LNF Node – part II

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ENP Collaboration meeting

U. Roma 1

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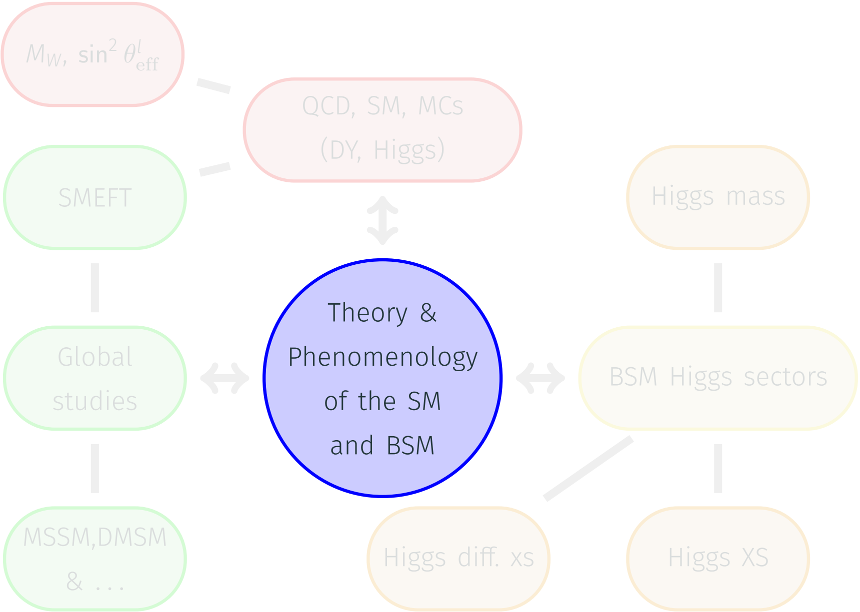
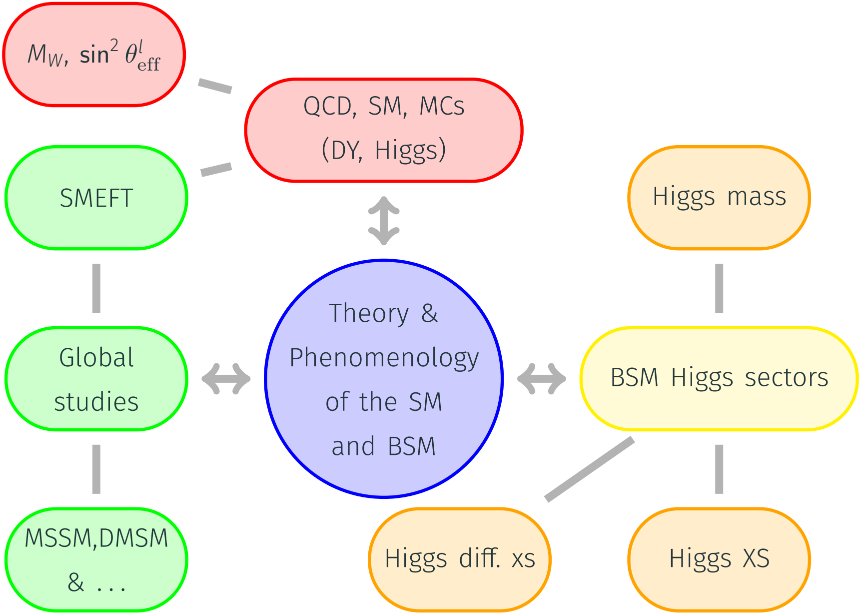
Who am I?

- New arrival at Laboratori Nazionali di Frascati
- Working on particle theory/phenomenology, mostly on collider but with links to other sectors
- International collaboration/connections with groups in Germany, France, Switzerland, Spain, Poland, the UK and CERN


M_W, $\sin^2\theta^l_{\rm eff}$
QCD, SM, MCs (DY, Higgs)
SMEFT
Higgs mass
Theory & Phenomenology of the SM and BSM
Global studies
BSM Higgs sectors
MSSM,DMSM & ...
Higgs diff. xs
Higgs XS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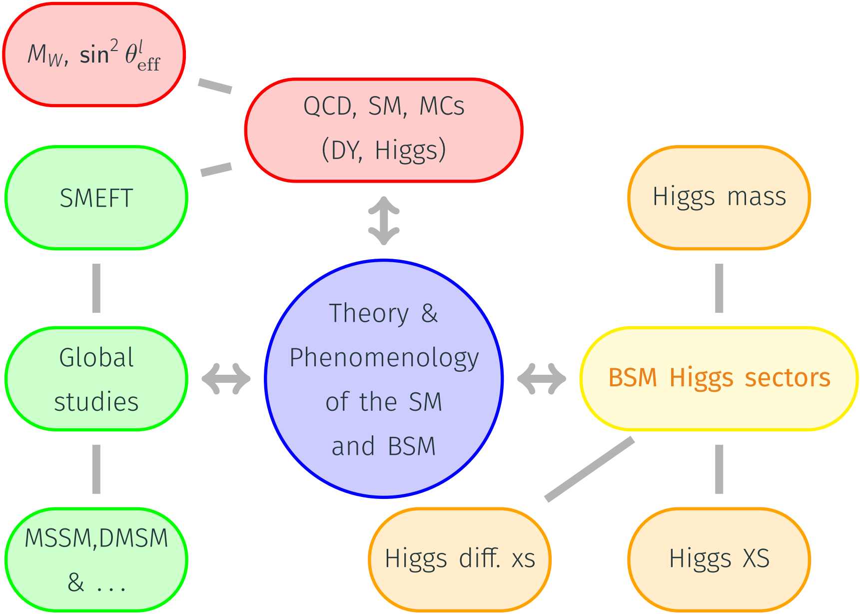
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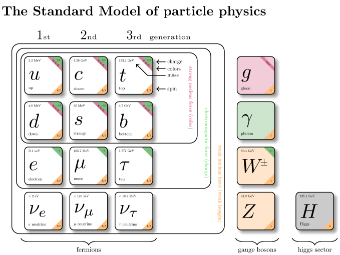
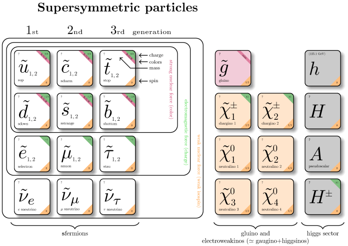
The MSSM





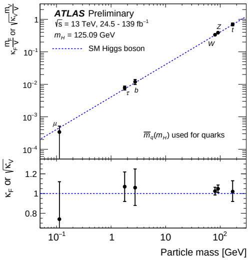
A few important phenomenological features

- After EWSB, gauginos and higgsinos mix to form the neutralinos ($\tilde{\chi}^0_{1,2,3,4}$) and the charginos ($\tilde{\chi}^{\pm}_{1,2}$)
- The Higgs sector is a two Higgs-doublet (2HDM) of type-II. Physical spectrum is composed of two neutral CP-even Higgs (h and H), one neutral CP-odd Higgs (A) and two charged Higgses ($H^{\pm}$)
- The light Higgs mass is *predicted* in the MSSM (in terms of the other parameters). The tree level upper bound is m_Z, however radiative corrections are very important and allow to reach the observable value

