Constraining BSM Higgs sectors at the LHC

Henning Bahl

DESY, Hamburg

PRC pre-meeting

7.4.2020, DESY Hamburg

Introduction

Specific model: constraining the MSSM Higgs sector

Effective model: constraining the Higgs $\mathcal{CP}$ properties

Conclusions

Introduction

Specific model: constraining the MSSM Higgs sector

Effective model: constraining the Higgs $\mathcal{CP}$ properties

Conclusions

Motivation

Current situation:

- no direct evidence for BSM physics at LHC yet,
- most known particles studied intensively confirming SM predictions.

Where to look for new physics? Obvious candidate: the **Higgs boson**

- Higgs boson properties still leave room for deviations from SM.
- Higgs boson can be coupled easily to BSM particles,
- Why should there be only one scalar particle?
  $\rightarrow$ Searches for additional Higgs bosons.

How much do we know already about the discovered Higgs boson?
How tightly constraint are extended Higgs sectors already?

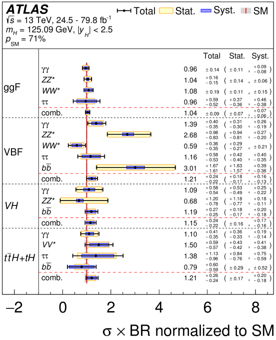
Higgs measurements: examples

- Higgs mass: [Aad et al.,1503.07589]

$$M_h^{\rm exp} = 125.08 \pm 0.21\ (\text{stat.}) \pm 0.11\ (\text{sys.})\ \text{GeV}$$

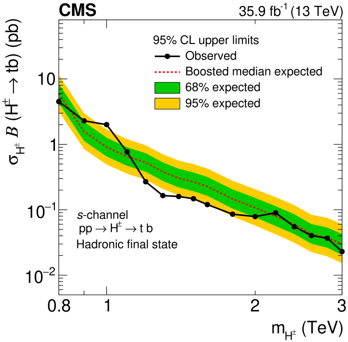
- Coupling measurements:

[1909.02845,ATLAS]



- Additional Higgs bosons:

[2001.07763,CMS]



→ Interpret constraints in **specific** or **effective** model.

Introduction

Specific model: constraining the MSSM Higgs sector

Effective model: constraining the Higgs $\mathcal{CP}$ properties

Conclusions

Interpretation in specific model: MSSM

Reminder

2 Higgs doublets $\rightarrow$ $\mathcal{CP}$-even h, H; $\mathcal{CP}$-odd A; charged $H^{\pm}$.

For constraining the model, we need not only

- precise **experimental measurements**,

but also

- precise **theoretical predictions**.

$\rightarrow$ discuss SM-like Higgs mass as example.

Prediction of SM-like Higgs mass

Special feature of the MSSM

Mass of SM-like Higgs, M_h, is calculable in terms of model parameters
$\Rightarrow$ can be used as a precision observable.

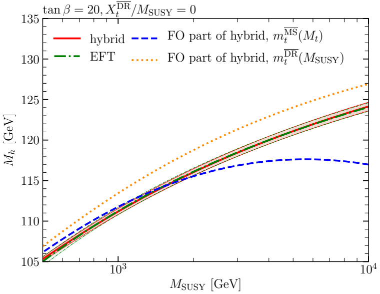
For the calculation of higher-order corrections, three approaches are used:

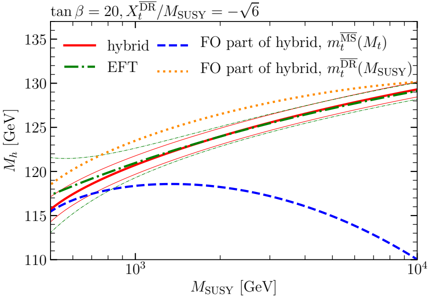
- Fixed-order approach (up to N^{3}LO) $\rightarrow$ precise for low SUSY scales,
- EFT approach (up to N^{3}LL) $\rightarrow$ precise for high SUSY scales,
- hybrid approach: combine fixed-order and EFT approaches
  $\rightarrow$ precise for low and high SUSY scales.

