# Future Physics Prospects with the CMS Detector at the High-Luminosity LHC

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On behalf of the CMS Collaboration

DIS 2021
12-16 April 2021

# Outline

- HL-LHC and planned CMS Detector Upgrades
- Heavy-Ion physics projections
- Higgs: couplings and di-Higgs production
- Top quark measurements
- Beyond SM searches: Dark matter; heavy resonances

# Intro to the HL-LHC

High-Luminosity LHC:

- Collision energy: 14 TeV
- Factor ~4-5 increase in instantaneous luminosity
- Benchmark scenario for most projections:
  3000 $fb^{-1}$ integrated luminosity

# HL-LHC (Phase 2) CMS Detector Upgrade

Technical proposal CERN-LHCC-2015-010 https://cds.cern.ch/record/2020886
Scope Document CERN-LHCC-2015-019 https://cds.cern.ch/record/2055167

## L1-Trigger/HLT/DAQ

https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193

- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

## Barrel Calorimeters

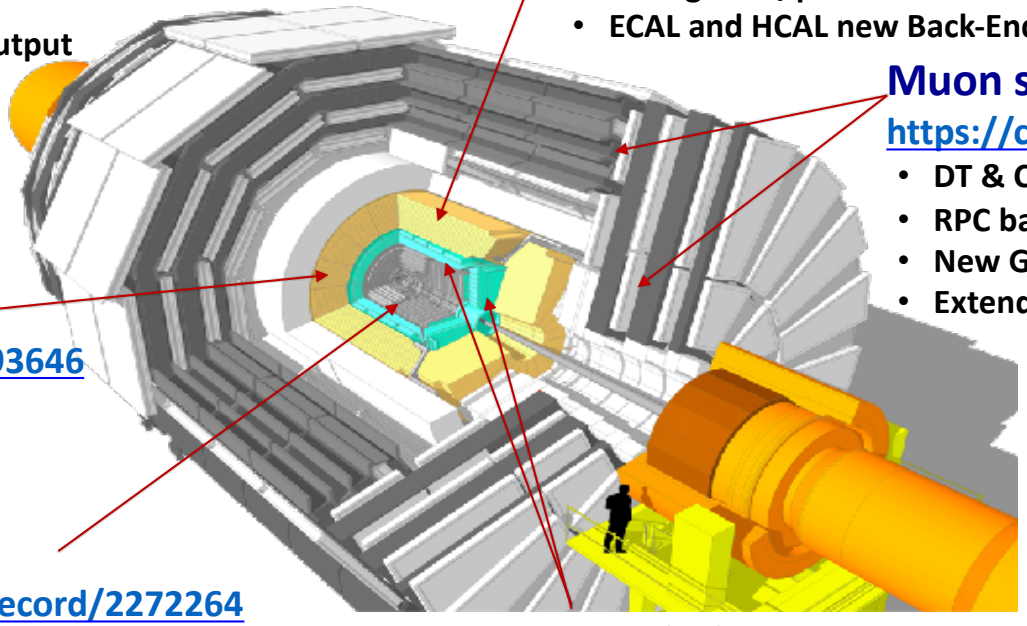
https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

## Muon systems

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



## Calorimeter Endcap

https://cds.cern.ch/record/2293646

- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

## Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure

https://cds.cern.ch/record/002706512

## Tracker https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

## MIP Timing Detector

https://cds.cern.ch/record/2296612

Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

**New paradigms (design/technology) for an HEP experiment to fully exploit HL-LHC luminosity**

# CMS Public HL-LHC Physics Projections

- Full list of CMS public HL-LHC physics projections:
- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/FTR/index.html

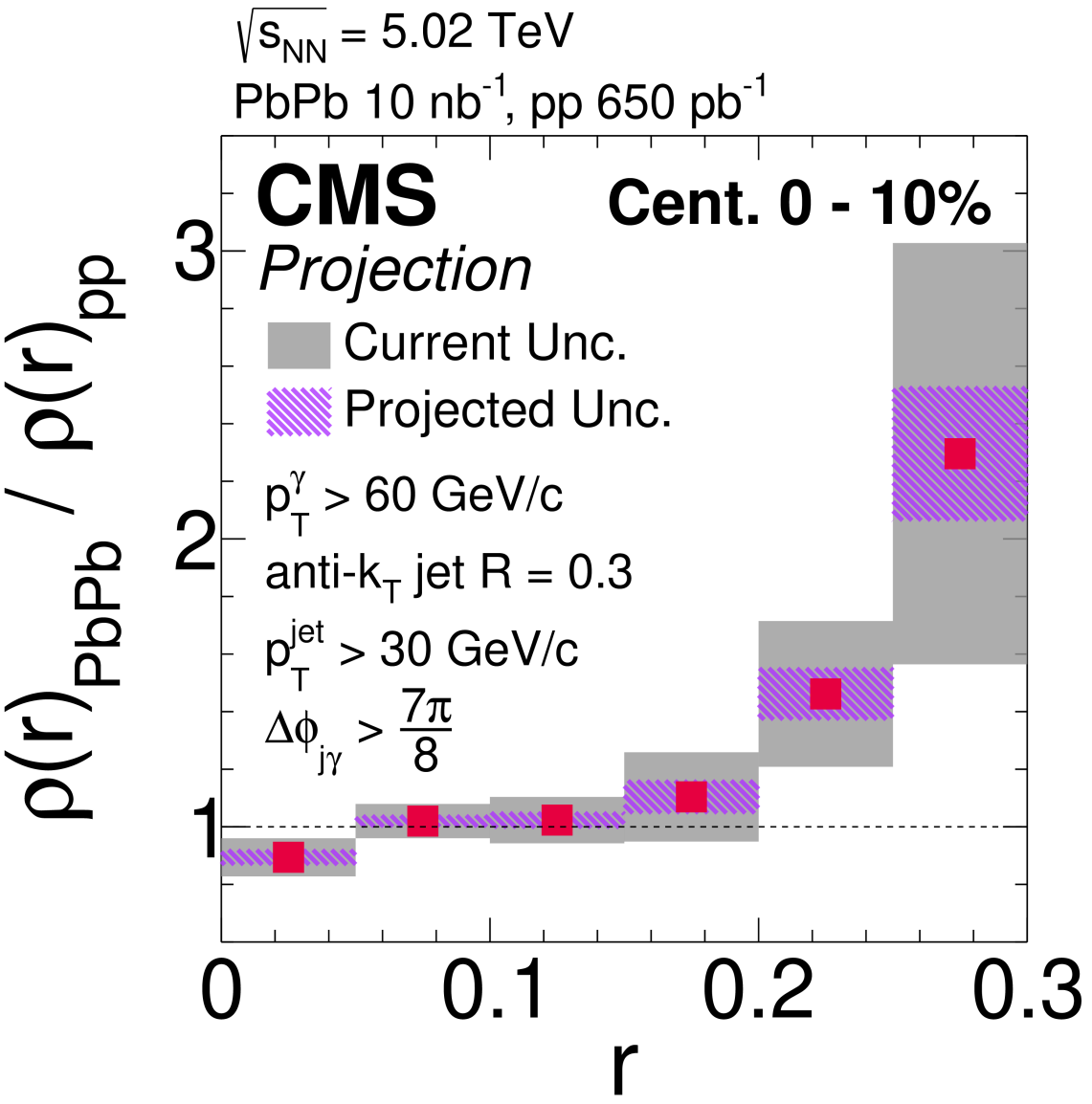
## Projected Physics Results

| | | | |
|---|---|---|---|
| CMS-PAS-FTR-18-040 | Search for a new scalar resonance decaying to a pair of Z bosons at the High-Luminosity LHC | | February 2019 |
| CMS-PAS-FTR-18-037 | HL-LHC searches for new physics in hadronic final states with boosted W bosons or top quarks using razor variables | | February 2019 |
| CMS-PAS-FTR-18-035 | Projection of searches for exotic Higgs boson decays to light pseudoscalars for the High-Luminosity LHC | | February 2019 |
| CMS-PAS-FTR-18-030 | Sensitivity study for a heavy gauge boson W' in the decay channel with a tau lepton and a neutrino at the High-Luminosity LHC | | February 2019 |
| CMS-PAS-FTR-18-019 | Prospects for HH measurements at the HL-LHC | | December 2018 |
| CMS-PAS-FTR-18-028 | Prospects for exclusion or discovery of a third generation leptoquark decaying into a $\tau$ lepton and a b quark with the upgraded CMS detector at the HL-LHC | | December 2018 |
| CMS-PAS-FTR-18-027 | Constraining nuclear parton distributions with heavy ion collisions at the HL-LHC with the CMS experiment | | December 2018 |
| CMS-PAS-FTR-18-036 | Anomalous couplings in the ttZ final state at the HL-LHC | | December 2018 |
| CMS-PAS-FTR-18-029 | Search for excited leptons in $\ell\ell\gamma$ final states in proton-proton collisions at the HL-LHC | | December 2018 |
| CMS-PAS-FTR-18-025 | Performance of jet quenching measurements in pp and PbPb collisions with CMS at the HL-LHC | | December 2018 |

# Heavy-Ions at HL-LHC

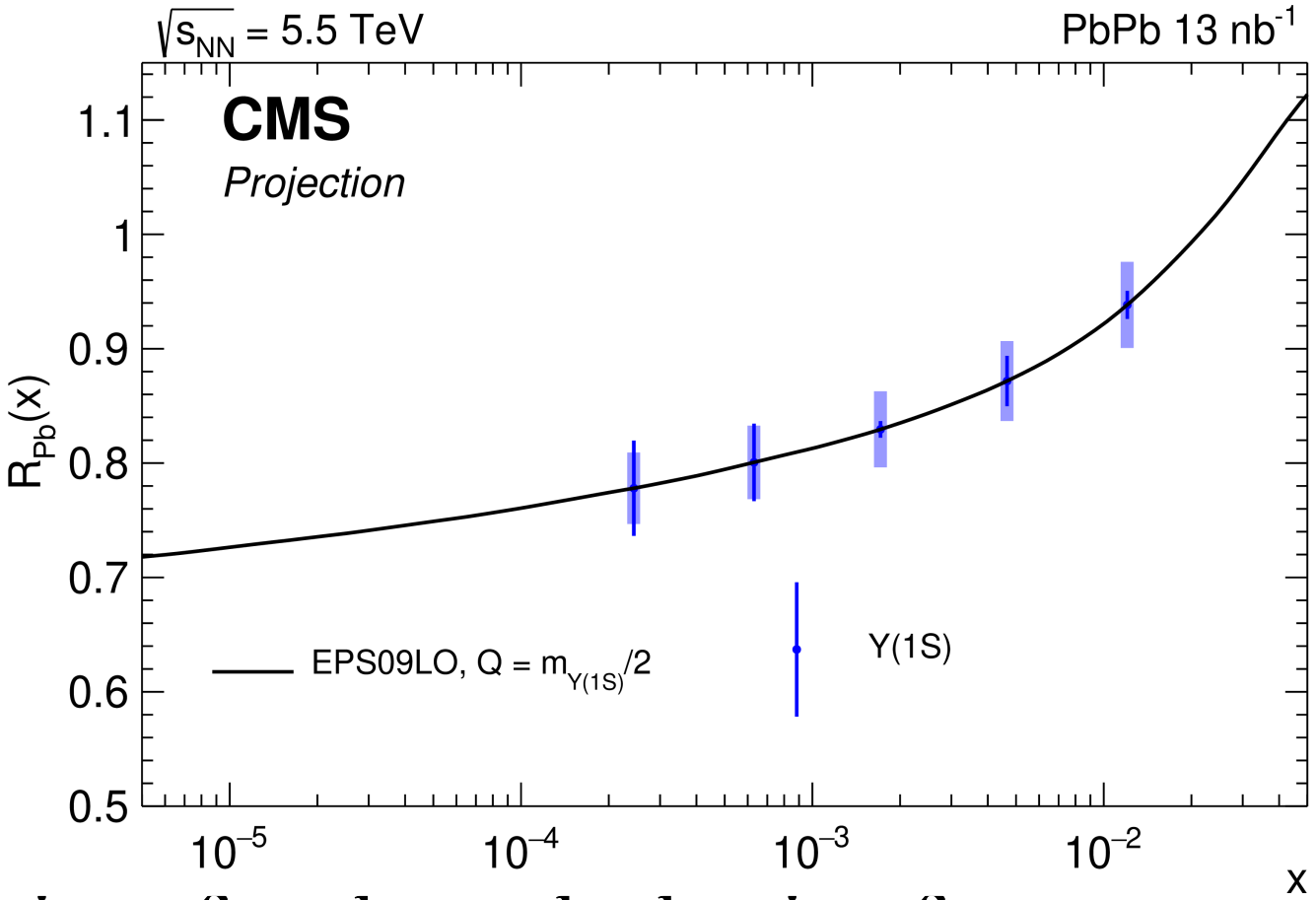
- LHC experiments have requested an integrated luminosity of about 10–13 $nb^{-1}$ and 2 $pb^{-1}$ using lead-lead (PbPb) and proton-lead (pPb) data at nucleon-nucleon center-of-mass energies ($\sqrt{s_{NN}}$) of 5.5 and 8.8 TeV, respectively.
- Heavy-ion projections presented here:
  - Jet quenching
  - Constraining nuclear PDFs

# Heavy Ions – Jet Quenching Projections




- Ratio of the density of particles produced at a radius *r* in photon-tagged jets in PbPb (0-10% most central) and pp collisions.
- Significant reduction in uncertainty projected for HL-LHC (FTR-18-025)

# Constraining Nuclear PDFs at HL-LHC



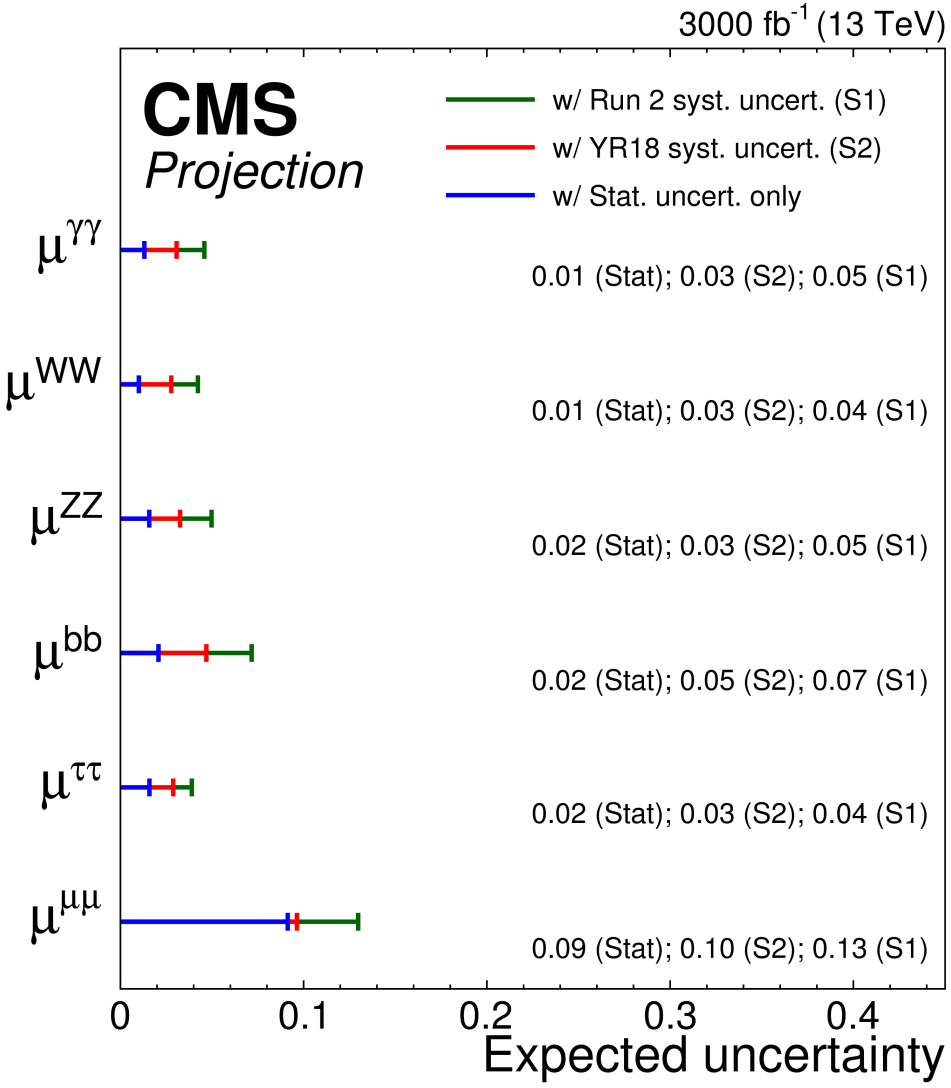

- Projections for gluon shadowing factor measured with Y(1S) photoproduction in ultraperipheral PbPb collisions at √sNN=5.5 TeV (FTR-18-027)
- HL-LHC will significantly extend Bjorken-x range probed

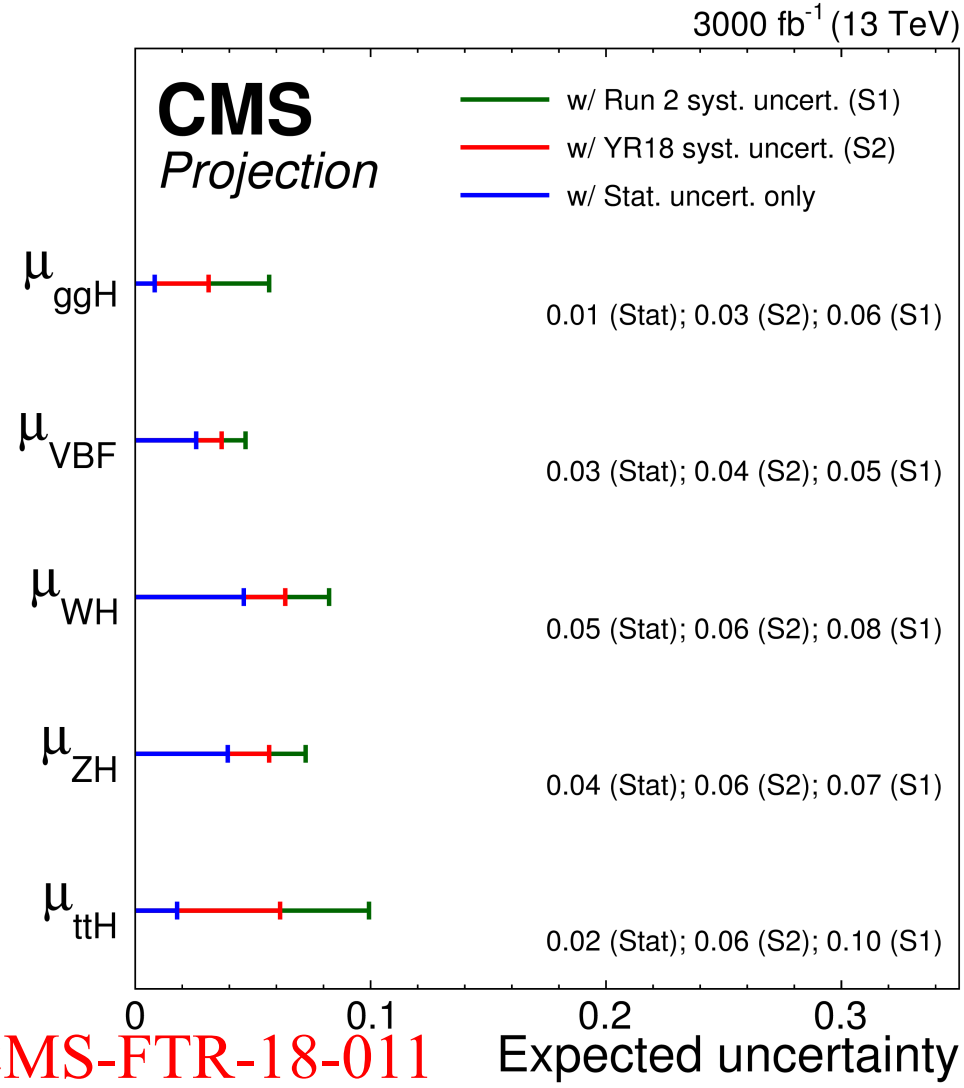
# Higgs at HL-LHC

- Projected sensitivity to Higgs coupling strength across decay channels
- Di Higgs production as direct probe of Higgs potential

