Perspectives in High Energy Physics

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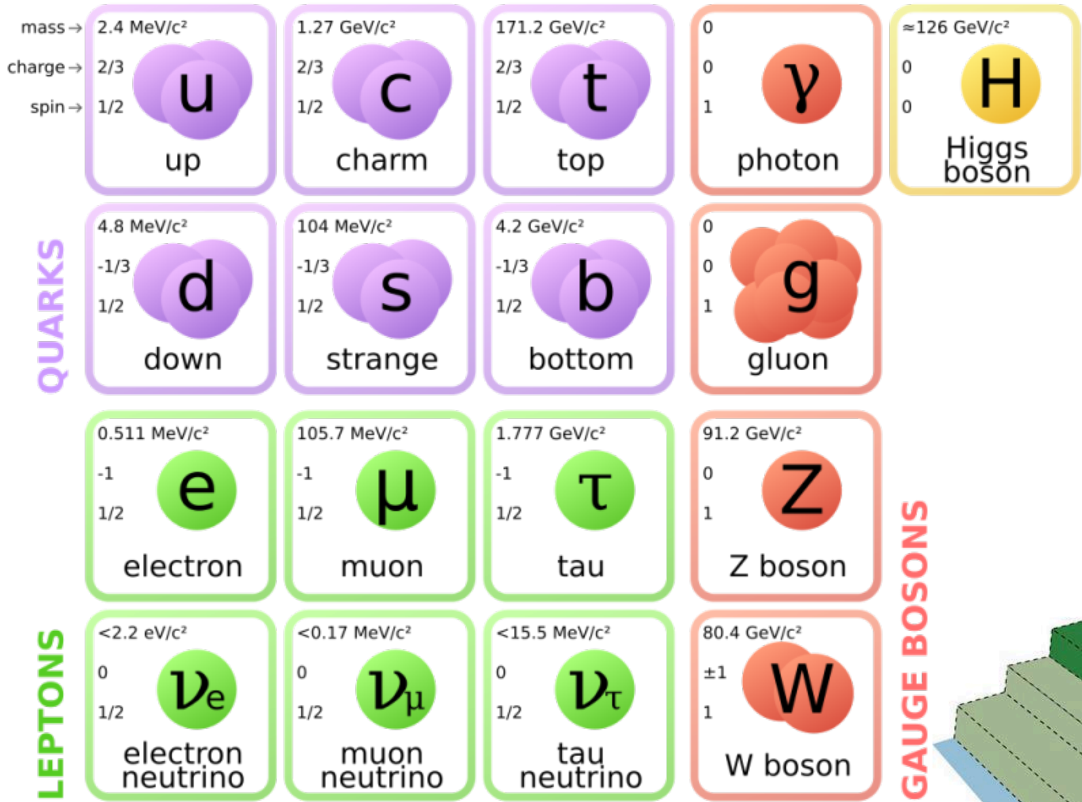
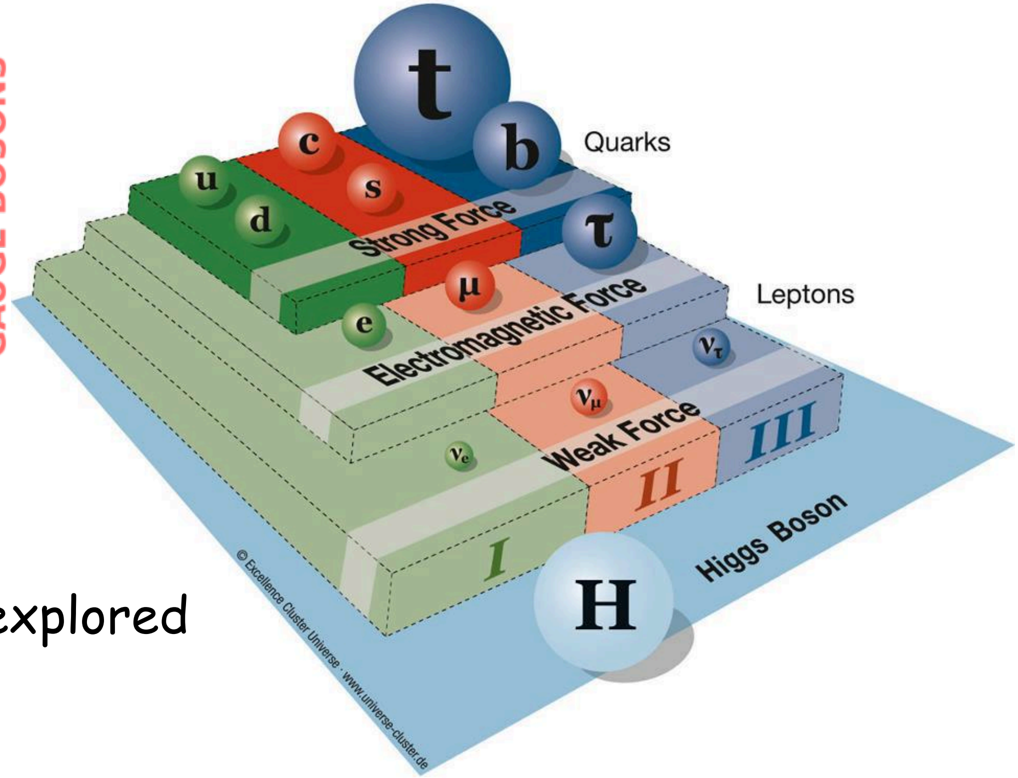
TEL AVIV UNIVERSITY אוניברסיטת תל אביב

- Status of Standard Model of particle physics
- What is missing?
- Future options

Status of the Standard Model





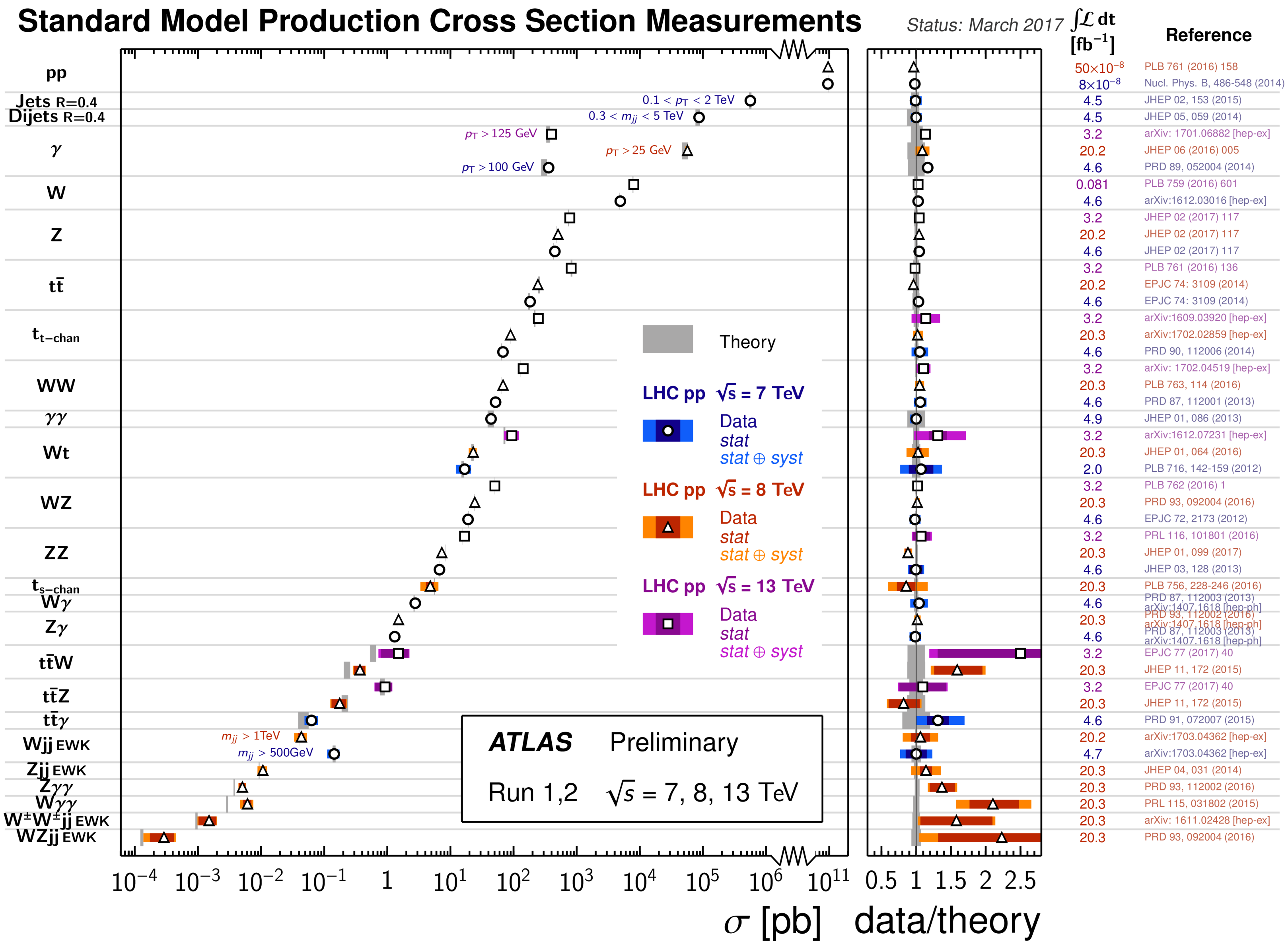
Higgs sector and top sector largely unexplored

Present Energy Frontier – Large Hadron Collider at CERN

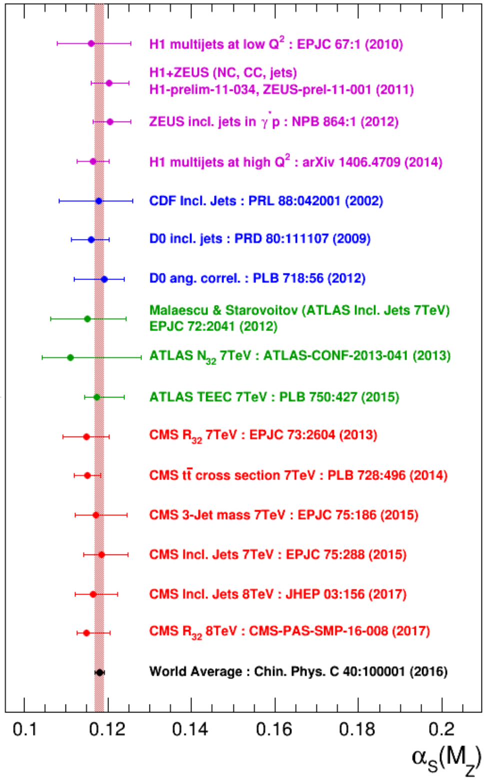
27km tunnel, up to 175m deep, 1232 SC bending magnets 1.9K, 14.3m long, 8T

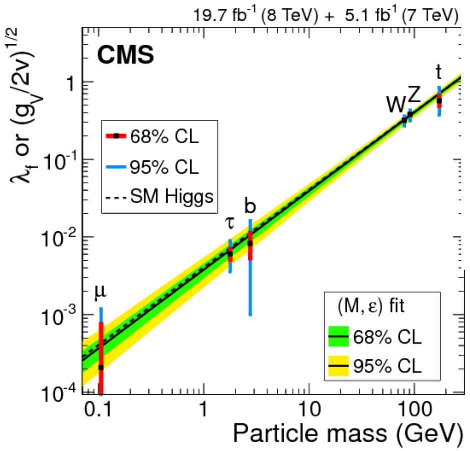
Collected pp data: 7TeV (2010/2011); 8TeV (2012); 13TeV (2015-now)

