# Overview on the energy frontier of particle physics beyond the standard model


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# Topics from Parallel Sessions (Sunday)

- BSM vision, Elina Fuchs
- Prospects for BSM at LHC (experimental vision), Livia Soffi
- BSM Higgs physics at LHC (Direct and indirect from Higgs couplings), Tiesheng Dai
- New physics searches with the ILD detector at ILC, Mikael Berggren
- EW SUSY production at the LHC, Holly Pacey
- Strong SUSY and third generation SUSY, Joshua Hiltbrand
- Probing dark matter with ILC, Aleksander Filip Zarnecki
- Search for dark matter at the LHC, Janna Katharina Behr
- Probing Higgs-portal dark matter with vector-boson fusion, Eric Madge

# Topics from Parallel Sessions (Wednesday)

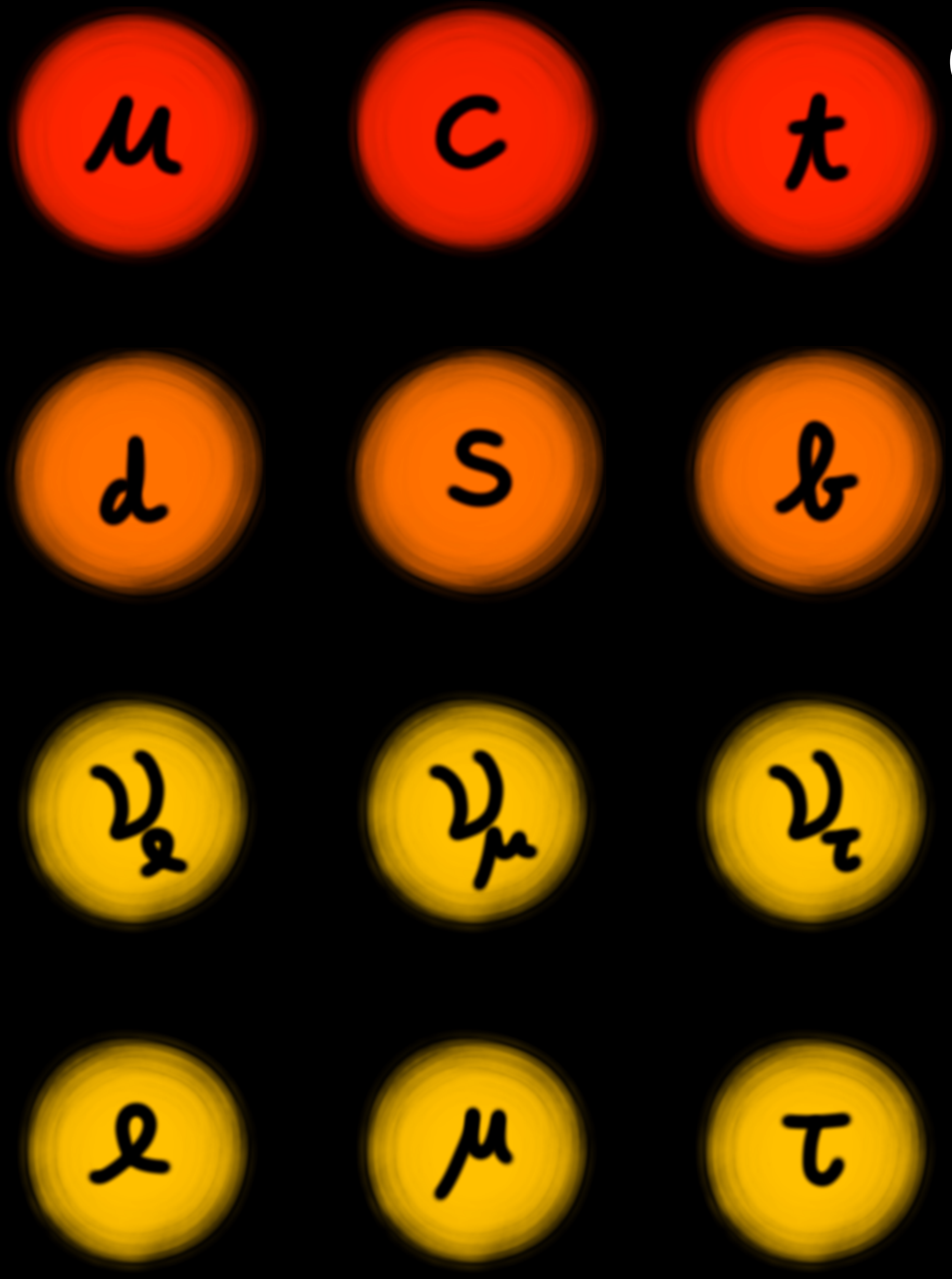
- SM anomalies and BSM interpretations, Claudia Cornelia
- Leptoquarks and HVB (in scenarios of LFU anomaly), Arne Christoph Reimers
- Constraints on colored scalars from global fits, Victor Miralles
- BSM with axions, Andrea Thamm
- Searches for Axion-Like particles, Adrian Casais Vidal
- Searches for long-lived particles at CMS, Malgorzata Kazana
- Long-lived particles and unconventional signatures at LHC, Monica Verducci
- Prospects for searches of new physics at future facilities beyond HL-LHC, Clement Helsens
- Search prospects for extremely weekly-interacting particles in gamma factory, Sreemanti Chakraborti
- Search for heavy resonances at LHC (ED, HVB, etc…), Dominik Duda
- Cosmological approaches to the Higgs hierarchy problem, Daniele Teresi

# THE STANDARD MODEL OF PARTICLE PHYSICS

All particle foreseen by the **Standard Model** have been observed

quarks

leptons

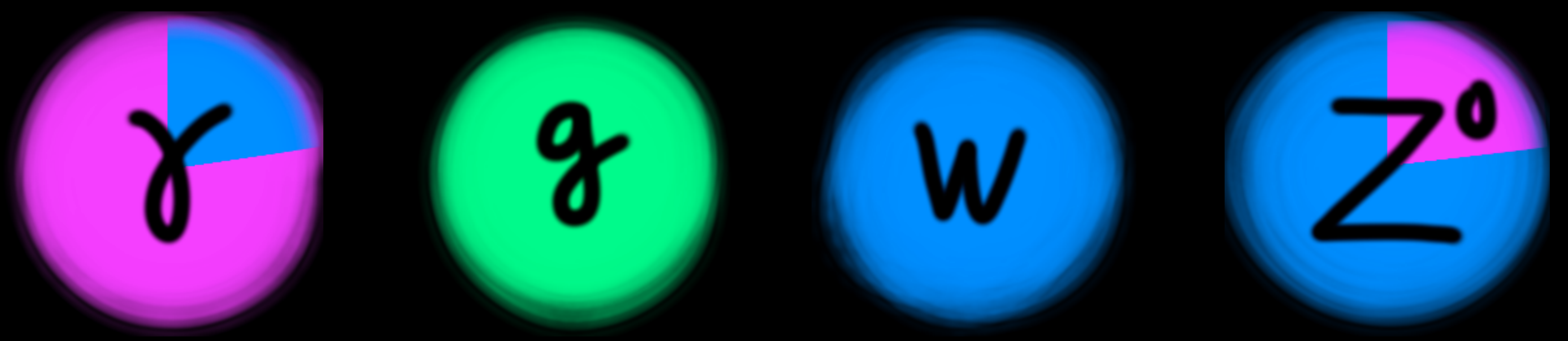


(1994)

+ anti-particles

(i.e. copies of opposite charge)

## Force Carriers



(All discovered already since 1983)

## The Higgs boson

(2012)

(after a 40-year search)

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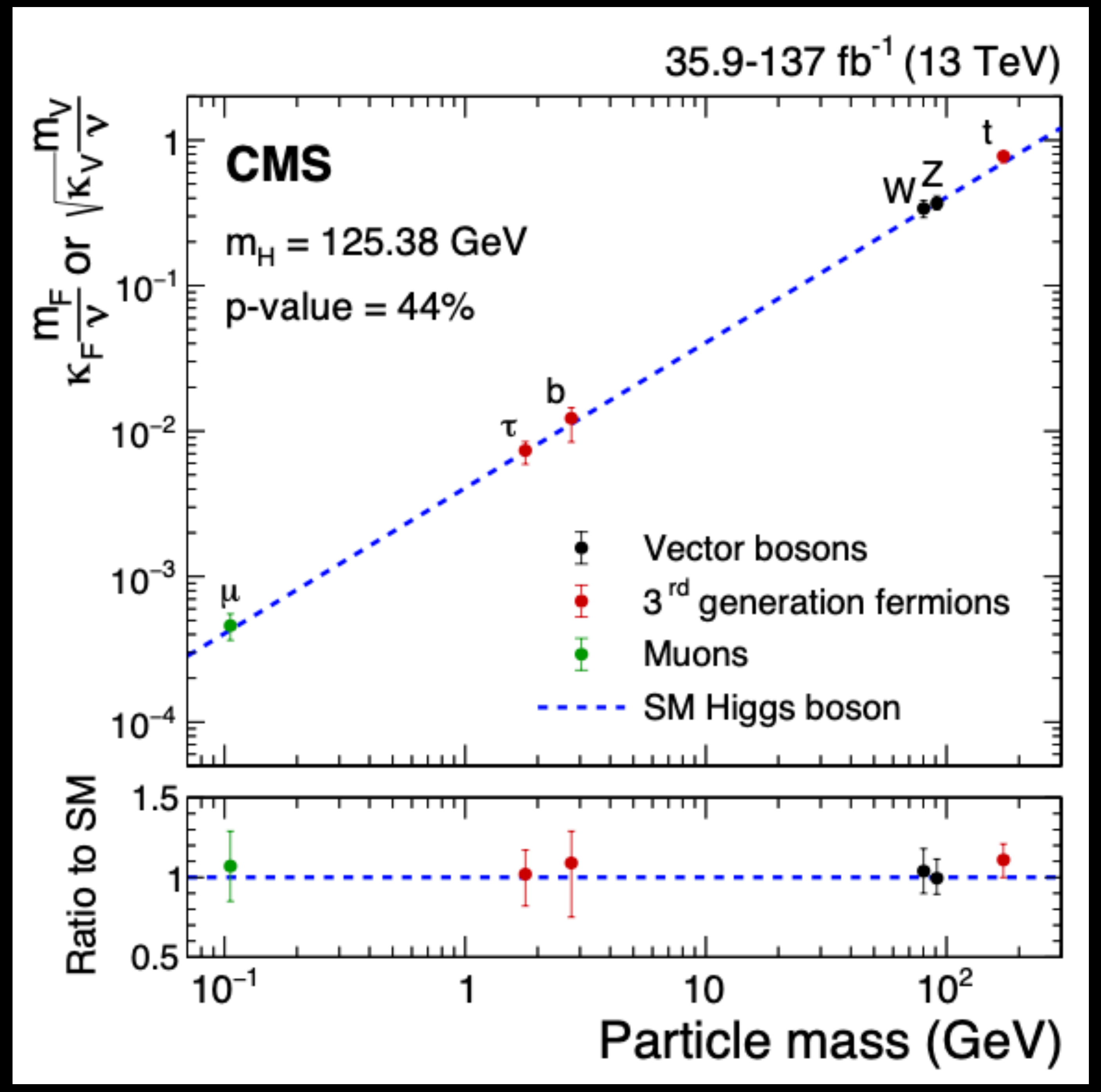

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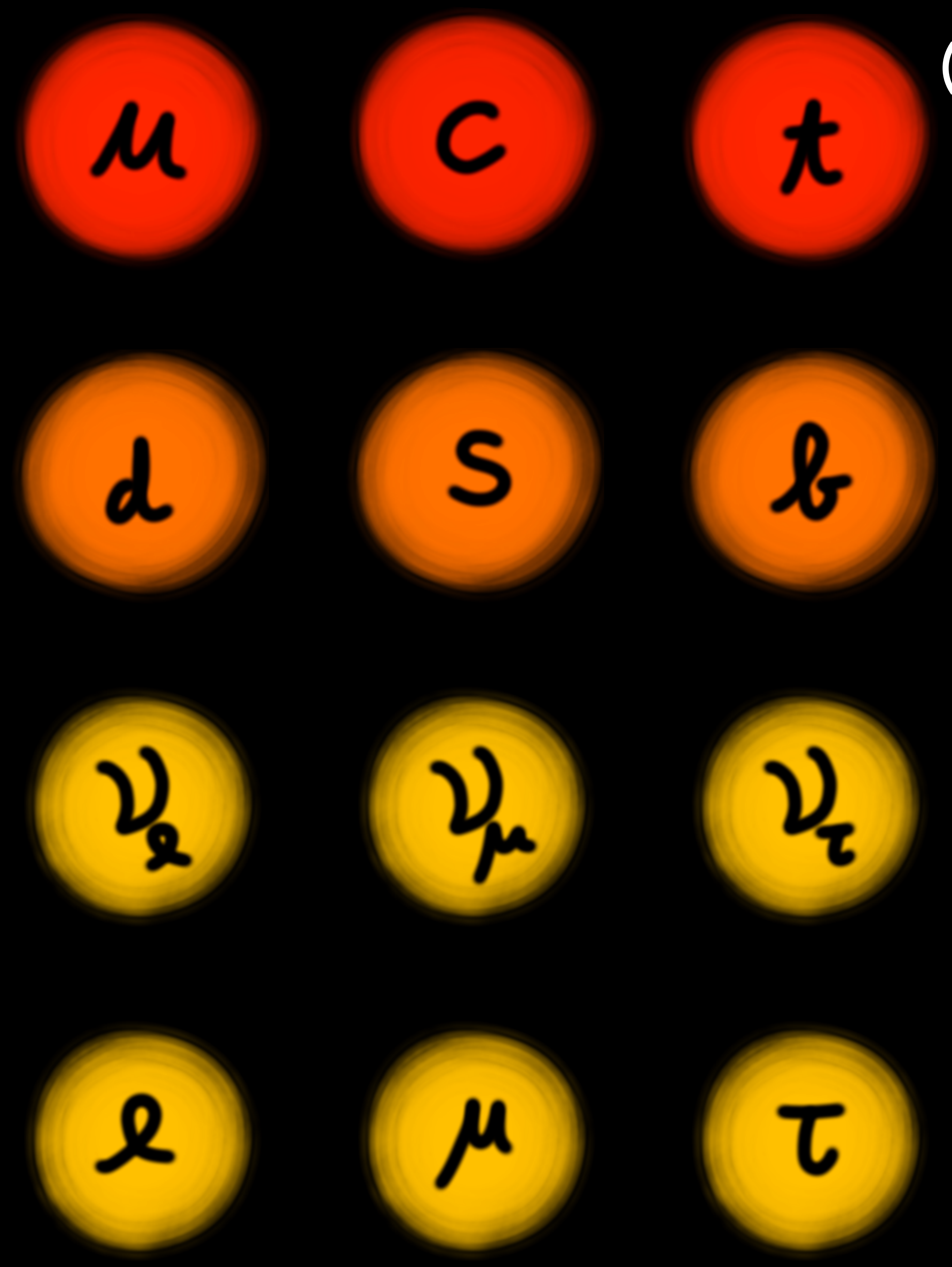


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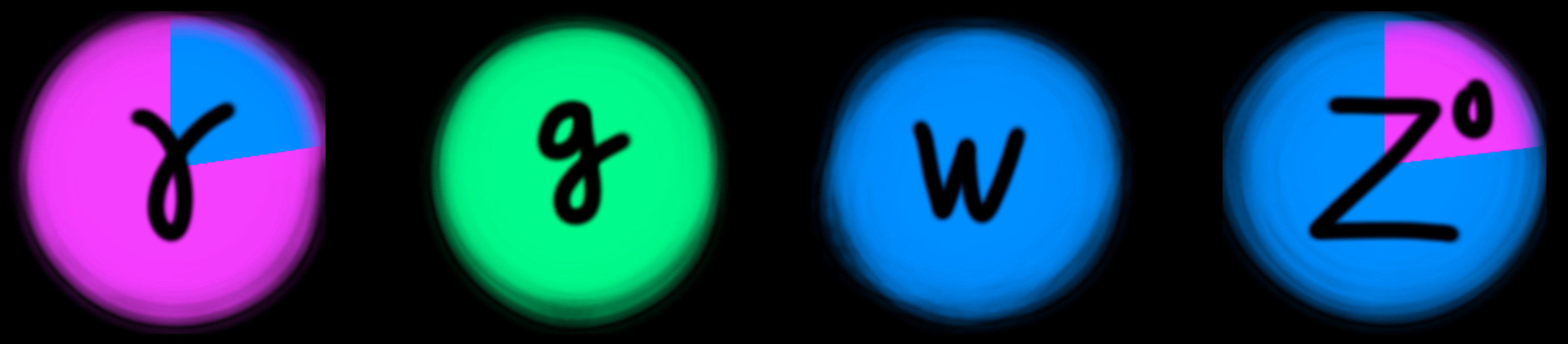
## Force Carriers




(All discovered already since 1983)

## The Higgs boson


(2012)

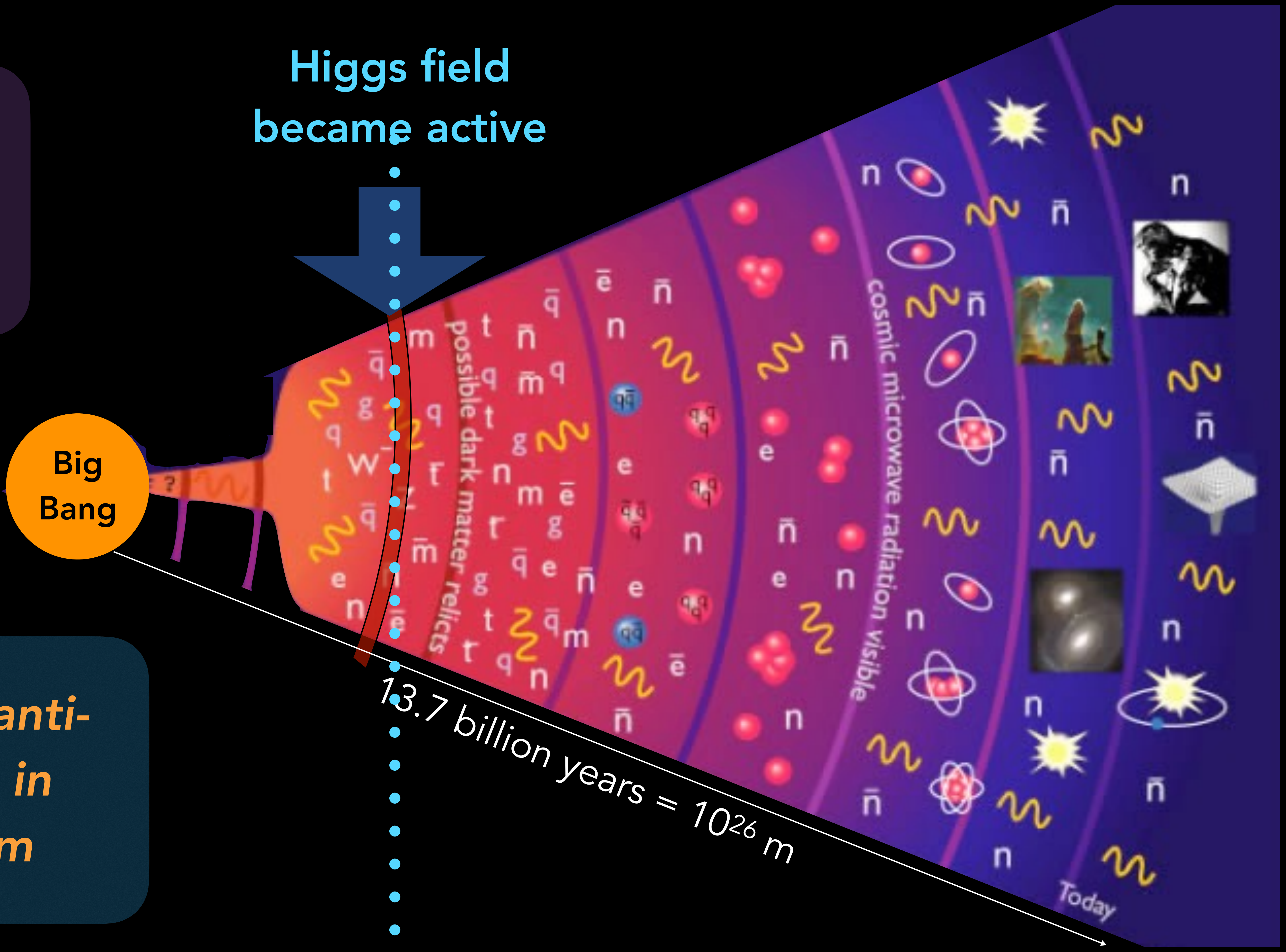
(after a 40-year search)

The end of Particle Physics?

