The next facility in high energy physics – the scientific potential of an e^+e^- Higgs/top/EW factory

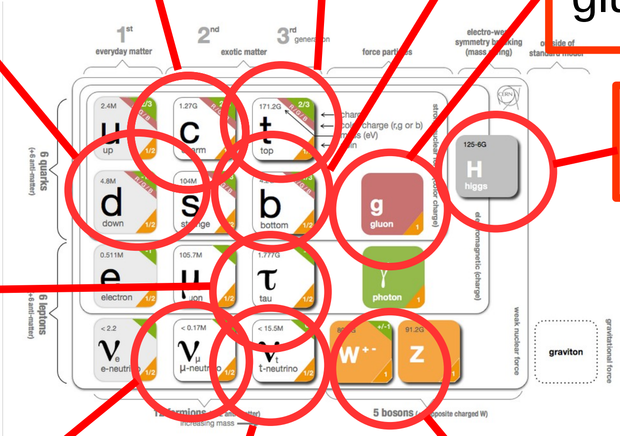
Marcel Vos,

IFIC, CSIC/UV, Valencia

NIKHEF colloquium

Amsterdam, March 2024

particle physics discoveries 1960-2022



top Tevatron 1995

charm BNL/SLAC 1974

bottom FNAL 1977

quarks, SLAC 1968

gluon DESY HERA 1975

Higgs CERN LHC 2012

τ, SLAC SPEAR, 1975

ν_μ, BNL, 1962

W/Z CERN Sp$\bar{p}$S 1984

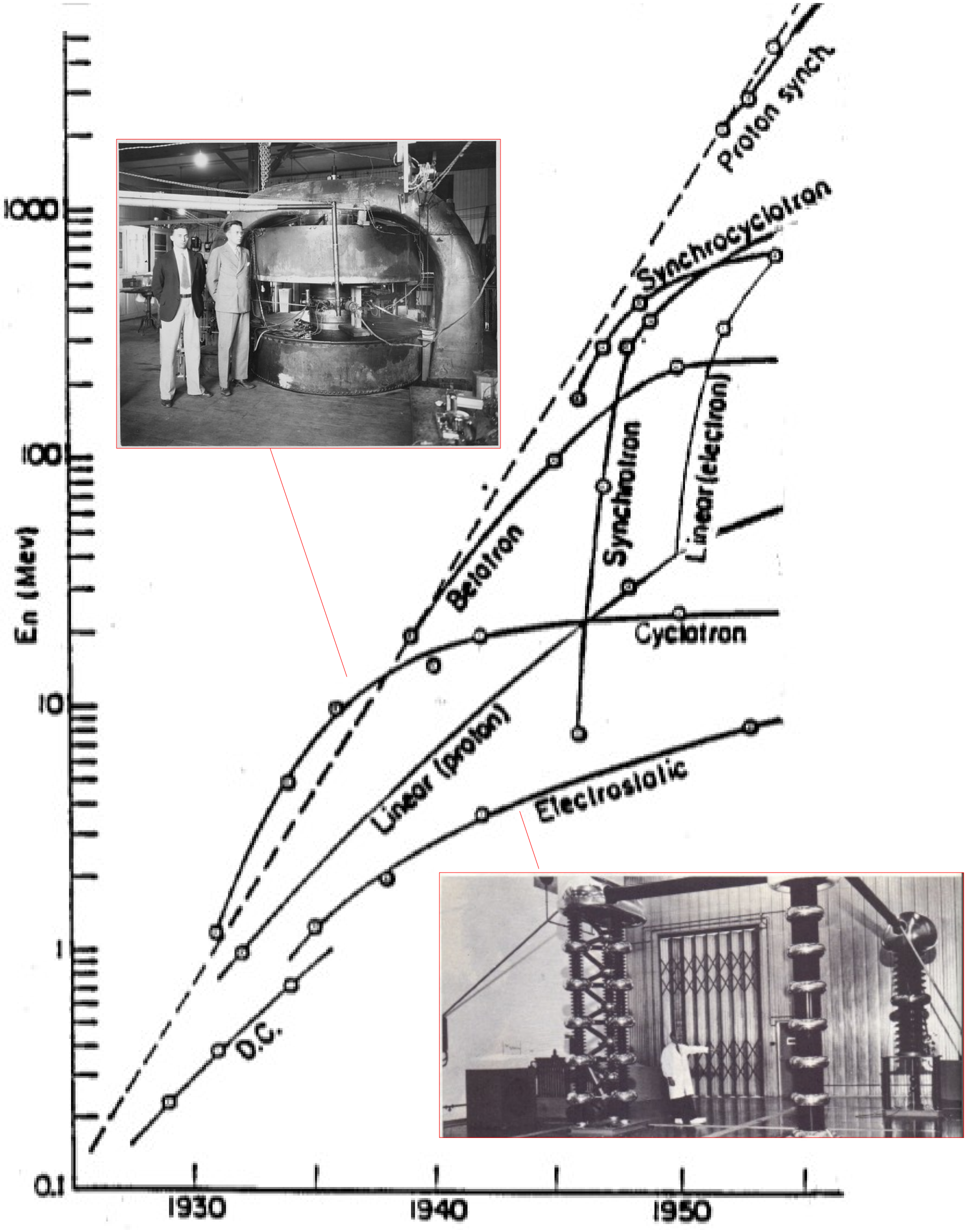
ν_τ, FNAL, 2000

marcel.vos@ific.uv.es

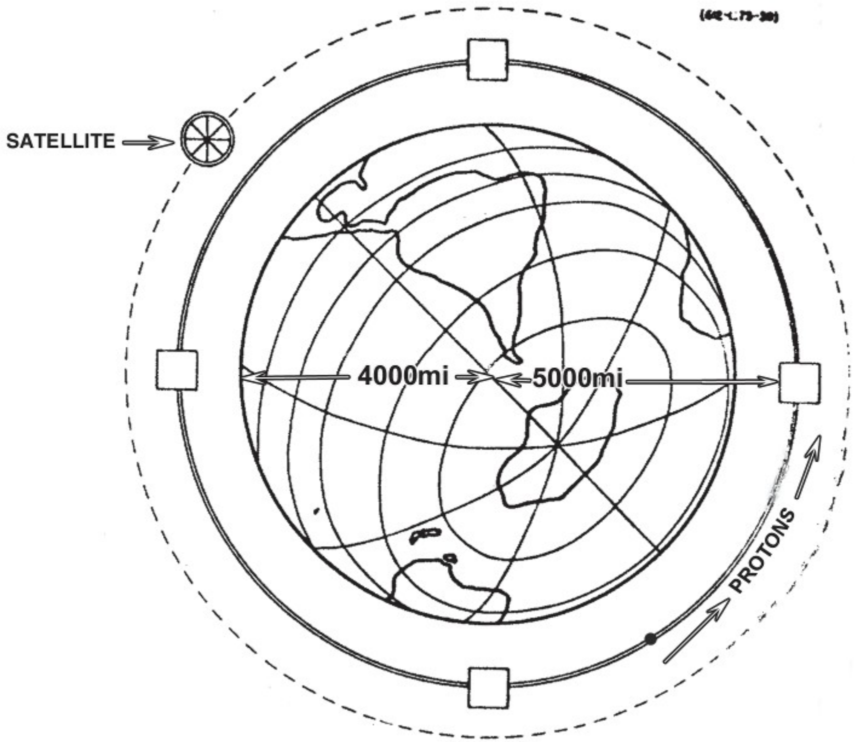
Accelerators...

The ‘30s, ‘40s and ‘50s saw a rapid succession of different machine designs: D.C and electro-static accelerators were replaced at the “energy frontier” by cyclotrons, then betatrons, sychrocyclotrons…

Livingston plot registers progress: The succession of techniques fueled decades of exponential progress, with a factor 10 in energy every six years



What’s next? In the 1950s...



Fermi, in 1954, speculated that in 1994 we’d need to build a planet-sized accelerator

Note: we didn’t. If the size of the LHC is a deception, its center-of-mass is close to what Fermi hoped for!!

The future is hard to predict, even for a genius

See also: Beacham & Zimmermann, A very high-energy hadron collider on the moon (11.000 km, 20 T magnets, 14 PeV pp), New J. Phys. 24 (2022)

Colliders

The quantity that matters is “center-of-mass” energy

In fixed-target experiments:

$$E_{CM} \propto \sqrt{E_{beam}}$$

With colliding beams:

$$E_{CM} \propto E_{beam}$$

The key realization: collide beams of particles and anti-particles

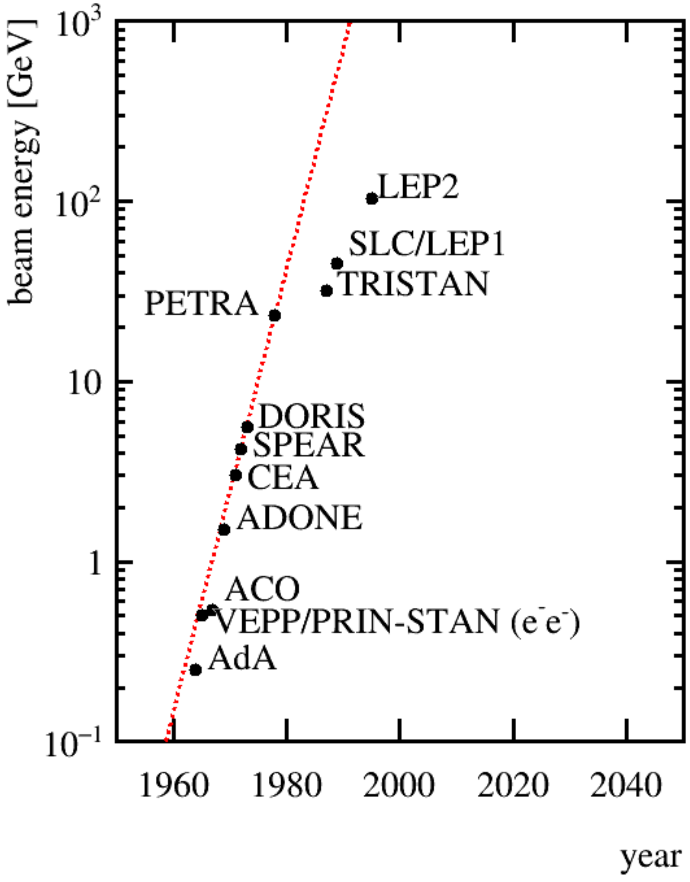
Touschek and he Frascati group in front of ADA (‘50s)

Colliders were pioneered by Wideroe and Touschek

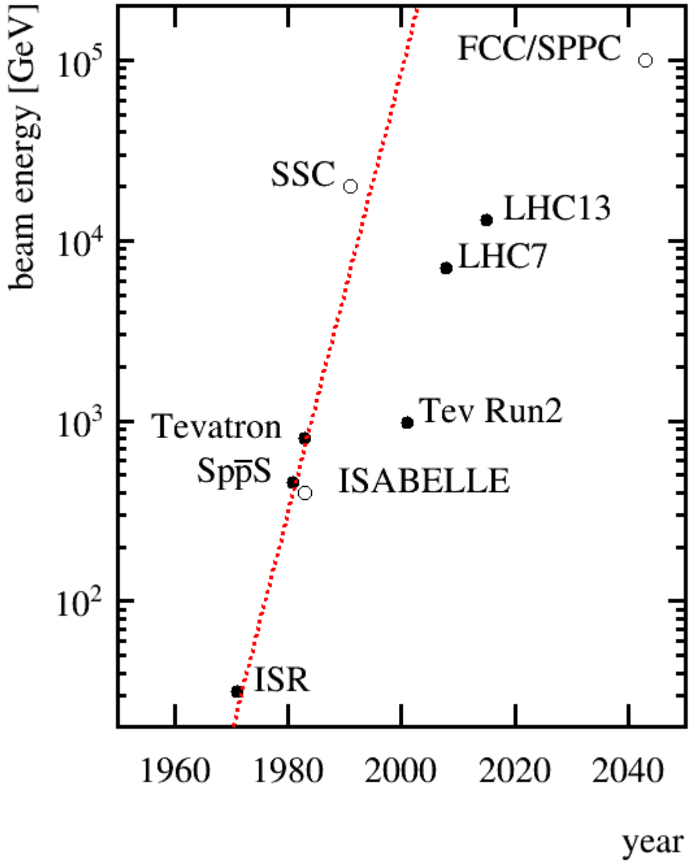
Recommended reading: biographical accounts from U. Amaldi and G. Pancheri

Colliders: progress 1960-2024

After WWII colliders fueled progress in particle physics.



The ‘60 and ‘70s marked the golden days of e^+e^- colliders.



Since the ‘80s proton colliders rule!

Further decades of exponential progress!

Synchrotron radiation

Synchrotron radiation master formula:

$$(\Delta E)_{sync} \propto \frac{E^4/m^4}{L}$$

Energy loss per turn as a function of beam energy E, particle mass m and circumference L

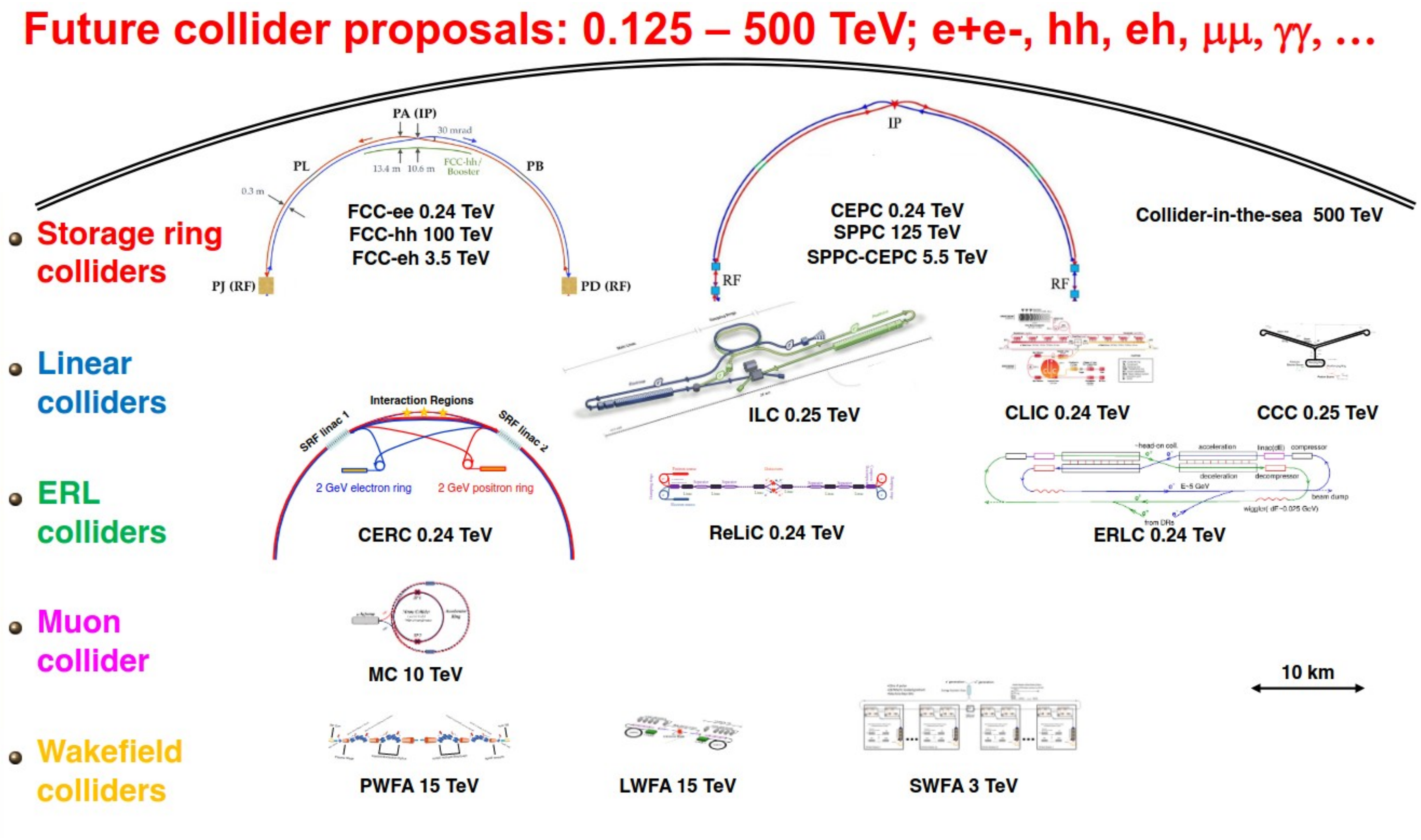
Energy must be restored (RF power) and removed from magnets (cooling power)

Solutions:

- large rings
  (LEP, FCCee/CEPC)
- linear colliders
  (SLC, XFEL, ILC/CLIC/CCC, wakefield)
- accelerate more massive particles
  (Tevatron/LHC, proton energy loss is 10^{13} times smaller than for electrons)
- accelerate more massive *elementary* particles
  (muon collider)

Question: which is HEP’s favourite solution?

Today's collider landscape…



Future collider proposals: 0.125 – 500 TeV; e+e-, hh, eh, μμ, γγ, …

- Storage ring colliders
- Linear colliders
- ERL colliders
- Muon collider
- Wakefield colliders

Answer: all of them! Accelerator R&D provides many options...

Global priorities

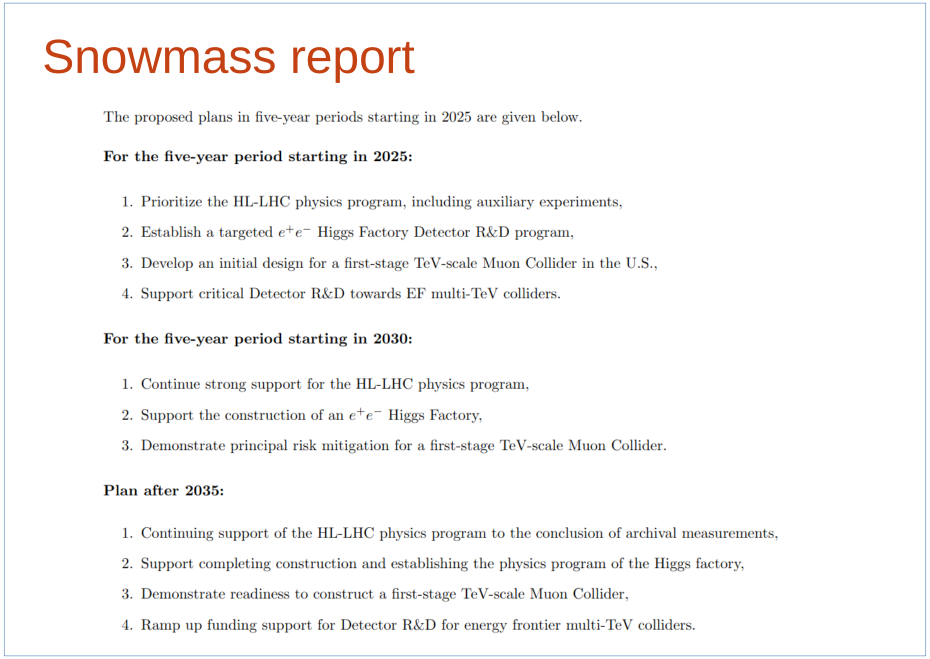
European, American and Asian strategies agree on big picture

— e^+e^- Higgs factory first:

large circular collider: FCC-ee (CERN) and CEPC (China)
linear collider: ILC (Japan), CLIC (CERN), CCC (US)

— exploration of the energy frontier next:

large pp collider: FCC-hh (CERN), SPPC (China)
muon collider: μ-collaboration (CERN+US)
plasma: R&D (EUPRAXIA, AWAKE), designs (i.e. ALEGRO, Hybrid)



Snowmass report

The proposed plans in five-year periods starting in 2025 are given below.

For the five-year period starting in 2025:

1. Prioritize the HL-LHC physics program, including auxiliary experiments,
2. Establish a targeted e^+e^- Higgs Factory Detector R&D program,
3. Develop an initial design for a first-stage TeV-scale Muon Collider in the U.S.,
4. Support critical Detector R&D towards EF multi-TeV colliders.

