Future Circular Collider Study (FCC)

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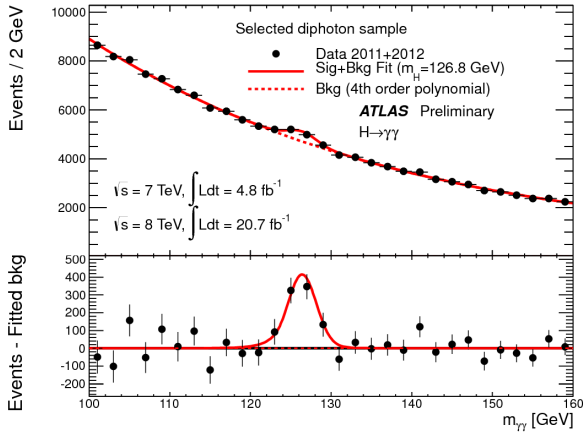
on behalf of the FCC Collaboration

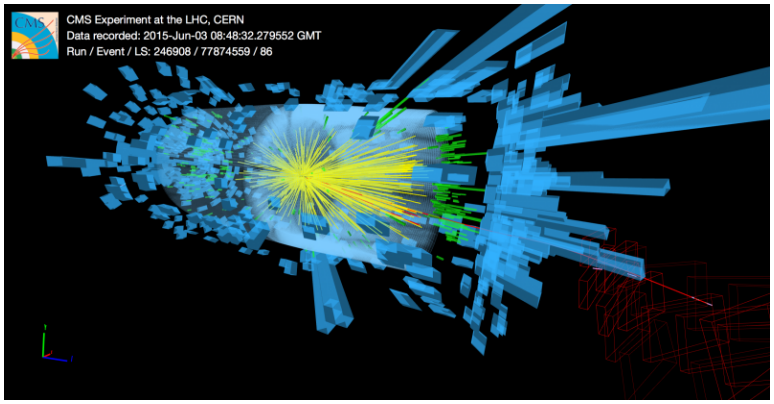
UNIVERSITÉ DE GENÈVE

Where do we stand in Collider Physics?

Run 1 Higgs discovery!



Run 2 in full swing!

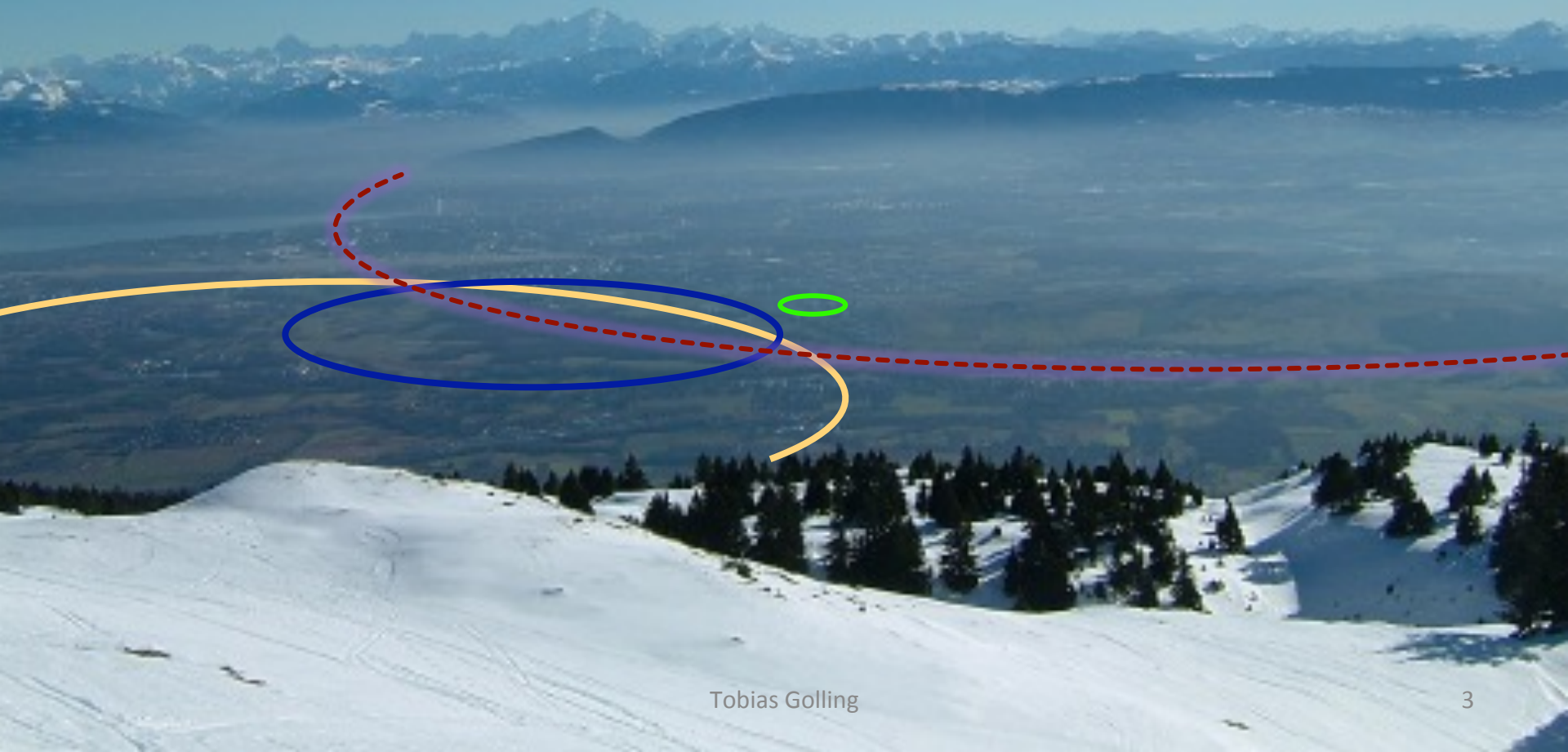


LHC physics program until 2035

High Luminosity LHC

The next leap forward ?

- Design study for an ambitious post-LHC project:
  - FCC-hh (100 TeV, ultimate goal, emphasis for infrastructure)
  - FCC-ee (H,Z,W,t factory, possible intermediate step)
  - e-p collider (optional)



How to get to 100 TeV

$$E \sim B_{dipole} * radius$$

Compared to LHC:

- factor ~2 in B field
- factor ~4 in radius

→ O(10) in E

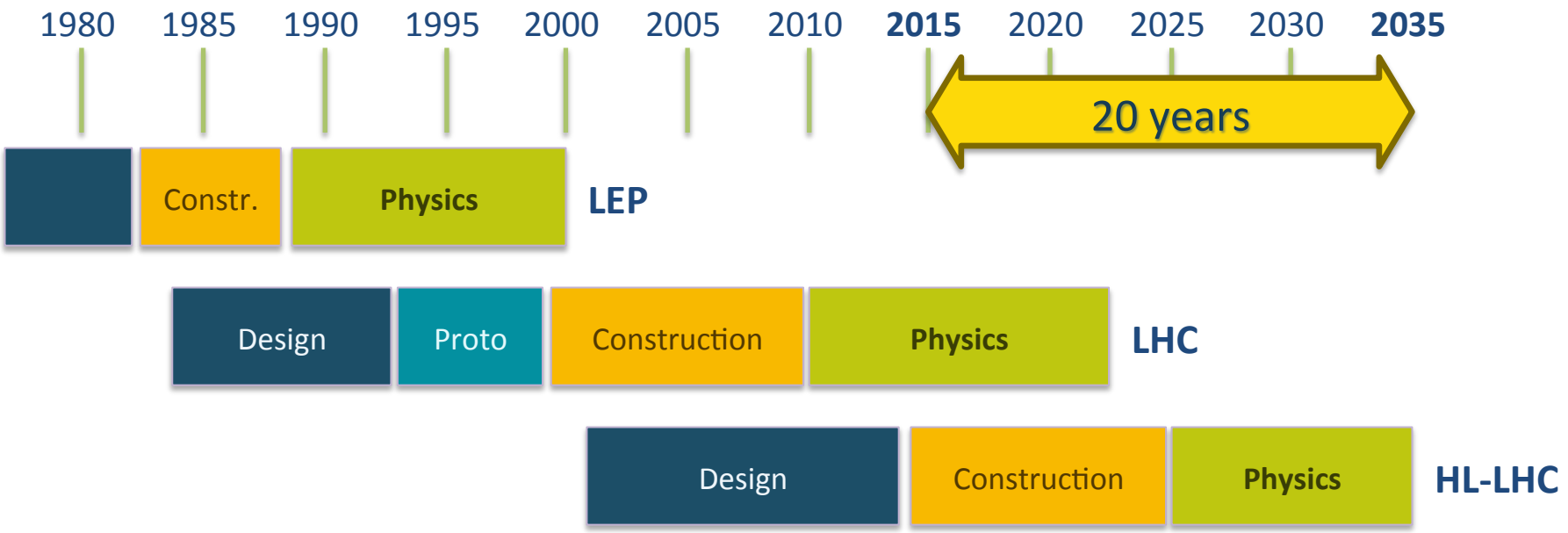
FCC-hh vs LHC – FCC-ee vs LEP2

Parameter	FCC-pp	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP_{main} [$cm^{-2}s^{-1}$]	5 - 25 x 10^{34}	1 x 10^{34}
Stored energy/beam [GJ]	8.4	0.39
Synchrotron rad. [W/m/aperture]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

Parameter	FCC-ee			LEP2
Energy/beam [GeV]	45	120	175	105
Bunches/beam	13000-60000	500-1400	51- 98	4
Beam current [mA]	1450	30	6.6	3
Luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**21 - 280**	**5 - 11**	**1.5 - 2.6**	0.0012
Energy loss/turn [GeV]	0.03	1.67	7.55	3.34
Synchrotron Power [MW]	100			22
RF Voltage [GV]	0.3-2.5	3.6-5.5	11	3.5

FCC-hh luminosity goal: 10-20 ab^{-1}

Timeline

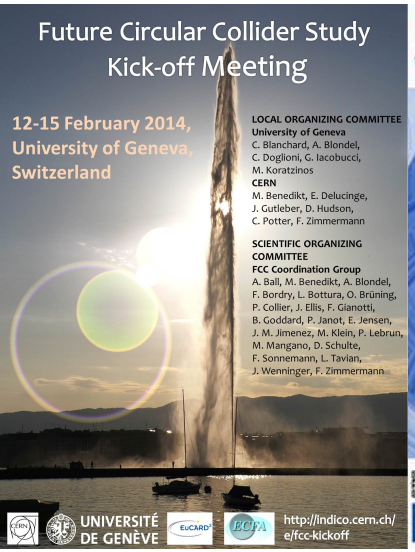


FCC preparation needs to start now!

FCC Preparation

2014				2015				2016				2017				2018			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4

Kick-off



Work towards baseline

FCC Week 2016, Rome

FCC Week 2017: Review cost model, LHC results, study re-scoping?

FCC Week 2018
→ CDR

- Many workshops, meetings,…
  - Discuss R&D, detector needs, physics benchmarks…
- Contributions welcome

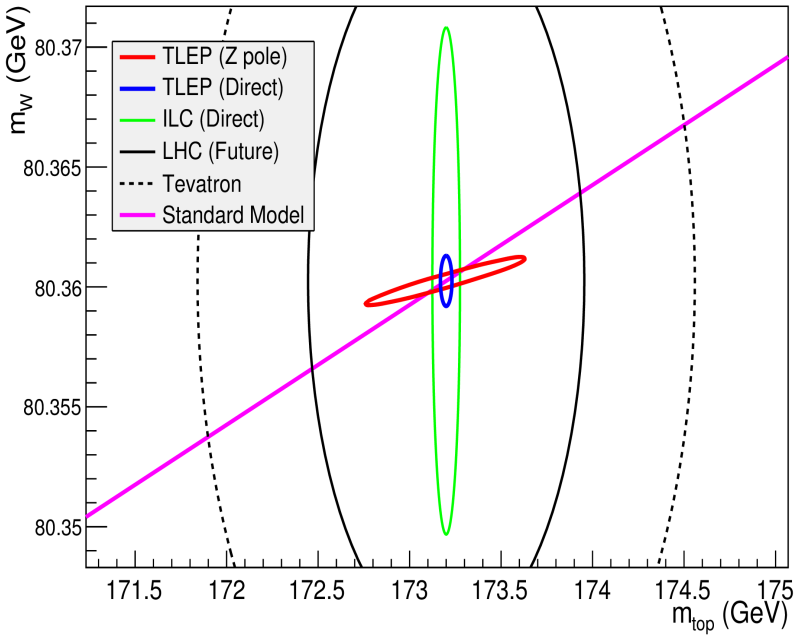
Collaboration Status

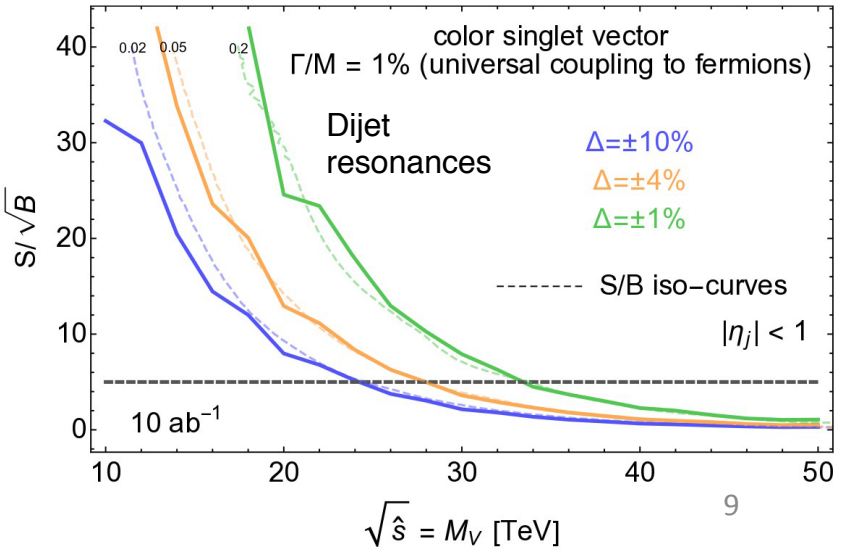
- 57 institutes
- 22 countries + EC

Status: July 30, 2015

Key Goals of the FCC

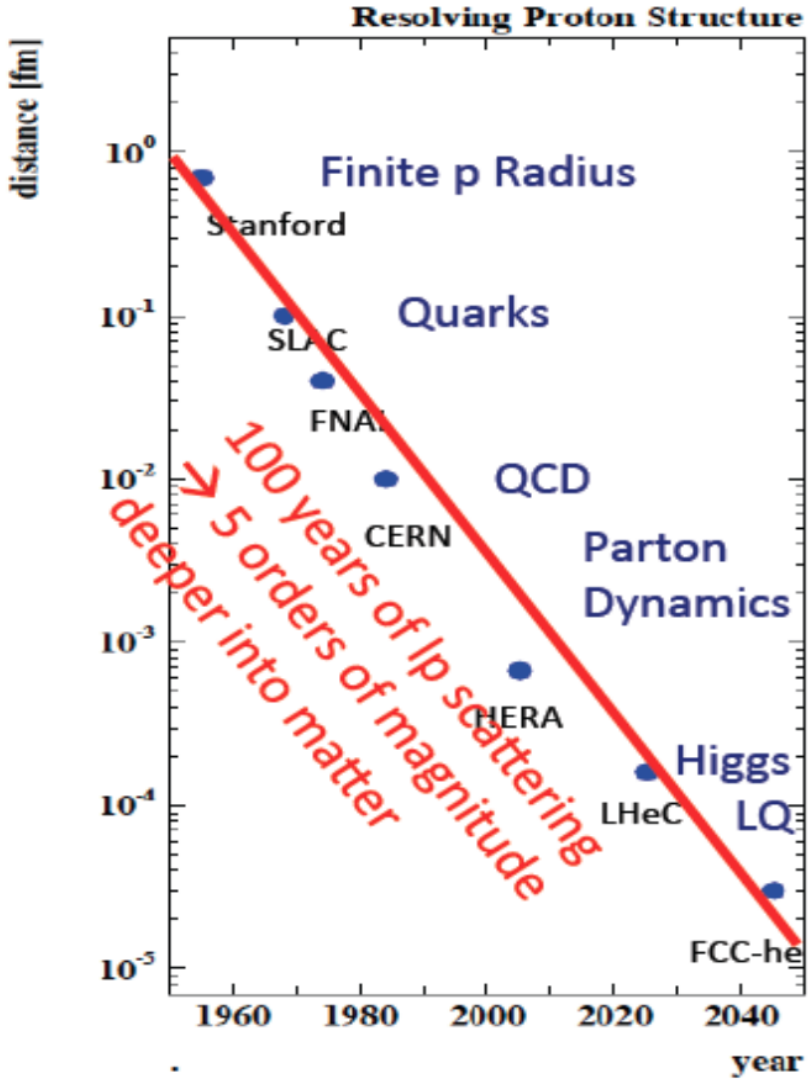
- Complete exploration of the Higgs boson and its dynamics
- Extended search for BSM
  - Indirect probes (high luminosity & rates (ee,hh) & precision (ee))
  - Direct searches (high mass reach (hh) & small couplings (ee,hh))
- Full exploitation of FCC requires the progress of theoretical calculations such as
  - PDFs
  - theoretical systematics (e.g. 3-loop EW calculations)





