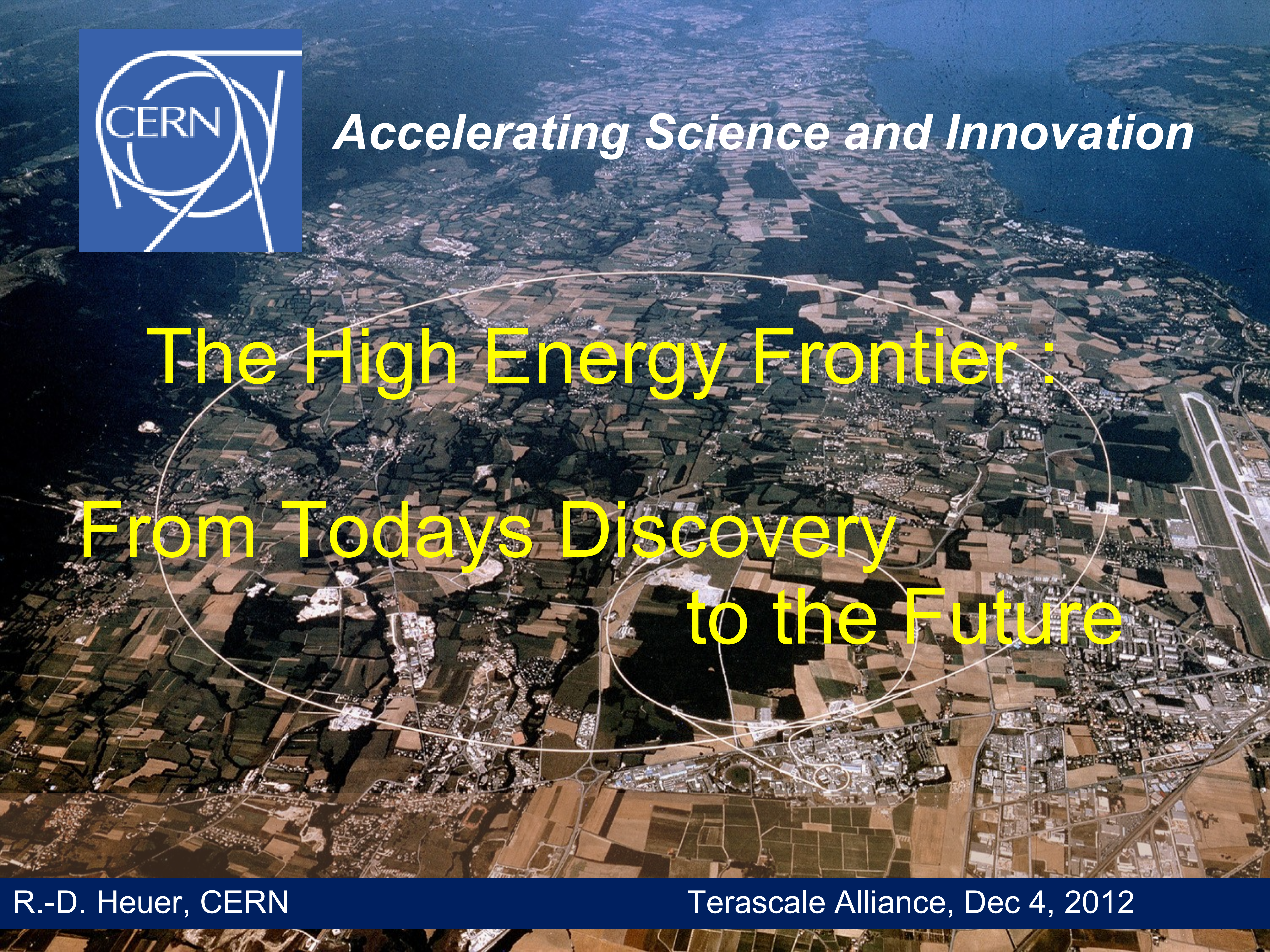


Accelerating Science and Innovation

The High Energy Frontier :

From Todays Discovery to the Future

R.-D. Heuer, CERN

Terascale Alliance, Dec 4, 2012

Past few decades

"Discovery" of Standard Model

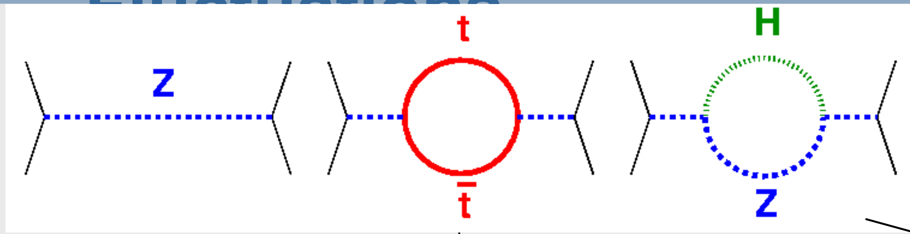
At the energy frontier through synergy of

hadron - hadron colliders (e.g. Tevatron)

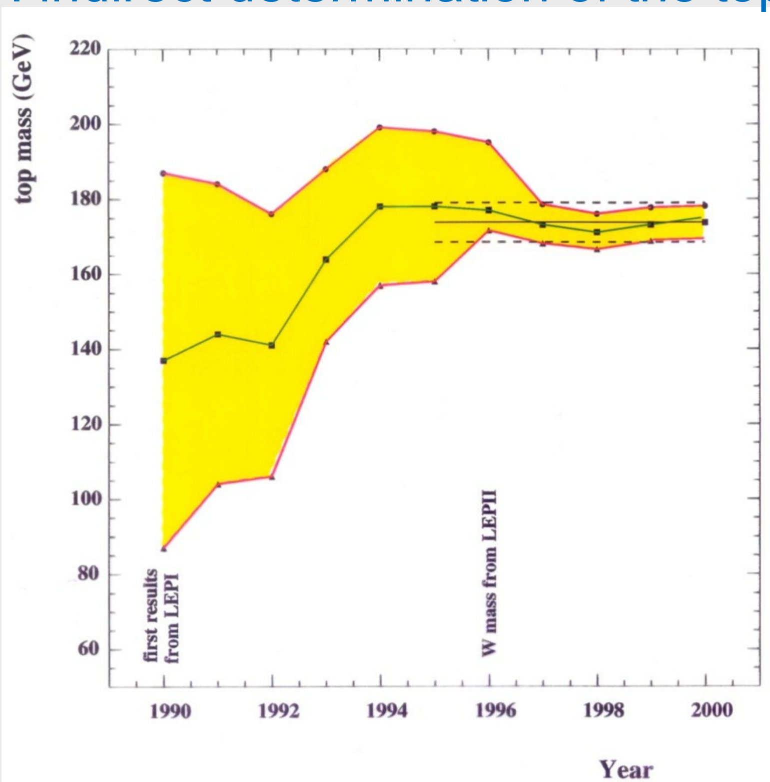
lepton - hadron colliders (HERA)

lepton - lepton colliders (e.g. LEP, SLC)

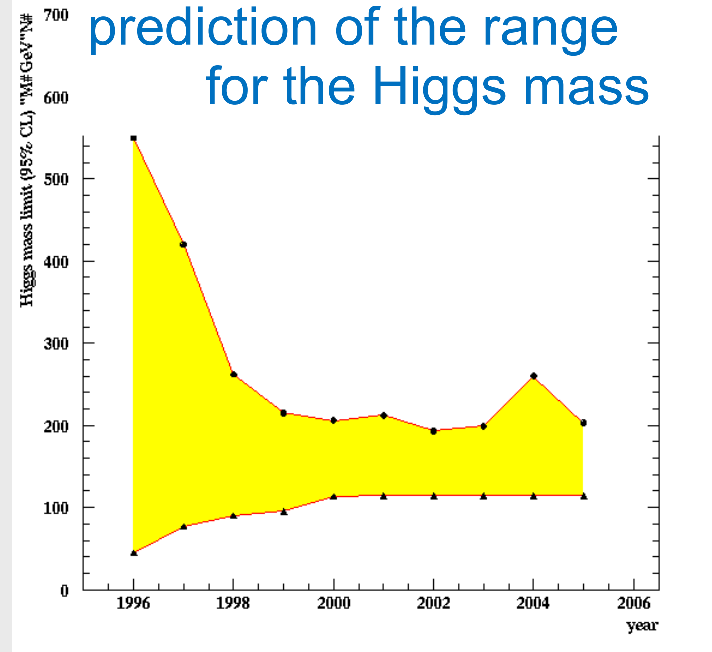
Test of the SM at the Level of Quantum Fluctuations



LEP: indirect determination of the top mass



prediction of the range for the Higgs mass



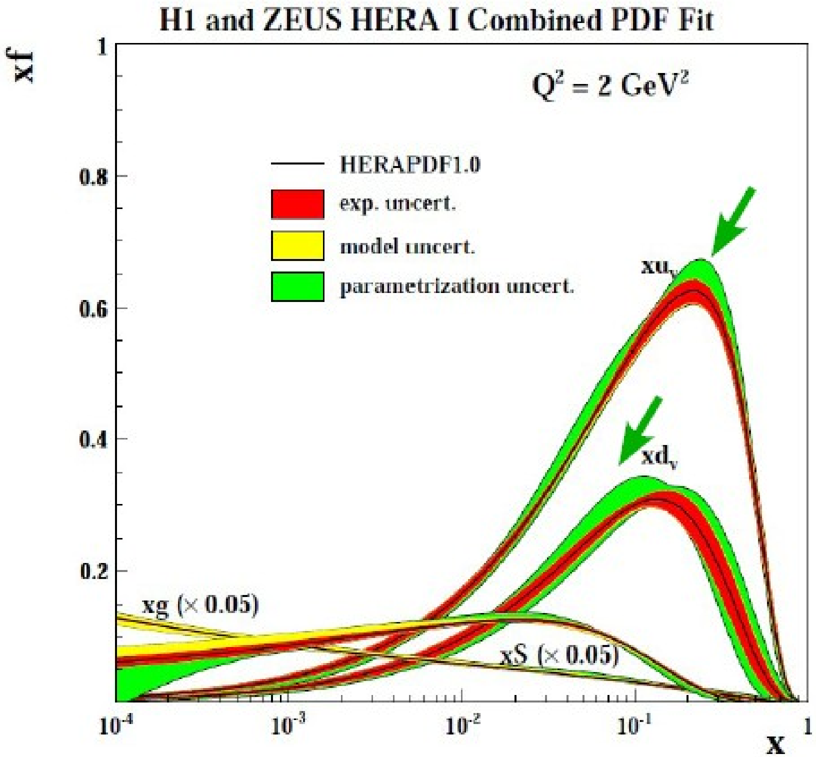
possible due to
- precision measurements
- known higher order electroweak corrections

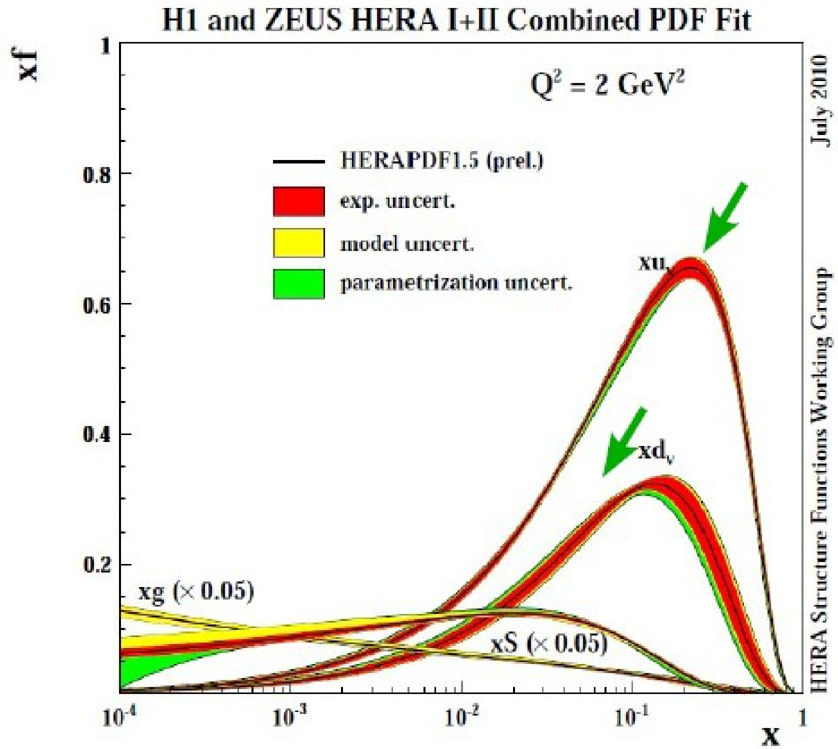
HERA: Impact on PDF

Fits to new combined HERA data: HERAPDF1.5

HERAPDF1.0

HERAPDF1.5





‘Today’

Exciting Times

At the energy frontier, the LHC brings us into unexplored territory:

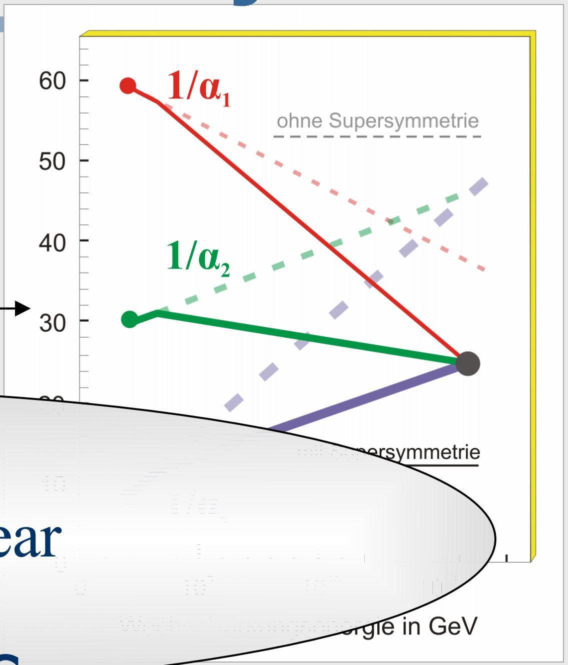
Excellent progress

Accelerator – Experiments – Grid Comp.

