Physics at the LHC … and Beyond

Geoffrey Taylor
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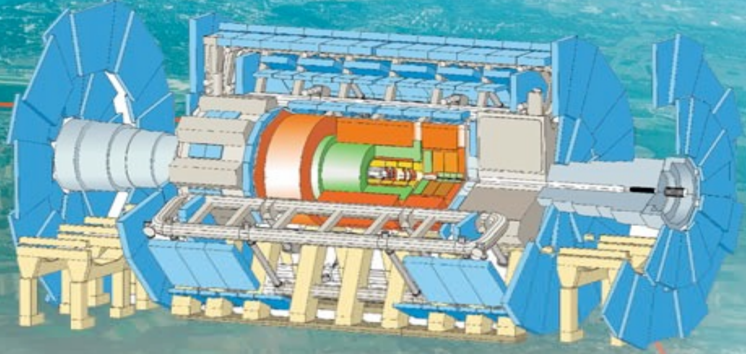
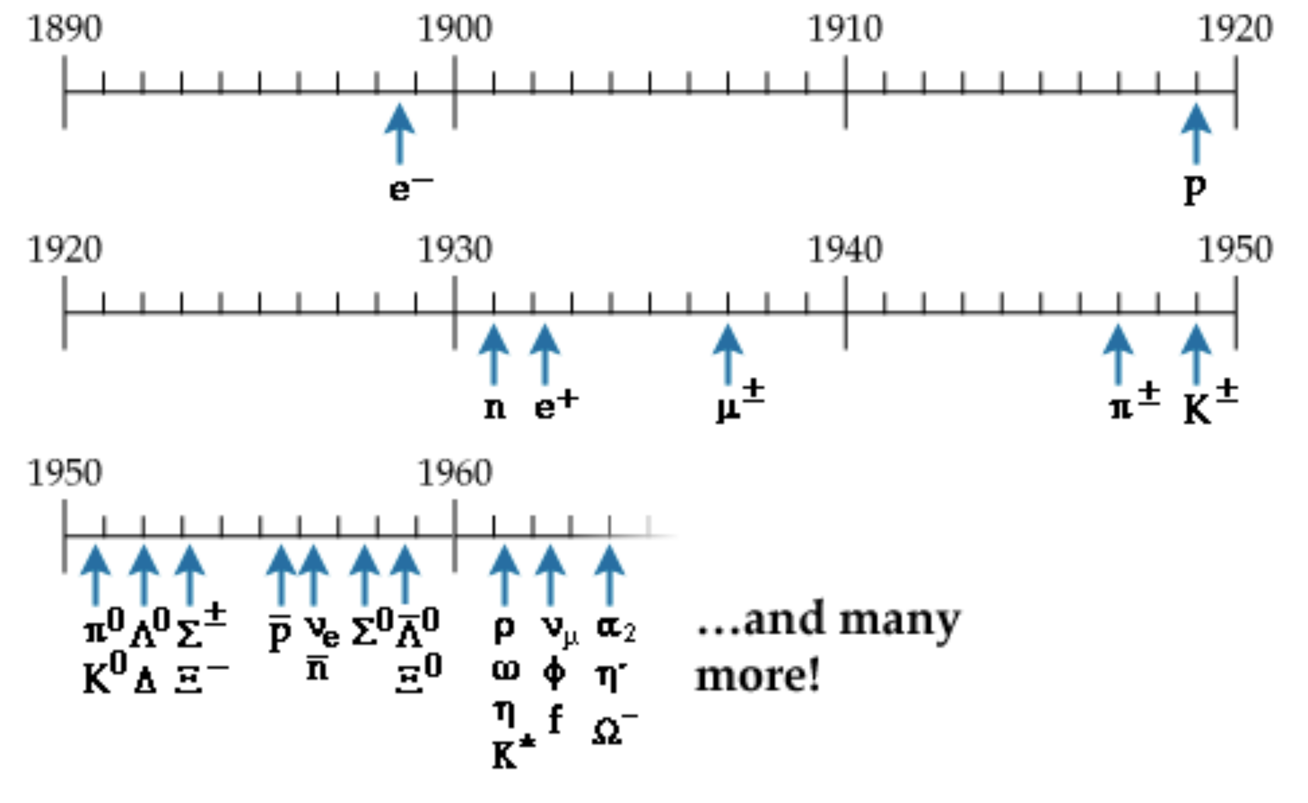


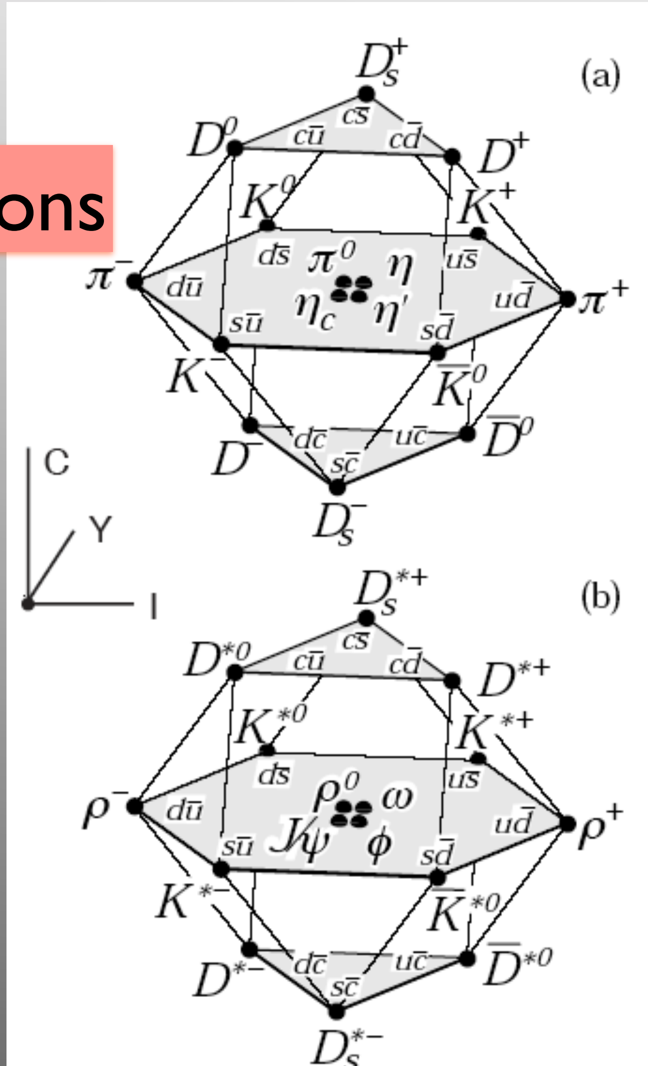
ARC Centre of Excellence for Particle Physics at the Terascale

Particles Discovered 1898 -1964

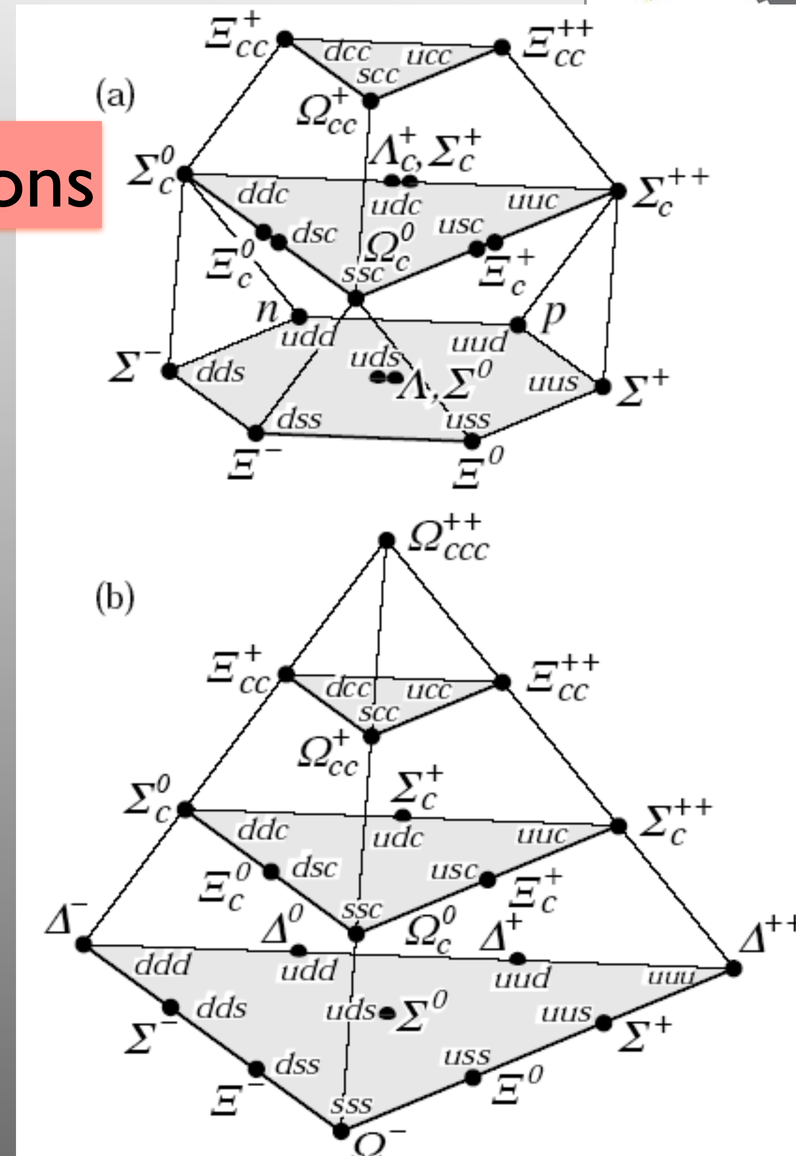


...but patterns, symmetry emerged...

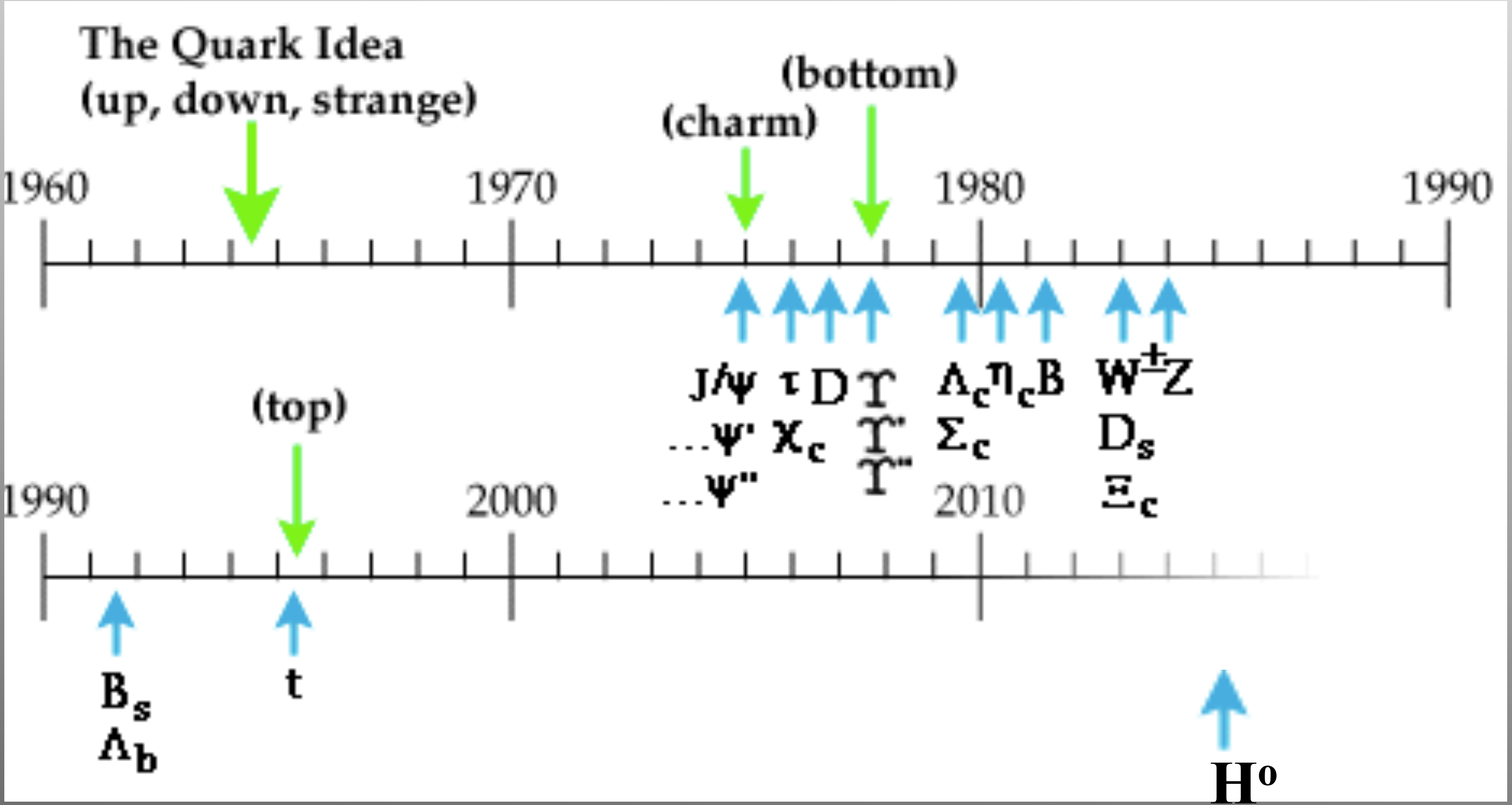
Mesons



Baryons

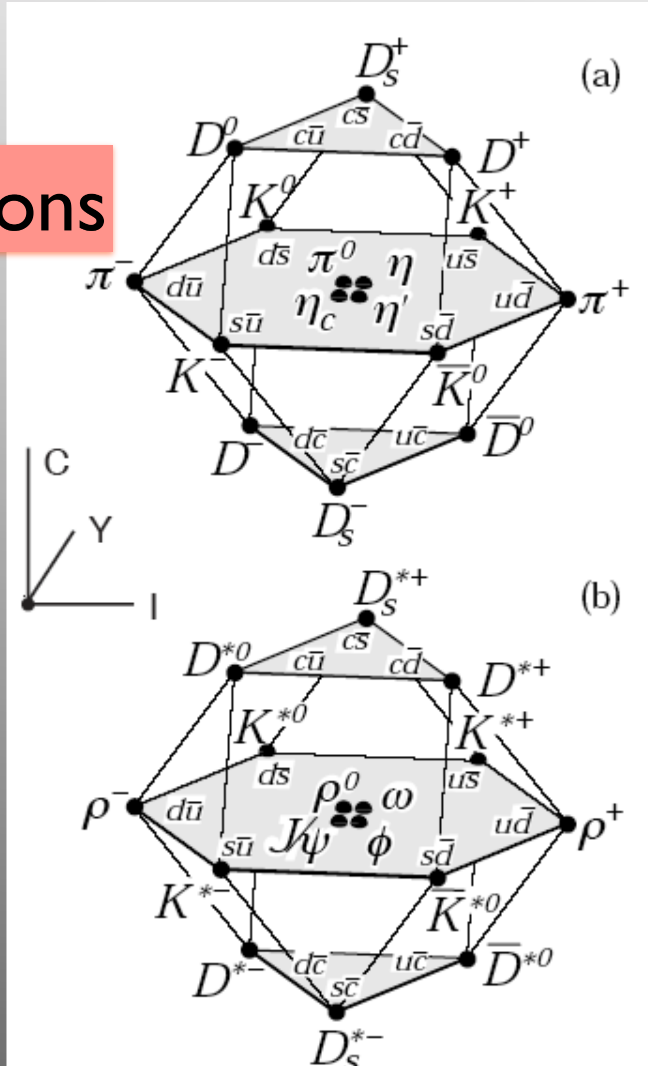


Particles Discover 1964 - present

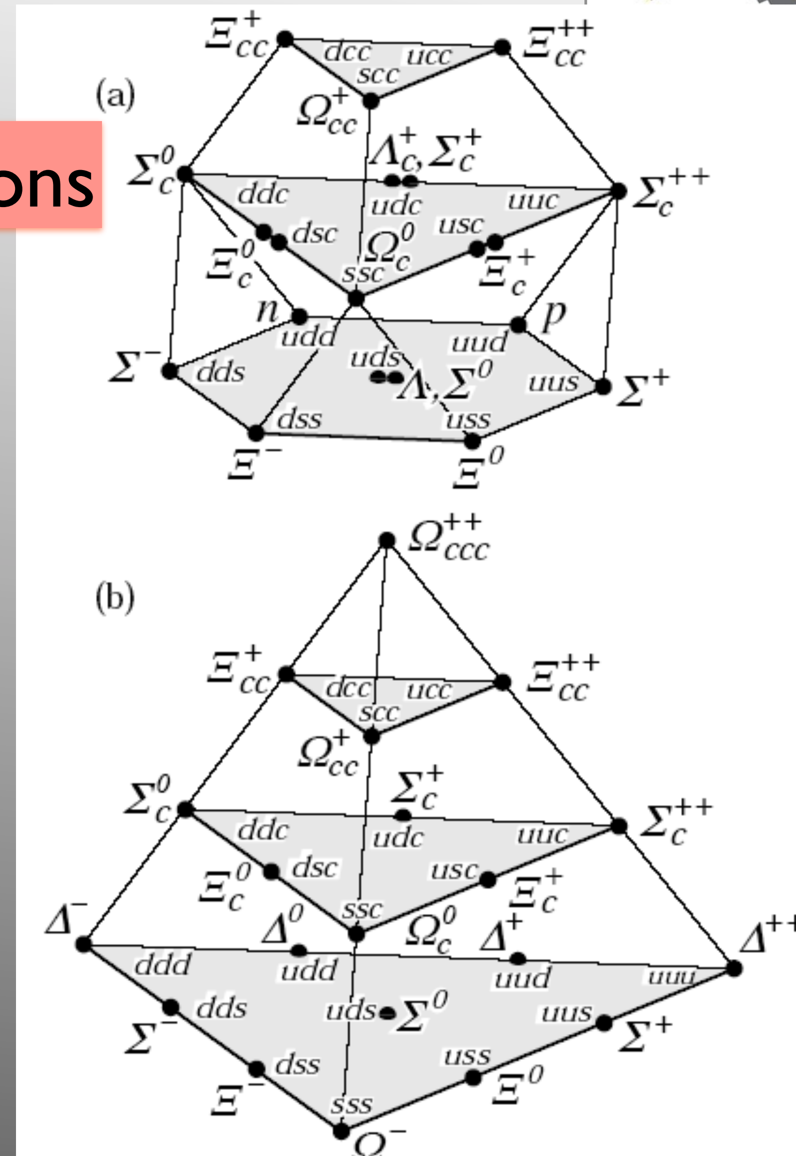


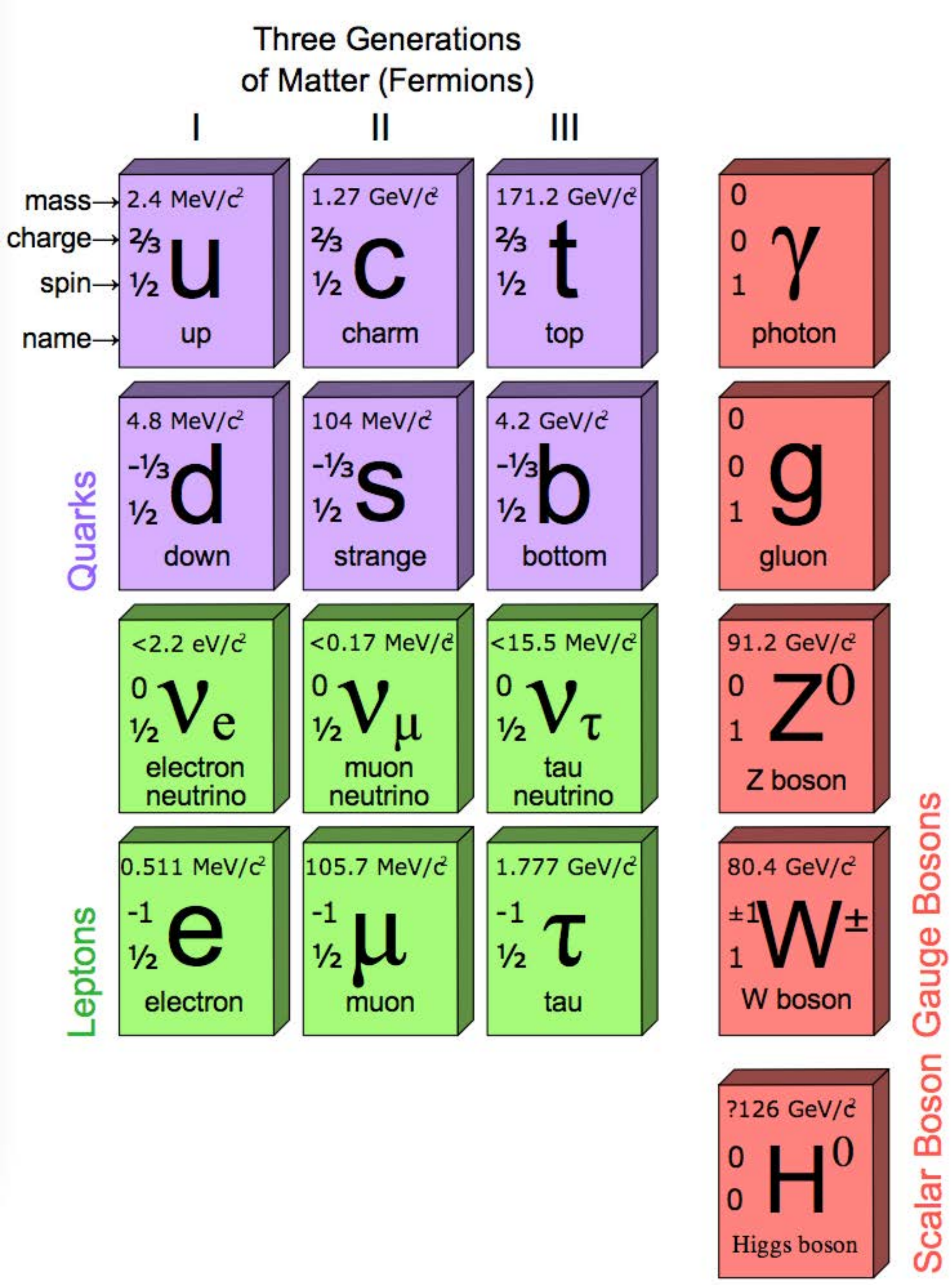
...but patterns, symmetry emerged...