One Word on FCC-eh

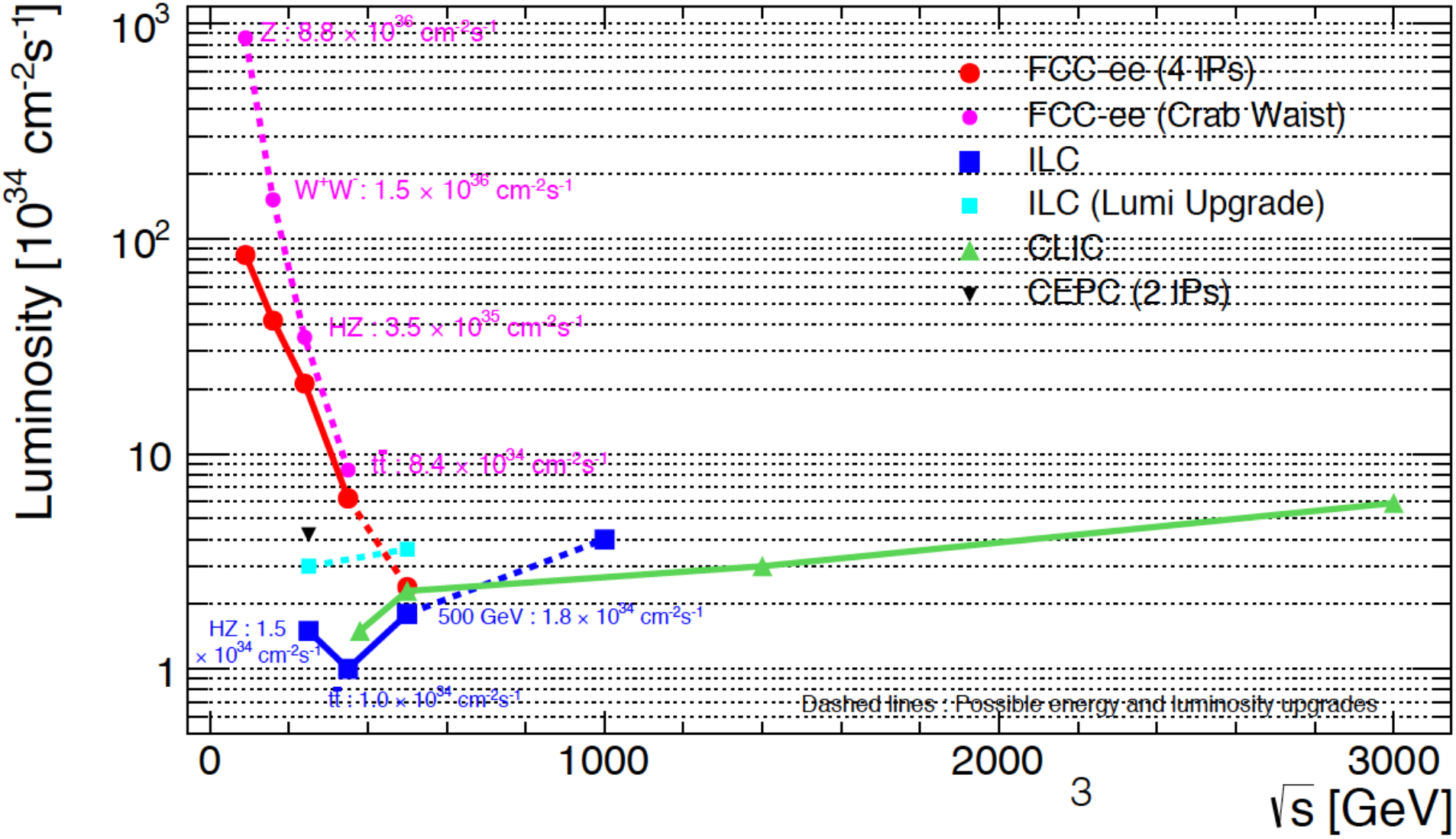
The world's cleanest microscope: pdf's



cf F.Olness, V.Radescu, M.Ploskon

+New Physics in Higgs, QCD, BSM

FCC-ee in Comparison



FCC-ee Core Physics Program

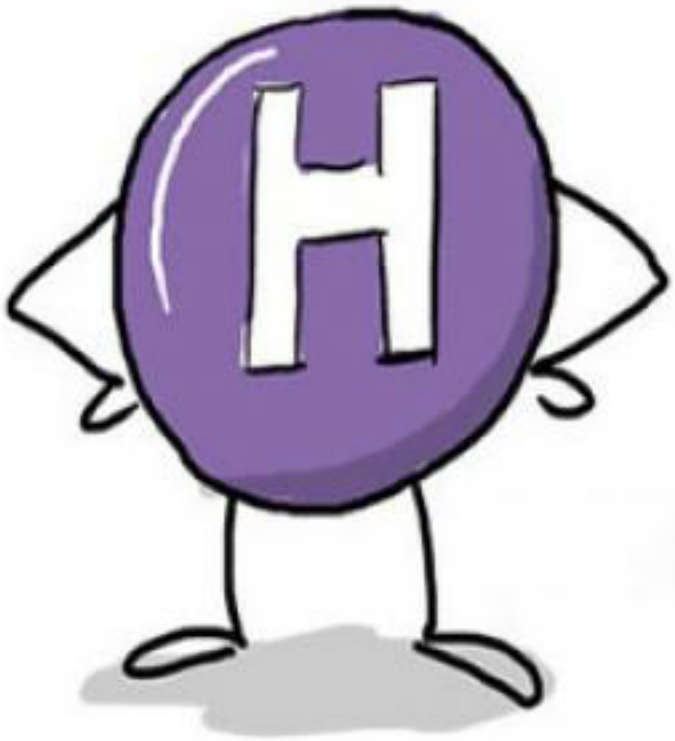
- The Higgs factory, $\sqrt{s}$ **= 240 GeV and above**
  - Improve HL-LHC precision on Higgs couplings by an order of magnitude
  - Measure the Higgs width to better than 1%, and BR_{invis} to 0.1%

- The Z pole scan, $\sqrt{s}$ **= 88-95 GeV**
  - m_Z, Γ_Z to 100 keV, $\alpha_s(m_Z)$ to 10^{-4}, R_b, A_{FB}, $\alpha_{QCD}(m_Z)$ to $2*10^{-5}$
  - Rare decay/process & flavour physics with up to 10^{13} Z (RH neutrinos!)