Key Questions of Particle Physics

origin of mass/matter or
origin of electroweak symmetry breaking

unification of forces



fundamental symmetry of forces and
matte

where is antimatter

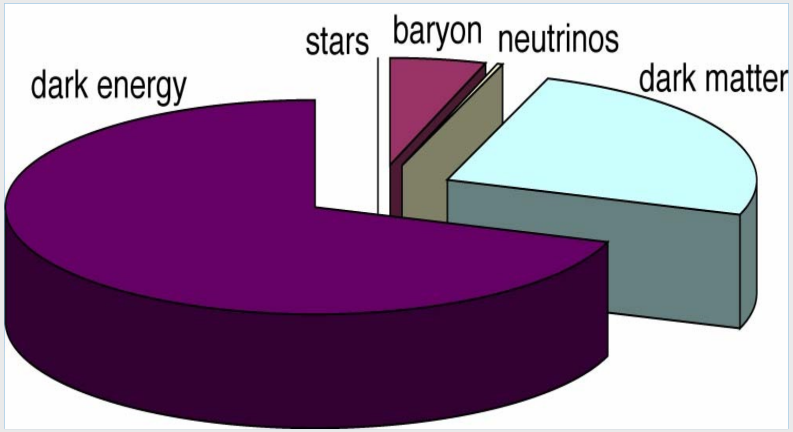
For most questions:
new particles should appear
at **TeV** scale or below
⇒ **territory of the LHC**

unification of quantum physics and
general relativity

number of space/time dimensions

what is dark matter

what is dark energy



Dark Matter

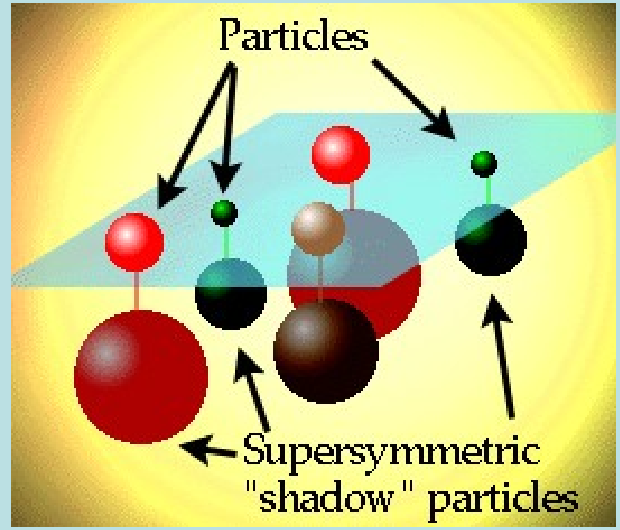
Astronomers & astrophysicists over the next two decades using powerful new telescopes will tell us how dark matter has shaped the stars and galaxies we see in the night sky.

Only particle accelerators can produce dark matter in the laboratory and understand exactly what it is.

Composed of a single kind of particle
or
more rich and varied (as the visible world)?

LHC may be the perfect machine to study dark matter.

Supersymmetry



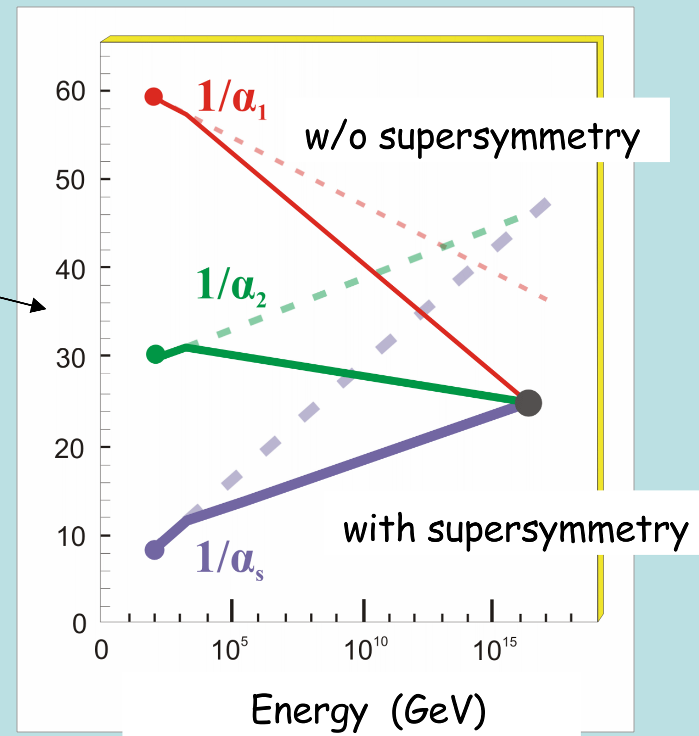
- unifies matter with forces

  for each particle a supersymmetric partner (*sparticle*) of opposite statistics is introduced

- allows to unify strong and electroweak forces

  $\sin 2\theta WSUSY = 0.2335(17)$

  $\sin 2\theta Wexp = 0.2315(2)$

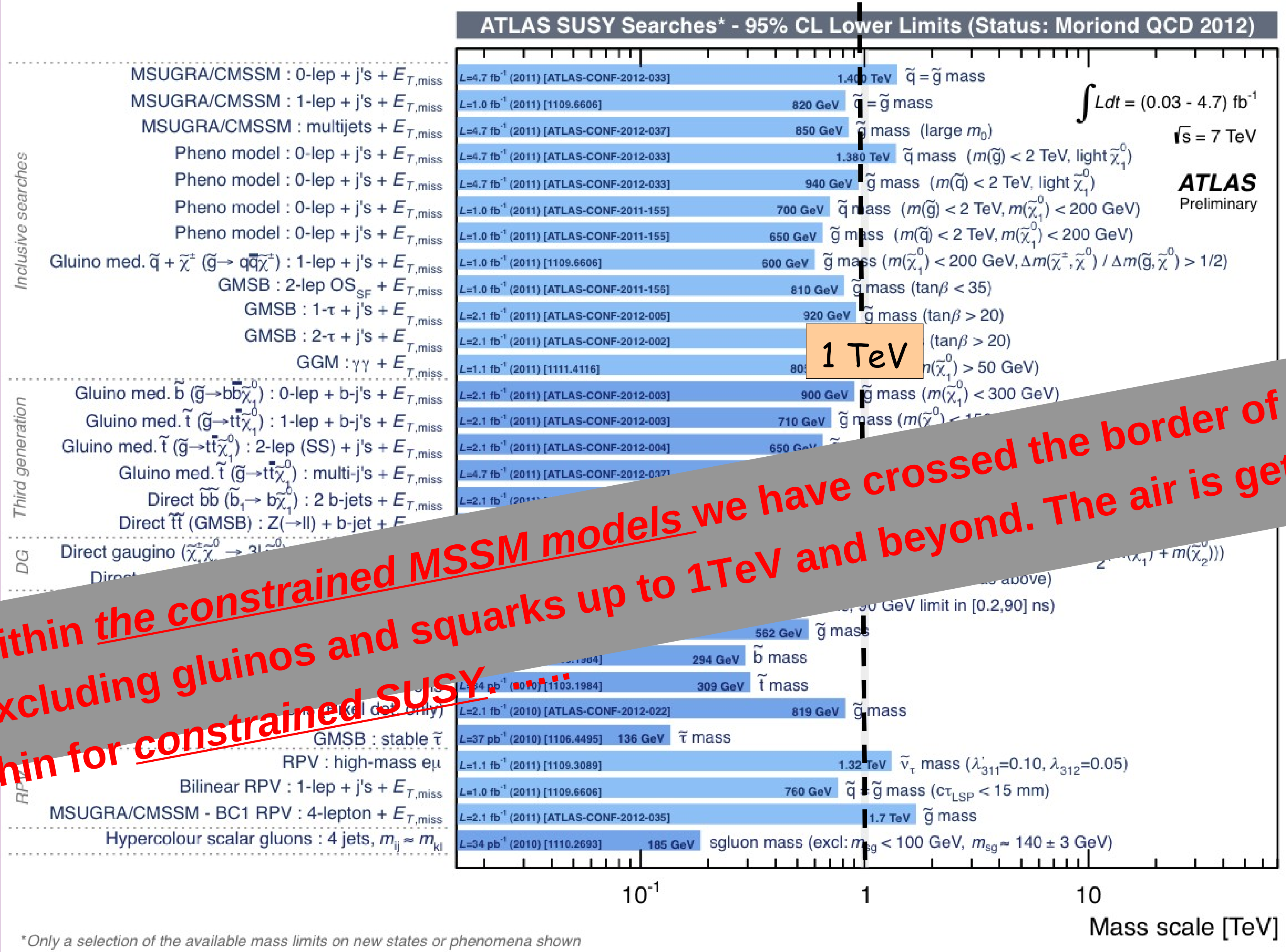


- provides link to string theories

- provides Dark Matter candidate

  (stable Lightest Supersymmetric Particle)

Main ATLAS results on SUSY searches



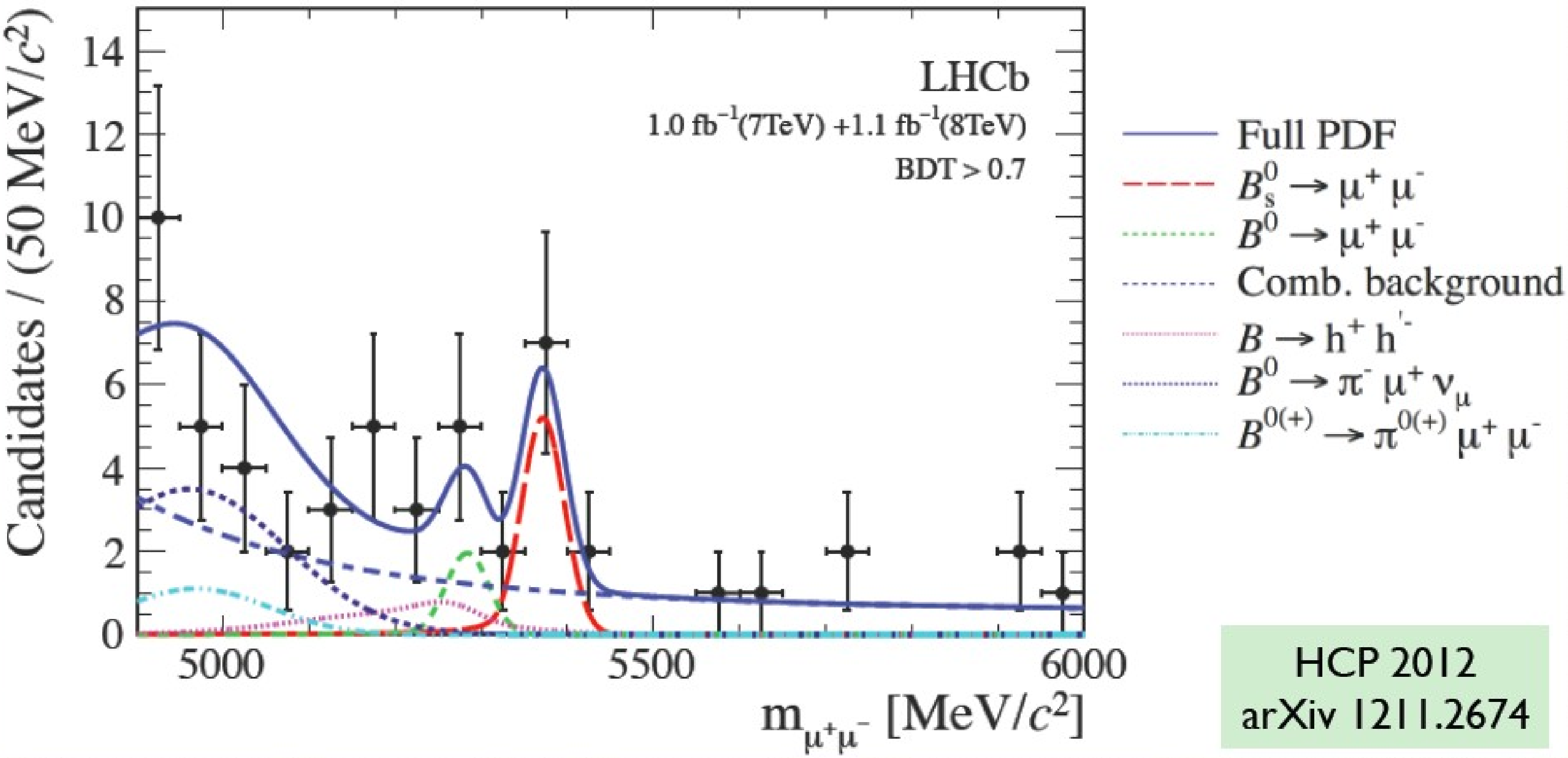
Within the constrained MSSM models we have crossed the border of excluding gluinos and squarks up to 1TeV and beyond. The air is getting thin for constrained SUSY. .....

