Aspen 2017 Winter Conference
"From the LHC to Dark Matter and Beyond"

Disambiguating New Physics in the Top Sector

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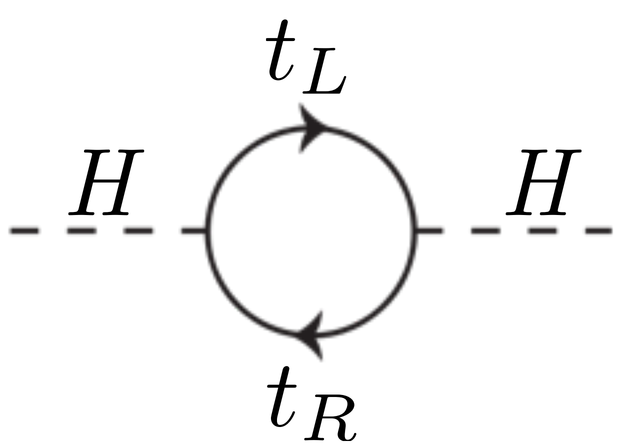
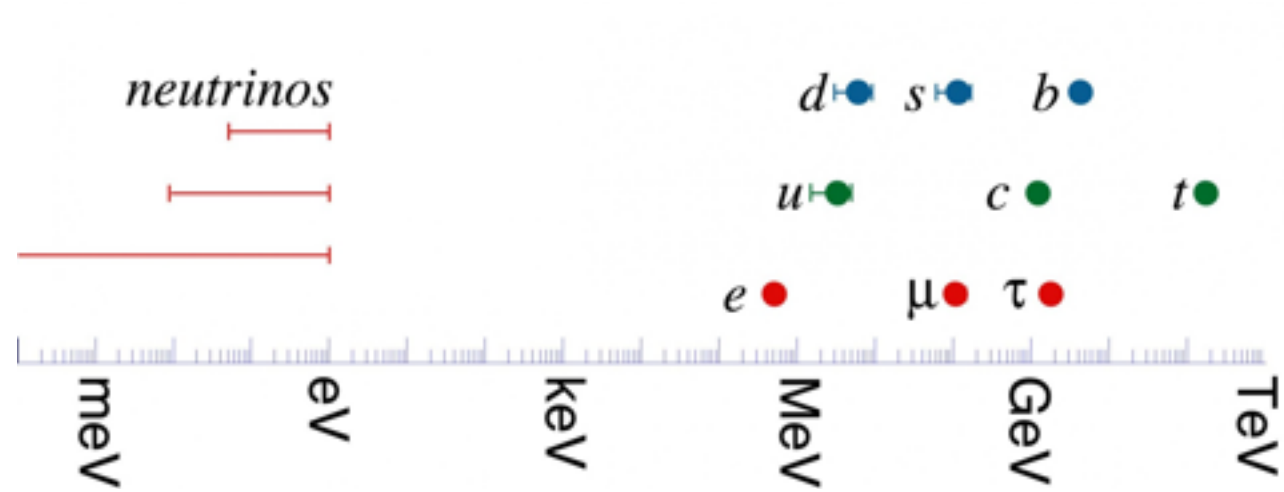
Top quark sector

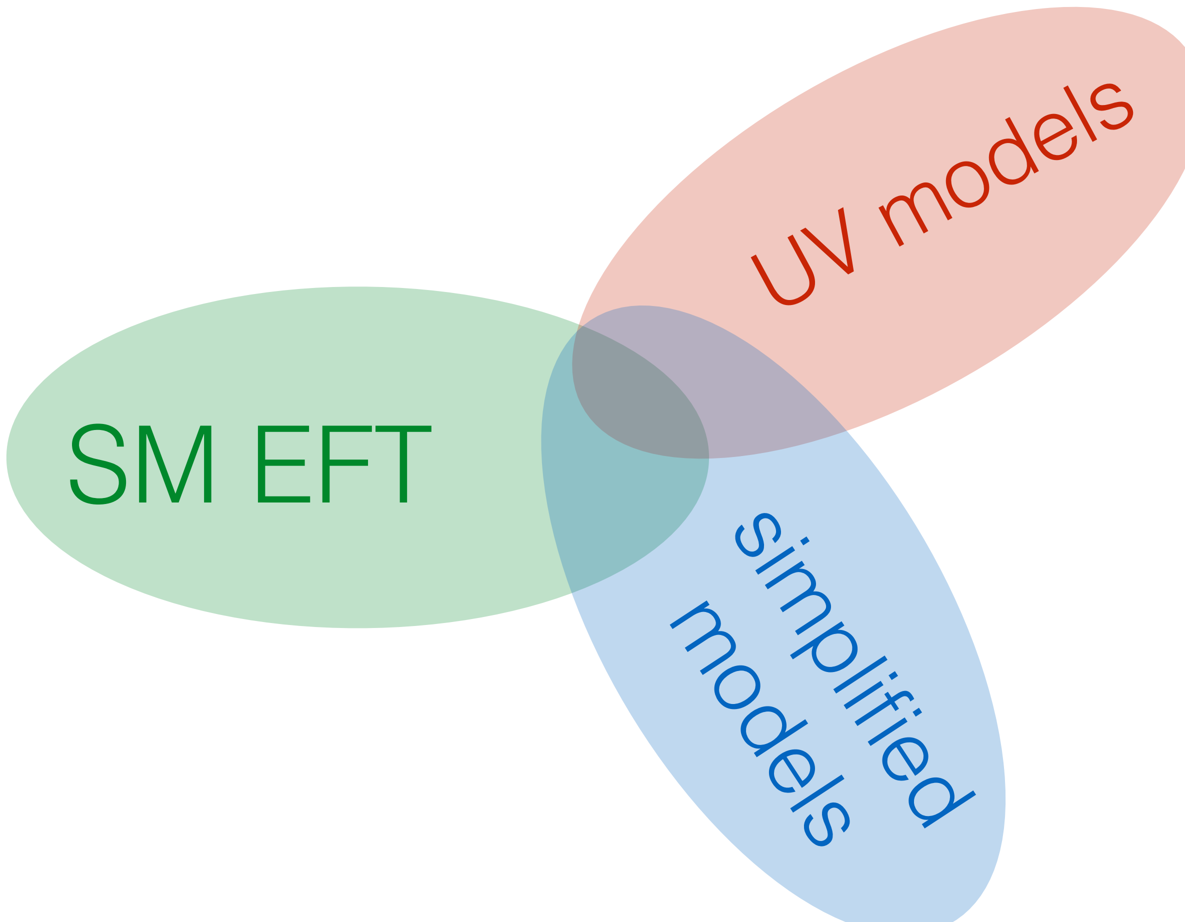
- Plays crucial role in EW hierarchy problem, SM flavor puzzle