(all approaches implemented into public code `FeynHiggs`)

Comparison of approaches [HB,Heinemeyer,Hollik,Weiglein,1912.04199]

Single-scale scenario with all non-SM particles at M_{SUSY}





"Rule of thumb"

Remaining theoretical uncertainties (for $\overline{\mathrm{DR}}$ stop input parameter):
$X_t/M_{\mathrm{SUSY}} = 0 \;\rightarrow\; \Delta M_h \sim\; 0.5$ GeV,
$X_t/M_{\mathrm{SUSY}} = \sqrt{6} \;\rightarrow\; \Delta M_h \sim\; 1$ GeV

Slightly higher for OS stop input parameters.

What happens in non-degenerate scenarios?

Large hierarchy between SUSY particles $\rightarrow$ EFT tower needed.

Available EFTs (NNLL accuracy):

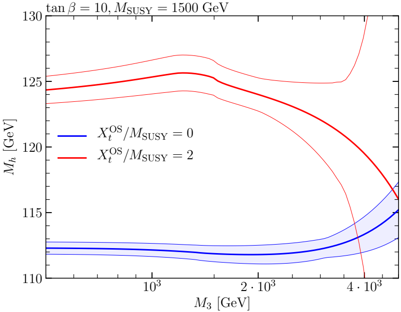
- SM (+ EWinos, + gluino),
- THDM (+ EWinos, + gluino)

$\rightarrow$ EFT tower with up to four EFTs (all matched at the 2-loop level)

For most phenomenological interesting scenarios, all large logs are resummed $\Rightarrow$ theoretical uncertainty under control.

One exception: gluinos are heavier than stops

Increasingly relevant due to tightening LHC gluino limits.



Large uncertainty due to terms enhanced by gluino mass, M_3, appearing at the two-loop level in EFT calculation. Needed EFT, MSSM without gluino, complicated...

Solution: Absorb power-enhanced terms into renormalization scheme [HB,Sobolev,Weiglein,1912.10002]

Use $\overline{\text{MDR}}$ instead of $\overline{\text{DR}}$ in EFT,

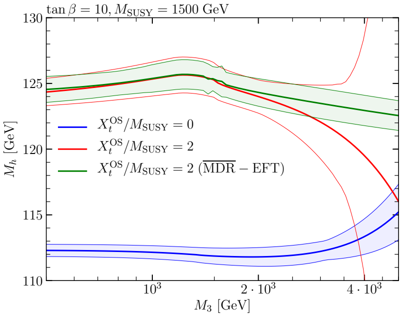
$$\left(m_{\tilde{t}_{L,R}}^{\overline{\text{MDR}}}\right)^2 = \left(m_{\tilde{t}_{L,R}}^{\overline{\text{DR}}}\right)^2 \left[1 + \frac{\alpha_s}{\pi} C_F \frac{|M_3|^2}{m^2_{\tilde{t}_{L,R}}} \left(1 + \ln\frac{Q^2}{|M_3|^2}\right)\right],$$

$$X_t^{\overline{\text{MDR}}}(Q) = X_t^{\overline{\text{DR}}}(Q) - \frac{\alpha_s}{\pi} C_F M_3 \left(1 + \ln\frac{Q^2}{|M_3|^2}\right),$$

resums all $\mathcal{O}(\alpha_s^n M_3^{2n}, \alpha_s^n M_3^n)$ terms.

$\Downarrow$

Drastically reduced uncertainty.



Combine all constraints: Higgs benchmark scenarios

[Bagnaschi,HB,Fuchs,Hahn,Heinemeyer,Liebler,Patel,Slavich,Stefaniak,Wagner,Weiglein,1808.07542],
[HB,Liebler,Stefaniak,1901.05933],[HB,Bechtle,Liebler,Heinemeyer,Stefaniak,Weiglein,to appear]

Consider combined MSSM Higgs sector constraints from

- searches for BSM Higgs bosons,
- measurements of SM-like Higgs boson,

$$\Downarrow$$

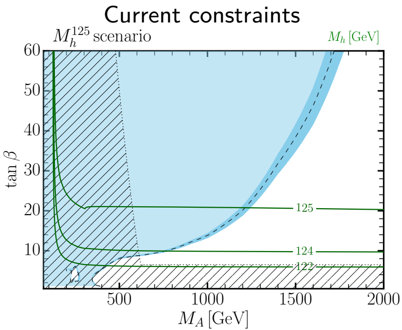
interpret them in benchmark scenarios with only two free parameters:

- Typically presented in M_A-$\tan\beta$ plane,
- use Higgs mass constraint to fix stop mass scale such that SM-like 125 GeV Higgs exist,
- choose scenarios with different LHC phenomenology.

