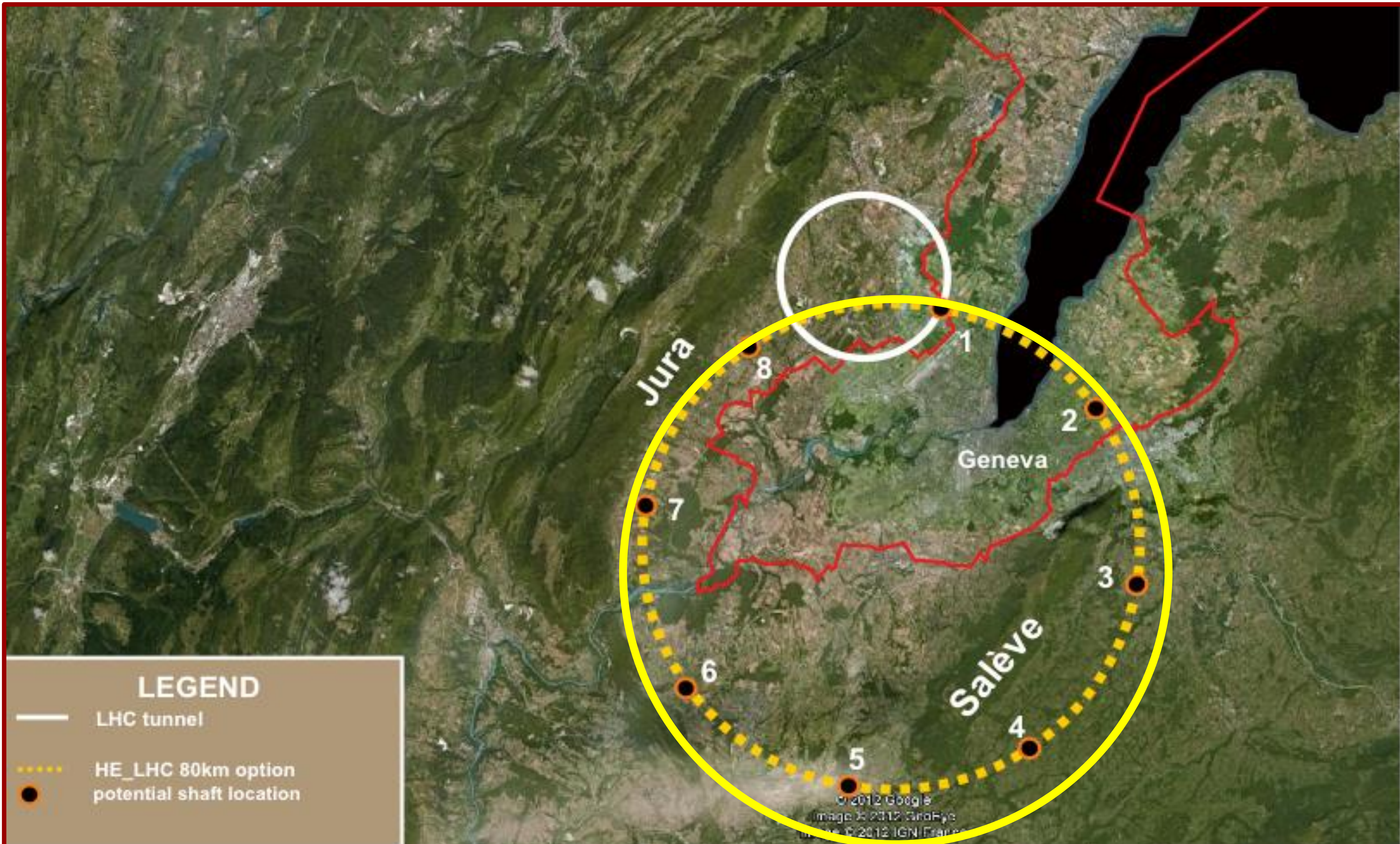
Future Circular Colliders (FCC) studies

Fabiola Gianotti (CERN)



From European Strategy deliberations

d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. *CERN should undertake design studies for accelerator projects **in a global context**, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, **in collaboration with national institutes, laboratories and universities worldwide**.*

- European ambition is energy frontier physics.
- The main motivation of the next ambitious machine is physics beyond Higgs.
- Cohegence with outside of Europe i.e. "global context" important

T. Nakada (European Strategy) | CERN | European Strategy for Particle Physics | CERN PH Meeting, Geneva, 30 September, 2013 | 12

In September 2013, CERN Management set up a FCC project, with the main goal of preparing a Conceptual Design Report by the time of the next ES (~2018)

CDR main scope is to describe physics motivations, technical feasibility (e.g. tunneling, magnets), design (machine, experiments, ..), cost

Project Leader: Michael Benedikt (CERN, Beam Department)

Emphasis on (and design driven by) high-energy pp collider requirements. An e^+e^- machine ("TLEP") and/or an ep machine could be built in the same tunnel if justified by physics in the international context (e.g. no ILC)

- A kick-off meeting is planned on 12-15 February 2014 (in full clash with ATLAS week … date driven by DG availability)
- Location: University of Geneva
- More details (including registration form) at: http://indico.cern.ch/conferenceDisplay.py?confId=282344

UNIVERSITÉ DE GENÈVE CERN FCC

Future Circular Colliders Study Kickoff Meeting

12-15 February 2014
University of Geneva, Geneva
Europe/Zurich timezone

Search

Future Circular Collider Kickoff Meeting

- Overview
- Organizing Committees
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This meeting is the starting point of a five-year international design study called "Future Circular Colliders" (FCC) with emphasis on a hadron collider with a centre-of-mass energy of the order of 100 TeV in a new 80-100 km tunnel as a long-term goal. The design study includes a 90-400 GeV lepton collider, seen as a potential intermediate step. It also examines a lepton-hadron collider option. The international kick-off meeting for the FCC design study will be held at the University of Geneva, Unimail site, on 12–15 February 2014. The scope of this meeting will be to discuss the main study topics and to prepare the groundwork for the establishment of international collaborations and future studies. The formal part of the meeting will start at noon on Wednesday 12 February and last until noon on Friday 14 February. It will be followed by break-out sessions on the various parts of the project on the Friday afternoon, with summary sessions until noon on Saturday 15 February.

FCC Study Scope and Structure

Future Circular Colliders - Conceptual Design Study for next European Strategy Update (2018)

Infrastructure

tunnels, surface buildings, transport (access roads), civil engineering, cooling ventilation, electricity, cryogenics, communication & IT, fabrication and installation processes, maintenance, environmental impact and monitoring, safety

Hadron injectors	Hadron collider	e+ e- collider
Beam optics and dynamics	Optics and beam dynamics	Optics and beam dynamics
Functional specs	Functional specifications	Functional specifications
Performance specs	Performance specs	Performance specs
Critical technical systems	Critical technical systems	Critical technical systems
Operation concept	Related R+D programs	Related R+D programs
	HE-LHC comparison	Injector (Booster)
	Operation concept	Operation concept
	Detector concept	Detector concept
	Physics requirements	Physics requirements

e- p option: Physics, Integration, additional requirements

Main areas for design study

Preparatory group for a kick-off meeting => Steering committee

Machines and infrastructure conceptual designs	Technologies R&D activities Planning	Physics experiments detectors
Infrastructure	High-field magnets	Hadron physics experiments interface, integration
Hadron collider conceptual design	Superconducting RF systems	$e^+ e^-$ coll. physics experiments interface, integration
Hadron injectors	Cryogenics	e^- - p physics and integration aspects
Lepton collider conceptual design	Specific technologies	
Safety, operation, energy management environmental aspects	Planning	

PP-131007-MBE_FCC Design Study

Here: focus on the pp part (FHC)

Team for kick-off and study preparation

Future Circular Colliders - Conceptual Design Study
Study coordination, host state relations, global cost estimate
Benedikt, Zimmermann

Hadron injectors
B. Goddard

VL Hadron collider
D. Schulte

Infrastructure, cost estimates
P. Lebrun

e+ e- collider
J. Wenninger

High Field Magnets
L. Bottura

Supercon-ducting RF
E. Jensen

Cryogenics
L. Tavian

Specific Technologies (MP, Coll, Vac, BI, BT, PO)
JM. Jimenez

Physics and experiments

Hadron physic Experiments, infrastructure
A. Ball, F. Gianotti, M. Mangano

e+ e- exper., physics
A. Blondel J.Ellis, P.Janot

e- p physics +
M. Klein

e- p option
Integration aspects **O. Brüning**

Operation aspects,
energy efficiency, OP & mainten., safety, environment.
P. Collier

Planning (Implementation roadmap, financial planning, reporting)
F. Sonnemann

PP-131007-MBE_FCC Design Study

Here: focus on the pp part (FHC)

FCC is intended to be an international study, involving colleagues from all over the world

→ Links established with other regions, e.g. US and China: R&D on high-field superconducting magnets, physics studies, cross-attendance of workshops, etc.