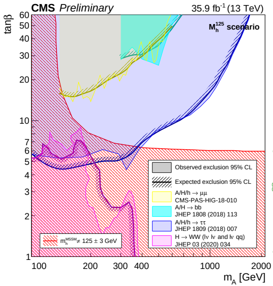
Characterizing the MSSM Higgs sector

Motivations

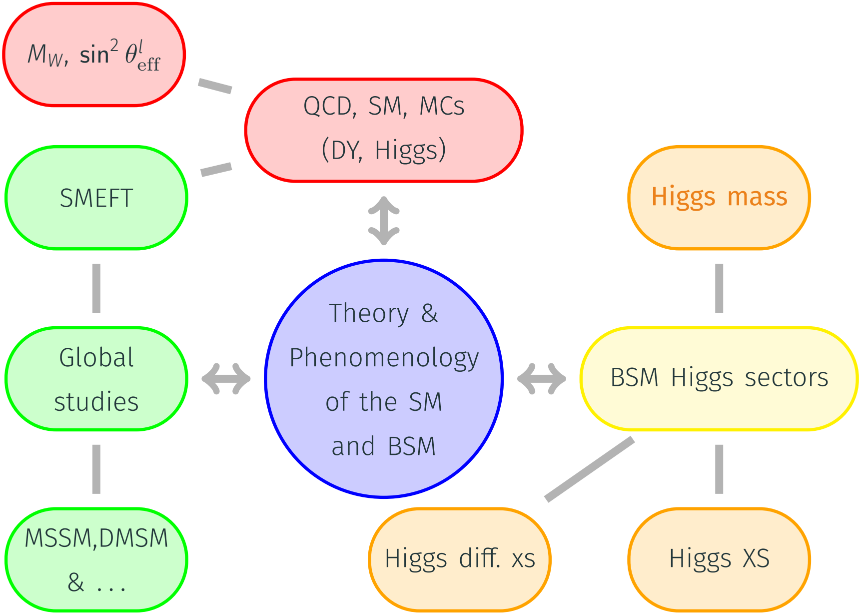
- A careful study of the Higgs sector of the MSSM is necessary to extract as many information as possible from the observed boson and detect possible signs of new physics
- In the following slides, we focus on the neutral Higgs bosons of the MSSM
- Light CP-even boson: Higgs mass, production processes and decay rates
- Heavy neutral bosons: differential predictions are important to compute the detector acceptance and therefore to properly interpret the experimental searches



[ATLAS Higgs WG website]



[CMS Higgs PAG website]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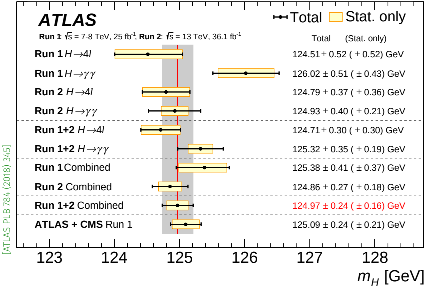
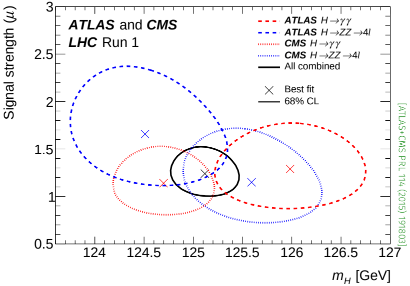
The case of the Higgs mass

Motivations

- Most important results from LHC run 1 is the discovery a SM-like Higgs boson
- Mass measured with high-accuracy during all runs
- We can use the mass a precision observable to constraint BSM models, namely the MSSM

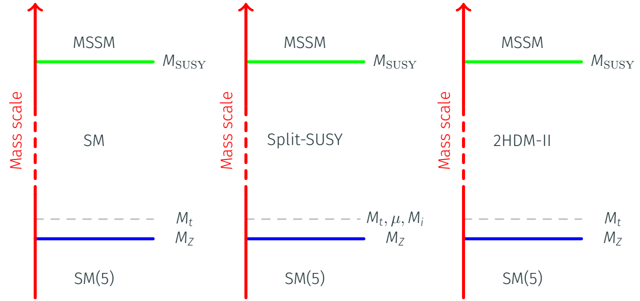




A tower of effective theories

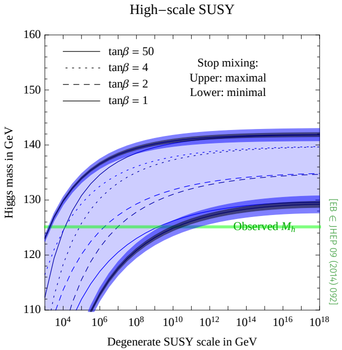
The Higgs mass and the MSSM

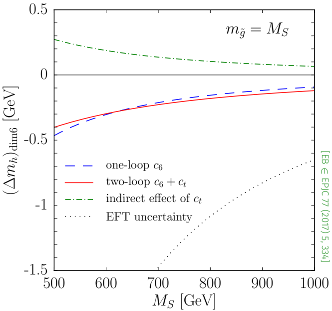
- **Motivation**: no evidence of SUSY states at the LHC, what if SUSY is heavy? Use the Higgs mass an handle to probe the spectrum
- **Problem**: mass gap in the physical spectrum makes large logs of the ratio $Q_{\text{EW}}/M_{\text{SUSY}}$ appears in the perturbative expressions
- **Solution**: For a proper computation these logs have to be resummed
- **Method**: tower of matched effective field theories; Use RGE to resum the large logarithms



Depending on the spectrum we have to consider different hierarchies

Results



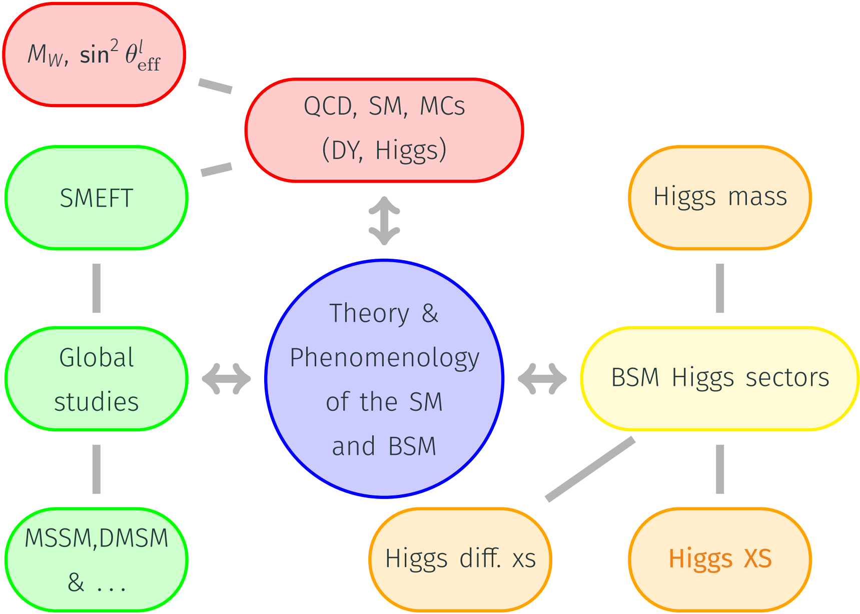


Improved accuracy

- Use the Higgs mass to probe very heavy SUSY scales
- Improvements in the accuracy of the matching conditions with new calculations across the years

SMEFT matching

- Matching on the SMEFT, with dimension-6 operators
- Aim was to understand the lowest bound for the application of the EFT approach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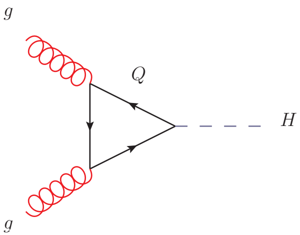
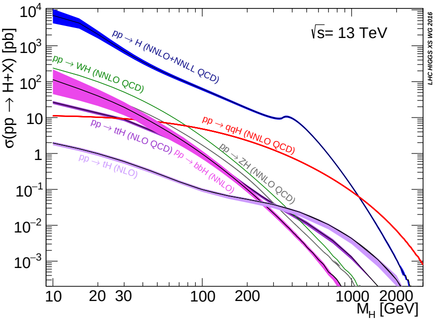
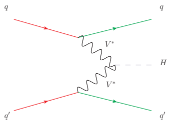
Higgs production channels at the LHC

