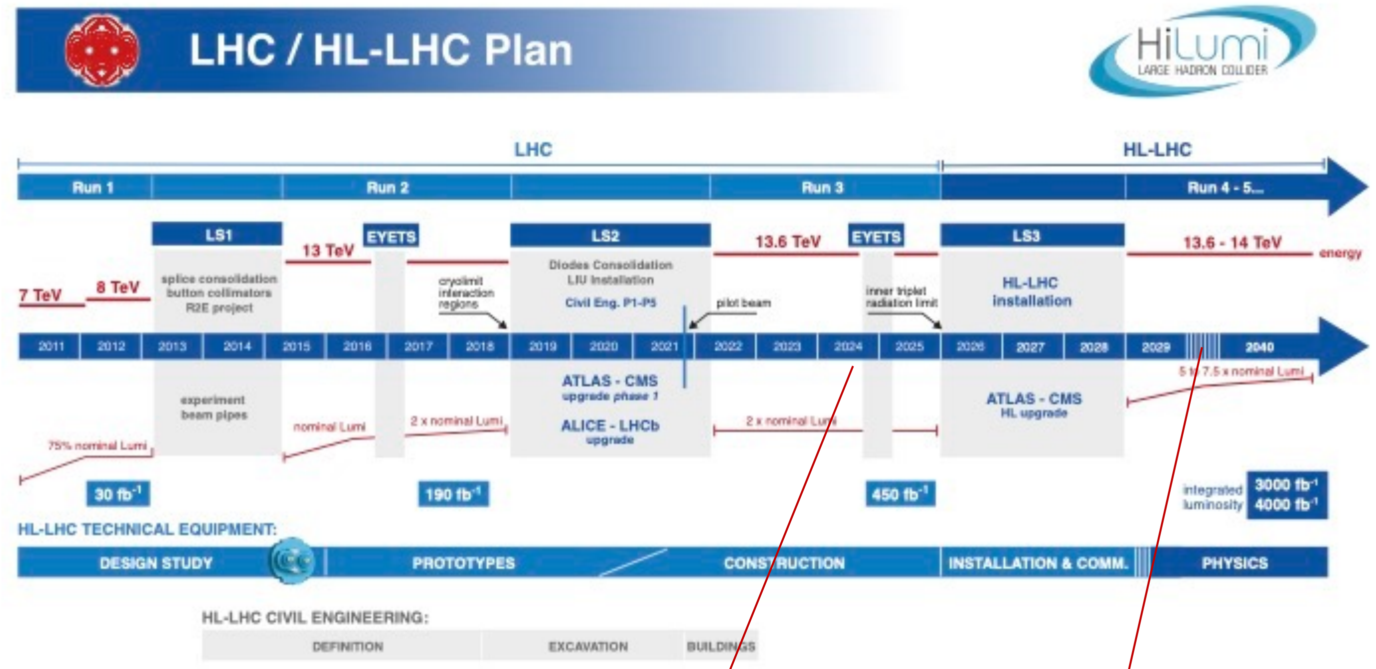
The LHC era: exploring the TeV scale



We are only here

Many years of HL running ahead of us

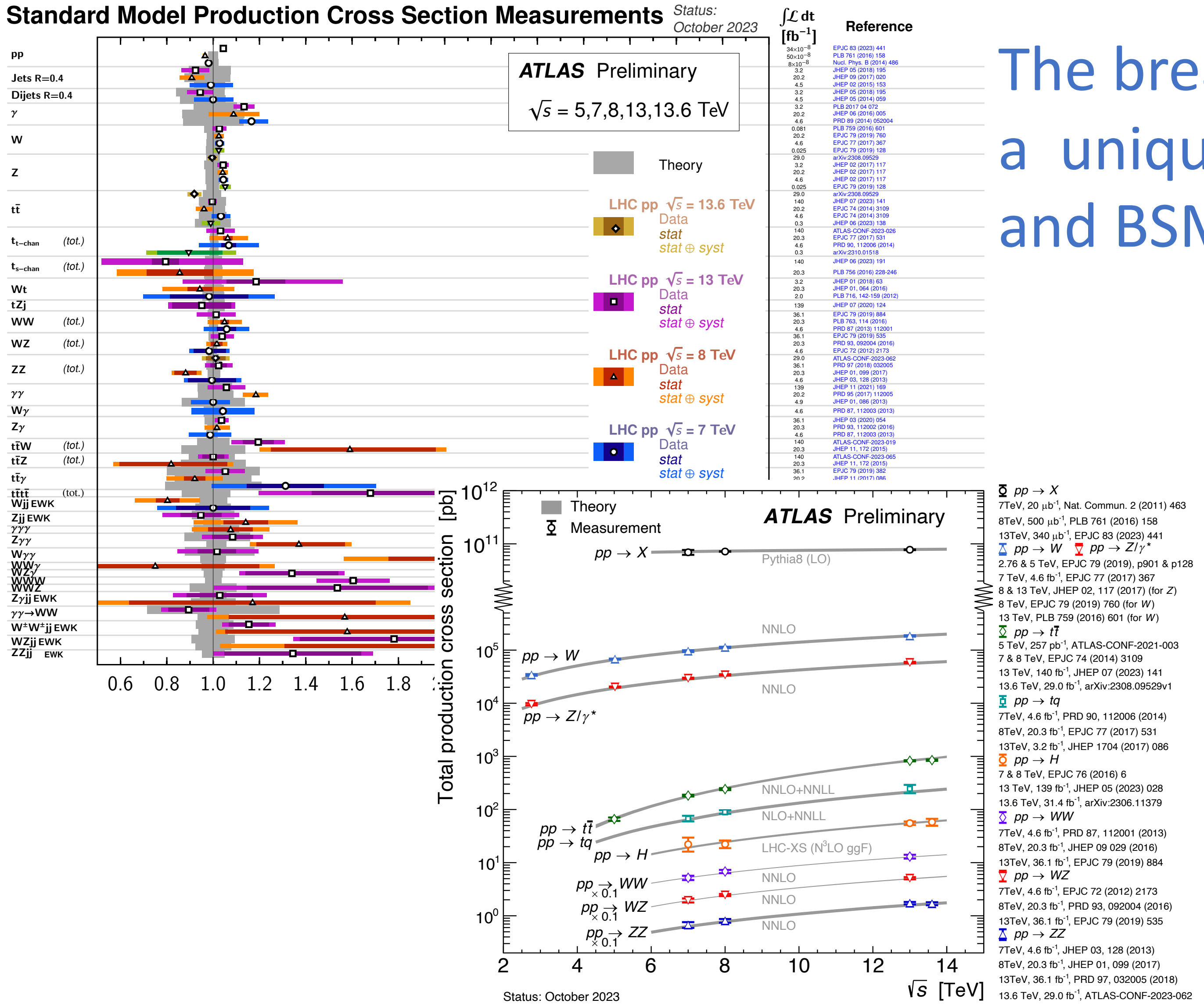
- **Run 1**: **Higgs discovery**
- **Run 2**: **Higgs couplings**
  - outperformed expectations
- **Run 3 to HL-LHC**
  - **Higgs precision program**
  - Unique **top physics reach** till the next high-energy collider
    - e^+e^- > 500 GeV
    - pp@100 TeV
    - $\mu^+\mu^-$ > 10 TeV
  - **Discovery?**