- One of most promising experimental windows to NP
- LHC the only running experiment able to produce tops

Interpretation of NP searches at LHC



- Challenging use of EFT (energy gap, degeneracy)
- Limited scope/generality of simplified models
- Dependence on high scale parameters/assumptions in UV complete models

Two top examples

- ‘top-philic’ dark matter
- is tth really probing y_t?

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➡ ‘top-philic’ dark matter

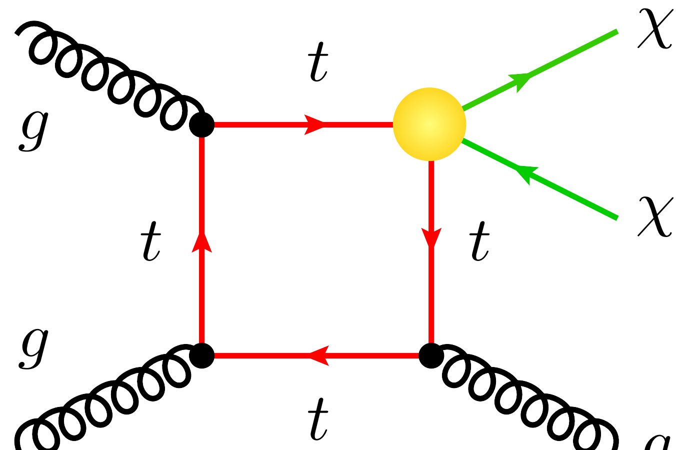
- is tth really probing y_t?

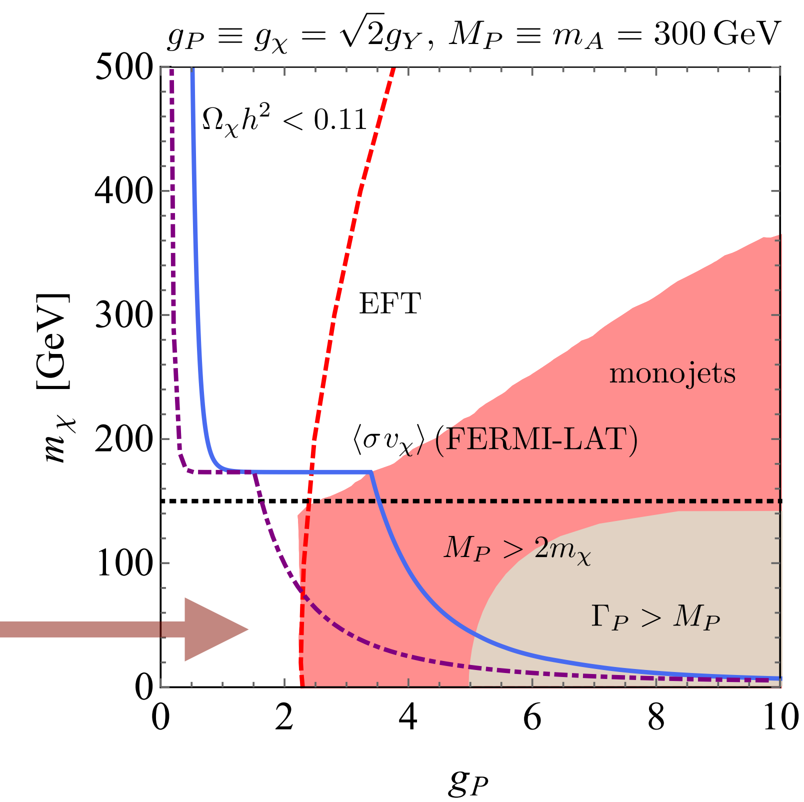
Simplified DM model with (pseudo)scalar mediator

$$\mathcal{L}_{\rm DM} = i\, g_\chi\, A\, \bar\chi \gamma^5 \chi + \sum_{f=q,\ell,\nu} i\, g_f\, A\, \bar f \gamma^5 f$$