For the five-year period starting in 2030:

1. Continue strong support for the HL-LHC physics program,
2. Support the construction of an e^+e^- Higgs Factory,
3. Demonstrate principal risk mitigation for a first-stage TeV-scale Muon Collider.

Plan after 2035:

1. Continuing support of the HL-LHC physics program to the conclusion of archival measurements,
2. Support completing construction and establishing the physics program of the Higgs factory,
3. Demonstrate readiness to construct a first-stage TeV-scale Muon Collider,
4. Ramp up funding support for Detector R&D for energy frontier multi-TeV colliders.

European strategy update

3

High-priority future initiatives

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

Global priorities

European, American and Asian strategies agree on big picture

— e^+e^- Higgs factory first:

large circular collider: FCC-ee (CERN) and CEPC (China)
linear collider: ILC (Japan), CLIC (CERN), CCC (US)

— exploration of the energy frontier next:

large pp collider: FCC-hh (CERN), SPPC (China)
muon collider: μ-collaboration (CERN+US)
plasma: R&D (EUPRAXIA, AWAKE), designs (i.e. ALEGRO, Hybrid)

Cool Copper Collider: high accelerating gradient in normal-conducting cavities at low temperature
https://arxiv.org/abs/2203.07646

Muon collider R&D is reinforced in EU and US
https://arxiv.org/abs/2209.01318

Hybrid asymmetric collider: e- benefit from plasma wakefield acceleration, e+ use classical acceleration: 3 km Higgs factory
https://arxiv.org/abs/2303.10150

Global priorities

European, American and Asian strategies agree on big picture

— e$^+$e$^-$ Higgs factory first:

large circular collider: FCC-ee (CERN) and CEPC (China)
linear collider: ILC (Japan), CLIC (CERN), CCC (US)

— exploration of the energy frontier next:

large pp collider: FCC-hh (CERN), SPPC (China)
muon collider: μ-collaboration (CERN+US)
plasma: R&D (EUPRAXIA, AWAKE), designs (i.e. ALEGRO, Hybrid)

Cool Copper Collider: high accelerating gradient in normal-conduct
cavities at low temperature
https://arxiv.org/abs/2203.07646

Muon collider R&D is reinforced in EU and US
https://arxiv.org/abs/2209.01318

Hybrid asymmetric collider: e- benefit from plasr id acceleration,
e+ use classical acceleration: 3 km Higgs fact
https://arxiv.org/abs/2303.10150

Compact colliders are possible

Global priorities

European, American and Asian strategies agree on big picture

— e^+e^- Higgs factory first:

large circular collider: FCC-ee (CERN) and CEPC (China)
linear collider: ILC (Japan), CLIC (CERN), CCC (US)

— exploration of the energy frontier next:

large pp collider: FCC-hh (CERN), SPPC (China)
muon collider: μ-collaboration (CERN+US)
plasma: R&D (EUPRAXIA, AWAKE), designs (i.e. ALEGRO, Hybrid)

Cool Copper Collider: high accelerating gradient in normal-conduct
cavities at low temperature
https://arxiv.org/abs/2203.07646

Muon collider R&D is reinforced in EU and US
https://arxiv.org/abs/2209.01318

Hybrid asymmetric collider: e- benefit from plasm d acceleration,
e+ use classical acceleration: 3 km Higgs fact
https://arxiv.org/abs/2303.10150

Colliders can be built in the US

The NEXT collider

The 2020 update of the European Strategy for Particle Physics approved by the CERN council in May 2020 provides a concise and clear answer:

“An electron-positron Higgs factory is the highest-priority next collider”

This colloquium deals with the NEXT collider,

Read the complete document:

https://home.cern/sites/home.web.cern.ch/files/2020-06/2020%20Update%20European%20Strategy.pdf

2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

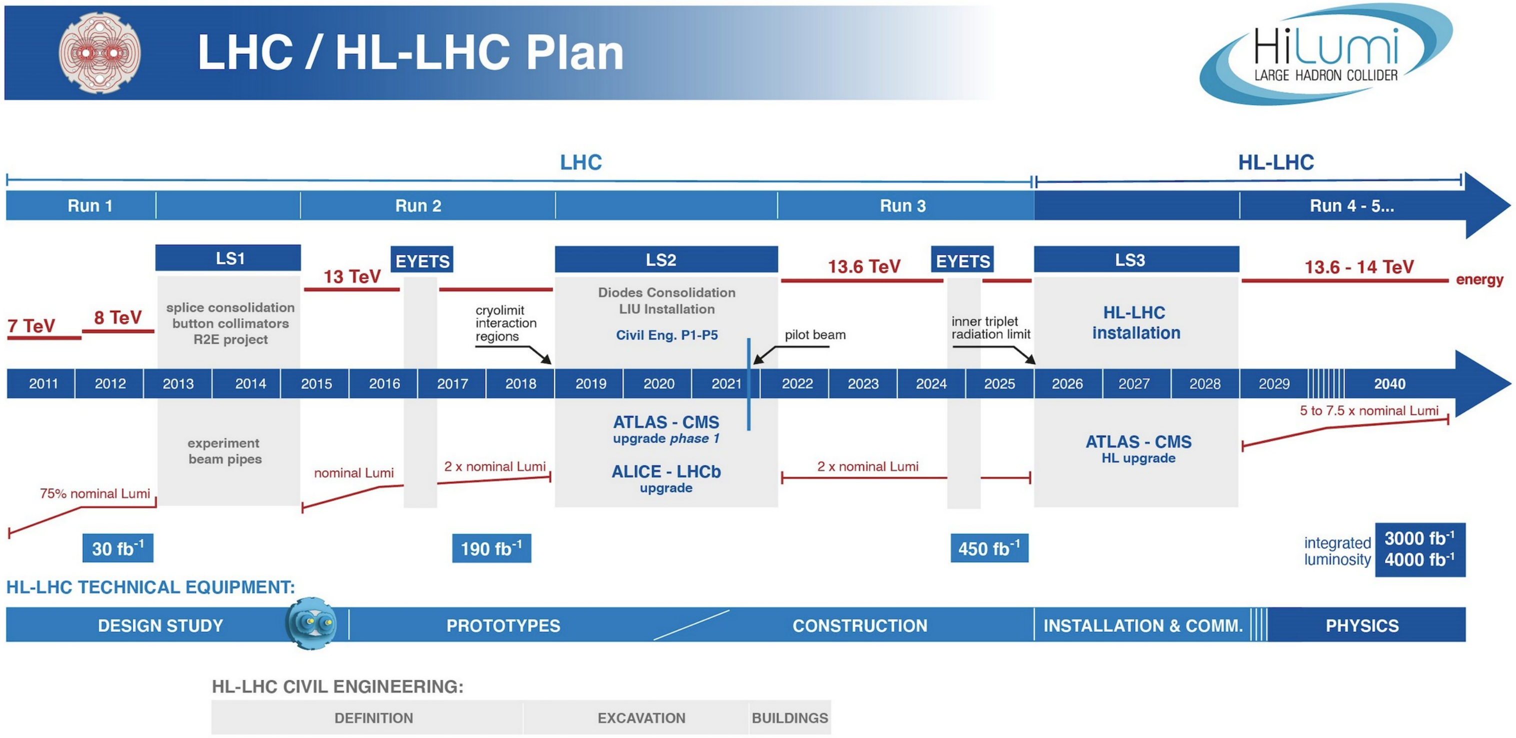
by the European Strategy Group

Long live the LHC!

marcel.vos@ific.uv.es

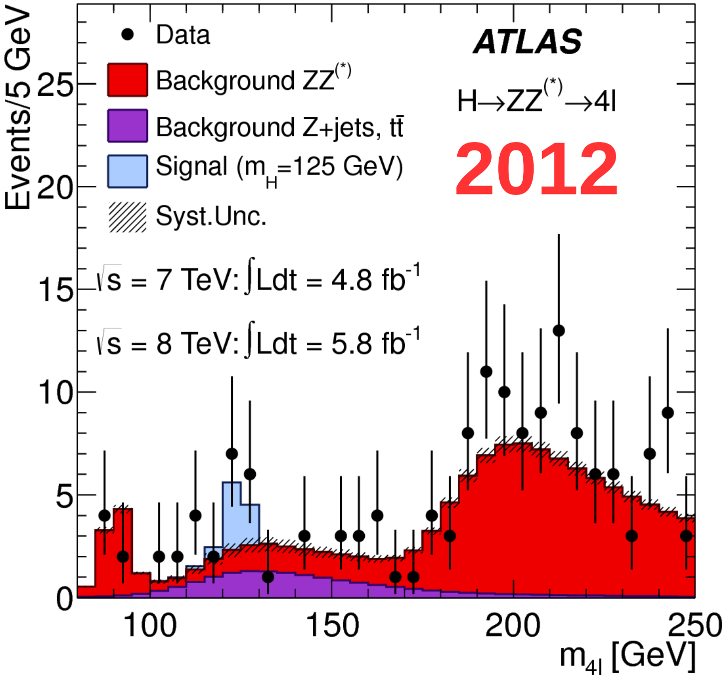
Long live the LHC

The LHC will continue to deliver science for another decade+



The HL-LHC is no longer a future collider; in our long game it’s practically the present

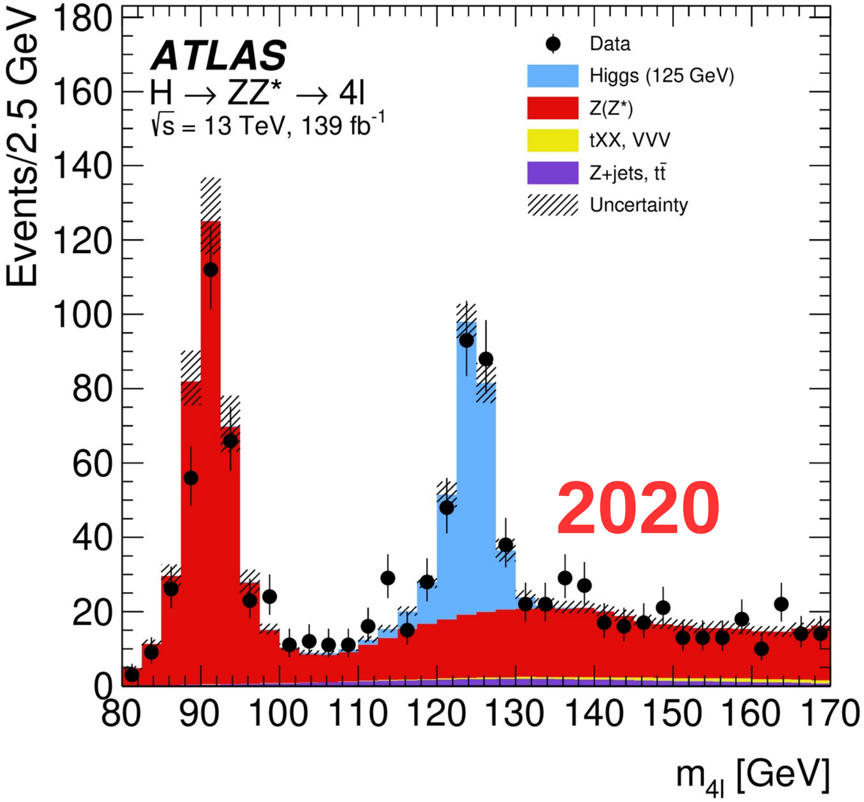
The Higgs boson – from run 1 to run 2 to HL-LHC



LHC run 2 delivered 140 fb^{-1}

LHC run 3 reached 70 fb^{-1}

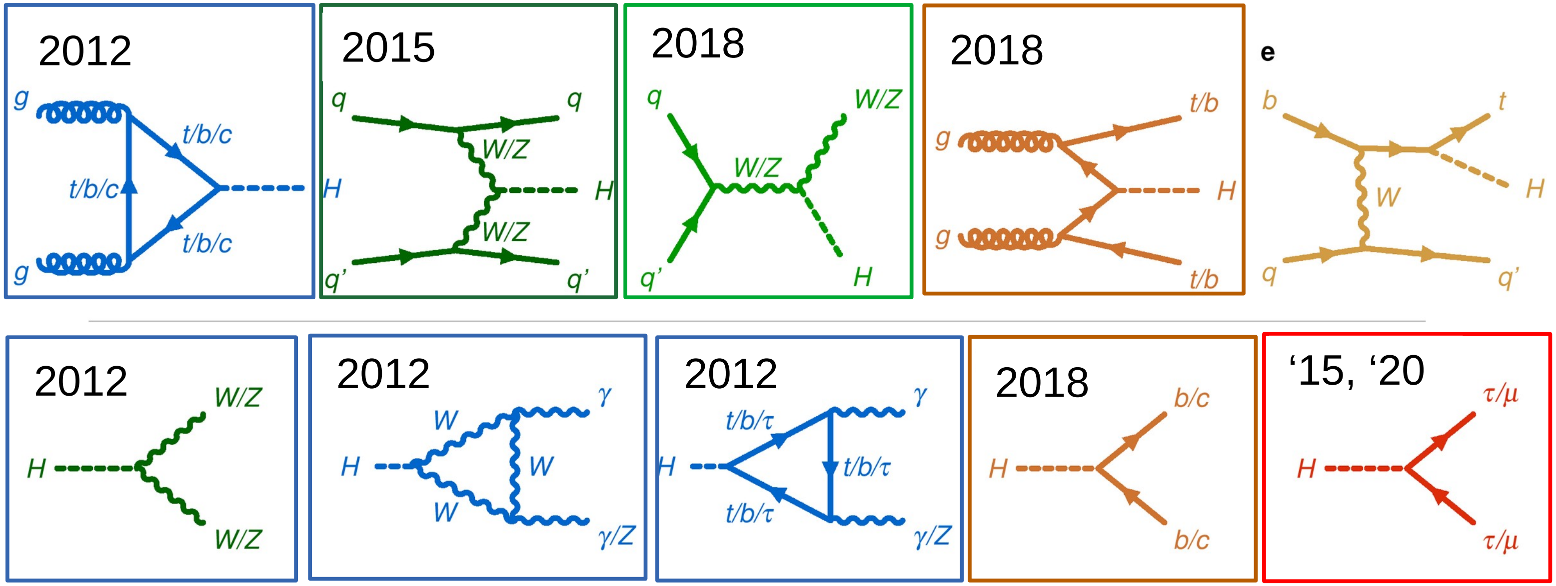
HL-LHC to reach 3 ab^{-1}



The signal in the “discovery channels” has grown very robust

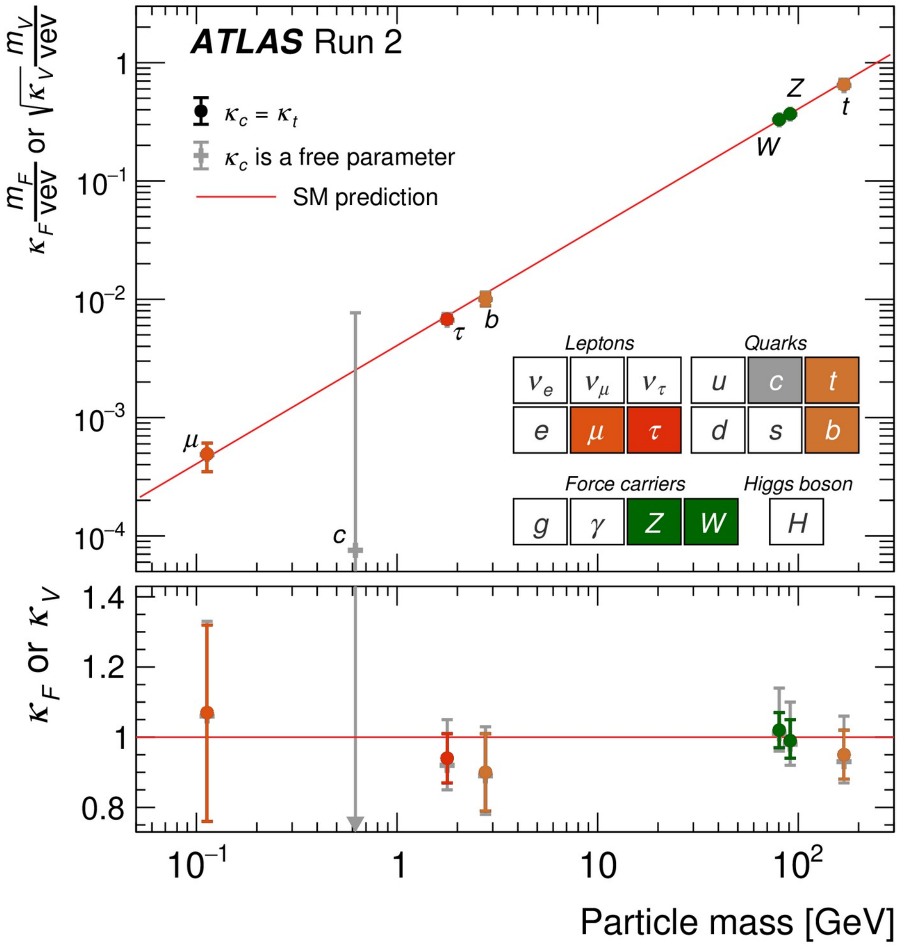
Higgs boson news

The initial discovery channels (gg → H, H → γγ and H → ZZ) are joined by many other production and decay modes



2012: one out of four production mechanisms, two decay modes
2015: Vector-boson-fusion, H → ττ (fermions!)
2018: Associated ttH production, H → bb decay
2020: evidence H → μμ (2nd gen.)
Still missing: decays to charm, tH production, di-Higgs production

Higgs boson summary



Fabiola Giannotti: “we got very lucky”

John Ellis: ”it looks and quacks like a Higgs boson”

ATLAS & CMS:
arXiv:2207.00043/92

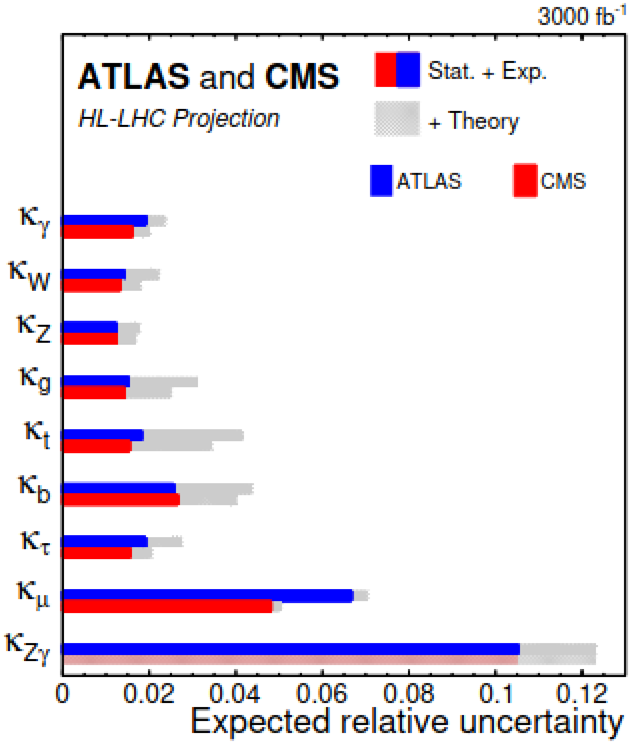
Salam, Wang, Zanderighi,
arXiv: 2207.00478