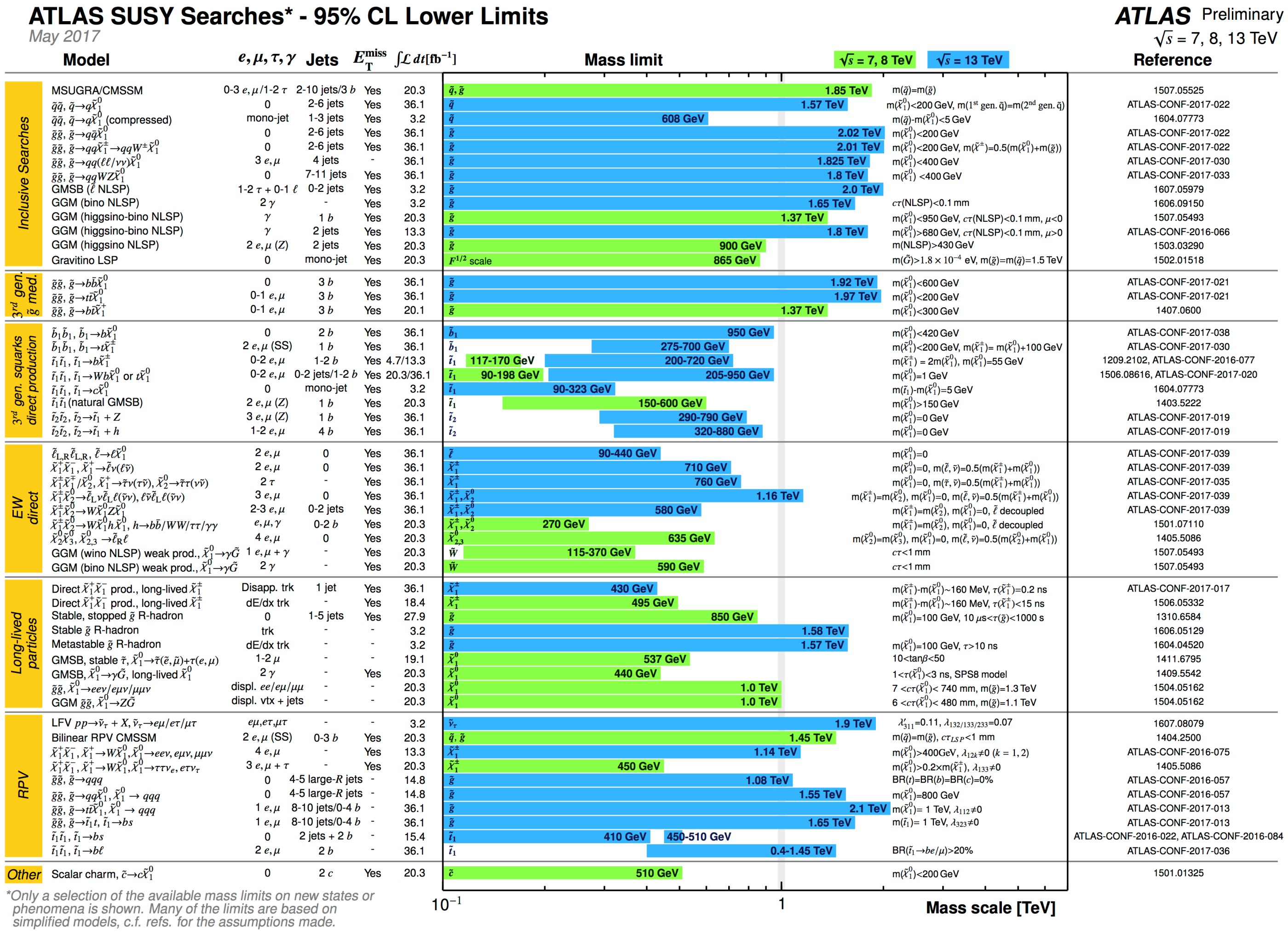
Stress test of SM at the LHC



Stress test of SM at the LHC







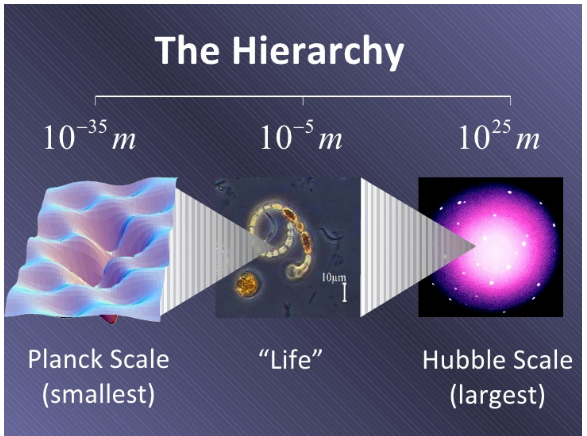
Guidelines from LHC results

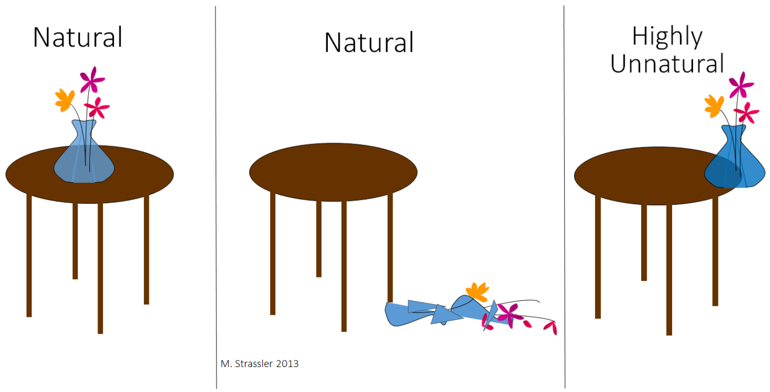
- The Standard Model is doing amazingly well
- The Higgs scalar is very much like expected in the Standard Model
- There is no indication of physics BSM up to scales of the order of 1 to 3 TeV

however

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???)
- There are theoretical arguments that theory is not complete

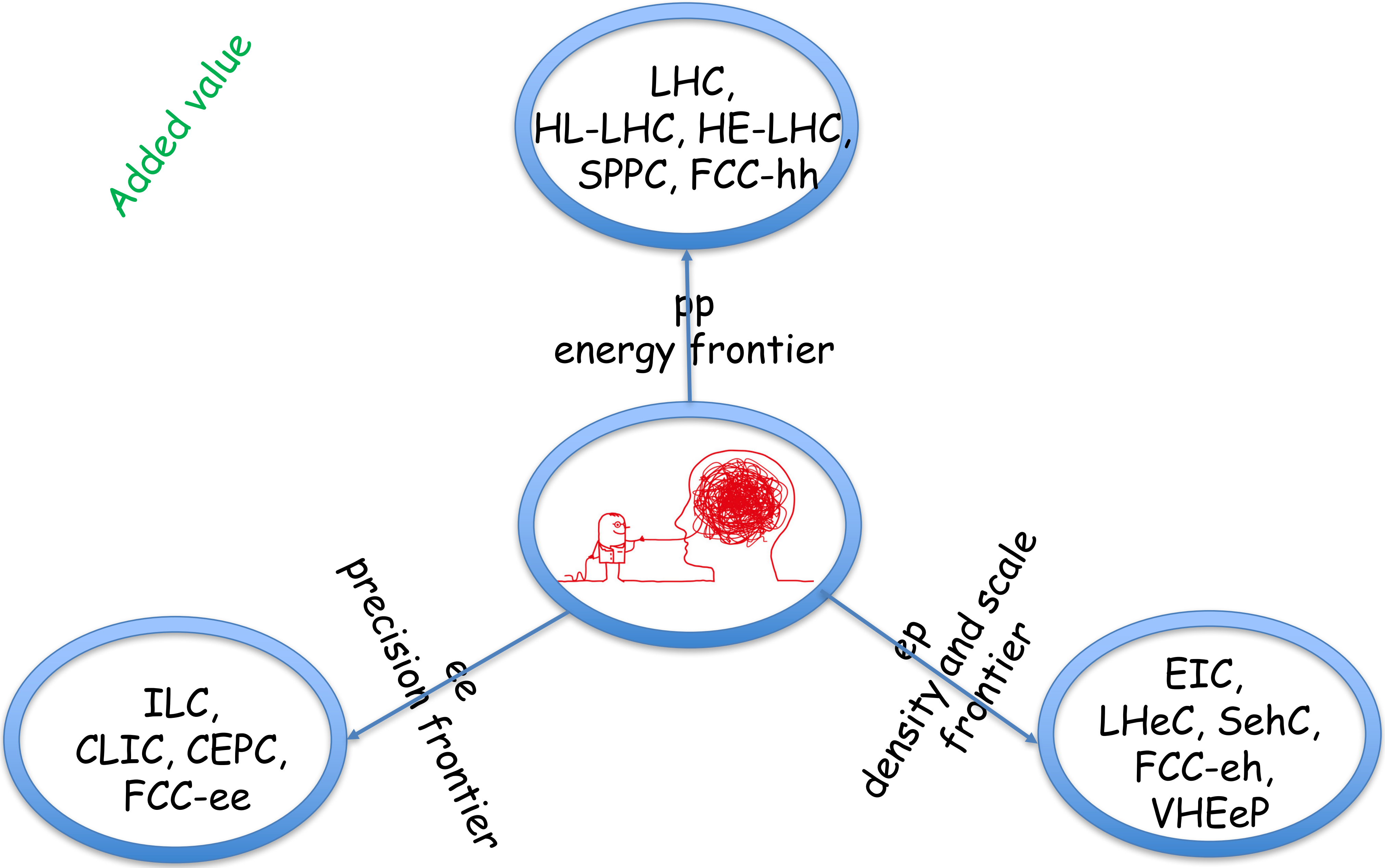




How should we go about understanding all these issues ?

Controlled experiments at accelerators

Added value

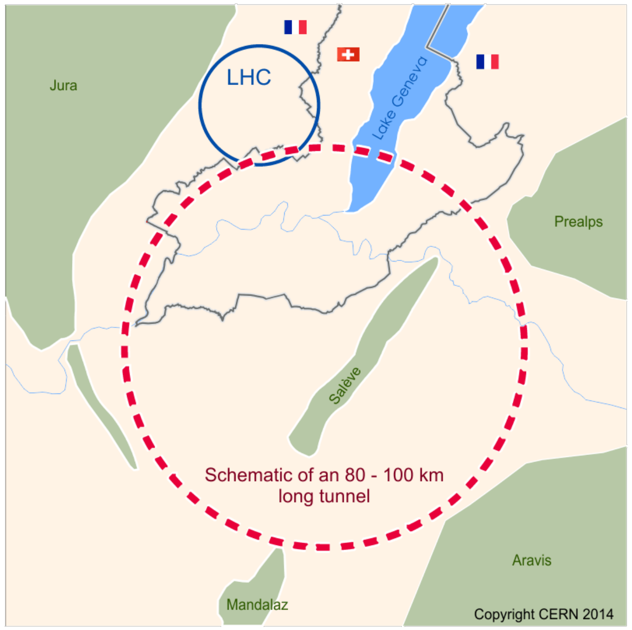


Energy frontier

- Hadron colliders

CERN: HE – LHC, pp 28 TeV - replace dipoles with 16 T HTS Nb_3Sn → 20 T
CERN: FCC – pp 100 TeV, 80 to 100 km tunnel, 16 to 20 T magnets
China: SppC – pp 35 to 65 TeV, 60 km to 100 km tunnel with 12 T HTS →24 T
US: SSC – pp 100 to 300 TeV, 270 km tunnel, 5 T to 15 T magnets