- See dedicated “Prospects for Higgs Physics at the HL-LHC” talk by Corinne Mills for additional Higgs projections

# Higgs Coupling Sensitivity at HL-LHC




CMS-FTR-18-011

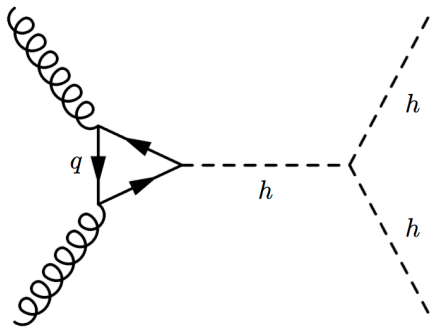
- Projected HL-LHC uncertainties on Higgs couplings and production modes, extrapolated from Run 2 results

# Testing the Higgs Potential with Di-Higgs

- SM Higgs potential fixed:

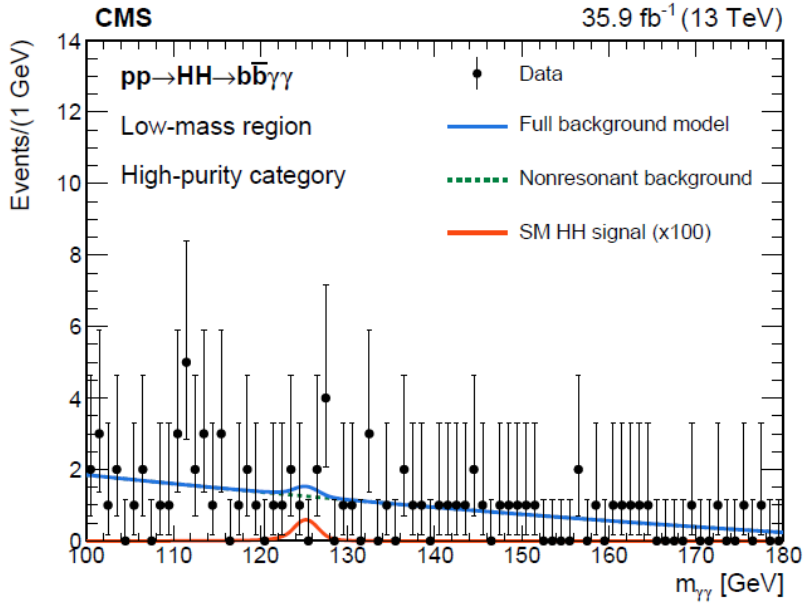
$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2.$$

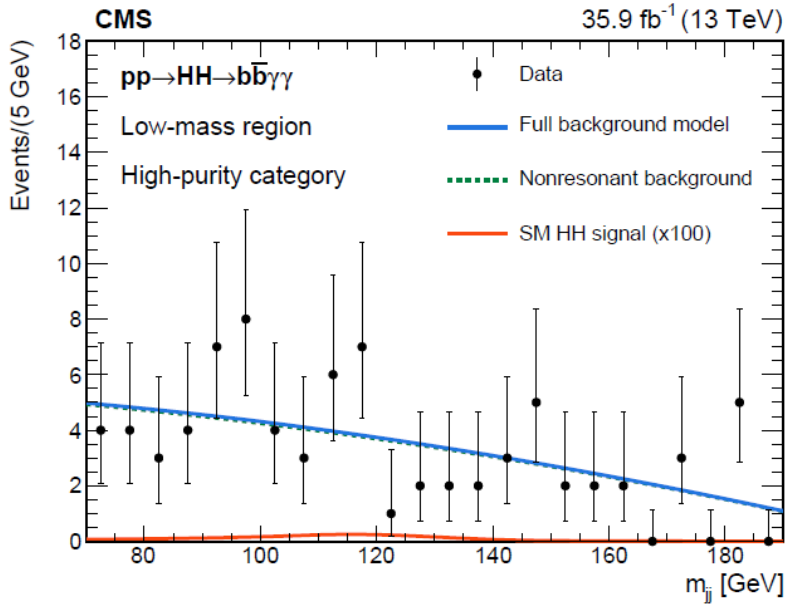
- Observation of Di-Higgs production can probe the Higgs self-coupling and test *actual* H potential




- Run 2 search for HH→(bb)(γγ) limit ~24x SM HH

CMS-HIG-17-008



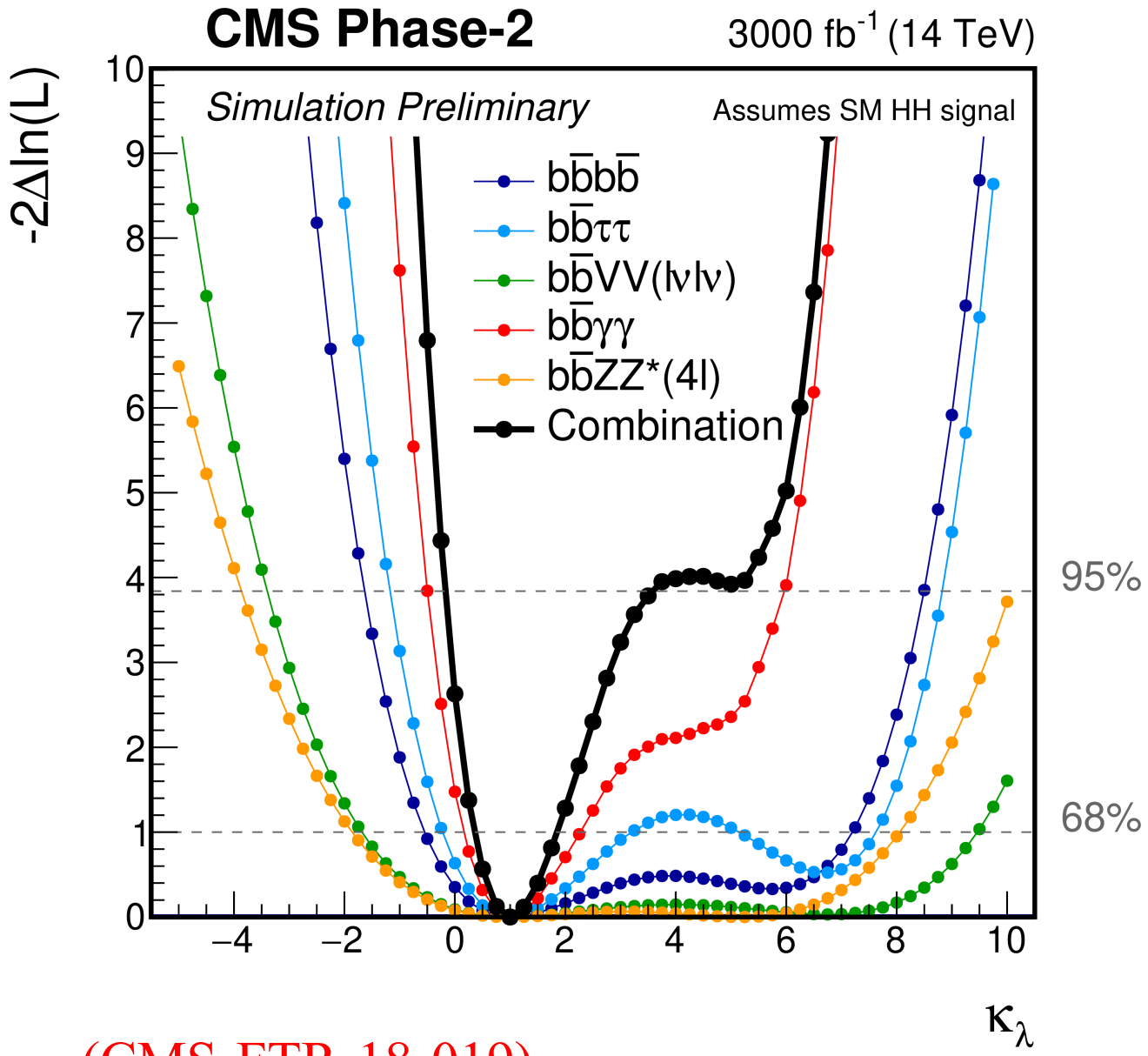



# Di-Higgs HL-LHC CMS Projection

- For di-H at HL-LHC, CMS projects combination of channels to yield 2.6 sigma significance for SM HH process (CMS FTR-18-019)

| Channel | Significance | | 95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$ | |
|---|---|---|---|---|
| | Stat. + syst. | Stat. only | Stat. + syst. | Stat. only |
| bbbb | 0.95 | 1.2 | 2.1 | 1.6 |
| bb$\tau\tau$ | 1.4 | 1.6 | 1.4 | 1.3 |
| bbWW($\ell\nu\ell\nu$) | 0.56 | 0.59 | 3.5 | 3.3 |
| bb$\gamma\gamma$ | 1.8 | 1.8 | 1.1 | 1.1 |
| bbZZ($\ell\ell\ell\ell$) | 0.37 | 0.37 | 6.6 | 6.5 |
| Combination | 2.6 | 2.8 | 0.77 | 0.71 |

# Di-Higgs HL-LHC CMS Projection




(CMS-FTR-18-019)

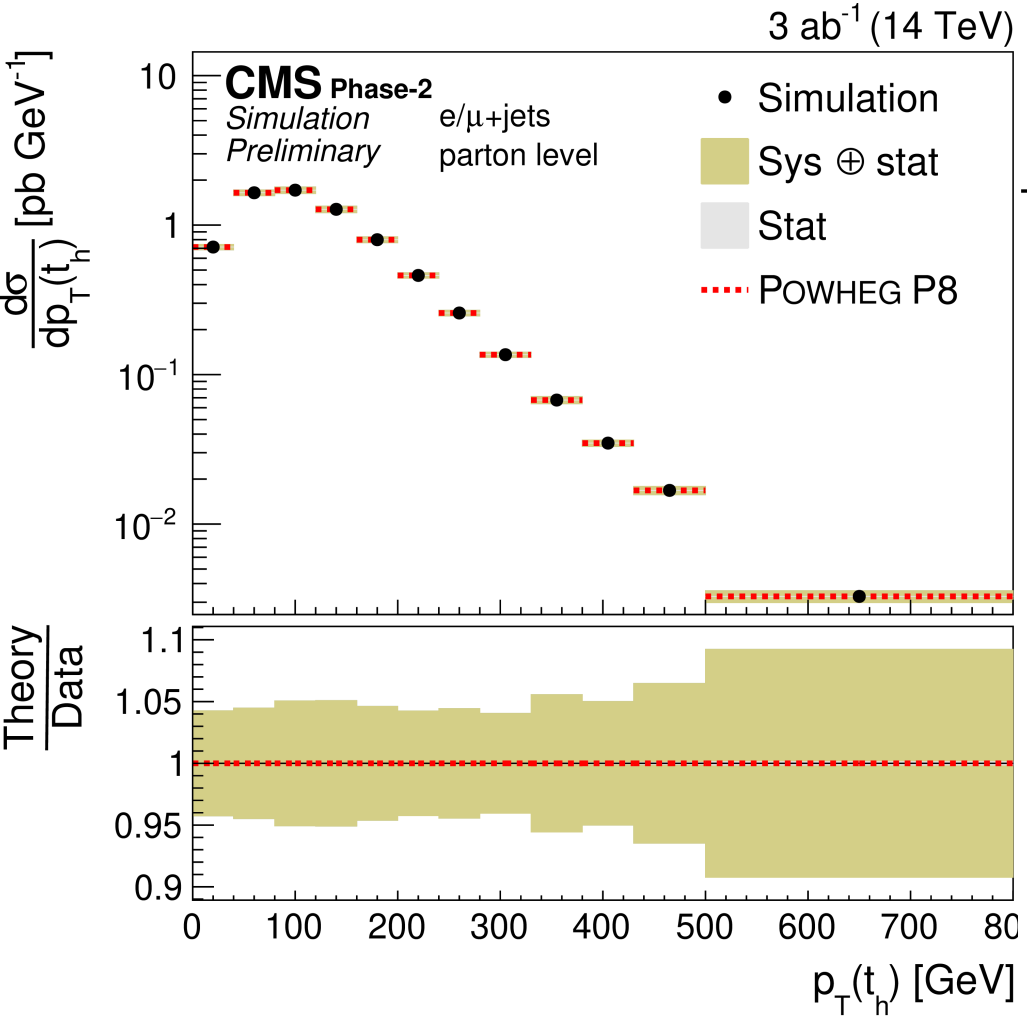
- From likelihood scan, expected 95% CL interval on coupling modifier $\kappa_\lambda$ (ratio relative to SM expectation) = [−0.18, 3.6]

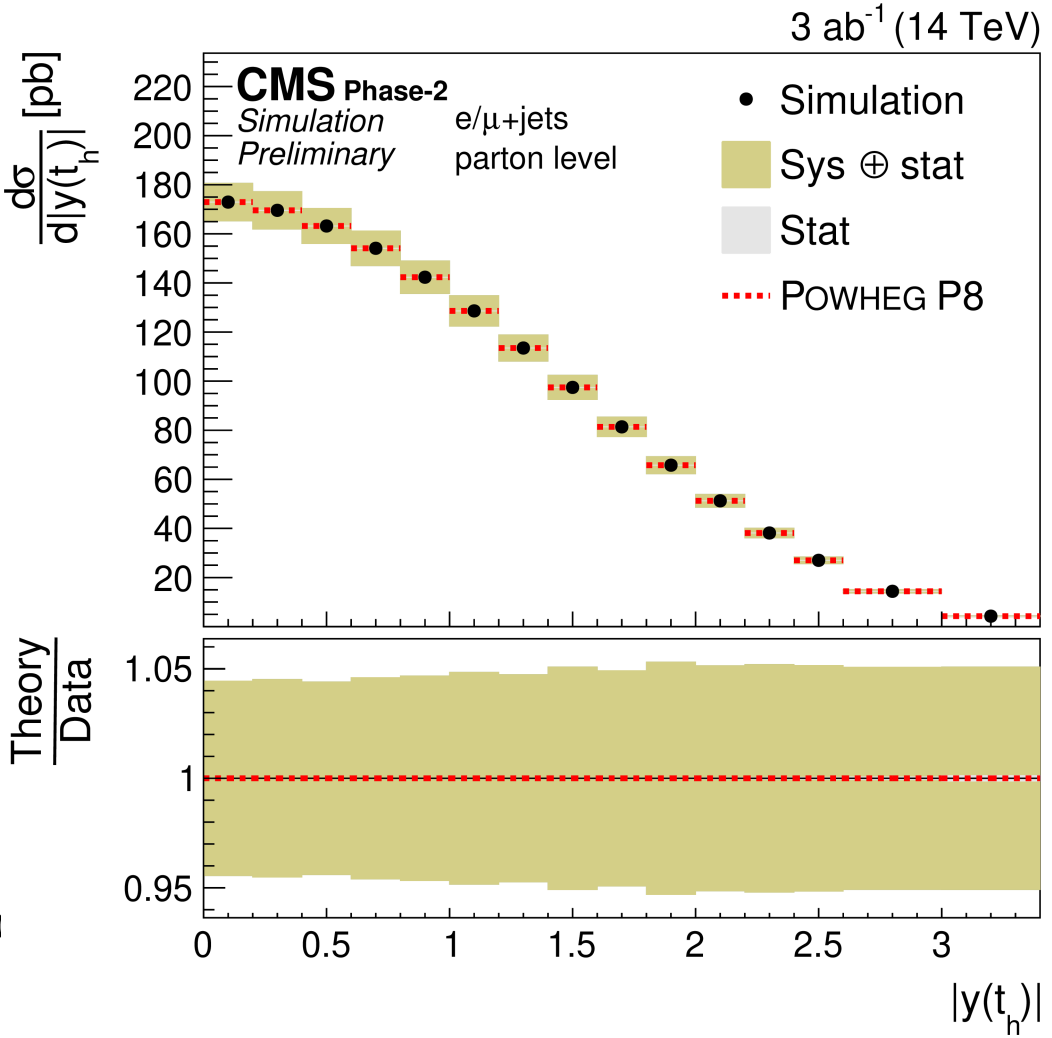
# Top Quark Measurements

Presented here:

- Top-antitop differential cross section projections
- Search for four tops

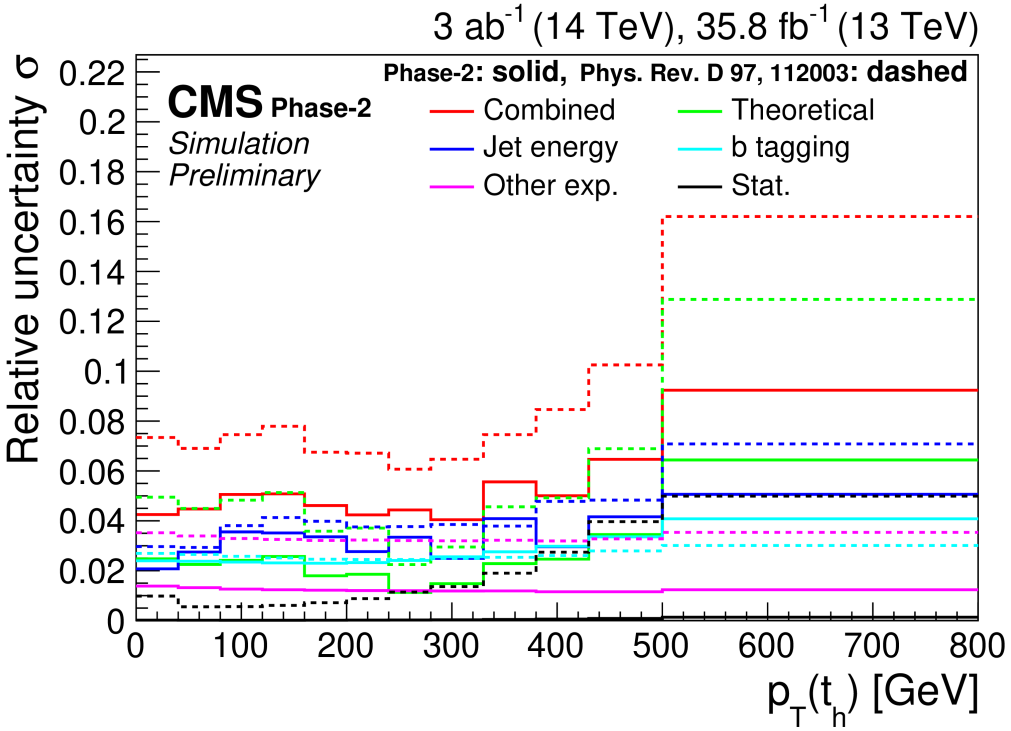
# $t\bar{t}$ Differential Cross sections

