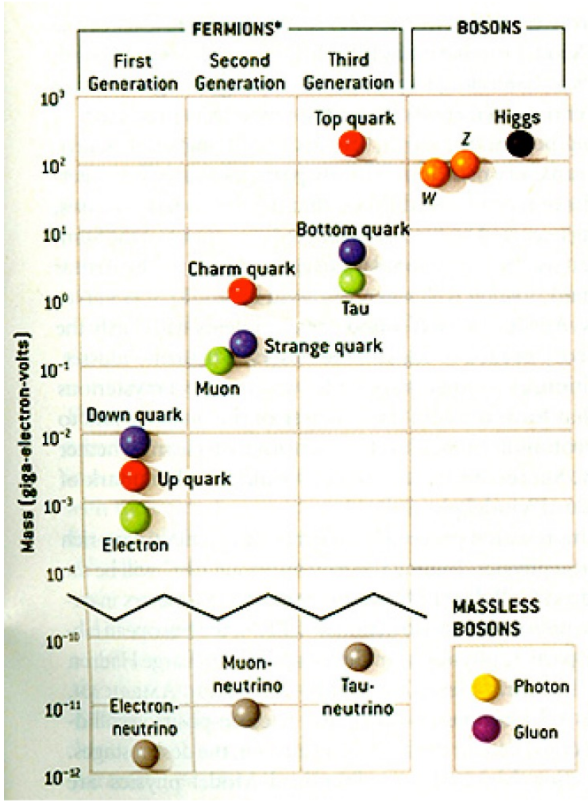
Shaping the future of High-Energy Physics (Experiment)

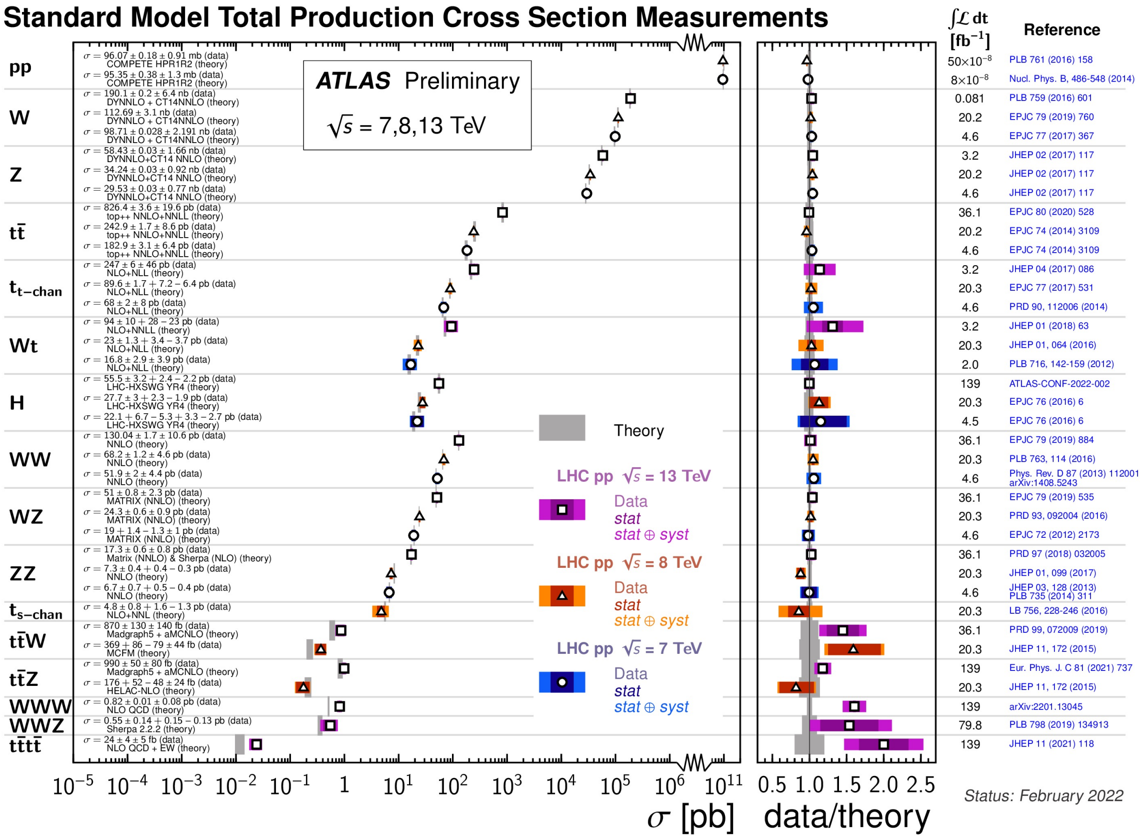
Paris Sphicas
CERN & NKUA
JENAS 2022
Madrid, May 3-6, 2022

- **Introduction**
  - **Where we stand & the road to obtaining answers**
- **The (fundamental?) scalar sector of the SM and direct search for BSM physics**
  - **Couplings as per SM? Self-coupling? Fundamental or composite?**
  - **Direct searches for new interactions or new particles around or above the electroweak scale.**
- **Dark Matter**
  - **Interplay of Direct and Indirect (collider) searches**
- **Physics of Flavor**
  - **Quark sector: CP violation, rare decays of K and B mesons**
  - **Neutrinos: New source of CP violation(?) Mass ordering? Nature? New particles/new interactions?**
  - **Other high-precision measurements (e.g. g-2); tests of fundamental symmetries**
- **Pseudo-summary**

Where we stand

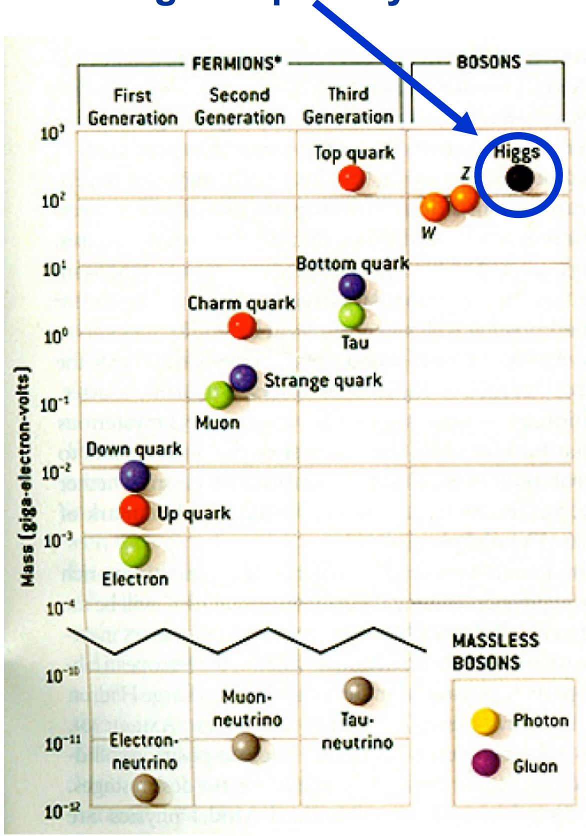
- **Most successful Theory ever: Standard Model (Theory) of Particle Physics**

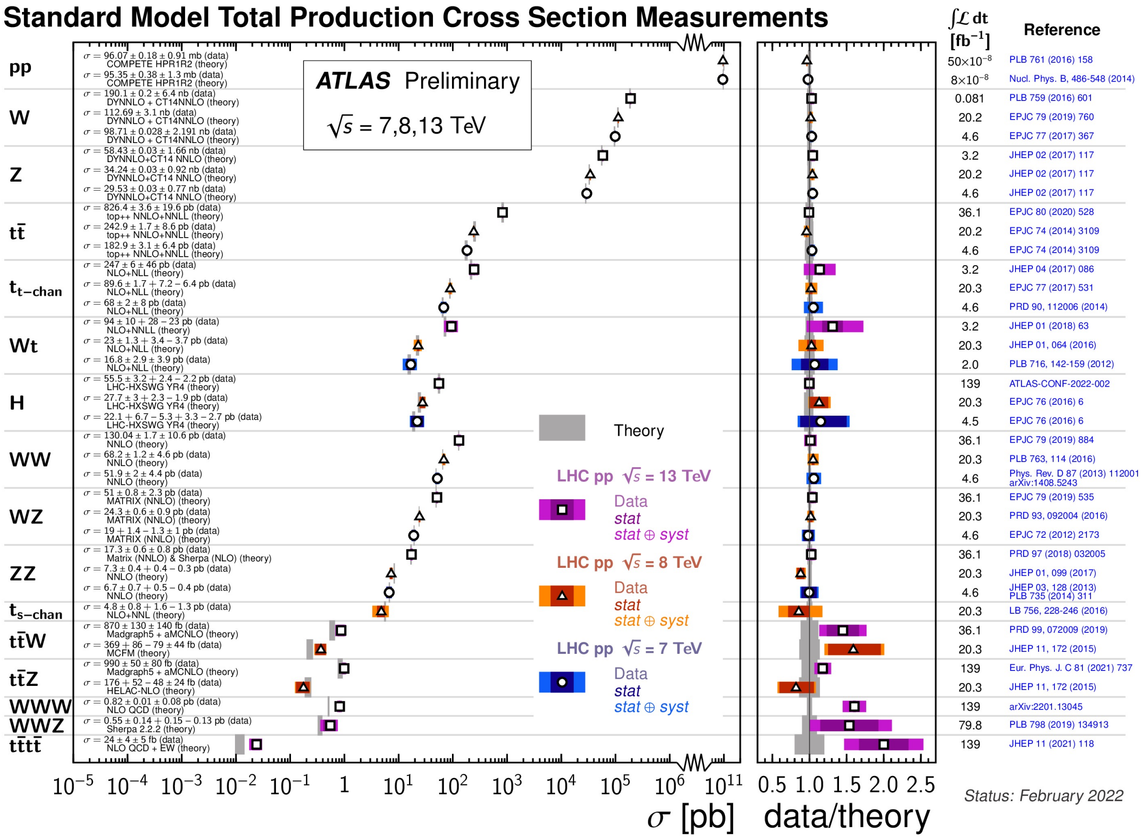




Where we stand

- **Most successful Theory ever: Standard Model (Theory) of Particle Physics**
  - **Highest priority:** ***extend understanding of SM and its newly discovered scalar sector*.**

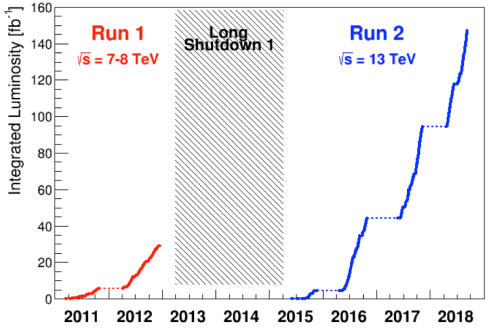




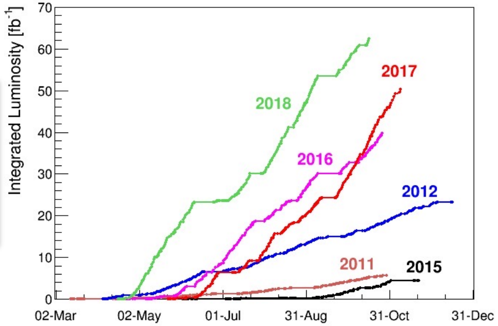
The road to obtaining answers: measurements…

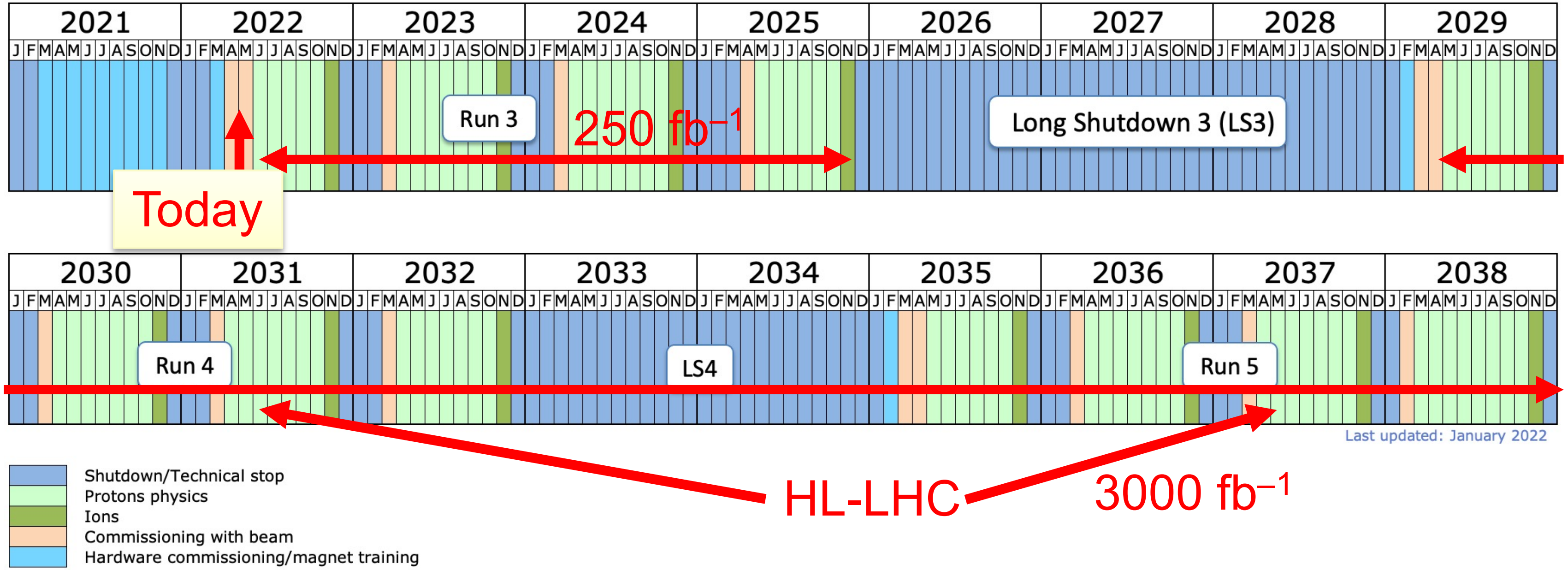
- Physics of fundamental scalars and direct searches for New Physics
  - LHC, HL-LHC & future collider(s) (FCC-ee, FCC-hh, FCC-eh, CEPC, ILC, CLIC)
    - Understand the strangest of all elements of the SM.
    - Search for new particles and physics phenomena.
- Dark Matter searches
  - Very large number of experiments aiming at detecting DM
    - Direct detection, indirect detection (→ talk by S. DeJongh);
    - Matter-matter collisions (→ this talk)
- Physics of Flavor:
  - Neutrinos: Complementarity: beams [DUNE (US), HyperK (JP)], reactors (JUNO), atmosph (ORCA)
    - Is there CP violation in the lepton sector? PMNS matrix (à la CKM)?
    - Mass hierarchy of three ν generations (“normal” or “inverted”)? Dirac or Majorana?
  - Quark sector: Kaon and B hadron decays (LHC, HL-LHC, Fixed-Target (CERN, JP), Belle II (JP)
    - Measure CP sources as precisely as possible. Probe sacred (but also accidental…) laws (e.g. lepton number conservation). Universality? Probe rarest decay modes.
  - High-precision measurements; tests of Fundamental Symmetries

LHC & HL-LHC schedule



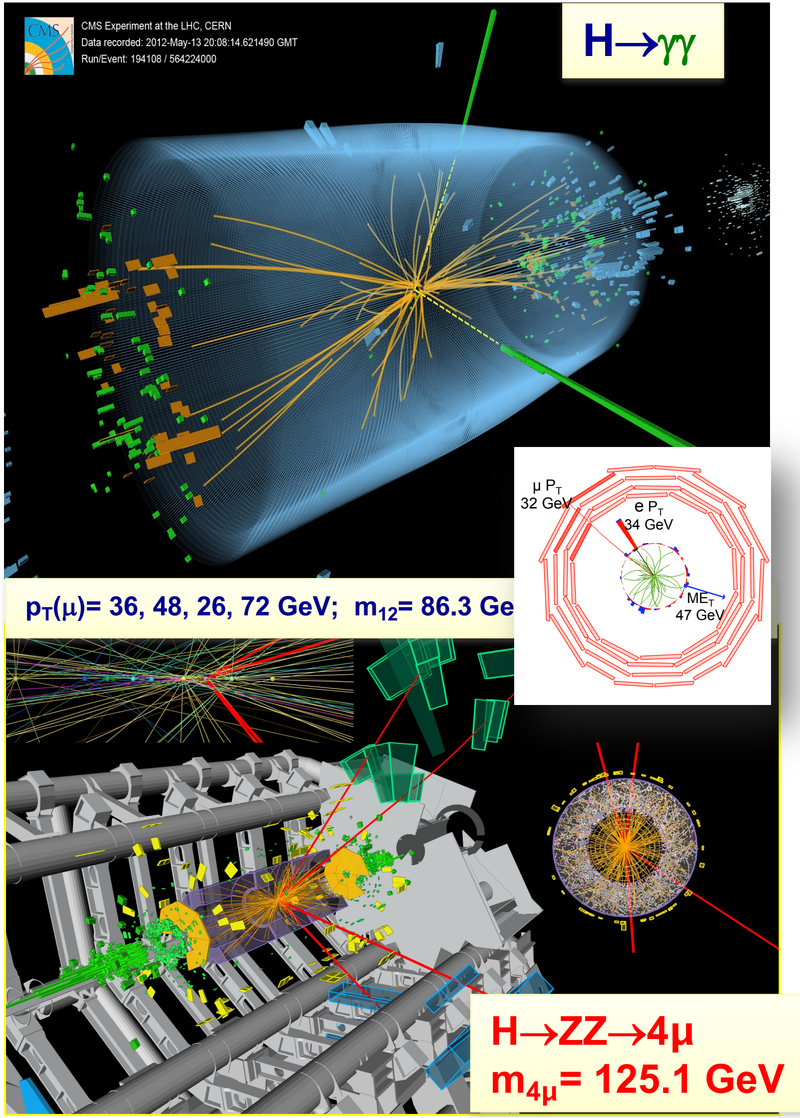
Run 1: 2010-2012; total L~30 fb^{-1}
Run 2: 2015-2018 (150 fb^{-1})
Peak lumi ≈ 2.1 x 10^{34} cm^{-2}s^{-1} (2018)





Shutdown/Technical stop
Protons physics
Ions
Commissioning with beam
Hardware commissioning/magnet training

Recall… new particle @ m≈125 GeV s=0 or 2 boson (decays to γγ, ZZ)

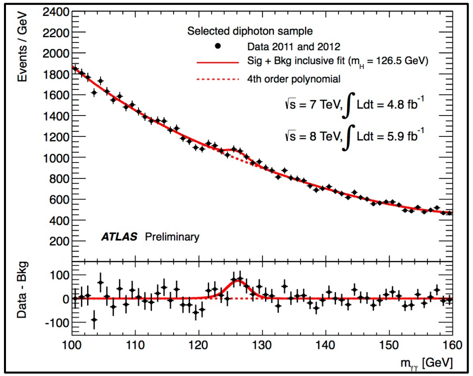


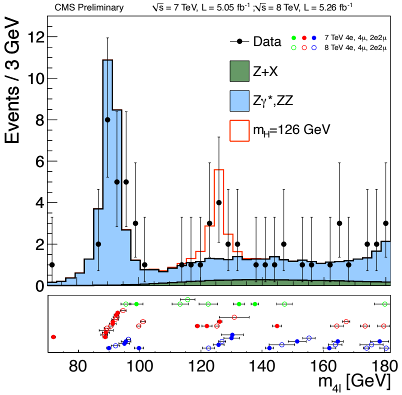
H→γγ

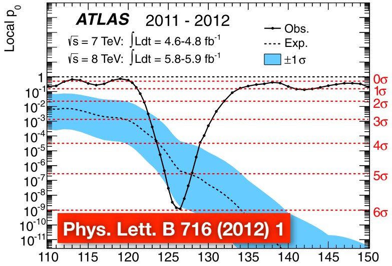
$p_T(\mu)$= 36, 48, 26, 72 GeV; m_{12}= 86.3 Ge

H→ZZ→4μ

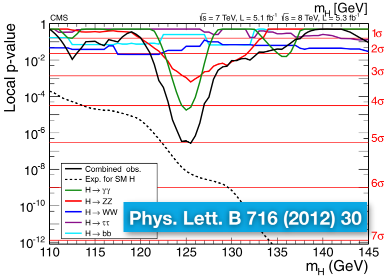
$m_{4\mu}$= 125.1 GeV



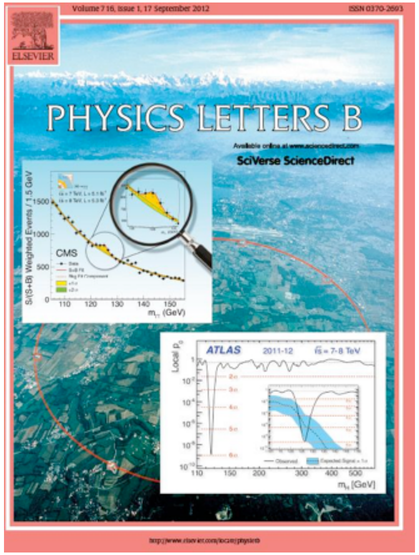




Phys. Lett. B 716 (2012) 1



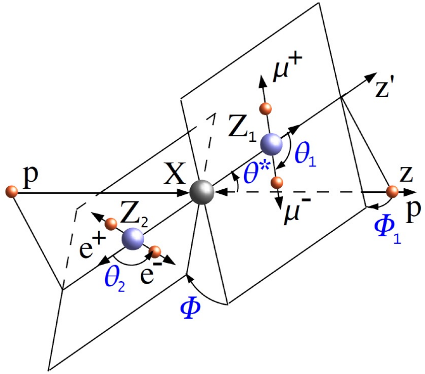
Phys. Lett. B 716 (2012) 30



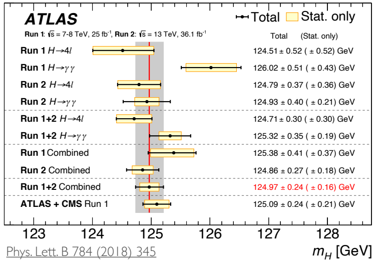
Higgs Physics: after the discovery

- **Measurement of Spin-Parity, mass: it IS the vaccuum particle…**

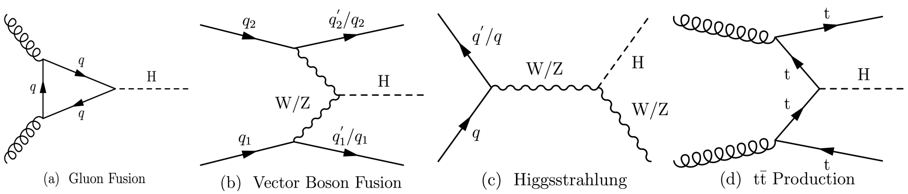
Production mechanisms, differential distributions



$\delta M_H/M_H \sim 0.2\%$ (!)

