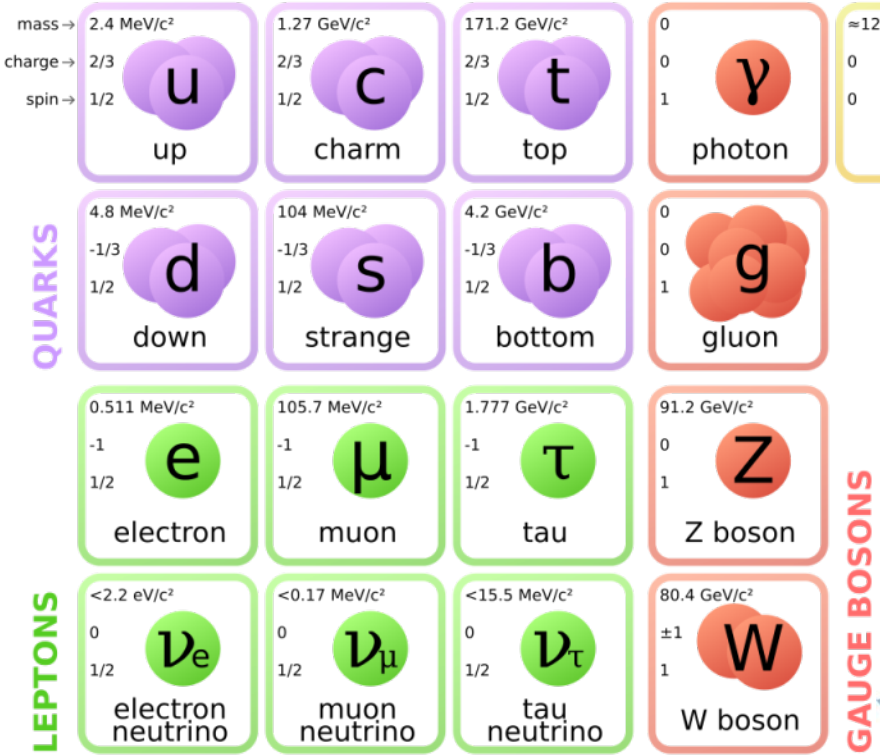
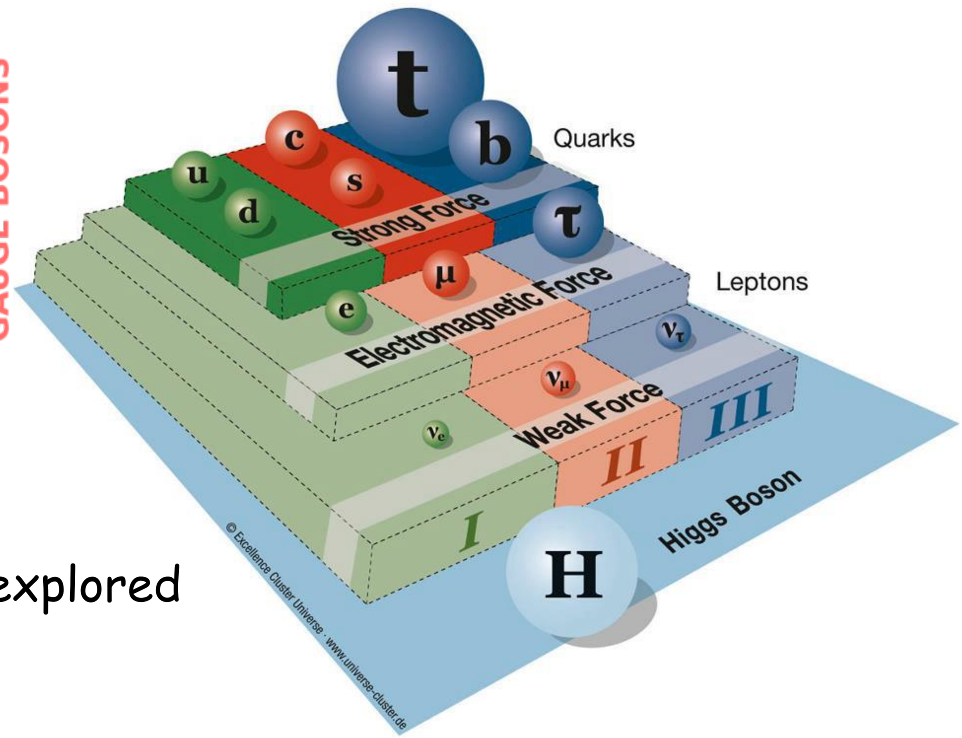
Perspectives in High Energy Physics

Halina Abramowicz
Tel Aviv University

- Status of Standard Model of particle physics
- What is missing?
- Future options
  - High energy colliders
  - Neutrino Physics (Ken Long)
  - Physics beyond colliders (Claude Vallee)

Status of the Standard Model





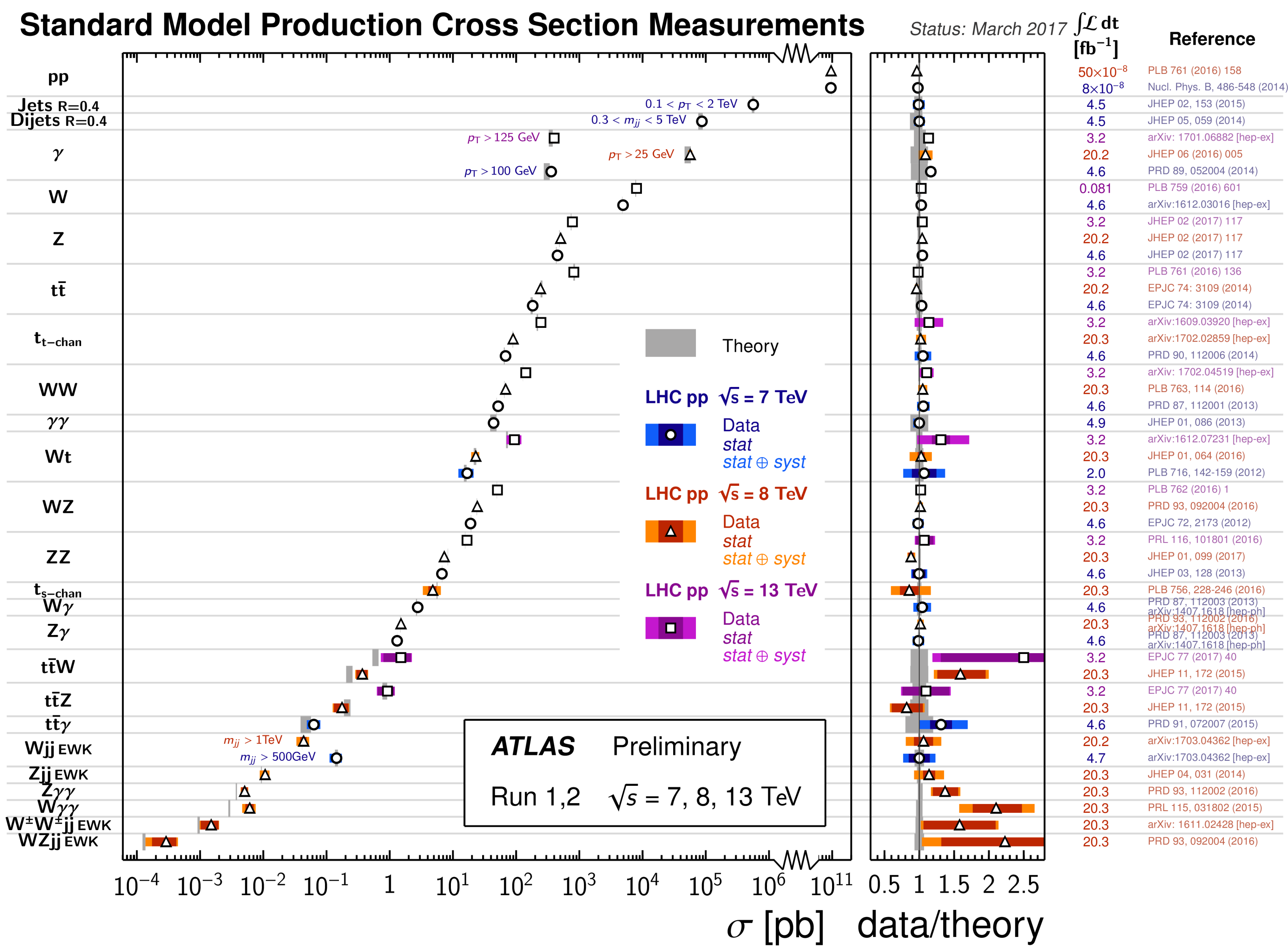
Higgs sector and top sector largely unexplored

Present Energy Frontier – Large Hadron Collider at CERN

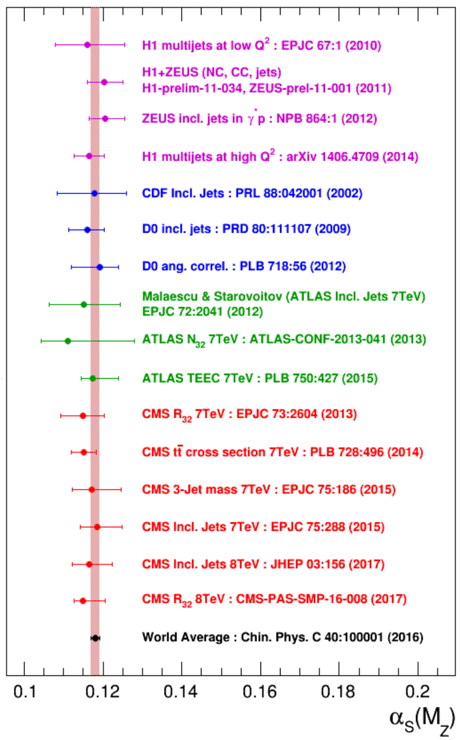
27km tunnel, up to 175m deep, 1232 SC bending magnets 1.9K, 14.3m long, 8T

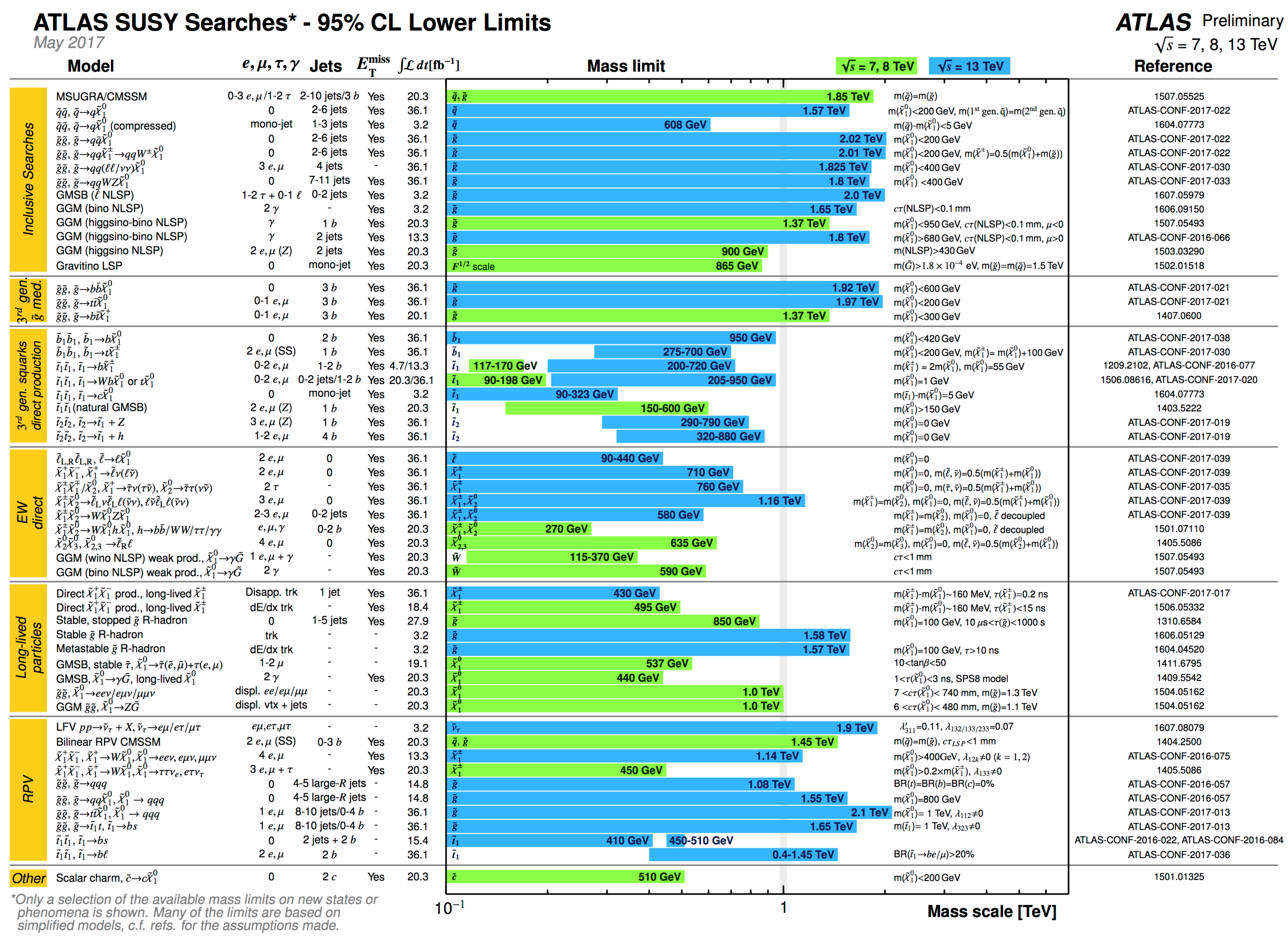
Collected pp data: 7TeV (2010/2011); 8TeV (2012); 13TeV (2015-now)

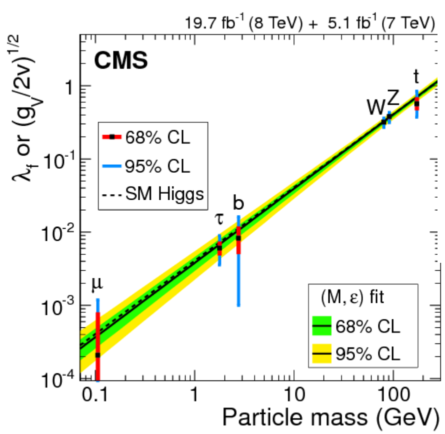
Stress test of SM at the LHC



Stress test of SM at the LHC





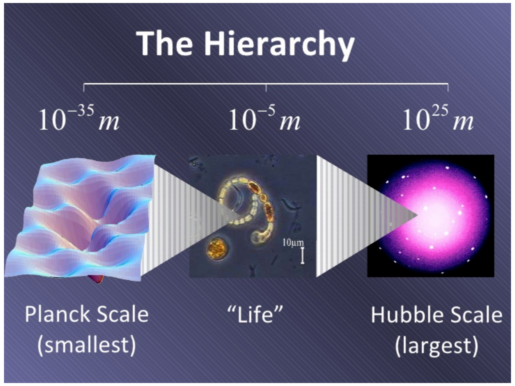


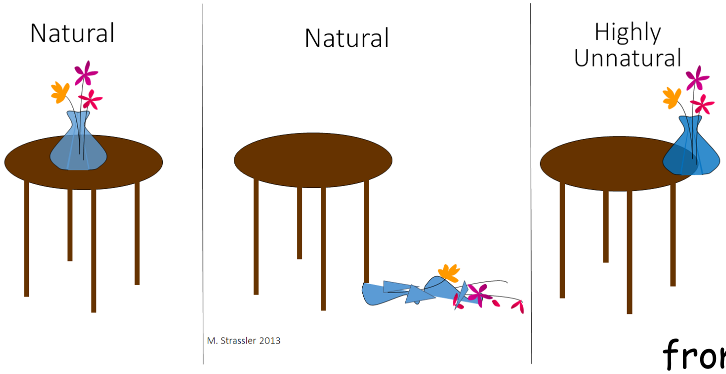
Guidelines from LHC results

- The Standard Model is doing amazingly well
- The Higgs scalar is very much like expected in the Standard Model
- There is no indication of physics BSM up to scales of the order of 1 to 3 TeV
- Lepton/flavor conservation – hints from LHCb in c/b-decays???

