Top Properties and BSM.

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- What BSM physics and what top properties?

- Top-higgs mass interplay as a probe of BSM and its scale

- Use of top polarisation/spin spin correlations through kinematic distributions of the decay products of the top, to probe new physics and/or modified top couplings!

- Probes of modified top couplings from cross-sections and/or top distributions.

- Correlation between the probes of top polarisation and the anomalous top decay vertices.unambiguous determination of anom. couplings of the top?

Now we know the size of **SELF** coupling $\lambda = \frac{m_h}{\sqrt{2}v} \simeq 0.36$.

$m_t \simeq m_h \simeq m_W \simeq \mathcal{O}(v)$

Higgs is observed to be weakly coupled.!

So electroweak scale seems to be stable under radiative corrections .

Keeping this scale stable WAS one of the motivations of expecting physics beyond the SM.

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

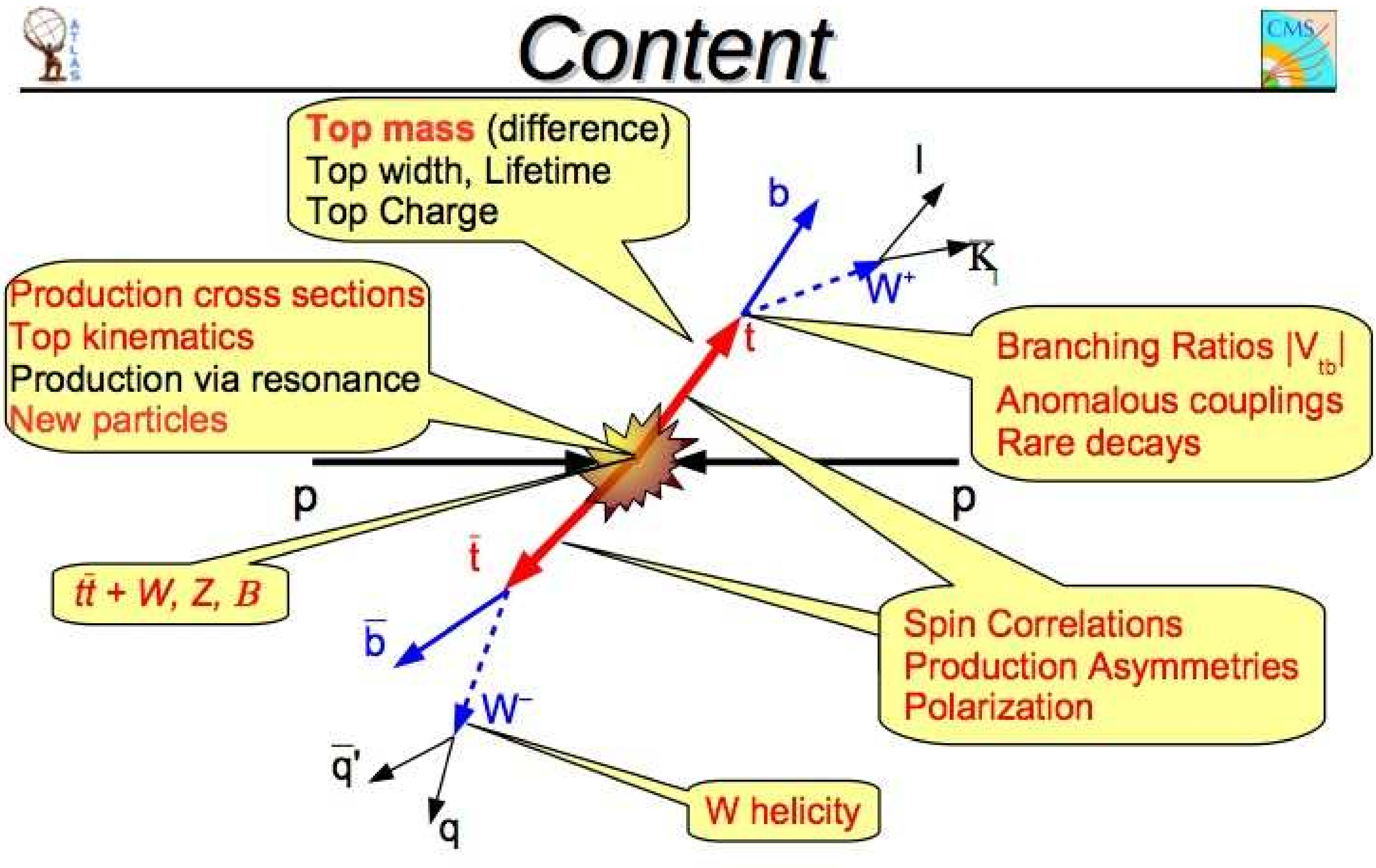
Whenever, one starts analyzing the observed features of the Higgs sector, the ubiquitous top plays an important role everywhere!

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 is ONE way towards BSM!

Peeping through the Higgs and top window!



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
tt̄ + W, Z, B
Spin Correlations
Production Asymmetries
Polarization
W helicity
b
l
K
W+
t
p
p
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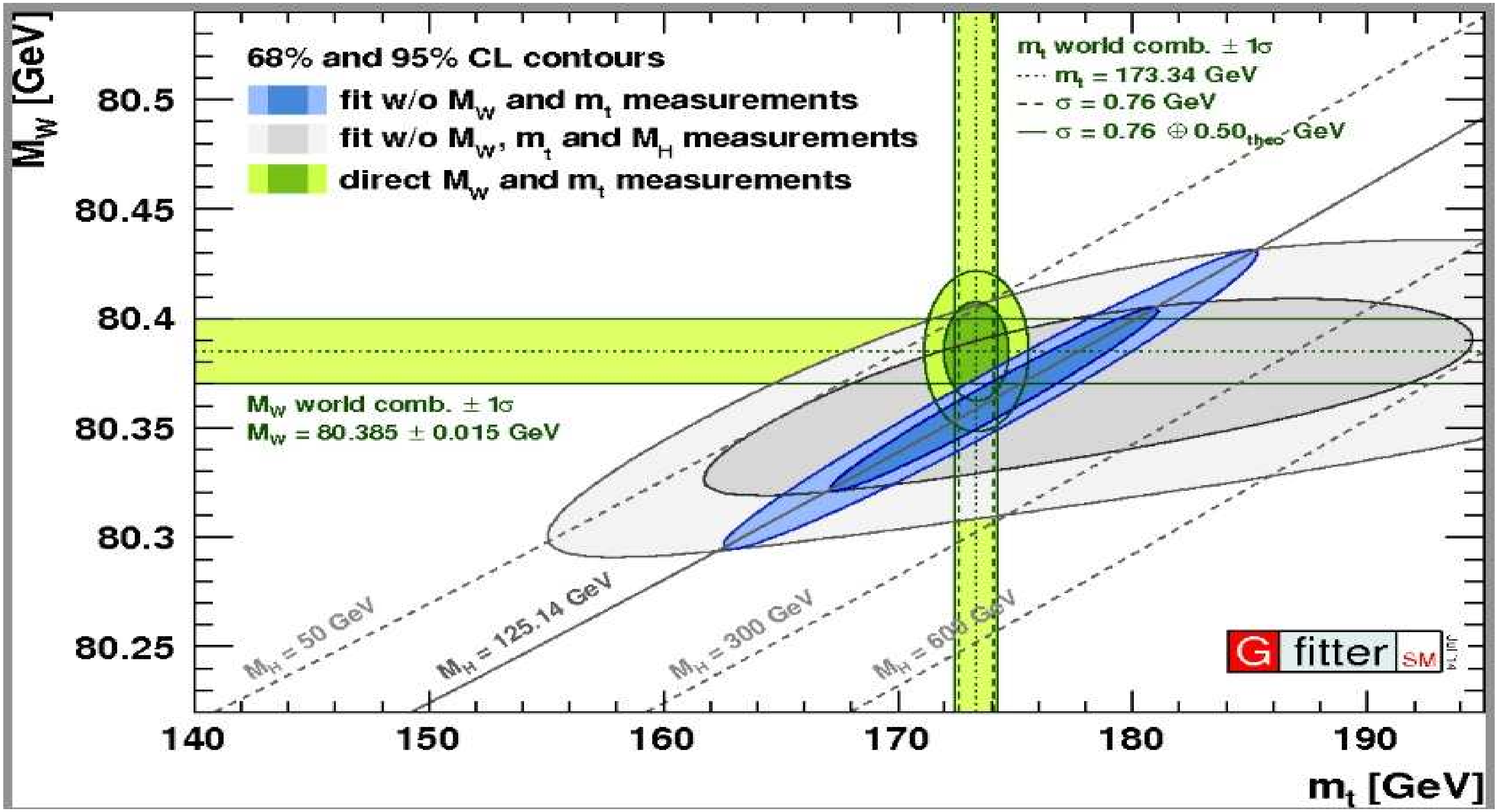
W−
q̄'
q



SM rocks! *At LOOP level*

Top mass has implications for the scale of BSM!

Vacuum Stability: the higgs and top connection allows us to probe BSM through just these values.

Vacuum stability bounds imply that unless M_h is large enough SM will become inconsistent at some large scale Λ!

The mass is just large enough to make us suspect that SM is all there is! ie. it **may** remain consistent all the way to Planck scale!

$M_h = 125$GeV is really critical, in all senses of the word. Knowledge of M_t crucial here.