The search for $B_{s\,(d)} \rightarrow \mu\,\mu$

Branching fractions extracted from unbinned maximum likelihood fit to the mass spectra in 8 (7 TeV) and 7 (8 TeV) bins in BDT

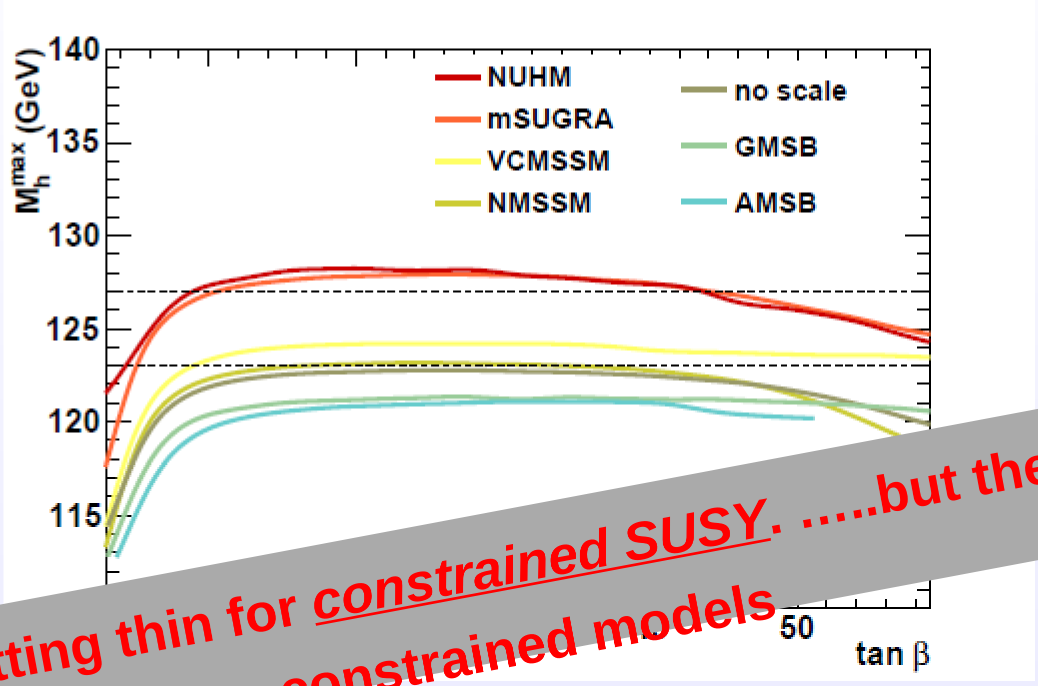
$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$

SM: $BR(B_s \rightarrow \mu\,\mu) = 3.5 \pm 0.2\ 10^{-9}$



HCP 2012
arXiv 1211.2674

SUSY requires a low mass Higgs Boson with severe constraints on the max. mass value



Mahmoudi

The air is getting thin for <u>constrained SUSY</u>. ….but there is still much room in less constrained models

A. Arbey, M. Battaglia, A. Djouadi, F.M., J. Quevillon, Phys.Lett. B708 (2012) 162

Model	AMSB	GMSB	mSUGRA	no-scale	cNMSSM	VCMSSM	NUHM
M_h^{max}	121.0	121.5	128.0	123.0	123.5	124.5	128.5

End

. . . potential for discovery of SUSY sizeable at all LHC energies

Higgs mass o

LHC results should allow,
together with dedicated dark matter searches,
first discoveries in the dark universe

around 73% of the Universe is in some mysterious "dark energy". It is evenly spread.

Challenge:
get first hints about the world of dark energy in the laboratory

The Higgs is Different!

All the matter particles are spin-1/2 fermions.
All the force carriers are spin-1 bosons.

Higgs particles are spin-0 bosons (scalars).
The Higgs is neither matter nor force.
The Higgs is just different.
This would be the first fundamental scalar ever discovered.

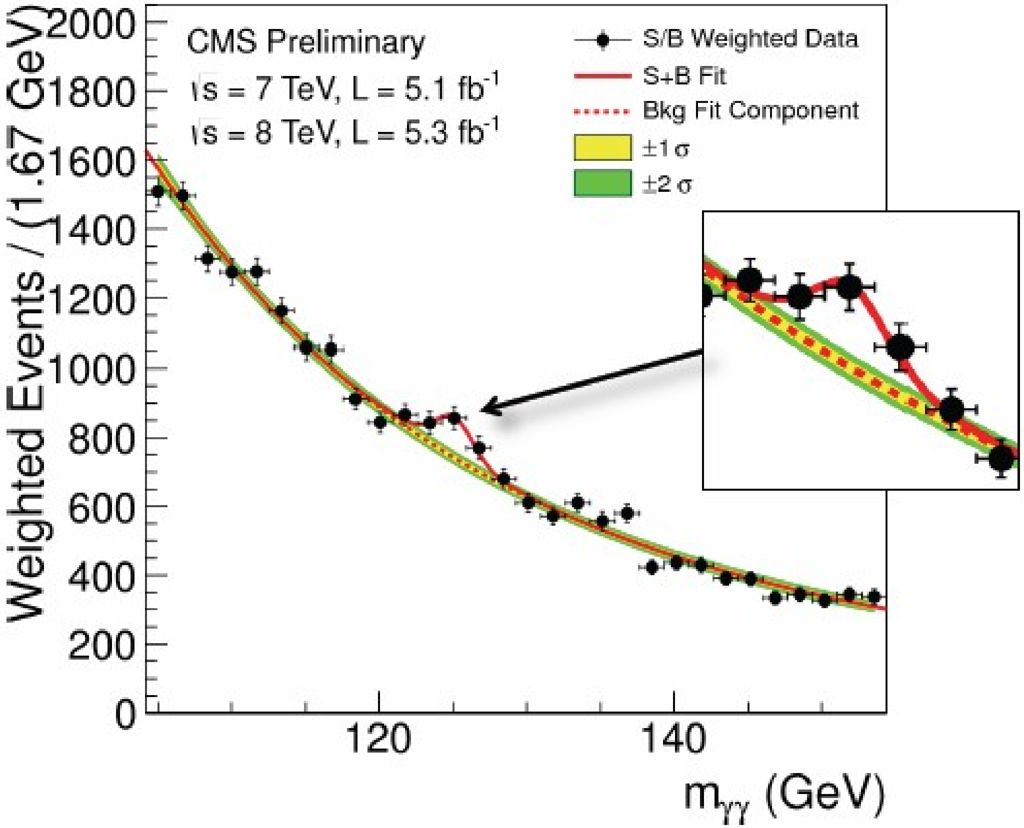
The Higgs field is thought to fill the entire universe.
Could it give some handle of dark energy (scalar field)?

Many modern theories predict other scalar particles like the Higgs.
Why, after all, should the Higgs be the only one of its kind?

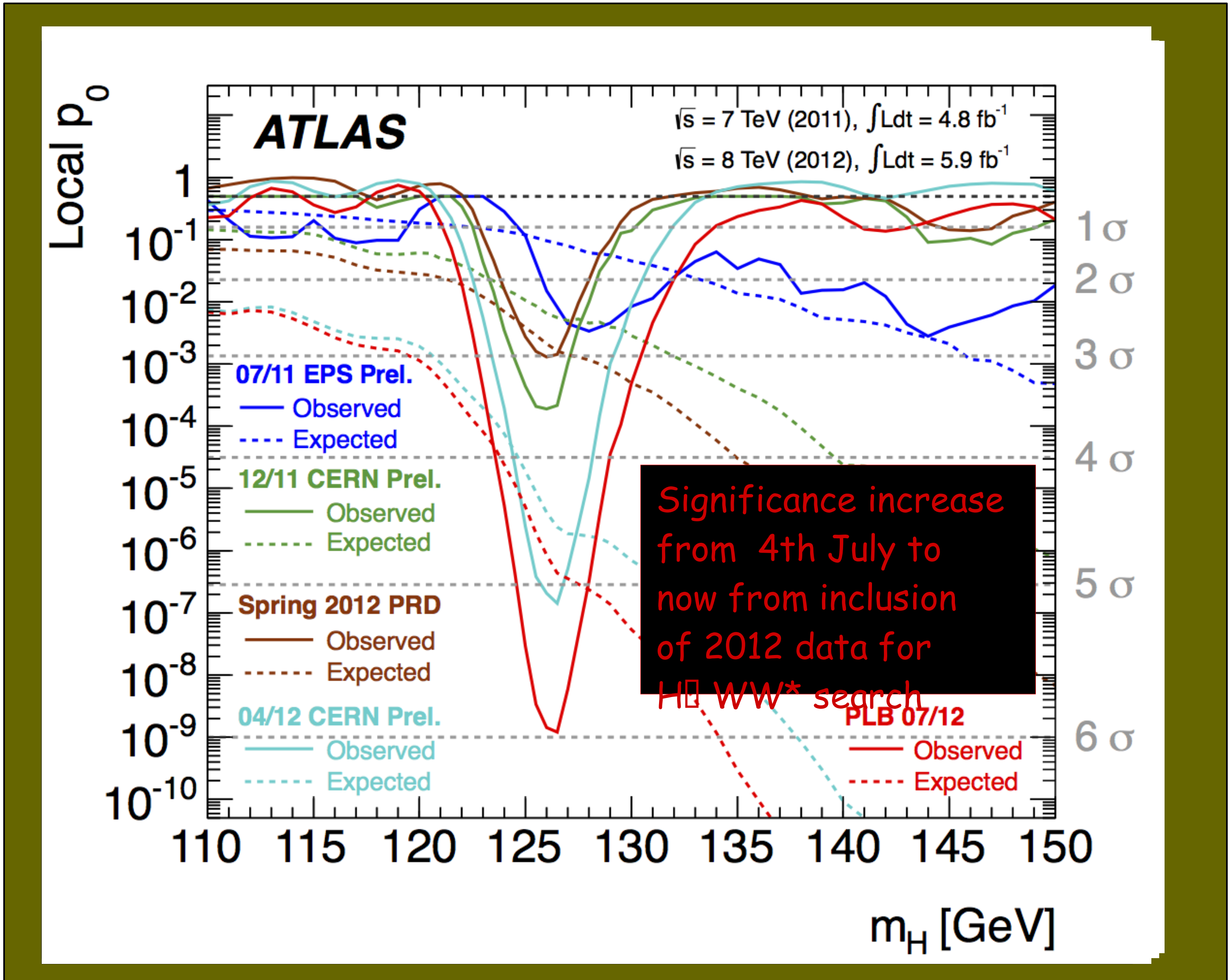
LHC can search for and study new scalars with precision.

S/B Weighted Mass Distribution

- Sum of mass distributions for each event class, weighted by S/B
  - B is integral of background model over a constant signal fraction interval

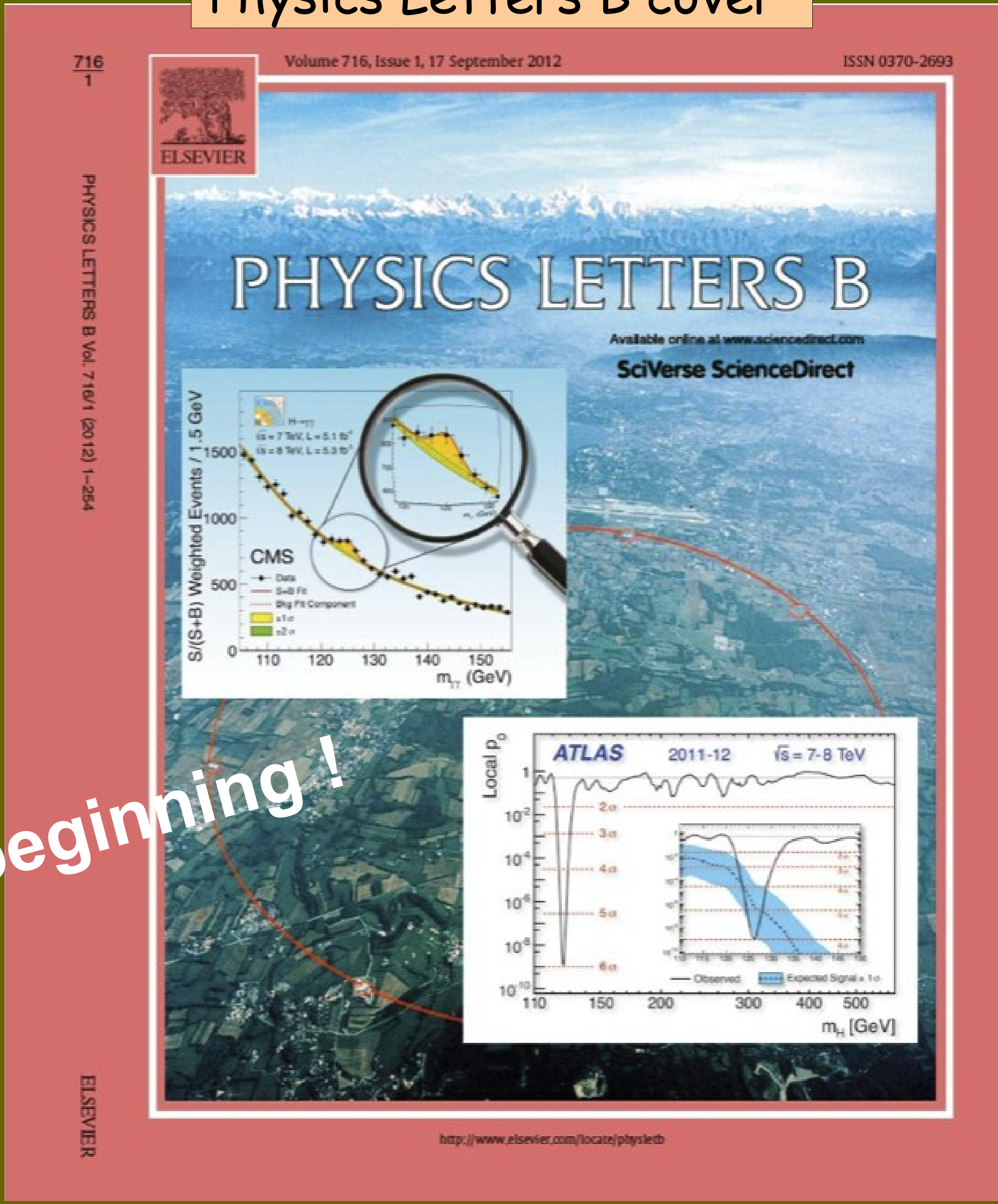


Evolution of the excess with time



ATLAS and CMS “Higgs discovery” papers published side by side in Phys. Lett. B716 (2012)

Physics Letters B cover



… but that’s only the beginning !
What’s next ?

