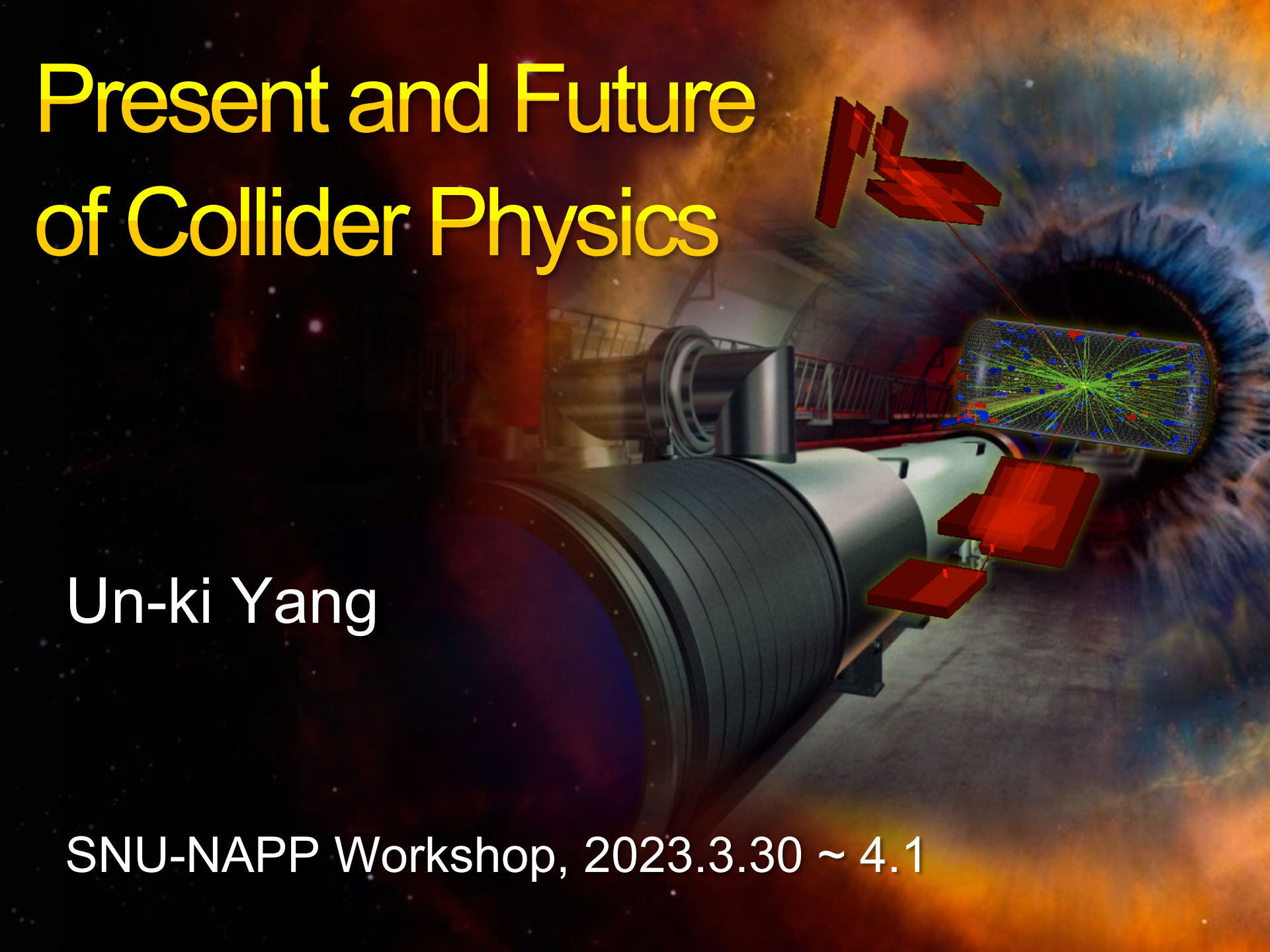
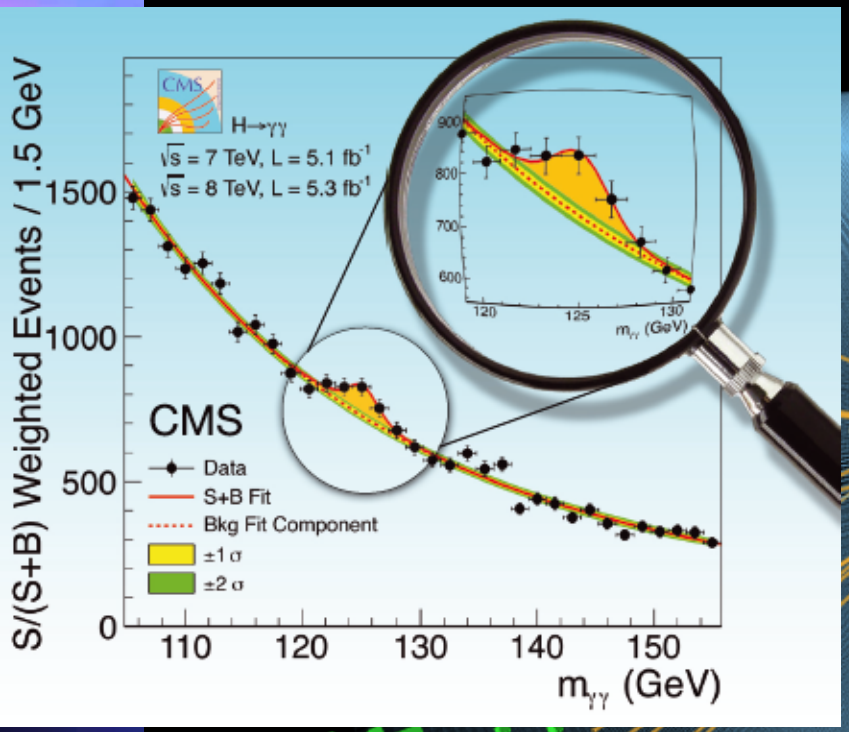
Present and Future of Collider Physics



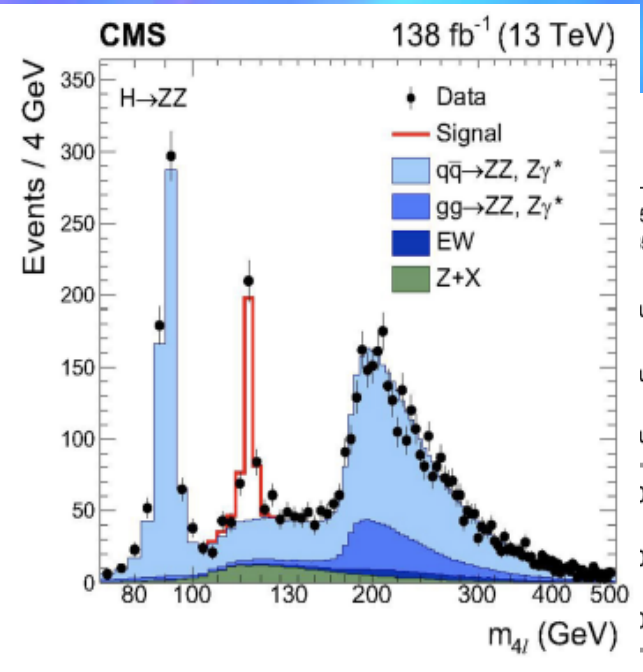
Un-ki Yang

SNU-NAPP Workshop, 2023.3.30 ~ 4.1

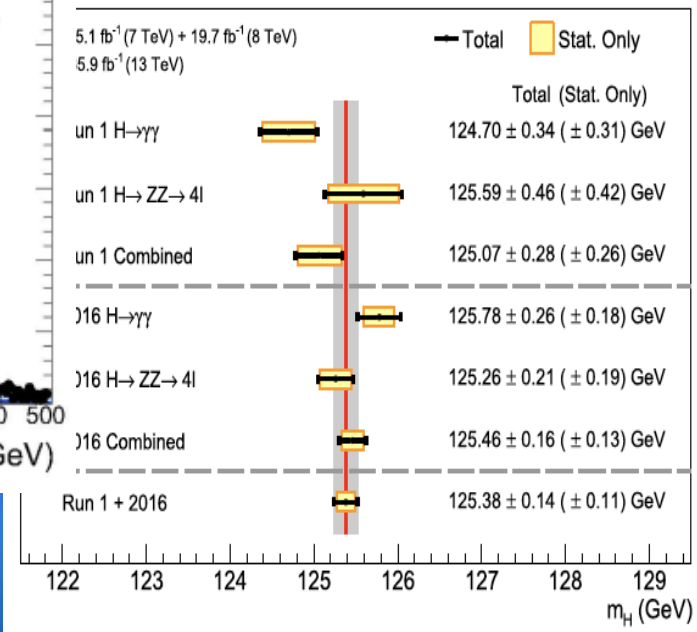
Discovery of a Higgs Boson (2012)