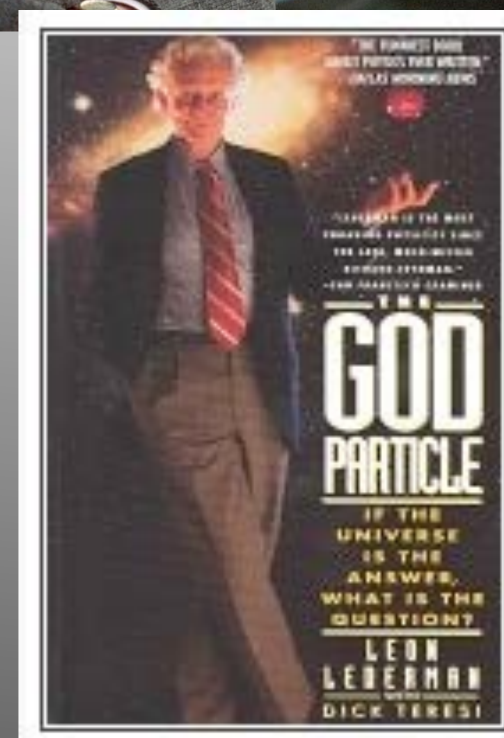
Mesons



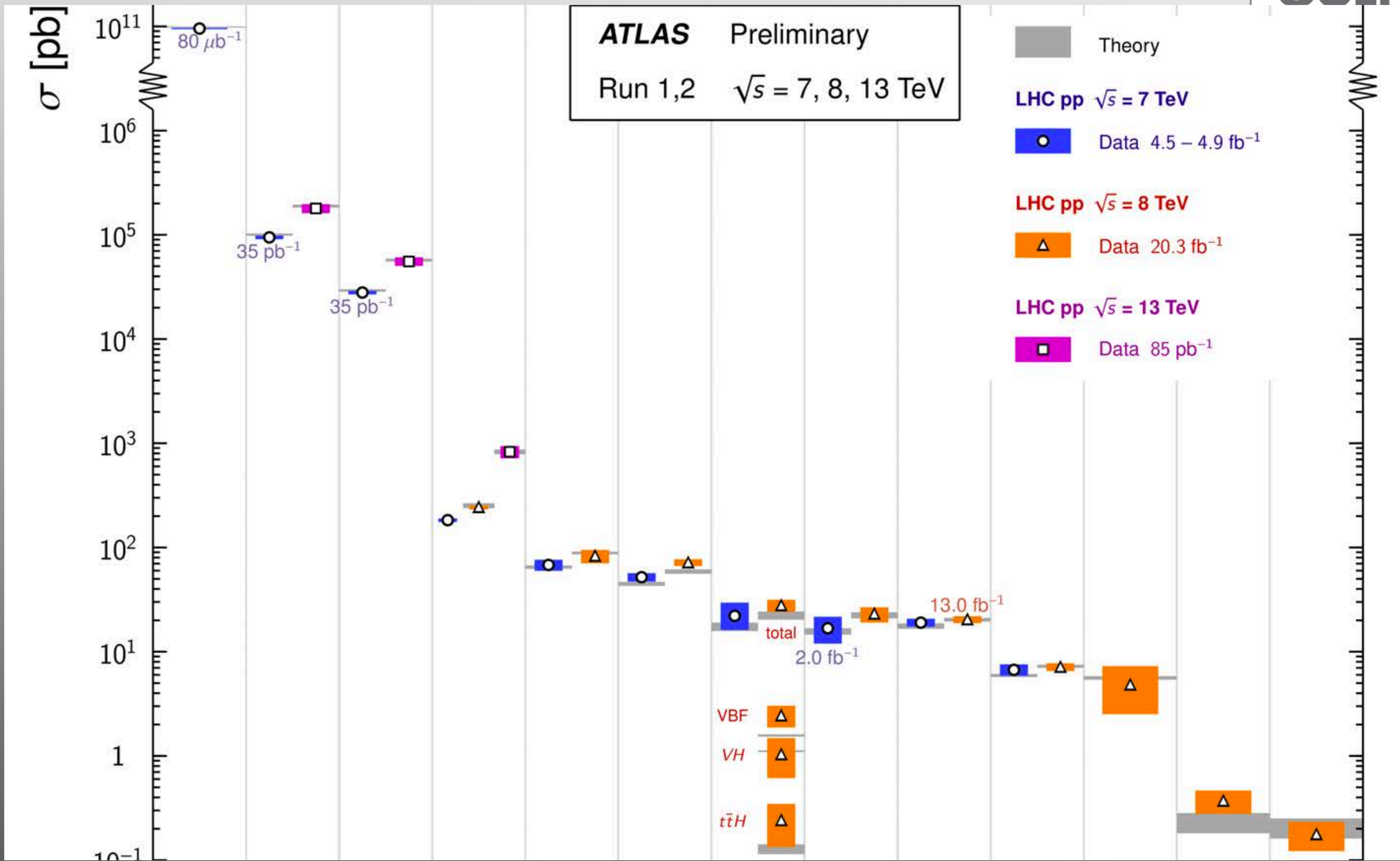
Baryons



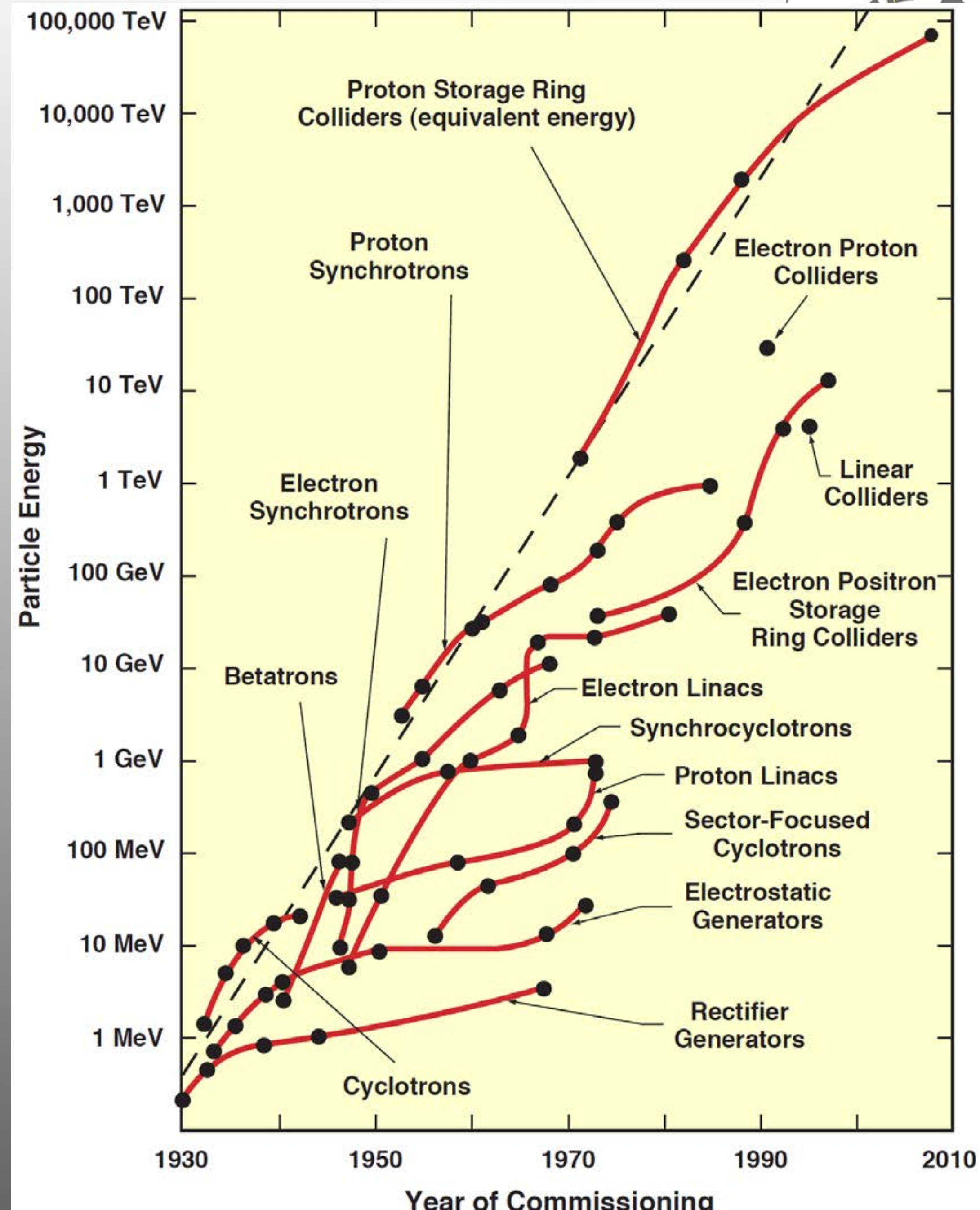

Three Generations of Matter (Fermions)
I
II
III
mass→
charge→
spin→
name→
2.4 MeV/c²
2/3
1/2
u
up
1.27 GeV/c²
2/3
1/2
c
charm
171.2 GeV/c²
2/3
1/2
t
top
0
0
1
γ
photon
4.8 MeV/c²
-1/3
1/2
d
down
104 MeV/c²
-1/3
1/2
s
strange
4.2 GeV/c²
-1/3
1/2
b
bottom
0
0
1
g
gluon
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
91.2 GeV/c²
0
1
Z0
Z boson
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
80.4 GeV/c²
±1
1
W±
W boson
?126 GeV/c²
0
0
H0
Higgs boson
Quarks
Leptons
Scalar Boson
Gauge Bosons

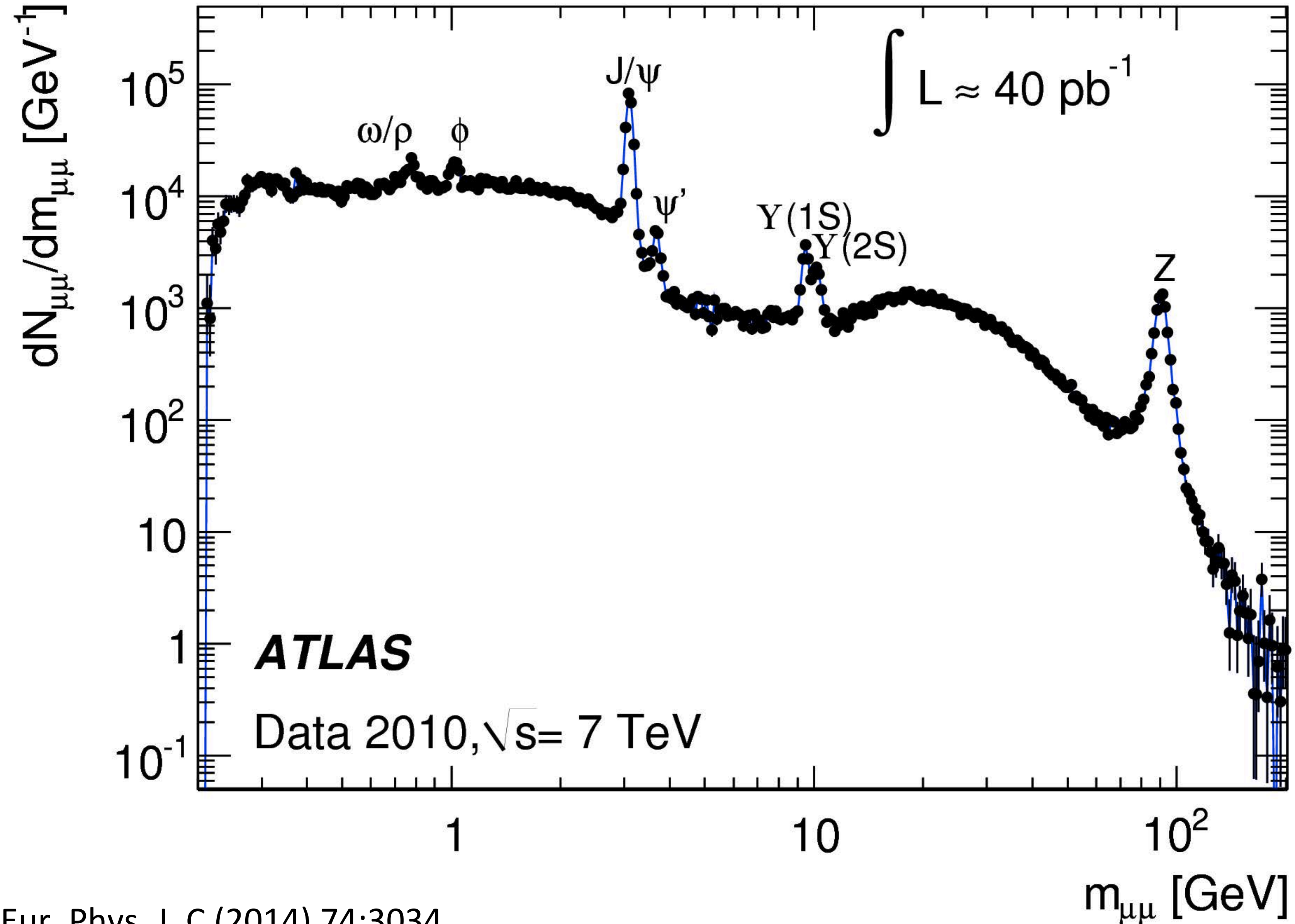

THE GOD PARTICLE
IF THE UNIVERSE IS THE ANSWER, WHAT IS THE QUESTION?
LEON LEDERMAN
DICK TERESI

Standard Model Comparisons



The Livingston chart shows the steady growth of accelerator energy (or equivalent collider energy). The increase is a factor of 10 every 7 years.





Eur. Phys. J. C (2014) 74:3034

What is a "bump"?

Relativity

4-vectors: $$p_\mu = (\underline{p}, E)$$

Lorentz Invariant: $$p_\mu . p^\mu = E^2 - \underline{p}.\underline{p} = m^2$$

(= (rest mass)^2 … frame invariant.)

eg. $$H \rightarrow \gamma_1 \gamma_2$$

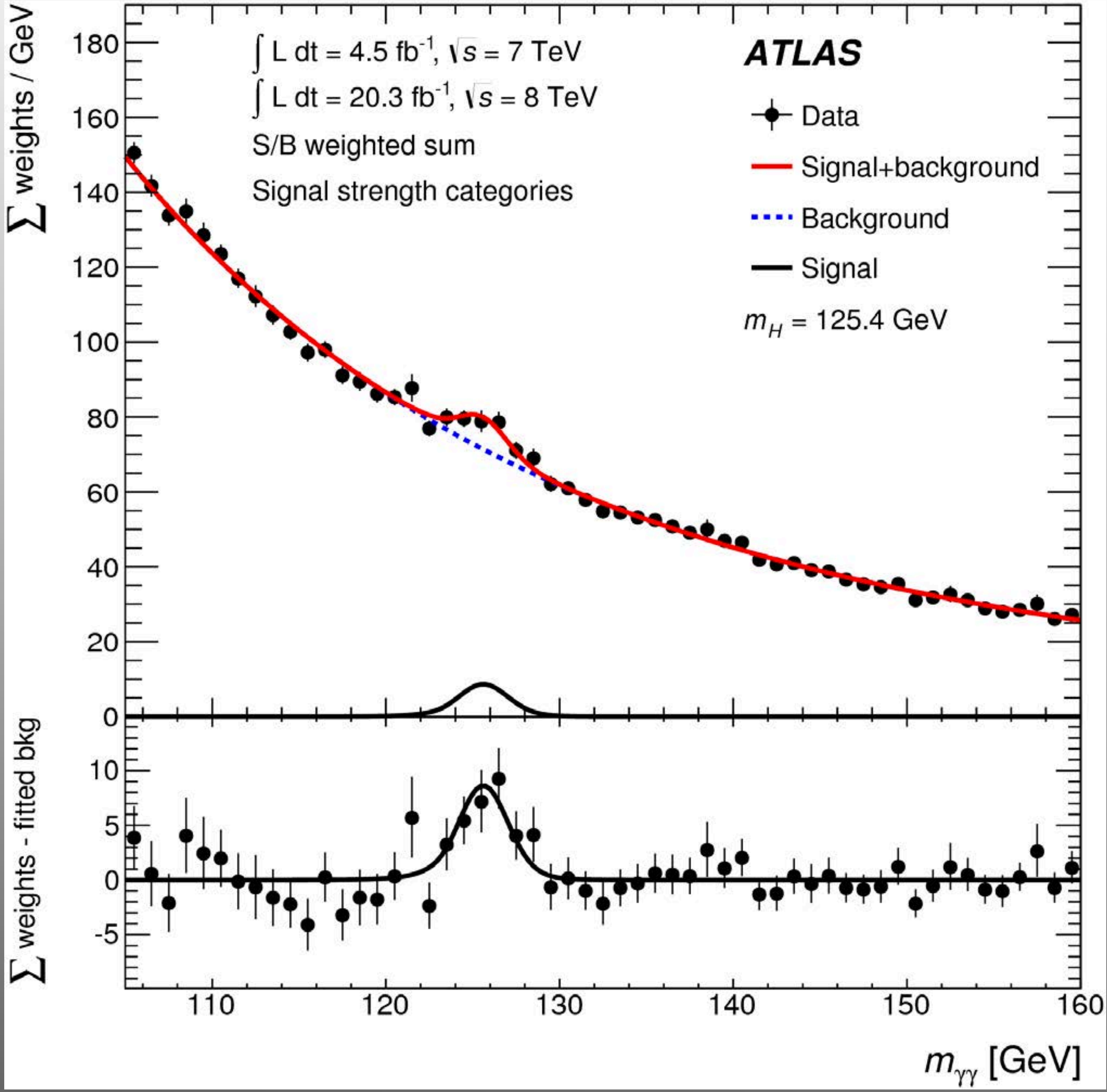
Energy/momentum conservation:

$$(p_\mu^H)^2 = (\underline{p}^H, E^H)^2 = m_H^2$$

$$= (p_\mu^{\gamma_1} + p_\mu^{\gamma_2})^2 = p_\mu^{\gamma_1} p^{\mu\gamma_1} + p_\mu^{\gamma_2} p^{\mu\gamma_2} + p_\mu^{\gamma_1} p^{\mu\gamma_2}$$

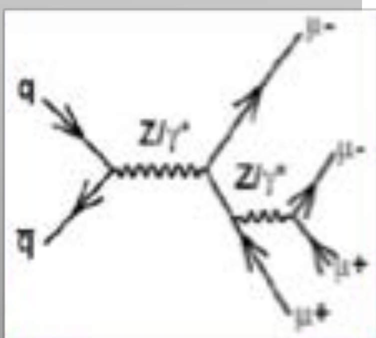
$$= m_{\gamma_1}^2 + m_{\gamma_1}^2 + 2E^{\gamma_1} E^{\gamma_2} - 2\underline{p}^{\gamma_1} . \underline{p}^{\gamma_2}$$

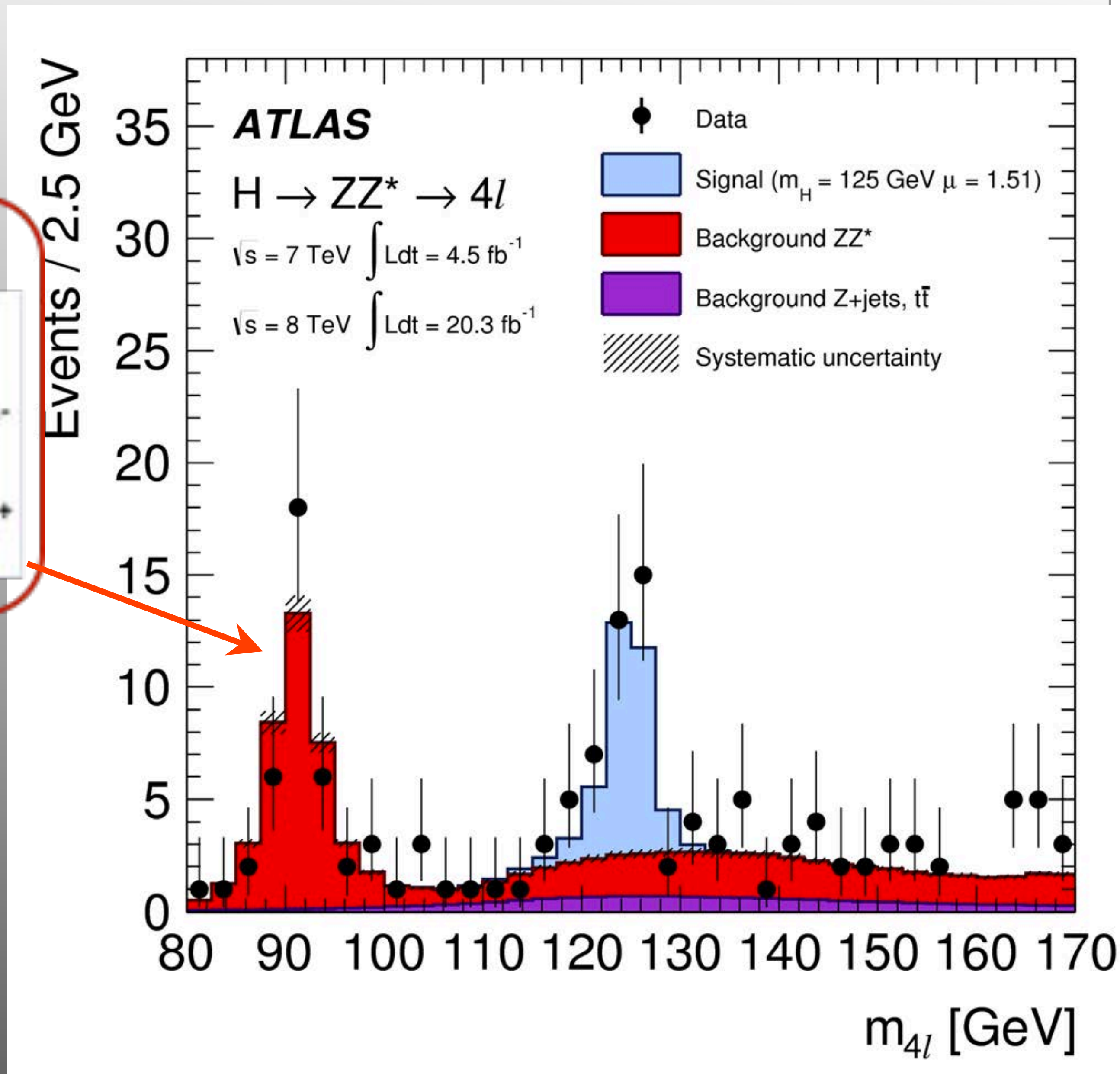
But if the gammas are NOT from the same H-particle, their invariant mass will not have a specific value.



[ATLAS Phys. Rev. D. 90, 112015 (2014)](#)

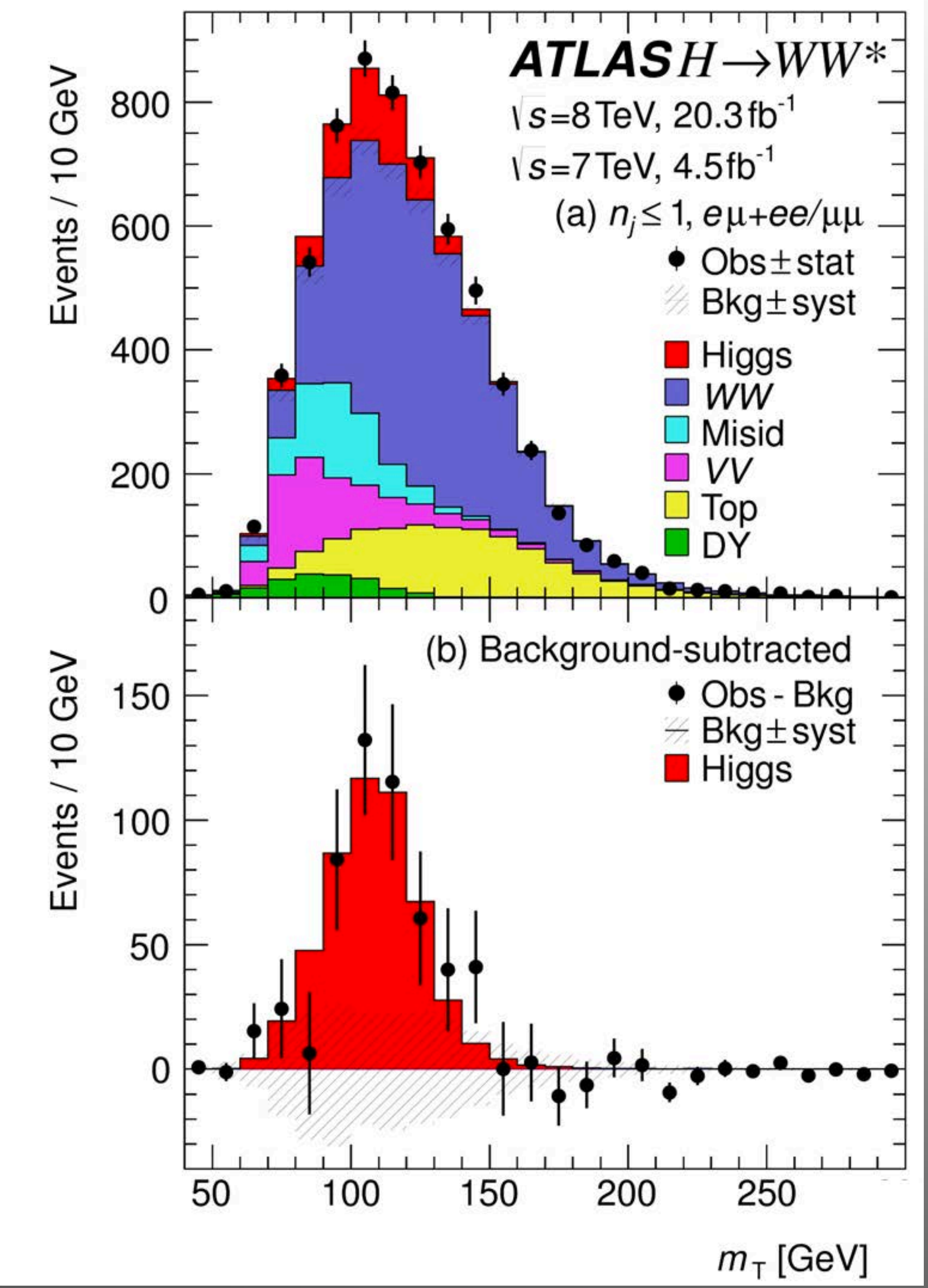
Why a Z peak ?

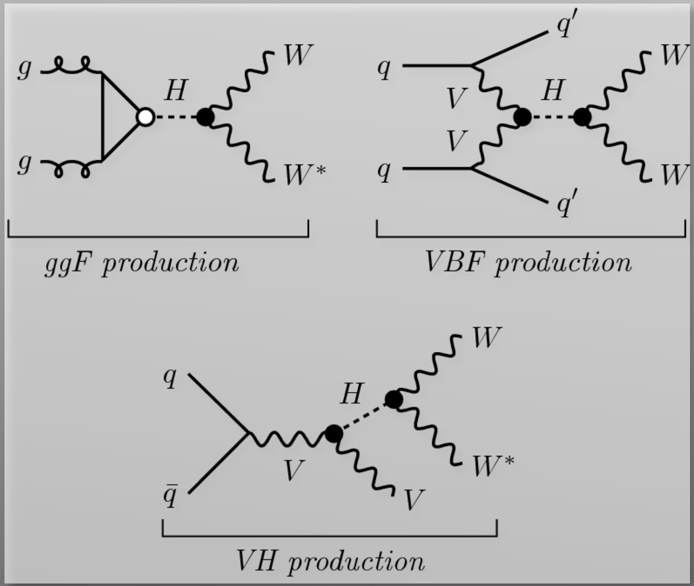




[ATLAS, Phys. Rev. D 91, 012006 (2015)]

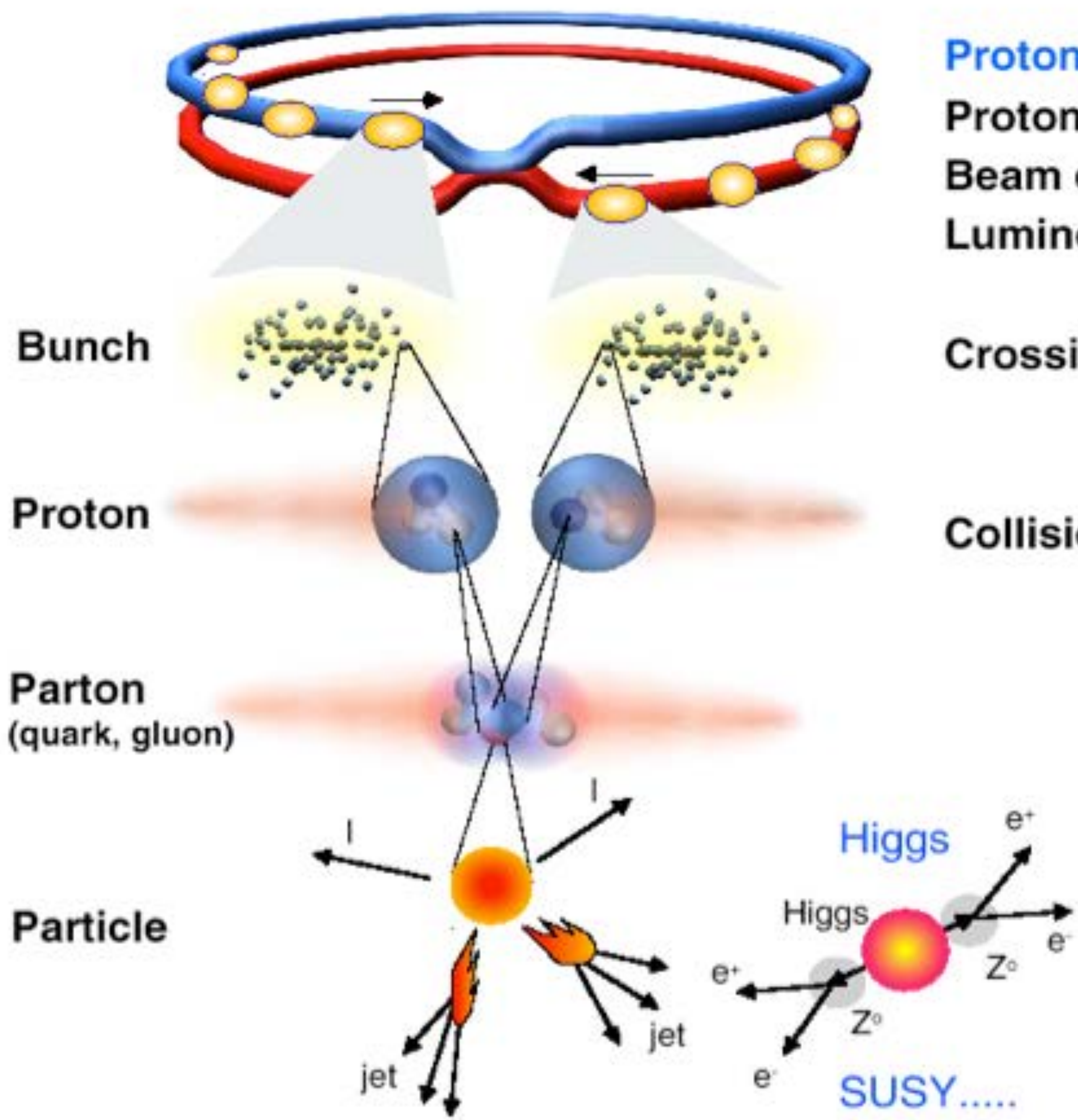
H-> WW*





ATLAS, Phys. Rev. D 92, 012006 (2015)

