Physics exploration from the MeV to TeV scale: New results from the CMS experiment

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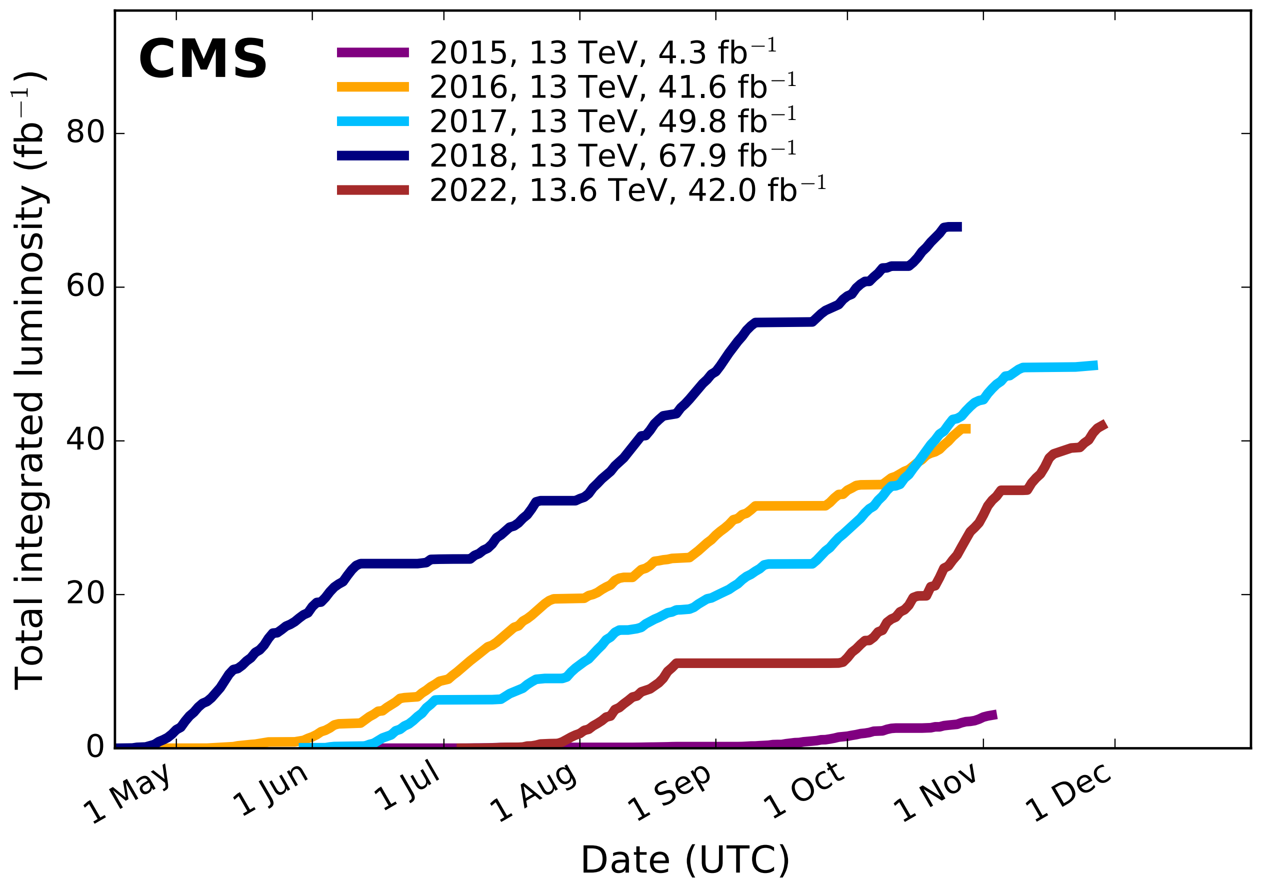
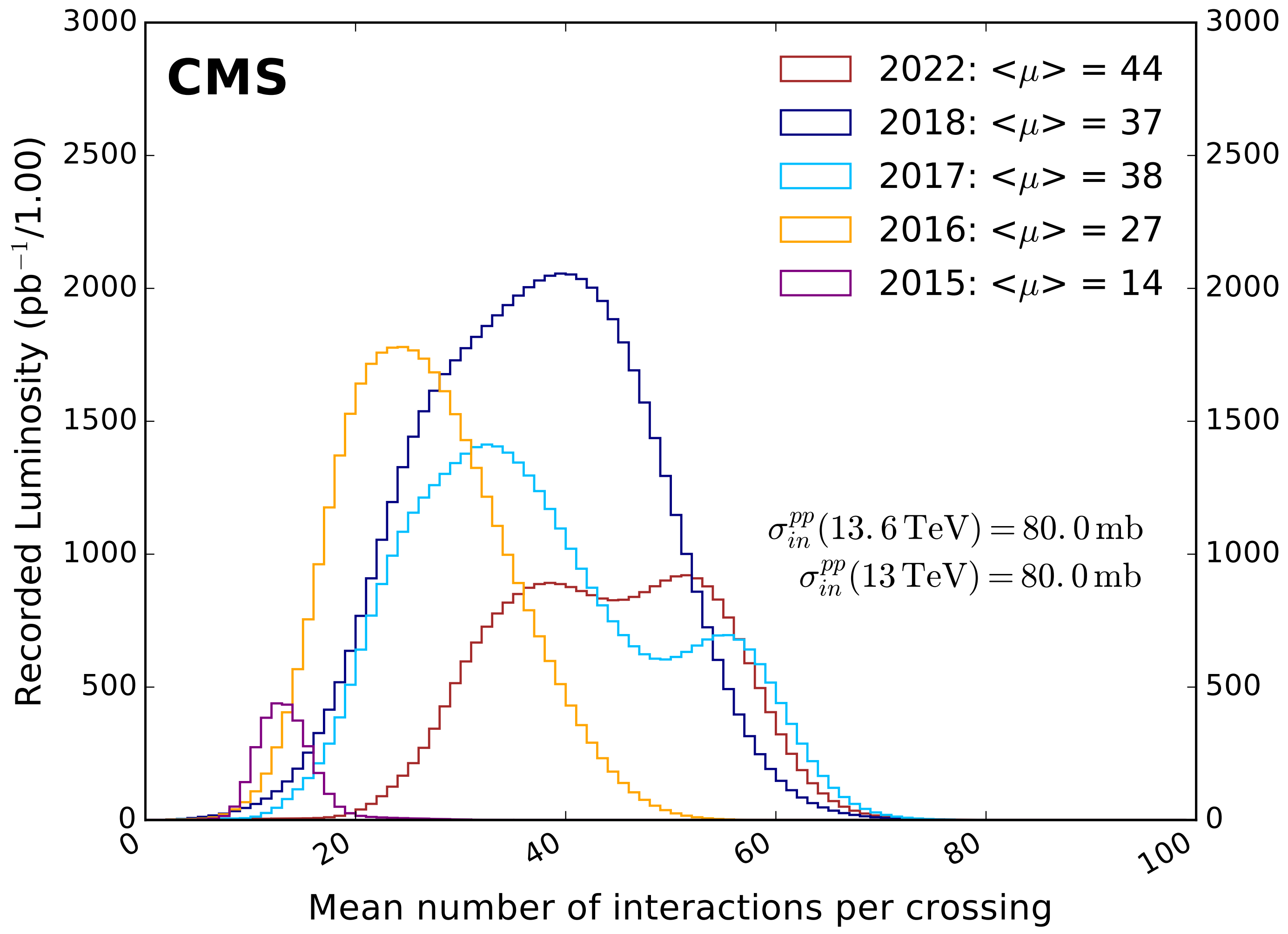
on behalf of the CMS experiment

Fermilab Wine & Cheese Seminar
2023/04/07

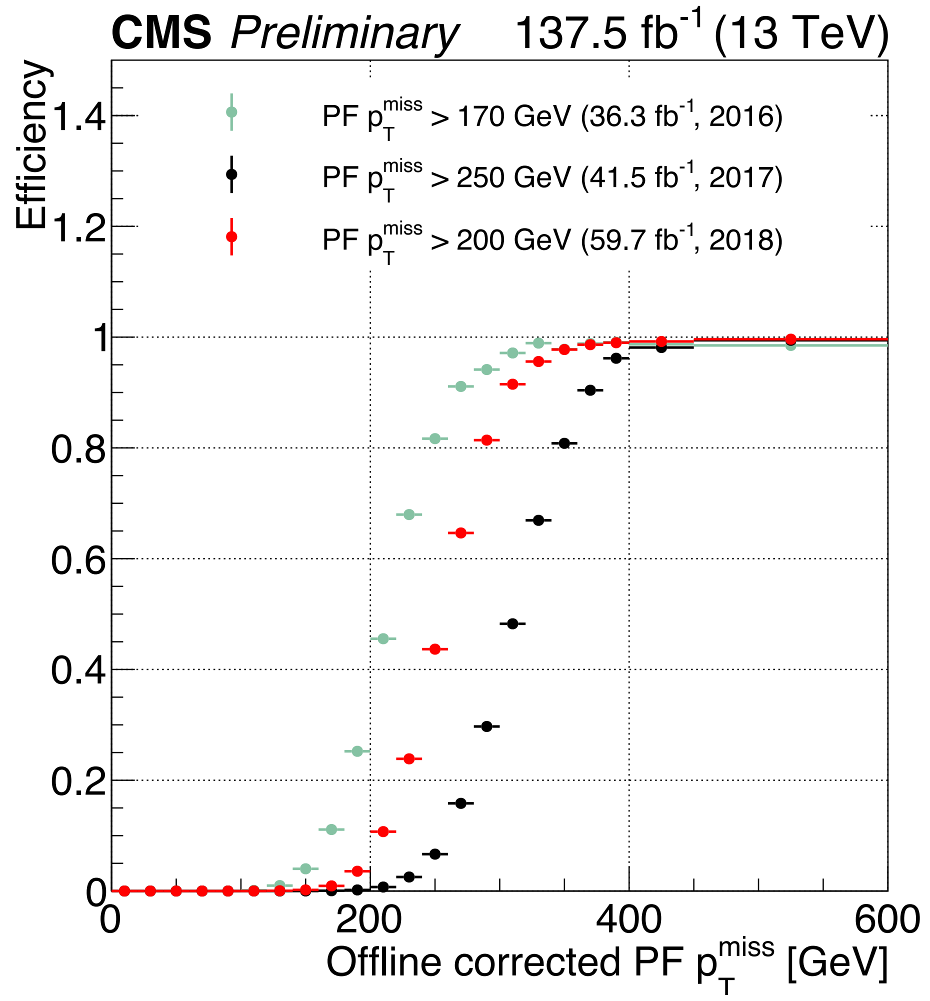
CMS data taking in Run 2 & 3

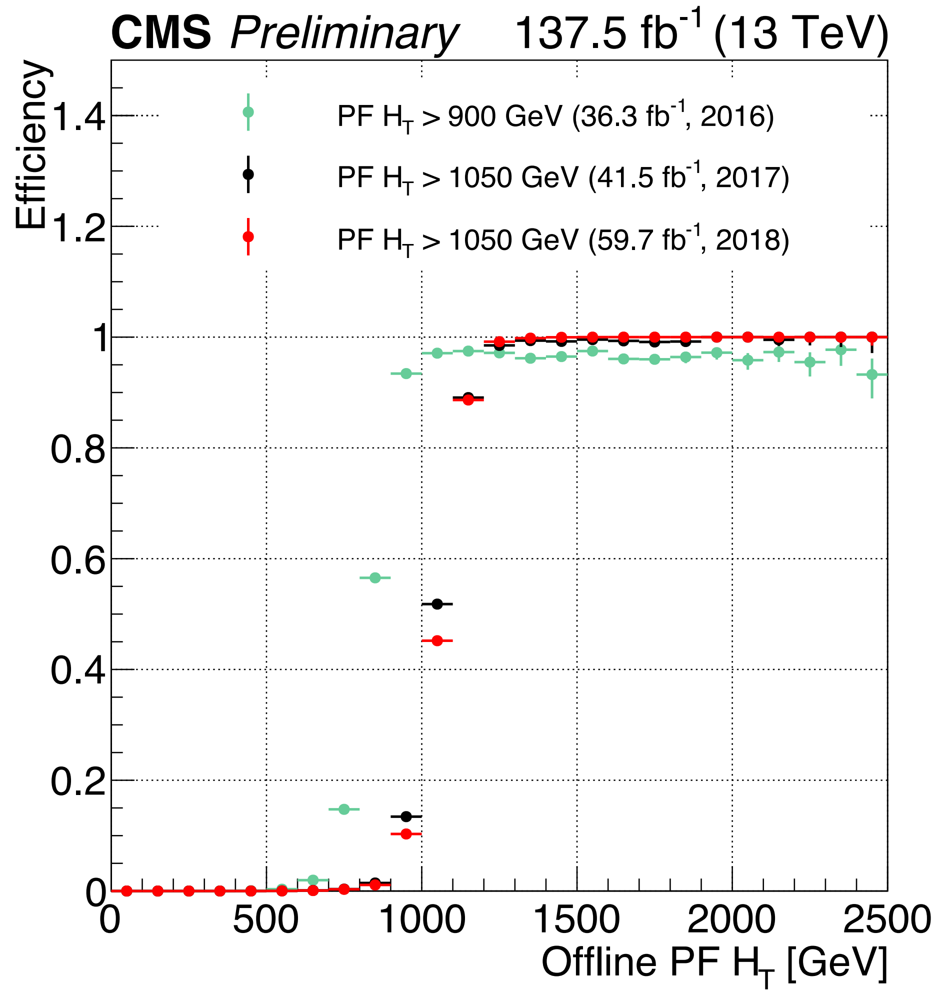
LHC delivers collisions

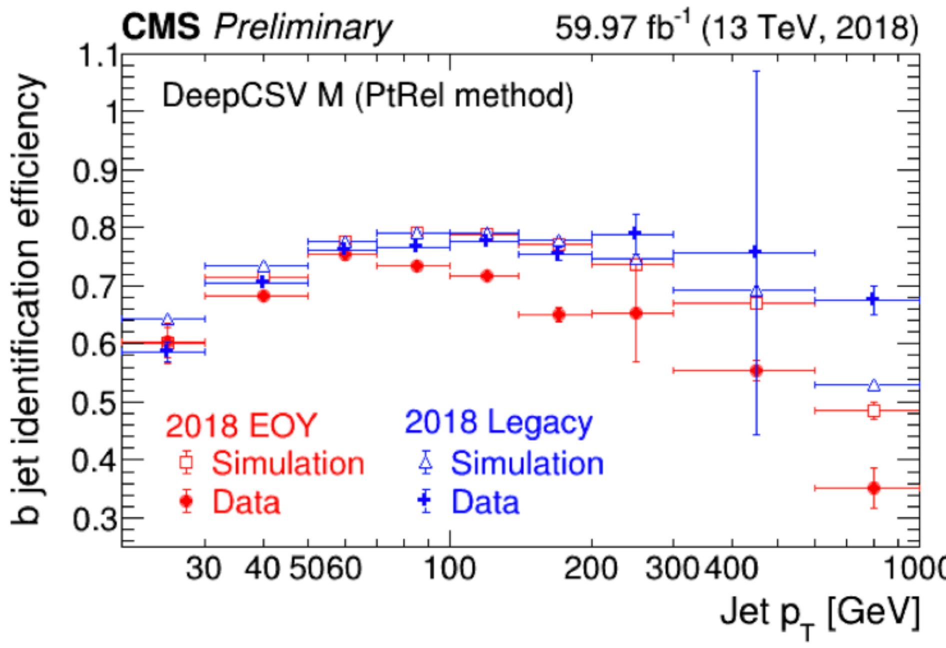


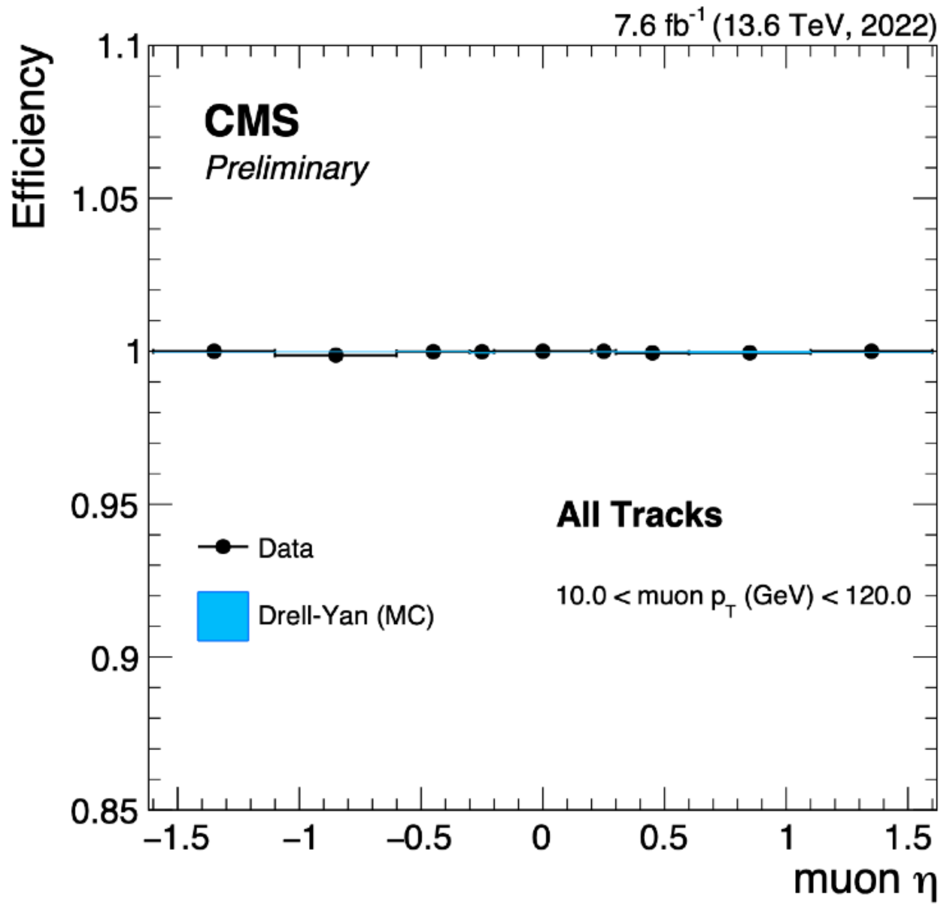


CMS detects collisions









Papers are published

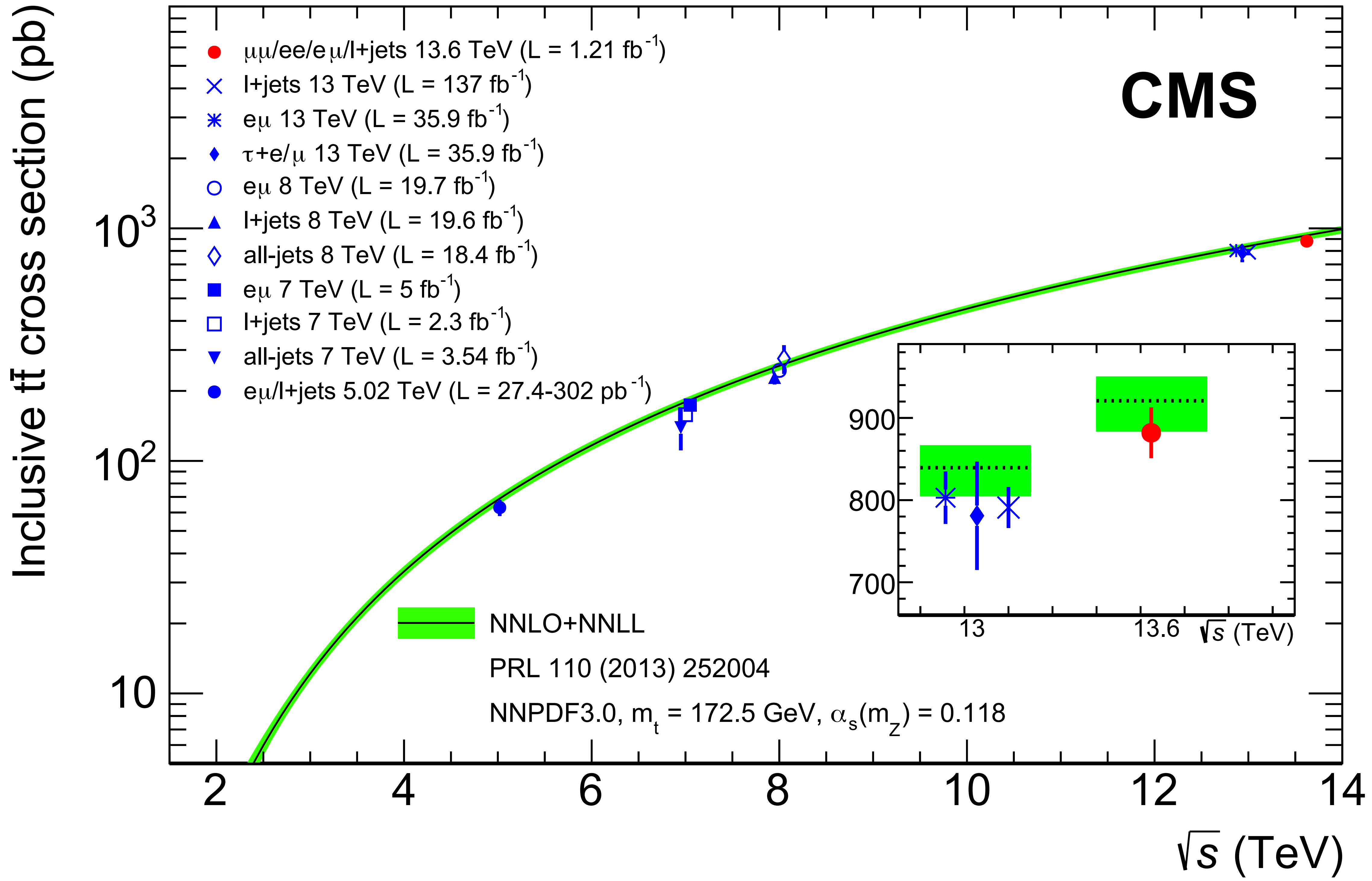
>1100 papers submitted using collision data

Including 1 with Run 3 data!

TOP-22-012

2022 data

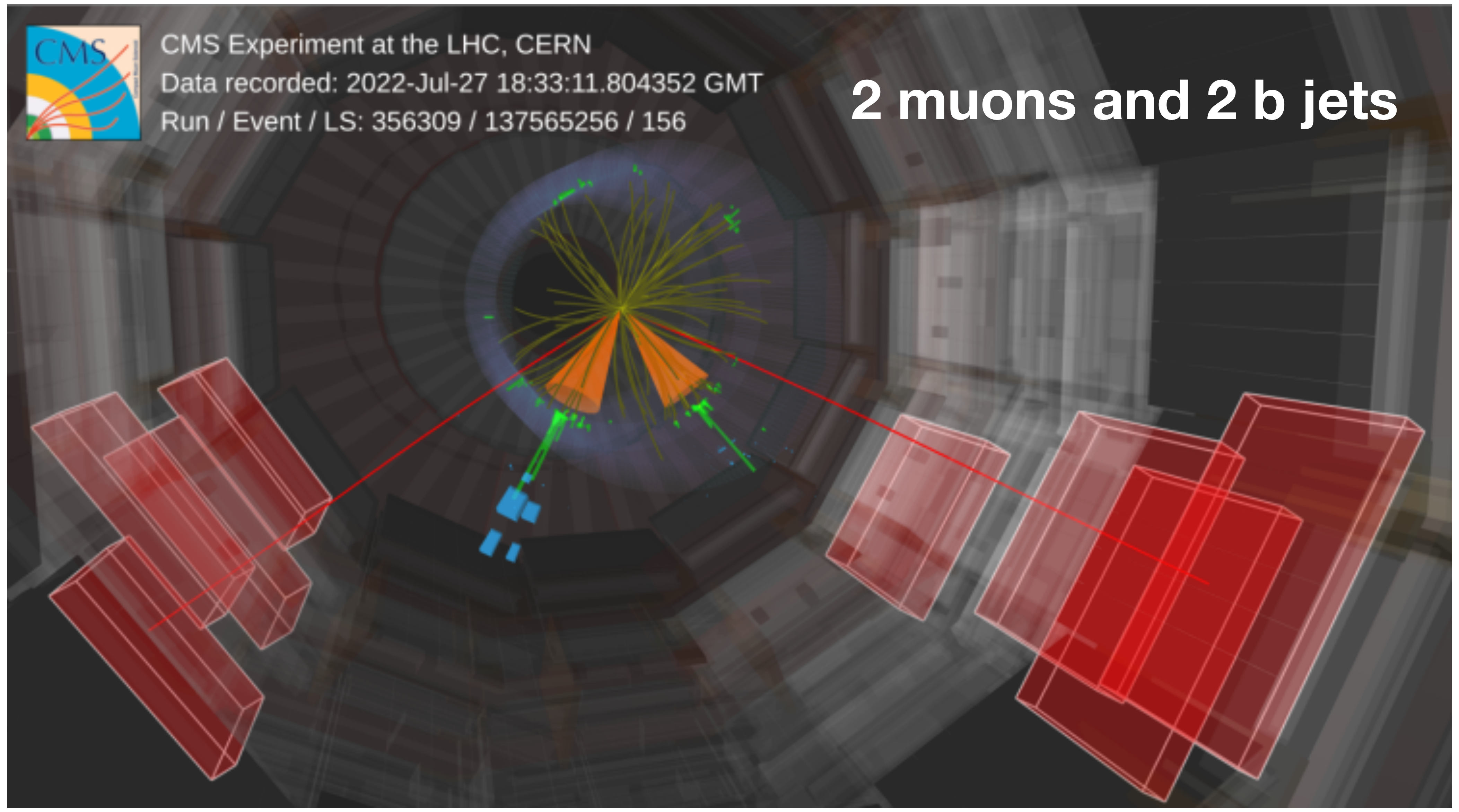
$t\bar{t}$ cross section at 13.6 TeV



First CMS result at 13.6 TeV data using 1.21 fb^{-1} of data taken from July 28 to August 3, 2022

- Uses events with 1 or 2 electrons or muons and additional jets
- Maximum likelihood fit to event yields in 11 categories based on lepton number/type, N_j and N_b

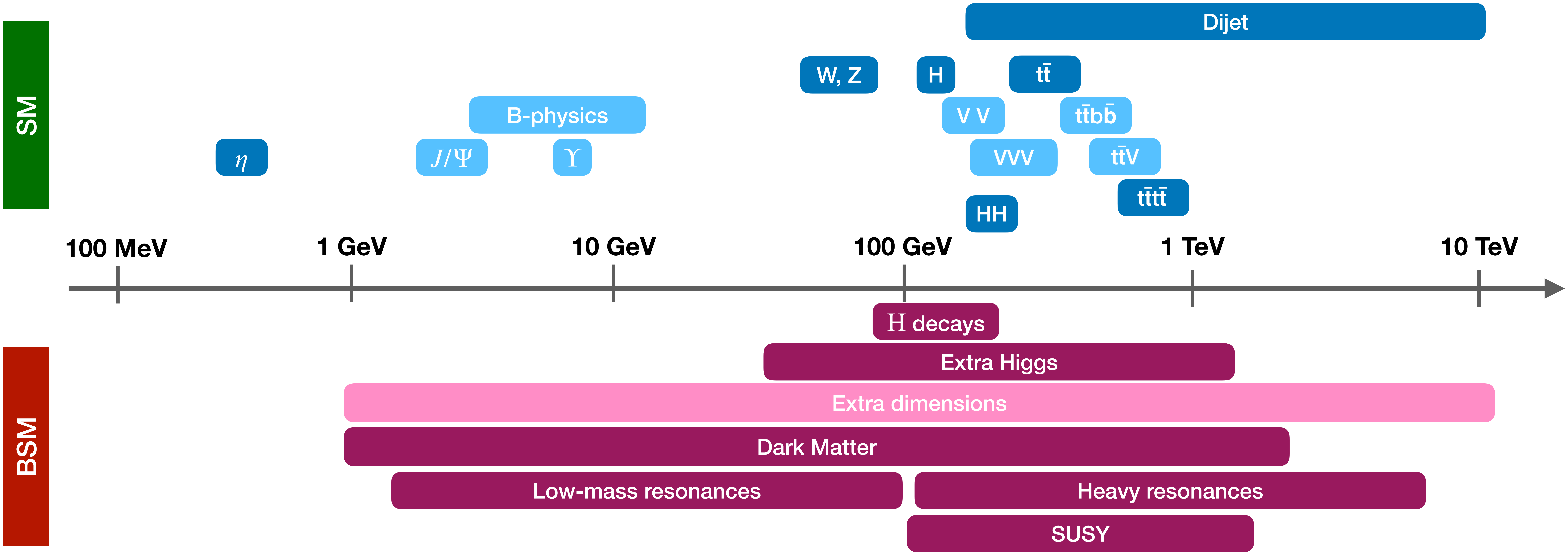
Source	Uncertainty (%)
Lepton ID efficiencies	1.6
Trigger efficiency	0.3
JES	0.7
b tagging efficiency	1.1
Pileup reweighting	0.5
ME scale, $t\bar{t}$	0.6
ME scale, backgrounds	0.1
ME/PS matching	0.1
PS scales	0.3
PDF and α_S	0.3
Single t background	1.0
Z+jets background	0.3
W+jets background	0.0
Diboson background	0.5
QCD multijet background	0.3
Statistical uncertainty	0.5
Combined uncertainty	2.6
Integrated luminosity	2.3



$$\sigma_{t\bar{t}} = 882 \pm 23\,(\mathrm{stat+syst}) \pm 20\,(\mathrm{lumi})\,\mathrm{pb}$$

Measurement agrees with the Standard Model prediction of $\sigma_{t\bar{t}}^{\mathrm{SM}} = 921^{+29}_{-37}\,\mathrm{pb}$

CMS Run 2 legacy: from MeV to TeV scale

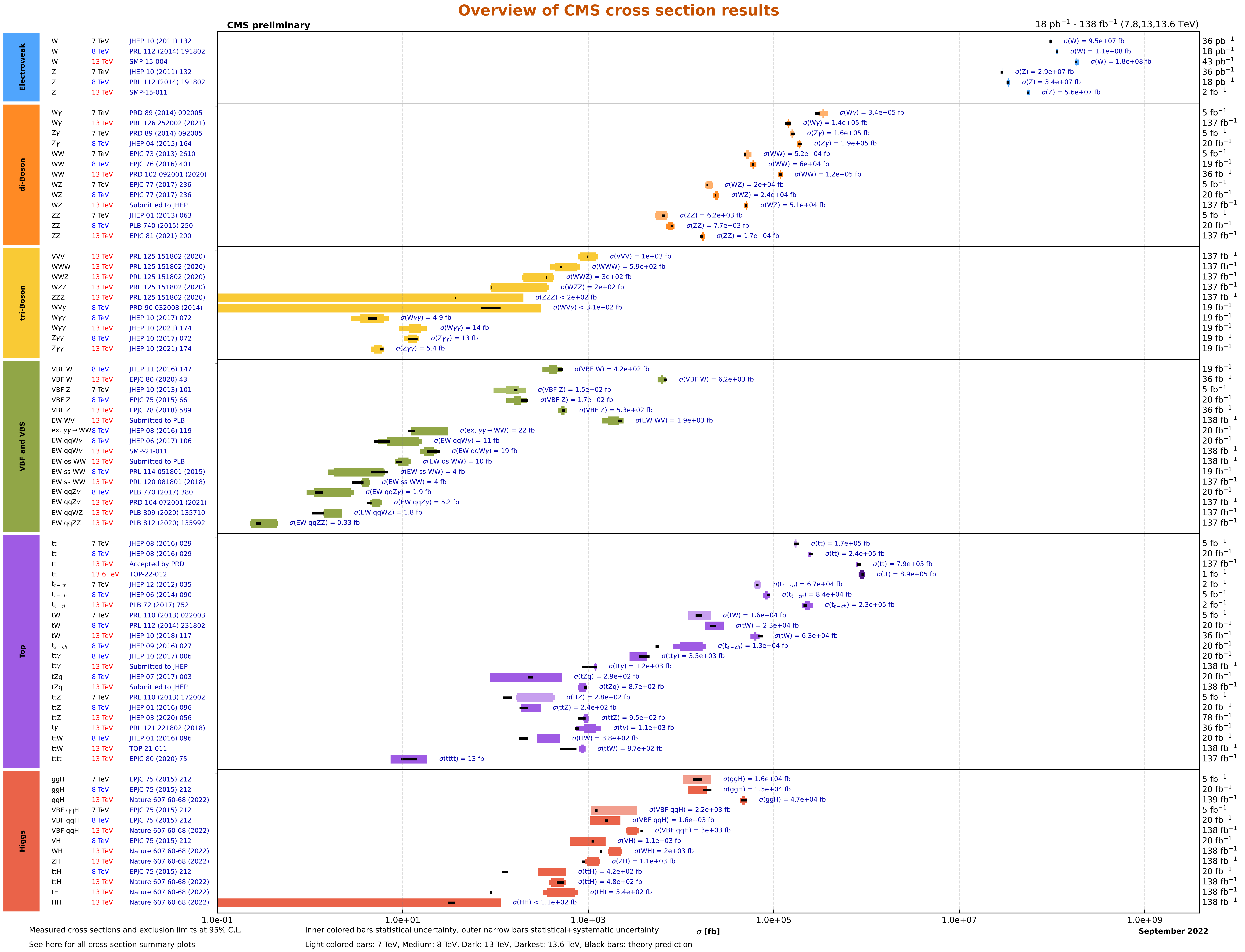


Over 4 orders of magnitude in mass!

Note: not covering heavy ion results today

9 orders of magnitude in cross section!

not including multijet…



BPH-22-003

2017+2018 data

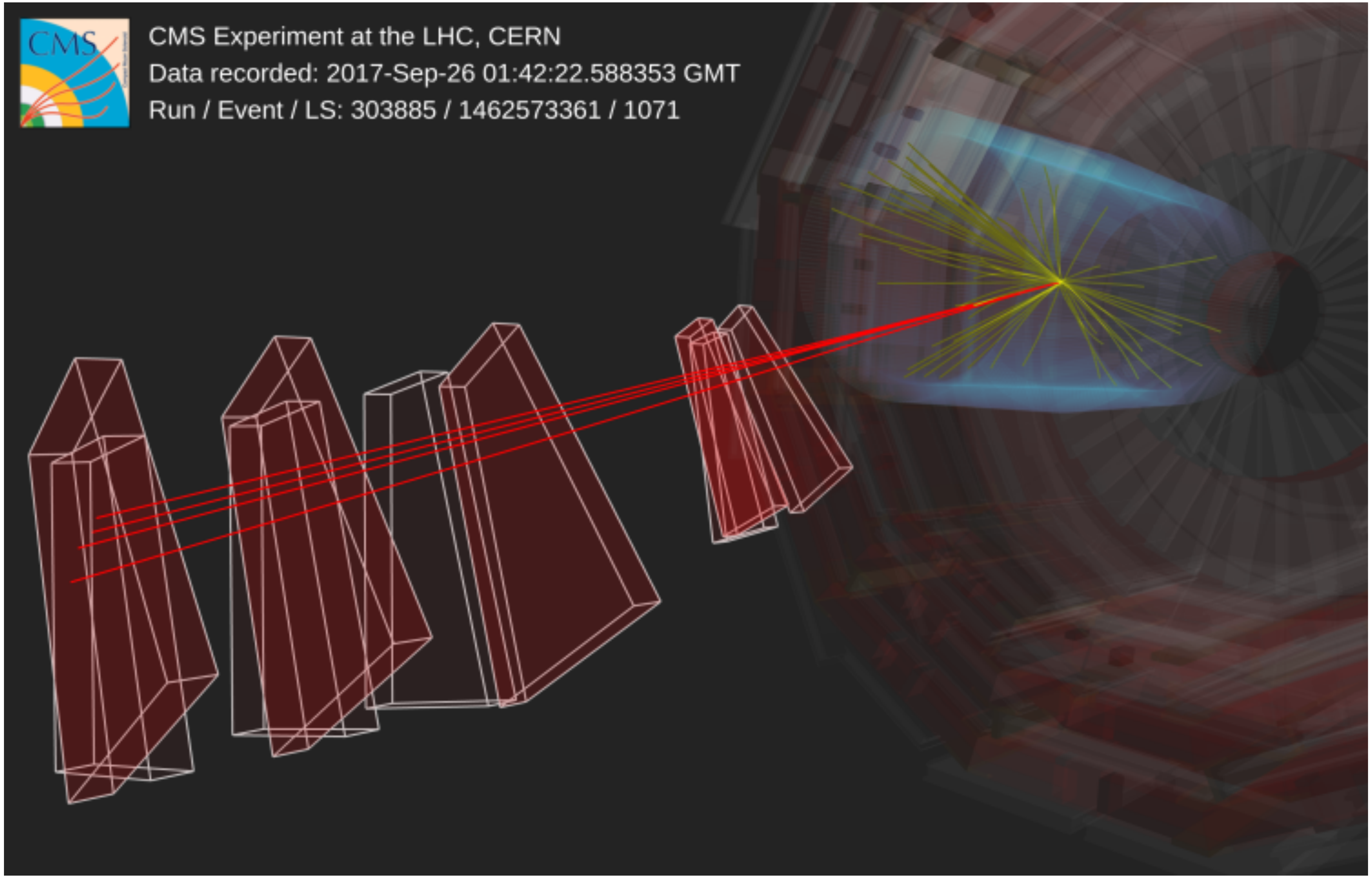
First observation of rare $\eta \to 4\mu$ decay

PDG 2022

η $I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 547.862 \pm 0.017$ MeV
Full width $\Gamma = 1.31 \pm 0.05$ keV

4 collimated muon tracks!



First observation of rare $\eta \to 4\mu$ decay

Leptonic radiative decays of the η and η' mesons

- happen via internal conversion of one or more photons
- not all observed yet!

Measurements are important

- Test Standard Model
- Sensitive to BSM scenarios (hidden photons, ALPs, …)
- Contributes to hadronic light-by-light contribution to a_μ

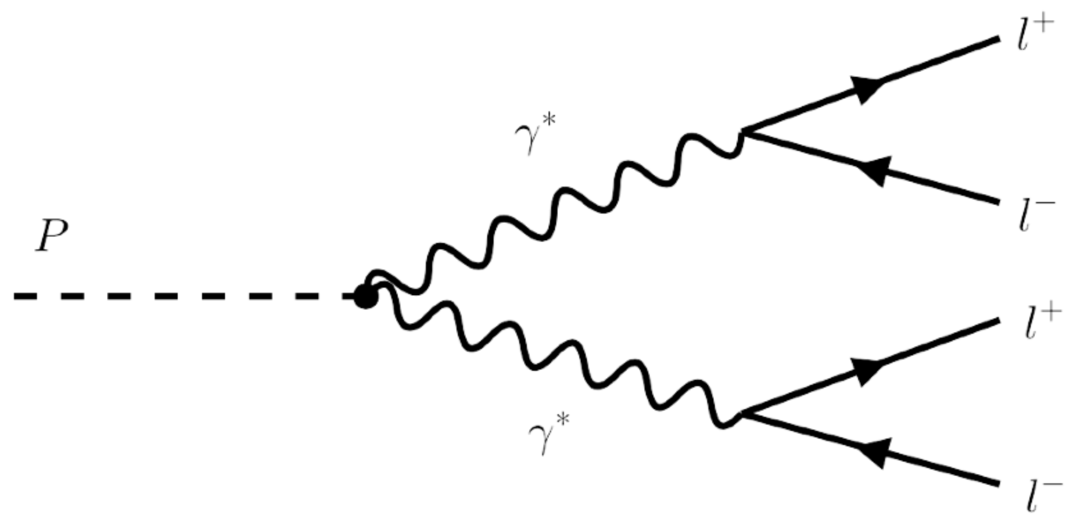
CMS obtained the first observation of the double dalitz decay of $\eta \to \mu^+\mu^-\mu^+\mu^-$

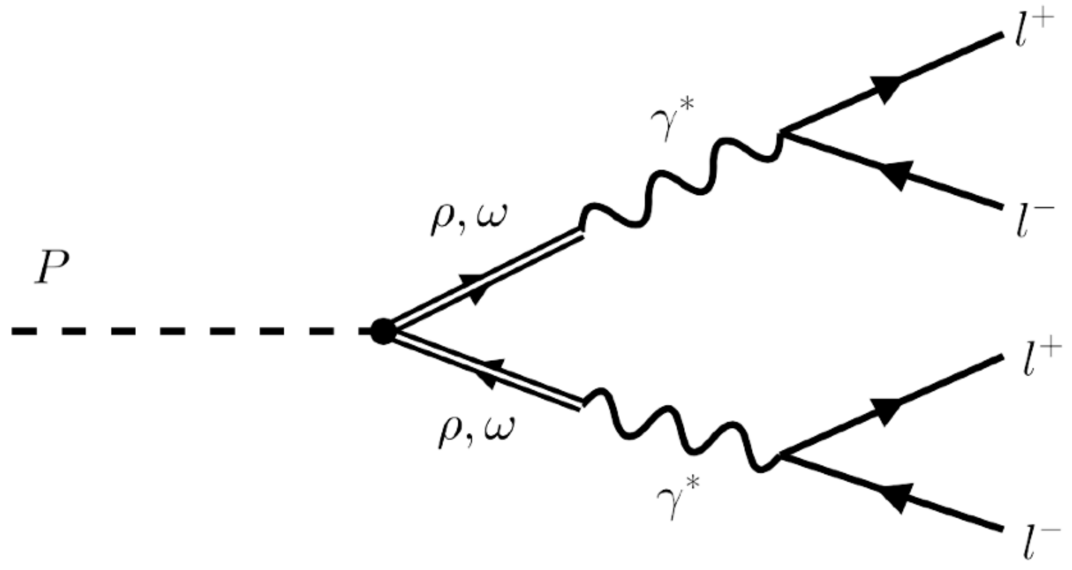
- Using 101 fb^{-1} (2017+2018) of **high-rate muon trigger data**
- Uses decay $\eta \to \mu^+\mu^-$ as normalization (13.8% precision)
- Acceptance x Efficiency (and systematics) is estimated from simulation for both channels

PDG 2022

Charged modes

Γ_8	charged modes	(28.04±0.30) %	S=1.3
Γ_9	$\pi^+\pi^-\pi^0$	(23.02±0.25) %	S=1.2
Γ_{10}	$\pi^+\pi^-\gamma$	(4.28±0.07) %	S=1.1
Γ_{11}	$e^+e^-\gamma$	(6.9 ±0.4) $\times 10^{-3}$	S=1.2
Γ_{12}	$\mu^+\mu^-\gamma$	(3.1 ±0.4) $\times 10^{-4}$	
Γ_{13}	e^+e^-	< 7 $\times 10^{-7}$	CL=90%
Γ_{14}	$\mu^+\mu^-$	(5.8 ±0.8) $\times 10^{-6}$	
Γ_{15}	$2e^+2e^-$	(2.40±0.22) $\times 10^{-5}$	
Γ_{16}	$\pi^+\pi^-e^+e^-(\gamma)$	(2.68±0.11) $\times 10^{-4}$	
Γ_{17}	$e^+e^-\mu^+\mu^-$	< 1.6 $\times 10^{-4}$	CL=90%
Γ_{18}	$2\mu^+2\mu^-$	< 3.6 $\times 10^{-4}$	CL=90%

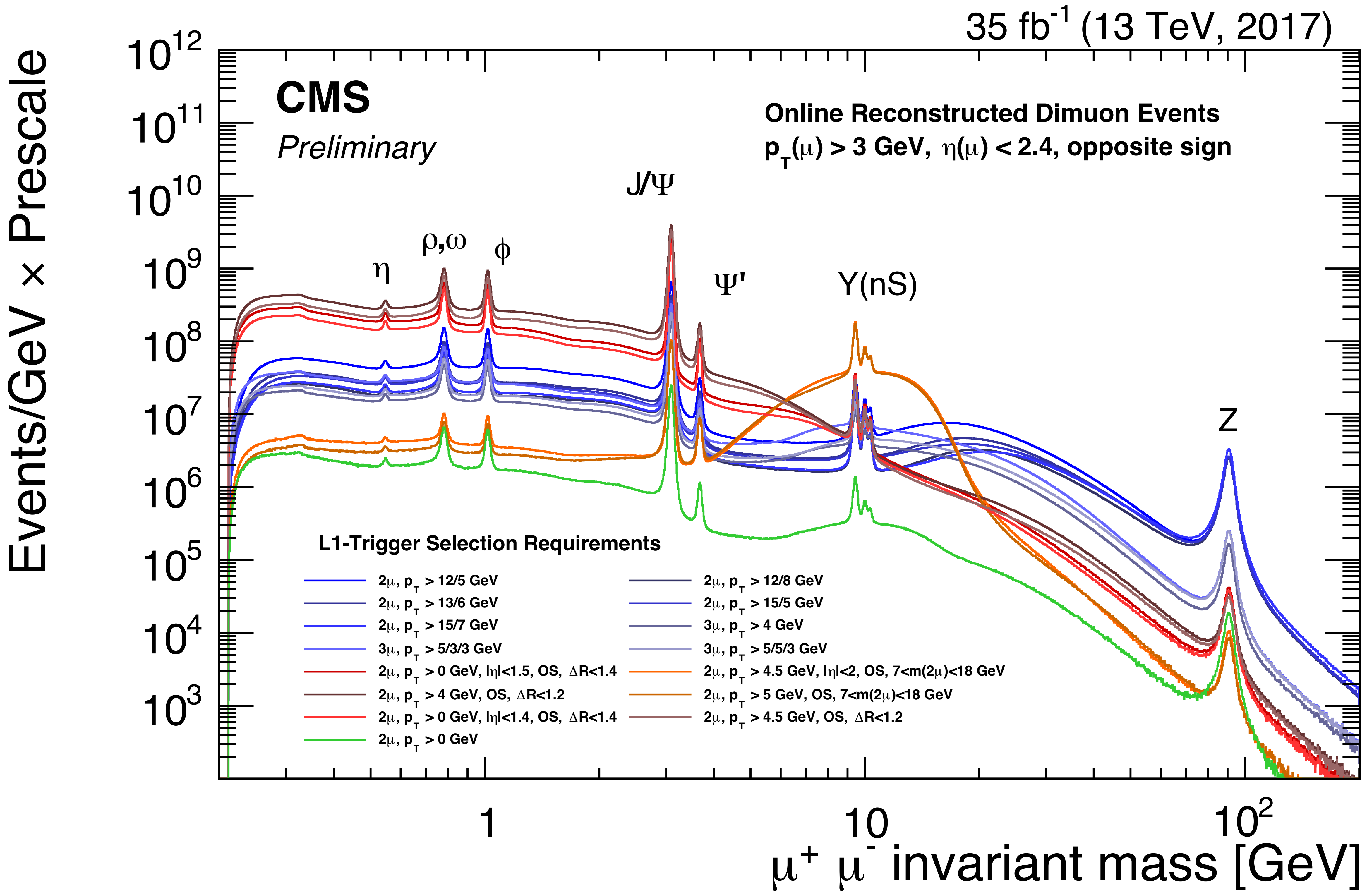




2017+2018 data

Interlude: muon data scouting

- Standard dimuon triggers require muon $p_T > 17$ (8) GeV, resulting in rate of 30 Hz at $\mathscr{L} = 2 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Poor efficiency for $m_{\mu\mu} < 40\,\mathrm{GeV}$
- Data Scouting = Dedicated trigger stream storing **reduced event information at higher rate**
  - Starts from several L1 trigger paths (see table)
  - HLT selection: 2 muons with $p_T > 3\,\mathrm{GeV}$
  - Store only information from muons reconstructed at the HLT: 4–8 kB/event instead of 1MB, allowing storing 2kHz
- Data Scouting succesfully used in CMS for dijet resonance searches as well (jet H_T triggers)
- Program continuing in Run 3



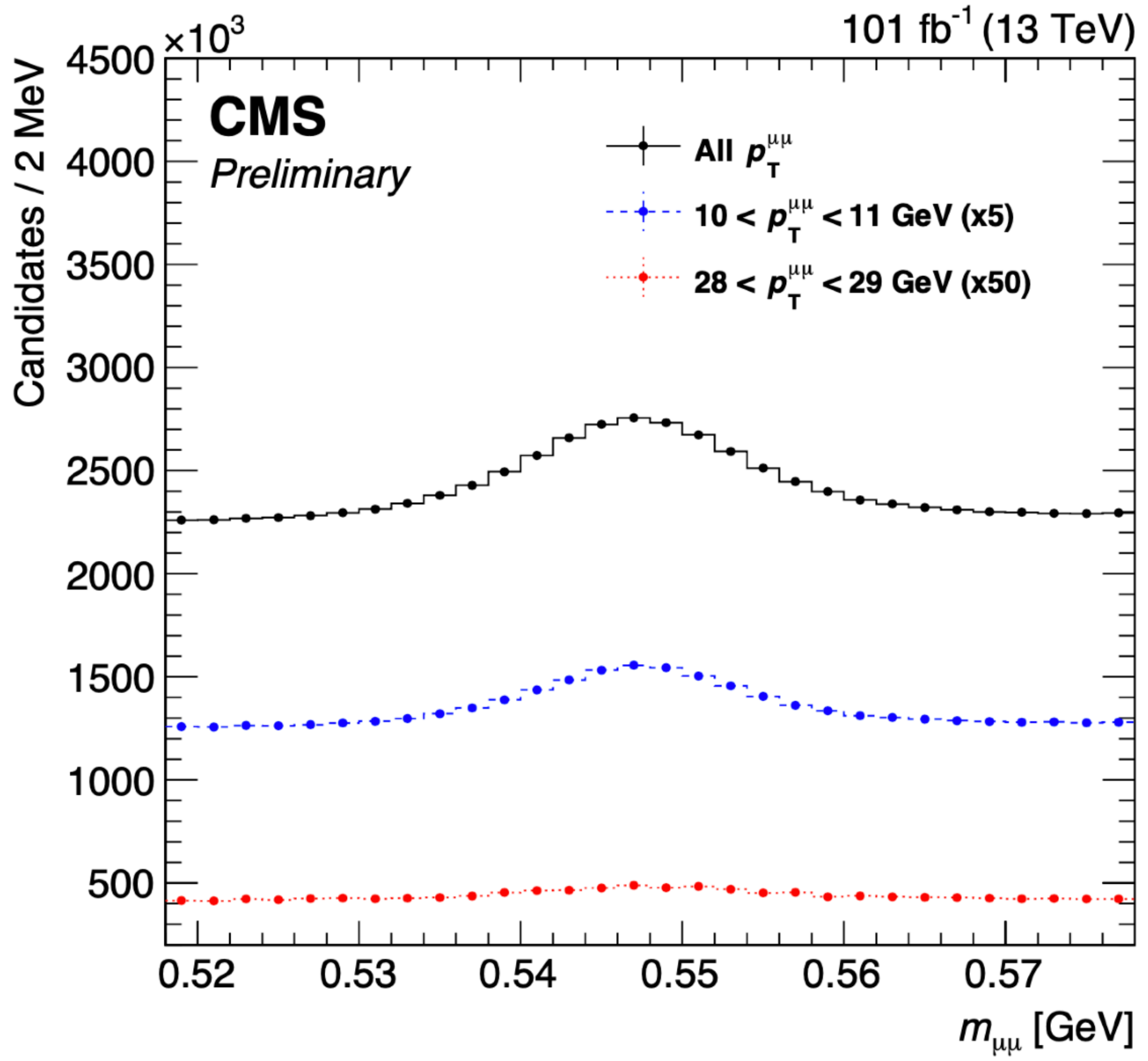
L1 path	p_T [GeV]	$\lvert\eta\rvert$	ΔR	$m_{\mu\mu}$ [GeV]	Efficiency
#1	$> 4{,}4.5$	–	< 1.2	–	83%
#2	–	< 1.5	< 1.4	–	44%
#3	$> 15/7$	–	–	–	42%
#4	> 4.5	< 2.0	–	7–18	8%

BPH-22-003

2017+2018 data

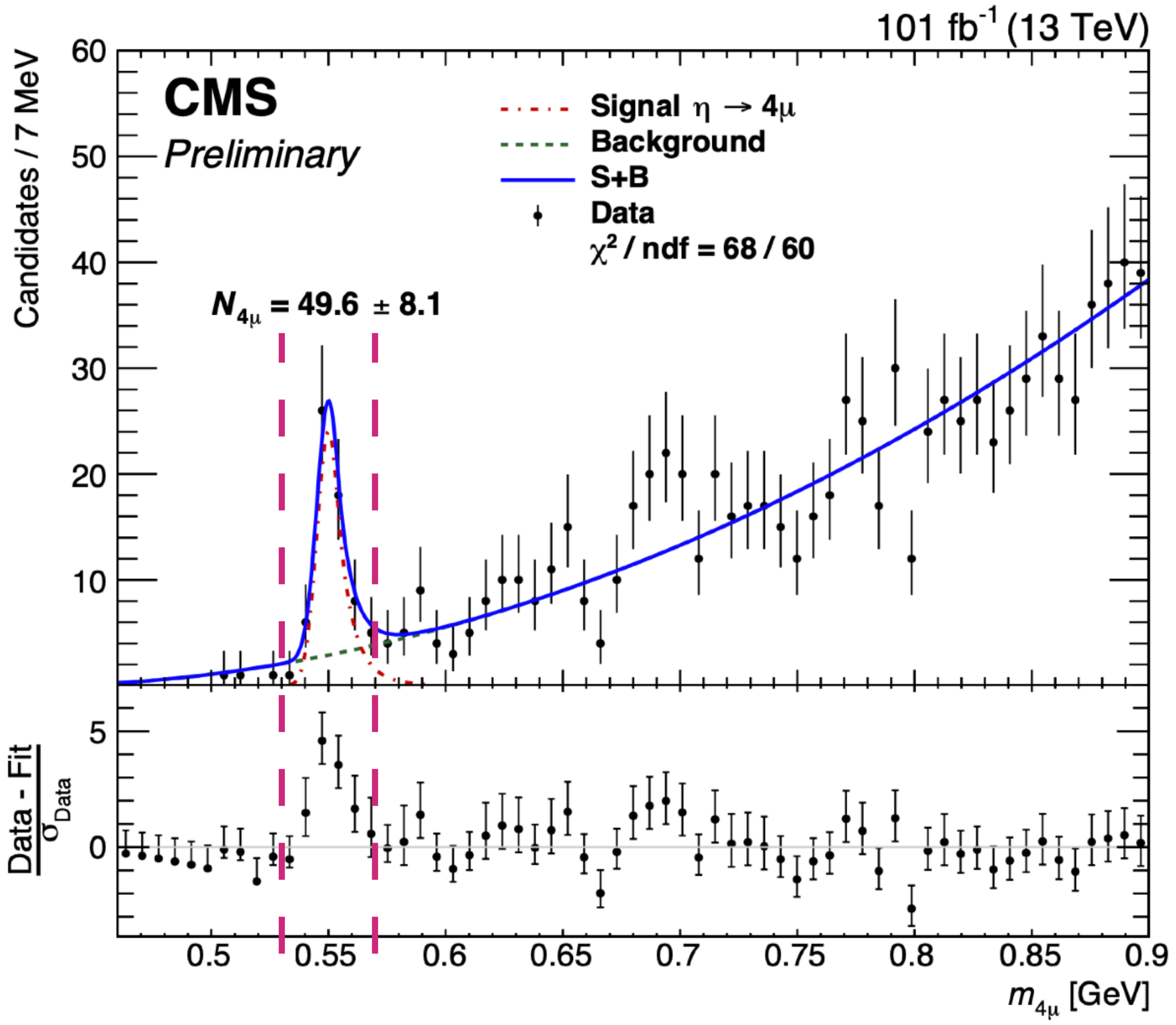
First observation of rare $\eta \to 4\mu$ decay