Geneva



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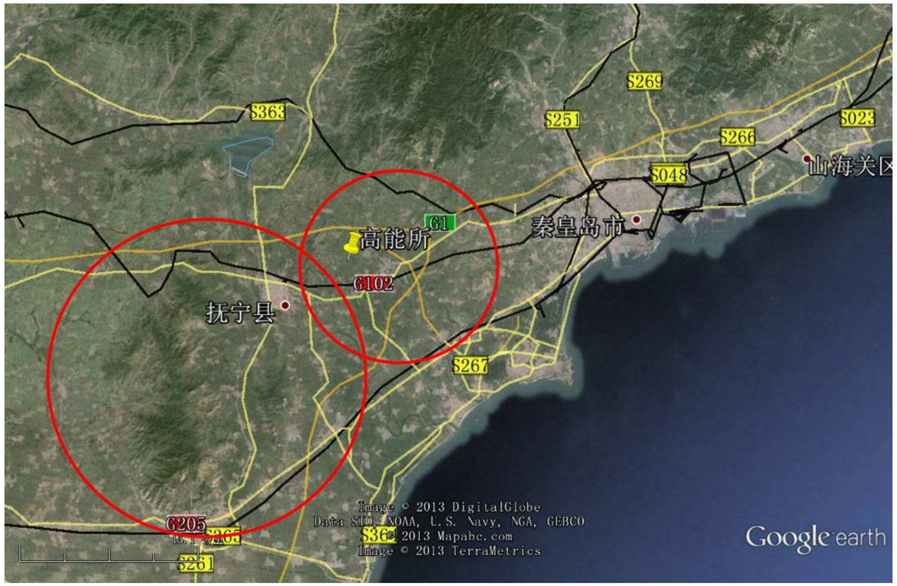
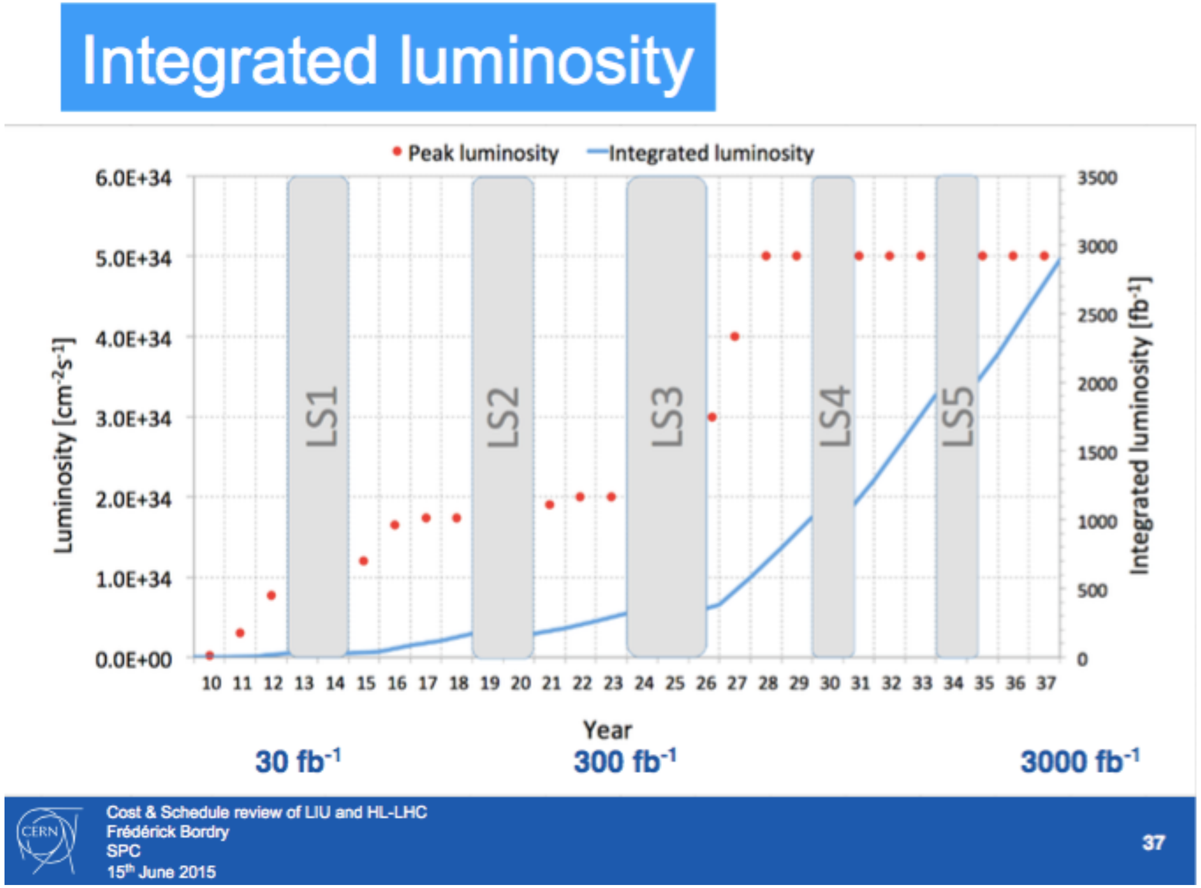
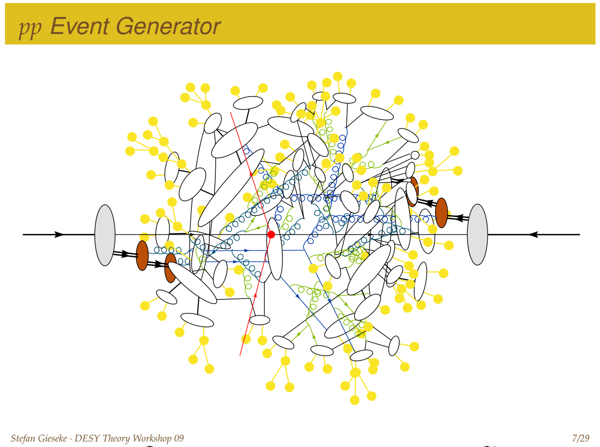


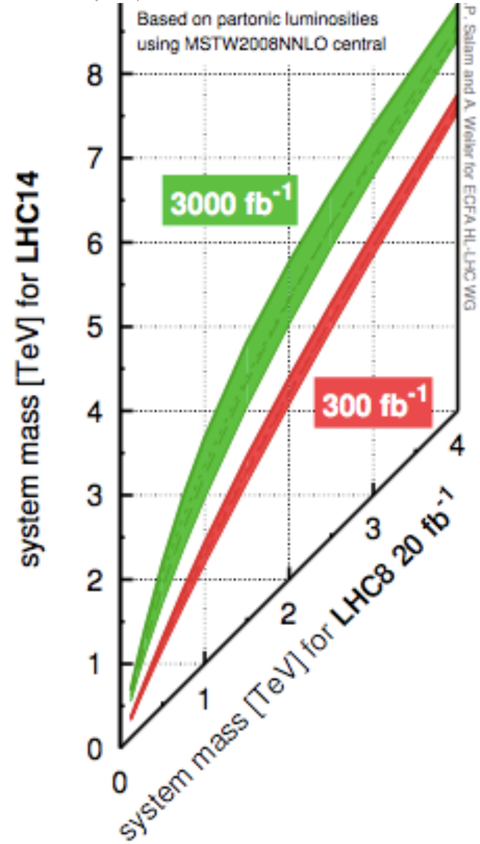
Energy Frontiers

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

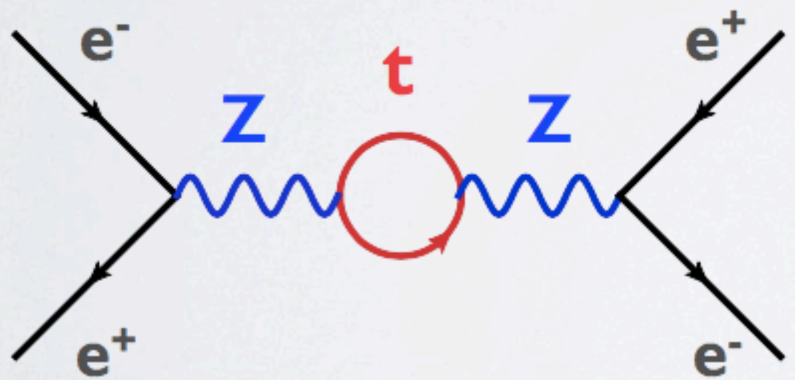
At 14 TeV and 3 ab^{-1} mass reach<10 TeV





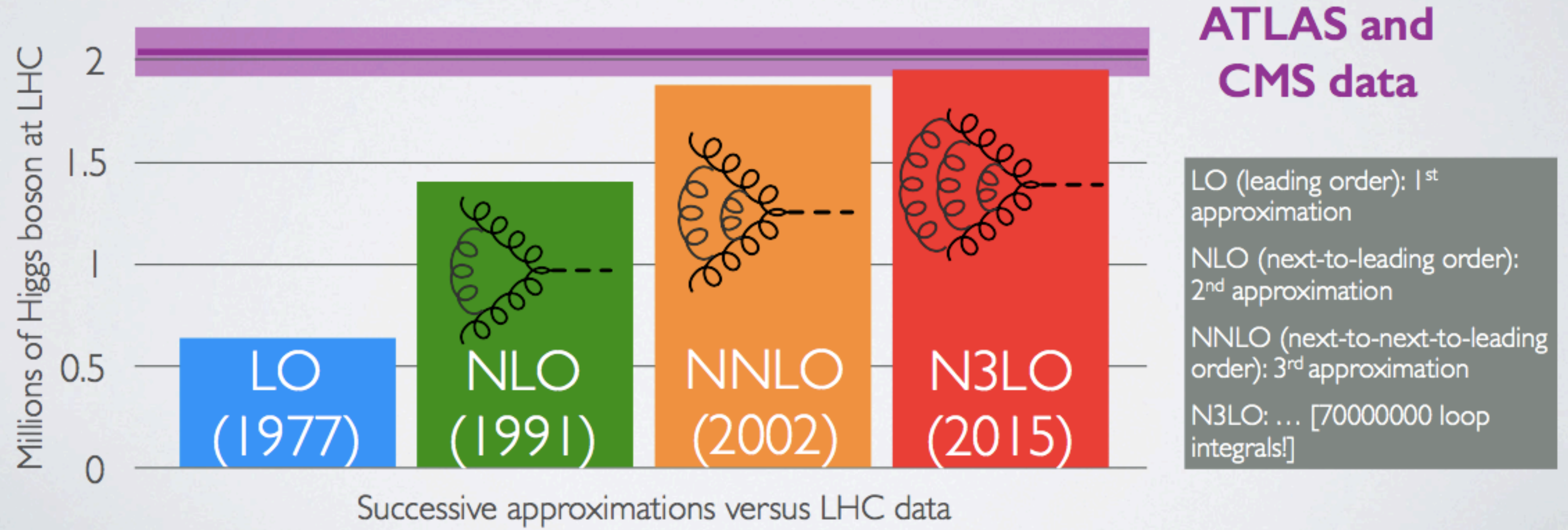


Precision Frontier



- 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

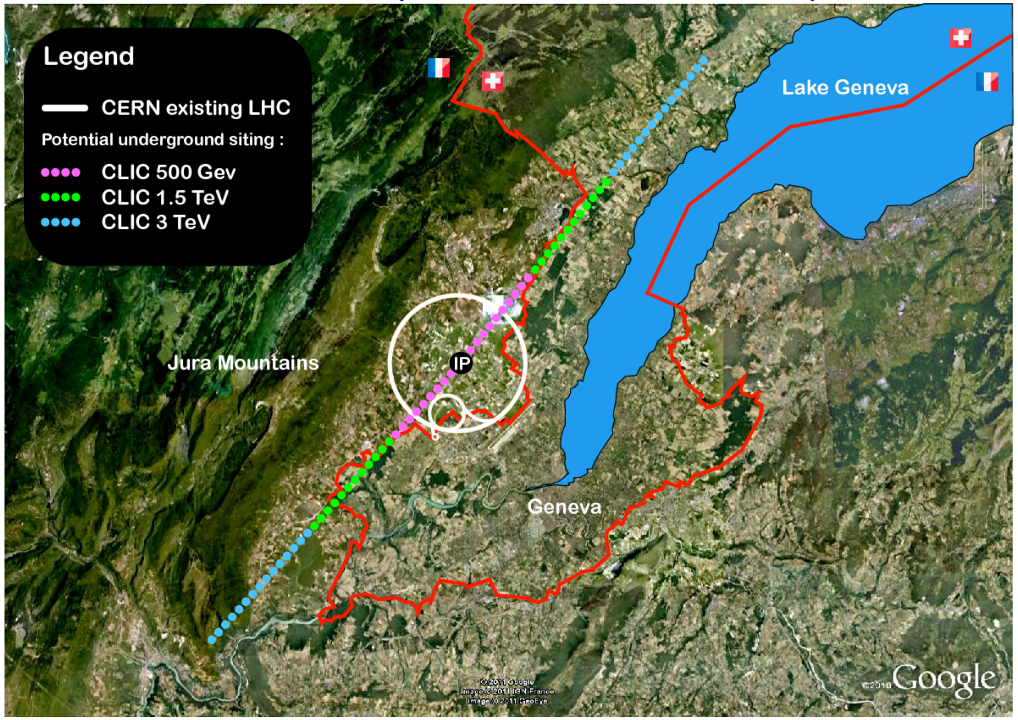


Precision frontier

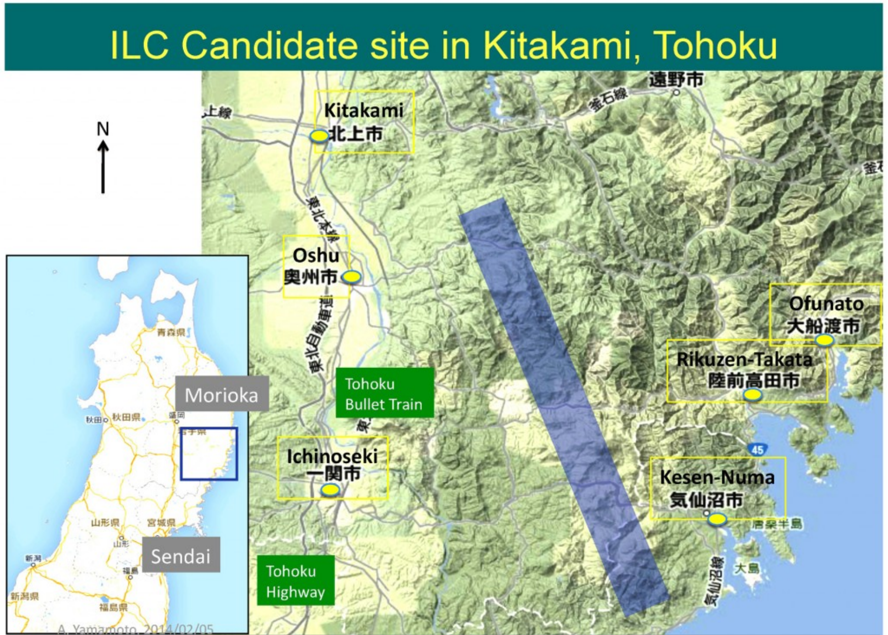
- Electron-positron machines

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)



