Search for BSM physics at LHC

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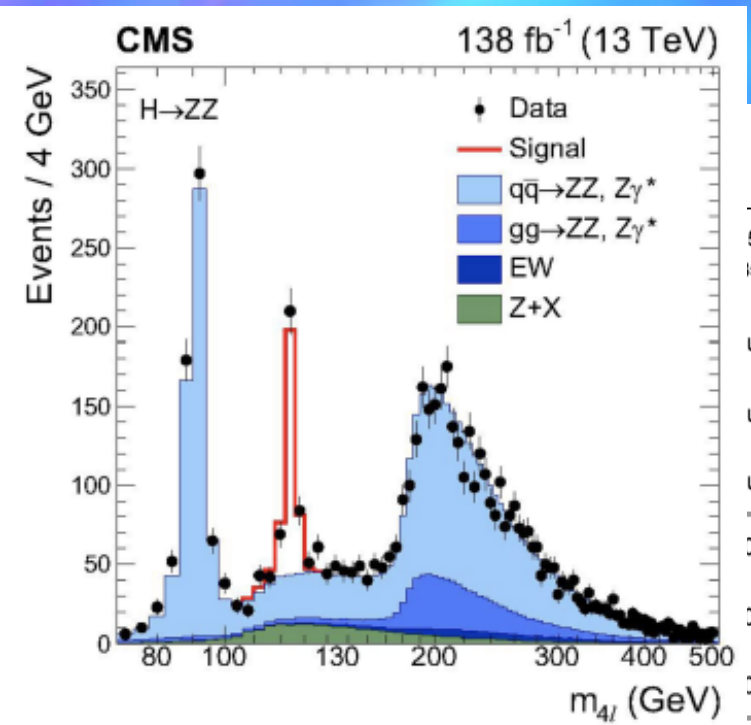
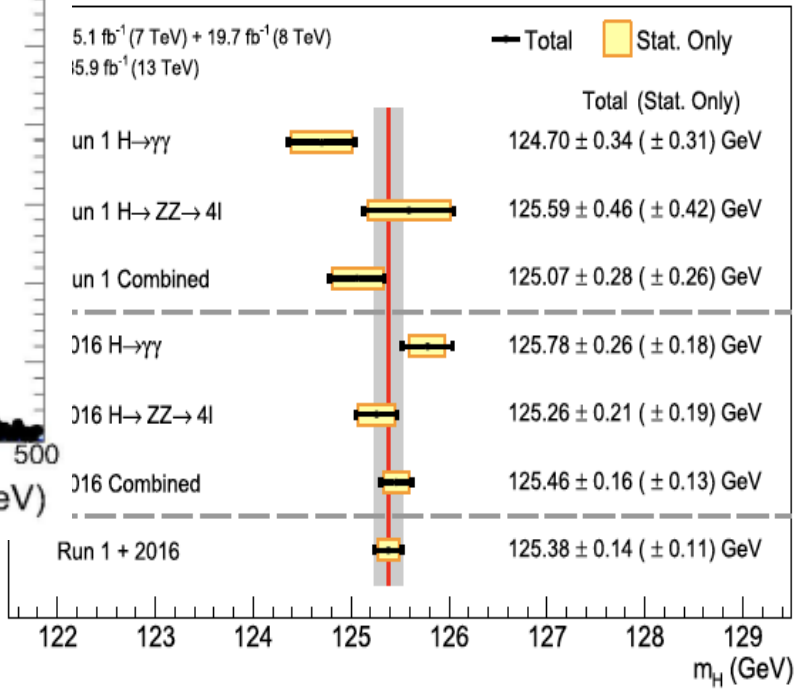
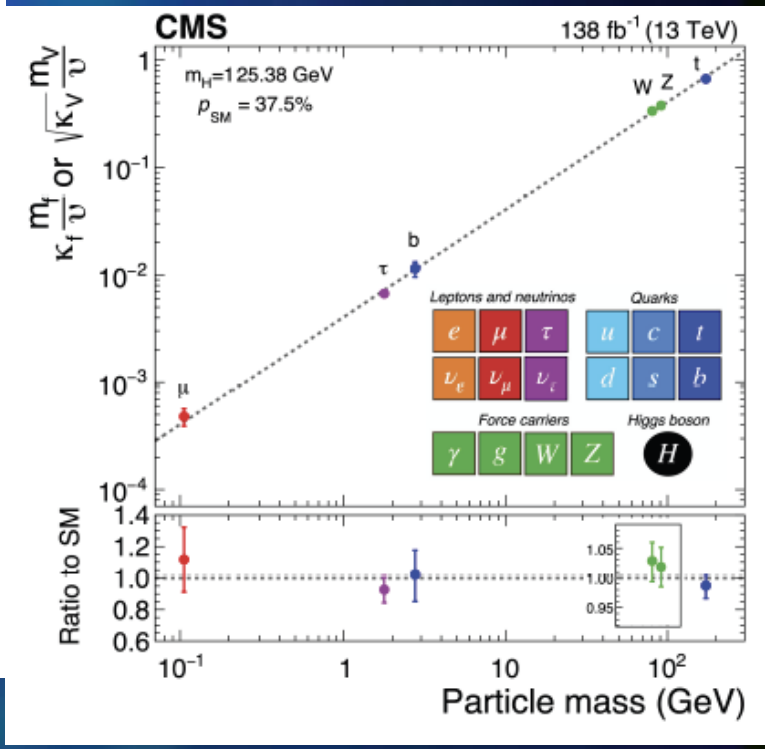
Round-Table Discussion Workshop, Feb. 26-28, IBS

Very successful SM completed with the Higgs discovery



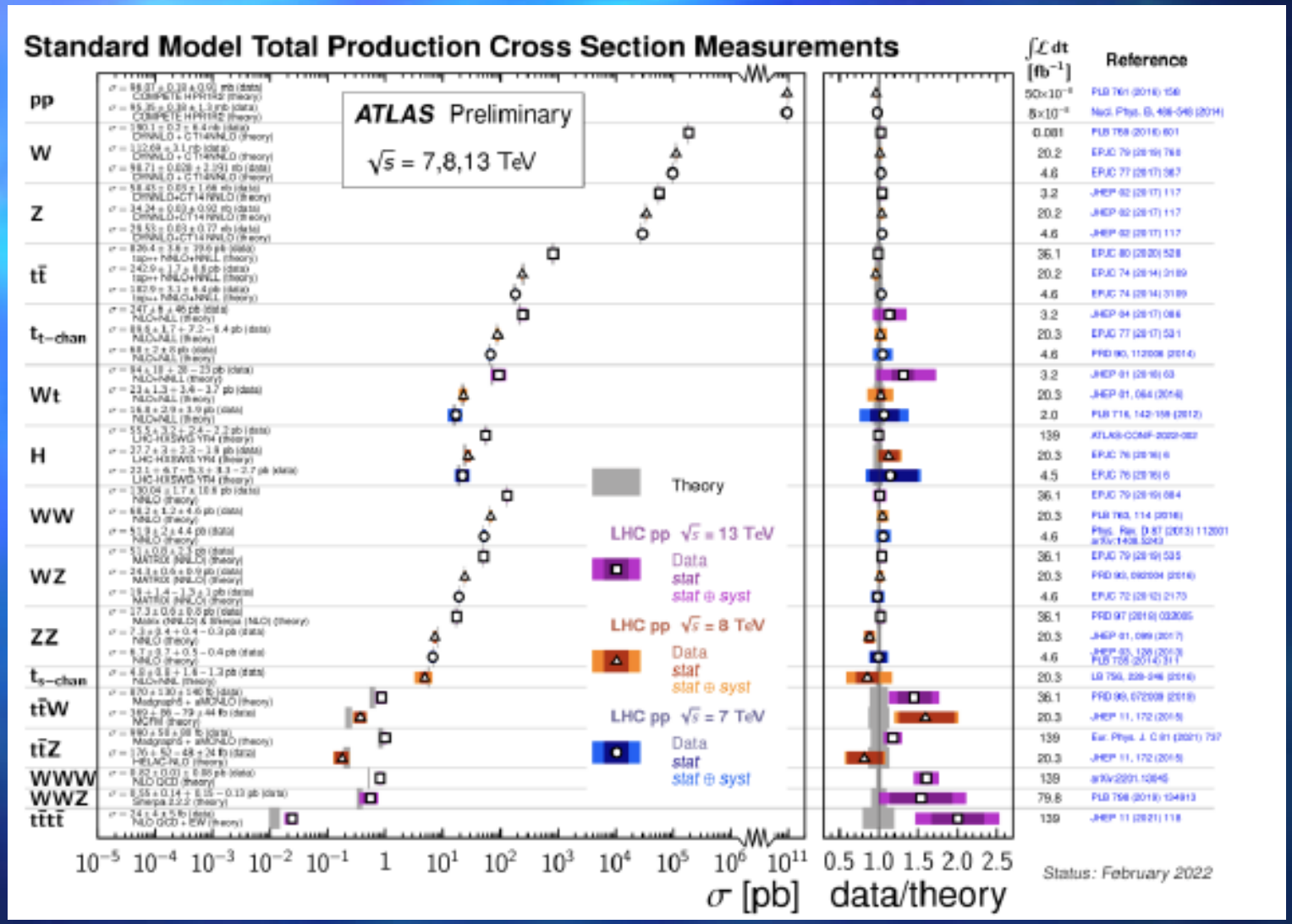
$m_H = 125.38 \pm 0.14\ GeV$





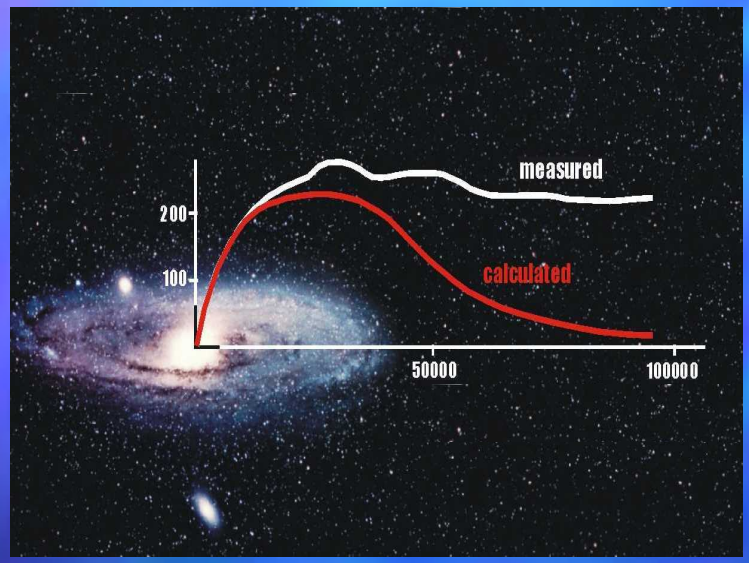
- Higgs mass: 125.38 V with 0.1% precision
- Couplings to the SM particles: consistent with the SM predictions

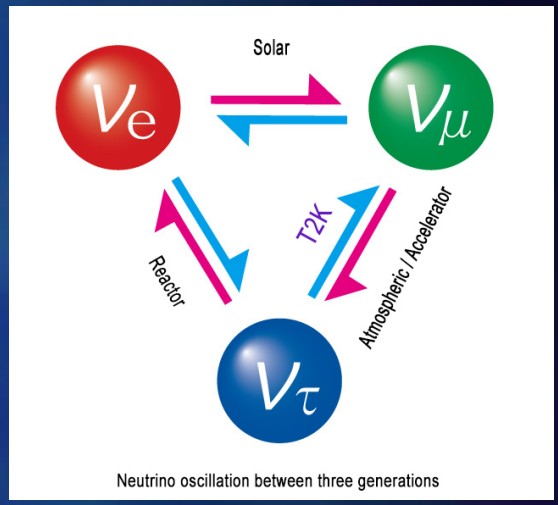
Very successful SM



- Good agreement, mostly in V, VV channels

With the most successful SM, why care for BSM?

