SM and BSM through the Higgs/Top and Flavour portal!

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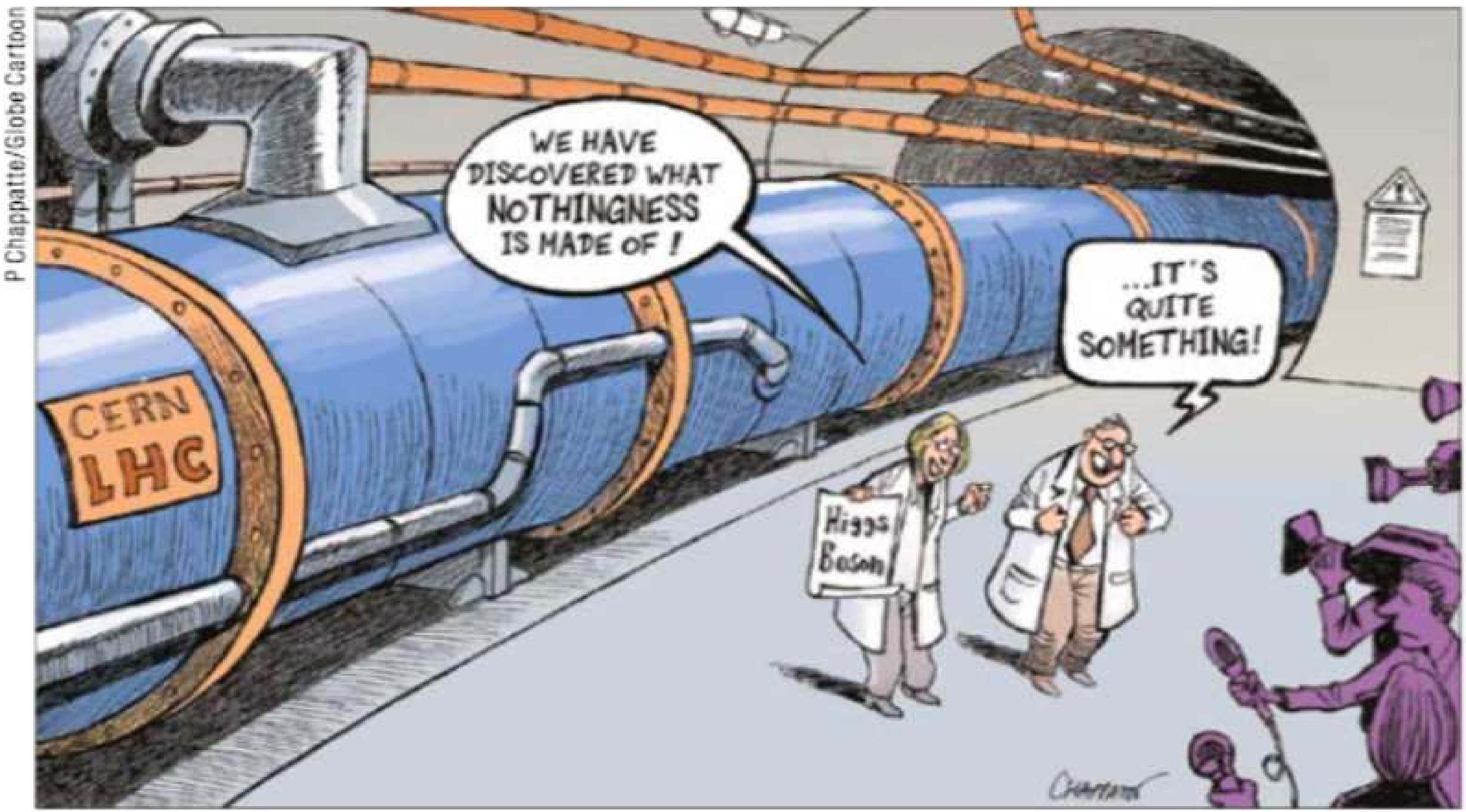
- Current state of particle physics: Hurrah for the SM!

- LHC paradox!

- Peering at BSM through known unknowns (In the context of particular BSM models) and unknown unknowns(Model independent analyses). In this part some of the examples will be from own my work .☺


P Chappatte/Globe Cartoon
WE HAVE DISCOVERED WHAT NOTHINGNESS IS MADE OF !
...IT'S QUITE SOMETHING!
CERN LHC
Higgs Boson

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 will discuss here implications of the Higgs discovery and (non) discovery of anything else!

I) Mostly what does it say about our theoretical perceptions of both the SM and beyond!

II) 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 of in the universe which is picturesquely called the Dark Matter DM

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

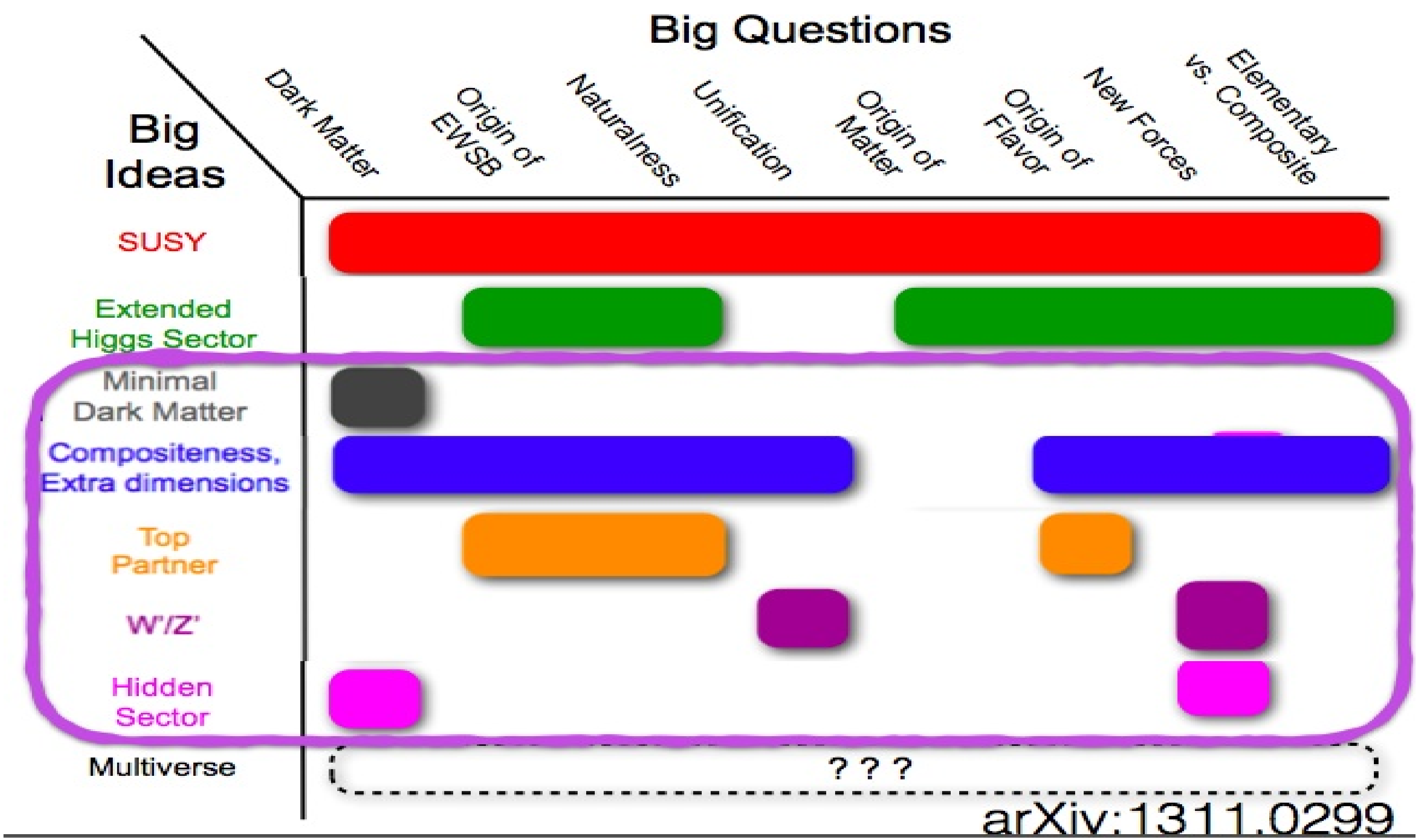
4)However the masses are generated at the cost of many more free parameters of the SM. Even worse they span at least 15 orders of magnitude!. No real understanding of the generation of this hierarchy of masses! The non zero masses of neutrinos has even more additional facets. flavour issue

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

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, $ZZ^* \rightarrow 4\ell$

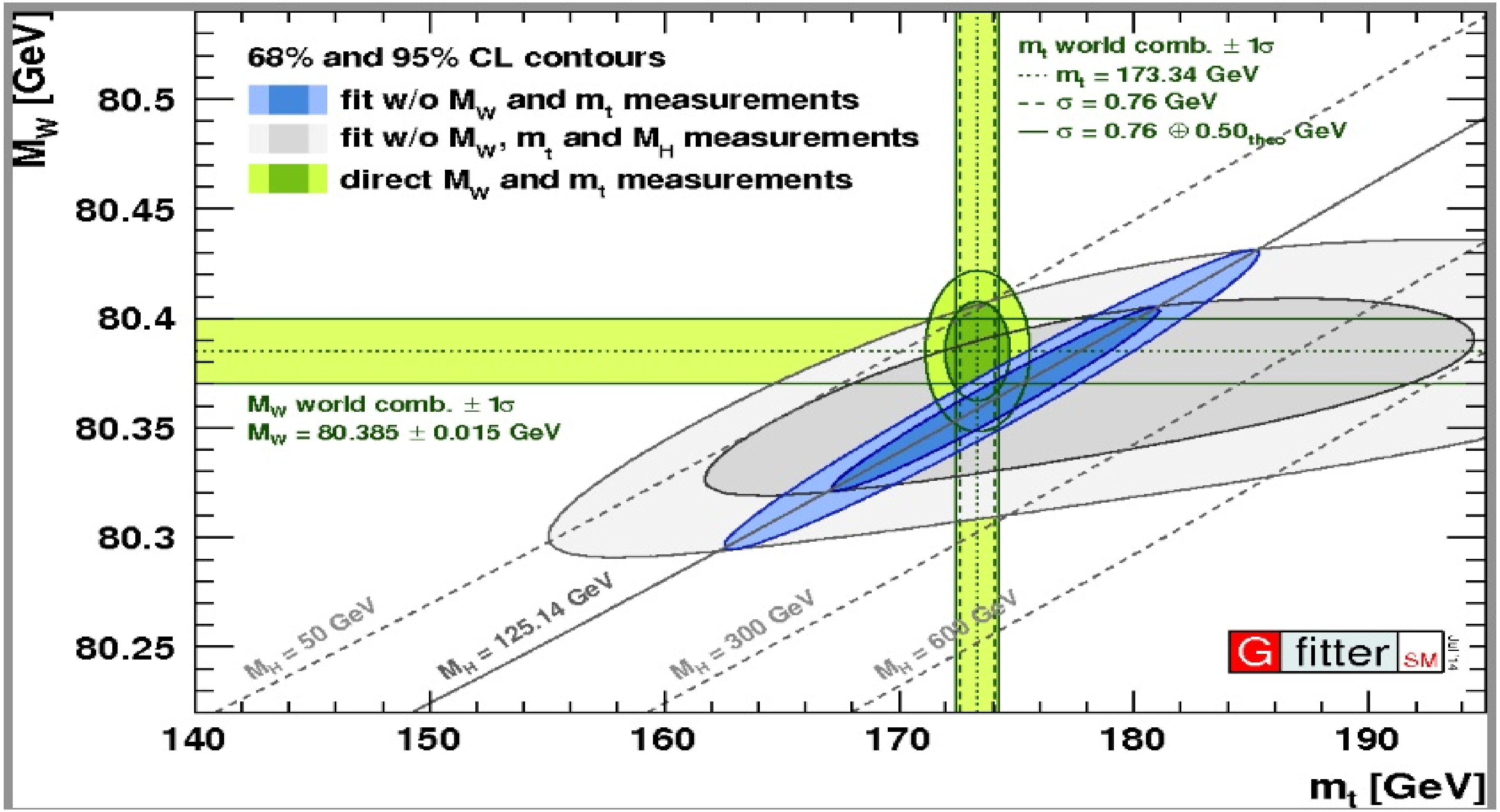
HTTP://PDG.LBL.GOV Page 4 Created: 10/1/2016 20:06

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!



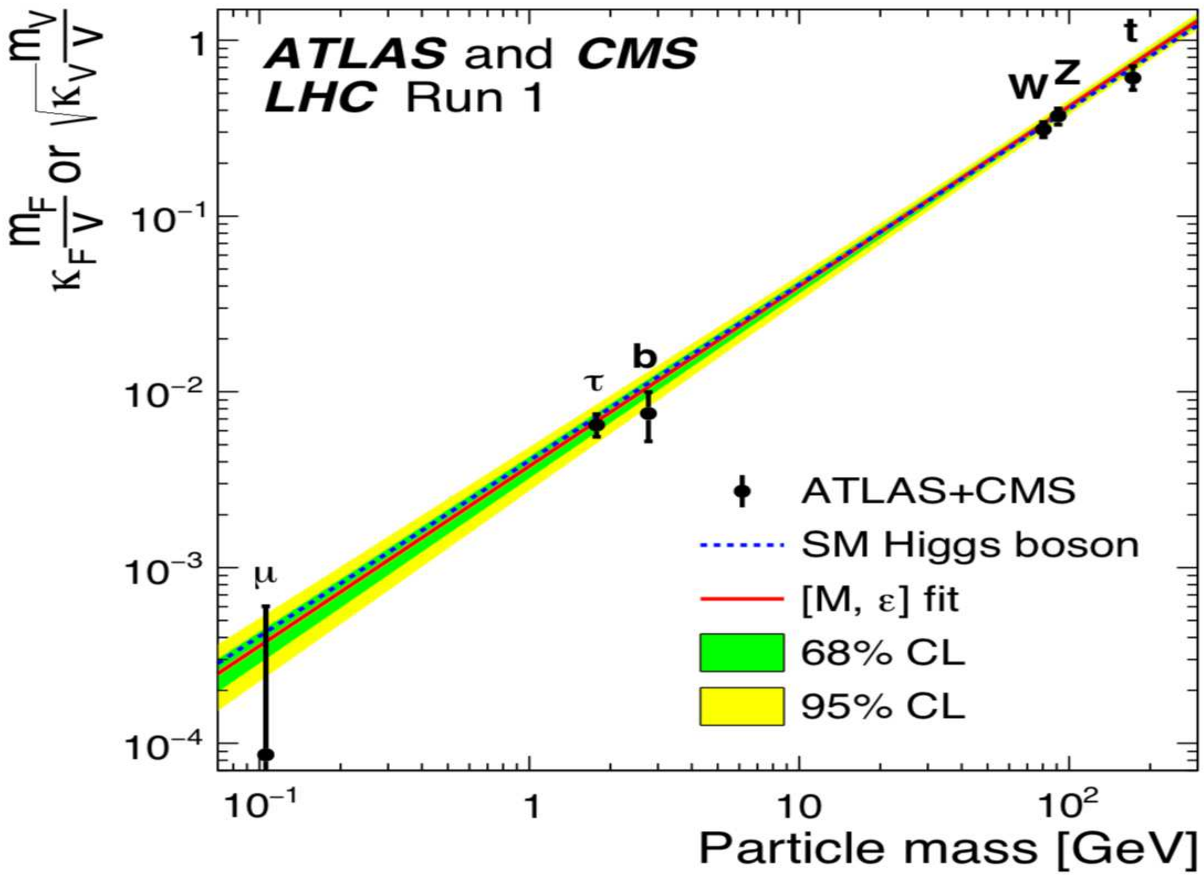
SM rocks! *At LOOP level* **Connection with top absolutely essential**