- The WW threshold scan, $\sqrt{s}$ **= 160-165 GeV**
  - m_W to 300 keV, $\alpha_s(m_W)$ to 10^{-4}, ...

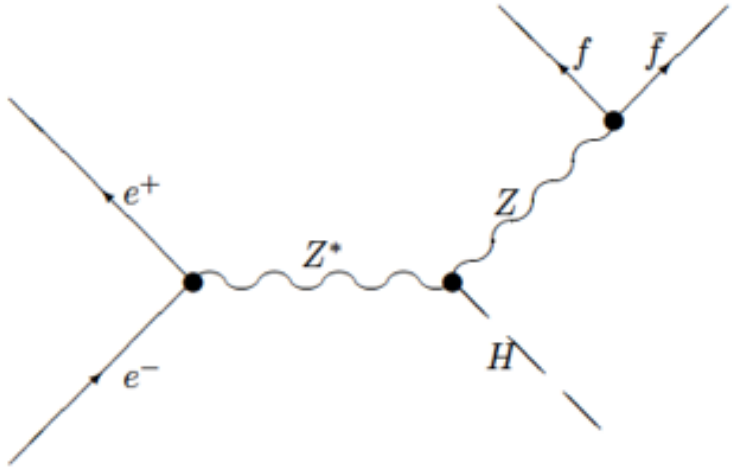
- The $t\bar{t}$ threshold scan, $\sqrt{s}$ **= 340-350 GeV**
  - m_{top} to 10-20 MeV, ttZ couplings to << %

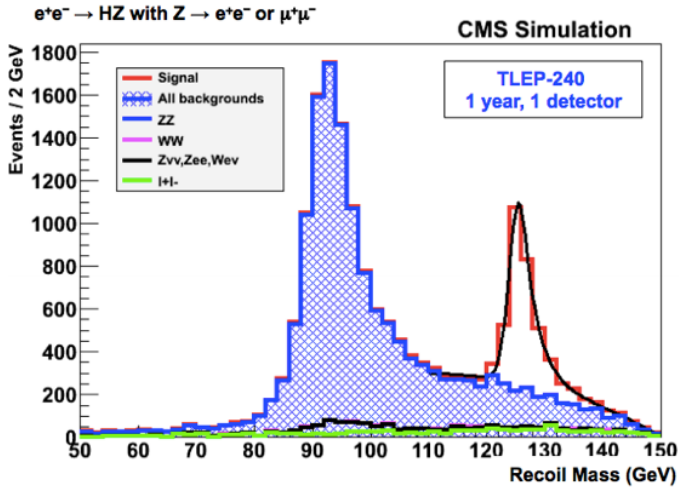
Higgs



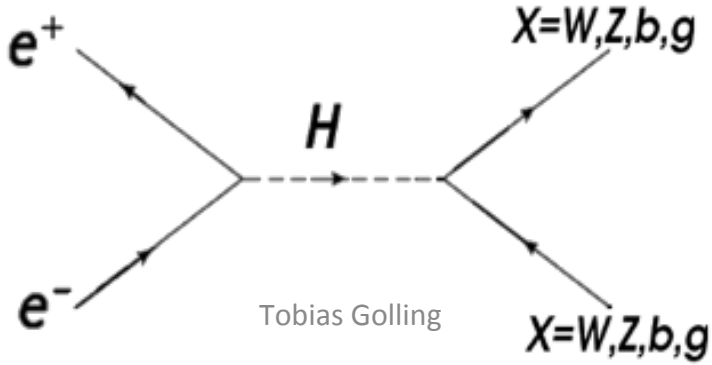
Exploiting the Higgs: FCC-ee

- Recoil method unique to lepton collider
  - Tag Higgs event independent of decay mode



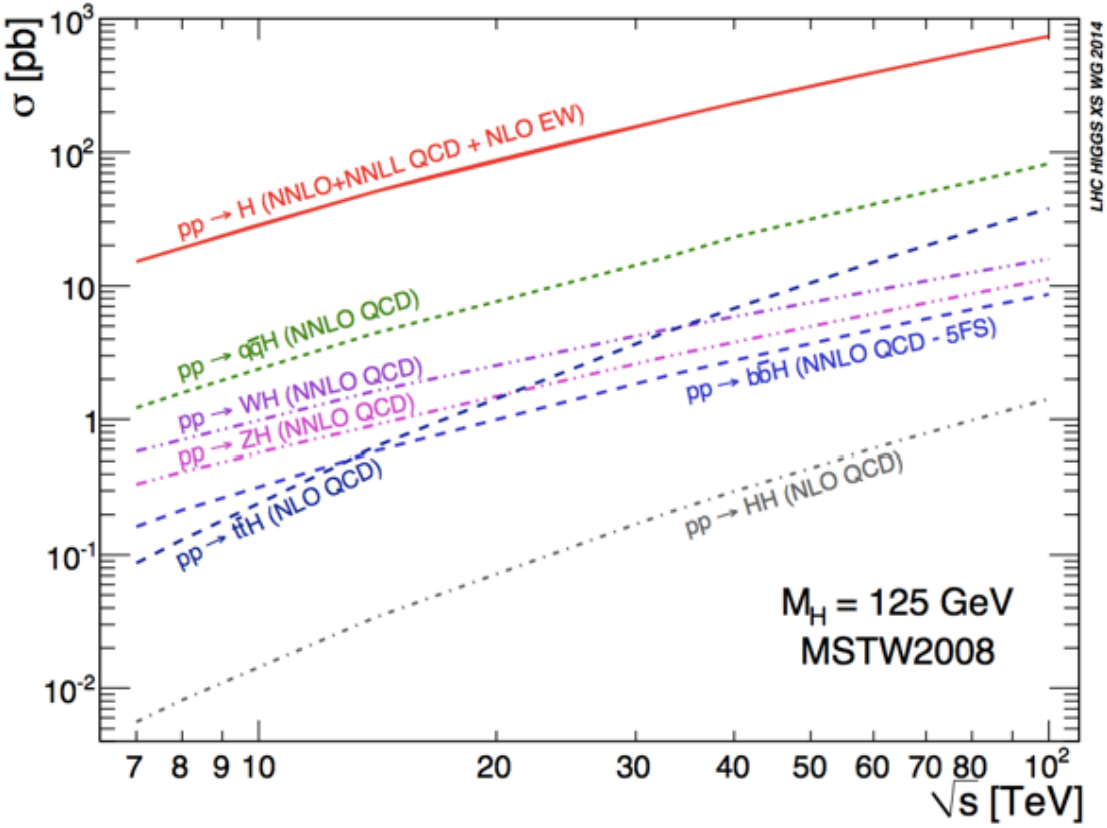


- L = 10 ab^{-1}: κ_e < 2.2 at 3σ (H in s-channel, under study)