Pergamon

Prog. Part. Nucl. Phys., Vol. 37, pp. 1–90, 1996

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S0146-6410(96)00059-2

Top Quark and Higgs Boson Masses: Interplay Between Infrared and Ultraviolet Physics

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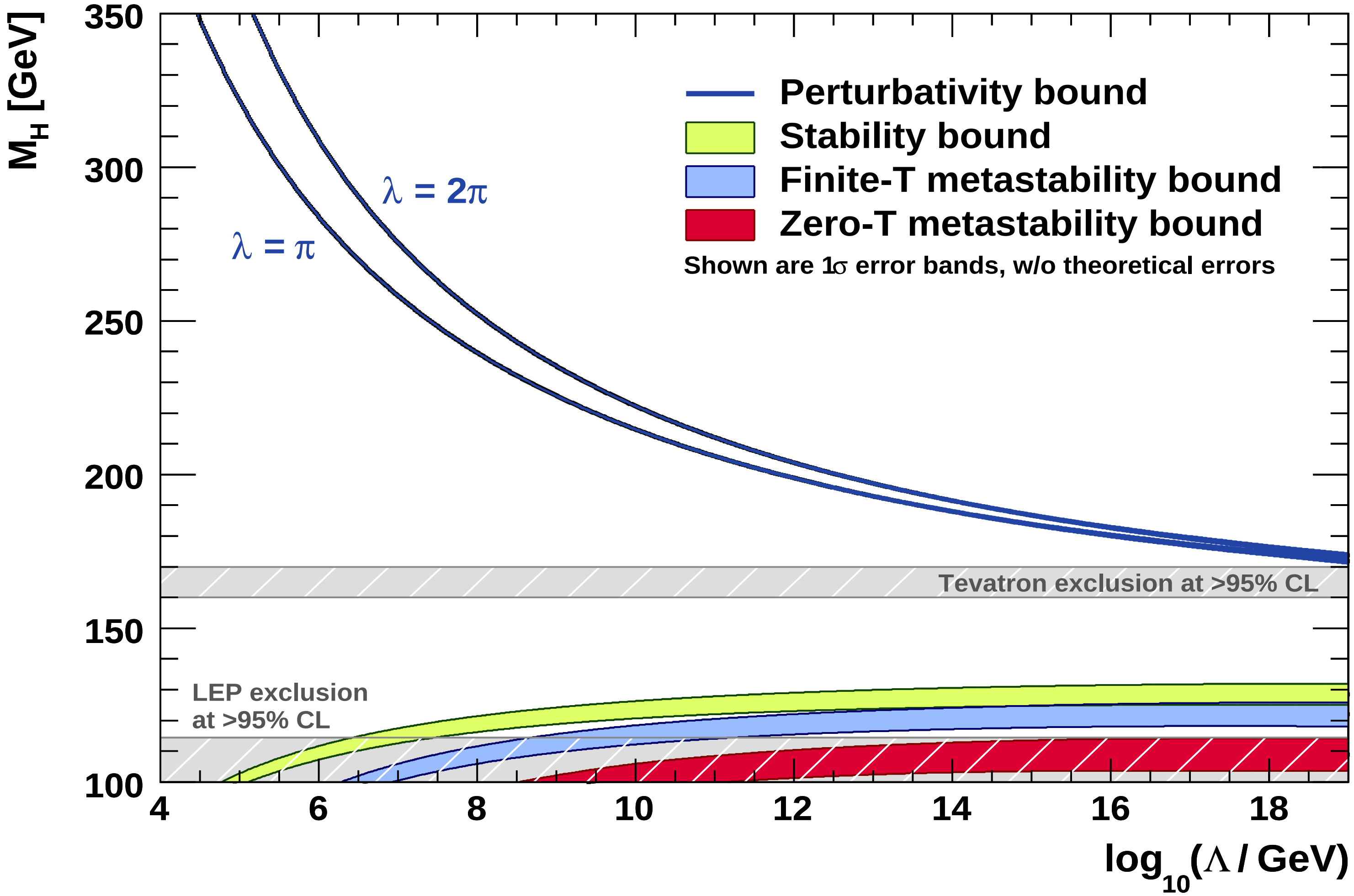
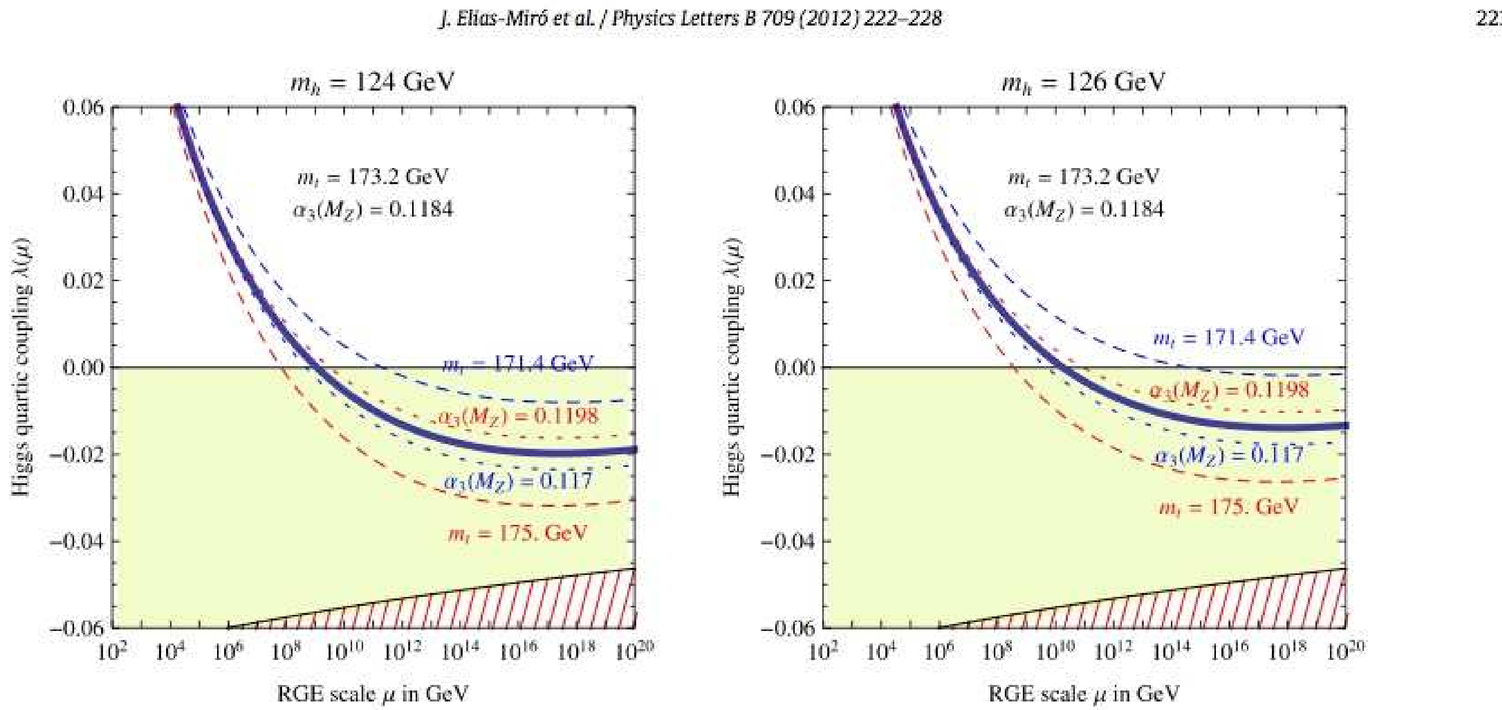
ABSTRACT

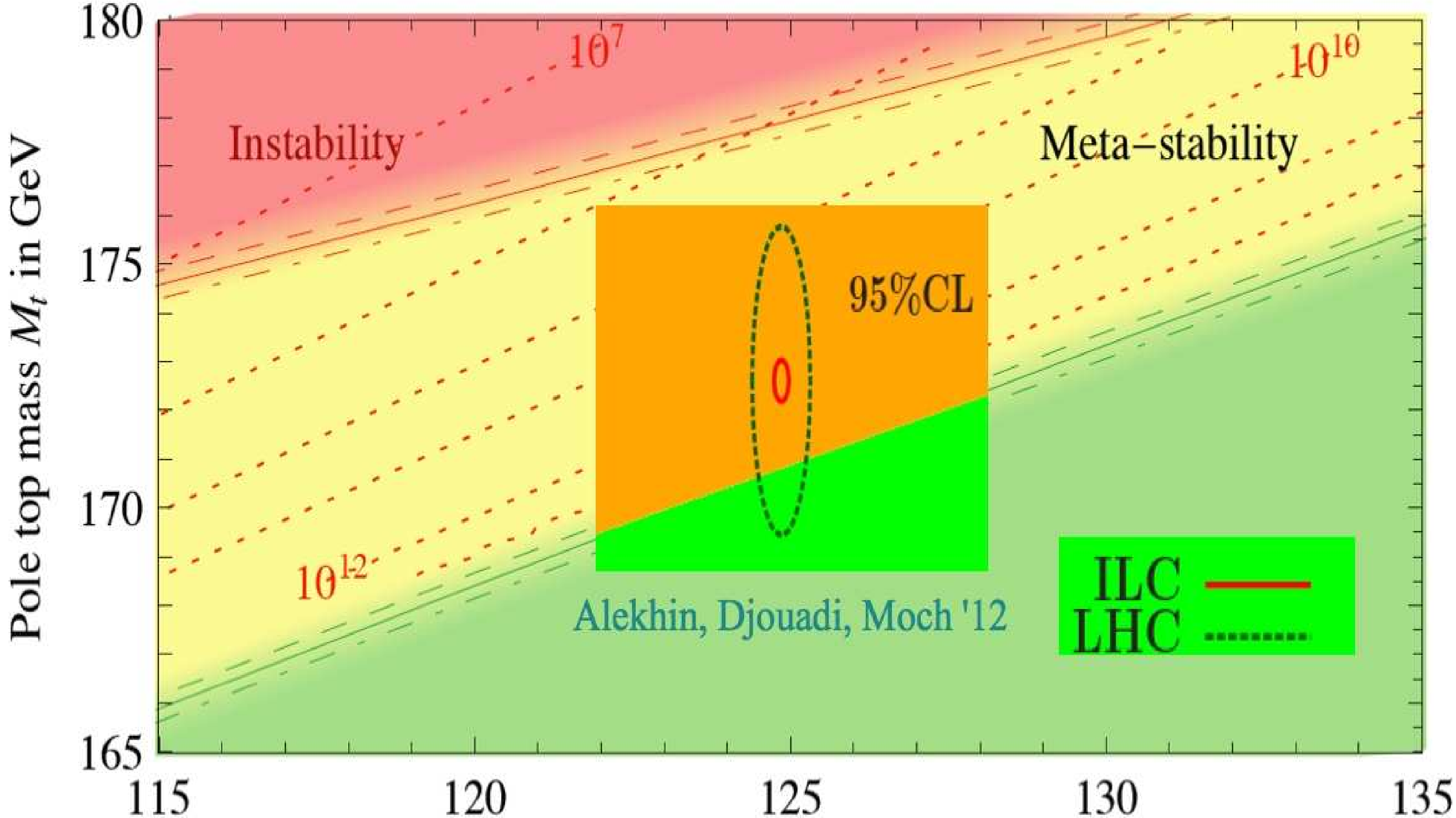
We review recent efforts to explore the information on masses of heavy matter particles, notably of the top quark and the Higgs boson, as encoded at the quantum level in the renormalization group equations. The Standard Model (SM) and the Minimal Supersymmetric Standard Model (MSSM) are considered in parallel throughout.

A very nice (early) discussion of these connections The times when t had just been discovered and h was far in future. Knowledge on mass of M_t was still stabilizing! Essentially through Renormalisation Group Equations.