Three lessons to be learnt from the plot

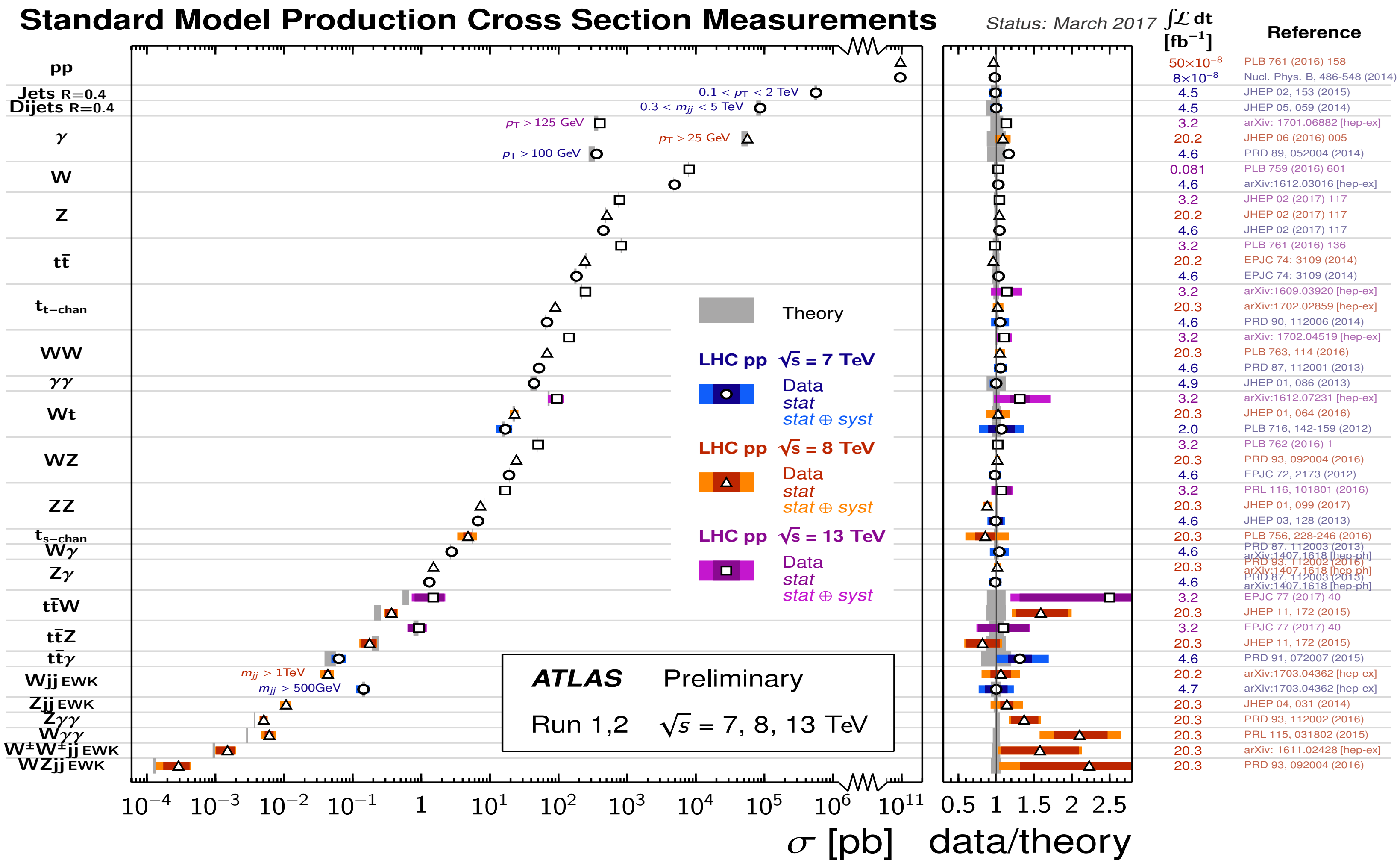
1) SM works really spectacularly!

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)


Standard Model Production Cross Section Measurements
Status: March 2017
∫L dt [fb⁻¹]
Reference
pp
Jets R=0.4
Dijets R=0.4
γ
W
Z
tt̄
t t−chan
WW
γγ
Wt
WZ
ZZ
t s−chan
Wγ
Zγ
tt̄W
tt̄Z
tt̄γ
Wjj EWK
Zjj EWK
Zγγ
Wγγ
W±W±jj EWK
WZjj EWK
Theory
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
σ [pb]
data/theory

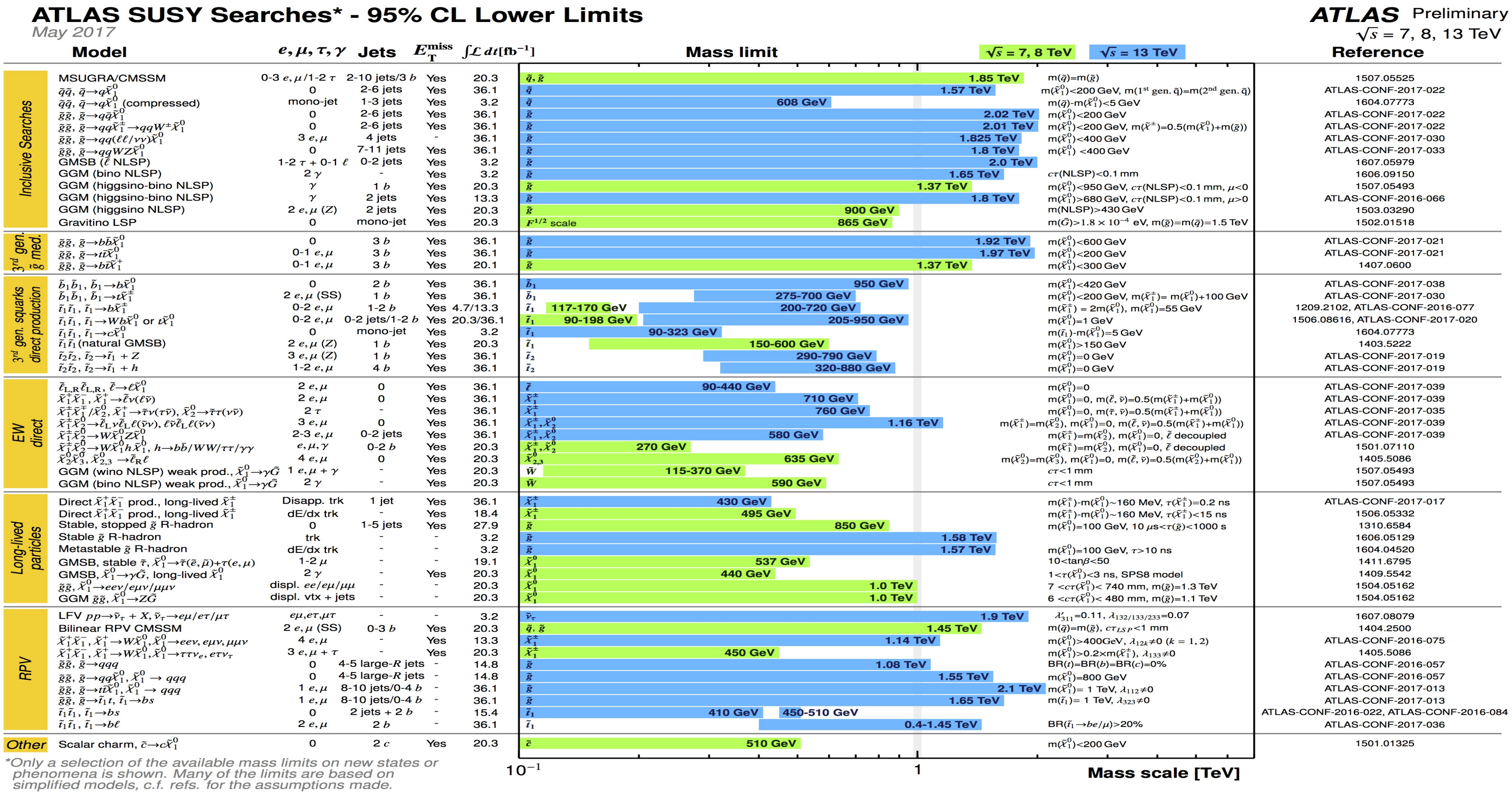
Observed Higgs mass is small enough to believe in SUSY miracle. It also implies that Sparticle masses need to be large ! Which is consistent with the fact that we have not seen any so far!

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!

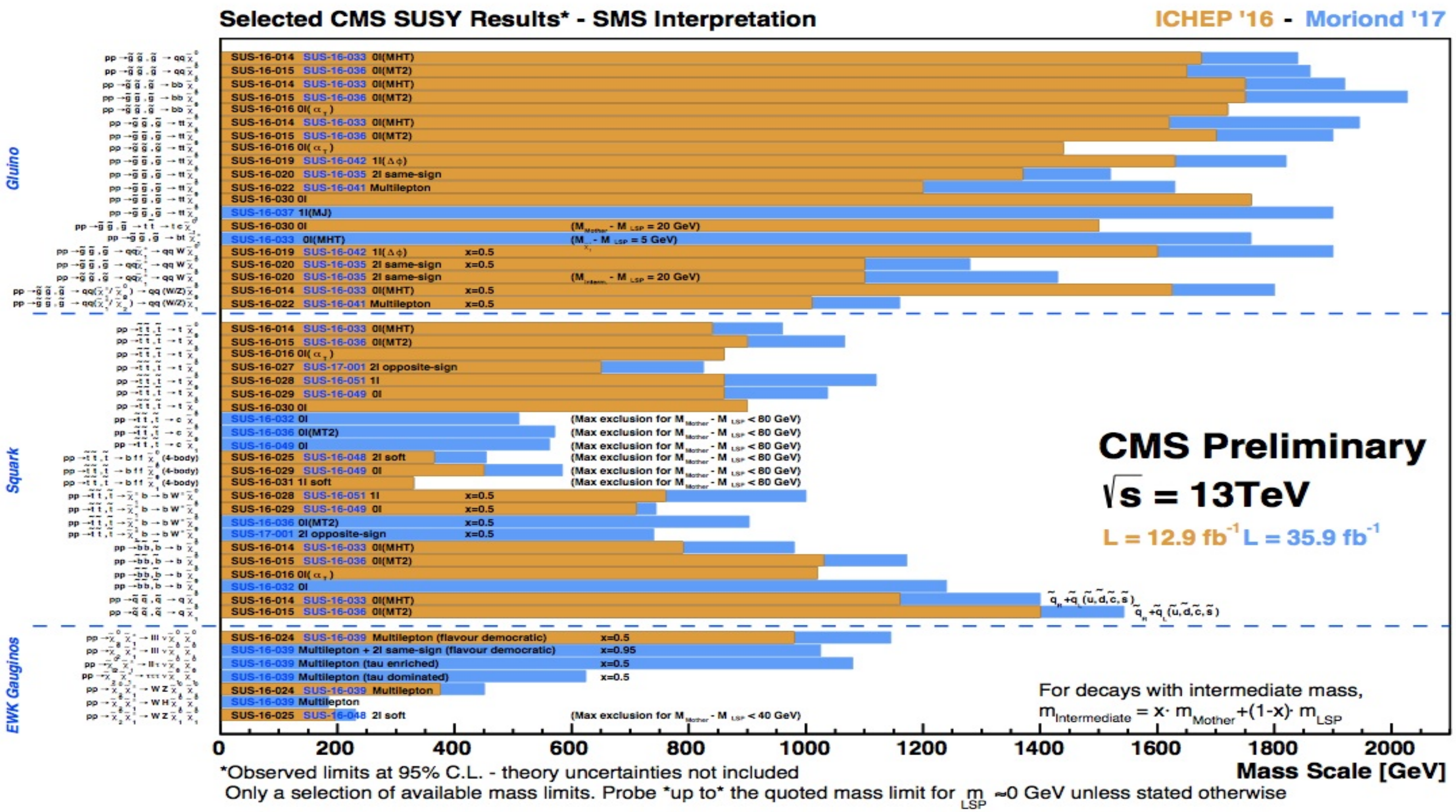
In composite Higgs models (SILH)JHEP 0706 (2007) 045, the observed Higgs mass implies lower scales for BSM, but nothing seen at that scale. The basic idea under tension and needs extension!

Will mention some of them later.

