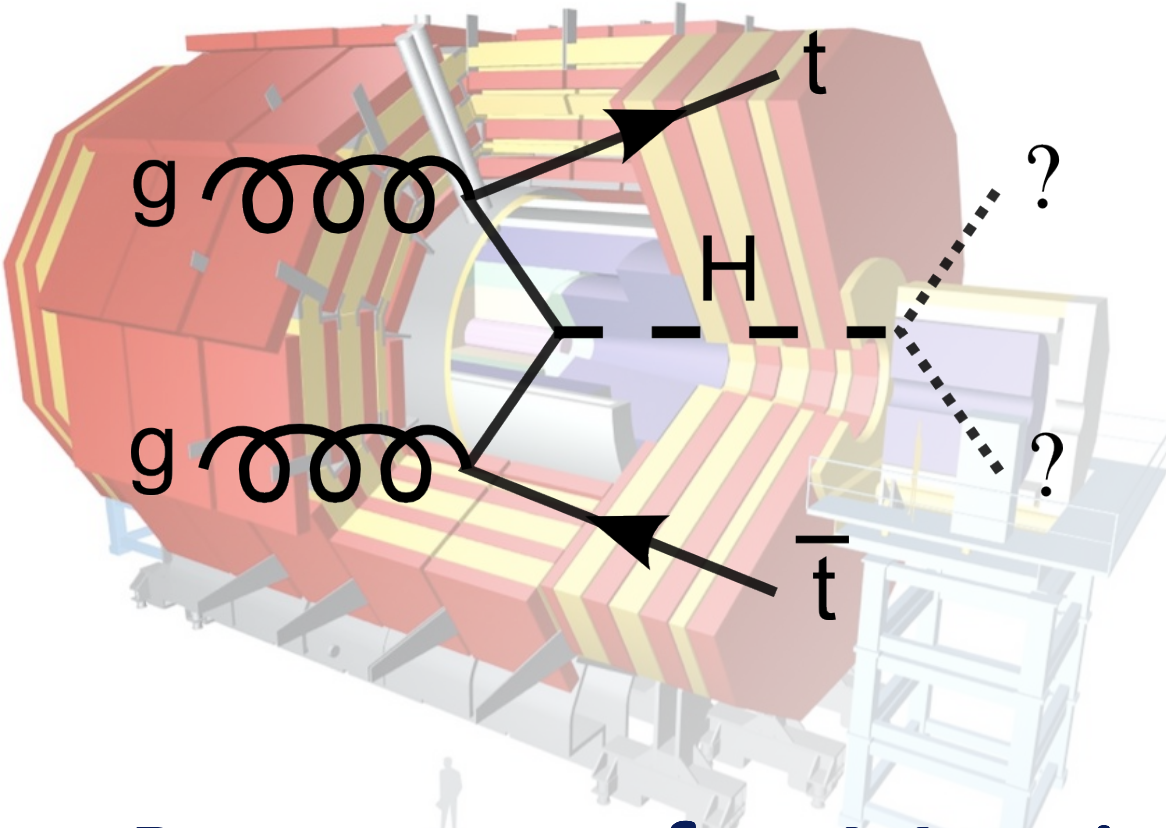

$$t\bar{t}(H \rightarrow b\bar{b})$$

$$t\bar{t}(H \rightarrow \text{inv.})$$

Prospects for Matrix Element-based Analyses in tt+X Topologies

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Outline

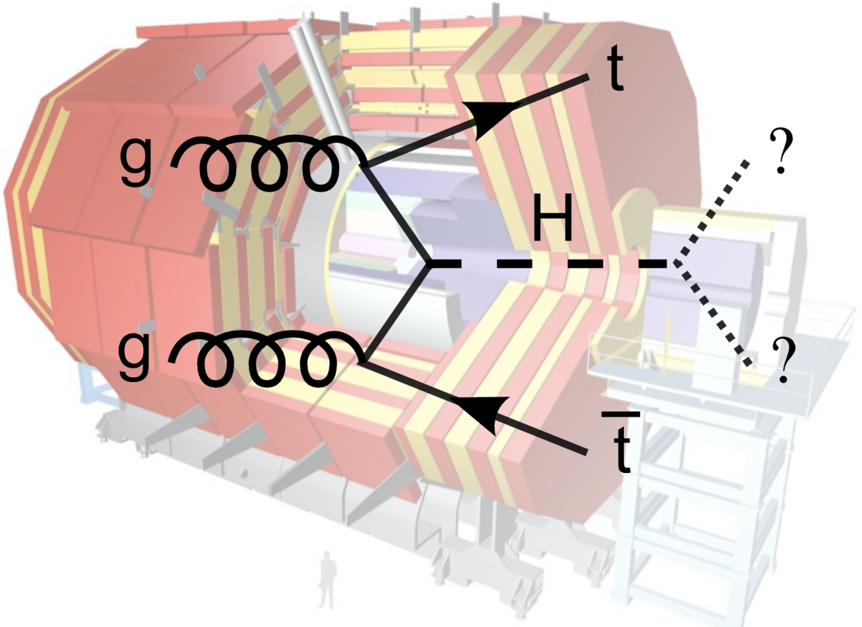
disclaimer: **no results!**
discussion on plans is welcome

- state-of-the-art: ttH @ CMS

- methodology
  - introduction: matrix element method
  - application to $\mathrm{t\bar{t}(H \rightarrow b\bar{b})}$