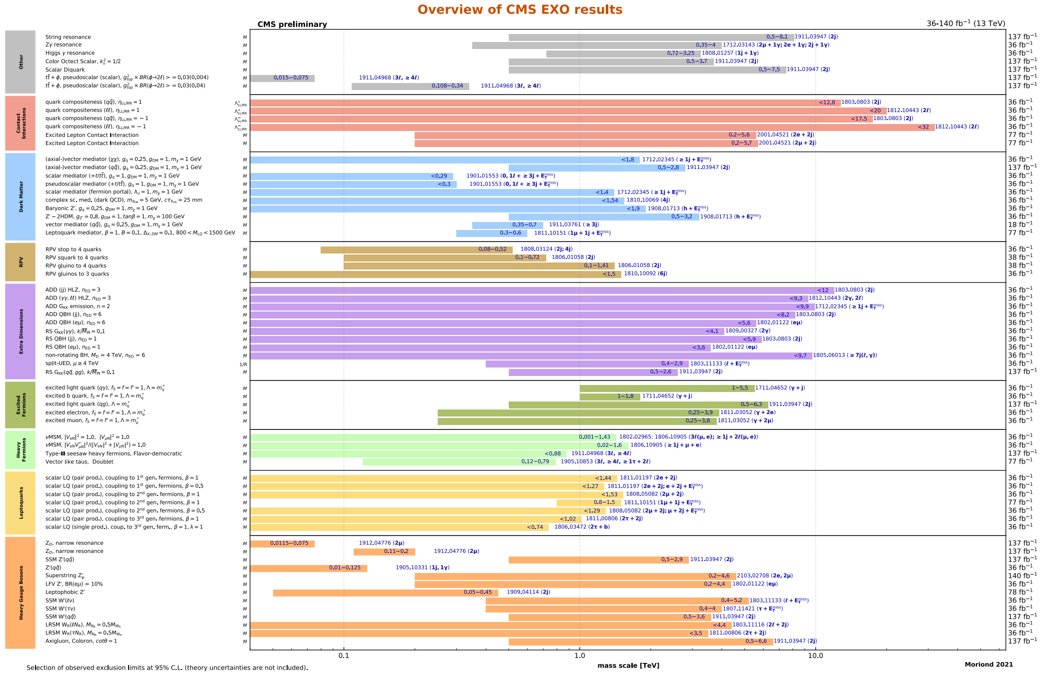
Statistical limitations will be overcome for a very large number of observables

Reach % level precision

- ➔ 2-fold increase in statistics by the end of Run 3
- ➔ 20-fold increase in statistics by the end of HL-LHC!

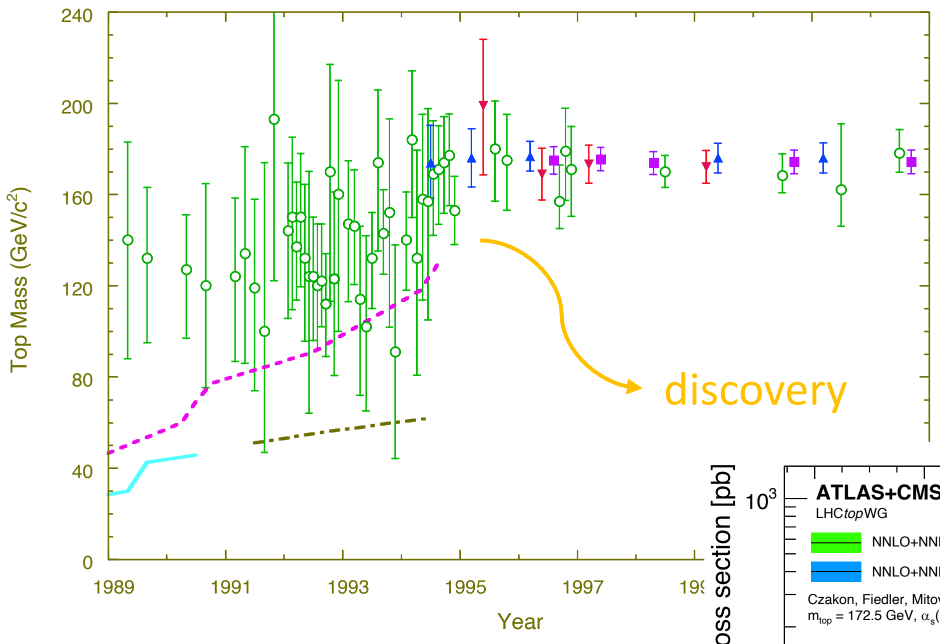
The breadth of collider physics program: a unique spectrum of SM measurements and BSM direct searches!