US:

- Snowmass studies, Summer 2013: http://snowmass2013.org/tiki-index.php?page=Energy+Frontier
- Physics at a 100 TeV Collider, SLAC, 23-25 April 2014: https://indico.fnal.gov/conferenceDisplay.py?confId=7633
- Next steps in the Energy Frontier: Hadron Colliders, FNAL, 28-21 July 2014

China:

- Future High-Energy Circular Colliders WS, Bejing, 16-17 December 2013: http://indico.ihep.ac.cn/conferenceDisplay.py?confId=3813
- 1st CFHEP (= Center for Future High Energy Physics) Symposium on Circular Collider Physics, Beijing, 23-25 February 2014: http://cfhep.ihep.ac.cn

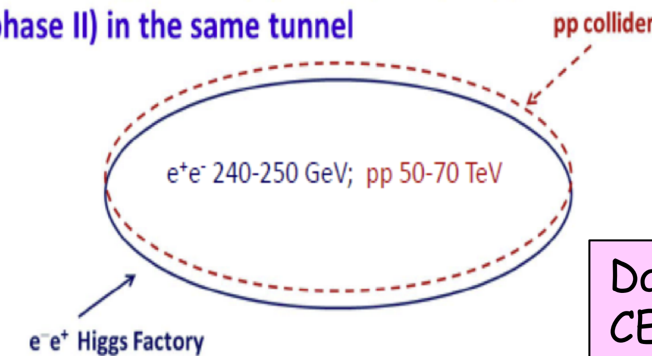
The Chinese plans

Yifang Wang, Director of IHEP Bejing,
Future High-Energy Circular Colliders WS,
Bejing, 16 December 2013

CEPC+SppC

- We are looking for a machine after BEPCII
- A circular Higgs factory fits our strategic needs in terms of timing, science goal, technological & economical scale, manpower reality, etc.
- Its life can be extended to a pp collider: great for the future

- Circular Higgs factory (phase I) + super pp collider (phase II) in the same tunnel



- ➢ Circular Higgs factory is complementary to ILC
  - ➢ Push-pull option
  - ➢ Low energy vs high energy

Data-taking:
CEPC: 2028-2035
SppC: 2042 -

We hope to collaborate with anyone who is willing to host this machine. Even if the machine is not built in China, the process will help us to build the HEP in China

Machine parameters: √s vs ring size and magnets

Facility	Ring (km)	Magnets (T)	√s (TeV)
(SSC)	87	6.6	40
LHC	27	8.3	14
HE-LHC	27	16-20	26-33
FHC	80 80 100	8.3 20 16	42 100 100

Note:

- ❑ big jump in technology from 15-16T magnets (Nb_3Sn) to 20T magnets (HTS)
- → the latter may require many more years of R&D than the former
- → optimum balance between tunnel size (cost ?) and magnet technology (time and cost ?)
- ❑ for a cost-affordable and technically-viable (big) machine need "routine" industrial production of magnets …

For the kick-off meeting, we agreed on the following baseline machine parameters.
They give similar pile-up as HL-LHC → can extrapolate from HL-LHC physics studies

Parameter	LHC	HL-LHC		HE-LHC	VHE-LHC
c.m. energy [TeV]	14			33	100
circumference C [km]	26.7				80
dipole field [T]	8.33			20	20
dipole coil aperture [mm]	56			40	≤ 40
beam half aperture [cm]	2.2 (x), 1.8 (y)			1.3	< 1.3
injection energy [TeV]	0.45			>1.0	>3.0
no. of bunches	2808	2808	1404	2808	8420
bunch population [10^{11}]	1.125	2.2	3.5	0.81	[illegible]
init. transv. norm. emit. [μm]	3.73,	2.5	3.0	1.07	1.70
initial longitudinal emit. [eVs]	2.5			3.48	13.6
no. IPs contributing to tune shift	3	2	2	2	2
max. total beam-beam tune shift	0.01	0.021	0.028	0.01	0.01
beam circulating current [A]	0.584	1.12	0.089	0.412	0.401
RF voltage [MV]	16			16	22
rms bunch length [cm]	7.55			7.55	7.55
IP beta function [m]	0.55	0.73 → 0.15		0.3	0.9
init. rms IP spot size [μm]	16.7	15.6 → 7.1	24.8 → 7.8	4.3	5.3

	LHC	HL-LHC	HE-LHC	VHE-LHC
Stored energy [MJ]	362	694	601	4573
Peak luminosity [10^{34} cm^{-2}s^{-1}]	1	(7.4)	5	5

Note: table being remade now, some parameters may change slightly

Bunch-spacing: 25 ns

Average pile-up: ~140/xing

In parallel and longer-term: optimize machine parameters for highest possible integrated luminosity with smallest possible pile-up: considering bunch spacing down to 5 ns (can detector benefit from bunch spacing smaller than 25 ns ?)

Physics case and goals

This is one of the main goals of the CDR
→ will need to be studied in detail in the years to come …

Two scenarios:

- ❑ LHC and/or HL-LHC find new physics:
  the heavier part of the spectrum may not be fully accessible at $\sqrt{s}$ ~ 14 TeV
  → strong case for a 100 TeV pp collider: complete the spectrum and measure it in some detail
- ❑ LHC and/or HL-LHC find indications for the scale of new physics being in the 10-50 TeV region (e.g. from dijet angular distributions → Compositeness)
  → strong case for a 100 TeV pp collider: directly probe the scale of new physics

LHC and HL-LHC find NO new physics and indications of the next scale:

- ❑ several Higgs-related questions (naturalness, HH production, $V_L V_L$ scattering) call for high-E machine (higher than a 1 TeV ILC)
- ❑ a significant step in energy, made possible by strong technology progress (from which society also benefits), is the only way to look directly for the scale of new physics

Where is the scale of new physics ?

The present paradox ….

On one hand, the LHC results imply that the SM technically works up to scales much higher than the TeV scale, and limits on new physics seriously challenge the simplest attempts (e.g. minimal SUSY) to fix its weaknesses

On the other hand: there is strong evidence that the SM must be modified with the introduction of new particles and/or interactions at some energy scale to address fundamental outstanding questions, including: naturalness, dark matter, matter/antimatter asymmetry, the flavour/family problems, incorporating gravity in quantum field theory, etc.

No theoretical/experimental preference today for new physics in the 10-50 TeV region.

However: the above and other (BIG, IMPORTANT) questions require concerted efforts to be addressed successfully, using all possible approaches: astroparticles, precision experiments, neutrino physics, high-E colliders, …

The two main goals (Higgs boson and new/heavy physics) are quite different in terms of machine and detector requirements:

Exploration of E-frontier → look for heavy objects, including high-mass $V_L V_L$ scattering:
- requires as much integrated luminosity as possible (cross-section goes like 1/s)
  → maximising mass reach may require operating at higher pile-up than HL-LHC
- events are mainly central → ATLAS/CMS-like geometry is ok
- main experimental challenges: muon momentum resolution up to ~50 TeV; size of detector to contain up to ~50 TeV showers; forward jet tagging; pile-up

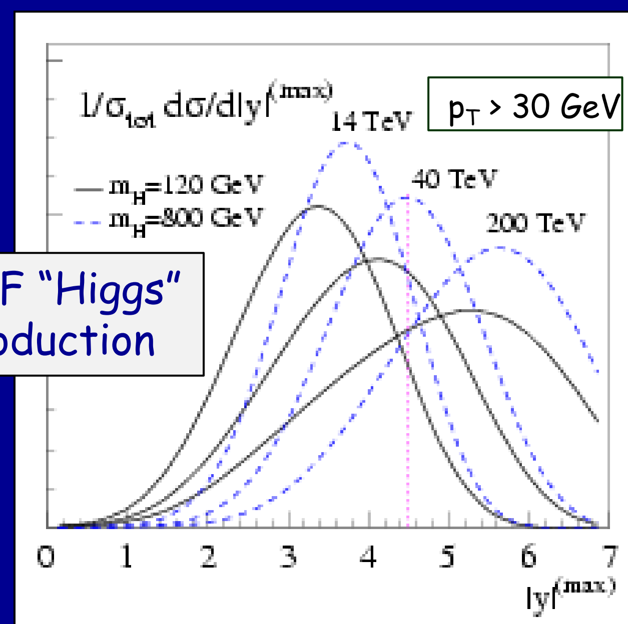
Precise measurements of Higgs boson (beyond HL-LHC and TLEP/ILC-if-any):
- would benefit from moderate pile-up
- light-objects (Higgs !) production becomes flatter in rapidity with increasing $\sqrt{s}$
- main experimental challenges: higher acceptance for precision physics than ATLAS/CMS: tracking/B-field and good EM granularity down to $|\eta|$~4-5 ?; forward jet tagging; pile-up