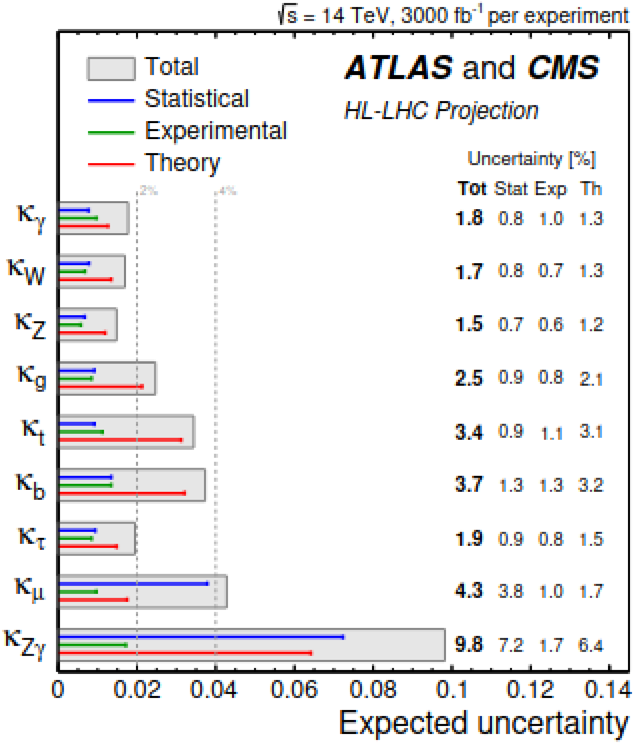
Discovered “yesterday”, now slowly turning into precision physics

Higgs boson: HL-LHC prospects

Projections for Higgs coupling measurements

S2 scenario: assumes 3000/fb and progress on all fronts, halving theory uncertainties and scaling experimental uncertainties with 1/sqrt(L)





	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

CERN Yellow Rep.Monogr. 7 (2019) 221-584, arXiv:1902.00134

How can a new e^+e^- collider help?

marcel.vos@ific.uv.es

Precision measurements

The LHC as a precision machine (example)

$$\sigma_{t\bar{t}} = 829 \pm 1\ (\text{stat}) \pm 13\ (\text{syst}) \pm 8\ (\text{lumi}) \pm 2\ (\text{beam})\ \text{pb},$$

ArXiv:2303.15340

	Stat.	Syst.	Lumi.	Theory
LHC tour-de-force	0.1%	1.5% modelling	0.8% *arXiv:2212.09379*	4% *NNLO+NNLL*
e+e- hyper precision	few x *0.1%* *arXiv:1807.02441*	*0.1%*	*0.1%*	*0.1%* N3LO, *arXiv:2209.14259*

LHC is reaching surprising precision, and theory is not far behind
However, e+e- colliders can do an order of magnitude better

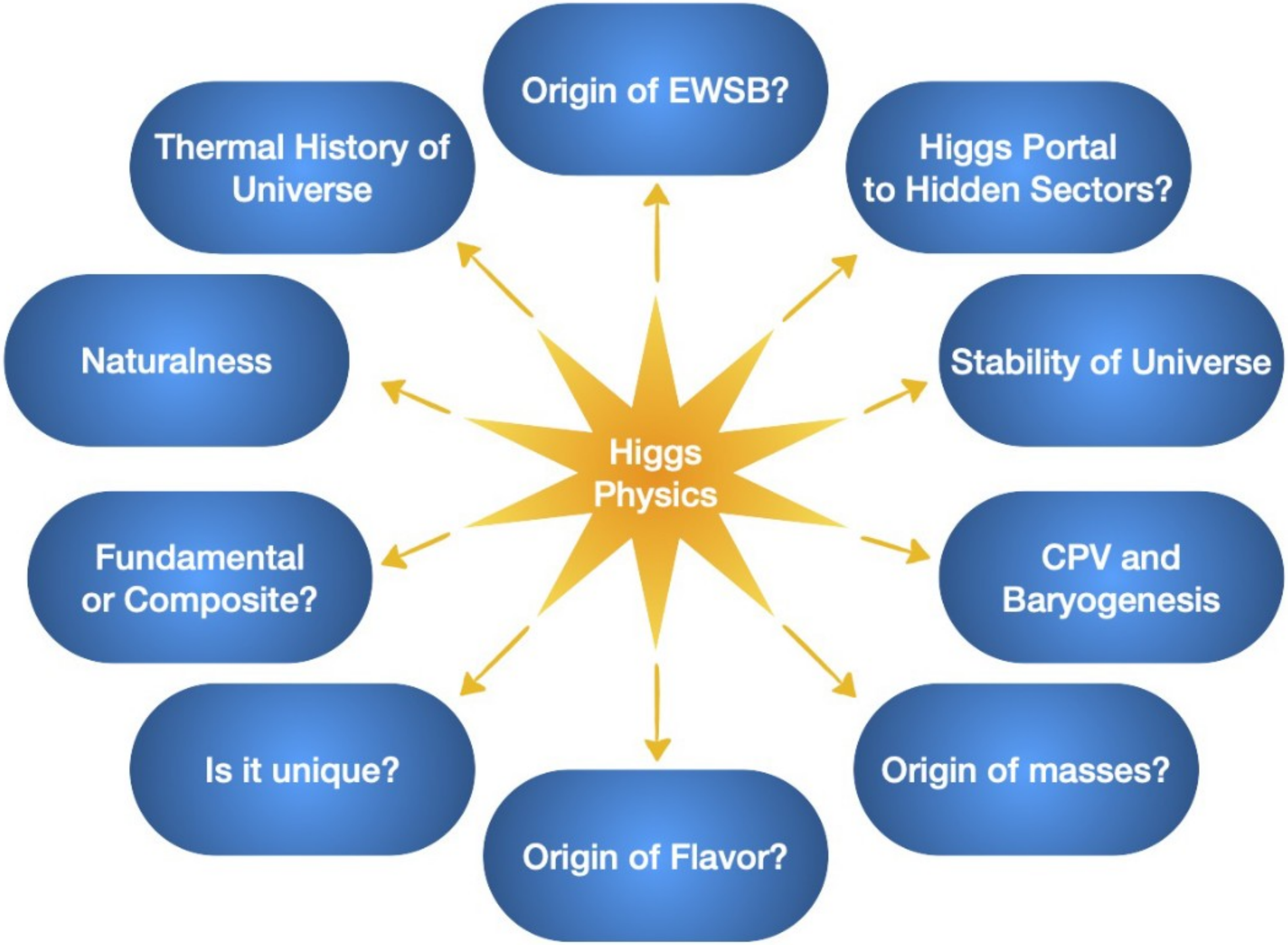
Caveats: LHC can do better differential measurements; theory still has time to catch up

marcel.vos@ific.uv.es

Precision Higgs physics

marcel.vos@ific.uv.es

The Higgs boson and the big questions



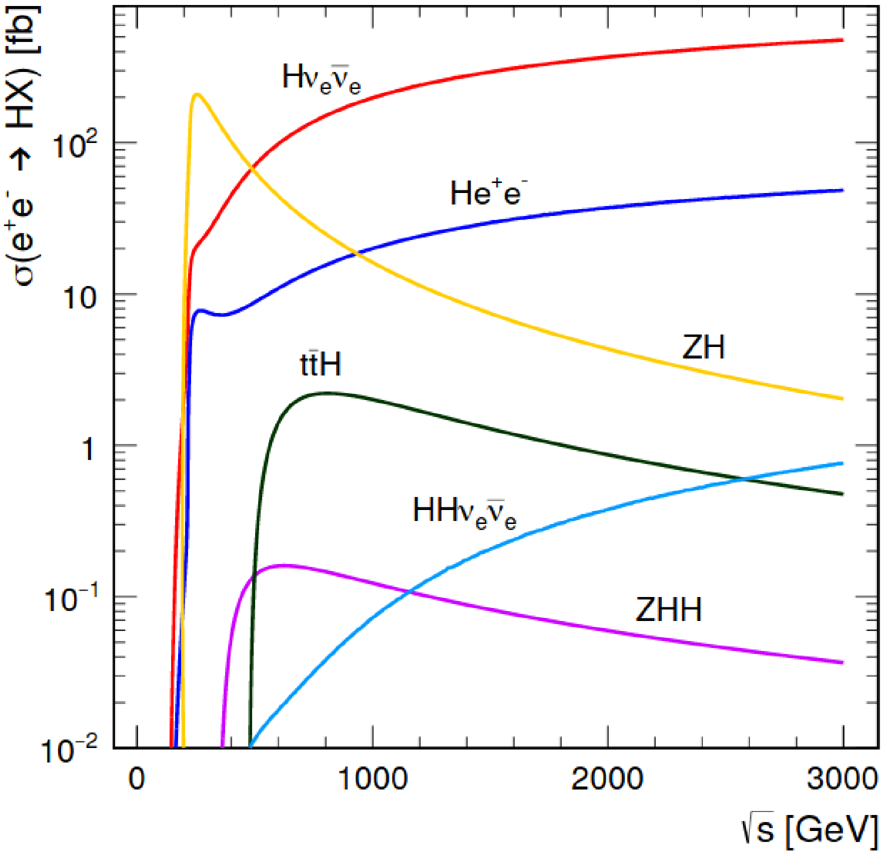
Higgs Physics

- Origin of EWSB?
- Higgs Portal to Hidden Sectors?
- Stability of Universe
- CPV and Baryogenesis
- Origin of masses?
- Origin of Flavor?
- Is it unique?
- Fundamental or Composite?
- Naturalness
- Thermal History of Universe

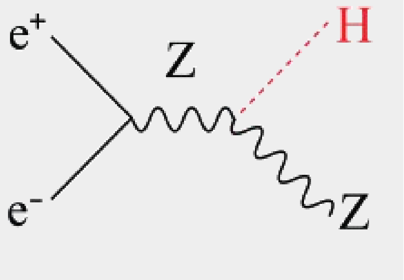
https://gsalam.web.cern.ch/gsalam/talks/repo/202403-NIKHEF-symposium-NIKHEF-symposium.pdf

marcel.vos@ific.uv.es

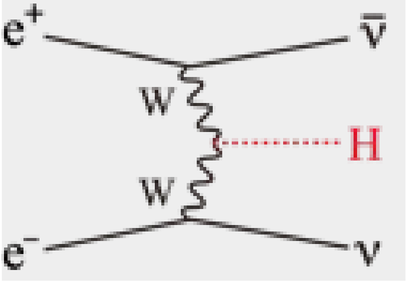
The electron-positron program



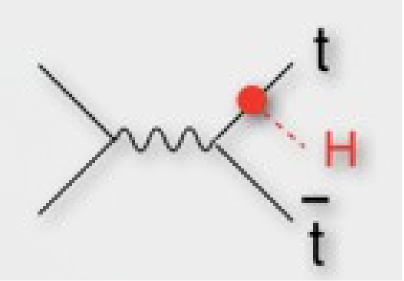
Higgs-strahlung



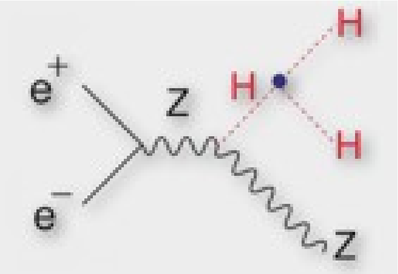
Vector-boson-fusion (VBF)



Associated production with a top quark pair

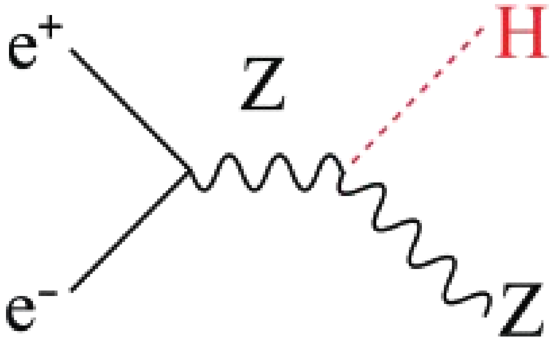


Di-Higgs production

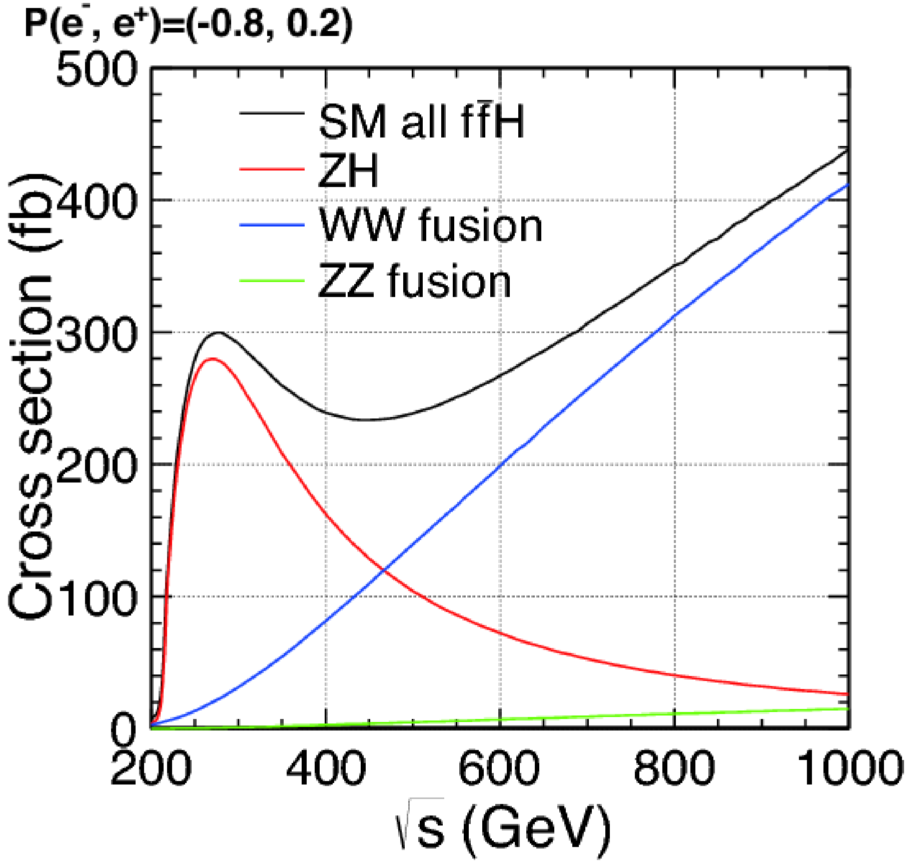


The next collider: the Higgs factory run

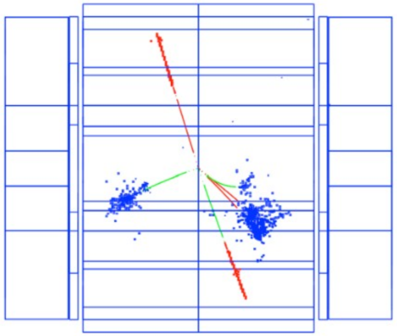
A Higgs factory is an e^+e^- collider operated at ~250 GeV, where the rate of the Higgs-strahlung process is maximum



Produce approx. 1 million Higgses
in perfectly controlled conditions



Higgs factory advantages

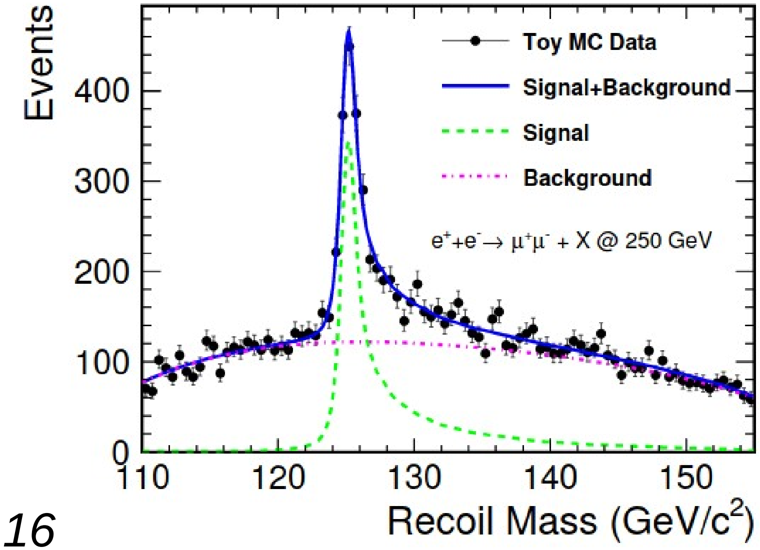


$e^+e^- \rightarrow ZH \rightarrow \mu\mu\tau\tau$

Well-known initial state
(e^+e- annihilate and transfer all their energy)
Excellent detector performance
(rates and radiation levels limit LHC detectors)
Machine induced backgrounds nearly negligible
(Pile-up and Underlying Event limit LHC analyses)
SM backgrounds of same order as signal
(LHC analyses muddle through orders of magnitude)
SM rates can be precisely predicted
(QCD and PDF uncertainties limit LHC precision)

Recoil-mass analysis yields sharp Higgs peak without ever touching the Higgs decay products → ideal laboratory to count Higgs decays

Absolute normalization of Higgs couplings as total width is accessible



ILD interim design report, arXiv:2003.01116

Higgs couplings

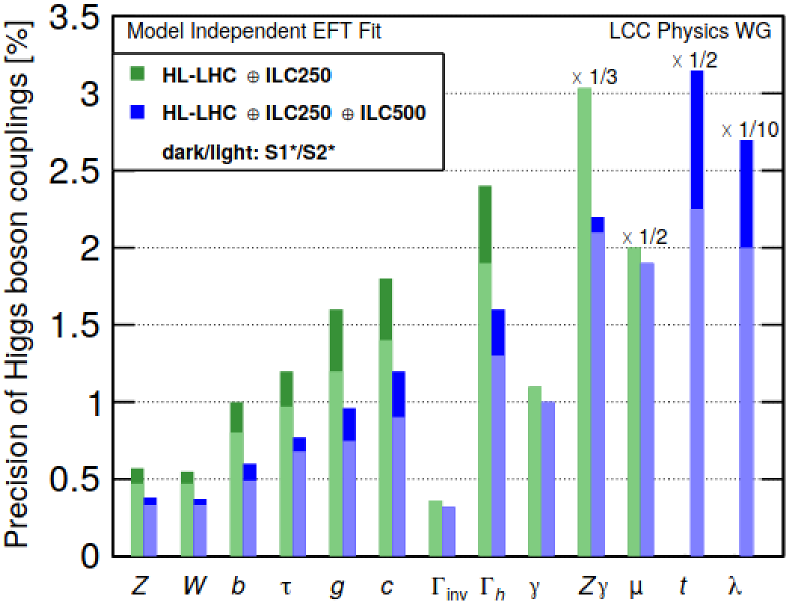
Improve Higgs couplings to
Z, W and b to sub-% precision

Precision measurements also for
gluon and charm (hard at LHC)

Strange and electron Yukawa
coupling accessible?