Gluon fusion

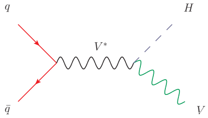




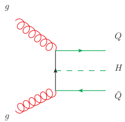
Vector Boson Fusion (VBF)



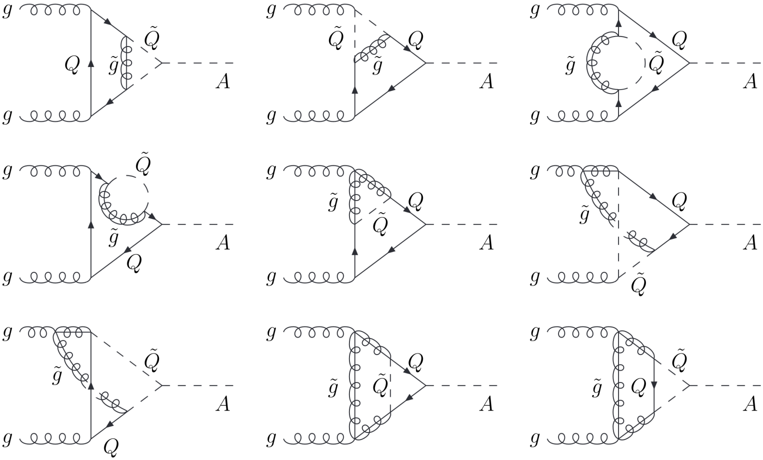
Higgs Strahlung



Quark associated production



2-loop SQCD contribution to $gg \to A$



[EB et al., JHEP 03 (2023) 124]

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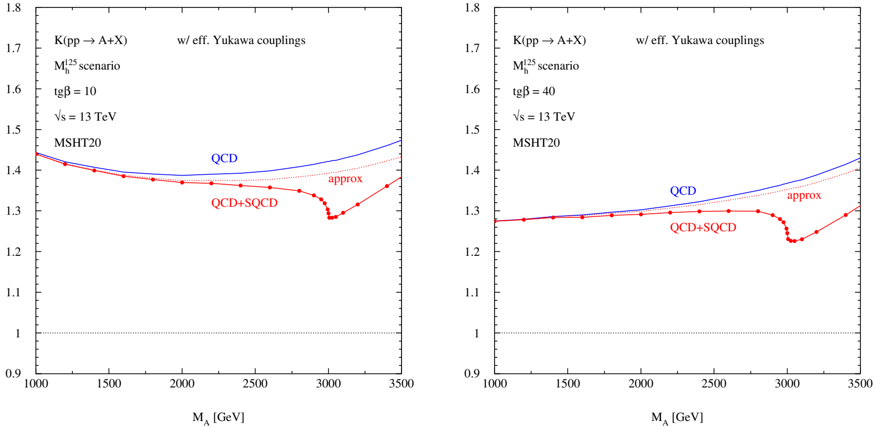

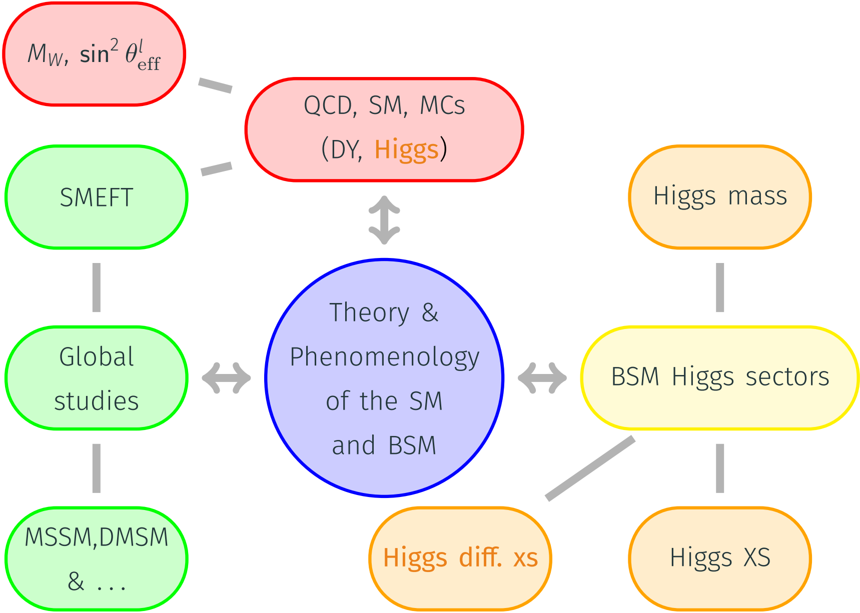
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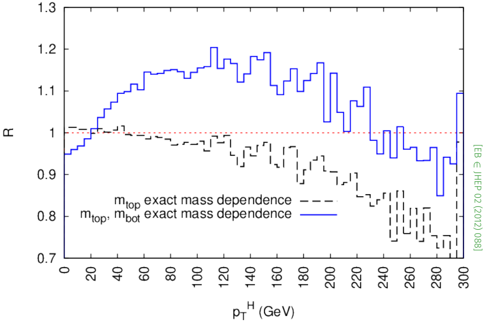
Gluon fusion: QCD radiation and the loop dynamics

Overview

- The Higgs acquires a transverse momentum due to the recoil against QCD radiation.
- Matched calculation required for a proper physical description



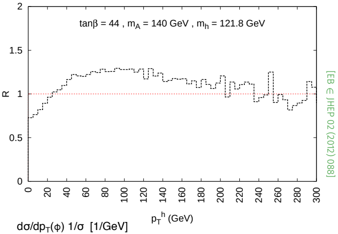
Quark mass effects

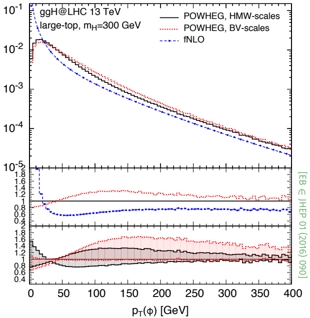
- First implementation in a Monte Carlo event generator
- High-p_T region inaccurate if HQEFT used
- Top-mass effect sizable, quickly greater than 50% suppression as soon as $p_T > m_t$
- Studies spurred a lot of activity in the theory/pheno community

Shape distortion: SM vs MSSM

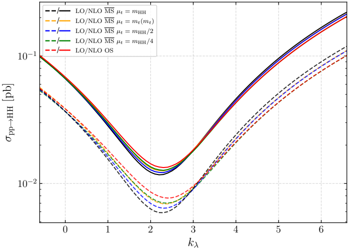
BSM effects

- Exactly as one can have an effect on total rates due to the presence of additional BSM particles in the gluon fusion loops, one can have effects on the shape of the p_T^h distribution
- Change in the relative weight of the Yukawa couplings to top and bottom can affect the shape too (e.g. 2HDM)
- For heavy Higgs production, important for the acceptance determination
- Non-trivial choice of scales for bottom-dominated scenarios and/or heavy Higgs production

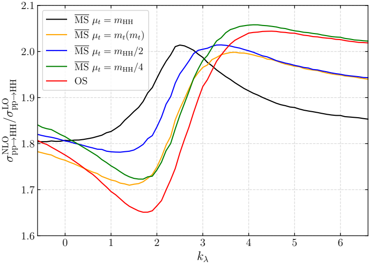




Double Higgs production



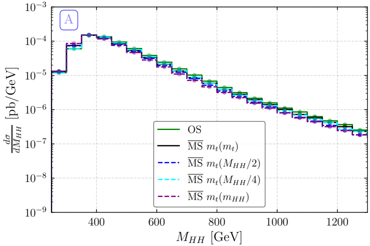
- Total inclusive cross section at LO and NLO for different values of k_λ and different choices of the top mass renormalization scheme

