New colliders

Whither Colliders? At the dawn of Run-II

Rohini M. Godbole
Centre for High Energy Physics, IISc, Bangalore, India

- Hurrah for the SM!

- How did colliders help us on this journey?

- What are the next steps? **Whither**/Whether [*Wither?*] Colliders?

The SM Lagrangian consists of Gauge sector, flavor sector and the Scalar sector:

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + i\bar{\psi}\, \not{D}\psi + f_e^* (\bar{\nu}, \bar{e})_L \Phi e_R + f_u^* (\bar{u}, \bar{d})_L \Phi^C u_R$$

$$+ \ldots.. + h.c. + |D_\mu \Phi|^2 - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

Gauge sector in very good shape Given that the Strong interaction part as well as idea of Spontaneous Symmetry breaking AND EW unified model all got the Nobel prizes before July 4, 2012.

But the EW gauge theory needs the Scalar sector for it to be consistent!

H^0 $J = 0$

In the following H^0 refers to the signal that has been discovered in the Higgs searches. Whereas the observed signal is labeled as a spin 0 particle and is called a Higgs Boson, the detailed properties of H^0 and its role in the context of electroweak symmetry breaking need to be further clarified. These issues are addressed by the measurements listed below.

Concerning mass limits and cross section limits that have been obtained in the searches for neutral and charged Higgs bosons, see the sections "Searches for Neutral Higgs Bosons" and "Searches for Charged Higgs Bosons ($H^{\pm}$ and $H^{\pm\pm}$)", respectively.

2014 PDG! This was possible courtesy LHC!

H^0 MASS

A combination of the results from ATLAS and CMS, where a recent unpublished result from CMS is used, yields an average value of 125.6 ± 0.3 GeV, see the review on "Status of Higgs Boson Physics."

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
125.7±0.4 OUR AVERAGE				
$125.5 \pm 0.2 ^{+0.5}_{-0.6}$	[1,2] AAD	13AK	ATLS	pp, 7 and 8 TeV
$125.8 \pm 0.4 \pm 0.4$	[1,3] CHATRCHYAN	13J	CMS	pp, 7 and 8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$126.8 \pm 0.2 \pm 0.7$	[2] AAD	13AK	ATLS	pp, 7 and 8 TeV, $\gamma\gamma$
$124.3 ^{+0.6}_{-0.5} {}^{+0.5}_{-0.3}$	[2] AAD	13AK	ATLS	pp, 7, 8 TeV, $ZZ^* \rightarrow 4\ell$
$126.2 \pm 0.6 \pm 0.2$	[3] CHATRCHYAN	13J	CMS	pp, 7, 8 TeV, $ZZ^* \rightarrow 4\ell$
$126.0 \pm 0.4 \pm 0.4$	[1,4] AAD	12AI	ATLS	pp, 7 and 8 TeV
$125.3 \pm 0.4 \pm 0.5$	[1,5] CHATRCHYAN	12N	CMS	pp, 7 and 8 TeV

[1] Combined value from $\gamma\gamma$ and $ZZ^* \rightarrow 4\ell$ final states.

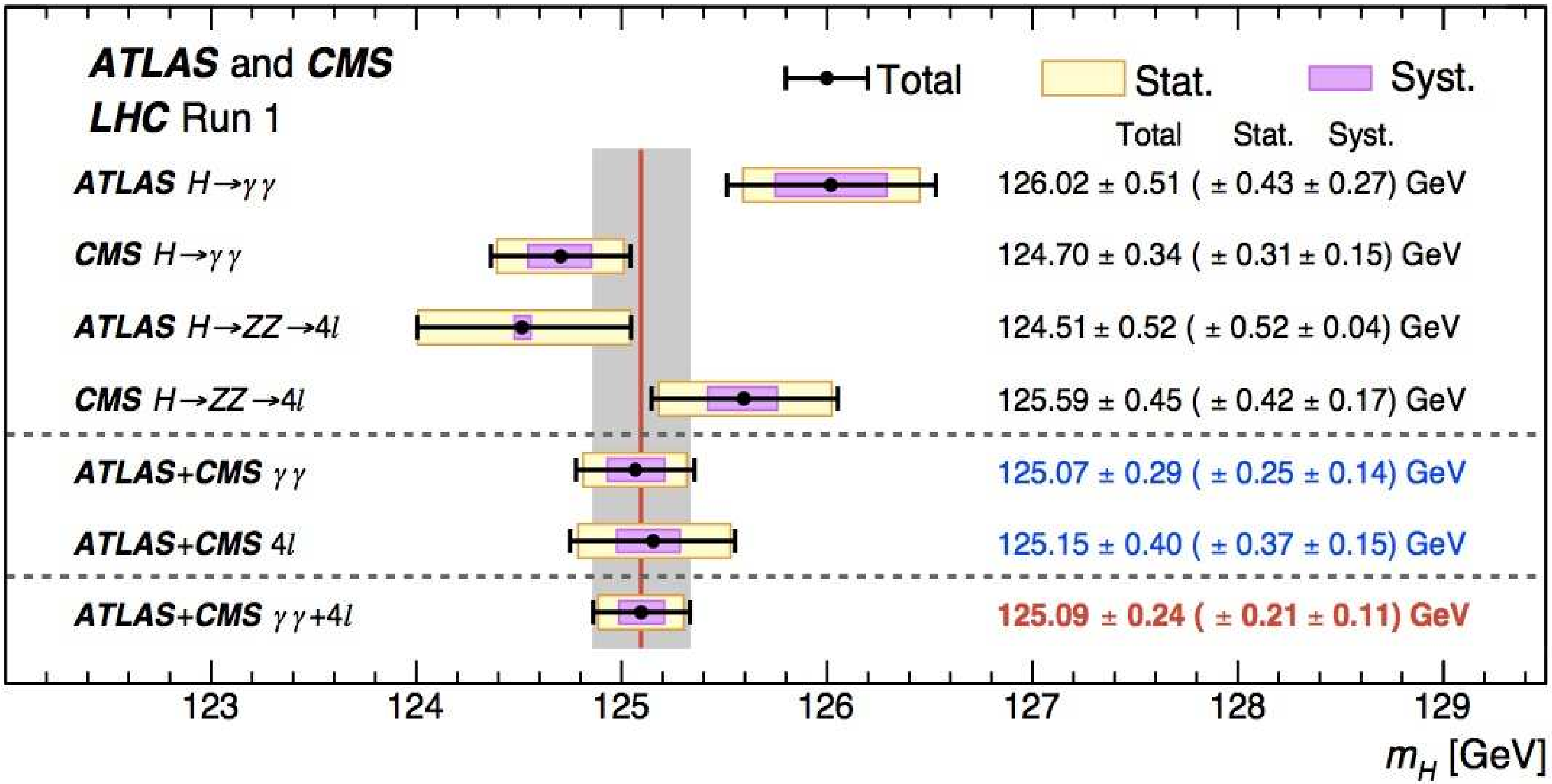
[2] AAD 13AK use 4.7 fb^{-1} of pp collisions at E_{cm}=7 TeV and 20.7 fb^{-1} at E_{cm}=8 TeV.

[3] CHATRCHYAN 13J use 5.1 fb^{-1} of pp collisions at E_{cm} = 7 TeV and 12.2 fb^{-1} at E_{cm} = 8 TeV.

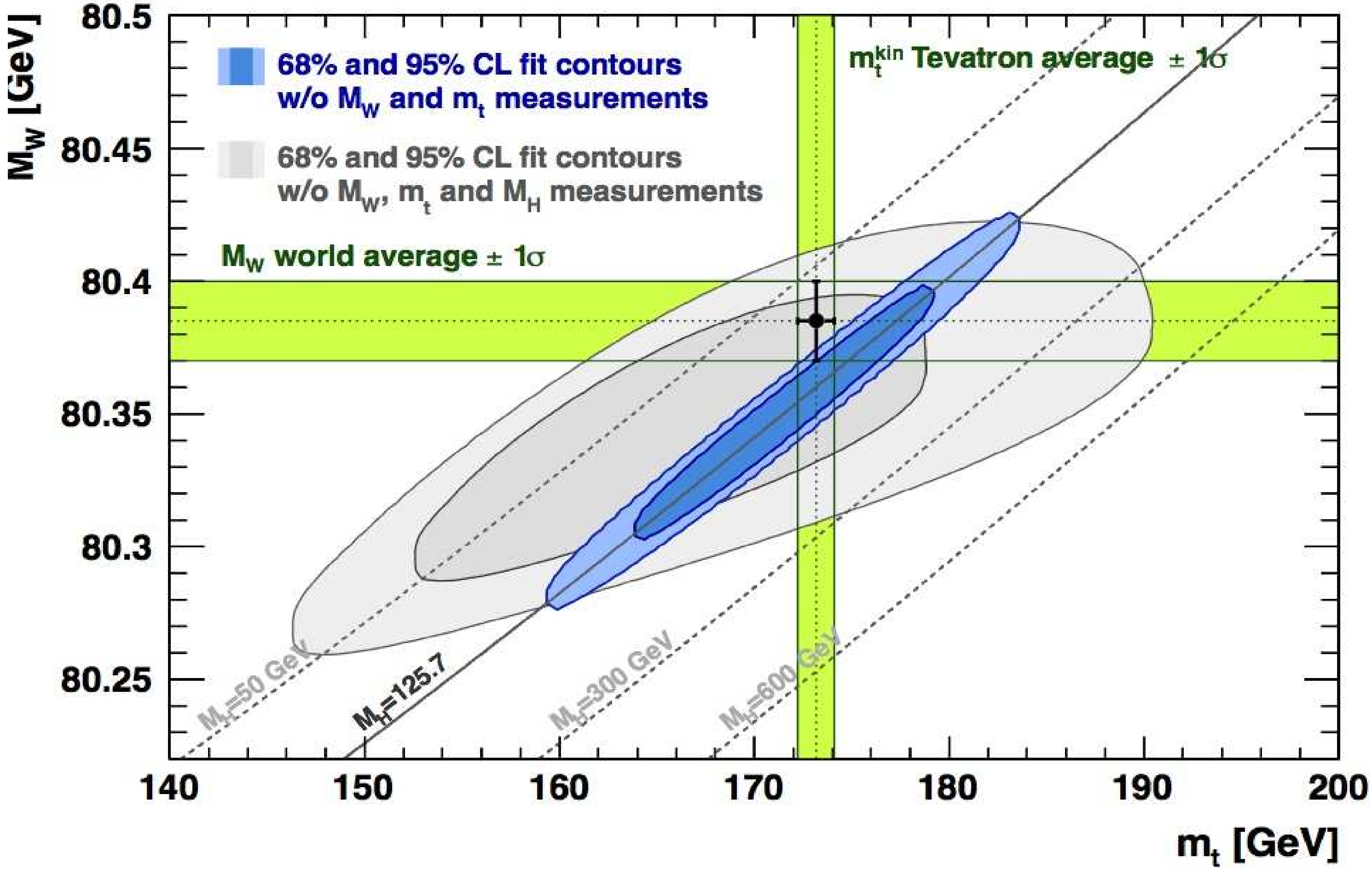
[4] AAD 12AI obtain results based on 4.6–4.8 fb^{-1} of pp collisions at E_{cm} = 7 TeV and 5.8–5.9 fb^{-1} at E_{cm} = 8 TeV. An excess of events over background with a local significance of 5.9 σ is observed at m_{H^0} = 126 GeV. See also AAD 12DA.

[5] CHATRCHYAN 12N obtain results based on 4.9–5.1 fb^{-1} of pp collisions at E_{cm} = 7 TeV and 5.1–5.3 fb^{-1} at E_{cm} = 8 TeV. An excess of events over background with a local significance of 5.0 σ is observed at about m_{H^0} = 125 GeV. See also CHATRCHYAN 12BY and CHATRCHYAN 13Y.

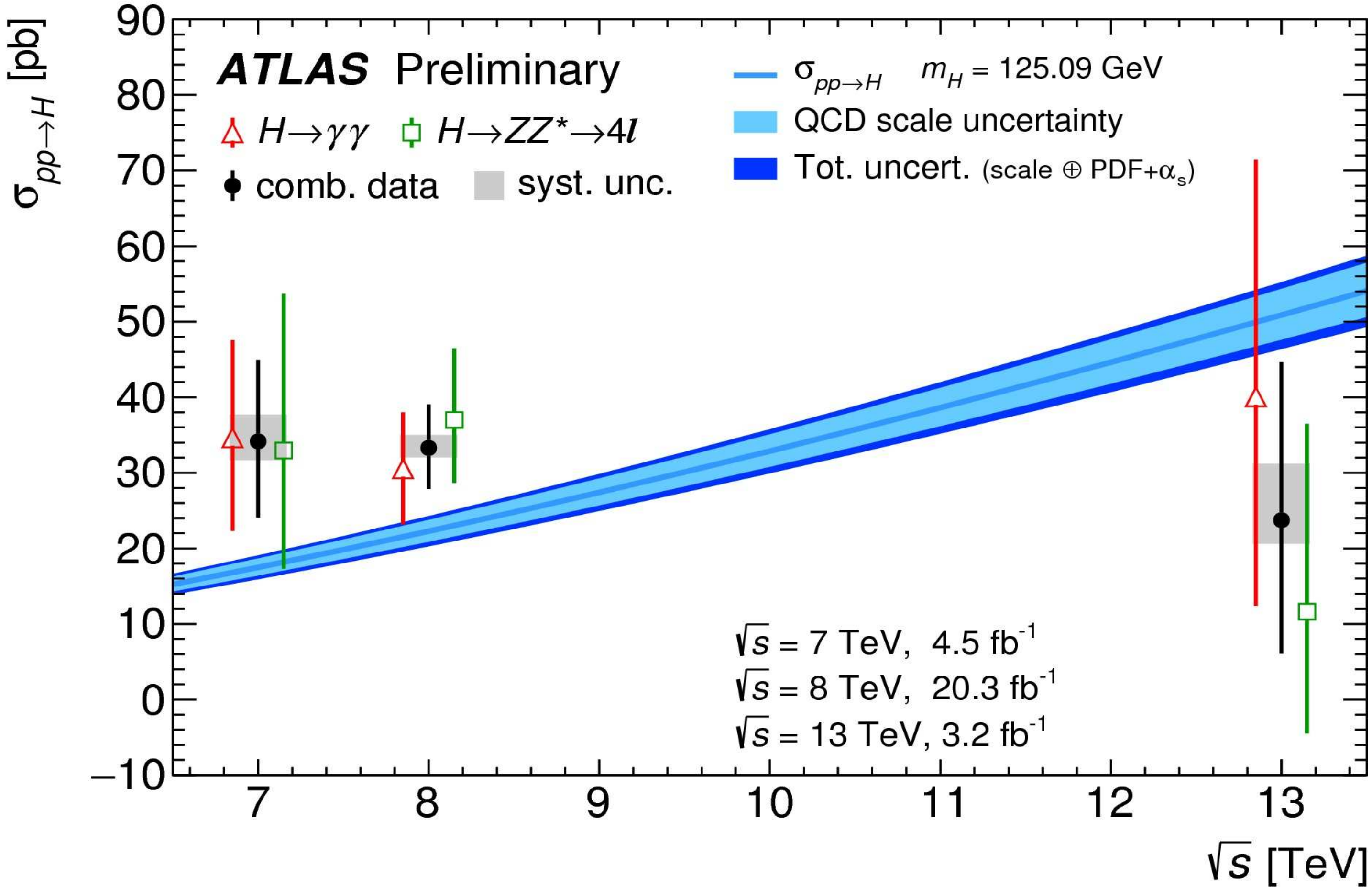
1503.07589v1.