- Direct DM detection (spin, momentum) suppressed $\sigma^N_{\rm SD} \propto \frac{q^4}{m_N^4}$
- Naturally SM Yukawa-like couplings: $g_f = \sqrt{2}\, g_Y\, m_f / v$
  - DM becomes effectively 'top-philic'
  - ➡ Reduced LHC mono-X sensitivity

Haisch & Re, 1503.00691





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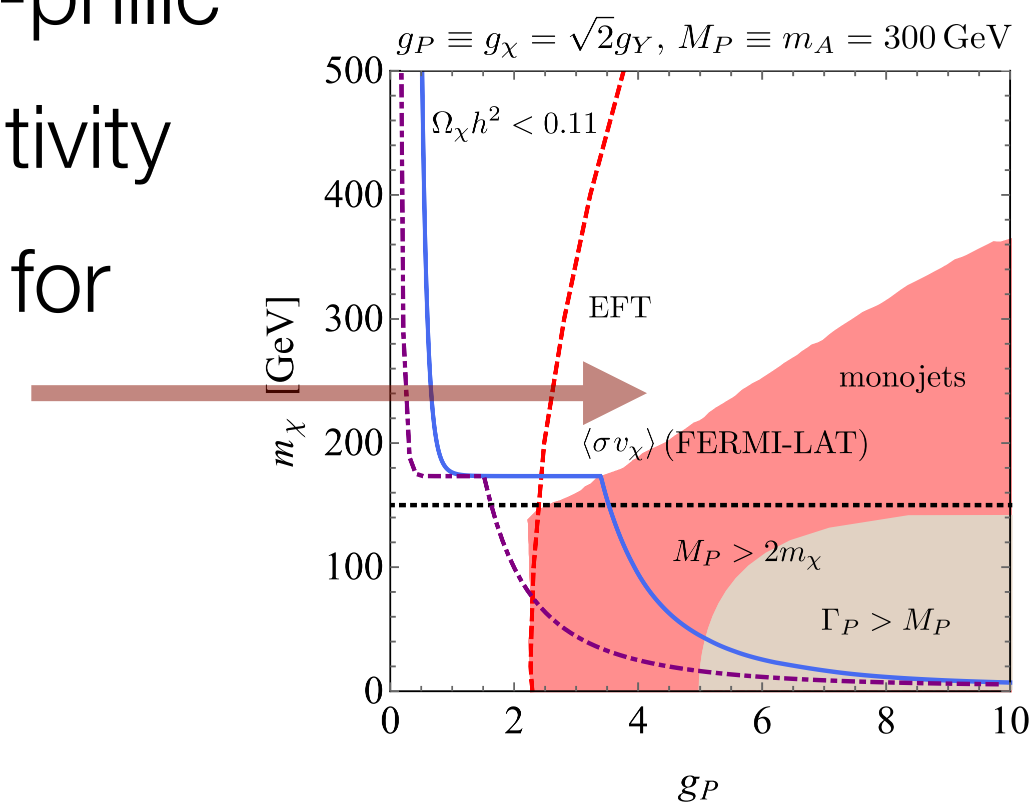
Haisch & Re, 1503.00691

- Suppressed missing E_T signals for $m_\chi > m_A/2$



Bounding simplified NP with less assumptions?

LHC signatures based on resonant A production need to make several assumptions:

$$\sigma(i \to A \to f) \sim \mathcal{L}(i) \frac{\overbrace{\Gamma(A \to i)}^{\propto g_i^2}\overbrace{\Gamma(A \to f)}^{\propto g_f^2}}{\underbrace{\Gamma_A}_{\propto \sum_i g_i^2 \gamma_i(m_A, m_i)}}$$

Non-resonant (off-shell) effects can be complementary:

- Well known (standard) in flavor physics see e.g. Bauer et al. 1701.07427
- At LHC used to bound Higgs width from $\sigma(pp \to 4\ell)$

e.g. CMS-HIG-14-032 based on Kauer & Passarino, 1206.4803,
Campbell & Ellis, 1311.3589,
Caola & Melnikov, 1307.4935

Non-resonant NP in LHC 4t production

Alvarez, Faroughy, J.F.K., Morales & Szynkman, 1611.05032

In SM, LHC 4t production rare $\mathcal{O}(\alpha_S^4)$ QCD process:

see e.g.
Bevilacqua & Worek, 1206.3064

$$\sigma^{NLO}(t\bar{t}t\bar{t}) = 12.32 \text{ fb}$$

(LHC@13TeV using aMC@NLO)

- Off-shell $\mathcal{O}(\alpha_S^2 y_t^4)$ Higgs, $\mathcal{O}(\alpha_S^2\alpha^2)$ Z contributions ~10% each!