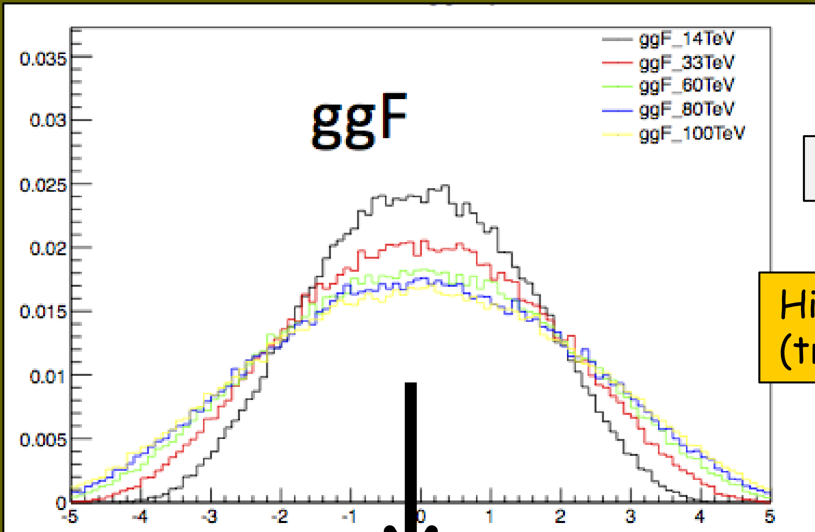
Forward jet tag expected to be crucial for both, Higgs and VV scattering studies

Maximum jet rapidity vs $\sqrt{s}$
(from an old US-VLHC study)

→ Calo coverage up to $|\eta|$ ~ 6 needed

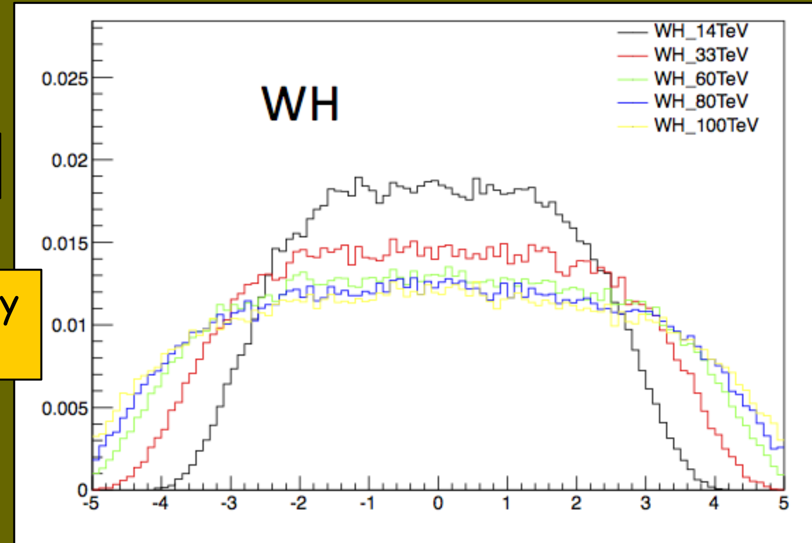
VBF "Higgs" production





C. Helsen

Higgs rapidity (truth level)

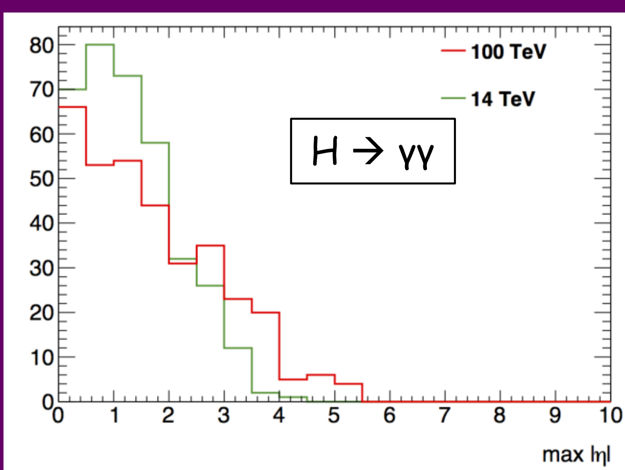


Higgs acceptance vs η coverage: ggF only; standard photons and leptons p_T cuts applied

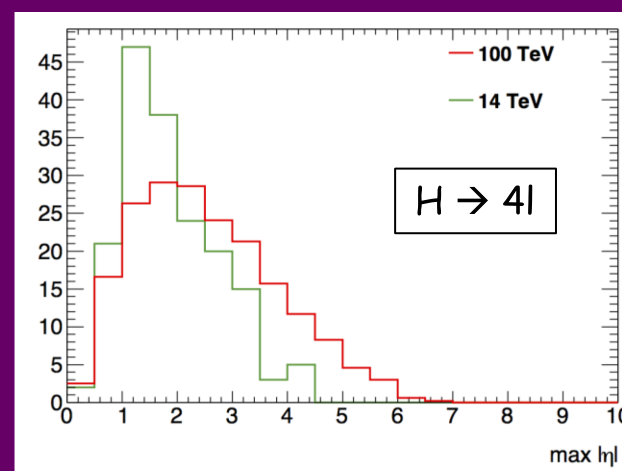
$H \rightarrow \gamma\gamma$	14 TeV	100 TeV
$\lvert\eta\rvert < 2.5$ $\lvert\eta\rvert < 4$	0.96 1.0	0.83 0.97

H. Gray

$H \rightarrow 4l$	14 TeV	100 TeV
$\lvert\eta\rvert < 2.5$ $\lvert\eta\rvert < 4$	0.87 1.0	0.66 0.91