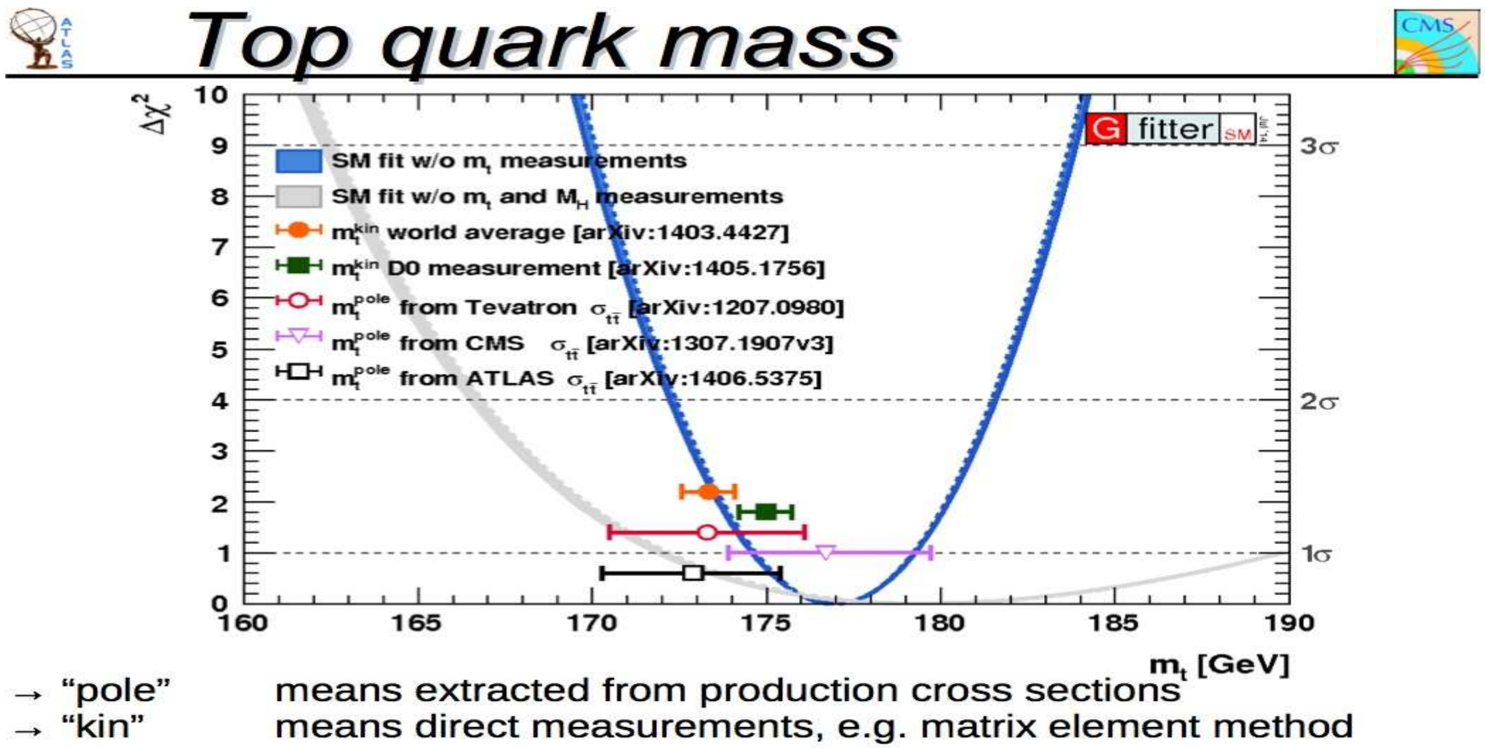

Perturbativity bound
Stability bound
Finite-T metastability bound
Zero-T metastability bound
Shown are 1σ error bands, w/o theoretical errors
λ = 2π
λ = π
Tevatron exclusion at >95% CL
LEP exclusion
at >95% CL
M_H [GeV]
log_10(Λ / GeV)
350
300
250
200
150
100
4
6
8
10
12
14
16
18

Vacuum stability limit on M_h depends on M_t



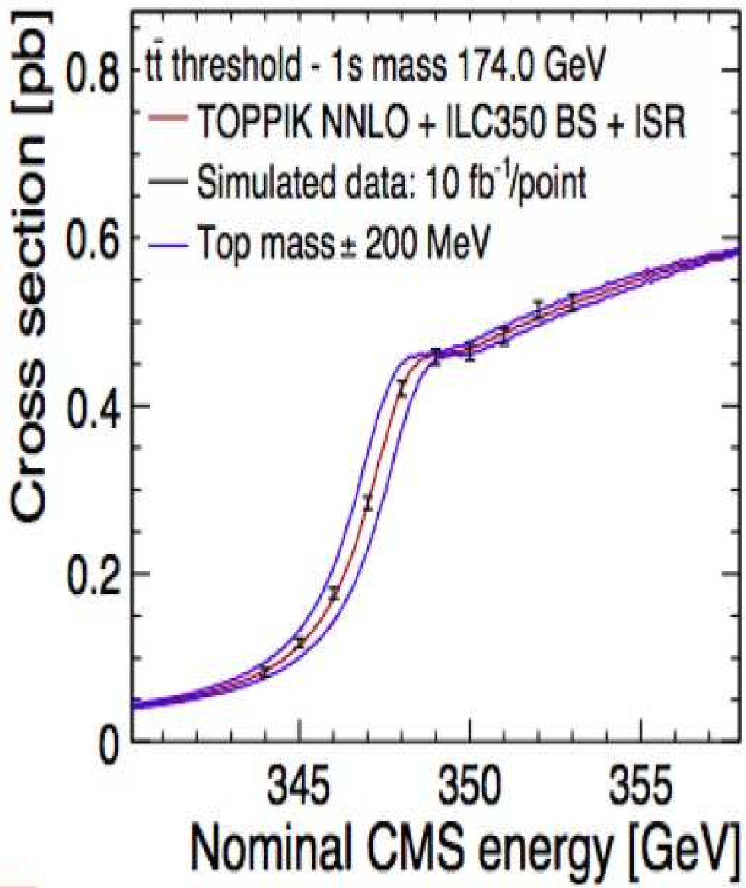


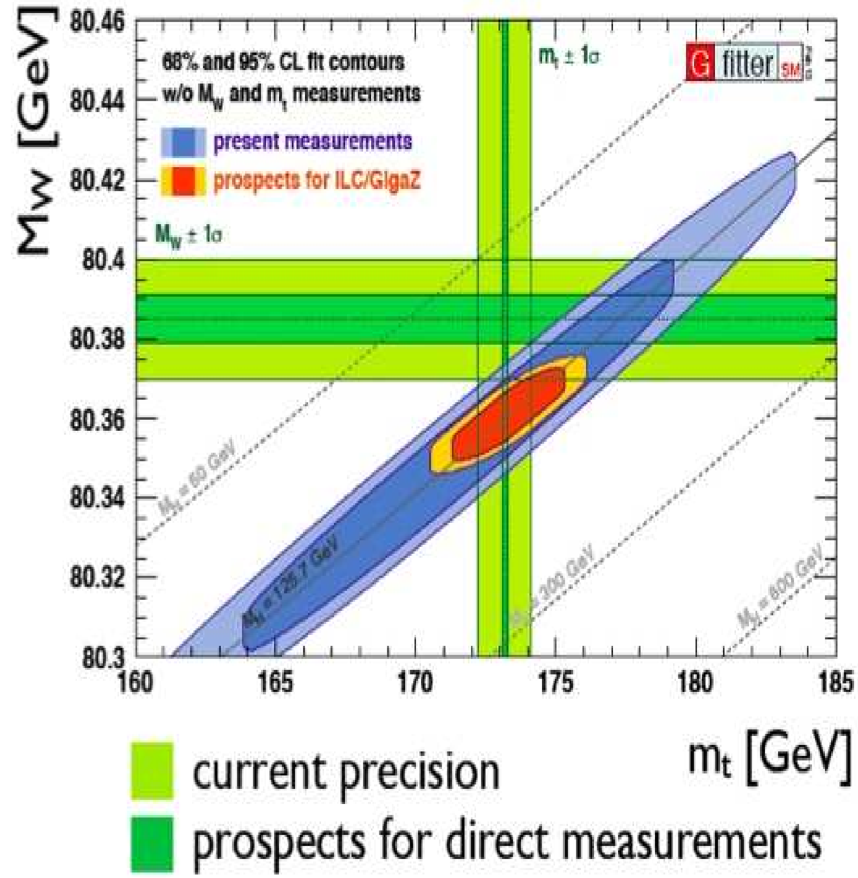
M_h value indeed critical.



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



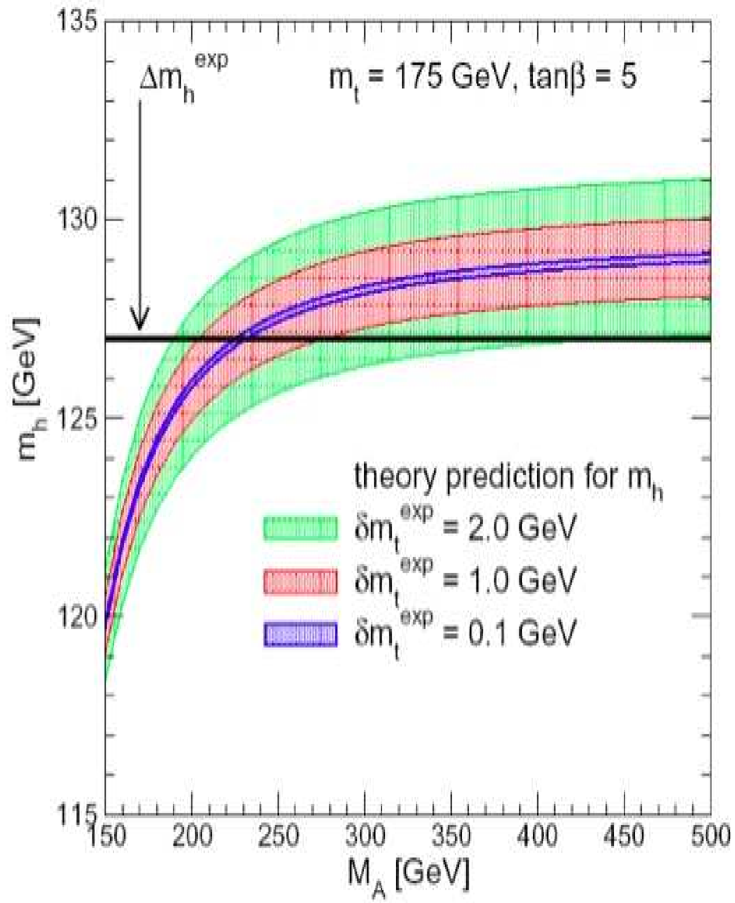


Precision: $\simeq$ 100 MeV!

In fact this can be an excellent way to look for BSM!

