Quo-vadis: Colliders? (Particle Physics?)

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- Current status of particle physics Presentation of the LHC paradox.

- How did colliders help us on this journey?

- What are the next steps? **Whither(how and what)**/Whether [*Wither?*] Colliders?

- Where next? through known unknowns (In the context of particular BSM models) and unknown unknowns(Model independent analyses).

P Chappatte/Globe Cartoon

Over the last decade three important experiments have presented us with historic discoveries which have firmed up our fundamental understanding of the universe functions and also how it came into being:

1) Discovery of the Higgs boson at the Large Hadron Collider (LHC). The last step towards establishing the SM

2) High precision cosmology with the PLANCK satellite. Further nailed down the standard model of Cosmology

3) Detection of Gravitational waves: Ultimate verification of Einstein's theory of gravitation.

i) How did colliders help us on this journey.

Ii) Implications of the Higgs discovery and (non) discovery of anything else! Mostly what does it say about our theoretical perceptions of both the SM and beyond!

iii) How do we go ahead and what role can the colliders play?

IIi) Indicate ways of probing the SM and BSM *indirectly* through the studies of Higgs and the heavy flavours t and b!

We have found a 'light' Higgs boson which looks/smells like a SM higgs boson but no NP which we thought must exist to keep the Higgs light!

Particle physics finds itself in a very peculiar place.

To steal from 'A tale of two cities': (Apologies to Charles Dickens!)

It is the best of times , it is the worst of times

It is the epoch of belief , it is the epoch of incredulity

It is the season of 'Light' , it is the season of Darkness

It is the spring of hope, it is the winter of despair

We have everything before us, we have nothing before us.

We have found the SM Higgs, proved the SM, we have no glimmer of BSM that the Higgs properties promise!

So we all can feel a bit like Lord Kelvin who thought that

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

Mere mortals today:

All that remains is **more and more precise measurement** of the Higgs, top properties and B decays *OR Higher and higher energies?*

One question : Is BSM only a theorists dream or do we have observations that force us to believe that BSM should exist?

- Dark Matter makes up 27% of the Universe.!

- Need quantitative explanation of the Baryon Asymmetry in the Universe!

- Observed Cosmic Acceleration.

- We have found a light Higgs boson at the LHC!

- We have direct evidence for the nonzero ν masses

- We feel the force of gravity but do NOT have a QUANTUM description!

A variety of mass generations:

1)Nonzero mass of the gauge boson: Spontaneous Symmetry Breakdown via the the celebrated Higgs Mechanism! Elegantly makes nonzero fermions masses also consistent with gauge invariance! The highly successful Standard Model!

2) Generation of the 'invisible' mass in the universe, picturesquely called the Dark Matter DM.

3) Mass of the Higgs boson itself! Why is it light?

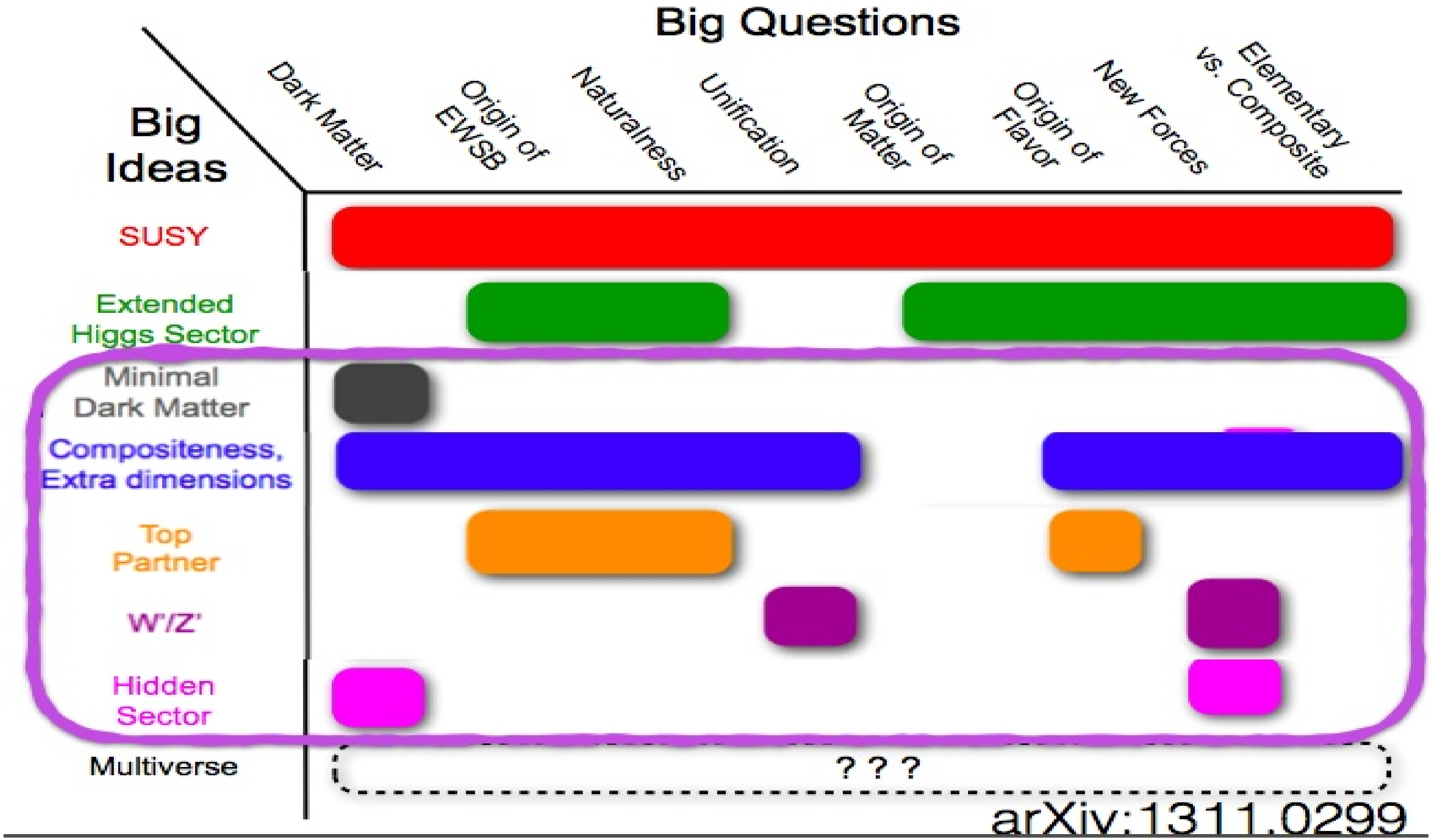
4)However the masses are generated at the cost of many more free parameters of the SM. Even worse they span at least 15 orders of magnitude!. No real understanding of the generation of this hierarchy of masses! The non zero masses of neutrinos has even more additional facets. flavour issue

All these require BSM ideas!!

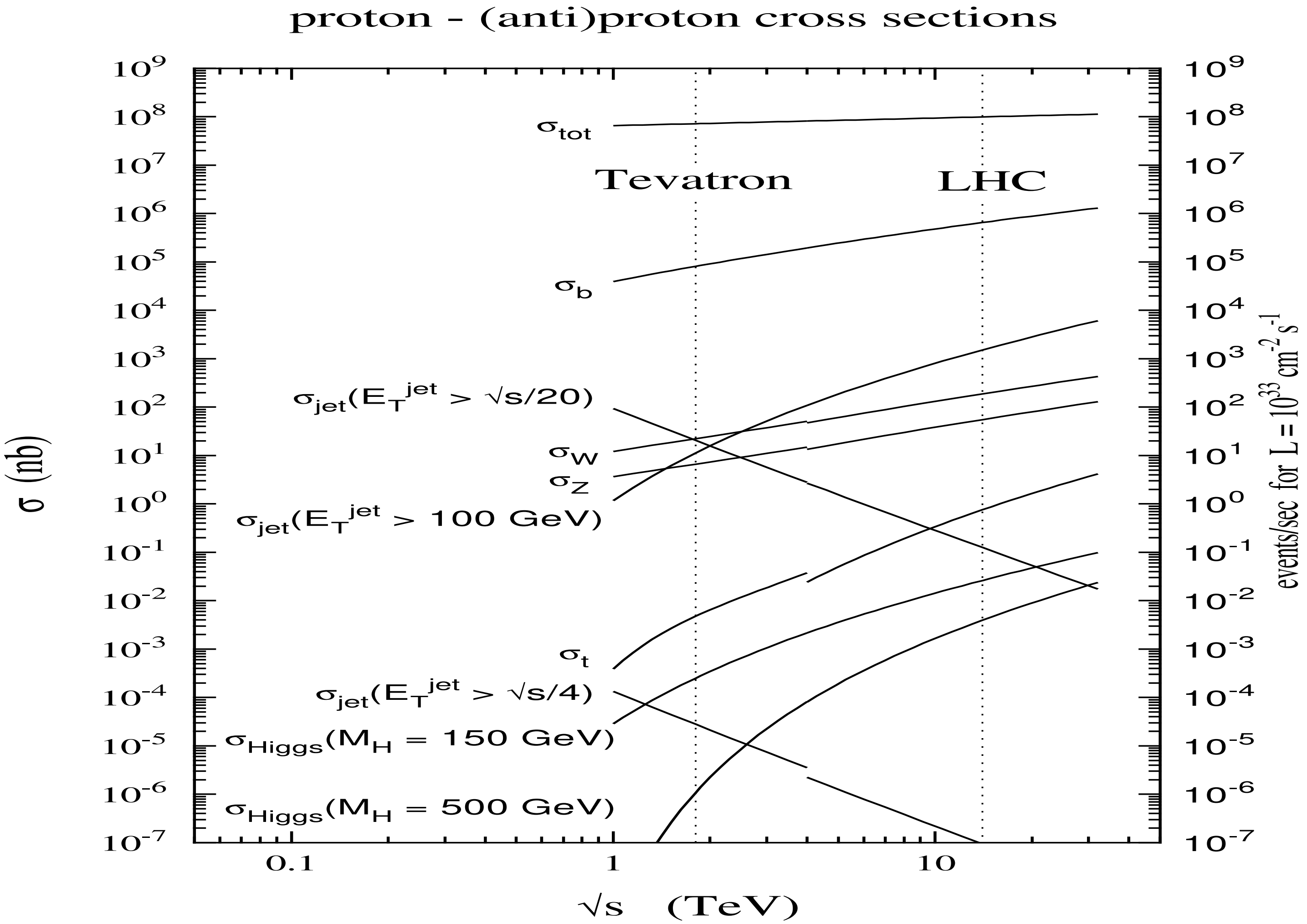
The last un-understood bit of mass is the generation of mass of the protong:

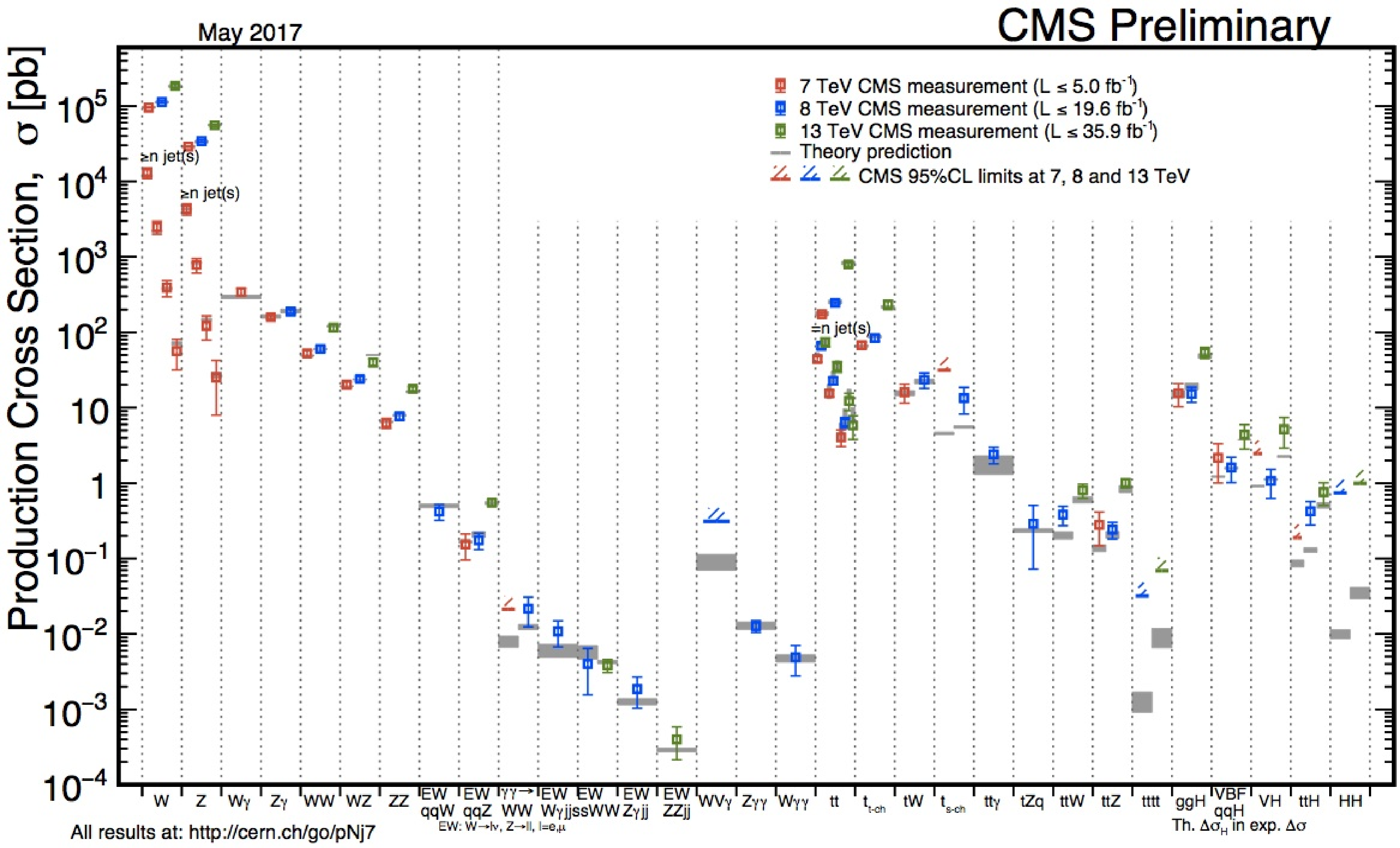
5) Generation of the mass of the proton! One of 8 problems in the list of Clay Mathematical Institute.