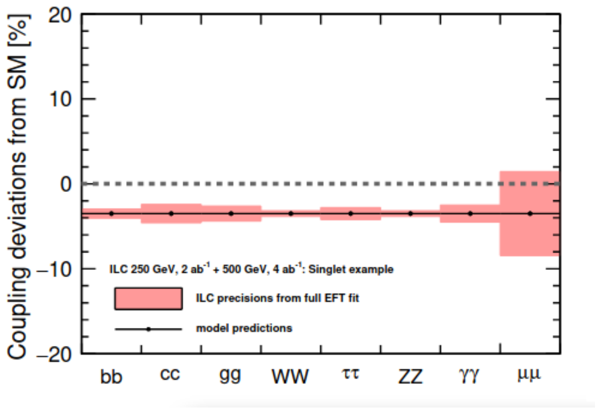
LHC data remain crucial for
muons, photons and top

arXiv:1903.01629

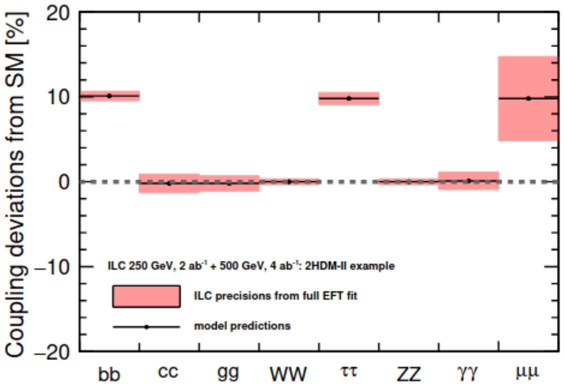


Higgs couplings

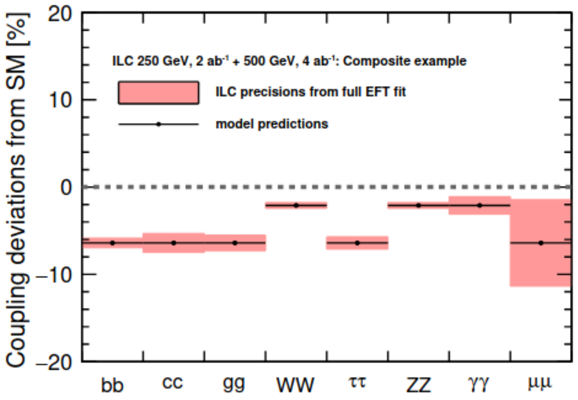
ILC input to Snowmass, arXiv:2203.07622



singlet (all)



2HDM-II (b, τ)

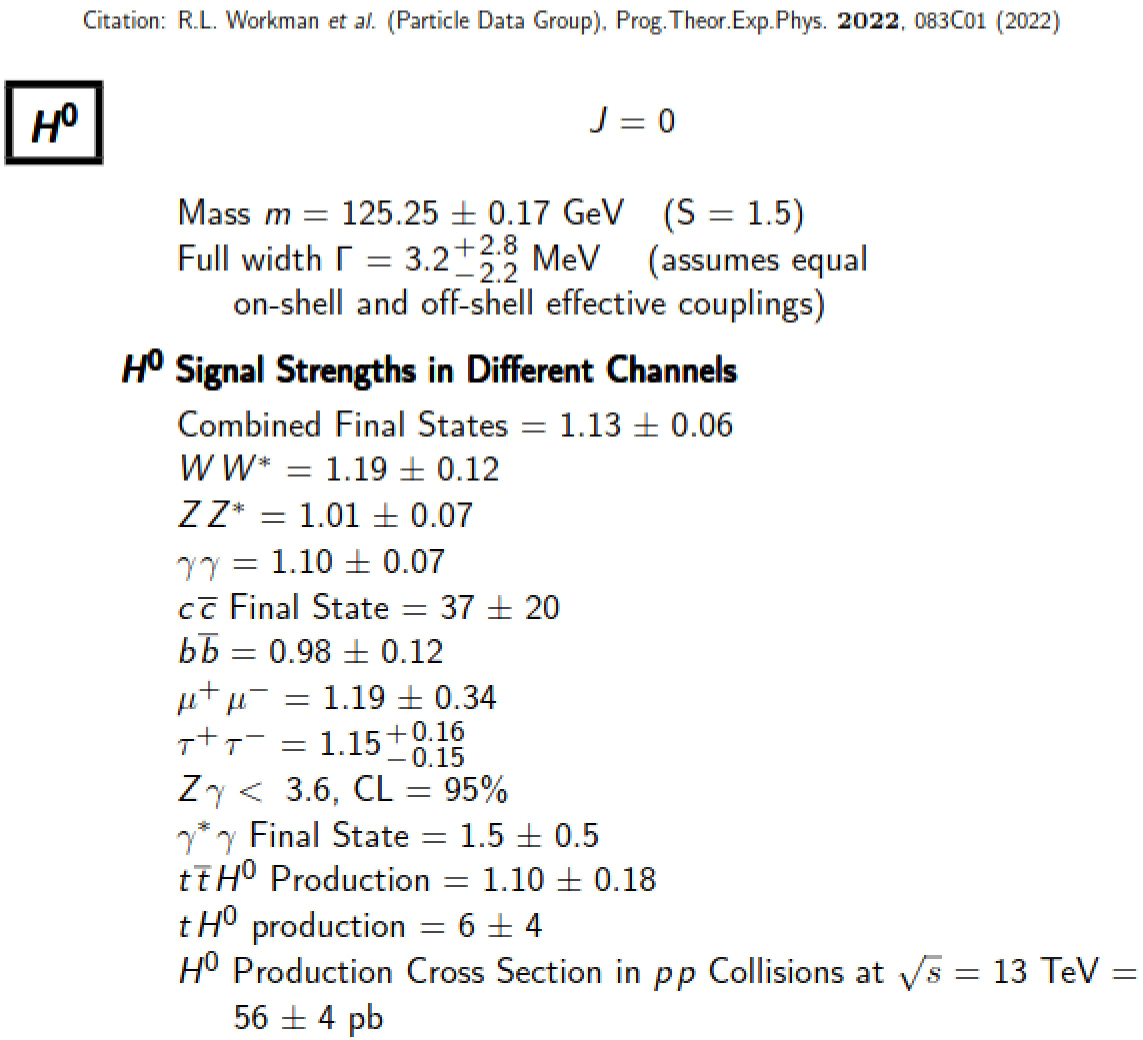


composite (b,c,g τ)

Qualitative (charm) and quantitative (few % → few per mille) improvements over HL-LHC precision, important complementarity

Viable BSM scenarios provide different patterns of experimentally accessible deviations in coupling measurements

The Higgs boson data sheet



Citation: R.L. Workman *et al.* (Particle Data Group), Prog.Theor.Exp.Phys. **2022**, 083C01 (2022)

$\boxed{H^0}$ $J = 0$

Mass $m = 125.25 \pm 0.17$ GeV (S = 1.5)
Full width $\Gamma = 3.2^{+2.8}_{-2.2}$ MeV (assumes equal on-shell and off-shell effective couplings)

H^0 Signal Strengths in Different Channels

Combined Final States = 1.13 ± 0.06
$WW^* = 1.19 \pm 0.12$
$ZZ^* = 1.01 \pm 0.07$
$\gamma\gamma = 1.10 \pm 0.07$
$c\overline{c}$ Final State = 37 ± 20
$b\overline{b} = 0.98 \pm 0.12$
$\mu^+\mu^- = 1.19 \pm 0.34$
$\tau^+\tau^- = 1.15^{+0.16}_{-0.15}$
$Z\gamma <$ 3.6, CL = 95%
$\gamma^*\gamma$ Final State = 1.5 ± 0.5
$t\overline{t}H^0$ Production = 1.10 ± 0.18
tH^0 production = 6 ± 4
H^0 Production Cross Section in pp Collisions at $\sqrt{s} = 13$ TeV = 56 ± 4 pb

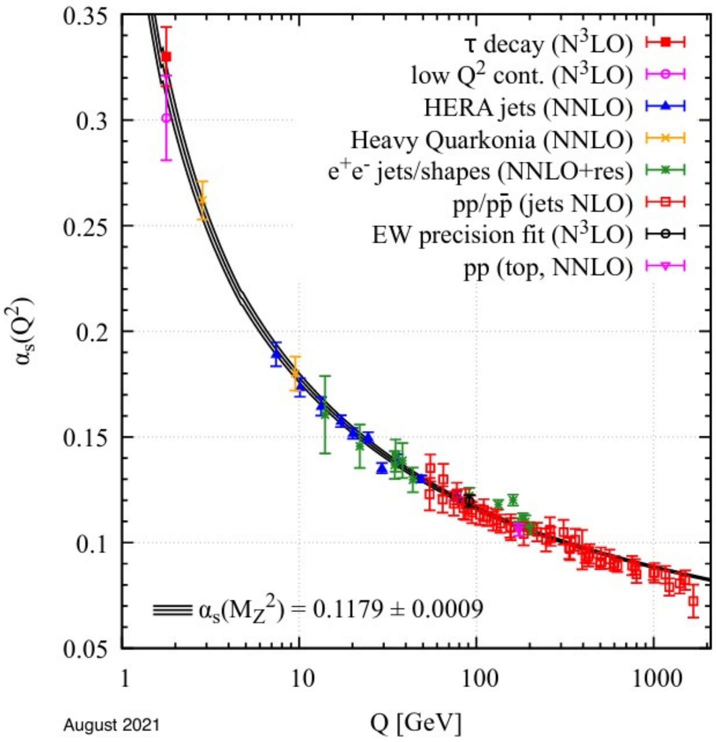
Enough data to fill the PDG data sheet on the H^0 boson

Beyond Higgs couplings

Running couplings

Scale evolution of the strong coupling predicted by QCD:

$$\mu_R^2 \frac{d\alpha_s}{d\mu_R^2} = \beta(\alpha_s) = -(b_0\alpha_s^2 + b_1\alpha_s^3 + b_2\alpha_s^4 + \cdots)$$



Precise determinations from 1 GeV to > 1 TeV!

Reference $\alpha_s(m_Z) = 0.118 \pm 0.001$ (PDG, <1%)

This plot collects α_s value extracted from measurements of many observables in several processes over a broad energy range

marcel.vos@ific.uv.es

Running constants

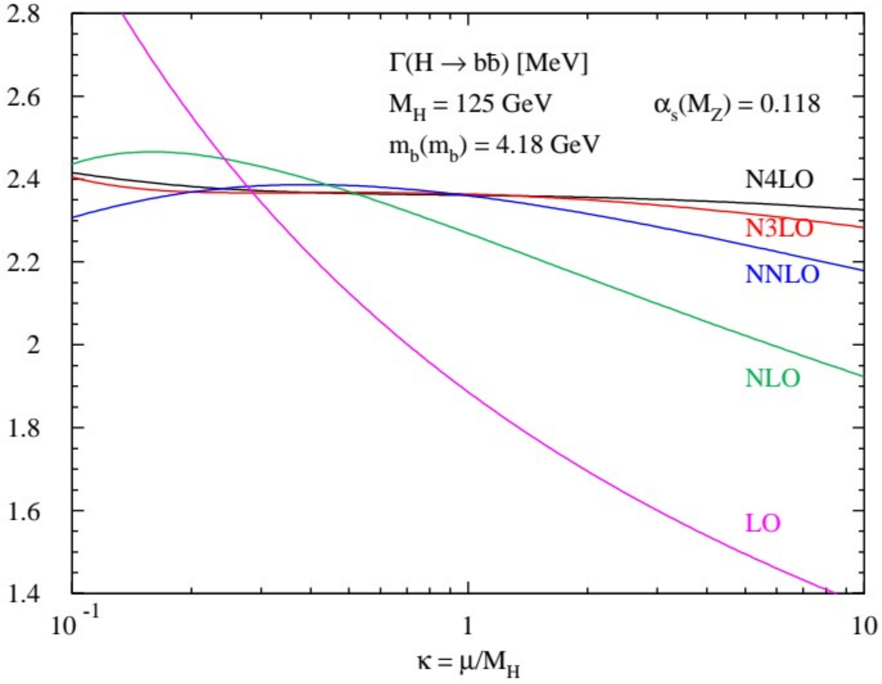
Quark masses – parameters of the QCD Lagrangian – **must run too**

$$\frac{\partial m_q(\mu)}{\partial \log(\mu^2)} = \gamma_m[\alpha_s(\mu)]\, m_q(\mu)$$

Anomalous mass dimension

Experimentally testable with Higgs decay to bottom quarks:

- quadratic dependence on m_b
- EW process, independent (LO) from α_s
- precise predictions available
- **well-defined natural scale m_h**



QCD series for $\Gamma(H \rightarrow bb)$ for $\mu = m_H$:

$$1 + \delta_{\rm QCD} = 1 + 0.2030 + 0.0374 + 0.0019 - 0.0014.$$

And for $\mu = m_b$:

$$1 + \delta_{\rm QCD} = 1 - 0.5665 + 0.0586 + 0.1475 - 0.1274.$$

Running of the bottom quark mass

Quark masses are not predicted by the SM, but Renormalization Group Equations do give a (testable) prescription for their scale evolution

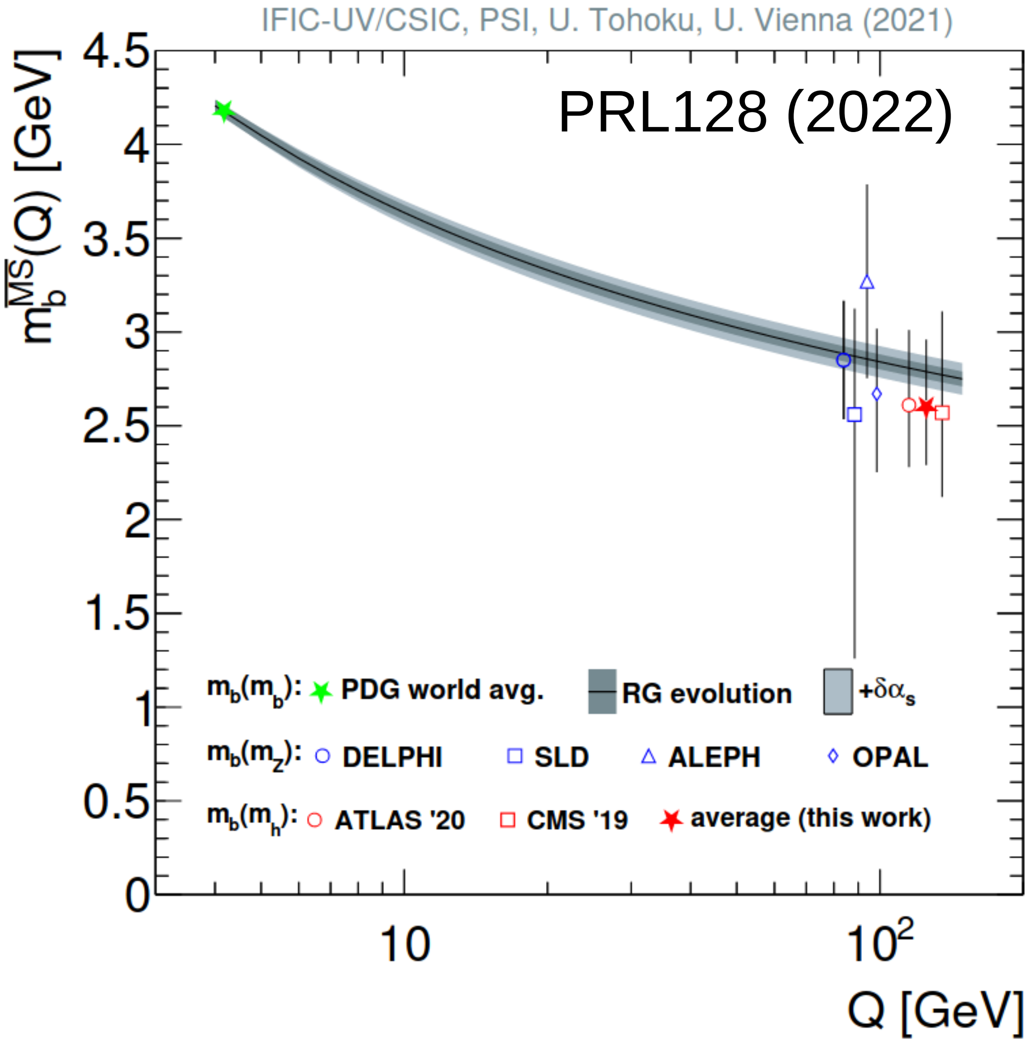
Measurements at several center-of-mass energies:

- $m_b(m_b)$ from low-energy expts
- $m_b(m_Z)$ from LEP/SLD
- $m_b(m_H)$ from LHC Higgs

Uncertainties on evolution:

- reference $m_b(m_b)$ → PDG
- $\alpha_s \pm 0.001$ (PDG $\alpha_s(m_Z)$ ■)
- $\alpha_s \pm 0.004$ (BSM evolution ▒)
- missing higher orders (negligible)

RG evolution from Revolver, arXiv:2102.01085


IFIC-UV/CSIC, PSI, U. Tohoku, U. Vienna (2021)

PRL128 (2022)

LHC $m_b(m_h)$ today is as precise as LEP $m_b(m_Z)$
All data together: observation of scale evolution

marcel.vos@ific.uv.es

Running of the bottom quark mass

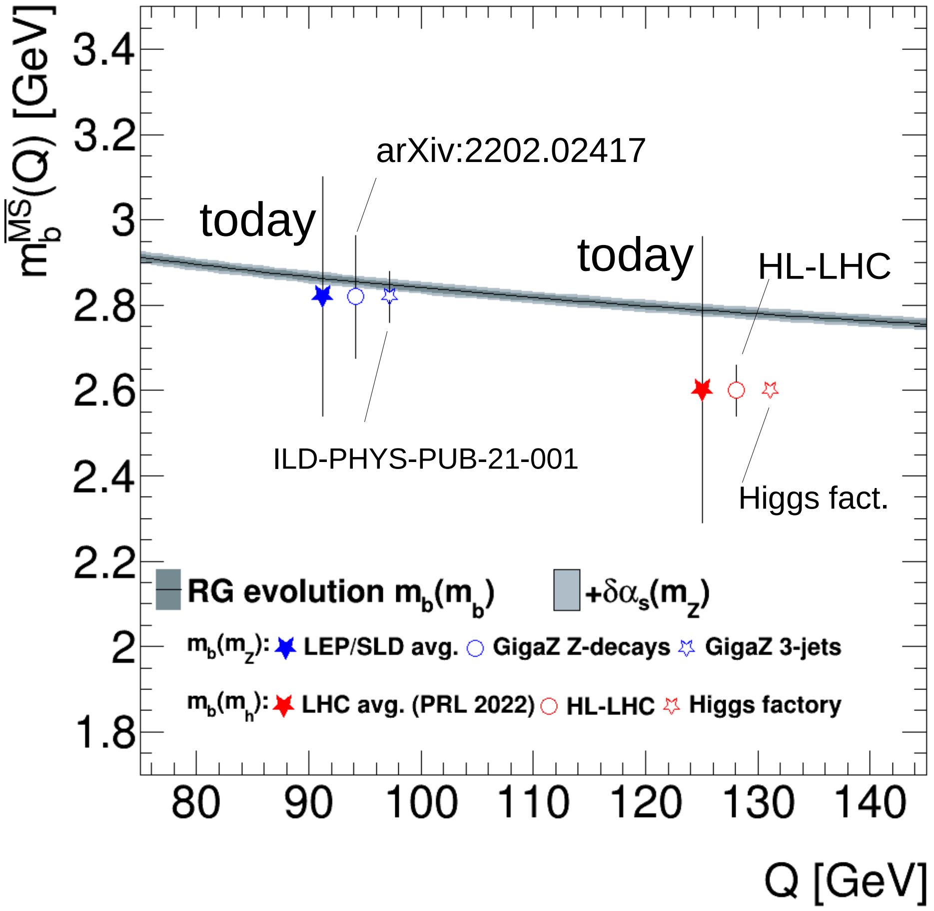
Quark masses are not predicted by the SM, but Renormalization Group Equations do give a (testable) prescription for their scale evolution

Measurements at several center-of-mass energies:

- $m_b(m_b)$ from low-energy expts
- $m_b(m_Z)$ from LEP/SLD
- $m_b(m_H)$ from LHC Higgs
- $m_b(m_H)$ from HL-LHC
- $m_b(m_H)$ from Higgs factory
- $m_b(m_Z)$ from GigaZ/TeraZ

Uncertainties on evolution:

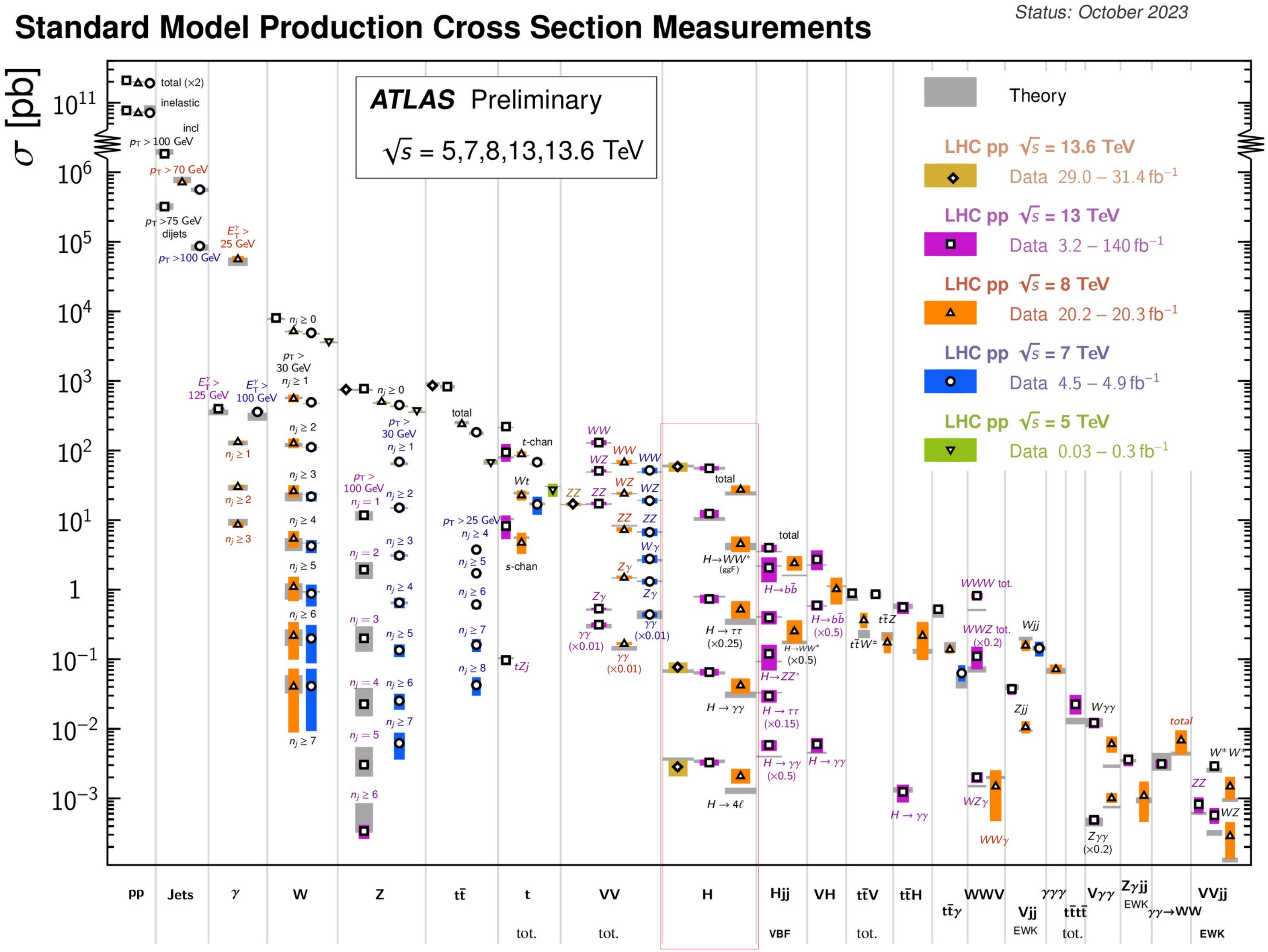
- modest improvement in α_s



The next years at the LHC will see rapid progress in $m_b(m_H)$; the Higgs factory will further improve $m_b(m_H)$ and $\alpha_s(m_Z)$

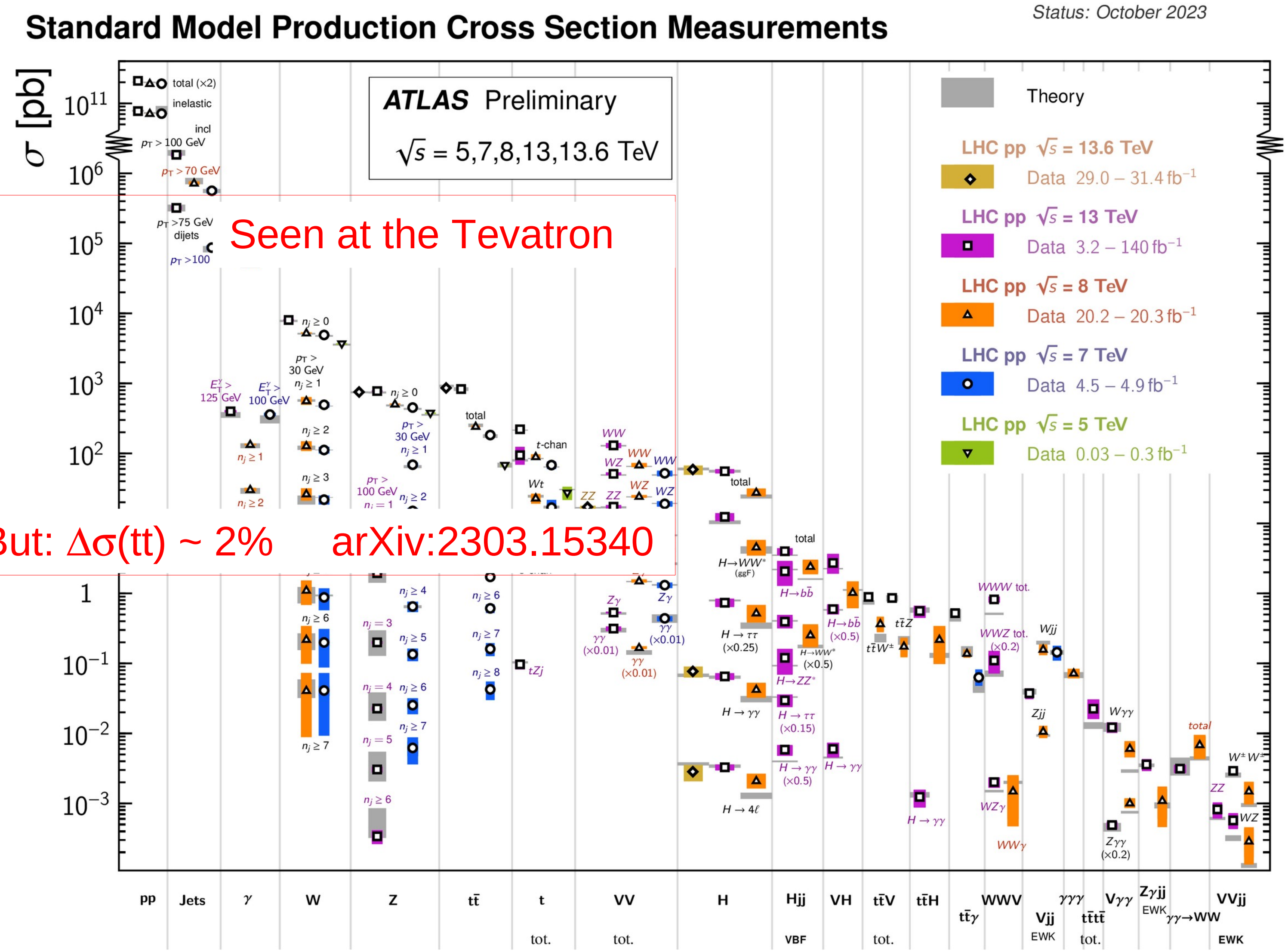
Beyond Higgs physics

Full SM characterization



The Higgs programme

Full SM characterization

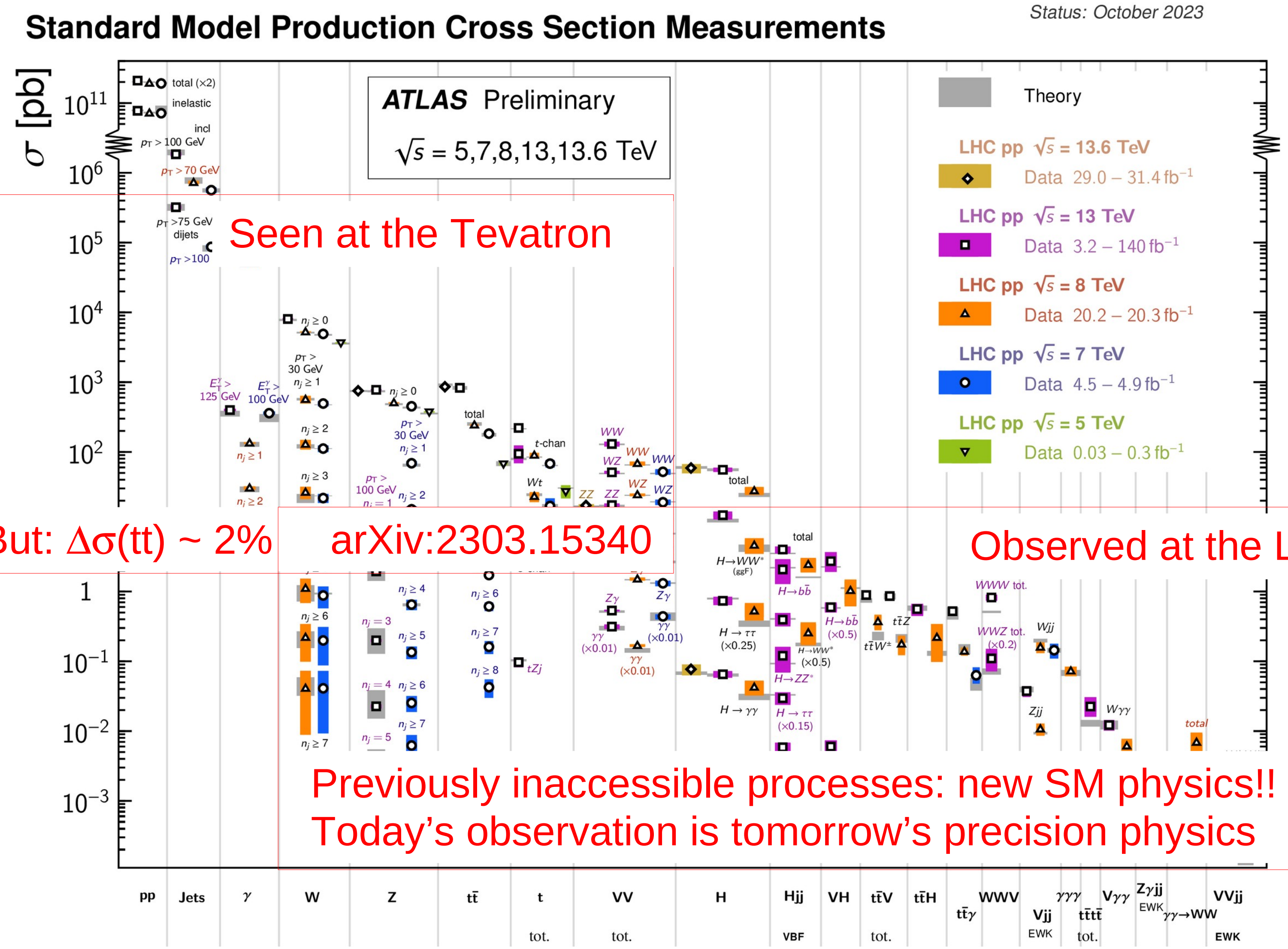


Seen at the Tevatron

But: Δσ(tt) ~ 2% arXiv:2303.15340

marcel.vos@ific.uv.es

Full SM characterization



Seen at the Tevatron

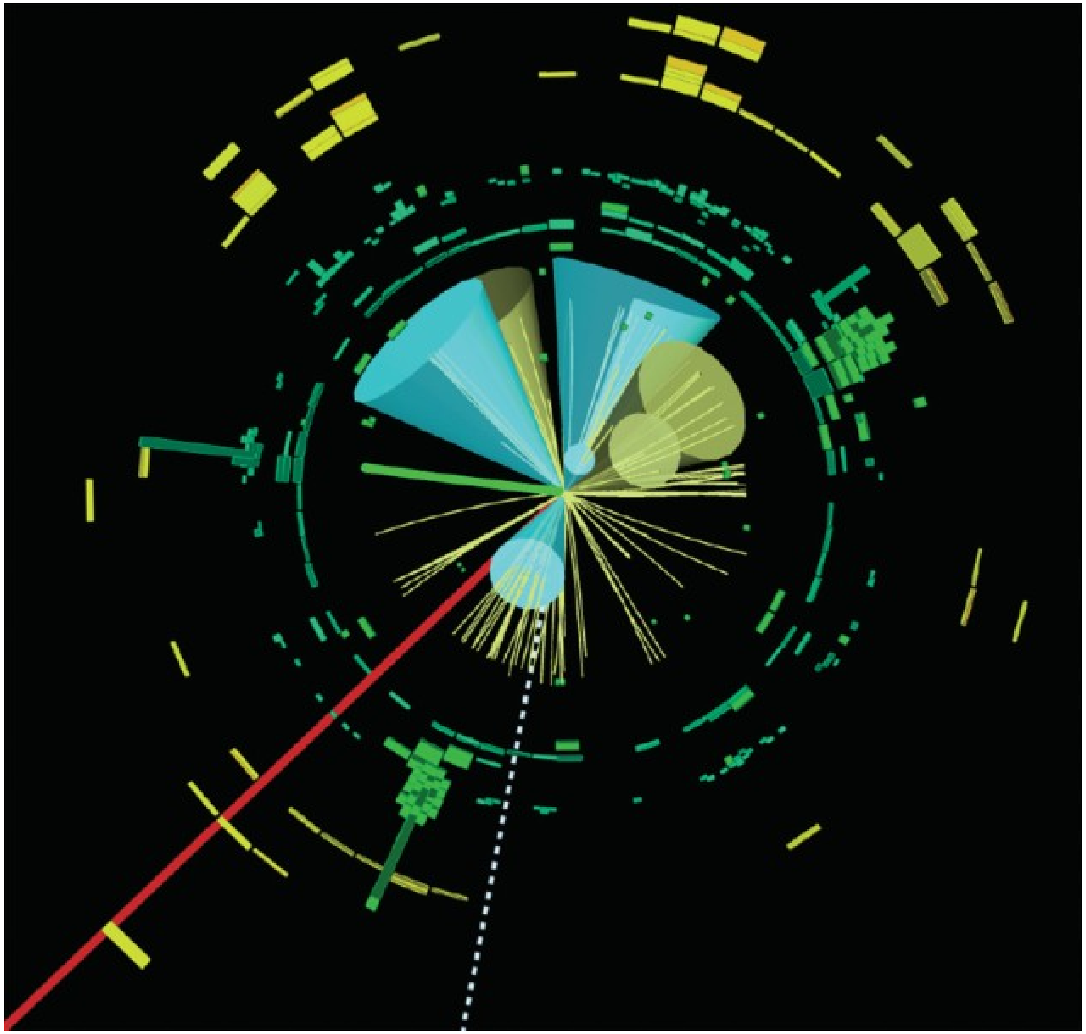
But: Δσ(tt) ~ 2%

arXiv:2303.15340

Observed at the LHC

Previously inaccessible processes: new SM physics!!
Today's observation is tomorrow's precision physics

Observation of 4-top production



Just another SM process? Maybe. But definitely “new SM physics” !

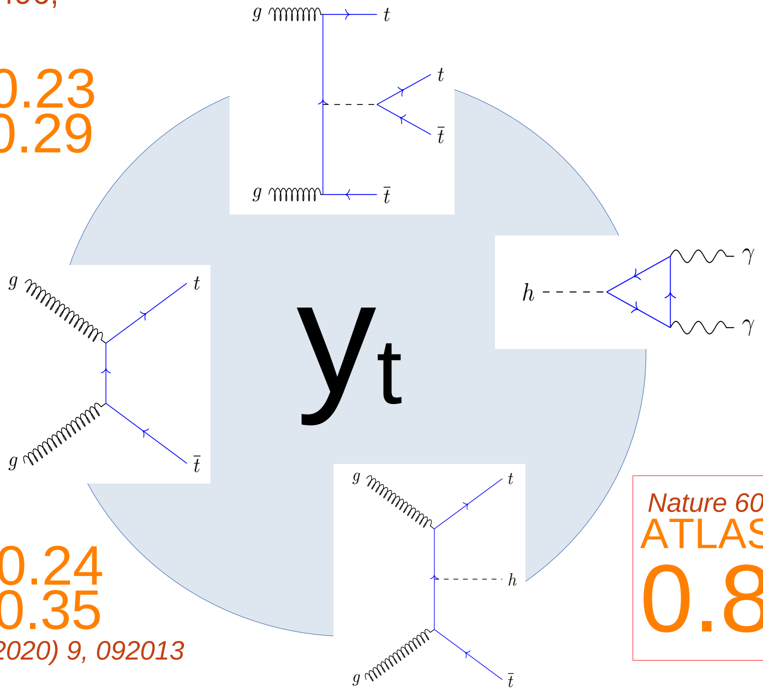
marcel.vos@ific.uv.es

Example: overconstrain the SM

Cornering the top Yukawa with tree-level (ttH and tttt) and loop-induced bounds (H → γγ, gg → H, pp → $t\bar{t}$)

EPJC83 (2023) 496,
ATLAS tttt

$1.48^{+0.23}_{-0.29}$



Nature 607 (2022) 7917, 60-68
CMS Higgs

$1.01^{+0.11}_{-0.10}$

Nature 607 (2022) 7917, 52-59
ATLAS Higgs

$0.94^{+0.11}_{-0.11}$

CMS tt

$1.16^{+0.24}_{-0.35}$

Phys.Rev.D 102 (2020) 9, 092013

Nature 607 (2022) 7917, 52-59
ATLAS ttH (H → bb)

$0.83^{+0.28}_{-0.44}$

Values in % units		LHC	HL-LHC
δy_t	Global fit	12.2	5.06
	Indiv. fit	10.2	3.70

250 GeV e+e- run offers excellent “indirect” sensitivity

Δy/y < 1% from H → gg

Δy/y < 1% from H → γγ

Mitov et al., arXiv:1805.12027

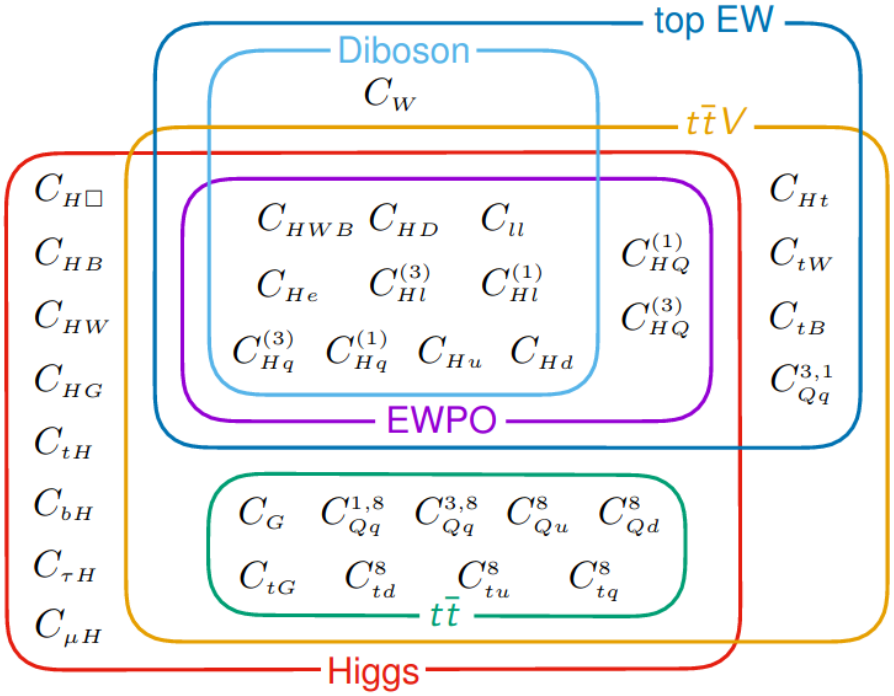
Jung et al., arXiv:2006.14631

SMEFT characterization

Over-constrain all sectors of the SM Effective Field Theory: Higgs + EW + top

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

Ellis et al., arXiv:2012.02779
SMEFiT, arXiv:2105.00006
SMEFT+PDF, arXiv:2303.06159