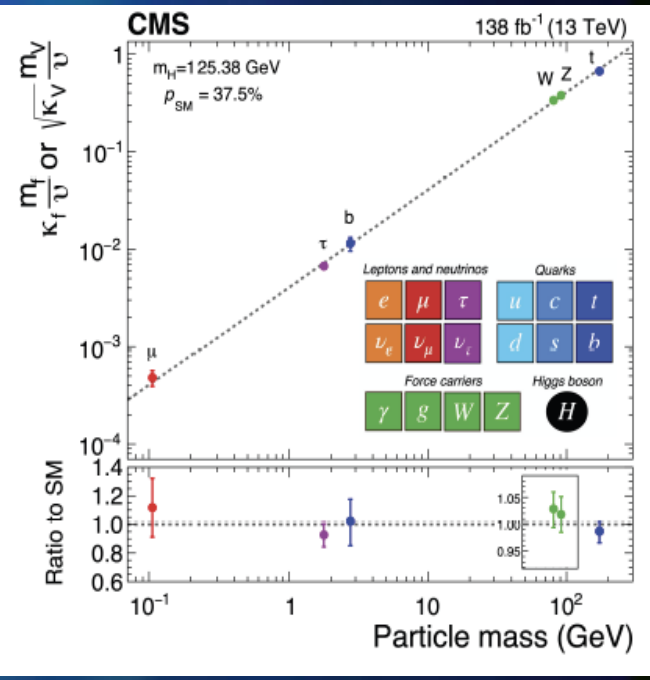


10 years after the Higgs discovery



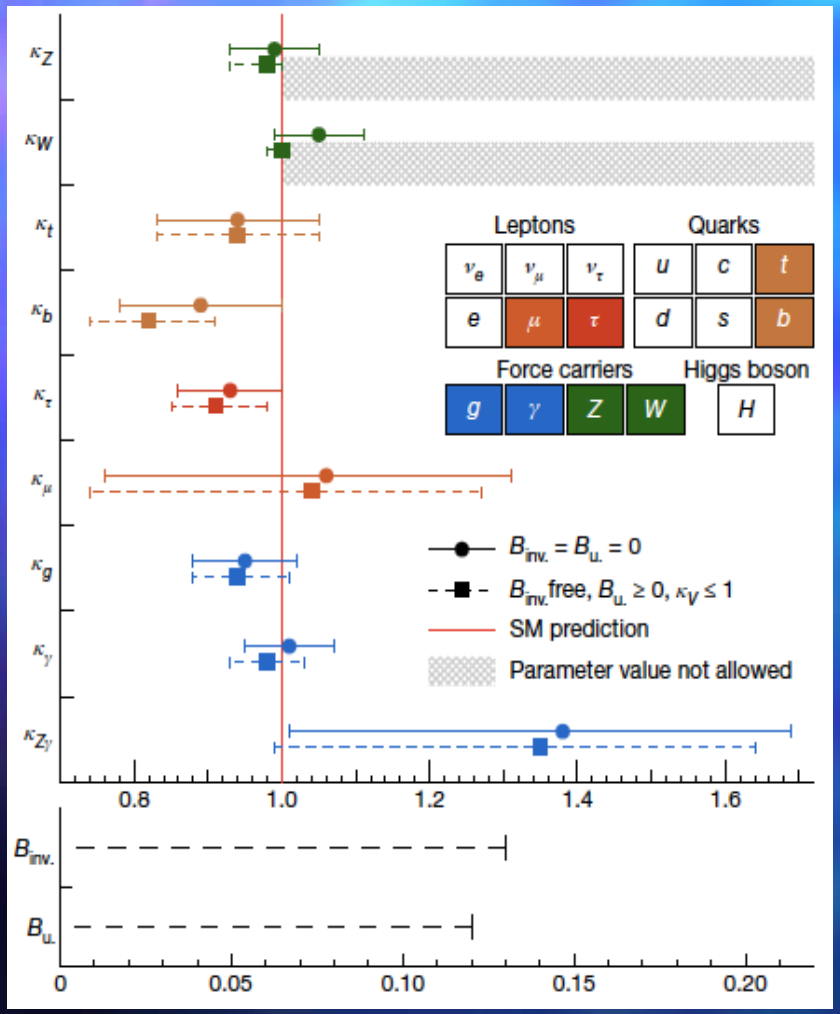
$m_H = 125.38 \pm 0.14\ GeV$





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

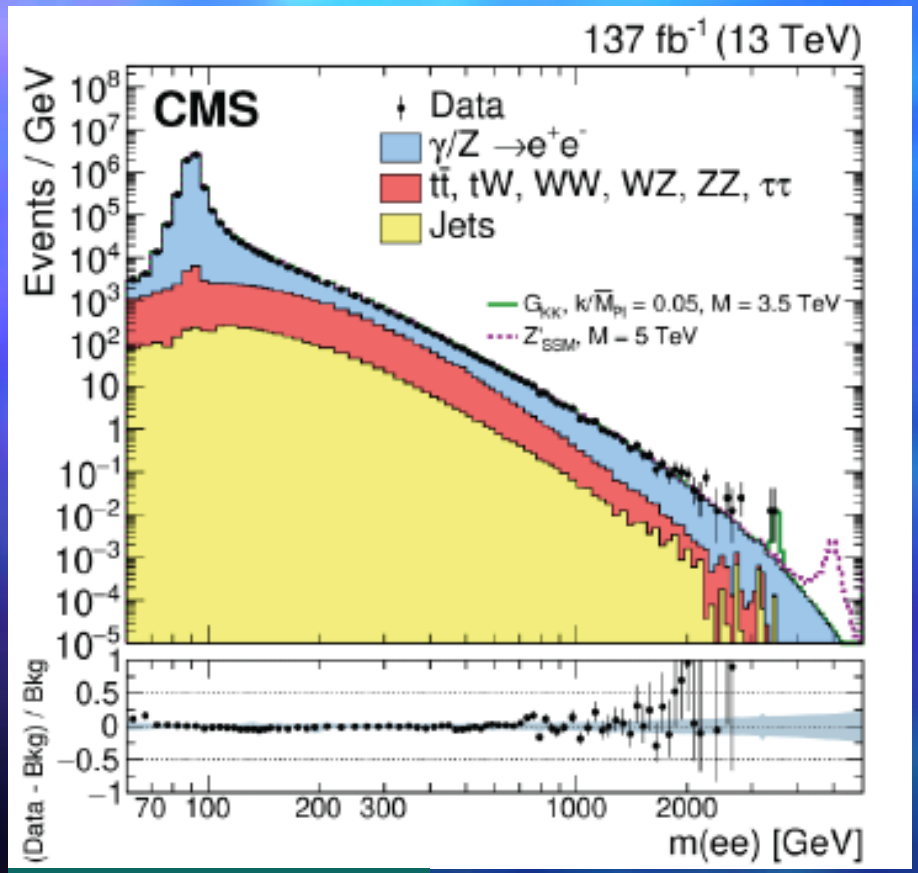
Room for new physics

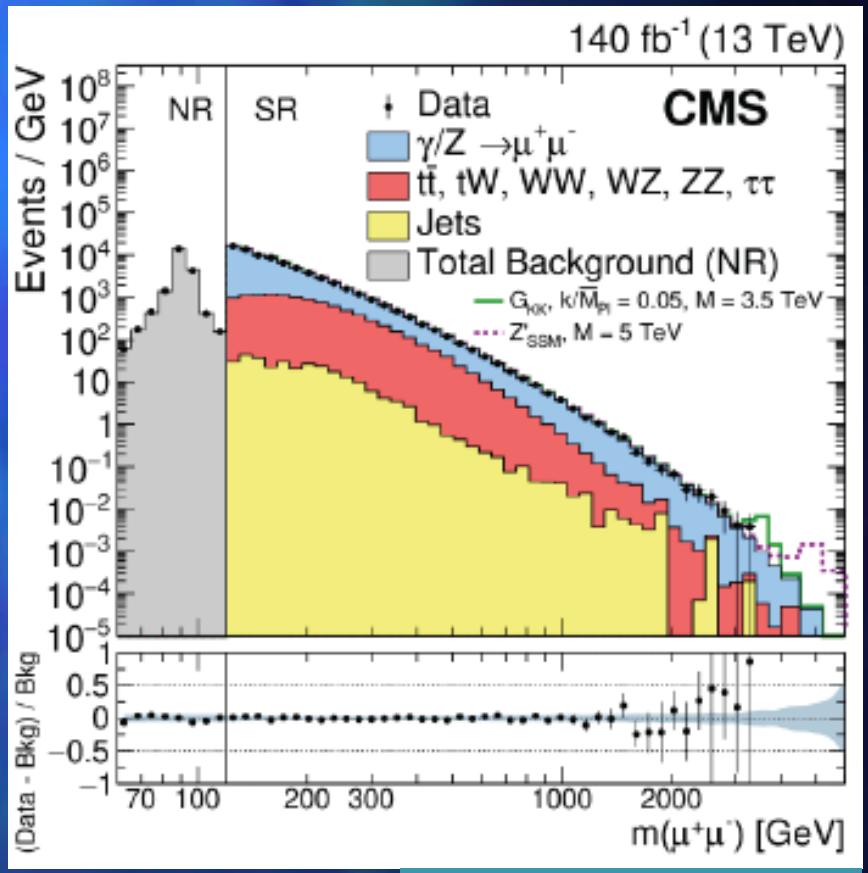


- Higgs to invisible decay mode:< 13%

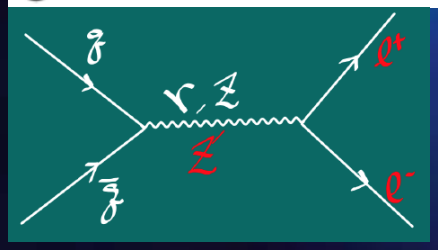
Nature 607, 52 (2022)

Search for New Boson at LHC



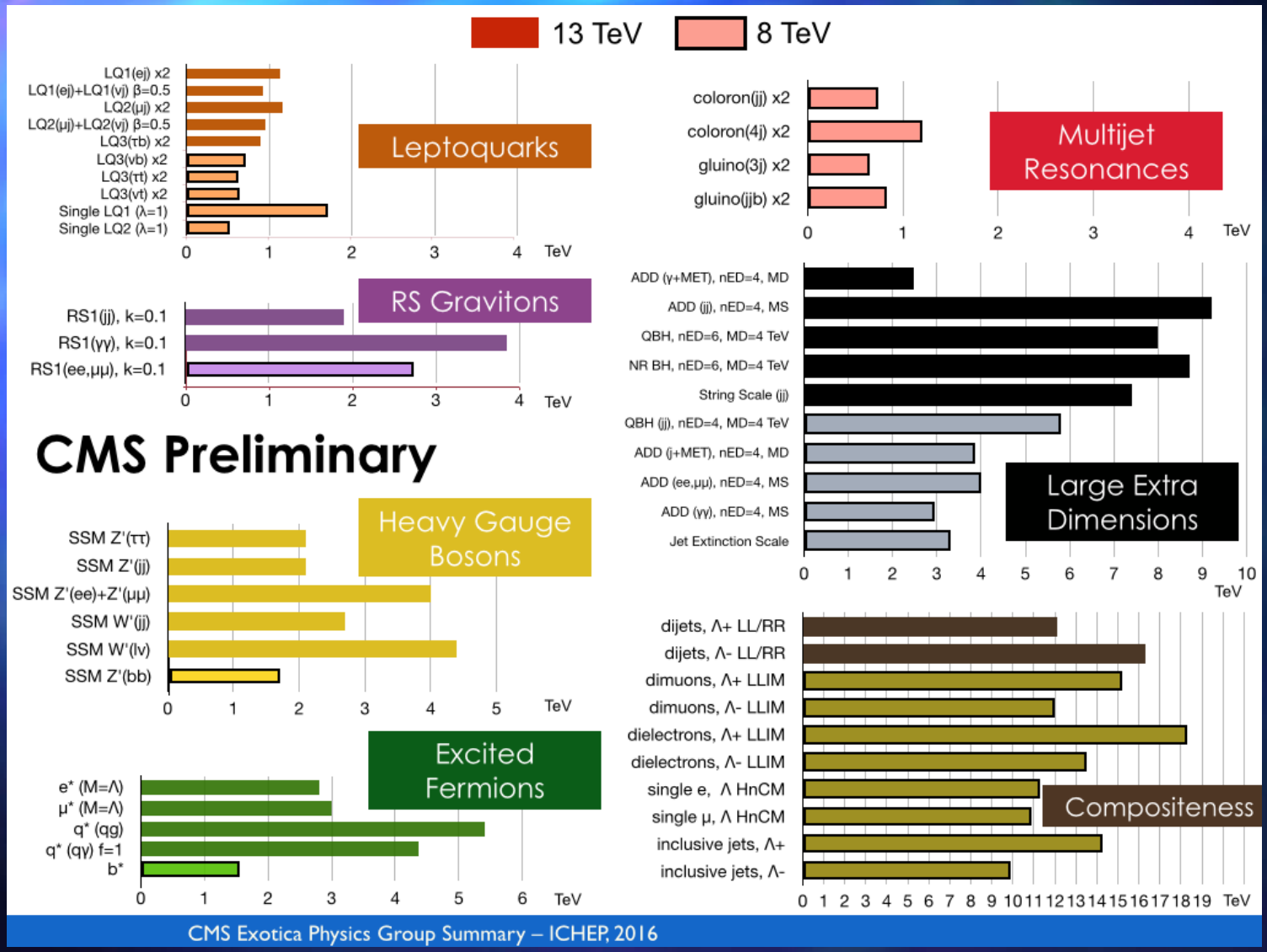


JHEP07(2022)067



➢ No new Z' or W' below 4 TeV

Searches for new particles

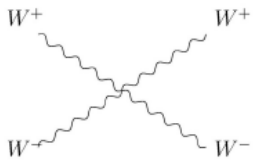


Pre-Higgs

- 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

Search Results

- No new fundamental particle or interaction except Higgs particle so far at LHC, regardless of very successful operations for last 13 years

- Why do we keep looking at Beyond Standard Model?
  - dark matter
  - matter-antimatter asymmetry in the Universe,
  - neutrino oscillation→ mass, right-handed neutrino
  - Higgs mass naturalness

New physics searches

- Look for a new resonance
- Excess of events in the tail at the energy frontier
- Search for new process
- Search for rare decay (quantum loop)
- Precision measurements (quantum loop)
- Search for asymmetry (left vs right etc)
- Searches for regions we have not checked
  (long-lived particles, very weak coupling,
  low mass particle etc)

CMS Search Strategy

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

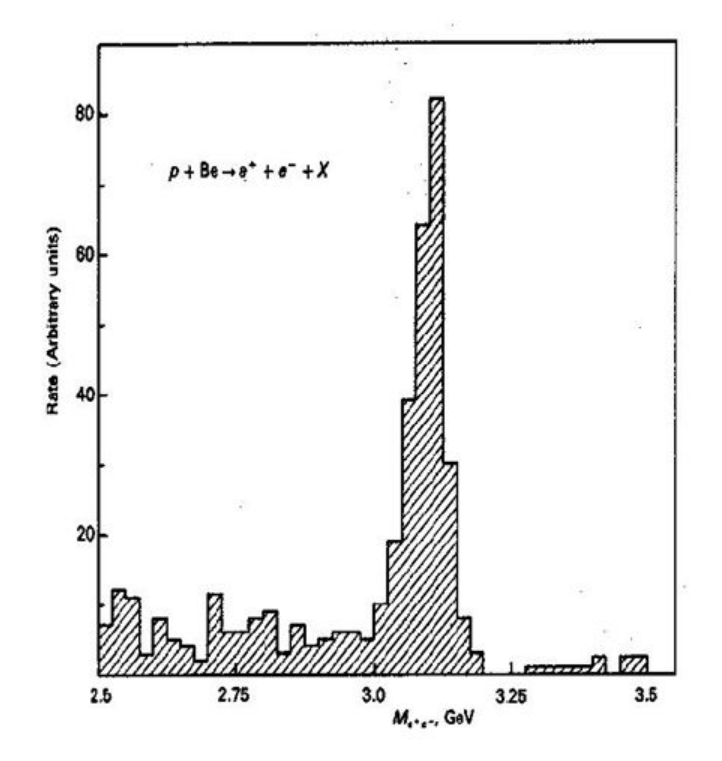
- Weak coupling (DM, fractional charge etc)
- Small mass
- Longer lifetime

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

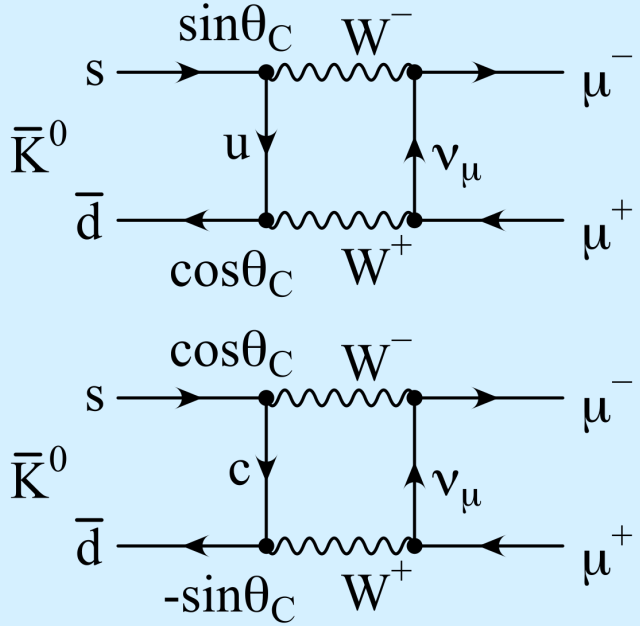
New Resonance & rare decay

- Discovery of charm quark

New resonance (J/Psi)