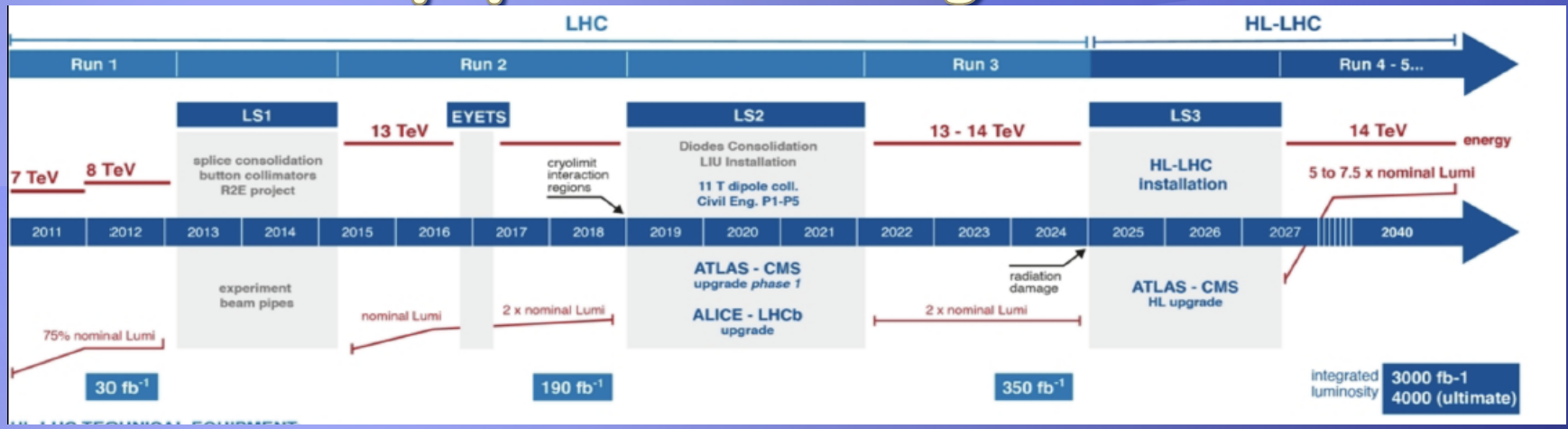


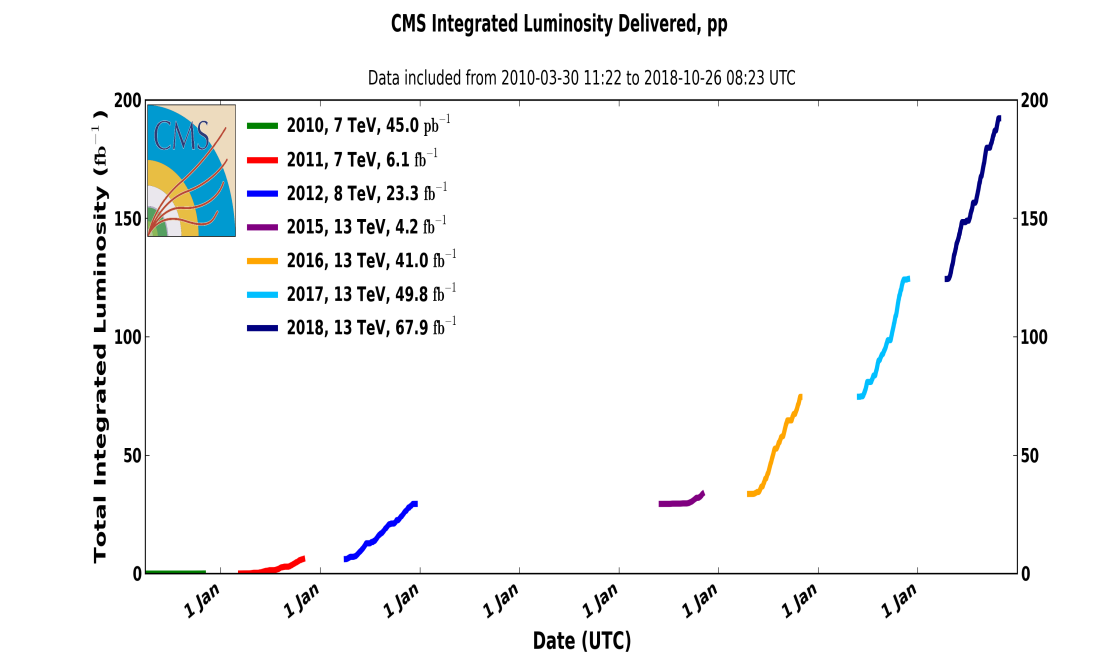


Neutrino oscillation between three generations

- Evidence for Beyond SM (BSM)
  - Dark matter, matter-antimatter asymmetry, neutrino mass
  - Higgs mass stability

Opportunity at LHC



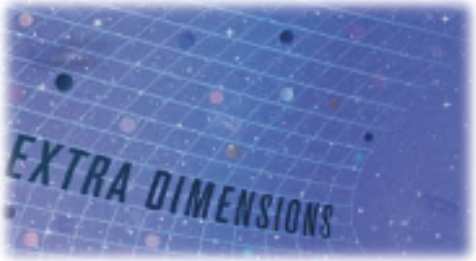


Events at CMS in Run 2 (~ 137 fb^{-1})

- W bosons 27000×10^6
- Z bosons 8000×10^6
- t quarks 130×10^6
- H bosons 8×10^6

- LHC High Energy Beam (5% of the data taken so far)
- A factor of 20 more data

BSM Searches



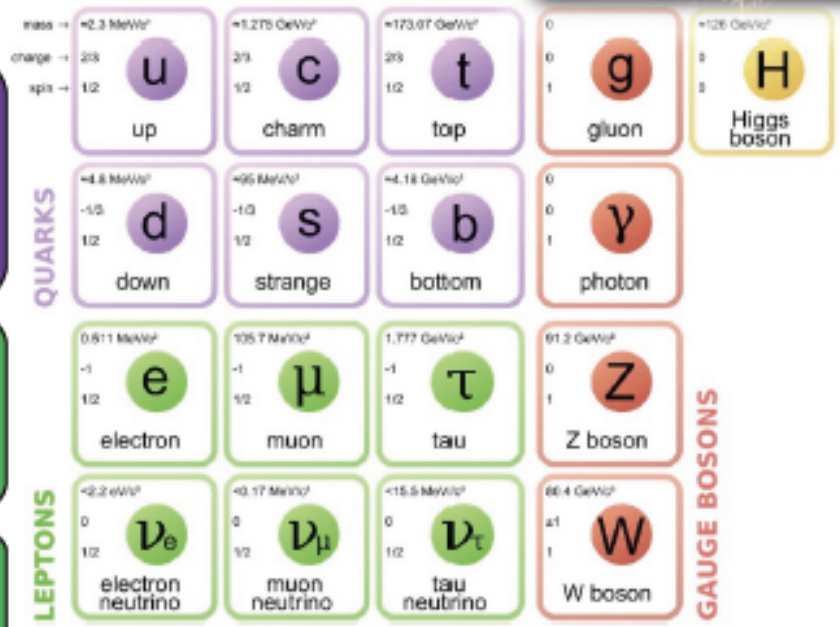
- KK excitations
- Quantum black holes

compositeness

New heavy quarks:
- Vector-Like Quark
- Excited quarks

New heavy lepton
- Vector-Like Lepton
- Excited lepton

Heavy Neutral Lepton



SUSY RPV

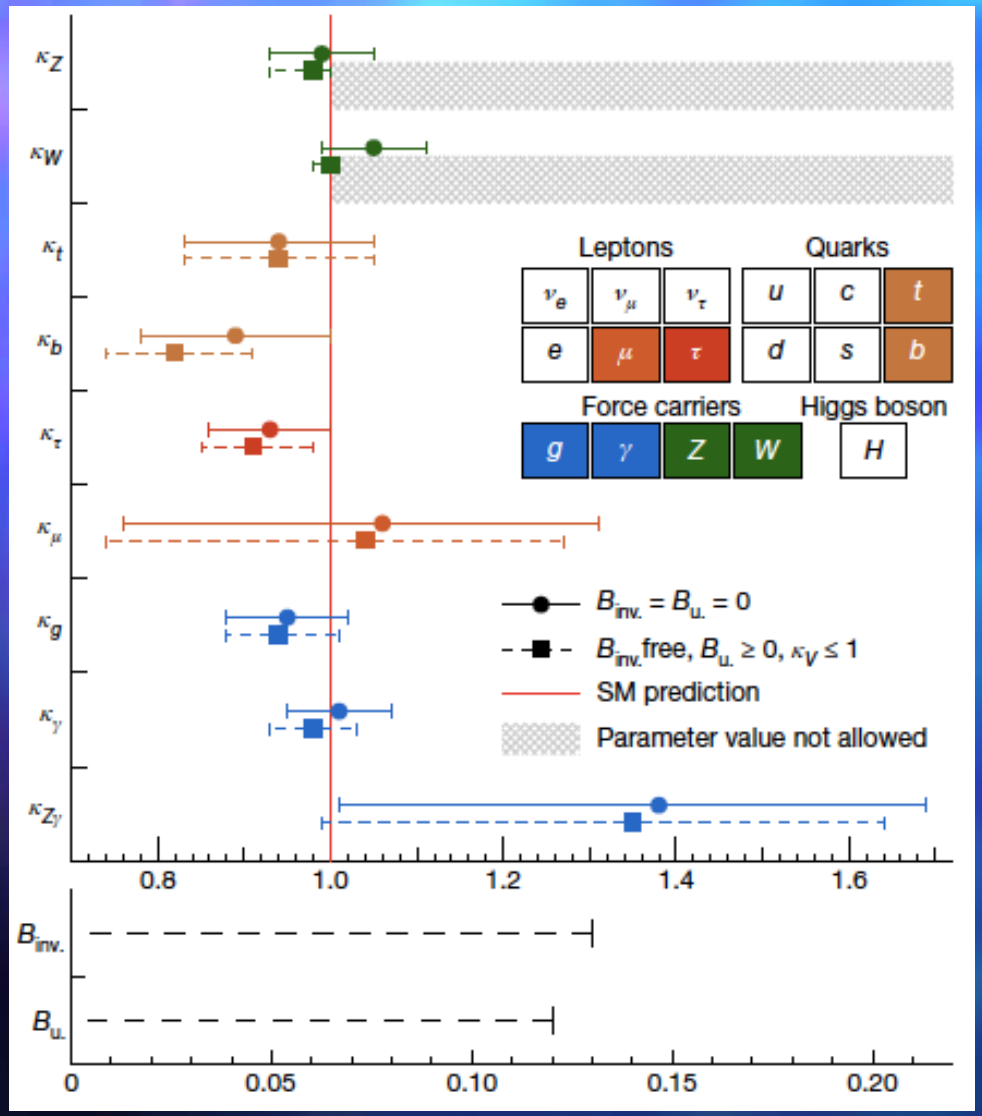
Extended Higgs sector:
- 2 HDM
- NMSSM …

Extended gauge sector:
- W', Z'

Leptoquarks

+ ….