Tools used: `FeynHiggs`, `SusHi`, `HiggsBounds`, `HiggsSignals`

Example scenario: M_h^{125} scenario

- all SUSY particles at the TeV scale → similar to type-II THDM with SUSY inspired Higgs couplings

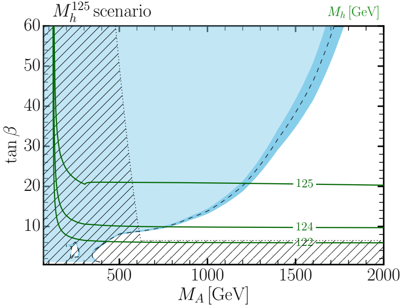


- Blue: Excluded by direct searches for heavy Higgs bosons,
- hashed: Excluded by SM-like Higgs signal strengths / mass.

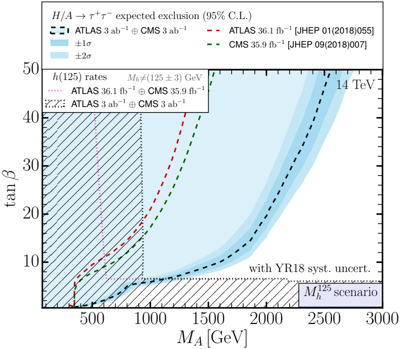
Example scenario: M_h^{125} scenario

- all SUSY particles at the TeV scale → similar to type-II THDM with SUSY inspired Higgs couplings

Current constraints



HL-LHC projection



- Blue: Excluded by direct searches for heavy Higgs bosons,
- hashed: Excluded by SM-like Higgs signal strengths / mass.

Introduction

Specific model: constraining the MSSM Higgs sector

Effective model: constraining the Higgs $\mathcal{CP}$ properties

Conclusions

What do we know about Higgs $\mathcal{CP}$ properties so far?

Joint project with DESY ATLAS group, [HB,Bechtle,Heinemeyer,Katzy,Klingl,Peters,Saimpert,Stefaniak,Weiglein,to appear]

- Focus on top Yukawa coupling,
- global fit to all Higgs measurements using `HiggsSignals` (including uncertainty correlations),
- also include kinematic information,
- interpret measurements in effective model,

$$\mathcal{L}_{\text{yuk}} = -y_t^{\text{SM}}\bar{t}\,(c_t + i\gamma_5\tilde{c}_t)\,tH,$$

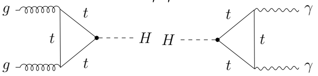
- can allow for additionally free c_V (rescaling HVV couplings), κ_g (rescaling $gg \to H$), κ_γ (rescaling $H \to \gamma\gamma$).

Consider three models:

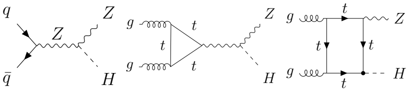
1. $(c_t, \tilde{c}_t)$ free,
2. $(c_t, \tilde{c}_t, c_V)$ free,
3. $(c_t, \tilde{c}_t, c_V, \kappa_g, \kappa_\gamma)$ free