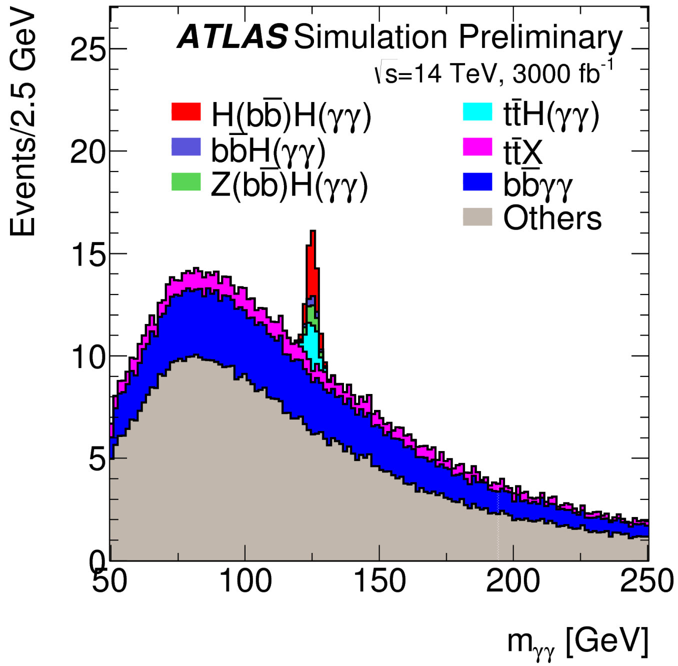
Accelerating structures 72 to 100 MV/m



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

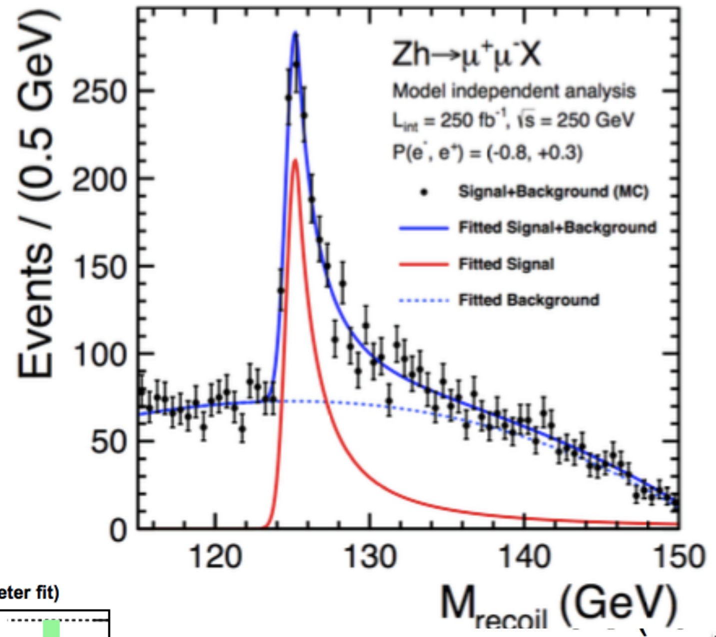
Precision Frontier

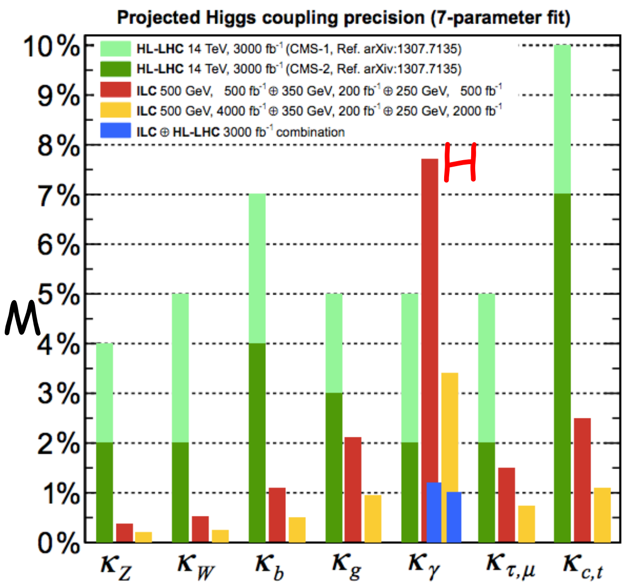
Precision Higgs/top physics

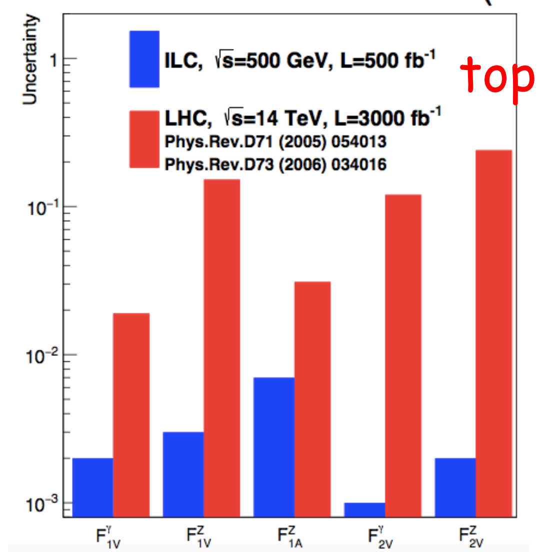


HL-LHC

ILC

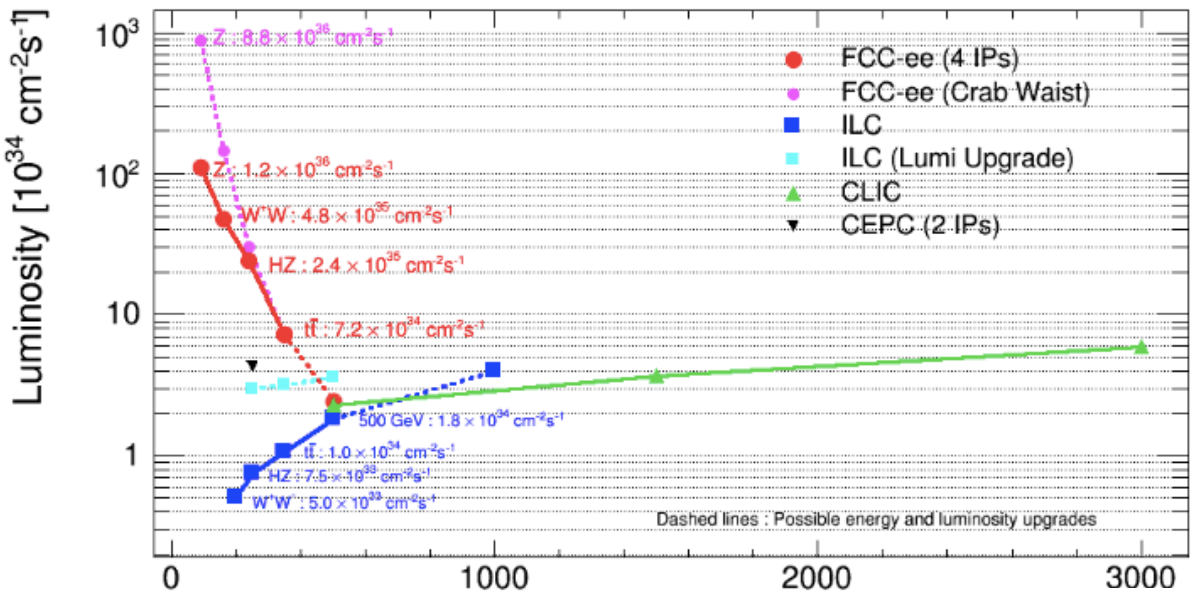






Higgs couplings – sensitive to BSM
ILC below 1%, except *γγ*
LHC 2% to 3% except *bb cc tt*

Precision Frontier



Luminosity vs energy for ee colliders

Comparison of expected Precision on H couplings

Coupling	LHC	CepC	FCC-ee	ILC	CLIC	FCC-hh
√s (TeV)→	14	0.24	0.24 +0.35	0.25+0.5	0.38+1.4+3	100
L (fb^{-1}) →	3000(1 expt)	5000	13000	6000	4000	40000
K_W	2-5	1.2	0.19	0.4	0.9	
K_Z	2-4	0.26	0.15	0.3	0.8	
K_g	3-5	1.5	0.8	1.0	1.2	
K_γ	2-5	4.7	1.5	3.4	3.2	< 1
K_μ	~8	8.6	6.2	9.2	5.6	~ 2
K_c	--	1.7	0.7	1.2	1.1	
K_τ	2-5	1.4	0.5	0.9	1.5	
K_b	4-7	1.3	0.4	0.7	0.9	
$K_{Z\gamma}$	10-12	n.a.	n.a.	n.a.	n.a.	
Γ_h	n.a.	2.8	1.	1.8	3.4	
BR_{invis}	<10	<0.28	<0.19	<0.29	<1	
K_t	7-10	--	13% ind. tt scan	6.3	<4	~ 1 ?
K_{HH}	?	35% from K_Z model-dep	20% from K_Z model-dep	27	11	5-10