Rare decay (GIM Mechanism)

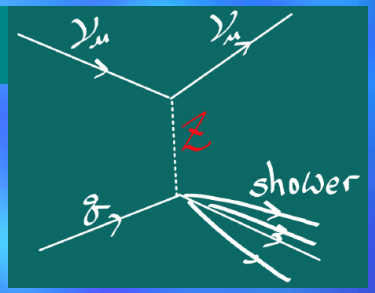


$$BR(K_L^0 \rightarrow \mu^+\mu^-) = 6.84 \times 10^{-9}$$

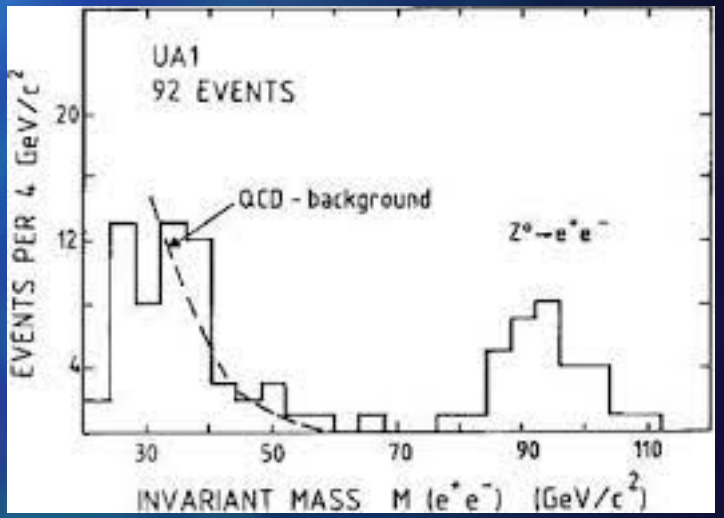
New Process and resonance

- Evidence of Z boson (neutral current)

Neutral Current



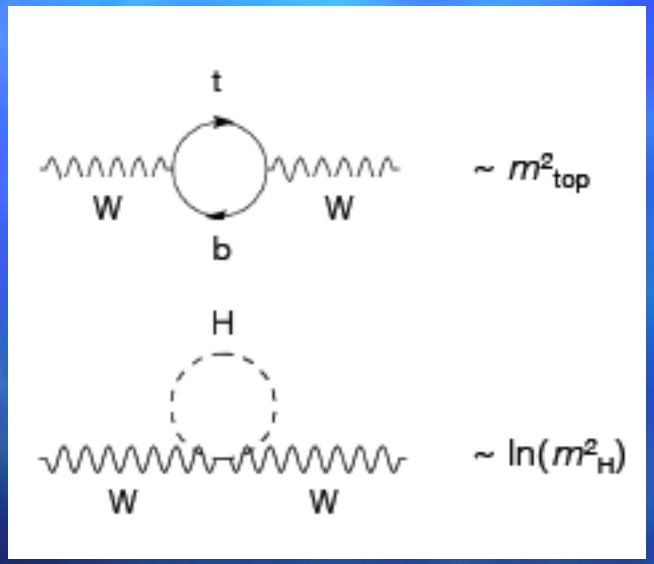
New resonance (Z)



Precisions and resonance

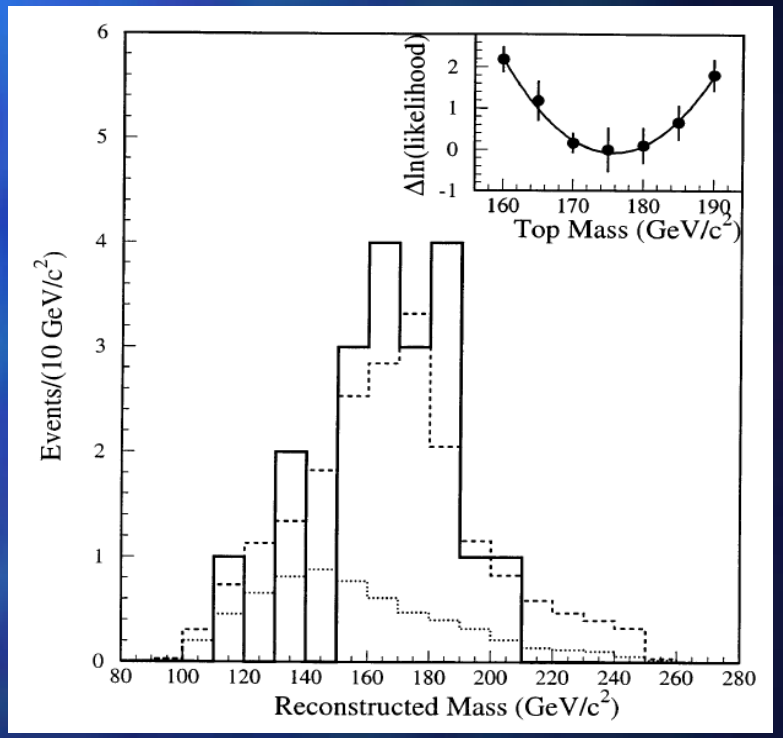
- Discovery of top quark

Precision Measurement on W mass (quantum Loop correction)



$$150 \leq M_t \leq 210\ \mathrm{GeV}/c^2$$

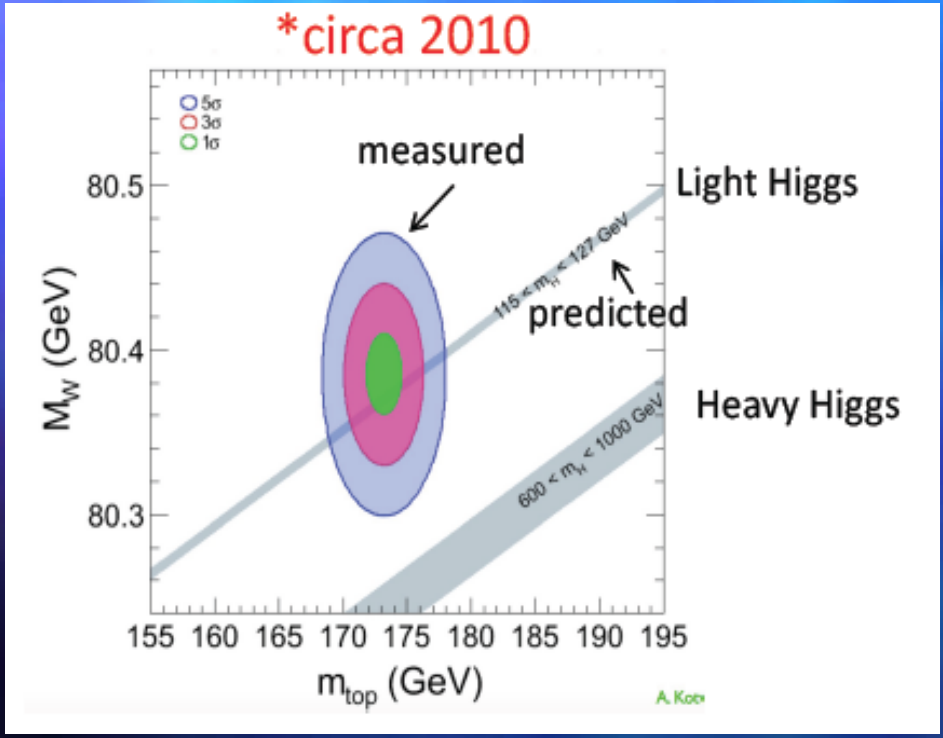
New resonance (top)



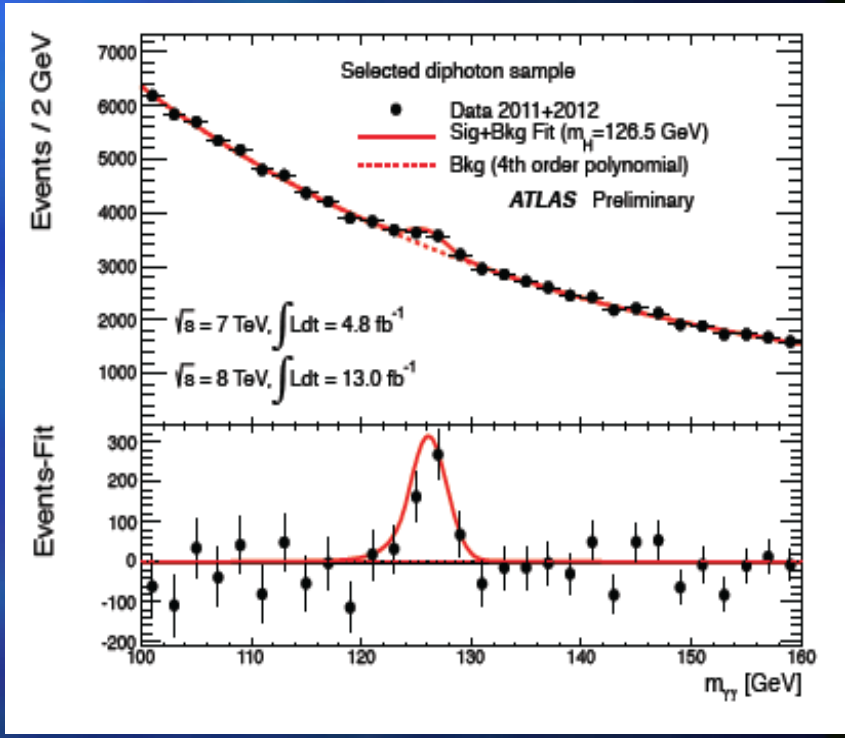
$$M_t = 176 \pm 8\ (\mathrm{stat}) \pm 10\ (\mathrm{syst})\ \mathrm{GeV}/c^2$$

Precisions and resonance

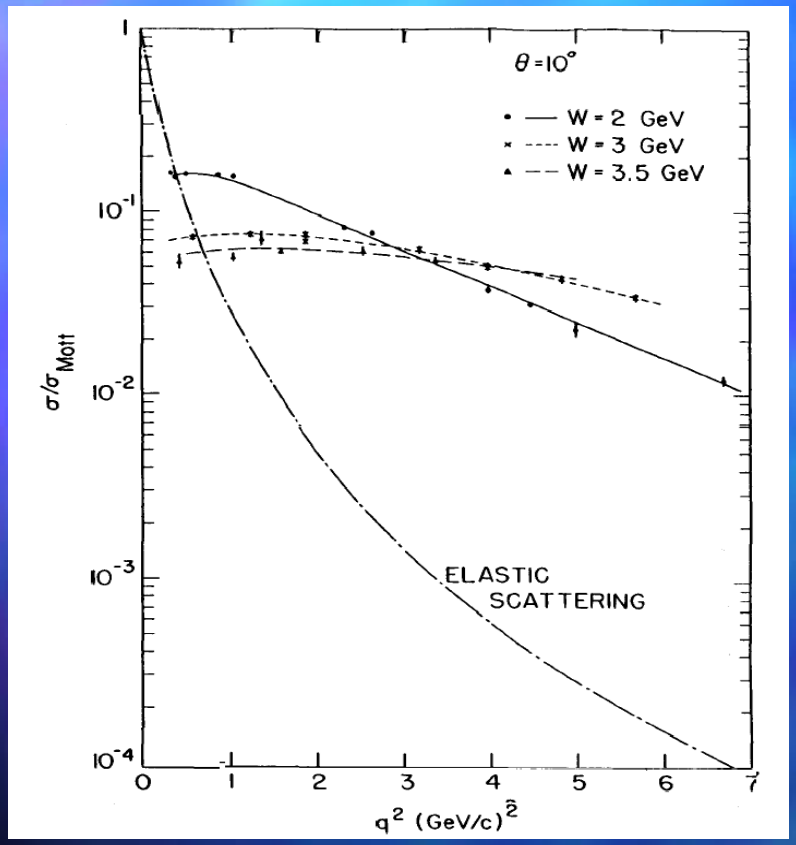
Precision Measurements (W and top mass)



New resonance (top)

