Higgs and top portal

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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

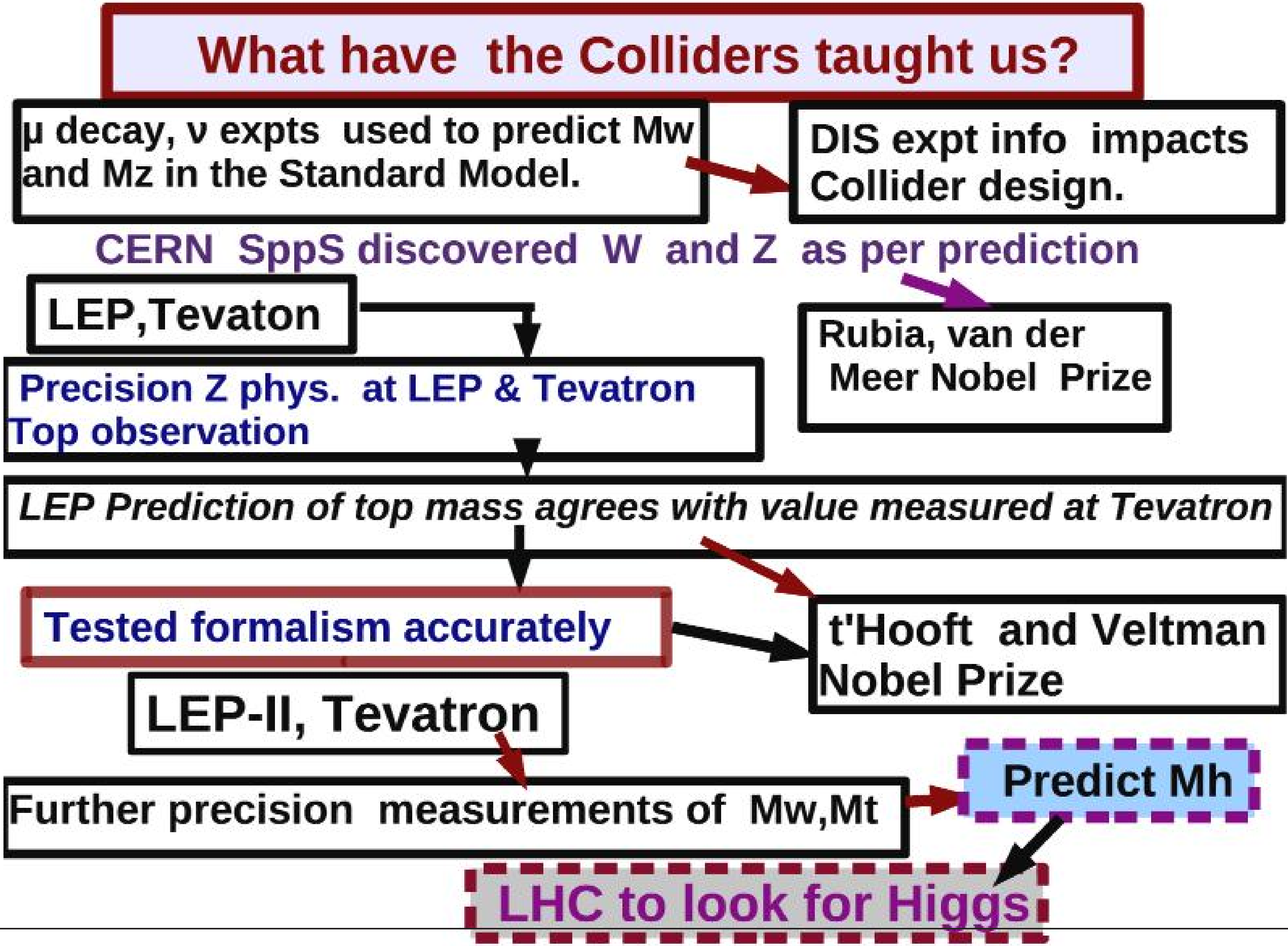
These experiments also caught the public imagination and questions like **what next** became very important in public mind as well.

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.

Studying the interplay between the top and the Higgs is of great relevance.

P Chappatte/Globe Cartoon


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

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 and top properties! *OR Higher and higher energies?*

Are these two directions the path of collider physics ahead?

We found the higgs boson at the small mass indicated by the SM BUT No evidence for physics beyond the SM that to us justify the fact that the Higgs is light!

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!

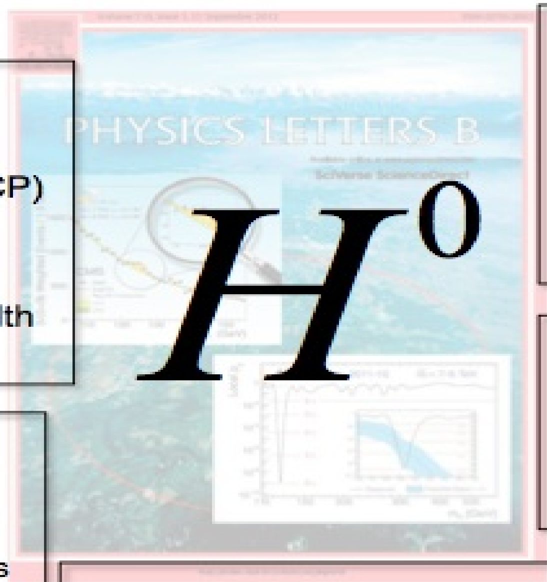
The mass and the couplings of this light state and top might be the window through which we can get a view of BSM at present!

Model independent analyses perhaps one way ahead ? **(Data driven!)** The 'unprincipled' way. *talk by C. Quigg*