top EW

Diboson

C_W

$t\bar{t}V$

$C_{H\Box}$ C_{HB} C_{HW} C_{HG} C_{tH} C_{bH} $C_{\tau H}$ $C_{\mu H}$

C_{HWB} C_{HD} C_{ll}

C_{He} $C_{Hl}^{(3)}$ $C_{Hl}^{(1)}$

$C_{Hq}^{(3)}$ $C_{Hq}^{(1)}$ C_{Hu} C_{Hd}

$C_{HQ}^{(1)}$ $C_{HQ}^{(3)}$

EWPO

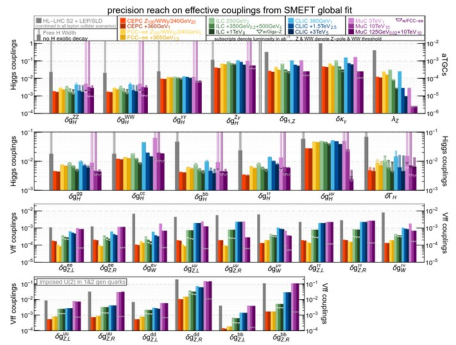
C_{Ht} C_{tW} C_{tB} $C_{Qq}^{3,1}$

C_G $C_{Qq}^{1,8}$ $C_{Qq}^{3,8}$ C_{Qu}^8 C_{Qd}^8

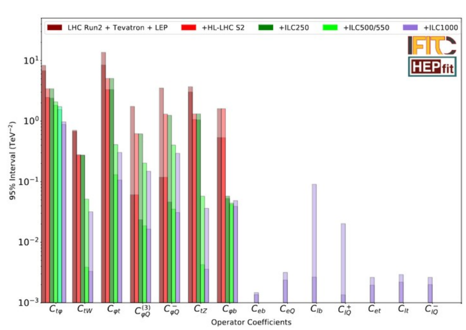
C_{tG} C_{td}^8 C_{tu}^8 C_{tq}^8

$t\bar{t}$

Higgs

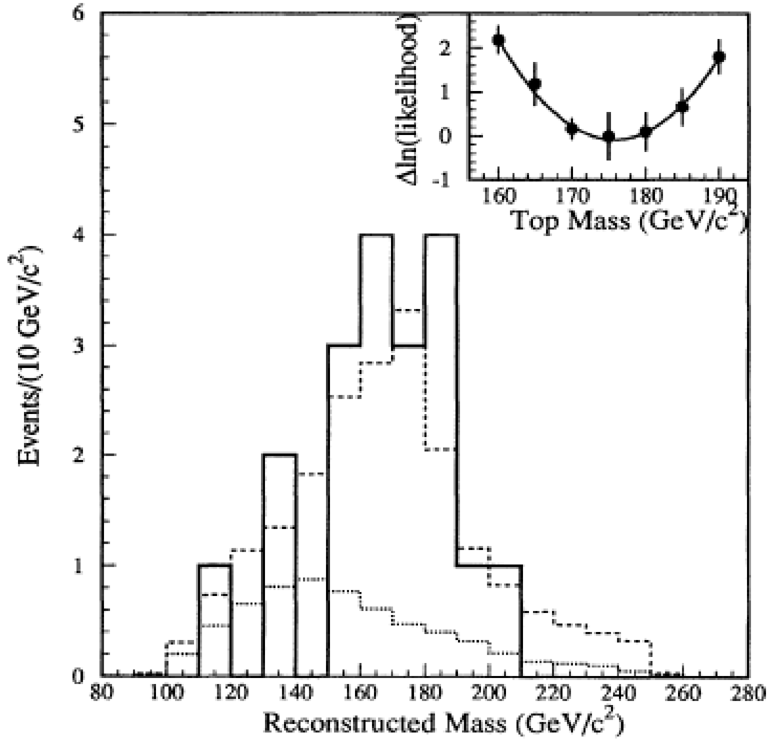


Future collider prospects:
separate Higgs/EW and top
de Blas et al., 2206.08326



marcel.vos@ific.uv.es

Top quark mass



Top mass at LHC & HL-LHC, interpretation

Direct mass measurements are experimentally the most precise:

m_t ~ 172.52 ± 0.33 GeV
(ATLAS+CMS run 1 **combination***)*

Theory status quo: *"the difference between the top mass in direct measurements and the top pole mass is of the order of few hundred MeV"*,
Corcella, Nason, Hoang, Yokoya, arXiv:1902.04070

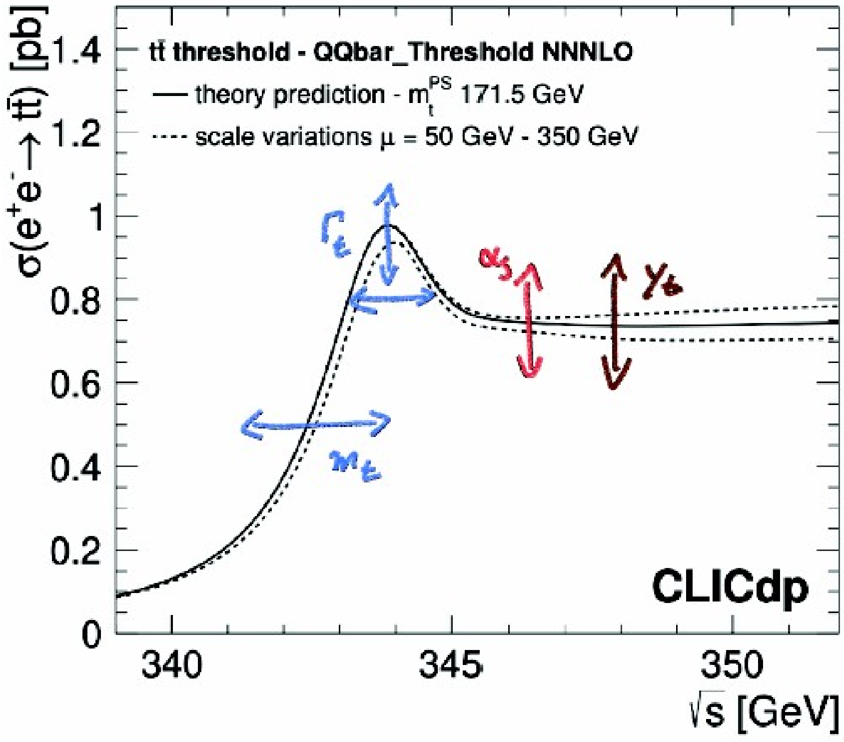
Cross-section-based measurements
inclusive ~ 2 GeV precision, differential ~1 GeV
Combination very powerful, arXiv:2311.05509

HL-LHC projections in Snowmass report, arXiv:2209.11267

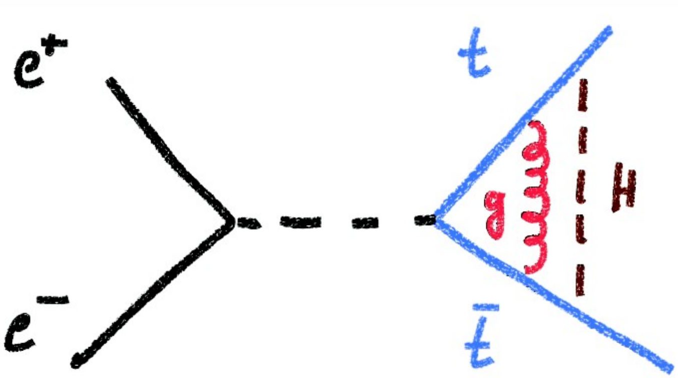
Combination of direct measurements: < 200 MeV (exp.) + ?? (theo.)
Combination of x-sec-based extractions: ~ 500 MeV (theo.+exp.)

e+e- threshold scan

A scan of the e^+e^- center-of-mass energy through the pair production threshold allows for the ultimate mass measurement *(Gusken & Kuhn ‘85, Peskin & Strassler ‘91)*



Calculation: Beneke et al.
Art-work: Frank Simon

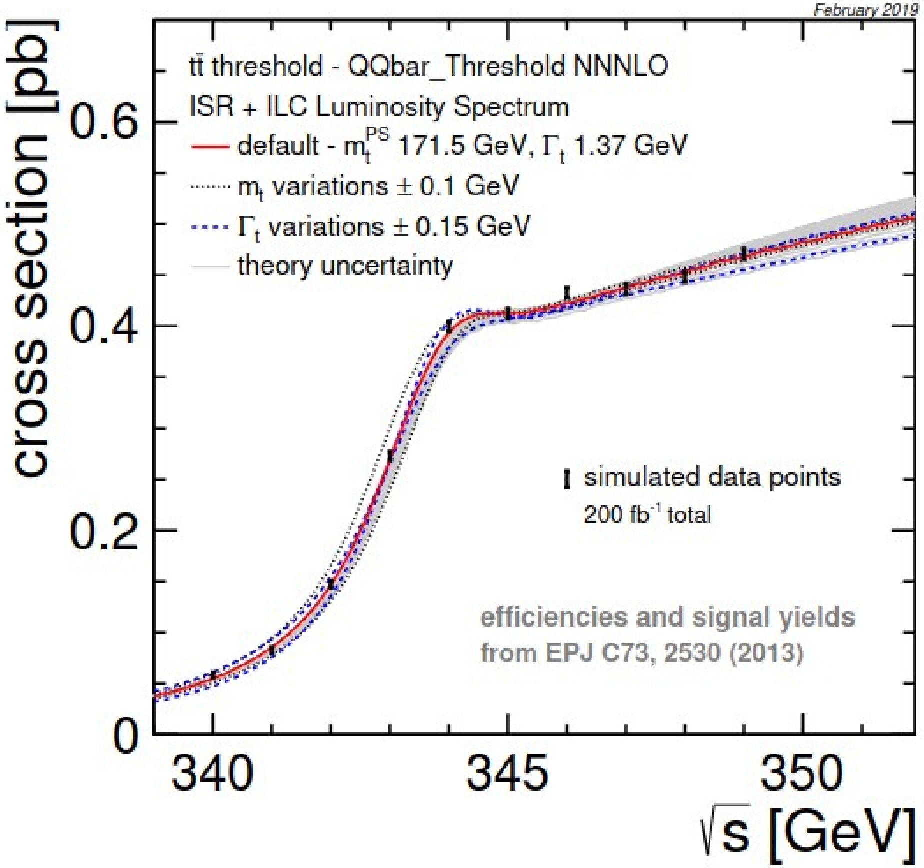


The threshold position is sensitive to the top quark mass, the shape to the width
The normalization is sensitive to strong coupling and top quark Yukawa coupling

Top quark mass

N3LO NRQCD at threshold *Beneke et al., PRL 115 (2015)*

Experimental studies:
Martinez & Miquel, hep-ph/020735,
Seidel et al., arXiv:1303.3758
Ongoing ECFA Focus Topic study



Threshold scan yields well-understood top mass measurement, with < 50 MeV uncertainty

Included in all e+e- collider project operation scenarios (but not necessarily in first stage)

The Higgs/top/EW factory(*): which one?

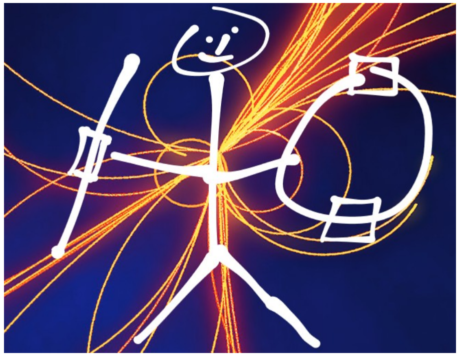
(*) I assume one will be built, but see:

Blondel & Janot, Circular and linear e^+e^- colliders: another story of complementarity, arXiv:1912.11771

Circular or linear

FCCee/CEPC excell at low energy (10^{12} Z-bosons!)

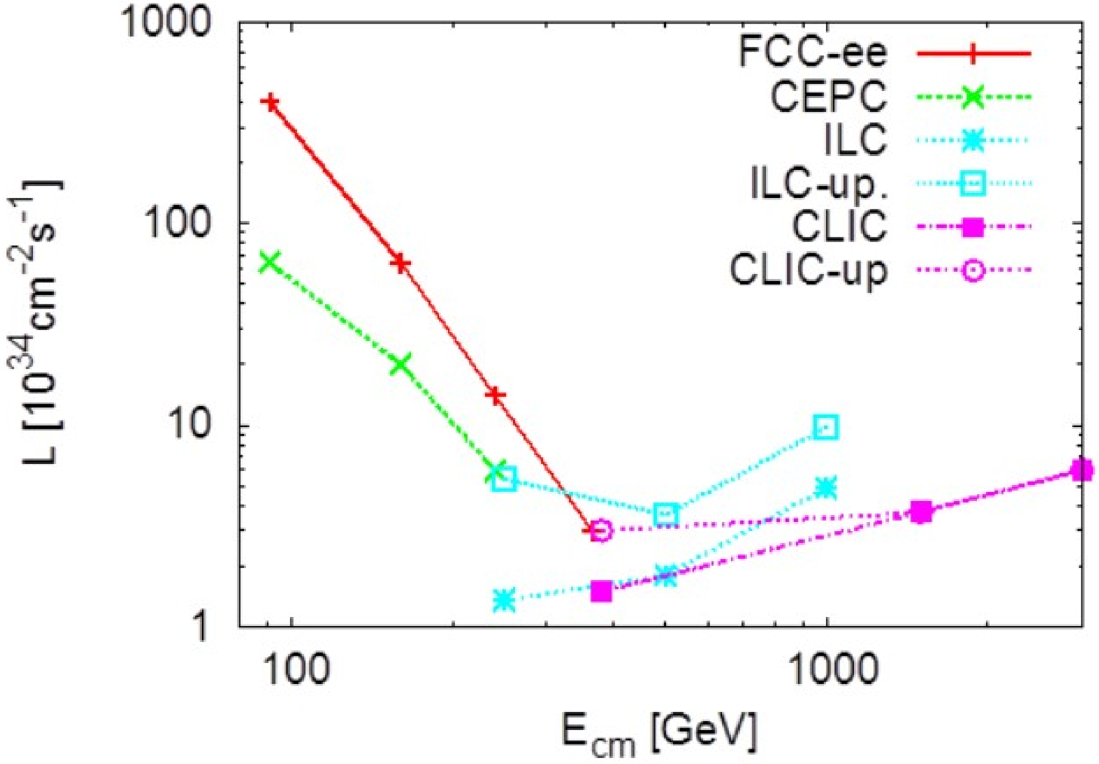
Synchrotron radiation prevents operation above ~360 GeV



At linear colliders luminosity increases with sqrt(s)

ILC/CCC/CLIC are the avenue to reach 400-1000 GeV

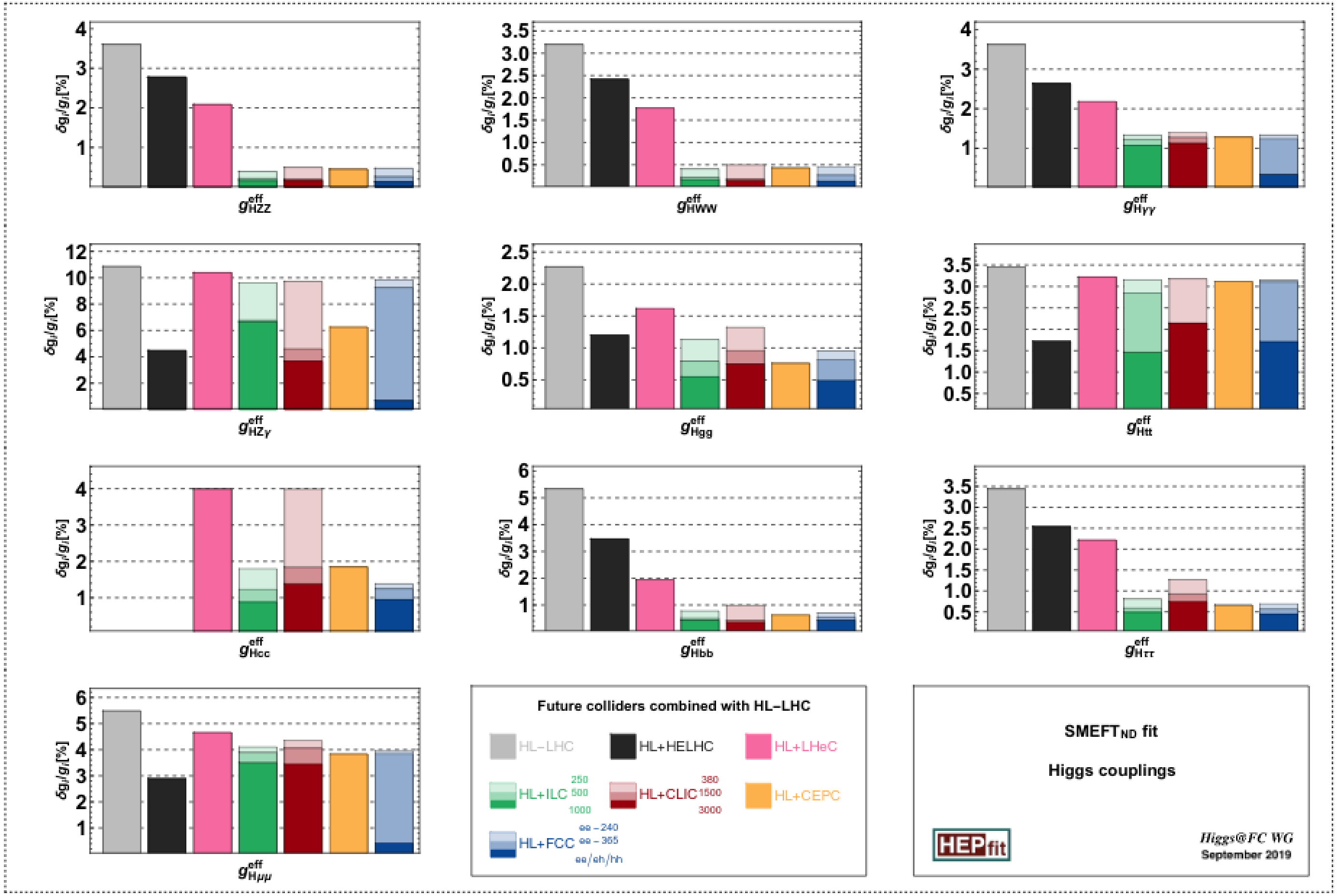
https://arxiv.org/pdf/1910.11775.pdf



Small print: there is a trade-off between luminosity and power consumption, instantaneous luminosity must be folded with operation schedule

Higgs couplings

https://arxiv.org/pdf/1910.11775.pdf



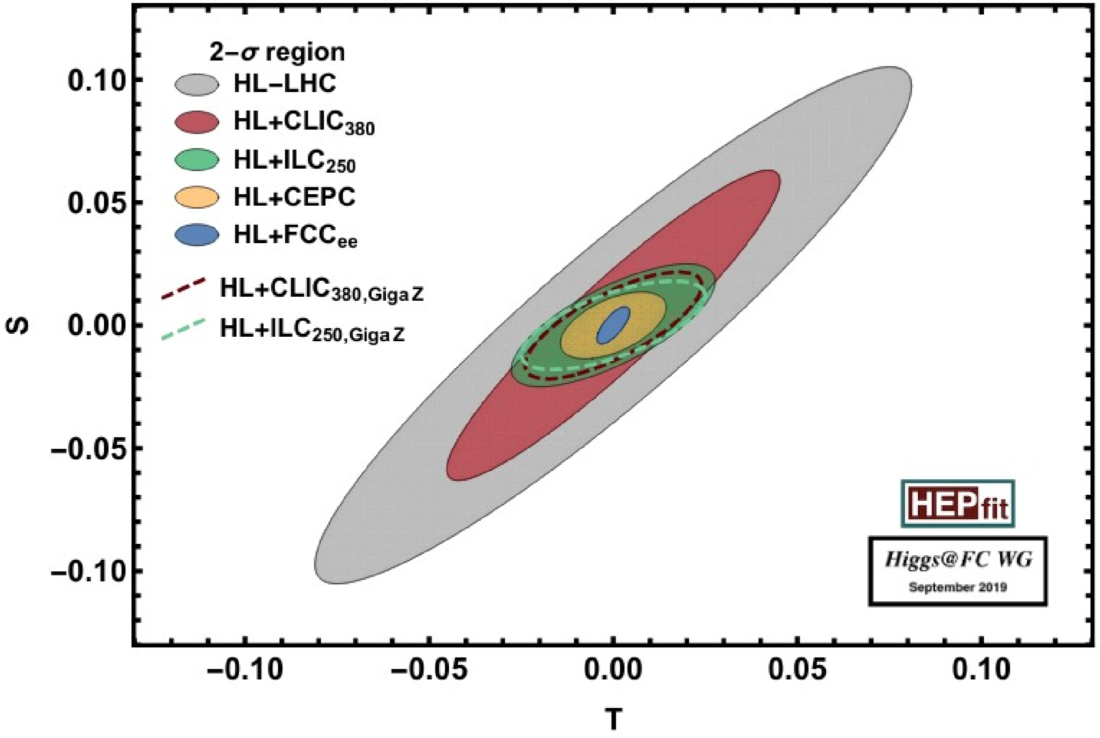
All Higgs factory projects (🟩/🟥/🟨/🟦) do excellent Higgs physics; great improvement over LHC legacy (◼)