… is it a scalar particle ?

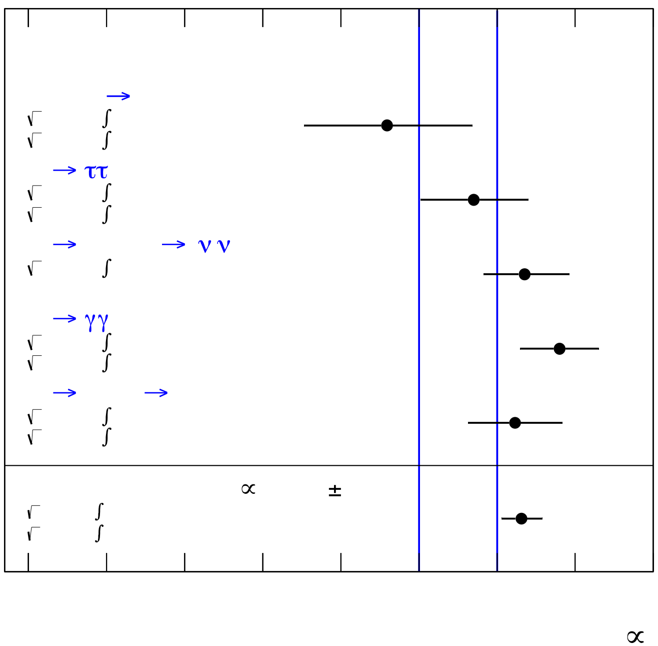
… is it *the* Higgs Boson?
or one of several?

… its properties could give information
on Dark Matter

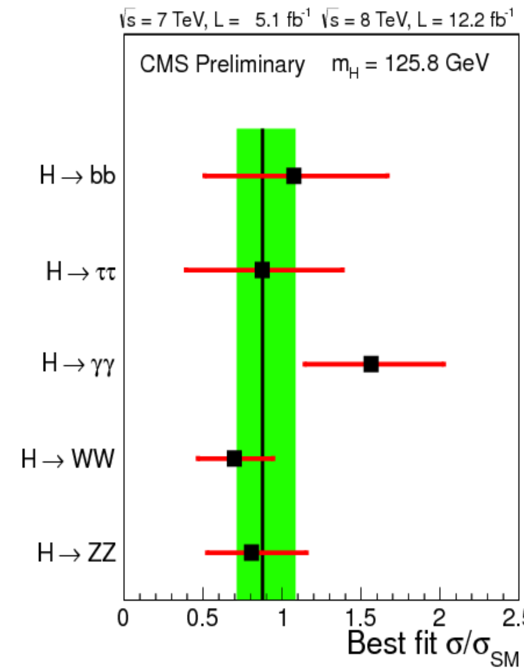
… its properties could give first hints
on Dark Energy

Signal strength $\mu = \sigma BR/\sigma BRSM$ *new* HCP results

ATLAS
WW*, ττ, bb: 13fb-1 – 2012
γγ and ZZ* as PLB 4th July



CMS
ZZ*, WW*, ττ, bb: 12 fb-1 2012
γγ as PLB 4th July



ATLAS $\mu = 1.3 \pm 0.3$

CMS $\mu = 0.88 \pm 0.21$

Agreement with SM prediction (and CMS/ATLAS) Precision already ~20%

Mass Measurement

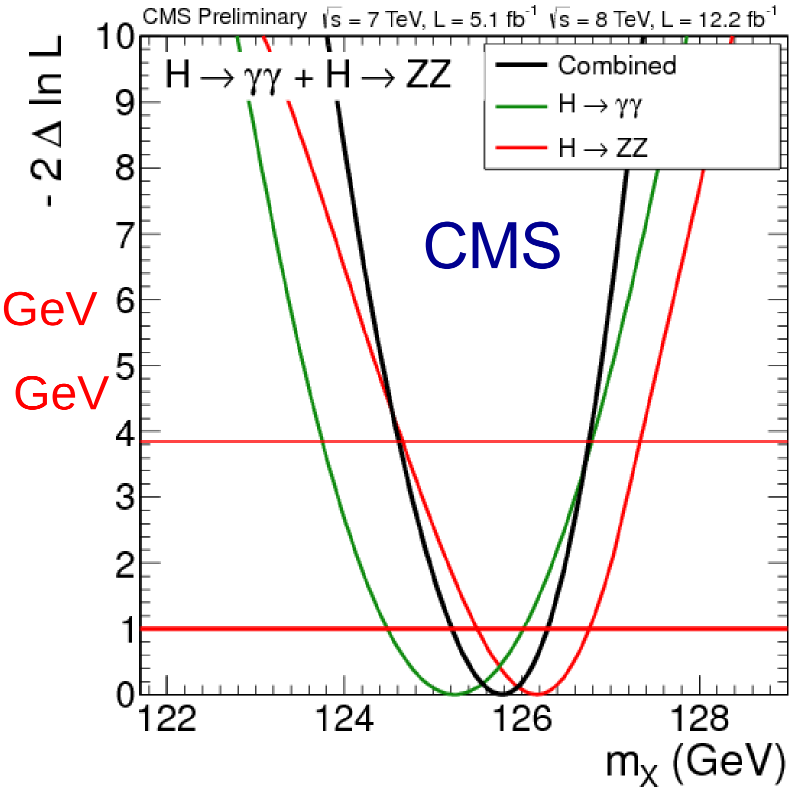
Only missing SM parameter

- From $\gamma\gamma$ and ZZ*(4l) mass spectrum
  - ATLAS: MH = 126.0 ± 0.4stat ± 0.4sys GeV
  - CMS: MH = 125.8 ± 0.4stat ± 0.4sys GeV

Error on the average (*guess the value*)

will be …:

~ 0.4 GeV (3 per mill)



New HCP Update
ZZ* 4l

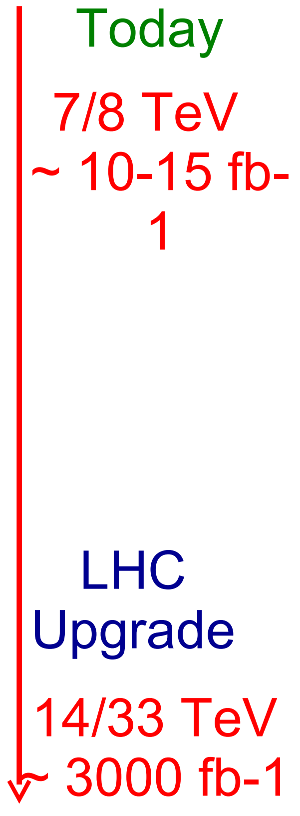
- Impact of mass error on LHC **yields**
  - **less than 4%** (WW/ZZ most sensitive)

Strategy for the LHC

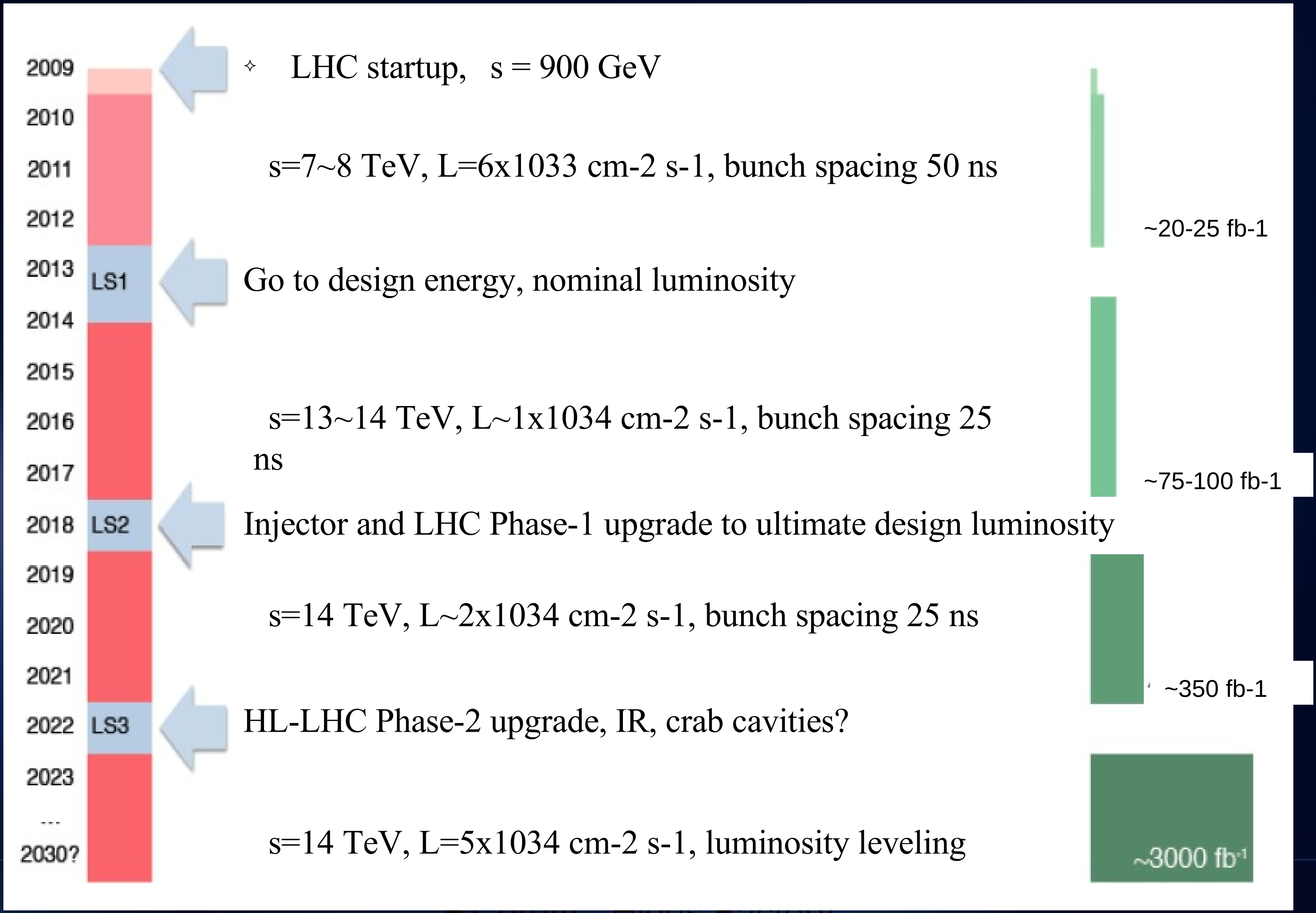
The Couplings roadmap

Test Higgs boson couplings depending on available L:

- Total signal yield μ: tested at 20% (κ tested at 10%)
- Couplings to Fermions and Vector Bosons 20-30%
- Loop couplings tested at 40%
- Custodial symmetry W/Z Couplings tested at 30%
- Test Down vs Up fermion couplings
- Test Lepton vs Quark fermion couplings
- Top Yukawa direct measurement ttH: κt
- Test second generation fermion couplings: κμ
- Higgs self-couplings couplings HHH: κH