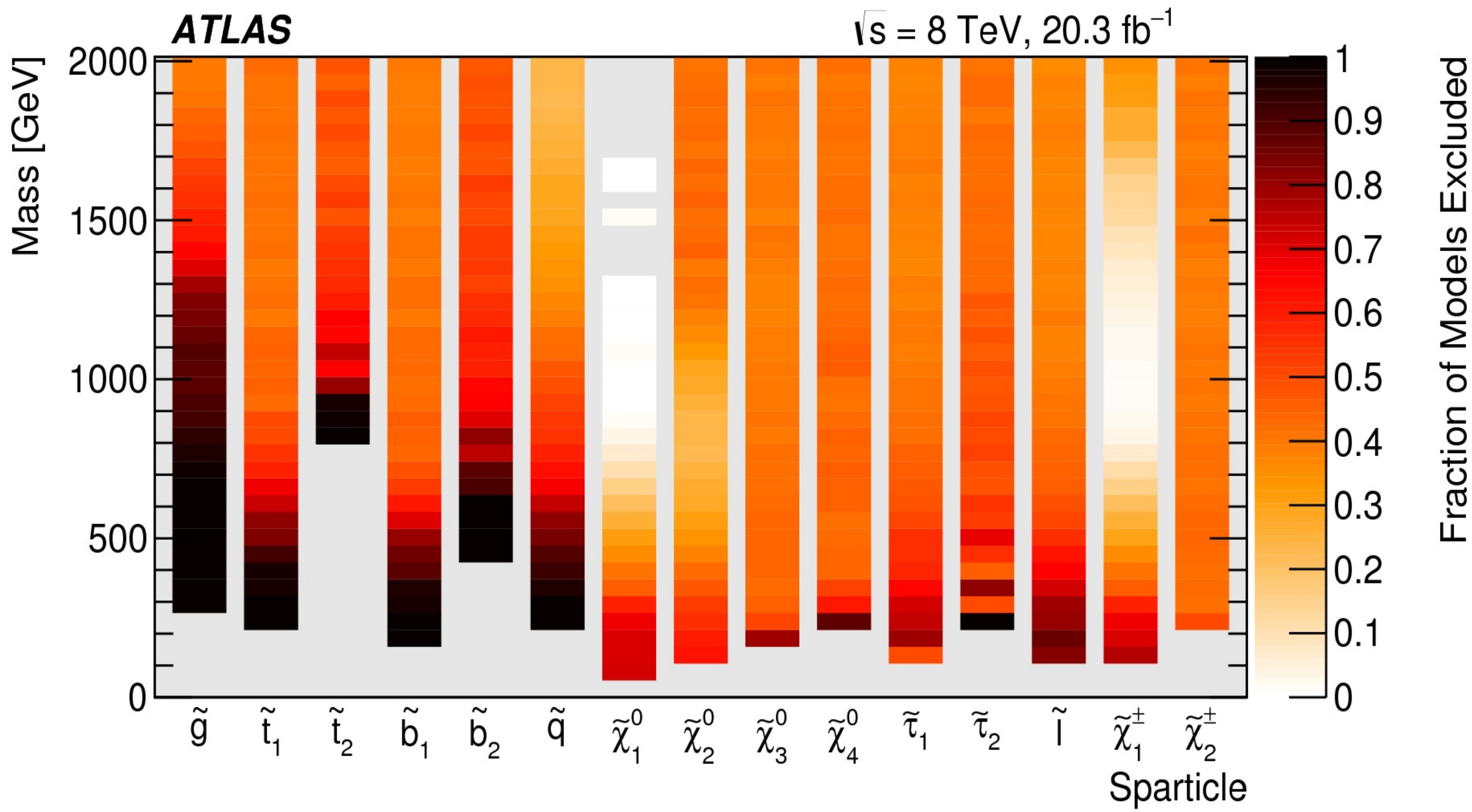
BSM Status report



Simplifed models

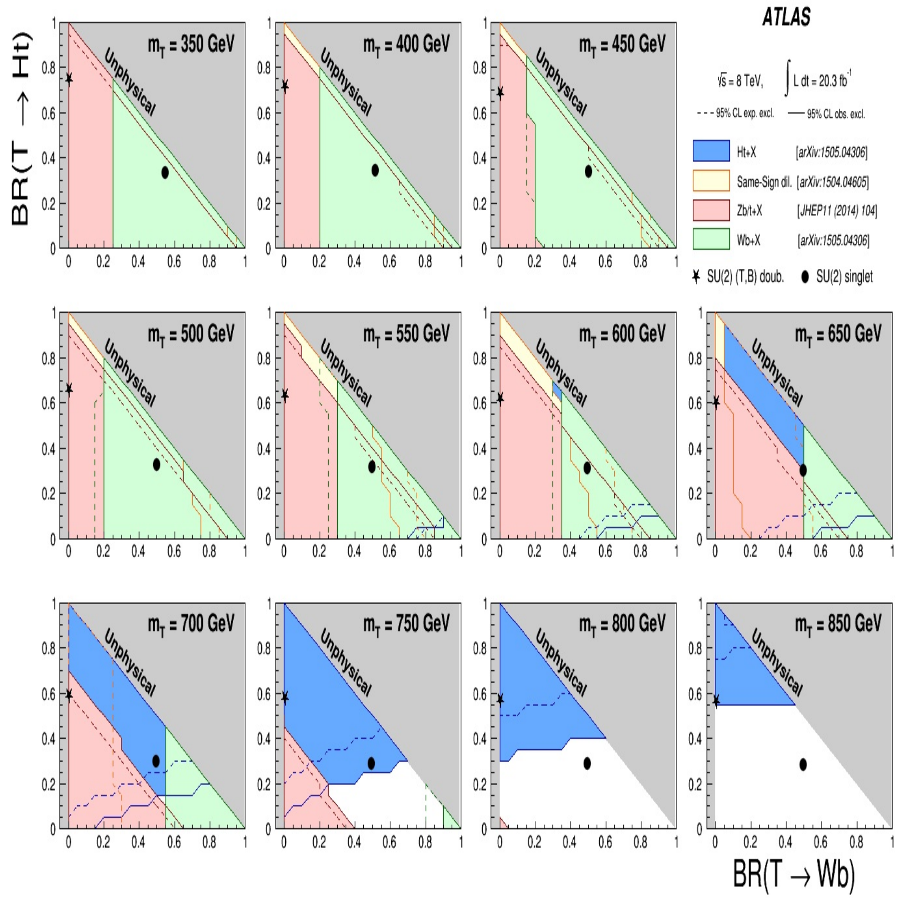


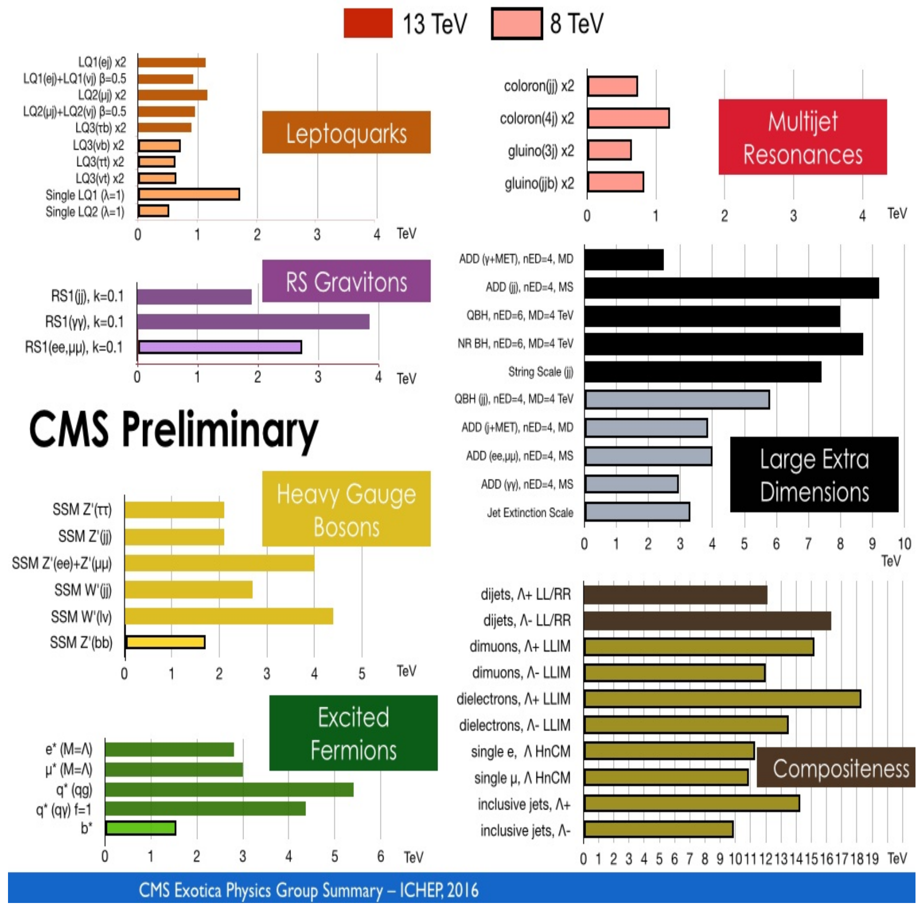
Simplified models.



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

Analysis in PMSSM: more about this later.


ATLAS
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
BR(T → Ht)
BR(T → Wb)


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!

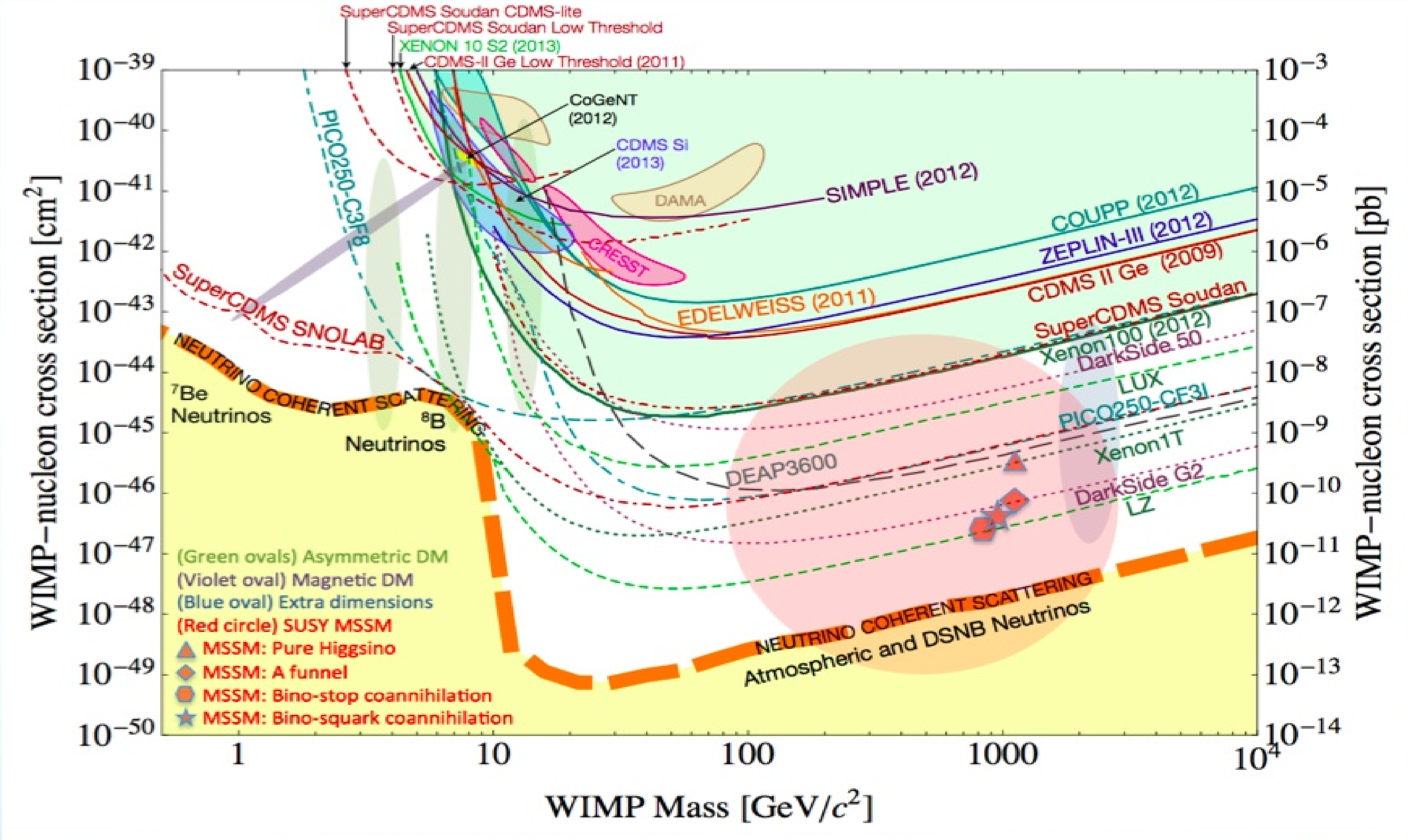
Light Higgs AND NO BSM till now!

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?



1310.8327v2

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 'naturlaness' idea in some form or the other have connections with Higgs and top sector always.

Examples: 1810.09467: N. Criag 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.

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.

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

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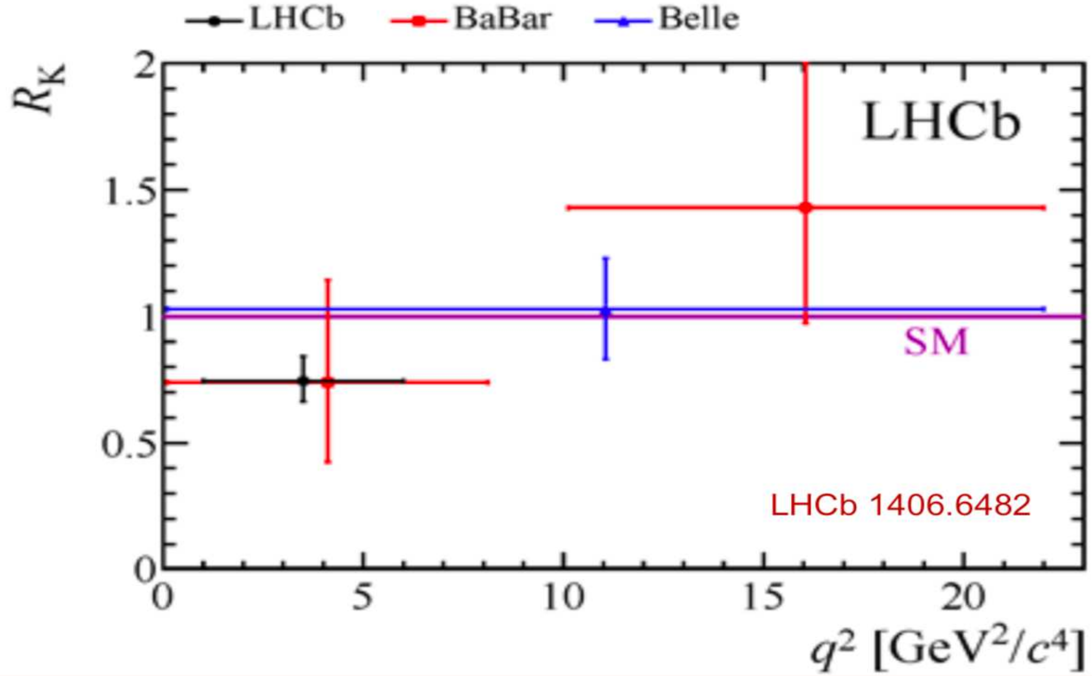
- 2.2-2.6σ deviation from the theoretically rather clean SM expectation



