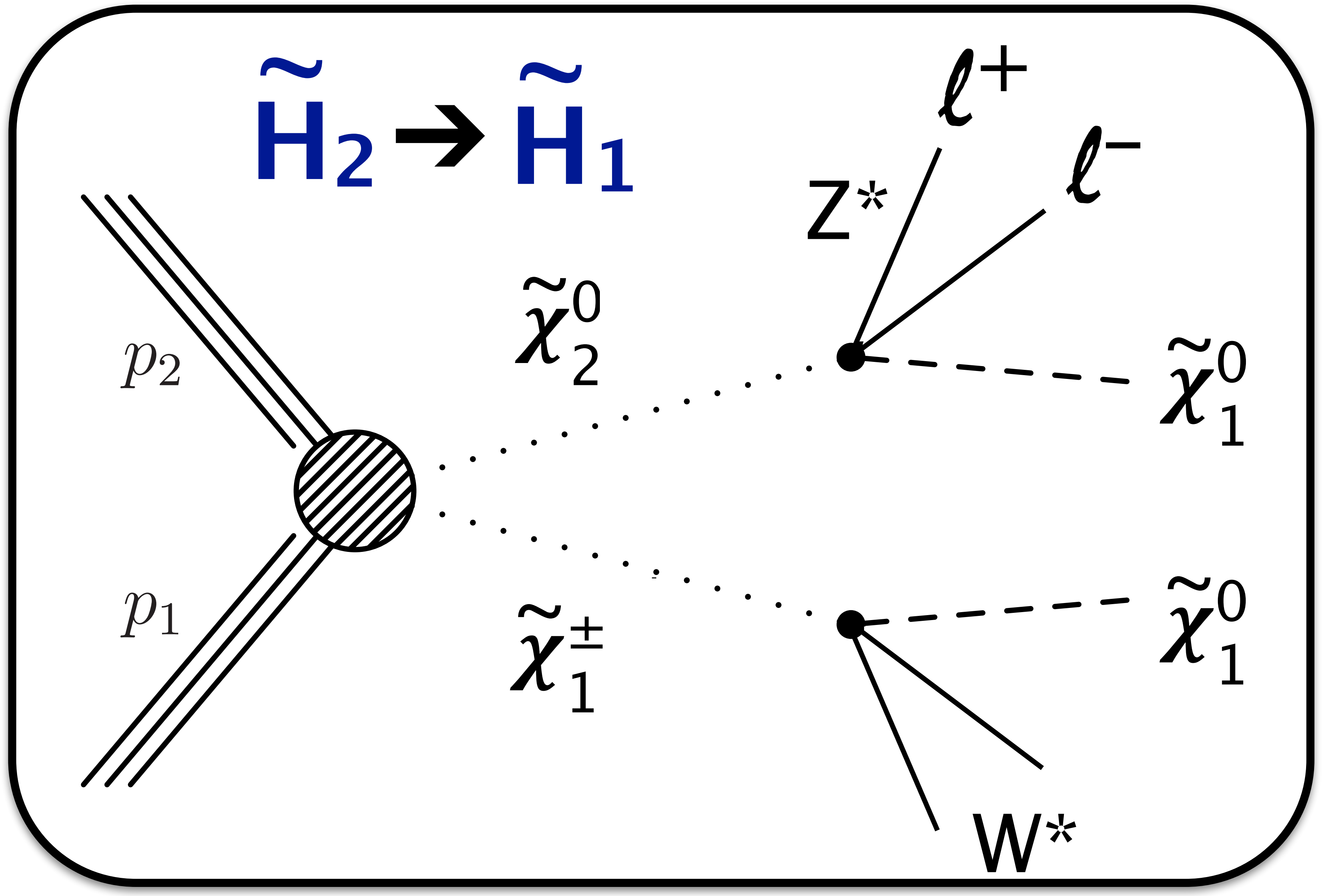

Typically $m_{\tilde{\chi}^0_2} \approx m_{\tilde{\chi}^{\pm}_1}$

# Example EWKino spectrum and decays

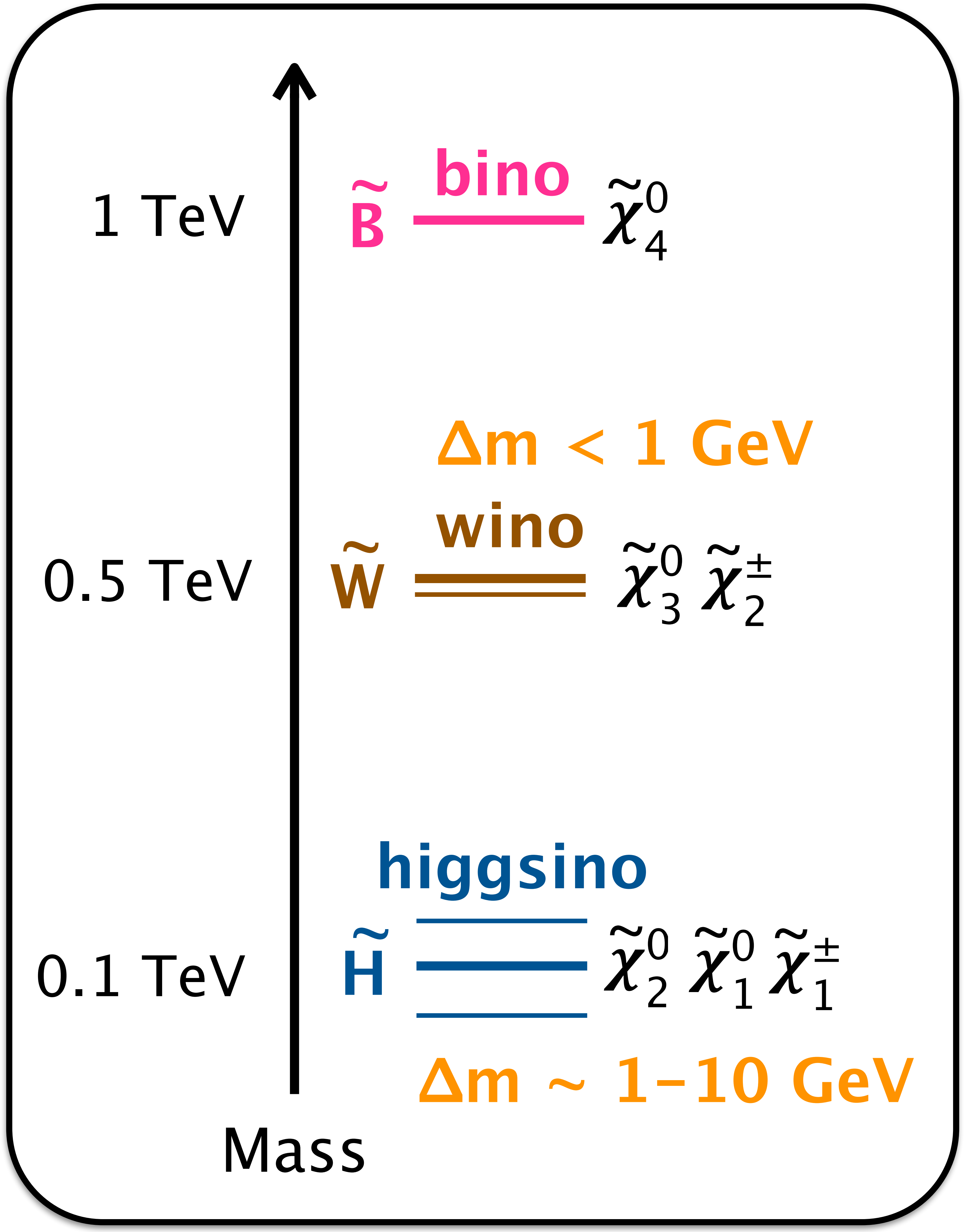


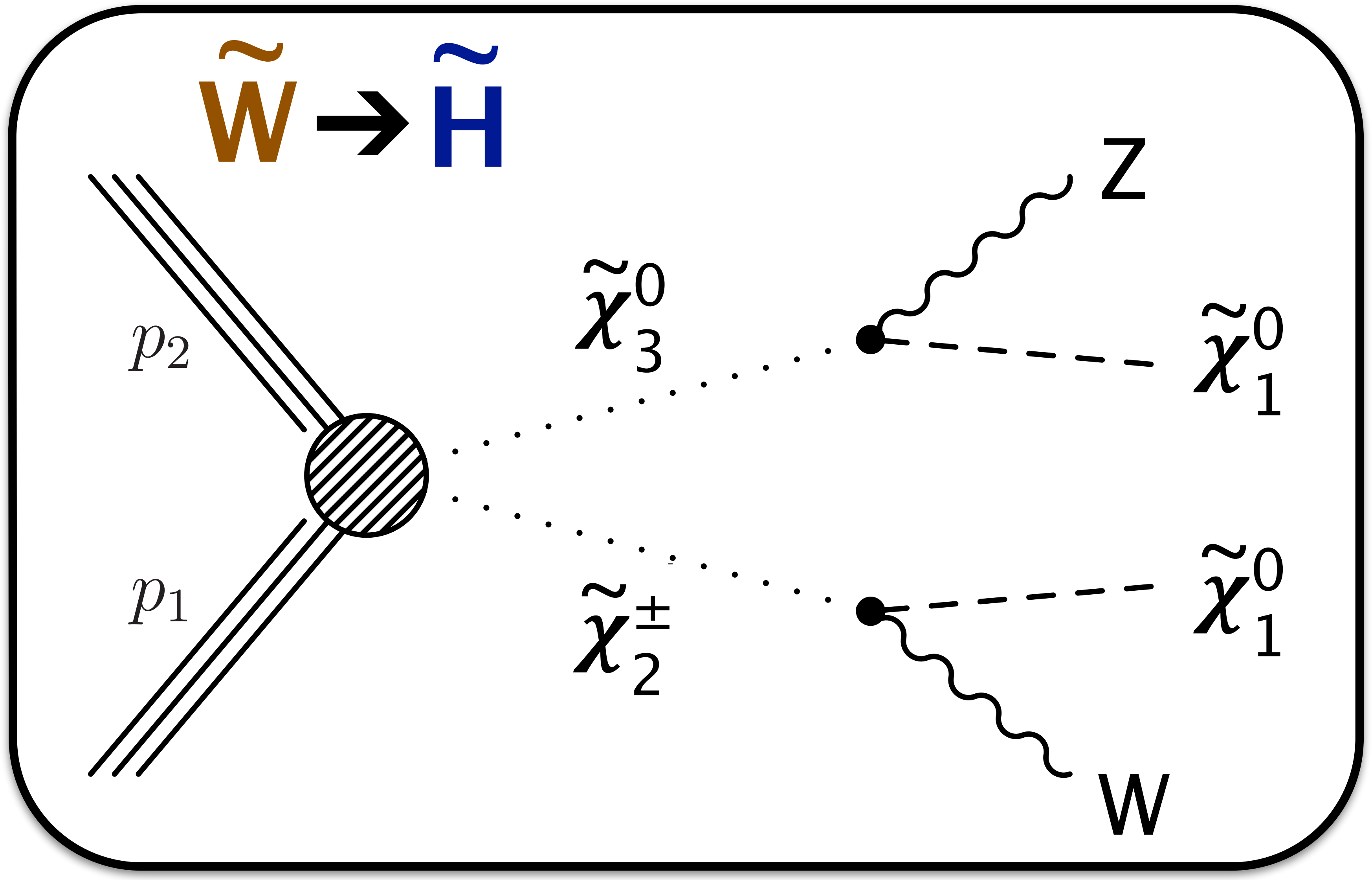



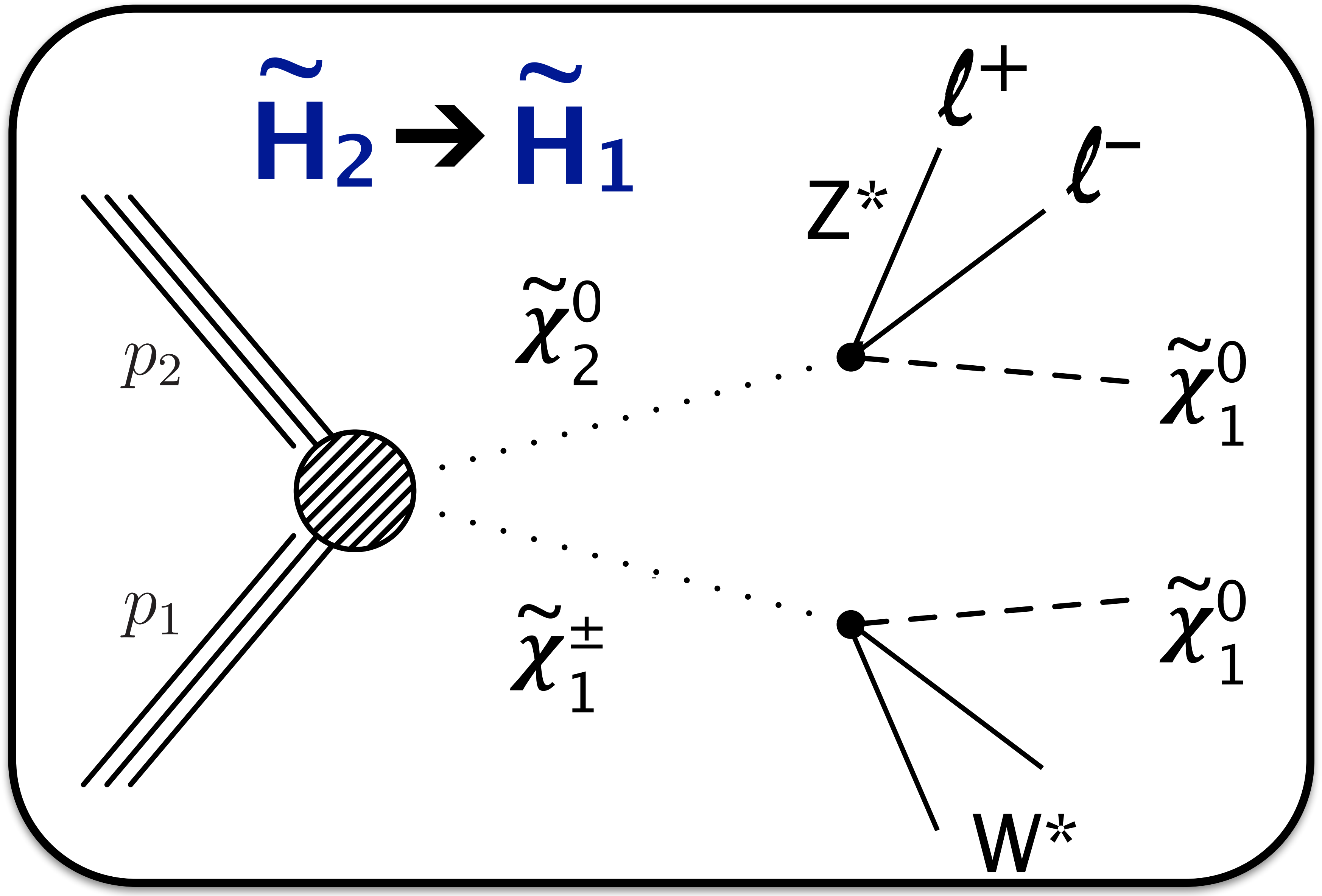
# Example EWKino spectrum and decays




**any Δm** possible for decays from $\tilde{W} \rightarrow \tilde{H}$



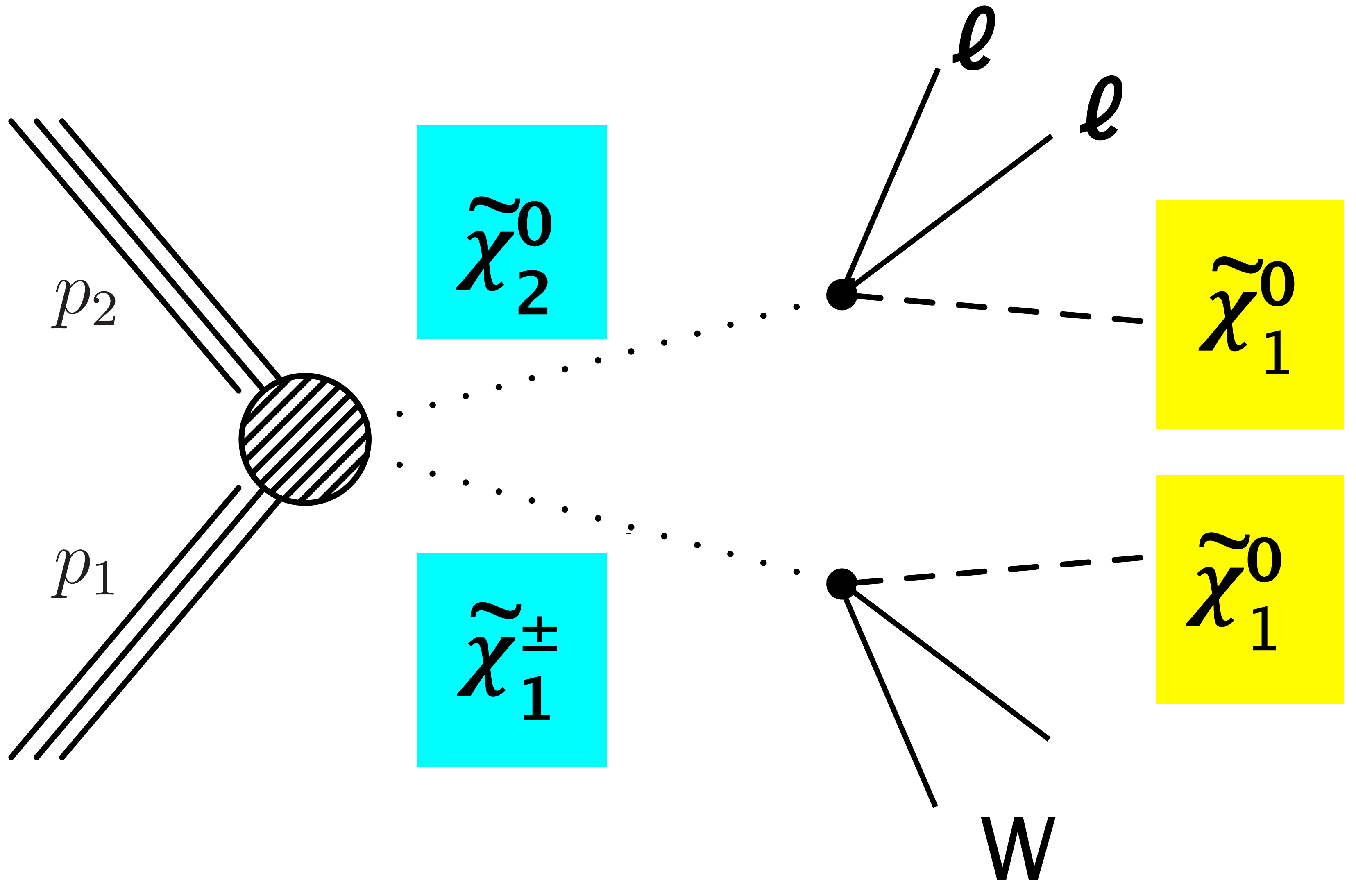

**small Δm** most likely for decays between higgsinos

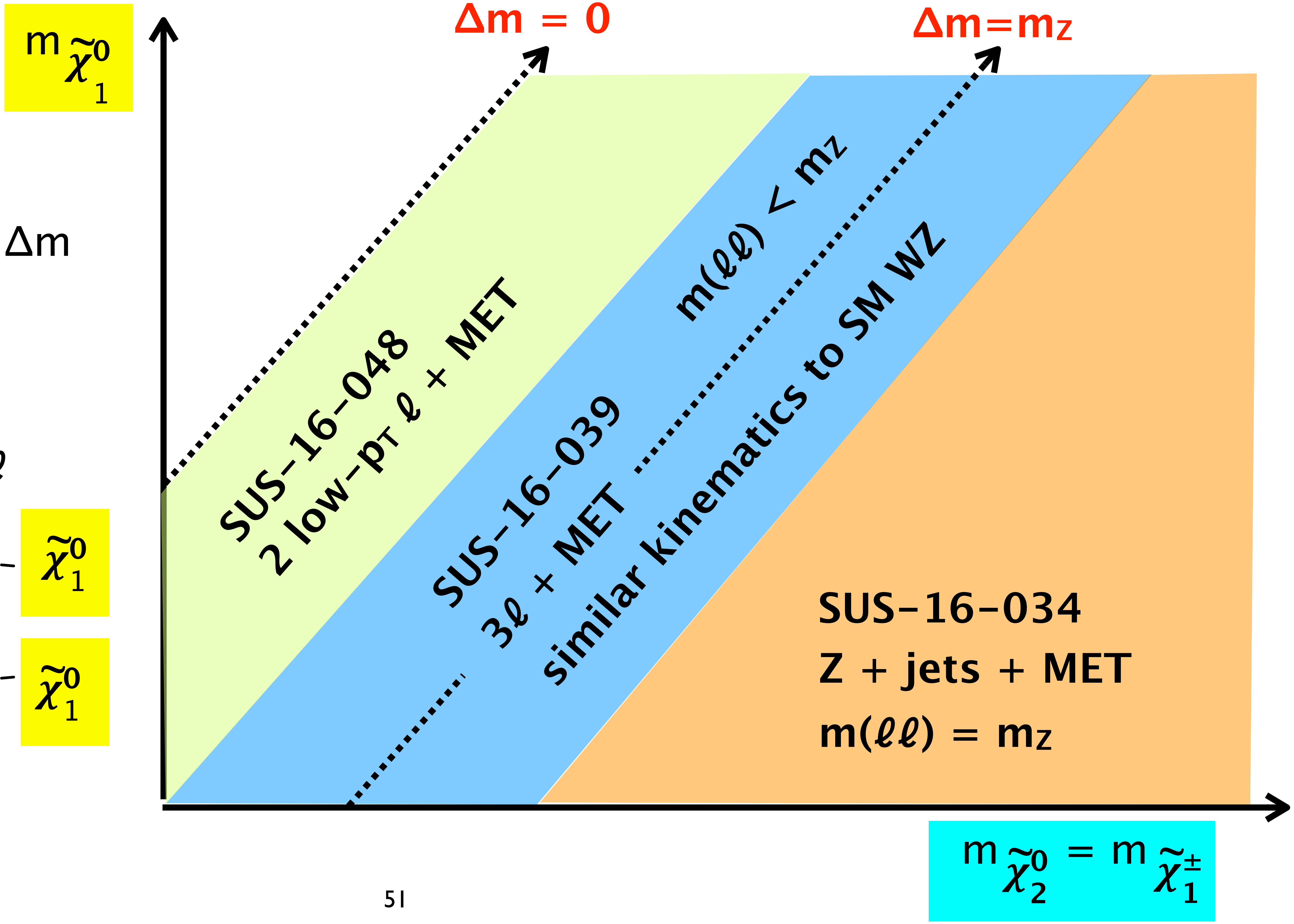


# Lepton kinematics

$\Delta m = m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}$

1. $\tilde{W} \rightarrow \tilde{H}$ with large $\Delta m$
2. $\tilde{W} \rightarrow \tilde{H}$ with moderate $\Delta m$
3. $\tilde{H}_2 \rightarrow \tilde{H}_1$ with small $\Delta m$