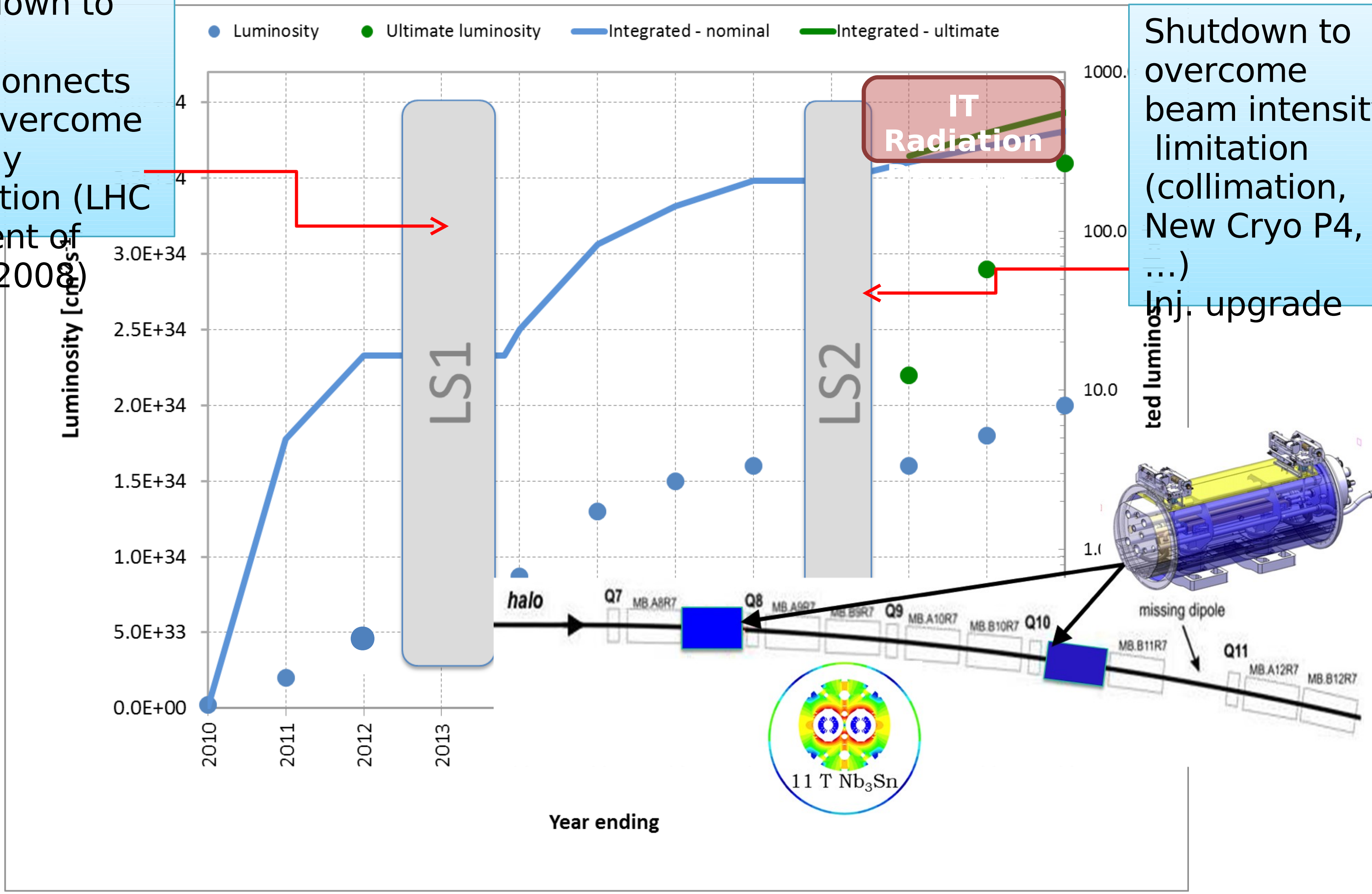
The LHC Timeline



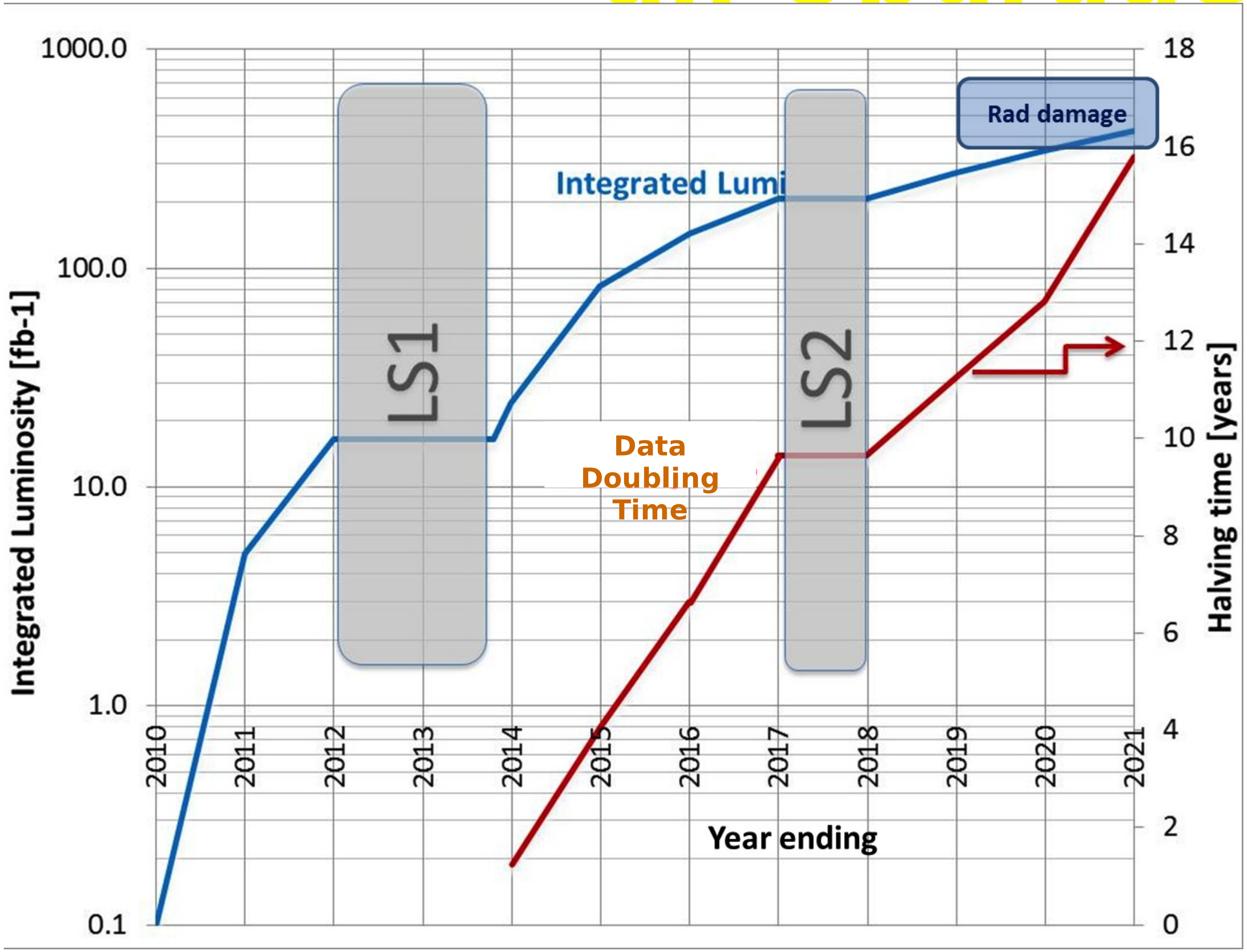
Luminosity: Best Guess for the next 10 years

Shutdown to fix interconnects and overcome energy limitation (LHC incident of Sept 2008)

Shutdown to overcome beam intensity limitation (collimation, New Cryo P4, …) Inj. upgrade



HL-LHC: The need for an Upgrade



Around 2022 the Present Triplet magnets reach the end of their useful life (due to radiation damage) …and will anyway need replacing.

In addition the Luminosity of the LHC will saturate by then

Time for an upgrade!

HL-LHC: The need for an Upgrade

Machine(s):

Perform continuous Performance Improving Consolidation and (during LS3) *HL-upgrade*

Detectors:

Need **important upgrades** to stand the harsher running conditions after LS3

Need to keep detector performance for main physics objects at the same level as we have today

25

Extending the reach…

- Weak boson scattering
- Higgs properties
- Supersymmetry searches and measurements
- Exotics
- t properties
- ….

Experiments are planning a Aachen-type workshop in 2013 to assess their physics reach and the implications on the detector upgrades

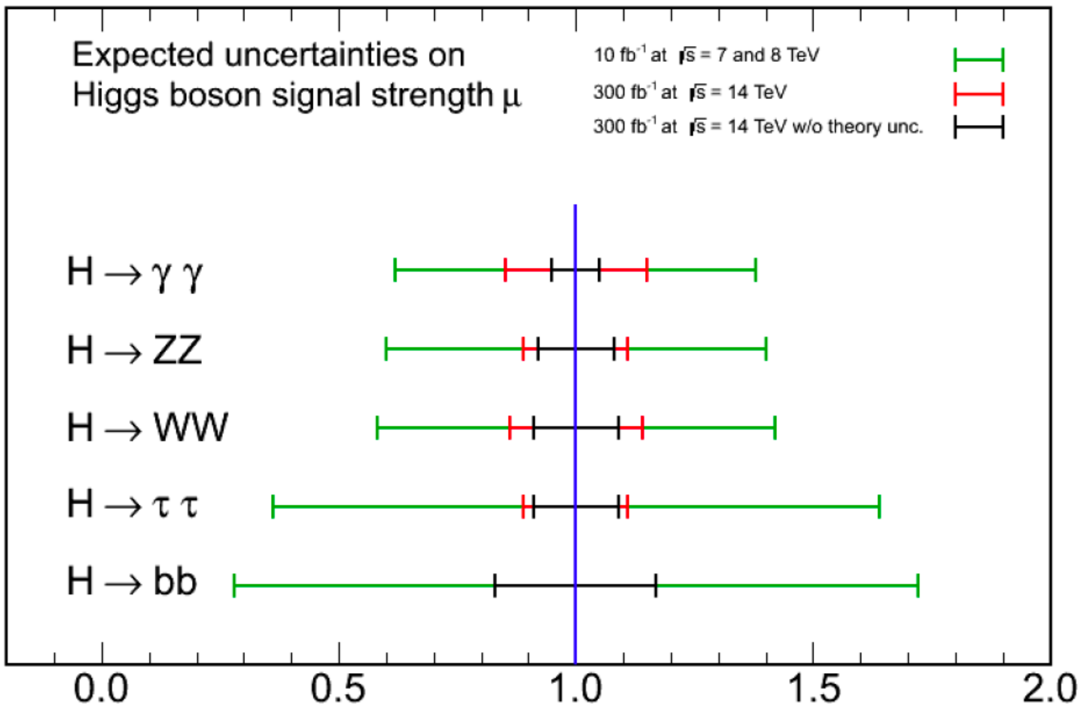
An example…

SM Higgs Boson Prospects

@ High Luminosity LHC

Signal Strength: μ at 300 fb-1

CMS Projection



$\mu = \sigma/\sigma SM$

300 fb-1 at 14 TeV

Red: Scenario 1

Black: Scenario 3

Theory errors dominant for γγ

Most difficult channel bb

Measurements at:

μ~10-20%

κ ~5-10%

Similar results obtained by ATLAS

In conclusion….

Approved LHC 300 fb-1 at 14 TeV:

- Higgs mass at 100 MeV
- Disentangle Spin 0 vs Spin 2 and main CP component in ZZ*
- Coupling rel. precision/Exper.
  - Z, W, b, τ 10-15%
  - t, μ 3-2 σ observation
  - $\gamma\gamma$ and gg 5-11%

HL-LHC 3000 fb-1 at 14 TeV:

- Higgs mass at 50 MeV
- More precise studies of Higgs CP sector
- Couplings rel. precision/Exper.
  - Z, W, b, τ, t, μ 2-10%
  - $\gamma\gamma$ and gg 2-5%
  - H→HH >3 σ observation (2 Exper.)

Assuming sizeable reduction of theory errors

In Summary

- LHC experiments have entered the precision era in the Higgs properties assessment, while keeping pushing for discoveries.
- This is just the beginning….
- **Machine and experiments upgrades are crucial to fully exploit the physics potential of LHC**

Key message

There is a program at the energy frontier with the LHC for at least 20 years:

7 and 8 TeV
14 TeV design luminosity
14 TeV high luminosity (HL-LHC)


beyond LHC ?

Next decades

Road beyond Standard Model

At the energy frontier through synergy of

hadron - hadro… colliders (…HC, HE-LHC?)

lept… …on colliders (LHeC ??)

…epton - lepton colliders (LC (ILC or CLIC) ?)