This is very much in the perview of the SM and not relevant for this talk! No 'in principle' new theoretical development seems to be necessary... we still can not compute it for sure! May be Lattice will deliver one day?


Big Questions
Big Ideas
Dark Matter
Origin of EWSB
Naturalness
Unification
Origin of Matter
Origin of Flavor
New Forces
Elementary vs. Composite
SUSY
Extended Higgs Sector
Minimal Dark Matter
Compositeness, Extra dimensions
Top Partner
W'/Z'
Hidden Sector
Multiverse
? ? ?
arXiv:1311.0299

SM works very well indeed!


proton - (anti)proton cross sections
σ (nb)
events/sec for L = 10^33 cm^-2 s^-1
√s (TeV)
0.1
1
10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
σtot
Tevatron
LHC
σb
σjet(ET^jet > √s/20)
σW
σZ
σjet(ET^jet > 100 GeV)
σt
σjet(ET^jet > √s/4)
σHiggs(MH = 150 GeV)
σHiggs(MH = 500 GeV)



CMS Preliminary
May 2017
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
13 TeV CMS measurement (L ≤ 35.9 fb-1)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
≥n jet(s)
≥n jet(s)
=n jet(s)
W Z Wγ Zγ WW WZ ZZ EW qqW EW qqZ γγ→WW EW Wγjj EW ssWW EW Zγjj EW ZZjj WVγ Zγγ Wγγ tt t t-ch tW t s-ch ttγ tZq ttW ttZ tttt ggH VBF qqH VH ttH HH
EW: W→lν, Z→ll, l=e,μ
Th. ΔσH in exp. Δσ
All results at: http://cern.ch/go/pNj7

Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016)

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.

H^0 MASS

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
125.09±0.21±0.11	[1,2] AAD	15B	LHC	pp, 7, 8 TeV

VALUE (GeV)		*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<1.7		95	[1] KHACHATRY...	15AM	CMS	pp, 7, 8 TeV
>3.5	$\times 10^{-12}$	95	[2] KHACHATRY...	15BA	CMS	pp, 7, 8 TeV, flight distance
<5.0		95	[3] AAD	14W	ATLS	pp, 7, 8 TeV, $\gamma\gamma$
<2.6		95	[3] AAD	14W	ATLS	pp, 7, 8 TeV, $ZZ^* \rightarrow 4\ell$

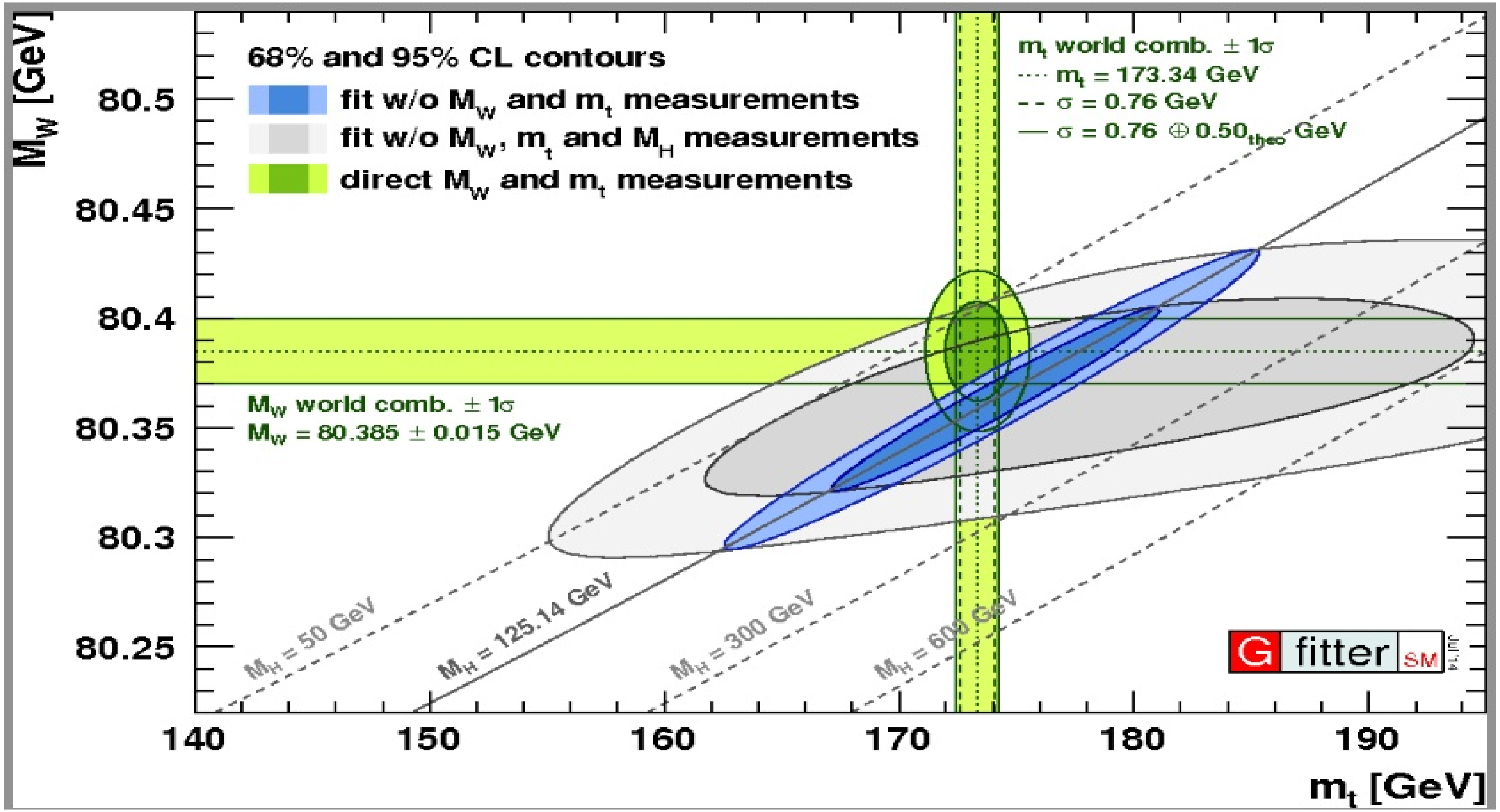
HTTP://PDG.LBL.GOV Page 4 Created: 10/1/2016 20:06

Next steps: couplings and CP! Still not in the PDG! Makes the case of precision measurements

Why did we believe the Higgs signal when it came first even if it was somewhat tenuous?

The signal had all the connections with the top that we expected the SM Higgs to have.

Note the intimate connection between the top and the Higgs!



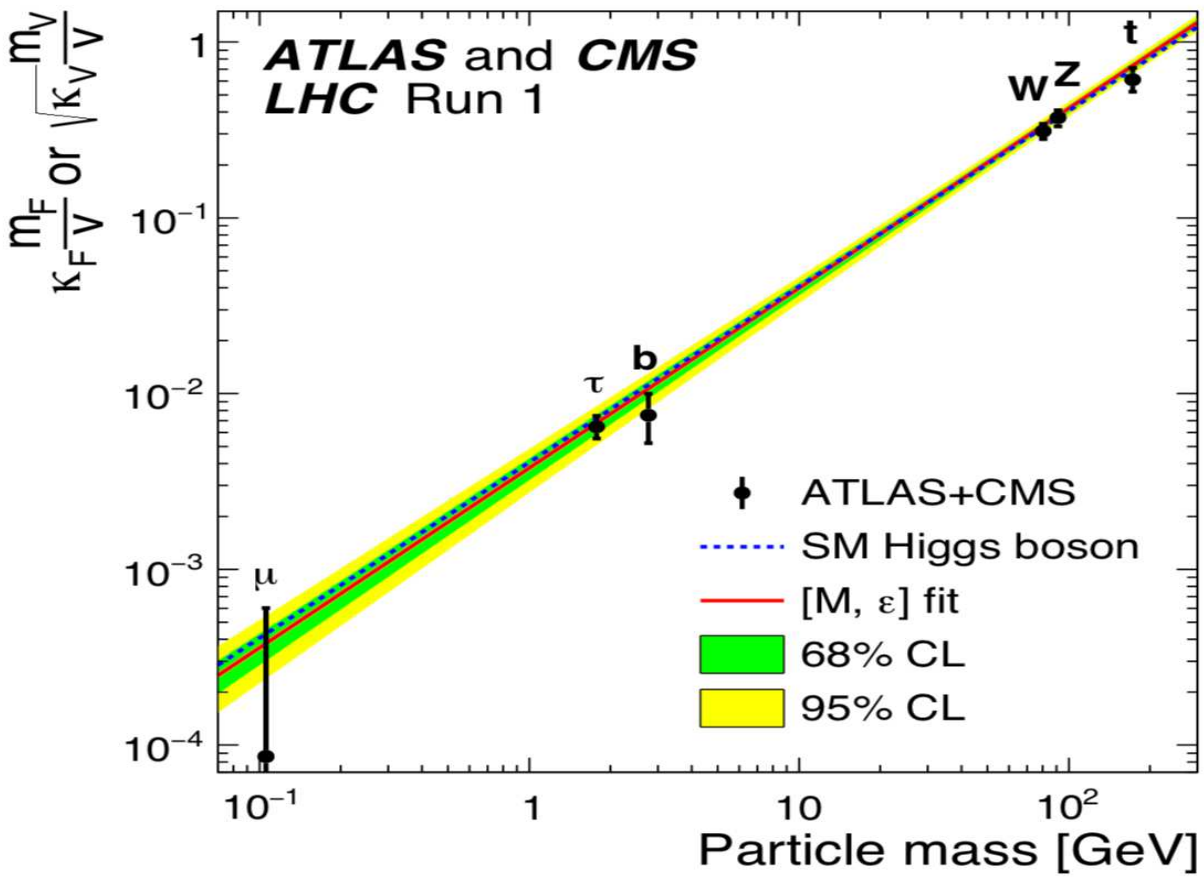
SM rocks! *At LOOP level* **Connection with top absolutely essential**

Three lessons to be learnt from the plot

1) SM works really spectacularly!

2) Space allowed for new physics contributions very limited. But this can be indeed the way to probe **BSM** ! Recall after all there was a time when top was not found and the mass was 'predicted ' from the same precision studies!

3) We know the Higgs mass as well (or better) as we will ever need for this exercise! **If anything we will need to increase precision of m_t and m_W to probe the BSM through this kind of plot.**. Makes the case for precision measurements of m_t, m_W: higher precision at the e^+e^- colliders. Compare HL LHC with e^+e^- machines!



From ATLAS + CMS combined analysis: 1606.02266 (published in JHEP)

Ideas like sequential chiral fourth generation were almost ruled out the day Higgs was discovered!

This was simply the result of the fact that the ggh lcoupling induced by heavy fermions is non decoupling in nature.

However vector like fermions are still very much allowed. Vector like Fermions: This is a BSM that is present quite often in Brane world models.

Observed Higgs mass is small enough to believe in SUSY miracle. It also implies that Sparticle masses need to be large ! Which is consistent with the fact that we have not seen any so far!