Guidelines from outside LHC

- Neutrinos have masses (oscillations) – not acquired in the SM
- There is dark matter in the Universe with no candidates within the SM (axions???)
- Prevalence of matter over anti-matter
- Theorist believe that the theory is not complete

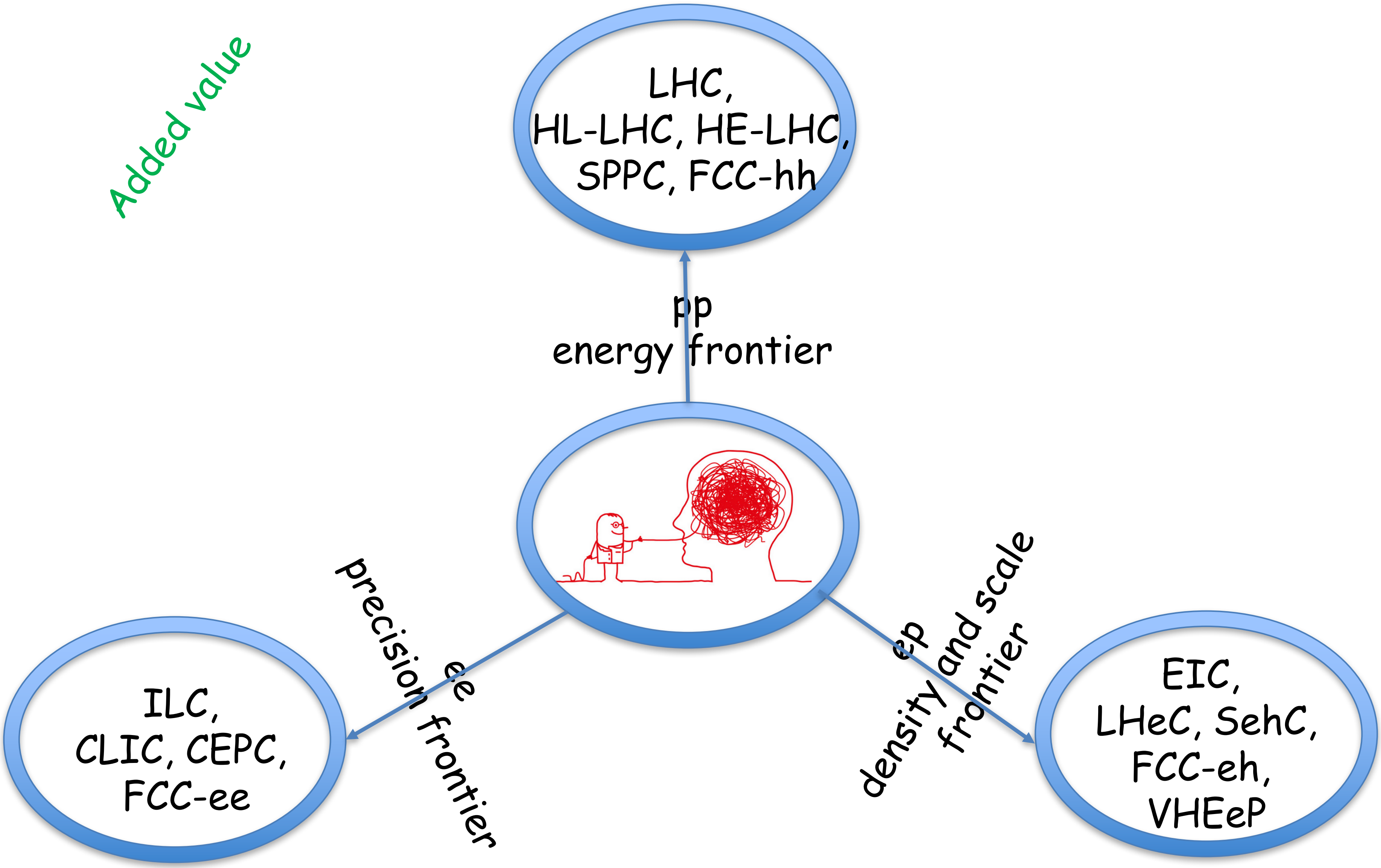




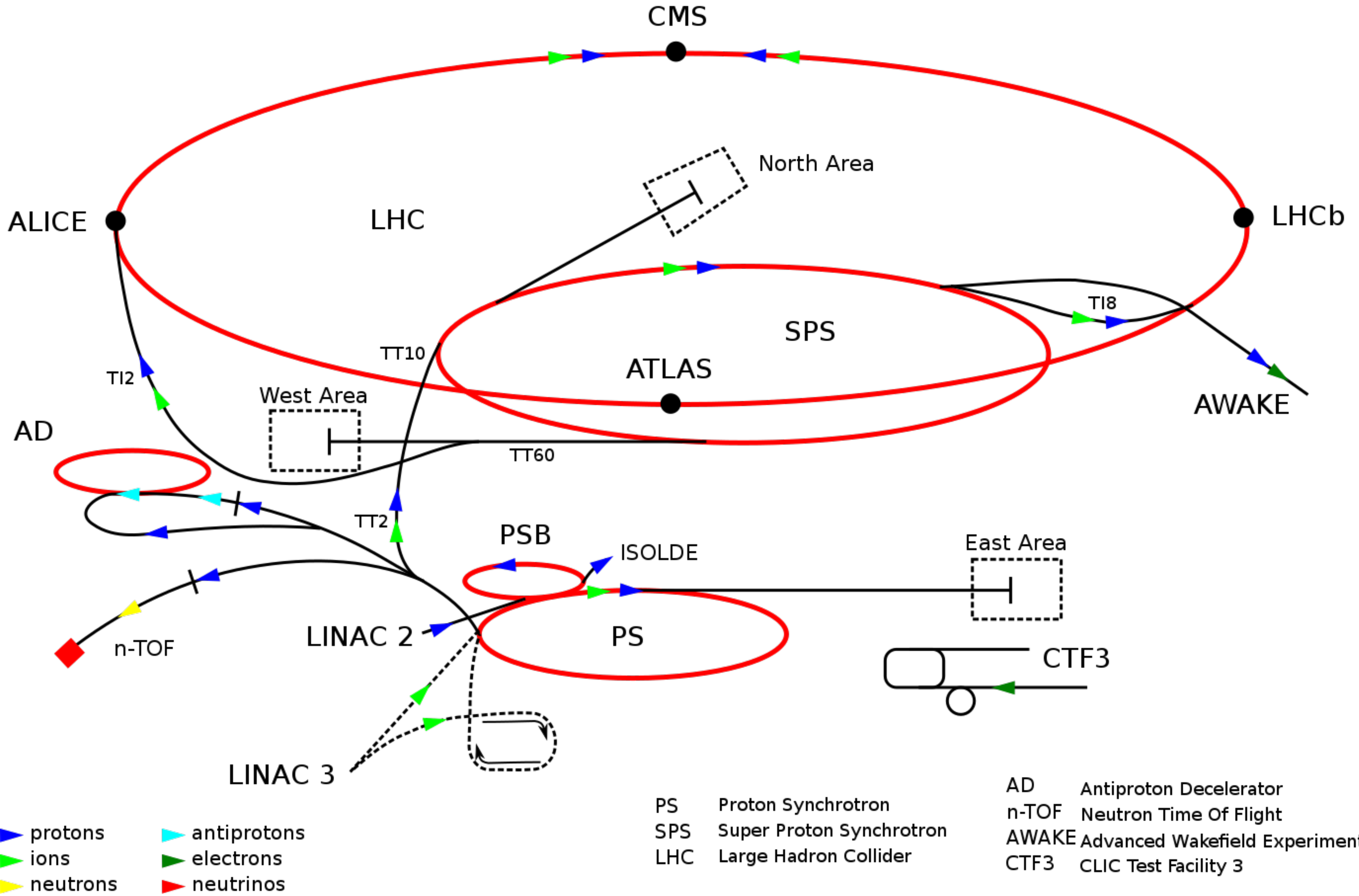
from M. Strassler

How should we go about understanding all these issues ?

Controlled experiments at accelerators

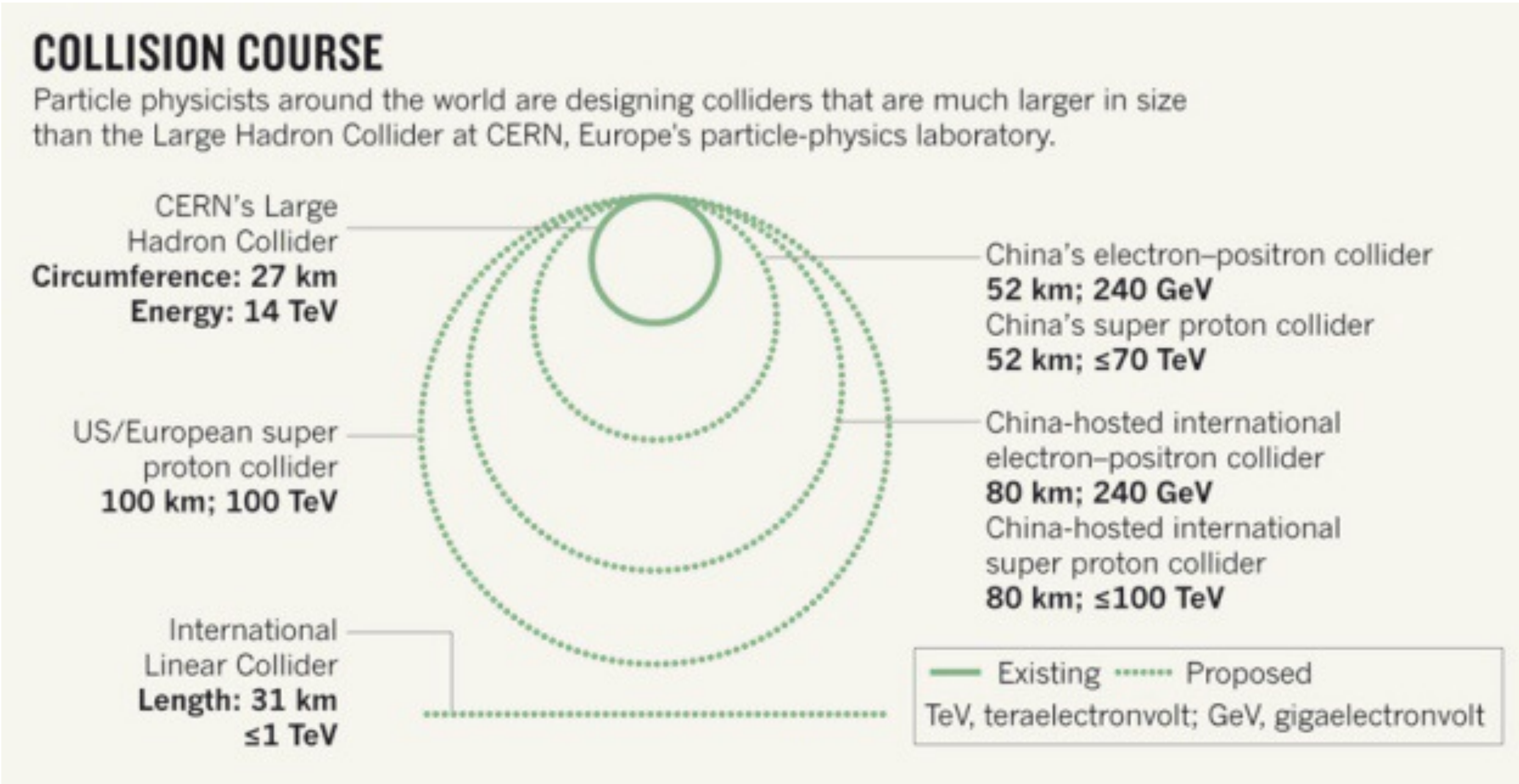


Present Accelerator Complex at CERN



PS	Proton Synchrotron
SPS	Super Proton Synchrotron
LHC	Large Hadron Collider
AD	Antiproton Decelerator
n-TOF	Neutron Time Of Flight
AWAKE	Advanced Wakefield Experiment
CTF3	CLIC Test Facility 3

Collision Course

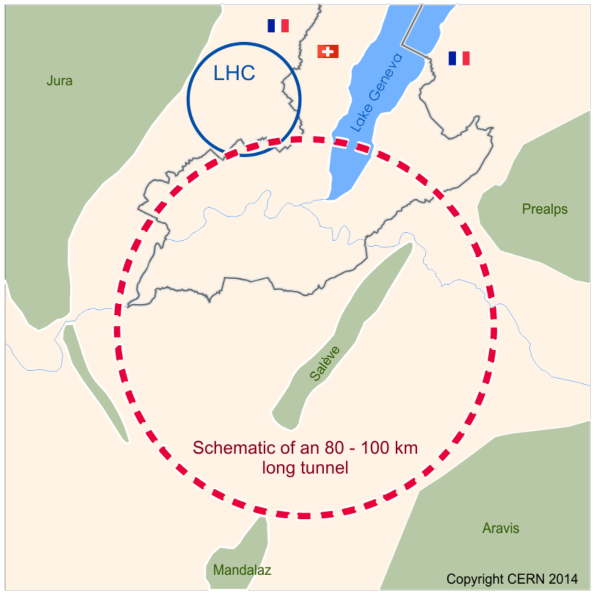


Energy frontier

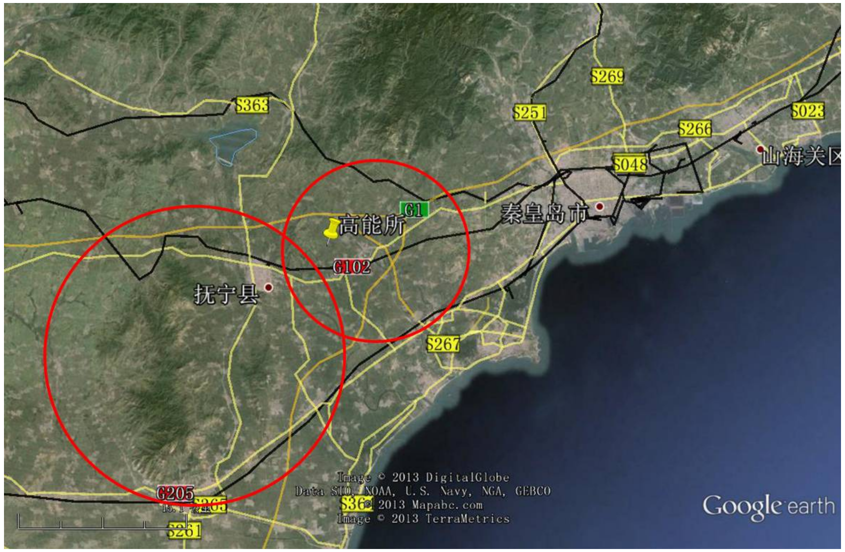
- Hadron colliders

CERN: HE – LHC, pp 28 TeV - replace dipoles with 16T HTS Nb_3Sn → 20T
CERN: FCC – pp 100 TeV, 80 to 100 km tunnel, 16 to 20T magnets
China: SppC – pp 35 to 65 TeV, 60 km to 100 km tunnel with 12T HTS →24T

Geneva

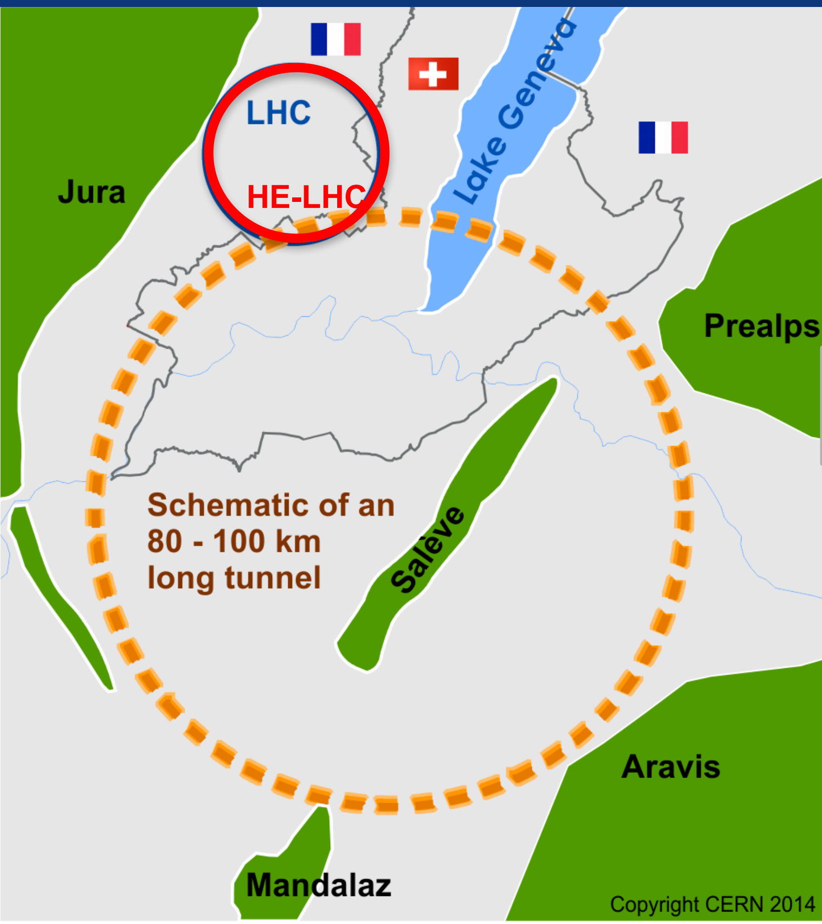


Qinghuada



US: SSC – pp 100 to 300 TeV, 270 km tunnel, 5 T to 15 T magnets

Future Circular Collider (FCC) Study

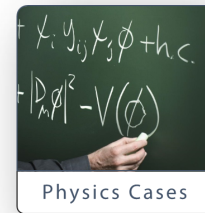


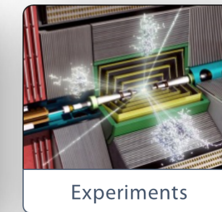
International FCC collaboration (CERN as host lab) to study:

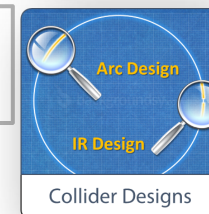
- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

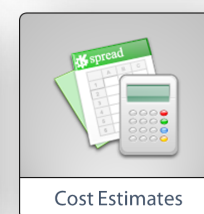
~16 T ⇒ 100 TeV *pp* in 100 km

- **~100 km tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (*FCC-ee*),** as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option,** IP integration, e^- from ERL









From M. Benedikt, PECFA Nov. 2017, CERN

FCC study: physics and performance targets

FCC-ee:

- Exploration of 10 to 100 TeV energy scale via couplings with precision measurements
- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass) ($m_{Z,}$ m_W, m_{top} , $\sin^2 \theta_w^{eff}$, R_b , α_{QED} (m_z) α_s (m_z m_W m_τ), Higgs and top quark couplings)

➢ Machine design for highest possible luminosities at Z, WW, ZH and ttbar working points

FCC-hh:

- Highest center of mass energy for direct production up to 20 - 30 TeV
- Huge production rates for single and multiple production of SM bosons (H,W,Z) and quarks

➢ Machine design for 100 TeV c.m. energy & integrated luminosity $\sim$ 20ab^{-1} within 25 years

HE-LHC:

- Doubling LHC collision energy with FCC-hh 16 T magnet technology
- c.m. energy = 27 TeV $\sim$ 14 TeV x 16 T/8.33T, target luminosity ≥ 4 x HL-LHC

➢ Machine design within constraints from LHC CE and based on HL-LHC and FCC technologies

