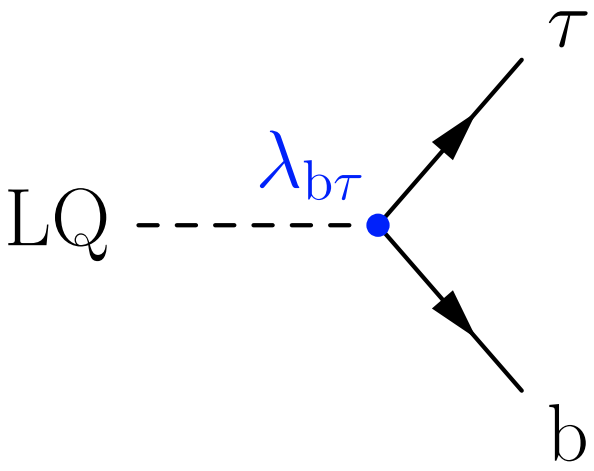
Universität Zürich[UZH]
Physik-Institut



A Search for Leptoquarks Coupling to τ Leptons and Bottom Quarks in Proton-Proton Collisions at the CMS Experiment

Izaak Neutelings
izaak.neutelings@uzh.ch

PhD defense, 23/02/2022

Overview

Part I: Motivation & setup

- Standard Model & beyond
- CMS detector

Part II: τ leptons

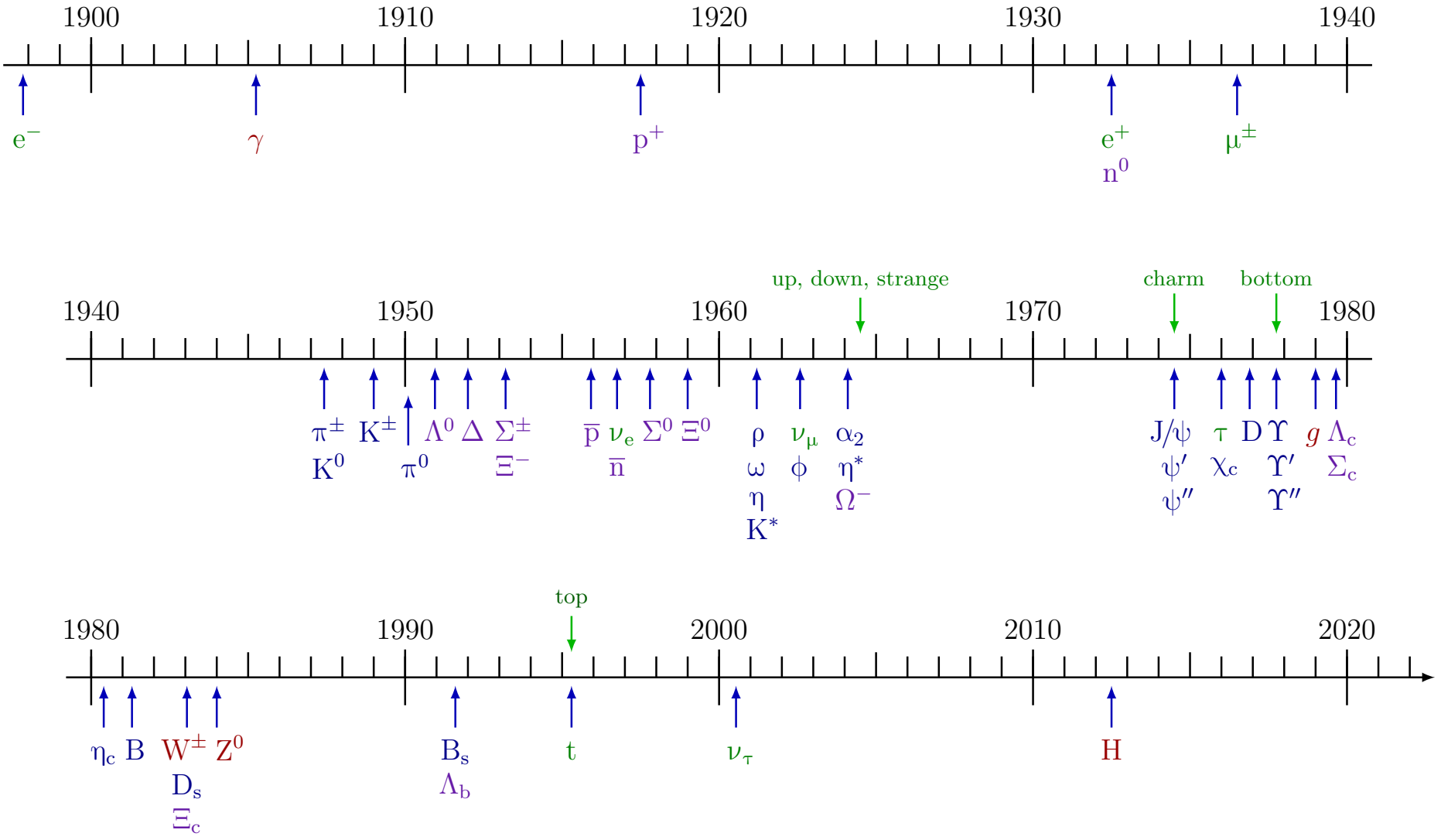
- Reconstruction
- Identification

Part III: LQ search

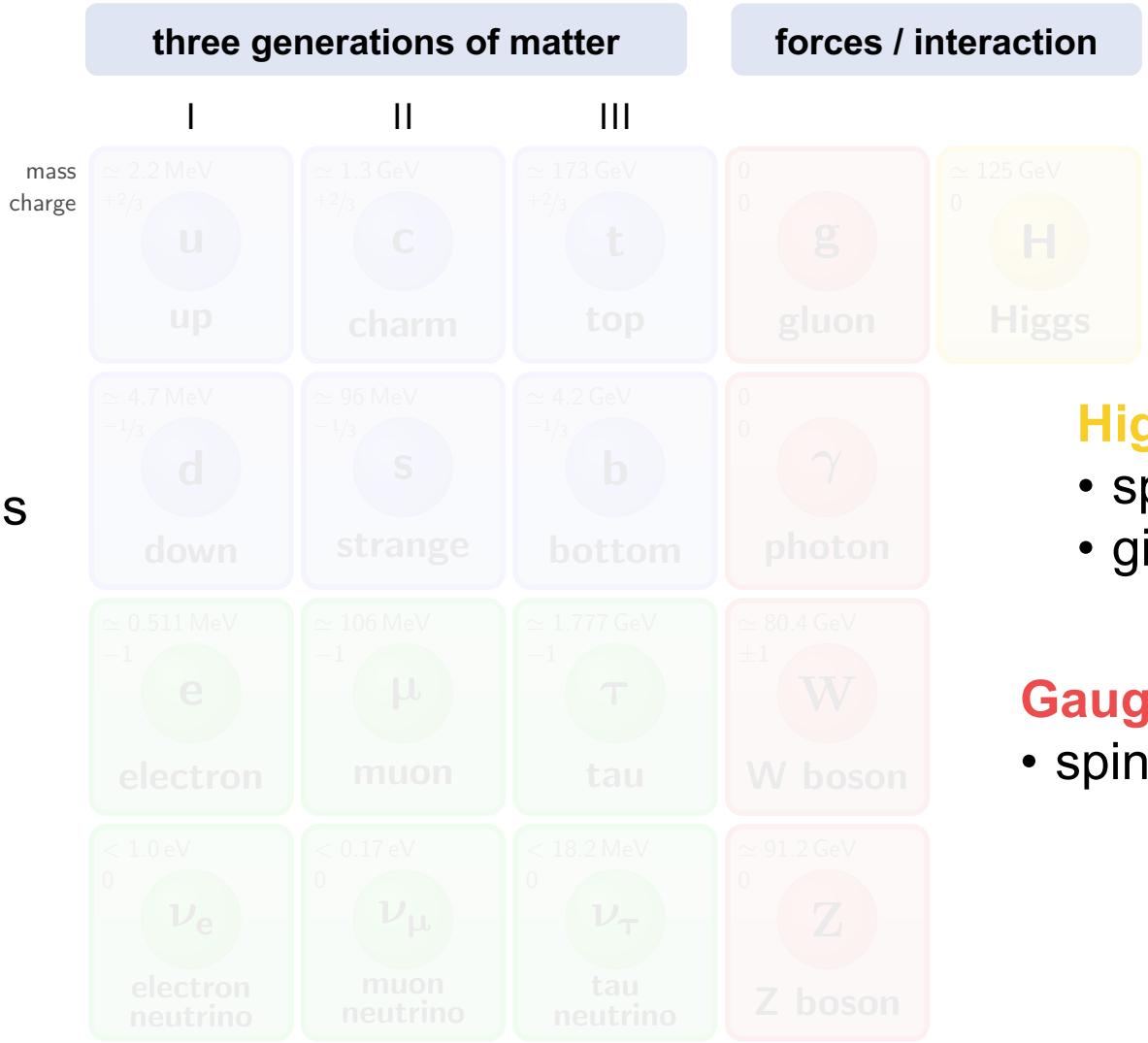
- Analysis strategy
- Results
- Summary

PART I:
MOTIVATION & SETUP

Brief history of particles...



Standard Model of Particle Physics



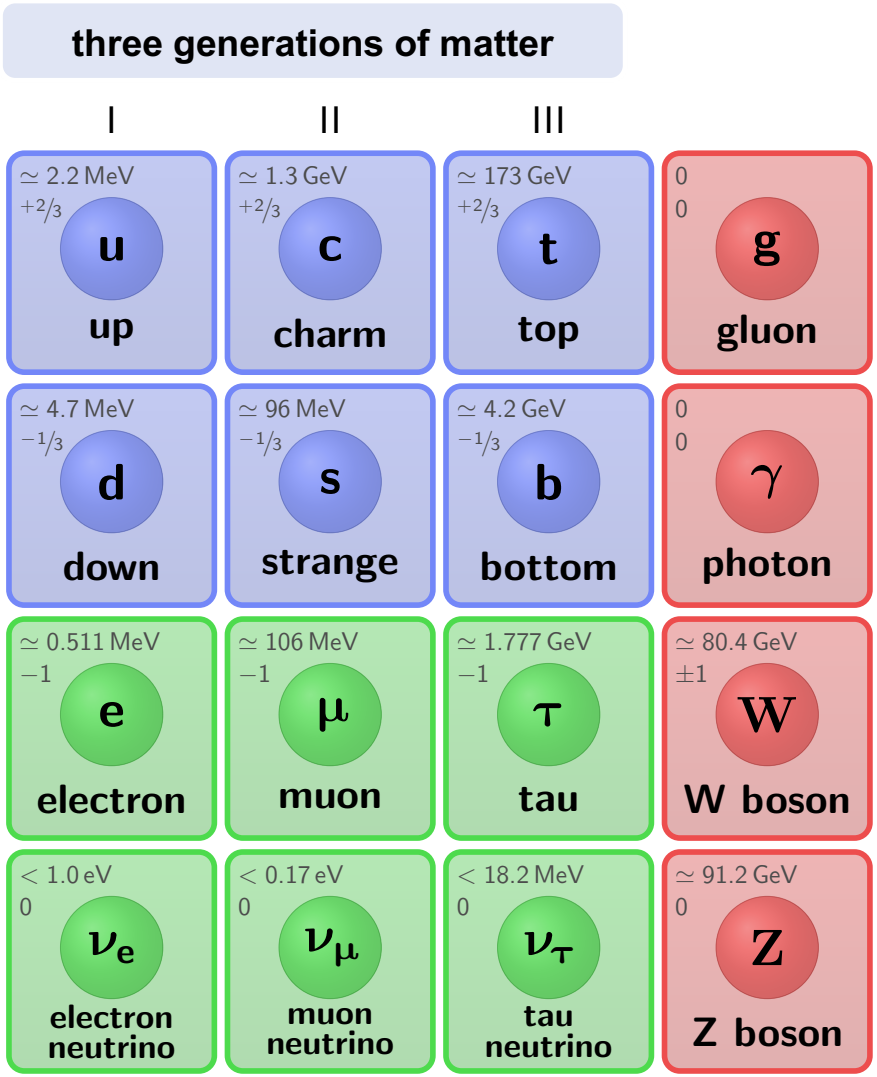
Quarks
- spin ½
- 6 flavors
- forms hadrons

Leptons
- spin ½
- 6 flavors

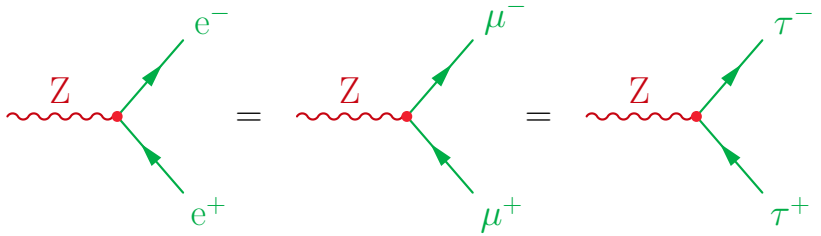
Higgs boson
- spin 0 (scalar)
- gives mass

Gauge bosons
- spin 1 (vector)

Lepton flavor universality ?



gauge bosons cannot differentiate **lepton flavors**



why three generations ?

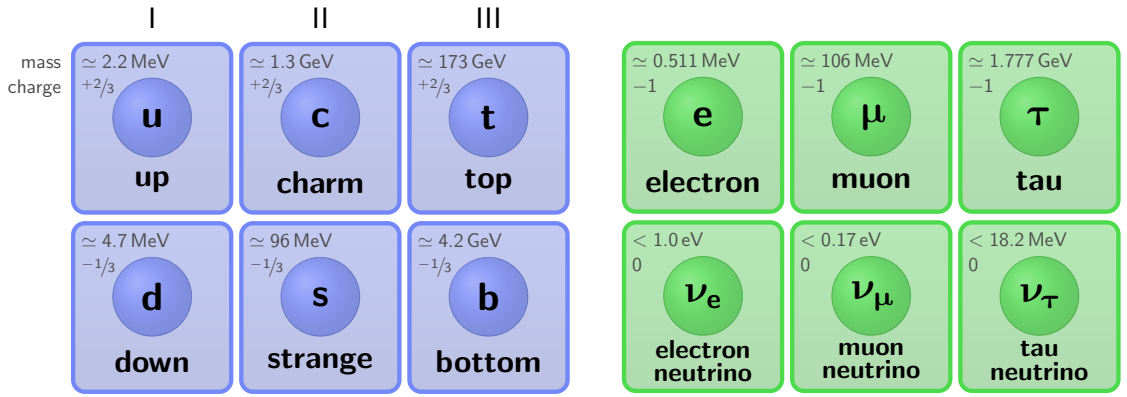
why hierarchical mass pattern ?

⇒ can "**new physics**" with preferential couplings to 3rd generation explain ?

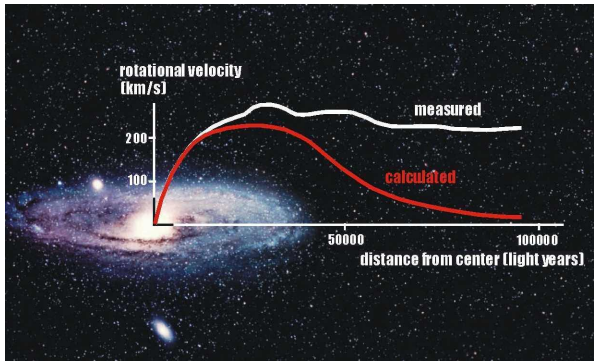
⇒ test LFU in Nature !

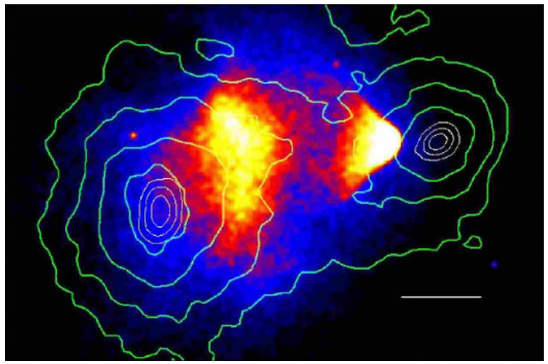
The Standard Model is incomplete

Flavor puzzle ?



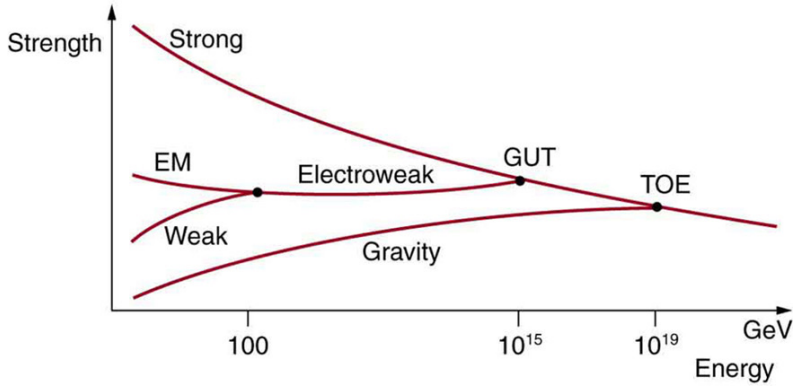
Dark Matter ?





galaxies

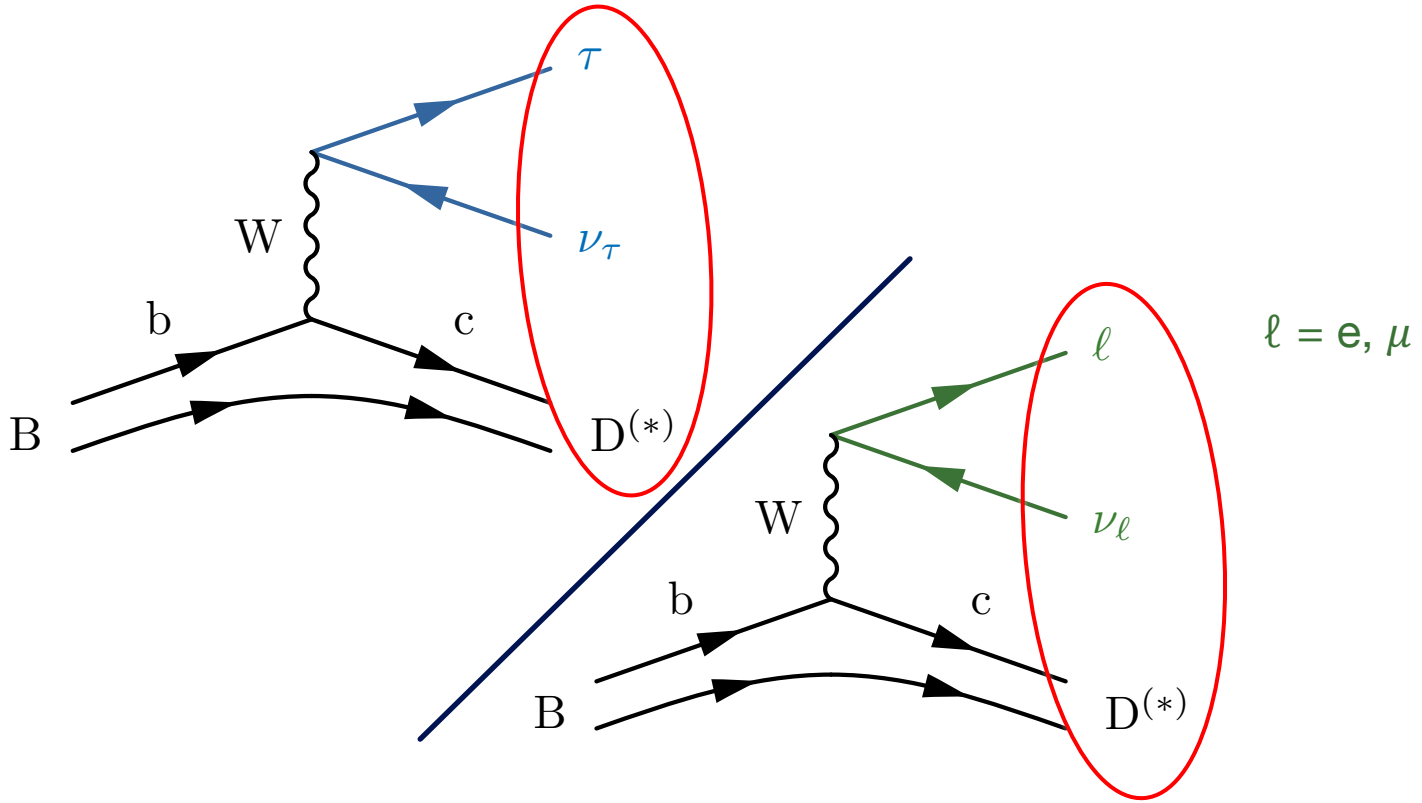
Gravity ?



grand unification ?