Extended Higgs sector: additional doublets/singlets preferred but doublets have to be 'aligned'! This comes NOT from higgs mass but its couplings! **2HDM**. Perhaps one model under the least tension!

In composite Higgs models (SILH)JHEP 0706 (2007) 045, the observed Higgs mass implies lower scales for BSM, but nothing seen at that scale. The basic idea under tension and needs extension!

The mass of the observed state very very interesting!

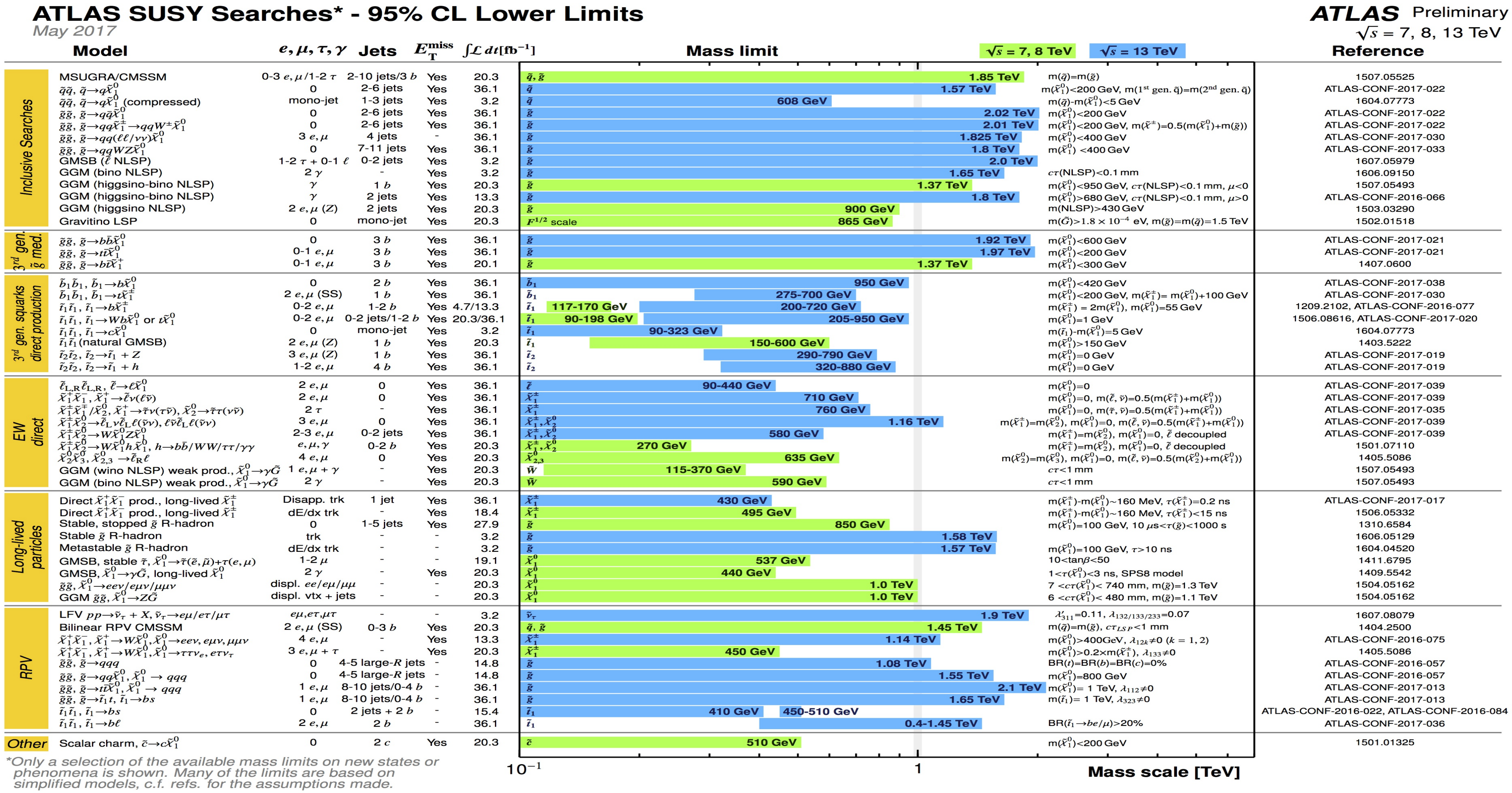
Small enough to keep us still thinking of a mechanism like SUSY to stabilize it.

But large enough to already provide some interesting constraints on SUSY breaking ideas.

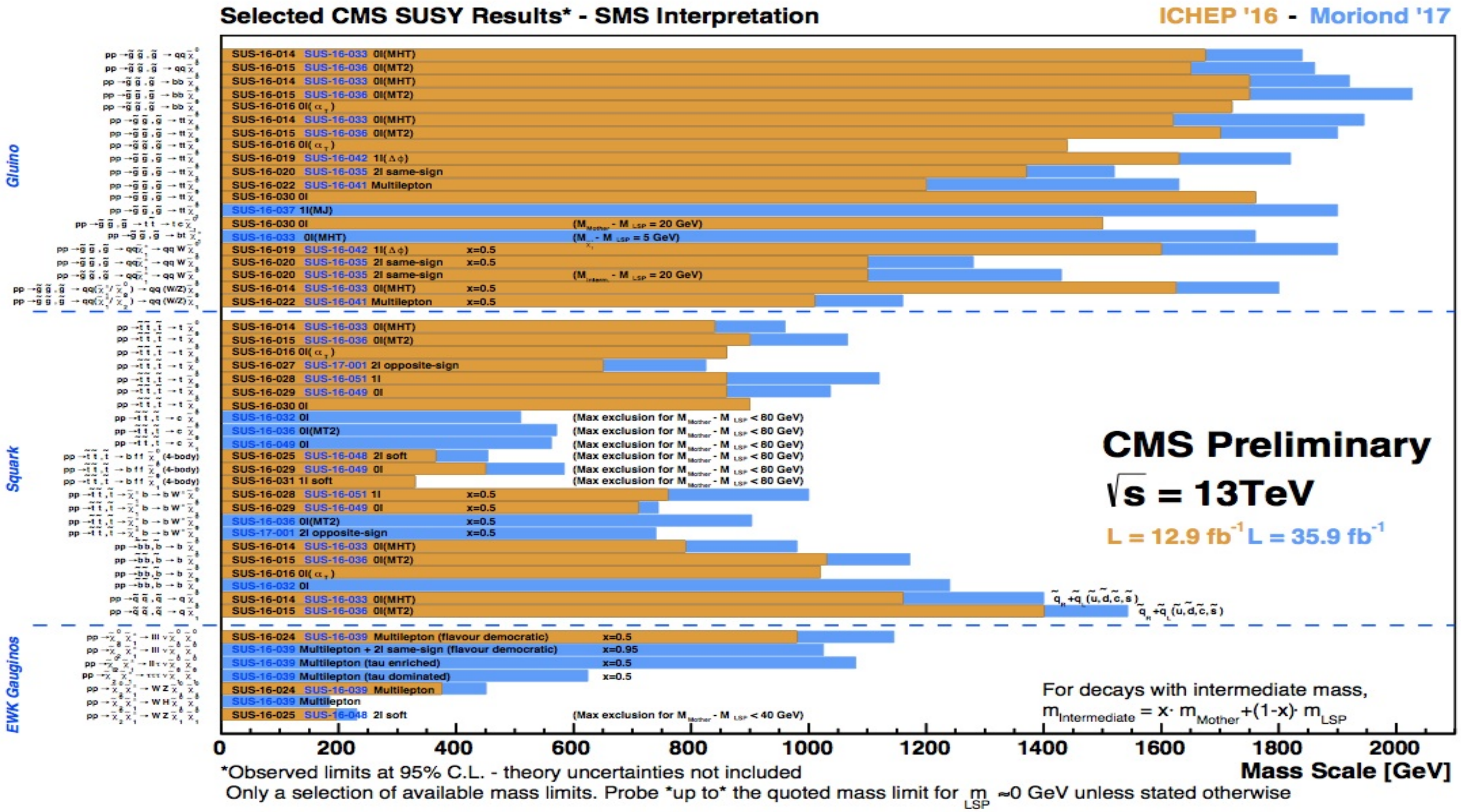
$M_h = 125$ GeV points at large values of SUSY scale and large mixing in the stop sector and large A_t values.

So GMSB, which was liked pre Higgs discovery days for providing a 'natural' solution to flavour problem in SUSY became disfavoured.