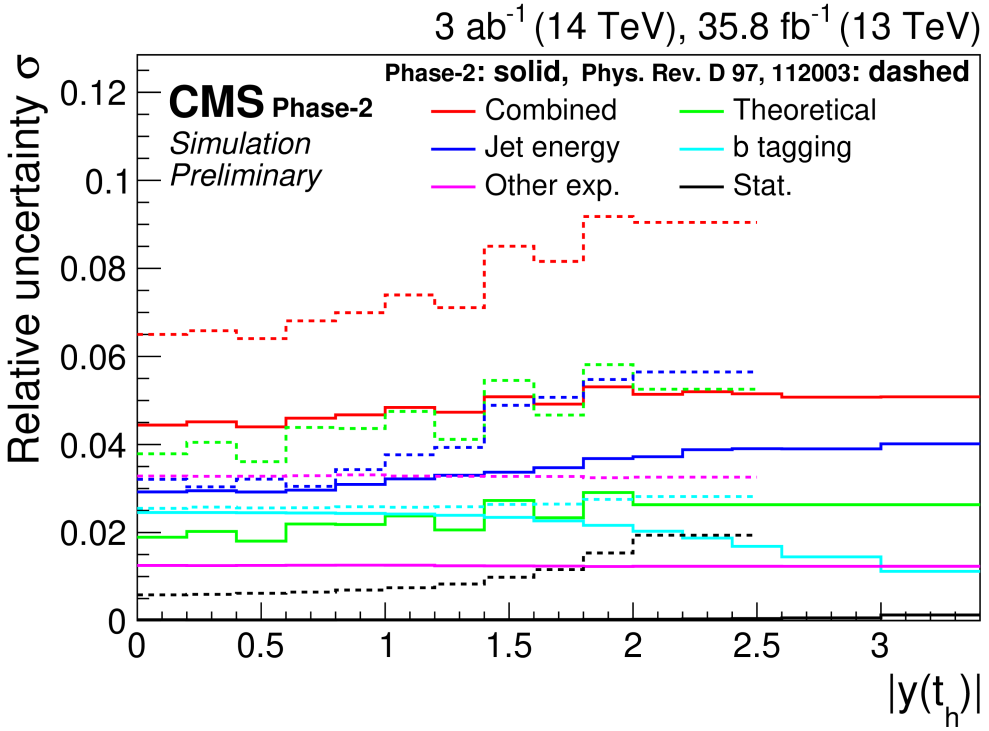



- $t\bar{t}$ differential cross sections as functions of $p_T$(top) and y(top) (CMS-FTR-18-015)

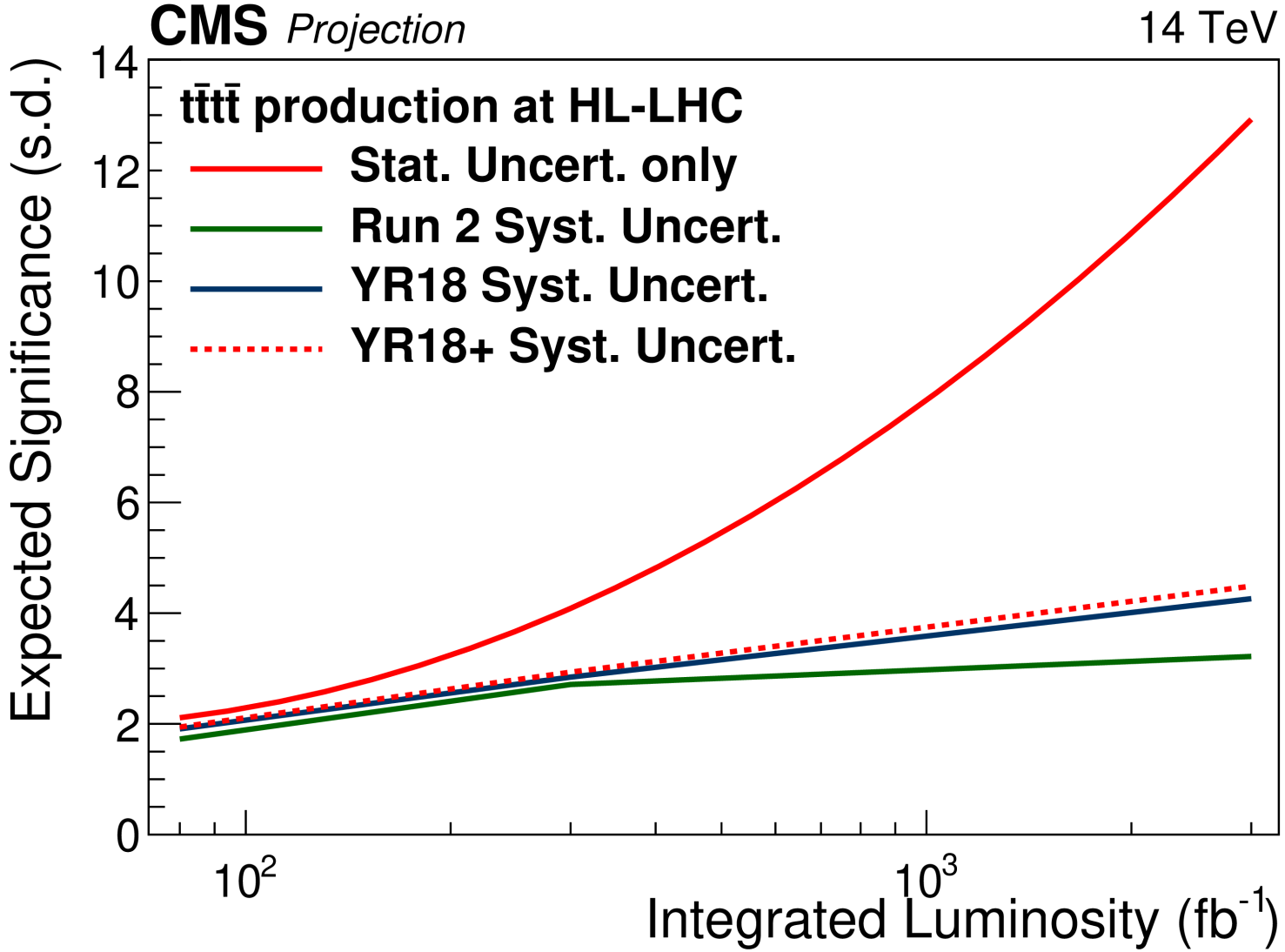
# $t\bar{t}$ Differential Cross sections - Uncertainty




- Relative uncertainty in $t\bar{t}$ differential cross sections for HL-LHC compared to 2016 dataset (CMS-FTR-18-015)
- Dashed Lines: 2016 dataset result
- Solid lines: HL-LHC projection

# Search for Four Tops (FTR-18-031)




- With 3000 $fb^{-1}$ at HL-LHC, the four top cross section can be constrained to 18-28%

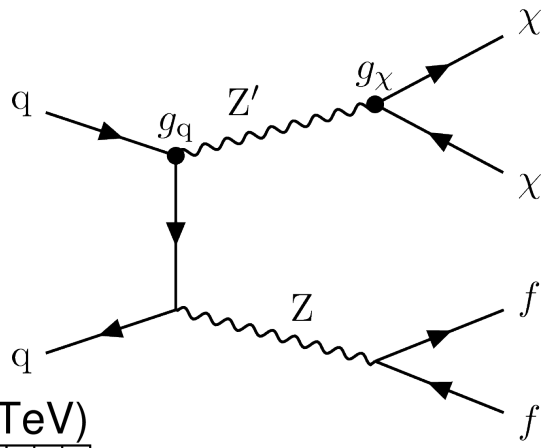
# Beyond-SM Search Projections

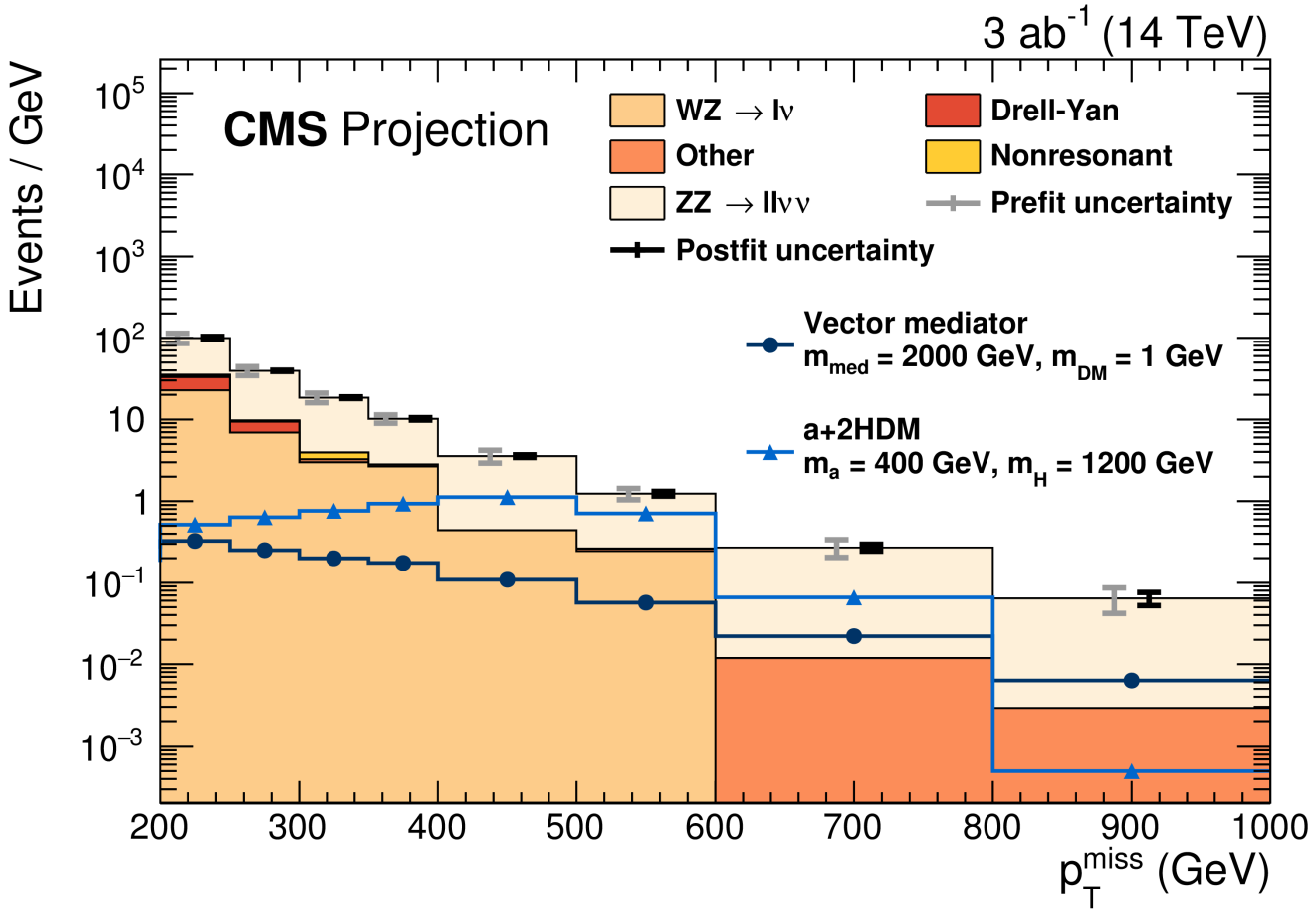
Projections for many BSM scenarios studied; presented here are:

- Dark Matter (in association with a Z boson)
- Heavy resonances decaying to:
  - ZZ
  - top pair

# Search for Dark Matter (FTR-18-007)

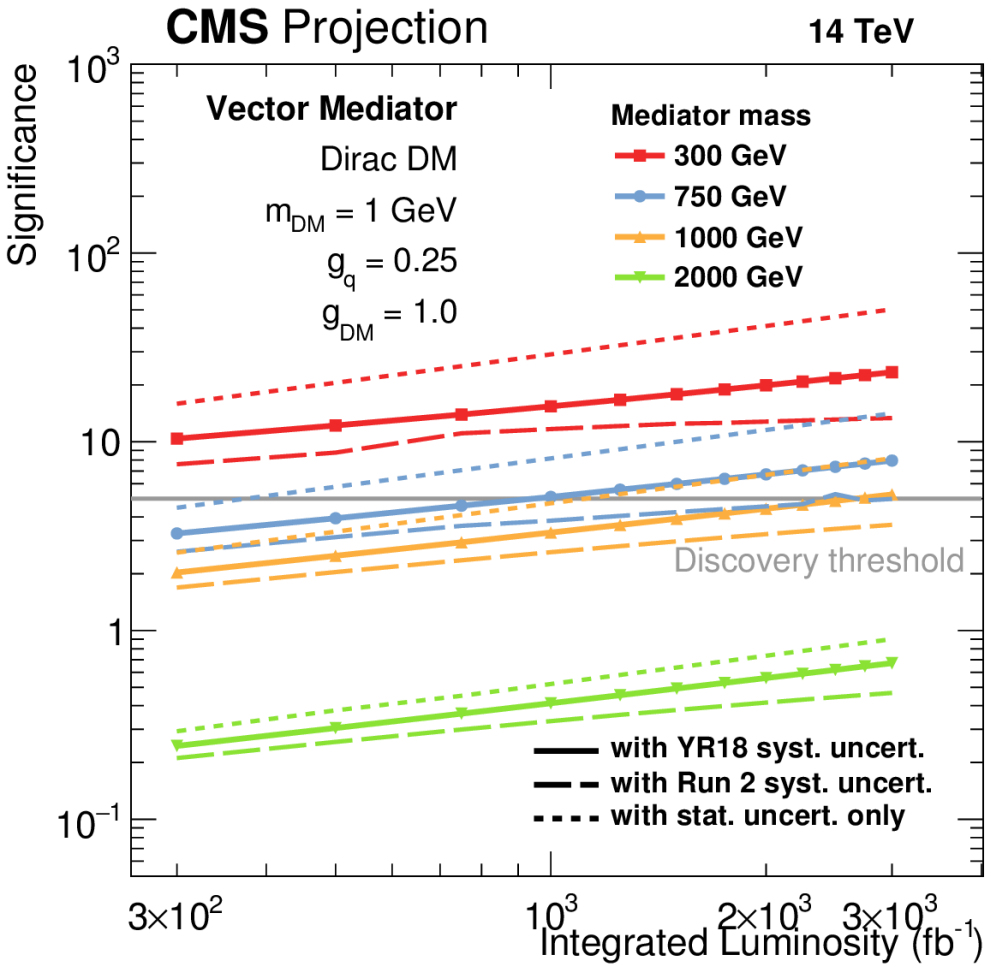
- Search for new invisible particles in events with Z boson and missing $p_T$