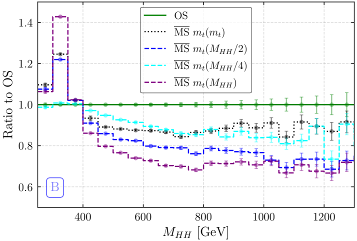


- K-factors for different top mass scheme choices

- Minimum of the cross section depends on the top scheme
- As expected, the difference between the schemes is smaller at NLO
- We have found some disagreement with existing calculations, currently under investigation $\to$ see Gudrun's talk at the recent *Discussion on MC at NLO QCD* meeting event for an update of the existing `POWHEG-BOX` Monte Carlo

SM top scheme dependence: M_{HH}

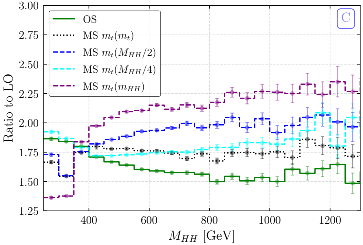


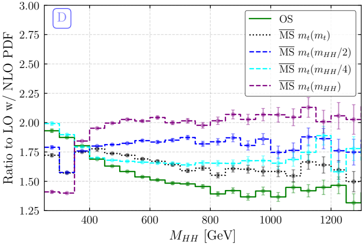


- Absolute distributions for different top mass schemes
- Ratio to the OS prediction at NLO

- Different top mass scheme $\longrightarrow$ tilt of the distribution around the peak
- Largest effect for $m_t(M_{HH})$

SM top scheme dependence: M_{HH}

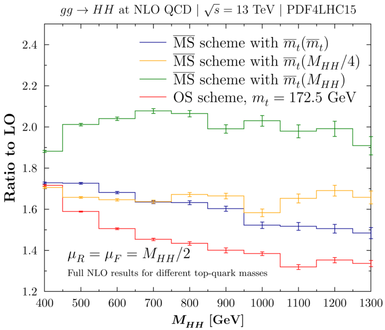


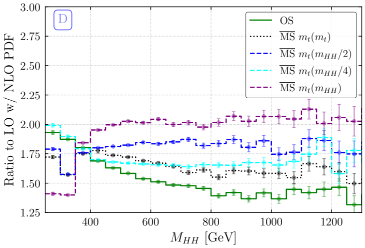


- K-factor for various scheme choices

- Ratio to LO while using the same PDFs and α_s $\rightarrow$ highlight the difference in the ME (cfr. 2008.11626)

- Smallest k-factor for the OS above the peak
- Largest k-factor for the $\overline{\text{MS}}$ scheme and $m_t(m_{HH})$

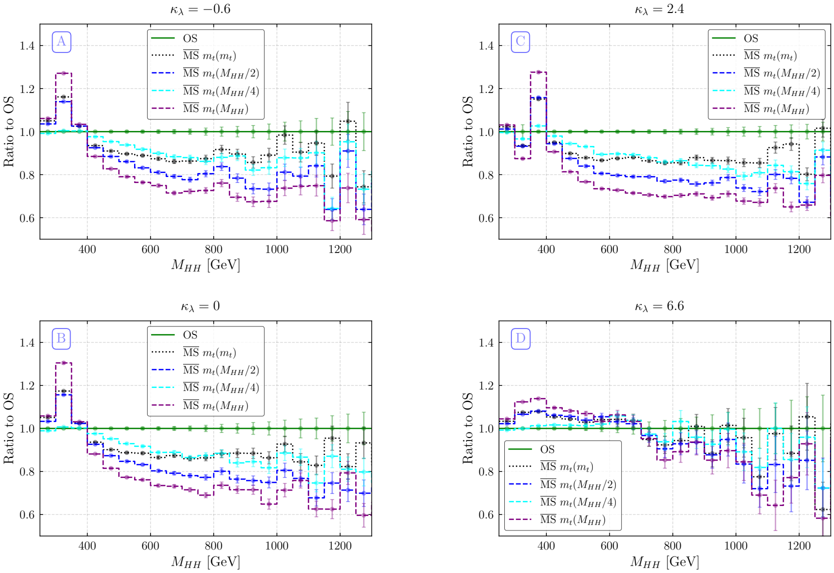




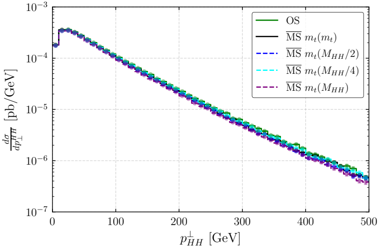
[Baglio et al., PRD 103 (2021) 5, 056002, hep-ph/2008.11626]

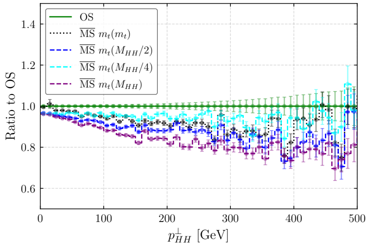
- Very good agreement even if the setup is different (NLO vs NLO+PS)

Top scheme dependence with a modified trilinear



Transverse momentum distribution of the Higgs pair





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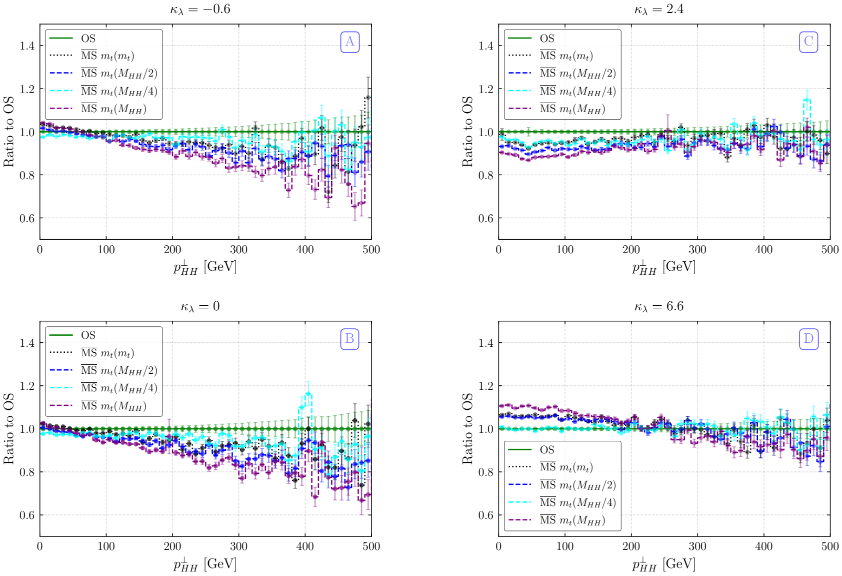
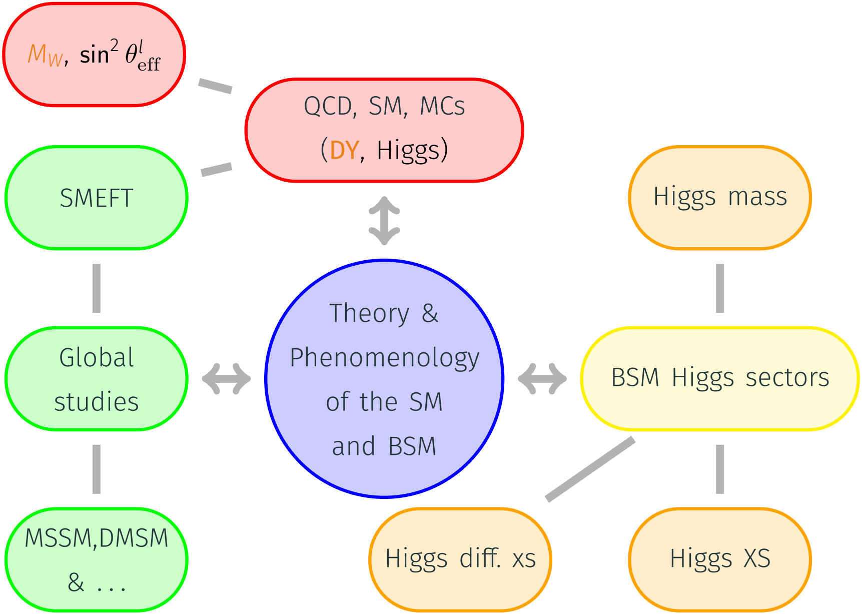
- Ratio to the OS prediction at NLO

