Workshop Nazionale INFN Acceleratori – 7 Aprile 2021

INFN-CSN1

Particle Physics with accelerators

Roberto Tenchini

INFN - Pisa

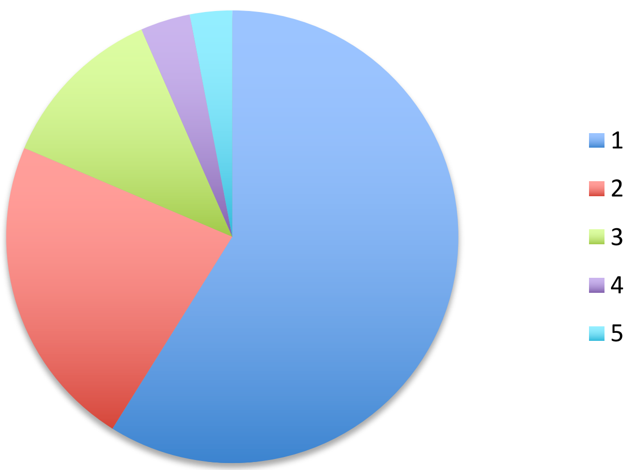
INFN ACCELERATORI GIORNATA ACCELERATORI

CSN1 and Accelerators

- **CSN1** deals with **particle physics experiments at accelerators**, therefore even if its task is not strictly related to the construction of new accelerators, **the availability of the right machines is a pre-requisite for carrying out CSN1 projects**.
- In this sense **CSN1 promotes**, in a broad sense, **physics and detector studies to motivate the R&D and the construction of the most appropriate machines to reach the energy and intensity frontiers.**

This presentation

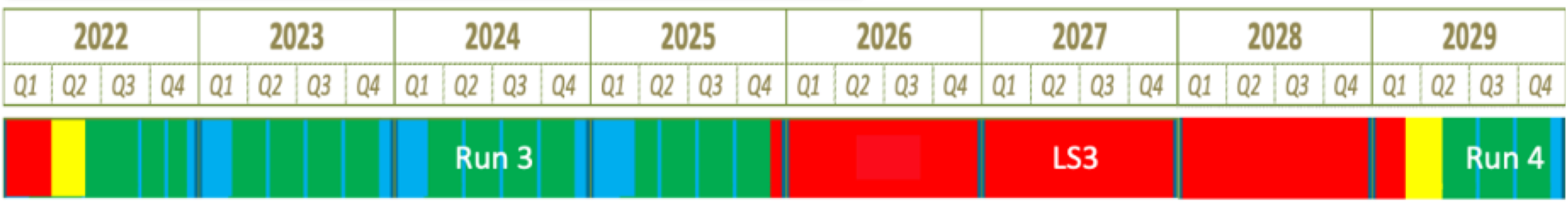
- LHC and its upgrades
- Other projects and accelerators
- Future accelerators



CSN1 Sectors, FTE and budget (%): year 2022

CSN1 Sector in 2022	FTE (%)	Budget (%)
Physics at hadron colliders (LHC)	58,90	58,89
Flavor Physics (with LHCb)	25,97	22,52
Charged Lepton Physics	9,20	12,01
Proton Structure	3,15	3,56
R&D for Future Accelerators	2,79	3,02

LHC getting ready for RUN 3



→ **LS3 (3 years) to cover 2026 – 2028**

- Run3 → Physics from June 2022 to Nov 2025
- 100 fb^{-1}/year ($1.8x10^{11}$ p/bunch) or 85 fb^{-1}/year ($1.4x10^{11}$ p/bunch)
- Final confirmation of Run 3 beam energy: **6.8 TeV**

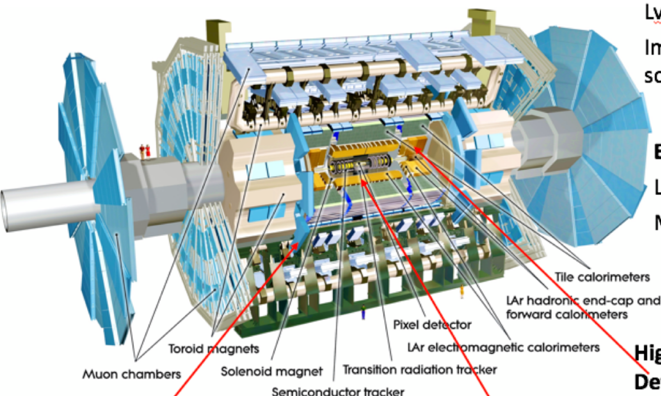
- **2029: start of HL-LHC (instead of mid 2027)**
- **2038: official end of HL-LHC (this is subject of discussions ...)**

HL-LHC – ATLAS and CMS Phase 2 upgrades
(a huge construction efforts by CSN1 experiments ...)

INFN FTE ATLAS+CMS: 207,3 + 245,2

ATLAS upgrade Phase 2

Core Budget: 19M€



Upgraded Trigger & DAQ

LvL0 Trigger at 1 MHz

Improved HLT (150 kHz full-scan tracking)

Electronics Upgrades

LAr & Tile Calorimeter

Muon system

High Granularity Timing Detector (HGTD)

Forward region ($2.4 < |\eta| < 4.0$)

Low-Gain Avalanche Detectors

(30 ps track resolution

New Inner Tracking Detector (ITk)

All silicon, up to $|\eta| = 4$

New Muon Chambers

Inner barrel region with new RPC and sMDT detectors

small upgrades

Lumi.detectors (1% precision goal) HL-ZDC

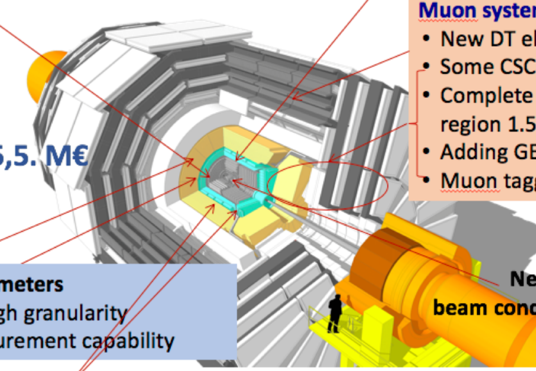
CMS upgrade Phase-2

New Tracker
- Rad. tolerant, high granularity and light
- 40 MHz selective readout for hardware trigger
- Extend coverage to $\eta \simeq 3.8$

Barrel Electromagnetic calorimete
- New electronics
- Lower operating temperature (8°)

Muon systems
- New DT electronics
- Some CSC electronics
- Complete RPC coverage in region $1.5 \lesssim \eta \lesssim 2.4$
- Adding GEM detectors
- Muon tagging $2.4 \lesssim \eta \lesssim 3$

Core Budget: 25,5. M€



New Endcap Calorimeters
- Rad. tolerant - high granularity
- 4D shower measurement capability

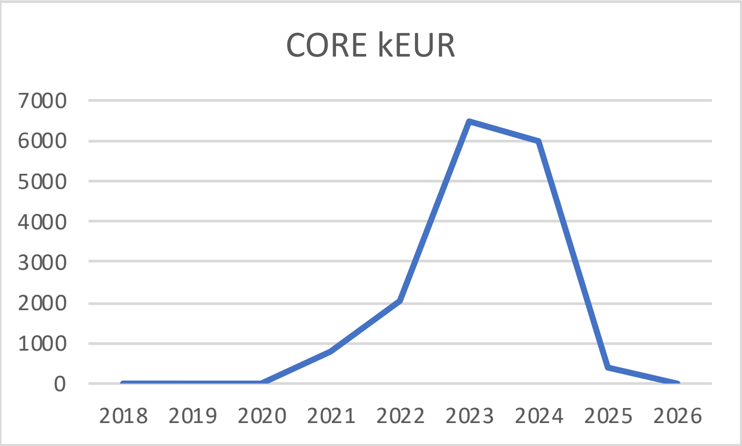
New Luminosity and beam conditions monitoring

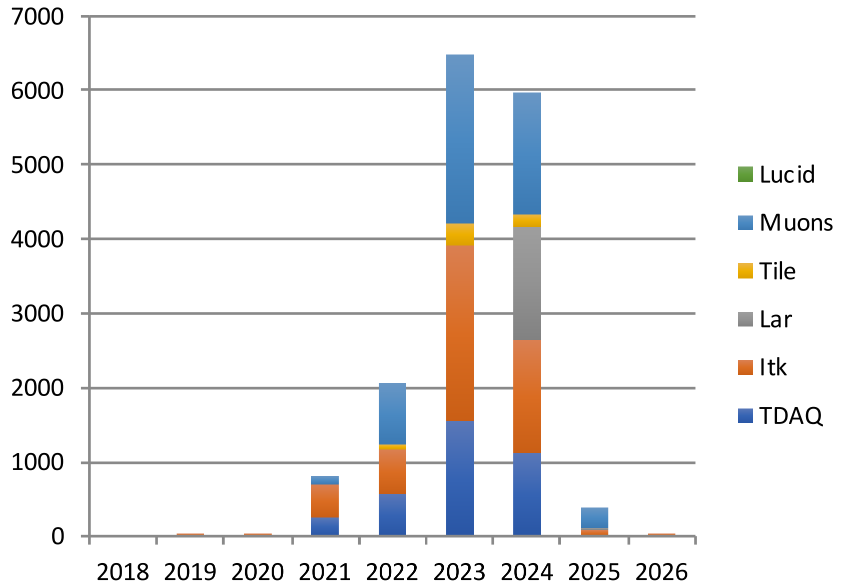
New detector for MIP timing measurement
- Barrel layer: Lyso Crystals
- Endcap layer: silicon LGADs

Trigger/DAQ
- Implement track information at 40 MHz
- Full readout at ≃ 750 kHz after 12.5 µs
- Register ≃ 7.5 kHz after computing selection

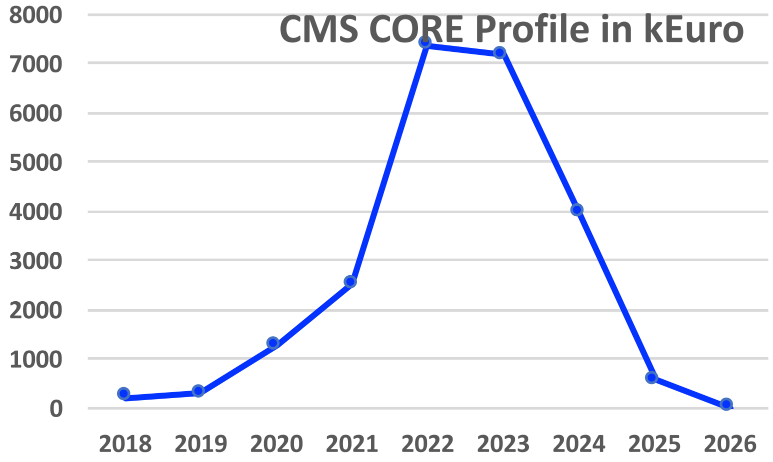
HL-LHC – ATLAS and CMS Phase 2 upgrades
(a huge financial effort by the experiments ... and CSN1)