100 MeV precision on M_t would be required to match the precision on $\sin^2\theta_W$ and M_W at ILC/Giga Z.

100 MeV precision on M_t can be used to better exploit the LHC (and ILC) precision measurement on M_h.



How does BSM affect the produced top?

We must then have some idea how the BSM affects the properties of the top quark that is produced at the colliders.

BSM has new particles and almost always there are partners of the top scalar top $\tilde{b}$ in SUSY, spin 1/2 T in Composite Higgs models / UED models.

Most BSM options involve new particles, for example $H^{\pm}$, Z'.

Tree level couplings of the t quark to these new particles have different chiral structure than in the SM!

In the SM:

$\bar{t}t$ couplings with a gauge boson

Either pure vector for a gluon (QCD) : $\mathcal{L}^{int} \sim \bar{t}_{L/R}\gamma^{\mu}t_{L/R}G_{\mu}$

V-A for a Z: $\bar{t}_{L/R}\gamma\mu t_{L/R}Z_{\mu}$ and $\bar{t}_{L/R}\gamma\mu\gamma_5 t_{L/R}Z_{\mu}$

Pure left handed for W: $\bar{t}_L\gamma^{\mu}b_L W_{\mu}$

AND

The chirality flipping $t\bar{t}h$ coupling: $\bar{t}_L t_R h$

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.

When t and $\bar{t}$ are produced, a useful observable is top spin correlation:

(Bernreuther, Uwer, Si: extensive calculations)

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_a d\cos\theta_b} = \frac{1}{4}(1 + B_1\cos\theta_a + B_2\cos\theta_b - C\cos\theta_a\cos\theta_b)$$

This has been very well studied theoretically (for example: $t\bar{t}H$, $t\bar{t}$ produced in RS Graviton decay etc.)

It is conceivable that single top polarization can give better statistics

Happy coincidence:

The happy coincidence is that top quark is the only quark whose polarisation we can measure quite easily.

Why? The top quark being very heavy decays before it hadronises. The decay products therefore carry memory of the direction of the top spin!

One can measure these either by reconstructing the top rest frame OR kinematical distributions in the laboratory.

Measurements are on spin correlations available from the Tevatron and the LHC: CDF conference note 10719, D0: PRL, 108, 032004, (2012), ATLAS: 1307.6511 (Submitted to PRL)..

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.

Construct observables using this effect which probe the top property!

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

J.A. Aguilar-Saavedra, NPB,843, (2011), 638, + J. Bernabeu, NPB 840 (2010), 349...., C. Degrande, N. Greiner, W. Kilian, O. Mattelaer, H. Mebane, T. Stelzer, S. Willenbrock and C. Zhang, Annals Phys. **335**, 21 (2013)

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

Various studies exist. I will talk only in terms of the strengths of anom. couplings which can then be translated in terms of the scale of new physics! Operators involving Higgs expected to have smaller suppression!

A partial summary of LHC prospects available in J. Adelman et al, 1309.1947, 1308.5274 Latest: A. Buckley et al.JHEP **1604** (2016) 015 Also a talk here!

General $\bar{t}bW$ vertex can be written as

$$\Gamma^\mu = \frac{g}{\sqrt{2}} \left[\gamma^\mu (f_{1L} P_L + f_{1R} P_R) - \frac{i\sigma^{\mu\nu}}{m_W} (p_t - p_b)_\nu (f_{2L} P_L + f_{2R} P_R) \right].$$

In SM, $f_{1L} = 1$, $f_{1R} = f_{2L} = f_{2R} = 0$.

Deviations from these values will denote "anomalous" couplings

Older limits: Bernreuther W., J. Phys. G., Nucl. Part. Phys. 35 (2008) Only f_{2R} can be nontrivial. $-0.57 < f_{2R} < 0.15$

CMS constraint: $-0.070 \pm 0.053(+0.073 - 0.081)$ Using W-helicity fractions from t-decay in $t\bar{t}$ events.

Will discuss probing CP violation in this as well as effects of this on probes of top polarisation.

Calculations for BSM extensions:

Older papers: W. Bernreuther, et al, EPJC 60 (2009) 197, L. Duarte et al, JHEP **1311** (2013) 114

Recent analyses: A. Jueid and A. Arhrib,JHEP **1608** (2016) 082, C. Ayala et al,arXiv:1611.0775

Dominated by QCD corrections.

The last calculates imaginary part (CP violating) to f_{1R}, f_{2R}. Pure EW. Can be larger than the SM expectations! Worth making the effort to measure these!

$$\phi f \bar{f} \;:\; -\bar{f}(a_f + i b_f \gamma_5) f \frac{g m_f}{2 m_W}, \quad \textbf{(mixedCP)}$$

$$\phi^+ \bar{t} b \;:\; (m_b \tan\beta \bar{t}_L b_R + \bar{t}_R b_L m_t \cot\beta) \frac{g}{\sqrt{2} M_W} \quad \textbf{(Type II 2HDM)}$$

In the SM $a_f = 1, b_f = 0$

In 2HDM and SUSY: There exist both CP even and CP odd scalars.

For a pure CP even state $b_f = 0$. For a pure CP odd state $a_f = 0$. For case of CP violation both a_f, b_f nonzero simultaneously.

The charged Higgs vertex involves t of both chiralities.

This can be probed through top polarisation.

Top chromomagnetic or chromoelectric dipole moment:

$$\Gamma^{\mu} = \frac{g_s}{m_t}\, \sigma^{\mu\nu} \left(\rho + i\rho' \gamma_5\right) q_{\nu}$$

q 4 momentum of the gluon and color matrices left out.

$\rho = \rho' = 0$ in the SM at tree level.

ρ' : CP violating arises in the SM only at three loop level.

ρ Arises at one loop level in the SM.

Examples of BSM predictions: MSSM: J. M. Yang and C. S. Li, Phys. Rev. D **54**, 4380 (1996) 2HDM: R. Martinez and J. A. Rodriguez, Phys. Rev. D **65**, 057301 (2002)

The new couplings affect rates of production of top pair, single top AND Higgs!

Can be used to probe these couplings: Some of the recent papers:

Top pair: S.K. Gupta, G. Valencia PRD 81, 034013, 2010, S.K. Gupta, G. Valencia, A.S. Mete, PRD80, 2009, 034013, Z. Hioki and K. Ohkuma, EPJC, 71, 2011, 1535 , .. D. Choudhury and P.Saha, Pramana, 77, 2011, 1079 S. Biswal, S.D. Rindani, P. Sharma, hep-ph/1211.4075, Baumgart and Tweedi, hep-ph/1212.4888

Higgs signal strength: C. Grojean et al, 1205.1065, P. Saha and D. Choudhury, 1201,4130

The papers in this color consider rates. Already interesting constraints. BUT depend on QCD uncertainties on the rates. The papers in in this color consider either polarisation and/or spin spin correlations.

Important to use these cross-checks. Also CP violation can be probed unambiguously ONLY using polarisation.

F.D. Aguila and J.A. Aguilar-Saavedra, PRD 64 (2003), J.A. Aguilar-Saavedra NPB 804 160 (2008), and collab. EPJC 53, 689, 2008... : use W-helicity and probe the anom. coupling independent of polarisation of the produced top!

Recent NLO analysis : use rates to probe tbW: Q. H. Cao et al, arXiv:1504.03785.

S.D. Rindani and collab: PLB 712 (2012) 413-418, JHEP 1111 (2011) 082,Phys.Lett. B761 (2016) 25-30 , Use polarisation to get information about tbW vertex.

Simultaneous measures of polarisation and anom. couplings generic analysis: Arunprasath , RG and Rindani: Eur.Phys.J. C75 (2015) no.9, 402

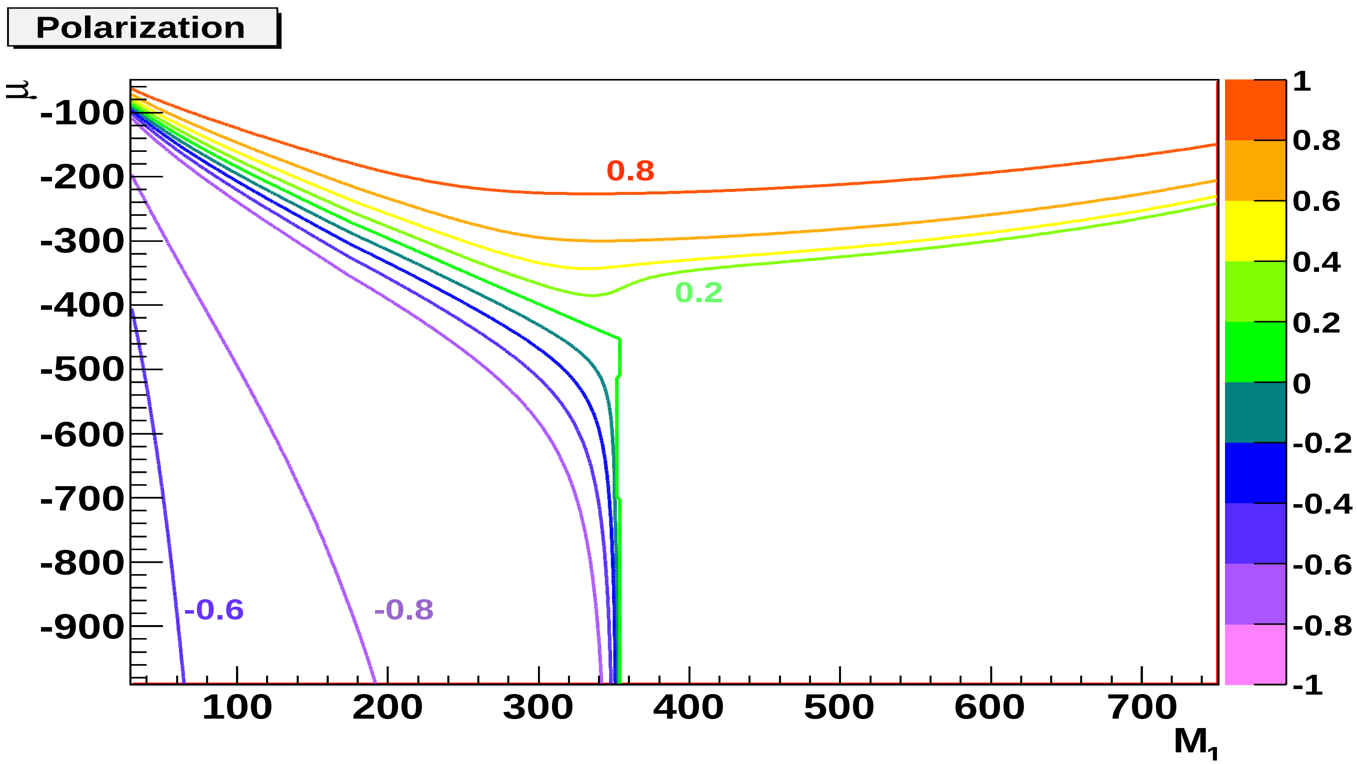
Specific to single top including NLO effects: Jueid, Boudjema and RG, in preparation

M. Perelstein and A. Weiler, JHEP **0903**, 141 (2009), B. Bhattacherjee, S. K. Mandal and M. Nojiri, JHEP **1303**, 105 (2013), G. Belanger, R. M. Godbole, L. Hartgring and I. Niessen, JHEP **1305**, 167 (2013), G. Belanger, R. M. Godbole, S. Kraml and S. Kulkarni, arXiv:1304.2987 [hep-ph]

In these relationship of expected polarization on model parameters as well as measurement strategies explored and effects of polarization on kinematics of the decay products considered.

