Searching for Lepton Flavor Violation with CMS Run 2 data

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Introduction

- Neutrino oscillations provided the first evidence that neutrinos change flavor as they travel, suggesting lepton flavor violation (LFV) in nature
- Observation of LFV in the charged sector would be a unambiguous sign of BSM physics
- The potential tension between SM and the low-energy B decay measurements could indicate LF(U)V
  - Heavy particles with lepton-family-dependent couplings, inducing LFUV at low energy
- The CMS experiment has an active area of searches for LFV in various regimes
  - Measuring decay rates of SM particles: i.e. τ lepton, top quark, Higgs boson
  - Direct search for new particles motivated by LFV: i.e. leptoquark, Z'
- This talk focuses on the very recent results, using the full data set recorded by CMS in LHC Run of 2016-2018 at 13 TeV, corresponding to 138 fb^{-1}

Measuring decay rates of SM particles

Search for LFV decays of $\tau \rightarrow 3\mu$

CMS BPH-21-005

[CMS BPH-21-005](#)

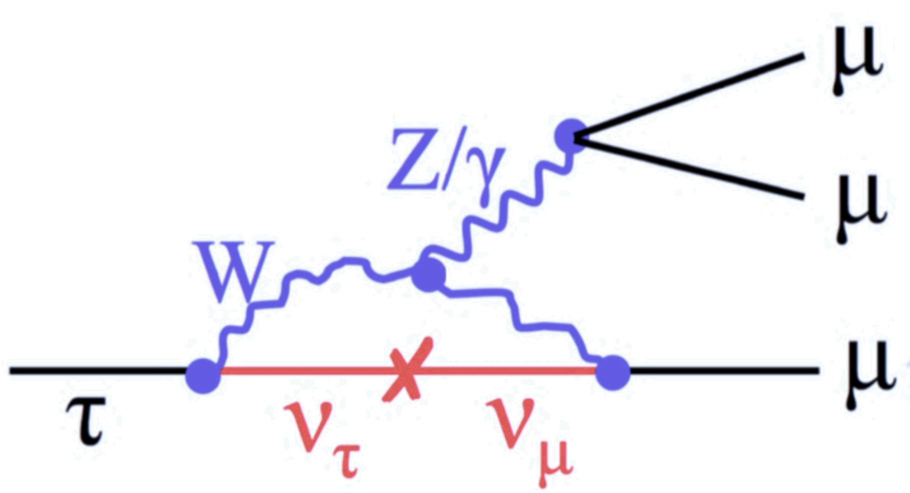
$\tau \to 3\mu$: introduction

- The large τ mass means large phase space for decays
- Coupling of new physics might be enhanced for the 3rd generation
- $\tau \to 3\mu$ has a clean signature at LHC (as opposed to $\tau \to \mu\mu e$, μee, $3e$, $\mu\gamma$, etc)

- The present best upper limit: $Br(\tau \to 3\mu) < 2.1\times10^{-8}$ @ 90% CL, set by the Belle experiment
  - 3.3×10^{-8} @ 90% CL by Babar experiment
  - Both are e^+e^- collisions

Current published results from LHC experiments:

- LHCb Run I ~ 4.6×10^{-8}
- ATLAS Run I ~ 38×10^{-8}
- CMS 2016 ~ 8.0×10^{-8}



$Br(\tau \to 3\mu)$ through neutrino oscillation ~ 10^{-55}

The sources of τ at LHC

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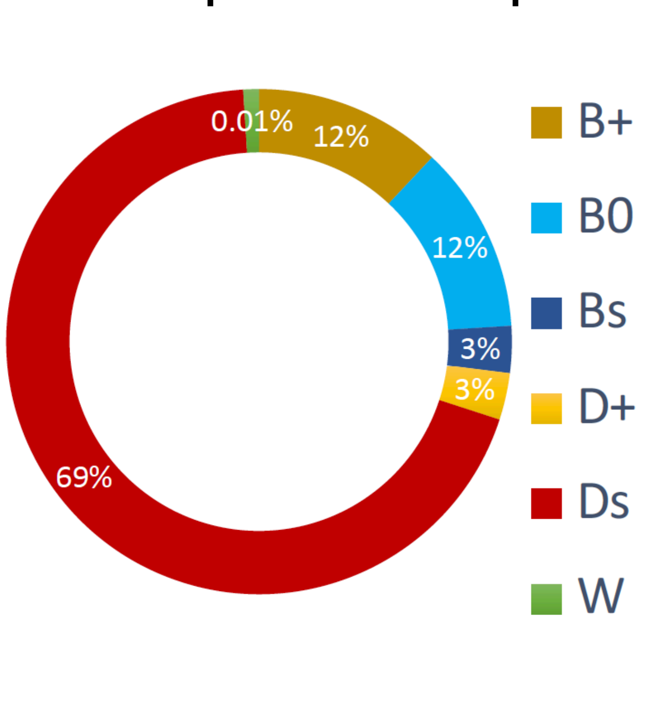
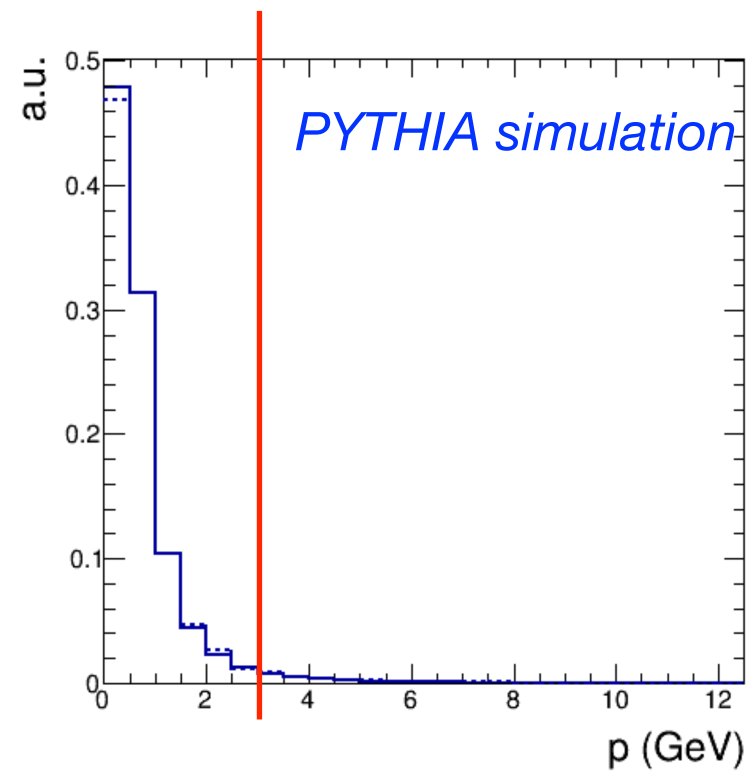
10^{13} τ produced per 100 fb^{-1}





CMS muon detection acceptance => two orders of magnitude reduction of D/B → τ

Two complementary approaches

- Heavy flavor (charm and bottom) hadron decays: large cross section; low p_T; high background
- W boson decays: relatively small cross section; higher p_T; isolated from hadronic activities; large missing transverse energy (MET); low background

This search explores both heavy-flavor (HF) analysis and W analysis using 2017+2018 data, and then combined with the published 2016 data results

HF analysis: trigger and preselections

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"B-physics style" trigger

- L1 trigger (hardware):
  - 2 muons with pseudo-rapidity $|\eta| < 1.5$ or $p_T > 4$ GeV (dominant)
  - Complemented by a trigger of 3 muons of $p_T > 5, 3, 0$ GeV, respectively
- High level trigger (HLT, software)
  - Three reconstructed tracks, two of which must be identified as muons with $p_T > 3$ GeV; the 3rd one $p_T > 1.2$ GeV
  - Fitted to a displaced common vertex; the invariant mass in 1.60-2.02 GeV
  - "2 muon + 1 track" HLT collects events of $\tau \to 3\mu$ signal and $D_s \to \phi(2\mu)\pi$ normalization channel at the same time with the same trigger

The offline pre-selection

- As loose as possible, only to consolidate the trigger selections
- Three muon tracks refitted using the common vertex constraint, to improve resolution

Signal yield normalization

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- The HF analysis is complicated by the uncertainties in the HF hadron production, and signal acceptance and efficiencies

=> utilizing a normalization channel

- Signal:
  - Ds → τ + nu (including prompt Ds and B → Ds)
  - B^+ or B0 → τ + X
- Normalization channel for Ds → τ events
  - Ds→$\phi(2\mu)\pi$ (event selections as close as possible to those for the signal channel)

- Non-Ds contributions
  - B→τ (~25% of the total), based on MC, but verified by comparing decay length of B → Ds in data and MC
  - Very small contributions from Bs and D^+ based on MC and 100% uncertainty

Signal normalization: Ds→τ

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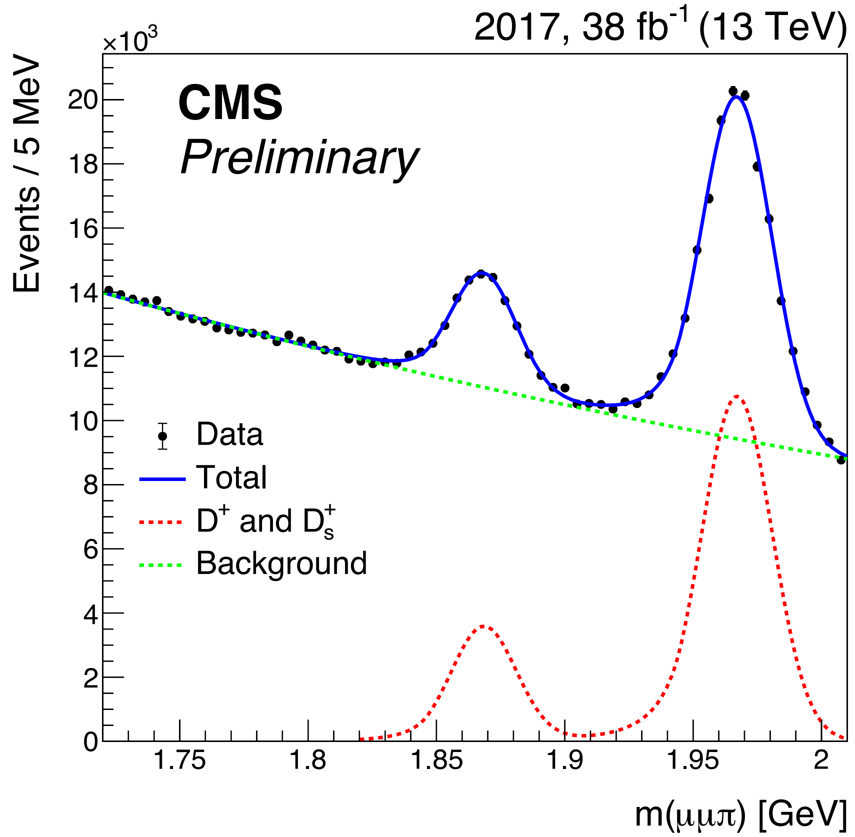
Large majority of the signal comes from Ds→τ.
These are related to the normalisation channel Ds→ϕ(2μ)π by:

$$N_{3\mu(D)} = N_{\mu\mu\pi} \frac{\mathcal{B}(D_s^+ \to \tau^+\nu)}{\mathcal{B}(D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+)} \frac{\mathcal{A}_{3\mu(D)}}{\mathcal{A}_{\mu\mu\pi}} \frac{\epsilon^{reco}_{3\mu(D)}}{\epsilon^{reco}_{\mu\mu\pi}} \frac{\epsilon^{2\mu trig}_{3\mu(D)}}{\epsilon^{2\mu trig}_{\mu\mu\pi}} \mathcal{B}(\tau \to 3\mu)$$

- Ds→ϕ(2μ)π yields and uncertainty
- BR and their uncertainties
- Acceptance uncertainty (studied by varying PYTHIA PDF+Tunes)
- Need single mu reco efficiency (measured with Tag&Probe)
- Trigger efficiency ratio, based on MC

Ds→ϕ(2μ)π



Background composition

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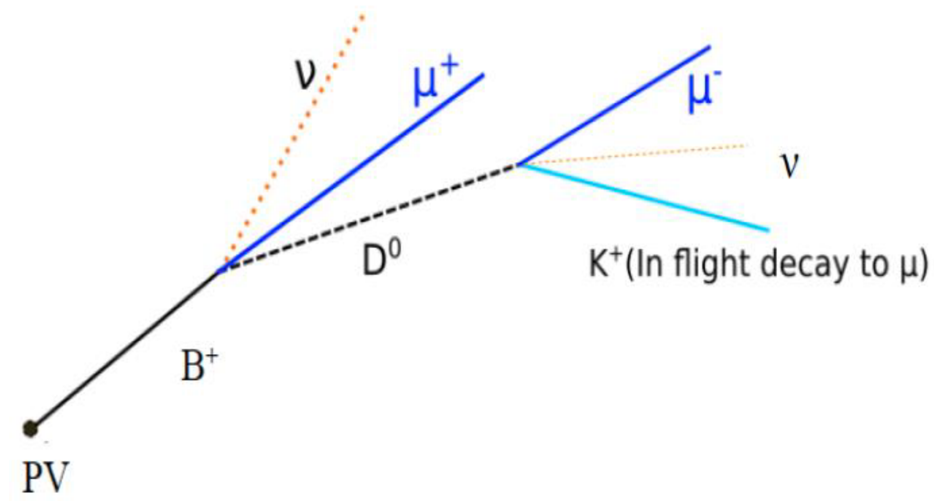
- The dominant background is combinatorial of two real muons plus one fake (typically decay-in-flight)
- Most common one is B→D cascade decay, for example
  - B → D + μ + X
    - D → μ + ν + Kaon
    - Kaon fakes muon



- Background with 3 genuine muons
  - two of which come from resonances
    - ϕ(1020) and omega(783) vetoed
  - Irreducible background: Ds → η (μμγ) μ ν

- There is no peaking background in the search region (1.6-2.0 GeV)
- Data sidebands are used as proxies of background

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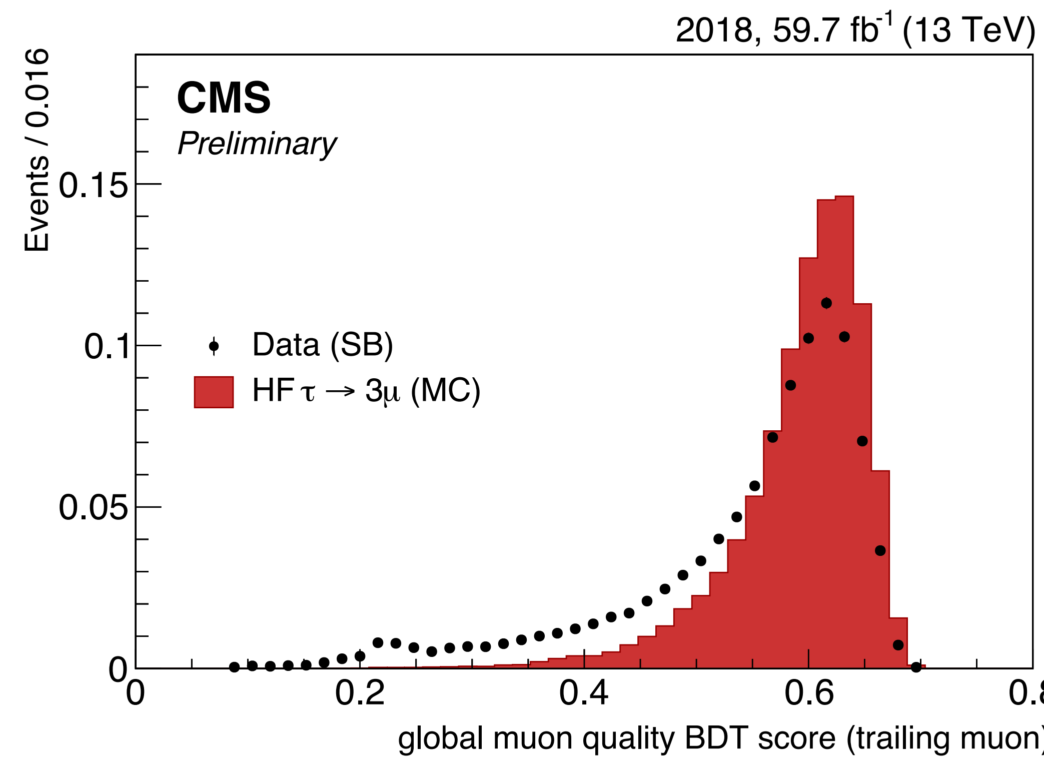
Muon reconstruction quality BDT