- Different top mass scheme $\rightarrow$ different slope of the p_{HH} distribution
- Largest effect for $m_t(M_{HH})$

Top scheme dependence with a modified trilinear

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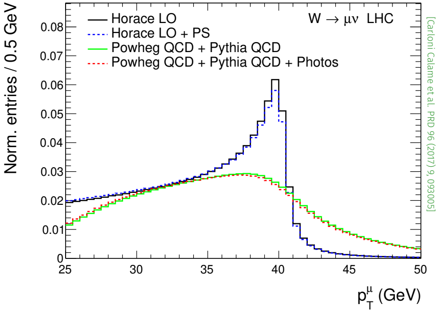
Measuring the W mass at the LHC

Three observables are especially sensitive to the W mass: p_T^l, M_T^W, p_T^{missing}.



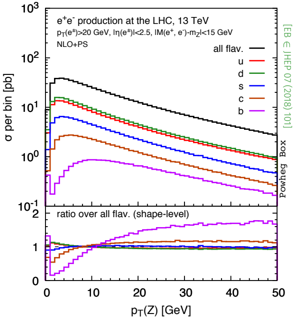
p_T^l characteristics

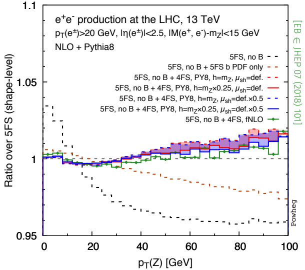
- High sensitivity to radiative corrections
- Detector modeling under control
- Peak around $m_W/2$

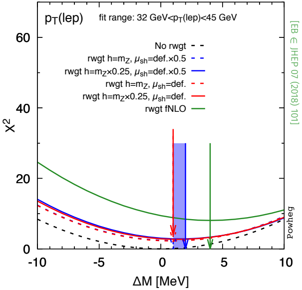
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
$\langle\mu\rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
$\Sigma\bar{E}_T$ correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)	1.4	3.1	1.4	3.1	1.4	3.1
Residual corrections ($Z \to W$ extrapolation)	0.2	5.8	0.2	4.3	0.2	5.1
Total	2.6	14.2	2.7	11.8	2.6	13.0

[ATLAS EPJC 78 (2018)]

The bottom quark and the W mass



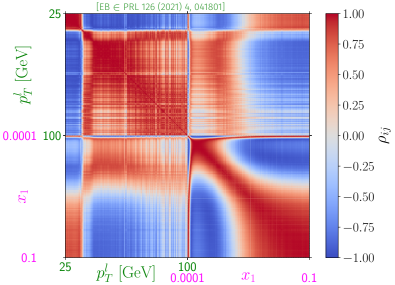


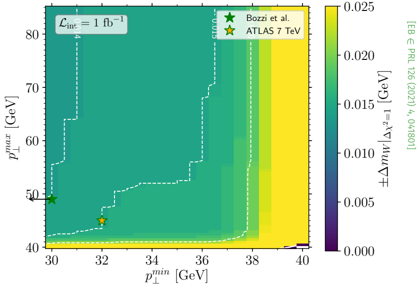


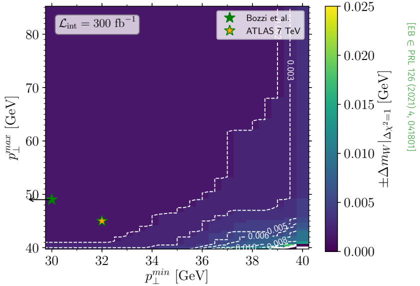
Bottom induced effects

- *Z* and *W* production correlated; estimate effect of improved treatment of the bottom induced contribution
- Shift on the *W* mass estimated to be a few MeV

The W mass and PDF uncertainties





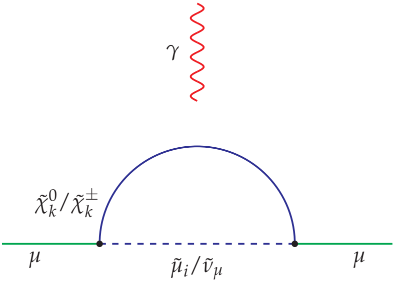


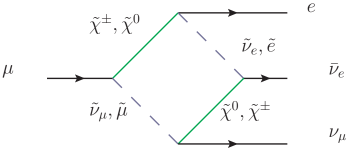
Impact of bin-bin PDF correlations

- PDF correlations important to reduce the uncertainty
- Non-trivial interplay with other source of uncertainty (e.g. statistical)

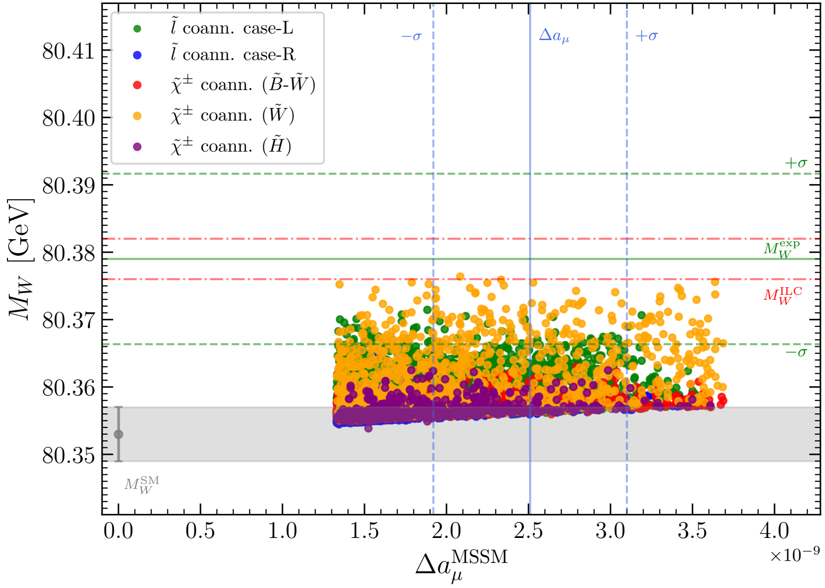
Correlating $(g-2)_\mu$ with M_W

- The lightest electroweakinos and the sleptons are important for both observables
- Is there a correlation between the values assumed by $(g-2)_\mu$ and M_W in the MSSM?
- Moreover, assuming that the $\tilde{\chi}_1^0$ contributes to the observed DM relic density, is there a correlation with specific dark matter mechanisms?



