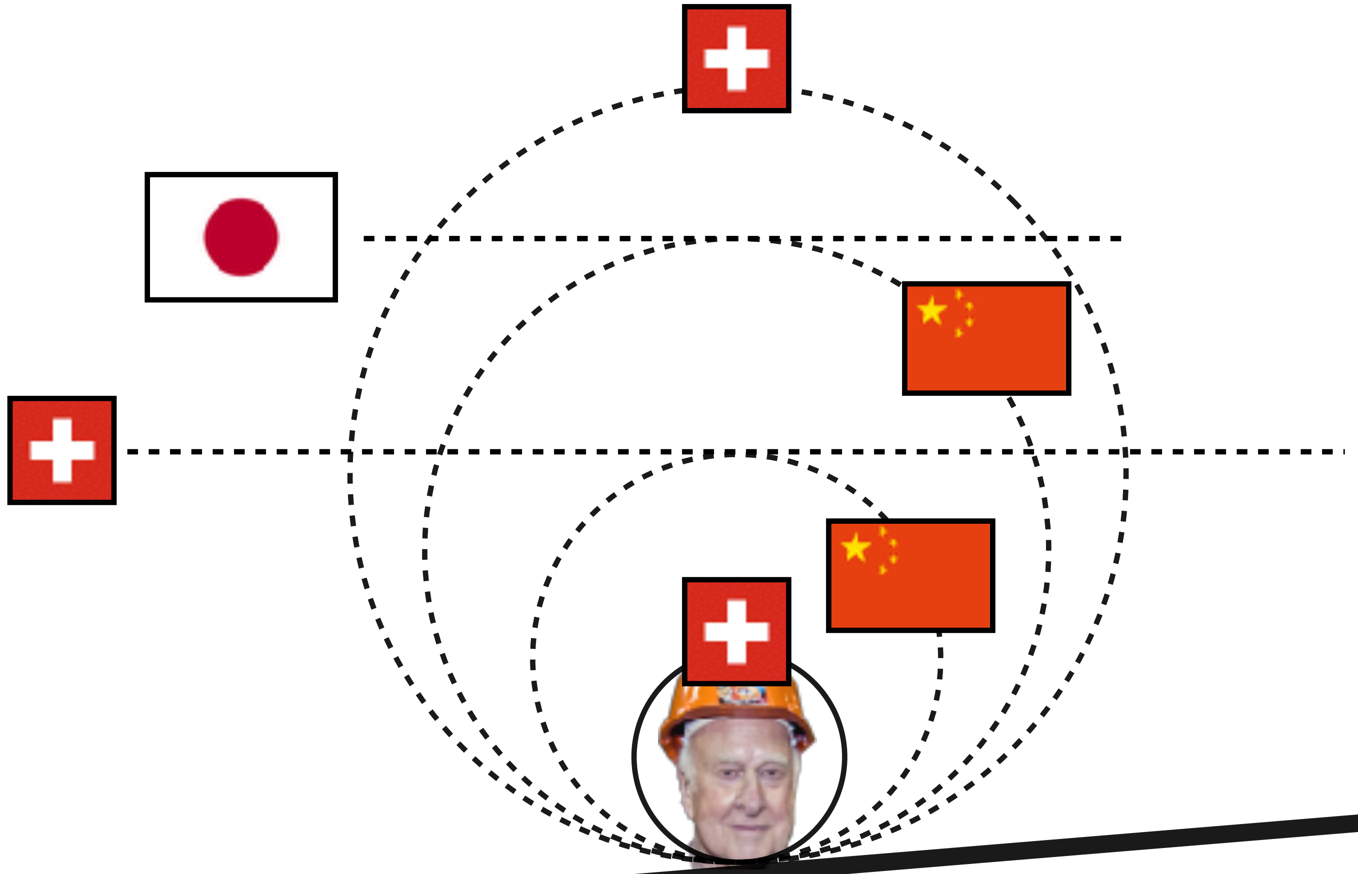
Future Colliders (1/3)

What the future colliders might how about the Higgs and BSM

Weihai High-Energy Physics School
August 26-28, 2019



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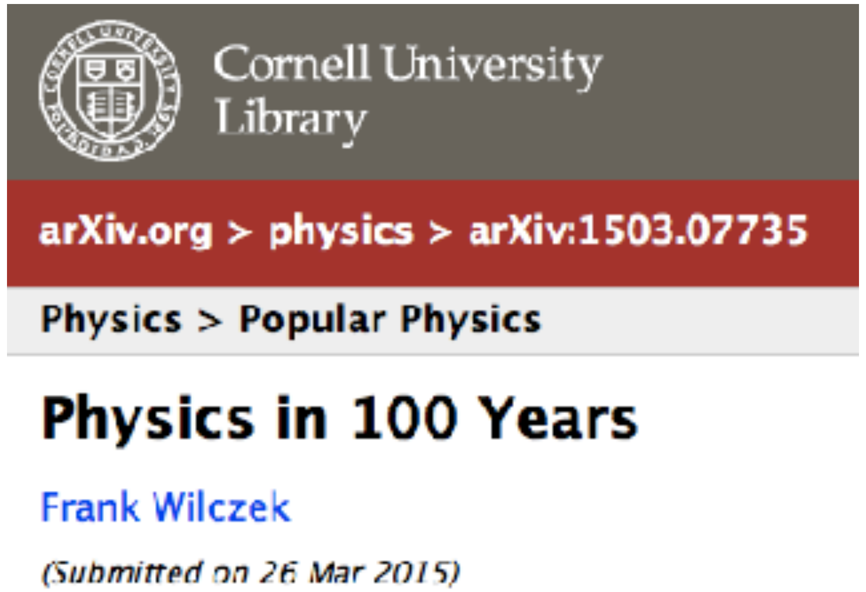
Physics Intro

A unique moment in the history of physics

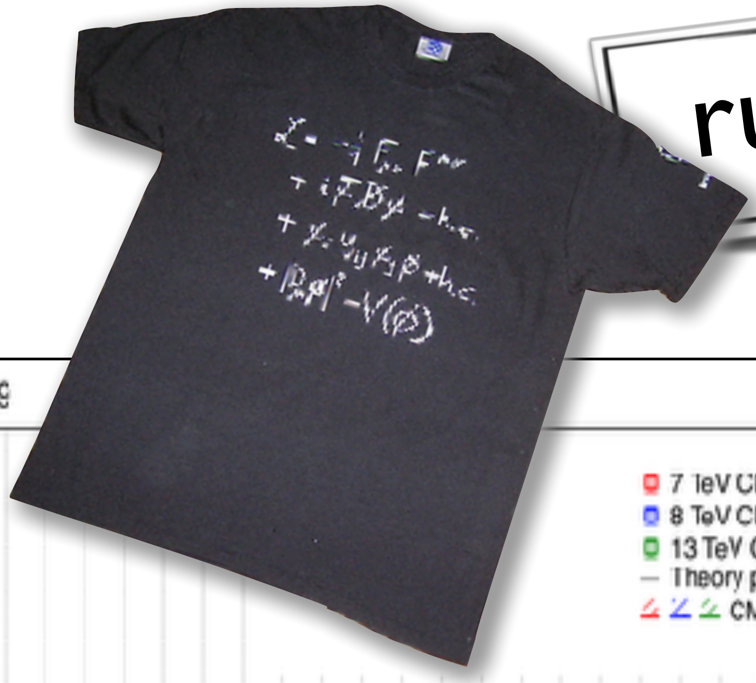
The Higgs discovery is the triumph of XXth century physics
combination of Quantum Mechanism + Special Relativity

For the first time in the history of physics,
we have a *consistent* description of the fundamental constituents of matter and their interactions and this description can be extrapolated to very high energy (up M_{Planck}?)



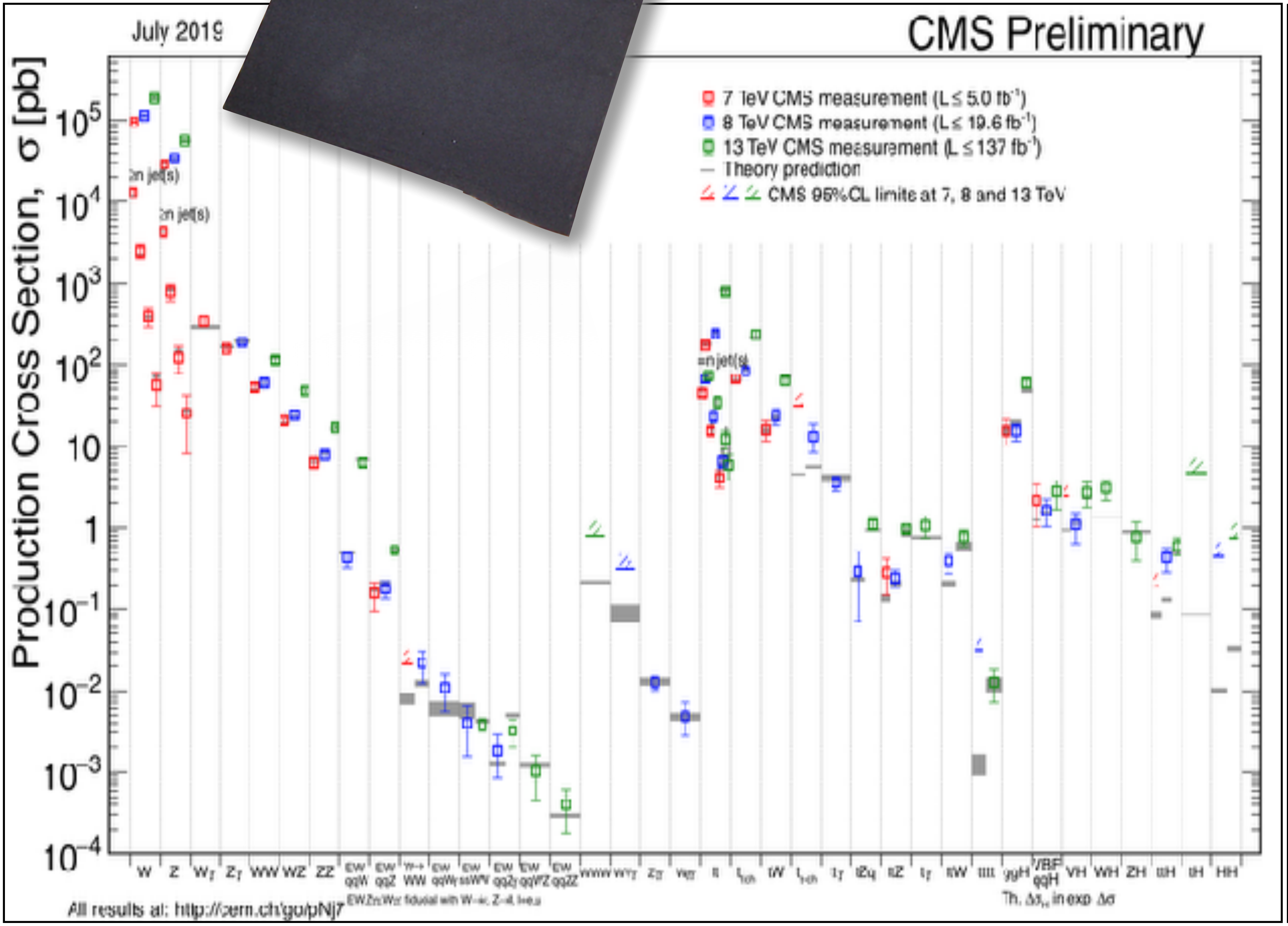
The equations of the [SM] have been tested with far greater accuracy, and under far more extreme conditions, than are required for applications in chemistry, biology, engineering, or astrophysics. While there certainly are many things we don't understand, we do understand the Matter we're made from, and that we encounter in normal life - even if we're chemists, engineers, or astrophysicists (sic: DM!)

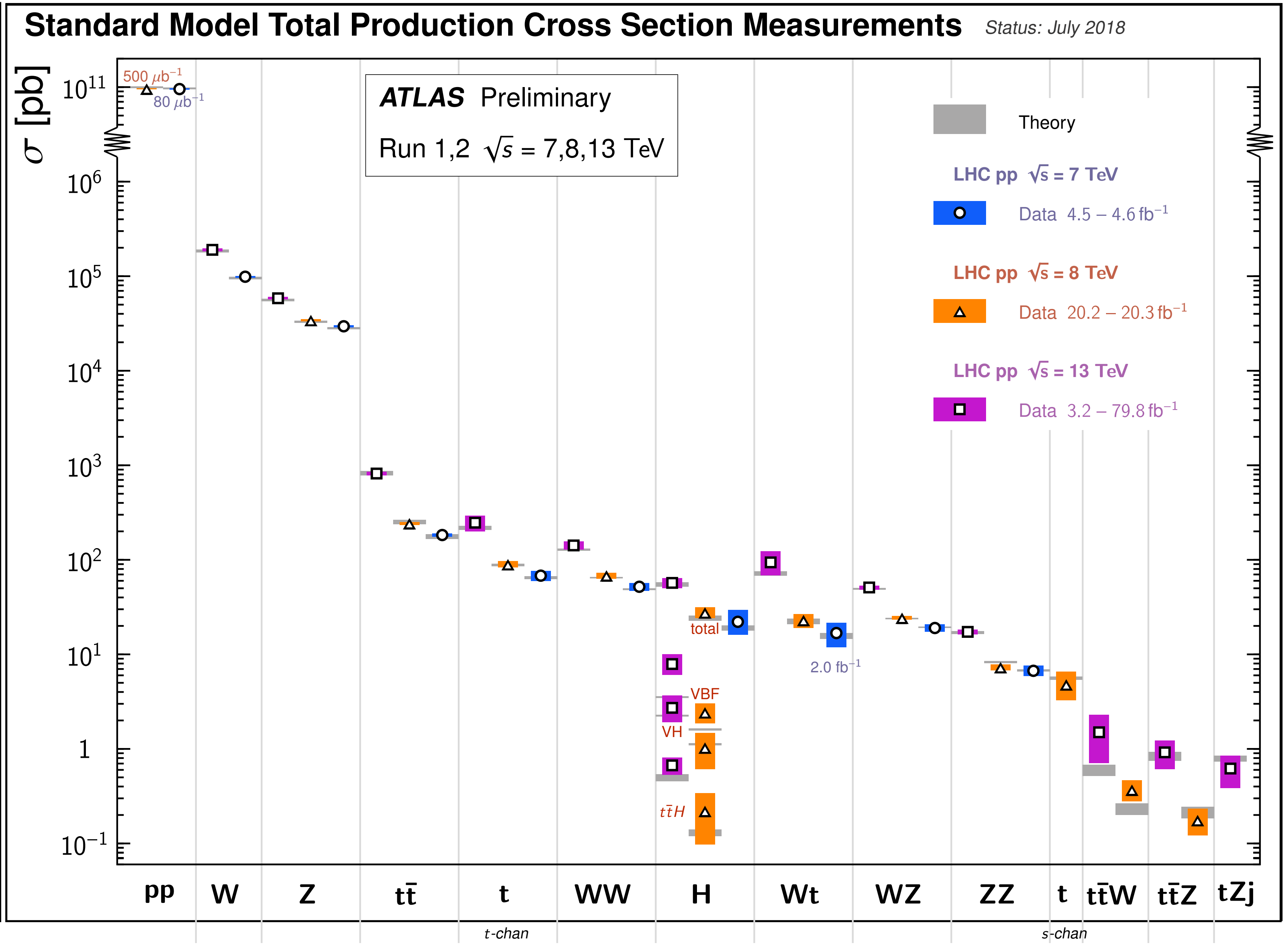
The SM and... the LHC data so far



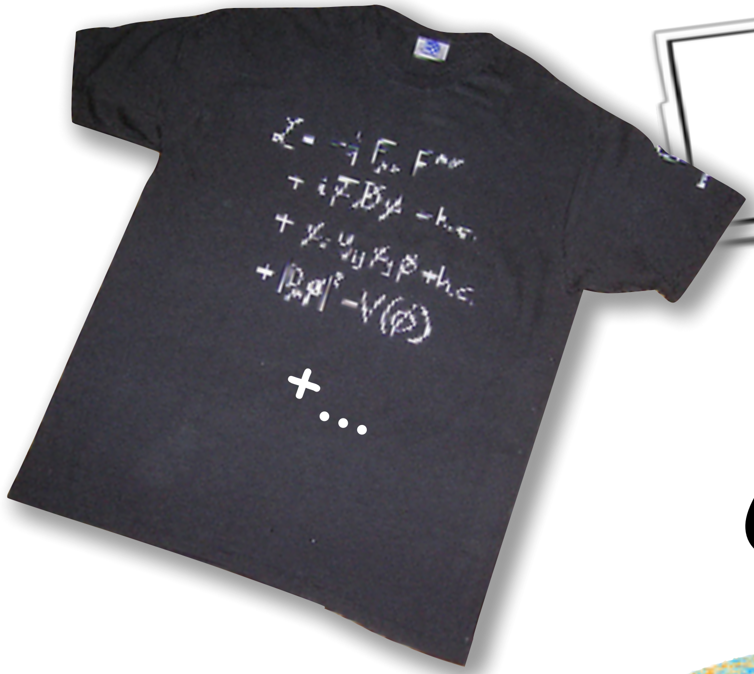
rules the world!

[and we, HEP practitioners, are all entitled for some royalties!]





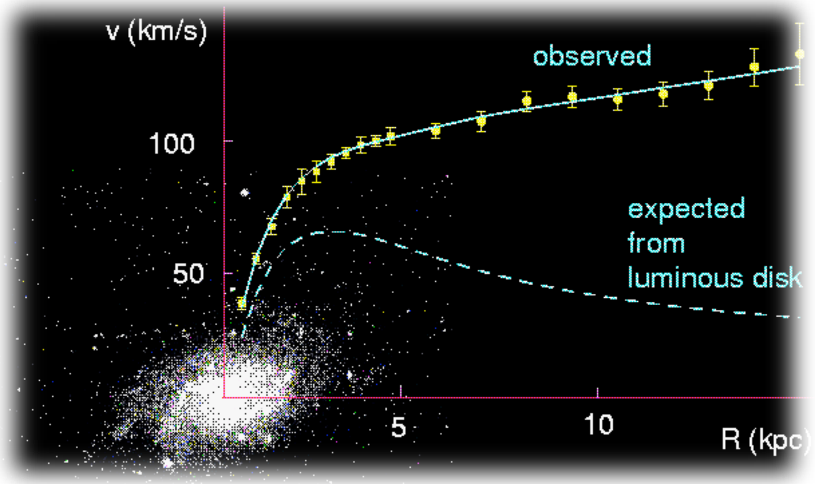
The SM and... the rest of the Universe

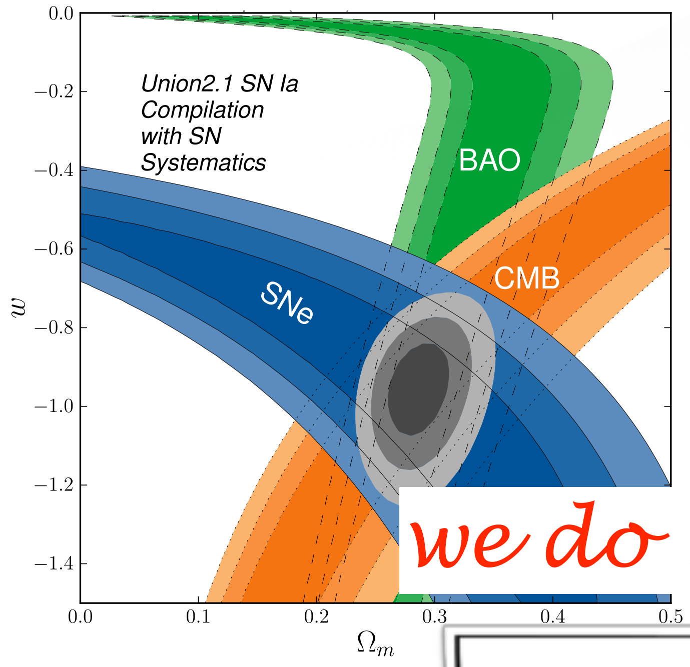


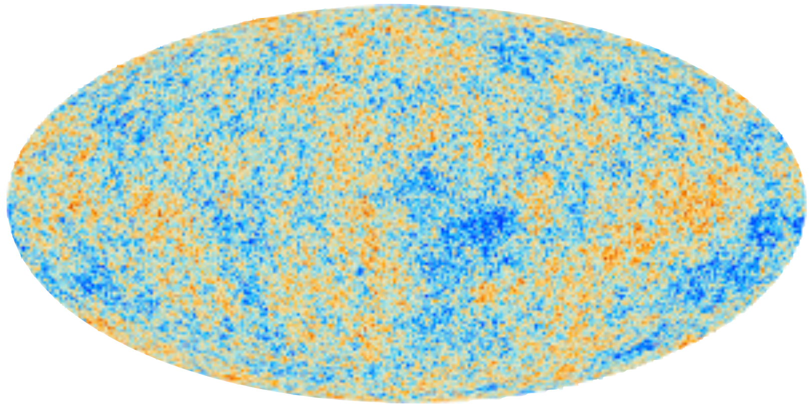
is not enough

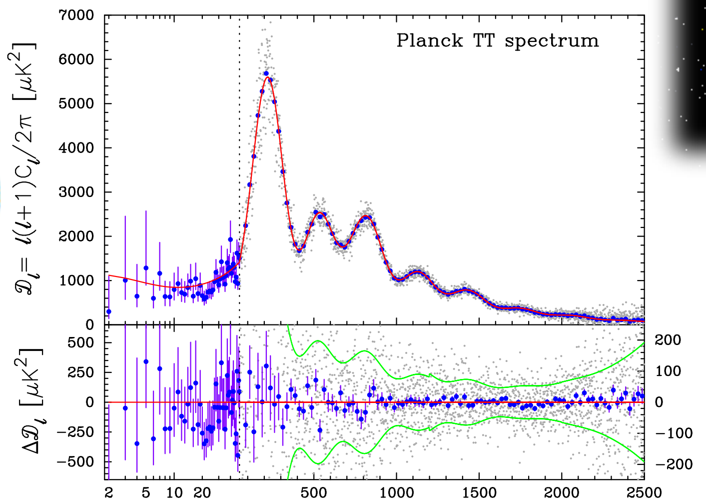
- Neutrino masses
- Dark Matter
- Dark Energy
- Quantum gravity

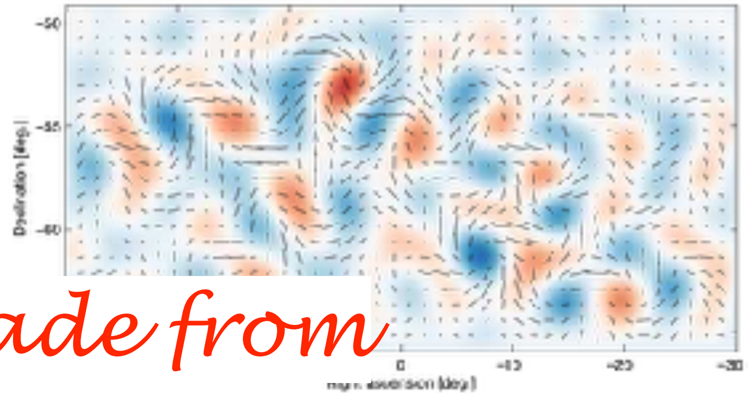
[and we all have to return our royalties!]











we do not understand the Matter the Universe is made from

Where and how does the SM break down?
Which machine(s) will reveal (best) this breakdown?

Which Machine(s)?

Hadrons

- large mass reach ⇛ exploration?
- S/B ~ 10^{-10} (w/o trigger)
- S/B ~ 0.1 (w/ trigger)
- requires multiple detectors
  (w/ optimized design)
- only pdf access to $\sqrt{\hat{s}}$
- ⇛ couplings to quarks and gluons

Leptons

- S/B ~ 1 ⇛ measurement?
- polarized beams
  (handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- ⇛ EW couplings

Circular

- higher luminosity
- several interaction points
- precise E-beam measurement
  (O(0.1MeV) via resonant depolarization)
- $\sqrt{s}$ limited by synchroton radiation

Linear

- easier to upgrade in energy
- easier to polarize beams
- "greener": less power consumption*
- large beamsthralung
- one IP only

*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders

Which Machine(s)?

The challenges of big colliders:
- energy: 10^{13} larger than everyday life batteries
- magnetic field: 10^{4} larger than everyday life magnets
Cannot use permanent magnets:
currents needed in 16T magnets ~ intramolecular fields (100 MV/m).
Going higher will imply a reorganisation of matter!
→ Plasma wakefield acceleration

Exercise: with 2 magnets of 1T, can you build a magnet of 2T?

Which Machine(s)?

Choice between different options: delicate balance between physics return, technological challenges and feasibility, time scales for completion and exploitation, financial and political realities

Exploration machines are at the heart of HEP
Current consensus towards European Strategy Update:
the best way to go to energy frontier is to start with a **e^+e^- Higgs factory**

Linear or Circular?

- Can be extended in energy
- Polarised beams

- Higher luminosity
- Z-pole run

Three relevant questions to address to help taking a decision:
1) Impact of Z pole measurements?
2) Benefit of beam polarisation?
3) Is low energy a limitation?

Fundamental Property of SM: Chirality

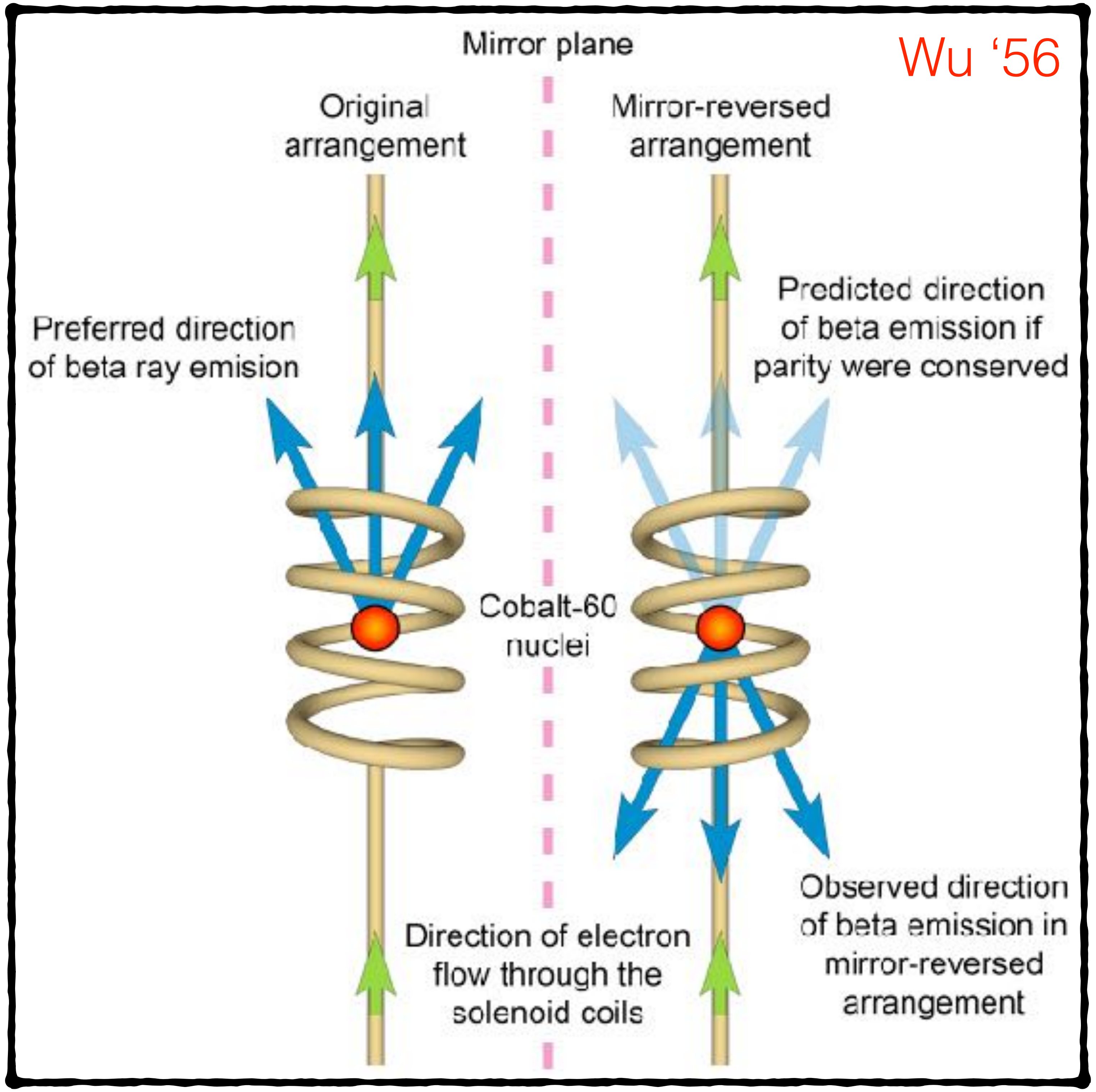
Weak interaction
(force responsible for neutron decay)
is chiral!