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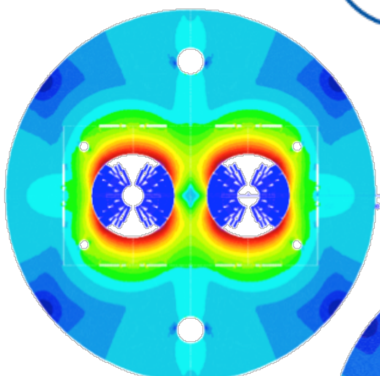
16 T dipole design activities and options

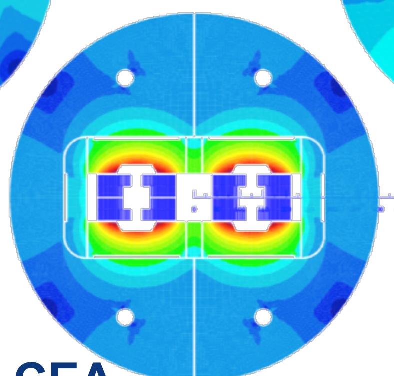
H2020

Cos-theta



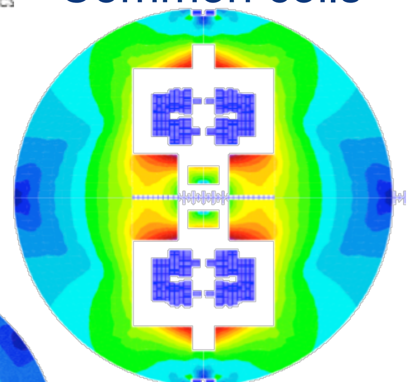
INFN

Blocks



CEA

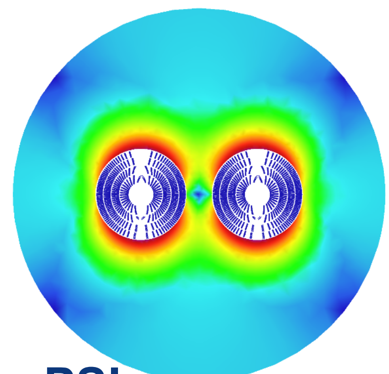
Common coils



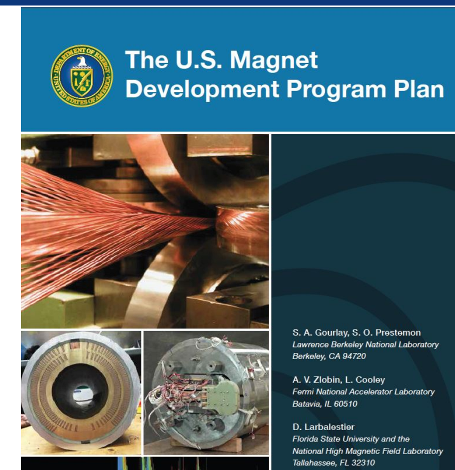
CIEMAT

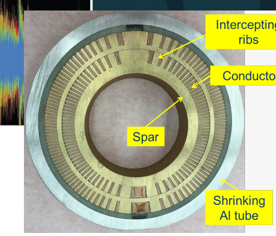
Swiss contribution

Canted Cos-theta

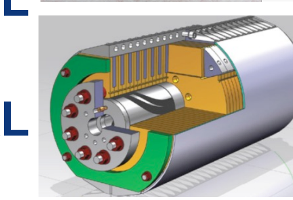


PSI





LBNL



FNAL

Short model magnets (1.5 m lengths) will be built from 2017 - 2022

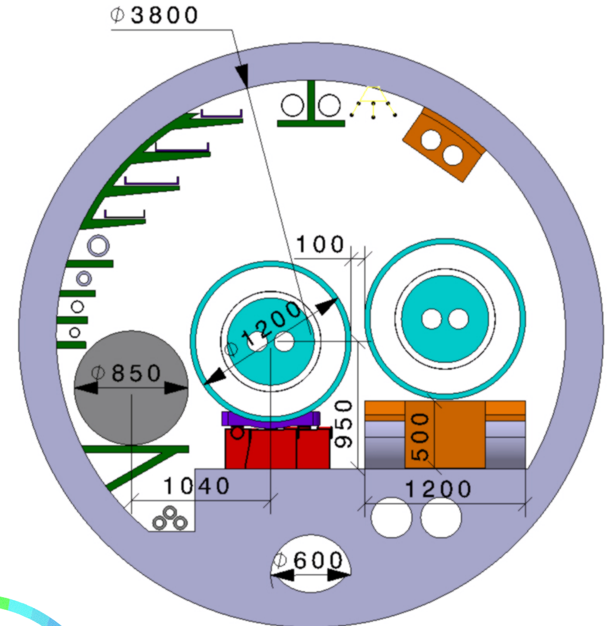
From M. Benedikt, PECFA Nov. 2017, CERN

HE-LHC integration aspects

Working hypothesis for HE LHC design:

No major CE modifications on tunnel and caverns

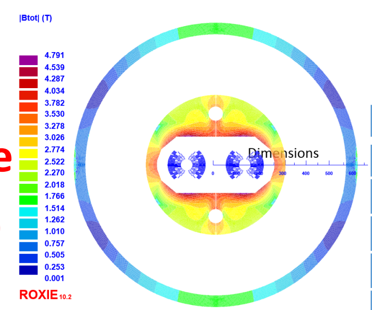
- Similar geometry and layout as LHC machine and experiments
- **Maximum magnet cryostat external diameter compatible with LHC tunnel ~1200 mm**
- **Classical cryostat design gives ~1500 mm diameter!**



Strategy: develop optimized 16 T magnet, compatible with both HE LHC and FCC-hh requirements:

- **Allow stray-field and/or cryostat as return-yoke**
- **Optimization of inter-beam distance (compact)**

→ **Smaller diameter also relevant for FCC-hh cost**

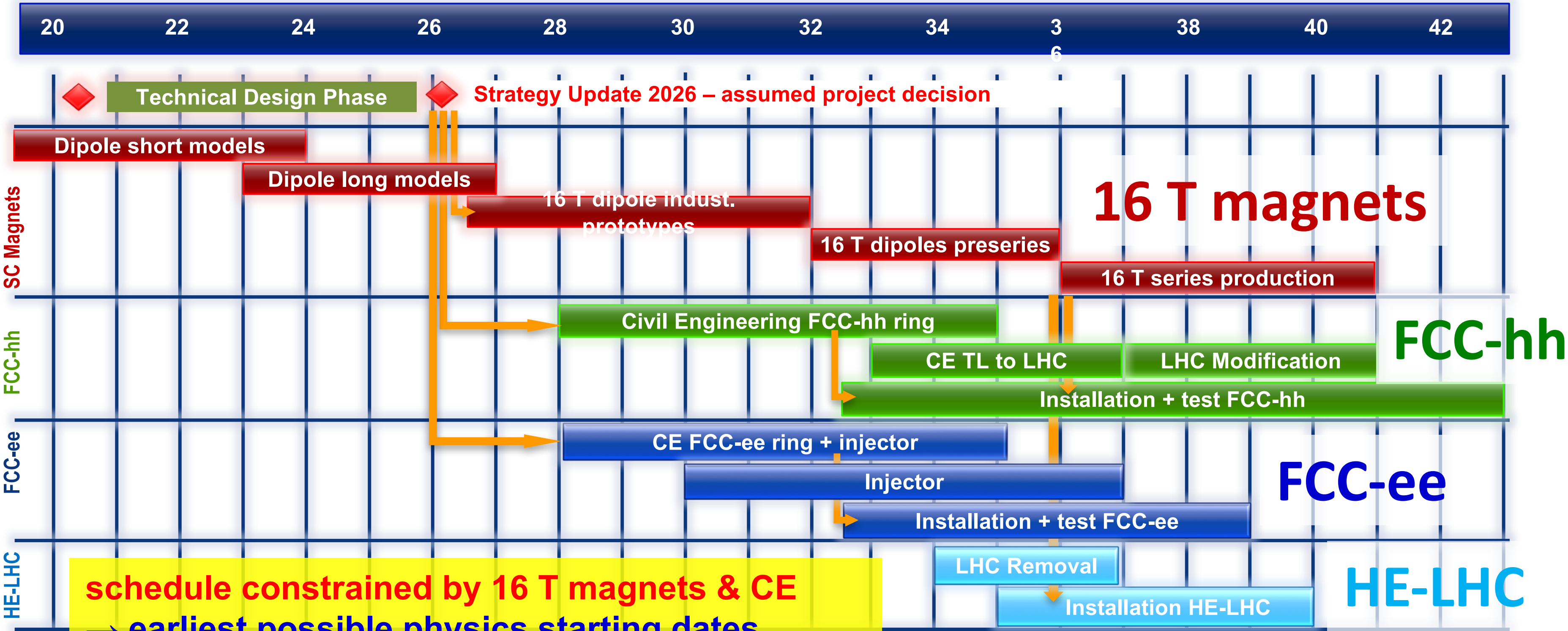


Only magnetic elements shown

Description	OD in mm
Iron yoke	600
Aluminium shrinking cylinder	740
Stainless steel He tight shell	760
Al radiation shield	940
Vacuum vessel (magnetic steel)	1220

From M.Lemont, PECFA Nov. 2017, CERN

Technical Schedule for each the 3 Options



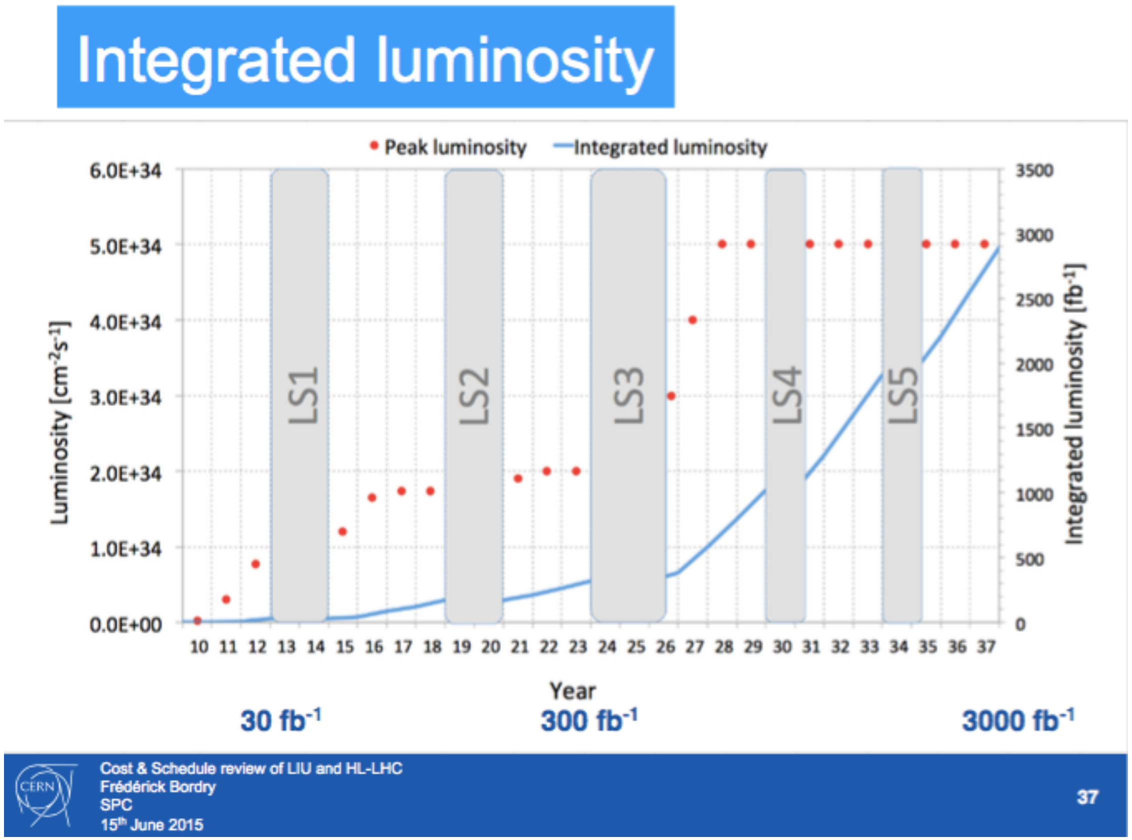
schedule constrained by 16 T magnets & CE
→ earliest possible physics starting dates
- **FCC-hh: 2043**
- **FCC-ee: 2039**
- **HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)**

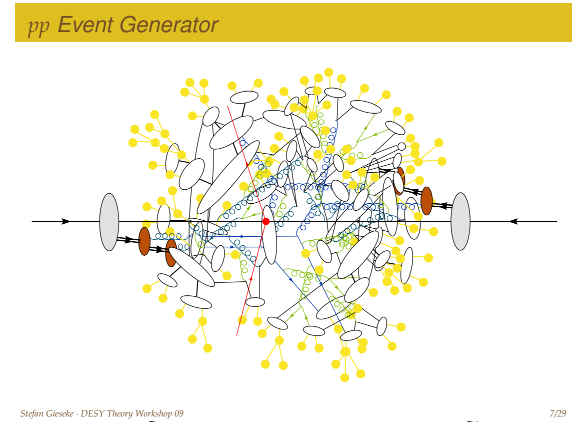
From M. Benedikt, PECFA Nov. 2017, CERN

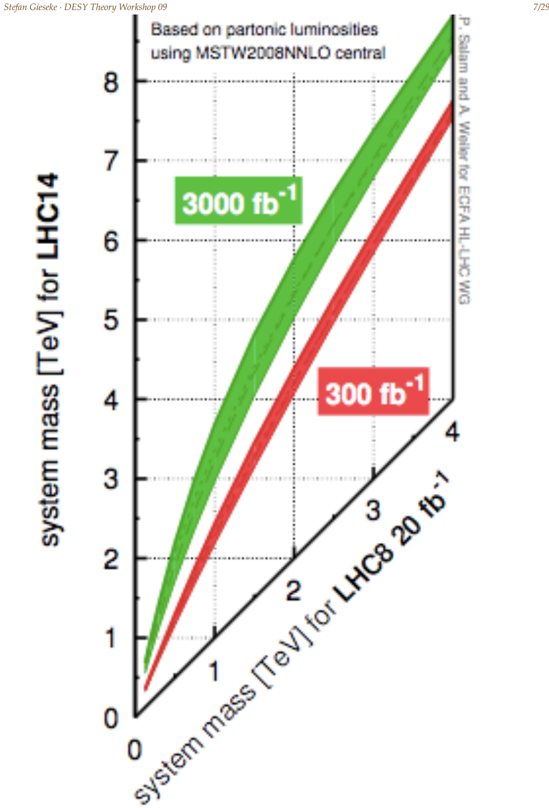
Energy Frontiers

pp interactions are not very efficient energy-wise but no-alternative

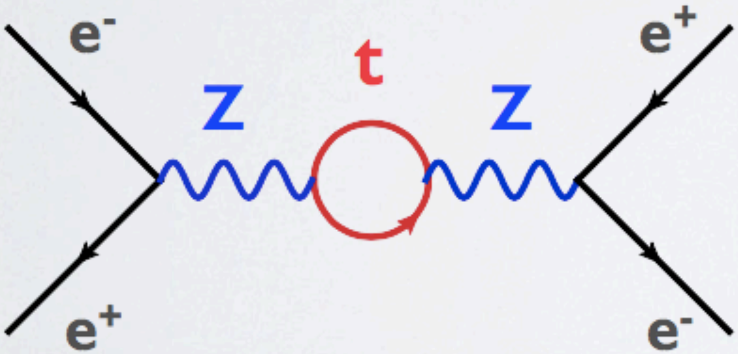
At 14 TeV and 3 ab^{-1} mass reach<10 TeV





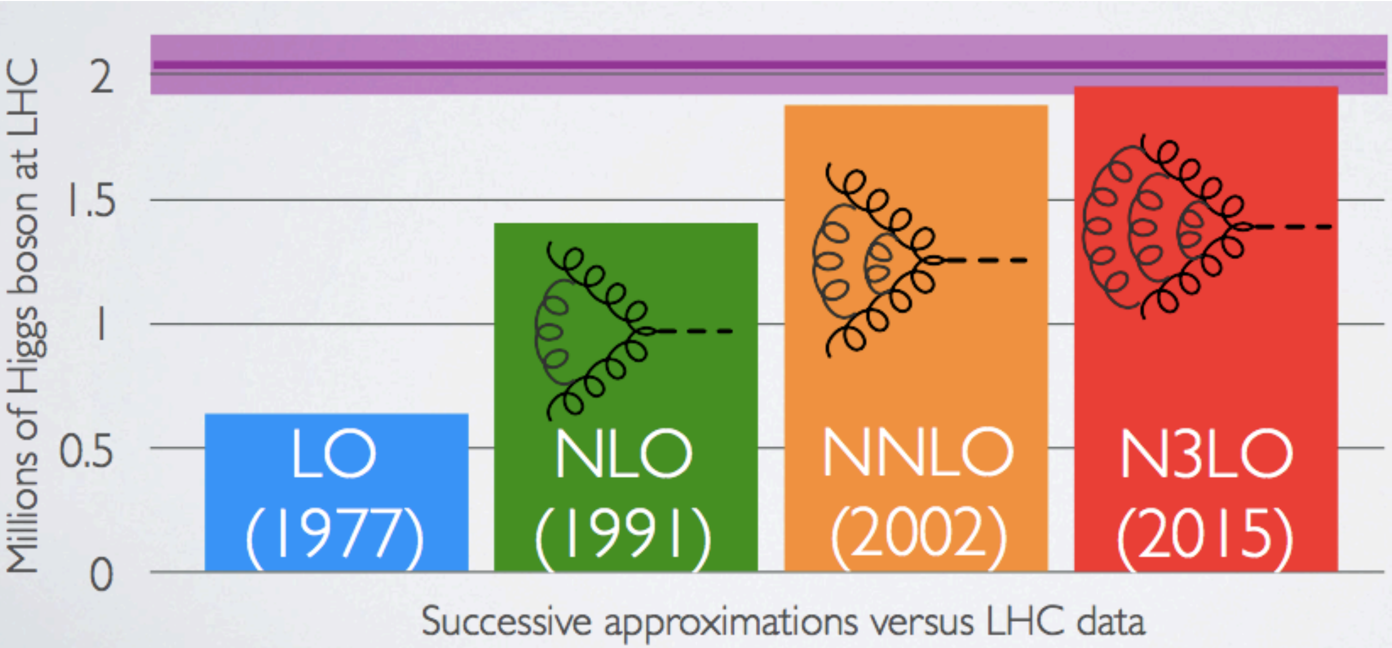


Precision Frontier



- Mass of the top quark from *indirect* determinations at LEPI and SLC in 1993: $m_{top} = (177 \pm 10)$ GeV
- First *direct* production at the Tevatron in 1994: $m_{top} = (174 \pm 16)$ GeV