- A BDT is used to suppress fake muons
- Trained using MC: real muons vs fake muons from pion/kaon decays
- The most useful BDT input observables are based on track features and on the compatibility between tracks and muon chamber information



The analysis BDT

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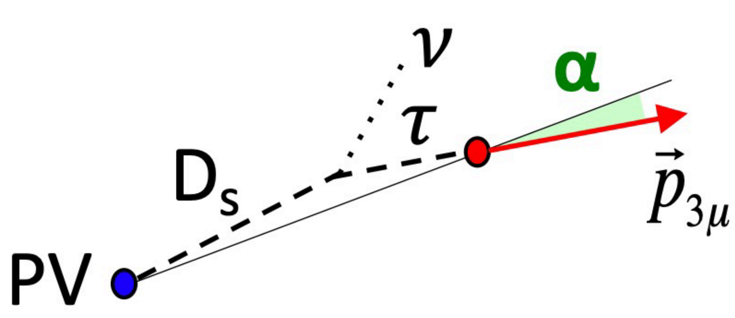
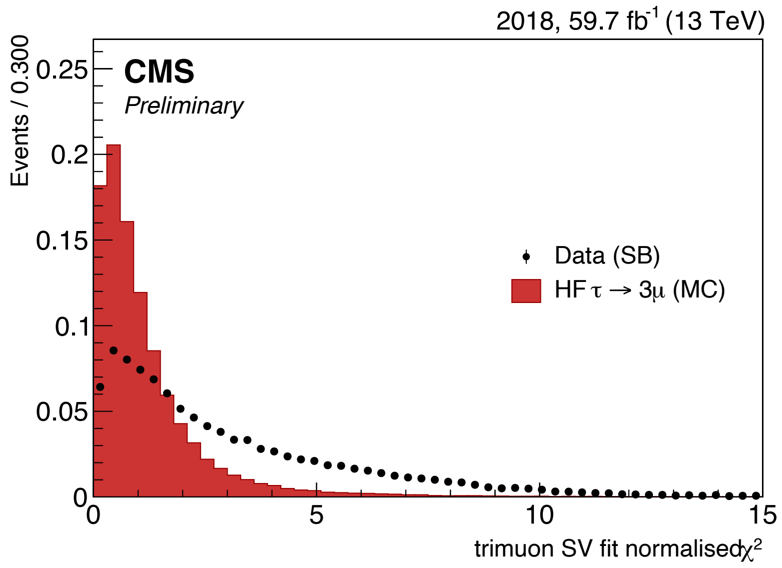
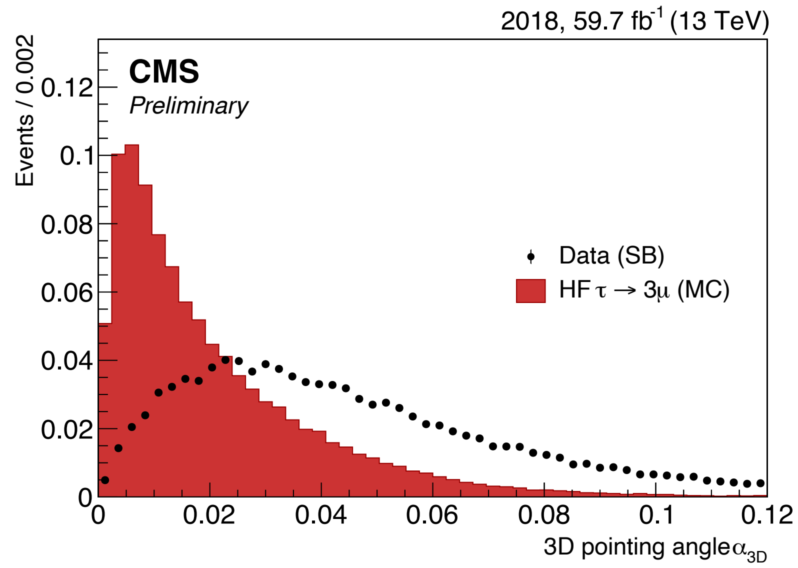
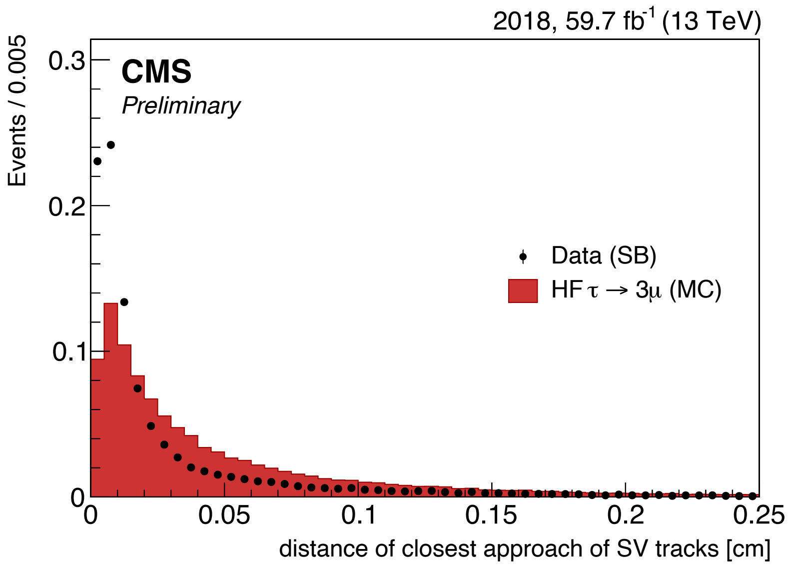
Multivariate analysis used to suppress dominant backgrounds

- Trained using signal MC vs data sideband
- The most useful BDT input observables
  - trimuon vertex fit chi2/ndof
  - "Pointing angle" between V(3μ)-PV and 3μ momentum vector
  - "Isolation": distance of other tracks to the trimuon vertex
  - Muon reconstruction quality BDT scores of all the 3 muons









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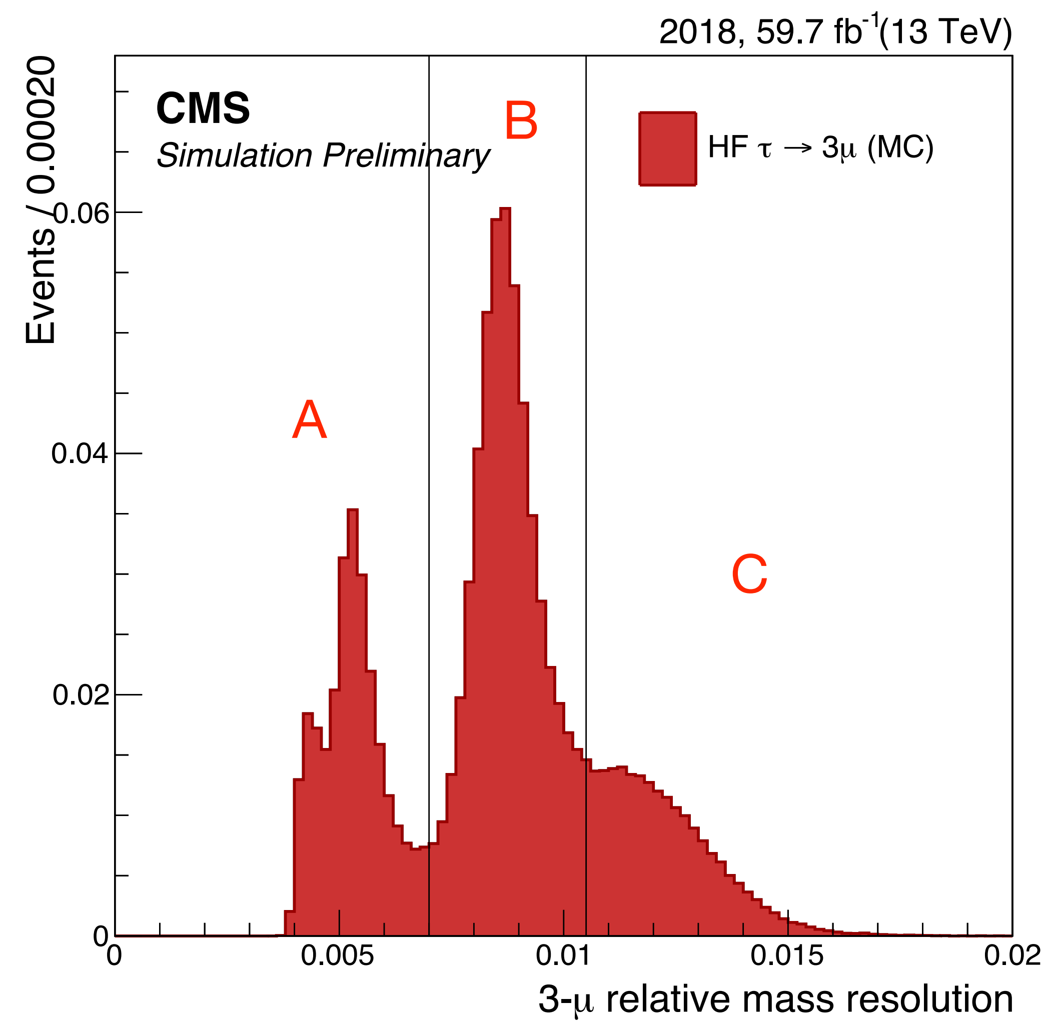
Event categorization

- Events are categorised according to the mass resolution, which is strongly correlated with the pseudo-rapidity
- Mass scale and resolution agreements in data and MC are studied using the $D_s \to \phi\pi$ events
- Three parts, labeled A, B, C



- A BDT is trained in each mass-resolution category to suppress background
- Each category is then further divided into several sub-categories based on the BDT score

Systematics

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Main uncertainties in signal yields

- Statistical uncertainty of the $D_s \to \phi\pi$ channel
- HF hadron decay branching fractions used in the signal normalization
- BDT requirement efficiency, studied using the $D_s \to \phi\pi$ channel

About 16% in total

Uncertainties in shapes

- Muon momentum scale and resolution impact on signal shapes
- Background function form choice (exponential, power low, polynomial)

HF analysis: results

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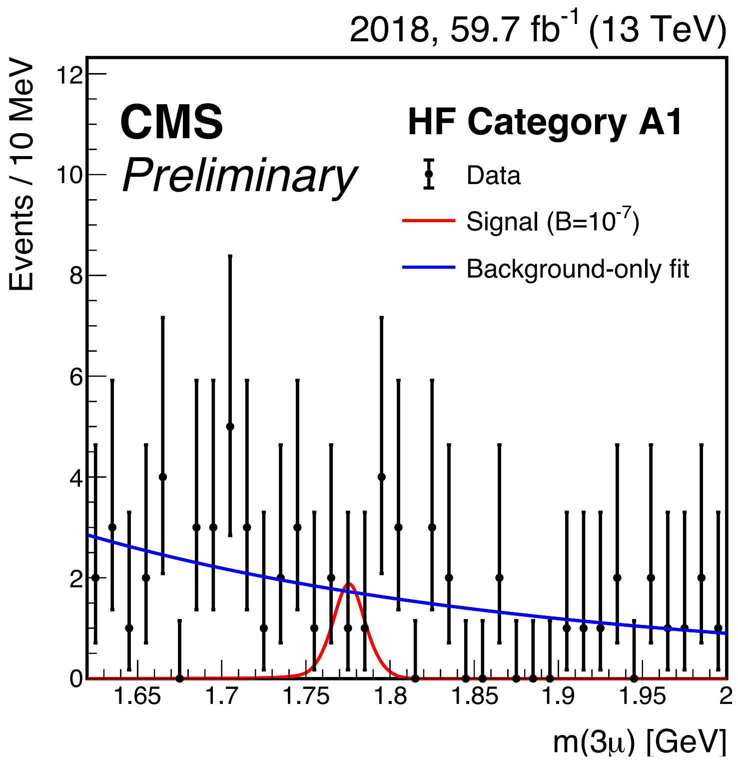

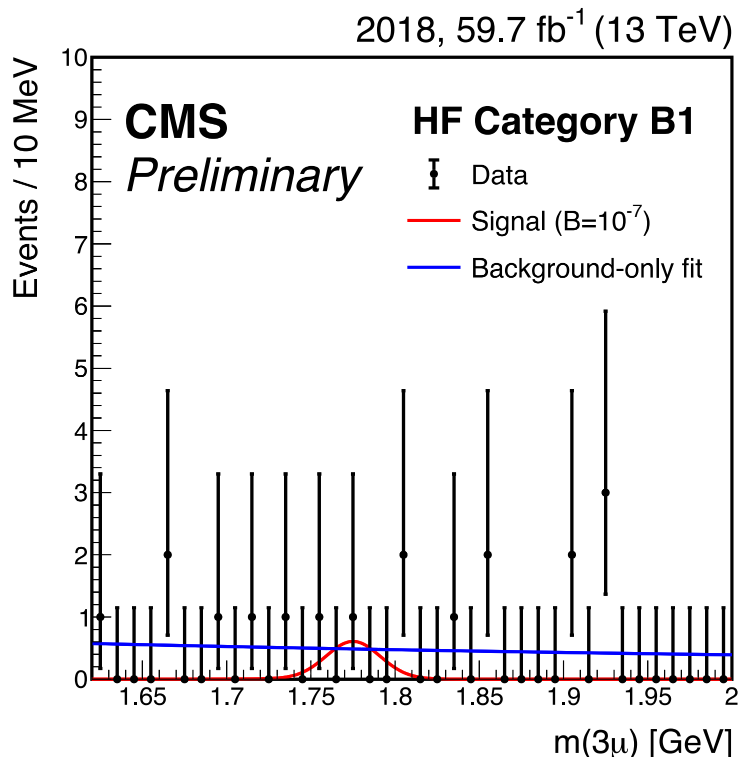

Exemplary trimuon mass plots of the best S/B categories

$Br(\tau \to 3\mu) = 10^{-7}$ is used in the plots for visibility

- Signal model: Gaussian + Crystal Ball function
- A simultaneous un-binned maximum likelihood fit to the trimuon mass distributions in all categories

The observed (expected) upper limit on $Br(\tau \to 3\mu)$ is found to be of 3.4×10^{-8} (3.6×10^{-8}) at 90% CL

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$W \rightarrow \tau$ analysis: introduction

- Th signal has a $W \rightarrow l\nu$ signature, though here “l” is a muon triplet
  - $p_T (3\mu) \sim m(W)/2$
  - 3μ is isolated from hadronic activities
  - Large missing transverse momentum (MET)
  - Transverse mass (m_T) of the 3μ and MET system is consistent with W
- Same L1 triggers as those in the HF analysis
- HLT: 3 muons of $p_T > 7, 1, 1$ GeV respectively, and in total > 15 GeV
- Same strategy as for the HF analysis:
  - Loose pre-selection
  - BDT to reduce background
  - Event categorisation and $m(3\mu)$ fit