[e_L and e_R are fundamentally two different particles
Only an accident of the history of physics that
they are both called electron]

SR+QM

m_e=0
One needs a new phenomena
to generate mass:
Higgs mechanism

**The Higgs boson is
a special element of the SM
It needs to be studied further**



Fundamental Property of SM: Chirality

Dextrorotation and Levorotation are essential for life to develop.
To the best of our knowledge,
in **molecular biology**, chirality seems an **emergent** property.
At least, there is no clear evidence that it follows from chirality of the weak interactions.
Are the chiral nature of the **weak** interactions **emergent** too?
Some models of grand unification predict it. But we still don't know for sure.

Discovering New Physics: the ways forward

new discoveries could follow from

- **Disagreements between theory predictions and experimental data**
  - ↪ e.g. Newton/Galileo mechanics and constant speed of light
- **Apparent fine-tunings**
  - ↪ charm quark to screen the Kaon mass difference
- **Theoretical inconsistencies**
  - ↪ W boson to regularise Fermi theory, Higgs boson to unitarize WW scattering
- **Serendipity**
  - ↪ CMB discovery
- **Surprises**
  - ↪ muon

Post-Higgs discovery: SM has no (major) theoretical inconsistencies

apart maybe black hole information paradox which might require soft hairs i.e. massless particles with zero momentum located at the infinite future boundary of the horizon

(Hawking, Perry, Strominger '16)

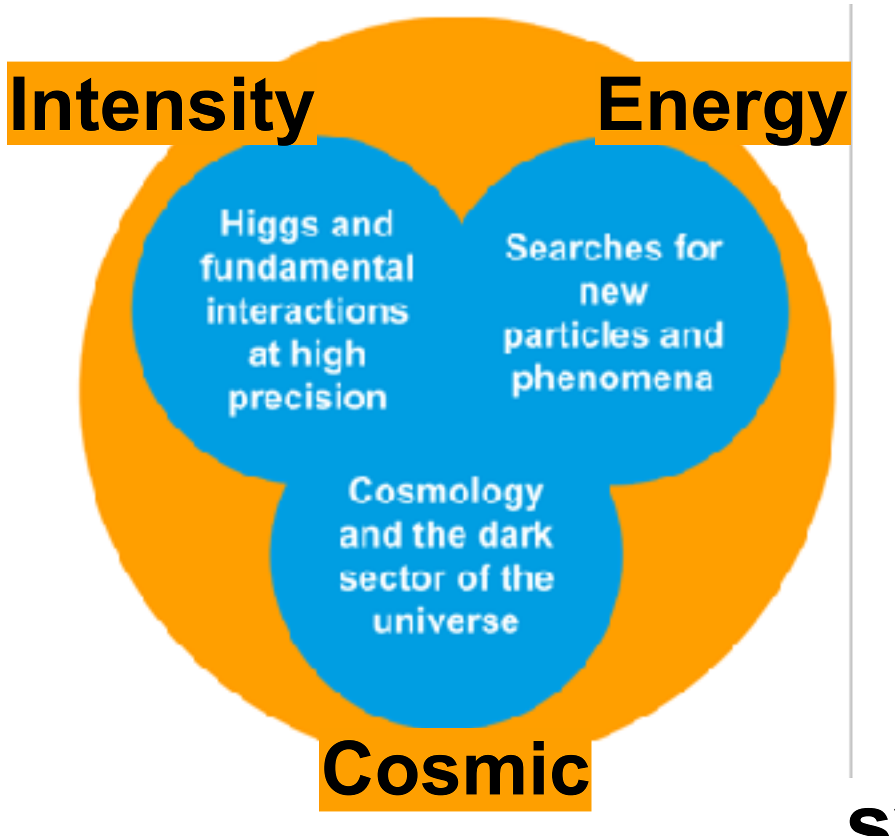
Need powerful machines to explore the unknown through the intensity and energy frontiers

The LHC Legacy (so far)

- **SM confirmed to high accuracy up to energies of several TeV**
- **Higgs boson discovered**
- **Absence of new physics** → { Traditional models are under siege; New approaches: relaxion, Nnaturalness, clockwork… }

Particle Physics Frontiers

Particle Physics Frontiers



Theory Frontiers

SM precision

BSM model building

synergy fuels progress

⤢ ⤡

the 3 frontiers are dynamical and might be more intertwined than originally thought

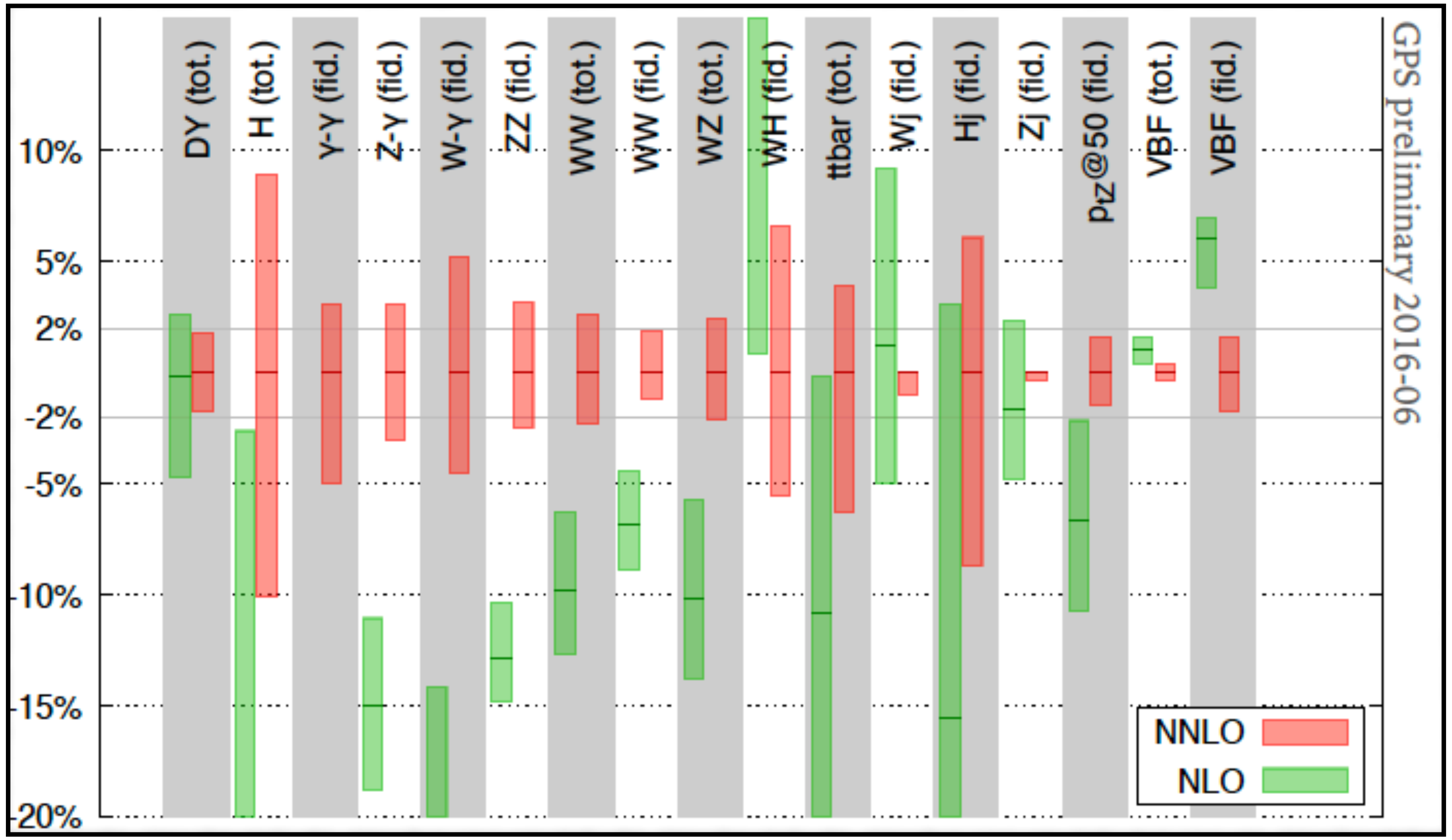
no BSM major discovery without a thorough understanding of SM background

The SM challenges

Statistical uncertainty will become less and less important ↔ Systematics wall will be faced

— So progress requires —

- Better control of parametric uncertainties, e.g. PDFs, α_s, m_t, m_H
- Higher order theoretical computations, e.g. N…NLO
- Access to phase-space limited regions
- Understand correlations among different bins in diff. distributions



Don't think future HEP is only EXP-business. Theorists have to work harder too!

The QCD frontiers

Zanderighi @ HL/HE-LHC kick-off '17

- NNLO 2 → 3 processes, e.g.
  - Production of 3 vector bosons (VVV) [quartic couplings]
  - Higgs plus di-jet production [background to VBF Higgs production]
  - VBF W/Z production
  - Productions of 3 jets [strong coupling, PDFs, …]
- Internal masses
  - Higgs at large transverse momentum, currently described only at LO accuracy
  - Mixed QCD+EW corrections (short term: assess ambiguity in how they are combined; long term: compute genuine mixed corrections)
- NNLO production and decay, e.g.
  - NNLO top production and decay
- Off-shell effects/interferences
- Merging of NNLO to parton showers for complicated processes
- Improve logarithmic accuracy of parton showers

What is the scale of New Physics?

High Scale Wishes

small FCNC: $\frac{gF_{\mu\nu}\bar{\psi}H\sigma^{\mu\nu}\psi}{M_{\rm NP}^2}$ 10^3TeV?

tiny neutrino masses: $\frac{(LH)^2}{M_{\rm NP}}$ 10^{14}GeV?

slow proton decay: $\frac{UUDE}{M_{\rm NP}^2}$ 10^{16}GeV?

Low Scale Wishes

small EDMs: $\mathrm{arg det Y} \leq 10^{-10}$
↪ axion?

tiny vacuum energy: $\Lambda \approx M_{\rm NP}^4 \gg \left(10^{-3}\mathrm{eV}\right)^4$
↪ ?

light Higgs boson: $m_H^2 \approx M_{\rm NP}^2 \gg (125\mathrm{GeV})^2$
↪ light susy?

Where is everybody?

even new physics at few hundreds of GeV might be difficult to see and could escape LHC detection

- **compressed spectra**
- **displaced vertices**
- **no MET, soft decay products, long decay chains**
- **uncoloured new physics**

~~R~~-susy

Neutral naturalness
(twin Higgs, folded susy)

Relaxion

What is the scale of New Physics?

going beyond theoretical prejudices

self-interacting DM

matter distribution in galaxies and clusters

light mediators

$$m_\phi \sim 1 - 100\,\mathrm{MeV}$$

$$\Downarrow \qquad\qquad \Downarrow$$

$$\sigma/m_\chi \sim 1\,\mathrm{cm}^2/\mathrm{g}$$

$\gg 10^{14}$

WIMP self-interactions

neutrino mass

$$m_\nu \approx \frac{y^2 v^2}{M_R}$$

$y \sim \mathcal{O}(1)$

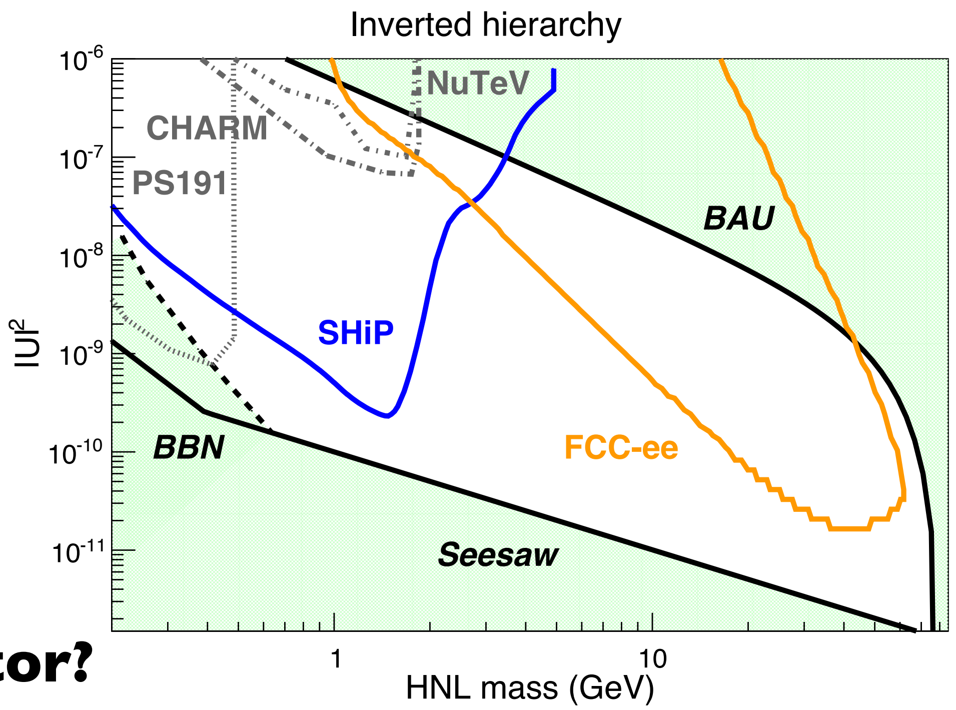
$M_R \sim 10^{14}\,\mathrm{GeV}$

$y \sim \mathcal{O}(10^{-7})$

$M_R \sim 10\,\mathrm{GeV}$

sensitivity to light sterile neutrinos
from 10^{12} Z decays at FCC-ee

(Blondel et al '14)



light sterile neutrinos could provide DM
and generate matter-antimatter asymmetry
= worth experimental exploration !

Pending question: is CP violated in neutrino sector?

What is the scale of New Physics?

going beyond theoretical prejudices

self-interacting DM

matter distribution in galaxies and clusters

light mediators

$m_\phi \sim 1 - 100\,\mathrm{MeV}$

$\Downarrow \qquad \Downarrow$

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WIMP self-interactions

neutrino mass

$$m_\nu \approx \frac{y^2 v^2}{M_R}$$

$y \sim \mathcal{O}(1)$ | $y \sim \mathcal{O}(10^{-7})$

$M_R \sim 10^{14}\,\mathrm{GeV}$ | $M_R \sim 10\,\mathrm{GeV}$

Inverted hierarchy

need for a versatile machine
capable to adjust to very different new physics scenario

(FCC-ee + FCC-eh + FCC-hh) offer a complete programme
(CepC+SppC) too

HNL mass (GeV)

Future colliders as BSM probes

in order to address the physics questions outside the SM boundaries
the physics program of the future colliders is built around four key goals

1. Measurement of the properties of the newly-discovered **Higgs** boson with very high precision.
   ⇛ Is it elementary? Does it have siblings/relatives? What keeps it light? Why does it freeze in?

2. Measurement of the properties of the **top** quark with very high precision to indirectly constrain new physics

3. Precision measurements of the EW observable: the **Z** boson will be the atomic clock of HEP

4. Direct searches for and studies of (uncoloured) **new particles** expected in models of physics at the TeV energy scale. Complementary to LHC searches.

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Guaranteed deliverables
machine than can achieve
landmark textbook measurements

Exploration potential
HEP remains a frontier science

The way forward

• increased energy

• increased statistics

• increased precision

• increased sensitivity

• High rates allow the exploration of rare phenomena and extreme phase space configurations

• High rates also shift the balance between systematic and statistical uncertainties. It can be exploited to define different signal regions, with better S/B, better systematics, pushing the potential for better measurements beyond the "systematic wall" of low statistic measurements

The Future Collider Projects

A lot of documents available online
only a brief (and personal/biased) review

Future of HEP

ECFA Higgs study group '19

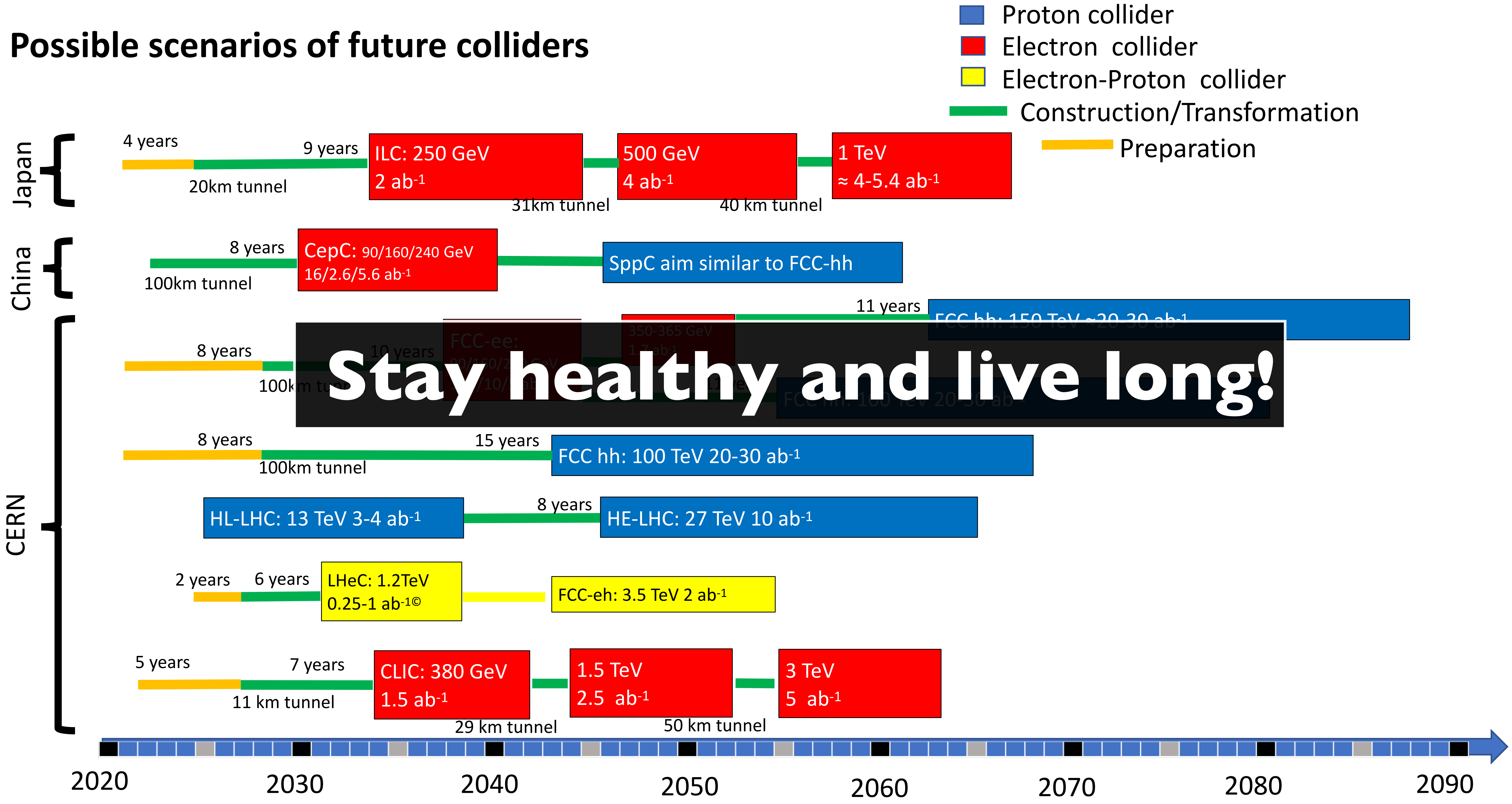
Subject to large uncertainty
1) need a scientific consensus
2) political approval

	T_0, +5, +10, +15, +20, …, +26	T_0
ILC	0.5/ab 250 GeV; 1.5/ab 250 GeV; 1.0/ab 500 GeV; 0.2/ab $2m_{top}$; 3/ab 500 GeV	2032
CEPC	5.6/ab 240 GeV; 16/ab M_Z; 2.6 /ab $2M_W$; SppC =>	2030
CLIC	1.0/ab 380 GeV; 2.5/ab 1.5 TeV; 5.0/ab => until +28 3.0 TeV	2035
FCC	150/ab ee, M_Z; 10/ab ee, $2M_W$; 5/ab ee, 240 GeV; 1.7/ab ee, $2m_{top}$; hh,eh =>	2037
LHeC	0.06/ab; 0.2/ab; 0.72/ab	2030
HE-LHC	10/ab per experiment in 20y	2040
FCC eh/hh	20/ab per experiment in 25y	2045

+ muon-collider + gamma-gamma collider + …

Future of HEP

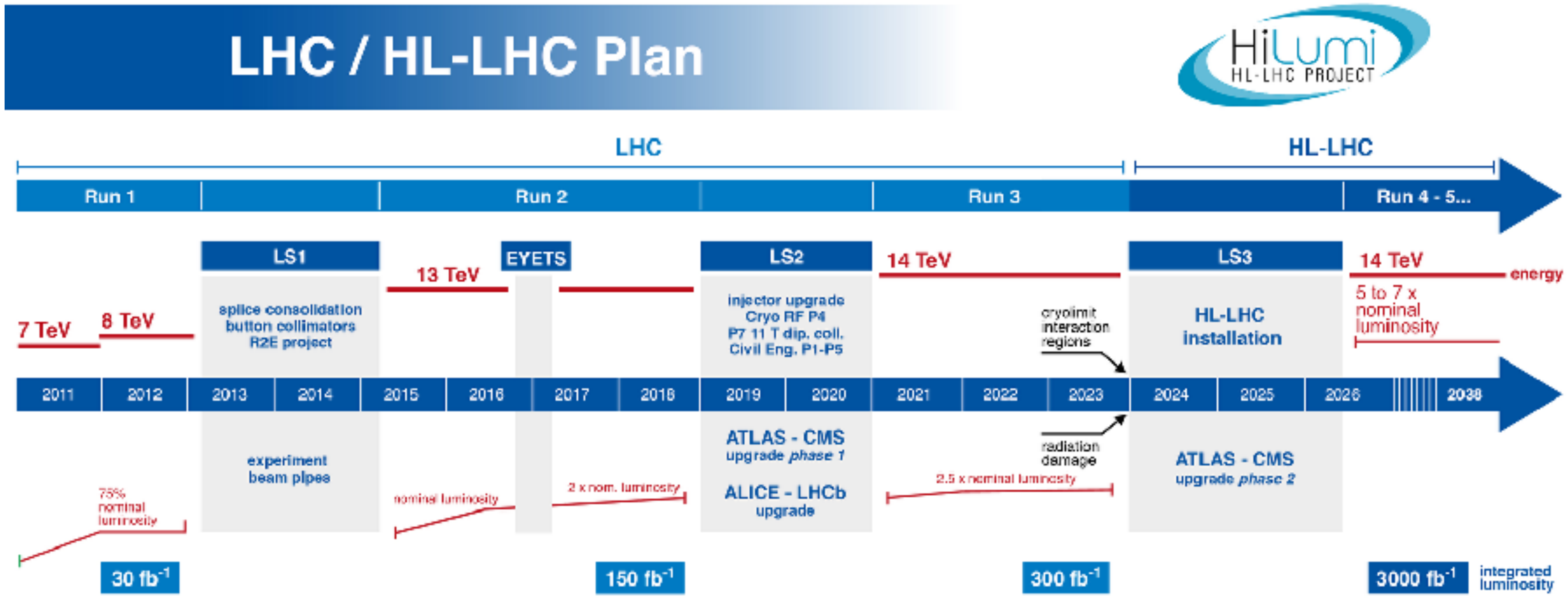
Possible scenarios of future colliders



Ursula Baesler, Granada 13.05.2019

HL-LHC (2023-2035)

14 TeV - 3/ab



A Higgs factory on its own

	Higgs bosons at √s=14TeV
HL-LHC, 3000fb^{-1}	170M
VBF (all decays)	13M
ttH (all decays)	1.8M
H->Zγ	230k
H->μμ	37k
HH (all)	121k

Main issue: how to cope with pile-up?