We found it where the SM expected it from **'indirect'** constraints.

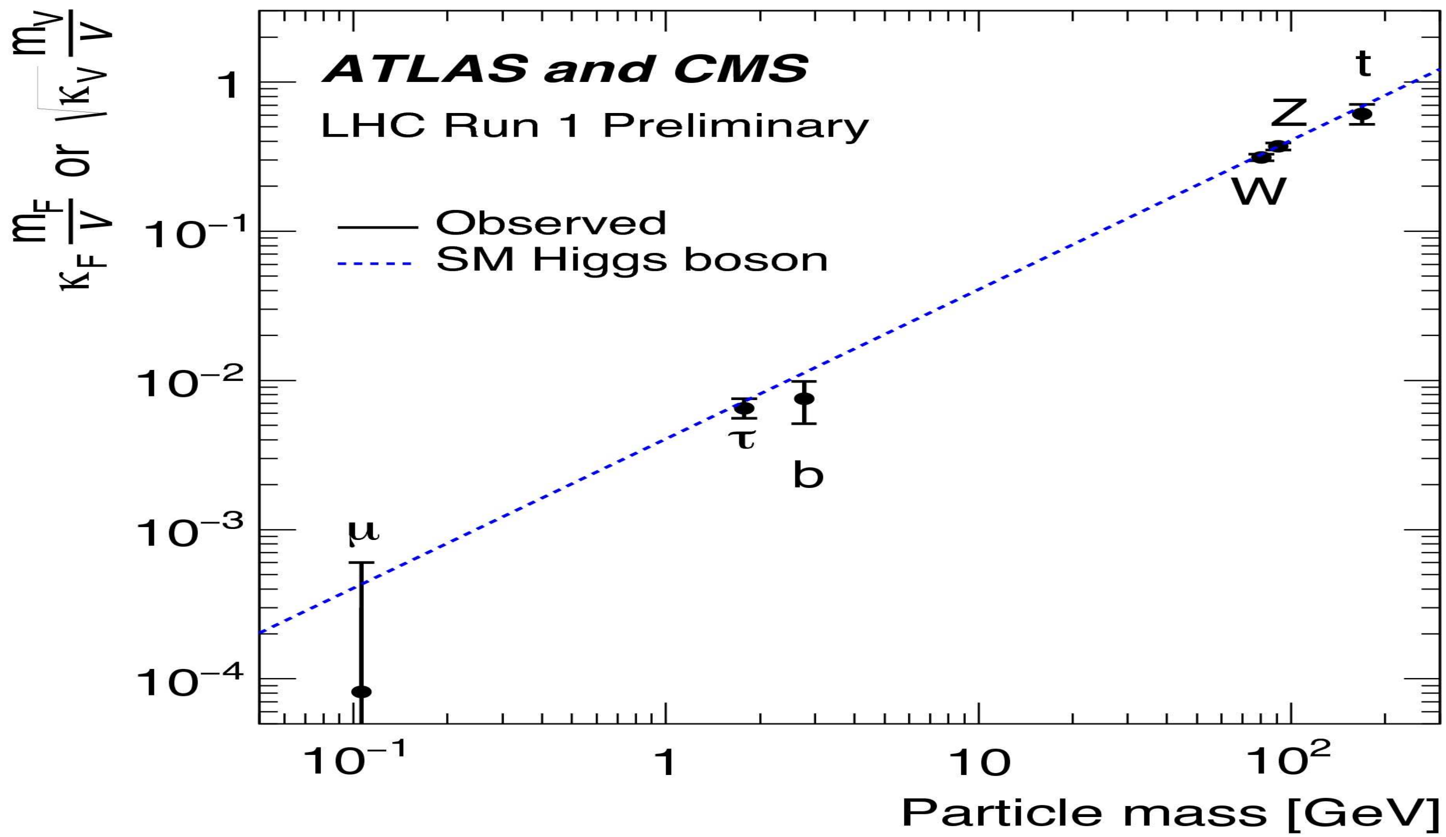


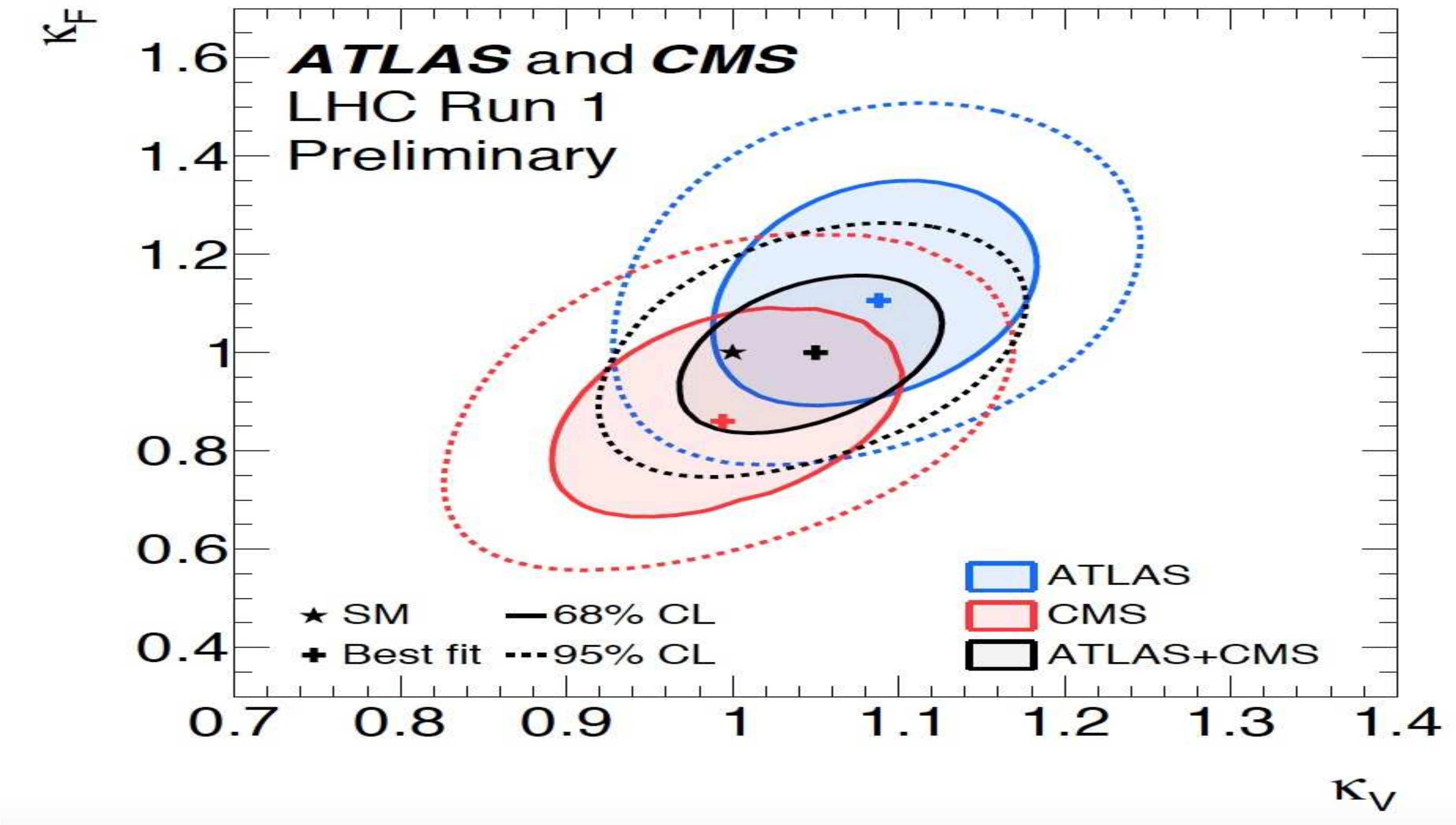
SM rocks! **LOOP Level**!



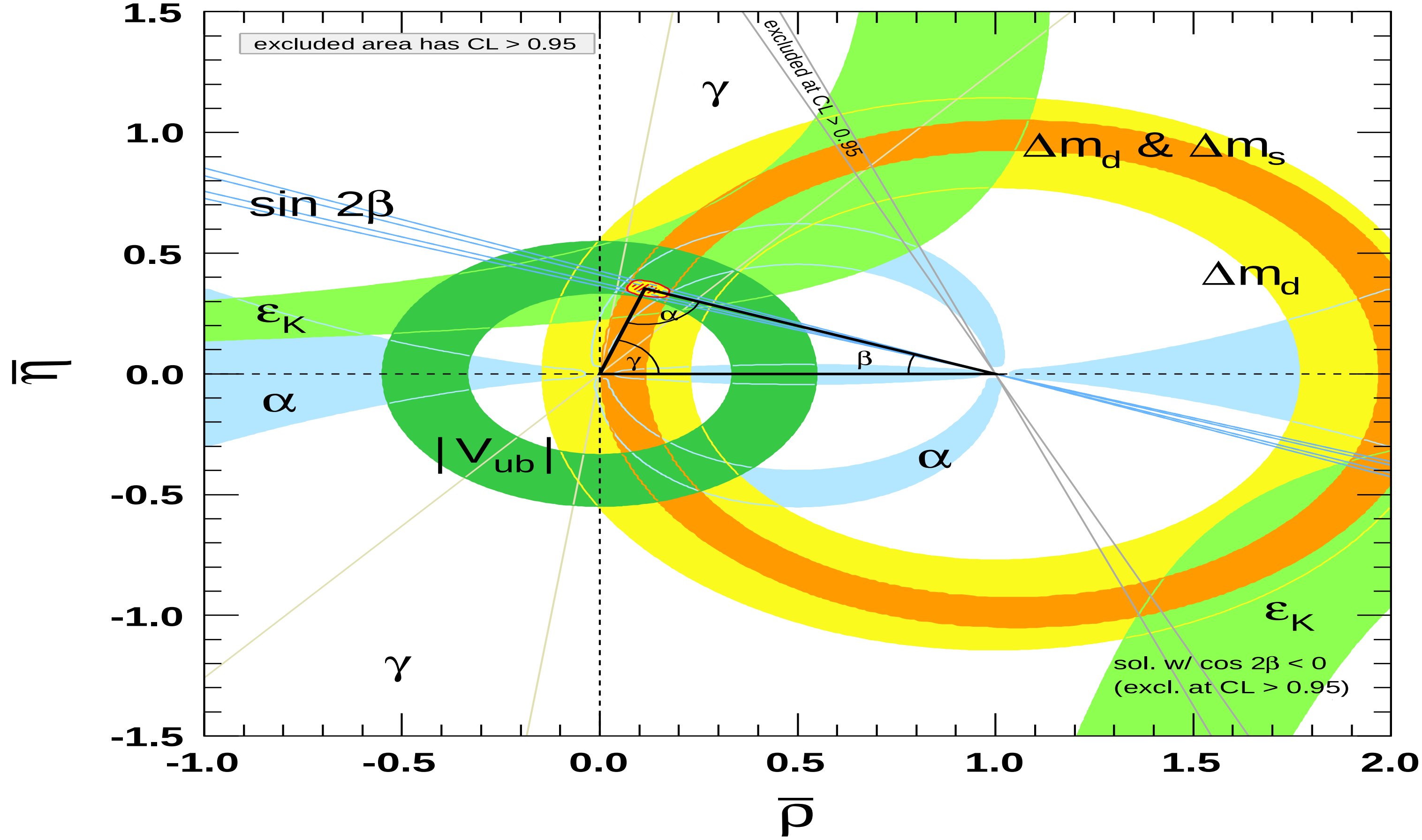
From ATLAS web page

SSB works: ATLAS public web page. ATLAS-CMS combination





The couplings agree with SM within 20 %.