Lepton flavor universality tests

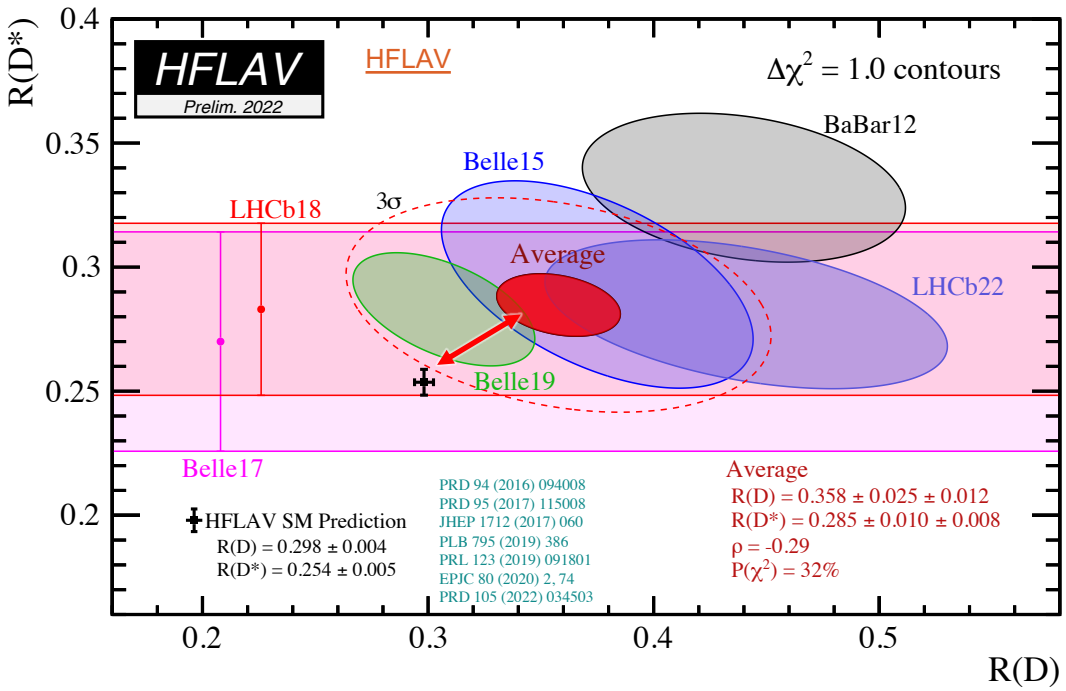
$$R_D = \frac{\Gamma\left(B \to D\tau\bar{\nu}\right)}{\Gamma\left(B \to D\ell\bar{\nu}\right)} \sim 0.30 \quad \text{SM} \qquad R_{D^*} = \frac{\Gamma\left(B \to D^*\tau\bar{\nu}\right)}{\Gamma\left(B \to D^*\ell\bar{\nu}\right)} \sim 0.25 \quad \text{SM}$$



ratio of decay rates

R(D*) vs. R(D) anomaly

$$R_D = \frac{\Gamma(B \to D\tau\bar{\nu})}{\Gamma(B \to D\ell\bar{\nu})} > 0.30 \quad \text{(SM)} \qquad R_{D^*} = \frac{\Gamma(B \to D^*\tau\bar{\nu})}{\Gamma(B \to D^*\ell\bar{\nu})} > 0.25 \quad \text{(SM)}$$



measured by the BaBar, Belle, LHCb experiments

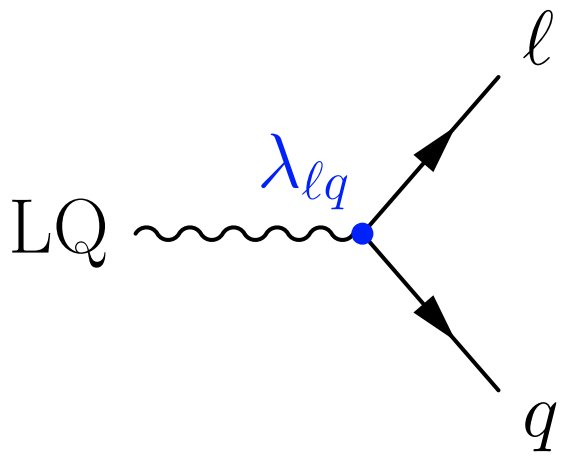
R(D(*)) combined 3.2σ deviation

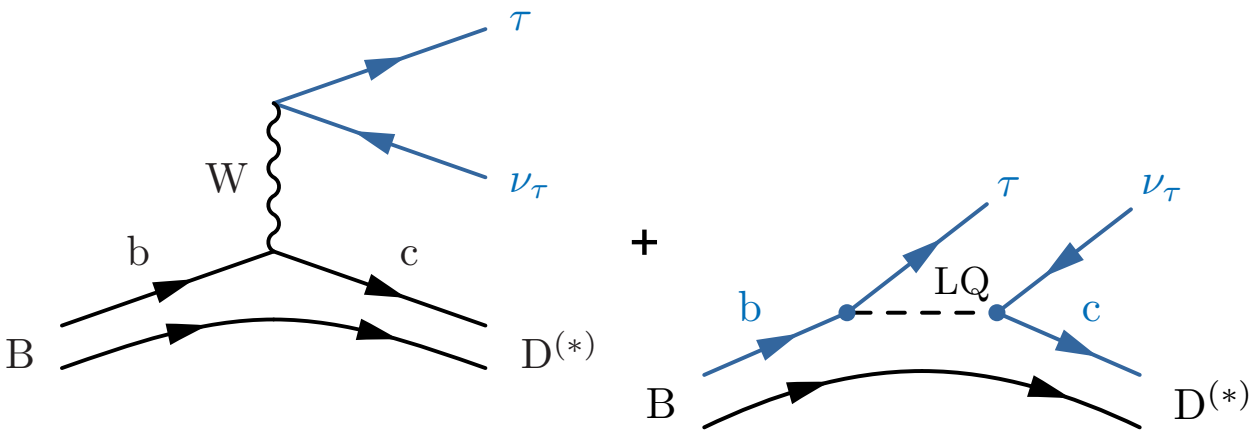
⇒ signs of new physics violating lepton flavor universality ?

Leptoquarks

spin 0 spin 1

- **scalar** or **vector** boson
- couple/decay to ***ℓq***
- coupling strength $\lambda_{\ell q}$

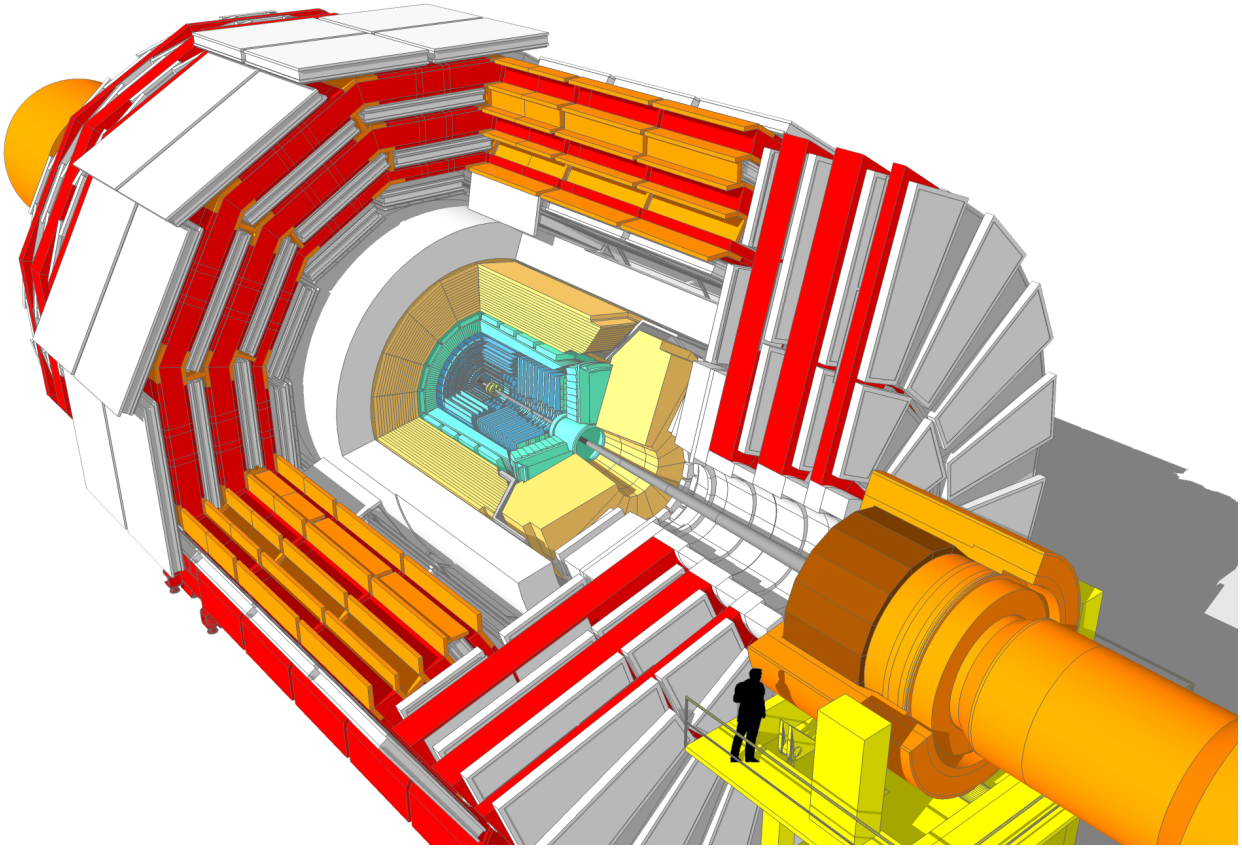




indirect evidence of a LQ ?

explanation for R($D^{(*)}$) anomaly ?

LQ with stronger coupling to bτ



THE CMS DETECTOR

proton beams in both directions

collisions of 13 TeV

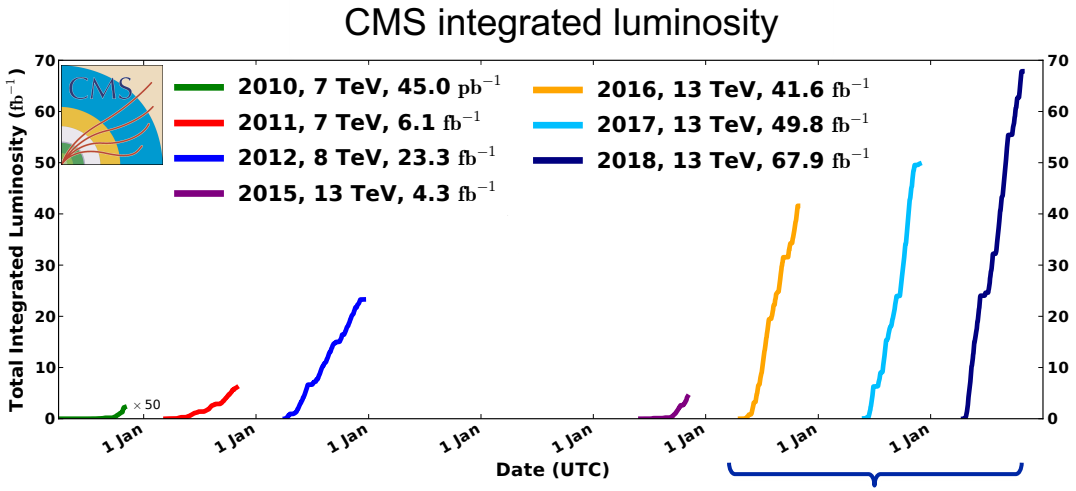
LHC accelerator

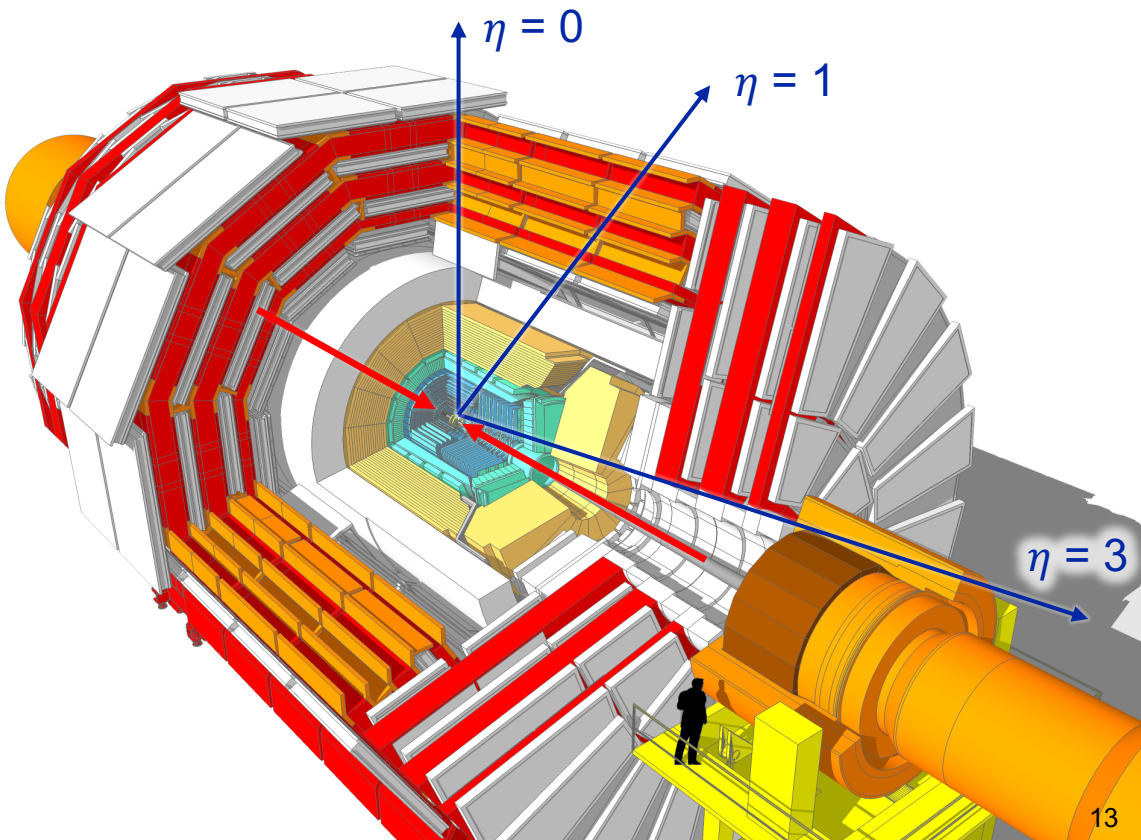
CMS detector

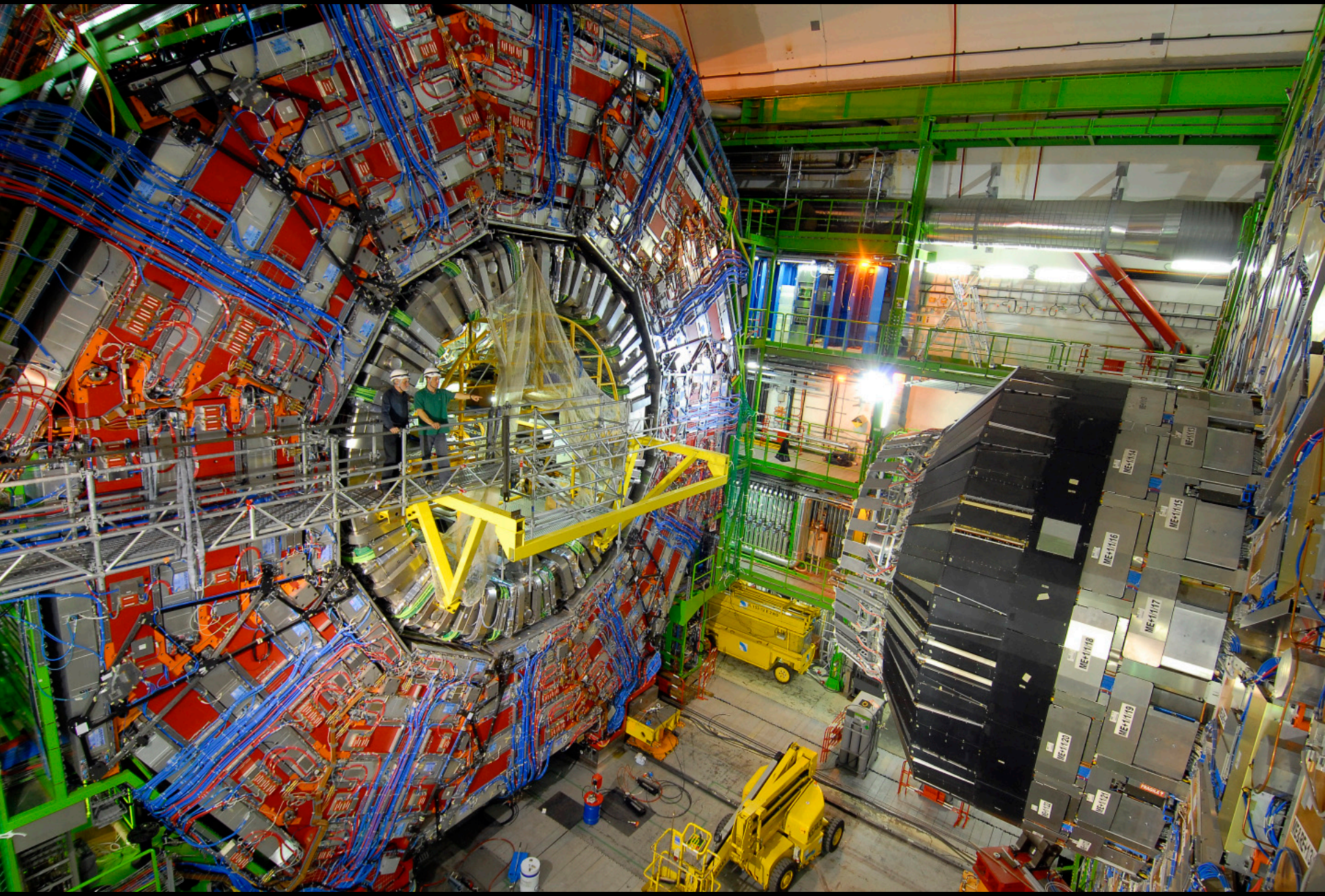
- measure particle
  - trajectory
  - momentum
  - energy
  - charge
- pseudorapidity η
  - **η = 0**: “central”
  - **η = 3**: “forward”
- 1 billion collisions / second