Relevant processes

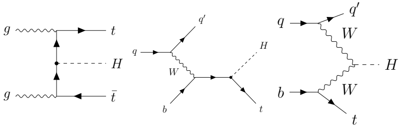
$gg \to H$ & $H \to \gamma\gamma$



ZH production

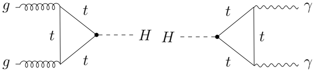


ttH and tH production

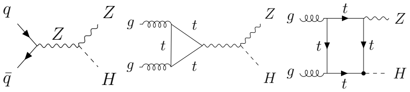


Relevant processes

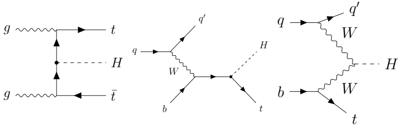
$gg \to H$ & $H \to \gamma\gamma$

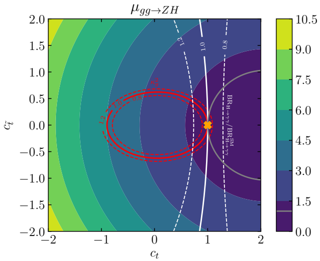


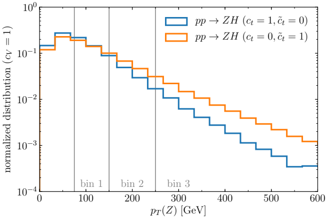
ZH production



ttH and tH production

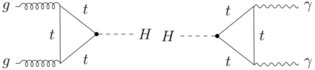




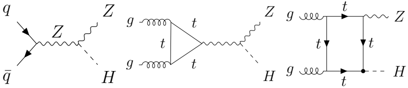


Relevant processes

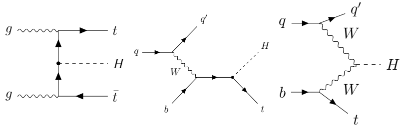
$gg \to H$ & $H \to \gamma\gamma$

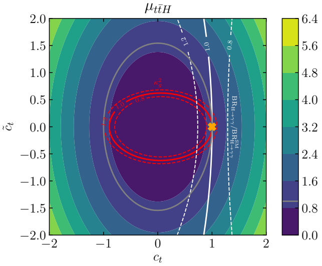


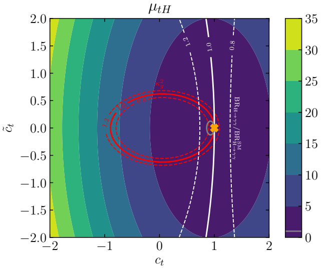
ZH production

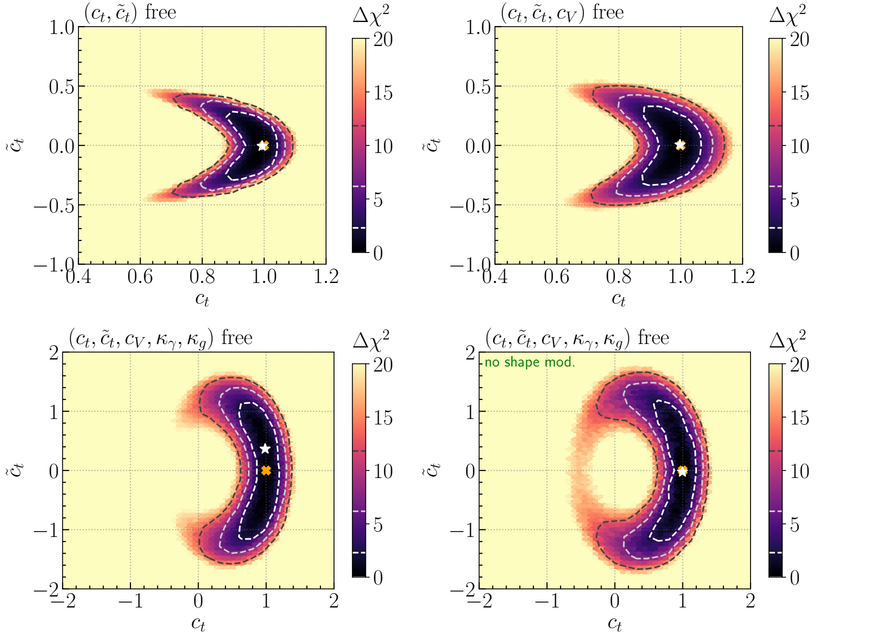


ttH and tH production

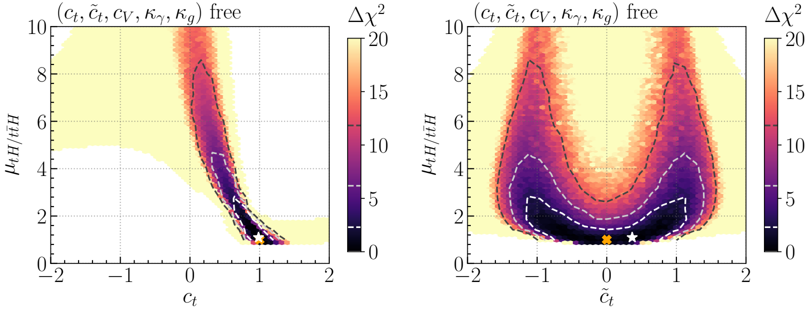







$(c_t, \tilde{c}_t)$ free
$(c_t, \tilde{c}_t, c_V)$ free
$(c_t, \tilde{c}_t, c_V, \kappa_\gamma, \kappa_g)$ free
$(c_t, \tilde{c}_t, c_V, \kappa_\gamma, \kappa_g)$ free
no shape mod.
$\Delta\chi^2$
c_t
$\tilde{c}_t$

- Best fit-point very close to SM,
- most general model still leaves room for sizeable $\mathcal{CP}$-odd coupling,
- how can we constrain this model further?