SM does not 'explain' the flavor mixing and CP violation observed in from 'first principles' but 'describes' it in terms of a unitary mixing matrix. Courtsey: BELLE, BABAR and LHCB

To steal from 'Tale of two cities'

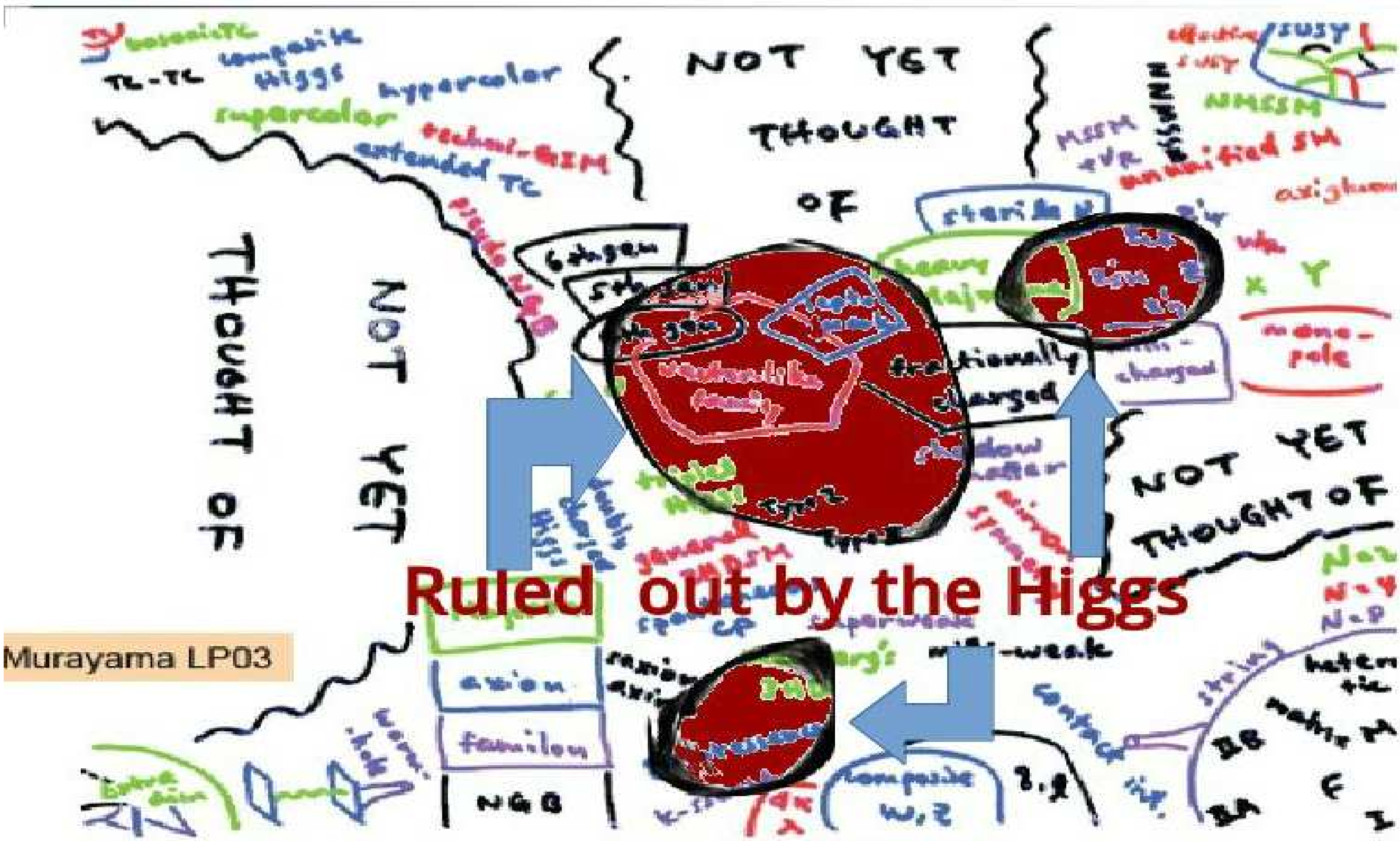
It is the BEST of the times ; it is the WORST of the times!

WHY?

Found the 'light' Higgs but as yet **NO** evidence for the physics that we **think** must exist to keep it so!

Peeping through the Higgs window!

Murayama LP03


NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
Ruled out by the Higgs
Murayama LP03
TC-TC
composite Higgs
hypercolor
supercolor
extended TC
SUSY
NMSSM
MSSM
fractionally charged
monopole
axion
familon
NGB
composite W,Z
mid-weak

LHC:

Seems to have found the light Higgs

BUT

So far no evidence/indication for the different BSM particles.

The mass and the couplings of this light state might be the window through which we can get a view of BSM at present!

’Anticipating’ the scale of BSM physics is a bit like anticipating the Higgs mass in the SM. We had no prediction for it, but then there were precision constraints.

Can we probe BSM like this: through the mass of the Higgs and through the Higgs couplings, through vacuum stability?

Statement number 1:

"In the present state of physical science, therefore, a question of extreme interest arises: Is there any principle on which **an absolute thermometric scale** can be founded?"

Statement number 2:

" There is nothing new to be discovered in physics now, All that remains is **more and more precise measurement**."

1. Existence of a EW scale **stable under radiative corrections** revealed. Is there a guiding principle on which the stability can be founded? We 'thought' we knew!..may be our thinking is right but...may be not!

2. All that remains is **more and more precise measurement** of the Higgs and top properties! *OR Higher and higher energies?*

It is not as though we are only agonising over non discovery of a beautiful theory which we think must be realised in nature because of its aesthetic beauty!

MANY pragmatic reasons to expect physics : either interactions or particles beyond what we have found!

DM : the direct detection experiments and astrophysics both are challenging usual DM folklores just as much as LHC 'paradox' is challenging the 'hierarchy' folklore or 'fine tuning' folklore!

DM at the colliders is throwing out results that too we do not seem to understand!

May be we are at a cusp and some people are asking the question whether it is time for a paradigm shift!

What is the way forward?

Before discussing and thinking about these things better to take stock of things as they are!

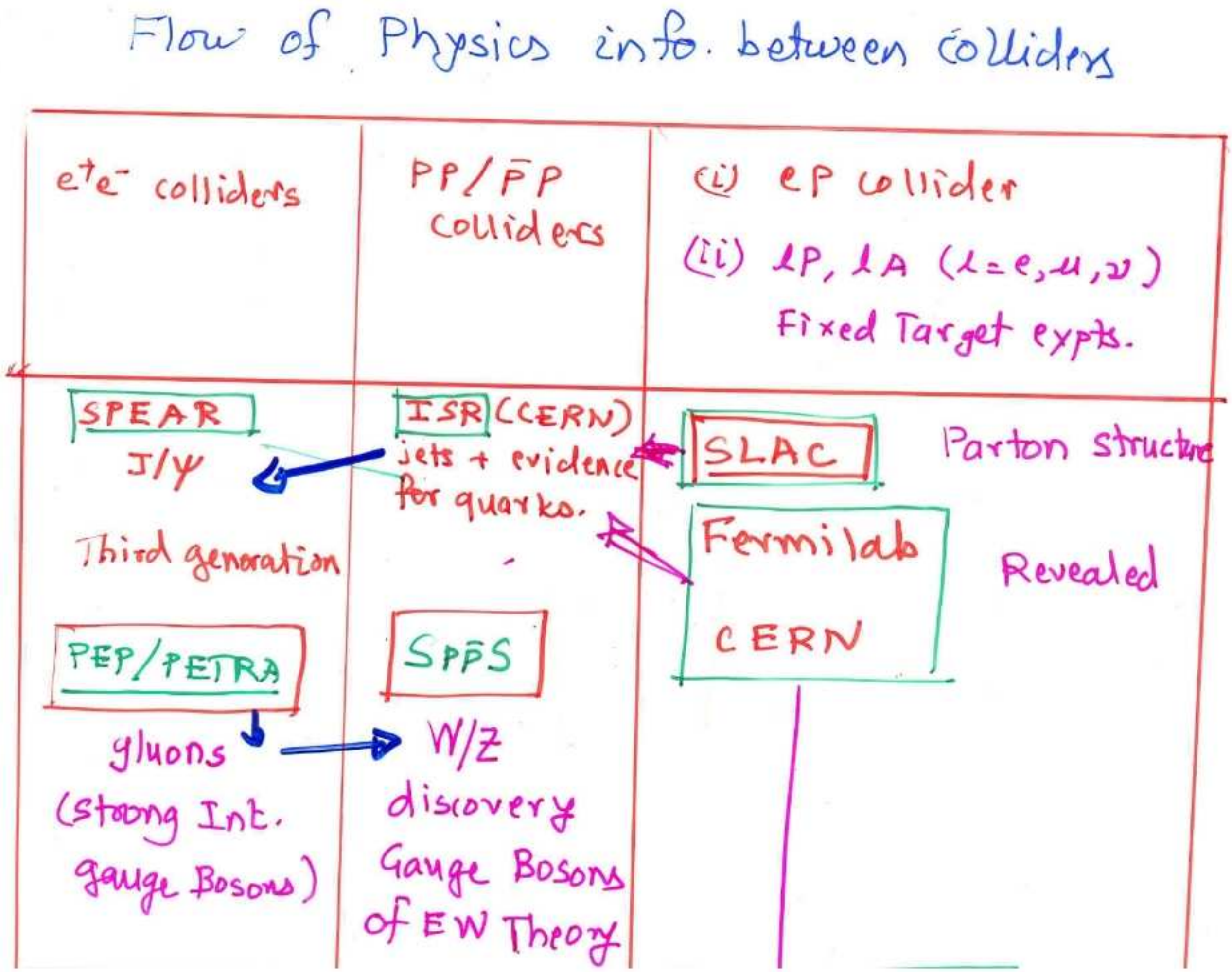
How we came to be here?

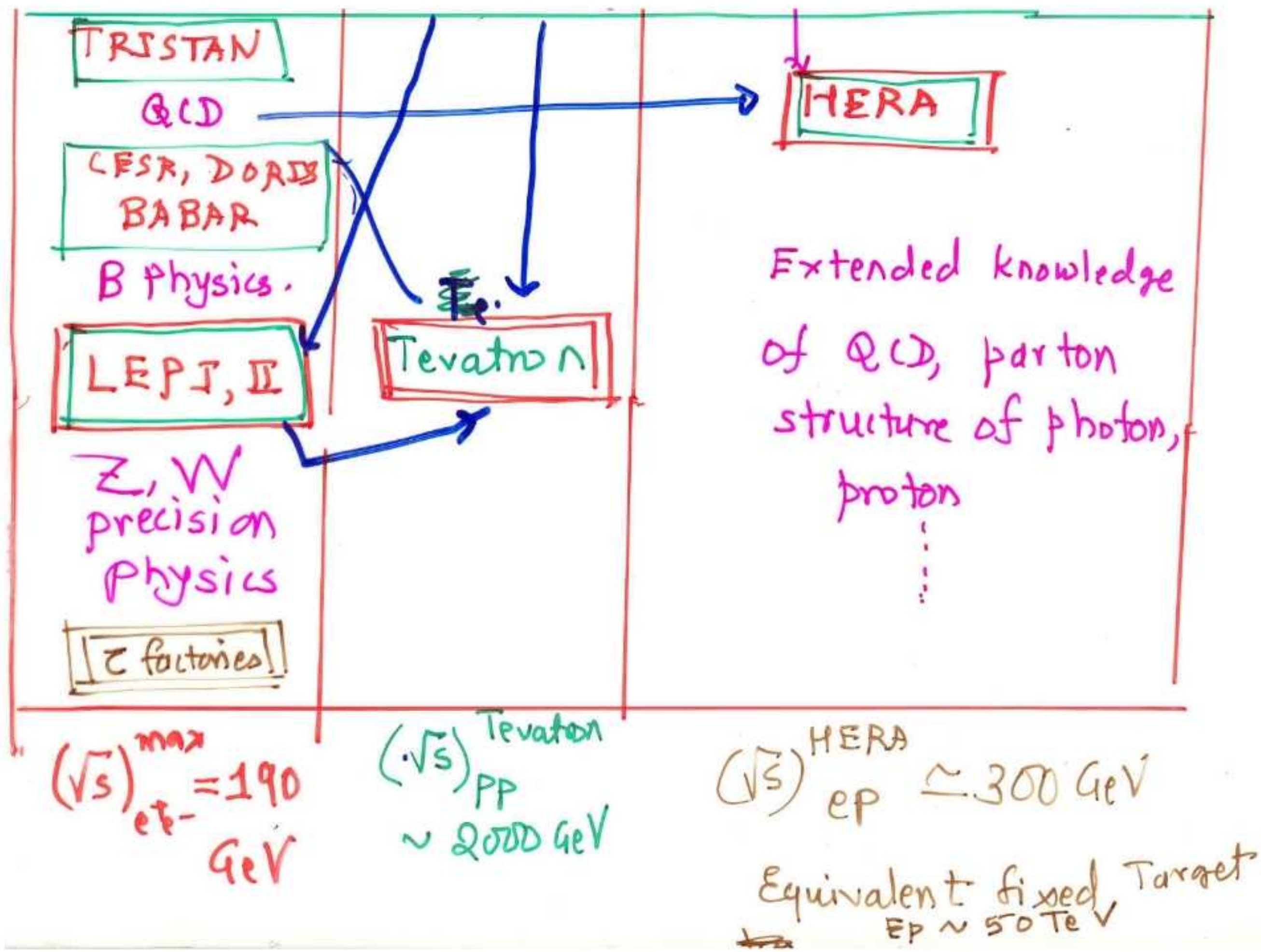
The baton at the frontier has passed from one type of machine to another back and forth.