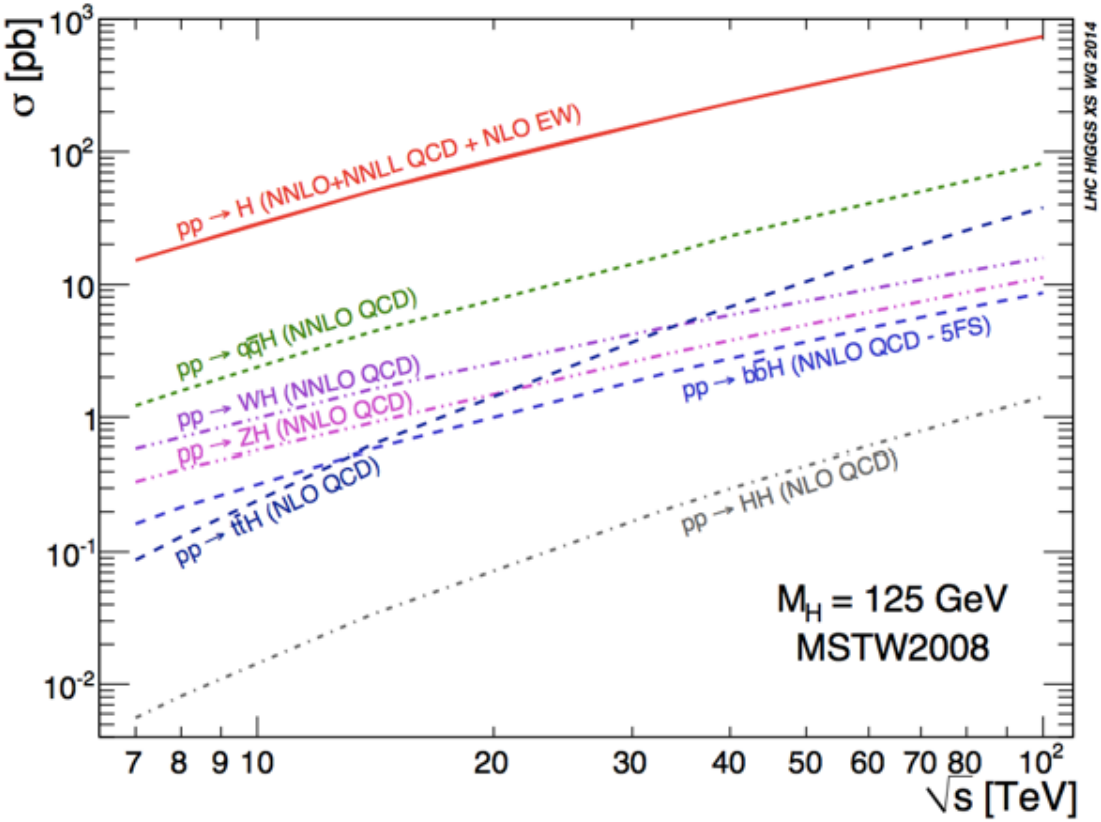
Exploiting the Higgs: FCC-hh

Process	8 TeV	14 TeV	100 TeV
gF	19.3 pb	50.35 pb	740.3 pb
VBF	1.58 pb	4.40 pb	82.0 pb
WH	0.70 pb	1.63 pb	15.9 pb
ZH	0.42 pb	0.90 pb	11.3 pb
ttH	0.13 pb	0.62 pb	37.9 pb
bbH	0.20 pb	0.58 pb	8.64 pb
gF to HH	8.15 fb	33.8 fb	1.42 fb



Exploiting the Higgs: FCC-hh

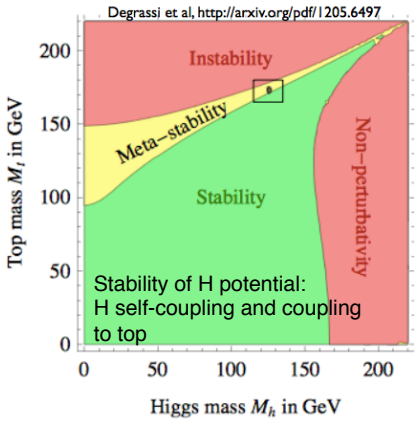
Process	8 TeV	14 TeV	100 TeV
gF	0.38	1	14.7
VBF	0.38	1	18.6
WH	0.43	1	9.7
ZH	0.47	1	12.5
ttH	0.21	1	61
bbH	0.34	1	15
gF to HH	0.24	1	42



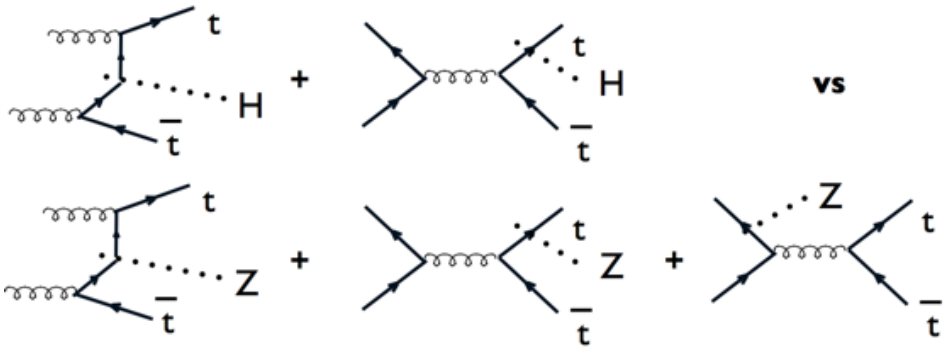
Proton-proton Higgs datasets — **LHC Run I** → (**x300-600**) **HL LHC** → (**x10-400**) **FCC pp**

Higgs Physics Program: FCC-hh/ee

- Higgs self coupling
- Rare SM and non-SM decays
  - $\delta\kappa_\mu \cong 2\%$ (FCC-hh extrapolated from HL-LHC)
- BSM (heavy) Higgs boson production
- Cascade decays including Higgs bosons



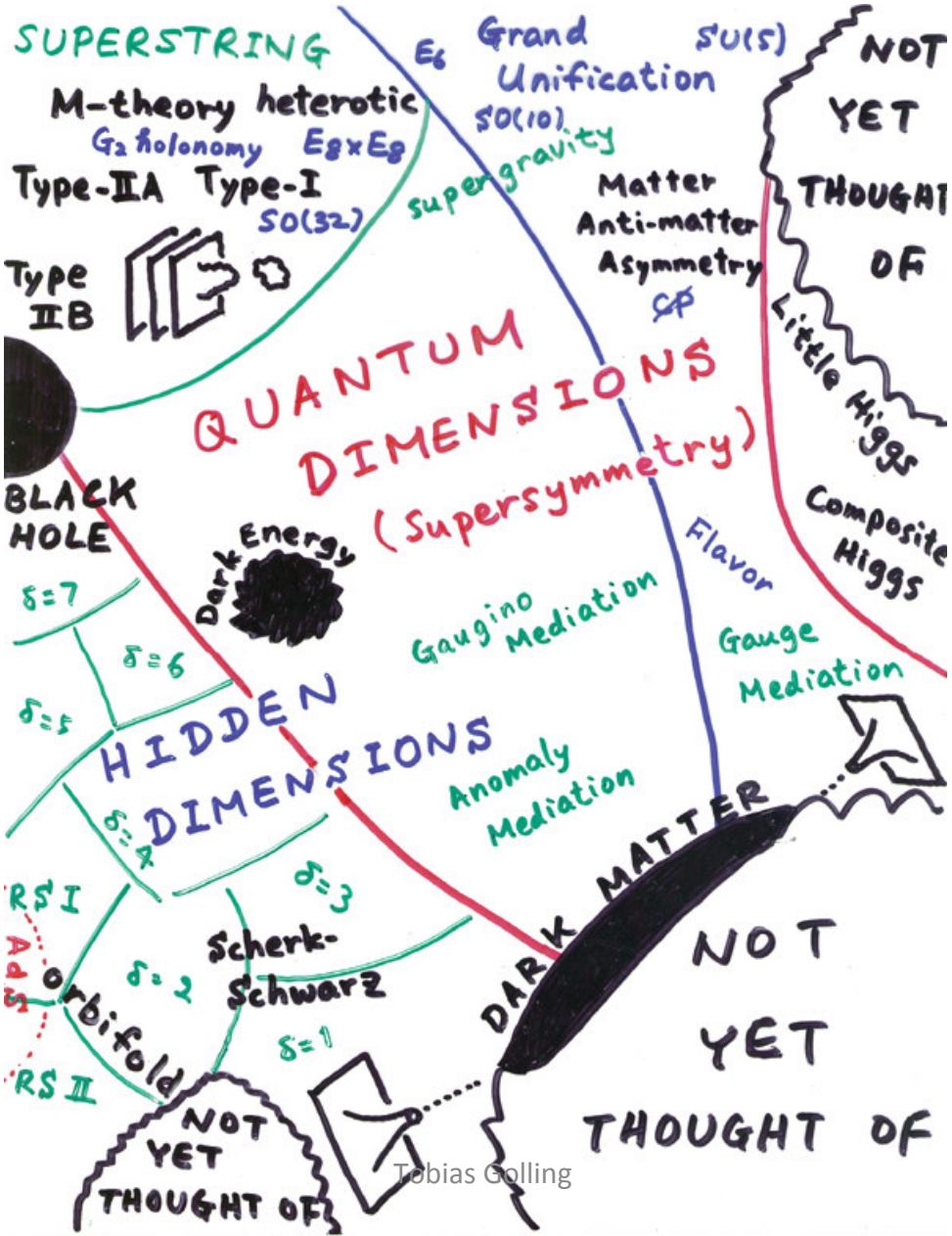
FCC-hh example: $t\bar{t}H/t\bar{t}Z$
e.g. BR(H→bb) from FCC-ee
⇒ measure top-Yukawa coupling with %-level precision



Complementarity, uncertainties in %, need significant theoretical improvements to exploit full potential

gH_{XY}	ZZ	WW	γγ	Zγ	tt	bb	ττ	cc	ss	μμ	uu,dd	ee	Γ_H	HH	BR_{exo}
FCC-ee	0.15	0.19	1.5			0.42	0.54	0.71	H→Vγ	6.2	H→Vγ	ee→H	0.9		<0.45
FCC-hh			<1?	1 ?	1 ?					2 ?				5 ?	$<10^{-6}$?

