# Current Highlights and Future Prospects from CMS


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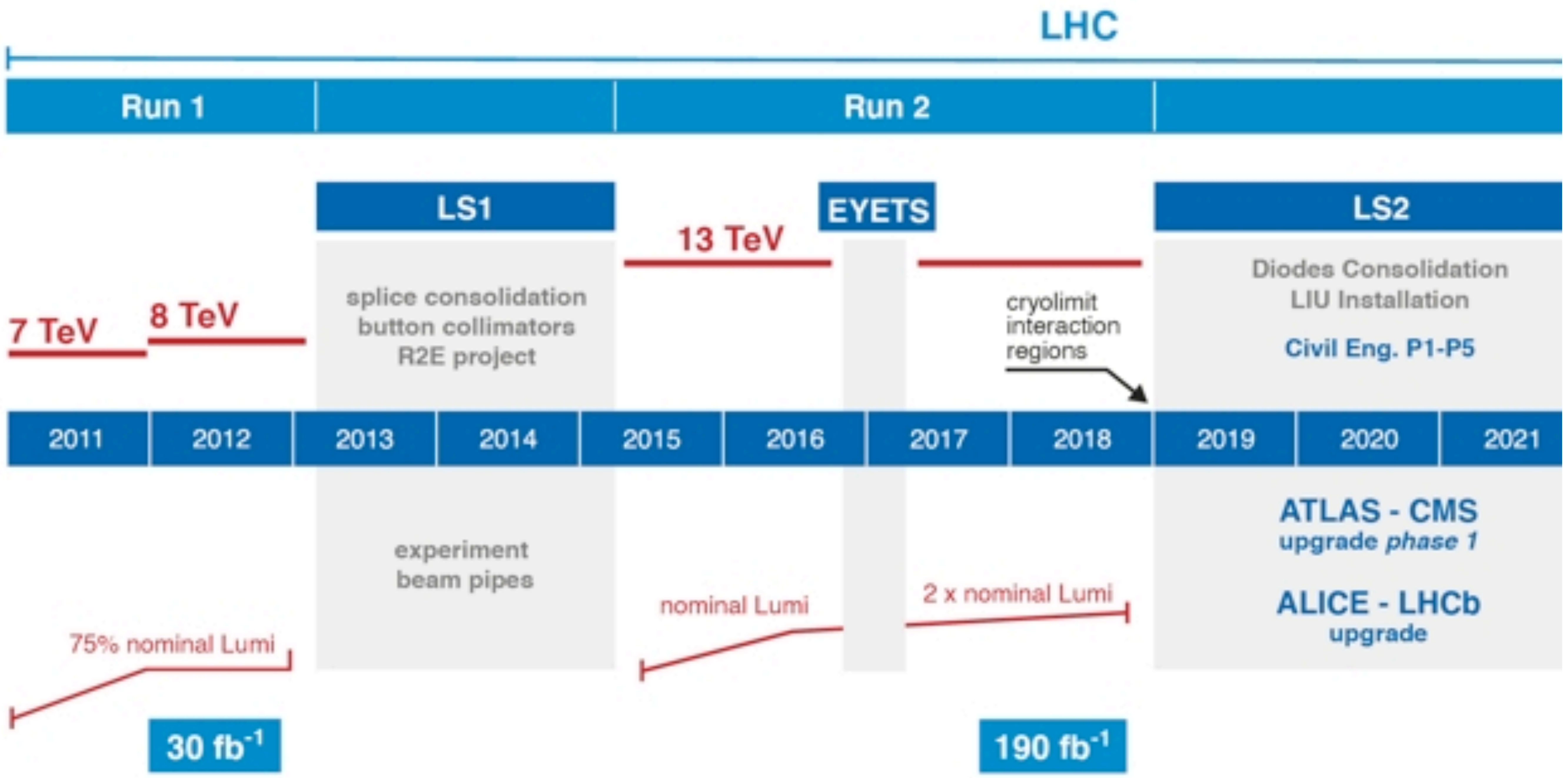
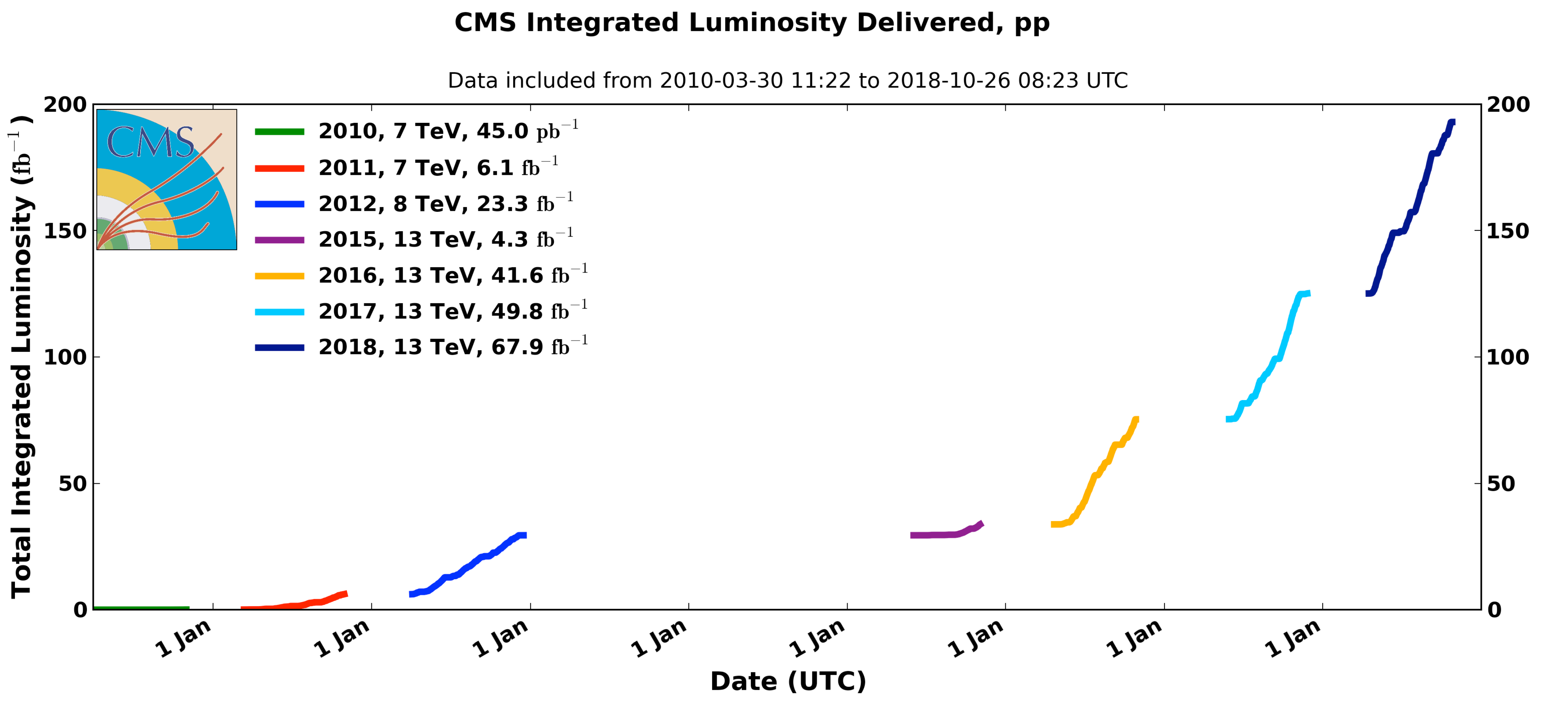
# Status at CMS




Run2 (2016-18):

- pp: 13 TeV, ~140 $fb^{-1}$,
- PbPb: 5.02 TeV/nucleon 2.26 $nb^{-1}$

Run2 measurements & searches in a huge diversity of physics channels:

- Target most challenging and interesting signatures.
- Innovative analysis methods, e.g. extensive use of machine learning.
- More refined use of detector capabilities, e.g. searches with long-lived particles.

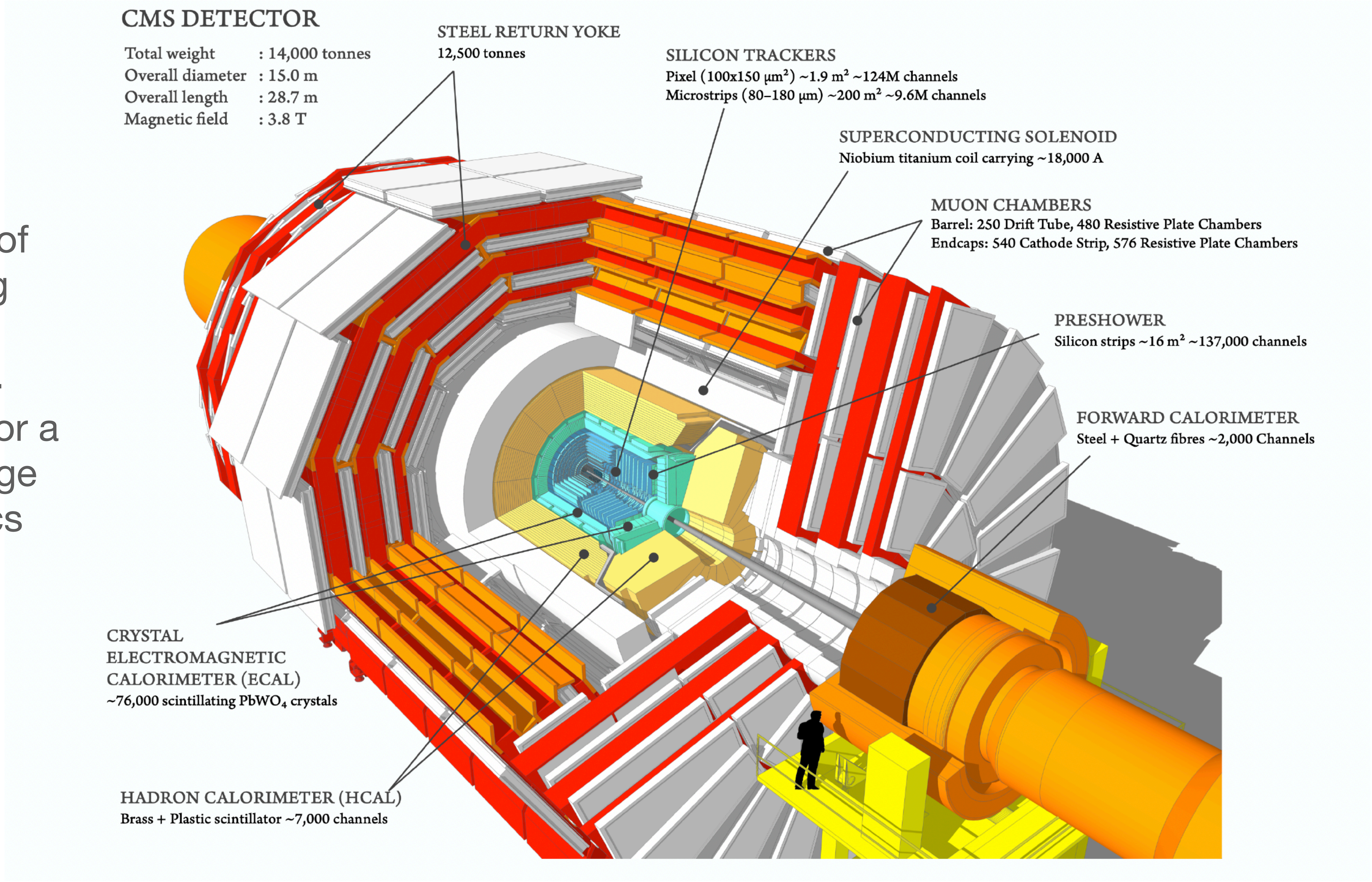
Publications:

- >1100 total.
- > 500 on Run2 data.

# CMS detector layout

General purpose detector capable of detecting different particles.

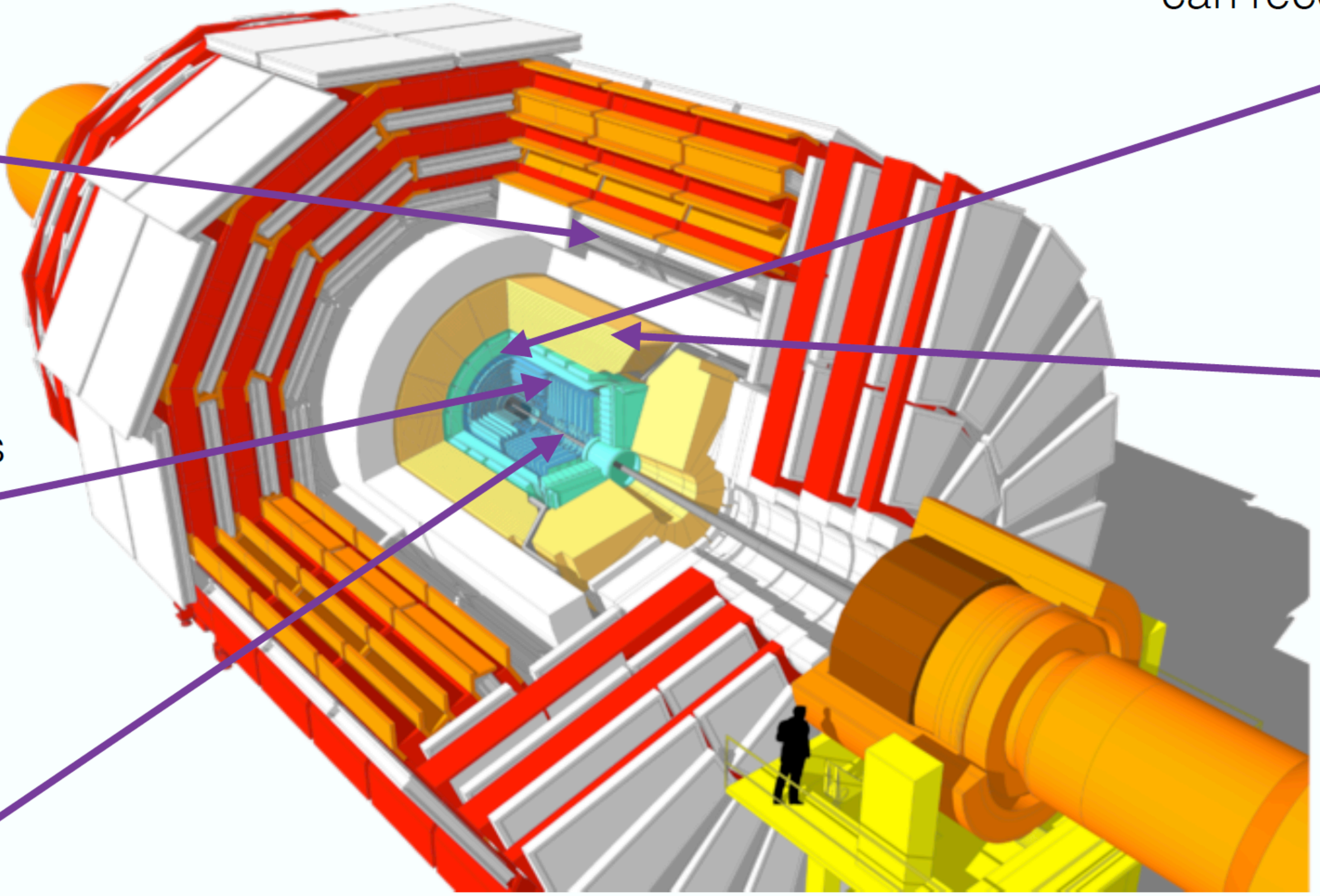
Eligible for a wide range of physics studies.



# Phase2 upgrade for the CMS detector

**Improved muon coverage and trigger**
increased RPC coverage (1.5 < |η| < 2.4)
new electronics
CMS-TDR-016

**New endcap calorimeters**
high granularity
can reconstruct showers in 3D
CMS-TDR-019



**Updates to calorimeter and trigger**
higher granularity
electronics for trigger
CMS-TDR-015

**New precision timing detector**
Timing resolution of 30-40 ps for MIPs
full coverage of |η| < 3.0
CMS-TDR-020

L1: CMS-TDR-021
DAQ/HLT: CMS-TDR-022

**New inner tracker**
all silicon tracker
4 layers of pixels
5 layers of strips
coverage to |η| < 4
CMS-TDR-014

Beam Radiation Instrumentation and Luminosity Detectors
CMS-TDR-023

**Upgrade to trigger and DAQ**
L1 rate increased to 750 kHz
High Level trigger rate to 7.5 kHz
Track information at L1

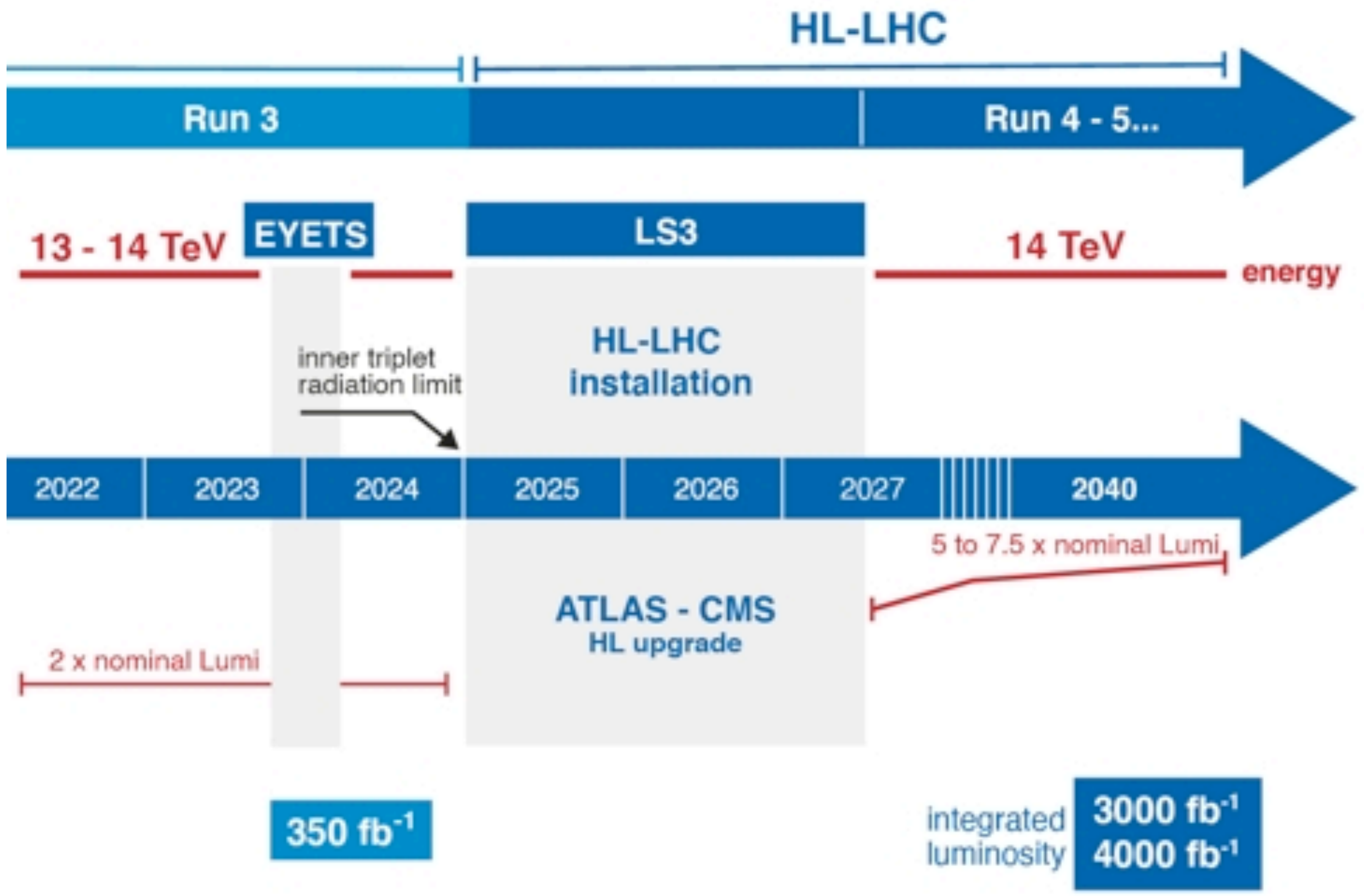
# Towards the HL-LHC

## High Luminosity LHC outlook

- Center of mass energy: 14 TeV
- Instantaneous luminosity: $5 \times 10^{34}$ $cm^{-2}s^{-1}$
- Total luminosity to be delivered: 3-4$ab^{-1}$
- Pileup: 140-200

Opportunities: More data, improved detector coverage, new detector features.

Challenges: High pile-up, high beam-induced backgrounds, high radiation.




Dedicated physics studies exploring full potential of the HL-LHC and upgraded detectors:

- Improve current searches, design new searches exploiting the new detector capabilities. and develop new analysis strategies.
- access scenarios with lower cross sections, lower acceptance and open new search channels.

Results mainly in CERN Yellow Reports: SM (CERN-LPCC-2018-03), Higgs (CERN-LPCC-2018-04), BSM (CERN-LPCC-2018-05) (LHC experiments + theorists). Others in Technical Design Reports.
More studies ongoing for the Snowmass 21 effort.

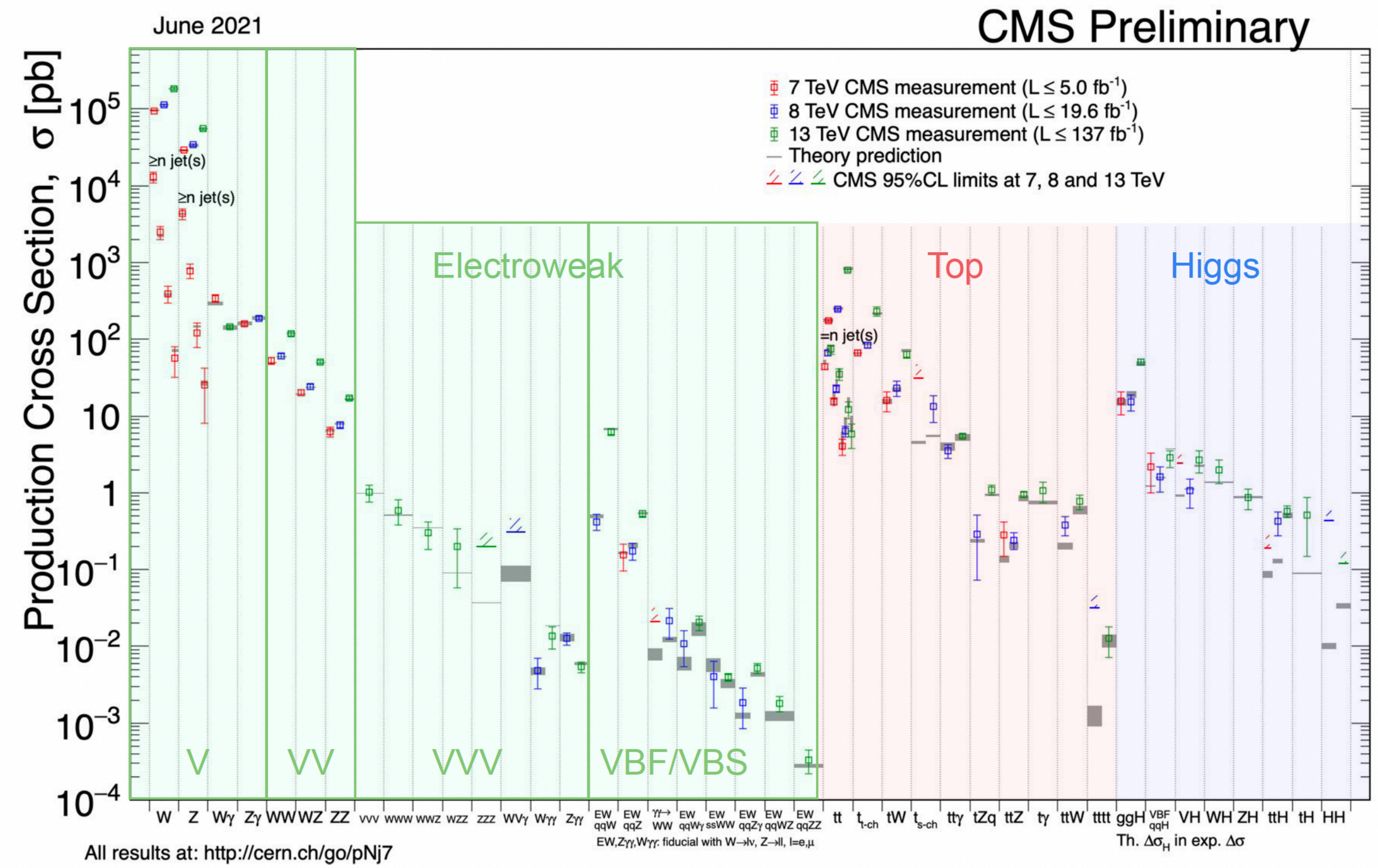
# Typical analysis flow

- Define final state describing the signal:
  - Analyses are mostly signature-based (designed around a given final state, e.g. dileptons, jets+$E_T^{miss}$, …). A final state often probes multiple models/scenarios.
- Apply trigger / online selection.
- Reconstruct, identify and select objects: electrons, muons, jets, boosted tops, …
- Apply an event selection to enhance signal and eliminate backgrounds.
  - Increased use of ML discriminants in Run2.
- Estimate backgrounds via data control regions and/or simulation.
- Apply systematic uncertainties.
- Do a blind analysis: validate analysis strategy before comparing data with background estimate in search regions.
- Perform statistical analysis.
- Interpret the results on on relevant physics models.

# Standard model physics


- CMS SM results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP
- CMS top results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
- CMS heavy ion results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

# SM cross sections




Measurements of total cross sections in various production channels.

Also performing measurements of differential cross sections.

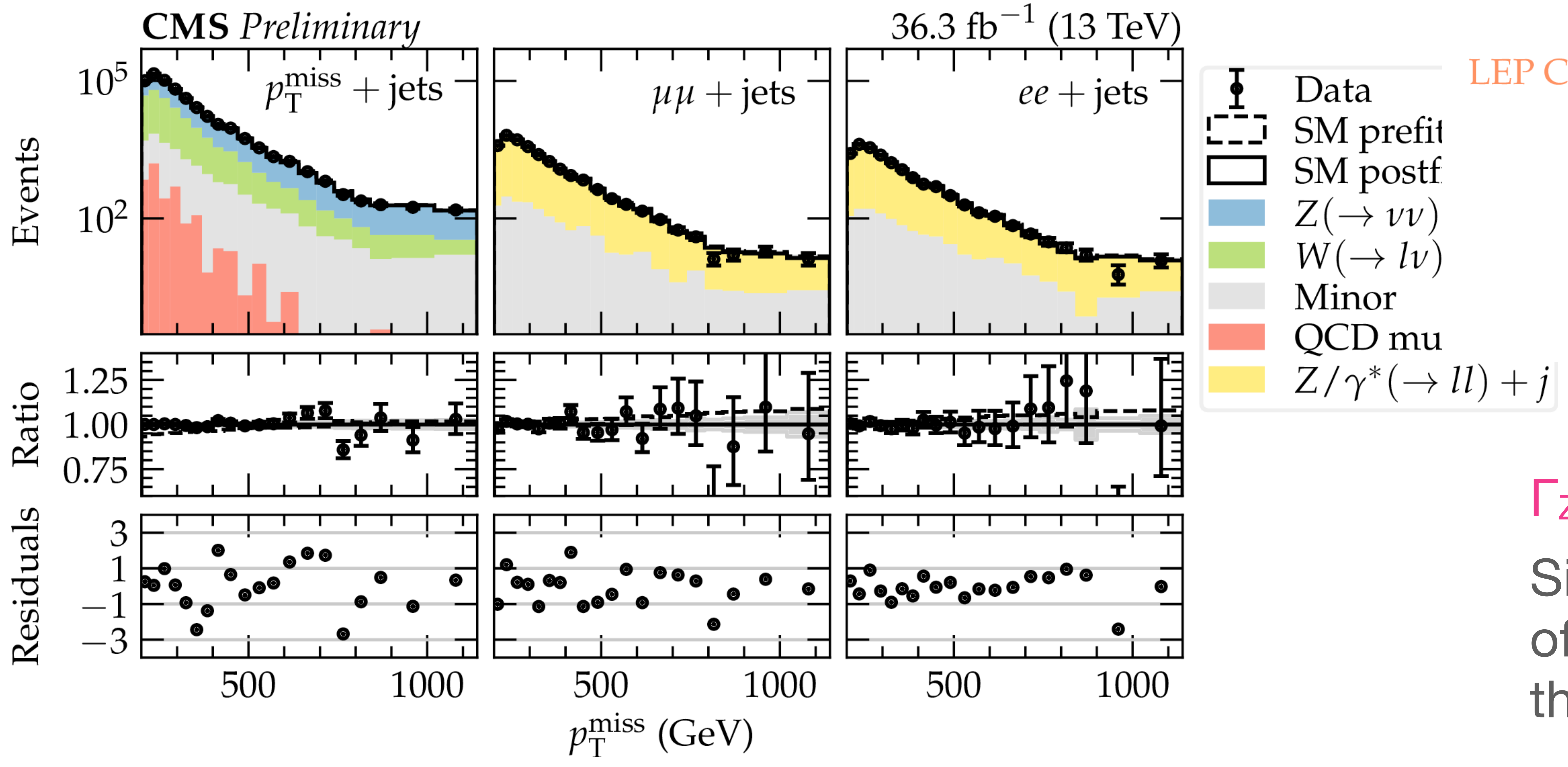
Deviations from SM prediction may indicate new physics.