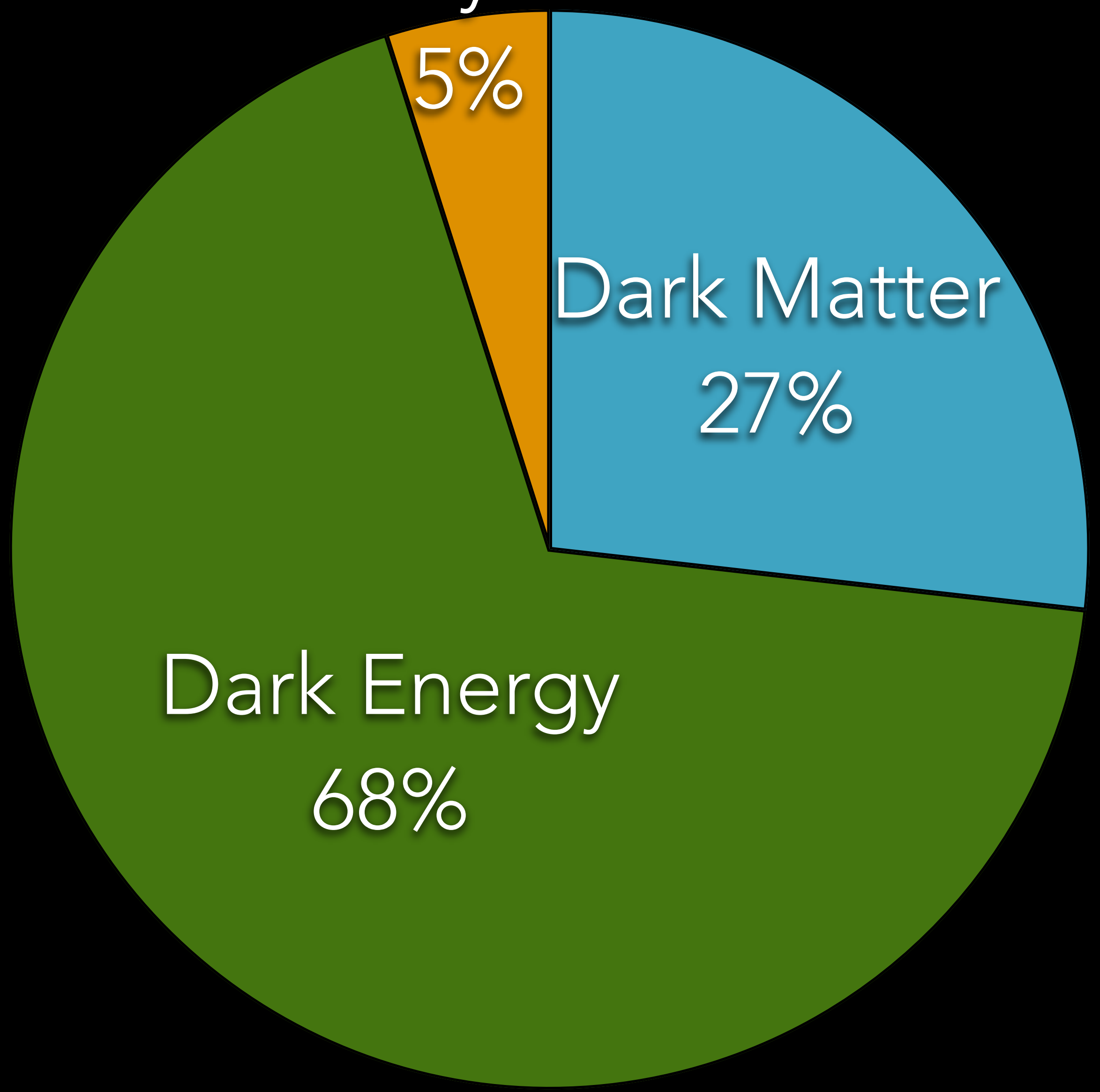
# EVIDENCE FOR BEYOND STANDARD MODEL PHYSICS

**Higgs mass**
**Hierarchy problem**
**Planck scale: $10^{18}$ GeV**
**Higgs mass: $10^{2}$ GeV**

*Matter and anti-matter are in equilibrium*



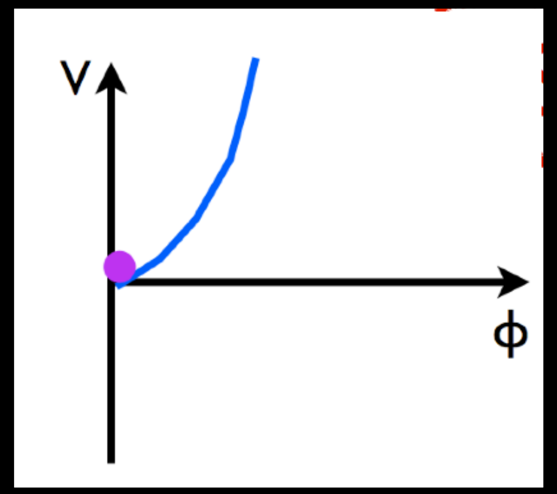

## Now




**Baryon Asymmetry**

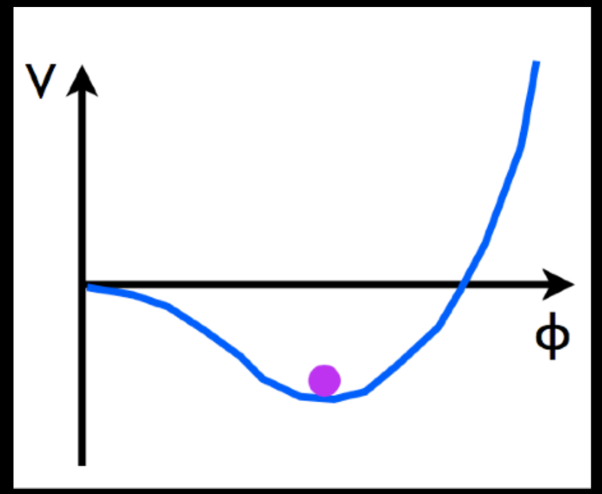
*There is matter, but not anti-matter*

**Particles are massless**




Higgs Boson potential

**Electroweak phase transition**




Higgs Boson potential

**Particles have mass**


Adapted from: Maury Tigner; *Physics Today* 54, 36-40 (2001) — Originally from Persis Drell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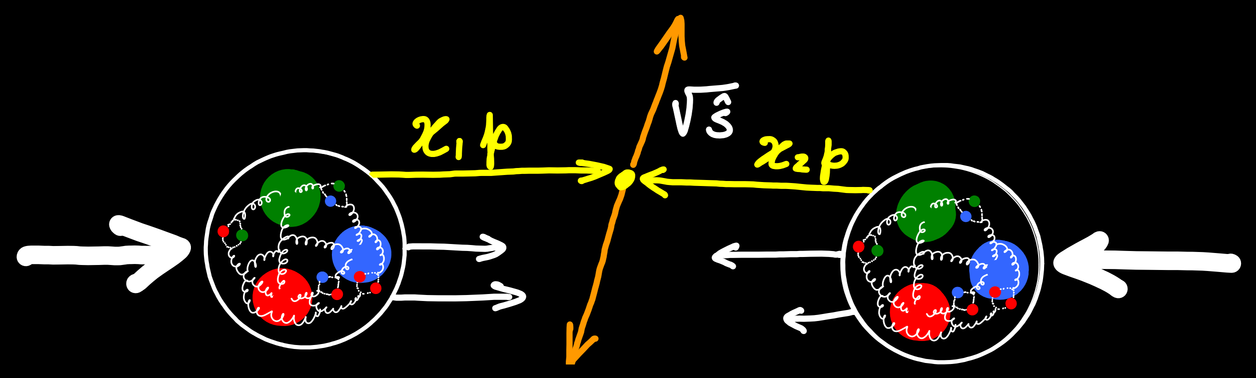
# THE LARGE HADRON COLLIDER

**Largest energy collider in the world → our current tool**



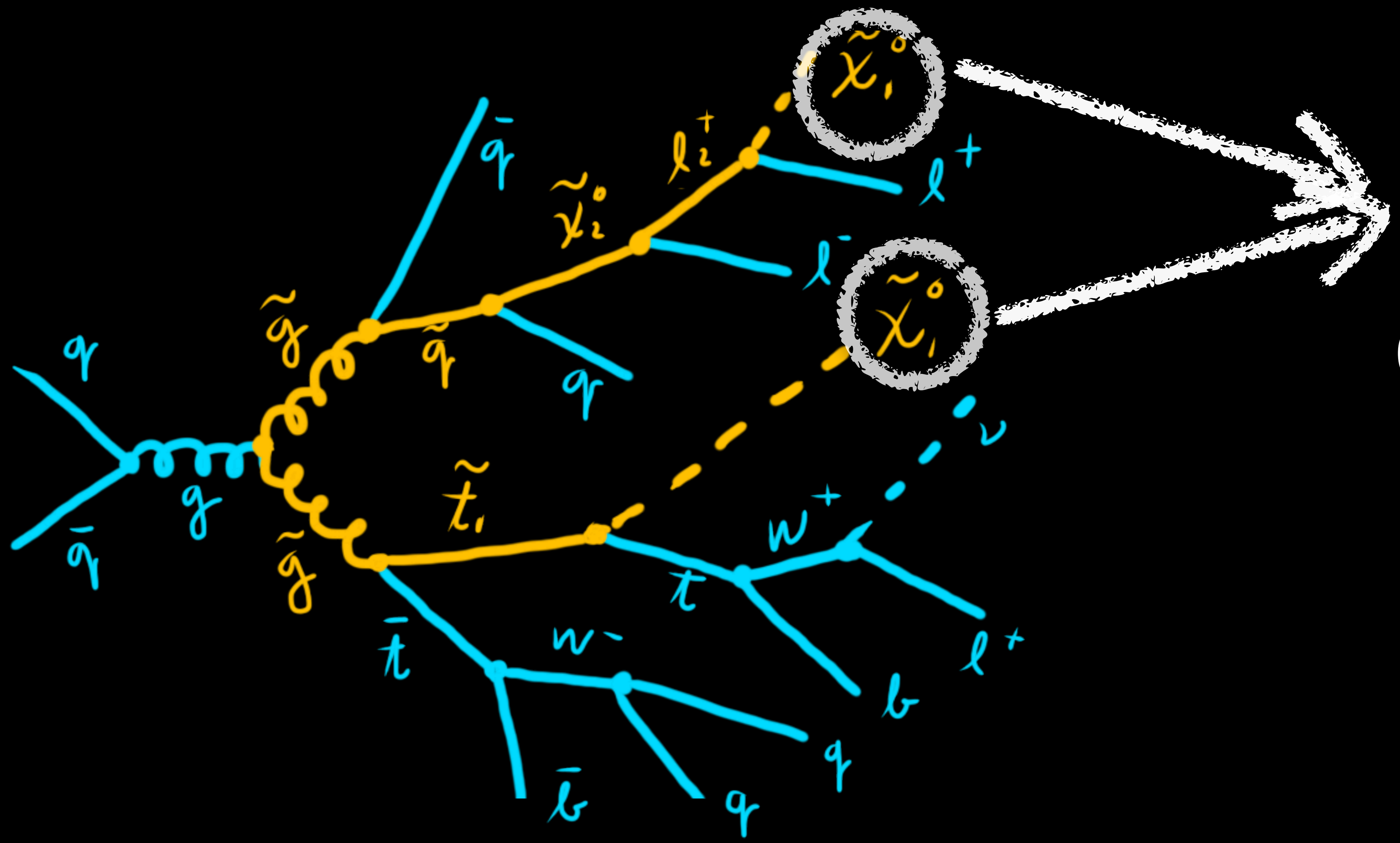

L= ~140 fb$^{-1}$

# SUPERSYMMETRY (SUSY)

- **A favorite, ideal, long-time candidate to explain most of questions raised**
  - Symmetry between bosons and fermions, provides dark matter candidate, provides unification of forces, no fine-tuning required for Higgs mass
- **Unfortunately, no evidence for SUSY found yet**

**Strong SUSY production**

**Large cross section**




**Dark Matter Candidates**

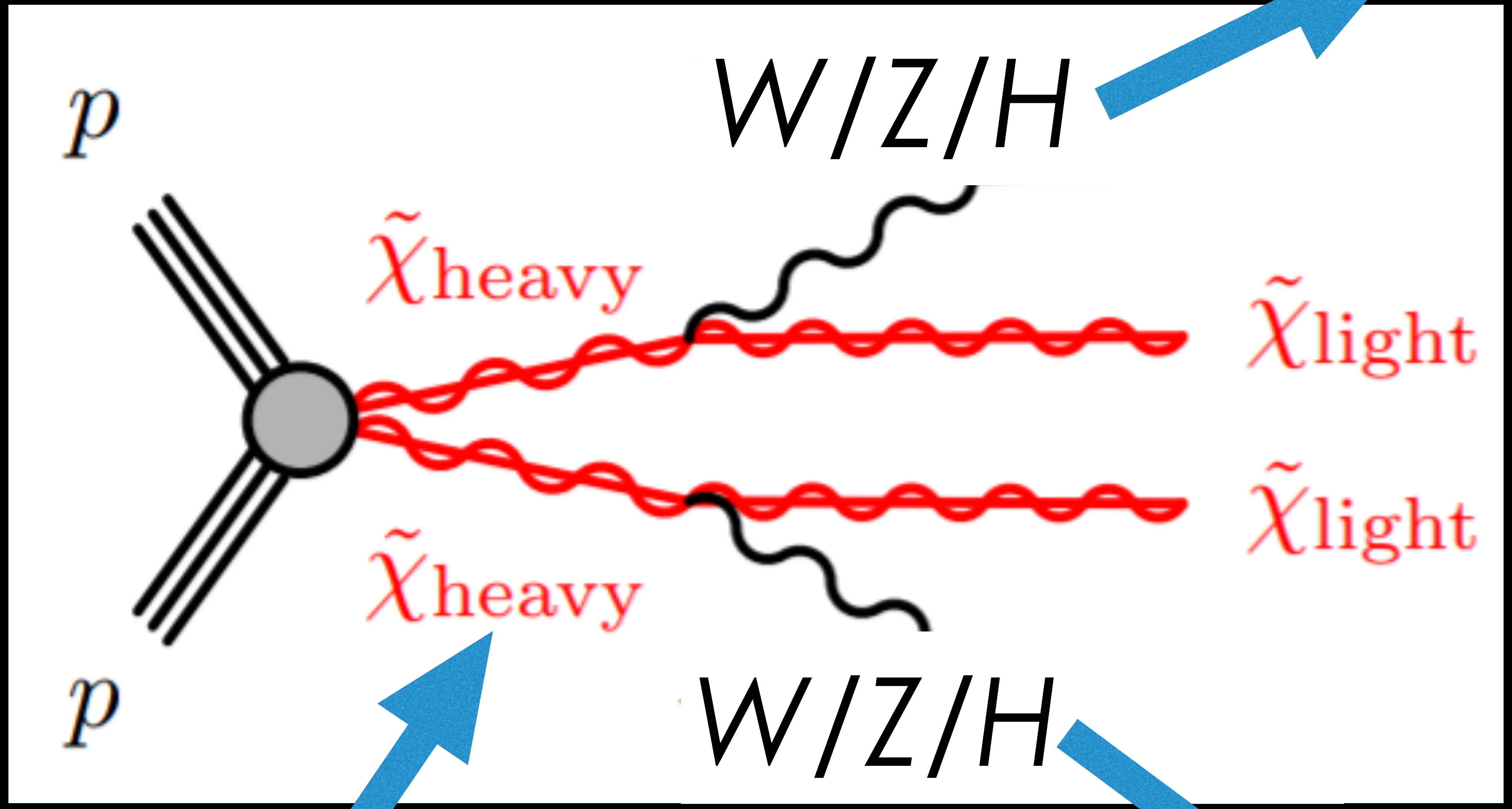
**(Assuming R-Parity Conservation)**

**Mass gluino > 1-2 TeV (depending on models)**

# ELECTROWEAK SUPERSYMMETRY

Rare signatures, less constrained than Strong SUSY

Several decay modes




Lightest SUSY Particle
Higgsino
Bino
Gravitino
Axino

Missing Energy

Several decay modes

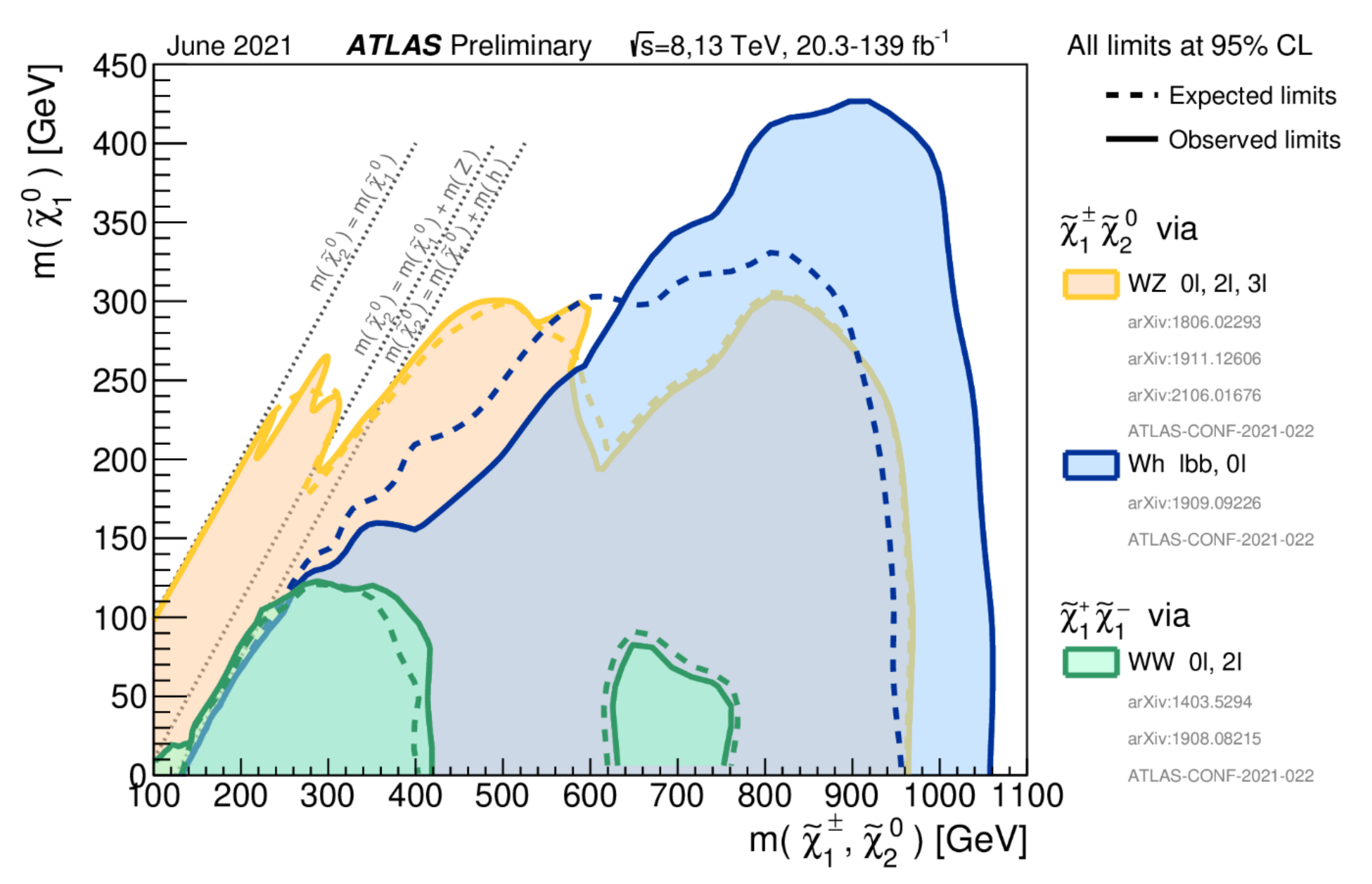
NLSP
Wino, Higgsino, sleptons

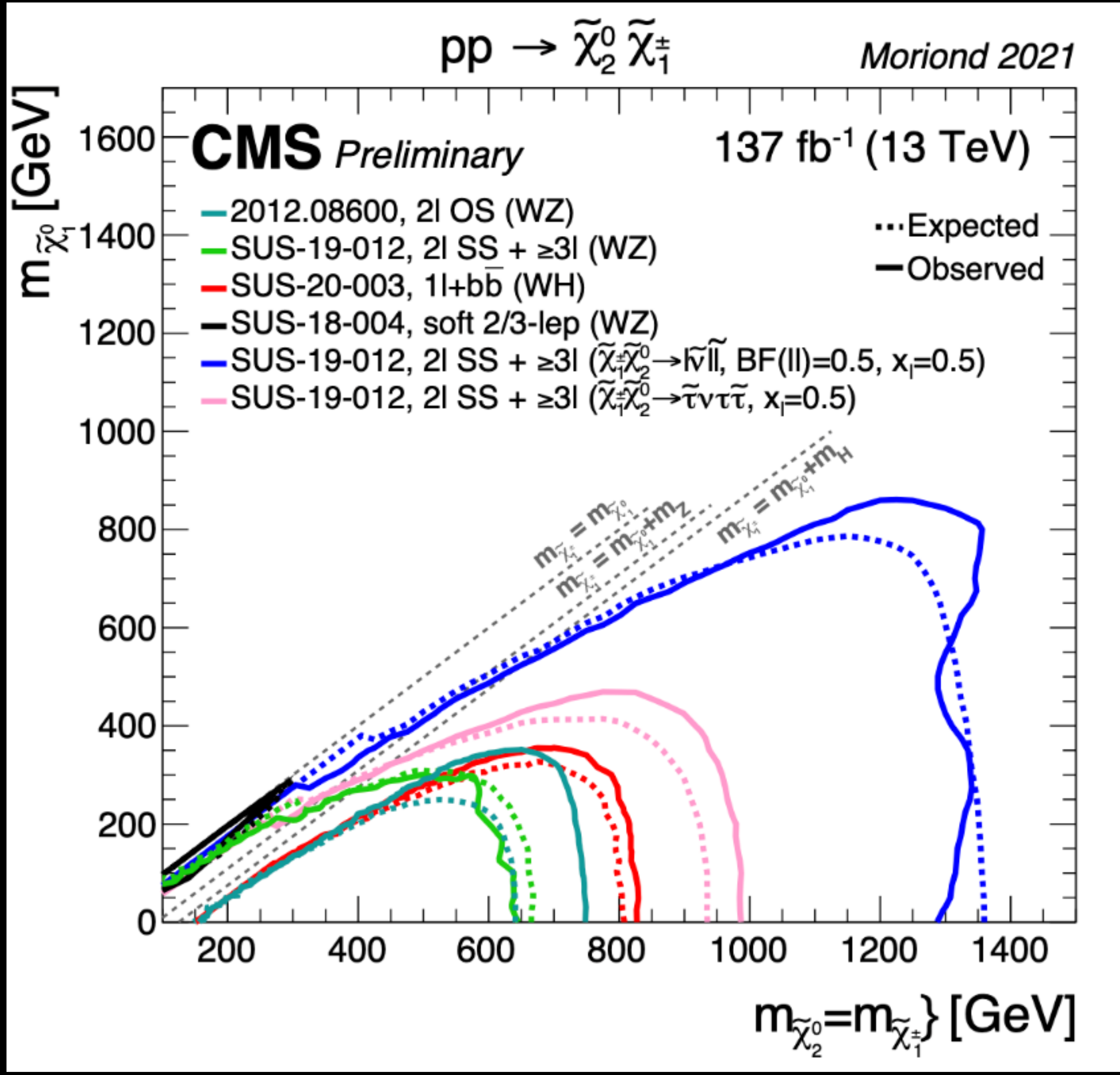
# ELECTROWEAK SUPERSYMMETRY

See talk by Holly Pacey

## Excluded gaugino phase space for several final states

(95% CL limits up to 1-1.3 TeV)