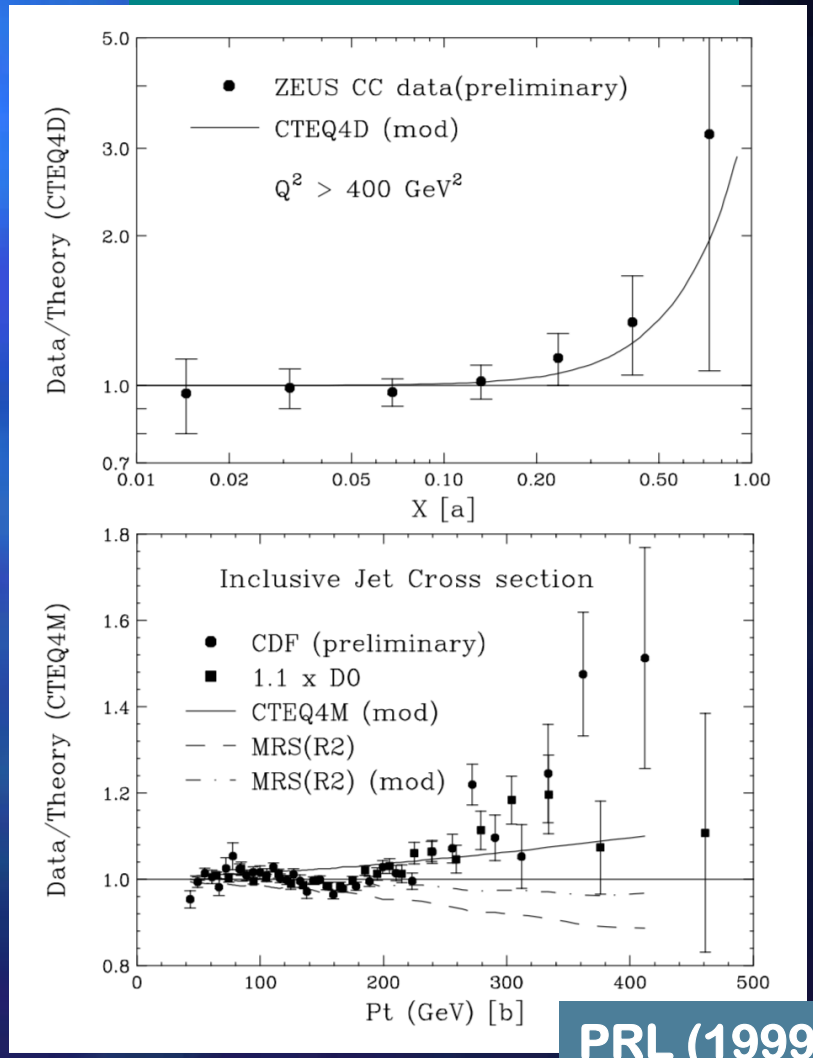


Substructure of quark?



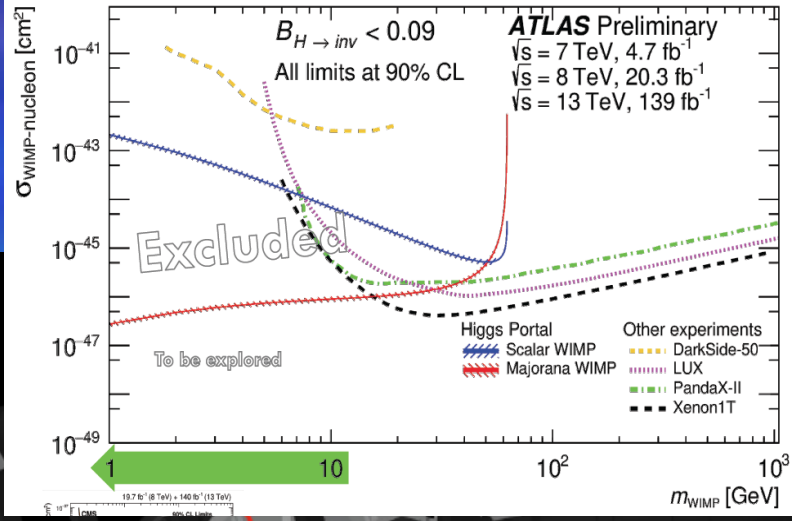
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{point} |F(q)|^2$$

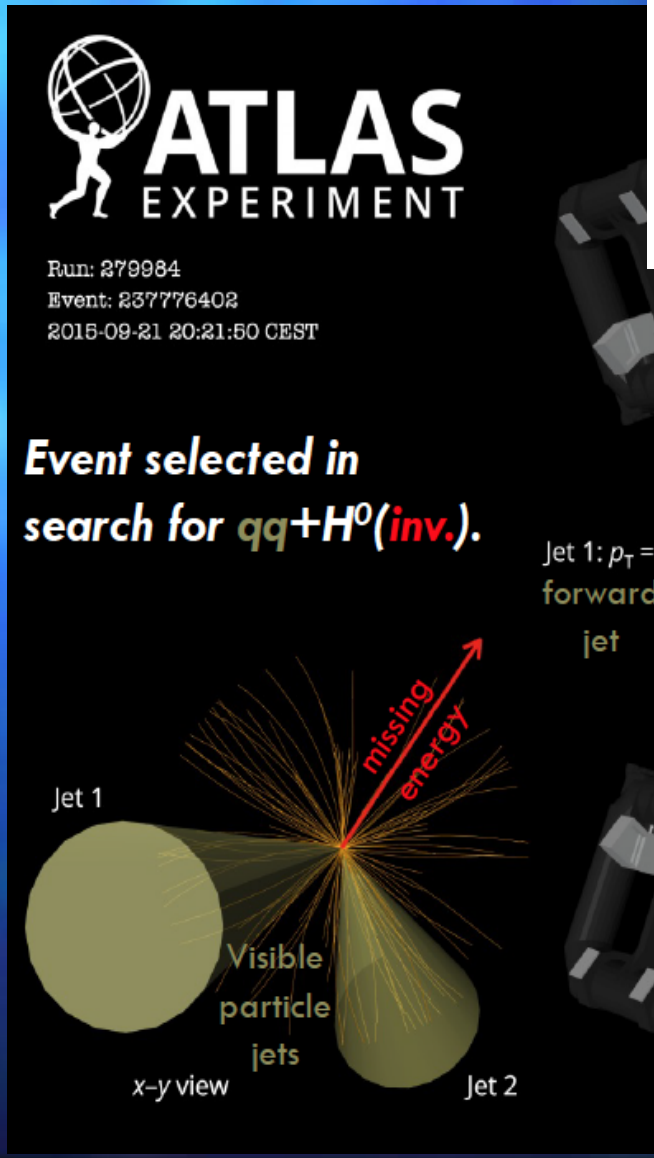
Excess in the tail ('1997)

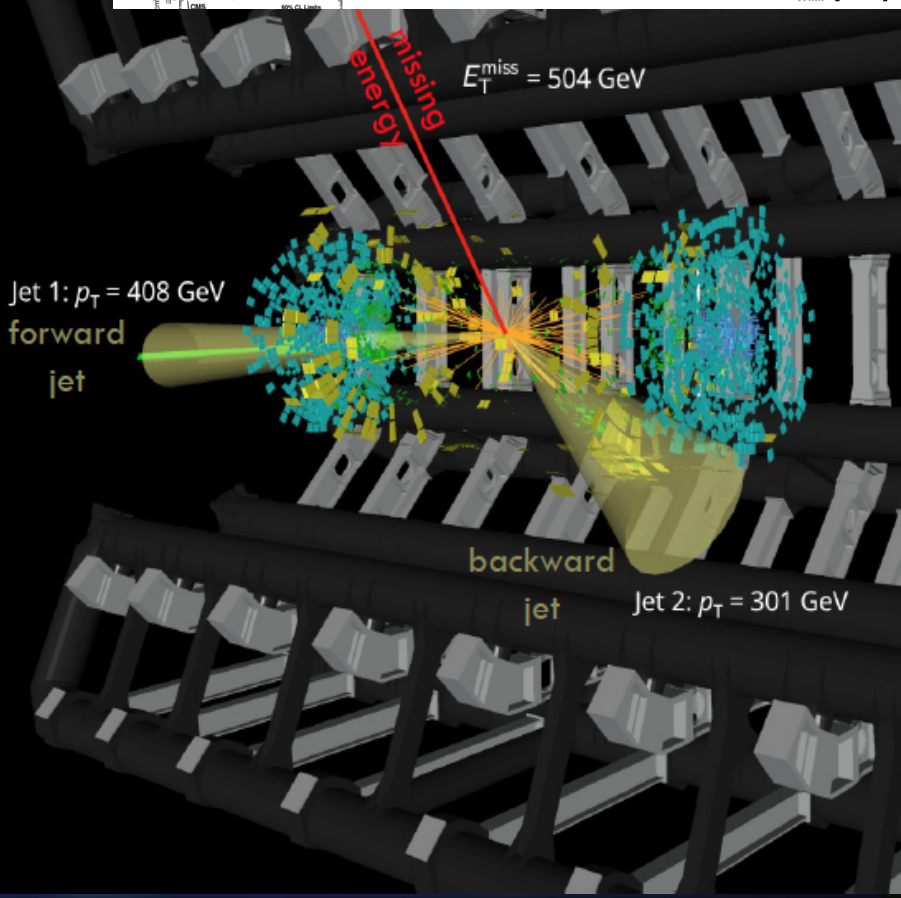


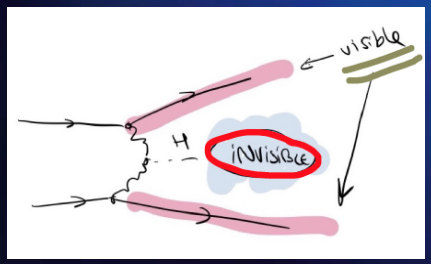
PRL (1999)