E. L. Berger, Q. -H. Cao, J. -H. Yu and H. Zhang, PRL **109**, 152004 (2012),

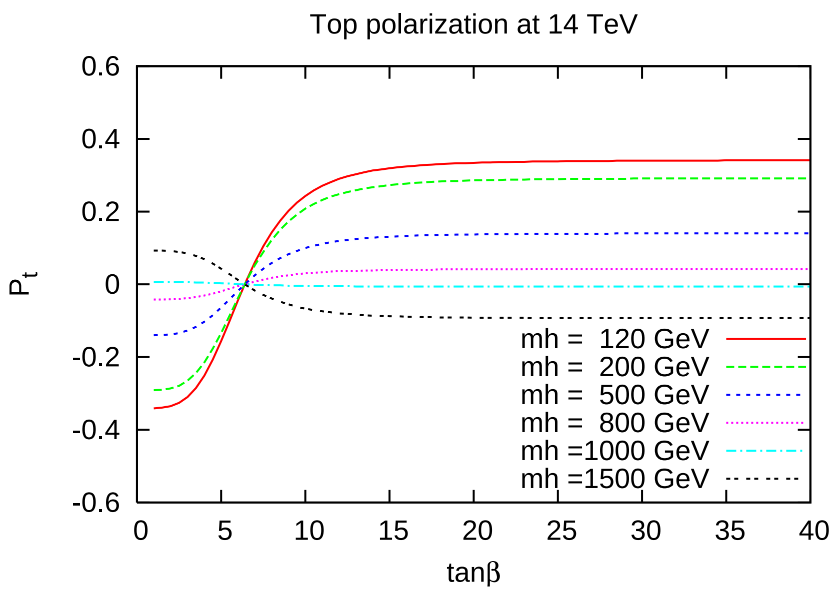
Here mainly effect on decay kinematics explored.

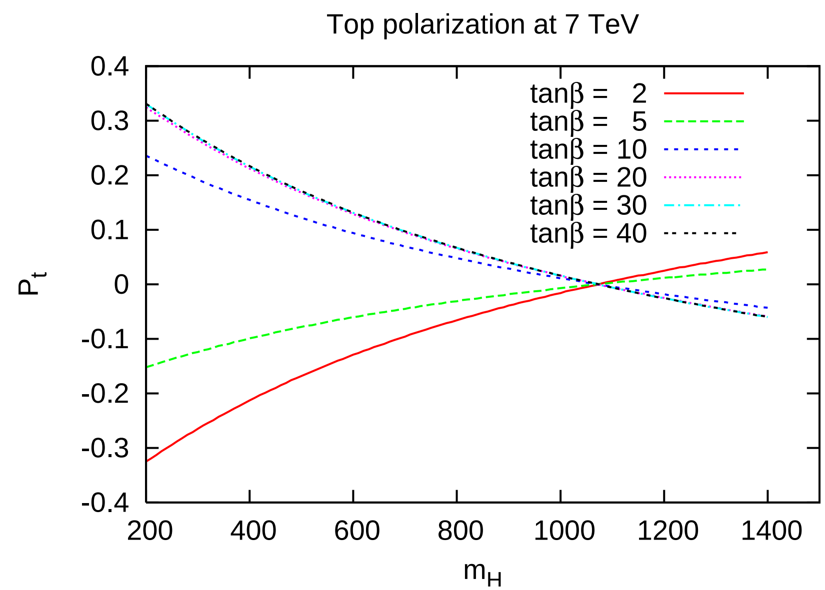


Belanger, Godbole, Niessen, Hartring: 1212.3526

W^-t production : t will be left polarised, H^-t production: t polarisation depends on $\tan\beta$, and m_t.

Extracting charged higgs couplings: K. Huitu, S. Kumar Rai, K. Rao, S. D. Rindani and P. Sharma, JHEP **1104**, 026 (2011), [arXiv:1012.0527 [hep-ph].





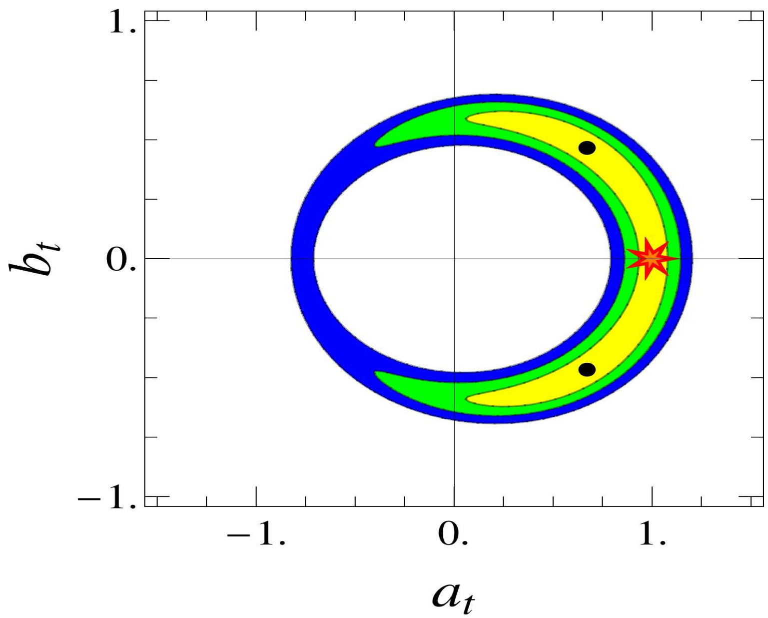
First and foremost: a 'direct' measurement of the strength of this coupling (lot of work and discussions!)

Check CP property of the coupling :

a)Use cross-section and kinematical observables for tth.

b)Use cross-sections for th and $t\bar{t}h$

c)Use polarization information for th



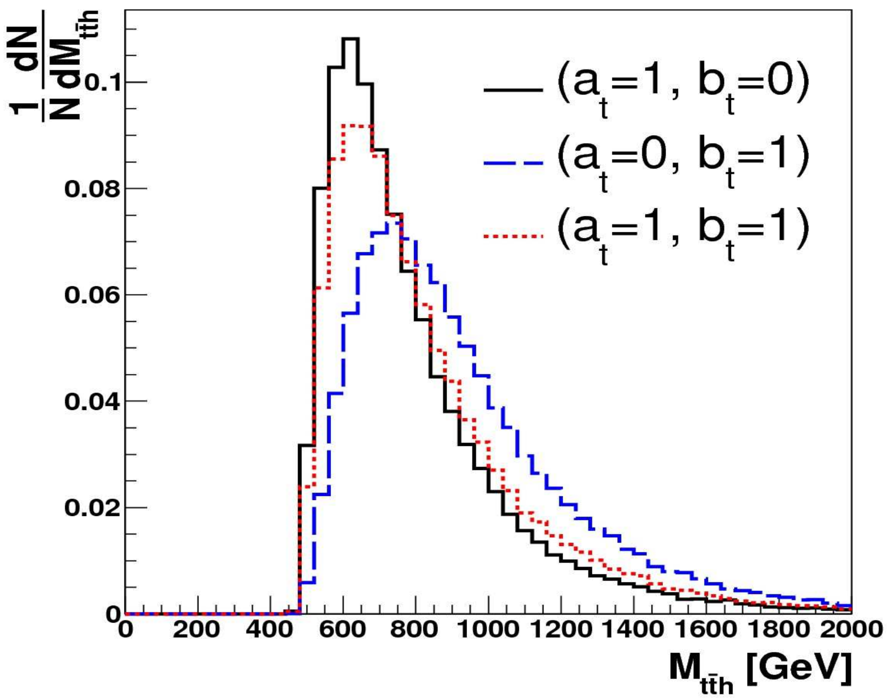
All the other couplings other than the t are taken to be SM couplings.

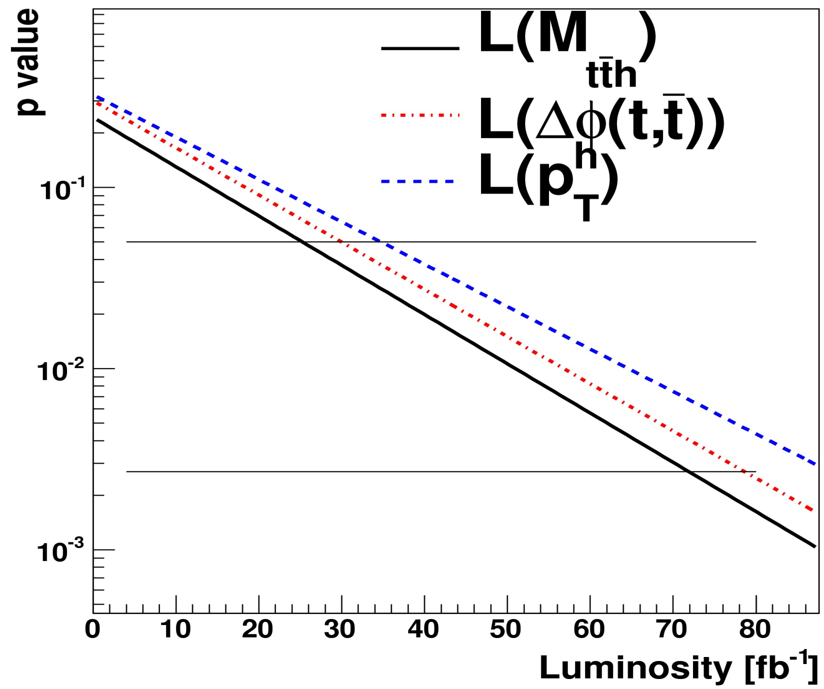
Rates are more sensitive to the pseudo scalar part b_t than a_t Does allow $b_t \neq 0$ and will continue for a while!

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.