Reference channel



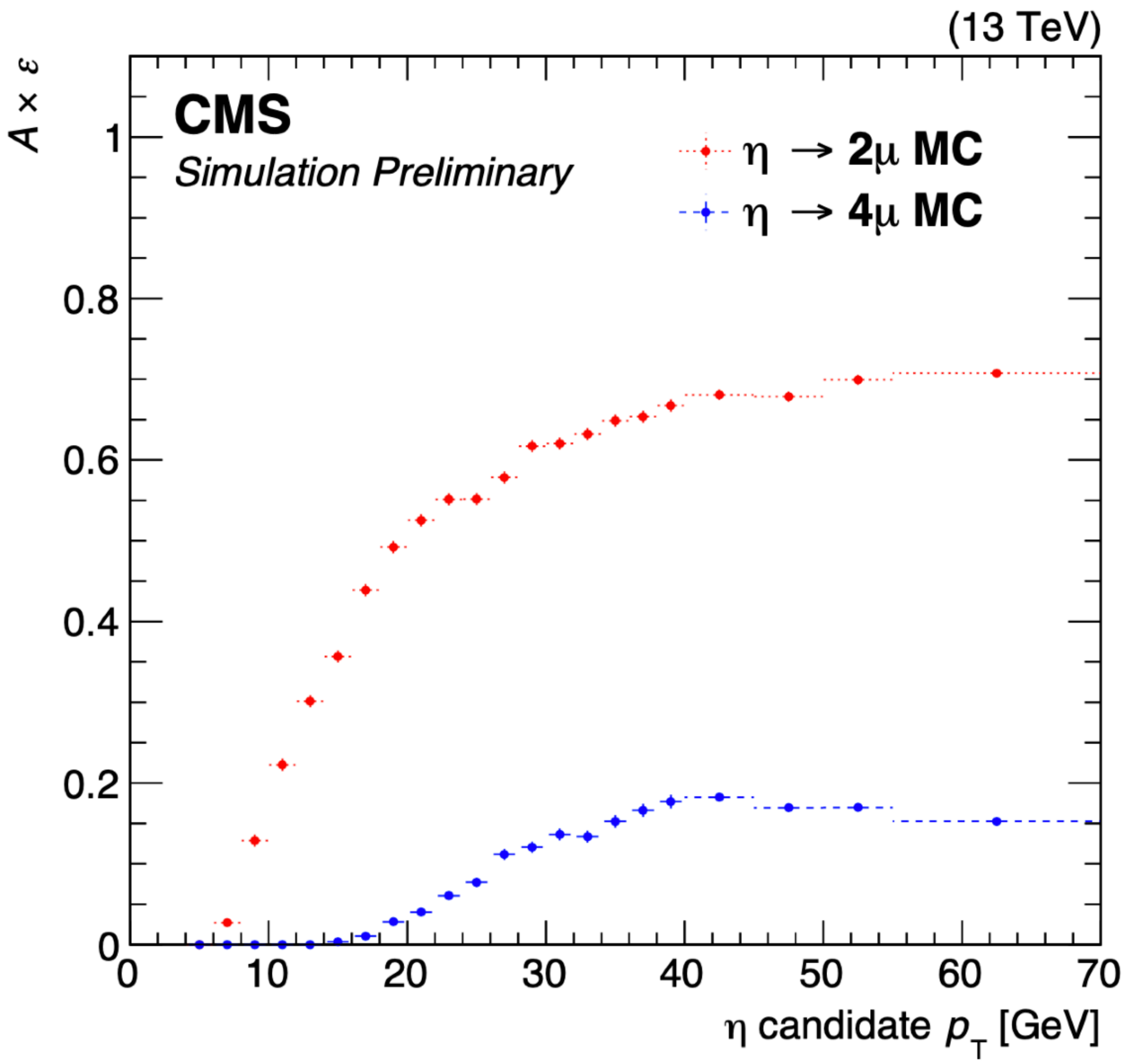
- $N(\eta \to 2\mu) \approx 4.5\text{M}$
- 10^{12} η **produced** ($\mathscr{B}(\eta \to 2\mu)$)
- Huge sample size enables study of rare decay channels

4μ channel



- $N(\eta \to 4\mu) = 49.6 \pm 8.1$
- $N(\text{background}) = 16.6 \pm 0.6$
- **Significance > 5σ**

$A \times \epsilon$ correction



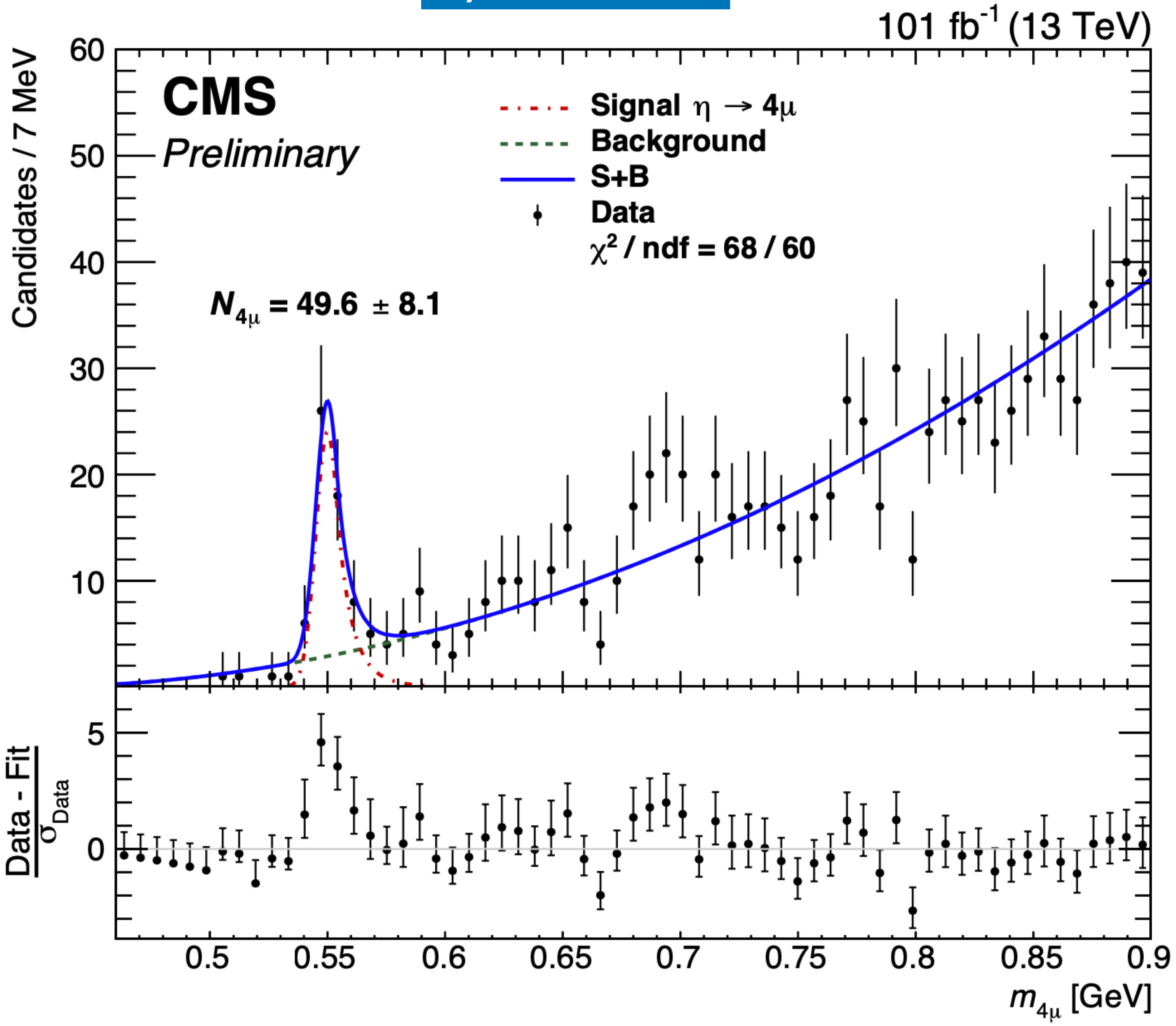
- To extract branching fraction, need to correct for the difference in acceptance and efficiency

BPH-22-003

2017+2018 data

First observation of rare $\eta \rightarrow 4\mu$ decay

4μ channel



- Extract $\mathscr{B}(\eta \rightarrow 4\mu)$ using $\eta \rightarrow 2\mu$ as a normalization, including corrections based on different acceptance

$$\frac{\mathscr{B}(\eta \rightarrow 4\mu)}{\mathscr{B}(\eta \rightarrow 2\mu)} = \frac{N_{4\mu}}{\sum_{i,j} N_{2\mu} \frac{A^{i,j}_{4\mu}}{A^{i,j}_{2\mu}}}$$

$$\frac{\mathscr{B}(\eta \rightarrow 4\mu)}{\mathscr{B}(\eta \rightarrow 2\mu)} = (0.9 \pm 0.1\,(\text{stat}) \pm 0.1\,(\text{syst})) \times 10^{-3}$$

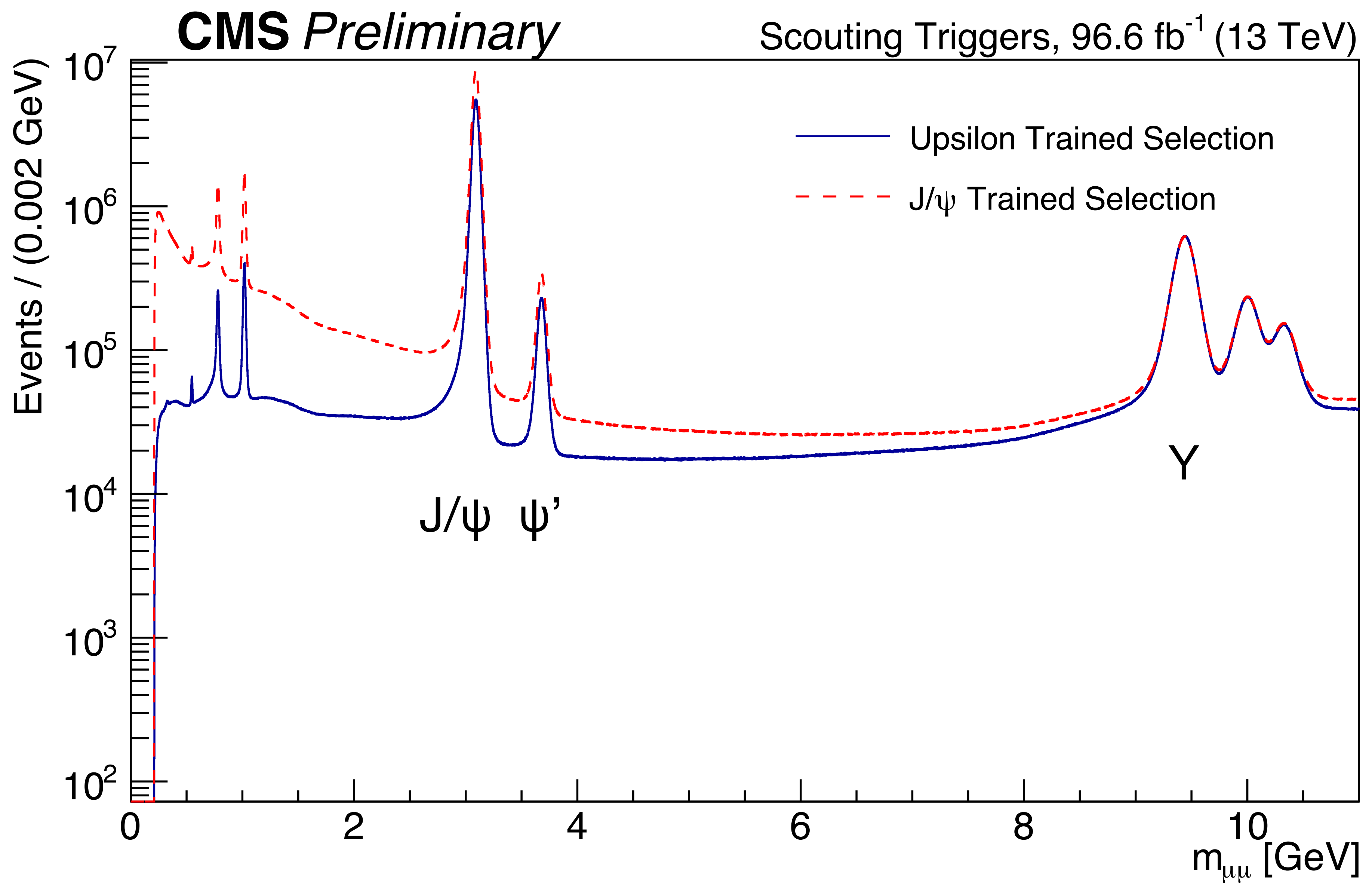
- Reference branching fraction: $\mathscr{B}(\eta \rightarrow 2\mu) = (5.8 \pm 0.8) \times 10^{-6}$

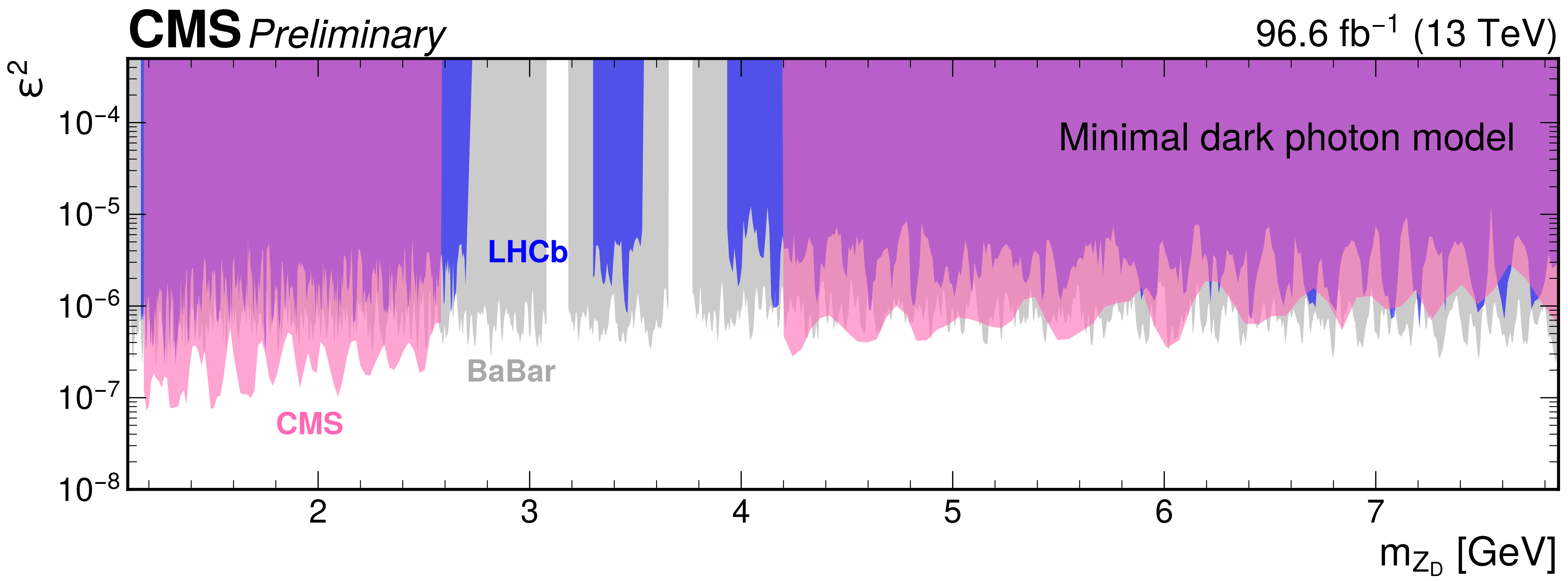
$$\mathscr{B}(\eta \rightarrow 4\mu) = (5.0 \pm 0.8\,(\text{stat}) \pm 0.7\,(\text{syst}) \pm 0.7\,(\mathscr{B})) \times 10^{-9}$$

- Branching fraction expected from the SM: $\mathscr{B}(\eta \rightarrow 4\mu)^{SM} = (3.98 \pm 0.15) \times 10^{-9}$
- **Measurement is in agreement within uncertainties**

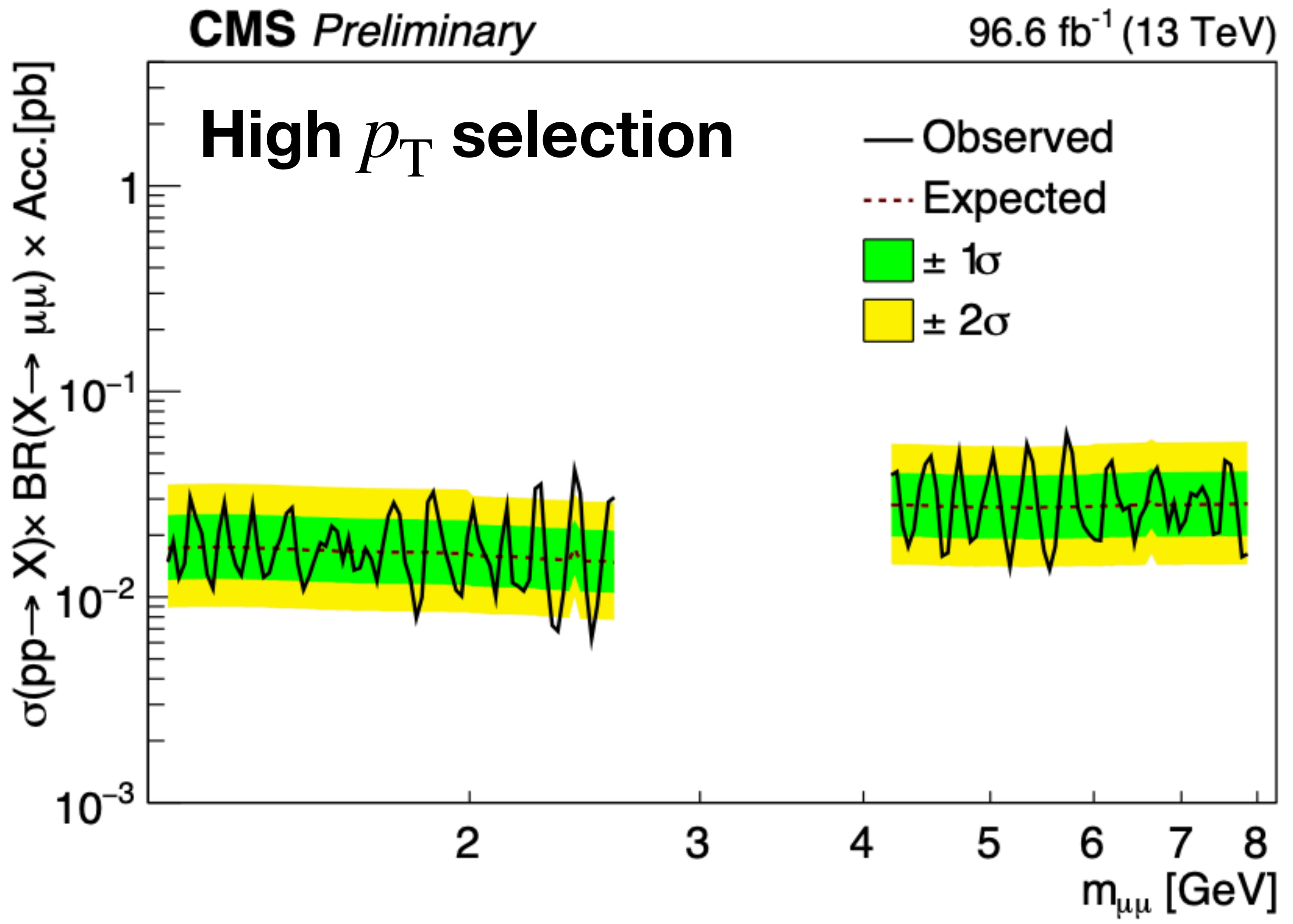
Scouting for low-mass dimuon resonances

- **Can also use data scouting to extend reach in search for dimuon resonances to lower masses**
  - Targeted mass range: 1.1-2.6 GeV and 4.2-7.9 GeV, excluding region of J/ψ, ψ’ and Υ(1S)
  - Motivated by e.g. **dark photons** Z_D with kinetic mixing ε or 2HDM with extra scalar
  - Analysis assumes narrow resonance coming from the primary vertex
- Offline analysis:
  - 2 muons with $p_T > 4$ GeV, $|\eta|<1.9$
  - Optimized muon identification for low masses using two BDTs
  - Fit to dimuon invariant mass spectrum in discrete mass windows of 5x experimental resolution (1.3%)



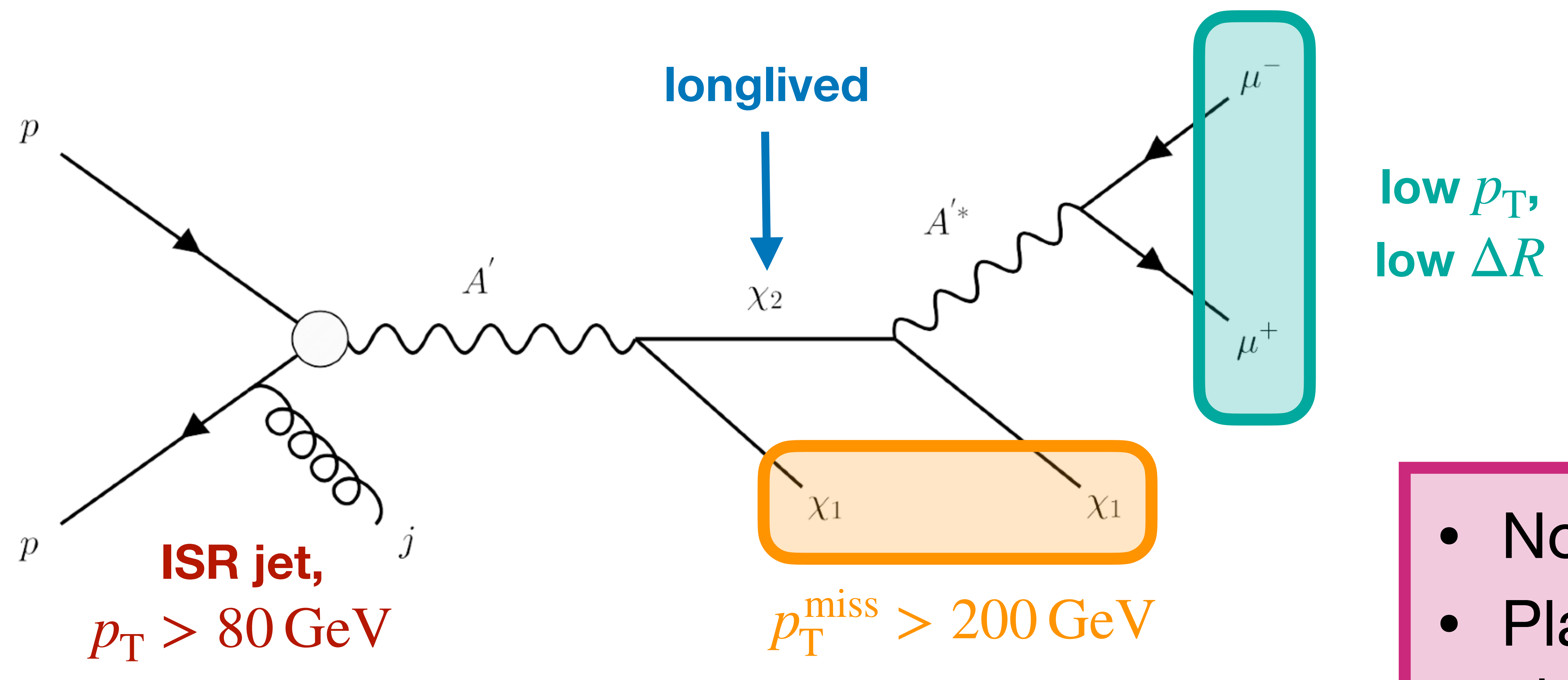


Largest excess at 2.41 GeV, local: 3.2σ, global: 1.3σ
side note: 3.1σ LHCb excess at 2.42 GeV



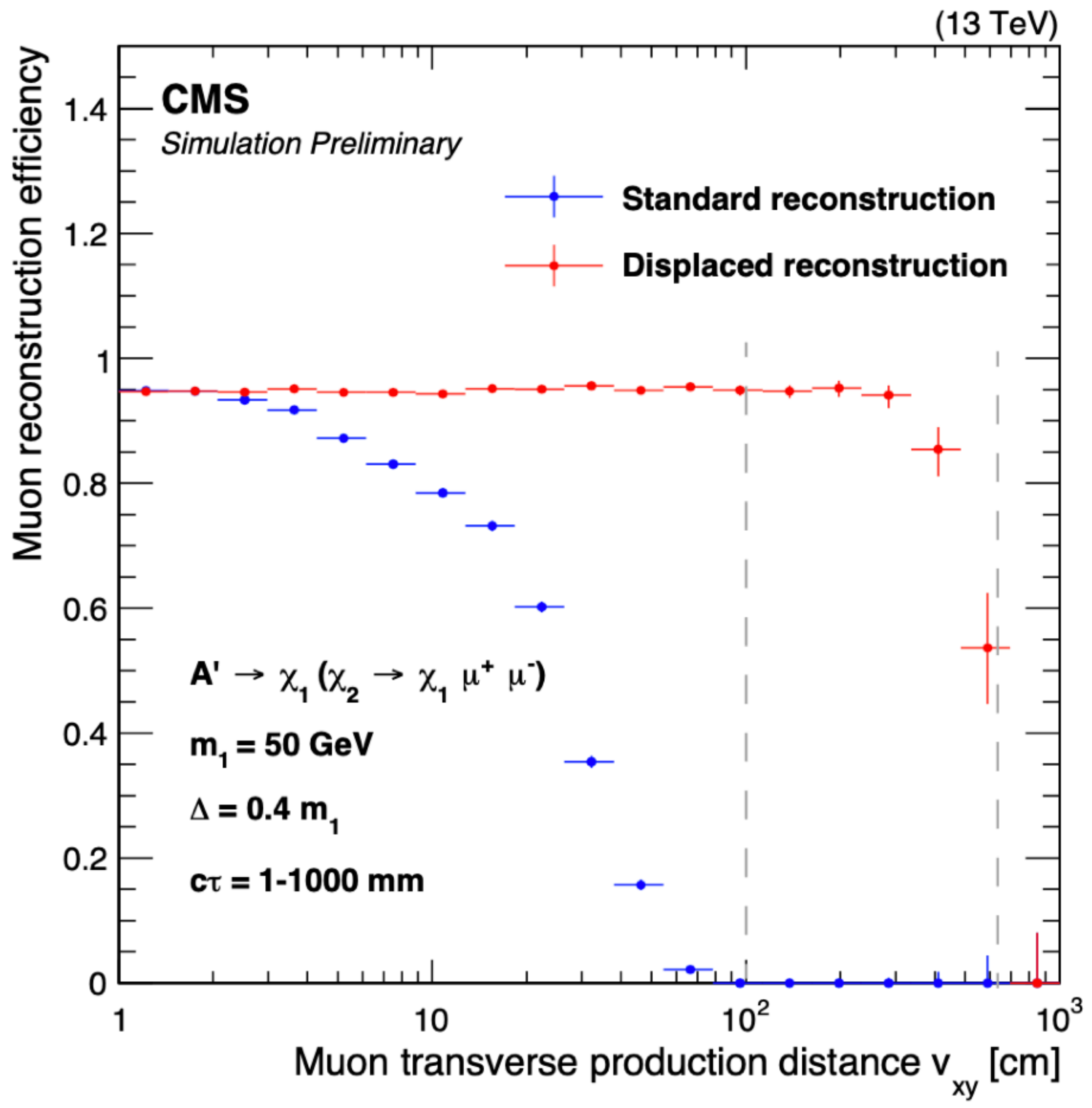
Search for inelastic dark matter

- **First search for inelastic DM at a hadron collider**
  - ≥2 DM states χ_1 & χ_2 + dark photon A' with kinetic mixing with SM hypercharge (ε)
  - Search targeting small $\Delta = m_{\chi_2} - m_{\chi_1} \in [0.1 - 0.4] m_{\chi_1}$
  - Large production cross section, small selection efficiency
- **Signature: p_T^{miss} collimated with 2 displaced muons**

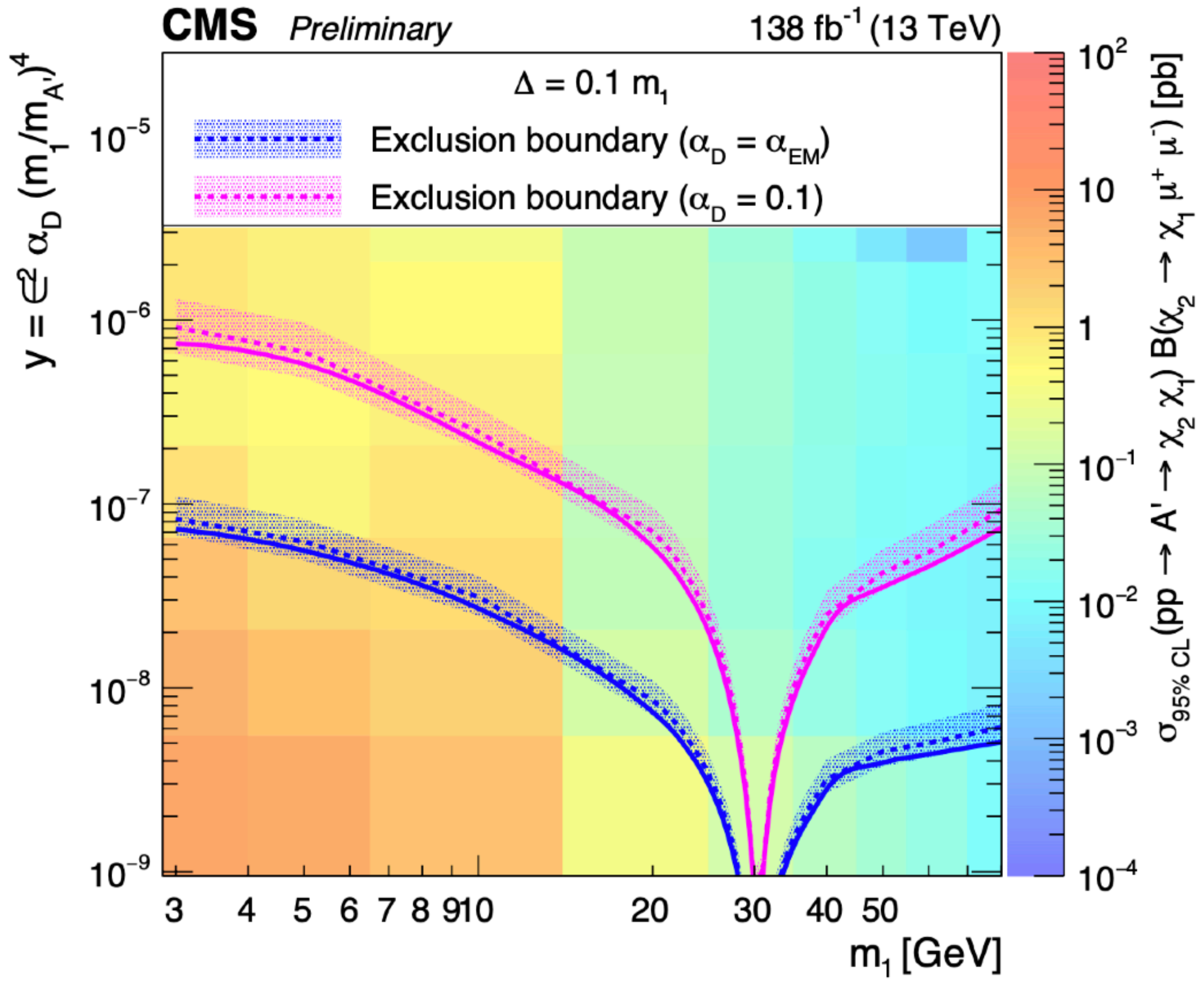


- Signal regions defined by number of displaced muons matched with standard muons
- Backgrounds predicted via ABCD method using min-d_{xy} vs. relative isolation or $\Delta\phi(\mu\mu, p_T^{miss})$

Dedicated displaced muon reconstruction
- Using only muon system
- Efficient up to large displacements (few meters)

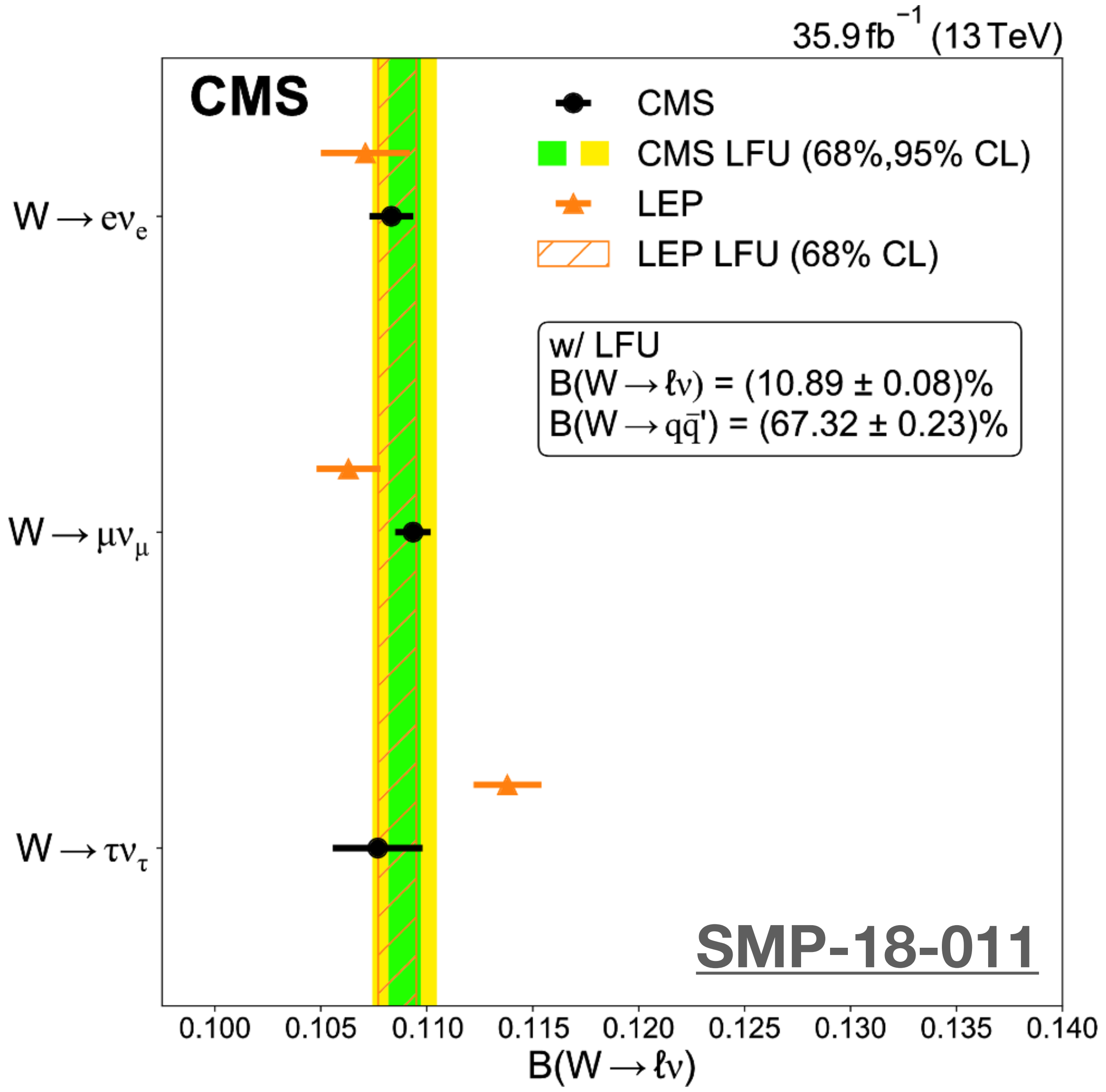


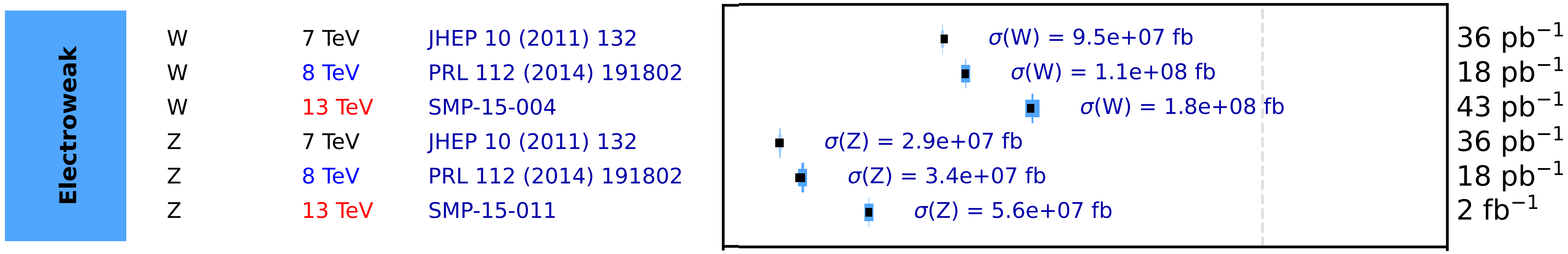
- No excess observed
- Place constraints on interaction strength vs DM mass
- Sensitivity enhanced at $m_{\chi_1} = 30$ GeV because of mixing between A' and Z ($m_{A'} = 3m_{\chi_1}$)

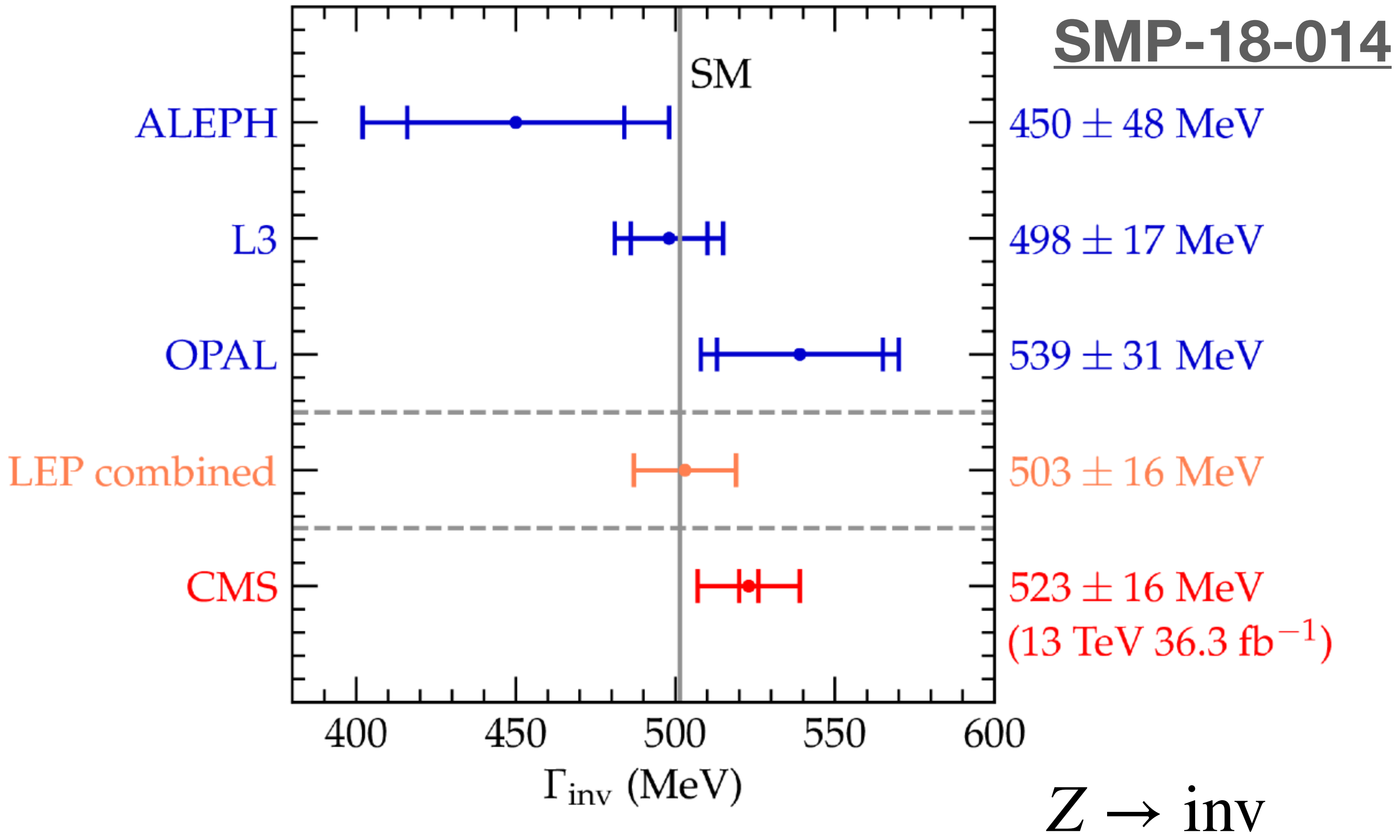


W(ine) & Z(eese)

- W and Z production are some of the best understood processes at hadron colliders, both theoretically & experimentally
- Clean laboratory to study QCD
  - Study PDF's, subtle pQCD effects
  - Important background to Higgs & BSM searches
- Precision electroweak measurements are sensitive to BSM physics
- Many results published since 2010!
  - Differential cross section measurements of W, Z, diboson, triboson, …
  - Properties such as branching fractions/width, asymmetries
  - Searches for rare/exotic decays
  - …





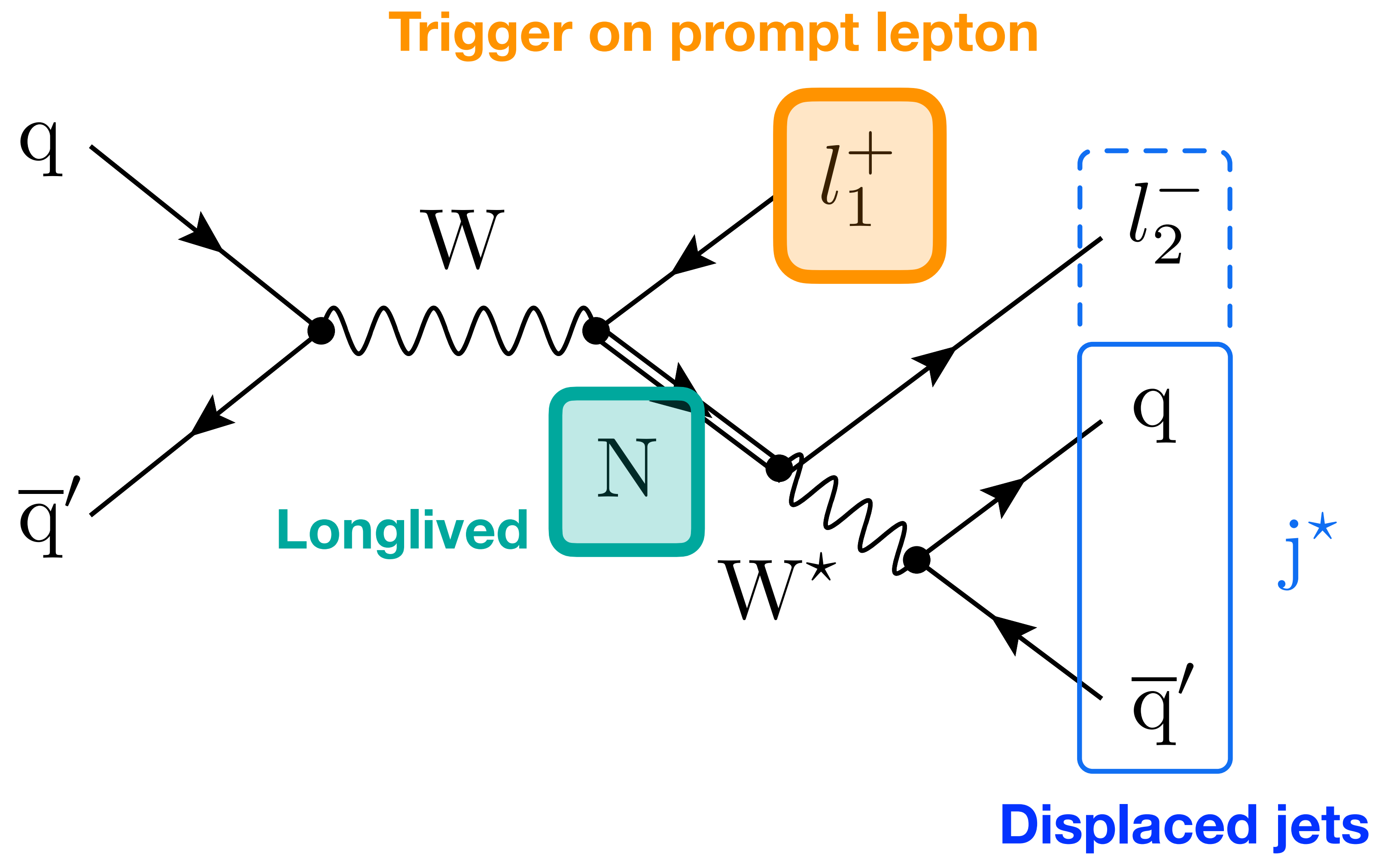


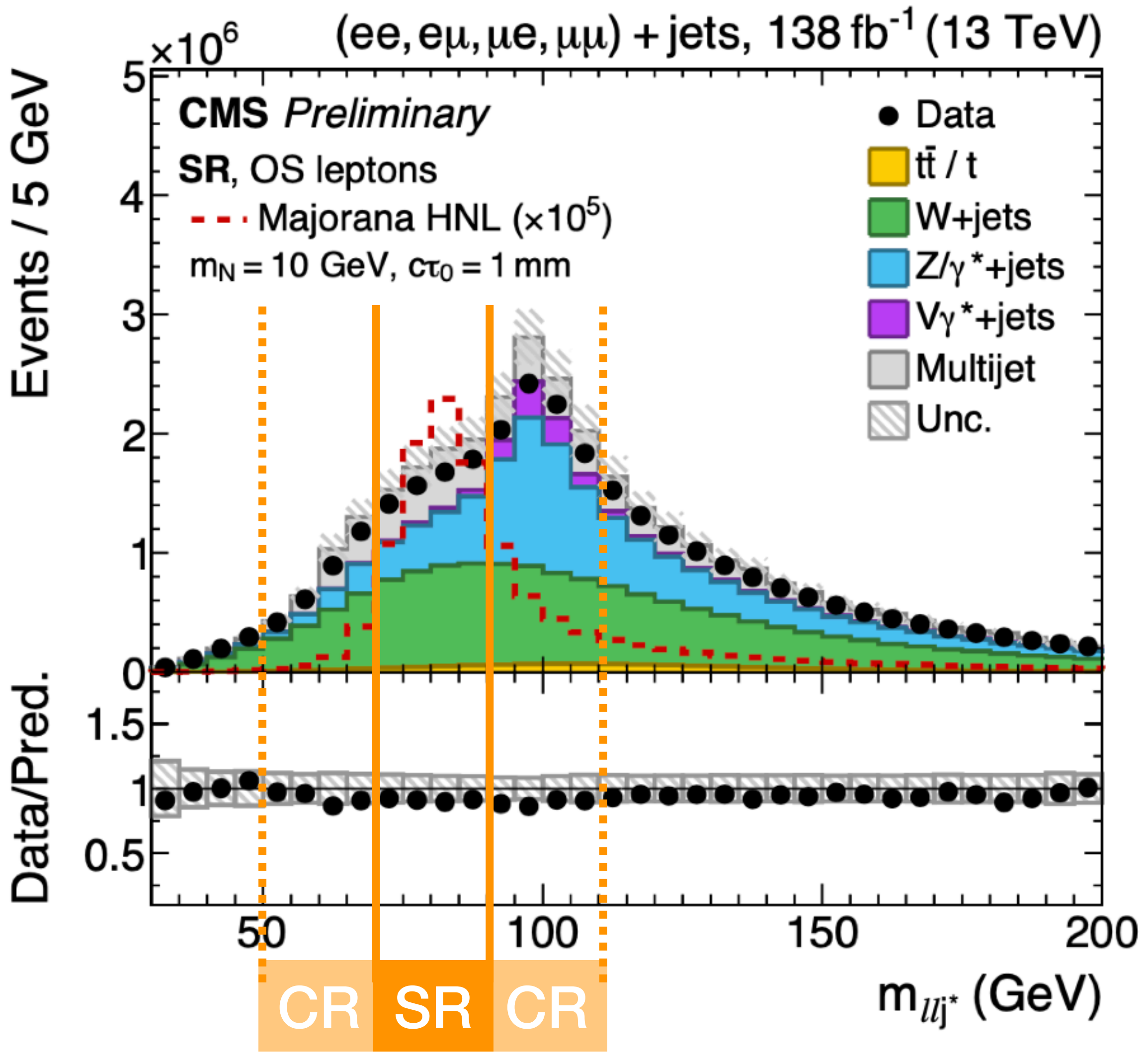
EXO-21-013

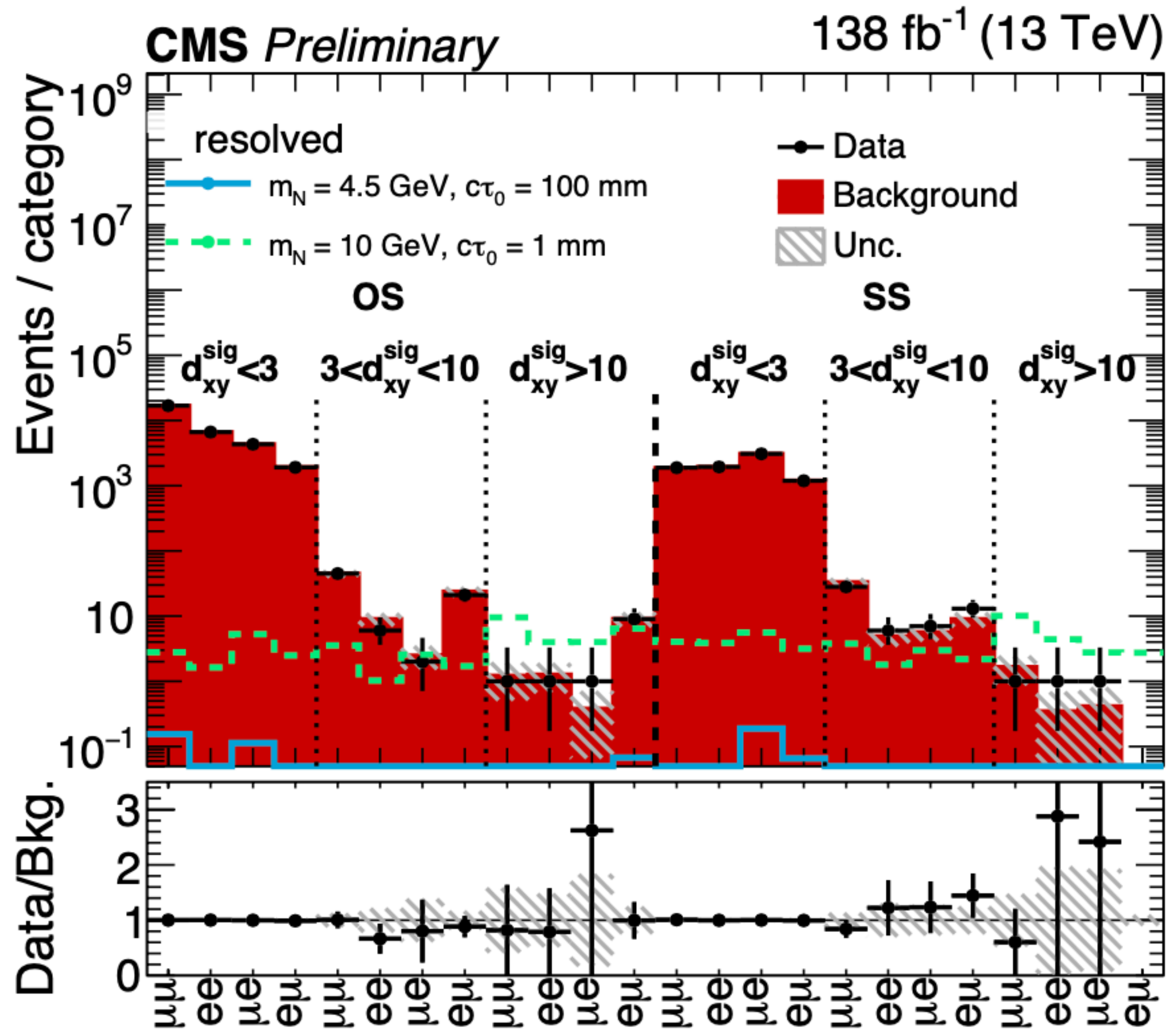
2016-2018 data

Search for long-lived heavy neutral leptons decaying to jet + e/μ/τ

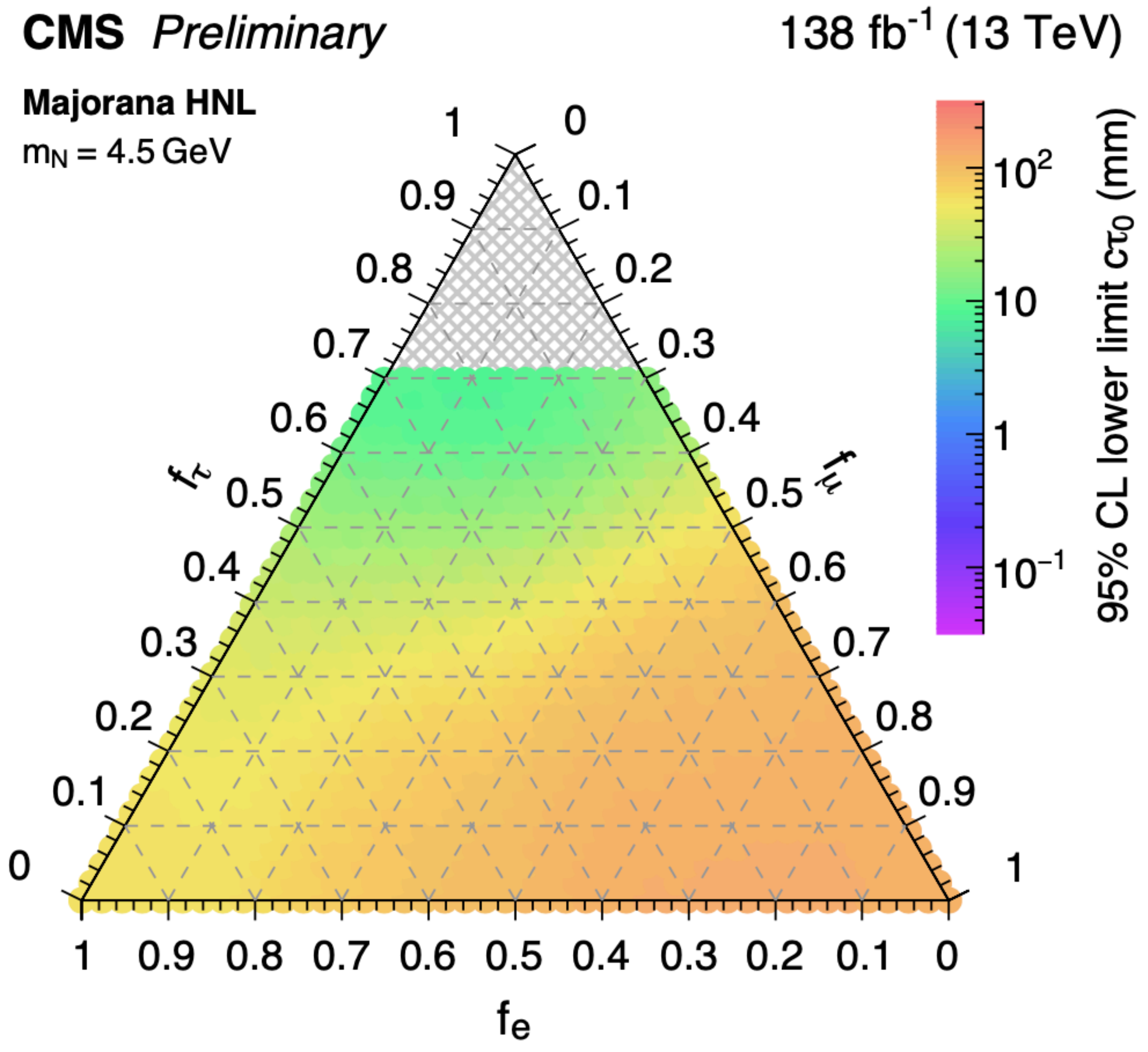
- HNL with small masses or couplings are longlived: $c\tau \propto \frac{1}{|V_{lN}|^2 (m_N)^5}$
  Coupling not restricted to single generation
- Search relies on **displaced jet tagger**
  - Deep neural network, domain adaptation to reduce data vs MC differences
  - Multi-class output: jets from q/g, pileup, prompt ℓ/γ, displaced jet
- Search categories based on lepton flavor & charge, $\Delta R(l_2, \mathrm{jet})$, and displacement
- Backgrounds estimated via ABCD method in data using m_{llj*} and NN score