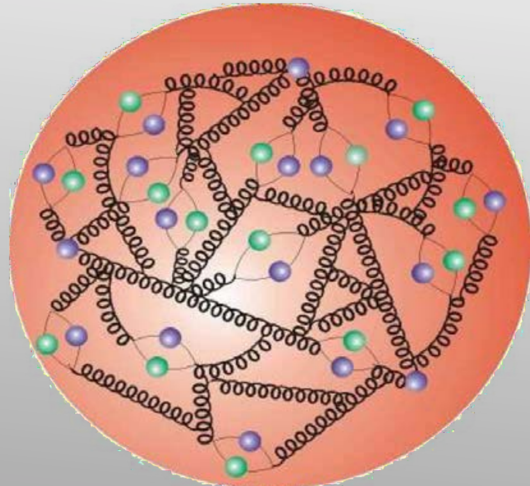
Collisions at LHC

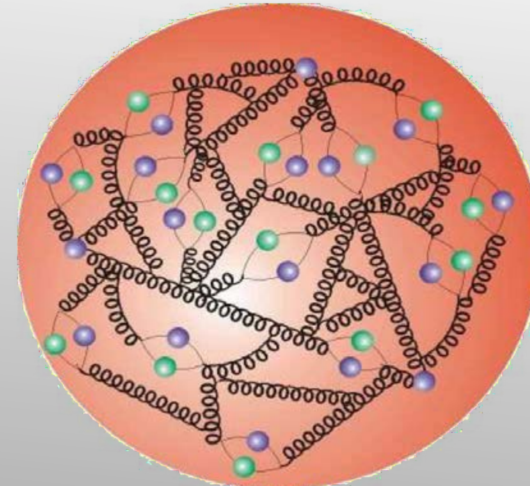


Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^{7} - 10^{9} Hz

Selection of 1 in 10,000,000,000,000

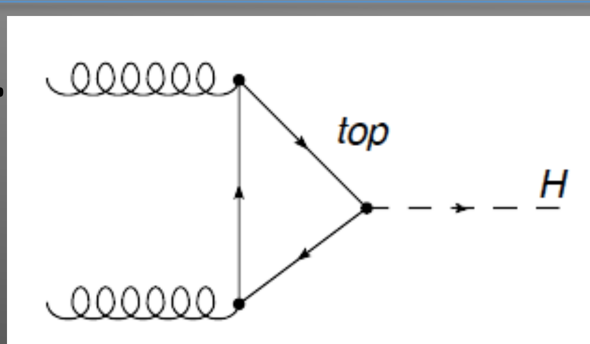
Proton-proton collisions



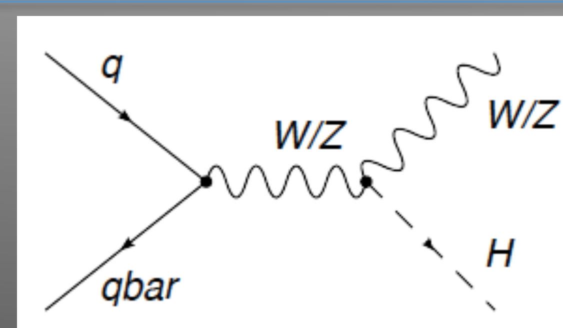


Composite objects but looking for point-interactions within a large background of underlying activity

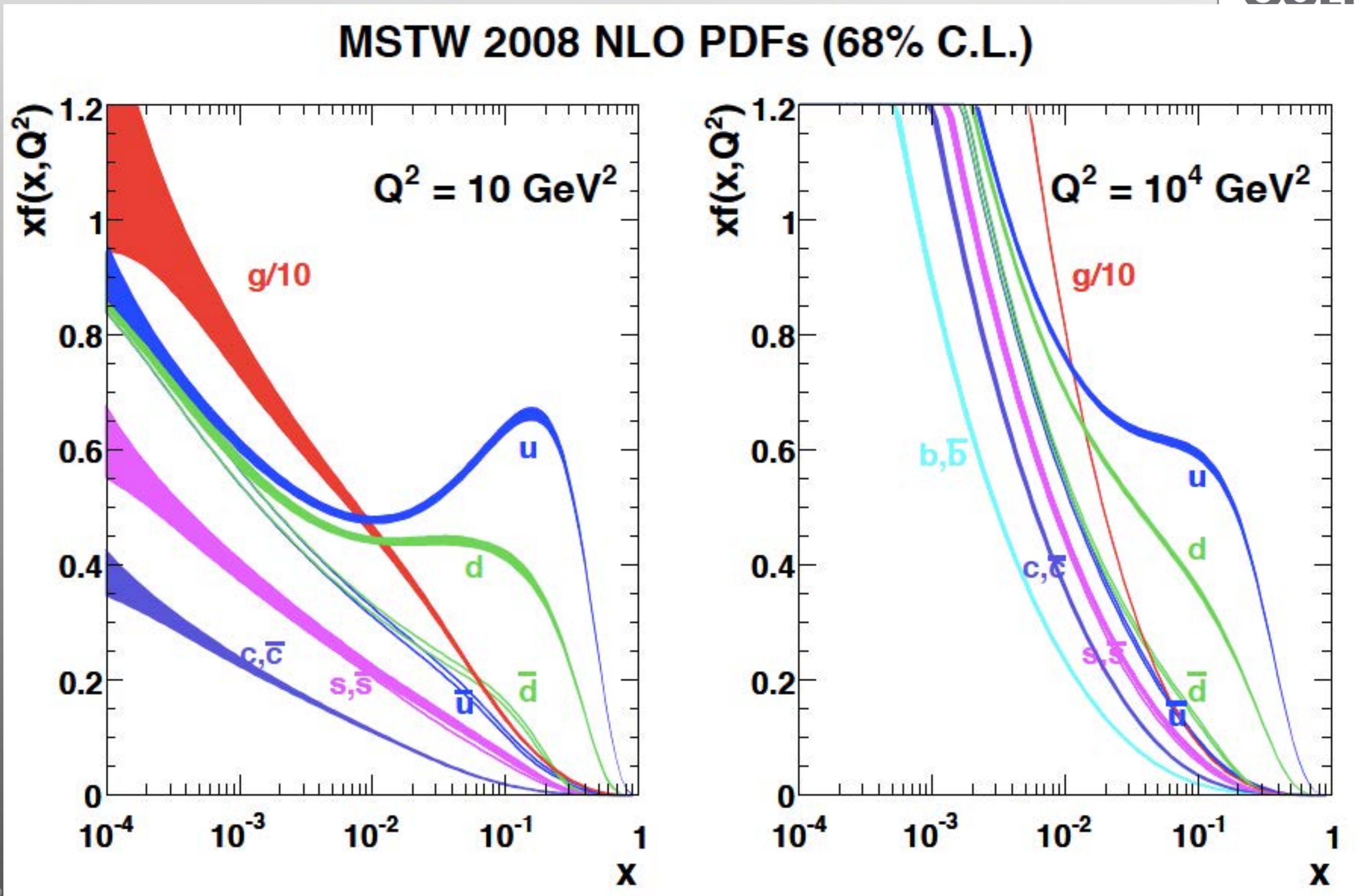
Eg.

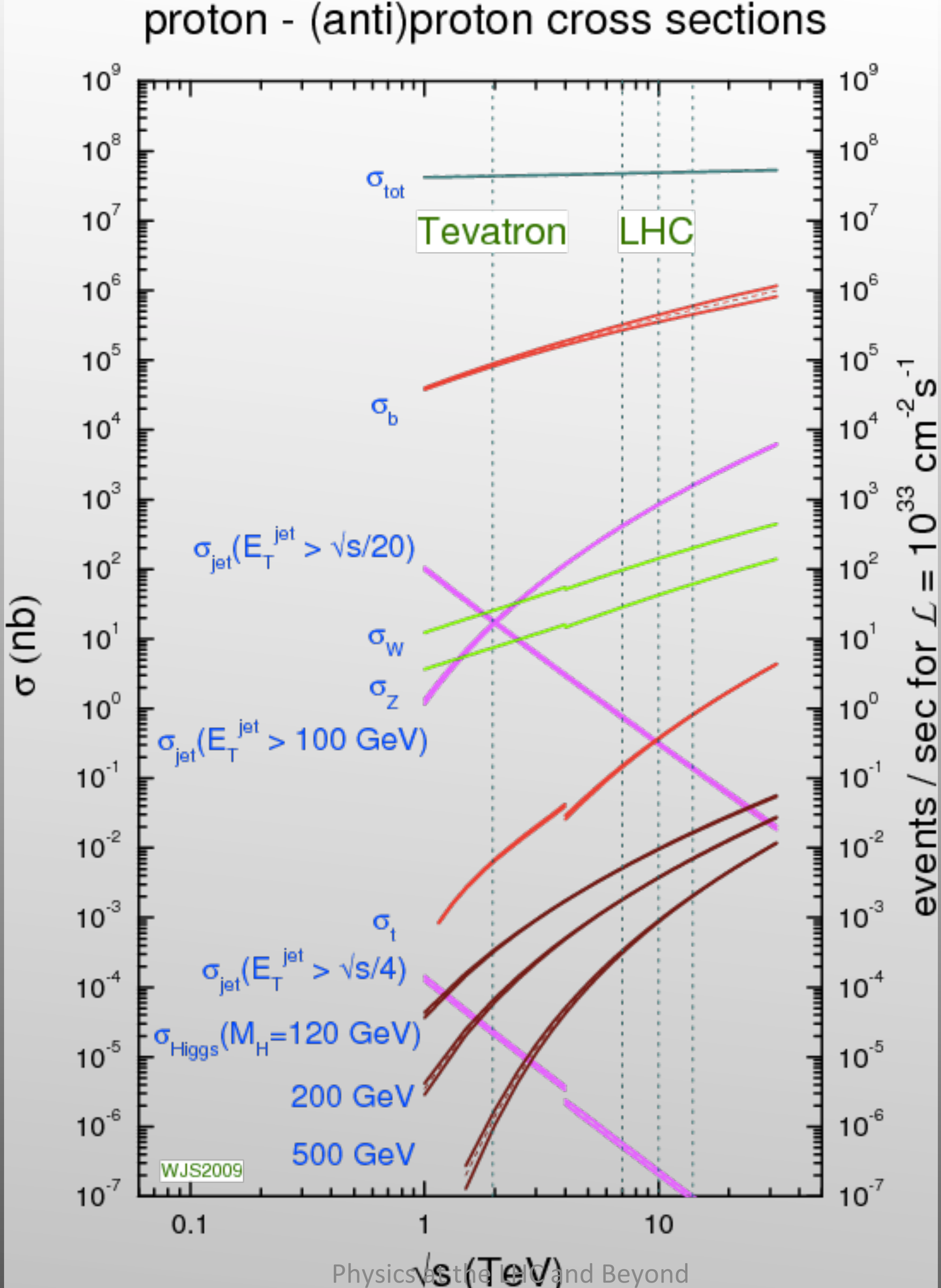


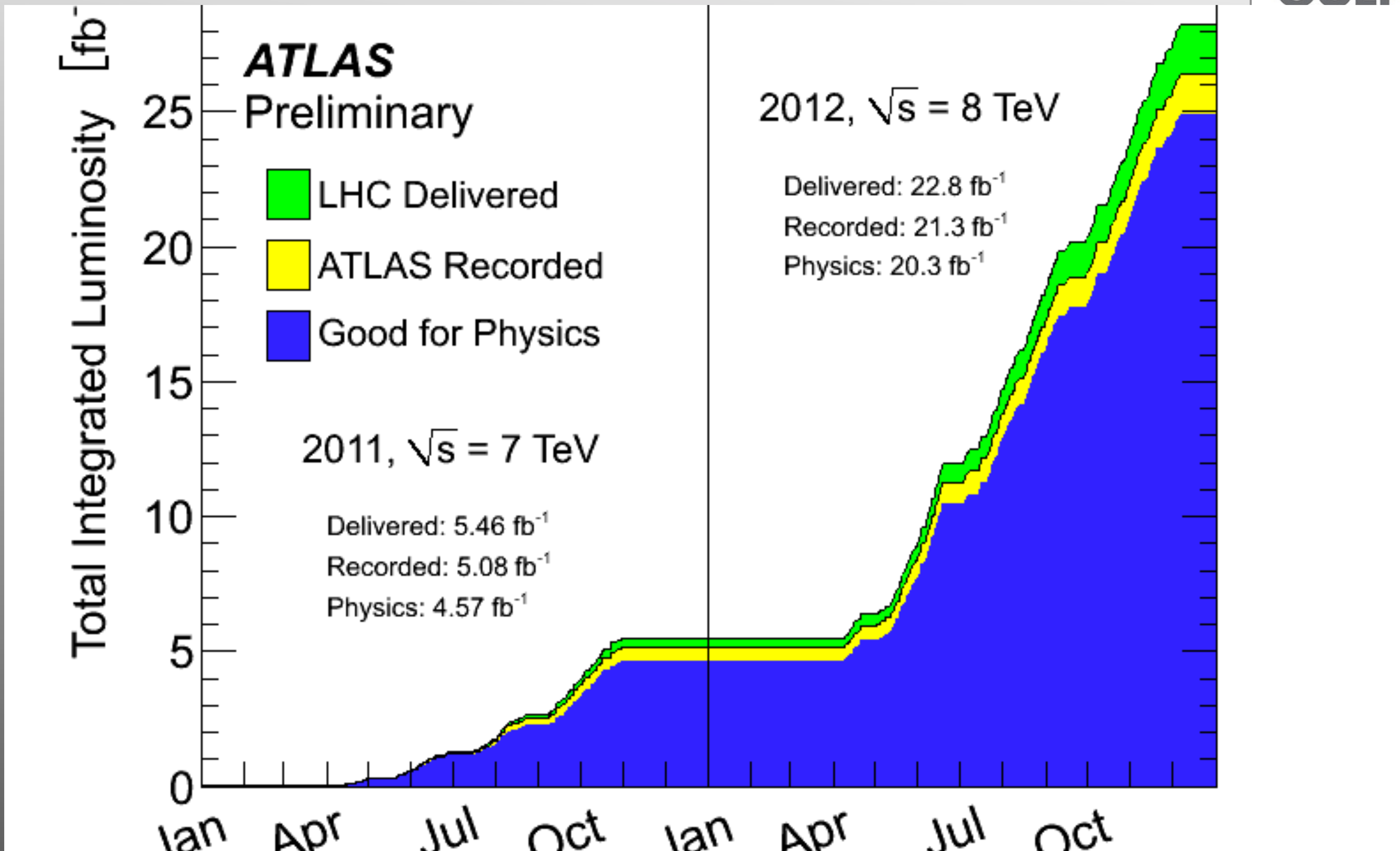
Or

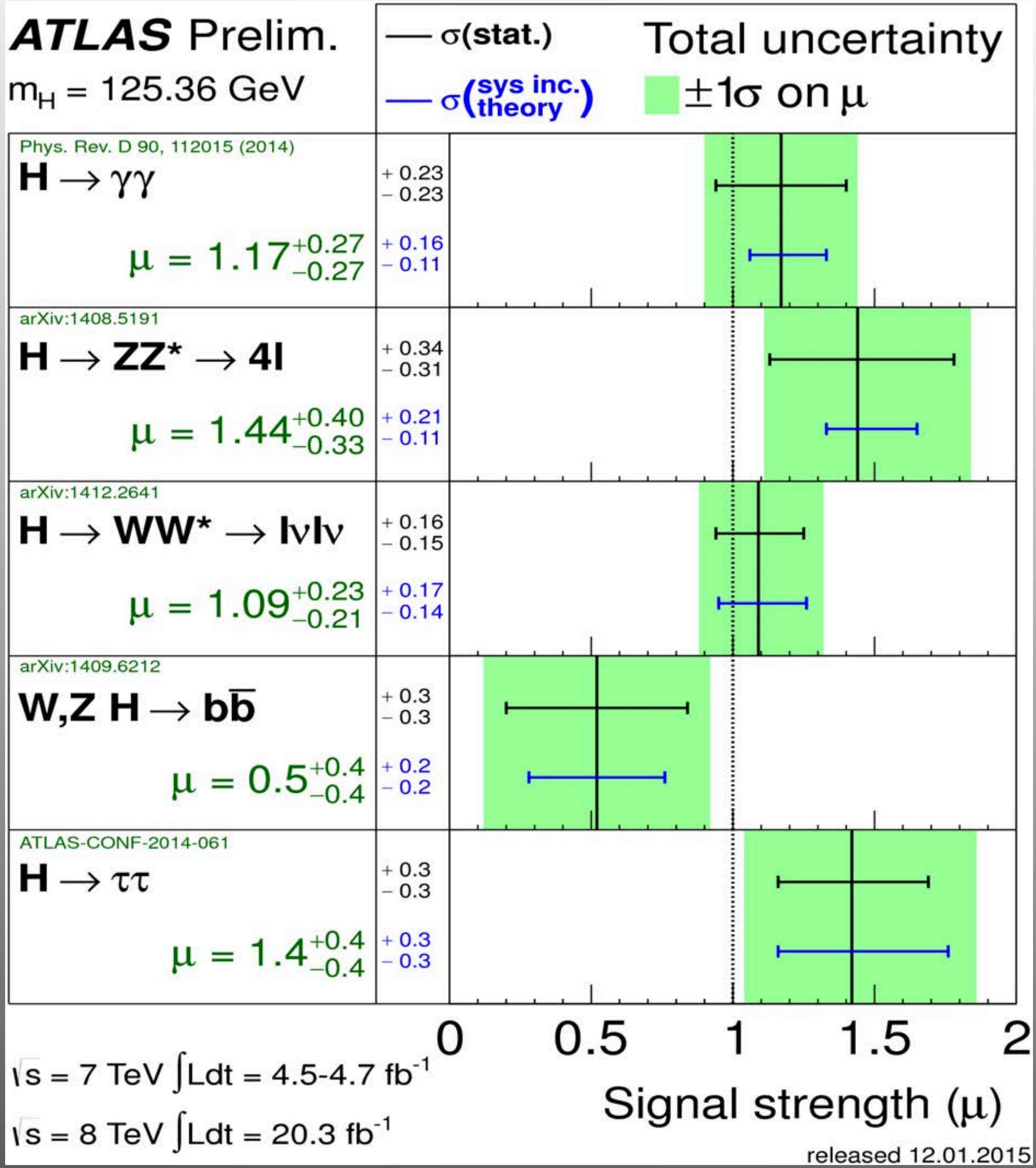


Fraction of Proton Momentum carried by various partons as seen at two different scales (set by Q^2)




proton - (anti)proton cross sections
σ_tot
Tevatron
LHC
σ_b
σ_jet(E_T^jet > √s/20)
σ_W
σ_Z
σ_jet(E_T^jet > 100 GeV)
σ_t
σ_jet(E_T^jet > √s/4)
σ_Higgs(M_H=120 GeV)
200 GeV
500 GeV
WJS2009
σ (nb)
events / sec for ℒ = 10^33 cm^-2 s^-1
√s (TeV)
0.1
1
10


ATLAS
Preliminary
LHC Delivered
ATLAS Recorded
Good for Physics
2011, √s = 7 TeV
Delivered: 5.46 fb⁻¹
Recorded: 5.08 fb⁻¹
Physics: 4.57 fb⁻¹
2012, √s = 8 TeV
Delivered: 22.8 fb⁻¹
Recorded: 21.3 fb⁻¹
Physics: 20.3 fb⁻¹
Total Integrated Luminosity [fb⁻¹]
0
5
10
15
20
25
Jan
Apr
Jul
Oct
Jan
Apr
Jul
Oct


ATLAS Prelim.
mH = 125.36 GeV
σ(stat.)
σ(sys inc. theory)
Total uncertainty
±1σ on μ
Phys. Rev. D 90, 112015 (2014)
H → γγ
μ = 1.17 +0.27 −0.27
+ 0.23 − 0.23
+ 0.16 − 0.11
arXiv:1408.5191
H → ZZ* → 4l
μ = 1.44 +0.40 −0.33
+ 0.34 − 0.31
+ 0.21 − 0.11
arXiv:1412.2641
H → WW* → lνlν
μ = 1.09 +0.23 −0.21
+ 0.16 − 0.15
+ 0.17 − 0.14
arXiv:1409.6212
W,Z H → bb̄
μ = 0.5 +0.4 −0.4
+ 0.3 − 0.3
+ 0.2 − 0.2
ATLAS-CONF-2014-061
H → ττ
μ = 1.4 +0.4 −0.4
+ 0.3 − 0.3
+ 0.3 − 0.3
0
0.5
1
1.5
2
√s = 7 TeV ∫Ldt = 4.5-4.7 fb-1
√s = 8 TeV ∫Ldt = 20.3 fb-1
Signal strength (μ)
released 12.01.2015

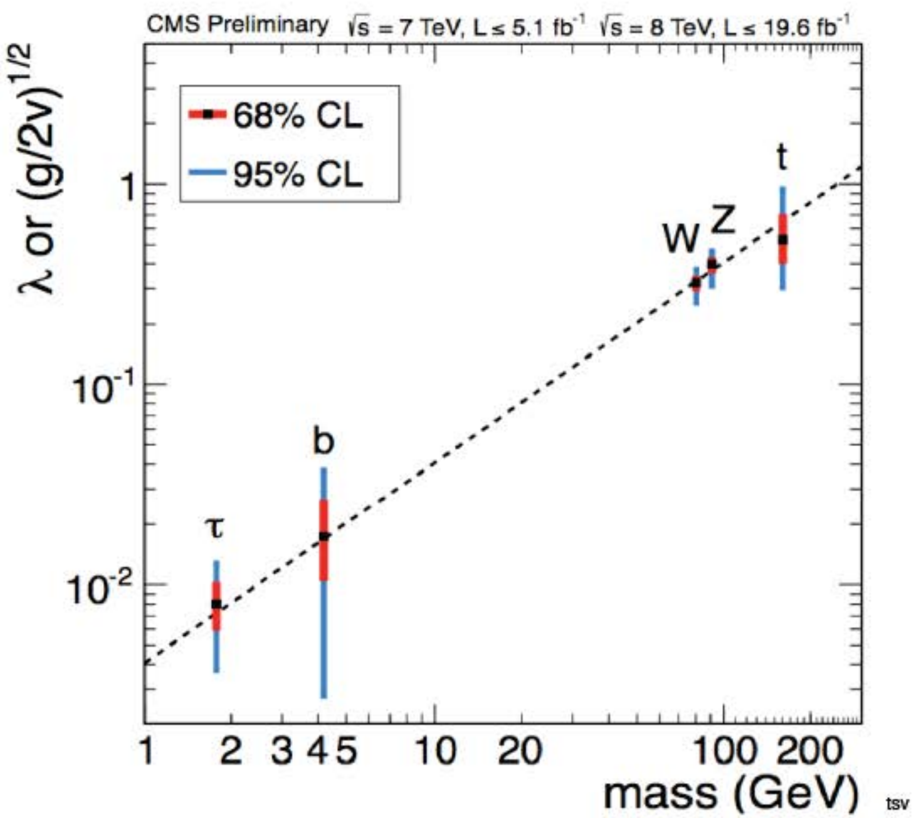
Imperial College London

Mass and Couplings

CMS

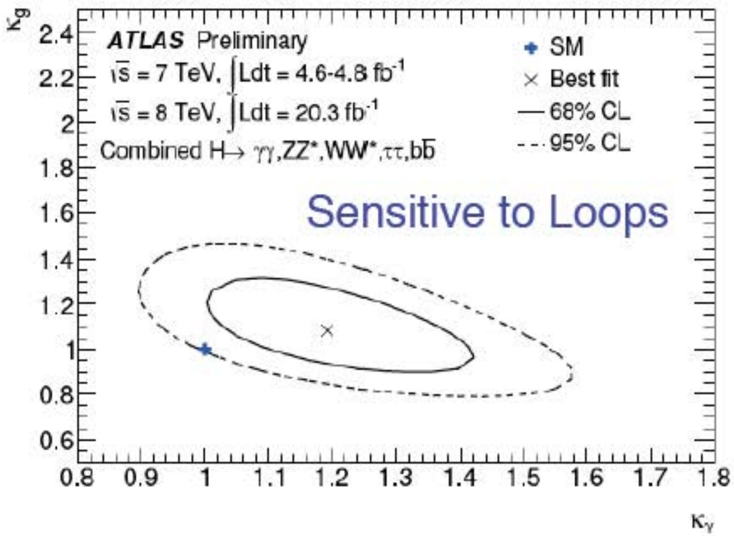
125.6 ± 0.4 (stat) ± 0.2 (syst) GeV

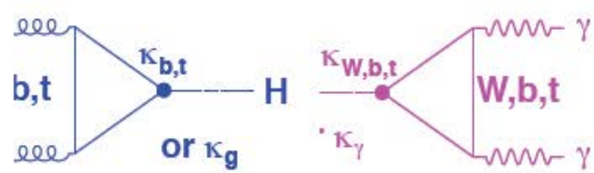
From $H \rightarrow ZZ^{(*)} \rightarrow 4l$