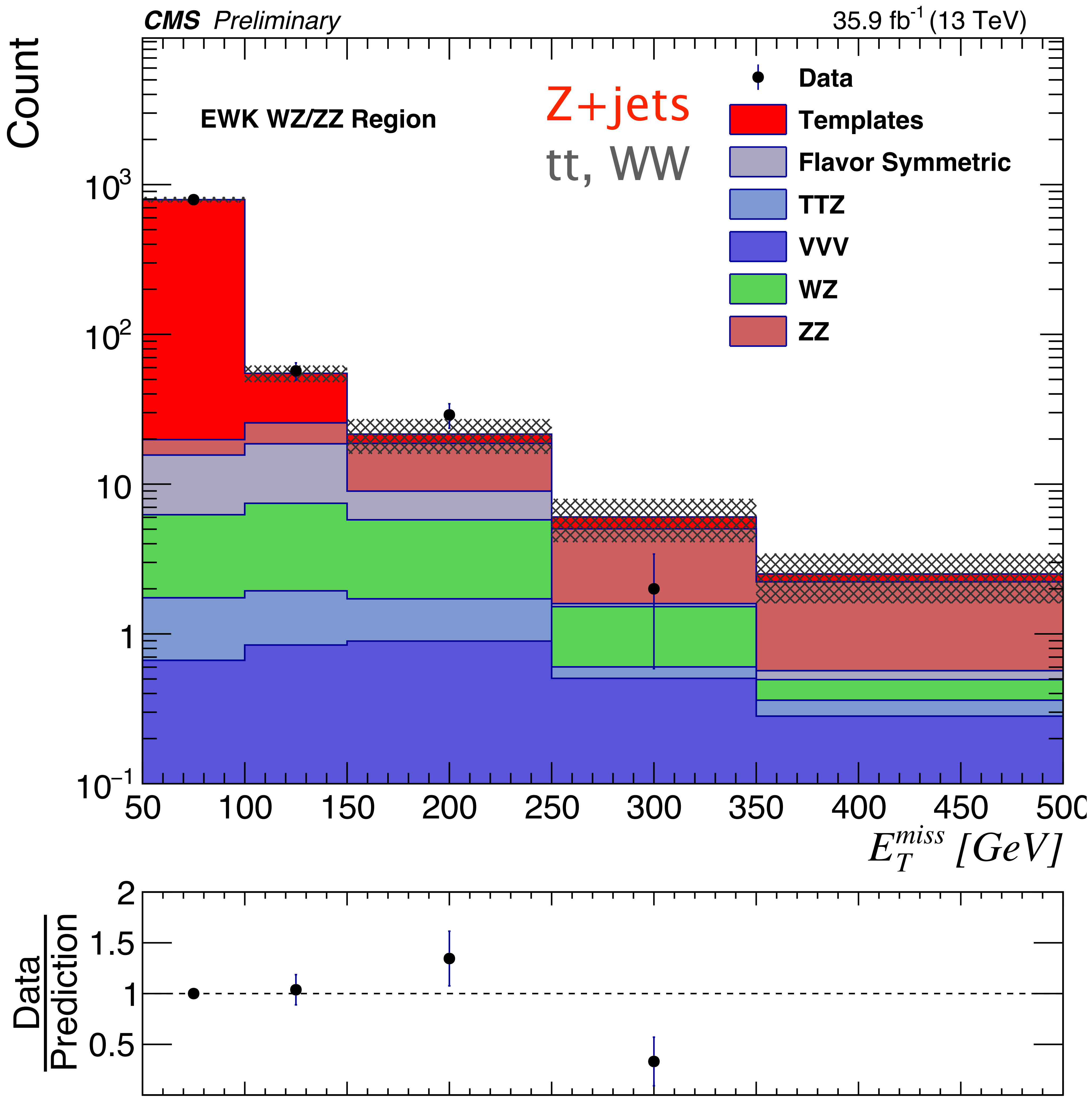



# Z+jets+MET search ($\Delta m > m_Z$)

SUS-16-034

## Selection

| | Selection | motivation |
|---|---|---|
| Leptons | $e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$ | |
| MET | >100 GeV | reduce SM |
| $m(\ell\ell)$ | consistent with Z | reduce tt |
| $N_b$ | 0 | |
| $MT2(\ell\ell)$ | >80 GeV | |
| Nj | >=2 | reduce Z+jets |
| m(jj) | < 110 GeV | |




## Backgrounds

- Z+jets with mismeasured jet
  - MET shape from γ+jets
- VV: simulation estimate validated in $3\ell$ & $4\ell$ data
- tt + WW : estimate from $e^{\pm}\mu^{\mp}$

SUS-16-039

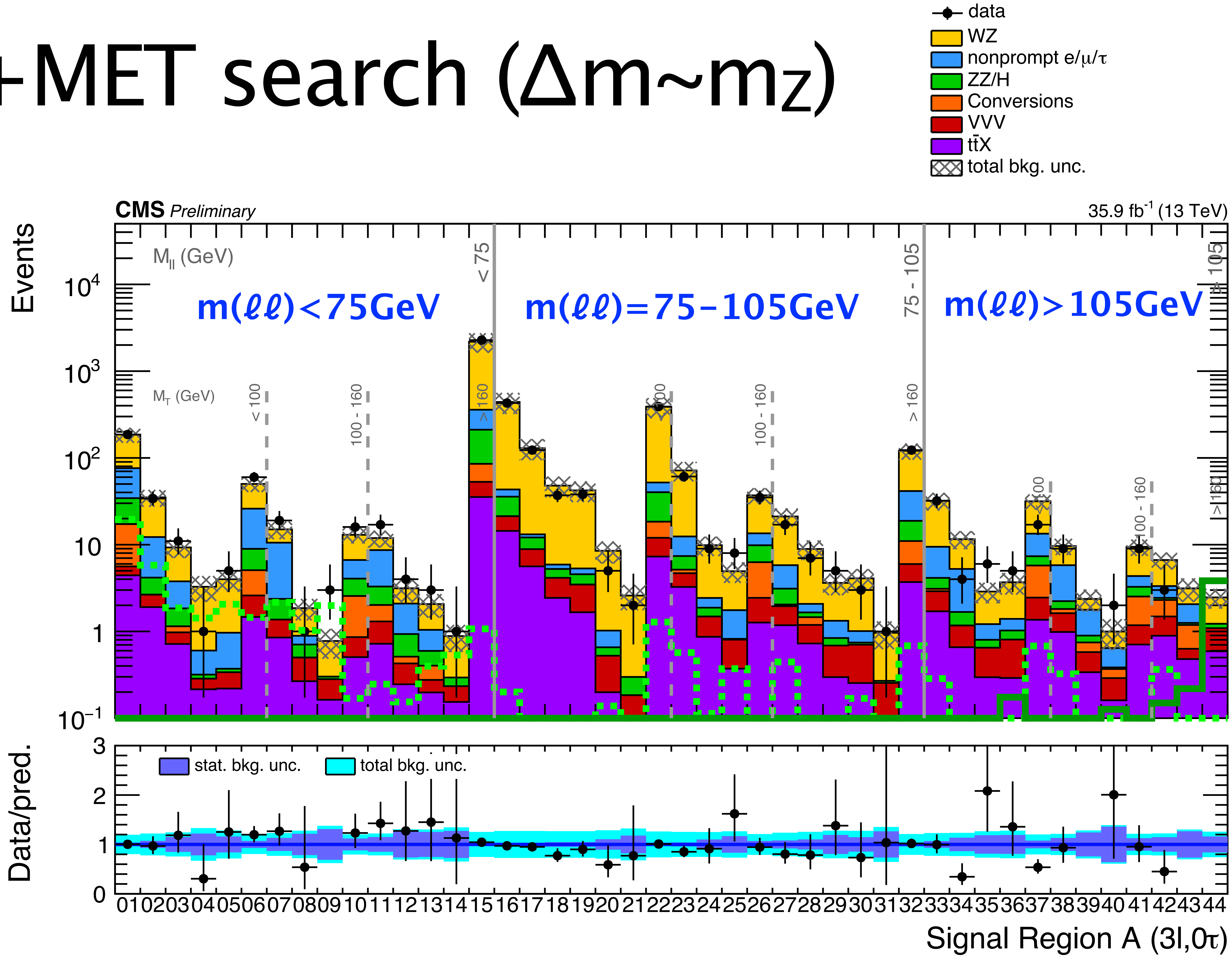
# 3ℓ+MET search (Δm~$m_Z$)

**Select**

- $e^{\pm}e^{\mp}$+ℓ or $\mu^{\pm}\mu^{\mp}$+ℓ
- MET > 50 GeV
- $N_b$=0 suppresses $t\bar{t}$
- Categorize by m(ℓℓ), $m_T$($\ell_3$, MET), MET.