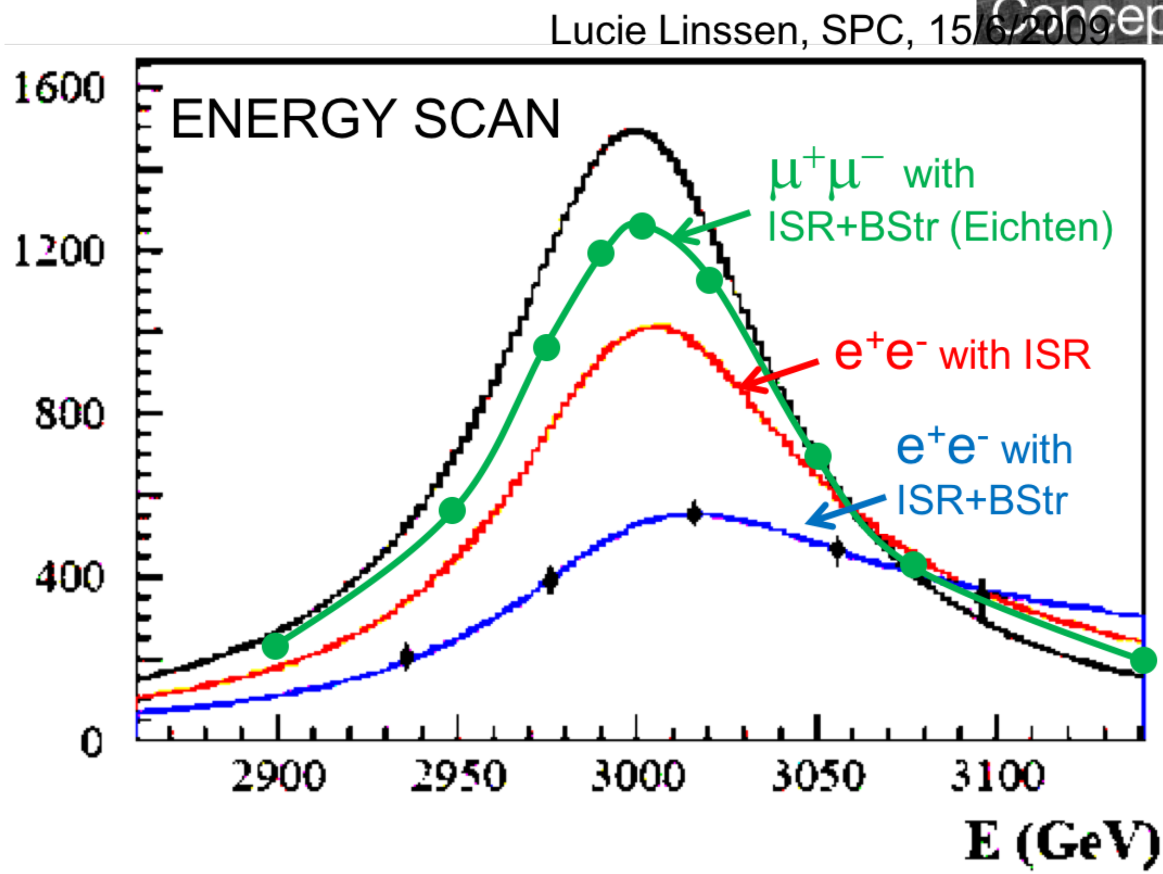
Units are %

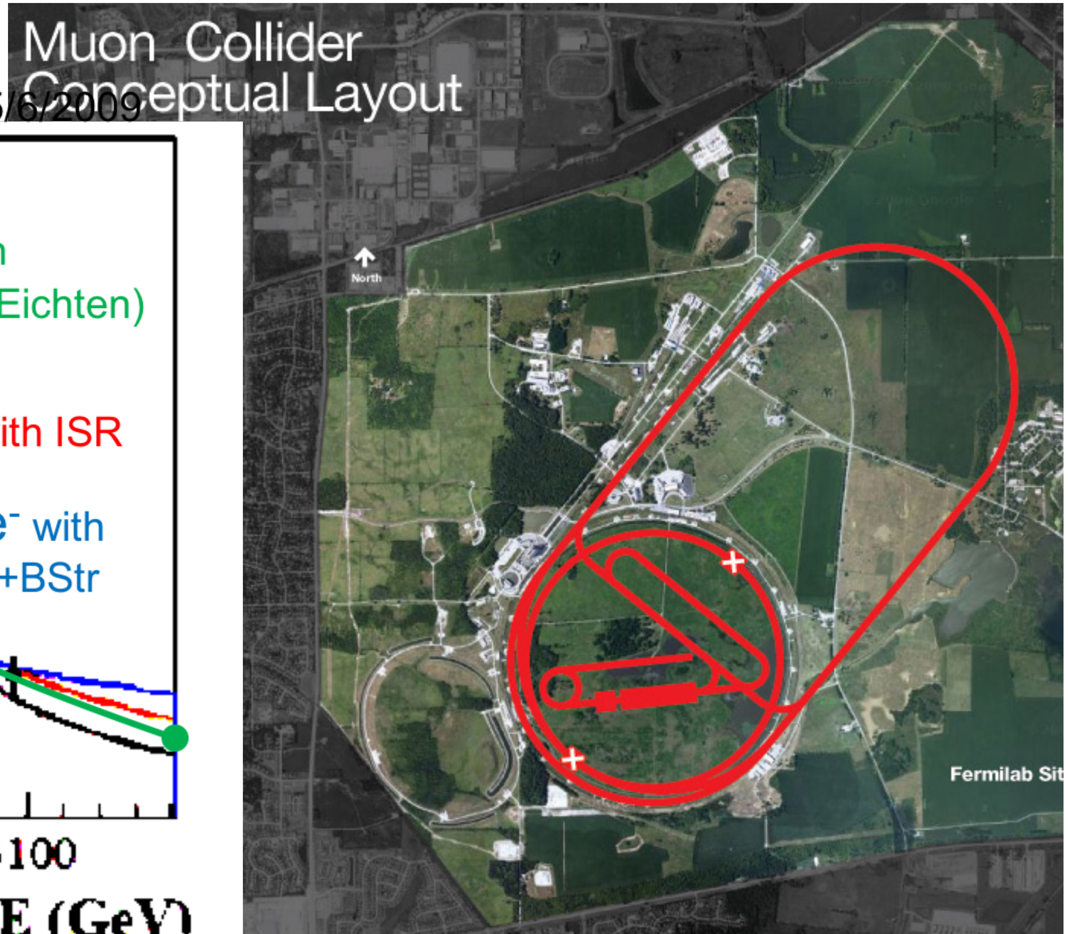
summary table from Fabiola Gianotti LP15

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)



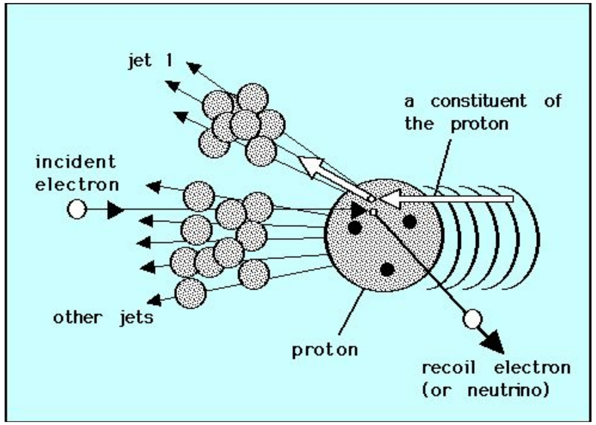


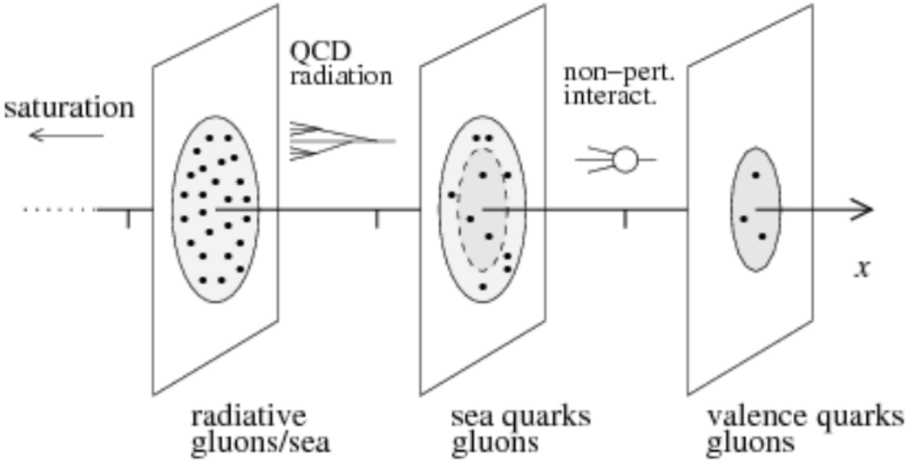
Challenges: to produce enough muons, cool them and compress the beam and all very fast

Density frontier and more

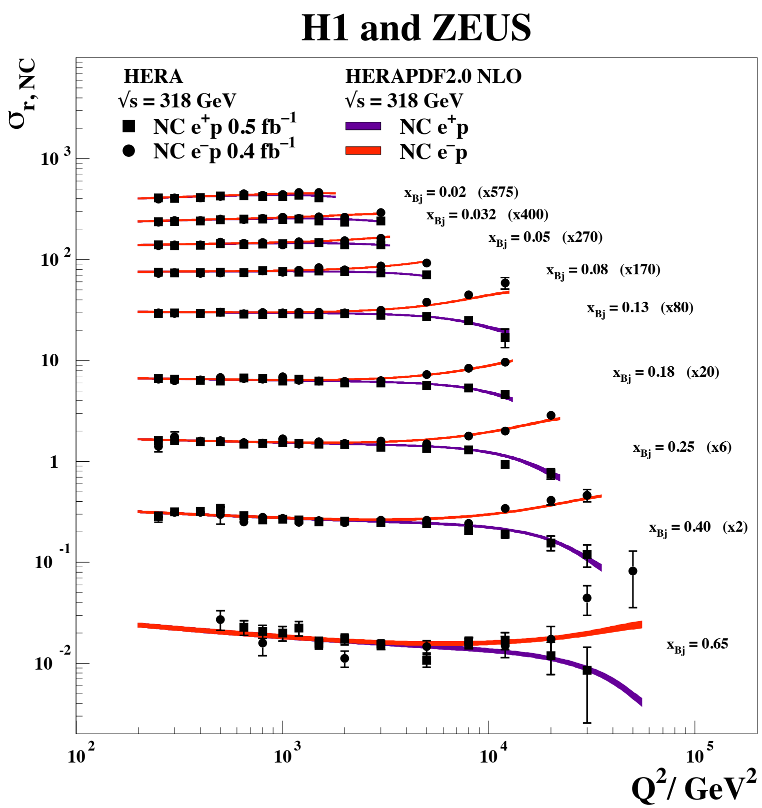
Proton – composite object consisting of quarks and gluons