Higgs to Dark Matter

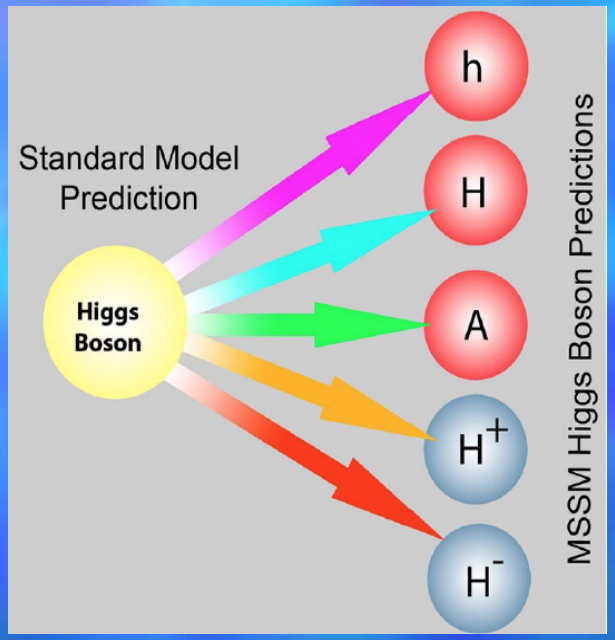


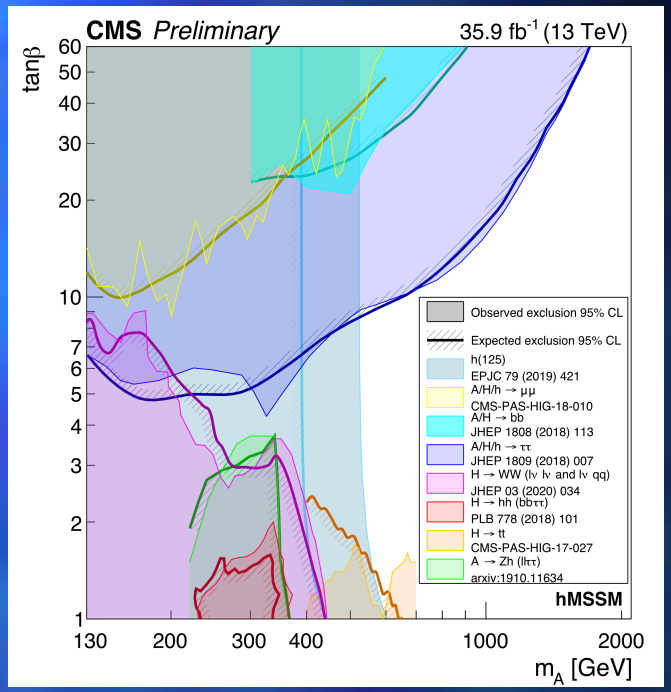


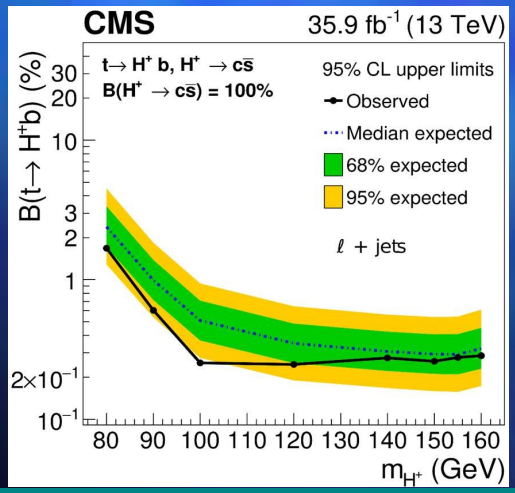




Other Higgs

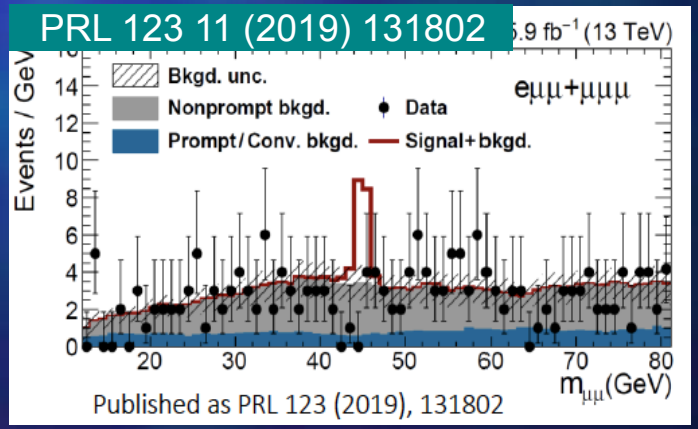




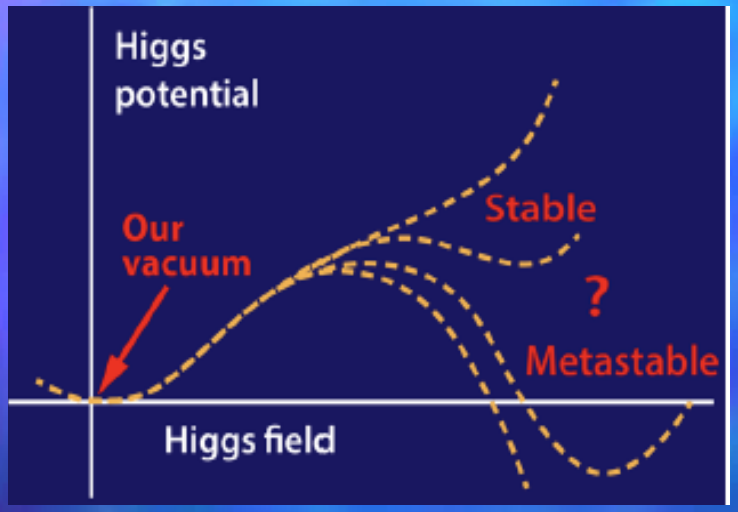


PRD 102 (2020) 072001

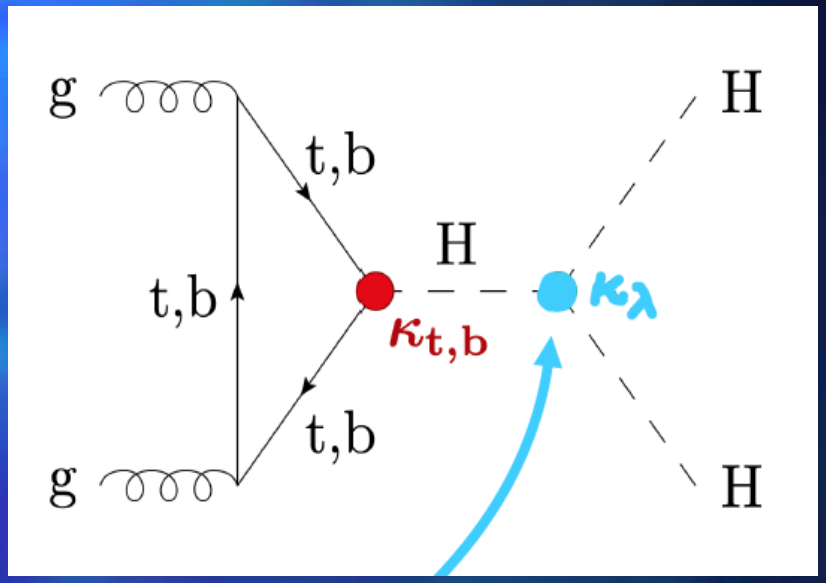
PRL 123 11 (2019) 131802



But the real world … the BSM Higgs(?) world

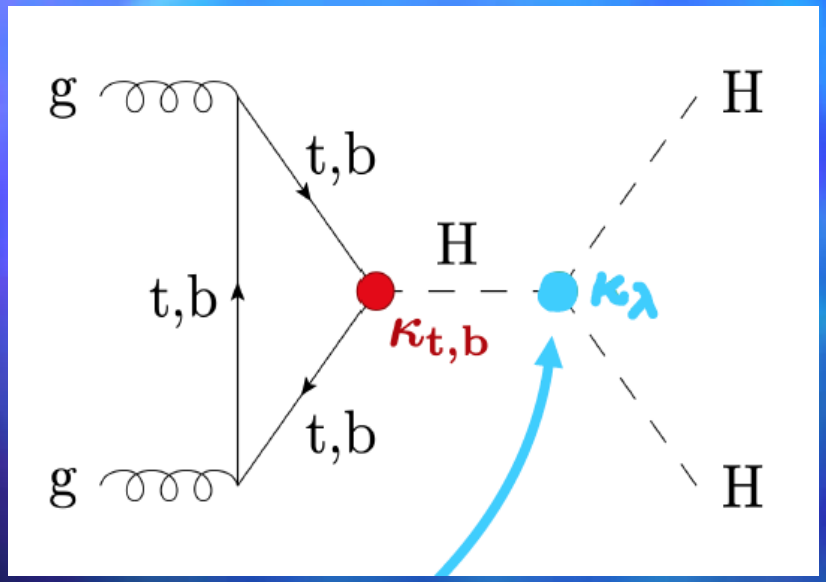


$$V = \frac{M_H^2}{2}H^2 + \frac{M_H^2}{2v}H^3 + \frac{M_H^2}{8v^2}H^4$$

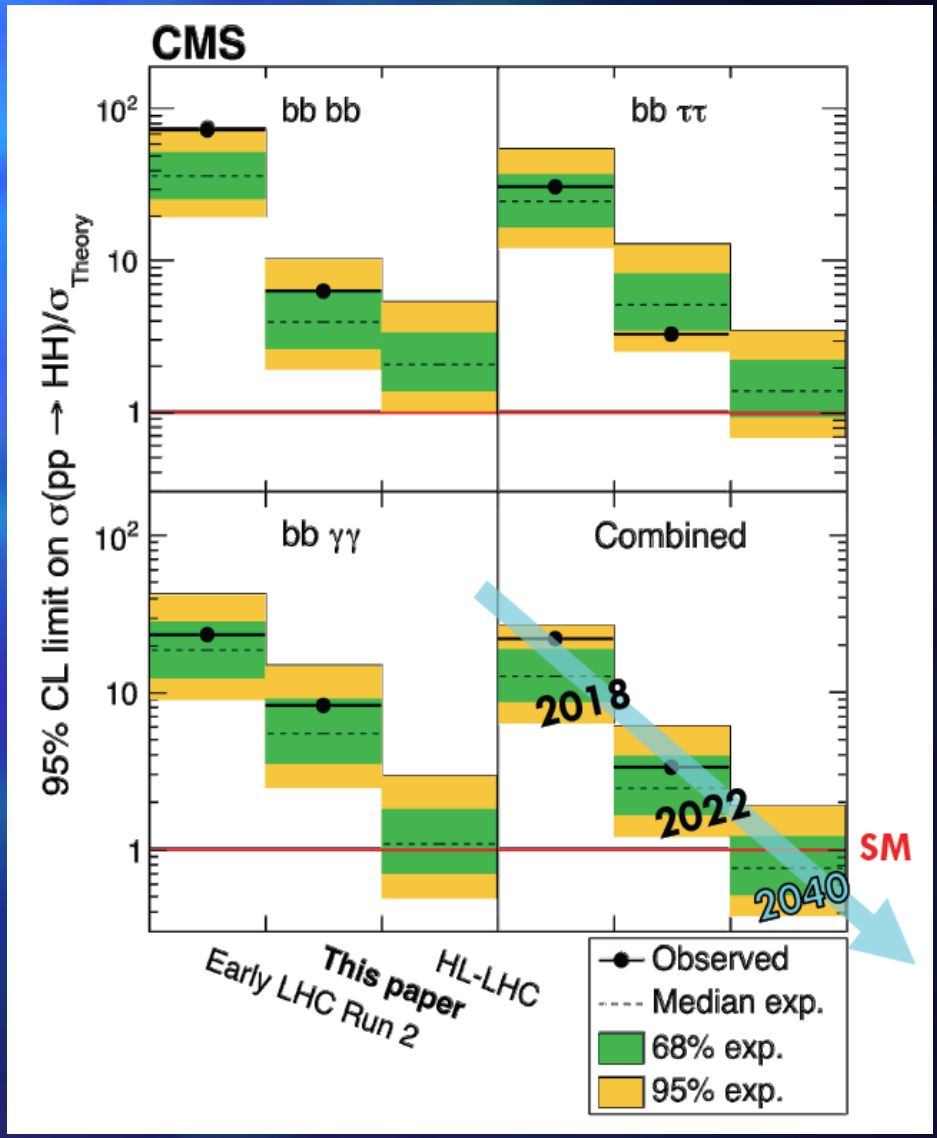


- Unstable Higgs mass, stability of our vacuum depending on Higgs potential

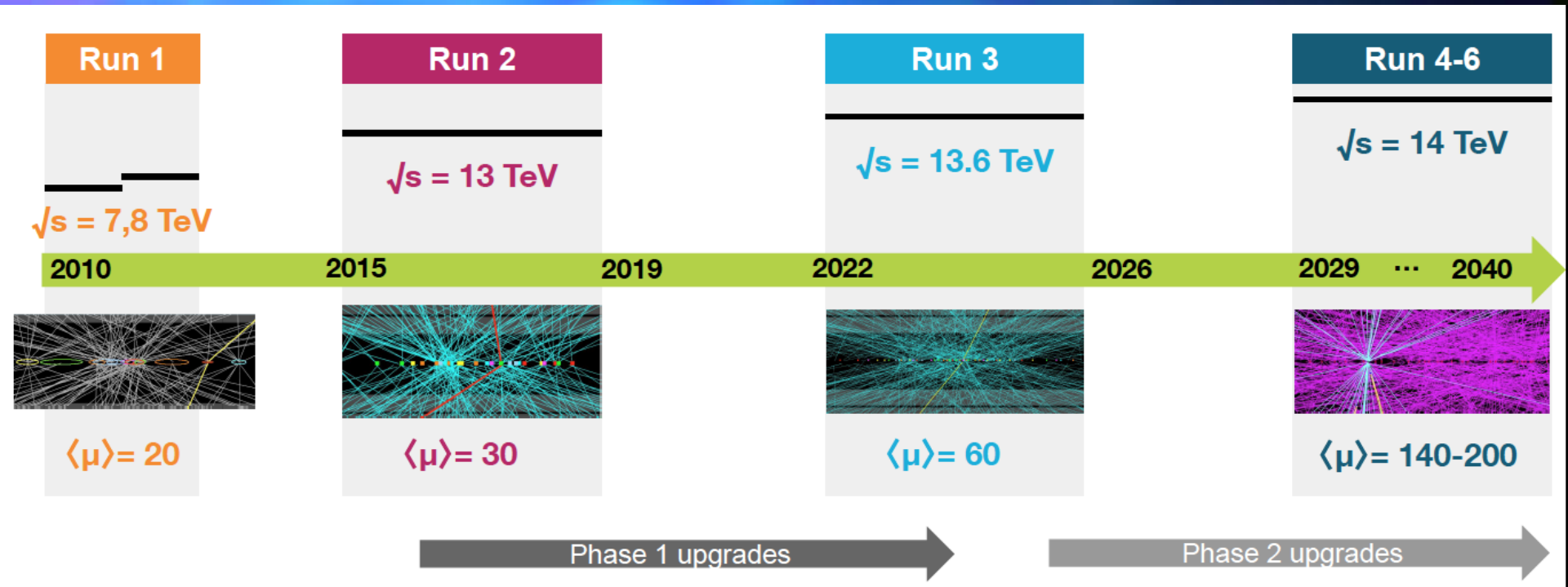
Can we measure Higgs Potential?



Higgs pairs are predicted to be 1000× rarer than single Higgs.