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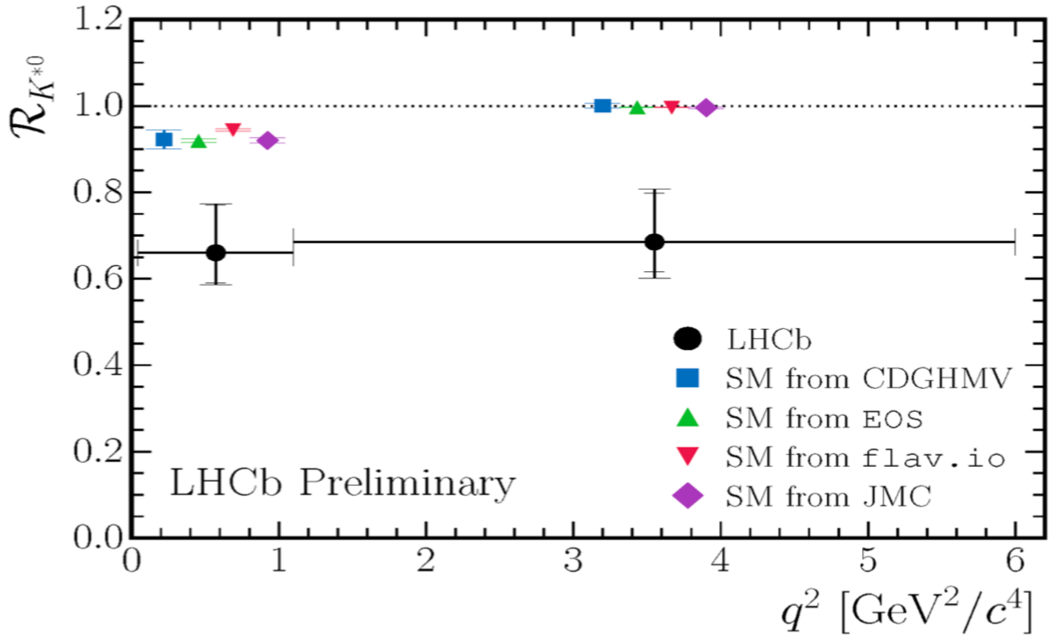
- 2.2-2.6σ deviation from the theoretically rather clean SM expectation



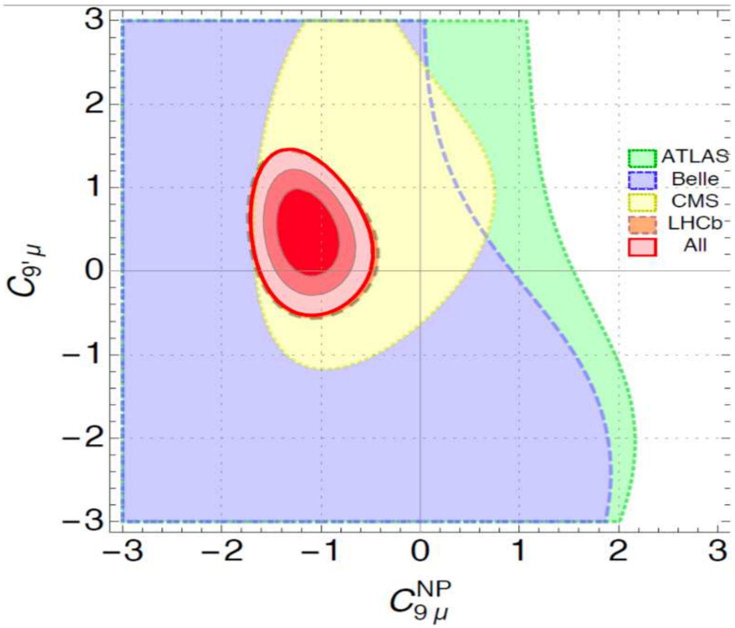
Lepton Flavour Violation in B decays?

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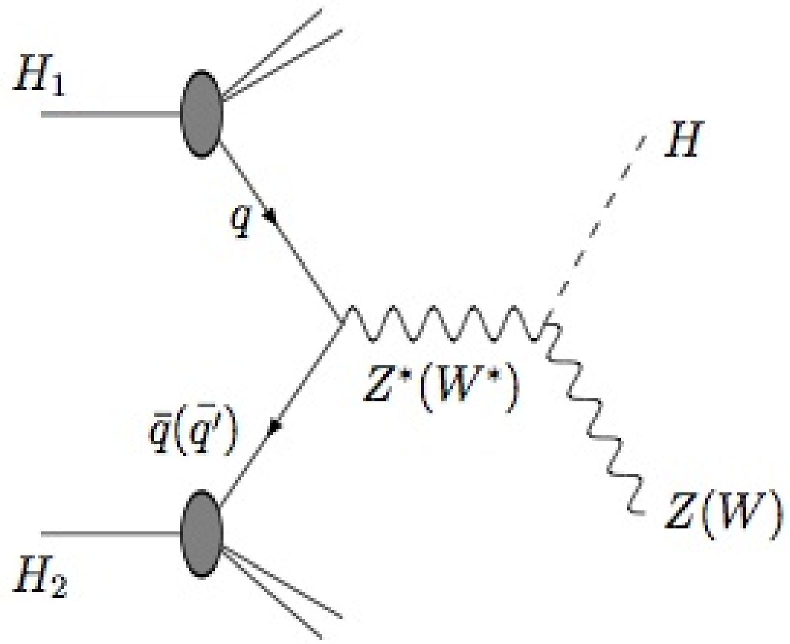
In some cases we do have limits which are not so tight.

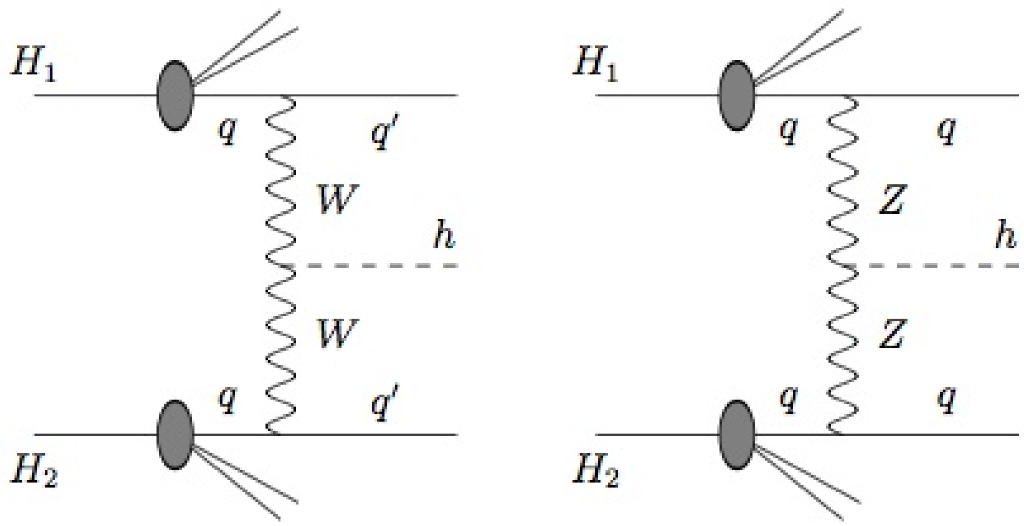
Interesting because if the DM provides right relic density through Higgs interactions then it can contribute to decays of Higgs into DM and hence 'invisible'!

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 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!

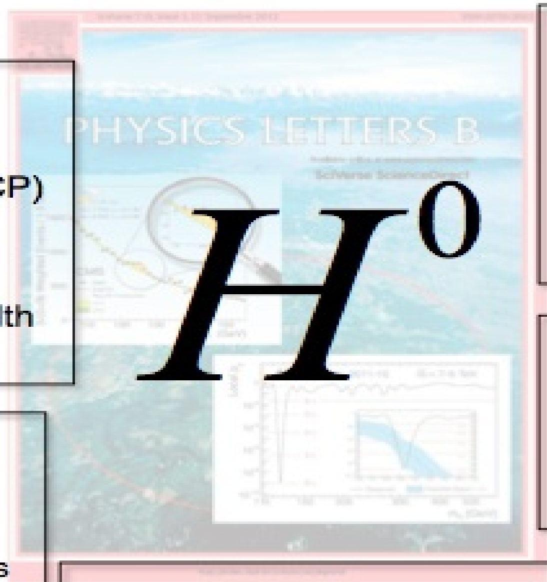
Peeping at the BSM through the known Higgs and Top/bottom and through the unknown: DM *if it has anything to do with particle physics*. Look for the 'unknown' through the 'known' or 'unknown'.

Absence of Evidence is not Evidence of Absence!

Peeping through the Higgs and the top window!

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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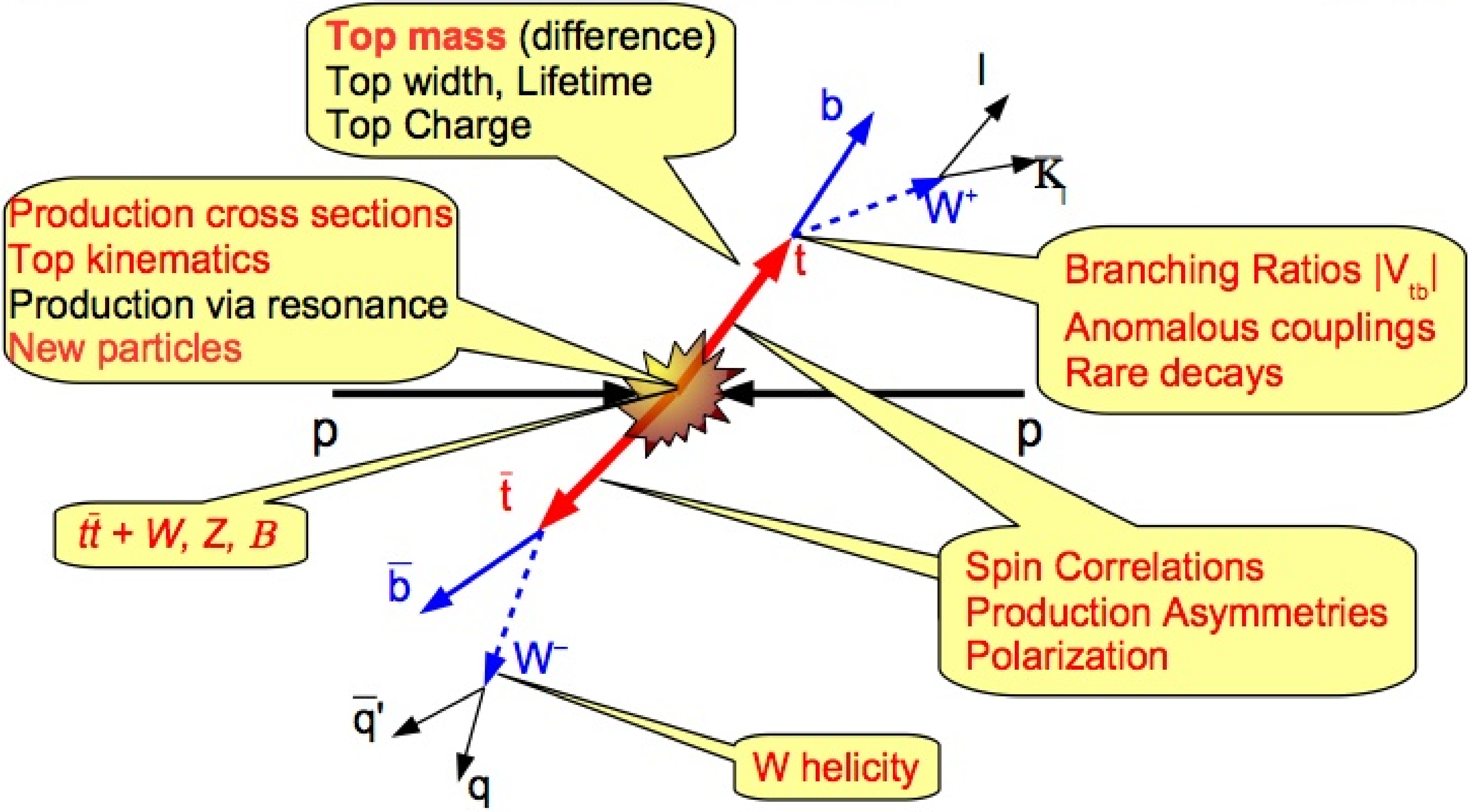
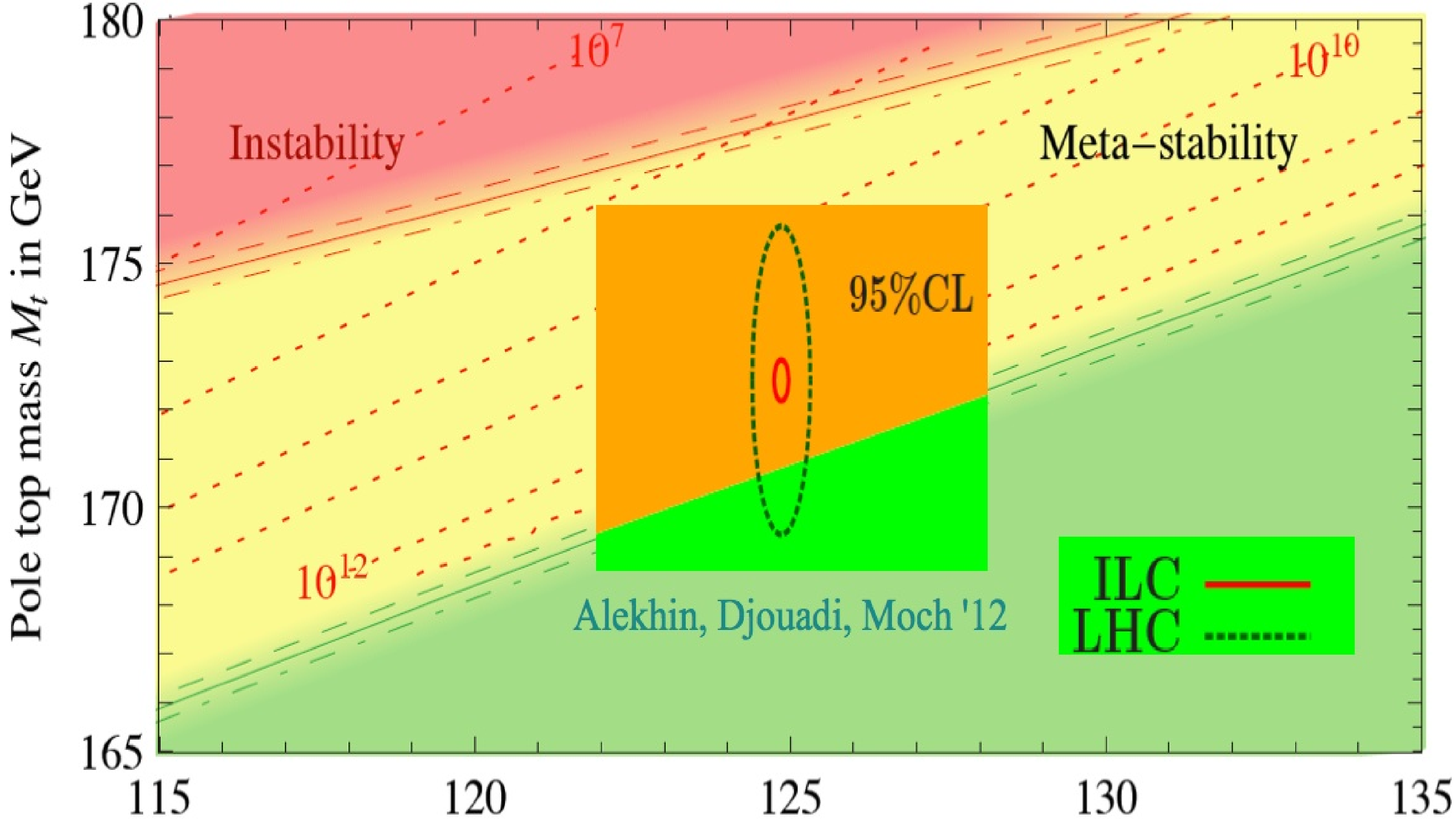
Content