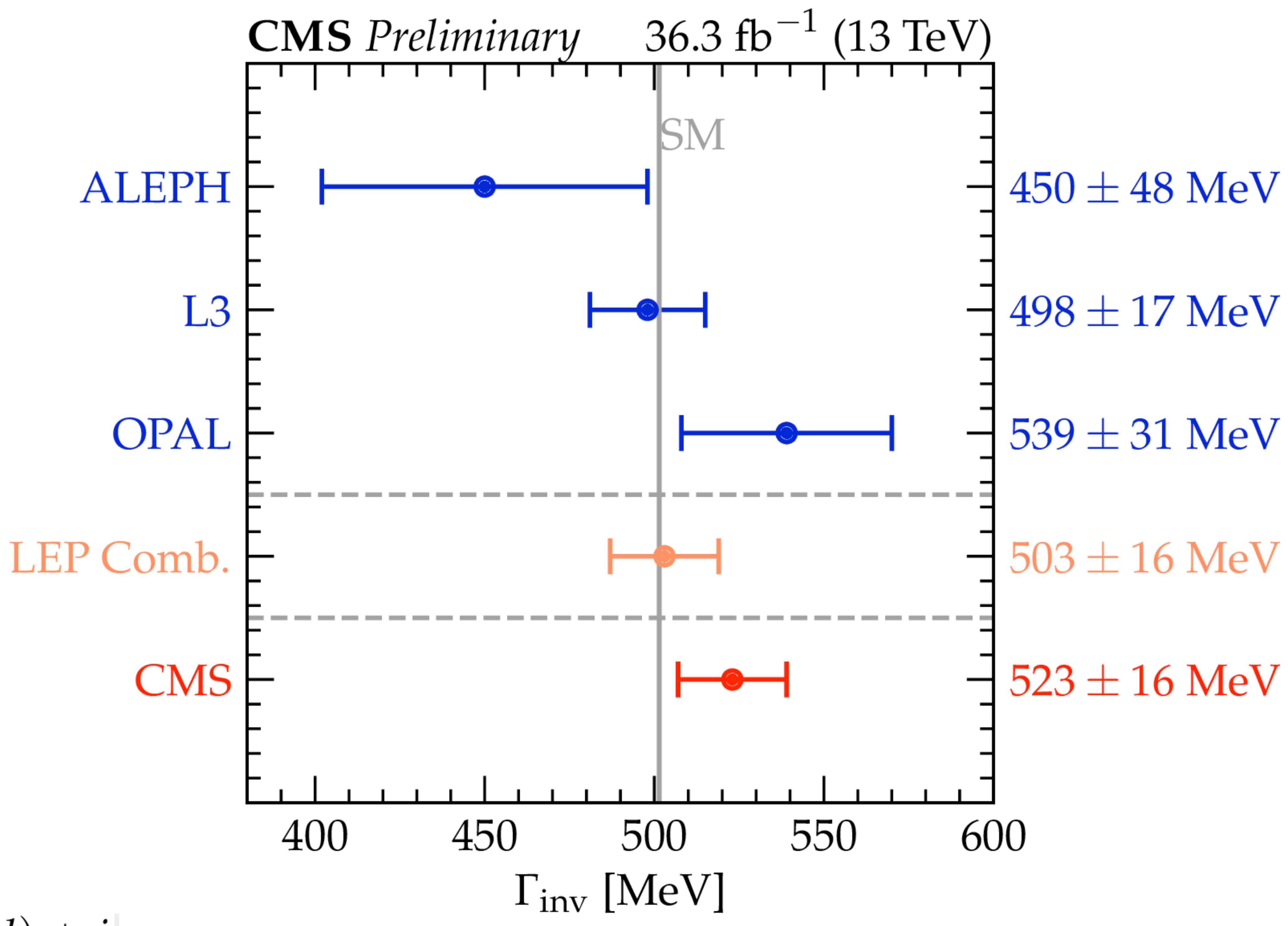
# Z —> invisible width measurement

CMS-PAS-FTR-21-001

First measurement of the Z→νν (Z to invisible) width at a hadron collider. Based on 2016 data.

Ratio of $\Gamma_{\nu\nu}$ / $\Gamma_{ll}$ from a simultaneous fit of Z→νν, Z→ee and Z→μμ enriched event categories.



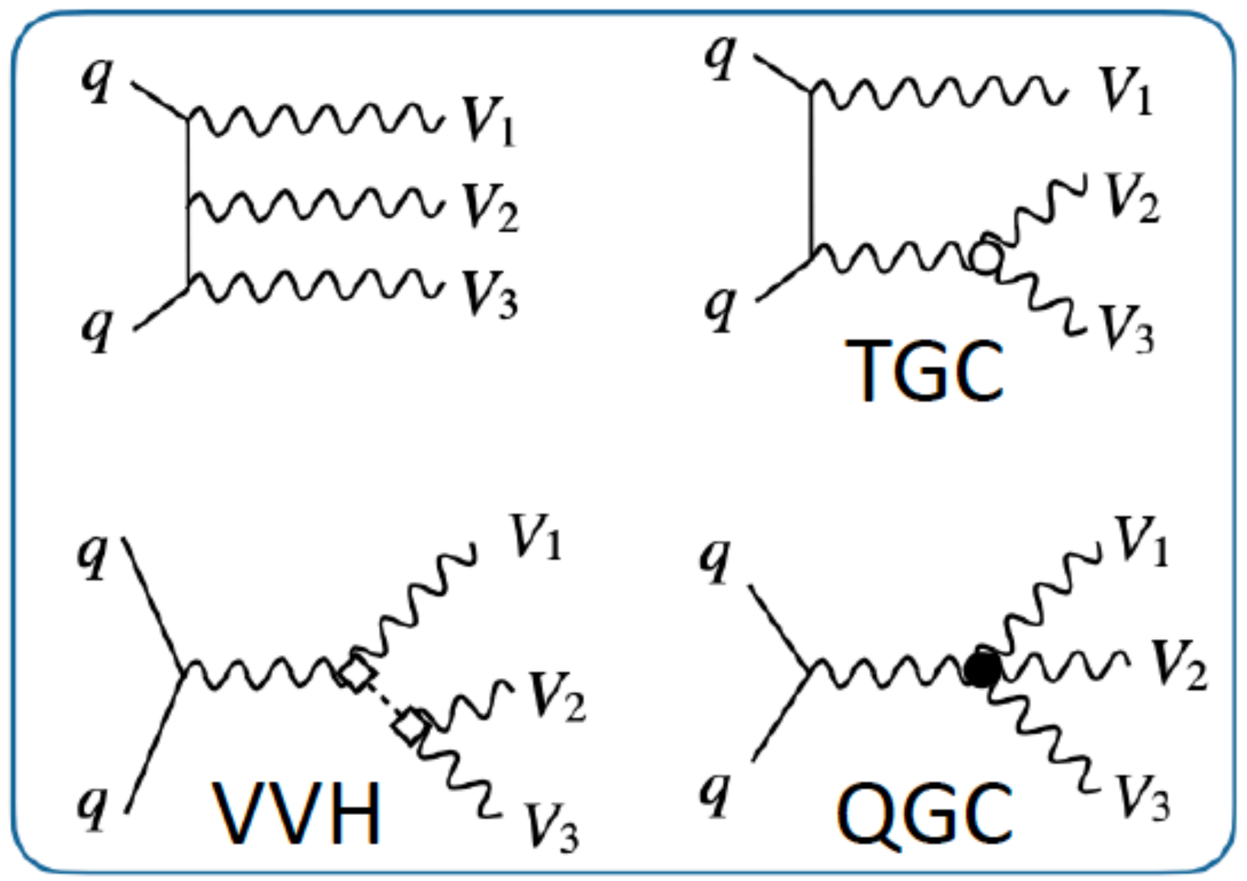

$\Gamma_{Zinv}$ = 523 ± 3 (stat) ± 16 (syst) MeV.

Single most precise direct measurement of the Z to invisible width competitive with the direct LEP result.

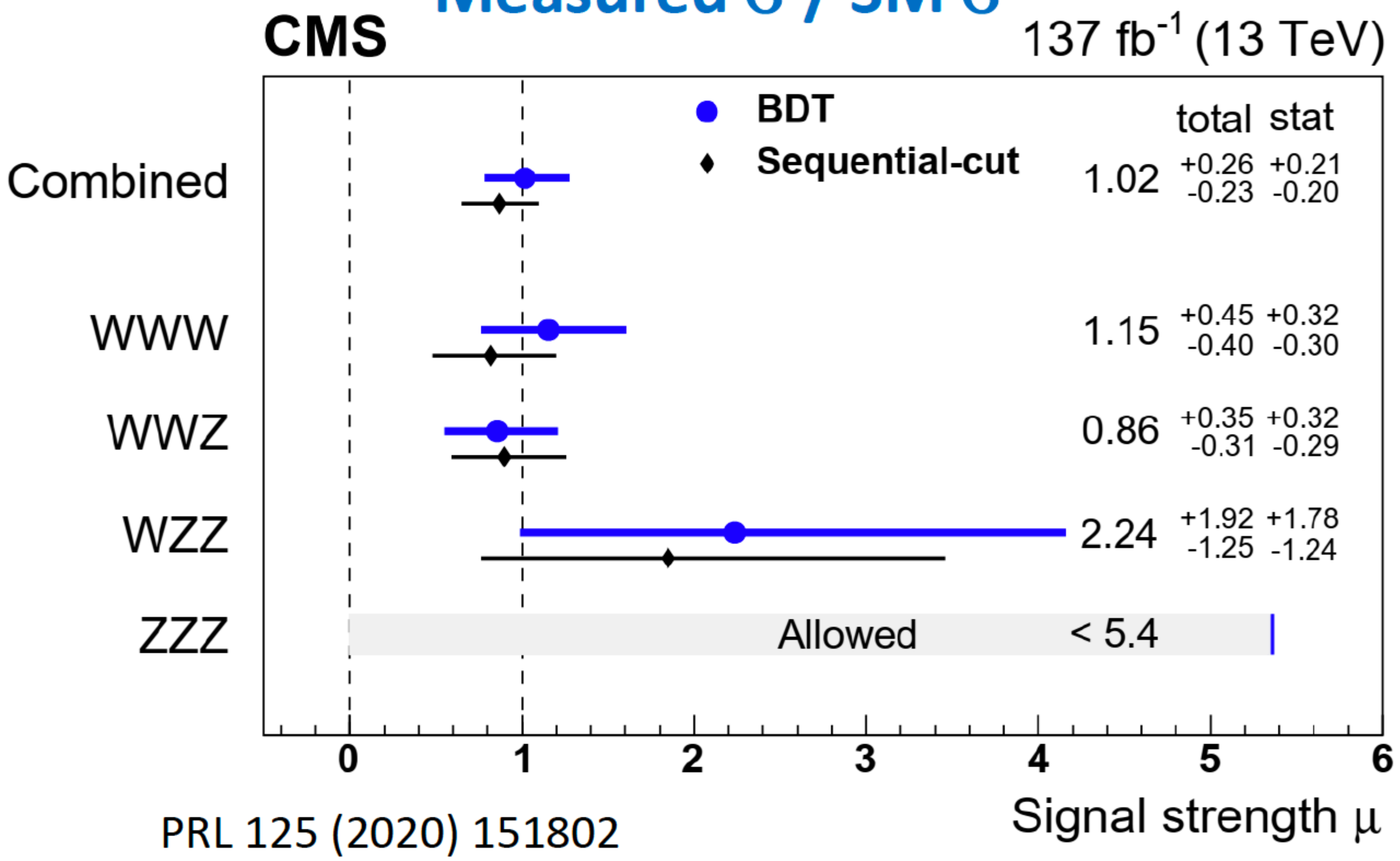
# Observation of VVV production

CMS-PAS-FTR-21-001

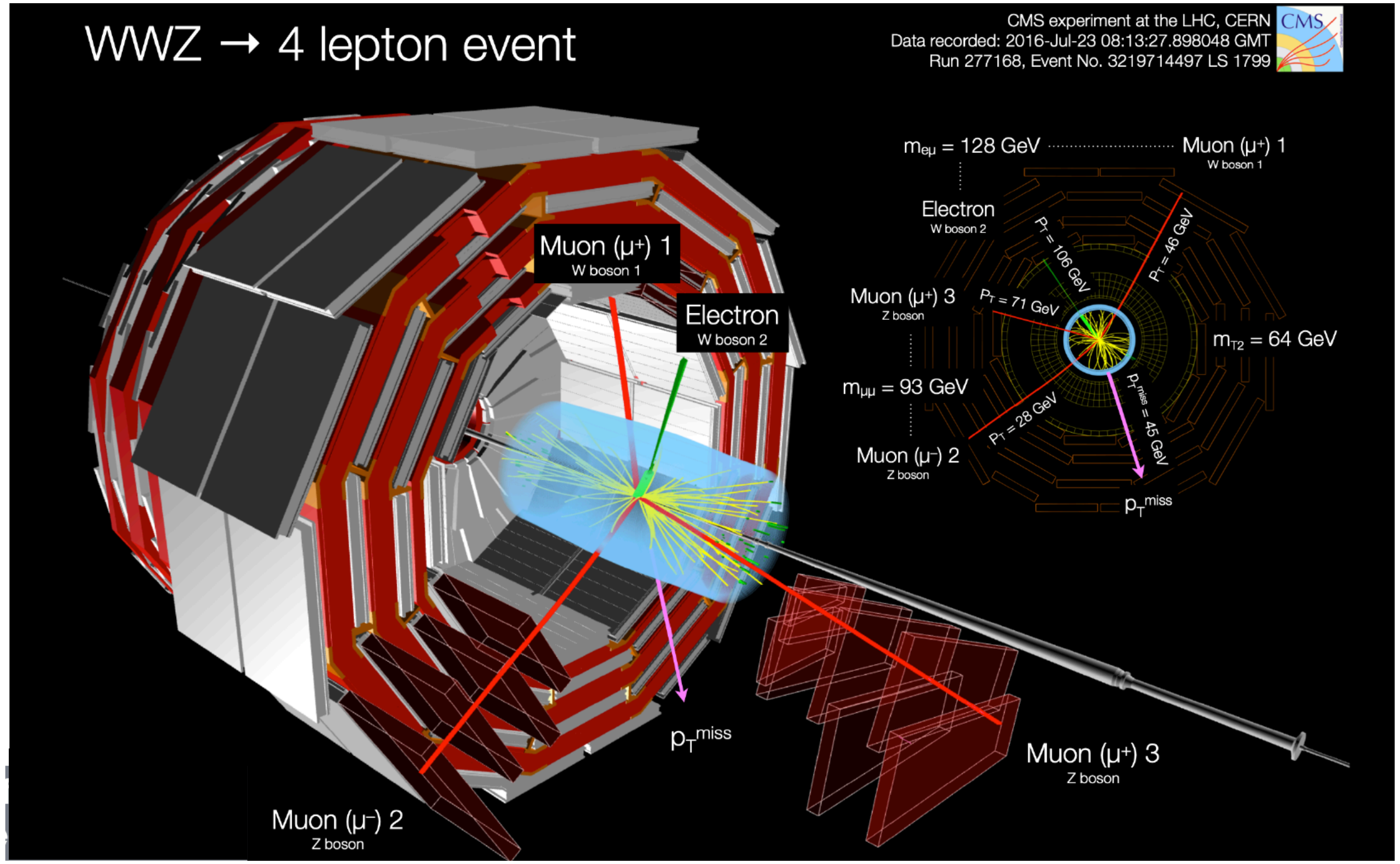
Triple vector boson (VVV, V=W,Z) final state is sensitive to new particles coupling to V or modifying SM couplings.




Measured σ / SM σ




PRL 125 (2020) 151802




VVV observed for the first time in 2020 (search in clean leptonic final states).

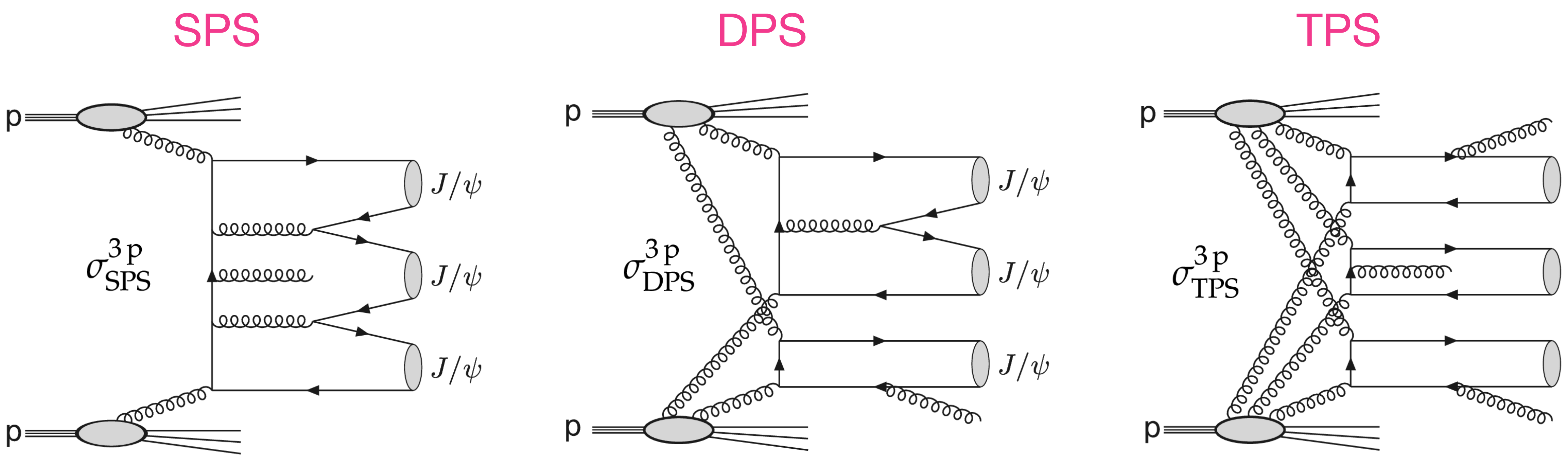
Compatible with the SM.

# Observation of triple J/ψ meson production

CMS-BPH-21-004

## First observation of triple J/ψ meson production

Contributions from single (SPS), double (DPS) and triple (TPS) parton scattering final states:




Significance > 5σ. Measured the fiducial cross section:

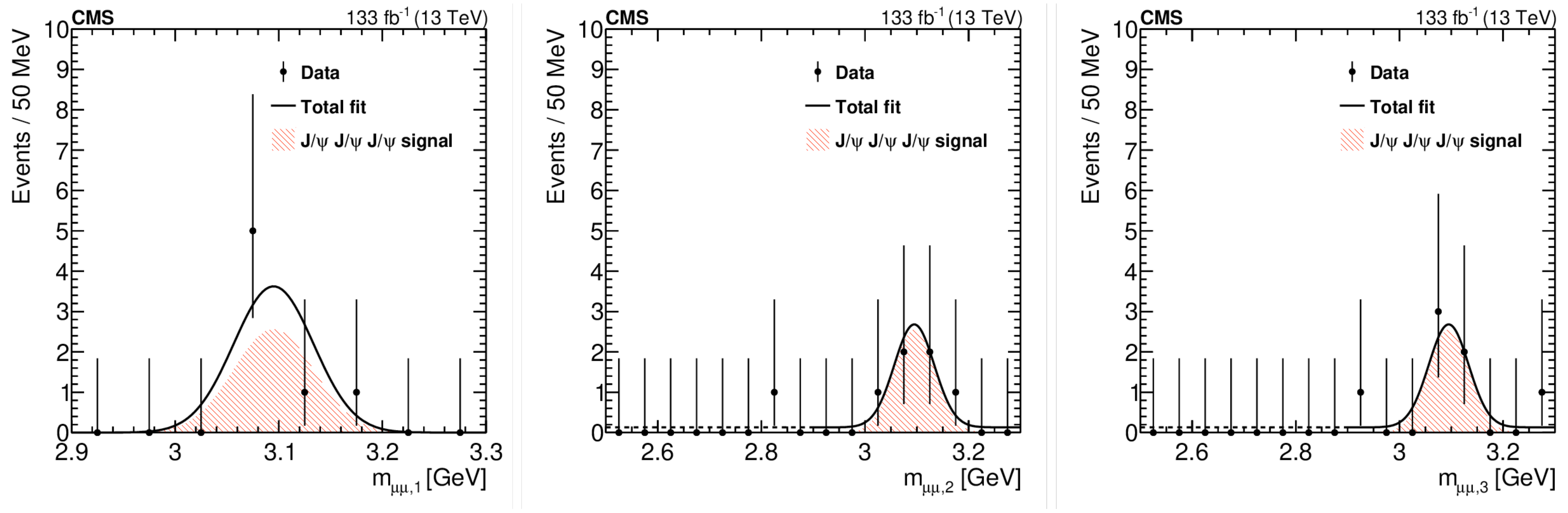
$\sigma(pp \rightarrow J/\psi\ J/\psi\ J/\psi\ X) = 272^{+141}_{-104}(stat) \pm 17\ (syst)$ fb.

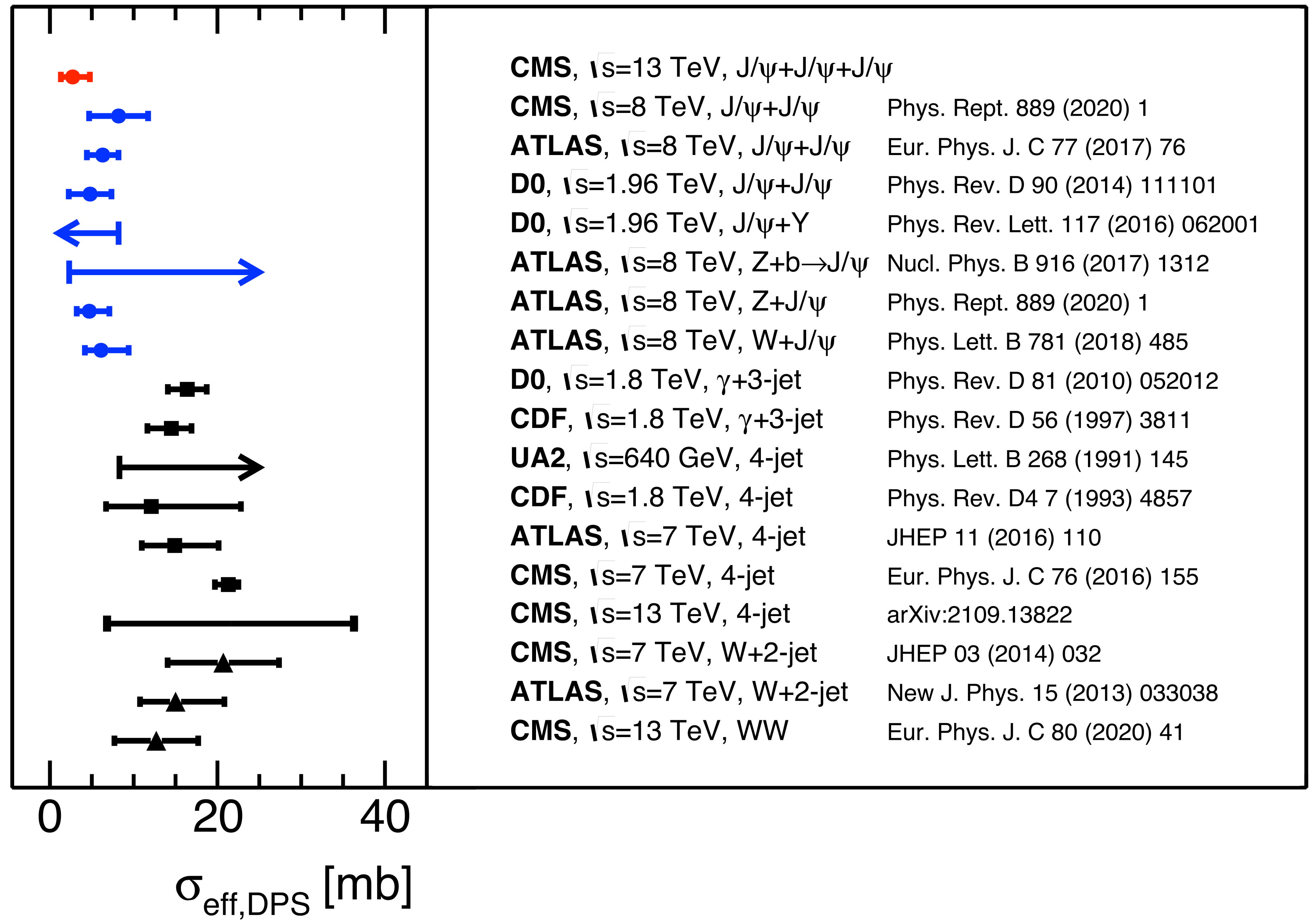
Measured process dominated by DPS and TPS contributions.

Extracted $\sigma_{eff,DPS}$: DPS-associated effective cross section parameter. Consistent with measurements in other processes. ➡

Candidate channel for first observation of TPS.

## 3 J/Ψ→μμ candidates per event, ordered by $p_T$:



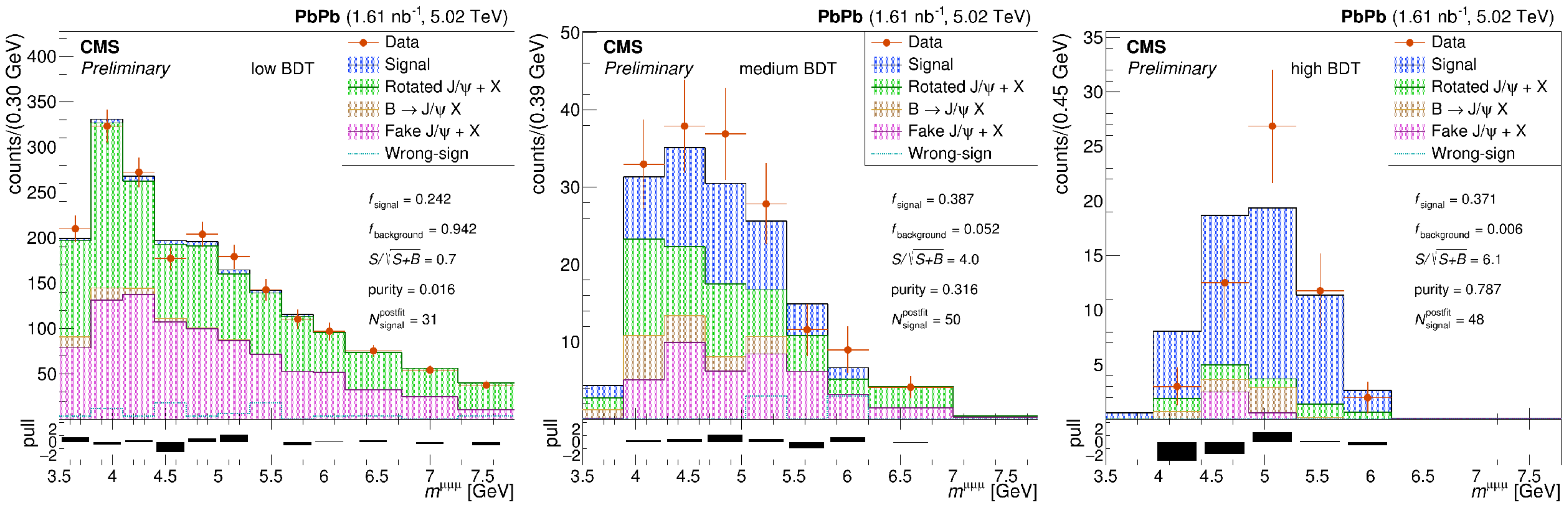



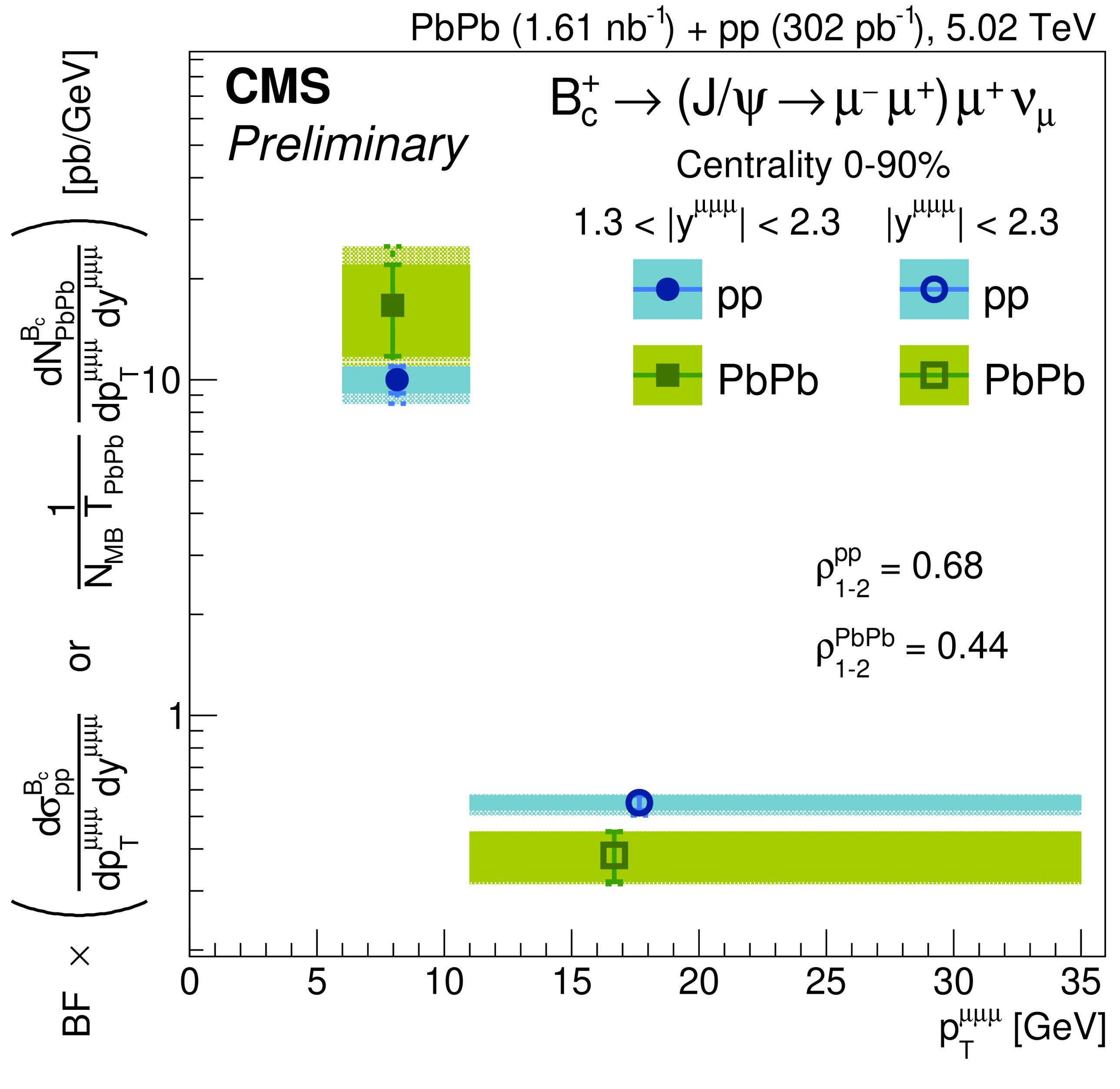
# First observation of $B_c^+$ meson in PbPb collisions