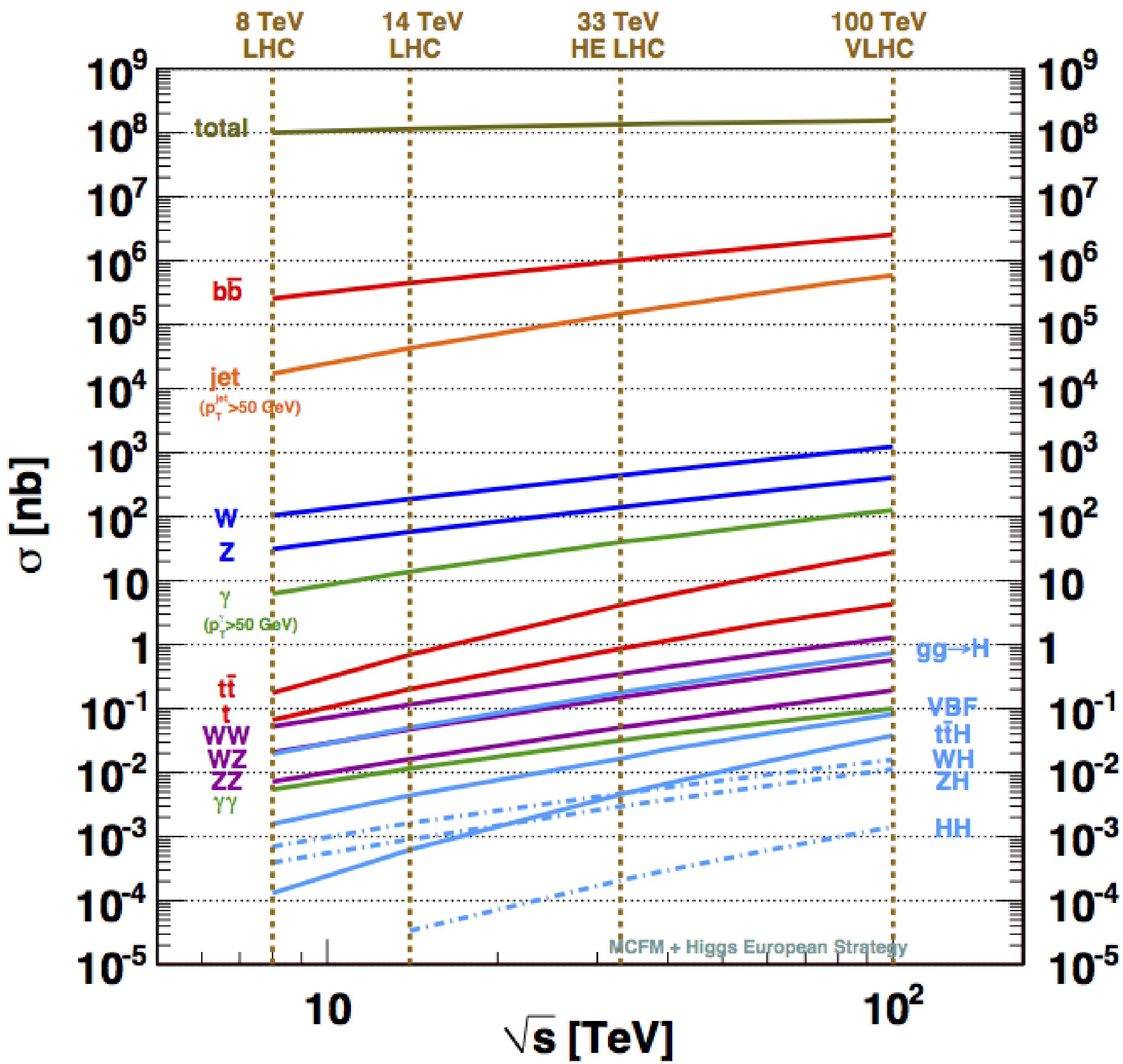


Rapidity of most forward γ/lepton



Cross sections vs √s

Snowmass report: arXiv:1310.5189



Process	R(100 TeV/14 TeV)
W	6.7
Z	7.2
WW	9.6
ZZ	10.3
tt	~ 30
bb	~ 3

Studies will be made vs √s:
- comparison with HE-LHC
- if cost forces machine staging

Process	√s = 14 TeV	√s = 33 TeV	√s = 40 TeV	√s = 60 TeV	√s = 80 TeV	√s = 100 TeV
ggF [a]	50.35 pb	178.3 pb (3.5)	231.9 pb (4.6)	394.4 pb (7.8)	565.1 pb (11.2)	740.3 pb (14.7)
VBF [b]	4.40 pb	16.5 pb (3.8)	23.1 pb (5.2)	40.8 pb (9.3)	60.0 pb (13.6)	82.0 pb (18.6)
WH [c]	1.63 pb	4.71 pb (2.9)	5.88 pb (3.6)	9.23 pb (5.7)	12.60 pb (7.7)	15.90 pb (9.7)
ZH [c]	0.904 pb	2.97 pb (3.3)	3.78 pb (4.2)	6.19 pb (6.8)	8.71 pb (9.6)	11.26 pb (12.5)
ttH [d]	0.623 pb	4.56 pb (7.3)	6.79 pb (11)	15.0 pb (24)	25.5 pb (41)	37.9 pb (61)
$gg \rightarrow HH^{e}(\lambda=1)$	33.8 fb	207 fb (6.1)	298 fb (8.8)	609 fb (18)	980 fb (29)	1.42 pb (42)

Higgs cross sections (LHC HXS WG)

Why Higgs physics in 2040++ ?

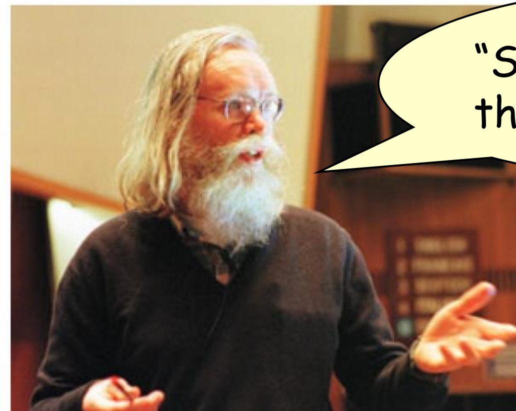
HH production (including self-couplings) difficult at any facility (√s mainly needed ..)

	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000	500	1600‡	500/1000	1600/2500‡	1500	+2000	3000	3000
λ	[redacted]	83%	46%	21%	13%	21%	10%	20%	8%

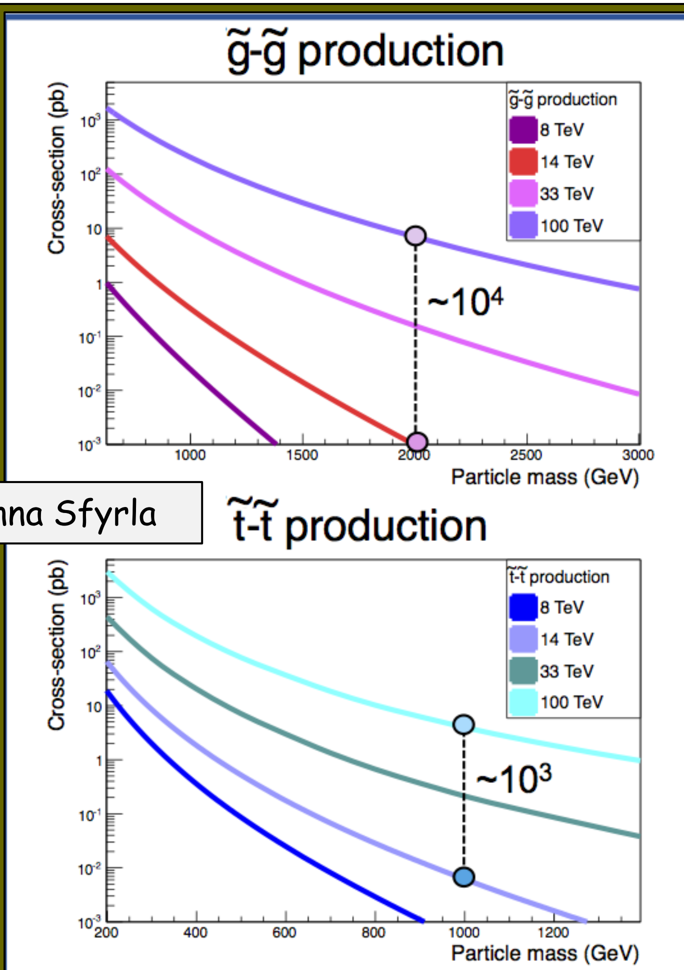
Plus "rare" (clean) processes, e.g. ttH→ ttμμ, ttZZ

Why still SUSY in 2040++ ?

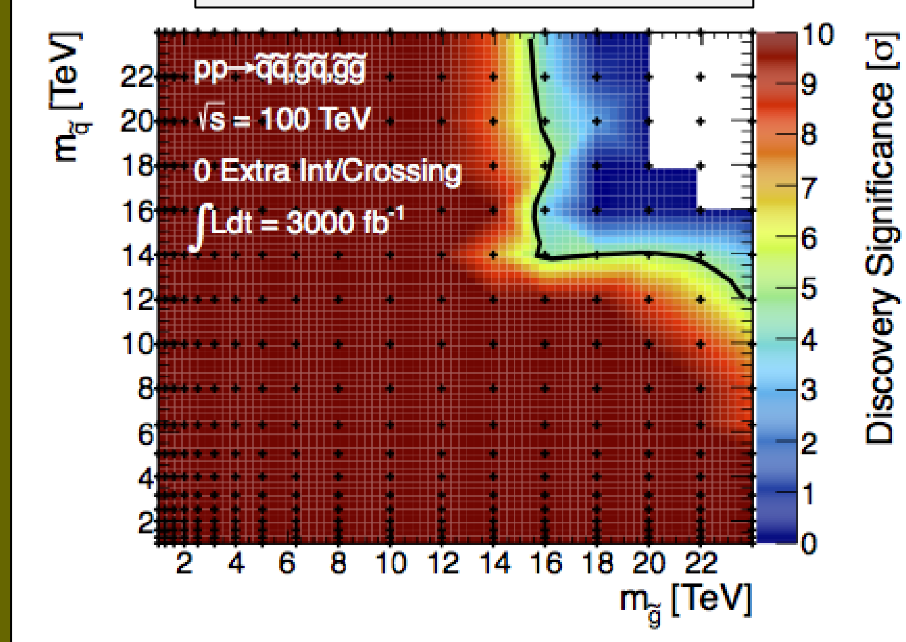
Indeed, even if fine-tuned,
it makes our universe more likely