ATLAS

M_H= 125.5 $^{+0.5}_{-0.6}$ (stat) ± 0.2 (syst) GeV

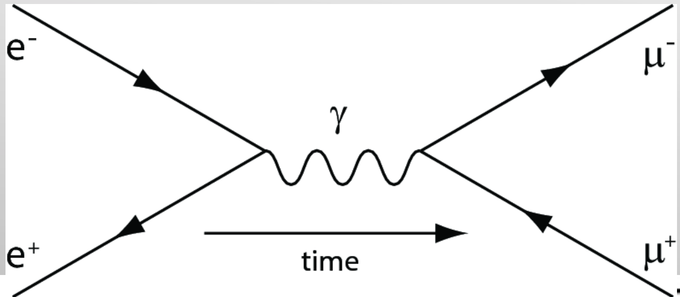


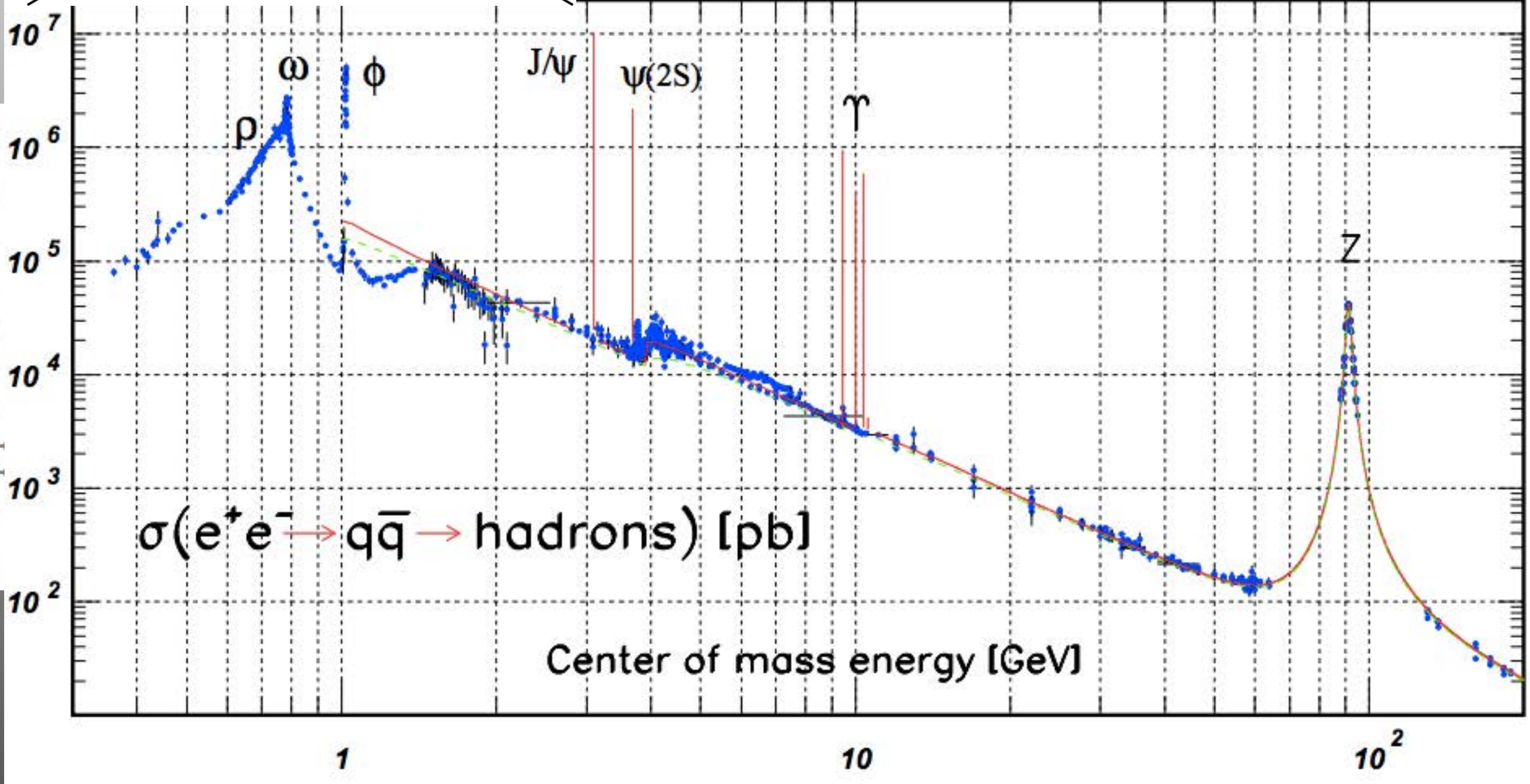


tsv

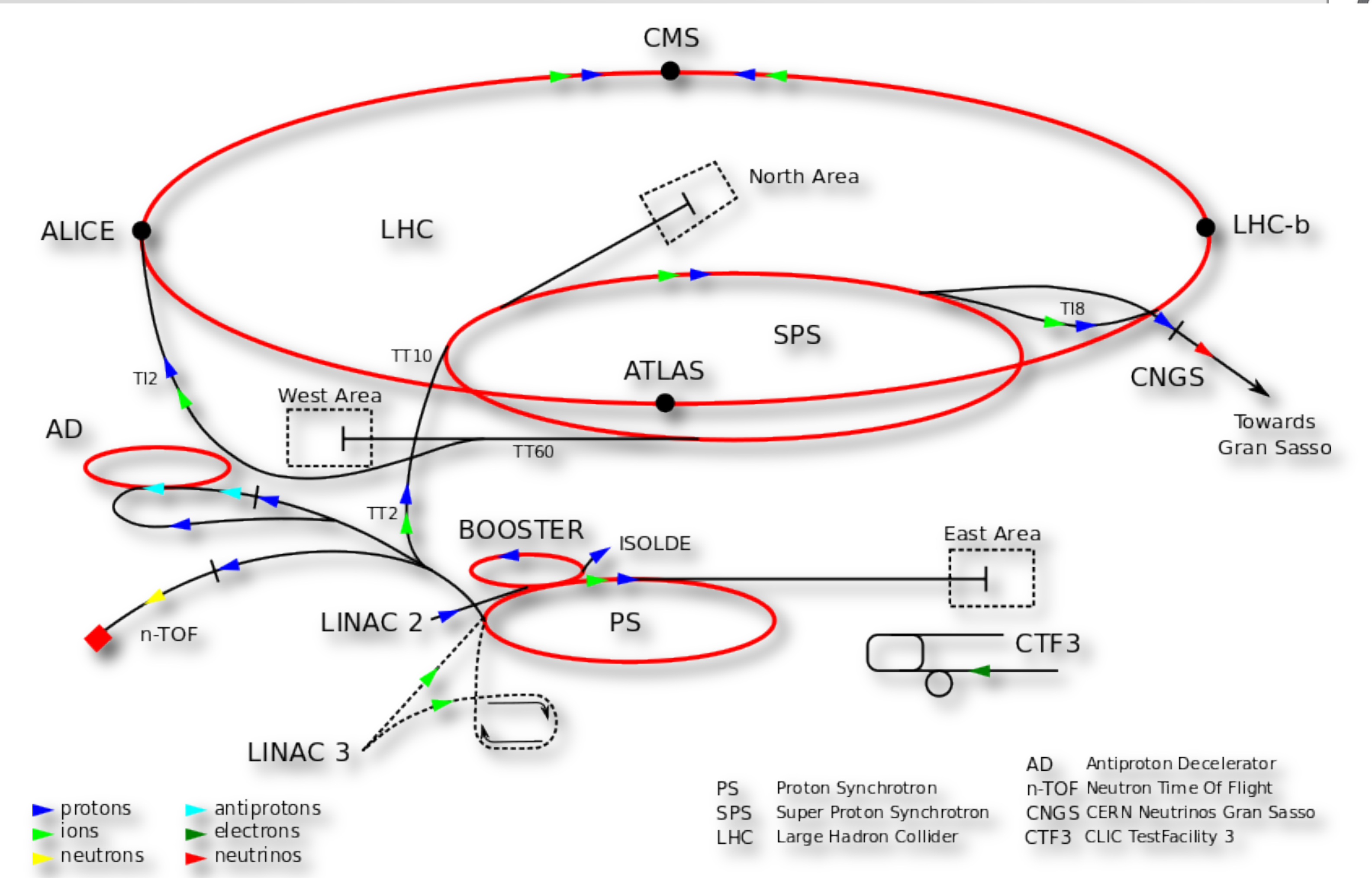
41

- Proton accelerators – particle explosion
  - *Quark model*
- Electron scattering – proton structure
  - *Quarks as real objects*

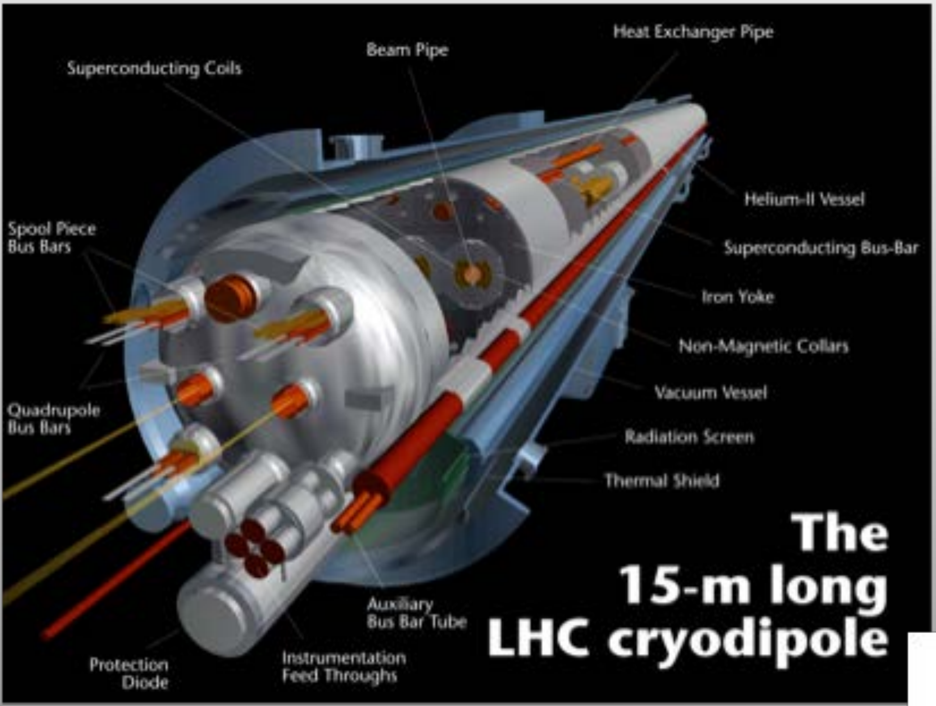

e⁻
e⁺
γ
μ⁻
μ⁺
time


ρ
ω
φ
J/ψ
ψ(2S)
ϒ
Z
σ(e⁺e⁻ → qq̄ → hadrons) [pb]
Center of mass energy [GeV]

CERN Accelerator Complex



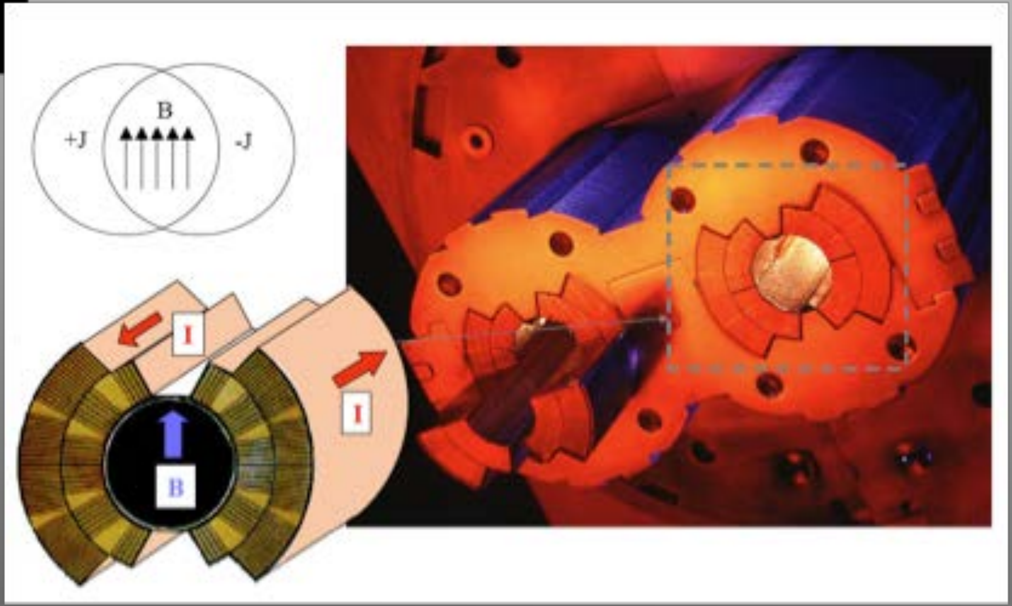
LHC Magnets



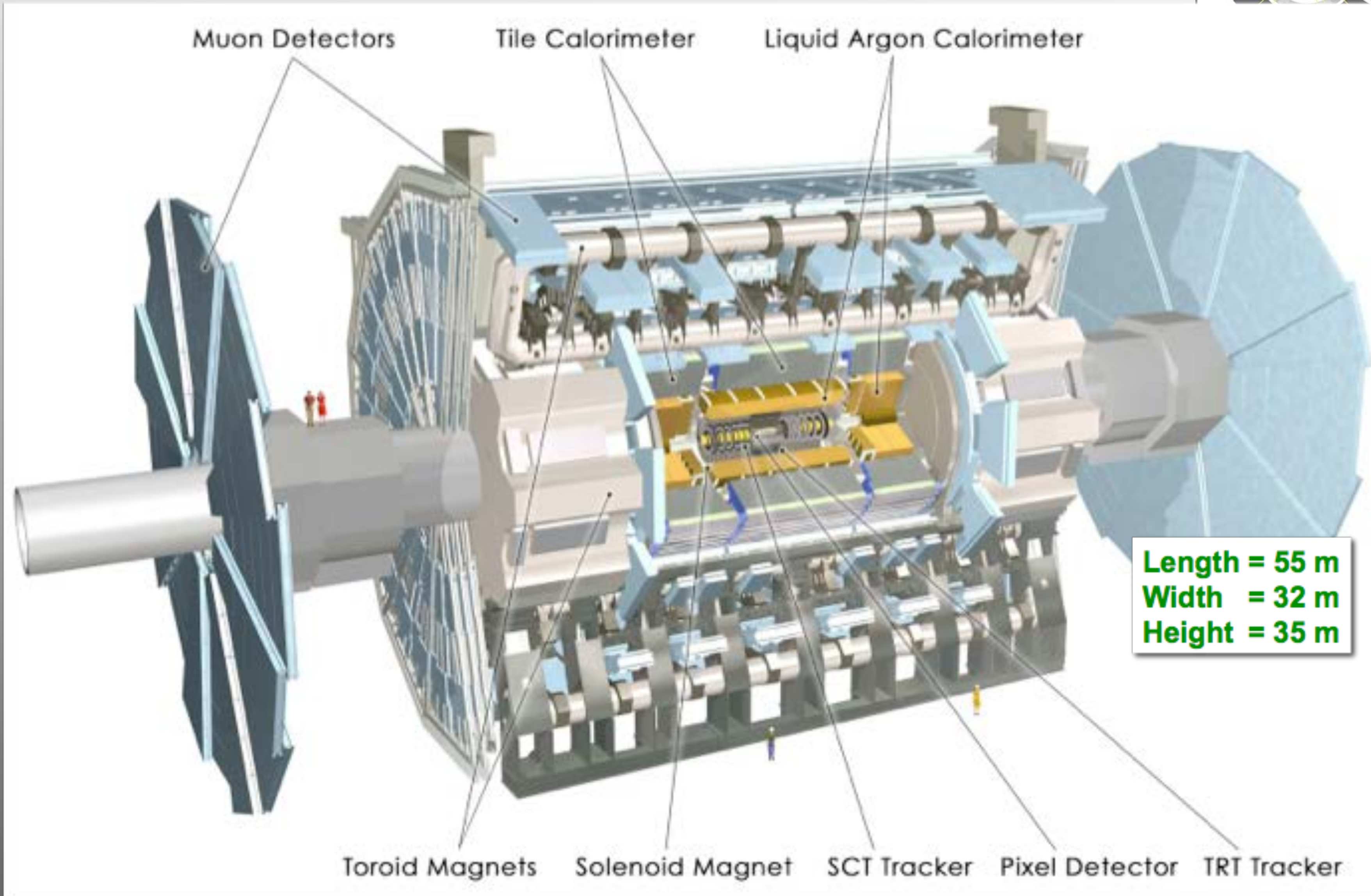
Magnetic Field for Dipoles
p (TeV) = 0.3 B(T) R(km)

For p = 7 TeV and R = 4.3 km
⇨ B = 8.4 T
⇨ Current 12 kA

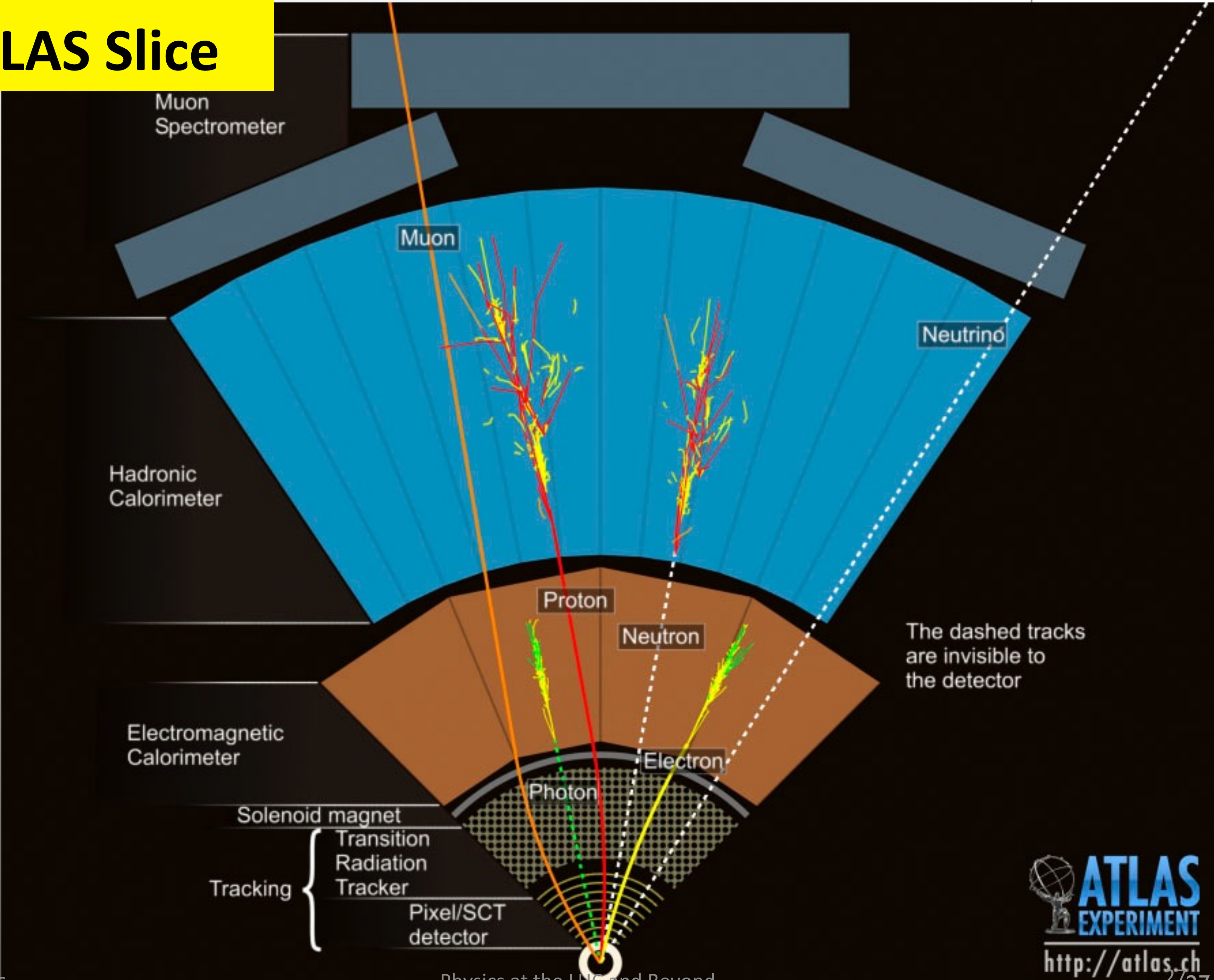
LHC magnets are cooled with pressurized superfluid helium



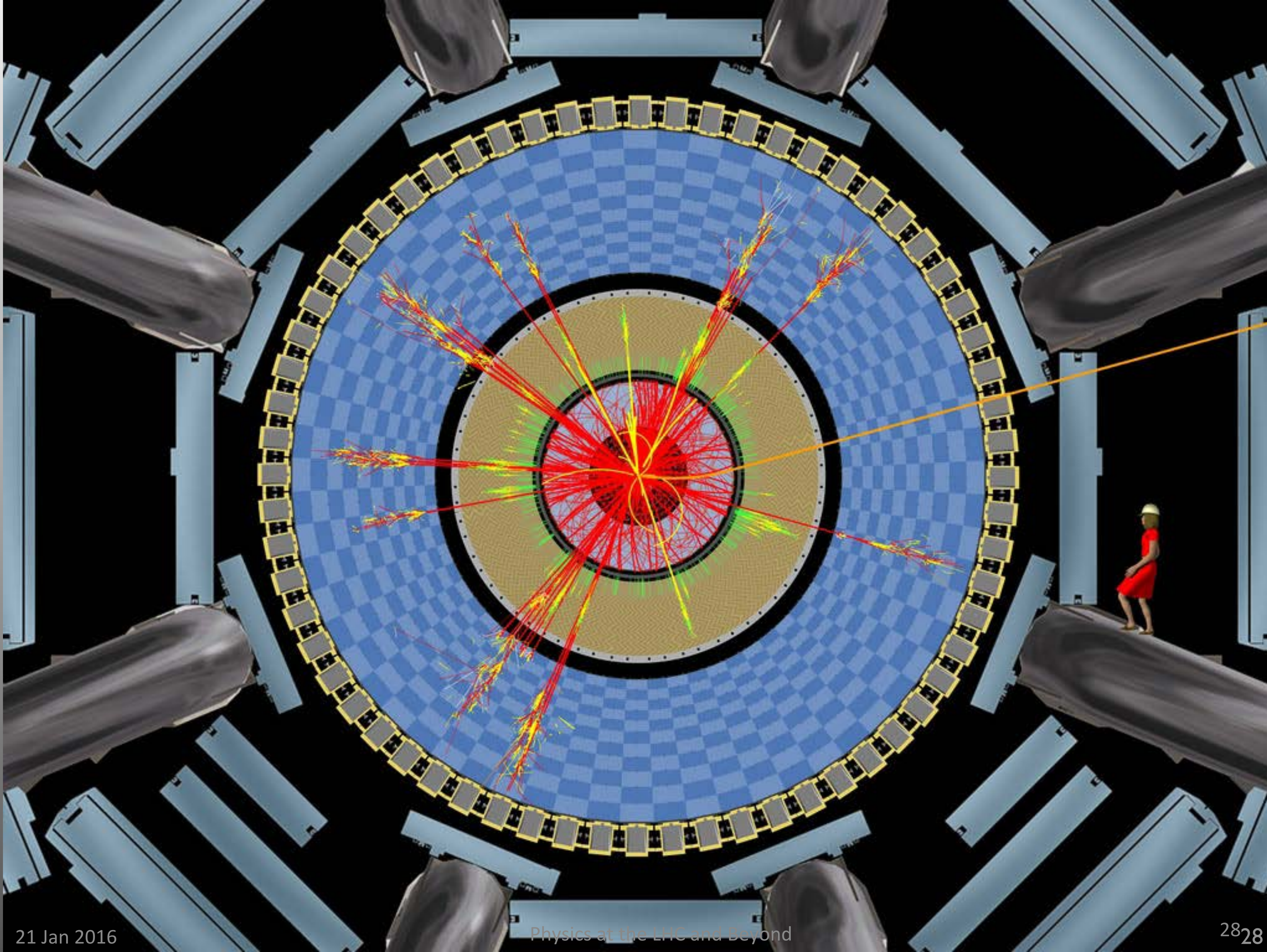
ATLAS


Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Length = 55 m
Width = 32 m
Height = 35 m
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

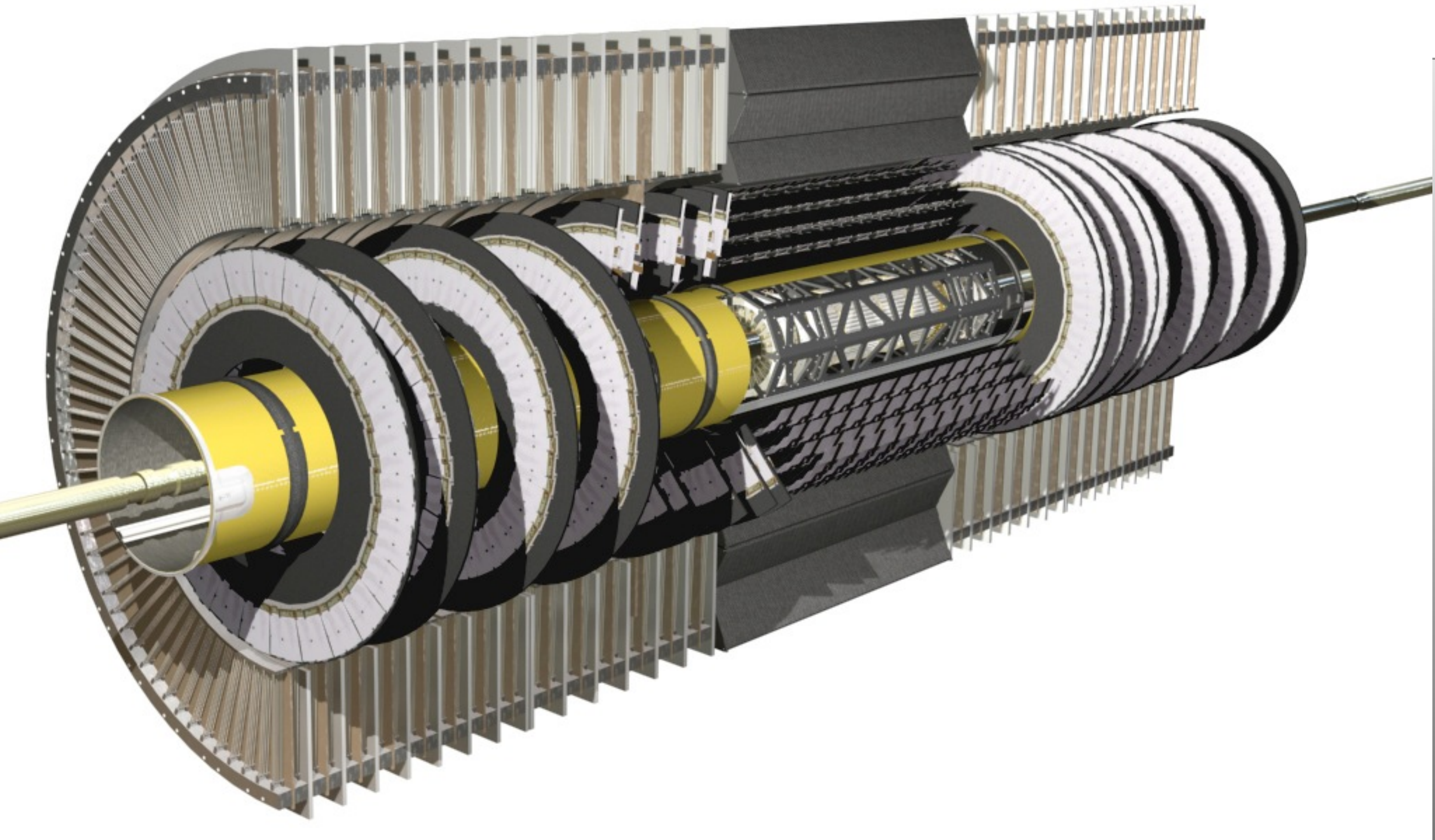
ATLAS Slice



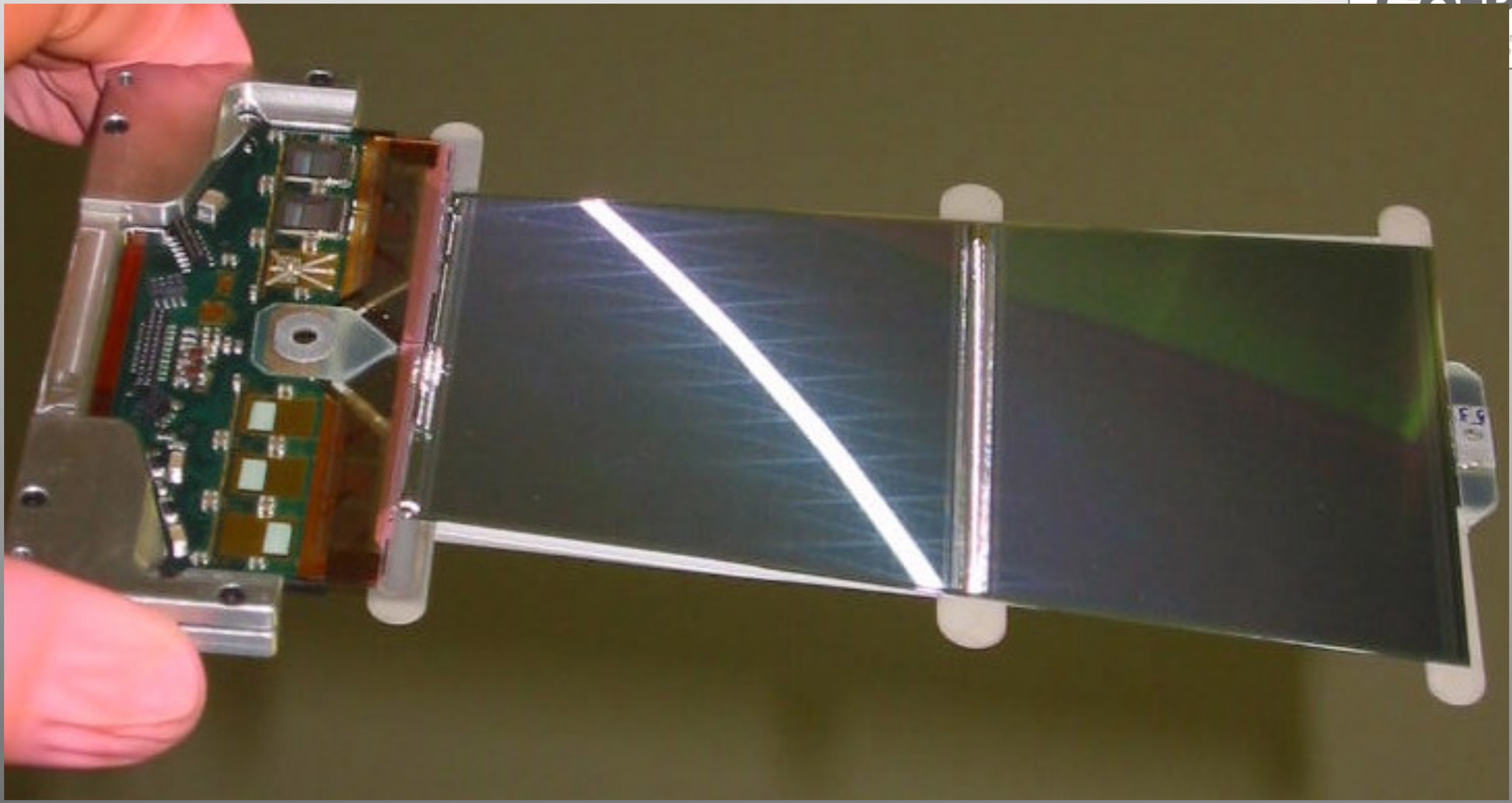
Muon Spectrometer
Muon
Neutrino
Hadronic Calorimeter
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Electron
Photon
Solenoid magnet
Transition Radiation Tracker
Tracking
Pixel/SCT detector
ATLAS EXPERIMENT
http://atlas.ch