Top mass (difference)
Top width, Lifetime
Top Charge
Production cross sections
Top kinematics
Production via resonance
New particles
$t\bar{t}$ + W, Z, B
Branching Ratios $|V_{tb}|$
Anomalous couplings
Rare decays
Spin Correlations
Production Asymmetries
Polarization
W helicity
b
l
W+
t
p
p
$\bar{t}$
$\bar{b}$
W−
$\bar{q}'$
q

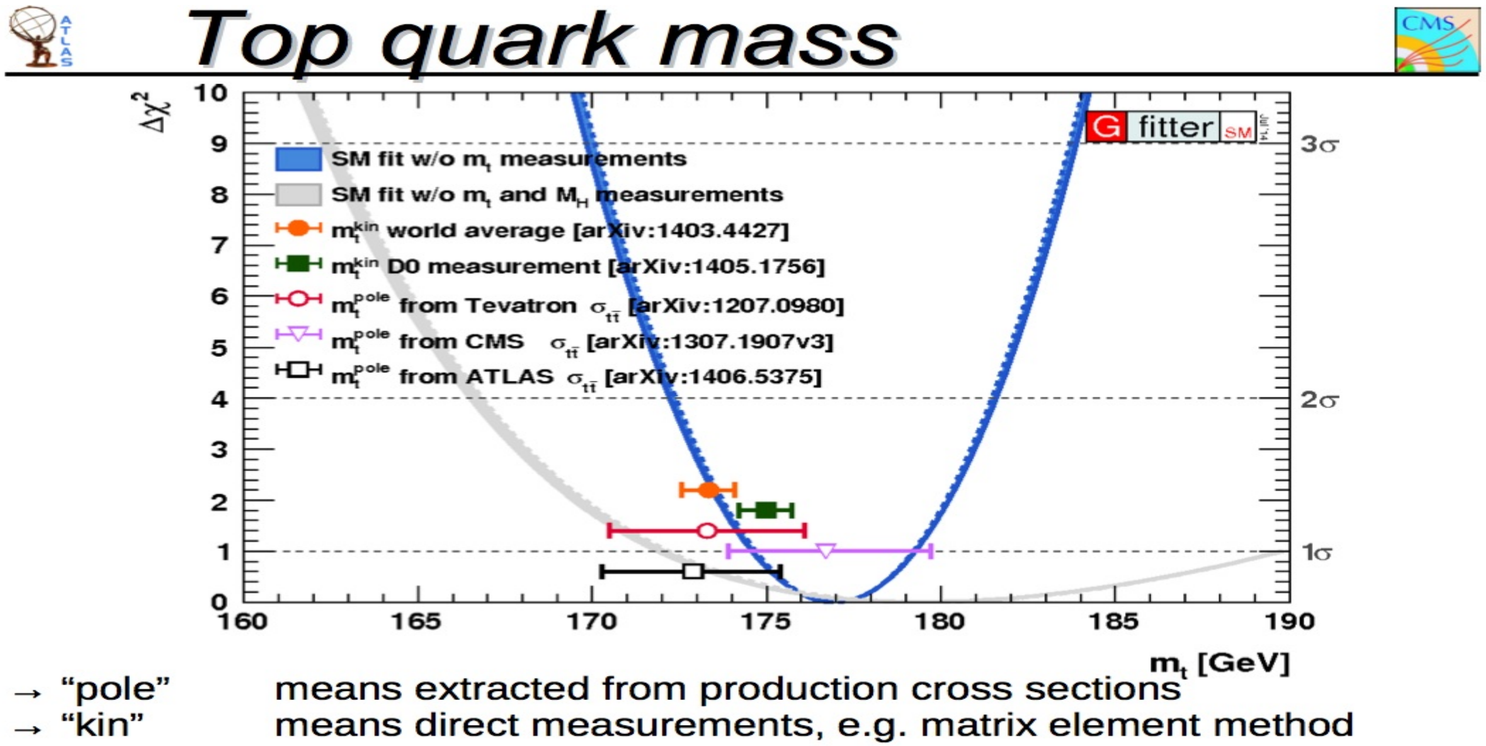
Higgs and top mass critical as far as SM is concerned.

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.

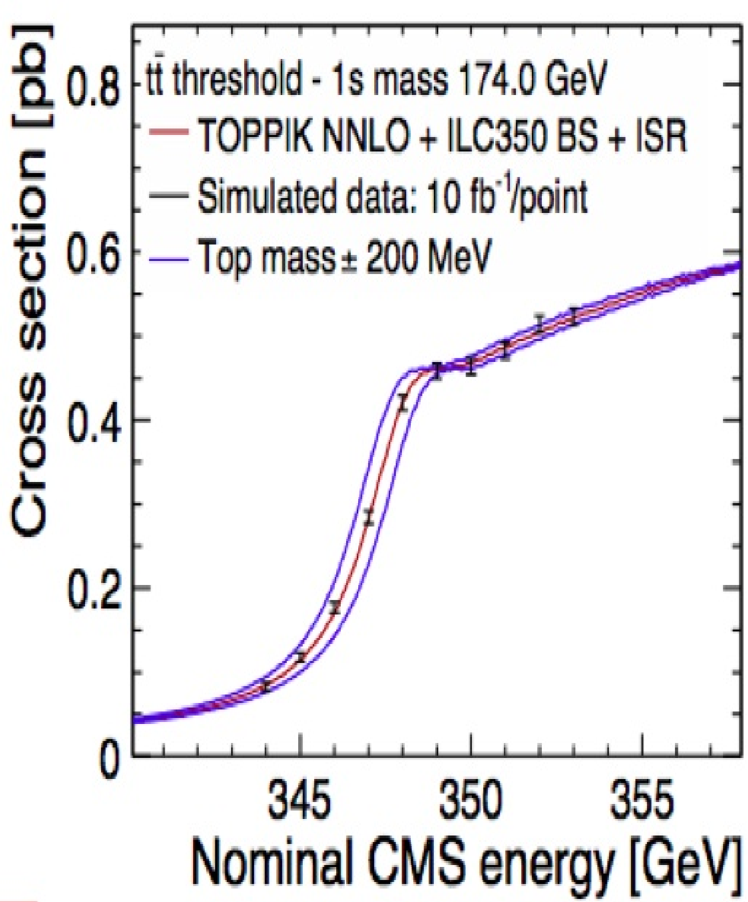


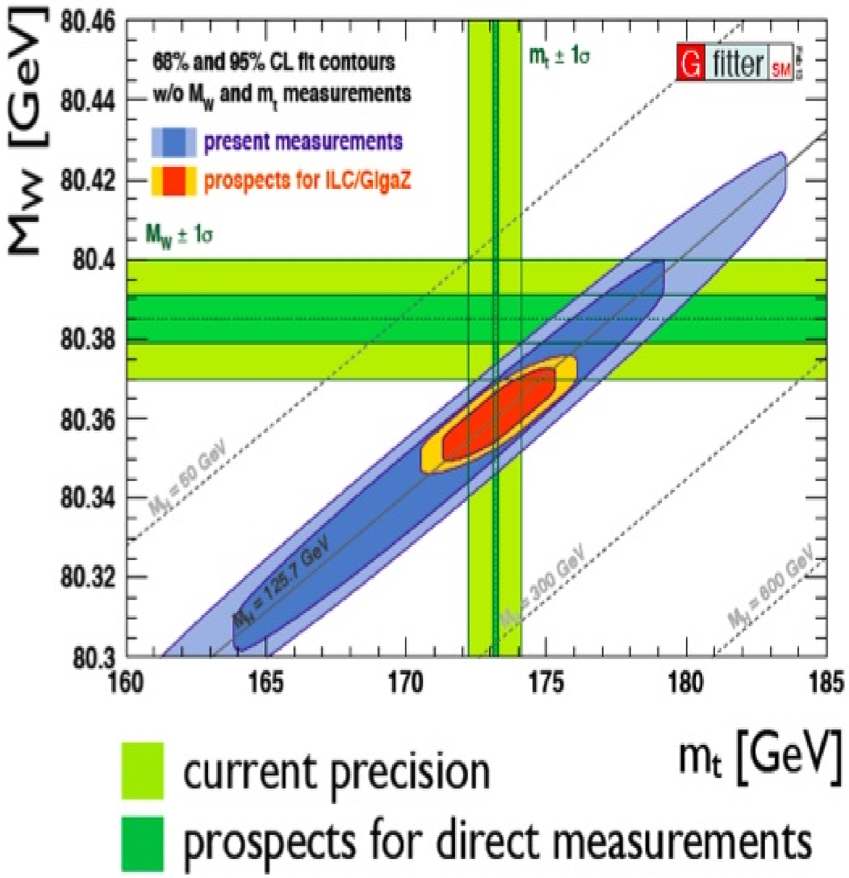
M_h value indeed critical.



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.





Precision: $\simeq$ 100 MeV!

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.

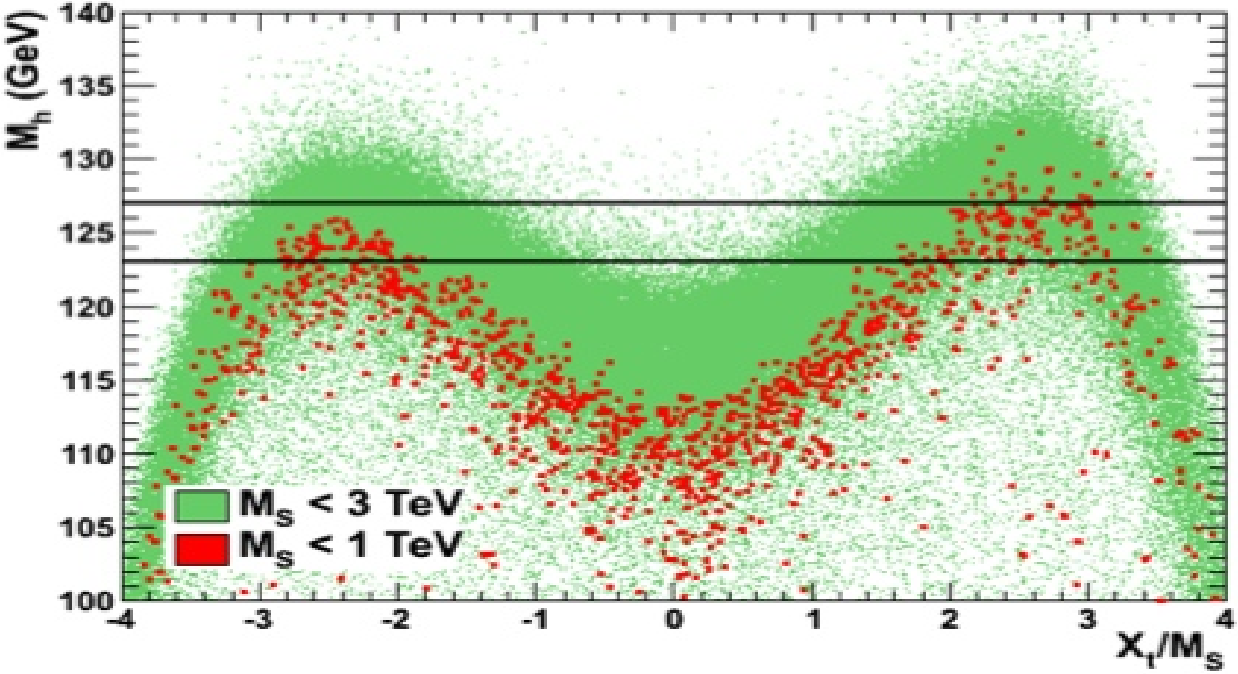
The mass of the observed state very very interesting!

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

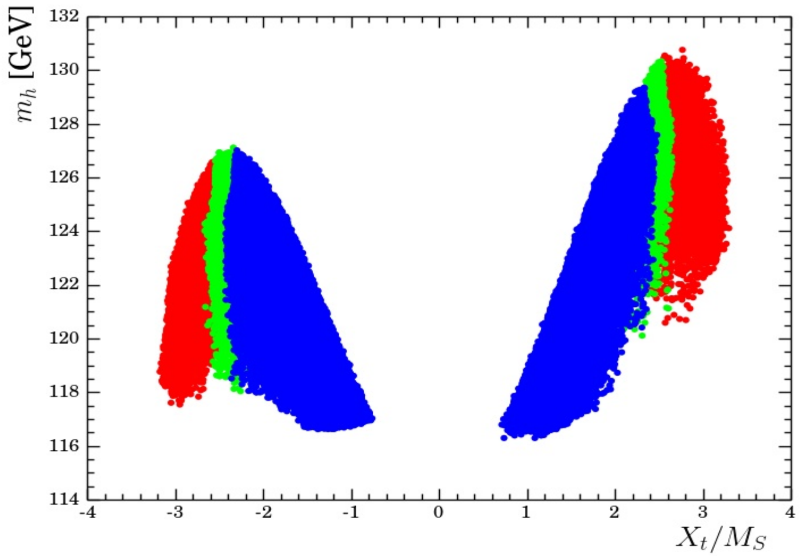
But large enough to already provide some interesting constraints on SUSY breaking ideas.

$M_h = 125$ 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.