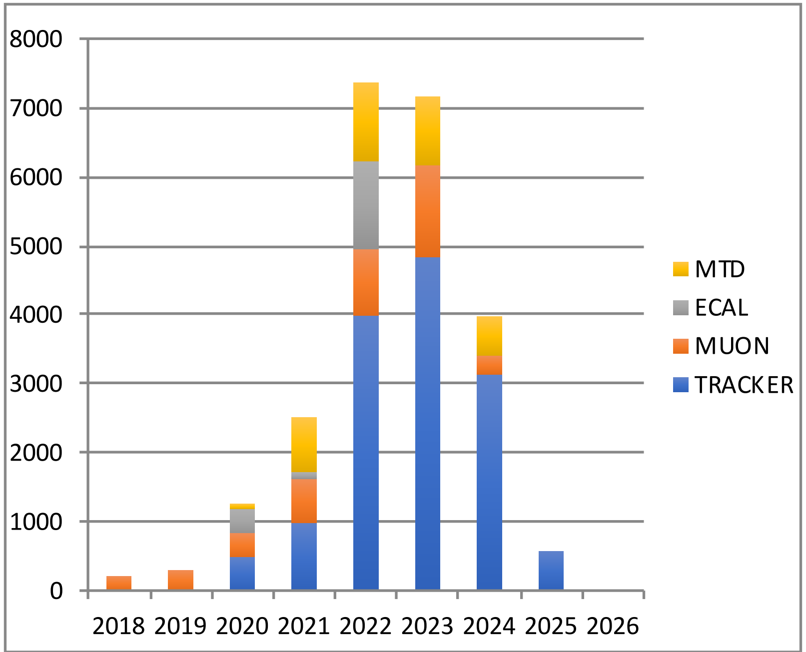
ATLAS





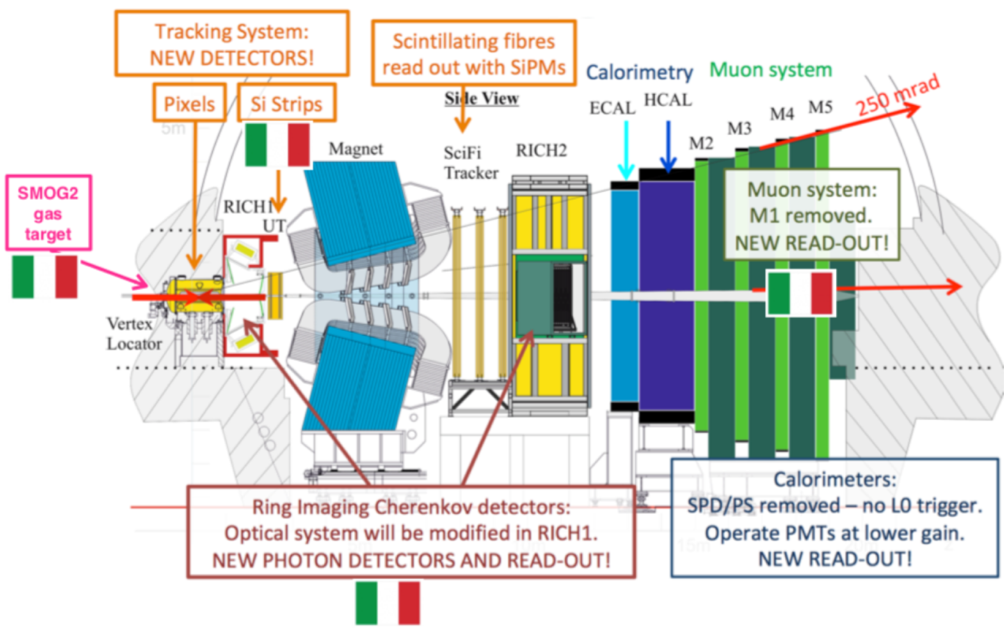
CMS





LHCb phase 1 upgrade (RUN 3): reach and goals

- INFN Core contribution to LHCb upgrade : 5.6 Meur
  - the new apparatus is designed to take data at a factor of 5 higher instantaneous luminosity
  - the trigger will work without level zero, with 2-3 times higher efficiency for hadron-based triggers
- The target is to collect 50 fb-1 in Run 3 compared to the 9 fb-1 of the Run1+2 current sample.
  - **uncertainty on the CKM γ angle should from the current 4 degrees to 1 degree**.
  - **uncertainty on the B_s to $\mu\mu$ branching ratio reaching 10%**
  - **uncertainty on b → s$\ell\ell$ lepton universality tests expected to decrease by a factor 3**

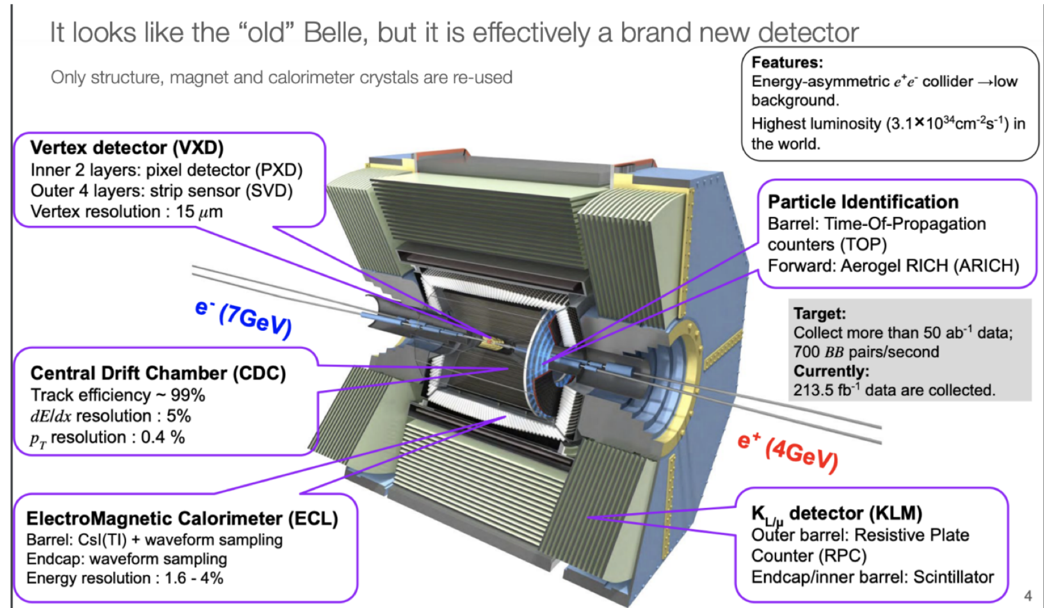


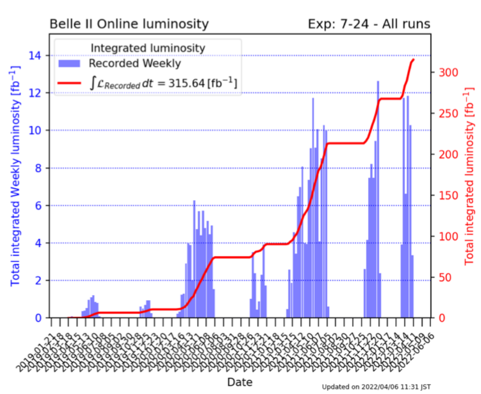
... and coming next: LHCb Upgrade 2 for Run-5

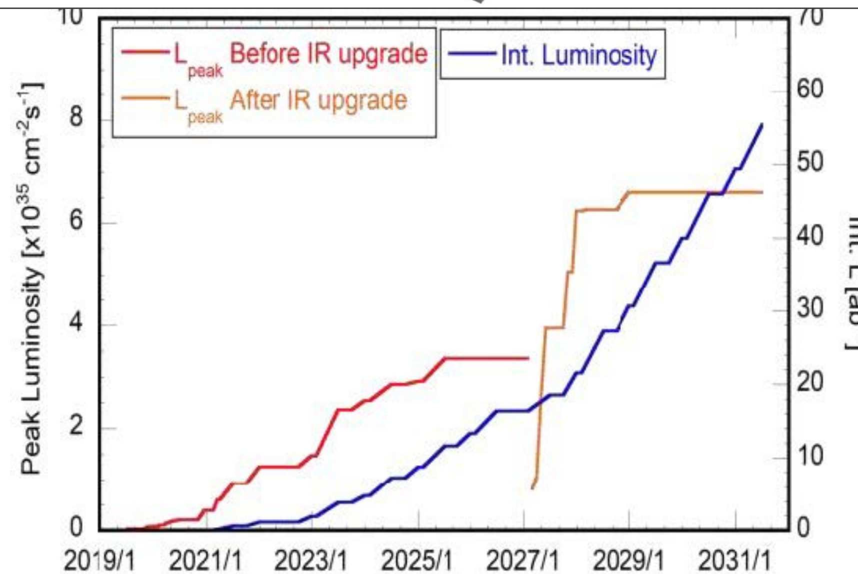
Belle II at SuperKEKB

INFN FTE: 49,5

- The integrated luminosity was more than doubled in 2021, with respect to the 2020 and 2019 runs, for <u>a total of 270 fb-1.</u>
- Restarted in 2022 with record luminosity 3.8 10^{34}
- Detectors of INFN responsibility (SVD, PID, ECL, KLM) performing well
- Operated remotely
- Some concern for beam losses: effort on monitoring and beam abort system
- First physics publications
- <u>Concerns about reaching the nominal performance with superKEKB</u>