**Backgrounds**

- WZ estimated with MET<100 GeV sample
- nonprompt ℓ with relaxed ℓ sample



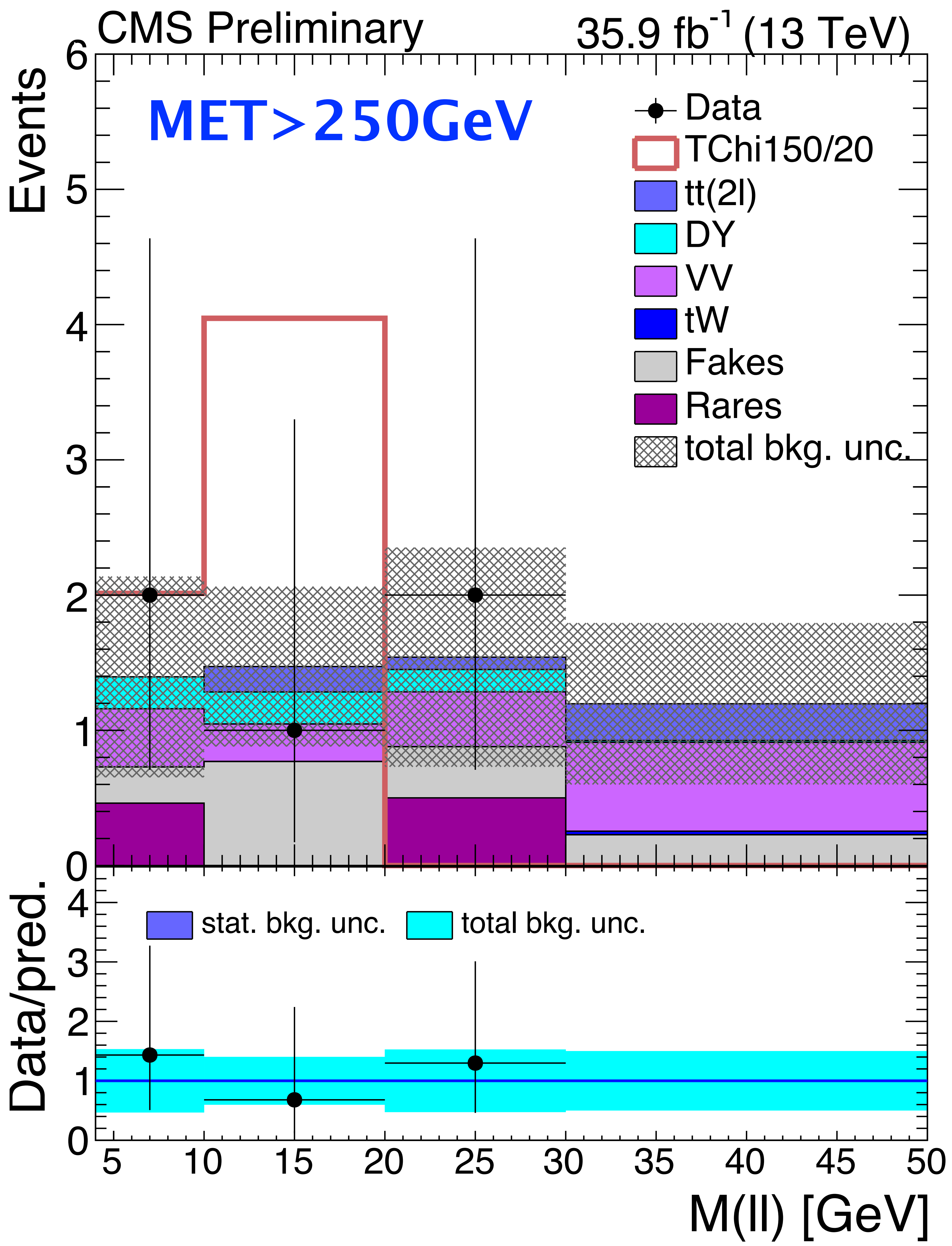
# 2 low-$p_T$ $\ell$ + MET (small $\Delta m$)

SUS-16-048

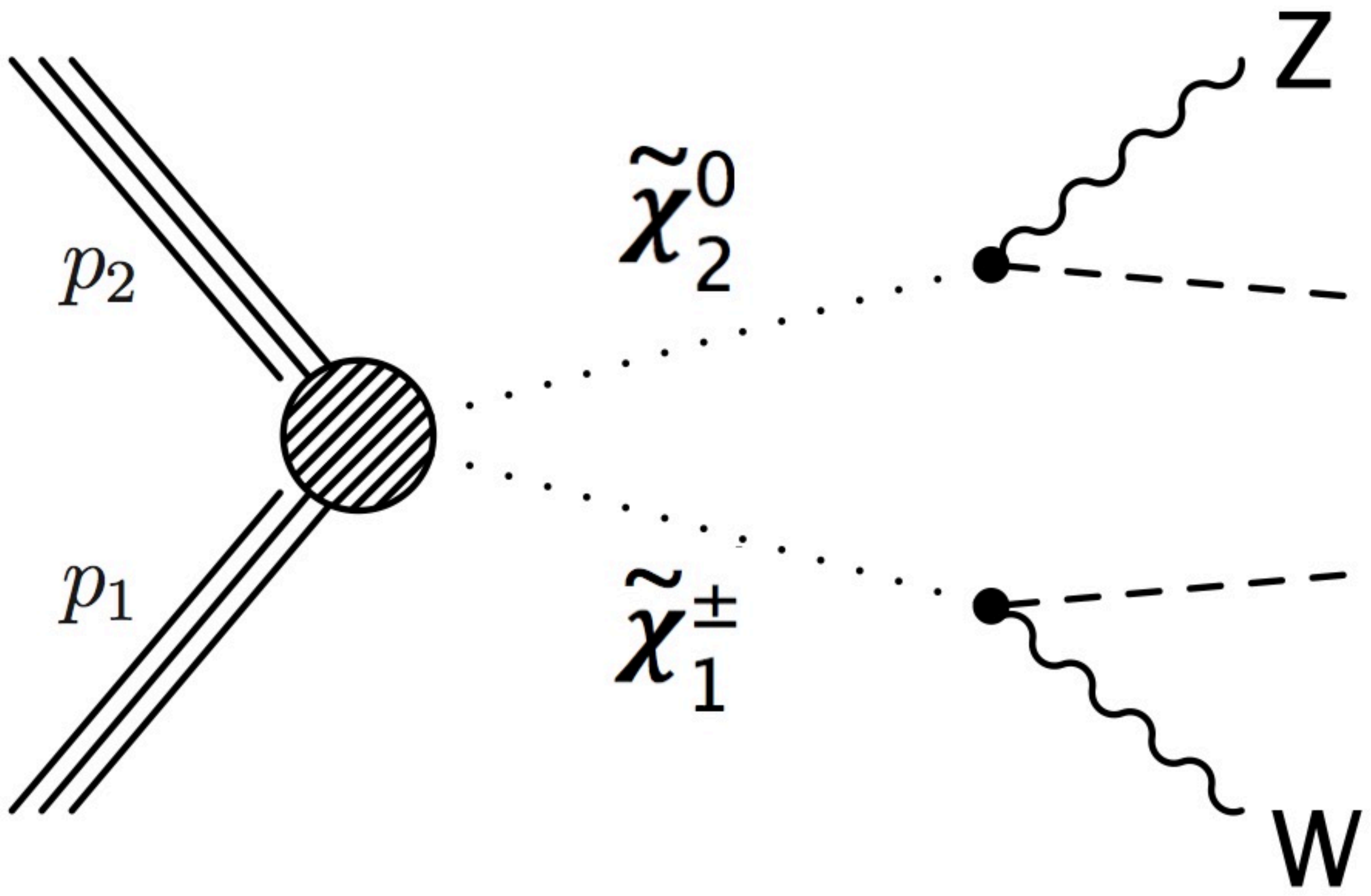
- Special trigger: 2 muons with $p_T$>3GeV and MET>50 GeV (from ISR boost)

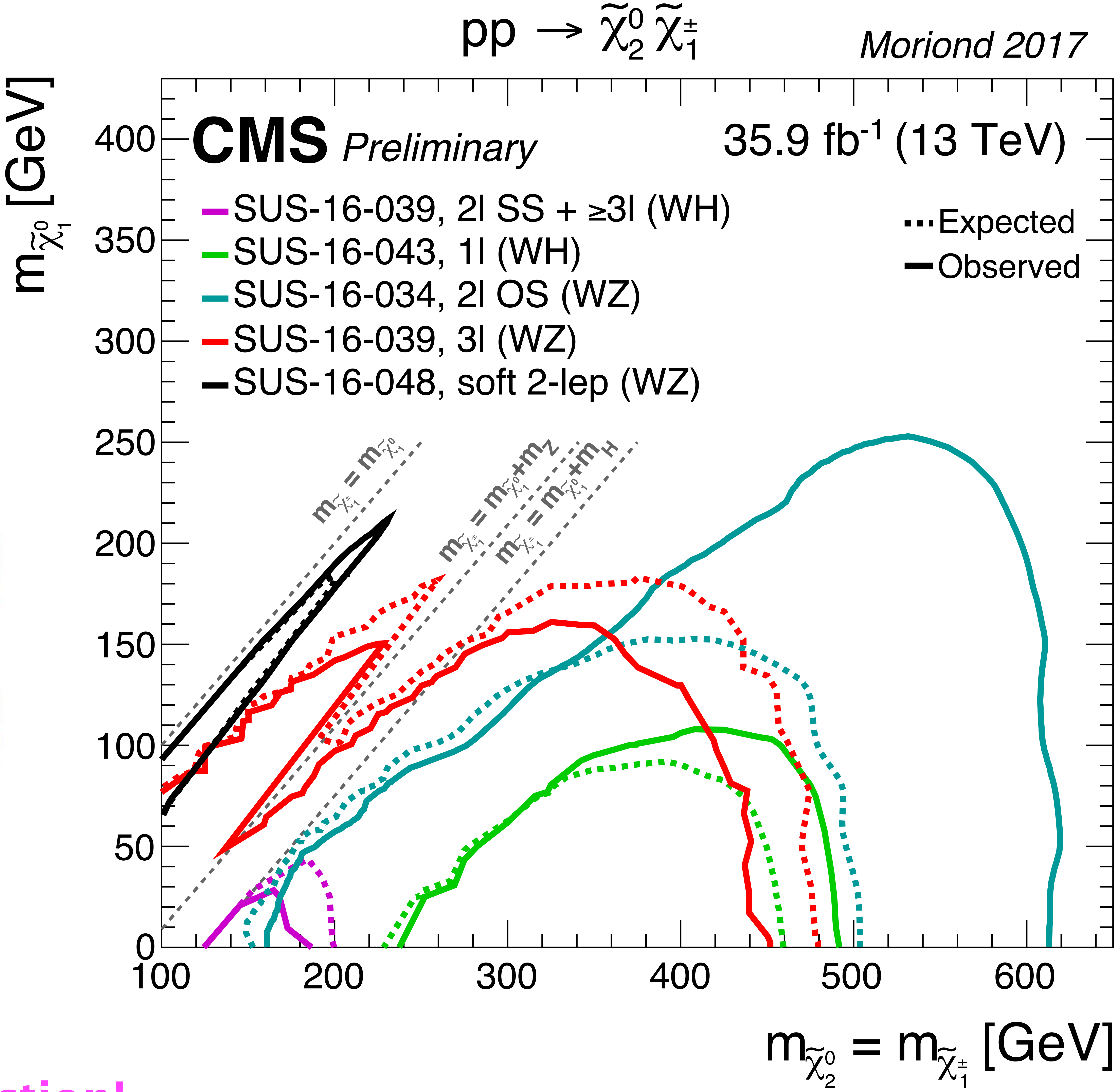
| | Selection | motivation |
|---|---|---|
| Leptons | $e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$ | |
| MET | >125 GeV | trigger |
| Nj (ISR) | ≥1 | trigger |
| $\ell$ $p_T$ | 5–30 GeV | reduce tt |
| $N_b$ | 0 | reduce tt |
| $m_T(\ell$, MET) | < 70 GeV | reduce tt |
| MET/HT | 0.6 – 1.4 | reduce QCD |
| $m(\ell\ell)$ | [4,9], [10.5,50] GeV | reduce SM $\ell\ell$ resonances |

- Bkg estimates from data; e.g. VV in $m_T$ ctrl sample
- Categorize based on $m(\ell\ell)$ and MET.



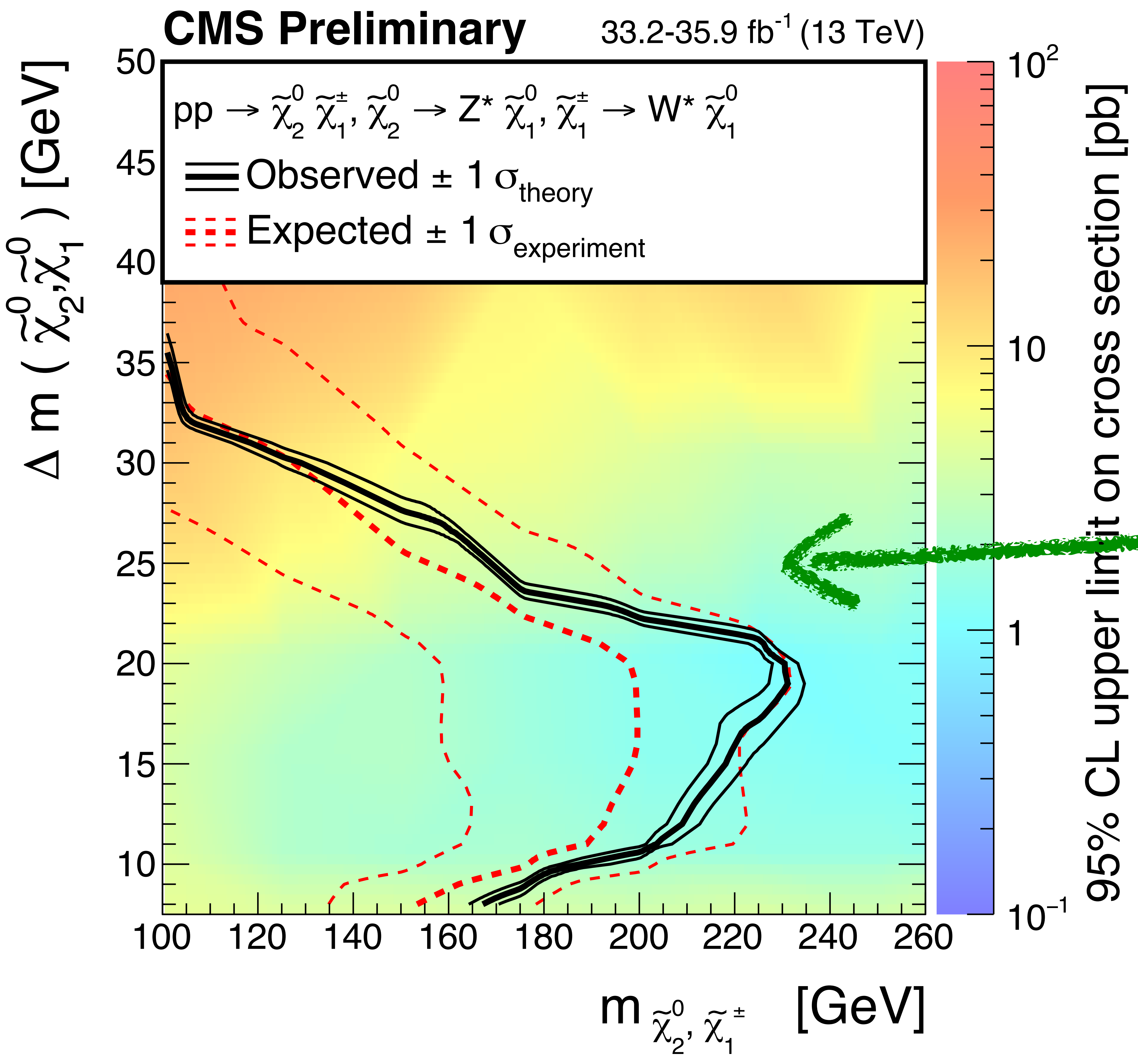
# EWKino sensitivity

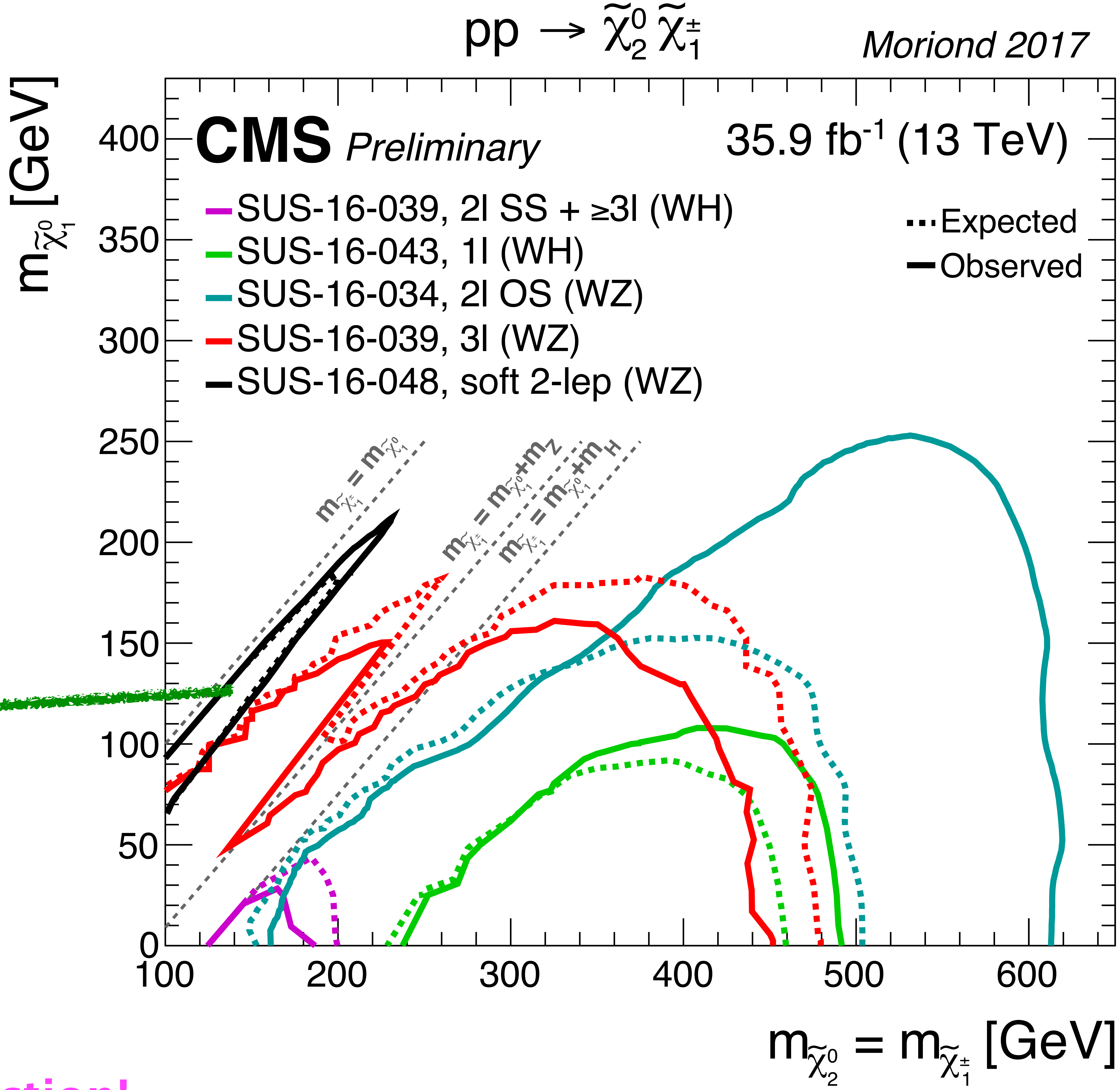



NB: assumes wino-like cross section!