- 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

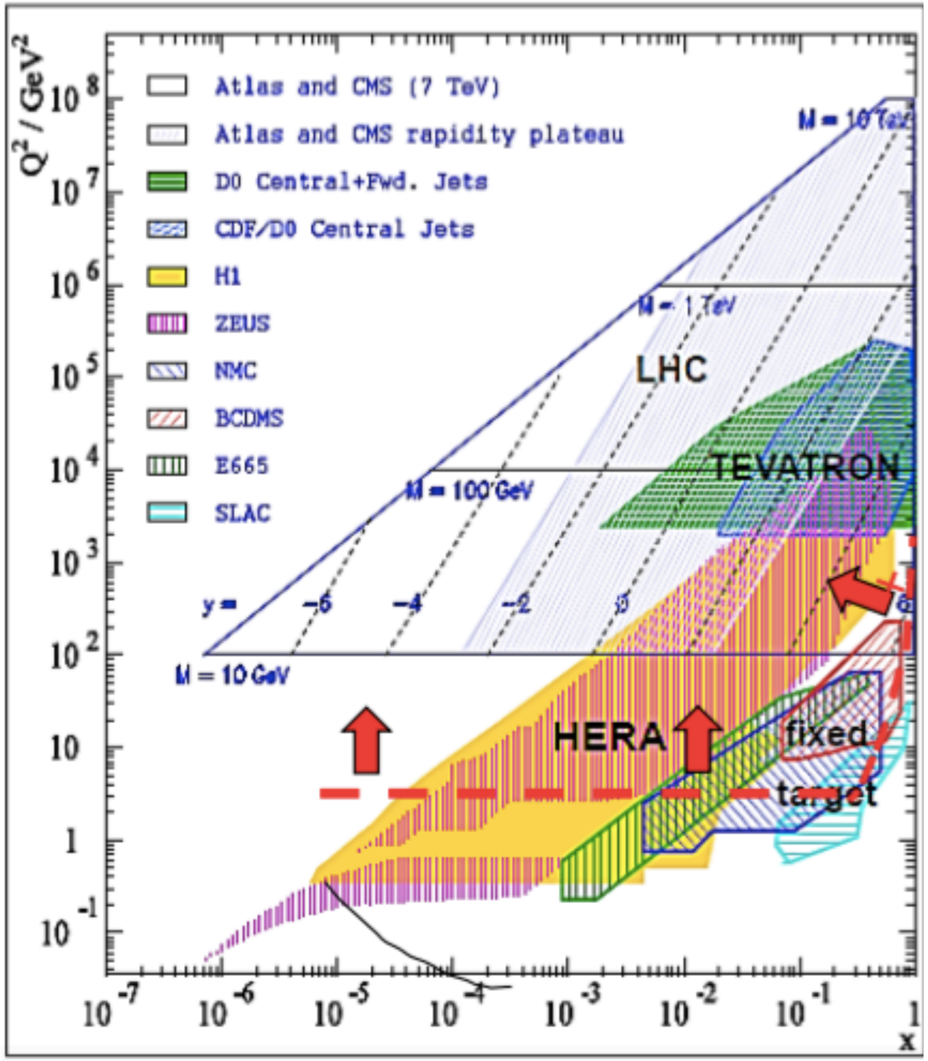


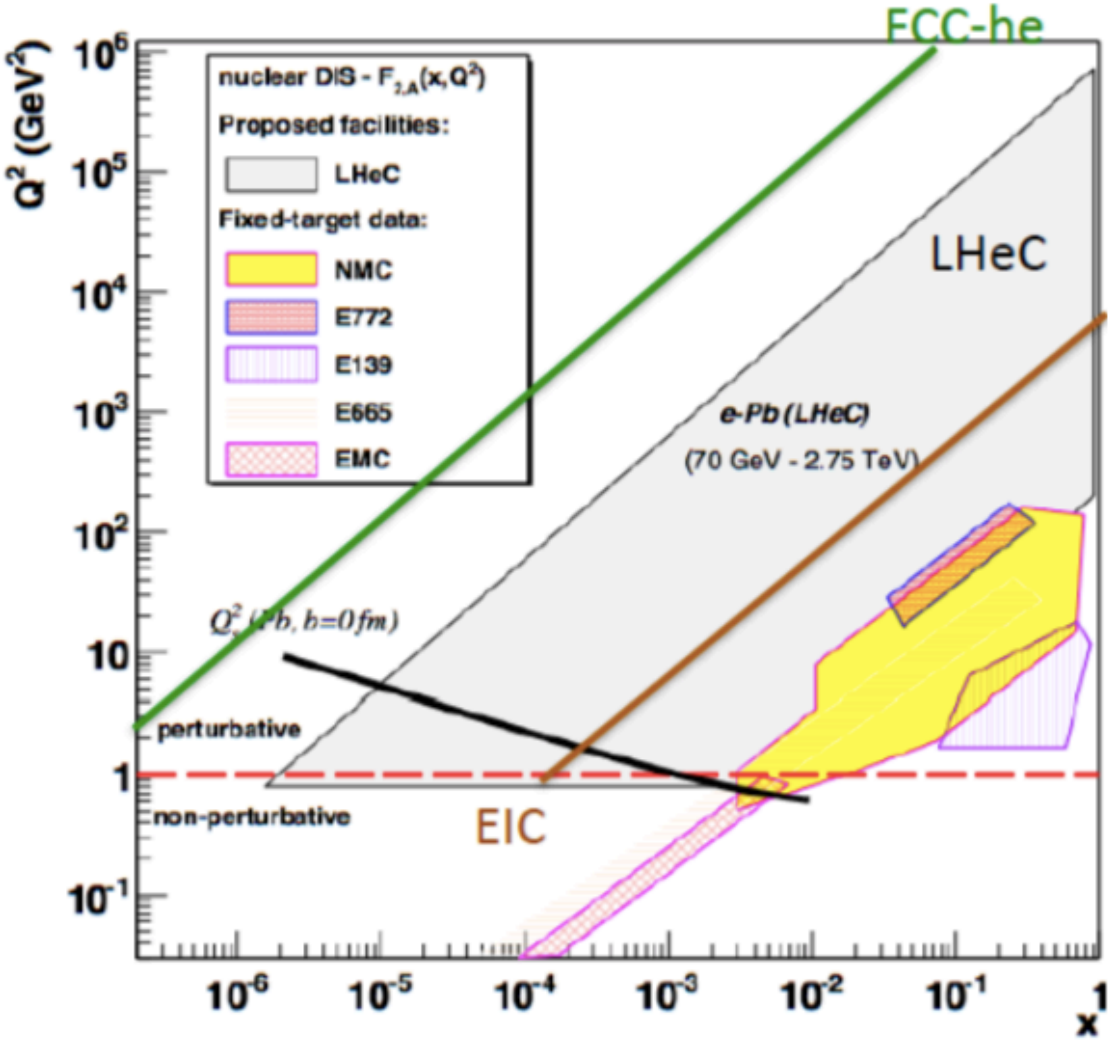


Legacy of ep collider HERA



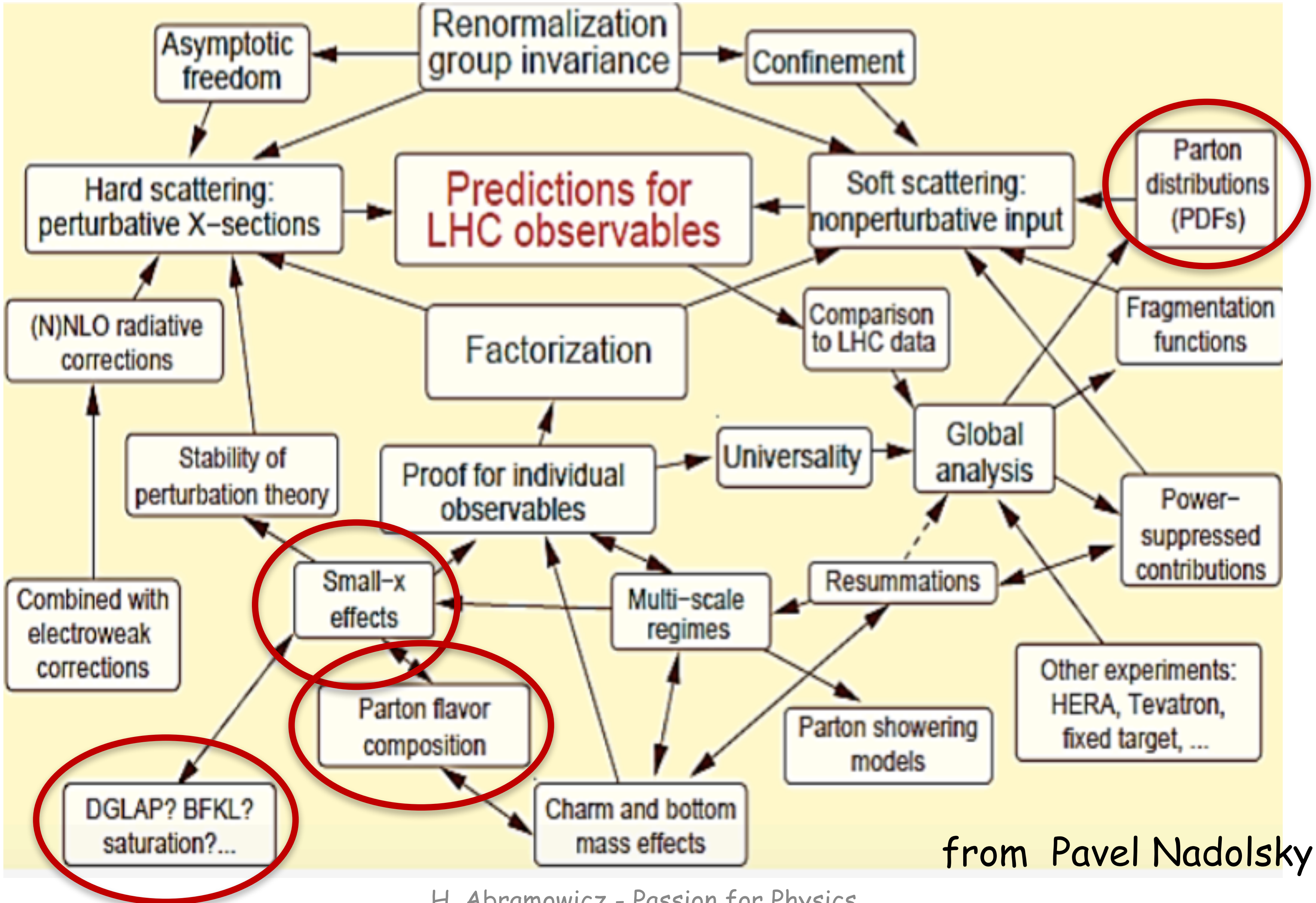
Density frontier and more





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

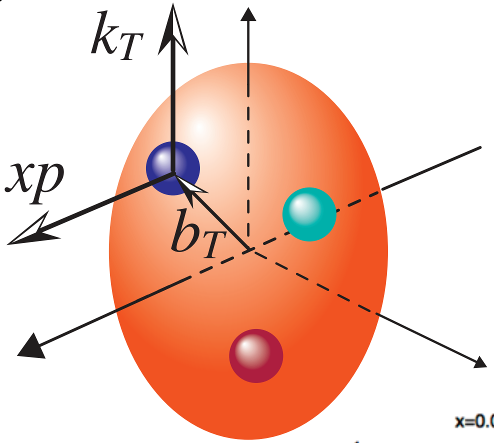
$W(x,b_T,k_T)$

Momentum space

$\int d^2b_T$

$\int d^2k_T$

Coordinate space

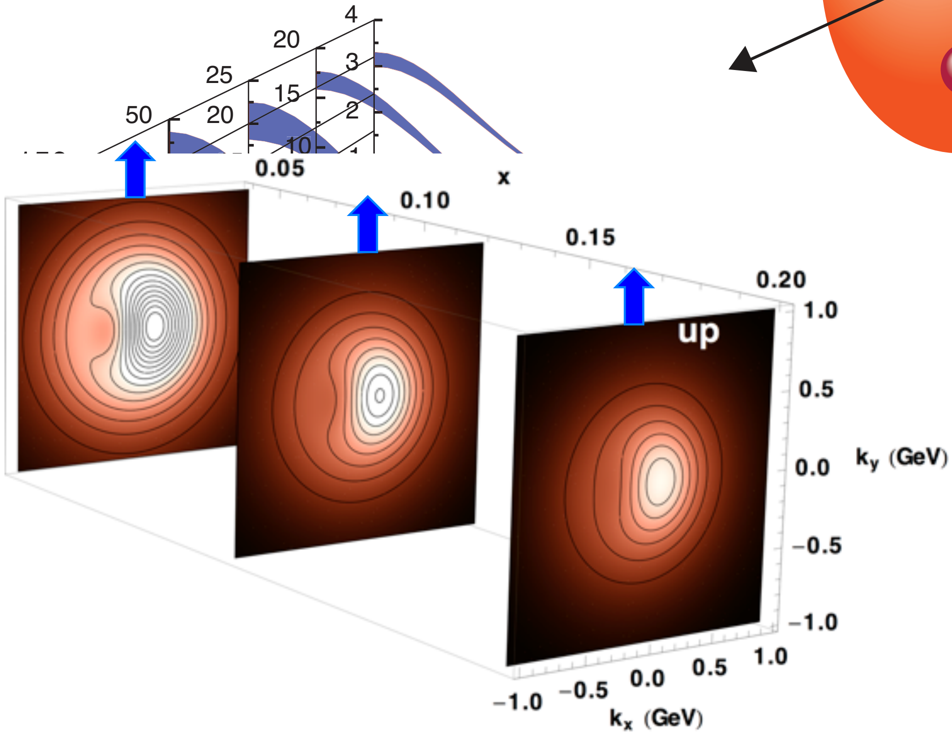