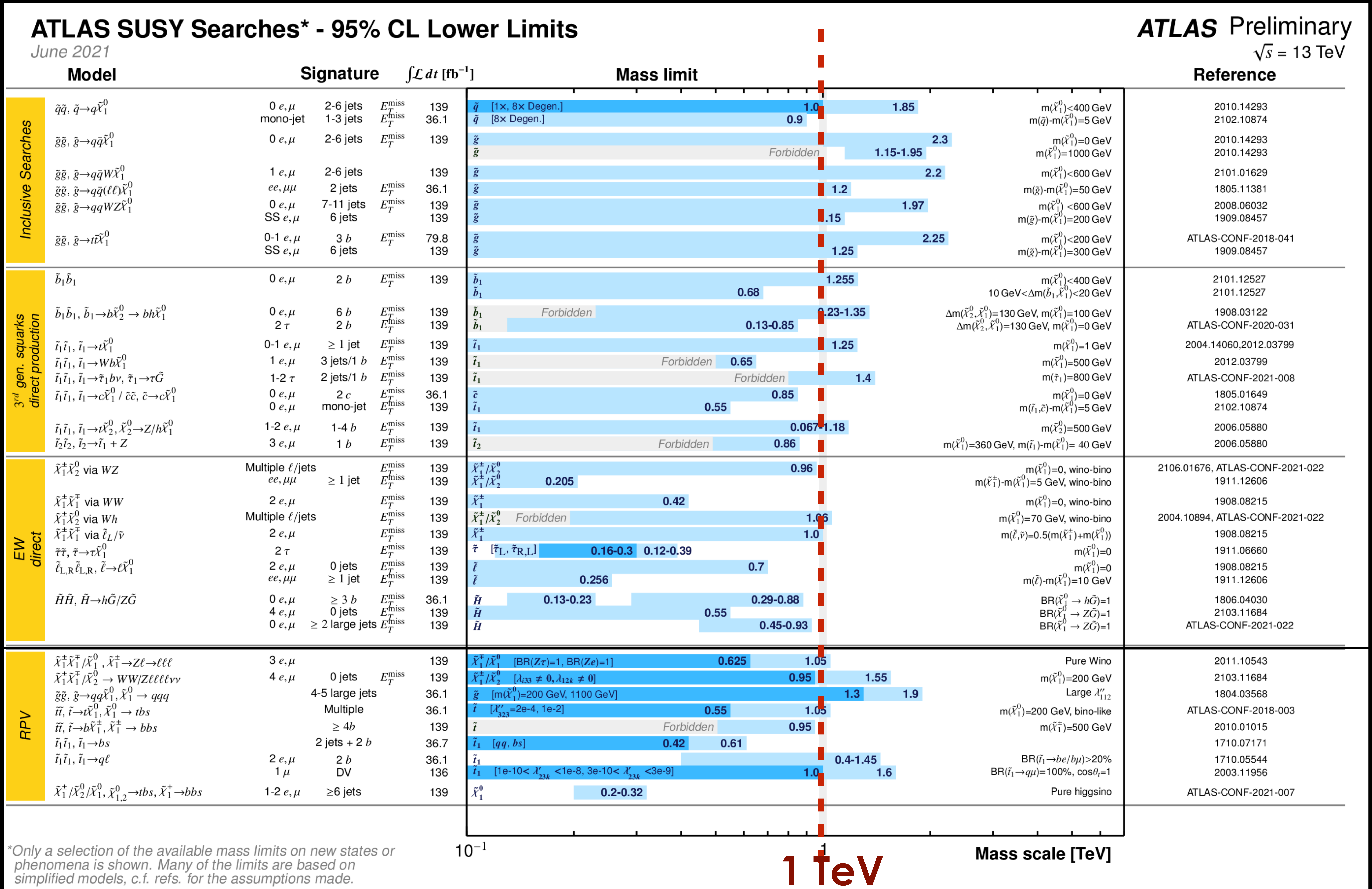




ATLAS Summary Plots

CMS Summary Plots

# STANDARD ATLAS SUSY SEARCHES SUMMARY

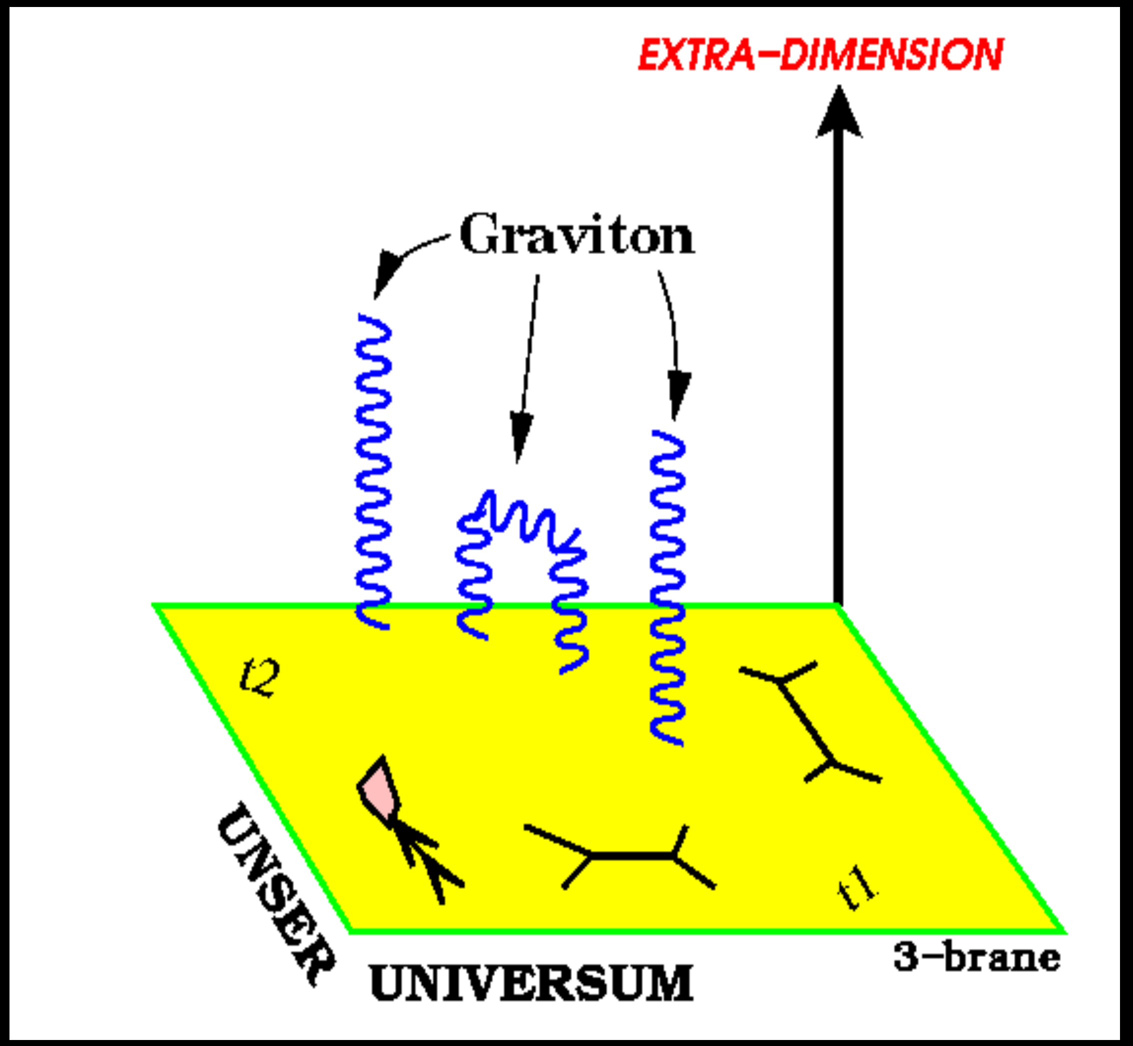
Observed exclusion limits at 95%

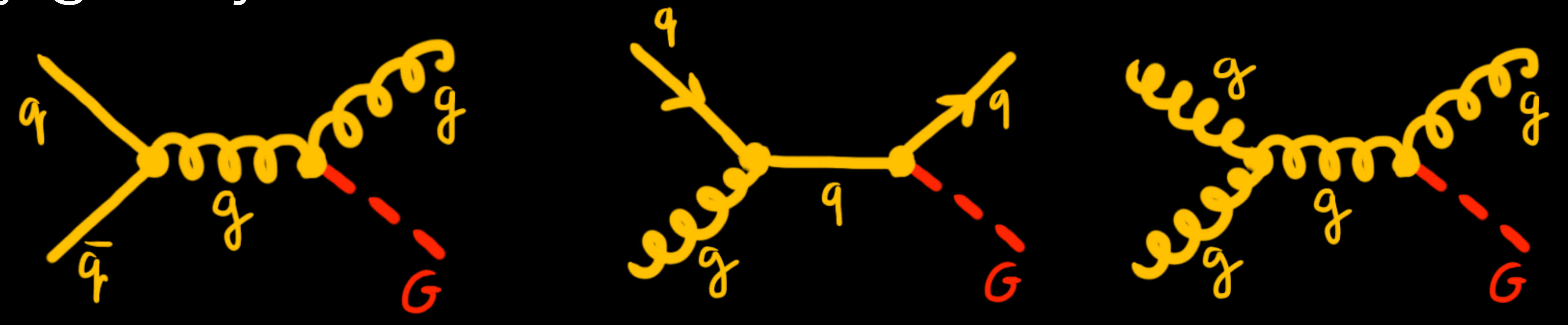


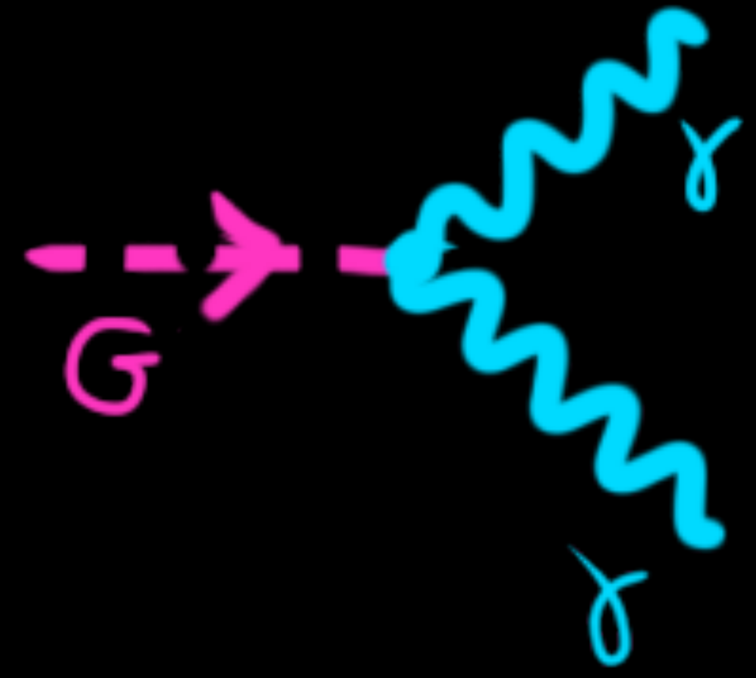

1 TeV

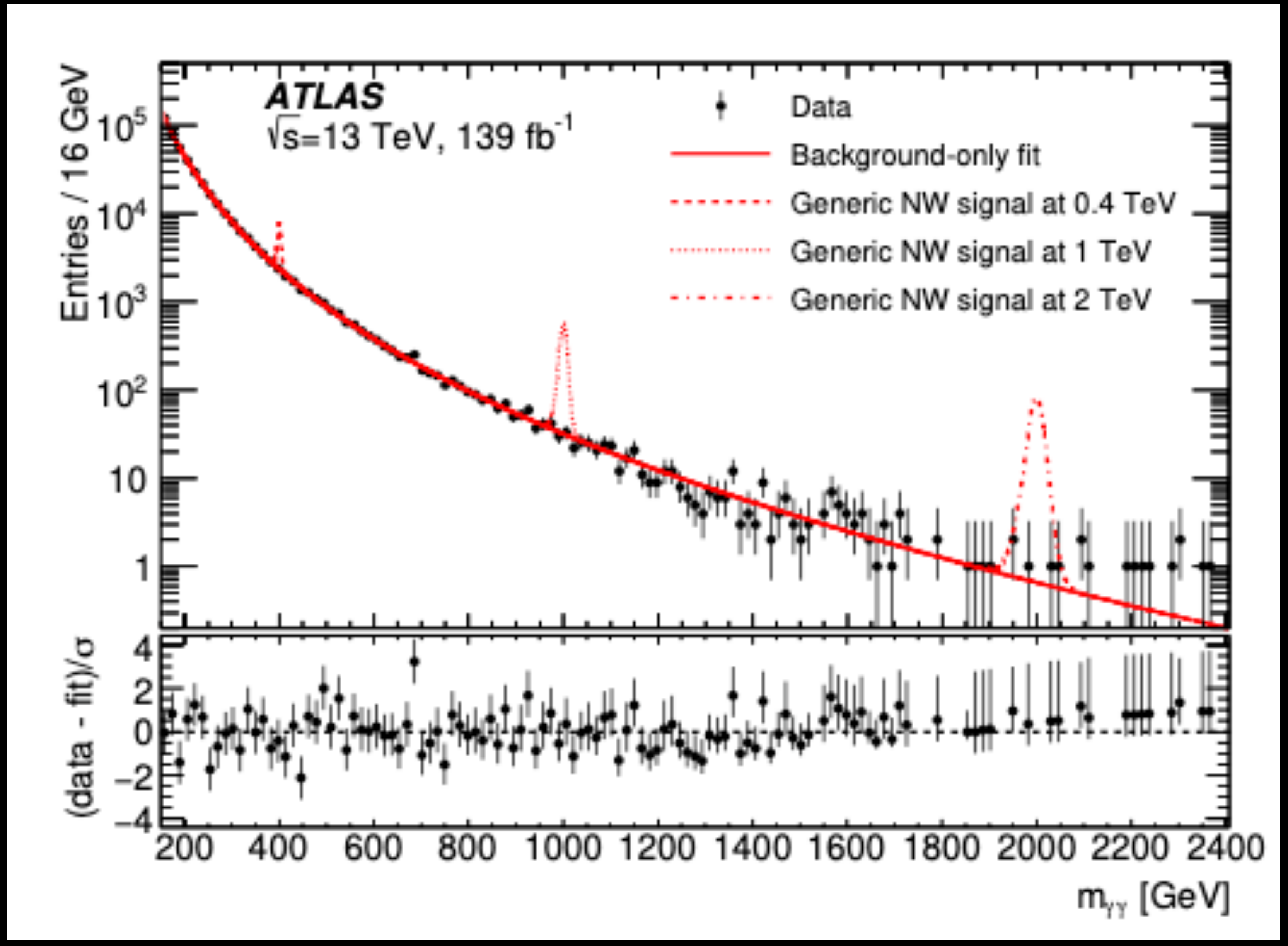
# EXTRA DIMENSIONS

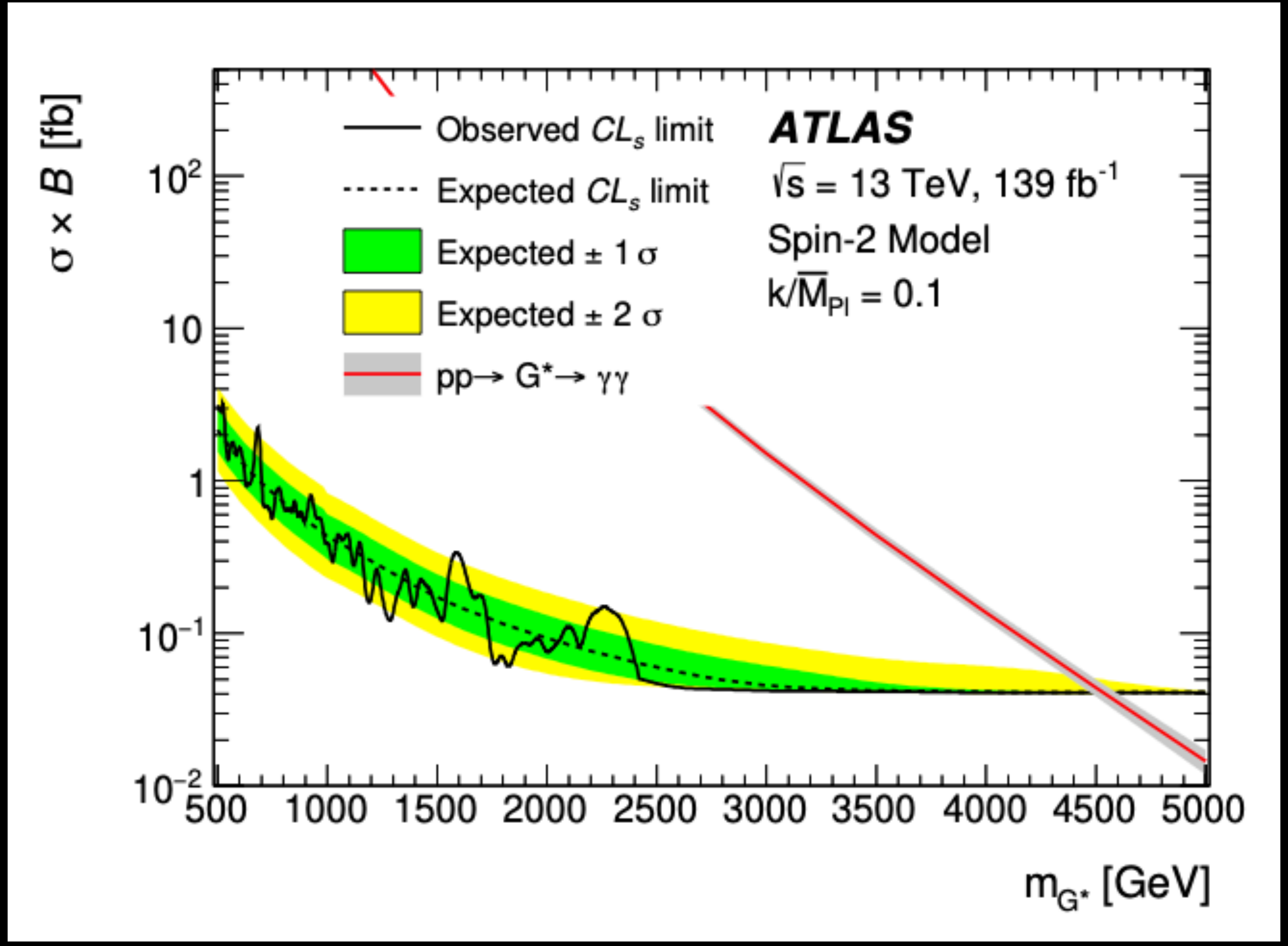
- **Hierachy problem solved by bringing down Planck scale**
  - n extra dimensions, compactified at radius R
  - SM confined to brane in a higher dimensional space
  - Only gravity can access extra dimensions



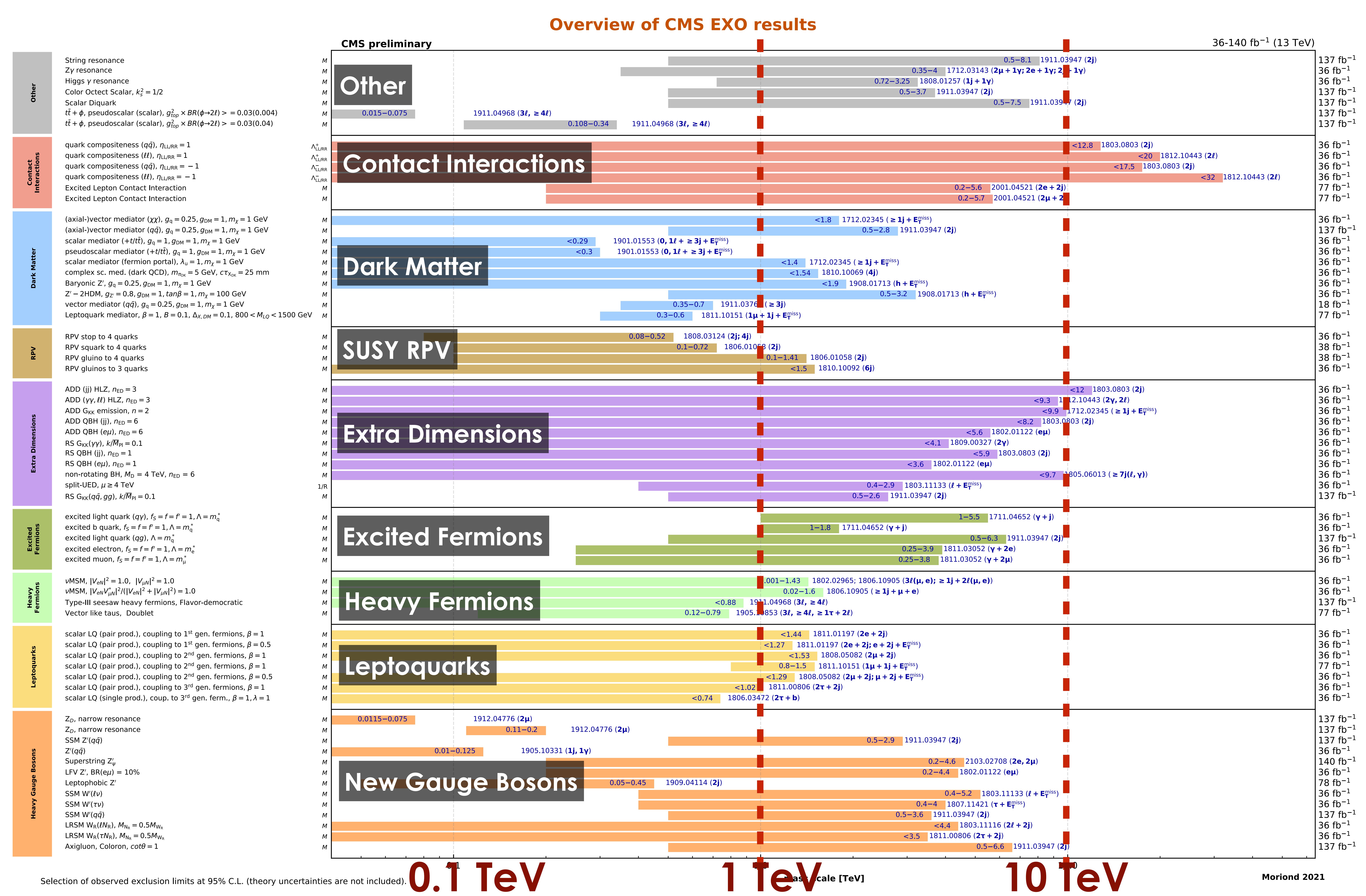



# DIRECT NEW PHYSICS SEARCHES FROM LHC

Observed exclusion limits at 95%



# NEW INTERESTING ANOMALIES

- Flavor: B, K and D meson sector
- Muon magnetic moment from g-2 (expect updated results soon)
- Dark Matter (AMS, Fermi-LAT, Xenon1T)
- Neutrinos
  - MiniBoone, LSND: $\nu_\mu \rightarrow \bar{\nu}_e$ excess
  - Gallium, Reactors: $\nu_e$, $\bar{\nu}_e$ disappearance

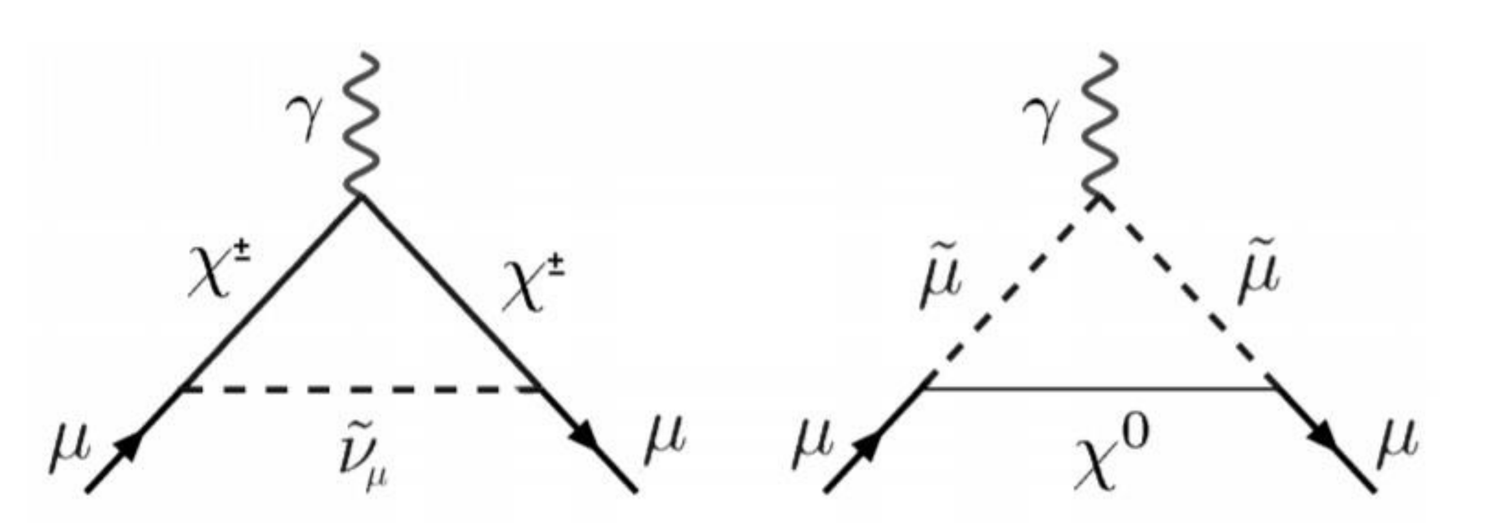
**No convincing discoveries yet, but intriguing tensions**