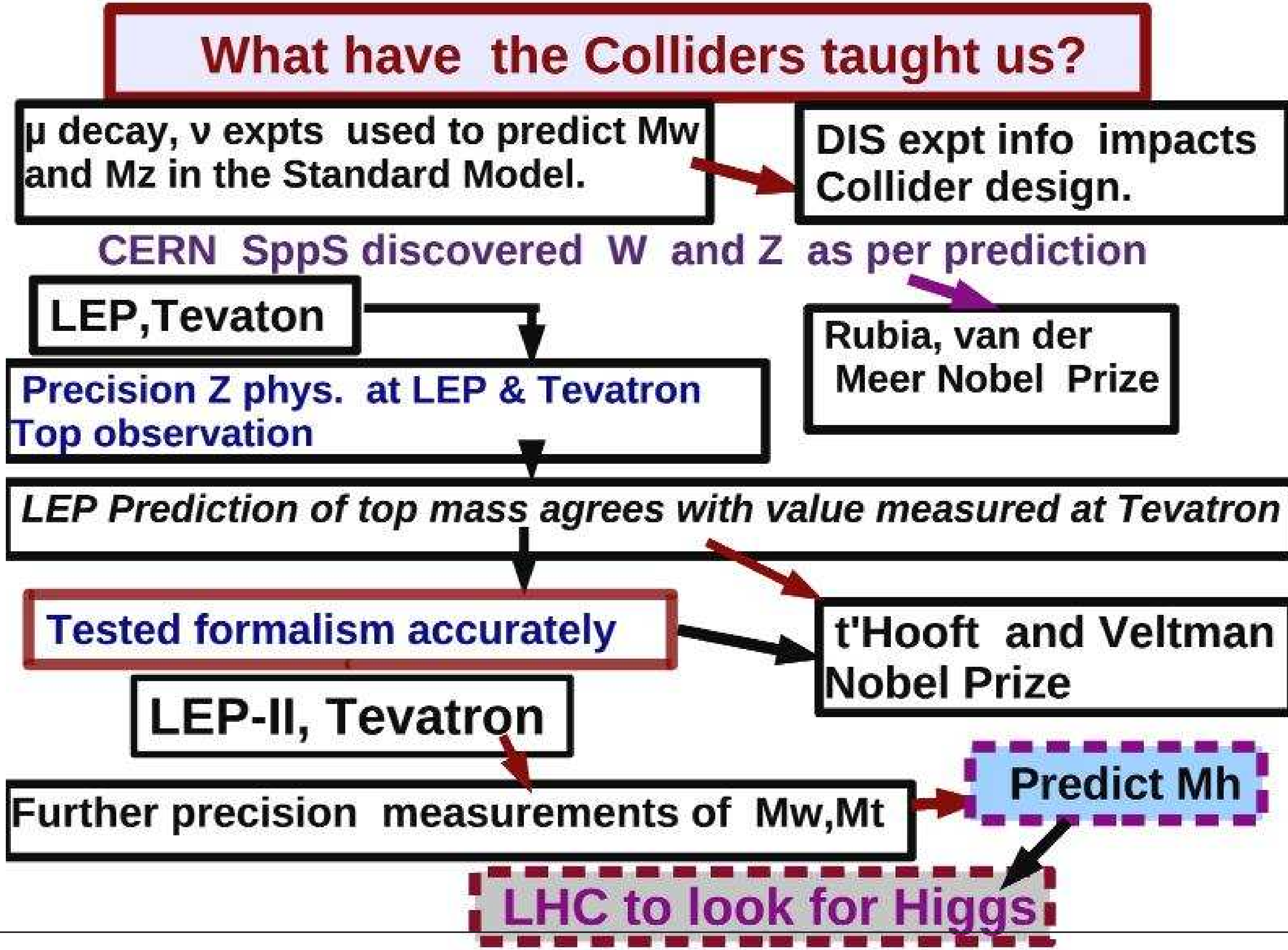
Hadronic colliders make broad sweep measurements

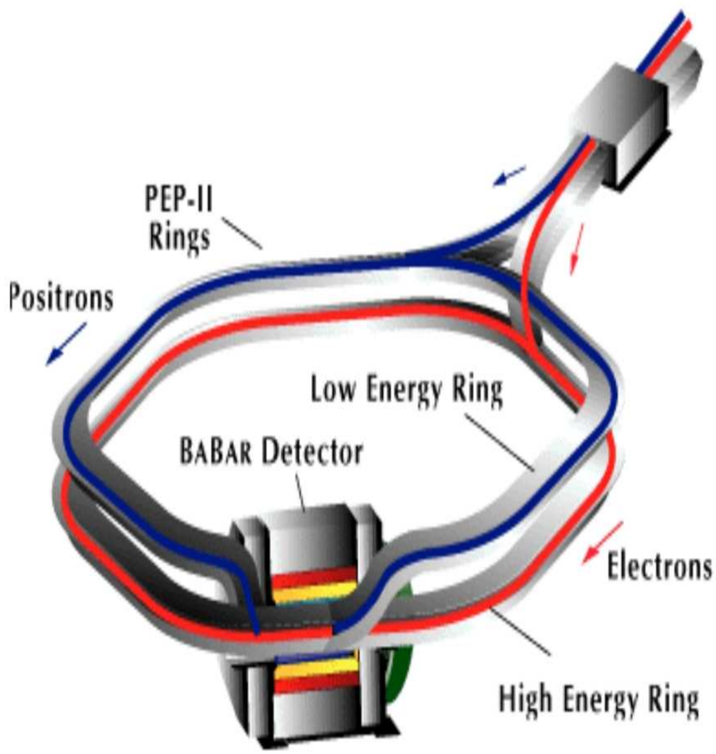
Leptonic colliders offered precision measurements

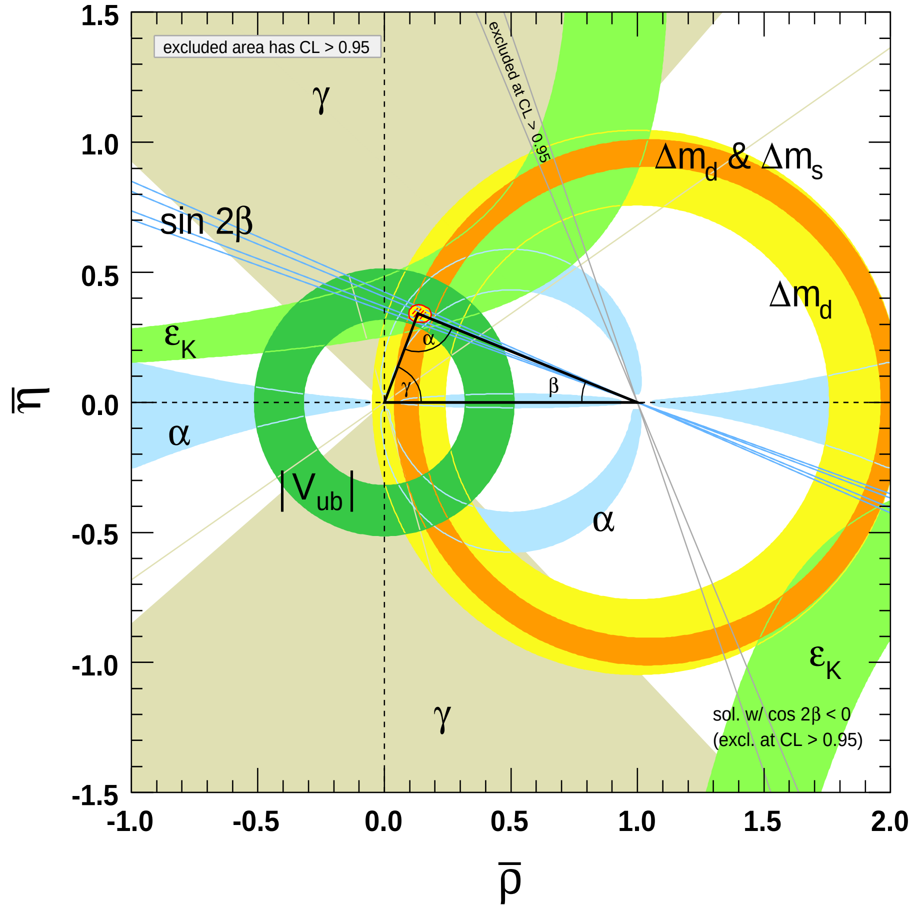
Both necessary for development


Flow of Physics info. between colliders
e+e- colliders
PP/P̄P colliders
(i) eP collider
(ii) ℓP, ℓA (ℓ = e, μ, ν)
Fixed Target expts.
SPEAR
J/ψ
Third generation
ISR (CERN)
jets + evidence for quarks.
SLAC
Parton structure
Fermilab
CERN
Revealed
PEP/PETRA
gluons
(strong Int. gauge Bosons)
SpP̄S
W/Z
discovery
Gauge Bosons of EW Theory


TRISTAN
QCD
CESR, DORIS
BABAR
B physics.
LEP I, II
Z, W
precision
physics
τ factories
Tevatron
HERA
Extended knowledge
of QCD, parton
structure of photon,
proton
(√s)^max e+e- = 190 GeV
(√s)^Tevatron pp ~ 2000 GeV
(√s)^HERA ep ≃ 300 GeV
Equivalent fixed Target
Ep ~ 50 TeV


What have the Colliders taught us?
μ decay, ν expts used to predict Mw and Mz in the Standard Model.
DIS expt info impacts Collider design.
CERN SppS discovered W and Z as per prediction
LEP,Tevaton
Rubia, van der Meer Nobel Prize
Precision Z phys. at LEP & Tevatron Top observation
LEP Prediction of top mass agrees with value measured at Tevatron
Tested formalism accurately
t'Hooft and Veltman Nobel Prize
LEP-II, Tevatron
Predict Mh
Further precision measurements of Mw,Mt
LHC to look for Higgs


PEP-II
Rings
Positrons
Low Energy Ring
BABAR Detector
Electrons
High Energy Ring


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
|V_ub|
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
η̄
ρ̄
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
2.0

At present we do not quite know the answer to the question 'Whither next'?

Following the 'discovery ' of the Higgs at the LHC, next logical step is to make precision studies of the properties of the Higgs.

Just like precision study of all the other particles in the SM gave information on the missing piece the Higgs, now one can learn about Beyond the SM(BSM) physics.

Can LHC offer high enough precision in the studies of the properties (mass, spin, parity) of the Higgs.

The energy scale for BSM seems to be high (initial LHC results) ☹

Historically baton has passed from hadronic to leptonic colliders and vice versa. So then may be it is the turn of high energy e^+e^- colliders.

- The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)
- This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

A postscript: In december 2015 we *MAY* have seen our first glimpse of BSM from the LHC!

Experiments with these machines helped us discover the physics at the heart of matter

LHC has given us our latest fundamental particle.

Is this now the end of the journey?

We need results from LHC to help us answer this query as well. Now we have some answers and weak pointers where to go ahead! **Look forward to run II for more!**

The mass of the observed state very very interesting from a lot of points of view!

Small enough to keep us still thinking of a mechanism like SUSY to stabilize it (case for a higher energy pp machine?)

and

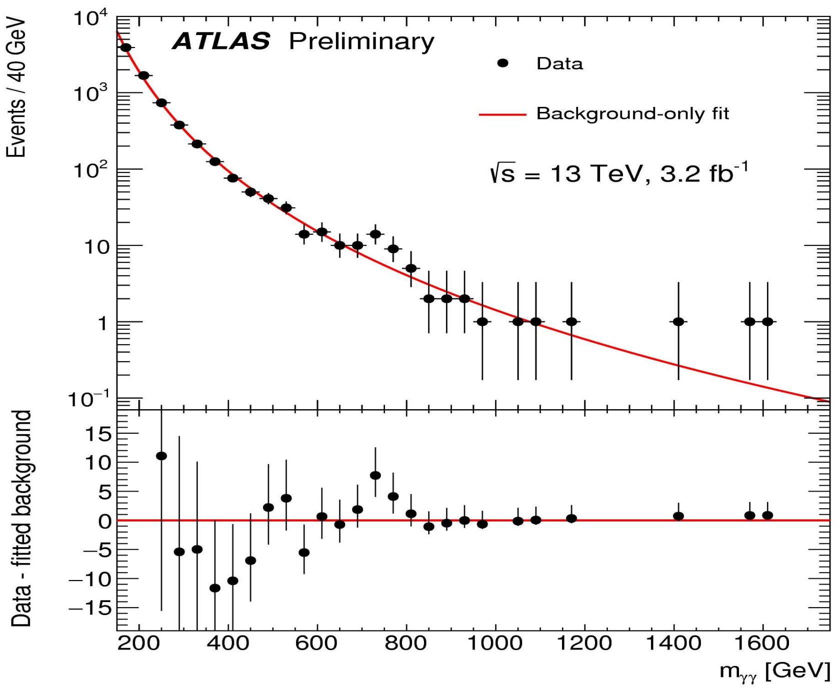
Large enough to make us wonder whether SM is the ONLY thing all the way to the Planck Scale! (strengthened by absence of any BSM signal!)**case for precision measurement?**

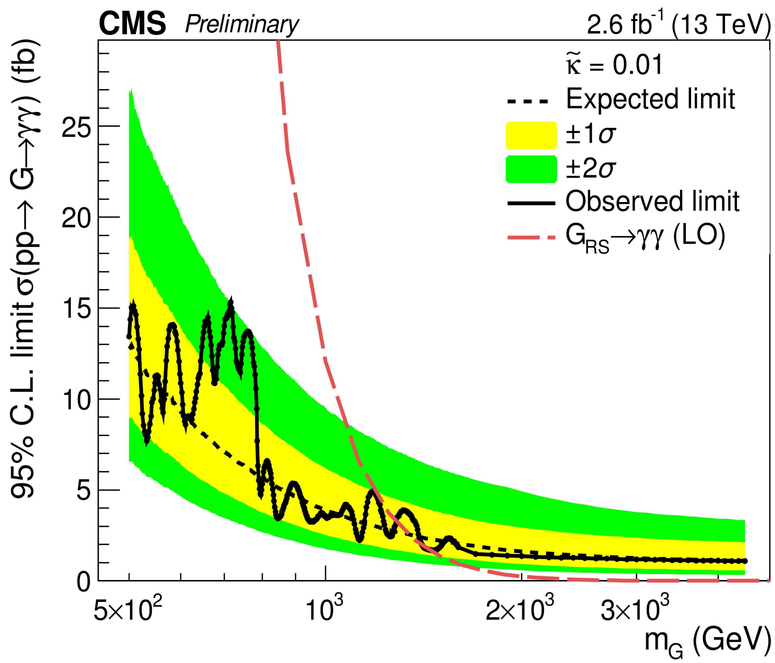
and

A unique value where decays into almost all final states are substantialGood for precision measurement

To all this a postscript to be added!