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

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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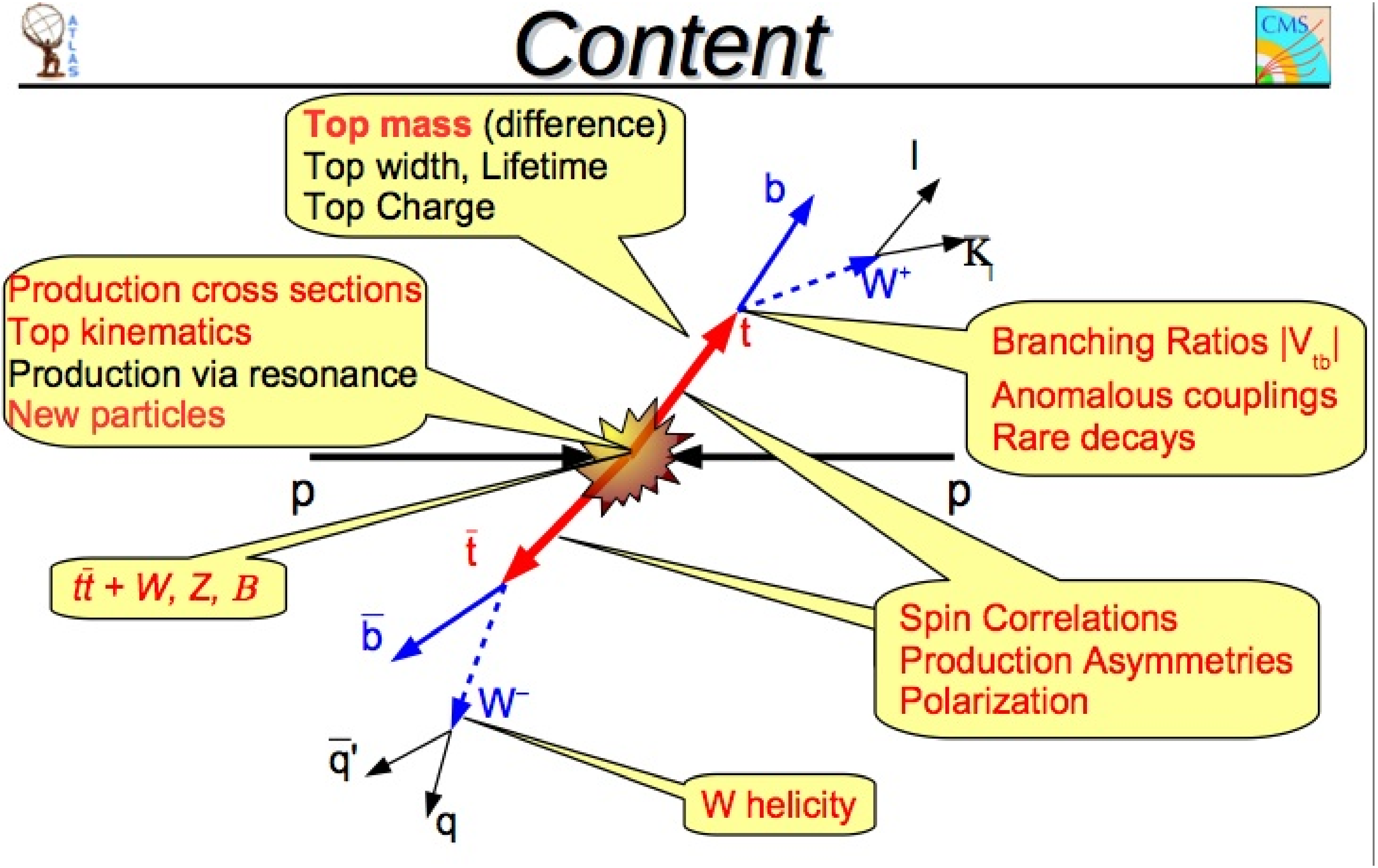

Content
Top mass (difference)
Top width, Lifetime
Top Charge
Production cross sections
Top kinematics
Production via resonance
New particles
Branching Ratios |V_tb|
Anomalous couplings
Rare decays
t̄t + W, Z, B
Spin Correlations
Production Asymmetries
Polarization
W helicity
b
l
W+
t
p
p
t̄
b̄
W−
q̄'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

I will mention a few examples how one can try to tease out new physics , either in the framework of a model or in model independent agnostic way!

I] Things that can be done at 'on mass shell' colliders in the near future!

1)Study of the CP property of the top Yukawa

2)Use of top polarisation in single top production.

II] Some new tools that can be of help

3)A new feature of LLP decays that one can use in the upgrades (hep-ph/1706.07407)

4)Top polarisation: ideas to measure top polarisation for boosted tops. (in preparation)

III] Invisible decay of the Higgs and light LSP:

Combination of the LHC, DIrect Detection experiments and future electron-positron colliders and 'natural SUSY'

Why? A combination of 'principled' and 'unprincipled'?

Expected theoretical connections between top and higgs.

Particularly for CP structure the fermion couplings are more democtratic, as tree level couplings of a pesduoscalar to a V pair are zero, hence expected to be small.

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) Production of Higgs + 2jets, V. Hankele, G. Klamke and D. Zeppenfeld, arXiv:hep-ph/0605117 LHC studies using this have started!

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

c)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]].

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

Higgs coupling to top quarks

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

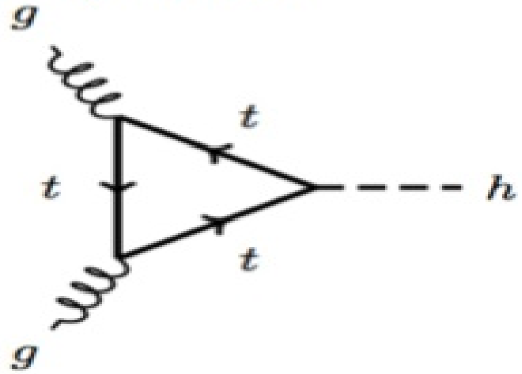
$g_{tth} = m_t/v$

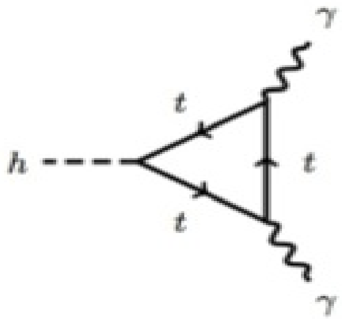
In SM $a = 1$ and $b = 0$.

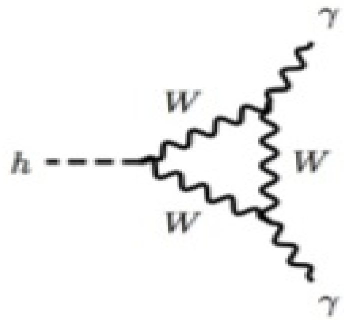
For a pure pseudoscalar $a = 0$ and $b \neq 0$.

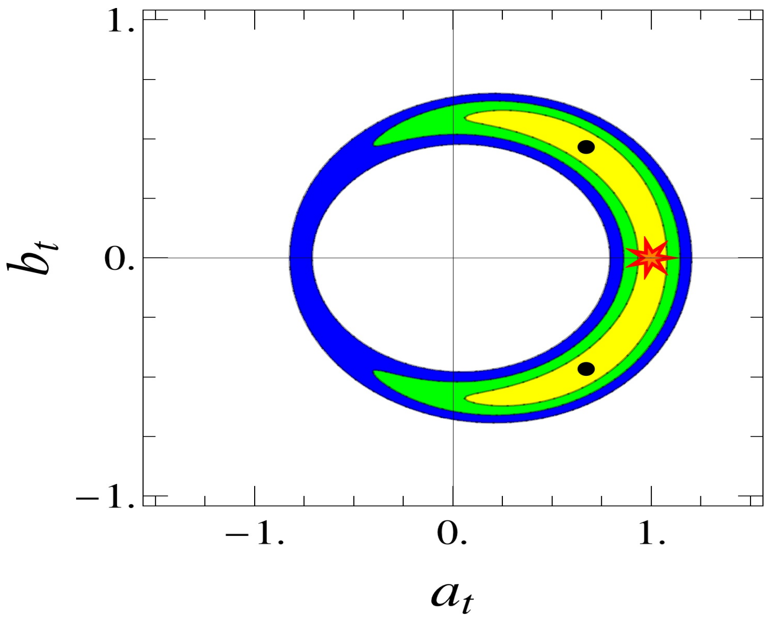
Higgs of mixed CP properties $a \neq 0$ and $b \neq 0$.

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.