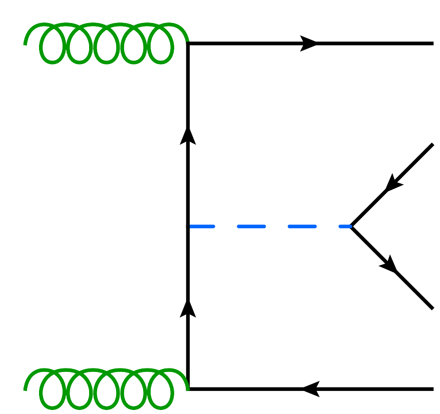
➡ Potential sensitivity to NP with O(1) couplings to tops

- for masses below $2m_t$ effects off-shell

➡ only depend on mass and coupling to tops

- for masses above $2m_t$ resonant production

➡ reintroduce decay width dependence



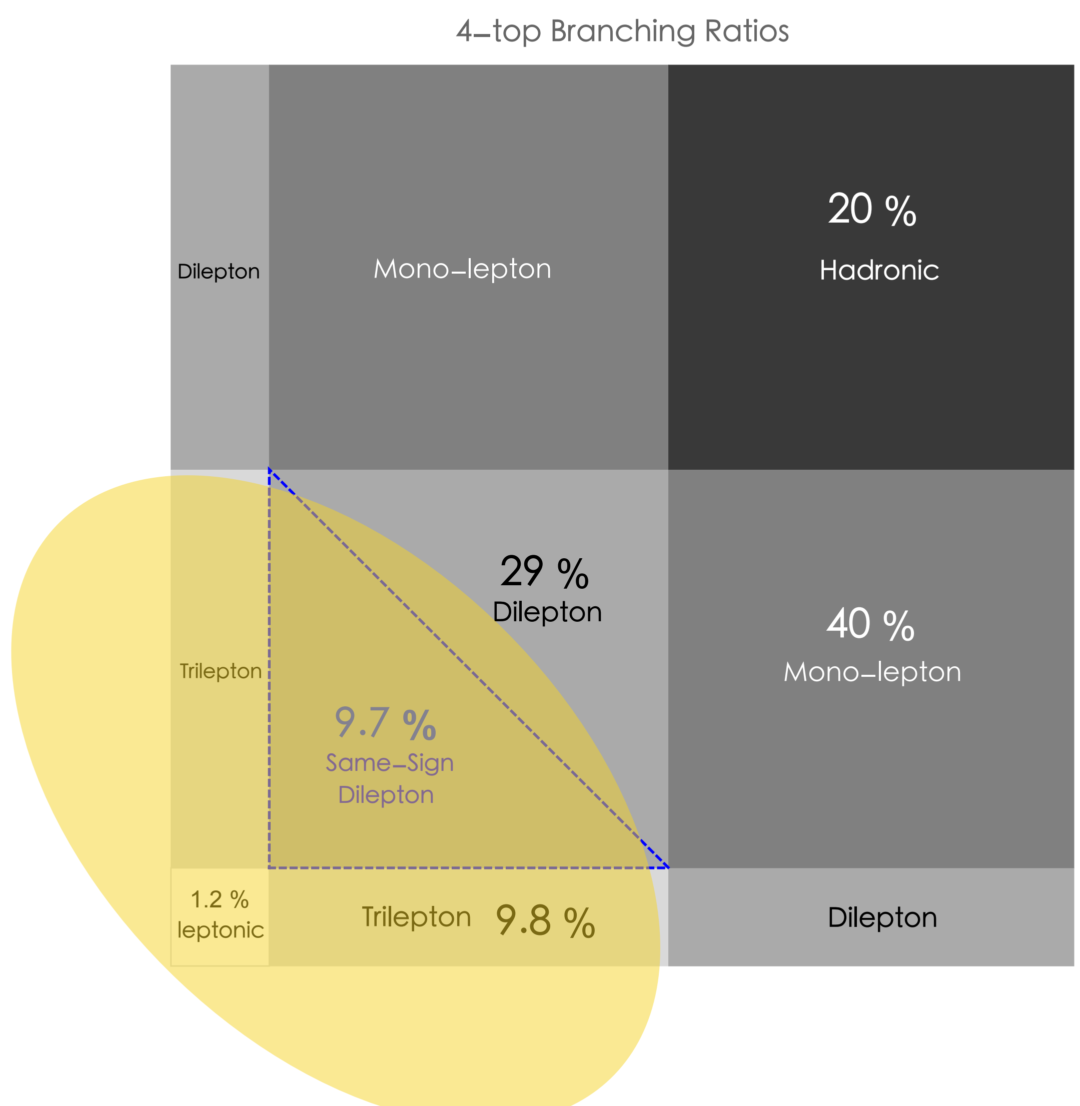
Gerbush et al., 0710.3133,
Acharya et al., 0901.3367,
Gregoire et al., 1101.1294,
Liu & Mahbubani, 1511.09452
Gori et al., 1602.02782
Kim et al., 1604.07421

Non-resonant LHC 4t search strategy

Alvarez, Faroughy, J.F.K., Morales & Szynkman, 1611.05032

Challenging signatures (many jets, affecting lepton isolation)