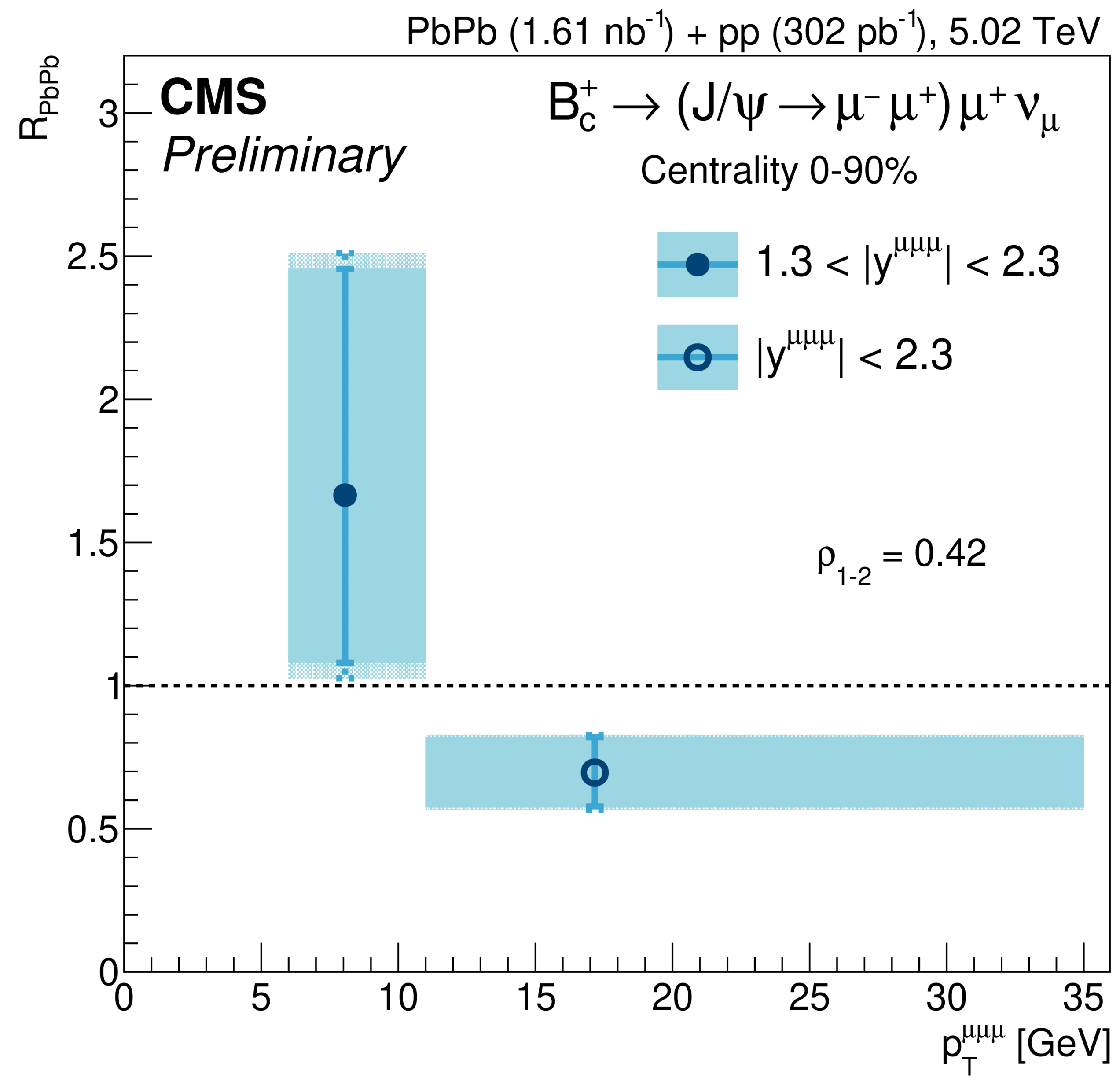
CMS-PAS-HIN-20-004

Observation in $B_c^+ \to J/\psi\ (\to \mu\mu)\ \mu\nu$ decay channel in pp and PbPb collisions with >5σ:

- 3 displaced muons final state.
- $B_c^+$ is the only meson containing both b and c quark: bridge between charmonia, bottomonia and open heavy mesons.
- Provides unique insight into the interplay between suppression and recombination (at low $p_T$).
- Measured cross section and nuclear modification factor in two bins of trimuon $p_T$ and in two ranges of collision centrality.

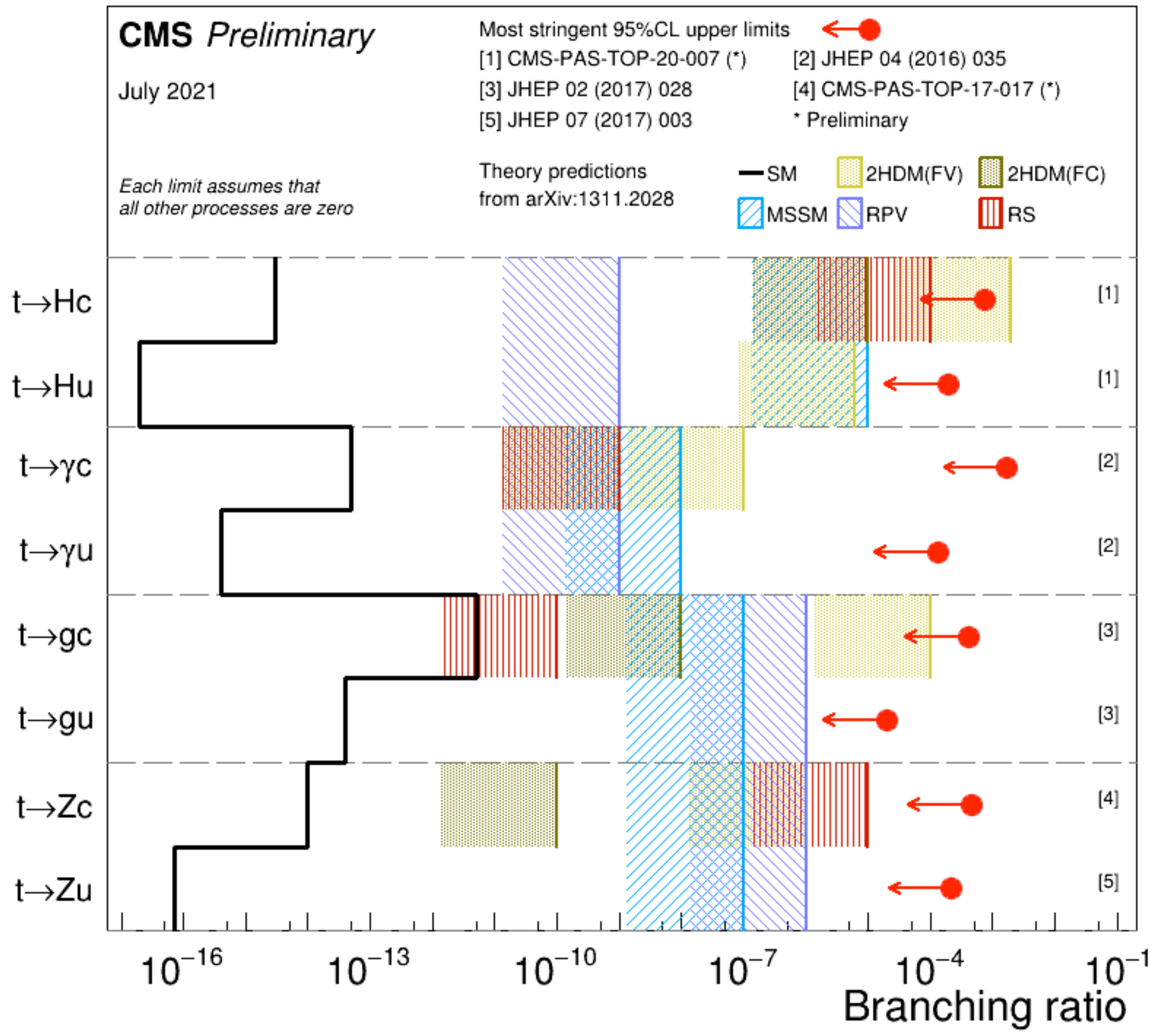


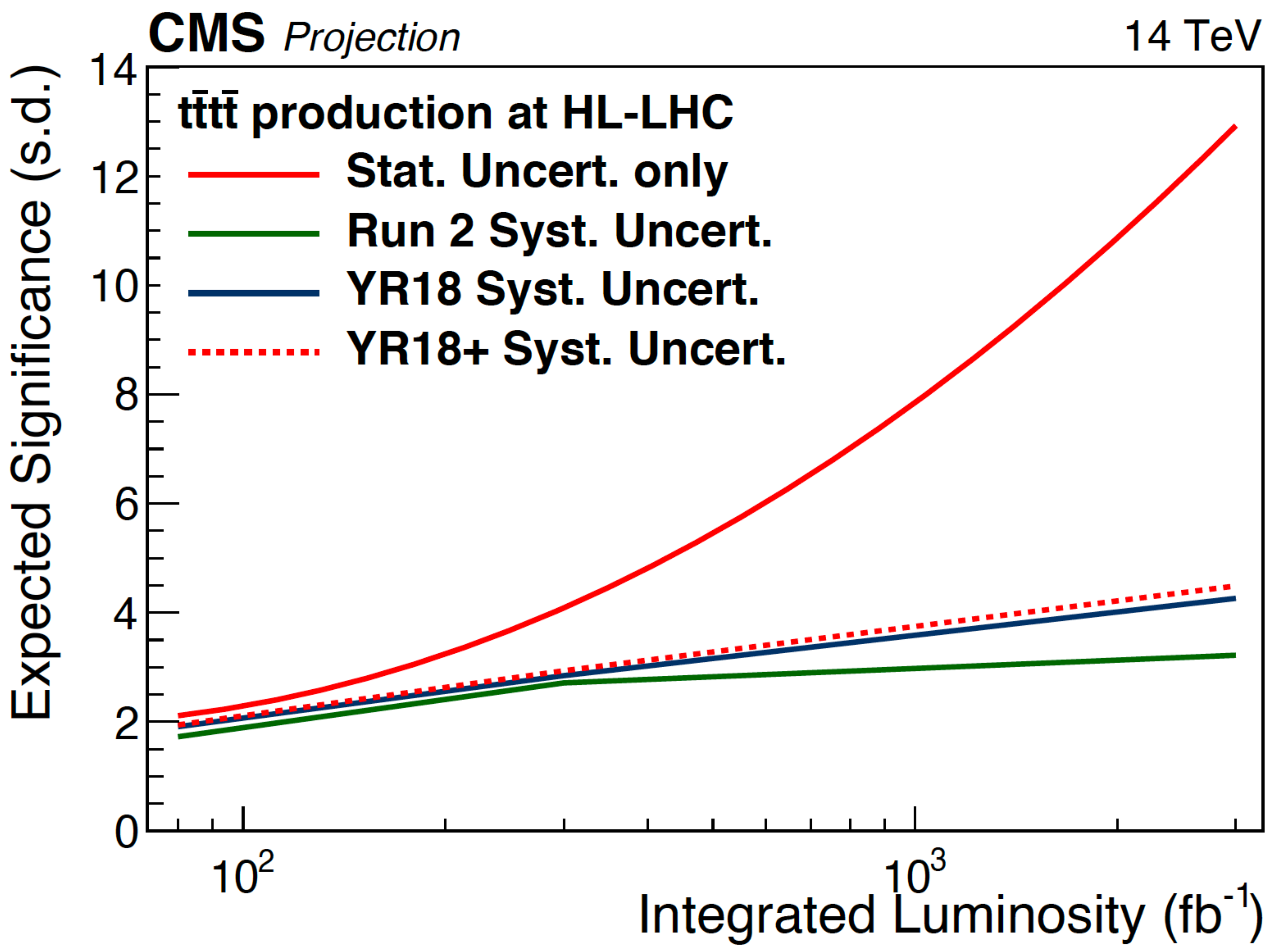
# Top quark measurements

**Top rare decays at Run2:** Observed upper limits above the SM predictions. A good probe for new physics.



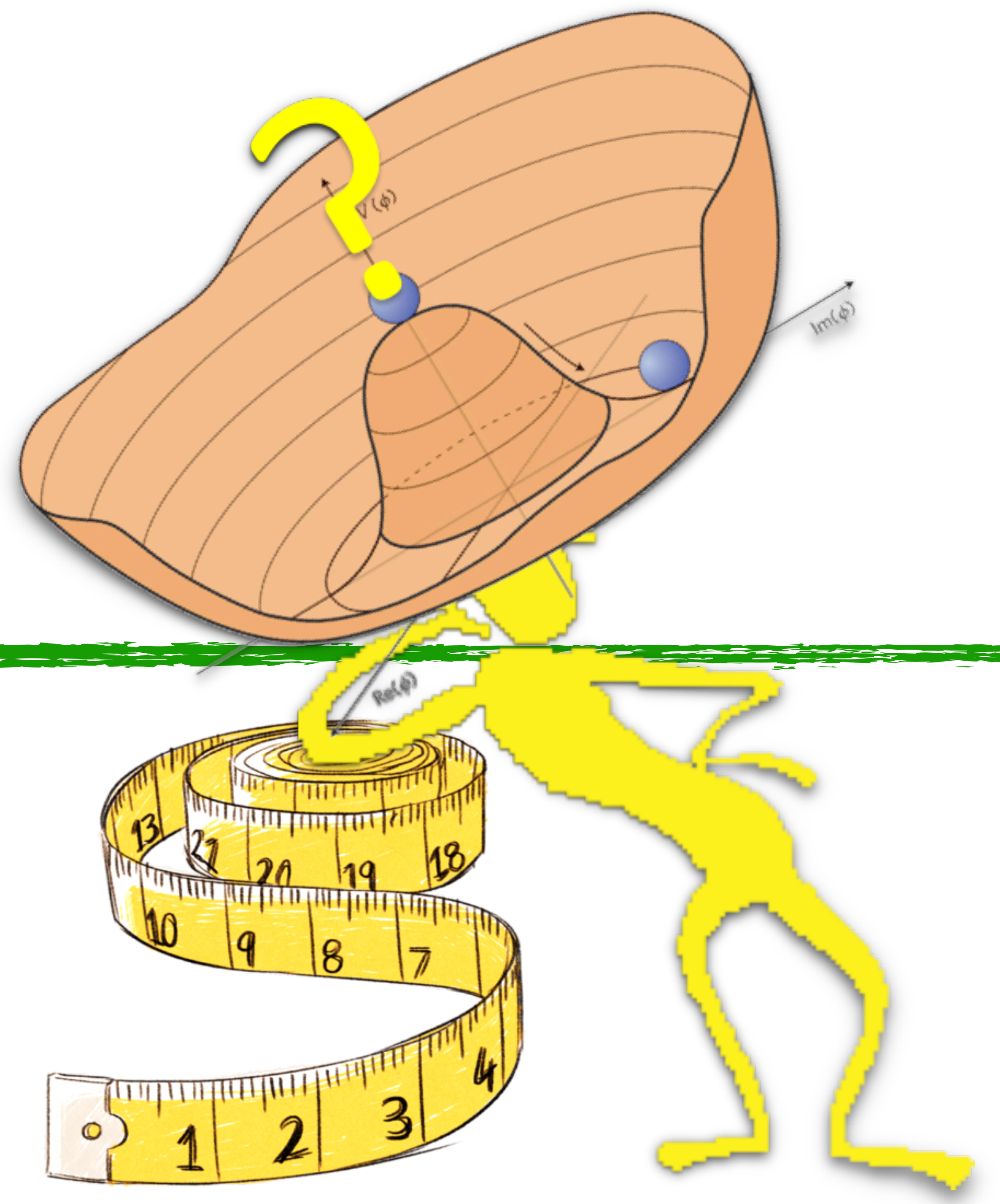

**4-tops production at HL-LHC:** Expect 10-30% uncertainty.

Currently only projections done for Phase2. Expect dedicated analyses with sophisticated methods for Phase2.



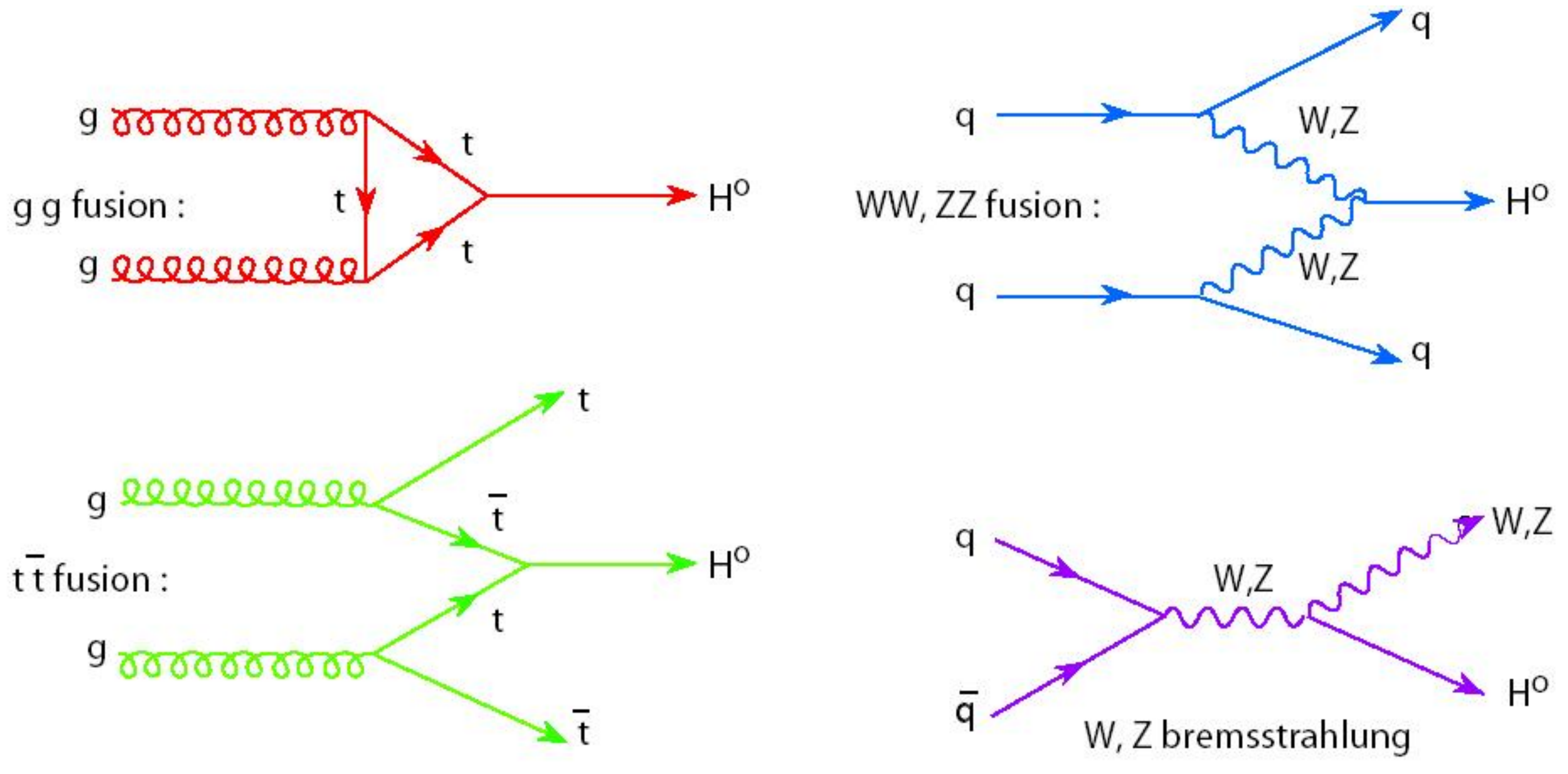

CMS-PAS-FTR-18-031

# Higgs physics



- CMS Higgs results
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
- CMS exotic Higgs results:
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

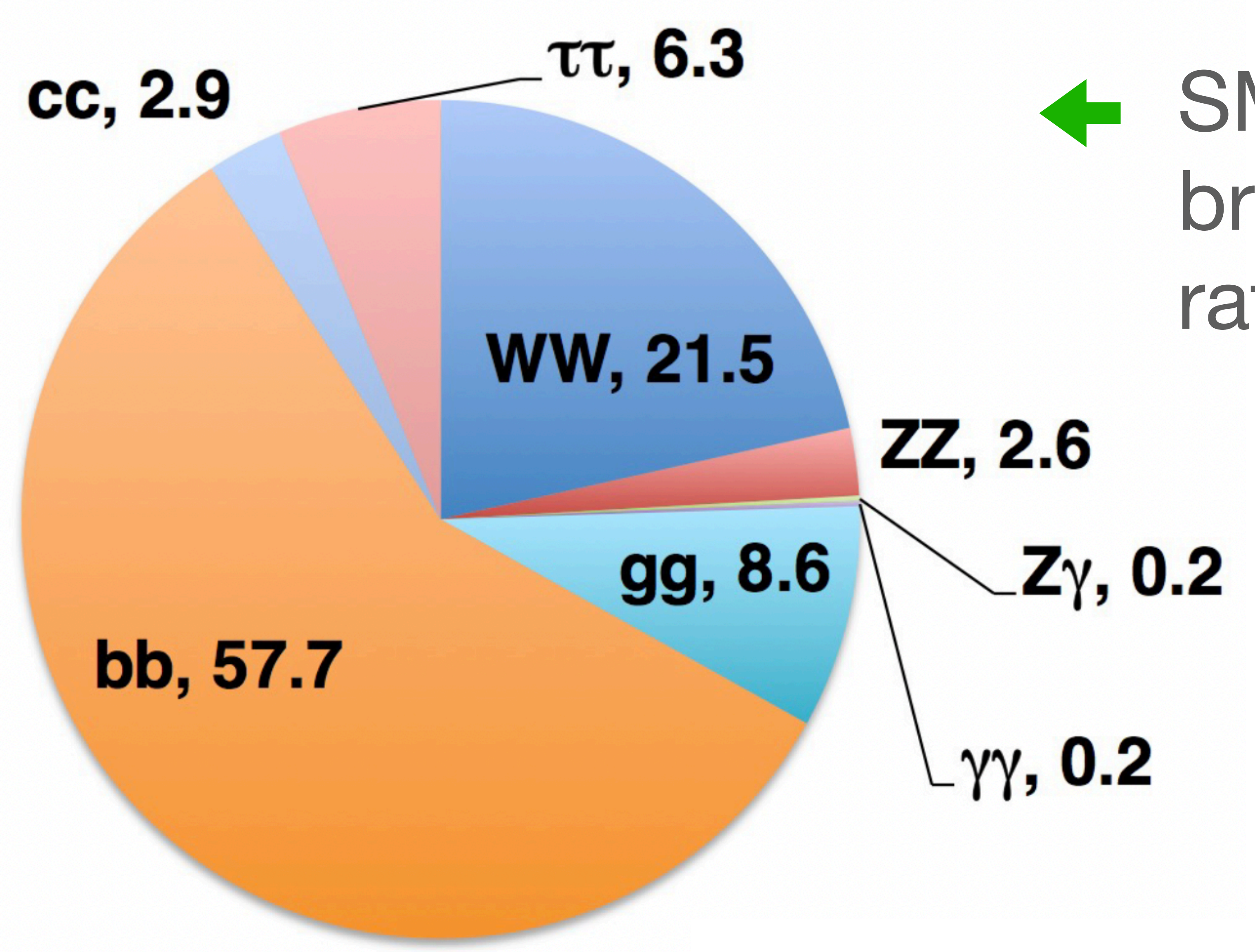
# SM Higgs boson: LHC production and decay




- Higgs boson can be produced via several processes and decay into several final states.
- Observed mass 125 GeV presents a particular diversity of decay channels.
  —> multiple probes for studying the Higgs!

SM Higgs production channels and cross sections:

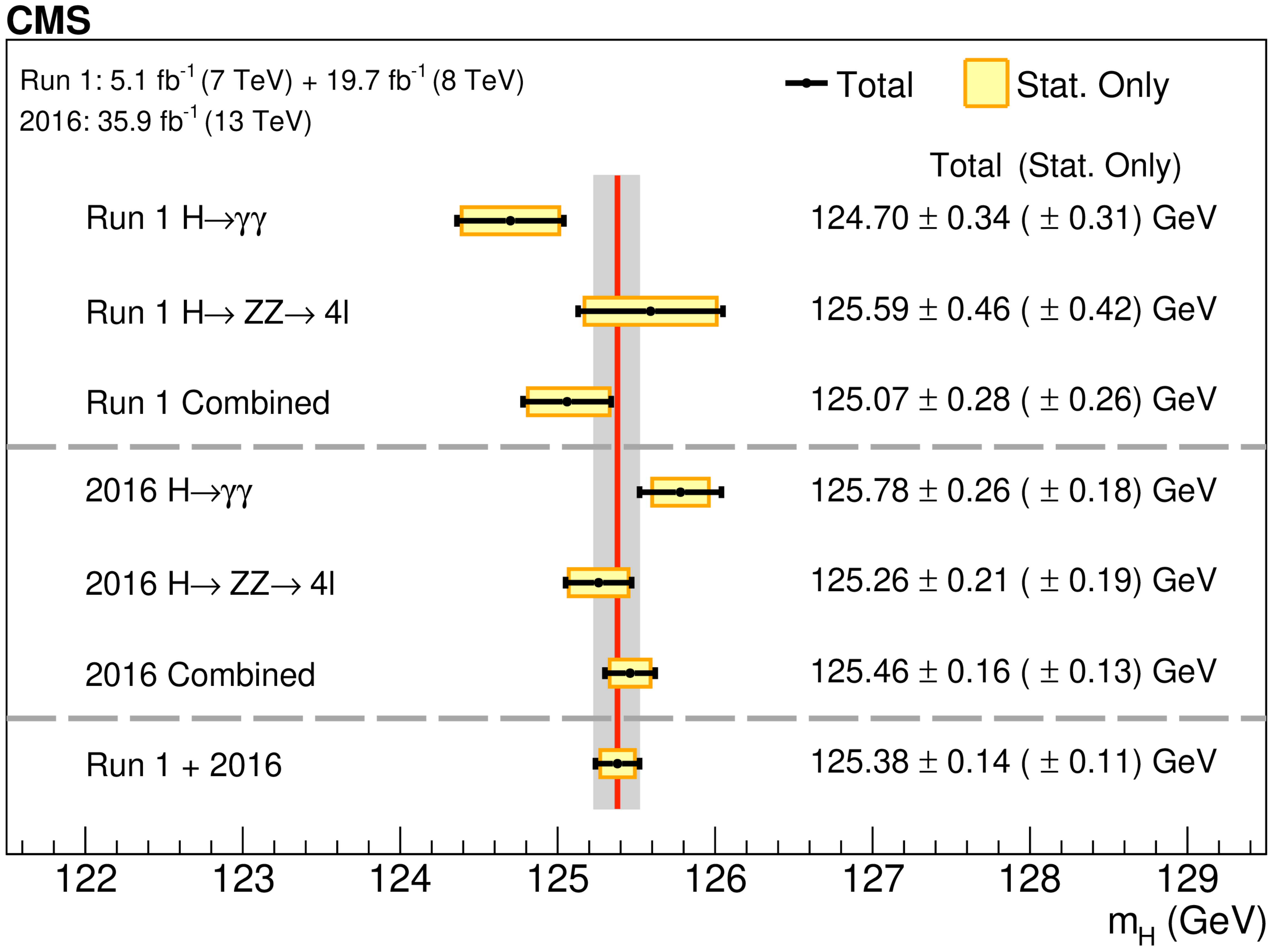
| | process | 13 TeV |
|---|---|---|
| **ggF** | gluon-gluon fusion | 49 pb |
| **VBF** | vector-boson fusion | 3.8 pb |
| **VH** | associated production | 2.3 pb |
| **ttH** | associated production | 0.51 pb |