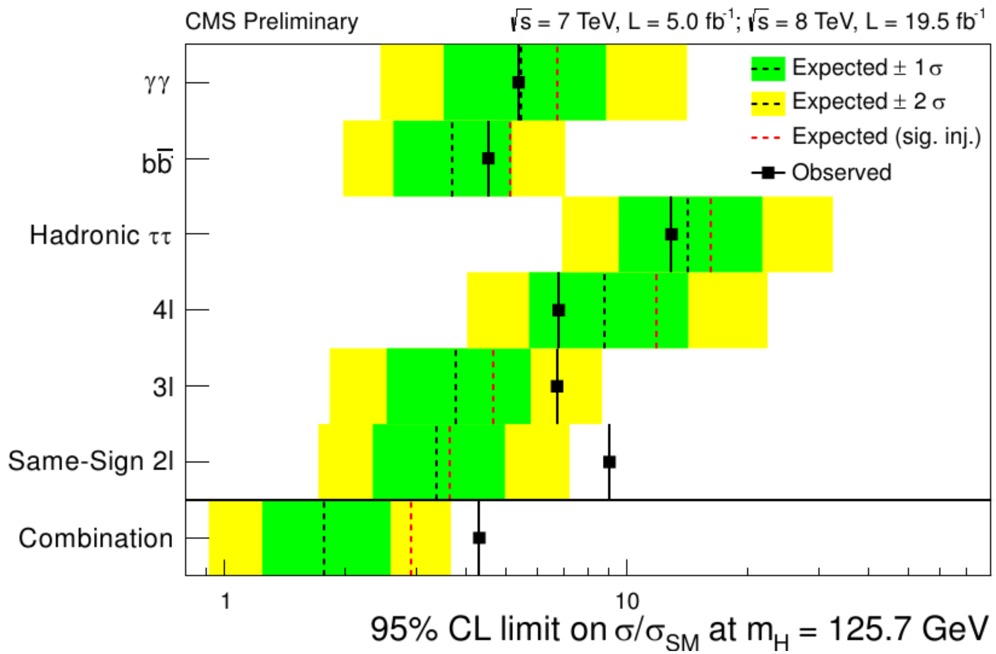
- further analysis plans: $\mathrm{t\bar{t}(H \rightarrow inv.)}$
  - motivation
  - review of LHC results
  - review of other experiments
  - goals

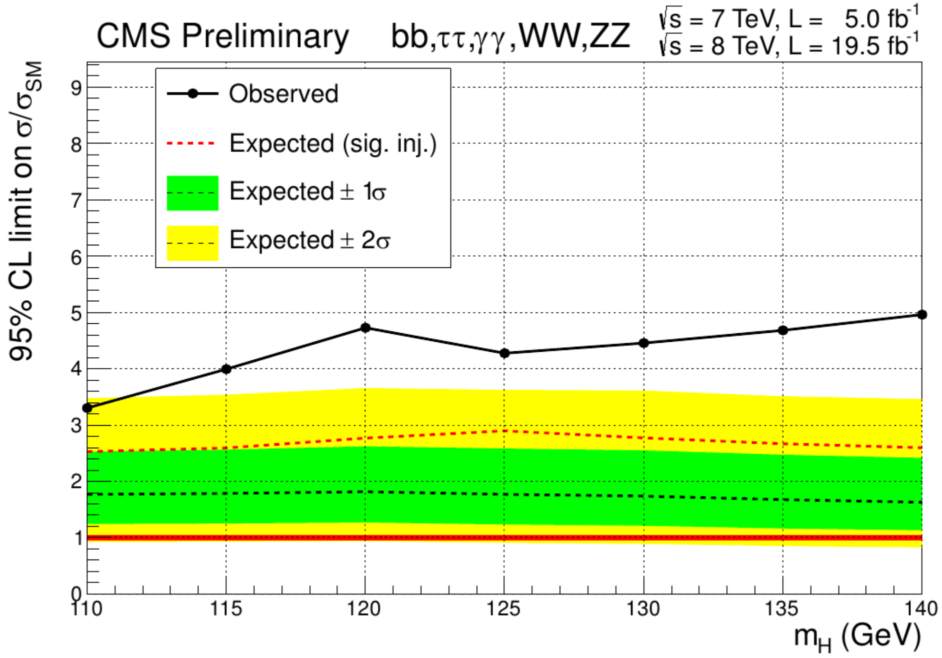
- discussion



State-of-the-Art: ttH @ CMS

- combination





→ exclude $\frac{\sigma_{\mathrm{ttH}}}{\sigma_{\mathrm{ttH}}^{\mathrm{SM}}} > 4.3\ (1.8\ \mathrm{exp.})$

CMS Collaboration, *Search for Higgs Boson Production in Association with a Top-Quark Pair and Decaying to Bottom Quarks, Photons, or Leptons*, to be published

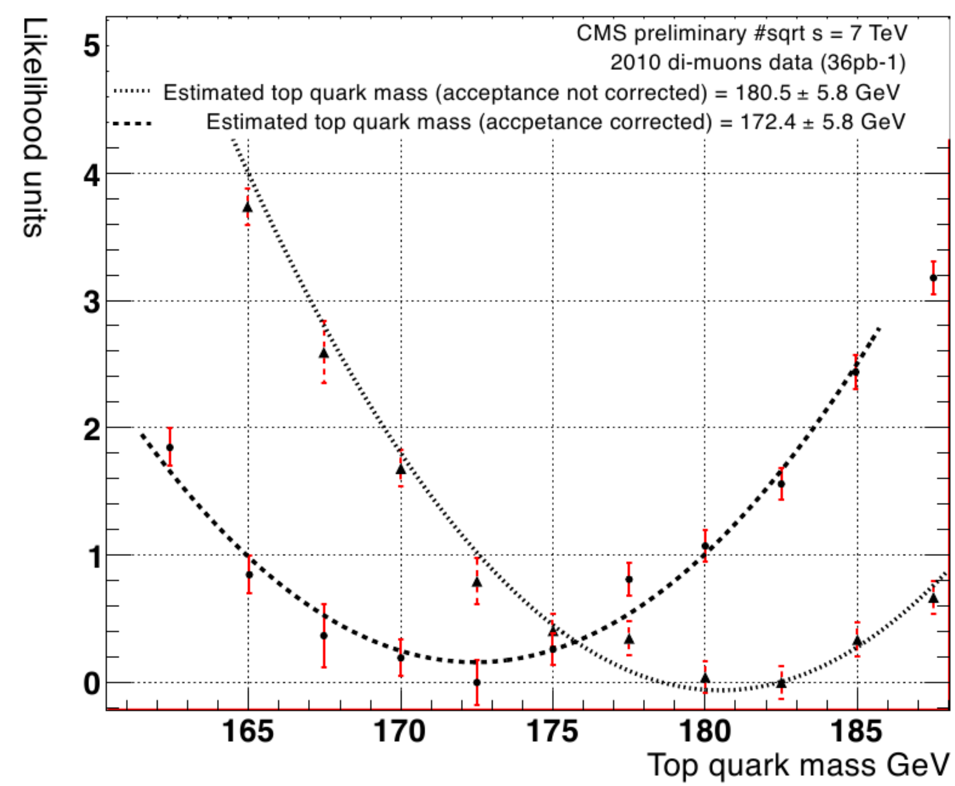
Matrix Element-based Analyses

$$P(\vec{x};\vec{\alpha}) = \underbrace{\frac{1}{\sigma^{obs}}\frac{1}{N}}_{\text{normalization}} \cdot \underbrace{\int d\varphi_y}_{\text{integration over ME phase space \& PDF}} \cdot \underbrace{|M(\vec{y})|^2}_{\text{matrix element}} \cdot \underbrace{W(\vec{y}\rightarrow\vec{x})}_{\text{mapping detector effects (transfer function)}}$$