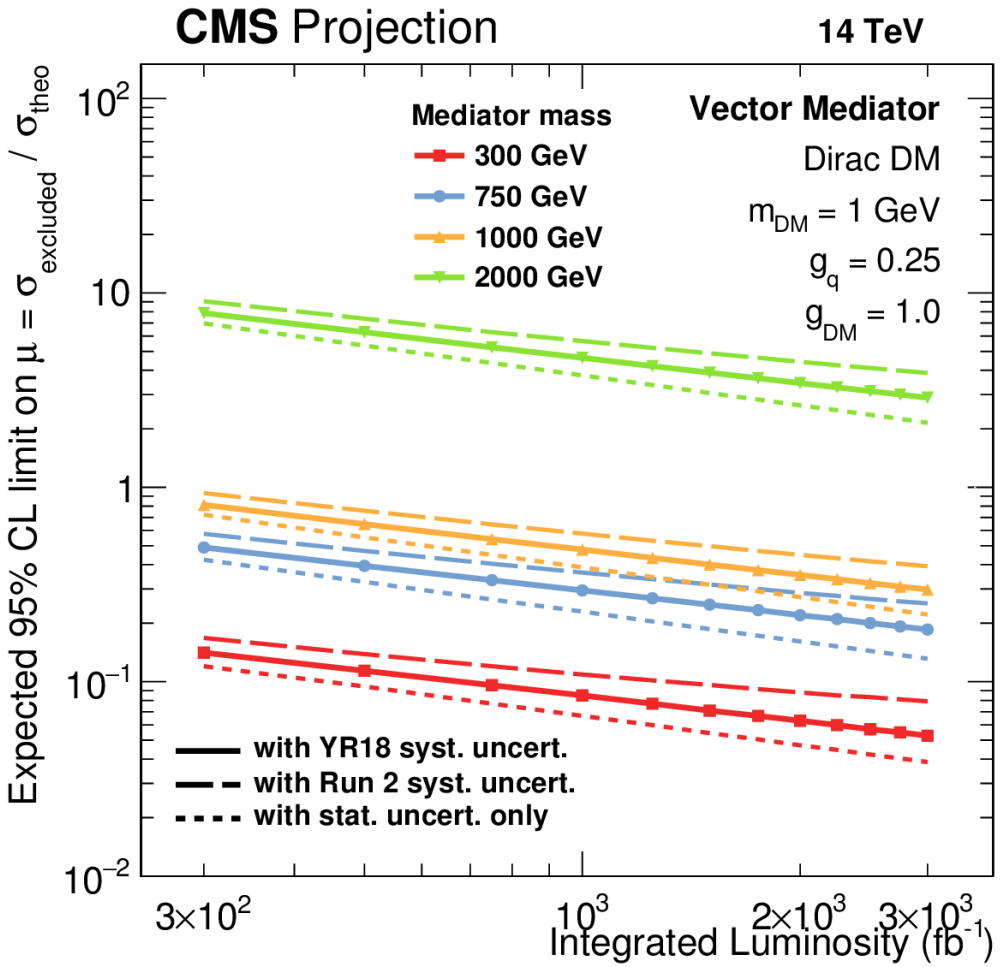


# Search for Dark Matter (FTR-18-007)

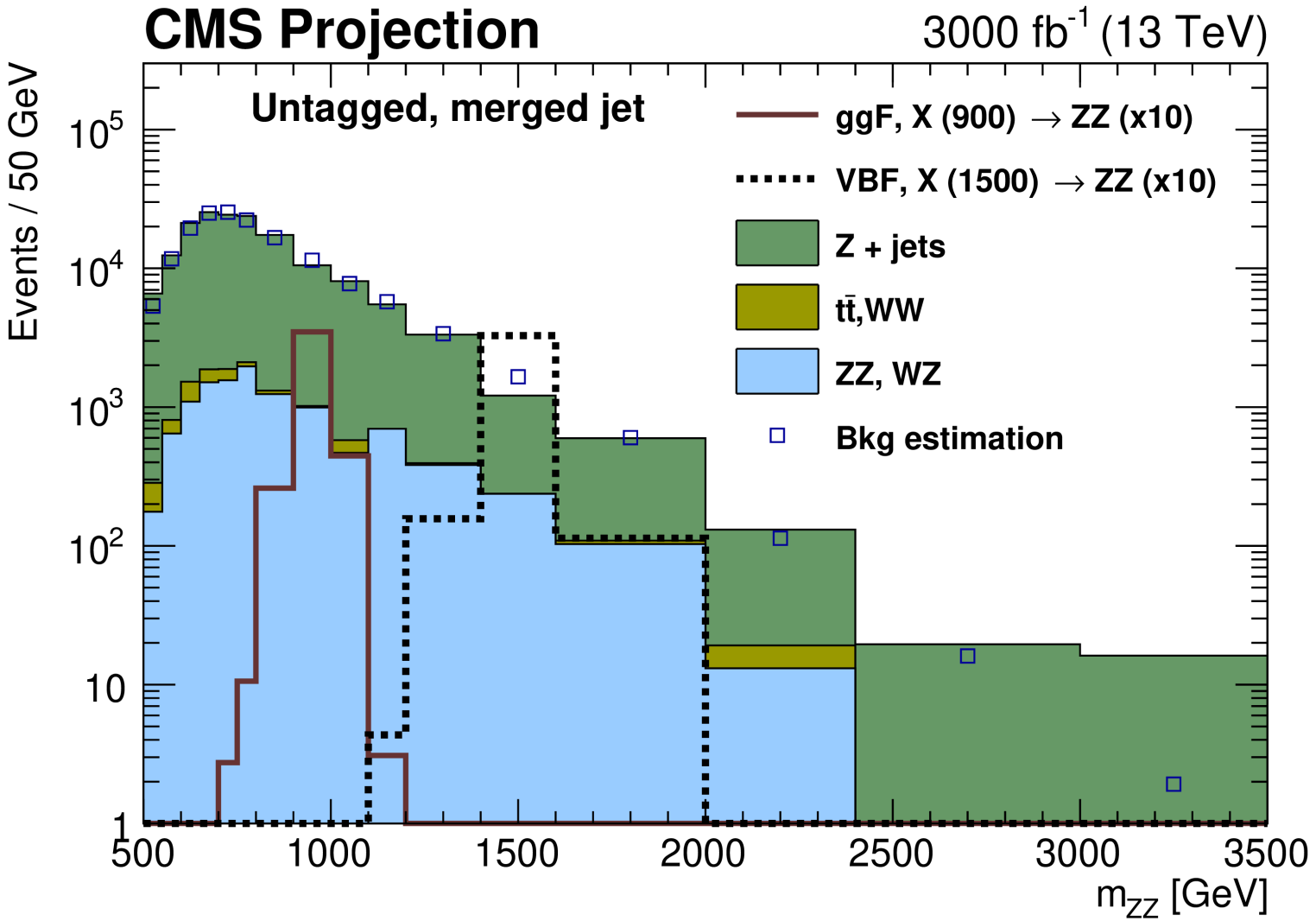
- Discovery significance and expected exclusion limits



# New Scalar → ZZ (CMS FTR-18-040)

- Heavy scalar X → ZZ → 2l 2q
- Consider both merged and resolved jet categories

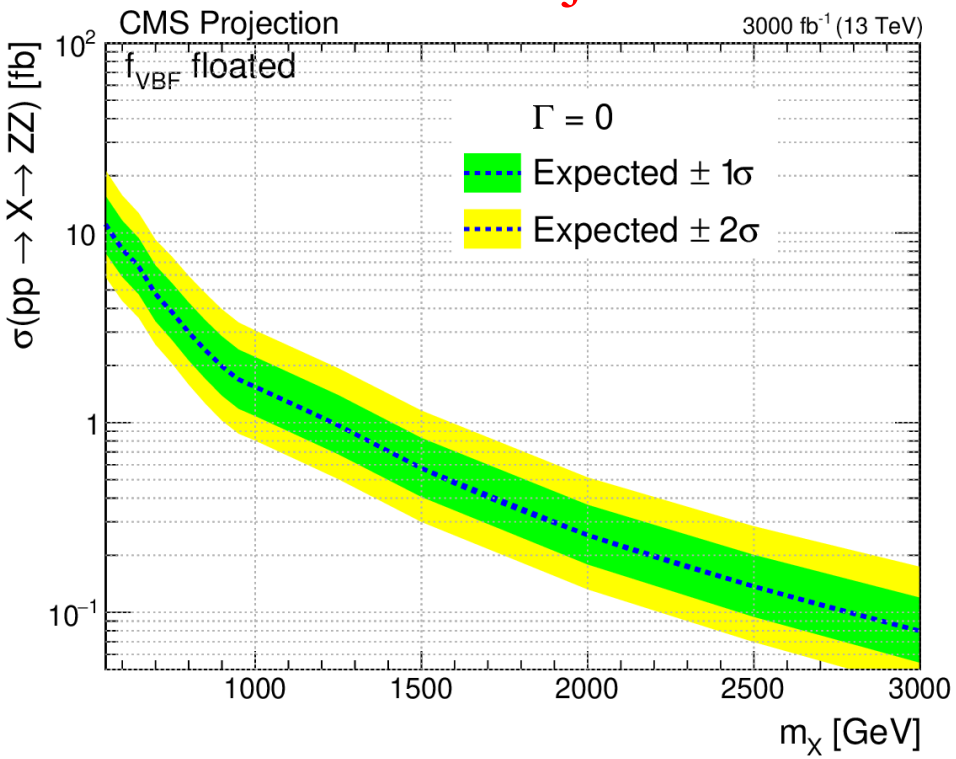



- Based on CMS 2016 result HIG-17-012: arXiv 1804.01939, JHEP 06 (2018) 127

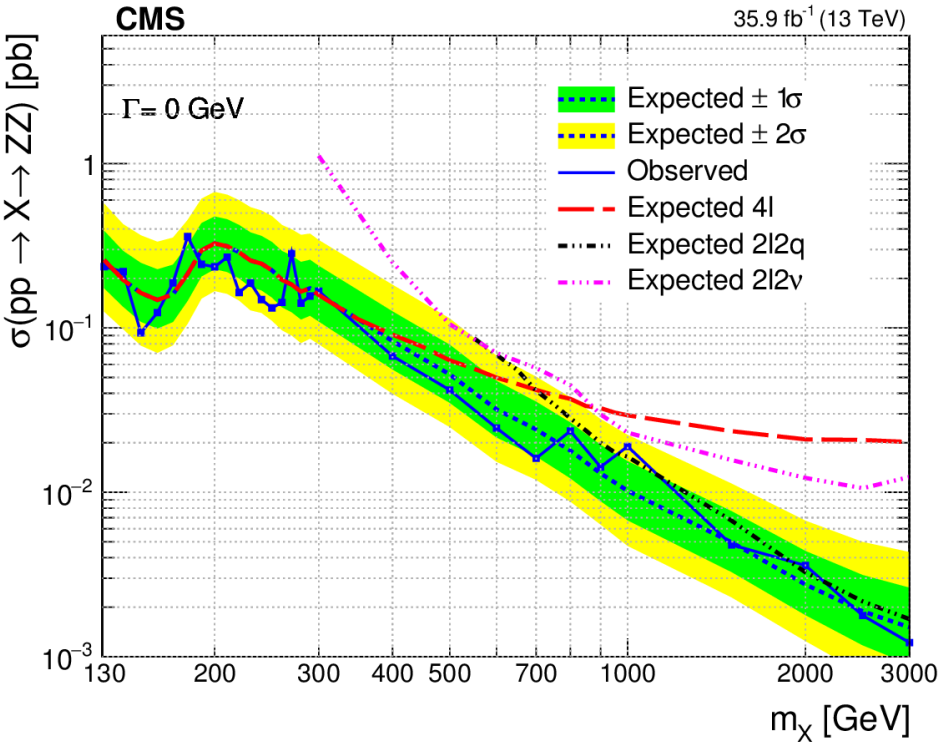
# New Scalar → ZZ (CMS FTR-18-040)

- Expected sensitivity:

HL-LHC Projection



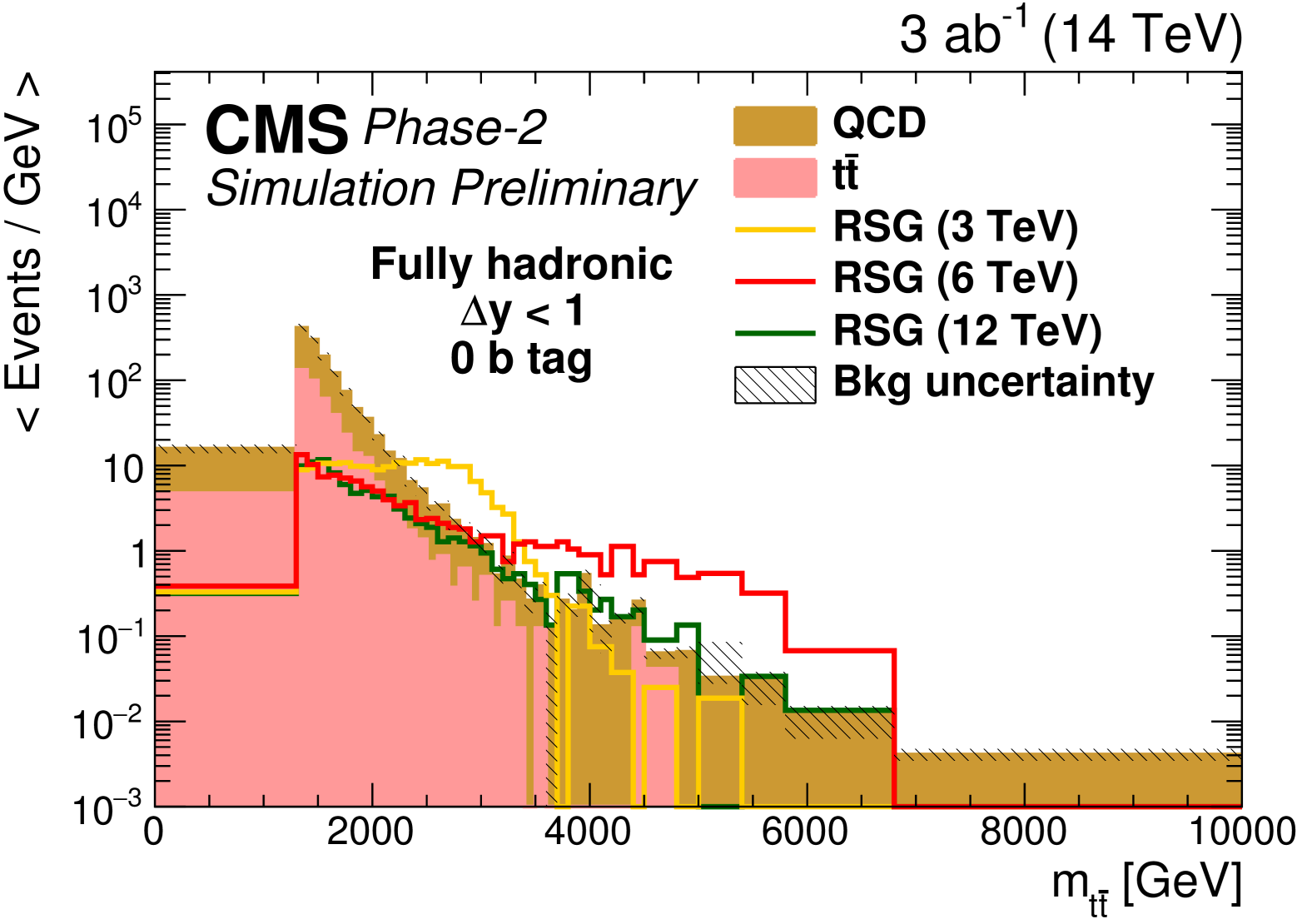

2016 Result




- CMS FTR-18-040: https://cds.cern.ch/record/2658263

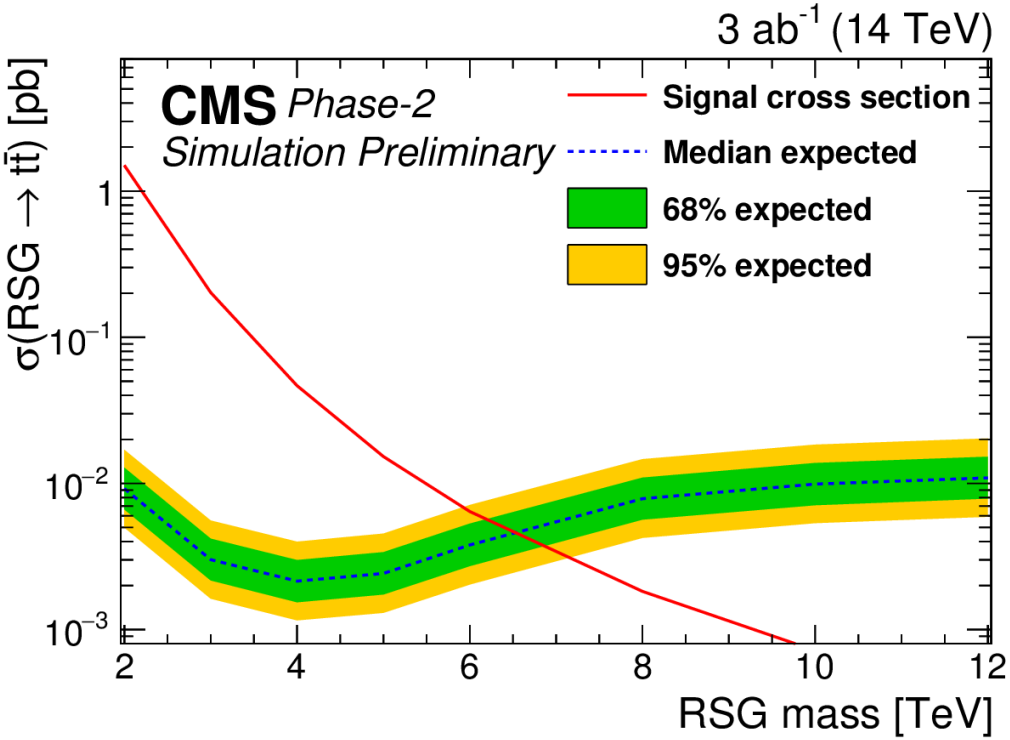
# Search for ttbar Resonance (RS Gluon)

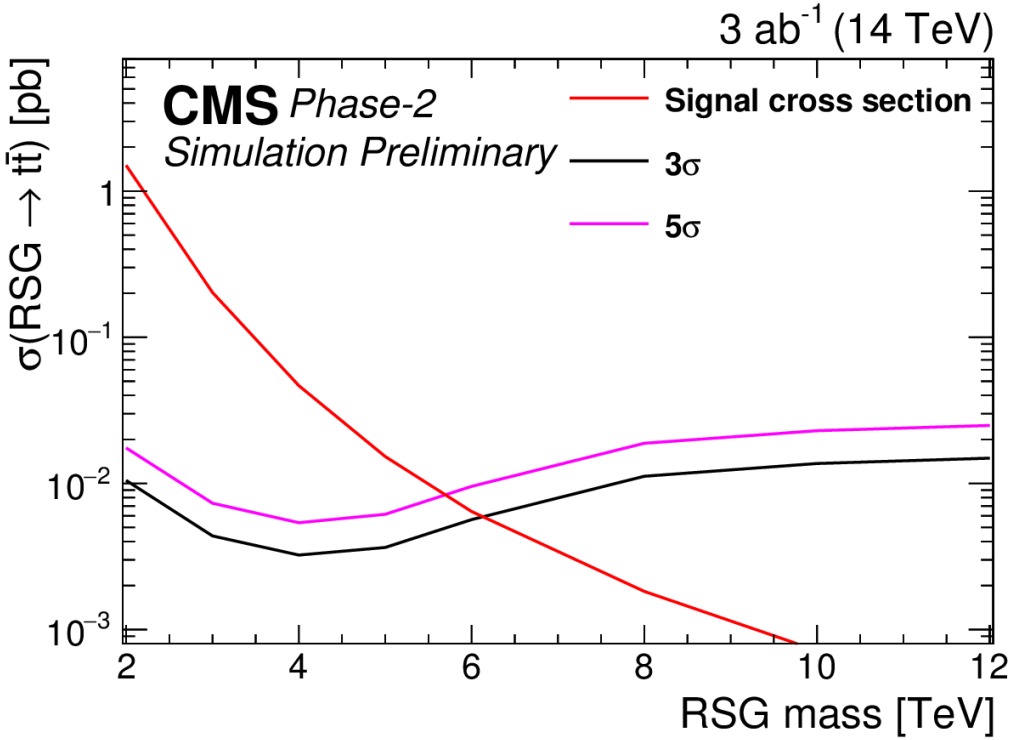
- Lepton+jets and fully-hadronic modes; b-tag categories



# Search for ttbar Resonance (RS Gluon)

- Projected exclusion and discovery potential:




- CMS FTR-18-009: https://cds.cern.ch/record/2649032

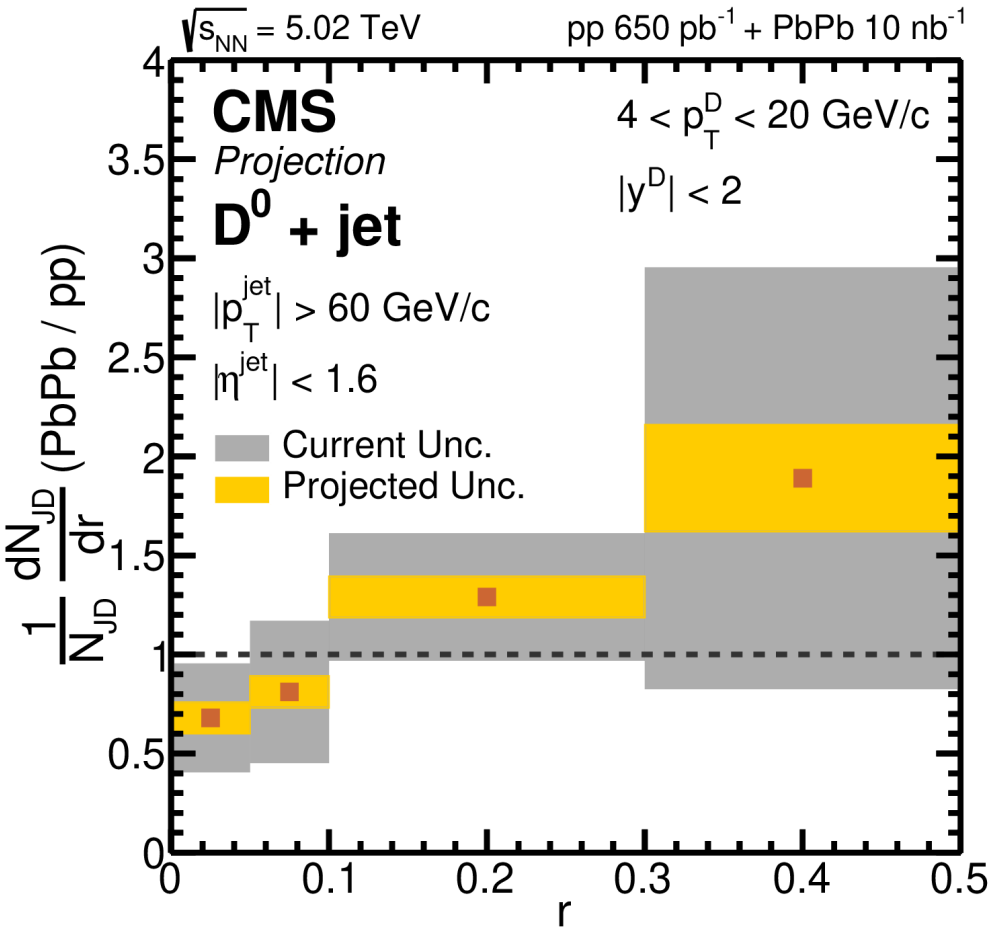
# Summary

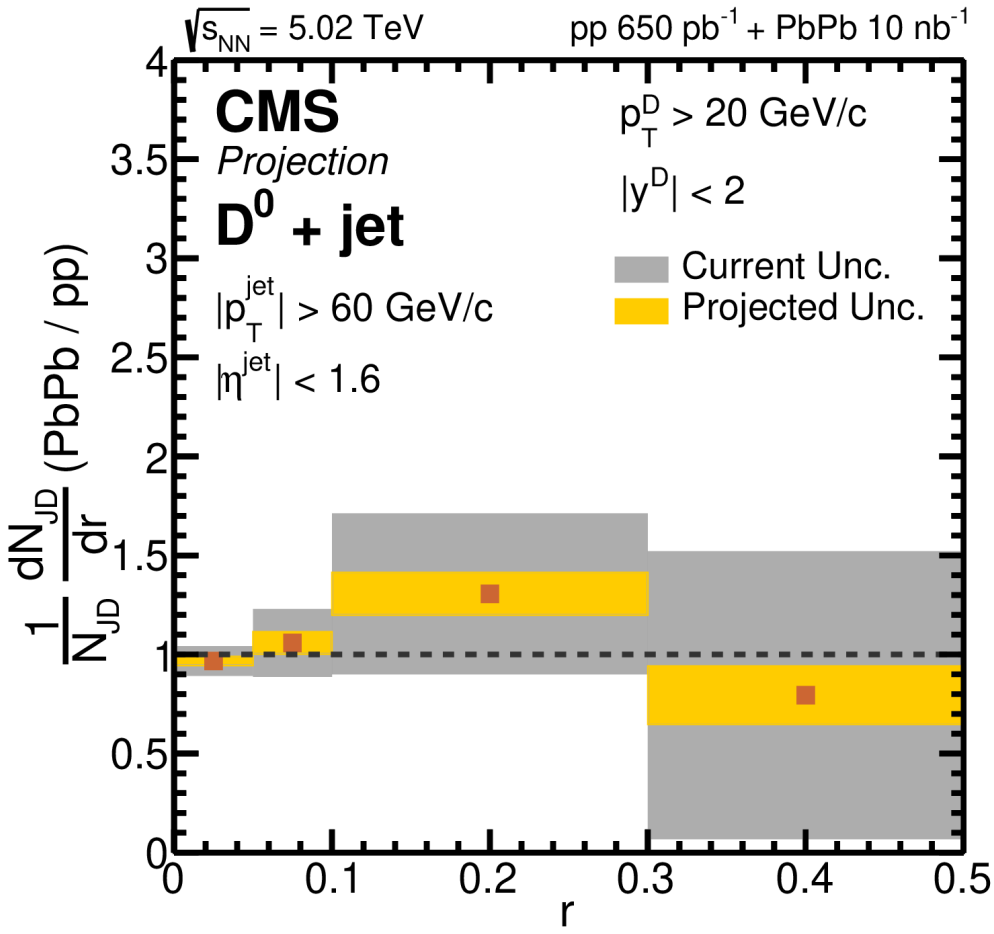
HL-LHC CMS physics projections shown for:

- Heavy-ions: jet quenching; nuclear PDF constraints
- Higgs: coupling strength precision; di-Higgs
- SM: ttbar differential cross section; four tops
- Beyond SM: Dark matter; ZZ and ttbar resonances
- All public CMS HL-LHC physics projections:
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/FTR/index.html

# Backup

# Heavy Ions – Jet Quenching Projections

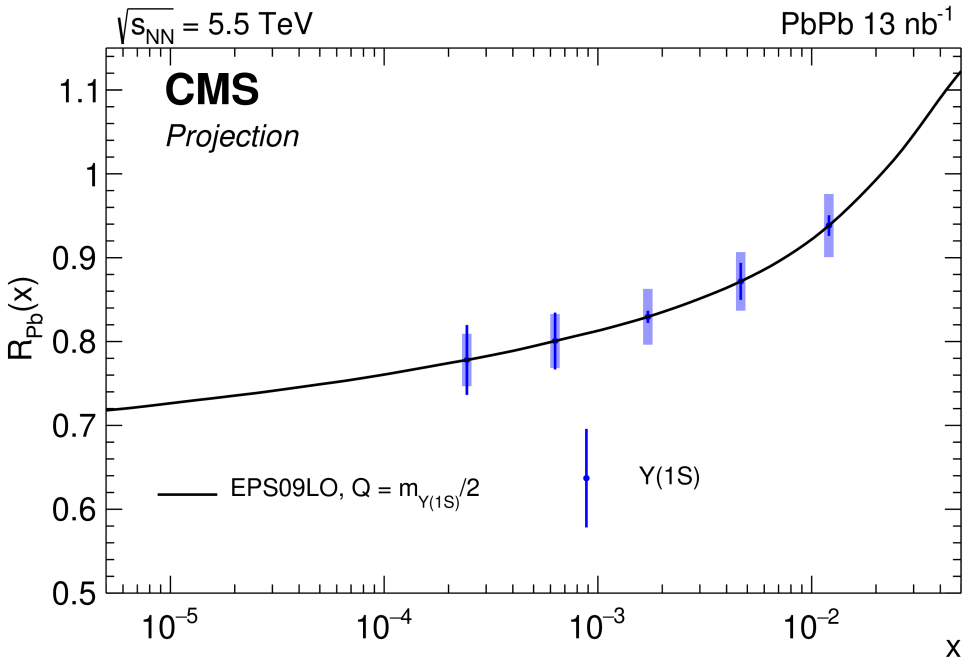



- Ratios for PbPb over pp collisions of the radial distributions of D0 mesons within jets, as a function of their distance *r* from the jet axis

# Constraining Nuclear PDFs at HL-LHC

- Photoproduction cross section of vector mesons proportional to squared gluon density
- By comparing results of photoproduction cross section in both γ+Pb and γ+p, can extract information about the nuclear gluon density
- Measurements from Υ(1S) photoproduction will serve as important tests to theoretical models that can describe the J/ψ data

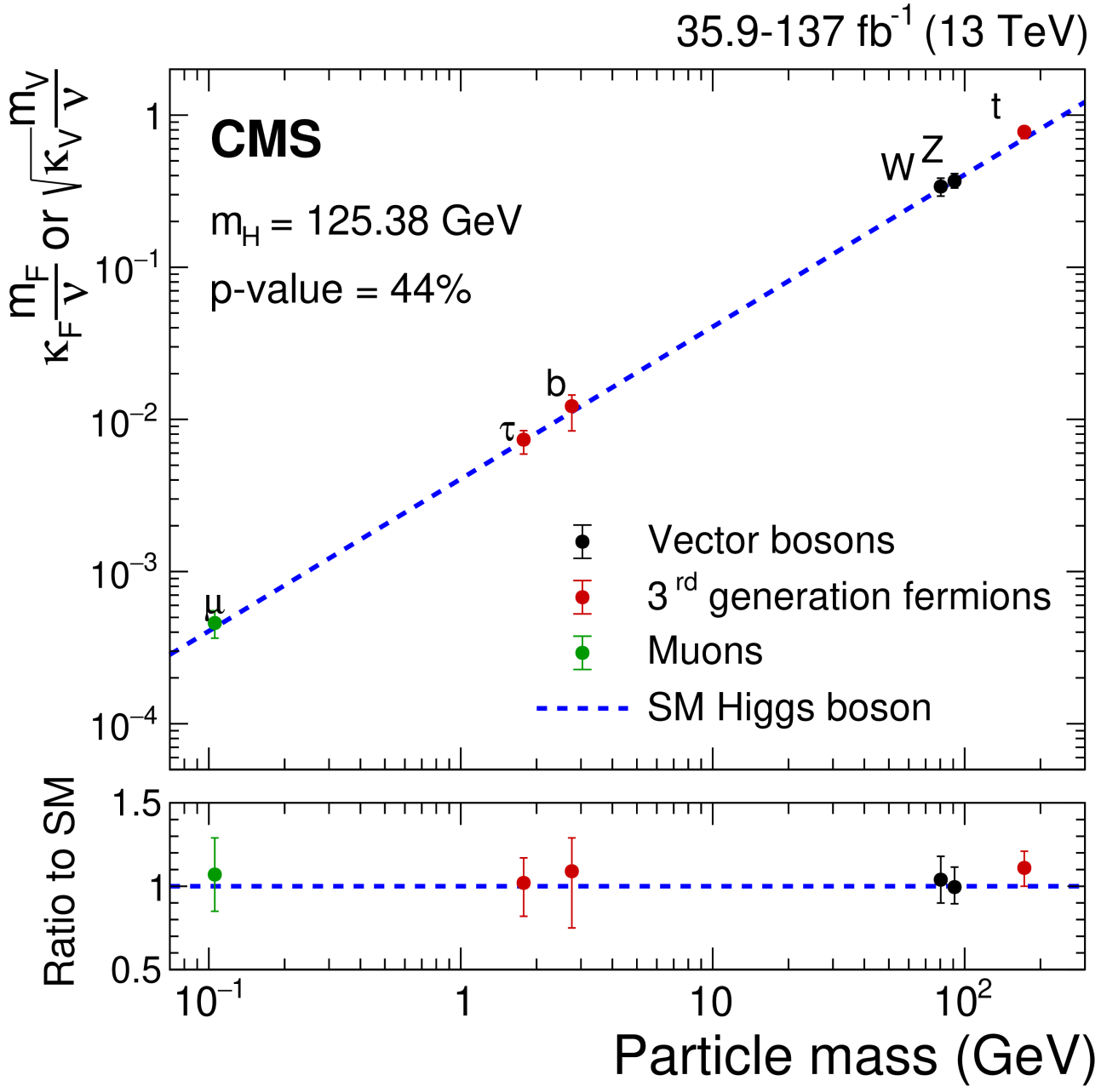



CMS FTR-18-027

$$R_{\mathrm{Pb}}(x) = \sqrt{\left(\frac{\sigma_{\gamma\mathrm{Pb}}(x)}{\sigma_{\mathrm{IA}}(x)}\right)}, \quad \text{where} \quad x = \frac{m_{\mathrm{V}}}{\sqrt{s_{\mathrm{NN}}}}\exp(-y). \qquad (1)$$

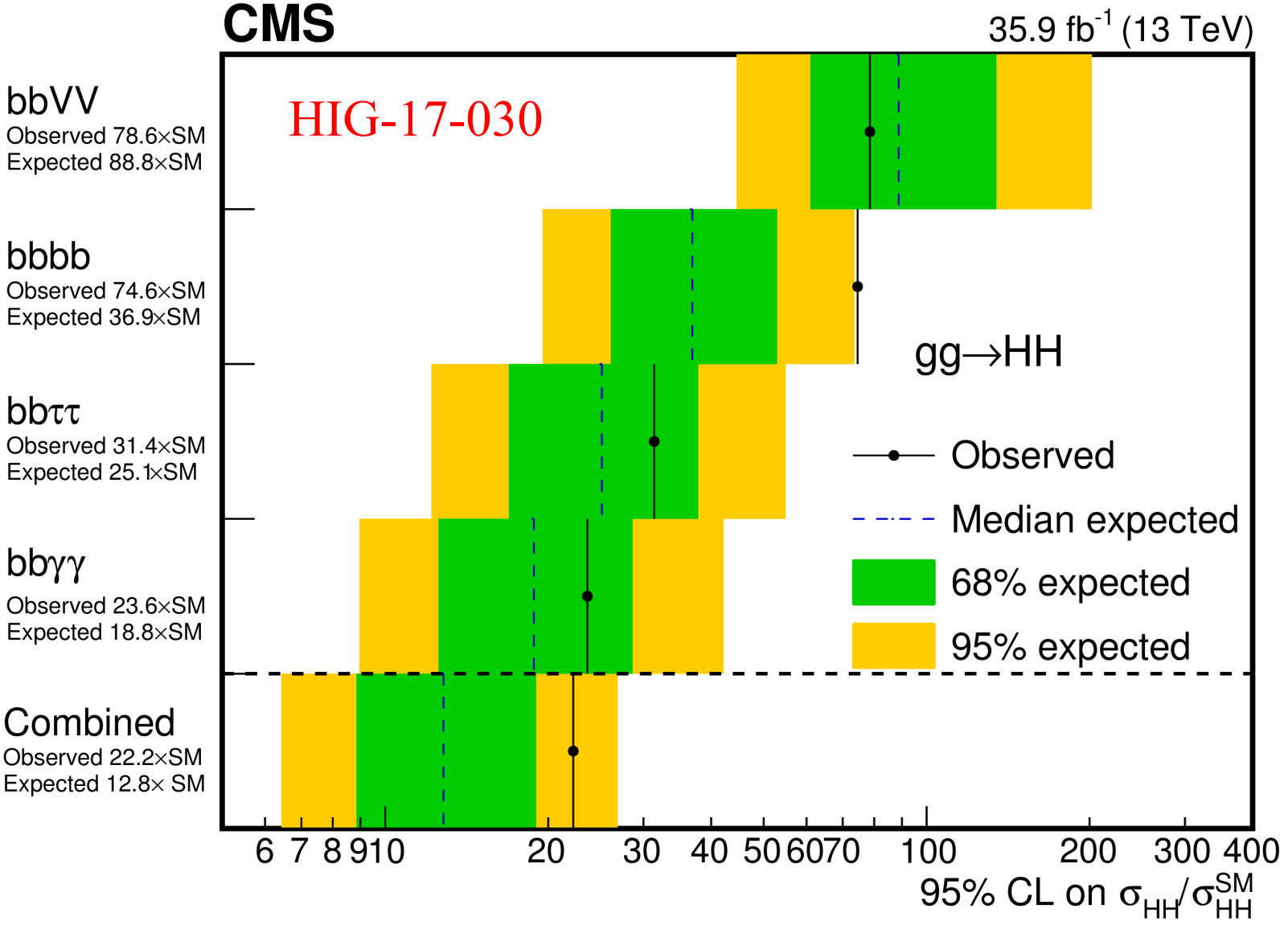
The Impulse Approximation is computed using data from the photoproduction of the vector meson in $\gamma + \mathrm{p}$ scaled by the integral over the squared Pb form factor as described in [22]. The impulse approximation calculation neglects all nuclear effects such as the expected modification of the gluon density in the lead nuclei compared to that of the proton. A recent CMS study of coherent $J/\psi$ photoproduction has followed this procedure to estimate the nuclear gluon shadowing as reported in [14].