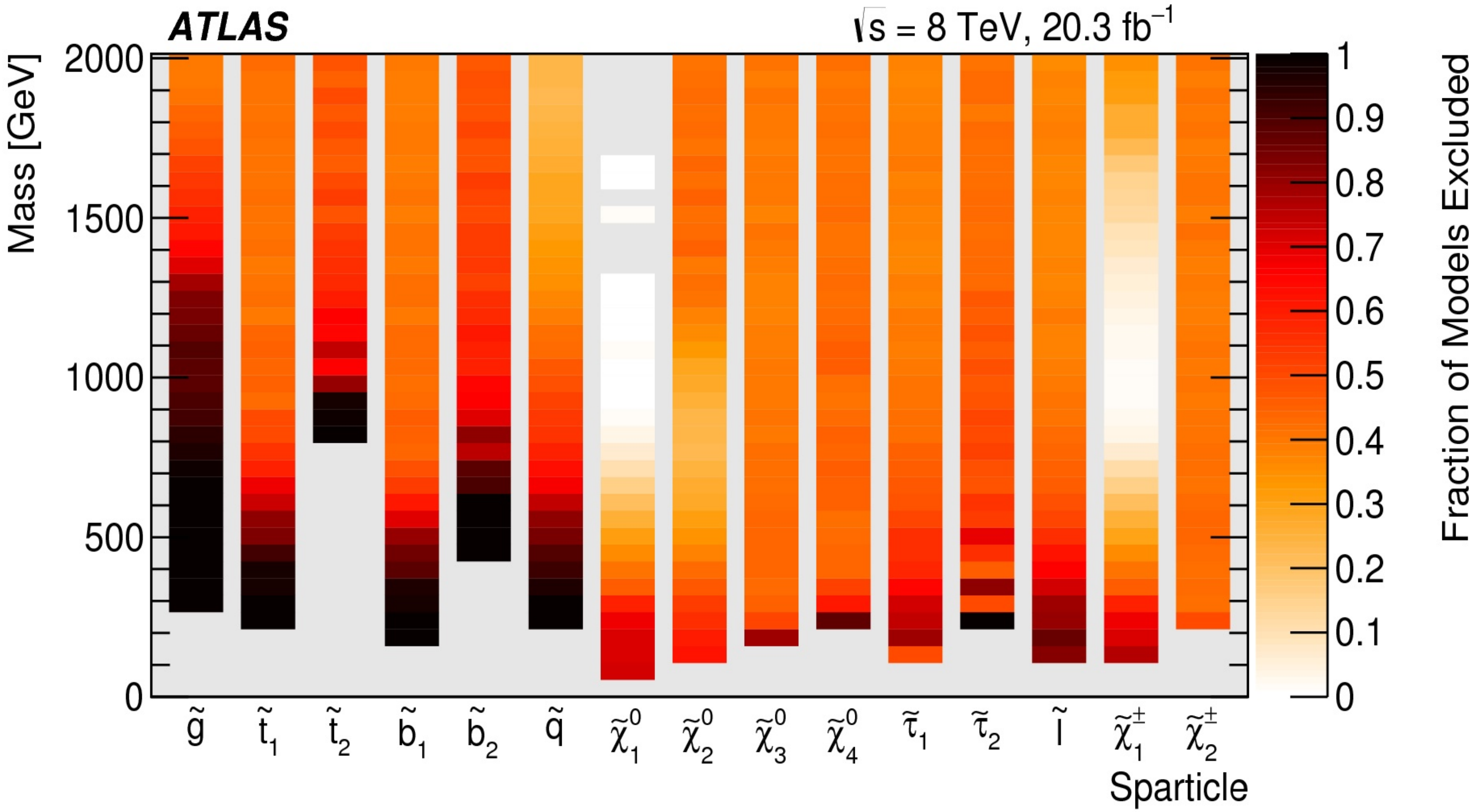
BSM Status report



Simplififed models

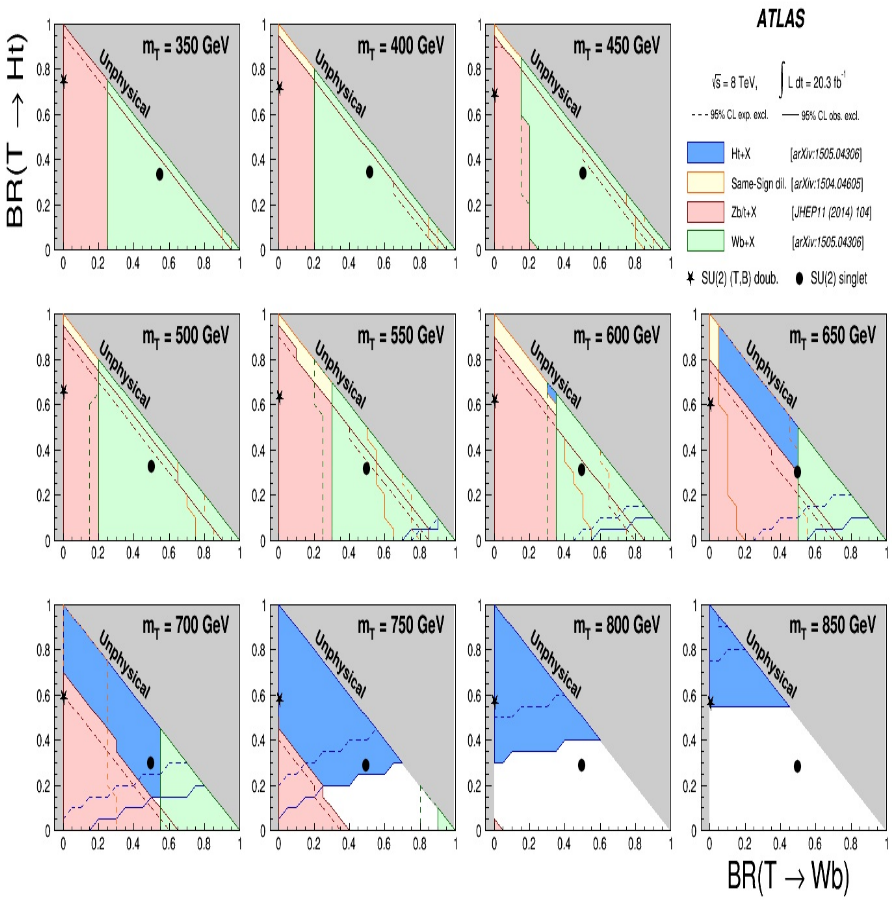


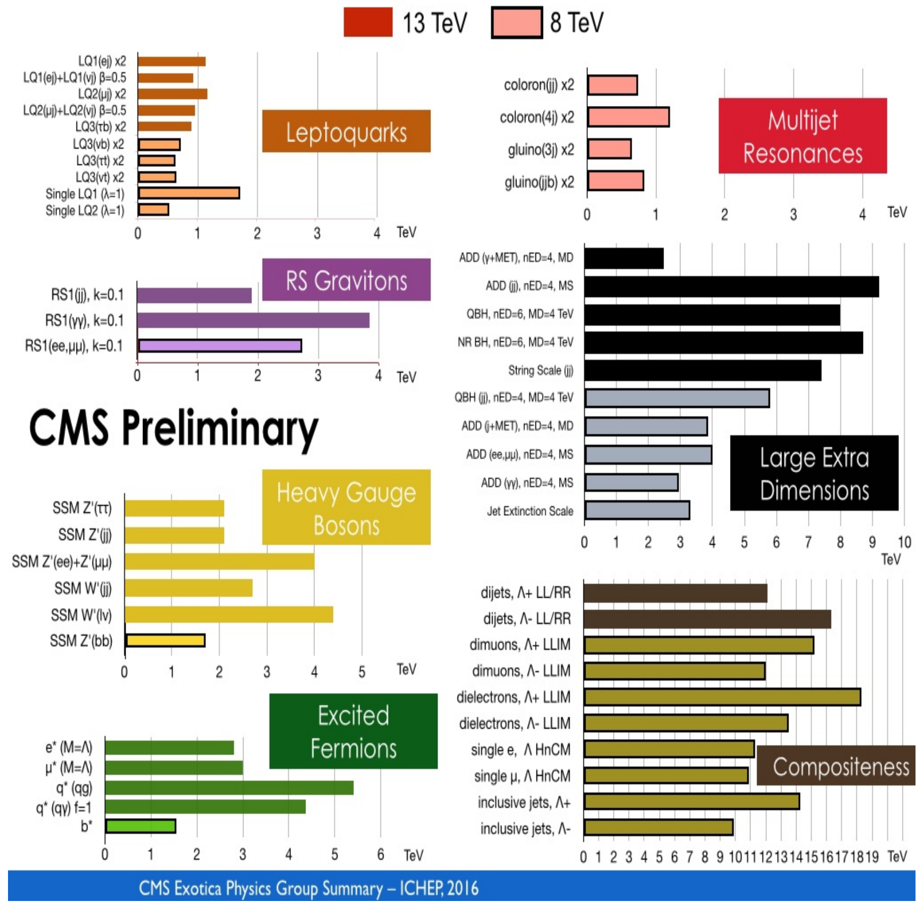
Simplified models.



Attempts to quantify results against the 'branching ratio' warning!

Analysis in PMSSM: more about this later.


ATLAS
BR(T → Ht)
BR(T → Wb)
m_T = 350 GeV
m_T = 400 GeV
m_T = 450 GeV
m_T = 500 GeV
m_T = 550 GeV
m_T = 600 GeV
m_T = 650 GeV
m_T = 700 GeV
m_T = 750 GeV
m_T = 800 GeV
m_T = 850 GeV
Unphysical
√s = 8 TeV, ∫ L dt = 20.3 fb⁻¹
95% CL exp. excl.
95% CL obs. excl.
Ht+X [arXiv:1505.04306]
Same-Sign dil. [arXiv:1504.04605]
Zb/t+X [JHEP11 (2014) 104]
Wb+X [arXiv:1505.04306]
SU(2) (T,B) doub.
SU(2) singlet


13 TeV
8 TeV
Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(νj) β=0.5
LQ2(μj) x2
LQ2(μj)+LQ2(νj) β=0.5
LQ3(τb) x2
LQ3(νb) x2
LQ3(τt) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
RS Gravitons
RS1(jj), k=0.1
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
CMS Preliminary
Large Extra Dimensions
ADD (γ+MET), nED=4, MD
ADD (jj), nED=4, MS
QBH, nED=6, MD=4 TeV
NR BH, nED=6, MD=4 TeV
String Scale (jj)
QBH (jj), nED=4, MD=4 TeV
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
Jet Extinction Scale
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM Z'(bb)
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ) f=1
b*
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
TeV
CMS Exotica Physics Group Summary – ICHEP, 2016

All the big questions gave rise to some big ideas!

Almost all of them indicated scale of physics to be TeV.

LHC results have constrained them!

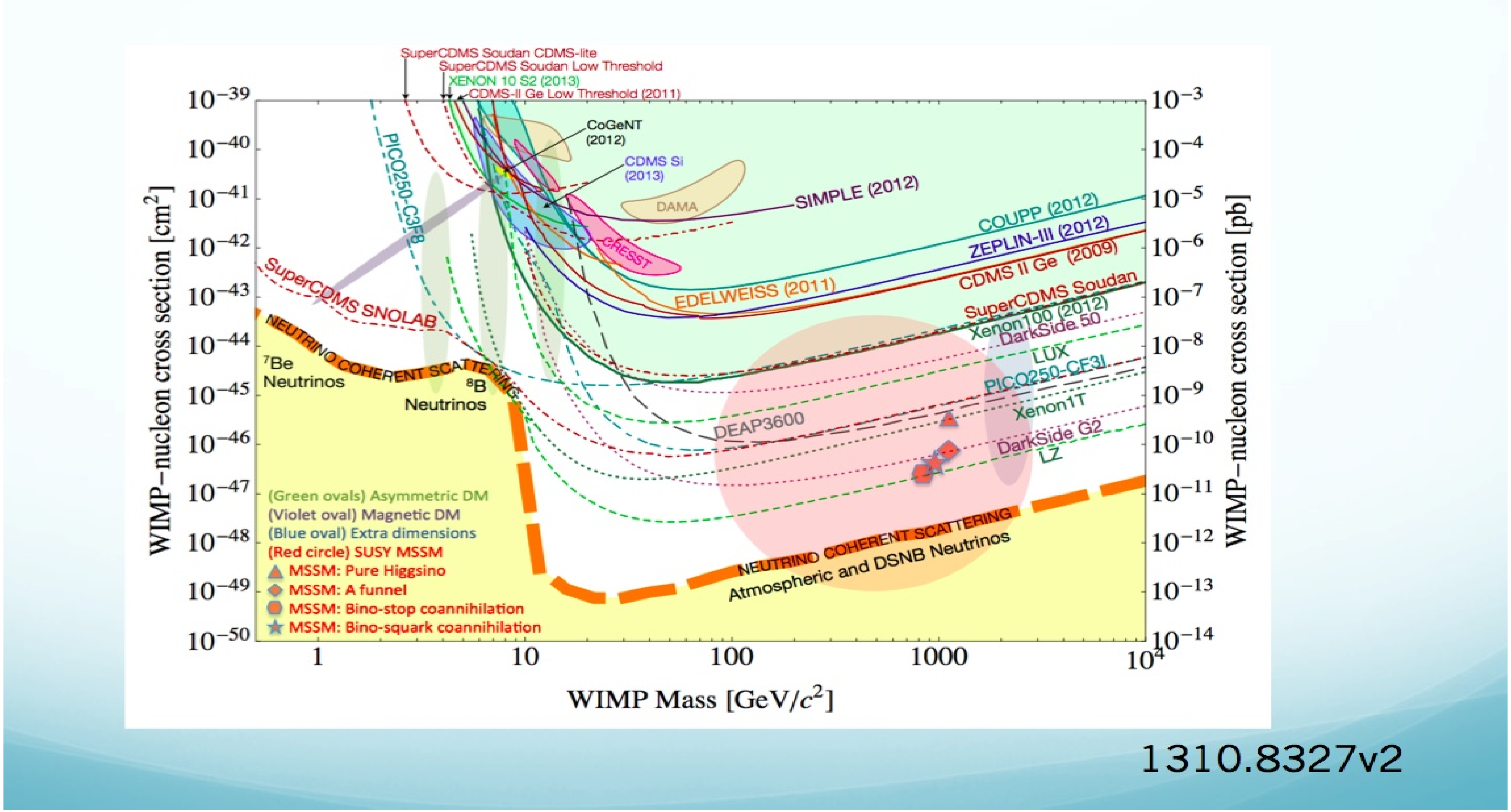
Light Higgs AND NO BSM till now!

is challenging (for example) the 'hierarchy' folklore or 'fine tuning' folklore!

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! Are the results from direct detection and colliders compatible?

Does the DM have ANYTHING to do with particle physics?



Older result. Limits now pushed further down ☹

There has been a lot of activity in analyzing Higgs, Top couplings and B-physics results in an effective field theory framework! Even DM results are being analysed in the so called simiplfied models.

General studies in terms of effective operators is the most popular. Particularly since the scale of new physics is being pushed higher!

EFT fits for Higgs: Handbook 1610.07922, SMEFT,C. Degrande et al, Eur. Phys. J. C **77** (2017) no.4, 262, 1803.03252, Falkowski 1505.00046, Falkowski et al 1611.01112

Topfitter: J. A. Aguilar-Saavedra *et al.*, arXiv:1802.07237 [hep-ph], A. Buckley et al, JHEP **1604** (2016) 015

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \sum \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

Various studies exist. Operators involving Higgs expected to have smaller suppression! Hence the top and Higgs study can probe BSM!

Higgs mass close to the upper limit of 132 GeV in MSSM means larger values of SUSY breaking scale M_S!

This smells of 'unnaturalness'! For example Dine: "Naturalness Under Stress"

Achilee's heel of SUSY theories: SUSY breaking mechanism?

Basically this is where we theorists are ignorant. We have different biases , pointers.

X. Tata et al: Our measures of naturalness have high values as we see it now. But it is possible that correlations among parameters of the SUSY models can make the value of the measure small **for the same particle spectrum!**.PRD87, 115028, 2013

So they construct a measure, which if large **definitely** points towards losing naturalness!

With this they claim theory **can** be natural with heavy stops, heavy gluinos but **light electroweakinos.**

Post LHC paradox there are newer model ideas as well. Those which try to keep somehow still 'naturalness' idea in some form or the other have connections with Higgs and top sector always.

Examples: 1810.09467: N. Craig et al, 'Twin Turtle Models: essentially carrying the composite Higgs idea further': predicts many new scalar/pseduoscalar states and hence precision study of the Higgs sector is indicated.

1810.09467: Tim Tait et al: Propose some new physics in the anom. magnetic moments in the τ sector, which due to $SU(2)_L$ invariance modifies the Higgs couplings!

1811.01961: C. Csaki et al: 'Naturalness sum rules': top partners same spin or zero spin

Various DM models: additional (pseudo)scalars: modify Higgs phenomenology or top phenomenology.