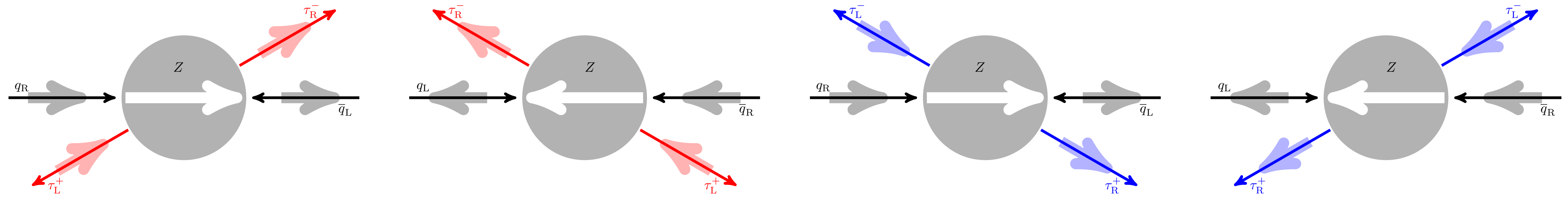


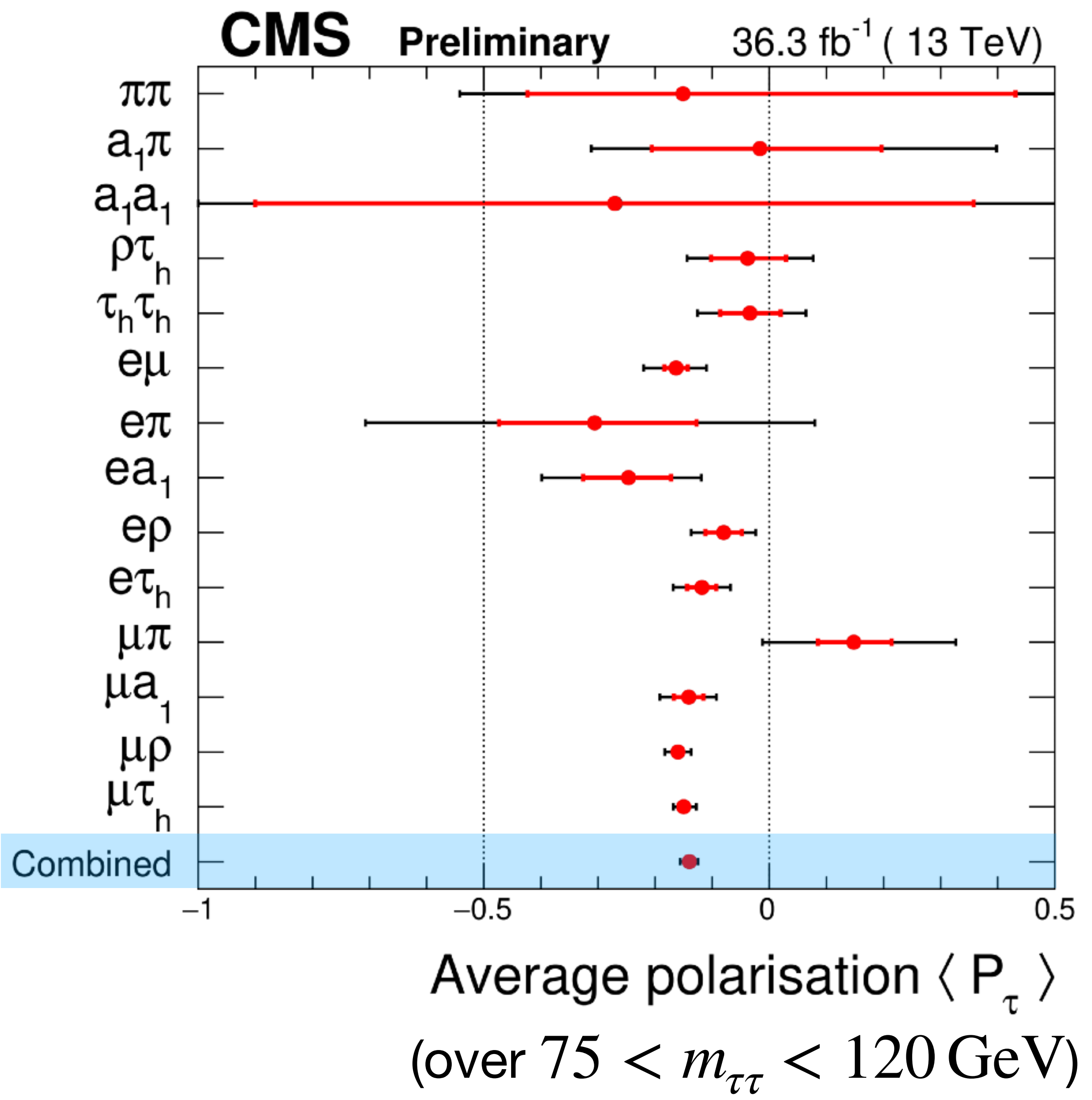
- No excess observed
- Best limit on the coupling strength for pure muon scenario, excluding values of $|V_{\mu N}|^2 > 5(4) \times 10^{-7}$ for Dirac (Majorana) HNLs with a mass of 10 GeV

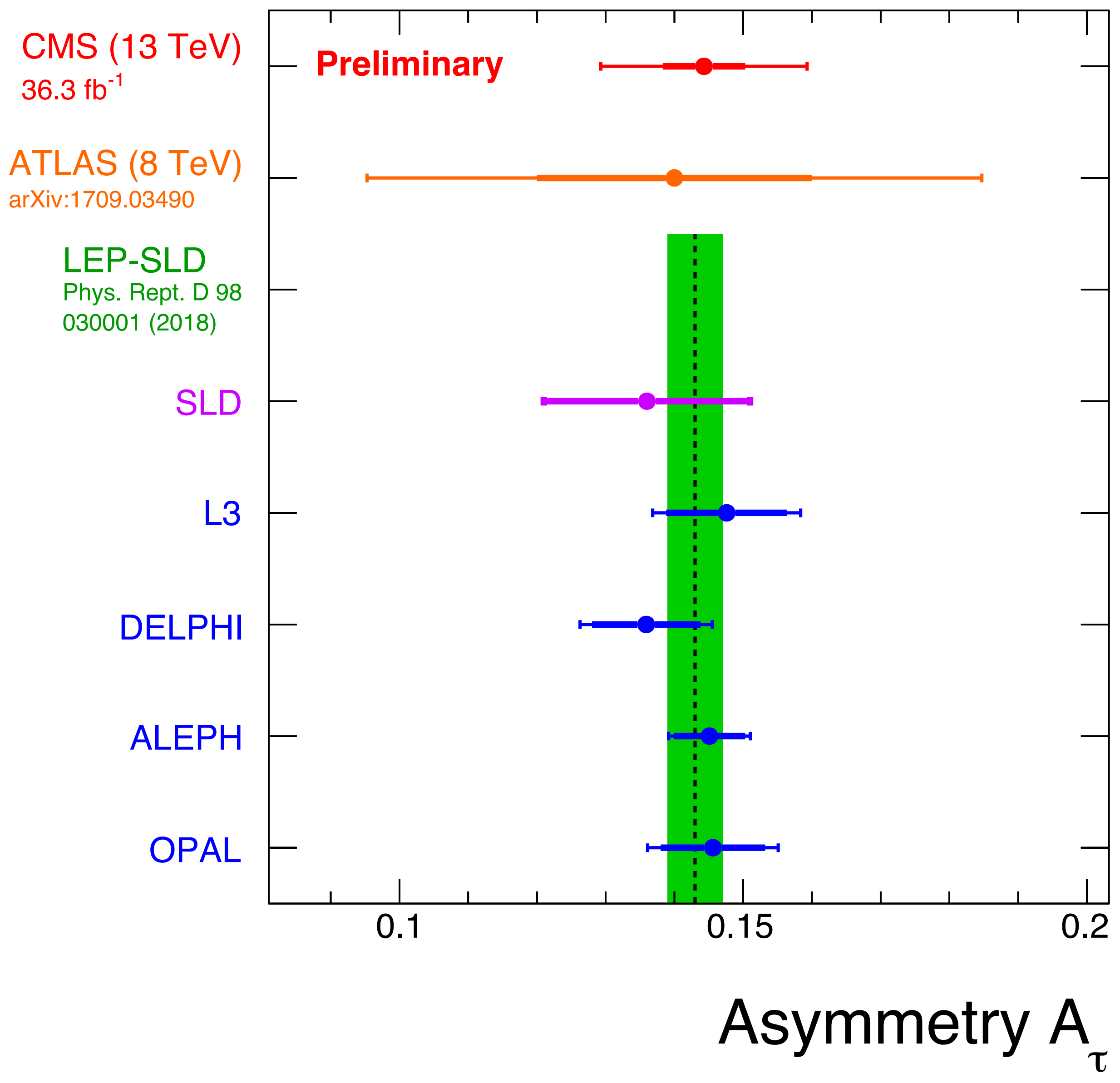


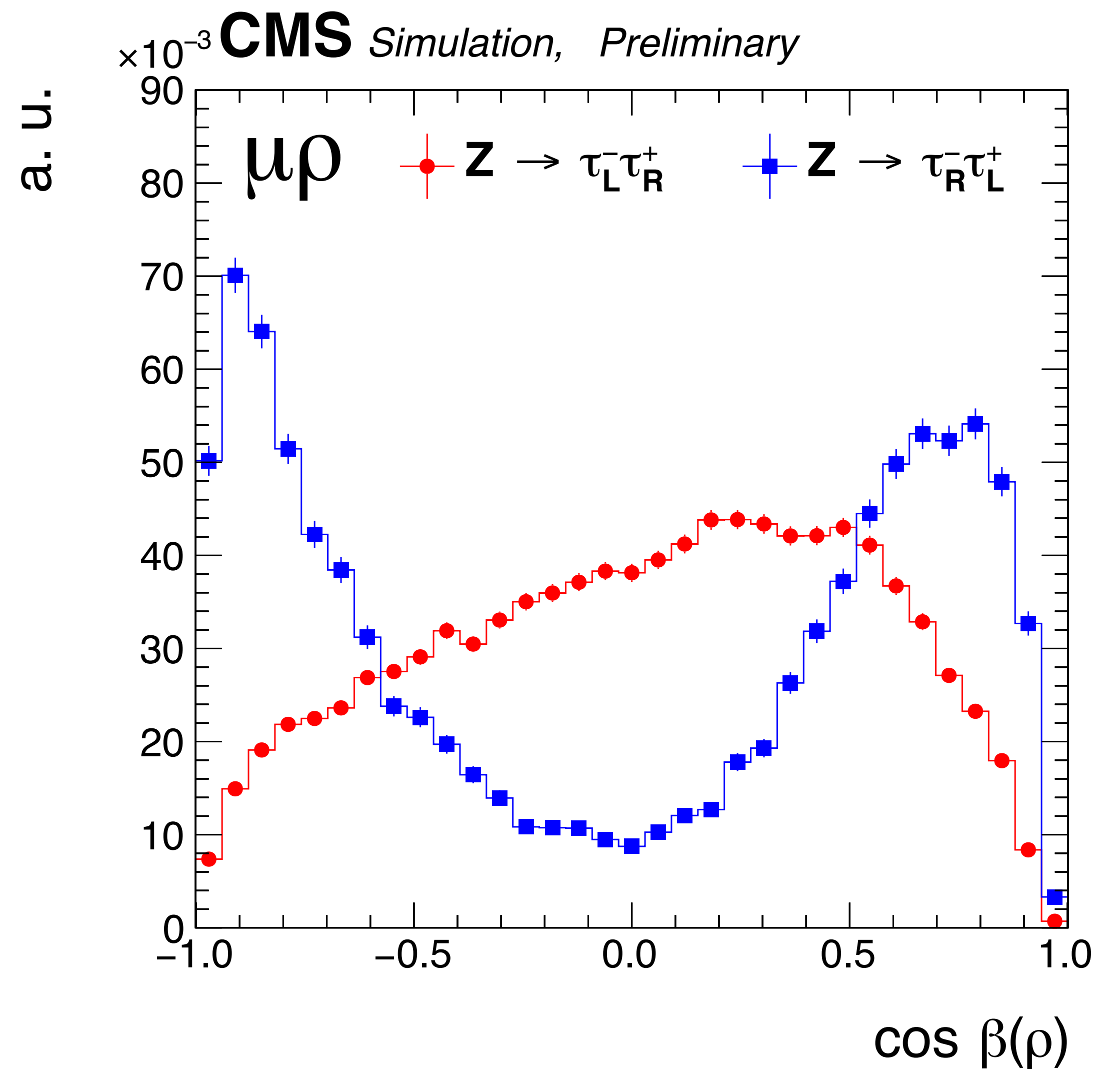
Measurement of τ polarization in Z decays

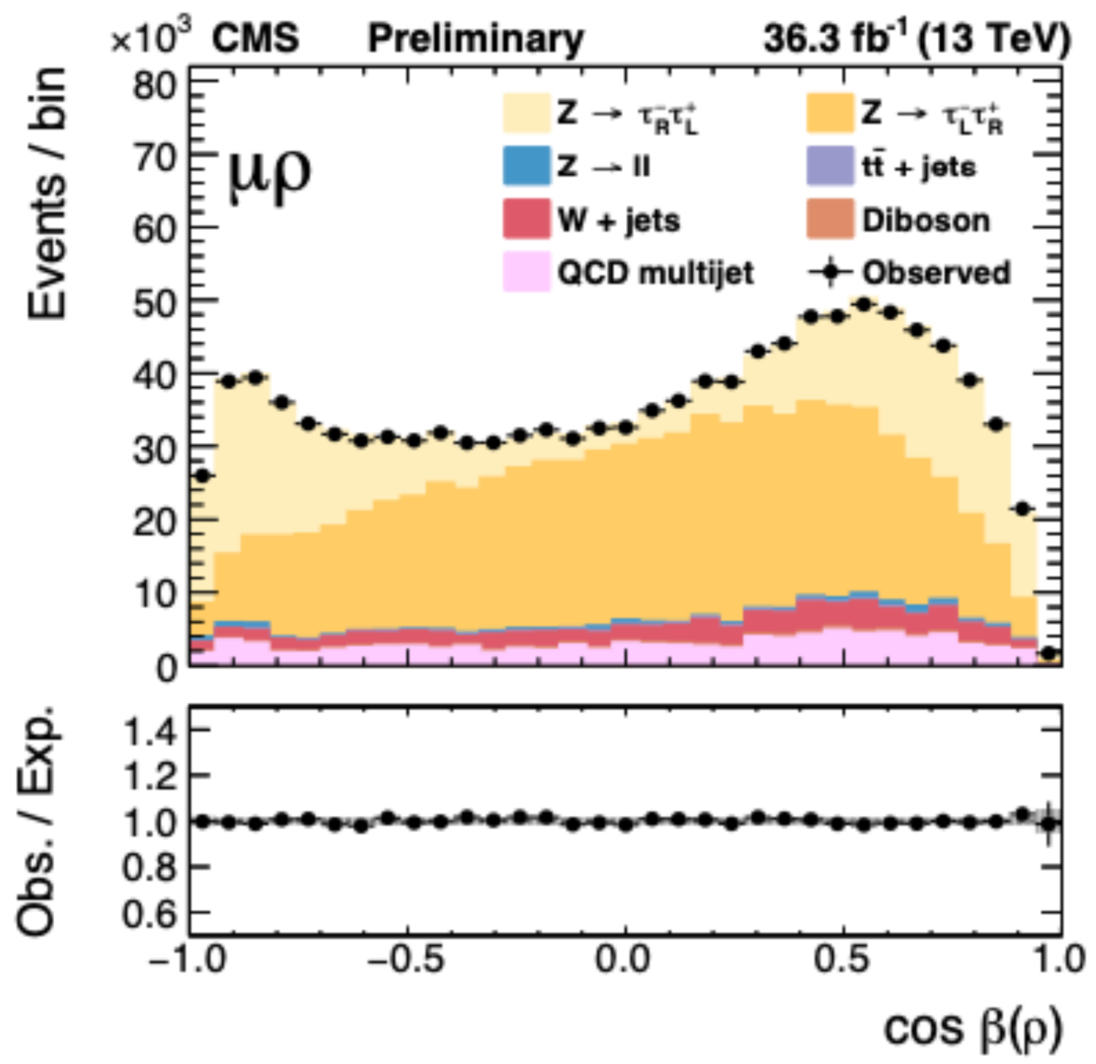
- τ polarization measurements can probe underlying EWK parameters A_τ, $\sin^2(\theta_W)$
- Measurement considers 11 different categories of τ decays (leptonic & hadronic)
    - Uses optimal observables depending on category
    - Backgrounds estimated using data control regions
    - Simultaneous fit over all categories to extract polarization (Muon channels most sensitive)
- Comparable precision to single LEP experiments!







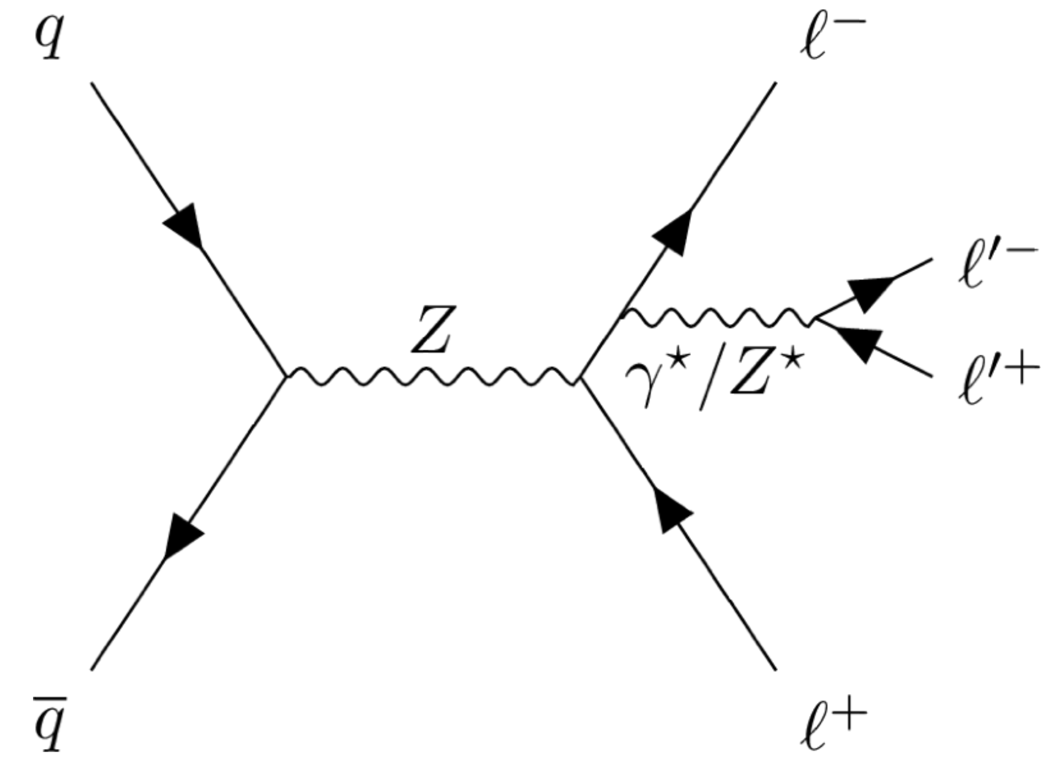




- $P_\tau(Z) = -0.144 \pm 0.006\,(\text{stat}) \pm 0.014\,(\text{syst})$
- Agrees with SM value of $A_\ell = 0.1468 \pm 0.0003$
- Results in $\sin^2\theta_{\text{eff}} = 0.2319 \pm 0.0019$

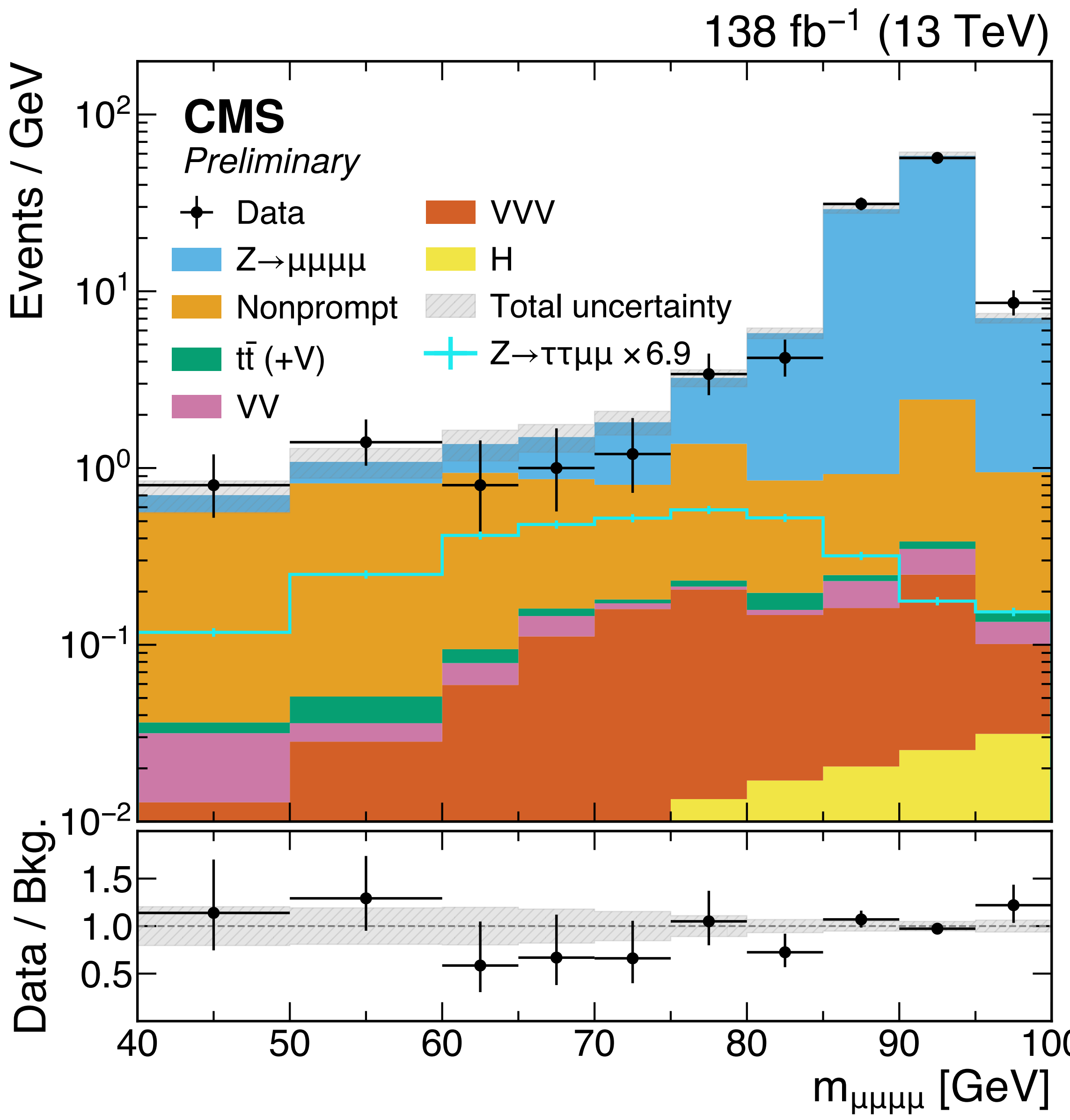
Search for $Z \to \mu\mu\tau\tau$ decay

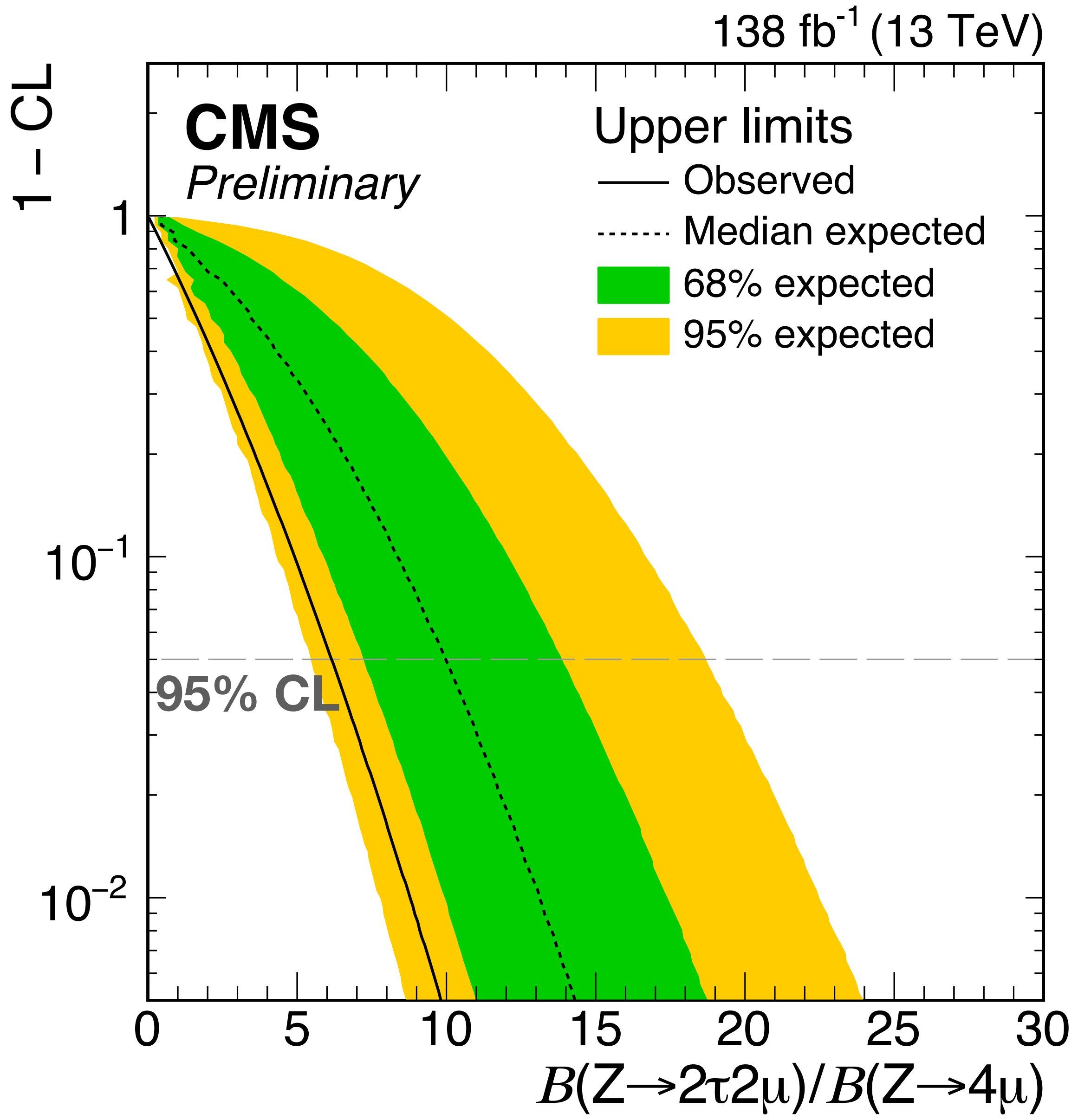
CMS was first to measure rare decays $Z \to J/\psi \ell^+\ell^-$ and $Z \to \ell^+\ell^-\ell'^+\ell'^-$ (with $\ell = e, \mu$), which are sensitive to BSM physics (e.g. new Z' particles)



Effort goes on with decays to τ, which are especially motivated in some BSM models ($\mathscr{B}_{\mathrm{SM}} \approx 10^{-6}$)

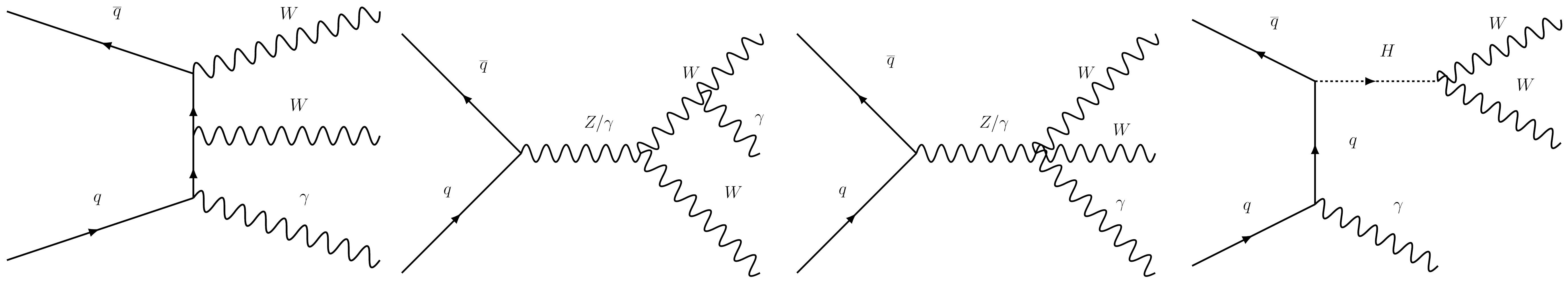
- Search only considers $\tau \to \mu\bar{\nu}_\mu\nu_\tau$ decays
- Final state: 4 isolated muons with sum(charge) = 0, $40\,\mathrm{GeV} < m_{\mu\mu\mu\mu} < 100\,\mathrm{GeV}$, $12\,\mathrm{GeV} < m^{\max}_{\mu^+\mu^-} < 75\,\mathrm{GeV}$
- Background from nonprompt muons estimated via isolation sidebands in data
- Signal expected as broad distribution peaking below m_Z



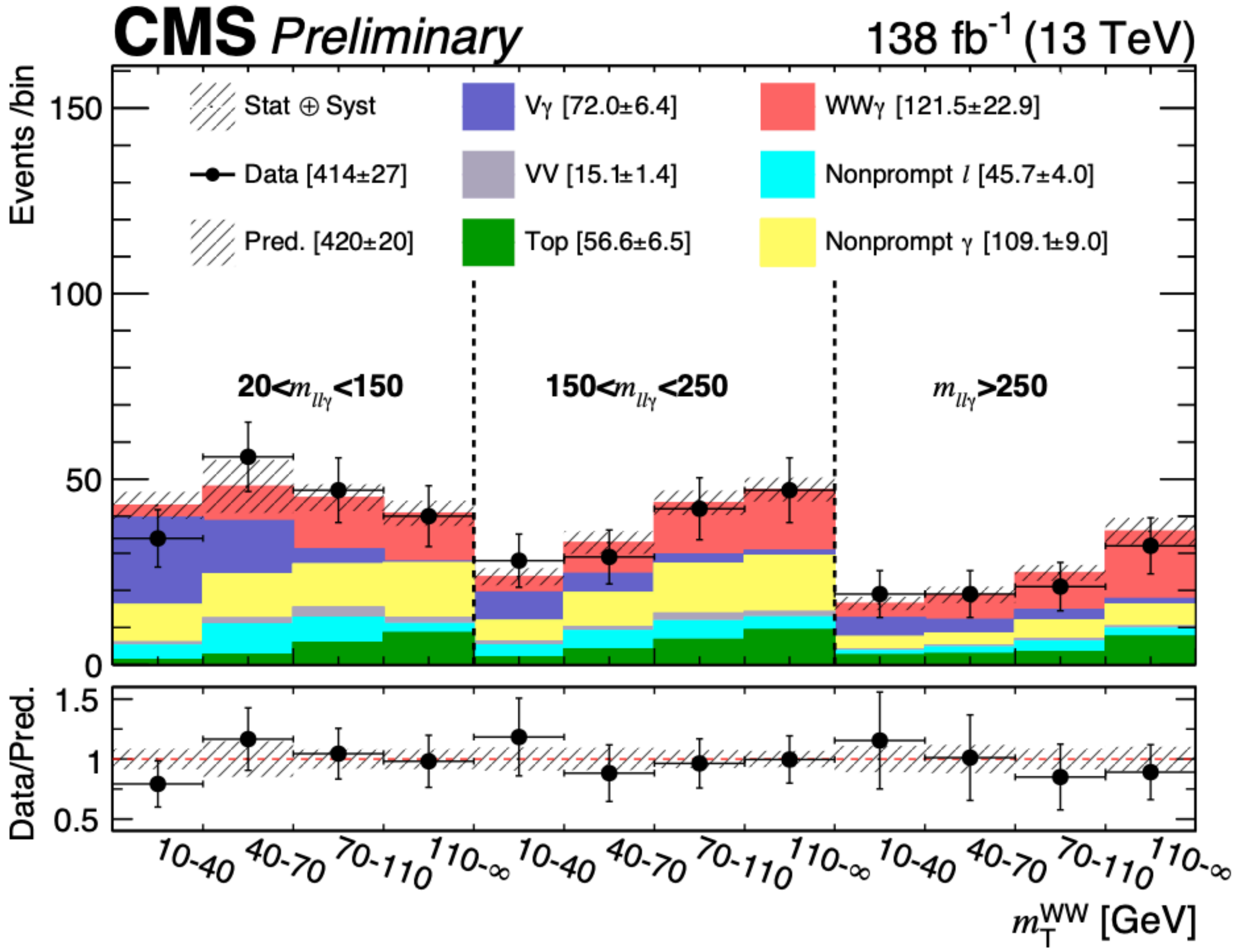


- No observation so far
- $\dfrac{\mathscr{B}(Z \to \mu^+\mu^-\tau^+\tau^-)}{\mathscr{B}(Z \to \mu^+\mu^-\mu^+\mu^-)} < 6.2$
- $\mathscr{B}(Z \to \mu\mu\tau\tau) < 6.9 \times \mathscr{B}_{\mathrm{SM}}(Z \to \mu\mu\tau\tau)$

Observation of $\mathrm{WW}\gamma$ production



- **First observation of $\mathrm{WW}\gamma$** (previously observed $\mathrm{W}\gamma\gamma$, $\mathrm{Z}\gamma\gamma$, and VVV)
    - Important for measuring triple and quartic gauge couplings
- Only considering $e\mu$ final state
- Uses data-driven non-prompt background estimation
- Cross section extracted from maximum likelihood fit of $m_{\mathrm{T}}^{\mathrm{WW}}-m_{\ell\ell\gamma}$ distributions
- Also used as search for $\mathrm{H}(\rightarrow\mathrm{WW})\gamma$ production, which is sensitive to couplings with light quarks



Process	σ_{up} pb exp.(obs.)	Yukawa couplings limits exp.(obs.)
$\mathrm{u\bar{u}} \rightarrow \mathrm{H}+\gamma \rightarrow \mathrm{e}\mu\gamma$	0.067 (0.085)	$\lvert\kappa_{\mathrm{u}}\rvert \leq 13000$ (16000)
$\mathrm{d\bar{d}} \rightarrow \mathrm{H}+\gamma \rightarrow \mathrm{e}\mu\gamma$	0.058 (0.072)	$\lvert\kappa_{\mathrm{d}}\rvert \leq 14000$ (17000)
$\mathrm{s\bar{s}} \rightarrow \mathrm{H}+\gamma \rightarrow \mathrm{e}\mu\gamma$	0.049 (0.068)	$\lvert\kappa_{\mathrm{s}}\rvert \leq 1300$ (1700)
$\mathrm{c\bar{c}} \rightarrow \mathrm{H}+\gamma \rightarrow \mathrm{e}\mu\gamma$	0.067 (0.087)	$\lvert\kappa_{\mathrm{c}}\rvert \leq 110(200)$

Observation with 5.6σ

$\sigma = 6.0 \pm 1.7\,\mathrm{fb} = 6.0 \pm 1.0\,(\mathrm{stat}) \pm 1.0\,(\mathrm{syst}) \pm 0.9\,(\mathrm{th})\,\mathrm{fb}$

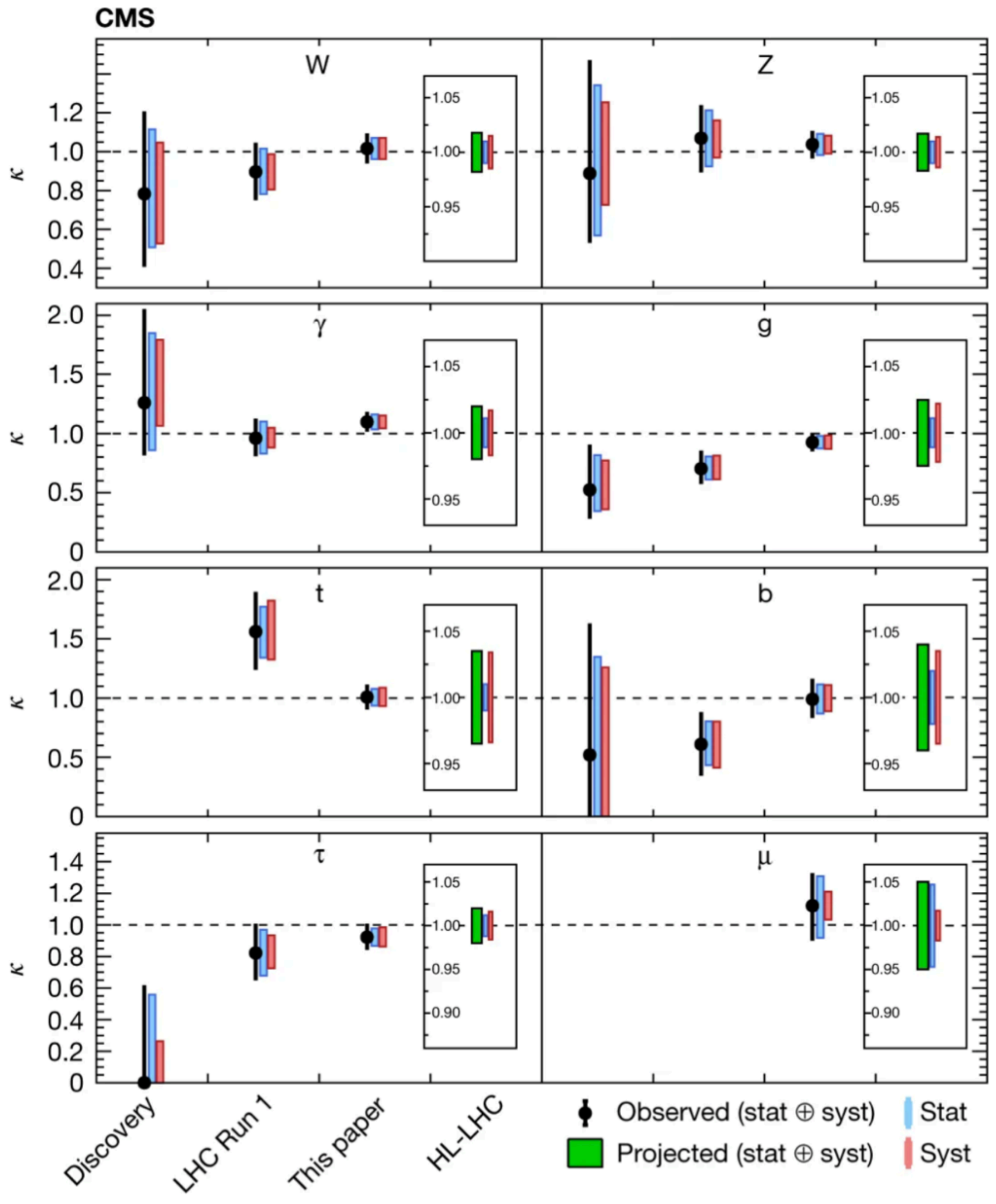
In agreement with the SM prediction

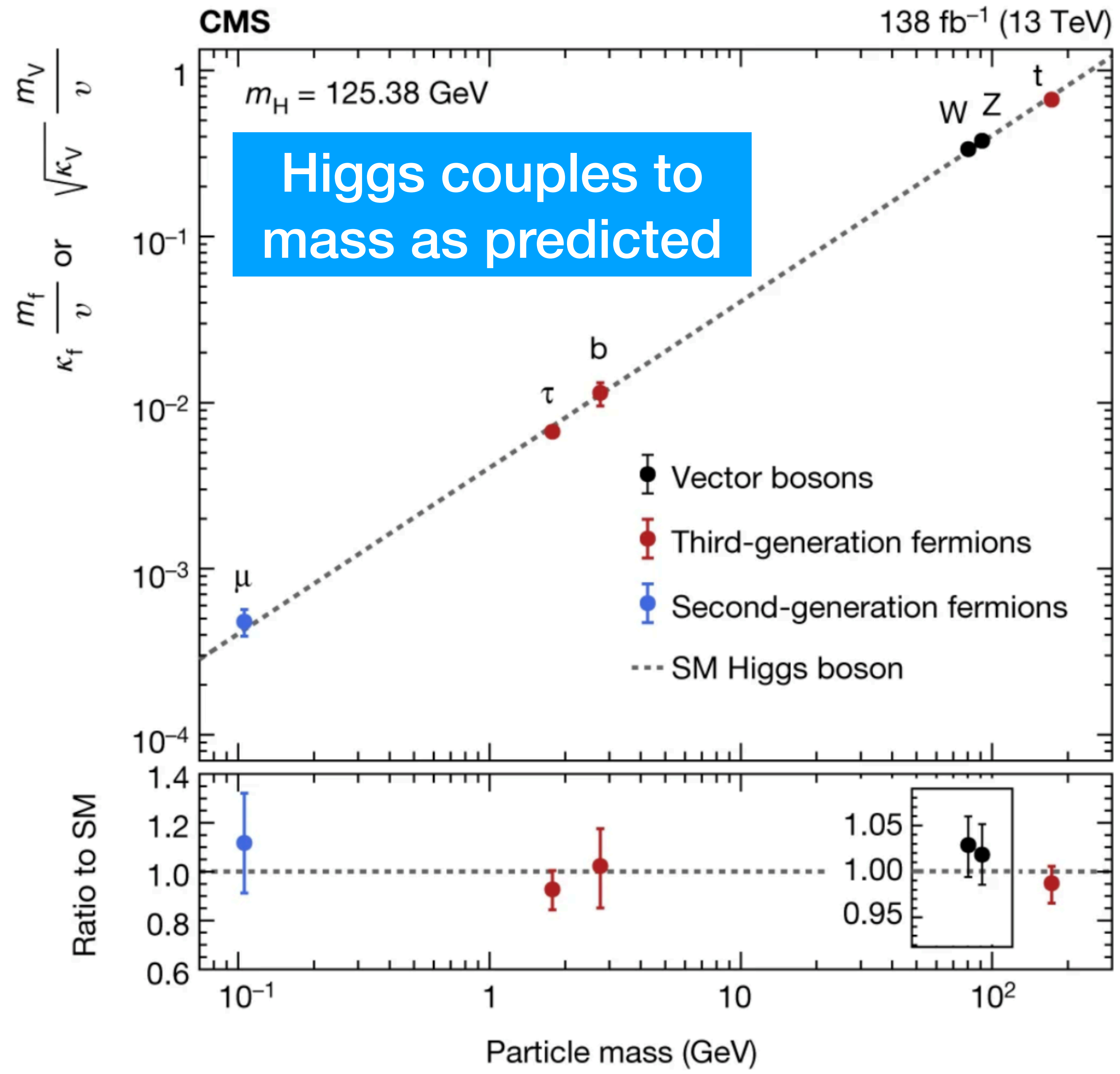
Nature 607, 60-68 (2022)

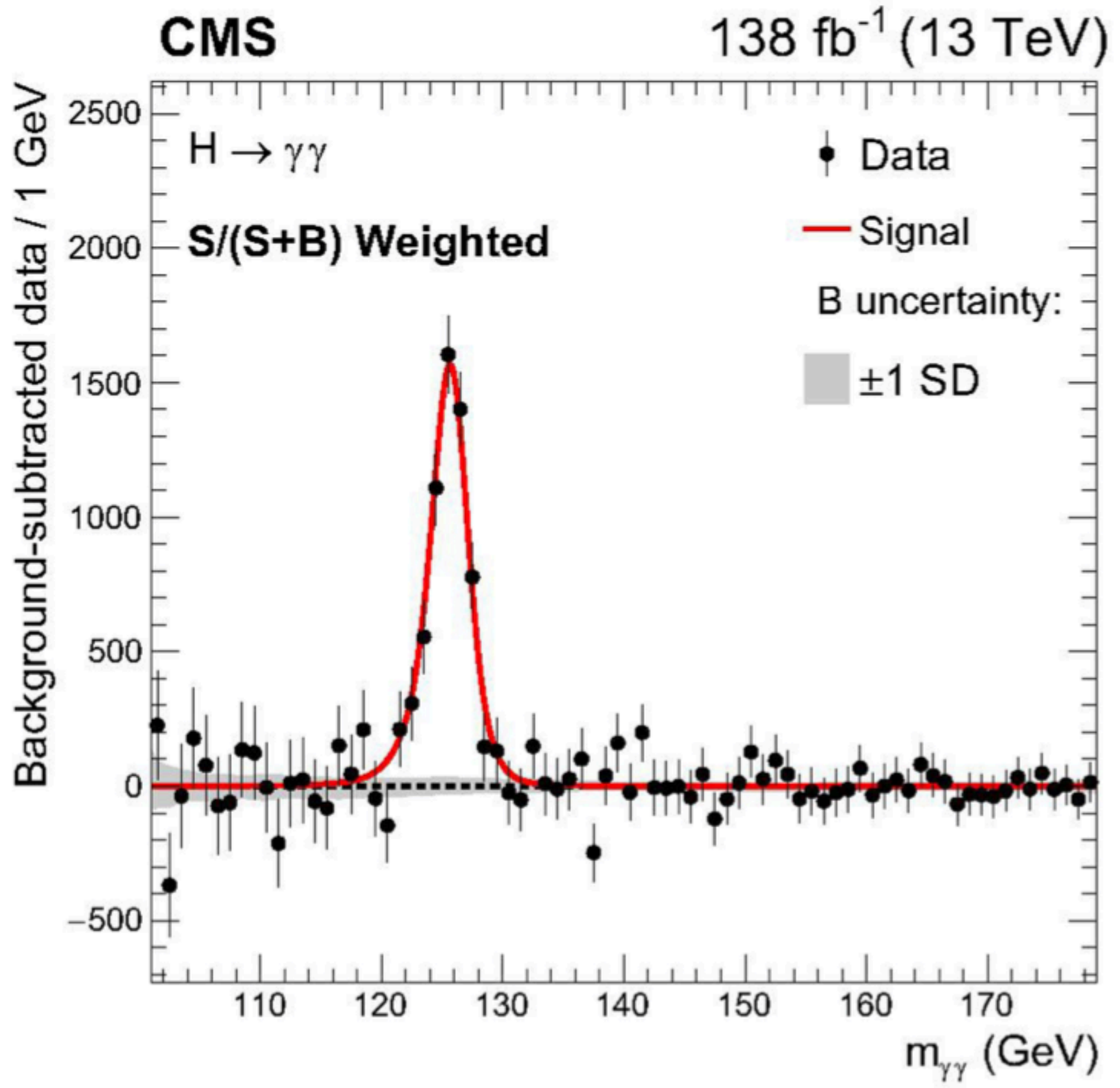
Higgs

- Celebrated 10 year anniversary of the Higgs boson discovery in 2022!
- Remarkable transition from initial discovery to precision measurements
- Efforts expanding into exotic decays, searching for other Higgs-like particles, etc