# Higgs Coupling Results from Run 2

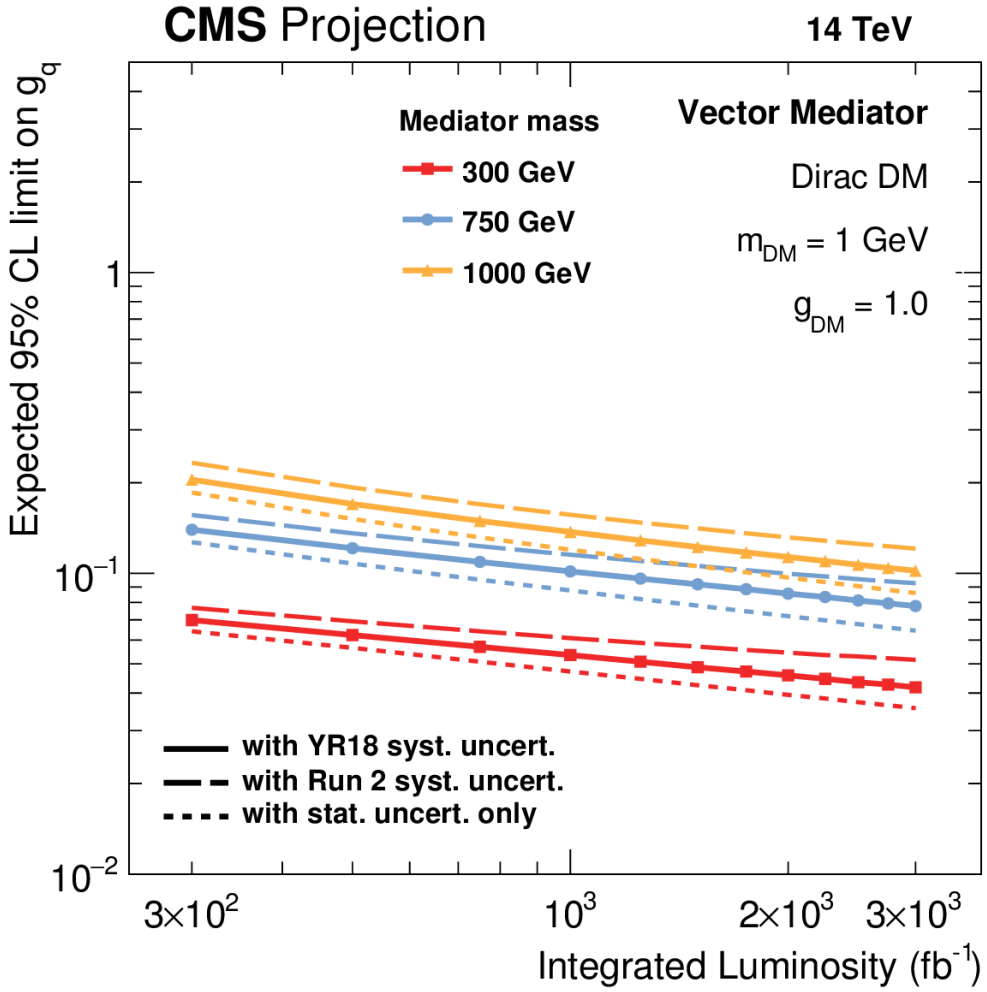


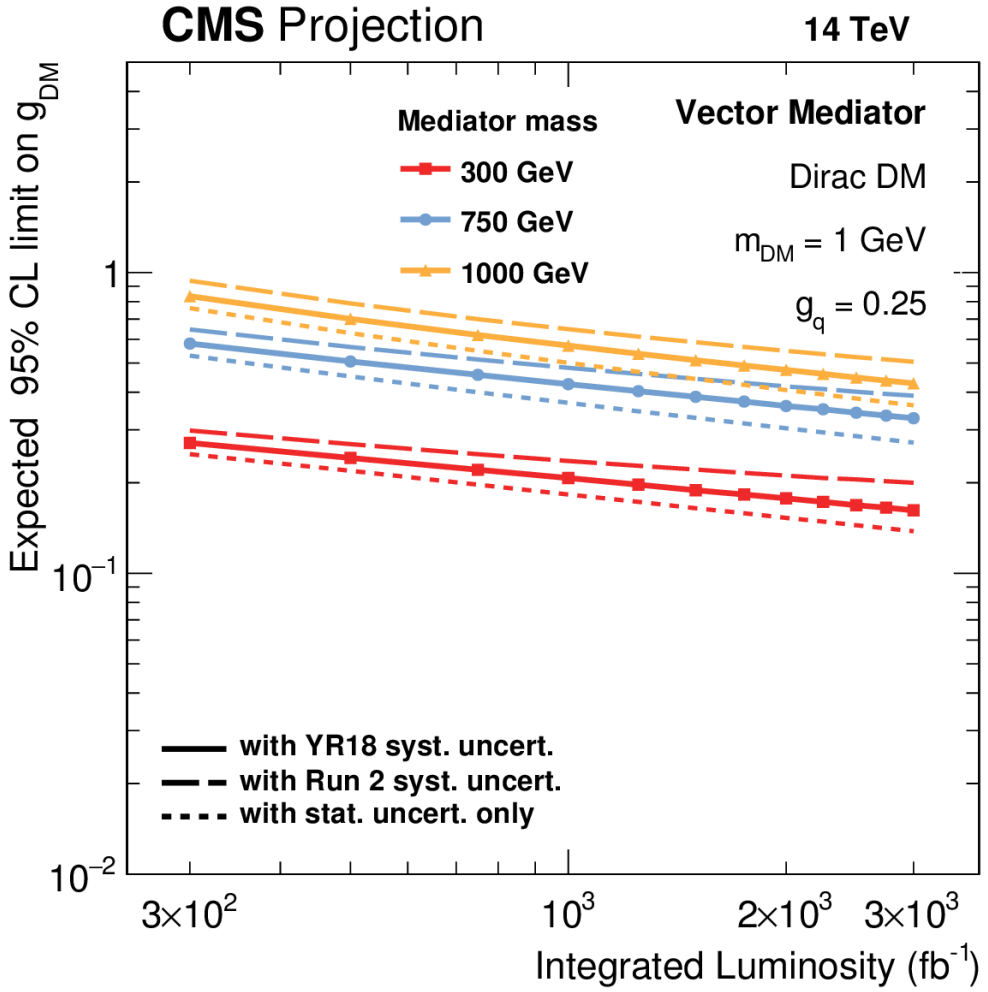
# CMS Di-Higgs Search Results

- Combination of HH→bbγγ, bbbb, bbττ, bbVV channels:



# Search for Dark Matter (FTR-18-007)

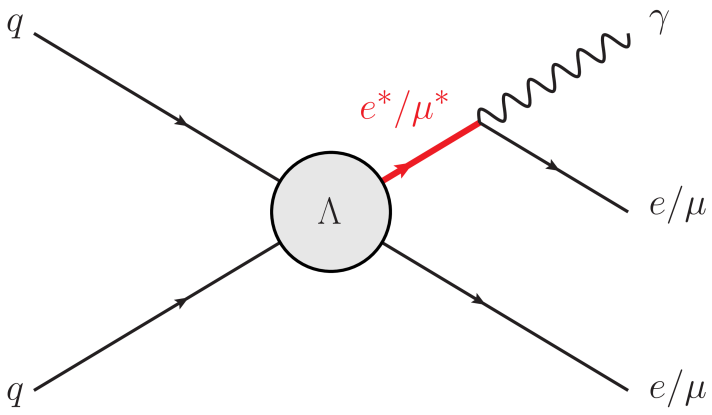


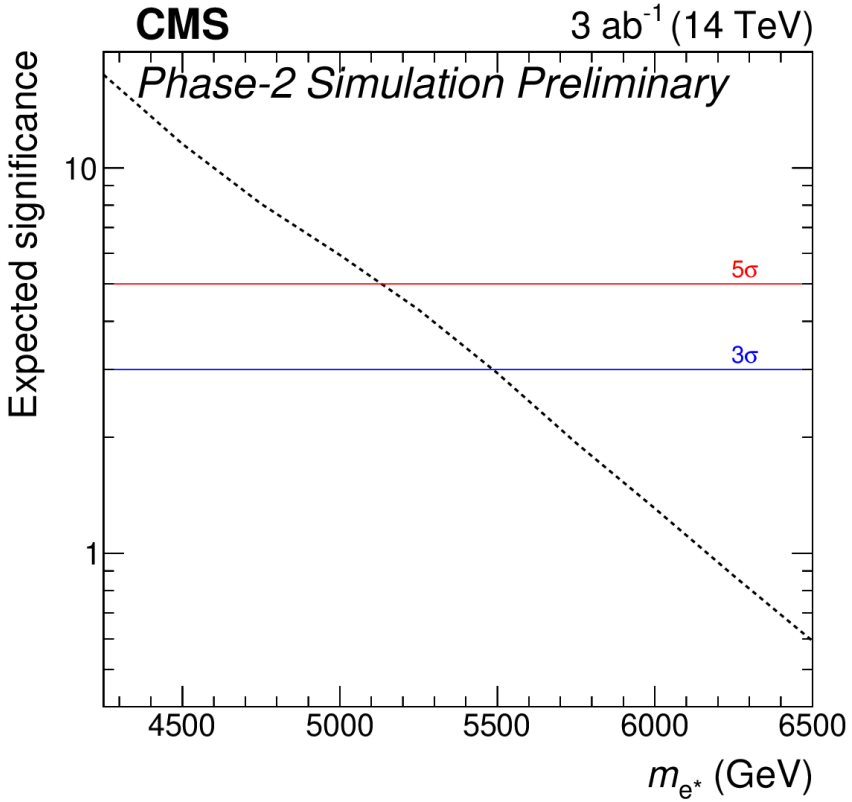



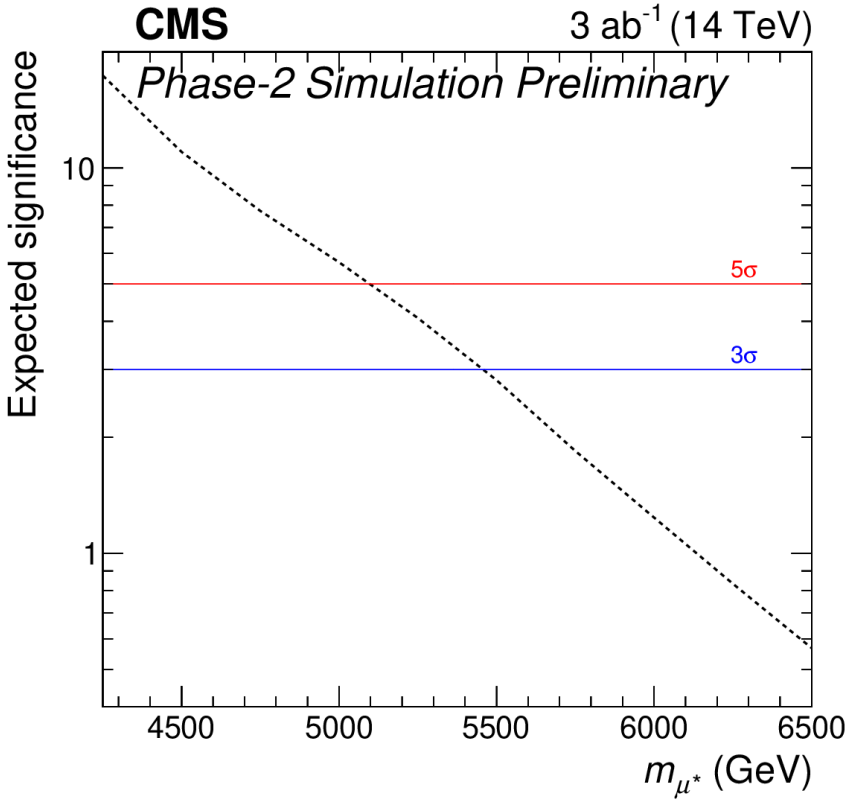

- Exclusion sensitivity for the couplings *gq* (left) and *gDM* (right) in vector-mediated DM scenario

# Search for Excited Leptons (FTR-18-029)

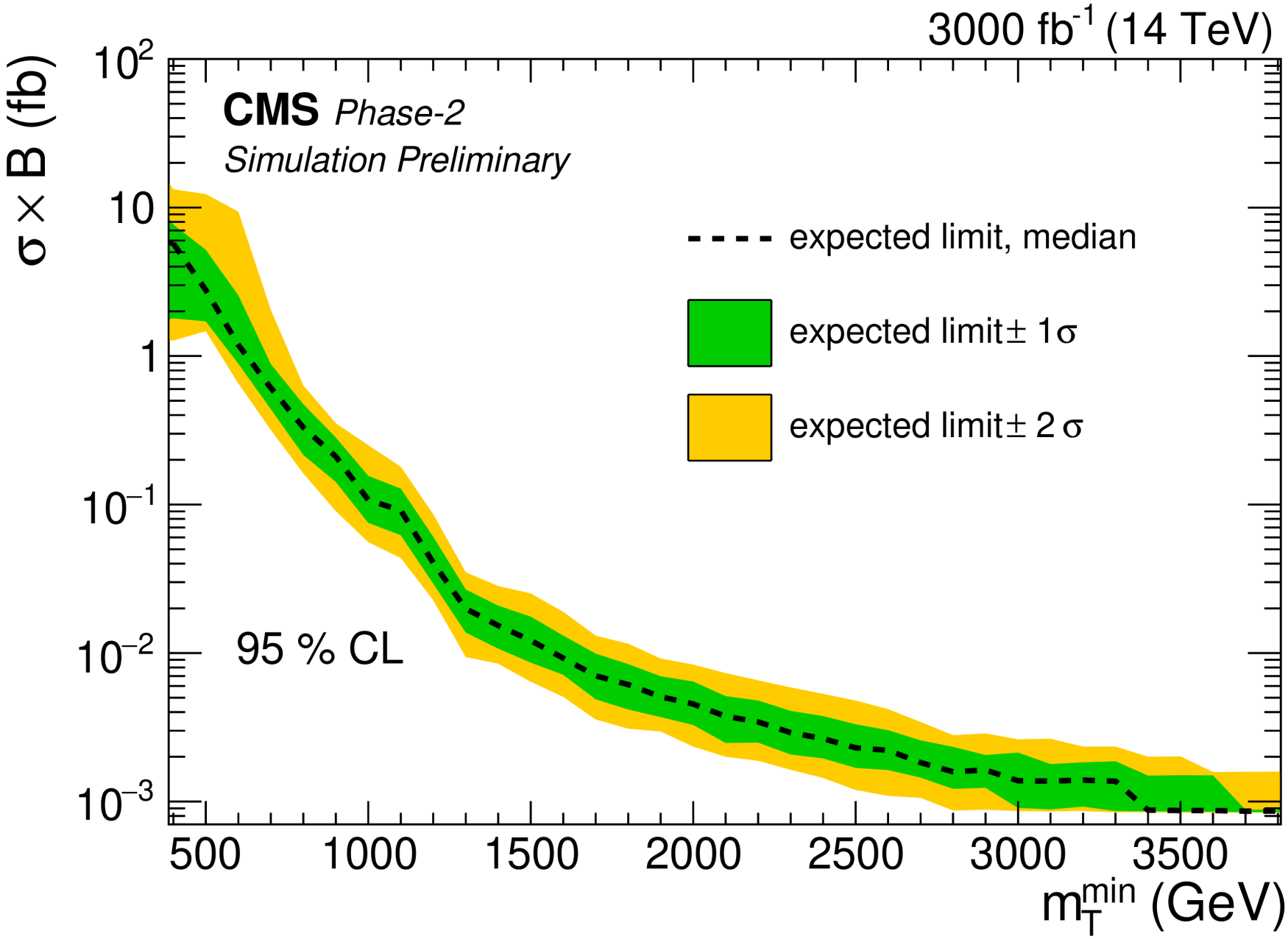
- Excited lepton →lγ,
- Analysis based on EXO-18-004
- Phase 2 Sensitivity for $m_{l*} = \Lambda$:



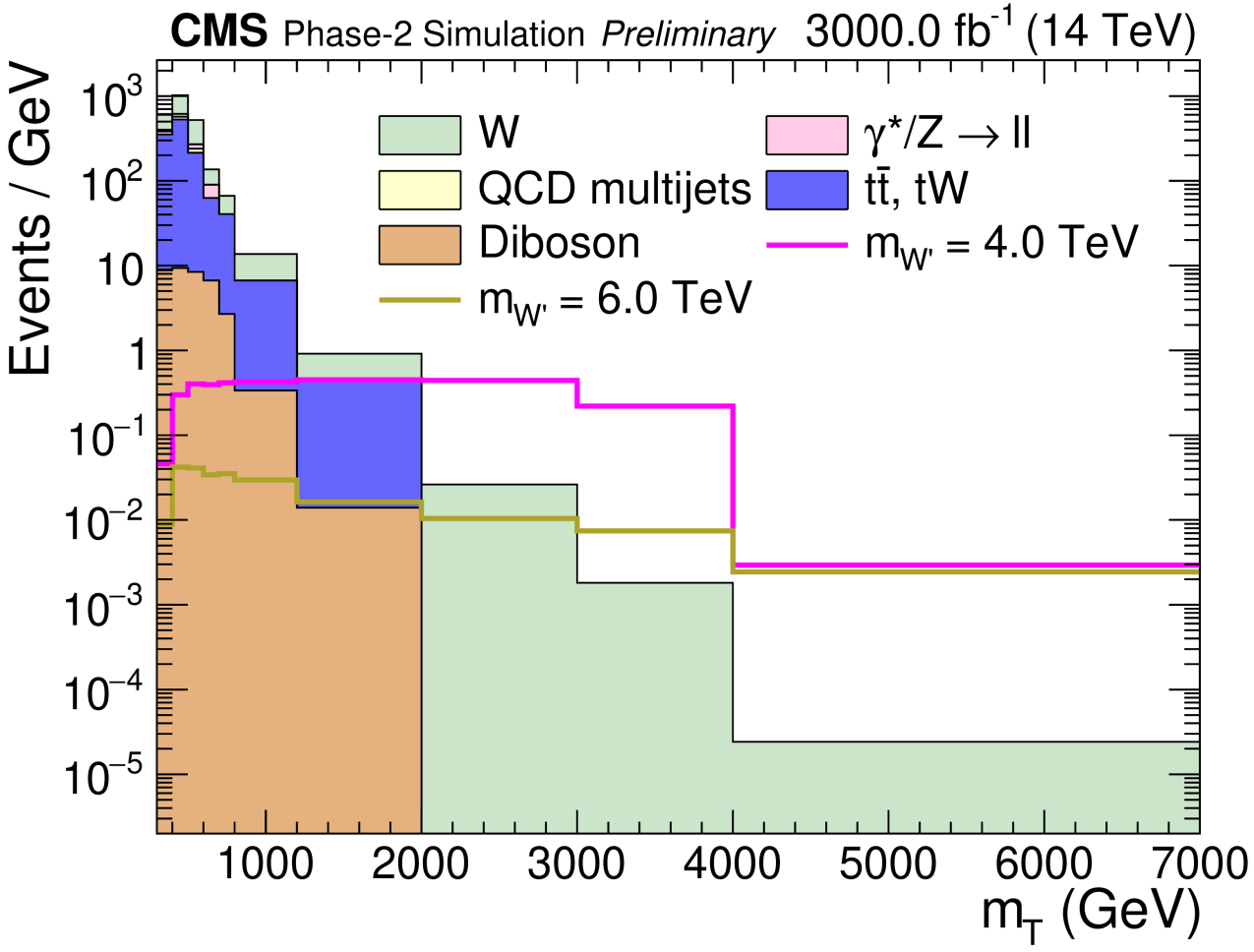



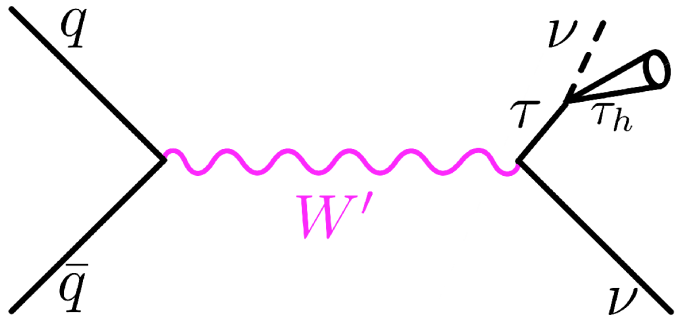
# W' → τν (CMS FTR-18-030)



# W' → τν (CMS FTR-18-030)

- Selection: $0.7<p_T^{\tau}/p_T^{miss}<1.3$ and $\Delta\varphi(p_T^{\tau},p_T^{miss}) > 2.4$