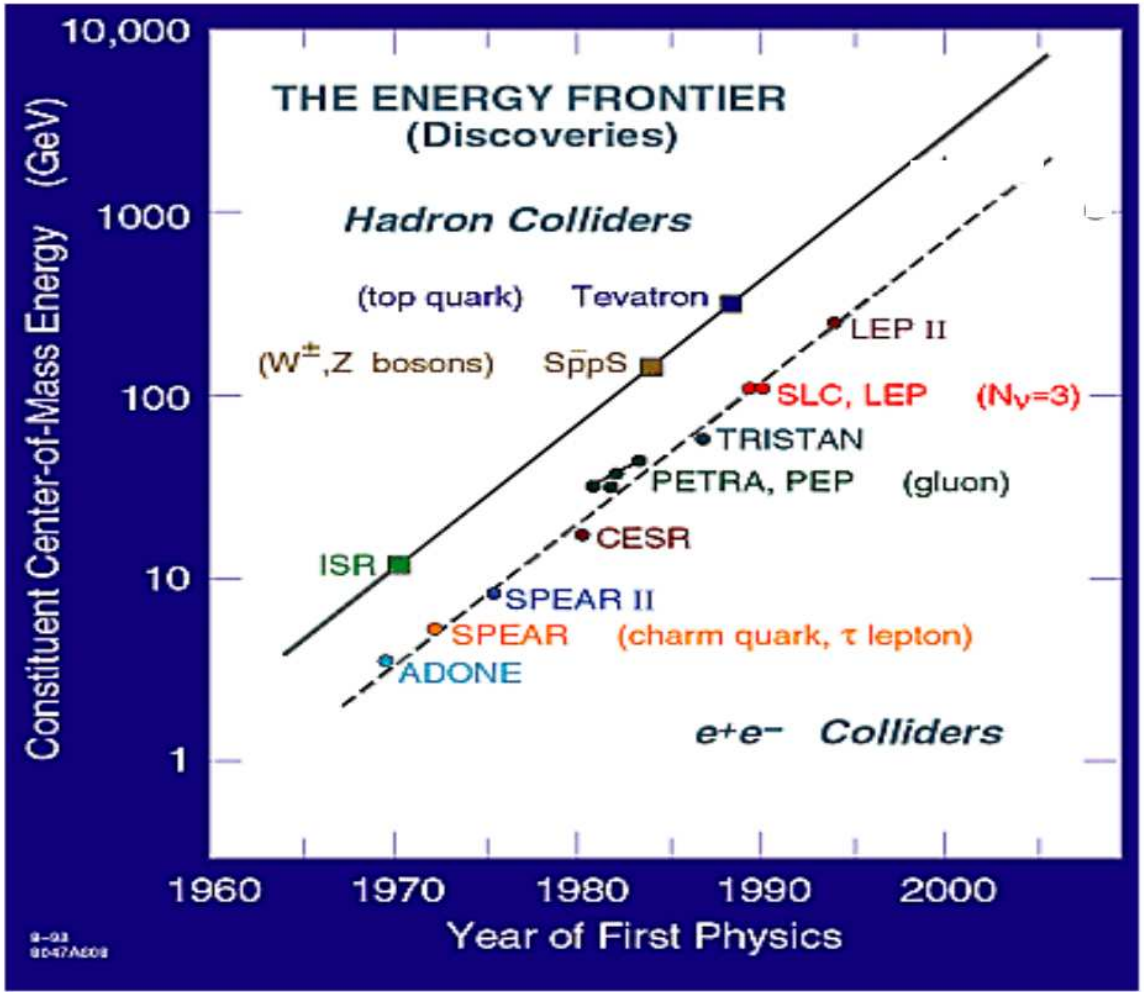
LHC Jamboree: LHC results at $\sqrt{s} = 13 TeV$ Lum. 3.2 fb^{-1} and 2.6 fb^{-1}.





ATLAS sees 3.9 σ local excess, **750** GeV, reduces to 2.3σ after LEE! Width $\sim$ 45 GeV, lower width possible.

Small width preferred, significance 2.6σ at **760** GeV, reduces to 1.2σ after LEE. Analysis targets spin 2. Consistency with 8 TeV data?


THE ENERGY FRONTIER
(Discoveries)
Hadron Colliders
(top quark)
Tevatron
LEP II
(W±,Z bosons)
SppS
SLC, LEP
(Nν=3)
TRISTAN
PETRA, PEP
(gluon)
CESR
ISR
SPEAR II
SPEAR
(charm quark, τ lepton)
ADONE
e+e− Colliders
10,000
1000
100
10
1
Constituent Center-of-Mass Energy (GeV)
1960
1970
1980
1990
2000
Year of First Physics

Hadronic colliders can make precision measurements too!

Example: M_W (Tevatron)

Case for High Luminosity LHC!

Make use of the precision of e^+e^- colliders to study Higgs and top sector with high precision!

Should we push to increase the energy frontier of hadronic colliders further?

13/14 TeV LHC!

High Luminosity HL 13/14 TeV : 3000 fb^{-1}

LHeC : Electron-proton collider with $E_p = 7$ TeV and $E_e = 50 - 120$ GeV.

Far future: HE 100 TeV?

ILC: 250 GeV, 500 GeV and 1 TeV: Interesting developments in Japan!

FCC: future circular colliders: FCC(ee) upto 350 GeV

Same tunnel : 100 TeV pp and also high energy eP?

Chinese: thinking seriously about the FCC!

On the intensity front : Super Belle. Will provide precision information on flavor physics!

Colliders:

Current knowledge provides the physics justification, motivation for the next machine. The physics case as one would like to call it.

a)It provides the goals for the accelerators in terms of energy and luminosity

b)It provides goals for the measurements that the detectors must be capable of

There has been a world wide process over last 10 years

Americas, Asia and Europe made Road Maps.

Now we need to decide which fork in those road maps will be most useful!

European Strategy Group had many Asian and American members (global effort)

Japan is pushing for the ILC project.

Any project has to be global!

The Physics Case for an e+e- Linear Collider

James E. Brau, Rohini M. Godbole, Francois R. Le Diberder, M. A. Thomson, Harry Weerts, Georg Weiglein, James D. Wells, Hitoshi Yamamoto

This document presents an overview of the physics potential of a future electron-positron linear collider. It represents a common input from the CLIC and ILC communities.

Comments: Submitted to the Open Symposium of the European Strategy Preparatory Group, 10-12 September 2012, Krakow, Poland, 15 page limit.

arXiv:1210.0202 [hep-ex]

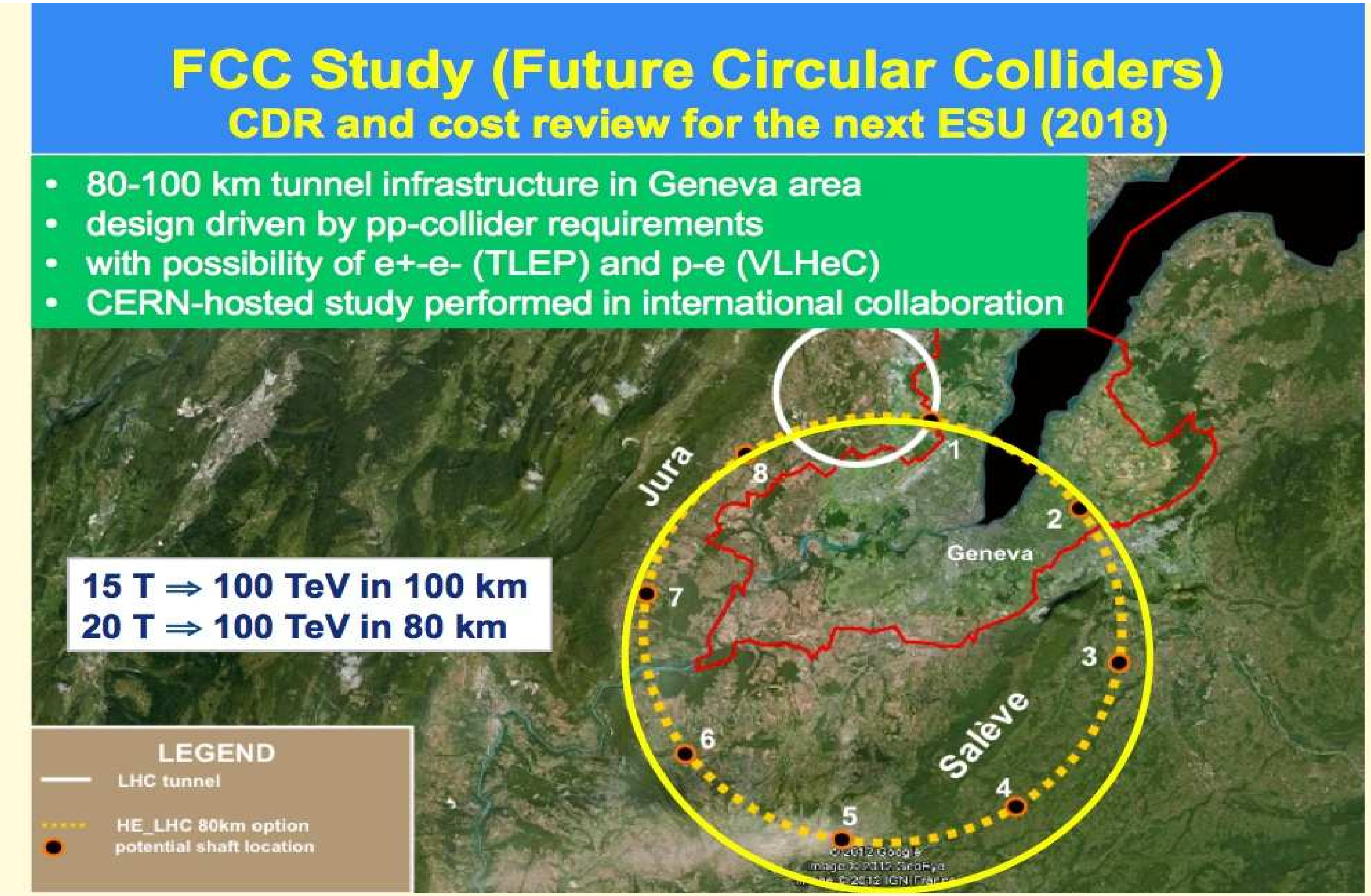
Now various 'white papers' have come out of the US Snowmass papers.

Europe, Japan seems strongly in favor of a staged, e^+e^- at present with possibilities of CLIC, $\gamma\gamma$ colliders etc. to be decided by physics discoveries of the next decades.

Japanese Government has sanctioned in its budget 'ILC designated' budget to evaluate feasibility of an **International project**.

USA, China, Europe: studying the possibilities of a circular electron-positron collider: FCC

Support for ILC in the HEPAP report as well as in European Strategy report!


FCC Study (Future Circular Colliders)
CDR and cost review for the next ESU (2018)
• 80-100 km tunnel infrastructure in Geneva area
• design driven by pp-collider requirements
• with possibility of e+-e- (TLEP) and p-e (VLHeC)
• CERN-hosted study performed in international collaboration
15 T ⇒ 100 TeV in 100 km
20 T ⇒ 100 TeV in 80 km
Jura
Geneva
Salève
1
2
3
4
5
6
7
8
LEGEND
LHC tunnel
HE_LHC 80km option
potential shaft location

UNIVERSITÉ DE GENÈVE FCC

Future Circular Collider Study Kickoff Meeting

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

Search

Future Circular Collider Kickoff Meeting

International Workshop on Future High Energy Circular Colliders

16-17 December 2013
IHEP

FCC (hh) is the goal, FCC(ee) on the way!

What is required:

A 80-100 km Tunnel

(Talk at ICHEP by R. Tenchini, 1412.2928): Requires 1/4 RF power of LEP with an increase in radius by a factor 3 and total power consumption 5 times that of LEP for energy of 240 GeV.

A Working group formed to discuss , compare and contrast the capabilities of different machines!

Centre for Future High Energy Physics: CFHEP Design and physics potential studies for future circular colliders. A Higgs factor with $\sqrt{s} = 240$ GeV and then a high energy pp machine.

Regular workshops: so far two have taken place.

See for details the webpage and talk by Yifang Wang at the ICFA seminar in Beijing in October 2014.

We want precision in the SM sector: why? If there are anomalies hiding in tall 'elephant grass' we need to have pinpointed search lights! A very tough ask to decide whether the deviations are statistically significant!

We want precision determination in the Higgs sector: Not just the signal strengths μ, but also the tensor structure of the vertices. The latter can provide model independent studies of the BSM in terms of effective operators!

We want precision determination of the top sector! mass and the strength and the structure of Yukawa coupling of the top!

Precision determination of m_t and m_h necessary to conclude about possible scale of 'BSM'!

We want precision prediction for the Higgs mass: recent progress has a big effect on analyzing implications of observed Higgs mass for SUSY. 'Invisible' decays of the Higgs!

Precision determination of the K, D and B physics and probing the BSM through these effects!LHCB, Super Belle and Kaon Factories.