probability: $P(\vec{x};\vec{\alpha})$

- in a nut-shell...
  - event-by-event probability through matrix elements feed with event kinematics
    - construct discriminator
    - scan model parameter
  - first application at Tevatron for top quark mass measurement
  - method in "exploration phase"
    - active development of new tools
    - community workshops (LLN May '13, Zurich Jan '14)

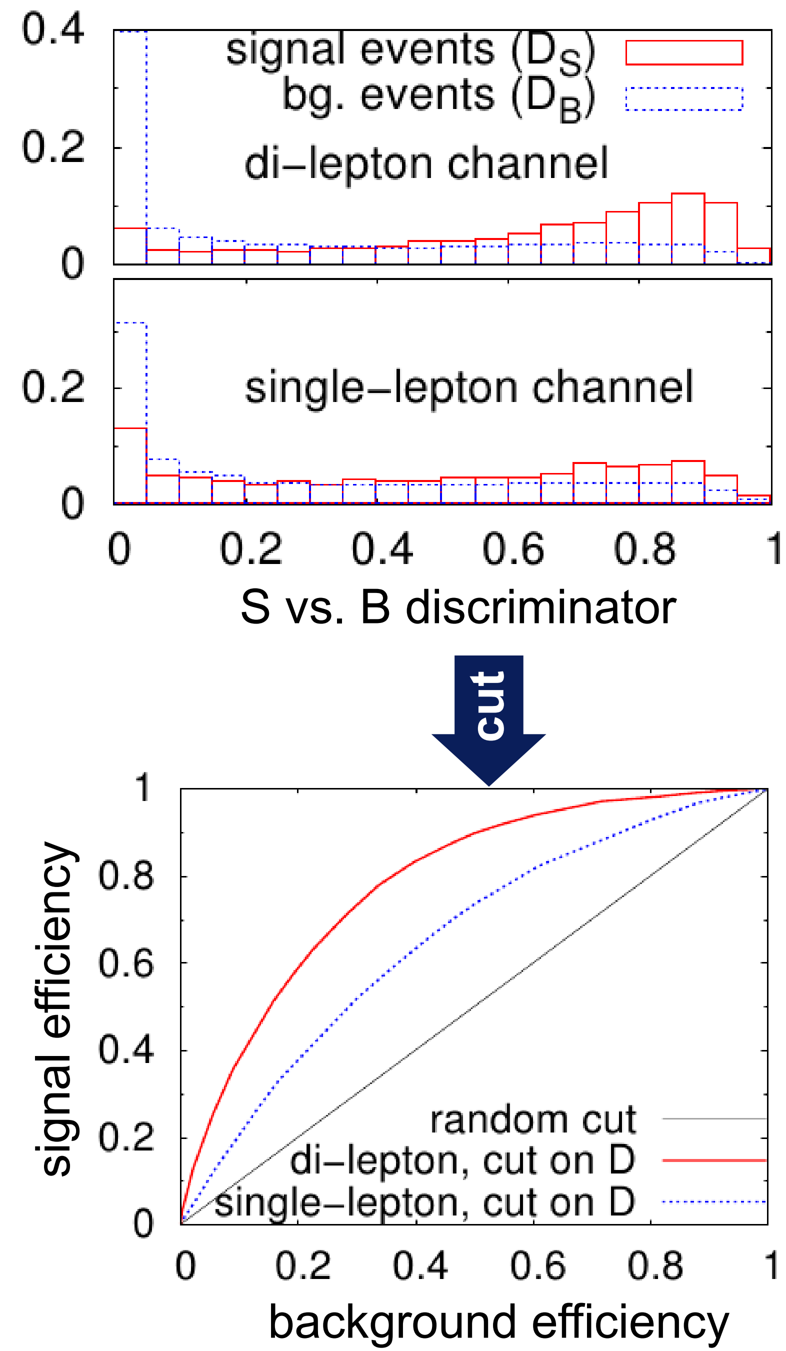
from Arnaud Pin's thesis (UCL) with first CMS data:



MEM in Action

- utilizing the matrix element method
  - proof of principle: pheno-study $t\bar{t}(H \to b\bar{b})$ [1]
    - considered background: $t\bar{t} + \text{jets}$
    - demonstrates reasonable performance
    - handles final state with 2 neutrinos well
  - $t\bar{t}(H \to b\bar{b})$ @ CMS [2]
    - talk by Lorenzo Bianchini on 8.1.14 at MEM workshop in Zurich
    - confirms proof of principle with own implementation
    - complex strategy to deal with out-of-acceptance particles, (e.g. 1 final parton missing & 1st add. jet selected)
  - my idea: $t\bar{t}(H \to \text{inv.})$

    see rest of slides...