$\rightarrow$ Disentangling *tH* and *ttH* is promising future direction.

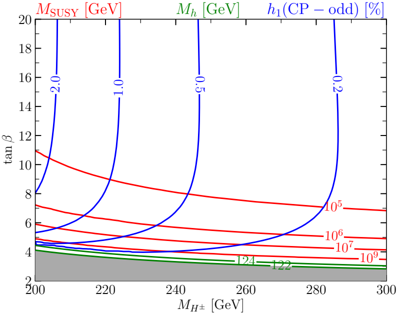
MSSM: $\mathcal{CP}$-odd component of the SM-like Higgs boson

[HB,Murphy,Rzehak,to appear]

Predictions based on complex THDM EFT of the MSSM combined with 2L fixed-order calculation.

Large $\mathcal{CP}$-odd component requires

- Large mixing with $\mathcal{CP}$-odd A boson
  - imaginary parts of couplings have to be large
  - $\tan\beta$ and $M_{H^\pm}$ must be small
- large SUSY scale required to ensure $M_h \sim 125$ GeV $\rightarrow$ $\mathcal{CP}$-mixing decouples



Potential discovery of $\mathcal{CP}$-odd component at the LHC hard to explain within the MSSM.

Introduction

Specific model: constraining the MSSM Higgs sector

Effective model: constraining the Higgs $\mathcal{CP}$ properties

Conclusions

Conclusions

LHC Higgs measurements can be interpreted in

- specific models: MSSM
  - SM-like Higgs mass as precision observable,
  - combining fixed-order and EFT calculations $\to$ theoretical uncertainty ~ 1 GeV,
  - combined with Higgs searches and coupling measurements in Higgs benchmark scenarios.
- effective models: $\mathcal{CP}$ properties of the top-Yukawa coupling
  - Strong constraints from $gg \to H$ and $H \to \gamma\gamma$,
  - sizeable $\mathcal{CP}$-odd coupling allowed if κ_g and κ_γ are varied freely,
  - future disentanglement of ttH and tH could further constraint $\mathcal{CP}$-odd coupling.

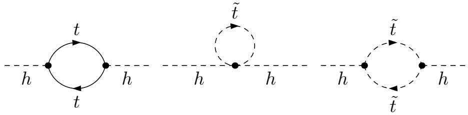
Conclusions

LHC Higgs measurements can be interpreted in

- specific models: MSSM
  - SM-like Higgs mass as precision observable,
  - combining fixed-order and EFT calculations $\rightarrow$ theoretical uncertainty ~ 1 GeV,
  - combined with Higgs searches and coupling measurements in Higgs benchmark scenarios.
- effective models: $\mathcal{CP}$ properties of the top-Yukawa coupling
  - Strong constraints from $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$,
  - sizeable $\mathcal{CP}$-odd coupling allowed if κ_g and κ_γ are varied freely,
  - future disentanglement of ttH and tH could further constraint $\mathcal{CP}$-odd coupling.

Thanks for your attention!

Fixed-order techniques



$$M_h^2 = m_h^2 + \frac{6 y_t^4}{(4\pi)^2} v^2 \left[\ln \frac{M_{\tilde{t}}^2}{M_t^2} + \left(\frac{X_t}{M_{\tilde{t}}}\right)^2 - \frac{1}{12}\left(\frac{X_t}{M_{\tilde{t}}}\right)^4 \right] + \dots$$

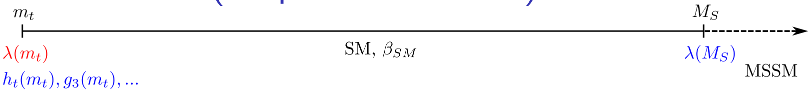
- Stop mass scale $M_{\tilde{t}} = \sqrt{M_{\tilde{t}_1} M_{\tilde{t}_2}}$,
- status: $\mathcal{O}(\text{full 1L}, \alpha_s(\alpha_b + \alpha_t), (\alpha_b + \alpha_t)^2, \alpha_s^2 \alpha_t)$.