Higgs coupling precision

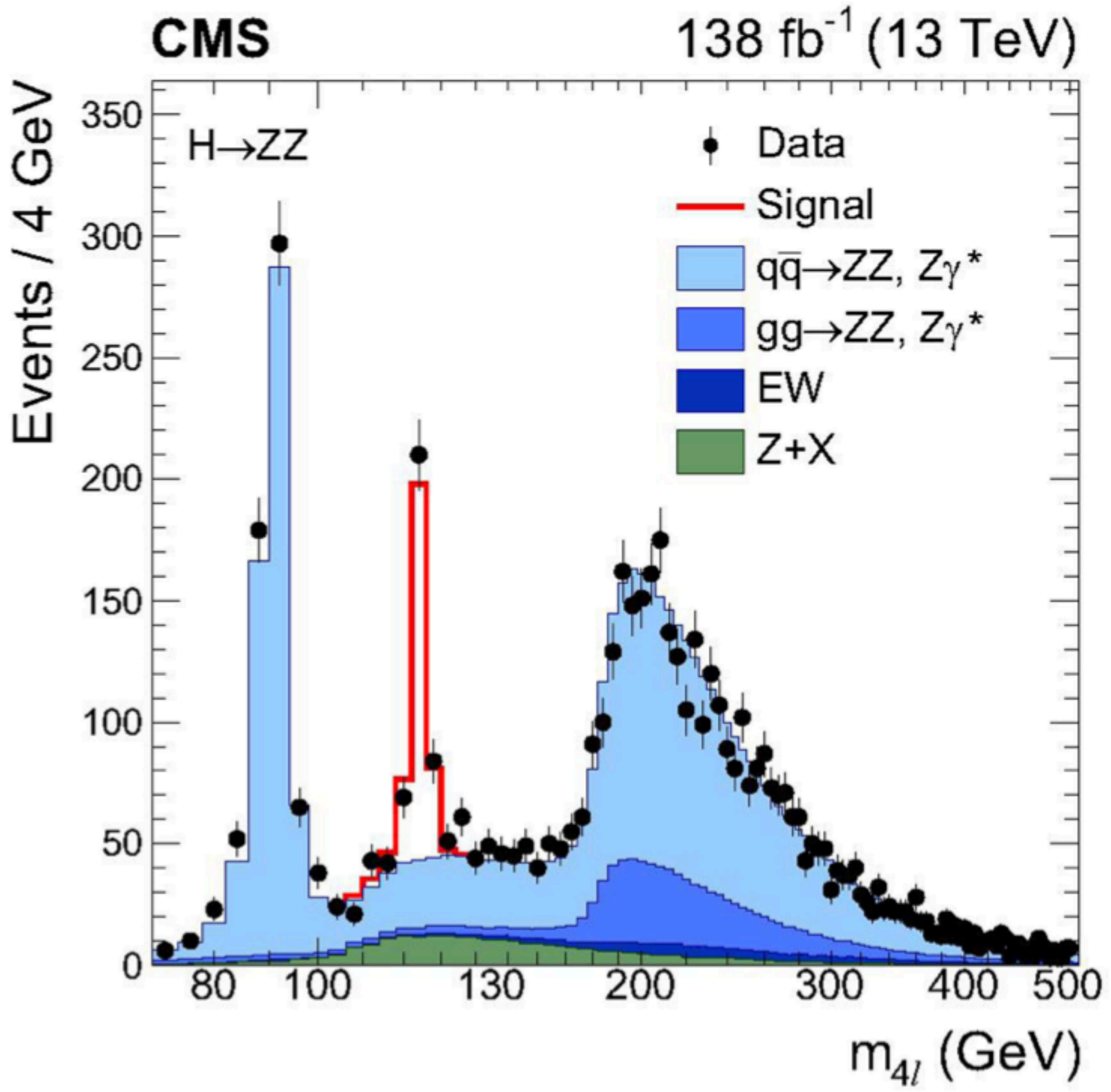






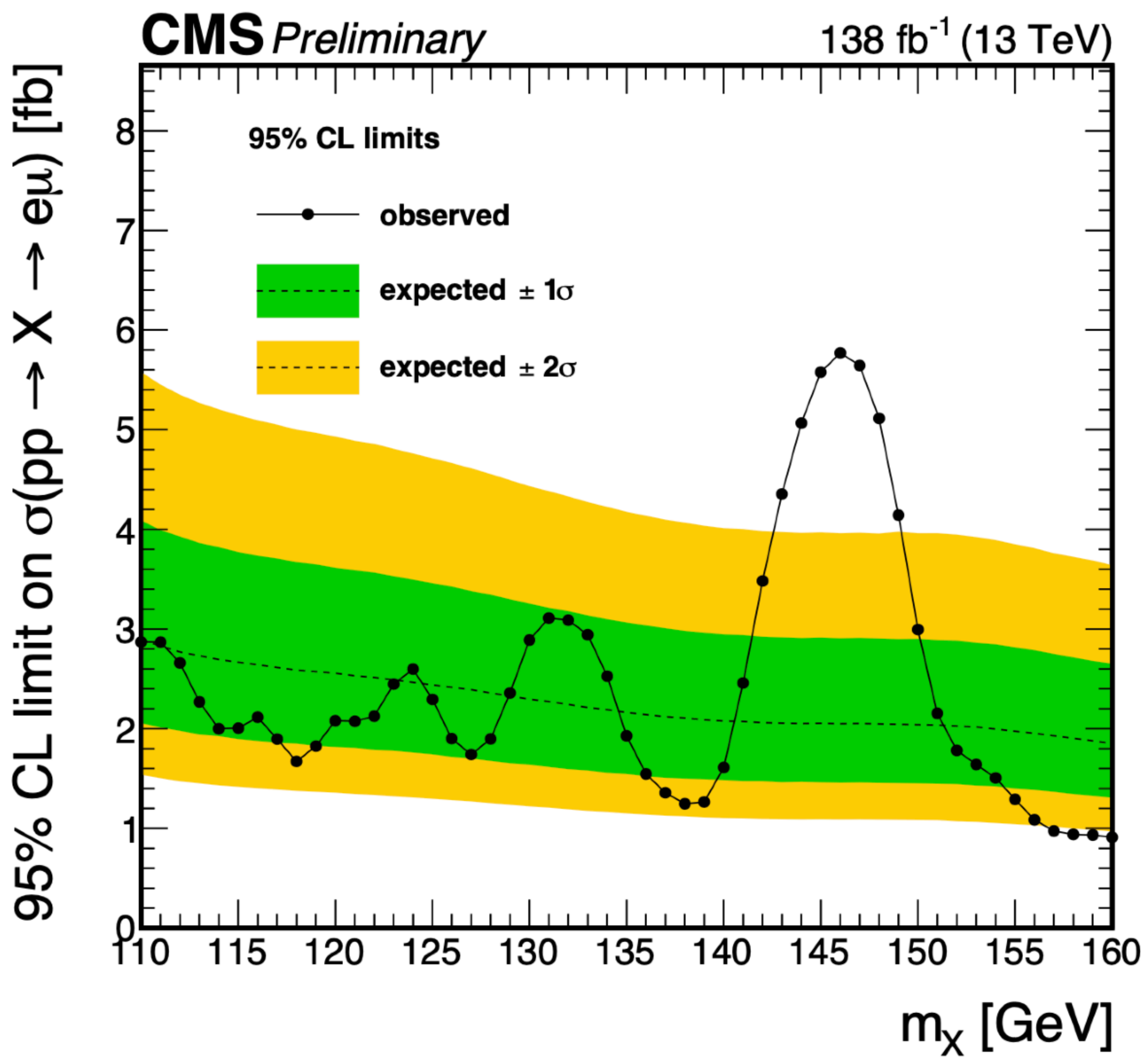
$m_H = 125.38 \pm 0.14\,\mathrm{GeV}$

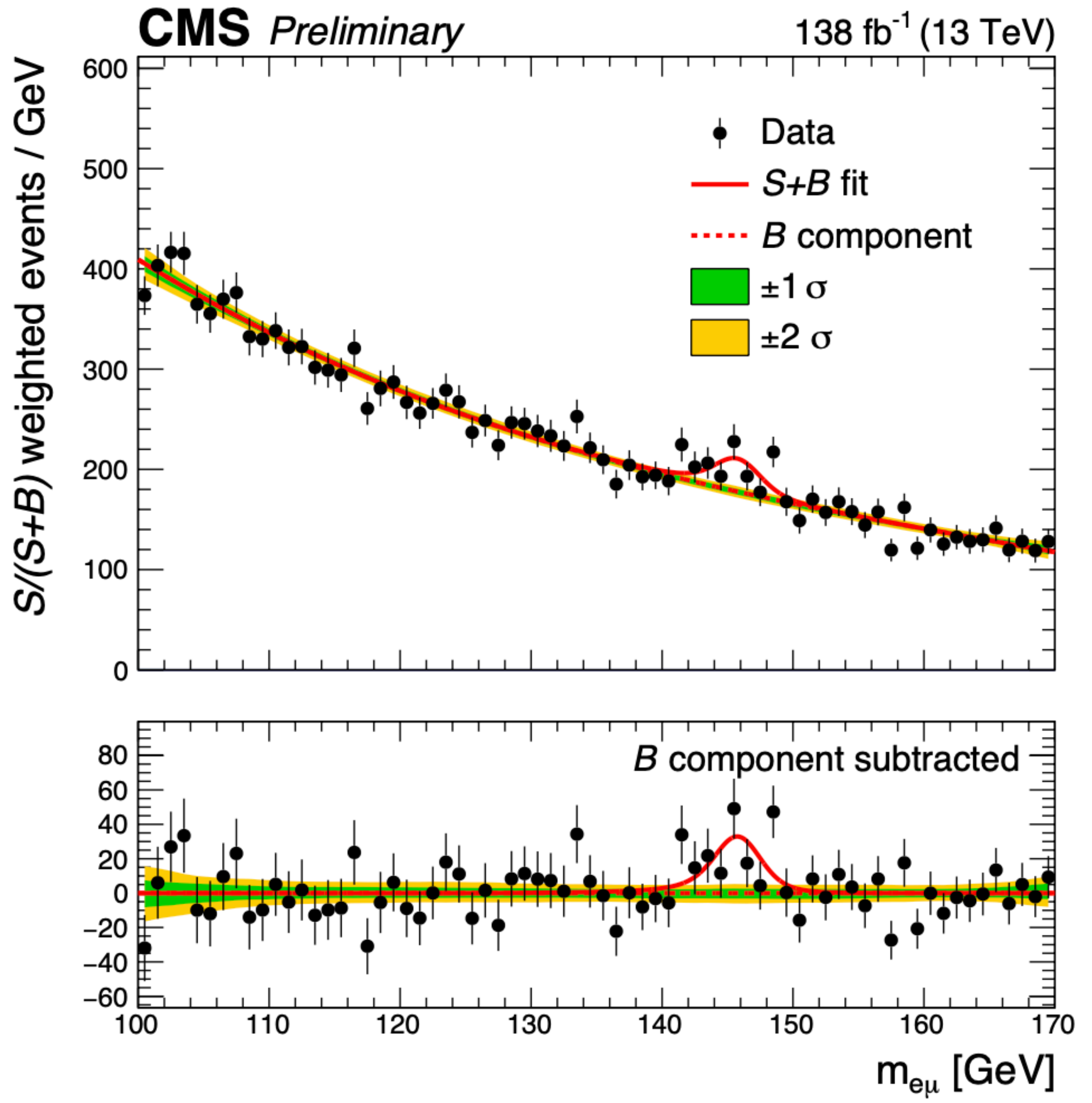
0.1% precision!



Lepton-flavor violation in Higgs sector: search for $H \rightarrow e\mu$

- LFV decays of Higgs forbidden in SM, but arise in BSM scenarios
  - Prior bound: $\mathscr{B}(\mathrm{H} \rightarrow \mathrm{BSM}) < 0.16$
- Search considers any resonance with mass of 110-160 GeV
  - Selects opposite-charge e-μ pair
  - Categorization based on production mode: ggF and VBF
  - Further categorized based on BDTs for signal vs background
  - $m_{e\mu}$ distribution fit in data with Bernstein polynomial for background, and interpolated sum of Gaussians for signal





No excess observed at mass of 125 GeV: $\mathscr{B} < 4.4\,(4.7) \times 10^{-5}$
ATLAS: $\mathscr{B} < 6.2\,(5.9) \times 10^{-5}$

Slight excess observed at mass of 146 GeV: 2.8σ global (3.8σ local)
Not observed in similar search by ATLAS

Exotic decays of the Higgs

2016-2018 data

- Light pseudoscalars appear in many BSM models (2HDM, 2HDM+S, NMSSM, ALPs)
- Possible search channels include $\mathrm{H} \to \mathrm{aa}$ and $\mathrm{H} \to \mathrm{Za}$

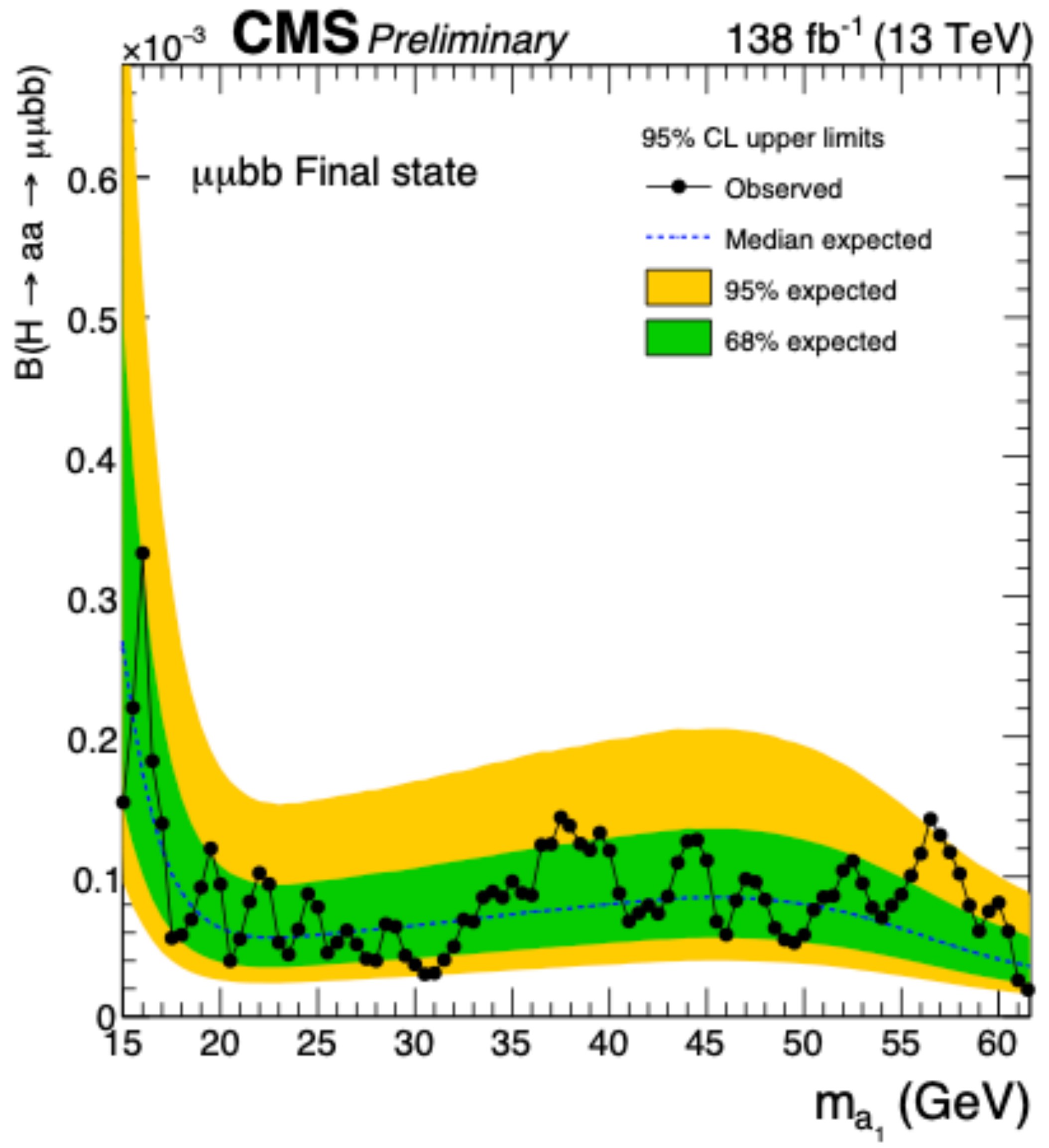
HIG-22-007

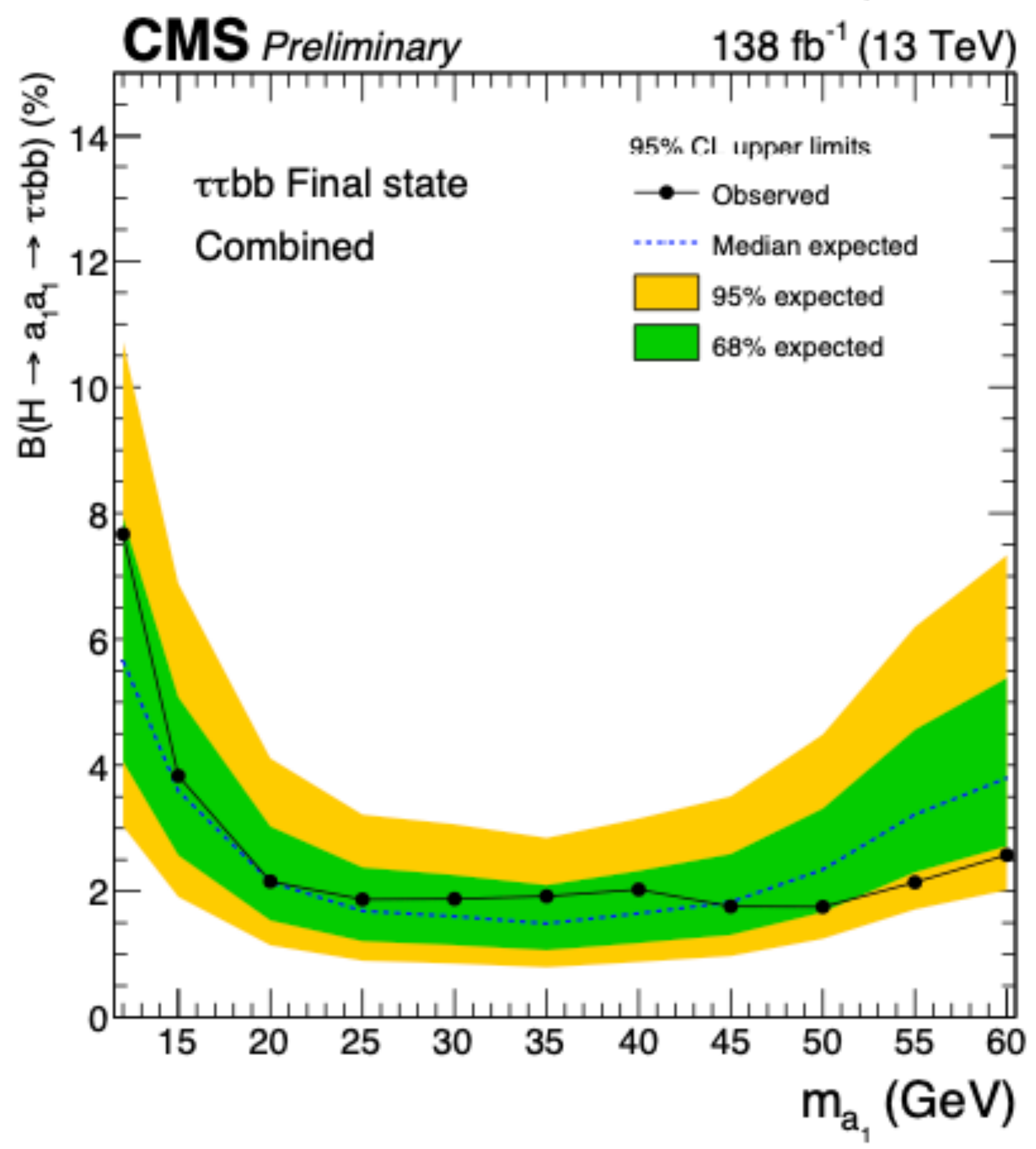
$\mathrm{H} \to \mathrm{aa} \to \mu\mu\mathrm{bb}/\tau\tau\mathrm{bb}$

$\mathrm{H} \to \mathrm{aa} \to \mu\mu\mathrm{bb}$
- 2 muons with $m_{\mu\mu}$ in 14-70 GeV
- Require compatibility of $m_{\mu\mu}$ with m_{bb} and $m_{\mu\mu\mathrm{bb}}$ with m_{H}

$\mathrm{H} \to \mathrm{aa} \to \tau\tau\mathrm{bb}$
- 3 final states: $e\mu$, $e\tau_h$, $\mu\tau_h$
- Use DNN for S vs B using kinematic variables as input

No significant excess observed



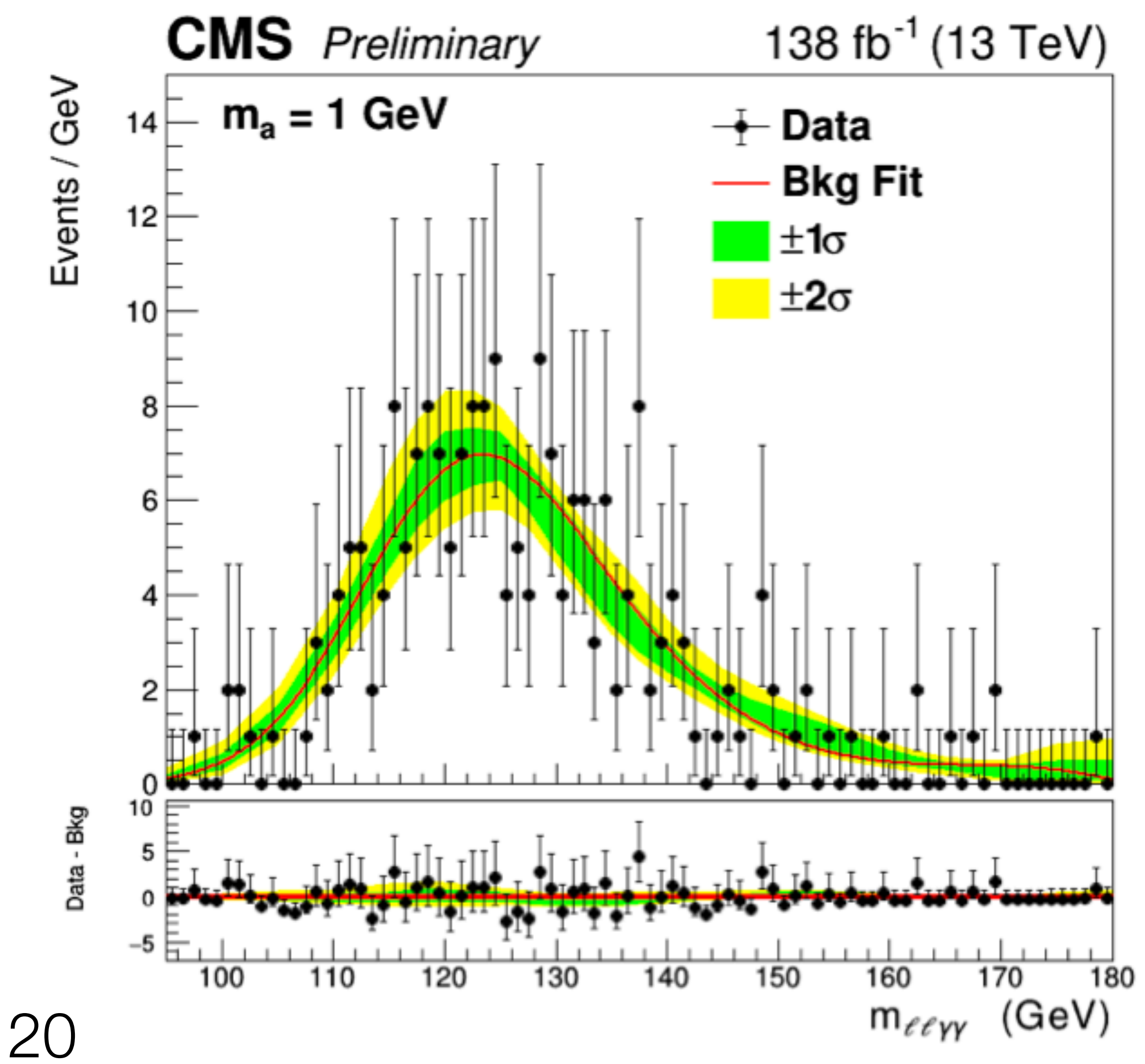


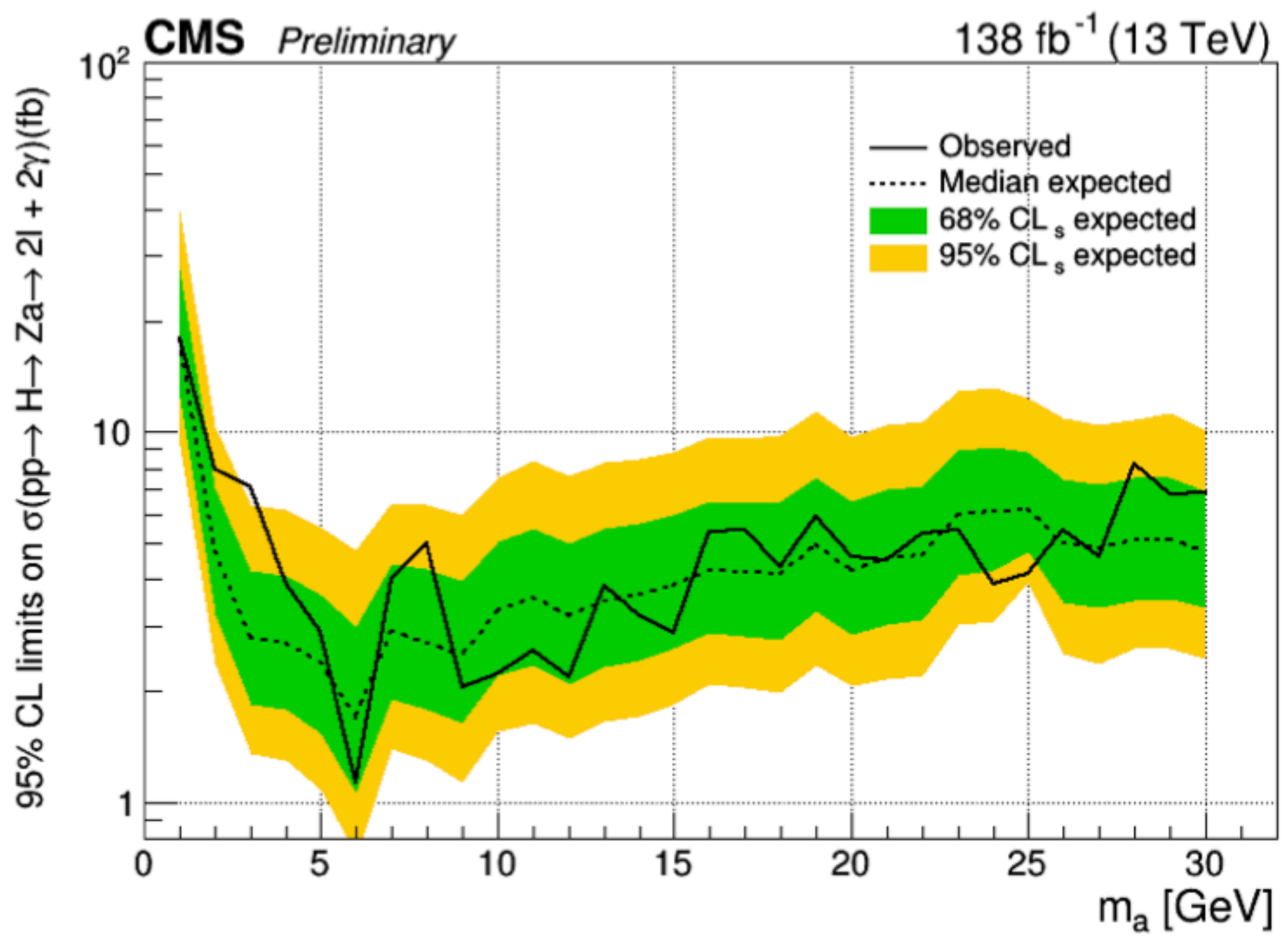
$\mathrm{H} \to \mathrm{Za} \to \ell\ell\gamma\gamma$

HIG-22-003

- Used BDT with $m_{a,\mathrm{hyp}}$ as input parameter to allow for single training with interpolation between signal masses
- Events categorized based on BDT output for each mass hypothesis

No significant excess observed



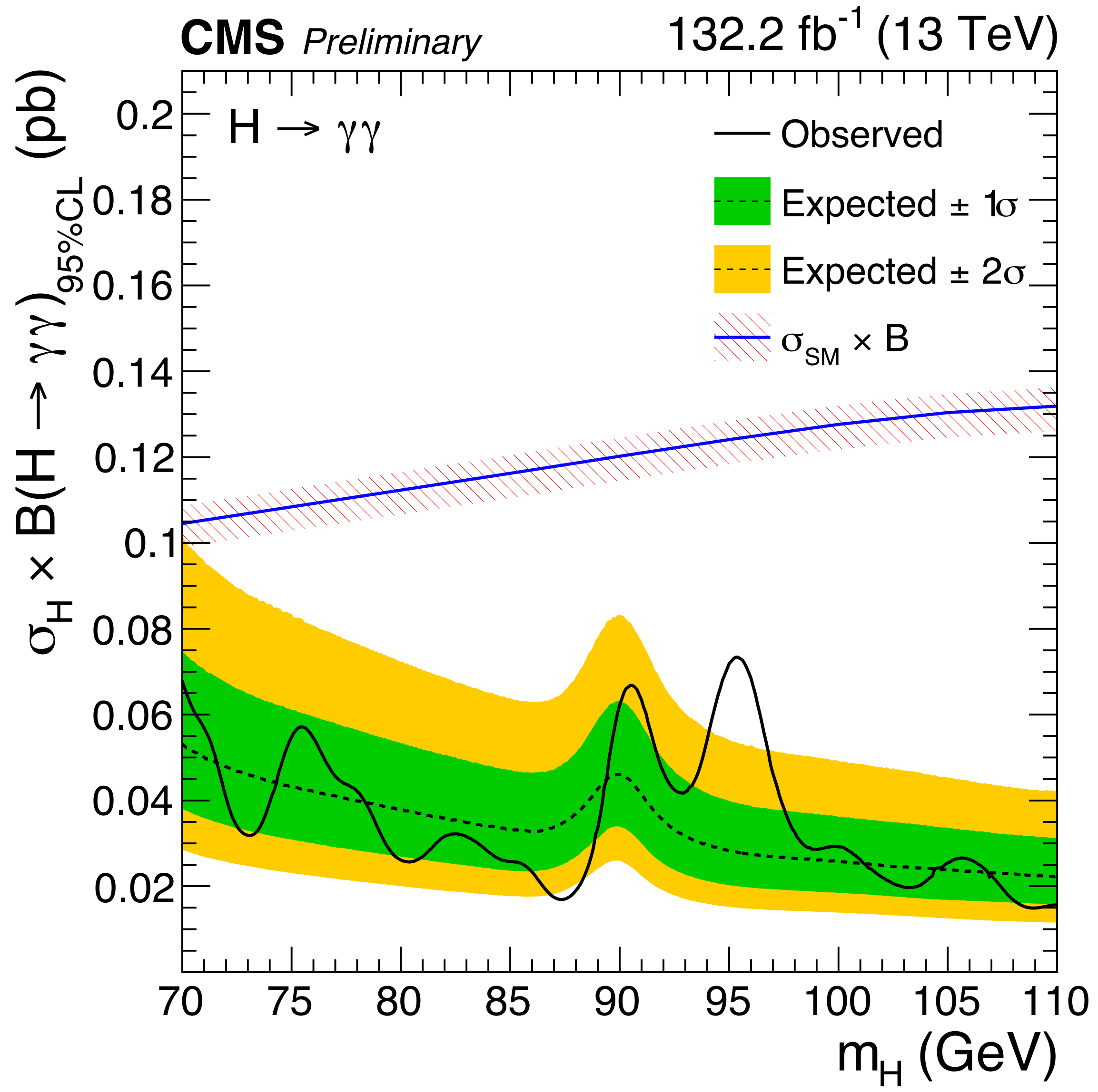


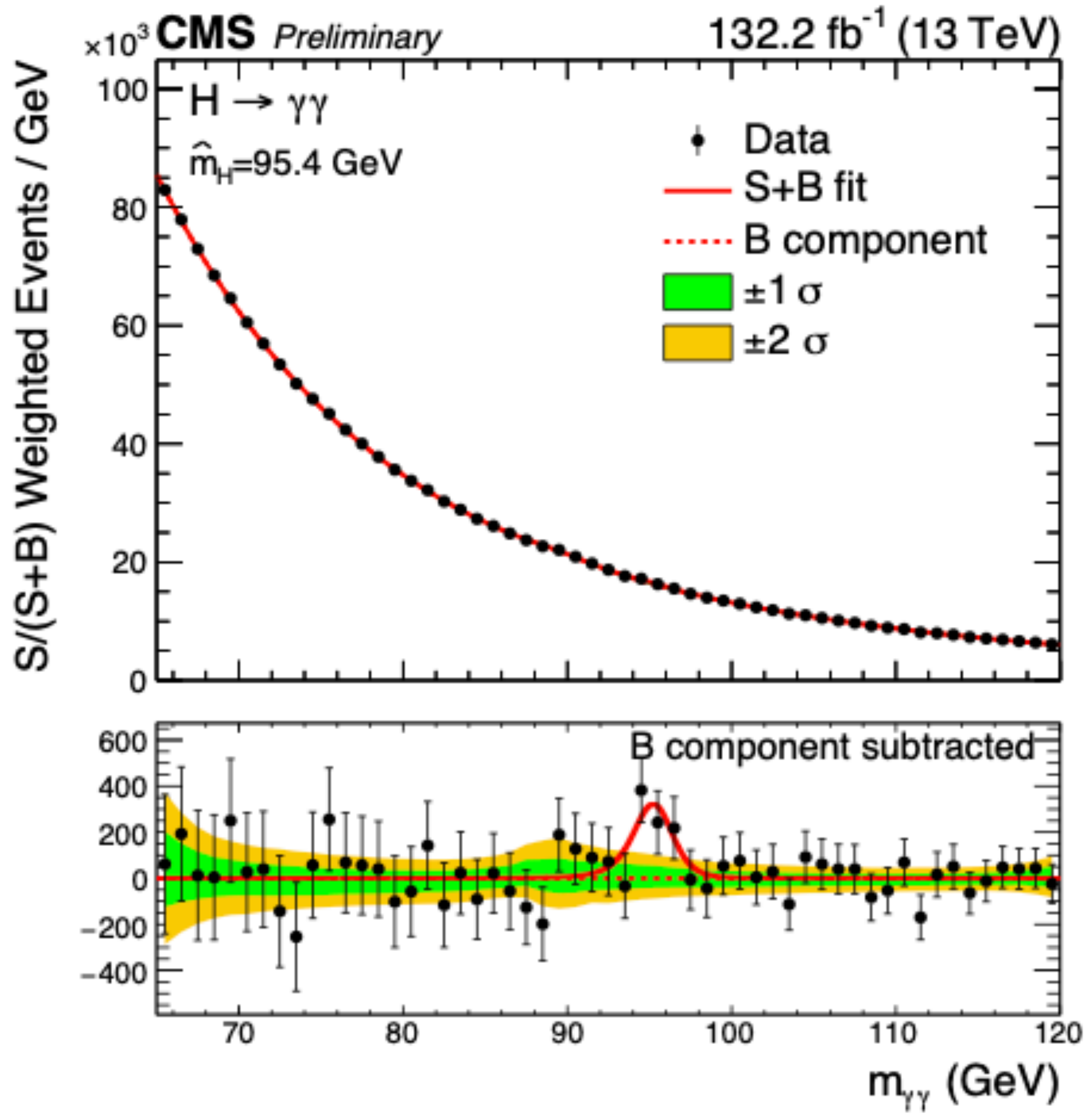
Search for SM-like Higgs [70–110 GeV] in $\gamma\gamma$ channel

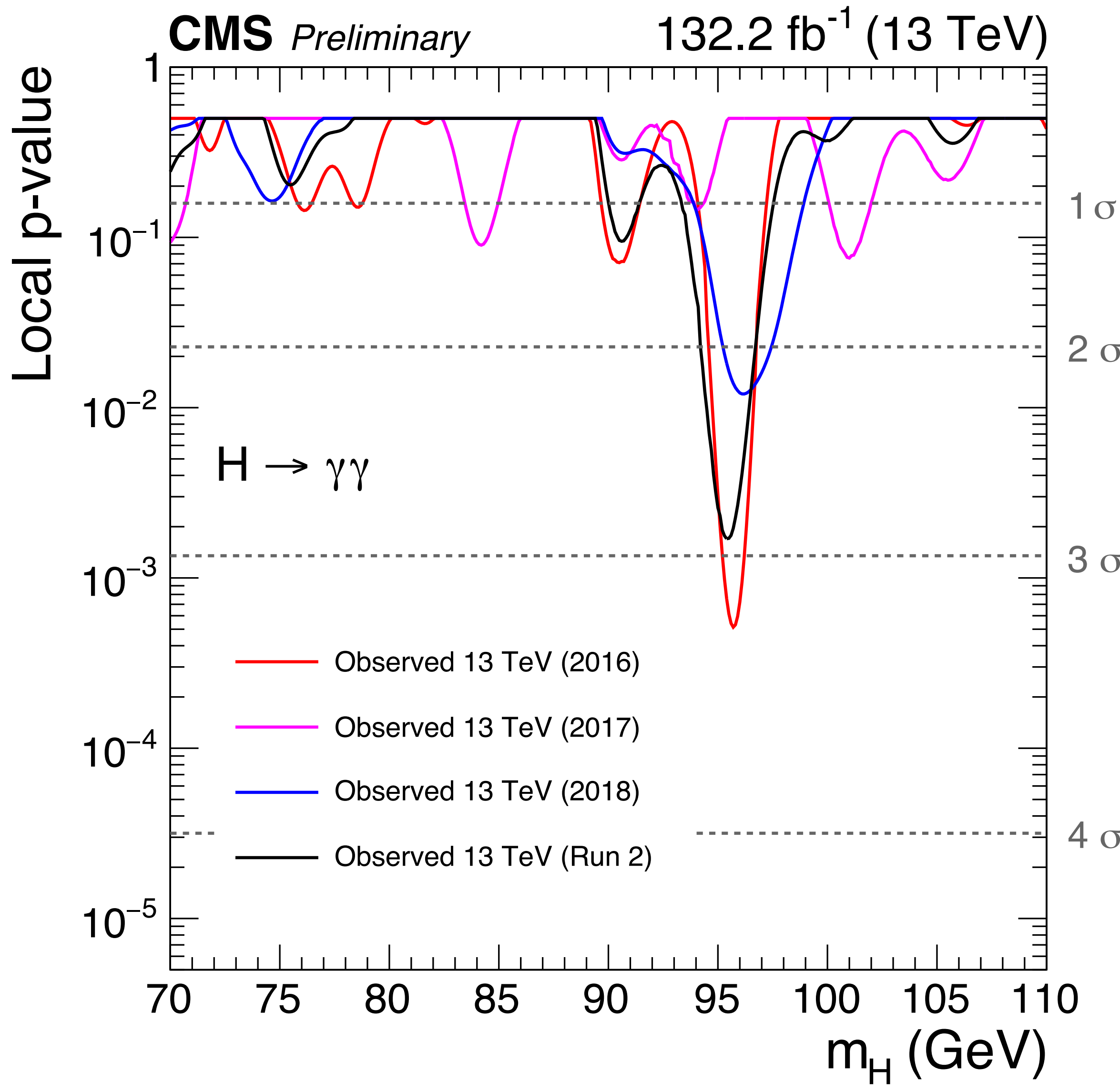
- BSM models (e.g 2HDM or NMSSM) predict additional Higgs bosons which could be lighter than 125 GeV and could evade the LEP bounds
- Search is done in final state with 2 photons with $m_{\gamma\gamma} \in [70{,}110]\,\mathrm{GeV}$
  - Extension of HIG-17-013 with final detector calibrations, full Run 2, and addition of VBF category
- MVA techniques used for photon identification and event classification
- Main backgrounds:
  - direct diphoton production
  - photon+jet and jet+jet production where jet is misidentified
  - DY to ee, where electrons are misidentified as photons
- Backgrounds fit with parametric functions using discrete profiling method

Largest excess at 95.4 GeV, local: 2.9σ, global: 1.3σ (Not visible in 2017)

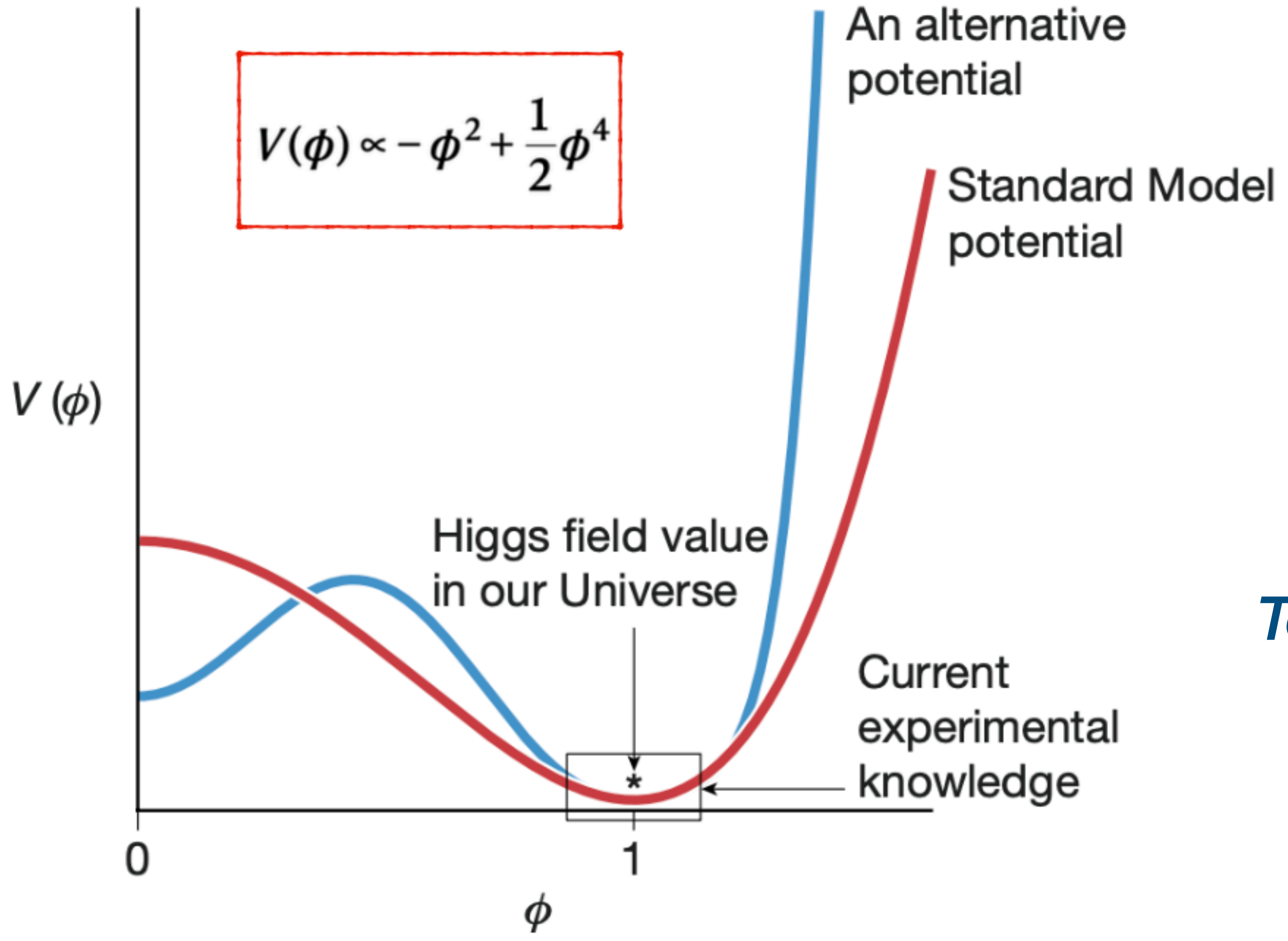
Exclude SM cross section x branching fraction for full considered mass range







Di-Higgs production



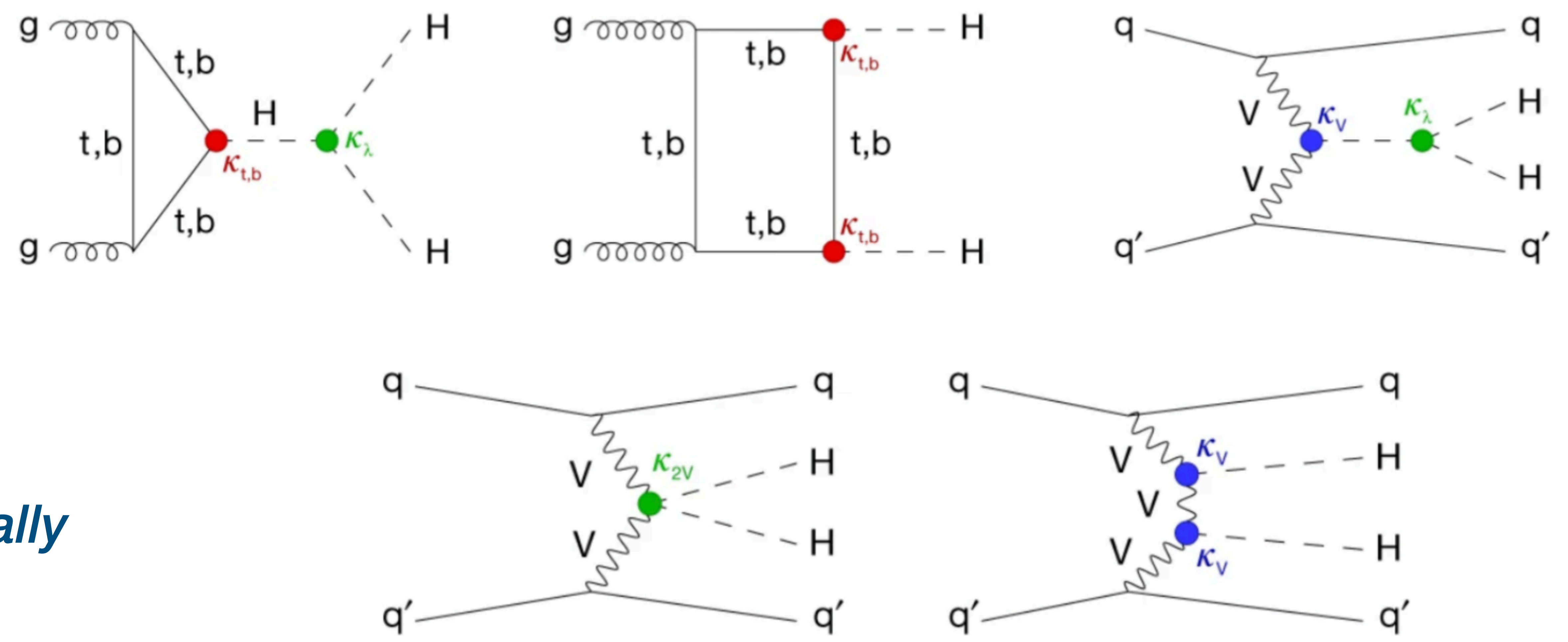
$$V(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$$

EW symmetry breaking

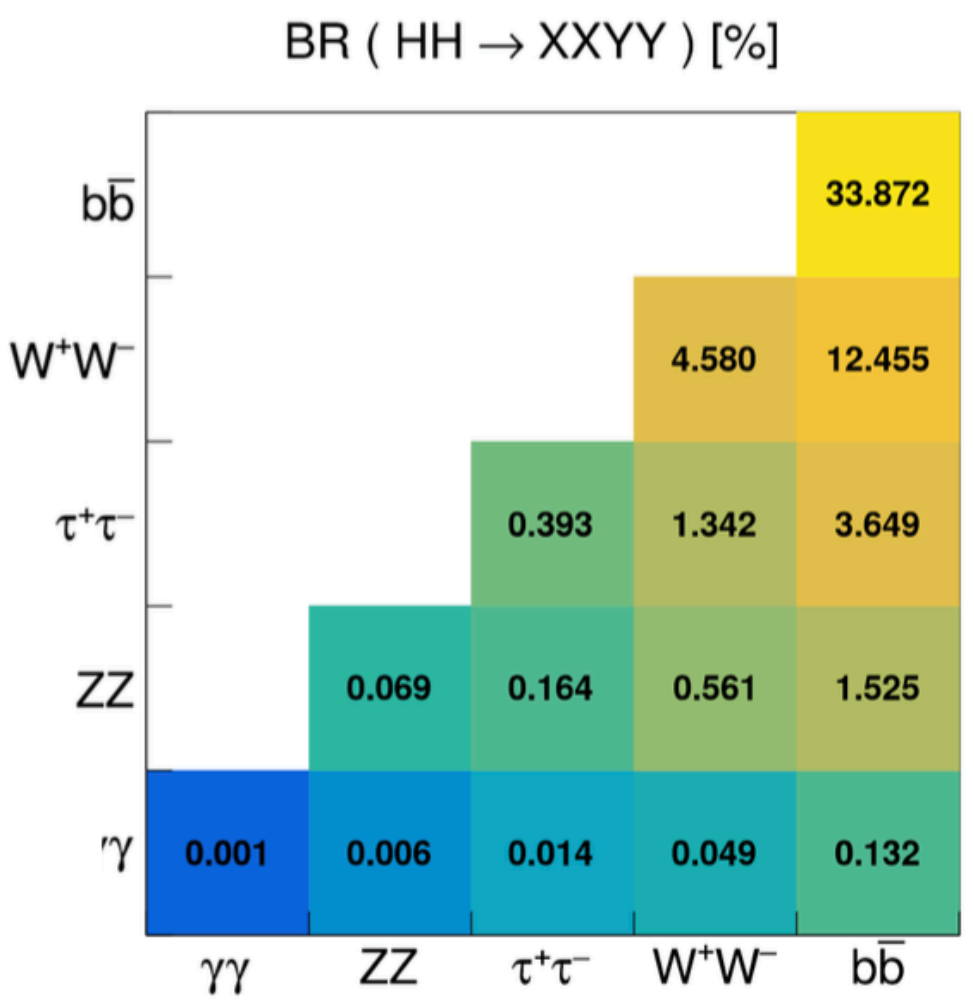
$$\mu^2 = \lambda v^2$$
$$m_H^2 = 2\lambda v^2$$

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4$$

Test experimentally



- Di-Higgs production probes the tri-Higgs and quartic couplings, κ_λ and κ_{2V}
- Dominant production is through ggF, 3 orders of magnitude smaller than single Higgs production!
- Explore as many decay modes as possible!



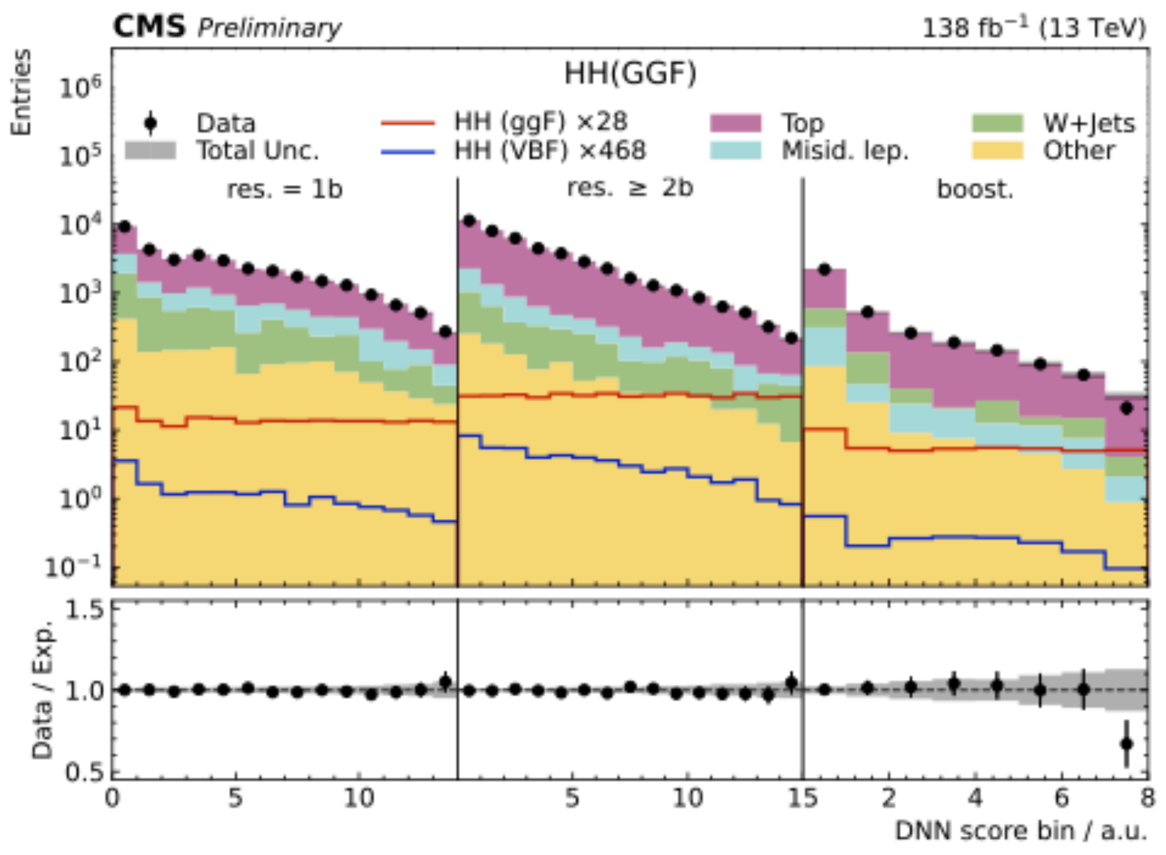
2016-2018 data

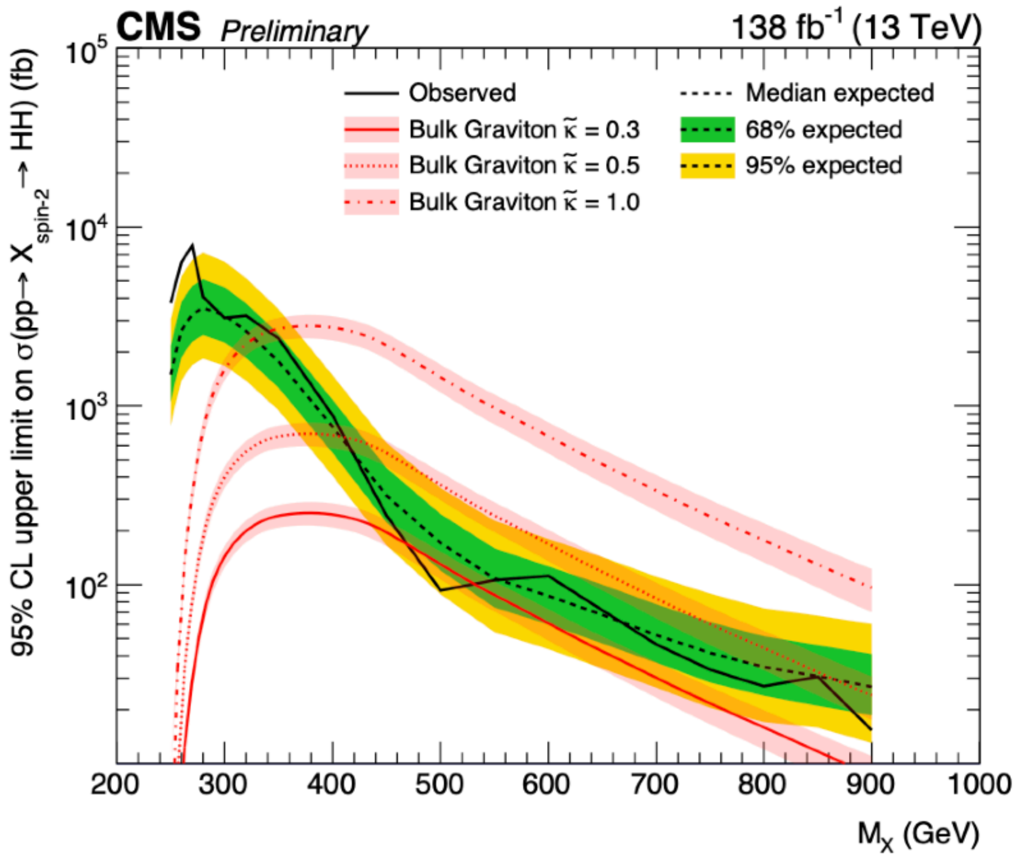
Searches for di-Higgs production

HIG-21-005

HH → bbWW

- Final states with ≥1 lepton
- H → bb decay identified using btagging for either small (resolved) or large (boosted) radius jets
- DNN used for signal extraction





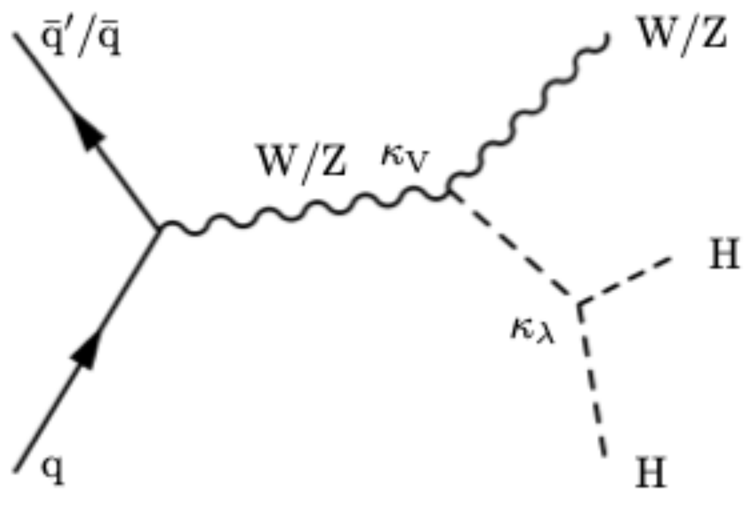
HH cross section constrained to be at most 14 (18) times the SM expectation.