Higgs @ HL-LHC

2013 projections

HL-LHC WS, Aix-les-Bains '13

		κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300fb^{-1}	ATLAS	[8,13]	[6,8]	[7,8]	[8,11]	N/a	[20,22]	[13,18]	[78,79]	[21,23]
	CMS	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000fb^{-1}	ATLAS	[5,9]	[4,6]	[4,6]	[5,7]	N/a	[8,10]	[10,15]	[29,30]	[8,11]
	CMS	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

Snowmass '13 Higgs report

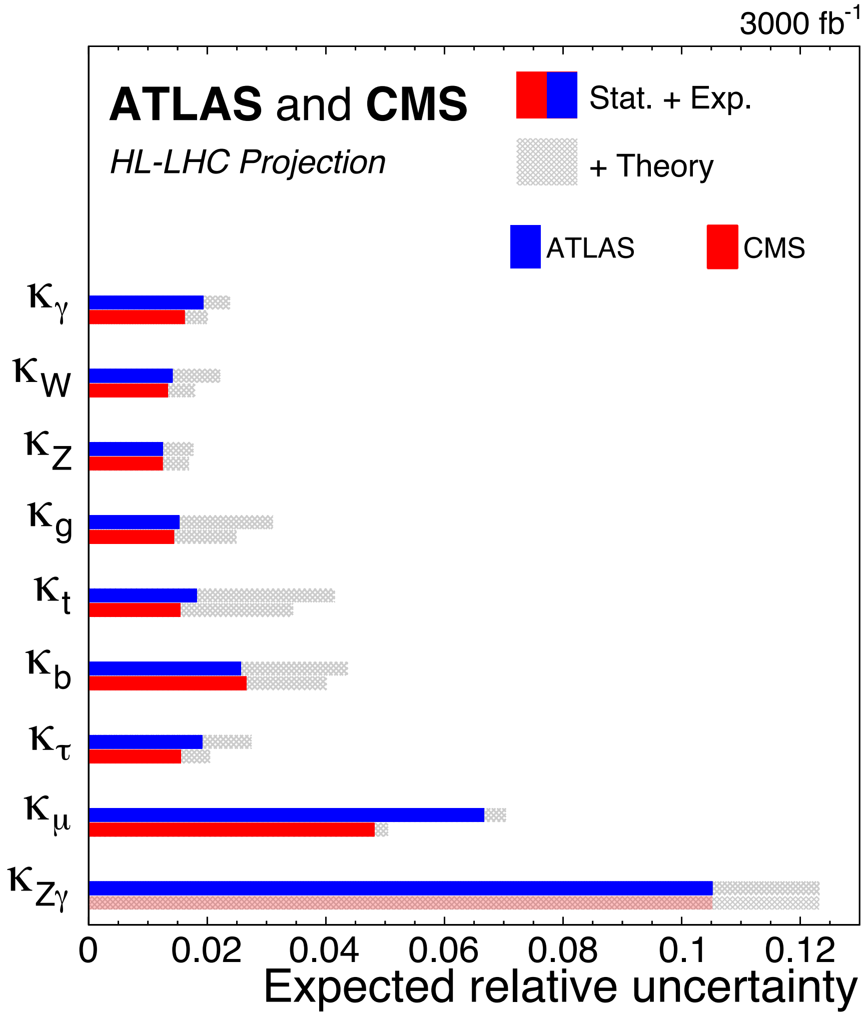
Table 1-14. *Expected per-experiment precision of Higgs boson couplings to fermions and vector bosons with 300 fb^{-1} and 3000 fb^{-1} integrated luminosity at the LHC. The 7-parameter fit assumes the SM productions and decays as well as the generation universality of the couplings ($\kappa_u \equiv \kappa_t = \kappa_c$, $\kappa_d \equiv \kappa_b = \kappa_s$ and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). The precision on the total width Γ_H is derived from the precisions on the couplings. The range represents spread from two assumptions of systematic uncertainties, see text.*

Luminosity	300 fb^{-1}	3000 fb^{-1}
Coupling parameter	7-parameter fit	
κ_γ	5 – 7%	2 – 5%
κ_g	6 – 8%	3 – 5%
κ_W	4 – 6%	2 – 5%
κ_Z	4 – 6%	2 – 4%
κ_u	14 – 15%	7 – 10%
κ_d	10 – 13%	4 – 7%
κ_ℓ	6 – 8%	2 – 5%
Γ_H	12 – 15%	5 – 8%
	additional parameters (see text)	
$\kappa_{Z\gamma}$	41 – 41%	10 – 12%
κ_μ	23 – 23%	8 – 8%
BR_{BSM}	< 14 – 18%	< 7 – 11%

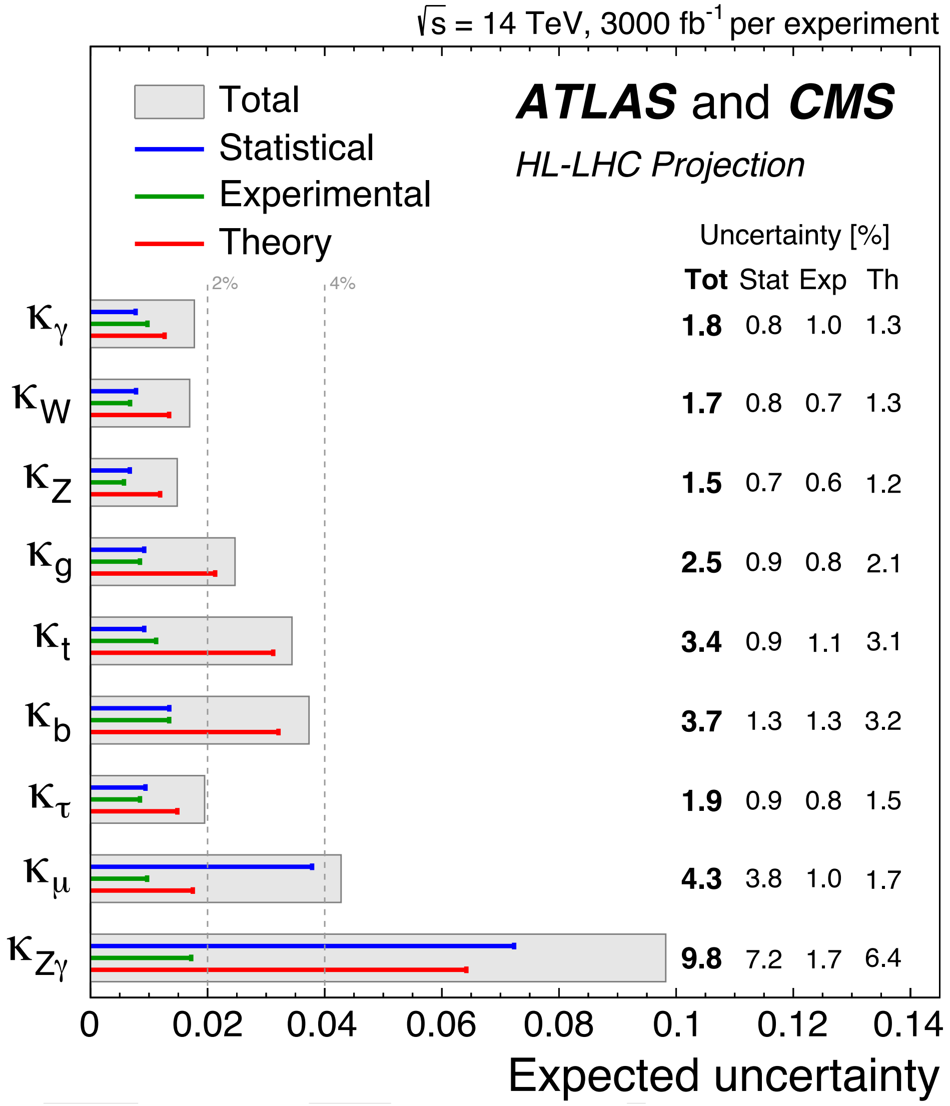
2018-2019 projections

HL/HE-LHC Higgs WG report

Individual



Combined



$Z\gamma$ and $\mu\mu$ are statistically limited but otherwise O(2-3%) precision

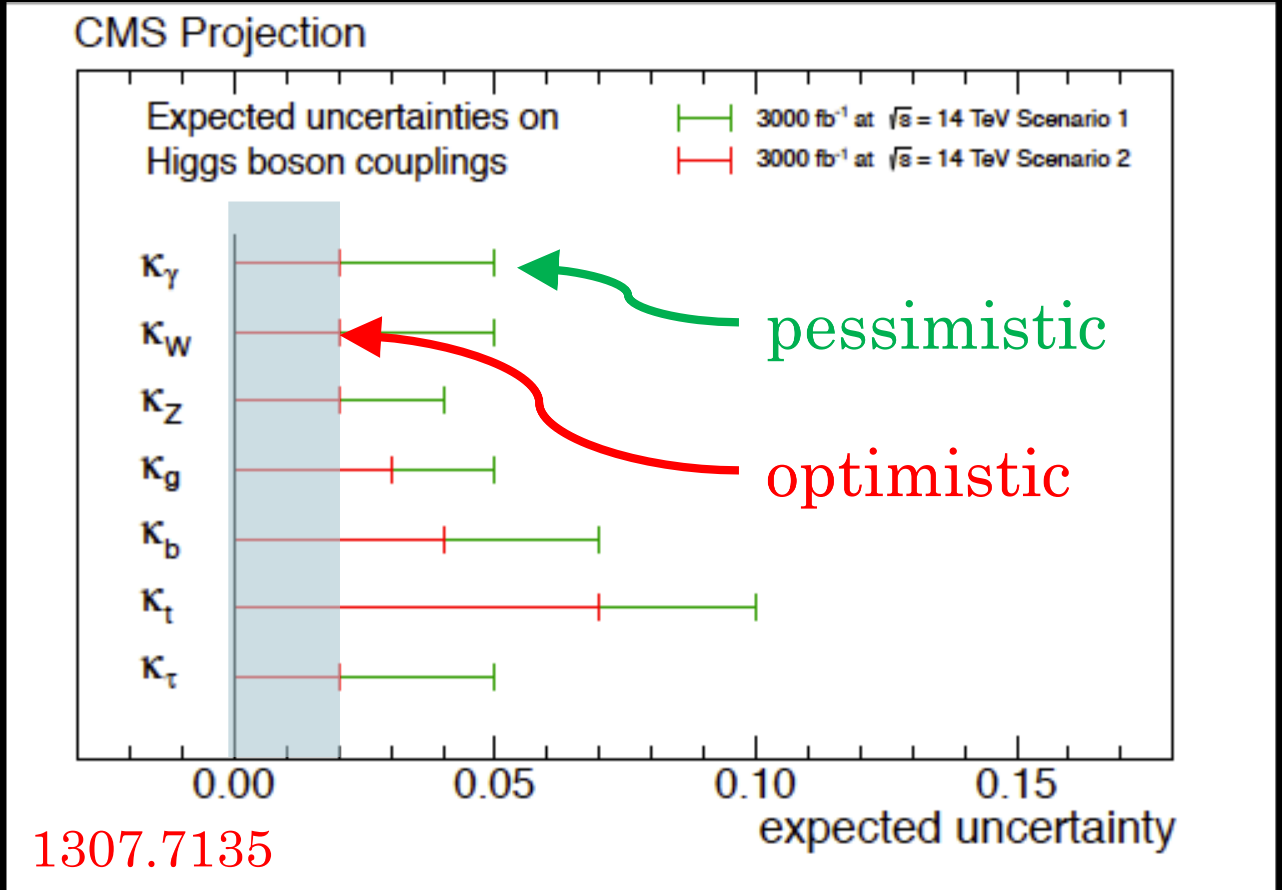
Higgs @ HL-LHC

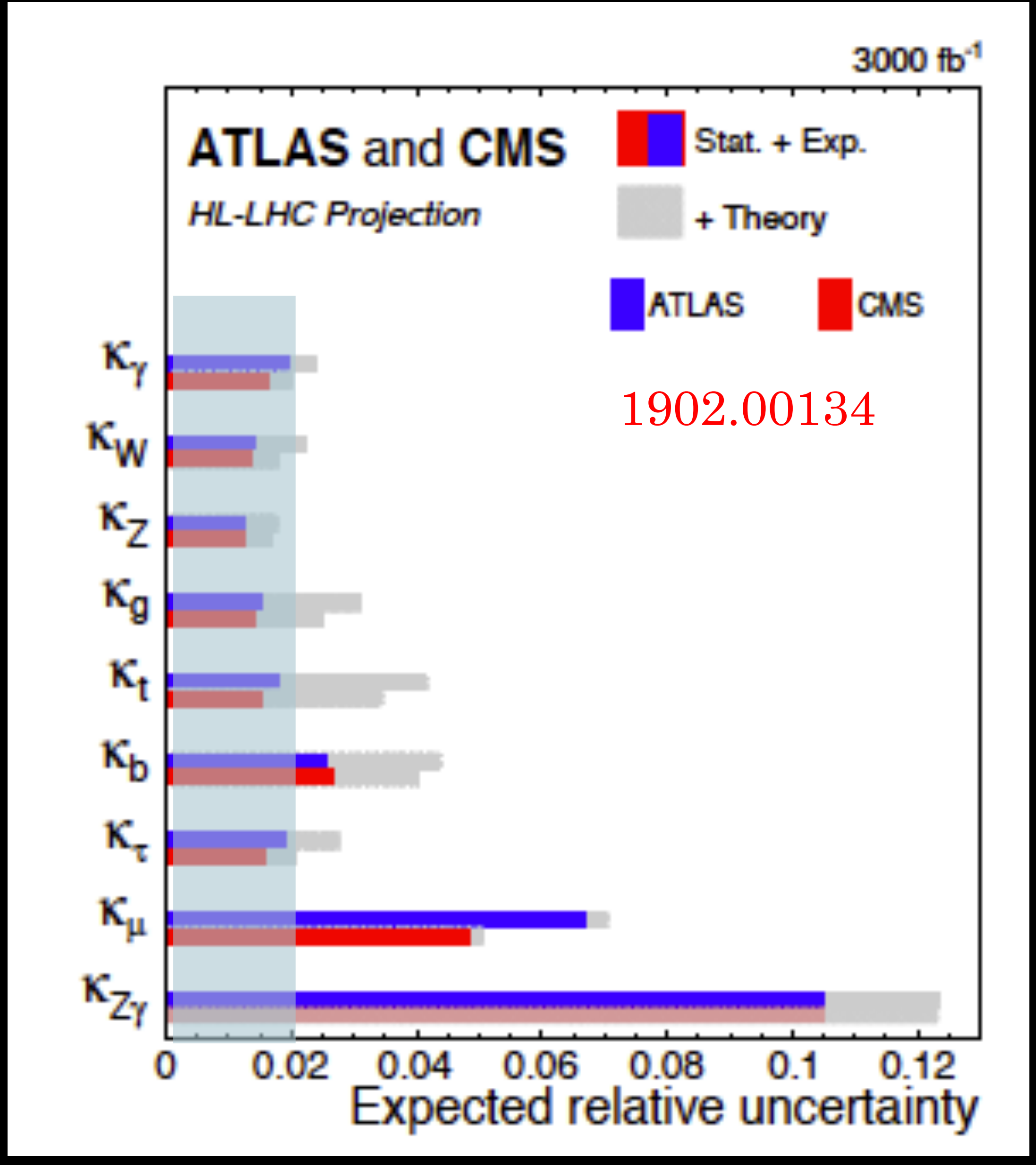
2013 projections

2018-2019 projections

Potential HL-LHC performance in Higgs couplings

anno 2013 versus anno 2019





Taking into account innovative thoughts and research experience, what was optimistic in 2013 seems realistic in 2019.

J. D'Hondt @ Higgs Hunting 2019

HE-LHC (TBD)

27 TeV - O(20)/ab

Main **technical** issue: 16T magnets (same magnets as in FCC-hh)
But also: SPS upgrade, detectors upgrade…

One **theoretical** issue: EW large Sudakov logs

Kick-off meeting Nov. 2017: indico.cern.ch/e/647676/

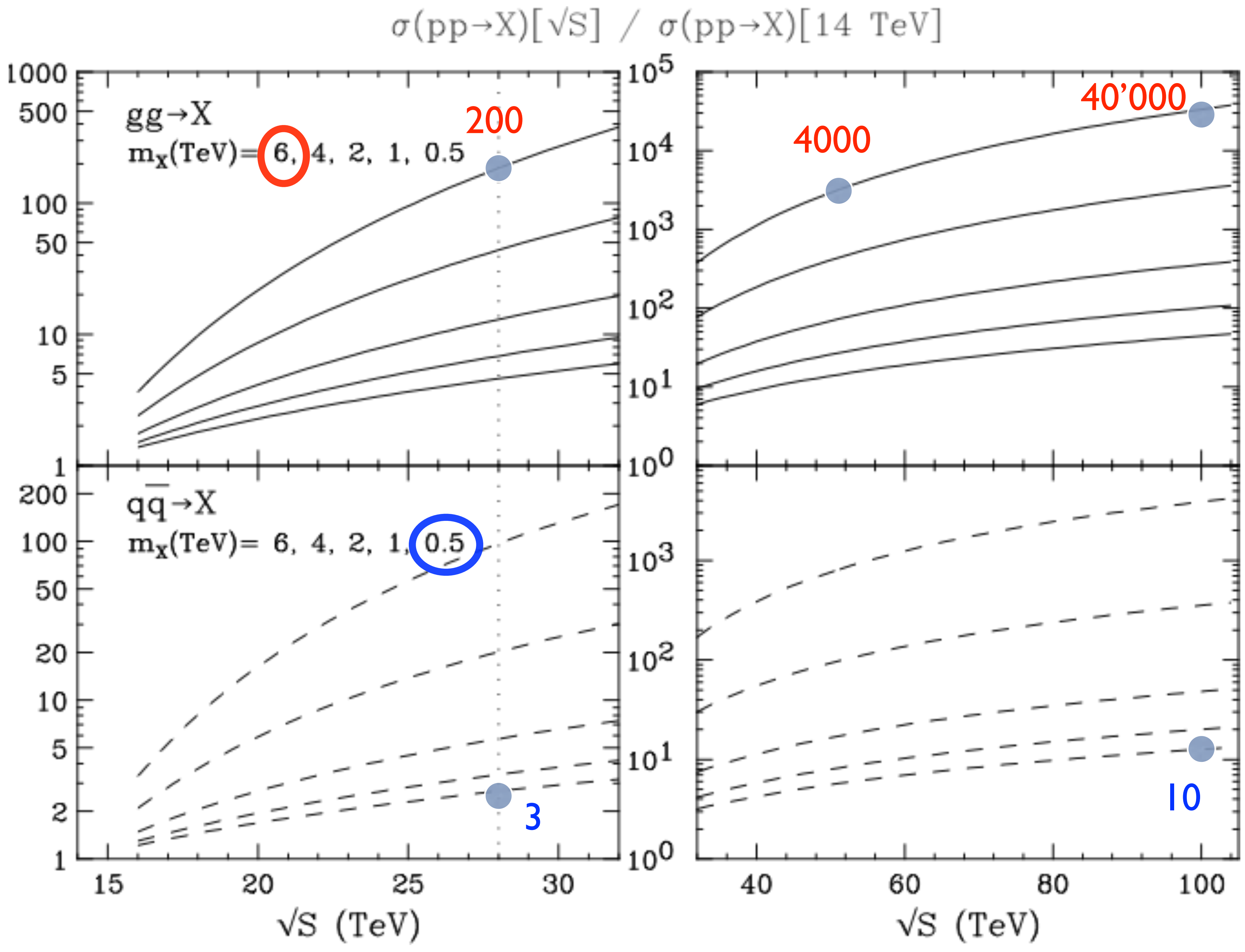
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop

- **The physics potential of HL-LHC** (input to the strategy) pdf
- **The physics potential of HE-LHC** (input to the strategy) pdf
- **Standard Model physics at the HL-LHC and HE-LHC** (WG1 report), CERN-LPCC-2018-03, CDS
- **Higgs physics at the HL-LHC and HE-LHC** (WG2 report), CERN-LPCC-2018-04, CDS
- **Beyond the Standard Model physics at the HL-LHC and HE-LHC** (WG3 report), CERN-LPCC-2018-05, CDS, arXiv
- **Flavour physics at the HL-LHC and HE-LHC** (WG4 report), CERN-LPCC-2018-06, CDS, arXiv
- **Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams** (WG5 report), CERN-LPCC-2018-07, CDS, arXiv

See furthermore:

- **Report on the Physics at the HL-LHC and Perspectives for the HE-LHC** (Collection of notes by the ATLAS and CMS Collaborations), CERN-LPCC-2019-01, to appear January 2019 CDS
- **Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era,** R. Aaij et al. (LHCb Collaboration), arXiv

HE-LHC (TBD)



- If m_X ~ 6 TeV in the gg channel, rate grows x 200 @28 TeV:
  - Do we wait 40 yrs to go to pp@100TeV, or fast-track 28 TeV in the LHC tunnel?
  - Do we need 100 TeV, or 50 is enough ($\sigma_{100}/\sigma_{14}\sim4\cdot10^4$, $\sigma_{50}/\sigma_{14}\sim4\cdot10^3$) ?
  - .... and the answers may depend on whether we expect partners of X at masses ≳ $2m_X$ (⇒ *28 TeV would be insufficient* ....)
- If m_X ~ 0.5 TeV in the qqbar channel, rate grows x10 @100 TeV:
  - Do we go to 100 TeV, or push by x10 ∫L at LHC?
  - Do we build CLIC?

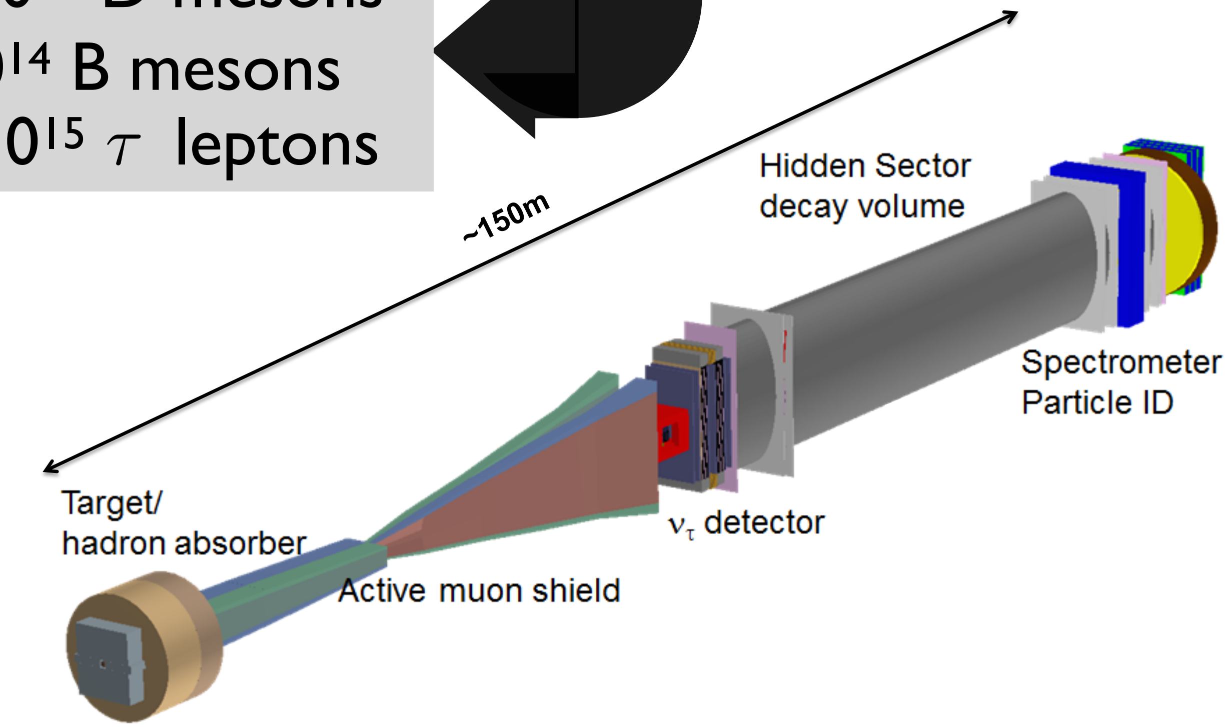
Mangano @ HK'18

SHiP (TBC: installation during LS3 and data taking starts 2026)

beam dump experiment: 400 GeV SPS protons on fixed target

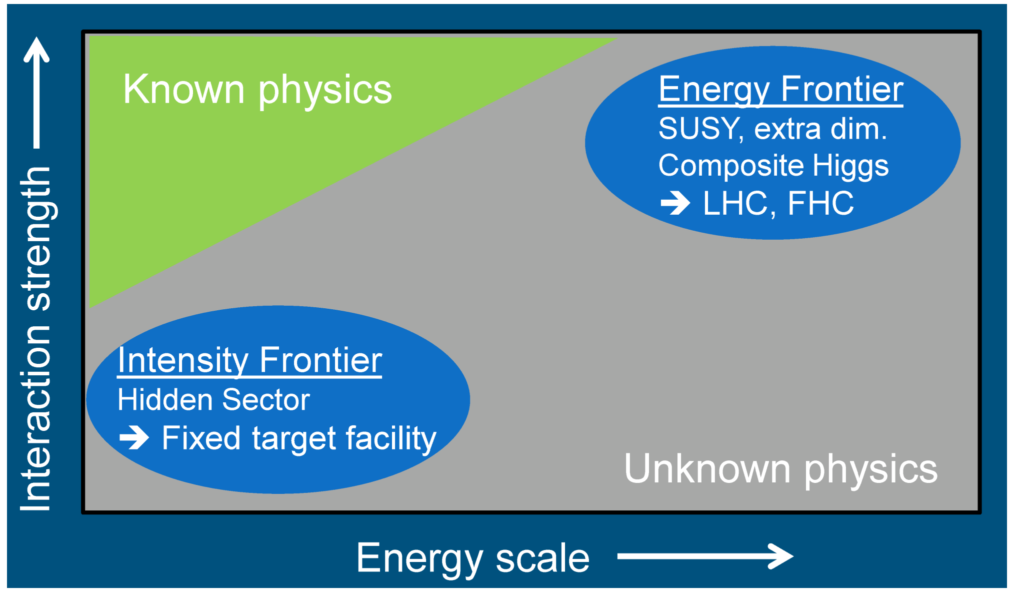
$\sqrt{s}$~28 GeV 10^{20} protons over 10 years, i.e. $\mathcal{L} = 10^{39}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

8×10^{17} D mesons
10^{14} B mesons
3×10^{15} τ leptons



Search for rare events triggered by light and weakly coupled new particles, e.g. in decays of B and D mesons

intensity frontier



Physics case

arXiv:1504.04855

- Searches for hidden photons
- Searches for heavy neutral leptons (ν_R)
- s-PDF sensitivity (via charm hadron production in neutrino scattering)
- Search for low mass (~GeV) DM with small recoil

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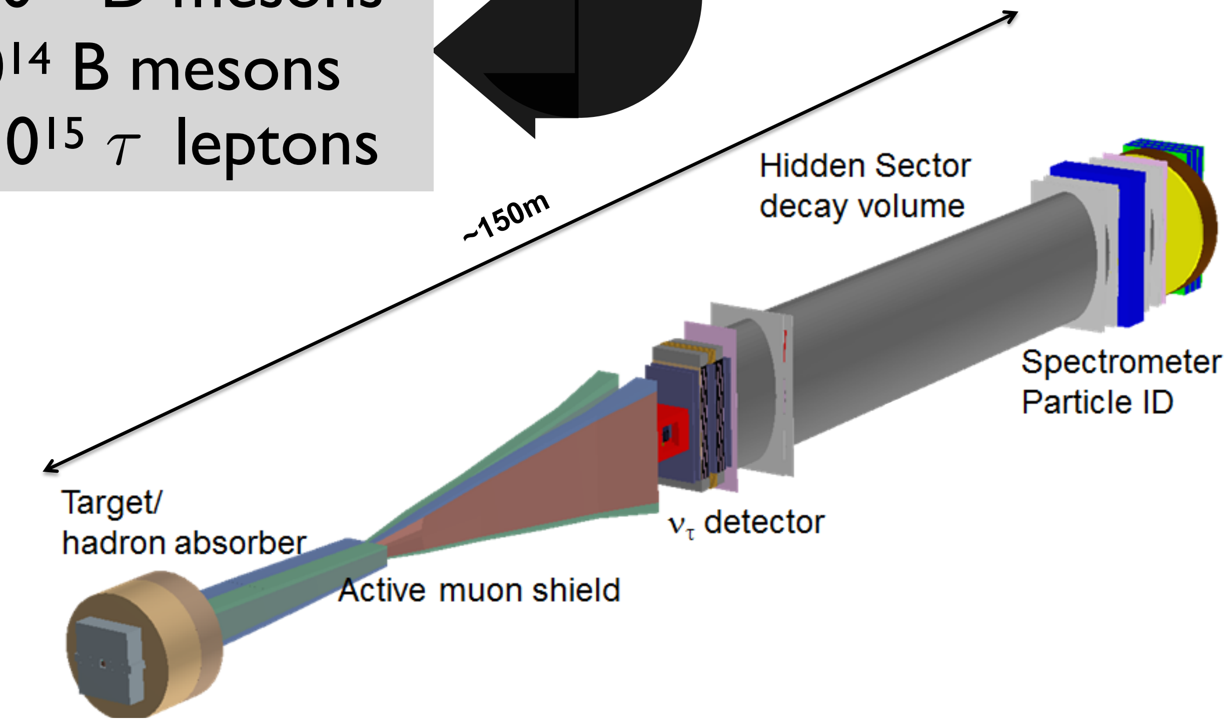
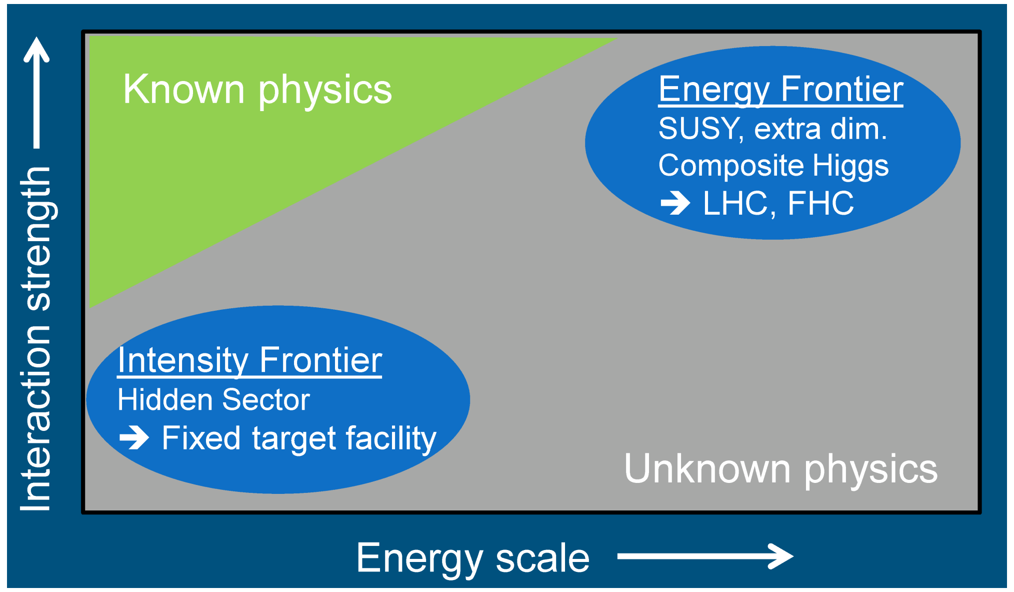
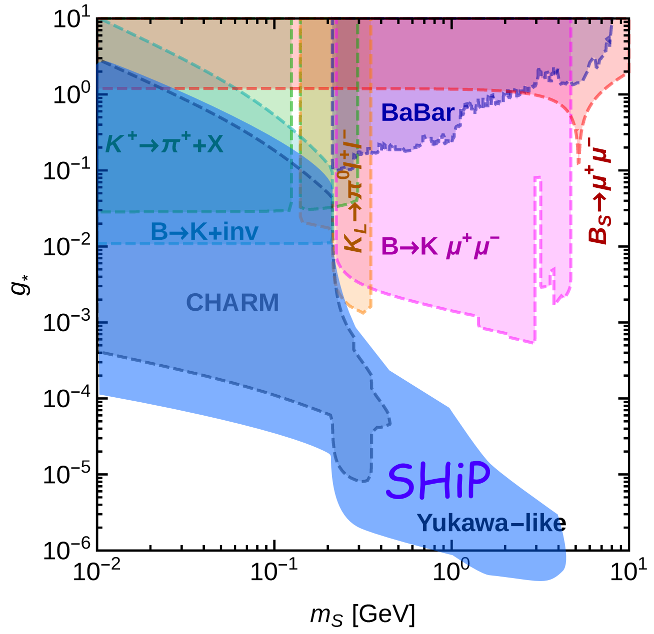