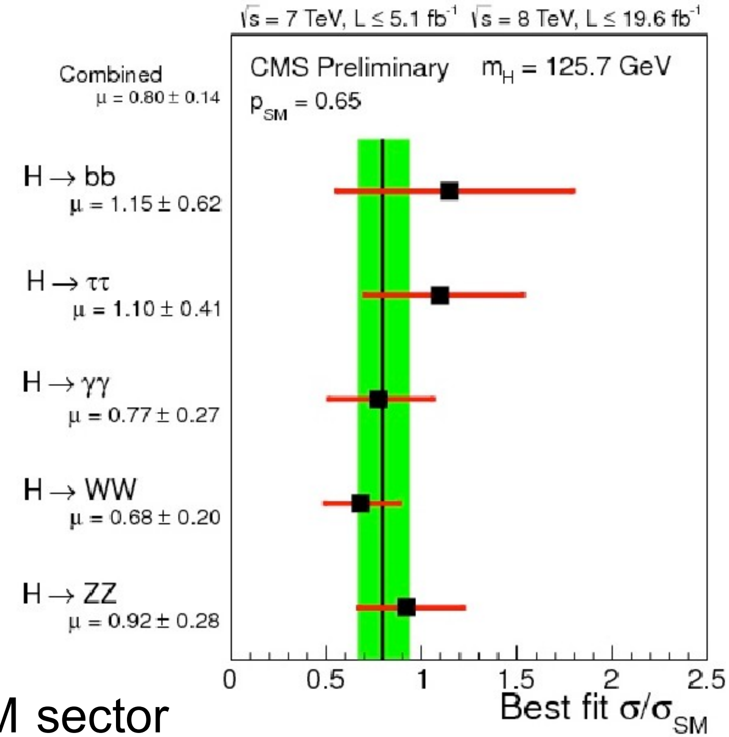
[1] P. Artoisenet et. al., *Unravelling tth via the matrix element method*, Phys.Rev.Lett. 111 (2013) 091802, arXiv:1304.6414 [hep-ph]
[2] https://indico.cern.ch/getFile.py/access?contribId=14&resId=0&materialId=slides&confId=280658

H125 & the incomplete theory

current LHC data → comprehensive picture of H125 production & decay

BUT what about...

naturalness, hierarchy problem, dark matter,...



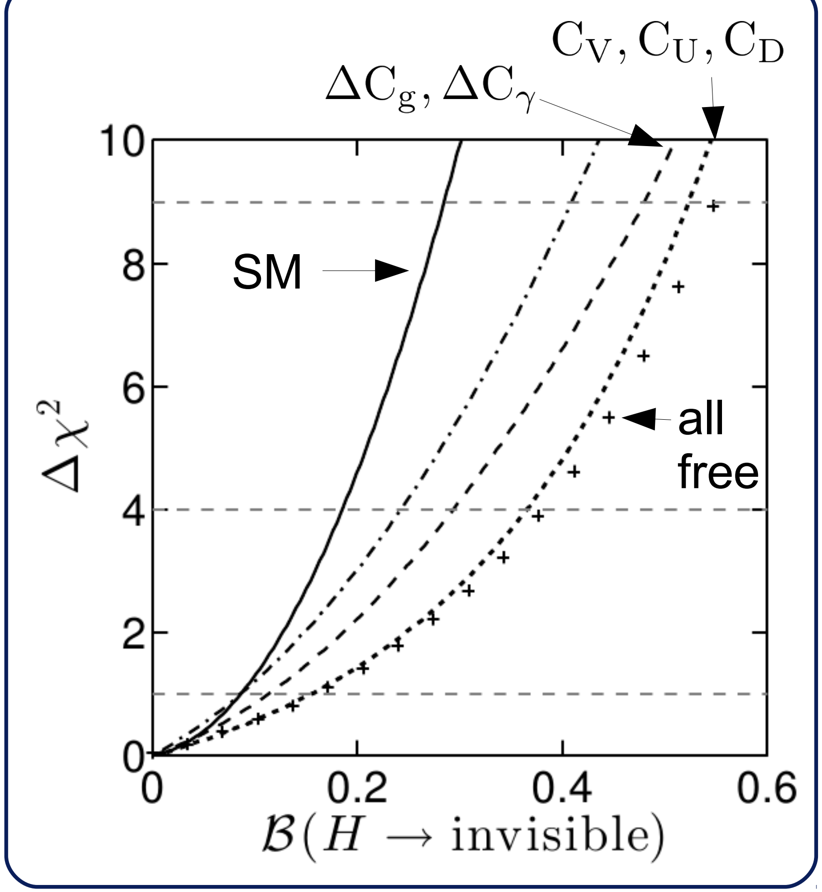
- dark matter
  - no evidence of SM-DM interactions yet
    - → DM decoupled from SM
    - → only a mediator (Higgs?) acts between SM & DM sector

- search for $\mathrm{H} \to \mathrm{inv.}$
  - BSM Higgs with exotic decay e.g. SUSY, graviscalars, ...
  - currently: only invisible Higgs decays in association with vector bosons probed
    - → ttH provides complementary experimental & theoretical phase space

- What $\mathrm{BR}(\mathrm{H} \to \mathrm{inv.})$ can be expected?

Limits on $\mathrm{BR}(\mathrm{H} \to \mathrm{inv.})$

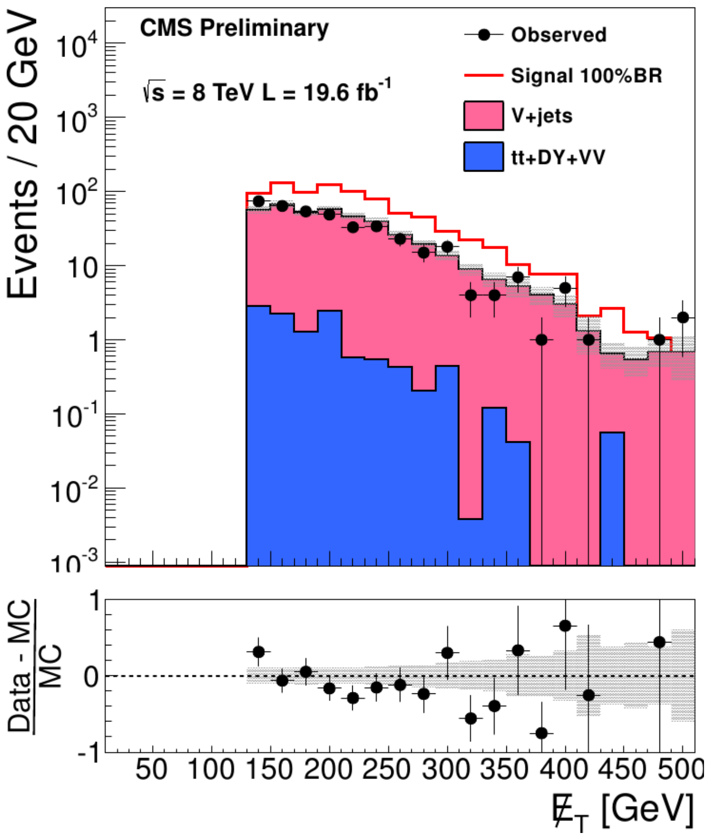
- global fit: $\mathcal{L} = g\left[\boxed{C_V}\left(M_W W_\mu W^\mu + \frac{M_Z}{\cos\theta_W} Z_\mu Z^\mu\right) - \boxed{C_U}\frac{m_t}{2M_W}\bar{t}t - \boxed{C_D}\frac{m_b}{2M_W}\bar{b}b - \boxed{C_D}\frac{m_\tau}{2M_W}\bar{\tau}\tau\right] H$
  - free parameters:
    - coupling to vector bosons $\mathrm{C_V}$
    - coupling to fermions $\mathrm{C_U, C_D}$
    - 1-loop couplings $\Delta\mathrm{C_g}, \Delta\mathrm{C_\gamma}$
  - input:
    - results from ATLAS, CMS & Tevatron
    - channels: $\mathrm{H} \to \gamma\gamma,\ \mathrm{H} \to \mathrm{ZZ},\ \mathrm{H} \to \mathrm{WW}$
      $\mathrm{H} \to \mathrm{b\bar{b}},\ \mathrm{H} \to \tau^+\tau^-,\ \mathrm{ZH} \to \mathrm{l^+l^-} + \mathrm{inv.}$
  - results @ 95 CL.
    - allow only SM couplings: $\mathrm{BR}(\mathrm{H} \to \mathrm{inv.}) < 19\%$
    - all couplings free: $\mathrm{BR}(\mathrm{H} \to \mathrm{inv.}) < 38\%$