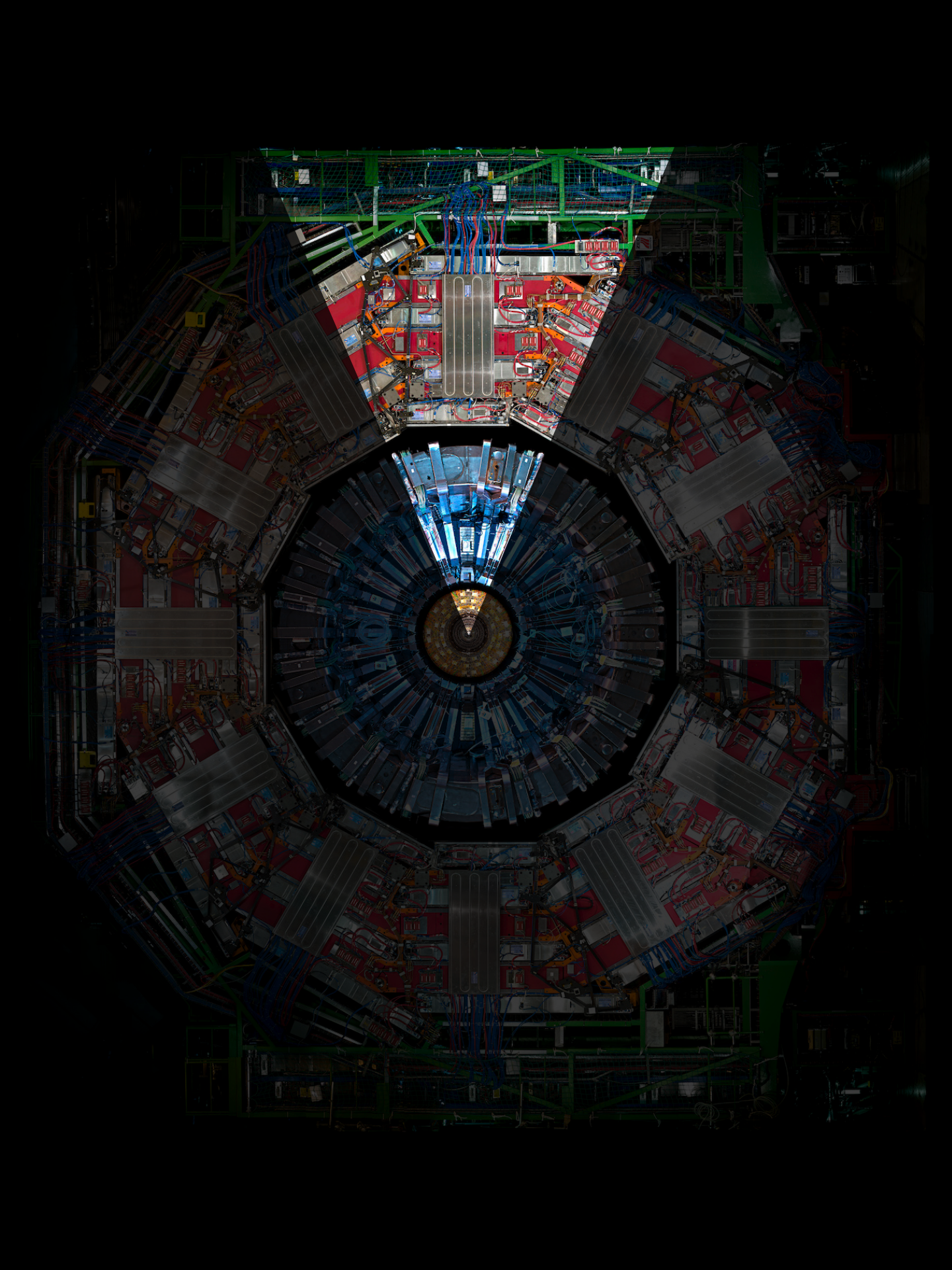
  ⇒ trigger system
  40 MHz → 1 kHz
- **Run-2** data (2016–2018)

  13 TeV, 138 fb^{-1}

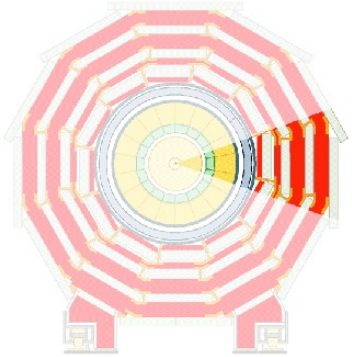


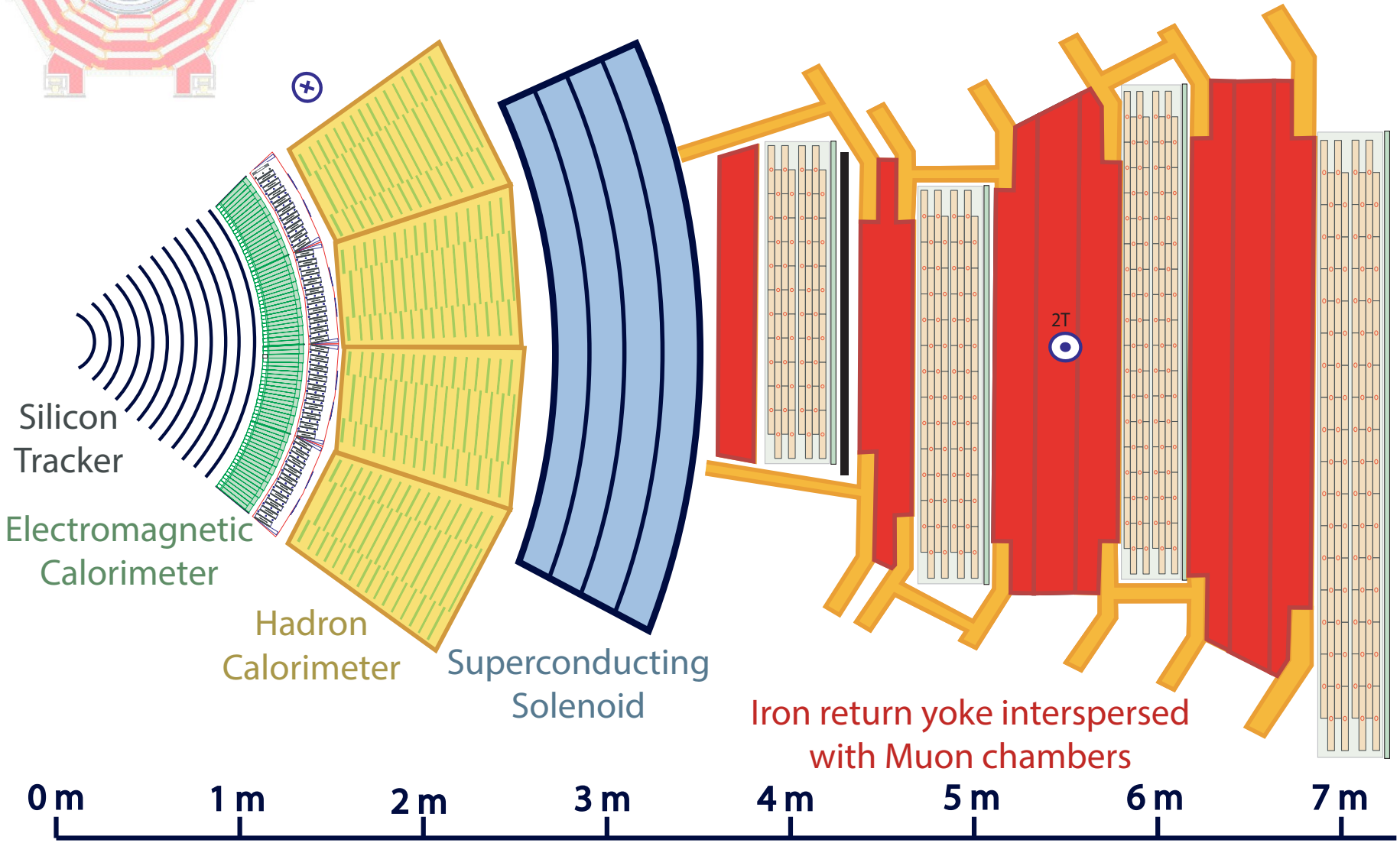



ME+1/1/4
ME+1/1/5
ME+1/1/6
ME+1/1/7
ME+1/1/8
ME+1/1/9

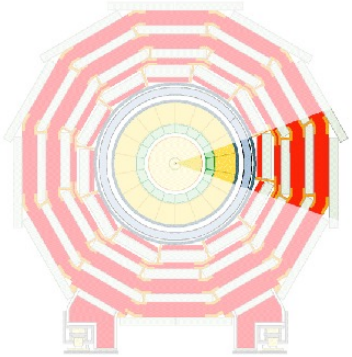


CMS subdetectors



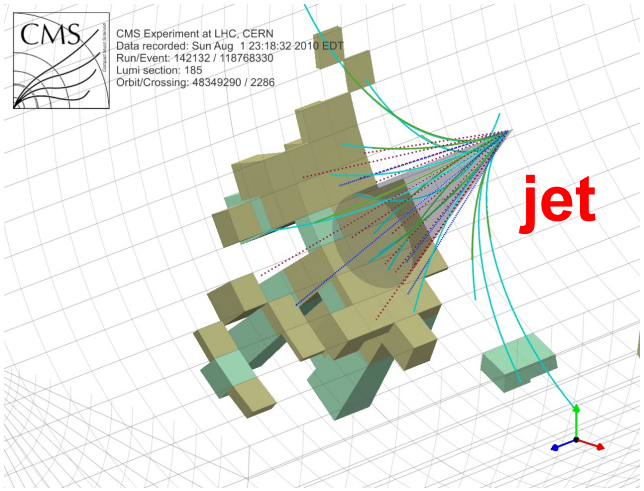


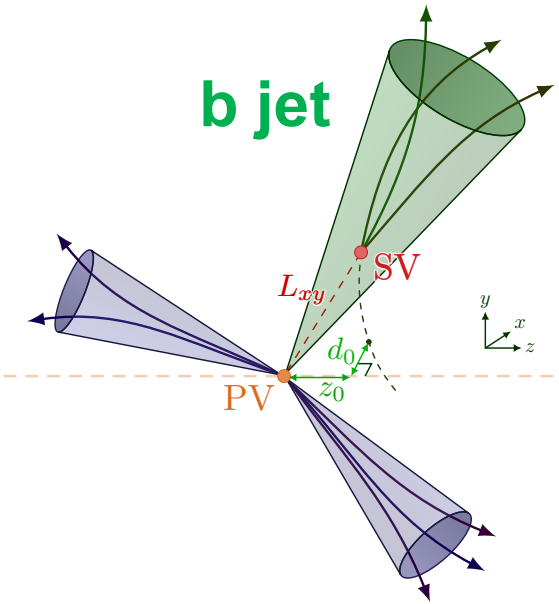
Particle signatures



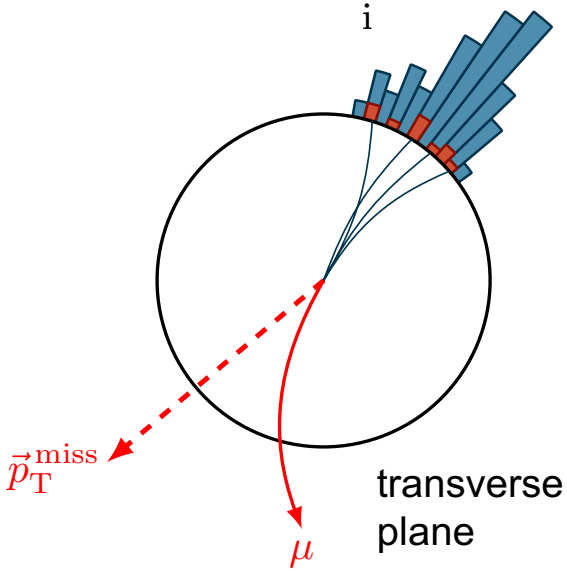
Particle signatures

- **electrons**: charged track + ECAL
- **muons**: charged track + muon detector
- **hadrons**: (charged track) + HCAL
- **quarks**, **gluons** create **jets** of hadrons
  - **b quarks** create **b jets**
- **neutrinos**: missing transverse momentum





$$0 = \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} + \sum_{\mathrm{i}} \vec{p}_{\mathrm{T}}^{\,i}$$



Overview

Part I: Motivation & setup

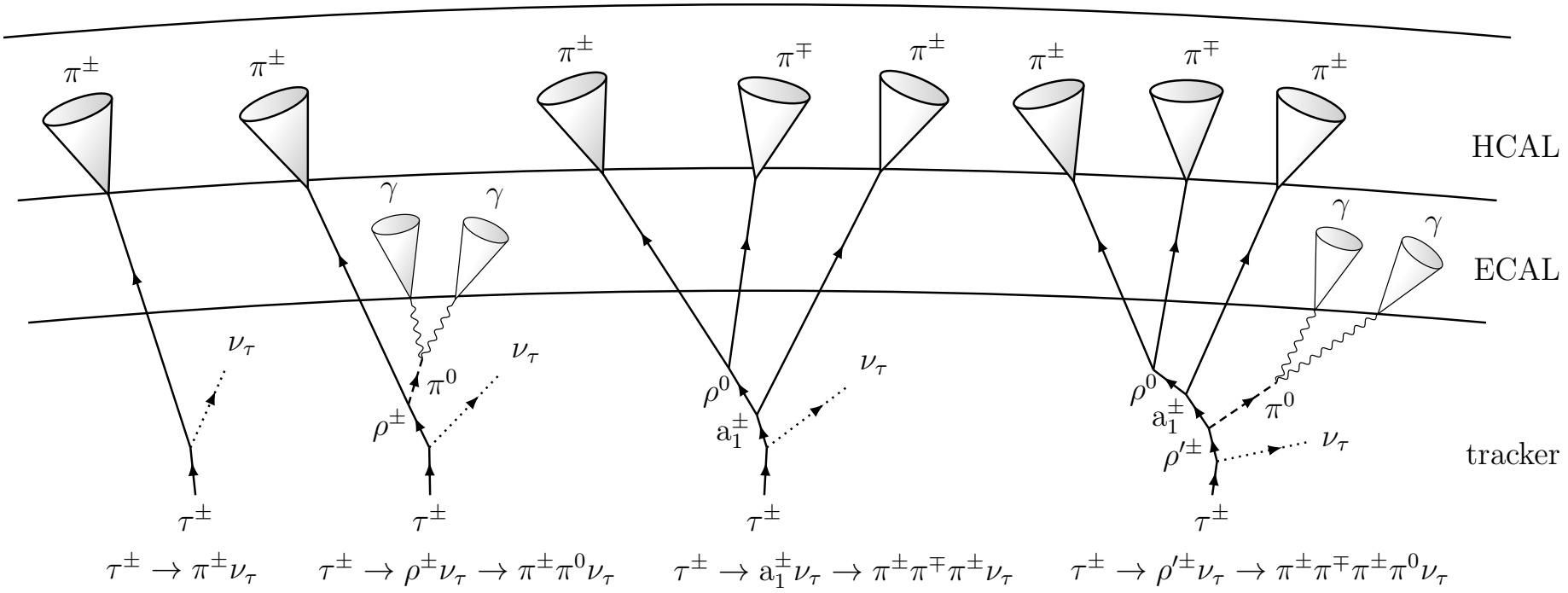
- Standard Model & beyond
- CMS detector

Part II: τ leptons

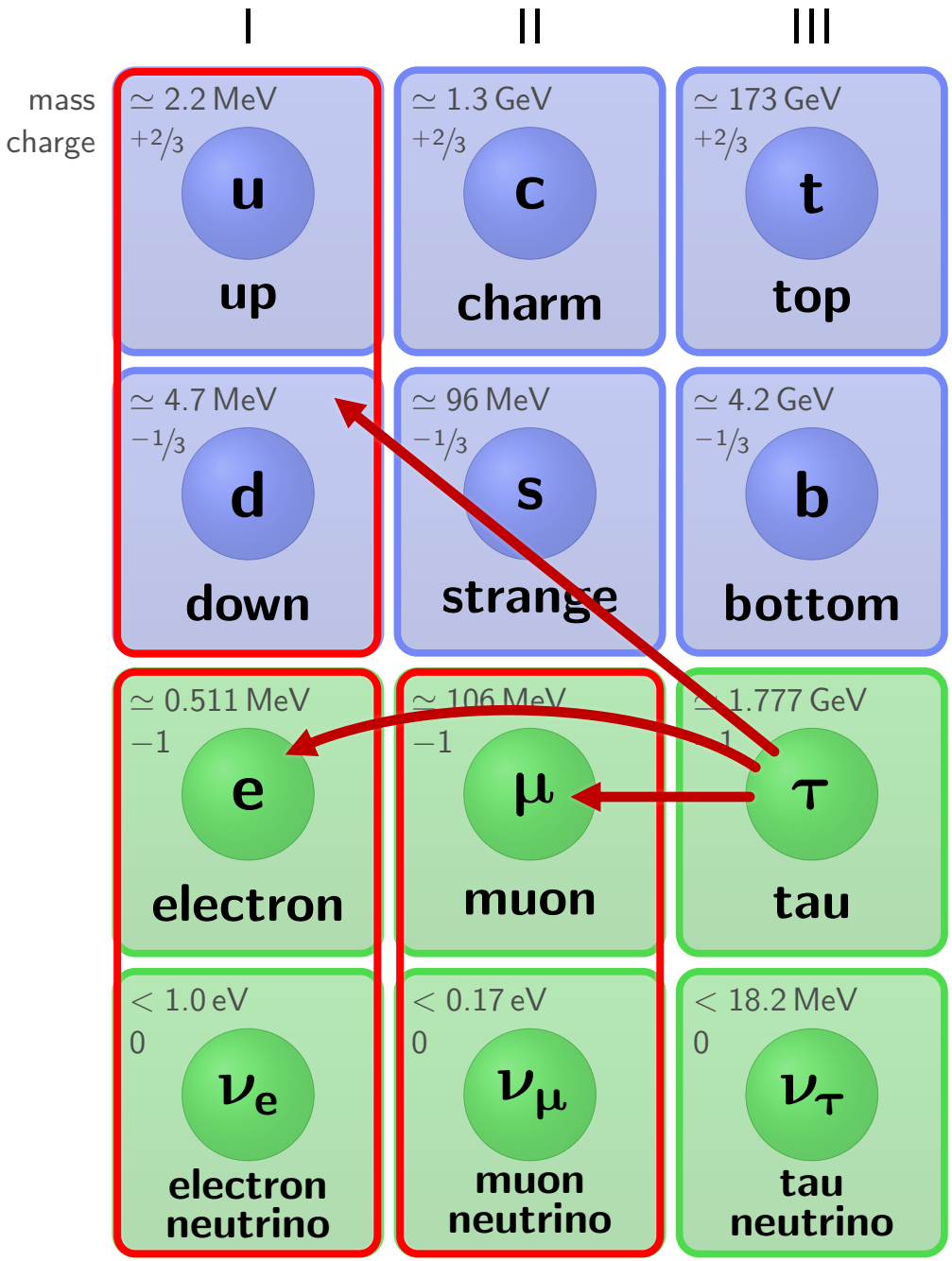
- Reconstruction
- Identification

Part III: LQ search

- Analysis strategy
- Results
- Summary



PART II: τ LEPTON

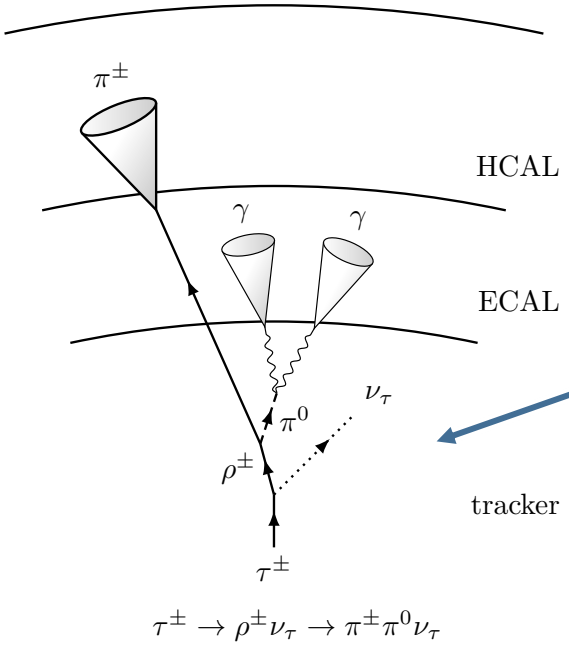


heaviest lepton
(m_τ ~ 1.78 GeV)