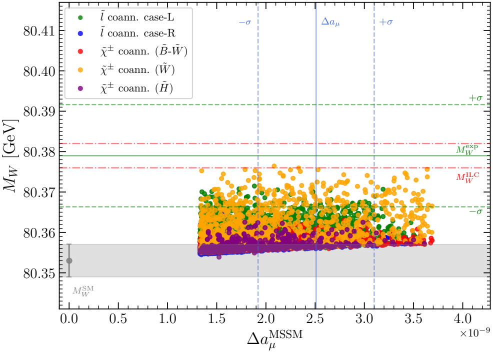


M_W vs $(g-2)_\mu$



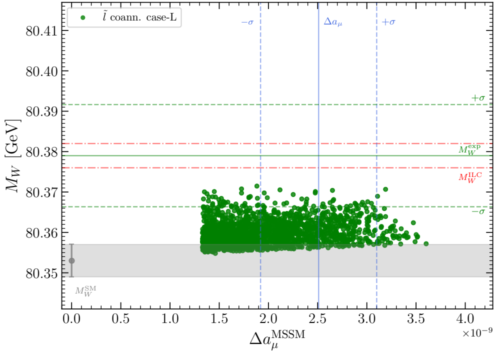
$\tilde{l}$ coann. case-L
$\tilde{l}$ coann. case-R
$\tilde{\chi}^\pm$ coann. ($\tilde{B}$-$\tilde{W}$)
$\tilde{\chi}^\pm$ coann. ($\tilde{W}$)
$\tilde{\chi}^\pm$ coann. ($\tilde{H}$)
$-\sigma$
Δa_μ
$+\sigma$
$+\sigma$
M_W^{exp}
M_W^{ILC}
$-\sigma$
M_W^{SM}
M_W [GeV]
80.41
80.40
80.39
80.38
80.37
80.36
80.35
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
$\times 10^{-9}$
$\Delta a_\mu^{\mathrm{MSSM}}$

M_W vs $(g-2)_\mu$



- There is a mild correlation between M_W and $(g-2)_\mu$, with interesting patterns arising in connection with DM mechanisms
- The MSSM covers well all the relevant range of Δa_μ
- For these scenarios, M_W is in general below the current exp. average, although many points lie within 1σ

M_W vs $(g-2)_\mu$



- There is a mild correlation between M_W and $(g-2)_\mu$, with interesting patterns arising in connection with DM mechanisms
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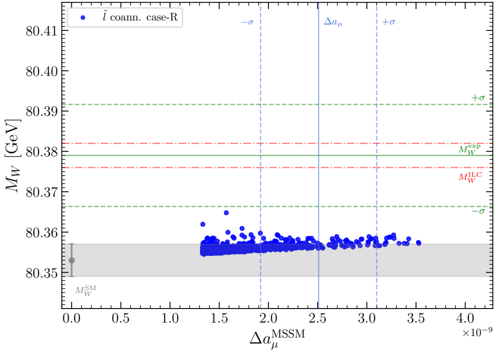

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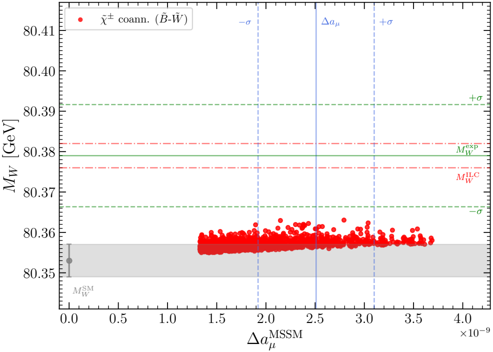

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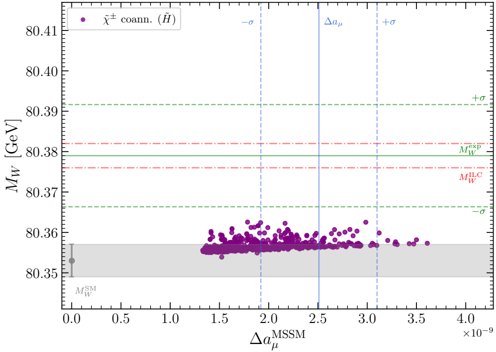

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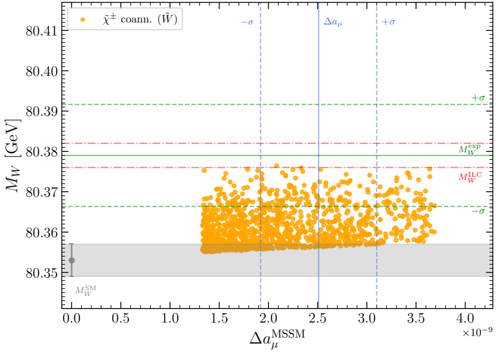

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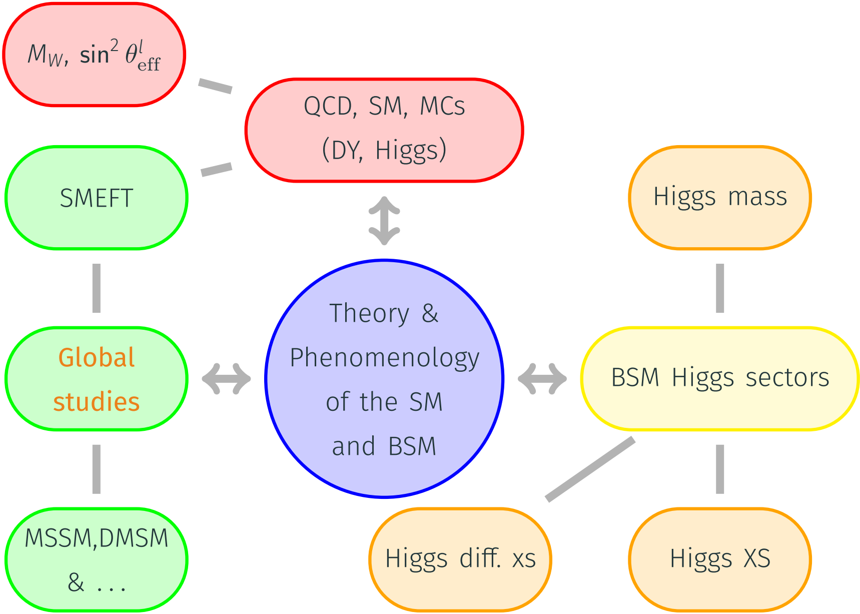
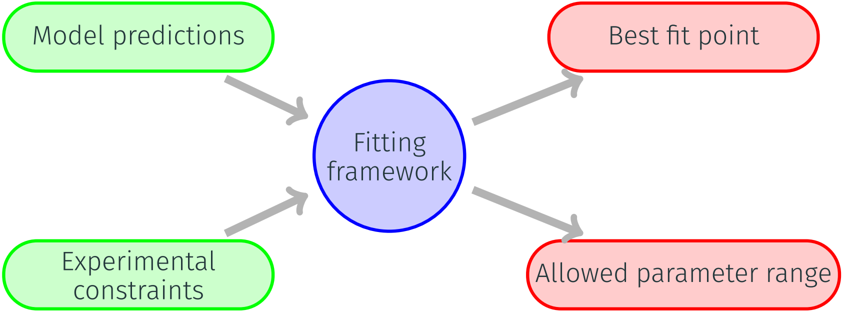

M_W, $\sin^2\theta^l_{\rm eff}$
QCD, SM, MCs (DY, Higgs)
SMEFT
Higgs mass
Theory & Phenomenology of the SM and BSM
Global studies
BSM Higgs sectors
MSSM,DMSM & . . .
Higgs diff. xs
Higgs XS

Global likelihood studies

Overview

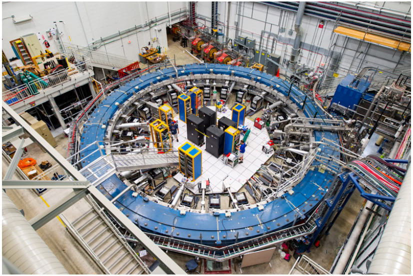
- Selection of a BSM physics model in light of specific interests (e.g. to explain DM, naturalness etc.), or SMEFT
- Global study means using the measurements coming from experiments at different scales, for instance direct searches at colliders, precision measurements, dark matter experiments etc. to determine the allowed regions of the parameter space
- With this approach one can cross-correlate different fields of research



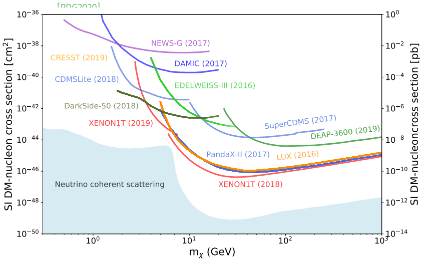
LHC constraints ... but not only

Indirect measurements

- $(g-2)_\mu$, 3.4σ discrepancy may be explained with relatively light new physics (e.g. $\mathcal{O}(100)$ GeV smuons)
- M_h, M_W and other EWPOs
- Flavor physics observables ($B_s \to \mu\mu$, $b \to s\gamma$, ...)