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

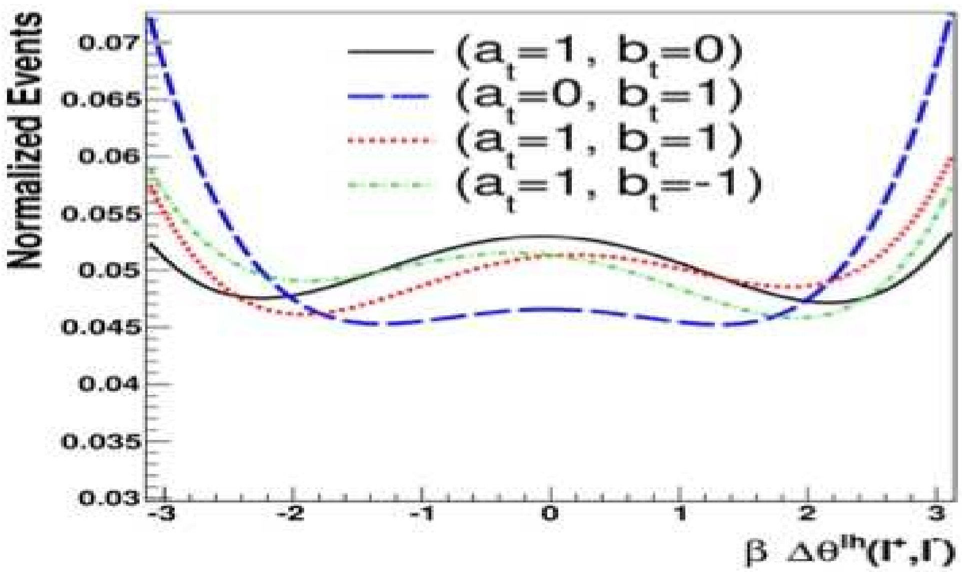




K. Mohan, F. Boudjema, RG, Diego G.,PRD 92 (2015) 015019.

One observable Linear in b

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



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

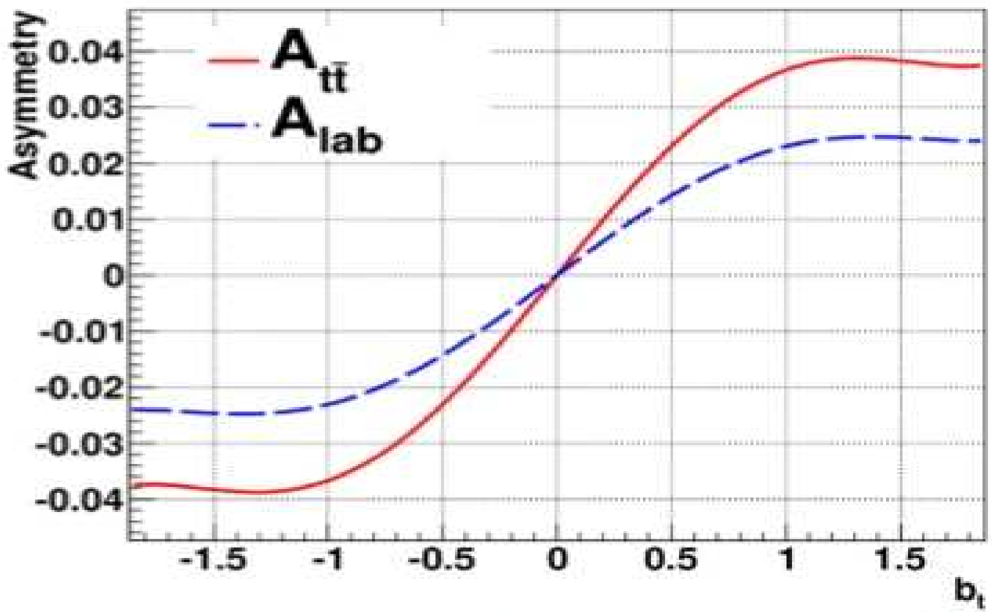
Indeed an effect linear in b

Completely in terms of lab observables.

No need to construct any particular frame

PRD 92 (2015) 015019

Asymmetries



Asymmetry: Linear behaiour in b, Uniquely CP violating.

Asymmetry of lab variables (blue) is smaller but easier to construct. Less systematic uncertainties.

th cross-section:

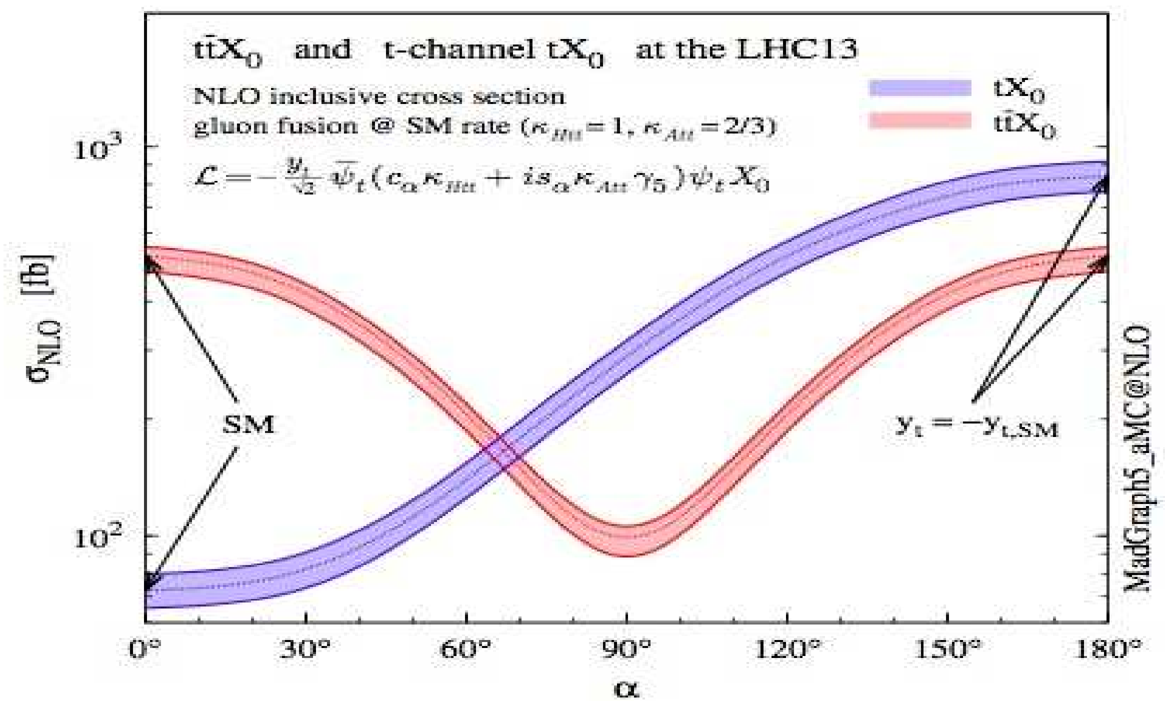


Fig. 12 NLO cross sections (with scale uncertainties) for $t\bar{t}X_0$ and t-channel tX_0 productions at the 13-TeV LHC as a function of the CP-mixing angle α, where κ_{Htt} and κ_{Att} are set to reproduce the SM GF cross section for every value of α

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

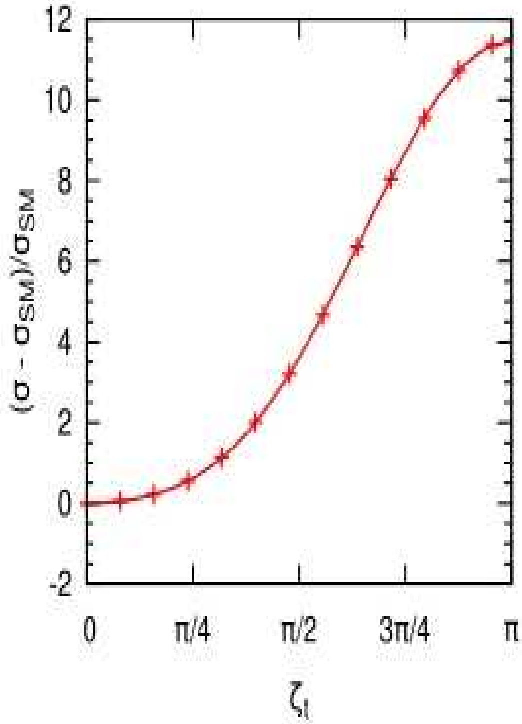


Fig. 2. The fractional deviation of the cross section from the SM value as a function of CP phase ζ_t in the $t\bar{t}h$ coupling for thj process at LHC14.