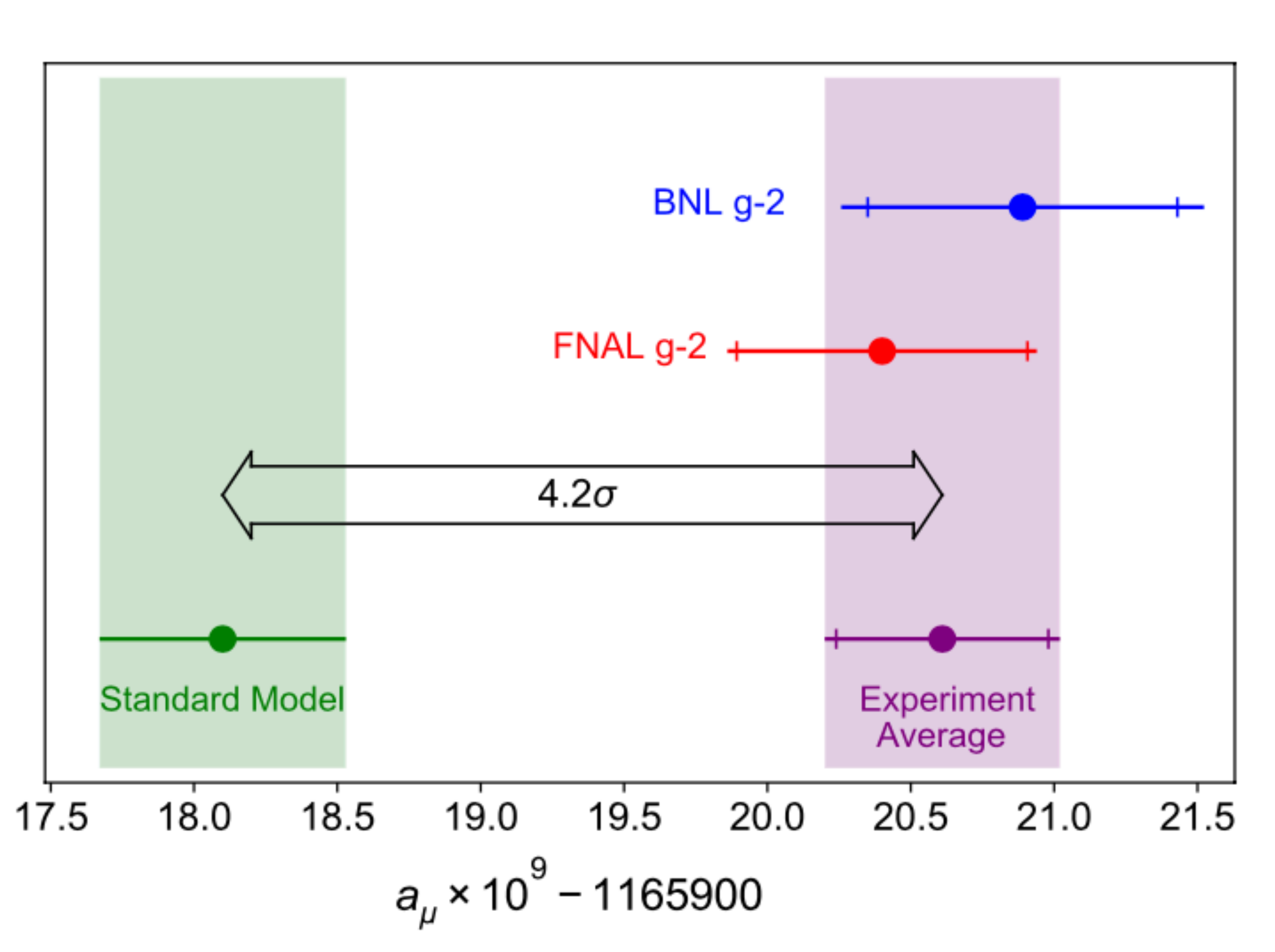
# MUON ANOMALOUS MAGNETIC MOMENT COMPATIBILITY WITH SUSY

## g-2 Experiment

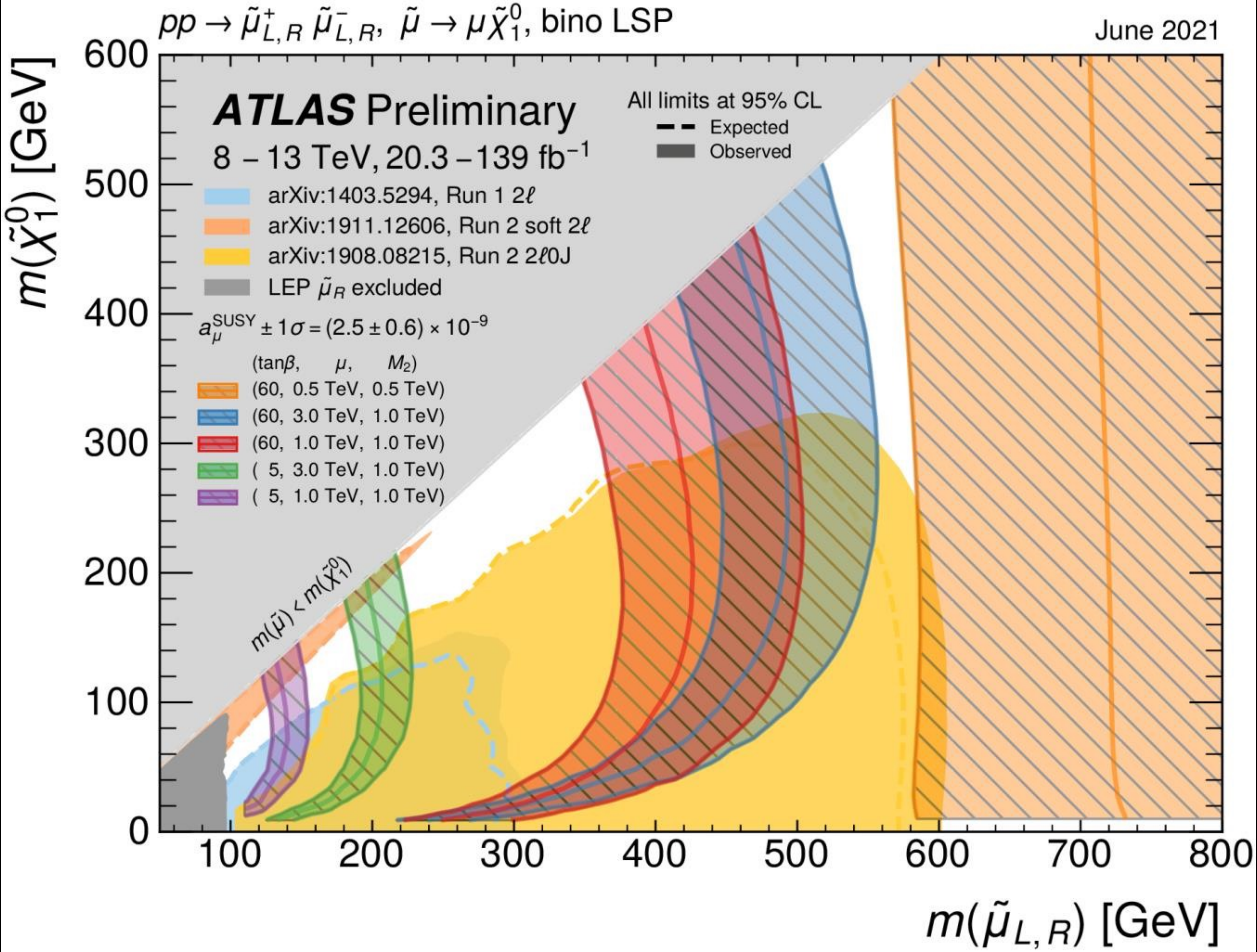
### Muon Anomalous Magnetic Moment

$$\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (251 \pm 59) \times 10^{-11} \; (4.2\sigma)$$






(arXiv:2104.03281)



# NO NEW PHYSICS OBSERVED

## → LOOK FURTHER/DEEPER

**Explore new tools and techniques**

# Long-lived particles (LLPs)

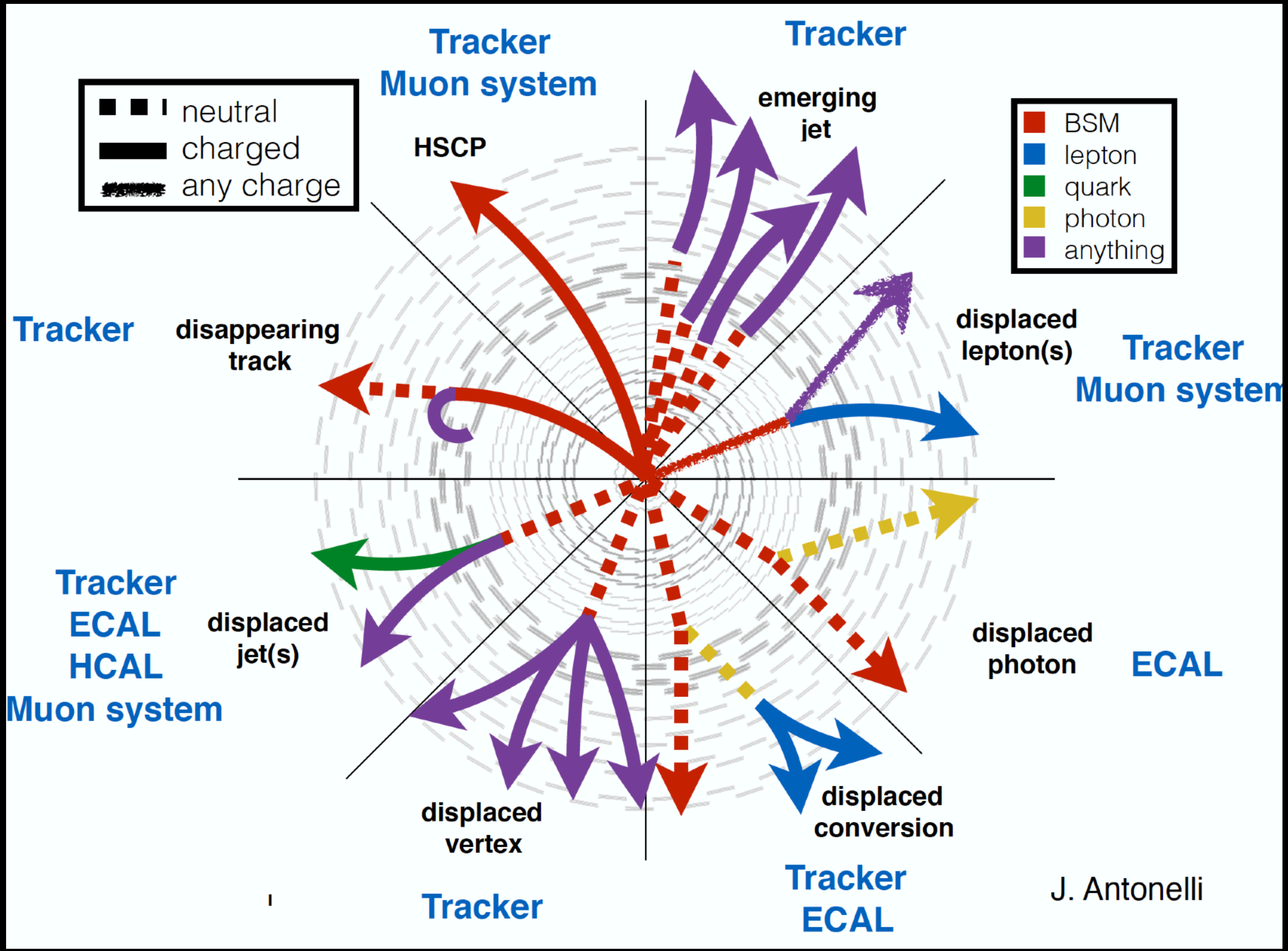
see talk by Małgorzata Kazana and Monica Verducci

**Long-lived particles (LLPs) are common in BSM**

- Small phase space for decay (e.g. Split SUSY)
- Small couplings to SM particles
  - Suppressed (e.g. Higgs/gauge portal to Dark Sector)
  - Forbidden by symmetry (SUSY R-parity)

**Could have escaped observation so far**

- **Challenges:**
  - Often requires new triggers
  - Exotic detector signatures (requiring new tools)
  - Non-standard backgrounds



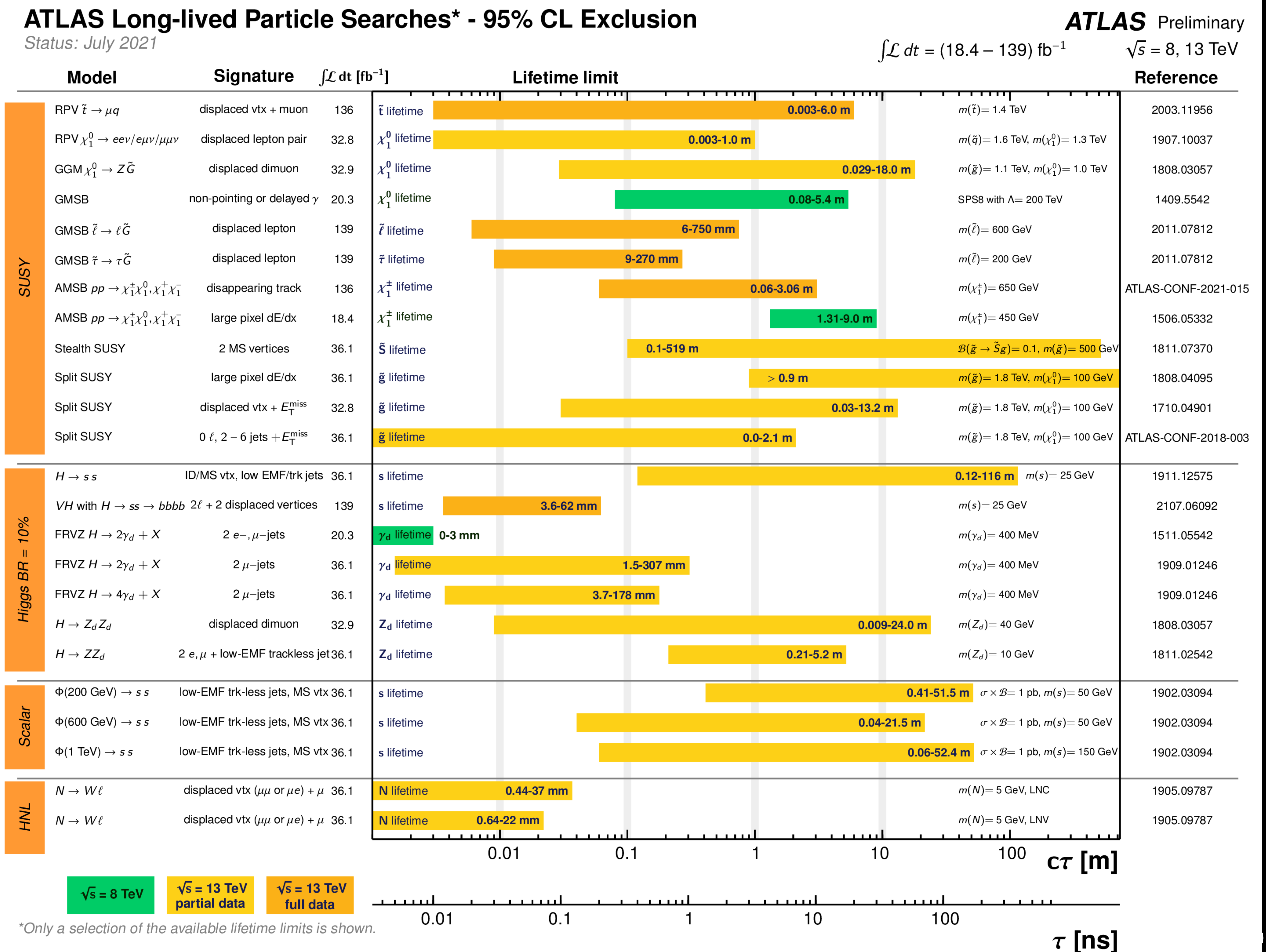
Displaced leptons

Disappearing track

Large pixel dE/dx

Track-less jets

Displaced vertices



# NO NEW PHYSICS OBSERVED

# → LOOK FURTHER/DEEPER

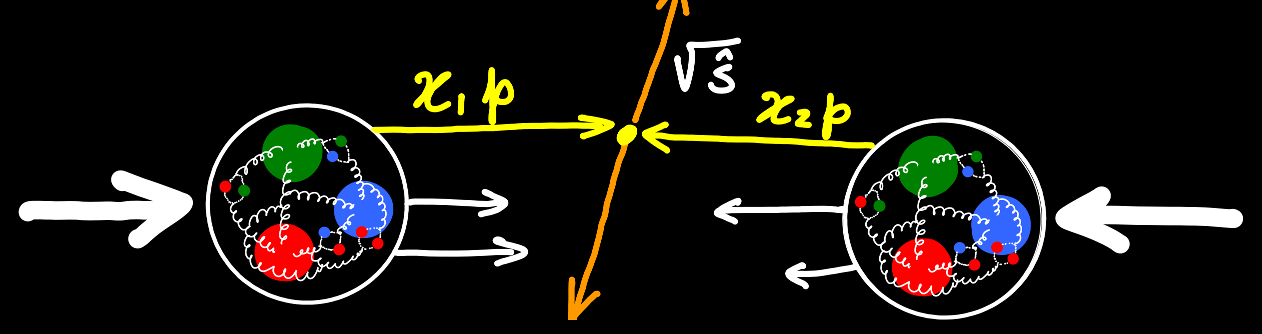
## Explore new tools and techniques

The highest **energy** possible

The highest **luminosity** possible

As **low backgrounds** as possible

# THE LARGE HADRON COLLIDER




**LHC** and experiments being upgraded

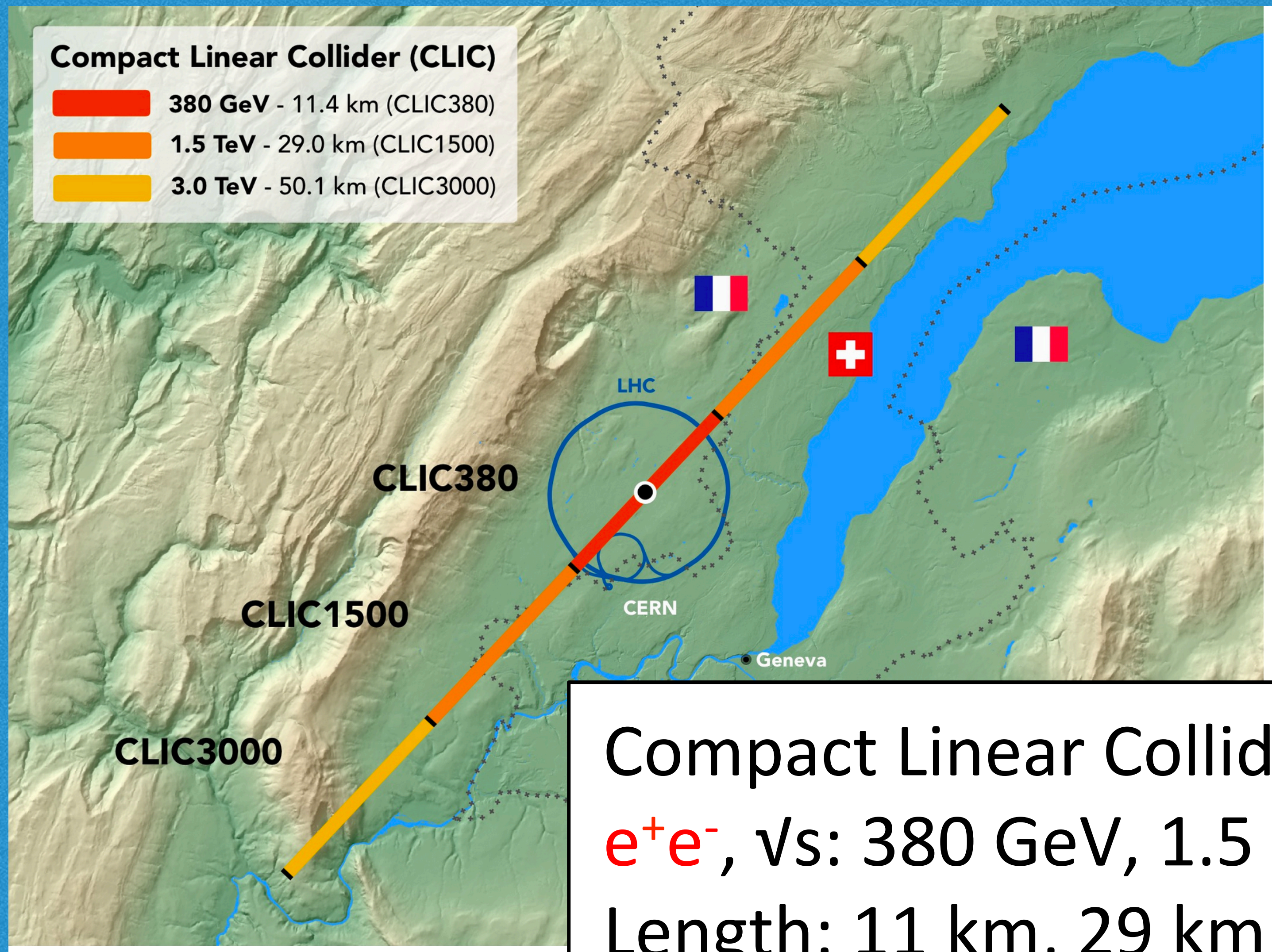
Restart in 2022 with slightly higher energy (13 TeV → 13.6/14 TeV)

L= ~140 fb$^{-1}$ ➡

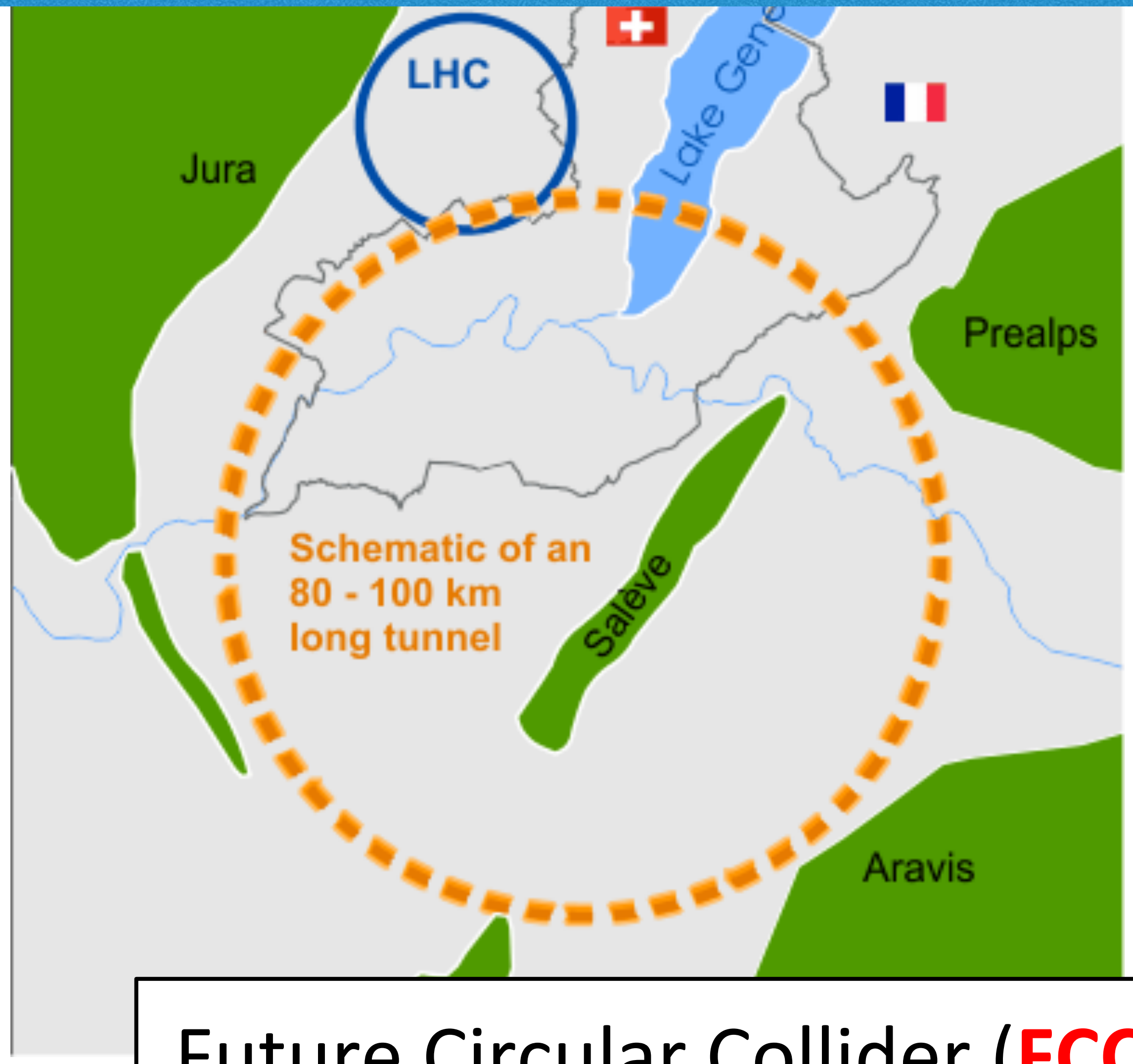
Next run: 300 fb$^{-1}$ (15 million Higgs particles)