For high M_S typical mixing possible, for low M_S only maximal mixing possible. Gives some indication of the character of stop. (From Mahamoudi, Arbey, DJouadi) $X_t = A_t - \mu \cot\beta$



Lot of scalar fields. The scalar potential may have charge and color breaking minima which can destabilize the vacuum away from the EW minimum.
Red: Unstable,
Green: metastable: tunneling time $> \tau_{Universe}$
Blue: stable

We can get $m_h = 125$ with 'light' (800 GeV to 1 TeV) stop but with large A_t. But with large A_t the Higgs potential develops charge and color breaking minima making vacuum unstable! So need to be careful!

JHEP 14 (2014) 110 (R.G. + K.Mohan, S. Vempati, D. Chowdhury)

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!

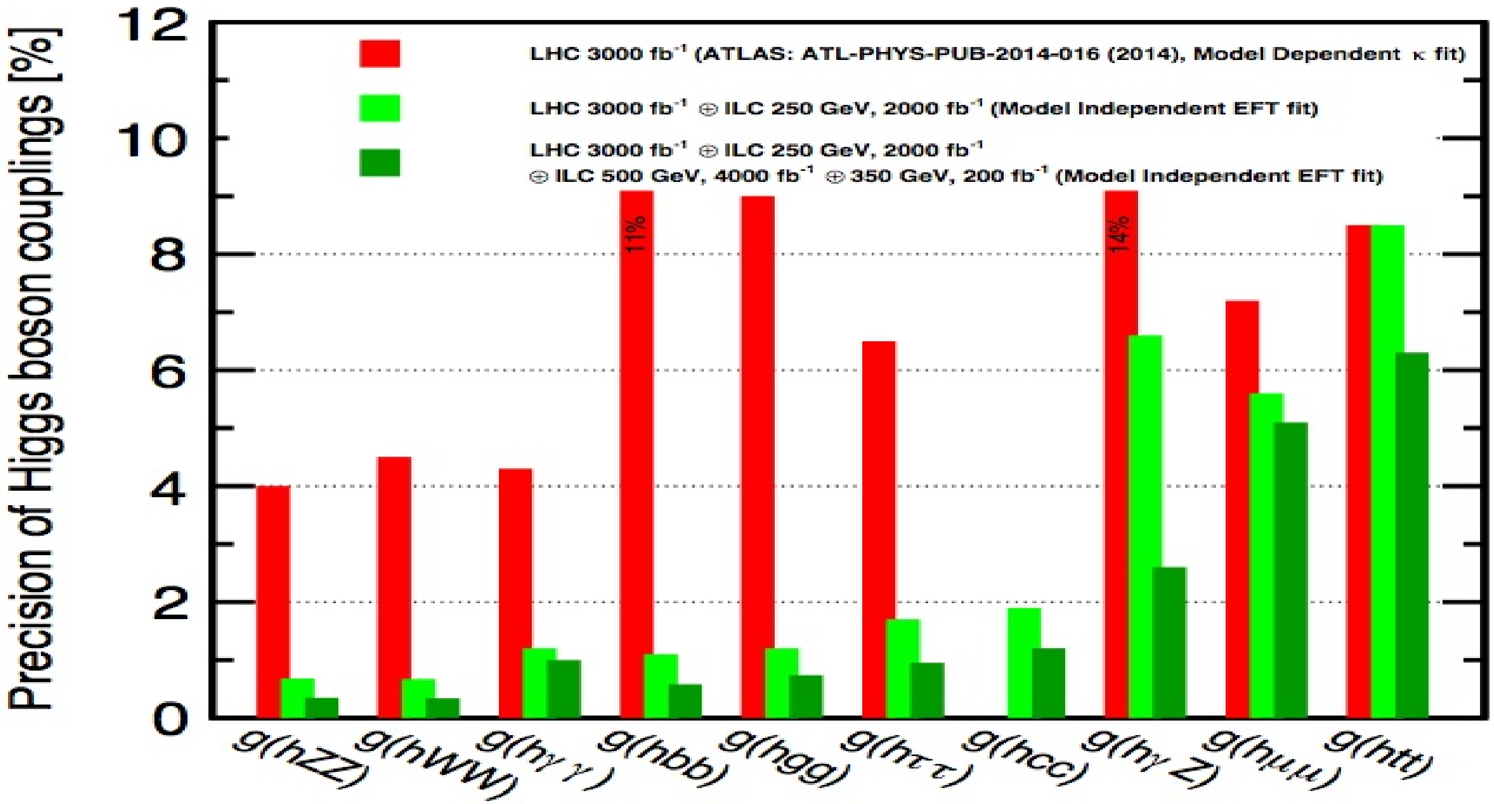
c) Use deviations from the SM values to probe the BSM. Are deviations only modification of the existing couplings from the SM values (κ formalism) OR does deviation mean additional operators?. Focus here on CP violation/CP mixing.

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.

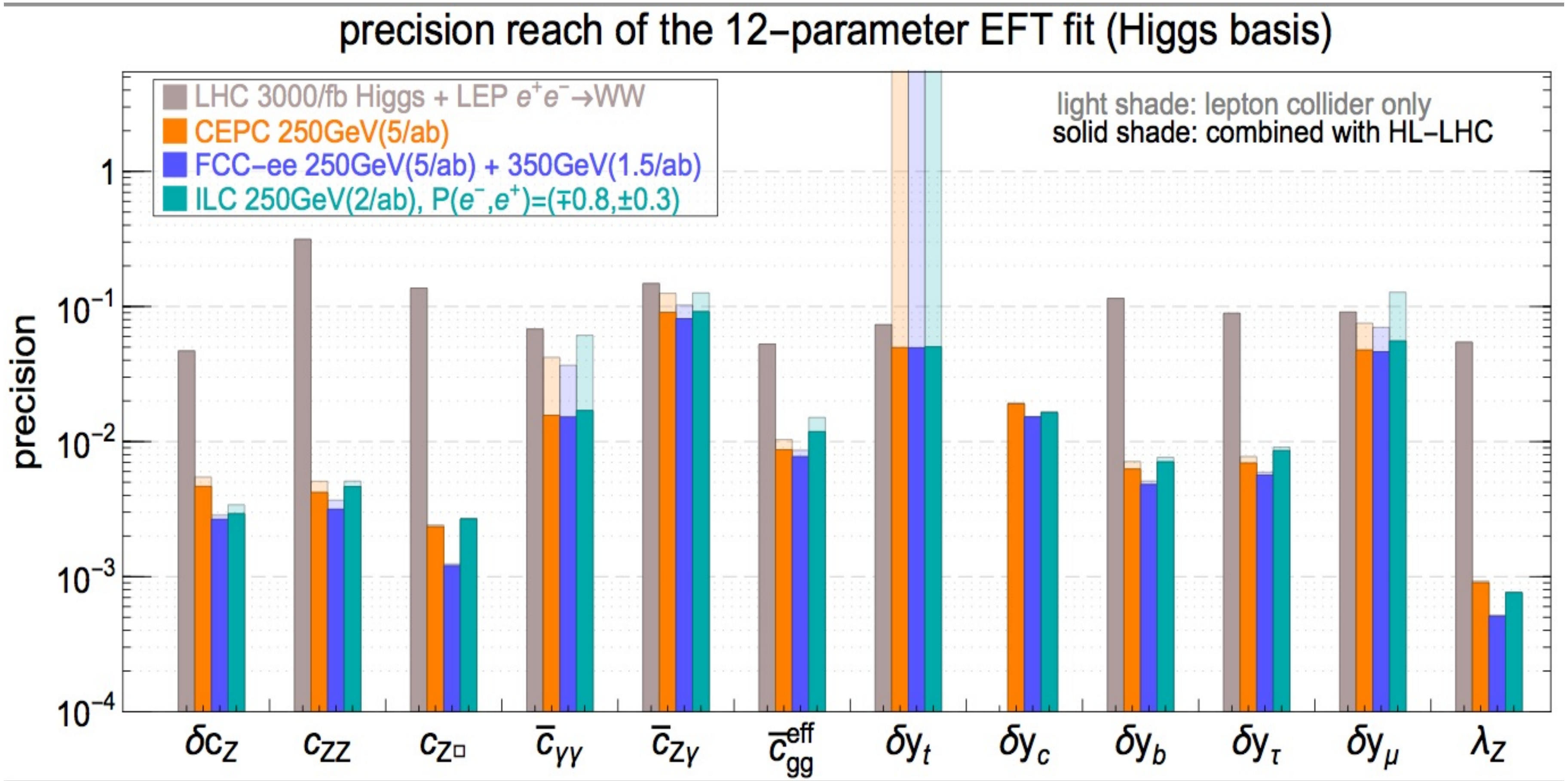
f) Effect of top coupling on rates of associated production of Higgs with top.

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!



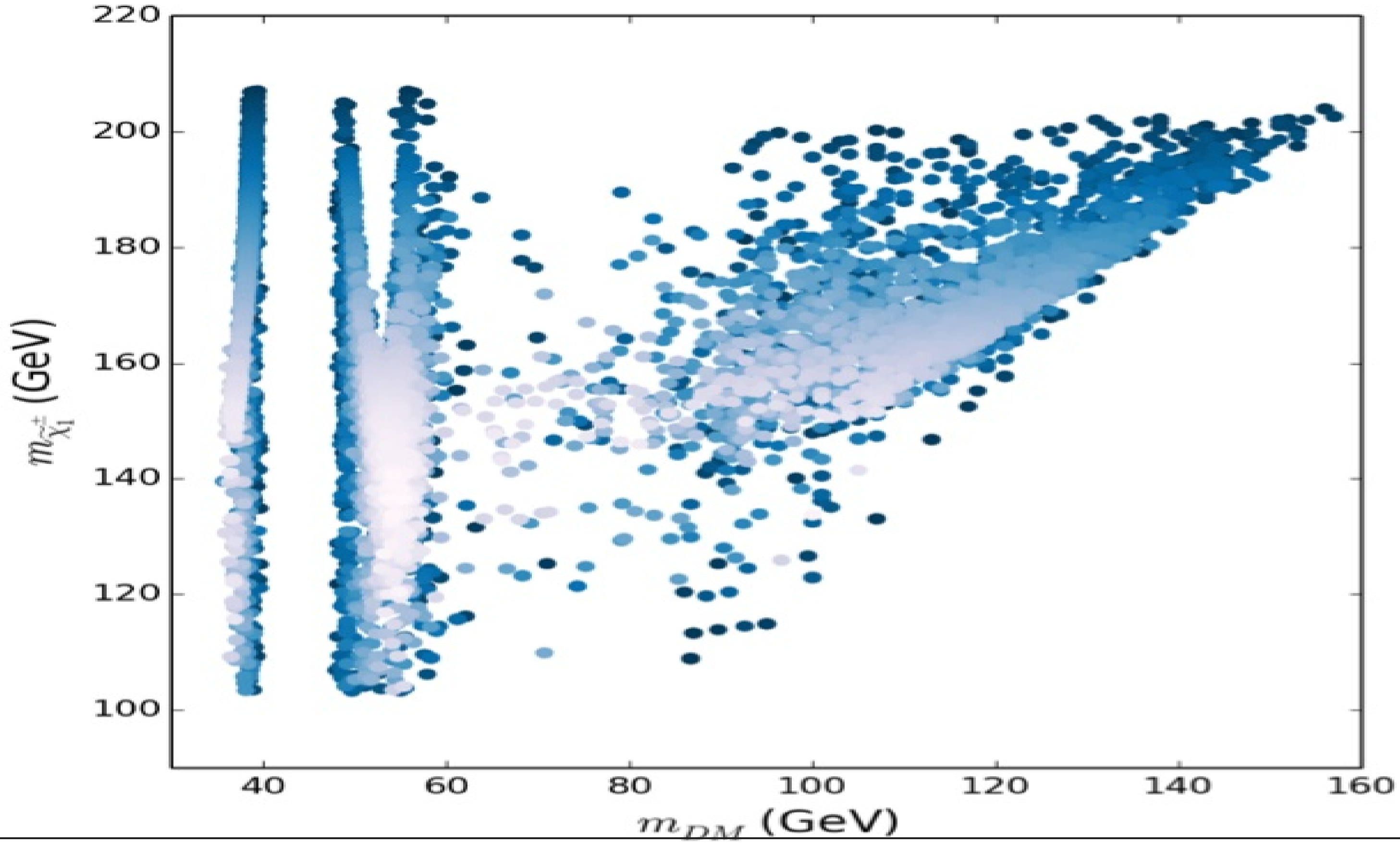
High accuracy measurements possible. Improvement over HL-LHC. ILC 250 GeV can in principle attain results similar to ILC 500. Polarisation plays important role. 1710.07621 (Peskin et al)

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.



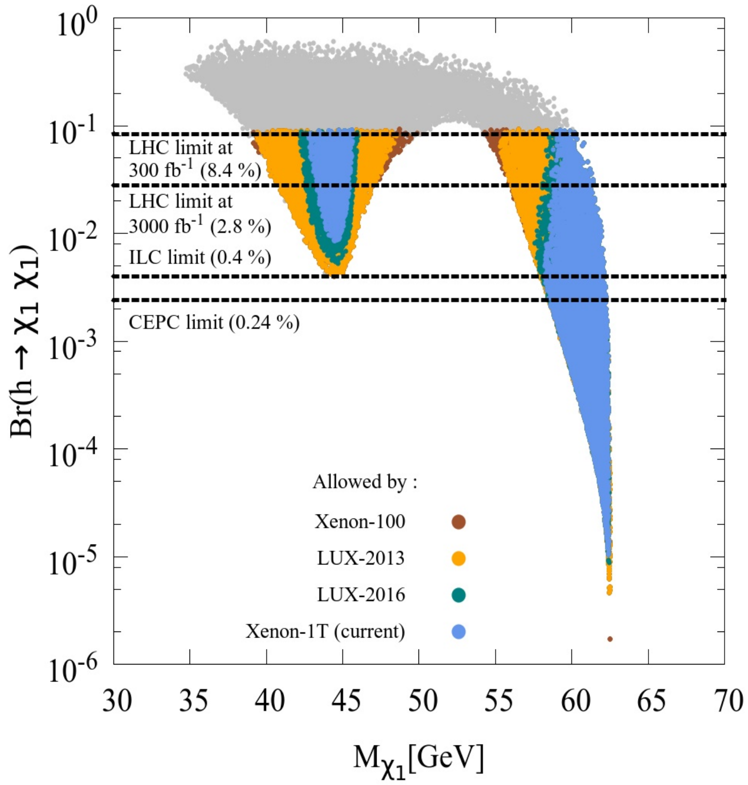
Courtesy : Lian Tao Wang , CEPC CDR (in preparation)

1612.06333v1: a light EW sector is 'natural' in this sense. 1612.06333v1: M. van Beekveld, W. Beenakker, Caron, Peeters and Austri. light to dark, Δ varies from 4 to 10.