In contrast to pp → H + X



ATLAS and CMS data

LO (leading order): 1st approximation

NLO (next-to-leading order): 2nd approximation

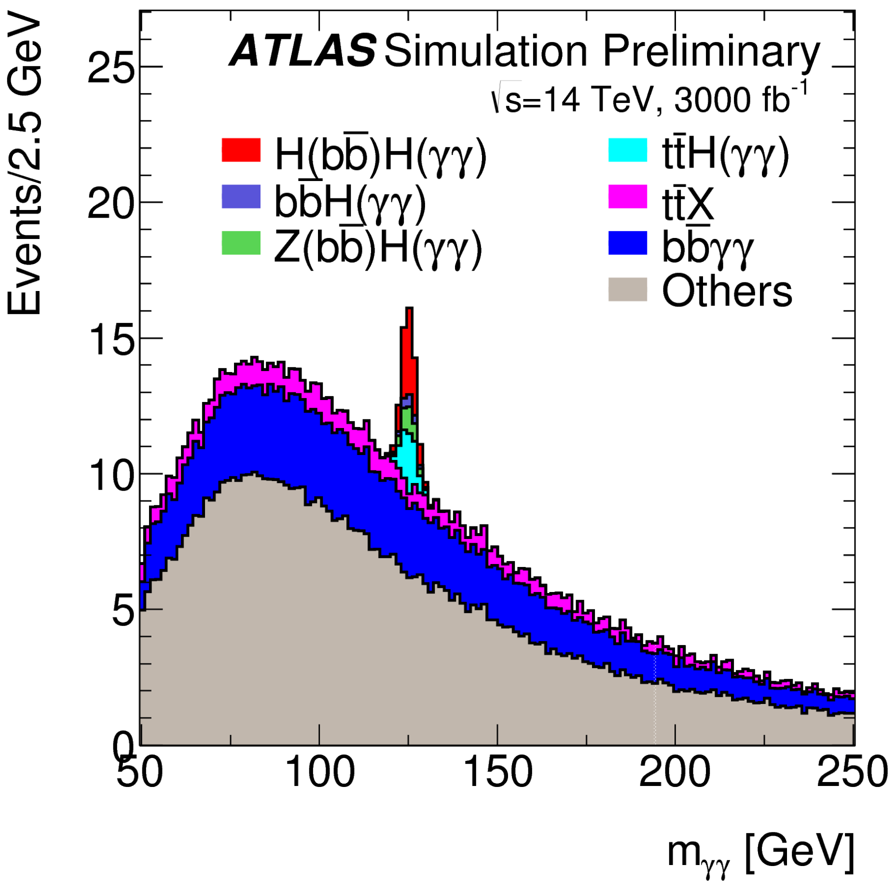
NNLO (next-to-next-to-leading order): 3rd approximation

N3LO: … [70000000 loop integrals!]

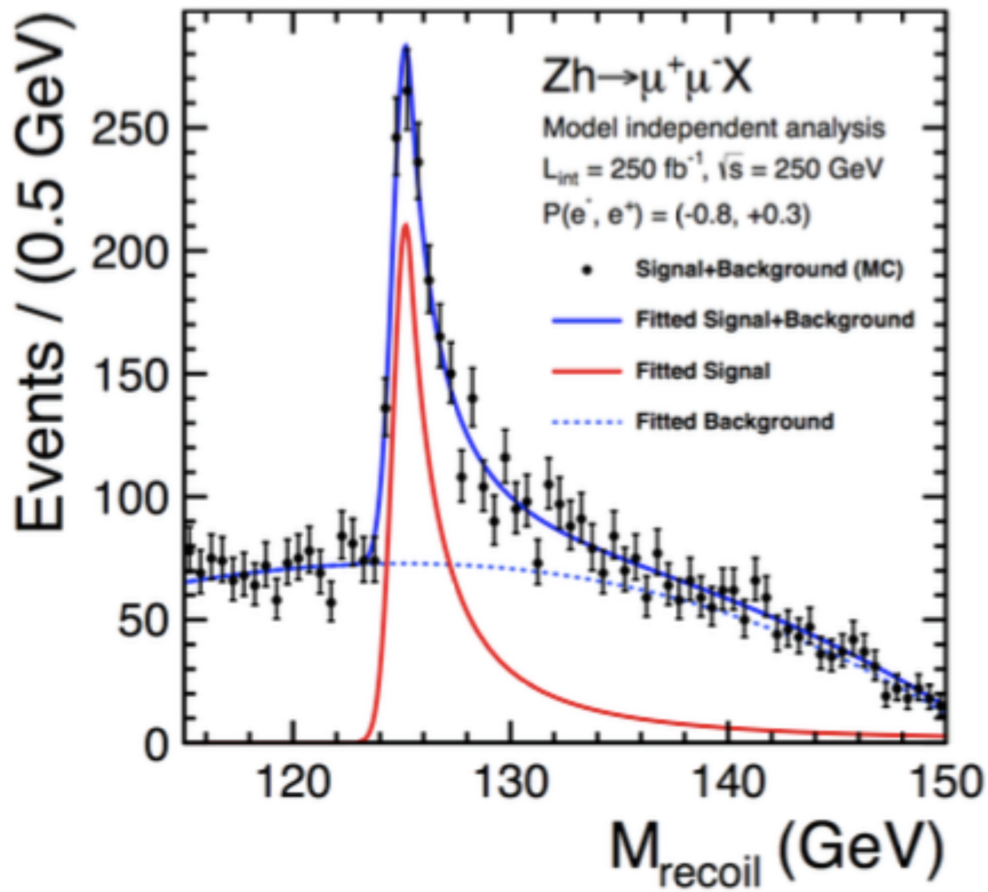
Precision Frontier

Precision Higgs

HL-LHC



ILC

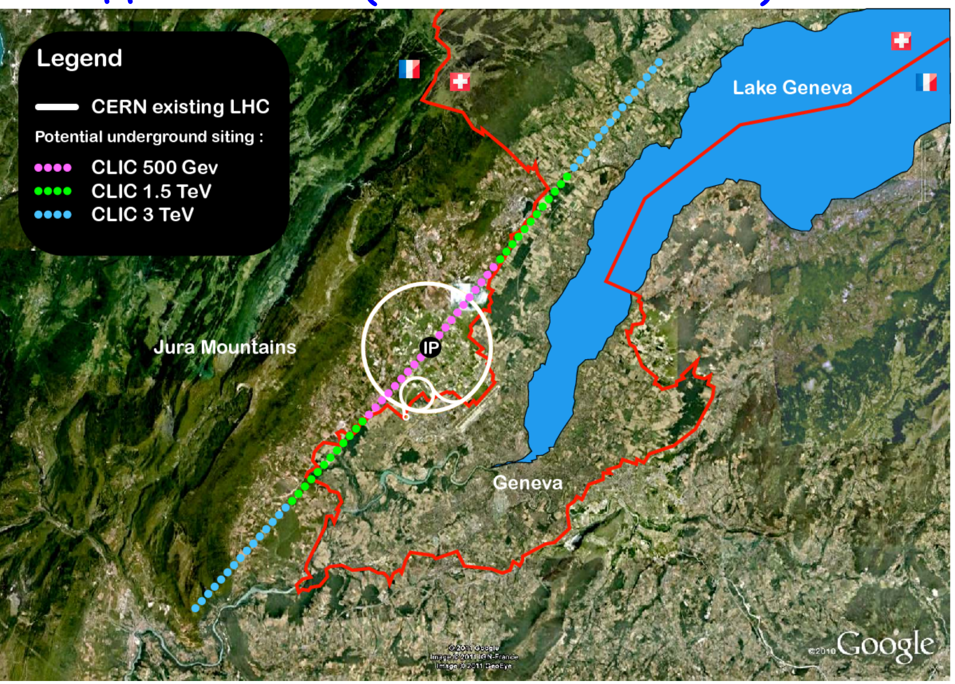


Precision frontier

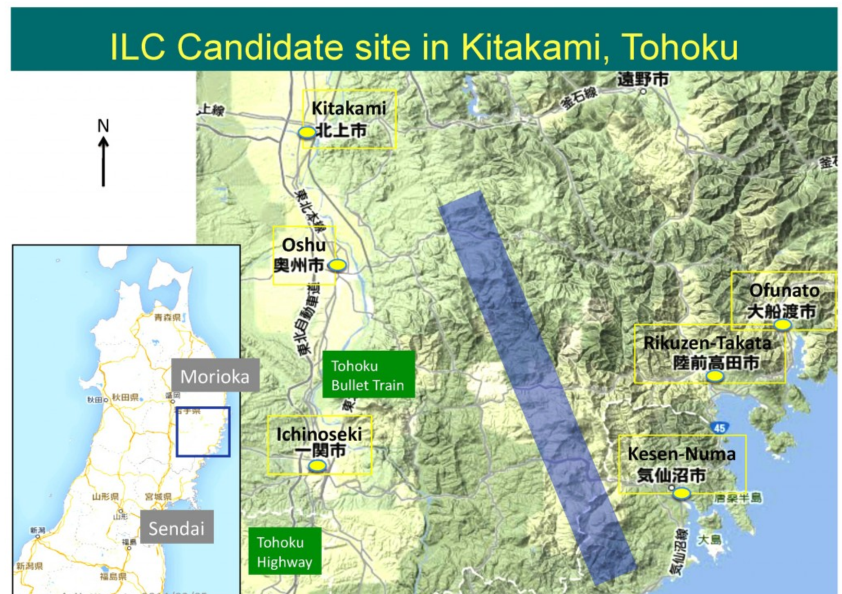
- Electron-positron machines

Kitakami: ILC –linear collider, 250 GeV baseline (up to 31 km, expandable to 1 TeV)
CERN: CLIC – linear collider, 380 GeV to 3 TeV (up to 50 km)
CERN: FCC ee – circular collider, 240 to 350 GeV
China: CEPC – circular collider, 240 GeV
US: SSC – resurrected 87 km tunnel for circular Higgs factory

- γγ colliders (derivatives of ee)

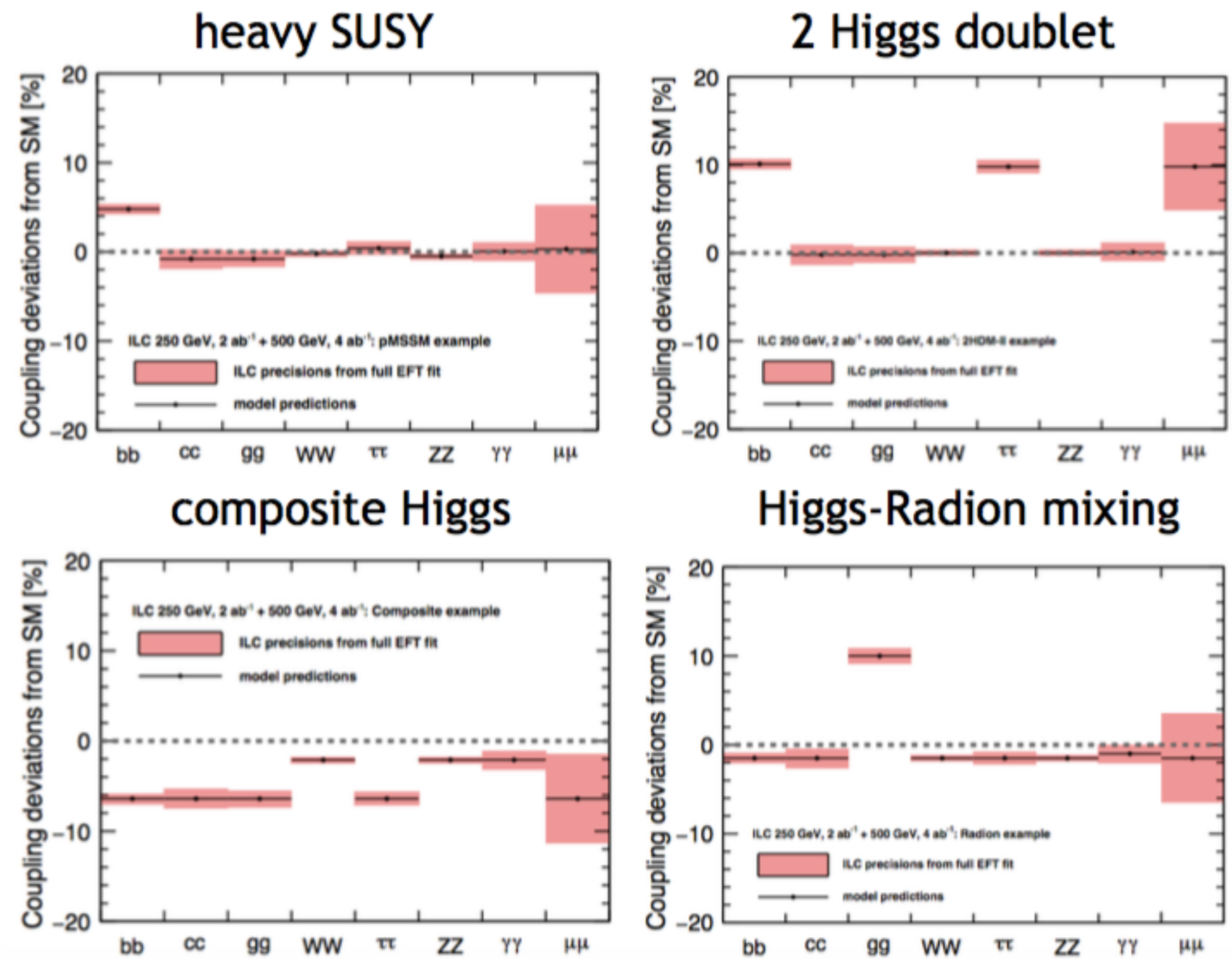


Accelerating structures 72 to 100 MV/m

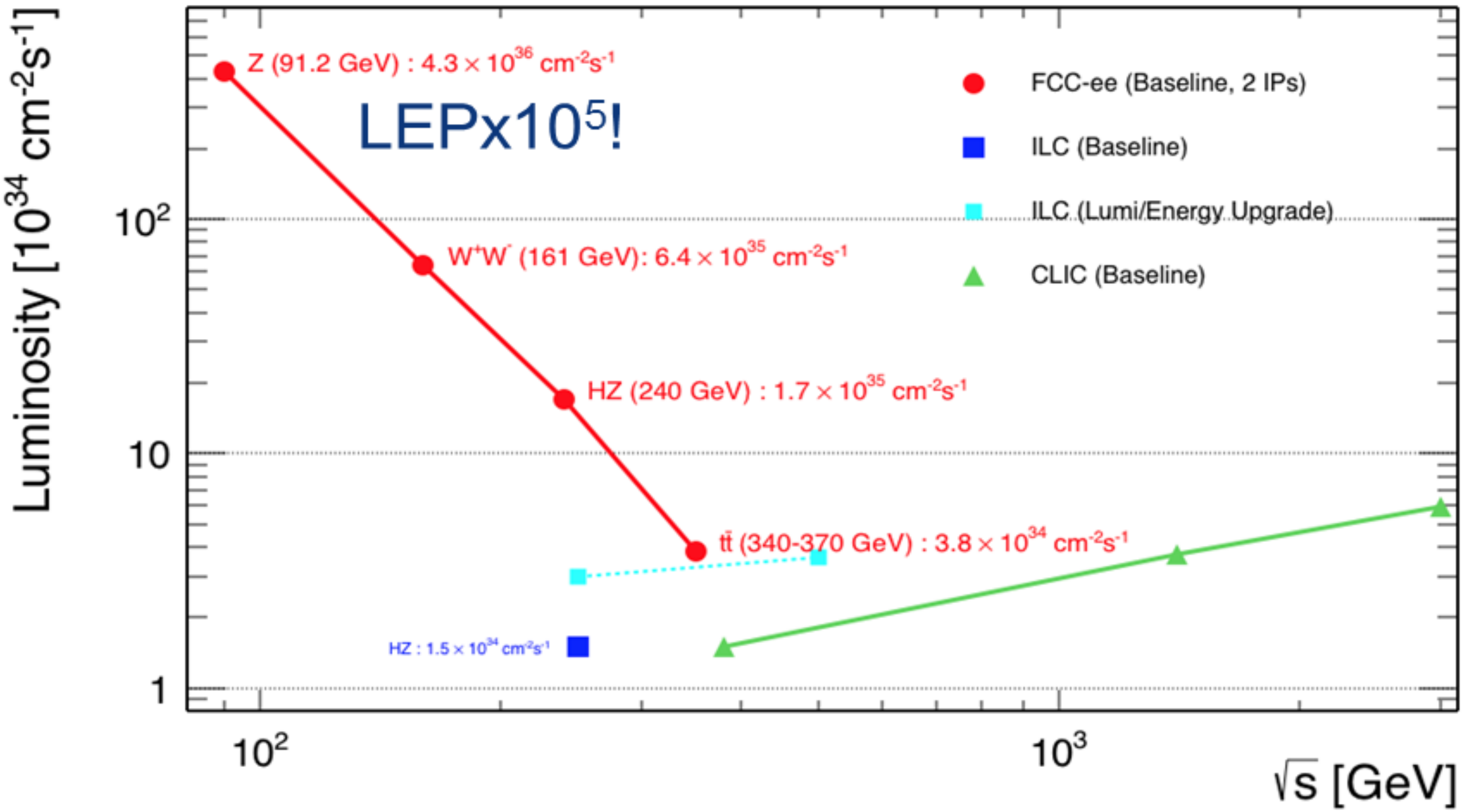


ILC (upgrade)
31km (50km), 30V/m (45V/m)
500 GeV (1 TeV)