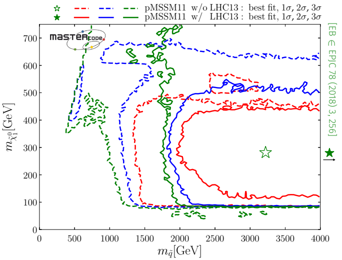
[$(g-2)_\mu$ collaboration website]

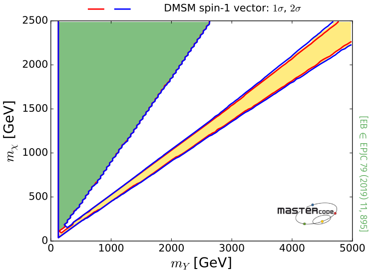


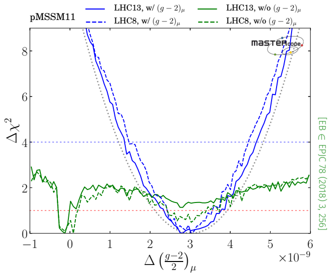
Dark Matter

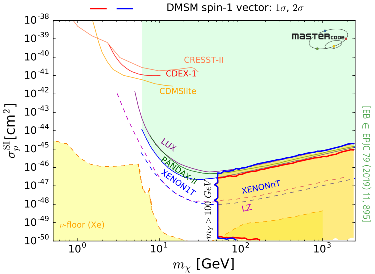
- Relic density constraint
- Strong constraint from direct detection experiment; indirect detection impact usually limited by large uncertainties

Outcome: new constraints and correlations









Fitmaker

The framework

- Python framework introduced in [Ellis et al. JHEP 04 (2021) 279]
- Used to perform a fit of Higgs, Electroweak, Higgs and top data using data from LHC Run 2
- Allows for a flexible implementations of constraints and various fit setups
- Fast analytical method for linear order fits; MCMC procedure to incorporate positivity priors in operator coefficients for specific BSM scenarios
- Available on Gitlab: https://gitlab.com/kenmimasu/fitrepo

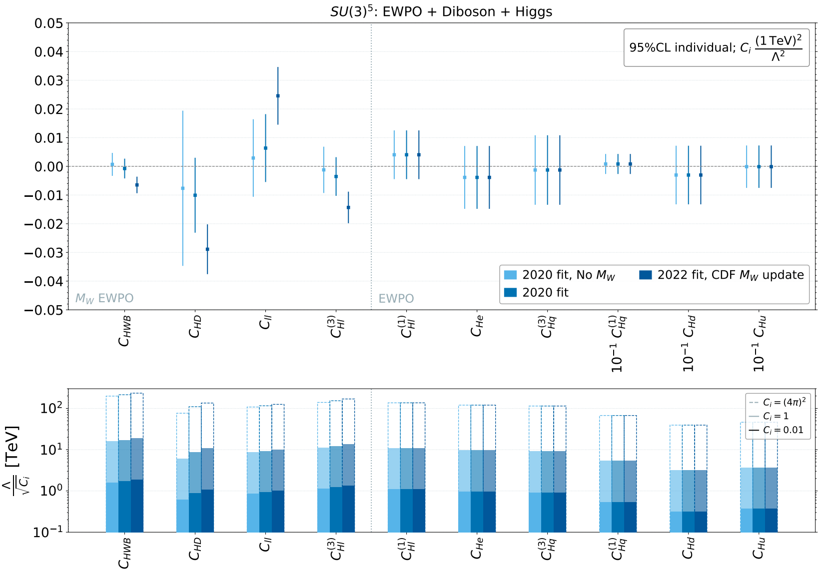
Fit strategy

- SMEFT predictions computed using MadGraph5_aMC@NLO with SMEFTsim and/or SMEFT@NLO
- Predictions used to extract the linear contribution a_i^X of a given Wilson coefficient

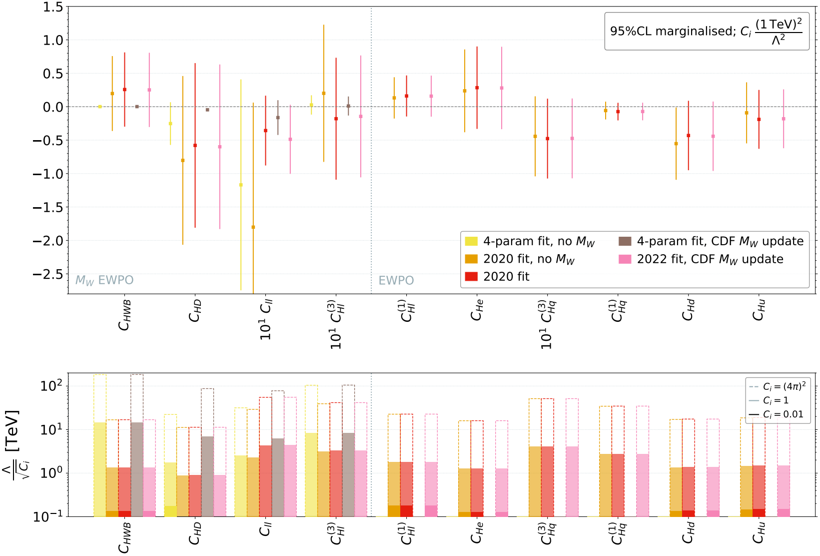
$$\mu_X \equiv \frac{X}{X_{SM}} = 1 + \sum_i a_i^X \frac{C_i}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

- No theory uncertainty on the SMEFT prediction, assumed to be subdominant w.r.t. the SM ones
- Quadratic dim-6 or dim-8 contributions neglected

Fit result – individual coefficients

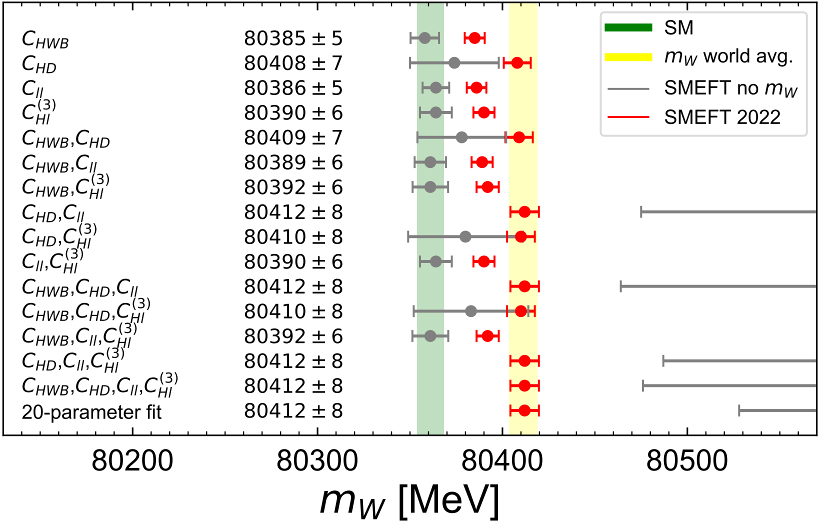


Fit result – marginalised coefficients



m_W – indirect determination vs measurment

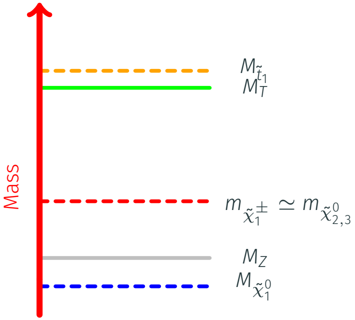
- All possible fits that include the four operators contributing to δm_W^2