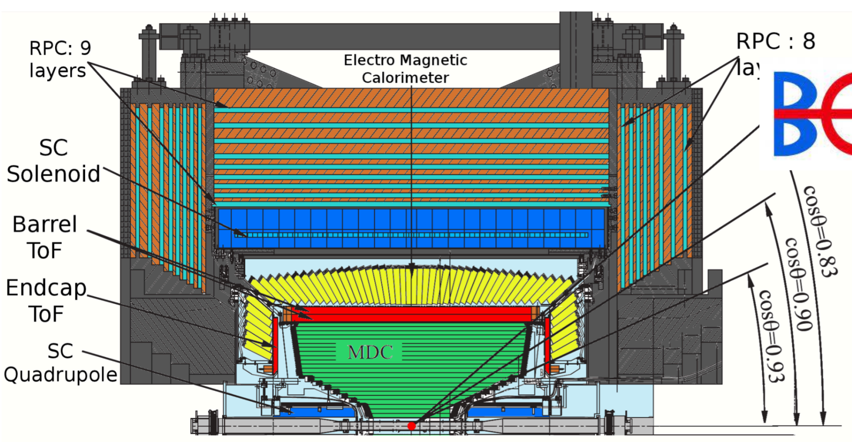




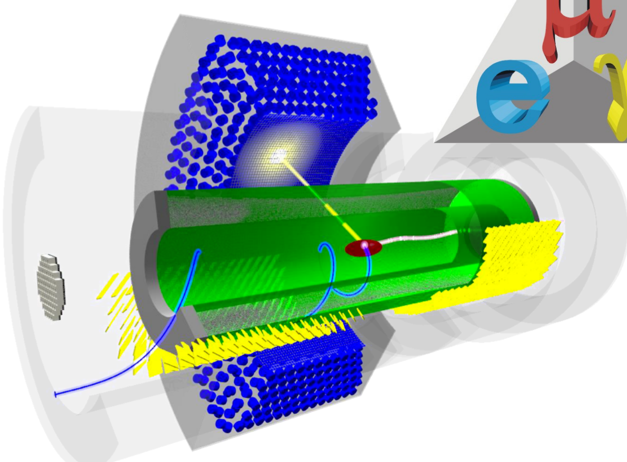


Other CSN1 interests/activities with accelerators

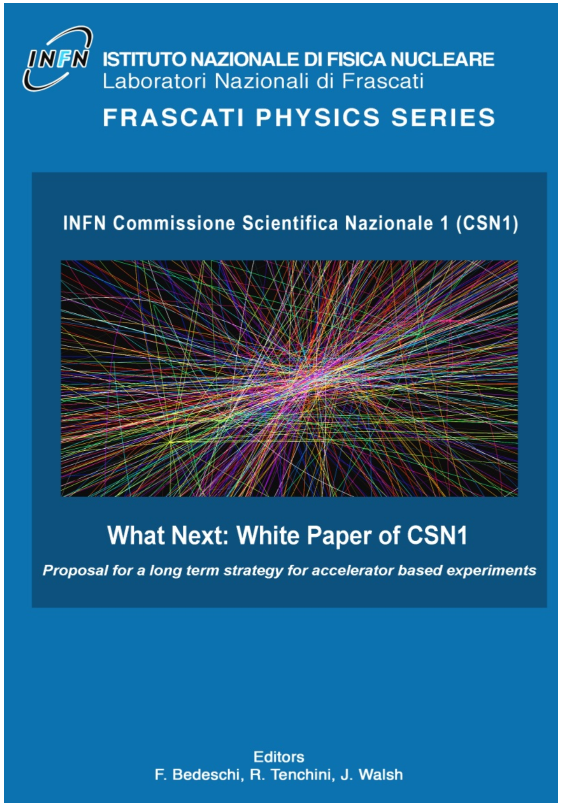
- Still significant activity with fixed target at the SPS (NA62, NA64, Compass, Amber, MUoNE) ≈ 75 FTE
- We are at Fermilab with g-2 and MU2E ≈ 40 FTE
- At PSI high intensity muon beam for MEGII
- At Beijing with BES III at BEPCII
- New proposal at DESY EU.XFEL (LUXE)
- PADME at LNF
- UA9 crystal activities at CERN



BESIII



CSN1 and future colliders at the frontier of energy and intensity

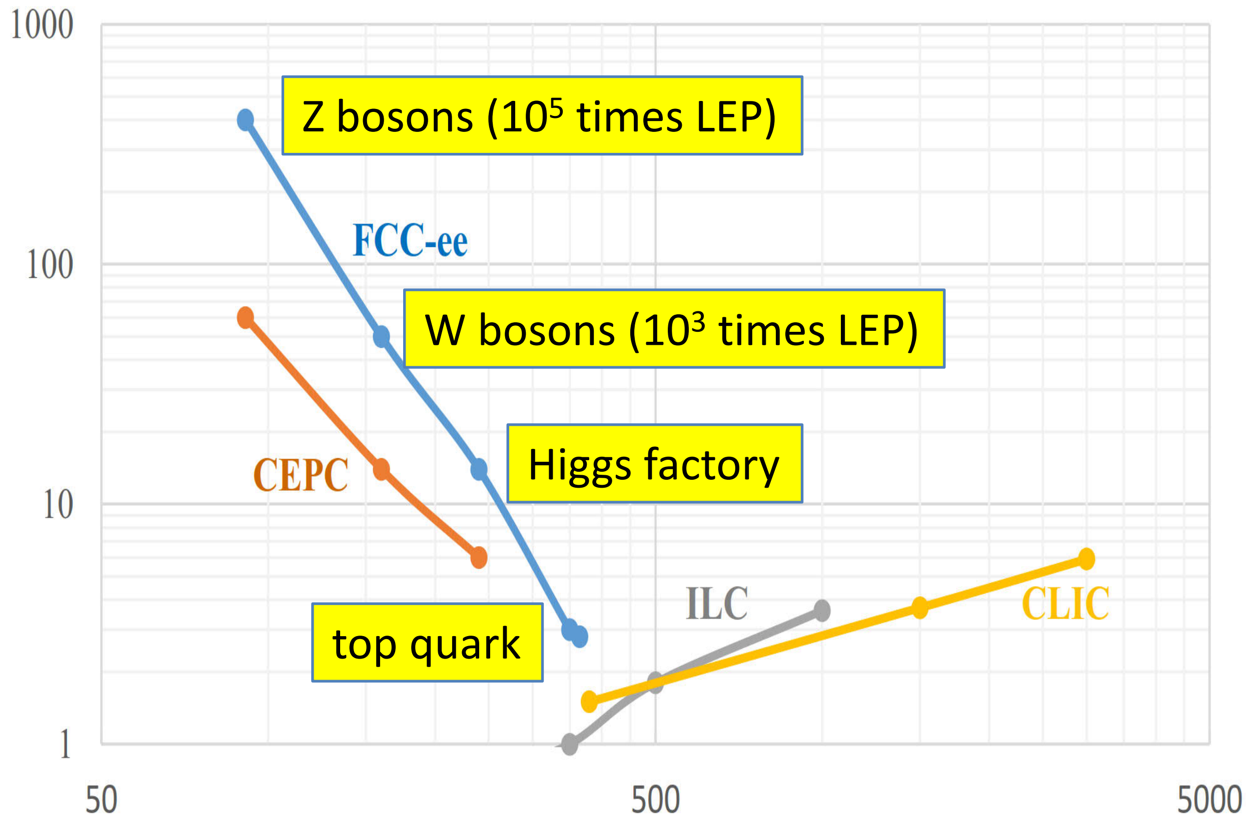


The physics drivers
(scenario consolidating in the past 10 years)

- **Higgs**: a **scalar boson** so light (125 GeV) that suits perfectly a circular e+e- collider
  - even LEP was close … sensitive up to 115 GeV, (125/115=1.09), synchrotron energy loss per turn goes as E^4/ρ , increase of radius by 1.4 corresponds to the same RF power as LEP
- **New Physics**: no sign of "easy BSM physics" in the 500 GeV – 1 TeV range

Where nature decided to put stuff (the electroweak playground)

total luminosity [10^{34} cm^{-2}s^{-1}]

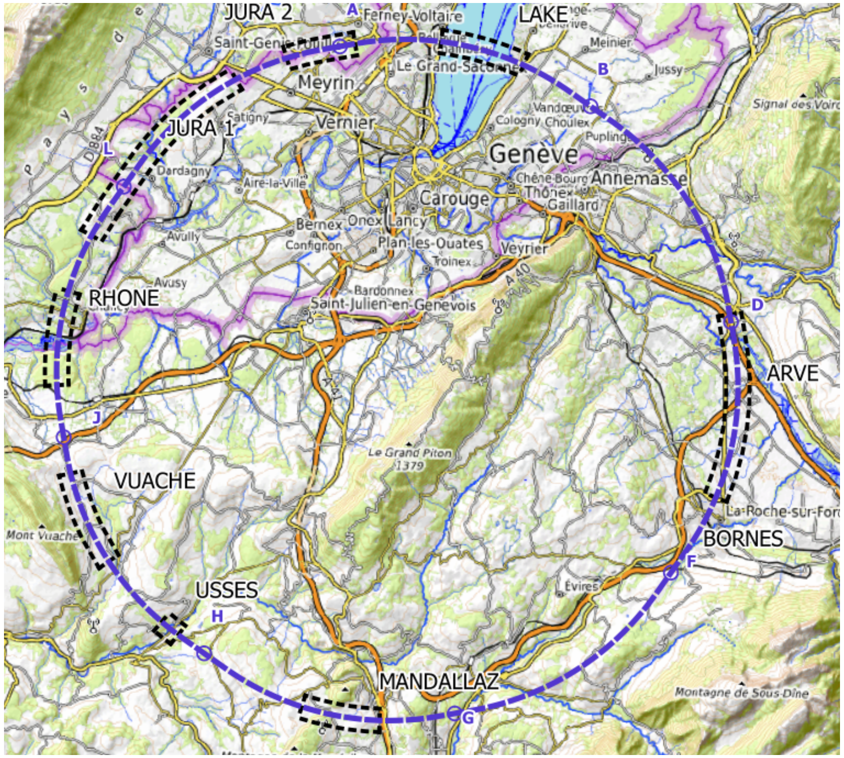


c.m. energy [GeV]

The natural choice

Comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- complementary physics
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after completion of the HL-LHC program



A first class infrastructure to maintain the leadership of European research in particle physics over the 21st century

FCC-ee collider parameters with 2 IPs

K. Oide, D. Shatilov,

Parameter [4 IPs, 91.2 km, T_{rev}=0.3 ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	12000	880	272	40
bunch intensity [10^{11}]	2.02	2.91	1.86	2.37
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.48/0	4.0/7.67
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.32	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
beam-beam parameter ξ_x / ξ_y	0.003/ .159	0.011/0.111	0.0187/0.129	0.096/0.138
rms bunch length with SR / BS [mm]	4.38 / 12.1	3.55 / 7.06	3.34 / 5.12	2.02 / 2.56
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	193	22	7.7	1.31
total integrated luminosity / year [ab^{-1}/yr]	46	5.3	1.9	0.33
beam lifetime rad Bhabha / BS [min]	35	32	9	16

FUTURE CIRCULAR COLLIDER

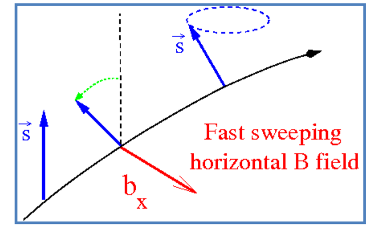
Stage 2: FCC-hh (pp) collider parameters