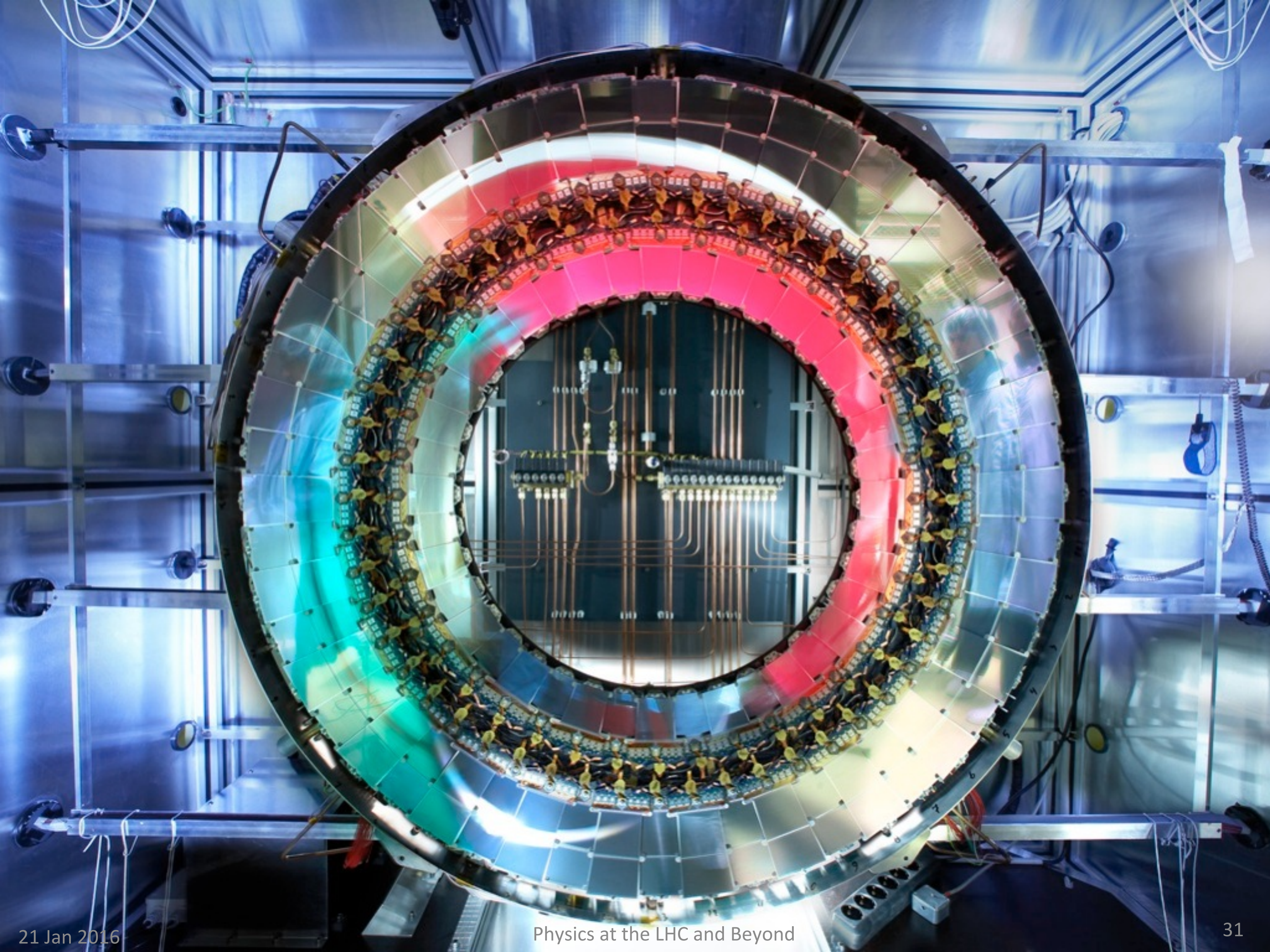
Inner Detector



Melbourne Module



30

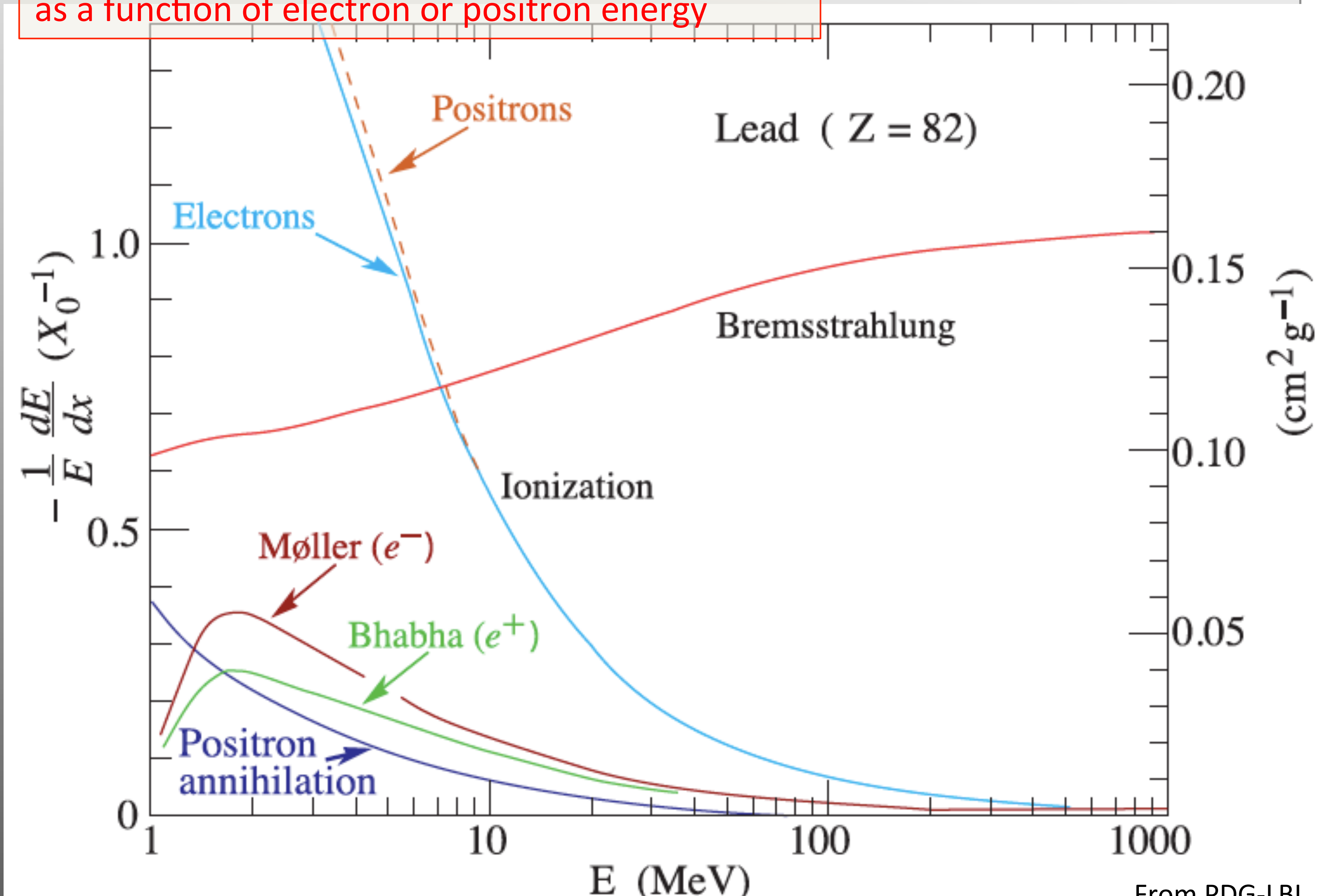


Calorimetry Priniciples

- Electro-magnetic Calorimeter
  - *Principally electrons and gamma rays*
  - *Above ~1MeV, shower formation with characteristic length ~ "radiation length" X_0*
  - *X_0 decreases with material Z (~6mm of Pb)*
  - *interleave Pb and active layers.*
  - *Electromagnetic showers develop in Pb, tracks counted in active element.*
- Hadronic Calorimeter
  - *Hadrons strongly interact with nuclei*
  - *"Hadronic shower", less dense, with much longer charactistic "interaction" length, λ_i.*
  - *λ_i saturates at ~10cm above Fe.*

Electromagnetic Showers, ctd

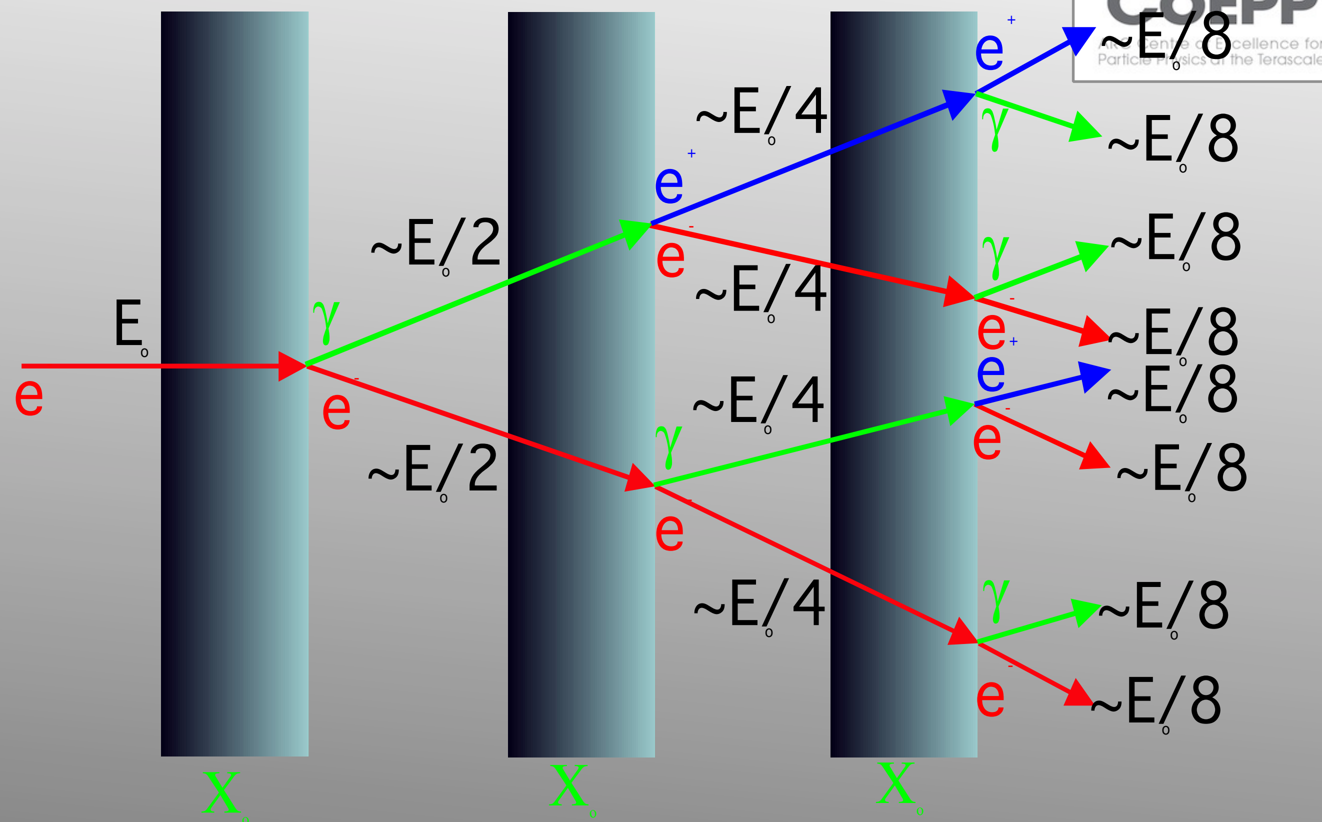
Fractional energy loss per radiation length in lead as a function of electron or positron energy



From PDG-LBL, PPG 2014

Electromagnetic Showers

- Radiation Length:
  - *The mean distance over which the electron energy has decreased to 1/e of its energy by bremsstrahlung radiation*
  - *The scale of electromagnetic showers or cascades*

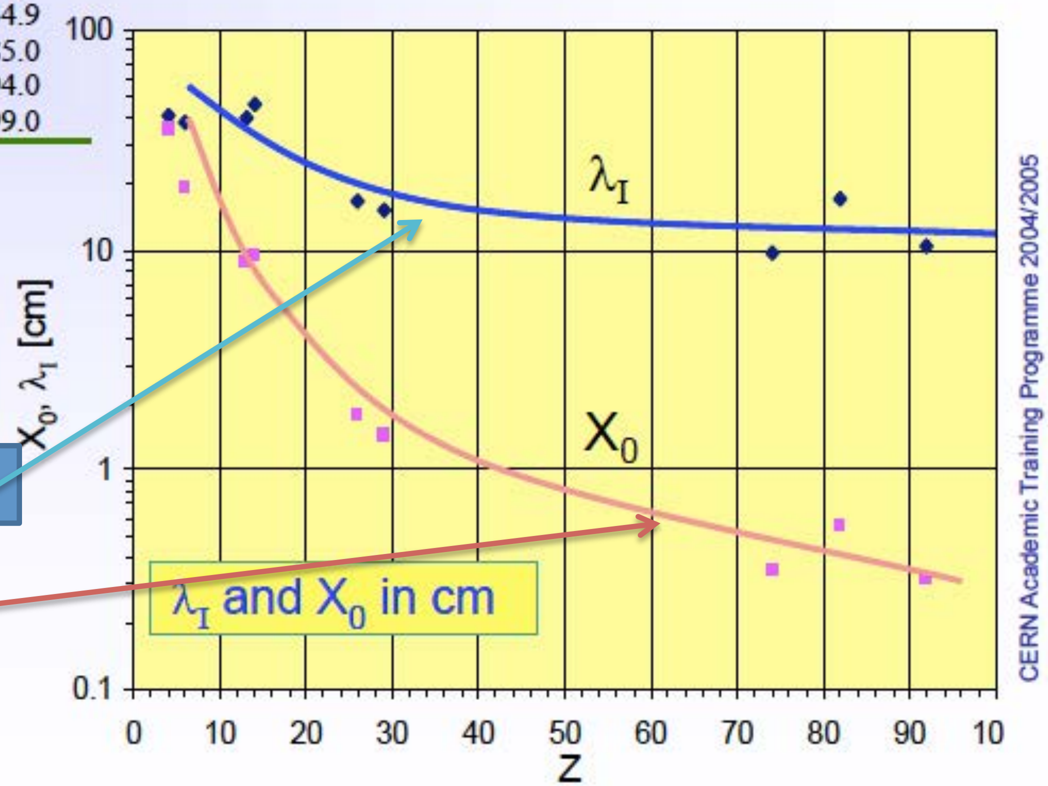


Thickness	t=0	t=X_o	t=2X_o	t=3X_o
Number of Particles		~2	~4	~8

Hadronic vs EM Calorimeter

Material	Z	A	ρ [g/cm³]	X_0 [g/cm²]	λ_I [g/cm²]
Hydrogen (gas)	1	1.01	0.0899 (g/l)	63	50.8
Helium (gas)	2	4.00	0.1786 (g/l)	94	65.1
Beryllium	4	9.01	1.848	65.19	75.2
Carbon	6	12.01	2.265	43	86.3
Nitrogen (gas)	7	14.01	1.25 (g/l)	38	87.8
Oxygen (gas)	8	16.00	1.428 (g/l)	34	91.0
Aluminium	13	26.98	2.7	24	106.4
Silicon	14	28.09	2.33	22	106.0
Iron	26	55.85	7.87	13.9	131.9
Copper	29	63.55	8.96	12.9	134.9
Tungsten	74	183.85	19.3	6.8	185.0
Lead	82	207.19	11.35	6.4	194.0
Uranium	92	238.03	18.95	6.0	199.0

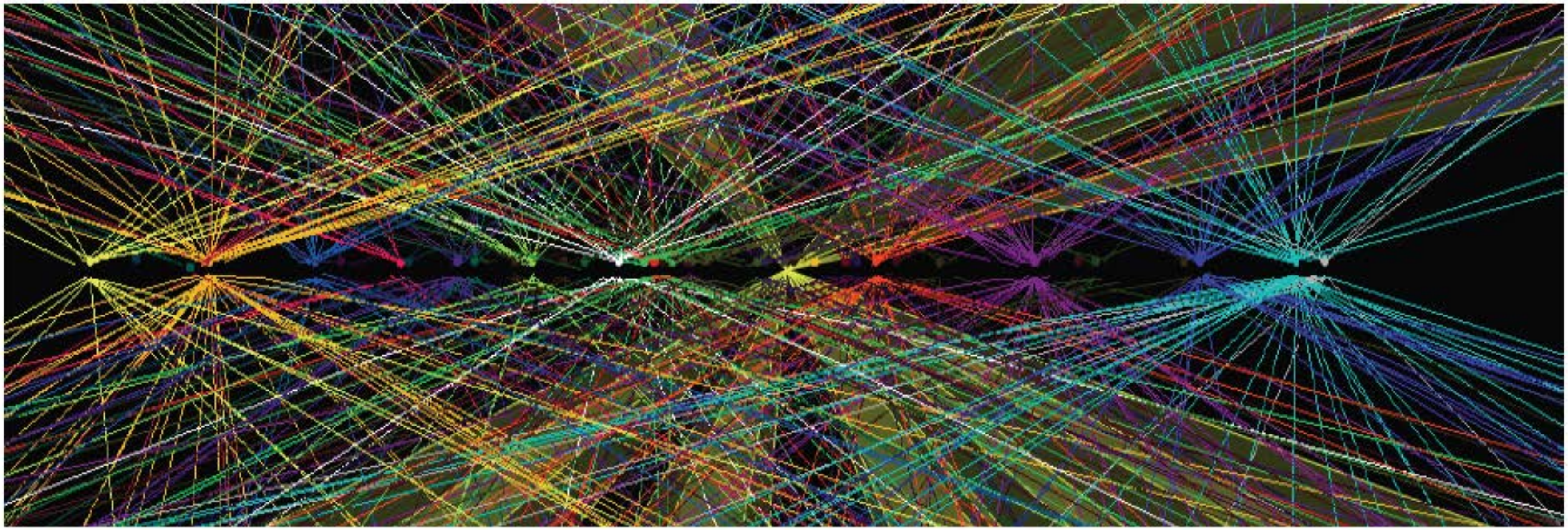
For Z > 6: $\lambda_I > X_0$

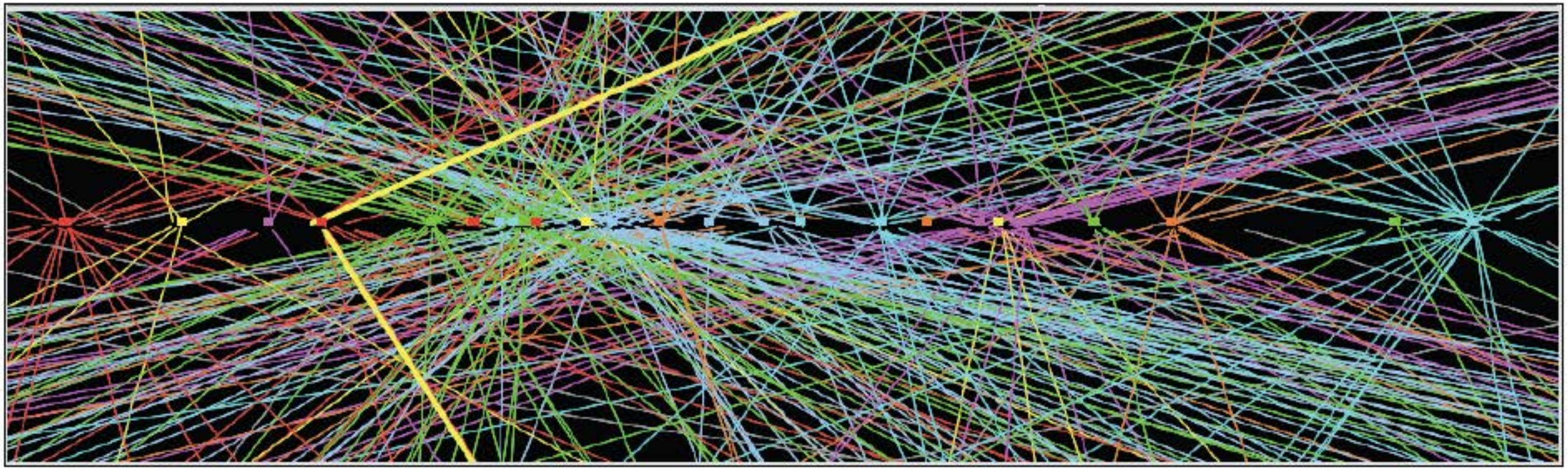


Hadron Calorimeter characteristic length

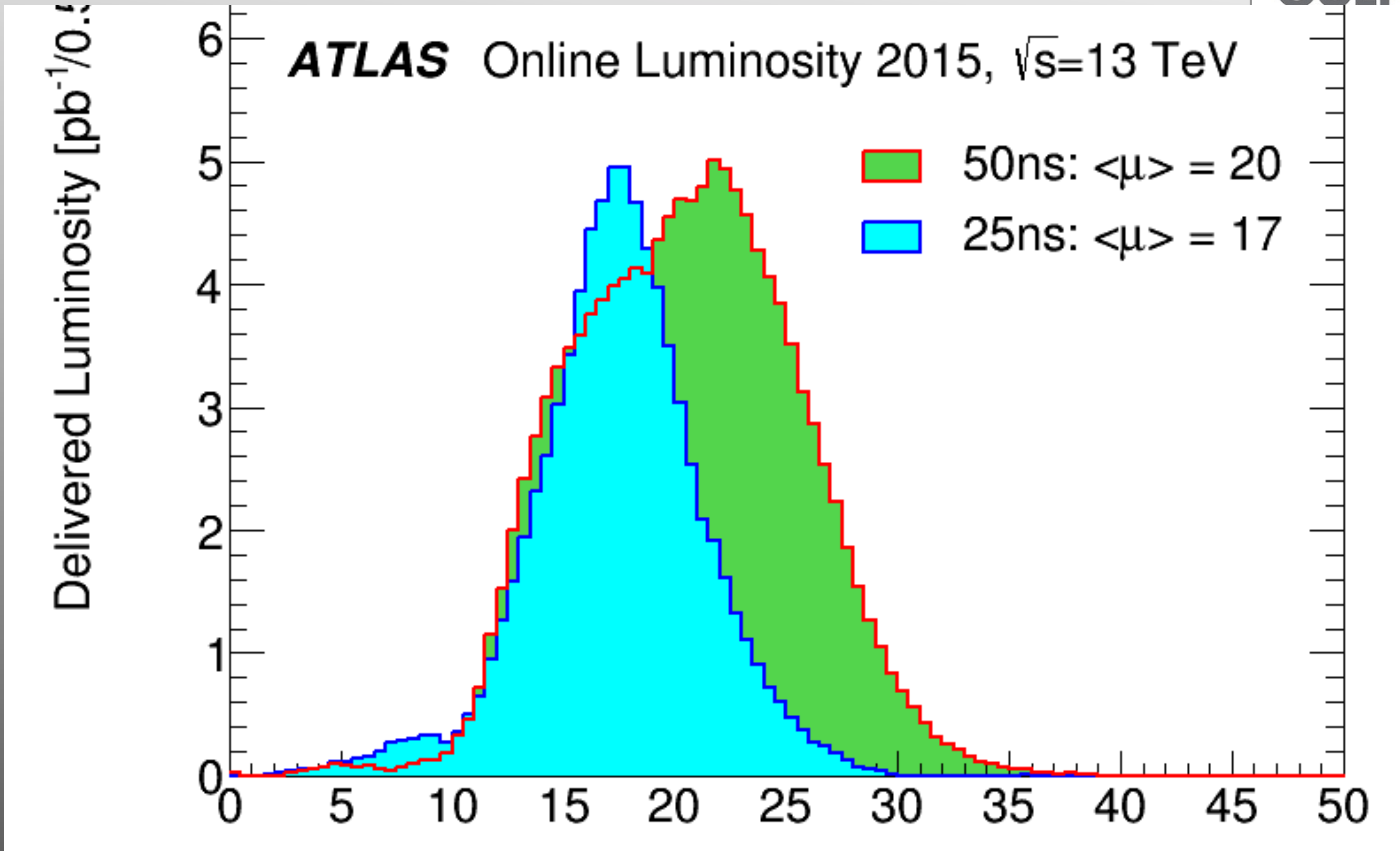
EM Calorimeter characteristic length

Try to visualize x5!