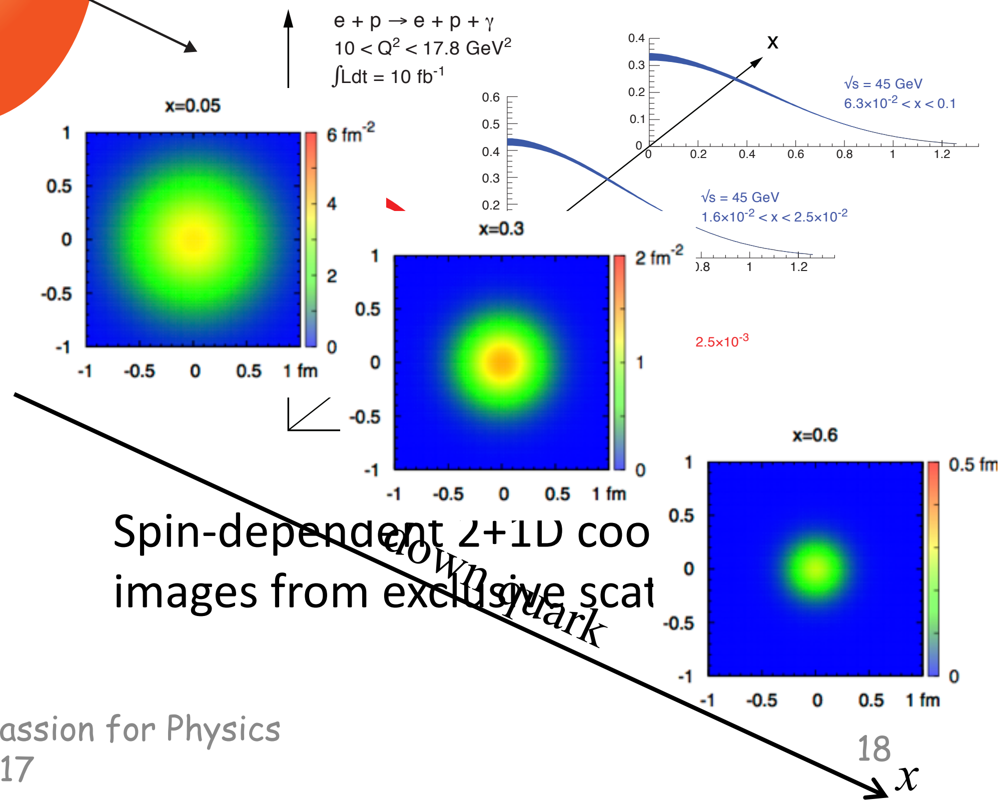
Quarks

$f(x,k_T)$

$f(x,b_T)$

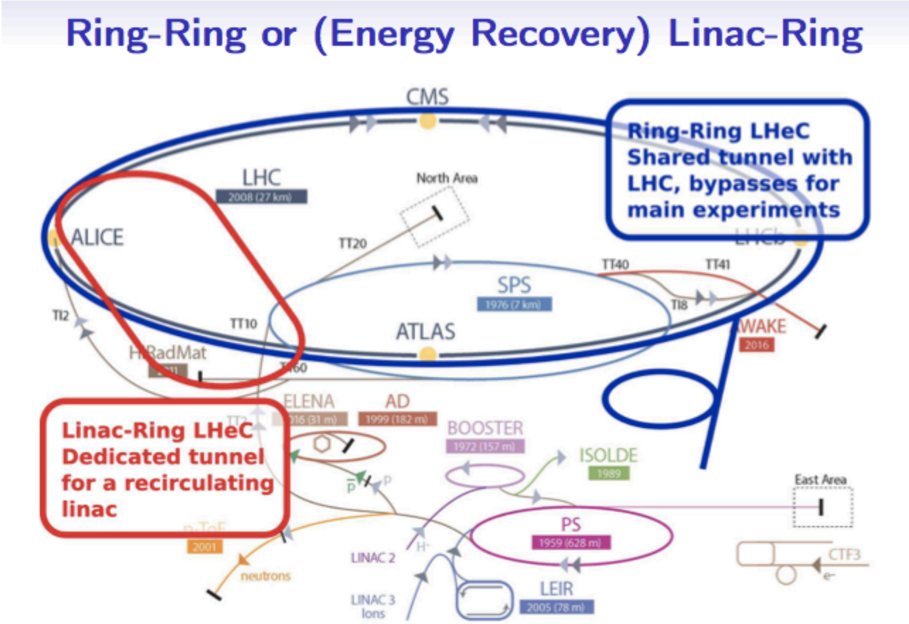
Quarks

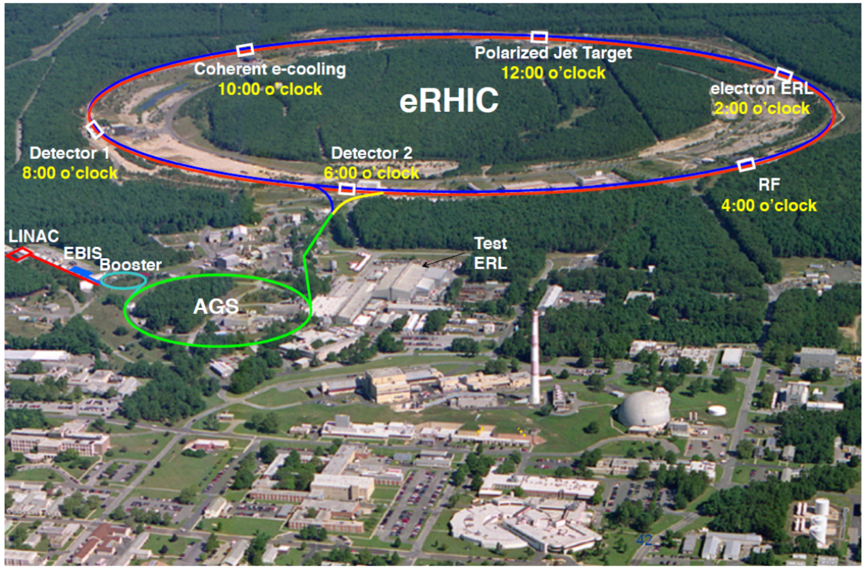


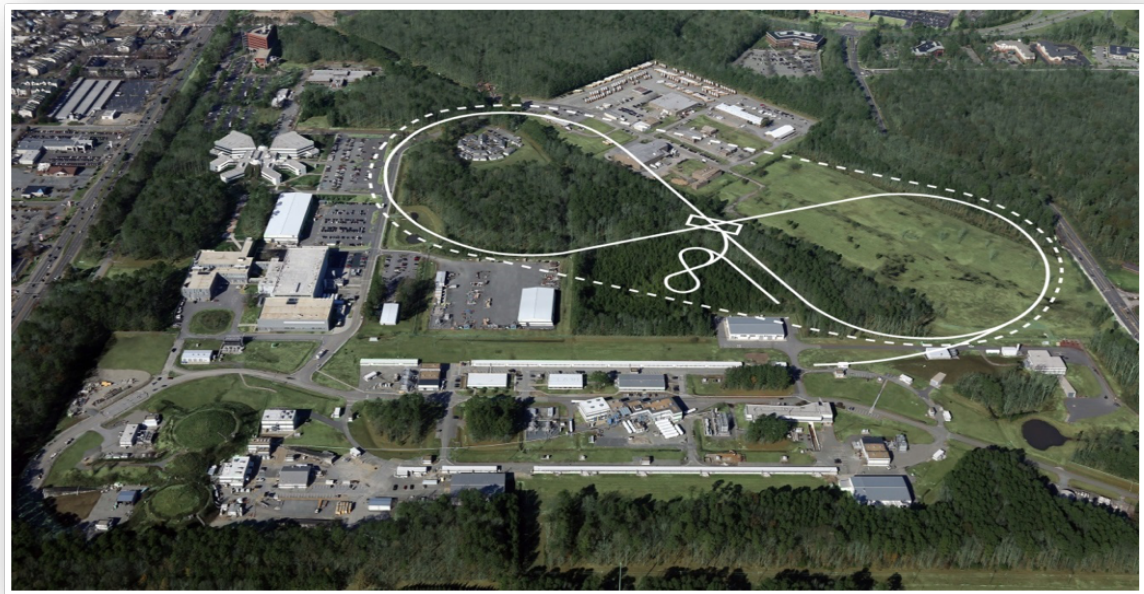


Spin-dependent 2+1D coo
images from exclusive scat

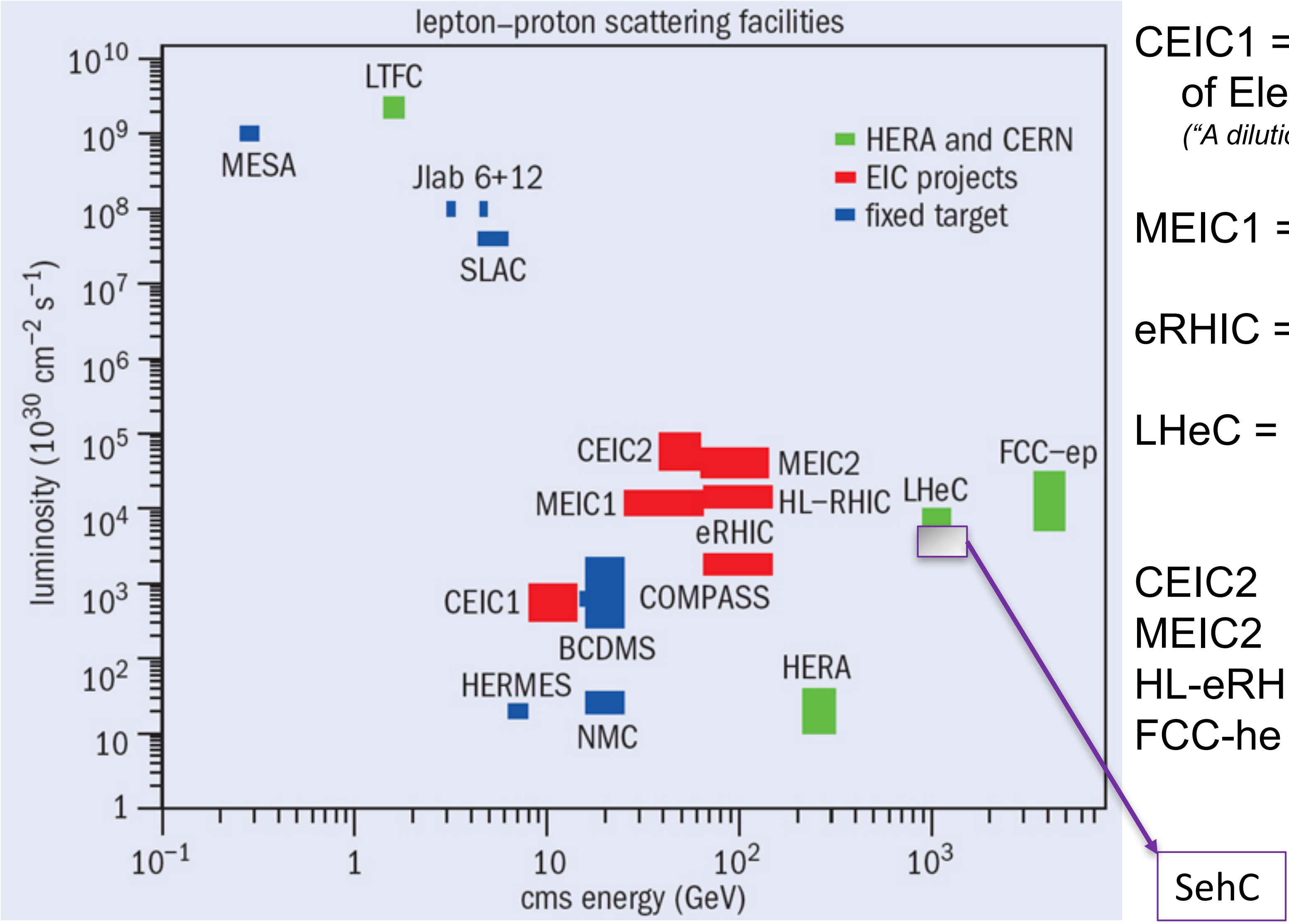
ep/eA colliders







ep/eA colliders



CEIC1 = Chinese version of Electron-Ion Collider

("A dilution-free mini-COMPASS")