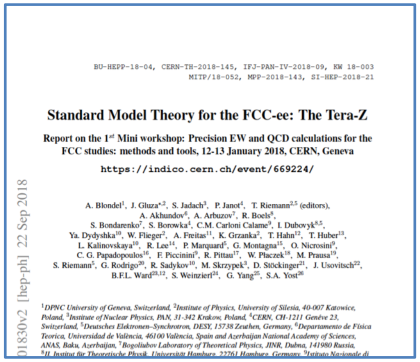
parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	16 ()		8.33	8.33
circumference [km]	97.75		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2400		7.3	3.6
SR power / length [W/m/ap.]	28.4		0.33	0.17
long. emit. damping time [h]	0.54		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	3.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	8.4		0.7	0.36

Update ongoing for FCCWeek Paris

Some key points about FCC

- **FCC-ee is not just about brute-force luminosity**
  - Continuous calibration of centre-of-mass energy (e.g. 100 keV at the Z) with resonant depolarization
  - Direct measurement of parameters, which were computed until now (e.g. direct measurement of α_{QED} running)
- **There is a well-defined theory effort, to successfully use data in a meaningful way (e.g. 3-loop calculations)**
- **It has been shown in various ways (e.g. EFT analyses) that a jump in precision in Z, W, H, top measurements is required for a comprehensive interpretation of the electroweak sector**
  - A deviation of a single coupling or operator will not provide the full picture
- **FCC-hh is eventually required to precisely investigate the Higgs self-coupling, to close important chapters (e.g. WIMP interpretation of Dark Matter) and to significantly extend direct searches**




BU-HEPP-18-04, CERN-TH-2018-145, IFJ-PAN-IV-2018-09, KW 18-003
MITP/18-052, MPP-2018-143, SI-HEP-2018-21

Standard Model Theory for the FCC-ee: The Tera-Z

Report on the 1st Mini workshop: Precision EW and QCD calculations for the FCC studies: methods and tools, 12-13 January 2018, CERN, Geneva

https://indico.cern.ch/event/669224/

A. Blondel[1], J. Gluza[*,2], S. Jadach[3], P. Janot[4], T. Riemann[2,5] (editors), A. Akhundov[6], A. Arbuzov[7], R. Boels[8], S. Bondarenko[7], S. Borowka[4], C.M. Carloni Calame[9], I. Dubovyk[8,5], Ya. Dydyshka[10], W. Flieger[2], A. Freitas[11], K. Grzanka[2], T. Hahn[12], T. Huber[13], L. Kalinovskaya[10], R. Lee[14], P. Marquard[5], G. Montagna[15], O. Nicrosini[9], C. G. Papadopoulos[16], F. Piccinini[9], R. Pittau[17], W. Płaczek[18], M. Prausa[19], S. Riemann[5], G. Rodrigo[20], R. Sadykov[10], M. Skrzypek[3], D. Stöckinger[21], J. Usovitsch[22], B.F.L. Ward[23,12], S. Weinzierl[24], G. Yang[25], S.A. Yost[26]

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01830v2 [hep-ph] 22 Sep 2018

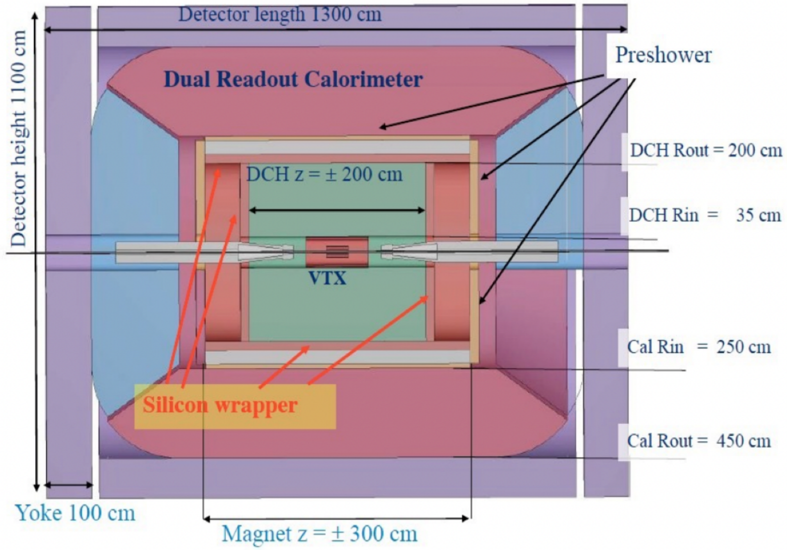
	# Higgs pairs to bbγγ
LHC: 14TeV 300fb^{-1}	36
HL-LHC: 14TeV 3ab^{-1}	360
FCC: 100TeV 20ab^{-1}	92 x 10^3 ← percent precision physics

CSN1: RD_FCC

105 scientists/15.3 FTE

~ 6-700 k€/yr (CSN1 & EU grants)

- IDEA detector: light tracker (Drift Chamber) , a dual-readout calorimeter, and a light-weight magnet.
  - Baseline for physics/performance studies and technology exploration.
  - Test-beams in progress
- Machine-Detector-Interface
- Activities in simulation/software
  - Algorithm development:jet flavour tagging, Particle ID, tau reconstruction
  - Physics studies: Higgs Recoil, Flavor, A_{FB}(bb,cc), ALPS, Top

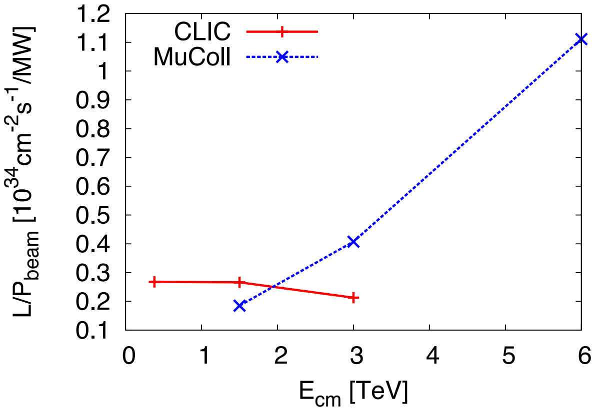


For general INFN FCC activities, prospects and opportunities **see the talk of Manuela Boscolo tomorrow**

https://agenda.infn.it/e/FCC-Italy

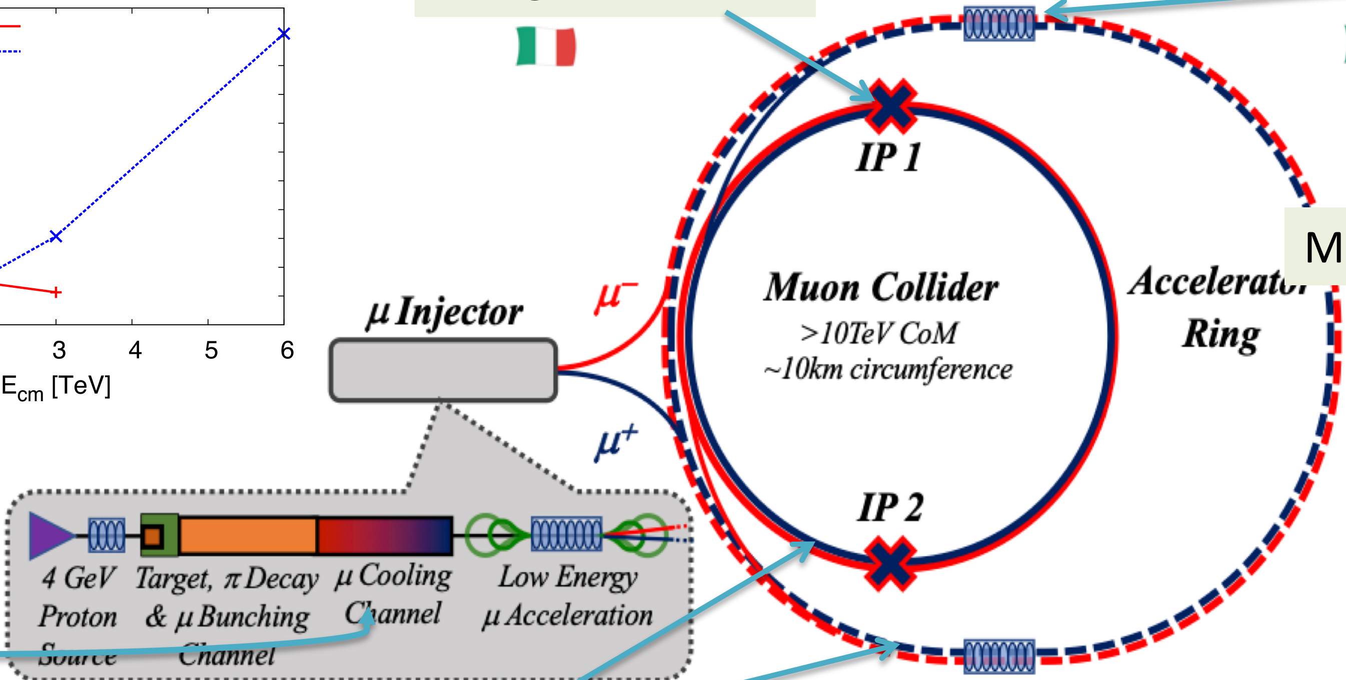
Muon Collider

International MUON Collider Collaboration



Beam induced background

MDI and Detector design



Magnets &RF

Cooling cell prototyping

Cost and **power** consumption drivers, limit energy reach e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring

ASSUMPTION/IP

$\mathcal{L} = (E_{CM}/10\text{TeV})^2 \times 10\ \text{ab}^{-1}$

@ 3 TeV 1 ab^{-1}/5 years

@ 10 TeV 10 ab^{-1}/5 y

@ 14 TeV 20 ab^{-1}/5 y

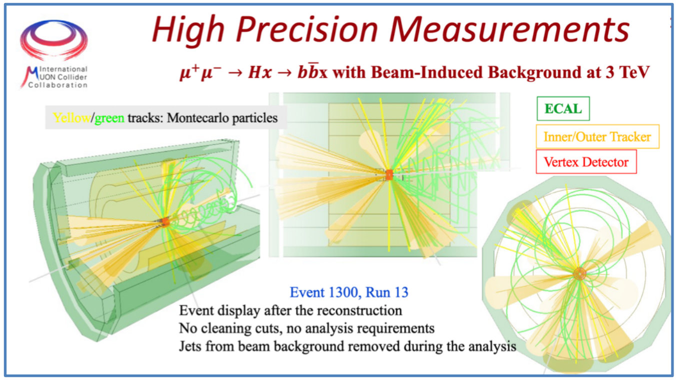
CSN1: RD_MUCOL

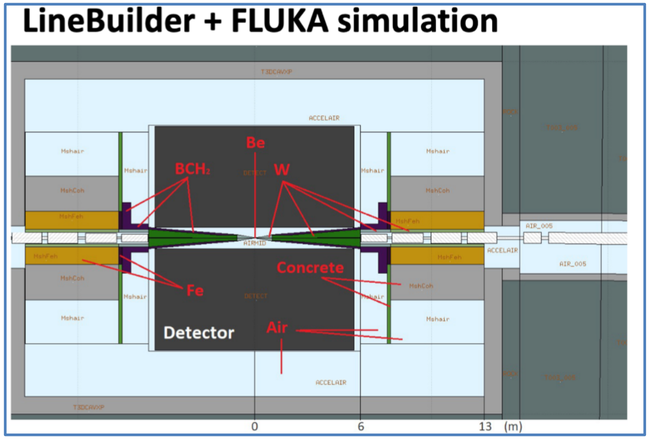
For general INFN Muon Coll activities, prospects and opportunities **see the talk of Nadia Pastrone tomorrow**