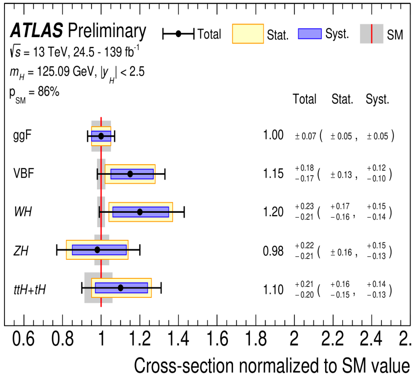


Phys. Lett. B 784 (2018) 345

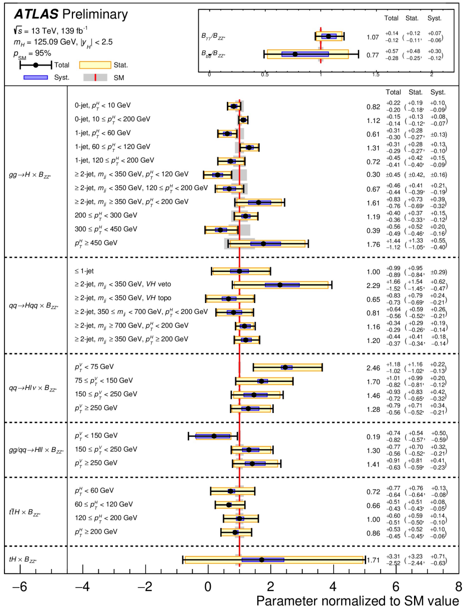


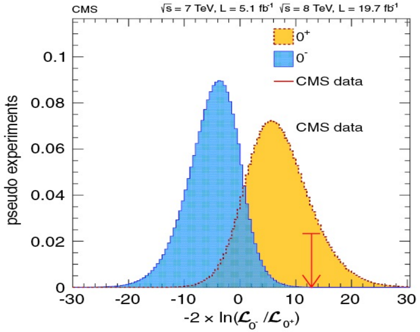
(a) Gluon Fusion (b) Vector Boson Fusion (c) Higgsstrahlung (d) $t\bar{t}$ Production

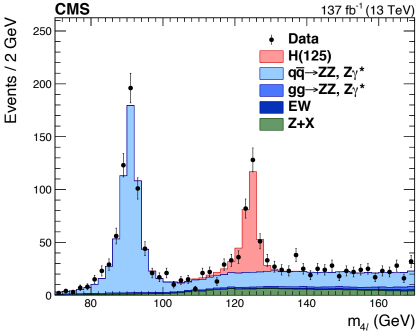
$J^P=0^+$(!!!)



$$\boxed{\mu = 1.06 \pm 0.07}$$

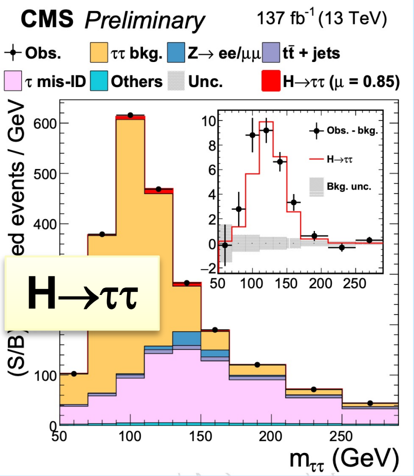






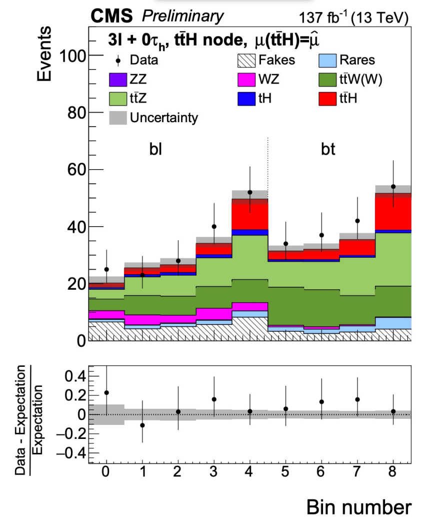
SM @ the highest E; EWSB ("Higgs" sector) (I)

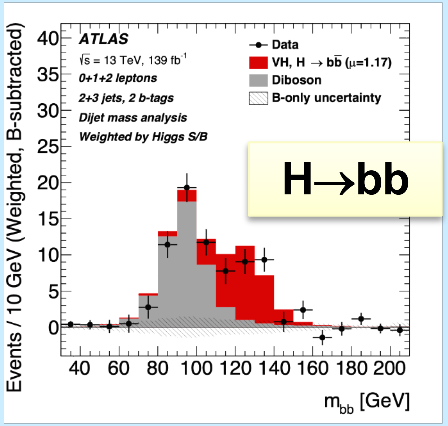
Clear observation of couplings to 3rd-gen fermions



H→ττ

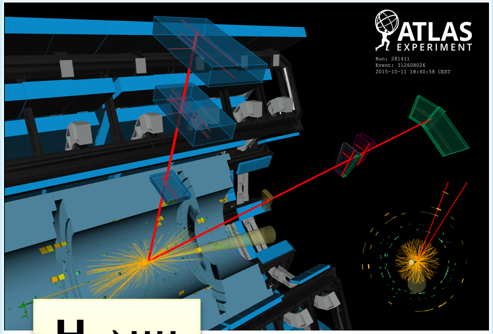
ttH





H→bb

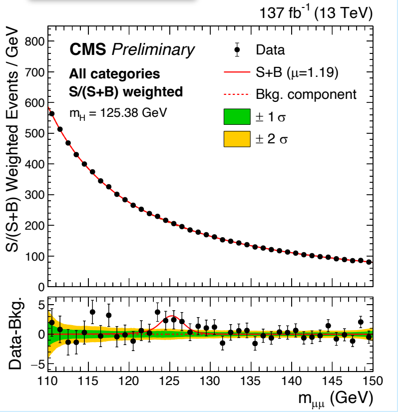
Evidence of coupling to 2nd-gen fermions



H→μμ

CMS:
obs: 3.0σ (exp: 2.5σ)
ATLAS:
obs: 2.0σ (exp: 1.7σ)

$\mu = 1.2 \pm 0.6$



H→cc

$\mu_{VZ(Z\to cc)} = 1.01^{+0.23}_{-0.21}$

$\mu_{VH(H\to cc)} < 14$ (7.6 exp.)

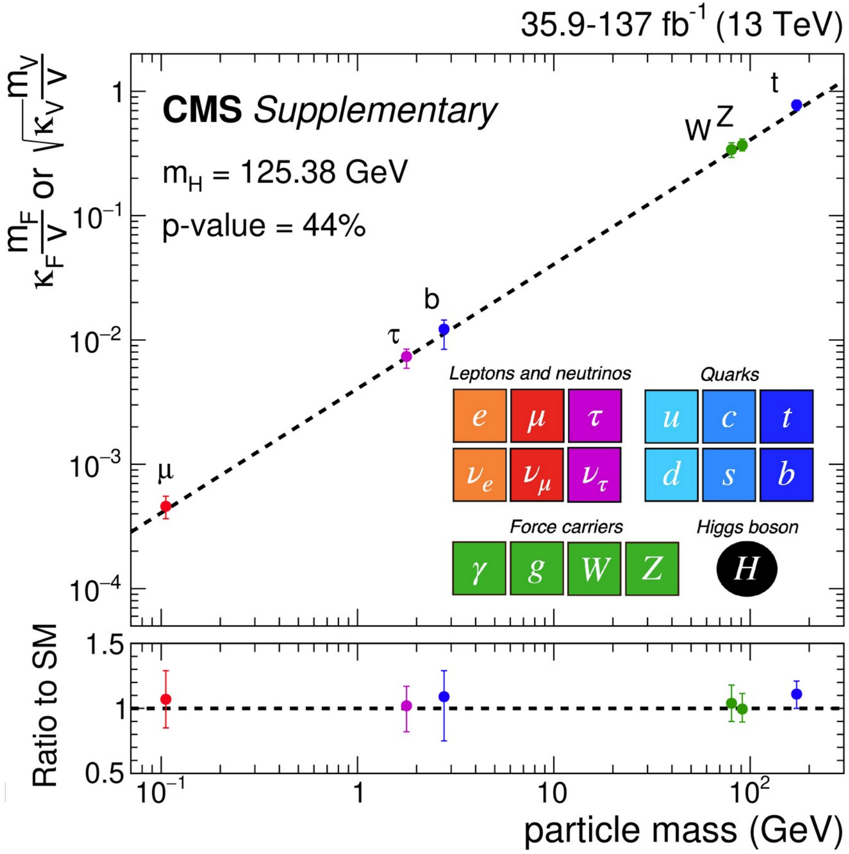
$1.1 < |\kappa_c| < 5.5$ ($|\kappa_c| < 3.4$ exp.)

The overall picture of the measured/seen Higgs couplings

$$\lambda_f = \kappa_f\left(\frac{m_f}{v}\right)$$

$$\left(\frac{g_V}{2v}\right)^{1/2} = \kappa_v^{1/2}\left(\frac{m_V}{v}\right)$$

A new kind of “force”, with non-universal coupling

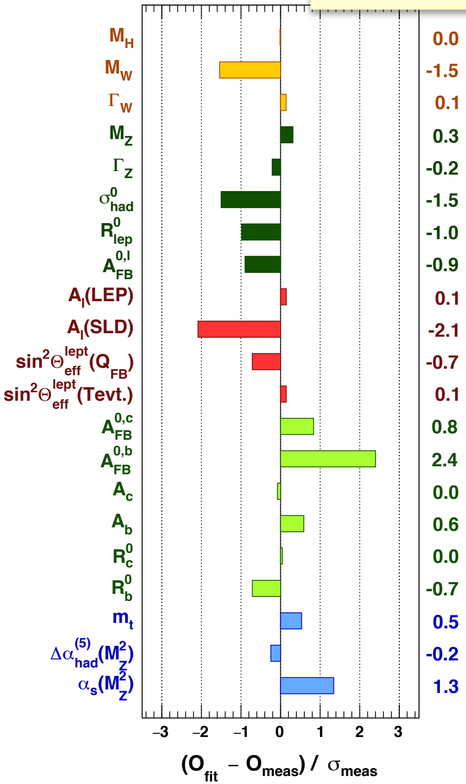


Putting it all together: SM reigns supreme

- **Goodness of fit**
  - χ^2_{min}=18.6 → Prob= 23%
- **Fit result often more accurate than measurement**
  - Small pulls for M_H, M_Z, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, m_c, m_b → input accuracies exceed fit requirements
- **Knowledge of m_H → huge improvement in:**
  - m_W (28→11 MeV)
  - m_t (6.2→2.5 GeV)
  - $\sin^2\theta_W$ ($2.3 \rightarrow 1.0 \times 10^{-3}$)
- **Largest discrepancy:**
  - $A_{FB}(b)$: 2.5 σ

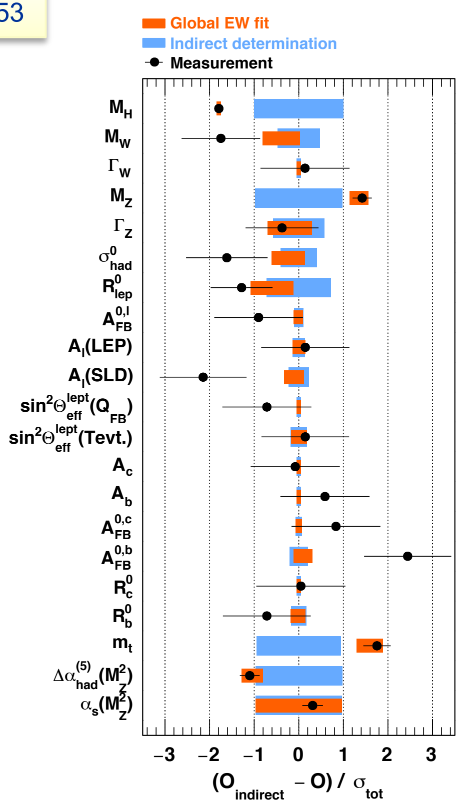
arXiv:1407.3792

arXiv:1803.01853



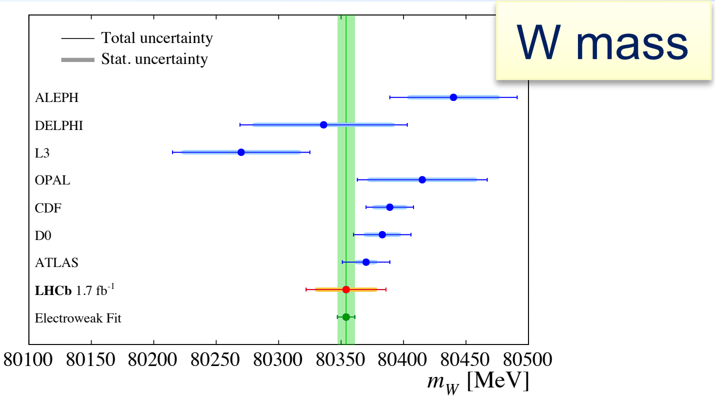
G fitter

https://project-gfitter.web.cern.ch/

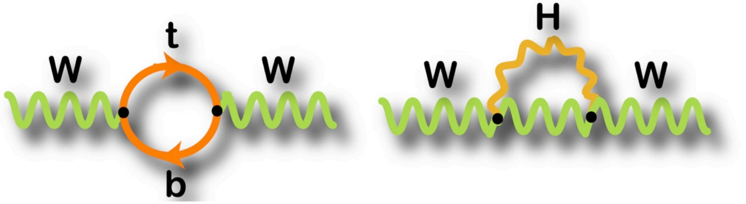


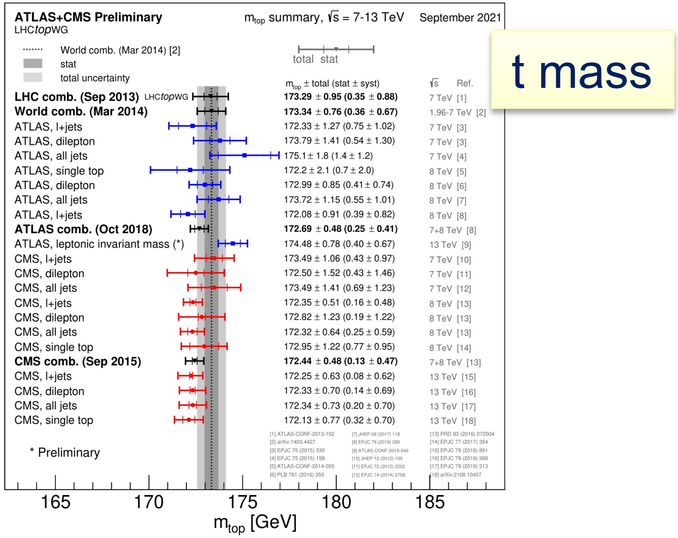
Light blue: fit excluding input from row

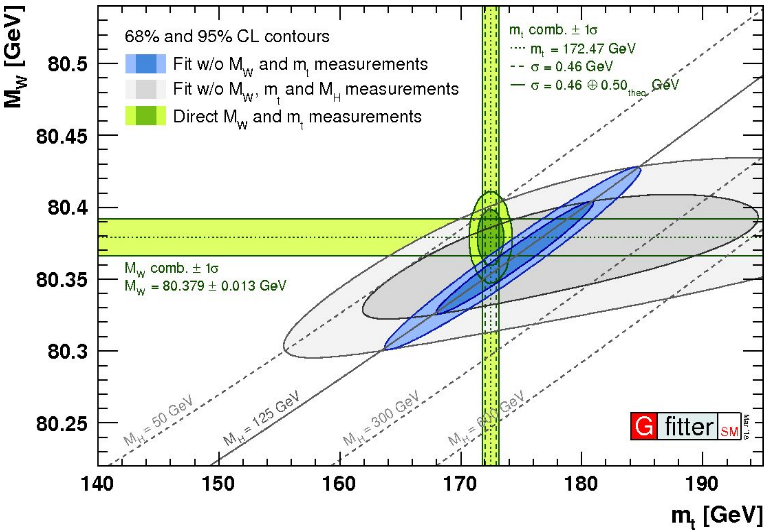
A very sensitive SM test: the m_W–m_t plane



$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

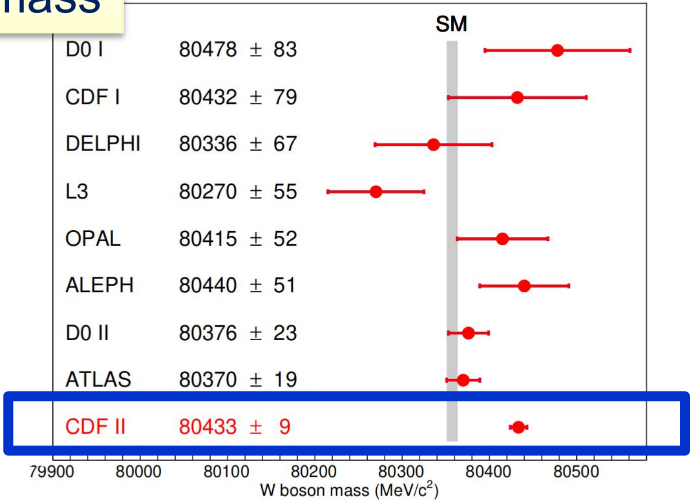






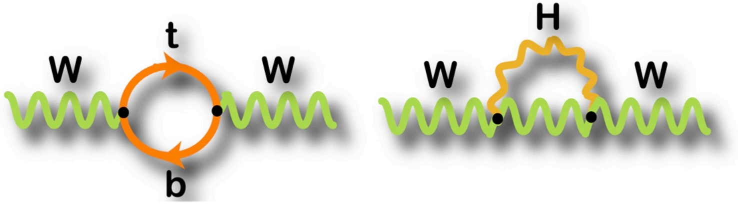
A very sensitive SM test: the m_W–m_t plane

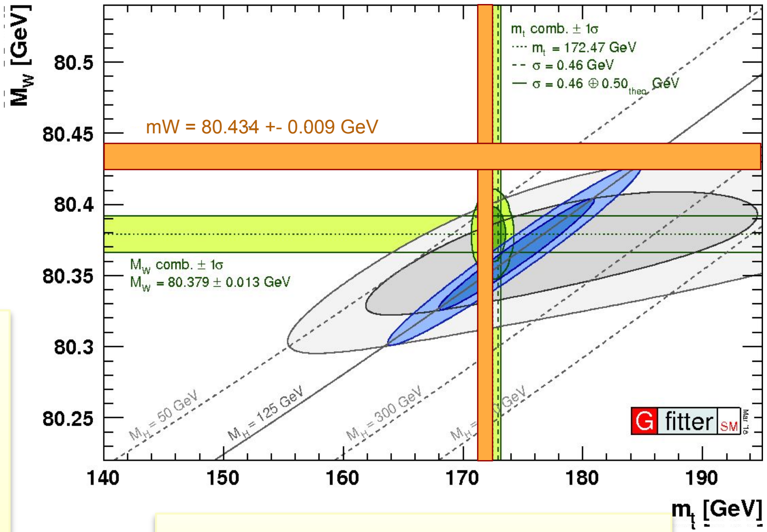
W mass



$m_W(\text{SM}) = 80375 \pm 4(\text{inp}) \pm 4(\text{th})$ MeV
$m_W(\text{CDF}) = 80433 \pm 9.4$ MeV
$\Delta m_W(\text{SM-CDF}) = 7\sigma$…

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$





More precise than all previous m_W measurements combined

~ 3σ higher than most precise other measurements

~ 3σ higher than previous CDF result (1/4 of data, correlations taken into account)

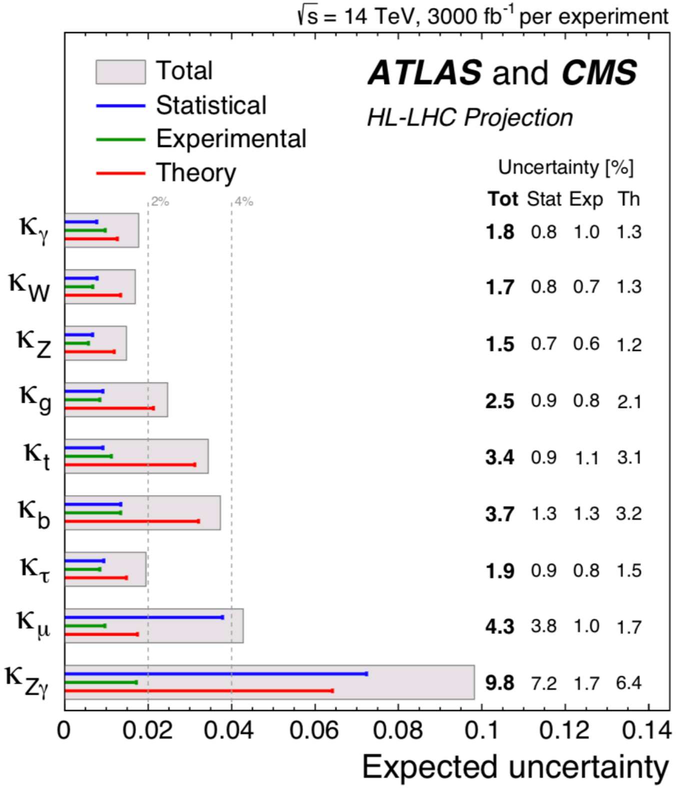
"in tension" with SM pred

The Standard Model

The Scalar Sector

Medium-term Higgs physics: the LHC/HL-LHC program

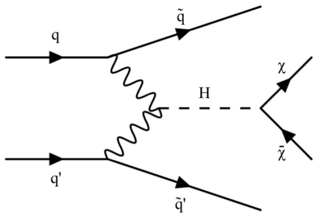
HL-LHC reach: Higgs



Uncertainty [%]

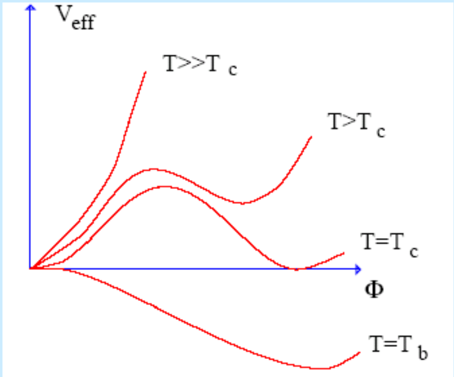
	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

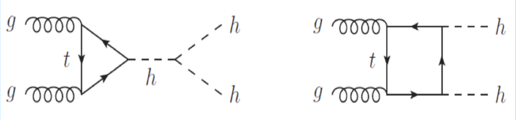
H width to invisible:
h(125)→XX.
Includes BSM decays
and rare SM decays: ≤4%

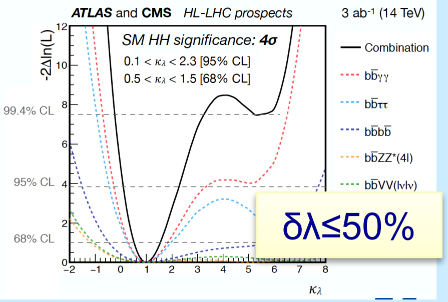


The ultimate frontier: Higgs self-coupling

$$V_h = \frac{m_h^2}{2}h^2 + (1+\boxed{\kappa_3})\lambda_{hhh}^{SM} v h^3 + \frac{1}{4}(1+\boxed{\kappa_4})\lambda_{hhhh}^{SM} h^4$$