Light Higgs still keeps one hopeful of seeing some new physics which should stabilize the Higgs mass without too much 'fine tuning'.

How much fine tuning is too much? somewhat subjective

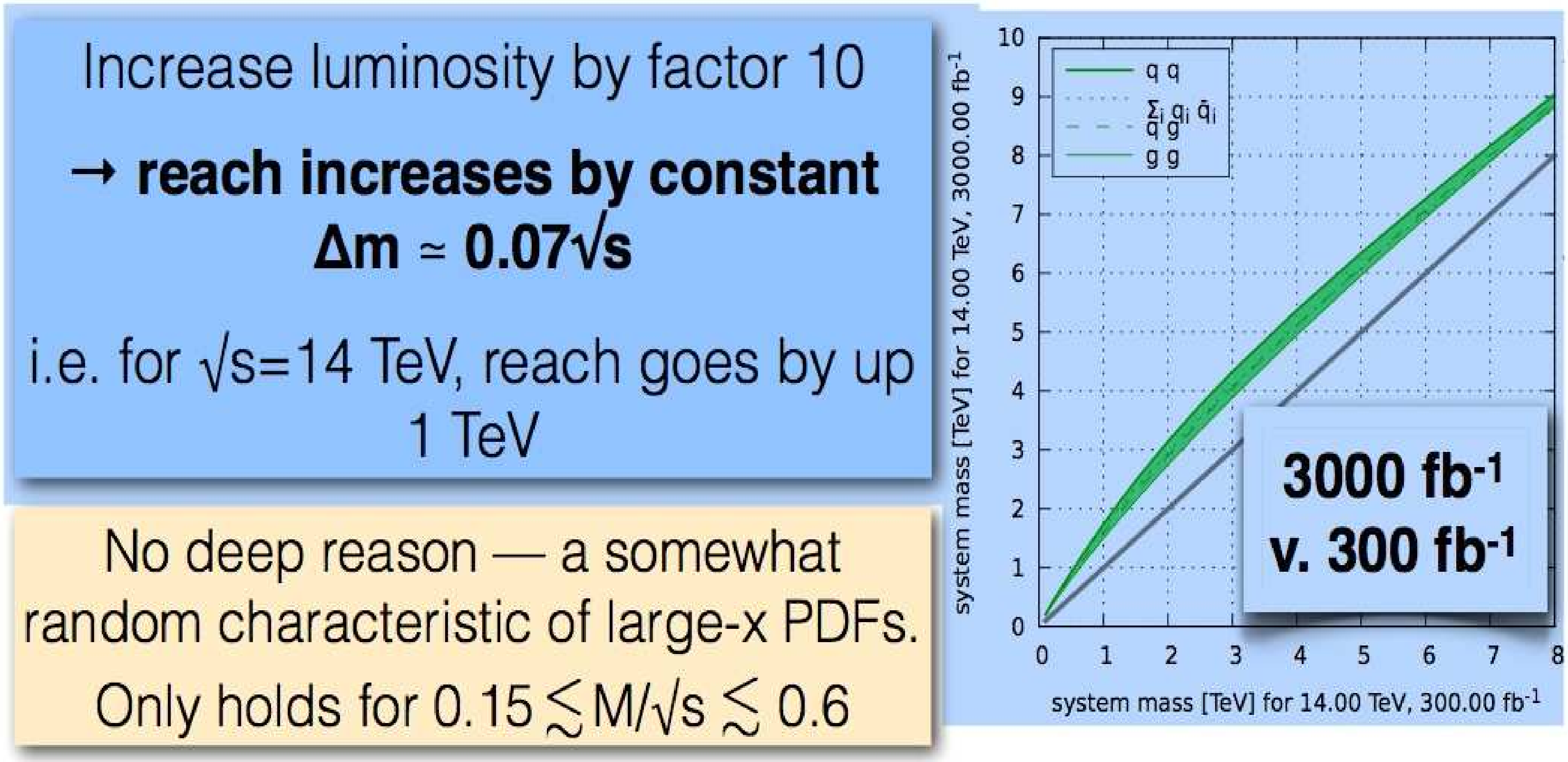
How does reach (for example) for SUSY increase with increasing Energy and increasing luminosity?

What does it mean if 750 GeV excess is confirmed as a resonance?

Rule of thumb for hadronic colliders?

Increase the energy by a factor 2 and luminosity by a factor 4, reach in M increases by a factor 2.

At a given energy increase in luminosity by a factor 10, reach seems to go up by $\Delta m = 0.07\sqrt{s}$ where Δm is the mass difference between the parent and daughter particles!



From a slide from G. Salam for a FCC workshop

Flavour physics constraints and precision study may push scale of new physics very high! Then a higher energy hh machine would be the only option!

Arkani Hamed argues that for him the expected SUSY reach at a 100 TeV collider will be at the edge of fine tuning he thinks is 'natural' !

The expected fine tuning if 100 TeV collider should find SUSY at that scale, it will be one part in 10^4

US: Snowmass studies.

Comparisons of HL LHC, FCC(ee) , ILC and CLIC!

FCC(ee) : Lower energy than ILC, can cover precision study of Higgs and $t\bar{t}$ in the second stage. Extension to higher energy to cover $t\bar{t}h$ seems a bit too expensive for the circular option.

Higher luminosity, so precisions for FCC(ee) almost always better than even ILC.

FCC (hh) requires magnetic fields of about 15-20 Tesla. This is about twice the current values.

Chinese option for FCC is looking at (right now) only the option with energy unto 240 GeV.

More than two decades required to achieve the performance for the beam and acceleration gradient that is required for the ILC to deliver!

This is the typical time scale!

So we have:

LHC: 13 TeV: current

SuperBelle : certain.

LHC(HL): Quite certain

ILC: Technology available and can be undertaken once money is available.

FCC (ee) and FCC(hh) seem more the 'future' machines: two or three decades in future.

Inclusive "SM" cross sections

Examples

	$\sigma(pp \to W^+W^- + X)$ [pb]	SM NLO [pb]
4.6fb^{-1} ATLAS 7 TeV	$51.9 \pm 2.0 \pm 3.9 \pm 2.0$	$44.7^{+2.1}_{-1.9}$
4.6fb^{-1} CMS 7 TeV	$52.4 \pm 2.0 \pm 4.5 \pm 1.2$	$44.7^{+2.1}_{-1.9}$
3.5fb^{-1} CMS 8 TeV	$69.9 \pm 2.8 \pm 5.6 \pm 3.1$	$57.3^{+2.4}_{-1.6}$
	stat syst lum	

Berryhill

~2σ off

>3σ if combined

Exptl syst's is theory dominated (jet veto efficiencies, PDFs, ...)

ATLAS, arXiv:1302.1283	$\sigma^{\text{ext-fid}}$[pb] Measurement	$\sigma^{\text{ext-fid}}$[pb] MCFM Prediction
	$N_{\text{jet}} \geq 0$	
$e\nu\gamma$	2.74 ± 0.05 (stat) ± 0.32 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$\mu\nu\gamma$	2.80 ± 0.05 (stat) ± 0.37 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$\ell\nu\gamma$	2.77 ± 0.03 (stat) ± 0.33 (syst) ± 0.14 (lumi)	1.96 ± 0.17
$e^+e^-\gamma$	1.30 ± 0.03 (stat) ± 0.13 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\mu^+\mu^-\gamma$	1.32 ± 0.03 (stat) ± 0.11 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\ell^+\ell^-\gamma$	1.31 ± 0.02 (stat) ± 0.11 (syst) ± 0.05 (lumi)	1.18 ± 0.05
$\nu\bar{\nu}\gamma$	0.133 ± 0.013 (stat) ± 0.020 (syst) ± 0.005 (lumi)	0.156 ± 0.012

Wγ: ~ 2σ off

Zγ: OK to < 1σ

- **How far can we take similar discrepancies, should they increase to the 3σ level and be confirmed at 14 TeV ? *They could be hiding charginos, sleptons, ...***

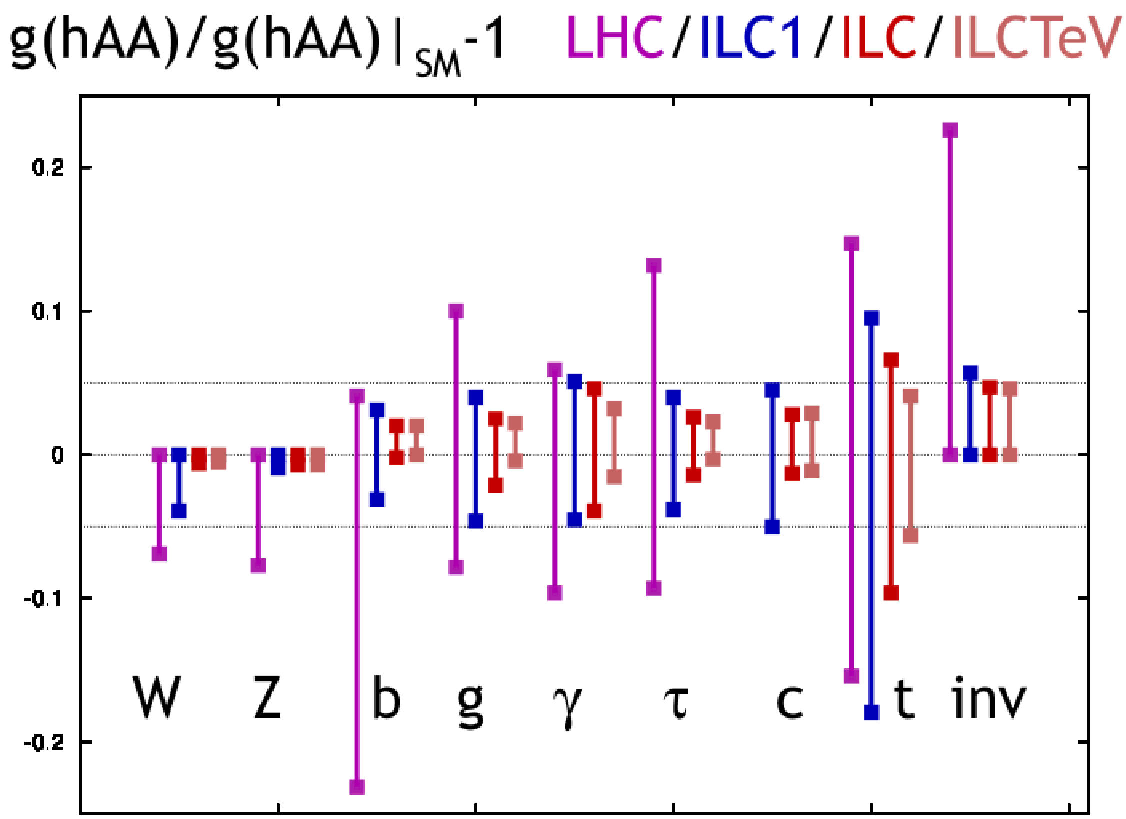
- **They appear to be syst limited: what more can be done to reduce the syst?**

17

Known right now to about 20%.

Precision measurement necessary!

1207.2516 :
M. Peskin



The knowledge of theory effects essential in deciding whether we have a smoking gun signal for BSM, especially when it is **indirect**.

Assumption about theoretical systematic aggressive. Would require NNNLO and above calculations.

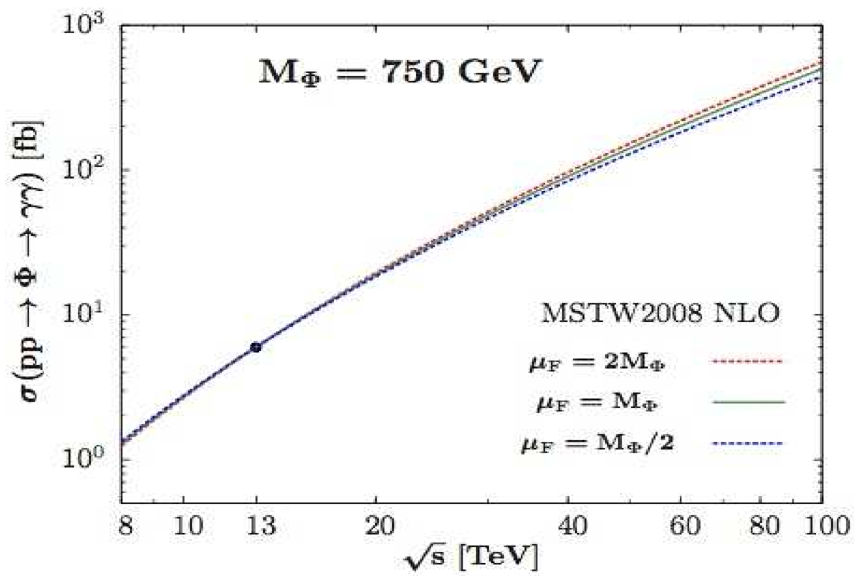
What does it mean for all these future colliders if there is a 750 GeV resonance?

It will light up the particle world!