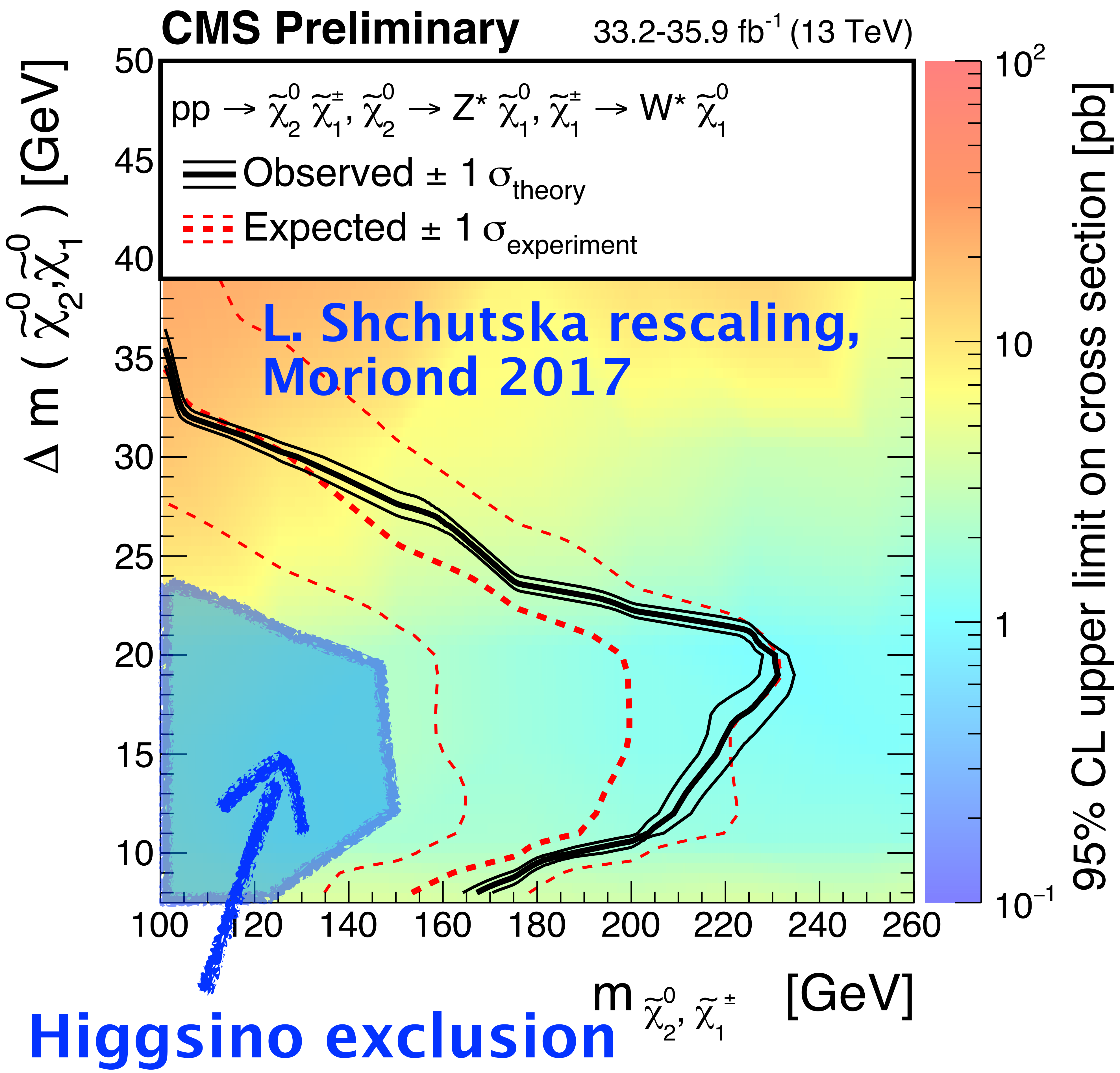
# EWKino sensitivity

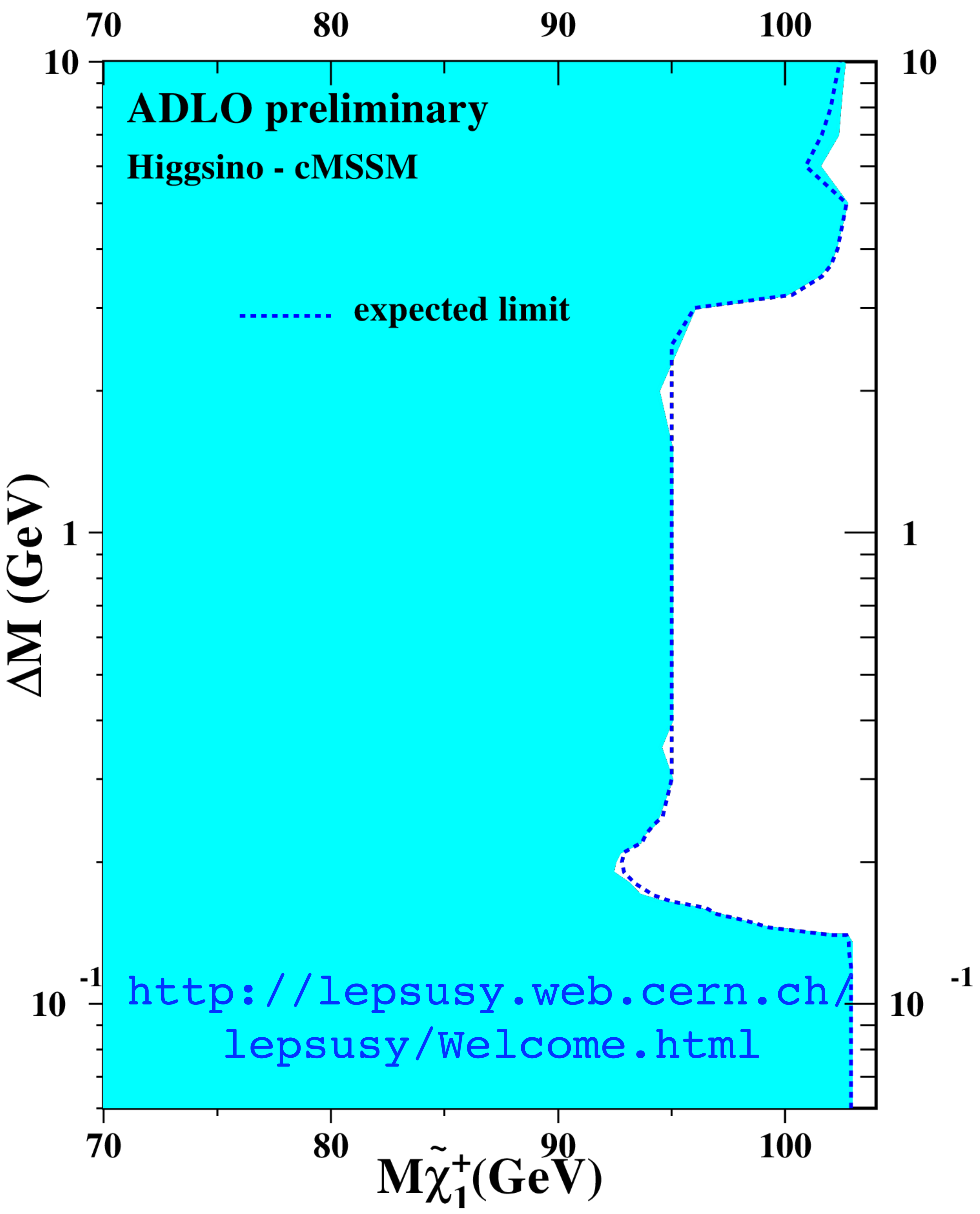



NB: assumes wino-like cross section!

# Higgsino sensitivity




At Δm=10 GeV:

- LEP limit is 100 GeV.
- CMS wino limit rescaled to higgsino xsec is 130 GeV.

**Only now pushing beyond LEP limits!**

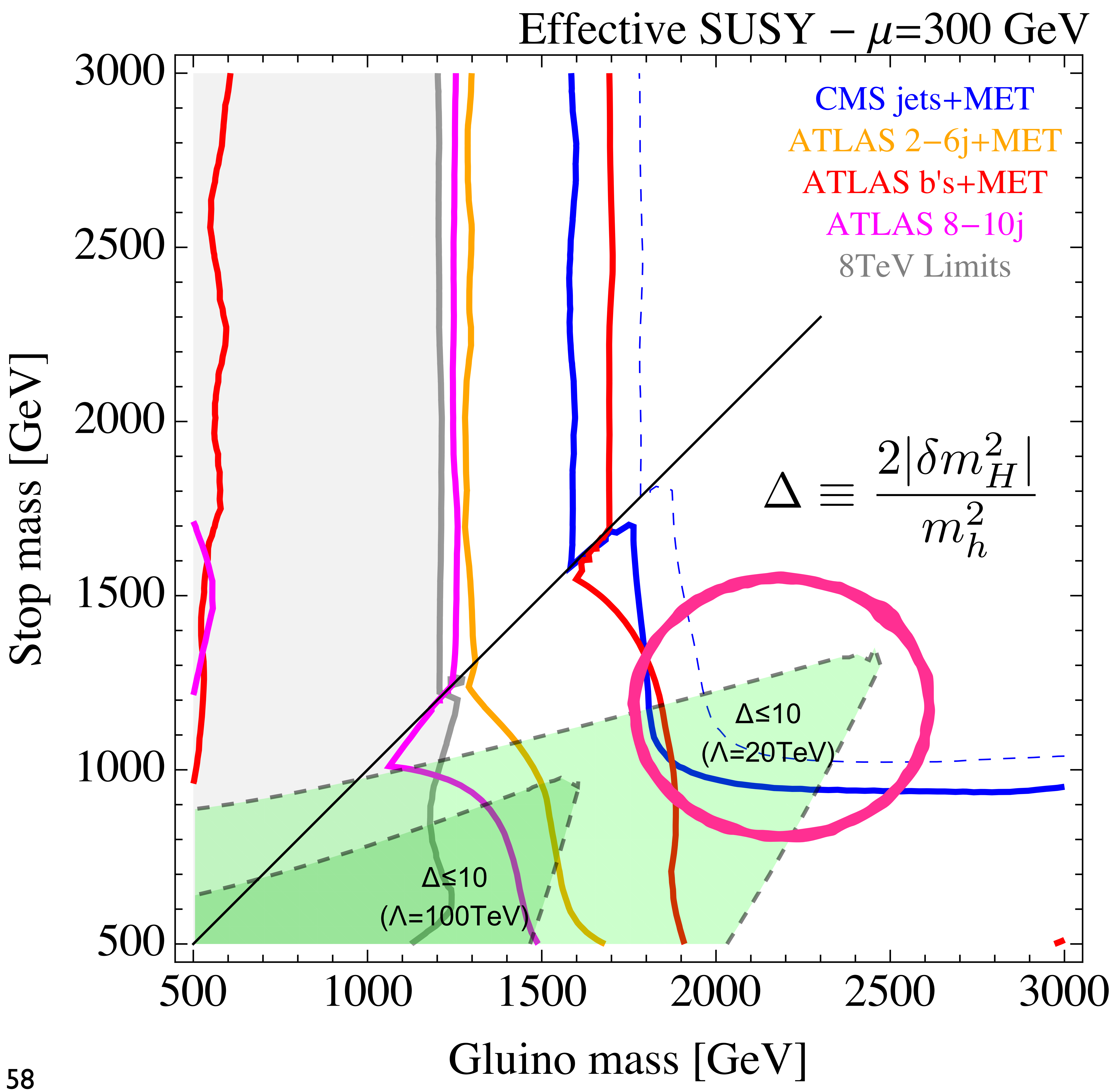
# Implication for natural SUSY

Buckley, Feld, Macaluso, Monteux, Shih; arXiv:1610.08059

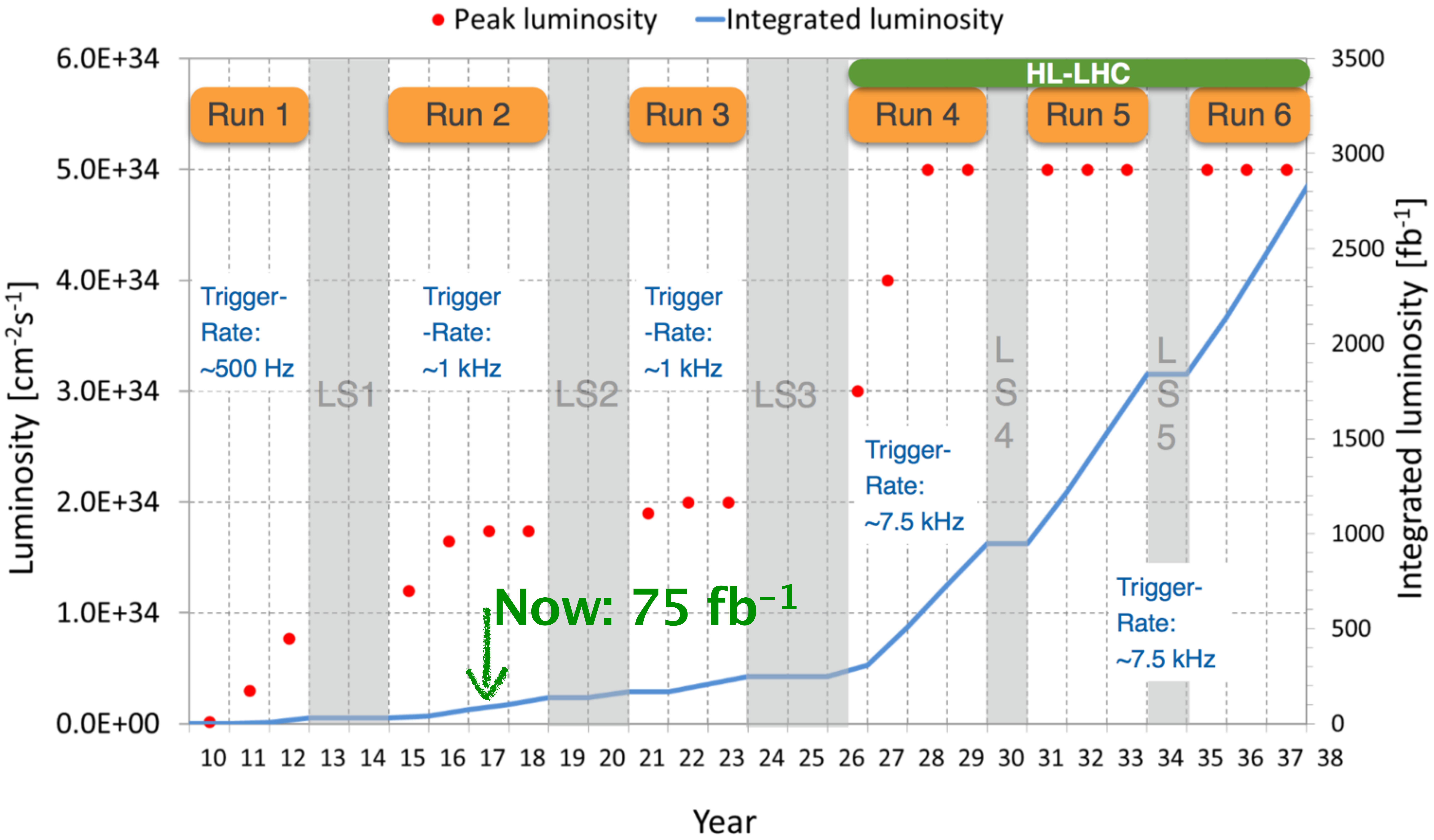
- Allowed phase space for **10% fine tuning with low Λ=20TeV**.
- Λ=GUT scale implies 0.5% fine tuning.

**Options:**

- **Accept** <1% fine tuning?
- **Reconsider** naturalness metric?
  H.Baer et al. arXiv:1611.08511
- **Hide** SUSY with stealth SUSY, R-parity violation?
- **Other** naturalness mechanism: Twin Higgs, Neutral Naturalness?