LHC results vital to guide the way at the energy frontier

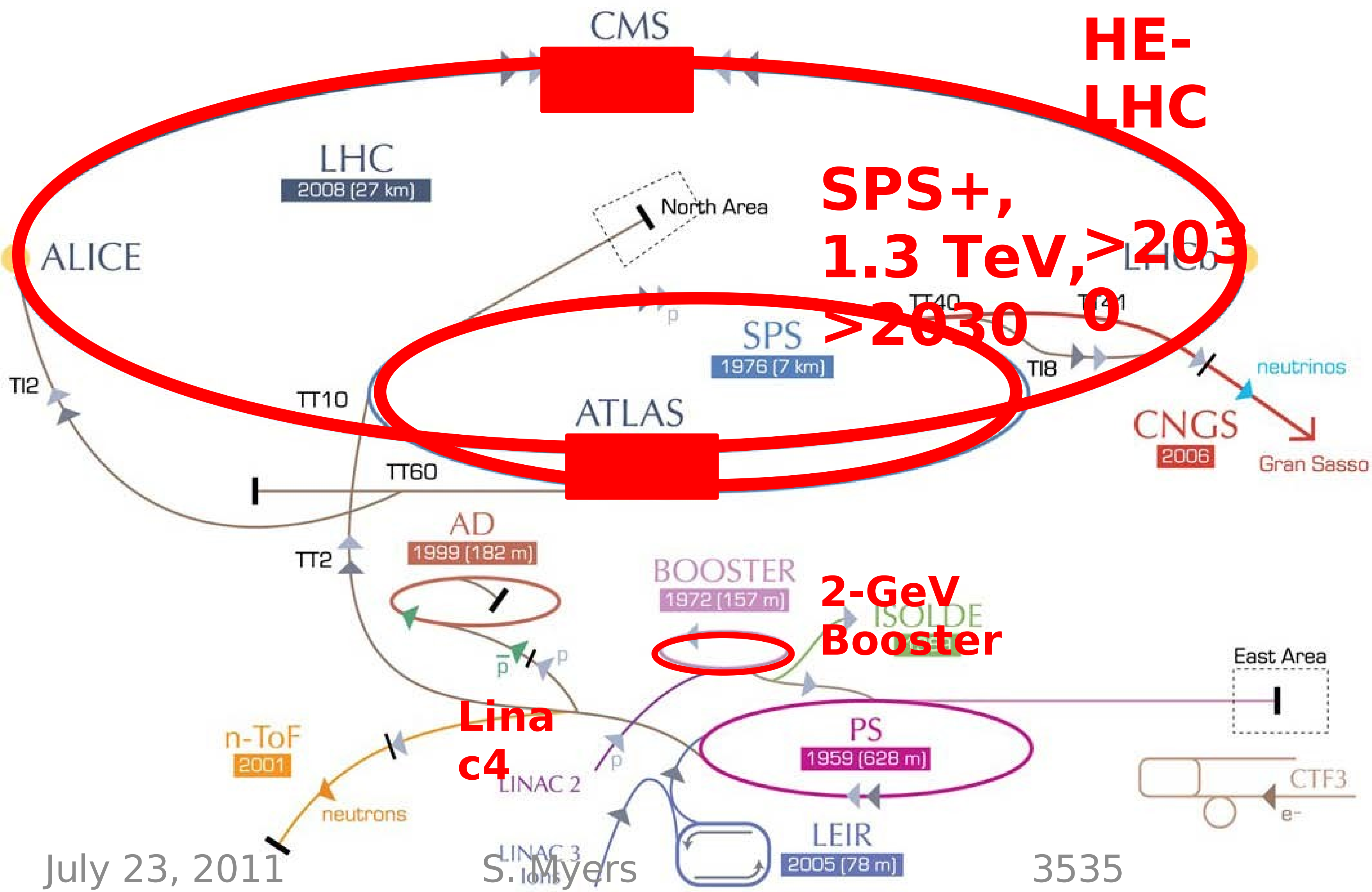
High Energy Hadron – Hadron Collider

HE - LHC

Study of New Physics Phenomena

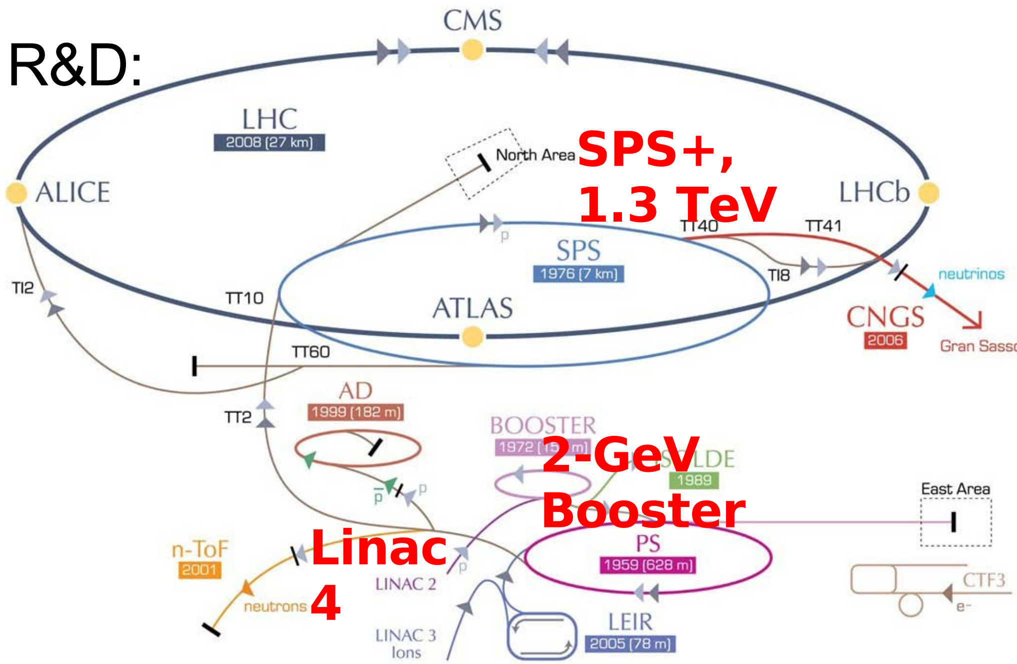
main challenge: High-Field Magnets

HE-LHC – LHC modifications



Very Long-Term Objectives: High-Energy LHC

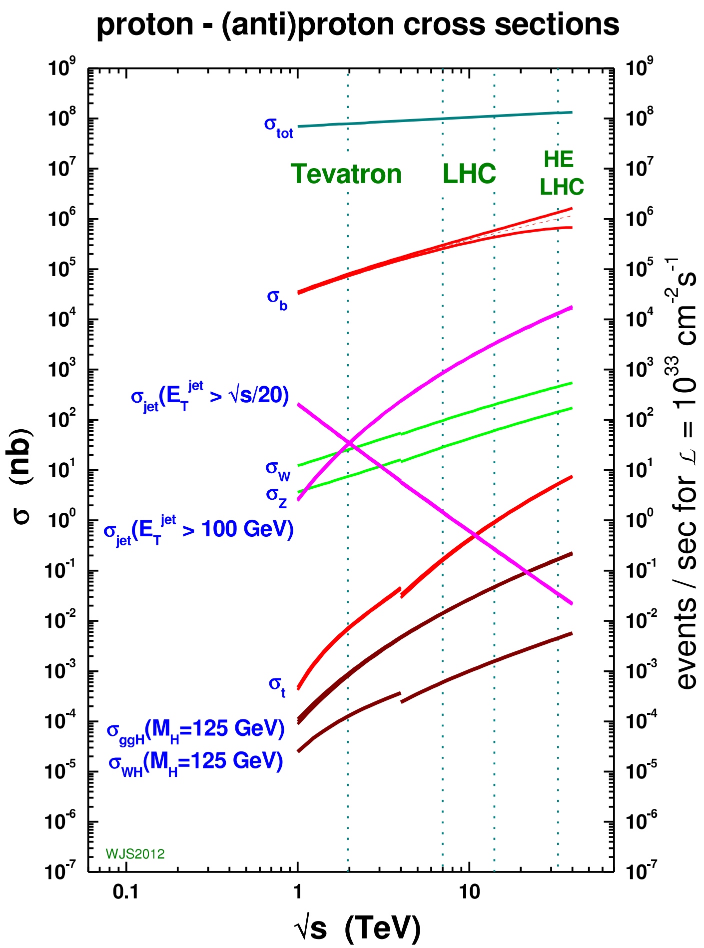
HE-LHC – main Issues and R&D:



- High-field 20T dipole magnets based on Nb3Sn, Nb3Al, and HTS
- High-gradient quadrupole magnets for arc and IR
- Fast cycling SC magnets for ~1.3 TeV injector
- Emittance control in regime of strong SR damping and IBS
- Cryogenic handling of SR heat load (first analysis; looks manageable)
- Dynamic vacuum

S. Myers, L. Rossi

Signal σ and Yields: HL/HE



Process	3000 fb-1 14 TeV	300 fb-1 33 TeV
ggH□γγ	350k	123k
ggH□4l	19k	6.7k
ttH□γγ	**42k**	**30k**
ttH□4l/μμ	**0.2k/0.4k**	**0.16k/0.3k**
ggH□HH□bbγγ	**270**	**160**

LHC upgrades give access to rare decays
Better signal Yields at HL-LHC
BUT Pile-up and S/B better at HE-LHC

Another option under investigation:

Very HE – LHC

civil engineering study for up to

80 km tunnel started

Beyond High Energy LHC

- **First studies on a new 80 km tunnel in the Geneva area**
  - **42 TeV with 8.3 T using present LHC dipoles**
  - **80 TeV with 16 T based on Nb3Sn dipoles**
  - **100 TeV with 20 T based on HTS dipoles**

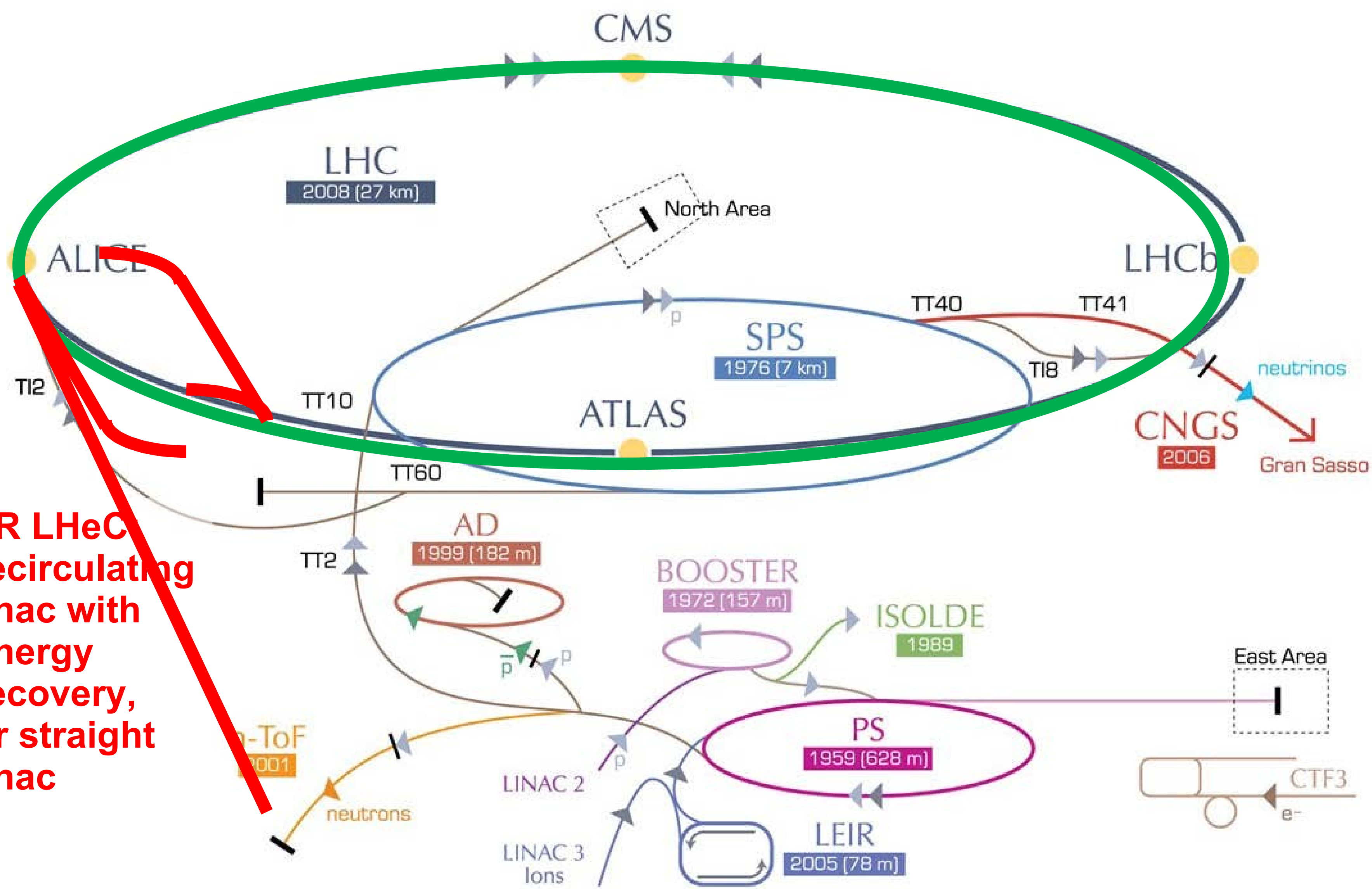
Figure 9. Two possible location, upon geological study, of the 80 km ring for a Super HE-LHC (option at left is strongly preferred)

Lepton – Hadron Collider

LHeC

QCD, Leptoquarks?

LHeC options: (RR) and LR



LR LHeC: recirculating linac with energy recovery, or straight linac

Lepton – Lepton Colliders

Linear e+e- Colliders: ILC / CLIC

Both projects are global endeavours

and part of the LC effort

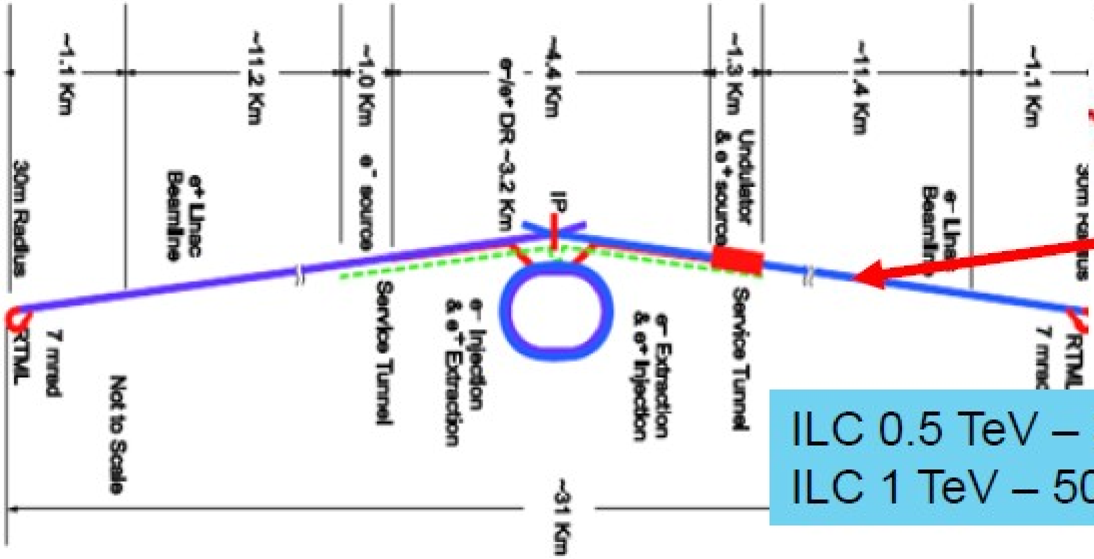
Wide range of Physics topics, e.g.