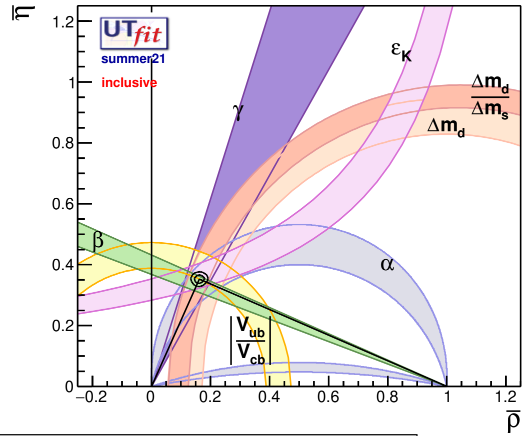
The realization of this program largely depend on theoretical progress

Top From prediction to discovery to precision

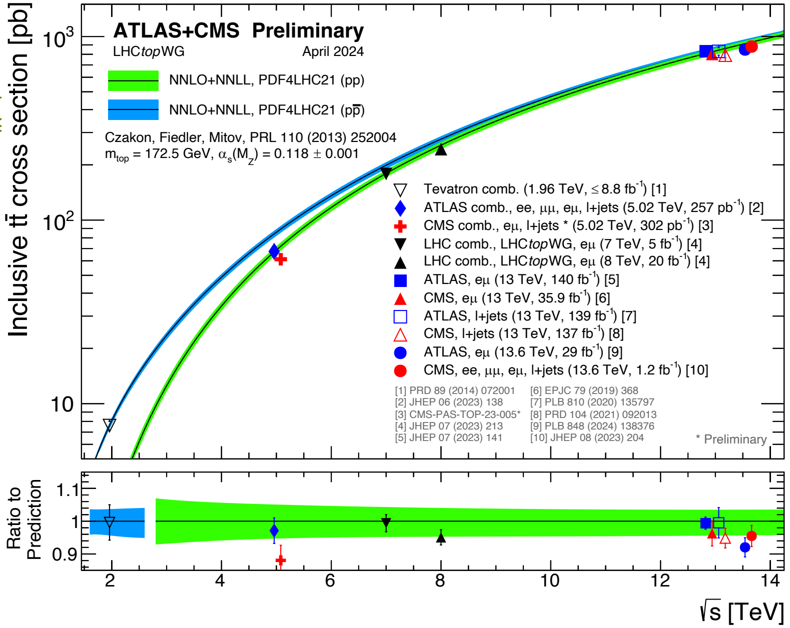


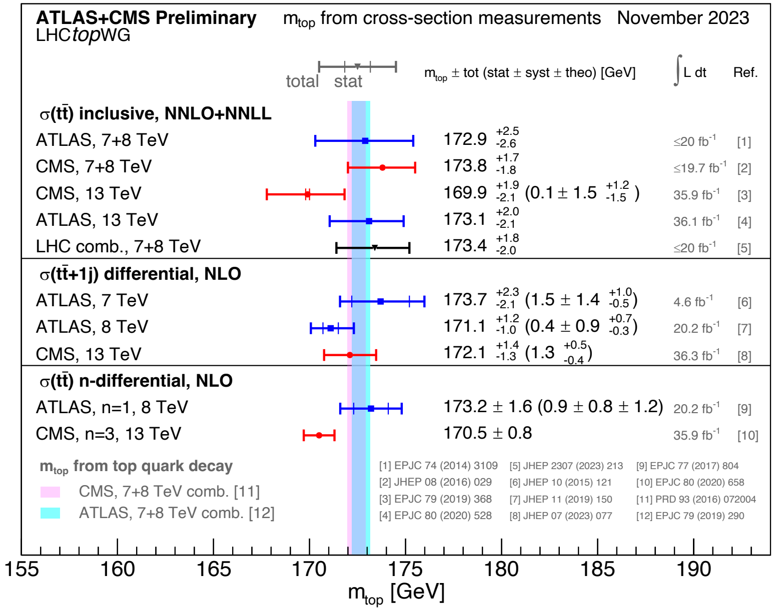
C. Quigg [hep-ph/0404228]

green dots ⟶ indirect fits
blue triangles ⟶ CDF
red triangles ⟶ D0
purple squares ⟶ world average
lines ⟶ various lower bounds



M_t becomes a crucial input in precision fits of the SM (including flavor)

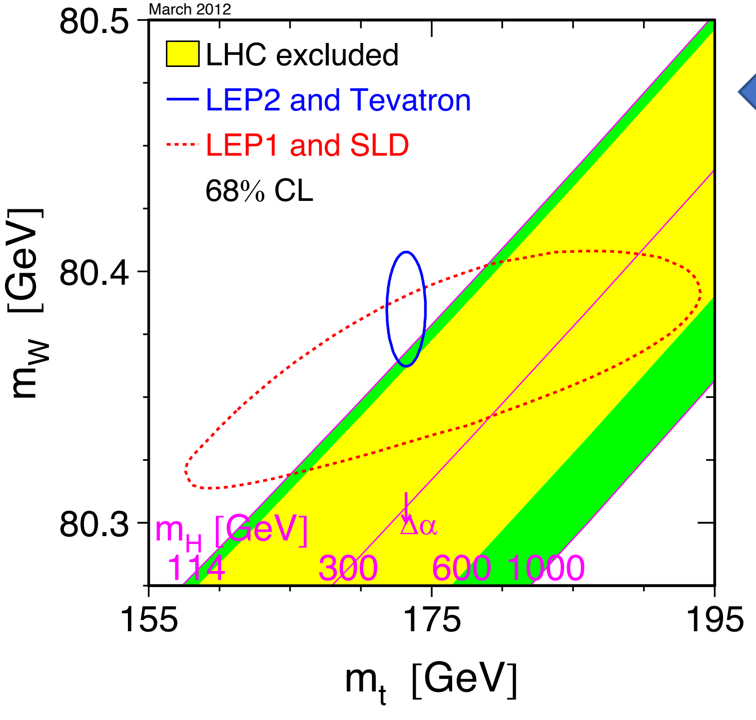




Anomalies in Top-quark EW couplings (W,Z,H) possible hint of BSM physics

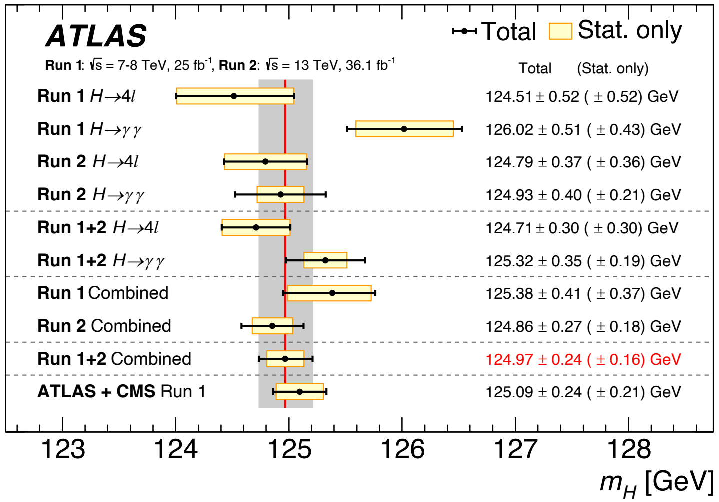
From prediction to discovery to precision