Note: inputs have large uncertainty; lepton and hadron colliders are hard to compare on the same footing

Z-pole

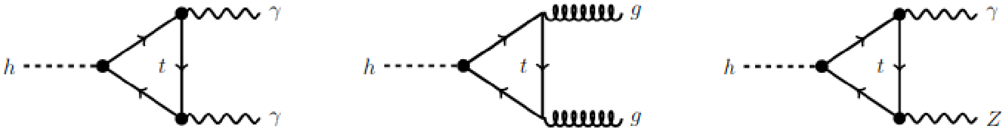
Revisit Z-pole physics expored by LEP and SLC, with much greater luminosity, better detectors and more advanced theory

Improve EW fit, but not only:
- flavour physics 10^{12} $Z \rightarrow bb/cc$
- tau-physics 10^{11} $Z \rightarrow \tau\tau$
- QCD with easy initial state



“TeraZ” run of circular colliders: 10^6 times LEP
“GigaZ” run of linear colliders: 10^3 times SLC

The top Yukawa coupling at a lepton collider



250 GeV run offers “indirect” sensitivity to the top Yukawa

$\Delta y/y < 1\%$ from $H \rightarrow gg$ — *Mitov et al., arXiv:1805.12027*

$\Delta y/y < 1\%$ from $H \rightarrow \gamma\gamma$ — *Jung et al., arXiv:2006.14631*

Assuming the SM for all other couplings

500+ GeV run offers a “direct” measurement in ttH production

<3% precision — *Price et al., arXiv:1409.7157*

robust in global analysis — *Jung et al.,arXiv:2006.14631*

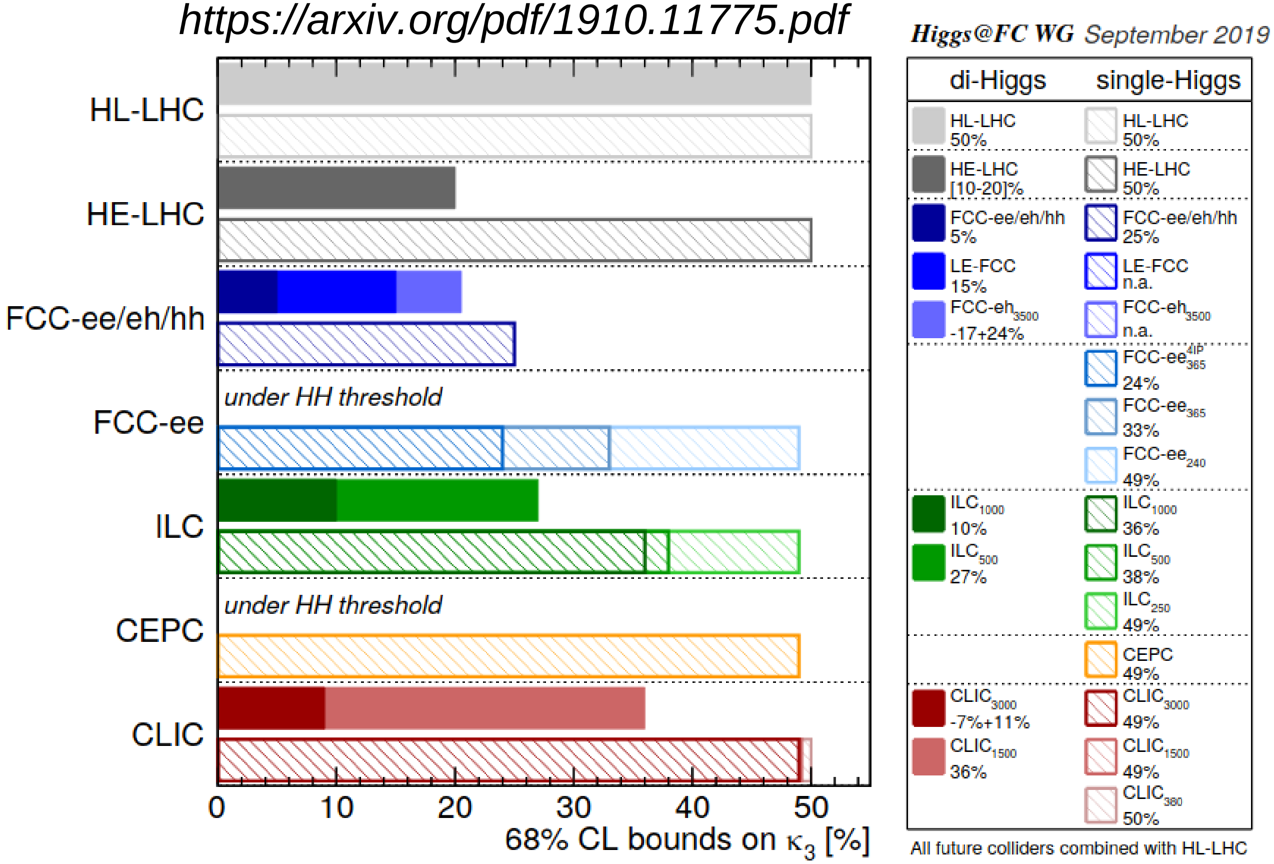
Values in % units		LHC	HL-LHC	ILC500	ILC550	ILC1000	CLIC
δy_t	Global fit	12.2	5.06	3.14	2.60	1.48	2.96
	Indiv. fit	10.2	3.70	2.82	2.34	1.41	2.52

Top-SMEFT fit on prospects, *de Blas et al., 2206.08326*

Higgs self-coupling: HEP's holy grail

The Higgs boson self-interaction is a key prediction of the Higgs mechanism

https://arxiv.org/pdf/1910.11775.pdf

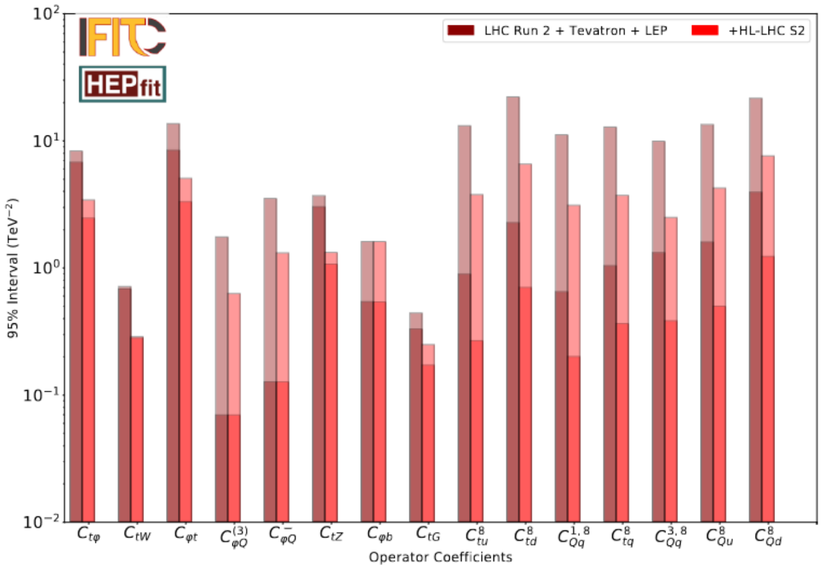


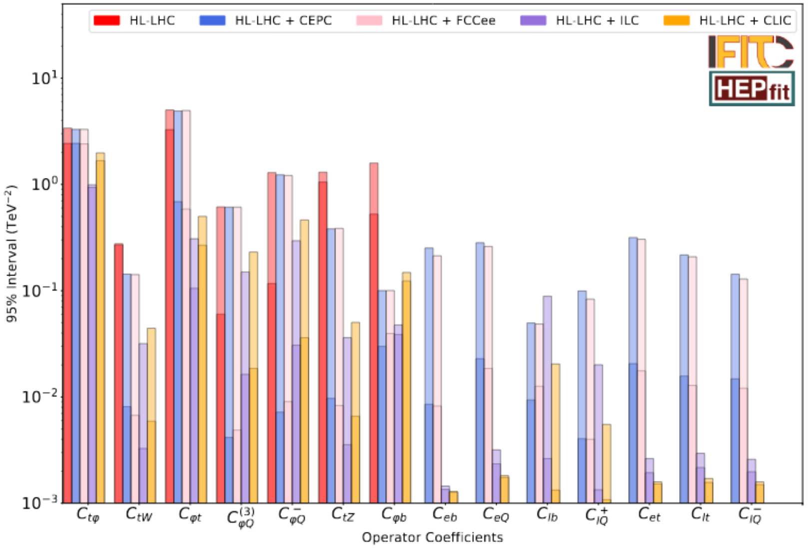
Complementary sensitivity
single-Higgs [////]
HH production [▢]

Loop effects yield an indirect determination at Higgs factory energy
High-energy operation for a direct measurement of Higgs self-coupling

Top physics at e+e-

From: arXiv:2206.08326





Complementarity pp vs. e+e-

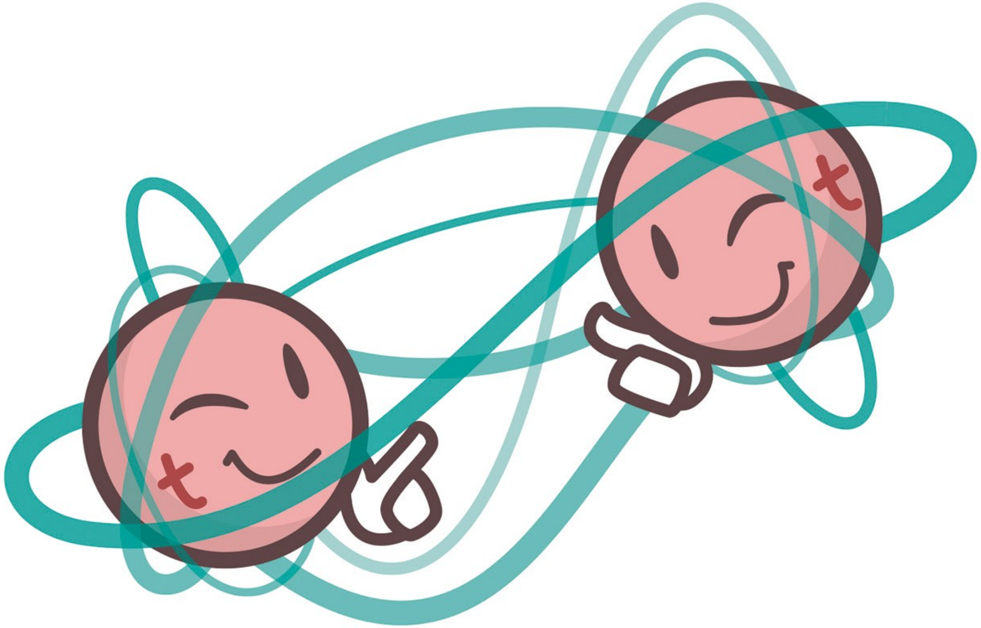
HL-LHC provides constraints on qqtt: O(1), ~3x better than today

HL-LHC ttX & e^+e^- for top+boson operators: O(10^{-1})

High-E e^+e^- excellent bounds on eett: O(10^{-2})

Expect the unexpected

Colliders as Quantum Information laboratories



ATLAS has shown that top quark pairs are entangled at the LHC
arXiv:2311.07288, Nature editor's pick

According to this GGI workshop,
collider experiments can:
- measure steering & discord
- perform full quantum tomography
- test Bell inequalities (w. loopholes)
- study entanglement in H → WW
- study entanglement over decays

See also: arXiv:2402.07972

What can e+e- colliders bring?

Which e+e- collider does best?

We don't know (yet).

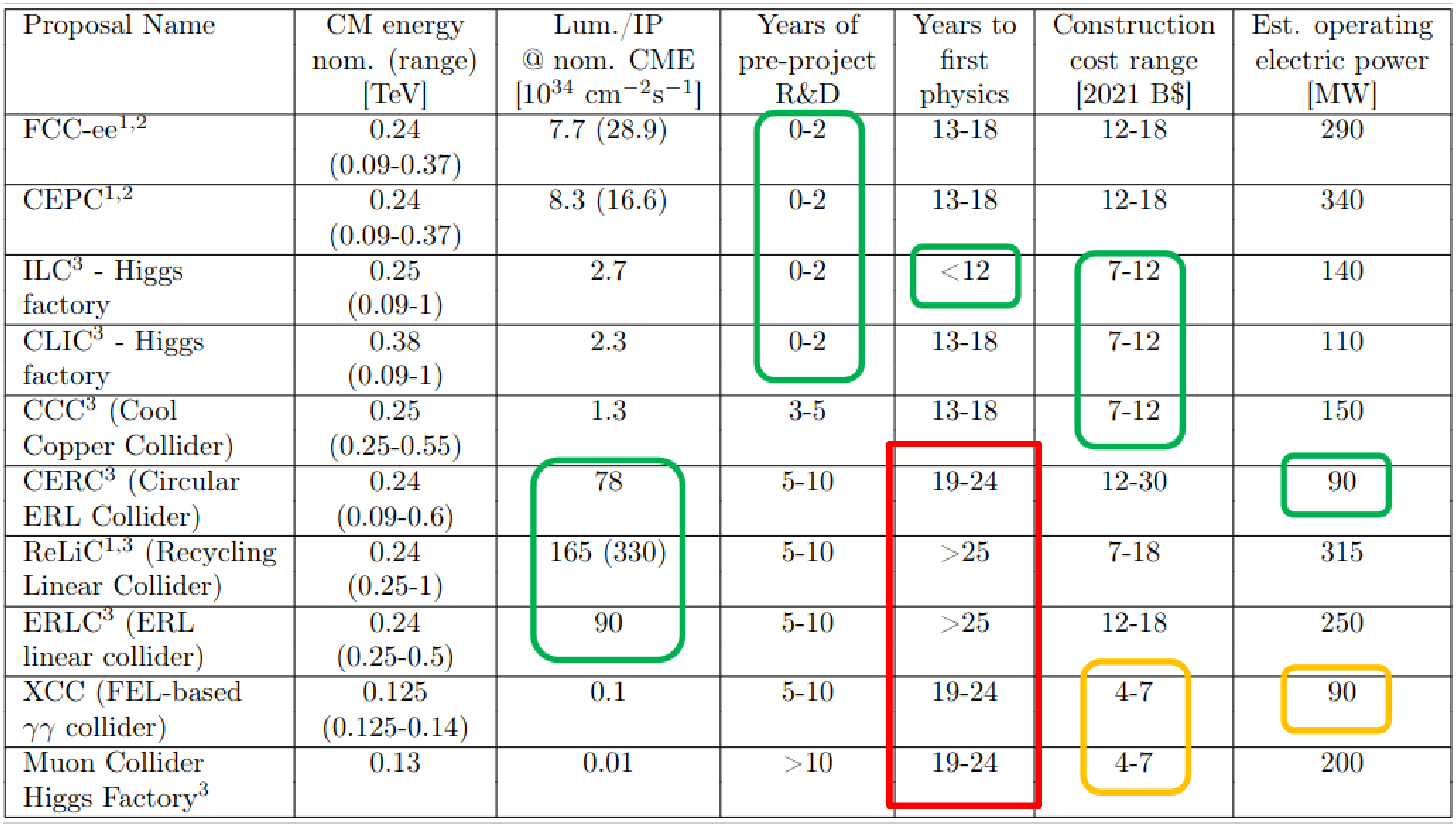
The Higgs/top/EW factory(*): when and where?

(*) I assume one will be built, but see: Blondel & Janot, Circular and linear e^+e^- colliders: another story of complementarity, arXiv:1912.11771

Politics: comparison of main figures of merit

(according to Snowmass Collider Implementation Task Force)

1) for two experiments, 2) accurate beam energy 3) polarized beams enhance cross sections



Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME $[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
FCC-ee^{1,2}	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
CEPC^{1,2}	0.24 (0.09-0.37)	8.3 (16.6)	0-2	13-18	12-18	340
ILC^{3} - Higgs factory	0.25 (0.09-1)	2.7	0-2	<12	7-12	140
CLIC^{3} - Higgs factory	0.38 (0.09-1)	2.3	0-2	13-18	7-12	110
CCC^{3} (Cool Copper Collider)	0.25 (0.25-0.55)	1.3	3-5	13-18	7-12	150
CERC^{3} (Circular ERL Collider)	0.24 (0.09-0.6)	78	5-10	19-24	12-30	90
ReLiC^{1,3} (Recycling Linear Collider)	0.24 (0.25-1)	165 (330)	5-10	>25	7-18	315
ERLC^{3} (ERL linear collider)	0.24 (0.25-0.5)	90	5-10	>25	12-18	250
XCC (FEL-based $\gamma\gamma$ collider)	0.125 (0.125-0.14)	0.1	5-10	19-24	4-7	90
Muon Collider Higgs Factory^{3}	0.13	0.01	>10	19-24	4-7	200

Higgs factory

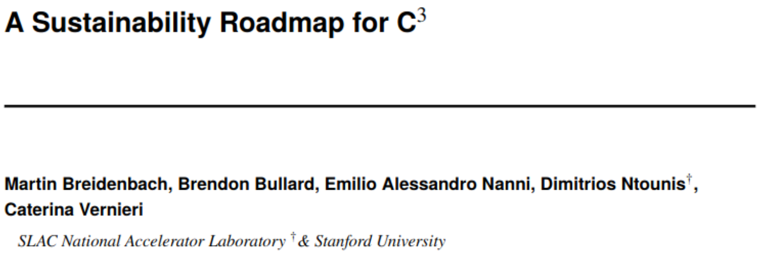
+ERL

Exotic HF

More complete report

More figures of merit

Carbon footprint of colliders
https://arxiv.org/pdf/2307.04084.pdf

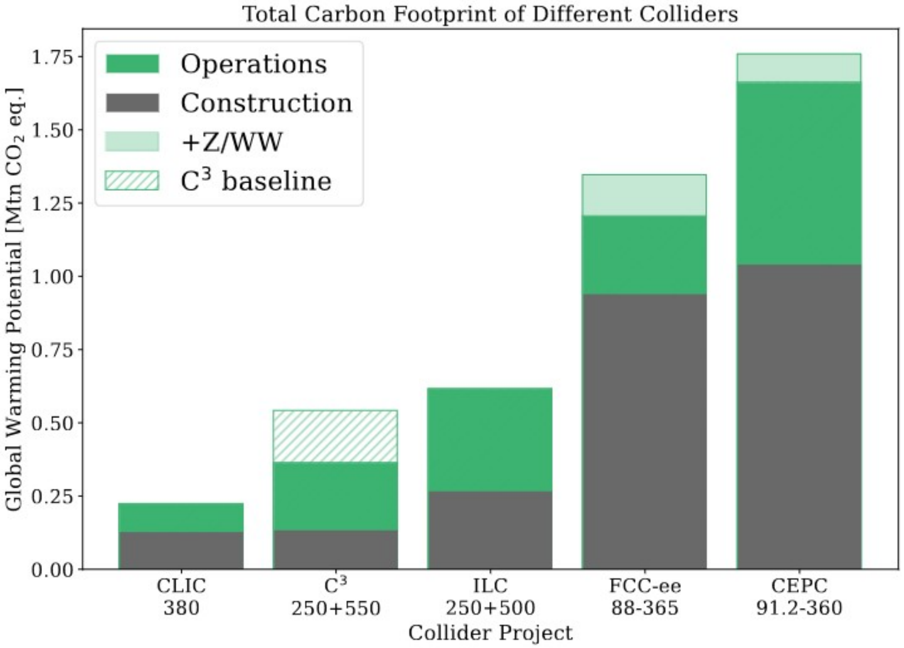


A Sustainability Roadmap for C^3

Martin Breidenbach, Brendon Bullard, Emilio Alessandro Nanni, Dimitrios Ntounis[†], Caterina Vernieri

SLAC National Accelerator Laboratory [†] & Stanford University

Complete ISO life-cycle assessment ongoing for several projects

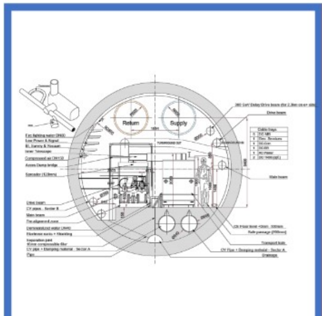


Lessons: construction of the facility (boring, concrete+steel for tunnel) has a large impact, more than the collider itself, or energy consumption during operation.