Sensitivity of Higgs couplings to BSM



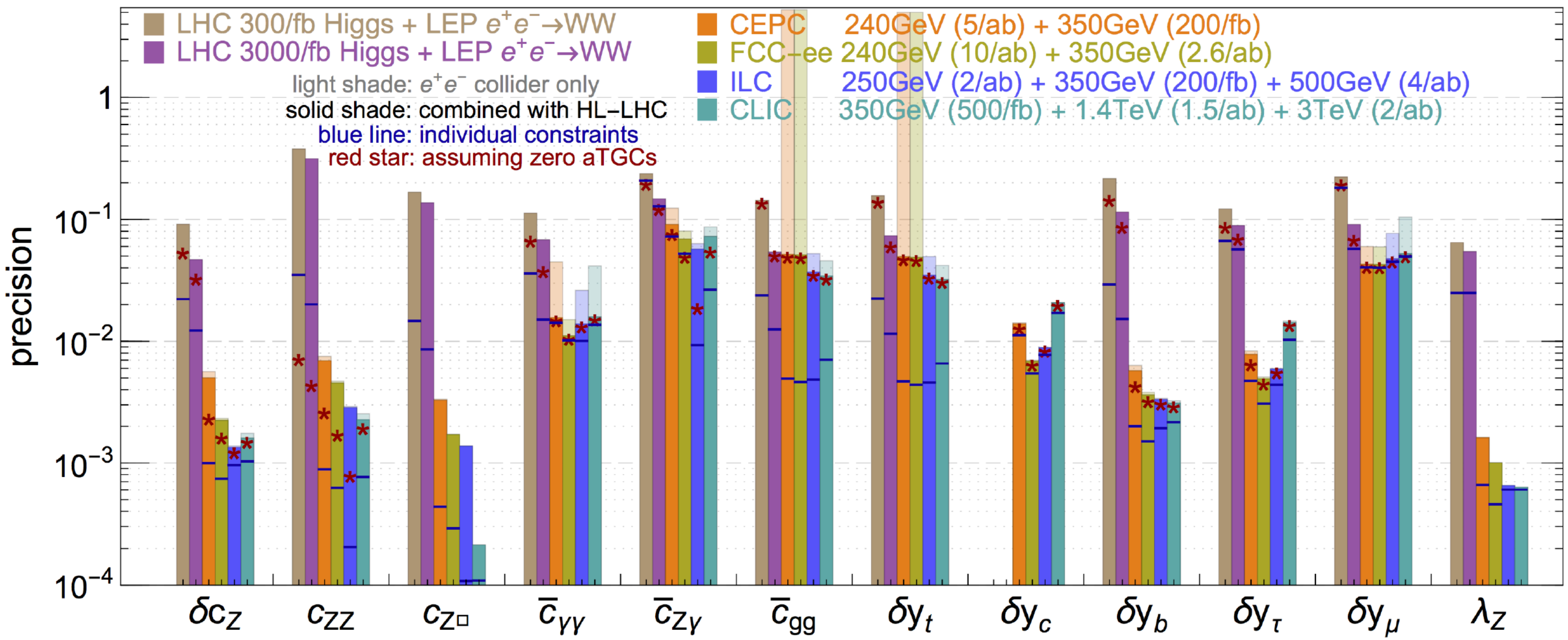
Precision Frontier



Luminosity vs energy for e^+e^- colliders

Comparison between collider options

Precision reach of the 12-parameter fit in Higgs basis



- Many EFT parameters can be measured significantly better at CLIC than at HL-LHC
- H→cc only accessible at lepton colliders

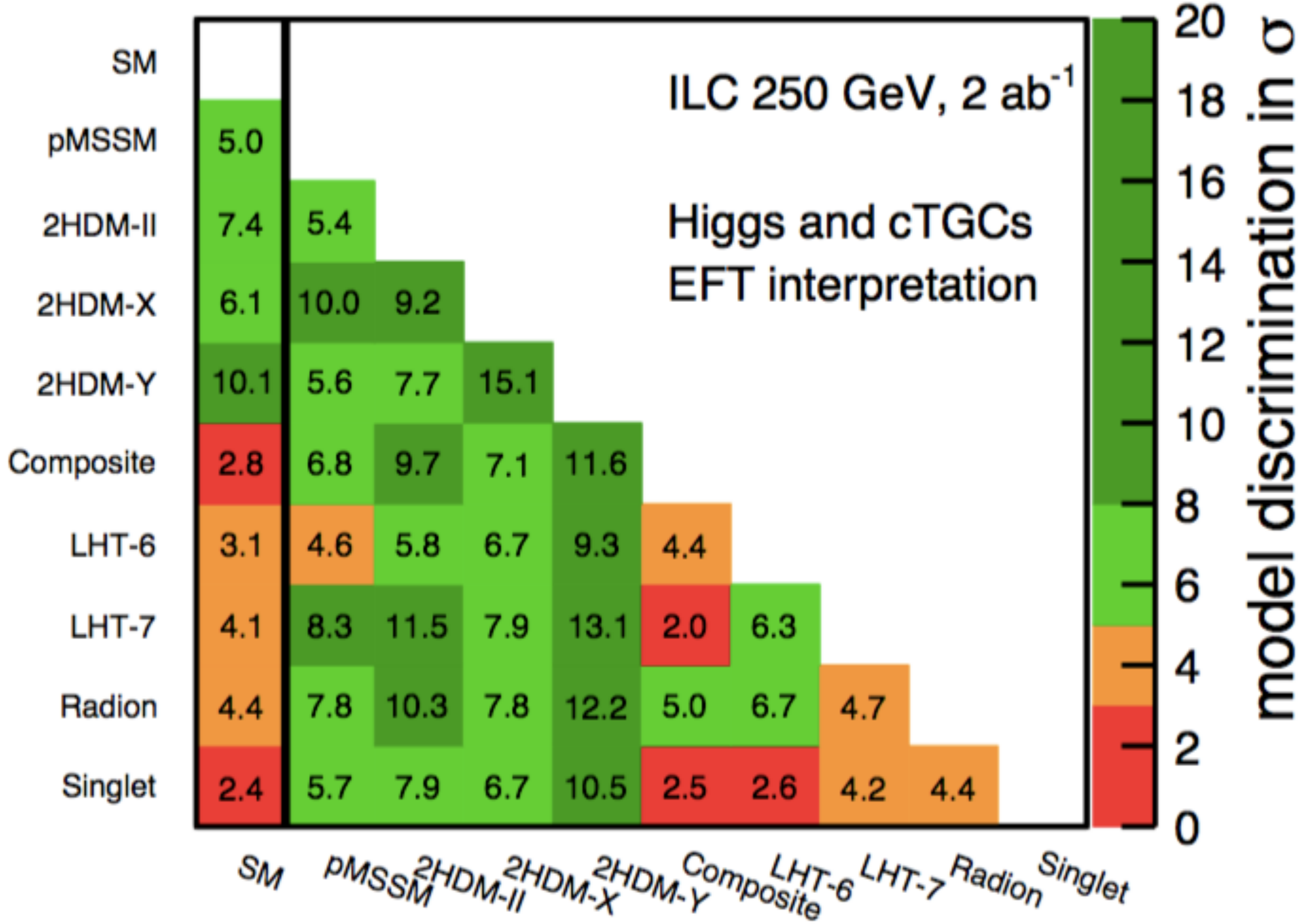
arXiv:1704.02333
See also JHEP 1705, 096 (2017)

Here are some final results for various proposed colliders:

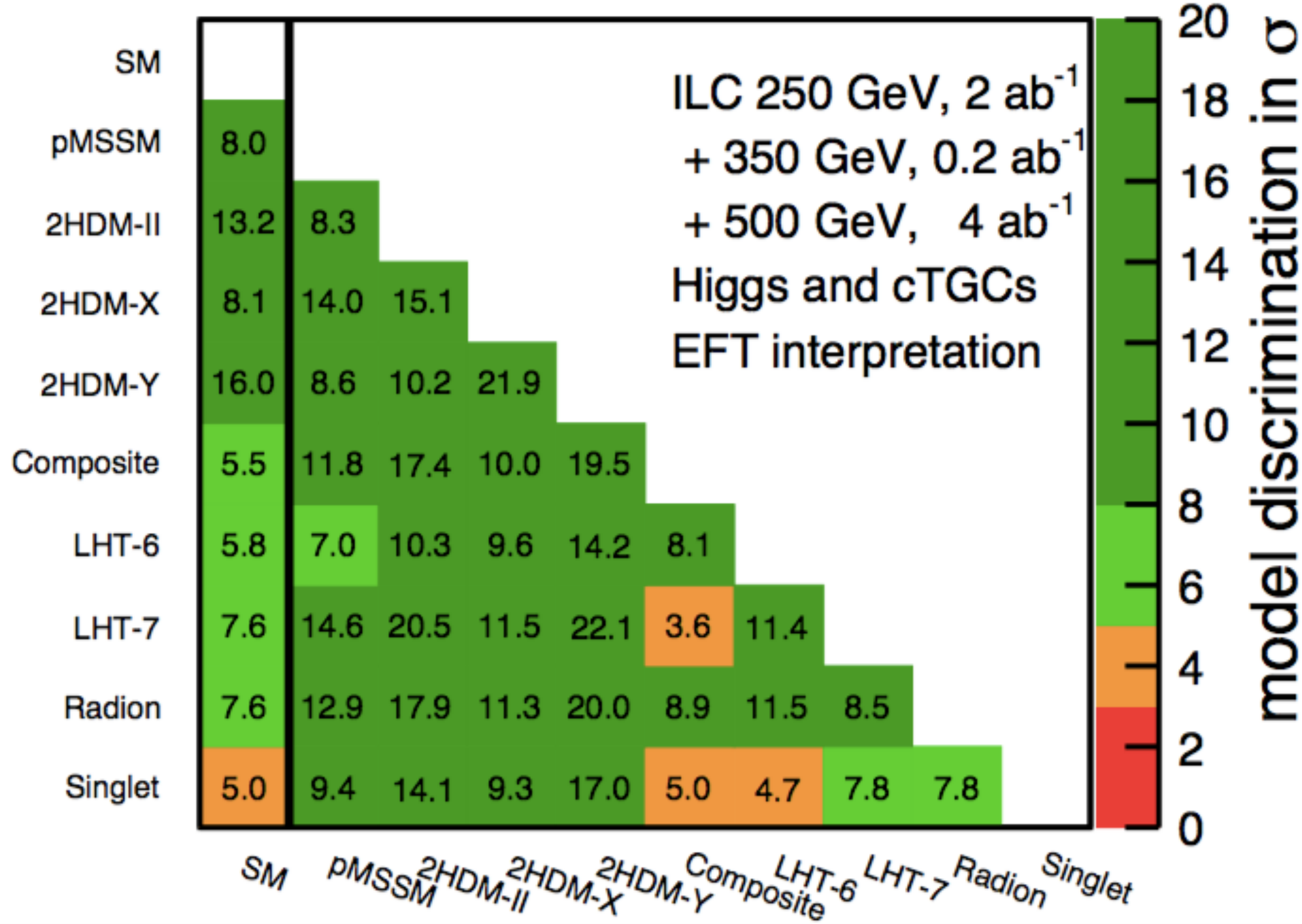
	ILC250	CLIC350	CEPC	FCC-ee	ILC250+500
	2 ab^{-1} w. pol.	2 ab^{-1} 350 GeV	5 ab^{-1} no pol.	+ 1.5 ab^{-1} at 350 GeV	full ILC 250+500 GeV
$g(hb\bar{b})$	1.1	1.1	0.98	0.66	0.58
$g(hc\bar{c})$	1.9	2.3	1.4	1.2	1.2
$g(hgg)$	1.7	1.7	1.3	0.99	0.95
$g(hWW)$	0.67	0.56	0.80	0.42	0.34
$g(h\tau\tau)$	1.2	1.4	1.1	0.75	0.74
$g(hZZ)$	0.68	0.57	0.80	0.42	0.35
$g(h\gamma\gamma)$	1.2	1.2	1.3	1.0	1.0
$g(h\mu\mu)$	5.6	5.7	5.1	4.87	5.1
$g(hbb)/g(hWW)$	0.88	0.90	0.58	0.51	0.46
$g(hWW)/g(hZZ)$	0.07	0.06	0.07	0.06	0.05
Γ_h	2.5	2.5	2.1	1.5	1.6
$BR(h \to inv)$	0.32	0.56	0.30	0.27	0.29
$BR(h \to other)$	1.6	1.6	1.1	0.94	1.2

errors in %

results: ILC 250 GeV 2 ab-1



results: ILC 250 GeV 2 ab-1 + 500 GeV 4 ab-1



Latest news from ICFA seminar in Ottawa

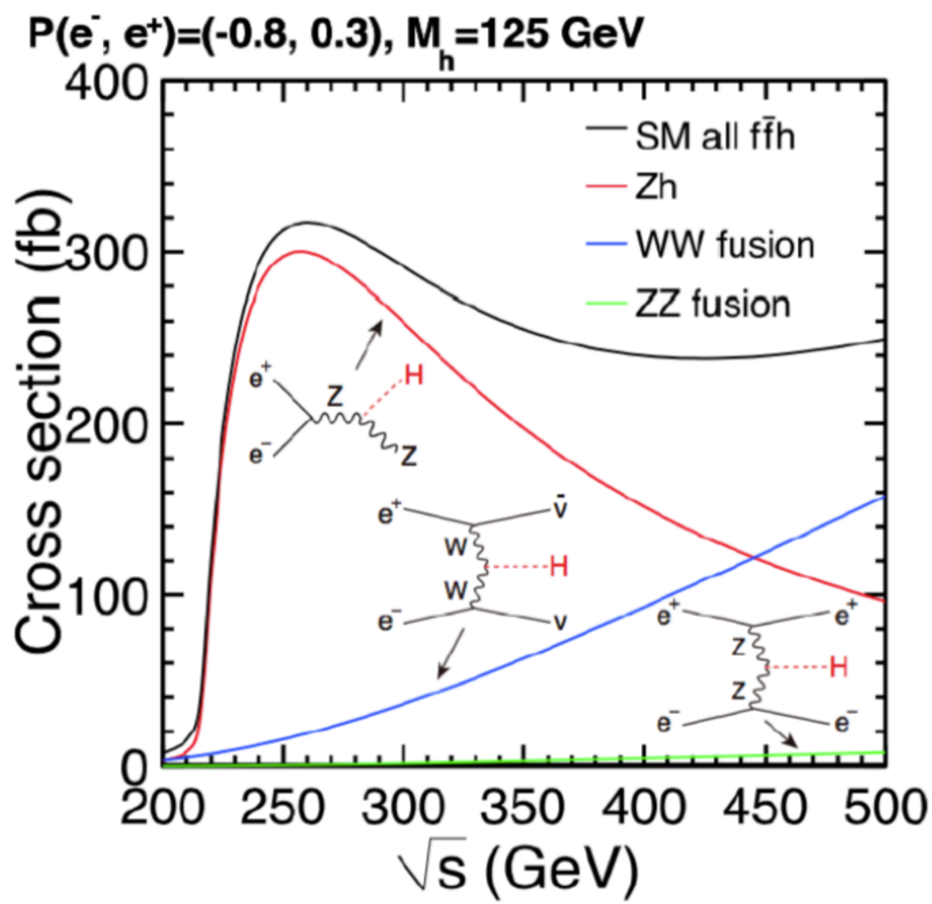
Japanese HEP community Statement

…, in light of the recent outcomes of LHC Run 2, JAHEP proposes to promptly construct ILC as a Higgs factory with the center-of-mass energy of 250 GeV in Japan

Linear Collider Board statement

- Compelling case for a Higgs factory at 250 GeV
- Substantial cost reduction compared to the original 500 GeV ILC
- Technology is mature, thanks to the European XFEL
- Operation energy of a linear collider is intrinsically upgradable by extending the tunnel and accelerating structures