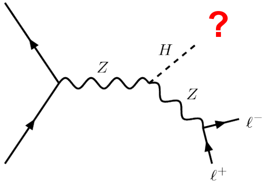




δλ≤50%

Long-term Higgs physics: a Higgs “factory”

- **Uniquely at lepton-lepton colliders:**
  - **Recoil method (detect H without reference to H decay)**
  - **Measure ZH cross section with high precision – no assumptions on decay**
- **Interpreted as quasi-direct measurement of width**



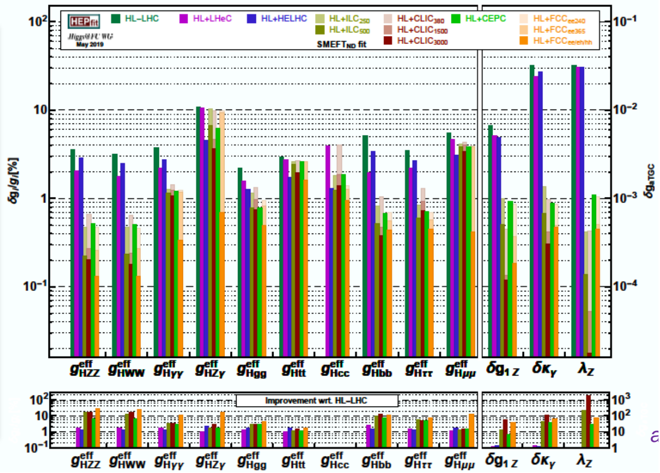
$$\frac{\sigma(e^+e^- \to ZH)}{\mathrm{BR}(H \to ZZ^*)} = \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)}\right]_{\mathrm{SM}} \times \Gamma_H \xrightarrow{\kappa \text{ framework}} \Gamma_H = \frac{\Gamma_H^{\mathrm{SM}} \cdot \kappa_H^2}{1-(BR_{inv}+BR_{unt})}$$

Collider	$\delta\Gamma_H$ (%) from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ (%) kappa-3 fit
ILC_{250}	2.4	EFT fit [3]	2.4
ILC_{500}	1.6	EFT fit [3, 11]	1.1
CLIC_{350}	4.7	κ-framework [85]	2.6
CLIC_{1500}	2.6	κ-framework [85]	1.7
CLIC_{3000}	2.5	κ-framework [85]	1.6
CEPC	3.1	$\sigma(ZH, \nu\bar{\nu}H)$, $\mathrm{BR}(H \to Z, b\bar{b}, WW)$ [90]	1.8
$\mathrm{FCC\text{-}ee}_{240}$	2.7	κ-framework [1]	1.9
$\mathrm{FCC\text{-}ee}_{365}$	1.3	κ-framework [1]	1.2

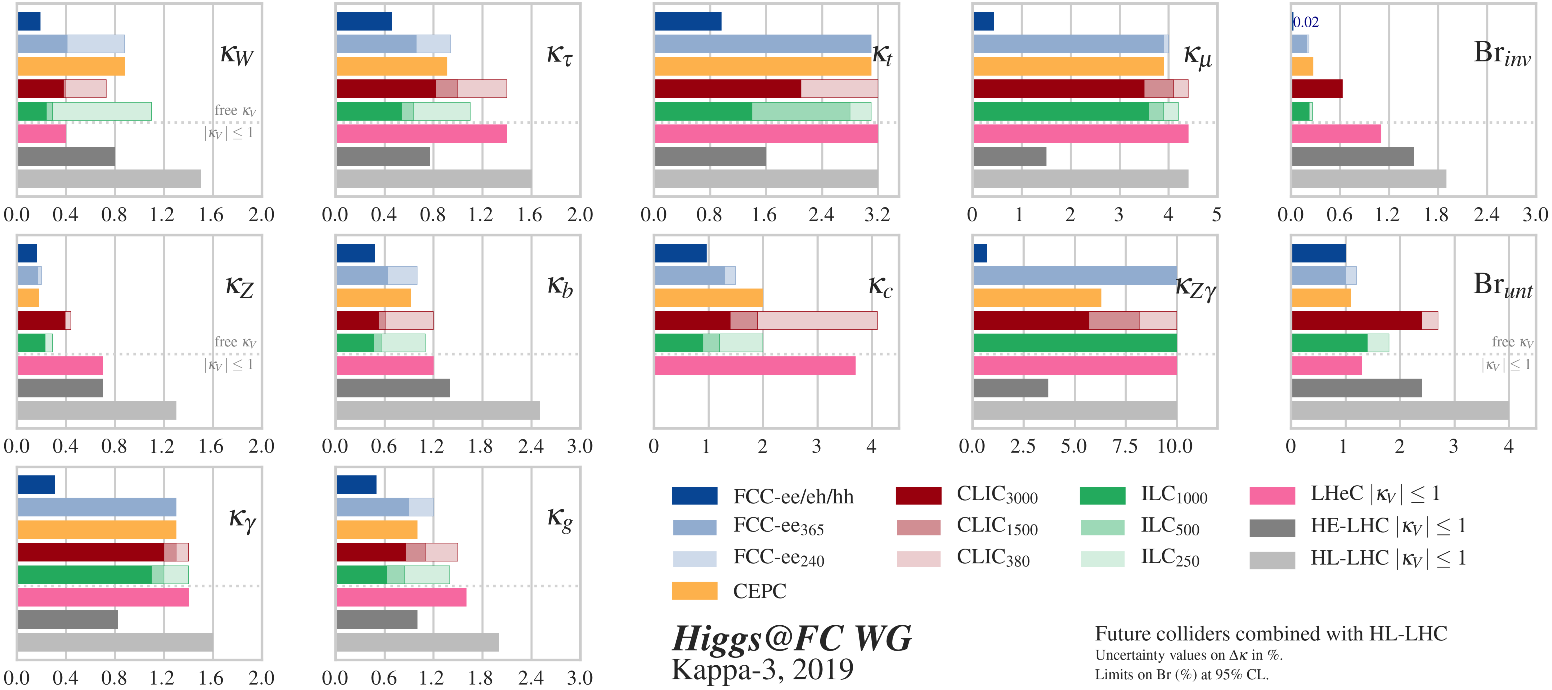
arXiv:1905.03764

Bottom line: $\delta\Gamma_H/\Gamma_H$~1-2%

EFT framework:
Gauge bosons: ~ 0.1% precision
Fermions: Major improvement wrt HL_LHC
Trilinear gauge couplings: 10^{-3}-10^{-4} precision
~ 2–3 orders of magnitude better than LEP



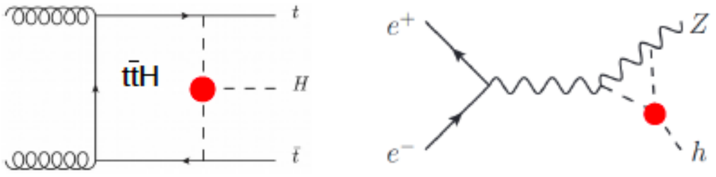
Grand summary: Higgs couplings (κ framework) (Future Collider+HL-LHC)



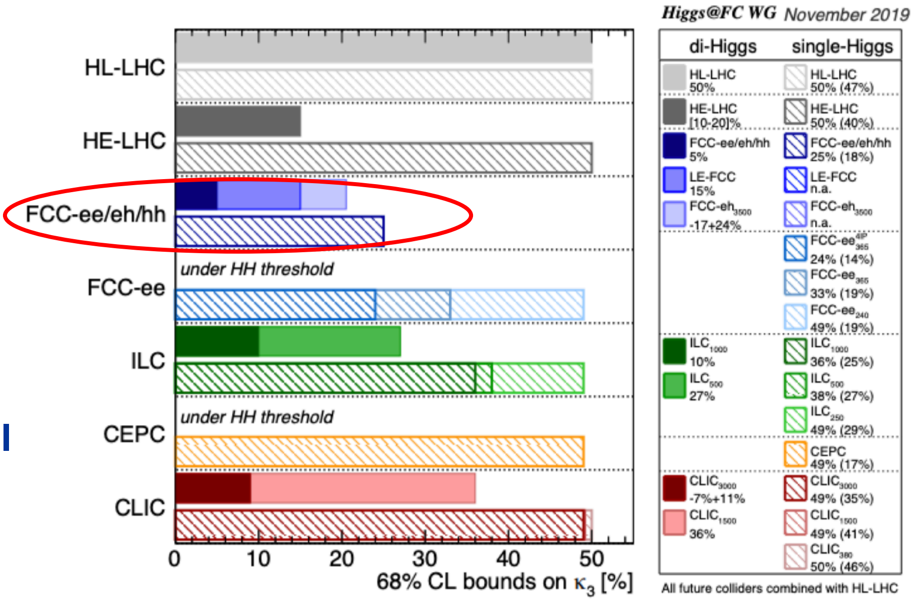
Plus of κ framework: it is simple; Minus: underestimates effects of polarization
Can show deviation from SM, but no real further information on nature of source of deviation;
Untagged and invisible BRs constrained by measurements.

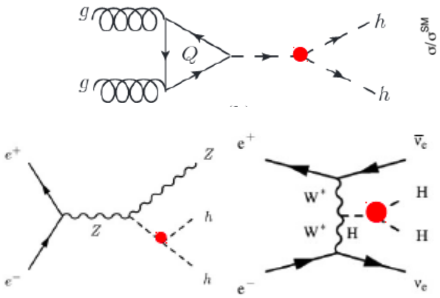
Higgs self-coupling

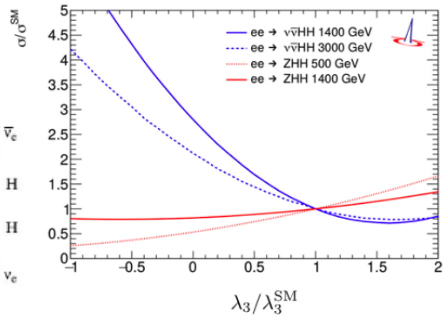
- **Single-H production**
  - **Sensitivity via loop diagrams**



  - **For k_λ=2, hh: 3%; ee: 1%.**
- **HH production**
  - **hh: σ(HH)~0.01σ(H); must use differential measurements;**
  - **ee: Complementarity of ZHH and VBF production**



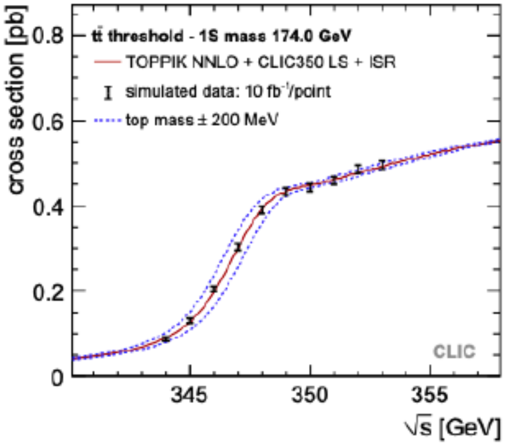




Single-H: FCC-ee or ILC ~ 35% (global analysis)
HH production:
HL-LHC: ~50% (can probably do better)?
HE-LHC: ~15%
ILC500: ~27%; CLIC1500 ~36%
CLIC3000: ~9%; FCC-hh ~5%

Precision EWK Observables

- **Top mass from threshold scan**

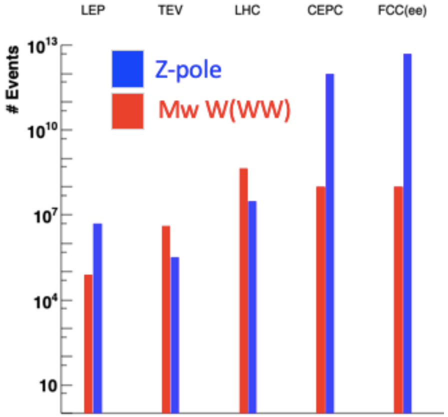


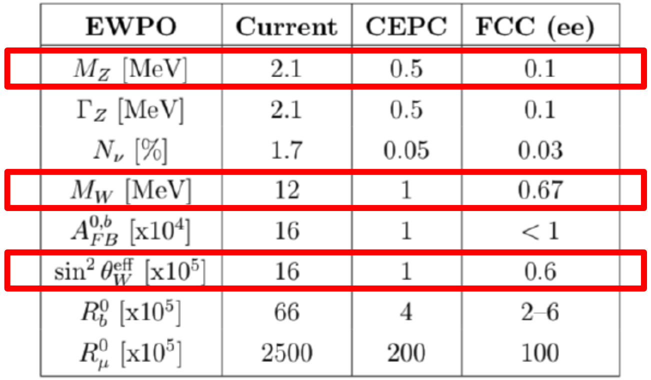
Currently:
$\delta m_t \approx 400$ MeV
ILC/CLIC/FCC: ~25 MeV
Note: δm_t^{TH}~40 MeV (α_s), 40 MeV (HO)
Theory errors should decrease from Z-pole running; e.g. FCC-ee: 5×10^{12} Z (!!!)

- **EWPO: circular ee colliders**

+ linear colliders for $\sin^2\theta_W$.

Note: currently, discussion/plan for a large Z run for the linear colliders…





EWPO	Current	CEPC	FCC (ee)
M_Z [MeV]	2.1	0.5	0.1
Γ_Z [MeV]	2.1	0.5	0.1
N_ν [%]	1.7	0.05	0.03
M_W [MeV]	12	1	0.67
$A_{FB}^{0,b}$ [x10^4]	16	1	<1
$\sin^2\theta_W^{\rm eff}$ [x10^5]	16	1	0.6
R_b^0 [x10^5]	66	4	2–6
R_μ^0 [x10^5]	2500	200	100

Beyond the Standard Model (I)

Composite Higgs?

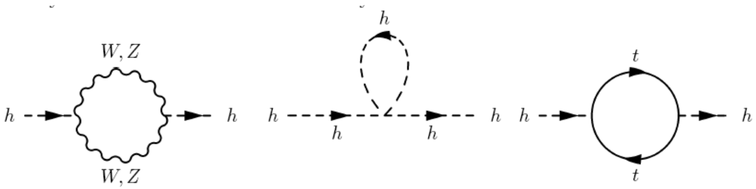
Sypersymmetry?

Contact Interactions?

New resonances?

The magic of the Higgs boson mass

- **Quantum Mechanics: ultimate destructor of small numbers (in nature) that are not protected by some symmetry (thus "law")**
- **Higgs boson: the ultimate example**
  - **Quadratic divergence in the Higgs mass**



$$m^2\left(p^2\right) = m^2\left(\Lambda^2\right) + Cg^2\int_{p^2}^{\Lambda^2} dk^2$$

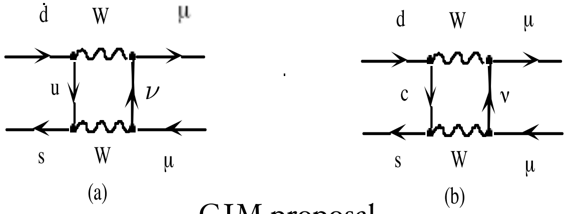
- **H mass should be ~ 10^{19}GeV**
  - **Yet, it lies at 125 GeV…**
- **Put differently: if cut off at Λ_{PL}, why $m_W \ll M_{Pl}$?**
  - **Or, why is gravity ($G \sim 1/M_{Pl}$) so weak?**

- **Reminder of just two past applications of naturalness argument:**
- **Weisskopf (1939): "the self-energy of charged particles obeying Bose statistics is found to be quadratically divergent...,"**

  → in theories of elementary bosons, new phenomena must enter at an energy scale of m/e

  → + positron, doubling of particles…

- **Rare Kaon decays: $K_L \to \mu^+\mu^-$**



(a) (b)

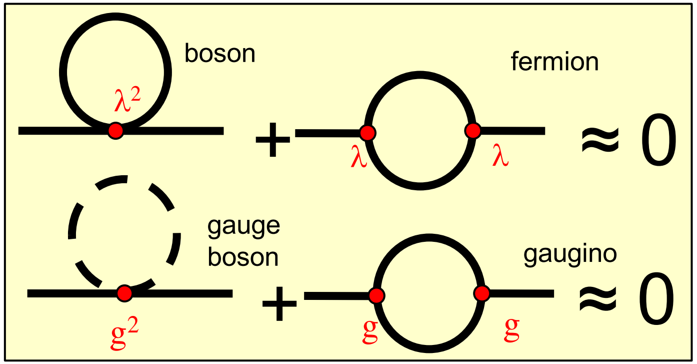
GIM proposal

$\sim G\,\Lambda^2 = G(m_c^2 - m_u^2)$

→ $\Lambda^2 \sim$ 3-4 GeV^2 !!!

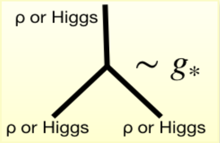
Solutions to the hierarchy problem

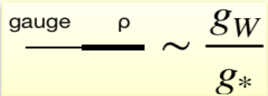
- Solution #1: a composite Higgs
  - H: bound state (e.g. due to some new strong interaction)
- Solution #2: supersymmetry
  - Partners for ALL SM particles, spin different by ½
  - Presumably broken symmetry (since partners unseen)



- Solution #3: little Higgs
  - H: pseudo-Goldstone boson of Ultimate Theory; just another effective theory, e.g. valid to ~10 TeV. Loops cancel by particles of same spin (so need to introduce these particles)
- Solution #4: extra dimensions
  - N-dim space; gravity propagates in all dims, SM only in “our” 3 dims; e.g. warped extra dimension can explain weakness of G
- All of these “solutions” introduce either deviations in tails or new particles, with masses whose “natural” values should be O(few TeV)

Higgs Compositeness?



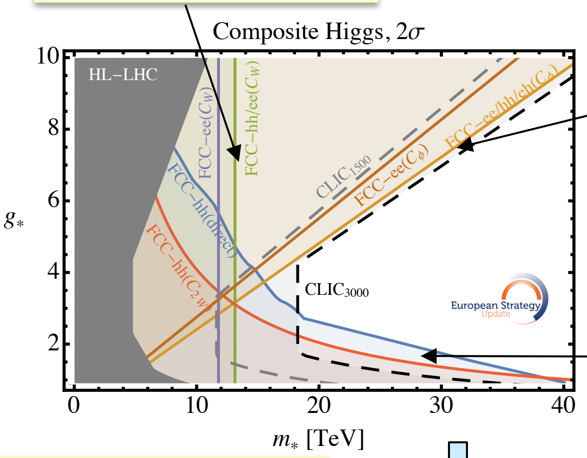


H
$$\frac{c_\phi}{\Lambda^2} = \frac{g_*^2}{m_*^2}$$

2f-2b
$$\frac{c_W}{\Lambda^2} = \frac{1}{m_*^2}$$

4f, W'/Z'
$$\frac{c_{2W}}{\Lambda^2} = \frac{1}{g_*^2 m_*^2}$$

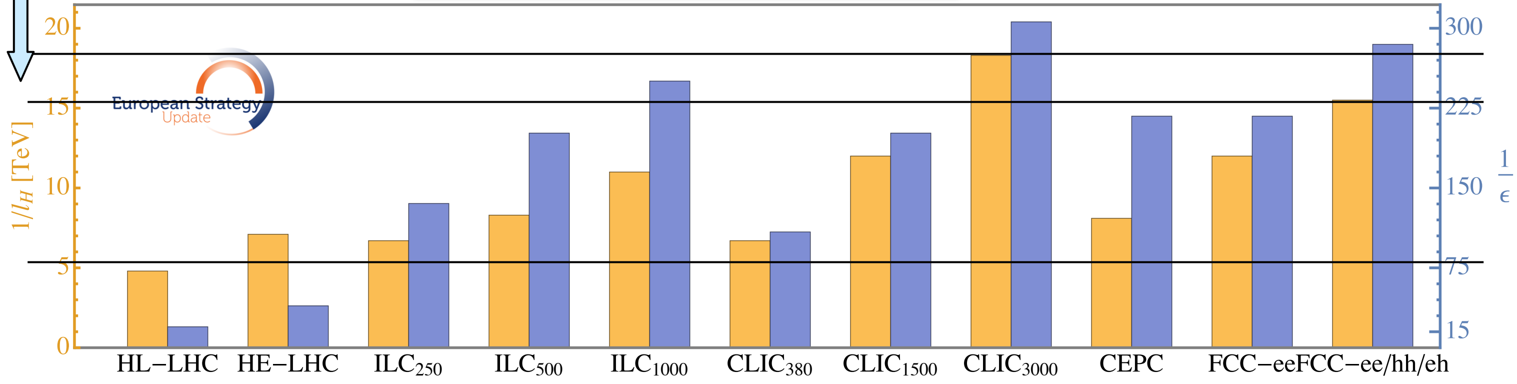
O_W (independent of g_*)



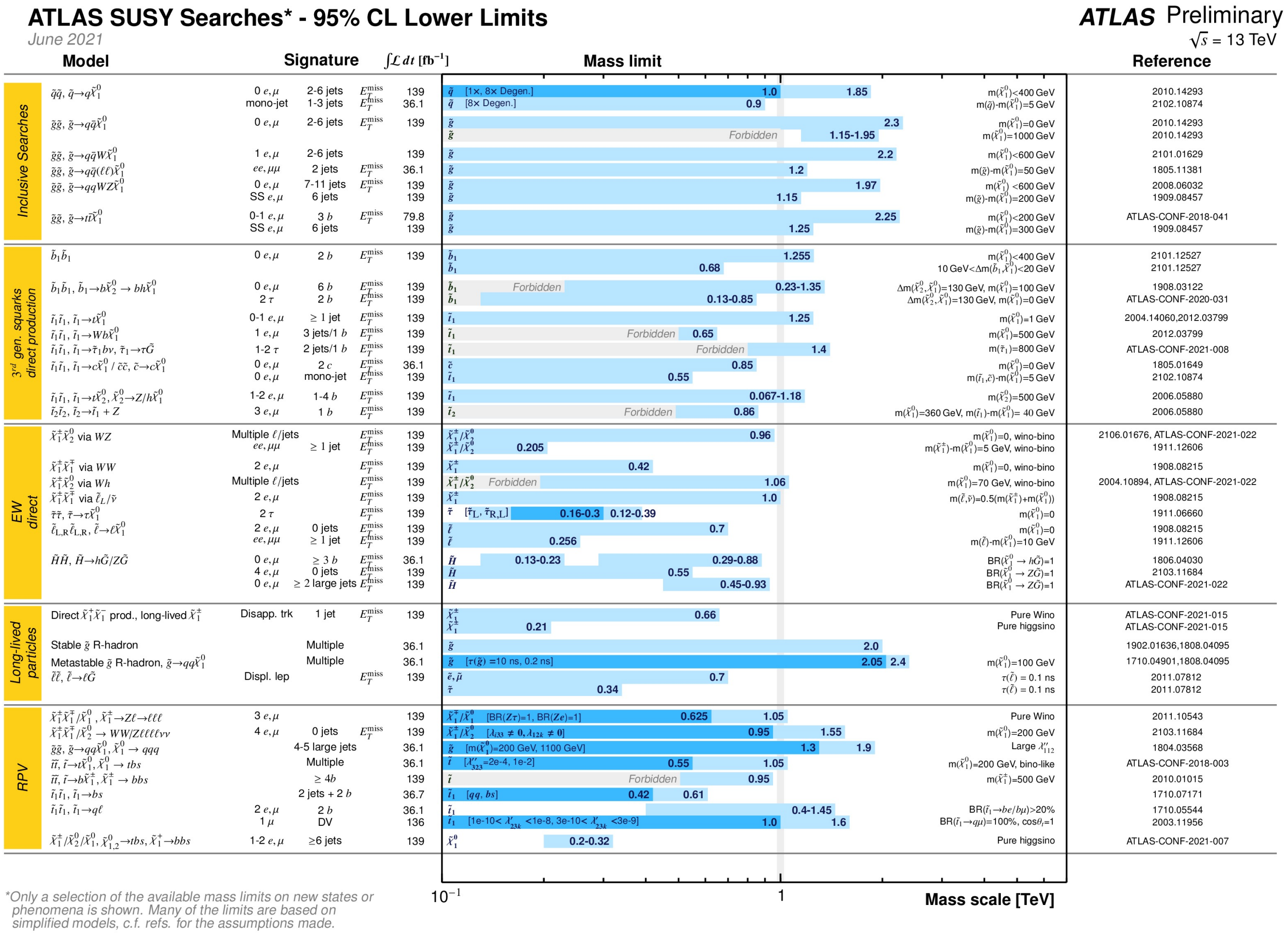
O_φ (Higgs measurements, primarily FCC-ee & CLIC)