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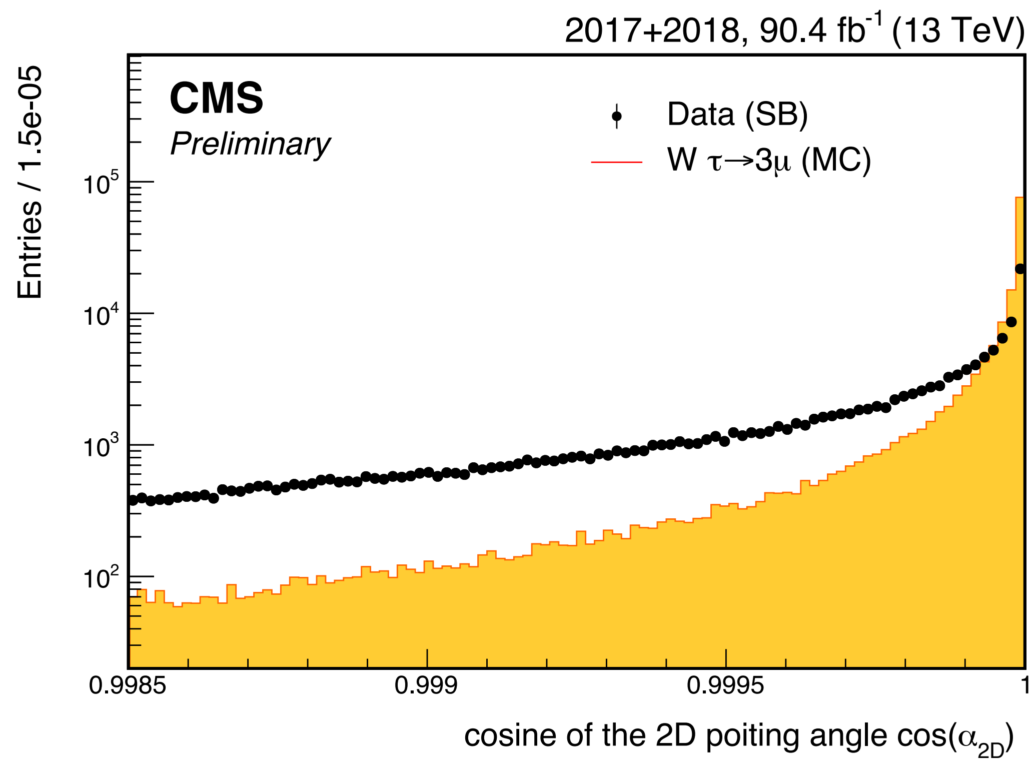
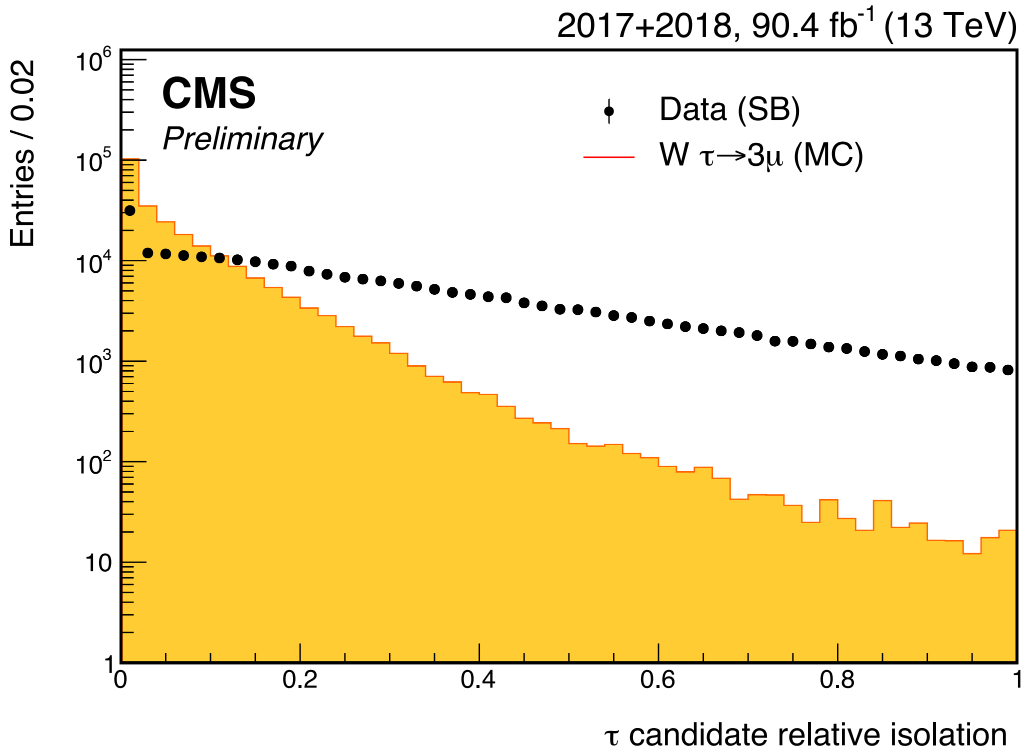
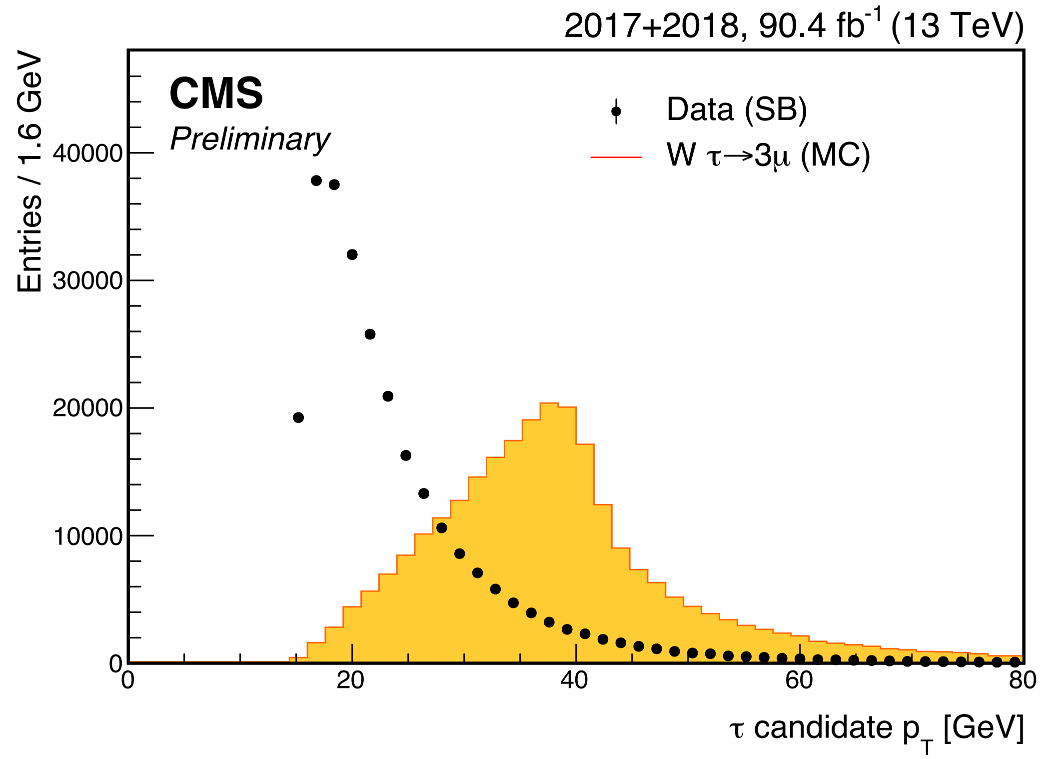
BDT analysis

Multivariate analysis used to suppress backgrounds

- BDT is trained using signal MC vs data sideband
- The most discriminating input observables are
  - The pointing angle
  - The isolation of the trimuon
  - p_T of the trimuon
- Other useful observations include the transverse mass, trimuon vertex fit quality, trimuon vertex displacement, etc



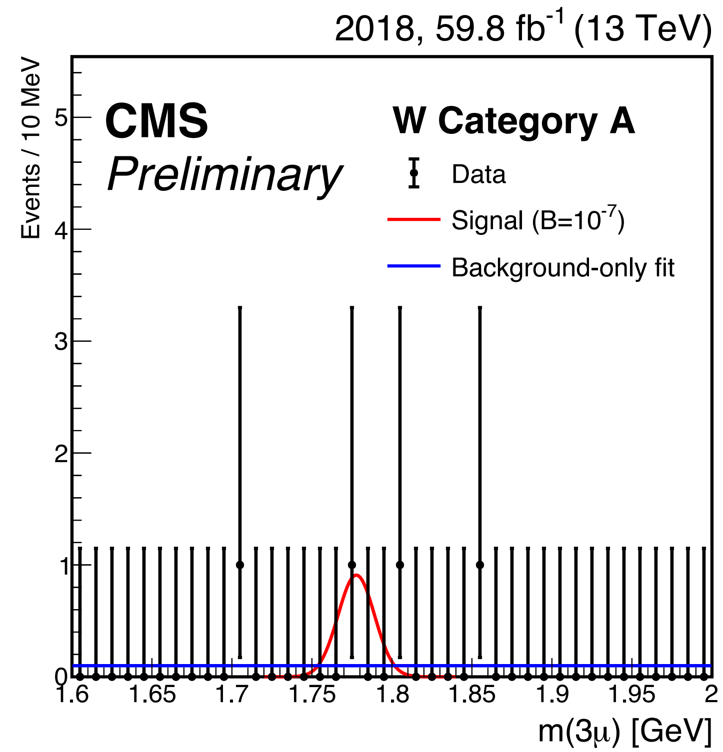


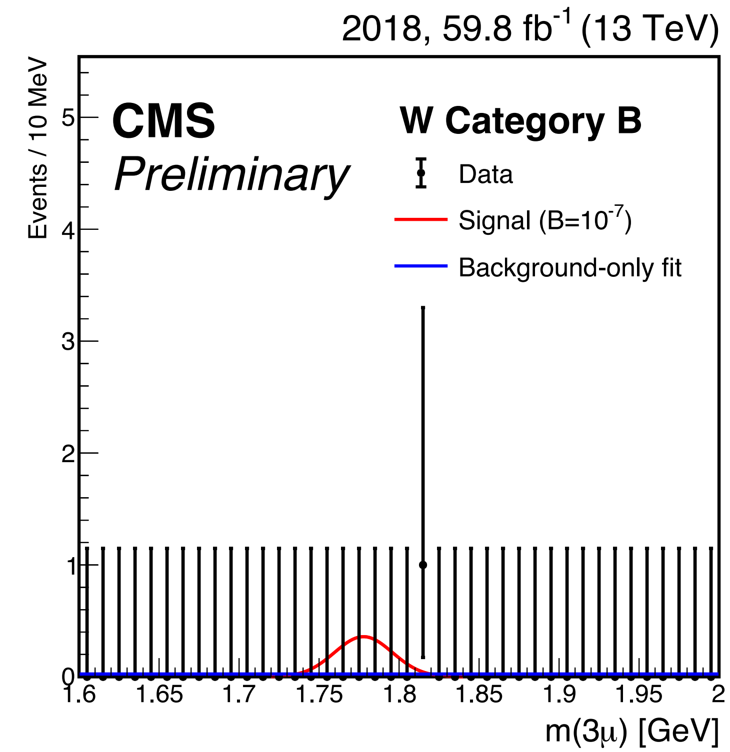


[CMS BPH-21-005](CMS BPH-21-005)

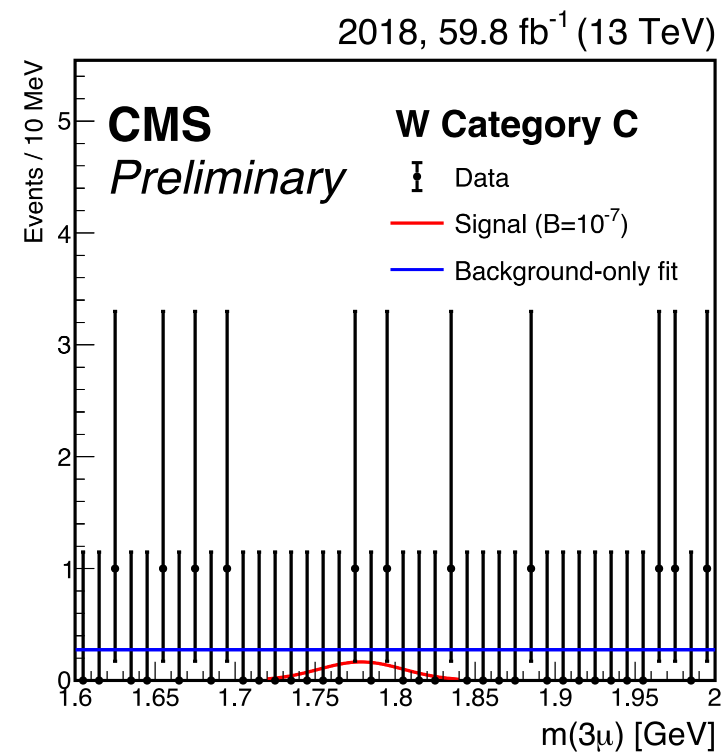
W analysis: results

- Events categorised based on mass resolution
- Signal model: Gaussian
- Background model: flat function





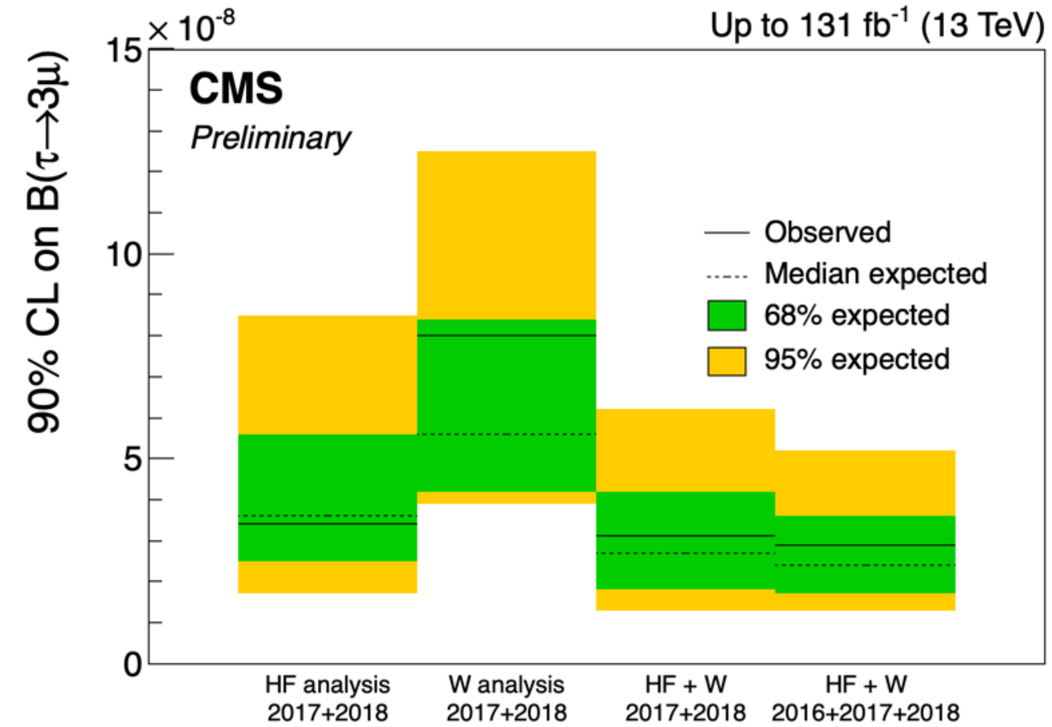
Observed (expected) upper limit on Br(τ→3μ) 8.0×10^{-8} (5.6×10^{-8}) at 90% CL



CMS Run 2 results on B(τ→3μ)

CMS BPH-21-005

- The HF and W analyses, together with the previously published 2016 data result, are combined
- Events that pass the final selections of both analyses are removed from the HF analysis
- Systematics are assumed to be uncorrelated between the HF analysis and the W analysis
- Results dominated by statistical uncertainty



The observed (expected) upper limit is 2.9×10^{-8} (2.4×10^{-8}) at 90% CL

Search for new heavy particles motivated by LFV

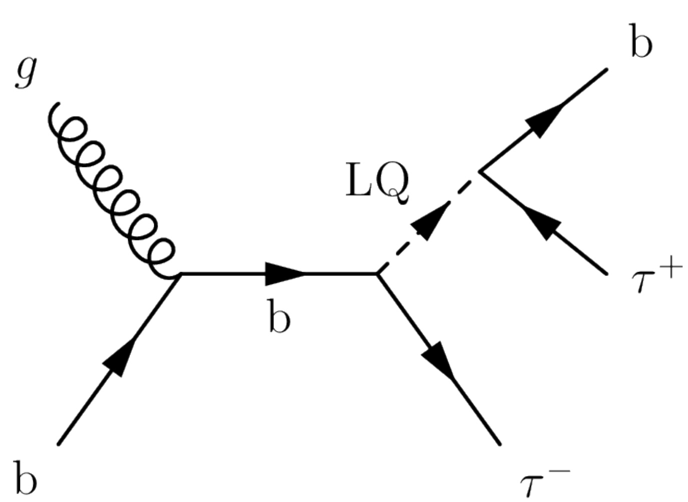
- Leptoquarks produced in lepton-quark collisions, CMS EXO-22-018
- Z’ associated with b-quarks, CMS EXO-22-016