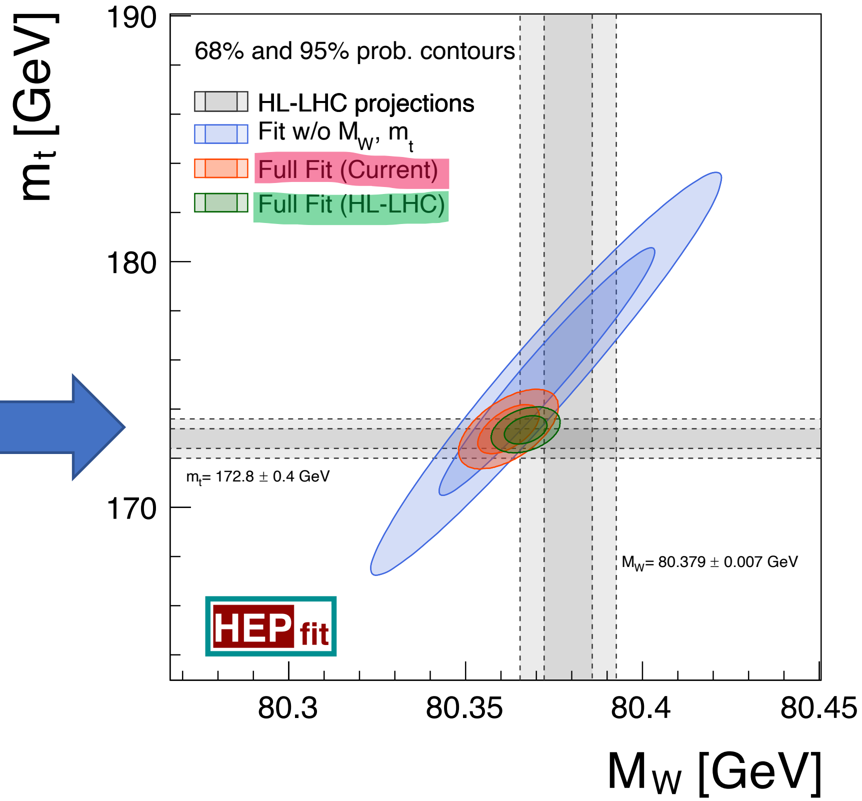
Global fits of precision EW observables gave us strong indications of where to find the SM Higgs boson and we now use its mass as one of the EW precision observables of the EW global fit to constrain new physics.



$$M_H = 94^{+29}_{-24}\ \text{GeV}$$

$$M_H < 152\,(171)\ \text{GeV}$$



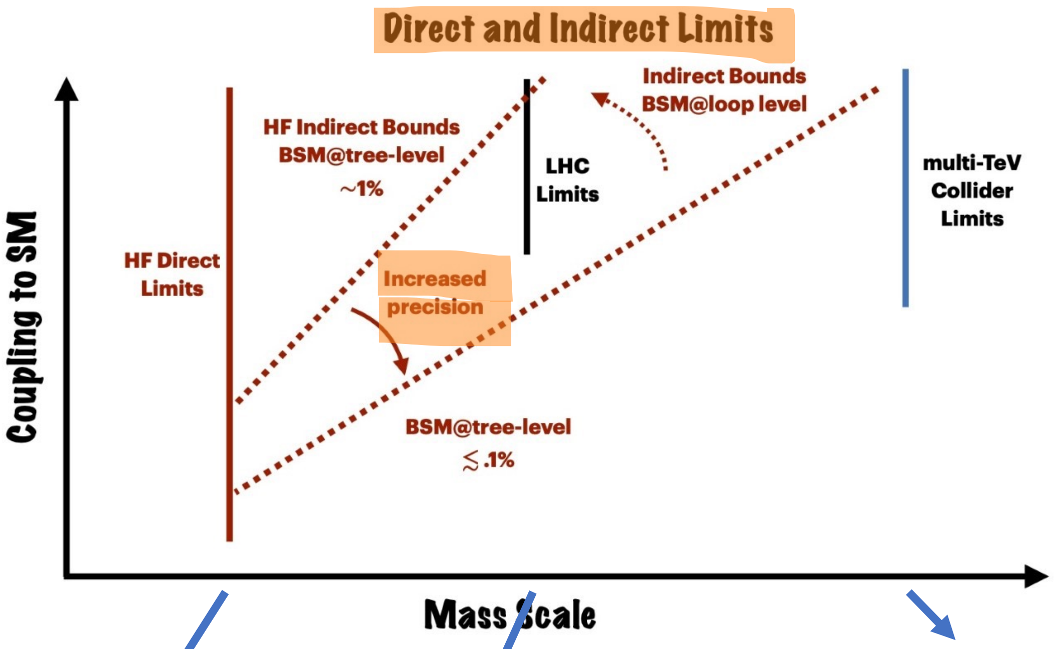


Future directions: energy and precision

Answering the big Open Questions via energy and precision

- **Origin of the EW scale** (SSB via Higgs mechanism, naturalness, flavor)
- Origin of Baryon Asymmetry, Dark Matter, Dark Energy
- …

EF Snowmass Report, 2211.11084



< 1 TeV (e^+e^-)

13-14 TeV
pCM ~ 1 TeV

~10-30 TeV ($\mu^+\mu^-$), ~100 TeV (pp)
pCM~ 10 TeV

Given the level of consistency of the SM, and no clear evidence of new particles in LHC searches so far, we expect new physics effects to be small.

Precision affects the sensitivity to both direct and indirect effects of new physics since it enhances sensitivity to small deviations.