intensity frontier





Higgs portal

$(\alpha_1 S + \alpha S^2) H^\dagger H + L_{SM} + L_{hidden}$

Physics case arXiv:1504.04855

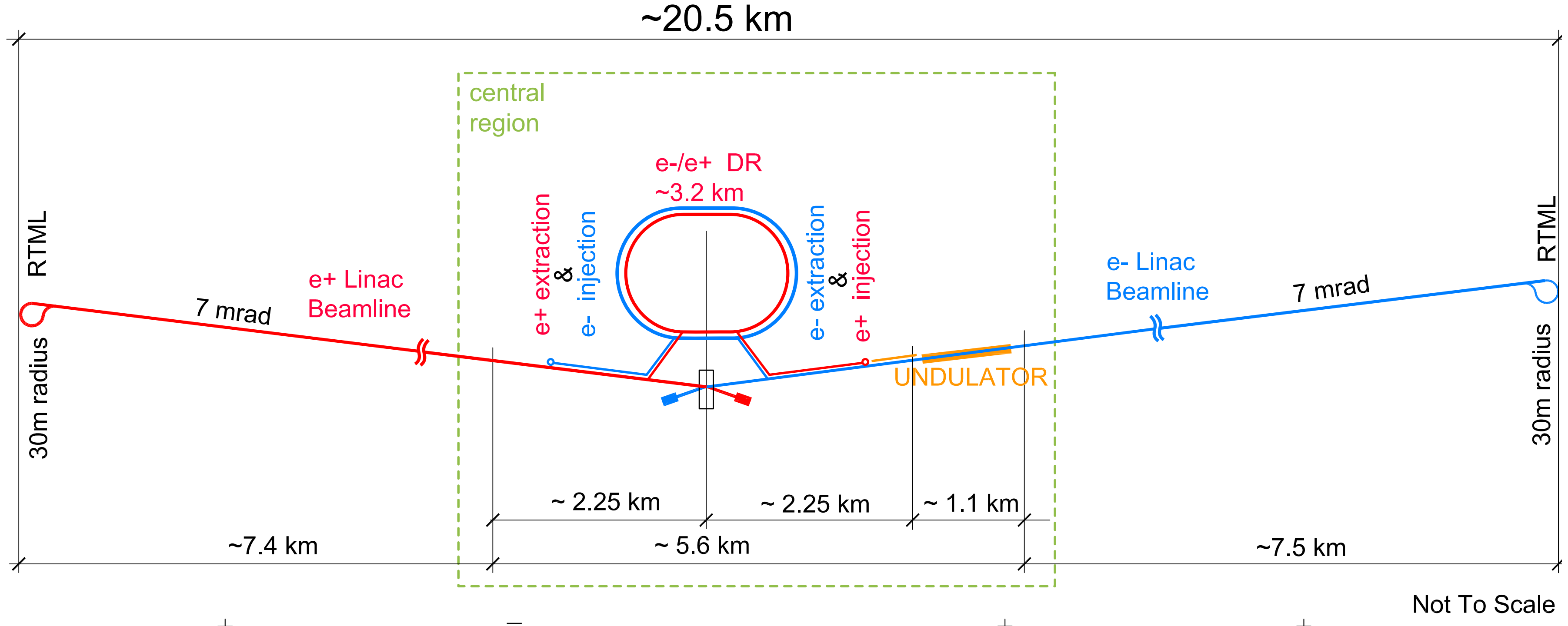
- Searches for hidden photons
- Searches for heavy neutral leptons (ν_R)
- s-PDF sensitivity (via charm hadron production in neutrino scattering)
- Search for low mass (~GeV) DM with small recoil

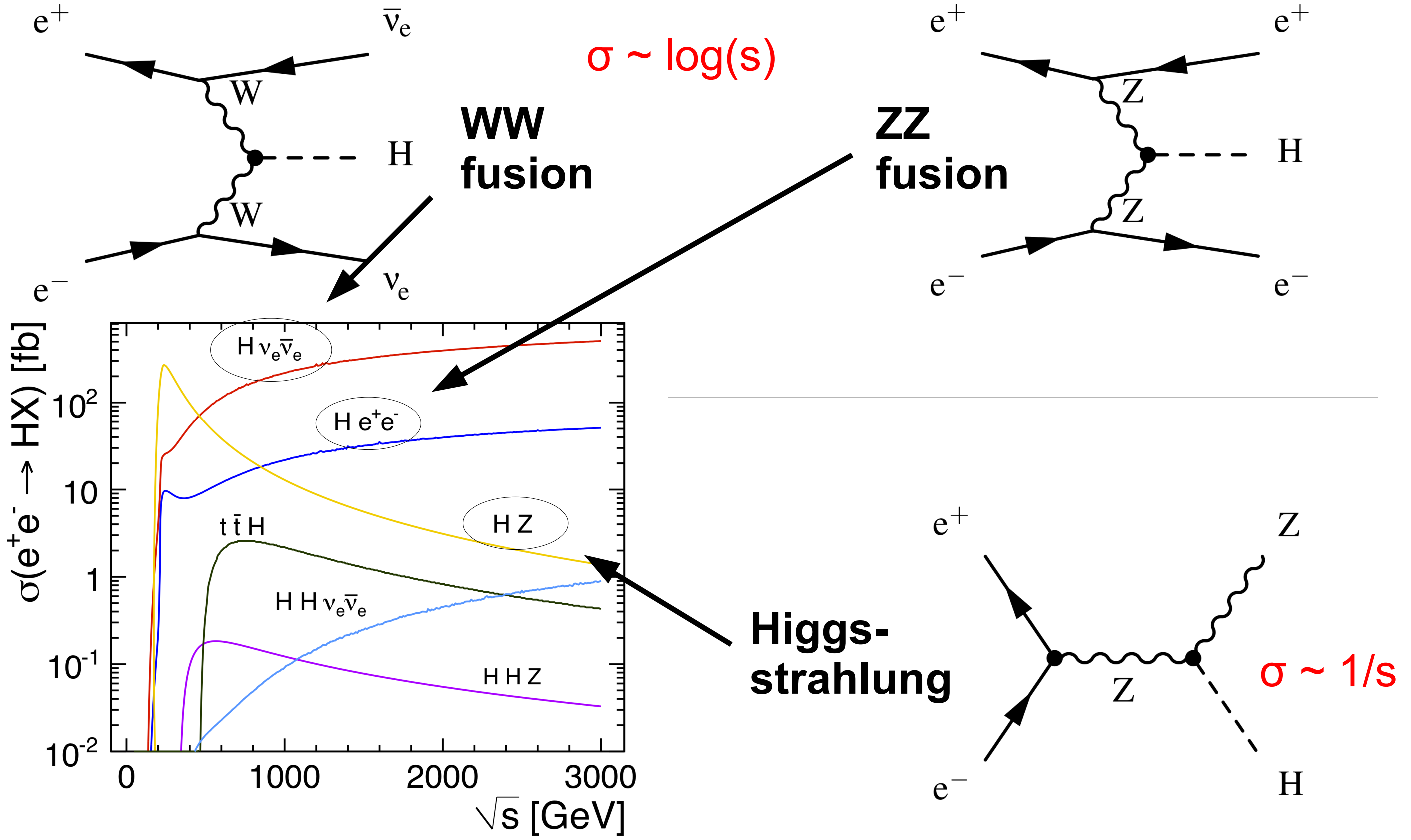
ILC (construction starts in 2023*, operation: 2030-2050)

*ready for construction once approved

250/350/500/1000 GeV - 5/ab

First stage
250 GeV





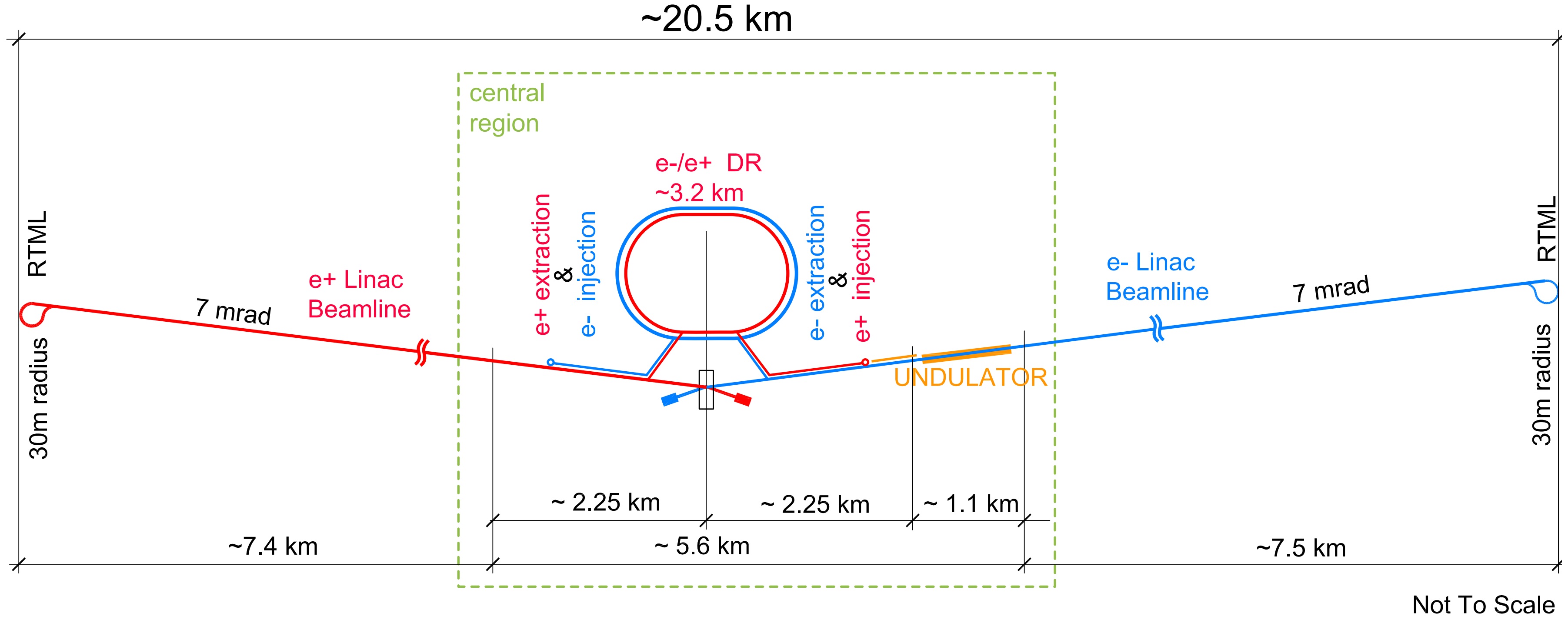
O(10^6) Higgs bosons
produced and reconstructed

ILC (construction starts in 2023*, operation: 2030-2050)

*ready for construction once approved

250/350/500/1000 GeV - 5/ab

First stage
250 GeV



Energy upgrades

~250 GeV ~350 GeV ~ 500 GeV ~ 1 TeV **Center of Mass Energy**

Zh — $t\bar{t}$ — Zhh(DHS) — VBF at 1 TeV improves HHH coupling by combining with Zhh

HHH opens up!

Top Yukawa via $t\bar{t}h$

m_h
Γ_h
higgs couplings

m_t
top Yuk.

ZZhh coupling
h^3 coupling
direct top Yuk

h^3 coupling

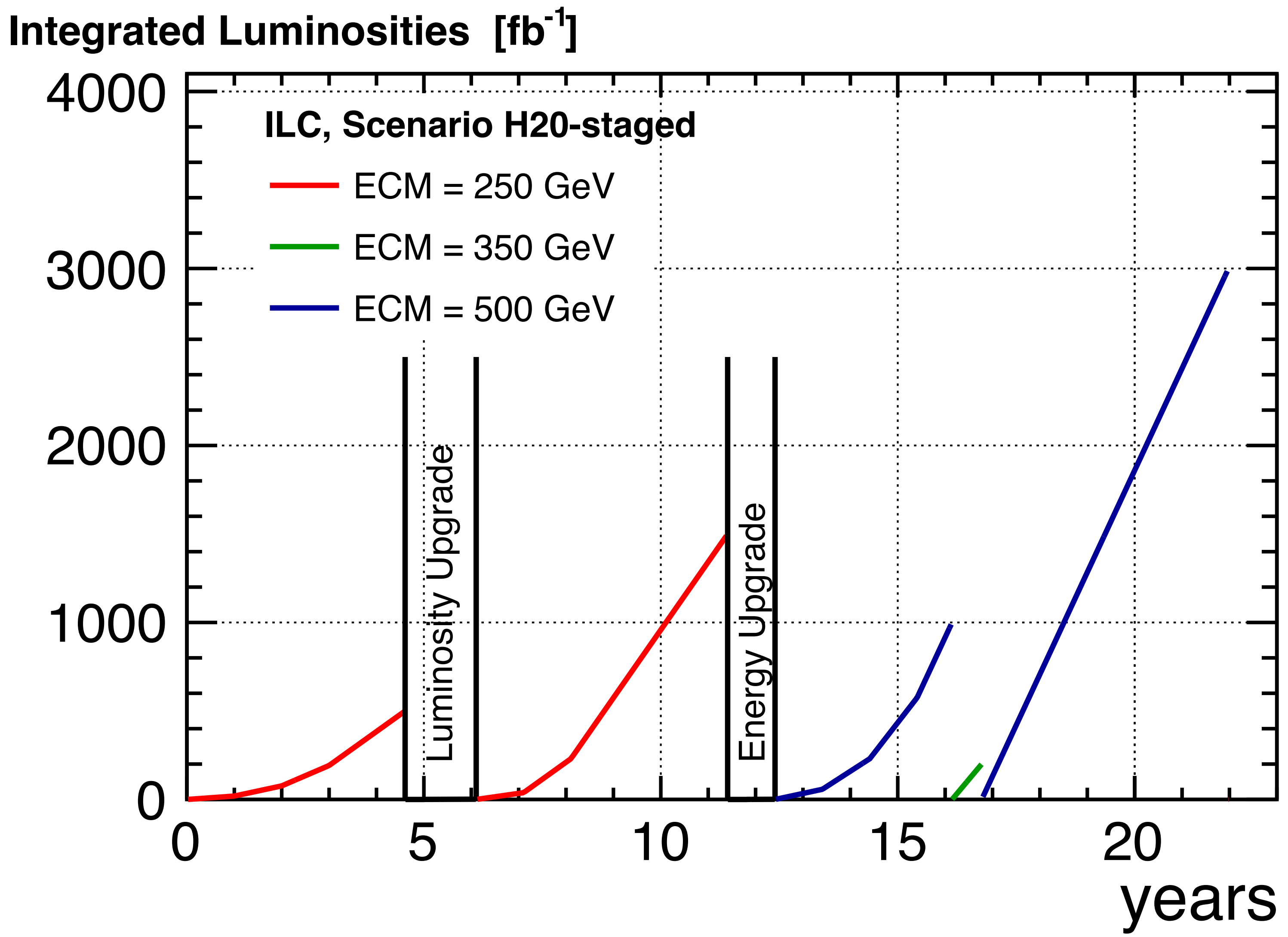
ILC Run Plan in brief

Material from ILC contribution to ESU

	$\int \mathcal{L}dt$ [fb^{-1}]			
$\sqrt{s}$	G-20	H-20	I-20	Snow
250 GeV	500	2000	500	1150
350 GeV	200	200	1700	200
500 GeV	5000	4000	4000	1600

	fraction with sgn$(P(e^-), P(e^+))$ =			
	(-,+)	(+,-)	(-,-)	(+,+)
$\sqrt{s}$	[%]	[%]	[%]	[%]
250 GeV (2015)	67.5	22.5	5	5
250 GeV (update)	**45**	**45**	5	5
350 GeV	67.5	22.5	5	5
500 GeV	40	40	10	10

$\sqrt{s}$	1 TeV	90 GeV	160 GeV
$\int \mathcal{L}dt$ [fb^{-1}]	8000	100	500



Polarised beams @ ILC_{250}

G. Moortgat-Pick et al '08 LCC Physics WG '18

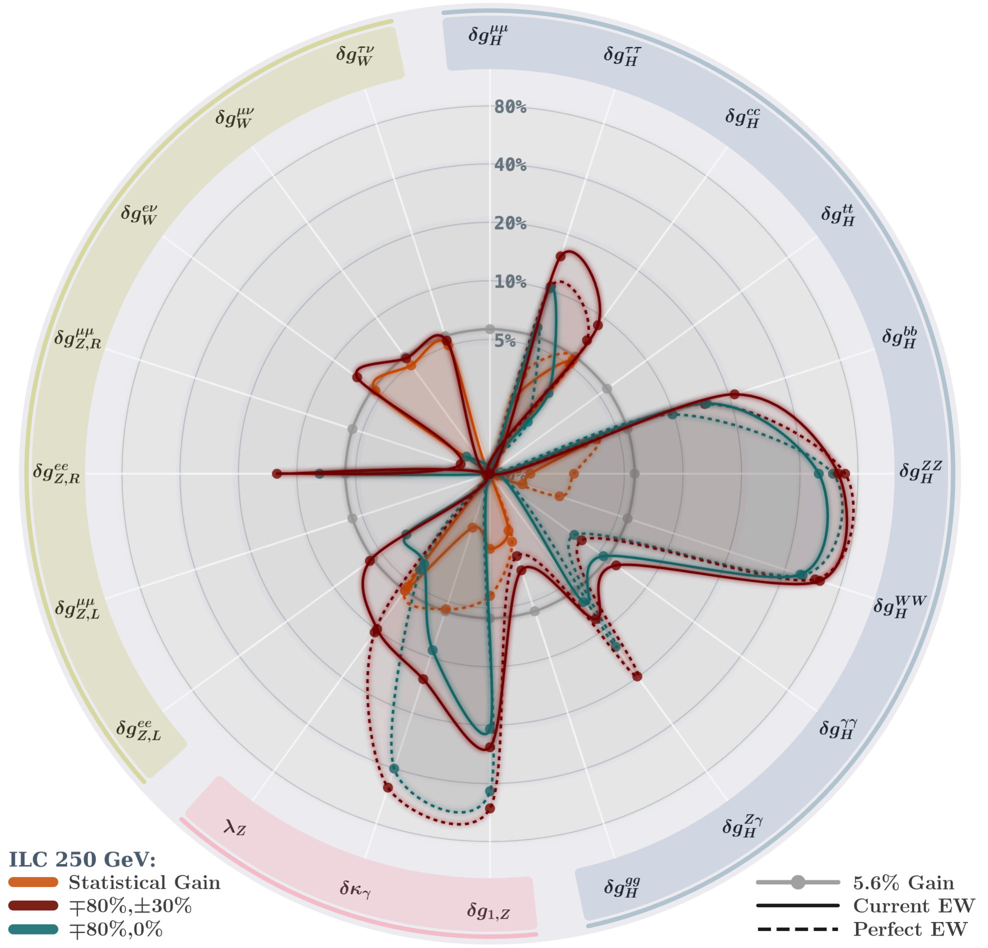
Various benefits of polarised beams:

- Higher signal rates and lower background rates (equivalent to 40% higher L)
- Different data sets → helps resolving degeneracies → gain is much more than increased rates (see later)
- Better control of systematics (thanks to exp. redundancy)

	no pol.	80%/0%	80%/30%
$g(hbb)$	1.33	1.13	1.09
$g(hcc)$	2.09	1.97	1.88
$g(hgg)$	1.90	1.77	1.68
$g(hWW)$	0.978	0.683	0.672
$g(h\tau\tau)$	1.45	1.27	1.22
$g(hZZ)$	0.971	0.693	0.682
$g(h\gamma\gamma)$	1.38	1.23	1.22
$g(h\mu\mu)$	5.67	5.64	5.59
$g(h\gamma Z)$	14.0	6.71	6.63
$g(hbb)/g(hWW)$	0.911	0.909	0.861
$g(h\tau\tau)/g(hWW)$	1.08	1.08	1.02
$g(hWW)/g(hZZ)$	0.070	0.067	0.067
Γ_h	2.93	2.60	2.49
$BR(h \to inv)$	0.365	0.327	0.315
$BR(h \to other)$	1.68	1.67	1.58

Table 1: Projected relative errors for Higgs boson couplings and other Higgs observables at 250 GeV, in %, comparing three cases of beam polarization: 2 ab^{-1} with $\mathcal{P}_{e^-} = \mathcal{P}_{e^+} = 0\%$, as well as the $\mathcal{P}_{e^+}=0$ and $\mathcal{P}_{e^+}=30\%$ scenarios defined in the Introduction.

LCC Physics WG '18

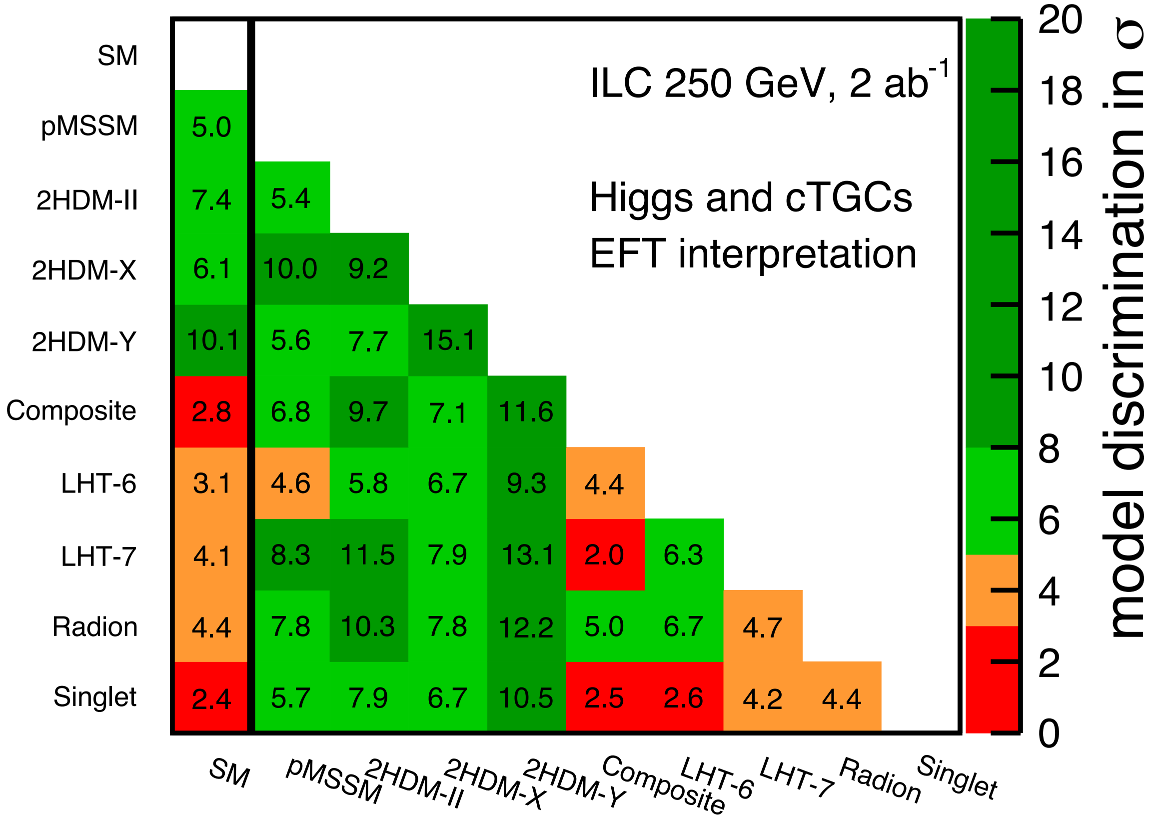


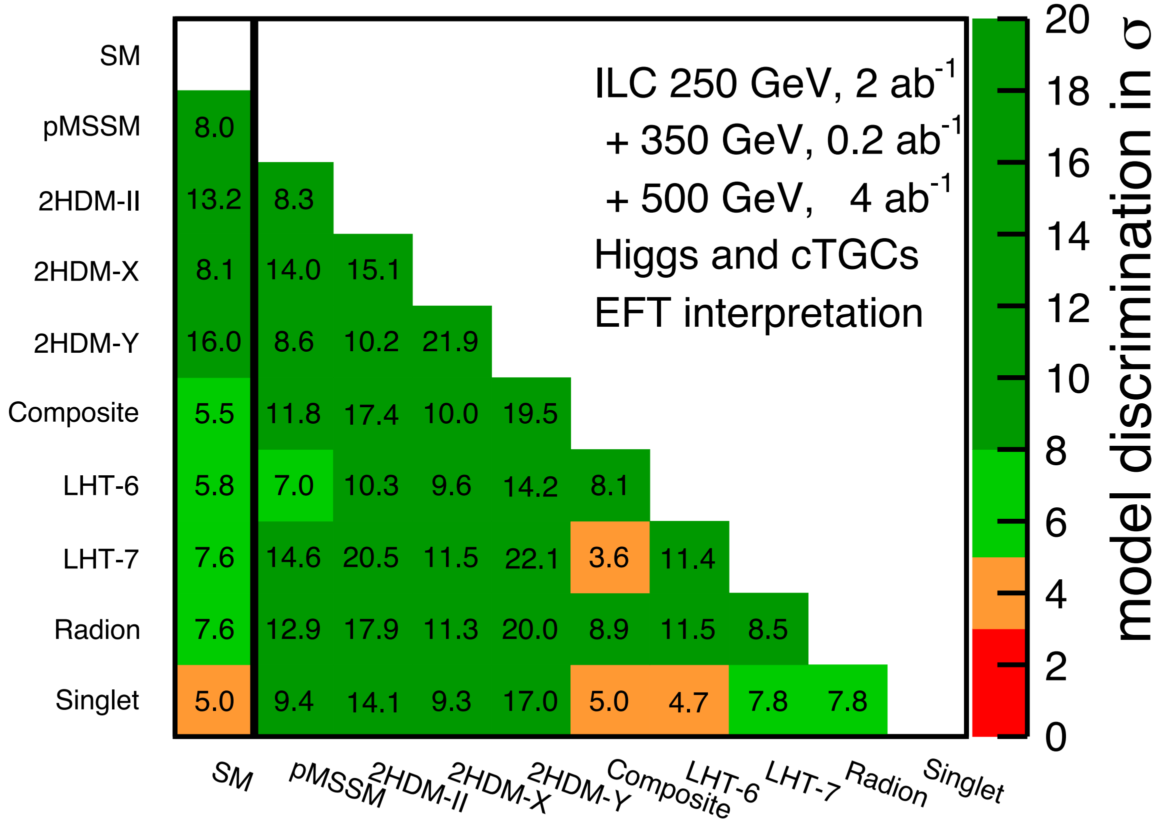
J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311