Room for new physics



- Higgs to invisible decay mode:< 13%
- Higgs to undetected decay mode: <12%

Nature 607, 52 (2022)

Pre-Higgs

- At the end of the 1980s, CERN was preparing the next hadron collider

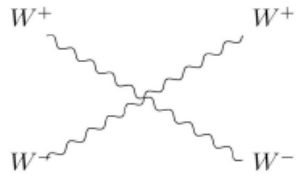
Two fundamental pieces were missing:

- the top quark:

  $m_t < 200$ GeV (indirect LEP 1) ; $m_t > 77$ GeV (CDF)

- the Higgs boson:

  $m_H > 44$ GeV (LEP 1); $m_H < 1$ TeV (Theory : WW scattering unitarity)



- No lose theorem: a machine is able to probe WW scattering up to ~1TeV
  - Higgs boson
  - New force beyond the SM

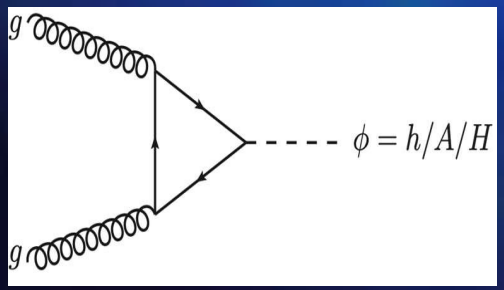
- Post-Higgs
  - what challenges do we see?

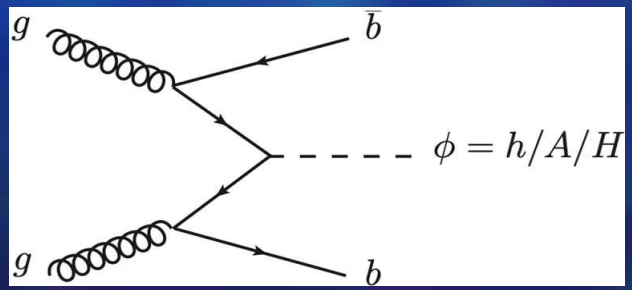
BSM Higgs

- Many BSM theories predict extended Higgs sector
- **Two-Higgs-Doublet models (2HDM) such as in SUSY**: five Higgs bosons
  - 2 neutral CP even (h, H), 1 neutral CP odd (A), 2 charged Higgs ($H^{+/-}$)
  - MSSM (m_A, $\tan\beta$): $h=h_{125}$, 2HDM Type-I/II : $h/H=h_{125}$
- **NMSSM: 2HDM + Singlet** : $h_1, h_2, h_3, a_1, a_2, h^{+-}$ (h_1 / h_2 = h_{125})
- Triplet model : double charged Higgs bosons ($H^{++/--}$)

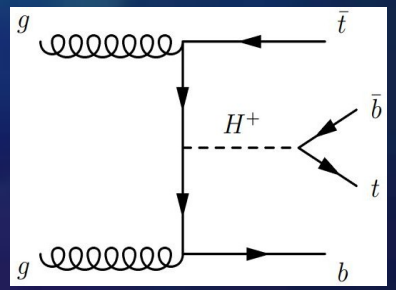
- **Find additional Higgs bosons**
- Find non-SM decay of h(125) particle
- Precision measurements of h(125) particle

Neutral Higgs Production

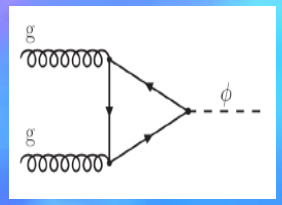


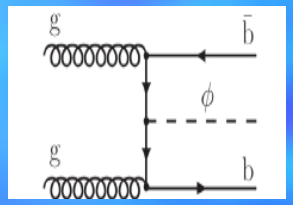


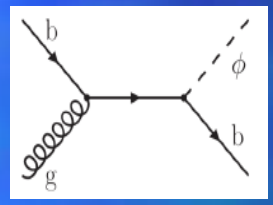
Charged Higgs Production



Neutral Higgs, $\phi(H/A) \rightarrow \tau\ \tau$

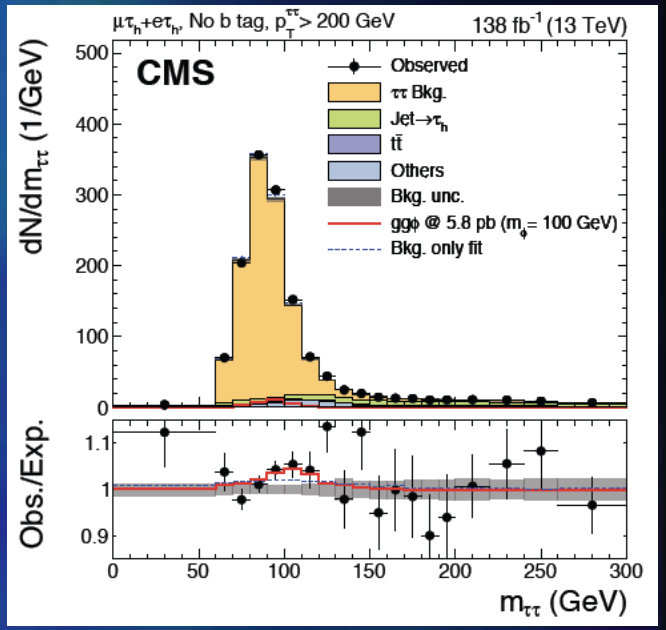


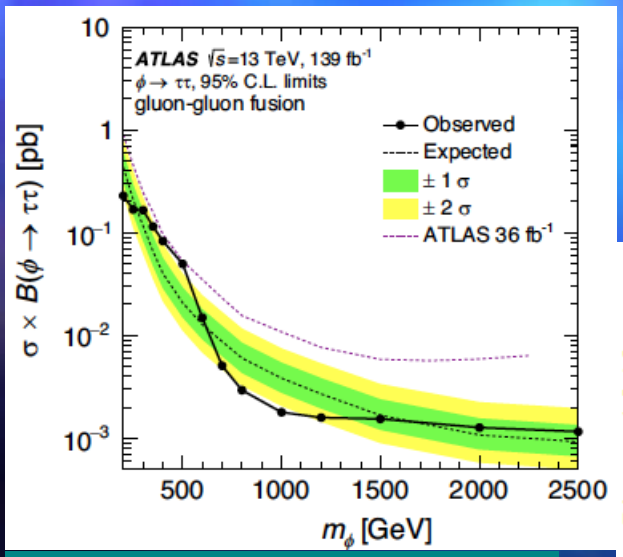




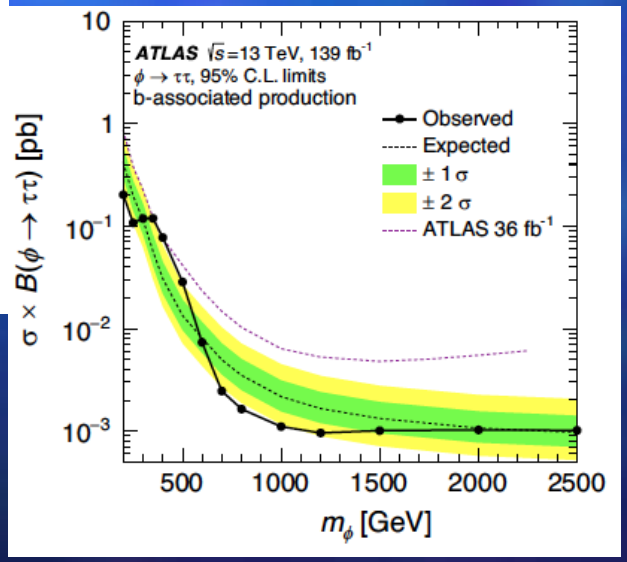
- ATLAS: 2.2 σ (ggF), 2.7 σ (bbH) at m=400 GeV
- CMS: 3.1 σ 100 GeV and 2.8 σ at 1.2 TeV