Anna Sfyrla



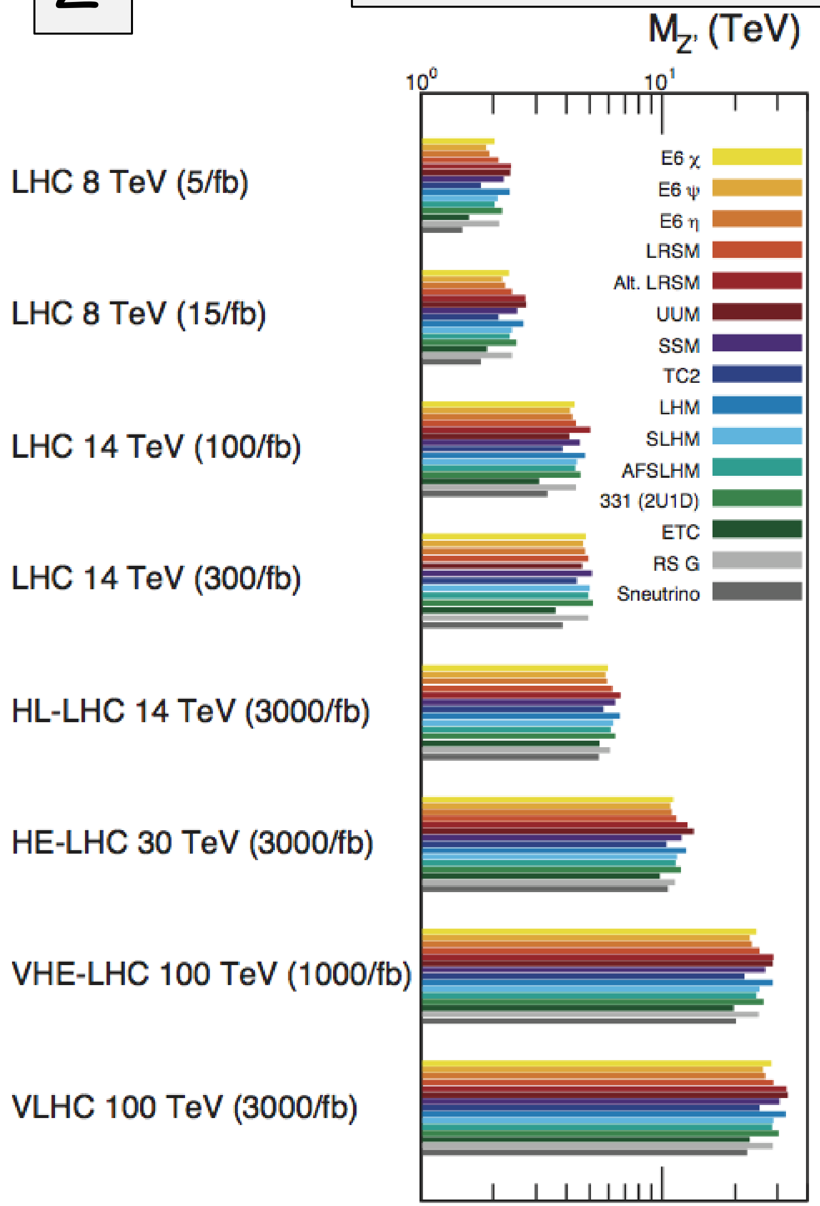
Snowmass report: arXiv:1311.6480



Squarks and gluinos discovery up to ~ 14 TeV

Z′

Snowmass report: arXiv:1309.1688



Expected reach in q* (strongly produced): M ~ 50 TeV

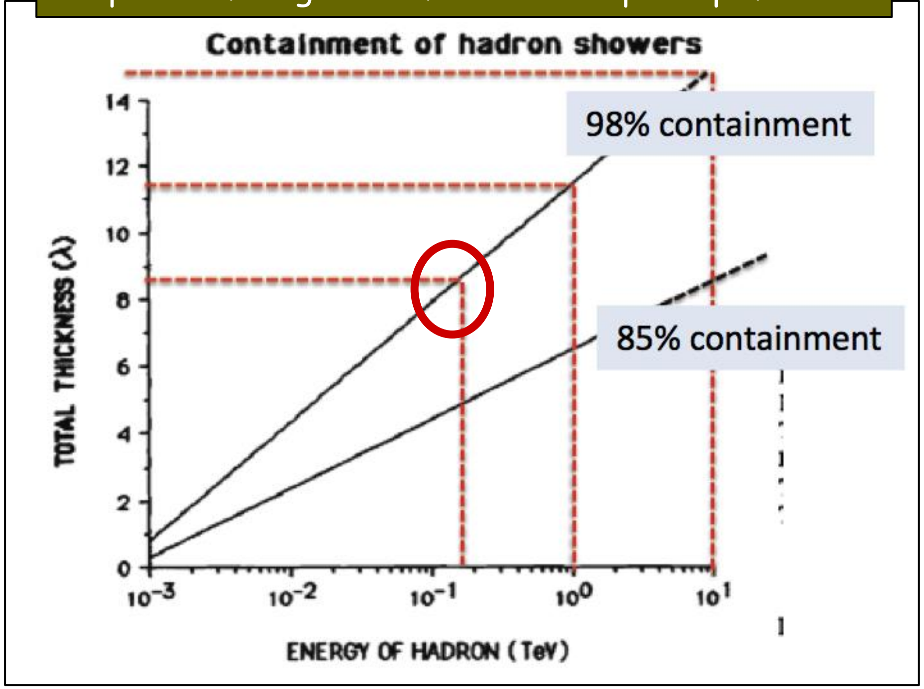
First ideas on detector layout

D.Fournier, A. Henriques,
H. TenKate, L.Pontecorvo,
J. VanNugteren, S.Vlachos, F.G.

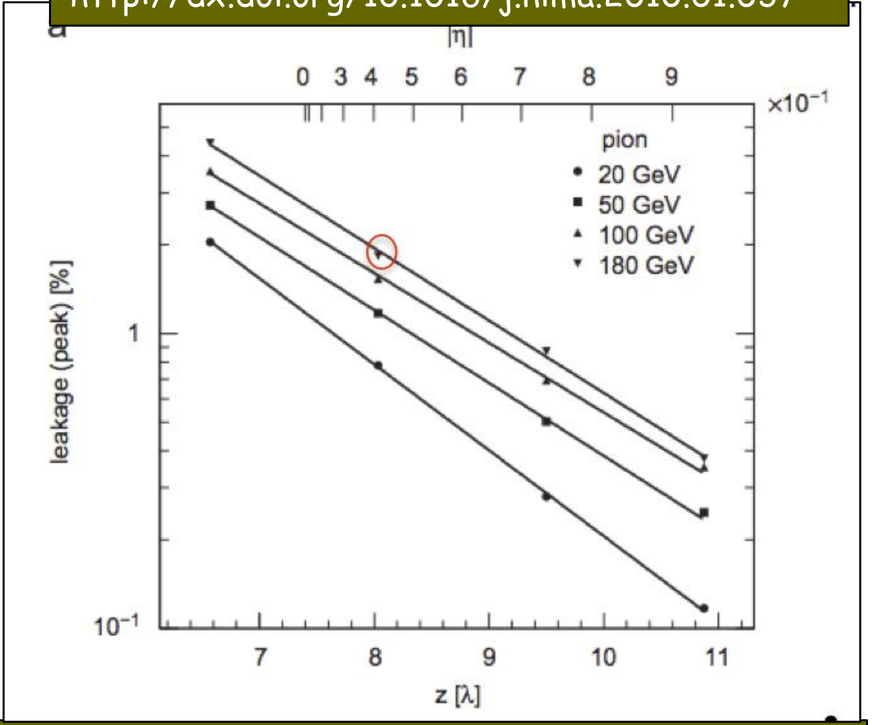
Main guidelines

- Muon momentum resolution in multi-TeV region: x 5-10 better than in ATLAS (BL^2 !)
- Tracking and precision-ECAL coverage up to $|\eta| \sim 4$-5
- Forward jet tagging up to $|\eta| \sim 5$-6
- Shower containment for up to 50 TeV jets