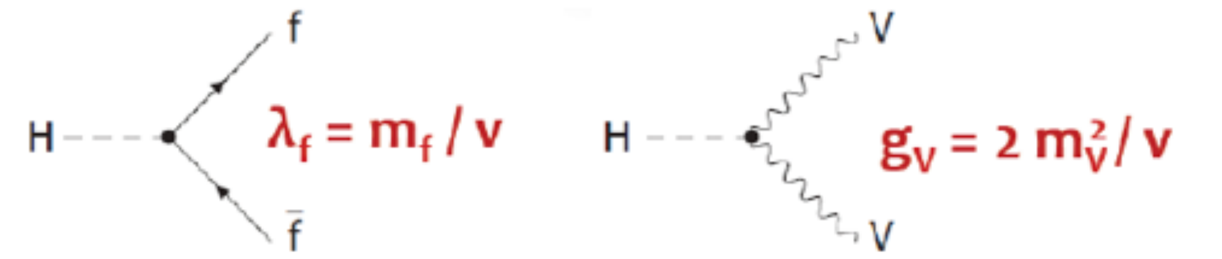

SM Higgs branching ratios

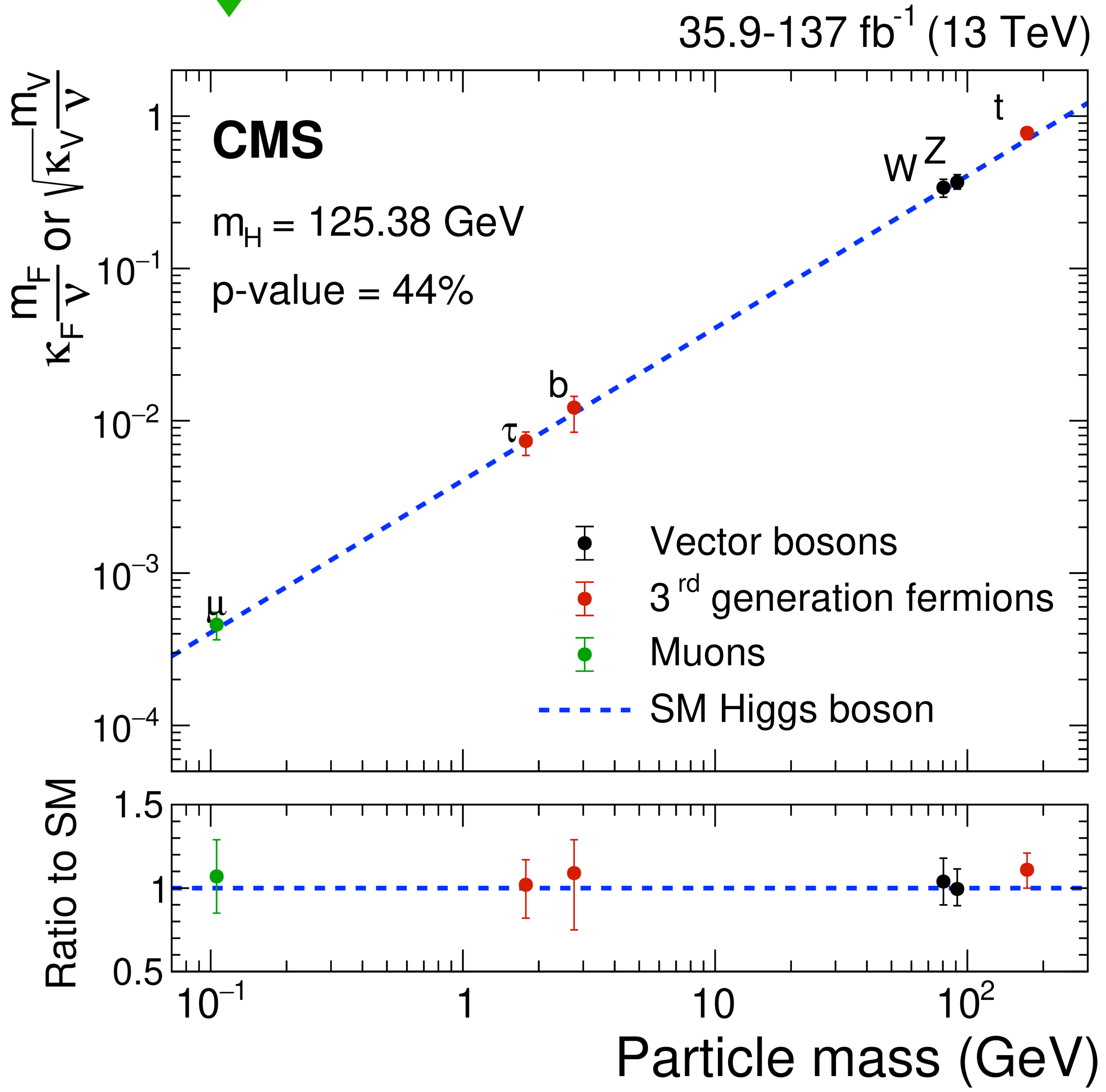
# SM Higgs: Mass and couplings

## Run2 Higgs mass measurements:




## Run2 Higgs coupling strength measurements:



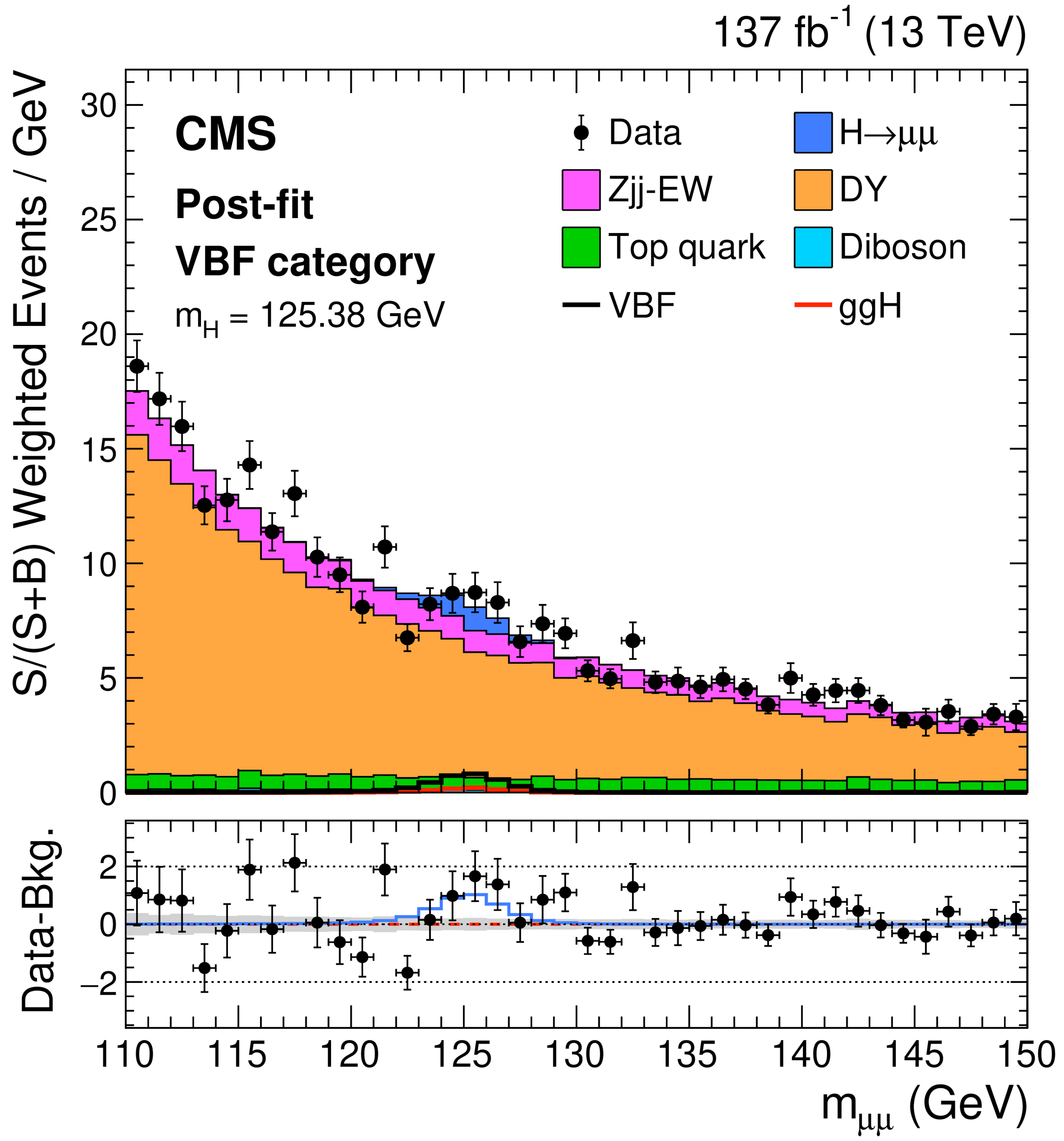



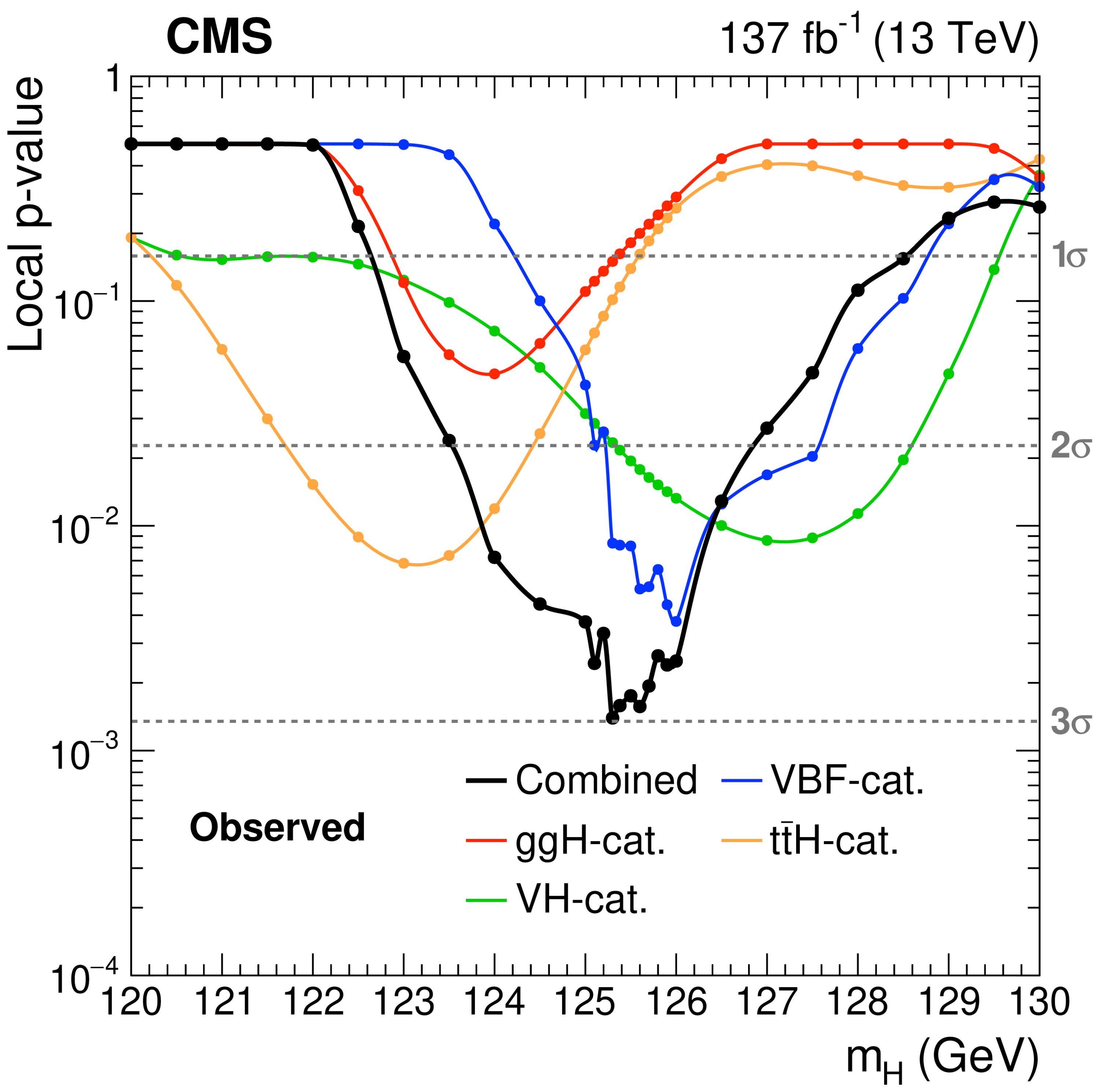
# SM Higgs: Evidence for Higgs to μμ

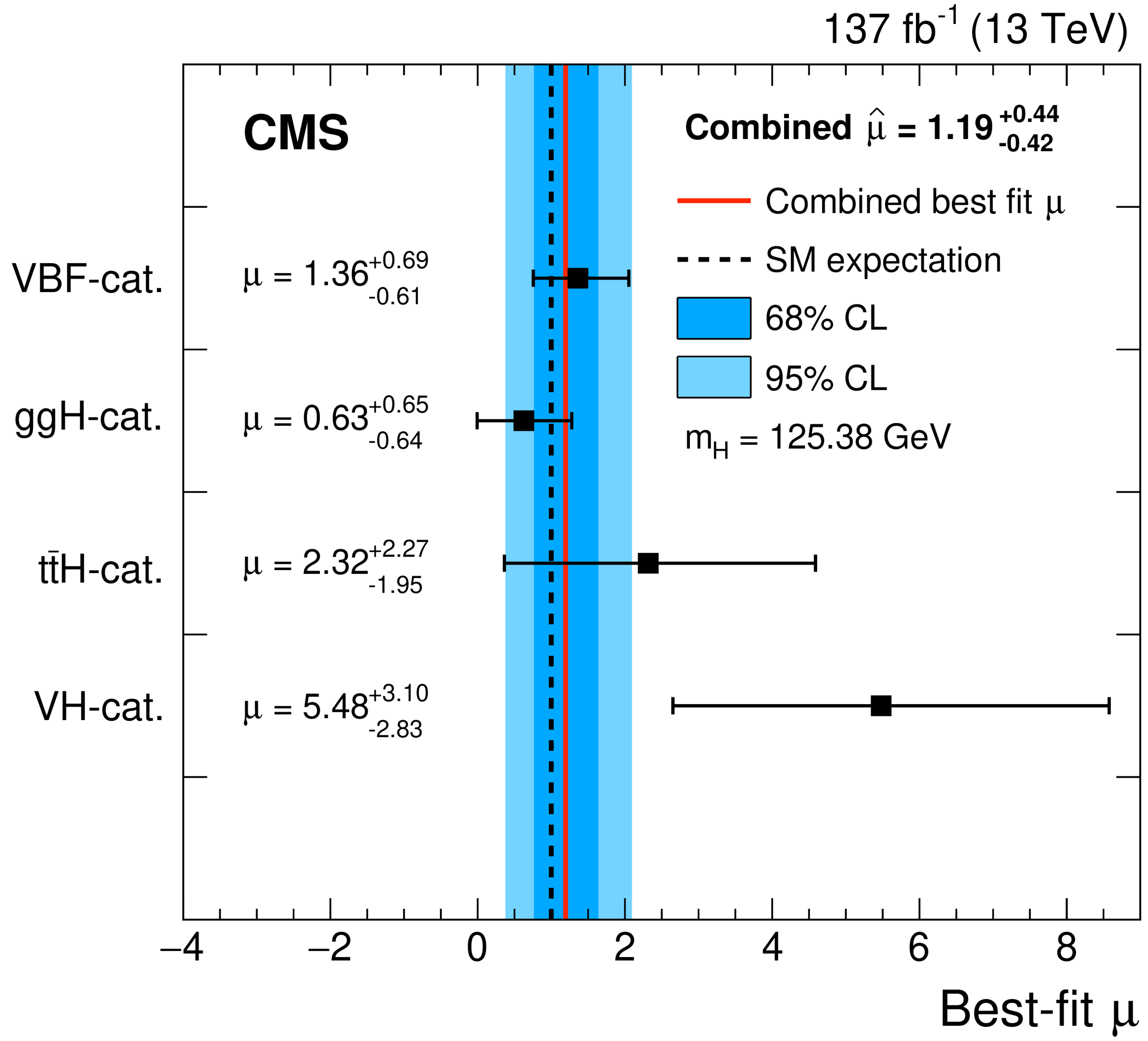
CMS-HIG-19-006

First evidence for H —> μμ:

- SM BR(H —> μμ) = 2.18x10$^{-4}$. Challenging signature.
- Analysis done for all 4 Higgs production channels.
- Backgrounds suppressed due to forward jets, leading to highest sensitivity in the vector boson fusion channels.



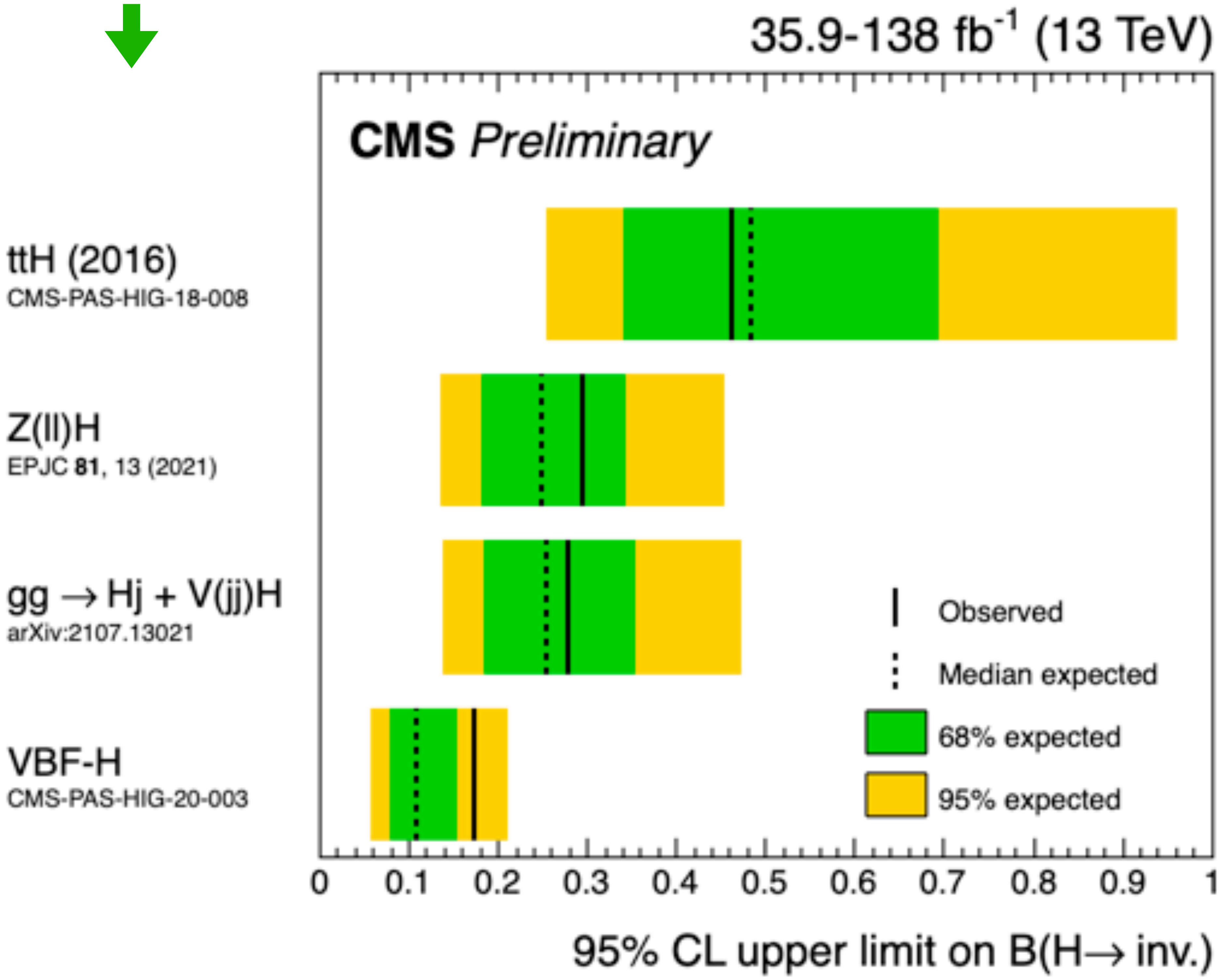

- 3σ excess.
- The most recent discovery.
- Run1+Run2 results combined to obtain the best sensitivity.

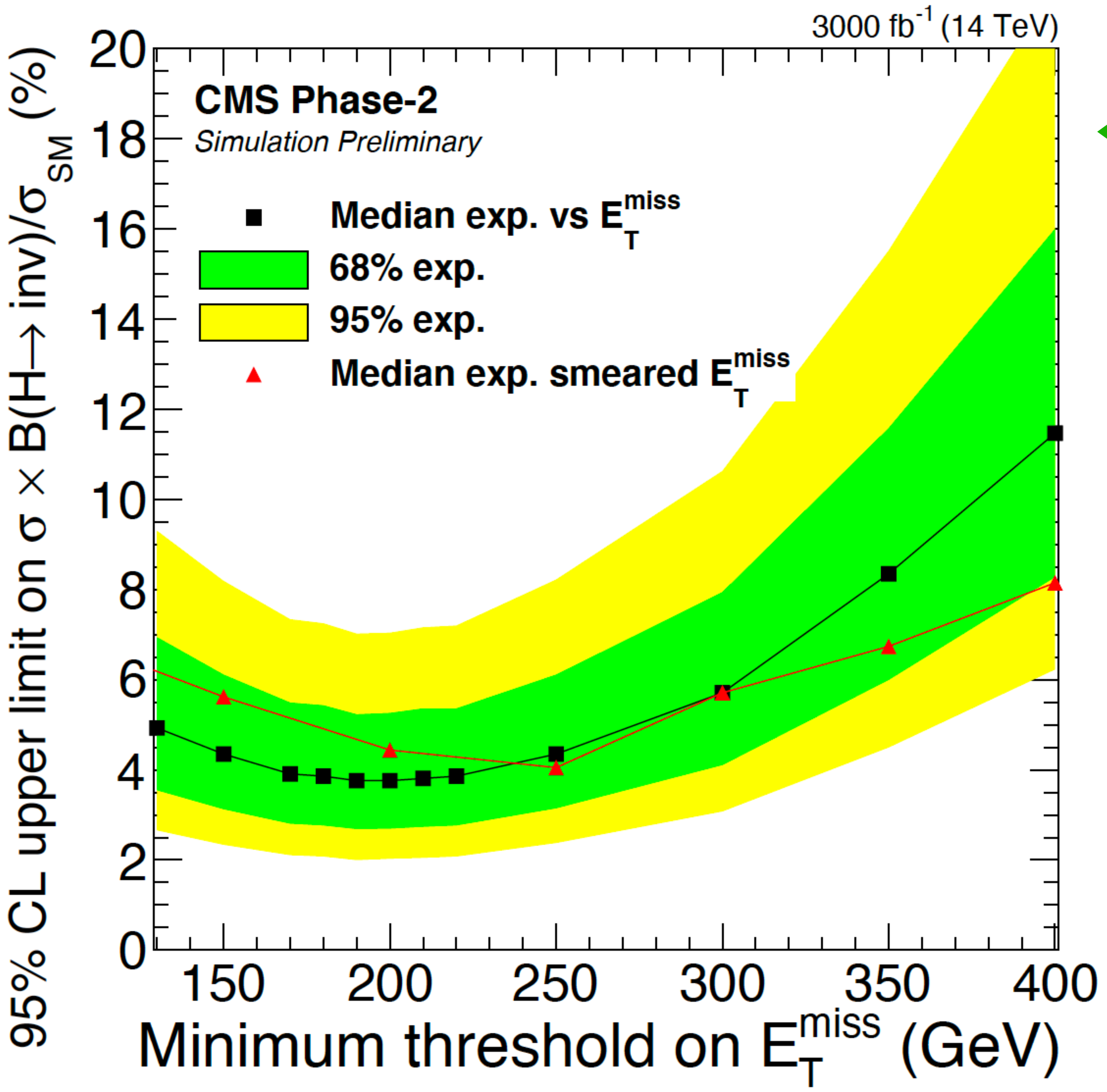
# SM Higgs: Higgs to invisible

H -> invisible: SM BR ~0.1%. Powerful probe for BSM, e.g. light DM coupling to Higgs.

- Measure in conjunction with a taggable object: Z, forward jets, high $p_T$ jet, etc.
- Most sensitive channel is vector boson fusion: 2 forward jets + $E_T^{miss}$. Challenging due to soft $E_T^{miss}$.

Run2 analyses exclusion limits summary:
Current limit: ~20-25%




HL-LHC: Optimized VBFH analysis.

$m_{jj}$ > 2500 GeV.

Exclusion limits on BH(H —> inv) vs. minimum $E_T^{miss}$ threshold.

CMS-PAS-FTR-18-016

Can be interpreted in various DM models.

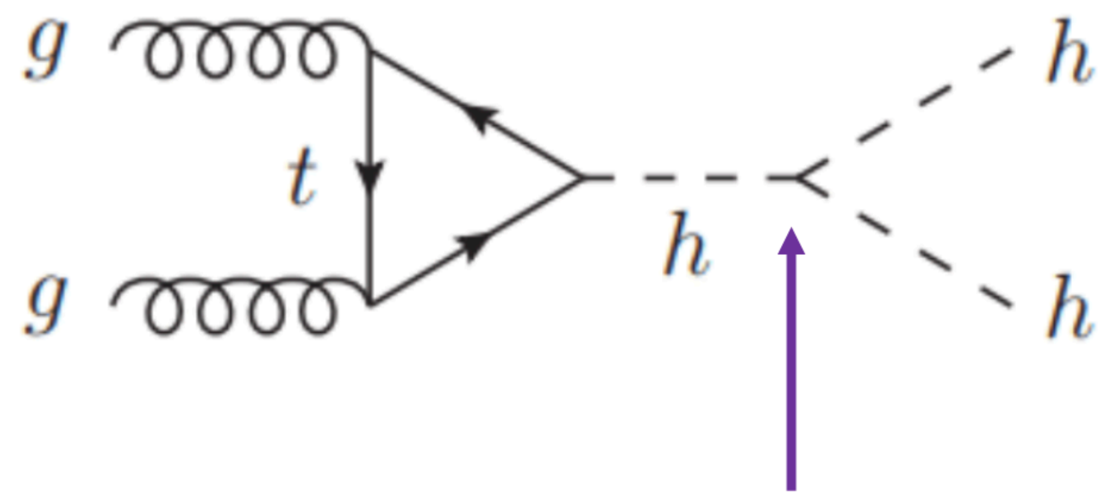
# SM Higgs: diHiggs and Higgs self coupling

CMS-PAS-FTR-18-019

HH allows to measure trilinear H self coupling $\lambda_{HHH} = m_H^2/2v$ —> constrain H potential shape, nature of EWSB. Also sensitive to BSM physics.

Combinations with Run2 2016 measurements reach $\sigma/\sigma_{SM} = 10$.
Full Run2 measurements in progress.

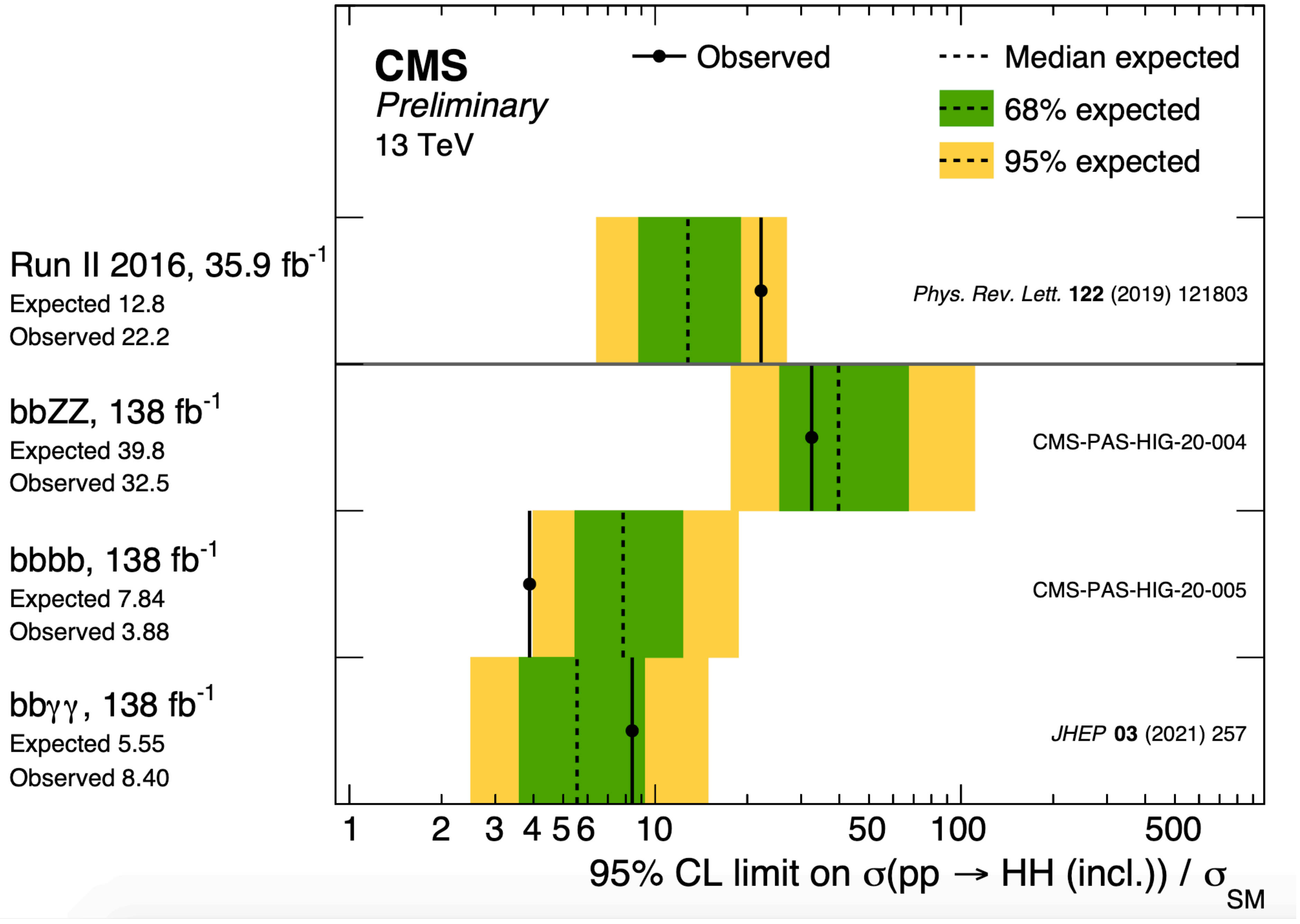
Observation requires HL-LHC and combining all channels. Expect 4σ from ATLAS+CMS for ggH. Most sensitive decay channels: bbγγ and bbττ.