97 scientists/15.7 FTE

~ 300+X k€/yr (CSN1 & EU grants)

- **Physics:**
  - evaluation of physics reach in the presence of machine background
  - studies experiment design, simulations
  - theoretical work (with CSN4) and analysis with full Higgs and BSM simulation
- **Ongoing detector R&D developments** in sinergy with AIDAinnova
- **Machine Detector Interface** background studies at various energies [arXiv:2105.09116]
- **Crystals for collimation and extraction:** collaboration with FCCee





Specific for the LEMMA option

Targets: Simulations, laboratory and beam tests being finalized

Test Beam @ CERN in 2022: $\mu^+\mu^-$ cross section at threshold

Summary

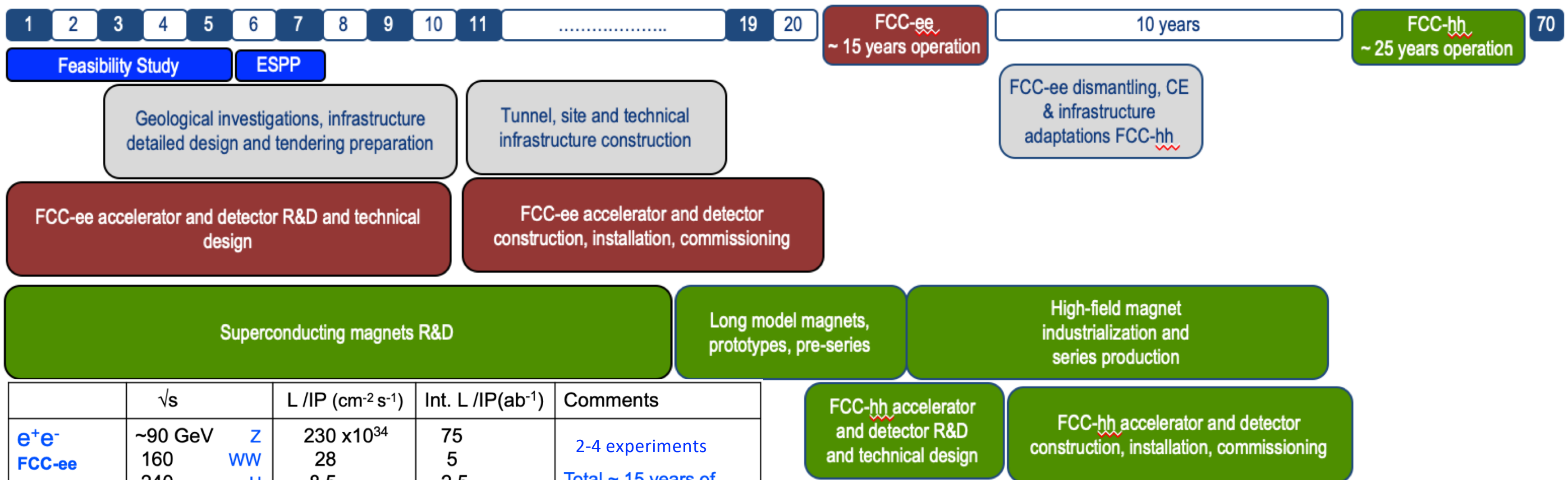
- Strong **CSN1** involvement in HEP experiments with **accelerators** at the **intensity and energy frontiers**
- **At present** most of the budget focused on projects at CERN
  - **LHC experiments upgrade taking most of the effort**, both from the personnel and financial point of view
- Significant resources dedicated also to other activities:
  - Special focus on **flavour** and **lepton sector**
  - New experiments in preparation (SND, AMBER, LUXE, MUonE, MU2E)
- Special attention dedicated to the preparation for the future of our field
  - Our **plan A** is **FCC** (FCC-ee followed by FCC-hh): **«A first class infrastructure to maintain the leadership of European research in particle physics over the 21st century»**
  - We support studies for the **Muon Collider** a splendid tool for physics if technologically demonstrated

B

Timeline of the FCC integrated programme

FUTURE CIRCULAR COLLIDER

Technical schedule

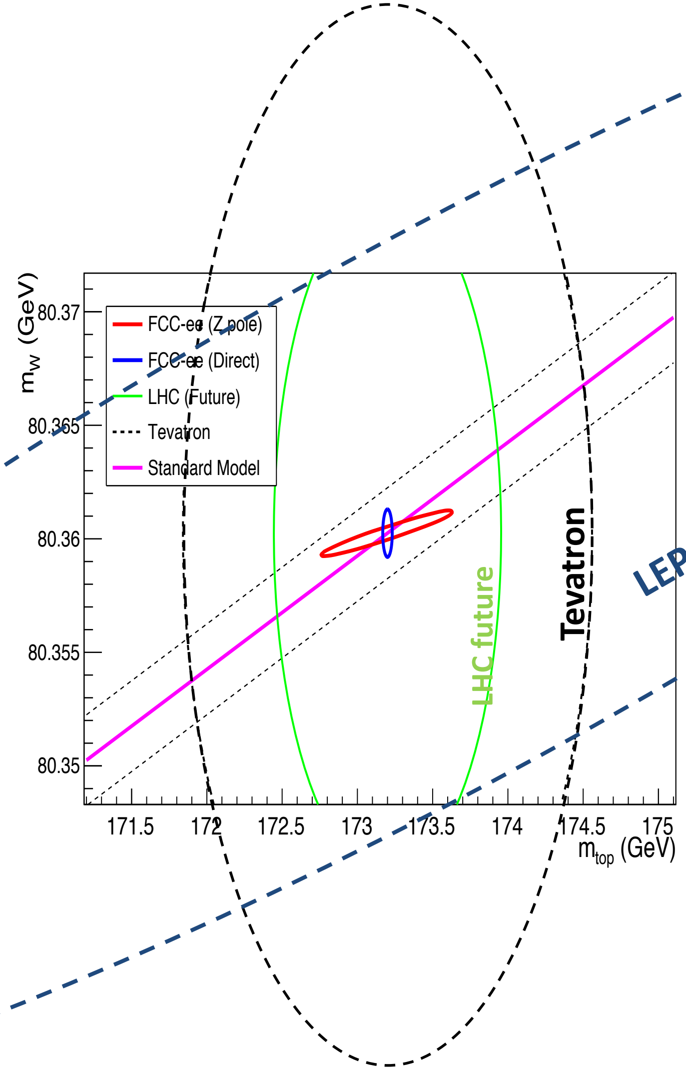


	√s	L /IP ($cm^{-2} s^{-1}$)	Int. L /IP(ab^{-1})	Comments
e^+e^- FCC-ee	~90 GeV Z 160 WW 240 H ~365 top	230 $\times 10^{34}$ 28 8.5 1.5	75 5 2.5 0.8	2-4 experiments Total ~ 15 years of operation
pp FCC-hh	100 TeV	5 x 10^{34} 30	20-30	2+2 experiments Total ~ 25 years of operation
PbPb FCC-hh	$\sqrt{s_{NN}}$ = 39TeV	3 x 10^{29}	100 nb^{-1}/run	1 run = 1 month operation
ep Fcc-eh	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb Fcc-eh	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb

F. Gianotti

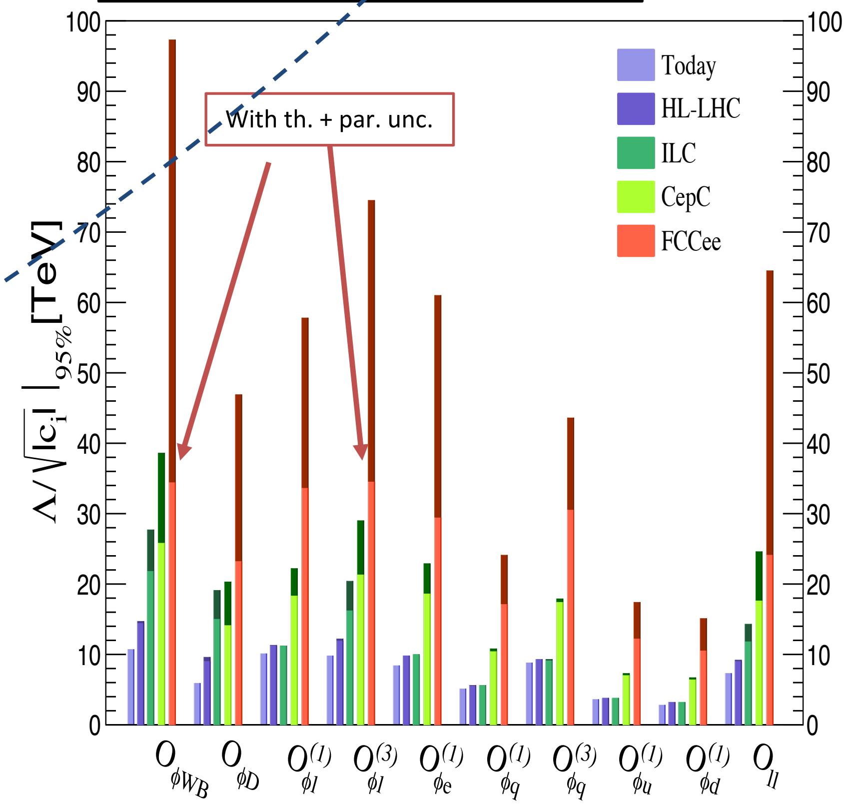
- ❑ Feasibility Study: 2021-2025
- ❑ If project approved before end of decade → construction can start beginning 2030s
- ❑ FCC-ee operation ~2045-2060
- ❑ FCC-hh operation 2070-2090++