MEIC1 = EIC@Jlab

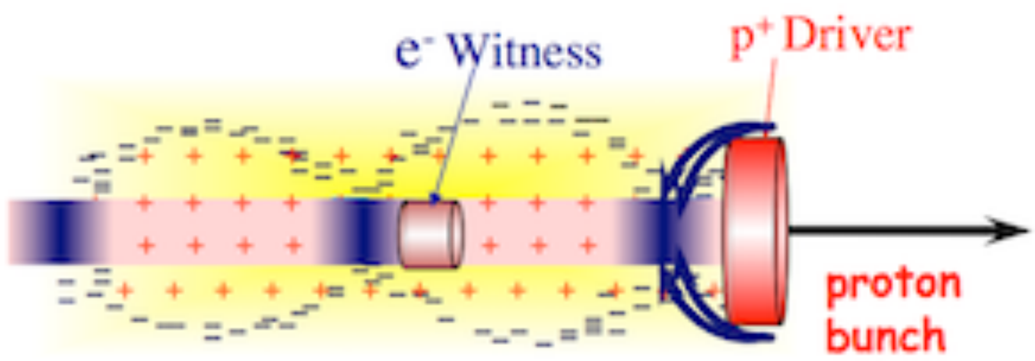
eRHIC = EIC@BNL

LHeC = ep/eA collider @ CERN

CEIC2
MEIC2
HL-eRHIC
FCC-he

New Accelerator Technologies

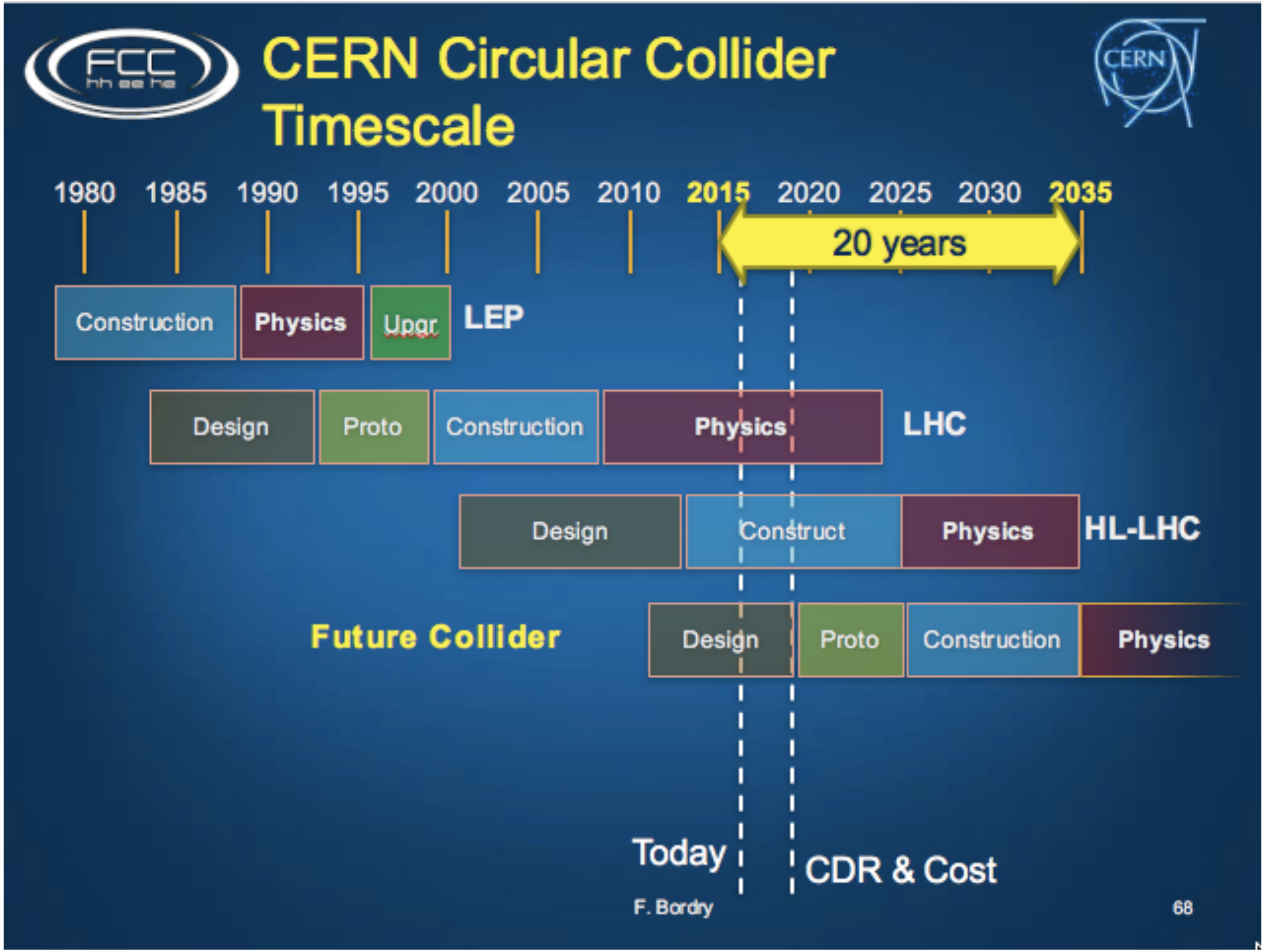
- Accelerators using RF cavities limited to *~100 MV/m;* high energies ⇒ long accelerators
- Gradients in plasma wakefield acceleration of ***~100 GV/m*** measured



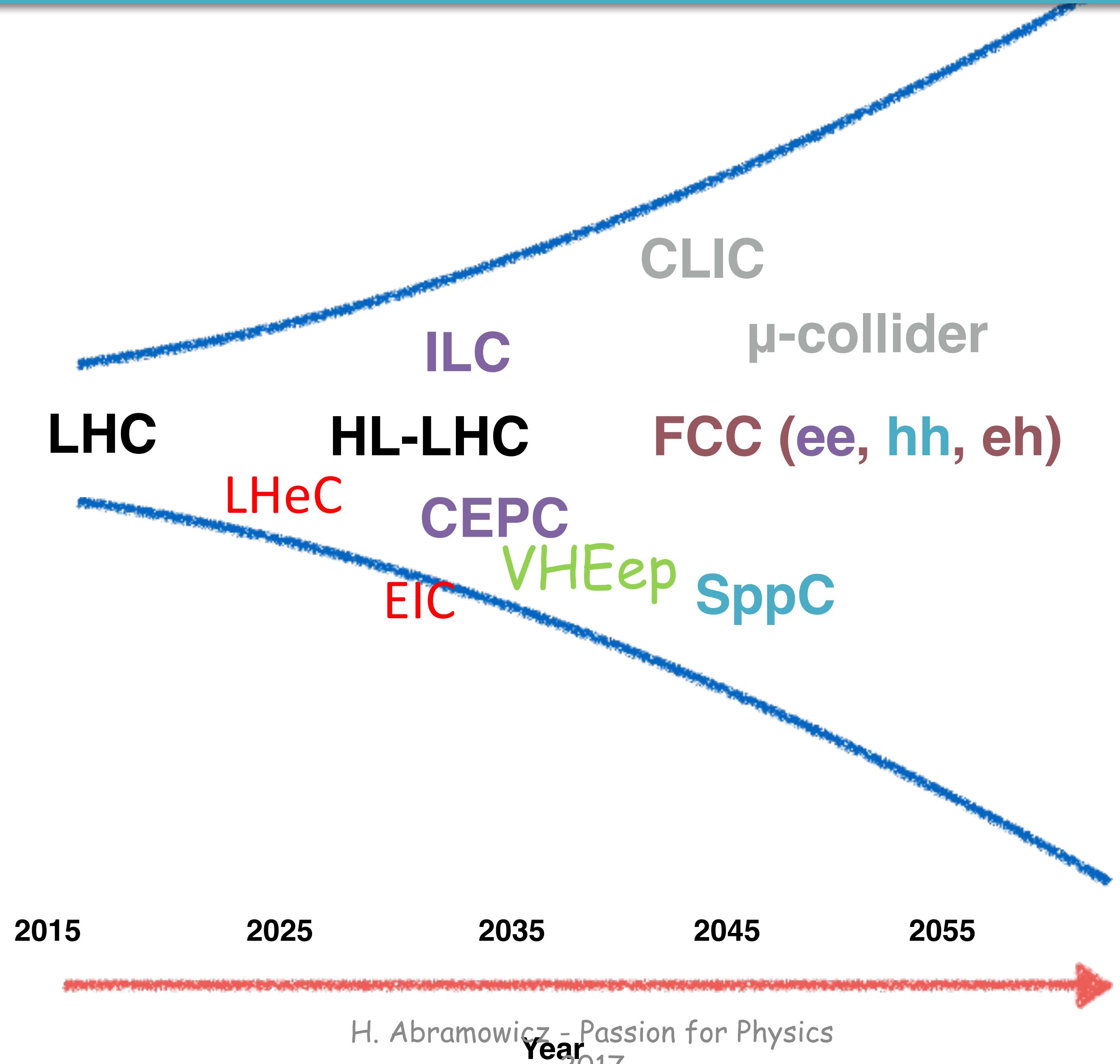
- ILC-CLIC, 0.5 TeV bunch with $2x10^{10}e^-$ - about 1.6kJ
- SPS, 400 GeV bunch with 10^{11}p - about 6.4kJ
  LHC, 7 TeV - 112kJ
- A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage
- Large average gradient (>1GV/m, 100's m)

Proof of principle under way at the SPS at CERN

Time scales


CERN Circular Collider
Timescale
CERN
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035
20 years
Construction
Physics
Upgr
LEP
Design
Proto
Construction
Physics
LHC
Design
Construct
Physics
HL-LHC
Future Collider
Design
Proto
Construction
Physics
Today
CDR & Cost
F. Bordry
68

Colliders of the 21st Century



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)

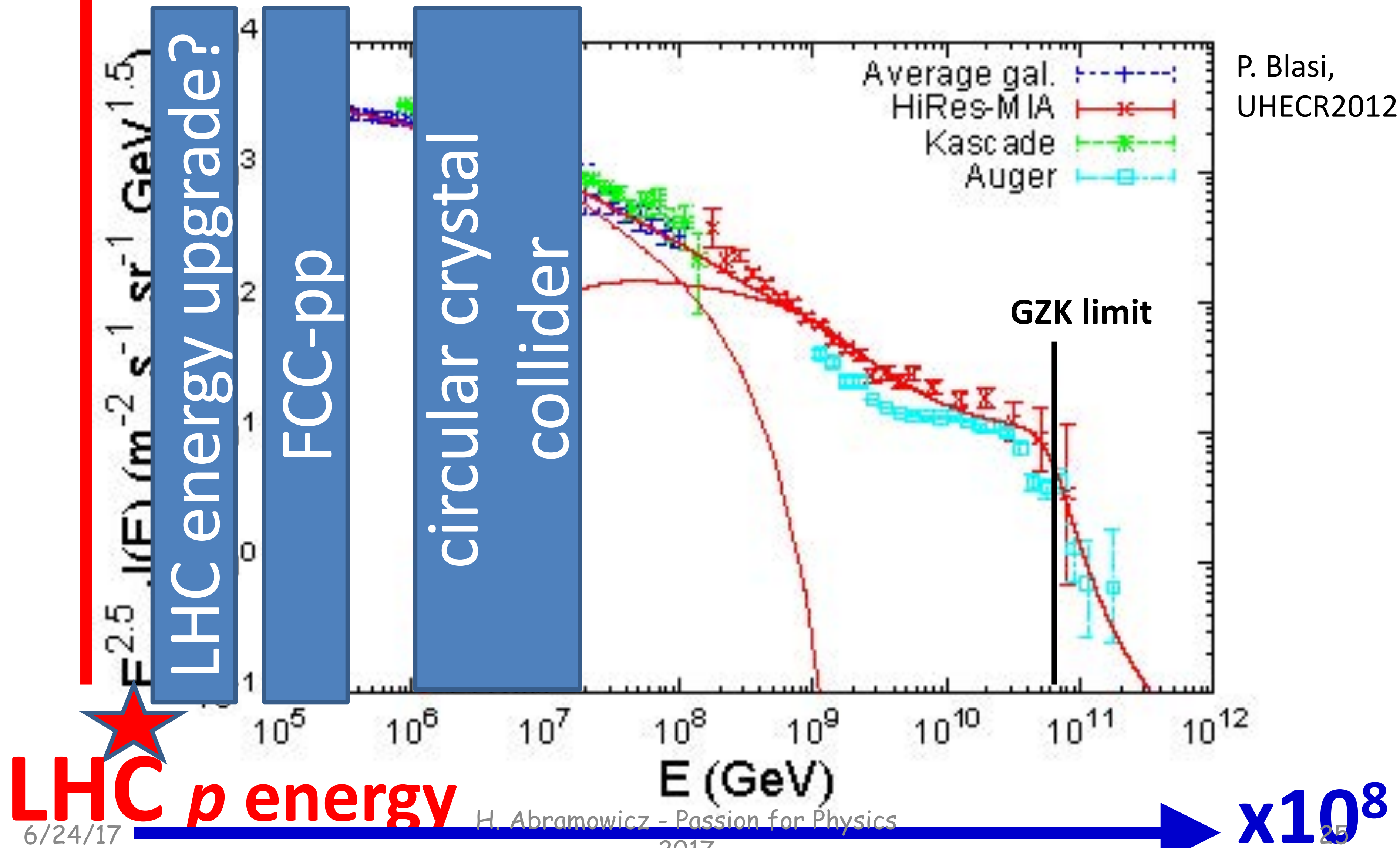
- CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron- positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme (CLIC, FCC hh,ee,ep … AWAKE)

- 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)

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

cosmic-ray energy spectrum



P. Blasi, UHECR2012

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 ESU

The European Physical Society Conference on High Energy Physics (EPS-HEP) is one of the major international conferences that reviews the field every second year since 1971. It is organized by the High Energy and Particle Physics Divison of the European Physical Society. The latest conferences in this series were held in Vienna, Stockholm, Grenoble, Krakow, Manchester, Lisbon and Aachen.

In 2017 the EPS-HEP will take place in Venice, Italy on 5-12 July. The conference is organized by Istituto Nazionale di Fisica Nucleare (INFN) and the Department of Physics and Astronomy of the Padua University.

If curious why HEP should be supported feel invited to
Special ECFA-EPS/HEPP session
"Particle Physics and Society: Extending our Vision and Reach"
July 8th, afternoon