Direct resonance searches (generic "ρ" EWK triplet); dileptons & dibosons)

Obtain limit on m*, i.e. on 1/length(H)



The never-ending search for SUSY…
(and it's not like we didn't look for them)



ATLAS SUSY Searches* - 95% CL Lower Limits

June 2021

ATLAS Preliminary

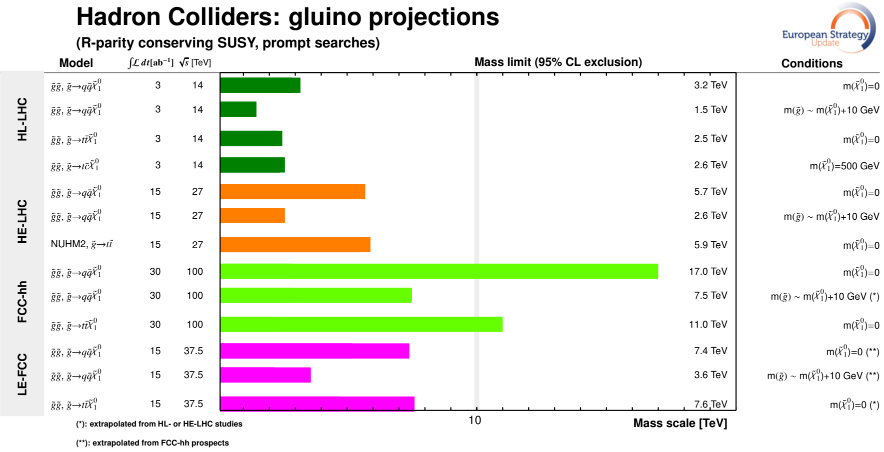
$\sqrt{s}$ = 13 TeV

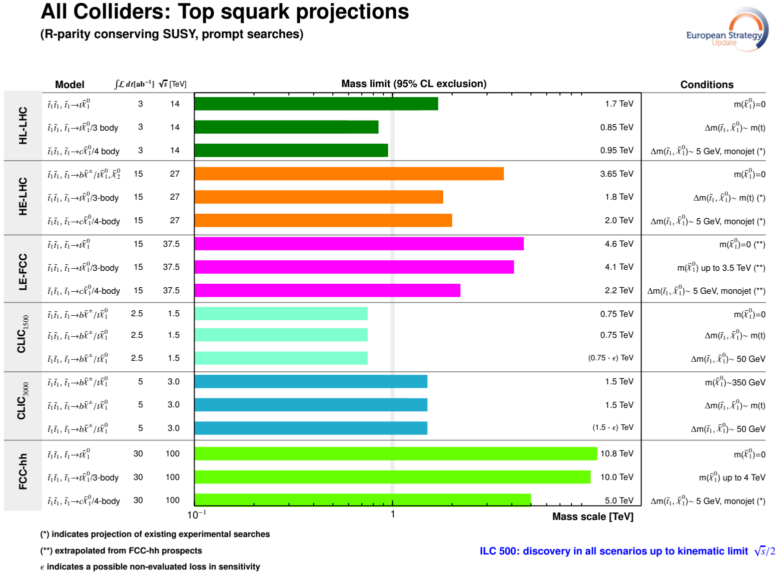
	Model	Signature			$\int \mathcal{L}\,dt$ [fb^{-1}]	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{q}$ [1×, 8× Degen.] 1.0 1.85	m($\tilde{\chi}_1^0$)<400 GeV	2010.14293
		mono-jet	1-3 jets	E_T^{miss}	36.1	$\tilde{q}$ [8× Degen.] 0.9	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	2102.10874
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{g}$ 2.3	m($\tilde{\chi}_1^0$)=0 GeV	2010.14293
						$\tilde{g}$ Forbidden 1.15-1.95	m($\tilde{\chi}_1^0$)=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}W\tilde{\chi}_1^0$	1 e,μ	2-6 jets		139	$\tilde{g}$ 2.2	m($\tilde{\chi}_1^0$)<600 GeV	2101.01629
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee,\mu\mu$	2 jets	E_T^{miss}	36.1	$\tilde{g}$ 1.2	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	0 e,μ	7-11 jets	E_T^{miss}	139	$\tilde{g}$ 1.97	m($\tilde{\chi}_1^0$) <600 GeV	2008.06032
		SS e,μ	6 jets		139	$\tilde{g}$ 1.15	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	1909.08457
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	E_T^{miss}	79.8	$\tilde{g}$ 2.25	m($\tilde{\chi}_1^0$)<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$ 1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1909.08457
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	E_T^{miss}	139	$\tilde{b}_1$ 1.255	m($\tilde{\chi}_1^0$)<400 GeV	2101.12527
						$\tilde{b}_1$ 0.68	10 GeV<Δm($\tilde{b}_1$,$\tilde{\chi}_1^0$)<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_2^0\to bh\tilde{\chi}_1^0$	0 e,μ	6 b	E_T^{miss}	139	$\tilde{b}_1$ Forbidden 0.23-1.35	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=100 GeV	1908.03122
		2 τ	2 b	E_T^{miss}	139	$\tilde{b}_1$ 0.13-0.85	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2020-031
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_1^0$	0-1 e,μ	≥ 1 jet	E_T^{miss}	139	$\tilde{t}_1$ 1.25	m($\tilde{\chi}_1^0$)=1 GeV	2004.14060,2012.03799
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$	1 e,μ	3 jets/1 b	E_T^{miss}	139	$\tilde{t}_1$ Forbidden 0.65	m($\tilde{\chi}_1^0$)=500 GeV	2012.03799
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to\tilde{\tau}_1 b\nu, \tilde{\tau}_1\to\tau\tilde{G}$	1-2 τ	2 jets/1 b	E_T^{miss}	139	$\tilde{t}_1$ Forbidden 1.4	m($\tilde{\tau}_1$)=800 GeV	ATLAS-CONF-2021-008
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}_1^0$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$ 0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	139	$\tilde{t}_1$ 0.55	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_2^0, \tilde{\chi}_2^0\to Z/h\tilde{\chi}_1^0$	1-2 e,μ	1-4 b	E_T^{miss}	139	$\tilde{t}_1$ 0.067-1.18	m($\tilde{\chi}_2^0$)=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	E_T^{miss}	139	$\tilde{t}_2$ Forbidden 0.86	m($\tilde{\chi}_1^0$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 40 GeV	2006.05880
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	Multiple ℓ/jets		E_T^{miss}	139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.96	m($\tilde{\chi}_1^0$)=0, wino-bino	2106.01676, ATLAS-CONF-2021-022
		$ee,\mu\mu$	≥ 1 jet	E_T^{miss}	139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.205	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=5 GeV, wino-bino	1911.12606
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via WW	2 e,μ		E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$ 0.42	m($\tilde{\chi}_1^0$)=0, wino-bino	1908.08215
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh	Multiple ℓ/jets		E_T^{miss}	139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ Forbidden 1.06	m($\tilde{\chi}_1^0$)=70 GeV, wino-bino	2004.10894, ATLAS-CONF-2021-022
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$ 1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1908.08215
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau}\to\tau\tilde{\chi}_1^0$	2 τ		E_T^{miss}	139	$\tilde{\tau}$ [$\tilde{\tau}_L$, $\tilde{\tau}_{R,L}$] 0.16-0.3 0.12-0.39	m($\tilde{\chi}_1^0$)=0	1911.06660
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0 jets	E_T^{miss}	139	$\tilde{\ell}$ 0.7	m($\tilde{\chi}_1^0$)=0	1908.08215
		$ee,\mu\mu$	≥ 1 jet	E_T^{miss}	139	$\tilde{\ell}$ 0.256	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	≥ 3 b	E_T^{miss}	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	E_T^{miss}	139	$\tilde{H}$ 0.55	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	2103.11684
		0 e,μ	≥ 2 large jets	E_T^{miss}	139	$\tilde{H}$ 0.45-0.93	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	ATLAS-CONF-2021-022
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$ 0.66	Pure Wino	ATLAS-CONF-2021-015
						$\tilde{\chi}_1^{\pm}$ 0.21	Pure higgsino	ATLAS-CONF-2021-015
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$ 2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		36.1	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns] 2.05 2.4	m($\tilde{\chi}_1^0$)=100 GeV	1710.04901,1808.04095
	$\tilde{\ell}\tilde{\ell}, \tilde{\ell}\to\ell\tilde{G}$	Displ. lep		E_T^{miss}	139	$\tilde{e},\tilde{\mu}$ 0.7	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
						$\tilde{\tau}$ 0.34	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
RPV	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_1^0$, $\tilde{\chi}_1^{\pm}\to Z\ell\to\ell\ell\ell$	3 e,μ			139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_1^0$ [BR($Z\tau$)=1, BR(Ze)=1] 0.625 1.05	Pure Wino	2011.10543
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.95 1.55	m($\tilde{\chi}_1^0$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$		4-5 large jets		36.1	$\tilde{g}$ [m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
	$\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}_1^0, \tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{t}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\to b\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{\pm}\to bbs$		≥ 4b		139	$\tilde{t}$ Forbidden 0.95	m($\tilde{\chi}_1^{\pm}$)=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956
	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0/\tilde{\chi}_1^0, \tilde{\chi}_{1,2}^0\to tbs, \tilde{\chi}_1^+\to bbs$	1-2 e,μ	≥6 jets		139	$\tilde{\chi}_1^0$ 0.2-0.32	Pure higgsino	ATLAS-CONF-2021-007

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Long-term future: SUSY at >1TeV…. <10 TeV?

- **The questions:**
  - If {SUSY} which masses (and mass differences) of strongly- or weakly-coupled super-partners can we reach?
  - Is nature fundamentally fine-tuned? If the solution is SUSY, how well can we test this?
  - Is dark matter a thermal SUSY WIMP?
- **Strongly-interacting SUSY (gluinos and squarks): simply, the purview of hadron colliders**

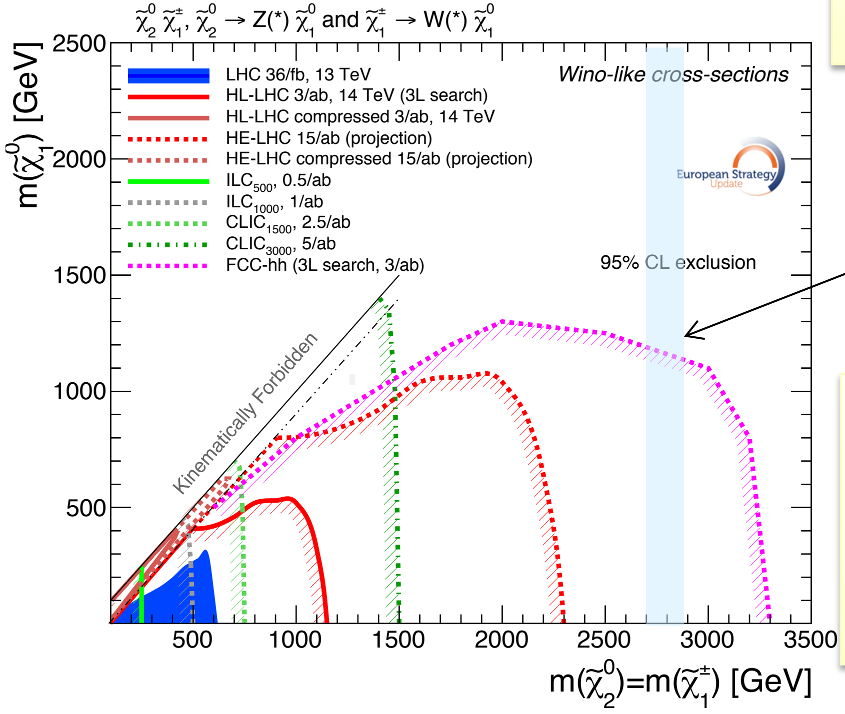




HE-LHC: ~ 2 x $M_{\text{HL-LHC}}$
FCChh: ~ 5 x $M_{\text{HL-LHC}}$

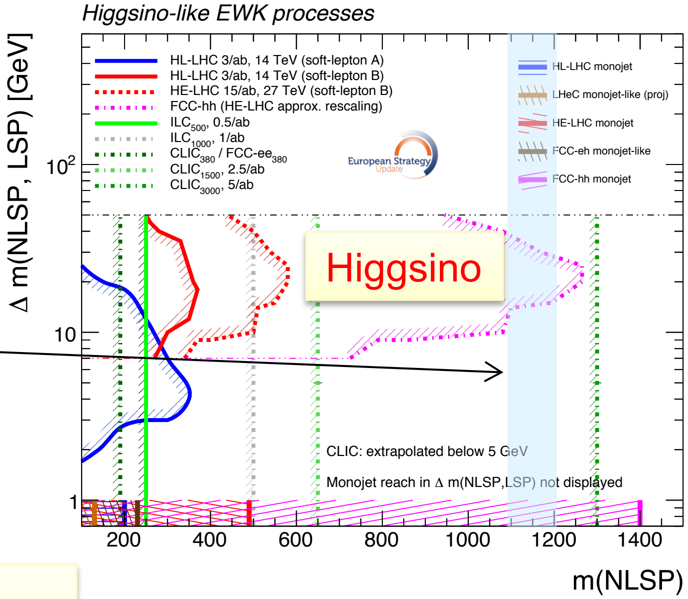
Long-term future: SUSY EWK sector

ee: mainly $\chi^0_2\chi^0_1$ and $\chi^+_1\chi^-_1$ (Δm>1GeV)
pp: mainly $\chi^0_2\chi^\pm_1$ (gaps at low Δm)



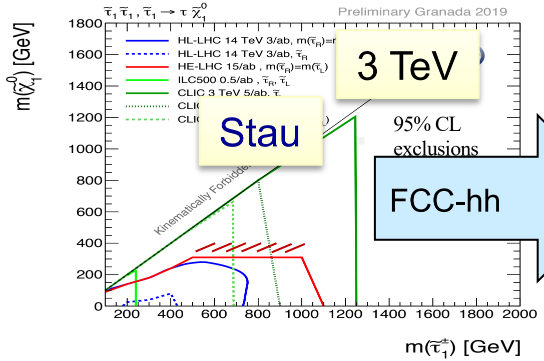
ee sensitivity ~independent of nature of LSP (but up to √s/2)

Thermal WIMP



Higgsino

pp sensitivity: depends on LSP; ISR jet for very low Δm (up to ~5 GeV); Pure Higgsino: stopped track



3 TeV

Stau

FCC-hh

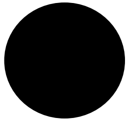
Beyond the Standard Model (II)

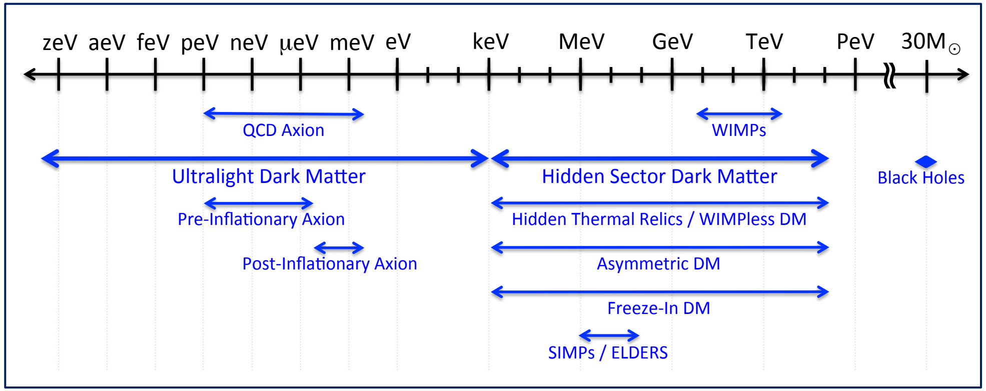
The Dark Sector

Feebly Interacting Particles

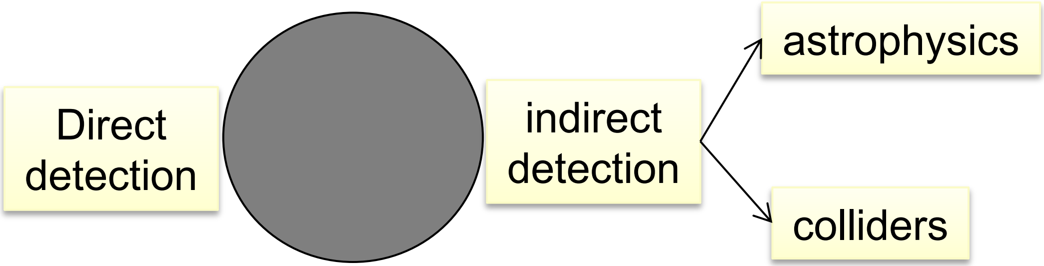
The Dark Sector

- **An experimental fact & yet, still a total mystery**
  - **And masses span over 80 orders of magnitude**
- **Nightmare scenario: totally dark**
  - **Only Gravity to play with…**





- **More promising: some shade of grey**



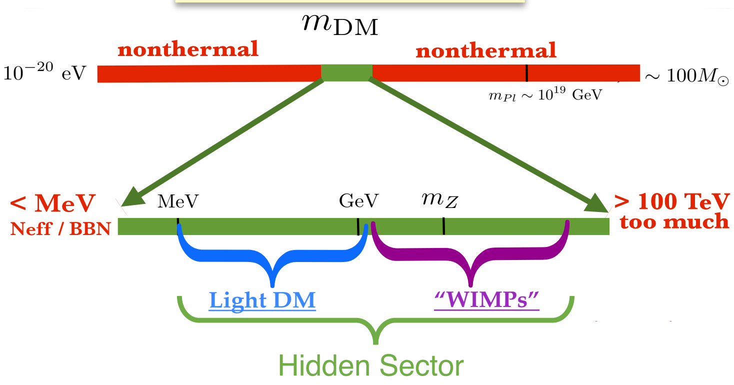
Direct detection

indirect detection

astrophysics

colliders

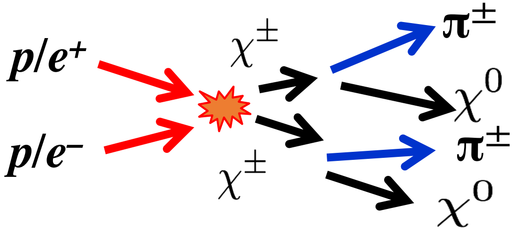
Thermal WIMPs



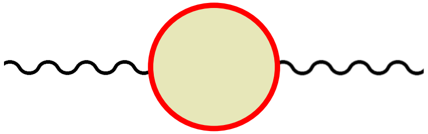
DM: Classic WIMPs

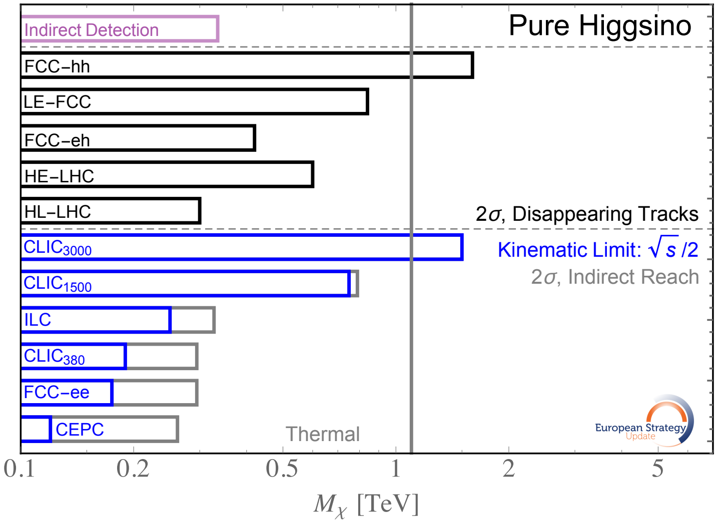
- **Two (SUSY) "extremes", pure Wino, pure Higgsino**
  - **Main "tools": disappearing track, propagator modifications**

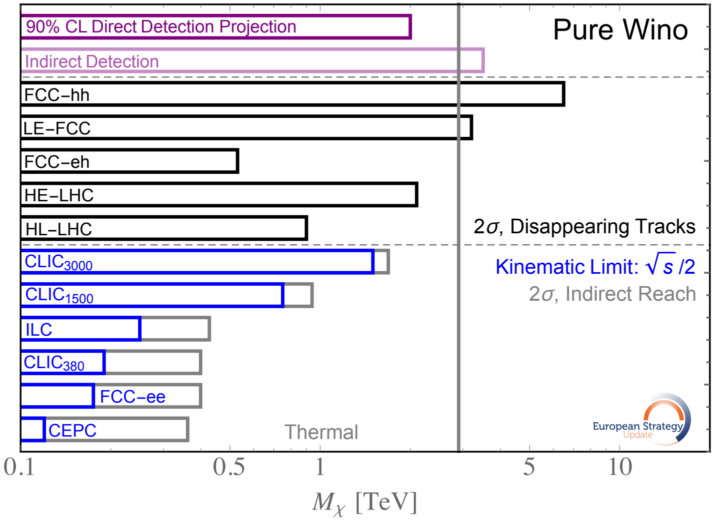
For small Δm, soft $\pi^{\pm}$...