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:

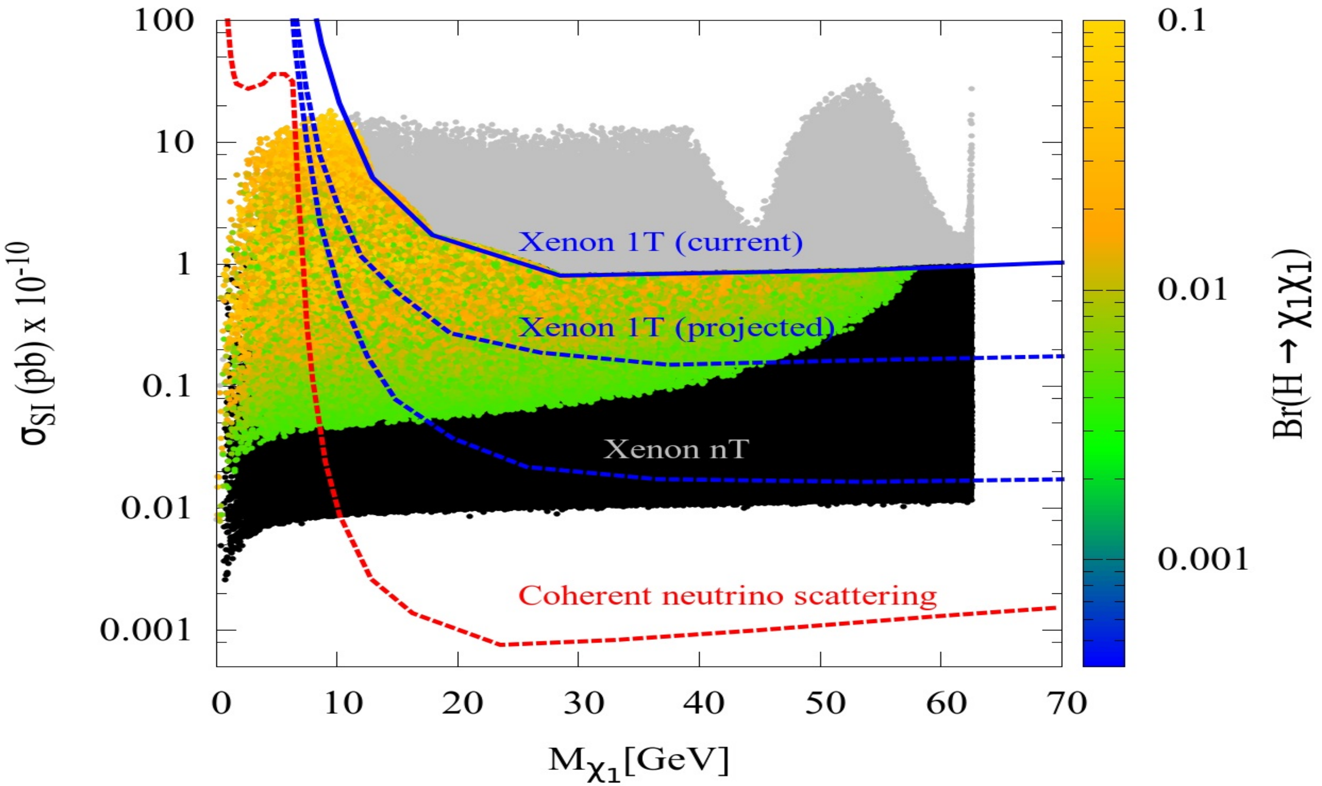
300 1/fb, 0.15; 3000 1/fb, 0.06 and the ILC: 0.3 %.

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.

For Nonthermal DM the light neutralinos can not be detected in the Direct Detection experiments and then invisible decay width might be the only way!



a)t effects on loop induced Higgs couplings

b)tree level processes affected by t Yukawa couplings

Sensitive observables:

Loop:

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

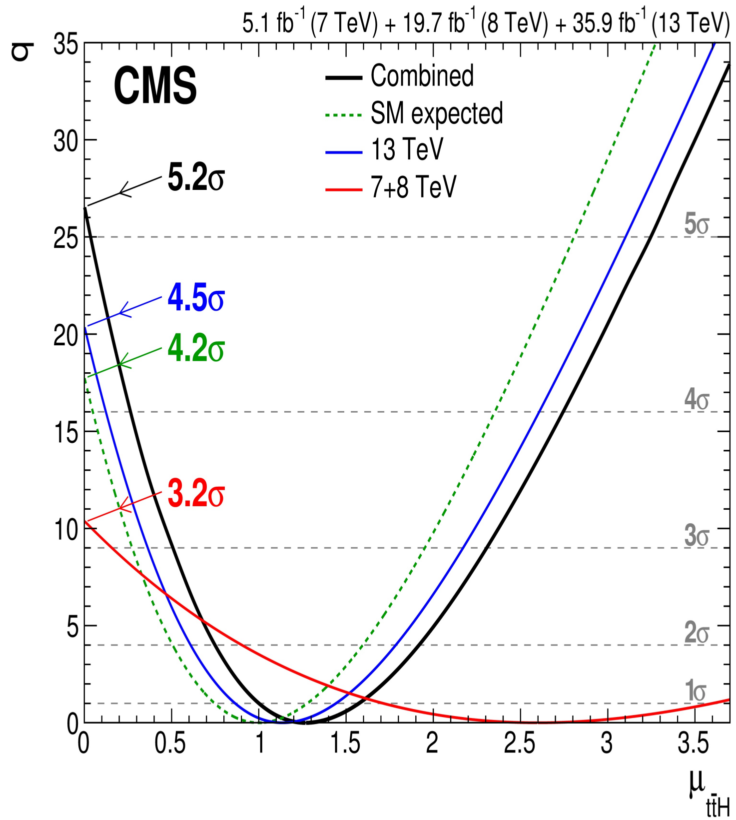
Tree level:

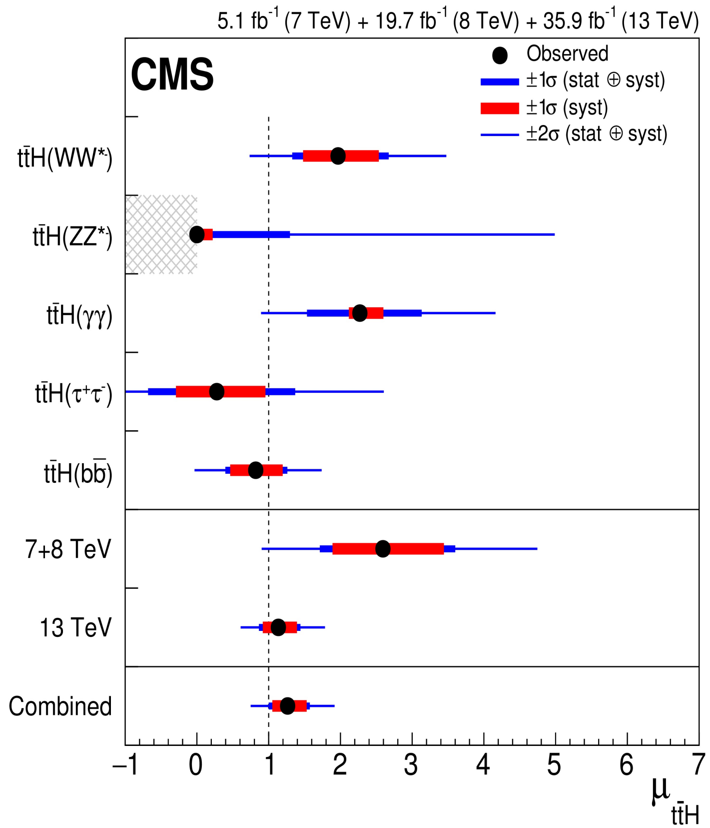
$\sigma(pp \to t\bar{t}h)$

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

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

Both CMS and ATLAS have observed $t\bar{t}h$ process.





First and foremost: a 'direct' measurement of the strength of this coupling (lot of work and discussions!). Can the additional source of CPV for BAU be this?

Check CP property of the coupling :

a)Use cross-section and kinematical observables for tth. F. Boudjema et al, Phys.Rev. D92 (2015) no.1, 015019

b)Use cross-sections for th and $t\bar{t}h$ Maltoni, Mawatari, Eur. Phys. J. C **75** (2015) no.6, 267, [arXiv:1504.00611 [hep-ph]].

c)Use polarization information for th as well. S. D. Rindani et al Phys. Lett. B **761** (2016) 25, arXiv:1605.03806 [hep-ph]]., R.G., Rindani et al (in preparation))

Higgs coupling to top quarks

$$\mathcal{L}_{tth} = g_{tth}\bar{t}(a + ib\gamma_5)\phi t$$

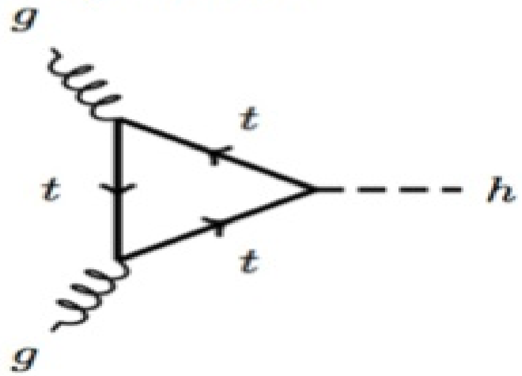
$g_{tth} = m_t/v$

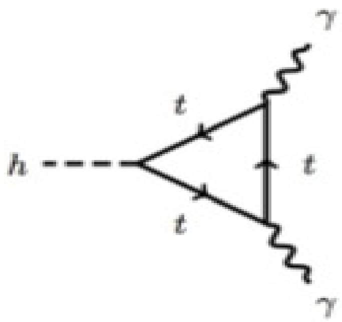
In SM $a = 1$ and $b = 0$.

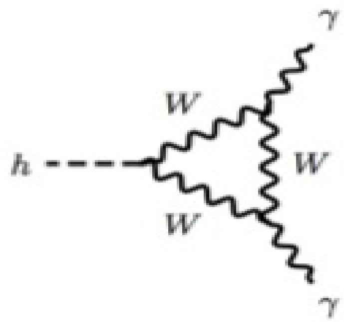
For a pure pseudoscalar $a = 0$ and $b \neq 0$.

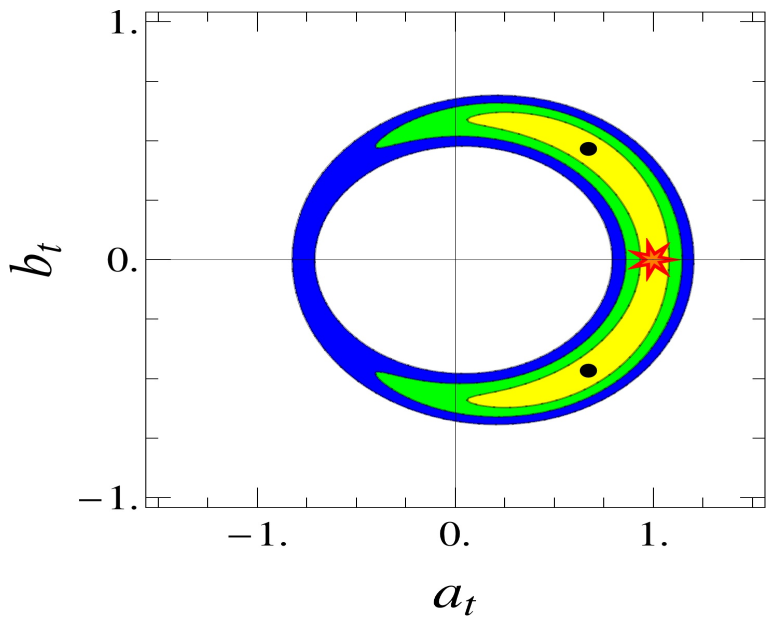
Higgs of mixed CP properties $a \neq 0$ and $b \neq 0$.

Non-SM couplings will affect higgs production and decay rates









F. Boudjema et al, Phys.Rev. D92 (2015) no.1, 015019 All the other couplings other than the t are taken to be SM couplings.

Rates are more sensitive to the pseudo scalar part b_t than a_t Does allow $b_t \neq 0$ and will continue for a while!

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

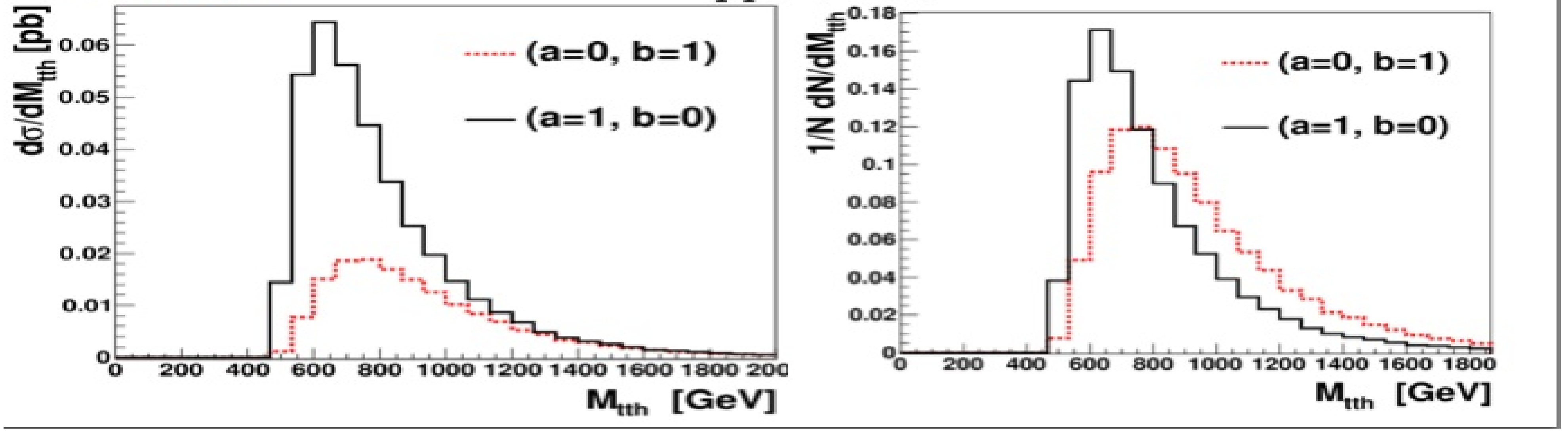
Such CP violation is allowed only if it happens only in the couplings to third generation of fermions!

Threshold behaviour of tth production

For qq initiated process angular momentum provide hints to origin of suppression.
For scalar overall angular momentum of tth =0.
For pseudoscalar overall angular momentum of tth =1.