BSM

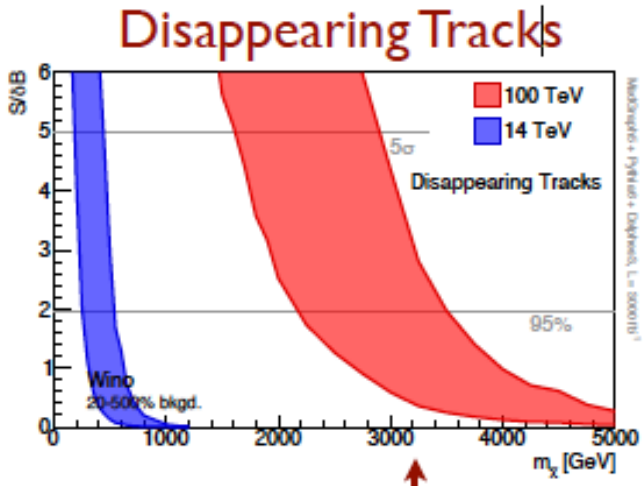

SUPERSTRING
M-theory heterotic
G_2 holonomy $E_8 \times E_8$
Type-IIA Type-I
SO(32)
Type IIB
E_6
Grand Unification
SU(5)
SO(10)
supergravity
NOT YET THOUGHT OF
Matter Anti-matter Asymmetry
CP
Little Higgs
Composite Higgs
QUANTUM DIMENSIONS (Supersymmetry)
BLACK HOLE
Dark Energy
Flavor
Gaugino Mediation
Gauge Mediation
Anomaly Mediation
HIDDEN DIMENSIONS
$\delta=7$
$\delta=6$
$\delta=5$
$\delta=4$
$\delta=3$
$\delta=2$
$\delta=1$
RS I
AdS
RS II
orbifold
Scherk-Schwarz
DARK MATTER
NOT YET THOUGHT OF
NOT YET THOUGHT OF

Dark Matter @ FCC-hh

See arxiv:1404.0682
Also arXiv:1311.6480

e.g. Pure Wino-like DM
(electroweak triplet):

$\chi^{\pm}$
χ^{0} ⇝ $\Delta m \gtrsim m_{\pi+}$



Thermal Relic Expectation
(non-thermal/partial DM equally plausible)

Probe TeV WIMP thoroughly

Final Word on Naturalness?

* Tuning probe $\propto E_{CM}^2$
* Higgs + nothing else @ 100 TeV
$\Rightarrow \sim 10^{-4}$ tuning!
* Never seen this level of tuning in particle physics.
* Qualitatively new, mortal blow to naturalness

Even more surprising things could be found:

~10 TeV scale

$H_2 \sim 1$ TeV

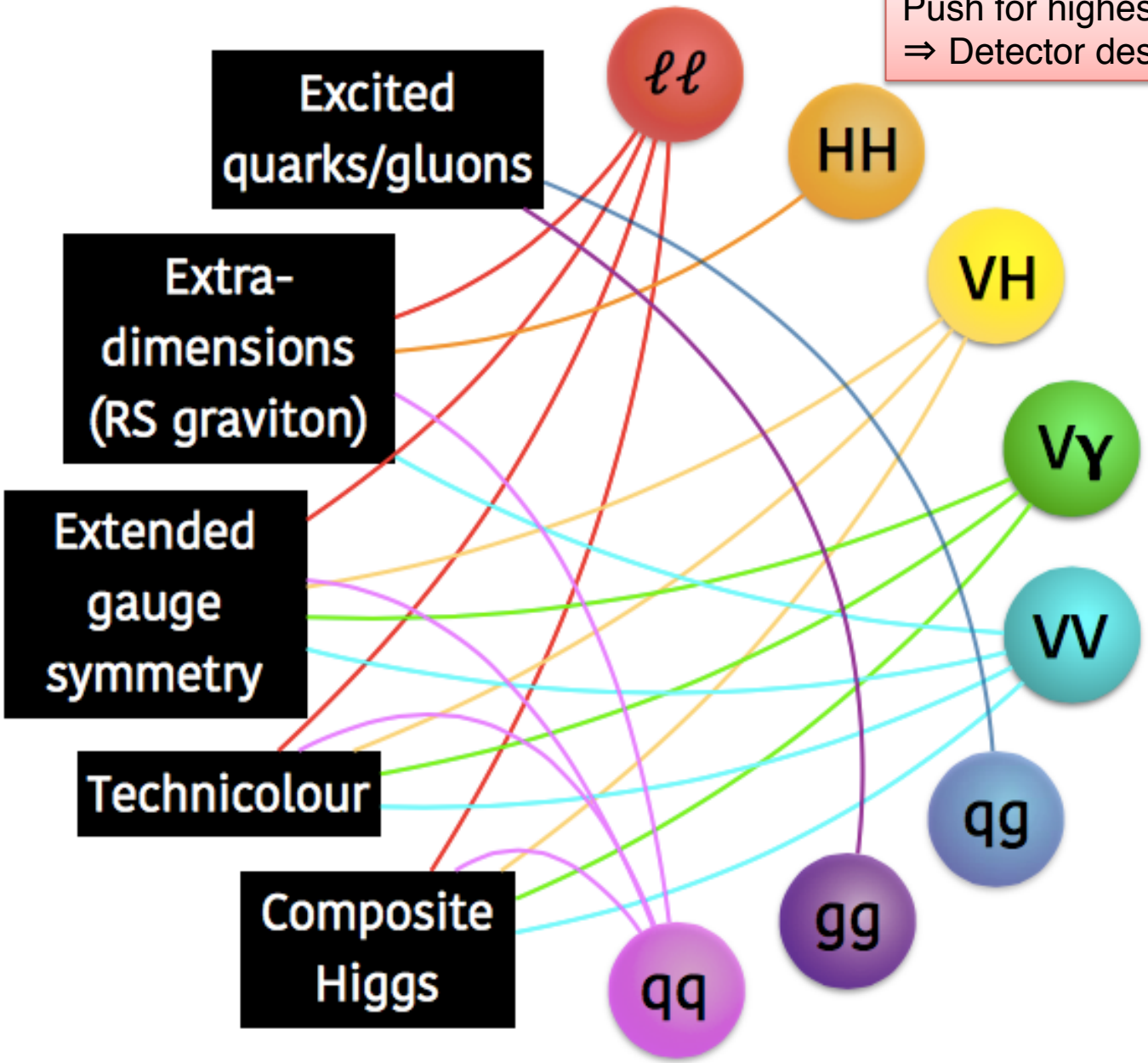
$H_1 \sim 125$ GeV

* Tuning $\sim (10^{-4}) \times (10^{-2}) \sim 10^{-6}$!
* Kills "anthropic" explanations