Single hadron shower containment (SSC)
http://lss.fnal.gov/conf/C860623/p355.pdf



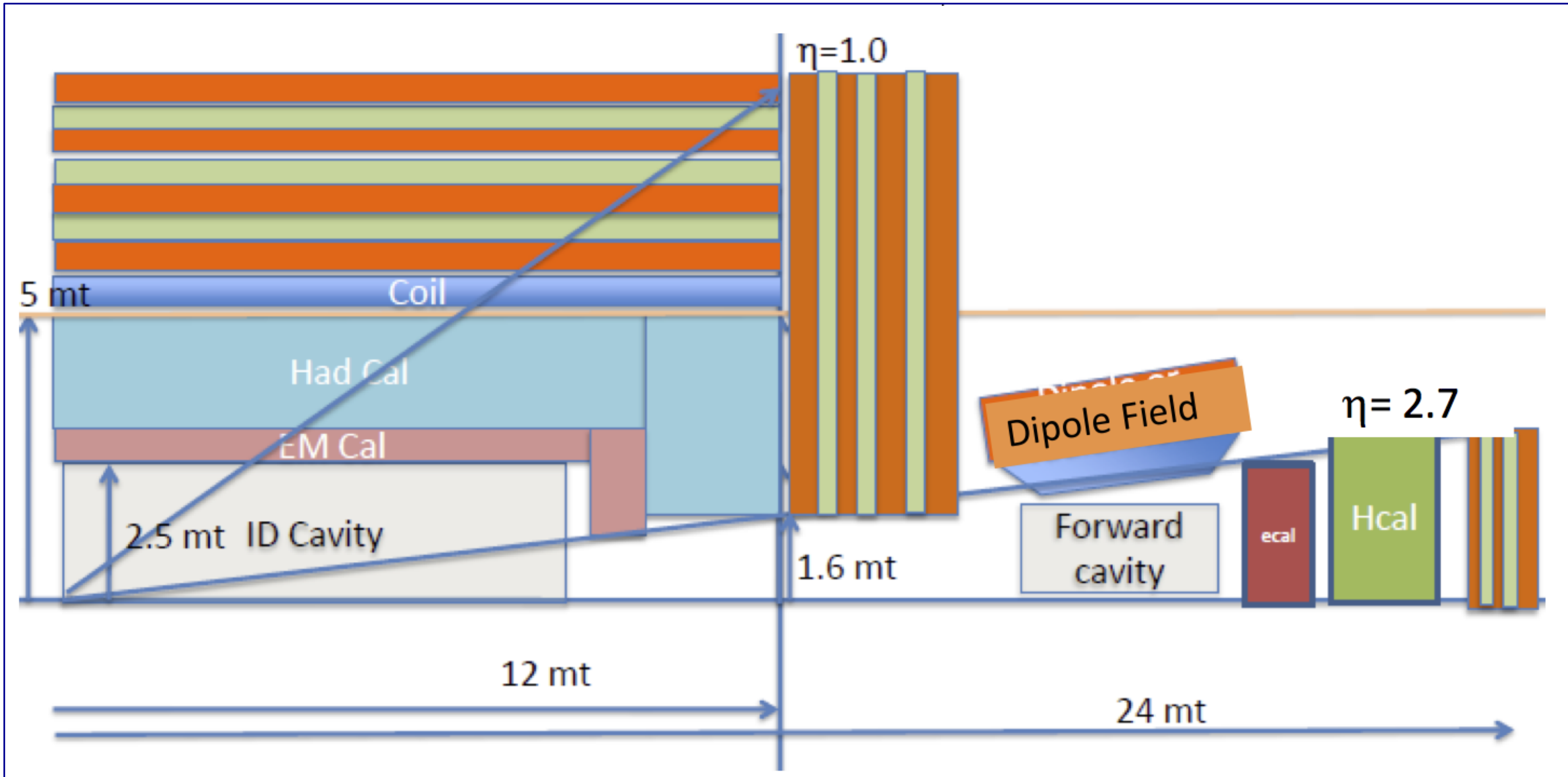
Validated with Tilecal test-beam data
http://dx.doi.org/10.1016/j.nima.2010.01.037



→ Not less than 12λ to contain 10-50 TeV jets (containing few 1-10 TeV single hadrons)

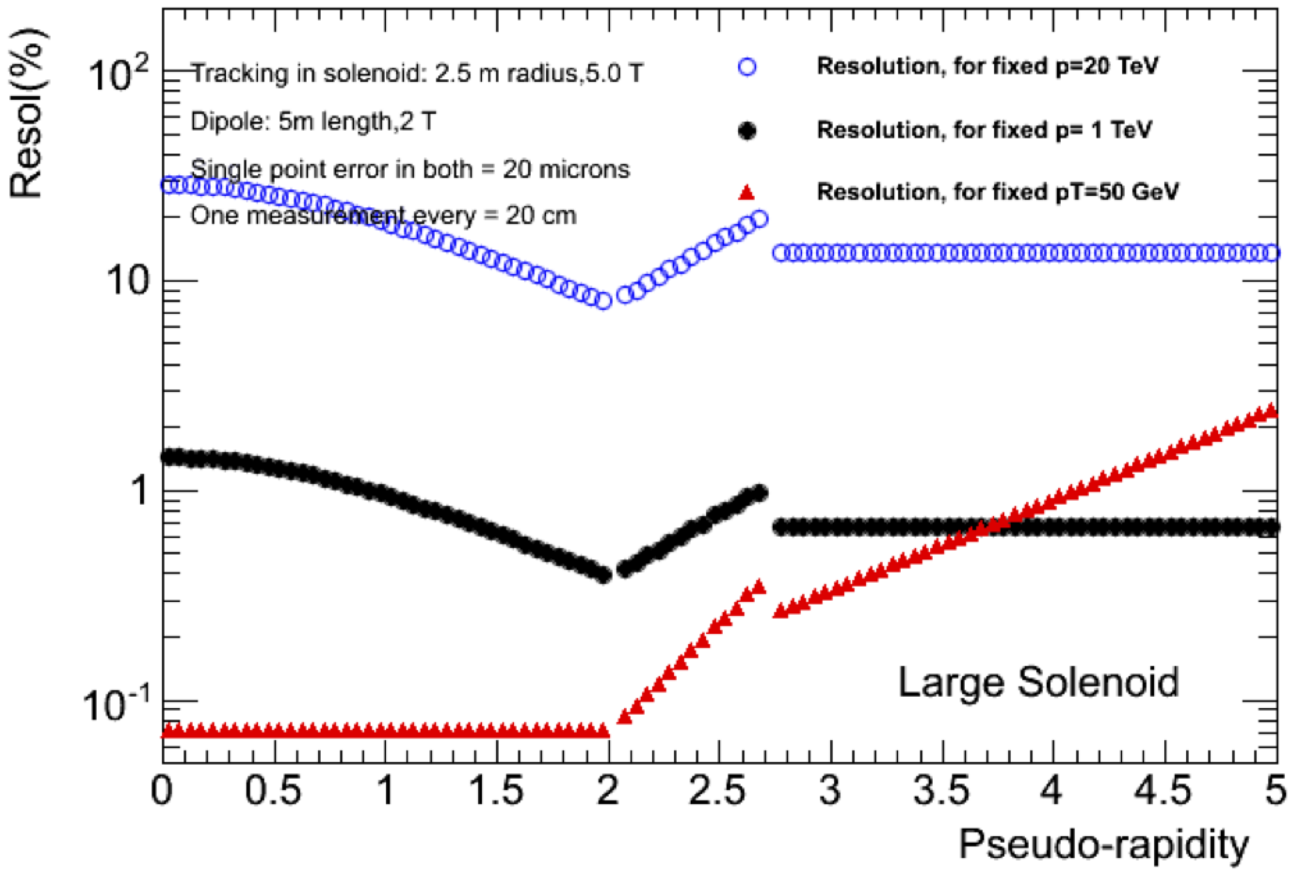
Layout 1 : Solenoid ("à la CMS")

D.Fournier, A. Henriques, H. TenKate,
L.Pontecorvo, J. VanNugteren, S.Vlachos, F.G.



- Solenoid: B=5T, R_{in}=6m (5m here, to be changed as not enough space for calorimeters); size is x2 CMS. Stored energy: ~ 50 GJ
- Forward dipole: 10 Tm
- > 50 000 m^3 of Fe → alternative: use thin (twin) lower-B solenoid at larger R to capture return flux of main solenoid ?
- 1.9K (instead of 4.5 K) operation would increase field by 1.5T for same coil
- Calorimeters: speed is an issue → Fe better than W (HCAL), Si better than LAr (EM) ?