Leptoquarks: introduction

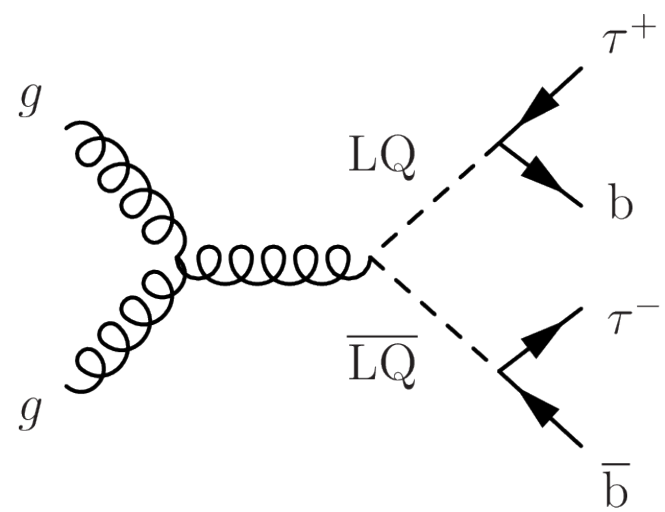
Leptoquarks (LQs) are hypothetical color-triplet bosons carrying both baryon and lepton number and having fractional electric charge

The “conventional” production mode:

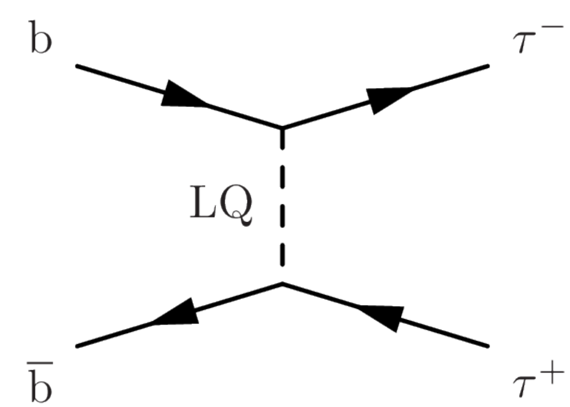
Single production



Pair production



Nonresonant production

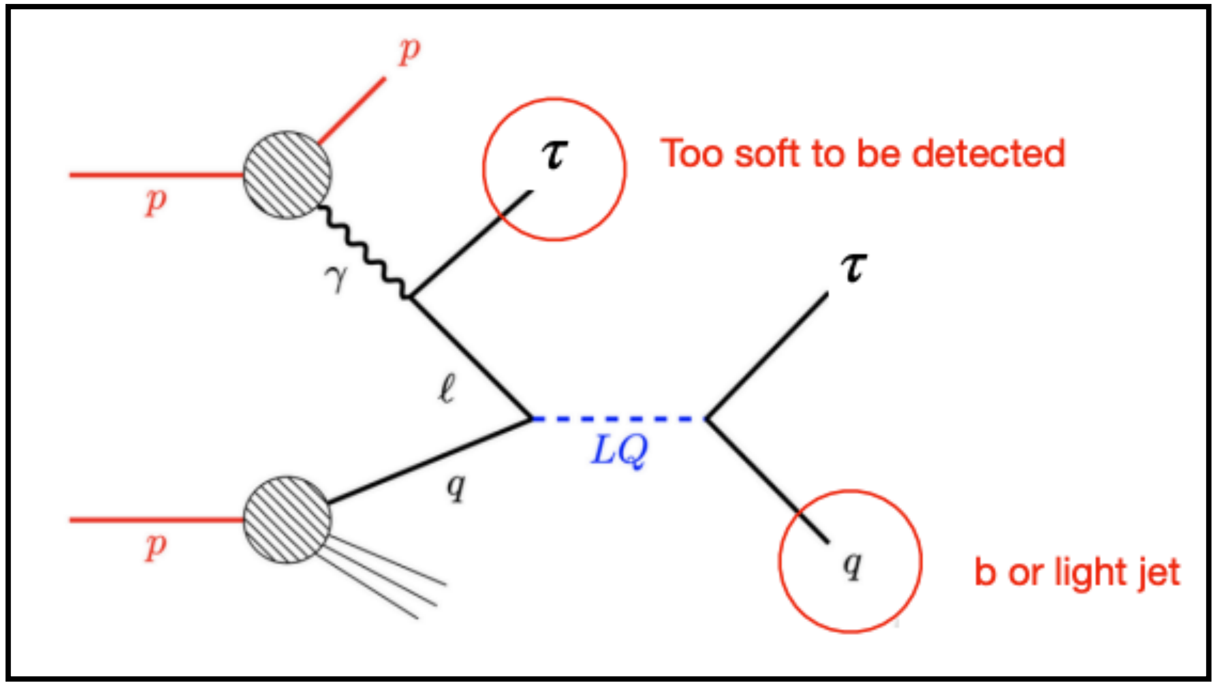


Two high p_T leptons, while the jet numbers vary

LQ produced in lepton-quark collisions

CMS EXO-22-018

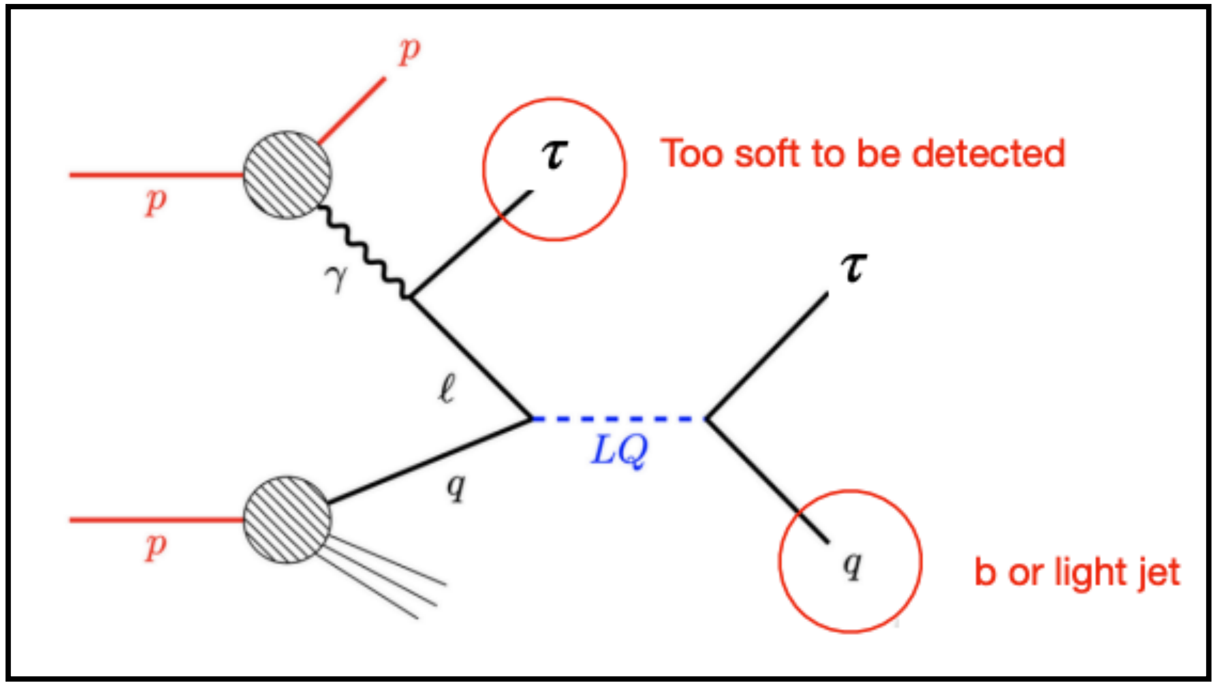
- First search for LQ using lepton-quark collisions
  - Recent developments in lepton PDF calculation allow for precise signal predictions (2005.06475, 2005.06477)
  - A lepton comes from the proton via vacuum fluctuations through a photon



- CMS utilize this production mode to search for leptoquarks coupling to τ and q (q= u, d, s, or b)

Leptoquarks produced in lepton-quark collisions: signature

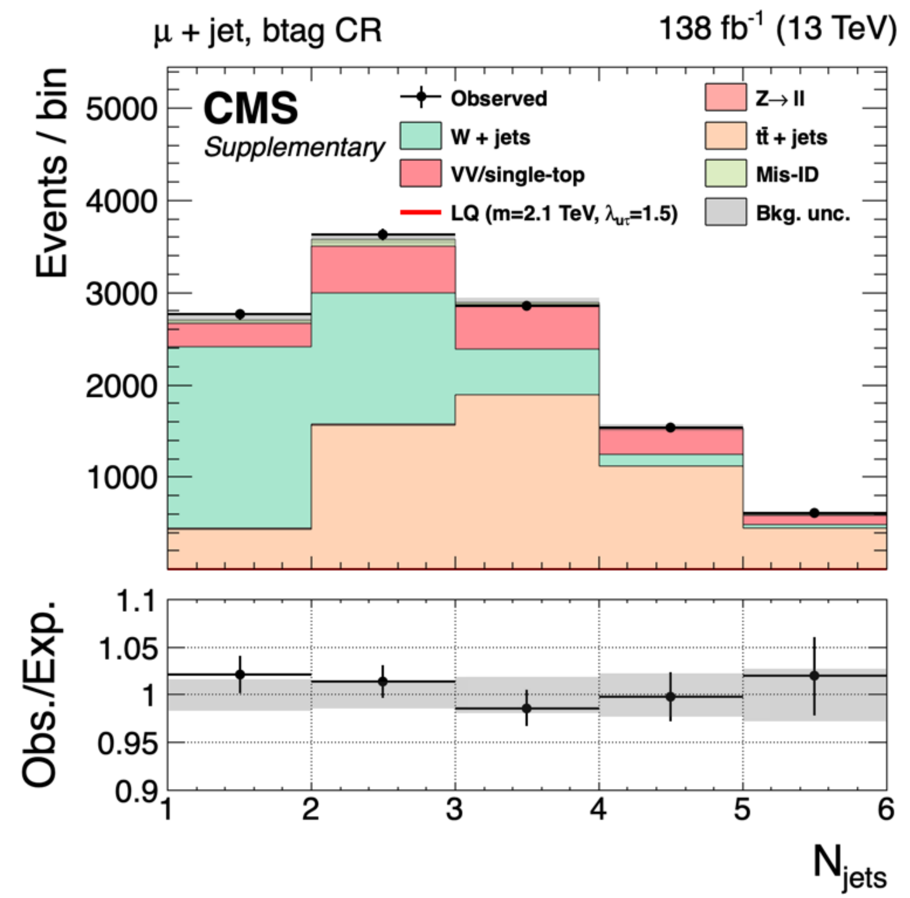
- One high p_T central τ-lepton from the LQ decay
    - Large MET aligned with visible τ decay products
- A high p_T central jet, back to back with the τ
- No additional high p_T lepton (the “2nd τ” is too forward and soft), a major difference than the other LQ production mechanisms
    - Apply lepton veto to make this analysis orthogonal to other LQ analyses
    - No ambiguity to reconstruct LQ mass



Leptoquarks produced in lepton-quark collisions: event selection

- The τ lepton is reconstructed through its leptonic or hadronic decays
    - e+jet, μ+jet, τ_h+jet final states
- Further divided into b-tagged/non-b-tagged categories in order to cover couplings to b or light flavor quarks
- **Main backgrounds:**
    - Jet misidentified as leptons: "fake factors" measured in control regions
    - Real lepton background
        - ttbar: MC prediction
        - W+jets: MC prediction; in b-tagged category, the normalisation relies on a control region
- **Analysis method:** BDT is trained to exploit different kinematics between signal and background