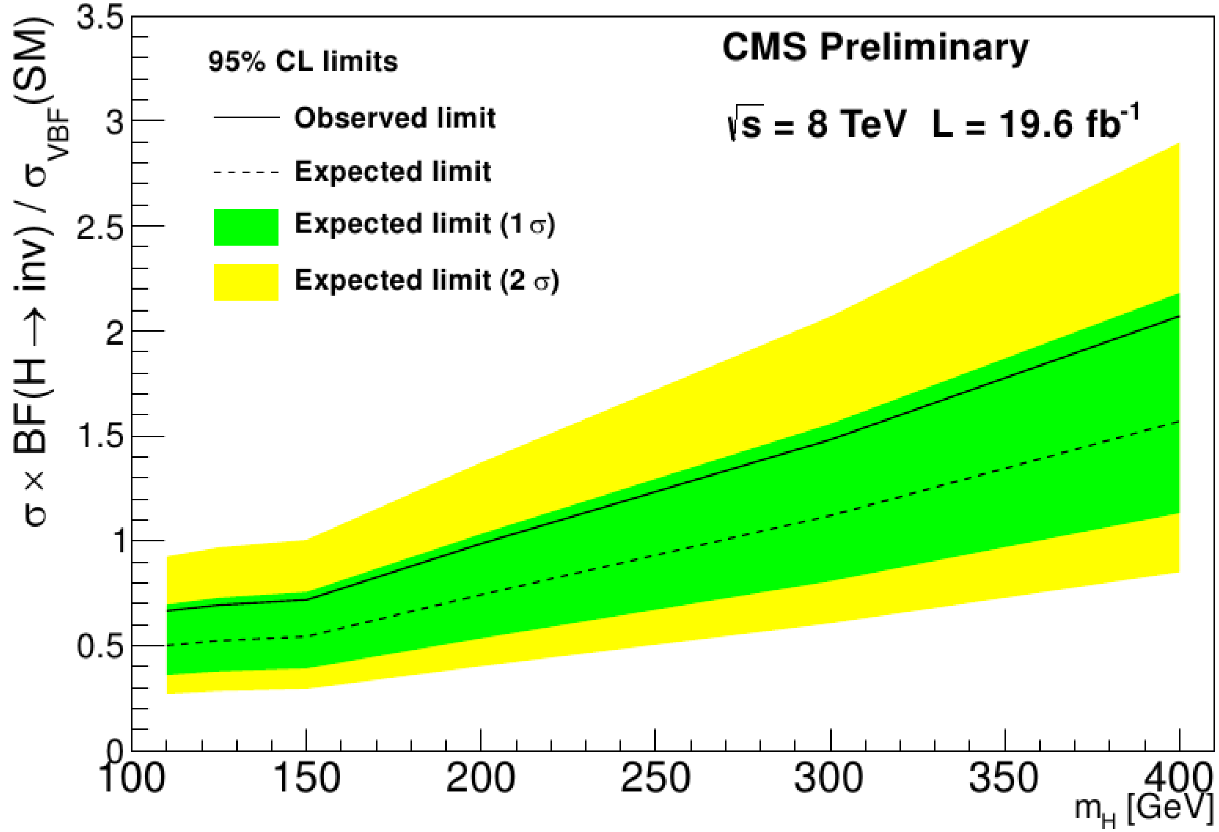


G. Belanger, *Global fit to Higgs signal strengths and couplings and implications for extended Higgs sectors*, Phys. Rev. D 88, 075008 (2013), arXiv:1306.2941

H → inv. Measurements at CMS

- vector boson fusion
  - event selection: 2 eta separated jets with high invariant mass, **high MET**, lepton vetos