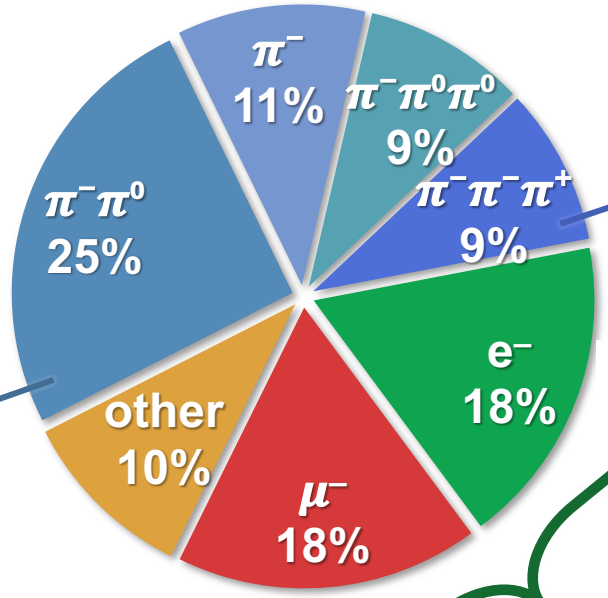
⇒ can decay to electrons, muons, light hadrons !

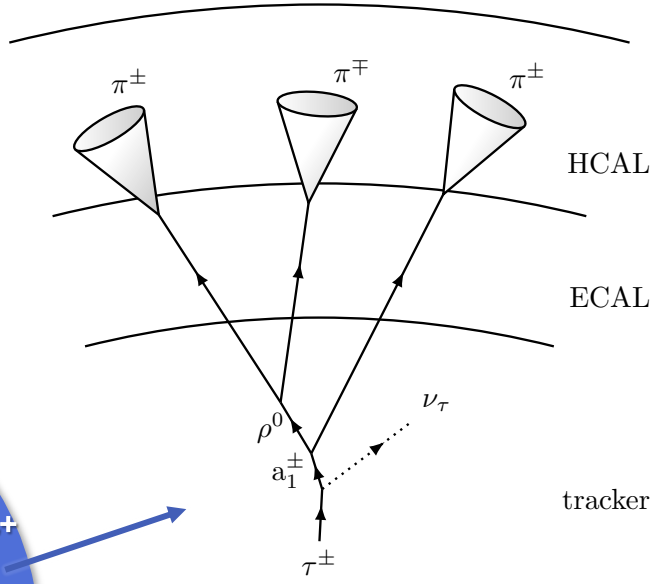
Particle signatures: τ lepton

64%
hadronic decay (τ_h)
$\tau^{\pm} \rightarrow$ hadrons + 1 neutrino



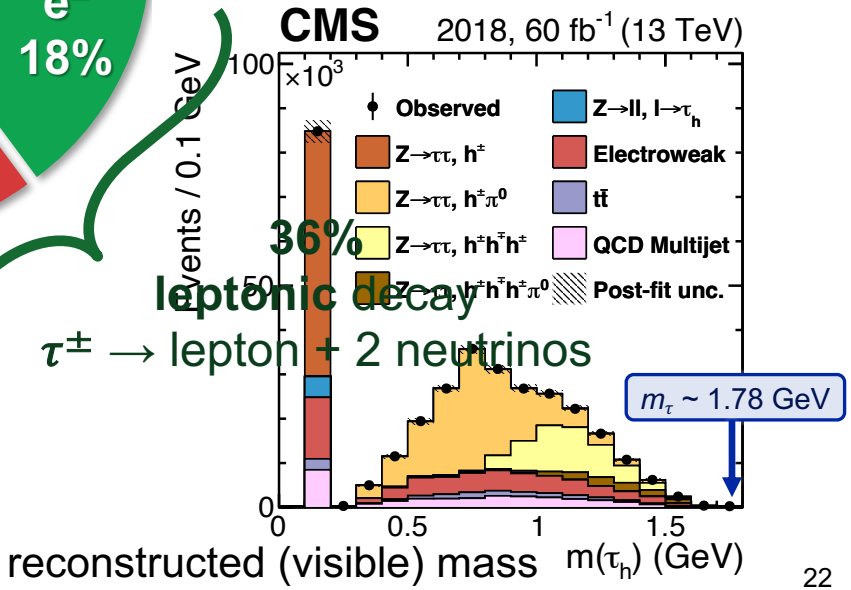
$\tau^{\pm} \rightarrow \rho^{\pm}\nu_\tau \rightarrow \pi^{\pm}\pi^0\nu_\tau$





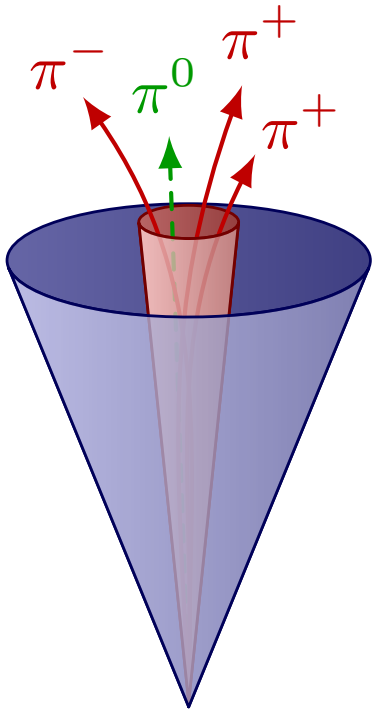
$\tau^{\pm} \rightarrow a_1^{\pm}\nu_\tau \rightarrow \pi^{\pm}\pi^{\mp}\pi^{\pm}\nu_\tau$

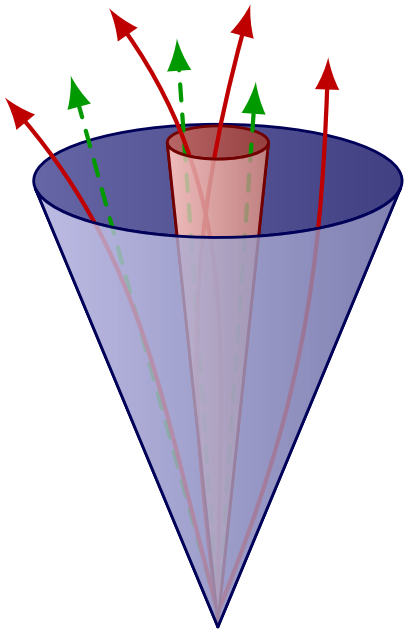
36%
leptonic decay
$\tau^{\pm} \rightarrow$ lepton + 2 neutrinos



τ_h background

red = **signal** cone
blue = **isolation** cone





real τ_h

jet initiated by a **quark/gluon**

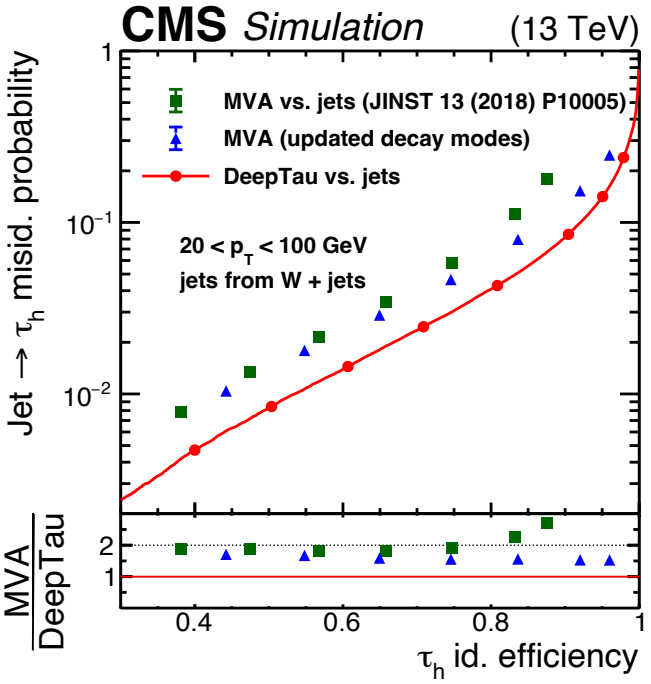
⇒ "***j*** → **τ_h fake**"

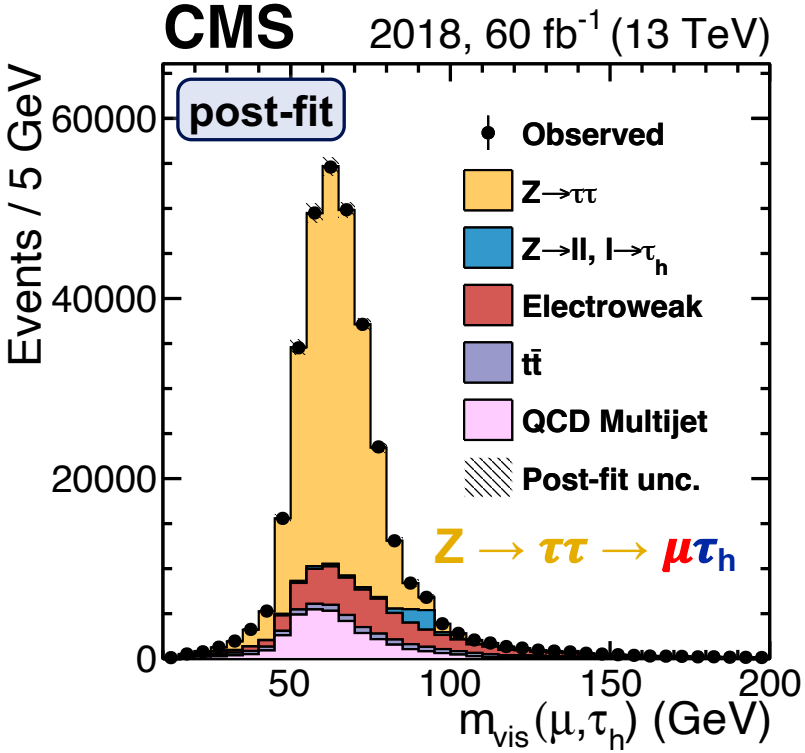
⇒ need for an efficient **identification algorithm** ("DeepTau")

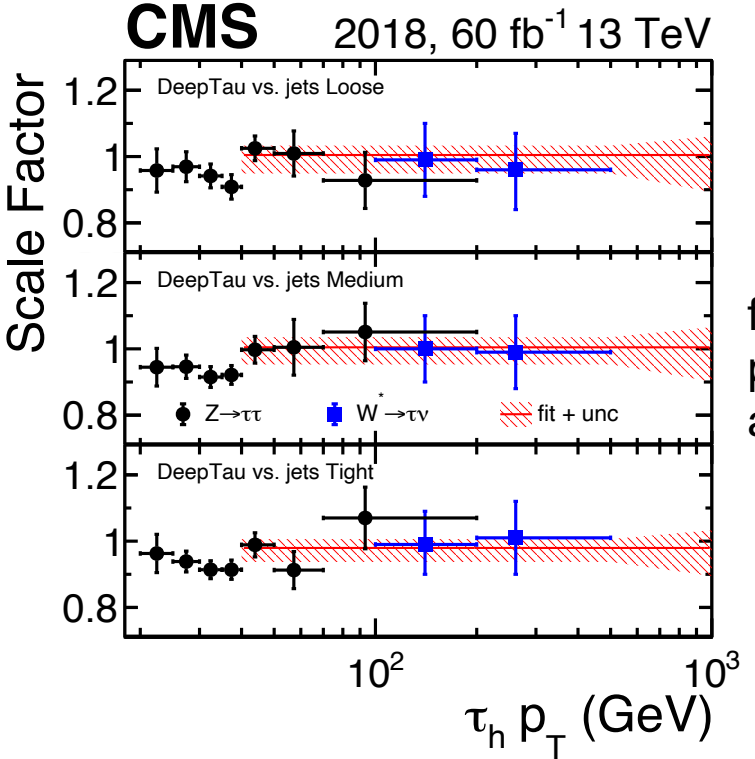
⇒ exploit τ_h properties: long lifetime, isolation, ...

τ_h identification efficiency

- typical efficiency: **60%** for **1%** fake rate
- we derived corrections for simulated τ_h
- measure efficiency in purified $Z \rightarrow \tau\tau$ sample using $\mu\tau_h$ events
- maximum likelihood fit of m_{vis}





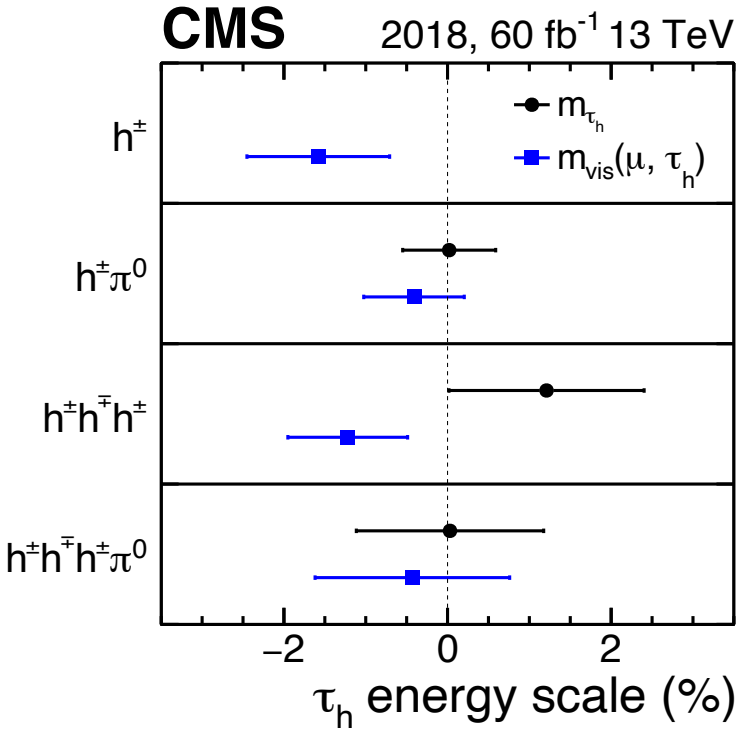


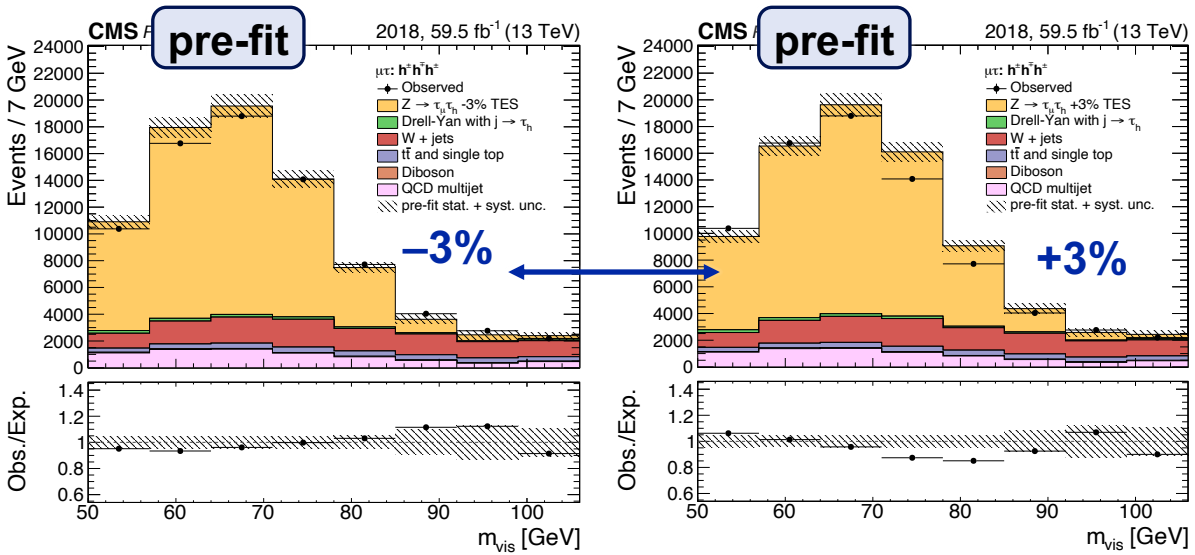
for CMS physics analyses

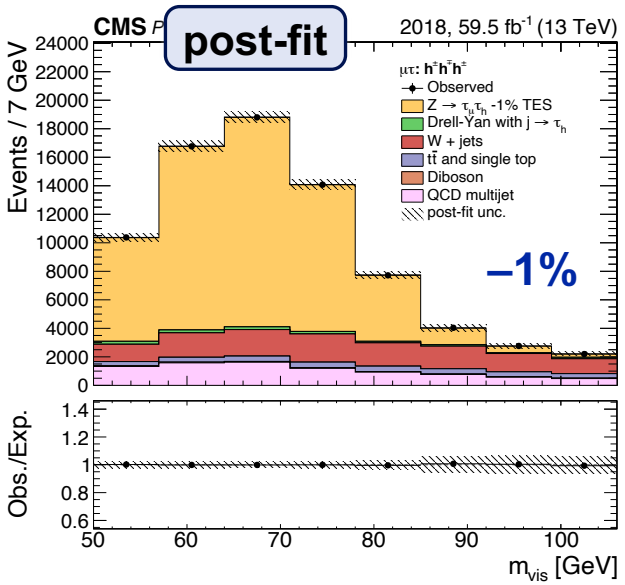
η_{vis}

τ_h energy scale

- corrections for simulated τ_h energy
- I measured τ_h energy scale in $Z \rightarrow \tau\tau \rightarrow \mu\tau_h$ events
- maximum likelihood fit to m_{vis} (or m_τ) in bins of hadronic decay modes
- challenge due to limited statistics: need for optimization
- energy scale in MC < 2%