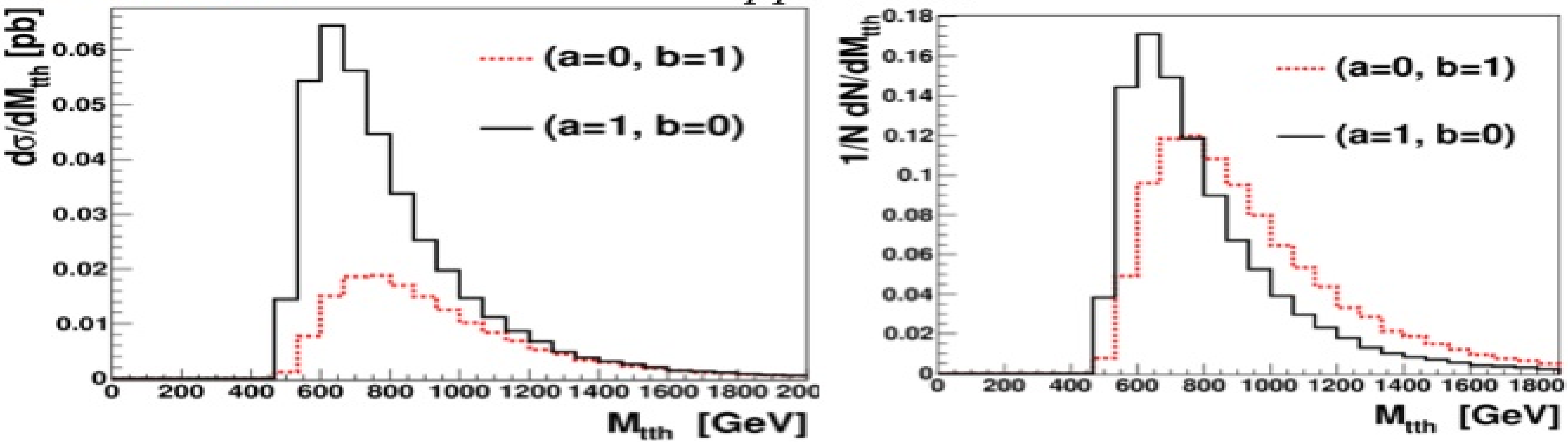
Rates are more sensitive to the pseudo scalar part b_t than a_t Does allow $b_t \neq 0$ and will continue for a while!

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.

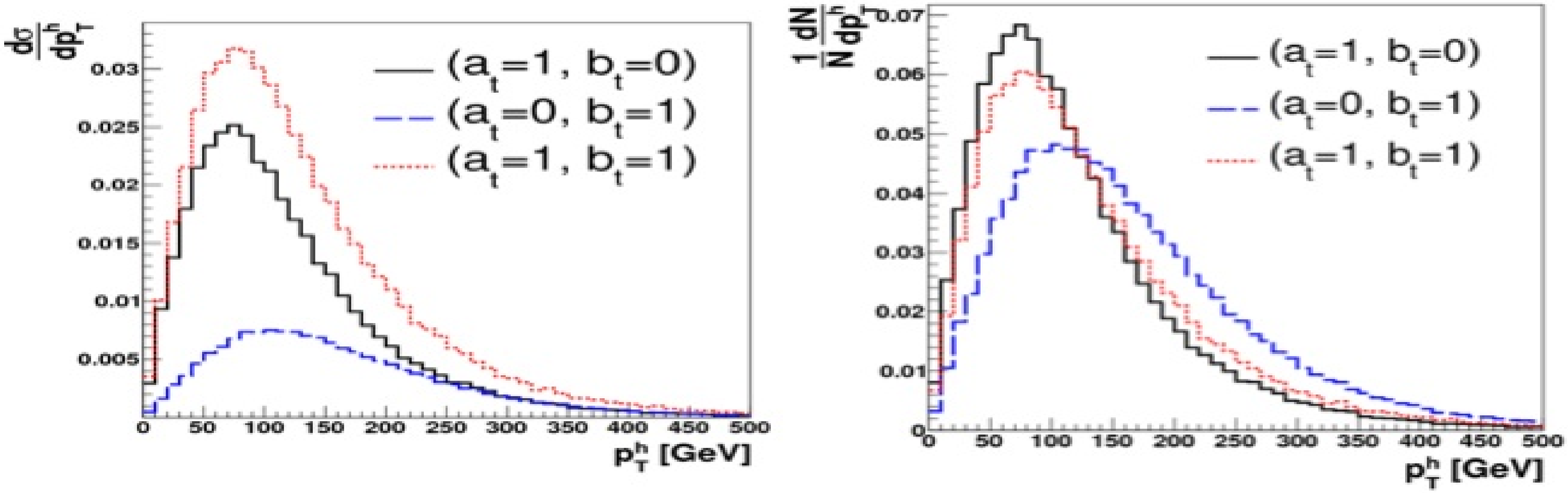
Dominant gg initiated process also suppressed but not as strongly.

$pp \rightarrow tth$



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

Noticed also by Maltoni et al:



The gamma_5 in the vertex makes a difference in the momentum flow at the vertex. Difference seen even in normalised distributions.

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

Ratios of tth cross-sections

If we construct ratios of tth cross-sections using different pt cuts, for example, the a_t and b_t terms will contribute differently

So this can give information on CP violation (ie. Simultaneous presence of a_t and b_t !.

$$\frac{\sigma}{\sigma_{SM}} = a_t^2 + X b_t^2$$

Where X depends on the pt cut , invariant mass cut., beam energy.

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

The $t\bar{t}h$ c.section is more sensitive to the scalar part than the pseudo scalar part.

Distributions in $p_T^h, \Delta(\phi)^{t\bar{t}}$ and $m_{t\bar{t}h}$ are sensitive to CP mixing.

Our study demonstrates that at high luminosity the $m_{t\bar{t}h}$ distribution does even better than angular observables.

Need High Lumi perhaps.

But distributions depend on b_t^2. Not linear in b_t

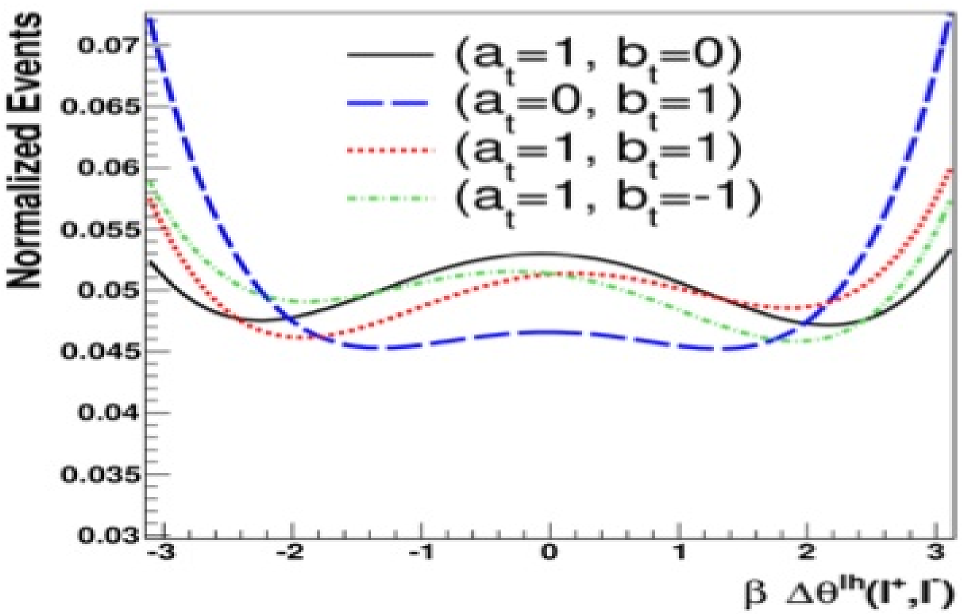
Those have been suggested: Some of the recent ones:

J. Ellis, Hwang, V. Sanz and You, JHEP **1211** (2012) 134

F. Boudjema et all, only ossible at high luminosity.

One observable Linear in b

$$\beta \equiv \mathrm{sgn}\left((\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_{\ell-} \times \vec{p}_{\ell+})\right).$$



The red and blue have different behaviour wrt sign of beta.