With A. Djouadi, J. Ellis and J. Quevillon, arXiv:1601.03696

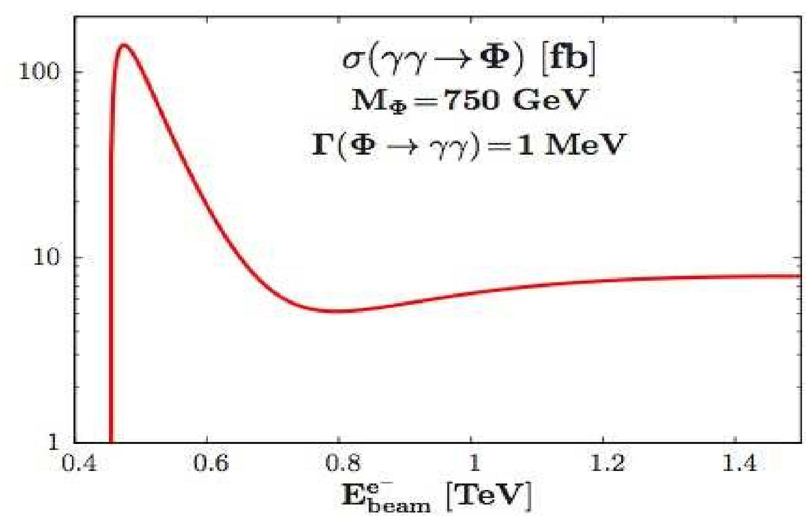
From 1601.03696: if the 750 GeV is a singlet

Reproduce Φ resonance in pp:
same prod. process $gg \to \Phi\gamma\gamma$
grows with the gluon luminosity



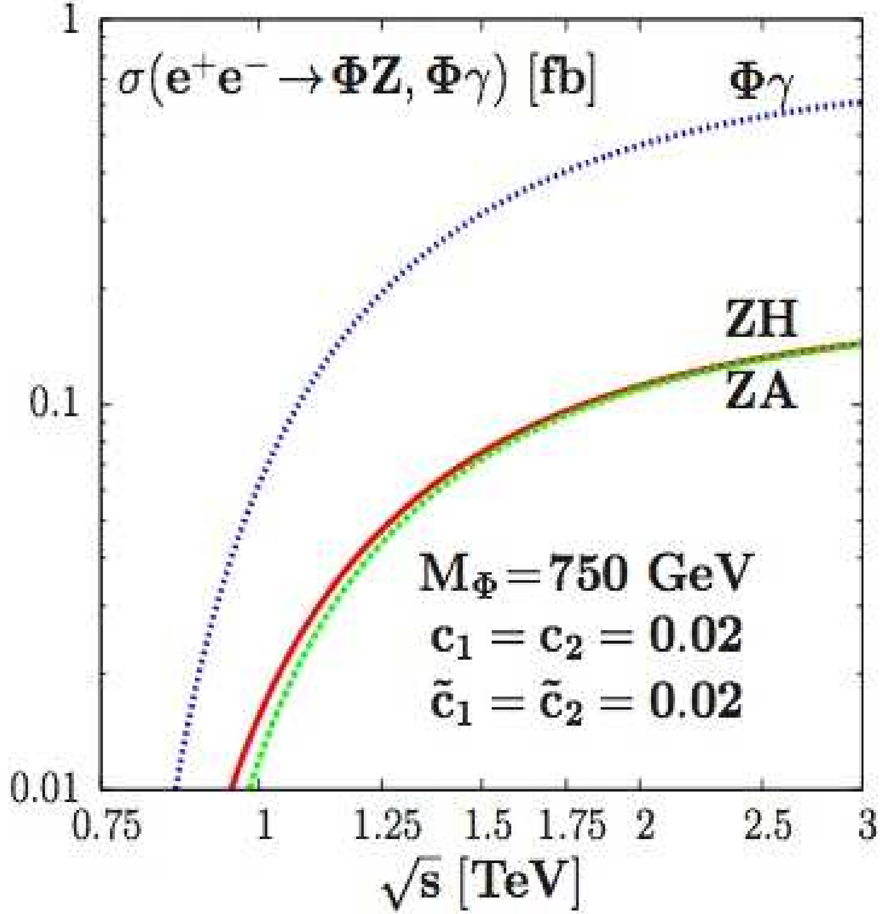
Ideal for HE-LHC, FCC-hh, SPPC
2 orders magnitude more at 100TeV
check other WW,ZZ,Zγ final states.

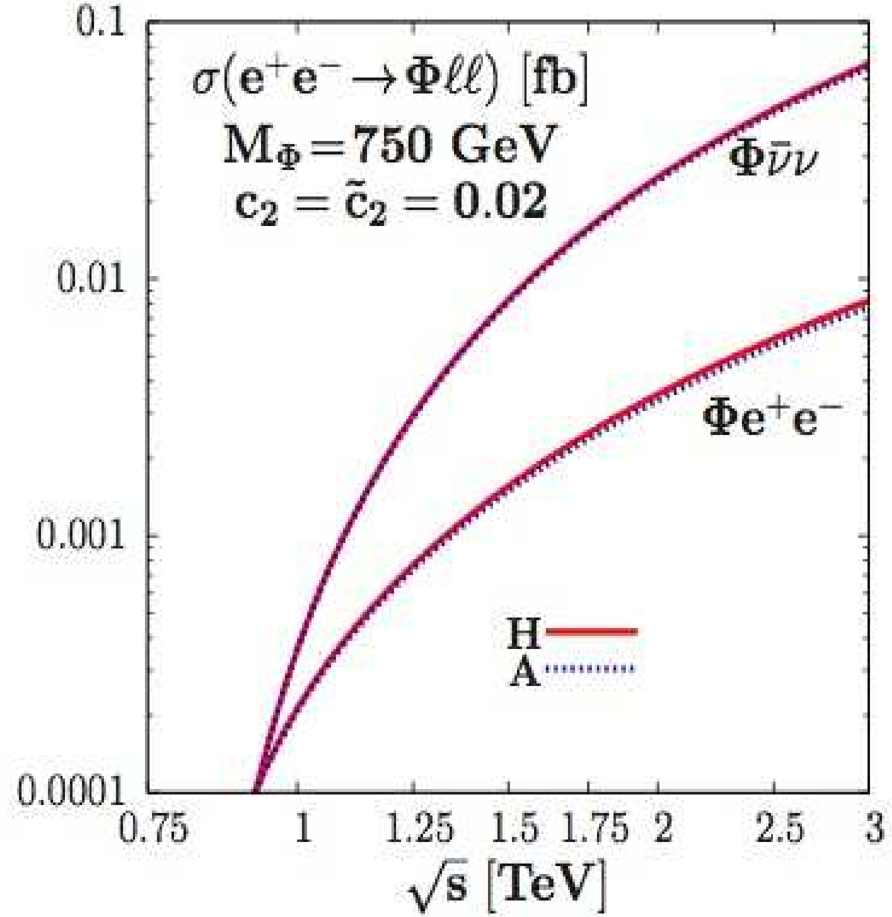
Future e+e- HE linear colliders
can be turned into $\gamma\gamma$ colliders
80% energy and same luminosity
$\Rightarrow$ Φ production in $\gamma\gamma \to \Phi$



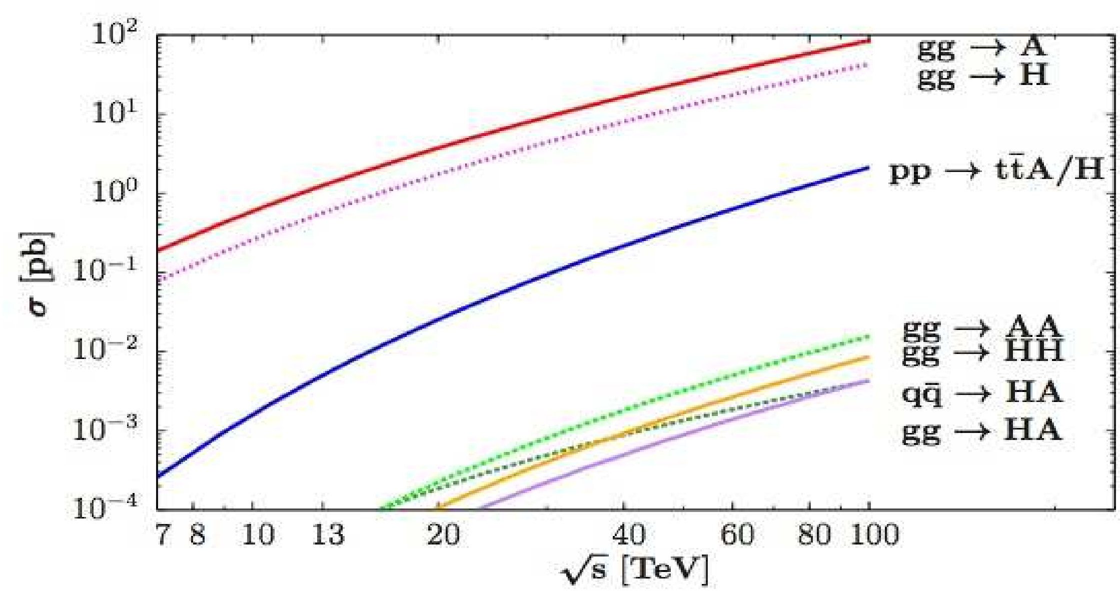
Ideal machine for a diphoton state:
Measure precisely $\Phi\gamma\gamma$ coupling
Check CP properties of resonance.

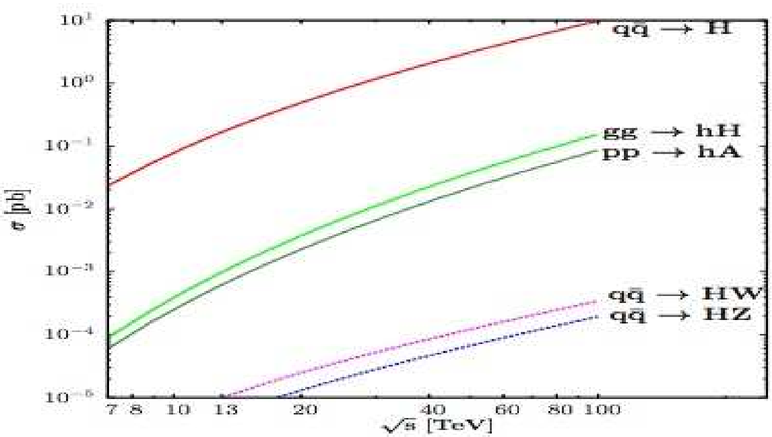
From 1601.03696:

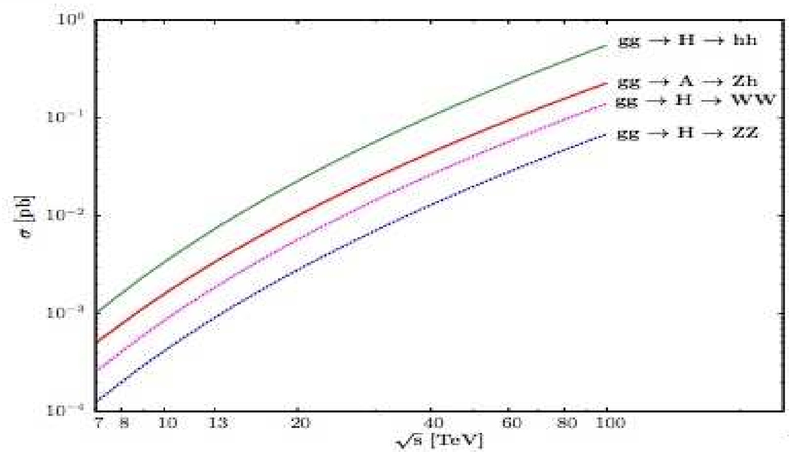




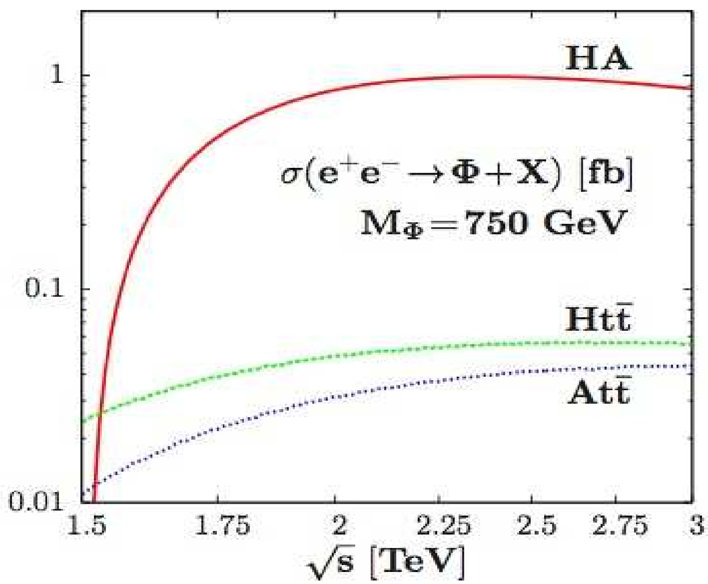
750 GeV : 2HDM

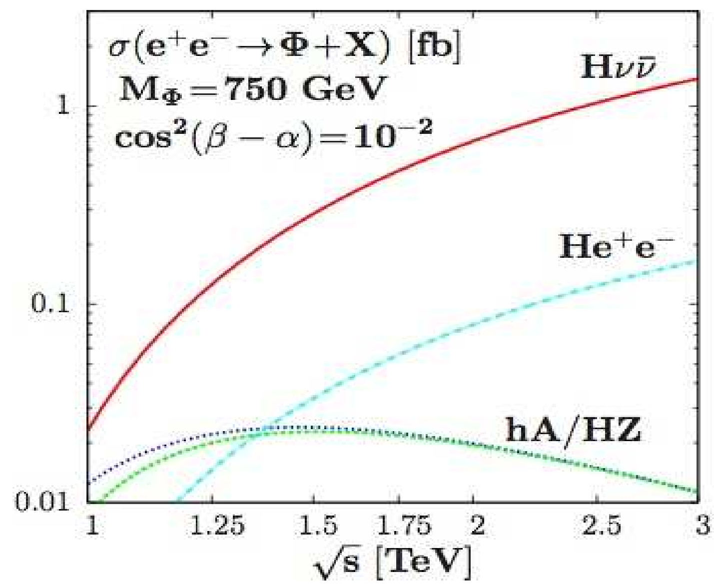

gg → A
gg → H
pp → $t\bar{t}$A/H
gg → AA
gg → HH
$q\bar{q}$ → HA
gg → HA
σ [pb]
√s [TeV]