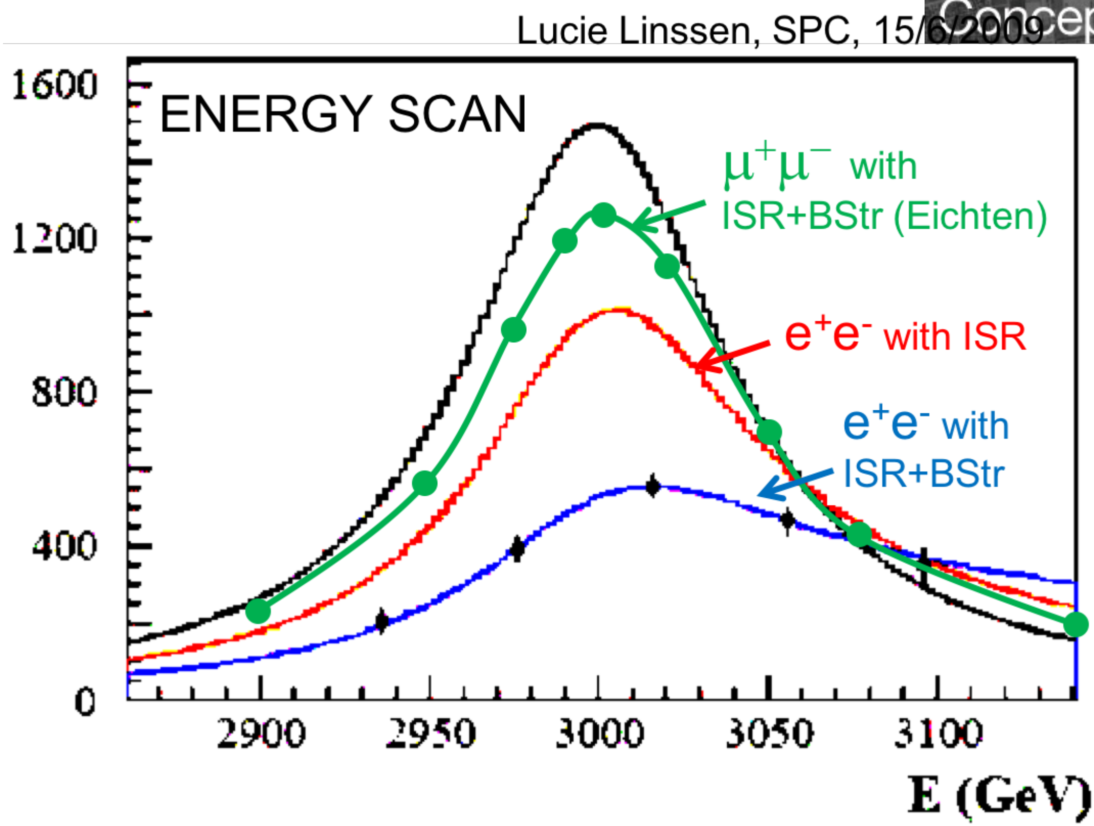
Subsequently endorsed by ICFA

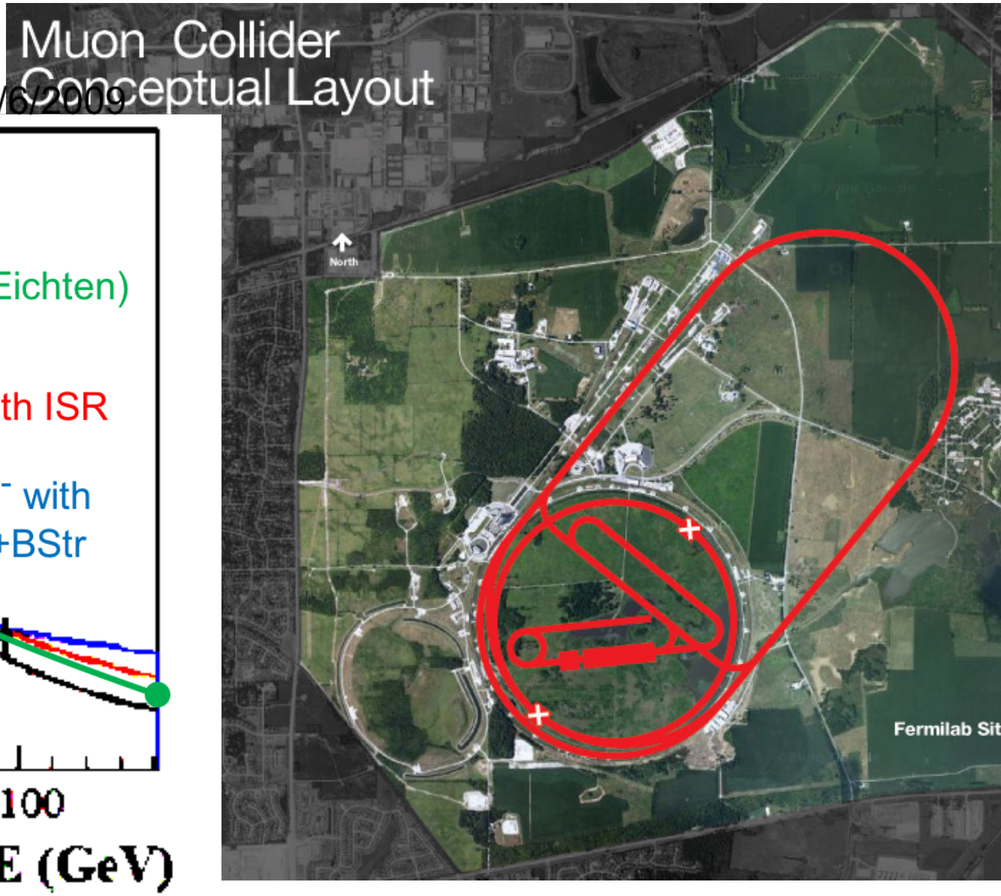


Prescision Frontier – muon collider

- Muon collider – Higgs factory and energy frontier

Circular collider – 120 GeV to 5 TeV, 300 m long (neutrino factory as added bonus)



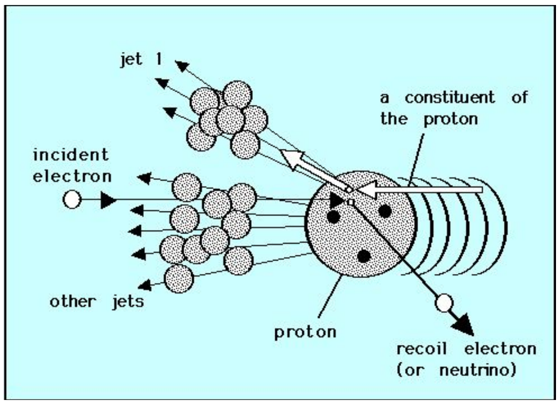


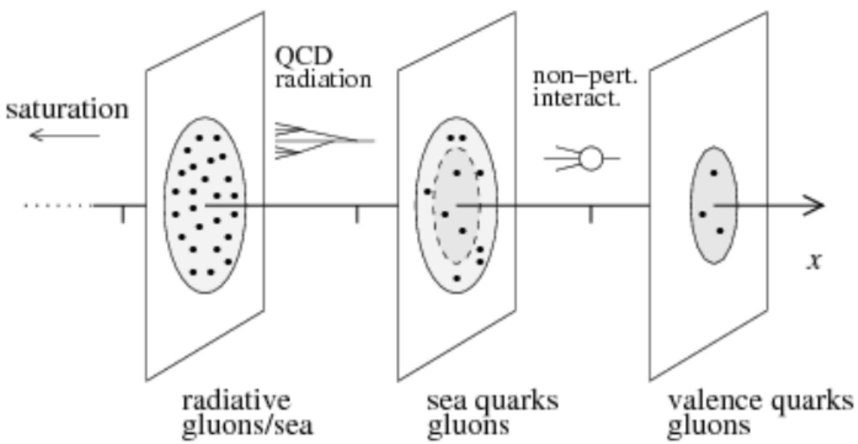
Challenges: to produce enough muons, cool them and compress the beam and all very fast

Density frontier and more

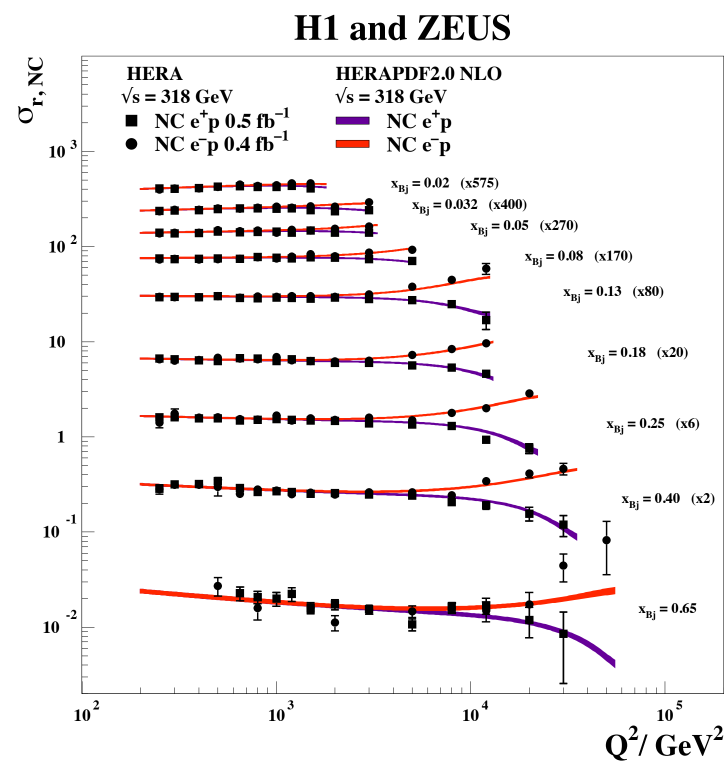
Proton – composite object consisting of quarks and gluons

- only 5% of its mass is generated through the Higgs mechanism
- 95% of its mass is due to QCD
- structure cannot be calculated (yet) from first principles