# We are just getting started



# Detector Upgrades

**Trigger**
- include track info at L1
- L1 output 750 kHz
- HLT output 7.5 kHz

**New tracker**
40MHz selective readout for trigger
extend η coverage

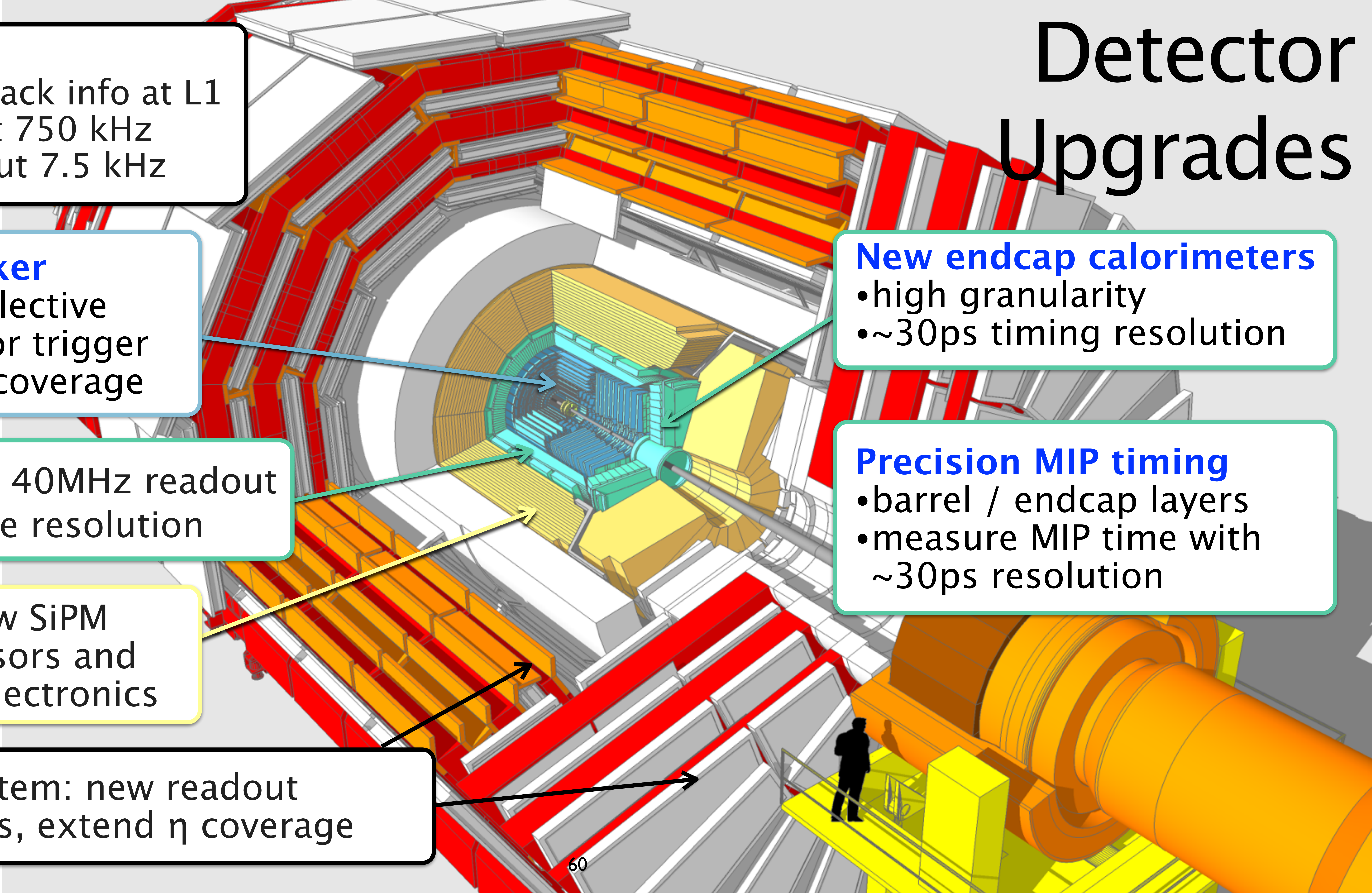
**ECAL:** full 40MHz readout
~30ps time resolution

**HCAL:** new SiPM photosensors and readout electronics

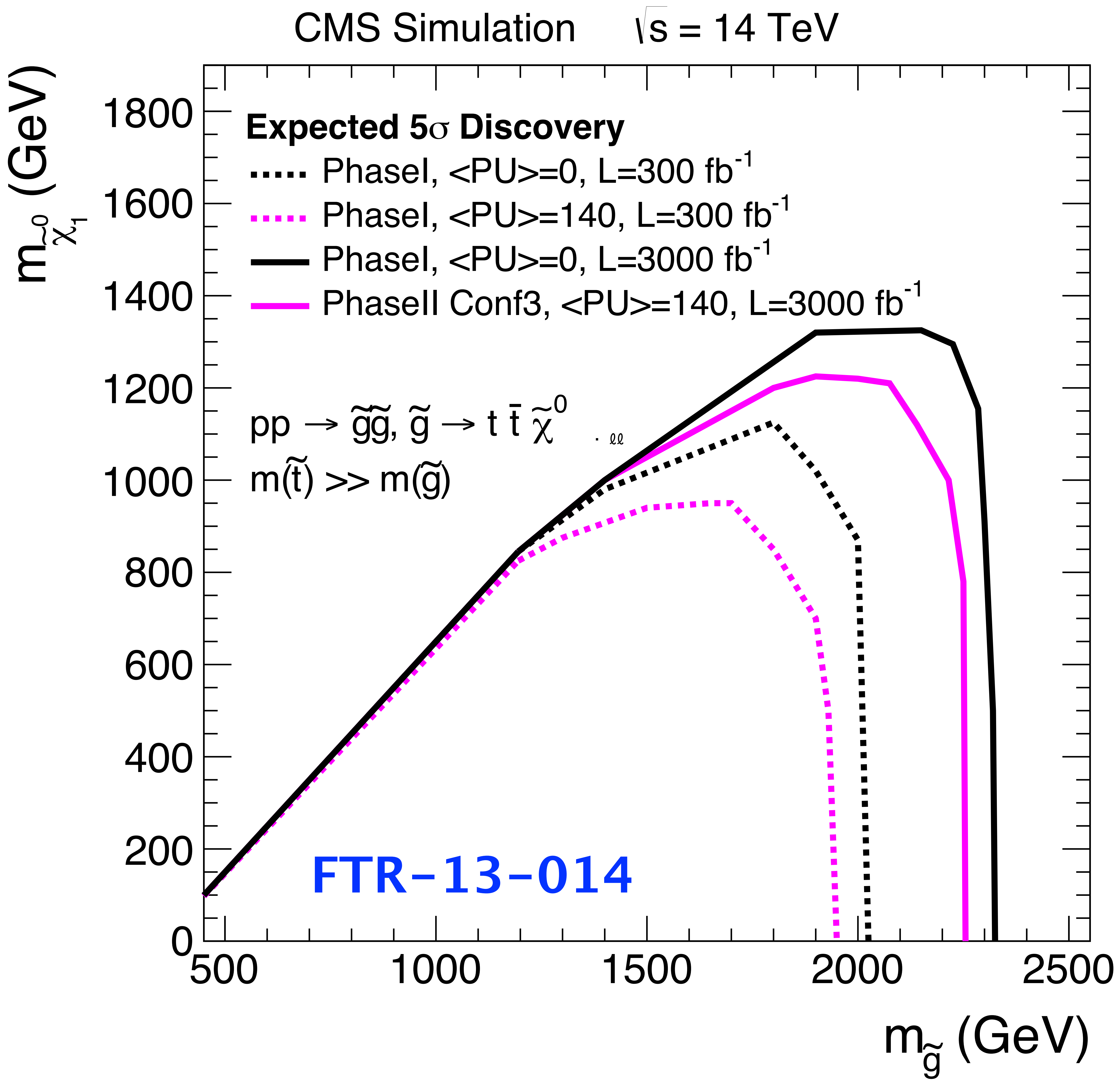
**Muon** system: new readout electronics, extend η coverage

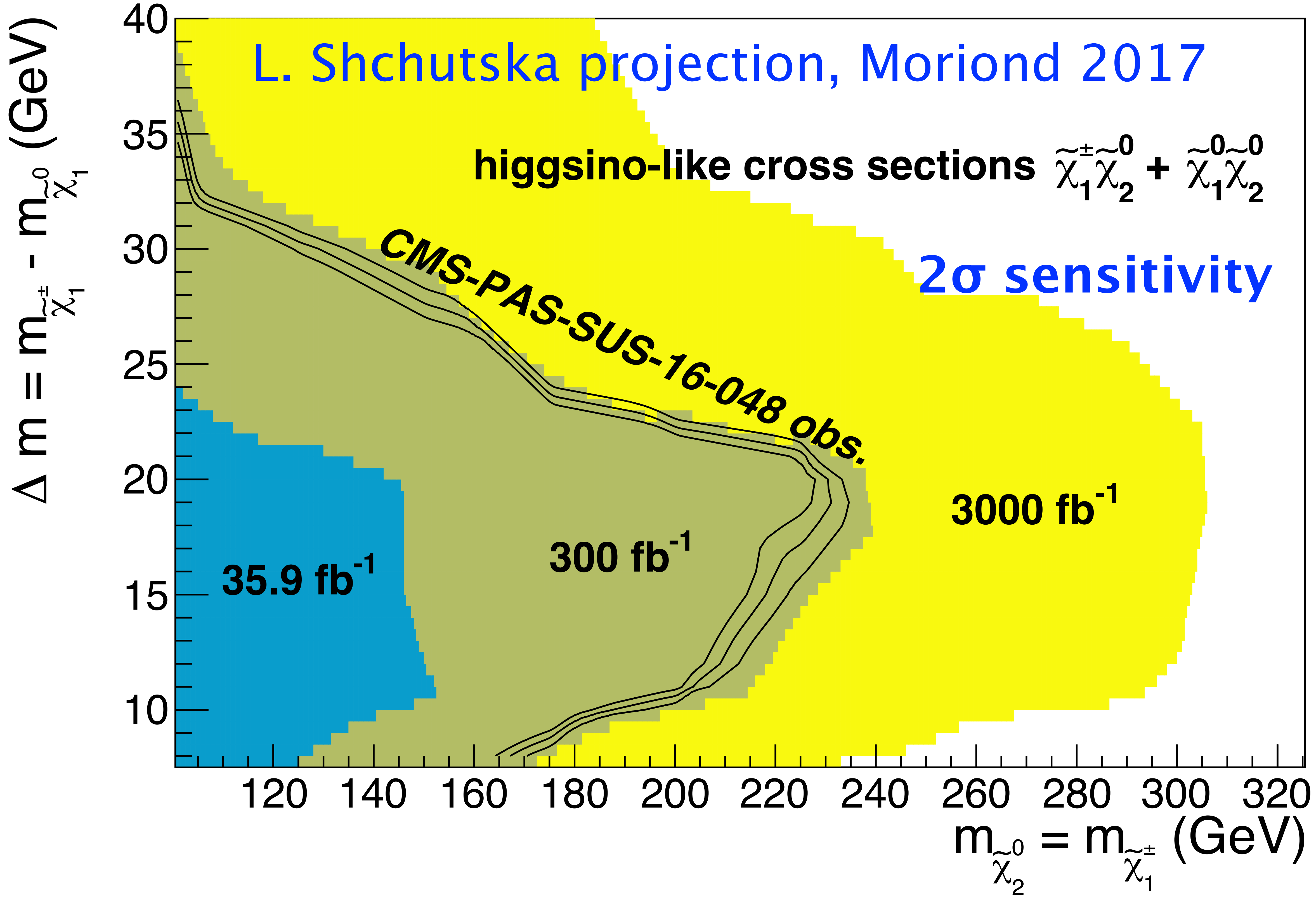
**New endcap calorimeters**
- high granularity
- ~30ps timing resolution

**Precision MIP timing**
- barrel / endcap layers
- measure MIP time with ~30ps resolution



# SUSY reach at HL-LHC

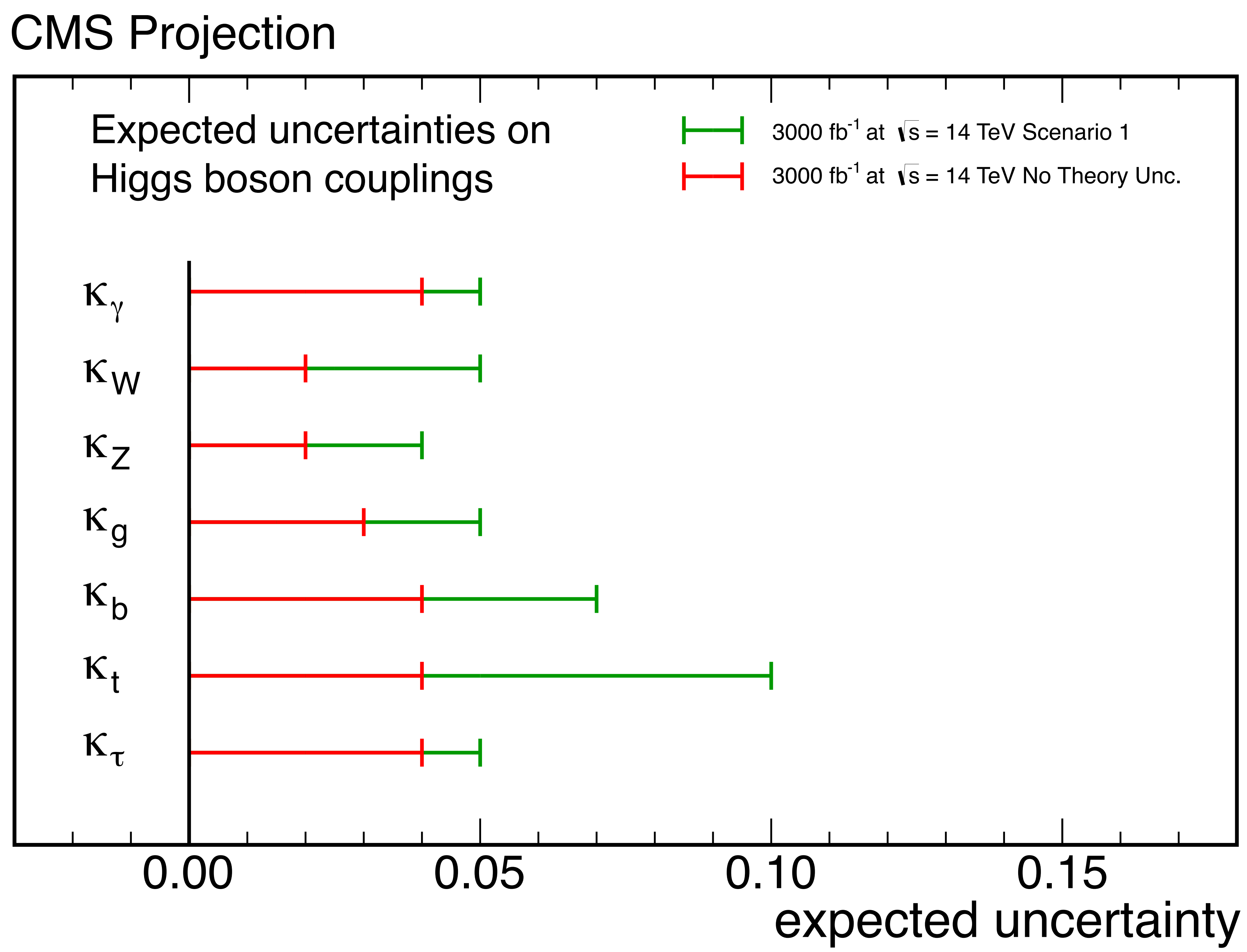



Higgsino reach 230 GeV
for small Δm.

# Higgs reach at HL-LHC

CMS NOTE-13-002
arXiv:1308.8361




In ATLAS+CMS HL-LHC combination

- 50% uncertainty and >2σ sensitivity for Higgs self-coupling in **pp → HH → bbγγ**.
- BR (**H → BSM**) < 7%.