Indeed an effect linear in b

Completely in terms of lab observables.

No need to construct any particular frame

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

Possibilities with high energy e^+e^- many studies, some recent ones
1)P. S. Bhupal Dev, A. Djouadi, R.G, M. M. Muhlleitner and S. D. Rindani, Phys. Rev. Lett. 100 (2008) 051801

2) R..G., C. Hangst, M. Muhlleitner, S.D.Rindani and P.Sharma, Eur. Phys. J. C **71** (2011) 1681b Not discussing here.

th cross-section:

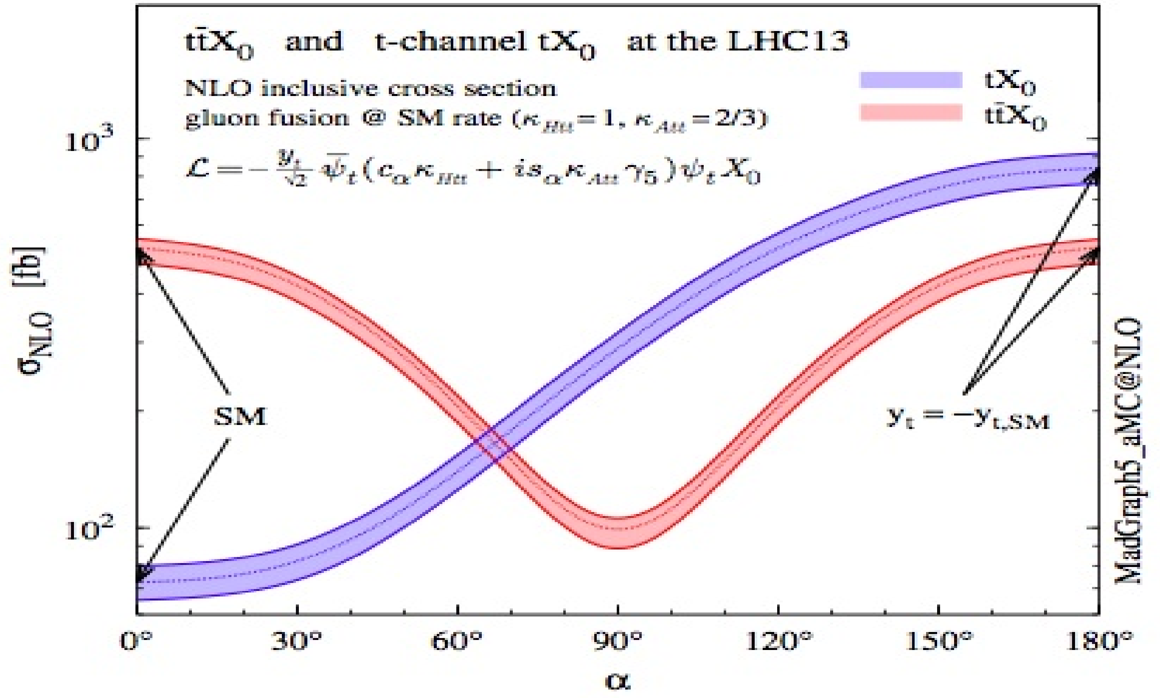


Fig. 12 NLO cross sections (with scale uncertainties) for $t\bar{t}X_0$ and t-channel tX_0 productions at the 13-TeV LHC as a function of the CP-mixing angle α, where κ_{Htt} and κ_{Att} are set to reproduce the SM GF cross section for every value of α

α measures the CP admixture: X_0 a scalar with indeterminate CP.

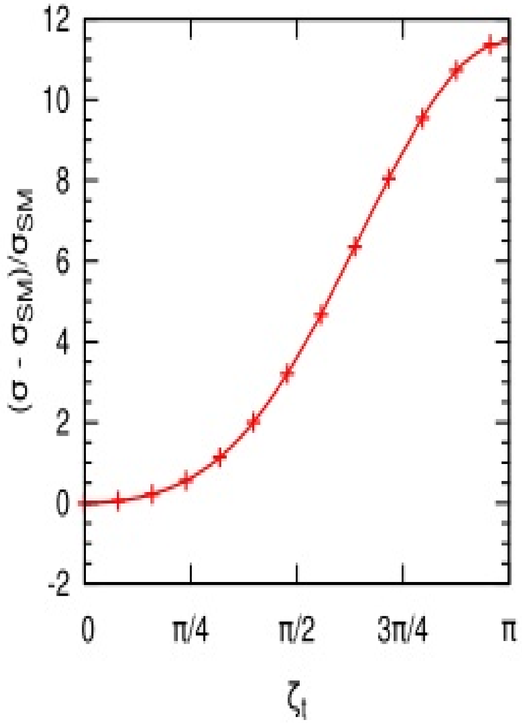


Fig. 2. The fractional deviation of the cross section from the SM value as a function of CP phase ζ_t in the $t\bar{t}h$ coupling for thj process at LHC14.