Dominant gg initiated process also suppressed but not as strongly.

$pp \to tth$



F. Boudjema et al, Phys.Rev. D92 (2015) no.1, 015019

We need to still learn how to use LHC optimally.

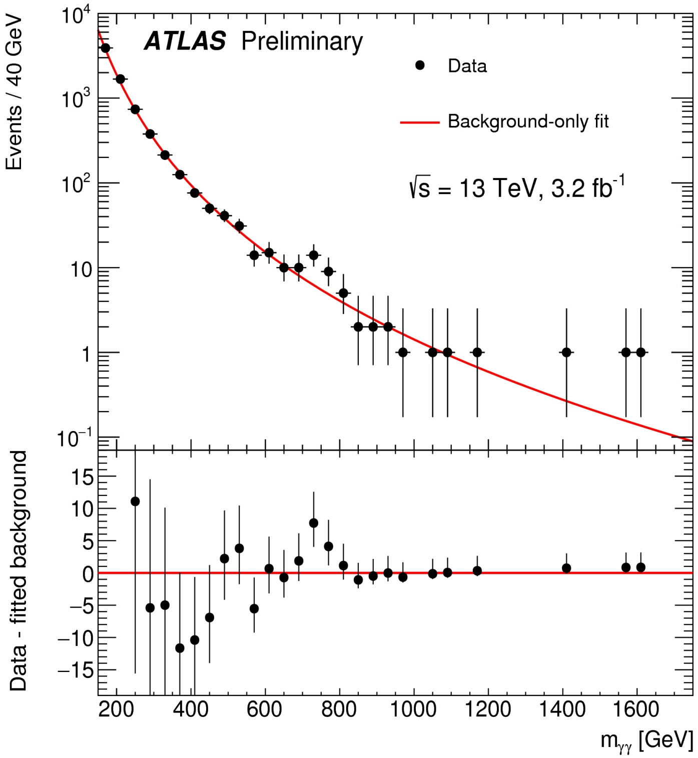
Many studies of the Higgs, top and the DM sector possible. e^+e^- precision studies will help for sure.

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!

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

BSM will appear ,most likely, as anomaly, as a 'blip' over SM bkgds!



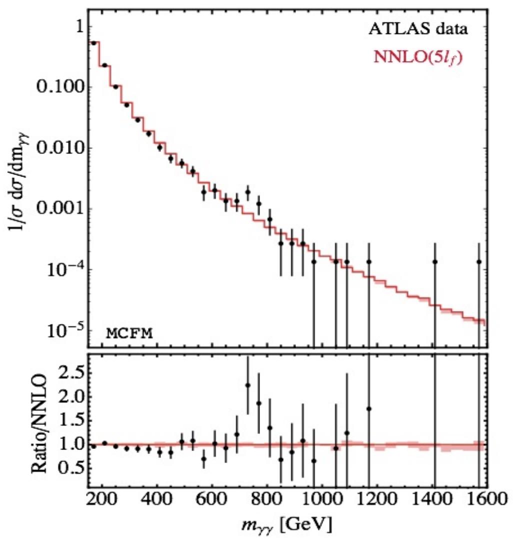


Figure 11. The rate-normalized shapes of the $m_{\gamma\gamma}$ distribution from the ATLAS collaboration and the MCFM NNLO prediction for $\mu = m_{\gamma\gamma}$. The lower panel indicates the ratio of the data to the NNLO prediction.

750 GeV with Fitted ATLAS bkgd! N^2LO QCD calculation!

At least the excess WAS not a 'loose cable' effect!

Even if more data did not confirm the excess, it taught us in some sense how new discoveries are going to happen and also reminded us of the days when developments in particle physics were data driven!

Emphasized the need and utility of precision calculations.

Precision measurements require precision calculations!

Active and strong interaction between theorists and experimentalists essential!

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!

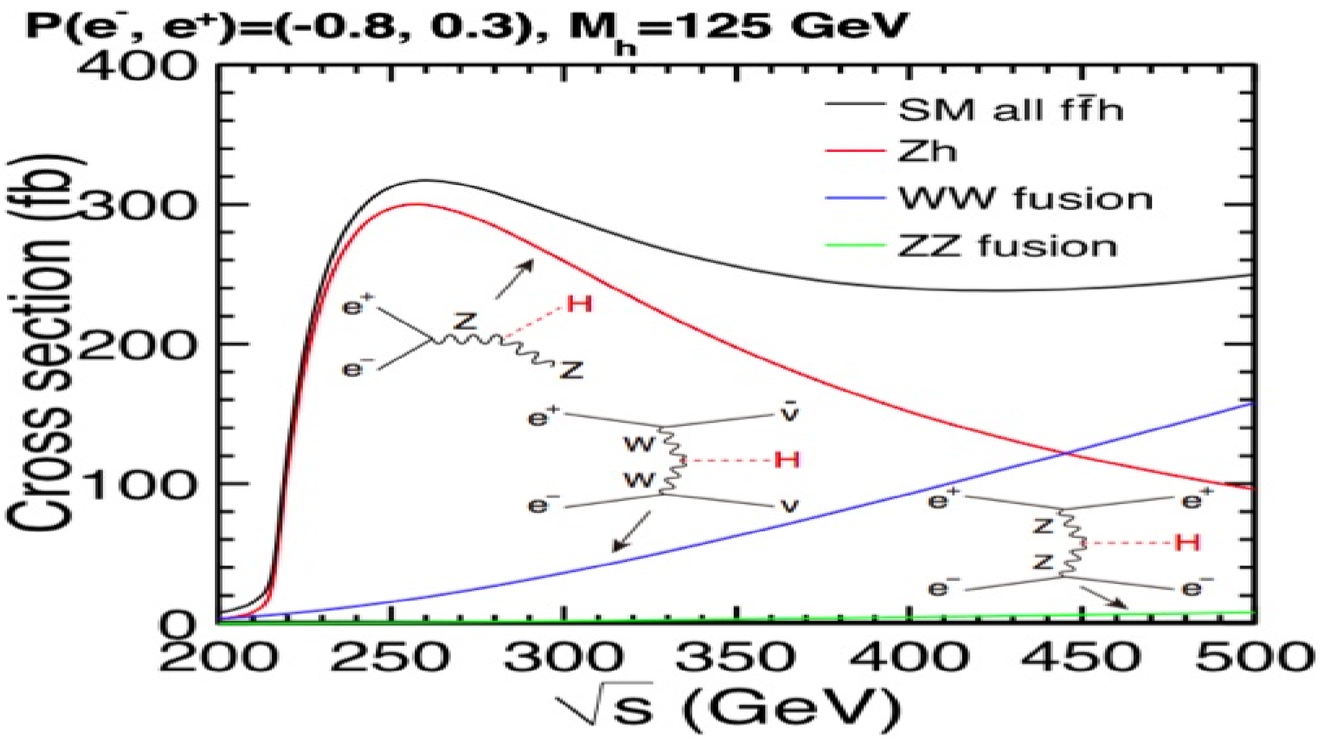
- Unification of couplings

- Inclusion of Gravity in the picture?

- Dark Energy!

Two ways: 1)κ formalism 2)EFT formalism Show results for EFT from 1710.07621 (Peskin et al).

κ formalism neglects momentum dependent Higher dimensional operators in determining width of the Higgs. Additionally accuracy at 250 GeV limited by smallness of $h \to ZZ^*$ rates.


P(e⁻, e⁺)=(-0.8, 0.3), Mh=125 GeV
Cross section (fb)
400
300
200
100
0
200
250
300
350
400
450
500
√s (GeV)
SM all ff̄h
Zh
WW fusion
ZZ fusion
e+
e−
Z
H
Z
e+
e−
W
W
H
ν̄
ν
e+
e−
Z
Z
H
e+
e−

With this we can fingerprint the BSM. Will give example for SUSY. Complementary to direct searches at the LHC! (1308.0297)..Similarly probes for large m_A possible.

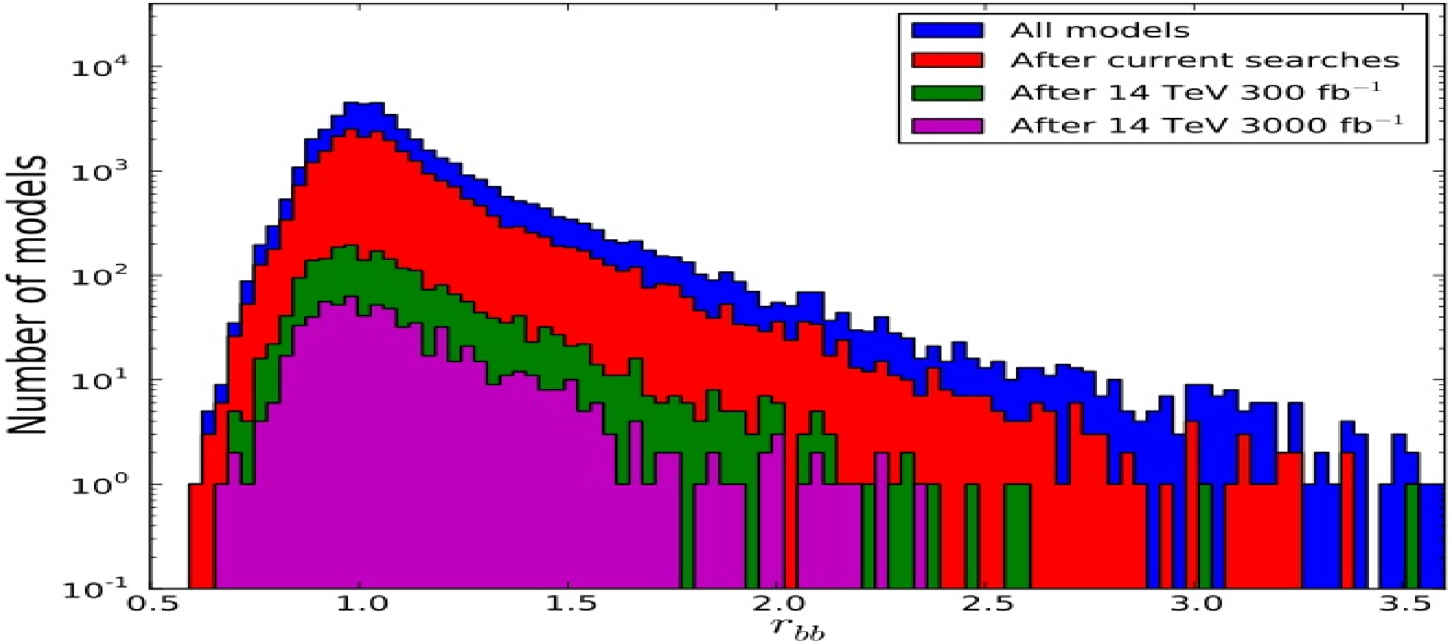
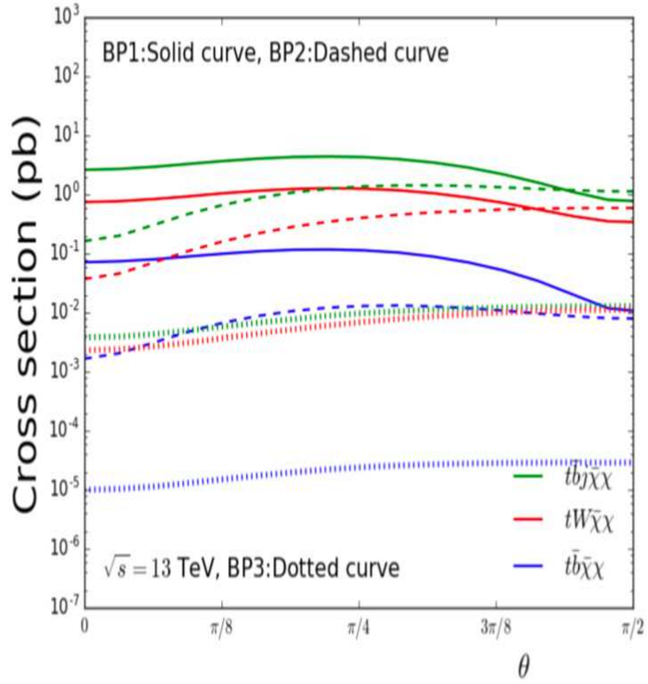


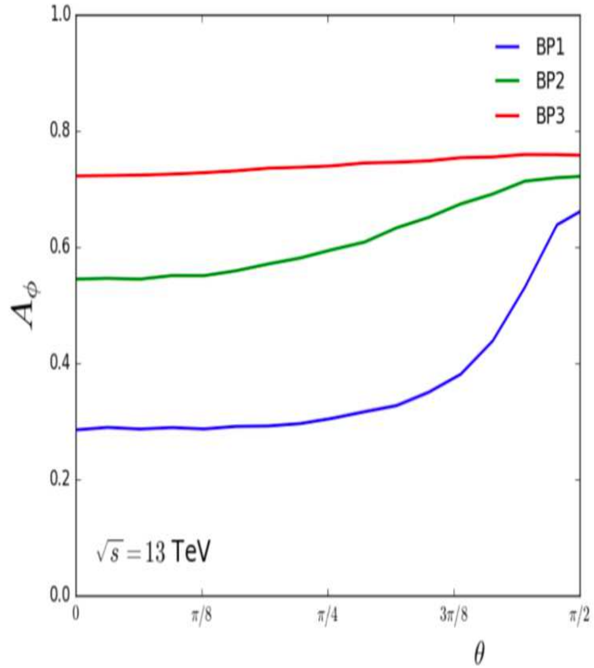
Figure 8: Histograms of the ratio $r_{bb} = \Gamma(h \to \bar{b}b)/\Gamma(h \to \bar{b}b)_{SM}$ within a scan of the approximately 250,000 supersymmetry parameter sets after various stages of the LHC, assuming the LHC does not find direct evidence for supersymmetry. The purple histogram shows parameter points that would not be discovered at future upgrades of the LHC (14 TeV and 3 ab^{-1} integrated luminosity). From [37].

Buckely et al have pointed out one can study DM which couples to heavy flavour through single top production using rates!

The polarization information of singly produced top can be translated into angular distributions and can be used for probing this DM candidate.

(Rindani, Charnjit Khosla, Bealnger, R.G., in preparation)


BP1:Solid curve, BP2:Dashed curve
Cross section (pb)
$\sqrt{s} = 13$ TeV, BP3:Dotted curve
$tbj\bar{\chi}\chi$
$tW\bar{\chi}\chi$
$t\bar{b}\bar{\chi}\chi$
0
π/8
π/4
3π/8
π/2
θ


BP1
BP2
BP3
A_ϕ
$\sqrt{s} = 13$ TeV
0
π/8
π/4
3π/8
π/2
θ