Snowmass 21:
EF Benchmark Scenarios

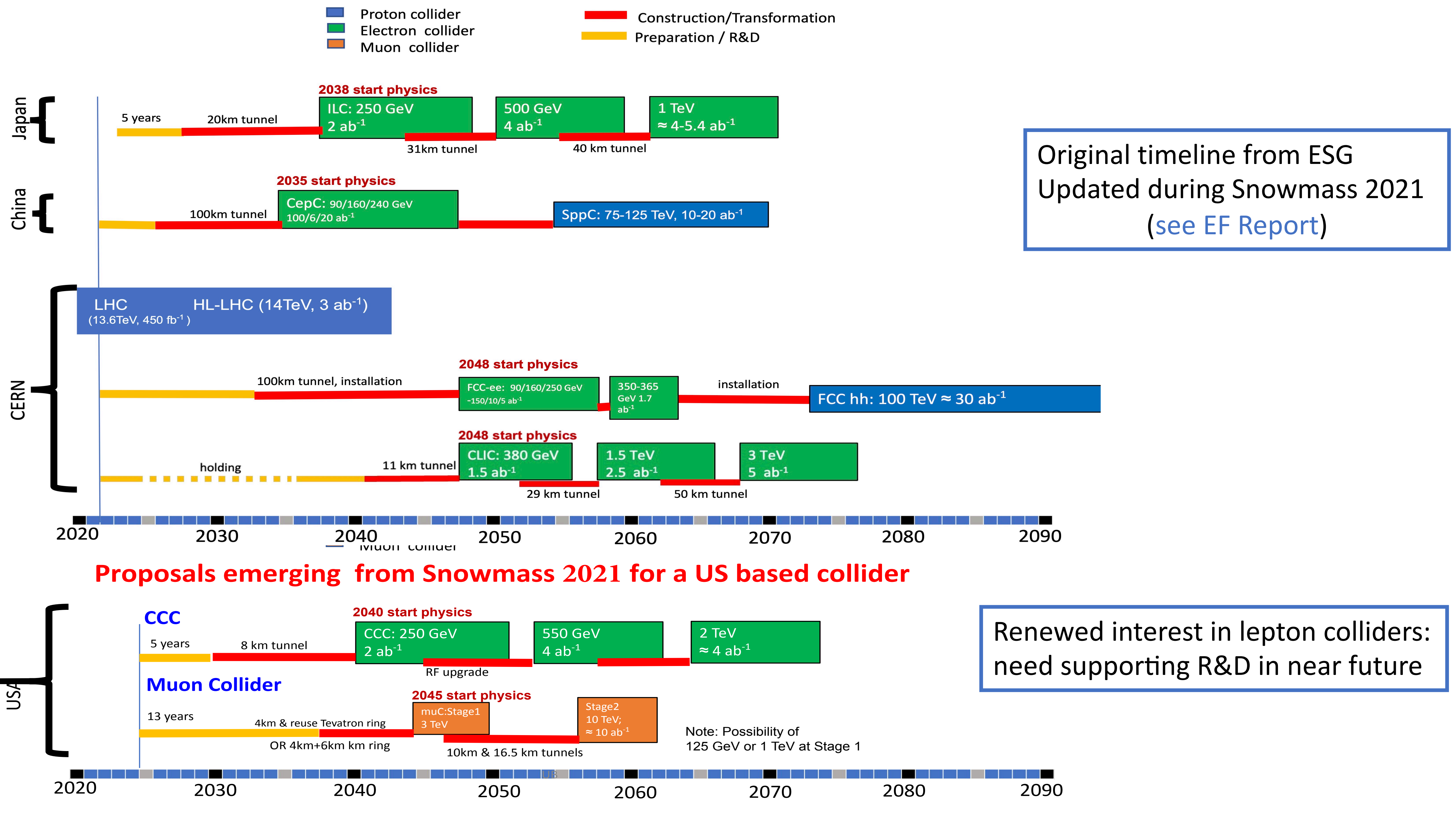
Higgs-boson factories
(up to 1 TeV c.o.m. energy)

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\rm int}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HL-LHC	pp	14 TeV		3		2027
ILC & C^3	ee	250 GeV	$\pm80/\pm30$	2	2028	2038
		350 GeV	$\pm80/\pm30$	0.2		
		500 GeV	$\pm80/\pm30$	4		
		1 TeV	$\pm80/\pm20$	8		
CLIC	ee	380 GeV	$\pm80/0$	1	2041	2048
CEPC	ee	M_Z		50	2026	2035
		$2M_W$		3		
		240 GeV		10		
		360 GeV		0.5		
FCC-ee	ee	M_Z		75	2033	2048
		$2M_W$		5		
		240 GeV		2.5		
		$2\ M_{top}$		0.8		
μ-collider	$\mu\mu$	125 GeV		0.02		

Multi-TeV colliders
(> 1 TeV c.o.m. energy)

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$. e^-/e^+	$\mathcal{L}_{\rm int}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HE-LHC	pp	27 TeV		15		
FCC-hh	pp	100 TeV		30	2063	2074
SppC	pp	75-125 TeV		10-20		2055
LHeC	ep	1.3 TeV		1		
FCC-eh		3.5 TeV		2		
CLIC	ee	1.5 TeV	$\pm80/0$	2.5	2052	2058
		3.0 TeV	$\pm80/0$	5		
μ-collider	$\mu\mu$	3 TeV		1	2038	2045
		10 TeV		10		

Timelines are taken from the Collider ITF report (arXiv: 2208.06030)


Proton collider
Electron collider
Muon collider
Construction/Transformation
Preparation / R&D
Japan
5 years
20km tunnel
2038 start physics
ILC: 250 GeV
2 ab-1
31km tunnel
500 GeV
4 ab-1
40 km tunnel
1 TeV
≈ 4-5.4 ab-1
China
100km tunnel
2035 start physics
CepC: 90/160/240 GeV
100/6/20 ab-1
SppC: 75-125 TeV, 10-20 ab-1
Original timeline from ESG
Updated during Snowmass 2021
(see EF Report)
CERN
LHC
(13.6TeV, 450 fb-1)
HL-LHC (14TeV, 3 ab-1)
100km tunnel, installation
2048 start physics
FCC-ee: 90/160/250 GeV
-150/10/5 ab-1
350-365
GeV 1.7
ab-1
installation
FCC hh: 100 TeV ≈ 30 ab-1
holding
11 km tunnel
2048 start physics
CLIC: 380 GeV
1.5 ab-1
29 km tunnel
1.5 TeV
2.5 ab-1
50 km tunnel
3 TeV
5 ab-1
2020
2030
2040
2050
2060
2070
2080
2090
Proposals emerging from Snowmass 2021 for a US based collider
USA
CCC
5 years
8 km tunnel
2040 start physics
CCC: 250 GeV
2 ab-1
RF upgrade
550 GeV
4 ab-1
2 TeV
≈ 4 ab-1
Renewed interest in lepton colliders:
need supporting R&D in near future
Muon Collider
13 years
4km & reuse Tevatron ring
OR 4km+6km km ring
2045 start physics
muC:Stage1
3 TeV
10km & 16.5 km tunnels
Stage2
10 TeV;
≈ 10 ab-1
Note: Possibility of
125 GeV or 1 TeV at Stage 1
2020
2030
2040
2050
2060
2070
2080
2090