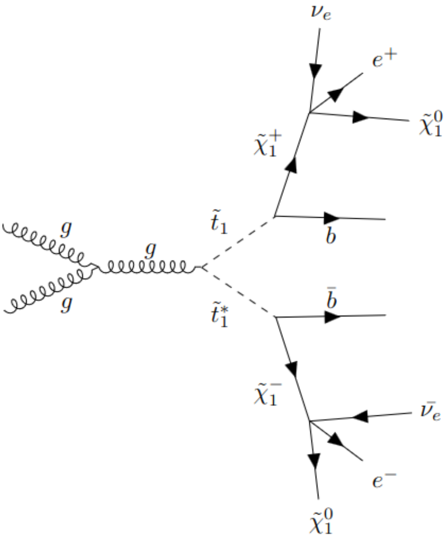
The scenario

The spectrum

- We consider a scenario with a light $\tilde{t}_1 \simeq \tilde{t}_R$
- Stop mass close to the top quark mass: $m_{\tilde{t}_1} \simeq M_T$
- Bino-like $\tilde{\chi}_1^0$ and a compressed spectrum of higgsino-like $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_{2,3}^0$
- The MSSM parameters are adjusted to keep the stop mass roughly constant as we vary the chargino (μ parameter) and the bino masses



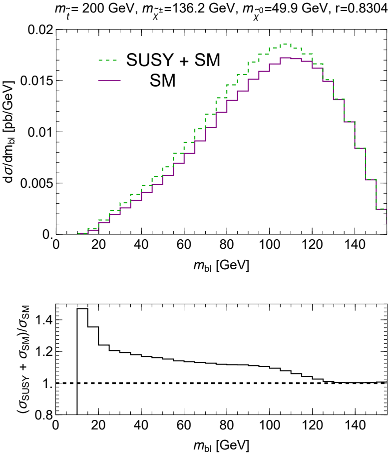
The signal



Stop-top contamination

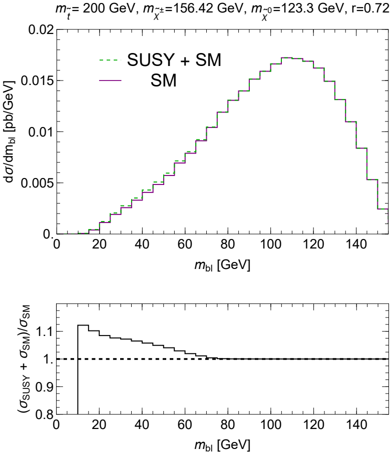
- The final state is similar to the top one
- $\tilde{\chi}_1^{\pm} \to W\tilde{\chi}_1^0 \to l + MET$
- W OS or not depending on the $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^0$ mass difference
- A similar signature could be obtained in the decay channel $\tilde{t}_1 \to t\tilde{\chi}_1^0$, which however is much strongly constrained

The m_{bl} distribution



Benchmark 1

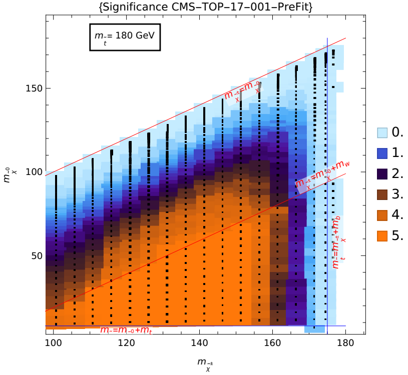
- Point allowed by `SModelS`
- $m_{\tilde{t}_1} \simeq 200 GeV$, $m_{\tilde{\chi}_1^{\pm}} \simeq$ 136 GeV, $m_{\tilde{\chi}_1^0} \simeq$ 50 GeV
- Significant effect that grows monoticallt as m_{bl} decreases



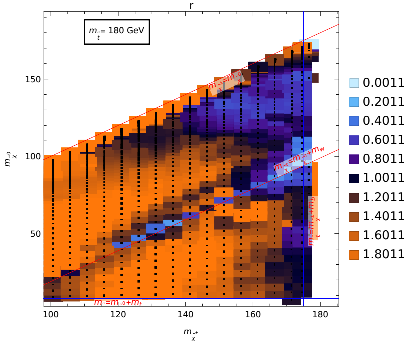
Benchmark 1

- Point allowed by `SModelS`
- $m_{\tilde{t}_1} \simeq 200 GeV$,
  $m_{\tilde{\chi}_1^{\pm}} \simeq$ 156 GeV,
  $m_{\tilde{\chi}_1^{0}} \simeq$ 132 GeV,
- Milder effect that grows monoticallt as m_{bl} decreases

Exclusion planes: $m_{\tilde{t}_1} = 180$ GeV



Uncertainties from [CMS, 1812.10505]



Exclusions from SModels, $r = \frac{\sigma(\text{signal})}{\sigma(UL)}$

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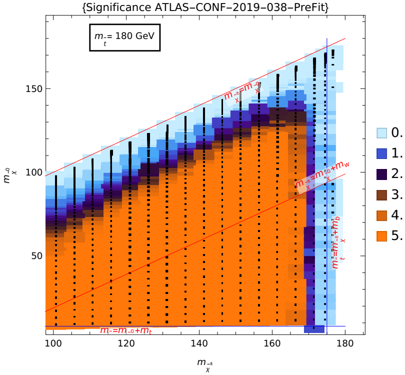
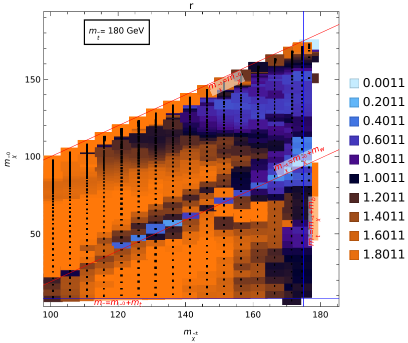


Uncertainties from [ATLAS-CONF-2019-03]



Exclusions from **SModels**, $r = \frac{\sigma(\text{signal})}{\sigma(UL)}$

Working group involvement

Working groups

- **LHCHWG** – theory convener of the MSSM subgroup; interaction with experimentalist. on various aspects of connected to MSSM higgs searches
- **DMWG** – contribution to the next white paper on DM t-channel model
- **ECFA** – At CERN, former representative for the Early Career Panel
- **ECFA** – Expert in the "HIGGS-TOP-EW and connection with LHC" (WG1-HTE) subgroup of the "ECFA e+e− Higgs/Top/EW Factory Study" working group; focus topic: two fermion final states
- **KUTS** – member, focus on precision calculations for BSM models
- Participation to the activities of the **EWWG**, and of the **reinterpretation forum**

IRN Terascale

International networks

- Member of the scientific committee of the IRN Terascale network (http://terascale.in2p3.fr/)
- Responsible of the Laboratori Nazionali di Frascati node