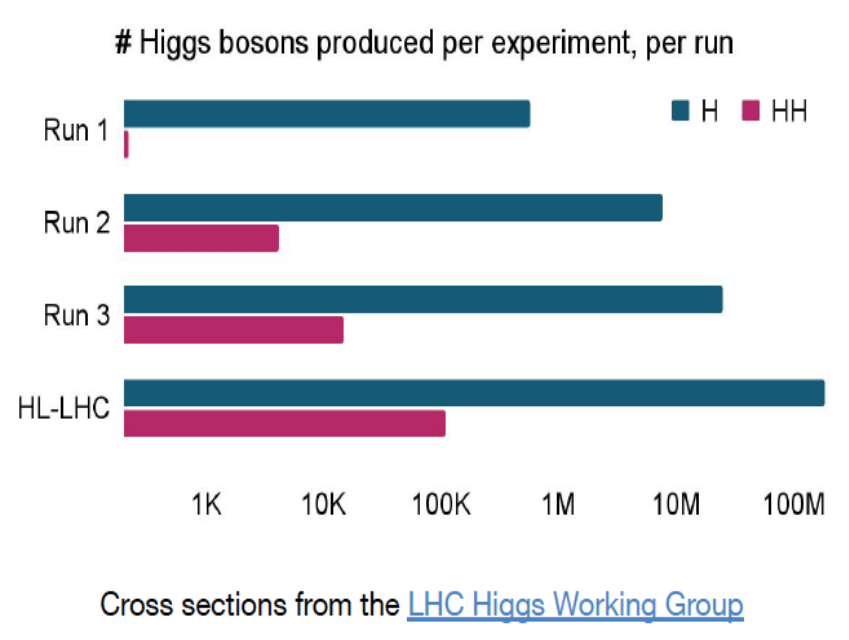
Present and Future of LHC

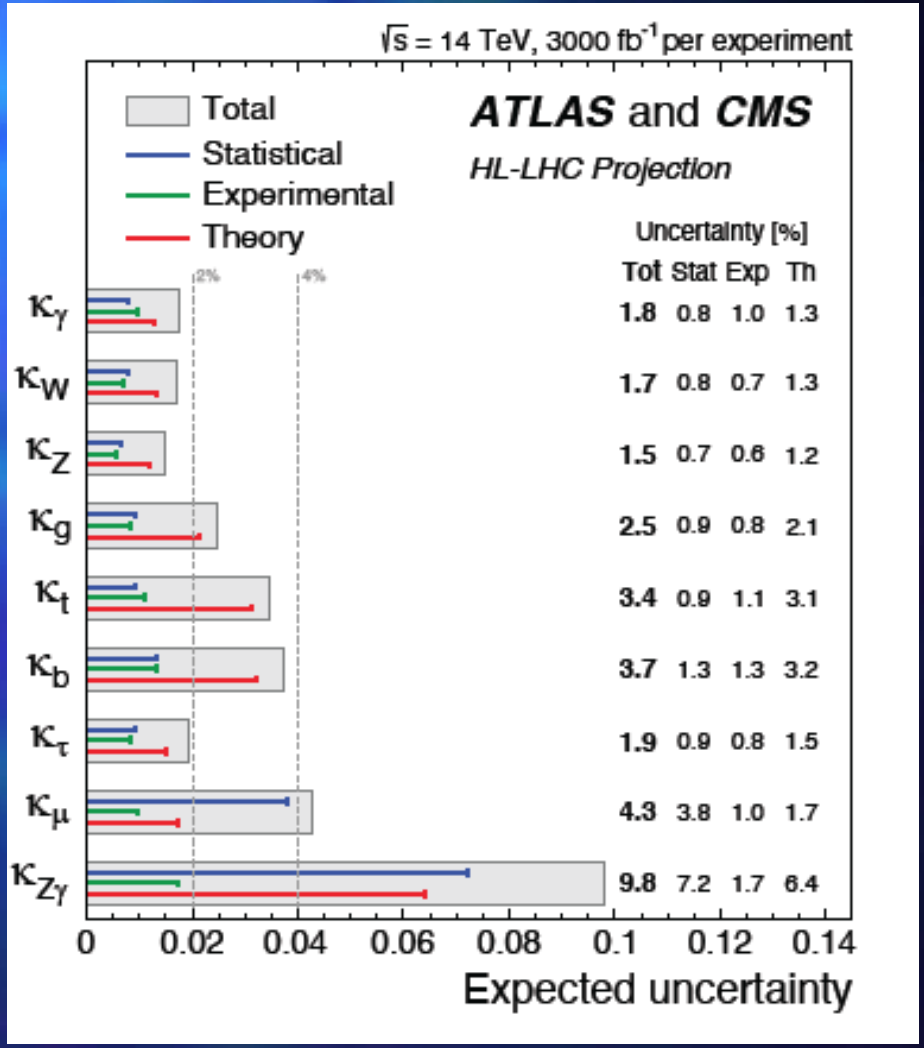


LHC Luminosity

- Only 5% data has been taken so far

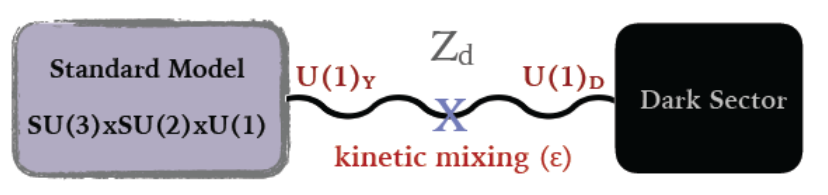
Future Measurements



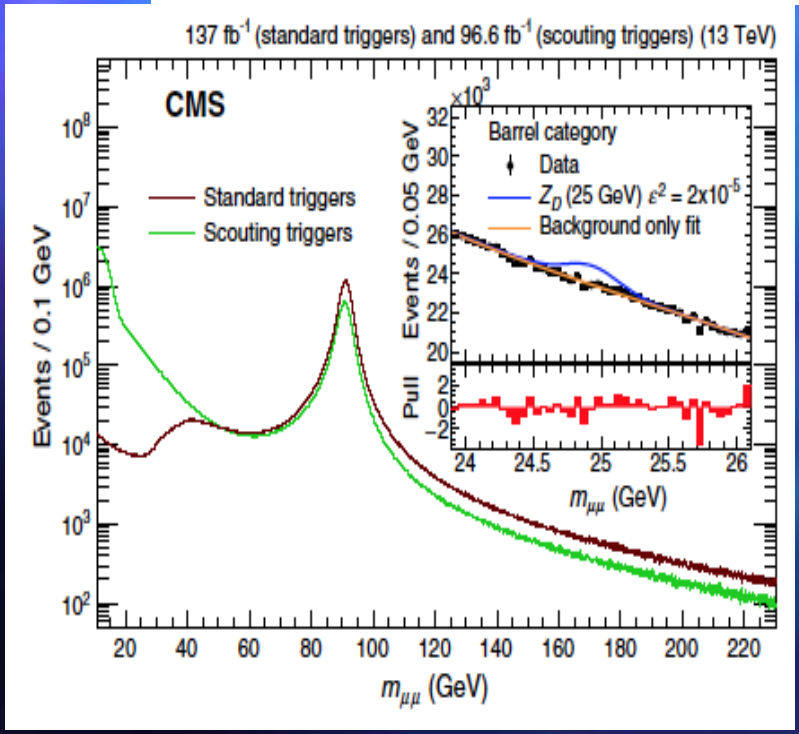


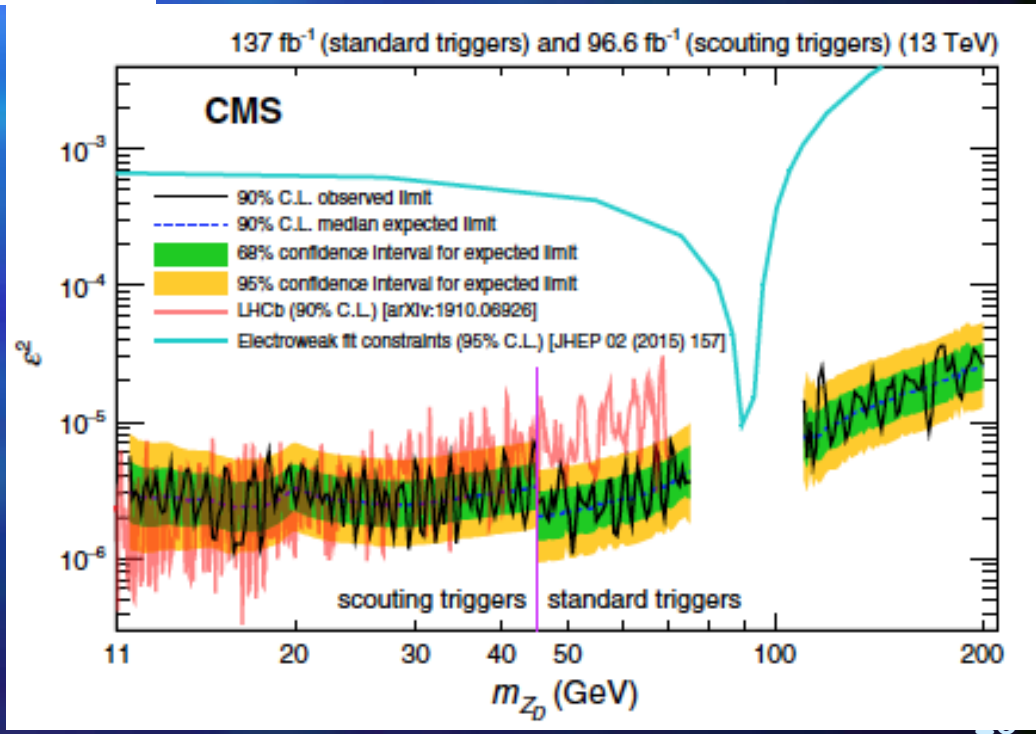
New Resonances at Low-mass

- Search for dark photon decaying to two muons
- Used CMS regular dimuon and scouting triggers