Lesson 1 – or "Why Collider Physics"

① Introductory remarks

- "Collider physics" or the physics of the high-energy collision of elementary particles.
  ↳ this is the domain from where most of our knowledge of subatomic physics has come so far.

The idea is simple: collide head-on two focused beams of very energetic particles (e^+e^-, pp, $p\bar{p}$), with equal & opposite momenta, and measure the outcome with clever detectors that can isolate and identify the different kinds of particles produced in the collision based on their properties.

$$p_1 = (E_1, 0, 0, \vec{p}_1)$$
$$p_2 = (E_2, 0, 0, \vec{p}_2)$$

H.E. collider → particles are ultrarelativistic

Center of momentum frame
$$\vec{p}_1 + \vec{p}_2 = 0$$
if $\vec{p}_1 \neq \vec{p}_2$ this condition is not verified in the lab. frame but if $\vec{p}_1 = \vec{p}_2$ it is.

$$s \equiv (p_1+p_2)^2 = (E_1+E_2)^2$$

Lorentz invariant ↔ frame independent → good choice to define the properties of a collider

$$\sqrt{s} = E_{CM} \quad (= 2E_1 = 2E_2 = 2E_{beam}) \text{ if } m_1 = m_2$$

For comparison: fixed target exp. ($\vec{p}_2 = 0$)

$$s = (p_1+p_2)^2 = m_1^2 + m_2^2 + 2p_1 \cdot p_2 = m_1^2 + m_2^2 + 2E_1 m_2$$

$$\sqrt{s} \simeq \sqrt{2E_1 m_2} \quad (E_1 \gg m_1, m_2)$$

We need to remember that in e+e− colliders the full E_{CM} is available in the final-state and "usable" to reach the desired energy threshold, while at hh (h = hadron) colliders only a fraction of it is.

↳ this is compensated however by the fact that hadron colliders can reach higher E_{CM}
<u>WHY</u>? because they do not loose much energy to synchrotron radiation

$$\Delta E \propto \frac{1}{R}\left(\frac{E}{m}\right)^4 \qquad (m_h \gg m_e)$$

(R: radius of a circular accelerator)

So, to reach high E_{CM}:
- → lepton colliders need to be linear (and long)
- → hadron colliders can be circular (with large R)

Once we know the $\sqrt{s} = E_{CM}$, we can calculate the probability for a given process to happen, i.e. the probability of a given event.

↳ proportional to what we call the "<u>cross section</u>" for a given process ($ab \to X$)

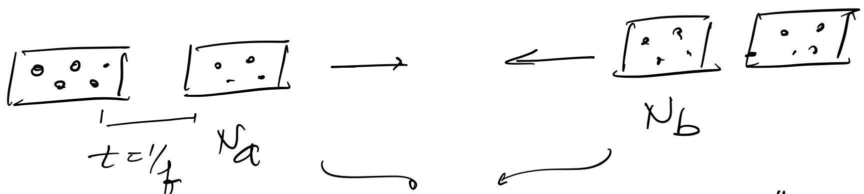
↳ which we calculate in the well-defined framework of QFT, for a given theory.

<u>Example</u> → the <u>Standard Model</u> (SM) or any of its <u>BSM extensions</u>, including generic <u>EFT</u> <u>extensions</u>.

(we will see several examples in the course of these lectures.)

Last, in order to estimate the rate with which a given kind of events are produced at a specific collider, we need to calculate how many one-on-one collisions happen per unit time -

→ we need to consider "A" (the cross area of the beams) and "f" (the bunch crossing frequency, since particles in the beams come in bunches)



$t = 1/f$ → time-spacing between bunches

f = bunch crossing frequency ← time-spacing between bunches

N_a, N_b → # of particles "a" and "b" in each bunch ($ab \to X$)

$$\#\text{ of events }(ab \to X) = \sigma \cdot \frac{N_a N_b}{A} \qquad (\sigma = \sigma(s))$$

$$\text{Rate} = R(s) = f \cdot \sigma \frac{N_a N_b}{A} \equiv \mathcal{L} \cdot \sigma(s)$$

"instantaneous luminosity" $\equiv f \dfrac{N_a N_b}{A}$ (collision rate)

Units!

$[\sigma] = [A] = l^2 = E^{-2} \quad (\hbar = c = 1)$

Traditional unit for σ is "$1 \text{ barn} = 10^{-24} \text{ cm}^2$"

$(\hbar = c = 1)$ $\quad 1 \text{ barn} = 2568 \text{ GeV}^{-2}$

$1 \text{ GeV}^{-2} = 3.894 \cdot 10^{-4}$ barn

Exercise: can you make sure of these conversion factors?

Calculated in "natural units" all σ are "naturally" given in GeV^{-2}.

"integrated luminosity" → L → given by $\mathcal{L}$ integrated over a given time (ex. time of running)

Ex.: LHC has $\mathcal{L} = 10^{34}\, cm^{-2} \cdot s^{-1} = 10\, Hz/nb$
(→ 10^{34} collisions / cm^2/s)

↳ nanobarn 10^{-9} barn

↳ on the LHC website you can find the integrated luminosity for each Run, including Run 3.

if $\sigma = 1\, nb$ → 10 events / sec

or: knowing σ one can estimate how long to run in order to collect the desired number of events.

Now: life is not that simple...