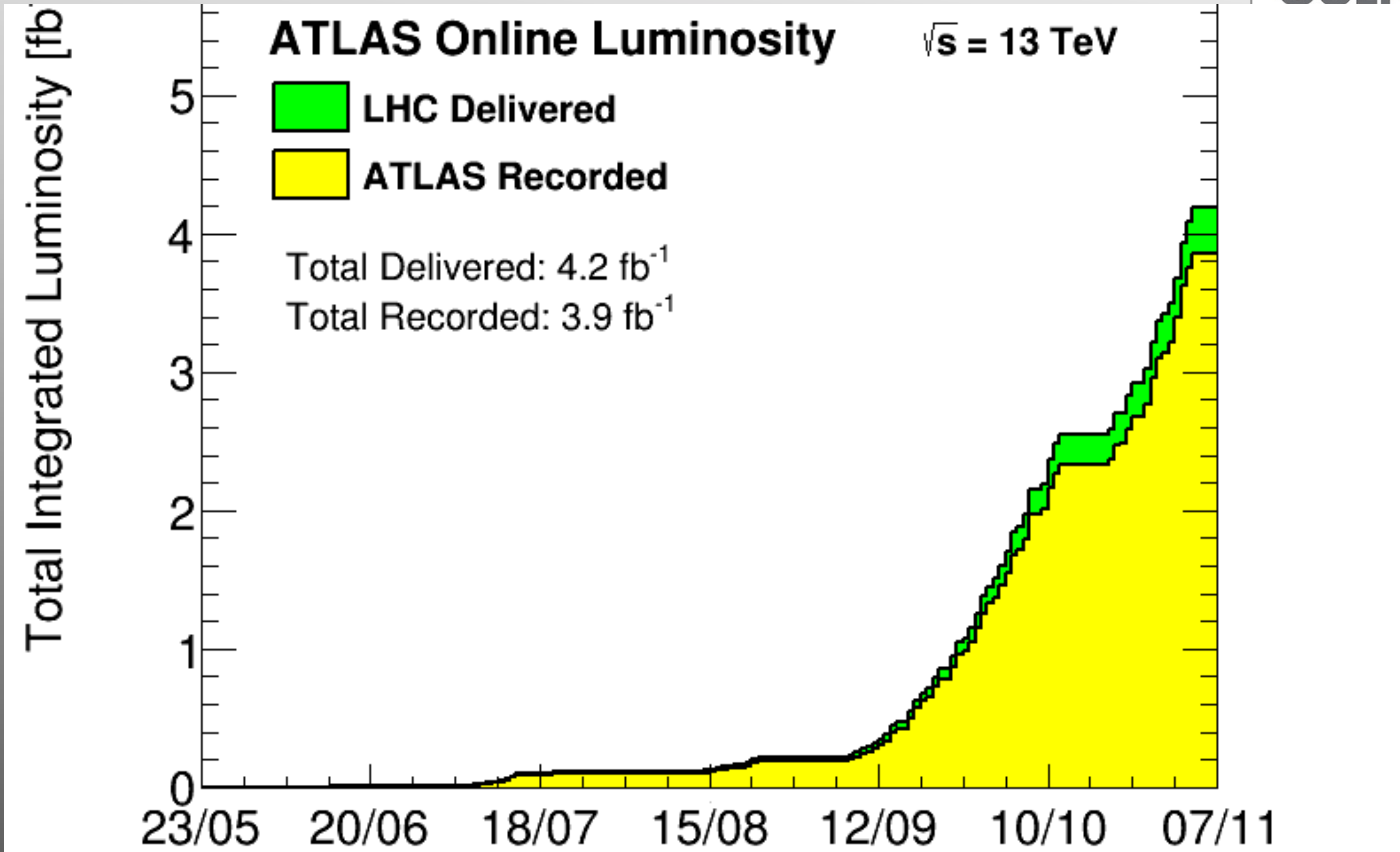


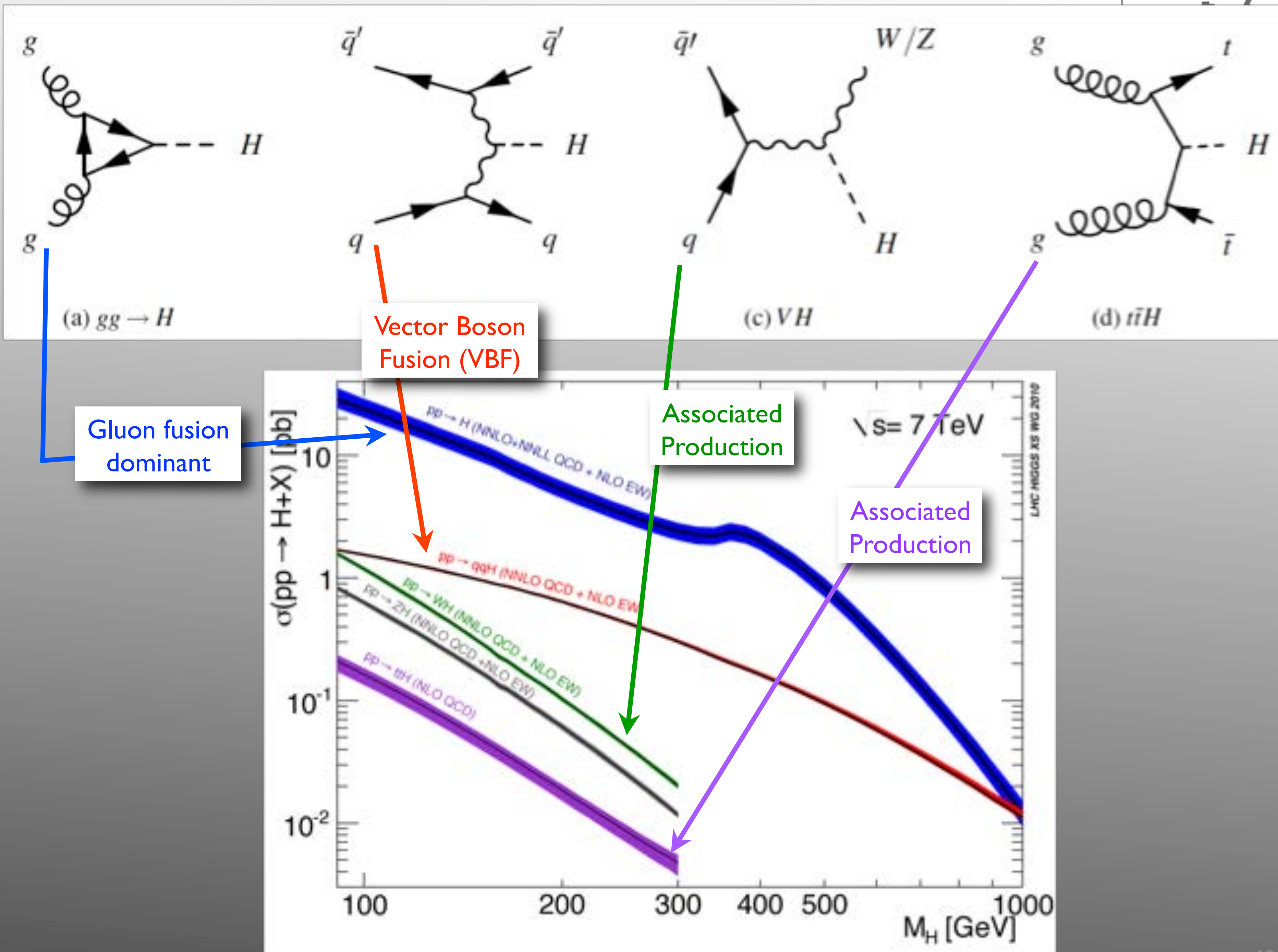


Multiple Interactions per Beam crossing

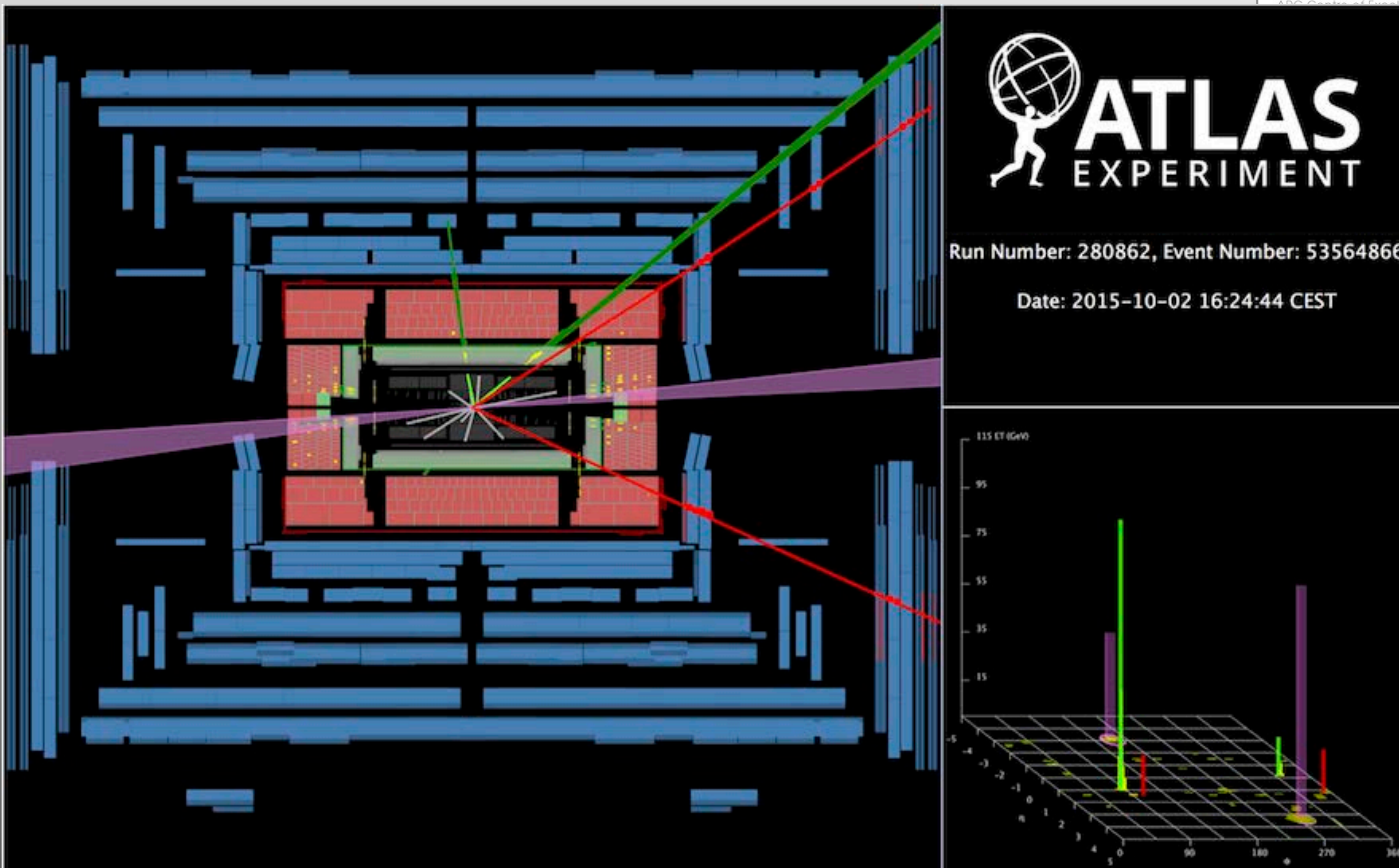


2015 – Higher Energy

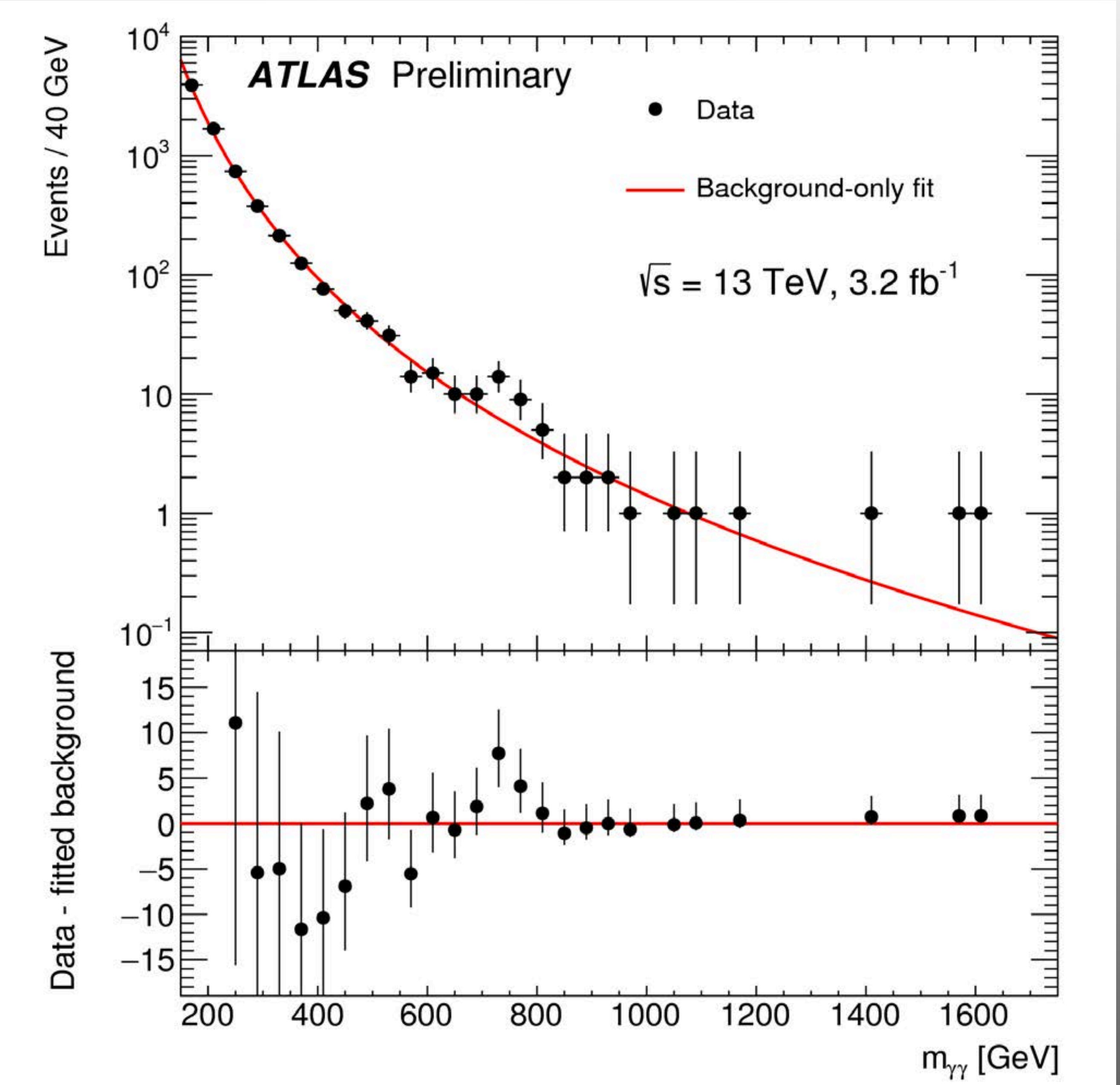


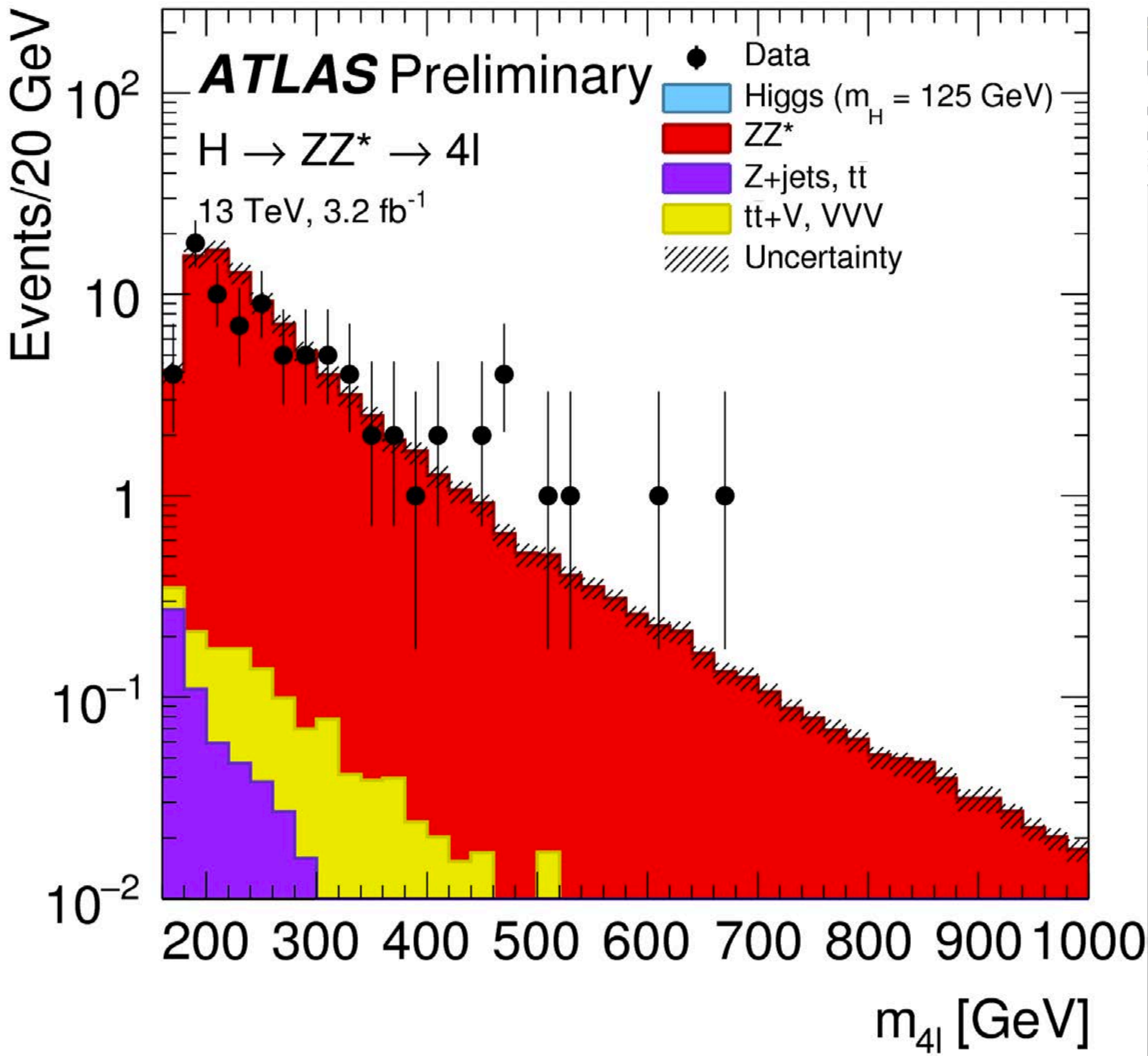

(a) gg → H
Vector Boson Fusion (VBF)
(c) VH
(d) ttH
Gluon fusion dominant
Associated Production
Associated Production
√s= 7 TeV
σ(pp → H+X) [pb]
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → ttH (NLO QCD)
LHC HIGGS XS WG 2010
M_H [GeV]

This event is consistent with VBF production of a Higgs boson decaying to four leptons.



Titillating?





ATLAS Preliminary
H → ZZ* → 4l
13 TeV, 3.2 fb-1
Data
Higgs (mH = 125 GeV)
ZZ*
Z+jets, tt
tt+V, VVV
Uncertainty
Events/20 GeV
10²
10
1
10⁻¹
10⁻²
200 300 400 500 600 700 800 900 1000
m4l [GeV]

Widening the horizon

1. SM contains too many apparently arbitrary features - *presumably these should become clearer as we make progress towards a unified theory.*

2. Clarify the e-w symmetry breaking sector

- **Use the Higgs boson as a new tool for discovery**

Answer will be found at **LHC energies**

3. SM gives nonsense at LHC energies

Probability of some processes becomes greater than 1 !! Nature's slap on the wrist!

Higgs mechanism provides a possible solution

4. Identify particles that make up Dark Matter

- **Identify the new physics of dark matter**

*If a new symmetry (Supersymmetry) is the answer, it must show up at O(***1TeV***)*

5. Search for new physics at the TeV scale

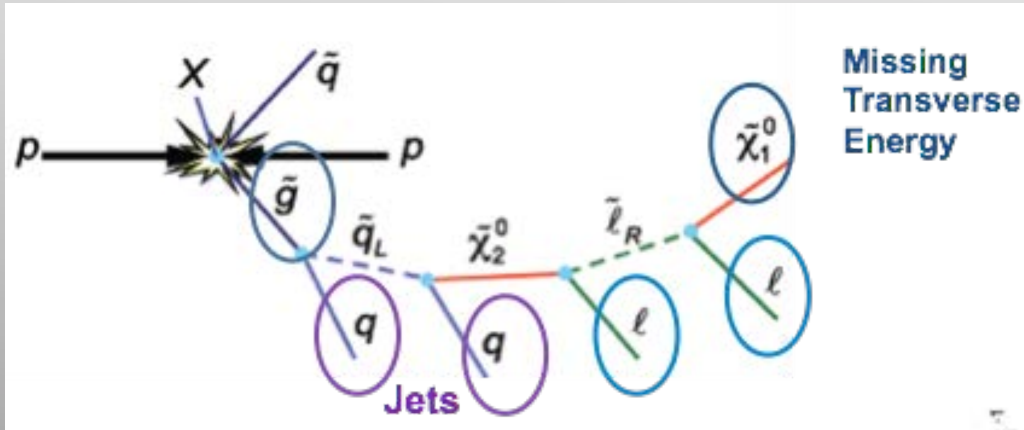
- **Explore the unknown: new particles, interactions, and physical principles.**

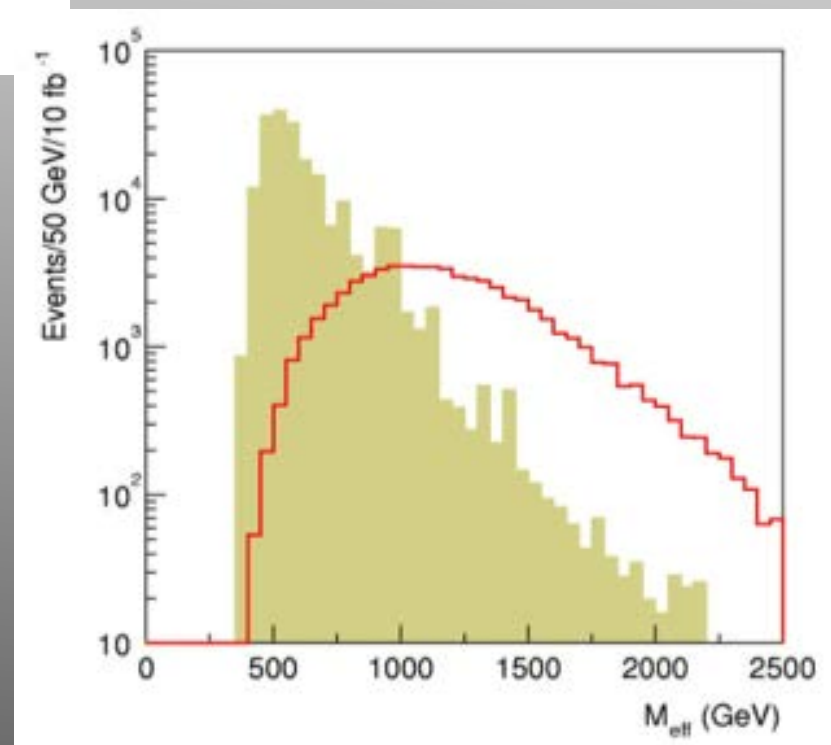
European Strategy for HEP

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

- c) The **discovery of the Higgs boson** is the start of a major programme of
- work to measure this particle's properties with the **highest possible precision** for testing the validity of the Standard Model and to search for further **new physics at the energy frontier**. The LHC is in a unique position to pursue this programme.
- ***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.***
- ***This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.***

SUSY Dark Matter??

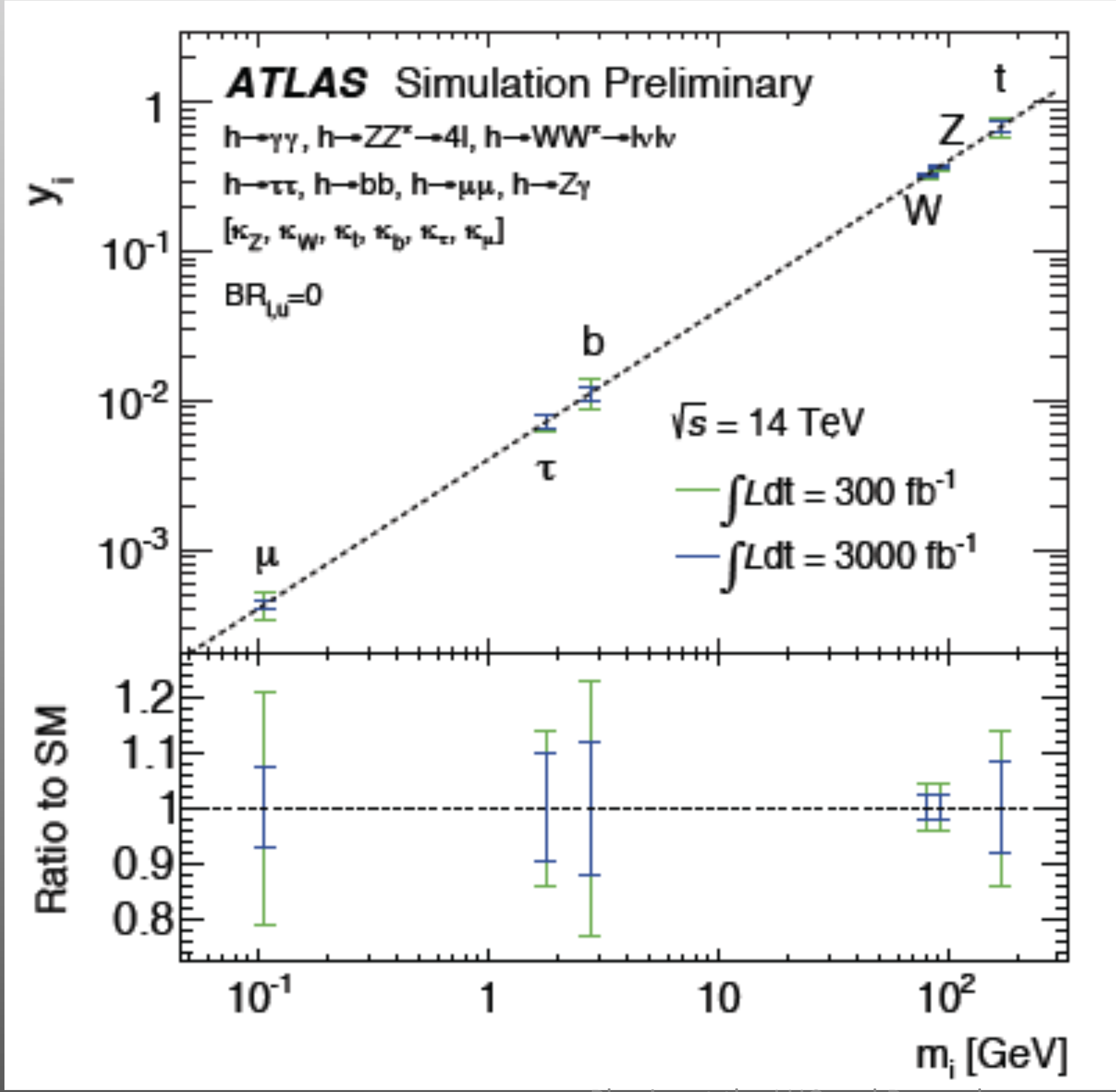




Why Luminosity Upgrade?