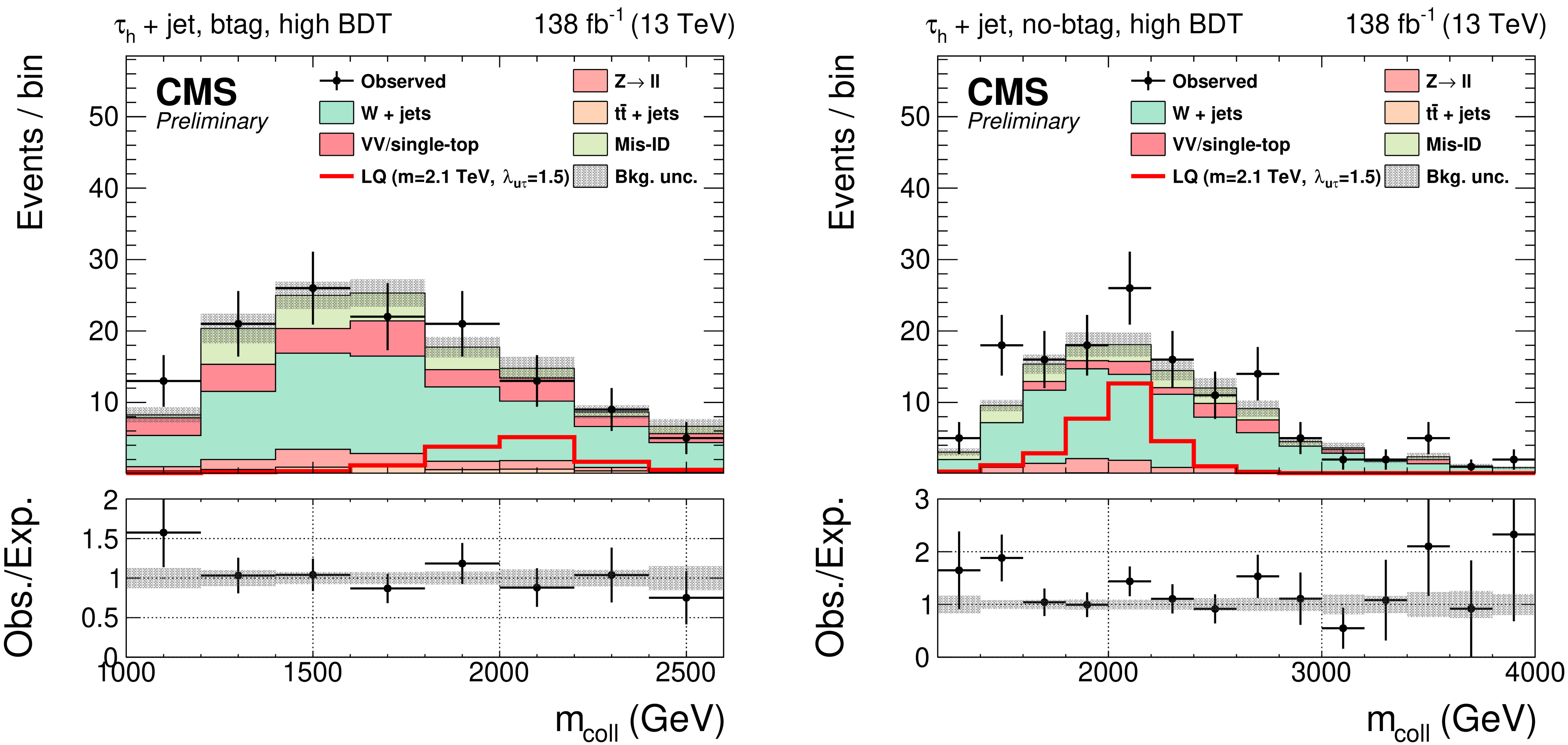
W+jets control region



CMS EXO-22-018

Leptoquarks produced in lepton-quark collisions: the final discriminant

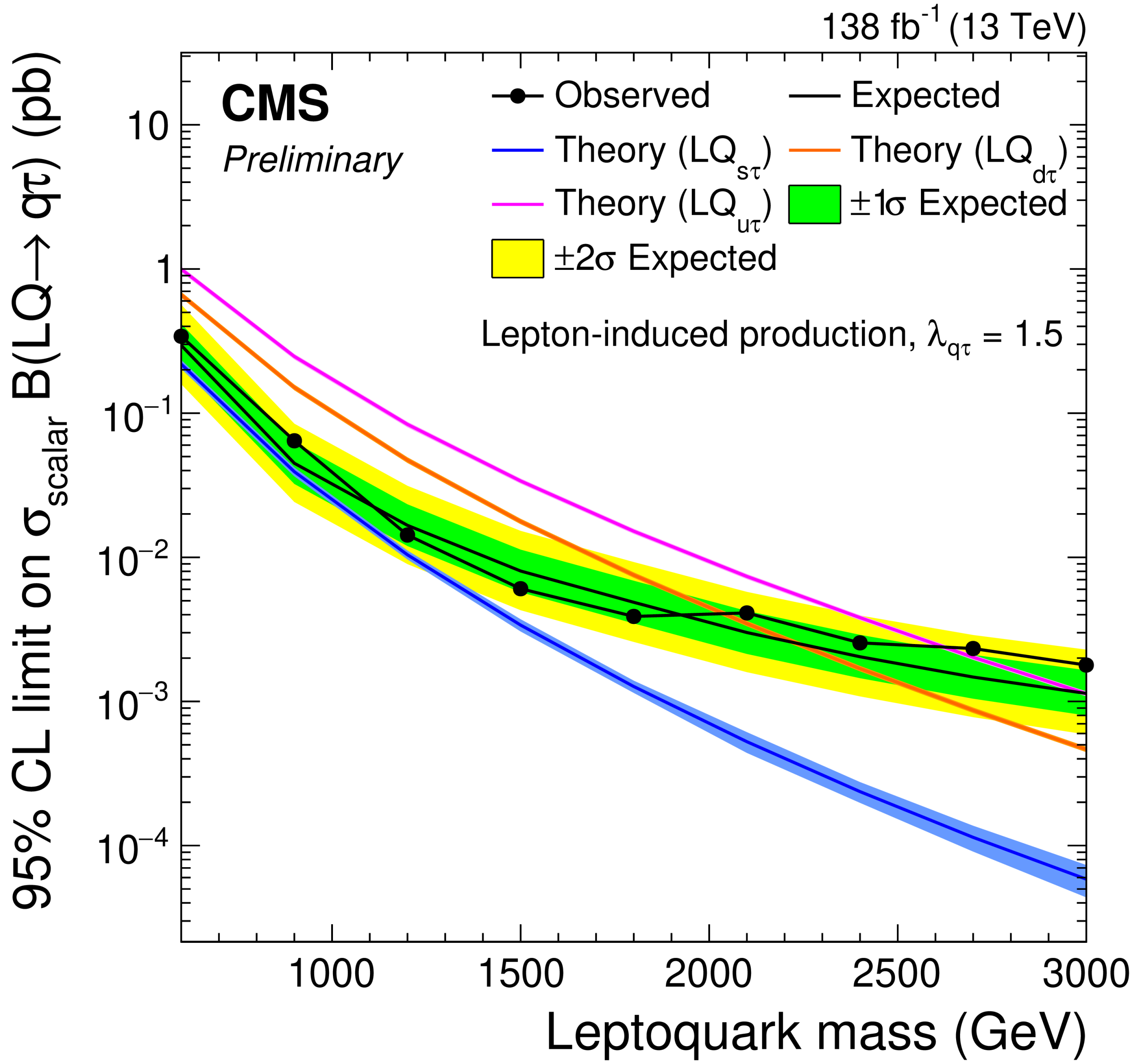
Collinear mass is reconstructed from the lepton, jet and MET, assuming the neutrinos are the only source of MET aligned with the visible τ decay products (~ 10% resolution)



The hadronic τ mode has the best sensitivity, thanks to larger branch fraction and smaller background

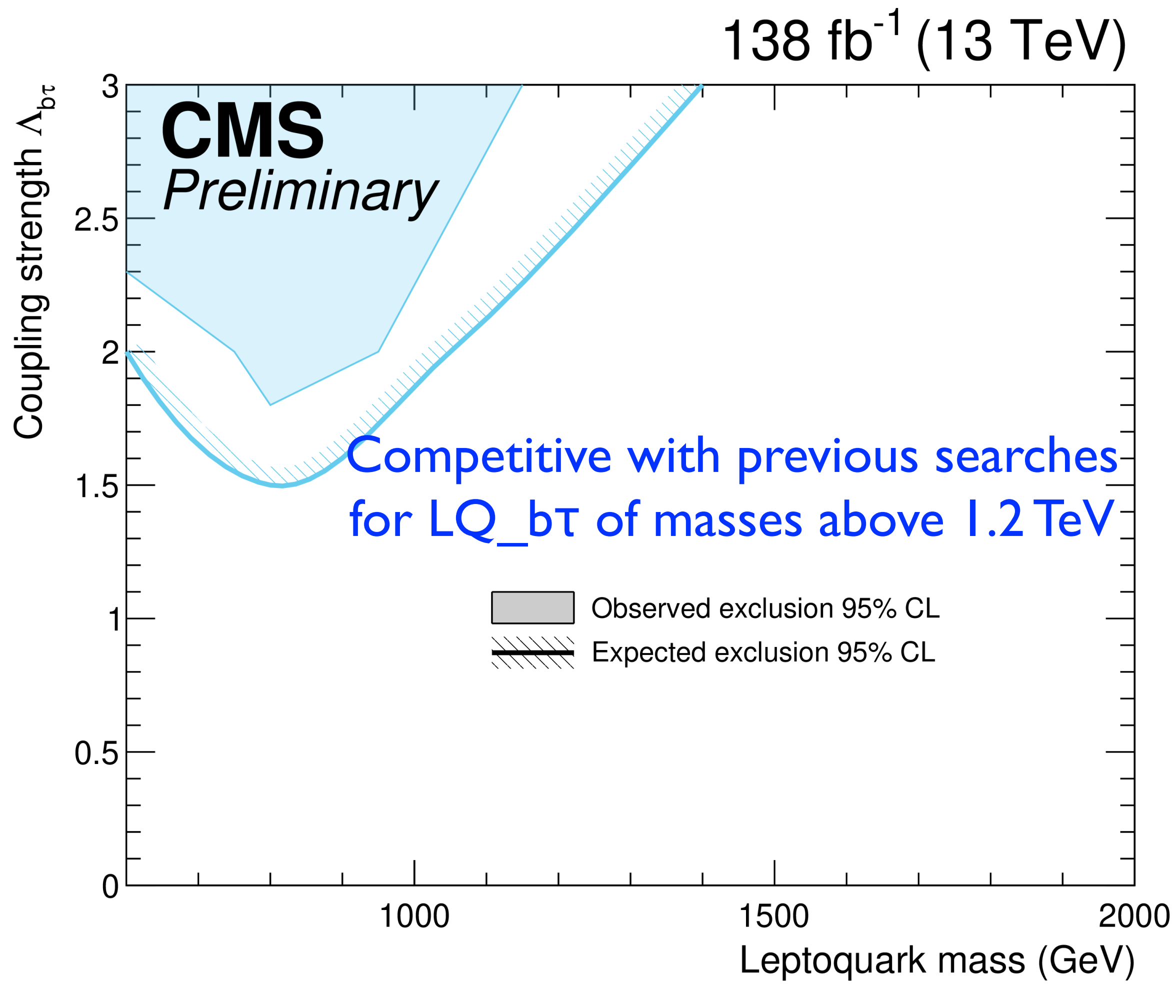
Leptoquarks produced in lepton-quark collisions: results

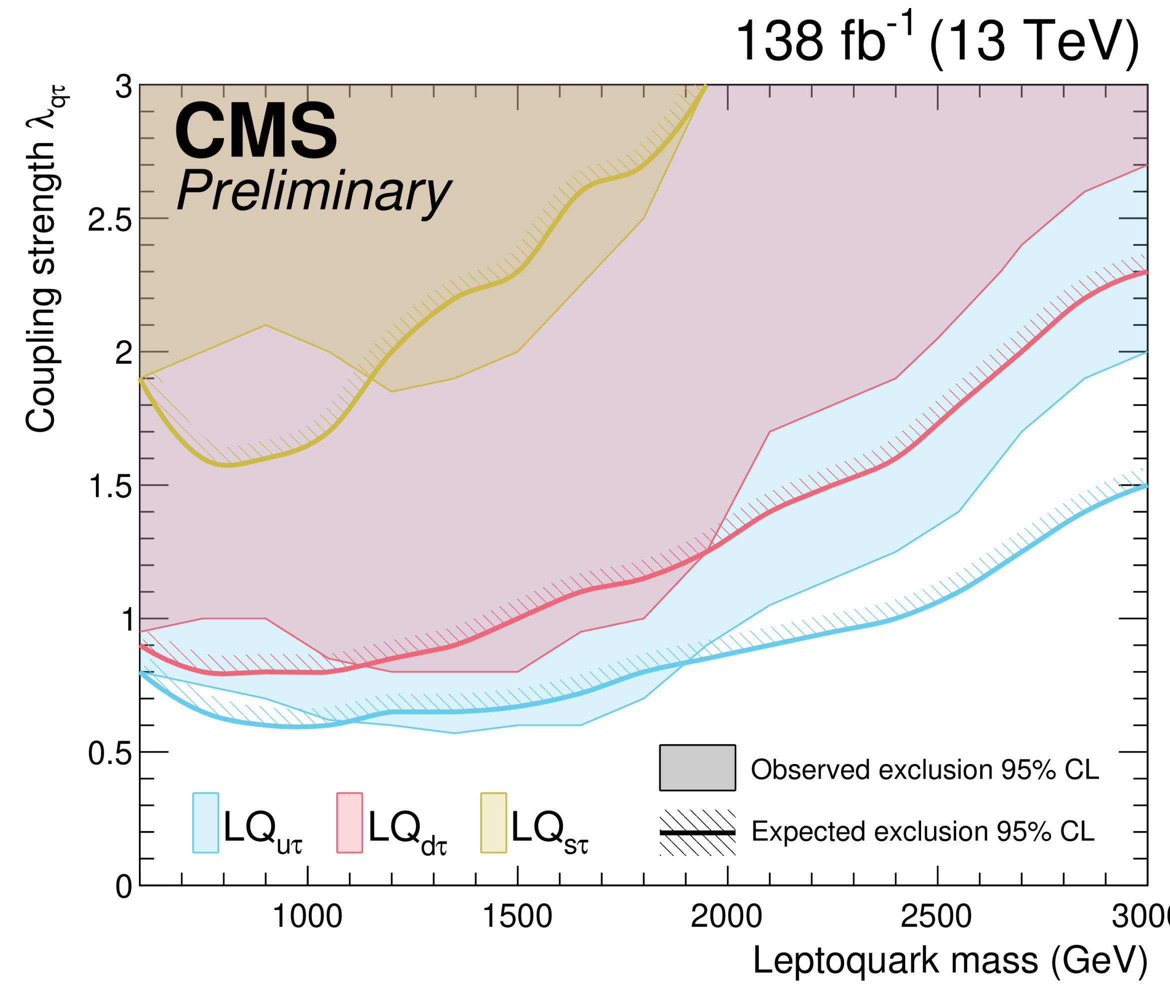
- For the first time, limits are set on LQ-τ-q couplings (q=u, d, s)
- LQ_uτ (LQ_dτ) with coupling strength 1.5 is excluded up to 2.6 TeV (2.0 TeV)



Leptoquarks produced in lepton-quark collisions: results

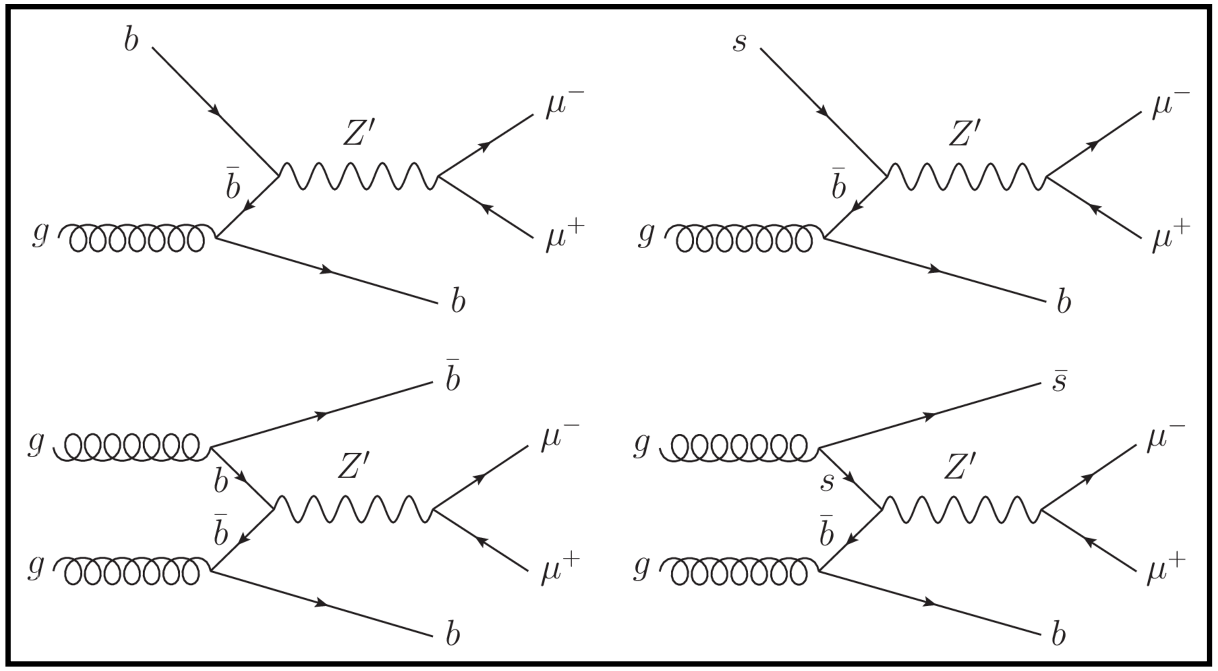
Exclusion regions in the mass-coupling 2D plan