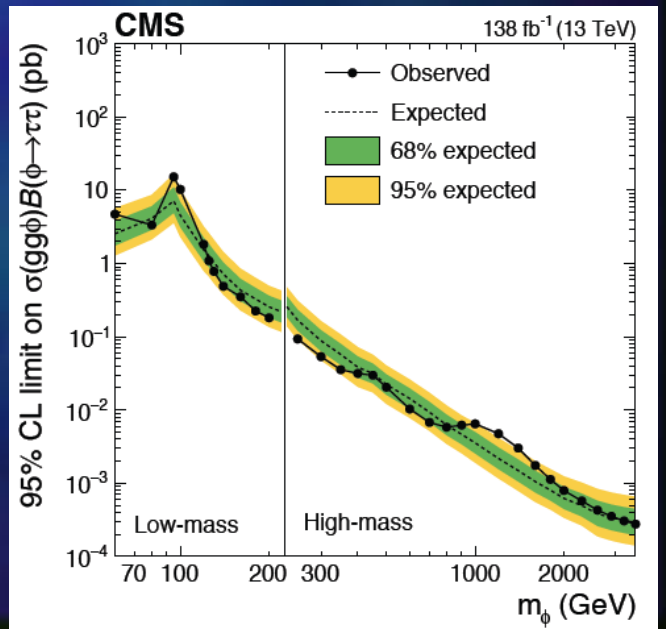
arXiv:2208.02717





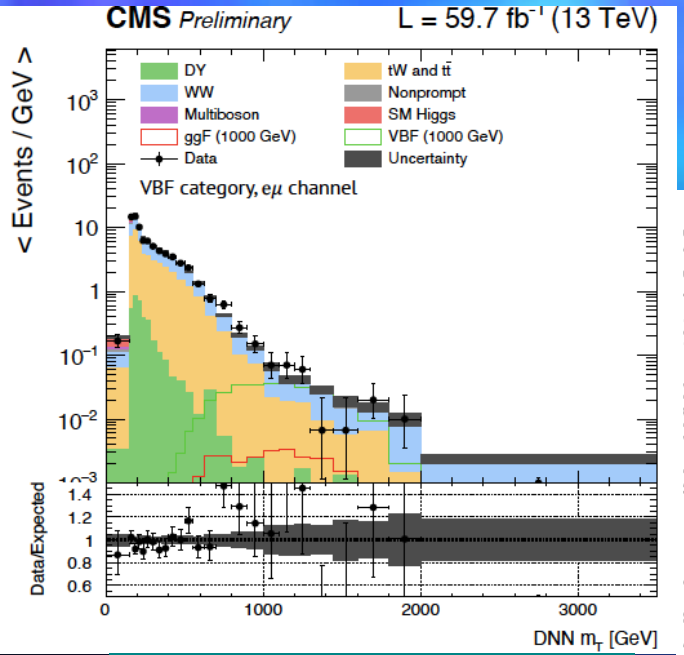
PRL 125 (2020) 051801



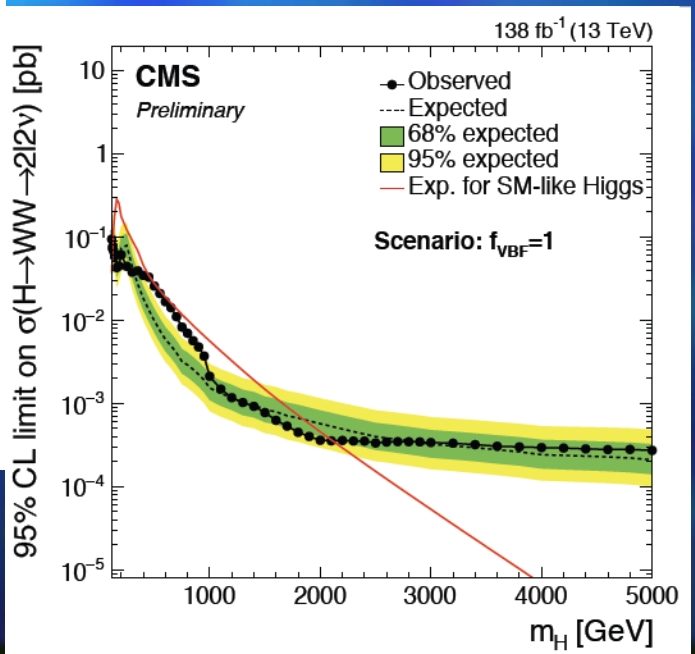


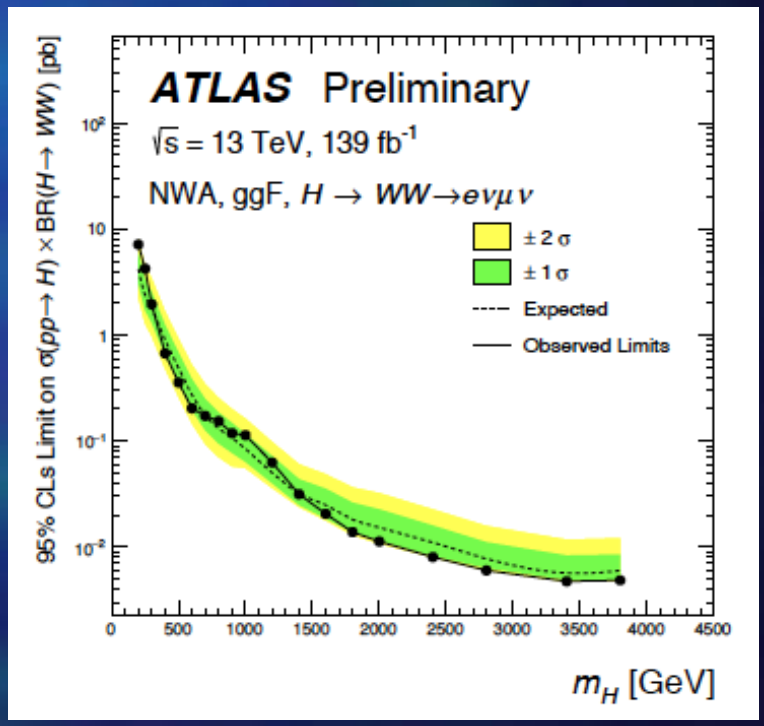
H→ WW (→2l 2 ν)

- Search for heavy Higgs in ggF and VBF production in a mass range:
- CMS: largest excess 3.8 σ at 650 GeV (only VBF) and 2.6 σ (ggF) at 950 GeV
- ATLAS: no similar excess



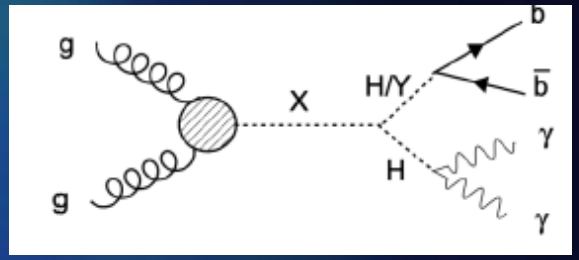
CMS-PAS-HIG-20-016



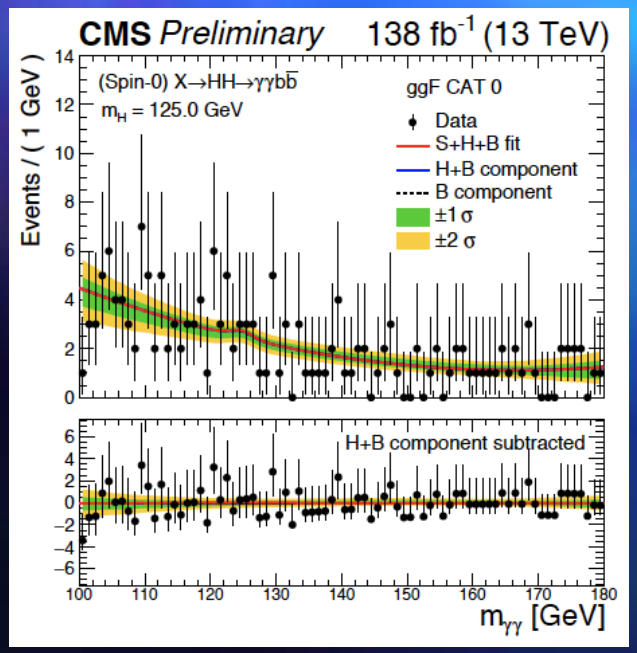


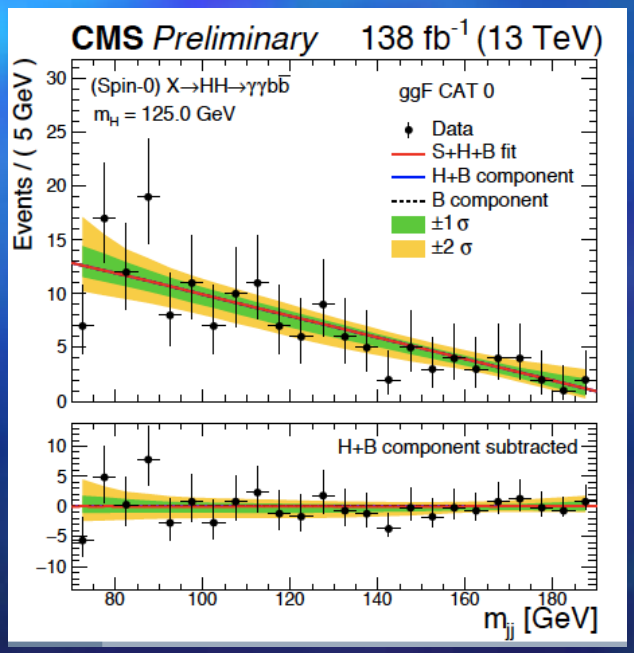
$H(A) \rightarrow a h_{125} \rightarrow bb\gamma\gamma$

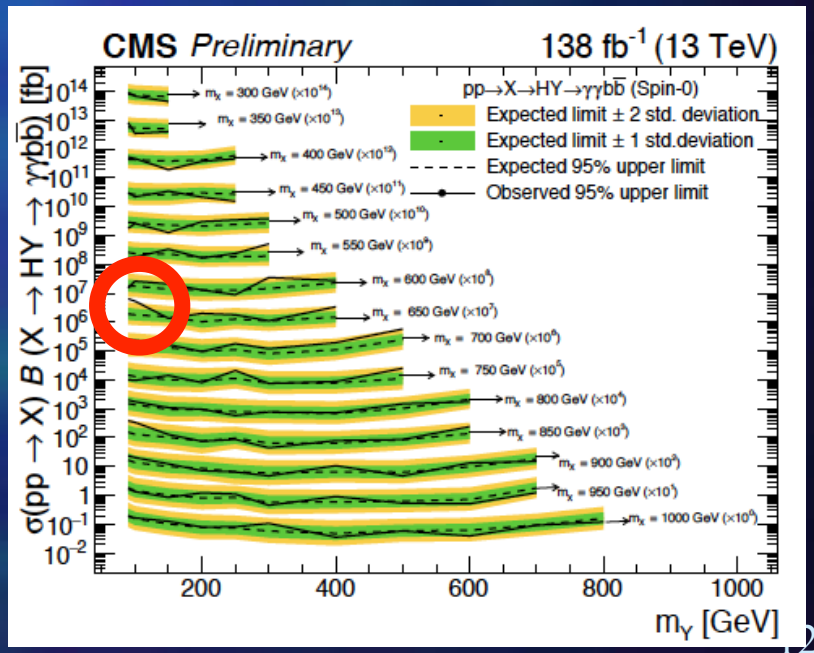
- Search for heavy Higgs decaying to a light Higgs and SM Higgs boson in NMSSM: 2HDM+S
- No significant excess over SM predictions
- Largest excess 3.8 σ at $(m_H, m_a) = (650, 90)$ GeV



CMS-PAS-EXO-21-011

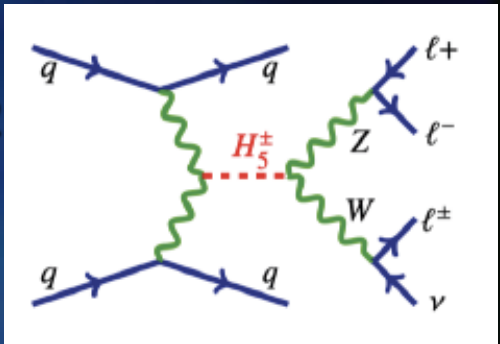




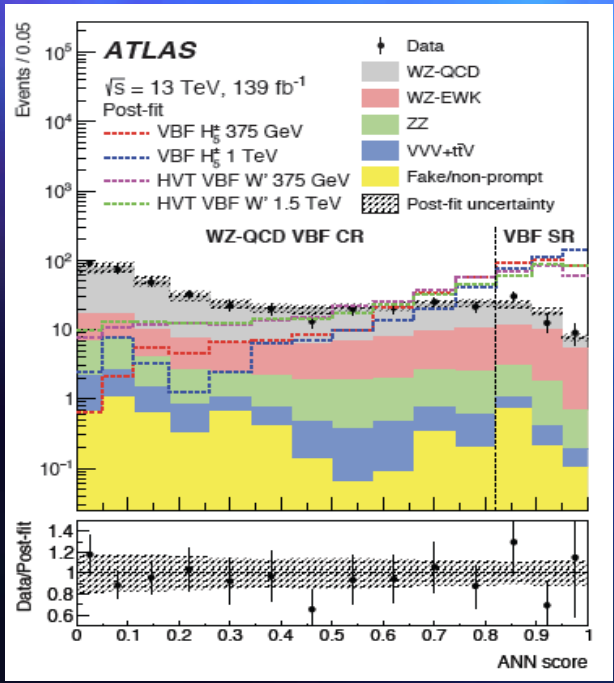


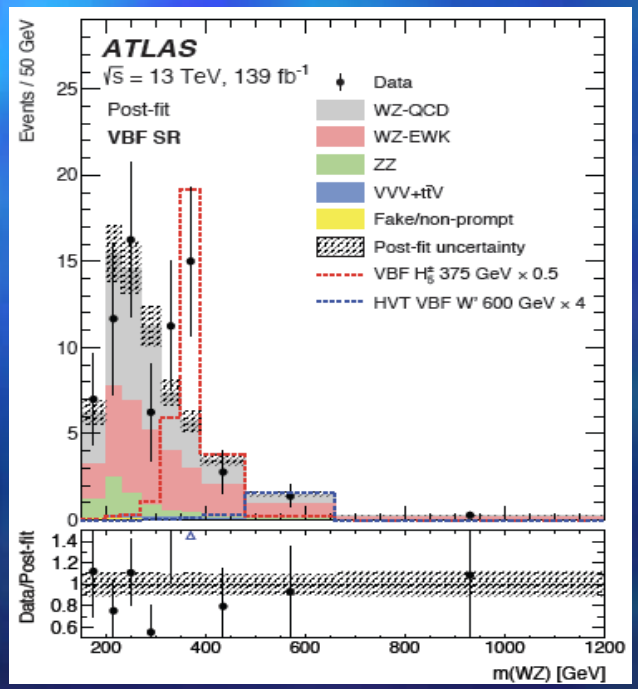
Heavy $H^+ \rightarrow WZ \rightarrow l\nu ll$