Overview

Part I: Motivation & setup

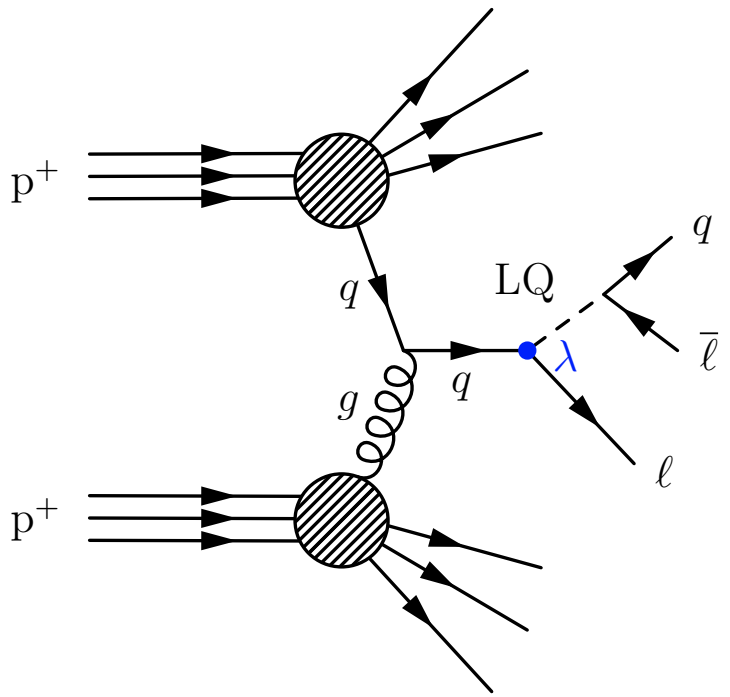
- Standard Model & beyond
- CMS detector

Part II: τ leptons

- Reconstruction
- Identification

Part III: LQ search

- Analysis strategy
- Results
- Summary



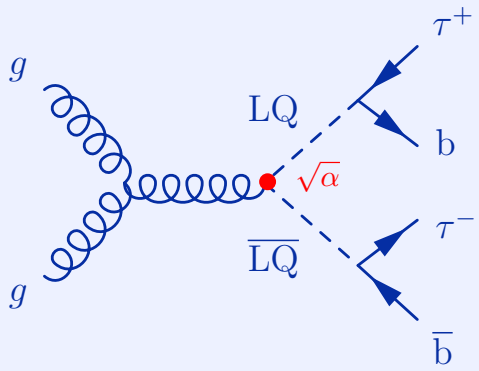
PART III:
SEARCH FOR LQ → bτ

LQ → bτ production at CMS

EXO-19-016

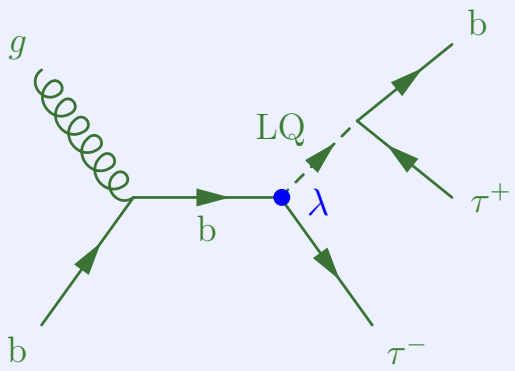
resonant

pair



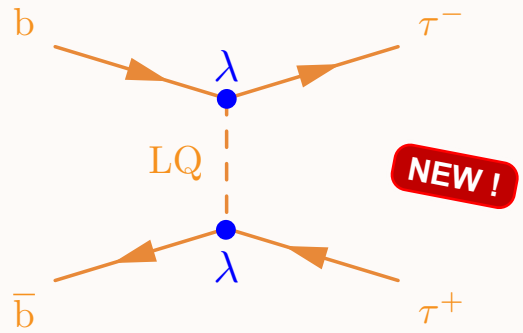
- large
- model independent

single

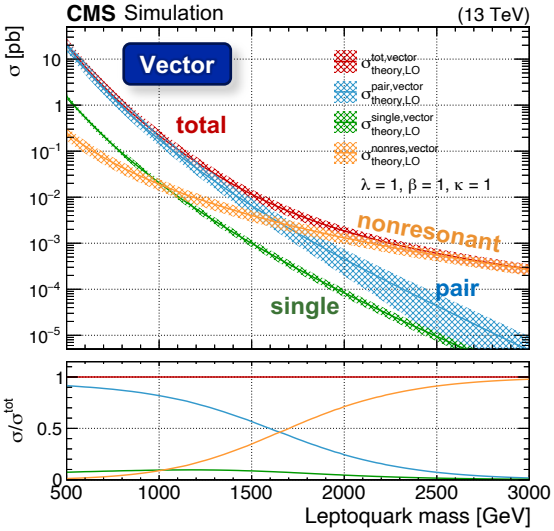


- $\sigma \propto \lambda^2$
- b-PDF suppression
  width $\propto \lambda^2$

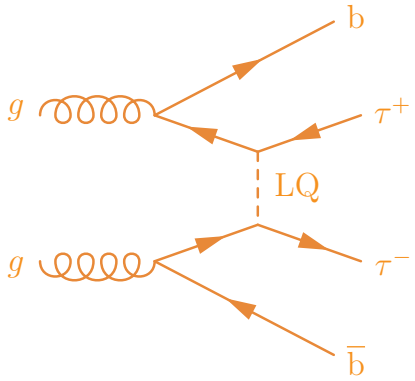
nonresonant



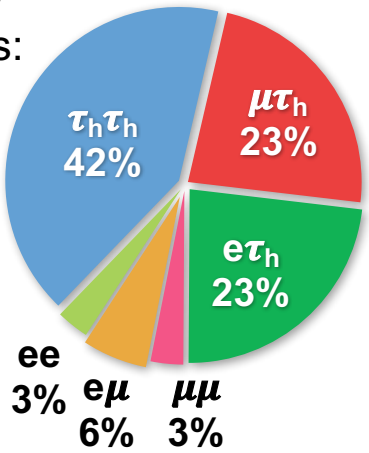
- $\sigma \propto \lambda^4$
- (PDF suppression)^2
- nonresonant



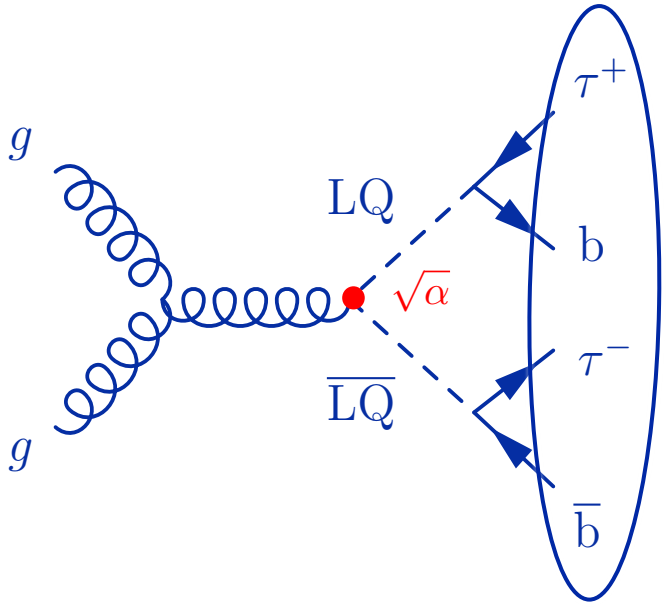
⇒ (b)(b)ττ signature



ττ decay channels:

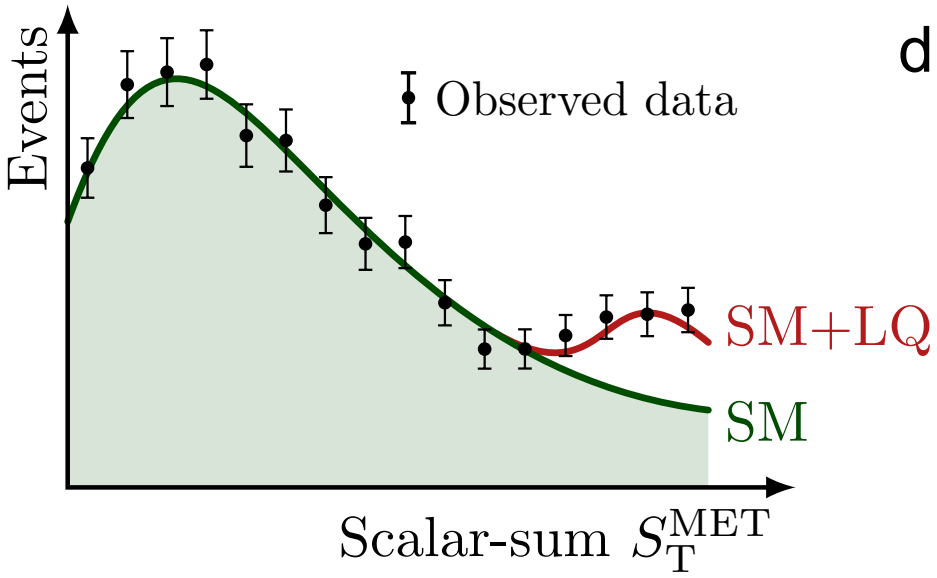


Extracting the resonant LQ signal



- **high-p_T** objects
- **combinatorics**

  ⇒ difficult to reconstruct the LQ correctly



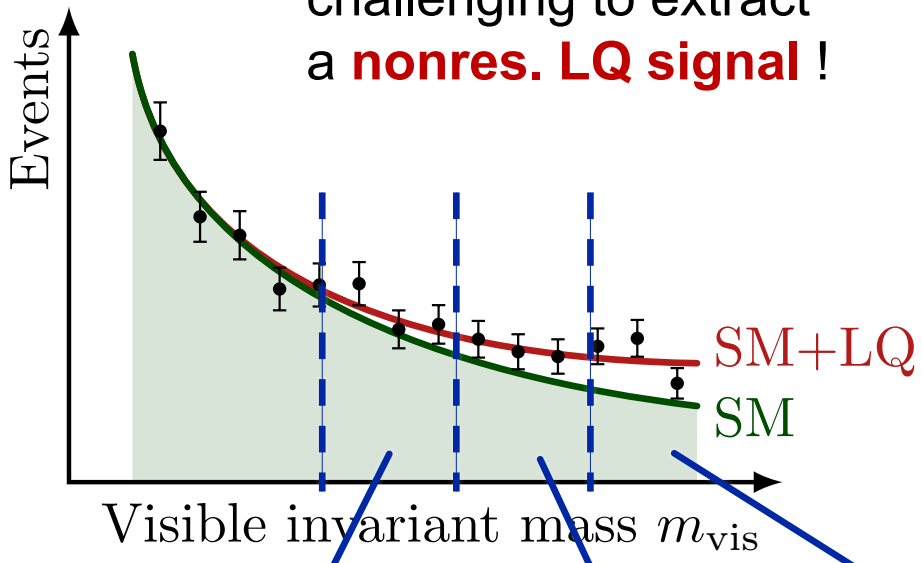
discriminating variable:

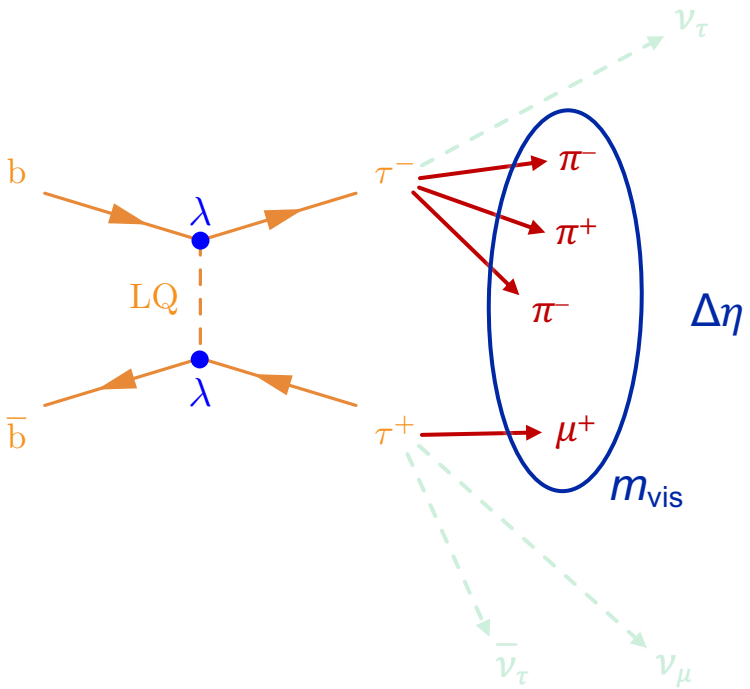
$$S_T^{MET} = p_T^{\tau_1} + p_T^{\tau_2} + p_T^{j} + p_T^{miss}$$

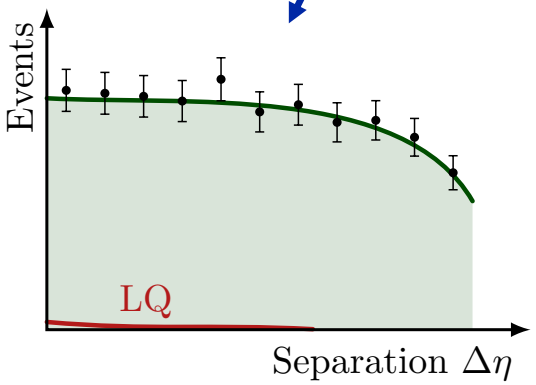
“resonance” !

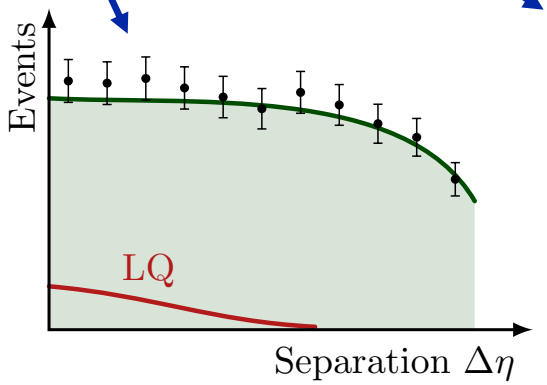
Extracting the nonresonant LQ signal

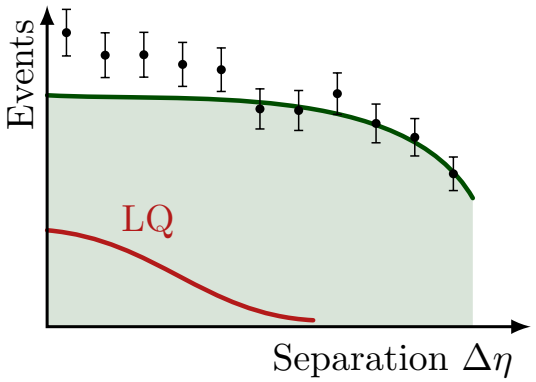
challenging to extract
a **nonres. LQ signal** !





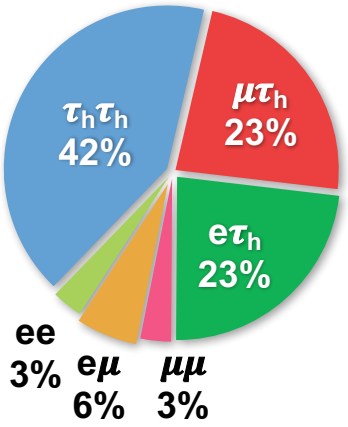






low purity → **high purity**

Event categorization



$e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$, $e\mu$ & $\mu\mu$ pre-selections

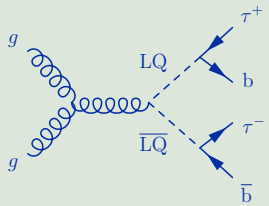
≥1 jet

0 b jet

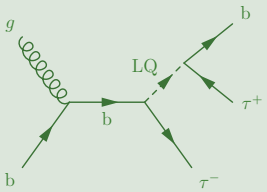
≥1 b jet

discriminating variable:

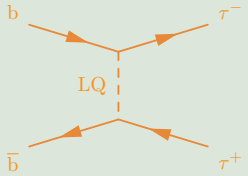
$$S_{\mathrm{T}}^{\mathrm{MET}} = p_{\mathrm{T}}^{\tau_1} + p_{\mathrm{T}}^{\tau_2} + p_{\mathrm{T}}^{j} + p_{\mathrm{T}}^{\mathrm{miss}}$$



pair



single



nonresonant

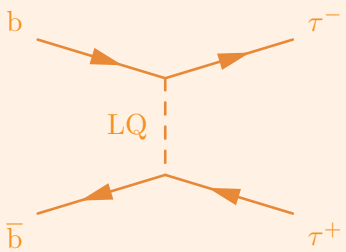
0 jet

m_{vis} bins

200–400 | 400–600 | >600

discriminating variable:

$$\chi = e^{\Delta\eta}$$



nonresonant

0 b tag

2016 2017 2018

≥1 b tag

$\mu\mu$

$e\mu$

$e\tau_h$

$\mu\tau_h$

$\tau_h\tau_h$

S_T^{MET}

3 years
×
5 channels
×
5 categories

$\chi = e^{\Delta\eta}$

m_{vis} 200–400 GeV

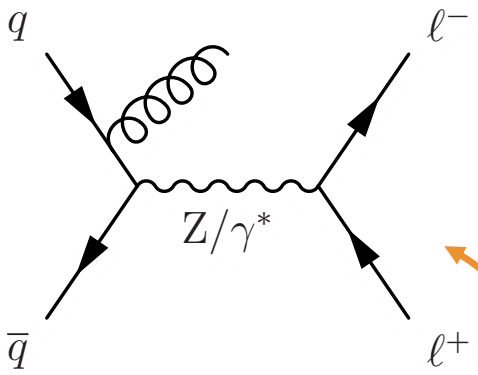
m_{vis} 400–600 GeV

m_{vis} > 600 GeV

Main backgrounds

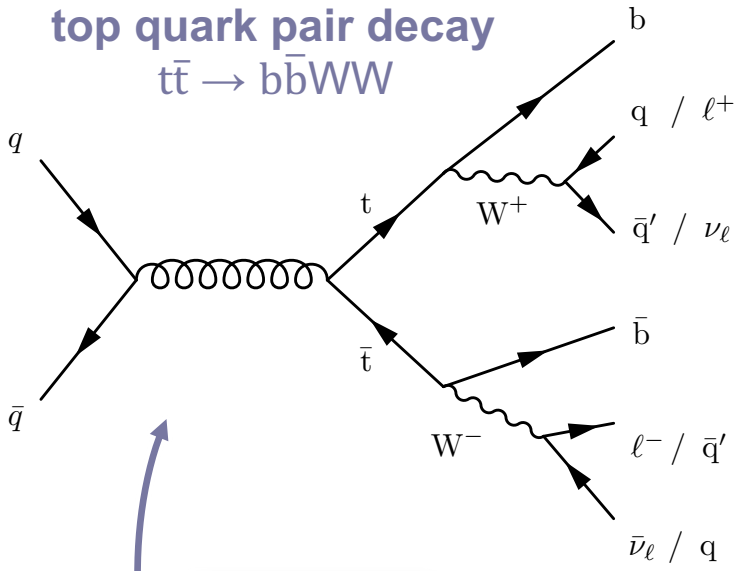
Drell-Yan + jets

$q\bar{q} \rightarrow j\,\ell^-\ell^+$



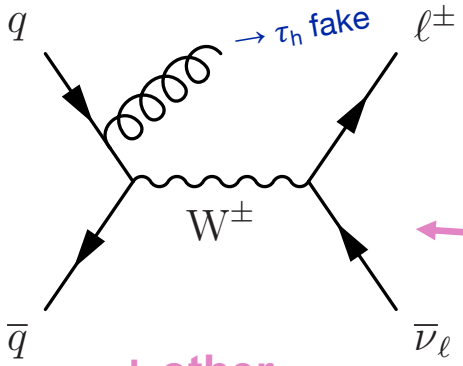
top quark pair decay

$t\bar{t} \rightarrow b\bar{b}WW$

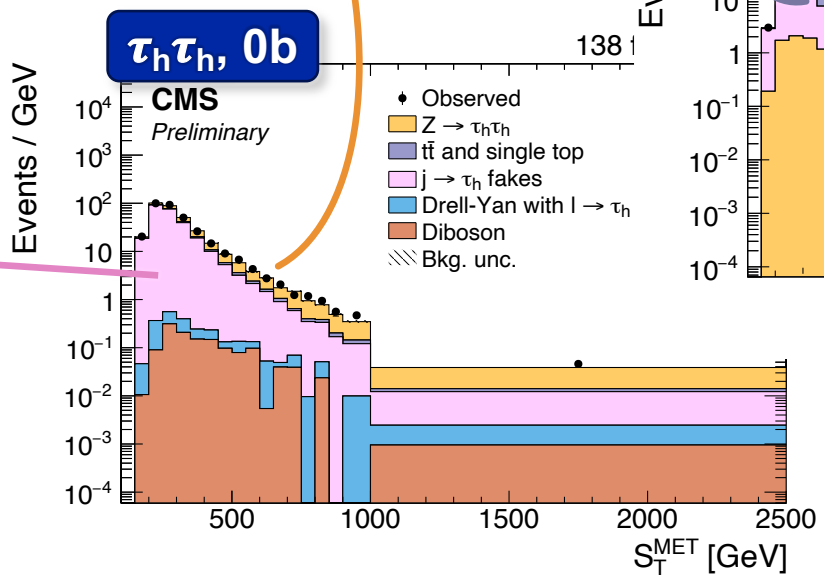


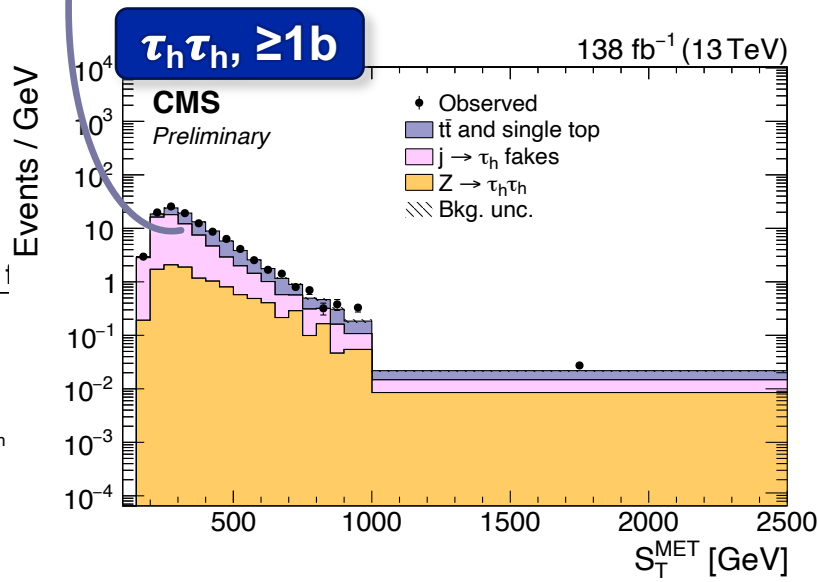
W + jets

$q\bar{q} \rightarrow j\,\ell^-\nu^+$

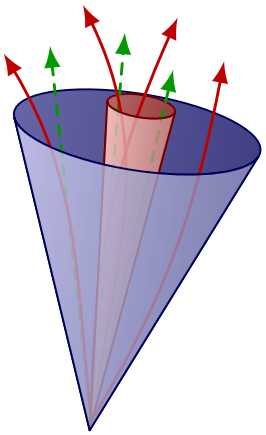


+ other





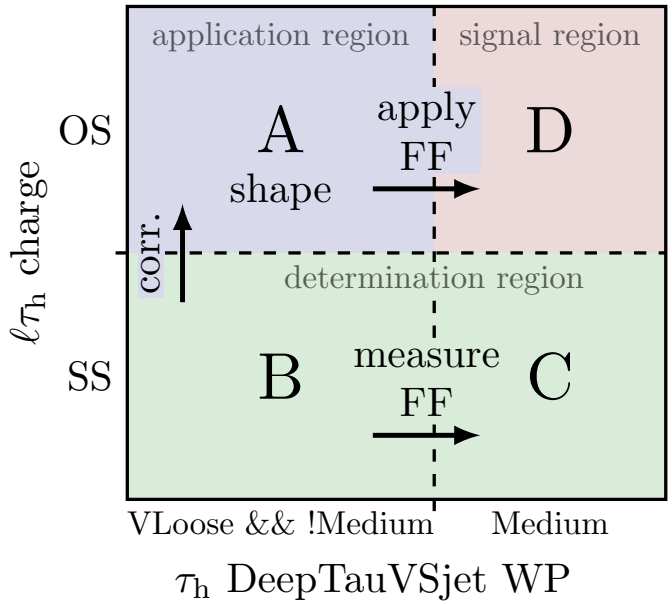
$j \rightarrow \tau_h$ fake background estimation



- most dominantly from QCD and W + jets
- data-driven "**fake factor**" method
- measure fake rates in special regions of data using different selection criteria
- measure separately for **3 backgrounds**:
  - **QCD** → more gluons
  - **W+jets** → more light quarks
  - **ttbar** → more b quarks

$$N_D = N_A \underbrace{\frac{N_C}{N_B}}_{FF}$$

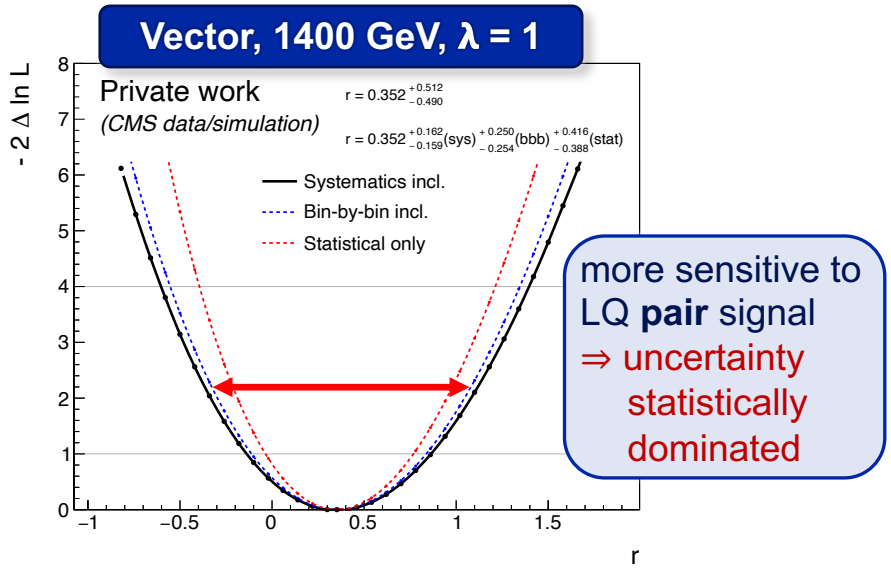
$$\mathrm{FF}(p_T^{\tau_h}, ...) = \frac{N(\texttt{Medium})_{DR}}{N(\texttt{VLoose \&\& !Medium})_{DR}}$$

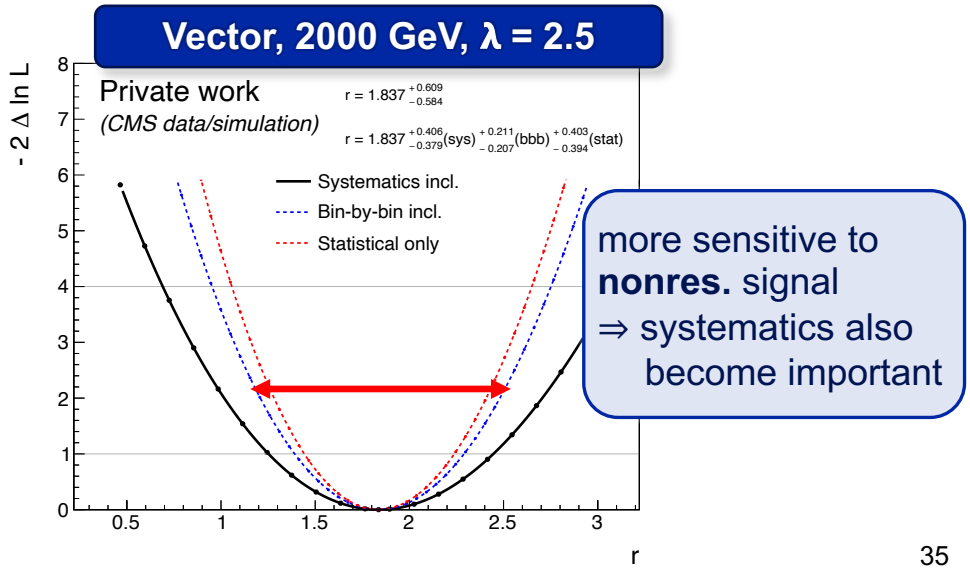


[HIG-17-020, HIG-21-001]

Systematic uncertainties

- τ_h modeling:
  ID efficiency, energy scale, ...
- $j \rightarrow \tau_h$ fake estimation:
  stat. & syst. fit uncertainties, corrections, ...
- theoretical uncertainties:
  (N)LO p_T spectrum, μ_R & μ_F scales, PDFs, ...

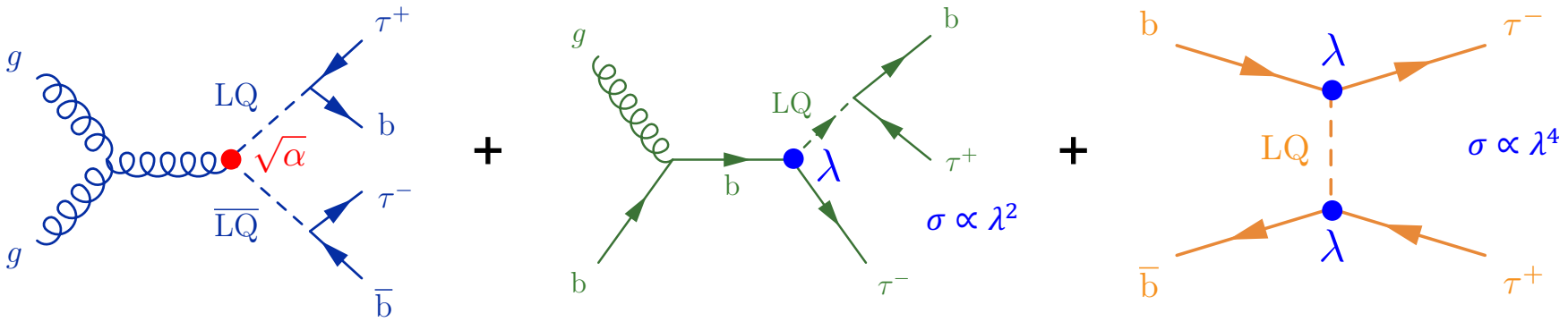




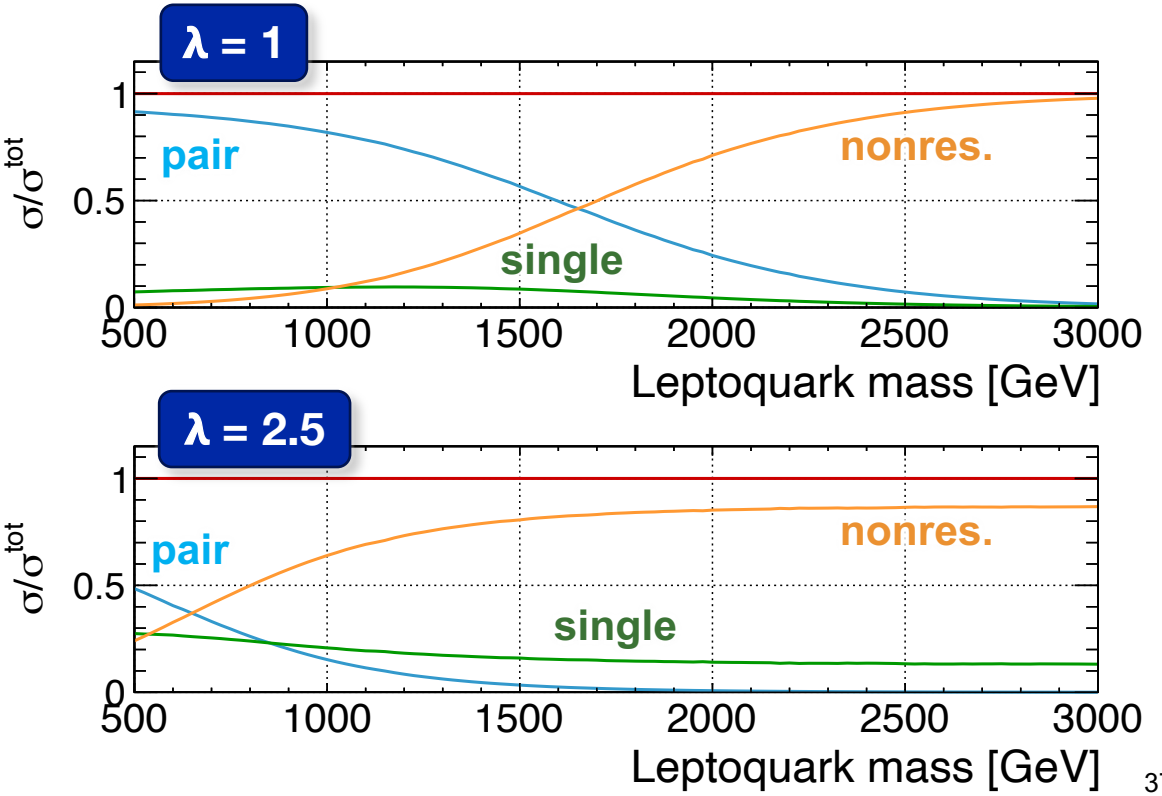
RESULTS

(Preliminary)

Total signal = pair + single + nonres.

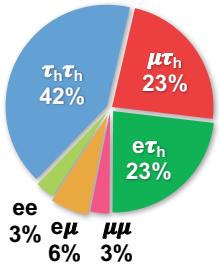


- combine 3 modes into **1 total LQ signal**
- relative contribution depends on **LQ mass** & **coupling strength λ**

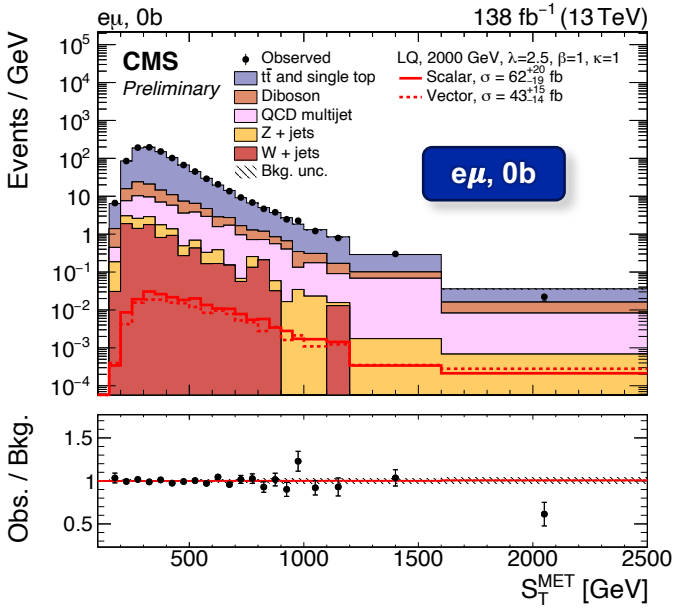


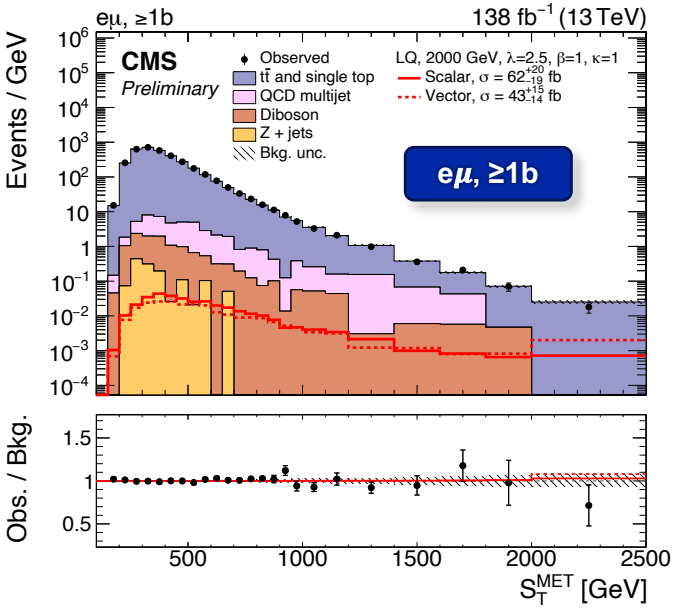
Postfit S_T^{MET} distributions in 0b & ≥1b