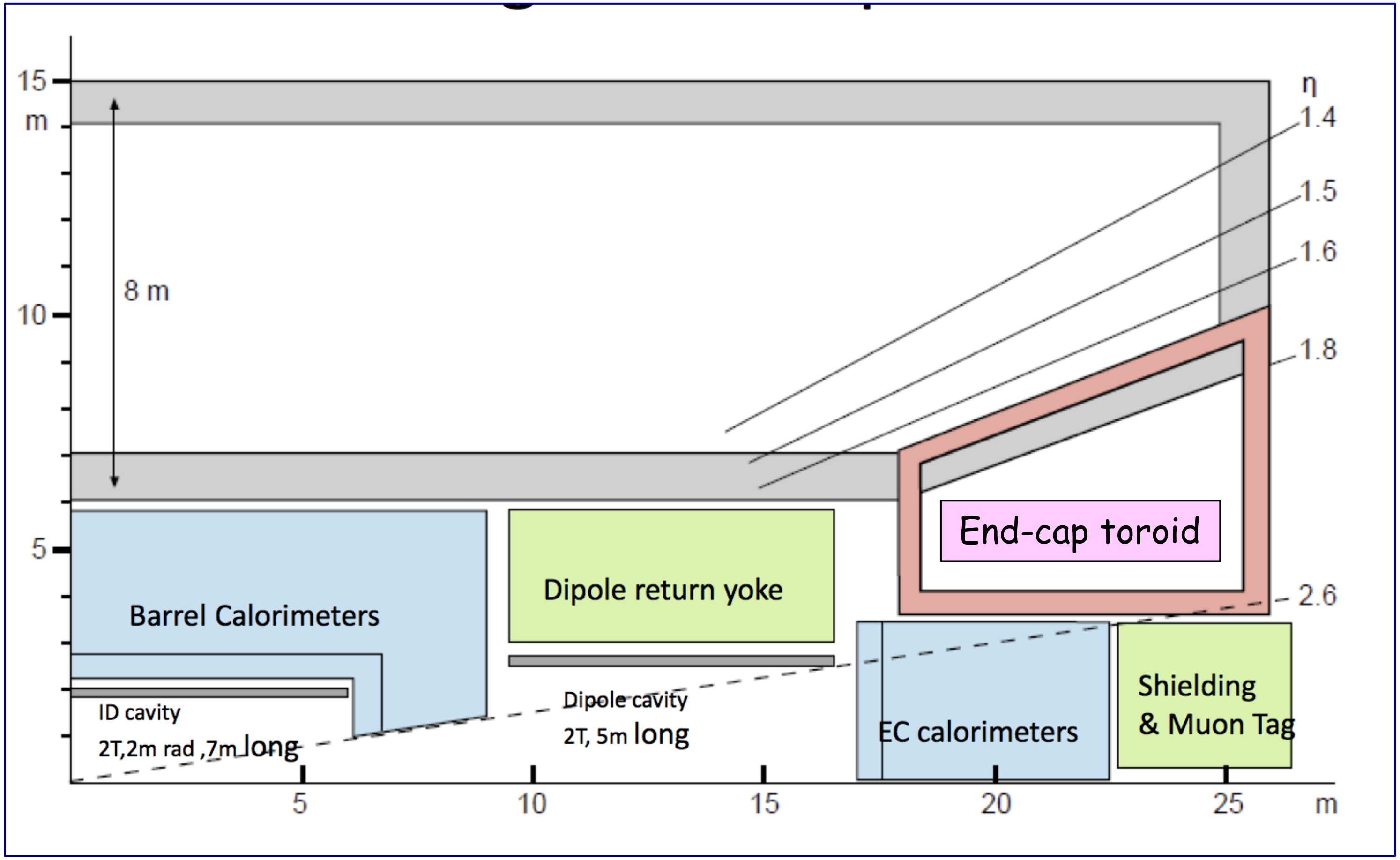
Ideal resolution: no multiple scattering, no misalignment



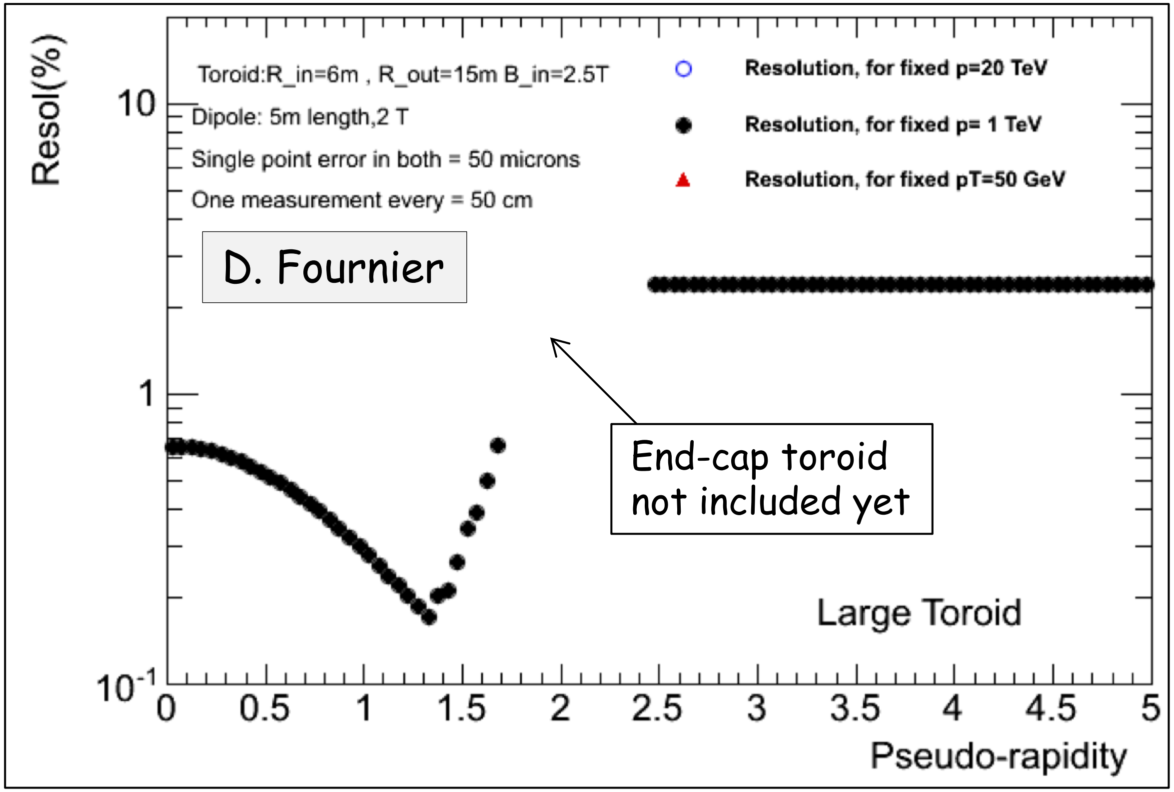
D. Fournier

CMS:
12% at 1 TeV

Layout 2 : Toroid ("à la ATLAS")

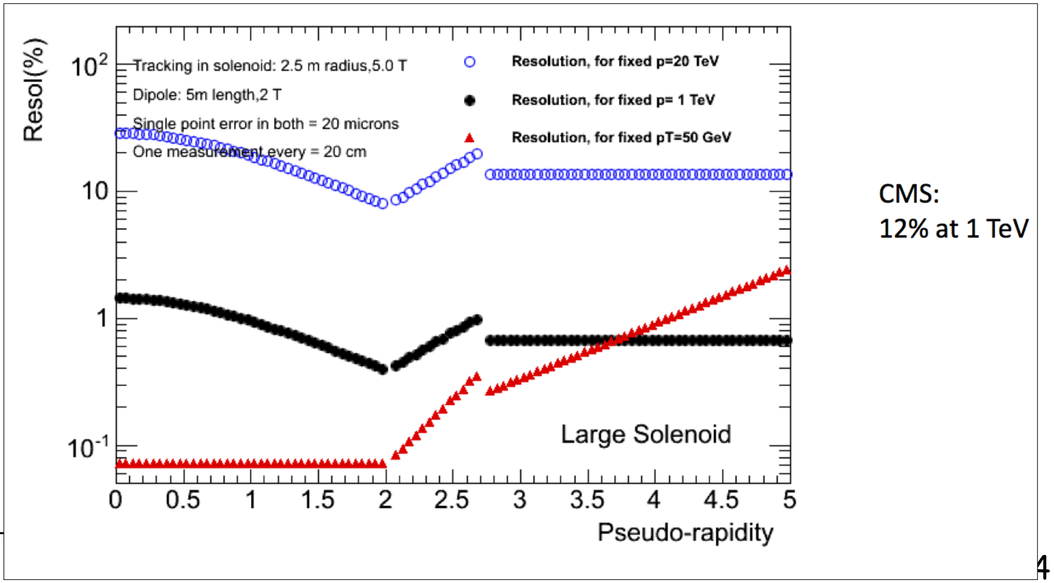


- ❑ R_{in}= $_{6m}$,peak field B=2.5T → bending 20 Tm (2.4 Tm ATLAS), 25m length (x2 ATLAS)
  Stored energy: close to 100 GJ
- ❑ Complemented by small end-cap toroid
- ❑ Forward dipole similar to previous case