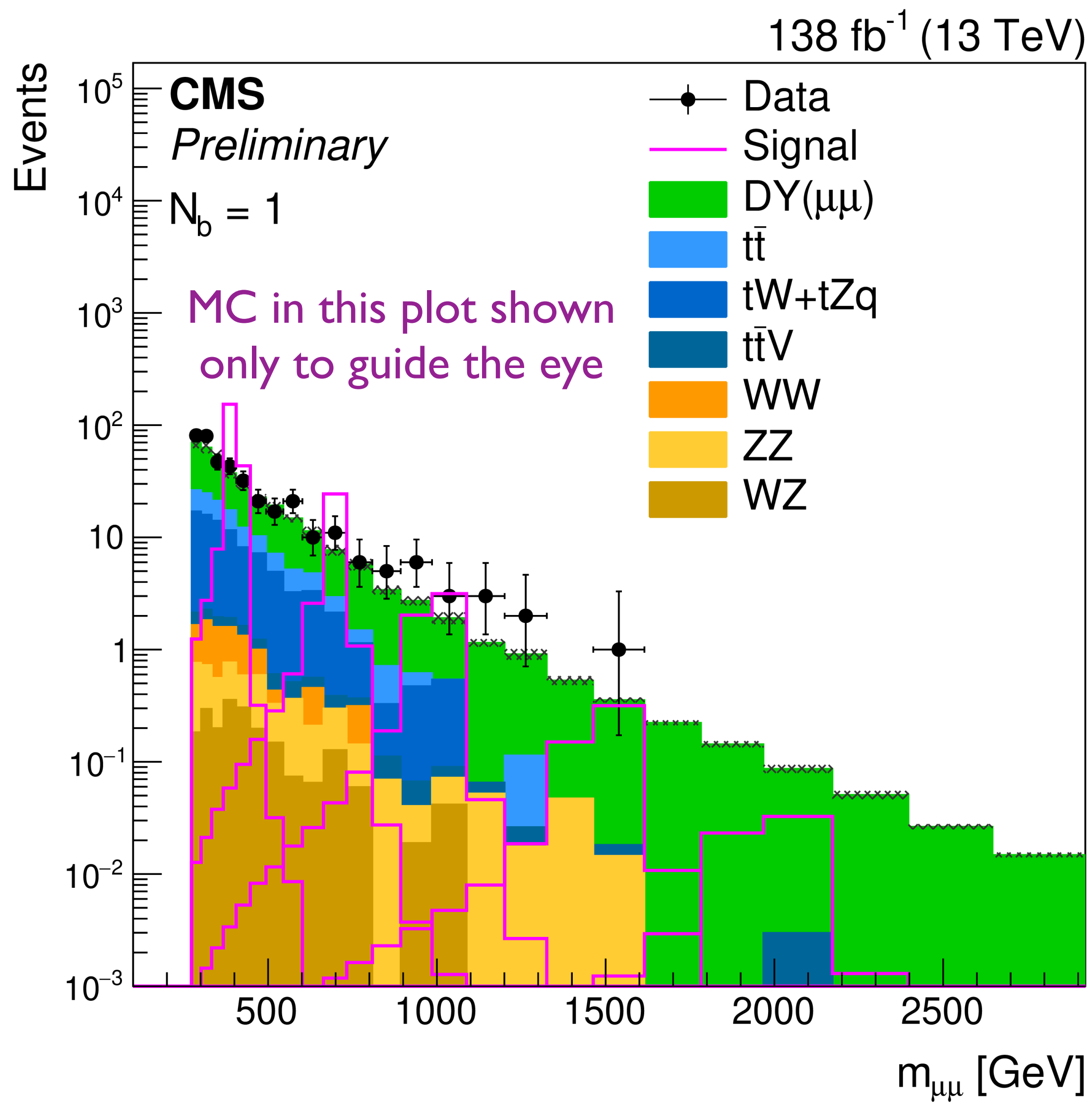
Search for Z’ + b quark jets

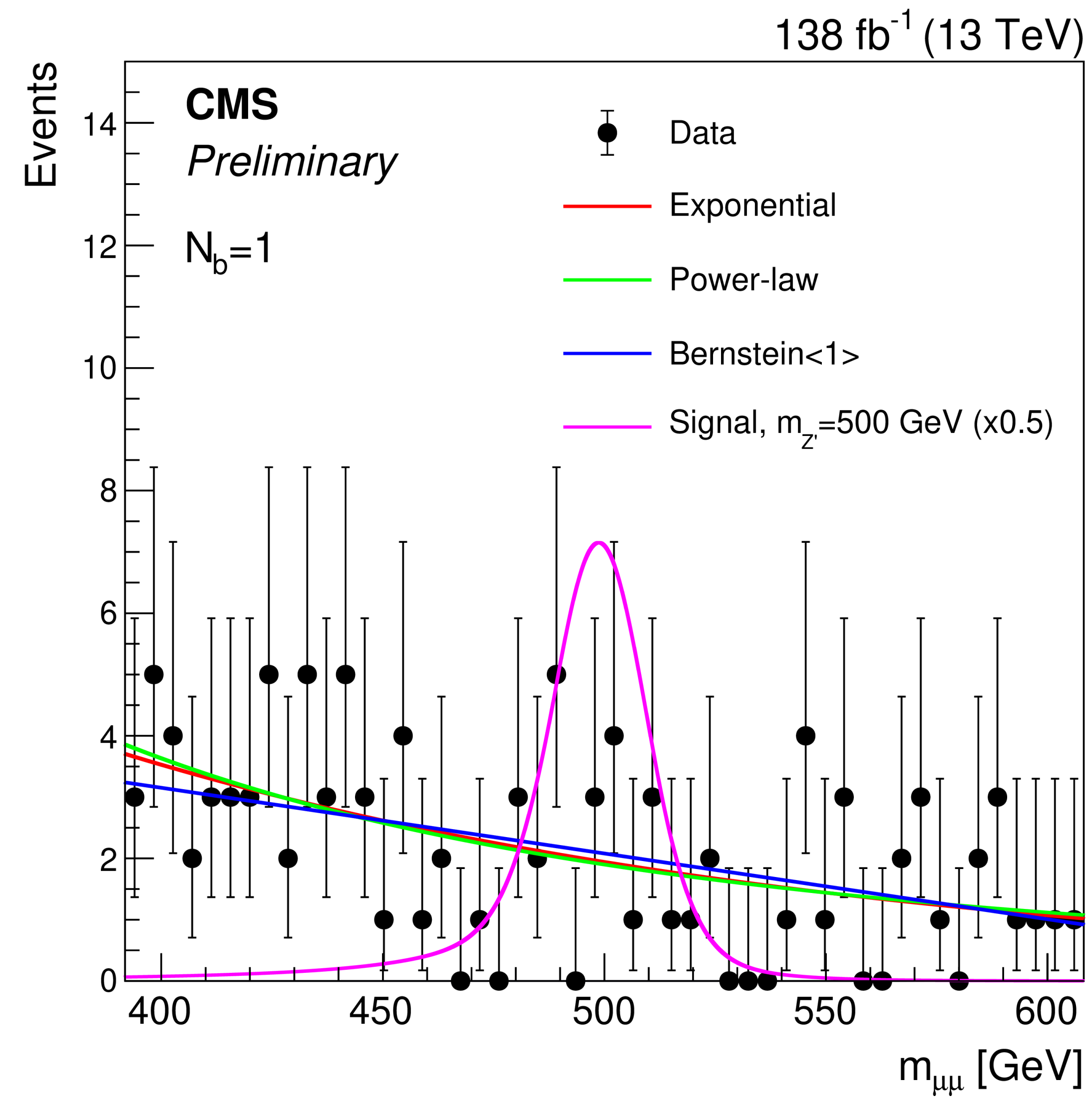
- Search for a neutral vector boson Z’→μμ with m(Z’) above 350 GeV, with at least one b quark jet
    - Width assumed to be small relative to the mass resolution
- If the Z’ couples to b and s quarks, and has preferential coupling to μμ => implications to low energy b→sll observables (e.g. B_3-L_2 model, JHEP04 2023 033)



- Analysis sensitivity enhanced by event categorization according to the multiplicity of b quark jets: N_b =1 and N_b ≥ 2
- Dominant backgrounds: Drell-Yan, ttbar
    - ttbar veto: min($m_{\mu b}$) > 175 GeV keeps < 1% of ttbar background

Search for Z' + b quark jets: m(μμ) distributions

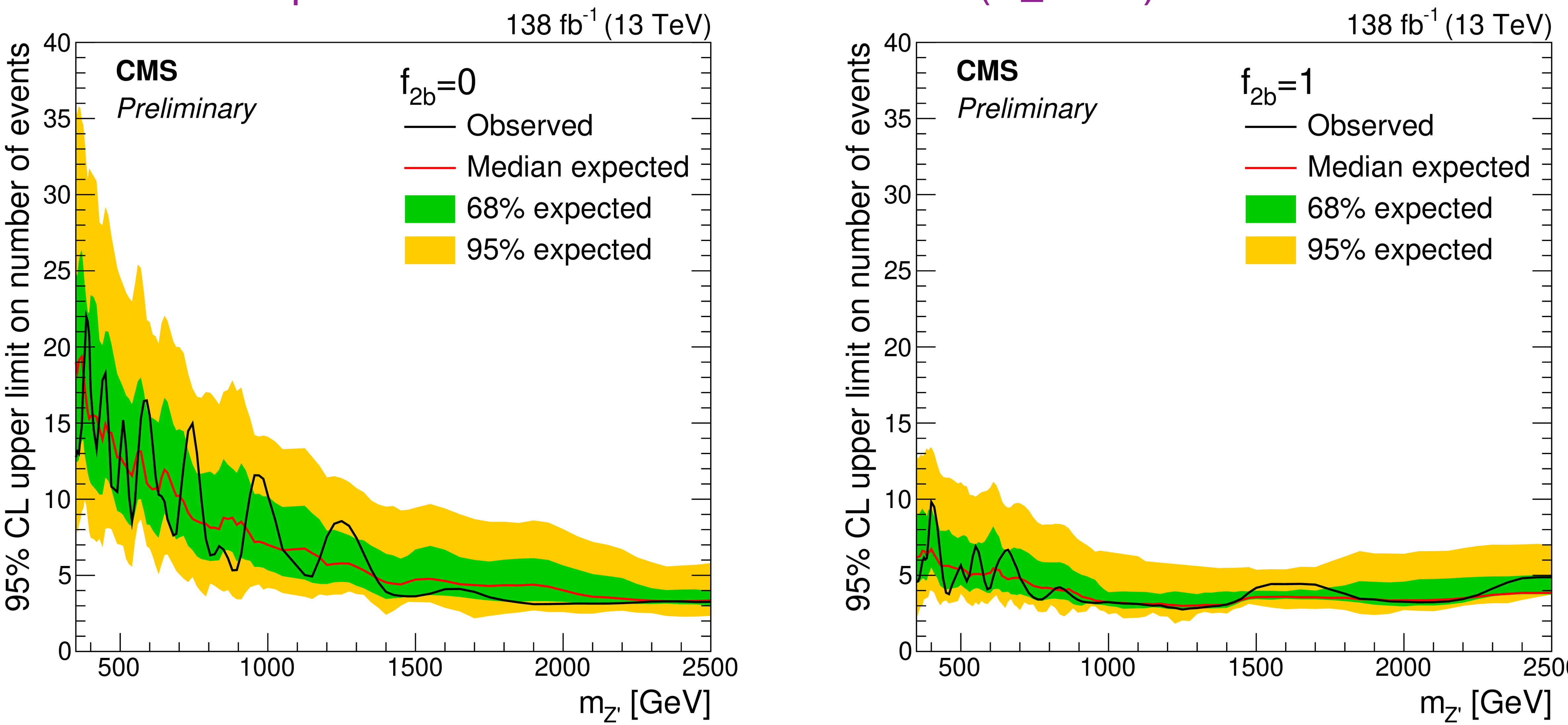




- To probe a wide mass range, sliding mass window fit of the m(μμ) distribution with an opening of +/-10 times the m(μμ) resolution, starting from 275 GeV onward
- Signal shape: Gaussian plus double-sided Crystal Ball
- Background: parametric shapes fit from the data in the window

Search for Z’ + b quark jets: results

Model independent limit on number of events (N_b ≥ 1)

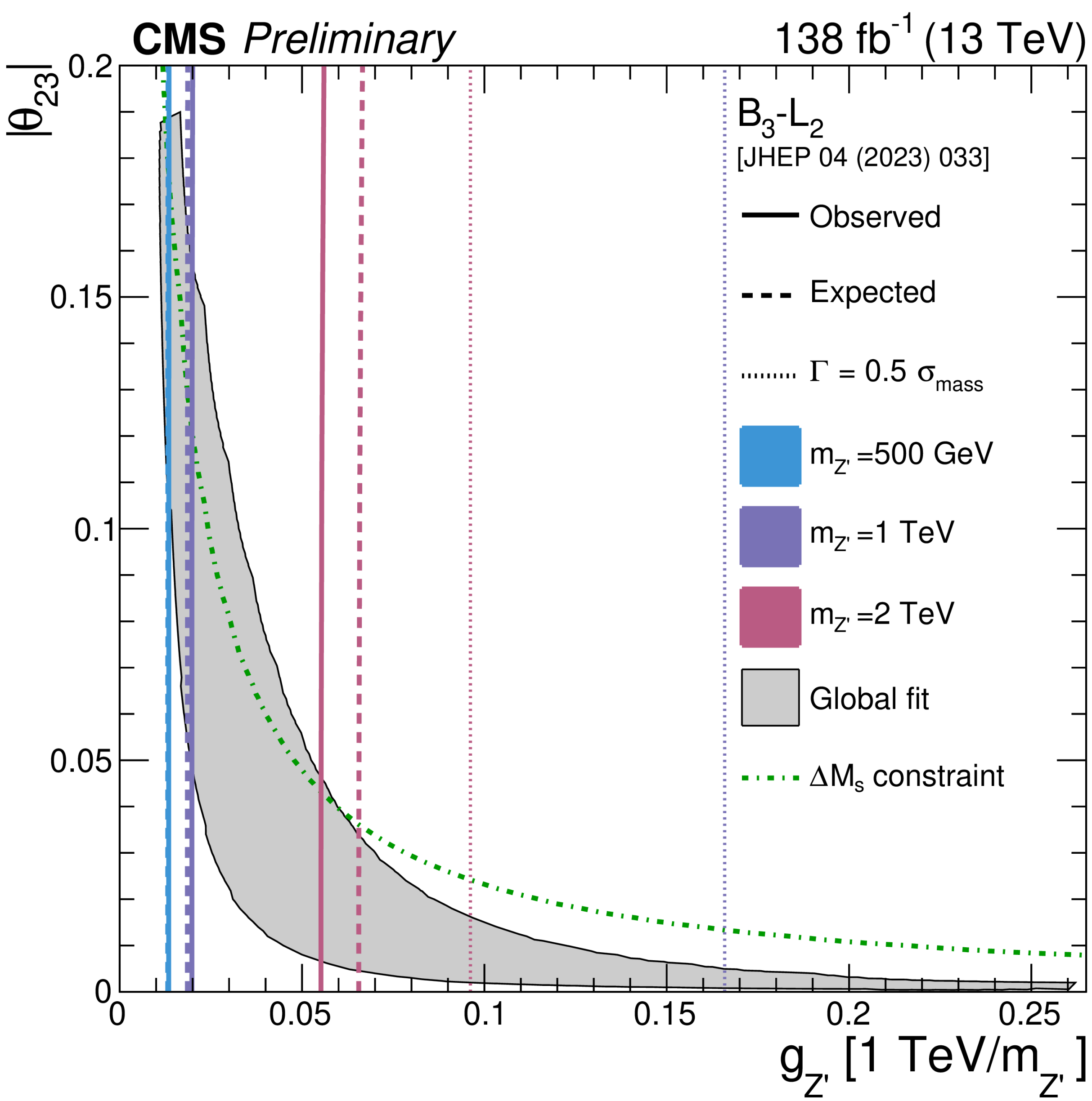


f(2b): the fraction of expected signal events in N_b ≥ 2 category.

f(2b) is varied to probe different signal hypotheses.

Search for Z' + b quark jets: results

Limits on B_3-L_2 model



- In this model, $g_{Z'}$ denotes the coupling of the Z' to SM fermions
- θ_{23} is the mixing angle between the 2nd and 3rd generation quarks
- Restrict to parameter space where the Z' width < $\sigma_{mass}/2$
- Most of the allowed parameter space is excluded for a Z' with a mass < 500 GeV
- The constraints are less stringent for higher m(Z')

Summary

- LFV searches are motivated by general considerations, though no lack of models predicting LFV

Who ordered that?