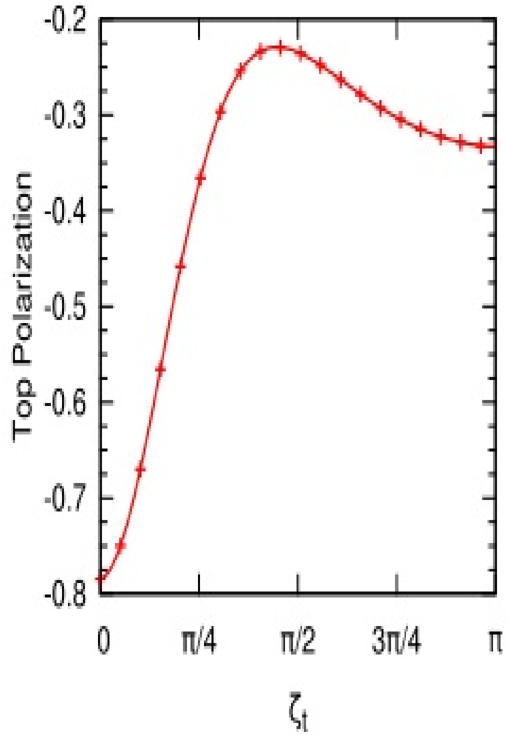


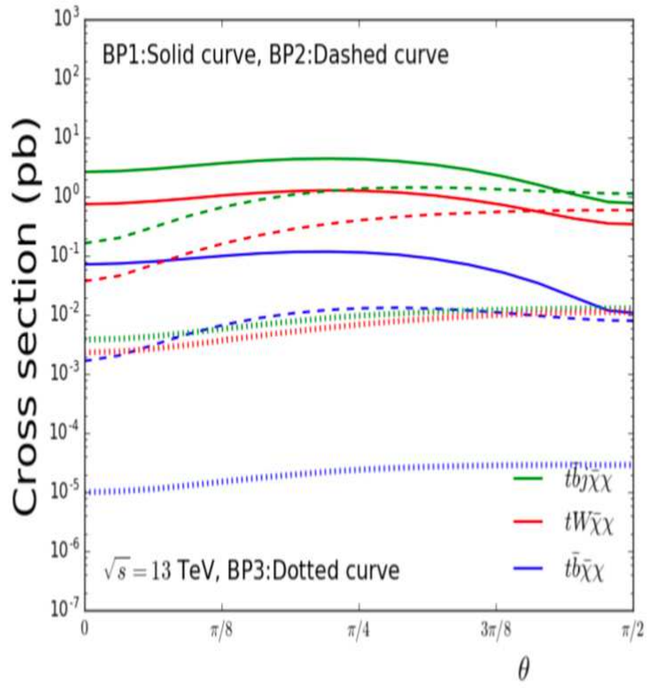
Fig. 3. Top polarization in $pp \to thj$ at LHC14 as a function of the CP phase ζ_t of the tth coupling.

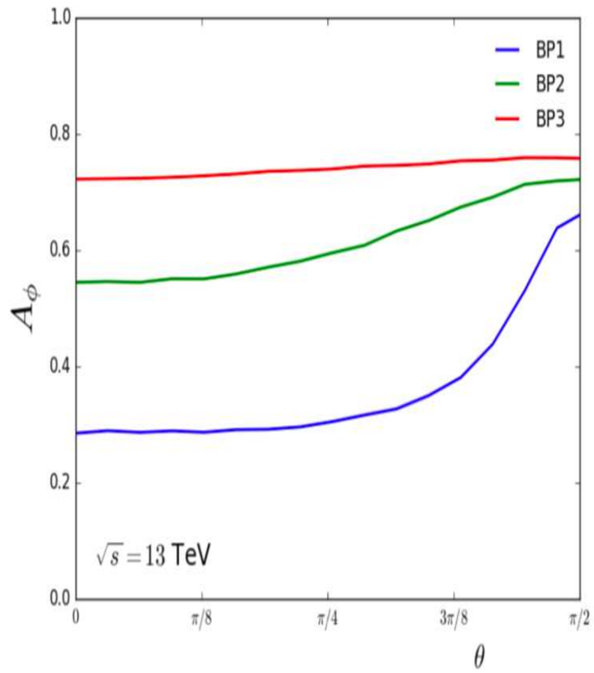
Sensitivity of c.section and polarization complimentary. (S.Rindani, P. Sharma)

Buckely et al (Phys. Rev. D **96** (2017) no.3, 035031) 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, Charanjit Khosa, Bealnger, R.G., in preparation)





Left: Dependence of the cross-section on the CP of the mediator. Production of single top with neutral DM mediator!

Right : Dependence of the polarisation

Studies using cross-sections have started already: CMS PAS EXO-18-010

Properties of the top produced in the processes involving the new BSM particles can be different from the top quarks produced via the SM processes and can carry the imprint of the BSM.

Since all the BSM options address the issue of EWSB, in many of them, the couplings of the top quark to the new particles can have a different chiral structure than the SM case.

Recall that **at the LHC** all the SM $t\bar{t}$ production via QCD will produce unpolarized top quarks! Only the single top will be polarized and the polarization completely predicted!

Hence polarization of the produced top quarks can be a very important discriminator of BSM physics.

Polarisation can be measured by studying the decay distribution of a decay fermion f in the rest frame of the top:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_f} = \frac{1}{2}\left(1 + P_t\kappa_f\cos\theta_f\right),$$

θ_f is the angle between the f momentum and the top momentum, P_t is the degree of top polarization, κ_f is the “analyzing power” of the final-state particle f.

κ_f depends on the weak isospin and the mass of decay product f.

The angular distribution of charged leptons (down quarks) from top decay in the rest frame not affected by anomalous tbW couplings (to linear order) Rindani, Singh, Godbole is:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_f} = \frac{1}{2}\left(1 + P_t \kappa_f \cos\theta_f\right),$$

Angular distributions of the decay lepton in the lab are not affected by the anomalous parts of the tbW vertex.

Recently we have gained an understanding: R.G., M. Peskin,S. Rindani, R. Singh (arXiv:1809.06285)

On the other hand the decay lepton energy distributions in the laboratory contain some piece due to the anomalous couplings as well.

So studying top polarisation and decay lepton distributions offer a probe in BSM with chiral structure difft. from the SM as well as BSM which changes tbW coupling.

A. Prasath V et al, Eur. Phys. J. C **75** (2015) no.9, 402, A. Jueid,1805.07763

Message: Very often polarisation adds substantially to how one can decipher new physics. Polarisation translates in angular and energy asymmetries which are sensitive to BSM physics present in production as well as decay of the top quark

Polarisation depends on the spin and parity of the particle produced in association with the t.

In the SM t channel single top production the poalrisation can carry an imprint of the anomalous tbW coupling present in production.

Study polarisation dependent observables **along with** cross-sections . We can get information.

Study in the EFT framework: M. de Beurs, E. Laenen, M. Vreeswijk and E. Vryonidou, arXiv:1807.03576 [hep-ph]

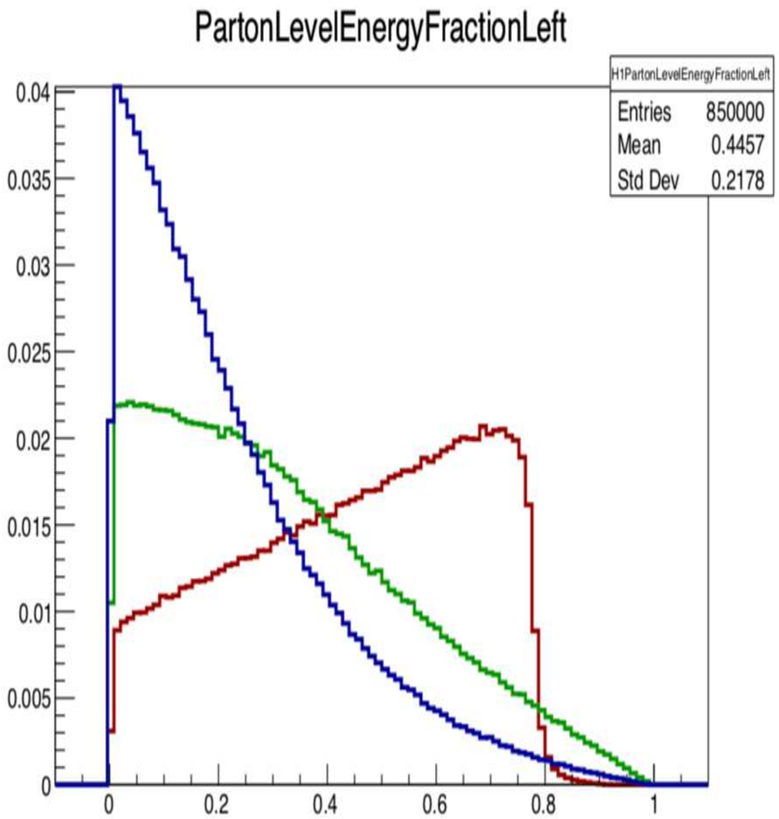
Study in terms of anomalous form factors: A. Jueid, Phys. Rev. D **98** (2018) no.5, 053006