EWKinos in loop change prop (W, Y parameters)

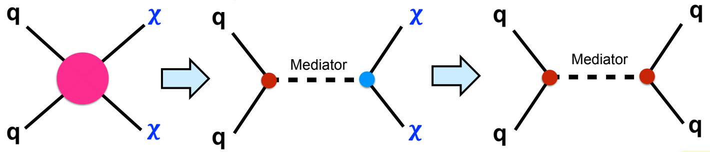






Simplified Models: (axial)vector&(pseudo)scalar mediator

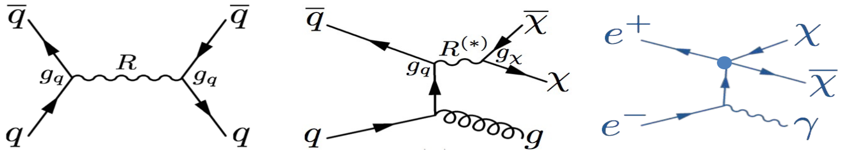
- **Light DM, m_χ=1GeV**



$$\frac{g_q g_\chi}{M^2-q^2} \approx \frac{g_q g_\chi}{M^2}\left(1+\frac{q^2}{M^2}+\cdots\right) = \frac{1}{\Lambda^2}\left(1+\frac{q^2}{M^2}+\cdots\right)$$

V/A: g_χ=1,g_q=0.25
P/S: g_χ=g_q=1

Resonances + mono-object (photon, jet, top, W/Z…)

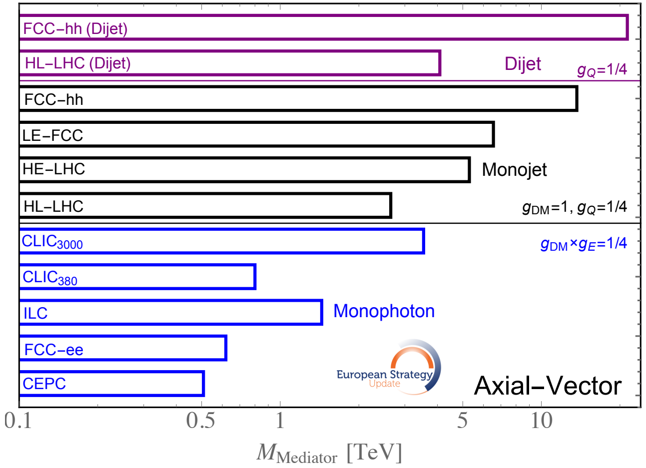


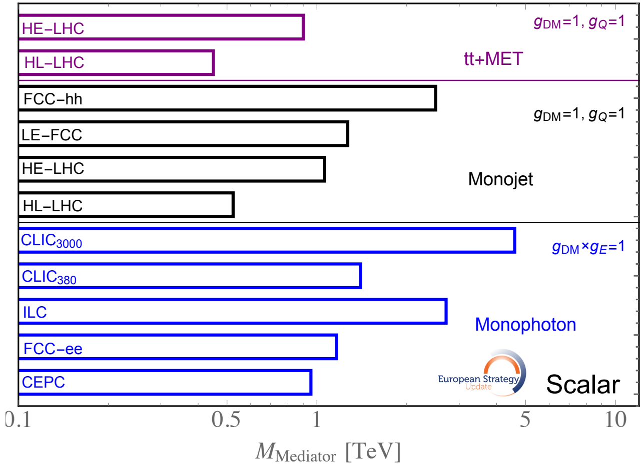
pp: assumes mediator couplings to quarks only.
750 GeV, HL-LHC
1.5 TeV, HE-LHC
3.9 TeV for FCC-hh
Note: Dependence on couplings!

ee: assumes mediator couplings to leptons only. Also in EFT limit, so can be easily rescaled for modified couplings.

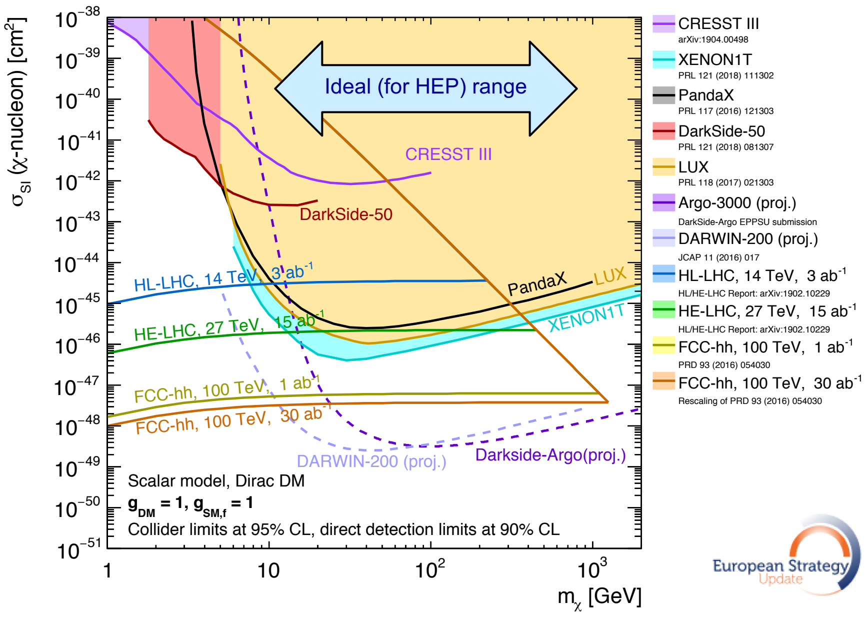
Note: taking EFT scale as free parameter, M_{DM} reach ~kinematic reach of collider.

Significant model dependence. UV models may have comparable quark and lepton couplings. If both present, can also use dilepton resonances.



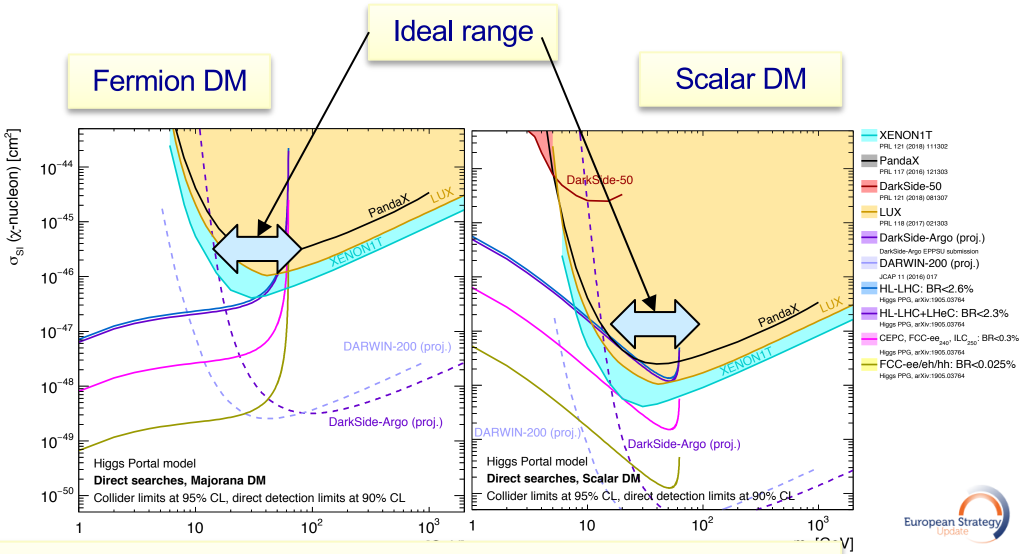


Scalar mediator: Higgs portal and BSM scalar



A collider discovery will need confirmation from DD/ID for cosmological origin

A DD/ID discovery will need confirmation from colliders to understand the nature of the interaction



A future collider program that optimizes sensitivity to invisible particles coherently with DD/ID serves us well. Need maximum overlap with DD/ID!

Feebly Interacting Particles (FIPs)

- **FIP mass(es) can span several orders of magnitude**
  - Though there are preferred regions for motivated models (Dark photon for thermal dark matter, relaxion in its natural region, right-handed neutrinos below EW scale down to the see-saw limit) that are within reach for accelerator-based experiments
- **Very (very…) wide range of possibilities .AND. Models**
  - How to search for such broad class of models? → Simplified models
  - How to compare frontiers & Experiments? → Use benchmarks.
  - Simplified models: four “portals”

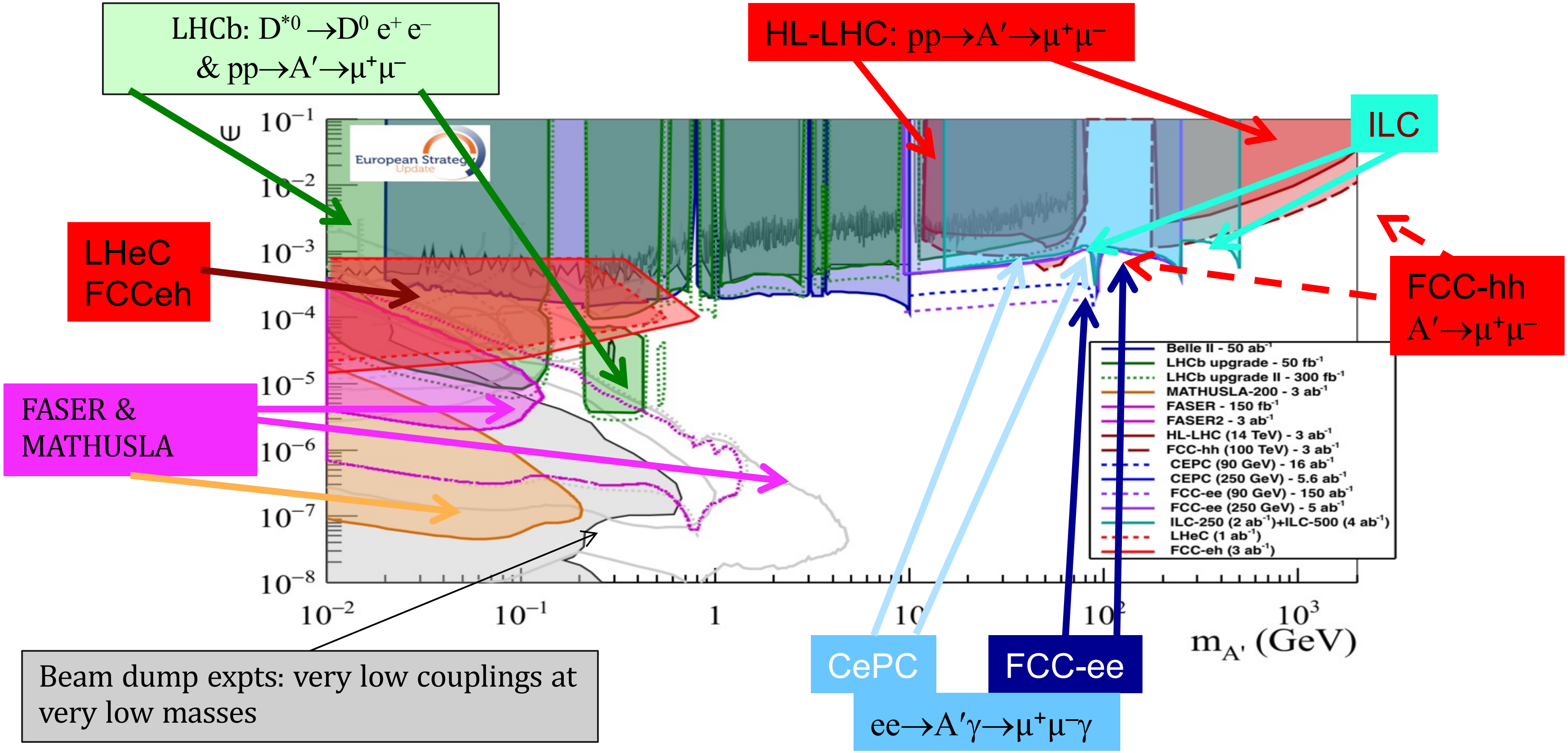
PBC report, arXiv:1901.09966

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

(Relaxion toy model, mixes \w Higgs)

- **Beam dump and collider experiments: complementary in reach**
  - Very significant reach in several places. Not exhaustive – but this is only the beginning.
    - Physics Beyond Colliders effort…
  - From portals: identify benchmark cases to evaluate experimental sensitivities. Common ground to compare machines/experiments and put them in worldwide context

FIPs: Example from Vector Portal (Dark Photon)



LHCb: $D^{*0} \to D^0 e^+ e^-$
& $pp \to A' \to \mu^+\mu^-$

HL-LHC: $pp \to A' \to \mu^+\mu^-$

ILC

LHeC
FCCeh

FCC-hh
$A' \to \mu^+\mu^-$

FASER &
MATHUSLA

Beam dump expts: very low couplings at very low masses

CePC

FCC-ee

$ee \to A'\gamma \to \mu^+\mu^-\gamma$

FIPs represent a new paradigm that requires systematic exploration on multiple fronts

Physics of Flavor

Neutrinos

Quarks

Charged Leptons

Super-brief Intro: from hopeless to lucky strike(s)

From invisible particle ($\sigma \sim 10^{-44} \mathrm{cm}^2$ @ $E_\nu \sim 2$ MeV) to major source of physics:
From Pontecorvo's few/day/ton with $\sim 10^{11} \nu/\mathrm{cm}^2/\mathrm{s}$ to → PMNS matrix & CP violation(?!?!)

$$P(\nu_\alpha \to \nu_\beta) \;=\; \sin^2 2\theta \, \sin^2\left(1.27 \frac{\Delta m^2(\mathrm{eV}^2)\, L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right) \qquad P(\nu_\alpha \to \nu_\alpha) \;=\; 1 - P(\nu_\alpha \to \nu_\beta)$$

SuperK, SNO: large mixing; good Δm
$\Delta m^2_{\mathrm{sol}} \approx 7 - 8 \times 10^{-5} \mathrm{eV}^2$

IMB, Kamiokande, Soudan(2)… SuperK:
large mixing; super Δm: $\Delta m^2_{\mathrm{atm}} \approx 2.5 \times 10^{-3} \mathrm{eV}^2$

$\Delta m^2_{\mathrm{sol}} \sim E_\nu(\mathrm{MeV})/\mathrm{L}(100\,\mathrm{km})$
→ Reactors! → KamLAND

$\Delta m^2_{\mathrm{atm}} \sim E_\nu(\mathrm{MeV})/\mathrm{L}(100\,\mathrm{m}) = (\mathrm{GeV})/(100\,\mathrm{km})$
→ Accelerators! → K2K, MINOS(+),…, T2K, NOVA
+ Short baselines: Daya Bay, RENO, …, xBOONe

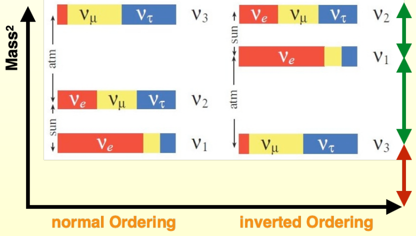
ν physics: PMNS; 3x3 or 4x4? nature (Majorana or Dirac); mass ordering

$$U_{3\times3} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times (U_{\mathrm{Maj}})$$

atmospheric + accelerator disapp

SBL reactor + accelerator app

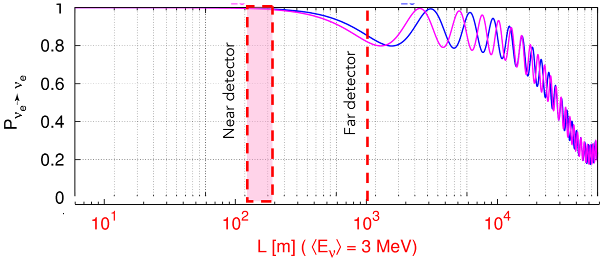
solar + KamLAND



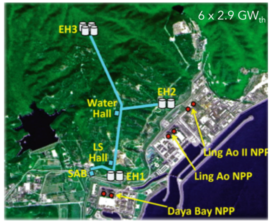
Neutrinos: Reactor expts, Short Baselines

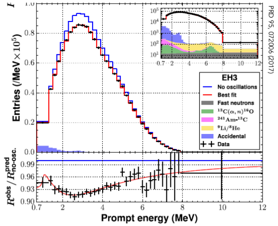
Principle: θ_{13}

$P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta_{13})\sin^2(\Delta m^2 L/E)$



The prized measurement

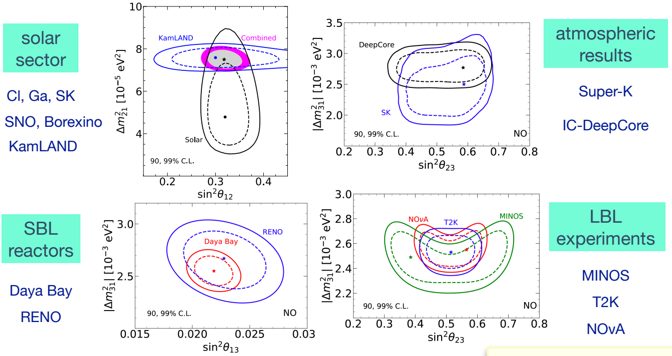




Third lucky strike (in ν phys)

$$J_{\rm CP}^{\rm lep} = \mathrm{Im}(U_{\mu3}U^*_{e3}U_{e2}U^*_{\mu2}) = (1/8)\times$$
$$\times \sin 2\theta_{12}\,\sin 2\theta_{23}\,\sin 2\theta_{13}\cos\theta_{13}\sin\delta_{\rm CP}$$
$$\approx 0.033\sin\delta_{\rm CP}\quad \text{BUT}: J^{\rm q}_{\rm CP} \approx 3\times10^{-5}$$

- **Long series of measurements have brought us to a "precision era"**



M. Tortola ICHEP2020

de Salas et al, arXiv:2006.11237

parameter	best fit ± 1σ	3σ range	relative 1σ uncertainty
Δm^2_{21} [10^{-5}eV^2]	$7.50^{+0.22}_{-0.20}$	6.94–8.14	2.7%
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (NO)	$2.56^{+0.03}_{-0.04}$	2.46–2.65	1.2%
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (IO)	2.46 ± 0.03	2.37–2.55	
$\sin^2\theta_{12}$ /10^{-1}	3.18 ± 0.16	2.71–3.70	5.2%
$\sin^2\theta_{23}$ /10^{-1} (NO)	$5.66^{+0.16}_{-0.22}$	4.41–6.09	4.9%
$\sin^2\theta_{23}$ /10^{-1} (IO)	$5.66^{+0.18}_{-0.23}$	4.46–6.09	4.8%
$\sin^2\theta_{13}$ /10^{-2} (NO)	$2.225^{+0.055}_{-0.078}$	2.015–2.417	3.0%
$\sin^2\theta_{13}$ /10^{-2} (IO)	$2.250^{+0.056}_{-0.076}$	2.039–2.441	
δ/π (NO)	$1.20^{+0.23}_{-0.14}$	0.80–2.00	17%
δ/π (IO)	1.54 ± 0.13	1.14–1.90	8%

3-5%

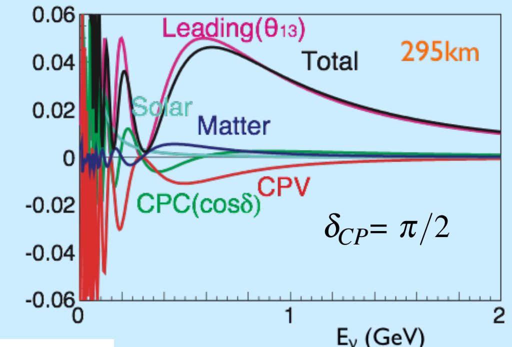
Neutrinos: oscillations & CPV

- **Currently (NOvA and T2K) a bit confused**

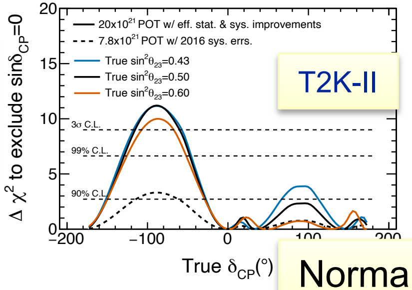
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \; = \; & \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta_{31}] \\
+ \; & \alpha^2\cos^2\theta_{23}\frac{\sin^2 2\theta_{12}}{A^2}\sin^2(A\Delta_{31}) \\
- \; & \alpha\frac{\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}\sin\delta_{CP}}{A(1-A)}\sin\Delta_{31}\sin(A\Delta_{31})\sin[(1-A)\Delta_{31}] \\
+ \; & \alpha\frac{\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}\cos\delta_{CP}}{A(1-A)}\cos\Delta_{31}\sin(A\Delta_{31})\sin[(1-A)\Delta_{31}]
\end{aligned}
$$

Favored (slightly): Normal Ordering & δ_{CP}~3π/2

But… fits are complicated

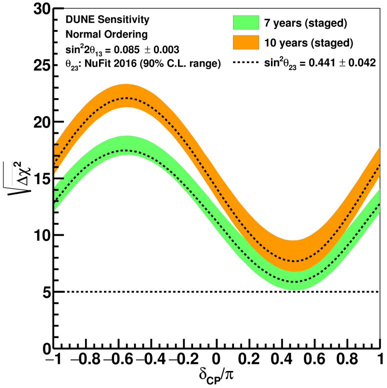


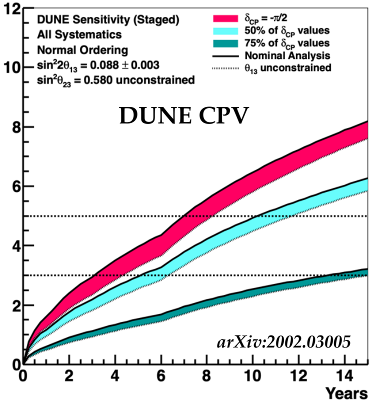
Unknown mass order

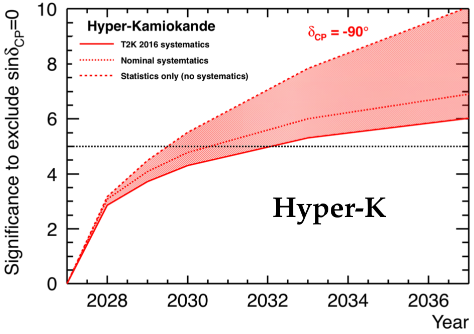


T2K-II

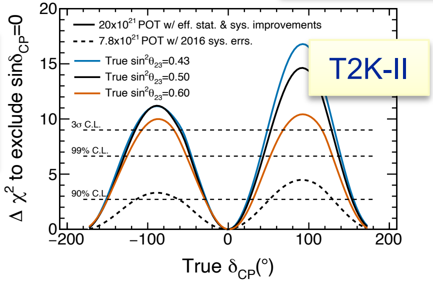
NormalO







Known mass order

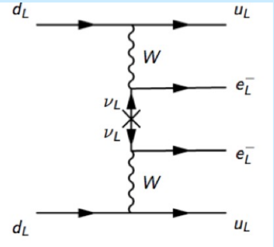


T2K-II

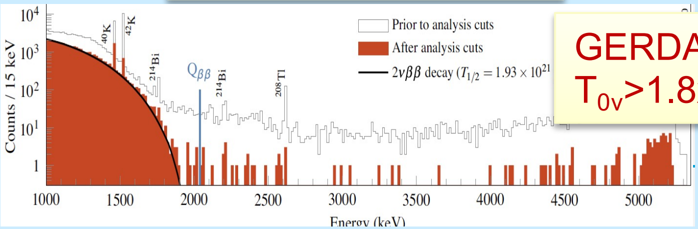
Very useful/nice: complementarity of NOvA/T2K and DUNE/HyperK: baseline (1300 vs 200 km) and detection technique

Neutrinos: Majorana/Dirac (0νββ) & mass measurement

As fundamental as a question can get & very hard to answer



$$(T_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot |m_{\beta\beta}|^2$$