- Relative precison on signal strengths (range for assumptions on uncertainties):

| $\int \mathcal{L}dt$ (fb$^{-1}$) | Higgs decay final state | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $\gamma\gamma$ | $WW^*$ | $ZZ^*$ | $b\bar{b}$ | $\tau\tau$ | $\mu\mu$ | $Z\gamma$ | BR$_{\rm inv}$ |
| 300 | 6 – 12% | 6 – 11% | 7 – 11% | 11 – 14% | 8 – 14% | 40 – 42% | 62 – 62% | < 17 – 28% |
| 3000 | 4 – 8% | 4 – 7% | 4 – 7% | 5 – 7% | 5 – 8% | 14 – 20% | 20 – 24% | < 6 – 17% |

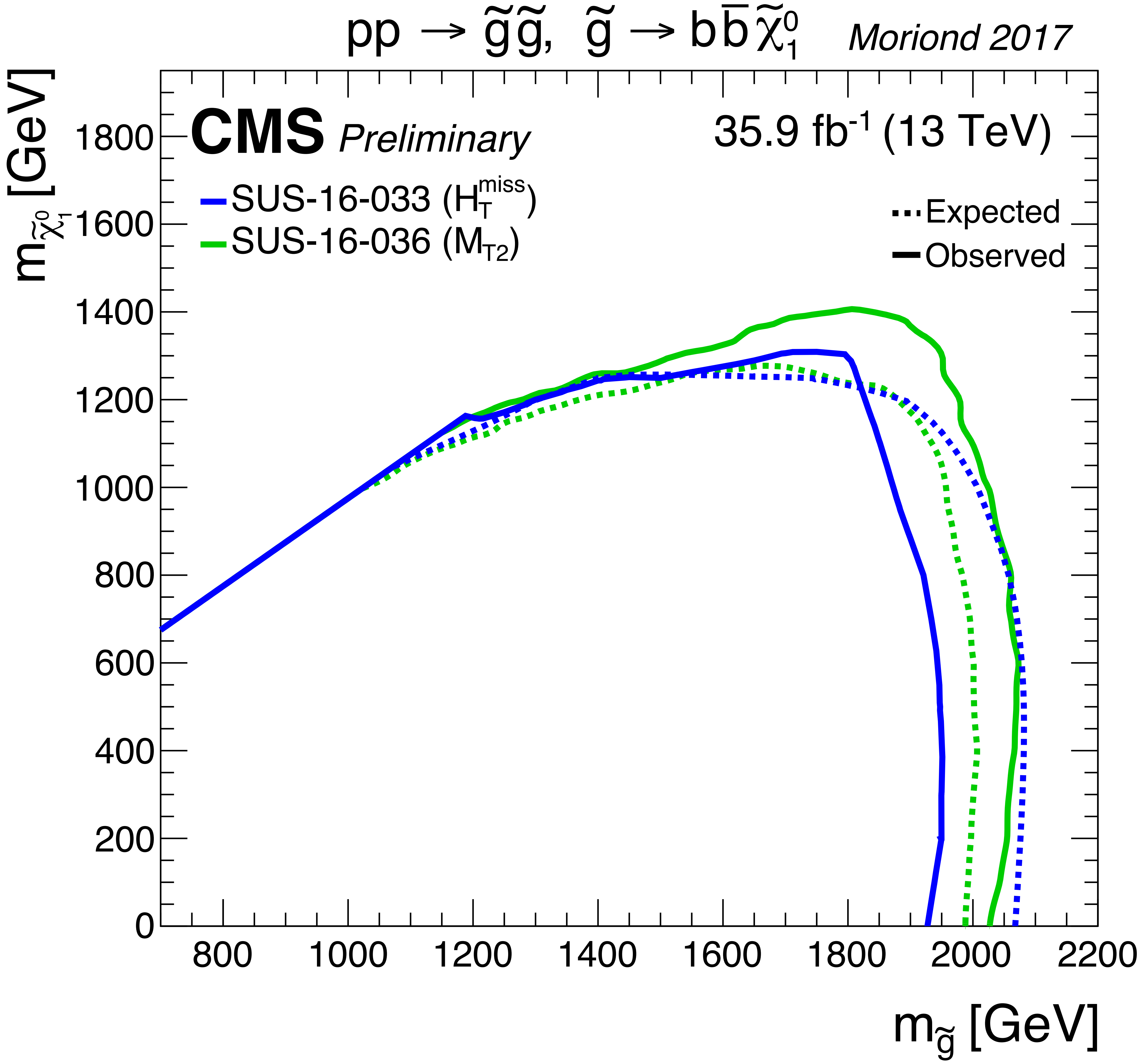
# Summary

- We continue to sail west.
- No land in sight, but perhaps just over the horizon?

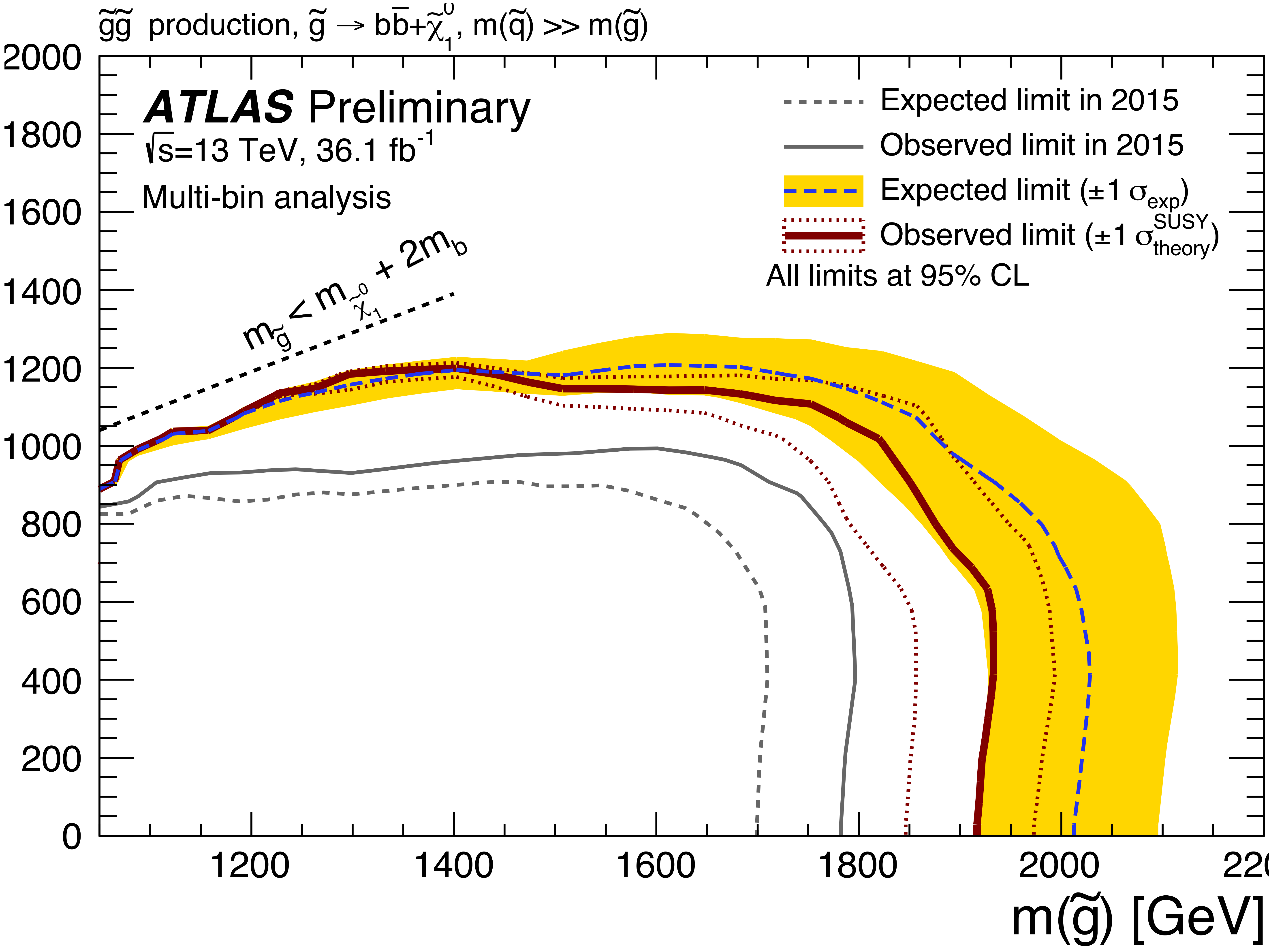
- We continue to unearth the $H^0$.
- Learned much already, but require HL-LHC to fully excavate the $H^0$.

# Additional Material

# ATLAS vs CMS



pp → g̃g̃, g̃ → bb̄χ̃⁰₁ Moriond 2017
CMS Preliminary
35.9 fb-1 (13 TeV)
SUS-16-033 (HTmiss)
SUS-16-036 (MT2)
Expected
Observed
m_χ̃⁰₁ [GeV]
m_g̃ [GeV]

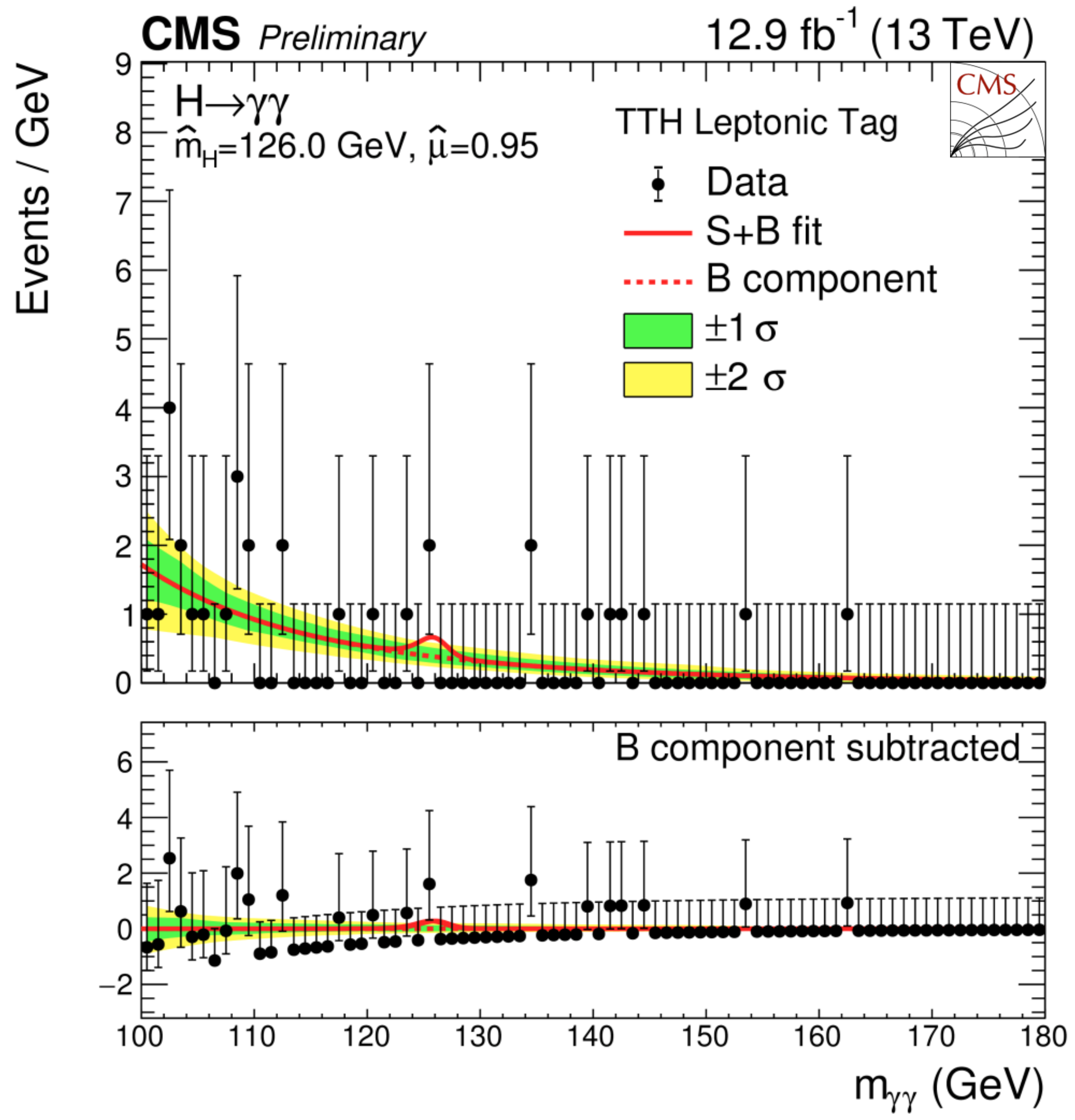
g̃g̃ production, g̃ → bb̄+χ̃⁰₁, m(q̃) >> m(g̃)
ATLAS Preliminary
√s=13 TeV, 36.1 fb-1
Multi-bin analysis
m_g̃ < m_χ̃⁰₁ + 2m_b
Expected limit in 2015
Observed limit in 2015
Expected limit (±1 σexp)
Observed limit (±1 σtheorySUSY)
All limits at 95% CL
m(g̃) [GeV]

# ATLAS vs CMS

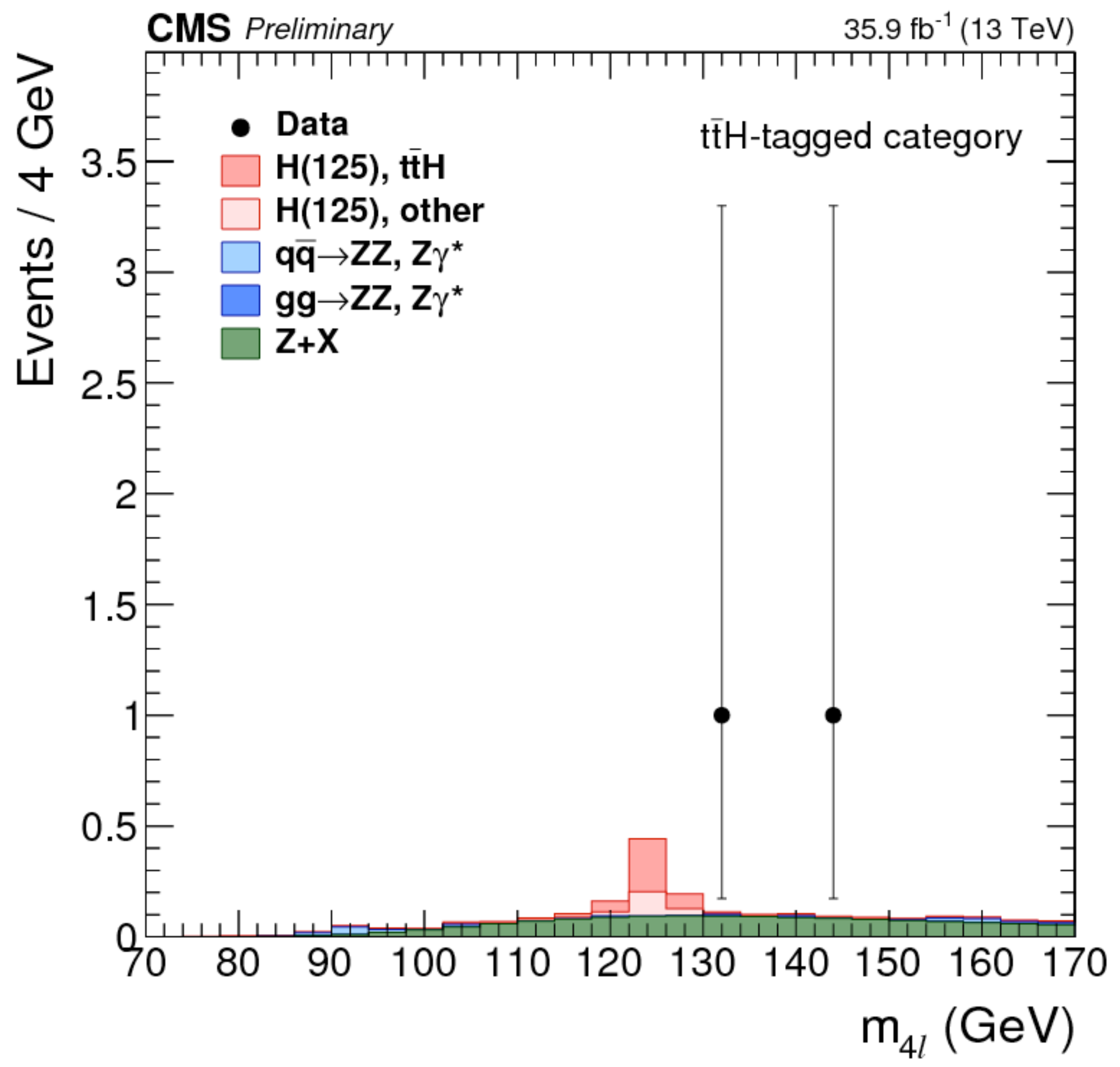
pp → g̃g̃, g̃ → tt̄ χ̃⁰₁ Moriond 2017
CMS Preliminary
35.9 fb-1 (13 TeV)
SUS-16-033, 0-lep (H_T^miss)
SUS-16-036, 0-lep (M_T2)
SUS-16-037, 1-lep (M_J)
SUS-16-042, 1-lep (Δφ)
SUS-16-035, ≥2-lep (SS)
SUS-16-041, ≥3-lep
Expected
Observed
m_χ̃⁰₁ [GeV]
m_g̃ [GeV]
g̃g̃ production, g̃ → tt̄+χ̃⁰₁, m(q̃) >> m(g̃)
ATLAS Preliminary
√s=13 TeV, 36.1 fb-1
Multi-bin analysis
Expected limit in 2015
Observed limit in 2015
Expected limit (±1 σ_exp)
Observed limit (±1 σ_theory^SUSY)
All limits at 95% CL
m_g̃ < m_χ̃⁰₁ + 2m_t
m(g̃) [GeV]