Physics case of ILC_{250}

BSM separation power

Models that cannot be distinguished from SM at the LHC are resolved with ILC





LCC Physics WG '17

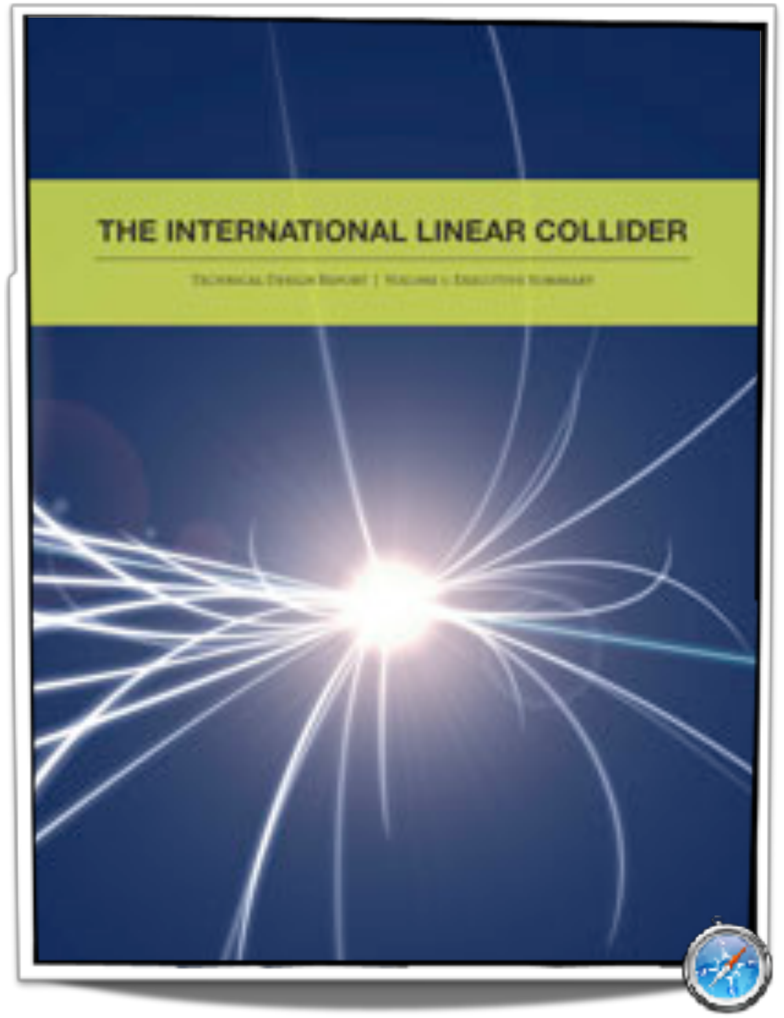
Literature on ILC

https://ilchome.web.cern.ch

arXiv:1506.05992
Physics Case for the International Linear Collider
LCC Physics Working Group
June, 2015

arXiv:1710.07621
Physics Case for the 250 GeV Stage of the International Linear Collider
LCC Physics Working Group
October 2017

arXiv:1903.01629
The International Linear Collider A Global Project
contribution to ESU
March 2019



The Potential of the ILC for Discovering New Particles
Document Supporting the ICFA Response Letter to the ILC Advisory Panel

The role of positron polarization for the inital 250 GeV stage of the International Linear Collider
LCC Physics Working Group

The International Linear Collider
Jim Brau[†], Paul Grannis[‡], Mike Harrison[#], Michael Peskin[*], Marc Ross[*], Harry Weerts[§]
for the ILC Collaboration
April 9, 2013
submitted to the Community Summer Study (Snowmass on the Mississippi), July 2013

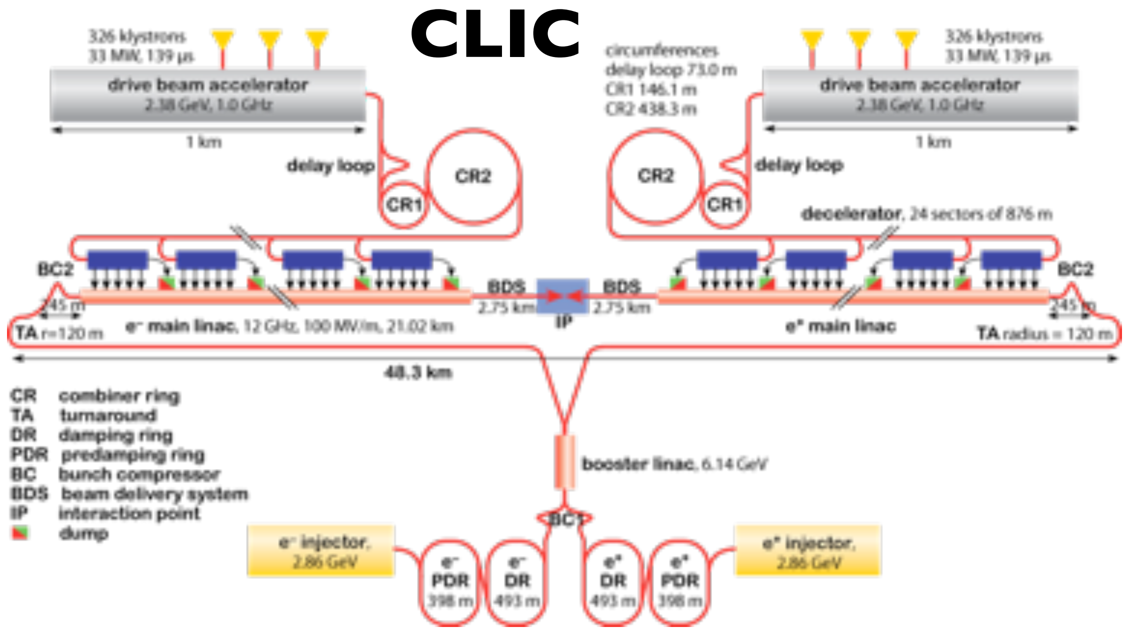
The Physics Case for an e^+e^- Linear Collider
James E. Brau[a], Rohini M. Godbole[b], Francois R. Le Diberder[c], M.A. Thomson[d], Harry Weerts[e], Georg Weiglein[f], James D. Wells[g], Hitoshi Yamamoto[h]
A Report Commissioned by the Linear Collider Community[†]

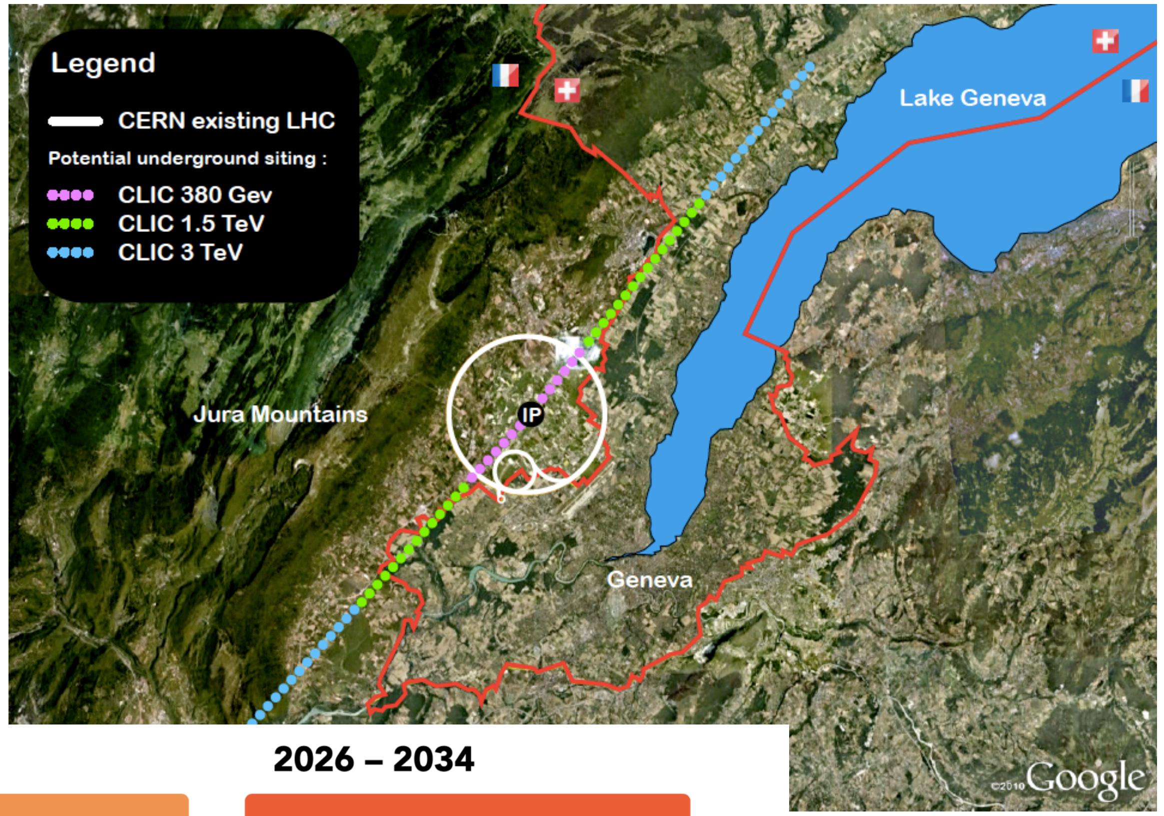
Physics Case for the ILC Project: Perspective from Beyond the Standard Model
Howard Baer[1], Mikael Berggren[2], Jenny List[2], Mihoko M. Nojiri[3,4], Maxim Perelstein[5], Aaron Pierce[6], Werner Porod[7], Tomohiko Tanabe[8]

Physics at the e^+e^- Linear Collider

CLIC (2035-2060??)

380/1000/3000 GeV - 5/ab





2013 – 2019

Development Phase
Development of a project plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 – 2025

Preparation Phase
Finalisation of implementation parameters, preparation for industrial procurement, pre-series and system optimisation studies, technical proposal of the experiment, site authorisation

2026 – 2034

Construction Phase
Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

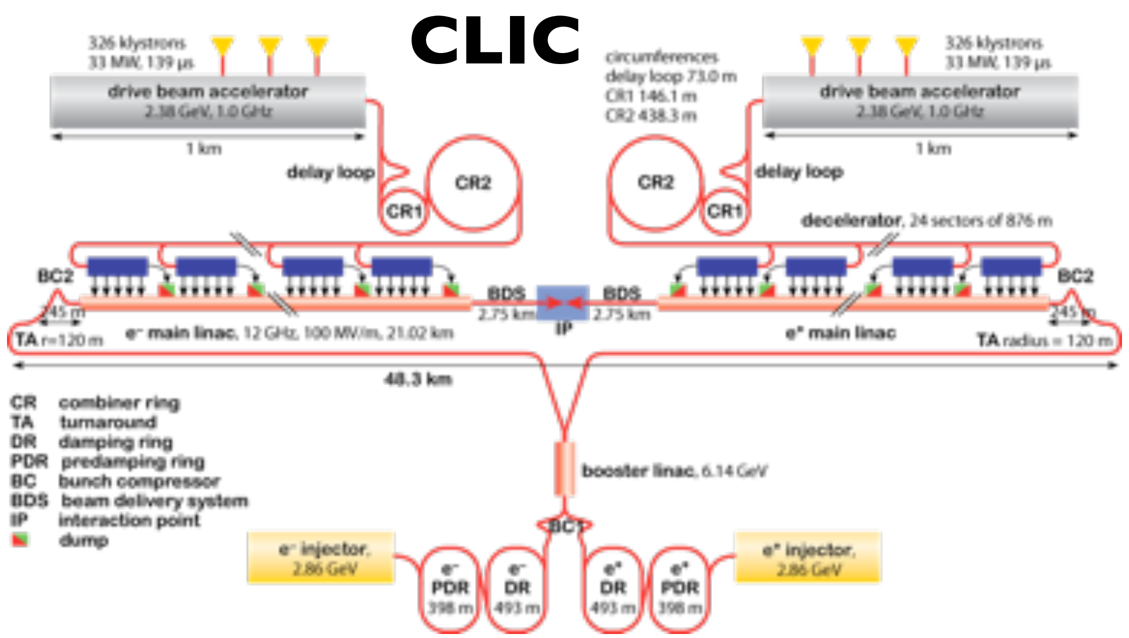
2020
Update of the European Strategy for Particle Physics

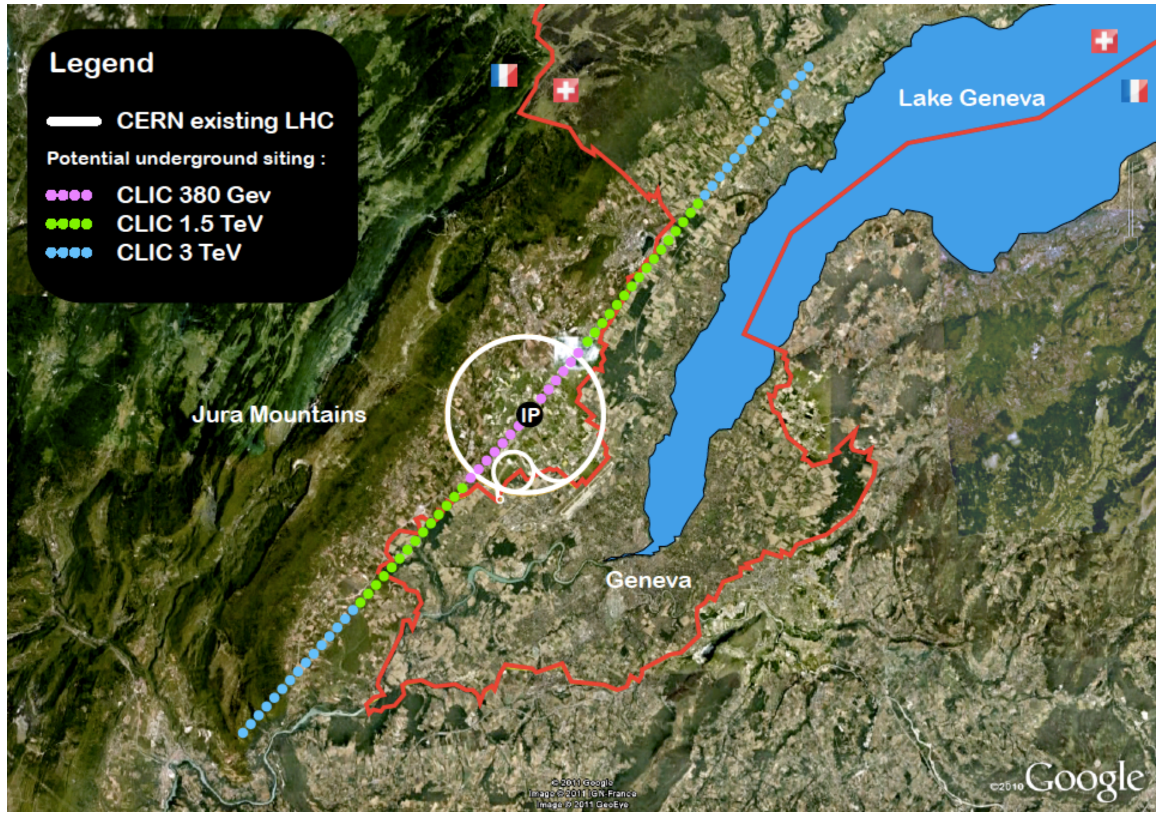
2026
Ready for construction

2035
First collisions

CLIC (2035-2060??)

380/1000/3000 GeV - 5/ab



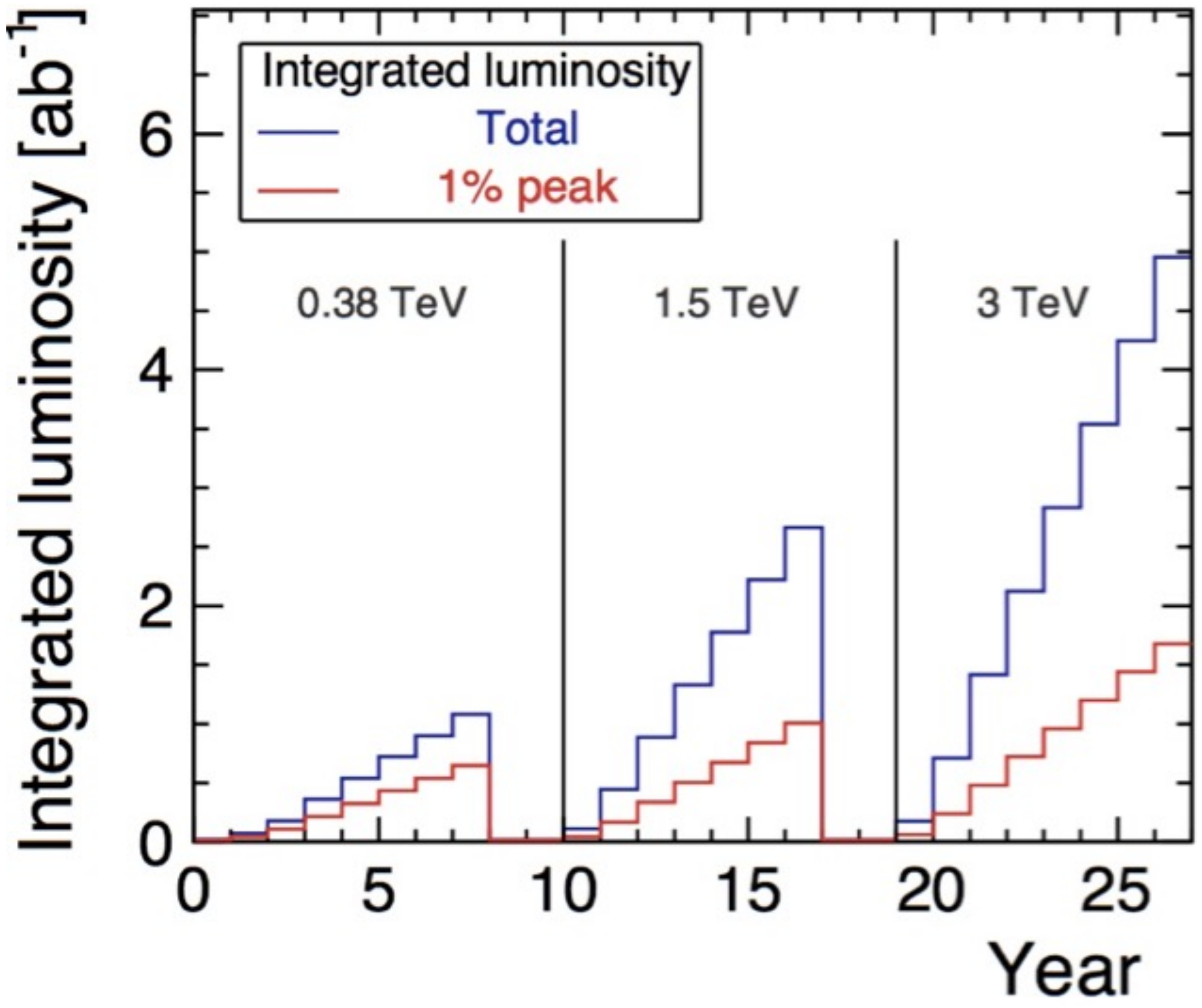


Parameter	Unit	380 GeV	3 TeV
Centre-of-mass energy	TeV	0.38	3
Total luminosity	$10^{34}cm^{-2}s^{-1}$	1.5	5.9
Luminosity above 99% of √s	$10^{34}cm^{-2}s^{-1}$	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5
Acceleration gradient	MV/m	72	100
Site length	km	11	50

- sub-percent Higgs coupling measurements
- few percents Higgs width
- top mass, top EW couplings
- direct BSM sensitivity in the multi-TeV region (direct and indirectly via precision)

CLIC Run Plan

Material from A. Robson



Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{\text{int}}$ [ab^{-1}]	increased from
1	0.38 (and 0.35)	1.0	0.5+0.1ab^{-1}
2	1.5	2.5	1.5ab^{-1}
3	3.0	5.0	3ab^{-1}

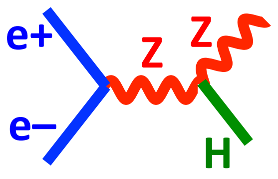
Electron polarisation enhances Higgs production at high-energy stages and provides additional observables

Baseline polarisation scenario adopted:
electron beam (–80%, +80%) polarised in ratio (50:50) at $\sqrt{s}$=380GeV ; (80:20) at $\sqrt{s}$=1.5 and 3TeV

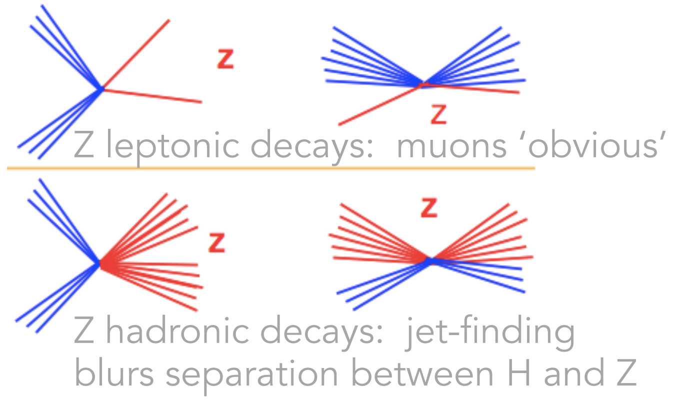
CLIC: Why 380 GeV?

Material from A. Robson

- Precise determination of g_{HZZ} from ZH recoil measurement at initial stage crucial for Higgs couplings at all energy stages

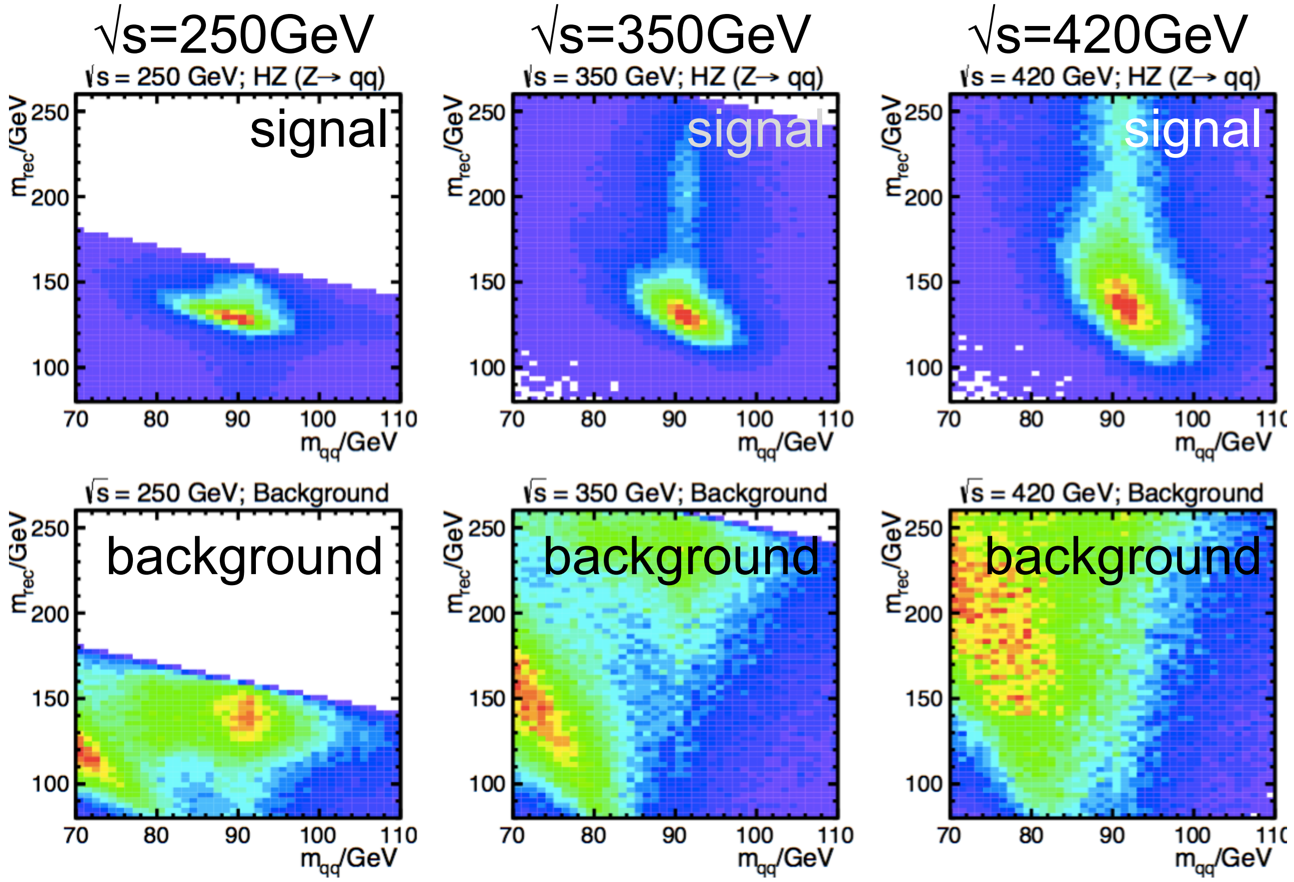


- ZH cross-section peak is at 250GeV
- At 380 GeV, Z hadronic decays provide the best sensitivity



- At 250GeV the background to Z hadronic is more signal-like
- At 420GeV the cross-section is lower and jet energy resolution worse

$\sqrt{s}$	L_{int}[ab^{-1}]	σ(ZH)[fb]	$\Delta\sigma$(ZH)
250	1	136	±2.6%
350	1	93	±1.3%
420	1	68	±1.9%



Eur. Phys. J. C 76 (2016) 72

- Overall, 380GeV allows best precision on g_{HZZ}
- 380GeV also gives access to top quark

–> 380GeV is optimal initial energy for e^+e^-

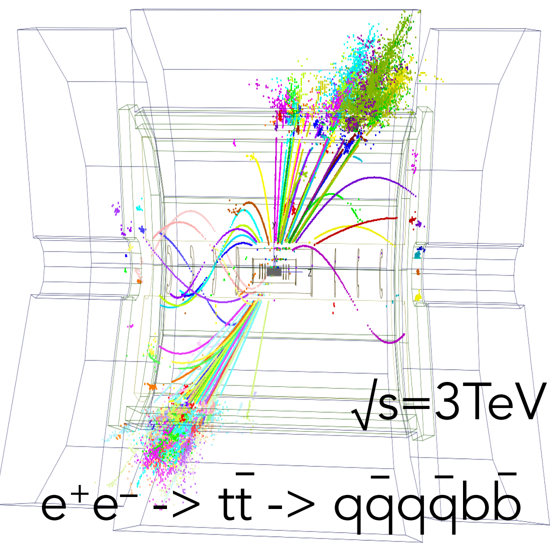
CLIC: What Do Higher Energies Buy You?

Material from A. Robson

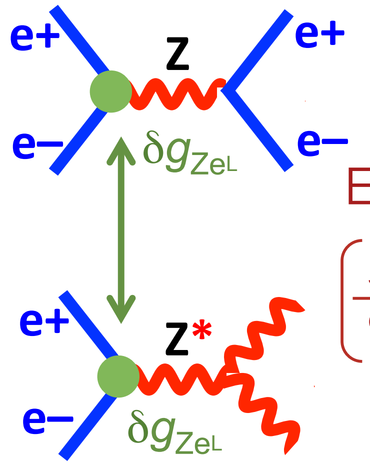
- Precision Higgs physics:
  - Increases VBF single-Higgs production
  - Adds ttH and HH production
  - Allows precise measurement of g_{HHH}
- Precision top-quark physics:
  - Cross-sections, asymmetries and optimal observables at all energies (necessary to disentangle effects), including boosted regime, study of ttH
- Precision two-fermion and multi-boson measurements
- BSM physics reach via precision measurements:

- Can probe CP-odd component of ttH coupling to $0.02<\Delta\sin^2\phi<0.08$ for full range of $\sin^2\phi$

First study of boosted top production in e^+e^-



At low energy ($\sqrt{s}=m_Z$)



At high energy ($\sqrt{s}$=3TeV)

Effect grows as s

$$\left(\frac{3000}{91.2}\right)^2 \sim 1000$$

Imagine measuring $\left.\frac{d\sigma}{\sigma_{SM}}\right|_{\sqrt{s}=m_Z} \sim 10^{-4} \Rightarrow \delta g_{ZeL} \sim 10^{-4}$

same precision!