Ideal resolution:
no multiple scattering,
no misalignment

Only p=1 TeV calculations
available → to be completed



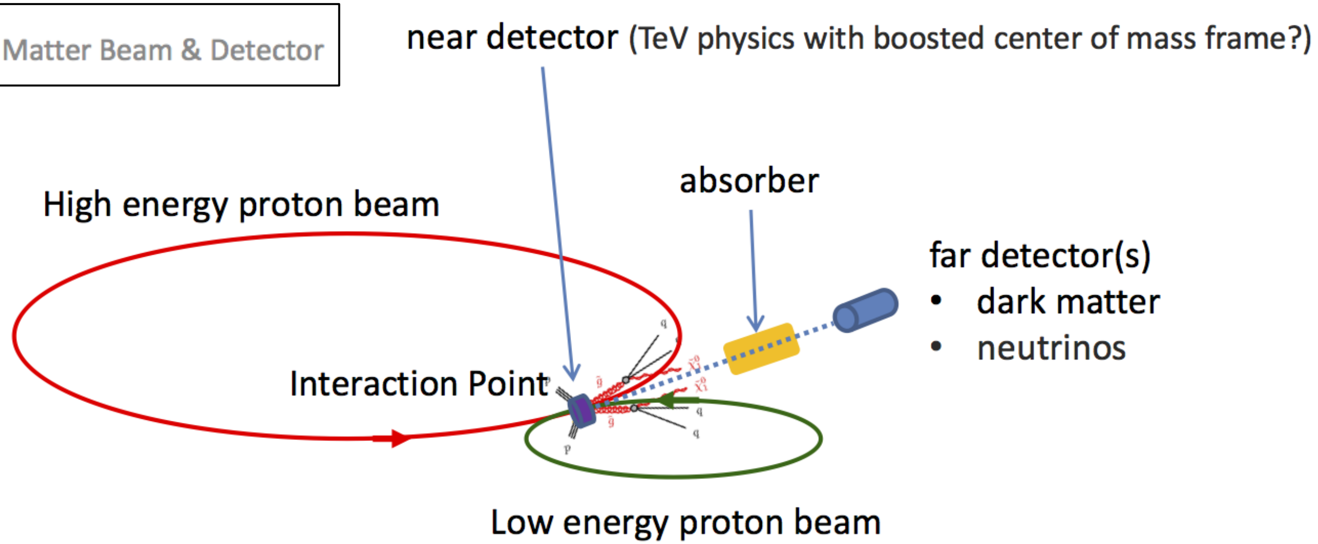
CMS:
12% at 1 TeV

Additional remarks

- Given complexity of these detectors (e.g. access), alternative would be to decouple new physics (i.e. big, mainly central, detector) from Higgs studies (smaller, forward coverage). The former could still do large part of the (high-p_T) Higgs physics.
- Likewise, "bread-and-butter" SM physics: W, Z, top, QCD could be addressed more specifically by dedicated experiments.
- Physics case for (dedicated) HI experiment is being studied
- "Intensity-frontier" type (LFV, etc.) smaller-scale (collider or fixed-target) experiments beyond present worldwide program could be envisaged with SPS or LHC extracted beams

→ FCC could become a facility … → room for ideas

D. Côté - Dark Matter Beam & Detector



F. Gianotti, Open EB, 28/1/2014

Conclusions

- A Future Circular Collider (FCC) project has been recently initiated by CERN Management, following recommendation by the European Strategy
- The main element is a ~100 TeV pp collider (FHC) in a ~100 km tunnel; intermediate steps may include an e^+e^- machine (TLEP) or/and an ep collider (FHeC).
- The project relies on strong international participation and is well linked to similar initiatives in other regions
- A kick-off meeting will take place at University of Geneva on 12-15 February 2014
- ATLAS colleagues are invited to join. Although we can only devote a small fraction of our time, it's a good opportunity (in particular for the young people) to conceive a challenging experiment at a challenging machine from scratch, exercise creativity, and inject ideas. Experience gained with LHC experiments and data is fundamental.

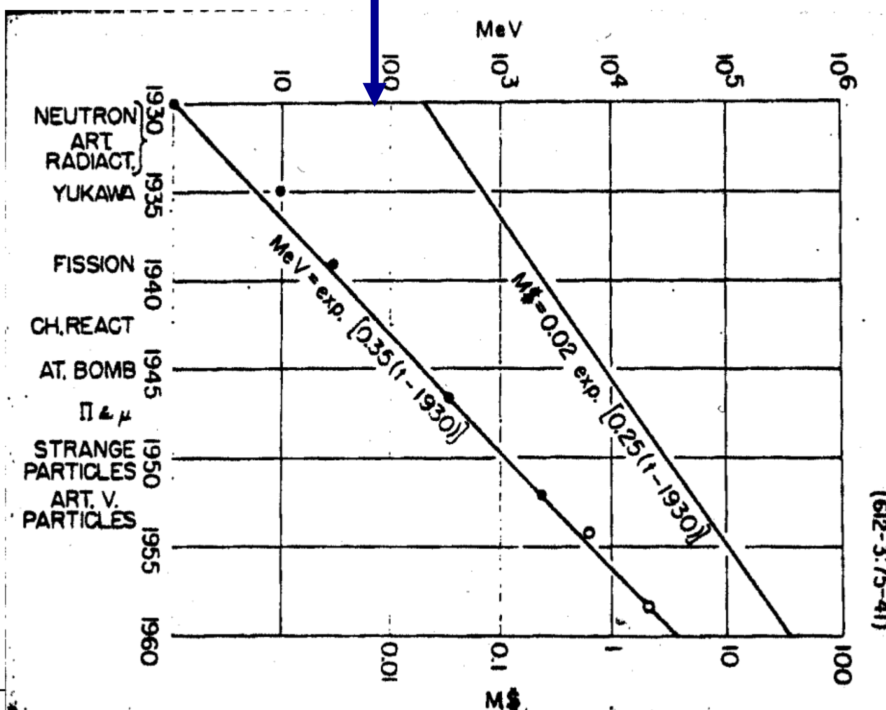
No doubt the FCC is an extremely challenging project (technical feasibility, cost … !!)
However: it is one of the (few) options for the future of our discipline.
As researchers in this field with have the duty and right to examine it and,
if justified by physics, ….

.. to be BRAVE and DREAM ….

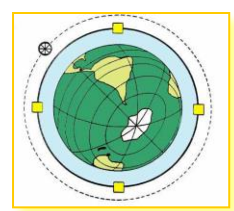
From E. Fermi, preparatory notes for a talk on
"What can we learn with High Energy Accelerators ? "
given to the American Physical Society, NY, Jan. 29th 1954

For these reasons....clamoring for higher and higher....
Slide 1 - MeV - M$ versus time.
Extrapolating to 1994...5 hi 9 Mev or hiest cosmic...170 B$....preliminary design....8000 km, 20000 gauss
Slide 2 - 5 hi 15 eV machine.

Whay we can learn impossible to guess....main element surprise....some things look for but see others.....Experiems on pions....sharpening knowledge.....~~spin zero and odd symmetry~~.....certainly look for multiple production...



Fermi's extrapolation to year 1994:
2T magnets, R=8000 Km (fixed target !),
E_{beam} ~ 5×10^3 TeV, cost 170 B$



Fortunately we have invented colliders and superconducting magnets …

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SPARES

CEPC+SppC

- When(dream):
  - CPEC
    - Pre-study, R&D and preparation work
      - Pre-study: 2013-15
      - R&D: 2015-2020
      - Engineering Design: 2015-2020
    - Construction: 2021-2027
    - Data taking: 2028-2035
  - SPPC
    - Pre-study, R&D and preparation work
      - Pre-study: 2013-2020
      - R&D: 2020-2030
      - Engineering Design: 2030-2035
    - Construction: 2035-2042
    - Data taking: 2042 -