Freeze-in (FIMP) DM models: change the story completely (talk by G. Belanger)

Nonstandard Cosmology: DM not themal relic. (Can this have traces at colliders?)

We have some hints in flavour physics which may signal new physics if confirmed with higher significance.!

B -physics:

In general one expected the FCNC decays of B mesons to give some clue about new physics. (remember we learnt about the charm from $K \to \mu^+\mu^-$) This has been studied with high precision and high expectations.

Right now we have a few anomalies in B-physics which might be the harbinger of new physics

Ratios of BR of $B \to K^{(*)}\mu^+\mu^-$) to $B \to K^{(*)}e^+e^-$ as well as a global fit fo data on $B \to s\mu^+\mu^-$ show deviations from the SM predictions.

$R(K^{(*)}) = B \to K^{(*)}\mu^+\mu^- / B \to K^{(*)}e^+e^-$

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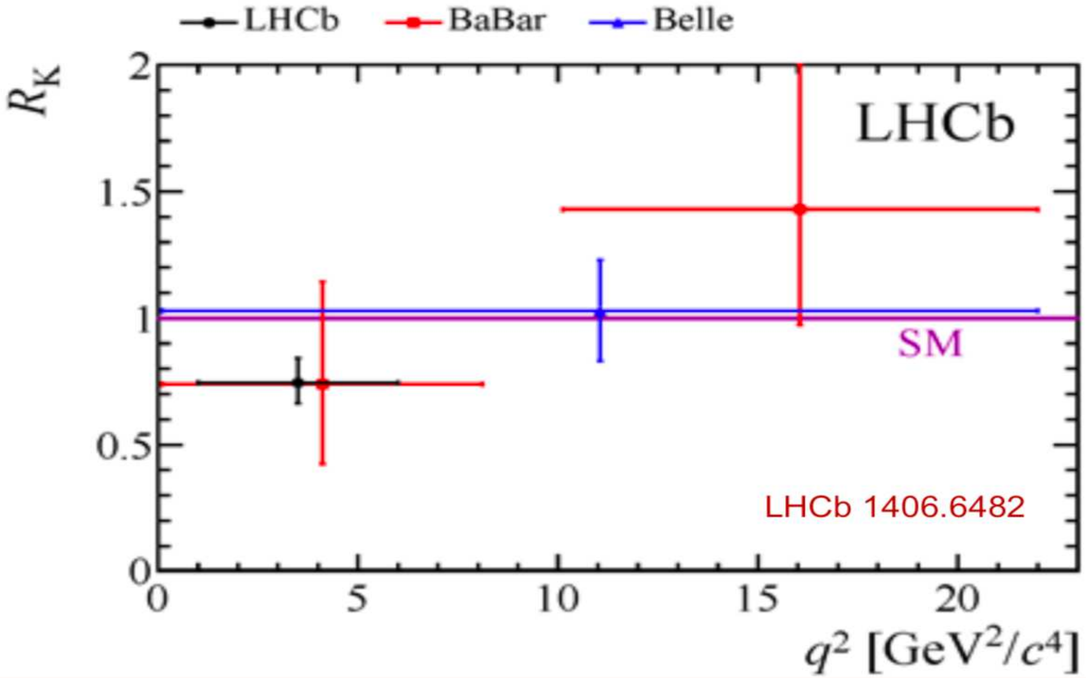
- 2.2-2.6σ deviation from the theoretically rather clean SM expectation



Lepton Flavour Violation in B decays?

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$R(K^{(*)}) = B \to K^{(*)}\mu^+\mu^- / B \to K^{(*)}e^+e^-$

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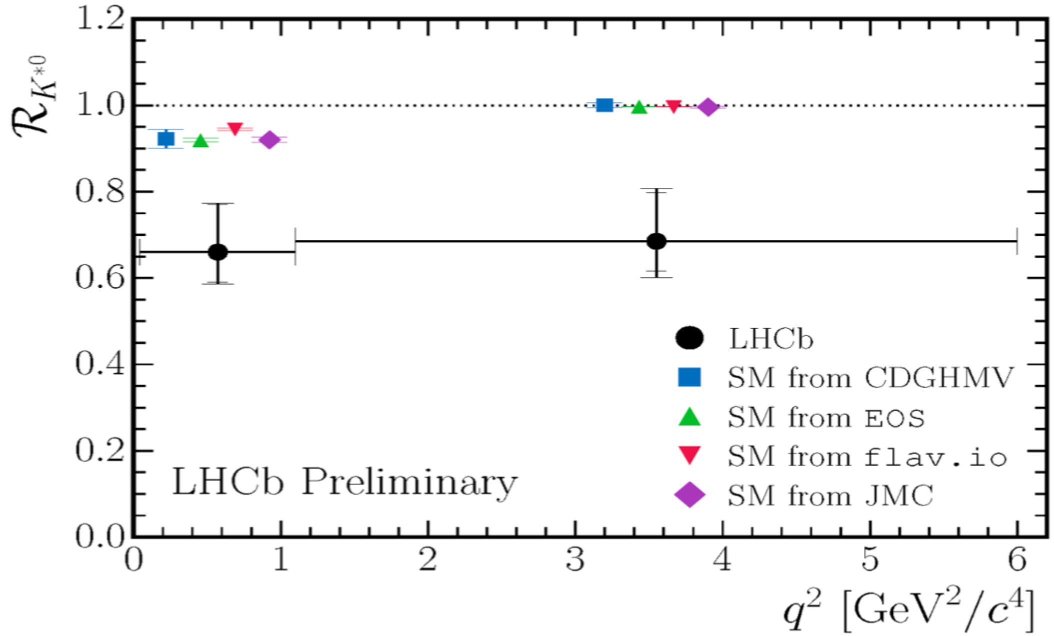

Lepton Flavour Violation in B decays?

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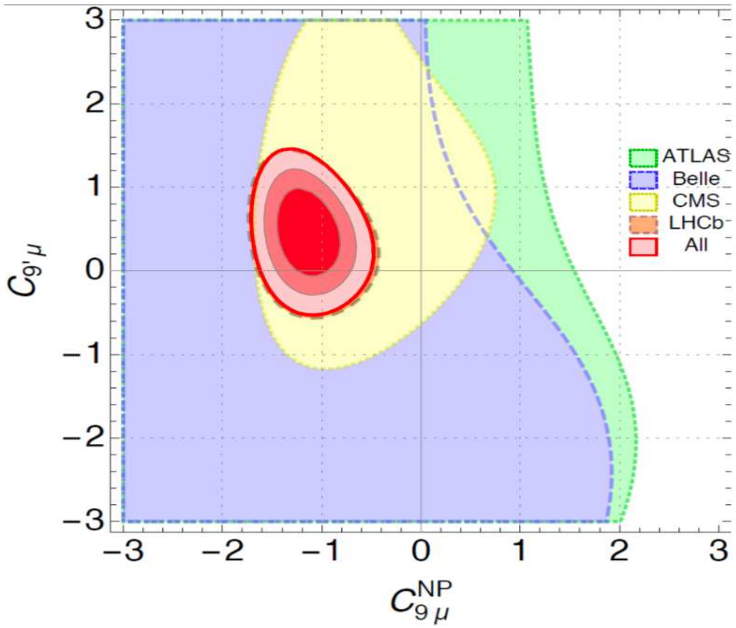
Global fit to b→sμ⁺μ⁻ data

- Global analyses give a very good fit to data
- Good fit to data:
  - C_9
  - $C_9 = -C_{10}$
  - $C_9 = -C'_9$

$$O_9 = \bar{s}\gamma^{\mu} P_L b \bar{\ell}\gamma_{\mu}\ell$$

$$O_{10} = \bar{s}\gamma^{\mu} P_L b \bar{\ell}\gamma_{\mu}\gamma^5\ell$$



B. Capdevila, AC, S. Descotes-Genon, J. Matias and J. Virto, arXiv:1704.05340 [hep-ph].

Fit is 5-6 σ better than the SM

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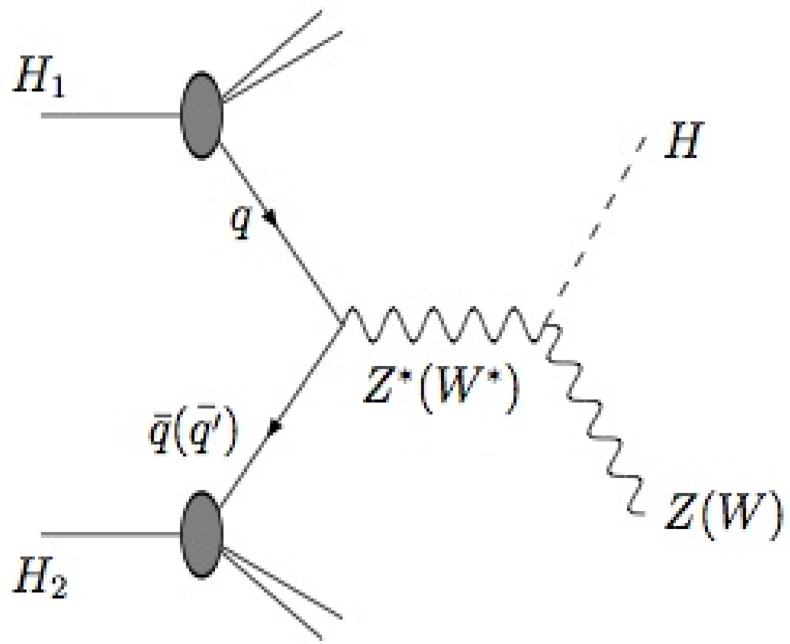
In some cases we do have limits which are not so tight.

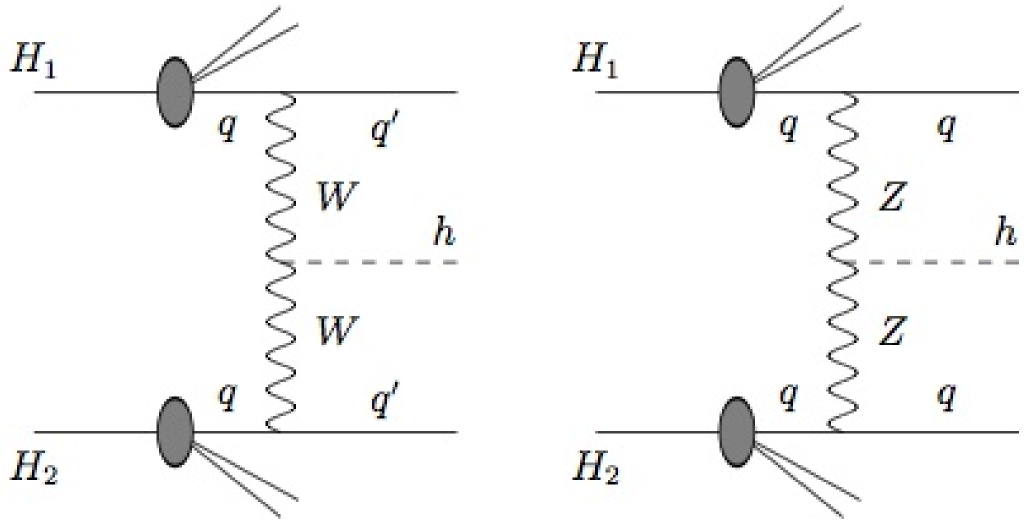
Interesting because if the DM provides right relic density through Higgs interactions then it can contribute to decays of Higgs into DM and hence 'invisible'!

Limits on BSM decay branching ratios of the Higgs from the Higgs production rates typically $\sim 10\%$. However it is indirect and ambiguous.



R. M. Godbole, M. Guchait, K. Mazumdar, S. Moretti and D. P. Roy (2003) "Search for 'invisible' Higgs signals at LHC via associated production with gauge bosons," *Phys. Lett. B* **571**, *pp. 184-192*

After the Higgs was discovered, we revisited the analysis, Included other processes (first suggested by Zeppendfled etal) as well.