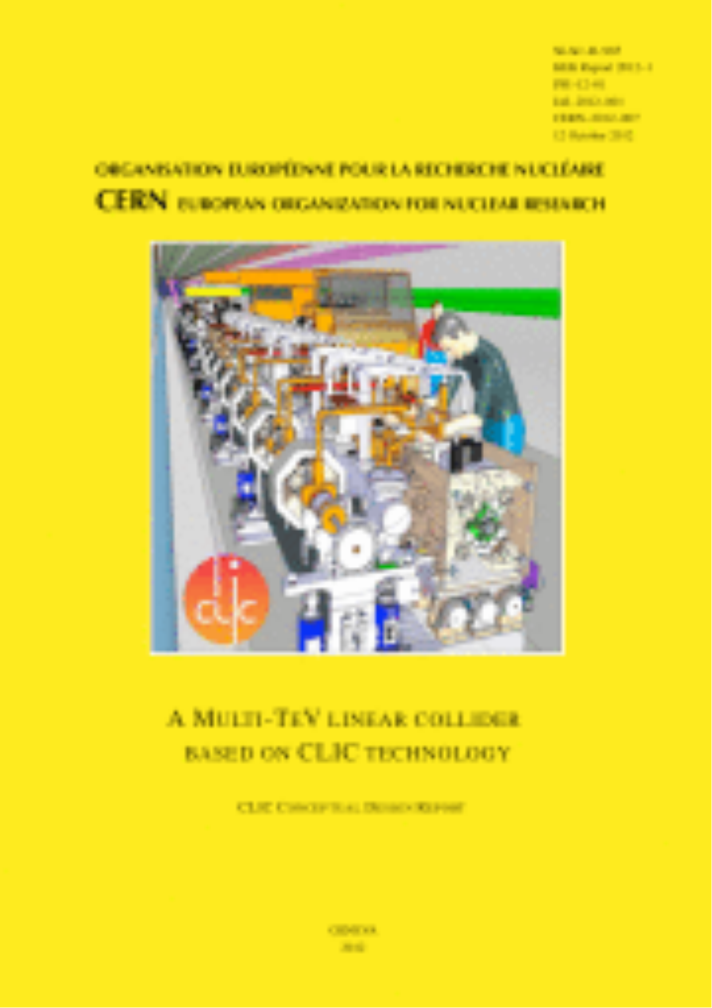
...equivalent to $\left.\frac{d\sigma}{\sigma_{SM}}\right|_{\sqrt{s}=3TeV} \sim 10\% \Rightarrow \delta g_{ZeL} \sim 10^{-4}$

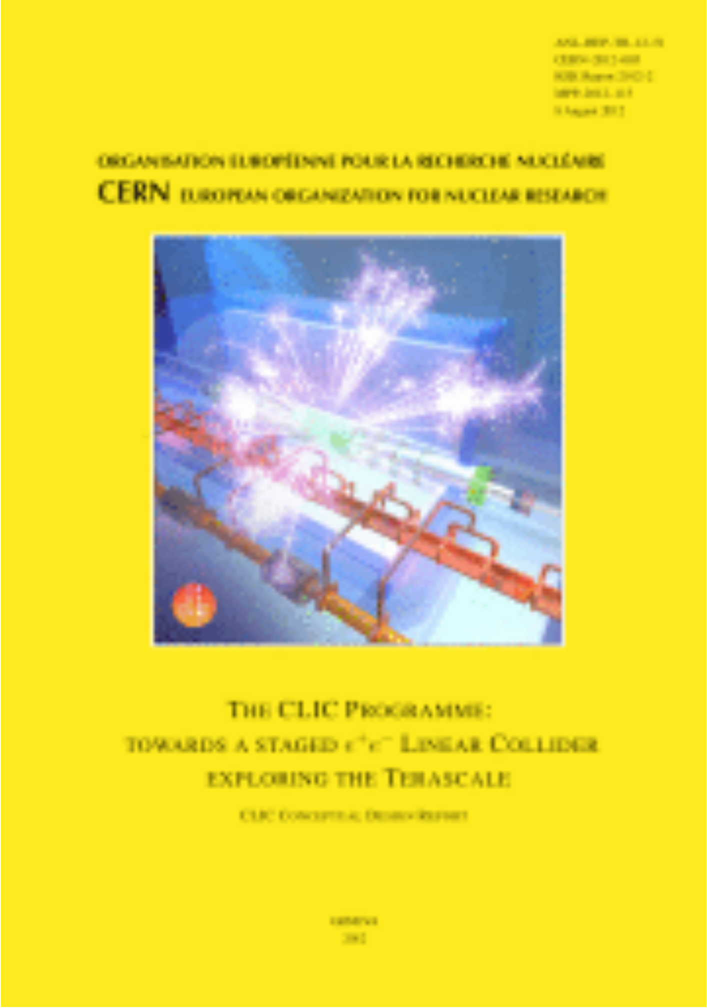
–> strongly benefit from high energies

Literature on CLIC

https://clic.cern

2012





2018

The CLIC Potential for New Physics

Editors: *J. de Blas* [1,2], *R. Franceschini* [3,4], *F. Riva* [5], *P. Roloff* [6], *U. Schnoor* [6], *M. Spannowsky* [7], *J. D. Wells* [8], *A. Wulzer* [1,6,9] *and J. Zupan* [10]

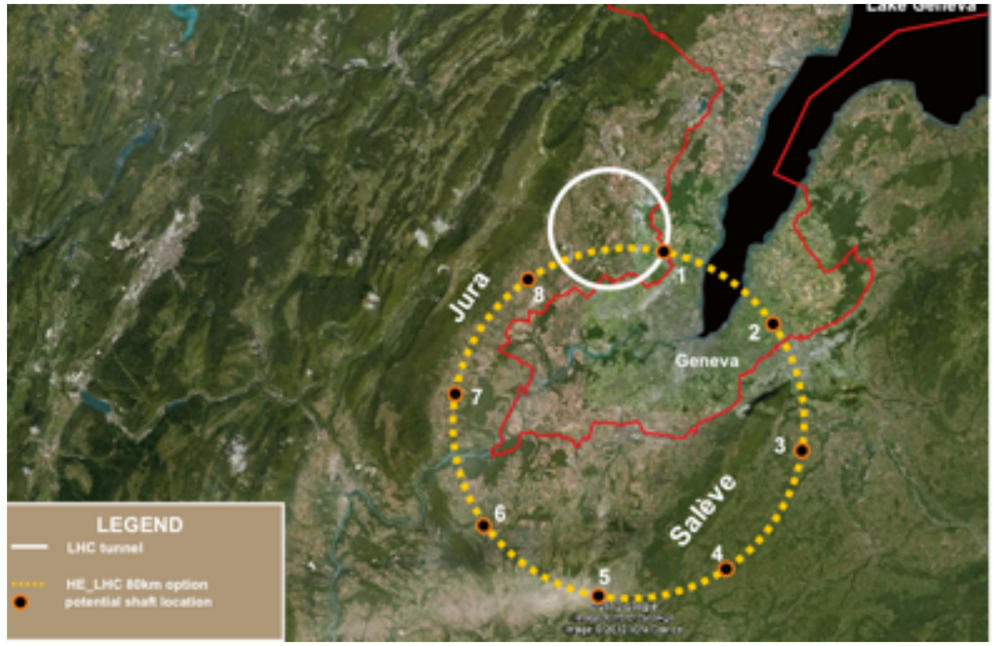
arXiv:1812.02093

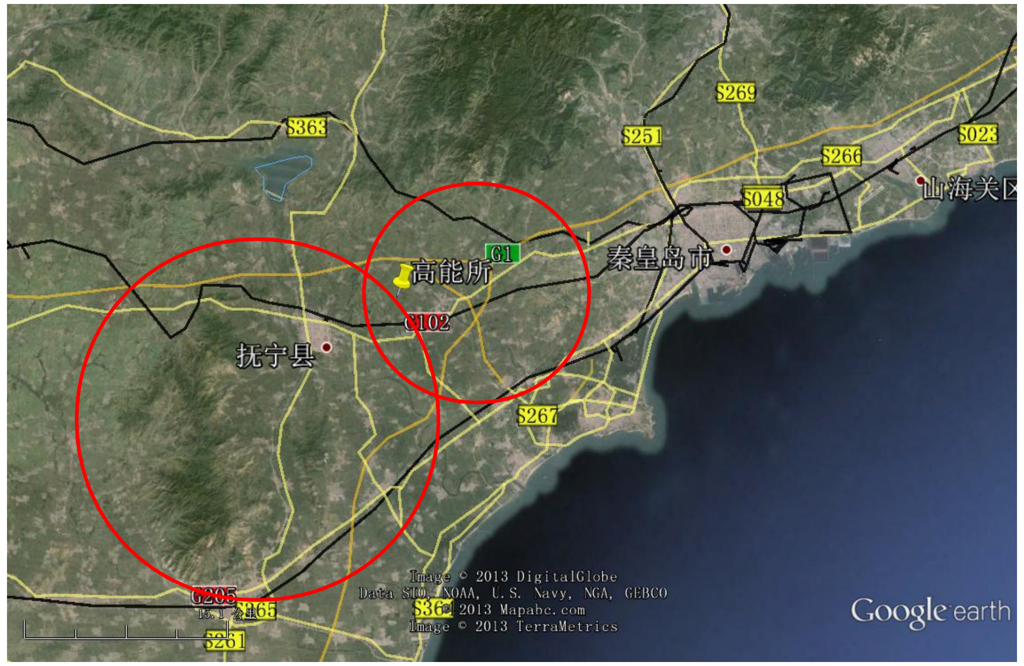
THE COMPACT LINEAR COLLIDER (CLIC) 2018 SUMMARY REPORT

arXiv:1812.06018

FCC-ee (x=post HL-LHC - x+20)/CEPC (2030??-2040??)

90/240/350/(500) - O(10/ab)





FCC-ee (x=post HL-LHC - x+20)/CEPC (2030??-2040??)

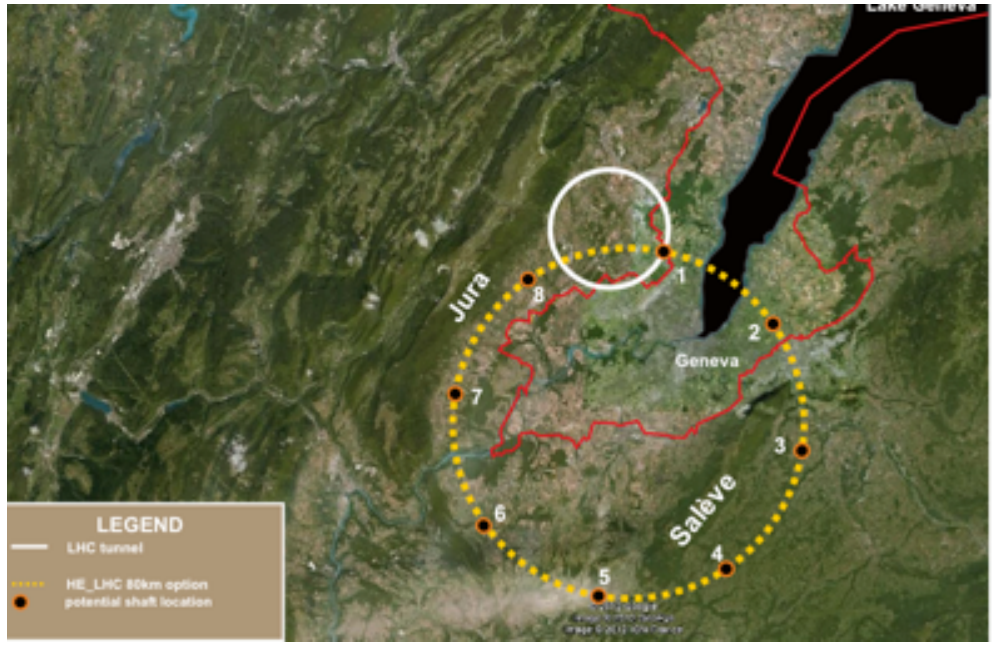
90/240/350/(500) - O(10/ab)

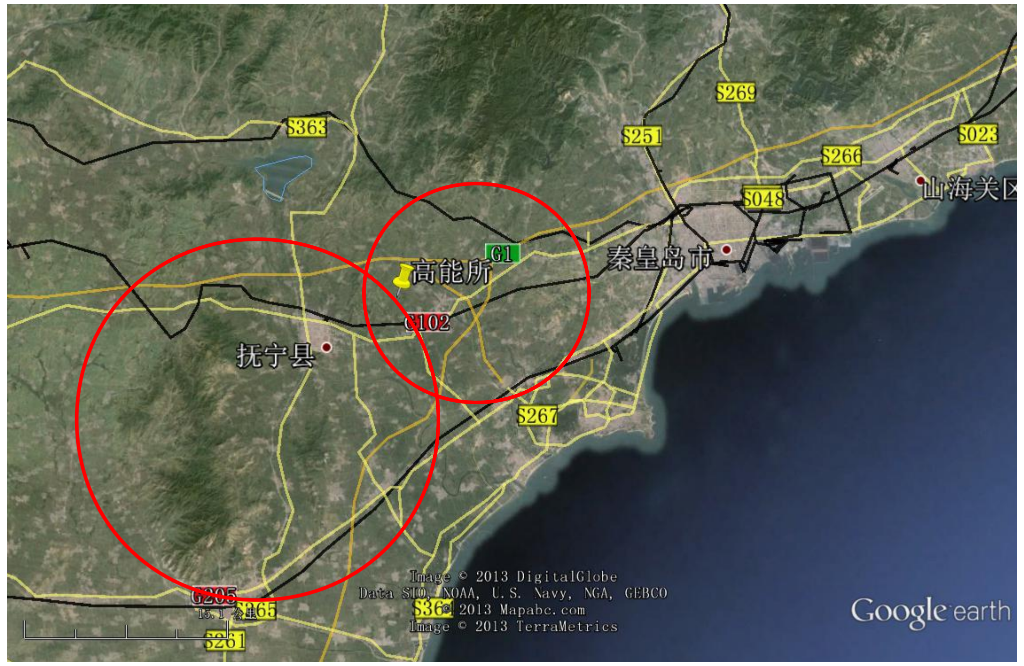
parameter	FCC-ee			CEPC	LEP2
energy/beam [GeV]	45	120	175	120	105
bunches/beam	13000-60000	500-1400	51- 98	50	4
beam current [mA]	1450	30	6.6	16.6	3
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	21 - 280	5 - 11	1.5 - 2.6	2.0	0.0012
energy loss/turn [GeV]	0.03	1.67	7.55	3.1	3.34
synchrotron power [MW]	100			103	22
RF voltage [GV]	0.2-2.5	3.6-5.5	11	6.9	3.5

FCC-ee run	Z pole	WW threshold	HZ	$t\bar{t}$ threshold	Above $t\bar{t}$ threshold
$\sqrt{s}$ [GeV]	90	160	240	350	> 350
$\mathcal{L}$ [ab^{-1}/year]	88	15	3.5	1.0	1.0
Years of operation	0.3 / 2.5	1	3	0.5	3
Events	$10^{12}/10^{13}$	10^{8}	2×10^{6}	2.1×10^{5}	7.5×10^{4}

FCC-ee (x=post HL-LHC - x+20)/CEPC (2030??-2040??)

90/240/350/(500) - O(10/ab)



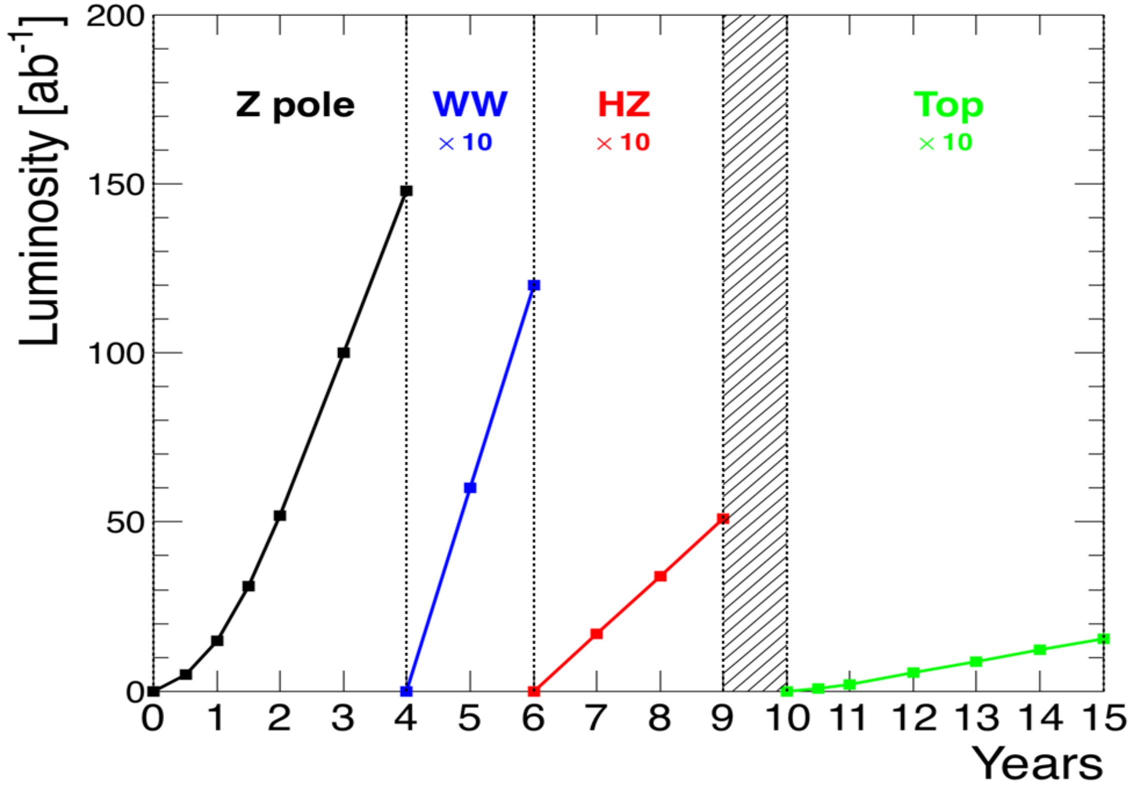


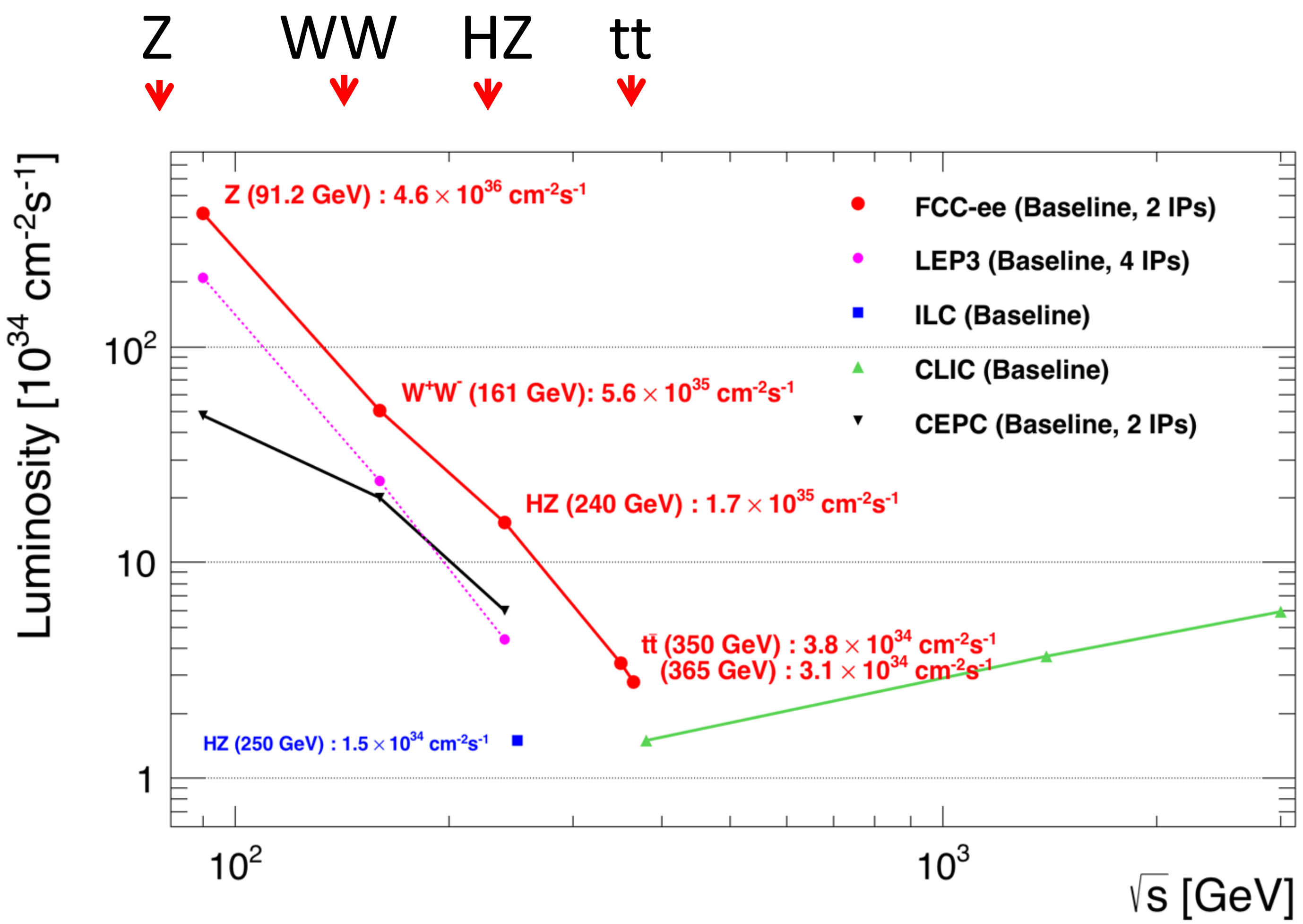
@FCC-ee

- 10^6 H
- 10^{12} Z possible upgrade to 10^{13} Z (line-shape, mass & width, probe rare (FCNC) decays)
- 10^8 W (mass)
- 3×10^{10} tau/muon pairs
- 2×10^{11} b/c quarks ⇒ >20'000 $B_s \to \tau^+\tau^-$
- TLEP@340/500: 10^6 top pairs (pole mass, probe FCNC decays, top Yukawa)

FCC-ee Run Plan

Material from A. Blondel, P. Janot et al.





Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})
FCC-ee-Z	4	88-95	150
FCC-ee-W	2	158-162	12
FCC-ee-H	3	240	5
FCC-ee-tt	5	345-365	1.5

Event statistics :

				E_{CM} errors:
Z peak	E_{cm} : 91 GeV	$5\ 10^{12}$	e+e- → Z	LEP x 10^5	100 keV
WW threshold	E_{cm} : 161 GeV	10^8	e+e- → WW	LEP x 2.10^3	300 keV
ZH threshold	E_{cm} : 240 GeV	10^6	e+e- → ZH	Never done	1 MeV
$t\bar{t}$ threshold	E_{cm} : 350 GeV	10^6	e+e- → $t\bar{t}$	Never done	2 MeV

Great energy range for the heavy particles of the Standard Model.

CEPC Run Plan

Material from J. Guimarães da Costa, L.T. Wang et al.

Particle type	Energy (c.m.) (GeV)	Luminosity per IP (10^{34} cm^{-2}s^{-1})	Luminosity per year (ab^{-1}, 2 IPs)	Years	Total luminosity (ab^{-1}, 2 IPs)	Total number of particles
H	240	3	0.8	**7**	5.6	1×10^6
Z	91	32	8	**2**	16	7×10^{11}
W	160	10	2.6	**1**	2.6	8×10^6

CEPC yearly run time assumption:

- Operation – 8 months, or 250 days, or 6,000 hrs
- Physics (60%) – 5 months, or 150 days, or **3,600 hrs**, or 1.3 Snowmass Unit.

No run above 240/250 GeV planned for the moment

Literature on FCCee/CEPC

2013-2015

- physics case: JHEP01(2014)164 arXiv:1308.6176

JHEP — Published for SISSA by Springer

Received: September 23, 2013
Accepted: December 25, 2013
Published: January 29, 2014

First look at the physics case of TLEP

The FCC and CepC are essentially equivalent proposals with different emphasis; FCC – hadrons via e+e-, CepC – e+e- then hadrons

Mike Harrison , SPC meeting Sept. 2015

pre-CDR:

IHEP-CEPC-DR-2015-01
IHEP-EP-2015-01
IHEP-TH-2015-01

CEPC-SPPC

Preliminary Conceptual Design Report

Volume I - Physics & Detector

The CEPC-SPPC Study Group

March 2015

IHEP-CEPC-DR-2015-01
IHEP-AC-2015-01

CEPC-SPPC

Preliminary Conceptual Design Report

Volume II - Accelerator

The CEPC-SPPC Study Group

March 2015

2018-2019

arXiv:1906.02693

FCC-ee: Your Questions Answered

Contribution to the European Particle Physics Strategy Update 2018-2020

IHEP-CEPC-DR-2018-02
IHEP-EP-2018-01
IHEP-TH-2018-01

CEPC

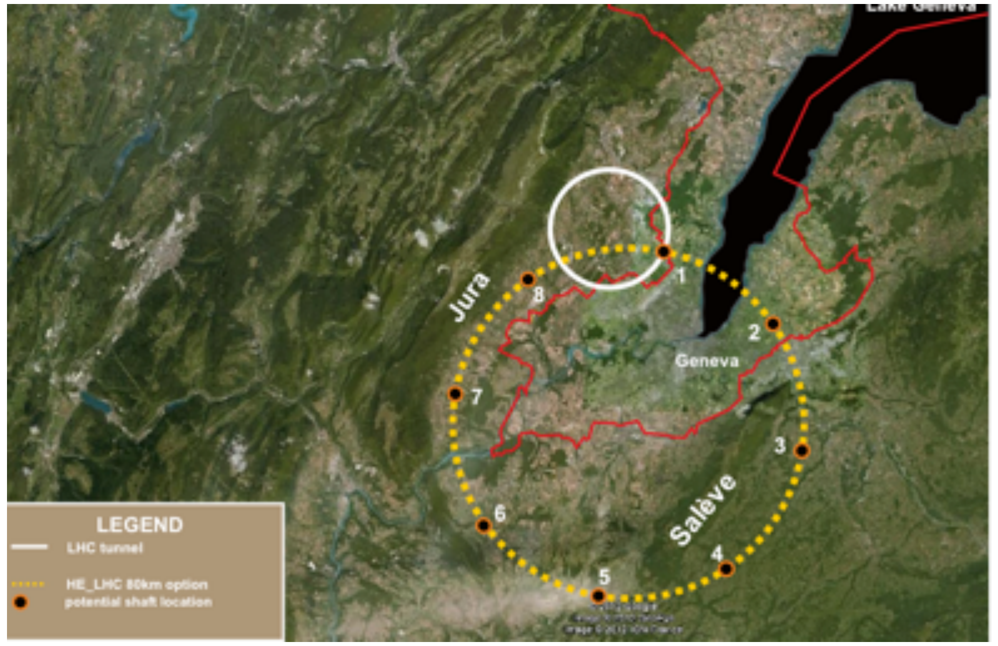
Conceptual Design Report

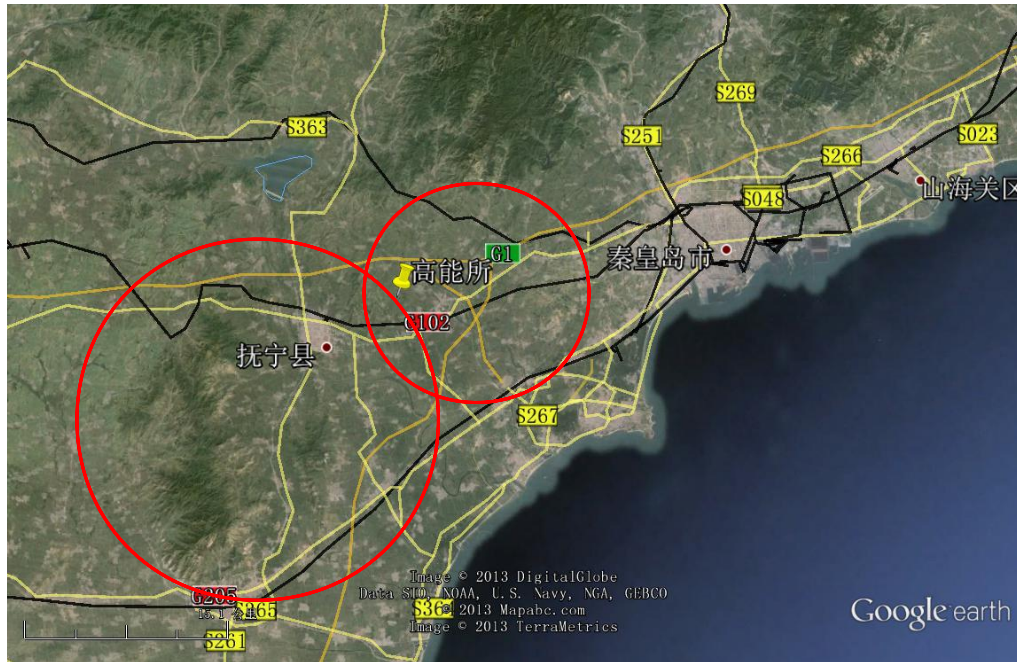
Volume II - Physics & Detector

The CEPC Study Group
October 2018

FCC-hh (2055-2075??)/SppC (??-??)