Global ewk fit and sensitivity to new physics



$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

Jorge de Bla
LHCP 2017



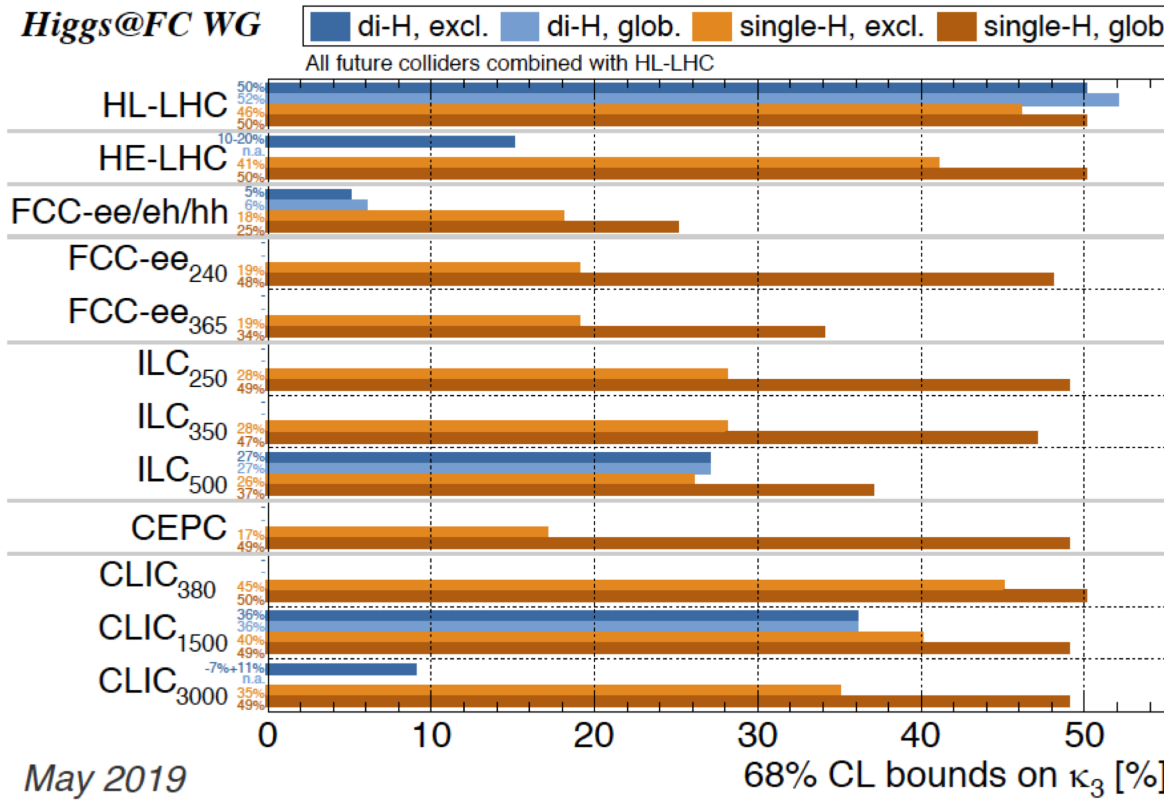
Sensitivity to λ: via single-H and di-H production

Di-Higgs:

- HL-LHC: ~50% or better?
- Improved by HE-LHC (~15%), ILC_{500} (~27%), $CLIC_{1500}$ (~36%)
- Precisely by $CLIC_{3000}$ (~9%), FCC-hh (~5%),
- Robust w.r.t other operators

Single-Higgs:

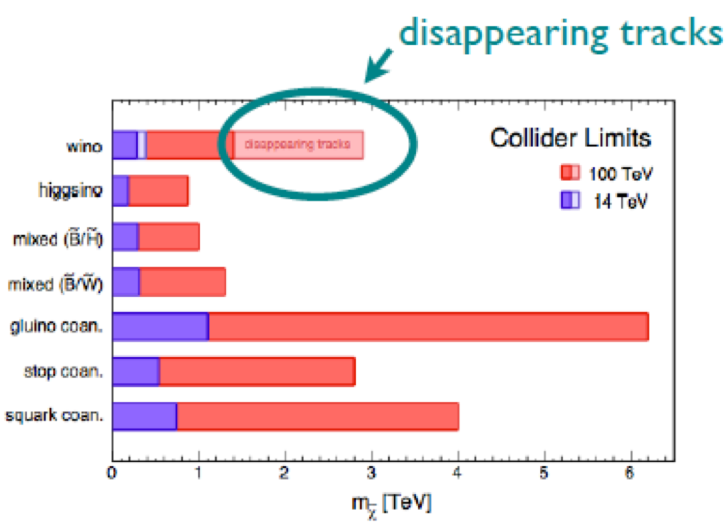
- **Global** analysis: FCC-ee365 and ILC500 sensitive to ~35% when combined with HL-LHC
  - ~21% if FCC-ee has 4 detectors
- **Exclusive** analysis: too sensitive to other new physics to draw conclusion

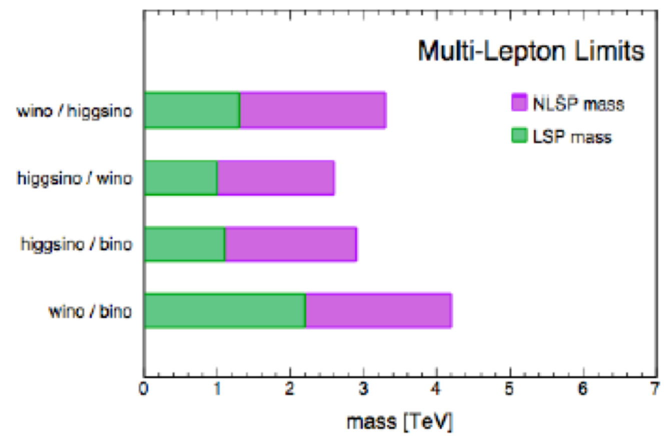


Towards no-lose arguments for Dark Matter scenarios:

WIMP searches at colliders

L.Wang @ FCC week

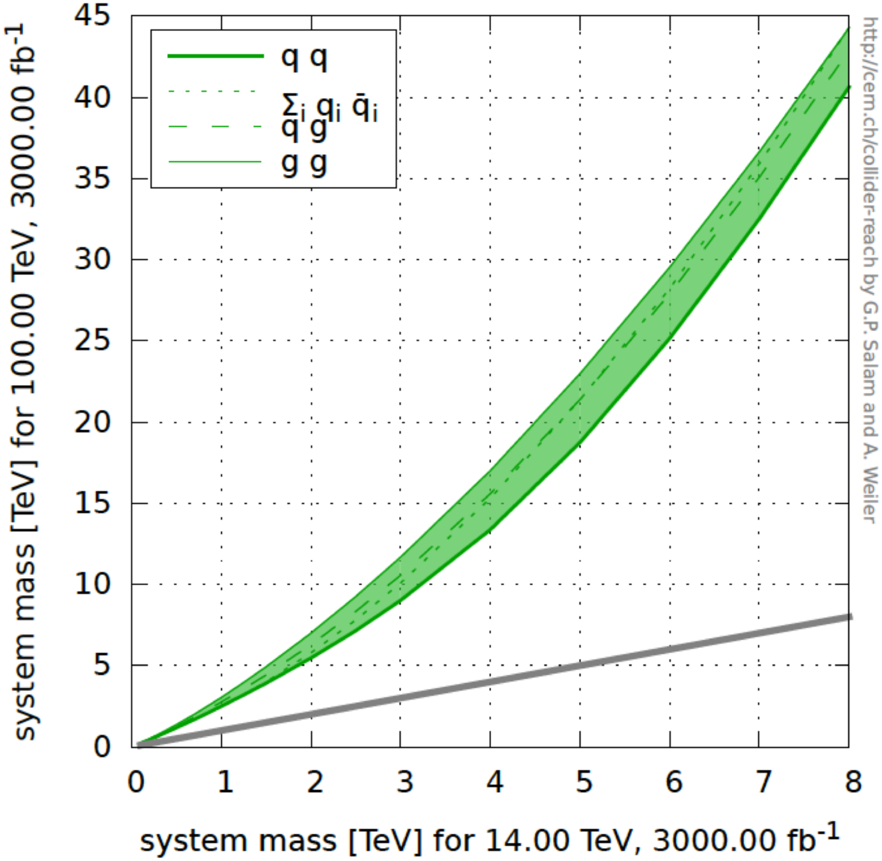




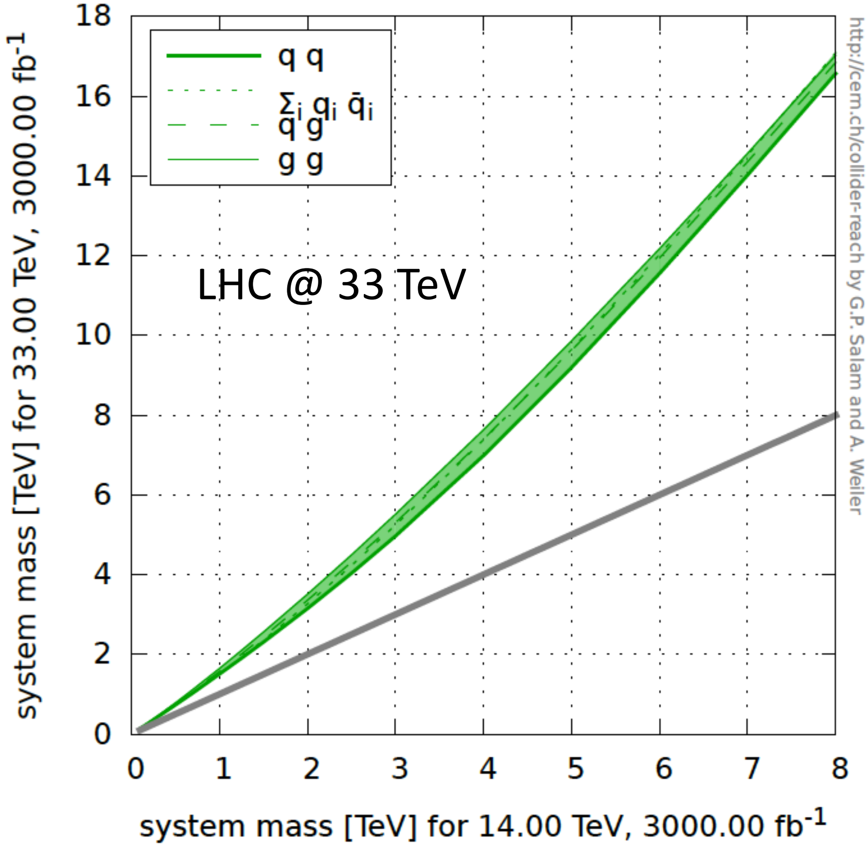
$$M_{\mathrm{WIMP}} \leq 1.8\ \mathrm{TeV}\ \left(\frac{g^2}{0.3}\right)$$