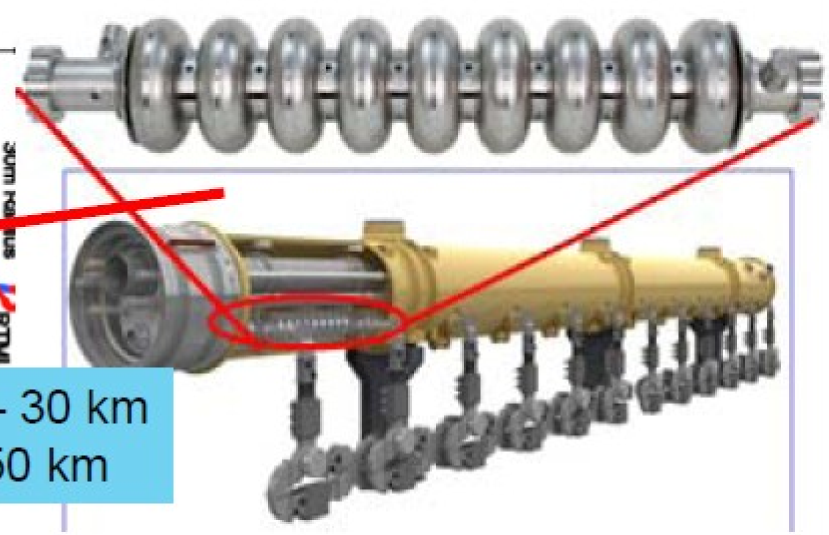
- Higgs couplings, in particular **self coupling**
- precision studies of Z, W, and **Top**
- new physics phenomena

Very interesting after the discovery of the Higgs-like Boson

Linear Collider layouts

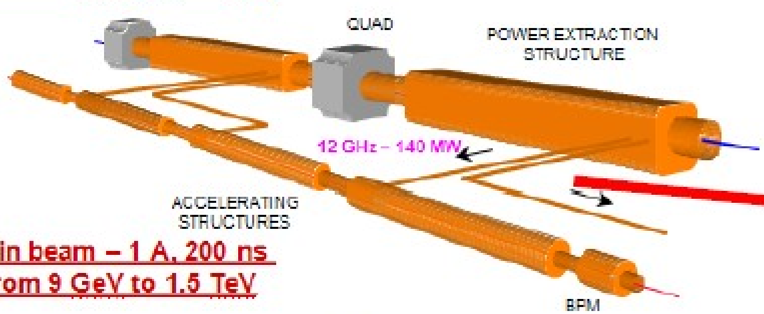
http://www.linearcollider.org/cms   http://clic-study.web.cern.ch/CLIC-Study/



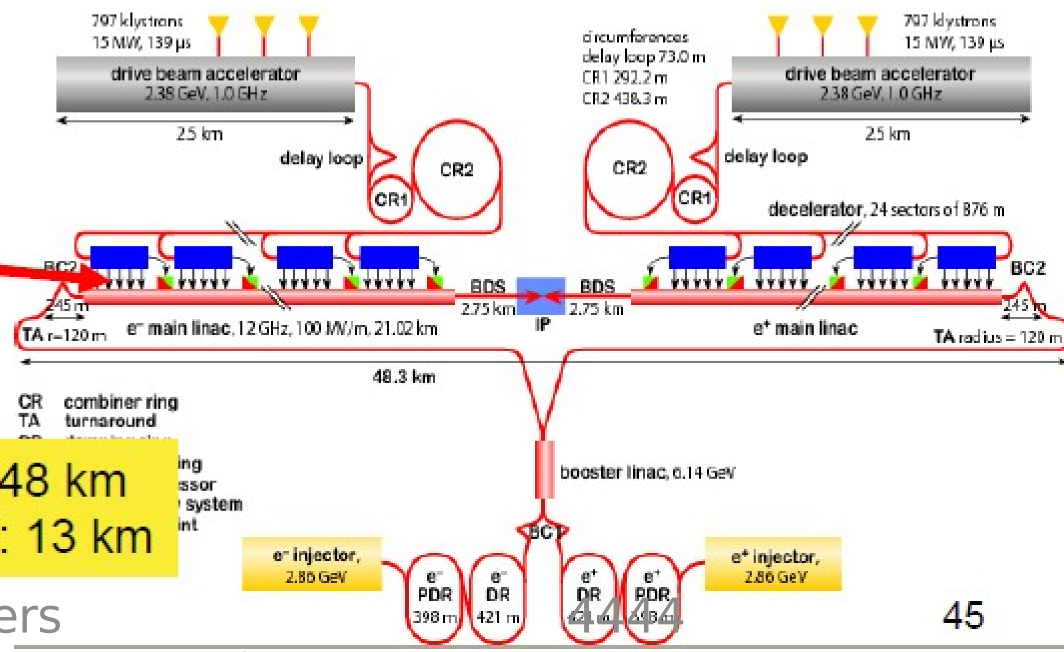


ILC 0.5 TeV – 30 km
ILC 1 TeV – 50 km

Drive beam - 95 A, 300 ns from 2.4 GeV to 240 MeV

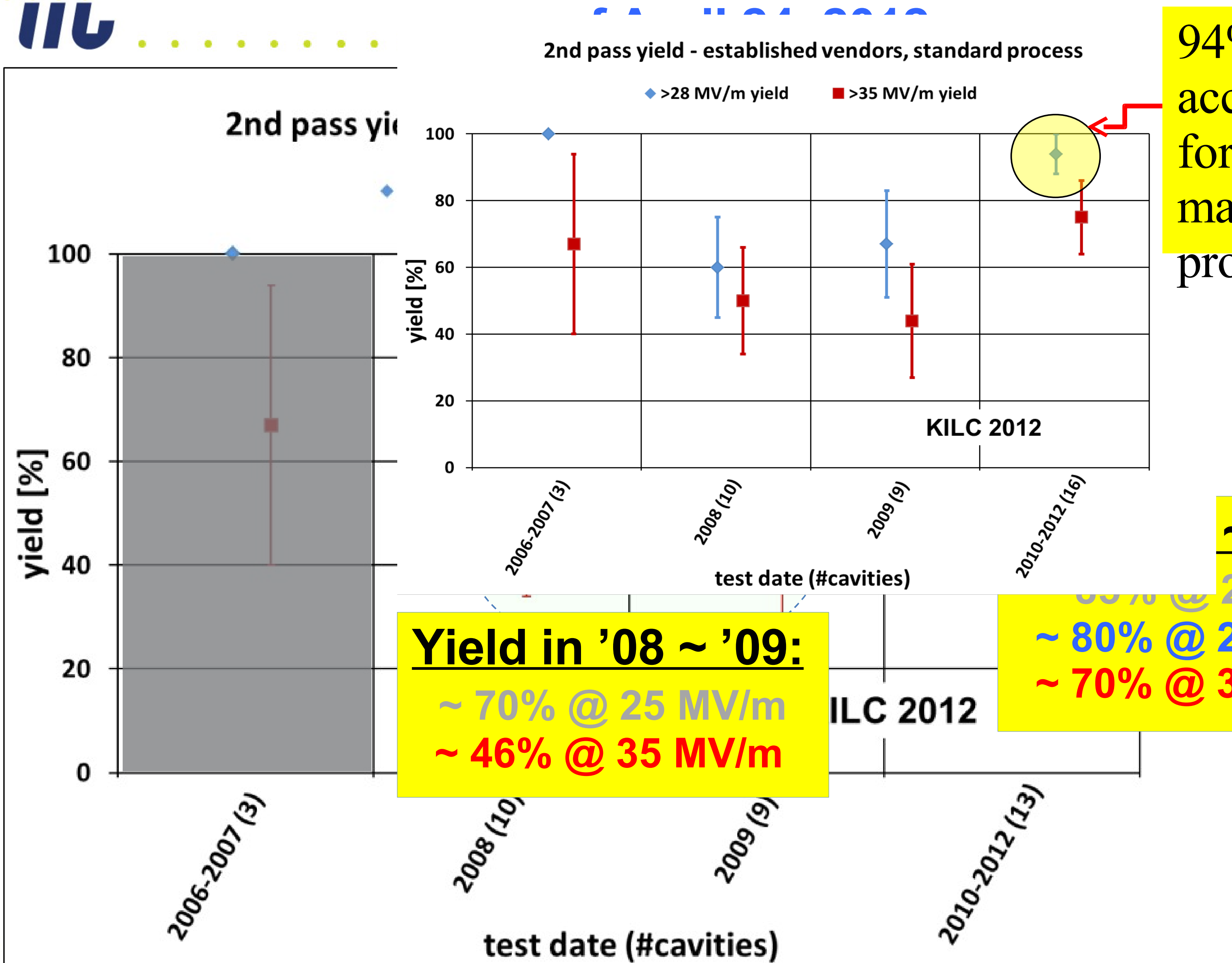


Main beam – 1 A, 200 ns from 9 GeV to 1.5 TeV



CLIC 3 TeV: 48 km
CLIC 0.5 TeV: 13 km

Yearly Progress in Cavity Gradient Yield



94% (±6%) acceptable for ILC mass production

Yield in '08 ~ '09:

~ 70% @ 25 MV/m

~ 46% @ 35 MV/m

~ '12:

@ 25 MV/m

~ 80% @ 28 MV/m

~ 70% @ 35 MV/m

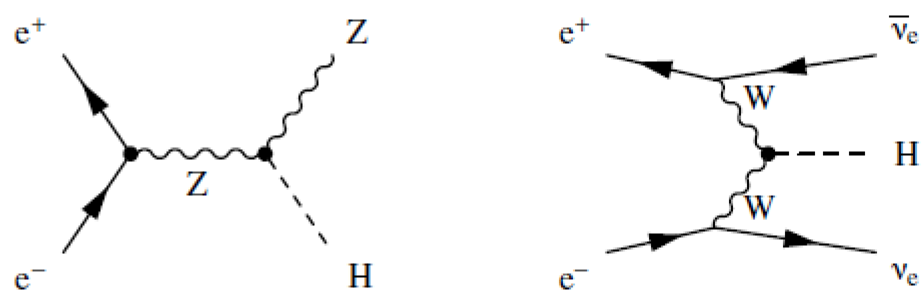
8-July-12
ILCSC -
Global Design Effort
45

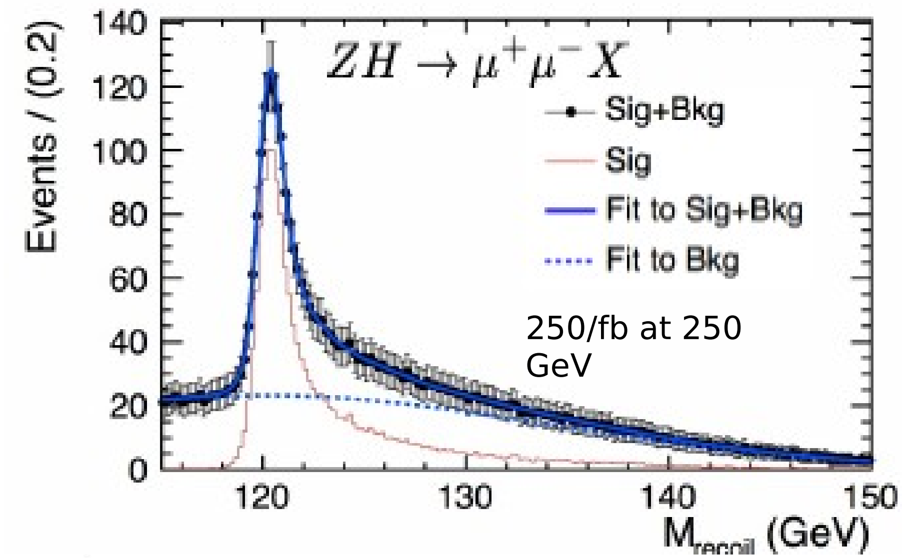
Conclusion of CLIC CDR studies

Main linac gradient	– Ongoing test close to or on target – Uncertainty from beam loading
Drive beam scheme	– Generation tested, used to accelerate test beam, deceleration as expected – Improvements on operation, reliability, losses, more deceleration (more PETS) to come
Luminosity	– Damping ring like an ambitious light source, no show stopper – Alignment system principle demonstrated – Stabilisation system developed, benchmarked, better system in pipeline – Simulations seem on or close to the target
Operation Machine Protection	– Start-up sequence defined – Most critical failure studied – First reliability studies – Low energy operation developed