HL-LHC: 3000-4000 fb$^{-1}$

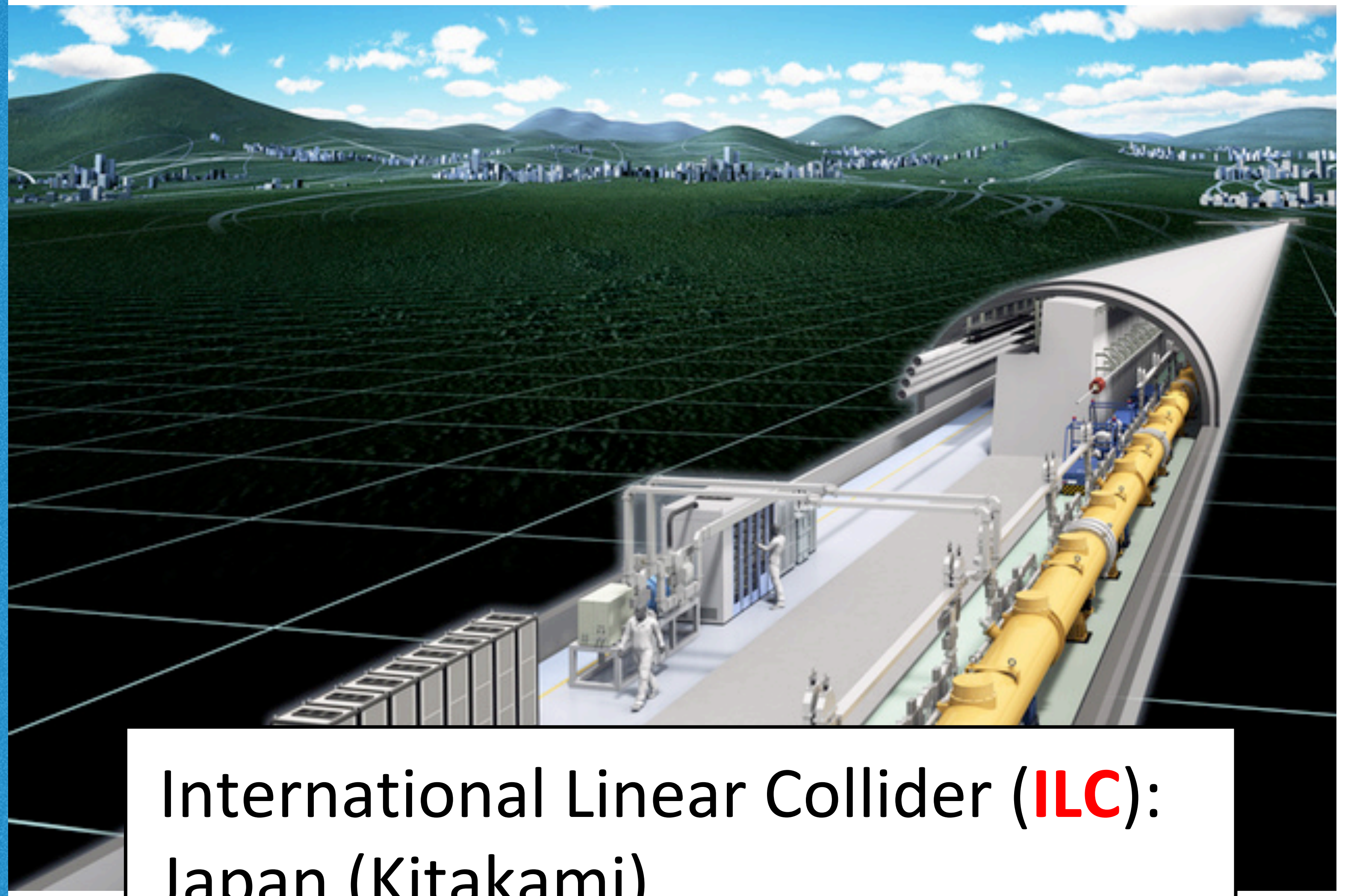
# New high-energy collider projects



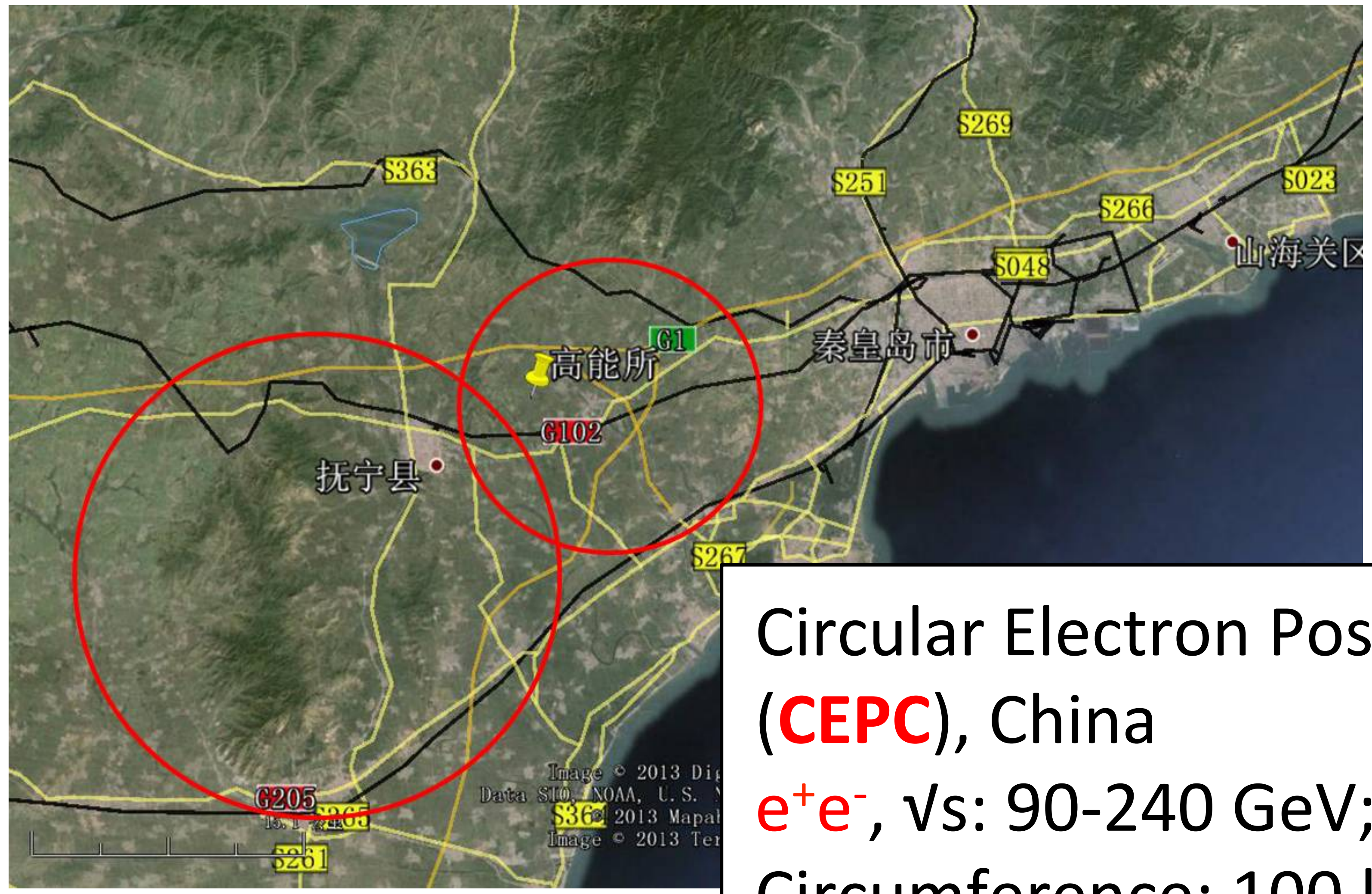

Compact Linear Collider (**CLIC**): CERN
$e^+e^-$, $\sqrt{s}$: 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km




Future Circular Collider (**FCC-ee**): CERN
$e^+e^-$, $\sqrt{s}$: 90 - 350 (365) GeV; FCC-hh pp
Circumference: 97.75 km

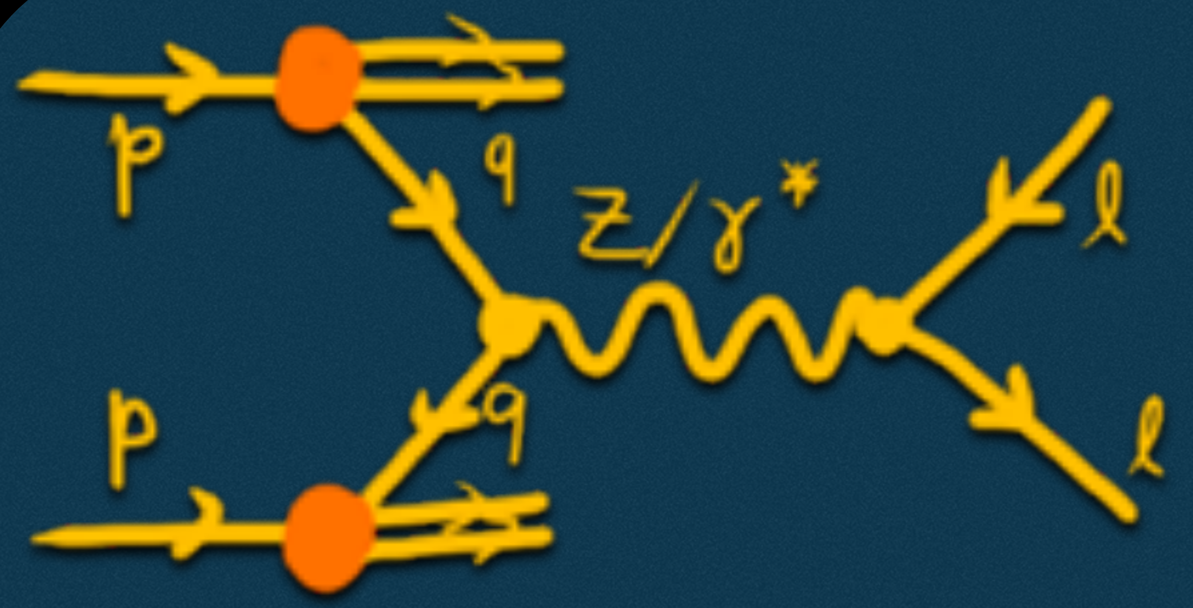


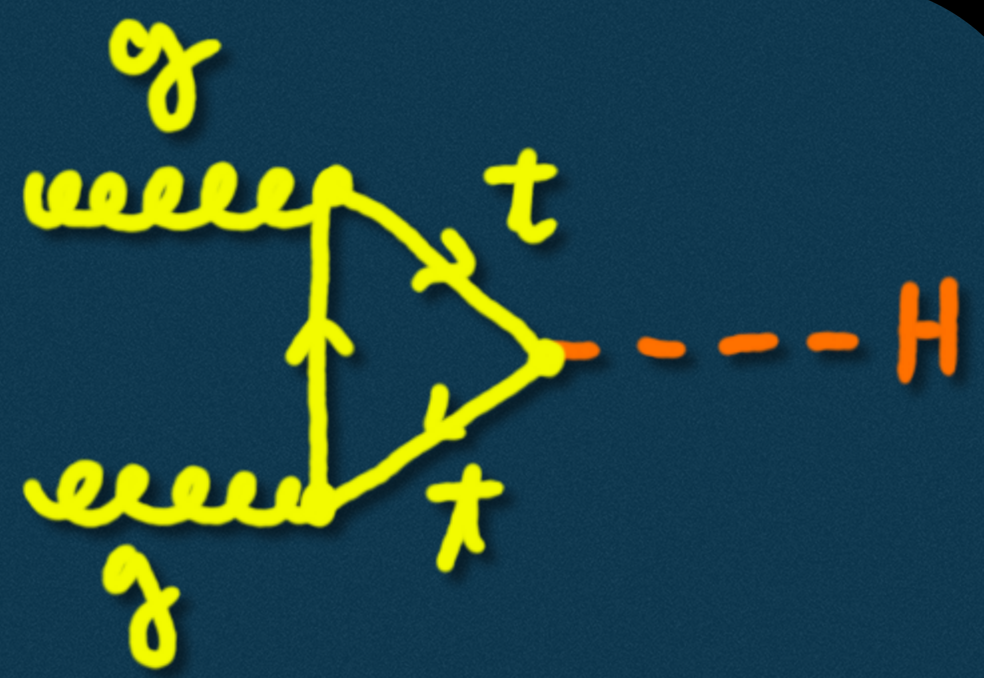
International Linear Collider (**ILC**):
Japan (Kitakami)
$e^+e^-$, $\sqrt{s}$: 250 – 500 GeV (1 TeV)
Length: 17 km, 31 km (50 km)




Circular Electron Positron Collider
(**CEPC**), China
$e^+e^-$, $\sqrt{s}$: 90-240 GeV; SPPC pp,
Circumference: 100 km

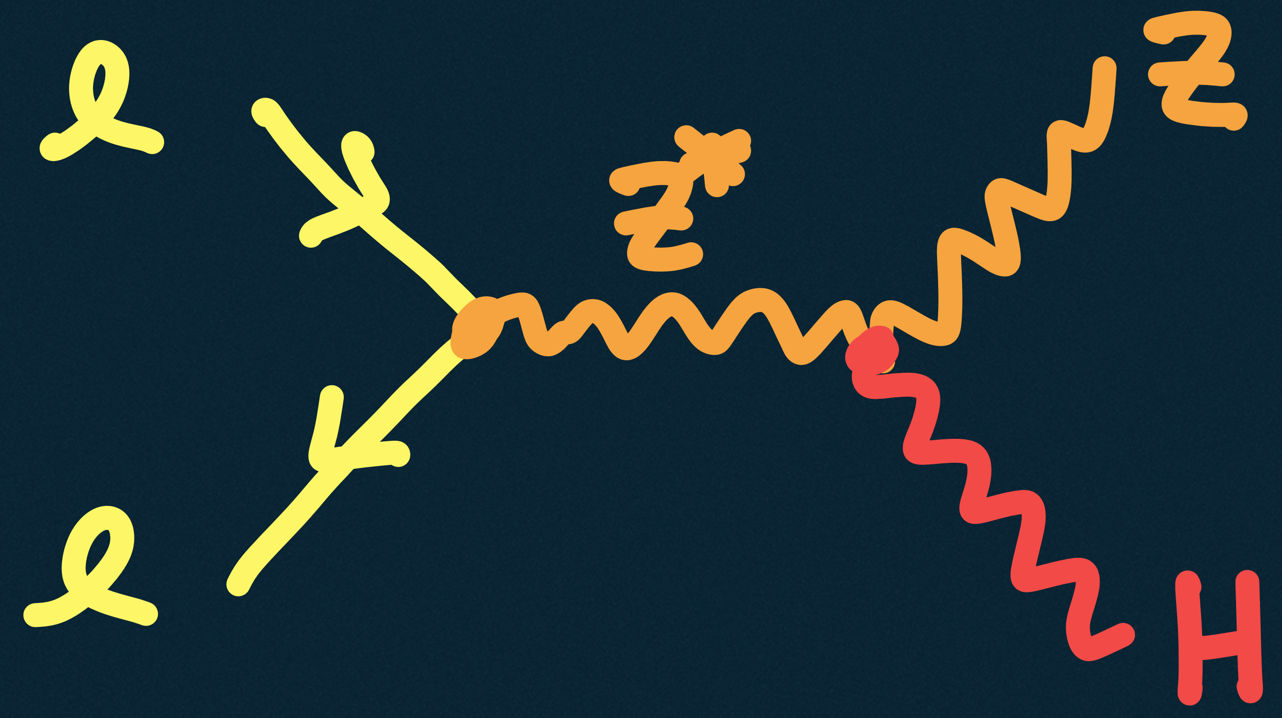
# Hadron versus lepton colliders




1. Proton are compound objects
   - Initial state unknown (particle and momentum)
   - Limits achievable precision
2. High rates of QCD background

   S/B ~ $10^{-10}$
   - Complex triggers
   - High levels of radiation
     - Detector design focus on radiation hardness of many sub-detectors
3. Very high-energy circular colliders feasible




1. Electrons are point-like particles
   - Initial state well-defined (particle, energy, polarization?)
   - High-precision measurements
2. Clean experimental environment S/B ~ $10^{-3}$
   - No (less) need for triggers
   - Lower levels of radiation
3. Very high-energies require linear colliders

# European Strategy for Particle Physics, 2020

https://cds.cern.ch/record/2720131?ln=en

An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting- edge technology:

- the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high- temperature superconductors;

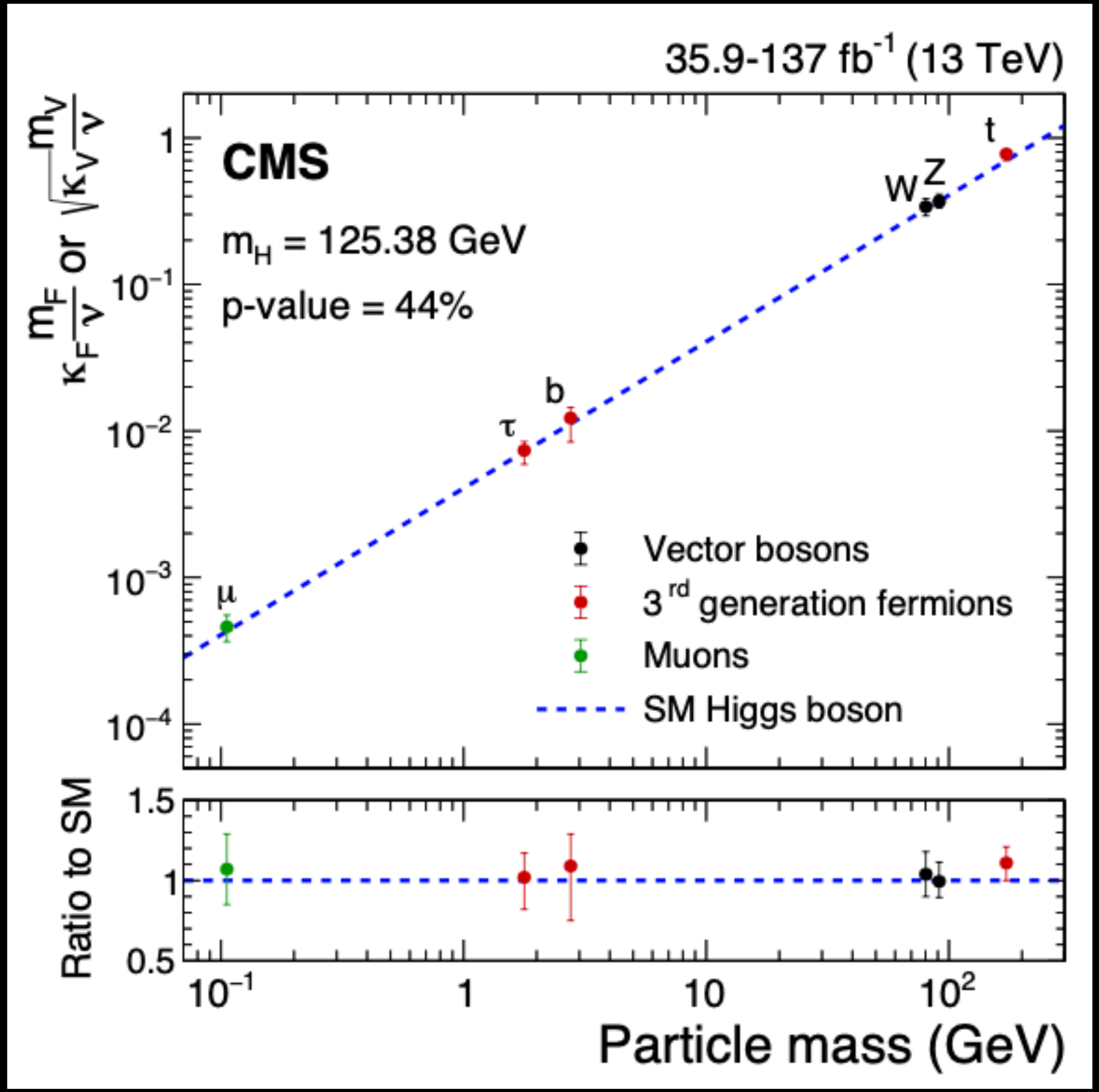
- Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

# What we know about the Higgs

- Gives mass to the **W** and **Z** bosons
- Gives mass to 3rd **generation fermions** via Yukawa interaction
- Evidence it couples to the 2nd **generation fermions** as expected
- Has **spin** 0
- Not composite (down to $10^{-19}$ m)

JHEP01(2021)148



# Higgs as a special probe

$$\mathscr{L}_{Higgs} = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi^\dagger \phi) - \bar{\psi}_L \Gamma \psi_R \phi - \bar{\psi}_R \Gamma^\dagger \psi_L \phi^\dagger$$

$$V(\phi^\dagger \phi) = -\frac{m_H^2}{2}\phi^\dagger \phi + \frac{1}{2}\lambda(\phi^\dagger \phi)^2$$

$$\lambda = \frac{m_H^2}{2v^2}$$

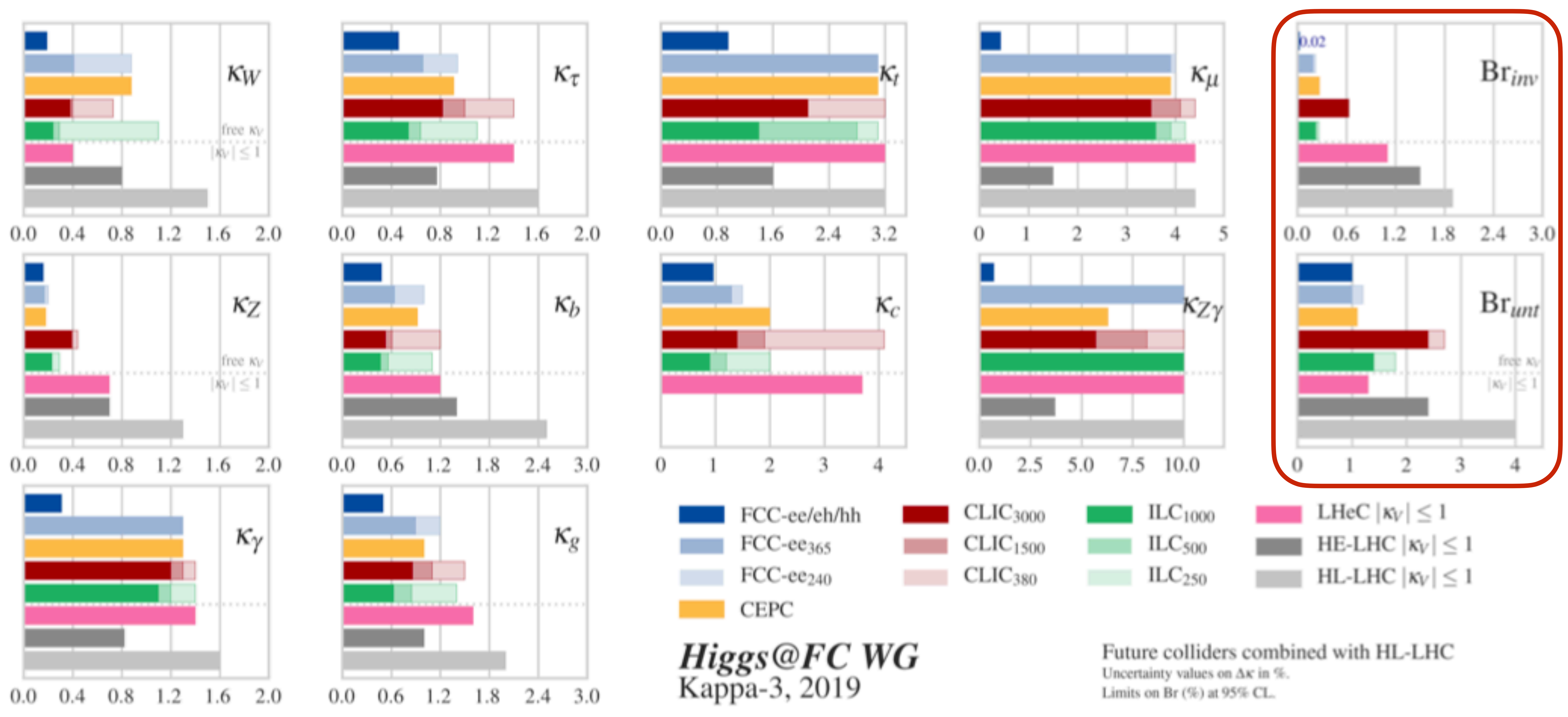
- **Measure Higgs properties with highest precision**
  - Couplings fixed by masses, yukawa hierarchy?
    - Does it couple to the lighter fermions?
  - $\lambda$ determines shape and evolution of the Higgs potential → cosmological implications
  - Is it a pure scalar or does it have a CP structure?
  - What stabilizes its mass much below the Planck scale?
  - New dark states? → Portal to new physics beyond SM
  - Search for rare processes, through high-accuracy studies of SM cross sections