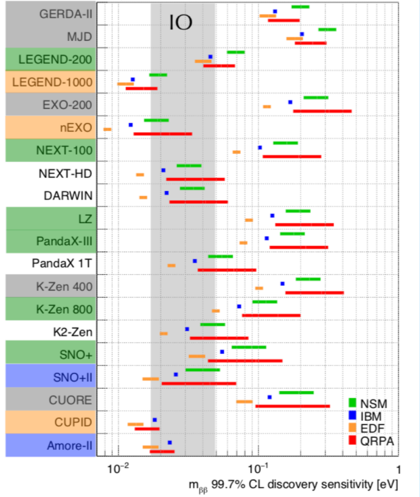


GERDA
$T_{0\nu} > 1.8 \times 10^{26}$ yr

Extremely active field

(J. Detwiler @ Neutrino2020)

- Bolometers (CUPID, AMoRE, CANDLES IV)
  - Measure *E* (σ ~ 0.1-0.3%) from phonons; granularity gives position info
  - Instrumenting with photon detectors for background rejection
- External trackers (SuperNEMO)
  - Trackers + calorimeters, measure *E* (σ ~ 3-10%) + tracks / positions + PID
- Scintillators (KamLAND2-Zen, SNO+, Theia, ZICOS)
  - Measure *E* (σ ~ 3-10%) + position from scintillation light; some PID
- Semiconductors (LEGEND, SELENA)
  - Measure *E* (σ ~ 0.05-0.3%) from ionization; some tracking / position sensitivity
- TPCs (nEXO, NEXT, PandaX, AXEL, NvDEx, DARWIN, LZ)
  - Collect scintillation + ionization: measure *E* (σ ~0.4-3%) + tracks / position + PID

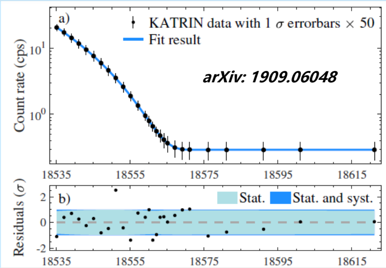


(But) one example: EXO-200 (0.2 t) → nEXO (5 t)
Xe; $T_{1/2} < 3.5 \times 10^{25}$ yr → $T_{1/2} < 10^{28}$ yr

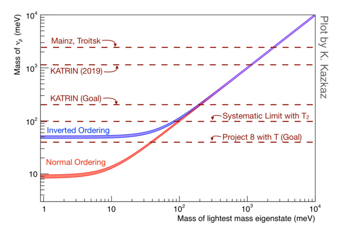
Mass limits (measurements…)

Today (BAO +struct. form):
$\Sigma m_\nu < 0.12$ (95% CL)
Ultimate (DESI+BAO): $\Sigma m_\nu < 0.02$

Direct m_ν measurement(s)
KATRIN: $m_\beta < 1.1$ eV (90% CL)
Asymptotic: $m_\beta < 0.2$ eV
Ultimate (Project-8): 40 meV



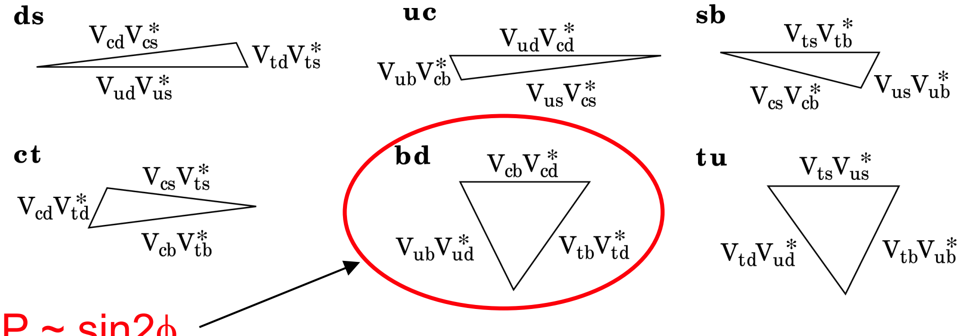
arXiv: 1909.06048



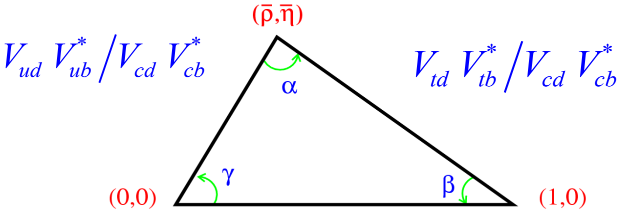
Flavor physics: quark sector (I)

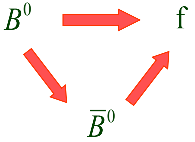
$$V_{CKM} = \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

$$\mathbf{V}_{ui}\,\mathbf{V}_{uj}^{*} + \mathbf{V}_{ci}\,\mathbf{V}_{cj}^{*} + \mathbf{V}_{ti}\,\mathbf{V}_{tj}^{*} = 0$$



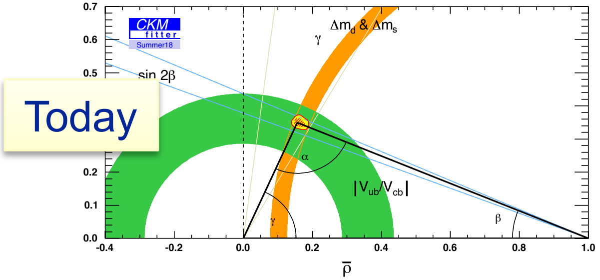
CP ~ sin2ϕ



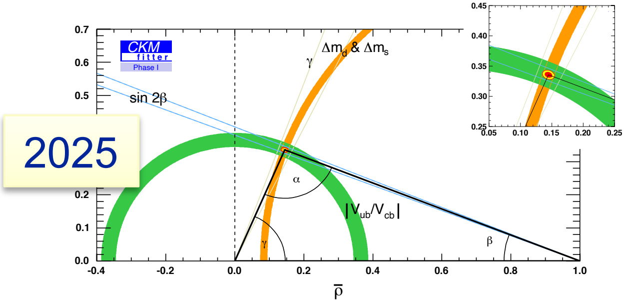


$$\frac{\Gamma(\bar B^0 \to \bar f) - \Gamma(B^0 \to f)}{\Gamma(\bar B^0 \to \bar f) + \Gamma(B^0 \to f)} = -\eta_f\ \sin(2\phi)\ \sin(\Delta M\, t)$$

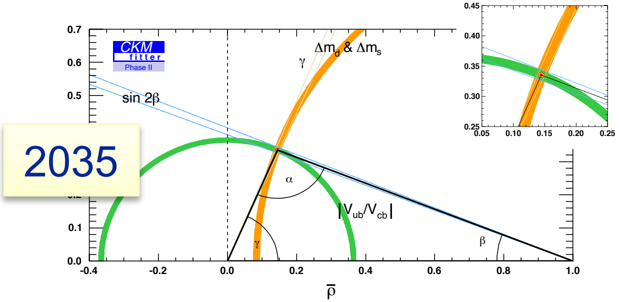
CKM triangle: extensive precision program en route



Today



2025



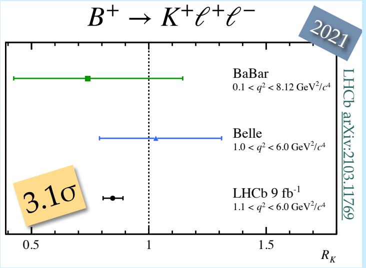
2035

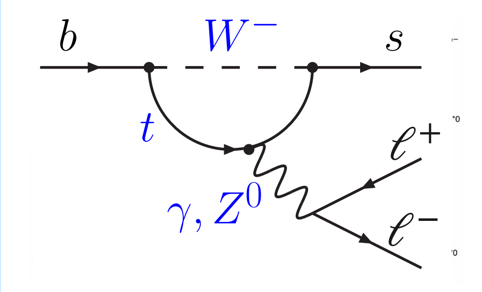
Flavor physics: quark sector (II)

Lots of attention on Lepton Universality.

$b \to s\ell^+\ell^-$

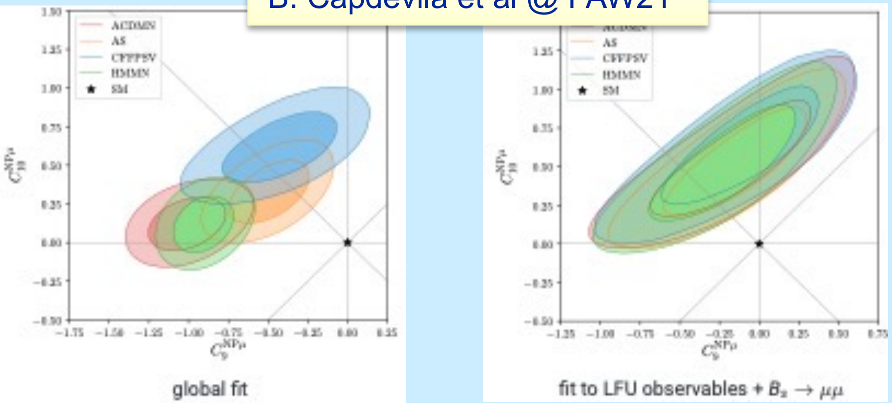
$R_K = \mu\mu K / eeK \quad R_{K^*} = \mu\mu K^* / eeK^*$





+semileptonic + ang. distrib.

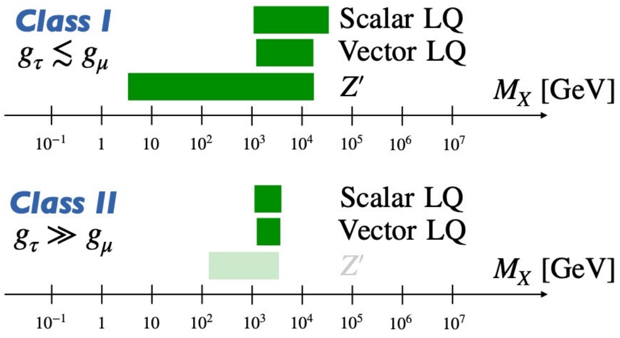
B. Capdevila et al @ FAW21*

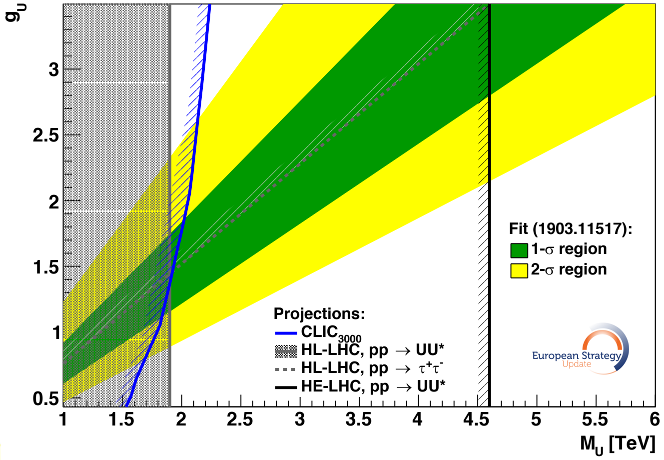


global fit

fit to LFU observables + $B_s \to \mu\mu$

A. Greljo @ FAW21*

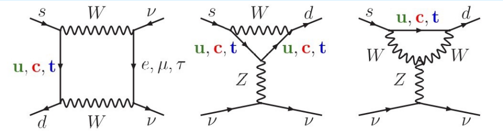




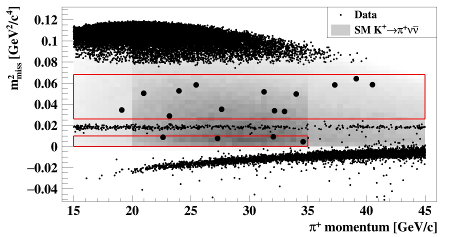
*Unpaid ad for FAW21: Flavour Anomaly Workshop 2021

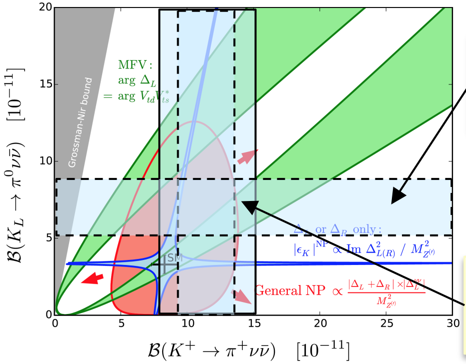
Flavor physics: quark sector (III)

Today: NA62



$$(K^+ \to \pi^+ \nu\bar{\nu}) = \left(11.0^{+4.0}_{-3.5}\right) \times 10^{-11}$$





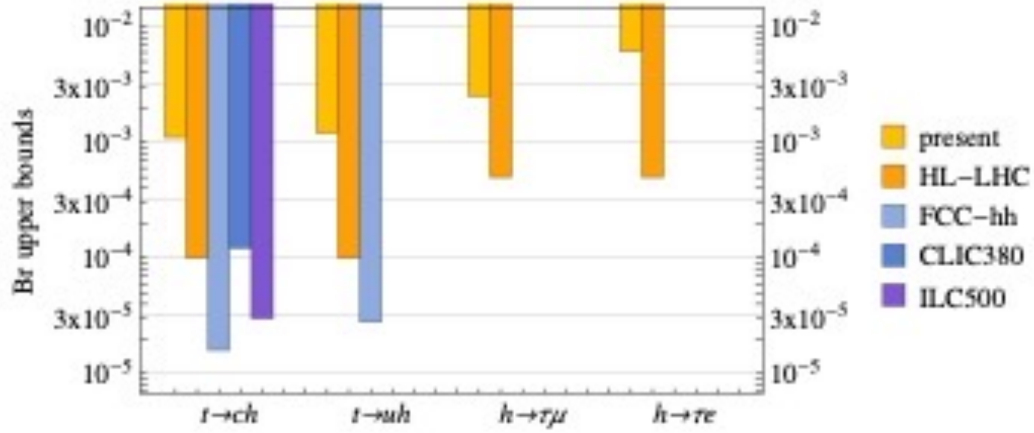
KOTO 2
KLEVER

NA62
(today+guess)

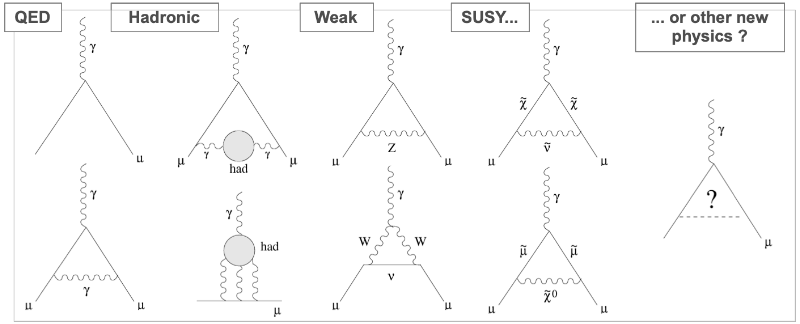
FCNC in top decays

$BR \times 10^5$	HL-LHC	HE-LHC	ILC_{500}	CLIC_{380}	LHeC	FCC-ee	FCC-hh	FCC-eh
$t \to Zq$	2.4 - 5.8		[illegible]	[illegible]	4	2.4	≈ 0.1	0.6
$t \to \gamma c$	7.4		≈ 1	2.6			0.024	
$t \to \gamma u$	0.86						0.018	
$t \to \gamma q$					1	1.7		0.085
$t \to gc$	3.2	0.19						
$t \to gu$	0.38	0.056						

FCNC with higgs decays



Muon $a_\mu = g_\mu - 2$

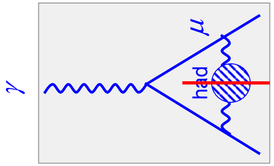


$$a_\mu^{\mathrm{QED}} = \frac{\alpha}{2\pi} + A_2\left(\frac{\alpha}{\pi}\right)^2 + A_3\left(\frac{\alpha}{\pi}\right)^3 + A_4\left(\frac{\alpha}{\pi}\right)^4 + A_5\left(\frac{\alpha}{\pi}\right)^5$$

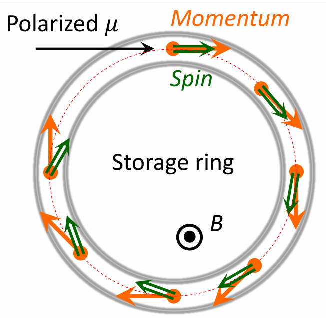
$$a_\mu^{\mathrm{EW}} = 153.6\,(1.0) \times 10^{-11}$$

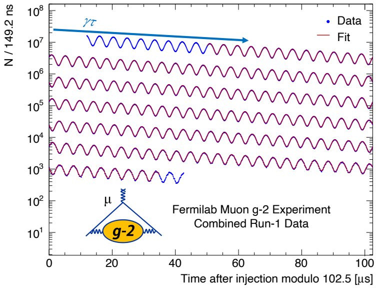
$$a_\mu^{\mathrm{HLbL}} = 94\,(19) \times 10^{-11}$$

Main uncertainty: Hadronic Vaccum Polarization

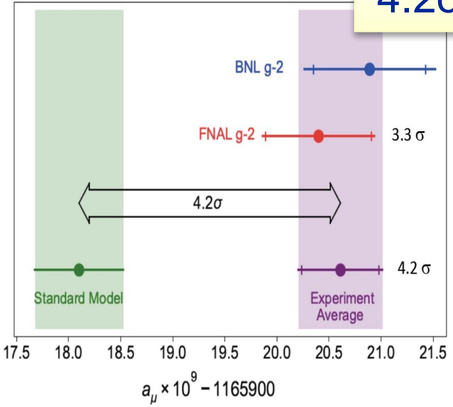


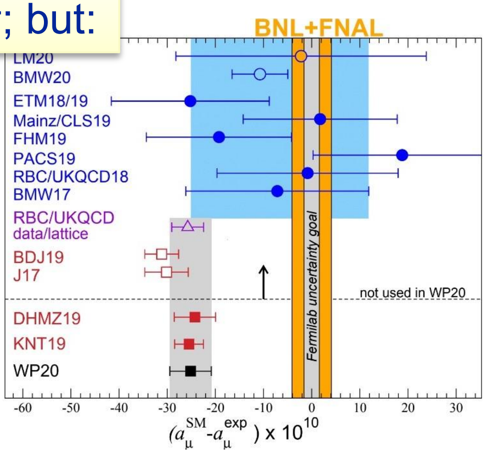
Low-energy e^+e^- or Lattice QCD

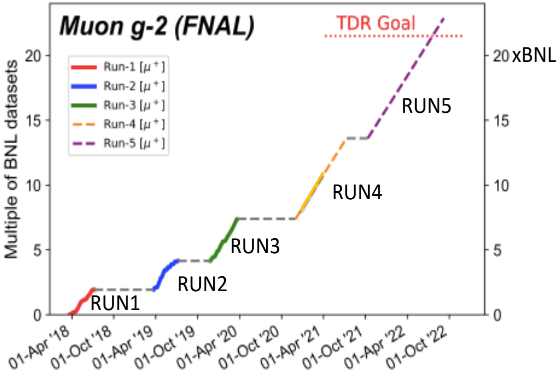




4.2σ; but:

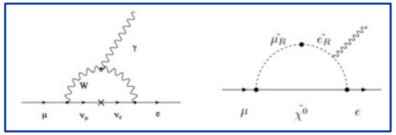




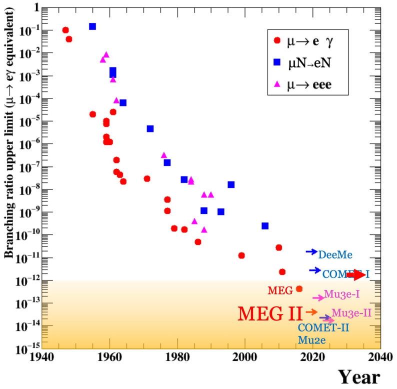


Flavor physics: charged lepton sector & summary

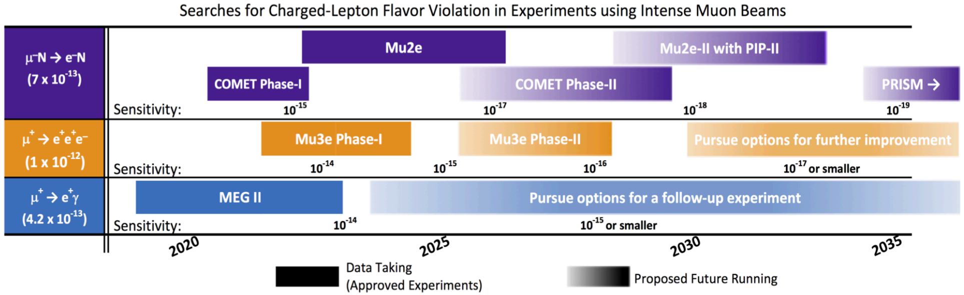
Final MEG upper limit
B(μ→eγ)<4.2 10^{-13}
@90% CL: there
since 2016…



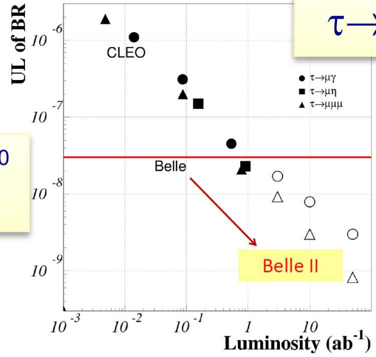
Muon LFV quiet since 2016…
Exciting times ahead with
MEGII, Mu2e, COMET, Mu3e…



μ→eγ
μ→eee
μN→eN

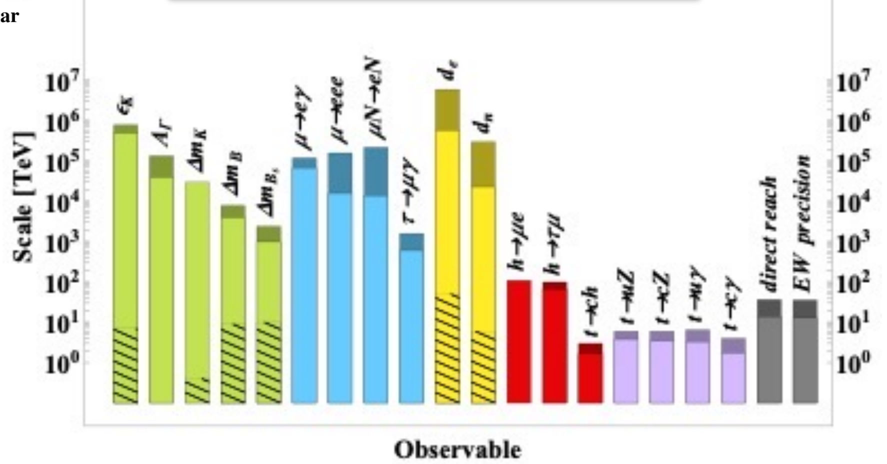


τ→μμμ



Expect 5x10^{10}
ττ evts…

Qualitative summary



Pseudo-summary

And, of course, the “other” issues

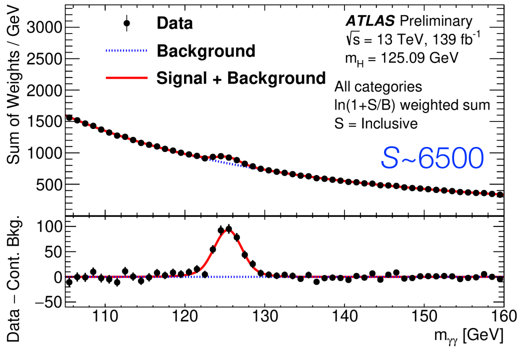
Pseudosummary/Outlook

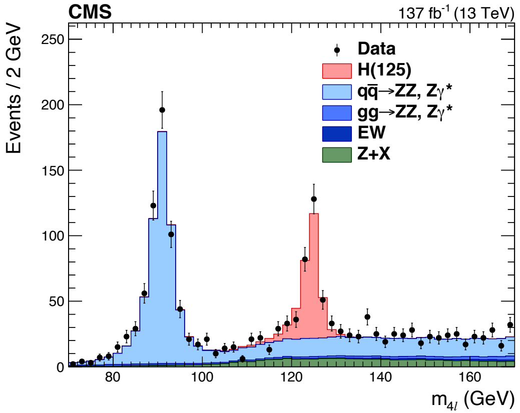
- Extremely rich physics program ahead to understand the scalar sector
  - The LHC and HL-LHC will get us to 3-5% couplings;
  - All options for a Higgs “factory” bring in ~O(10^{-2}–10^{-3}) understanding of couplings.
  - Important aspects: EWPO (needs next-gen Z factory) and top threshold.
    - Actually, the linear and circular options are quite complementary…
  - Fundamental scalar? Probe to 15-18 TeV. HE ee and pp colliders offer supplementary information.
  - FCC-ee/hh combination has the largest direct reach to new particles/phenomena. From new particles to Higgs self-coupling to Dark Matter searches…
- Dark Matter:
  - Complementarity with indirect searches at colliders (and astroparticle expts).
  - Next-gen colliders can cover the thermal WIMP scenario.
- Flavor Physics: neutrinos have all one could ask for (albeit it with small σ_{int}). But quark sector may hold the first genuine surprises(?)
  - In the next 5-10 years: could get very pleasant news on CP front. Definitive statement of mass hierarchy and CP from the full program (DUNE and HyperK).
    - Again: complementarity also important here.
  - Quark sector: the current situation will be resolved in the next five years. If current small deviations confirmed: we will have the first experimental evidence for New Physics from the current collider HEP program.
    - Kaon program complementary; Very important ongoing experiments on charged lepton flavor studies.
- It is the best of times; as long as there is (soon) an international move towards a new collider.