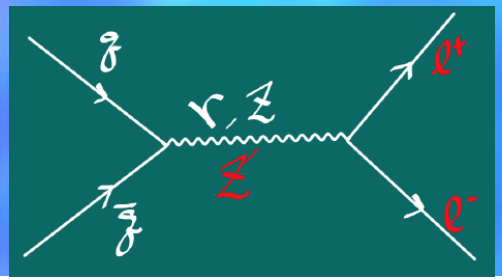
PRL 124 (2020) 131802

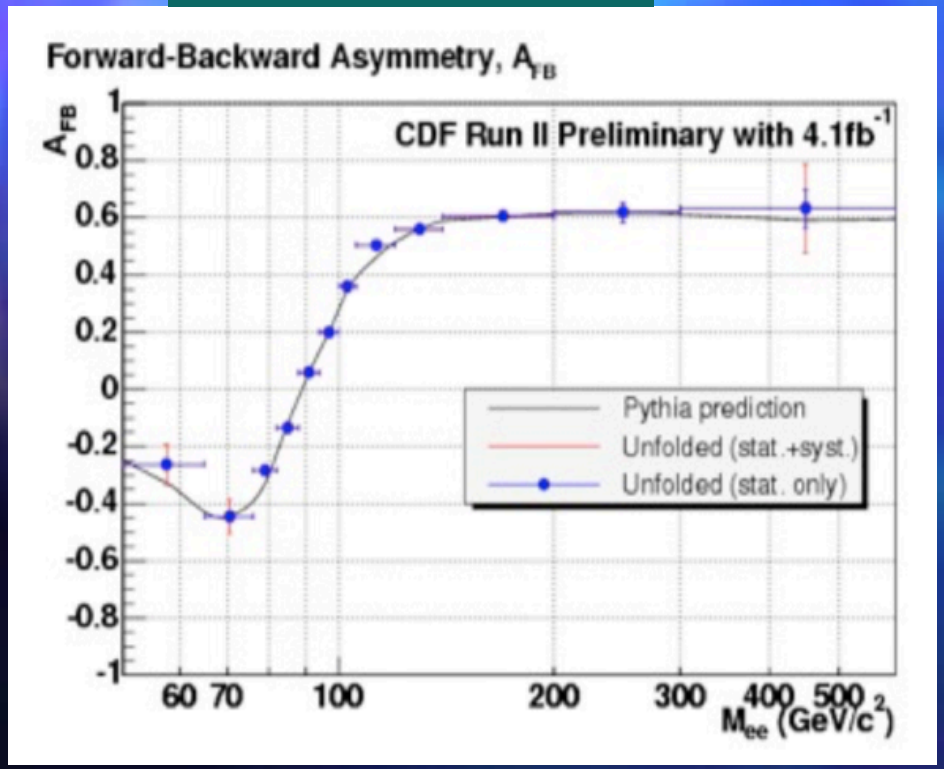


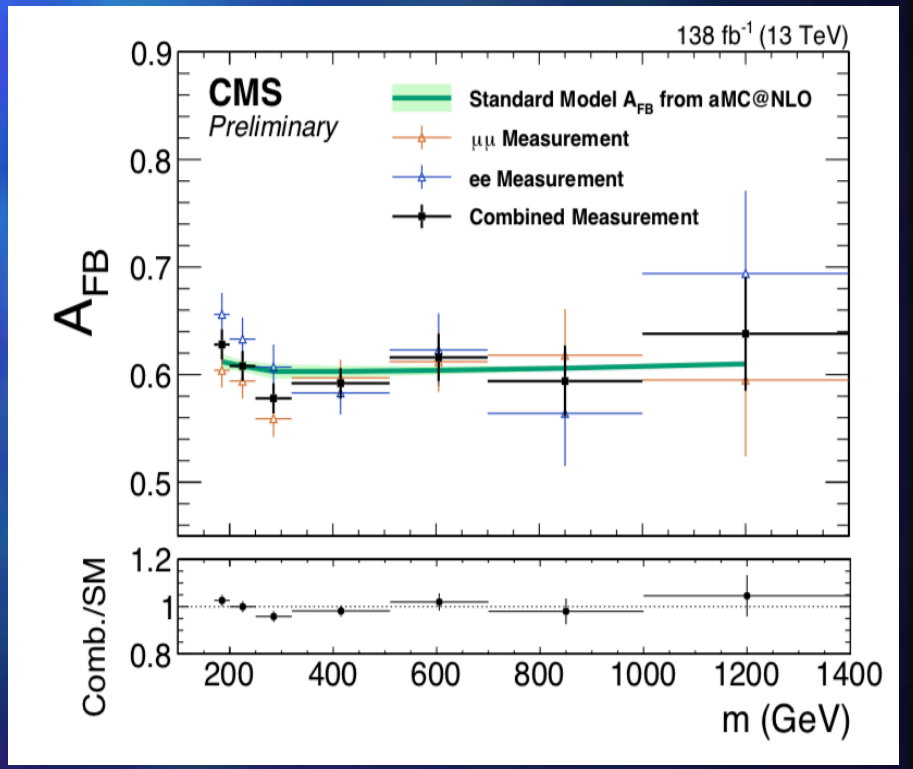


New Resonance with narrow width

- Forward-Backward asymmetry of Drell-Yan events

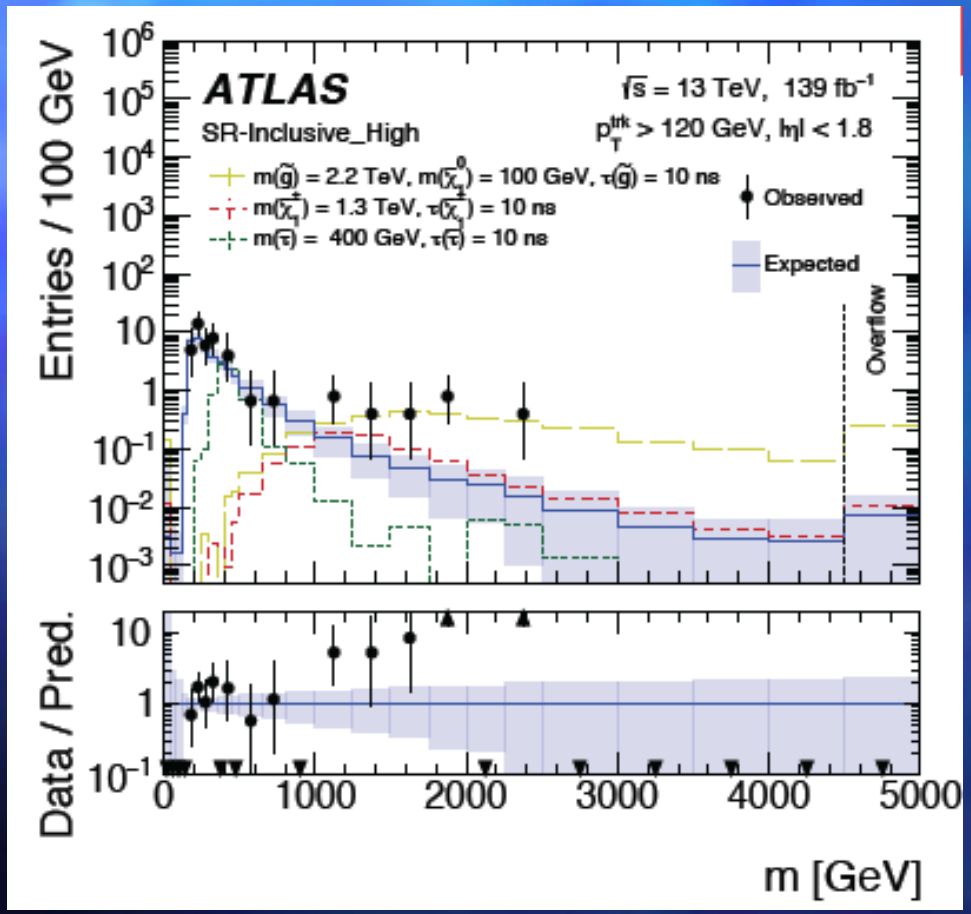






High-pt events:

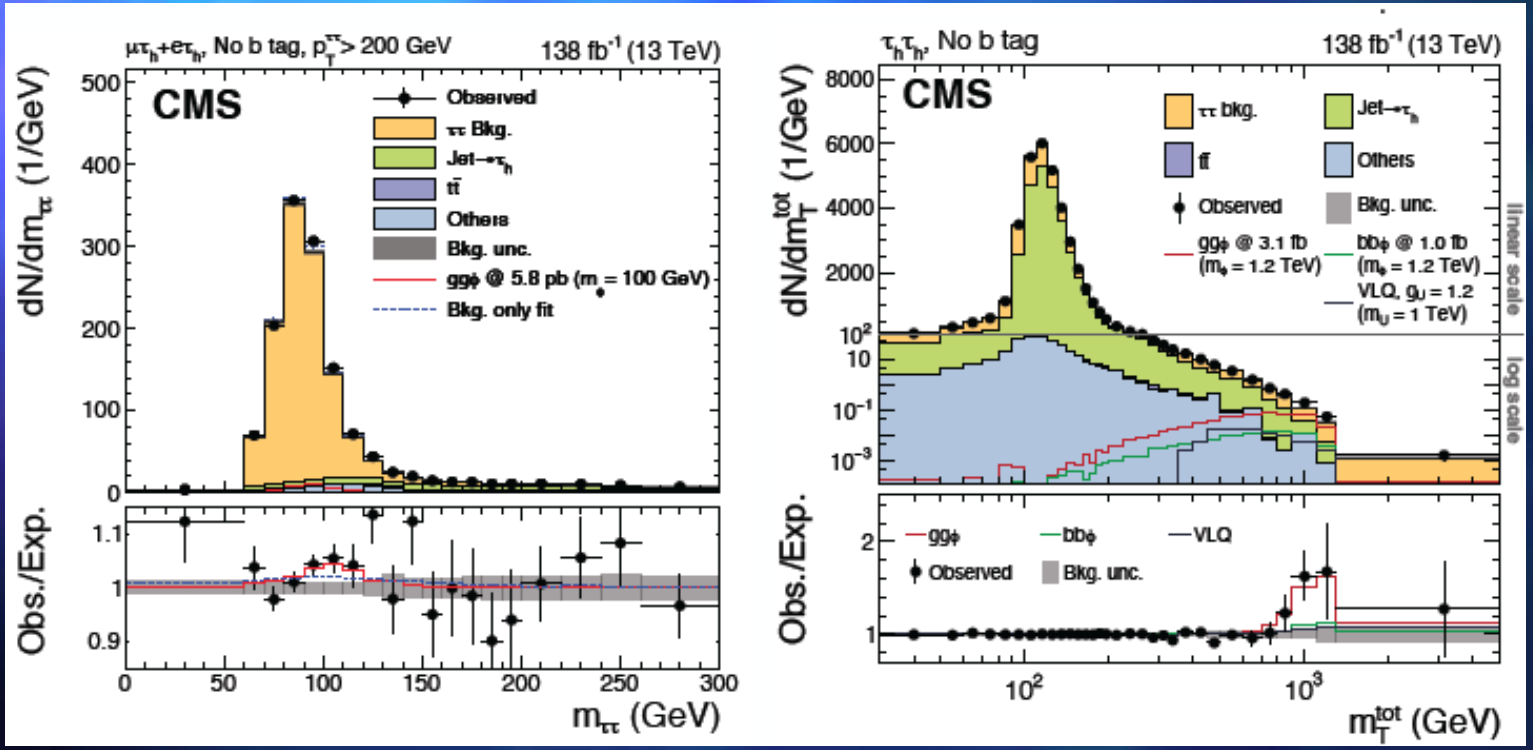
- Search using high-pt and high-dE/dx (3.6 sigma significance)
- No competitive CMS results



ATLAS: arXiv:2205.06013

MSSM Higgs boson decaying to ττ

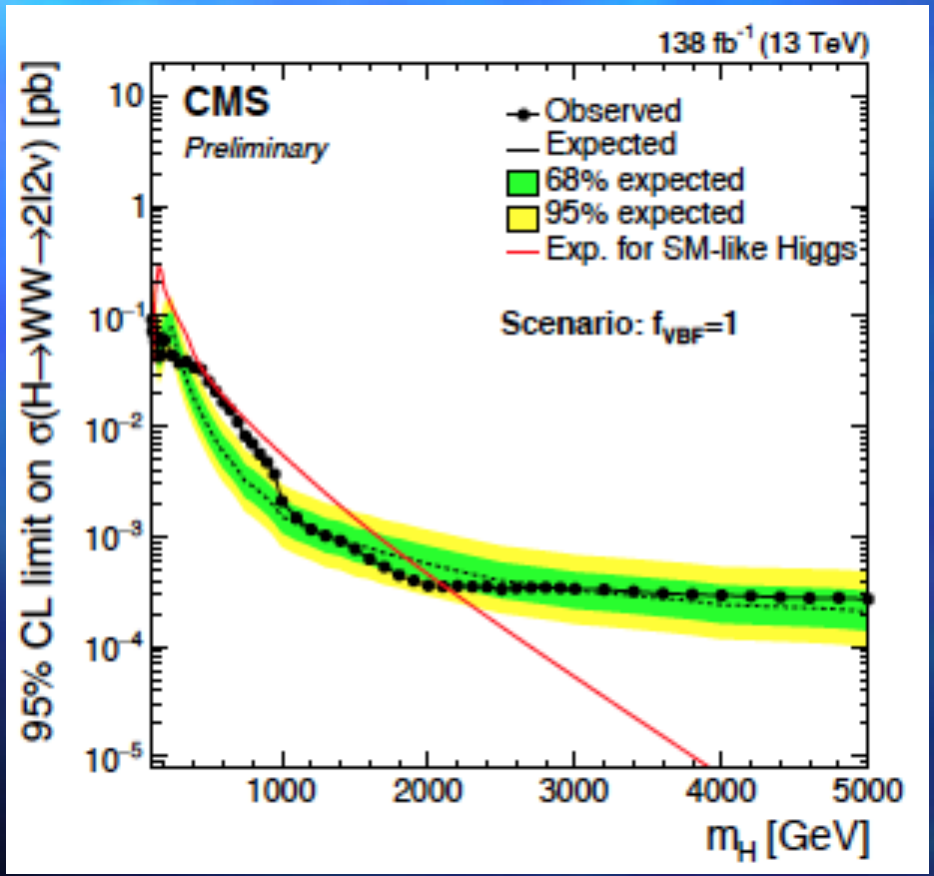
- Excess seen in di-tau mass (0.1 and 1.2 TeV)
- Excess in ~100 GeV also appears in diphoton



CMS: arXiv:2208.02717

Heavy H → WW

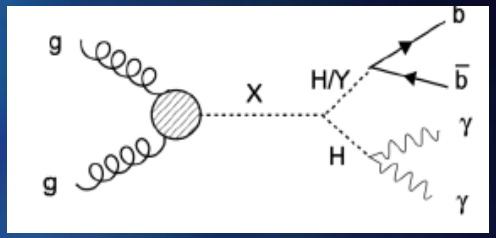
- 3.8 σ in WW (650 GeV)
- Not shown in the ATLAS data



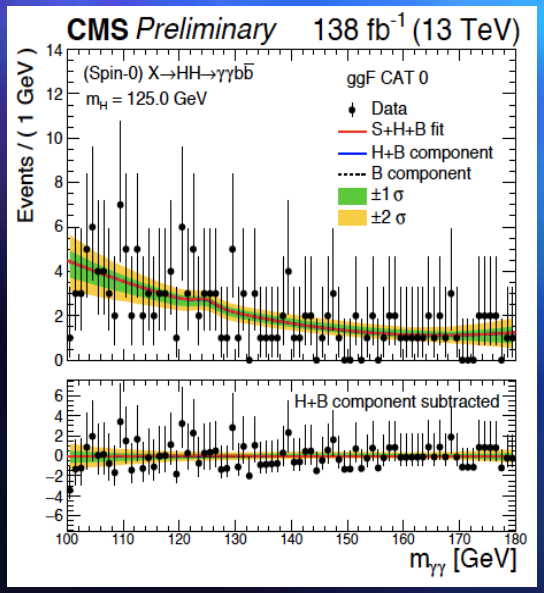
CMS-PAS-HIG-20-016

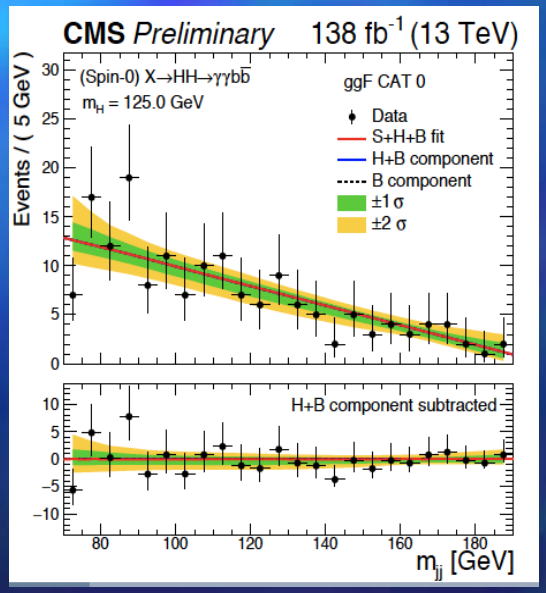
$H(A) \rightarrow a h_{125} \rightarrow bb\gamma\gamma$