**$e^+e^-$ colliders offer advantages due to the potentially high accuracy of measurements**

# Higgs coupling measurement at future colliders

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM}\kappa_i^2 \cdot \Gamma_f^{SM}\kappa_f^2}{\Gamma_H^{SM}\kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

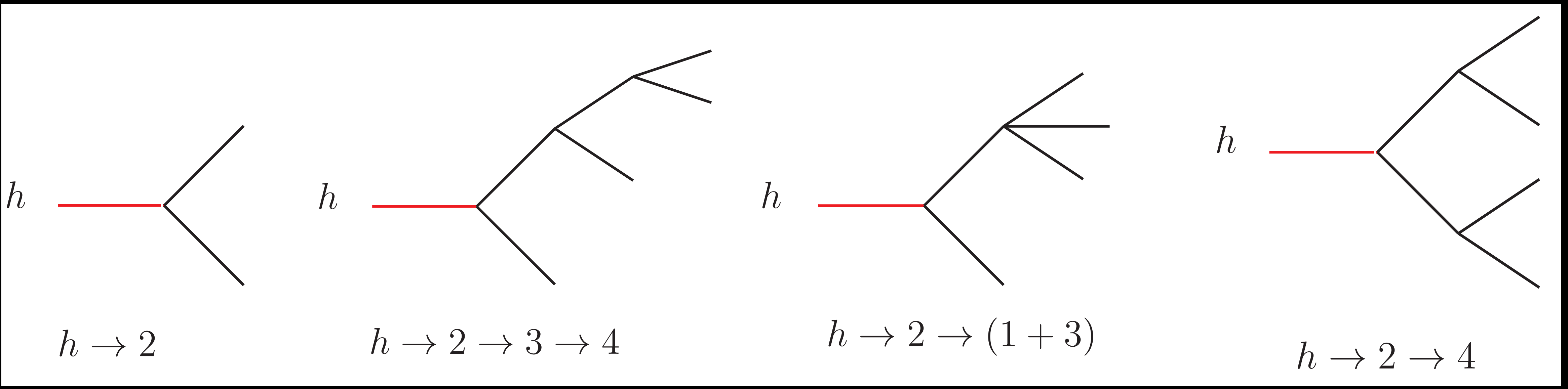
95% CL limits



# BSM Physics through Exotic Higgs Decays

**General search for BSM**

**$e^+e^-$ collider better than HL-LHC for MET+hadronic activity final states**





Z. Liu, H. Zhang, LT Wang, 1612.09284

# Higgs Self Coupling - $\lambda_{HHH}$

**A major goal of HL-LHC: Measurements of Higgs pairs production**

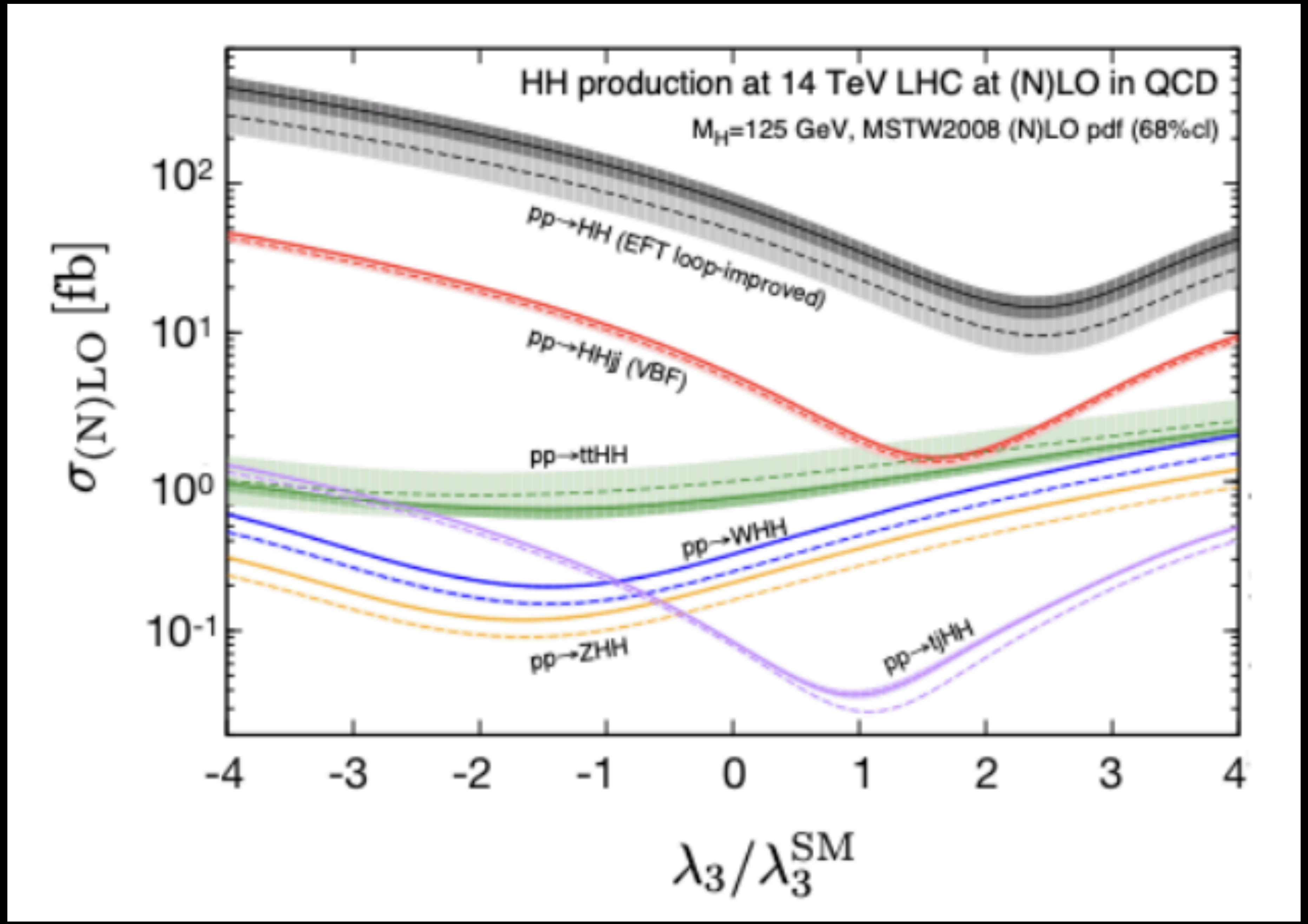

**Extremely small cross section at LHC: σ ~ 41 fb ± 11%**

| HH | Branching ratio | Total yield (3000 fb$^{-1}$) |
|---|---|---|
| bb + bb | 33% | 40,000 |
| bb+WW | 25% | 31,000 |
| bb + ττ | 7.3% | 8,900 |
| ZZ + bb | 3.1% | 3,800 |
| WW + ττ | 2.7% | 3,300 |
| ZZ+WW | 1.1% | 1,300 |
| γγ + bb | 0.26% | 320 |
| γγ + γγ | 0.0010% | 1.2 |

**Requires full HL-LHC luminosity to reach SM sensitivity**

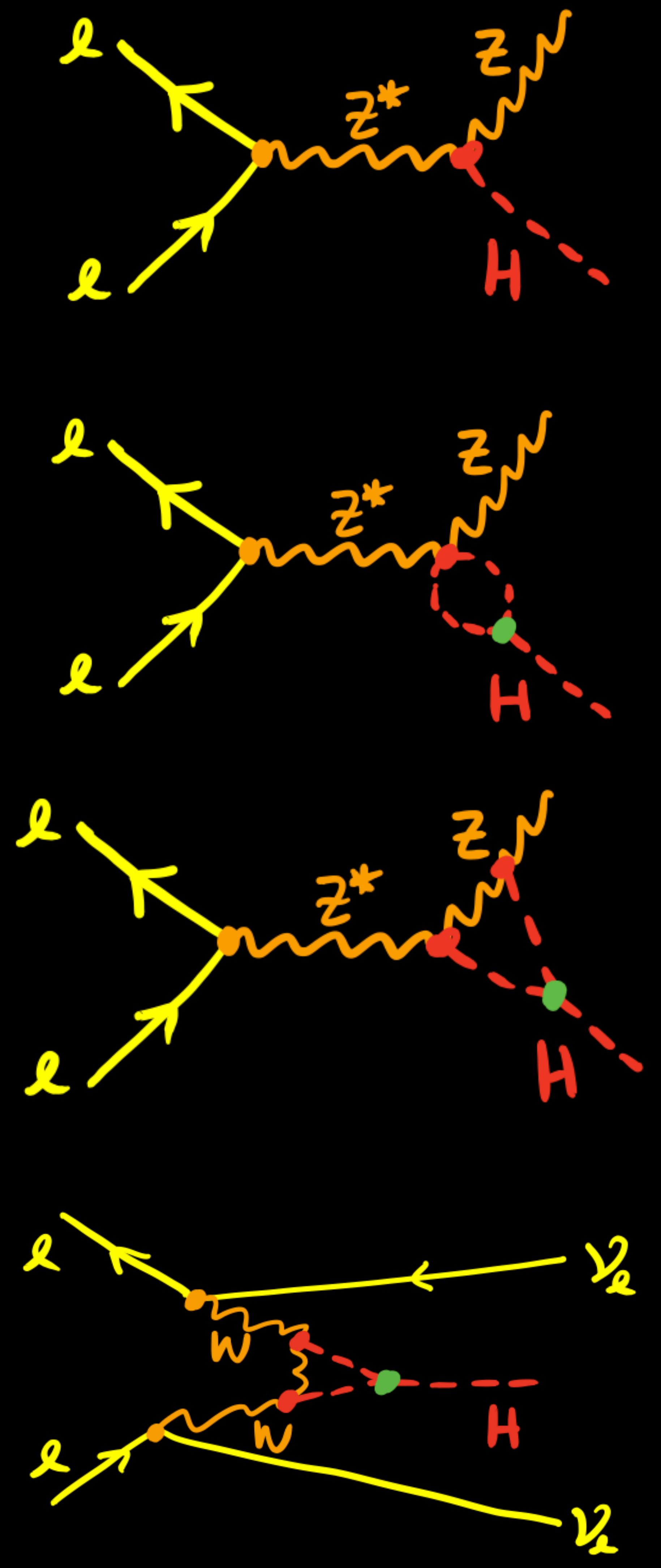
**Need to combine all channels**

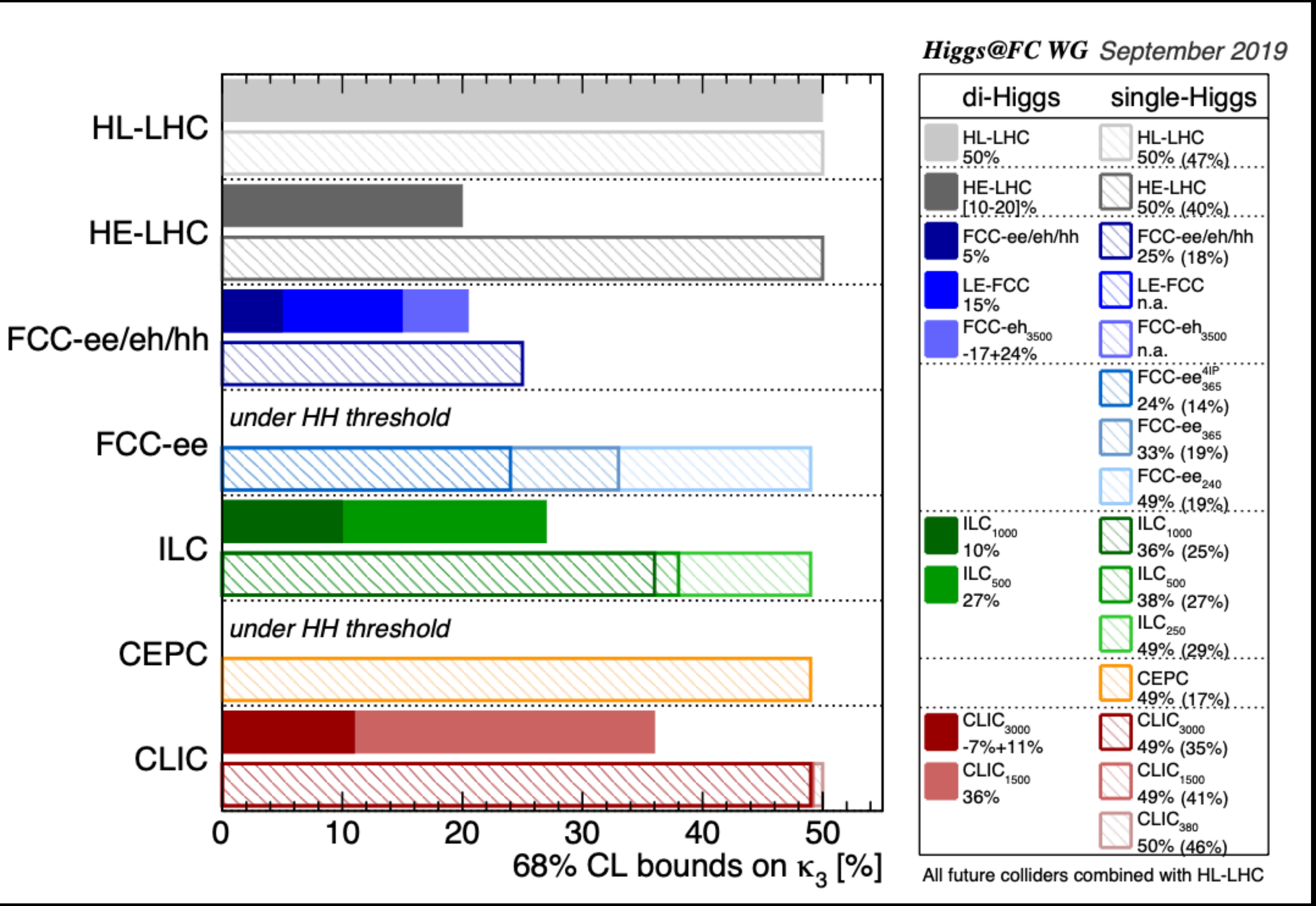
**Expected precision: 50%**



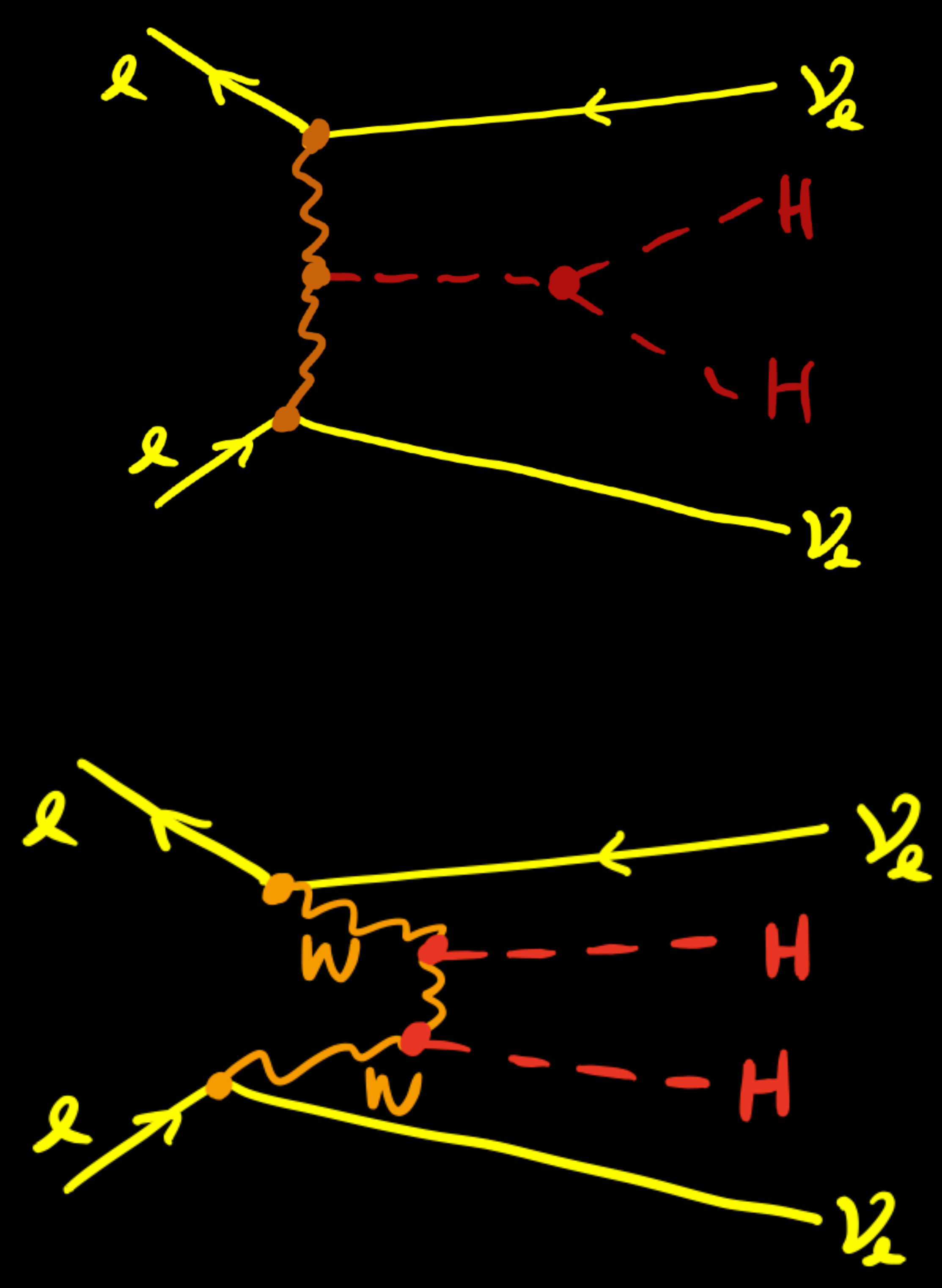
# Higgs self-coupling at lepton colliders

## Global effective-field-theory analysis can assess Higgs trilinear self-coupling




**Direct production at ILC and CLIC most important**



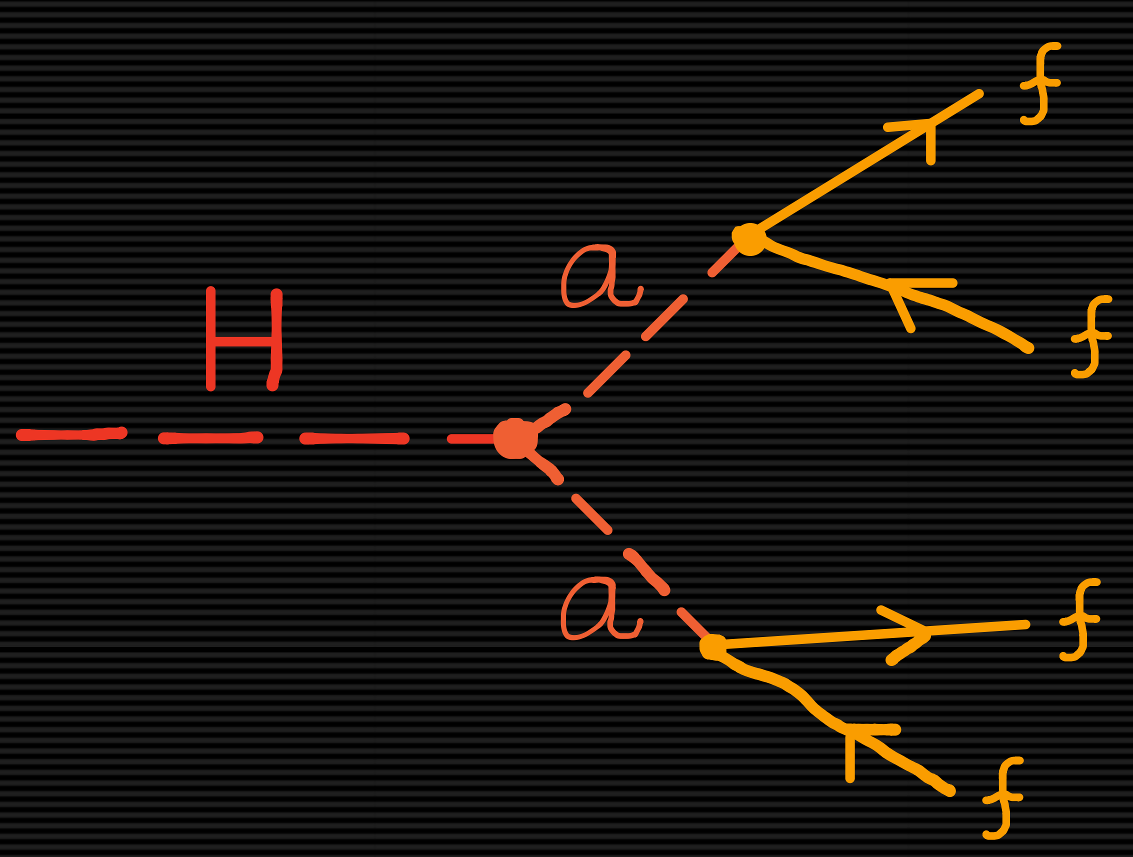
# A DARK OR HIDDEN SECTOR AS A POSSIBLE SOLUTION