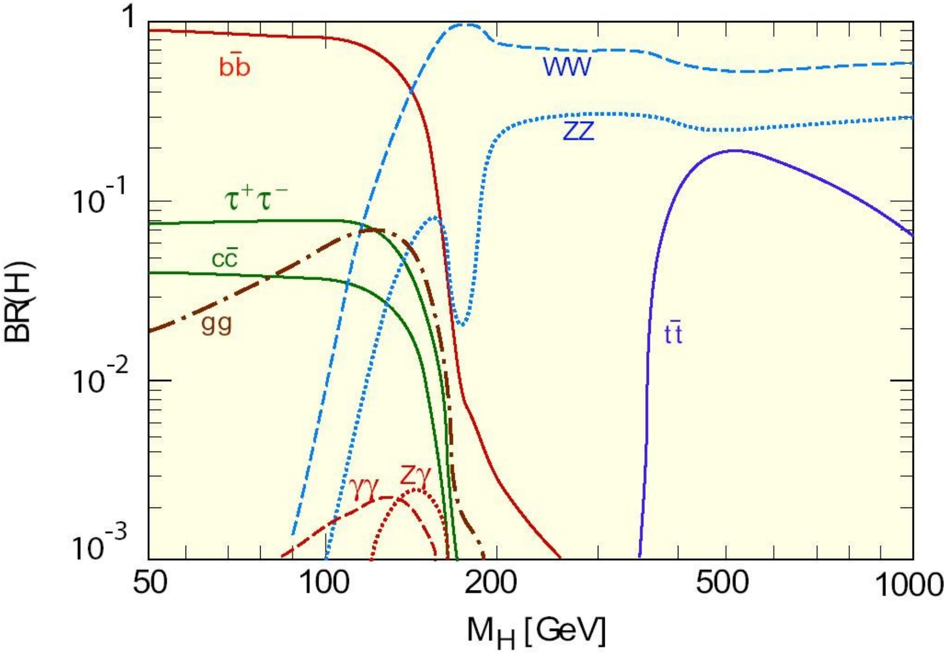
Higgs Factory

- **Higgs-Production in e+e–**



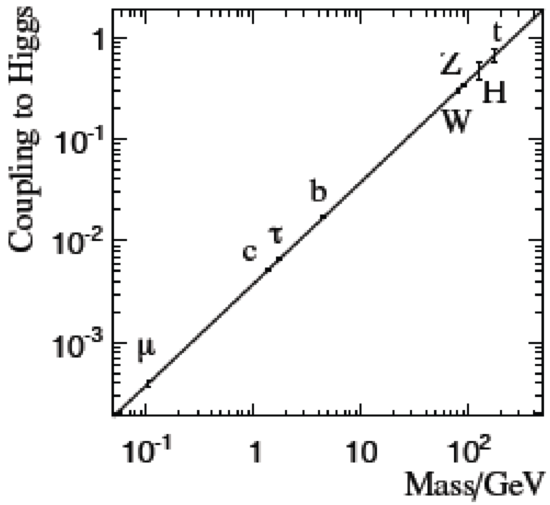


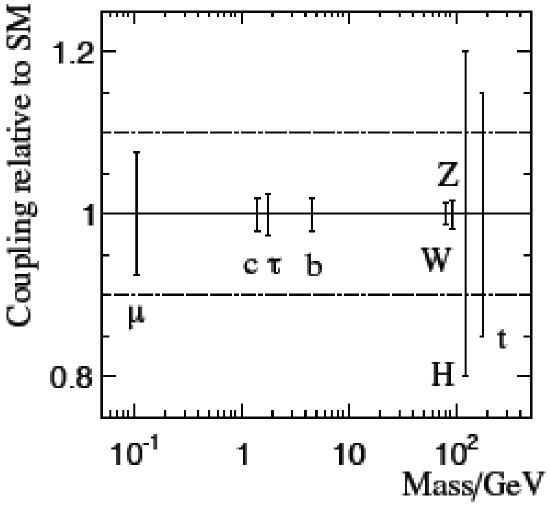
- **Higgs-Strahlung dominates at lower energies**
  - **max. cross section √s ≈ 250 GeV**
  - **no assumption about Higgs identify Higgs through Z decay**
  - **very clean, model independent signal using the recoil method**
  - **mH ≈ 125 GeV is ideal because many decay modes**



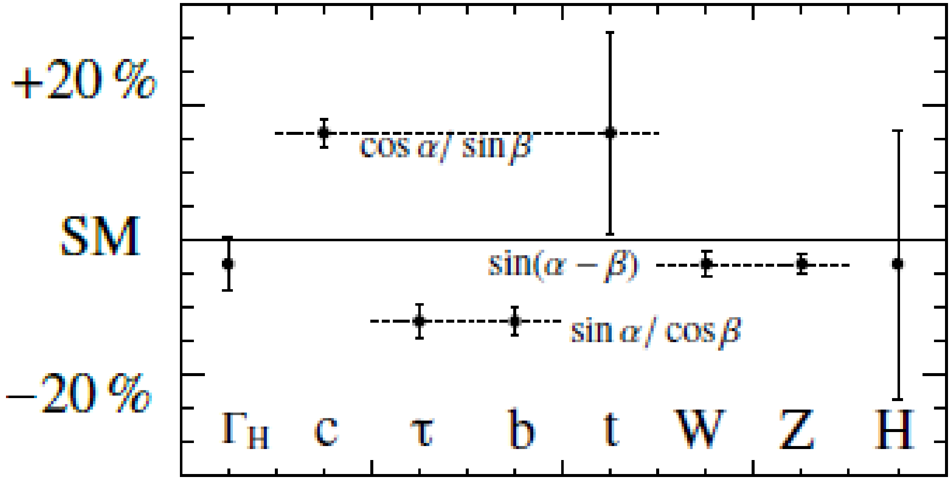
Precision at a Higgs Factory

- Absolute determination of Higgs (Yukawa)-couplings
- Precision O(1-2%) in some cases
  - example corresponds to 250/fb at 250 GeV plus 500/fb at 500 GeV
  - O(10 years) running time





- Typical deviations from SM couplings in a Two-Higgs-Doublet model



Key message

High Priority Items for Linear Collider Projects

ILC and CLIC projects → LC project

Construction Cost

Power Consumption

Value Engineering

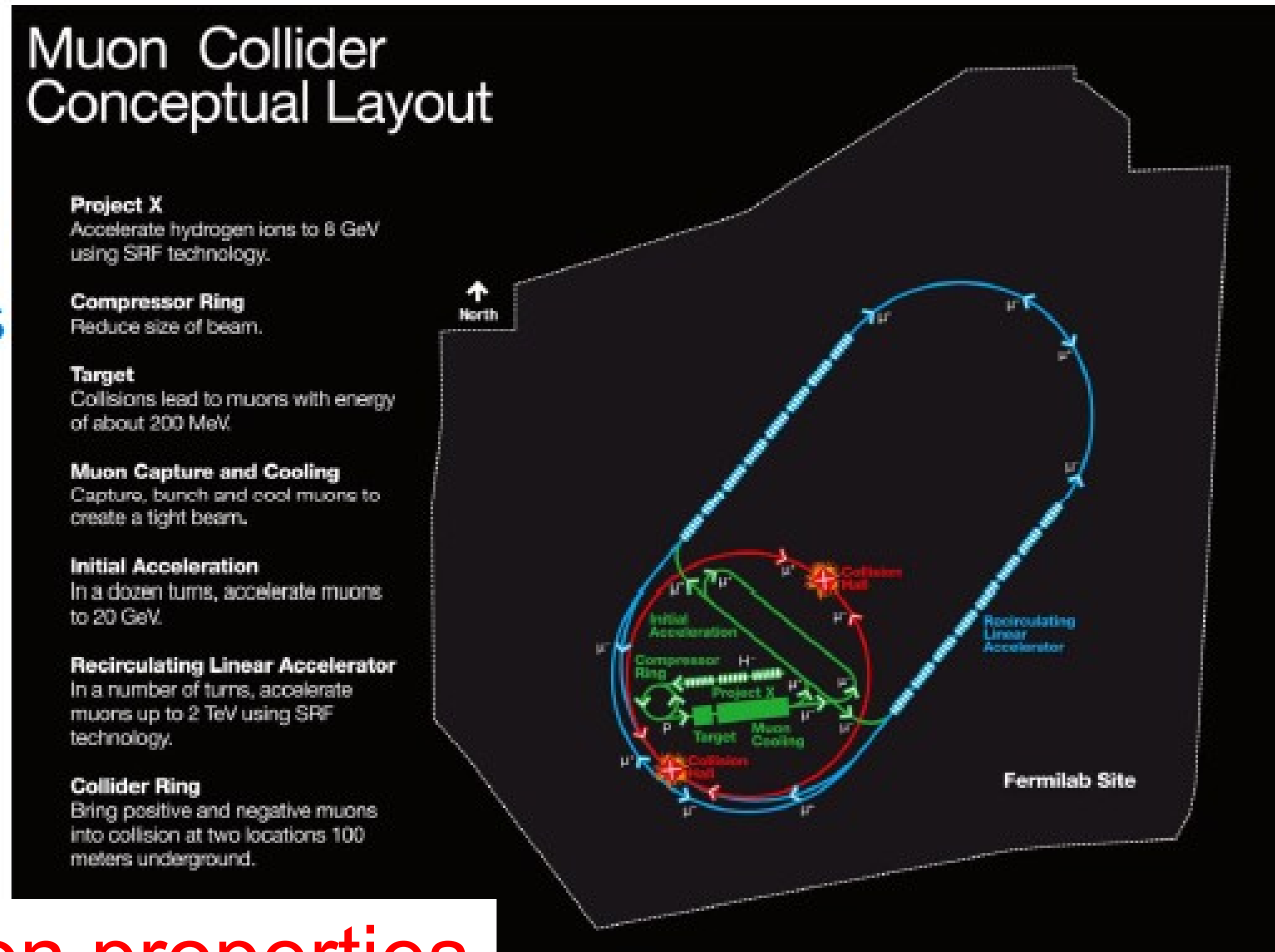
and beyond ???

Muon Collider

- Compact facility accelerating muons with recirculating linacs

<u>Major Challenges</u>

1. Muon generation
2. Cooling of muons
3. Cost-efficient acceleration
4. Collider ring and backgrounds from decays



– Higgs Boson properties

High Gradient Acceleration

- High gradient acceleration requires high peak power and structures that can sustain high fields
  - Beams and lasers can be generated with high peak power
  - Dielectrics and plasmas can withstand high fields

- Many paths towards high gradient acceleration
  - RF source driven superconducting structure… 40 MV/m
  - RF source driven metallic structure… MV/m
  - Beam-driven metallic stru…
  - Laser-driven die… …ures
  - Beam… …tric structures } ~1 GV/m
  - La… …ven plasmas
  - Beam-driven plasmas } ~10 GV/m

R&D on new technologies mandatory

From: T.Raubenheimer, EPS

Choices ?

- Rich variety of projects under study
  at the energy frontier
  and the intensity frontier
- Global – Regional – National Projects

 Need to present and discuss all these projects in an international context

 Need to present physics case(s) always taking into account latest results at existing facilities

 Need to present (additional) benefits to society from the very beginning of the project

from Choices ? *to* Choice !

- Roadmap (Japan) just published

- Roadmap discussion (US) next year

- Update of the European Strategy for Particle Physics in 2012/13 ≡ Strategy of Europe in a global context

  - Several Meetings with **international participation**

    - bottom-up process: lots of community input

  - drafting document: 21-25 January

  - Finalization: 23 May 2013

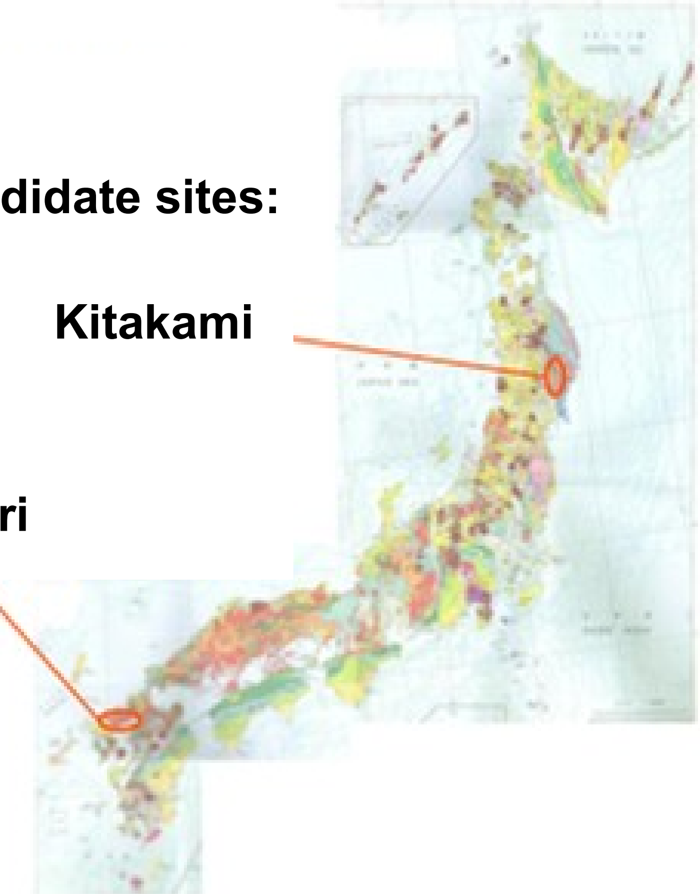
ILC Siting

- **ILC needs to be a global project**
- **Japan has expressed interest to host the ILC**
  - **top priority of Japanese particle physicist**
  - **support in Japanese politics, incl. significant financial contribution**
- **Possible staging scenario**
  - **250 GeV Higgs-factory**
  - **>350 GeV at tt-threshold**
  - **500 GeV → ~1 TeV**
- **This would define a physics programme for O(15 years)**

Two candidate sites:

Kitakami

Sefuri



Expectations from Japan . . .

- Japan has made important contributions at the energy and intensity frontier in particle physics
- Future contributions from Japan to particle physics are vital for our field
- This requires
  - to continue the engagement in global projects outside Japan, in particular LHC
  - to establish all conditions necessary to host a truly global project in Japan

CERN today….into the future

- CLIC conceptual design report by 2012
- Participation in all LC activities
- LHeC conceptual design report early 2012
- R&D for high-field magnets (towards HE-LHC)
- Generic R&D (high-power SPL, Plasma Acc)
- Participation in Neutrino-Projects studied

Position CERN as Laboratory at the energy frontier

CERN: opening the door…

- **Membership for Non-European countries**
- **New Associate Membership defined**
- **Romania, Israel, Serbia** in accession to membership
- **Cyprus** agreement signed, awaiting ratification
- Negotiations concerning membership ongoing with **Slovenia,** and **Turkey**
- Several countries expressed interest in Associate Membership (Ukraine, Brazil, Russia, . . .)
- **CERN participation in global projects independent of location**

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Today

Exciting Times

…. make use of it