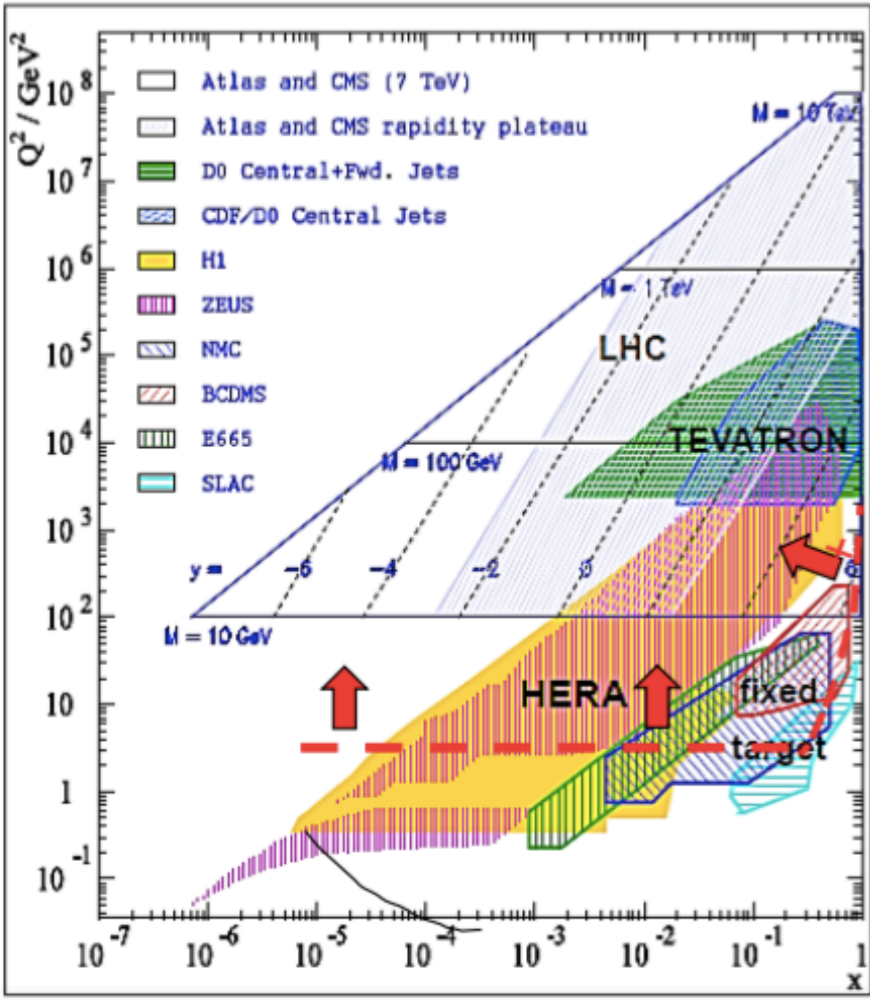


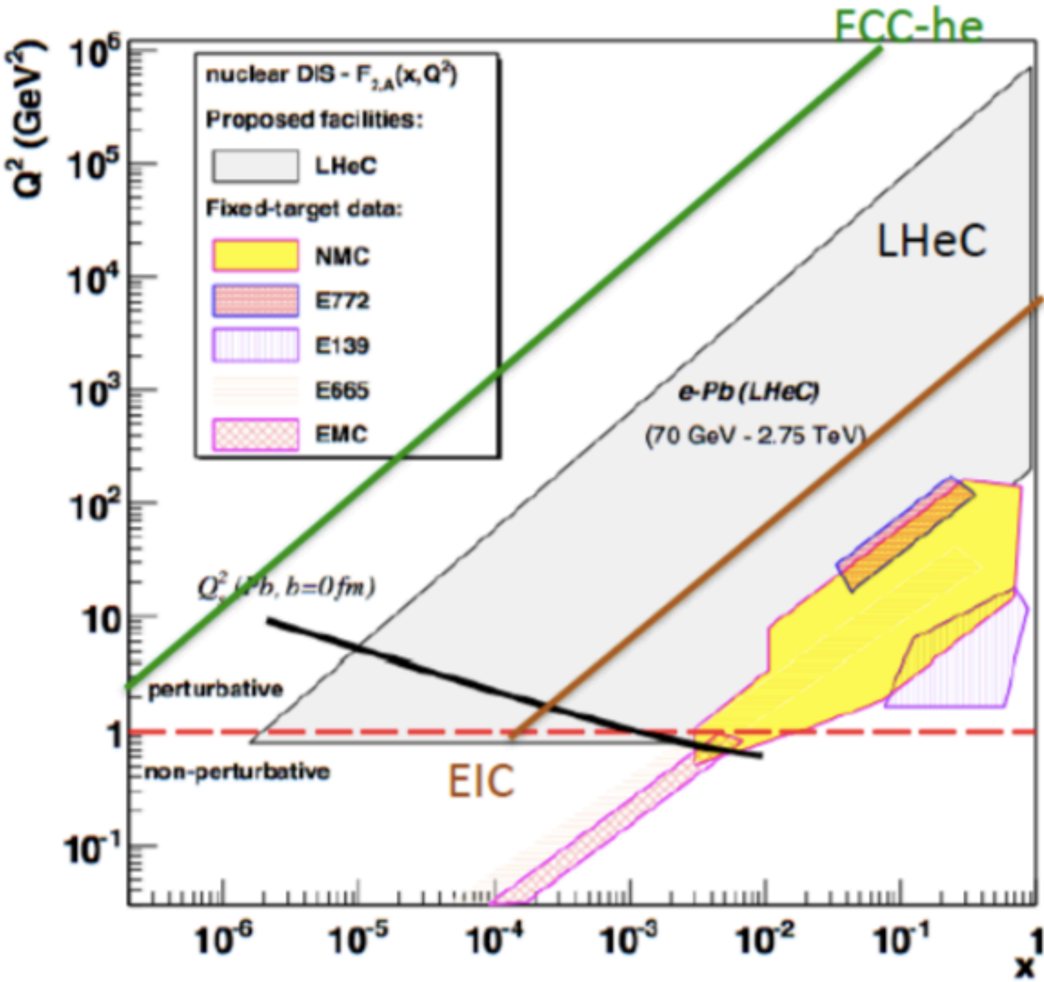


Legacy of ep collider HERA



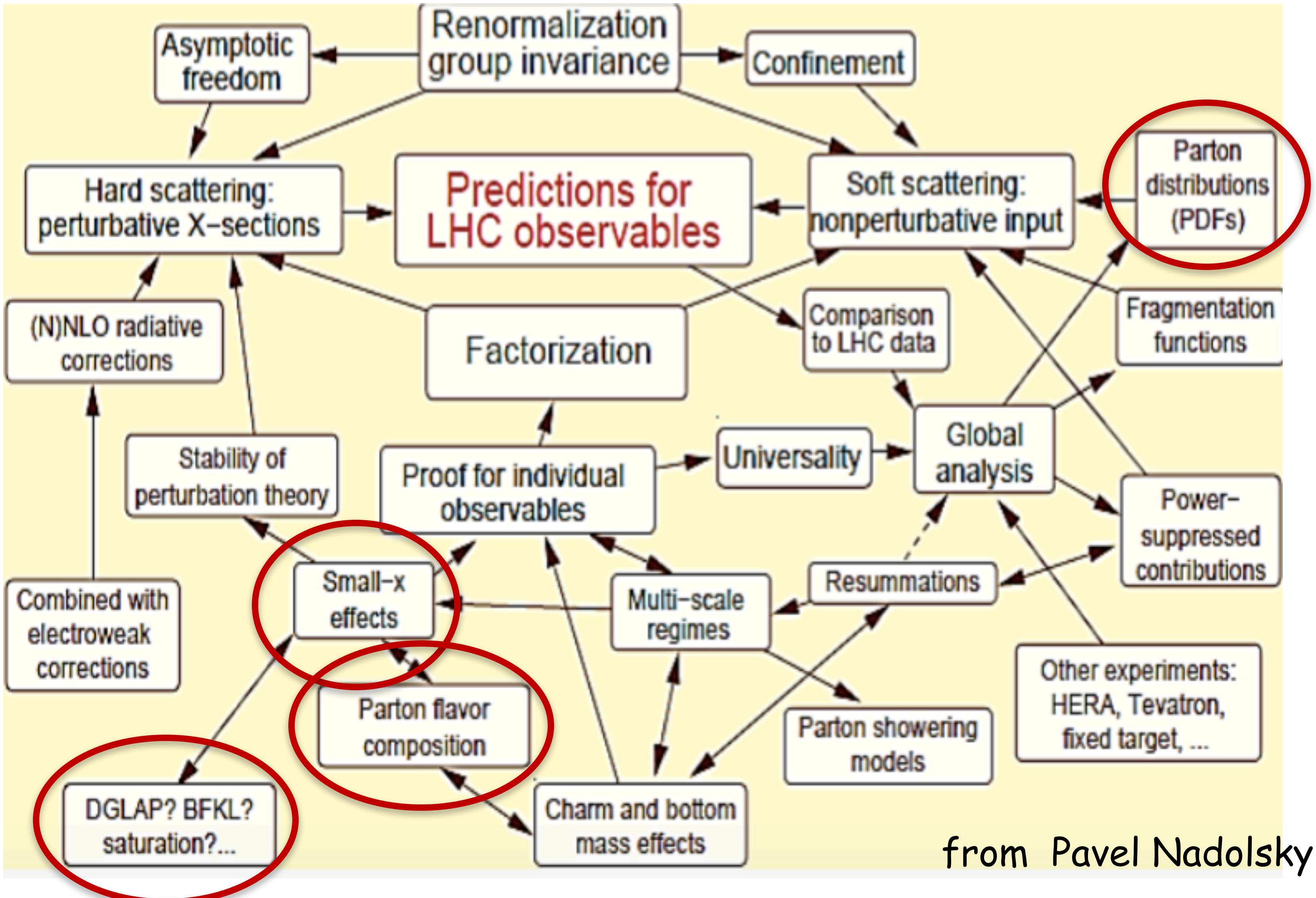
Density frontier and more





Proton structure and QCD

What it takes to get SM predictions for LHC



from Pavel Nadolsky

2+1 dimensional Imaging of Quarks & Gluons

Wigner function
$W(x,b_T,k_T)$

Momentum space

$\int d^2b_T$

$f(x,k_T)$

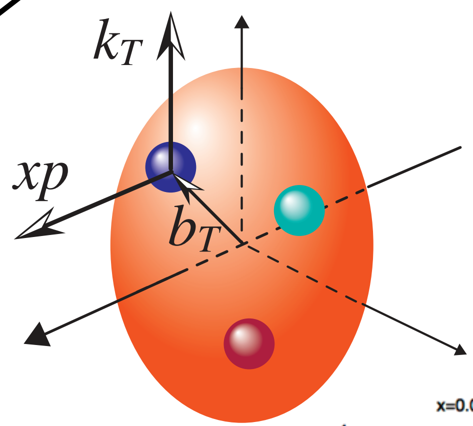
Quarks

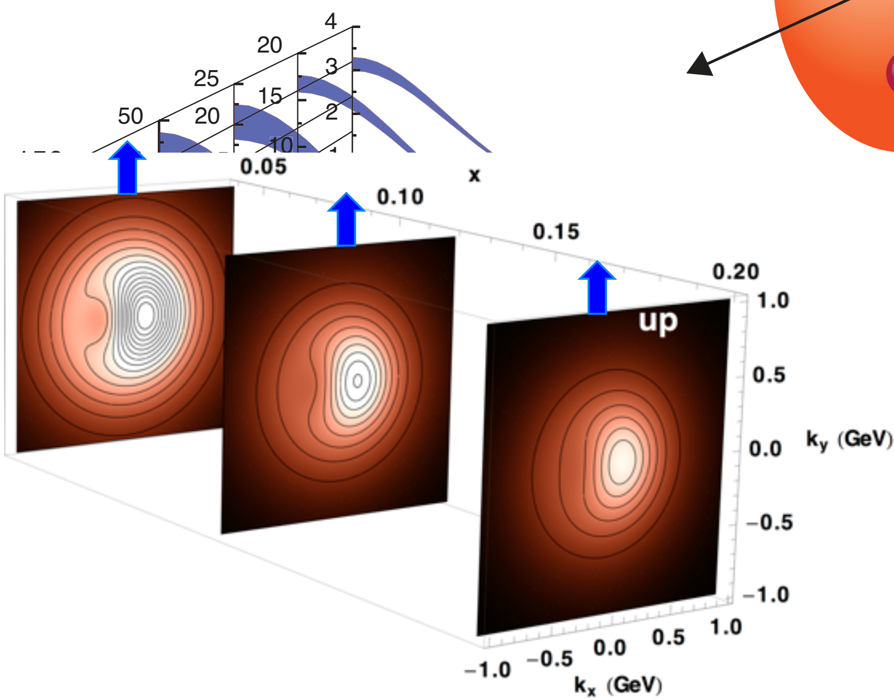
Coordinate space

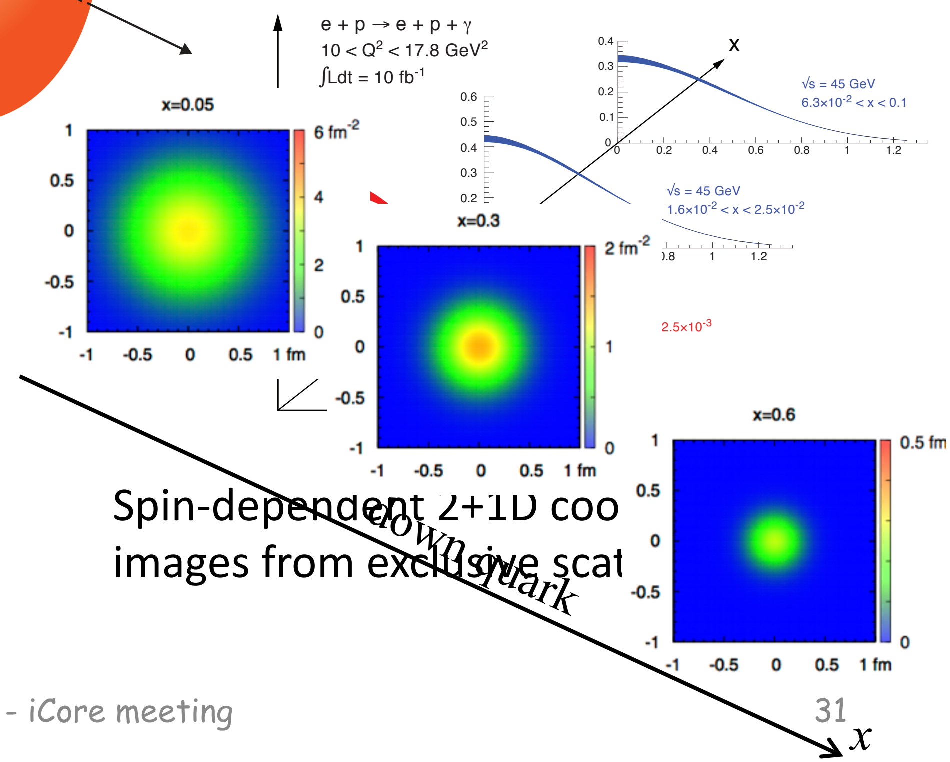
$\int d^2k_T$

$f(x,b_T)$

Quarks

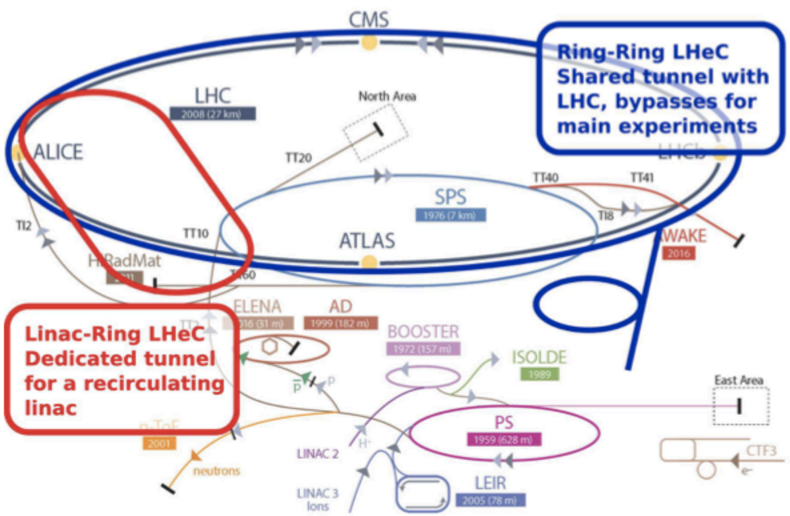


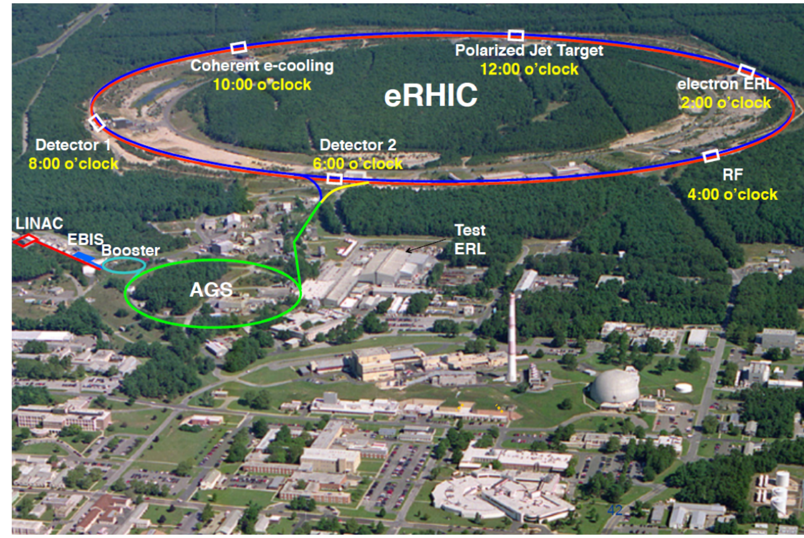


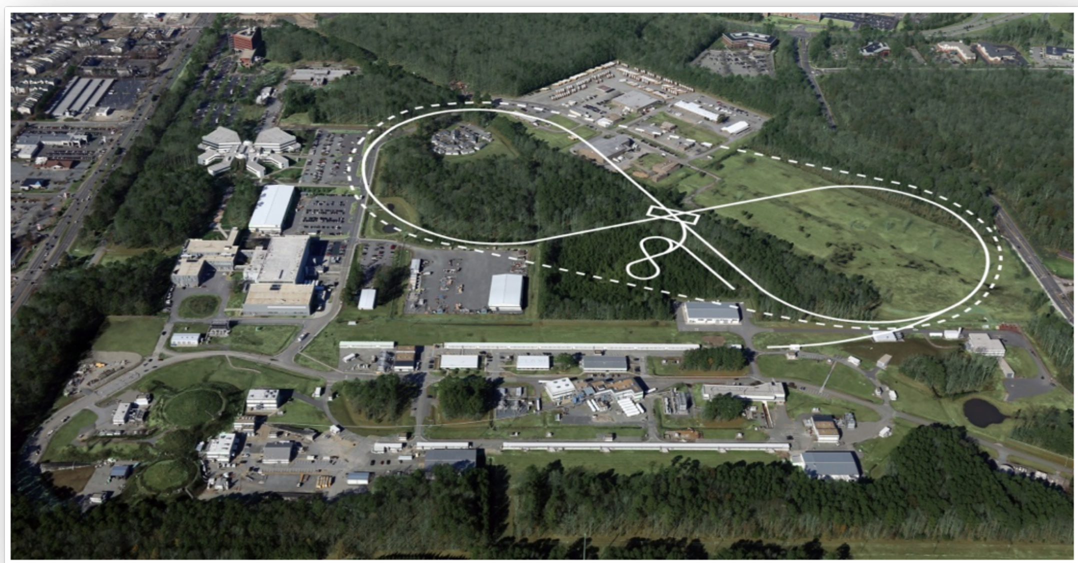


ep/eA colliders

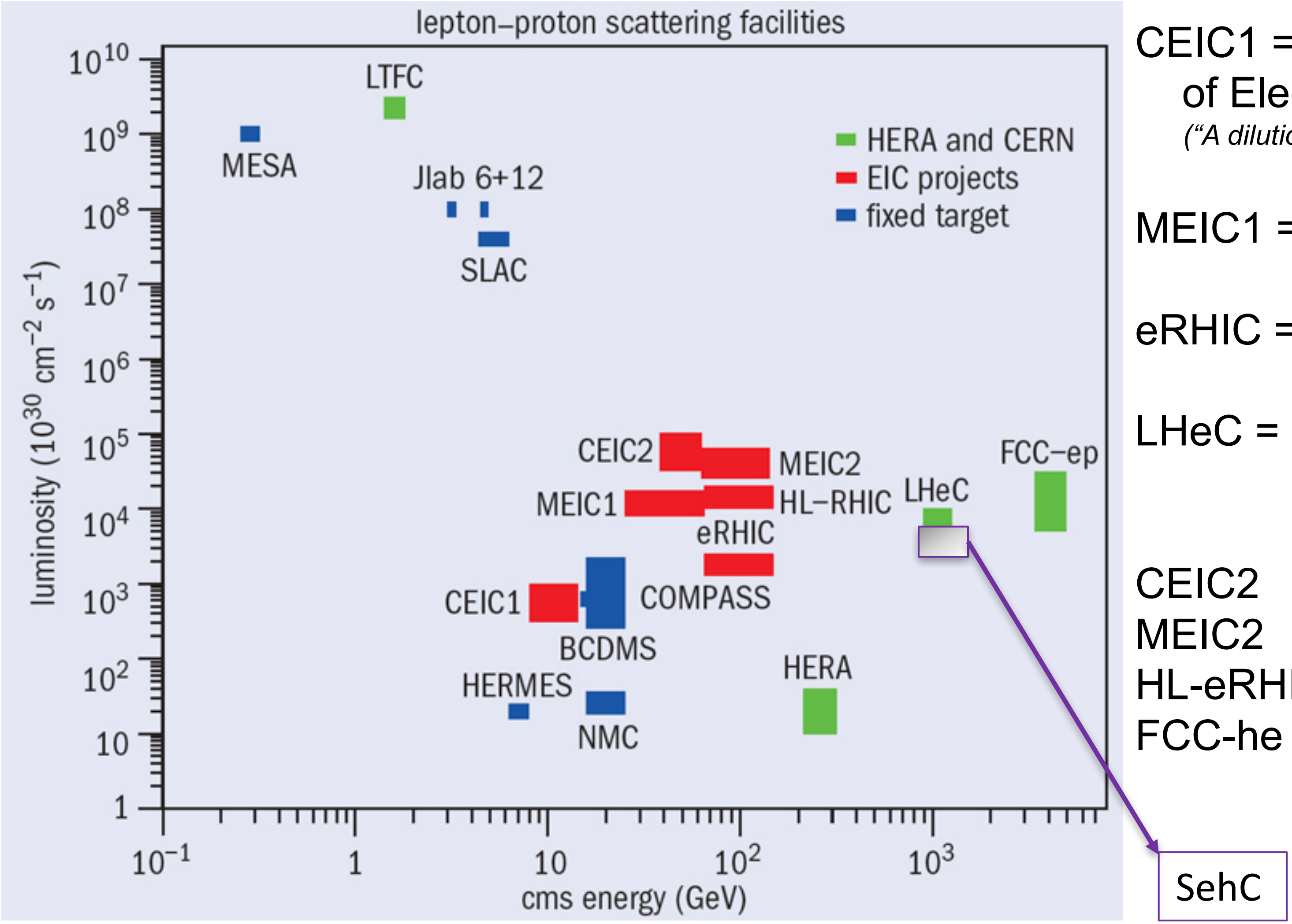
Ring-Ring or (Energy Recovery) Linac-Ring







ep/eA colliders



CEIC1 = Chinese version of Electron-Ion Collider

("A dilution-free mini-COMPASS")

MEIC1 = EIC@Jlab

eRHIC = EIC@BNL

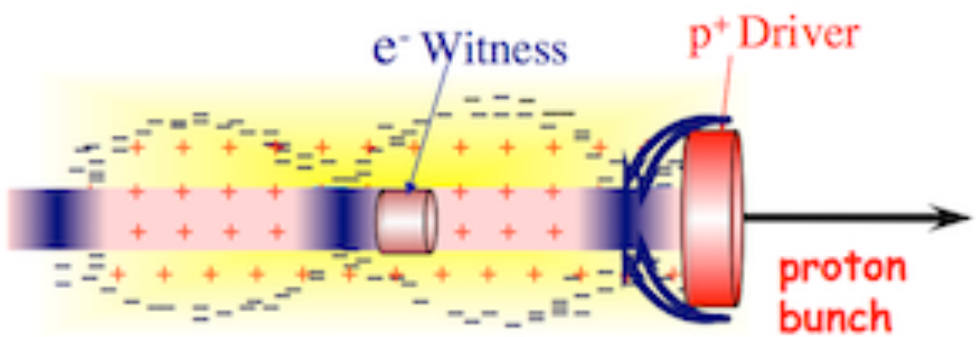
LHeC = ep/eA collider @ CERN

CEIC2
MEIC2
HL-eRHIC
FCC-he

New Accelerator Technologies

- *Accelerators using RF cavities limited to ~100 MV/m;* high energies ⇒ long accelerators

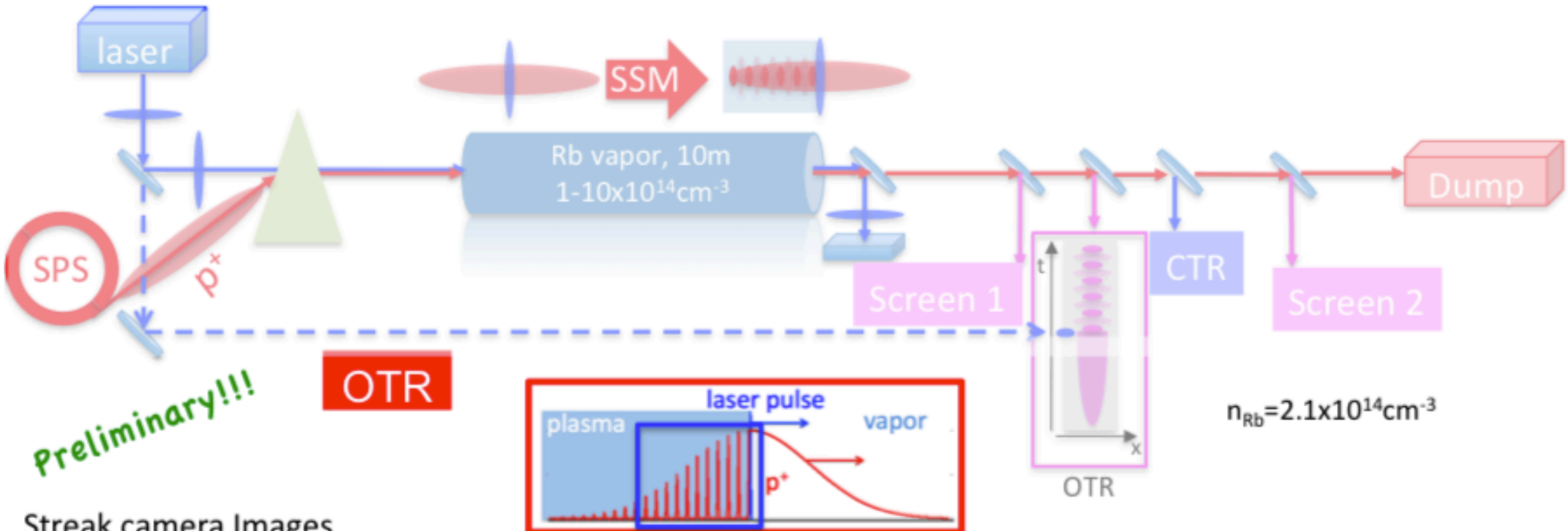
- Gradients in plasma wakefield acceleration of ***~100 GV/m*** measured