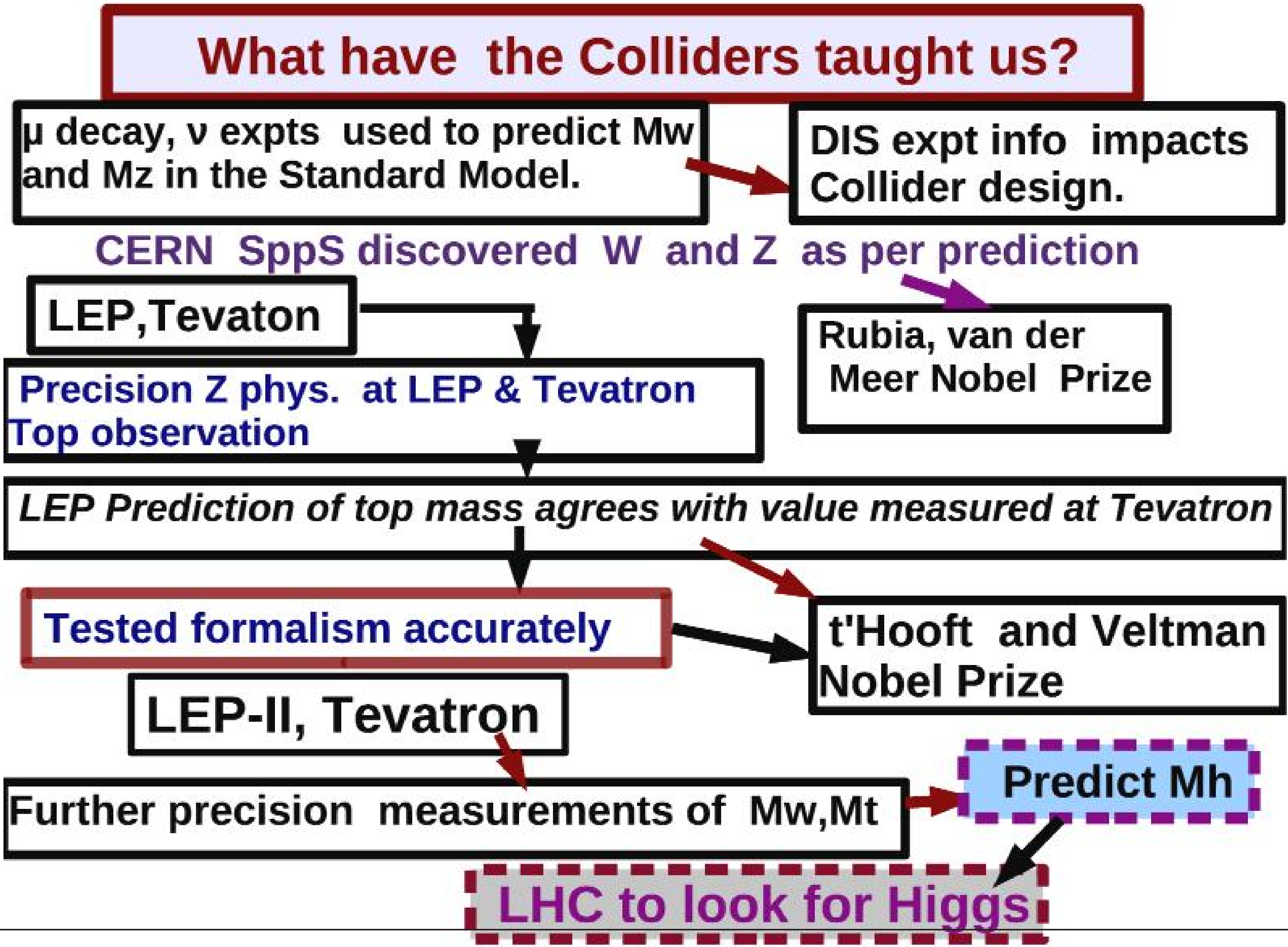


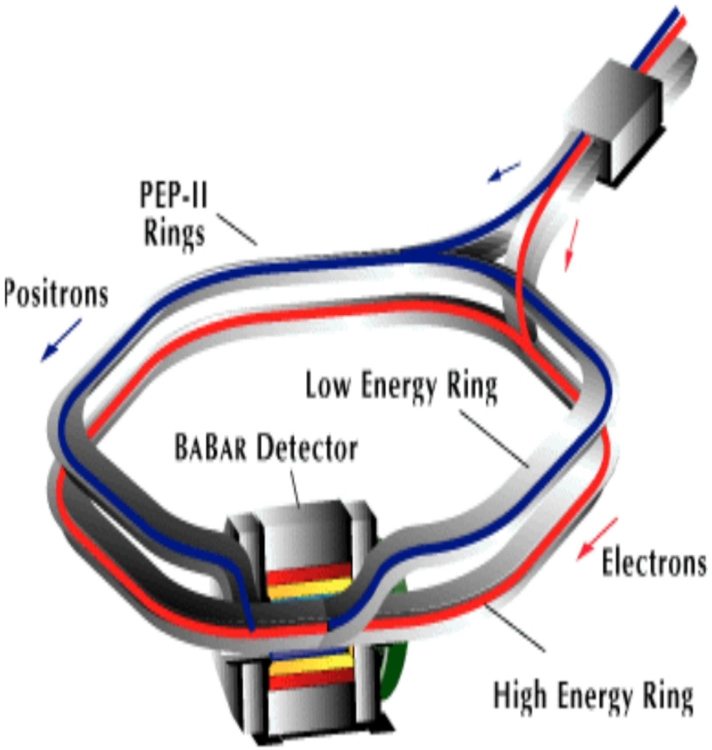
D. Ghosh, R. Godbole, M. Guchait, K. Mohan and D. Sengupta, (2013) "Looking for an Invisible Higgs Signal at the LHC," Phys. Lett. B 725, arXiv:1211.7015 [hep-ph]

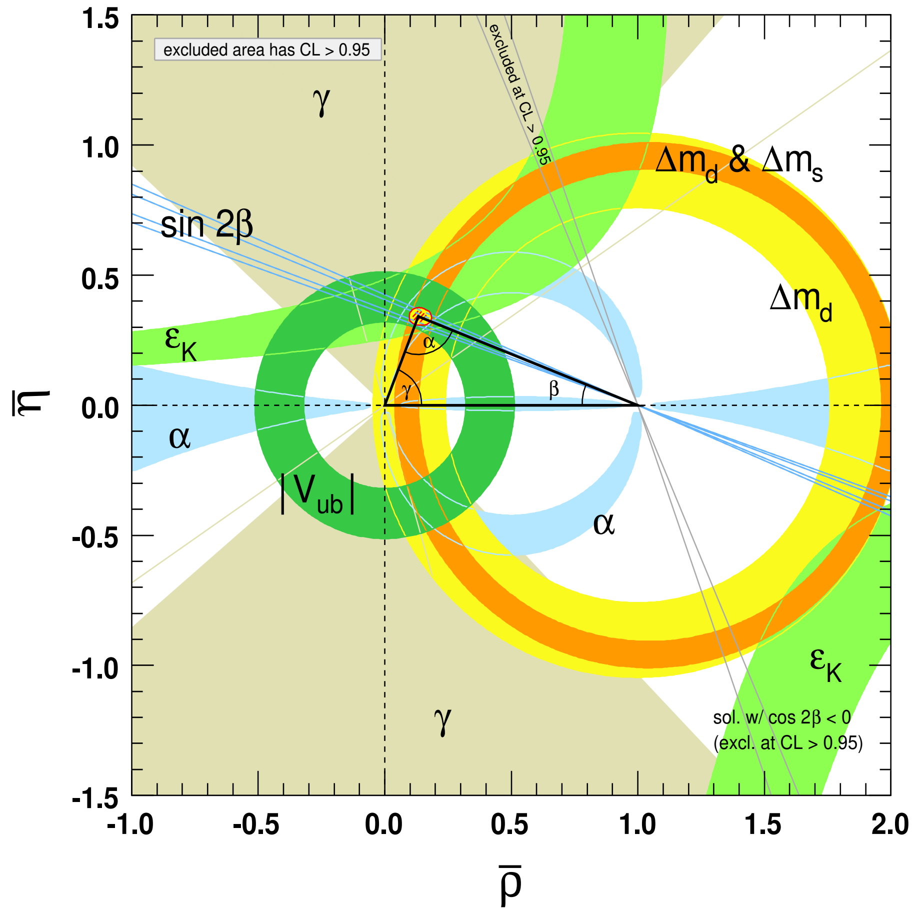
Limits on invisible branching ratio for the Higgs possible from direct searches via VBF, VH and Higgs + jet production:

CMS: 24 % EPJC 74, 2980, 2014; JHEP02, 135, 2017 With 35.9 fb $^{-1}$ data The limit is now 23 %. 1809.05937, talk at Higgs couplings 2017

ATLAS: 28% JHEP11, 206, 2015;JHEP01,172, 2016. 37% for 13 TeV data, WW Fusion: 1809.06682


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





BABAR/BELLE/LHCb helped us get here!

Theory driven paths!

One way ahead has to be through a precision study of the two heaviest particles the top and the Higgs that the nature has provides us!

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

Model independent analyses the best story of the day! (Data driven!)

Remember the SM started its life as an effective theory: Fermi's theory of β decay!

Peeping through the Higgs and the top window!

Same from B physics: LHCb and BABAR,.....

In fact B physics has potential of probing very high scale physics!

Again only model independent ways of looking at it are worthwhile!

Situation is now data driven and NOT theory driven!

In a specific model framework, already BSM scale constrained to values not easily reached at 14 TeV LHC!

Recent signals of lepton flavour universality violation may be the thin edge of the wedge. We need to wait and watch

'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 constraints from precision measurements which were given by comparison with established theory.

There was almost always a No-lose theorem!

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

The 'Big Ideas' are many! Ideas like SUSY had (have) a lot of appeal!
BUT NO OBSERVATION SO FAR!

May be time has come for a new paradigm for collider physics!

To quote Michelangelo Mangano

- 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

What is left?

Precision measurements of Higgs couplings to fermions and gauge bosons .

Tensor nature of the same and hence the CP property of the Higgs.

Self coupling of the Higgs!

So properties of the Higgs sector may be the window to the BSM land !

Whenever, one starts analyzing the observed features of the Higgs sector, the ubiquitous top plays an important role everywhere!

Remember! Within the SM, for the measured mass of the observed scalar, the conclusion about the state of the vacuum depends on m_t due to its large Yukawa couplings.

Top quark has an important role to play in almost all the ideas of BSM! **Along with the Higgs properties the Top properties may carry the imprint of the BSM physics!**

Studying the top properties can be ONE MORE way towards BSM!

As already said FCNC historically have been of great utility.

Before the discovery of the top quark $B\!-\!-\!\bar{B}$ mixiing had given indirect information on t mass!

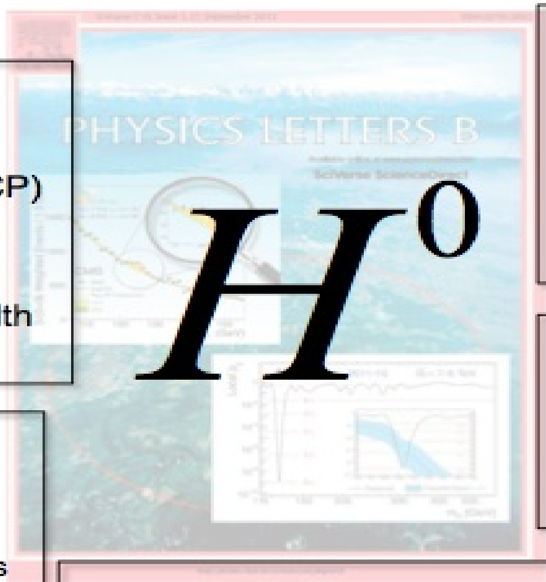
That is why B-physics with its anomalies is the third window!

Peeping at the BSM through the known Higgs and Top/bottom and through the unknown: DM *if it has anything to do with particle physics*. Look for the 'unknown' through the 'known' or 'unknown'.

Absence of Evidence is not Evidence of Absence!

Explosion of the Higgs Physics Landscape!

- Since the discovery of the Higgs boson, an entire new field has emerged.