# ttH with H➔γγ and H➔4ℓ

HIG-16-020



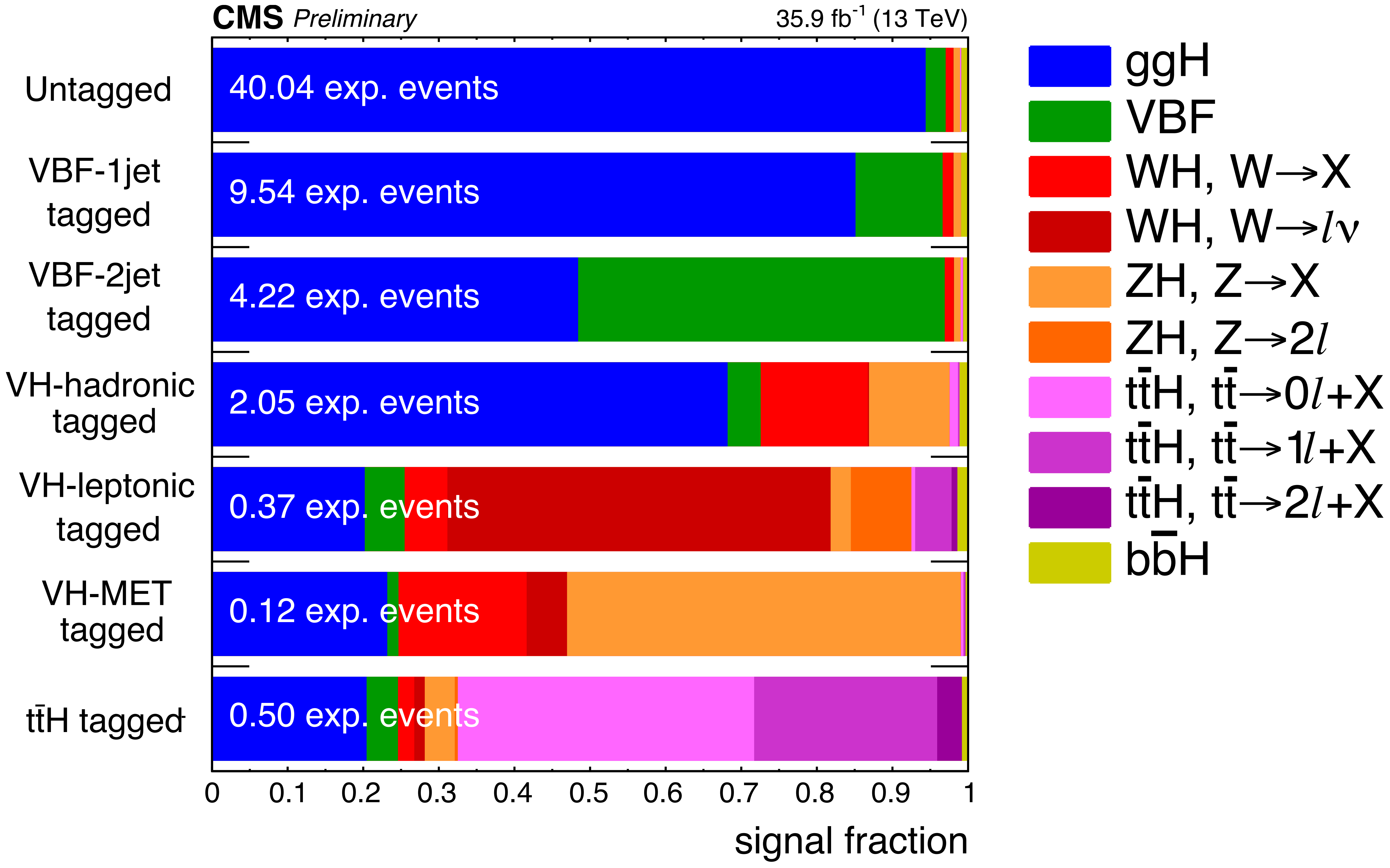

HIG-16-041




| | Signal exp. | Bkg exp. | Observed | μ | σ |
|---|---|---|---|---|---|
| H➔γγ | 1.1 | 2.7 | few | 1.9 | +1.5 -1.2 |
| H➔4ℓ | 0.5 | 0.3 | 0 | 0 | +1.2 -0.0 |

# H ➔ 4ℓ categories

- **VBF-2jet-tagged category** requires exactly 4 leptons. In addition there must be either 2 or 3 jets of which at most 1 is b-tagged, or at least 4 jets and no b-tagged jets. Finally, $\mathcal{D}_{\rm 2jet} > 0.5$ is required.
- **VH-hadronic-tagged category** requires exactly 4 leptons. In addition there must be 2 or 3 jets, or at least 4 jets and no b-tagged jets. Finally, $\mathcal{D}_{\rm VH} \equiv \max(\mathcal{D}_{\rm ZH}, \mathcal{D}_{\rm WH}) > 0.5$ is required.
- **VH-leptonic-tagged category** requires no more than 3 jets and no b-tagged jets in the event, and exactly 1 additional lepton or 1 additional pair of opposite sign same flavor leptons. This category also includes events with no jets and at least 1 additional lepton.
- **ttH-tagged category** requires at least 4 jets of which at least 1 is b-tagged, or at least 1 additional lepton.
- **VH-MET-tagged category** requires exactly 4 leptons, no more than 1 jet and $E_T^{\rm miss}$ greater than 100 GeV.
- **VBF-1jet-tagged category** requires exactly 4 leptons, exactly 1 jet and $\mathcal{D}_{\rm 1jet} > 0.5$.
- **Untagged category** consists of the remaining events.



# H ➔ 4ℓ fiducial phase space

Table 4: Summary of requirements and selections used in the definition of the fiducial phase space for the $H \to 4\ell$ cross section measurements.

| **Requirements for the $H \to 4\ell$ fiducial phase space** | |
|---|---|
| Lepton kinematics and isolation | |
| Leading lepton $p_T$ | $p_T > 20$ GeV |
| Next-to-leading lepton $p_T$ | $p_T > 10$ GeV |
| Additional electrons (muons) $p_T$ | $p_T > 7(5)$ GeV |
| Pseudorapidity of electrons (muons) | $\|\eta\| < 2.5(2.4)$ |
| Sum of scalar $p_T$ of all stable particles within $\Delta R < 0.3$ from lepton | $< 0.35 \cdot p_T$ |
| Event topology | |
| Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above | |
| Inv. mass of the $Z_1$ candidate | $40\,\text{GeV} < m_{Z_1} < 120\,\text{GeV}$ |
| Inv. mass of the $Z_2$ candidate | $12\,\text{GeV} < m_{Z_2} < 120\,\text{GeV}$ |
| Distance between selected four leptons | $\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$ |
| Inv. mass of any opposite sign lepton pair | $m_{\ell^+\ell'^-} > 4\,\text{GeV}$ |
| Inv. mass of the selected four leptons | $105\,\text{GeV} < m_{4\ell} < 140\,\text{GeV}$ |

# Transverse mass

Volume 122B, number 1 PHYSICS LETTERS 24 February 1983

**EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s}$ = 540 GeV**

UA1 Collaboration, CERN, Geneva, Switzerland

*10. Comparison between events and expectations from W decays.* The simultaneous presence of an electron and (one) neutrino of approximately equal and opposite momenta in the transverse direction (fig. 8) suggests the presence of a two-body decay, $W \to e + \nu_e$. The main kinematical quantities of the events are given in table 3. A lower, model-independent bound to the W mass $m_W$ can be obtained from the transverse mass, $m_T^2 = 2p_T^{(e)}\, p_T^{(\nu)}\,(1 - \cos\phi_{\nu e})$, remarking that $m_W \geqslant m_T$ (fig. 9). We conclude that:

$$m_W > 73\ \mathrm{GeV}/c^2 \quad (90\%\ \text{confidence level})\ .$$

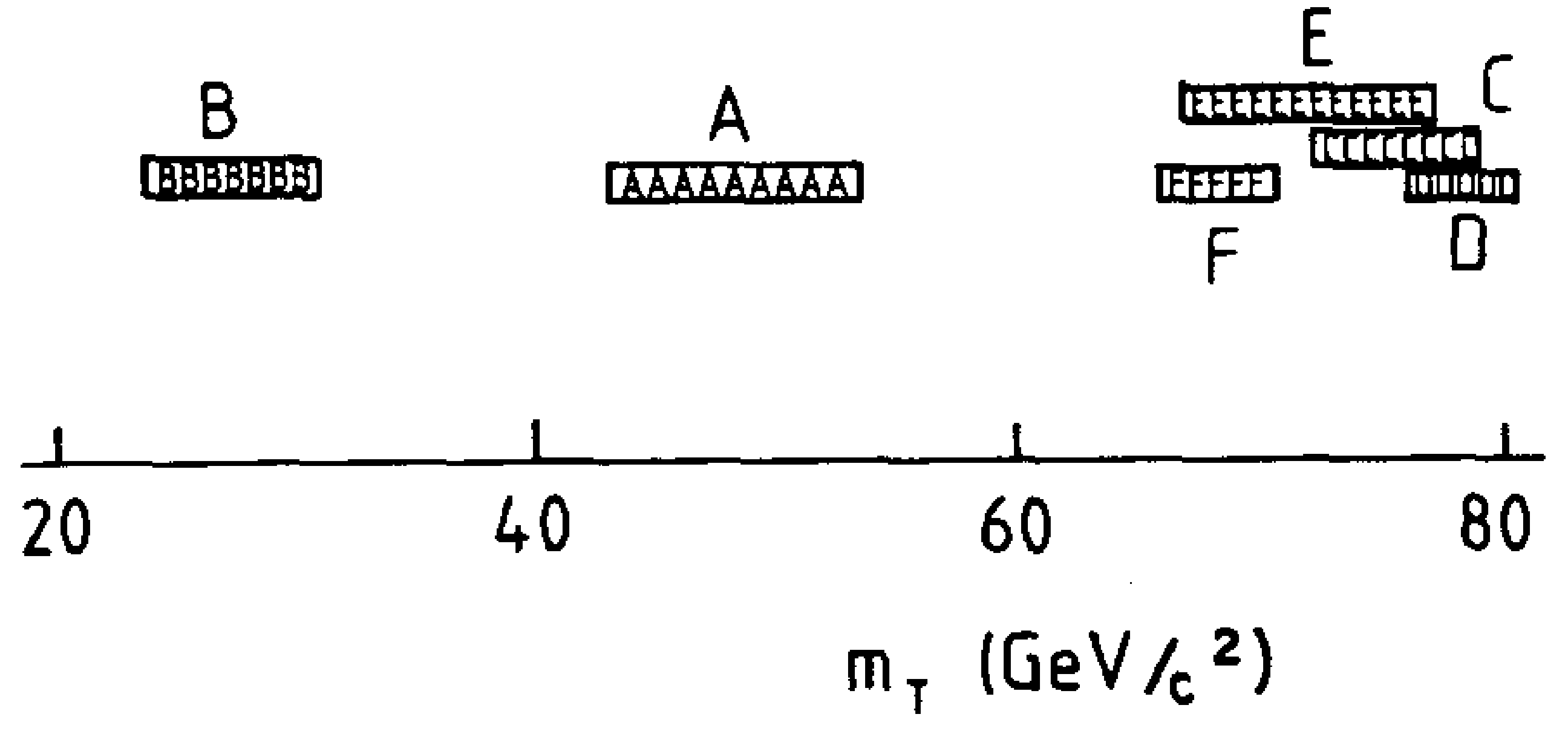
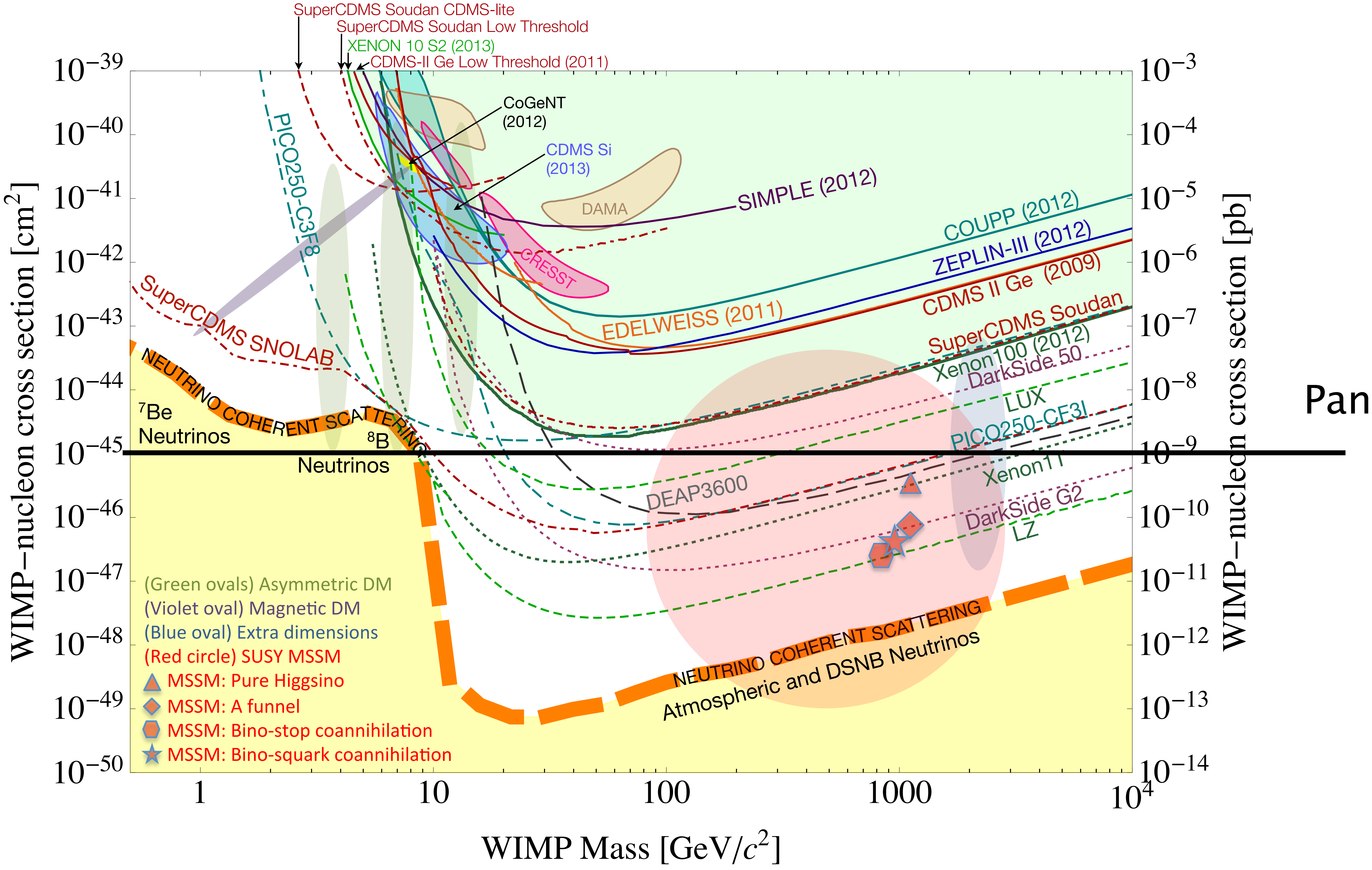



Fig. 9. The distribution of the transverse mass derived from the measured electron and neutrino vectors of the six electron events.