- clean s.s. dilepton & trilepton channels cover ~20% of total



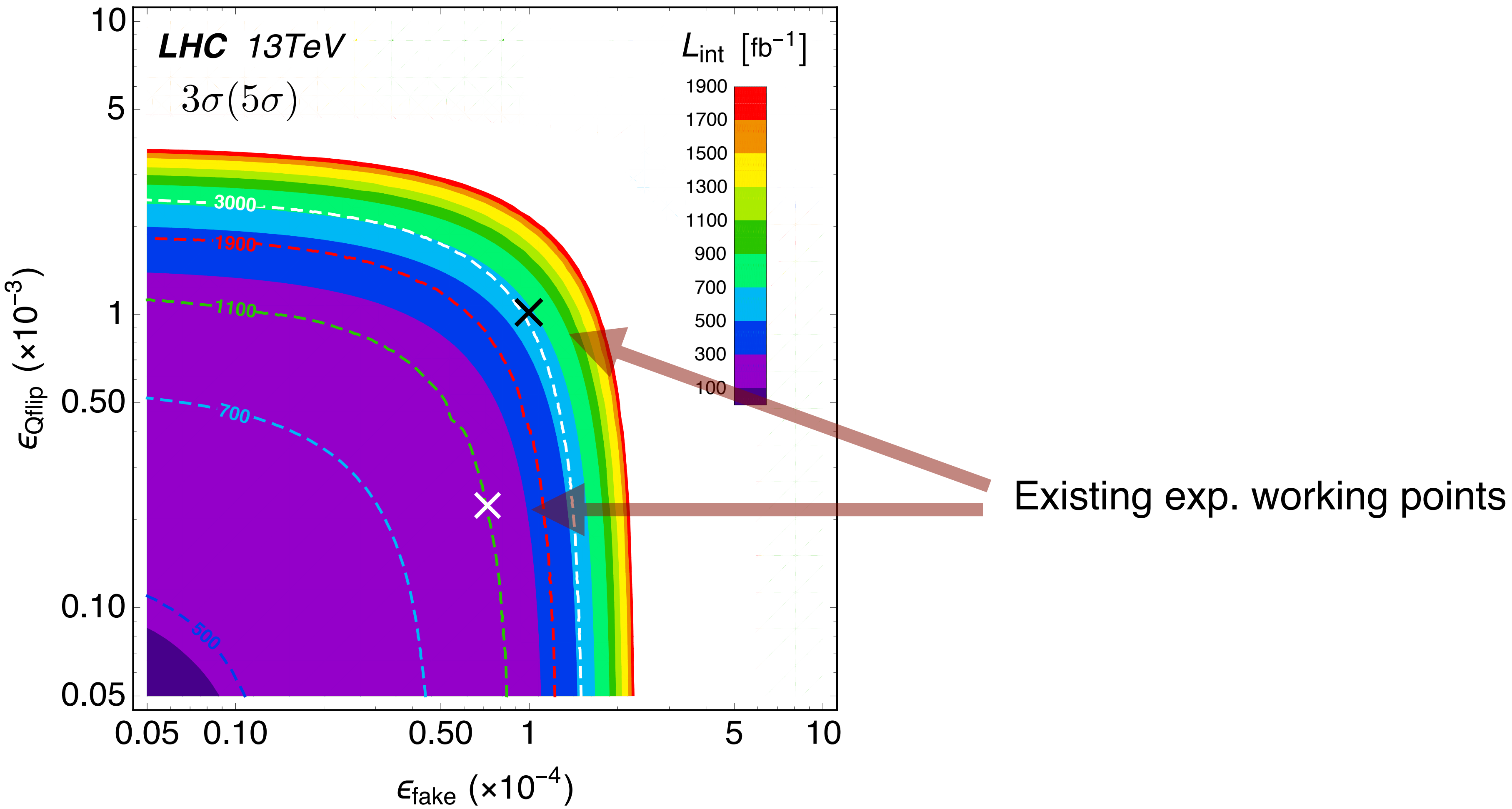
Non-resonant LHC 4t search strategy

Alvarez, Faroughy, J.F.K., Morales & Szynkman, 1611.05032

Separate strategies for s.s. dilepton & trilepton channels

- dominant backgrounds due to charge flip & jet-lepton mis-id

➡ cut-based, data-driven strategy



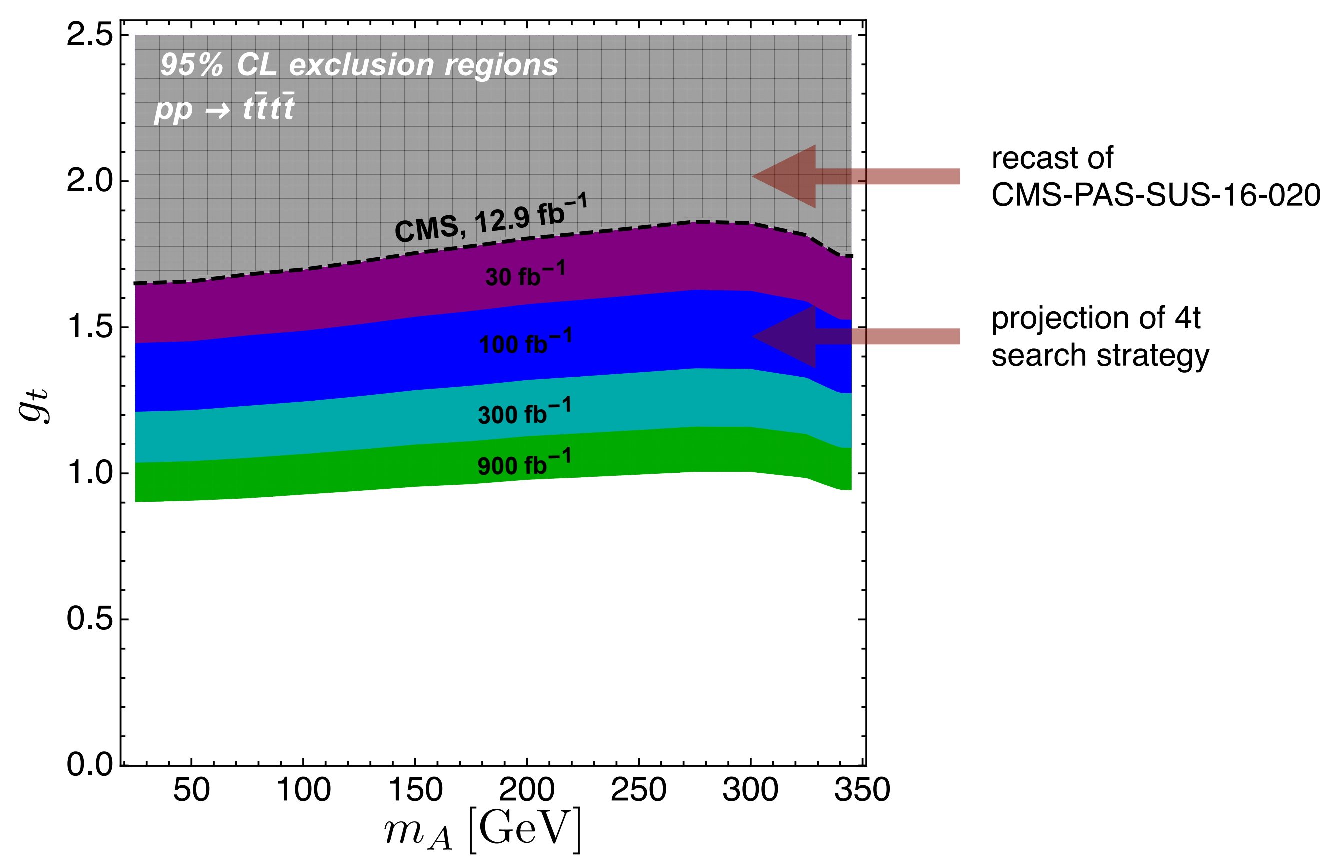
➡ observation of SM rate possible in LHC Run II

Bound on top-philic NP from LHC 4t measurement

Alvarez, Faroughy, J.F.K., Morales & Szynkman, 1611.05032

- Existing (SUSY optimized) search combining both channels by CMS using early 13TeV data CMS-PAS-SUS-16-020

➡ already non-trivial bounds on (light) top-philic NP



- More general compared to resonant constraints (γγ).

C. Arina et al. 1605.09242

Two top examples

- ‘top-philic’ dark matter

➡ is tth really probing y_t?

Mass generation in SM through Higgs mechanism

⇒ Higgs has hierarchical couplings to fermions

$$y_f^{\mathrm{SM}} = \sqrt{2} m_f / v$$

How well have we tested this?