Precision measurements
- Mass and width
- Quantum numbers (spin, CP)
- Coupling properties
- Differential cross sections
- Off-shell couplings and width
- Interferometry

Is the SM minimal?
- 2HDM searches
- MSSM, NMSSM searches
- Doubly-charged Higgs bosons

See Anna Goussiou's talk

Rare / BSM decays
- $H^0 \to \mu\mu$
- $H^0 \to Z\gamma$
- $H^0 \to J/\psi\gamma$, $\Upsilon(ns)\gamma$
- LFV $H^0 \to \mu\tau$, $e\tau$, $e\mu$
- $H^0 \to aa$

…and more!
- FCNC $t \to H^0 q$ decays
- Di-Higgs production
- Trilinear coupling
- … etc

Tool for discovery
- Portal to DM (invisible Higgs)
- Portal to hidden sectors
- Portal to BSM physics with H^0 in the final state (VH^0, H^0H^0)

See Farid Ould-Saada and Bjoern Penning's talks

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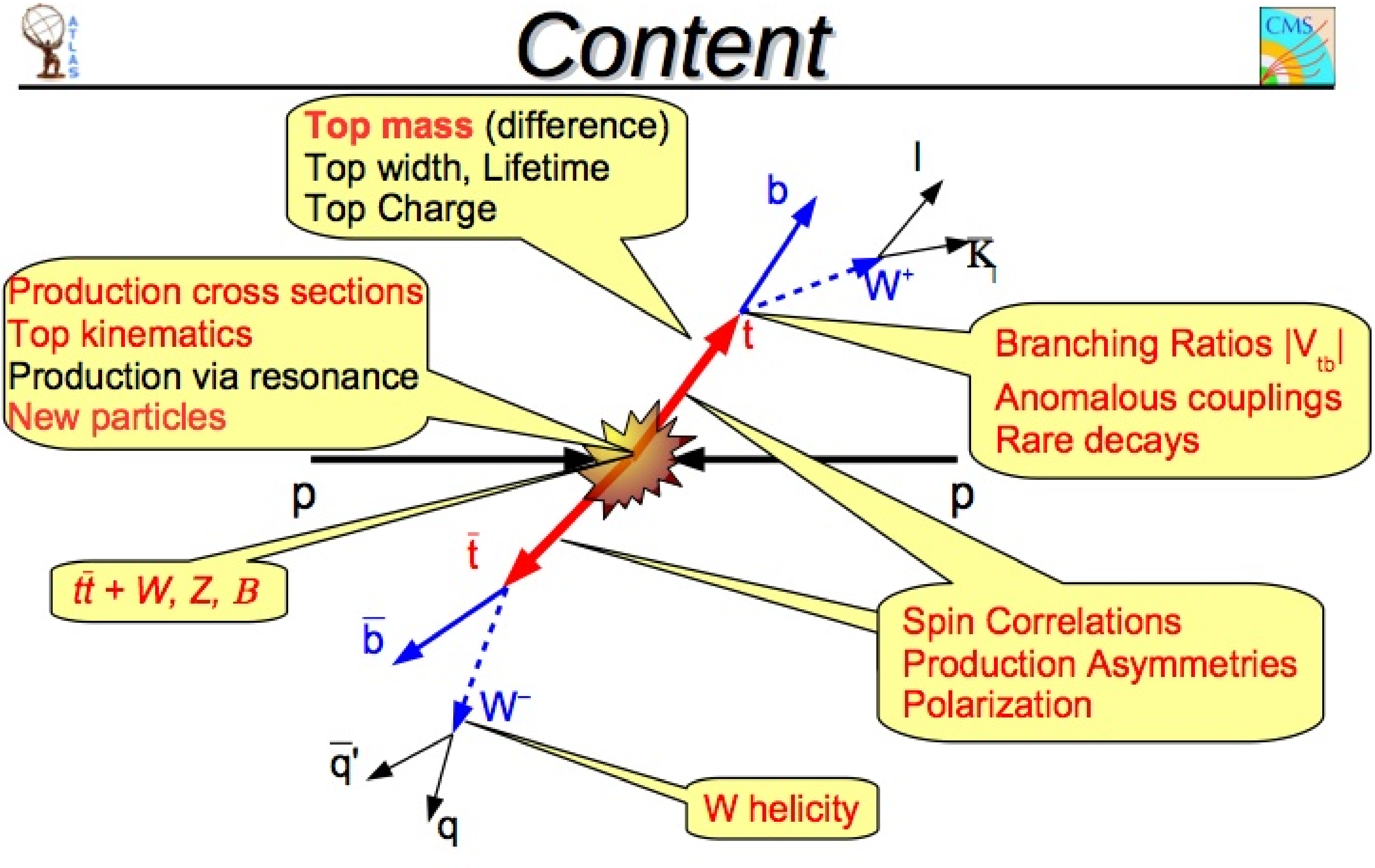
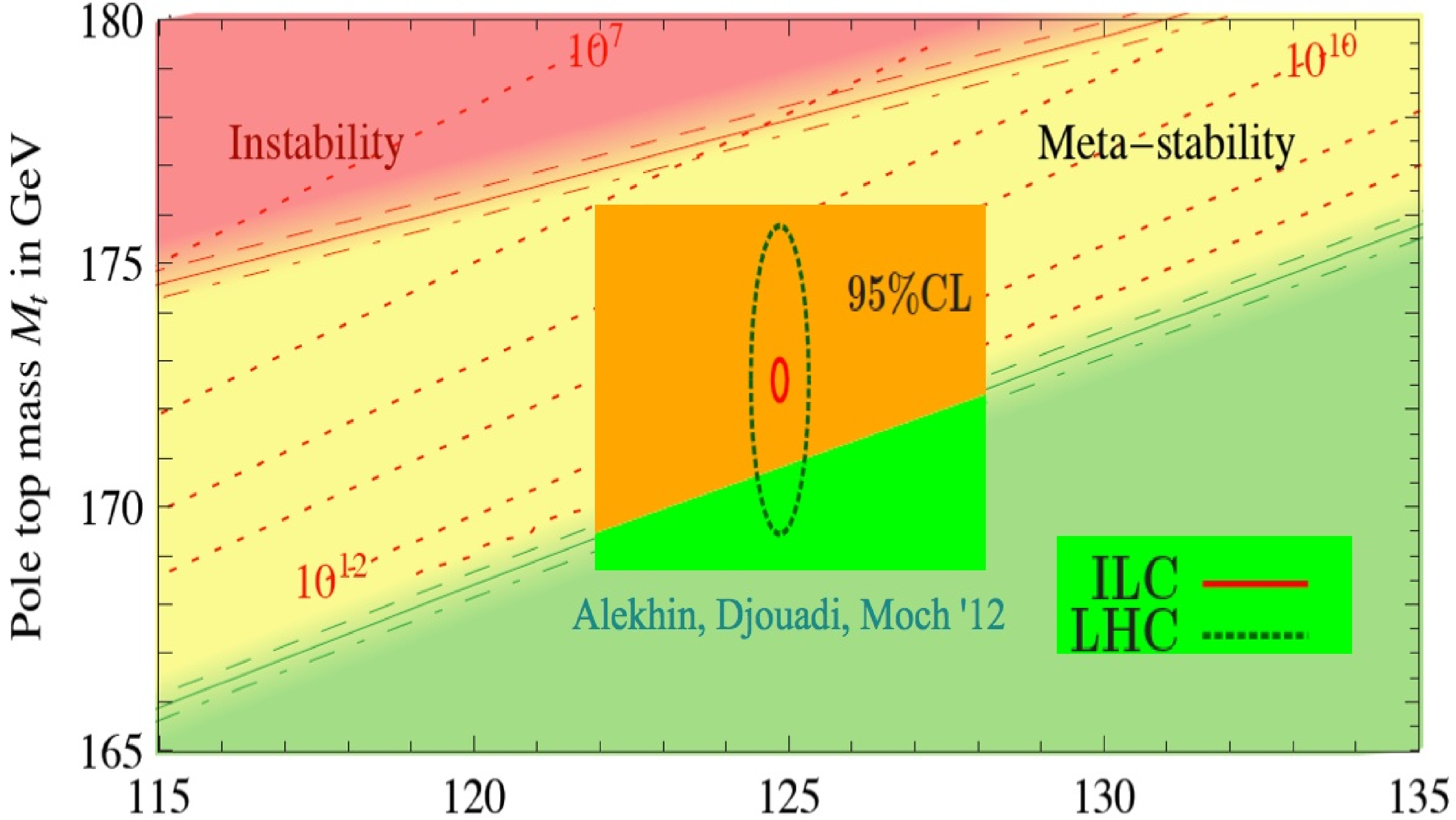

Content
Top mass (difference)
Top width, Lifetime
Top Charge
Production cross sections
Top kinematics
Production via resonance
New particles
Branching Ratios |V_tb|
Anomalous couplings
Rare decays
t̄t + W, Z, B
Spin Correlations
Production Asymmetries
Polarization
W helicity
b
l
W+
t
p
p
t̄
b̄
W−
q̄'
q

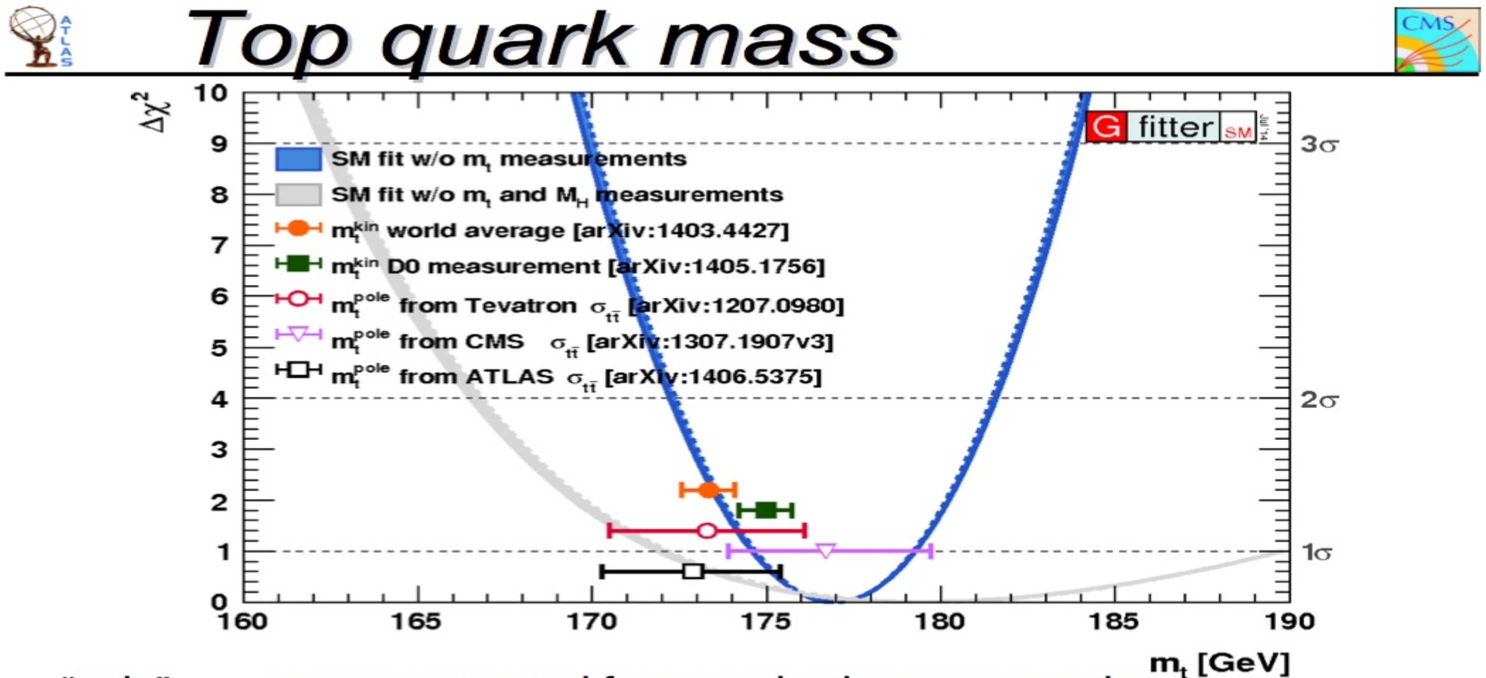
Higgs and top mass critical as far as SM is concerned.

Just large enough to think imply that the SM is all there is till the Planck scale!

M_h and M_t values just on the borderline for vacuum stability all the way to Planck scale.



M_h value indeed critical.



→ "pole" means extracted from production cross sections
→ "kin" means direct measurements, e.g. matrix element method

Precision at LHC (With 80 million top pairs) : 500 MeV, Ultimately 200 MeV may be possible!

Theoretical precision to relate pole mass to measured cross-sections is high! But cross-section predictions at leptonic colliders more accurate than at hadronic colliders.

a)t effects on loop induced Higgs couplings

b)tree level processes affected by t Yukawa couplings

Sensitive observables:

Loop:

$h \to \gamma\gamma,\ gg \to h$

Tree level:

$\sigma(pp \to t\bar{t}h)$

$\sigma(pp \to W + b + X \to t + h)$ (fabio),

$\sigma(pp \to thj)(S.Rindani)$, $\sigma(pp \to hh)$.

In principle edm's HAVE put big constraints if we assume CP violation to be universal in all couplings.

Hence depends on the models for CPV in the fermion couplings

D. Stockinger, J. Phys. G **34** (2007) R45,J. Brod et al JHEP **1311** (2013) 180,A. Arbey et al Eur. Phys. J. C **75** (2015) no.2, 85

Such CP violation is allowed only if it happens only in the couplings to third generation of fermions!

Further strong constraints on scale on new physics assuming maximal CPV phases. Can one probe this at the LHC?

Move away from models is the current line of attack.

a) Precision measurements of the Higgs properties which also need of course Precision calculations. Masses of Higgs and top already tell about the BSM! Example P_T^h for the Higgs produced inclusively in gluon fusion as well as in association with W/Z/top!

b) More neutral and charged Higgses? 2HDM, NMSSM..... LHC 13 TeV has produced big limits!