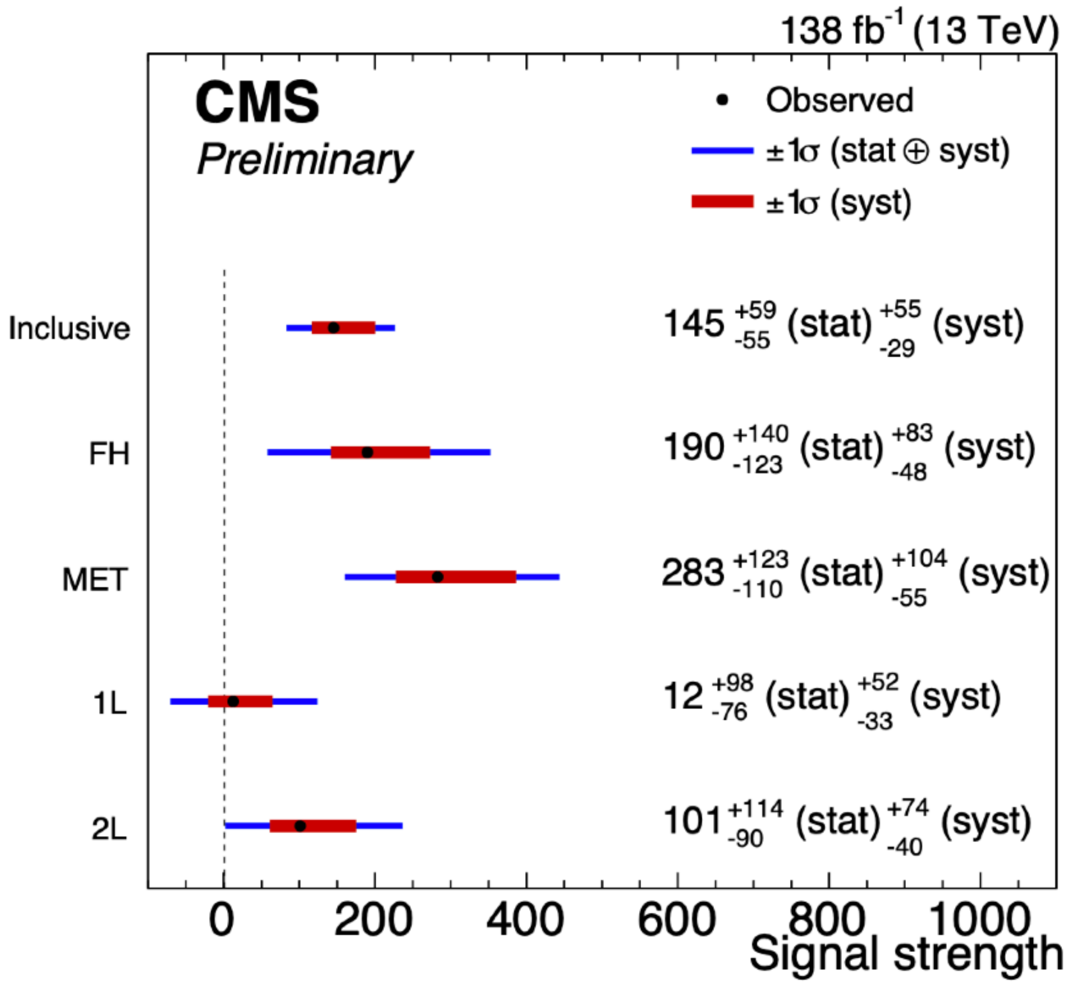
Also places limits on HH production via heavy resonance.

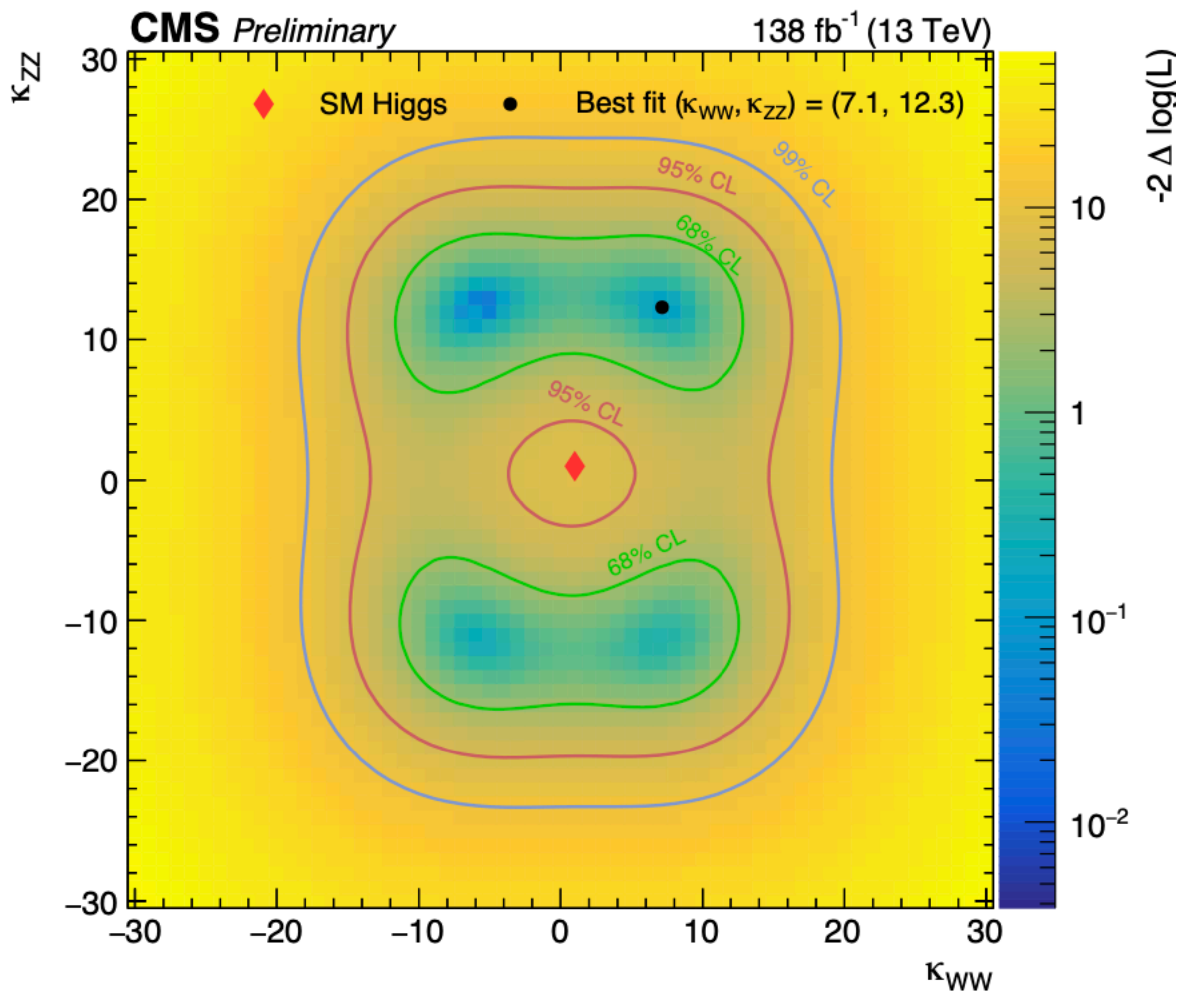
HH associated production with W/Z

HIG-22-006

- Construct HH → bbbb from 4 jets with highest b-tag scores
- All W/Z decays considered
- Use BDT to divide events into κ_λ and κ_{2V} enriched regions

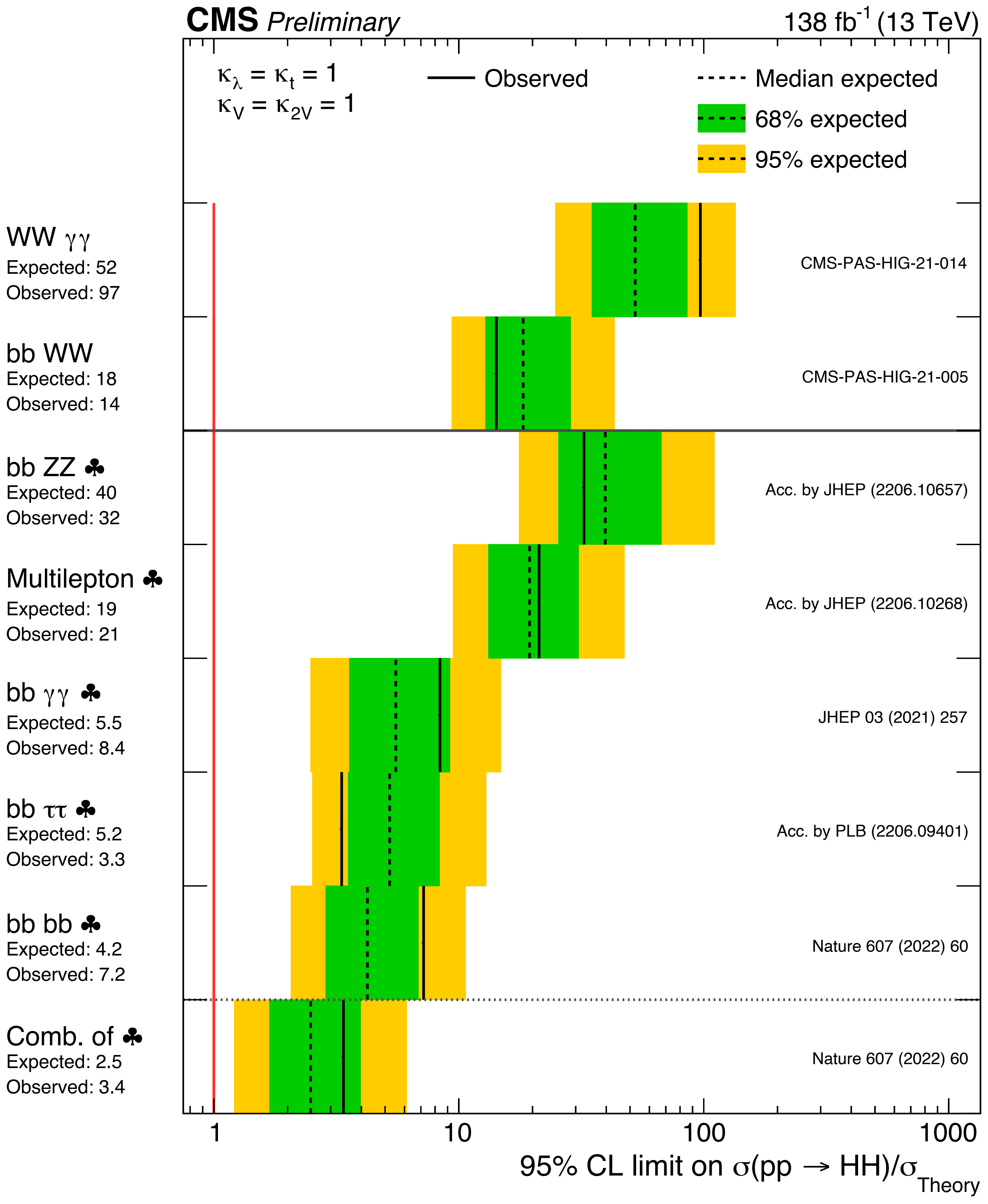


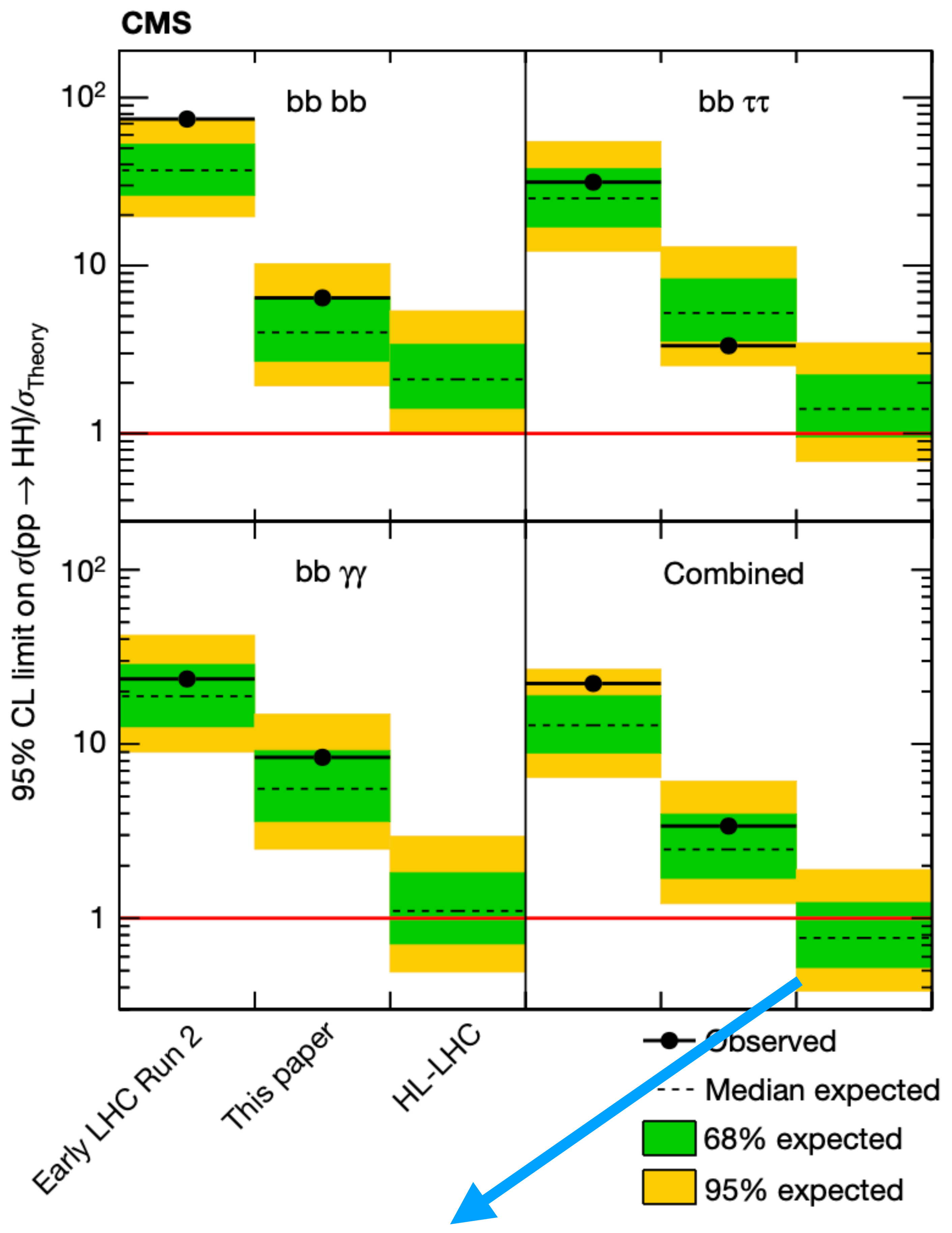




HH cross section constrained to be at most 288 (122) times the SM expectation.

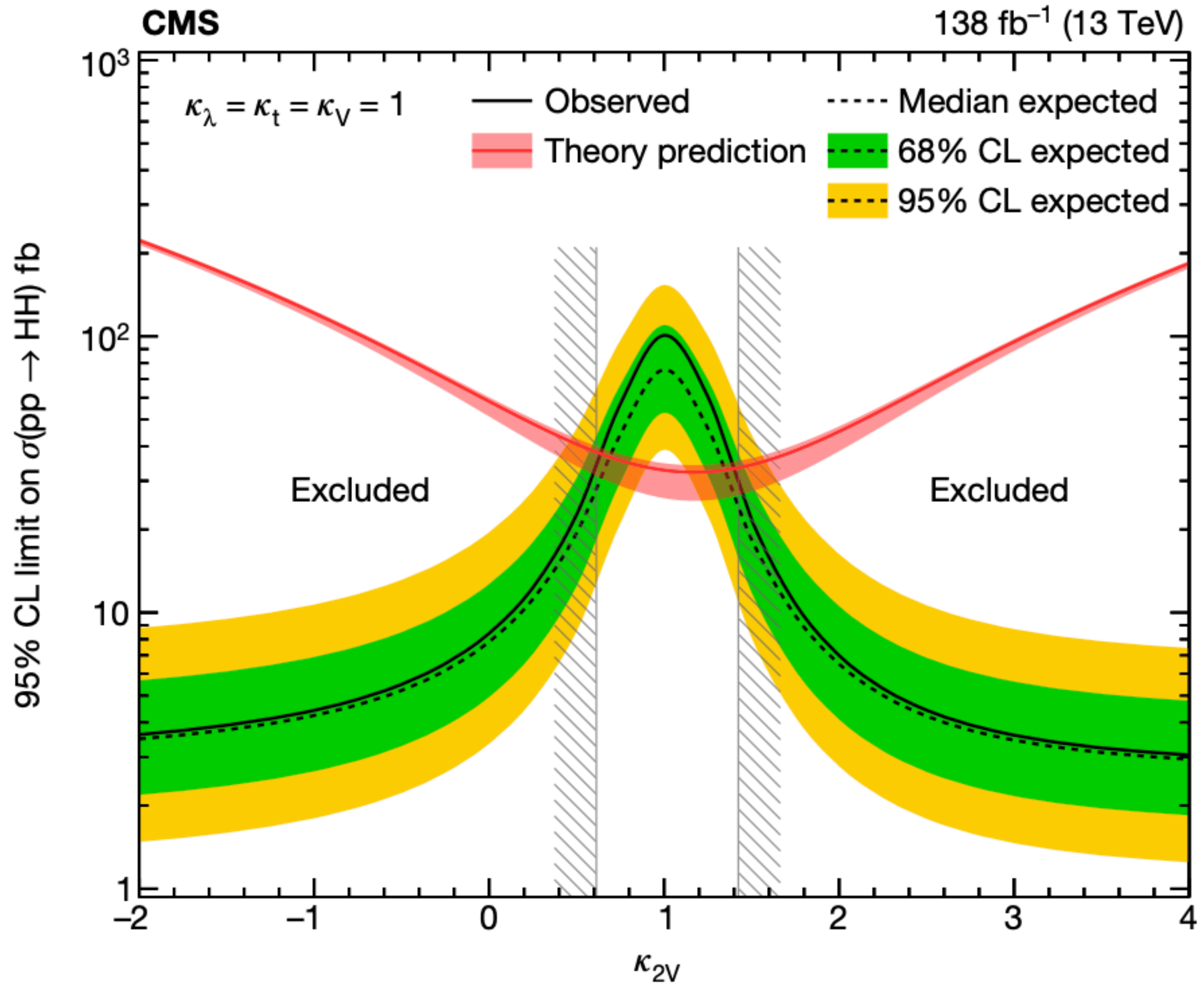
Di-Higgs production





Quartic coupling modifier: 0.67 < κ_{2V} < 1.38.

κ_{2V} = 0 is excluded with 6.6σ, establishing the existence of the quartic coupling VVHH

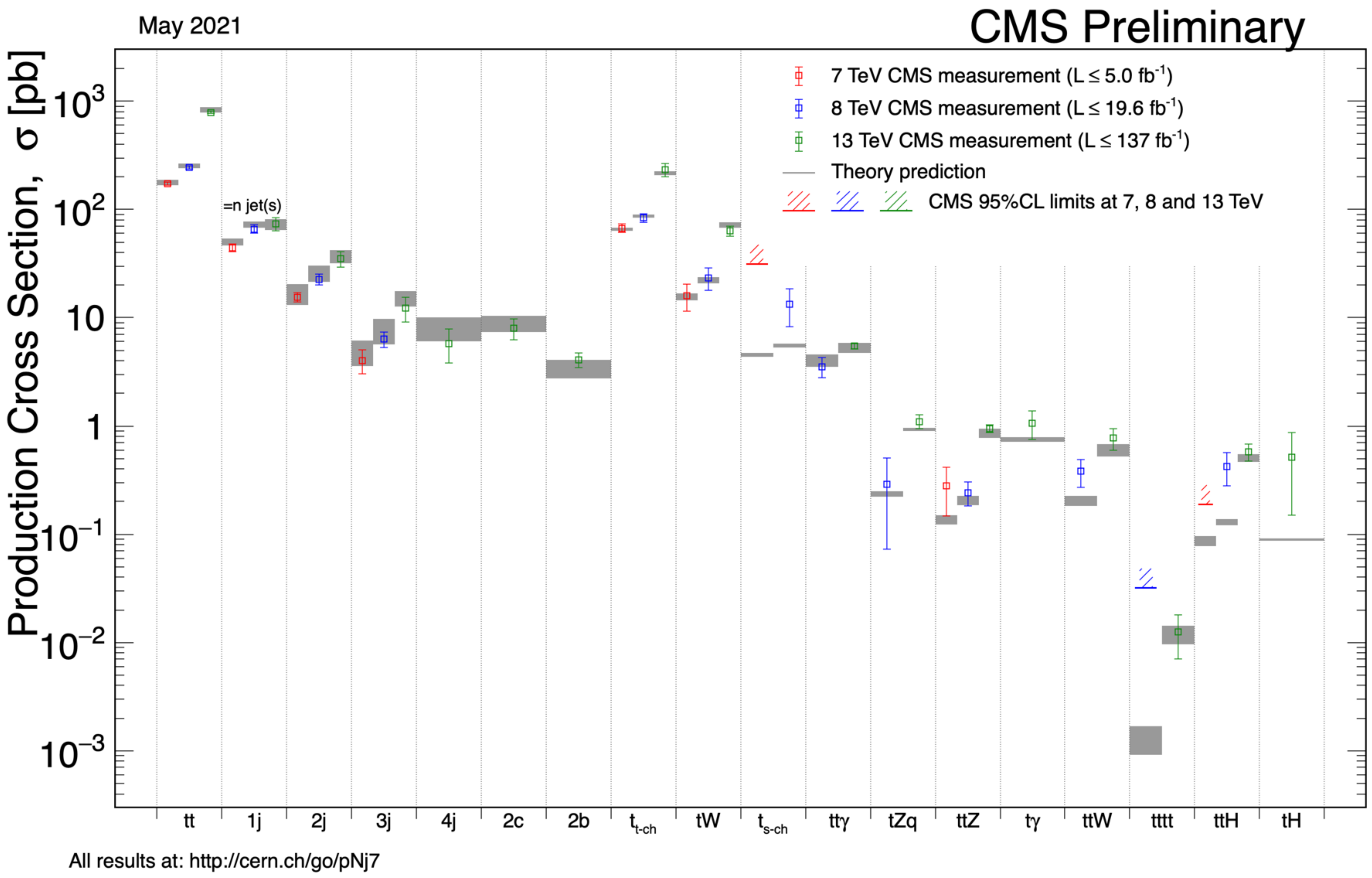


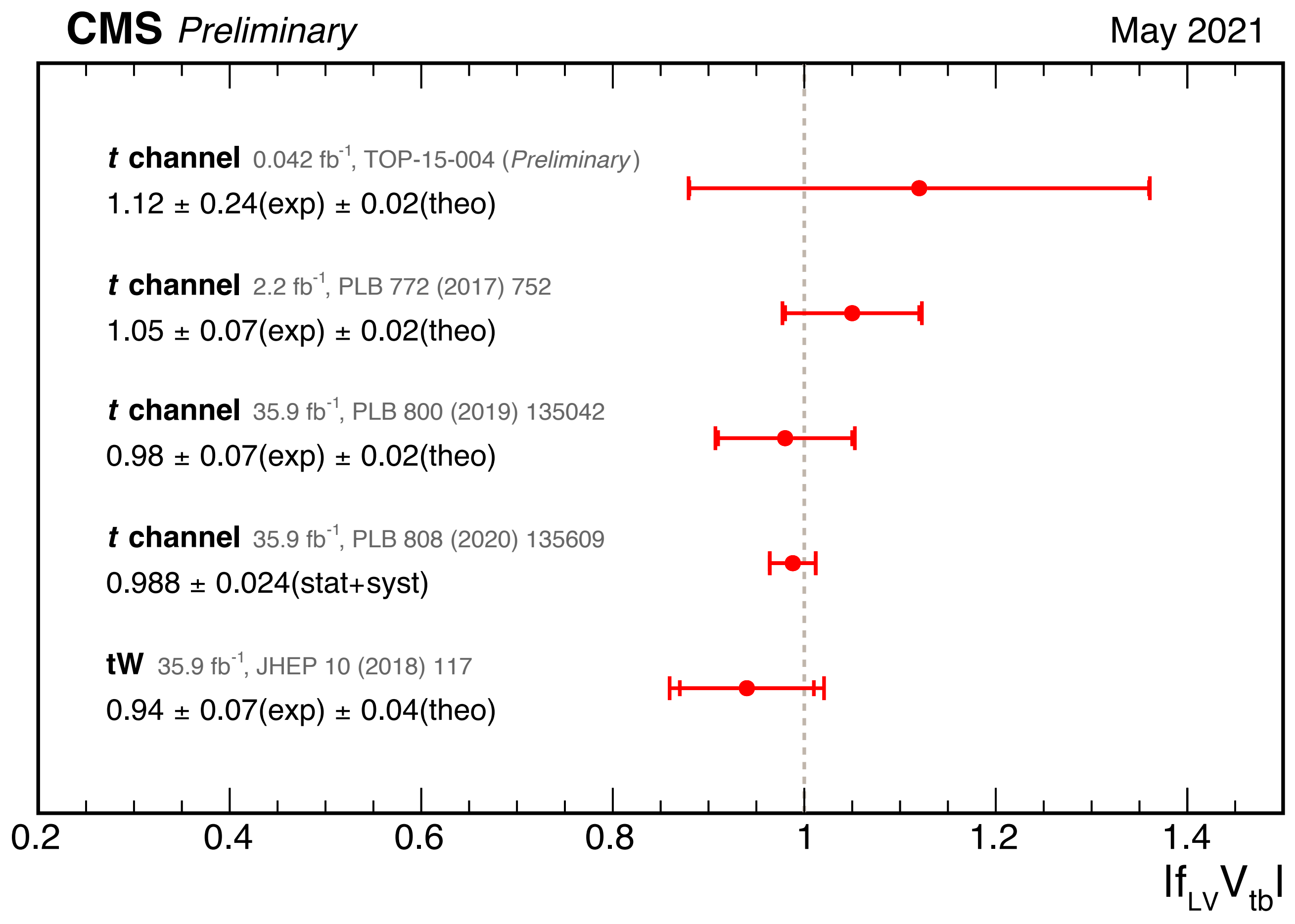
- Single experiment sensitivity below the SM @ HL-LHC
- 5-sigma evidence for di-Higgs production at the HL-LHC quite possible

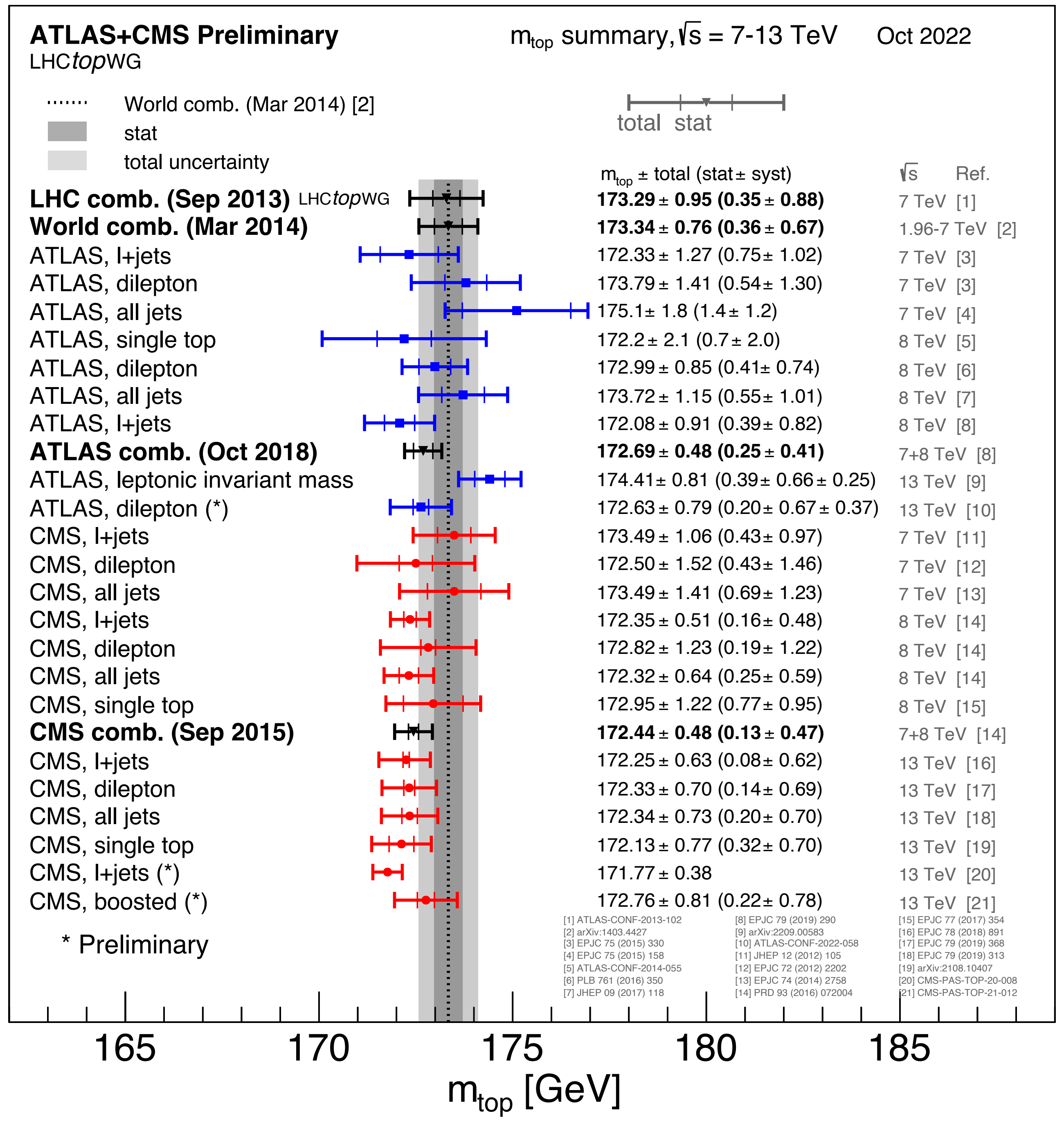
Top quarks

There is a vibrant top quark physics program at CMS!

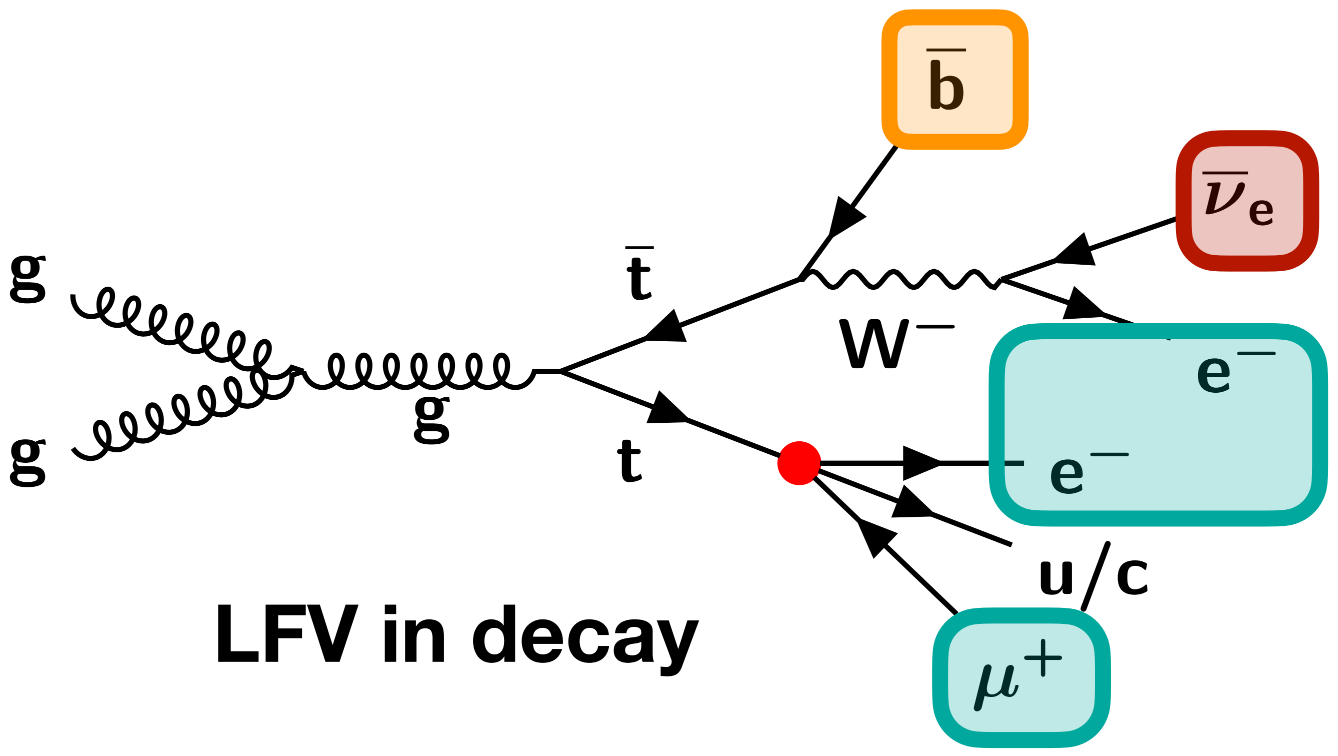
- Cross sections of many processes
- Top quark mass and other properties
- BSM in top quark decays

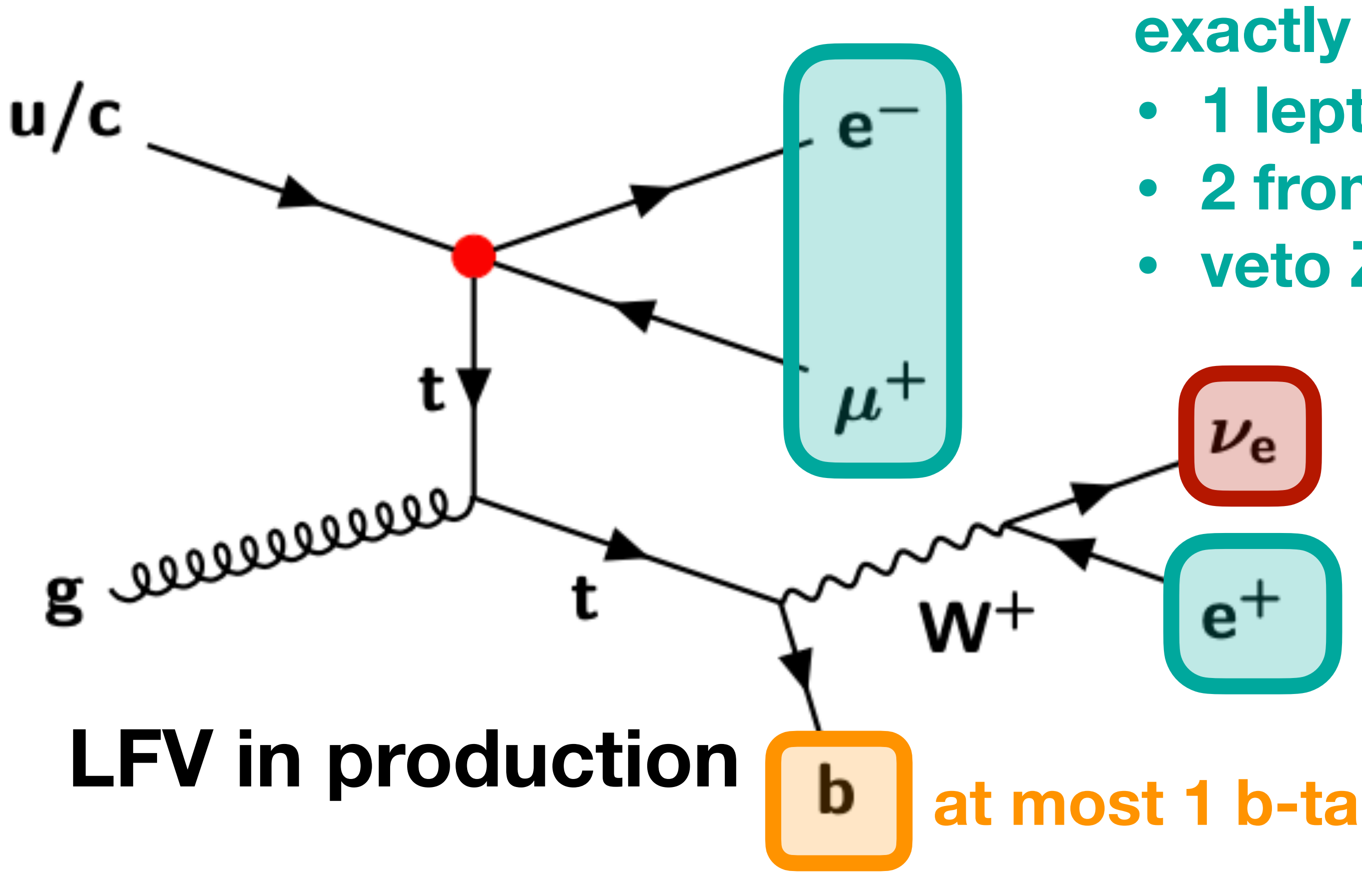






LFV in top quark sector



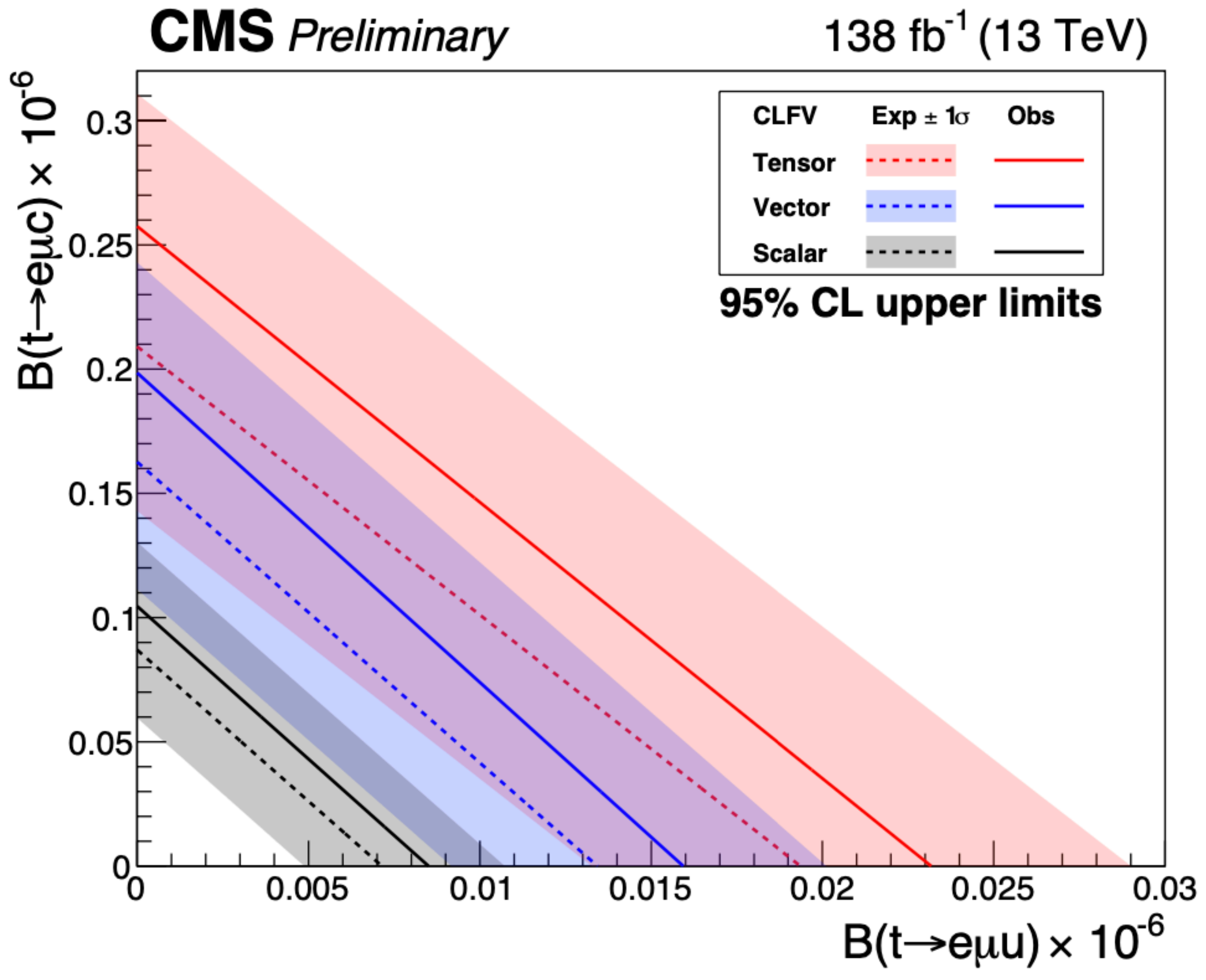


exactly 3 leptons ($e\mu l$)

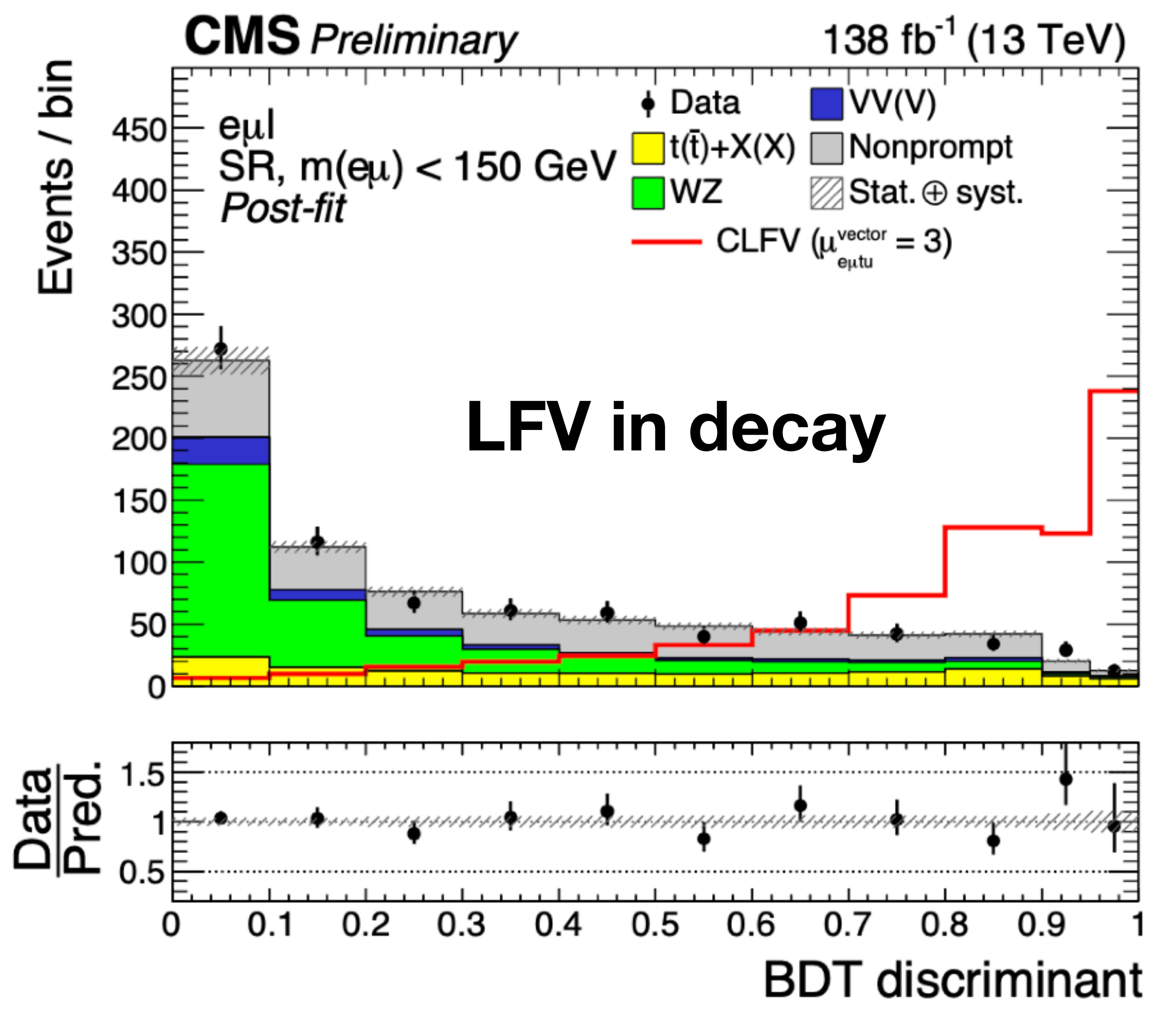
- **1 lepton from SM top decay**
- **2 from LFV**
- **veto Z mass window**

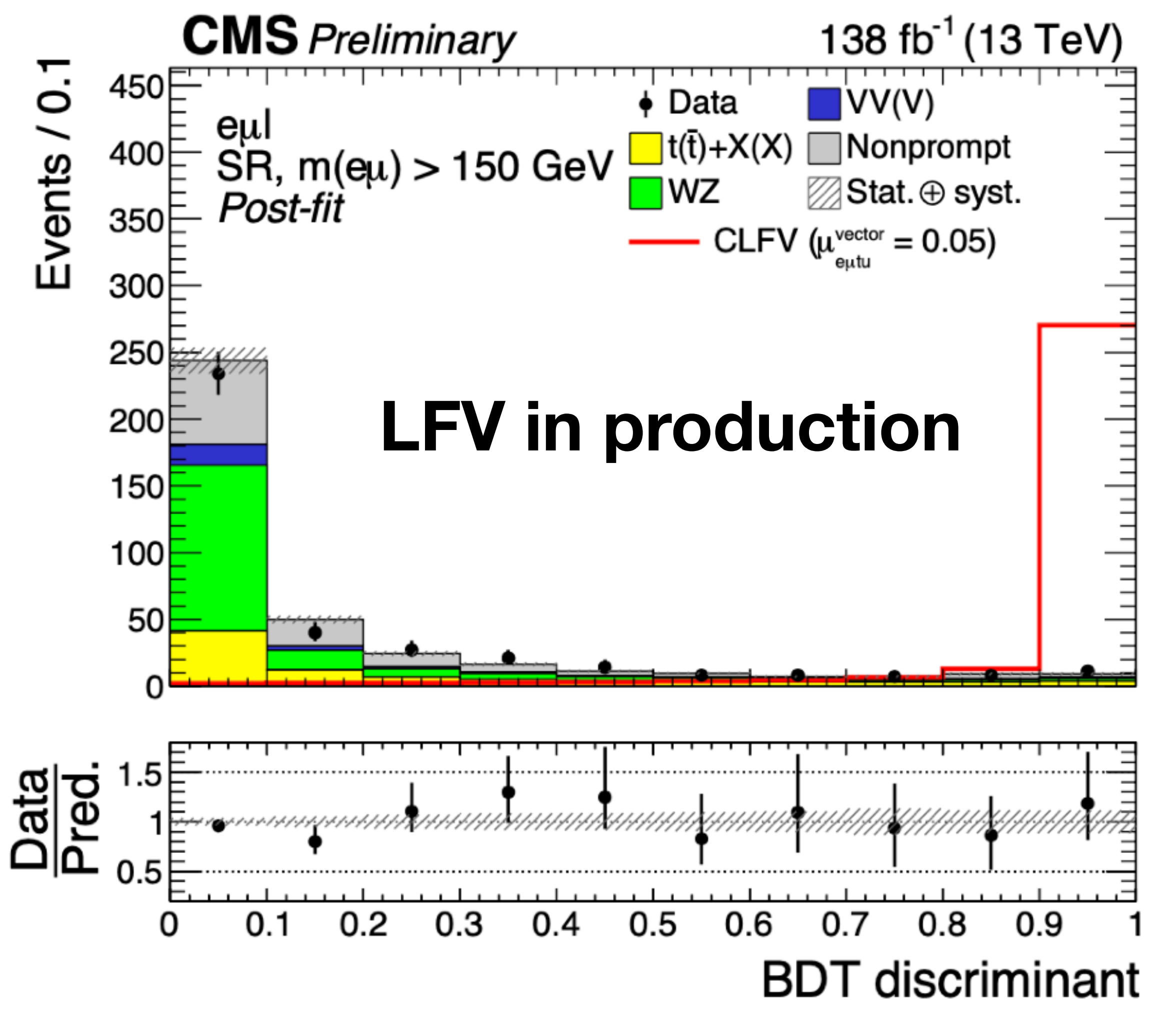
$p_T^{miss} > 20\,\mathrm{GeV}$

at most 1 b-tagged jet



- Two categories:
  - LFV production: $m_{e\mu} > 150\,\mathrm{GeV}$
  - LFV decay: $m_{e\mu} < 150\,\mathrm{GeV}$
- Background estimation:
  - prompt with MC & CR (WZ)
  - non-prompt (DY and $t\bar{t}$): data-driven using looser lepton selection, validated in validation regions using eee, $\mu\mu\mu$ events
- Signal extraction using binned BDT distribution





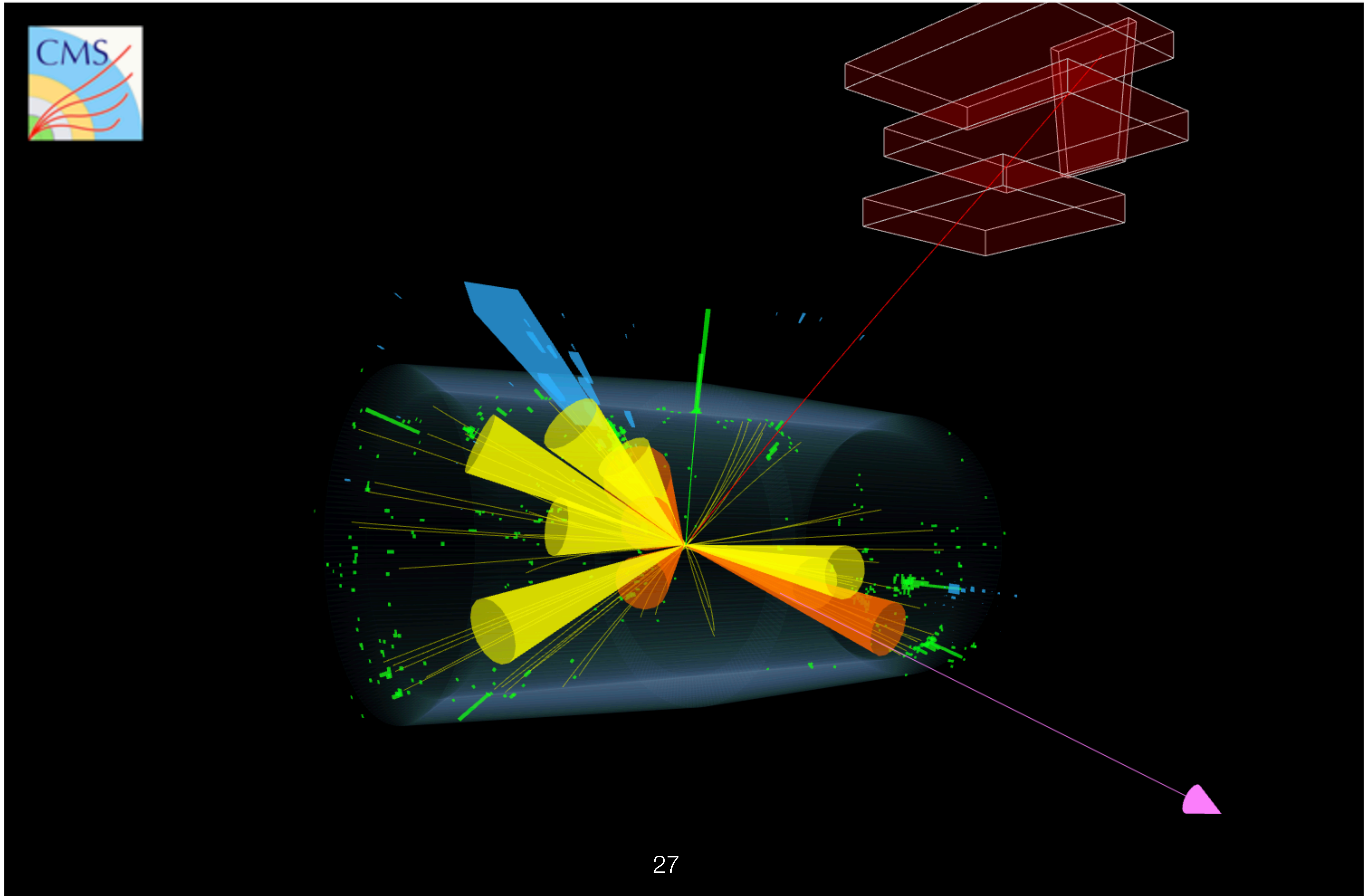
No evidence of LFV observed.