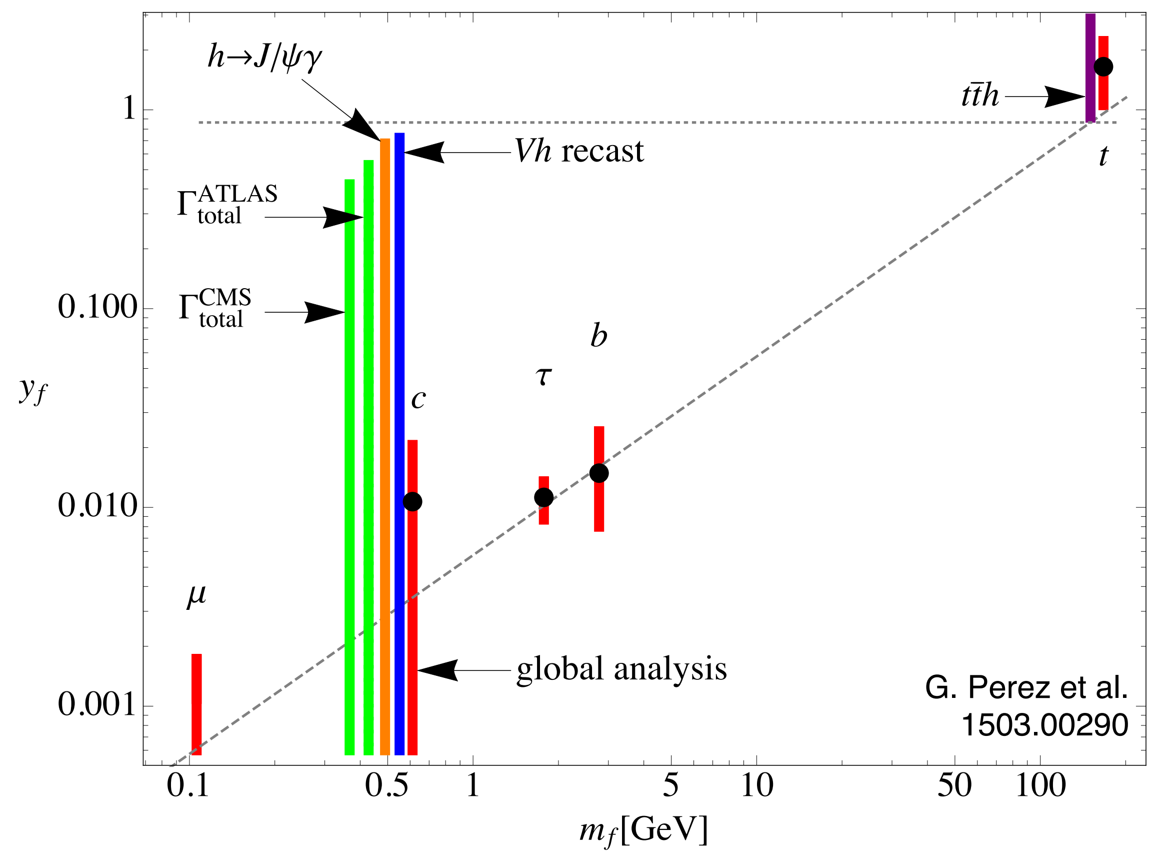
A. Dery et al., 1302.3229

- proportionality $\quad y_{ii} \propto m_i$
- factor of proportionality

$$y_{ii}/m_i = \sqrt{2}/v$$

- diagonality $\quad y_{ij} = 0, \quad i \neq j$

G. Blankenburg et al., 1202.5704,
R. Harnik et al., 1209.1397, …



Many recent proposals… 1306.5770, 1406.1722, 1503.04830, 1505.03870, 1606.09621

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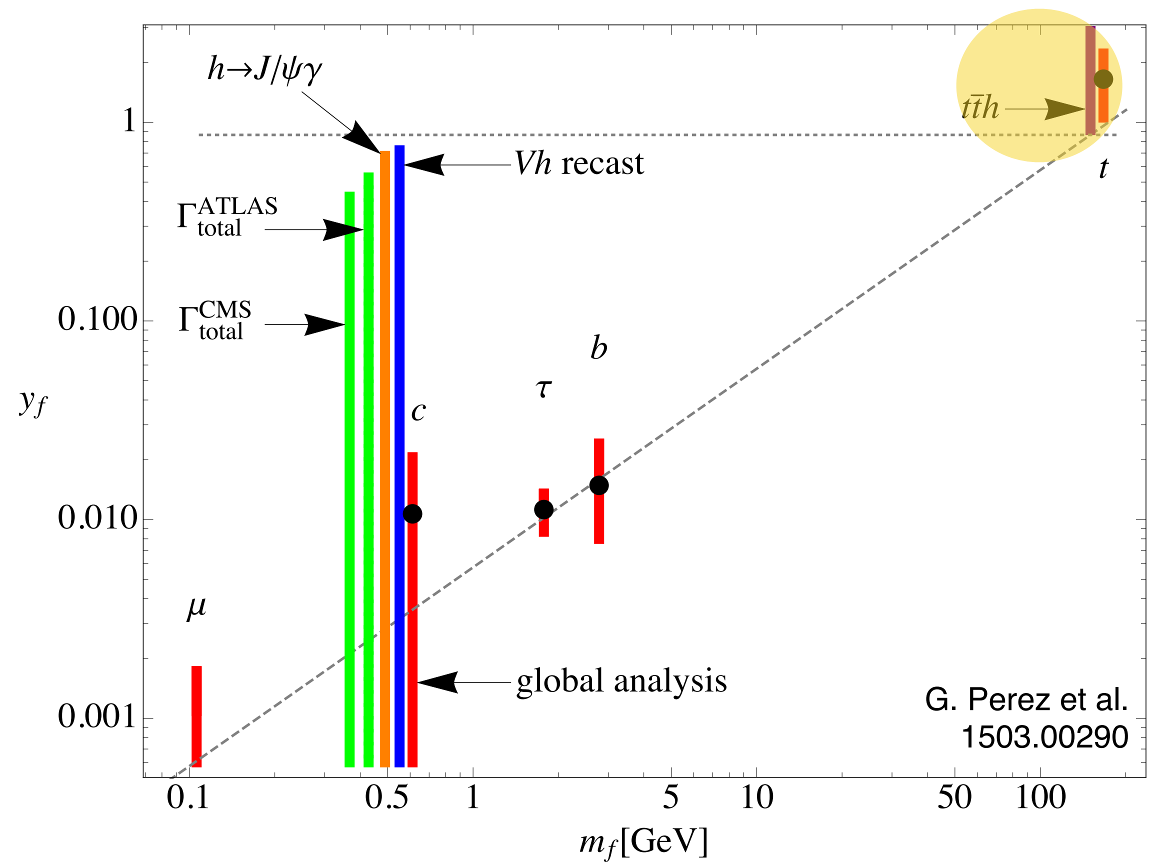