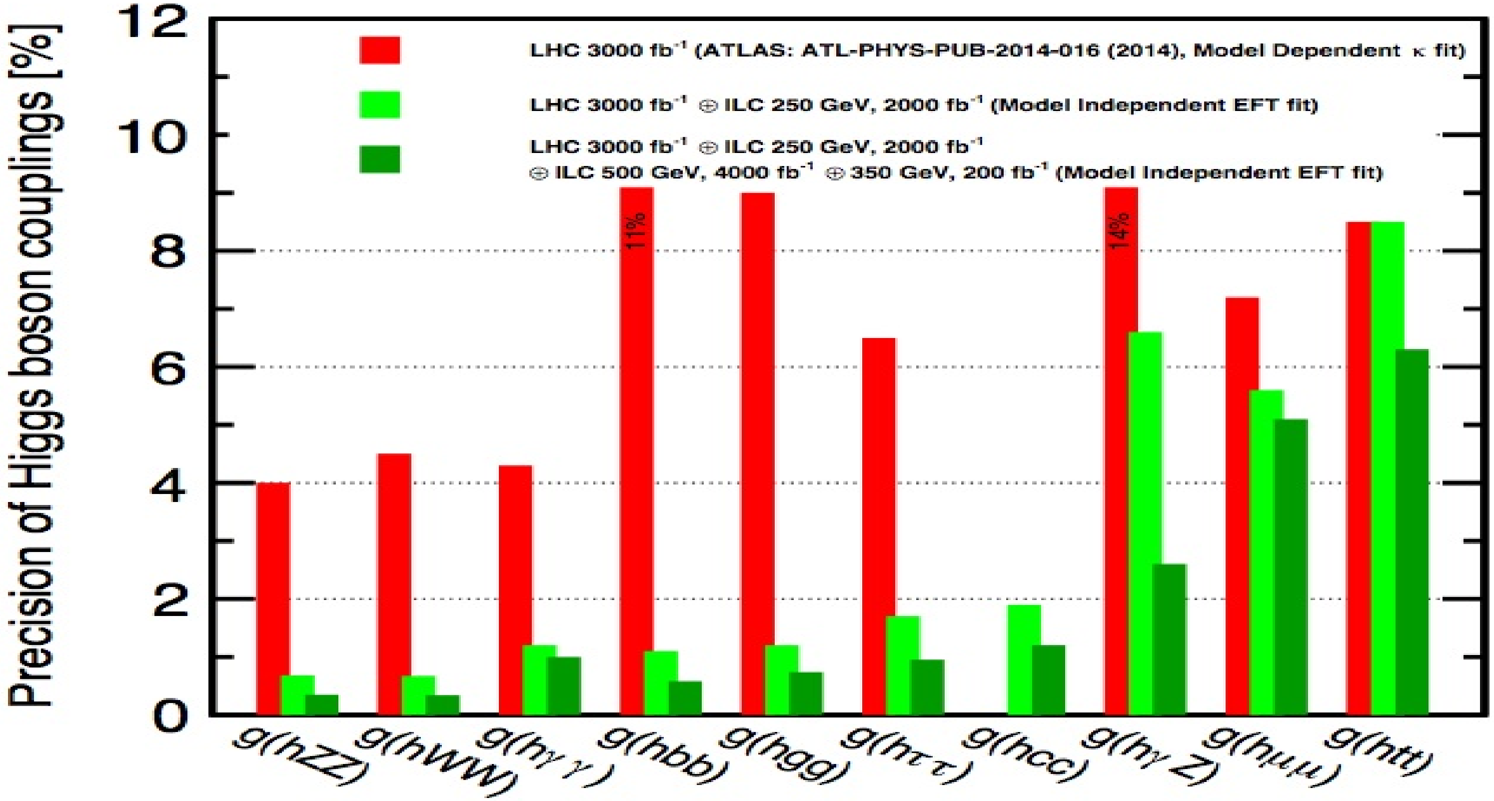
c) Use deviations from the SM values to probe the BSM. Are deviations only modification of the existing couplings from the SM values (κ formalism) OR does deviation mean additional operators?. Focus here on CP violation/CP mixing.

d) What is the best framework to study these? EFT, pseudo observables? Top fitter and Higgscision

e) Exotic Higgs decays? Example of the 'invisible' Higgs decays.

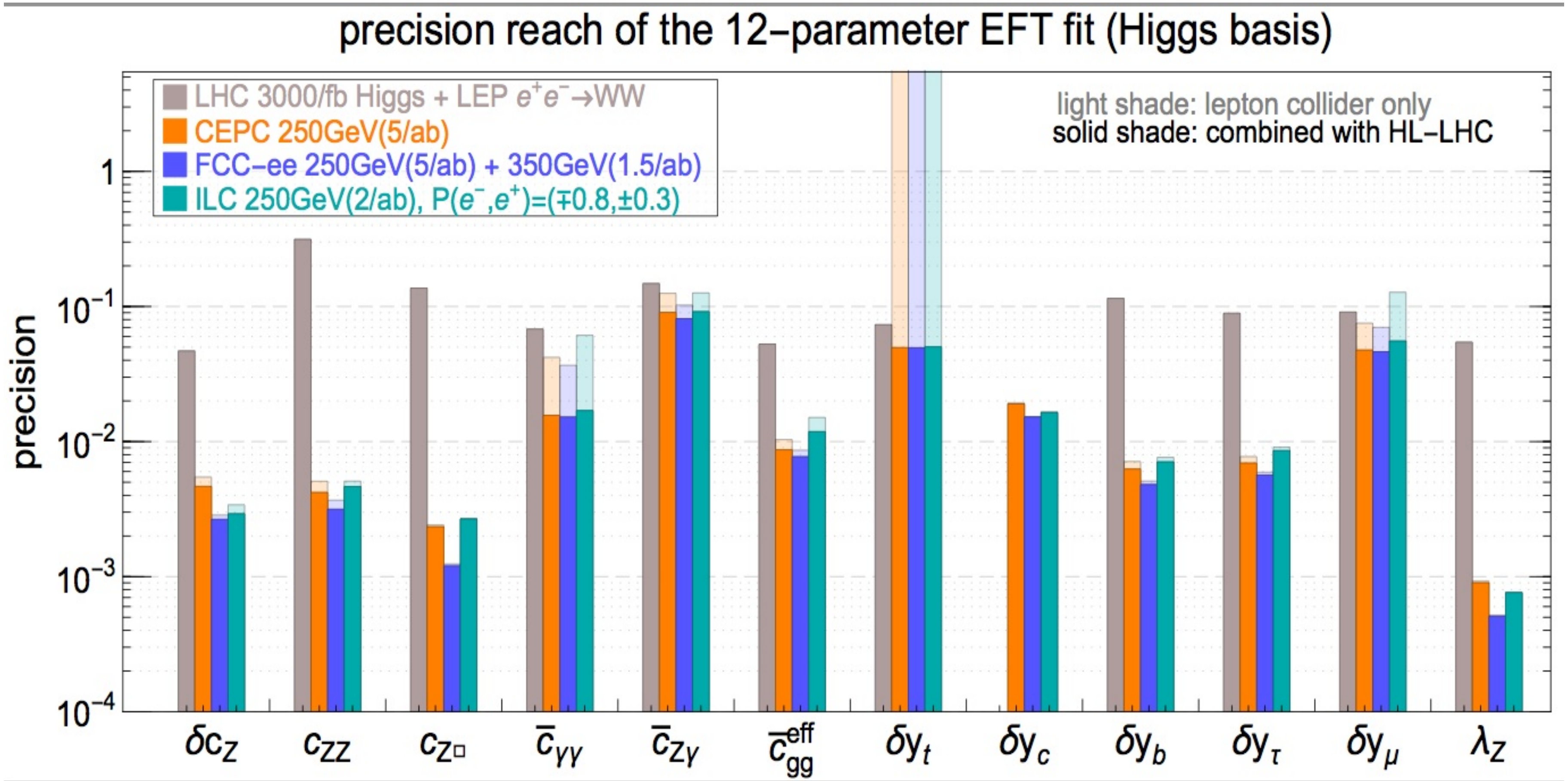
f) Effect of top coupling on rates of associated production of Higgs with top.

g) Probing Higgs sector through properties of the top produced in association with Higgs bosons : $t\bar{t}h, th, h$jet$, H^{\pm}t$ OR produced in H/A decays!



High accuracy measurements possible. Improvement over HL-LHC. ILC 250 GeV can in principle attain results similar to ILC 500. Polarisation plays important role. 1710.07621 (Peskin et al)

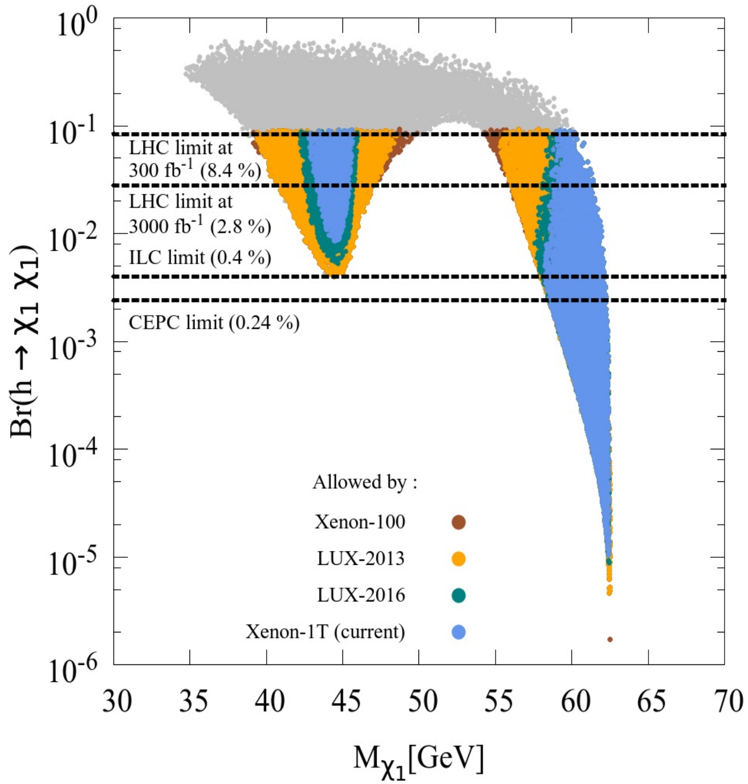
With polarization one can have additional observables such that number of observables is bigger than the number of parameters. As a result one can test the EFT and this can yield information about light particles.



Courtesy : Lian Tao Wang , CEPC CDR (in preparation)

A light LSP is still allowed in PMSSM, along with the relic constraints. For example, see R.K. Barman, G. Belanger, B. Bhattacharjee, R.G., D. Sengupta, G. Mendiratta,: PRD 95, 095018. Difft. from 1612.06333v1, **considered non thermal DM as well**.

This light LSP will mean invisible decay of the Higgs. Possible to probe it at LHC and future colliders. For example, D.Ghosh, R.G., M. Guchait and K. Mohan, PLB 725, 344, 2013 .



Projection for 13/14 TeV: 1310.8361 + HL LHC CMS/ATLAS studies:

300 1/fb, 0.15; 3000 1/fb, 0.06 and the ILC: 0.3 %.

Our scan allows relic to be less than observed. Most of the times one needs additional DM component.

Searches for invisibly decaying Higgs hold promise. Green(orange) (dis)allowed by LUX. (from PRD 95, 095018)

Connection between Higgs, BSM and DM! Connections between the LHC, e^+e^- colliders and Direct detection experiments.

We need to still learn how to use LHC optimally.

Many studies of the Higgs, top and the DM sector possible. e^+e^- precision studies will help for sure.

We need to still learn how LHC can also test new ideas which are still coming around, but to be honest we need to be guided by experimental results now more than ever!

Remember:

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!

Remember also: Higgs postulate : 1968

Machine design: 1984

Machine building start: 1998

Experiments : 2012!

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). 250 GeV ILC extendable to 500 GeV on cards!

FCC (ee) and CEPC are perhaps near future machines! FCC(hh) seem even further 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!

Of course we can probe and study BSM on many fronts at the high intensity frontier!

Neutrino experiments, low energy but high precision experiments..that is a different road and a road which holds many promises!

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!

This potential was also exemplified by the (now disproved) BICEP2 results!

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!
The road may be very long but 'physics case' for colliders is not 'withering' just yet!

BACKUP

- **To cure instability of the EW scale under radiative corrections and to keep the Higgs light!.**

- Need to get a basic understanding of the flavour issue: why the masses of fermions span at least 15 orders of magnitude!

- Unification of couplings

- Inclusion of Gravity in the picture?

- Dark Energy!