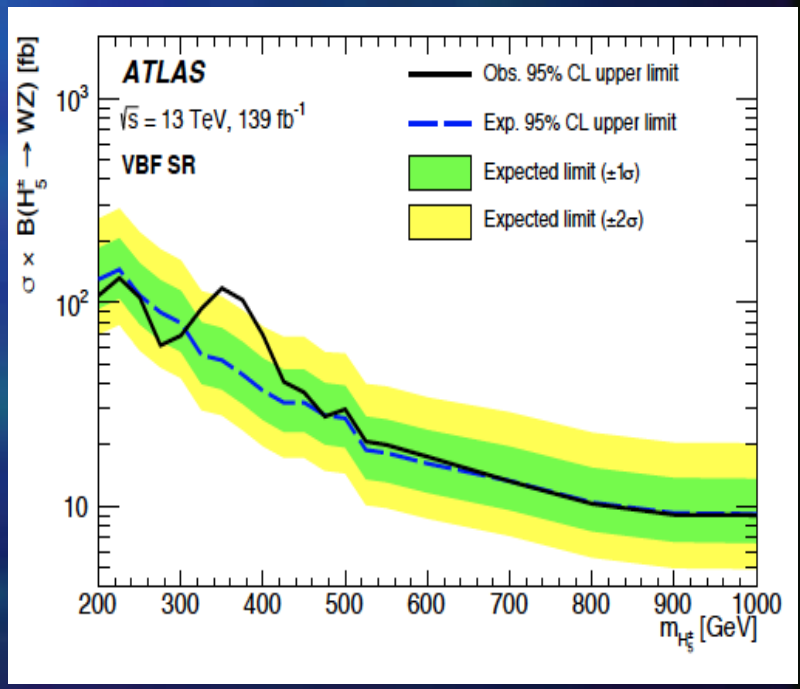
- Search for heavy Higgs to WZ decay in fully leptonic channel
- This channel is more sensitive for mass < ~ 1 TeV
- SR selection: 3l, MET, 2 VBF jets, m_{jj}>100 GeV, ANN>0.82
- Discriminating variable: m(WZ)
- Largest excess 2.8 σ at 375 GeV



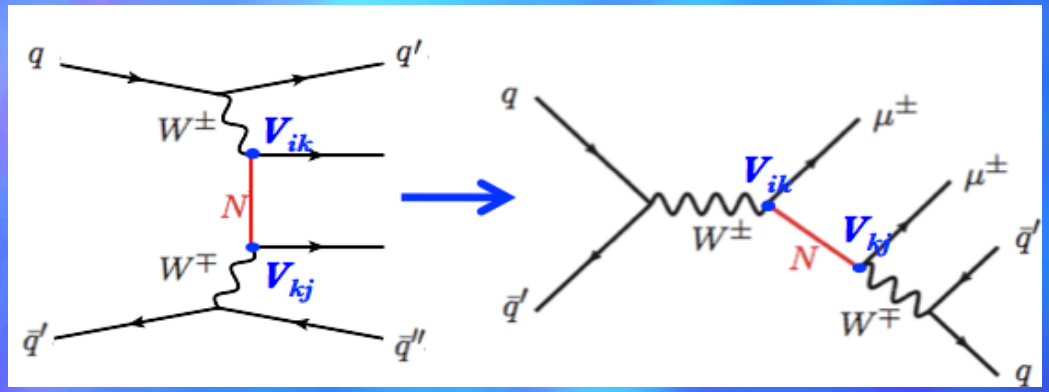
arXiv:2207.03925

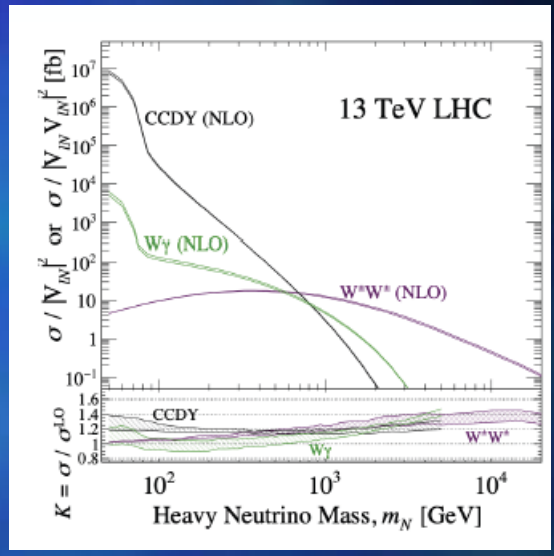


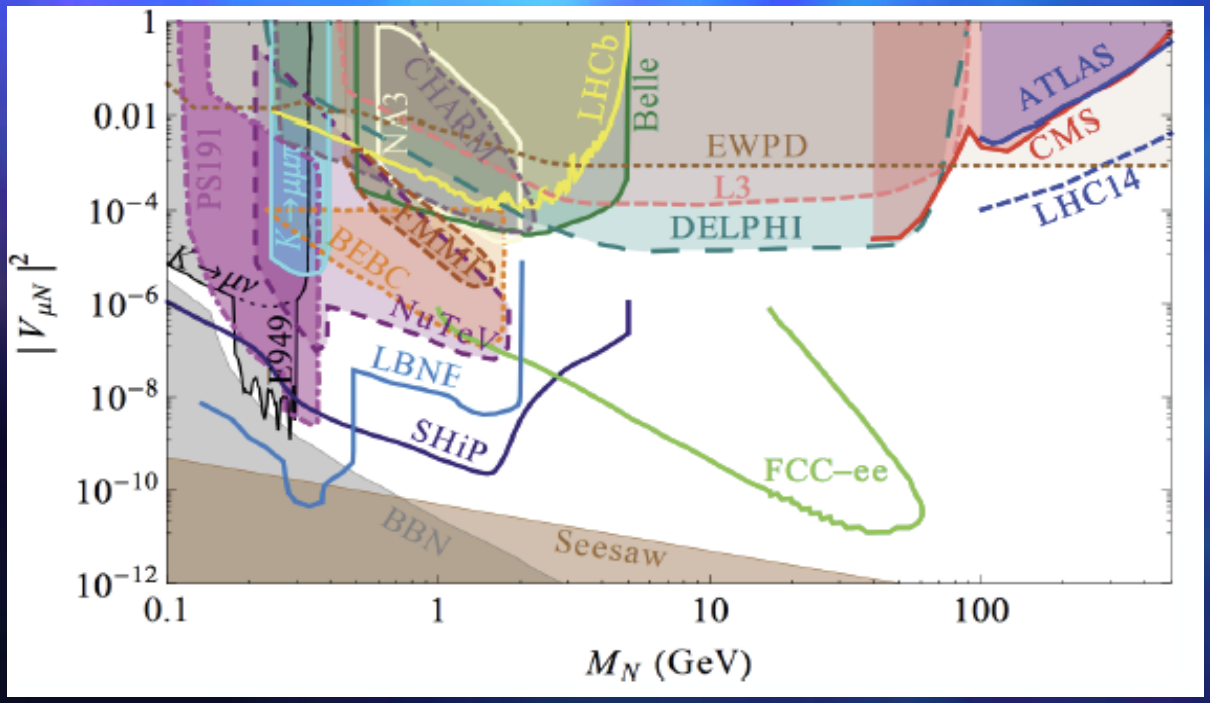


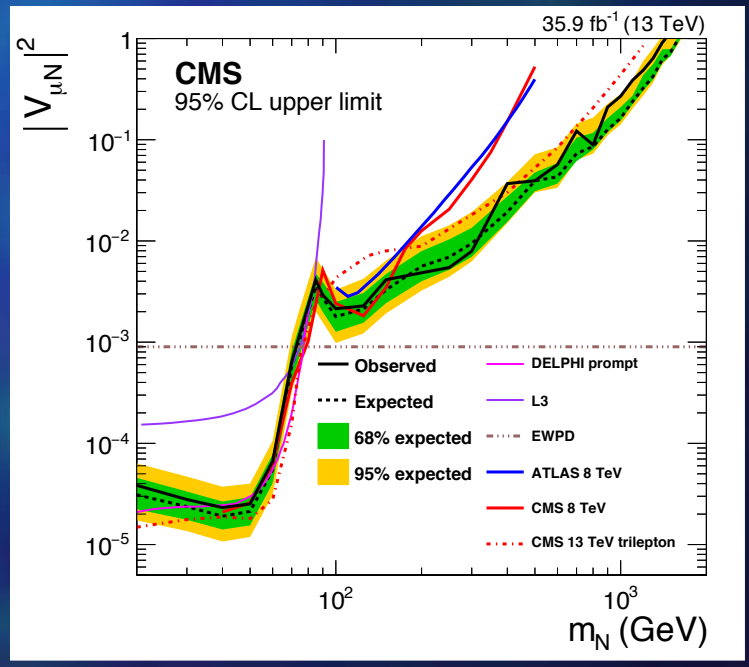


Heavy Neutrinos









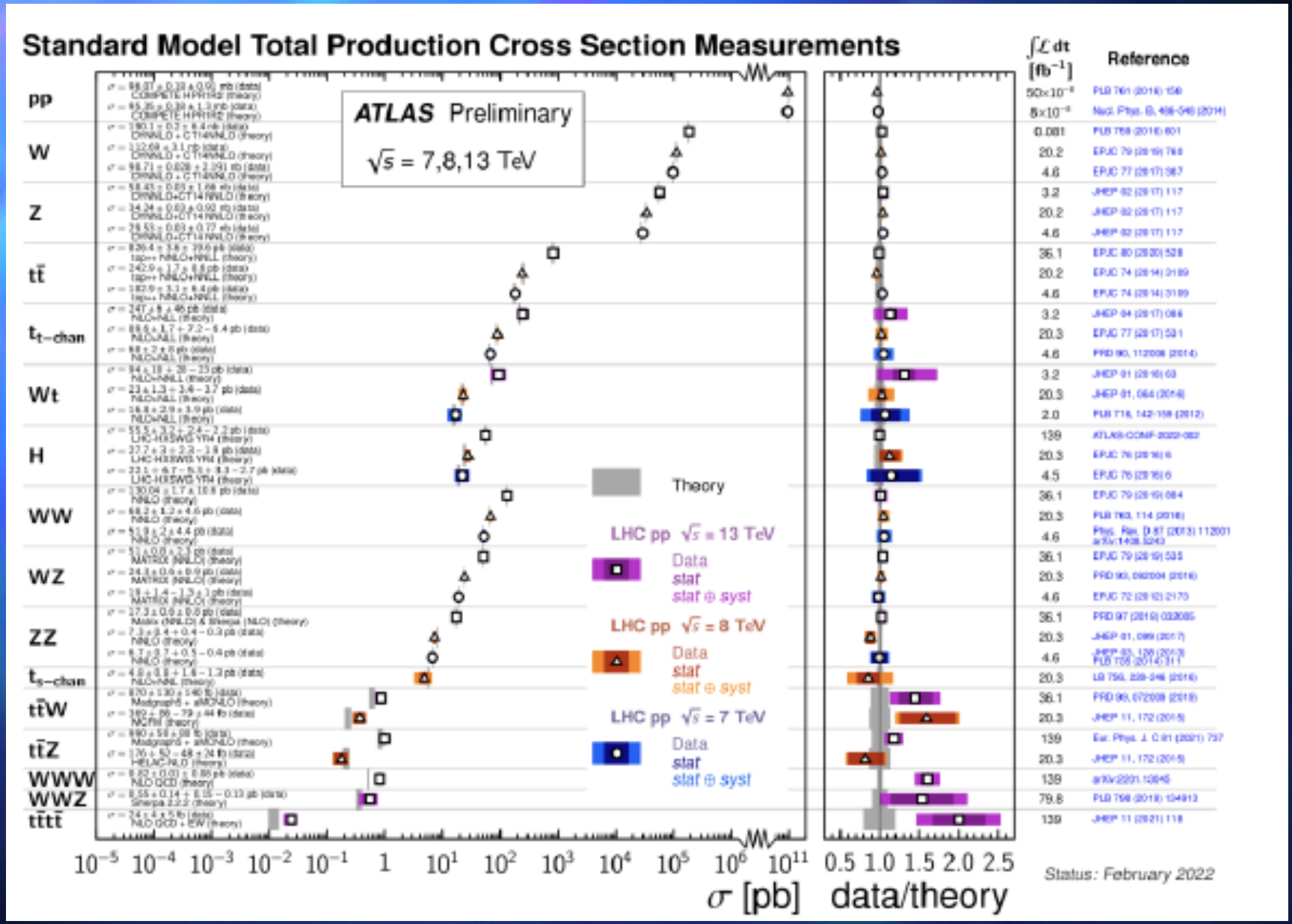
CMS Search Strategy

- Large mass with large coupling:
  - high mass resonance in the tail

- Weak coupling (DM, fractional charge etc)
- Small mass
- Longer lifetime

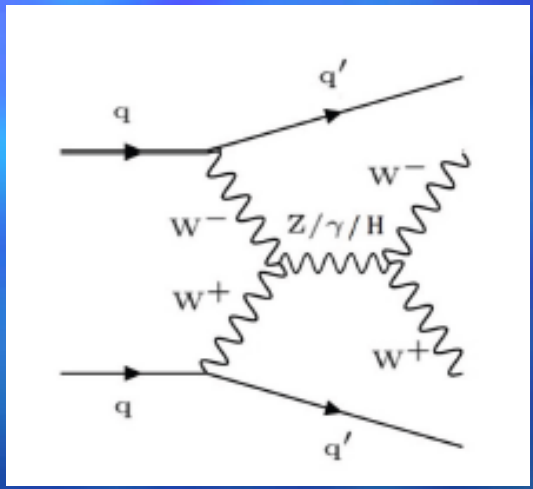
- ISR jet with large MET
- Long lived particle (displaced track, jets)
- Boosted particle/jet (jet substructure)