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

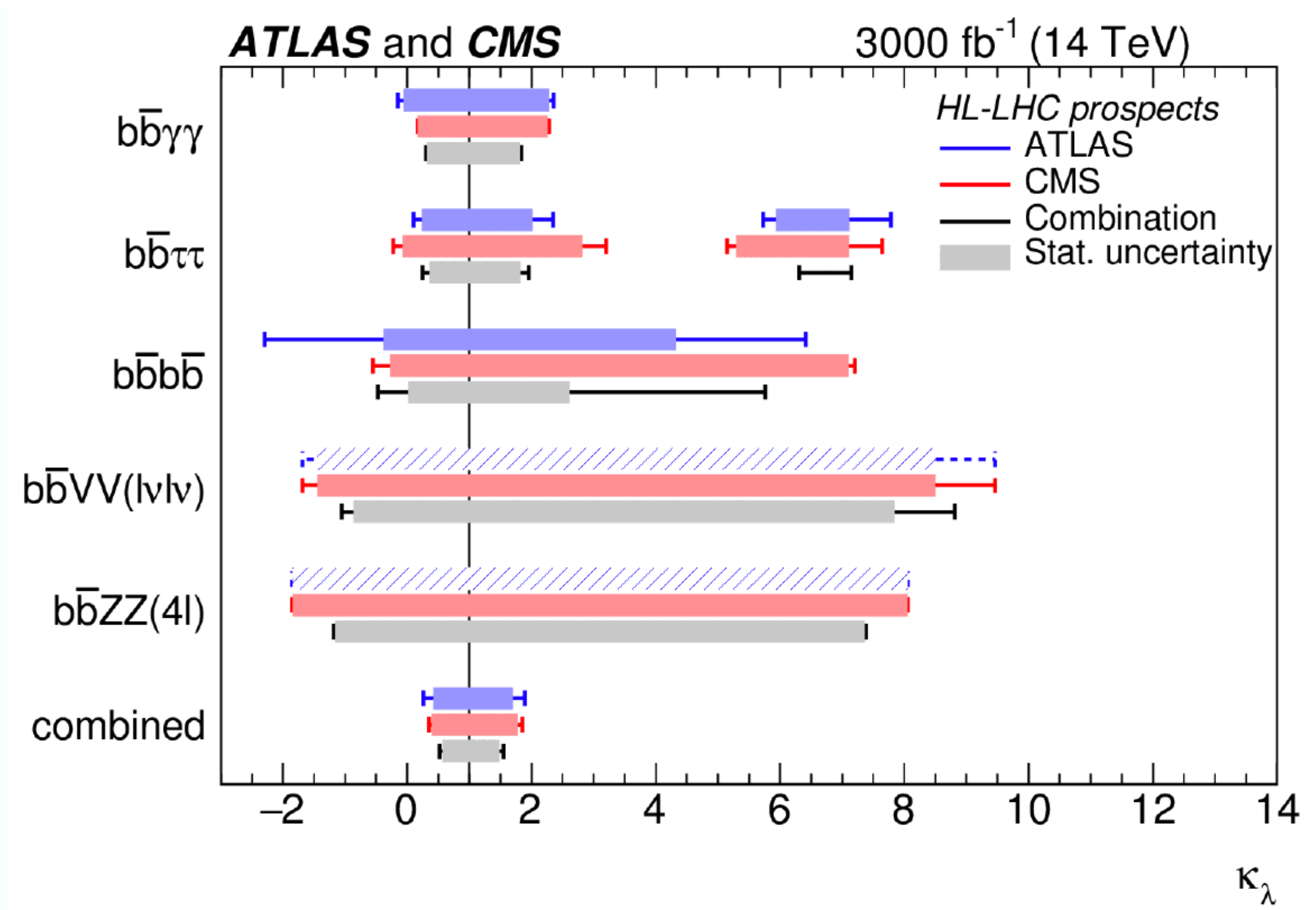
Coupling modifier:

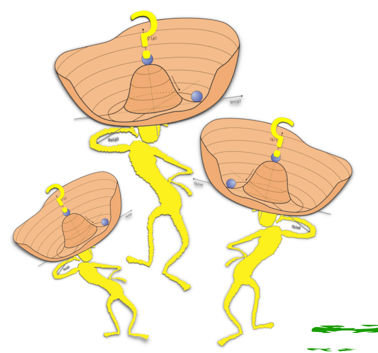
$$\kappa_\lambda = c_{hh} = \lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$$




Run2 2016 combination

HL-LHC projections



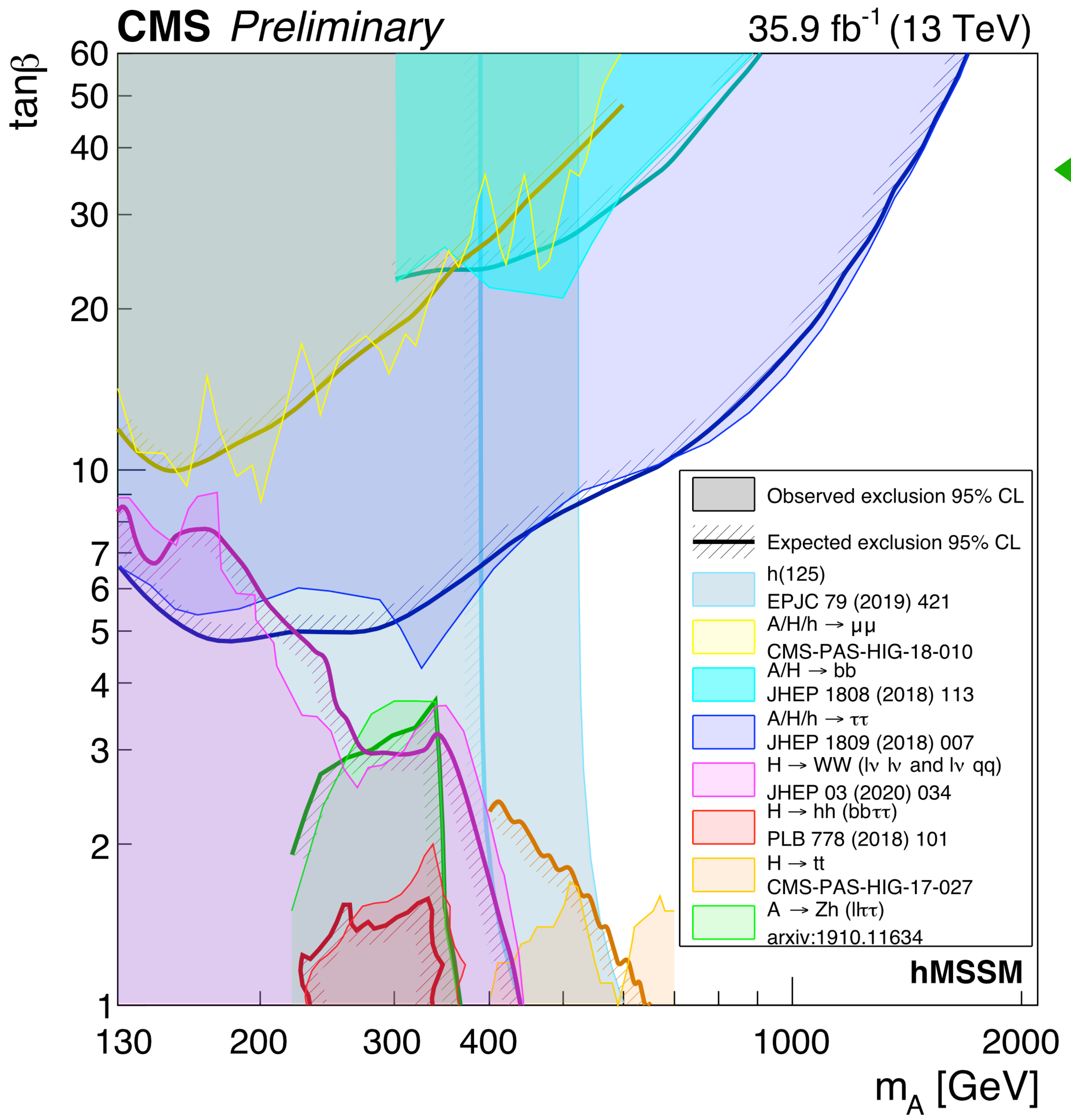


# BSM Higgses: Heavy Higgses in 2HDM

Extend SM with 2 Higgs doublets. Doublets couple to SM fermions in 4 different ways.
—> Results in 5 Higgs bosons: CP-even h (~$h_{125}$), neutral H, charged $H^{\pm}$, CP-odd A.

MSSM is a Type II 2HDM: One doublet couples to up-type, other couples to down-type fermions.
—> Higgs sector determined at tree level by 2 parameters: $m_A$ and $\tan\beta = v_1/v_2$.

Look for excess in invariant mass (for $H/A/H^{\pm} \rightarrow$ visible) or transverse mass ($H/A/H^{\pm} \rightarrow$ visible + neutrino).

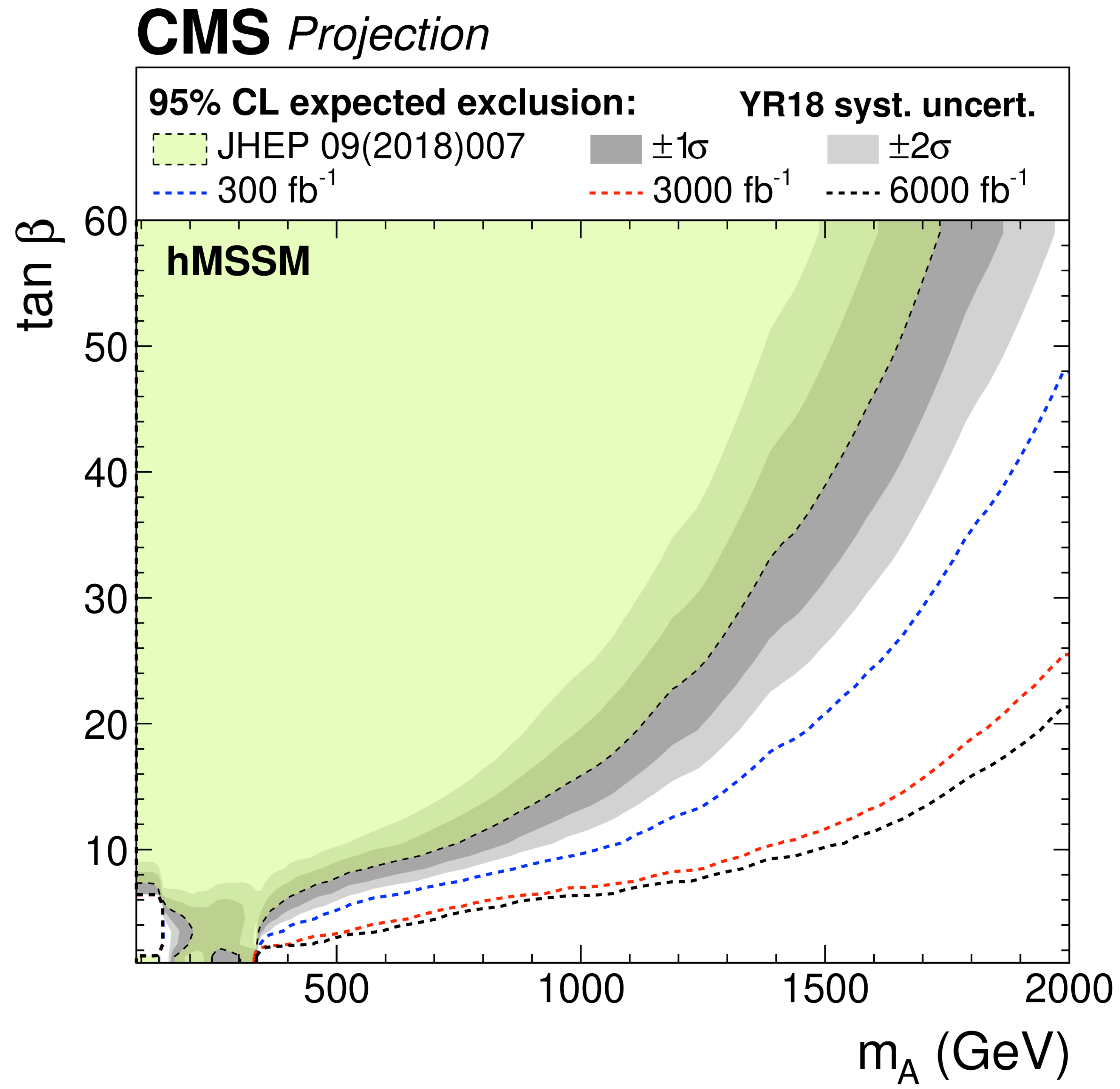



Run2 direct searches for heavy H/A.

CMS-PAS-FTR-18-017

HL-LHC search for H/A —> ττ ($\tau_{lep}\tau_{had}$ + $\tau_{had}\tau_{had}$ channels).

Increased sensitivity wrt Run2.

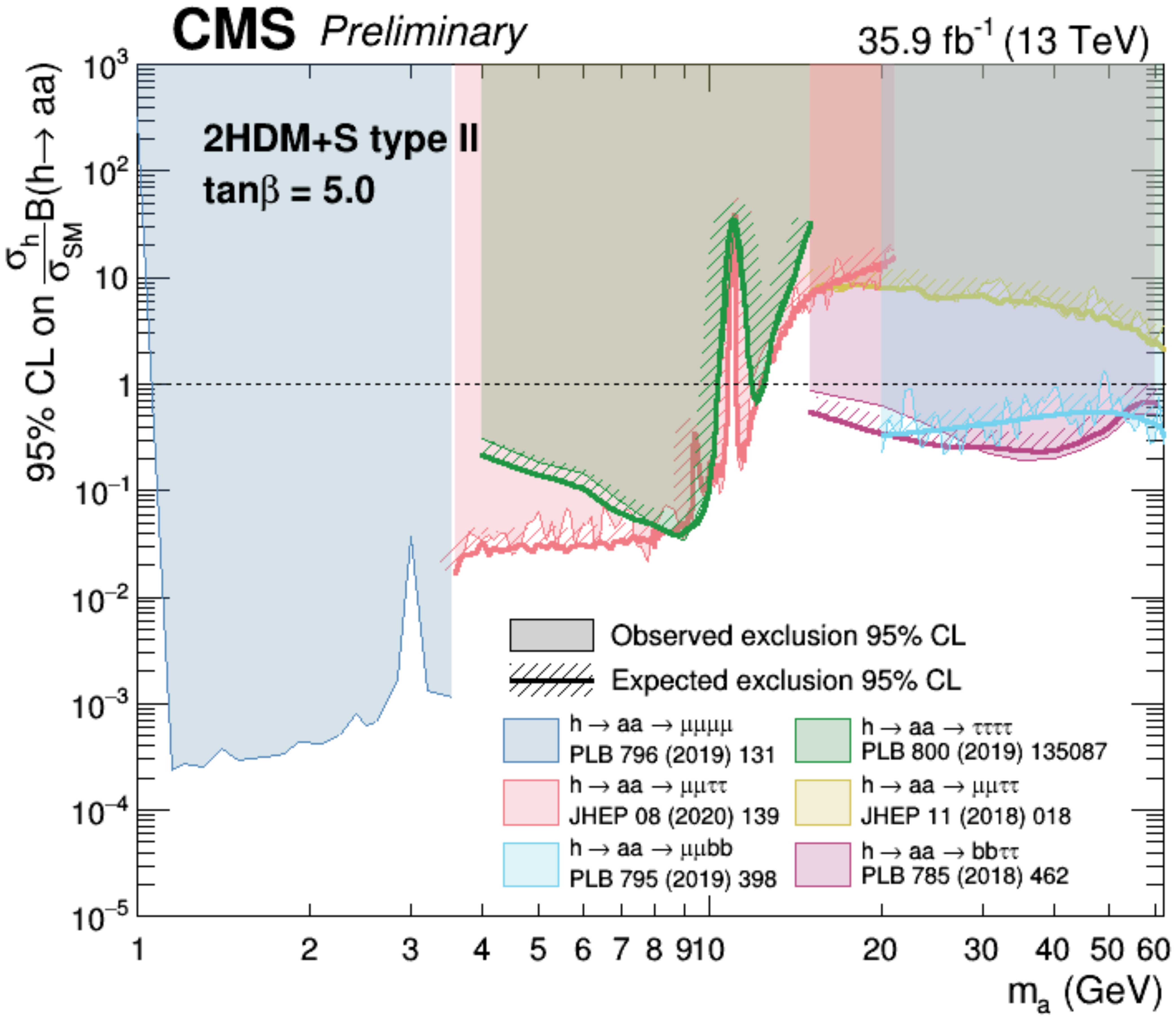


# BSM Higgses: 2HDM+S

MSSM Higgs sector + singlet field <— Motivated by next-to-MSSM Higgs sector.

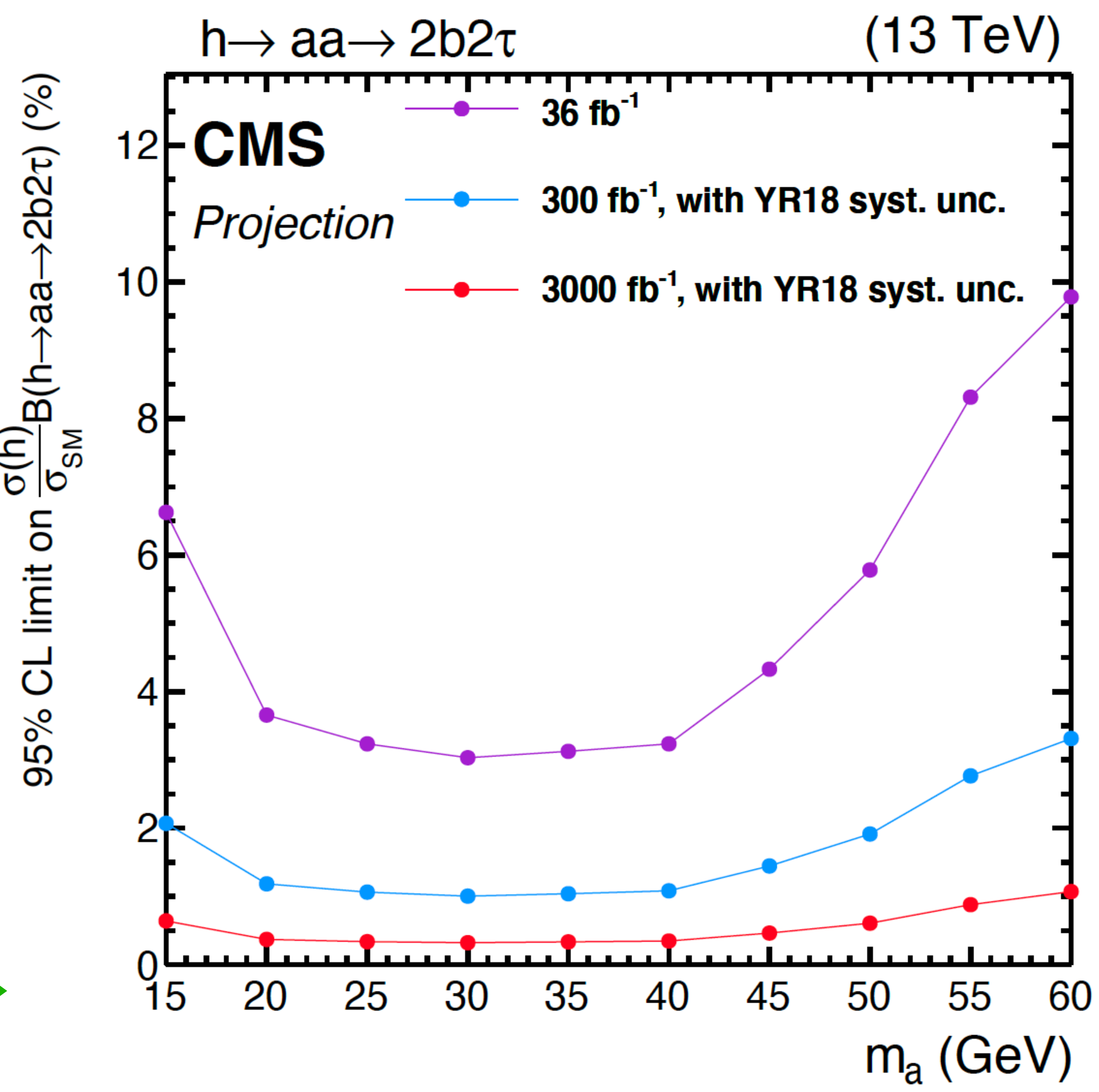
7 Higgs bosons: $h_1$, $h_2$, $H_3$, $A_2$, $a_1$, $H^\pm$. $h_{125} \rightarrow aa$ possible in NMSSM, where a is pseudoscalar or scalar.

Many final states analyzed by varying $m_a$ up to $m_{h125}/2$. Low $m_a$ —> boosted a decay products.




Search for excess in 4 object invariant mass (aa → visible) or transverse mass (aa → vis + invis).

HL-LHC search for $H \rightarrow aa \rightarrow bb\tau\tau$, $\mu\mu\tau\tau$ (hadronic and leptonic τ decays). Sensitivity of the order of SM $h_{125}$ cross section.

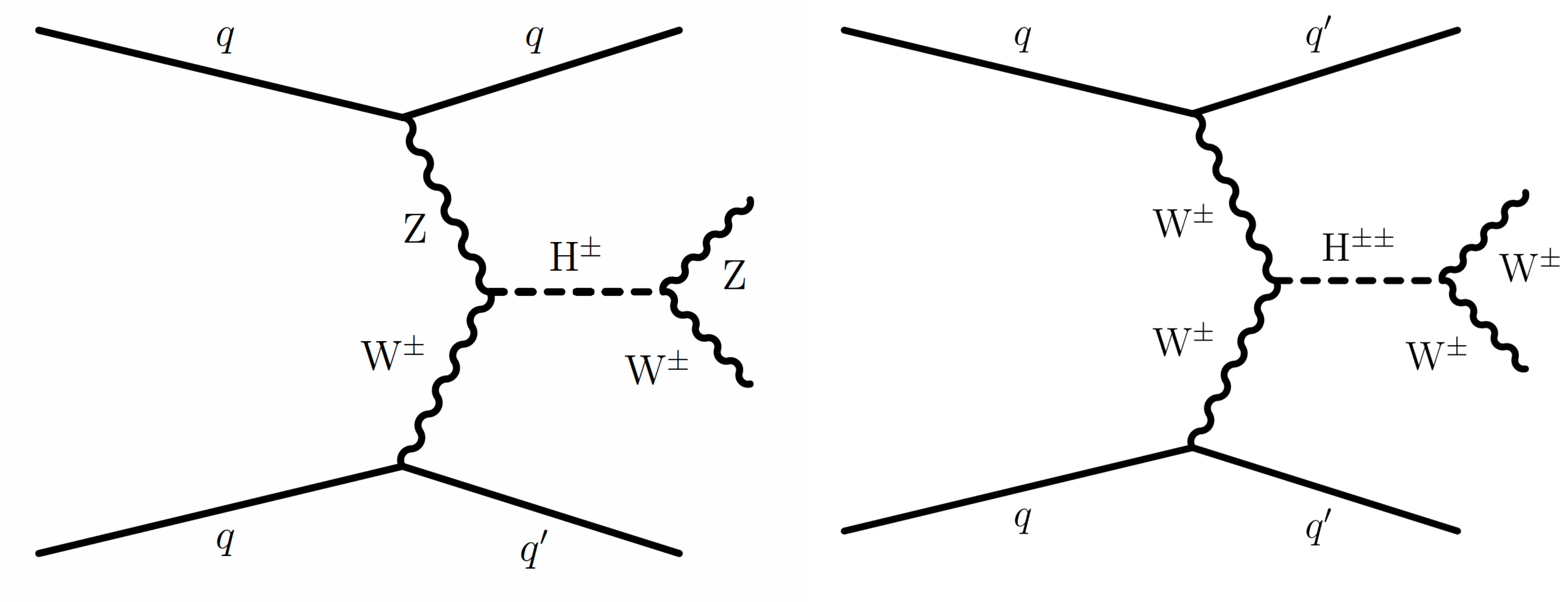



CMS-PAS-FTR-18-035

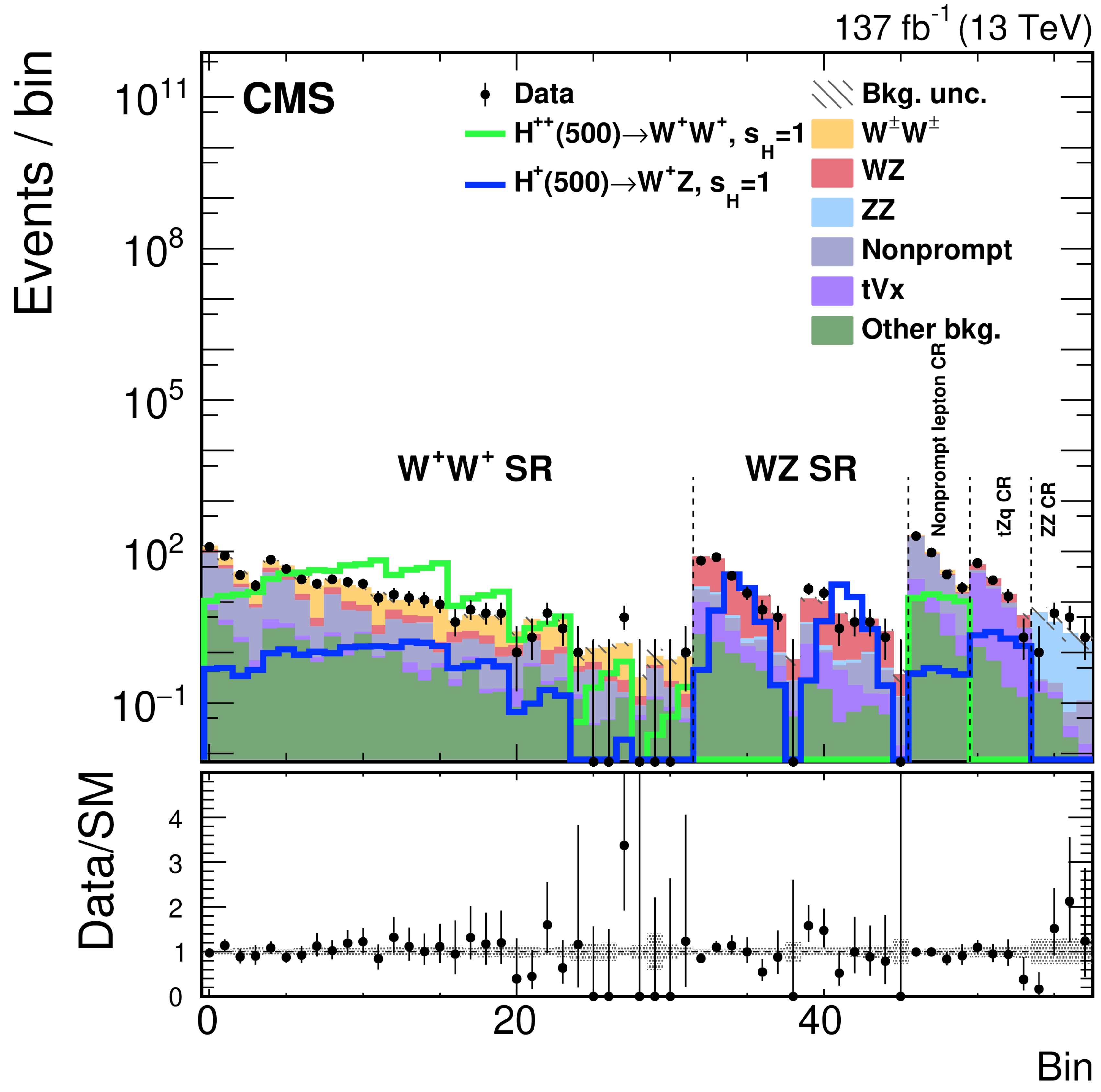
# BSM Higgses: Charged Higgs in Higgs triplet models

VBF production of charged and doubly-charged Higgses $H^{\pm\pm}$, $H^{\pm}$. decaying to vector bosons. $H^{\pm\pm}$, $H^{\pm}$ mass degenerate

- 2 same charge leptons or 3 leptons + 2 VBF jets.




CMS-HIG-20-017

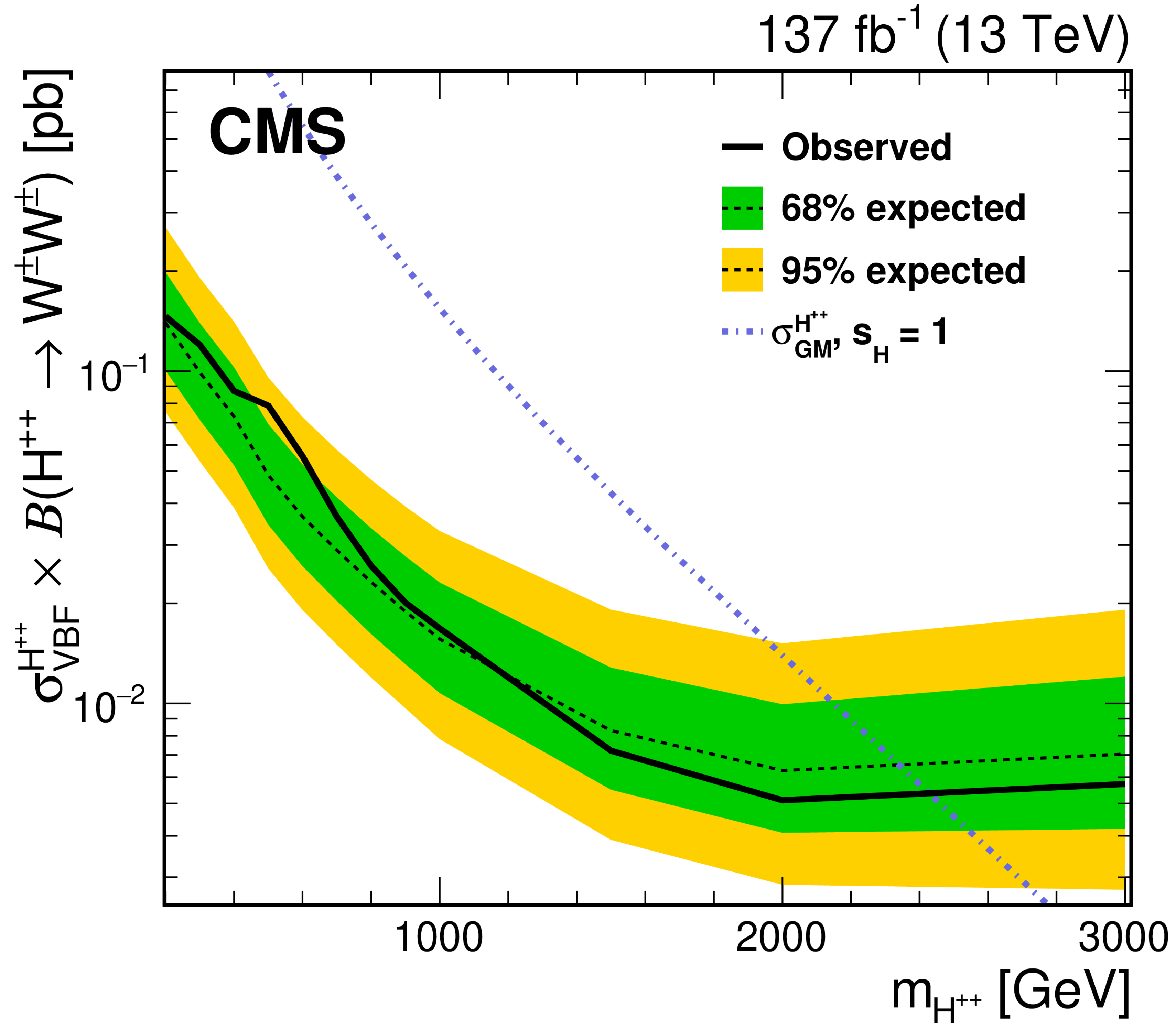



Extract signal via maximum likelihood fit to $m_{jj}$ & $m_T^{VV}$.