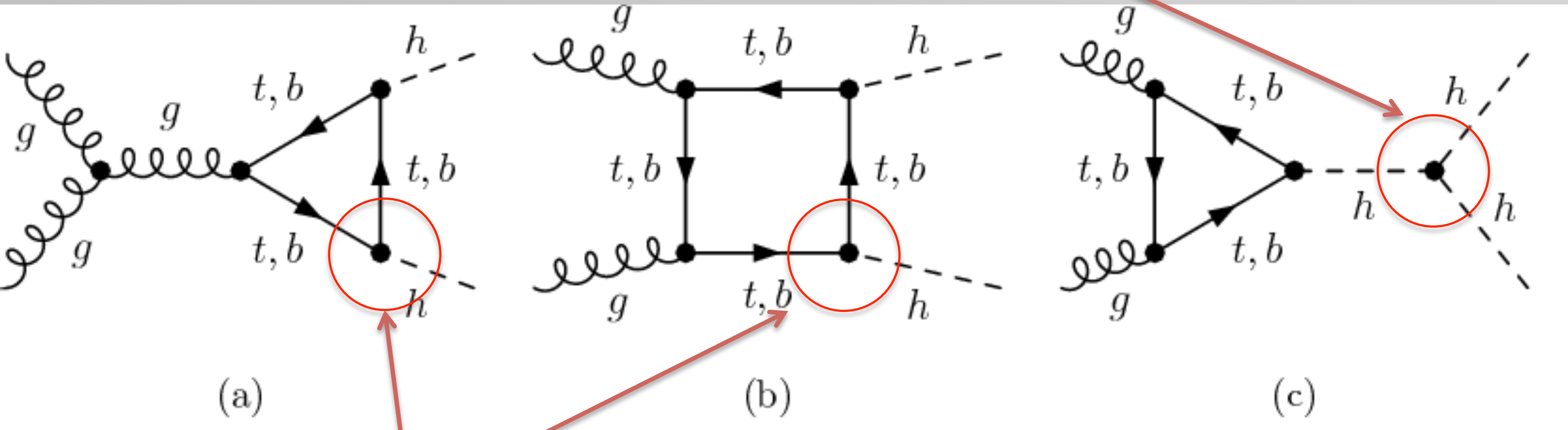
- Low cross section processes (eg. Higgs Production) need high integrated luminosity for statistical power.
- As (LHC) machine operation matures, difficult task of increasing luminosity becomes possible.
- Expensive dipole magnets don't need replacing.
- Fully exploit potential of LHC without changing magnets.

High Luminosity Upgrade
HL-LHC



Higgs Self-Coupling

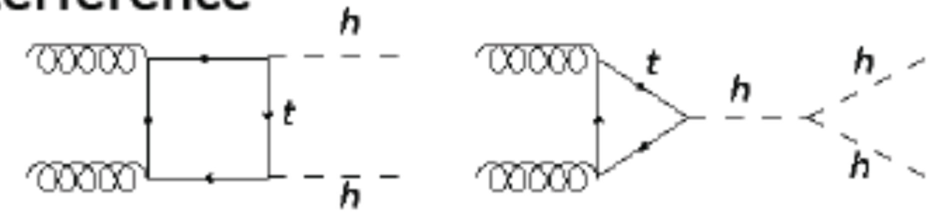
Critical that the SM Higgs self-interacts – but very hard experimentally.



Need to ttH coupling – different processes interfere.

Di-Higgs Production

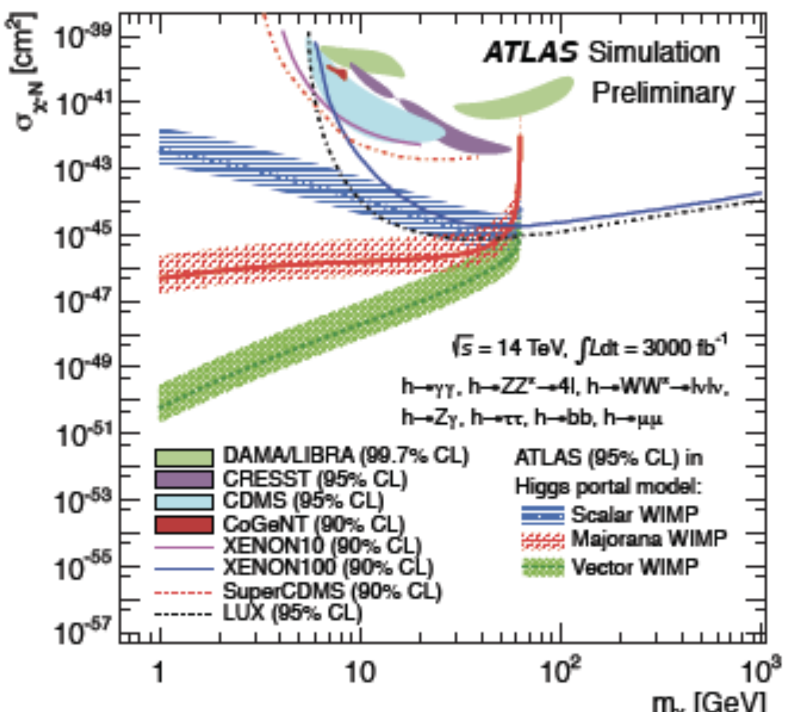
- One of the exciting prospects of HL-LHC
  - Cross section at $\sqrt{s}$=14 TeV is 40.2 fb [NNLO]
  - Challenging measurement
- Destructive interference



- Final states shown today
  - $bb\gamma\gamma$ [320 expected events at HL-LHC, 3000fb^{-1}]
    - But relatively clean signature
  - bbWW [30000 expected events at HL-LHC, 3000fb^{-1}]
    - But large backgrounds
- bbbb and $bb\tau\tau$ final states under consideration

Higgs portal to Dark Matter

- BR of Higgs decays to invisible final states
  - ATLAS: $BR_{inv} < 0.13$ (0.09 w/out theory uncertainties) at $3000 fb^{-1}$
  - CMS: $BR_{inv} < 0.11$ (0.07 in Scenario 2) at $3000 fb^{-1}$
- The coupling of WIMP to SM Higgs taken as the free parameter
- Translate limit on BR to the coupling of Higgs to WIMP



ATL-PHYS-PUB-2014-017

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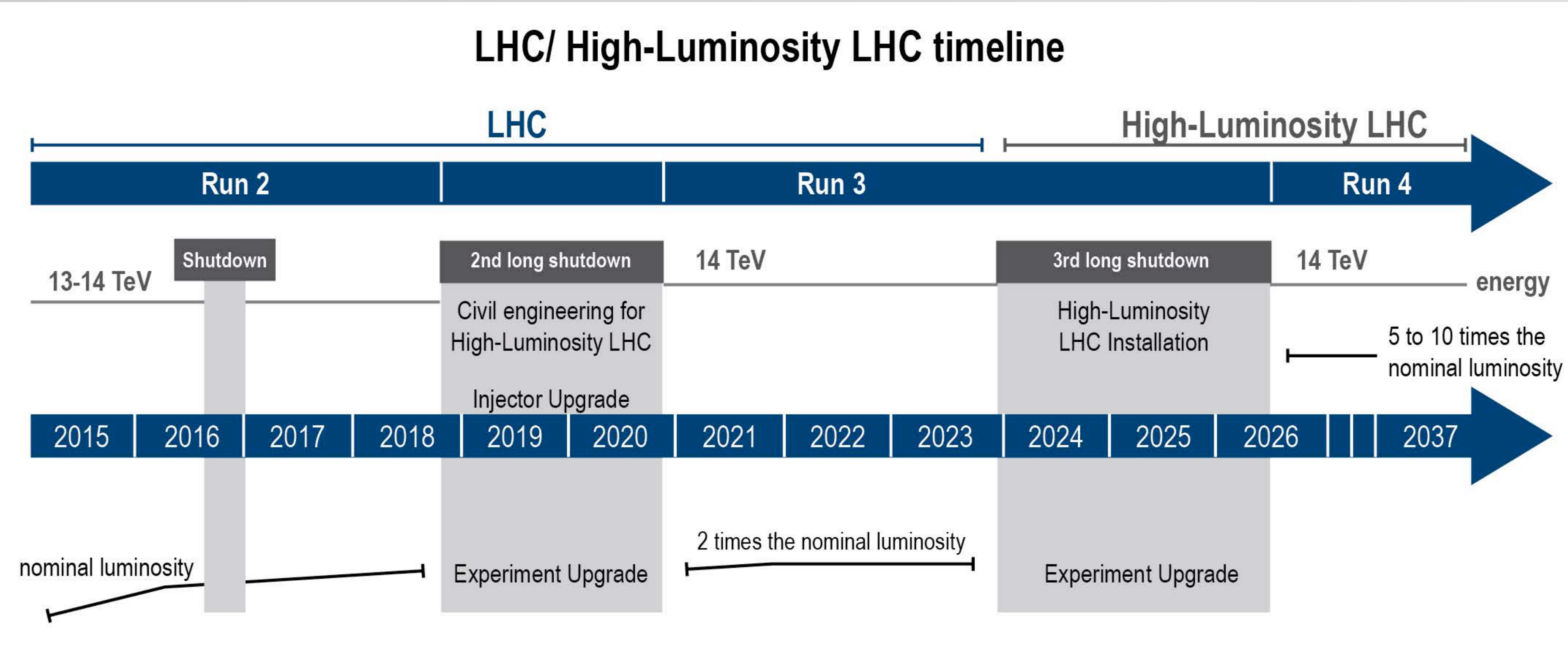
12

The LHC timeline

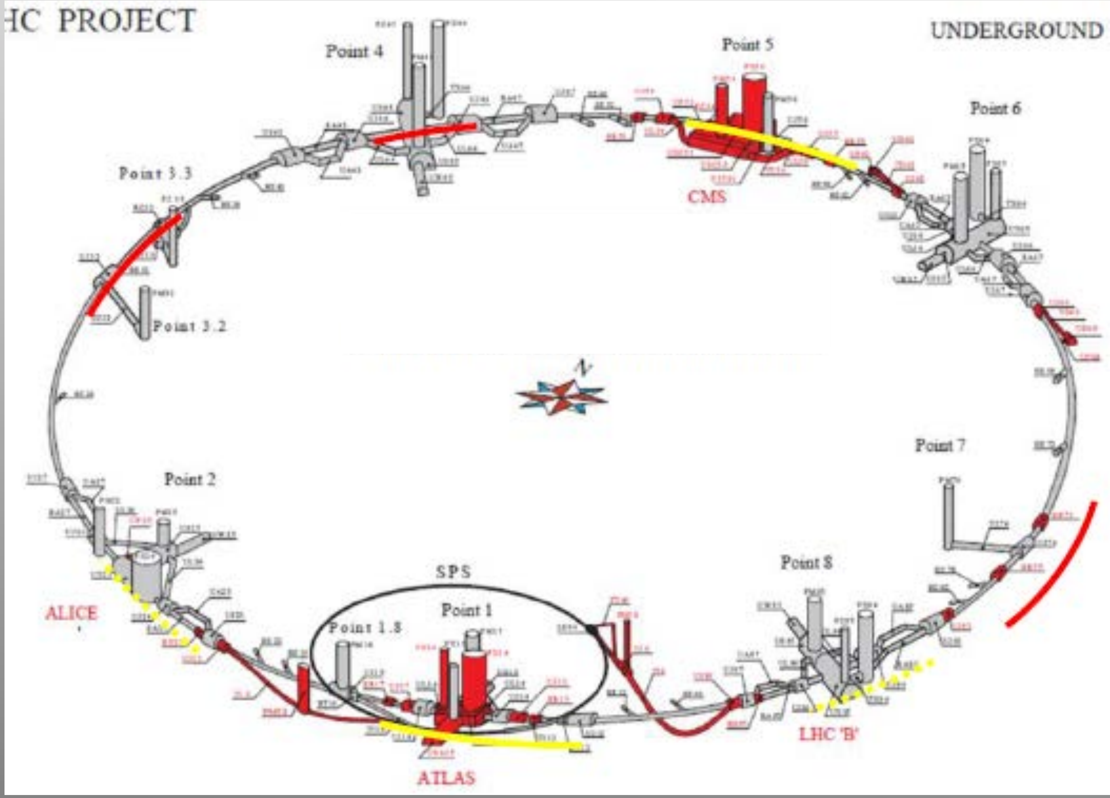


$L=1.6\times10^{34}$
Pile-up~30-45

$L=2\text{-}3\times10^{34}$
Pile-up~50-80

$L=5\times10^{34}$
Pile-up~ 130-200

The HL-LHC Project

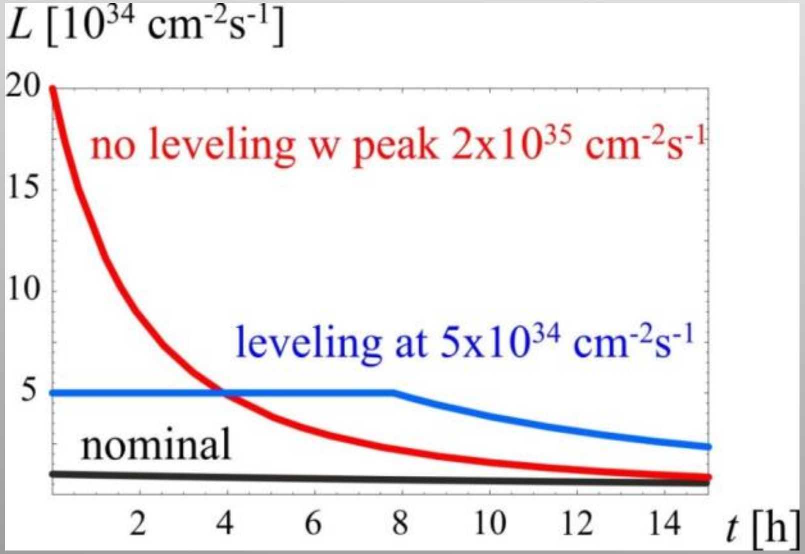


- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Major intervention on more than 1.2 km of the LHC

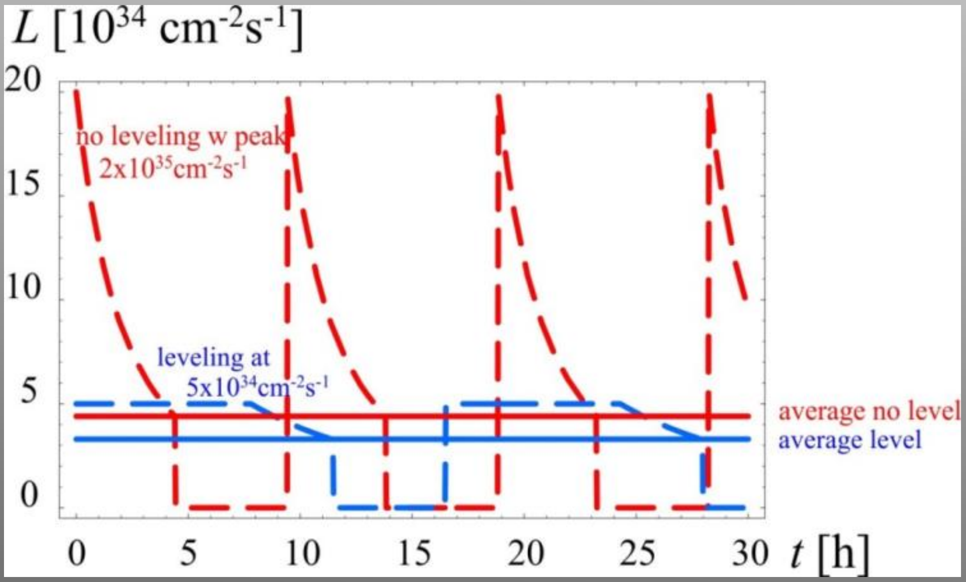
Project leadership: L. Rossi and O. Brüning

Luminosity Levelling, a key to success



- High peak luminosity
- Minimize pile-up in experiments and provide "constant" luminosity

- Obtain about 3 - 4 fb^{-1}/day (40% stable beams)
- About 250 to 300 fb^{-1}/year

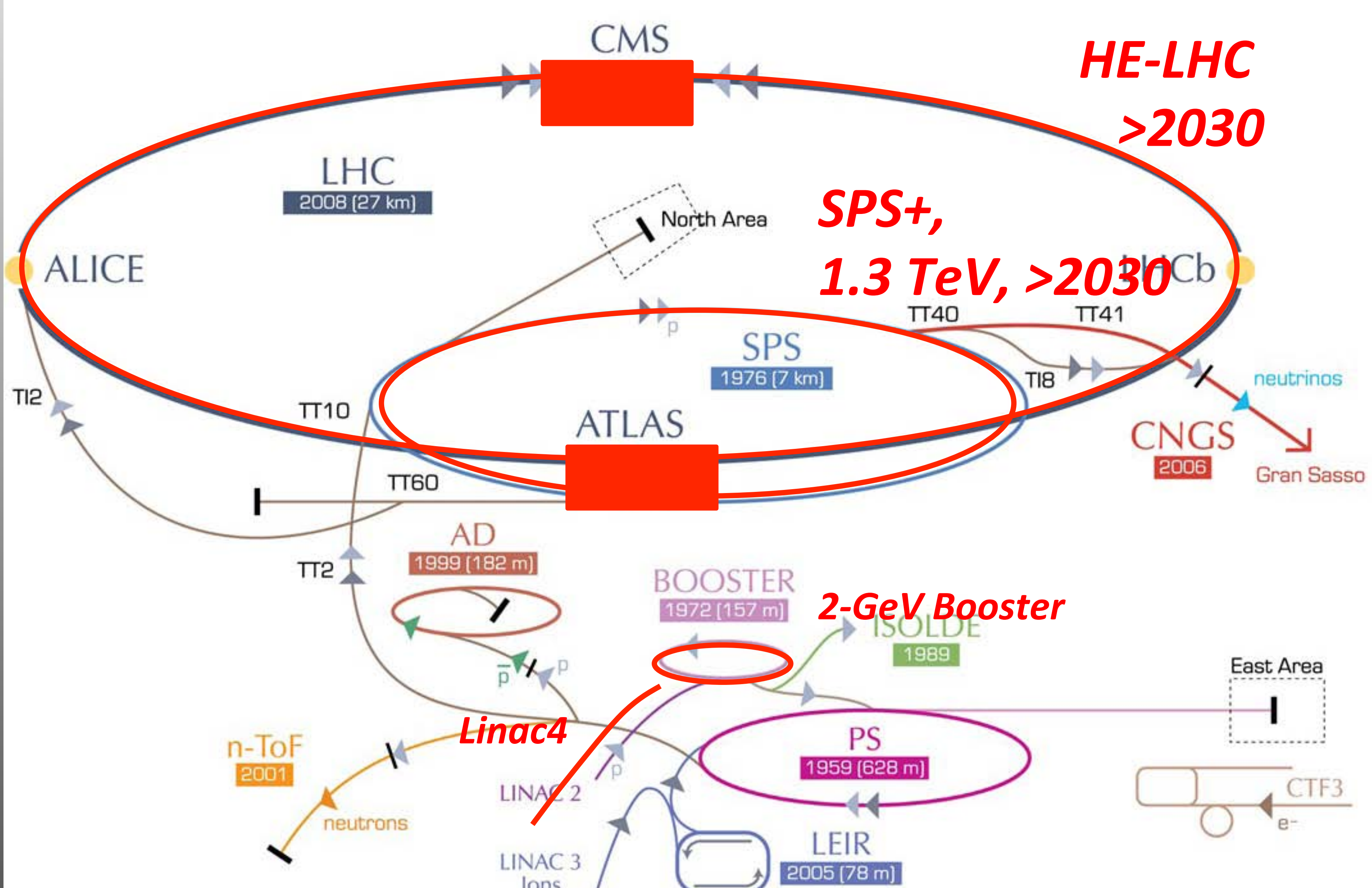


The detectors challenge

In order to exploit the LHC potential, experiments have to maintain full sensitivity for discovery, while keeping their capabilities to perform precision measurements at low p_T, in the presence of:

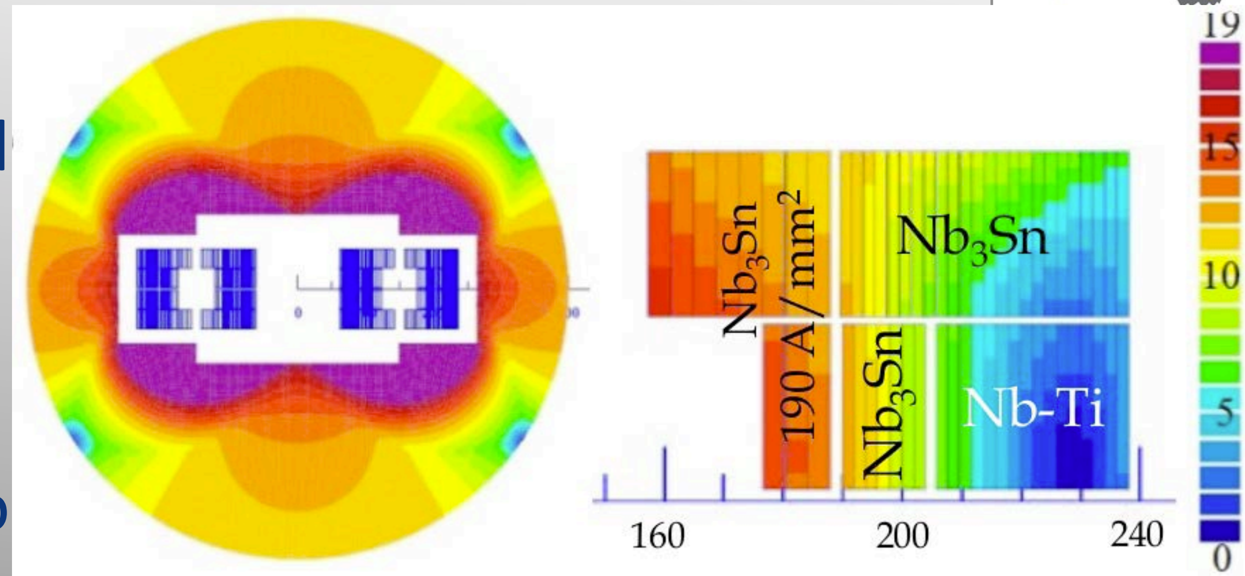
- Pileup
  - *<PU> ≈ 50 events per crossing by LS2*
  - *<PU> ≈ 60 events per crossing by LS3*
  - *<PU> ≈ 140 events per crossing by HL-LHC*
- Radiation damage
  - *Requires work to maintain calibration*
  - *Limits performance-lifetime of the detectors*
    - Light loss (calorimeters)
    - Increased leakage current (silicon detectors)

HE-LHC – LHC modifications



HE-LHC Dipoles?

- Arc dipoles are the main cost and parameter driver
- Baseline is Nb_3Sn at 16T
- HTS at 20T also to be studied as alternative



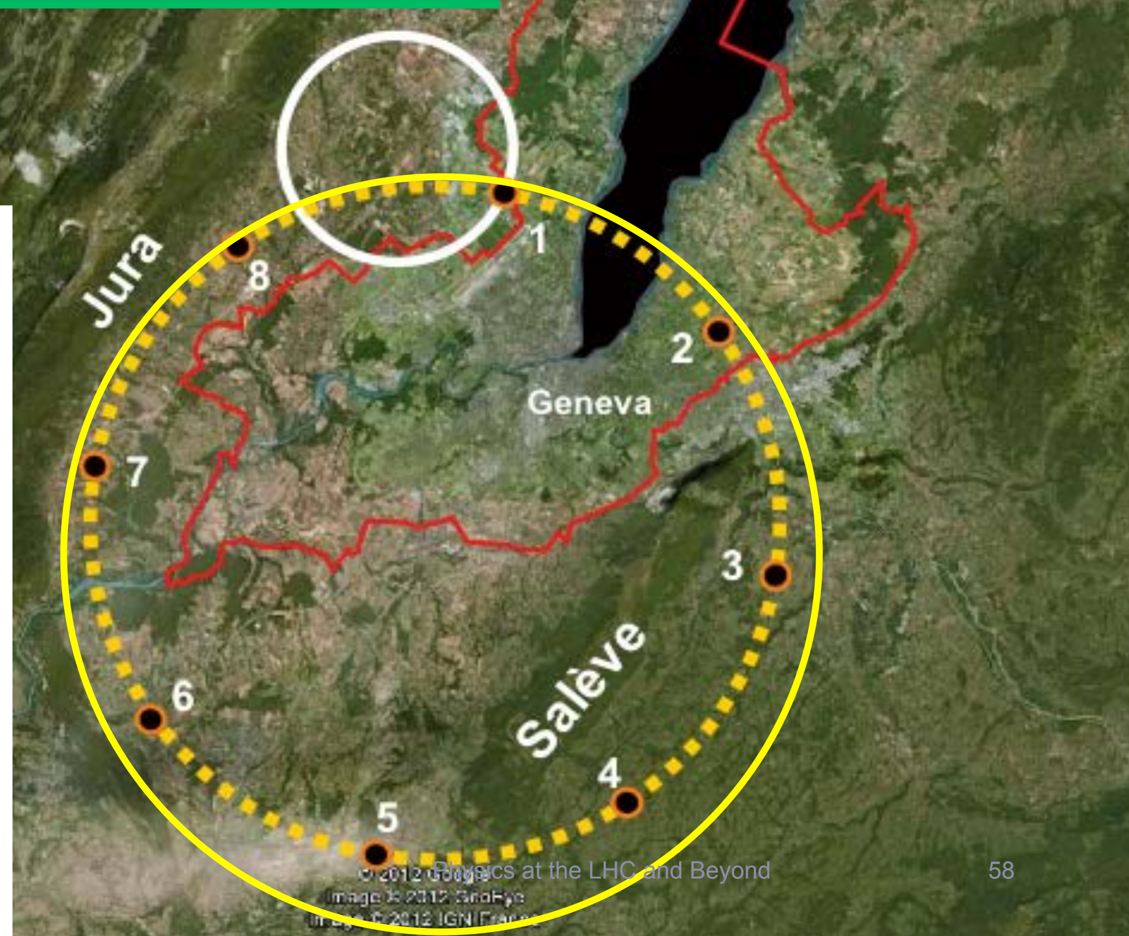
Coil sketch of a 15 T magnet with grading, E. Todesco

- Field level is a challenge but many additional questions:
- Field quality, aperture needs, …
- Different design choices (e.g. slanted solenoids) should be explored
- Goal is to develop prototypes in all regions

80-100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements

with possibility of e+-e- (TLEP) and p-e (VLHeC)

Conceptual Design Report and cost review for the next ESU *(≥2018)*

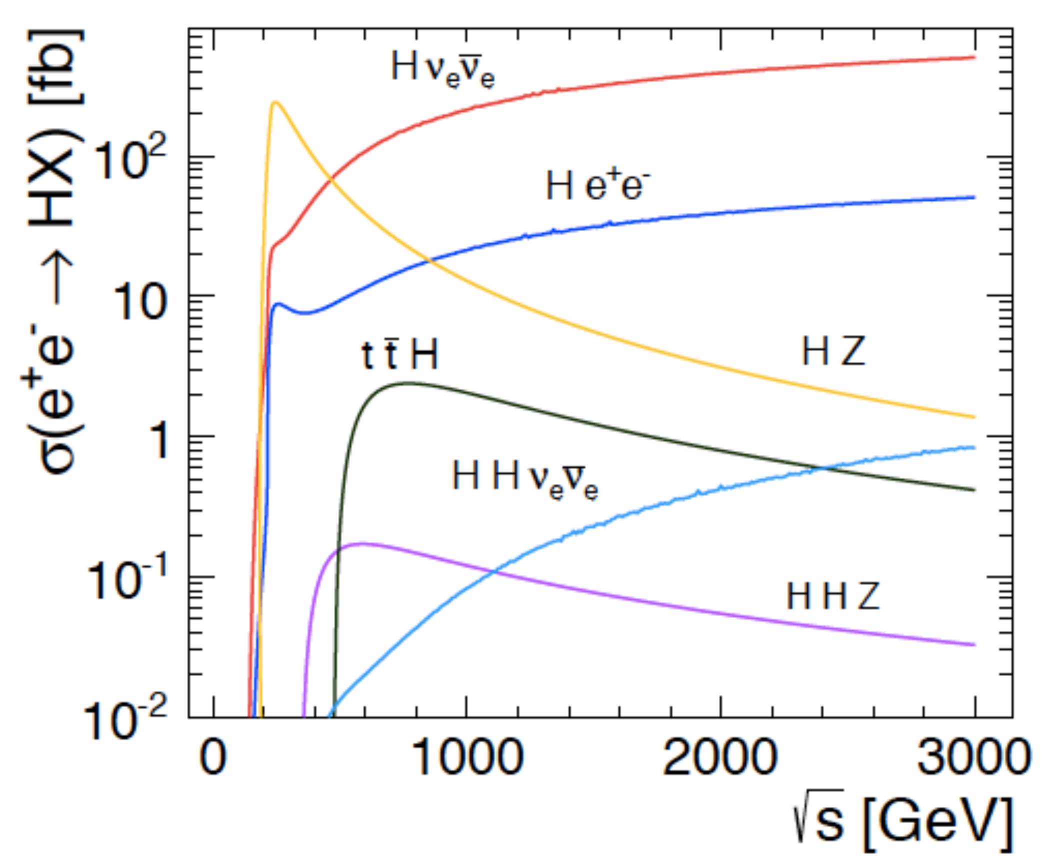


FCC Design Study Kick-off Meeting: 12-14. February 2014 in Geneva

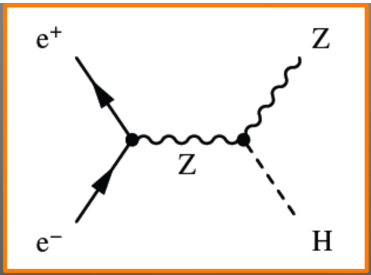
Establishing international collaborations

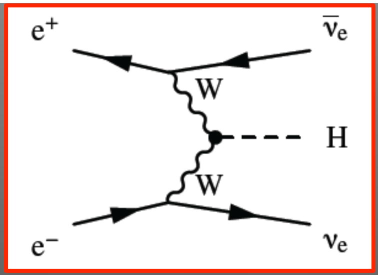
- ***Set-up study groups and committees***

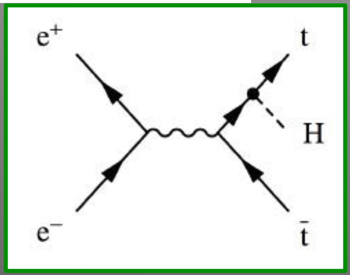
Higgs physics in e+e- collisions

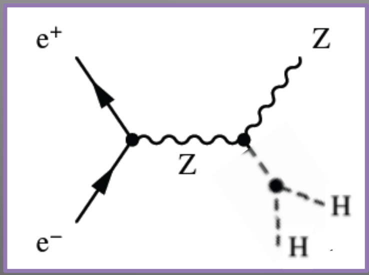


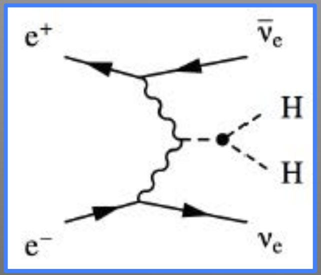
- **Precision Higgs measurements**
- Model-independent
  - Higgs couplings
  - Higgs mass
- Large energy span of linear colliders allows to collect a maximum of information:
  - ILC: 500 GeV (1 TeV)
  - CLIC: ~350 GeV – 3 TeV











ILC (International Linear Collider) – Will it start soon in Japan?