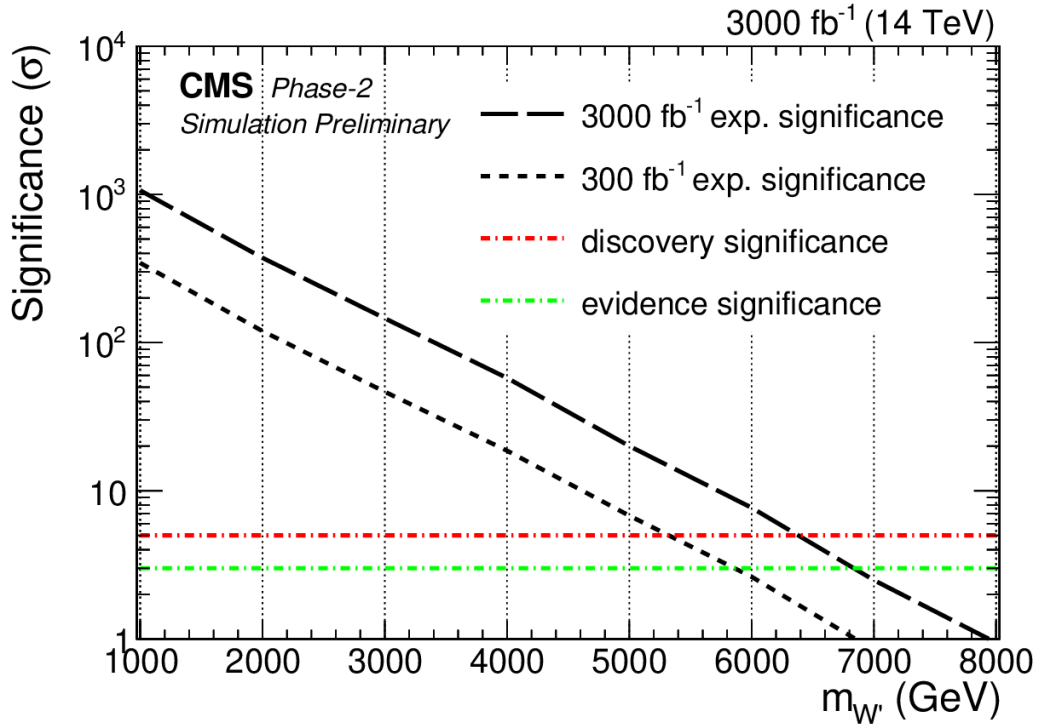



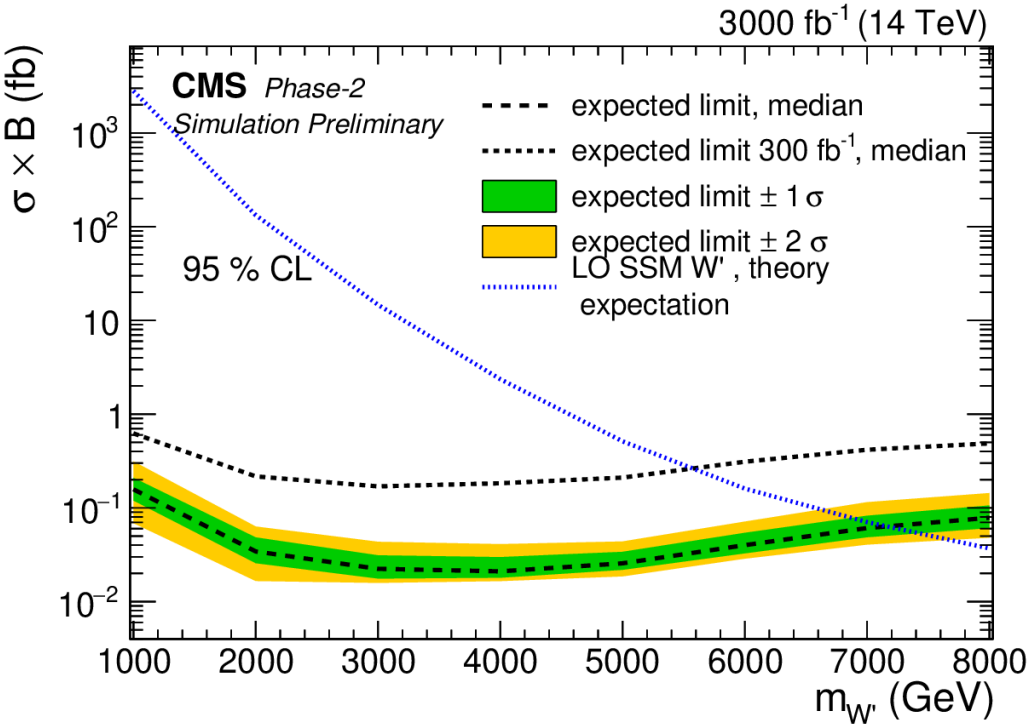

(Based on CMS 2016 data result: arXiv 1807.11421)

- CMS FTR-18-030: https://cds.cern.ch/record/2655312

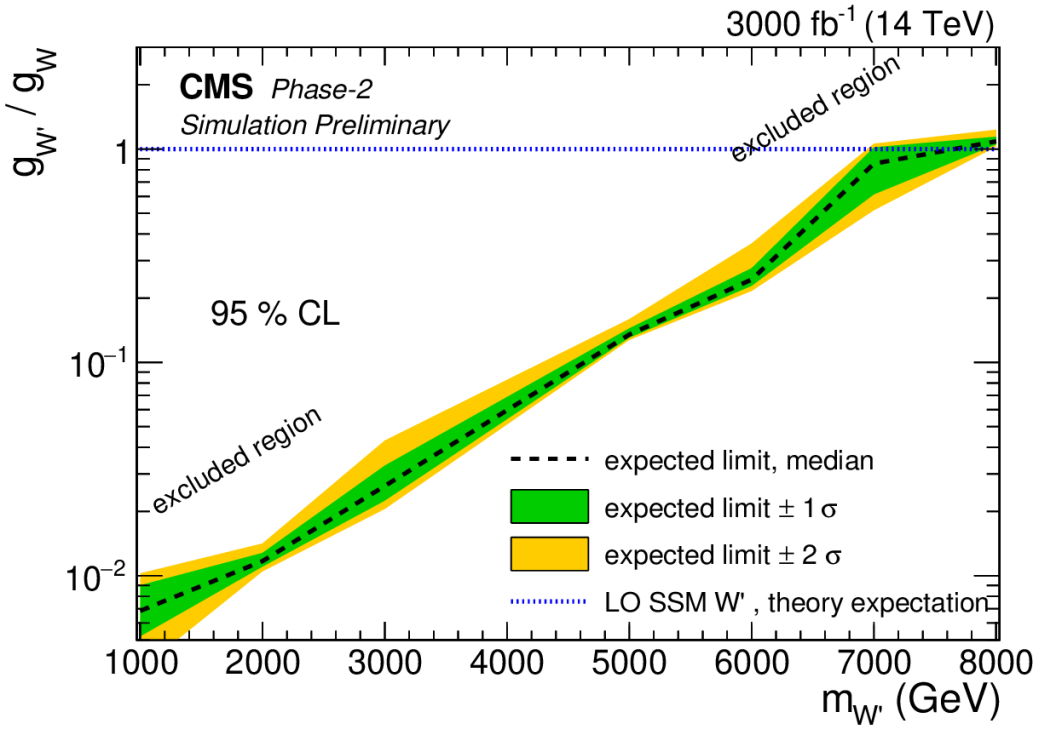
# W' → τν (CMS FTR-18-030)

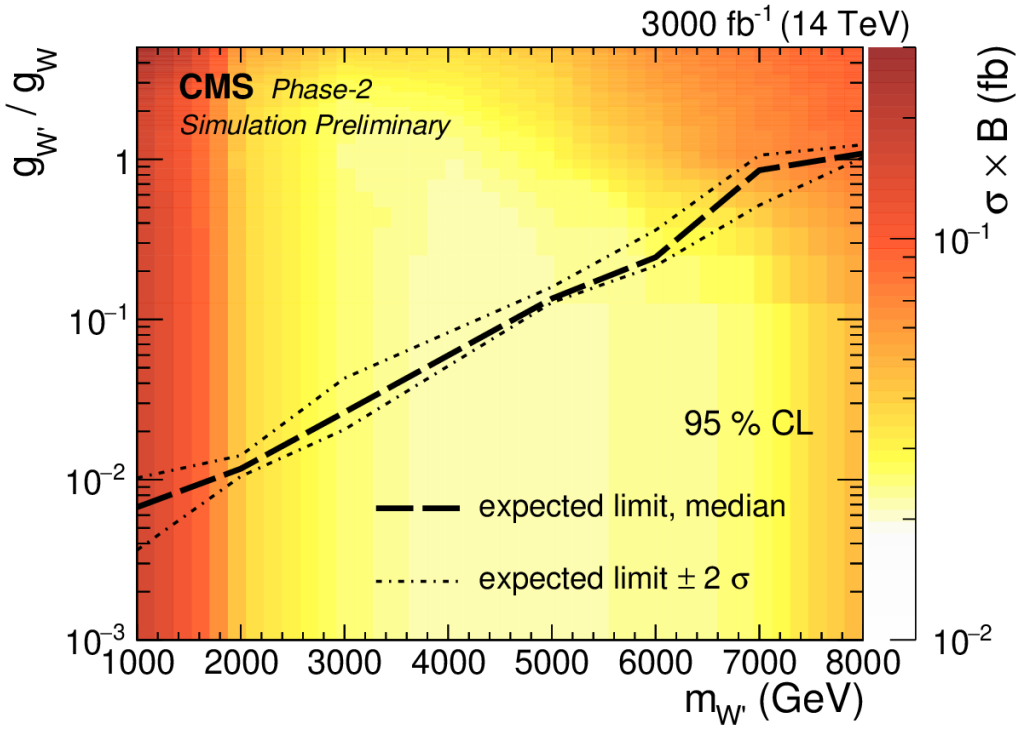
- Projected discovery potential and exclusion limits:



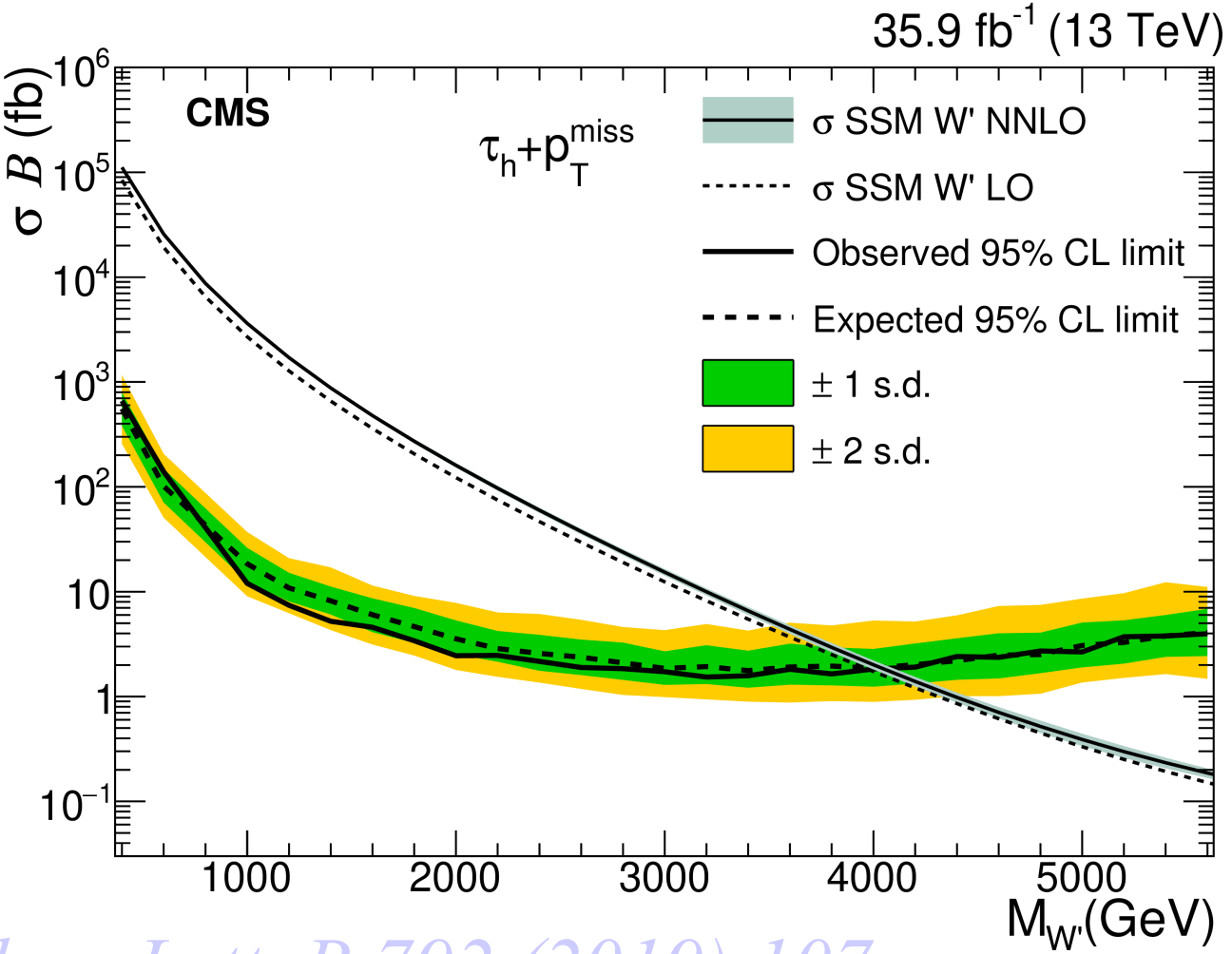
# W' → τν (CMS FTR-18-030)



# W' → τν (CMS EXO-17-008)

- CMS result with 2016 dataset:

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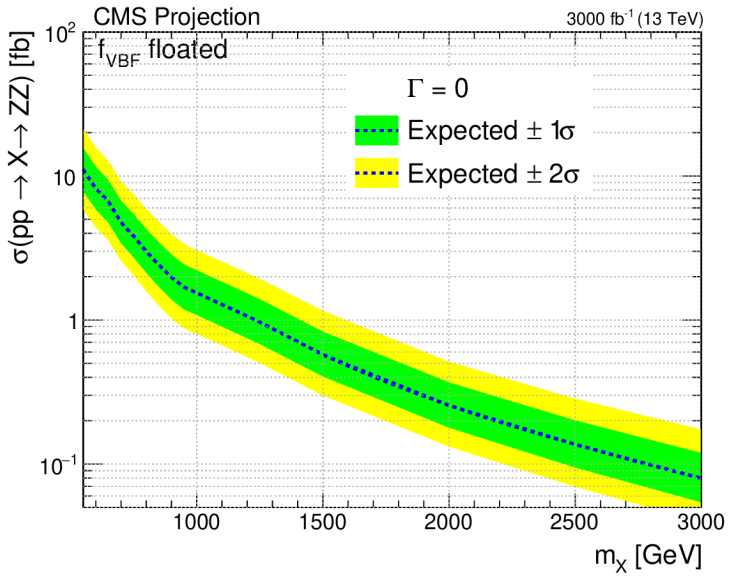
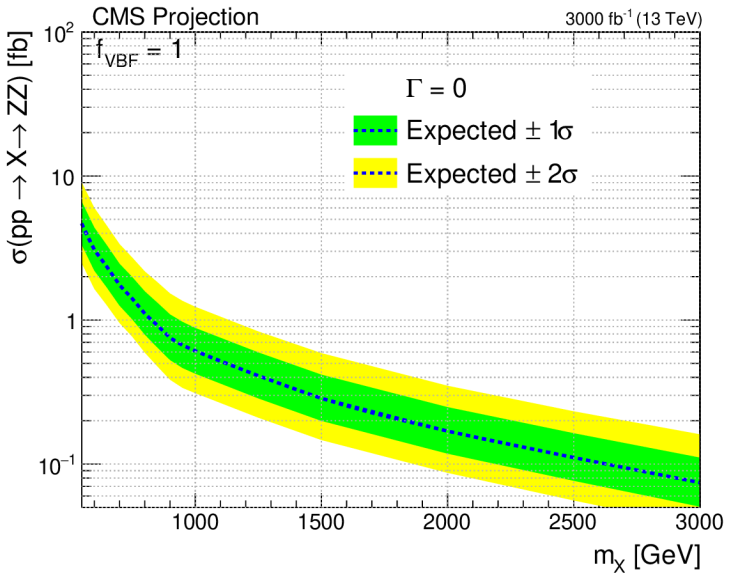
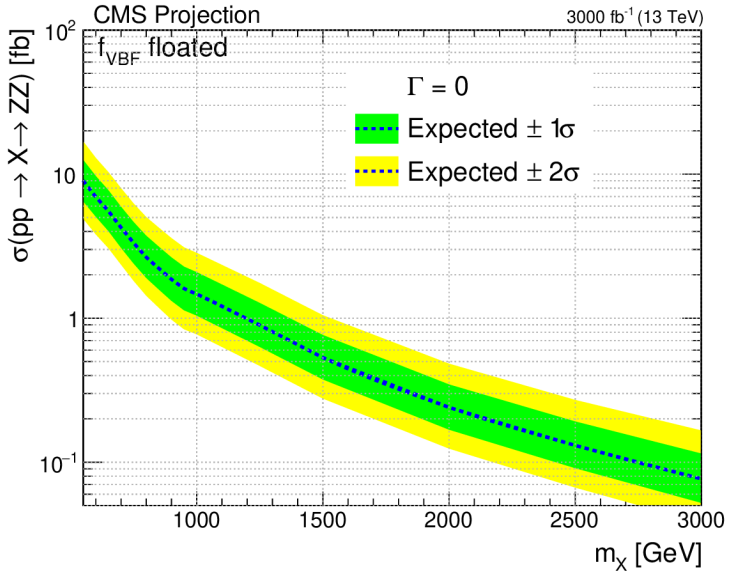
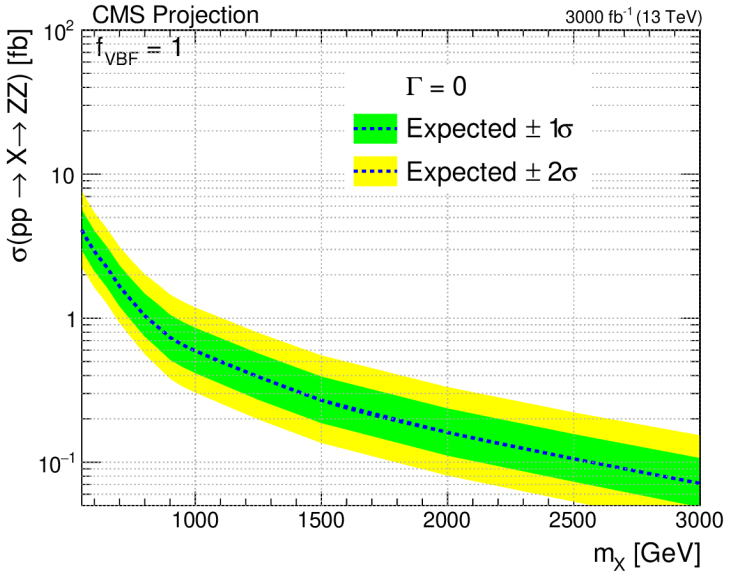
# New Scalar → ZZ (CMS FTR-18-040)