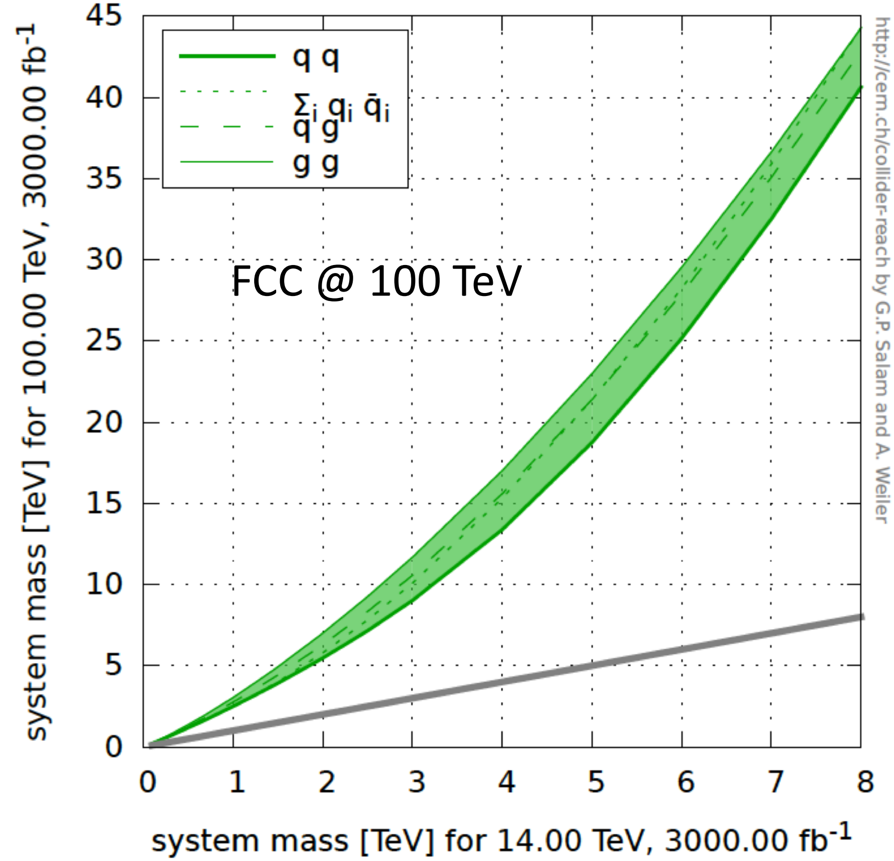
100 TeV pp collider will probe TeV WIMP very well.

Potenzialita' macchina adronica a 100 TeV

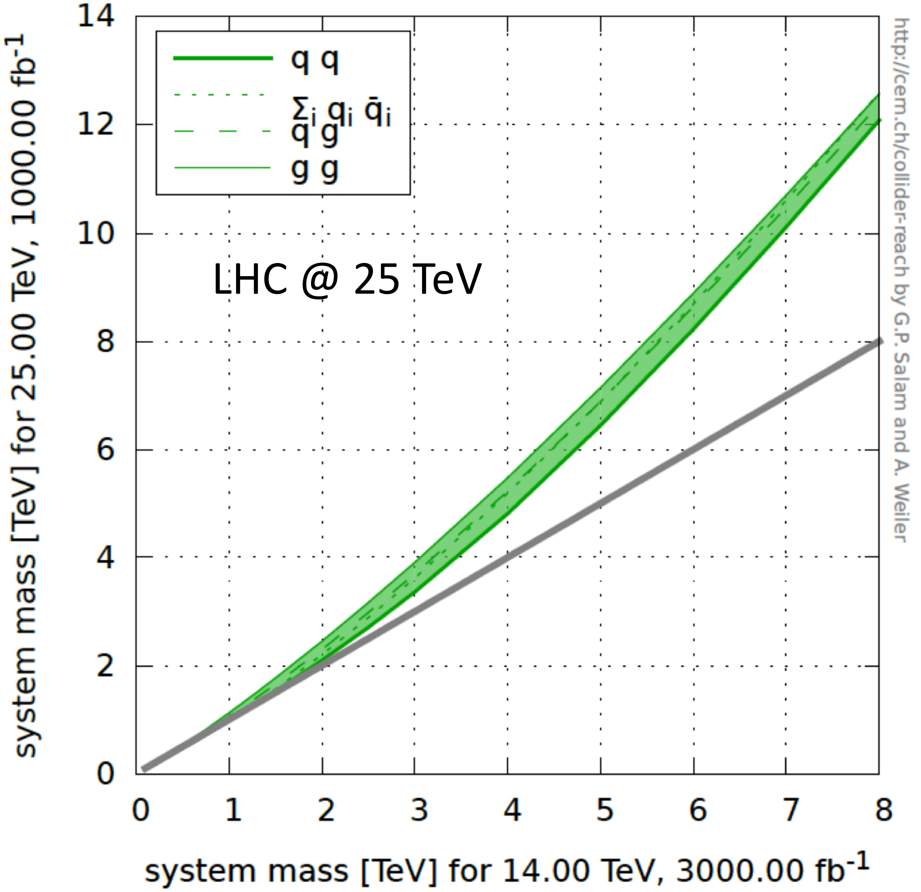


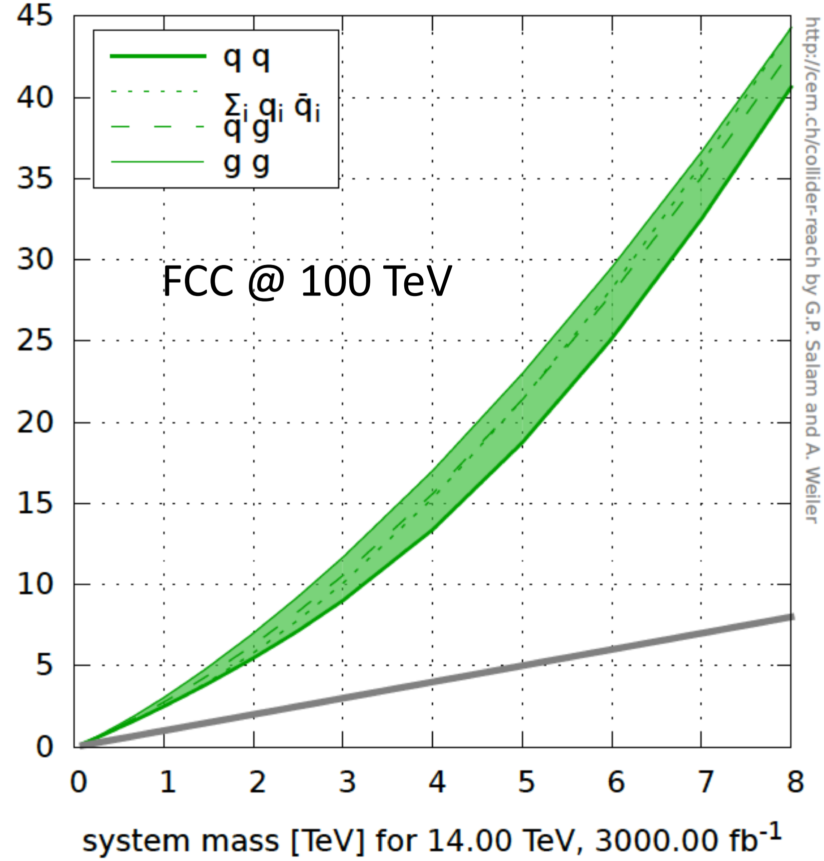
Physics reach from parton luminosities (normalized to 3 ab^{-1} @ 14 TeV)





Physics reach from parton luminosities (normalized to 3 ab^{-1} @ 14 TeV)





Global fit results

Improvement with respect to HL-LHC

	LHeC	HE-LHC	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
g^{eff}_{HZZ}	1.7	1.2	7.7	≥ 10	5.5	≥ 10	≥ 10	6.9	7.7	≥ 10	≥ 10
g^{eff}_{HWW}	1.8	1.3	6.7	≥ 10	4.9	≥ 10	≥ 10	6.3	7.0	≥ 10	≥ 10
$g^{eff}_{H\gamma\gamma}$	1.7	1.3	2.8	3.4	2.6	3.1	3.4	3.1	3.1	3.1	≥ 10
$g^{eff}_{HZ\gamma}$	1.1	2.4	1.1	1.6	1.1	2.3	3.0	1.7	1.1	1.2	≥ 10
g^{eff}_{Hgg}	1.4	1.7	2.0	2.8	1.7	2.3	2.9	2.8	2.3	2.7	4.5
g^{eff}_{Htt}	1.1	1.7	1.1	1.2	1.1	1.4	1.4	1.1	1.1	1.1	1.8
g^{eff}_{Hcc}	$\star$		$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$	$\star$
g^{eff}_{Hbb}	2.7	1.5	6.1	9.8	5.1	≥ 10	≥ 10	7.6	7.3	9.1	≥ 10
$g^{eff}_{H\tau\tau}$	1.6	1.3	4.1	5.8	2.7	3.8	4.8	5.0	5.0	6.1	7.8
$g^{eff}_{H\mu\mu}$	1.2	1.8	1.3	1.4	1.3	1.4	1.6	1.4	1.4	1.4	≥ 10
$\delta g_{1Z}[\times 10^2]$	1.3	1.4	6.7	≥ 10	≥ 10	≥ 10	≥ 10	7.3	7.8	≥ 10	≥ 10
$\delta \kappa_\gamma[\times 10^2]$	1.3	1.2	≥ 10	≥ 10	≥ 10	≥ 10	$\geq 10^2$	≥ 10	≥ 10	≥ 10	≥ 10
$\lambda_Z[\times 10^2]$	1.1	1.0	≥ 10	$\geq 10^2$	≥ 10	$\geq 10^2$	$\geq 10^3$	≥ 10	≥ 10	≥ 10	≥ 10