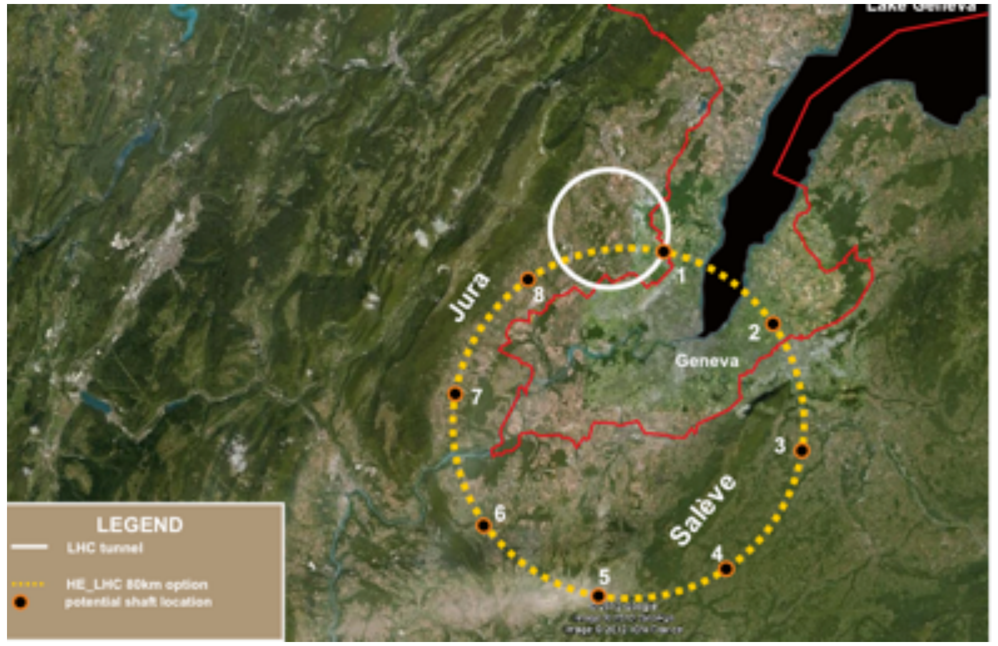
80/100 TeV - 20/ab

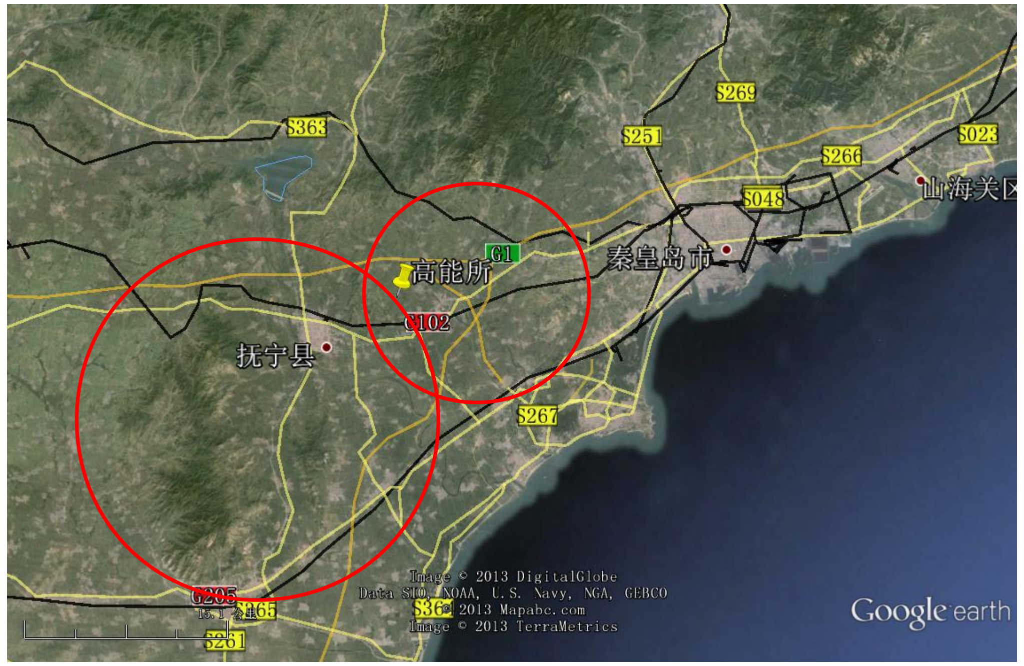




FCC-hh (2055-2075??)/SppC (??-??)

80/100 TeV - 20/ab





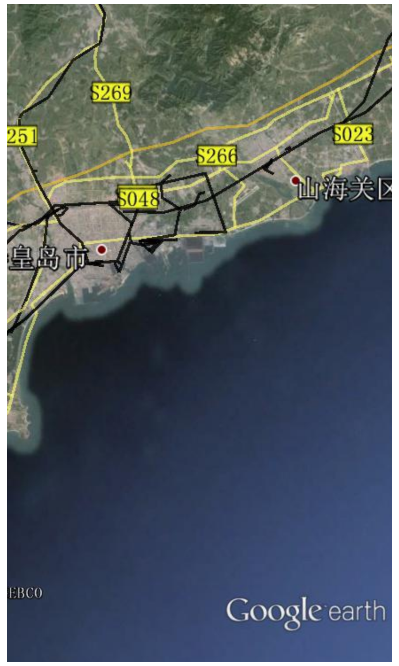
Parameter	FCC-hh		SPPC	LHC	HL LHC
collision energy cms [TeV]	100		71.2	14	
dipole field [T]	16		20	8.3	
# IP	2 main & 2		2	2 main & 2	
bunch intensity [10^{11}]	1	1 (0.2)	2	1.1	2.2
bunch spacing [ns]	25	25 (5)	25	25	25
luminosity/Ip [10^{34} $cm^{-2}s^{-1}$]	5	25	12	1	5
events/bx	170	850 (170)	400	27	135
stored energy/beam [GJ]	8.4		6.6	0.36	0.7
synchr. rad. [W/m/apert.]	30		58	0.2	0.35

FCC-hh (2055-2075??)/SppC (??-??)

Physics at the FCC-hh

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

- **Volume 1: SM processes** (238 pages) arXiv:1607.01831
- **Volume 2: Higgs and EW symmetry breaking studies** (175 pages) arXiv:1606.09408
- **Volume 3: beyond the Standard Model phenomena** (189 pages) arXiv:1606.00947
- **Volume 4: physics with heavy ions** (56 pages) arXiv:1605.01389
- **Volume 5: physics opportunities with the FCC-hh injectors** (14 pages)



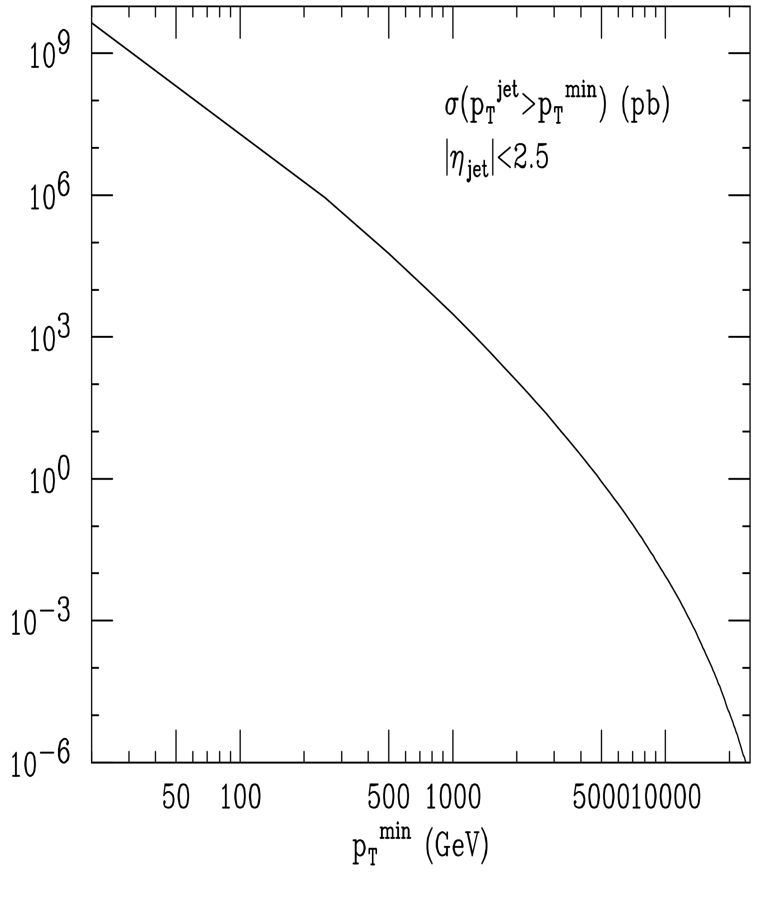
Parameter	FCC-hh		SPPC	LHC	HL LHC
collision energy cms [TeV]	100		71.2	14	
dipole field [T]	16		20	8.3	
# IP	2 main & 2		2	2 main & 2	
bunch intensity [10^{11}]	1	1 (0.2)	2	1.1	2.2
bunch spacing [ns]	25	25 (5)	25	25	25
luminosity/lp [10^{34} $cm^{-2}s^{-1}$]	5	25	12	1	5
events/bx	170	850 (170)	400	27	135
stored energy/beam [GJ]	8.4		6.6	0.36	0.7
synchr. rad. [W/m/apert.]	30		58	0.2	0.35

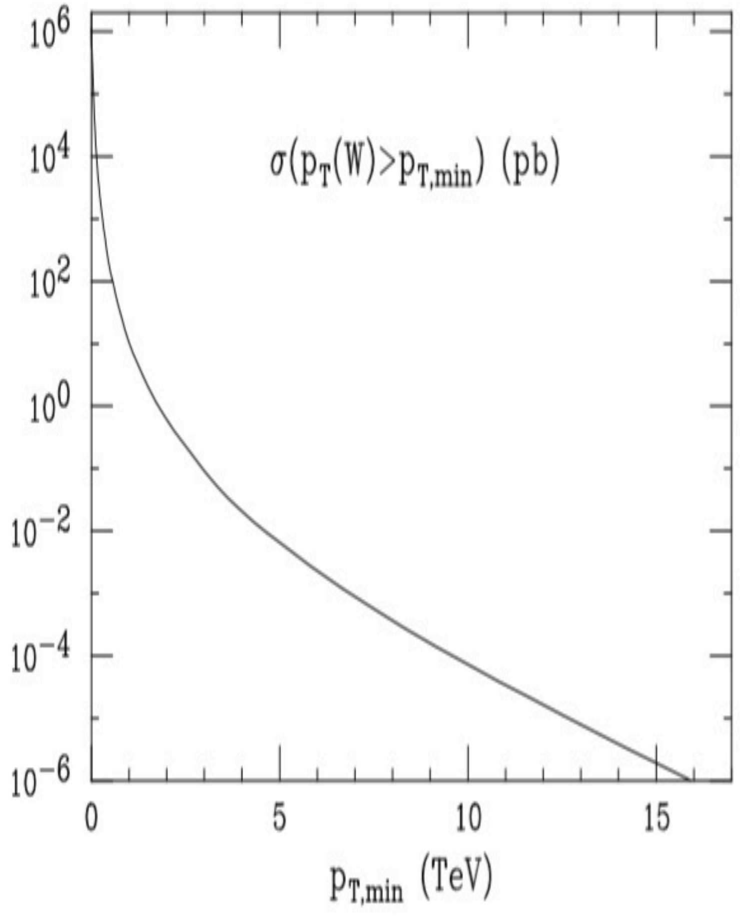
FCC-hh/SppC

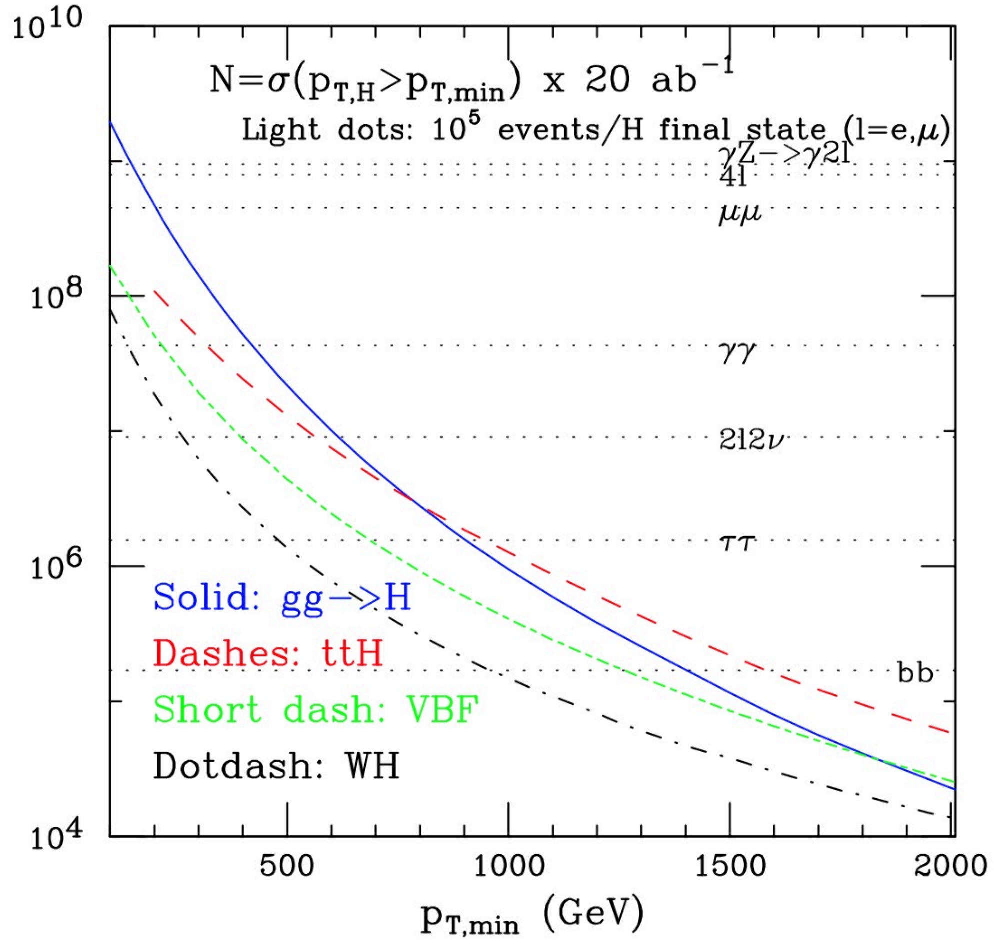
80/100 TeV - O(20/ab)

@FCC-hh

- 10^5 jet with p_T>10TeV
- 10^{11} Z in DY
- 10^{12} W in DY
- 10^{10} H in gg, 10^9 H in VBF, vH, ttH
- 10^{12} top pairs (rare/forbidden top decays, inclusive W decays triggerable by the other W)







FCC-hh/SppC

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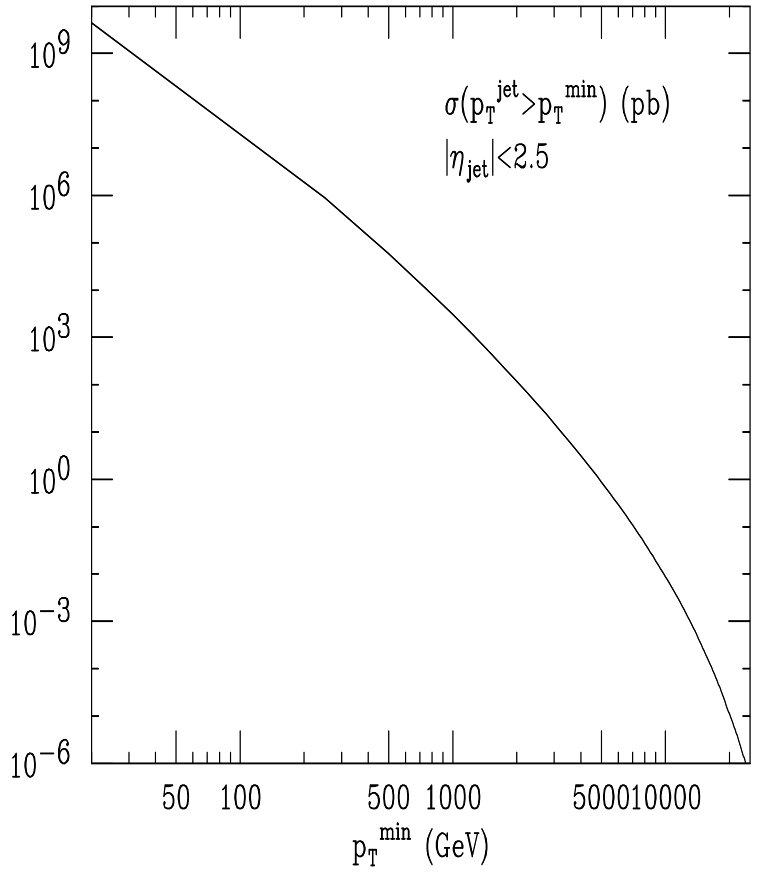
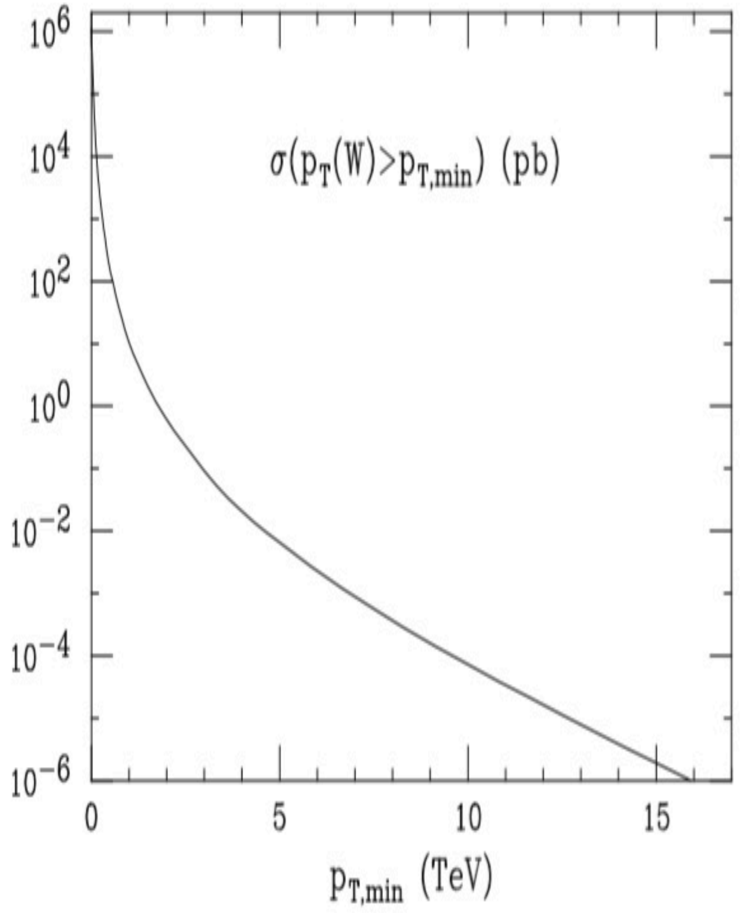
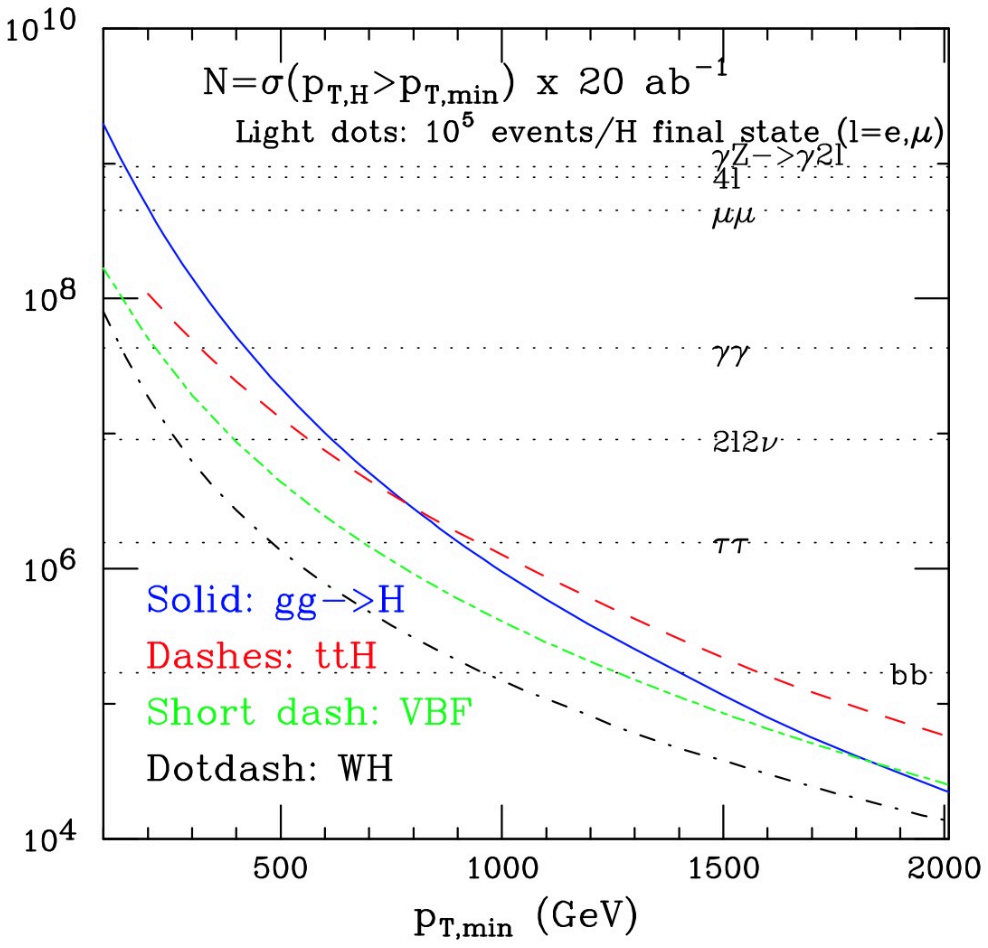
Event rates higher than what ee colliders can provide are needed to reach sub-% measurements of couplings such as Hγγ, Hμμ, HZγ, Htt



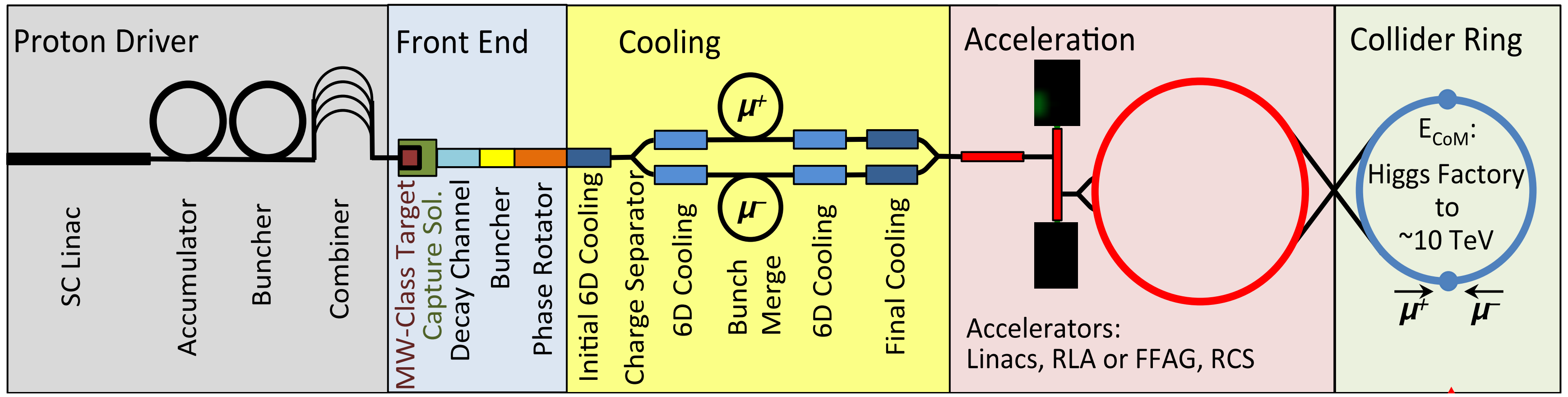




μ-collider aka project X (TBD: ?-?)