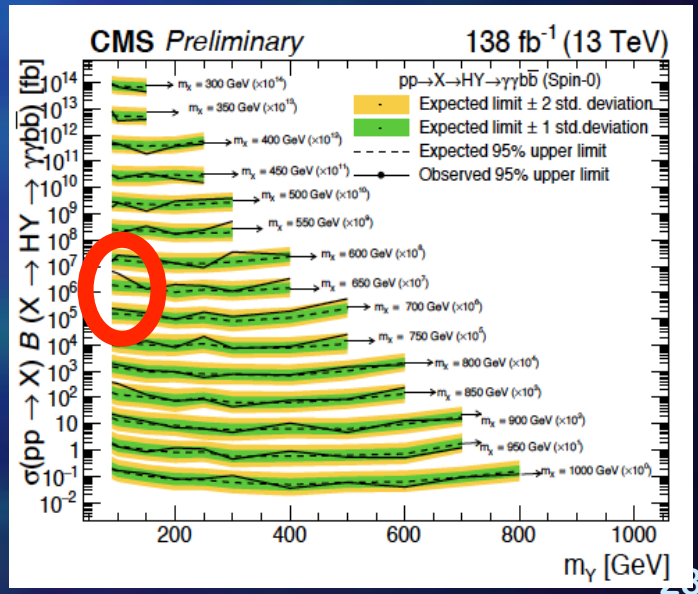
- Search for heavy Higgs decaying to a light Higgs and SM Higgs boson in NMSSM: 2HDM+S
- No significant excess over SM predictions
- Largest excess 3.8 σ at $(m_H, m_a) = (650, 90)$ GeV



CMS-PAS-EXO-21-011



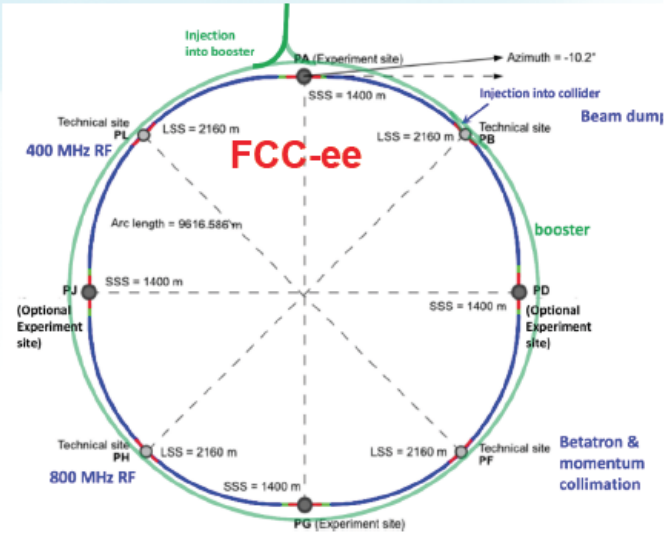




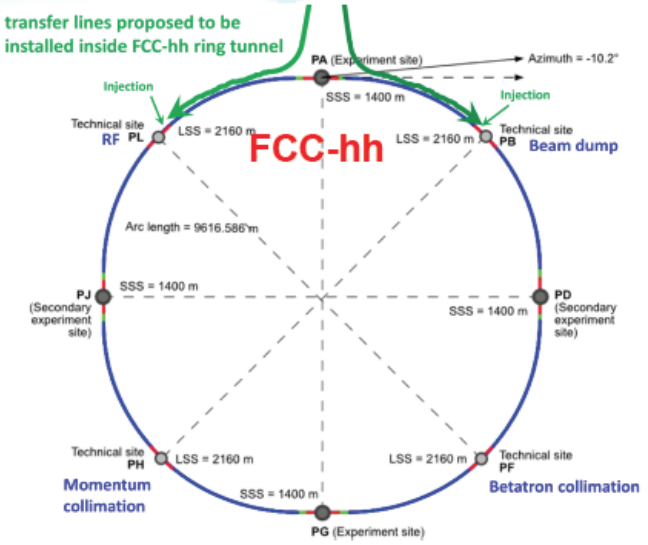
Future Collider

- More Sensitivity, more Precision, more Energy
  - Highest luminosity
  - Highest parton energy
  - Synergy between lepton and hadron colliders

2020 - 2040



2045 - 2060



2065 - 2090

Summary

- LHC experiments have done much better than expected in understanding detector and analysis technique
- LHC has verified the Standard Model and have searched for new physics at the Energy Frontier, but no new physics evidence except Higgs particle
- LHC stated new run, Run 3 from Feb 2022 with expected data of 300fb^{-1}
- This will continue at the current run and future HL-LHC to explore the physics beyond the SM

ILC/FCC-ee

Early 2000's grad school

LC is a precision machine
only useful after LHC
discovered something

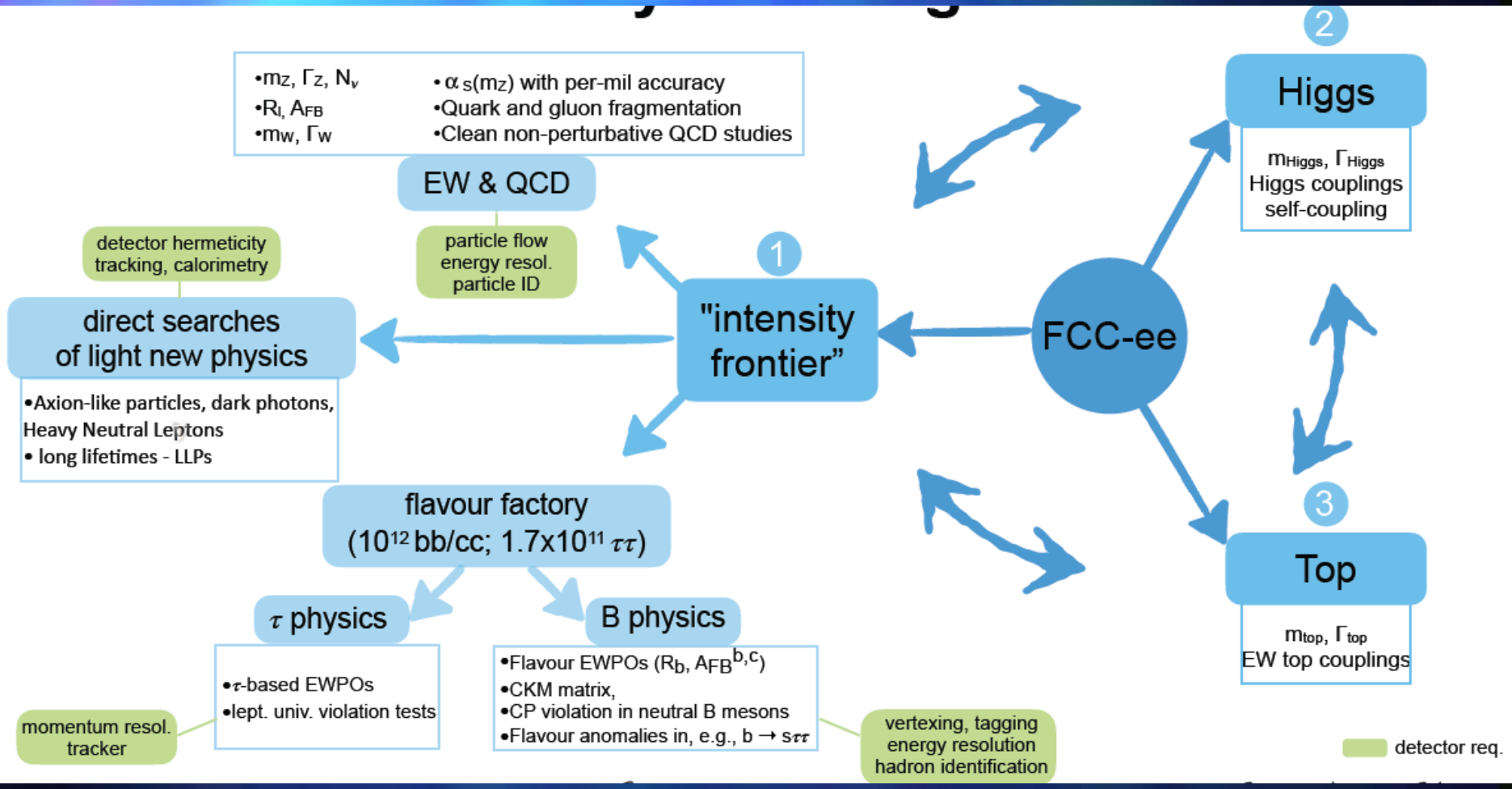
2012 Higgs Discovery

LC probably won't
see anything based
on LHC data

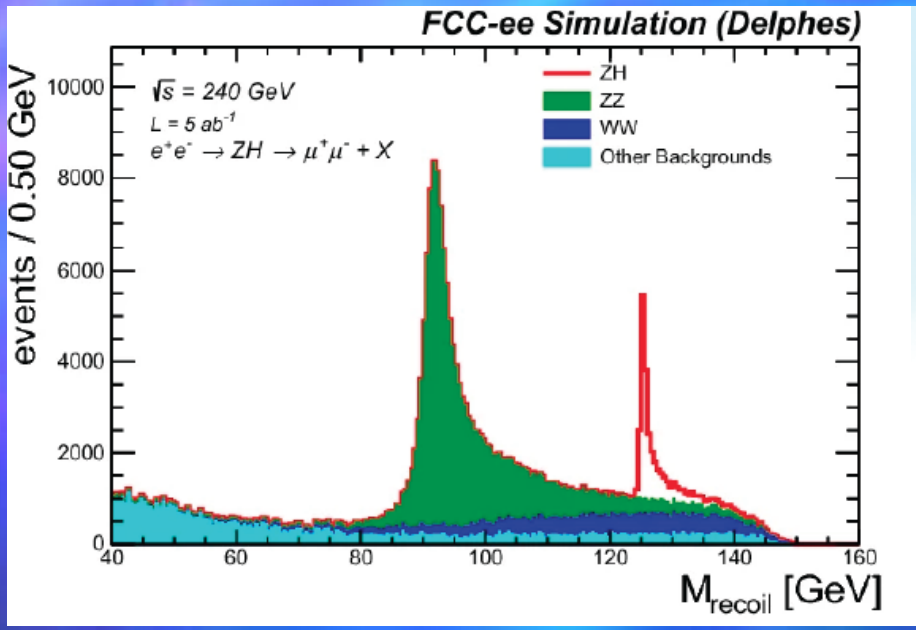
2018

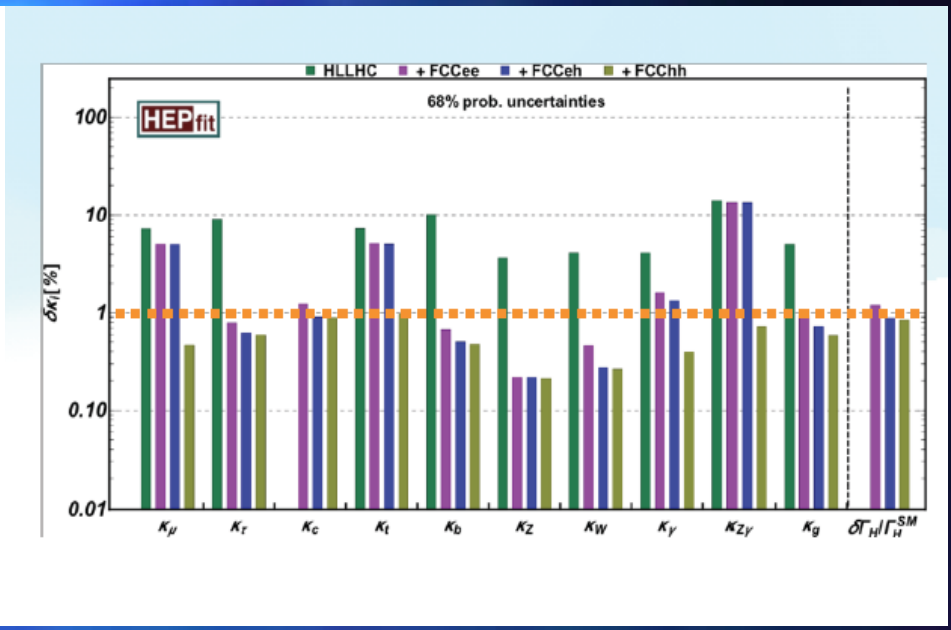
LC can be a
discovery machine!

FCC-ee Program



Higgs and Searches





Precision on k_λ	
FCC-ee	33 %
FCC-ee(4IP)	24 %
FCC(ee+hh)	5 %