**Dark Sector in particle physics has recently become very attractive**

Can solve **Dark Matter** and **Electroweak Phase Transition** problems

- **Dark Sector particles interact very weakly with the SM particles and hence could have evaded discovery so far**
  - **Higgs boson can play "portal" role mediating the interactions between the two worlds**
  - **Other SM "portal mediators": Dark Photon, $A\mu$, $Z_D$, Axion, a, Sterile Neutrino, N**

mixing of the hidden-sector field with other SM "portal" mediators





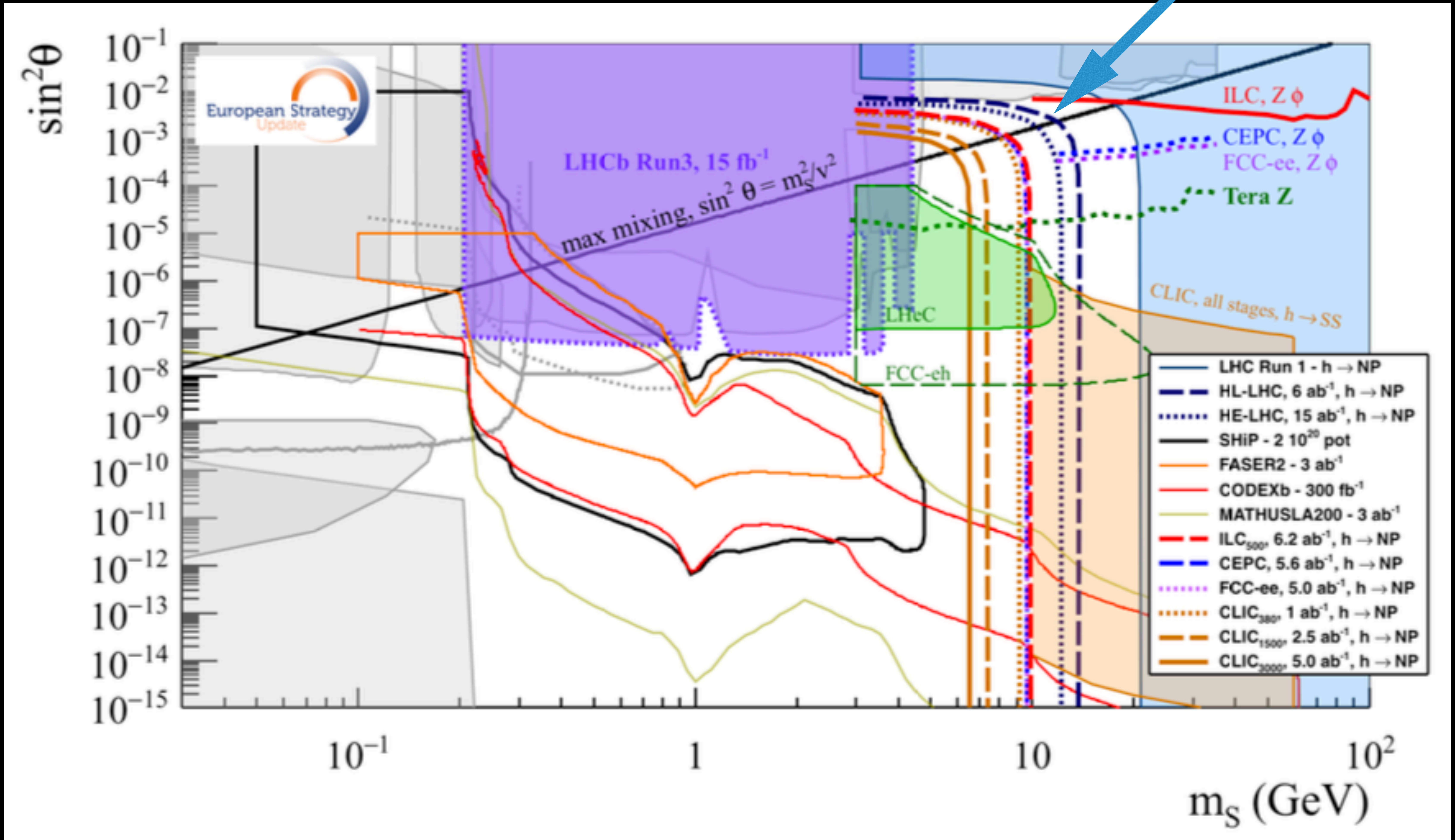
| Portal | Coupling |
|---|---|
| Dark Photon, $A'_\mu$ | $-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$ |
| Dark Higgs, $S$ | $(\mu S + \lambda S^2) H^\dagger H$ |
| Axion, $a$ | $\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\gamma^5\psi$ |
| Sterile Neutrino, $N$ | $y_N LHN$ |

# Scalar or Higgs portal

New scalar can:

- Generate the baryon asymmetry of the Universe
- Mediate between SM particles and light DM
- Address the Higgs fine-tuning problem

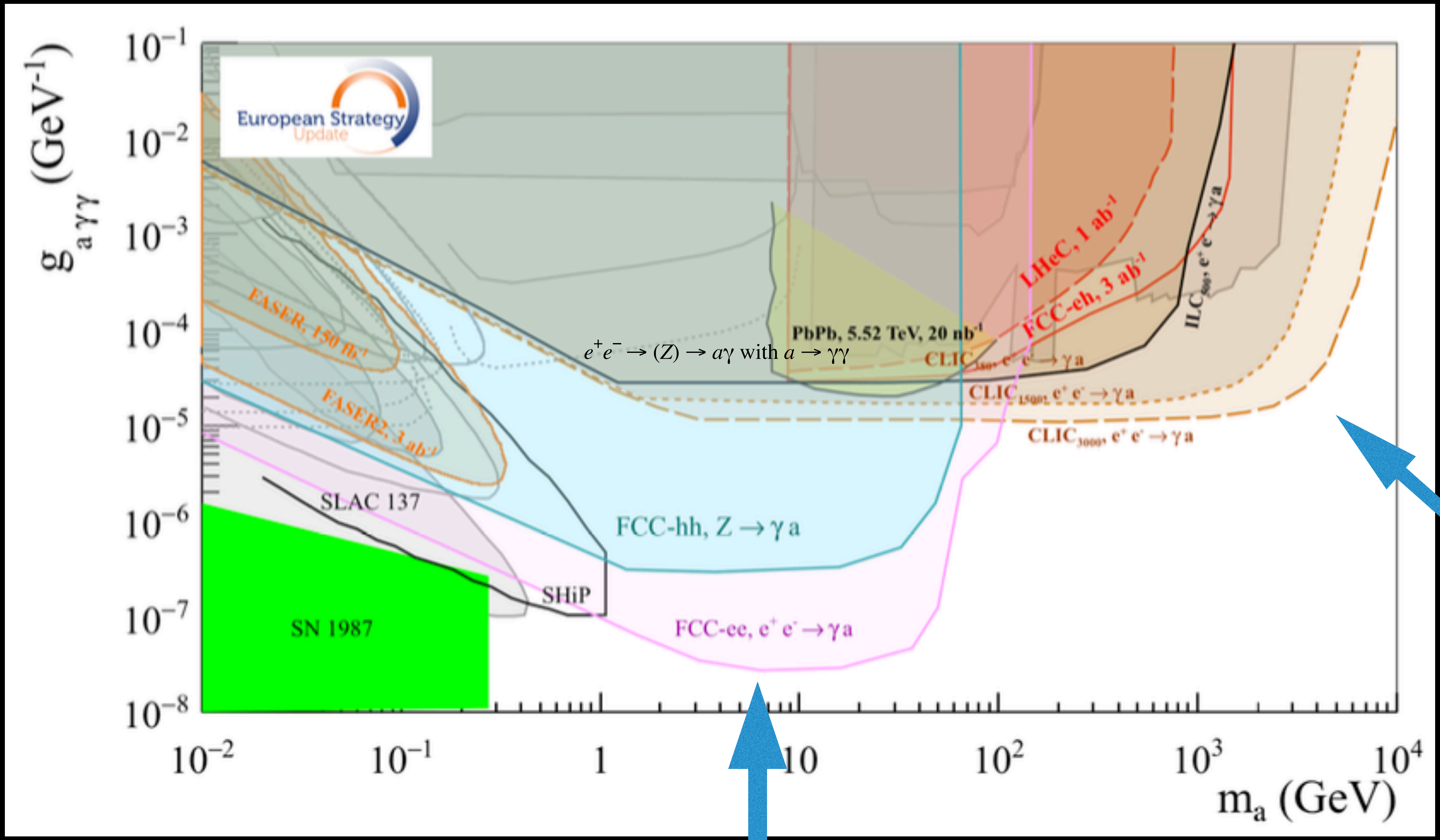
HL-LHC



# Axion-Like Particles

QCD axions are a central idea in particle physics to solve the strong CP problem

ALPs: can act as mediators between light DM and SM particles

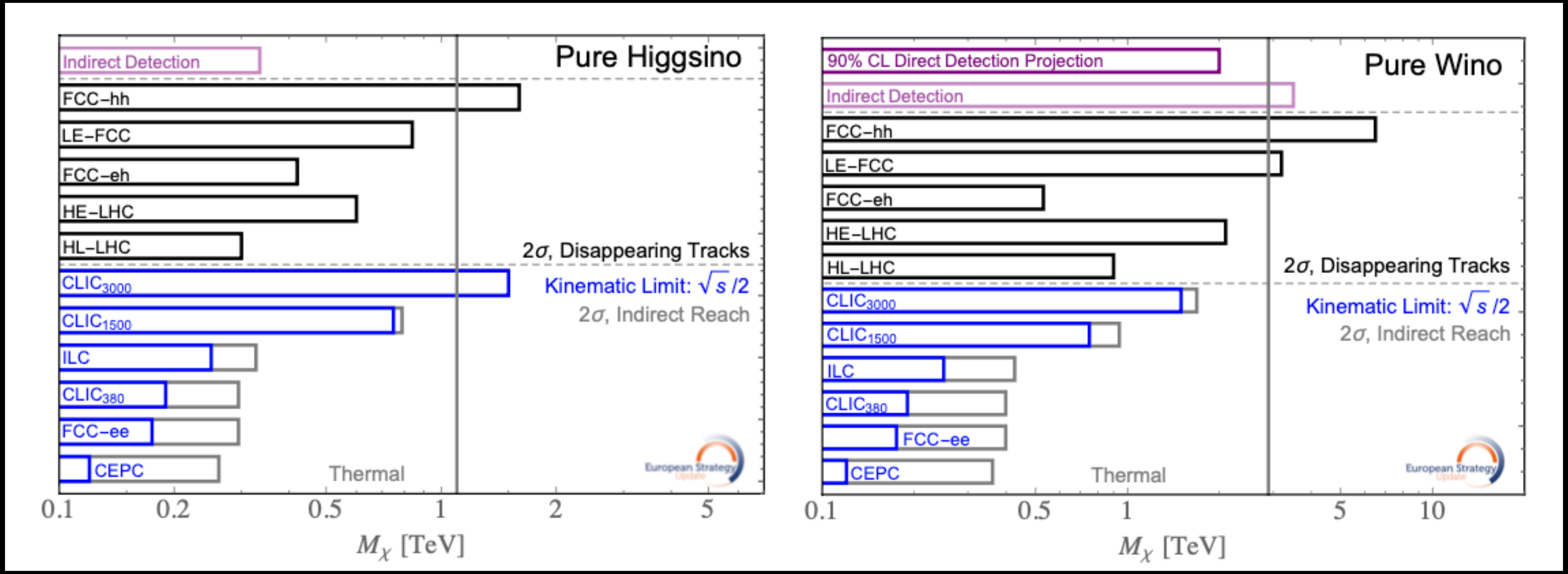



$e^+e^- \to (Z) \to a\gamma,\ a \to \gamma\gamma$

ALPs higher masses:
Linear collider

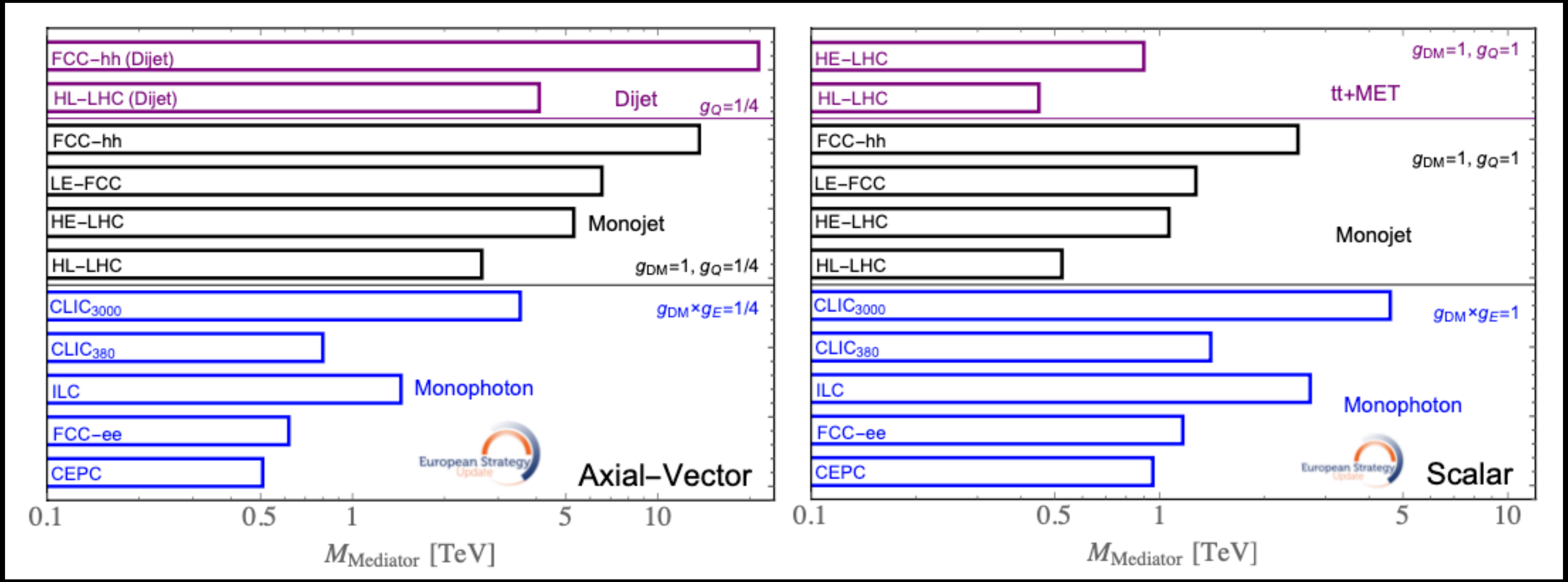
Circular collider at Z pole

# Dark Matter




## Higgsino and Wino DM

**FCC-hh can conclusively test the hypothesis of thermal DM for both scenarios**




## Simplified DM Models

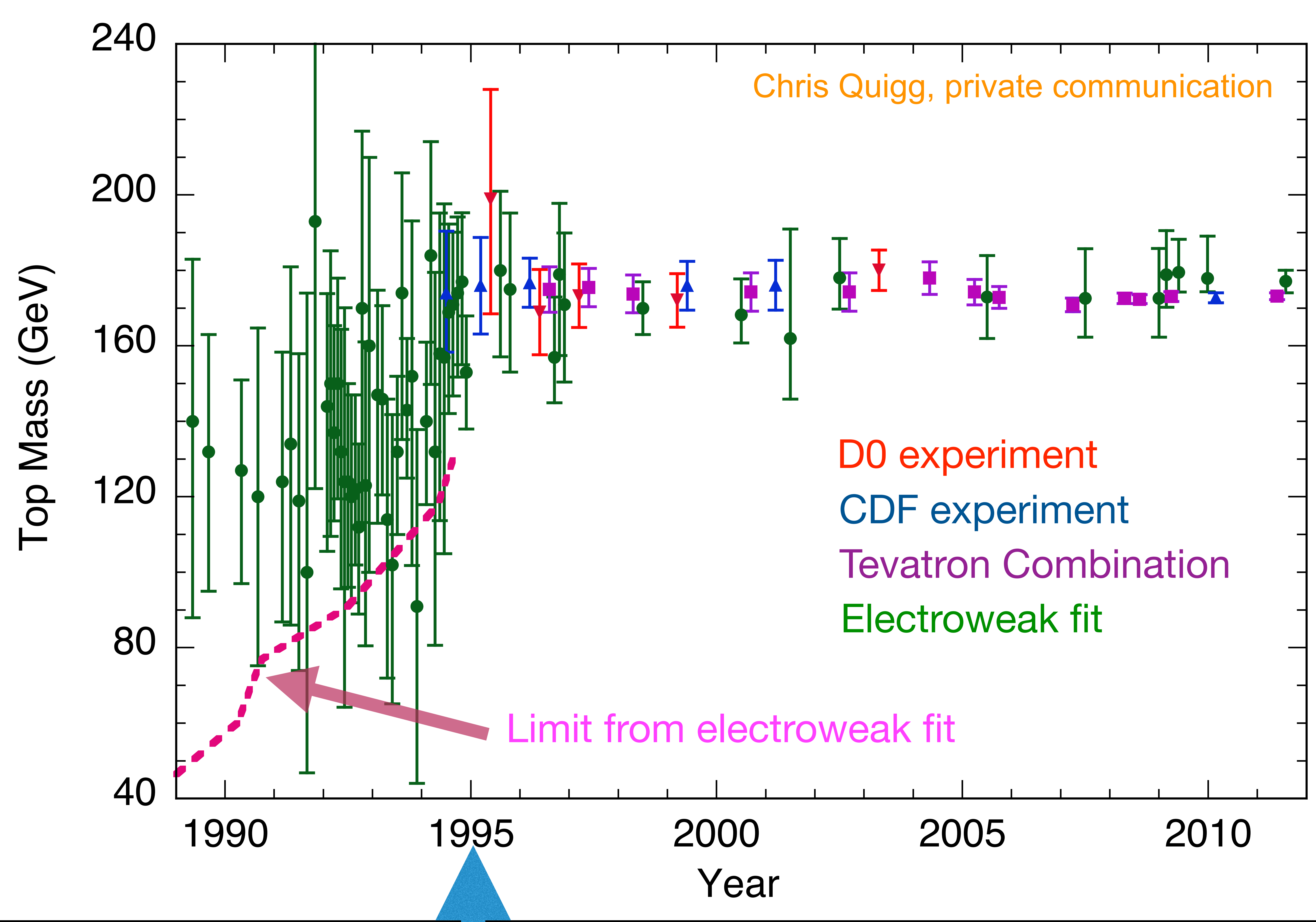
**DM particle + mediator**

strongly dependent on the choice of couplings

After the Higgs boson discovery, no other new physics found
Need to also pursue outstanding precision

**- PRECISION physics can play a key role -**

# Top Mass Prediction from Precision Electroweak data



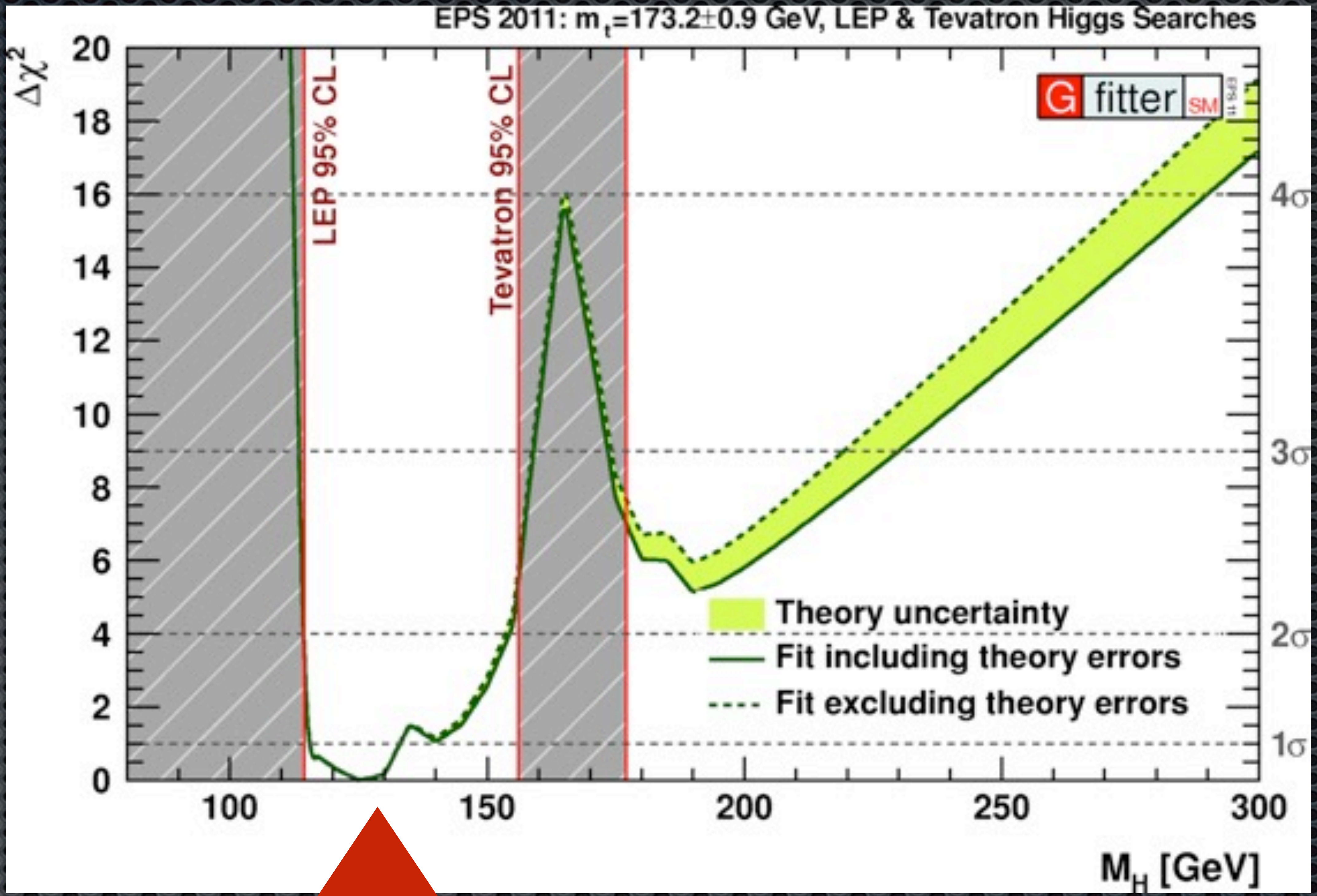

**$M_{top}$ = 175 —> 173 GeV**

**World average:**
**$m_{top}$ = 173.1 ± 0.6 GeV (0.35%)**

**Top discovery at Tevatron**

# Overnight update

- **Updated with EPS'01 results**
  - Excludes direct searches from ATLAS and CMS from EPS




**Standard Fit**

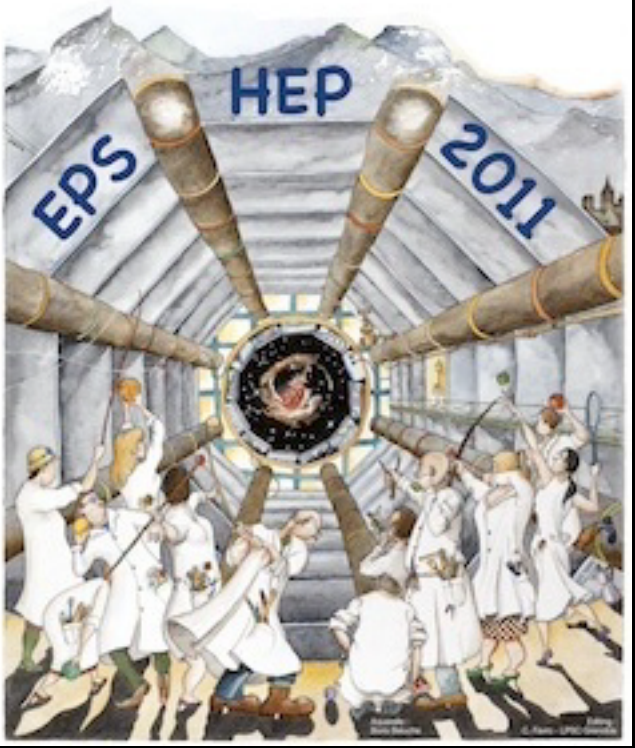
$m_H$ (minimum)= 94.5 GeV, Range $m_H$ = [71, 124], $m_H$ < 166.5 GeV @ 95%

**Complete Fit**

$\boxed{m_H \text{ (minimum)= 125.2 GeV,}}$ Range $m_H$ = [116, 133], $m_H$ < 153.9 GeV @ 95%