SM

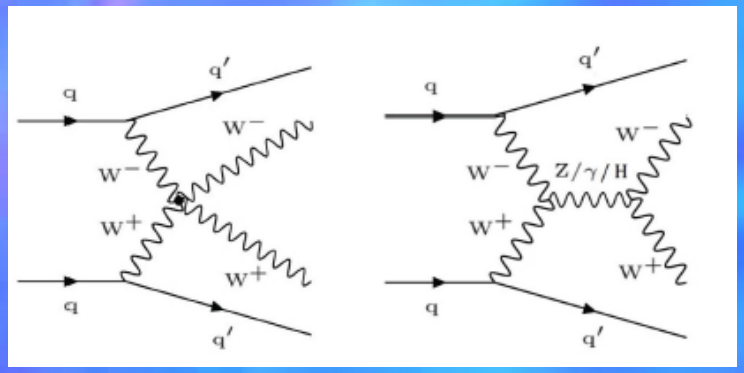

Standard Model Total Production Cross Section Measurements
ATLAS Preliminary
√s = 7,8,13 TeV
Theory
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
pp
W
Z
tt̄
t_t−chan
Wt
H
WW
WZ
ZZ
t_s−chan
ttW
ttZ
WWW
WWZ
tttt
∫L dt [fb⁻¹]
Reference
10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10¹¹
σ [pb]
0.5 1.0 1.5 2.0 2.5
data/theory
Status: February 2022

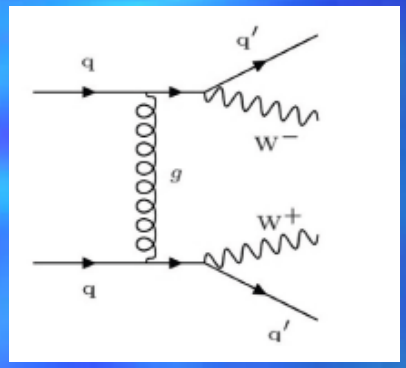
Precision SM

- SM processes:
  - Single object (W,Z) <5%
  - Double objects (VV) < 20%
  - **Triple objects (VV+X) or ratio of double ojects**
    - Suppressed rare process (VBF SS WW etc)



W+W- Xsection

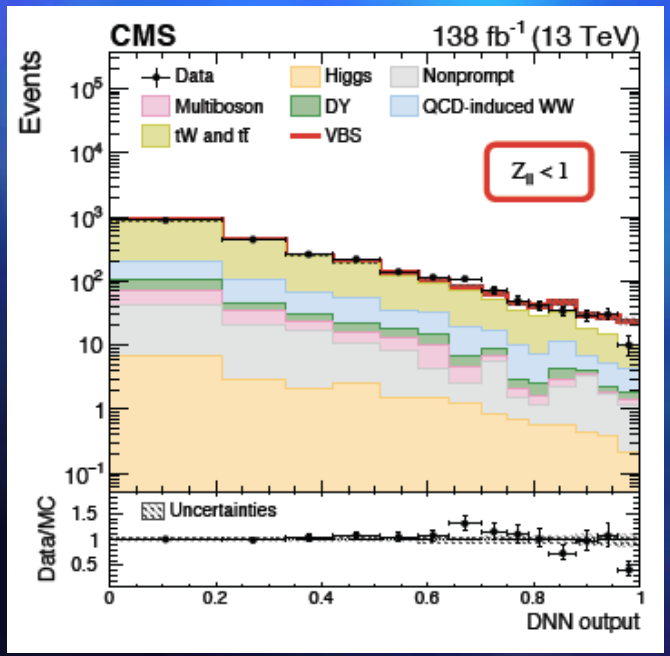


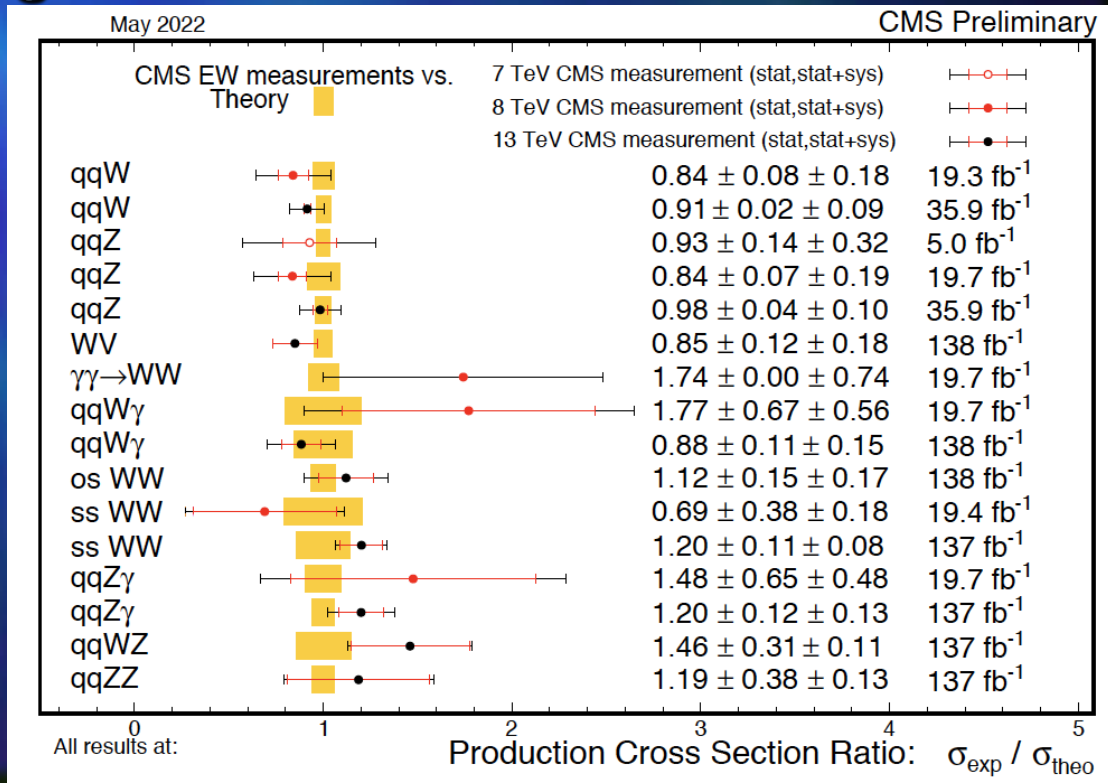


Measurement: 10.2 ± 2.0 fb

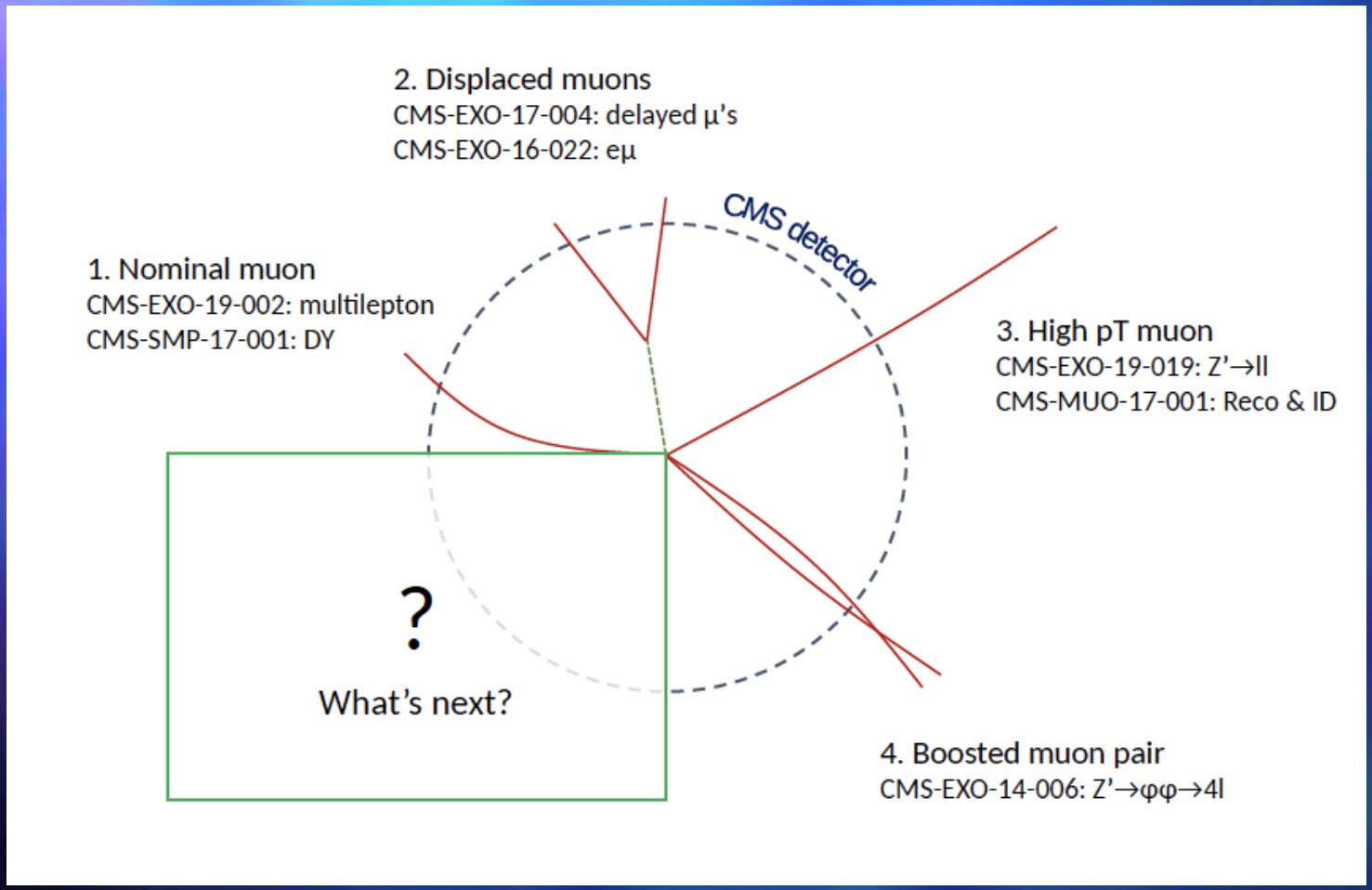
Prediction at LO: 9.1 ± 0.6 fb

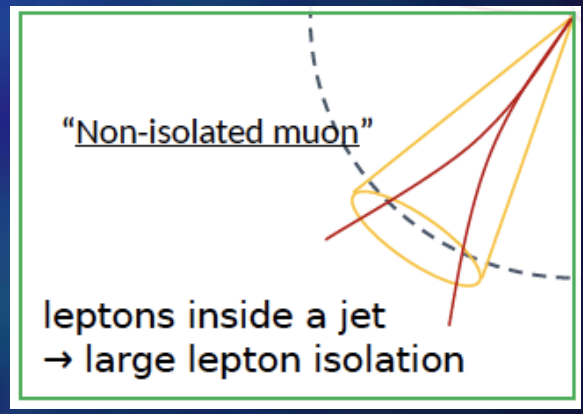
- Higgs boson: cancel divergence in calculations of VBS process: a good probe of the Higgs sector