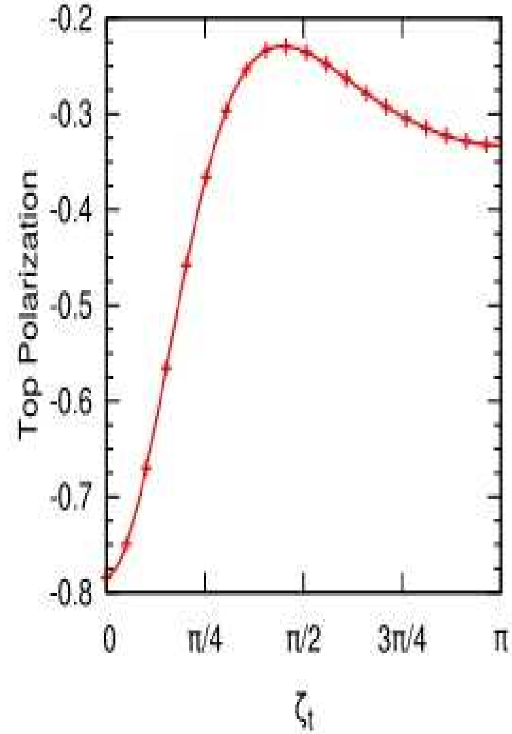
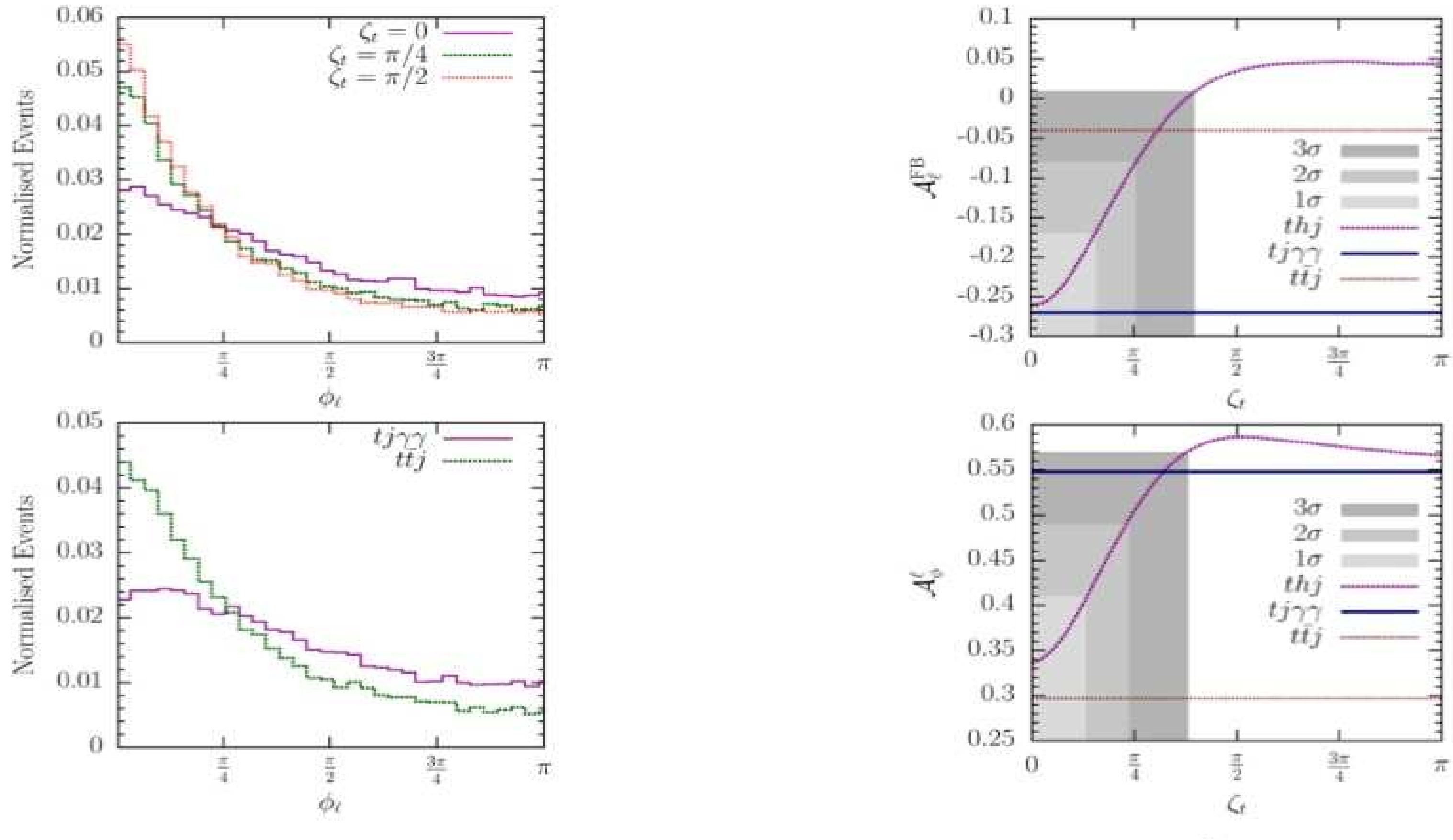


Fig. 3. Top polarization in $pp \to thj$ at LHC14 as a function of the CP phase ζ_t of the tth coupling.

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



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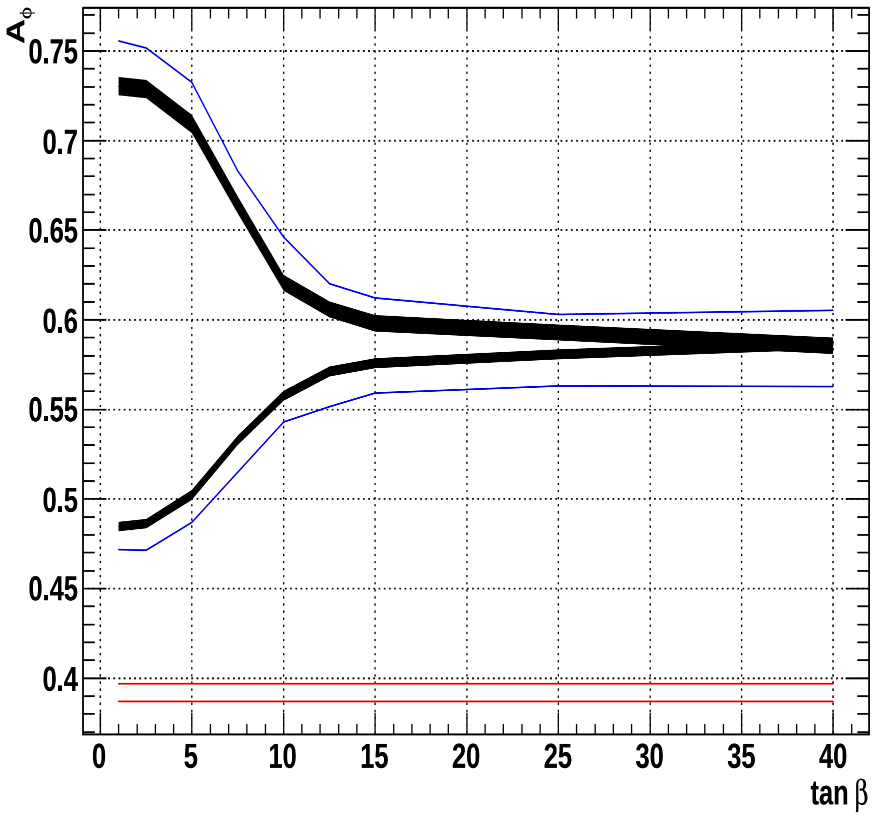


Separation between W^-t and H^-t for this observable is clear.

Thin line: LO result, thick black: NLO.

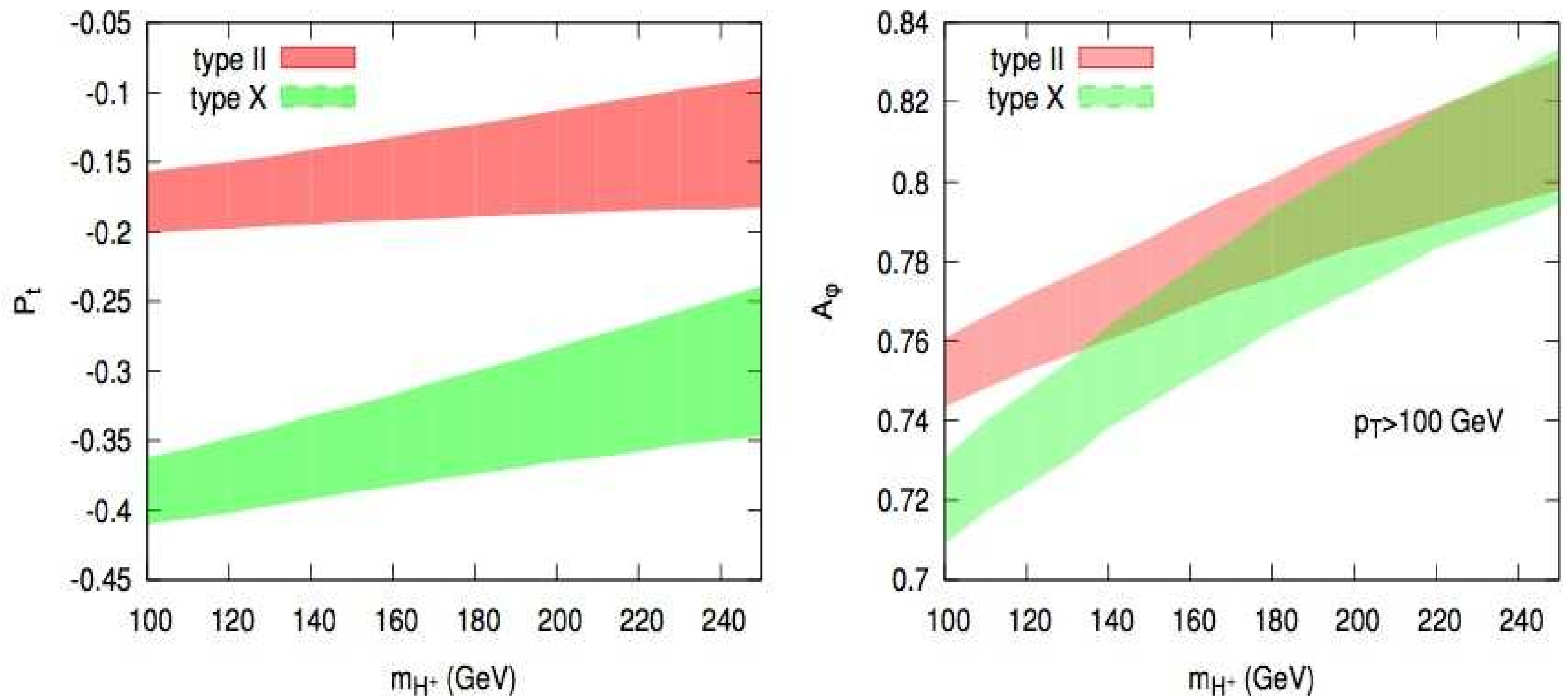
$M_{H^-} = 200$ lower curves, $M_{H^-} = 1500$ upper curves.