  [1708.05720,1802.09886,1901.03651,1910.02094,...]

Advantages and disadvantages:

+ Precise for low SUSY scales,
− but for high scales $\ln(M_{\tilde{t}}^2 / M_t^2)$ terms spoil convergence of perturbative expansion.

EFT calculation (simplest framework)



- Integrate out all SUSY particles $\to$ SM as EFT,
- Higgs self-coupling fixed at matching scale

$$\lambda(M_{\text{SUSY}}) = \frac{1}{4}(g^2 + g_y^2) + \frac{6y_t^4}{(4\pi)^2}\left[\left(\frac{X_t}{M_{\text{SUSY}}}\right)^2 - \frac{1}{12}\left(\frac{X_t}{M_{\text{SUSY}}}\right)^4\right],$$

- run Higgs self-coupling down to electroweak scale,
- calculate Higgs mass: $M_h^2 = \lambda(M_t)v^2 + \ldots,$
- status: full LL+NLL, $\mathcal{O}(\alpha_s, \alpha_t, \alpha_b)$ NNLL, partial N^{3}LL.

  [1703.08166,1807.03509,1807.03509,1908.01670,...]

Advantages and disadvantages:

+ Precise for high SUSY scales (logs resummed),
− but for low scales $\mathcal{O}(M_t/M_{\text{SUSY}})$ terms are missed if higher-dimensional operators are not included.

How to deal with intermediary SUSY scales?

For sparticles in the LHC range, both logs and suppressed terms might be relevant. We could try to improve

- fixed-order calculation $\rightarrow$ need to calculate more three- and two-loop corrections,
- EFT calculation $\rightarrow$ need to include higher-dimensional operators into calculation.

or ...

$\downarrow$

Hybrid approach

Combine both approaches to get precise results for both regimes

Such an approach is implemented e.g. in `FeynHiggs`

[HB,Hahn,Heinemeyer,Hollik,Paßehr,Rzehak,Weiglein;1312.4937,1608.01880,1706.0034,1812.06452]

other approaches: 1609.00371,1703.03267,1710.03760,1910.03595;

other codes: `FlexibleEFTHiggs`, `SARAH/SPheno`

Procedure in FeynHiggs

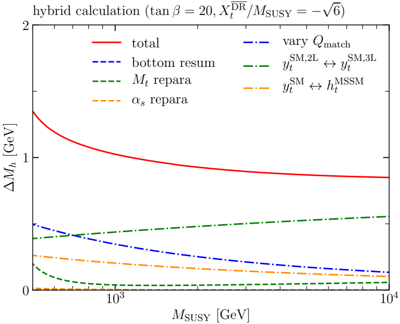
1. Calculation of diagrammatic fixed-order self-energies $\hat{\Sigma}_{hh}$
2. Calculation of EFT prediction $\lambda(M_t)v^2$
3. Add non-logarithmic terms contained in fixed-order result and the logarithms contained in EFT result

$$\hat{\Sigma}_{hh}(m_h^2) \longrightarrow \left[\hat{\Sigma}_{hh}(m_h^2)\right]_{\text{nolog}} - \left[v^2\lambda(M_t)\right]_{\text{log}}$$

In practice, this is achieved by using subtraction terms.

Additional complication:
FH by default uses OS scheme, for EFT calculation however $\overline{\text{DR}}$ parameters needed (i.e. $X_t^{\overline{\text{DR}}}$)
$\rightarrow$ 1L log only conversion of X_t sufficient

Remaining uncertainties – individual sources



Uncertainty estimate dominated by:

- Uncertainty from higher order threshold corrections:
  - vary matching scale between SM and MSSM,
  - reexpress treshold correction in terms of h_t^{MSSM} instead of y_t^{SM}.
- Uncertainty of SM input couplings:
  - $y_t(M_t)$ extracted at the 2- or 3-loop level out of OS top mass.

M_h^{125} scenario – ILC projections