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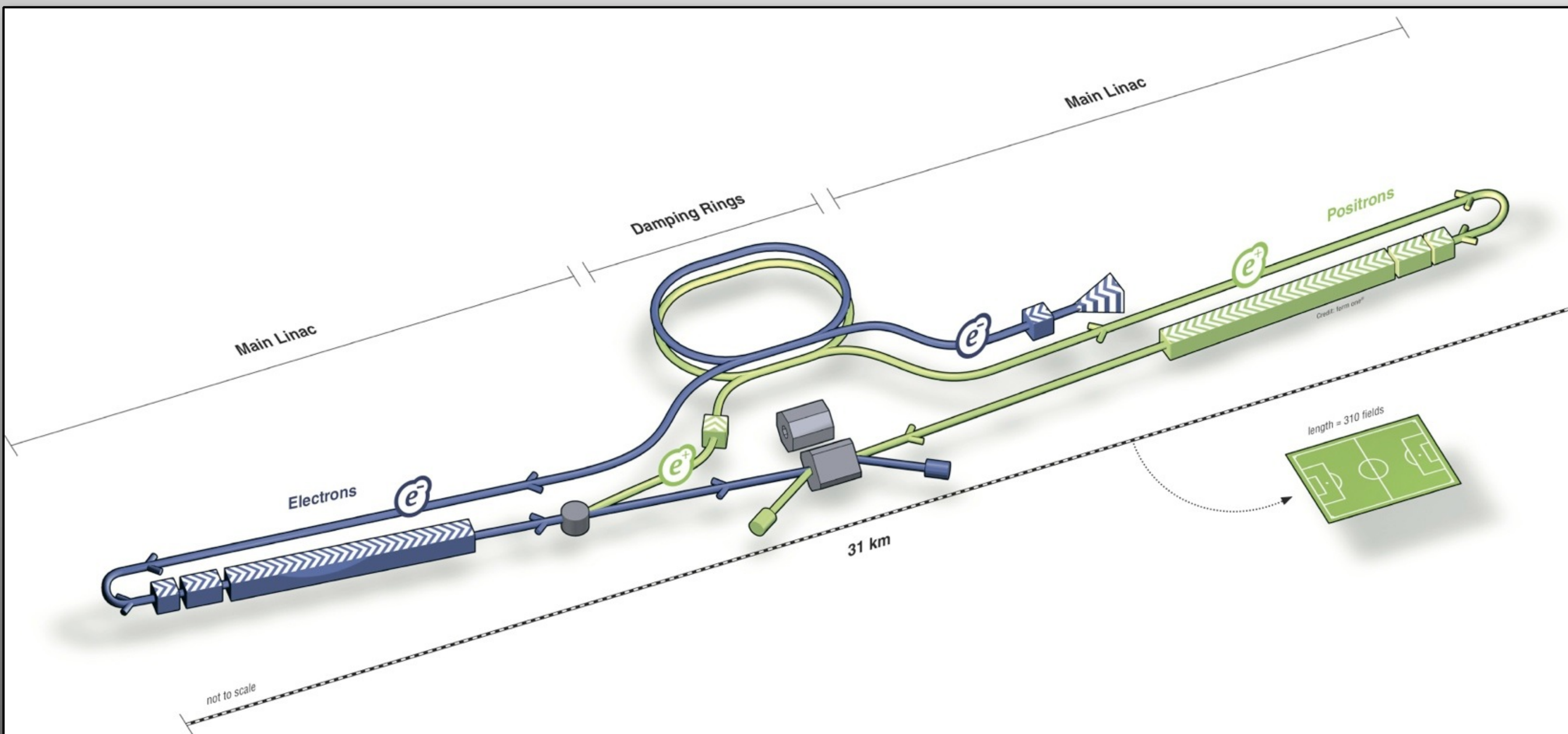
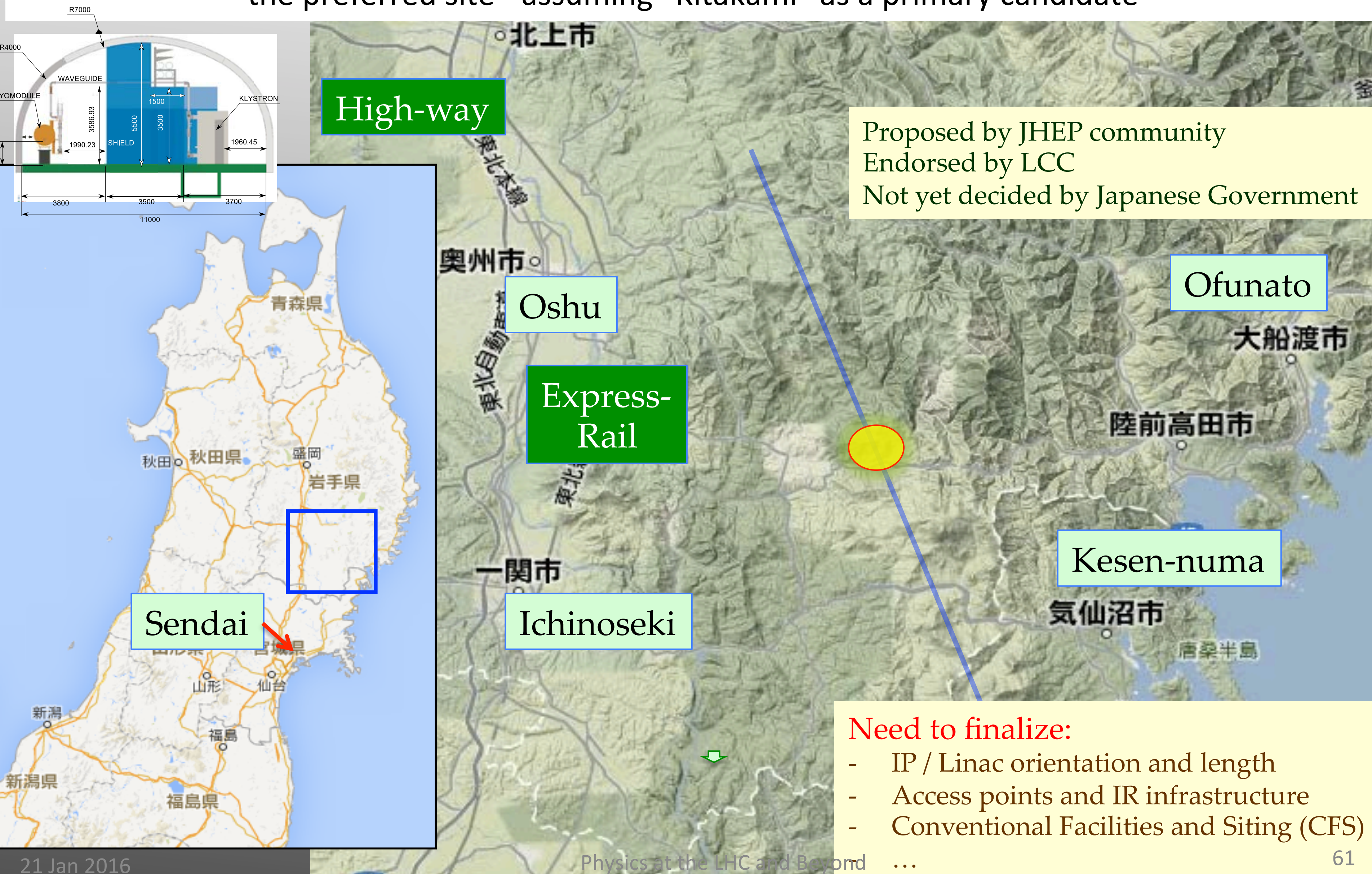


Site specific studies

Establish a site-specific Civil Engineering Design - map the (site independent) TDR baseline onto the preferred site - assuming "Kitakami" as a primary candidate



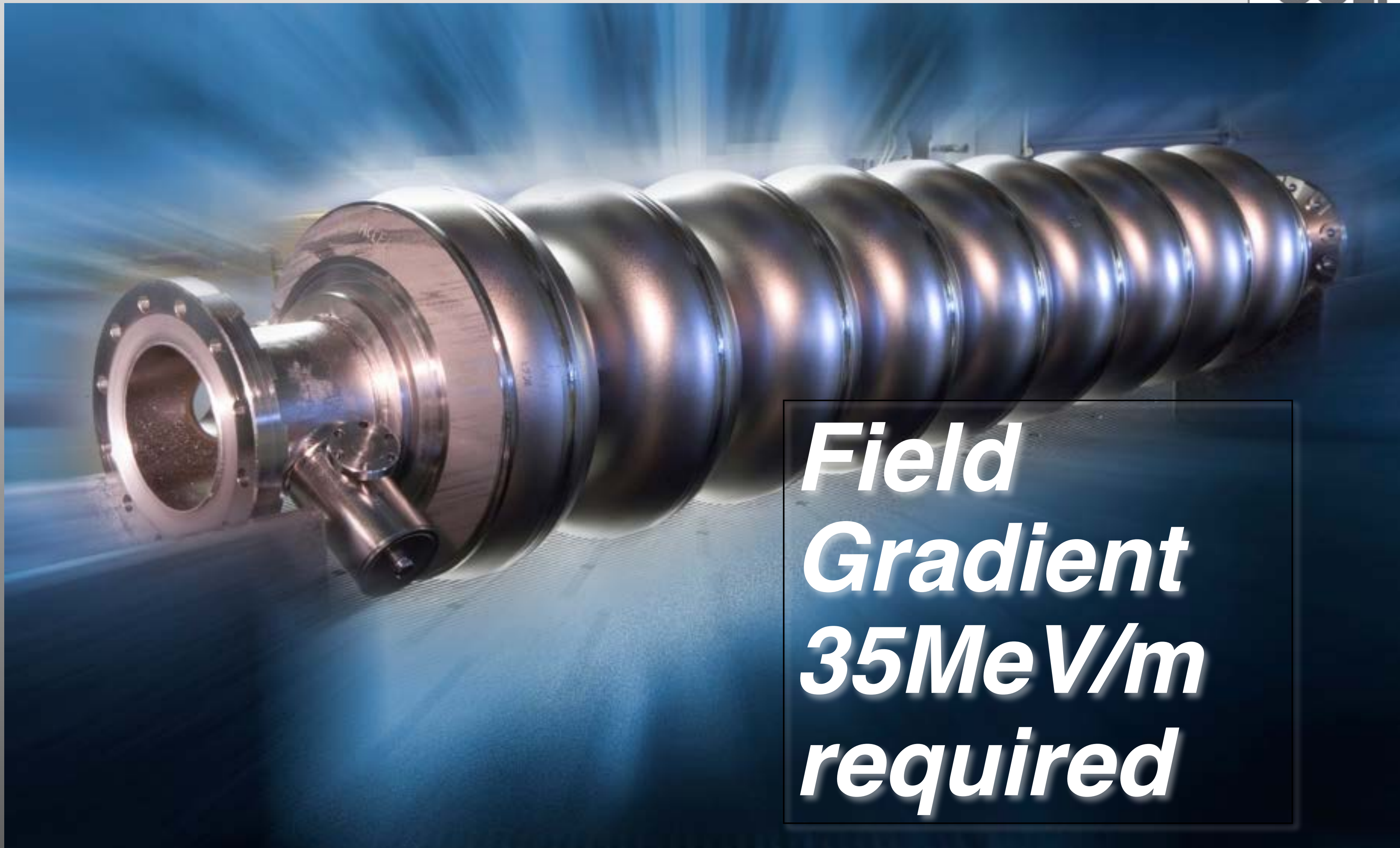
Proposed by JHEP community
Endorsed by LCC
Not yet decided by Japanese Government

Need to finalize:

- IP / Linac orientation and length
- Access points and IR infrastructure
- Conventional Facilities and Siting (CFS)

…

ILC – RF CAVITIES



FEL and advanced linacs with SCRF (Superconducting RF) modules

Largest deployment of this technology to date
- 100 cryomodules
- 800 cavities
- 17.5 GeV (pulsed)

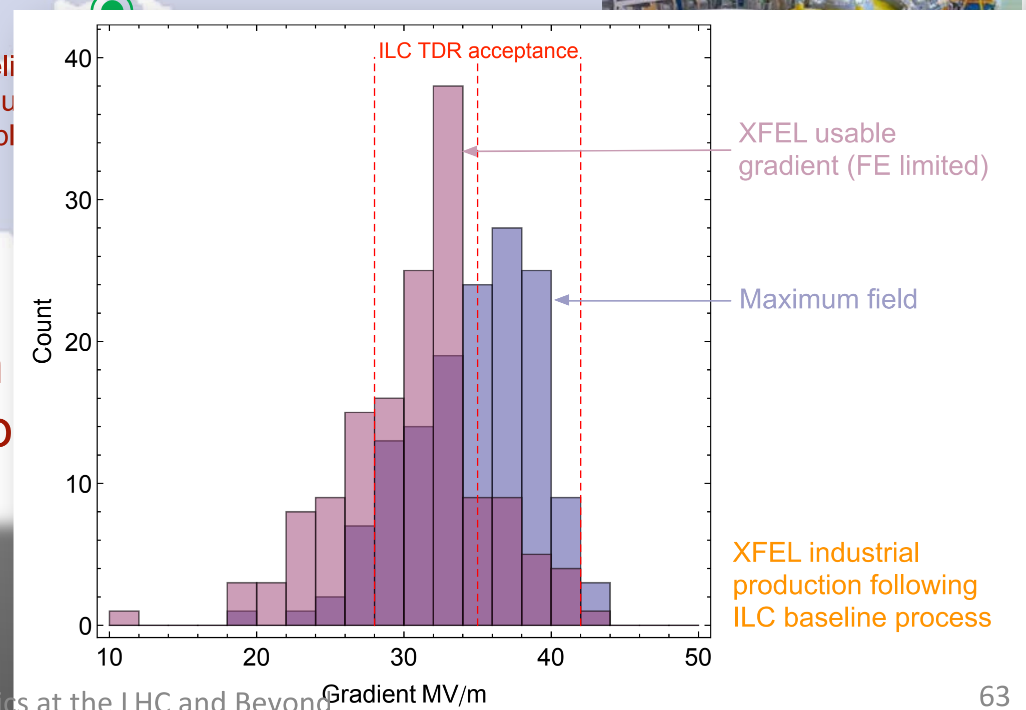
TRIUMF
FNAL/ANL
SLAC
Cornell
JLab
LAL
Saclay
CERN
DESY
INFN Milan
IHEP
PKU
KEK
Kitakami
proposed site

US infrastructure for
- 35 cryomodules
- 280 cavities

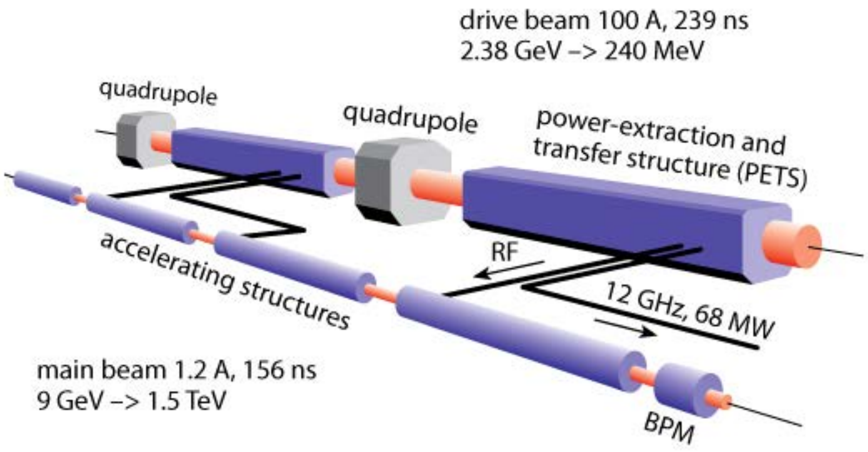
preli
resu
publ

roduction
of ILC co

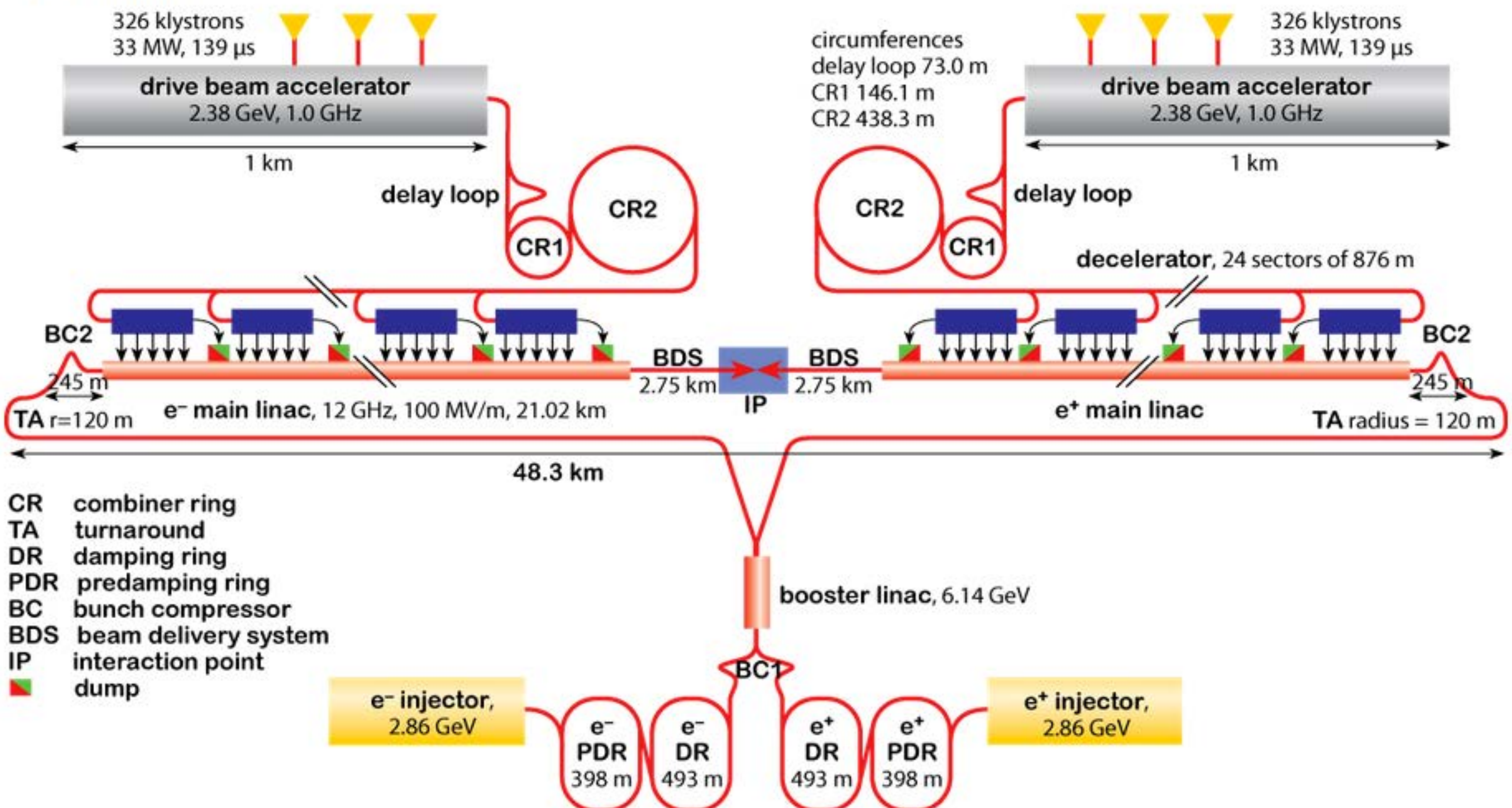
Year	Capable Industry
2006	2 ACCEL, ZANON
2011	4 RI, ZANON, AES, MHI,
2012	5 RI, ZANON, AES, MHI, Hitachi



CLIC module layout

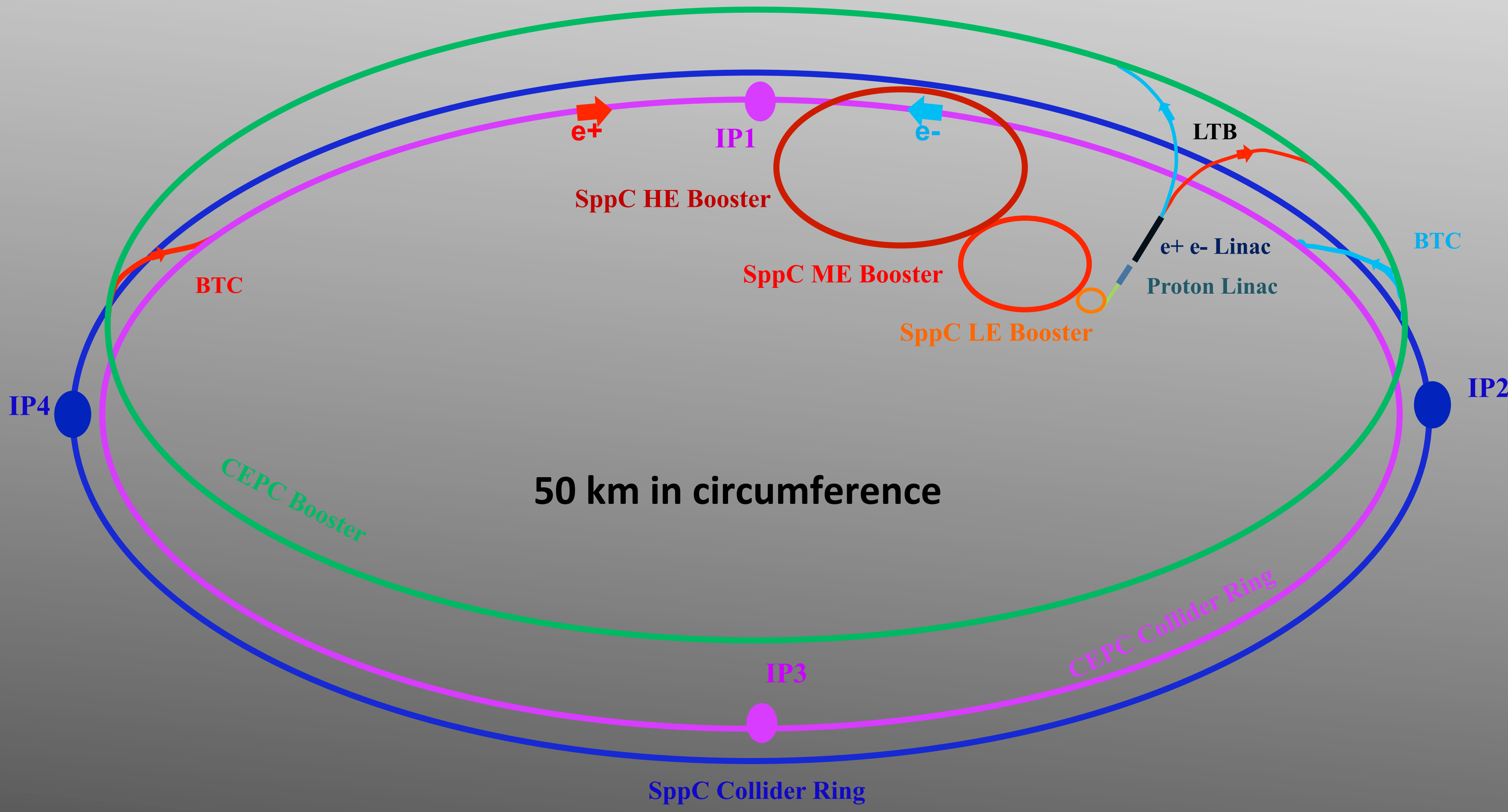


CLIC general layout



CEPC-SppC

CEPC is an 240 GeV Circular Electron Positron Collider, proposed to carry out high precision study on Higgs bosons, which can be upgraded to a 70 TeV or higher pp collider **SppC**, to study the new physics beyond the Standard Model.



CEPC – Site Investigation

A good example is 秦皇岛:

300 km from Beijing

3 hours by car; 1 hours by high speed train

Y. F. Wang

OUTLOOK

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- Higgs as Tool – detailed measurements to look for deviations from SM expectations
- Searches for Dark Matter production
- Increased Luminosity Underway – HL-HLC
- Electron-positron precision – ILC?, FCC?, CepC?
- Higher energy? HE-LHC?, FCC?, SppC