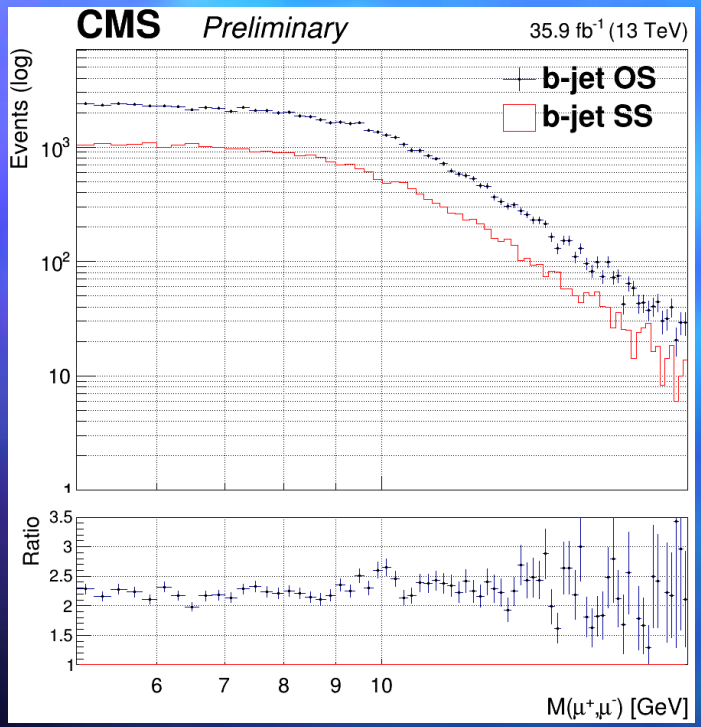
Physics with non-isolated muons

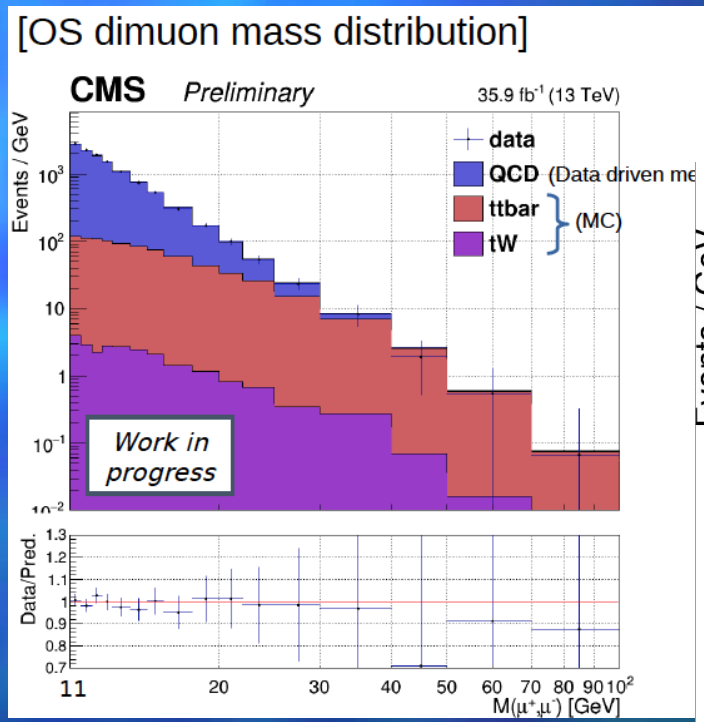


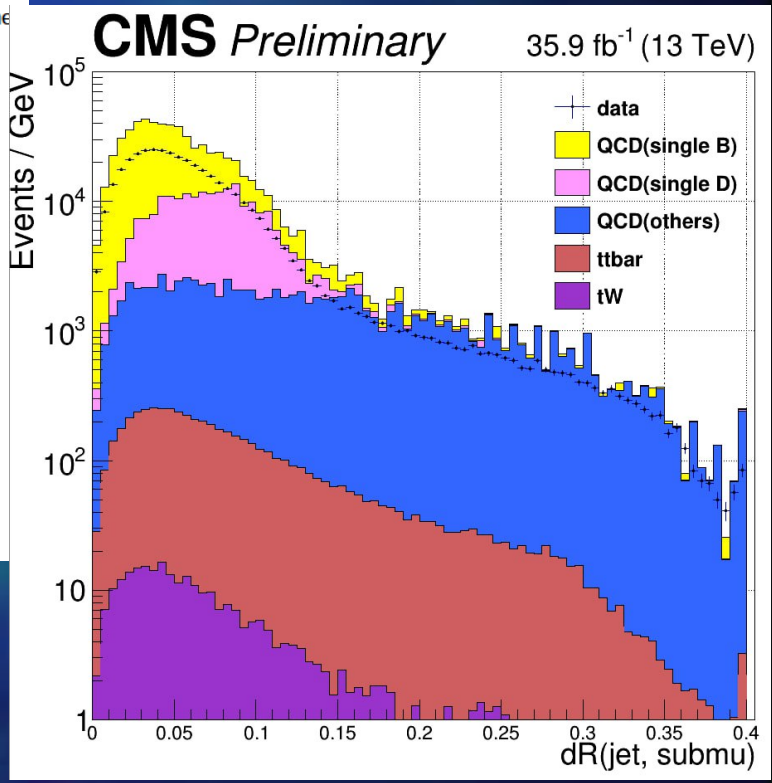


BSM search and heavy flavour studies using non-iso. muons

- Model independent search using muons inside jet
- Heavy flavour B/D studies inside b-jets

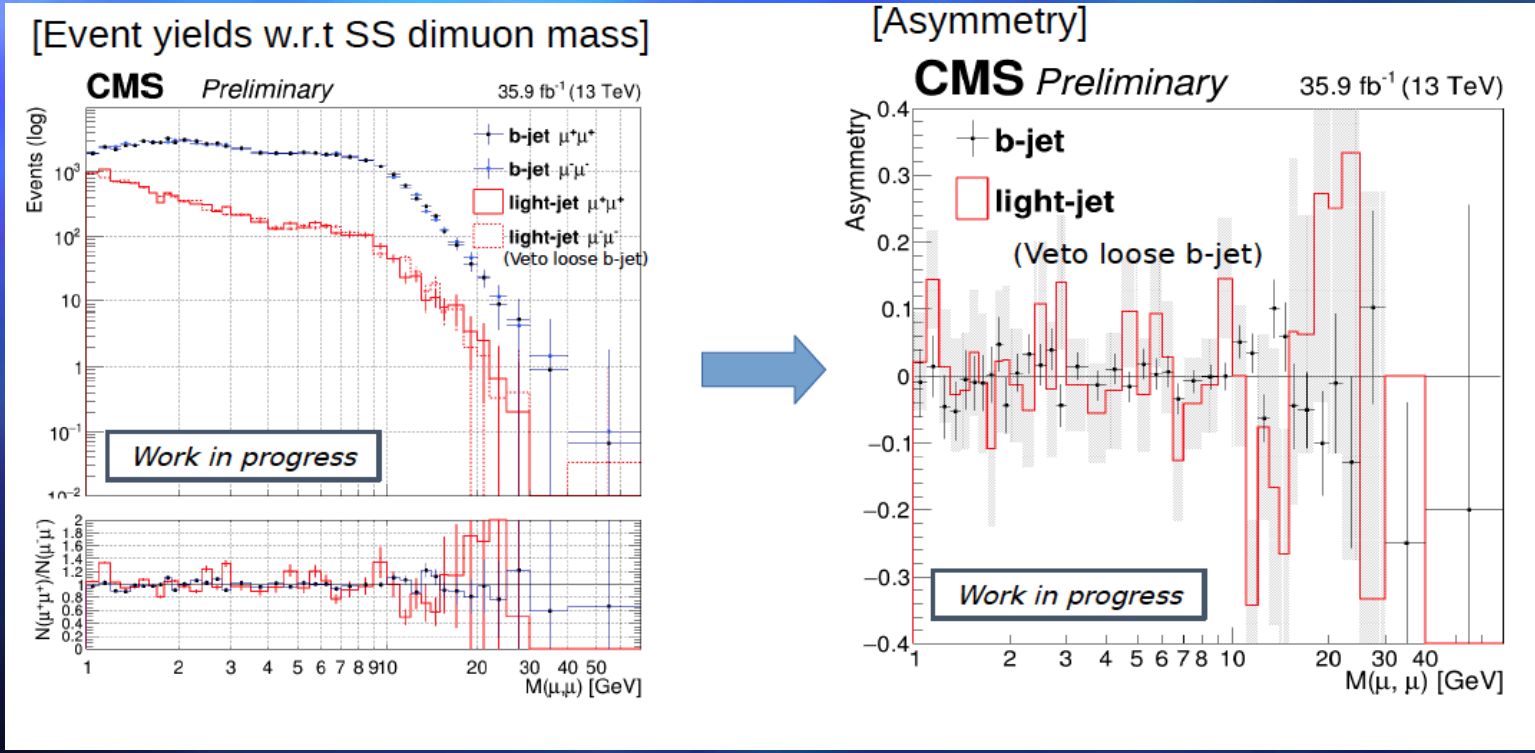




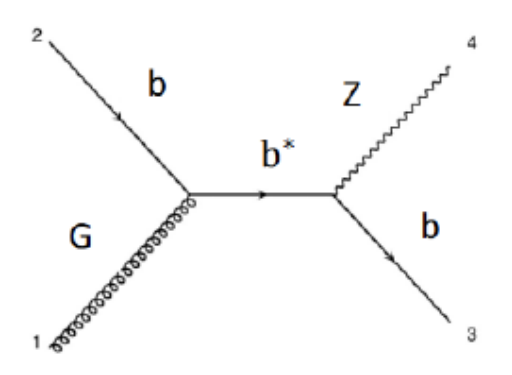


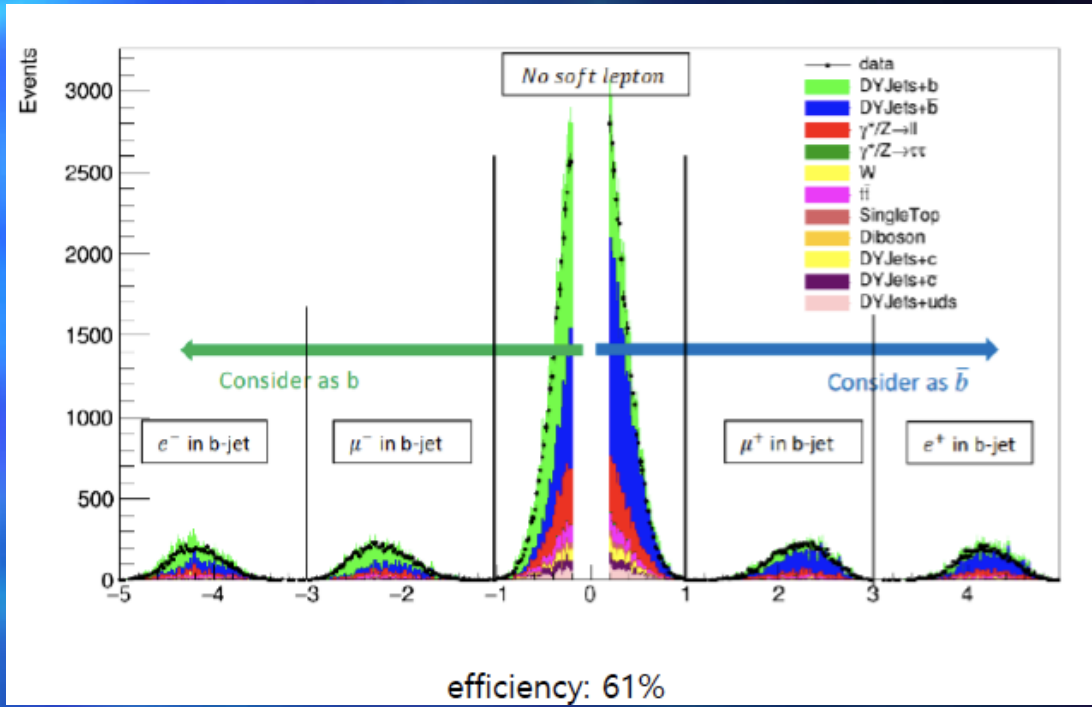
Dimuon charge asymmetry

- Anomalous production of same-sign dimuon events inside b-jets
- Asymmetry is not observed within 2 sigma