Scenario 1: assume Run 2 systematics

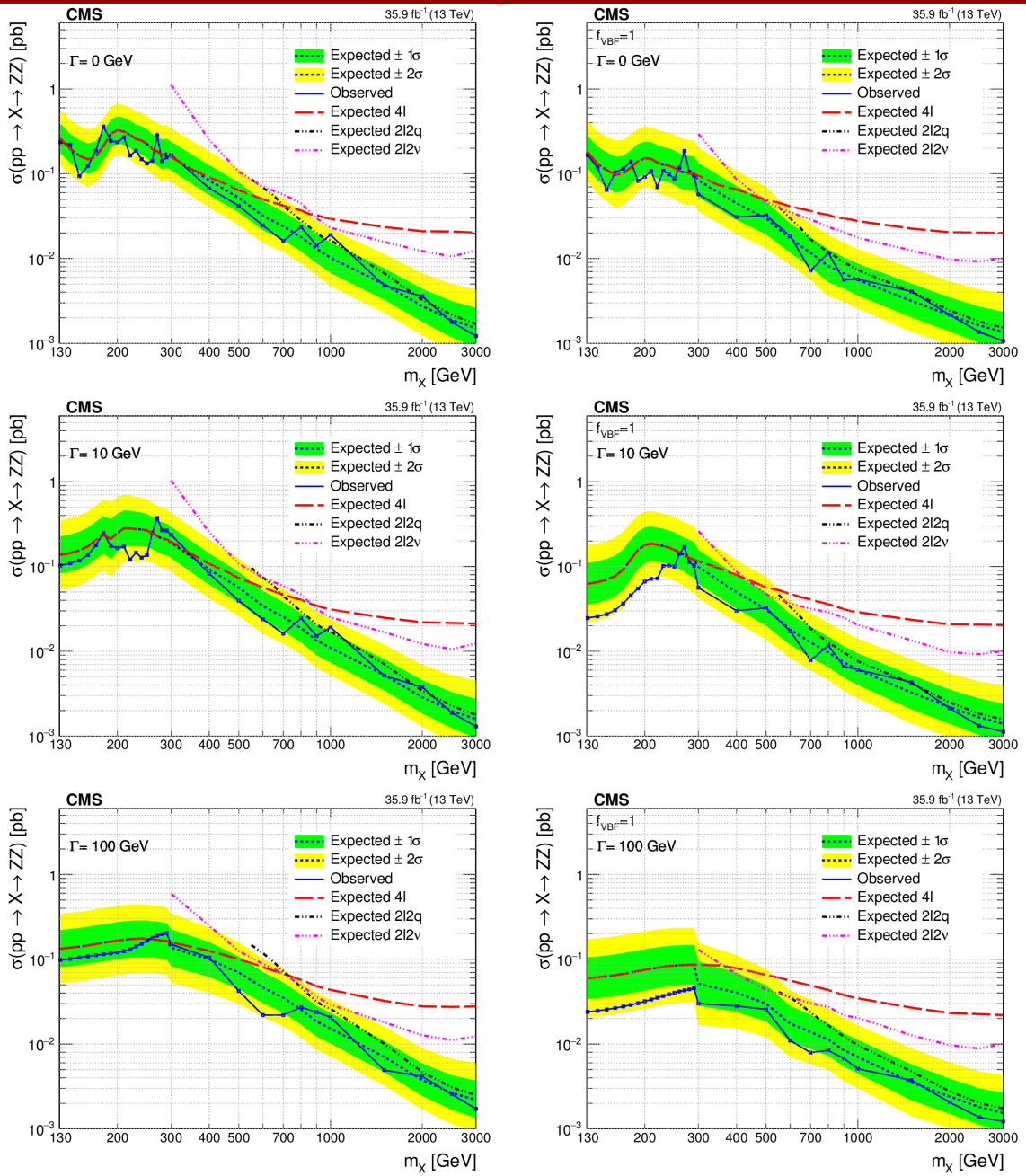



Scenario 2: Improved systematics

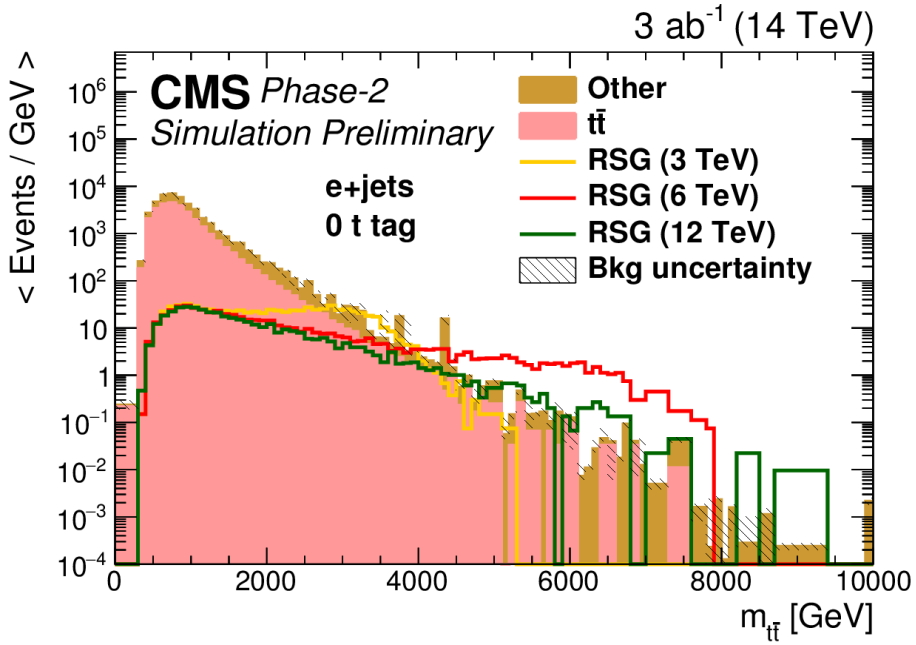
- CMS FTR-18-040: https://cds.cern.ch/record/2658263

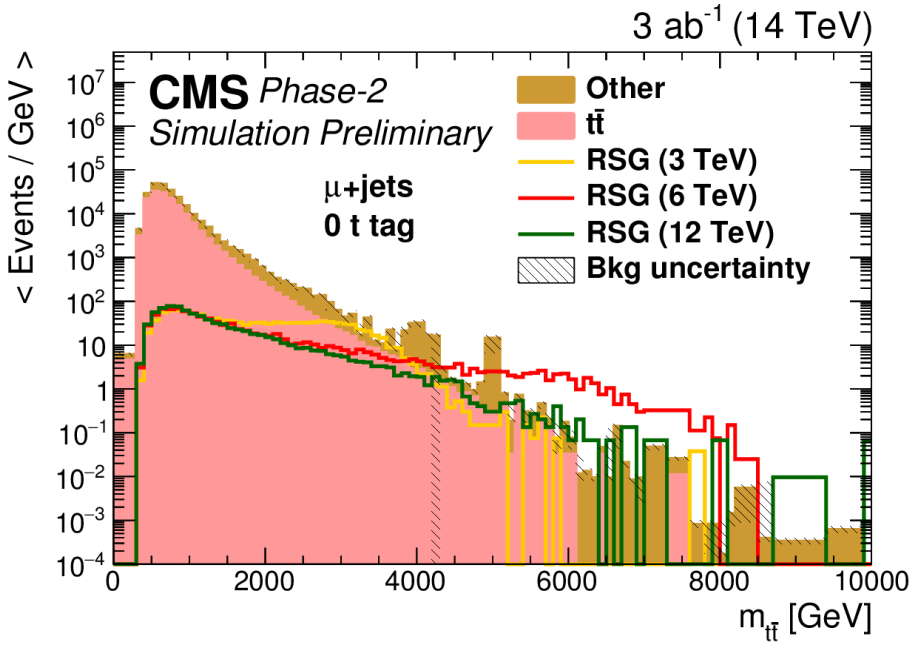
# New Scalar → ZZ (CMS HIG-17-012)

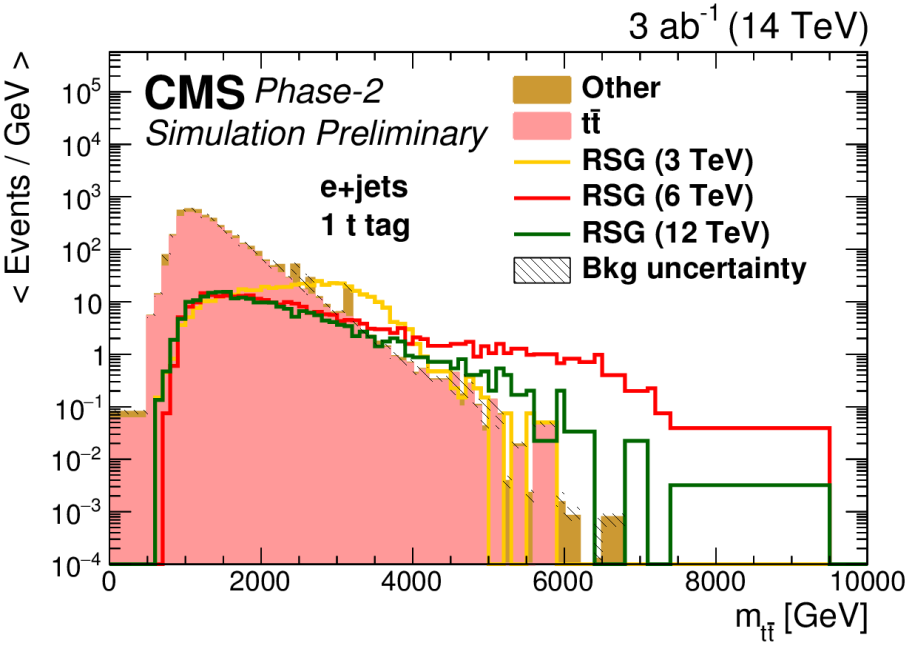


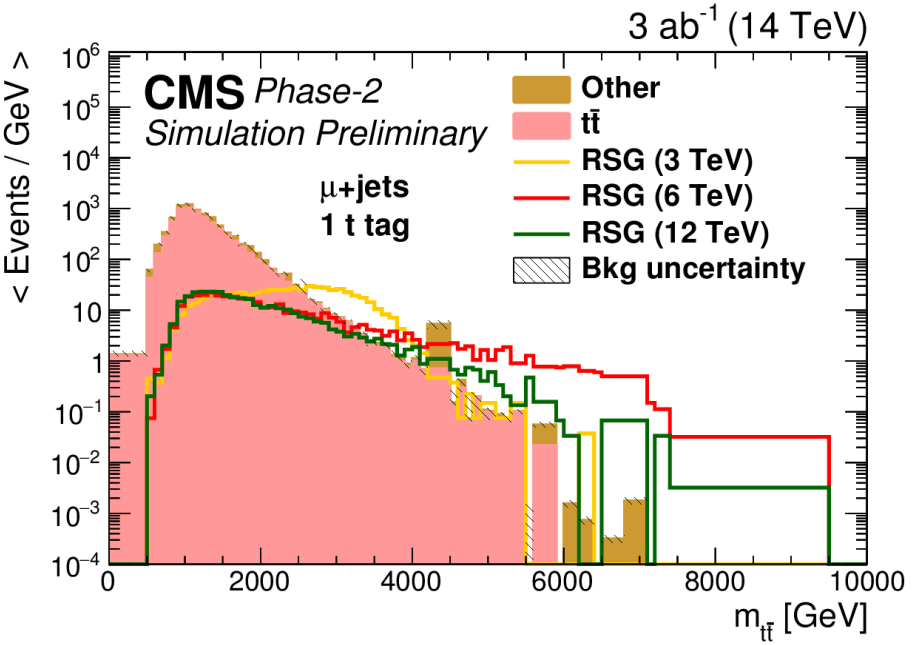

- From CMS 2016 result HIG-17-012: arXiv 1804.01939, JHEP 06 (2018) 127

# Search for ttbar Resonance (RS Gluon)

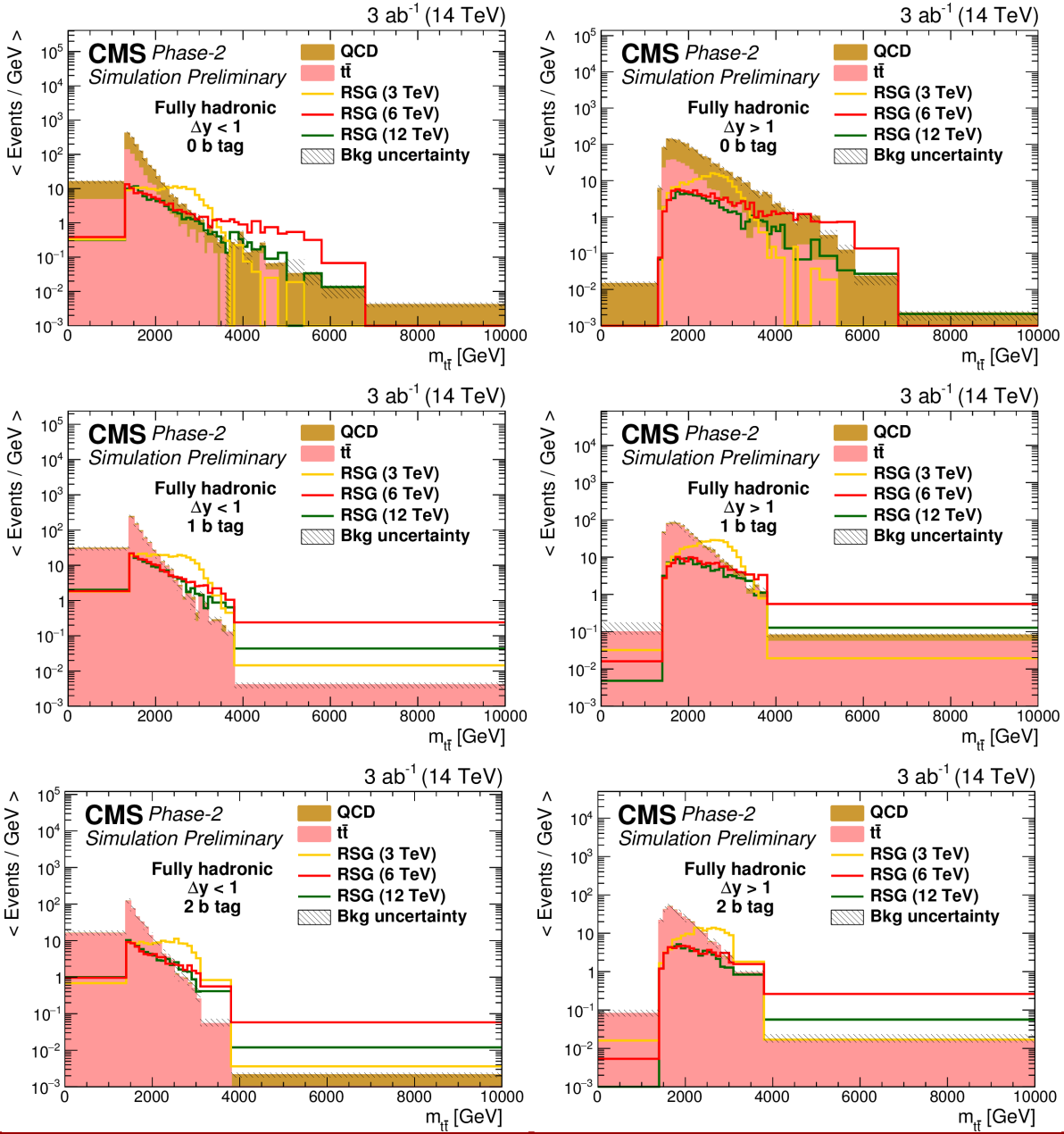


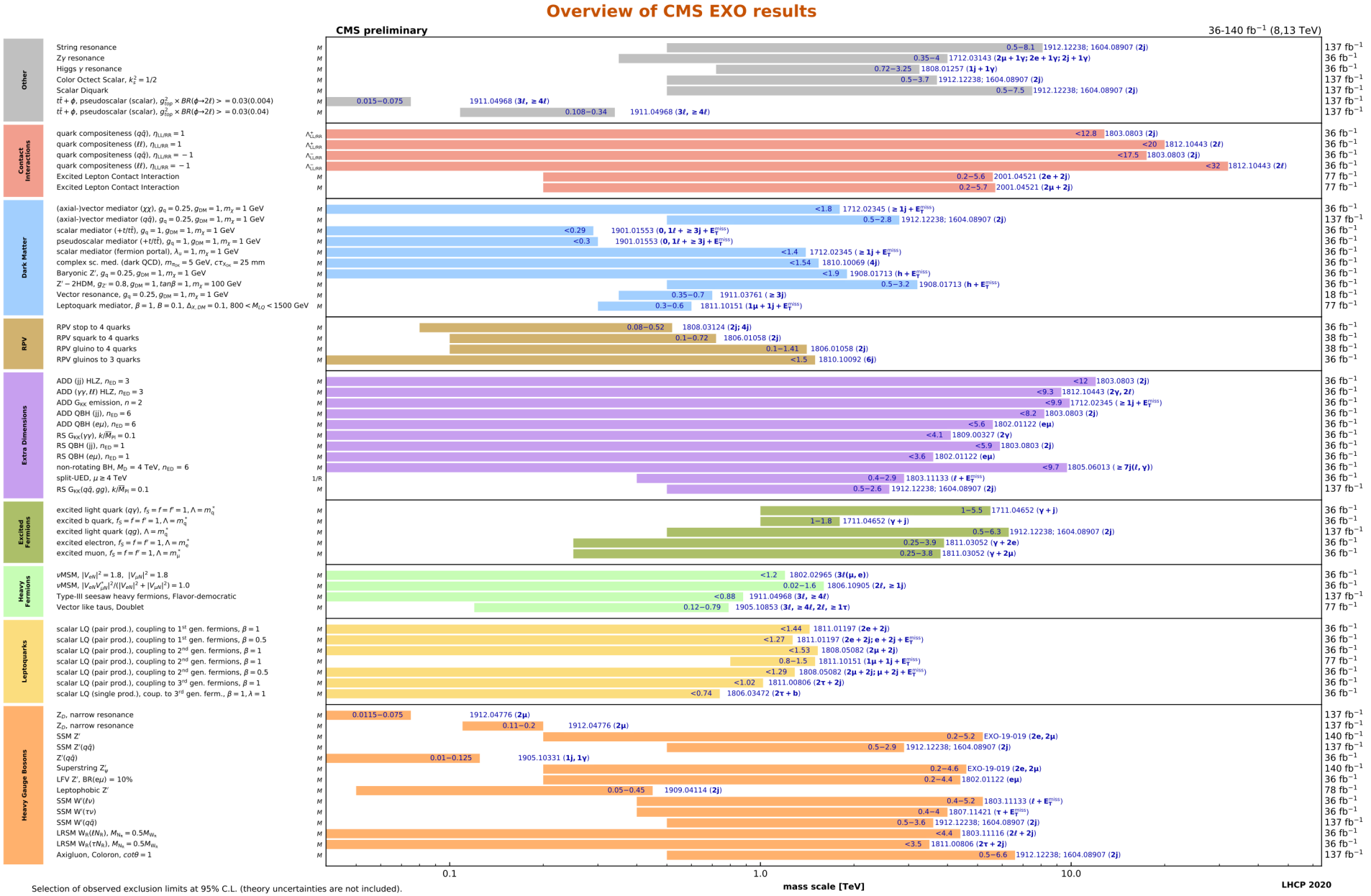



# Search for ttbar Resonance (RS Gluon)



# CMS EXO Results



# CMS EXO Results

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