Backups

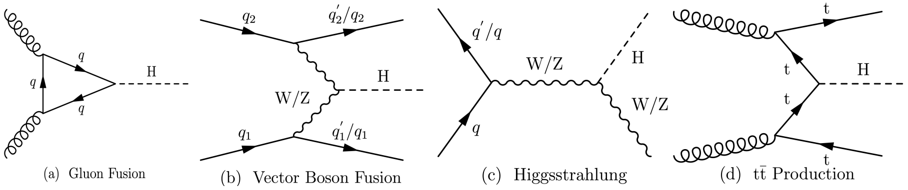
Higgs physics: probing its couplings/properties

Current LHC: increased stats…

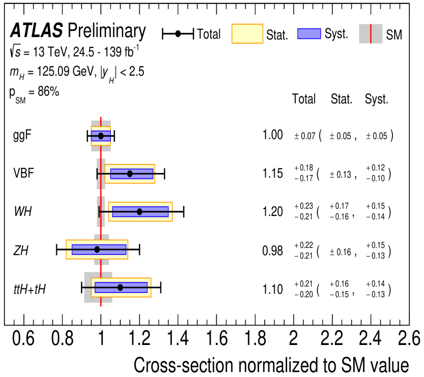




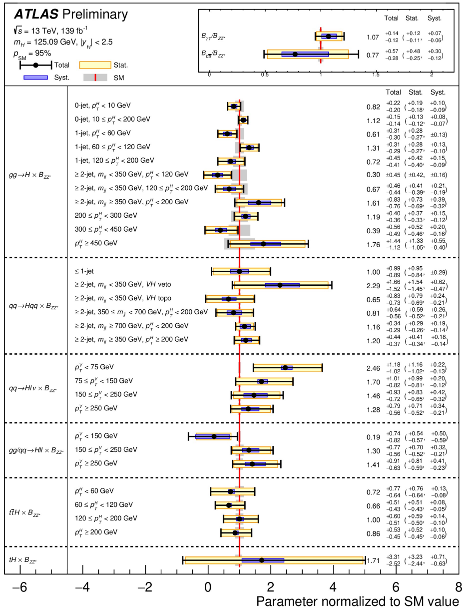
Production mechanisms, differential distributions



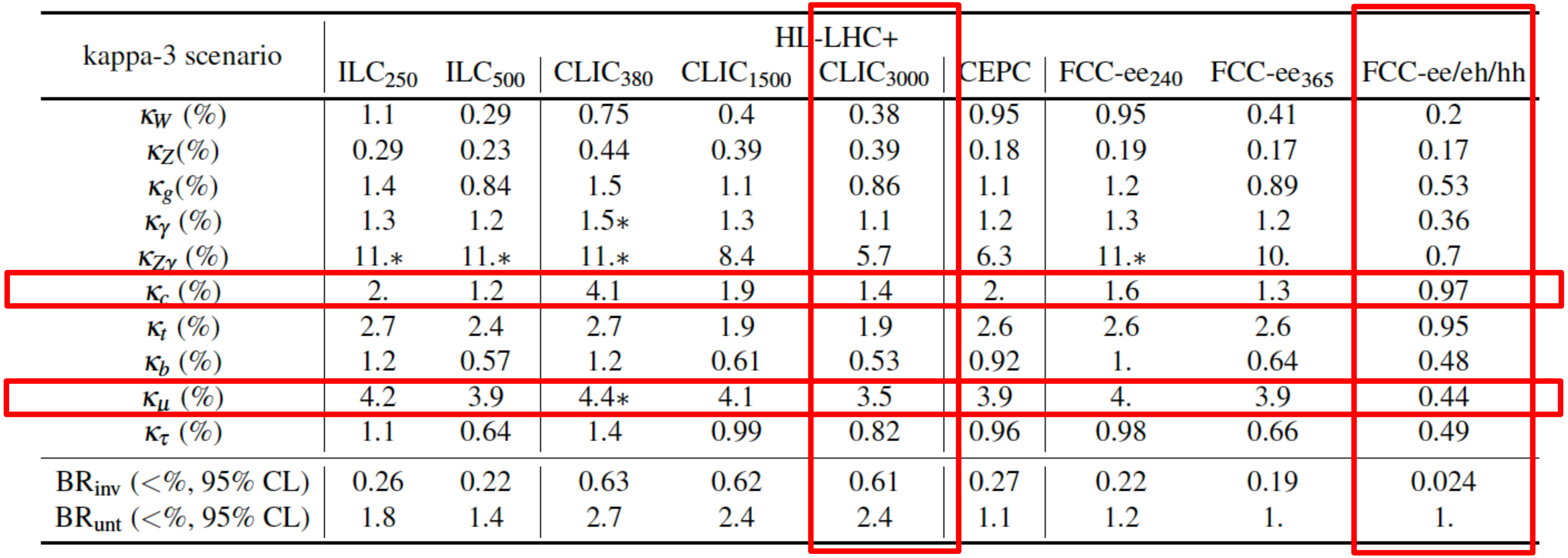
(a) Gluon Fusion (b) Vector Boson Fusion (c) Higgsstrahlung (d) $t\bar{t}$ Production



$$\boxed{\mu = 1.06 \pm 0.07}$$



Grand summary



kappa-3 scenario					HL-LHC+				
	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCC\text{-}ee_{240}$	$FCC\text{-}ee_{365}$	FCC-ee/eh/hh
κ_W (%)	1.1	0.29	0.75	0.4	0.38	0.95	0.95	0.41	0.2
κ_Z(%)	0.29	0.23	0.44	0.39	0.39	0.18	0.19	0.17	0.17
κ_g(%)	1.4	0.84	1.5	1.1	0.86	1.1	1.2	0.89	0.53
κ_γ (%)	1.3	1.2	1.5∗	1.3	1.1	1.2	1.3	1.2	0.36
$\kappa_{Z\gamma}$ (%)	11.∗	11.∗	11.∗	8.4	5.7	6.3	11.∗	10.	0.7
κ_c (%)	2.	1.2	4.1	1.9	1.4	2.	1.6	1.3	0.97
κ_t (%)	2.7	2.4	2.7	1.9	1.9	2.6	2.6	2.6	0.95
κ_b (%)	1.2	0.57	1.2	0.61	0.53	0.92	1.	0.64	0.48
κ_μ (%)	4.2	3.9	4.4∗	4.1	3.5	3.9	4.	3.9	0.44
κ_τ (%)	1.1	0.64	1.4	0.99	0.82	0.96	0.98	0.66	0.49
BR_{inv} (<%, 95% CL)	0.26	0.22	0.63	0.62	0.61	0.27	0.22	0.19	0.024
BR_{unt} (<%, 95% CL)	1.8	1.4	2.7	2.4	2.4	1.1	1.2	1.	1.

All ee colliders achieve major (and comparable) improvements in their first stage already in probing Higgs sector compared to HL-LHC: at least half of the couplings get improved by factor 5 or more

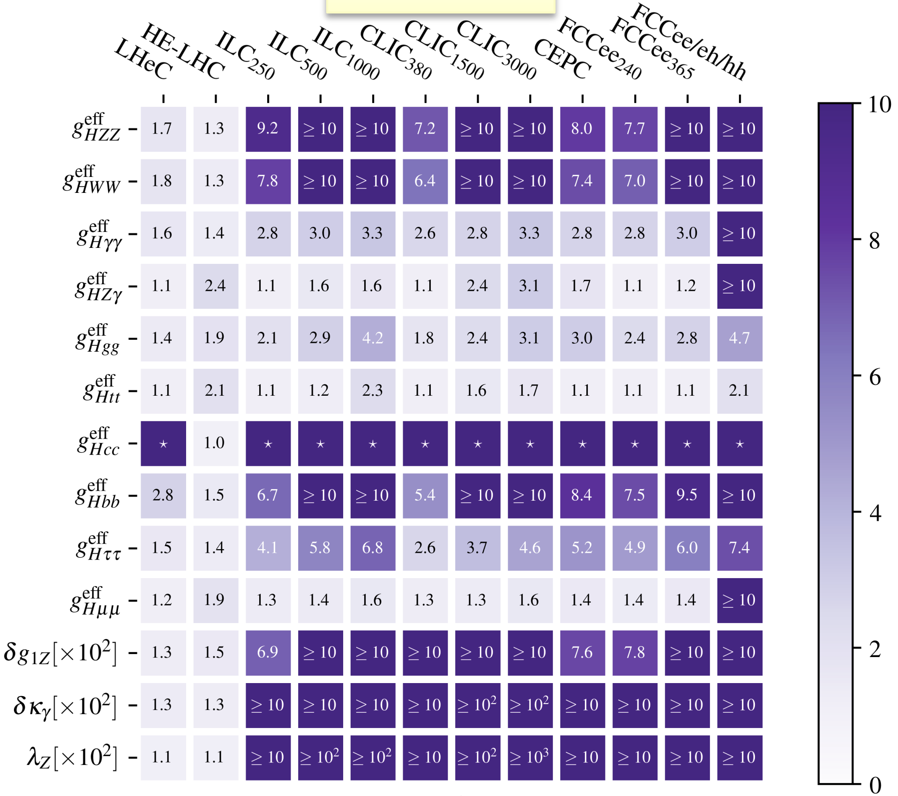
W/Z effective couplings and BR(H → invisible) probed to ~3×10^{-3}

Model-independent total cross section measurement → access to width, untagged BR

Clean environment to study H if/when anomalies are seen to understand underlying physics

Higgs couplings: SMEFT

Absolute

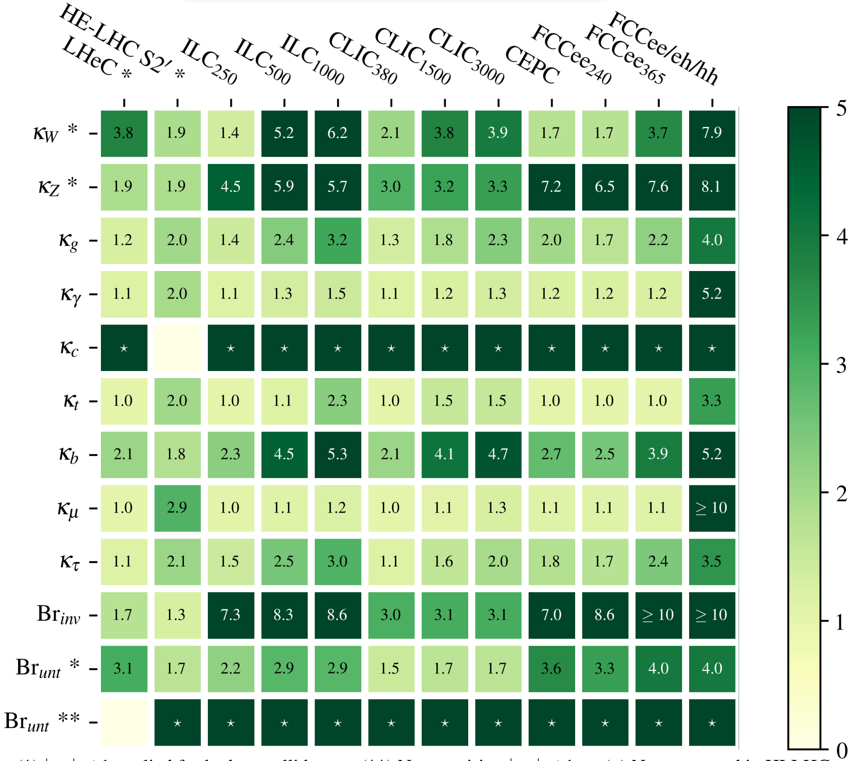


	LHeC	HE-LHC	ILC$_{250}$	ILC$_{500}$	ILC$_{1000}$	CLIC$_{380}$	CLIC$_{1500}$	CLIC$_{3000}$	CEPC	FCCee$_{240}$	FCCee$_{365}$	FCCee/eh/hh
g^{eff}_{HZZ}	1.7	1.3	9.2	≥ 10	≥ 10	7.2	≥ 10	≥ 10	8.0	7.7	≥ 10	≥ 10
g^{eff}_{HWW}	1.8	1.3	7.8	≥ 10	≥ 10	6.4	≥ 10	≥ 10	7.4	7.0	≥ 10	≥ 10
$g^{\mathrm{eff}}_{H\gamma\gamma}$	1.6	1.4	2.8	3.0	3.3	2.6	2.8	3.3	2.8	2.8	3.0	≥ 10
$g^{\mathrm{eff}}_{HZ\gamma}$	1.1	2.4	1.1	1.6	1.6	1.1	2.4	3.1	1.7	1.1	1.2	≥ 10
g^{eff}_{Hgg}	1.4	1.9	2.1	2.9	4.2	1.8	2.4	3.1	3.0	2.4	2.8	4.7
g^{eff}_{Htt}	1.1	2.1	1.1	1.2	2.3	1.1	1.6	1.7	1.1	1.1	1.1	2.1
g^{eff}_{Hcc}	⋆	1.0	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
g^{eff}_{Hbb}	2.8	1.5	6.7	≥ 10	≥ 10	5.4	≥ 10	≥ 10	8.4	7.5	9.5	≥ 10
$g^{\mathrm{eff}}_{H\tau\tau}$	1.5	1.4	4.1	5.8	6.8	2.6	3.7	4.6	5.2	4.9	6.0	7.4
$g^{\mathrm{eff}}_{H\mu\mu}$	1.2	1.9	1.3	1.4	1.6	1.3	1.3	1.6	1.4	1.4	1.4	≥ 10
$\delta g_{1Z}[\times 10^2]$	1.3	1.5	6.9	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	7.6	7.8	≥ 10	≥ 10
$\delta\kappa_\gamma[\times 10^2]$	1.3	1.3	≥ 10	≥ 10	≥ 10	≥ 10	$\geq 10^2$	$\geq 10^2$	≥ 10	≥ 10	≥ 10	≥ 10
$\lambda_Z[\times 10^2]$	1.1	1.1	≥ 10	$\geq 10^2$	$\geq 10^2$	≥ 10	$\geq 10^2$	$\geq 10^3$	≥ 10	≥ 10	≥ 10	≥ 10

SMEFT ND

(⋆) not measured at HL-LHC

Gain wrt HL-LHC



	LHeC *	HE-LHC S2′ *	ILC$_{250}$	ILC$_{500}$	ILC$_{1000}$	CLIC$_{380}$	CLIC$_{1500}$	CLIC$_{3000}$	CEPC	FCCee$_{240}$	FCCee$_{365}$	FCCee/eh/hh
κ_W *	3.8	1.9	1.4	5.2	6.2	2.1	3.8	3.9	1.7	1.7	3.7	7.9
κ_Z *	1.9	1.9	4.5	5.9	5.7	3.0	3.2	3.3	7.2	6.5	7.6	8.1
κ_g	1.2	2.0	1.4	2.4	3.2	1.3	1.8	2.3	2.0	1.7	2.2	4.0
κ_γ	1.1	2.0	1.1	1.3	1.5	1.1	1.2	1.3	1.2	1.2	1.2	5.2
κ_c	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
κ_t	1.0	2.0	1.0	1.1	2.3	1.0	1.5	1.5	1.0	1.0	1.0	3.3
κ_b	2.1	1.8	2.3	4.5	5.3	2.1	4.1	4.7	2.7	2.5	3.9	5.2
κ_μ	1.0	2.9	1.0	1.1	1.2	1.0	1.1	1.3	1.1	1.1	1.1	≥ 10
κ_τ	1.1	2.1	1.5	2.5	3.0	1.1	1.6	2.0	1.8	1.7	2.4	3.5
Br_{inv}	1.7	1.3	7.3	8.3	8.6	3.0	3.1	3.1	7.0	8.6	≥ 10	≥ 10
Br_{unt} *	3.1	1.7	2.2	2.9	2.9	1.5	1.7	1.7	3.6	3.3	4.0	4.0
Br_{unt} **		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆

(*) $|\kappa_V| \leq 1$ applied for hadron colliders (**) Not requiring $|\kappa_V| \leq 1$ (⋆) Not measured in HLLHC

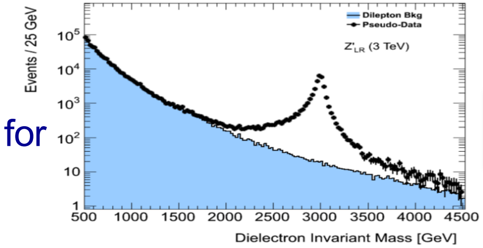
The scalar sector of the SM and direct search for BSM physics

- Challenge #1: what is the nature of the Higgs boson?
  - Is it really a fundamental scalar??? Not a composite structure?
  - Are its couplings to fermions and gauge bosons in full accord in with the SM? What about its coupling to itself?
  - How do precision electroweak observables inform us about the Higgs boson properties and/or BSM physics?
- Challenge #2: are there new interactions or new particles around or above the electroweak scale?
- Challenge #3: can particle physics experiments probe the full range of masses/couplings relevant to thermal relic WIMPs
- Challenge #3: maximize extent to which experiments probe feebly interacting sectors

New resonances/particles/forces?

Seeing the peak. Reach:

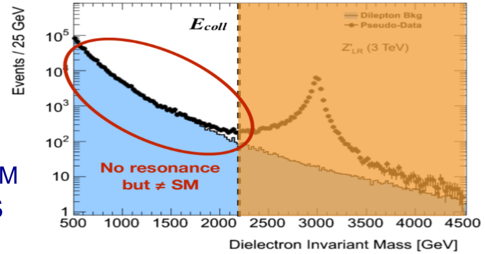
- $M < \sqrt{s}$ for lepton colliders
- $M \lesssim 0.3\text{-}0.5 \sqrt{s}$ in hadron colliders for couplings ~ weak couplings



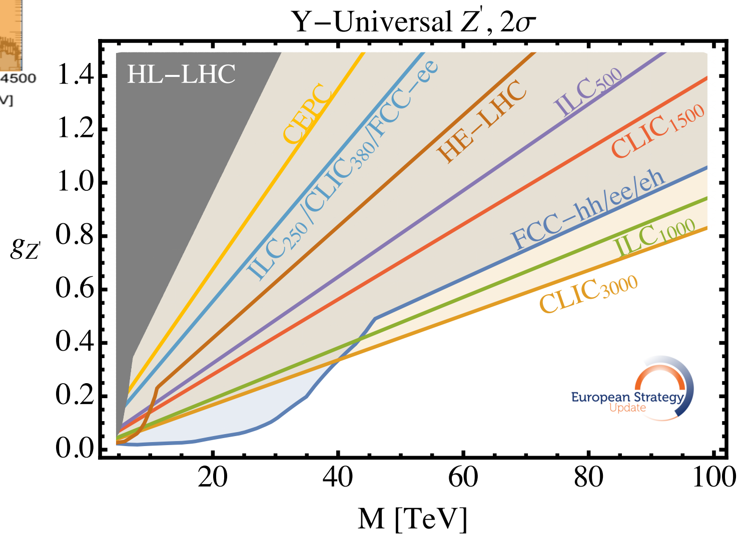
Courtesy:
J. De Blas

Deviations in high-M tails:

- Better suited for lepton colliders; sensitive to [mass/coupling] ≫ $\sqrt{s}$
- Hadron colliders relevant for $g_{Z'} > g_{SM}$ couplings: [mass/coupling] ≫ $0.5\sqrt{s}$

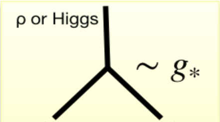


Use very simple model as example. Universal Z'. Clearly, many models with flavor dependence etc.



Higgs Compositeness?

- Using fits from EWK/Higgs group (arXiv:1905.03764)
  - Connection between notations:



$$\frac{c_\phi}{\Lambda^2} = \frac{g_*^2}{m_*^2}$$

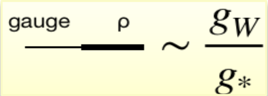
H

$$\frac{c_W}{\Lambda^2} = \frac{1}{m_*^2}$$

2f-2b

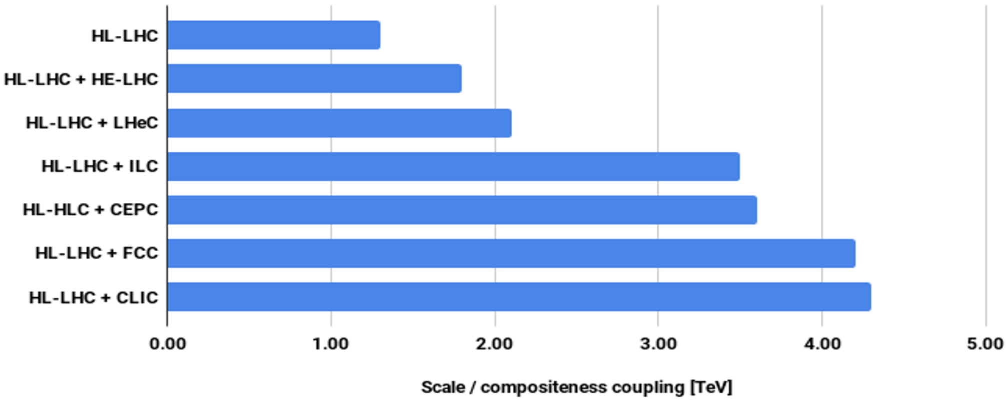
$$\frac{c_{2W}}{\Lambda^2} = \frac{1}{g_*^2 m_*^2}$$

4f, W'/Z'



  - For mass/coupling ~2 TeV → deviations ~1% in Higgs couplings

95% CL limits on compositeness scale (O_H operator)



Maximum sensitivities: @CLIC and FCC(ee+eh+hh)

Higgs Compositeness → fine-tuning?