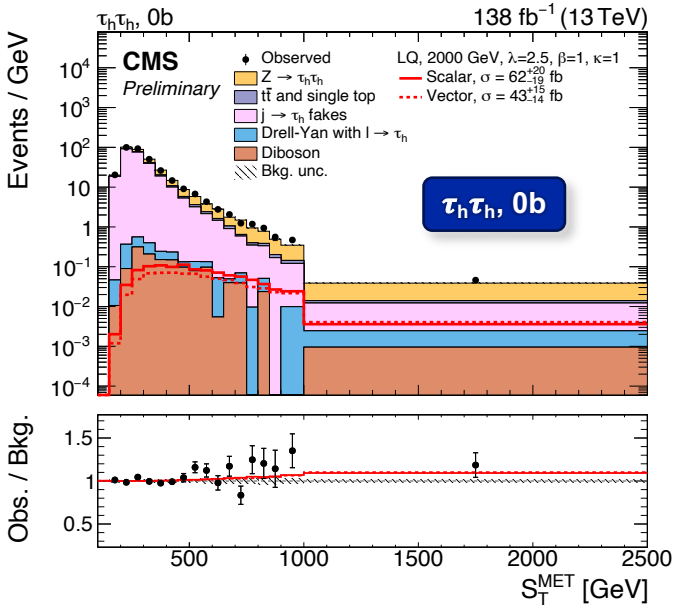
- constrain theoretical systematics
  - $\mu\mu$ for Z + jets
  - eμ for $t\bar{t}$
- nice agreement with **observed data**

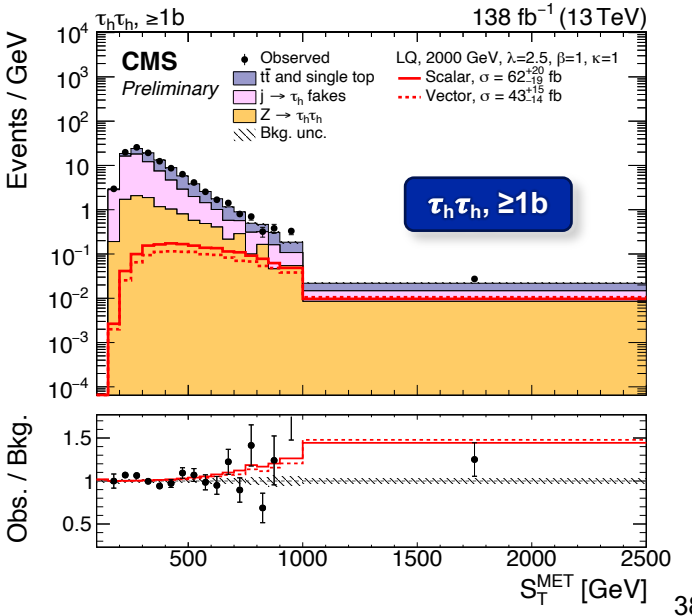


- fit **LQ signal**
  - scalar / vector
  - m = 2000 GeV
  - λ = 2.5
- sum of distributions in all three years
- some **excess** observed at high S_T^{MET} values



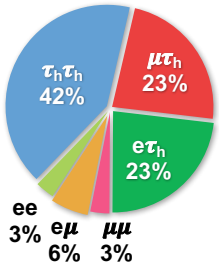




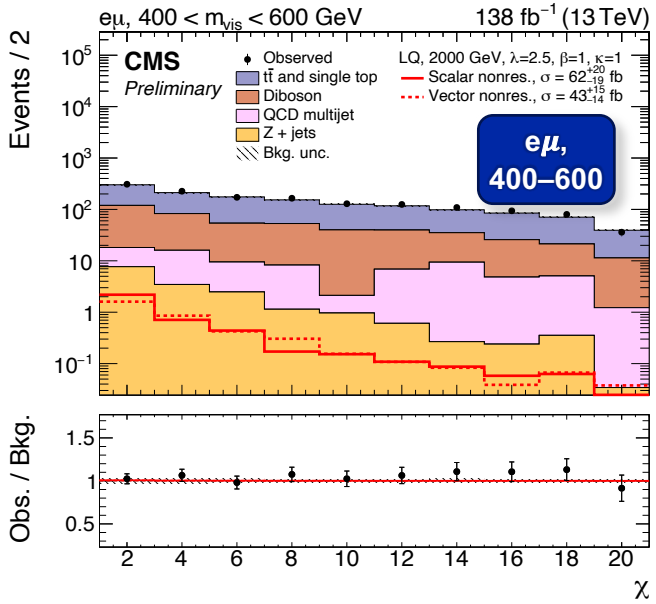


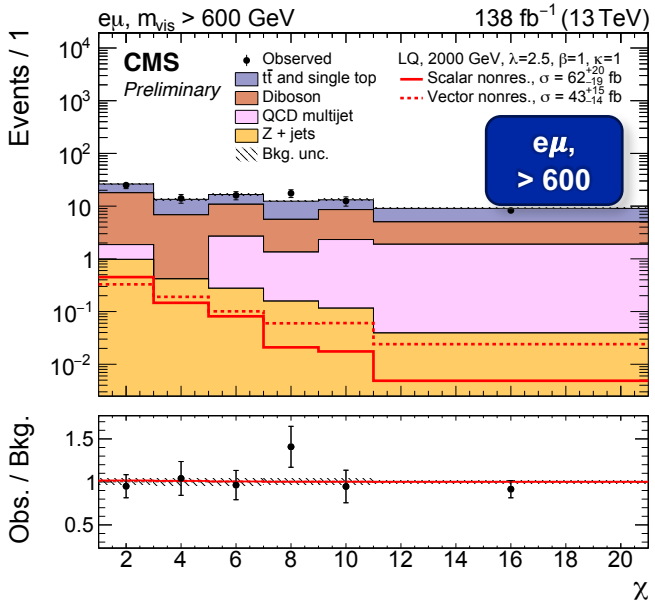
Postfit χ distributions in 0j

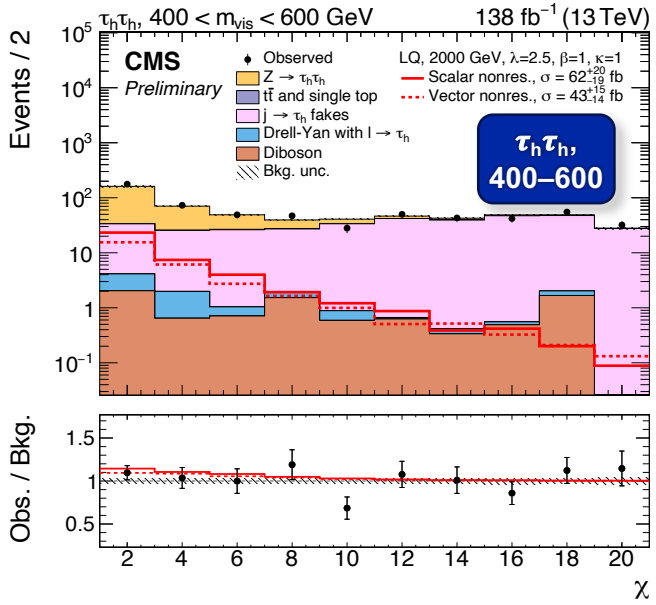
- constrain theoretical systematics
  - $\mu\mu$ for Z + jets
  - eμ for $t\bar{t}$
- nice agreement with **observed data**

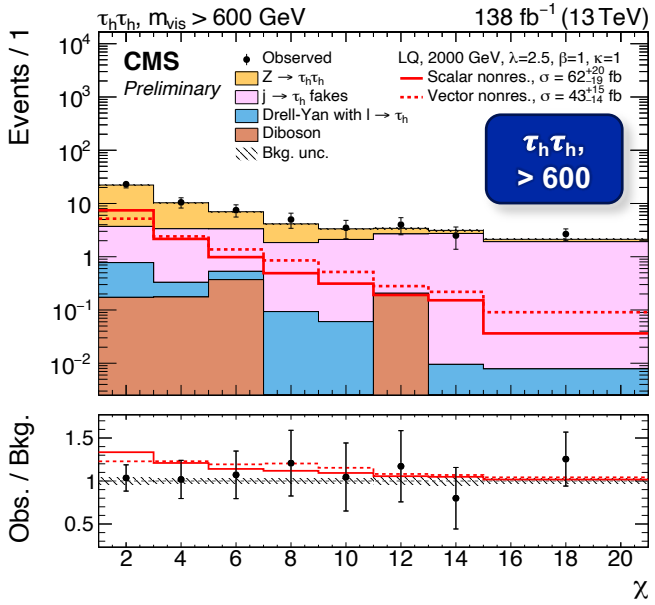


- fit **LQ signal**
  - scalar / vector
  - m = 2000 GeV
  - λ = 2.5
- sum of distributions in all three years
- small **excess** observed at low χ values

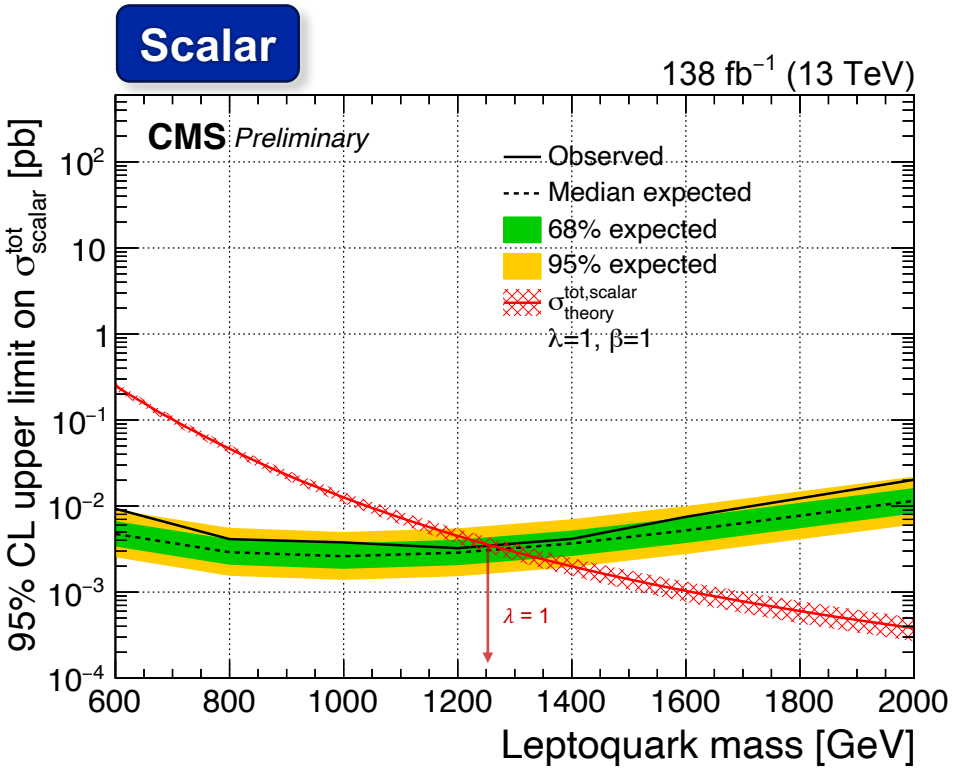


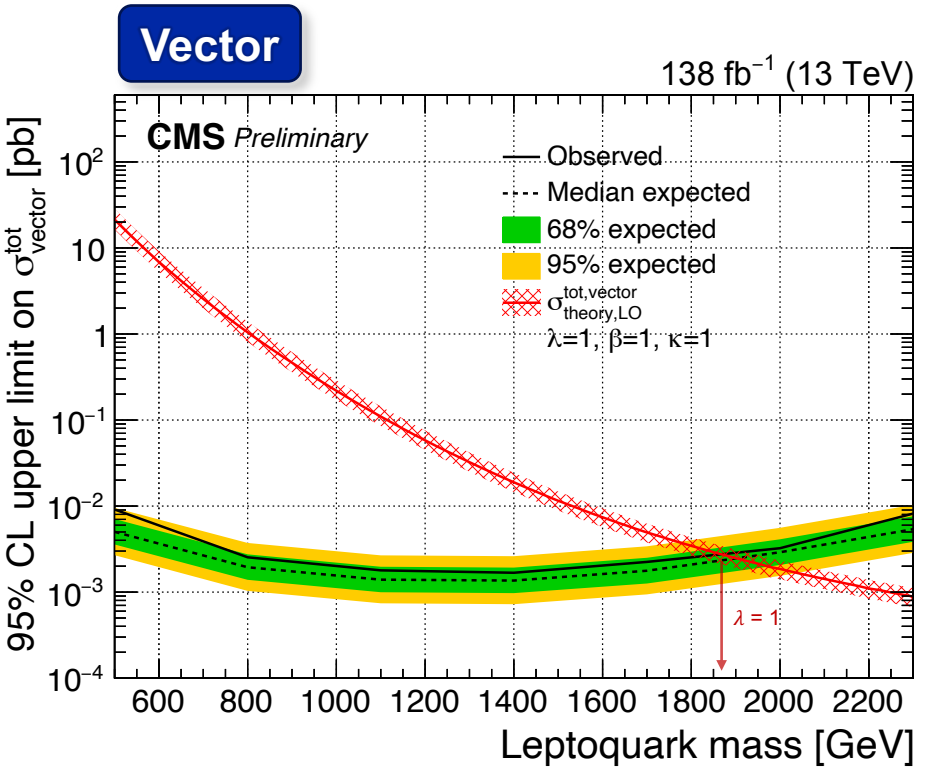






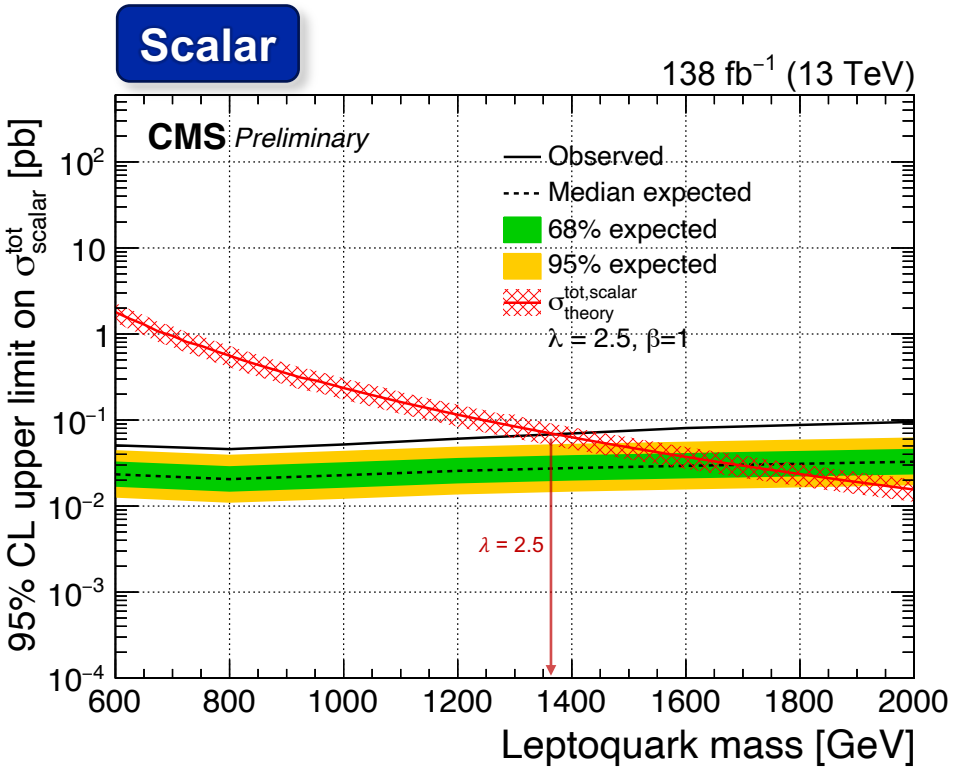
Combined upper limit, λ = 1

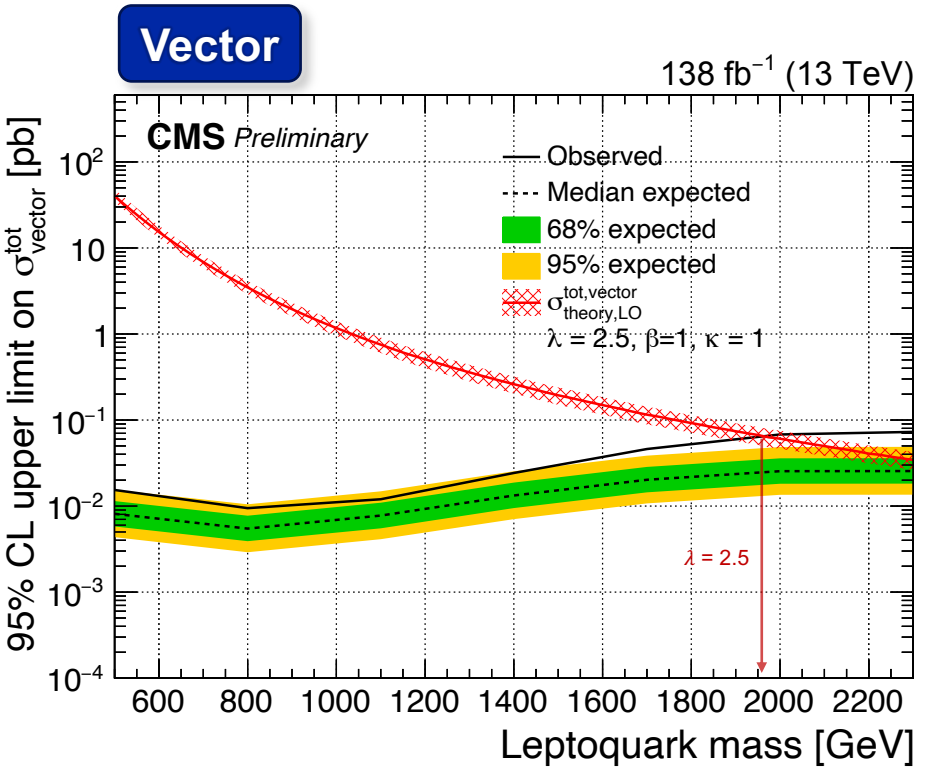




- no significant excess over the SM observed
- scalar (vector) LQ excluded up to **1.25** (**1.86**) TeV for $\lambda = 1$

Combined upper limit, λ = 2.5

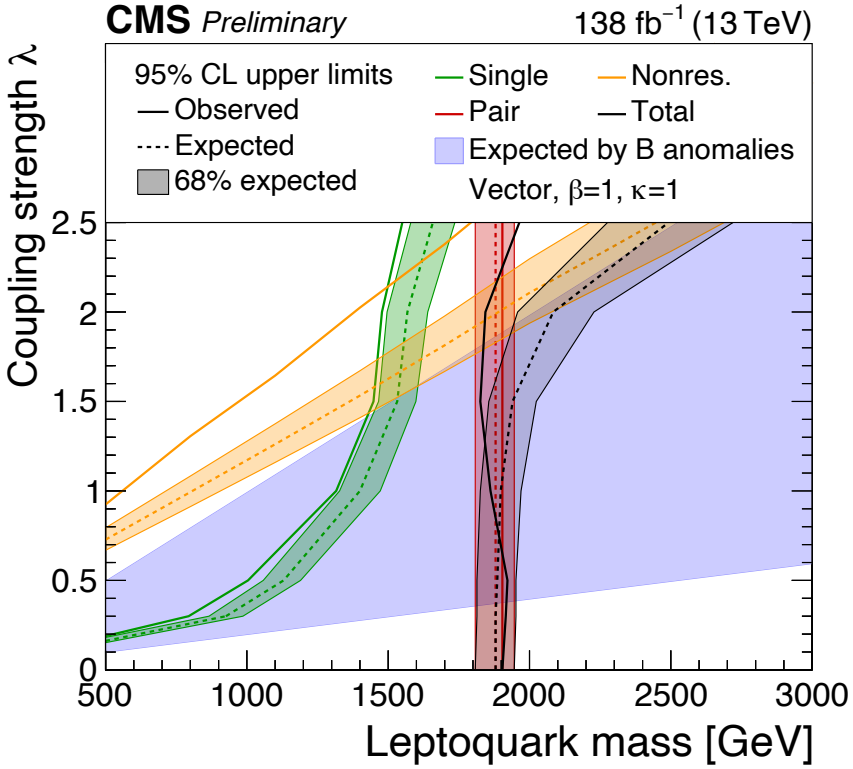




- ~3σ excess above M > 1800 TeV coming from nonresonant signal
- scalar (vector) LQ excluded up to **1.37** (**1.96**) TeV for λ = 2.5