No excess.

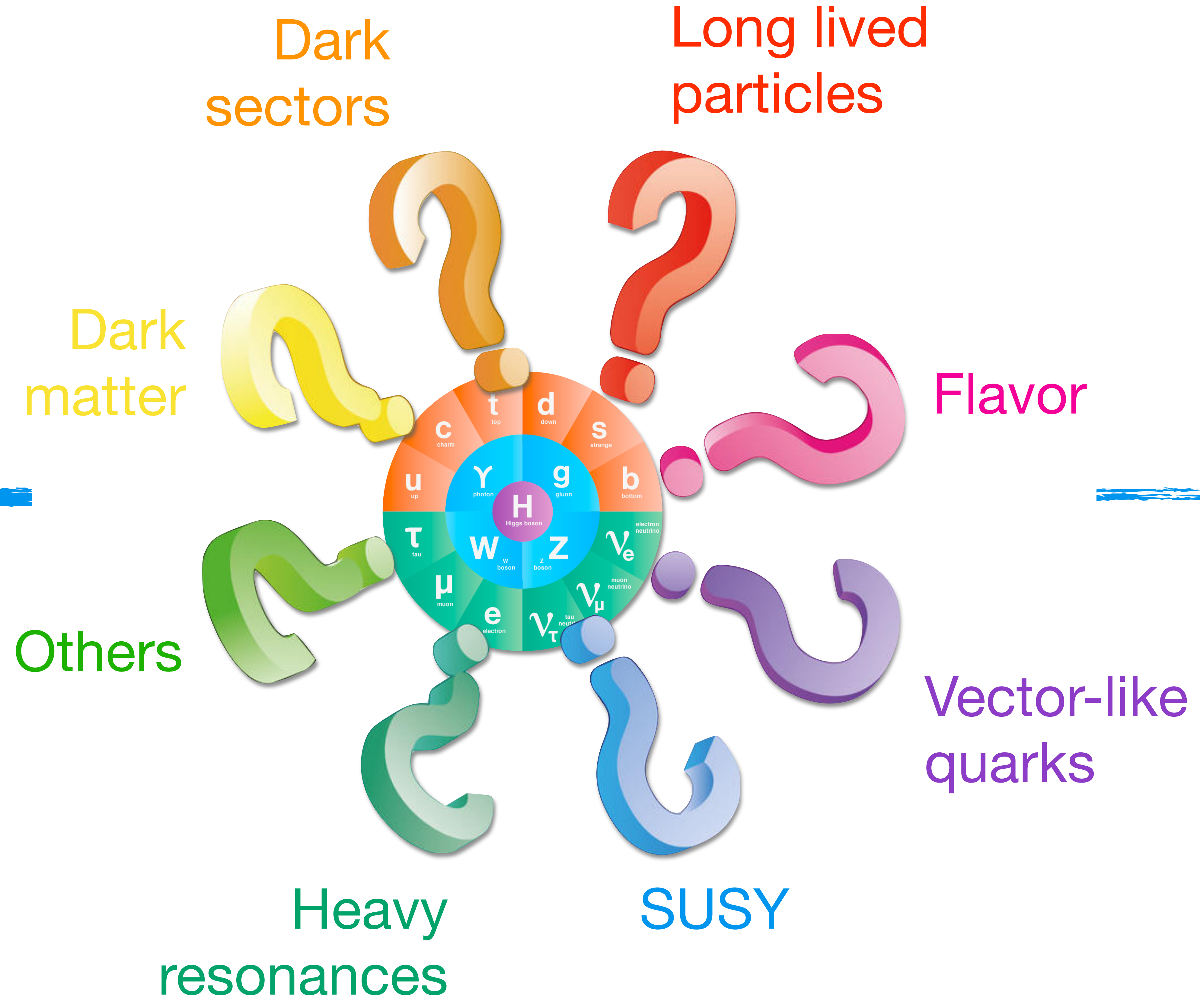
Interpreted in Georgi-Machacek (GM) model.

Exclude
$mH^{\pm\pm} < \sim 2.4$ TeV
$mH^{\pm} < \sim 1.6$ TeV.



# BSM physics

- CMS SUSY results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
- CMS Exotica results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
- CMS Beyond 2 Generations results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

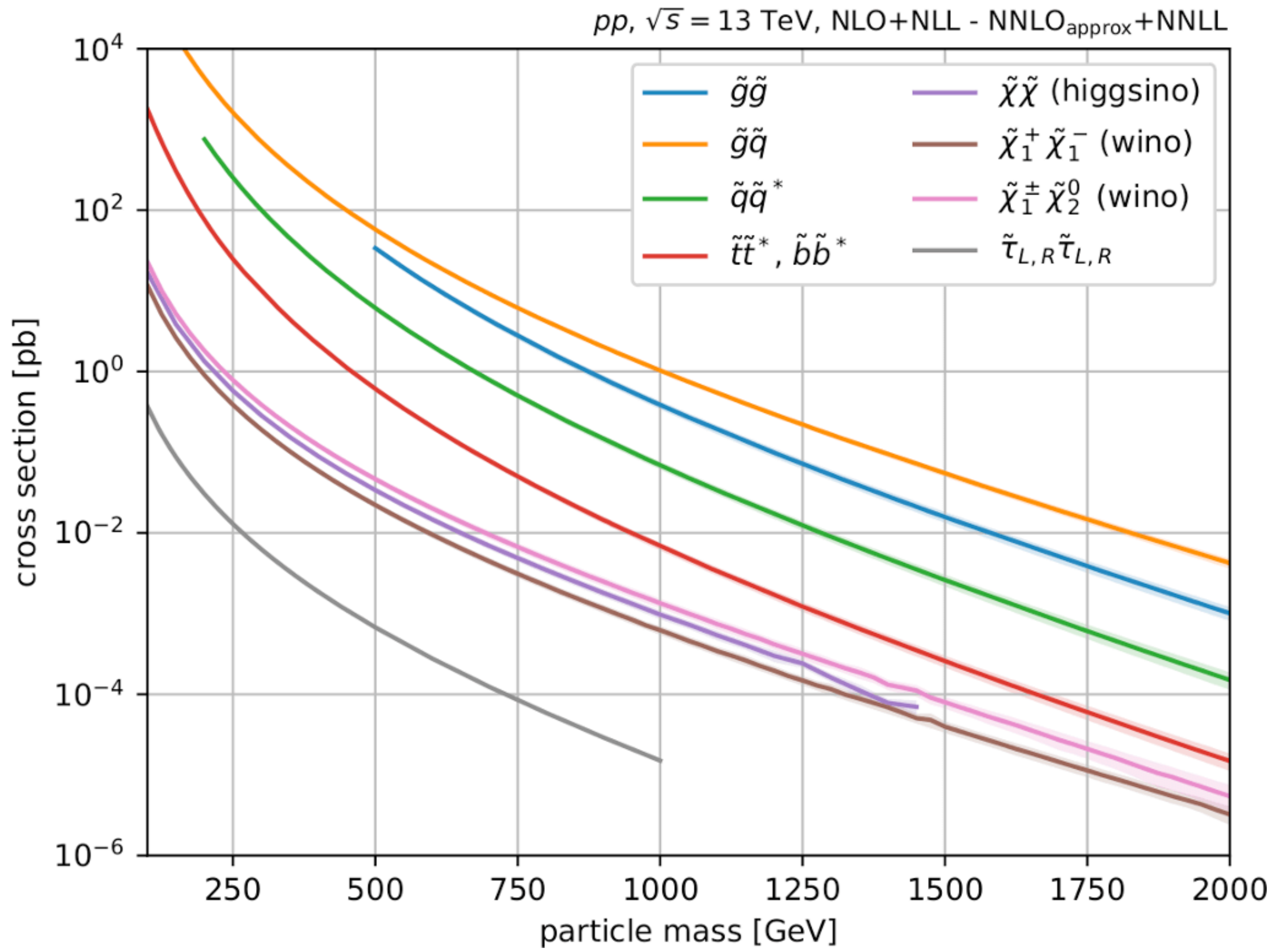


# Supersymmetry (SUSY): Overview

SUSY is a symmetry between bosons and fermions.

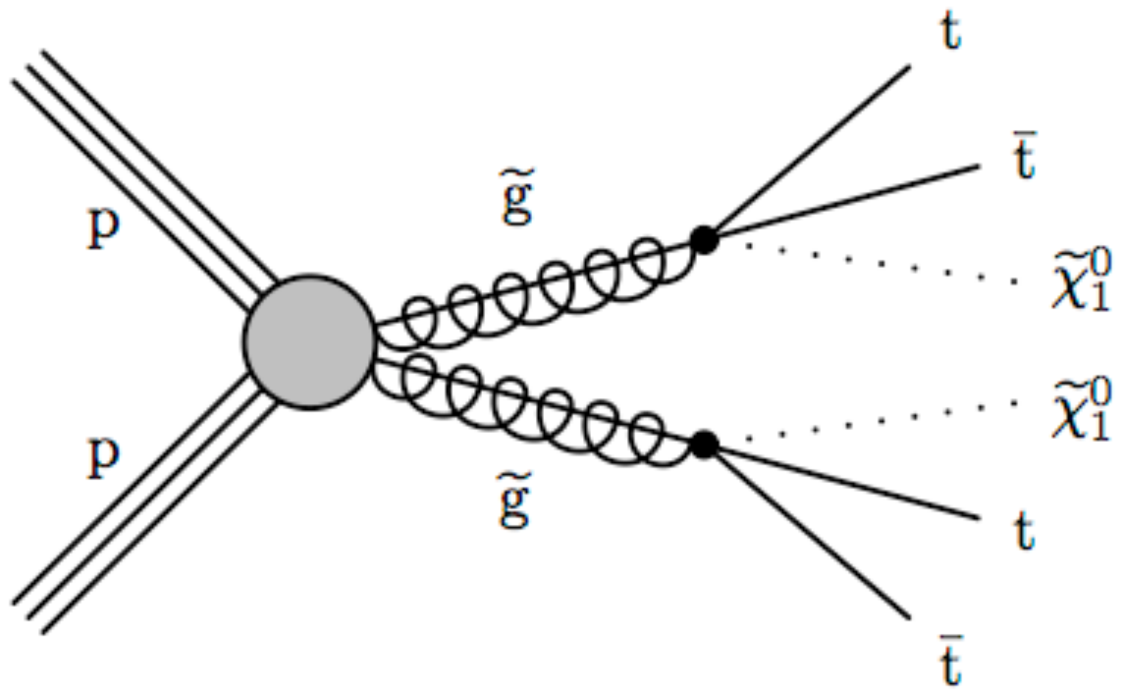
- Every SM particle has a superpartner with a different spin.
- SUSY is a broken symmetry: SUSY particles are heavier than SM particles.
- SUSY offers solutions to deficiencies of the SM.

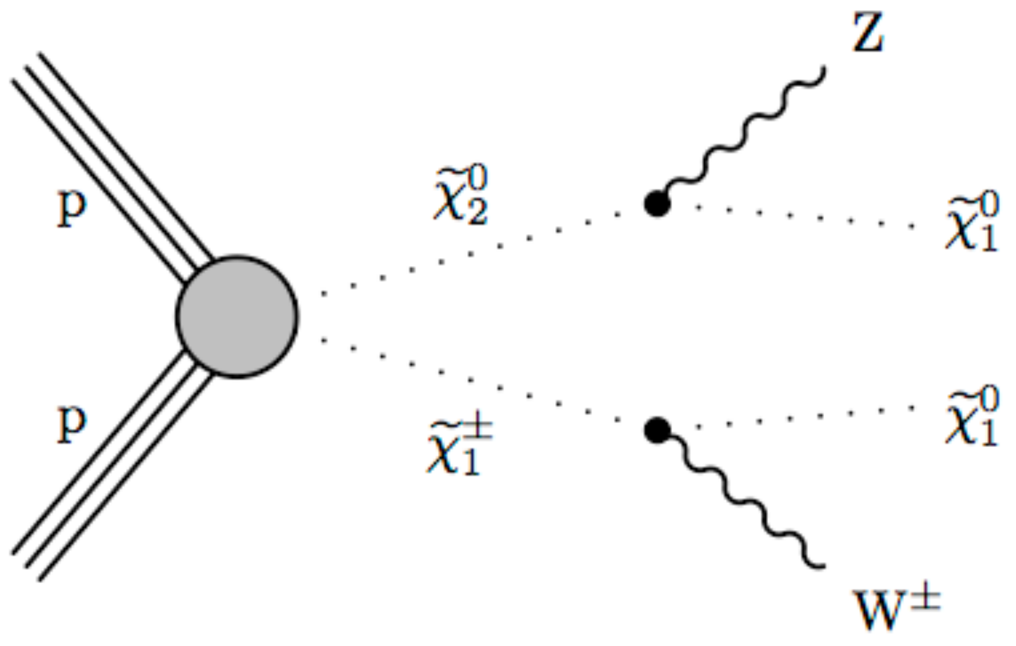
O(100) free parameters —> different sparticle masses, cross sections, branching ratios —> rich phenomenology and a broad set of signatures.




## LHC searches:

- Large diversity of searches targeting many flavors of SUSY and mass spectra.
- Interpreted using simplified models: Effective Lagrangian descriptions defined by sparticle masses, production and decay processes.
- Set upper limits on cross sections.

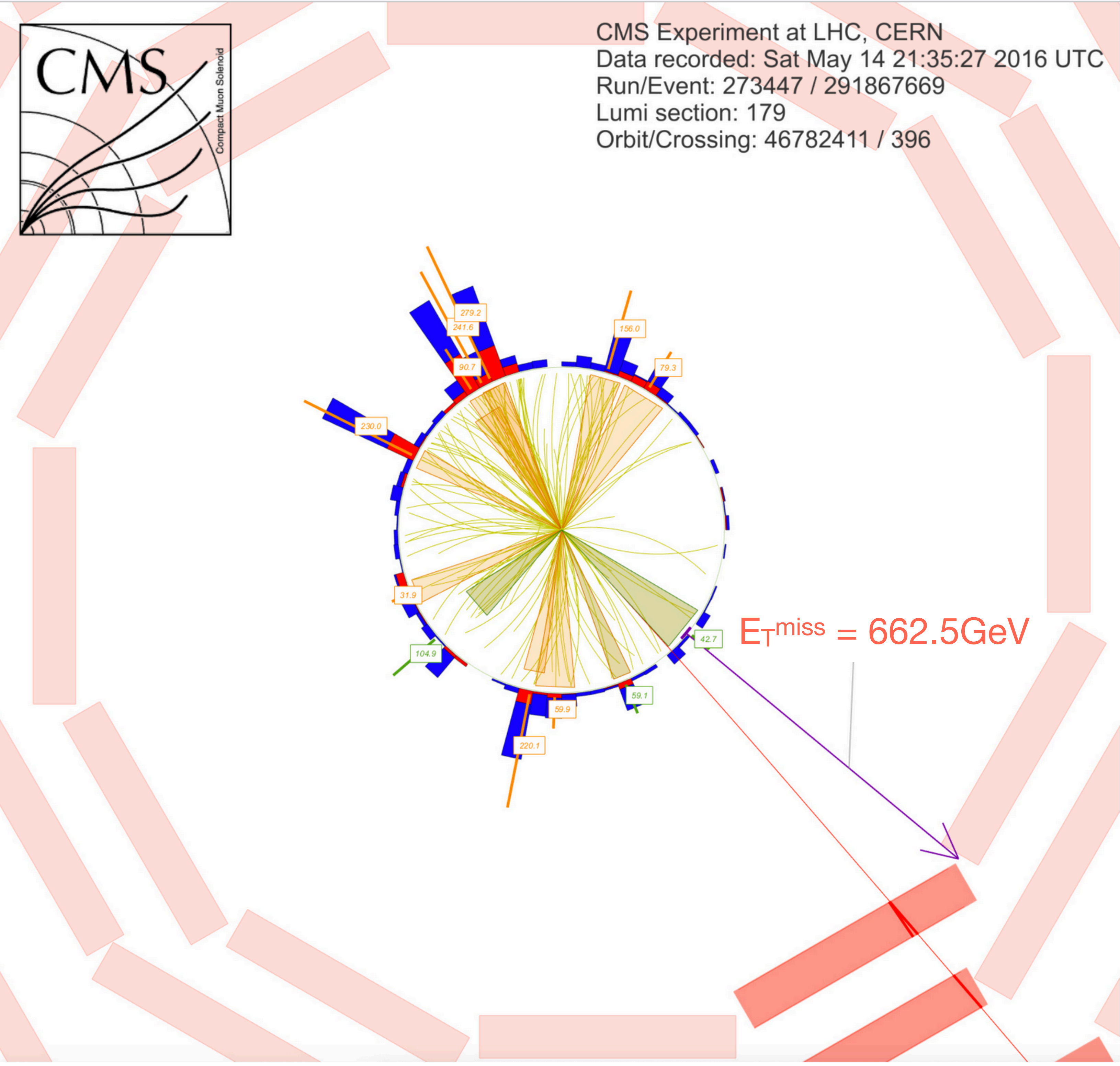


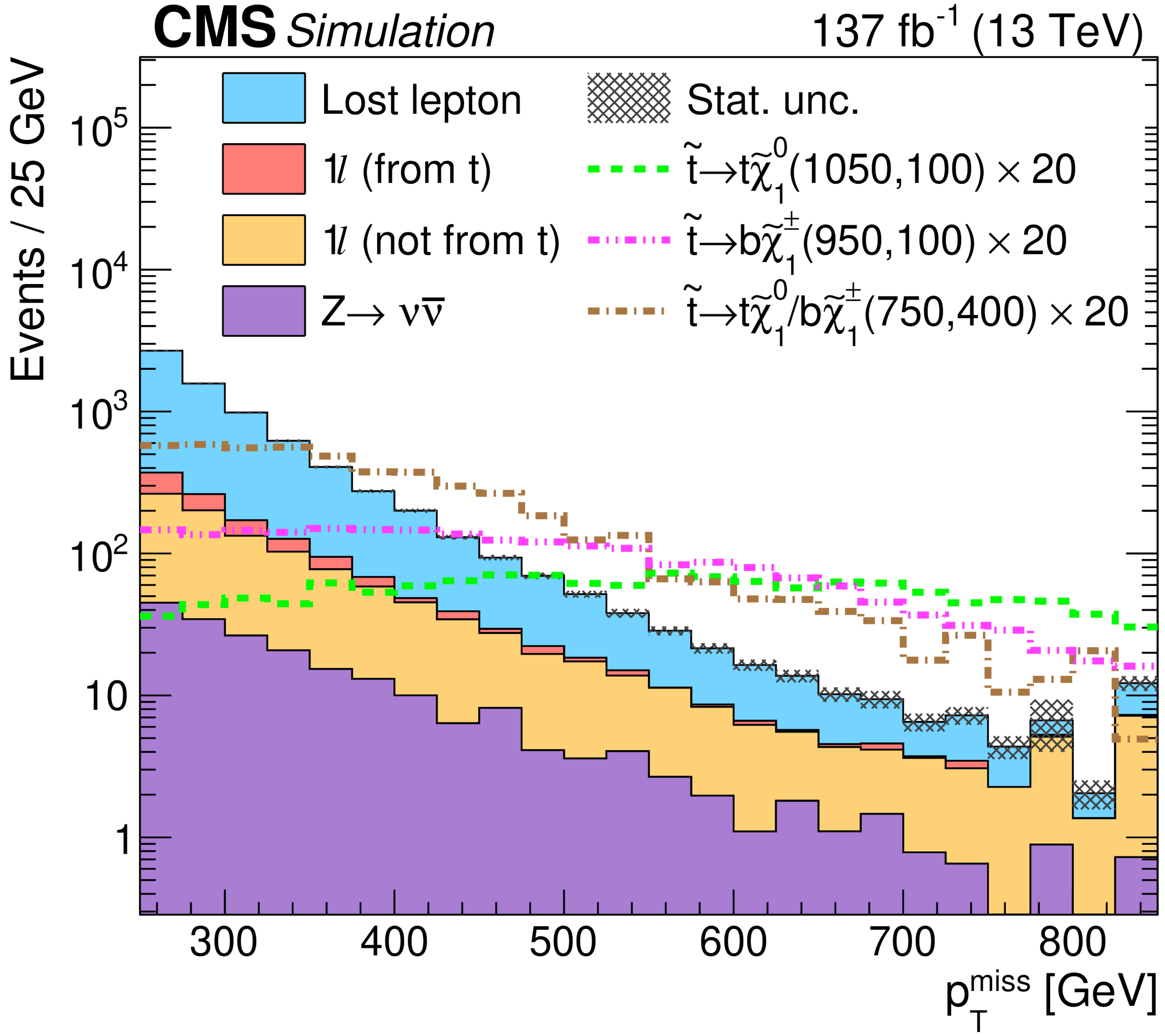



# SUSY: Characteristic signatures

CMS-SUS-19-006
CMS-SUS-19-009

- R parity conserving SUSY: Sparticle pair production, lightest SUSY particle is stable (dark matter candidate.)
  - High missing transverse energy $E_T^{miss}$ (or momentum $p_T^{miss}$), high object multiplicities, high visible transverse momentum…



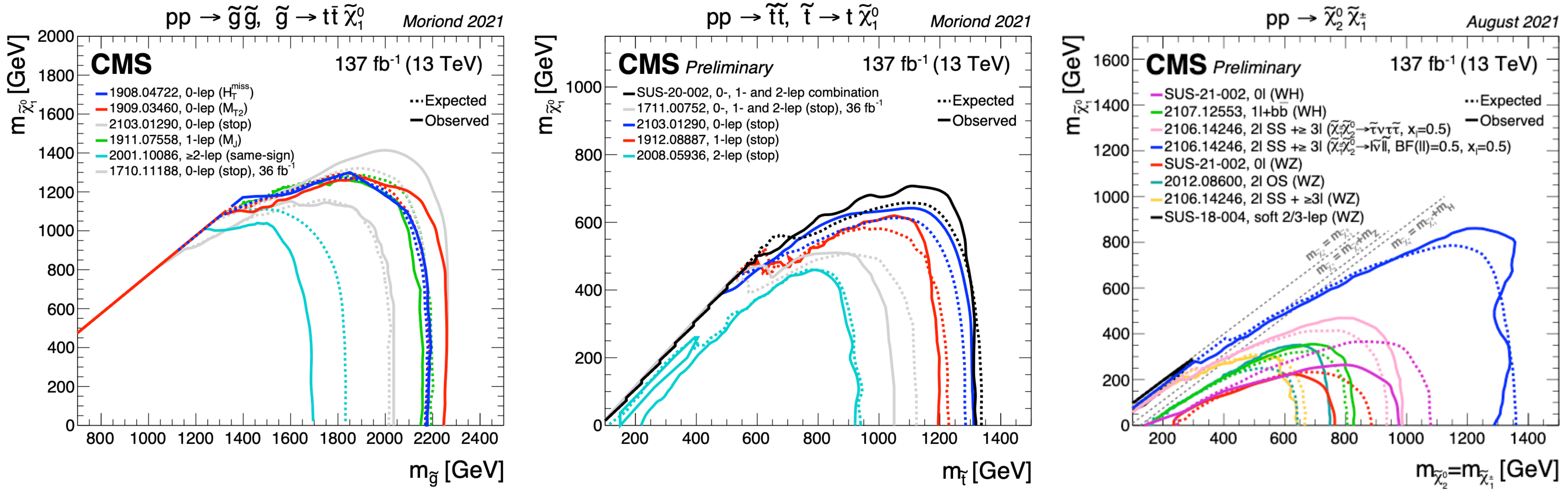

- RPV, compressed SUSY: multiple particles; small mass differences between sparticles —> low $E_T^{miss}$.

# SUSY: Gluinos, top squarks, charginos/neutralinos

Gluino, top squark and chargino/neutralino vs. neutralino mass limits: Decay BRs = 1 unless stated.

- Searches in diverse final states with jets, leptons, photons, giving complementary sensitivity.
- Multiple disjoint search regions defined by object multiplicities and kinematic variables.

Gluino vs NT1: Top squark vs NT1: CH1/NT2 vs NT1:



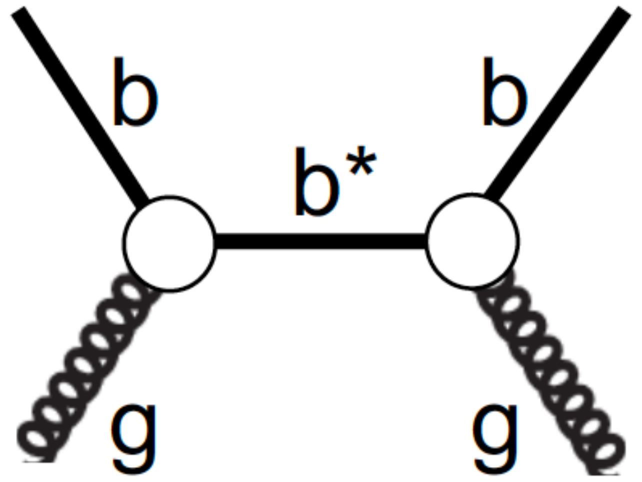

At HL-LHC, exclusion limits are expected to increase by ~O(few 100 GeV) - 1TeV.

# New fermions: Excited quarks

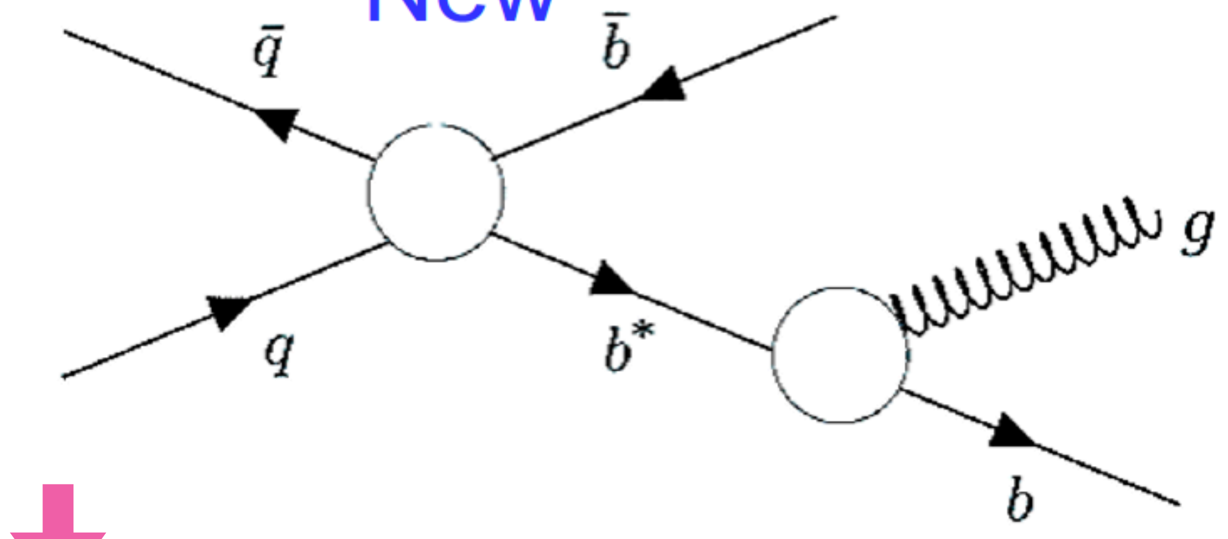
CMS-PAS-EXO-20-008

Compositeness models: Leptons and quarks are composite objects made of more fundamental constituents.

- Postulate excited states of quarks and leptons.
- New interactions occur above compositeness scale Λ.