N. Arkani-Hamed, FCC Kickoff

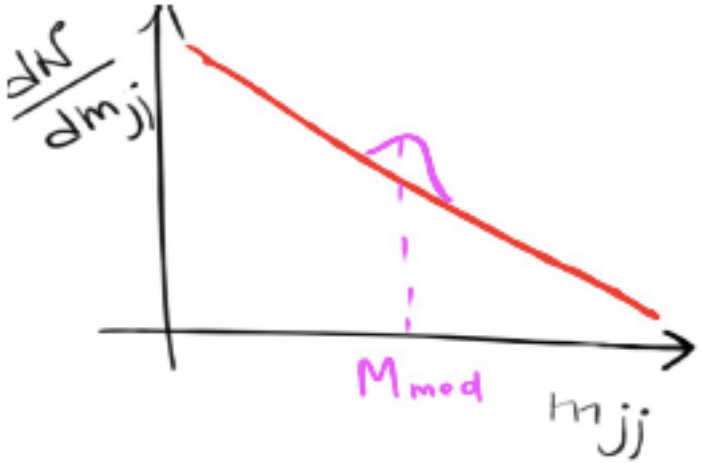
Example: Resonances

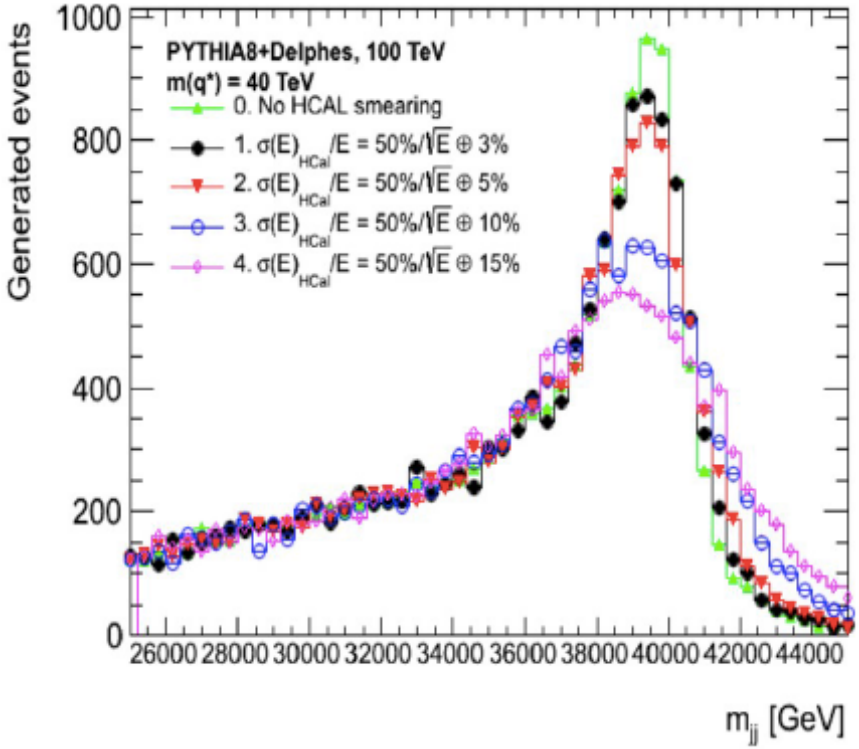
Push for highest mass reach
⇒ Detector design



Dijet Resonance Searches

Example: q* (40 TeV) → $q\bar{q}$





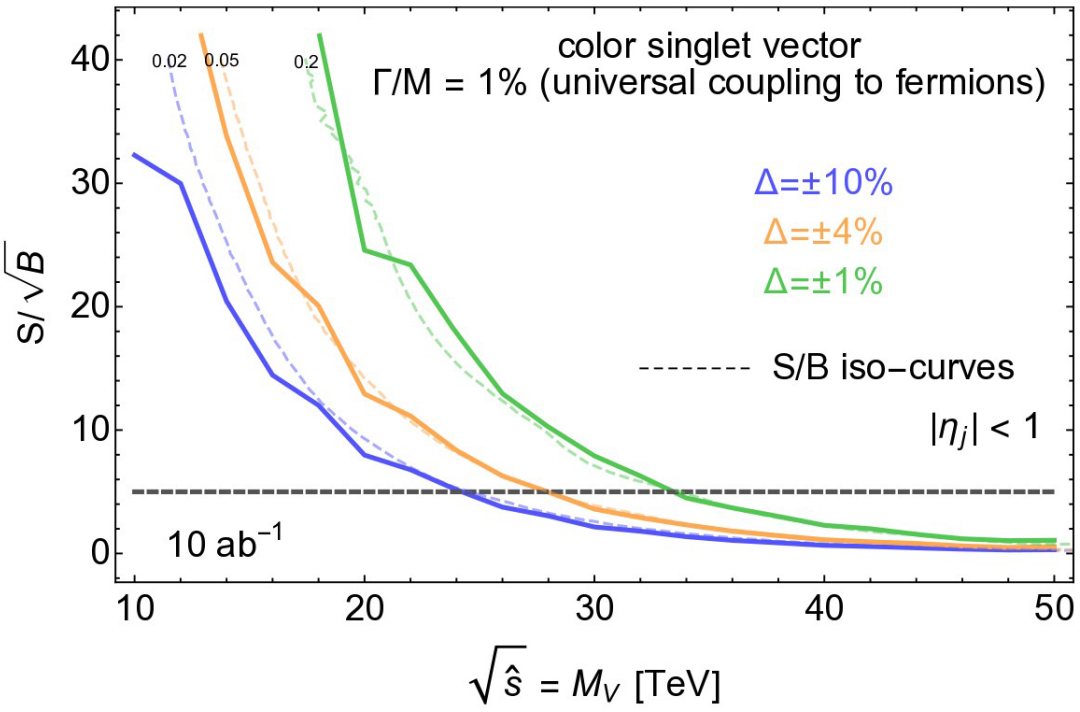
$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- Resolution hypotheses using Delphes
- Broadening of q* dijet mass for large E_T
- Depends on the constant term “C”

http://indico.cern.ch/event/352868/session/6/contribution/18/material/slides/0.pdf

Dijet Resonance Searches

Detector resolution smearing determines the achievable mass reach

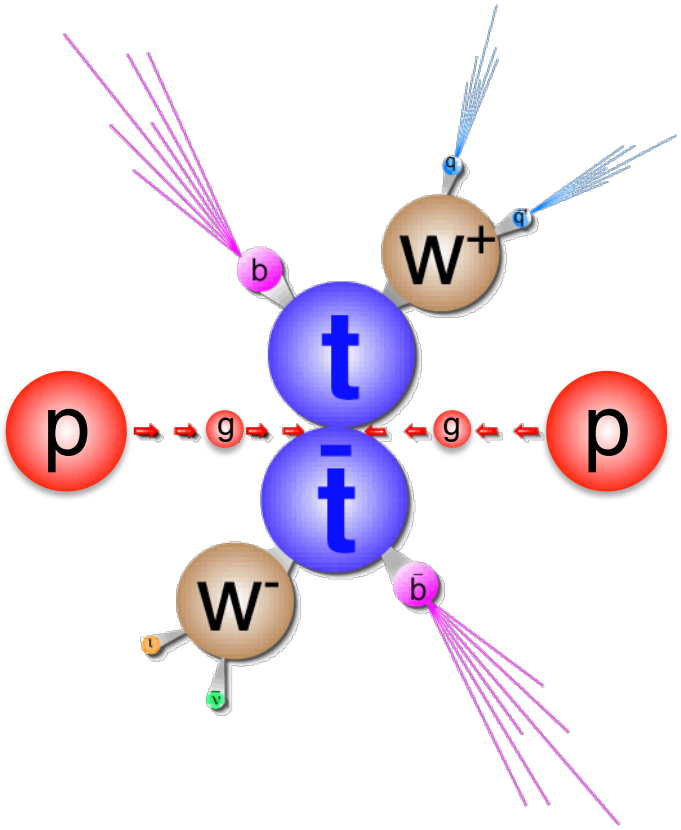


⇒ Impact on detector design

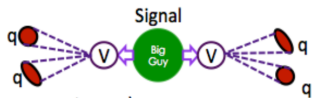
http://indico.cern.ch/event/352868/session/6/contribution/17/material/slides/