Input to ESU arXiv:1901.06150

125/1’000/15’000 GeV - O(1-100)/ab



M. Palmer, CERN '15

Physics Frontiers

- **Intense and cold muon beams ⇨ unique physics reach**
  - Tests of Lepton Flavor Violation
  - Anomalous Magnetic Moment (g-2)
  - Precision sources of neutrinos
  - Next generation lepton collider

$m_\mu = 105.7\, MeV/c^2$

$\tau_\mu = 2.2\,\mu s$

Colliders

- **Opportunities**
  - s-channel production of scalar objects
  - Strong coupling to particles like the Higgs
  - Reduced synchrotron radiation ⇨ multi-pass acceleration feasible
  - Beams can be produced with small energy spread
  - Beamstrahlung effects suppressed at IP
- ***BUT*** **accelerator complex/detector must be able to handle the impacts of μ decay**

$\triangleleft \left(\frac{m_\mu^2}{m_e^2}\right) \cong 4 \times 10^4$

Collider Synergies

- High intensity beams required for a long-baseline Neutrino Factory are readily provided in conjunction with a Muon Collider Front End
- Such overlaps offer unique staging strategies to guarantee physics output while developing a muon accelerator complex capable of supporting collider operations

$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

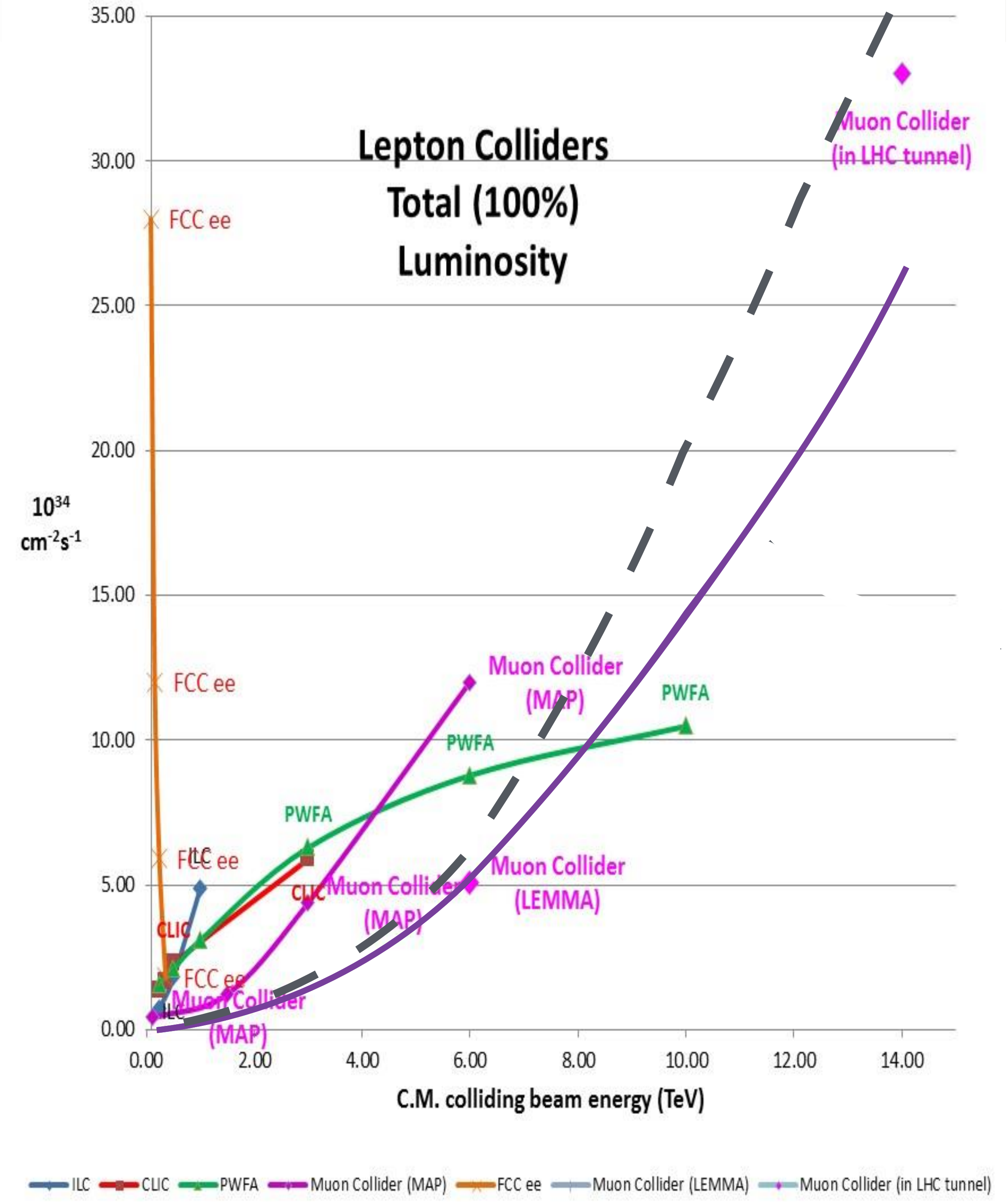
$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$

μ-collider in brief

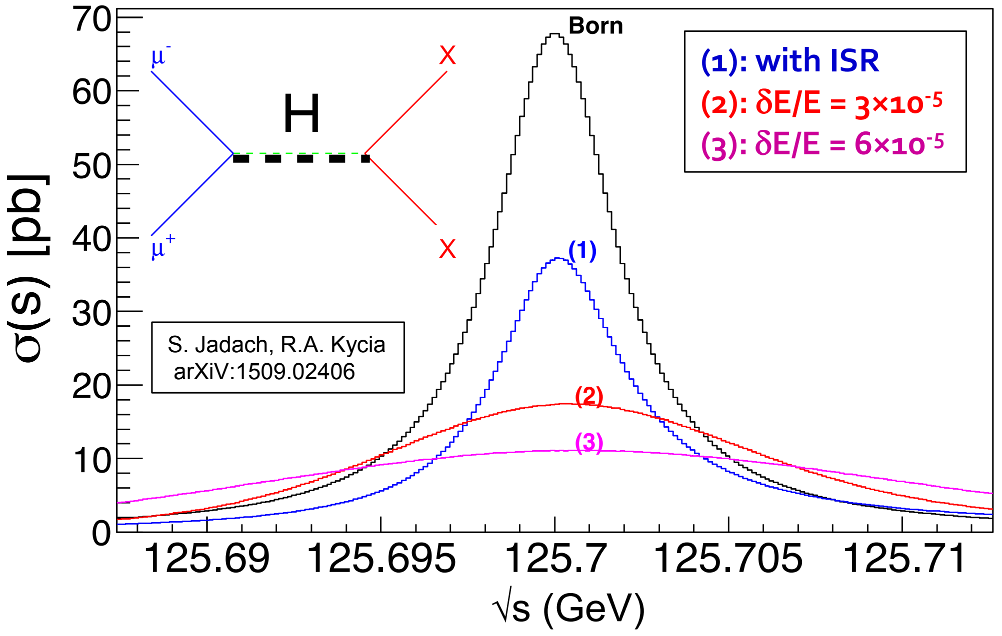
Material from A. Wulzer

No definite plan yet

Two milestones: 1) s-channel Higgs production and 2) highest energy possible



1)



μ-collider in brief

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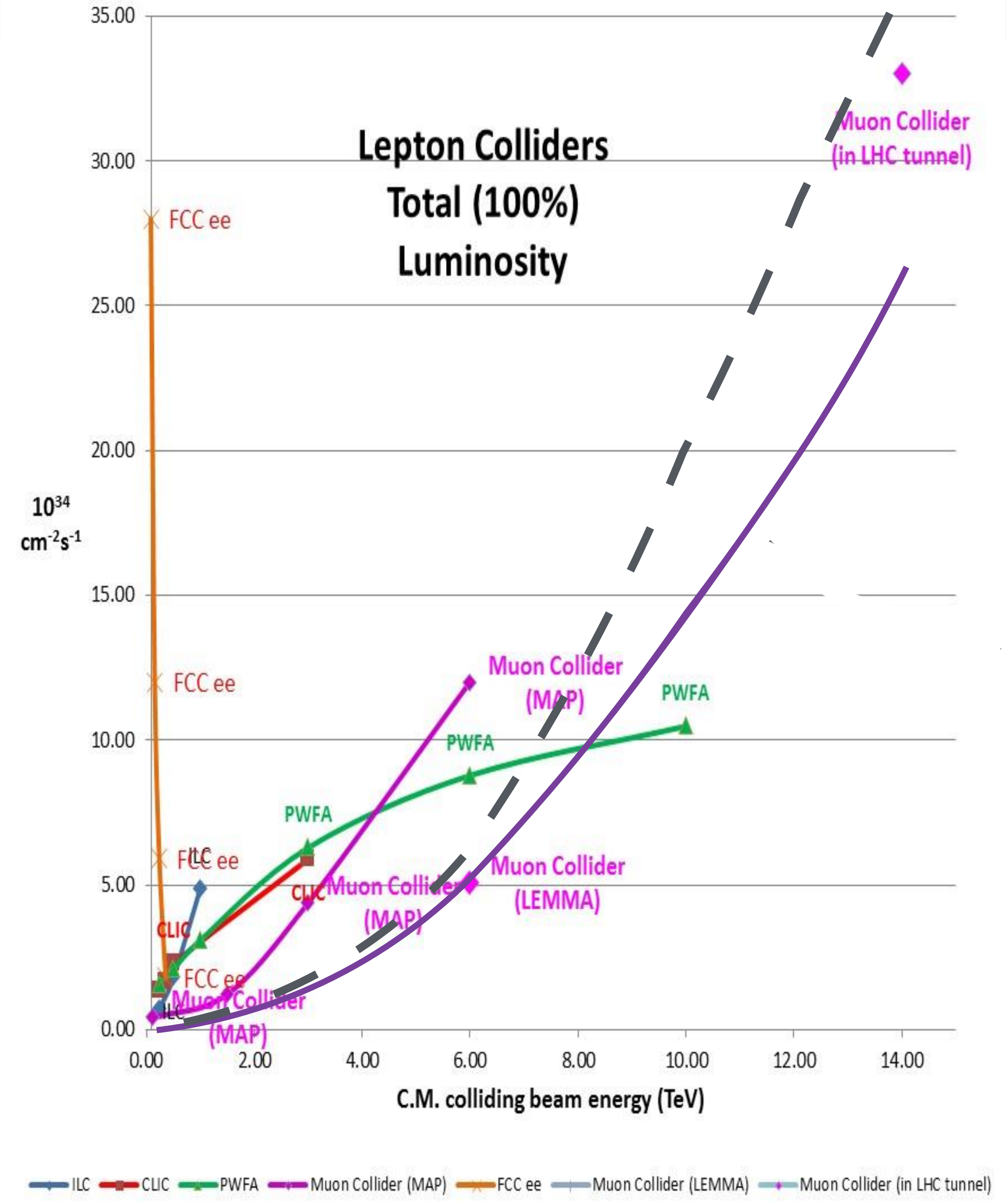

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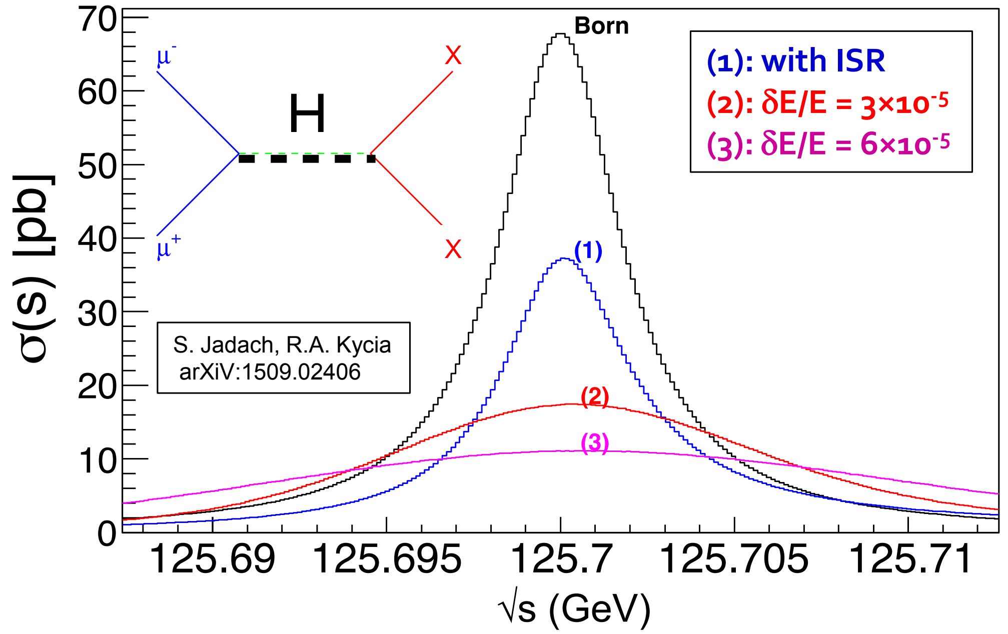
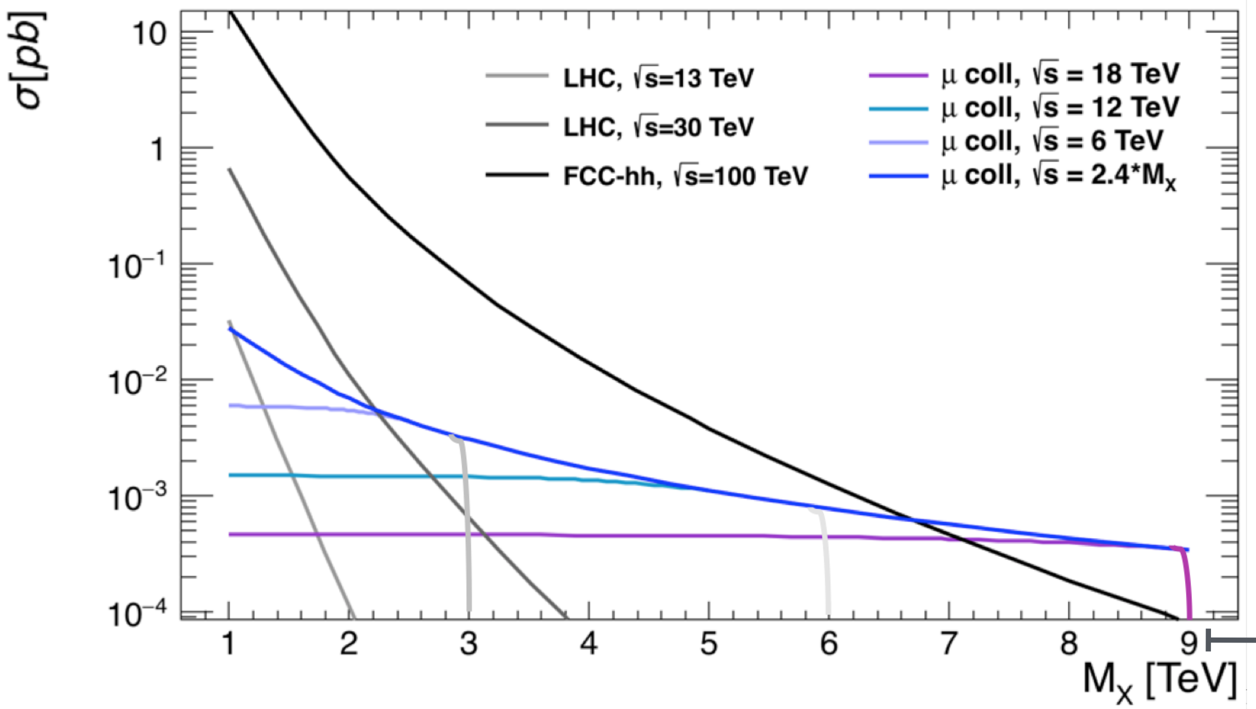


2)

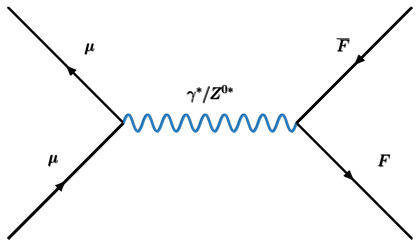
Fermionic top partners in Composite Higgs:



Estimated reach of the FCC-hh

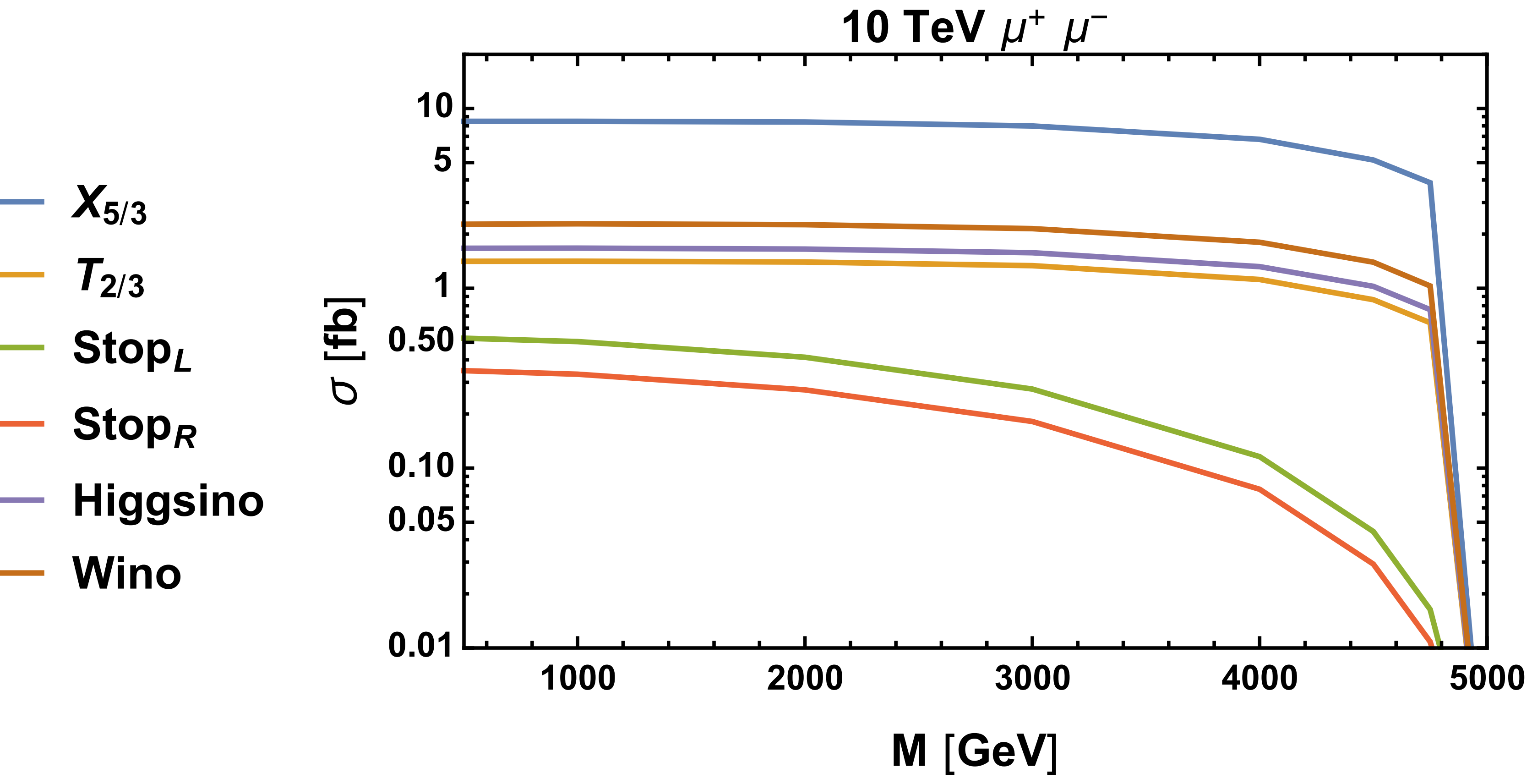
μ-collider in brief

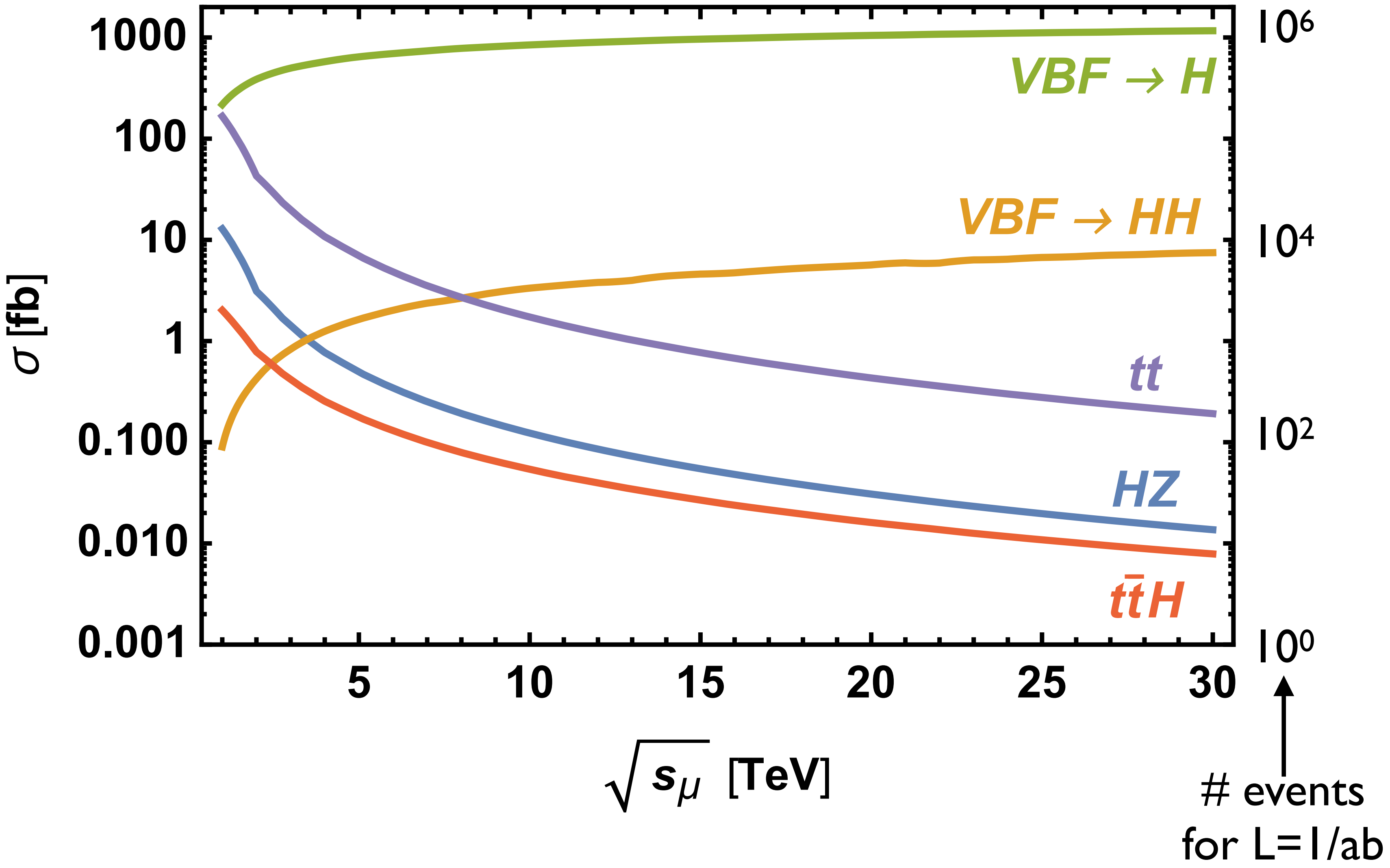
Input to ESU arXiv:1901.06150



up to $m_F < \sqrt{s}/2$

$$\sigma \sim \left(\frac{10\,\mathrm{TeV}}{\sqrt{s_{\mu\mu}}}\right)^2 \cdot 1\,\mathrm{fb}$$





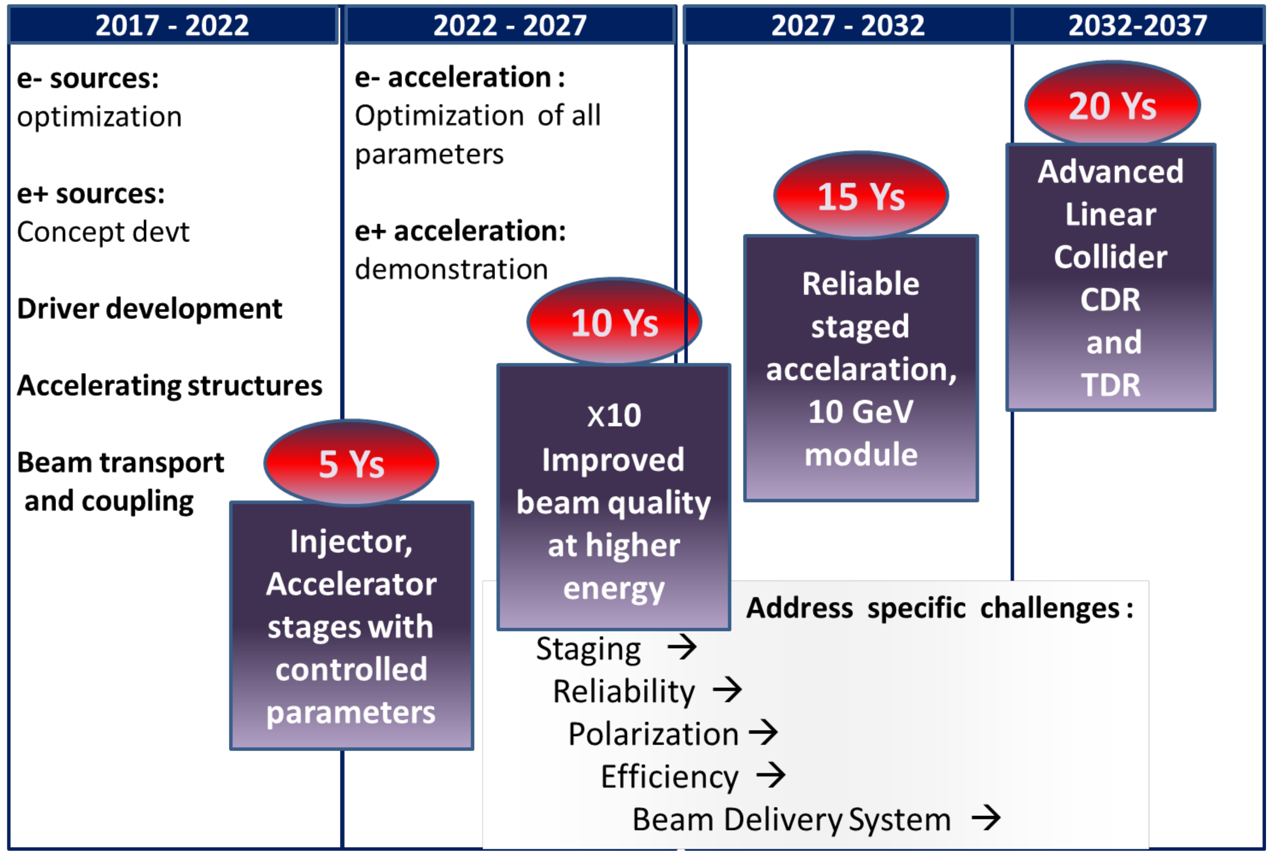
Alegro/Advanced Linear Collider (ALIC)

Input to ESU arXiv:1901.00370

No definite plan yet

R&D for new accelerating techniques (laser or plasma wakefield)

ee and γγ colliders from 100 GeV to 100 TeV



could be done at CepC, FCCee, ILC, CLIC

1. High-precision study of the Z resonance and high-precision measurement of the W mass, resolving current tensions among the precision electroweak measurements and testing the SM at the 10^{-4} level.
2. Model-independent measurement of the Higgs boson couplings to 1% precision. This accesses deviations from SM model predictions at the level at which effects of beyond-SM interactions would be visible.
3. Search for invisible or exotic decays of the Higgs boson to the parts-per-mil level of branching fraction.
4. Measurement of the top quark electroweak form factors to parts per mil precision. This accesses deviations from SM model predictions at the level at which effects of beyond-SM interactions would be visible.
5. Search for invisible particles pair-produced in e^-/e^+ collisions. An important objective is the pure Higgsino dark matter candidate, which would have a mass of 1 TeV.
6. Search for additional electroweak gauge bosons and signals of lepton and quark compositeness. A 3 TeV e^-/e^+ collider would be sensitive to new bosons at 15 TeV and compositeness scales of 60-80 TeV, far beyond the LHC capabilities.

need multi-TeV collider

7. Search for pair-production of any new particles with multi-TeV masses that couple to the electroweak interactions.
8. Search for "thermalization" of Higgs boson production, the production of events with hundreds of W, Z, and Higgs bosons at center of mass energies above 10 TeV.
9. Exploration of the resonances of the new strong interactions associated with composite Higgs boson models. These resonances are expected to appear above 10 TeV in the center of mass.
10. Determination of the geometry of extra space dimensions from the systematics of observed Kaluza-Klein resonances. Given current constraints, e^-/e^+ or $\gamma\gamma$ experiments above 20 TeV would be needed to draw firm conclusions.
11. Characterization of leptoquark bosons proposed to explain suggested anomalies in flavor physics, or other new particles that could be involved in explaining the systematics of flavor interactions.