Thanks to Matthias Schott from the GFitter group

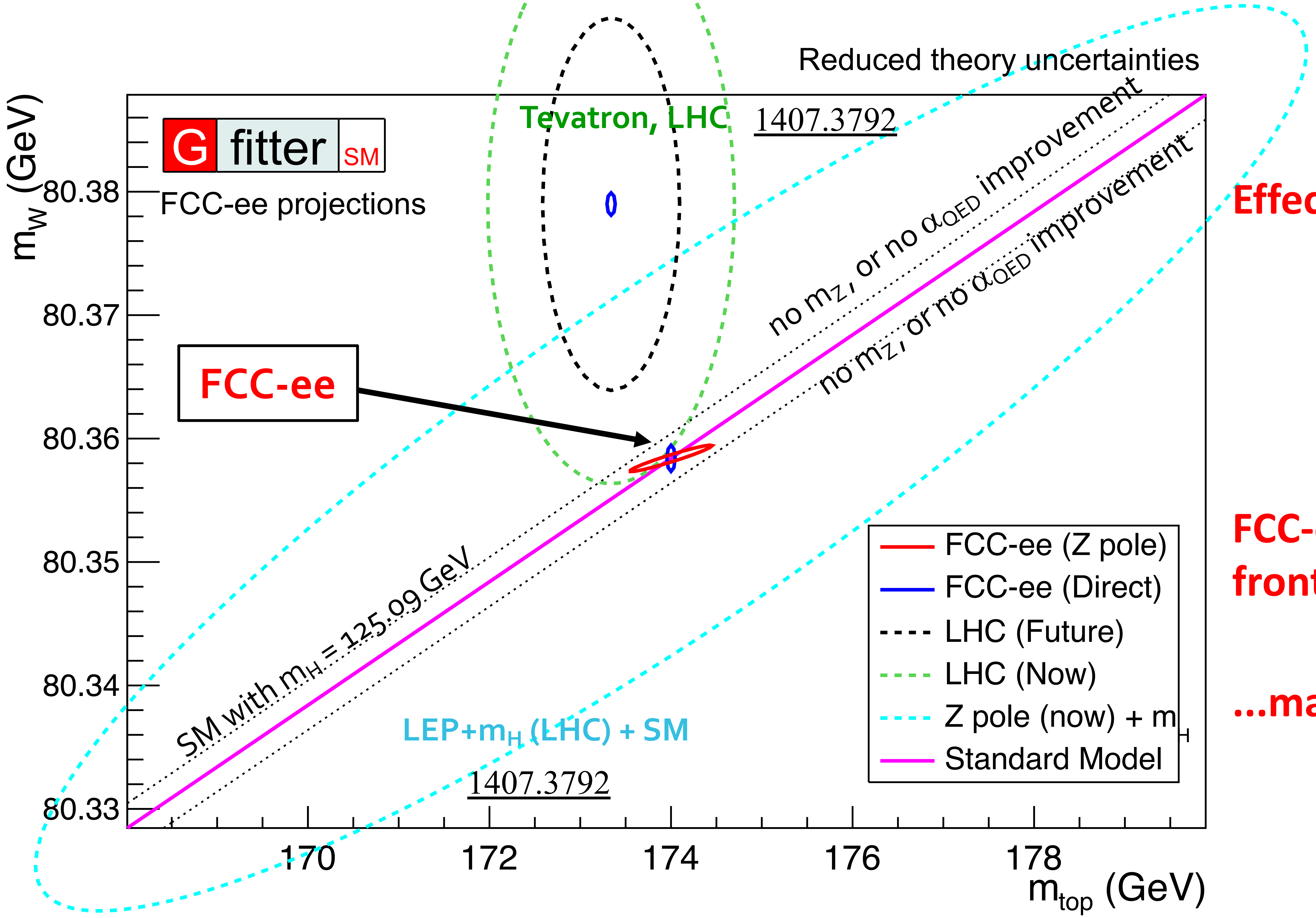
WARNING: Old Slide




July 21-27

PANIC 2011, July 28, 2011

# Combination of electroweak measurements




**Effect of BSM physics**

**Modify EW observables through quantum effects (*cf* top & H @ LEP)**

**Blue (direct) & red (Z pole) ellipses may not overlap**

**Standard Model may not fit**

**FCC-ee provides improvement from all fronts…**

**e.g. $m_Z$, $\alpha_{QED}$, $m_{top}$, …**

**…maximizing sensitivity to BSM physics**

- Precision of theory predictions needs to improve for full sensitivity to new physics
  - higher order calculations needed

# Final remarks

The standard Model is well established but many questions remain answered

LHC to provide still 20-30x more data
Hence, small discrepancies can still turn into discoveries

**Higgs self coupling measurement at HL-LHC is a major milestone**

**Planning for the next future accelerators has started**

Expect new exciting sensitivity for BSM physics and potential discoveries
**Higgs will continue to play an essential role**

**Both a future electron and hadron collider could play a significant role**

# Extra Slides

# ATLAS Diboson Searches - 95% CL Exclusion Limits

*Status: June 2021*

***ATLAS*** Preliminary

$\mathcal{L} = (36.1 - 139)\ \text{fb}^{-1}$ $\sqrt{s} = 13$ TeV

| | Model | Channel† | Strategy* | Limit | Reference |
|---|---|---|---|---|---|
| *Extra dimensions* | Bulk RS ($k\pi r_c = 35$, $\Lambda_R = 3$ TeV) | $R \to WW, ZZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$ | resolved, boosted | 0.3-3.2 TeV | Eur. Phys. J. C 80 (2020) 1165 |
| | Bulk RS ($k\pi r_c = 35$, $\Lambda_R = 3$ TeV) | $R \to WW, ZZ \to qqqq$ | boosted | 1.3-3.0 TeV | JHEP 06 (2020) 042 |
| | RS1 ($k/\overline{M}_{Pl} = 0.01$) | $G_{KK} \to \gamma\gamma$ | resolved | 0.5-2.2 TeV | arXiv:2102.13405 |
| | RS1 ($k/\overline{M}_{Pl} = 0.05$) | $G_{KK} \to \gamma\gamma$ | resolved | 0.5-3.9 TeV | arXiv:2102.13405 |
| | RS1 ($k/\overline{M}_{Pl} = 0.1$) | $G_{KK} \to \gamma\gamma$ | resolved | 0.5-4.5 TeV | arXiv:2102.13405 |
| | Bulk RS ($k/\overline{M}_{Pl} = 0.5$) | $G_{KK} \to WW \to e\nu\mu\nu$ | resolved | 0.2-0.75 TeV | Eur. Phys. J. C 78 (2018) 24 |
| | Bulk RS ($k/\overline{M}_{Pl} = 1.0$) | $G_{KK} \to ZZ \to \ell\ell\ell'\ell', \nu\nu\ell\ell$ | resolved | 0.6-1.75 TeV | Eur. Phys. J. C 81 (2021) 332 |
| | Bulk RS ($k/\overline{M}_{Pl} = 1.0$) | $G_{KK} \to WW \to e\nu\mu\nu$ | resolved | 0.2-1.1 TeV | Eur. Phys. J. C 78 (2018) 24 |
| | Bulk RS ($k/\overline{M}_{Pl} = 1.0$) | $G_{KK} \to WW, ZZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$ | resolved, boosted | 0.3-2.0 TeV | Eur. Phys. J. C 80 (2020) 1165 |
| | Bulk RS ($k/\overline{M}_{Pl} = 1.0$) | $G_{KK} \to WW, ZZ \to qqqq$ | boosted | 1.3-1.8 TeV | JHEP 06 (2020) 042 |
| *Gauge bosons* | HVT ($g_F = -0.55$, $g_H = -0.56$) | $W' \to WZ \to \ell\nu\ell'\ell'$ | resolved | 0.25-2.26 TeV | Phys. Lett. B 787 (2018) 68 |
| | HVT ($g_F = -0.55$, $g_H = -0.56$) | $W' \to WZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$ | resolved, boosted | 0.3-3.9 TeV | Eur. Phys. J. C 80 (2020) 1165 |
| | HVT ($g_F = -0.55$, $g_H = -0.56$) | $W' \to WH \to \ell\nu bb$ | resolved, boosted | 0.4-2.95 TeV | ATLAS-CONF-2021-026 |
| | HVT ($g_F = -0.55$, $g_H = -0.56$) | $W' \to WZ \to qqqq$ | boosted | 1.3-3.4 TeV | JHEP 06 (2020) 042 |
| | HVT ($g_F = -0.55$, $g_H = -0.56$) | $W' \to WH \to qqbb$ | boosted | 1.5-2.9 TeV | Phys. Rev. D 102 (2020) 112008 |
| | HVT ($g_F = -0.55$, $g_H = -0.56$) | $Z' \to WW \to e\nu\mu\nu$ | resolved | 0.2-1.3 TeV | Eur. Phys. J. C 78 (2018) 24 |
| | HVT ($g_F = -0.55$, $g_H = -0.56$) | $Z' \to WW \to \ell\nu qq$ | resolved, boosted | 0.3-3.5 TeV | Eur. Phys. J. C 80 (2020) 1165 |
| | HVT ($g_F = -0.55$, $g_H = -0.56$) | $Z' \to ZH \to \nu\nu bb, \ell\ell bb$ | resolved, boosted | 0.3-2.9 TeV | ATLAS-CONF-2020-043 |
| | HVT ($g_F = -0.55$, $g_H = -0.56$) | $Z' \to WW \to qqqq$ | boosted | 1.3-2.9 TeV | JHEP 06 (2020) 042 |
| | HVT ($g_F = -0.55$, $g_H = -0.56$) | $Z' \to ZH \to qqbb$ | boosted | 1.5-2.2 TeV | Phys. Rev. D 102 (2020) 112008 |
| | HVT ($g_F = 0.14$, $g_H = -2.9$) | $W' \to WZ \to \ell\nu\ell'\ell'$ | resolved | 0.8-2.46 TeV | Phys. Lett. B 787 (2018) 68 |
| | HVT ($g_F = 0.14$, $g_H = -2.9$) | $W' \to WZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$ | resolved, boosted | 0.8-4.3 TeV | Eur. Phys. J. C 80 (2020) 1165 |
| | HVT ($g_F = 0.14$, $g_H = -2.9$) | $W' \to WH \to \ell\nu bb$ | resolved, boosted | 0.8-3.15 TeV | ATLAS-CONF-2021-026 |
| | HVT ($g_F = 0.14$, $g_H = -2.9$) | $W' \to WZ \to qqqq$ | boosted | 1.3-3.6 TeV | JHEP 06 (2020) 042 |
| | HVT ($g_F = 0.14$, $g_H = -2.9$) | $W' \to WH \to qqbb$ | boosted | 1.5-3.2 TeV | Phys. Rev. D 102 (2020) 112008 |
| | HVT ($g_F = 0.14$, $g_H = -2.9$) | $Z' \to WW \to \ell\nu qq$ | resolved, boosted | 0.8-3.9 TeV | Eur. Phys. J. C 80 (2020) 1165 |
| | HVT ($g_F = 0.14$, $g_H = -2.9$) | $Z' \to ZH \to \nu\nu bb, \ell\ell bb$ | resolved, boosted | 0.8-3.2 TeV | ATLAS-CONF-2020-043 |
| | HVT ($g_F = 0.14$, $g_H = -2.9$) | $Z' \to WW \to qqqq$ | boosted | 1.3-3.1 TeV | JHEP 06 (2020) 042 |
| | HVT ($g_F = 0.14$, $g_H = -2.9$) | $Z' \to ZH \to qqbb$ | boosted | 1.5-2.65 TeV | Phys. Rev. D 102 (2020) 112008 |

0.2 0.4 0.6 0.8 1 2 3 4 5

**Excluded mass range [TeV]**

$\sqrt{s} = 13$ TeV, $\mathcal{L} = 36.1\ \text{fb}^{-1}$ $\sqrt{s} = 13$ TeV, $\mathcal{L} = 139\ \text{fb}^{-1}$

*small-radius (large-radius) jets are used in resolved (boosted) events

†with $\ell = \mu, e$

# ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

*Status: July 2021*

**ATLAS** Preliminary

$\int \mathcal{L}\, dt = (3.6 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

| | Model | $\ell, \gamma$ | Jets† | $E_T^{miss}$ | $\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$ | Limit | | Reference |
|---|---|---|---|---|---|---|---|---|
| Extra dimensions | ADD $G_{KK} + g/q$ | $0\ e, \mu, \tau, \gamma$ | 1 – 4 j | Yes | 139 | $M_D$ 11.2 TeV | $n = 2$ | 2102.10874 |
| | ADD non-resonant $\gamma\gamma$ | $2\ \gamma$ | – | – | 36.7 | $M_S$ 8.6 TeV | $n = 3$ HLZ NLO | 1707.04147 |
| | ADD QBH | – | 2 j | – | 37.0 | $M_{th}$ 8.9 TeV | $n = 6$ | 1703.09127 |
| | ADD BH multijet | – | ≥3 j | – | 3.6 | $M_{th}$ 9.55 TeV | $n = 6$, $M_D = 3$ TeV, rot BH | 1512.02586 |
| | RS1 $G_{KK} \to \gamma\gamma$ | $2\ \gamma$ | – | – | 139 | $G_{KK}$ mass 4.5 TeV | $k/\overline{M}_{Pl} = 0.1$ | 2102.13405 |
| | Bulk RS $G_{KK} \to WW/ZZ$ | multi-channel | | | 36.1 | $G_{KK}$ mass 2.3 TeV | $k/\overline{M}_{Pl} = 1.0$ | 1808.02380 |
| | Bulk RS $G_{KK} \to WW \to \ell\nu qq$ | $1\ e, \mu$ | 2 j / 1 J | Yes | 139 | $G_{KK}$ mass 2.0 TeV | $k/\overline{M}_{Pl} = 1.0$ | 2004.14636 |
| | Bulk RS $g_{KK} \to tt$ | $1\ e, \mu$ | ≥1 b, ≥1J/2j | Yes | 36.1 | $g_{KK}$ mass 3.8 TeV | $\Gamma/m = 15\%$ | 1804.10823 |
| | 2UED / RPP | $1\ e, \mu$ | ≥2 b, ≥3 j | Yes | 36.1 | KK mass 1.8 TeV | Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$ | 1803.09678 |
| Gauge bosons | SSM $Z' \to \ell\ell$ | $2\ e, \mu$ | – | – | 139 | $Z'$ mass 5.1 TeV | | 1903.06248 |
| | SSM $Z' \to \tau\tau$ | $2\ \tau$ | – | – | 36.1 | $Z'$ mass 2.42 TeV | | 1709.07242 |
| | Leptophobic $Z' \to bb$ | – | 2 b | – | 36.1 | $Z'$ mass 2.1 TeV | | 1805.09299 |
| | Leptophobic $Z' \to tt$ | $0\ e, \mu$ | ≥1 b, ≥2 J | Yes | 139 | $Z'$ mass 4.1 TeV | $\Gamma/m = 1.2\%$ | 2005.05138 |
| | SSM $W' \to \ell\nu$ | $1\ e, \mu$ | – | Yes | 139 | $W'$ mass 6.0 TeV | | 1906.05609 |
| | SSM $W' \to \tau\nu$ | $1\ \tau$ | – | Yes | 139 | $W'$ mass 5.0 TeV | | ATLAS-CONF-2021-025 |
| | SSM $W' \to tb$ | – | ≥1 b, ≥1 J | – | 139 | $W'$ mass 4.4 TeV | | ATLAS-CONF-2021-043 |
| | HVT $W' \to WZ \to \ell\nu qq$ model B | $1\ e, \mu$ | 2 j / 1 J | Yes | 139 | $W'$ mass 4.3 TeV | $g_V = 3$ | 2004.14636 |
| | HVT $Z' \to ZH$ model B | 0-2 $e, \mu$ | 1-2 b | Yes | 139 | $Z'$ mass 3.2 TeV | $g_V = 3$ | ATLAS-CONF-2020-043 |
| | HVT $W' \to WH$ model B | $0\ e, \mu$ | ≥1 b, ≥2 J | | 139 | $W'$ mass 3.2 TeV | $g_V = 3$ | 2007.05293 |
| | LRSM $W_R \to \mu N_R$ | $2\ \mu$ | 1 J | – | 80 | $W_R$ mass 5.0 TeV | $m(N_R) = 0.5$ TeV, $g_L = g_R$ | 1904.12679 |
| CI | CI $qqqq$ | – | 2 j | – | 37.0 | $\Lambda$ 21.8 TeV | $\eta^-_{LL}$ | 1703.09127 |
| | CI $\ell\ell qq$ | $2\ e, \mu$ | – | – | 139 | $\Lambda$ 35.8 TeV | $\eta^-_{LL}$ | 2006.12946 |
| | CI $eebs$ | $2\ e$ | 1 b | – | 139 | $\Lambda$ 1.8 TeV | $g_* = 1$ | 2105.13847 |
| | CI $\mu\mu bs$ | $2\ \mu$ | 1 b | – | 139 | $\Lambda$ 2.0 TeV | $g_* = 1$ | 2105.13847 |
| | CI $tttt$ | ≥1 $e,\mu$ | ≥1 b, ≥1 j | Yes | 36.1 | $\Lambda$ 2.57 TeV | $\lvert C_{4t}\rvert = 4\pi$ | 1811.02305 |
| DM | Axial-vector med. (Dirac DM) | $0\ e, \mu, \tau, \gamma$ | 1 – 4 j | Yes | 139 | $m_{med}$ 2.1 TeV | $g_q$=0.25, $g_\chi$=1, $m(\chi)$=1 GeV | 2102.10874 |
| | Pseudo-scalar med. (Dirac DM) | $0\ e, \mu, \tau, \gamma$ | 1 – 4 j | Yes | 139 | $m_{med}$ 376 GeV | $g_q$=1, $g_\chi$=1, $m(\chi)$=1 GeV | 2102.10874 |
| | Vector med. $Z'$-2HDM (Dirac DM) | $0\ e, \mu$ | 2 b | Yes | 139 | $m_{med}$ 3.1 TeV | $\tan\beta$=1, $g_Z$=0.8, $m(\chi)$=100 GeV | ATLAS-CONF-2021-006 |
| | Pseudo-scalar med. 2HDM+a | multi-channel | | | 139 | $m_{med}$ 560 GeV | $\tan\beta$=1, $g_\chi$=1, $m(\chi)$=10 GeV | ATLAS-CONF-2021-036 |
| | Scalar reson. $\phi \to t\chi$ (Dirac DM) | 0-1 $e, \mu$ | 1 b, 0-1 J | Yes | 36.1 | $m_\phi$ 3.4 TeV | $y$=0.4, $\lambda$=0.2, $m(\chi)$=10 GeV | 1812.09743 |
| LQ | Scalar LQ 1$^{st}$ gen | $2\ e$ | ≥2 j | Yes | 139 | LQ mass 1.8 TeV | $\beta = 1$ | 2006.05872 |
| | Scalar LQ 2$^{nd}$ gen | $2\ \mu$ | ≥2 j | Yes | 139 | LQ mass 1.7 TeV | $\beta = 1$ | 2006.05872 |
| | Scalar LQ 3$^{rd}$ gen | $1\ \tau$ | 2 b | Yes | 139 | $LQ^u_3$ mass 1.2 TeV | $\mathcal{B}(LQ^u_3 \to b\tau) = 1$ | ATLAS-CONF-2021-008 |
| | Scalar LQ 3$^{rd}$ gen | $0\ e, \mu$ | ≥2 j, ≥2 b | Yes | 139 | $LQ^u_3$ mass 1.24 TeV | $\mathcal{B}(LQ^u_3 \to t\nu) = 1$ | 2004.14060 |
| | Scalar LQ 3$^{rd}$ gen | ≥2 $e, \mu$, ≥1 $\tau$ | ≥1 j, ≥1 b | – | 139 | $LQ^d_3$ mass 1.43 TeV | $\mathcal{B}(LQ^d_3 \to t\tau) = 1$ | 2101.11582 |
| | Scalar LQ 3$^{rd}$ gen | $0\ e, \mu$, ≥1 $\tau$ | 0 – 2 j, 2 b | Yes | 139 | $LQ^d_3$ mass 1.26 TeV | $\mathcal{B}(LQ^d_3 \to b\nu) = 1$ | 2101.12527 |
| Heavy quarks | VLQ $TT \to Zt + X$ | 2e/2μ/≥3e,μ | ≥1 b, ≥1 j | – | 139 | T mass 1.4 TeV | SU(2) doublet | ATLAS-CONF-2021-024 |
| | VLQ $BB \to Wt/Zb + X$ | multi-channel | | | 36.1 | B mass 1.34 TeV | SU(2) doublet | 1808.02343 |
| | VLQ $T_{5/3}T_{5/3}\vert T_{5/3} \to Wt + X$ | 2(SS)/≥3 $e,\mu$ | ≥1 b, ≥1 j | Yes | 36.1 | $T_{5/3}$ mass 1.64 TeV | $\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1 | 1807.11883 |
| | VLQ $T \to Ht/Zt$ | $1\ e, \mu$ | ≥1 b, ≥3 j | Yes | 139 | T mass 1.8 TeV | SU(2) singlet, $\kappa_T$= 0.5 | ATLAS-CONF-2021-040 |
| | VLQ $Y \to Wb$ | $1\ e, \mu$ | ≥1 b, ≥1 j | Yes | 36.1 | Y mass 1.85 TeV | $\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1 | 1812.07343 |
| | VLQ $B \to Hb$ | $0\ e,\mu$ | ≥2b, ≥1j, ≥1J | – | 139 | B mass 2.0 TeV | SU(2) doublet, $\kappa_B$= 0.3 | ATLAS-CONF-2021-018 |
| Excited fermions | Excited quark $q^* \to qg$ | – | 2 j | – | 139 | $q^*$ mass 6.7 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | 1910.08447 |
| | Excited quark $q^* \to q\gamma$ | $1\ \gamma$ | 1 j | – | 36.7 | $q^*$ mass 5.3 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | 1709.10440 |
| | Excited quark $b^* \to bg$ | – | 1 b, 1 j | – | 36.1 | $b^*$ mass 2.6 TeV | | 1805.09299 |
| | Excited lepton $\ell^*$ | $3\ e, \mu$ | – | – | 20.3 | $\ell^*$ mass 3.0 TeV | $\Lambda = 3.0$ TeV | 1411.2921 |
| | Excited lepton $\nu^*$ | $3\ e, \mu, \tau$ | – | – | 20.3 | $\nu^*$ mass 1.6 TeV | $\Lambda = 1.6$ TeV | 1411.2921 |
| Other | Type III Seesaw | 2,3,4 $e, \mu$ | ≥2 j | Yes | 139 | $N^0$ mass 910 GeV | | ATLAS-CONF-2021-023 |
| | LRSM Majorana $\nu$ | $2\ \mu$ | 2 j | – | 36.1 | $N_R$ mass 3.2 TeV | $m(W_R) = 4.1$ TeV, $g_L = g_R$ | 1809.11105 |
| | Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$ | 2,3,4 $e, \mu$ (SS) | various | Yes | 139 | $H^{\pm\pm}$ mass 350 GeV | DY production | 2101.11961 |
| | Higgs triplet $H^{\pm\pm} \to \ell\ell$ | 2,3,4 $e, \mu$ (SS) | – | – | 36.1 | $H^{\pm\pm}$ mass 870 GeV | DY production | 1710.09748 |
| | Higgs triplet $H^{\pm\pm} \to \ell\tau$ | $3\ e, \mu, \tau$ | – | – | 20.3 | $H^{\pm\pm}$ mass 400 GeV | DY production, $\mathcal{B}(H^{\pm\pm}_L \to \ell\tau) = 1$ | 1411.2921 |
| | Multi-charged particles | – | – | – | 36.1 | multi-charged particle mass 1.22 TeV | DY production, $\lvert q\rvert = 5e$ | 1812.03673 |
| | Magnetic monopoles | – | – | – | 34.4 | monopole mass 2.37 TeV | DY production, $\lvert g\rvert = 1g_D$, spin 1/2 | 1905.10130 |

$\sqrt{s} = 8$ TeV | $\sqrt{s} = 13$ TeV partial data | $\sqrt{s} = 13$ TeV full data

$10^{-1}$ 1 10 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

# Overview of CMS long-lived particle searches


**Moriond 2021**

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

# ALPS LIMITS FROM HL-LHC