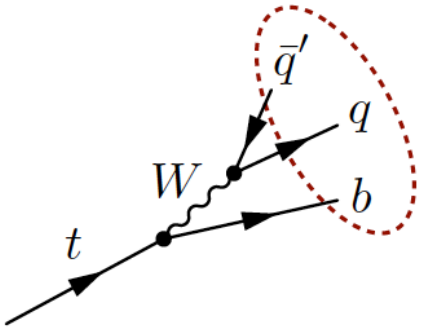
The Top Quark @ FCC-hh

- 10 ab^{-1} @ 100 TeV imply: 10^{12} top quarks
  - Precision measurements, rare decays, FCNC probes
  - 10^{12} b hadrons
  - 10^{12} W bosons
    - 10^{11} t→W→taus
      => few x10^{11} t → W → charm hadrons
    - ⇒ rare decays τ→3μ, μγ, CPV ⇒ rare decays D→μ+μ–, ..., CPV
- Optimize detector for object in 0.1 - 1 TeV region
- 5M top events with p_T(top)>3 TeV
- Search for X→$t\bar{t}$

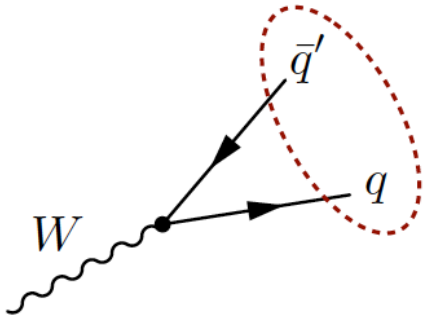


“Superboosted” Objects

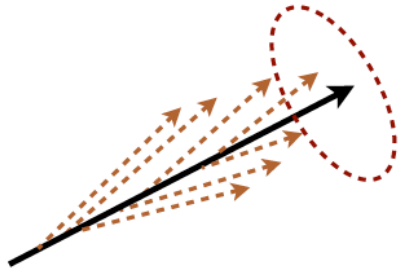




Boosted Top



Boosted W/Z/H



Quark/Gluon

<u>Superboosted jets</u>:

- “W/Z/H @ FCC looks like τ @ LHC”
- “top @ FCC looks like b @ LHC”

Substructure analyses may drive detector granularity / size

(+ new ideas how to deal with this, e.g. track-jets)

Detector Needs / Open Questions

- Calorimeter depth & resolution
  - 12 λ calorimetry, 1-2% constant term (high-p_T jets)
- Calorimeter lateral segmentation
  - Calorimeter granularity of 0.05x0.05 or 0.025x0.025 to mitigate pileup and measure jet substructure for superboosted top/W/Z/H
- Momentum resolution for multi-TeV muons
- Tracking in very dense environment
- High-p_T b-tagging, tau ID – possible at 100 TeV?
- Different detector designs pursued (2-4 IPs)
- Fast simulation crucial
- FCC-ee: adapt LEP/ILC/CLIC concepts, except for CW time structure

Concluding Remarks

- Physics opportunities for FCC being explored
- A lot of progress in last few years
- Still a lot to do for a conceptual design report in 2018
- If not we – who else? How can you get involved?
  - Attend meetings (see backup)
  - Pick up a small topic – talk to us
  - Great topics for e.g. a master student

Backup

Collaboration Status

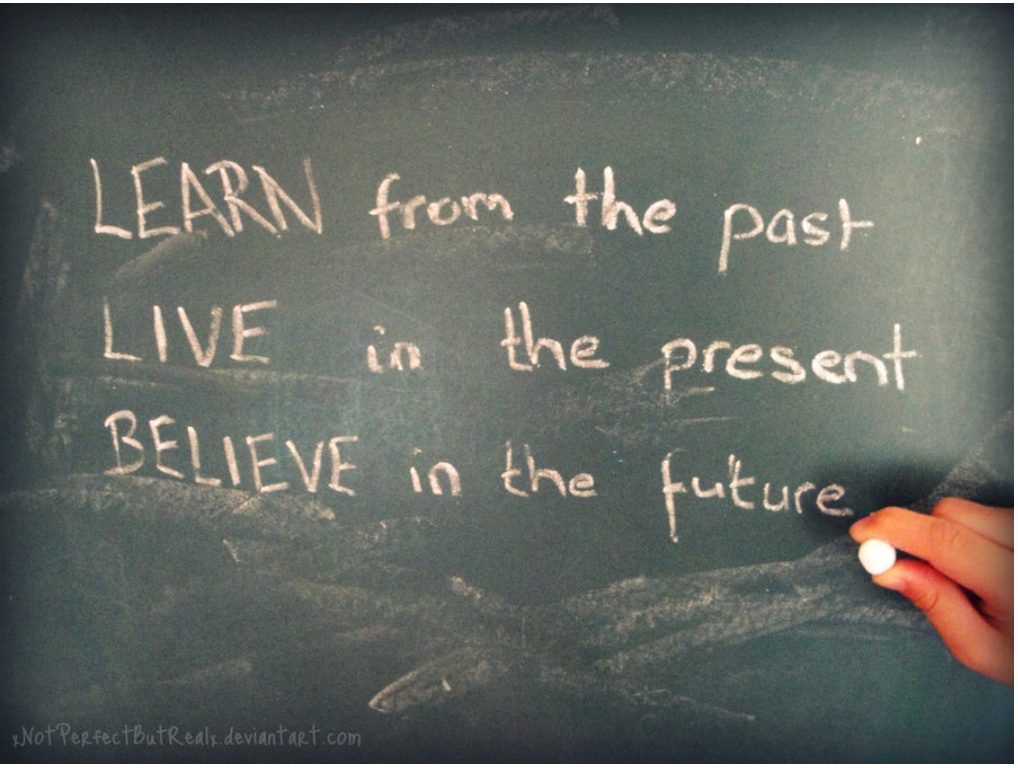
57 collaboration members & CERN as host institute, 29 June 2015

ALBA/CELLS, Spain
Ankara U., Turkey
U Belgrade, Serbia
U Bern, Switzerland
BINP, Russia
CASE (SUNY/BNL), USA
CBPF, Brazil
CEA Grenoble, France
CEA Saclay, France
CIEMAT, Spain
CNRS, France
Cockcroft Institute, UK
U Colima, Mexico
CSIC/IFIC, Spain
TU Darmstadt, Germany
DESY, Germany
TU Dresden, Germany
Duke U, USA
EPFL, Switzerland
GWNU, Korea
U Geneva, Switzerland
Goethe U Frankfurt, Germany
GSI, Germany
Hellenic Open U, Greece
HEPHY, Austria
U Houston, USA
IFJ PAN Krakow, Poland
INFN, Italy
INP Minsk, Belarus
U Iowa, USA
IPM, Iran
UC Irvine, USA
Istanbul Aydin U., Turkey
JAI/Oxford, UK
JINR Dubna, Russia
FZ Jülich, Germany
KAIST, Korea
KEK, Japan
KIAS, Korea
King's College London, UK
KIT Karlsruhe, Germany
Korea U Sejong, Korea
MEPhI, Russia
MIT, USA
NBI, Denmark
Northern Illinois U., USA
NC PHEP Minsk, Belarus
U. Liverpool, UK
U Oxford, UK
PSI, Switzerland
Sapienza/Roma, Italy
UC Santa Barbara, USA
U Silesia, Poland
TU Tampere, Finland
TOBB, Turkey
U Twente, Netherlands
Wroclaw UT, Poland

Some Links

- Software: https://twiki.cern.ch/twiki/bin/viewauth/FCC/FccSoftware
- Simulation: http://atlaswww.hep.anl.gov/hepsim/
- Regular meetings & workshops
  - https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider
  - cern.ch/fcc-ee
  - FCC-hh workshops: http://indico.cern.ch/category/6071/
  - FCC-hh informal meetings: http://indico.cern.ch/category/6067/

If not we – who else?



Learn from previous studies:
Italy (ELOISATRON 300km), USA (SSC 87km, VLHC 233km), Japan (TRISTAN-II 94km)

LHC Run 2 just started

FCC preparation needs to start now