Corollary question: is it “natural”?

$$(m_H^2)_{Phys.} = \int_0^\infty F_{true}(E;\, g_{true})$$

$$= \int_0^{\Lambda_{UV}} (\ldots) + \int_{\Lambda_{UV}}^\infty (\ldots)$$

SM Contribution

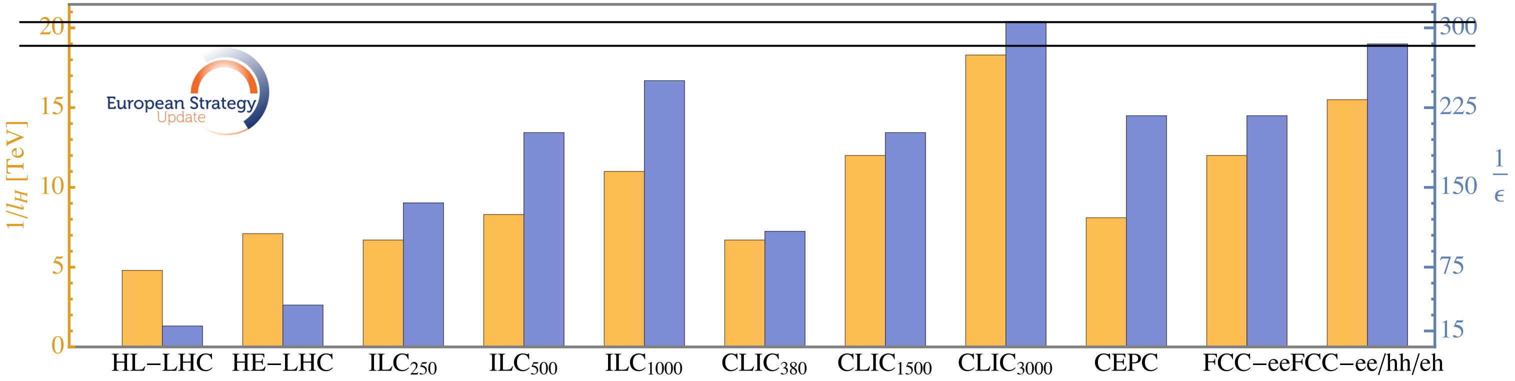
$$\delta m_H^2 = \frac{3y_t^2}{8\pi^2}{\Lambda_{UV}}^2$$

$$\Delta \geq \frac{\delta m_H^2}{m_H^2} \simeq \left(\frac{126\,\mathrm{GeV}}{m_H}\right)^2 \left(\frac{\Lambda_{UV}}{500\,\mathrm{GeV}}\right)^2$$

HL-LHC: gets to Λ~1.5TeV → Δ>10
(FCC-hh: Λ~5TeV → Δ>88)

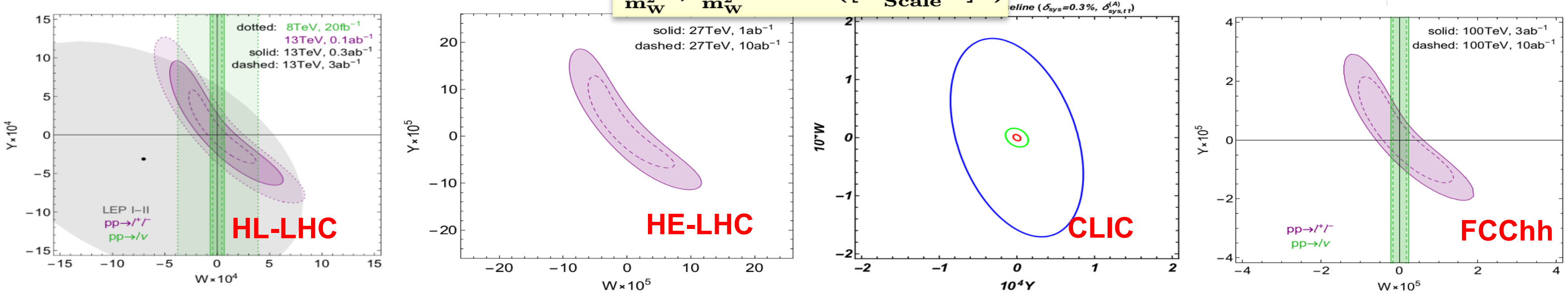
$$\frac{1}{\epsilon} > \left(\frac{m_T}{500\mathrm{GeV}}\right)^2 > \left(\frac{m_*}{g_* v}\right)^2$$

$$\frac{c_\phi}{\Lambda^2} = \frac{g_*^2}{m_*^2} = \frac{\epsilon}{v^2} \to \frac{1}{\epsilon} = \frac{1}{v^2}\left(\frac{c_\phi}{\Lambda^2}\right)^{-1}$$



Contact Interactions

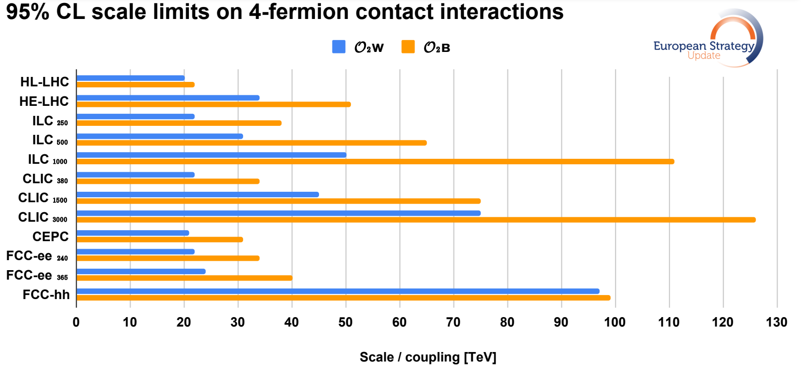
$$\frac{g^2 W}{m_W^2}, \frac{g'^2 Y}{m_W^2} \to \Delta\left(\left[\frac{\text{coupling}}{\text{Scale}}\right]^2\right)$$



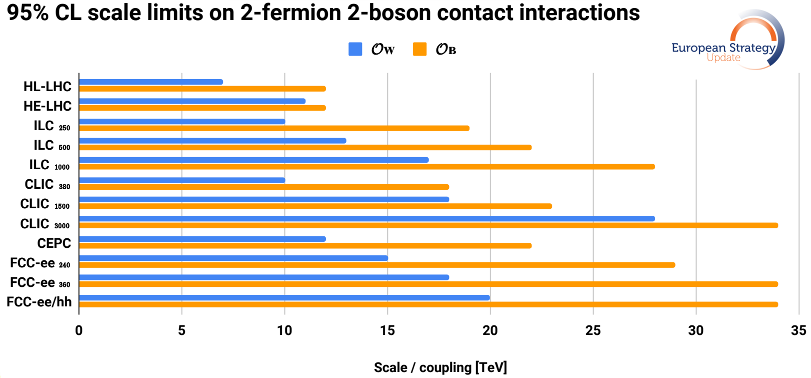
ee: all difermion final states, angular analysis (+polarization)
pp: Drell-Yan Z .AND. W

CLIC: ZH, angular analysis
FCC: $p_T(Z)$ in WZ production

95% CL scale limits on 4-fermion contact interactions



95% CL scale limits on 2-fermion 2-boson contact interactions

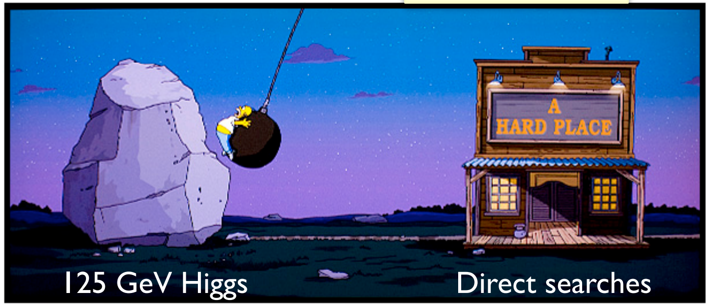


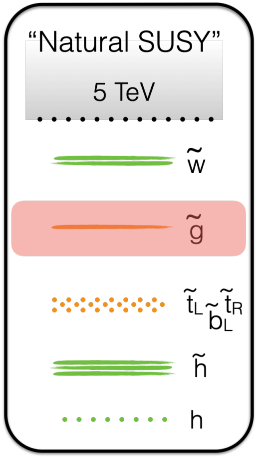
Sensitivity for ee colliders enhanced for couplings ≳ 1
(weak couplings → direct searches become more sensitive)
Searches for W’ & charged fermion currents more effective at hadron colliders

SUSY: what does it mean?

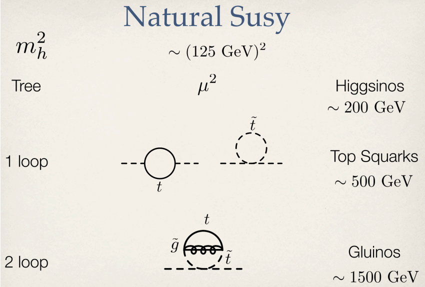
Corollary question: is SUSY "natural"?

Credit: D. Shih



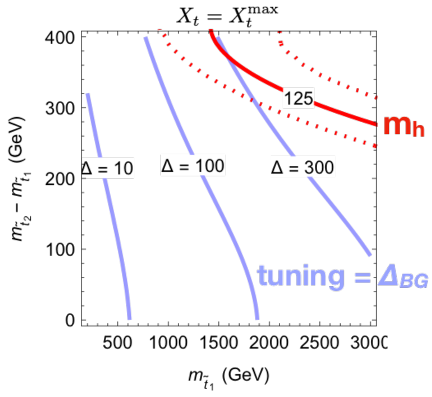


Fine tuning parameter: $$\frac{1}{\epsilon} = \frac{\Delta m_h^2}{m_h^2}$$



$$\frac{1}{\epsilon_{\tilde{t}}} = \frac{3 y_t^2 m_{\tilde{t}}^2}{2\pi^2 m_h^2} \ln\left(\Lambda / m_{\tilde{t}}\right)$$

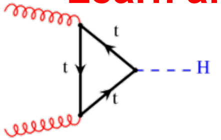
$$\frac{1}{\epsilon_{\tilde{g}}} = \frac{4 y_t^2 \alpha_s m_{\tilde{g}}^2}{\pi^3 m_h^2} \ln^2\left(\Lambda / m_{\tilde{g}}\right)$$



ε	$\ln(\Lambda/m_{\tilde{t},\tilde{g}}) \approx 30$ High-scale mediation	$\ln(\Lambda/m_{\tilde{t},\tilde{g}}) \approx 1$ Low-scale mediation
stop	$5 \times 10^{-5} \left(\frac{10 \text{ TeV}}{m_{\tilde{t}}}\right)^2$	$2 \times 10^{-3} \left(\frac{10 \text{ TeV}}{m_{\tilde{t}}}\right)^2$
gluino	$7 \times 10^{-6} \left(\frac{17 \text{ TeV}}{m_{\tilde{g}}}\right)^2$	$6 \times 10^{-3} \left(\frac{17 \text{ TeV}}{m_{\tilde{g}}}\right)^2$

MSSM: already unnatural

Learn also (though less) from indirect information



$$r_g - 1 \approx \frac{1}{4} \frac{m_t^2}{m_{\tilde{t}_1}^2} \approx 0.7\% \left(\frac{1 \text{ TeV}}{m_{\tilde{t}_1}}\right)^2$$

$$\frac{\delta \mathcal{O}_{\text{SUSY}}}{\mathcal{O}_{SM}} \sim \frac{m_{\text{SM}}^2}{m_{\text{SUSY}}^2}$$

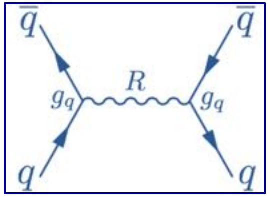
Thermal relic WIMPs (?)

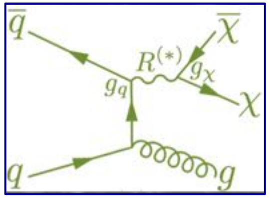
- **Motivation for direct, indirect and collider searchers:**

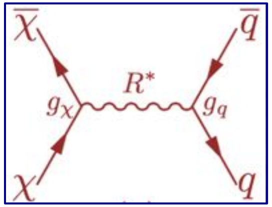
$$\Omega_{\rm DM}h^2 \sim 0.12 \times \left(\frac{M_{\rm DM}}{2\ {\rm TeV}}\right)^2 \left(\frac{0.3}{g_{\rm eff}}\right)^4 \Longrightarrow M_{DM} \sim \mathcal{O}(\text{few GeV}) \to \mathcal{O}(\text{10's TeV})$$

  - **WIMP miracle has been moving (moved) upwards – to ~TeV.**
- **Focus of these searches: GeV–TeV region; two classes**
  - **Classic electroweak WIMP candidates (SUSY inspired)**
    - **Winos and Higgsinos (and linear combinations…)**
  - **Simplified models with mediator particles**
    - **Axial-vector simplified models**
    - **Scalar simplified models**

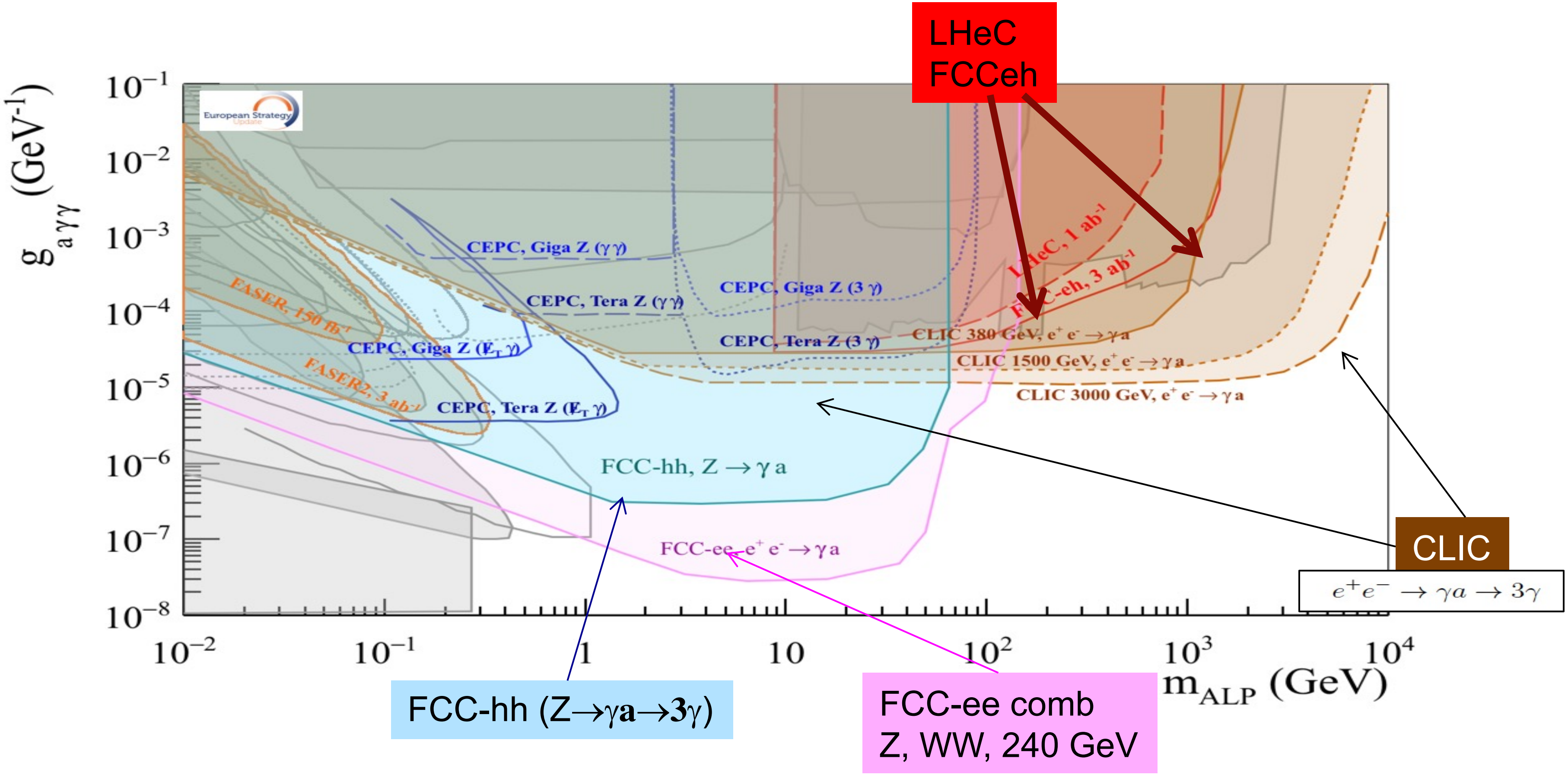
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_{\rm Int}$$







FIPs: Pseudo-Scalar Portal (Axions, ALPs)



LHeC
FCCeh

CLIC

$e^+e^- \to \gamma a \to 3\gamma$

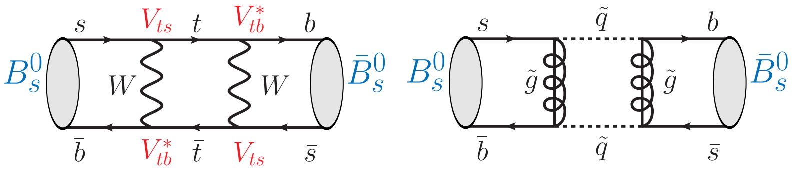
FCC-hh (Z→γ**a**→**3**γ)

FCC-ee comb
Z, WW, 240 GeV

FIPs represent a new paradigm that requires systematic exploration on multiple fronts

Flavor physics: quark sector (II)

Very rich B/D program (Belle II & LHCb, some ATLAS-CMS) in the next ten years.



Observables: γ_{CKM}; φ_s; φ_D; $B_d\to\mu\mu/B_s\to\mu\mu$…

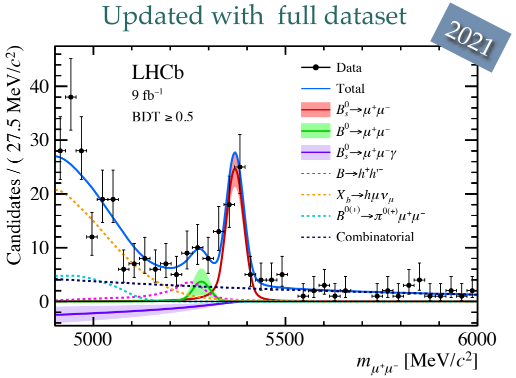
Next frontier in CP precision : D

$$A_{raw} = \frac{N(D^0\to f) - N(\bar{D}^0\to f)}{N(D^0\to f) + N(\bar{D}^0\to f)} = A_{CP} + A_D(\pi_s^+/\mu) + A_P(D^{*+}/D^0_{\text{from }B})$$

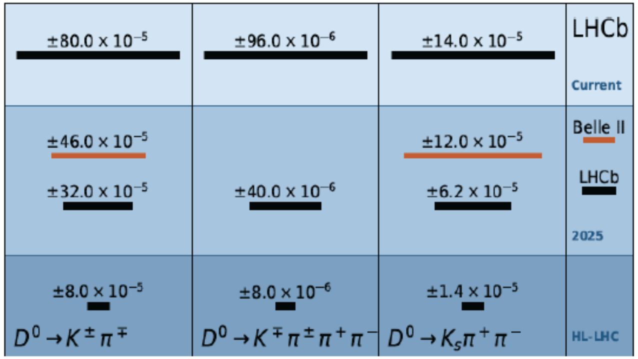
FCC-ee:
$5\text{x}10^{12}$ Z;
$7.5\text{x}10^{11}$ bb

Updated with full dataset

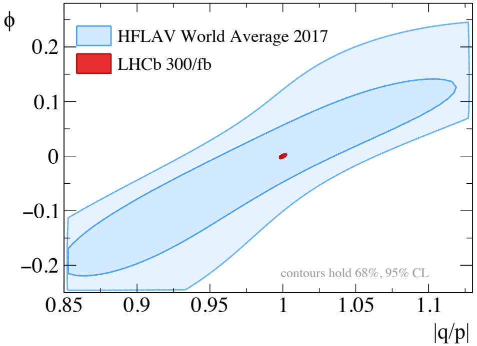
2021

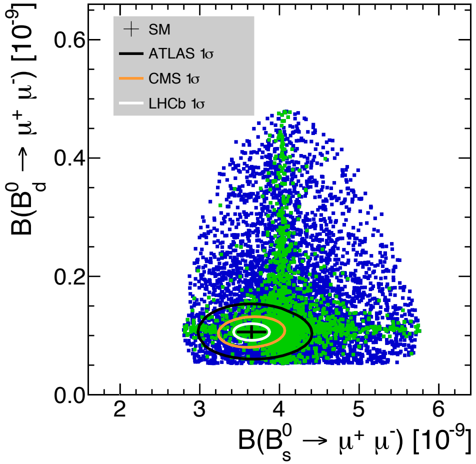


$D^0\to$KK, ππ; observation (5.3σ) ΔA_{CP}=-(0.185±0.029)% arXiv:1903.08726



±80.0 x 10^{-5}	±96.0 x 10^{-6}	±14.0 x 10^{-5}	LHCb Current
±46.0 x 10^{-5} ±32.0 x 10^{-5}	±40.0 x 10^{-6}	±12.0 x 10^{-5} ±6.2 x 10^{-5}	Belle II LHCb 2025
±8.0 x 10^{-5}	±8.0 x 10^{-6}	±1.4 x 10^{-5}	HL-LHC
$D^0\to K^\pm\pi^\mp$	$D^0\to K^\mp\pi^\pm\pi^+\pi^-$	$D^0\to K_s\pi^+\pi^-$	





Where we stand

- **Most successful Theory ever: Standard Model of Particle Physics**
  - **Highest priority:** ***extend understanding of SM and its newly discovered scalar sector*****.**
- **Evidence that SM is either incomplete or an Effective Theory of some Ultimate Theory (or another step in a series of Effective Theories…)**
  - **Experimental evidence**
    - **Dark Matter (DM): The "thing" we know the least about: Unknown nature, unknown number(s) of DM particles, unknown mass range(s) – 10^{80}.**
    - **Neutrino masses: SM gauge group allows for Majorana masses, "explaining" their tiny values; unknown (putative) Majorana scale.**
    - **Matter-antimatter asymmetry of the Universe: nowhere near what we measure in CP violation experiments. What about CP violation in the lepton sector?**
  - **Theory issues**
    - **Electroweak (EW) hierarchy problem. Why is the Higgs so light?**
    - **The flavour puzzle. Why three generations of quarks and leptons? With *very* different masses and mixings? Size of CP violation? (explain matter universe???)**
    - **And lots more… e.g. Strong CP problem. Another vacuum issue (this time QCD). Why is its θ parameter experimentally constrained to be extremely small? For a priori no good reason…. → Axions?**