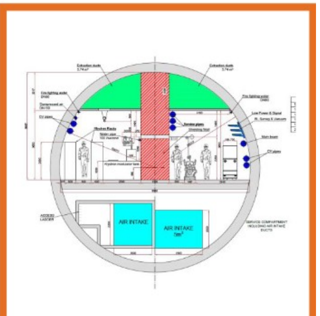
- Underlines importance of keeping projects compact

- Optimize project design to minimize impact

(example: CLIC drive beam vs. Klystrons)



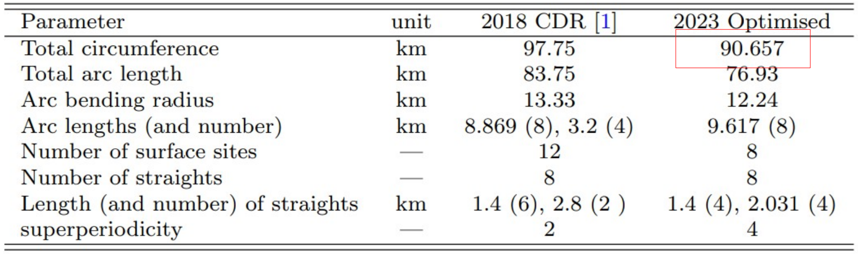
CLIC Drive beam, 5.6m dia.



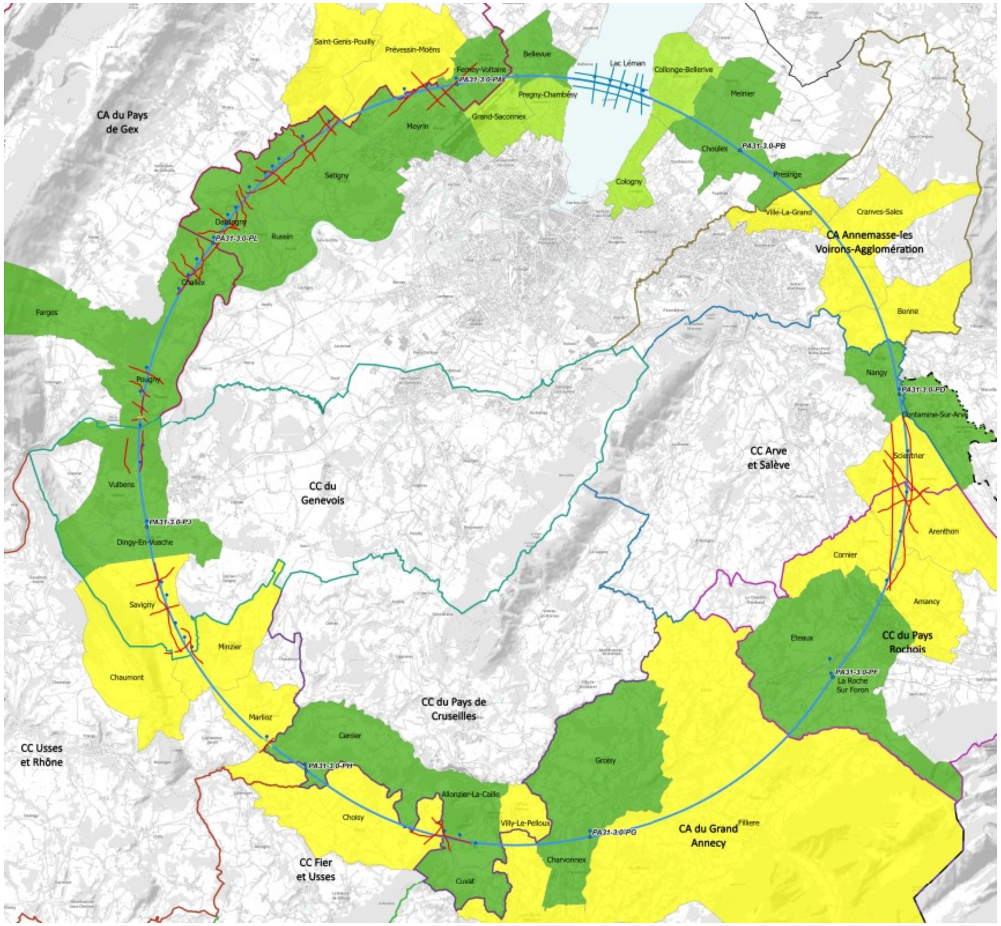
CLIC Klystron, 10m dia.

Higgs/top/EW factory project progress

Feasibility involves geology, road access, power supply, etc., but above all **political and financial support**



Parameter	unit	2018 CDR [1]	2023 Optimised
Total circumference	km	97.75	90.657
Total arc length	km	83.75	76.93
Arc bending radius	km	13.33	12.24
Arc lengths (and number)	km	8.869 (8), 3.2 (4)	9.617 (8)
Number of surface sites	—	12	8
Number of straights	—	8	8
Length (and number) of straights	km	1.4 (6), 2.8 (2)	1.4 (4), 2.031 (4)
superperiodicity	—	2	4



FCC mid-term report to CERN council,
http://cds.cern.ch/record/2888566?ln=en
https://doi.org/10.17181/mhas5-1f263

ILC: CERN-KEK agreement for common R&D programme

CEPC: Chinese Academy of Sciences pre-selects CEPC

US P5 panel provides recommendations
https://www.usparticlephysics.org/2023-p5-report/

Summary

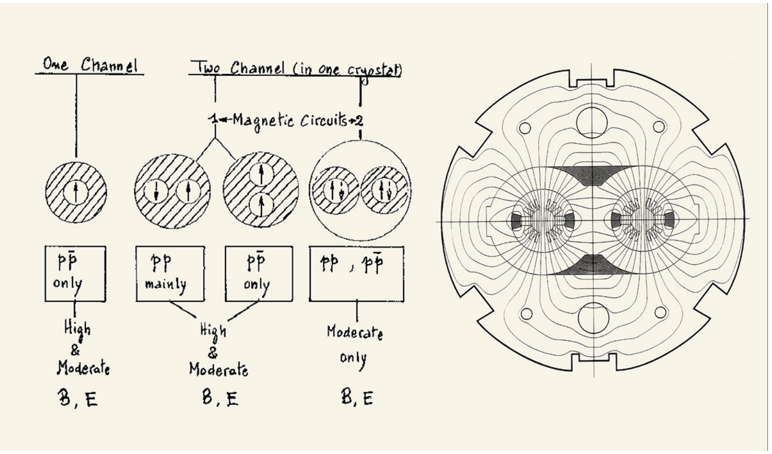
Colliders are a crucial tool to study fundamental particles and their interactions, exploring higher energy, new particles and new processes

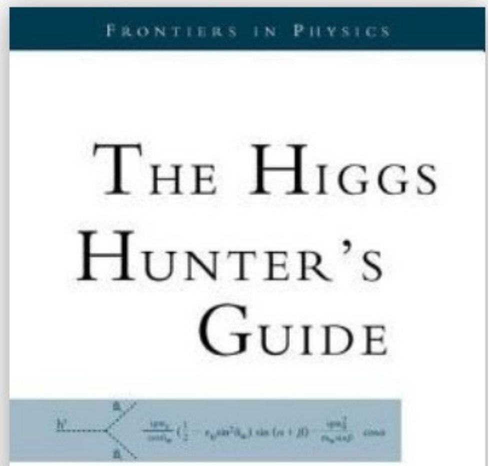
With the LHC in full swing and HL-LHC getting closer:
- Higgs discovery turns into characterization
- searches leave no stone unturned up to several TeV
- new SM physics: vector-boson-scattering, tri-boson, top+X, tttt… HH

A new e+e- collider can complete the program of the EW scale
- per-mille-level characterization of the Higgs, top and EW sectors
- precise tests of the relations predicted by the Standard Model
- redundant characterization of the SM and SM Effective Field Theory

The long game

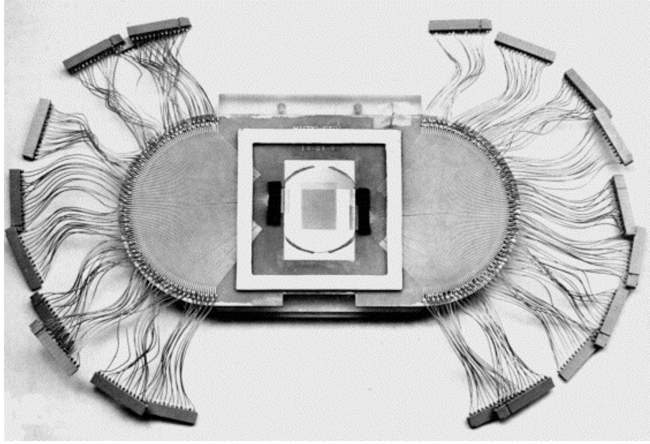
The success of the LHC is possible thanks to people in the ‘80s…





FRONTIERS IN PHYSICS

THE HIGGS HUNTER'S GUIDE



…doodling magnet designs, dreaming up the physics case, tinkering with new detectors

Sustainable exploration of the fundamental laws of nature needs a long-term view and requires long-term investments

marcel.vos@ific.uv.es

Electron-positron collider projects

Four main contenders:

Project	**Type**	**Energy (GeV)**	**Design report**	**Host**
ILC	linear	(91)-250-500-1000	TDR 2012	Japan
CLIC	linear	380-1500-3000	CDR 2013	CERN
CEPC	circular	91-240-360	CDR 2018	China
FCCee	circular	91-240-365	CDR 2019	CERN

Four “Higgs/EW/top factory” projects.

Note: The CLIC Higgs factory stage operates at 380 GeV. FCCee stretches to reach the top threshold at 365 GeV, ILC/CLIC have a “GigaZ” option.

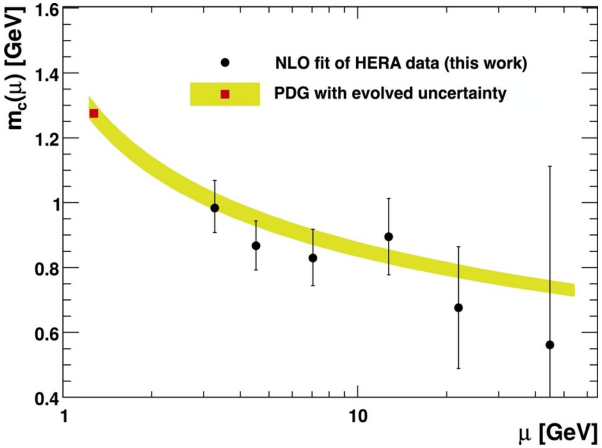
Running constants

Quark masses – parameters of the QCD Lagrangian – **must run too**

$$\frac{\partial m_q(\mu)}{\partial \log(\mu^2)} = \gamma_m[\alpha_s(\mu)]\, m_q(\mu)$$ Anomalous mass dimension

Scale evolution or “running” experimentally confirmed:

- charm quark mass, HERA [Ghizko et al., PLB775 (2017)]



- bottom quark mass, DELPHI,SLD,ALEPH,OPAL, see cf. Kluth [hep-ex/0603011])

- top quark mass, CMS[PLB803 (2020)] (see also Catani et al., JHEP08 (2020))

Accelerator R&D: most relevant new developments

Technology progress:
– High-efficiency klystrons (good for all projects): CERN&IHEP push to 80%
– High-gradient SCRF cavities: FNAL&IHEP push > 40 GV/m

Design studies:
– Energy-recovery LINACs, boost luminosity of e+e- colliders,
https://arxiv.org/abs/1909.04437 + first conceptual designs for real machines
– Cool Copper Collider, shrink Higgs factory to 8 km facility,
https://arxiv.org/abs/2203.07646
– Hybrid, asymmetric wakefield & RF collider, shrink Higgs factory to 3.3 km facility,
https://arxiv.org/abs/2303.10150
– Muon collider (the μC is back!), energy-efficient multi-TeV lepton collisions
https://arxiv.org/abs/2209.01318

Global R&D progress is pushing accelerator technology; several new collider concepts have been launched in recent years

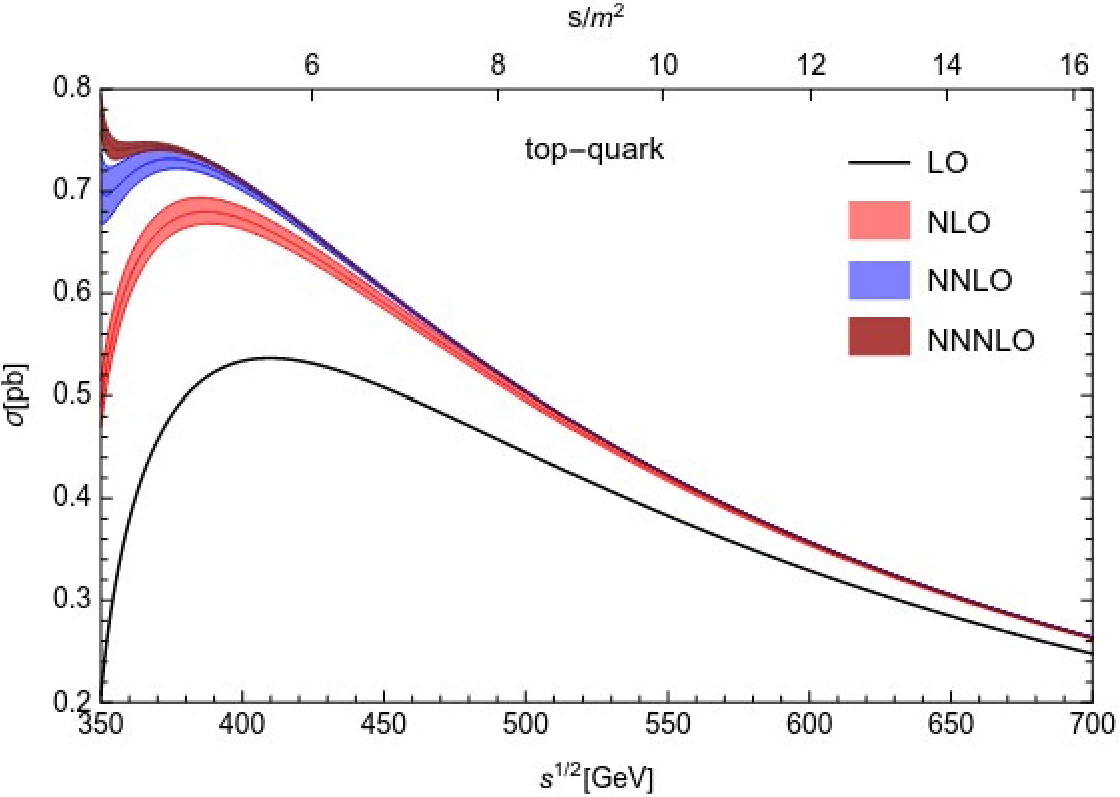
Precision: theory predictions at lepton colliders

X. Chen et al., Heavy-quark pair production at lepton colliders at NNNLO in QCD, arXiv:2209.14259

N^3LO QCD corrections are now available for e+e- → γ^* → tt

Very good convergence for “continuum” (sqrt(s) < 420 GeV)

Threshold region requires resummation



Still need: NNLO EW corrections + ISR + threshold matching + offshell

marcel.vos@ific.uv.es

Top mass at LHC & HL-LHC, interpretation

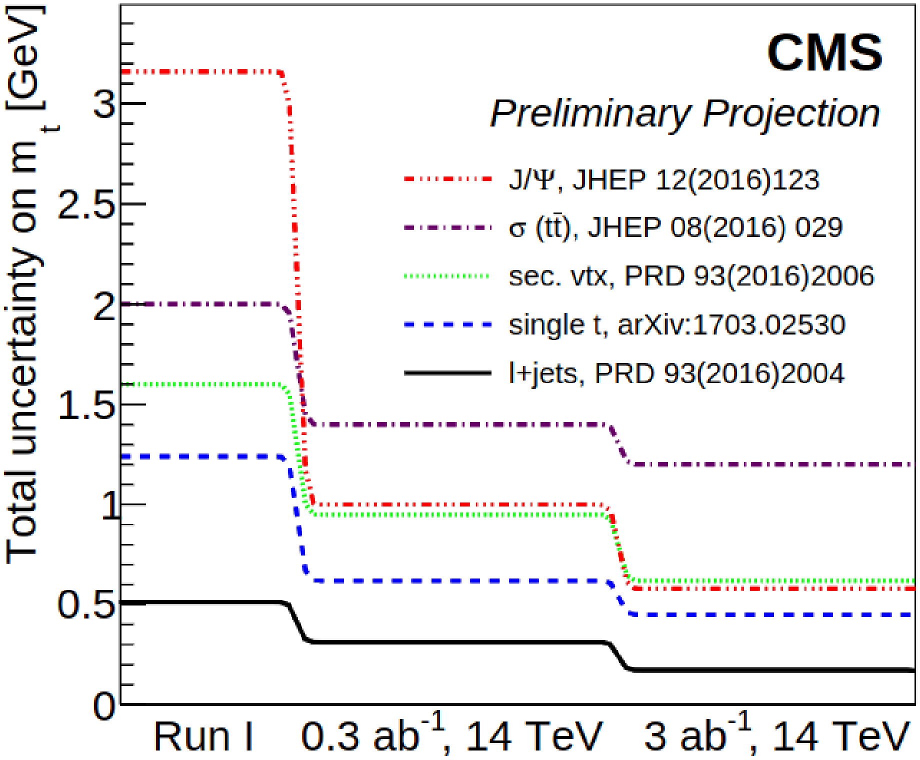
+ Snowmass report
arXiv:2209.11267
arXiv:2203.08064

Direct mass measurements are experimentally the most precise
m_t ~ 172.52 ± 0.33 GeV
(ATLAS+CMS run 1 **combination***)*

J/psi and **sec. vertex** methods are starting to deliver (CMS sec. Vtx., ATLAS soft-muon)

Boosted top mass improving rapidly
CMS 2.5 GeV in 2020→0.8 GeV in 2023

Cross-section-based mass extractions achieve O(1 GeV) precision/measurement. Theorist's combined fit yields 400 MeV (Zenaiev & Moch,).



Status quo interpretation: "the difference between the top mass in direct measurements and the top pole mass is of the order of few hundred MeV", Corcella, Nason, Hoang, Yokoya, arXiv:1902.04070

Combination of direct measurements:	**200 MeV (exp.) + ?? (theo.)**
Combination of x-sec-based extractions:	**500 MeV (theo.+exp.)**

The cost estimate presented here only concerns FCC-ee with two IPs and the first three stages of operation. All cost estimates have been prepared in Swiss francs (CHF), assuming 1 EUR = 1 CHF and in 2023 prices (without provisions for future inflation).

The FCC-ee project has been broken down into a Work Breakdown Structure (WBS), based on the six following main domains:

- Accelerators: 3 847 MCHF
- Injectors & transfer lines: 585 MCHF
- Civil engineering: 5 538 MCHF
- Technical infrastructure: 2 490 MCHF
- Experiments (CERN contribution only, including host lab responsibilities): 150 MCHF
- Territorial development: 191 MCHF

The total cost for FCC-ee, with two IPs for the experiments and the first three stages of operation (Z, W and ZH) is currently estimated to be 12 801 MCHF.

The total additional cost for two further IPs for experiments has been estimated at 710 MCHF.

To operate FCC-ee at the $t\bar{t}$ energy level would require an additional investment in RF equipment, together with the associated cryogenic equipment. The total extra amount is estimated at 1 465 MCHF.