Limits set on branching fraction and Wilson coefficients.

TOP-22-013

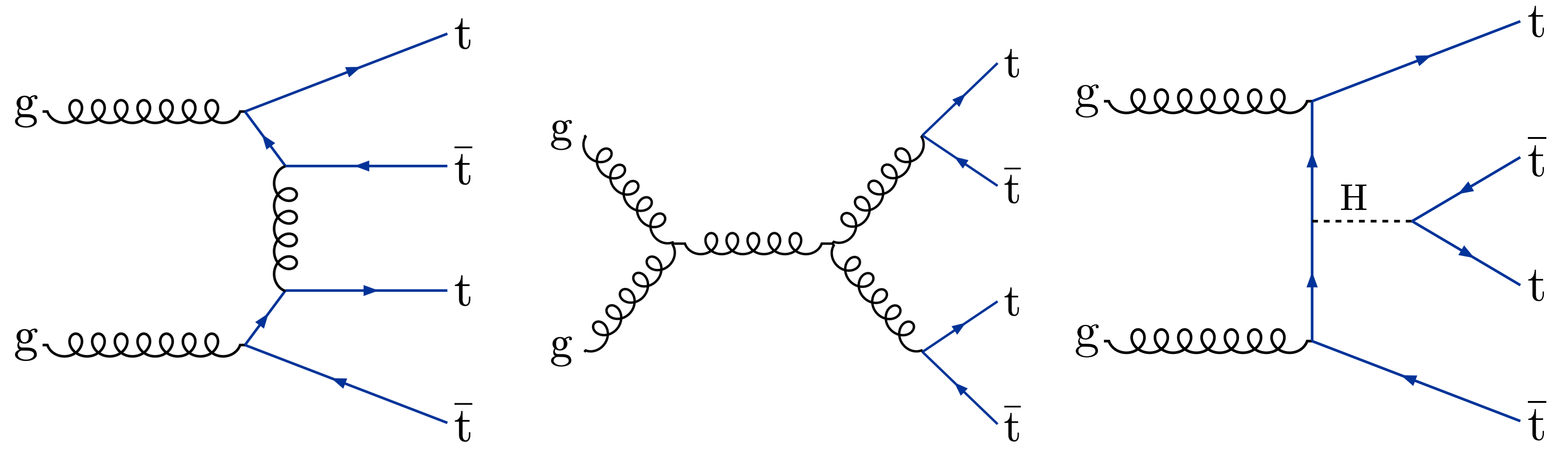
2016-2018 data

Observation of four top quark production

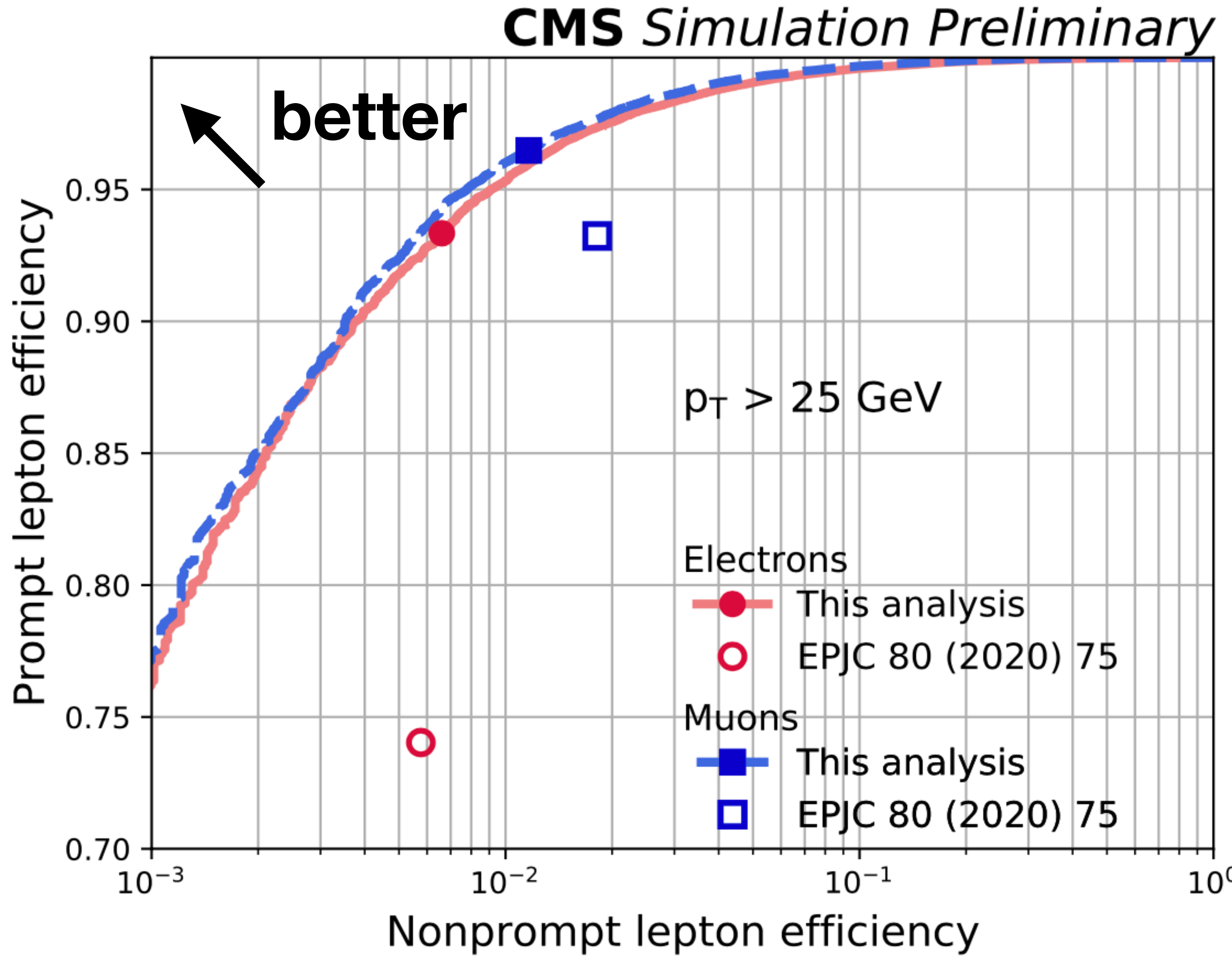


Observation of four top quark production

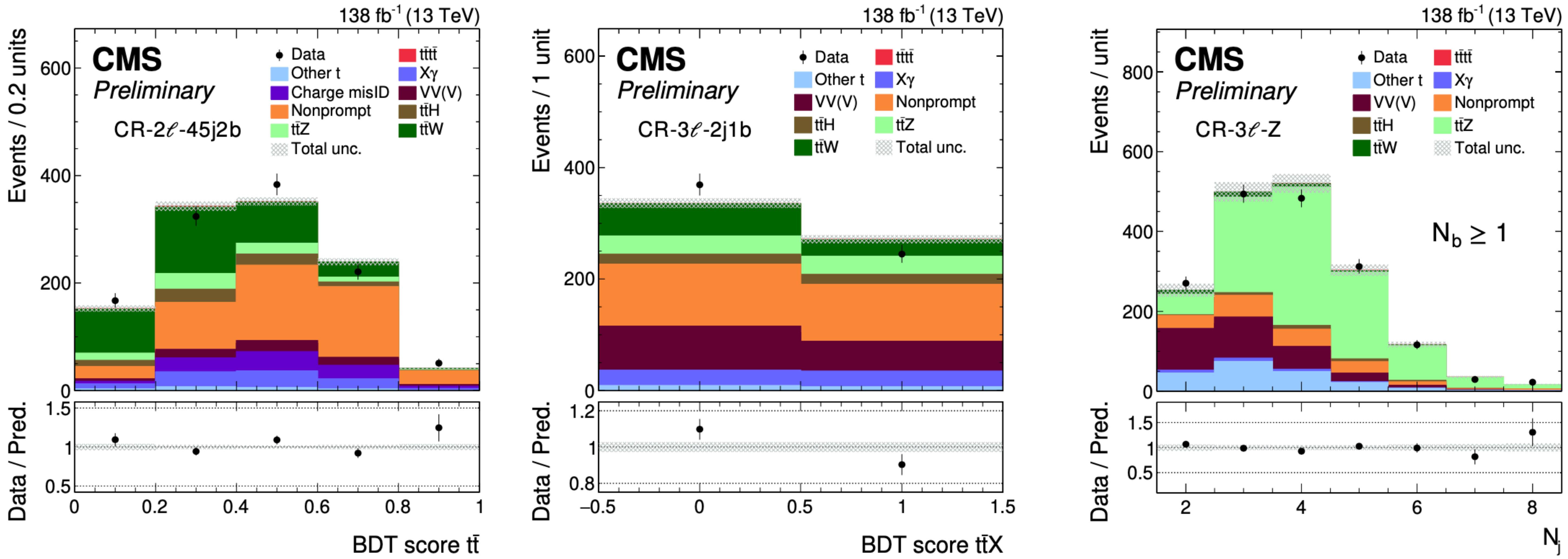
- $t\bar{t}t\bar{t}$ cross section sensitive to top quark Yukawa coupling, can constrain 2HDM, SUSY, and other BSM models, input to EFT interpretations



- Uses events with 2 SS, 3, and 4 leptons (e/μ) and additional jets
- Improved result by using ML methods for:
  - lepton identification and b jet tagging
  - distinguishing between signal & background processes via multiclassification ($t\bar{t}t\bar{t}$, $t\bar{t}X$, $t\bar{t}$), separately for 2 and 3/4 lepton events



- Background estimation:
  - Prompt backgrounds estimated from simulation with constraint from data control regions
  - Non-prompt backgrounds estimated using data sidebands
- Signal extraction using BDT scores and jet multiplicity distribution in signal and control regions



TOP-22-013

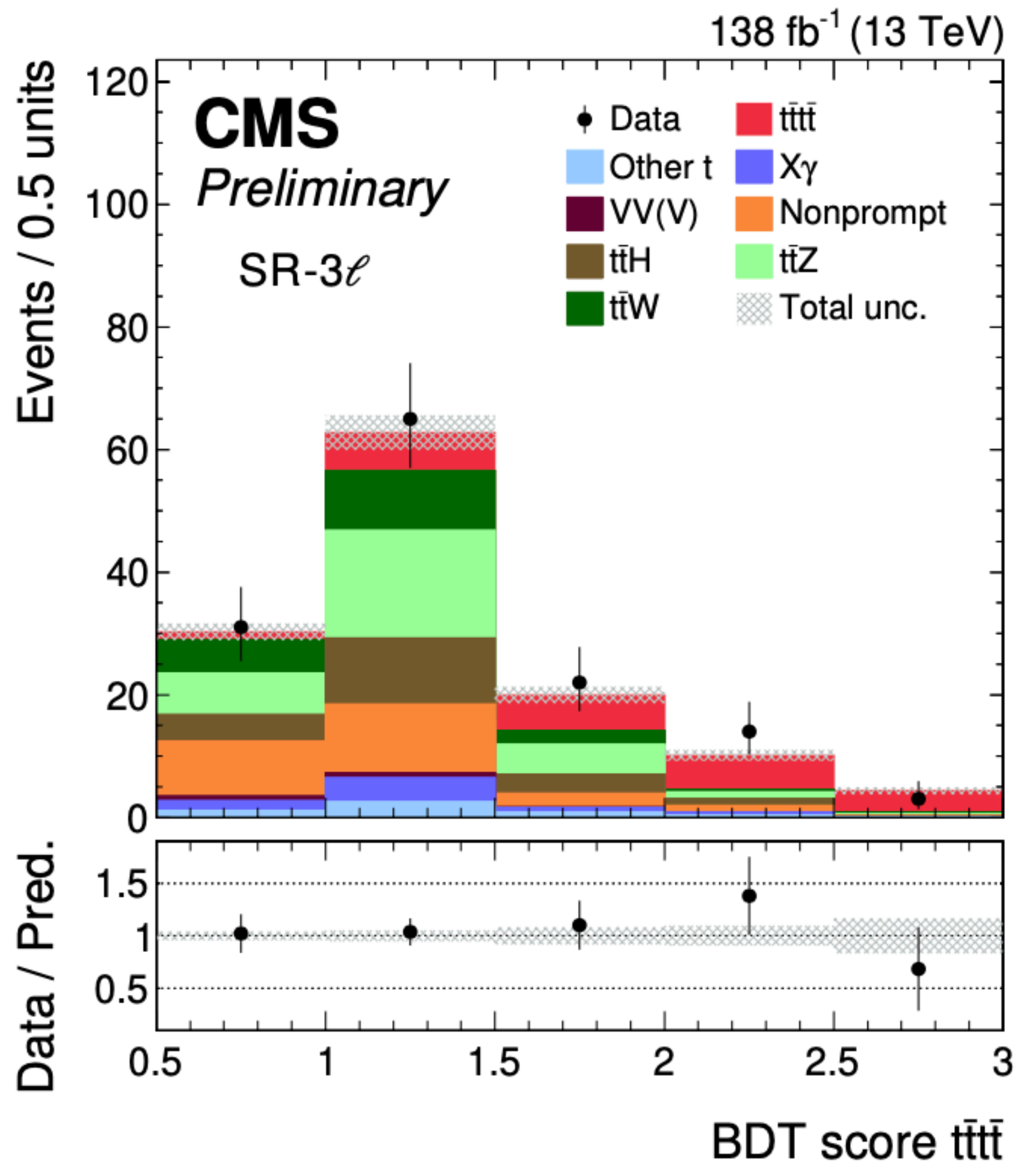
2016-2018 data

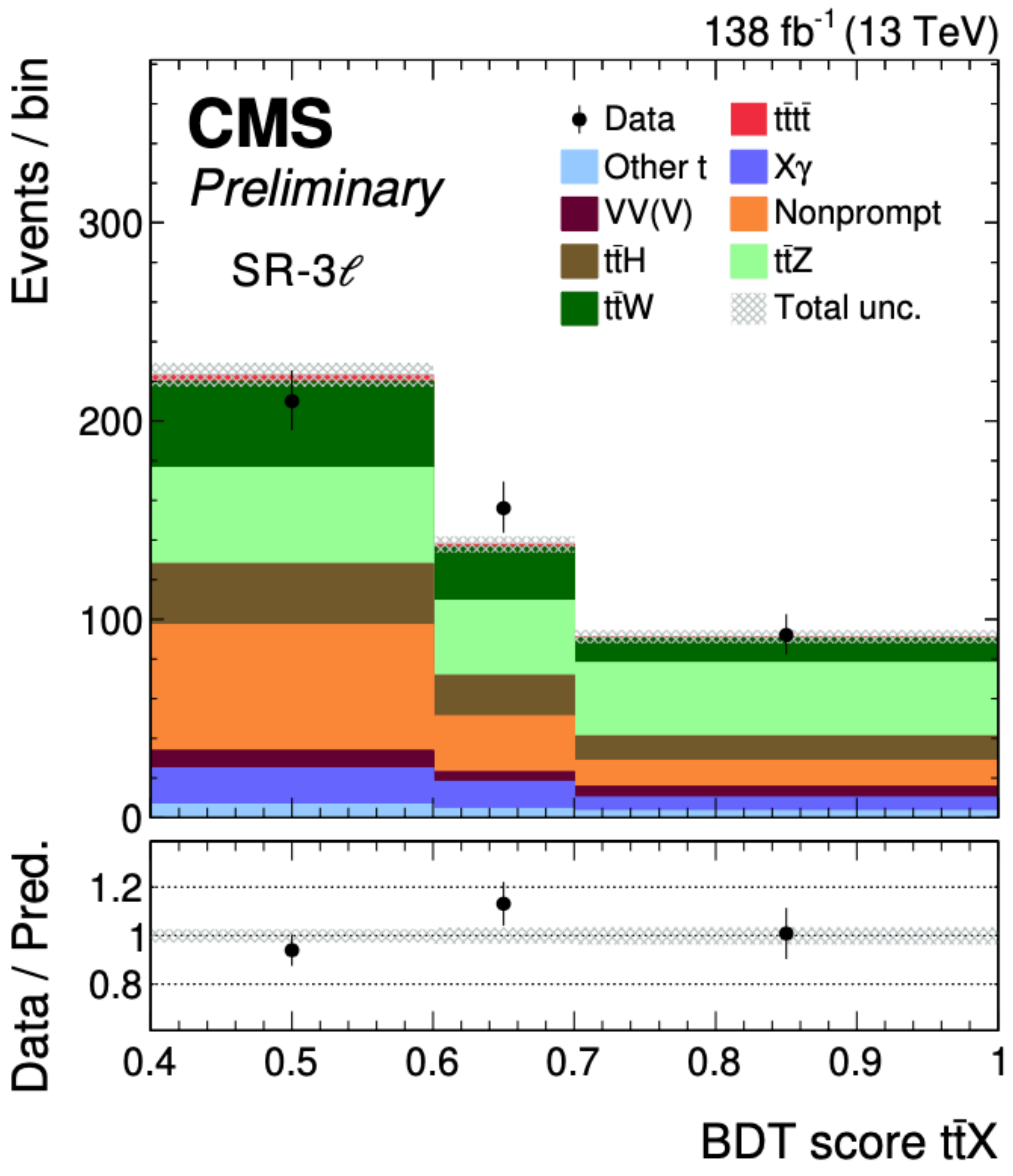
Observation of four top quark production

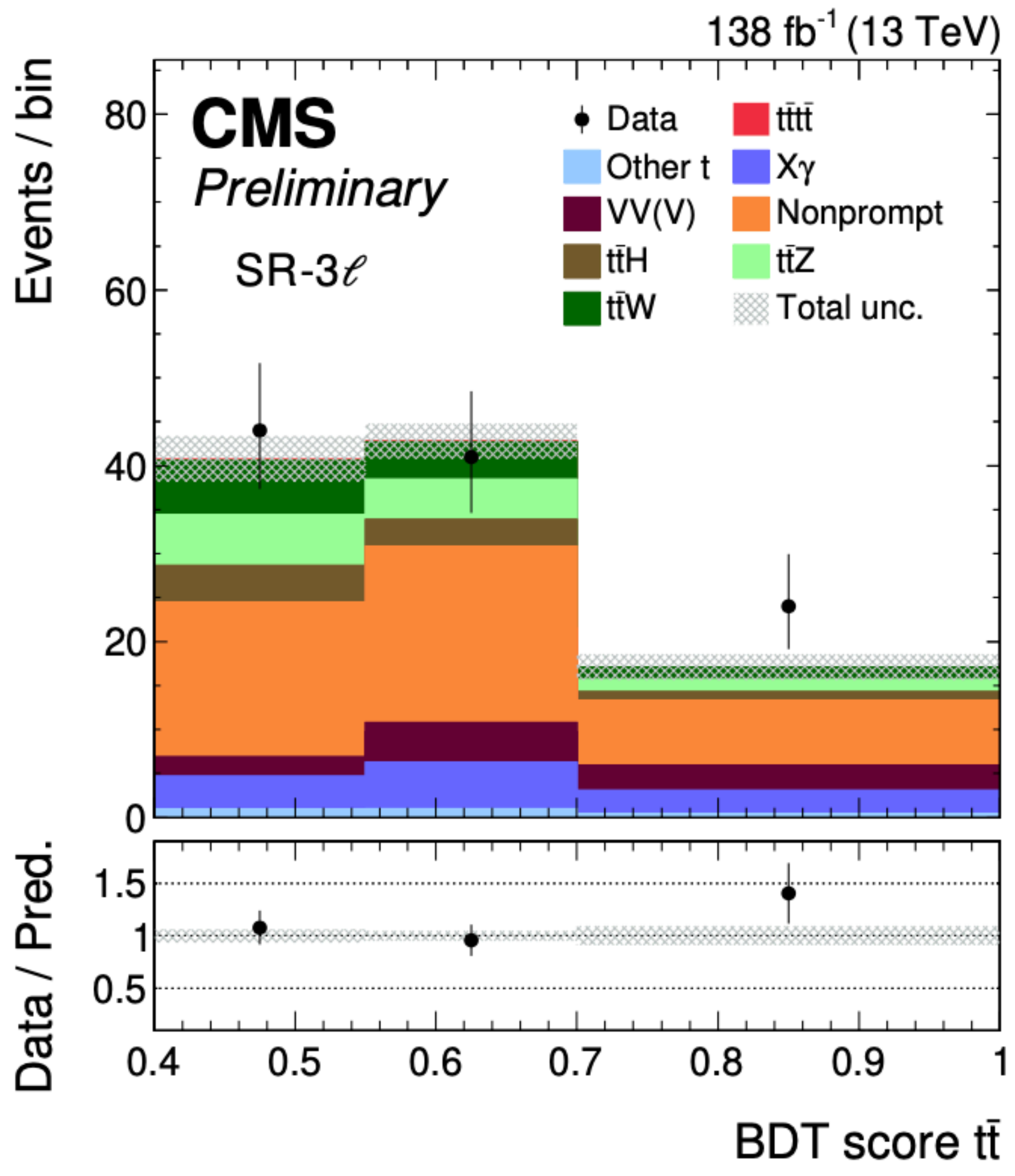
Result:

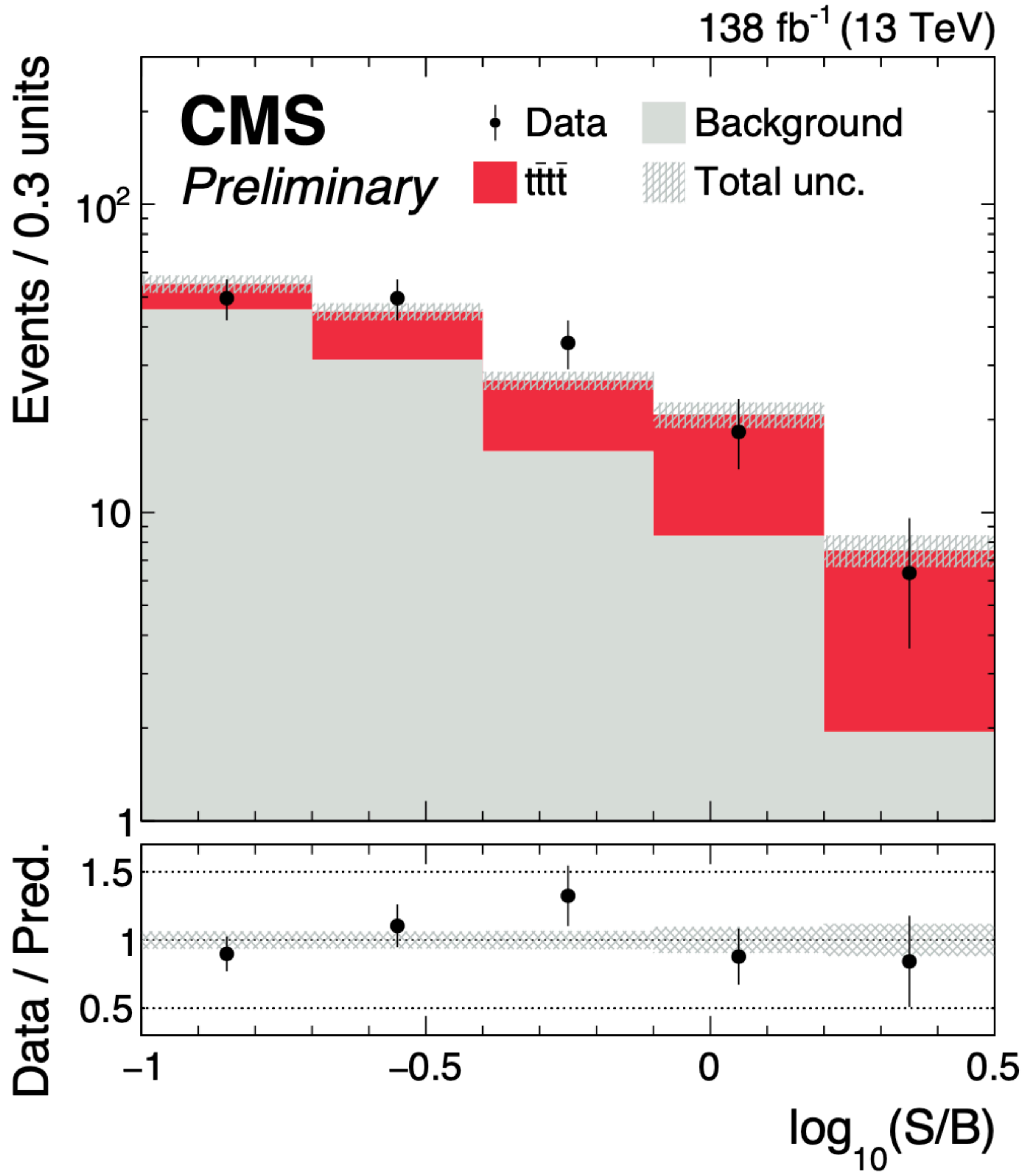
$$\sigma(pp \to t\bar{t}t\bar{t}) = 17.9\,^{+3.7}_{-3.5}\,(\text{stat})\,^{+2.4}_{-2.1}\,(\text{syst})\,\text{fb},$$
$$\sigma(pp \to t\bar{t}W) = 997 \pm 58\,(\text{stat})\,^{+79}_{-72}\,(\text{syst})\,\text{fb},$$
$$\sigma(pp \to t\bar{t}Z) = 1134\,^{+52}_{-43}\,(\text{stat}) \pm 86\,(\text{syst})\,\text{fb}.$$

- $\sigma(t\bar{t}t\bar{t})$ agrees with SM prediction of $\sigma_{SM}(t\bar{t}t\bar{t}) = 13.4\,^{+1.0}_{-1.8}$ fb at 1.1 standard deviation
  - 5.5 (4.9) standard deviations above background-only hypothesis
- Measured $\sigma(t\bar{t}W)$ and $\sigma(t\bar{t}Z)$ are larger than SM, in agreement at level of 2.2-2.3 standard deviations

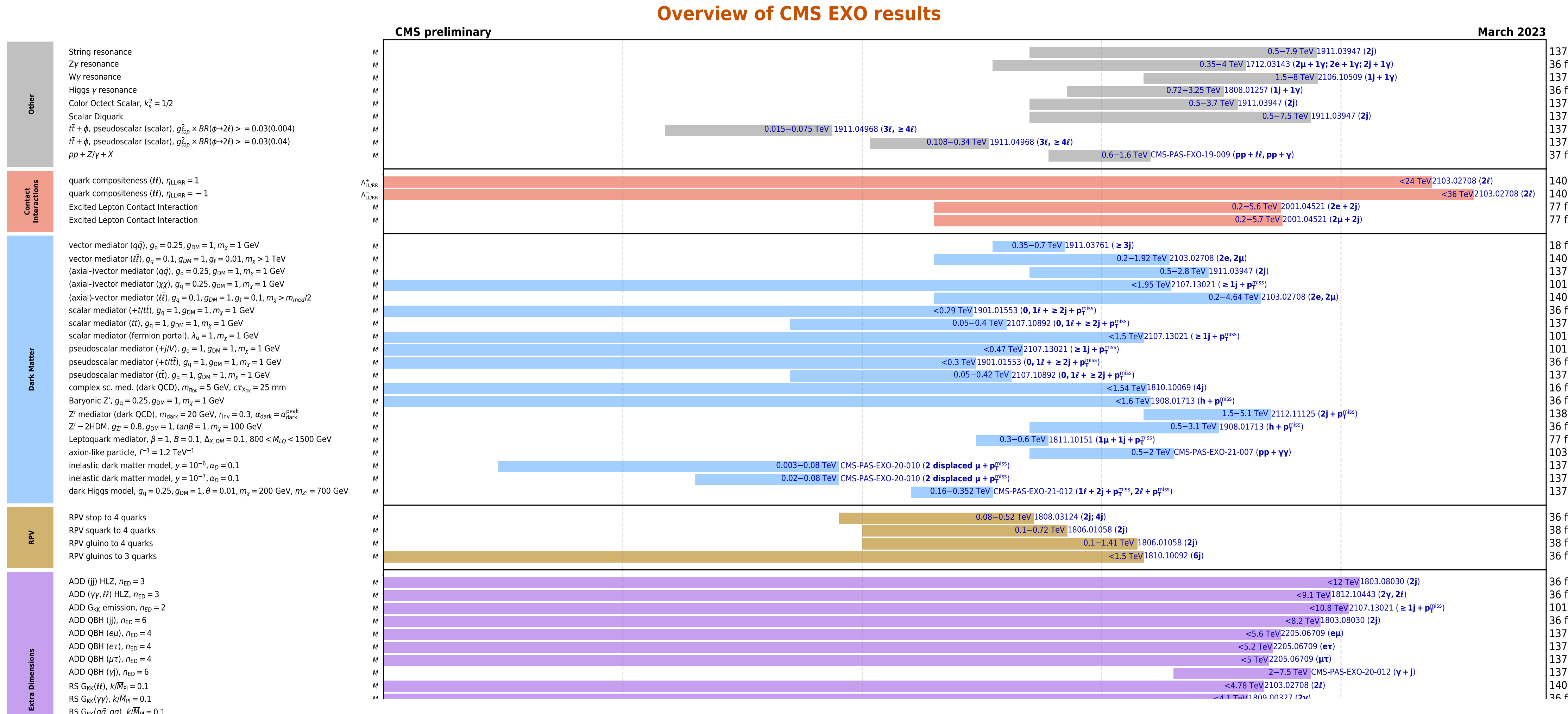


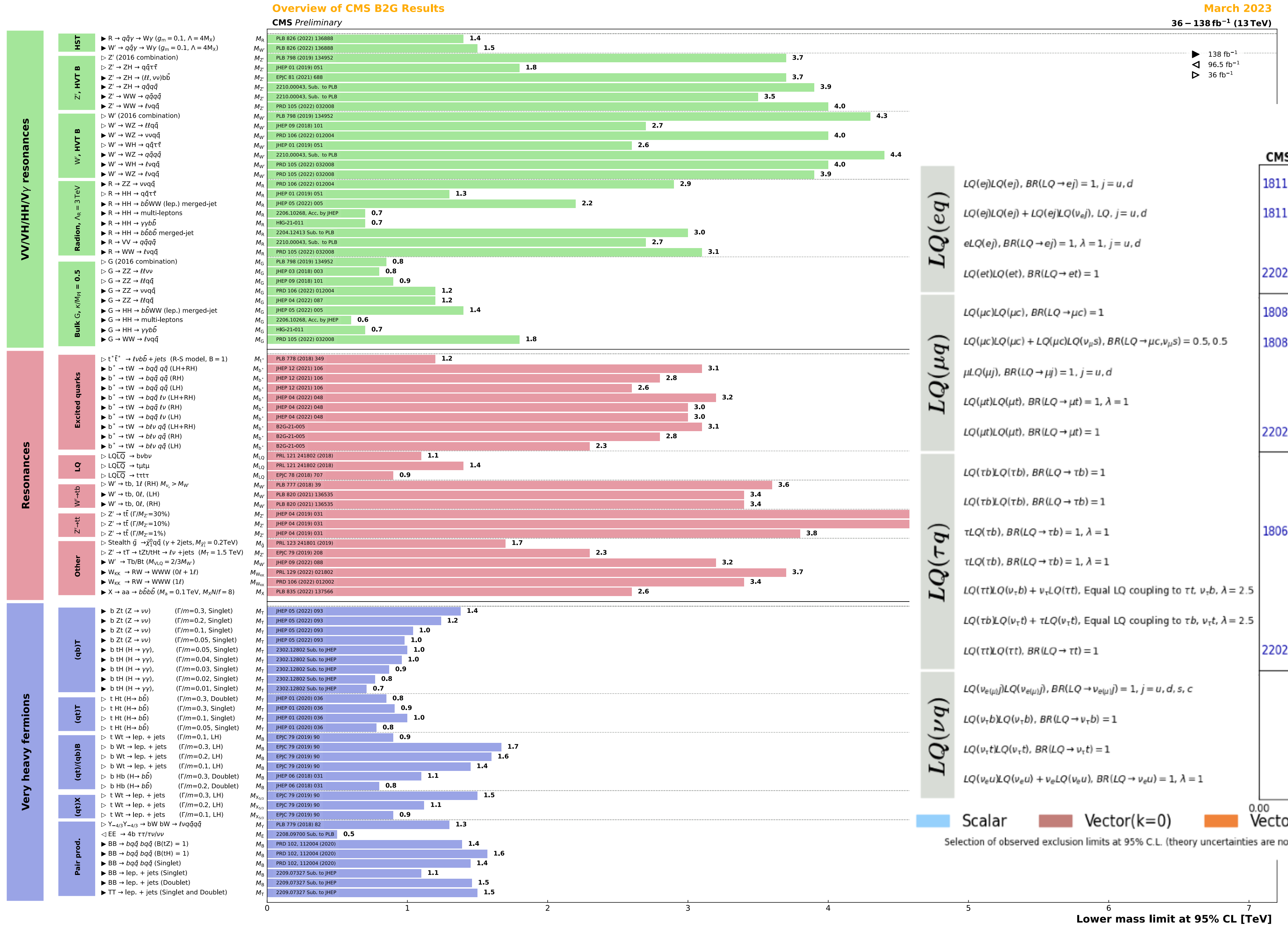


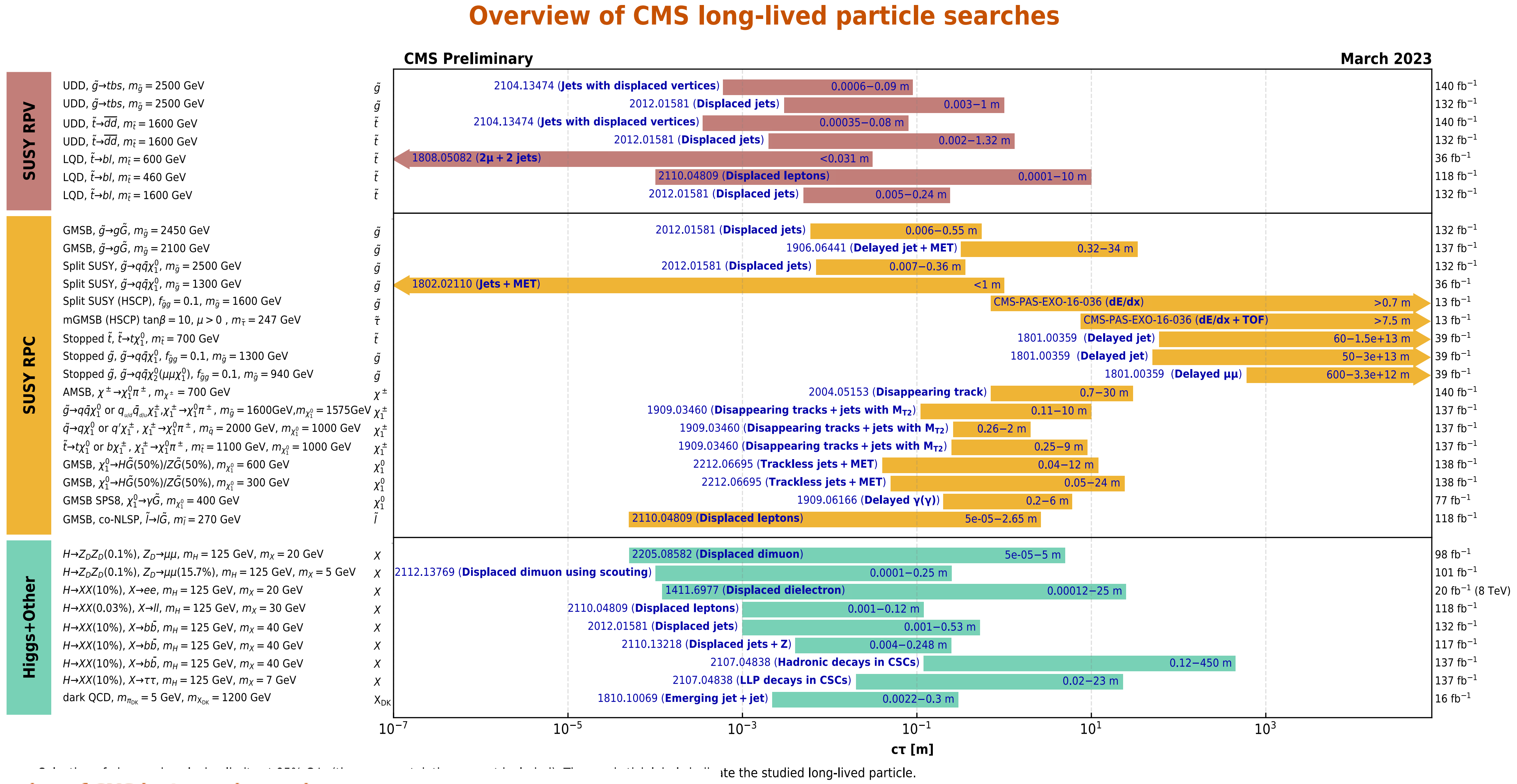


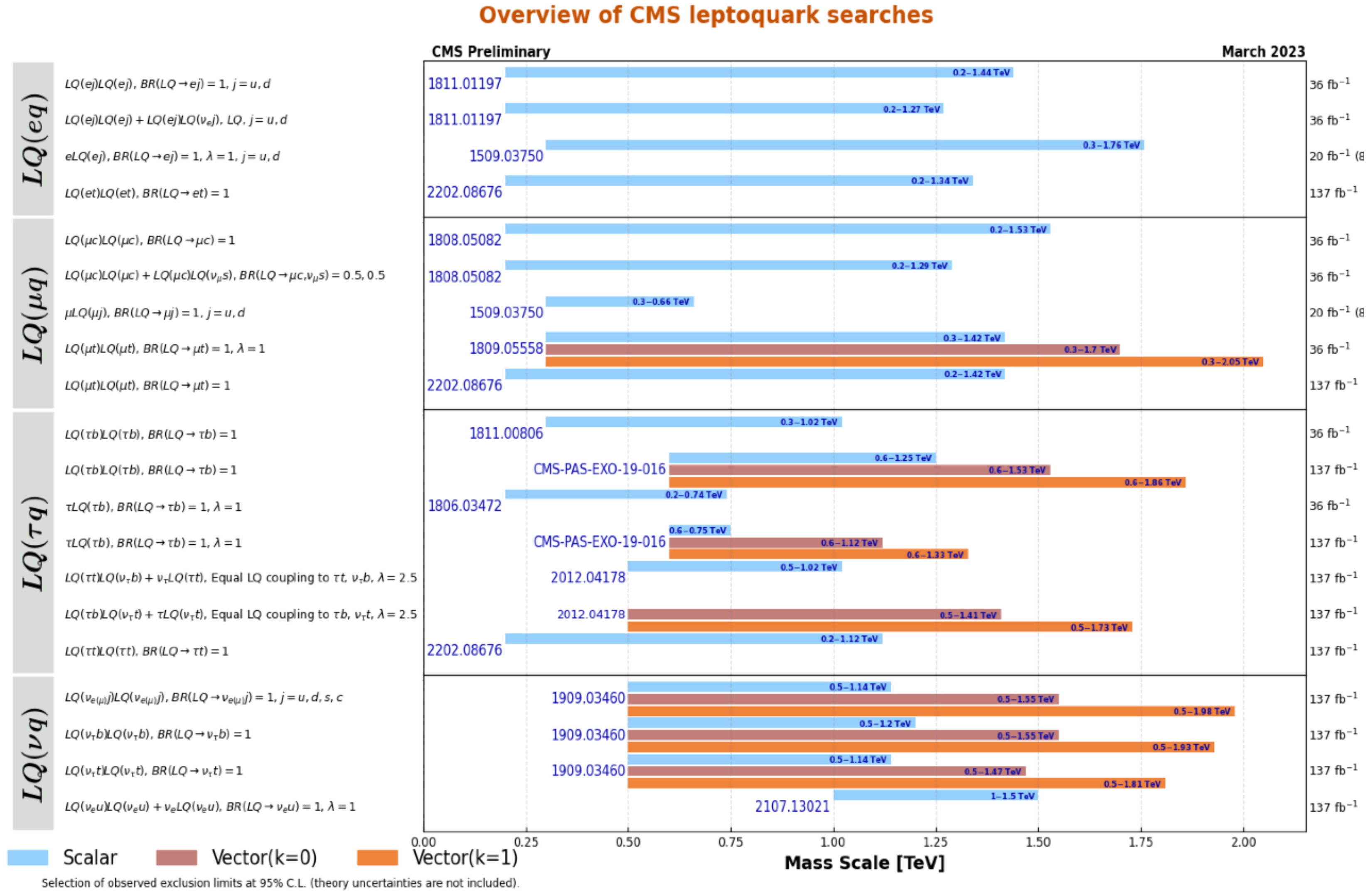


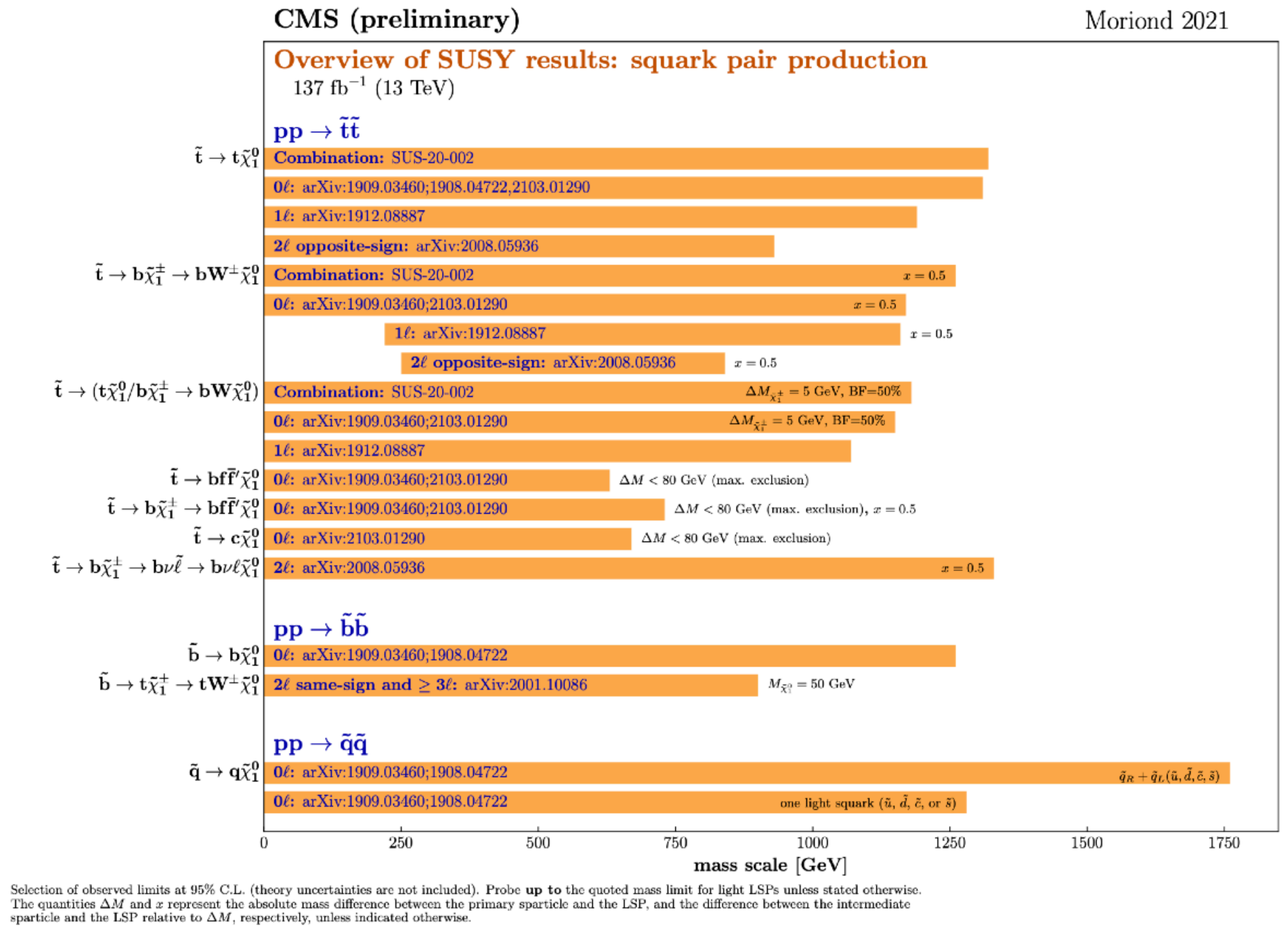
Searches for BSM physics: too many to count!