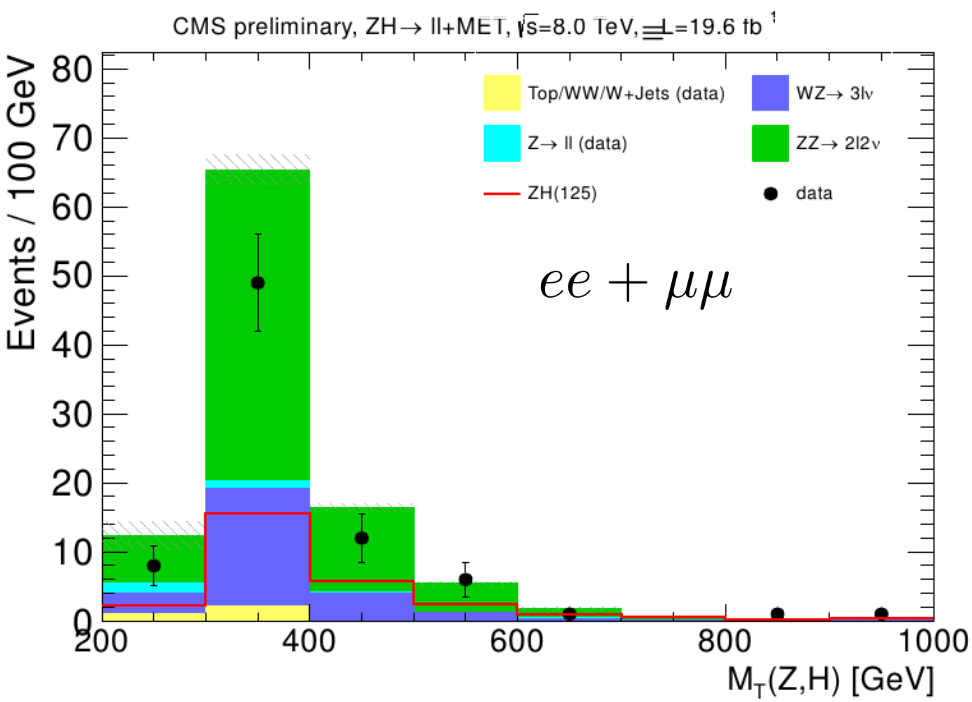


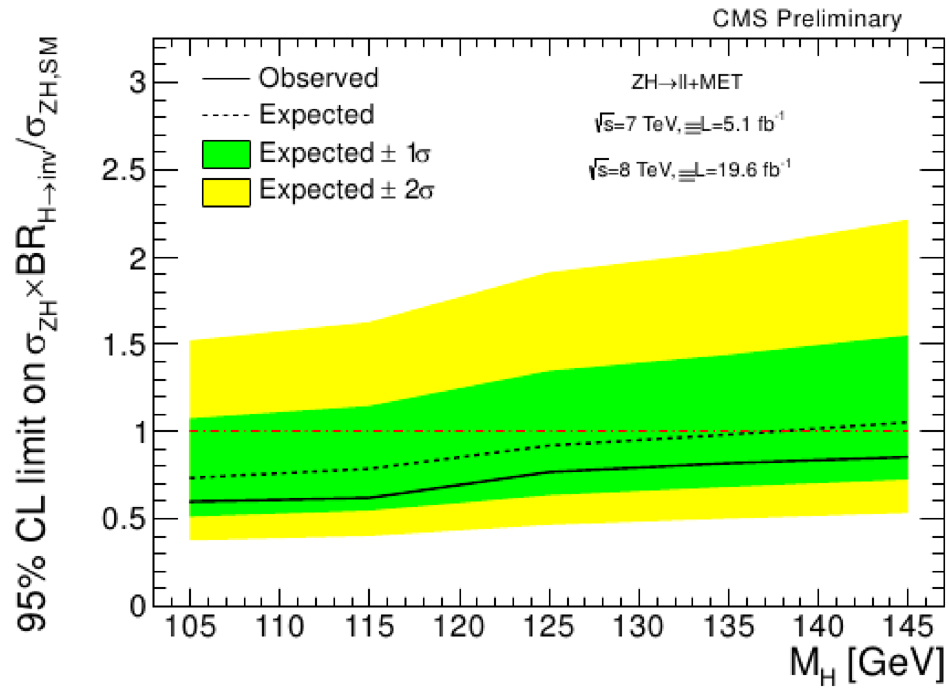
→ analysis excludes $\mathrm{BR}(\mathrm{H} \to \mathrm{inv.}) > 69\%\ (53\%\ \mathrm{exp.})$

CMS Collaboration, *Search for invisible Higgs decays in the VBF channel*, CMS PAS HIG-13-013

H → inv. Measurements at CMS (2)

- Z(ll)H(inv.) [1]
  - event selection: 2 high pT leptons compatible with Z decay, **high MET**, small jet activity





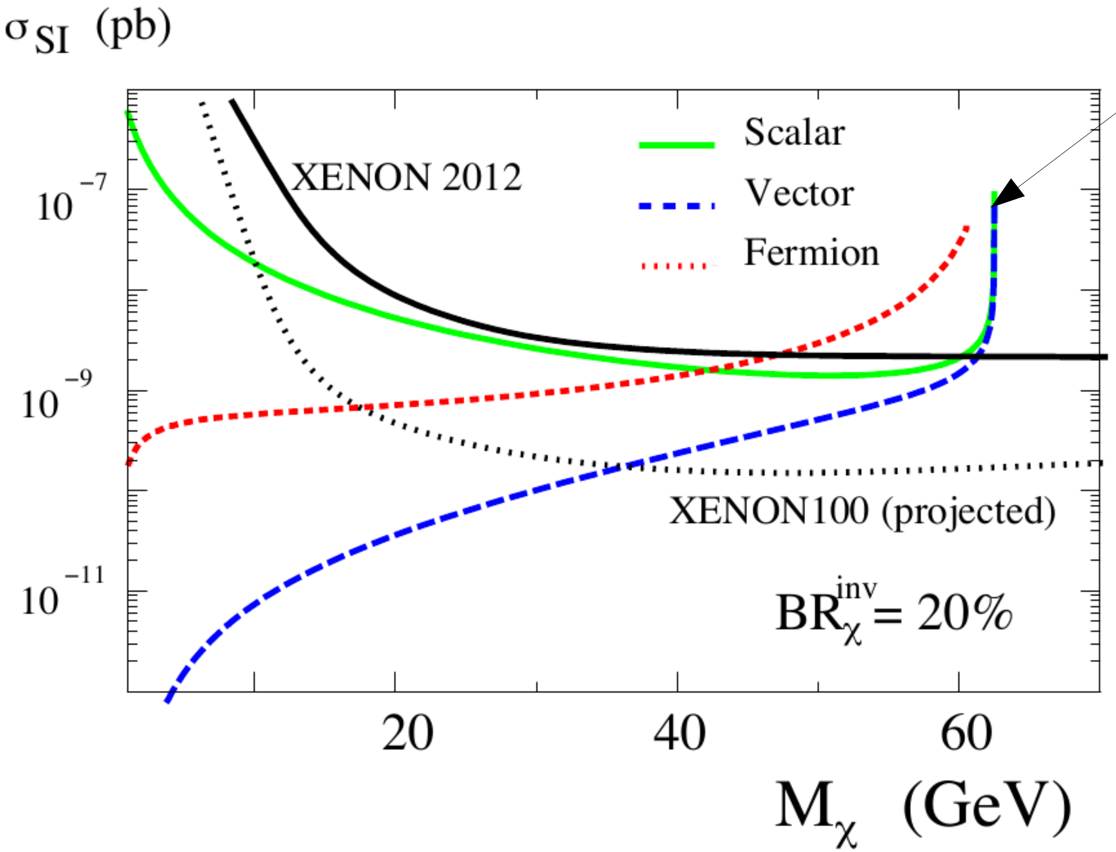
→ analysis excludes $\mathrm{BR(H \to inv.)} > 75\%\ (91\%\ \mathrm{exp.})$