↳ $R \to R \cdot \epsilon$ ($\sim 10^{-2}$)

↳ detector efficiency (in selecting given classes of events)

↳ particles decay and experiments measure the decay products.

$$\sigma \to \sigma \times Br$$

↳ vary ($1 - 10^{-3}$ or lower)

In summary

$(\sqrt{s}, \mathcal{L})$
$(\sqrt{s}, L)$ → define the properties of a collider + (lepton / hadron)

Exercise: $\sigma(gg \to h) \simeq 50\, pb$. (see e.g. ATLAS 2404.05498, CMS 2207.00043) accounts for most of H prodctn.

Estimate the # of Higgs boson produced by Run 2, or by the end of the HL-LHC. What about future colliders?

(2) Examples of past, present, and future colliders

"the Past"

Collider	$\sqrt{s}$ (GeV)	L (fb^{-1}) ($\mathcal{L}$ ($cm^{-2}s^{-1}$))	Years of opertn.	Detectors
• LEP (e^+e^-) (≃ 27 km)	91.2 (LEP1) 130-209 (LEP2)	≃ 200 (LEP1) ≃ 600 (LEP2) ($\mathcal{L} \simeq 10^{31} \to 10^{32}$)	1989-95 1996-2000	ALEPH, DELPHI, L3, OPAL (CERN)
• SLC (e^+e^-)	91.2	20 ($\mathcal{L} \simeq 10^{31}$)	1989-98	SLD (SLAC)
• Hera ($e^\pm p$)	320	500 ($\mathcal{L} \simeq 10^{31}$)	1992-2007	ZEUS, H1 (DESY)
• Tevatron ($p\bar{p}$) (6.3 km.)	1800 (Run1) 1960 (Run2)	160 (Run1) 10^4 (Run 2) ($\mathcal{L} \simeq 10^{32}$)	1987-96 2001-11	CDF, DØ (FNAL)

"the Present"

		($\mathcal{L} \simeq 10^{34}$)		
LHC (pp) (26.7 km)	7-8 TeV (Run1)	30 fb^{-1}	2010-13	ATLAS CMS LHCb ALICE
	13 TeV (Run2)	190 fb^{-1}	2015-18	
	13.6 TeV (Run3)	450 fb^{-1}	2022-25	
	↓	↓		
HL-LHC	≥ 14 TeV (Run4)	$3-4\times10^4$ fb^{-1} (30-40 ab^{-1}) ($\mathcal{L} \simeq 5-7.5\times10^{34}$)	2029-...	

→ see slide with LHC timeline & corresponding integrated luminosities.

"the Future" (precision & energy)

↳ under scrutiny

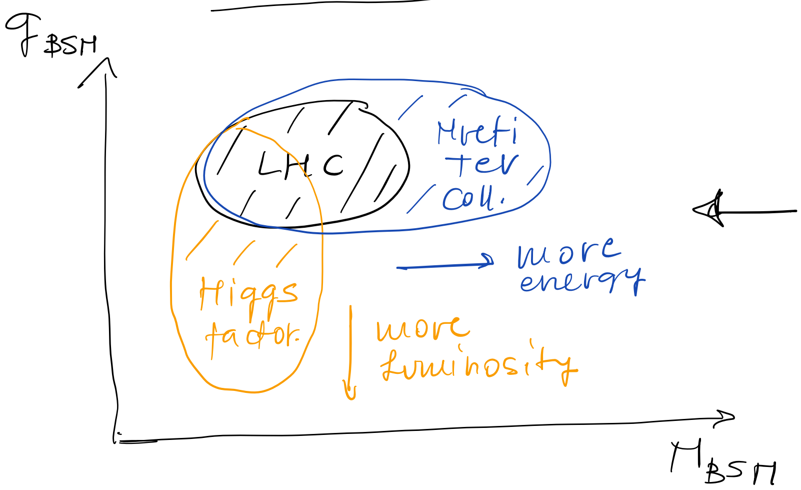
↳ see slide with Table of future colliders distinguished in:

- Higgs-boson factories ($\lesssim$ 1 TeV) E_{CM}
- Multi-TeV colliders (> 1 TeV)

SIMPLIFIED PICTURE

→ $BSM \equiv (M_{BSM}, g_{BSM})$

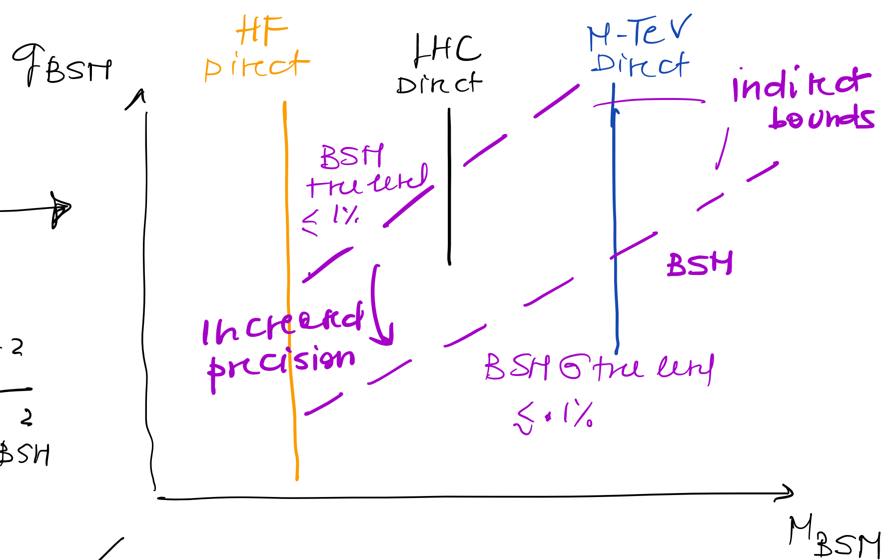
- M_{BSM}: Mass scale of BSM physics
- g_{BSM}: its coupling to SM particles



← Direct searches

can directly probe limited regions of this 2D parameter space

Direct + Indirect limits →



indirect limits
$$\delta m_{SM} \propto g_{BSM}^2 \frac{E^2}{M_{BSM}^2}$$

↓

COMPLEMENTARITY

③ Why the future?

↳ see lectures on SM and beyond (C. Grojean)

In a nutshell:

↳ understanding the scalar sector of the SM

→ Higgs-boson mass ↔ EW scale

→ Higgs potential (why?)

→ Yukawa sector: coupling to fermions (→ origin of flavor)

↳ Directly explore the ≃ 10 TeV scale

↙ this is self-explanatory!