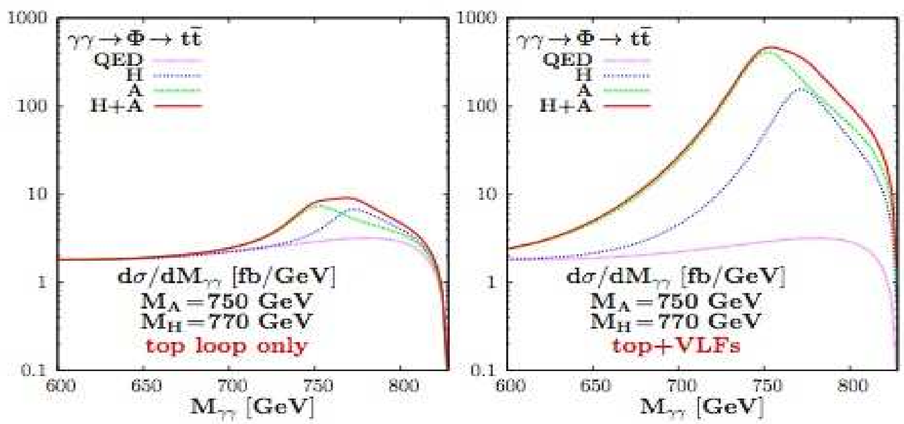

$q\bar{q}$ → H
gg → hH
pp → hA
$q\bar{q}$ → HW
$q\bar{q}$ → HZ
σ [pb]
√s [TeV]

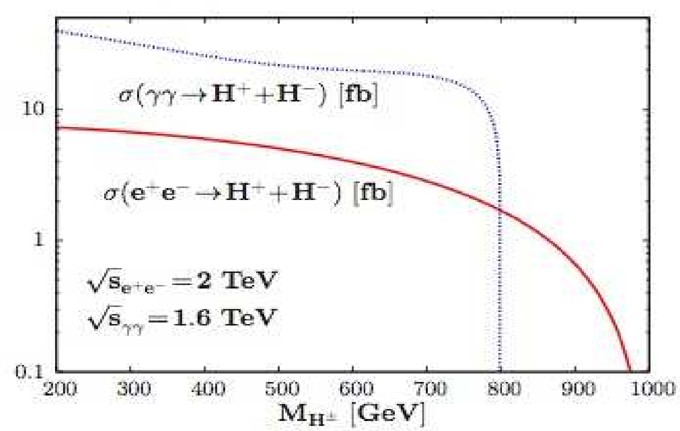

gg → H → hh
gg → A → Zh
gg → H → WW
gg → H → ZZ
σ [pb]
√s [TeV]

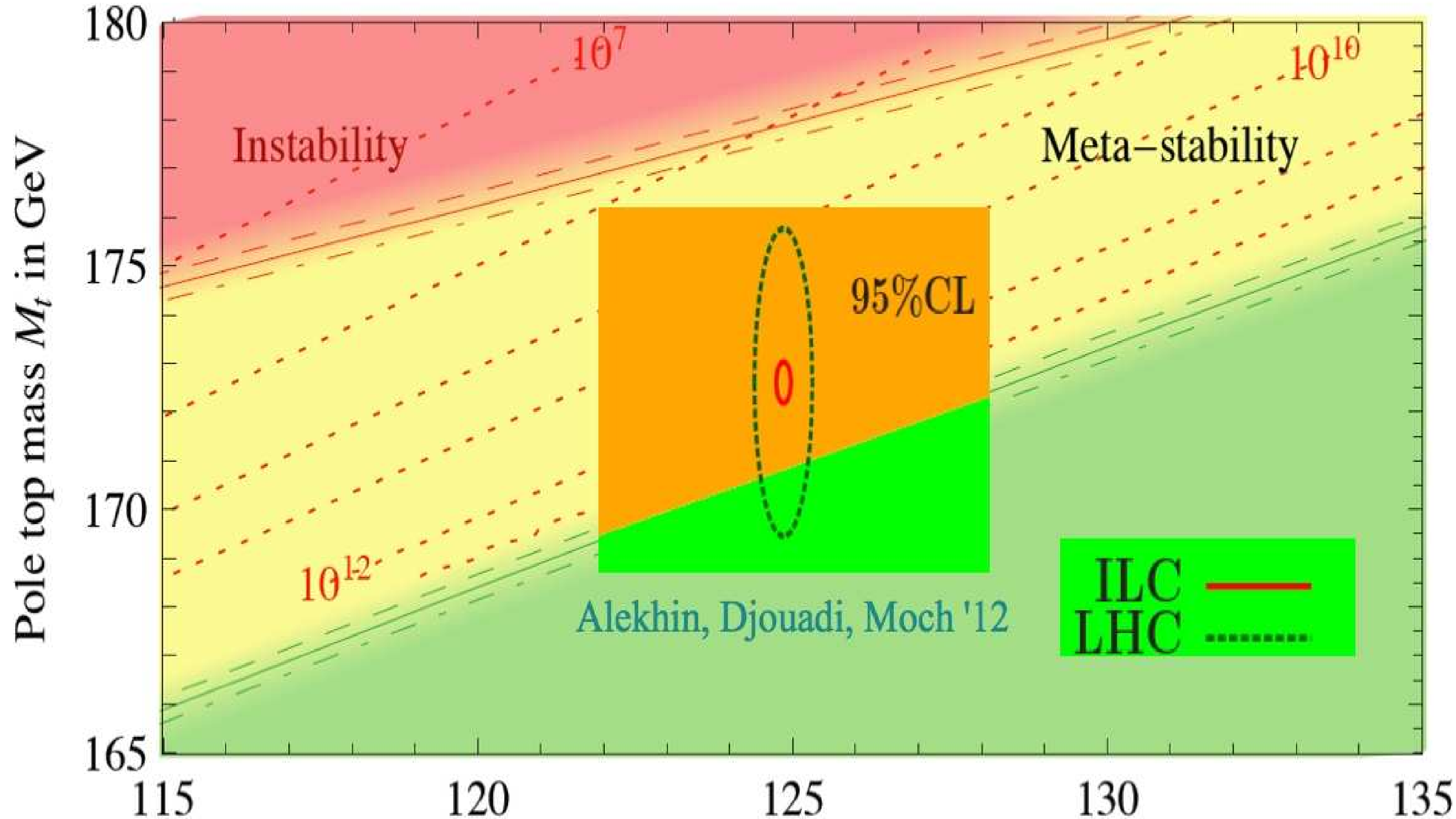
From 1601.03696










180
175
170
165
115
120
125
130
135
Pole top mass M_t in GeV
10^7
10^{10}
10^{12}
Instability
Meta−stability
95%CL
Alekhin, Djouadi, Moch '12
ILC
LHC

Earlier one thought that determination of J^{CP} of the boson will be a long term prospect.

But existence of the $h \to ZZ^*$ allowed this determination.

Determination of the J^{PC} quantum numbers about as 'certain' as India losing test series abroad!

What is important and difficult is to find if there is a CP mixing!

This is where perhaps the Linear Collider can really score!

Of course one wants to find out what LHC can do too!

In general e^+e^- colliders can do well here.

For establishing the $J^{PC} = 0^{++}$ as well as for measuring the CP mixing if it is not a CP eigenstate.

At electron-positron colliders using polarisation one can do even better.

In the units mentioned in the effective Lagrangian approach these will correspond to sometimes $\Lambda \lesssim 1.5$TeV and the LHC numbers to about $\Lambda \sim 400 - 500$ GeV.

New suggestions for studying CP violation in the HVV vertex using HV production (e.g. K.Mohan, R.G., Miller and White: hep-ph/1306.2573, hep-ph/1409.5449)

With HL option one can reach $\Lambda \sim 800 GeV$

Can measure also $t\bar{t}h$ coupling directly including the CP structure unambiguously! $e^{+}e^{-} \to t\bar{t}H$ has a different threshold rise for scalar and pseudoscalar: ZPC 71, 1681 (**For example** : R.G. M. Muhellleitner, etal) Can even measure/bound CP mixing in Higgs without ambiguity!

So where does the road go?

Is this the END?

It is not even beginning of the end !

If at all only the end of a beginning

☺

LHC run II all important!

Connections with Cosmology : Some can be tested through precision measurements at the Colliders! for example the **Invisible branching ratio** of the Higgs.

The Higgs mass and (in)stability of the Vacuum may say something about high scale physics and *MAY* have connections to some Planck Scale physics ideas!

The progress has to come through the joint investigations on the earth and in the sky!

So Colliders will do their bit! By precision measurements: either at hadronic colliders or at leptonic colliders!

LHC: 13 TeV: current

SuperBelle : certain.

LHC(HL): Quite certain

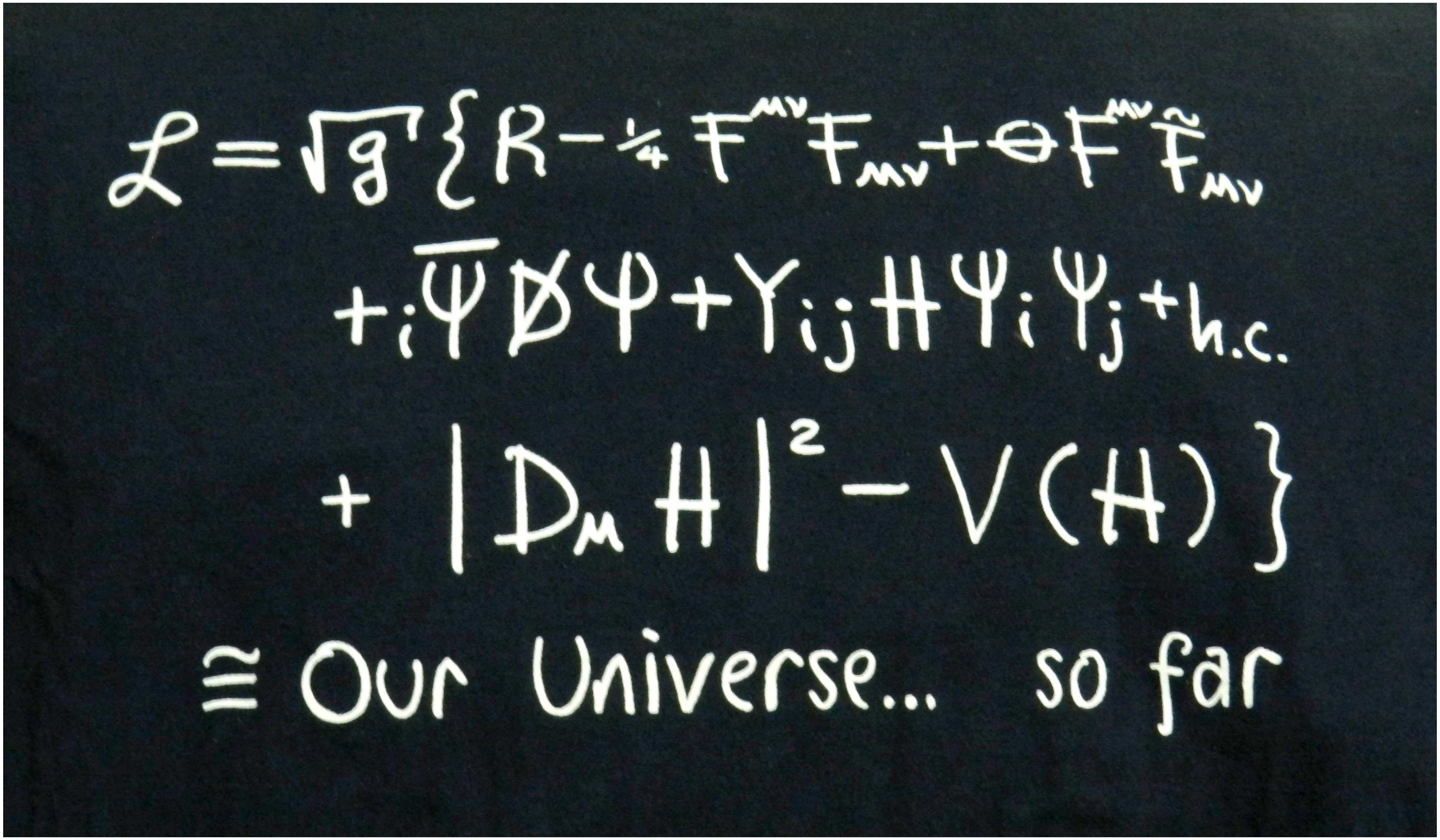
ILC: Technology available and can be undertaken once money is available. CLIC technology studies in advanced stage. (Linear Collider Board: LCB)

FCC (ee) and FCC(hh) seem more the 'future' machines: two or three decades in future.

Results form LHC 13 will play a role in deciding what we do!. May be in a few months we will have forgotten that we were agonizing over this 'absence' of new physics at LHC!

One thing for sure: we need precision calculations and precision measurements!

The road may be very long but colliders are not 'withering' just yet!


$\mathcal{L} = \sqrt{g}\{R - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \Theta F^{\mu\nu}\tilde{F}_{\mu\nu}$
$+ i\bar{\Psi}\not{D}\Psi + Y_{ij}H\Psi_i\Psi_j + h.c.$
$+ |D_\mu H|^2 - V(H)\}$
$\cong$ Our Universe... so far

- Existence of a light Higgs!
- Direct evidence for the nonzero ν masses
- Quantitative explanation of the Baryon Asymmetry in the Universe!
- Dark Matter makes up 30% of the Universe.!
- Inclusion of Gravity in the picture?
- Cosmological puzzles! Dark Energy! + understanding CMBR!

- **Stability of the EW scale under radiative corrections.**
- Unification of couplings
- Need to get a basic understanding of the flavour issue