→ this week: combination of CMS H → inv. analyses (VBF, Z(ll)H, Z(bb)H) [2]
$\mathrm{BR(H \to inv.)} > 58\%\ (46\%\ \mathrm{exp.})$

[1] CMS Collaboration, *Search for invisible decays of a Higgs produced in association with a Z boson*, CMS PAS HIG-13-018
[2] CMS Collaboration, *Combination of Invisible Higgs Direct Measurements*, to be published as HIG-13-030

In the Light of other Experiments

- invisible branching ratio → translated into Higgs-DM scattering cross section
  e.g. assume: $\mathrm{BR}(\mathrm{H} \to \mathrm{inv.}) = 20\%$
- compared to XENON limits (detector with liquid and gaseous XE at Gran Sasso)



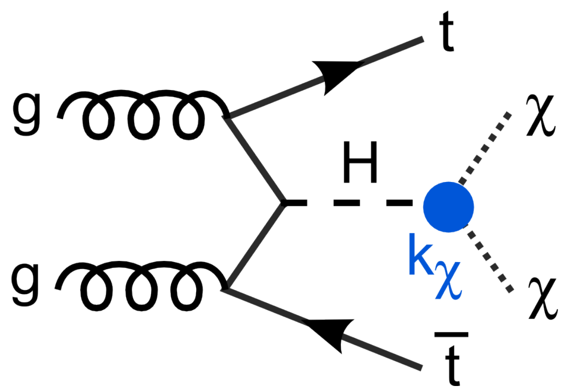
translated LHC limits

"...the LHC is currently the most sensitive dark matter detection apparatus..." [1]

[1] A. Djouadi et. al., *Direct detection of Higgs–portal dark matter at the LHC*,arXiv:1205.3169 [hep-ph]

Analysis Goals

- measurement of Higgs-mediated coupling strength to invisible particles



expected number of events (8 TeV, BR=38%)

$\sigma^{\mathrm{total}}_{\mathrm{pp}\to\mathrm{ttH}} = 126.2\ \mathrm{fb}$ → 2500

$\sigma^{\mathrm{semi\ lept.}}_{\mathrm{pp}\to\mathrm{ttH(inv.)}} = 11.2\ \mathrm{fb}$ → 220

$\sigma^{\mathrm{di.\ lept.}}_{\mathrm{pp}\to\mathrm{ttH(inv.)}} = 3.6\ \mathrm{fb}$ → 72

$\sigma^{\mathrm{semi.\ lept.}}_{\mathrm{pp}\to\mathrm{tt}} = 36\ \mathrm{pb}$ → 722k

$\sigma^{\mathrm{di.\ lept.}}_{\mathrm{pp}\to\mathrm{tt}} = 11.5\ \mathrm{pb}$ → 228k

- search for light DM candidates ($\mathrm{m}_\chi < \mathrm{m}_\mathrm{H}$)
  - limit on $\sigma \cdot \mathrm{BR}(\mathrm{H} \to \chi\chi)$
  - limit on $\mathrm{H} - \chi\chi$ scattering cross section
  - limit parameter space of selected models

- search for other mediators to the dark sector
  - heavy Higgs
  - **pseudoscalar Higgs (couples only to fermions!)**

Connecting with Cosmology

MadDM [1]

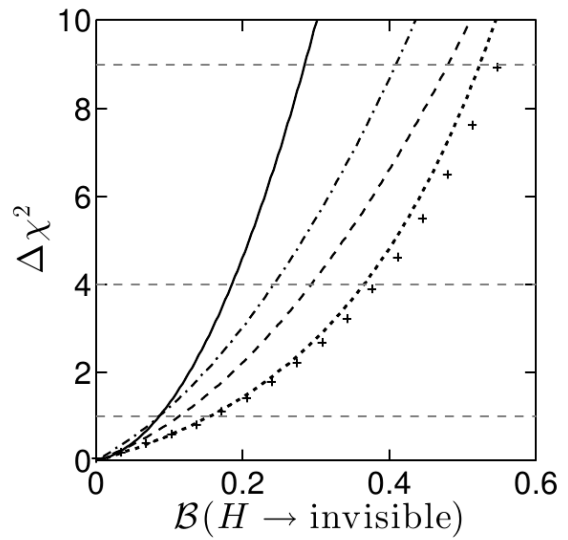
- tool to calculate the dark matter relic abundance: $\Omega \mathrm{h}^2 = \frac{\rho_\chi}{\rho_{\mathrm{crit.}}}$
- planck result: $\Omega \mathrm{h}^2 = 11.96 \pm 0.31\%$ [2]
- based on MadGraph5 framework → easy to use besides collider studies

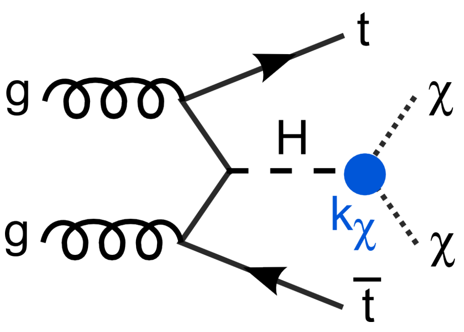
→ combine collider and cosmological results