New

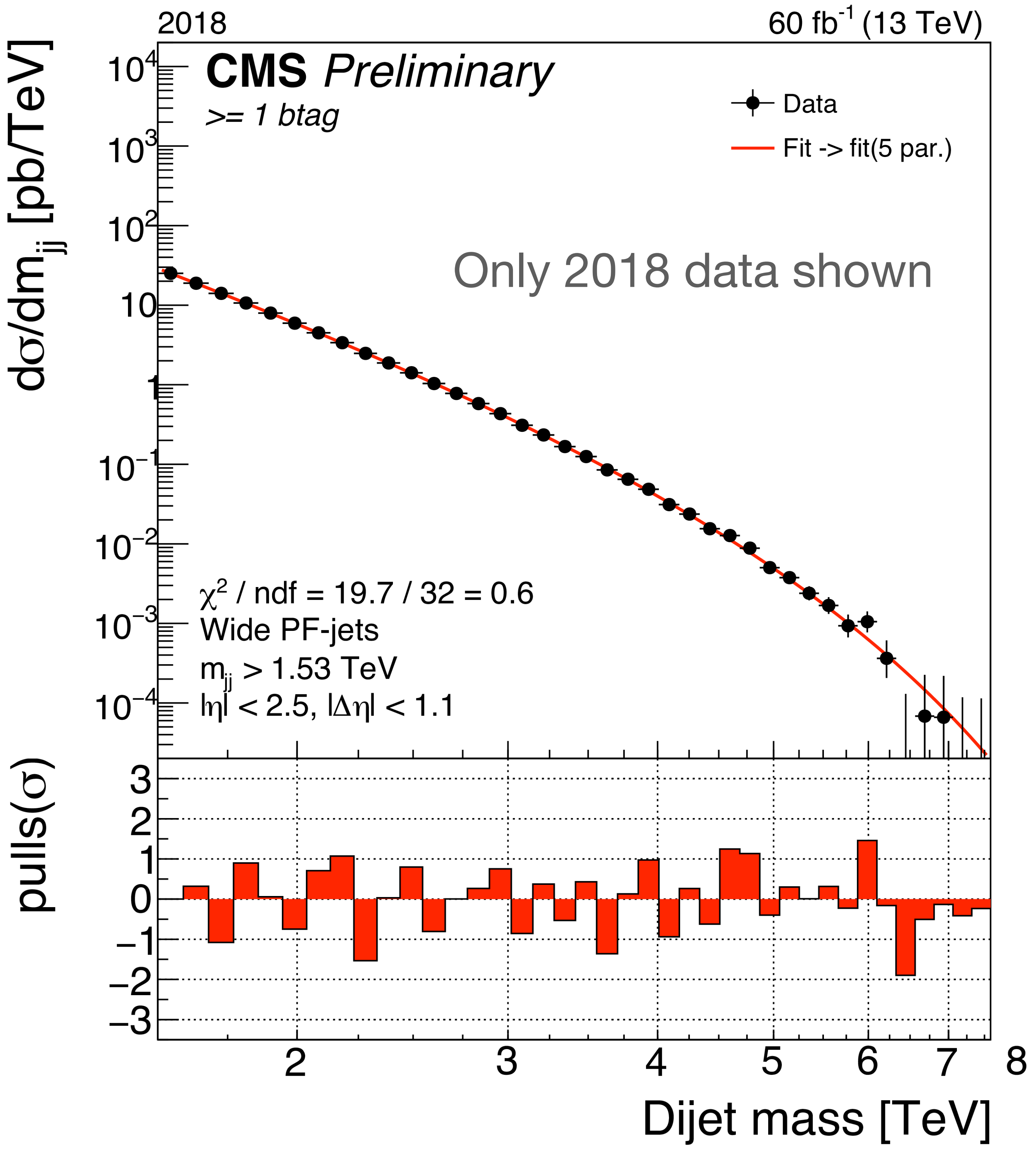


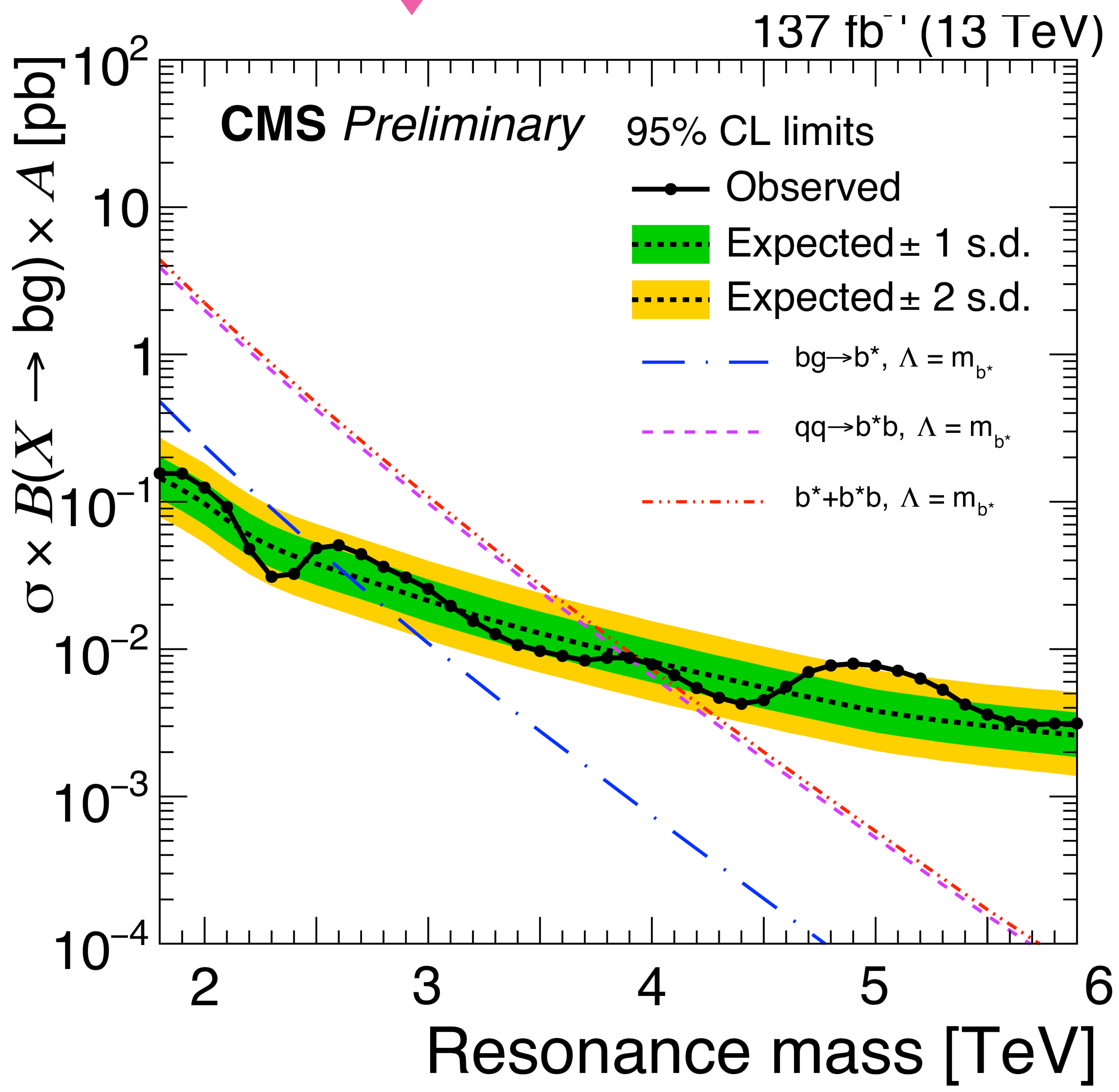

Excited b* search via dijet resonances with at least one jet coming from a b quark.

- Energetic b quarks in jets identified by a deep neural network.
- Look for excess in dijet inv. mass over fit to BG.

Exclude $m_{b^*} < 4$ TeV.

(Also interpreted for Z' in sequential standard model.)



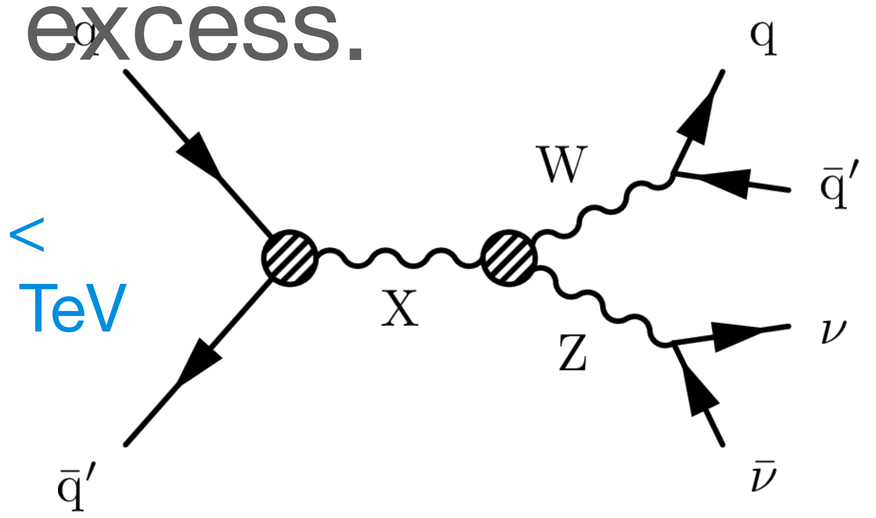



# New bosons: Resonances with vector bosons

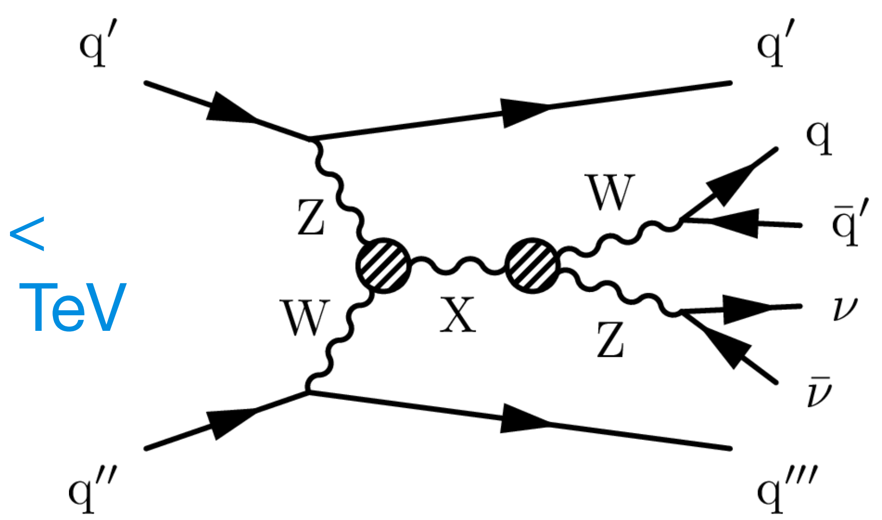
## Search for heavy resonances X decaying to ZW. ZZ pairs:

- Z → νν, boosted Z/W → jj : Merged jets + $E_T^{miss}$ + forward jets.
- Extract signal in a fit to transverse mass of merged jet + $E_T^{miss}$. No excess.

W' < 3.0 TeV

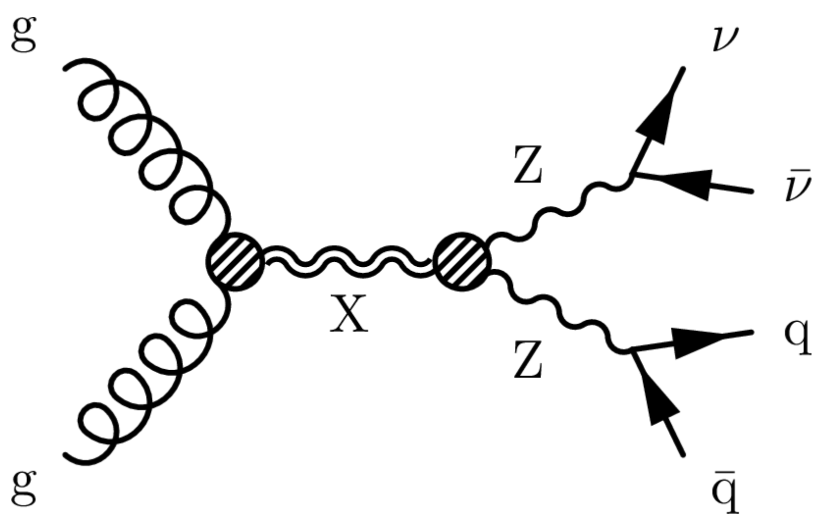


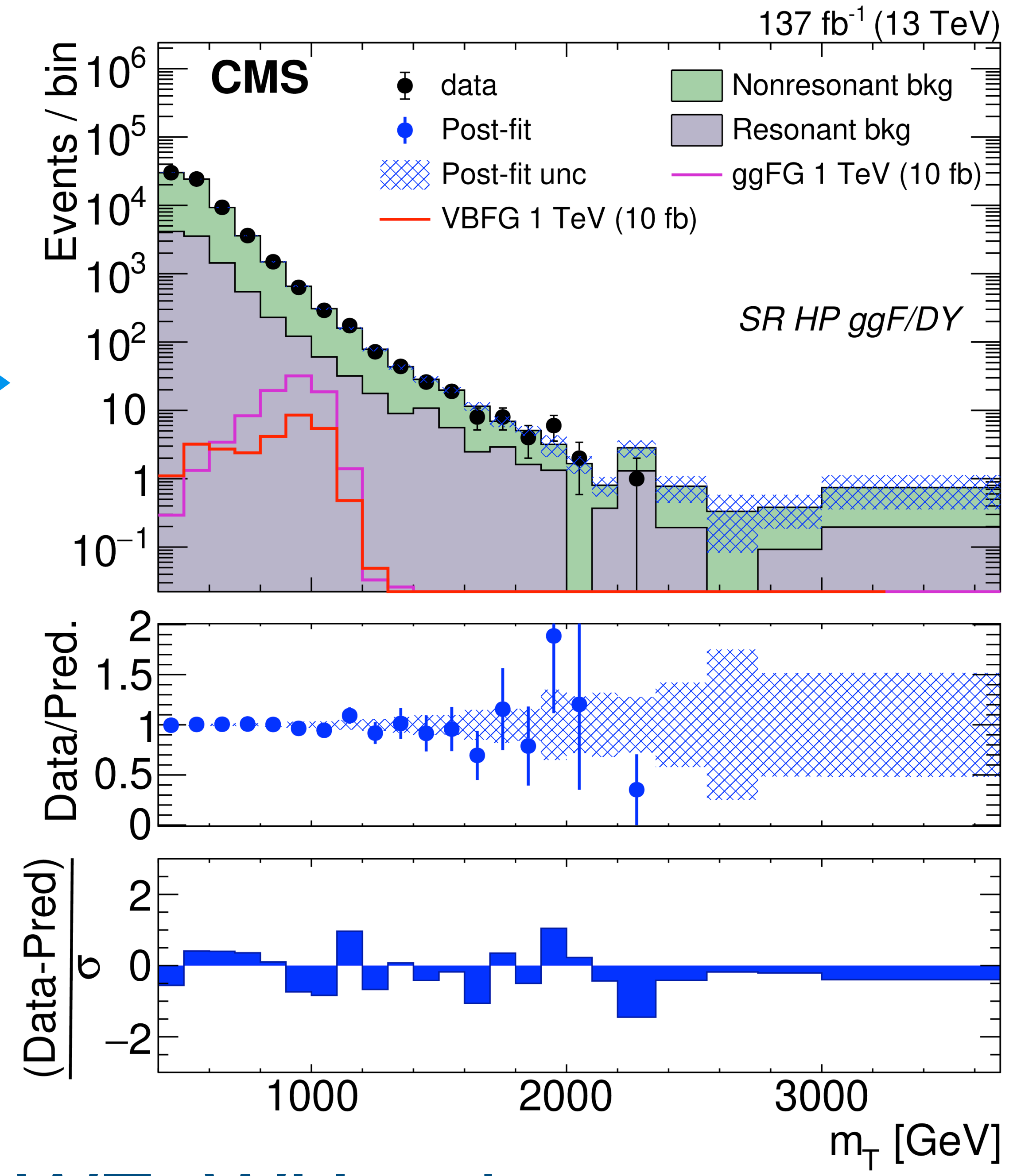

W' < 4.0 TeV




Radion < 3.0 TeV

Graviton < 1.2 TeV



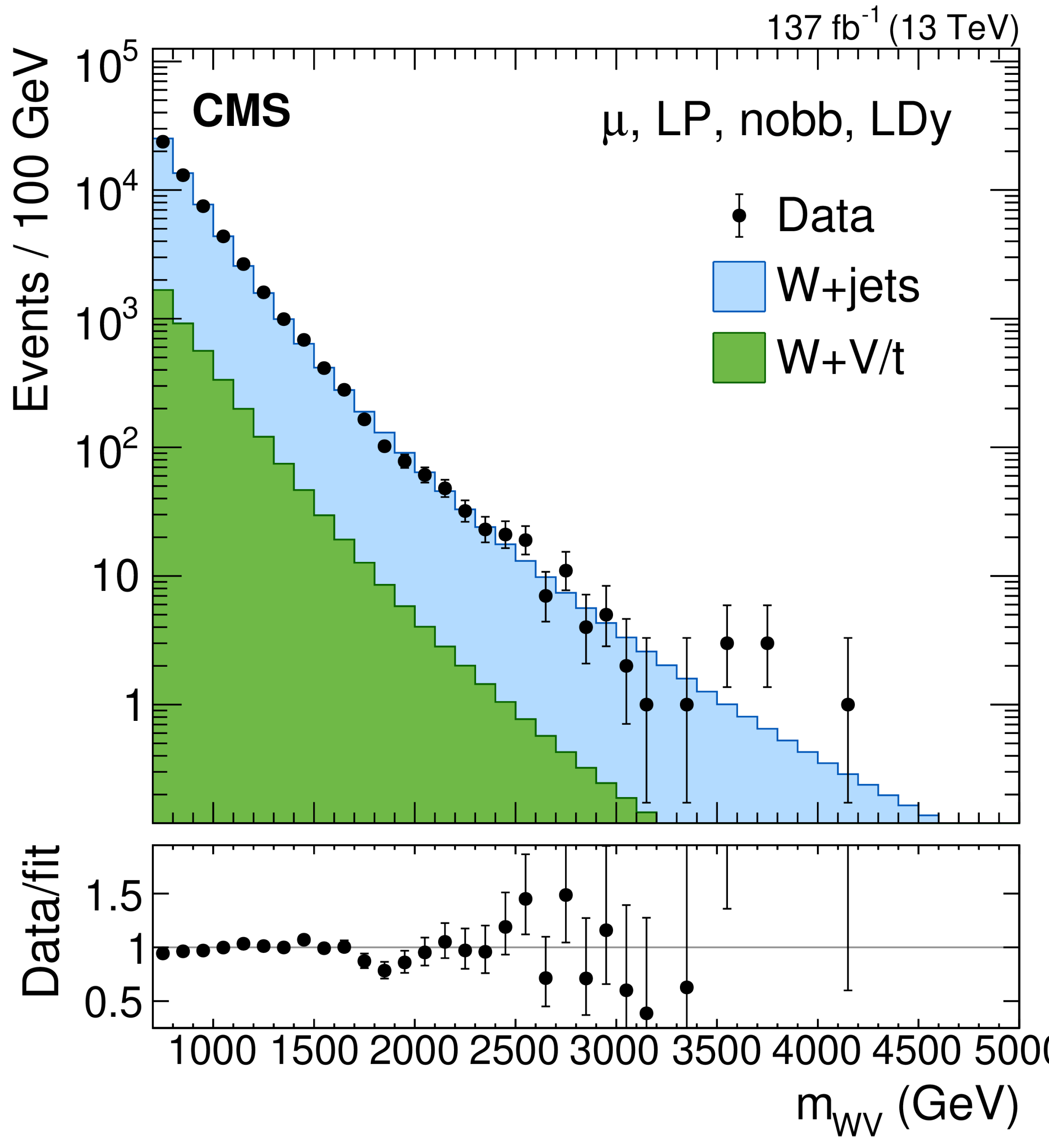




CMS-B2G-20-008

CMS-B2G-19-002

## Search for heavy resonances X decaying to WW, WZ, WH pairs:

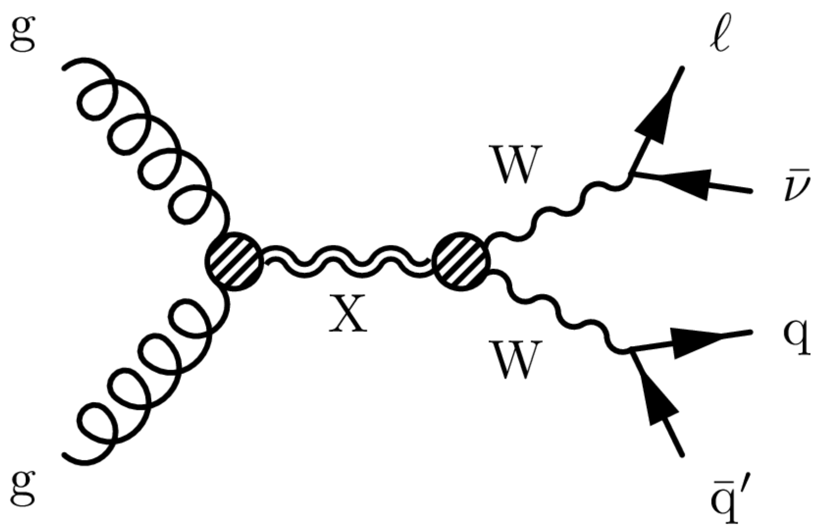
- W → lν, boosted W/Z/H → jj : Lepton + merged jet final state. Dedicated VBF selection via forward jets.
- Extract signal in 2D fit to $m_{jj}$ vs $m_{diboson}$. No excess.



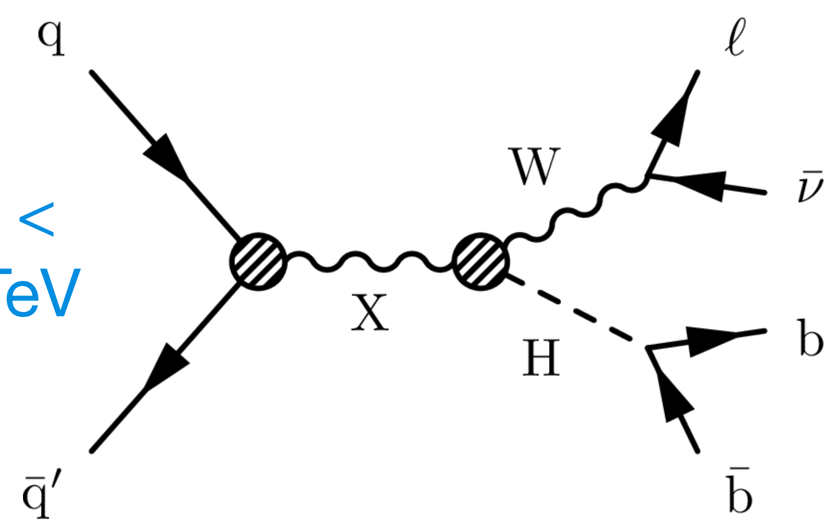

Spin-2 bulk graviton < 1.8 TeV

Radion < 3.1TeV

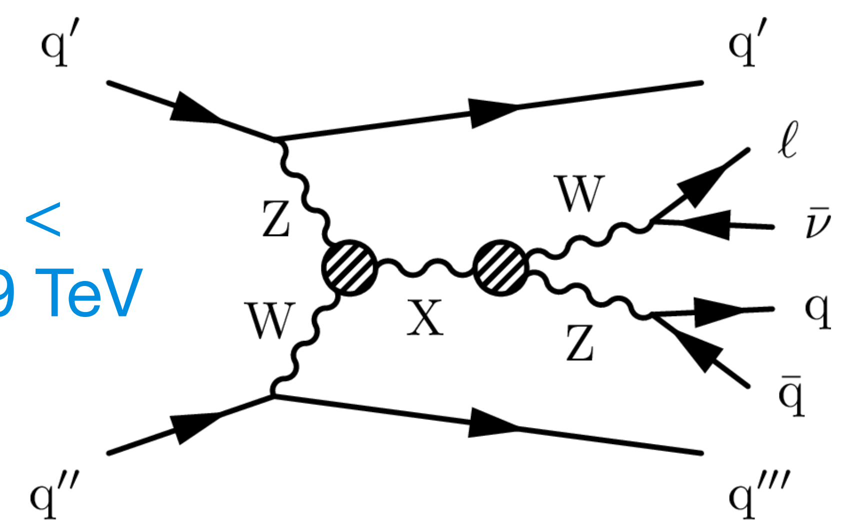
Z' < 3.9 TeV




W' < 4 TeV




W' < 3.9 TeV



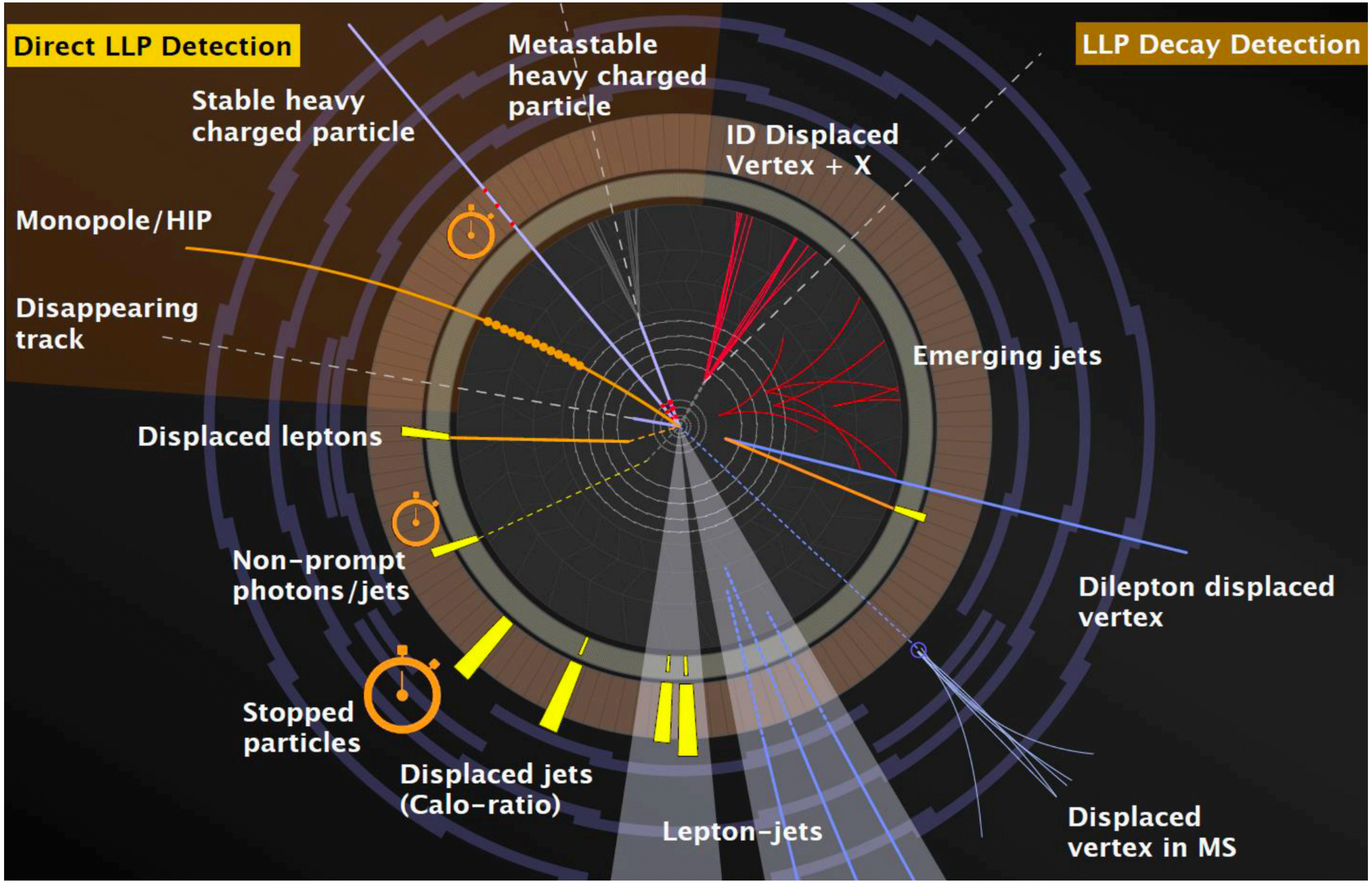
# Long lived particles (LLPs): Overview

Some BSM models predict long-lived particles decaying away from the interaction point.

- Leads to unique and challenging signatures.
- Measure timing or displacement information for an object.

Many searches at Runs 1&2.

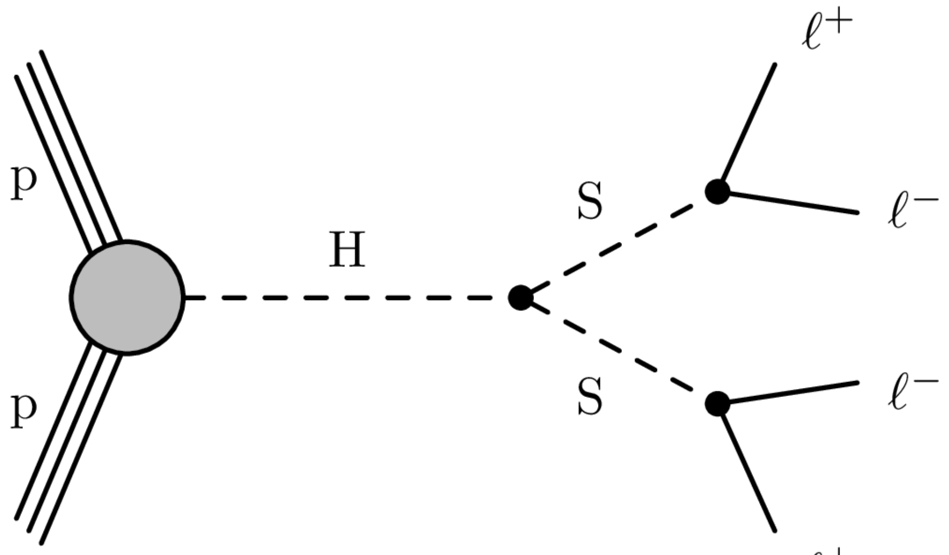
At HL-LHC, new Phase2 tracking and timing detectors, along with extended detector coverage and sensitivity will allow a wider diversity and reach.