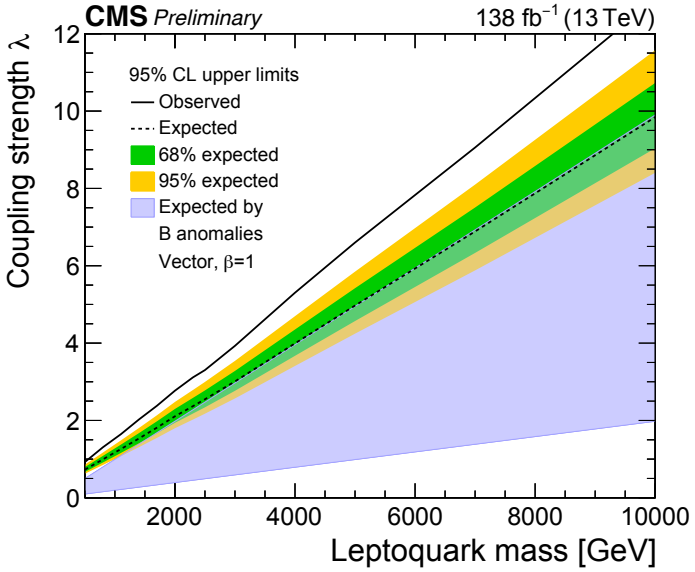
LQ → bτ exclusion limits of λ and mass

Resonant + nonresonant

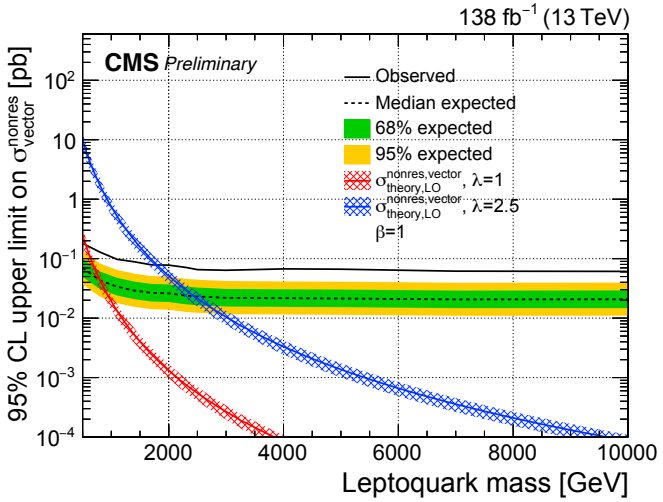


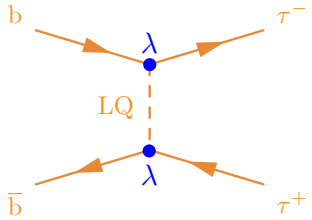
mass limit up to **~1.9 TeV**

Nonresonant only

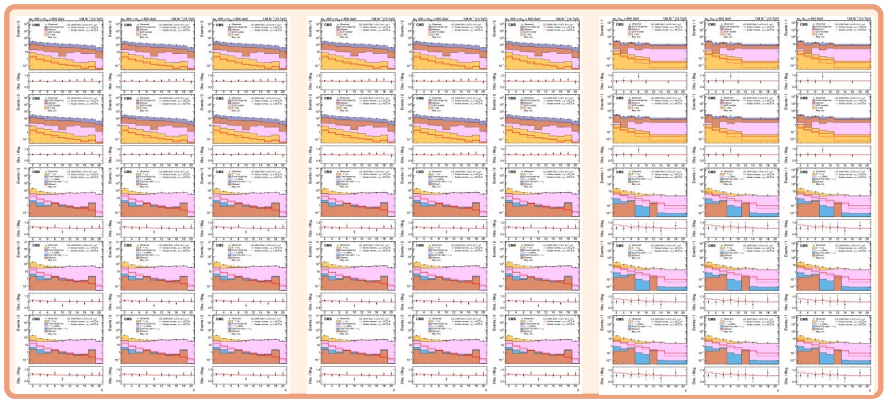


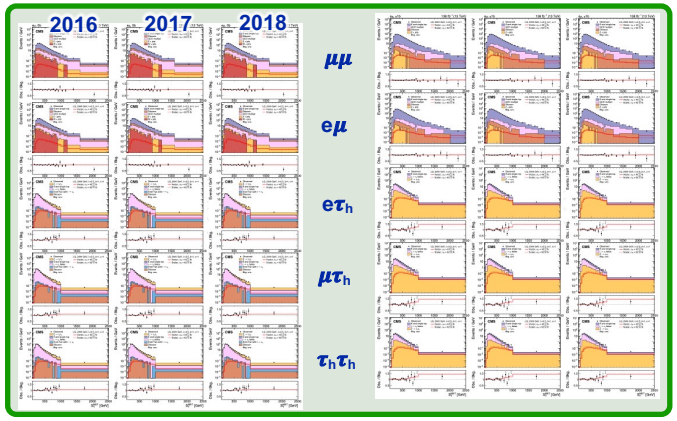
- ~3.5σ excess in nonresonant channel
- no sensitivity to mass or coupling:



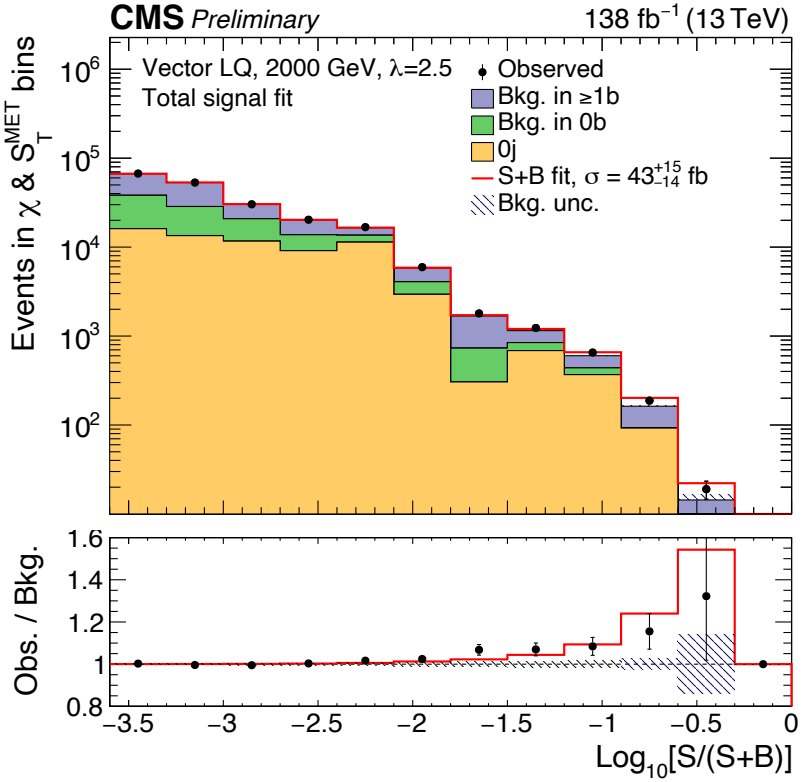


Reorder bins by S / (S+B)

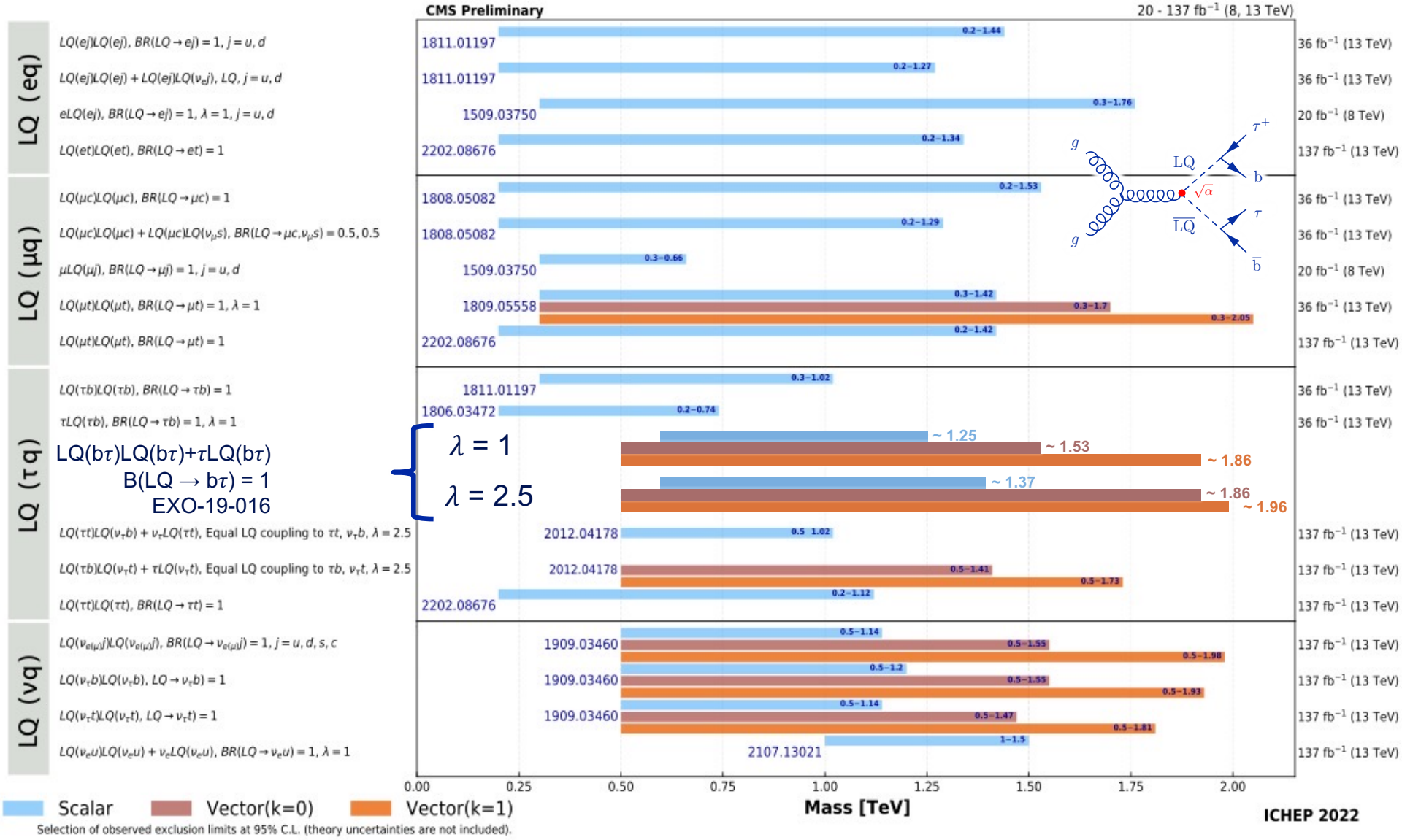




1. fit total signal (pair+single+nonres)
2. reorder and stack χ, S_T^{MET} bins by S/(S+B)
3. group backgrounds by category



CMS LQ summary

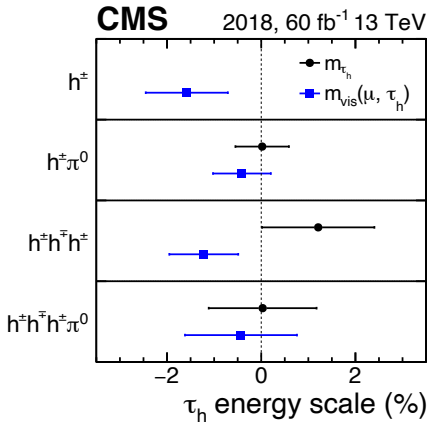


Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

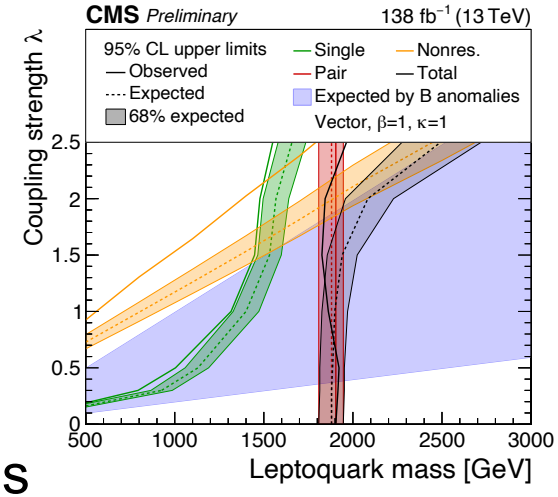
https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV#Leptoquark_summary_plot

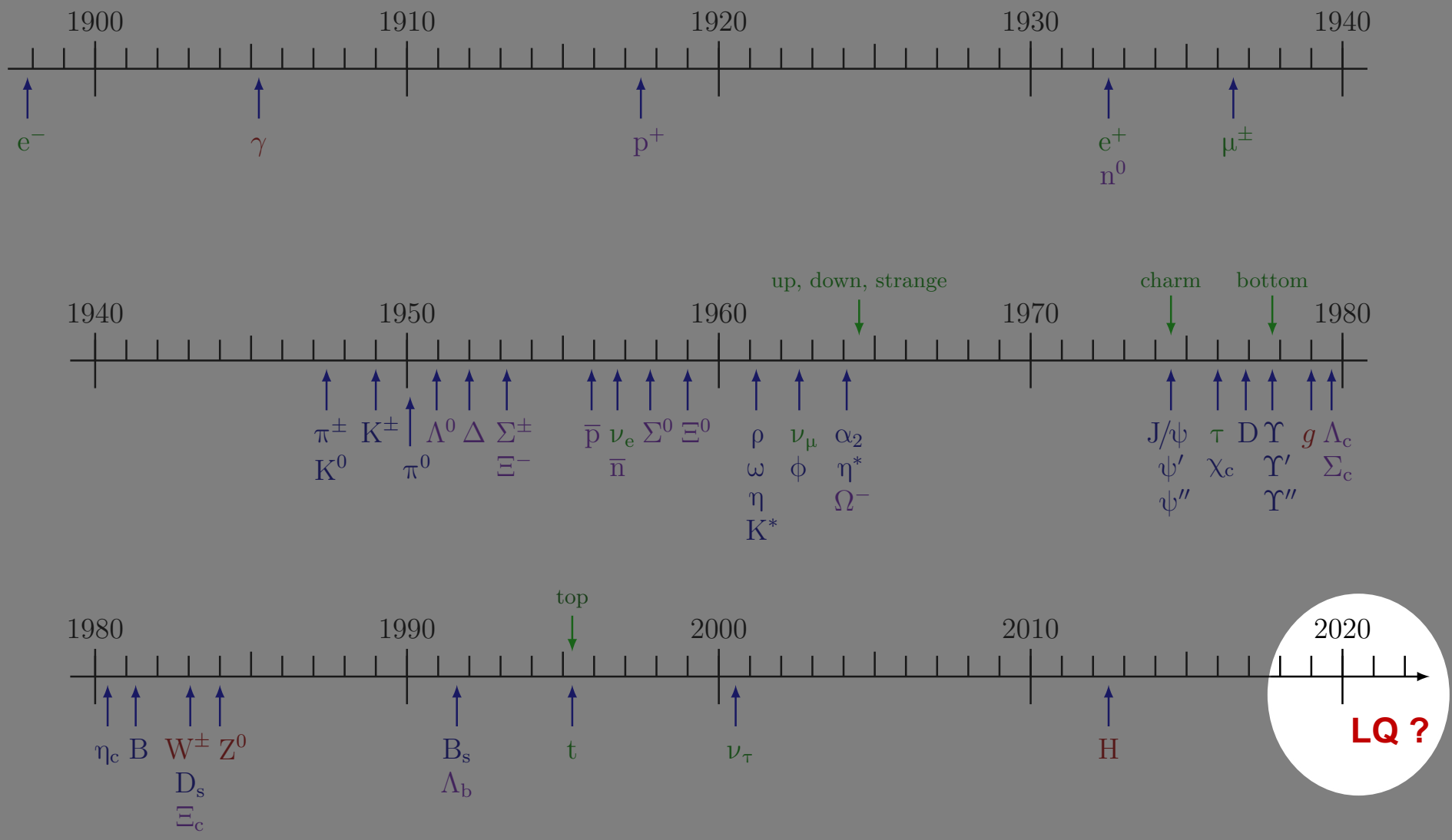
SUMMARY

Summary



- **LQ → bτ** couplings are well motivated by theory and recent experimental results like the B anomalies
- reconstruction & identification of τ_h at the CMS detector is important for physics analyses
  - derived corrections to **ID efficiency** & **energy scale** in simulation for CMS physics analyses
  - good modelling of the data can be achieved
- performed a search for **LQ** coupling to **bτ**
  - combined **single**, **pair**, and **nonresonant** production modes for the first time
  - scalar & vector
  - target **(b)(b)ττ** final state with (b) jet categories
  - found **excess** up to 3.4σ for a total LQ signal
- looking forward to
  - publication of the full & final results
  - follow-up studies




1900
1910
1920
1930
1940
e⁻
γ
p⁺
e⁺
n⁰
μ±
1940
1950
1960
1970
1980
up, down, strange
charm
bottom
π±
K⁰
K±
π⁰
Λ⁰
Δ
Σ±
Ξ⁻
p̄
n̄
νe
Σ⁰
Ξ⁰
ρ
ω
η
K*
νμ
ϕ
α2
η*
Ω⁻
J/ψ
ψ′
ψ″
τ
χc
D
ϒ
ϒ′
ϒ″
g
Λc
Σc
1980
1990
2000
2010
2020
top
ηc
B
W±
Z⁰
Ds
Ξc
Bs
Λb
t
ντ
H
LQ ?

Special thanks to my supervisors...

... and the great UZH CMS group !

Thank you for your attention !

References

- Flavor Anomaly Workshop 2021
  https://indico.cern.ch/event/1055780/timetable/
- EXO-19-016 PAS
  http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-19-016/index.html
- EXO-21-009
  http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-21-009/index.html
- HIG-21-001
  http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-21-001/
- B2G-21-004
  http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G-21-004/index.html
- CMS EXO results:
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV#Leptoquark_summary_plot