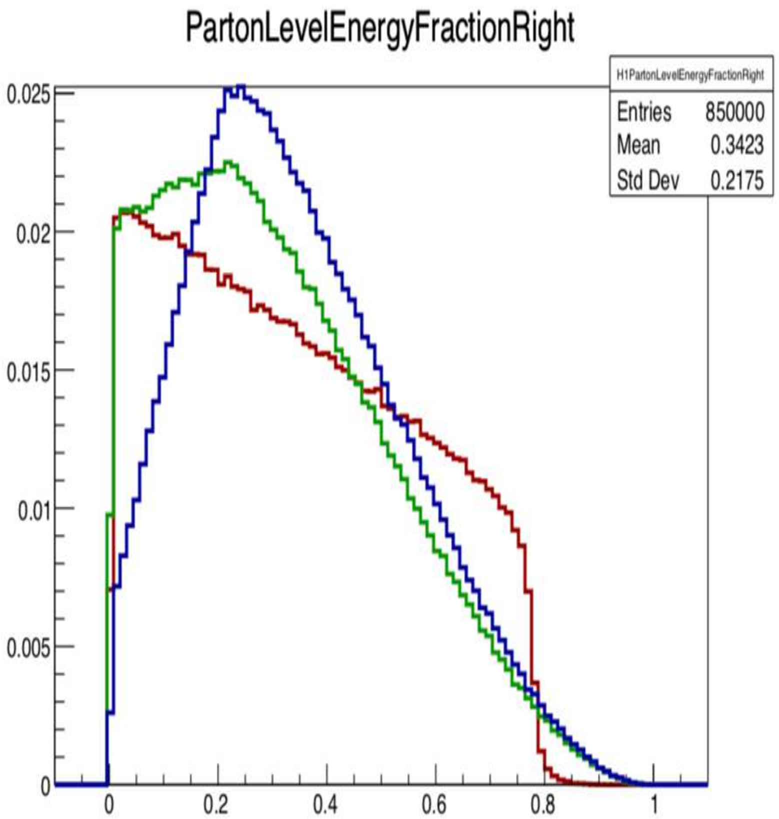
Polarisation dependent observables provide a good handle.

Angles are not very good. How do we still get polarisation information? For boosted quarks the differences in angular distributions translate into energy distributions. (D. Krohn, J. Shelton and L. T. Wang, JHEP **1007** (2010) 041)

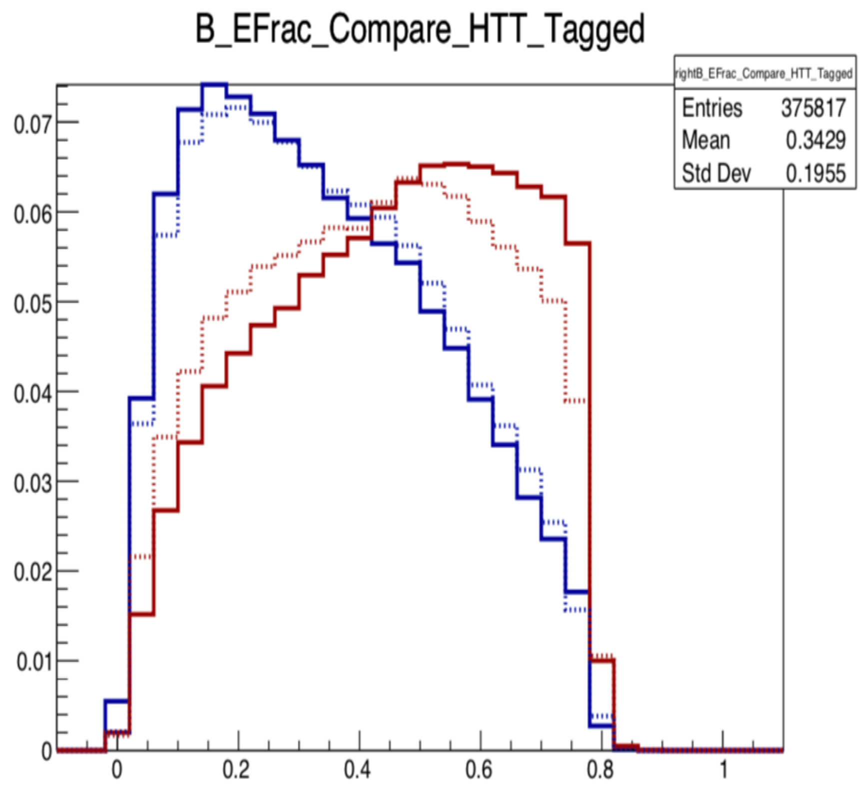
When will we get poalrised highly boosted tops ?

In the decay of heavy resonances, decay of gluinos and decay of stops in view of the mass limits on both.





$W' \to t + b$. Left plot for left handed top quark and right plot for right handed top quark, b (red), u(green) and $\bar{d}$ (blue).

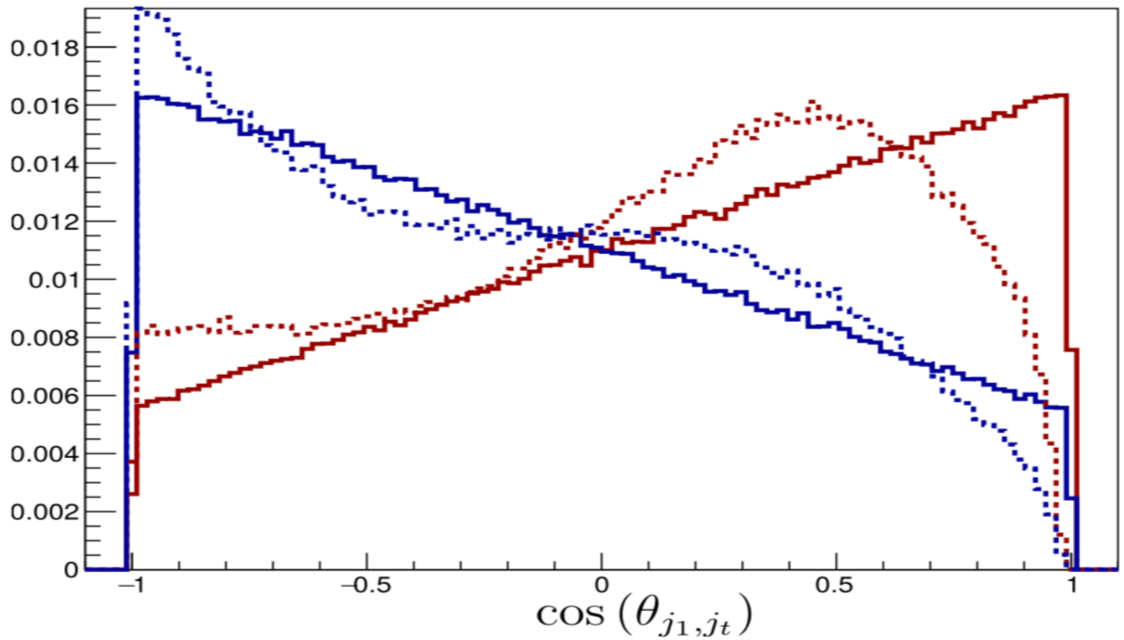


$W' \to t + b$ (red left handedand and blue right handed).