- I. I. Rabi, 1936

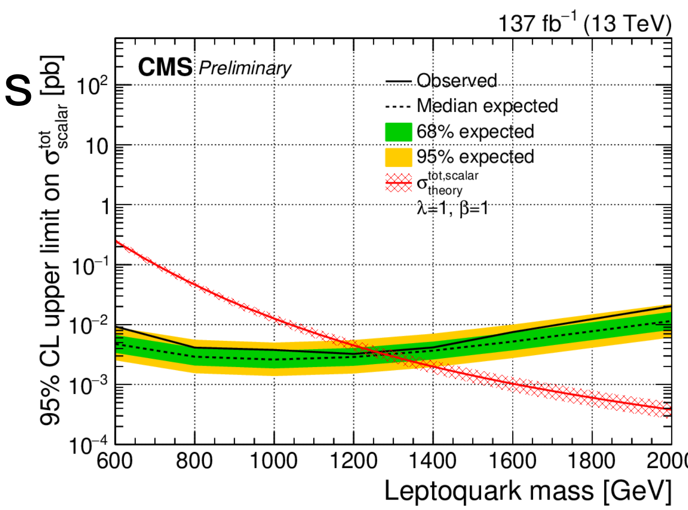
- CMS, as a general purpose experiment, searches for LFV in various regimes
  - Measuring decay rates of SM particles
  - Direct search for new particles motivated by LF(U)V
- Both high p_T and low p_T regions are explored - a broad physics reach and excellent detector performance of CMS
- LFV τ decays: an upper limit is set on $Br(\tau \rightarrow 3\mu) < 2.9 \times 10^{-8}$ @ 90% CL, with an expected limit of 2.4×10^{-8}; reaching comparable sensitivities to B-factories
- Leptoquark and Z’: parameter space further explored, notably the first search for LQ using the lepton-quark collision production mode
- Stay tuned

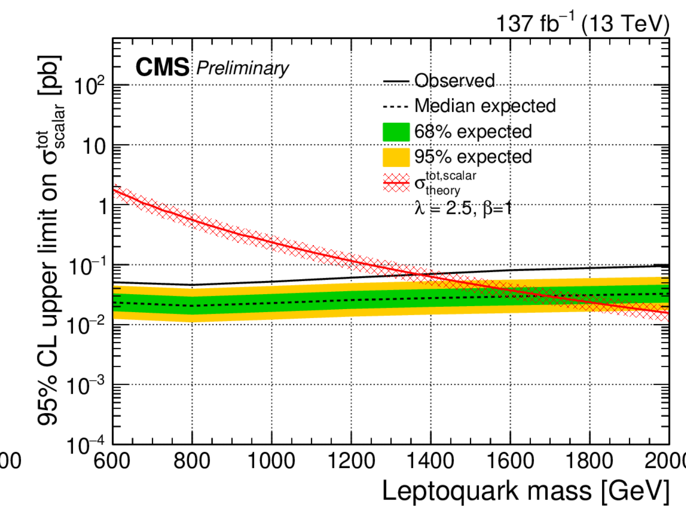
BACK-UP

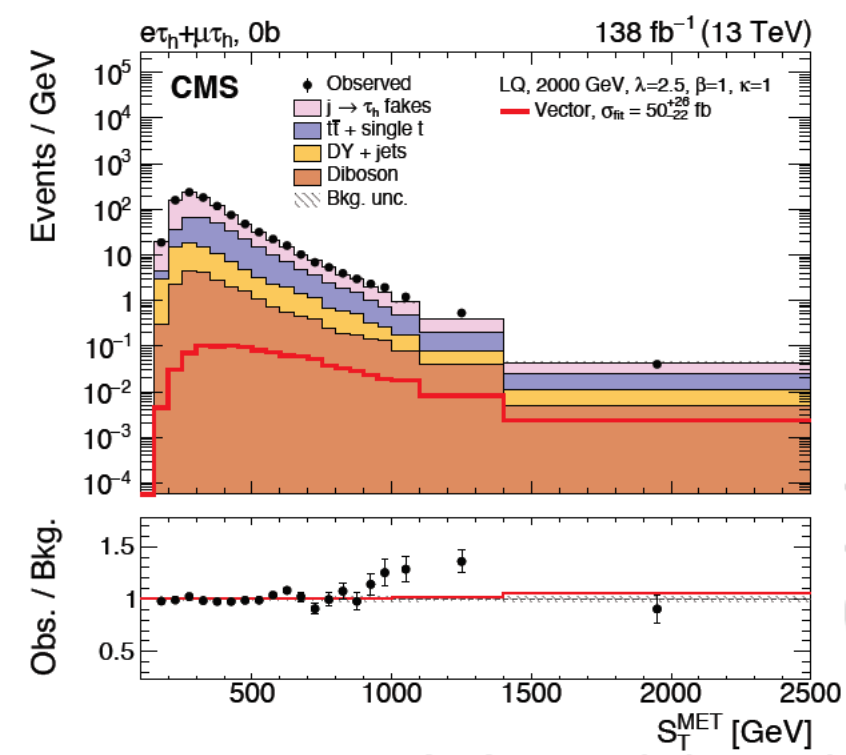
Di-τ search: LQ coupling to τ and b

CMS EXO-19-016

- Final state signature: two energetic τ leptons and b quark jets
- Various τ decay mode taken into account
  - $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$, $e\mu$, $\mu\mu$
- Events with at least one high-pT jet: the resonant production; main background ttbar
- Events with no high-pT jets: nonresonant production; main background Drell-Yan
- Large excess of events is observed in the 0b category in the high value of S_T (scalar sum of the two τ, the leading jet and the MET)
  - It has contributions from multiple channels
  - The excess seems to be un-signal-like in the strict sense of the probed LQ model here



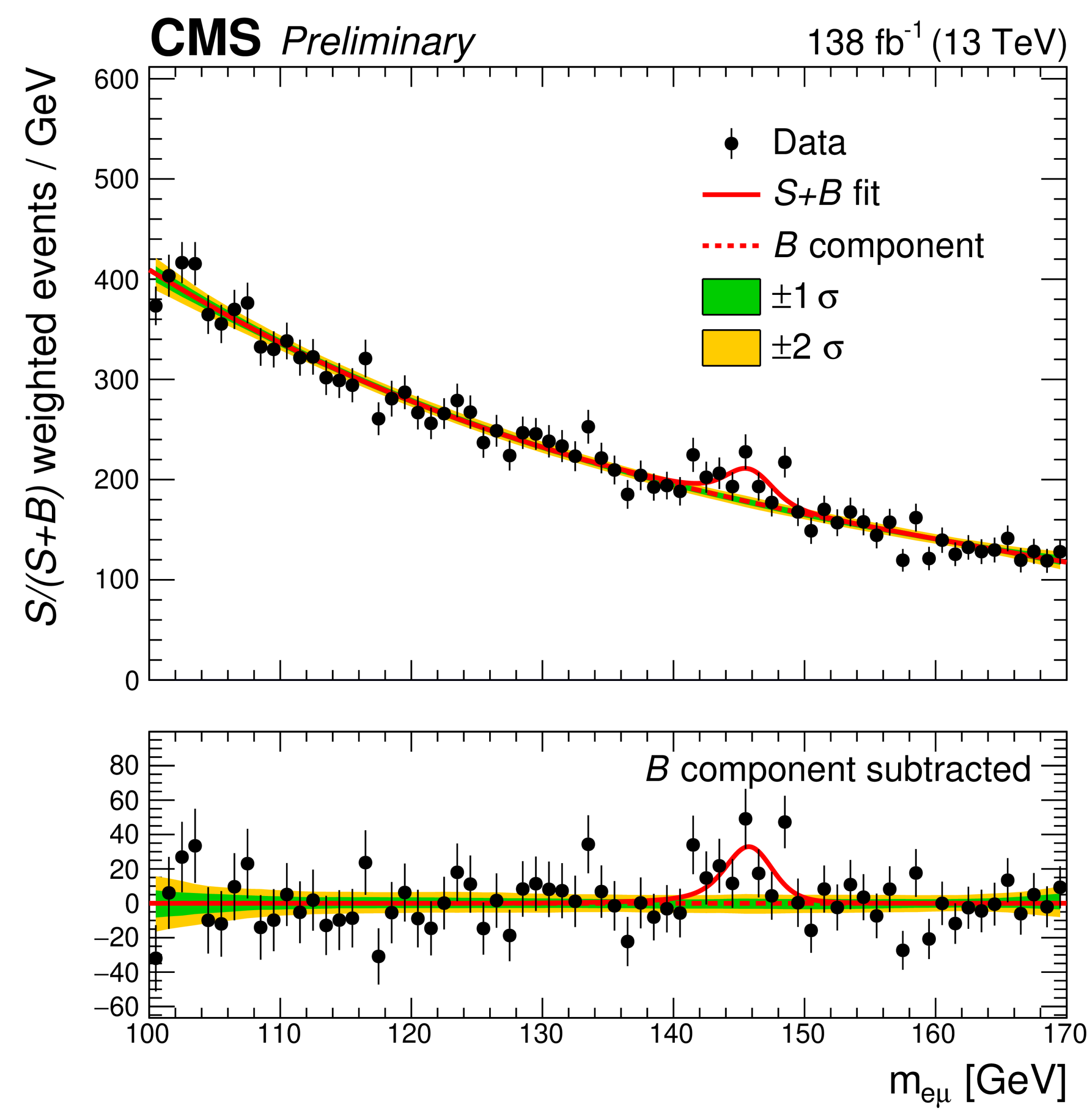


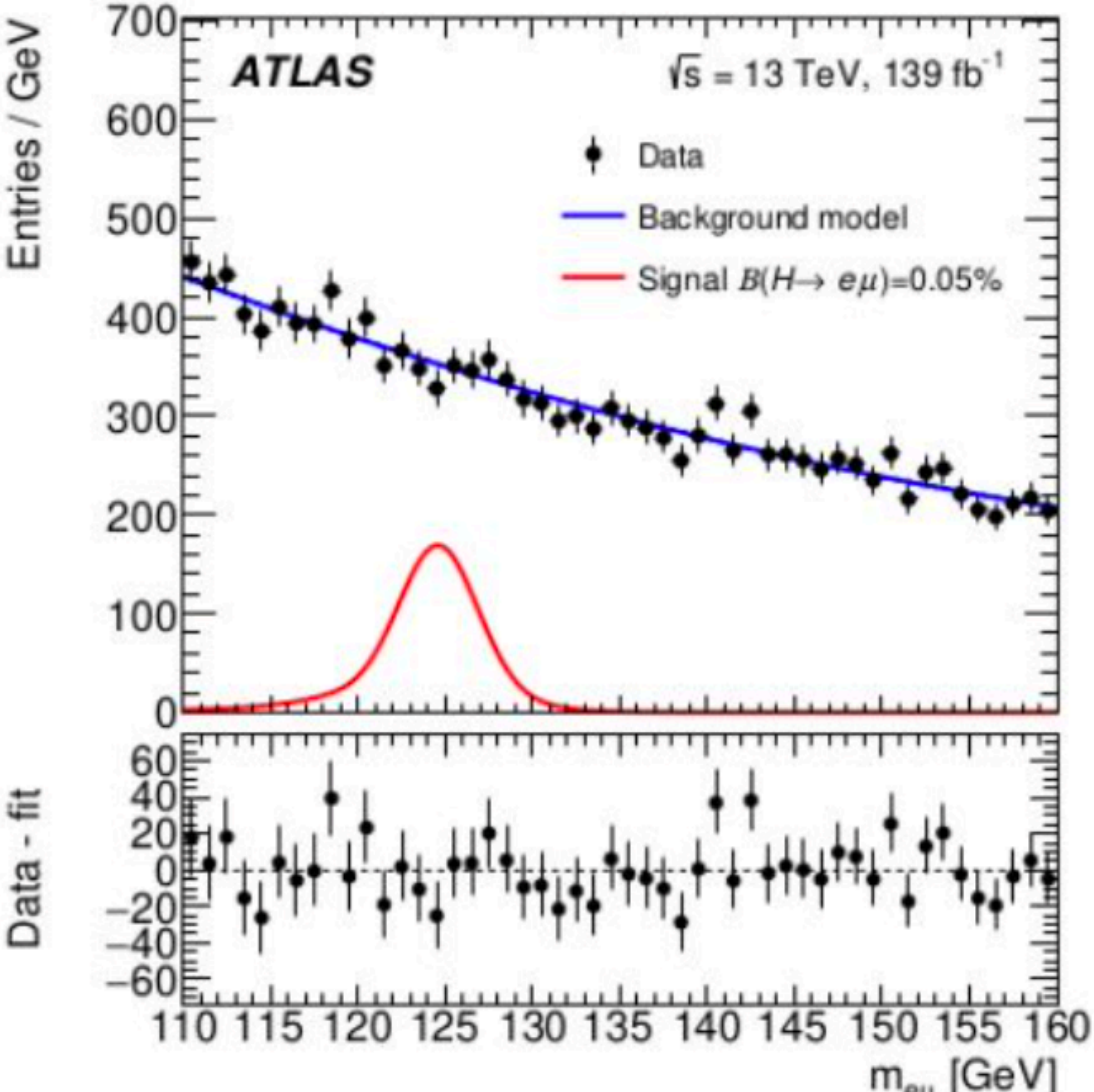


LFV Higgs decay

CMS HIG-22-002

- Search for Higgs→eμ LFV decays
- No significant excess is observed at around Higgs(125)
- The observed (expected) upper limit on B(H→eμ) is set to be 4.4 (4.7) x 10^{-5}, the most stringent from direct searches
- By product: a 2.8 sigma excess at ~146 GeV; which is however not confirmed looking at the sideband of the ATLAS analyses in H→eτ and H→μτ

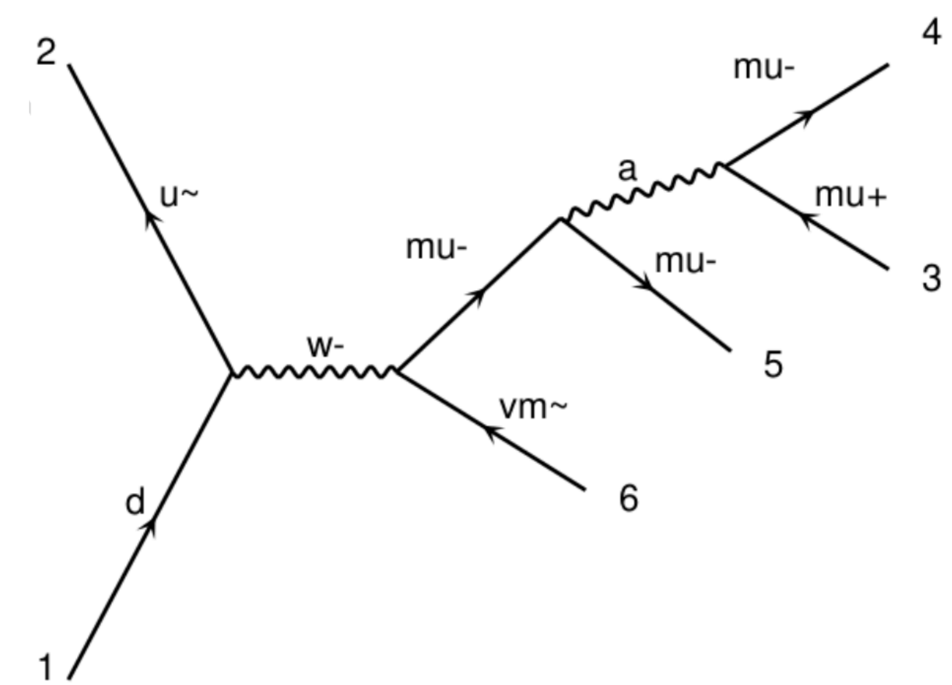



ATLAS
√s = 13 TeV, 139 fb⁻¹
Data
Background model
Signal B(H→ eμ)=0.05%
Entries / GeV
Data - fit
m_eμ [GeV]

CMS BPH-21-005

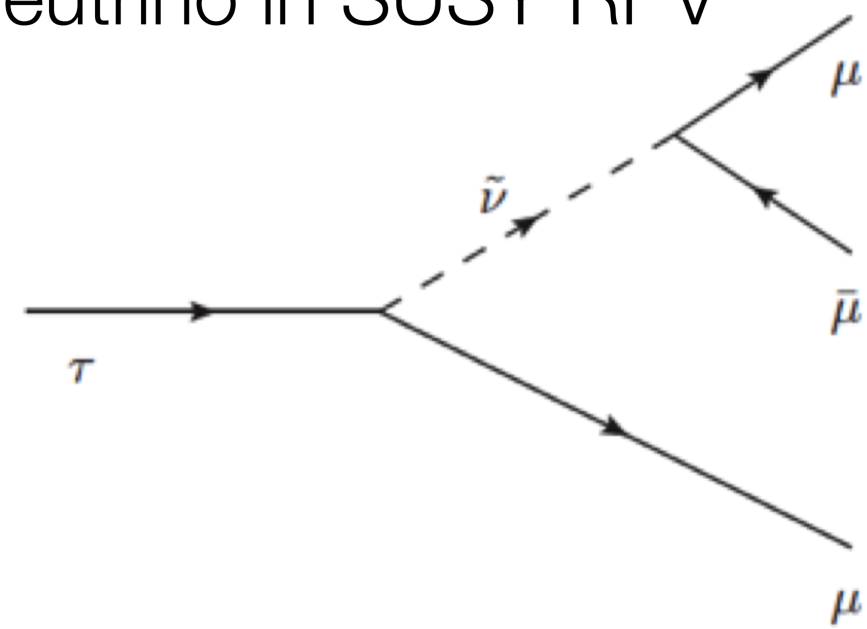
The W→3μ+ν background

- All selection criteria were determined in a blind way
- It was noticed only after unblinding that a significant fraction of events had the trimuon vertex not displaced from the primary vertex
  - Despite this displacement is one of the BDT input observables
- These events were found to be consistent with MC prediction of a W→μμμν sample
- An additional requirement is applied: the trimuon vertex must be displaced by at least 2 sigma