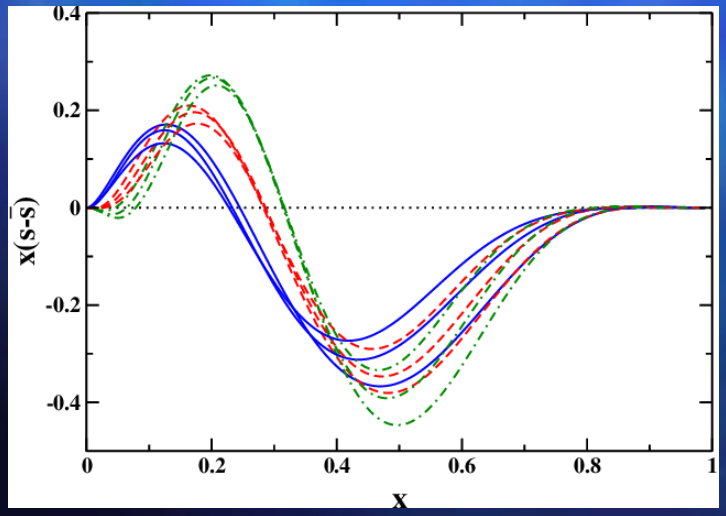


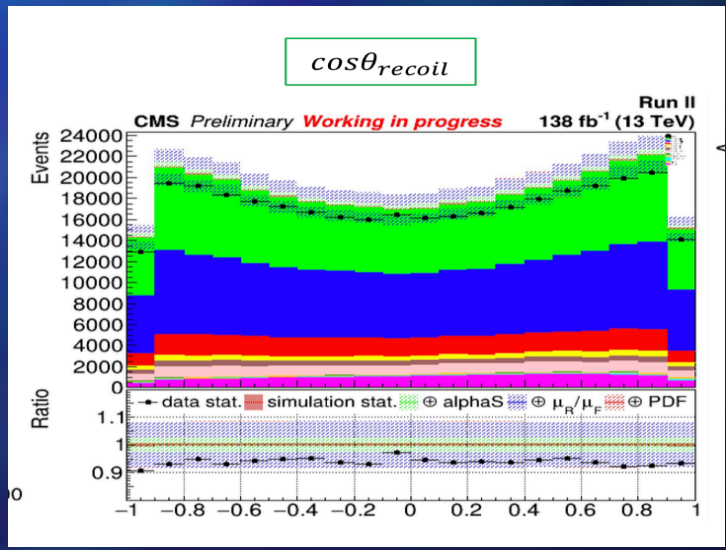
Z+bjet (QCD, EWK studies)



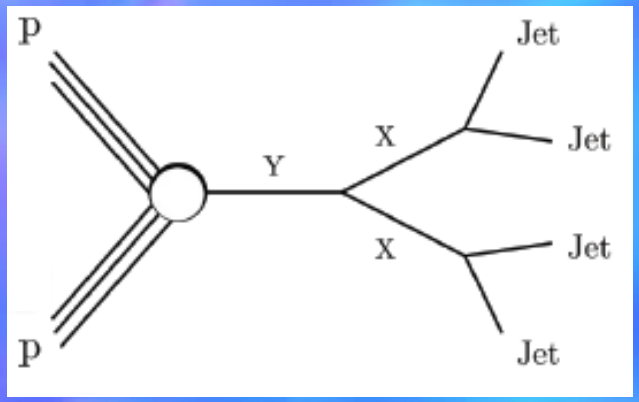


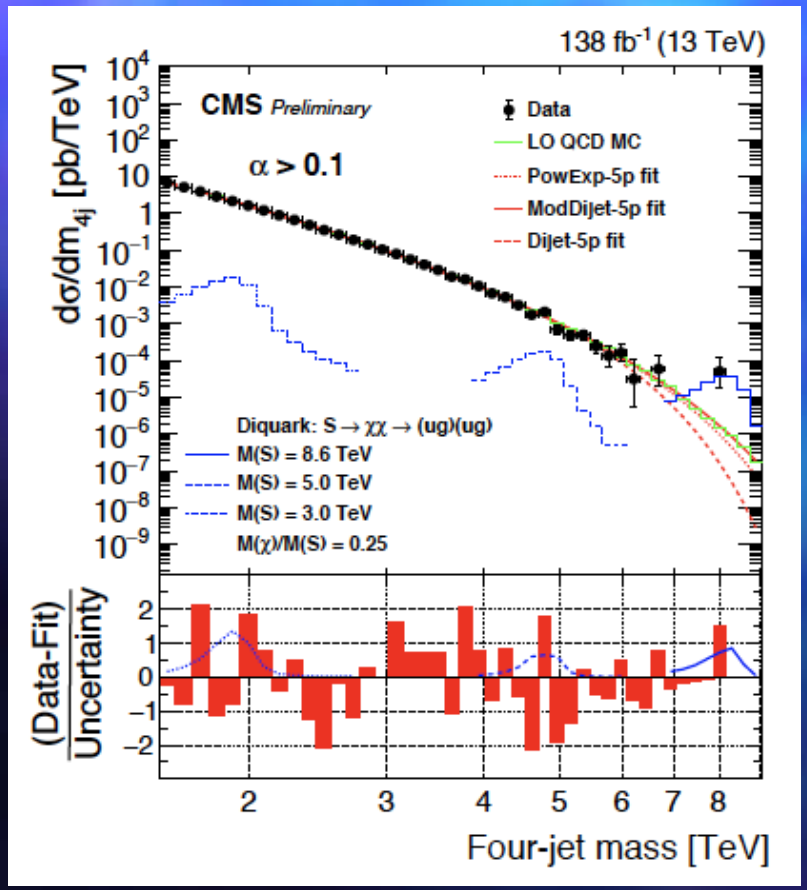
- Z+bet X section
- b/bbar pdf asymmetry inside proton?

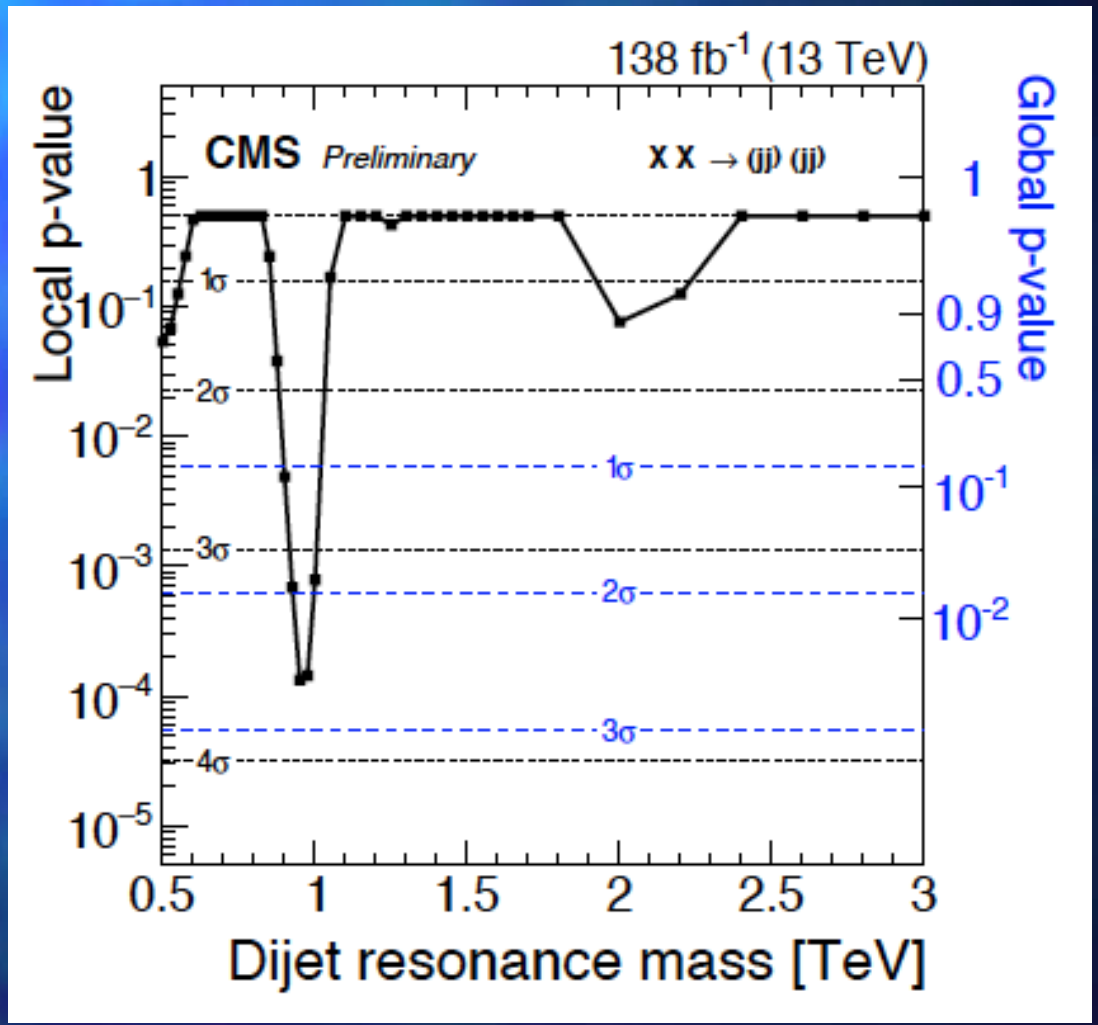




Di-jet pairs


p
p
Y
X
X
Jet
Jet
Jet
Jet


138 fb-1 (13 TeV)
CMS Preliminary
α > 0.1
Data
LO QCD MC
PowExp-5p fit
ModDijet-5p fit
Dijet-5p fit
Diquark: S → χχ → (ug)(ug)
M(S) = 8.6 TeV
M(S) = 5.0 TeV
M(S) = 3.0 TeV
M(χ)/M(S) = 0.25
dσ/dm4j [pb/TeV]
(Data-Fit)/Uncertainty
Four-jet mass [TeV]


138 fb-1 (13 TeV)
CMS Preliminary
X X → (jj) (jj)
Local p-value
Global p-value
1σ
2σ
3σ
4σ
Dijet resonance mass [TeV]