The BSM landscape

SUS-21-008

2016-2018 data

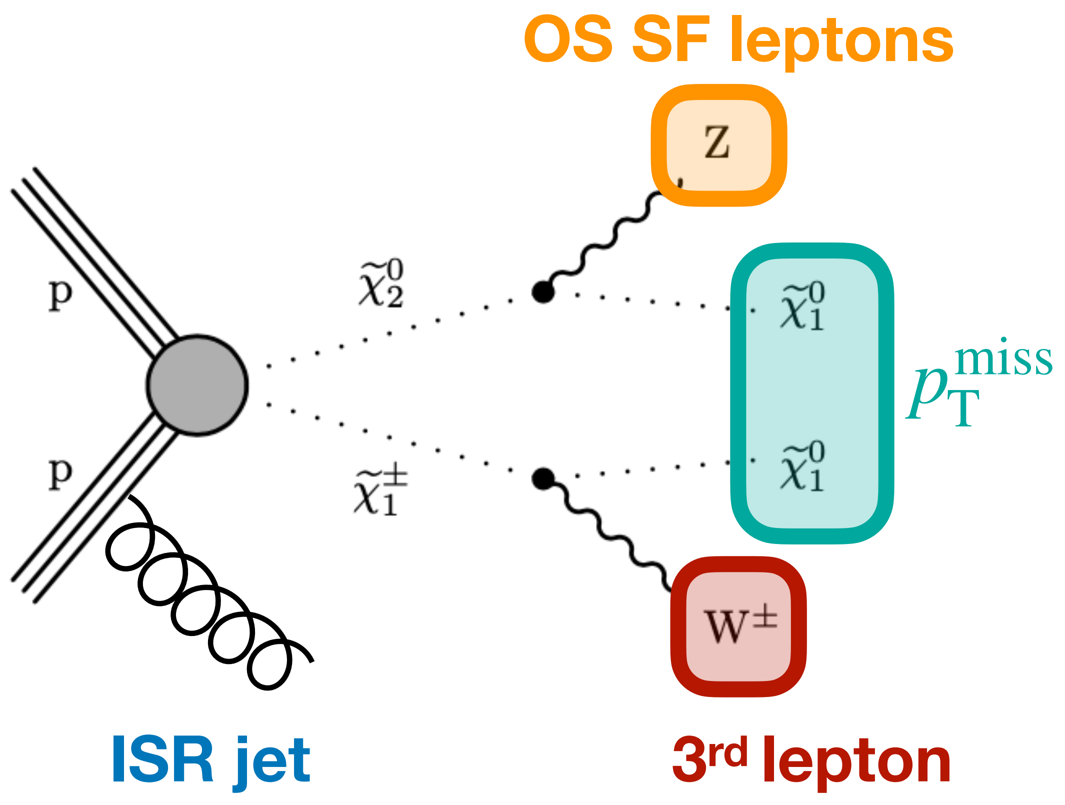
Combination of electroweak SUSY searches

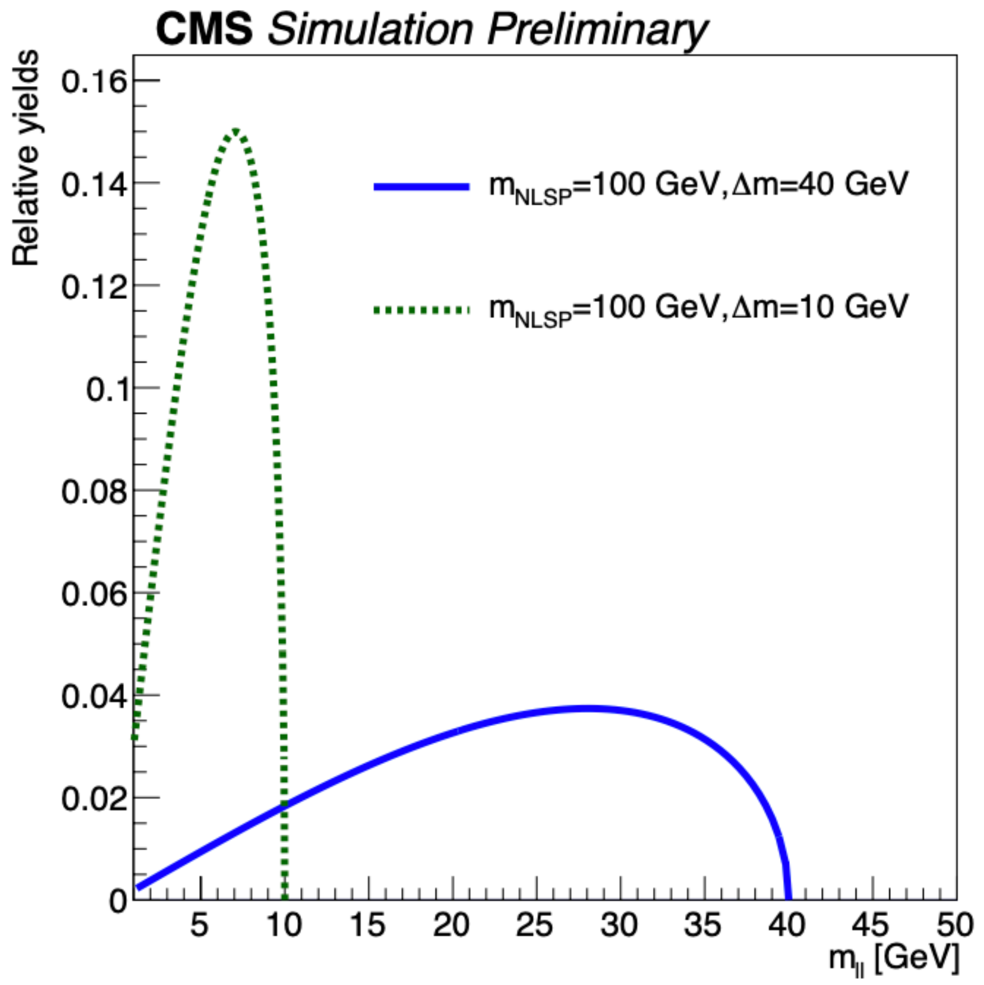
- Targets electroweak production of charginos and neutralinos, as well as sleptons for compressed and non-compressed mass spectra. Several new interpretations compared to earlier results.
- **Combines 6 searches using the full LHC Run 2 data set:**

OS/SS = opposite/same sign (charge)
SF = same flavor

Leptonic	**“2/3L soft”** 2 or 3 e(μ), including OS SF pair, 5(3.5)< lepton p_T < 30 GeV Targeting compressed spectra	**“≥ 3l”** 2 SS e/μ, or ≥3 leptons (up to 2 τ_{had}) Leading lepton p_T > 30 GeV	**“2l on-Z/non-resonant”** 2 e(μ) OS SF, Either on- or off-shell Z
(Semi) Hadronic	**“1l 2b” - WH** 1 e(μ), H→bb tag Targeting compressed spectra	**“4b” - HH** No leptons 2 tagged Higgs bosons (H→bb)	**“Hadr. WX”** Fully hadronic final state; ≥2 jets (AK8), and 2-6 jets (AK4)

- Hadronic WX analysis is new addition to the combination, improving the sensitivity in the non-compressed region
- 2/3L soft was updated for the combination to include a parametric signal extraction which improves the sensitivity to compressed mass spectra
  - m_{ll} binning optimized per $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ signal hypothesis to exploit kinematic end point

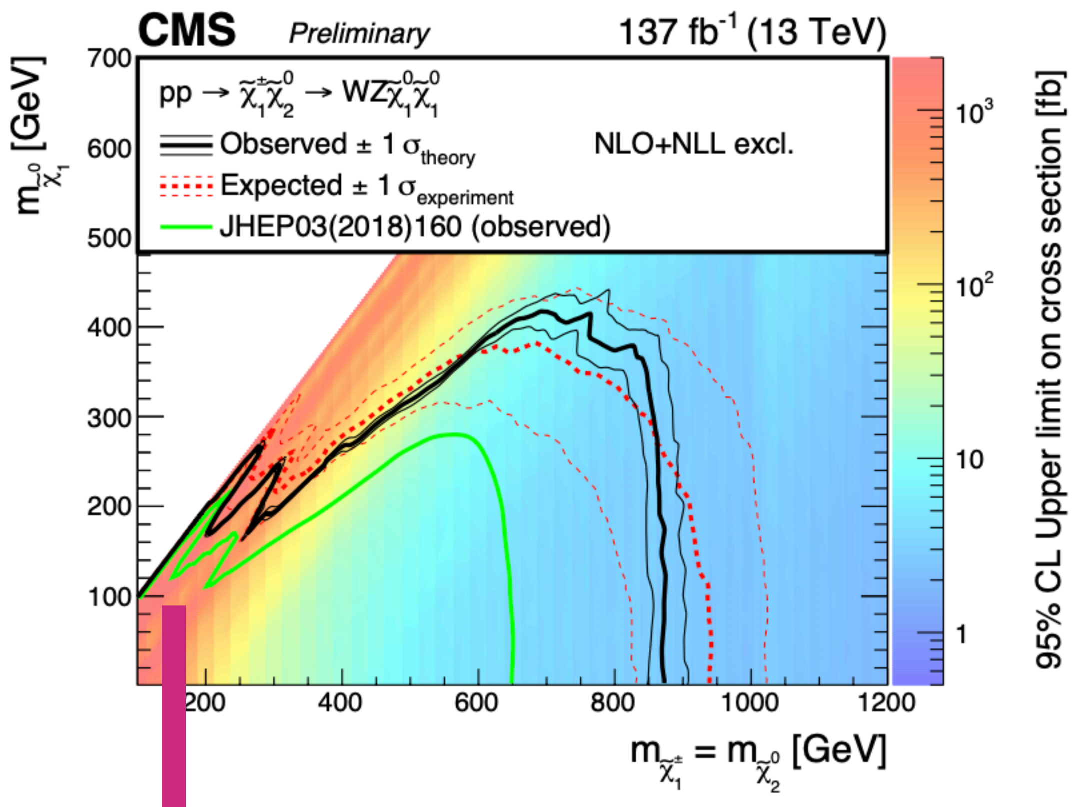


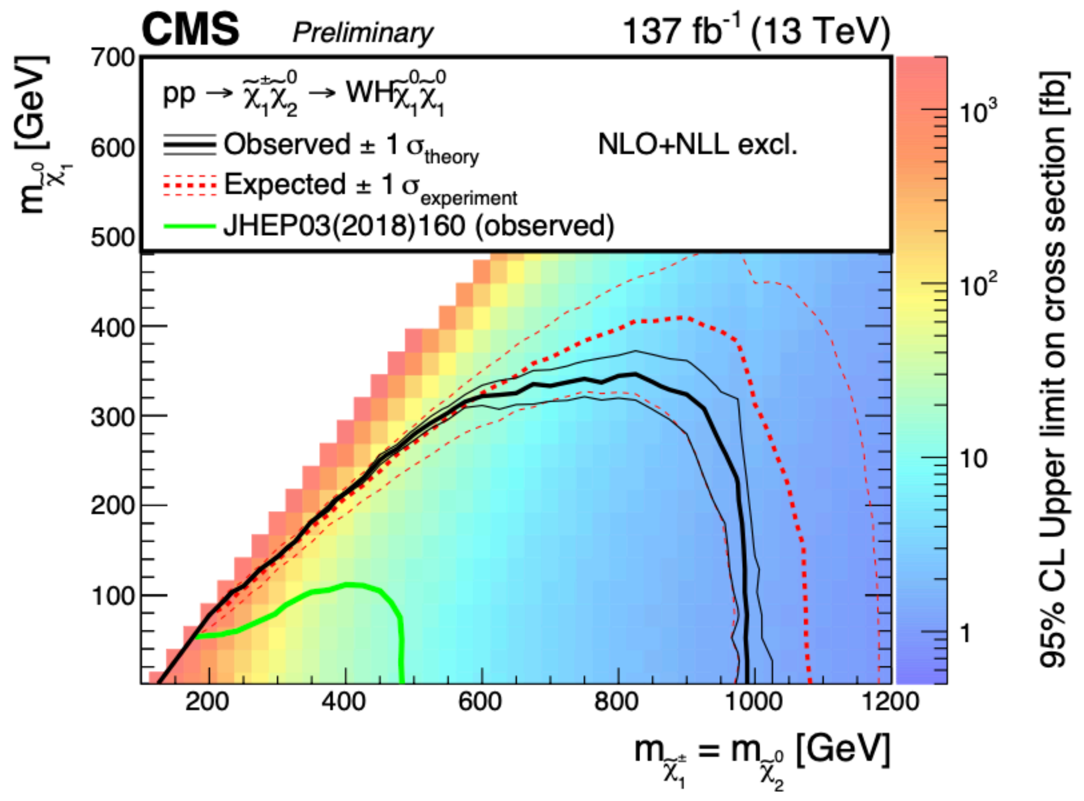


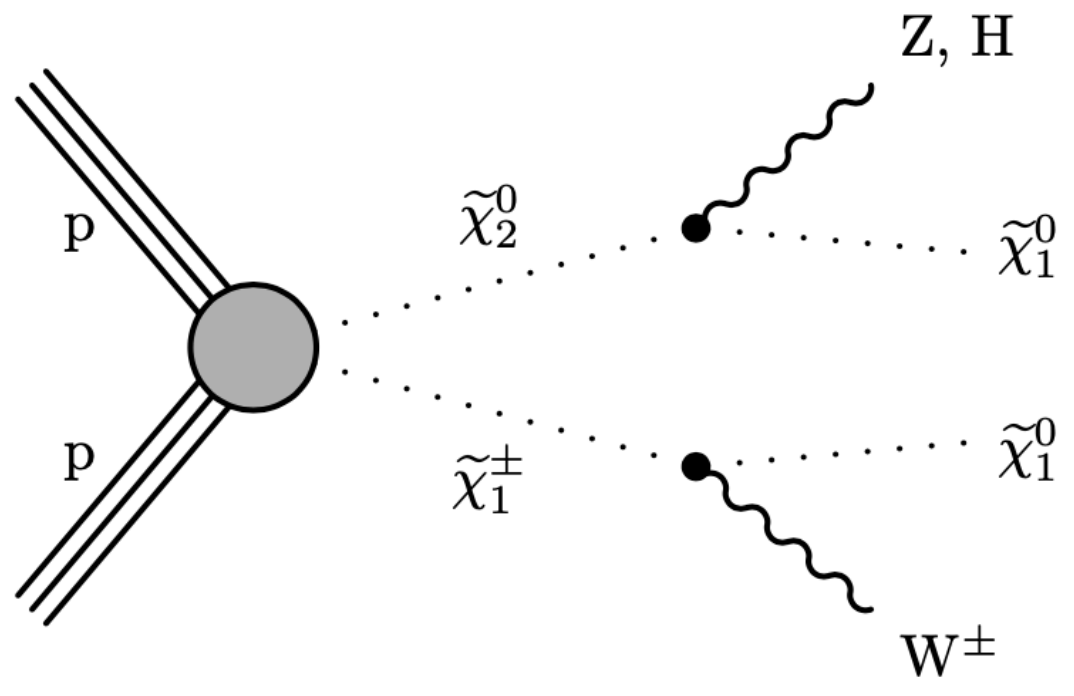
Combination of electroweak SUSY searches

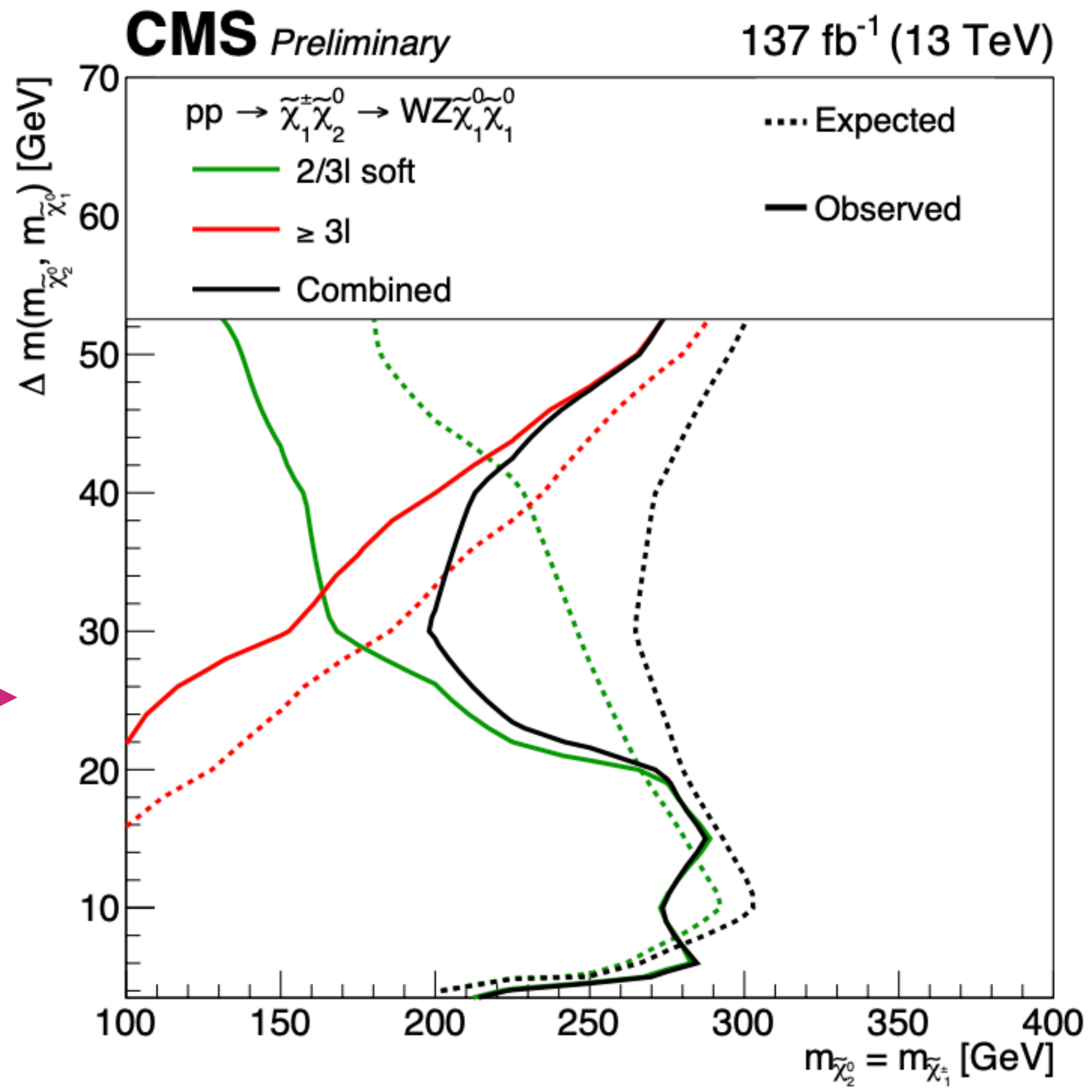
2016-2018 data

Results for wino-like $\tilde{\chi}_1^{\pm}$ & $\tilde{\chi}_2^0$ (with bino-like $\tilde{\chi}_1^0$)

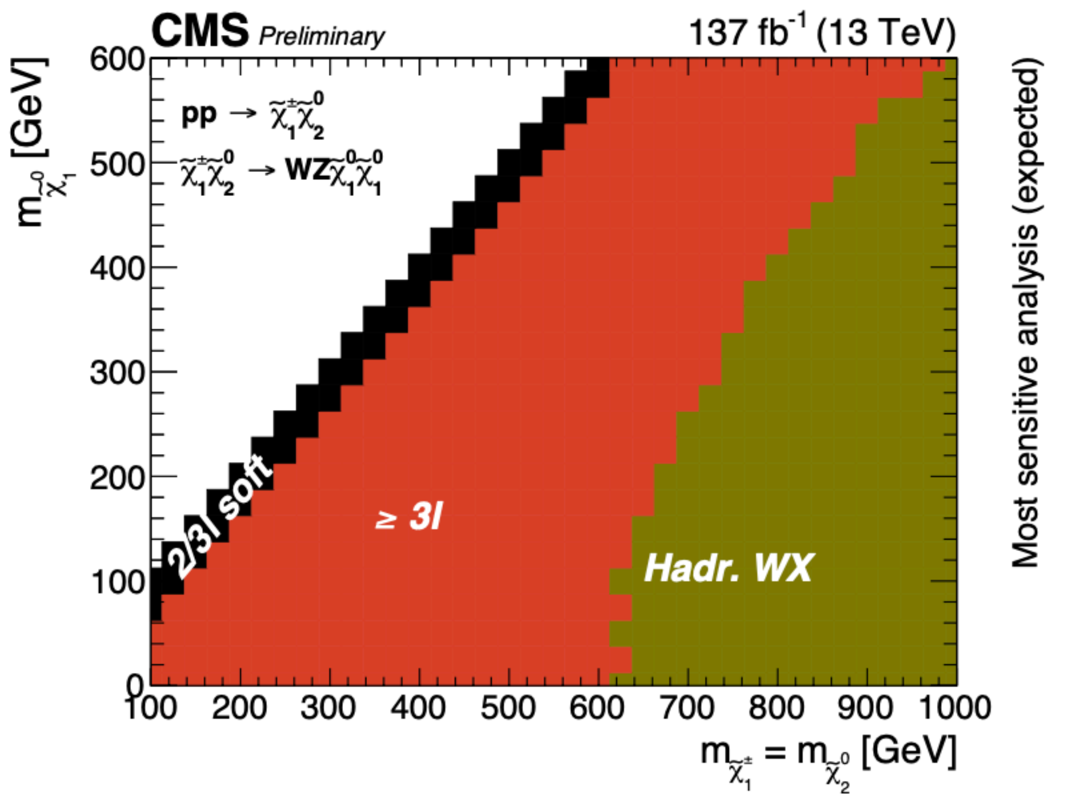


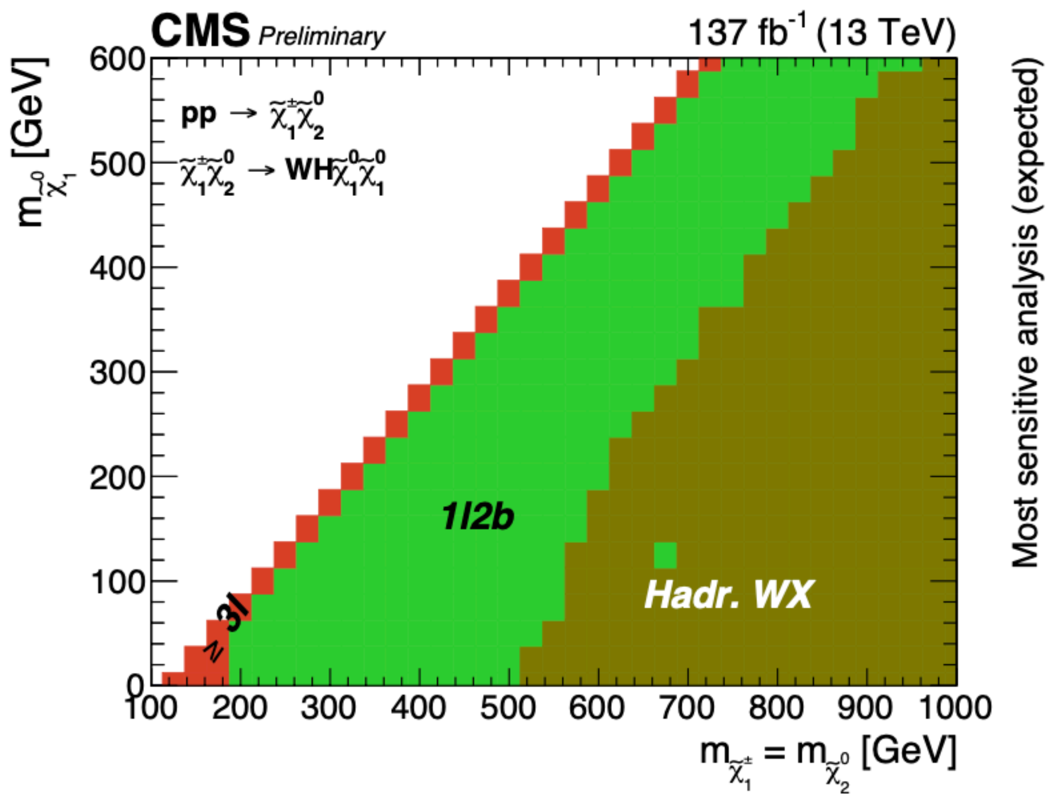






Zooming in on the compressed region





Addition of the **hadronic WX** search improves sensitivity to higher $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ masses in the uncompressed region

2/3L soft and ≥3L analyses are complementary

- orthogonal lepton p_T ranges
- Different selections (e.g. 2/3L soft requires p_T^{miss})

Combination closes the gap!

Mild excess observed around Δm = 30 and 40 GeV, stemming from both analyses

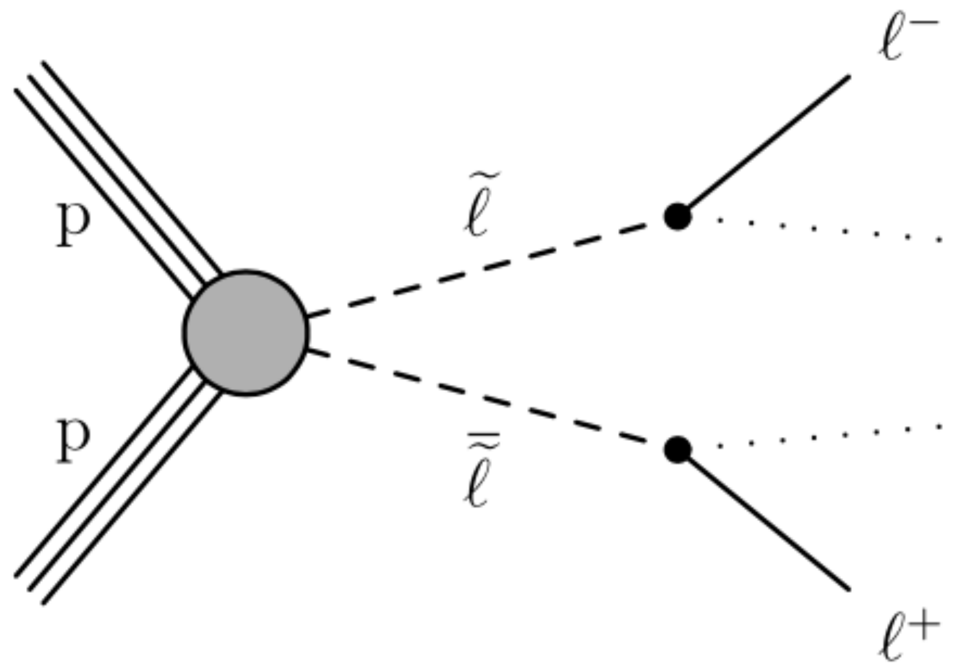
SUS-21-008

2016-2018 data

Combination of electroweak SUSY searches

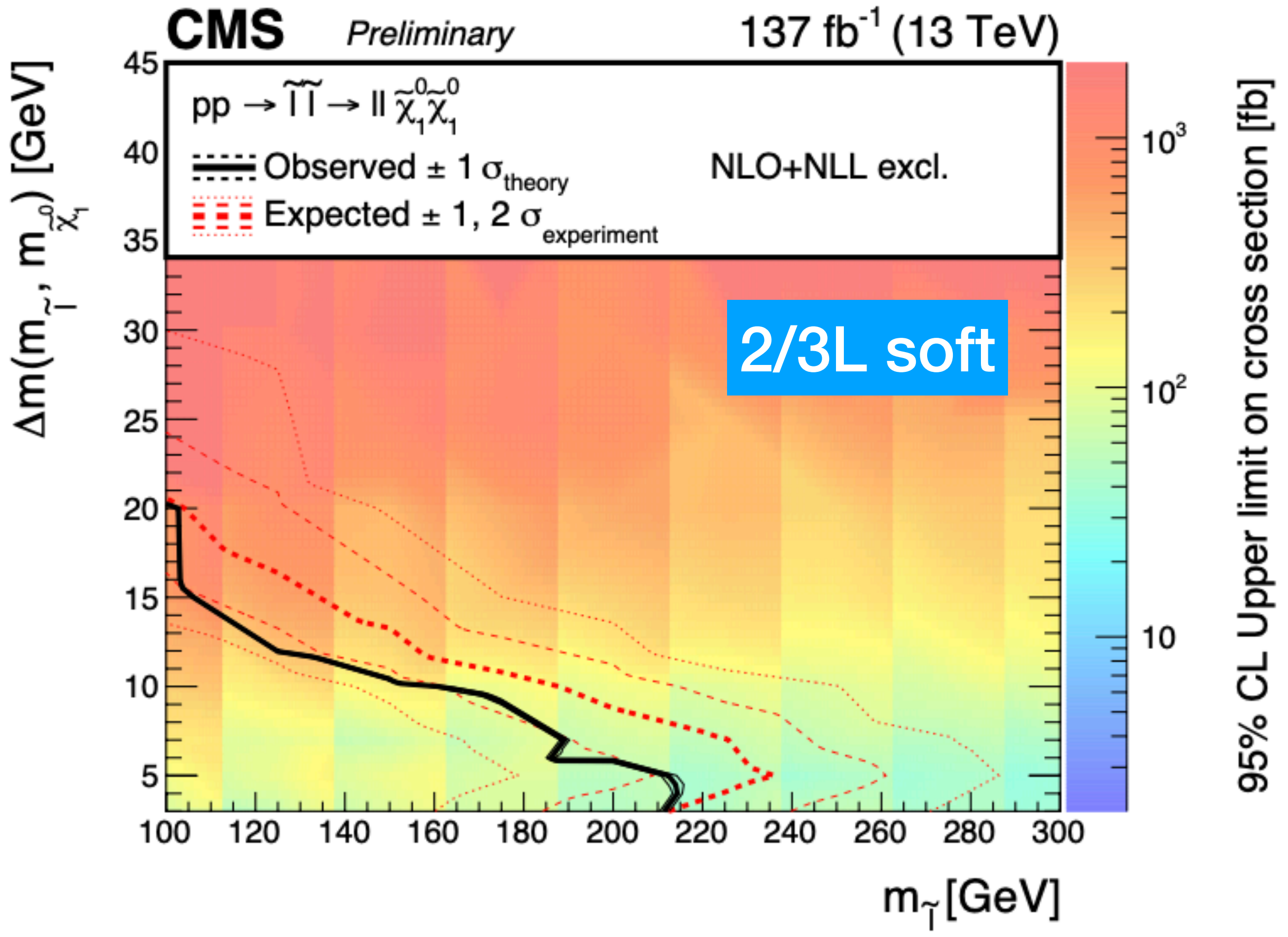
Results for sleptons & quasi-degenerate higgsinos in GMSB

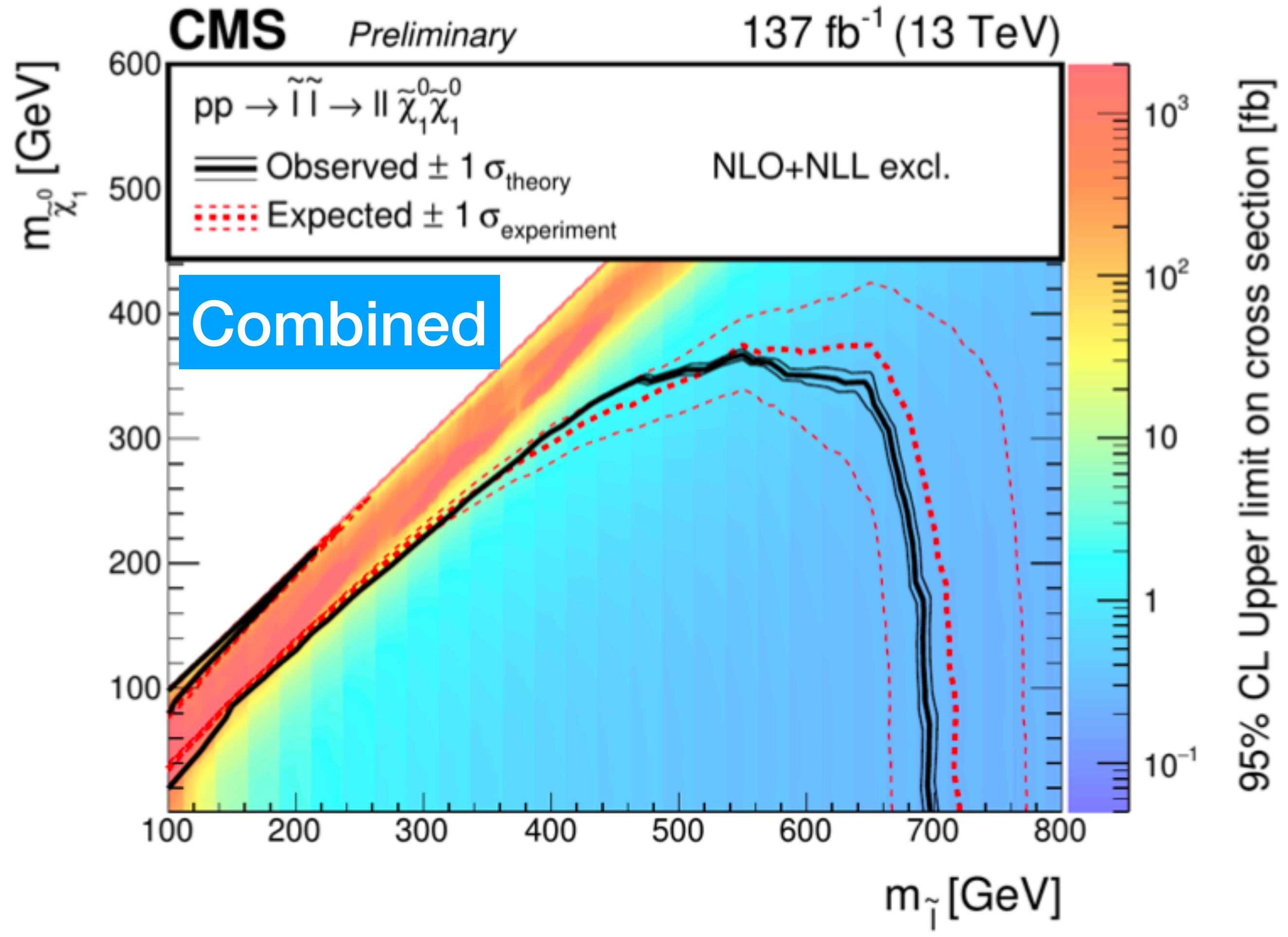
Sleptons (e/μ)



Uncompressed region covered by the 2-lepton non-resonant analysis

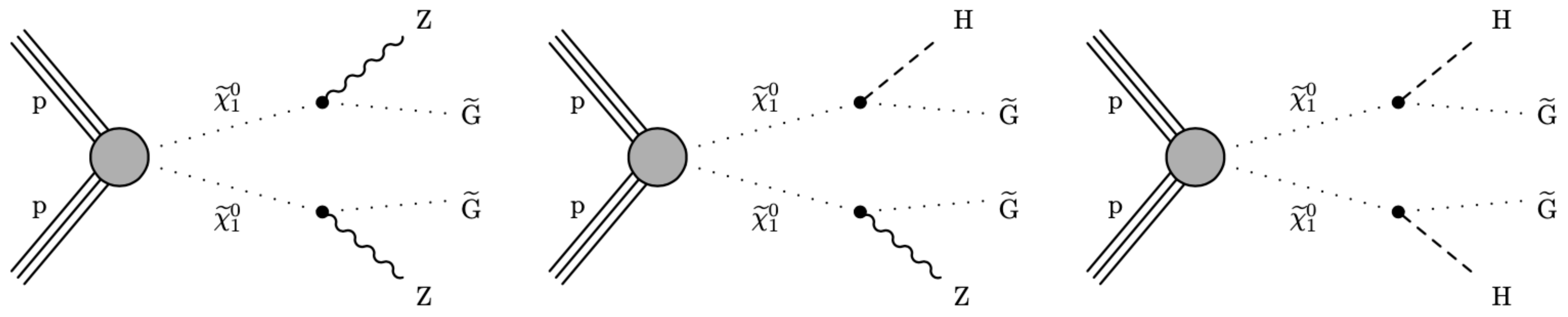
NEW: 2/3l soft analysis provides sensitivity to the compressed region (m_{ll} replaced by M_{T2})





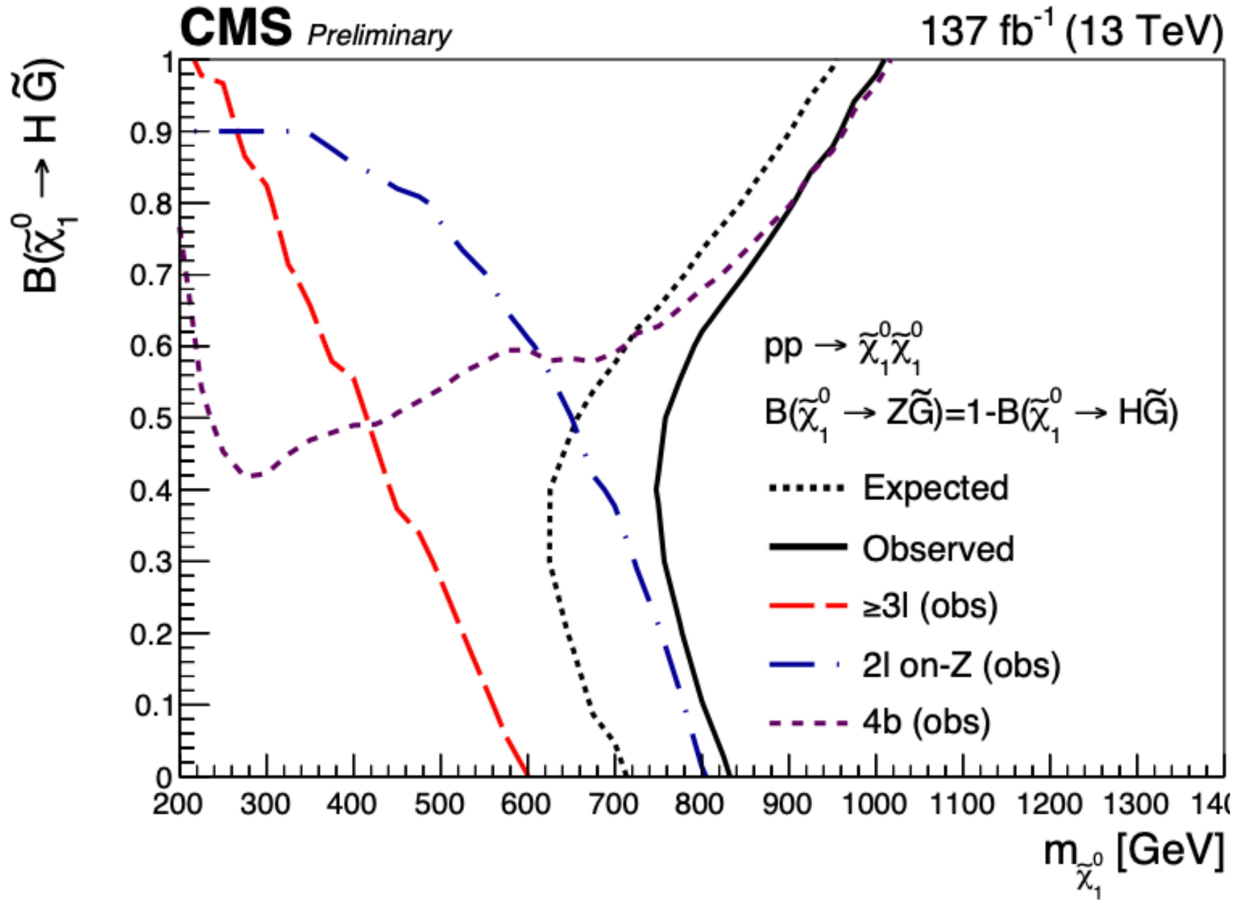
Sleptons excluded up to 215 (235) GeV at Δm=5 GeV

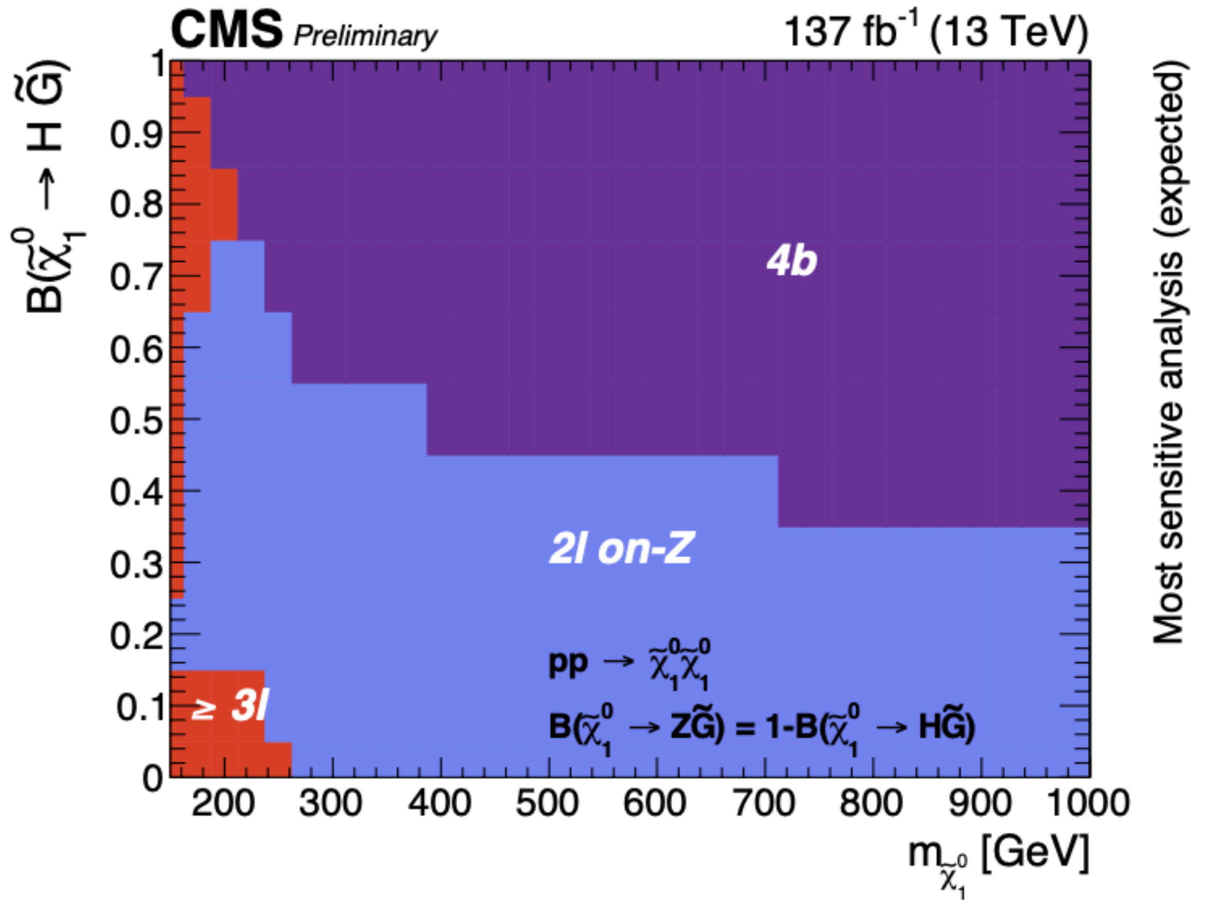
GMSB higgsinos



Higgsino triplet ($\tilde{\chi}_2^0, \tilde{\chi}_1^\pm, \tilde{\chi}_1^0$) with small Δm: results in effective $\tilde{\chi}_1^0\tilde{\chi}_1^0$ production, with $\tilde{\chi}_1^0 \to \tilde{G} + H/Z$

4b (HH) analysis most sensitive for large $\mathscr{B}(\tilde{\chi}_1^0 \to H\tilde{G})$



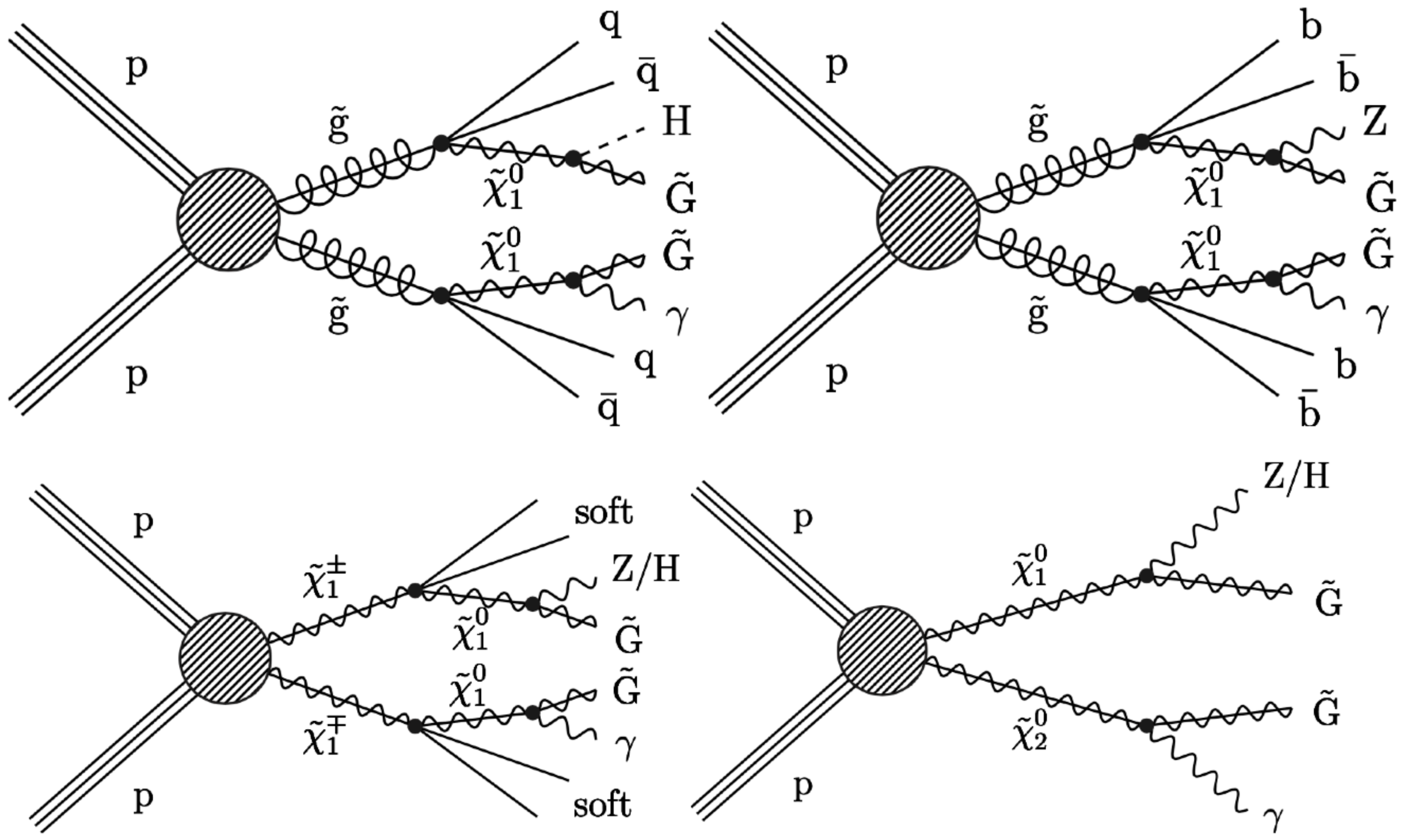


SUS-21-009

2016-2018 data

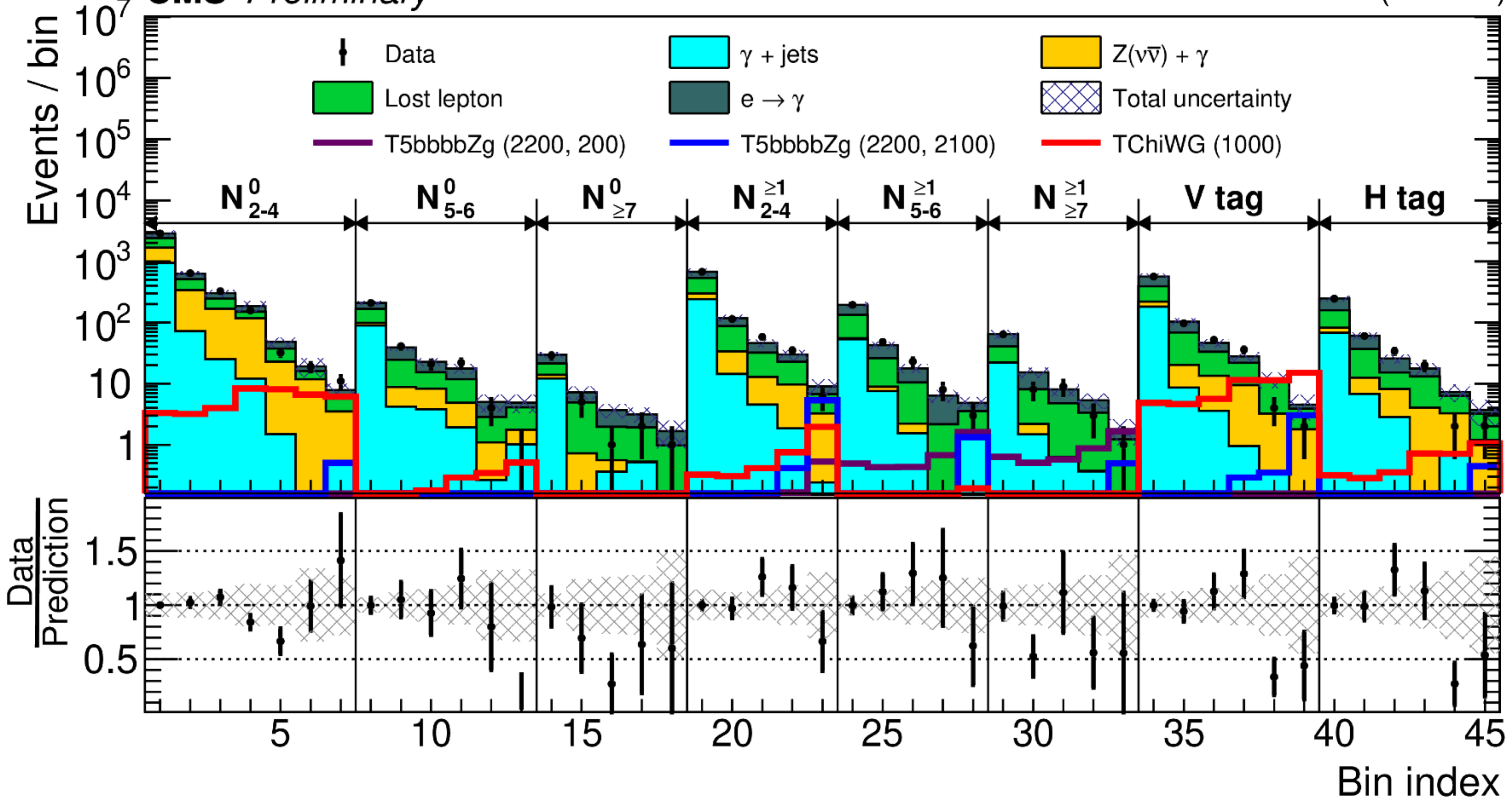
Search for SUSY with 1 photon, jets, and p_T^{miss}

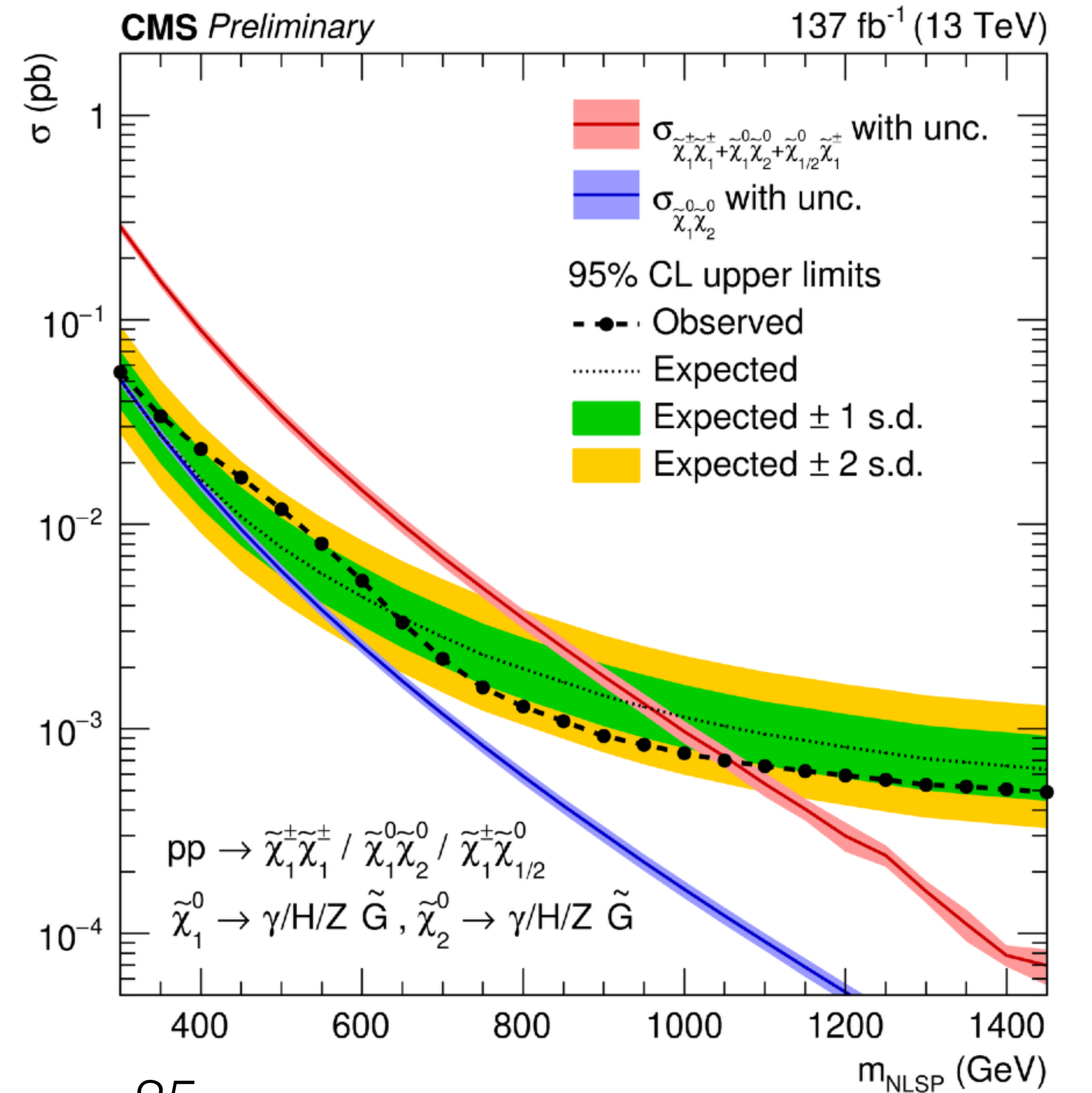
- Electroweak and strong production of neutralinos and charginos with fully hadronic final states and at least one photon from $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ decays (GMSB)
- Select ≥ 1 photon, ≥ 2 jets, 0 leptons, and p_T^{miss} > 300 GeV
  Require S_T > 300 GeV (scalar p_T sum of ɣ + jets)
- 2 categories with/without tagged W/Z/H boson, binned in p_T^{miss} and N_{jets}
- Main backgrounds: ɣ+jets and Wɣ+jets, ttɣ+jets... ("lost leptons")
  Data-driven estimations; ABCD-method or transfer factors

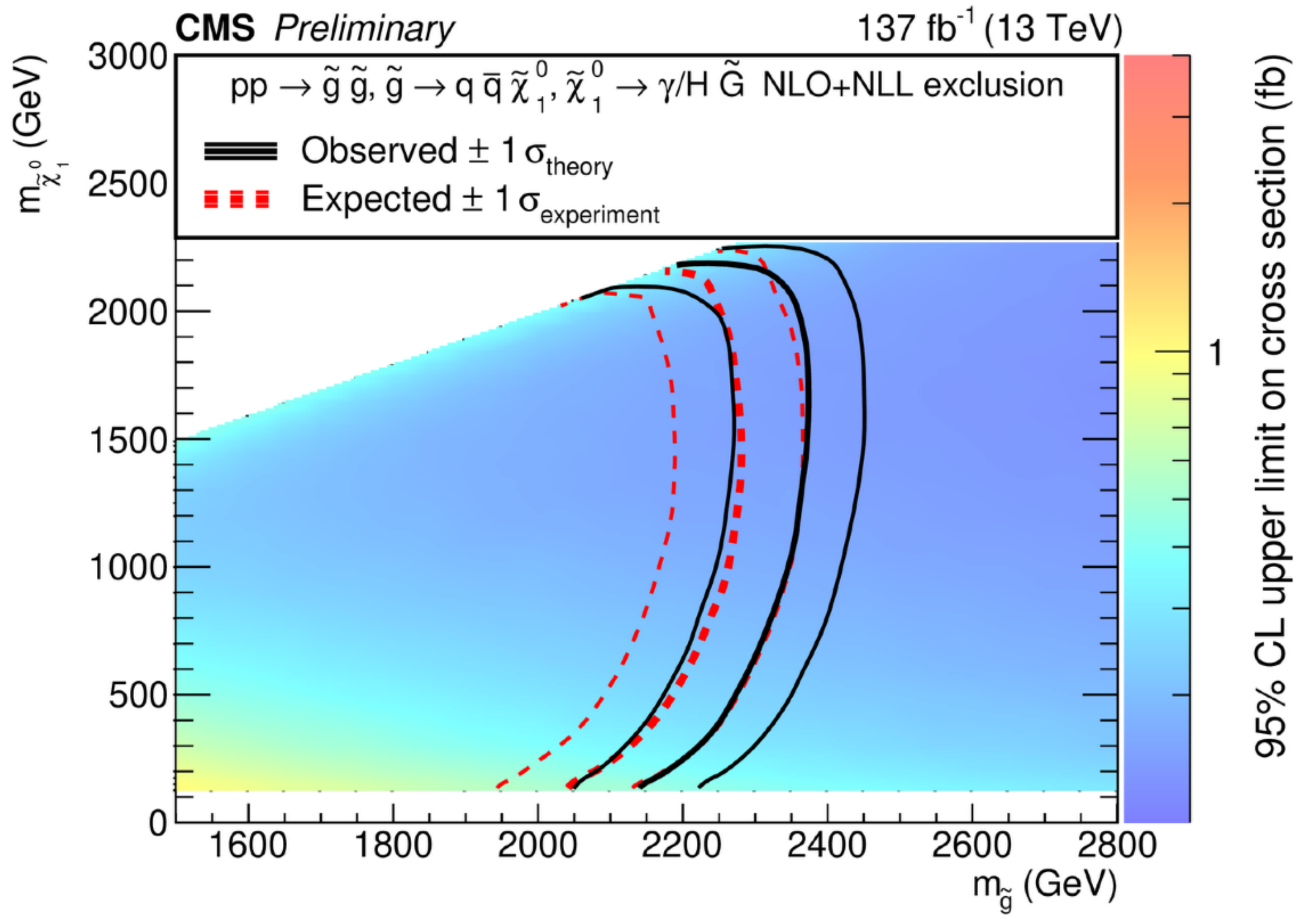


+ other models!