# Direct detection




Panda-X limit at 1 TeV

# H → BSM

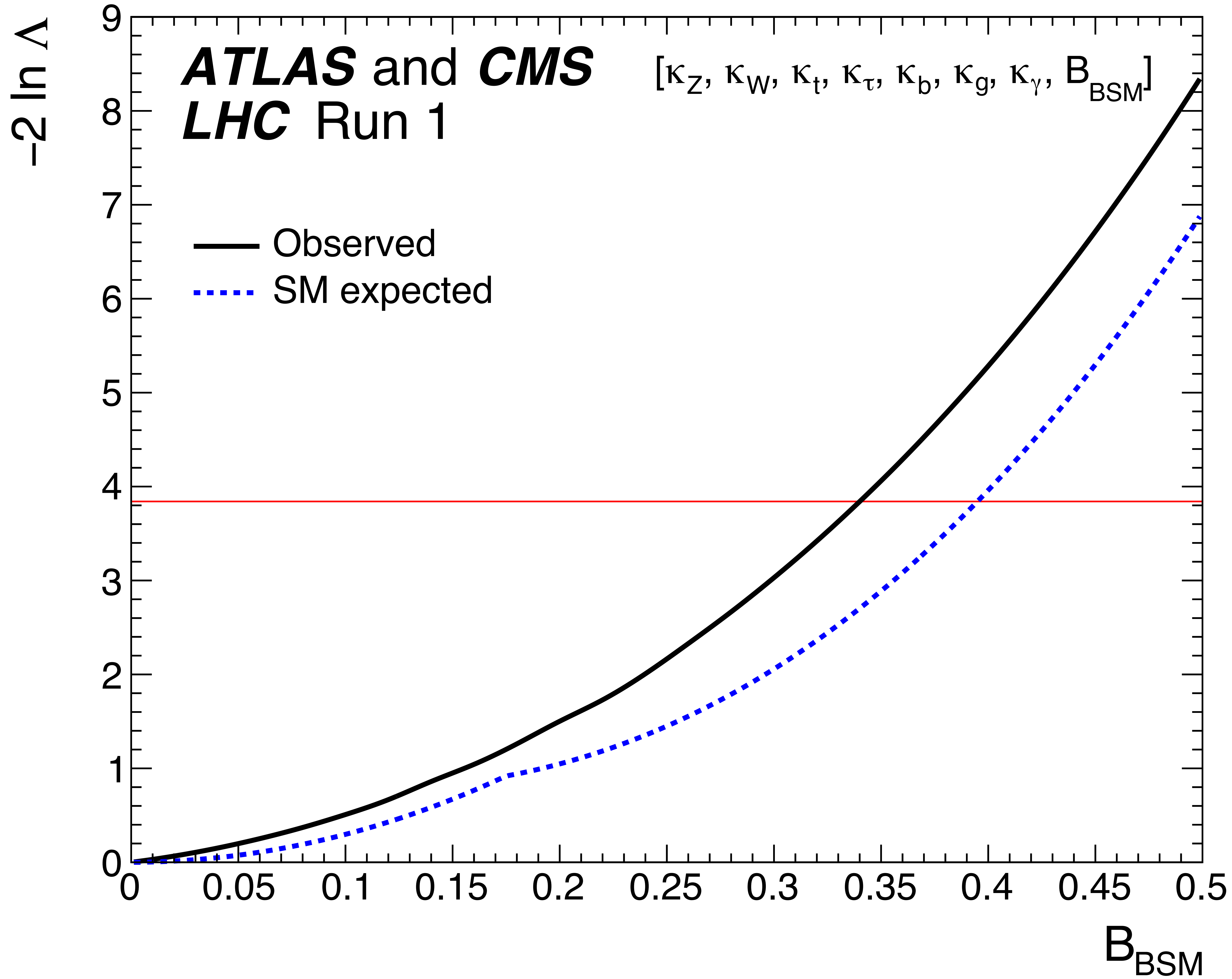
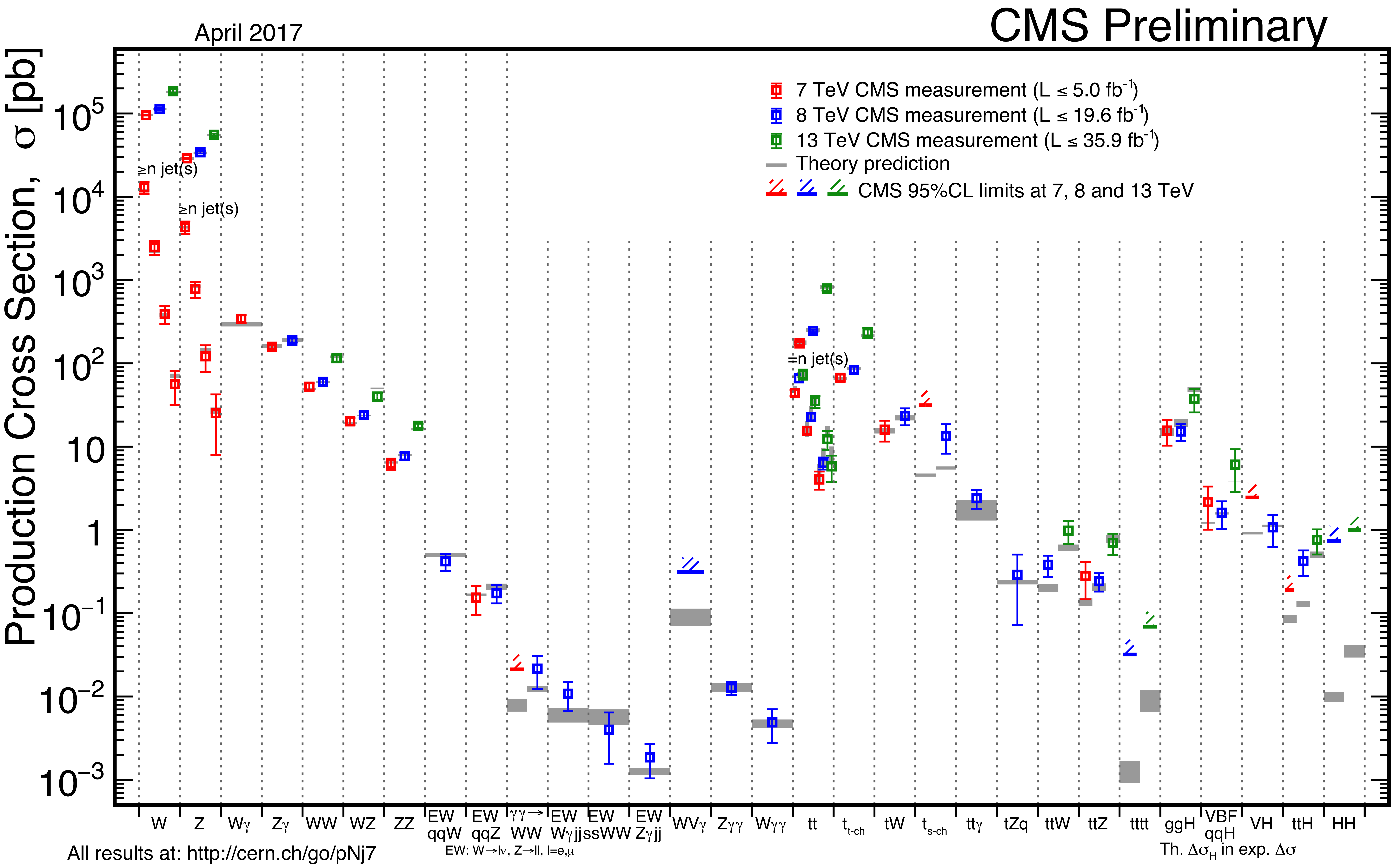


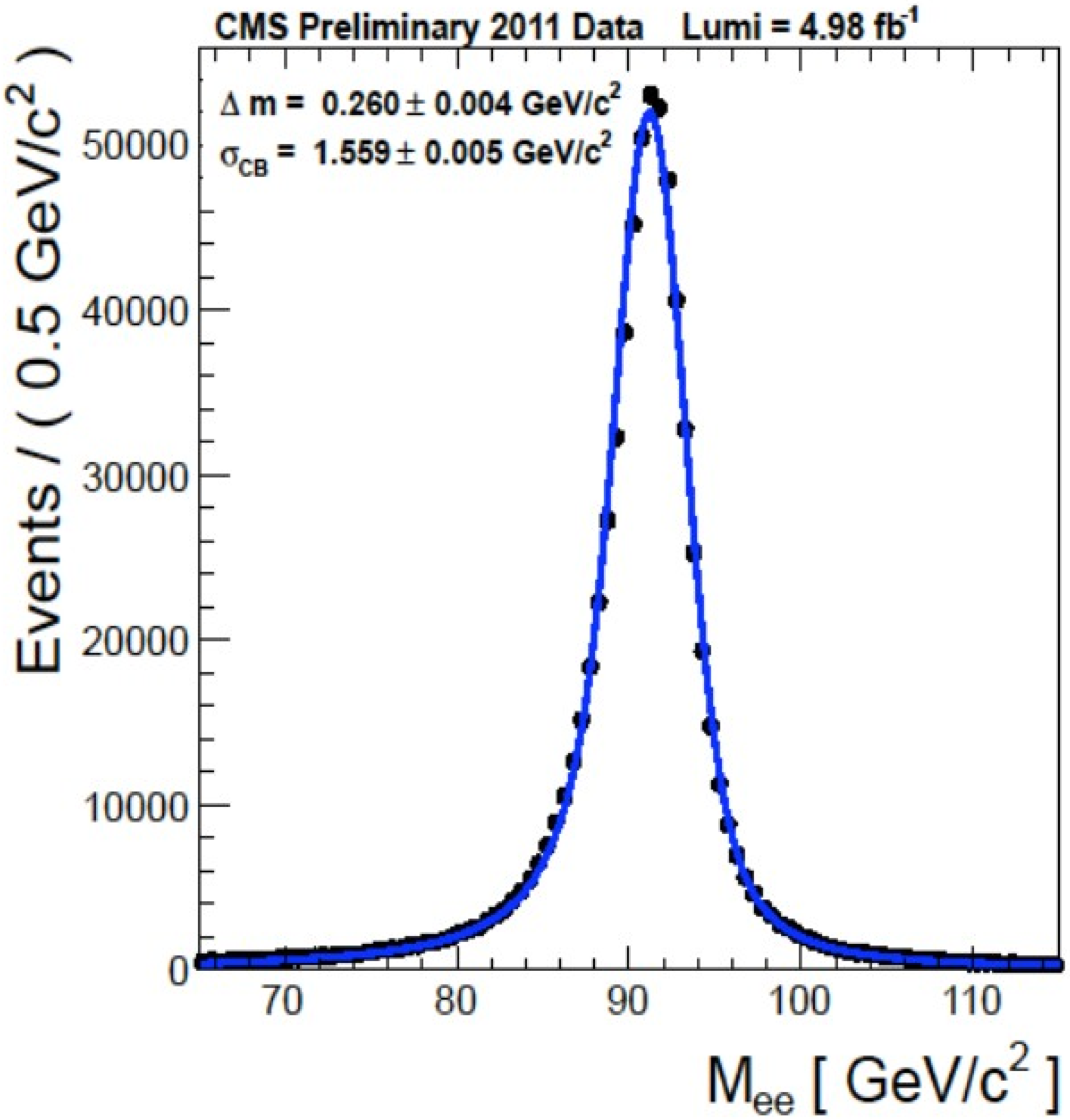

Figure 16: Observed (solid line) and expected (dashed line) negative log-likelihood scan of $B_{BSM}$, shown for the combination of ATLAS and CMS when allowing additional BSM contributions to the Higgs boson width. The results are shown for the parameterisation with the assumptions that $|\kappa_V| \leq 1$ and $B_{BSM} \geq 0$ in Fig. 15. All the other parameters of interest from the list in the legend are also varied in the minimisation procedure. The red horizontal line at 3.84 indicates the log-likelihood variation corresponding to the 95% CL upper limit, as discussed in Section 3.2.

# CMS Standard Model Results

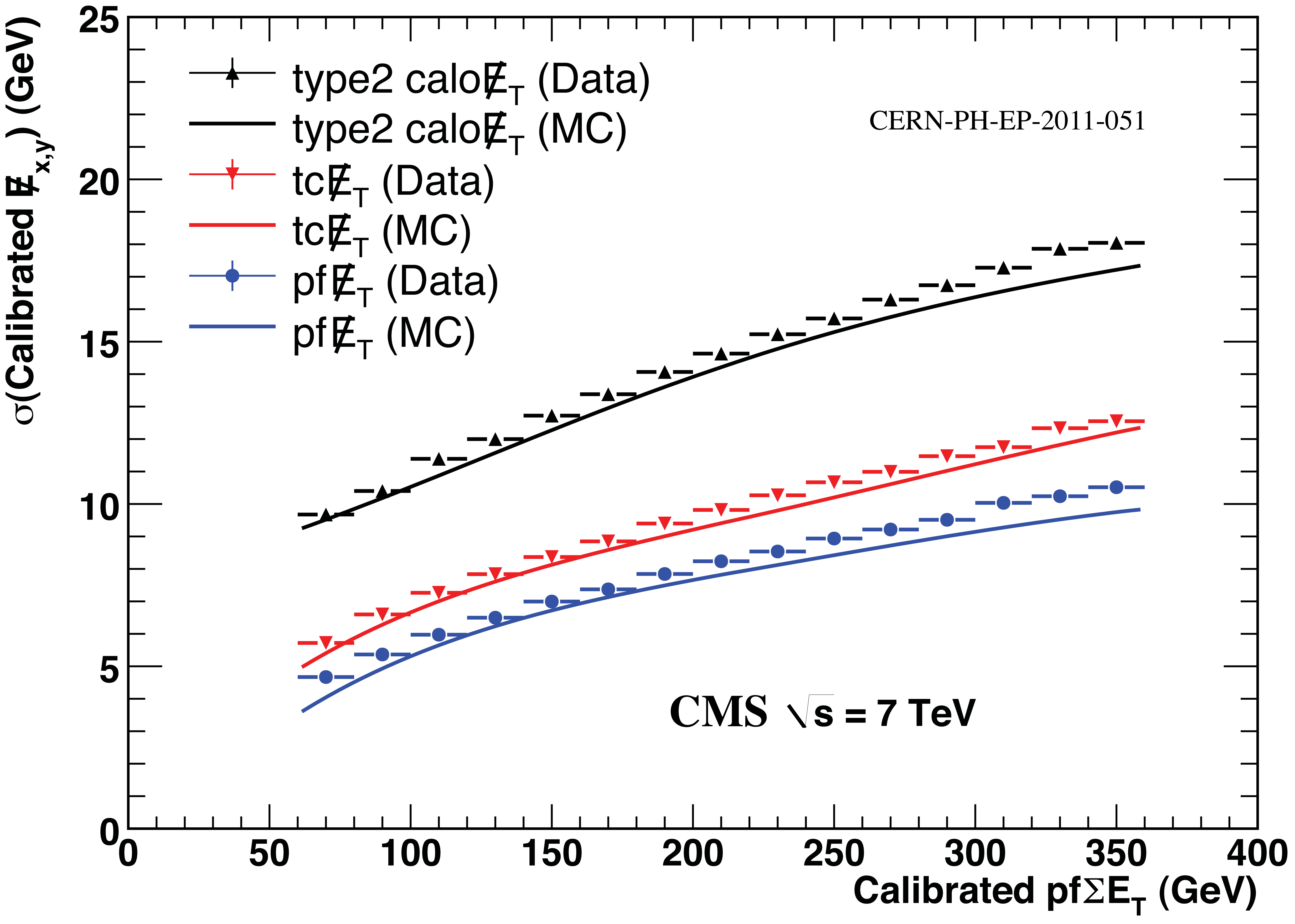


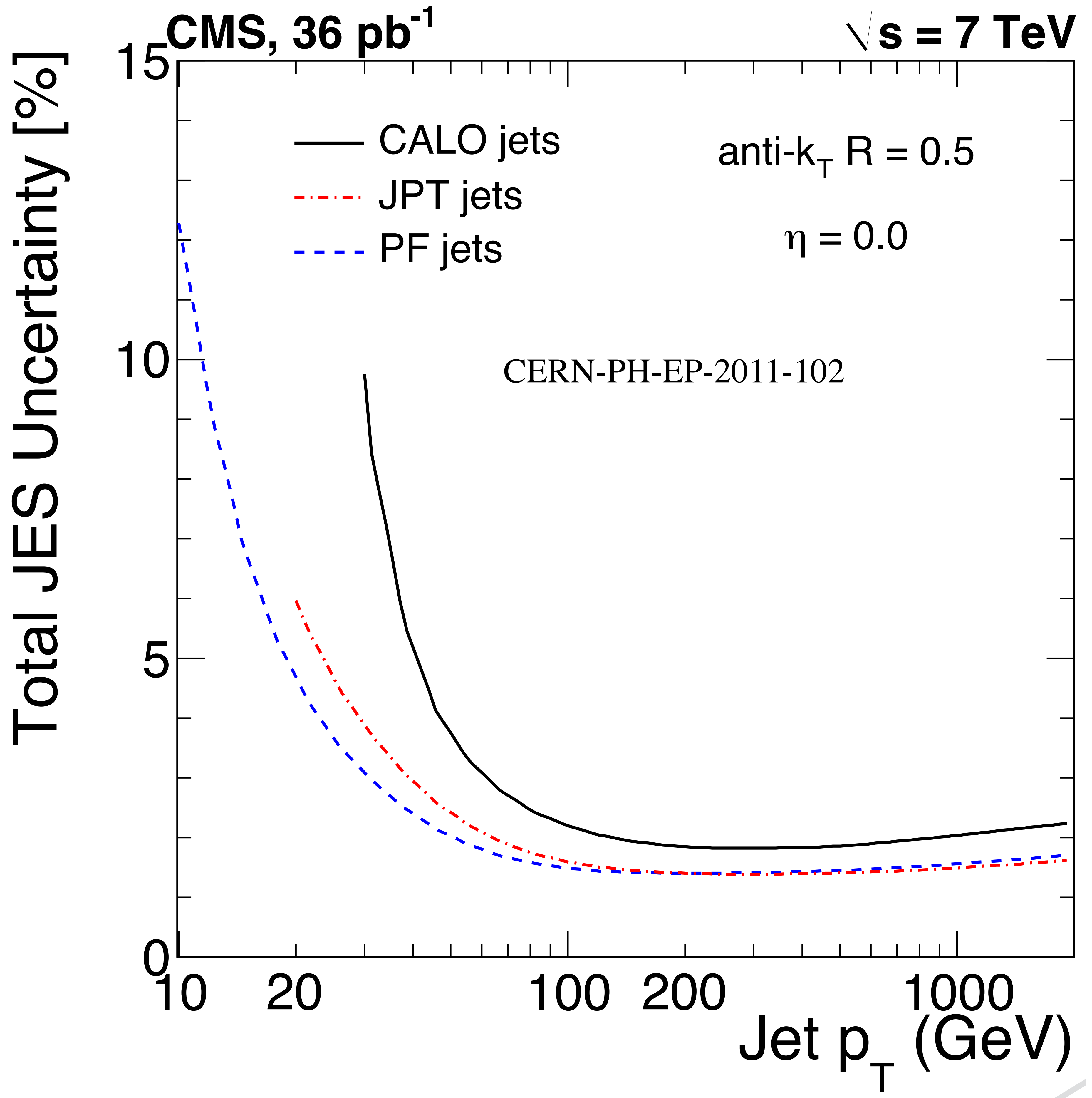
# ECAL performance

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{\approx 2.5\%}{\sqrt{E}}\right)^2 + \left(\frac{0.12}{E}\right)^2 + (0.3\%)^2$$



# Jets, MET, PFlow



# Muon performance