Important to have efficient high p_t b-tagging

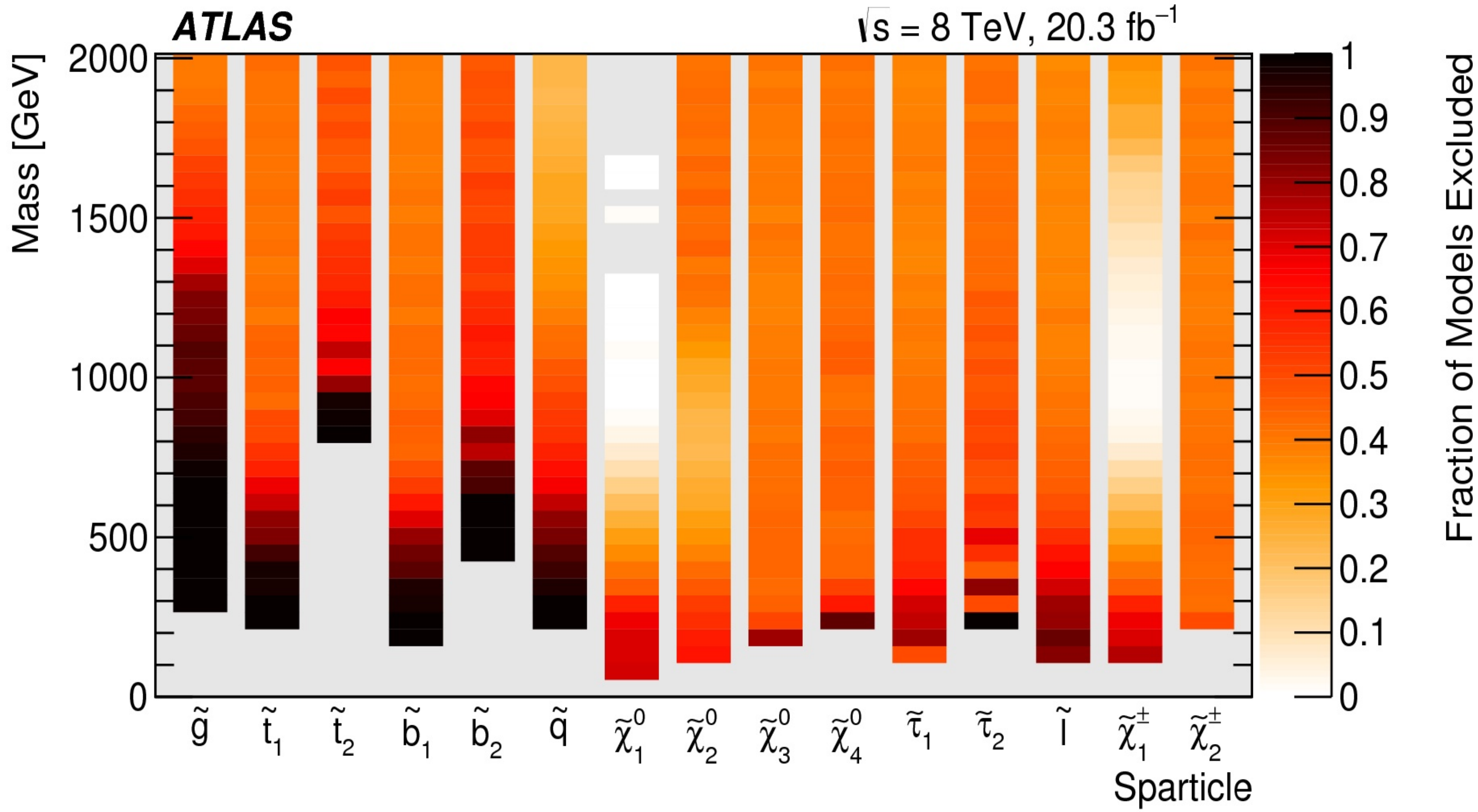
A new variable: $t \to bj_1j_2$

Invariant masses $m_{b_{j1}}$ and $m_{b_{j2}}$ information about spin correlation. We have found that angle between the j_1 and the spin direction of the top in the rest frame , where $j1$ is defined such that $bJ1$ system has a lower invariant mass of the two, carries information about the t polarisation. (Solid for parton level and dashed at HTT subjet level)



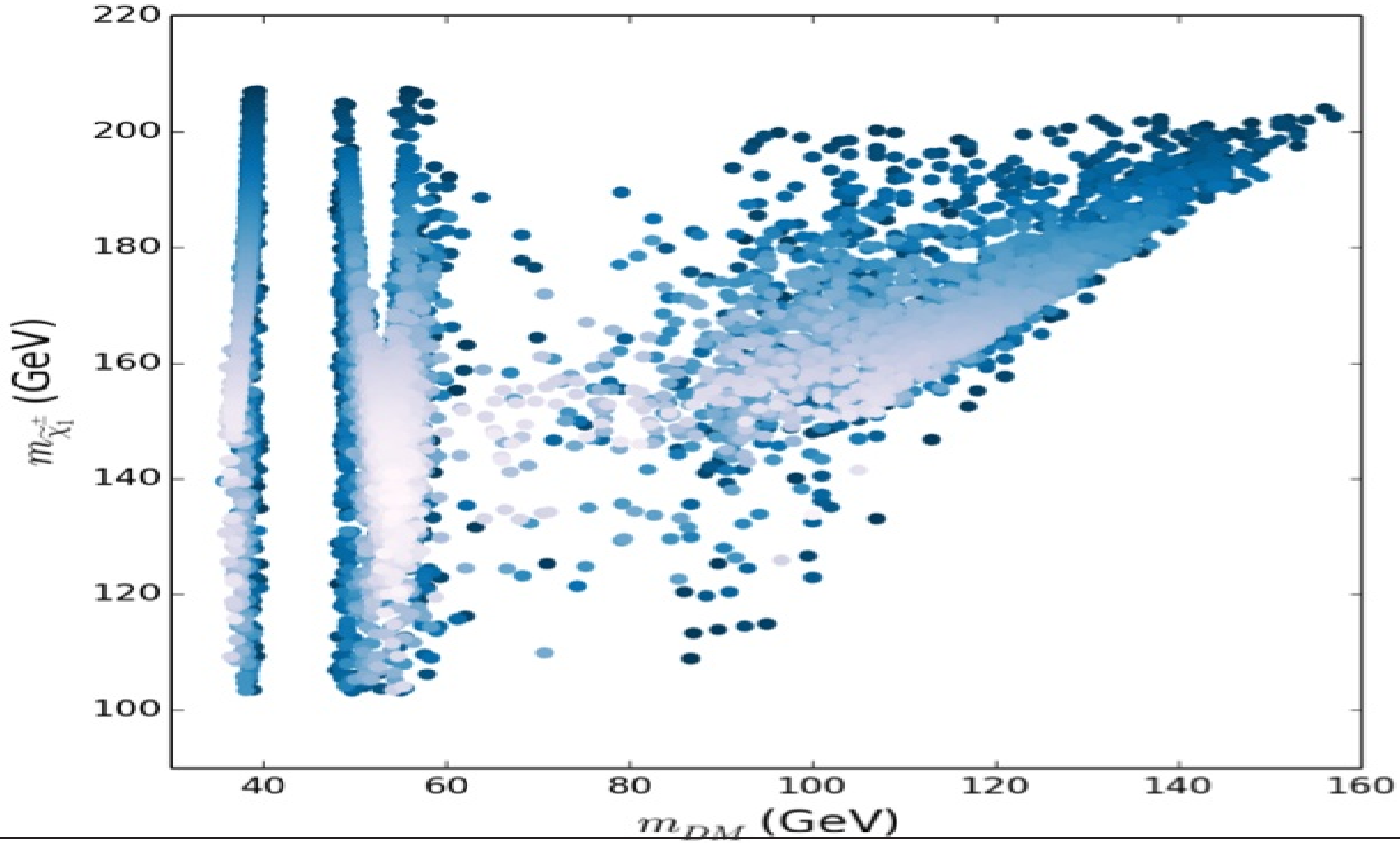
X. Tata et al: Our measures of naturalness have high values as we see it now. But it is possible that correlations among parameters of the SUSY models can make the value of the measure small **for the same particle spectrum!**.PRD87, 115028, 2013