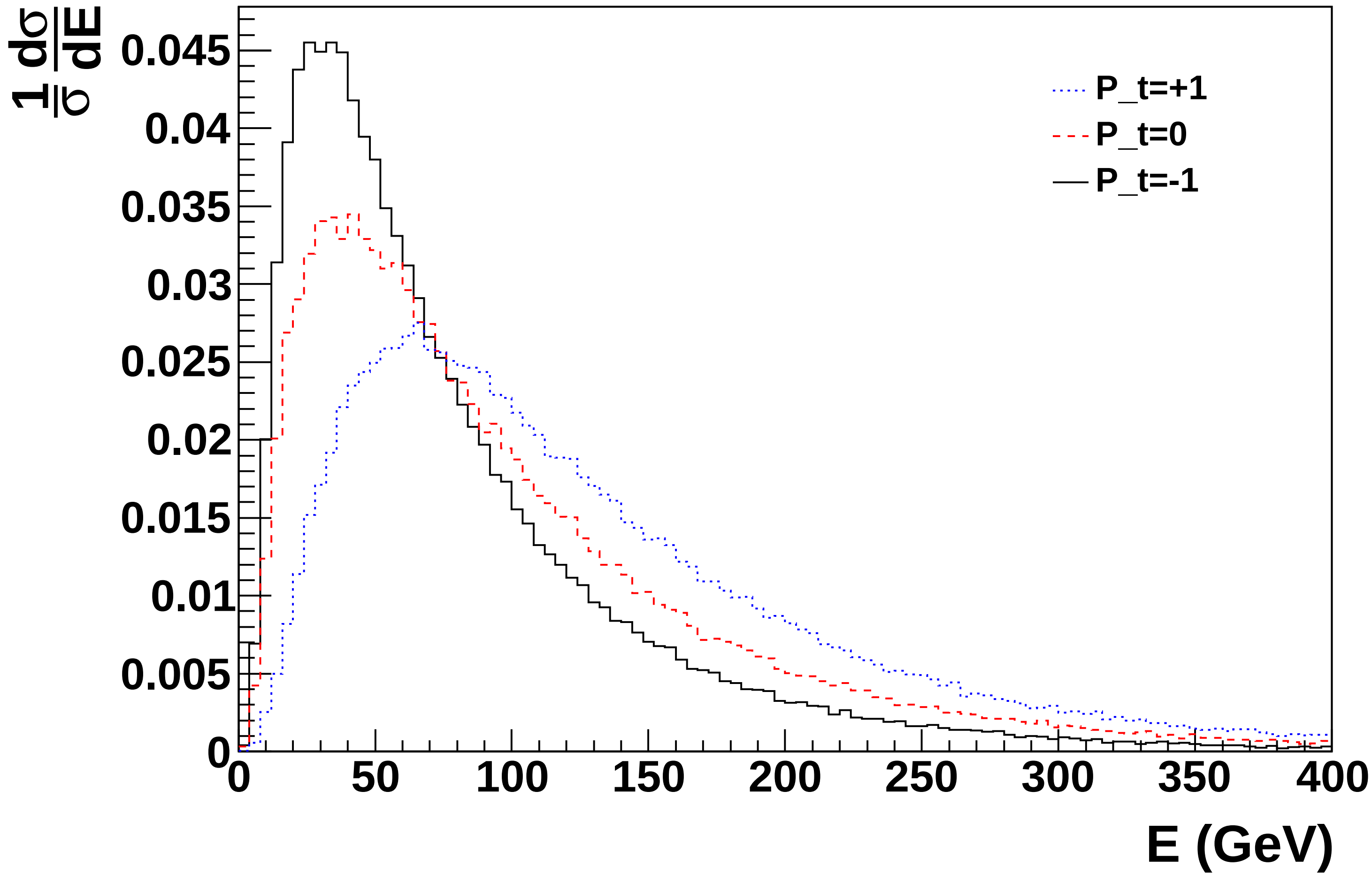
Constant contours at the bottom W^-t.

Correspond to different schemes to adjudge the effect of interference effects at NLO. Only if the two are close is the isolation of W^-t considered free of these ambiguities.

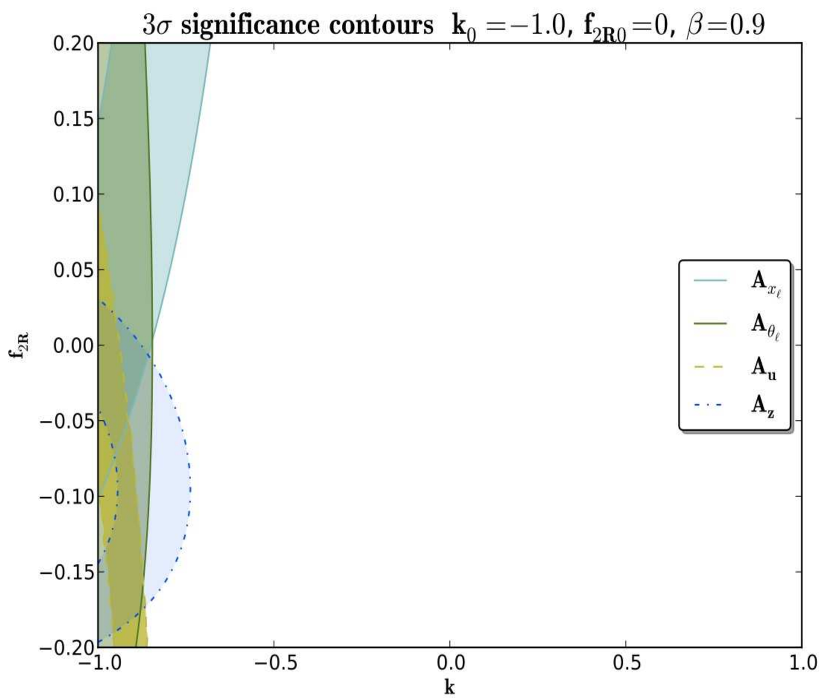
Polarisation tracked through azimuthal asymmetries (With C. White, L. Hartgring and I. Niessen:

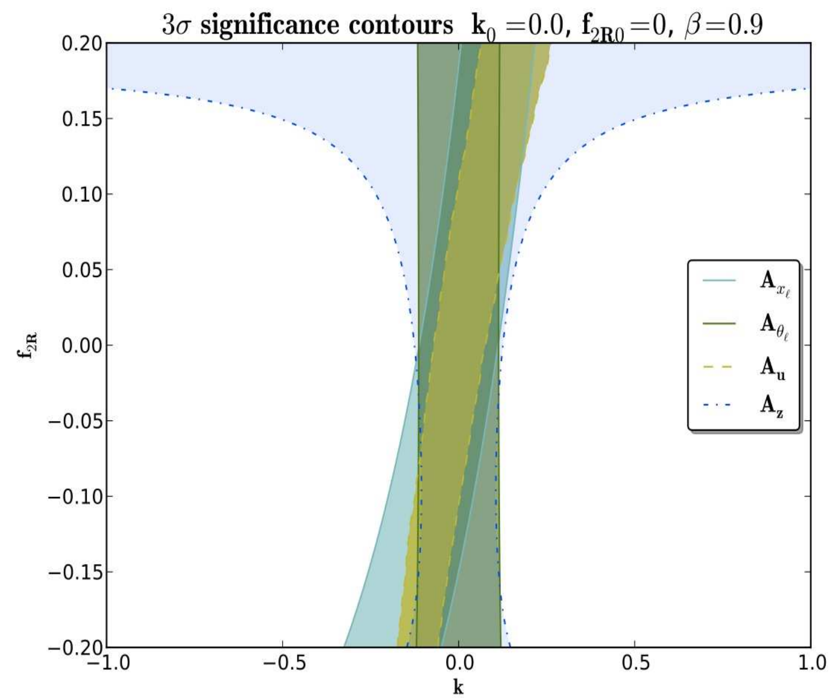
hep-ph/1307.1158v1



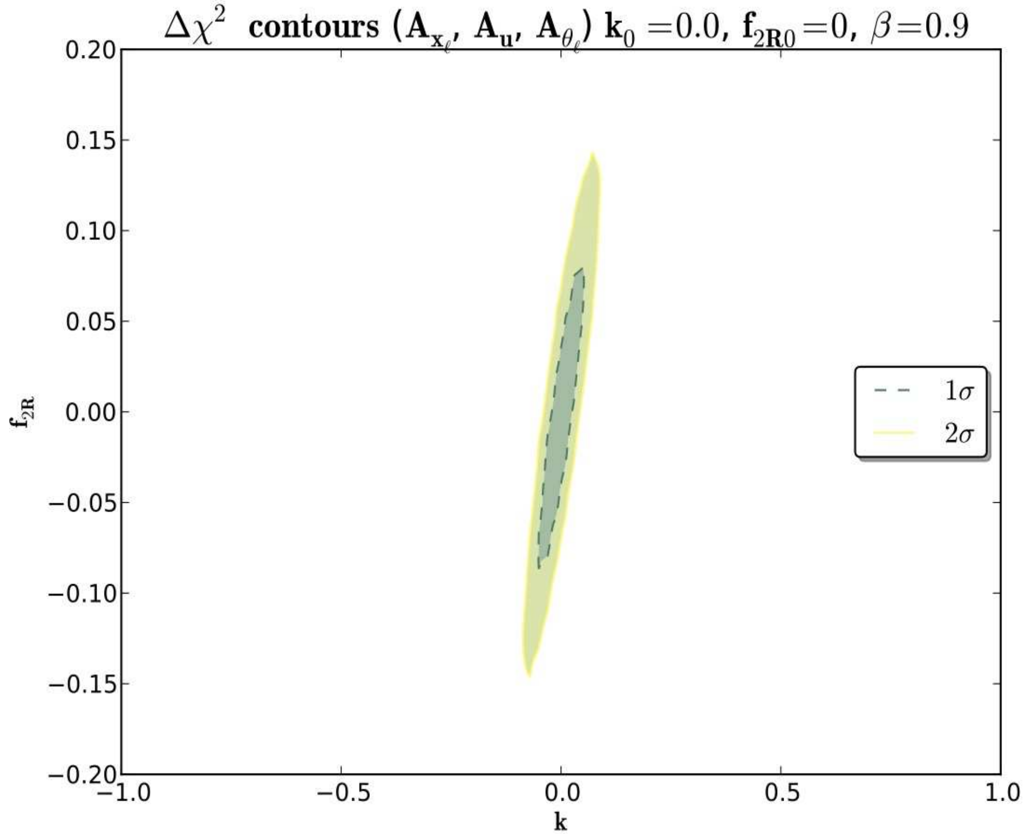


For the negatively polarised top distributions peak at lower values of energy. Effect small for smaller mass differences.





Used $t\bar{t}$ events with inv. mass between 1500 and 2000 GeV. For 100^{-1} fb. A. Prasath V et al EPJC **75** (2015) no.9, 402


$\Delta\chi^2$ contours (A_{x_ℓ}, A_u, A_{θ_ℓ}) k_0 =0.0, f_{2R0}=0, β=0.9
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
f_{2R}
−1.0
−0.5
0.0
0.5
1.0
k
1σ
2σ

- Mass of the top can probe BSM and its scale. Accurate measurement of top mass essential probe of BSM.

- The top yukawa very sensitive probe of BSM particularly using Higgs rates and associated production of top (pairs) with Higgs.

- BSM physics affects properties of the top quark produced.

- Kinematic properties of the produced top, cross-sections etc can be used to probe the BSM

- In addition polarization of the top quark provides an excellent probe for BSM

- Secondary decay lepton angular distributions are the most faithful polariometers, robust to effects of non standard tbW couplings as well as higher order corrections.

- At the LHC ϕ distibutions can be used to construct obeservables which probe polarization.

- The parameters of a 2HDM can be determined using the top polarization and the asymmetries

- Use of energy dependence of the total $t\bar{t}\Phi$ cross-section, along with the polarization can help establishing CP of the scalar state should it be a CP eigenstate

- Top quarks produced in the stop/sbottom decays are polarized and polarization affects kinematic distributions of the decay products. This can affect the search strategy and also can be used to measure the polarisation when we find the stops/sbottoms.

- The energy distributions of the decay leptons and hence the z, u distributions are sensitive to anomalous tbW couplings.

- Simultaneous study of different asymmetries can be used to determine both the polarization and the anom. tbW coupling.