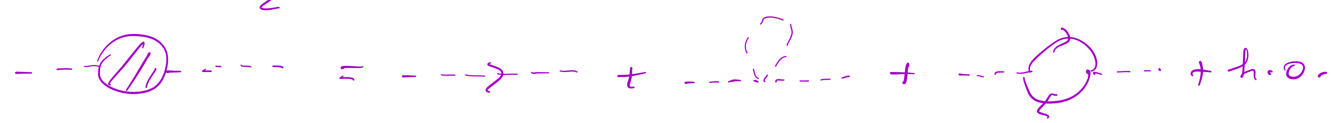
this needs to be elaborated more

③a

$$\mathcal{L} = \frac{1}{2}\partial^\mu\phi^\dagger\partial_\mu\phi - V(\phi^\dagger\phi) + \bar\psi(i\not\partial - m_F)\psi - \lambda_F\bar\psi\phi\psi + h.c.$$

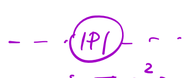
$$V \to -m_S^2\phi^\dagger\phi - \frac{\lambda_S}{4}(\phi^\dagger\phi)^2$$

m_S →



$$= \;..\; = \frac{i}{p^2 - m_S^2 - \Sigma(p^2)} \equiv \frac{i Z_2^\phi}{p^2 - m_{S,R}^2}$$

↳ pole of renormd. propagator



$i\Sigma(p^2)$

on-shell renormalizn.

Exercise: derive δm_S^2

$$\delta m_S^2 = m_S^2 - m_{SR}^2 = -\Sigma(p^2 = m_{S,R}^2) \longrightarrow \frac{a_1}{\epsilon} + \boxed{\text{finite}} \quad (\text{dim. reg.})$$

$$b_1\Lambda^2 + b_2 \ln\frac{\Lambda^2}{m_{F,S}^2} + \boxed{\text{finite}'} \quad (\text{cutoff})$$

these are the parts to consider

"finite" $\simeq (c_1 m_{S,R}^2 + c_2 m_{F,R}^2) \cdot f(m_{S,R}, m_{F,R}, \lambda_{S,R}, \lambda_{F,R})$

↳ it grows as the mass^2 of any scalar/fermion in the loop.

↳ M_H not protected against large quantum corrections.

Direct link to BSM

↳ less finetuning → Λ not too large (→ $\Lambda \sim 10$ TeV)

In contrast:

$m_F \to \delta m_F \to$

$= \; + \; h.o.$

Exercise: Derive δm_F →

$$\begin{cases} \lambda_F^2 \left[\frac{a_1}{\epsilon} + \text{finite} \right] \\ \lambda_F^2 \left[b_1 \ln \Lambda^2 / m_{F,S}^2 + \text{finite}' \right] \end{cases}$$

'finite' $\simeq m_F \lambda_F^2 \cdot f(\ldots)$

$= 0$ if $m_F = 0$ (masslessness protected by chiral symmetry)

(3b) → Higgs potential → why $\mu_F < 0$
why $\lambda\phi^4$?

↳ need to measure $\lambda_{3H}, \lambda_{4H}$ (cubic/quartic couplings)

SM: m_H^2/v^2

SM: m_H^2/v

(3c)

$$\mathcal{L}_{Yukawa} = - Y_U^{ij} \bar{Q}_L^i \phi^c u_R^j - Y_D^{ij} \bar{Q}_L^i \phi\, d_R^j$$

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ H+v \end{pmatrix}$$

$$i\sigma^2 \phi^* = \frac{1}{\sqrt{2}} \begin{pmatrix} H+v \\ 0 \end{pmatrix}$$

$$\begin{pmatrix} u \\ d \end{pmatrix}$$

arbitrary couplings

mass basis

$$u_L^i = u_L'^i = (U_{u,L}^{-1} u_L)^i$$

$$d_L^i = d_L'^i = (U_{d,L}^{-1} d_L)^i$$

$$\mathcal{L}_{gauge} = \cdots g (\bar{u}_L' U_{u,L}^{\dagger}) W^{\mu} \gamma_{\mu} (U_{d,L} d_L')$$

(CKM)

flavor ⟷ Yukawa sector

Is this a new force all together?

Bibliography

- Lectures on collider physics – General
  - Tao Han – "Collider phenomenology" – hep-ph/0508097
  - Matthew Schwartz – "TASI lectures on collider physics" arxiv: 1709.04533
  - Maxim Perelstein – "Introduction to collider physics" arxiv: 1002.0274
  - Many recordings!
- Books
  - "QCD and collider physics" by Ellis, Stirling & Webber
  - "Collider physics" by Barger & Phillips
  - QFT books (my favorite one for this purpose would be M. Schwartz's book)
  - the history of collider physics is fascinating "the experimental foundations of particle physics" by Cahn & Goldhaber
- Colliders – technology
  - Shiltsev & Zimmermann – "Modern & Future Colliders" arxiv: 2003.09084
  - Roser et al. – "On the feasibility of future colliders" arxiv: 2208.06030

- **Specific Topics** (with emphasis "at colliders")

→ **Higgs physics**

- TASI lectures (Dawson, Reina, Wells) — hep-ph/0512377 (Dawson); 2022 (video) (Reina); arXiv:1208.5504; arXiv:0512342 (Wells)
- CERN/Fermilab school on Hadron Collider Physics (Reina) — 2019 (video only)
- CTEQ summer school (Reina, video only)
- ICTP (Dawson) → hep-ph/9901280

→ **top physics**

- TASI lectures (Dawson) — hep-ph/0303191
- CTEQ schools (Reina, video only) 2009

→ **EW**

- TASI lectures (Matchev, Freitas) — hep-ph/0402031 (Matchev); arXiv:2012.11642 (Freitas)

→ **QCD & strong interactions**

- lectures by Gavin Salam (see his webpage)
- TASI (Reina - video 2020)

→ **BSM searches**

- TASI - (Liu - video 2022)

→ Recordings exist for many of these lectures

→ PDF slides are available for most of them.

→ Present & Future perspective

- TASI lectures on "Future Colliders" - Mangano
  arxiv: 1905.07489

- European Strategy → the website

- Snowmass 2021 – Report of the Energy Frontier
  (arxiv: 2211.11084)

  + Topical Groups' Reports

  + Report of the Accelerator Frontier
  (arxiv: 2209.14136)