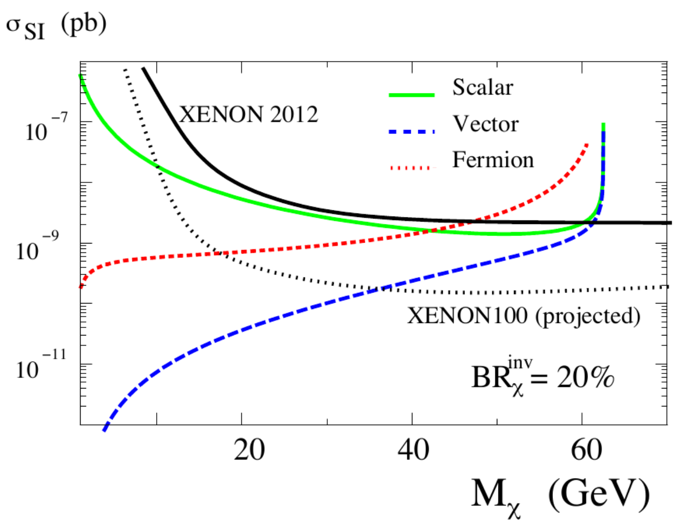
[1] M. Backovic et. al., *MadDM v.1.0: Computation of Dark Matter Relic Abundance Using MadGraph5*, arXiv:1308.4955 [hep-ph]
[2] Planck Collaboration, *Planck 2013 results. XVI. Cosmological parameters*, arXiv:1303.5076 [astro-ph.CO]

Discussion

- open questions
  - matrix elements method vs. standard MVA
    - what can be gained?
    - can both methods be compared?
    - gain the best out of both methods
  - how much model dependence is needed?
    - what models are out there?
    - use concrete or effective model?
  - can ttH(inv) outperform VBF & ZH analyses?
    - is there a pseudoscalar Higgs?
  - can the low MET region be used?
    - dedicated reconstruction of tt-system & propagate neutrino solution to MET
    - how much signal can be rescued
  - how to be sure that the mediator is the H125?
    - kinematic endpoint?
    - use MEM to find the most probable mass → differential-MEM



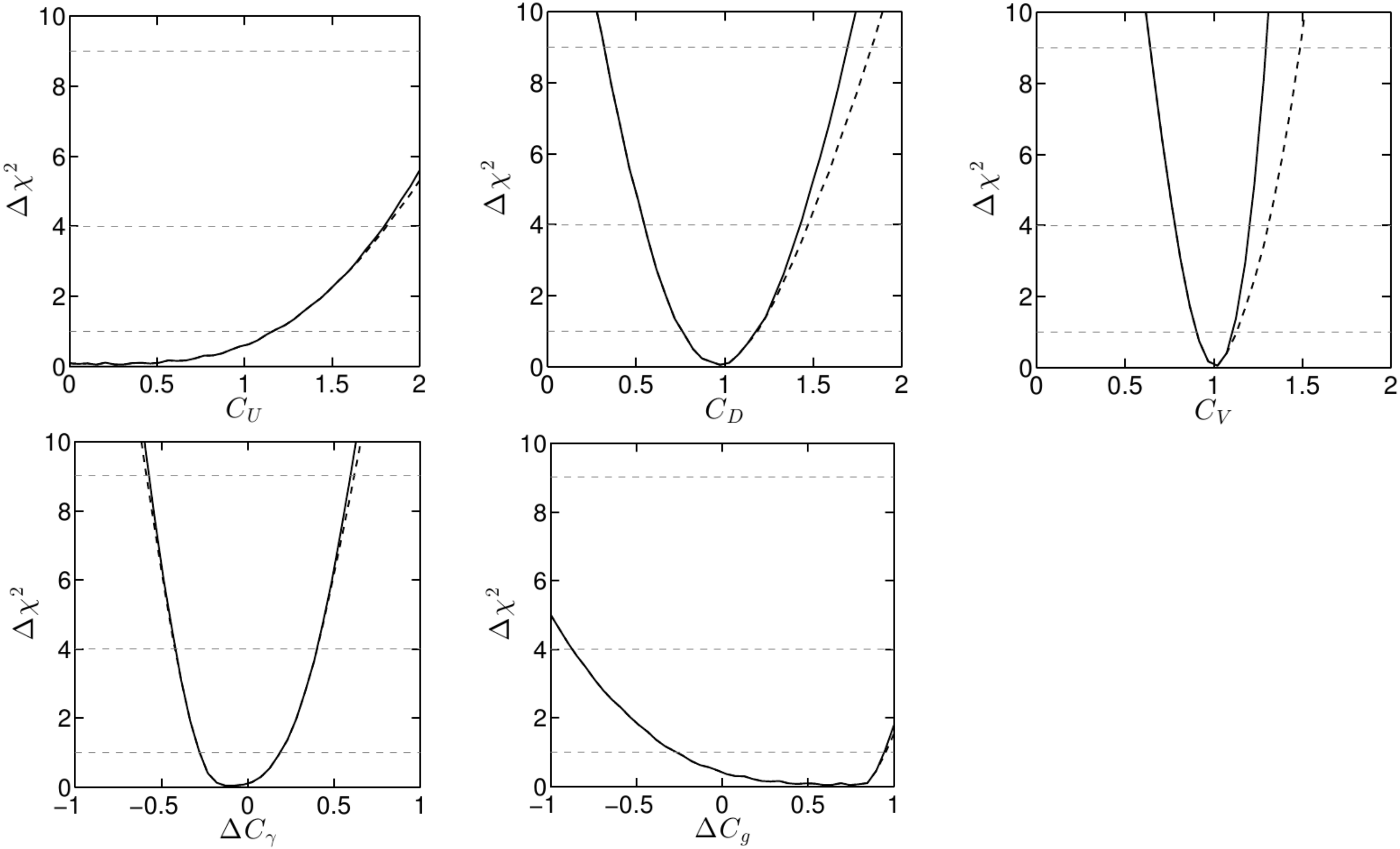




Backup

Global Fit

$$\mathcal{L} = g\left[C_V\left(M_W W_\mu W^\mu + \frac{M_Z}{\cos\theta_W} Z_\mu Z^\mu\right) - C_U \frac{m_t}{2M_W}\bar{t}t - C_D \frac{m_b}{2M_W}\bar{b}b - C_D \frac{m_\tau}{2M_W}\bar{\tau}\tau\right] H$$



[2] G. Belanger, *Global fit to Higgs signal strengths and couplings and implications for extended Higgs sectors*, Phys. Rev. D 88, 075008 (2013), arXiv:1306.2941

CMS H → inv. Combined Result on DM