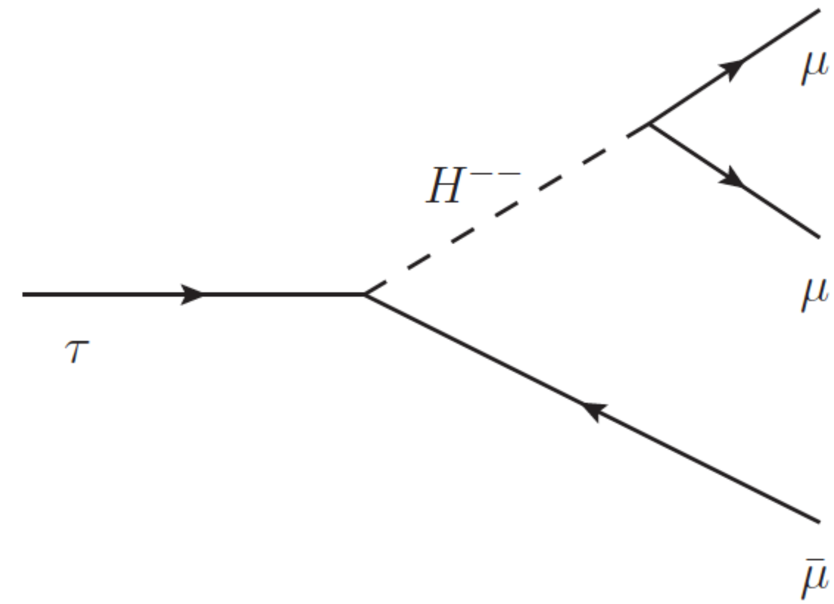


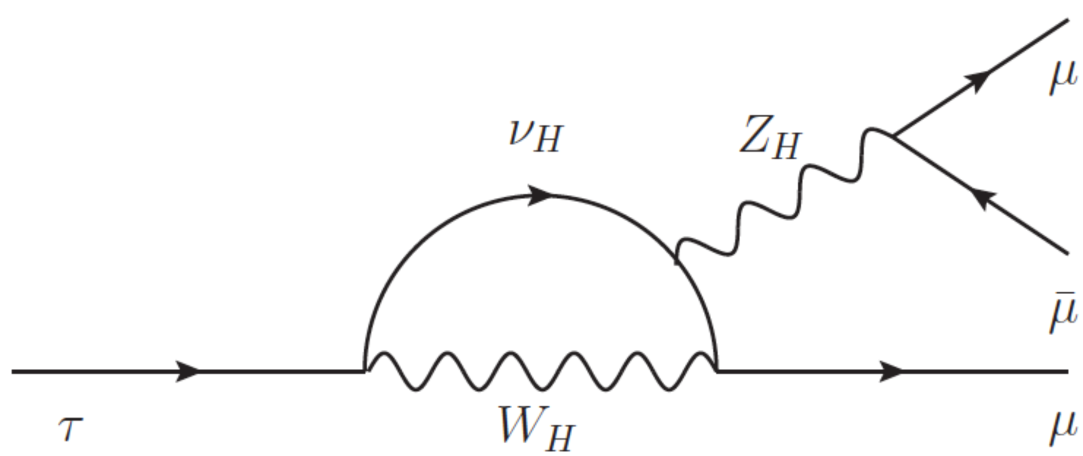
LFV models that predict Br($\tau \rightarrow 3\mu$) ~ 10^{-10} -10^{-8}

Sneutrino in SUSY RPV



Doubly-charged Higgs





Little Higgs model with T-parity

Indirect probes to New Physics scale ~> 10 TeV

Signal normalization: B→τ

(2) B→τ

$$N_{\mathrm{sig(B)}} = \mathcal{L}\,\sigma(pp \to B)\;\mathcal{B}(B \to \tau + ...)\;\mathcal{B}(\tau \to 3\mu)\;\mathcal{A}_{3\mu(B)}\;\epsilon^{3\mu}_{\mathrm{reco}}\;\epsilon^{2\mu}_{\mathrm{trig(sig)}}$$

Define f,

$$f = \frac{\sigma(pp \to B)\mathcal{B}(B \to D_s + ...)}{\sigma(pp \to D_s)}$$

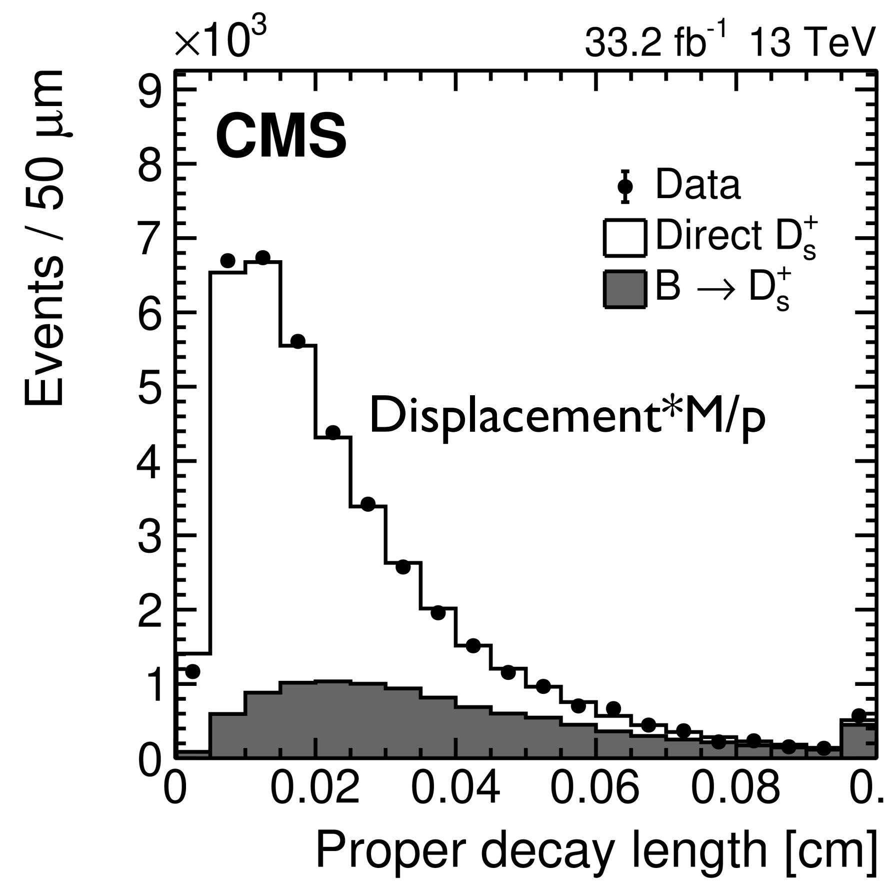
Together with the Ds→ϕ(2μ)π yields

$$N = \mathcal{L}\,\sigma(pp \to D_s)\;\mathcal{B}(D_s \to \phi\pi \to \mu\mu\pi)\;\mathcal{A}_{2\mu\pi}\;\epsilon^{2\mu\pi}_{\mathrm{reco}}\;\epsilon^{2\mu}_{\mathrm{trig}(\mu\mu\pi)}$$

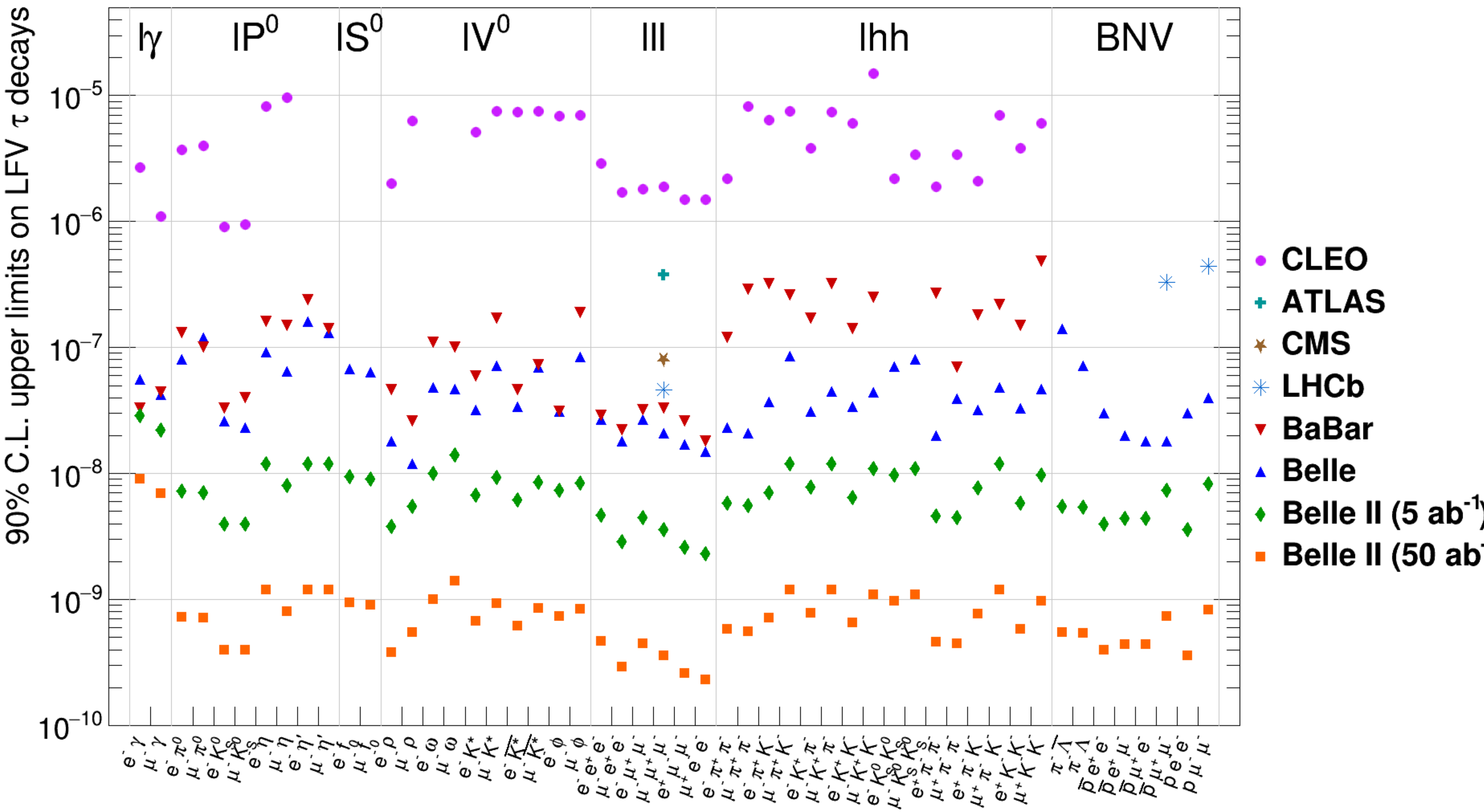
Then re-write:

$$N_{\mathrm{sig(B)}} = N \cdot f \cdot \frac{\mathcal{B}(B \to \tau + ...)}{\mathcal{B}(D_s \to \phi\pi \to \mu\mu\pi)\mathcal{B}(B \to D_s + ...)}\frac{\mathcal{A}_{3\mu(B)}}{\mathcal{A}_{2\mu\pi}}\frac{\epsilon^{3\mu}_{\mathrm{reco}}}{\epsilon^{2\mu\pi}_{\mathrm{reco}}}\frac{\epsilon^{2\mu}_{\mathrm{trig,sig}}}{\epsilon^{2\mu}_{\mathrm{trig}(\mu\mu\pi)}}\mathcal{B}(\tau \to 3\mu).$$

BR and their uncertainties

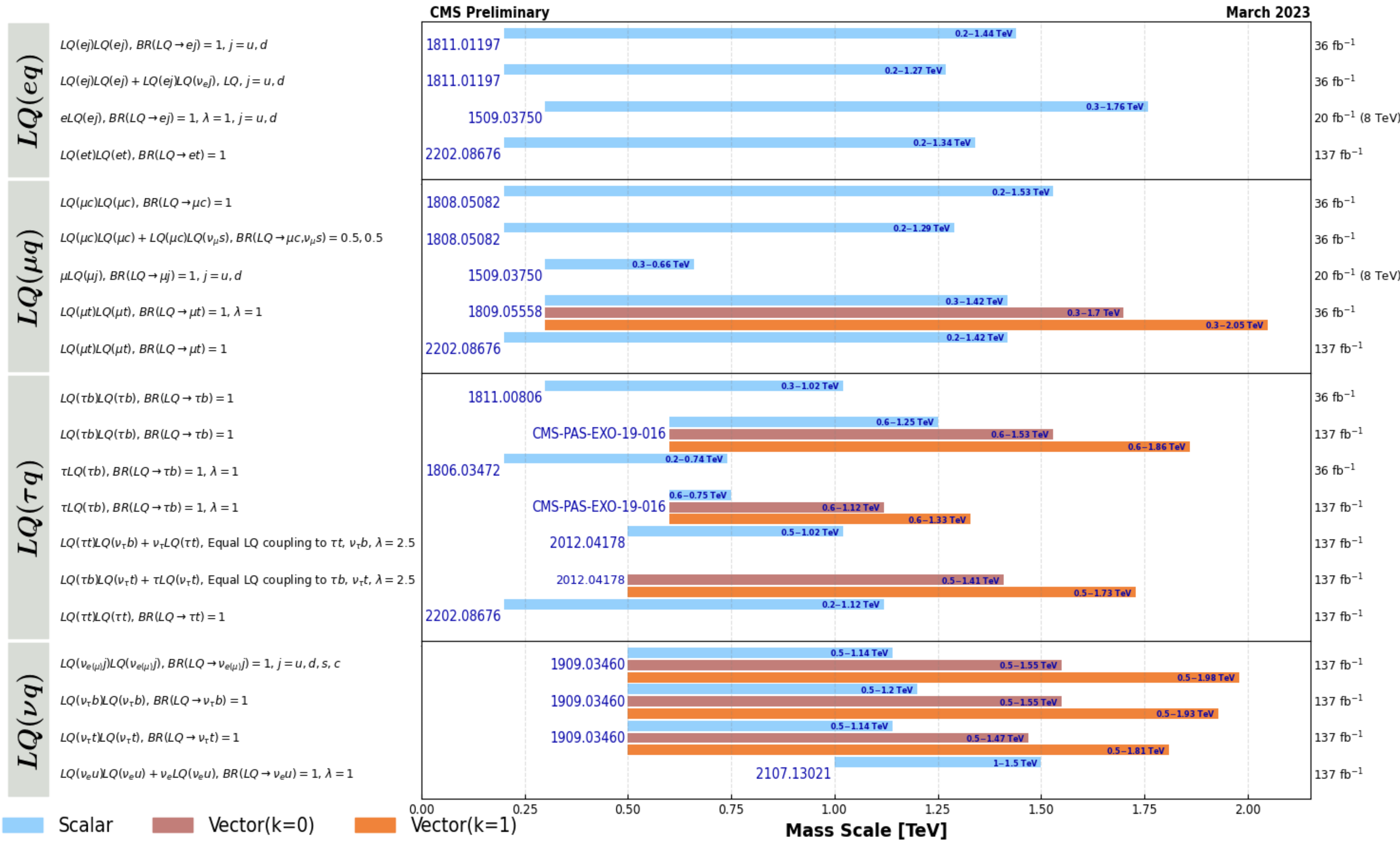


Fit prompt and non-prompt Ds→ϕ(2μ)π in data



2207.06307 Belle II Snowmass

Overview of CMS leptoquark searches



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).