SMEFT ND

($\star$) not measured at HL-LHC

Fig. by M. Cepeda

Global fit results

Improvement with respect to HL-LHC

	$g_L^{\nu_e}$	$g_L^{\nu_\mu}$	$g_L^{\nu_\tau}$	g_L^e	g_R^e	g_L^μ	g_R^μ	g_L^τ	g_R^τ	$g_L^{u=c}$	$g_R^{u=c}$	g_L^t	g_R^t	$g_L^{d=s}$	$g_R^{d=s}$	g_L^b	g_R^b
ILC_{250}	≥ 10	1.2	1.5	1.1	1.1	1.0	1.0	1.0	1.0	1.1	1.0	1.0		1.2	1.5	1.0	1.0
ILC_{500}	≥ 10	1.2	1.6	1.3	1.8	1.0	1.0	1.0	1.0	1.1	1.0	≥ 10	⋆	1.2	1.5	1.0	1.0
$CLIC_{380}$	≥ 10	5.1	9.6	1.7	1.4	1.1	1.1	1.0	1.0	1.1	1.0	1.0		1.2	1.6	1.0	1.0
$CLIC_{1500}$	≥ 10	5.3	≥ 10	2.7	1.9	1.1	1.1	1.0	1.0	1.1	1.1	≥ 10	⋆	1.3	1.6	1.0	1.0
$CLIC_{3000}$	$\geq 10^2$	5.4	≥ 10	3.1	2.4	1.1	1.1	1.0	1.0	1.1	1.1	≥ 10	⋆	1.3	1.6	1.0	1.0
CEPC	1.0	1.0	1.0	1.8	2.0	≥ 10	≥ 10	1.1	1.0	1.1	1.0	1.0		1.2	1.5	≥ 10	≥ 10
$FCCee_{240}$	≥ 10	≥ 10	≥ 10	7.9	9.2	≥ 10	≥ 10	≥ 10	≥ 10	4.2	2.9	1.0		4.6	4.4	4.6	4.4
$FCCee_{365}$	≥ 10	≥ 10	≥ 10	9.9	10.0	≥ 10	≥ 10	≥ 10	≥ 10	4.2	2.9	7.5	⋆	4.6	4.4	4.6	4.4
FCCee/eh/hh	≥ 10	≥ 10	≥ 10	9.9	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	9.1	⋆	≥ 10	≥ 10	4.6	4.4

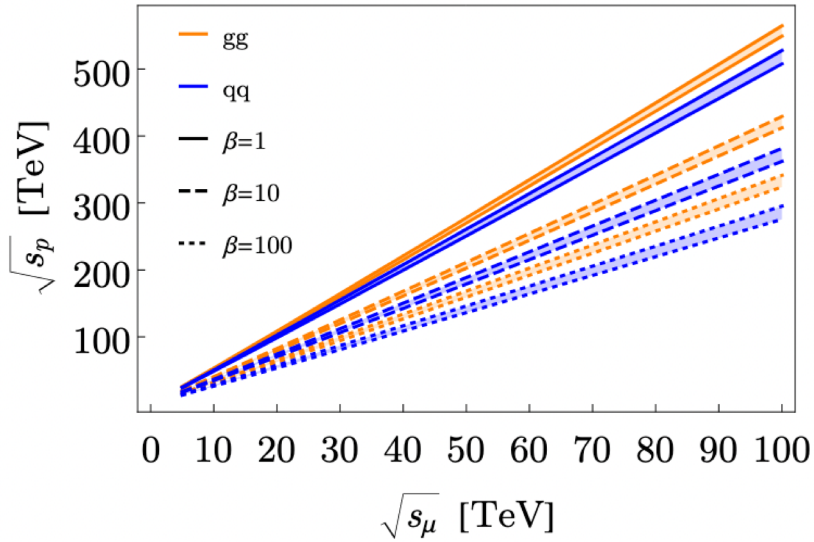
Colour scale: 0, 2, 4, 6, 8, 10

-**WARNING:** CEPC EWPO ~ FCCee EWPO (except 365 GeV: top).
Difference due to current status of EWPO projections (Flav. Non-univ, sys,…)

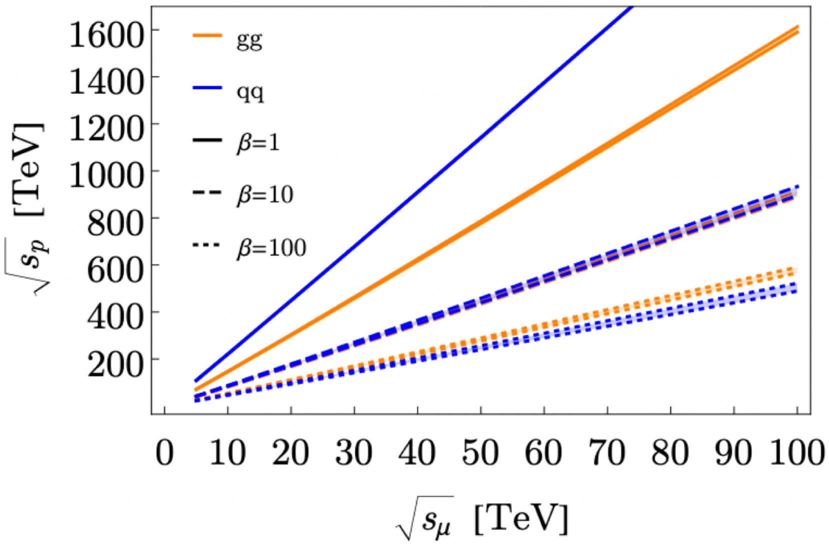
Fig. by M. Cepeda

Muon collider vs hadron collider

2→1 process

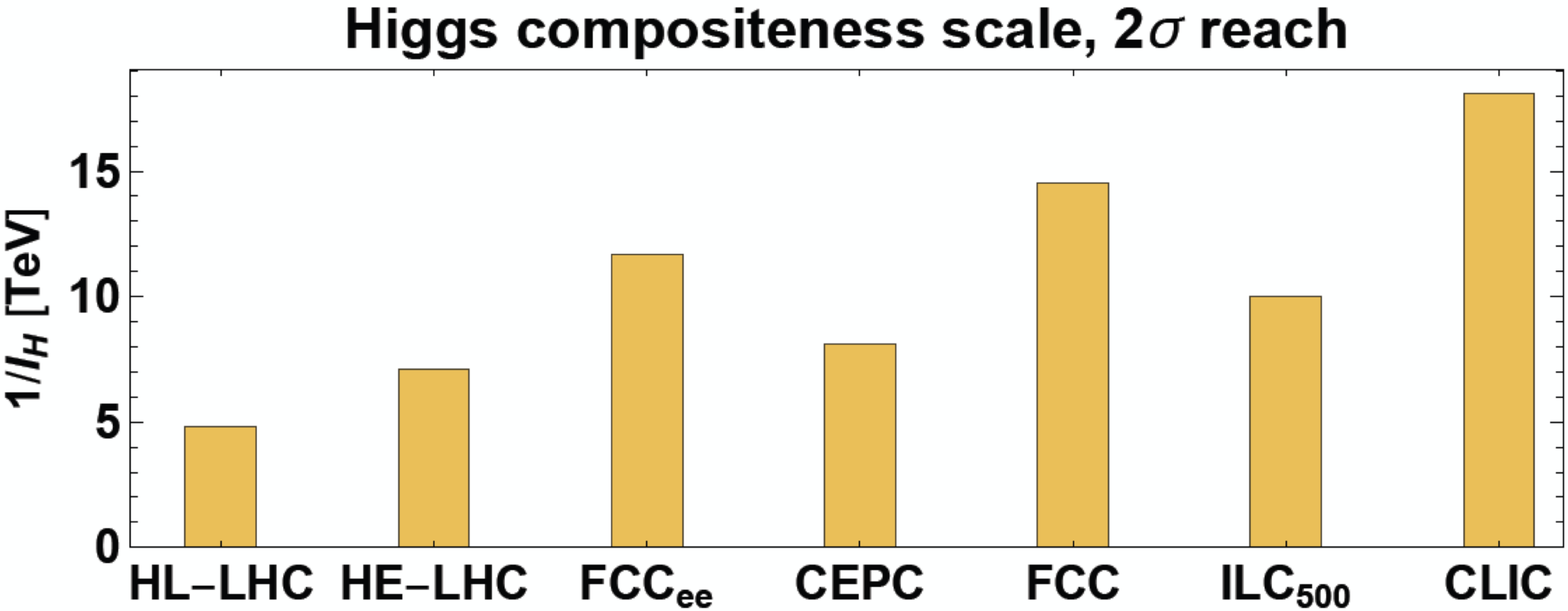


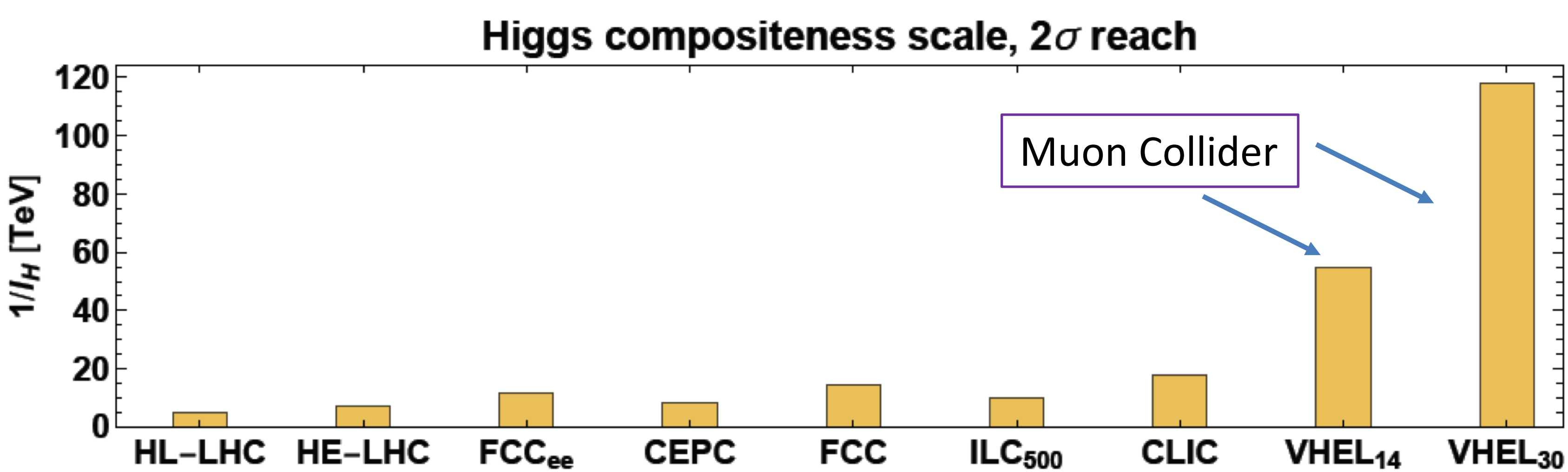
2→2 process



β represents different assumption on relations between parton luminosities

arXiv:2103.14043


Higgs compositeness scale, 2σ reach
1/l_H [TeV]
0
5
10
15
HL−LHC
HE−LHC
FCCee
CEPC
FCC
ILC500
CLIC


Higgs compositeness scale, 2σ reach
1/l_H [TeV]
0
20
40
60
80
100
120
Muon Collider
HL−LHC
HE−LHC
FCCee
CEPC
FCC
ILC500
CLIC
VHEL14
VHEL30