No excess observed







Search for Stealth SUSY with 2 photons and jets

Stealth SUSY: MSSM + light hidden sector containing singlino $\tilde{S}$ and singlet S, with gravitino LSP
→ naturally produces low $p_{\mathrm{T}}^{\mathrm{miss}}$ signatures

Search looks for gluino and squark production with decays
through the neutralino: $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{S},\ \tilde{S} \rightarrow S\tilde{G},\ S \rightarrow gg$

Selection:

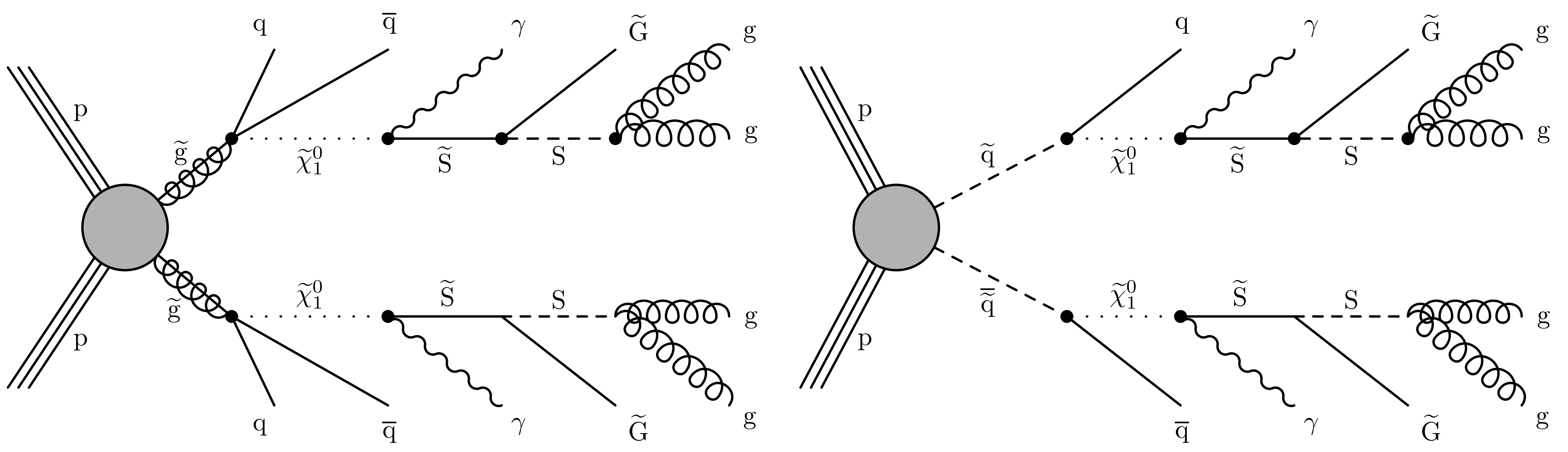
- 2 photons and ≥ 2 jets
- No requirement on $p_{\mathrm{T}}^{\mathrm{miss}}$
- S_{T} > 1300 GeV (scalar p_{T} sum of all objects)

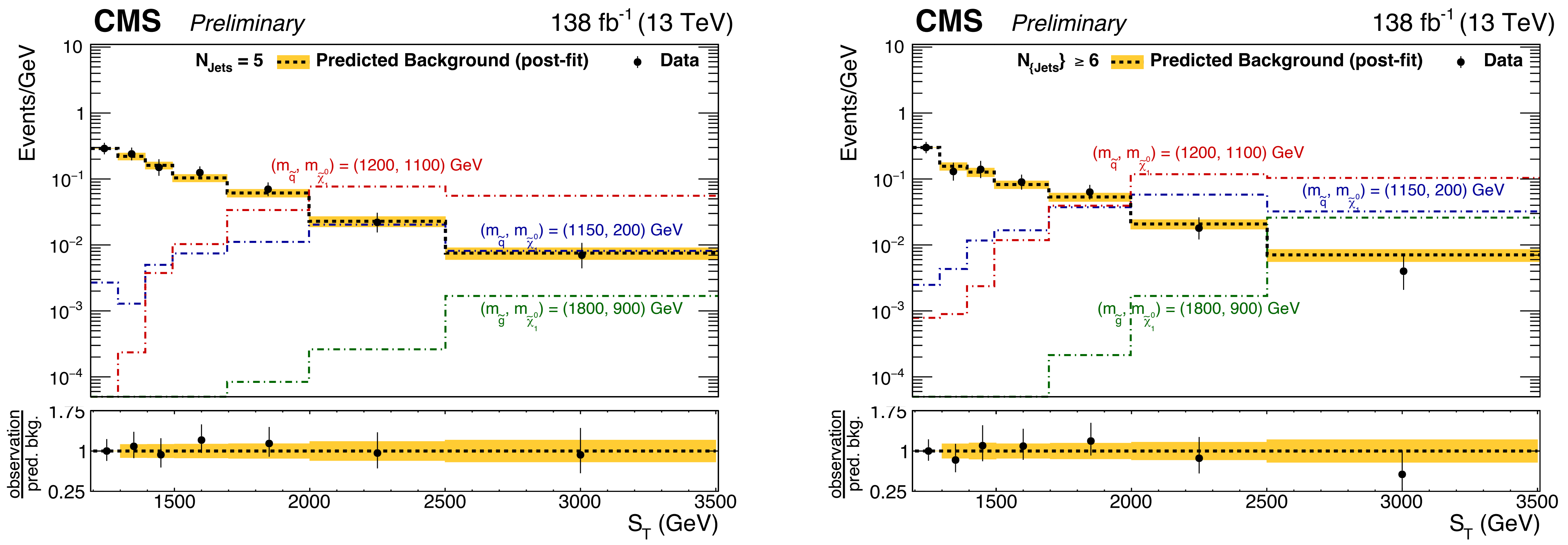
Signal extraction based on S_{T} and binned in jet multiplicity (4, 5, or ≥6 jets)

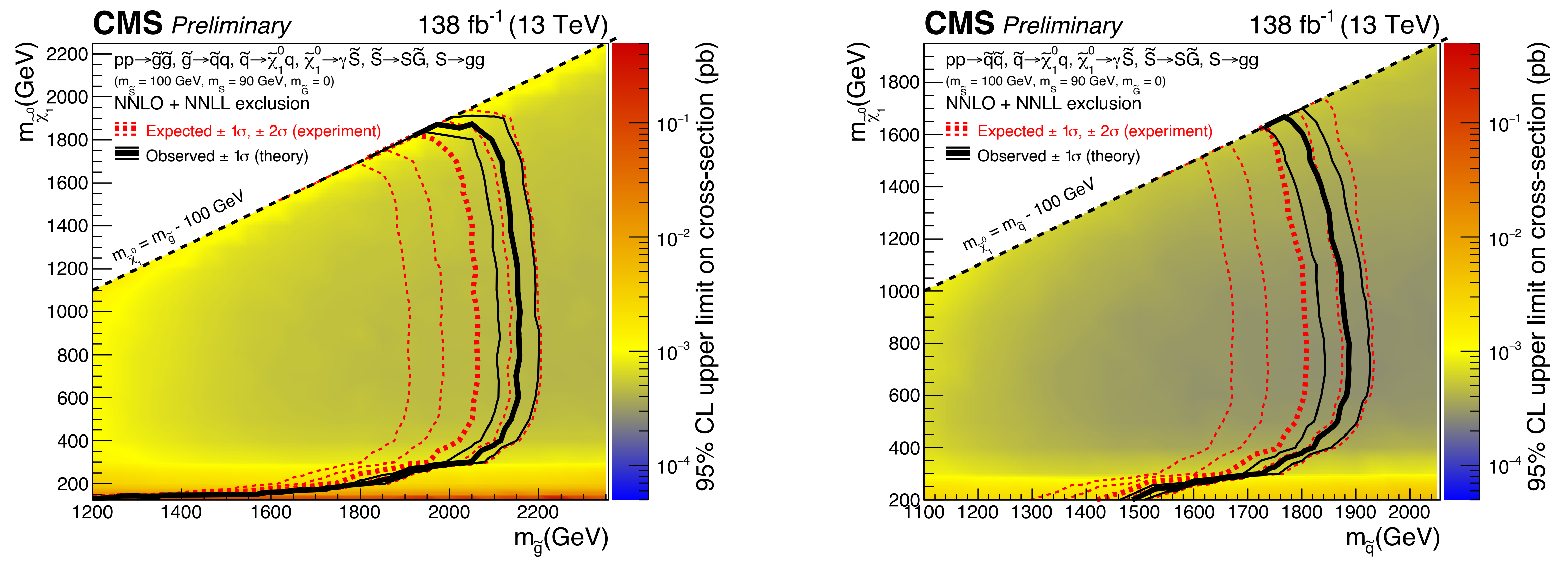
Data-driven background estimation using the S_{T} shape in events with low N_{jets}

Exclude gluinos & squarks with masses up to 2.15 & 1.85 TeV

Strongest limits to date for these models!

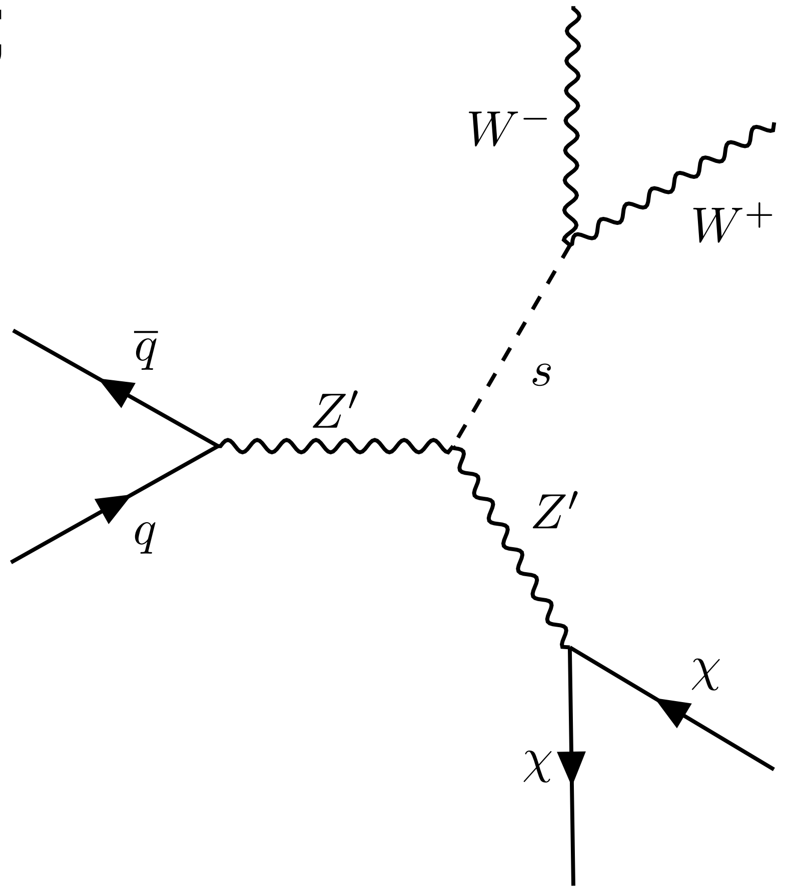


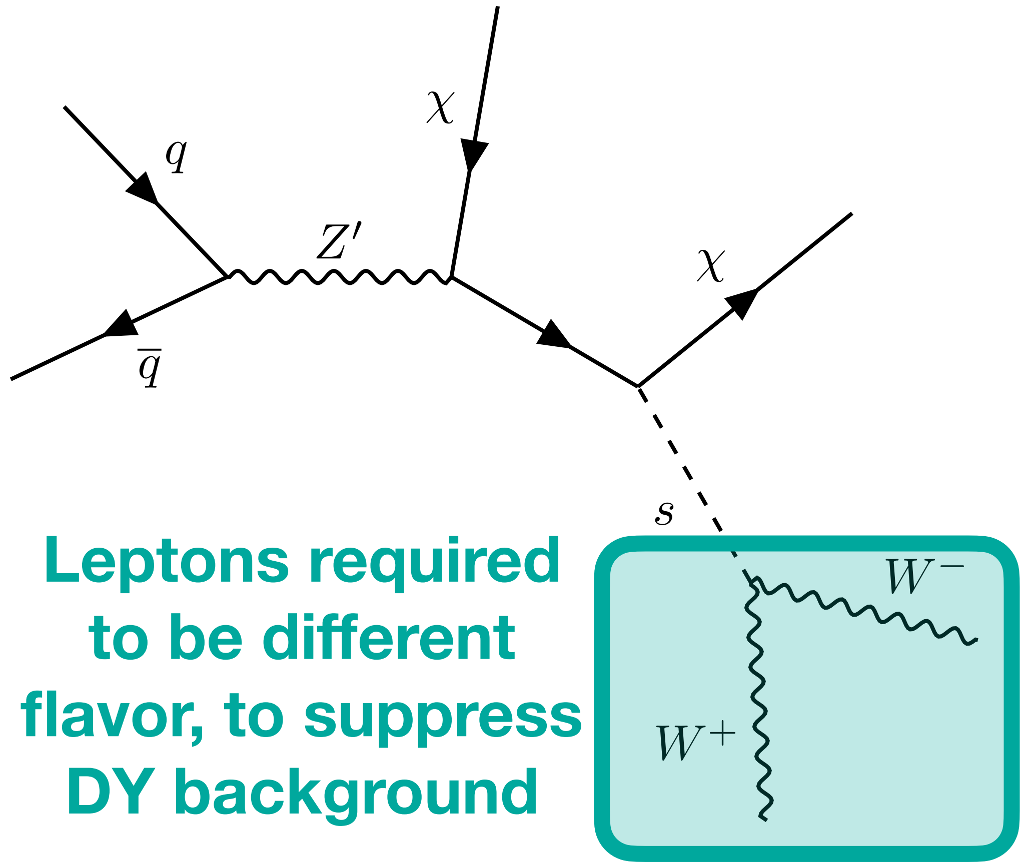




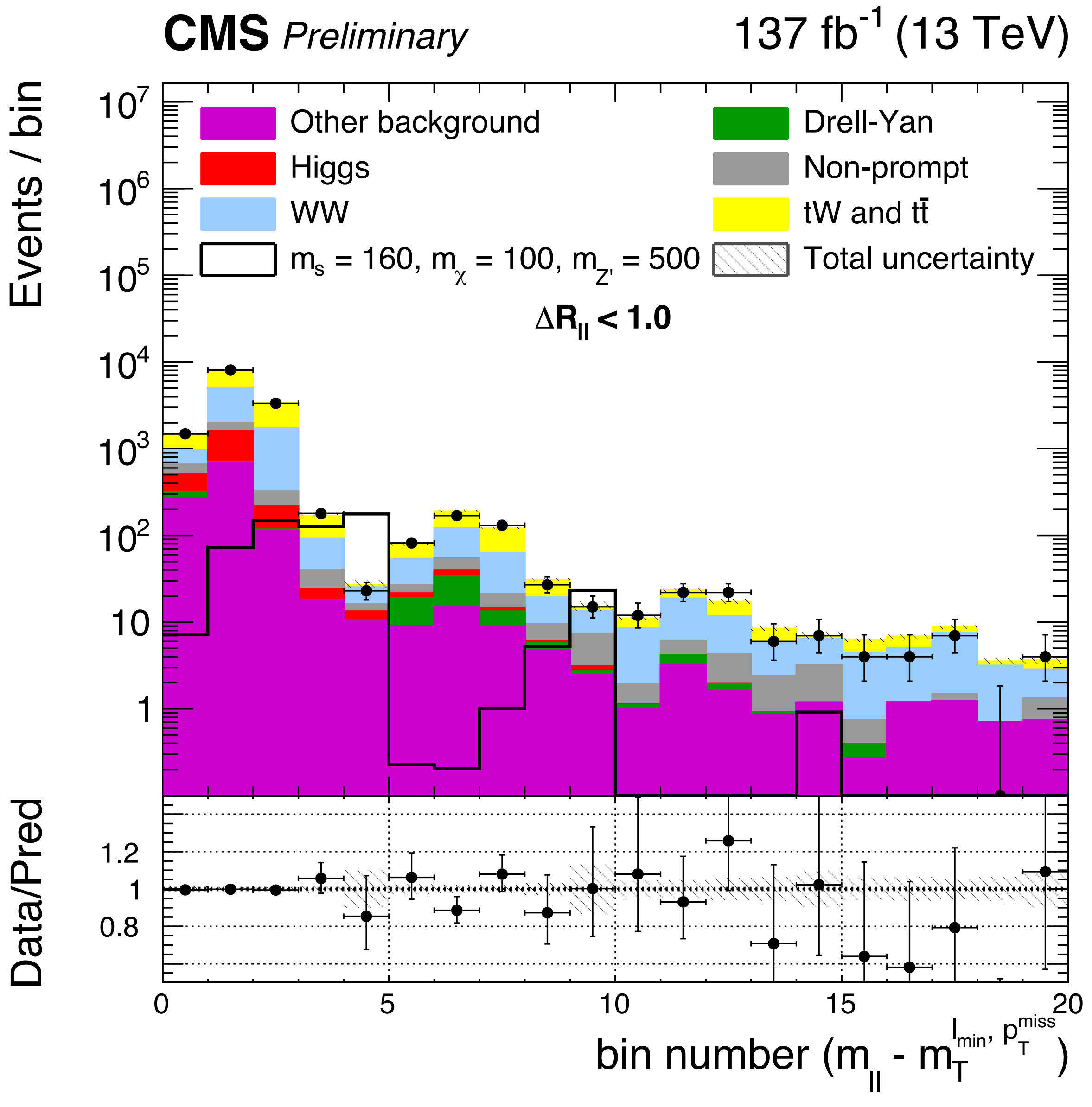
Search for dark matter in W+W- events with p_T^{miss}

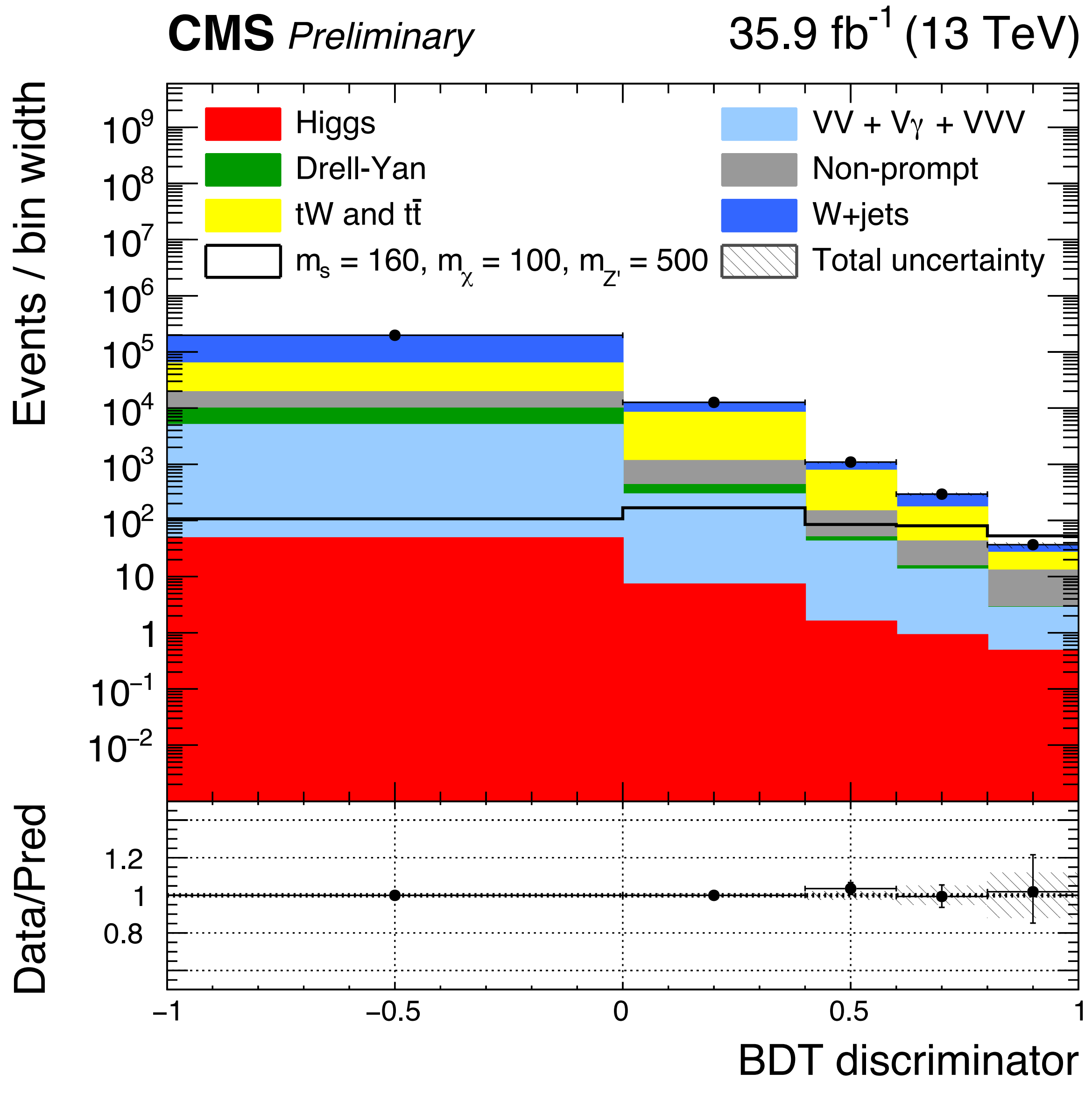
- Focuses on a Dark Higgs model including Dark Higgs s, Z', dark matter χ; assuming Z' production with decays to W^+W^- and two DM particles (dominant decay for $m_S > 160\,\mathrm{GeV}$)
- Selection: 1 or 2 leptons, no b-tagged jets
- 2-lepton final state: 2D profiled fit to $m_T(\ell_2, p_T^{miss})$ and $m_{\ell\ell}$
- 1-lepton final state: 1D binned fit to the shape of a BDT discriminant, trained for signal separation with kinematic variables related to the leptons and p_T^{miss}

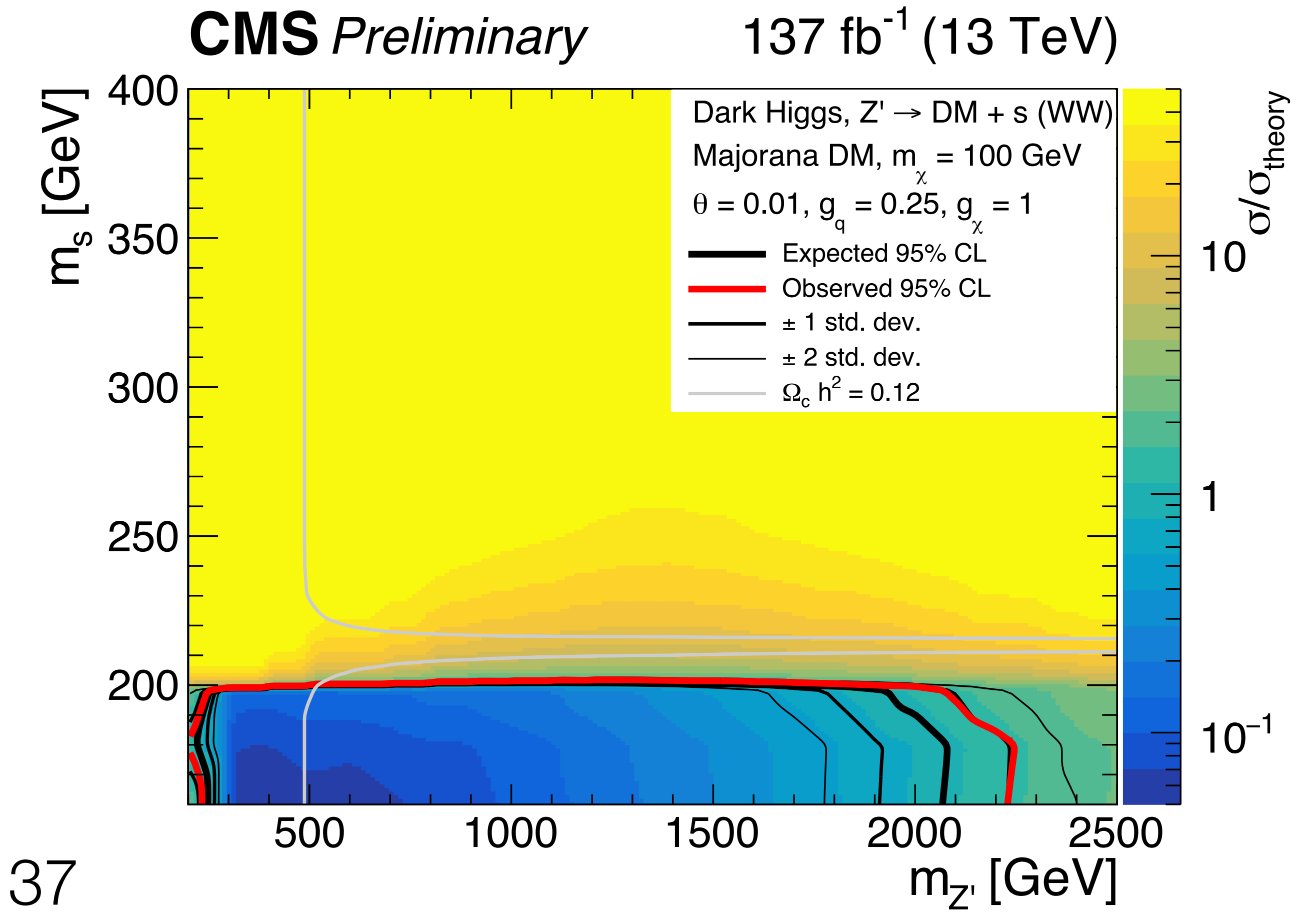


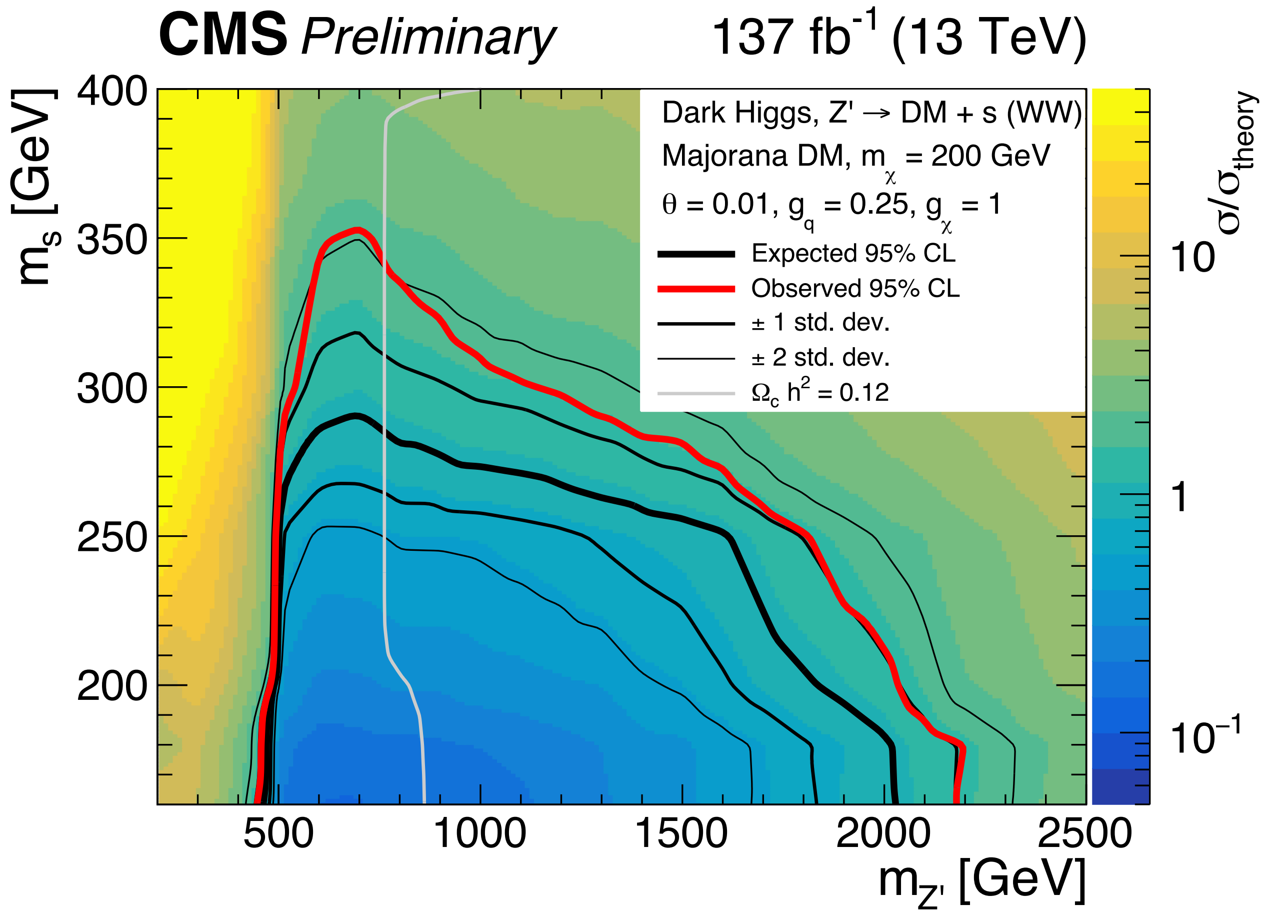


- No excess observed
- Strongest limit for $m_{DM} = 200\,\mathrm{GeV}$: exclude up to $m_S = 350(160)\,\mathrm{GeV}$ for $m_{Z'} = 700(2200)\,\mathrm{GeV}$



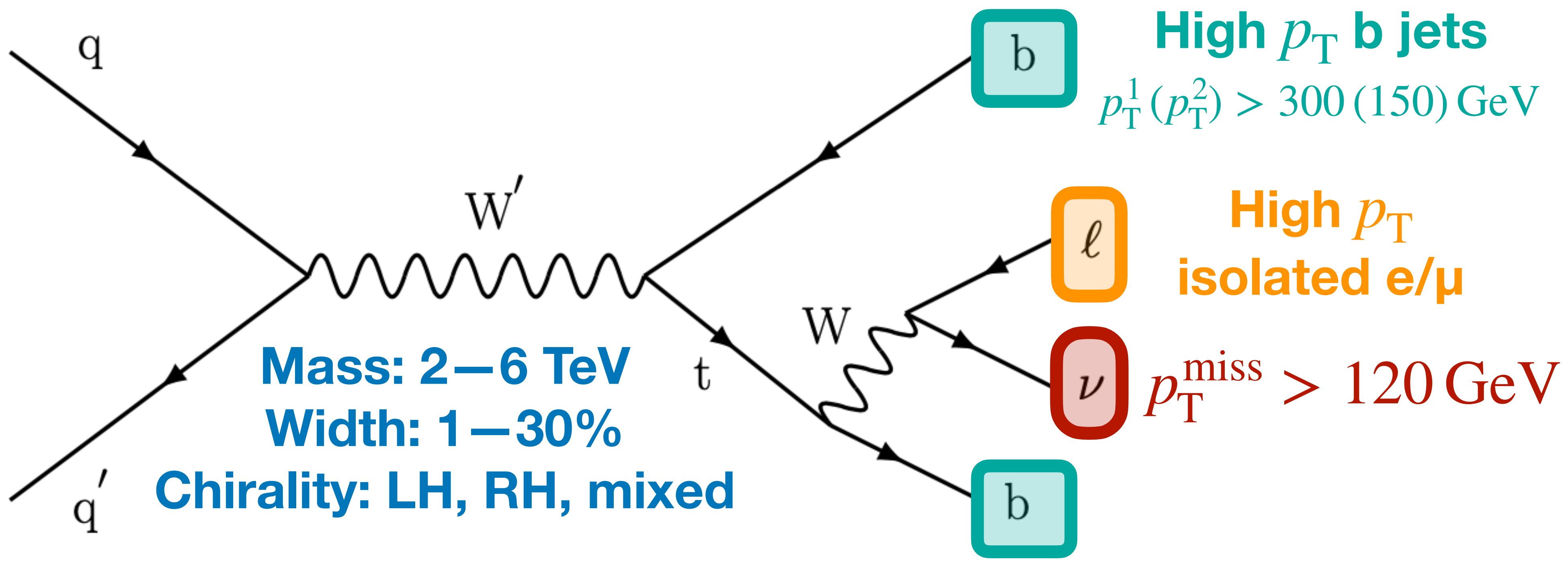




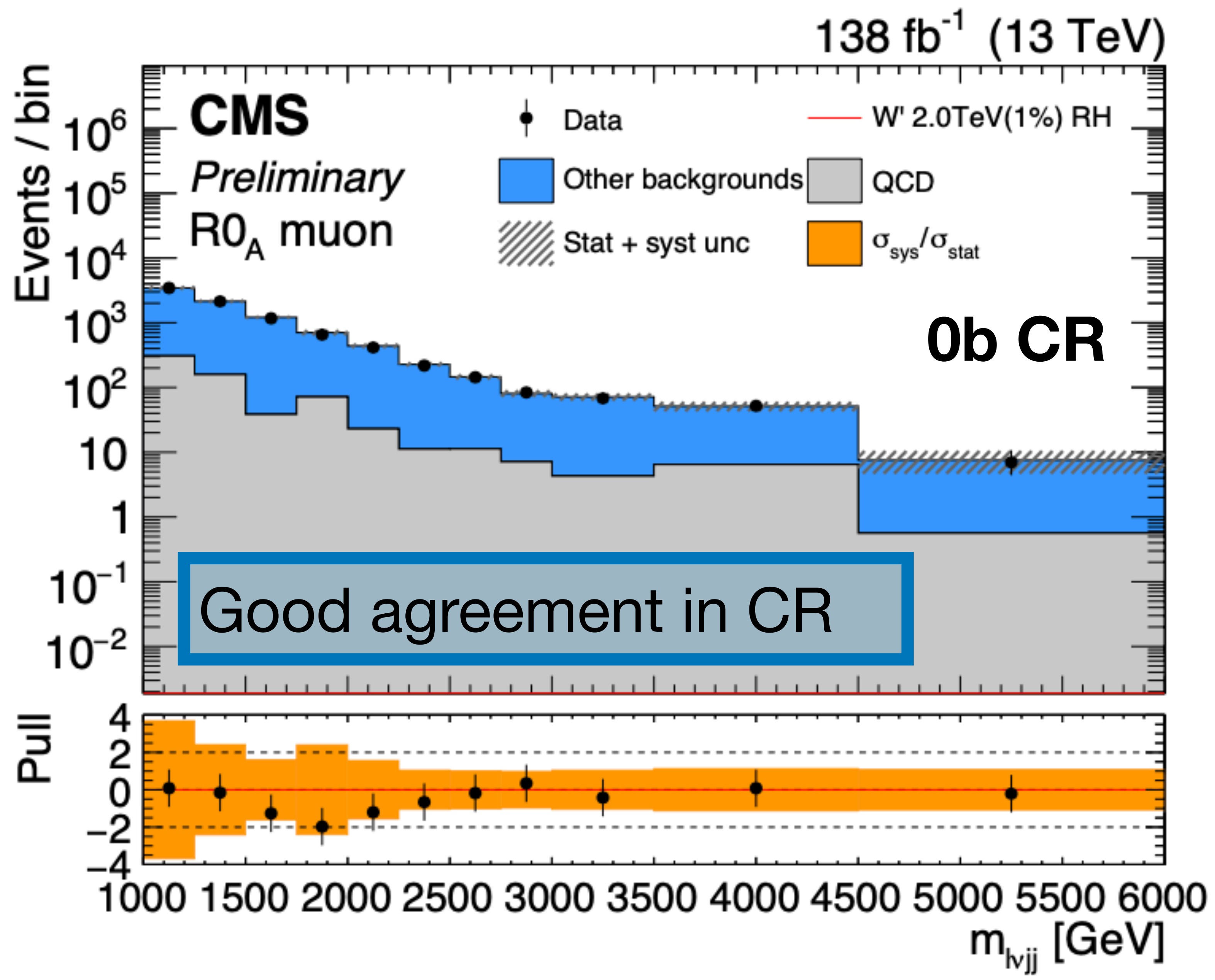


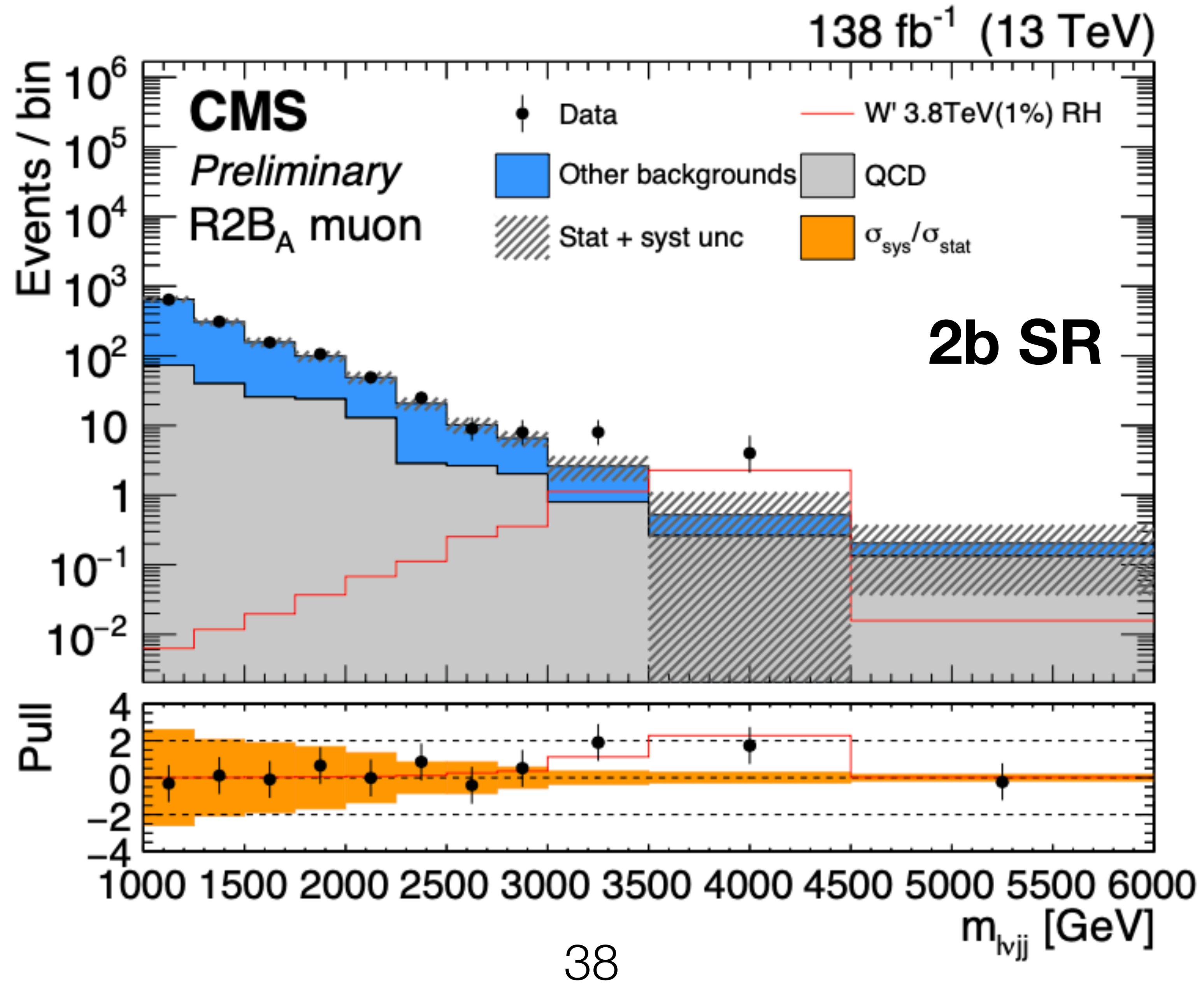
Search for $W' \rightarrow tb$ in leptonic final states

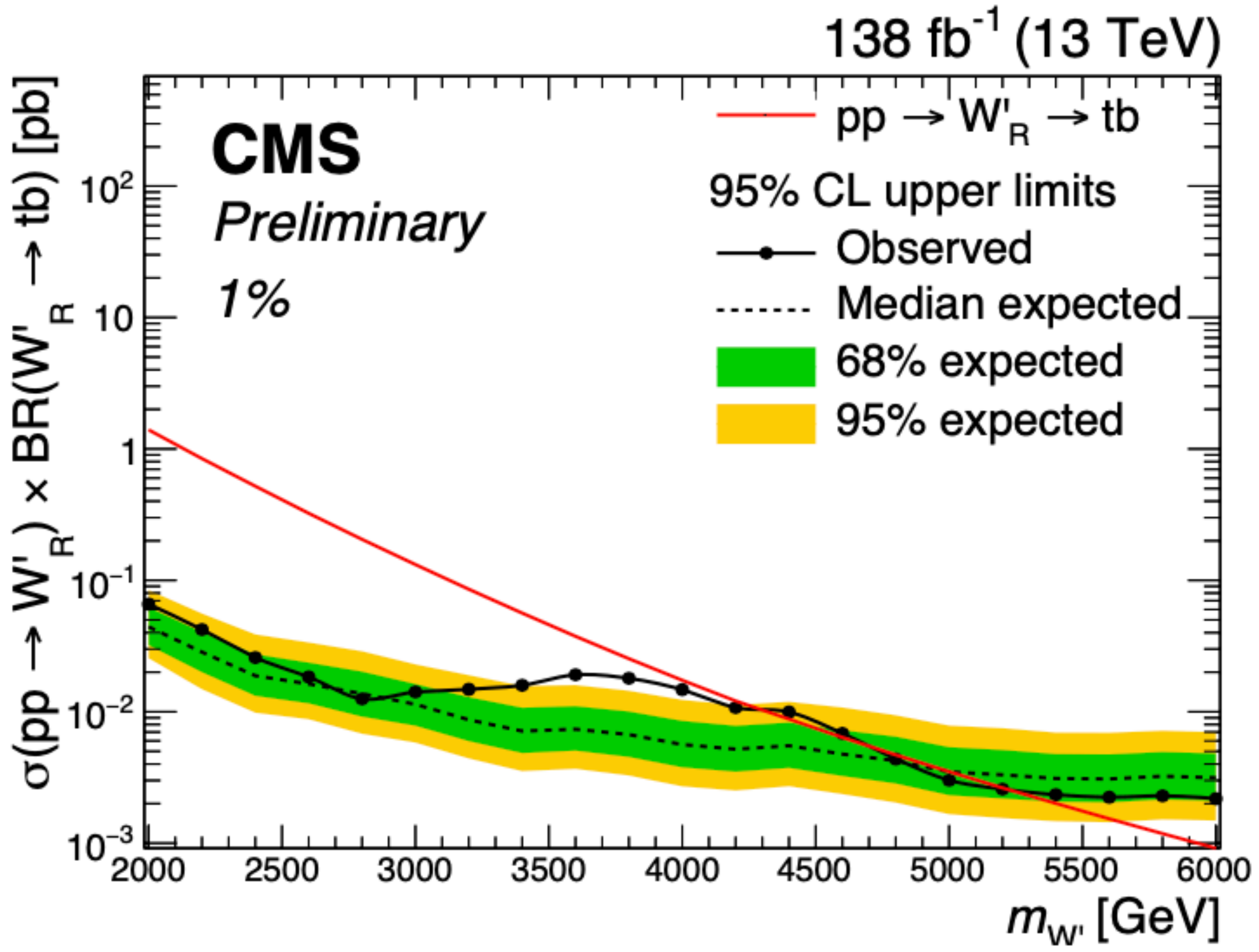
- **W' reconstruction from reconstructed top quark paired with other b jet**
  - High p_T leptonic top quark recontruction using lepton, p_T^{miss}, and b jet:
    - Use m_W to constrain neutrino p_z
    - pick jet using combo of m_{top}, $\Delta R(\ell, j)$, subleading b jet
  - W' candidate = top candidate + leading b jet not already used
  - If less than 2 bjets, procedure is applied to full jet collection
- 0b events used as CR; SRs binned based on which jet is b-tagged
- Simultaneous maximum likelihood fit to the $m_{\ell\nu jj}$ distribution, with backgrounds estimated via data sidebands using m_{top} and $m_{SD,AK8}$ (AK8 jet closest to W' jet)



Observed 2.6σ local (2.0σ global) excess at 3.8 TeV, for narrow W' (RH chirality)



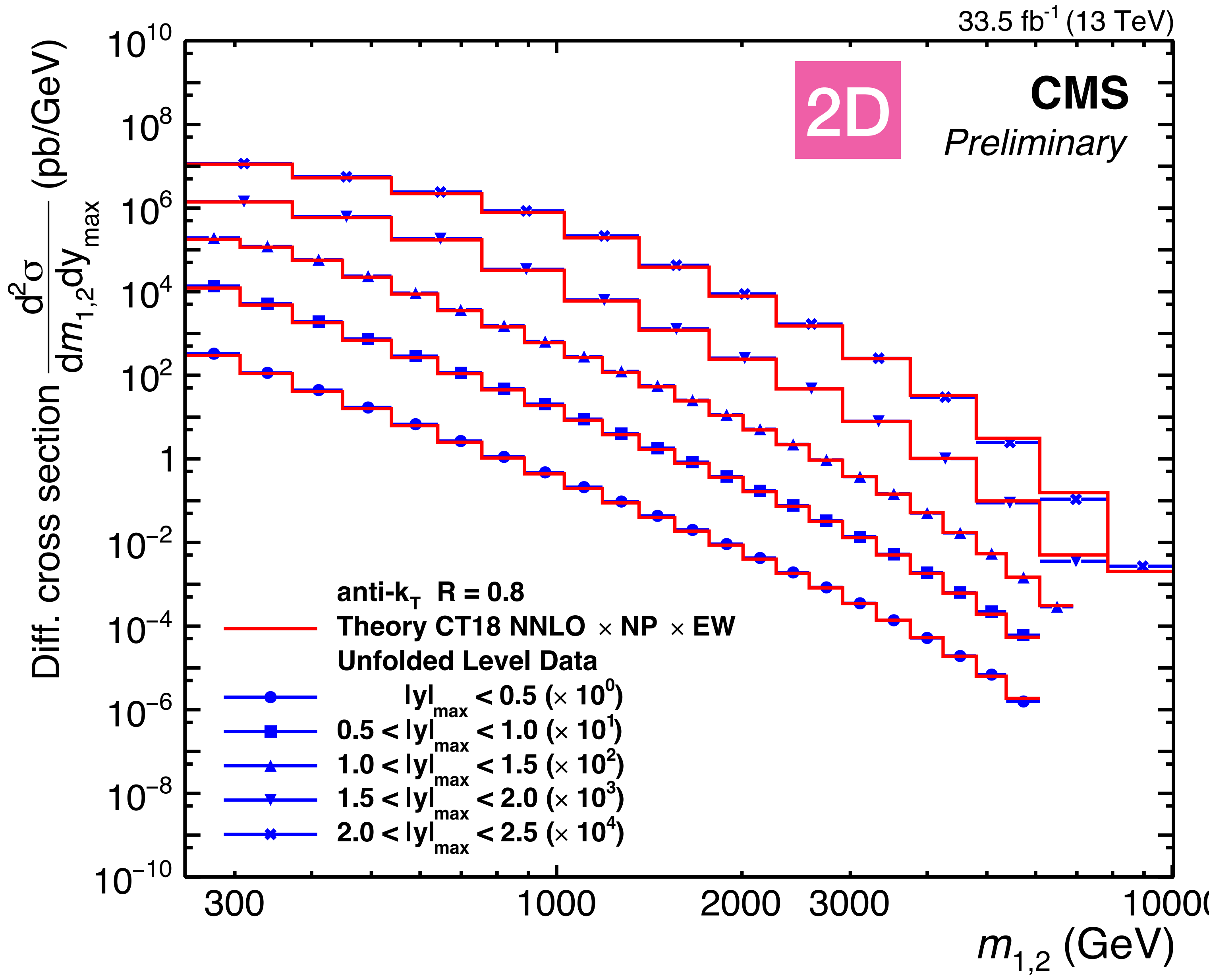




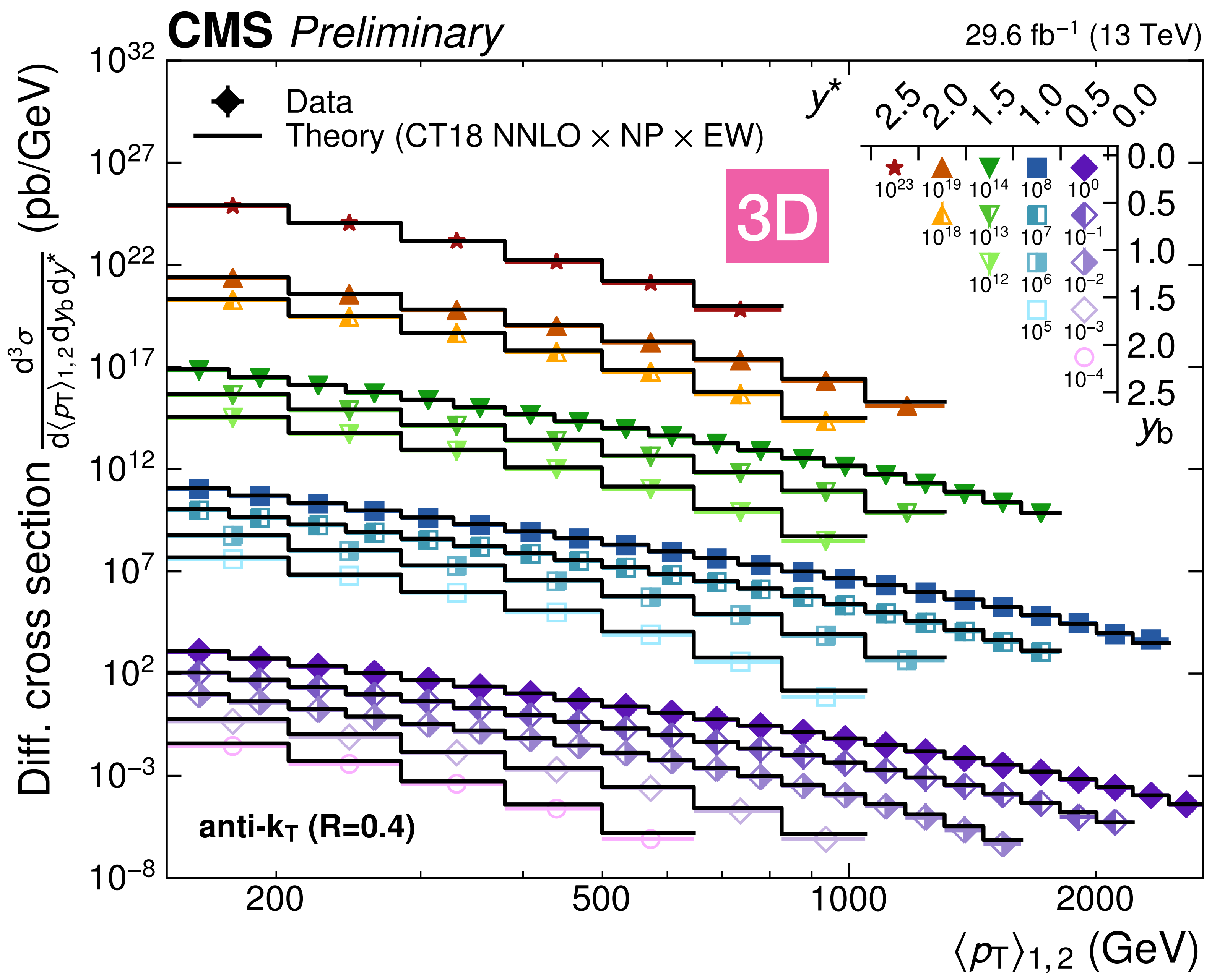
SMP-21-008

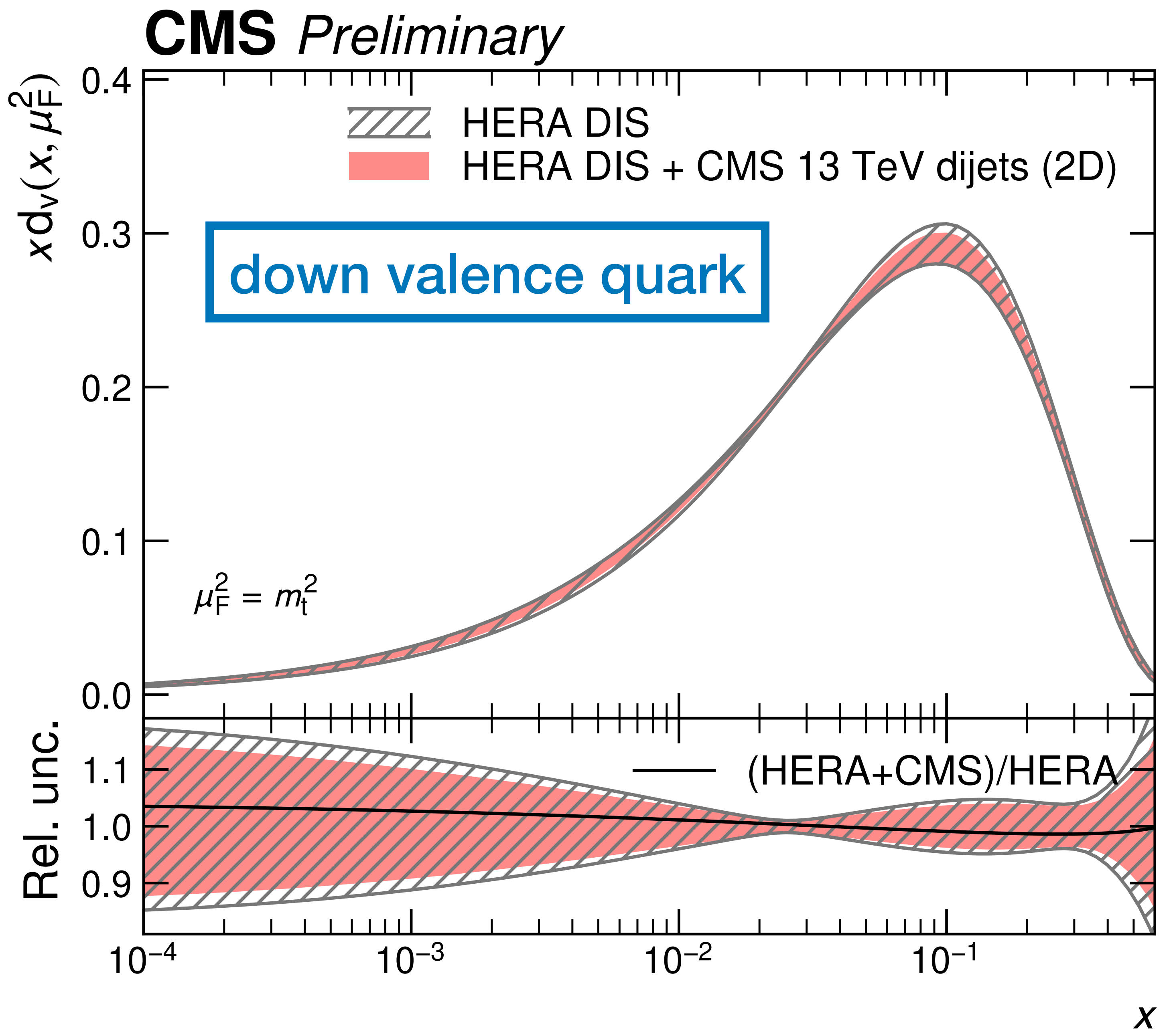
2016 data

Dijet cross section



Note the x-axis range up to 10 TeV!





- 2D in rapidity y_{max} and invariant mass $m_{1,2}$ of dijet system
- 3D in rapidity separation y^*, total boost y_b and either $m_{1,2}$ or the average p_T of the dijet system
- Unfolded results are compared to fixed order NNLO calculations from NNLOJET

- Extract PDFs using this data together with HERA DIS
- General reduction of systematic uncertainties
- General agreement with/without CMS data

Conclusion

- CMS continues the exploration of the particle physics landscape, both for precision measurements and searches
    - It is truly a multipurpose experiment!
- Analyses are using sophisticated analysis methods, including machine learning methods to extract the most from our excellent data
- For more results, please visit our public results web pages!
And stay tuned for Run 3 results in the future!