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



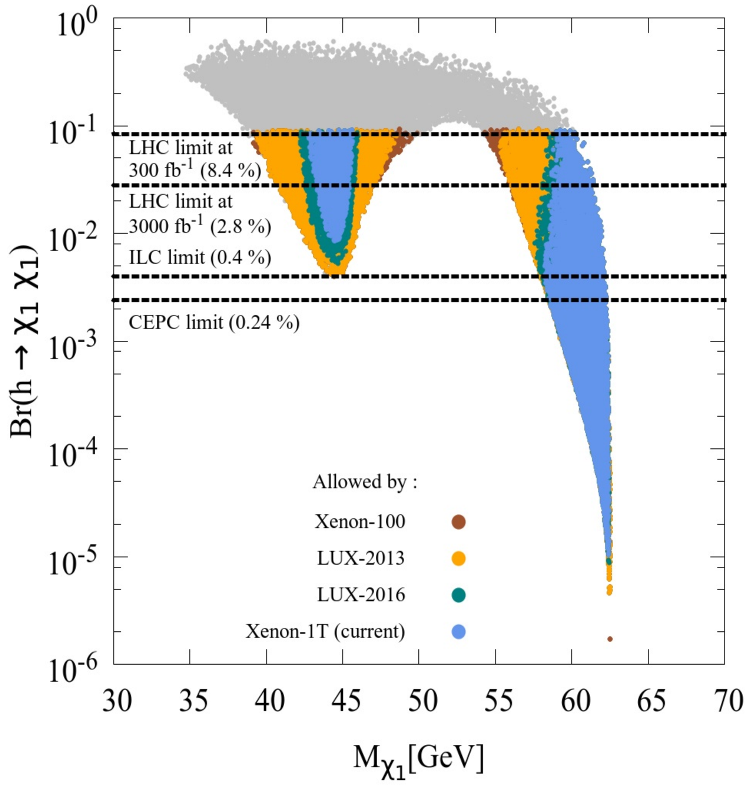
A Light LSP still allowed in PMSSM. It is 'natural' too!

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 Lighetst Supersymmetric Particle 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. Diff t. 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:

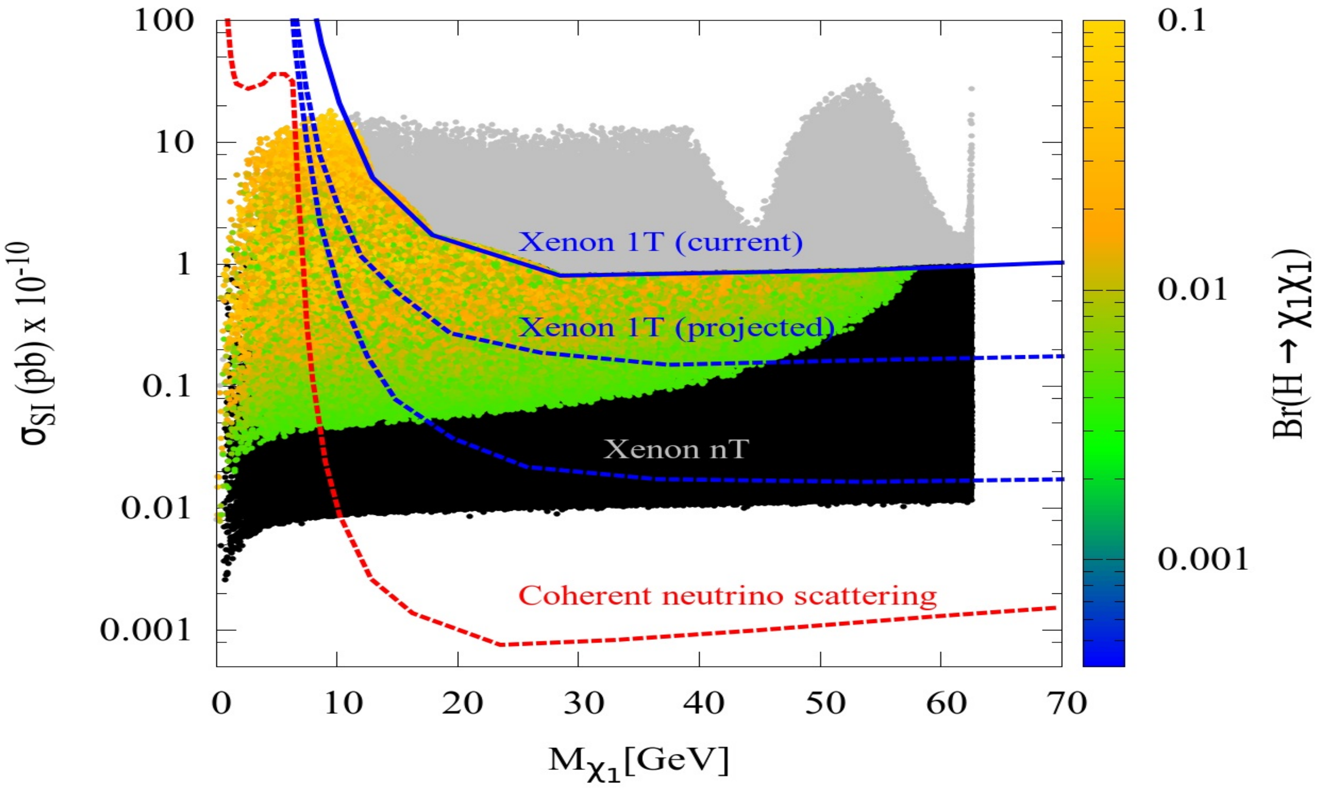
300 1/fb, 0.15; 3000 1/fb, 0.06 and the ILC: 0.3 %.

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!



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!