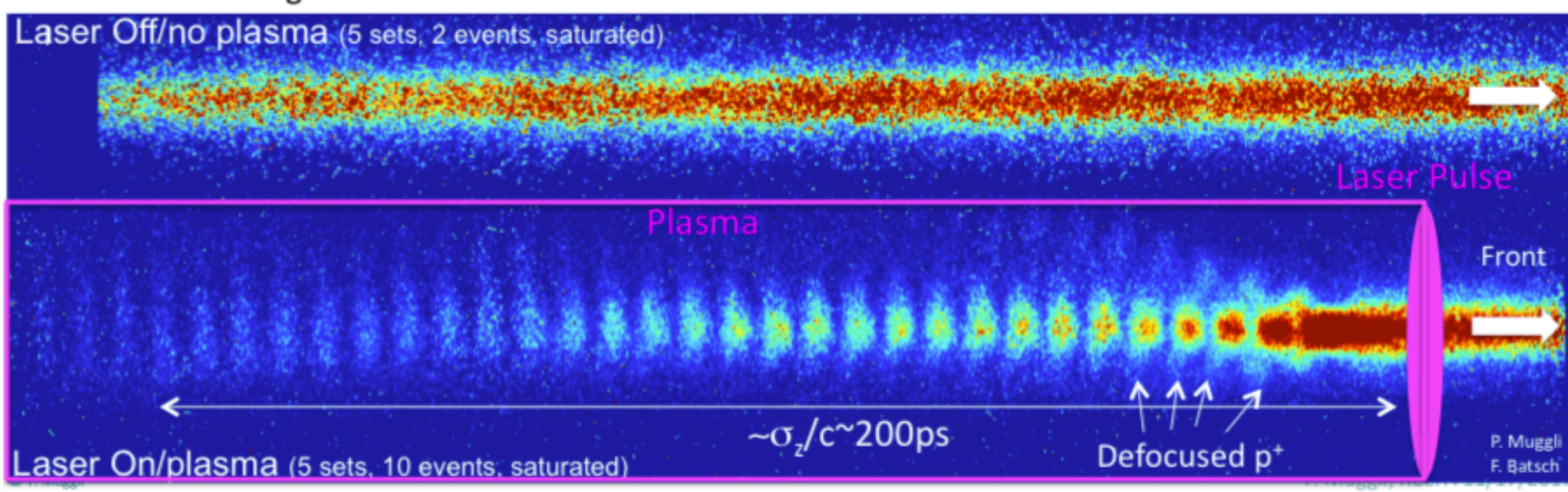
- ILC-CLIC, 0.5 TeV bunch with $2\times10^{10}e^-$ - about 1.6kJ
- SPS, 400 GeV bunch with $10^{11}p$ - about 6.4kJ
  LHC, 7 TeV - 112kJ
- A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage
- Large average gradient (>1GV/m, 100's m)

Proof of principle under way at the SPS at CERN

µBUNCH TRAiN

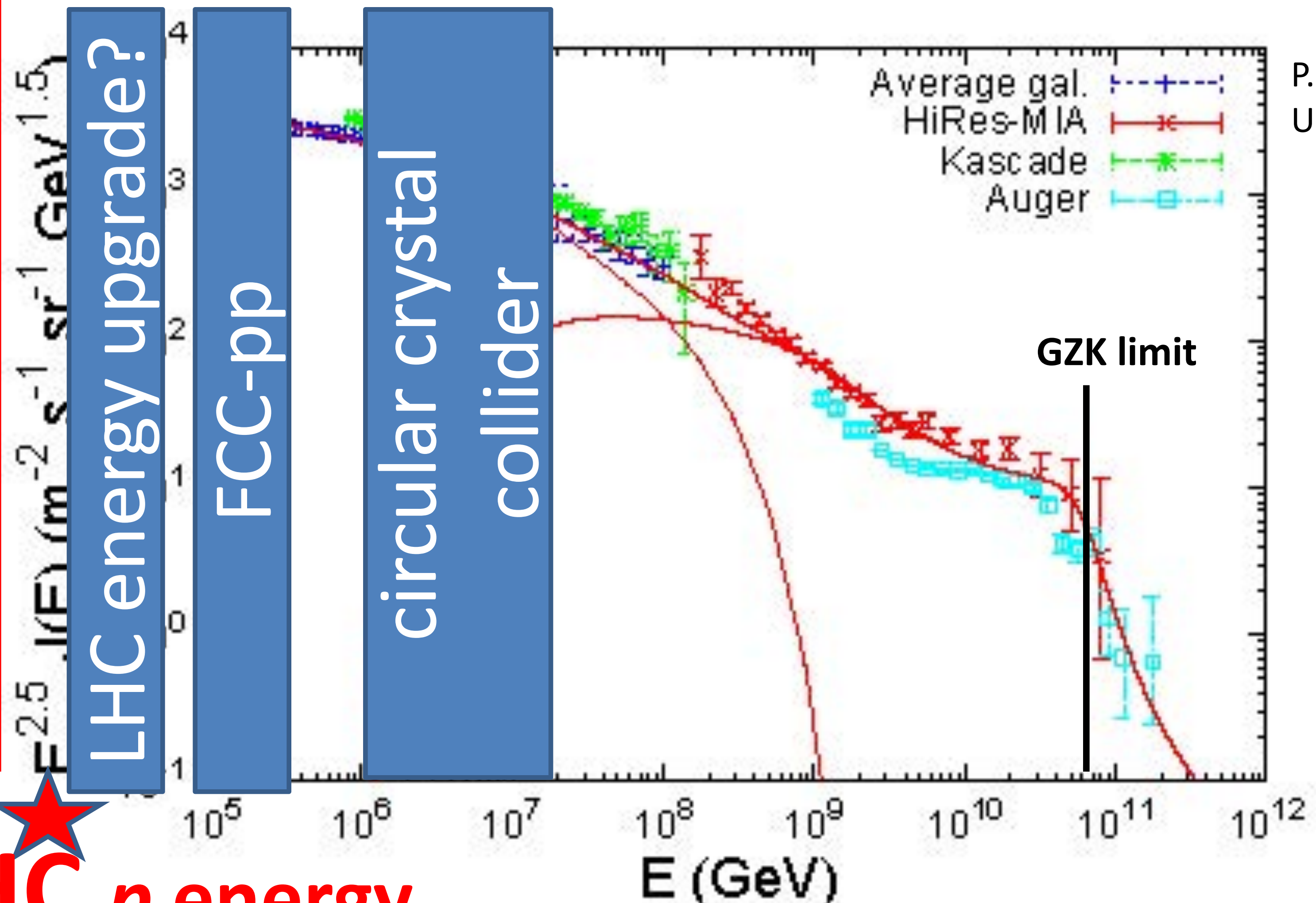


Streak camera Images



10^{45} m^{-2}s^{-1}sr^{-1}GeV$^{1.5}$!

cosmic-ray energy spectrum



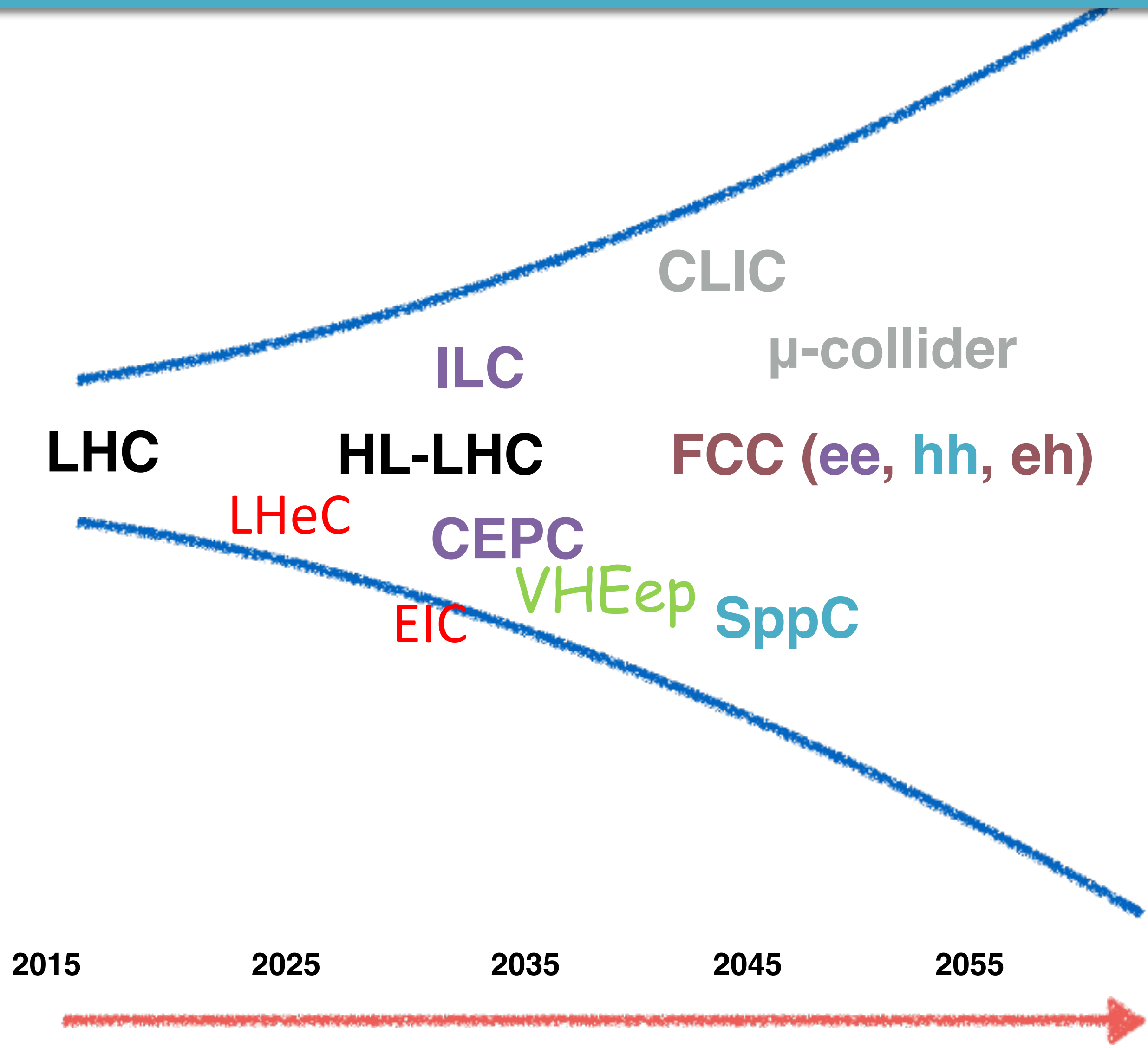
P. Blasi, UHECR2012

LHC *p* energy

x10^8

Colliders of the 21st Century

KLUTE



European Strategy 2013 – next update 2020

- Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. (HL-LHC)

- 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 (CLIC, FCC hh,ee,ep … AWAKE)

- There is a strong scientific case for an electron-positron collider… The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation... Europe looks forward to a proposal from Japan to discuss a possible participation. (Waiting for Japanese Gov. decision)

- CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan. (LBNF in FNAL – DUNE in S. Dakota)

Structure of the EPPSU process

- Strategy update approval by Council (date fixed, May 2020)
- The strategy update is drafted by the European Strategy Group (ESG)
- The drafting is based on input from the community – collaborations, projects, national institutes, national roadmaps, individuals
- The input is collected by the Physics Preparatory Group (PPG)
- The PPG organizes the Open Symposium to discuss the proposals
- The PPG summarizes the input, the discussions and their conclusions in a Briefing Book
- The Briefing Book constitutes the input for the ESG for drafting the update
- The drafting of the strategy update takes place during a dedicated Drafting Session (the conclave of the EPPSU process)
- The organization is handled by the Strategy Secretariat
- All the groups are chaired by the Strategy Secretary

Composition of the Strategy Secretariat

Members

- The Strategy Secretary - HA
- SPC chair – Keith Ellis
- ECFA chair – Jorgen D'Hondt
- Chair of *the European Laboratory Directors Group* – Lenny Rivkin

The European Laboratory Directors Group

- CERN
- CIEMAT
- DESY
- IRFU
- LAL
- NIKHEF
- LNF
- LNGS
- PSI
- STFC-RAL

Composition of the PPG

Members

- The Strategy Secretary (chair)
- Four members recommended by the SPC
- Four members recommended by ECFA
- SPC chair
- ECFA chair
- Chair of the the European Laboratory Directors Group
- One representative appointed by CERN
- Representative(s) from Asia (≤2)
- Representative(s) from the Americas (≤2)

15 to 17 people

Composition of the ESG

Members

- The Strategy Secretary (chair)
- One representative appointed by each CERN MS (22)
- One representative appointed by each of the Labs participating in the European Laboratory Directors Group including its Chairperson (9)
- CERN DG
- SPC chair
- ECFA chair

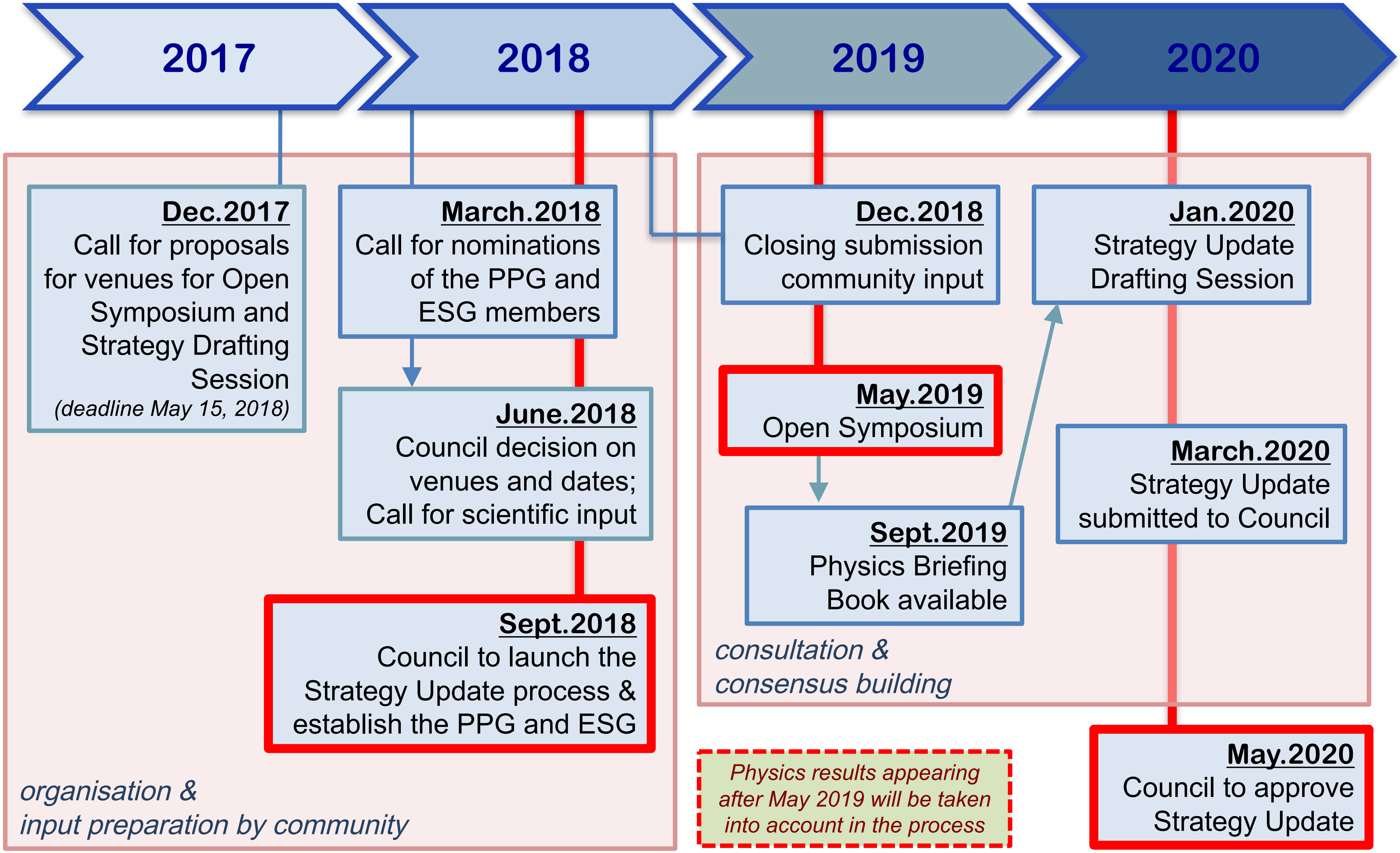
Invitees

- President of CERN Council
- One representative from each AMS and OS (7+3)
- One representative from the European Commission
- Chairs of ApPEC, NuPECC, FALC, ESFRI
- Members of the PPG (17 - Secretariat)

62 to 64 people

European Strategy Update

European Particle Physics Strategy *Update*



References

ILC - Technical Design Report
CLIC - Conceptual Design Report
CepC - pre-Conceptual Design report
FCCee - The Fcc-ee Design Study
SSC - Higgs Factory and 100 TeV Hadron Collider: Opportunity for a New World Laboratory within a Decade
FCC - Web pages
SppC - pre-Conceptual Design report
HE-LHC – high field magnetic design
EIC – JLAB (MEIC Design Summary)
EIC – BNL (eRHIC Design Study: An Electron-Ion Collider at BNL)
VHEep - VHEeP: A very high energy electron-proton collider
Muon Collider - A muon collider as a Higgs factory

Image of M. Strassler from "Conversations about Science with theoretical physicist Matt Strassler", Of Particular Significance

Outlook

- The community is busy thinking about the future, driven by the physics case
- Many exciting developments
- The timelines of the various projects very uncertain
  - Technology issues
  - Funding issues
- HL-LHC approved
- For the near future EIC looks like the most realistic project
- Expect heated discussions during the EPPSU