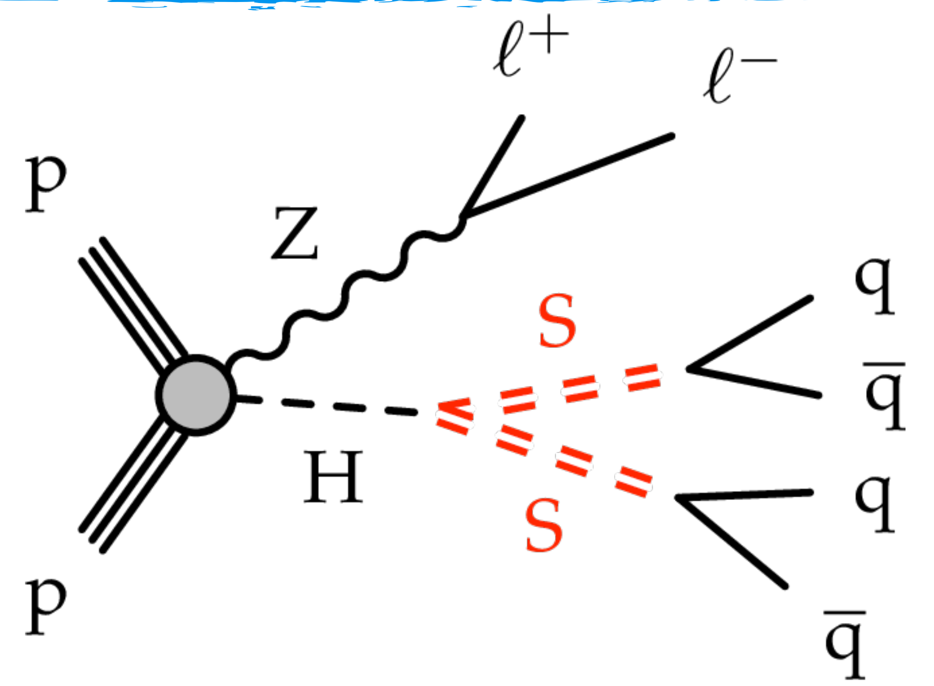


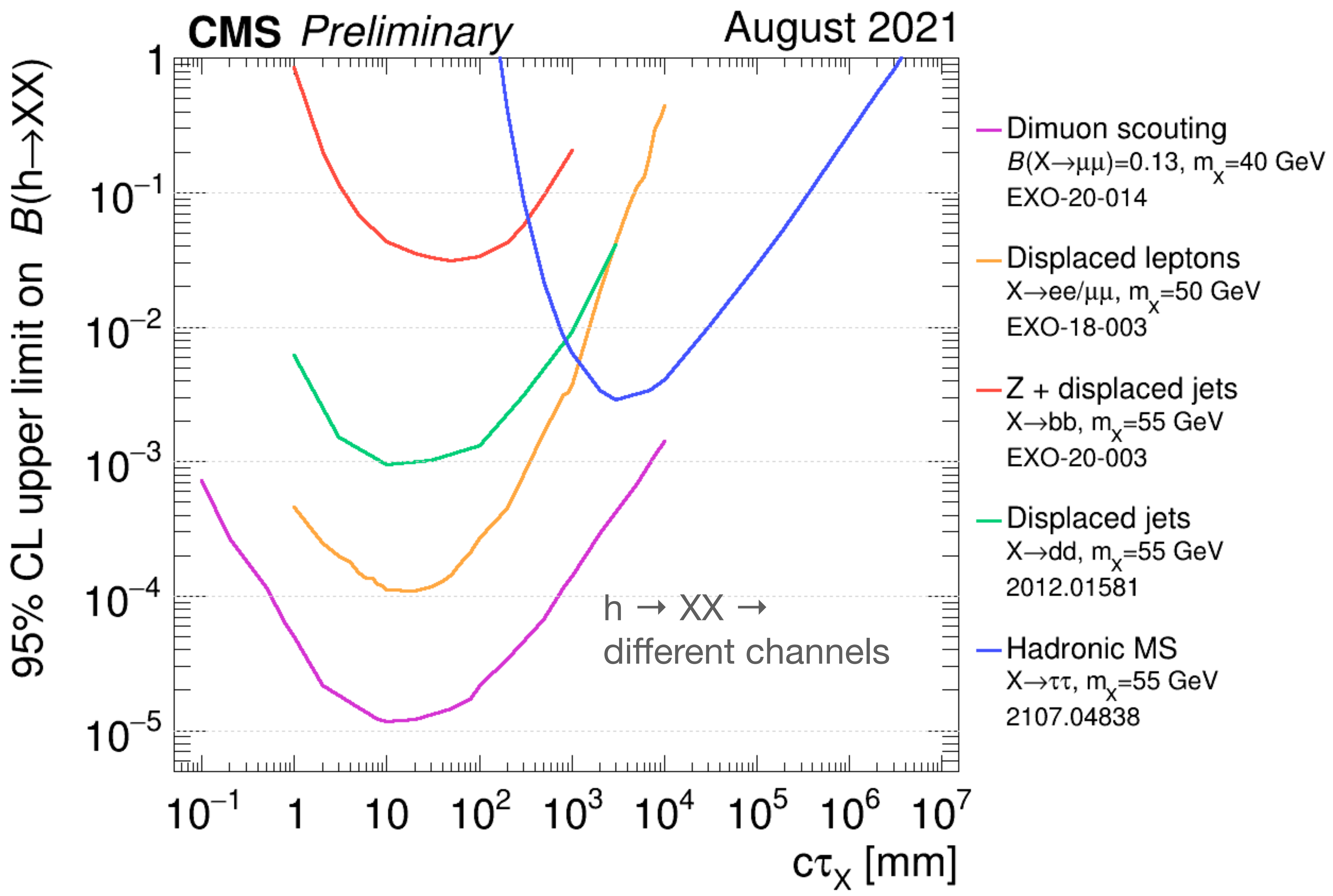
# LLPs: SM Higgs decays to long-lived BSM particles

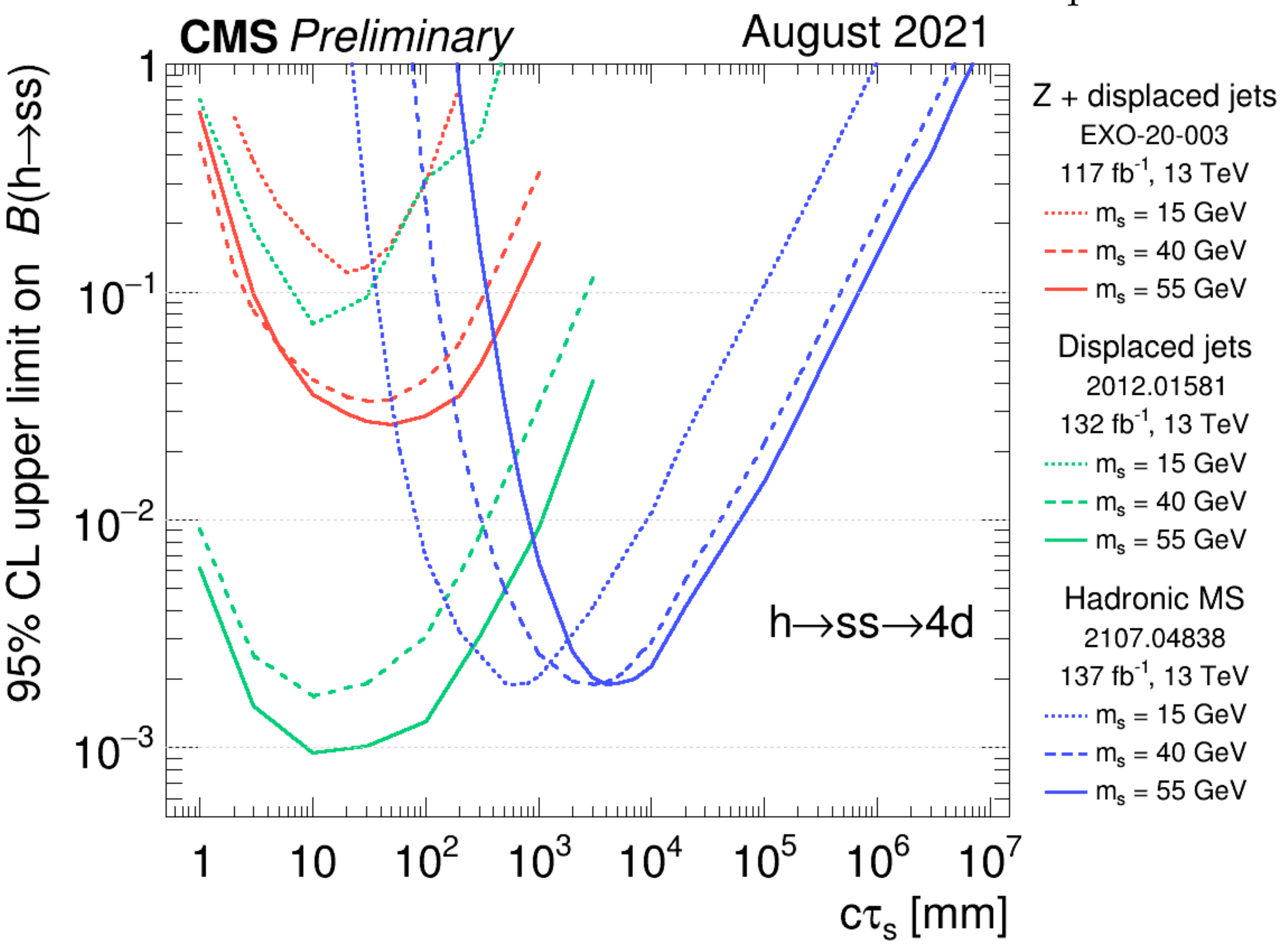
Complementarity of different LLP searches for SM Higgs decays to LL BSM particles.

Different searches sensitive to different LLP proper lifetime ranges.



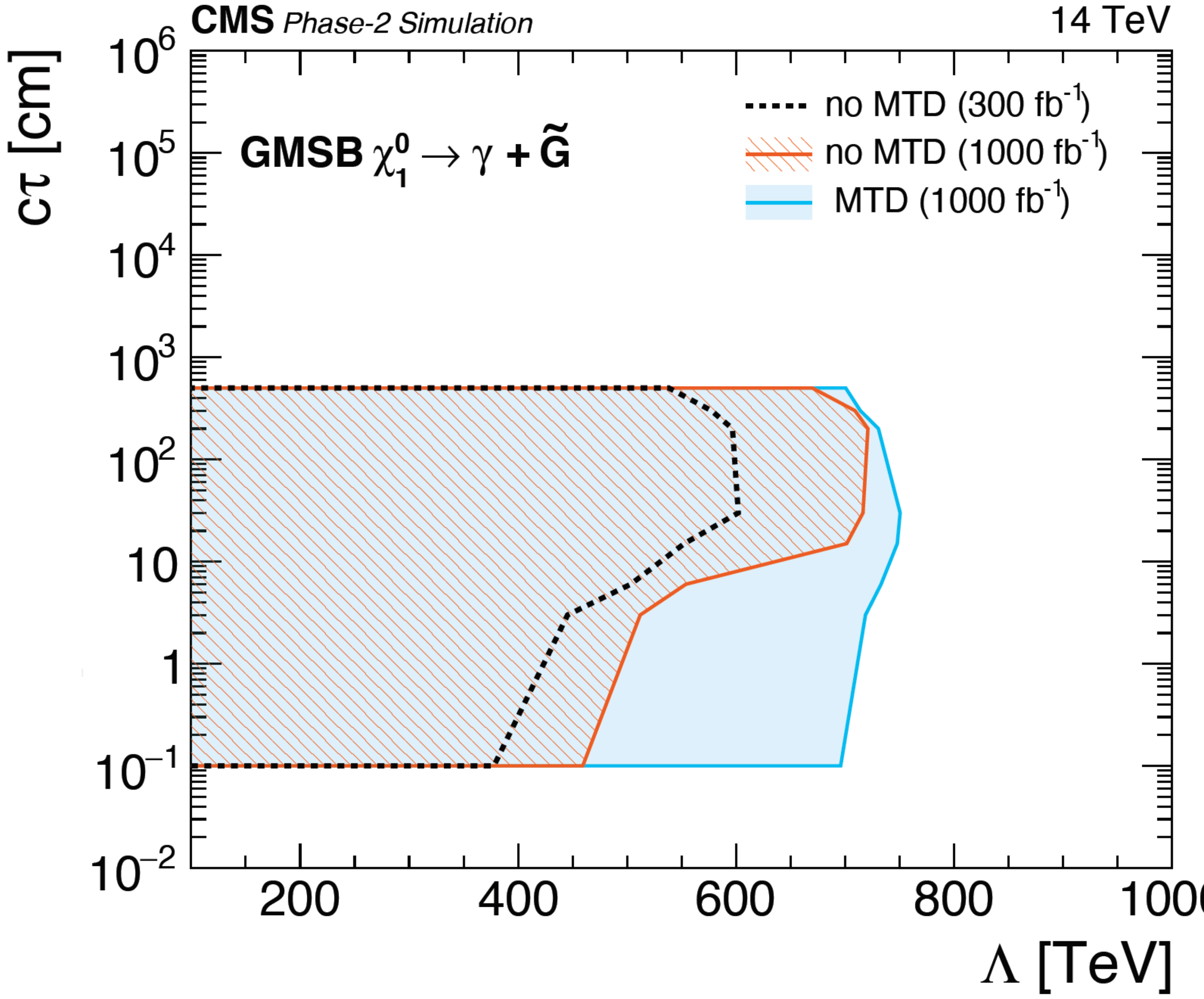
# LLPs: Phase2 timing detectors

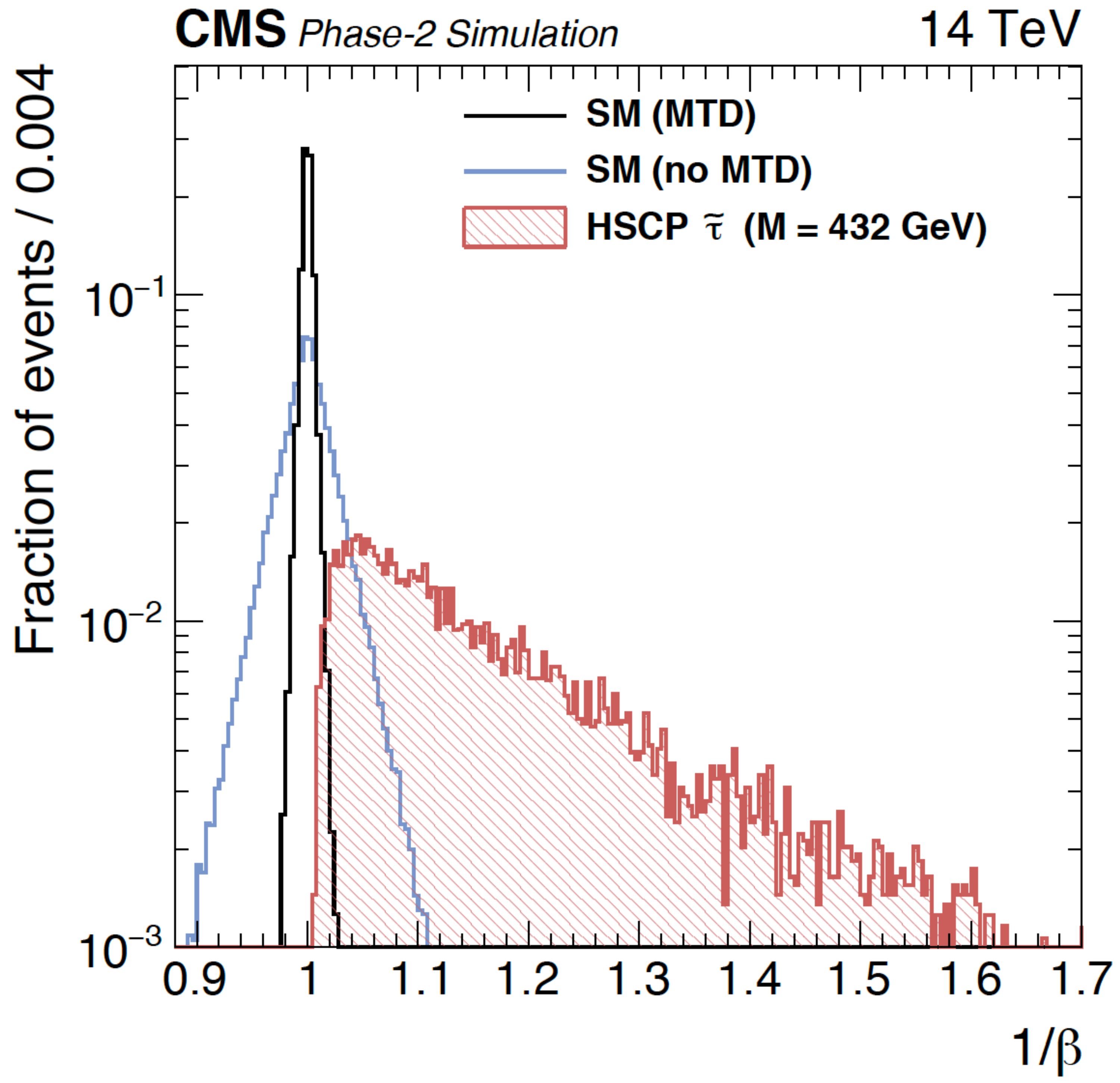
CMS-TDR-020

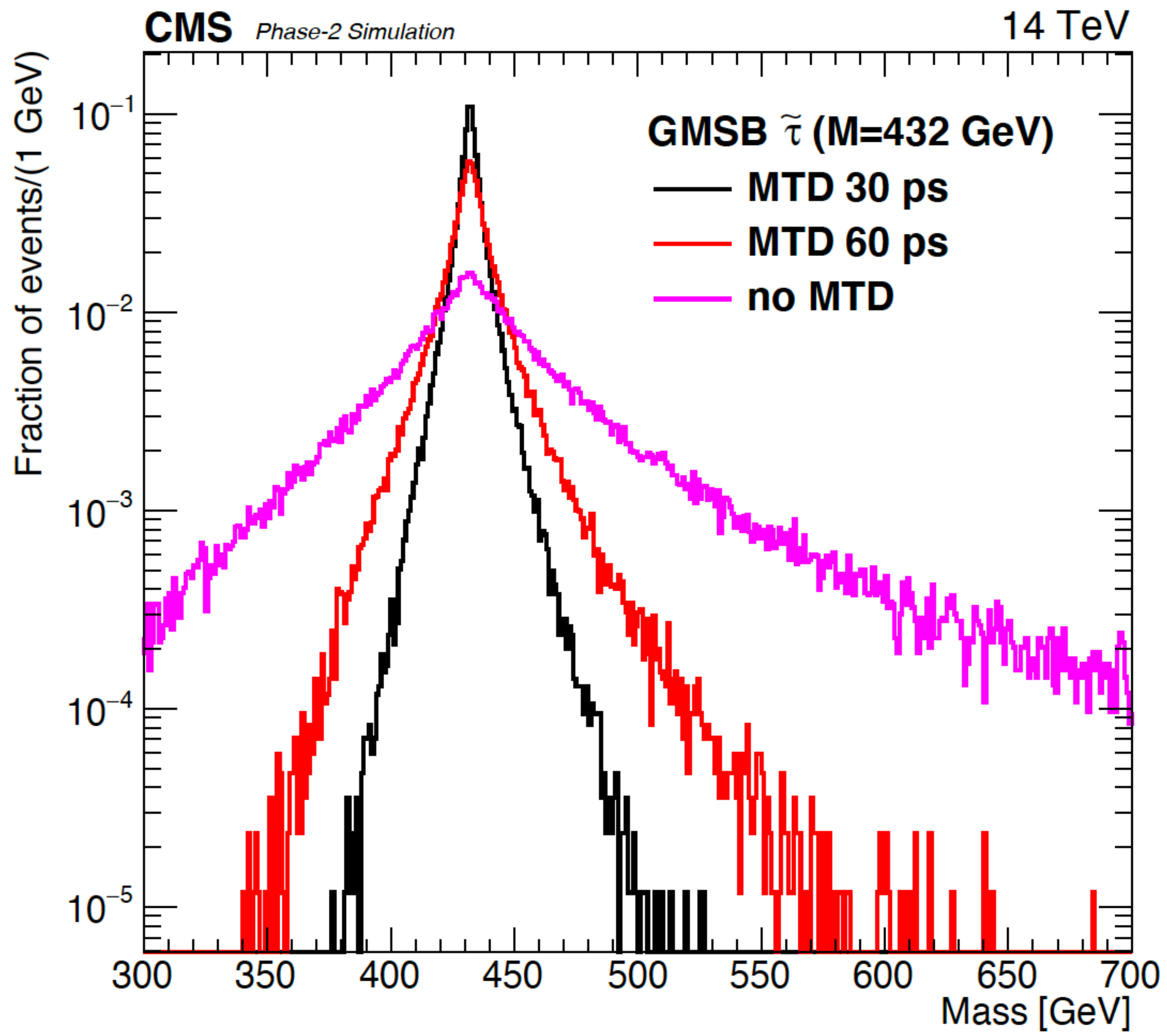
CMS MIP Timing Detector: MIP timing with 30ps precision. Acceptance of |η| < 3 for $p_T$, p < 0.7 GeV in barrel/endcap.

Displaced photons from GMSB (gauge-mediated SUSY breaking models): $\tilde{\chi}_0 \rightarrow \tilde{G} + \gamma$

Use time of arrival of photons to MTD to discriminate signal —> determine neutralino time of flight.
Increased sensitivity with MTD to short cτ and high masses.




Heavy charged stable particles: Long-lived GMSB stau:

Measure particle velocity β.

MTD improves time resolution.

Discriminate signals, extract mass.

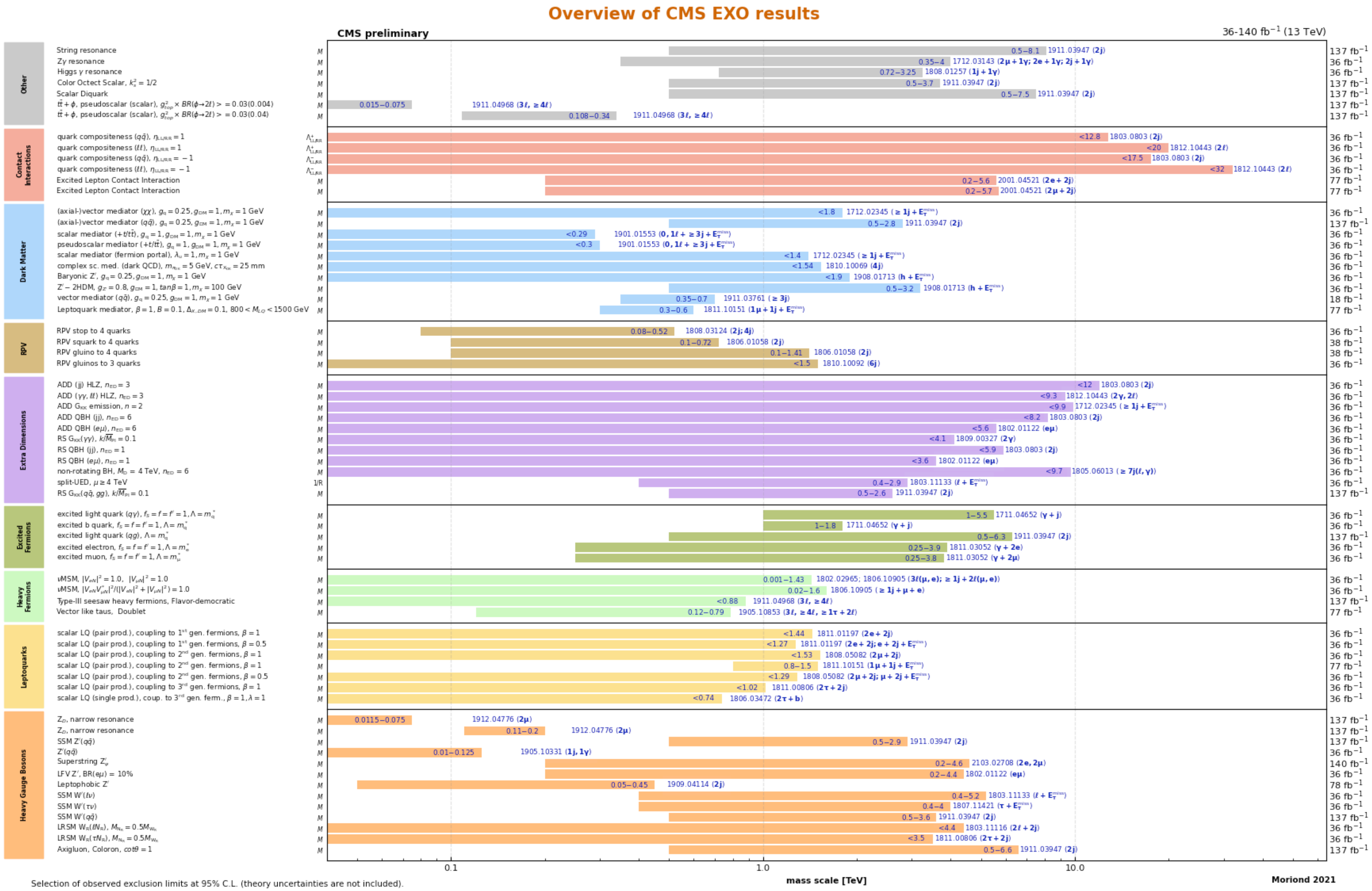
# Summary and outlook

- ~1000 SM measurements and new physics searches available with Run1/Run2 CMS data covering a large diversity of models and signatures.
  - Many precision measurements; no significant BSM signal observed.
- Preparations for Run3 ongoing.
- HL-LHC will offer unprecedented physics opportunities:
  - All technical design reports for Phase2 are ready.
  - Physics projections are ongoing.


"Data are coming! Data are coming!"

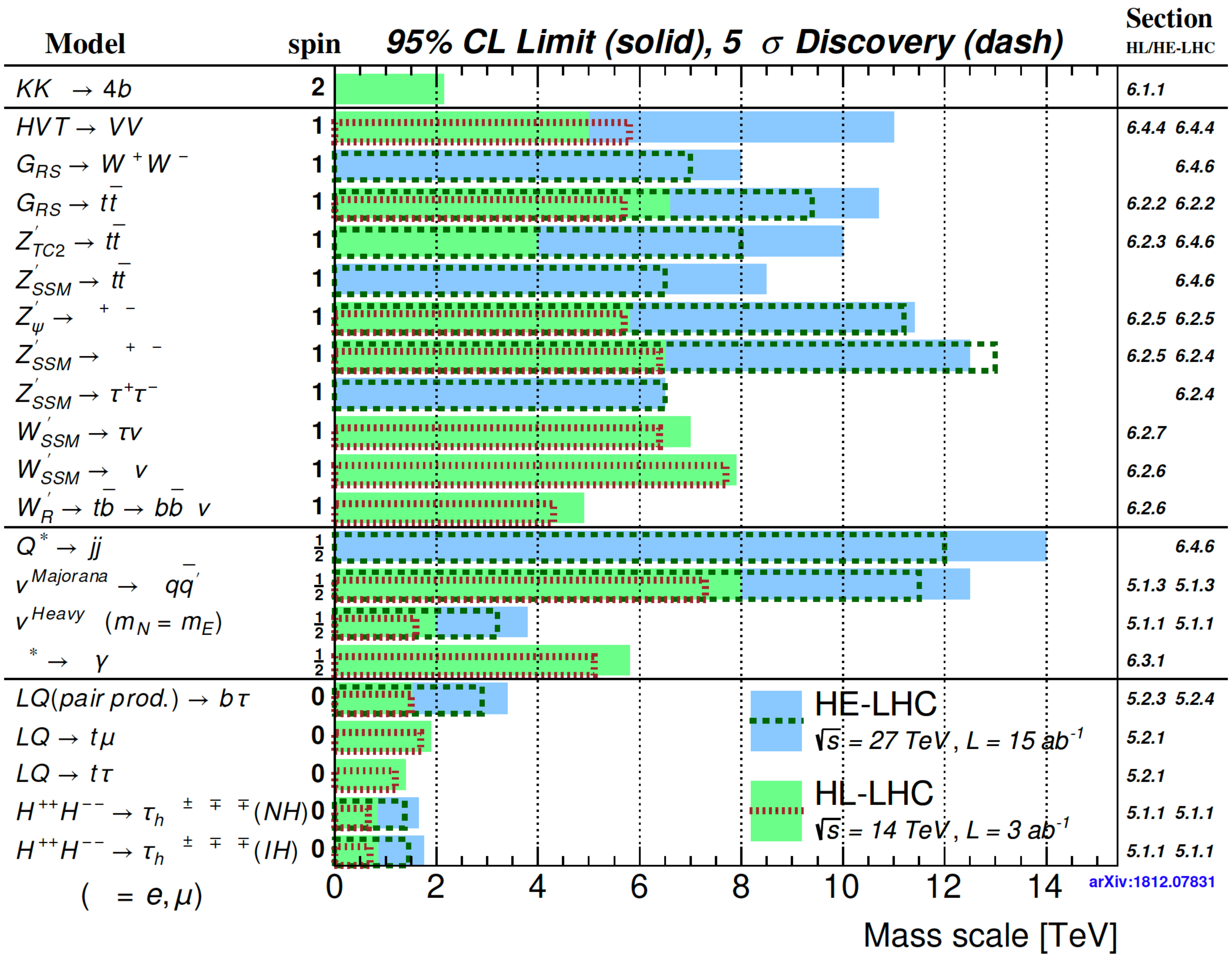
# Extra slides

# CMS Run2 exotic particles reach summary

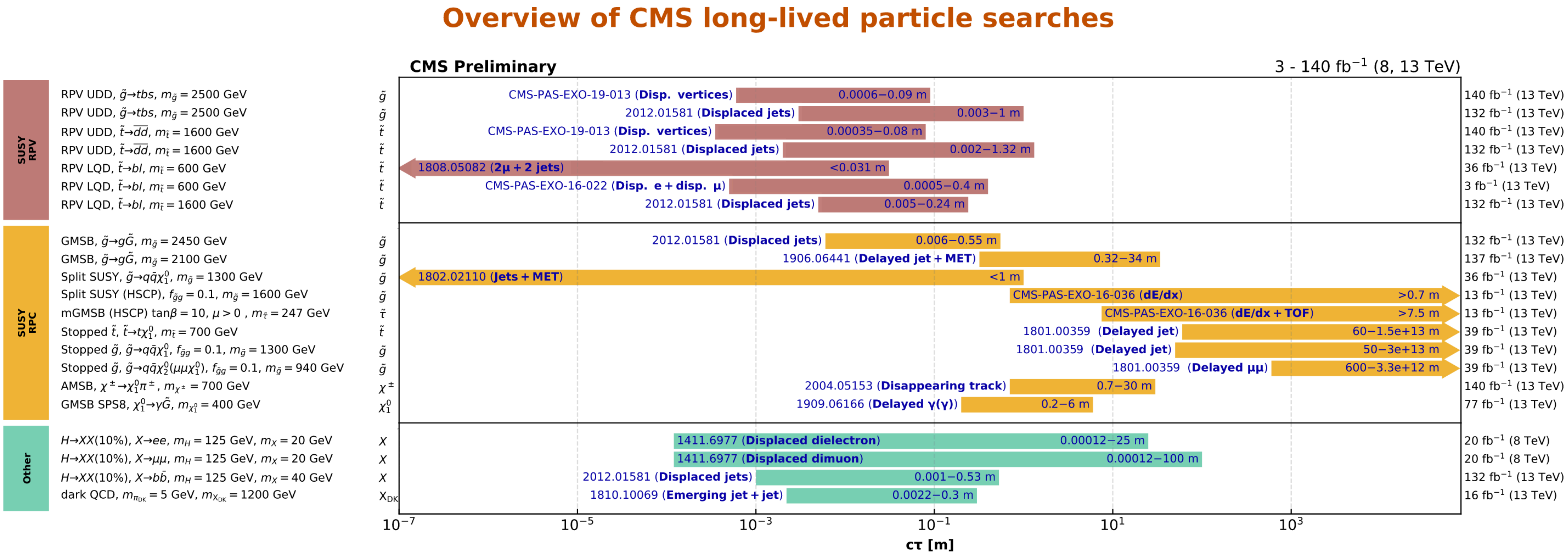


# HL-LHC exotic particles reach summary

CERN-LPCC-2018-005



# CMS Run2 long-lived particles reach summary




**Moriond 2021**

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

# HL-LHC SUSY reach summary

CERN-LPCC-2018-005