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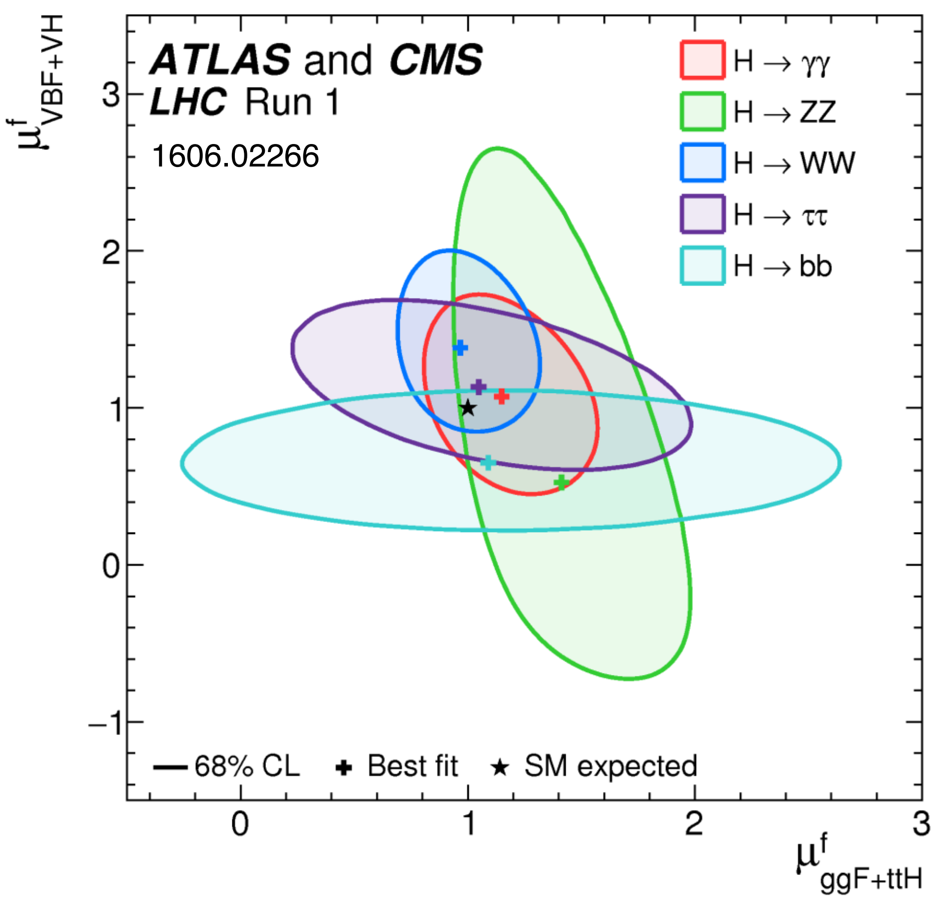
LHC bounds on top Yukawa

Current global Higgs fits extract bound on y_t (mostly) from its parametric dependence of $\sigma(pp \to h)_{\text{incl.}}, \quad \sigma(pp \to t\bar{t}h)$

$$\mu \equiv \frac{\sigma_{\text{obs.}}}{\sigma_{\text{SM}}}$$



Anomalous top Yukawa in EFT

Non-standard value of y_t effectively due to higher-dim operator

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2} O_i + \mathcal{O}(\Lambda^{-4}) + h.c.,$$

see e.g. Zhang & Willenbrock, 1008.3869

Several operators can contribute to relevant observables

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q} t)\, \tilde{\phi}\,,$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$$

$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}\,.$$

- modified y_t: $\delta y_t \equiv \dfrac{C_{t\phi} v^2}{2\sqrt{2}\Lambda^2}$ (← $O_{t\phi}$)
- point-like contribution to hGG (can compensate y_t effects in $\sigma_{\rm GGF}$) (← $O_{\phi G}$)
- Chromo MDM of top, also affects tt production (← O_{tG})

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$$O_{qq}^{(8,1)} = \frac{1}{4}(\bar{q}^i \gamma_\mu \lambda^A q^j)(\bar{q}\gamma^\mu \lambda^A q) \qquad O_{qq}^{(8,3)} = \frac{1}{4}(\bar{q}^i \gamma_\mu \tau^I \lambda^A q^j)(\bar{q}\gamma^\mu \tau^I \lambda^A q)$$

$$O_{ut}^{(8)} = \frac{1}{4}(\bar{u}^i \gamma_\mu \lambda^A u^j)(\bar{t}\gamma^\mu \lambda^A t) \qquad O_{dt}^{(8)} = \frac{1}{4}(\bar{d}^i \gamma_\mu \lambda^A d^j)(\bar{t}\gamma^\mu \lambda^A t)$$

$$O_{qu}^{(1)} = (\bar{q} u^i)(\bar{u}^j q) \qquad O_{qd}^{(1)} = (\bar{q} d^i)(\bar{d}^j q)$$

$$O_{qt}^{(1)} = (\bar{q}^i t)(\bar{t} q^j)$$

(assume CP, ~$U(2)_F$)

4fermion operators also enter tt and tth production in fixed combinations

$$\begin{aligned} C_u^1 &= C_{qq}^{(8,1)} + C_{qq}^{(8,3)} + C_{ut}^{(8)} \\ C_u^2 &= C_{qu}^{(1)} + C_{qt}^{(1)} \\ C_d^1 &= C_{qq}^{(8,1)} - C_{qq}^{(8,3)} + C_{dt}^{(8)} \\ C_d^2 &= C_{qd}^{(1)} + C_{qt}^{(1)} \end{aligned}$$

known at NLO in QCD

Maltoni et al., 1607.05330

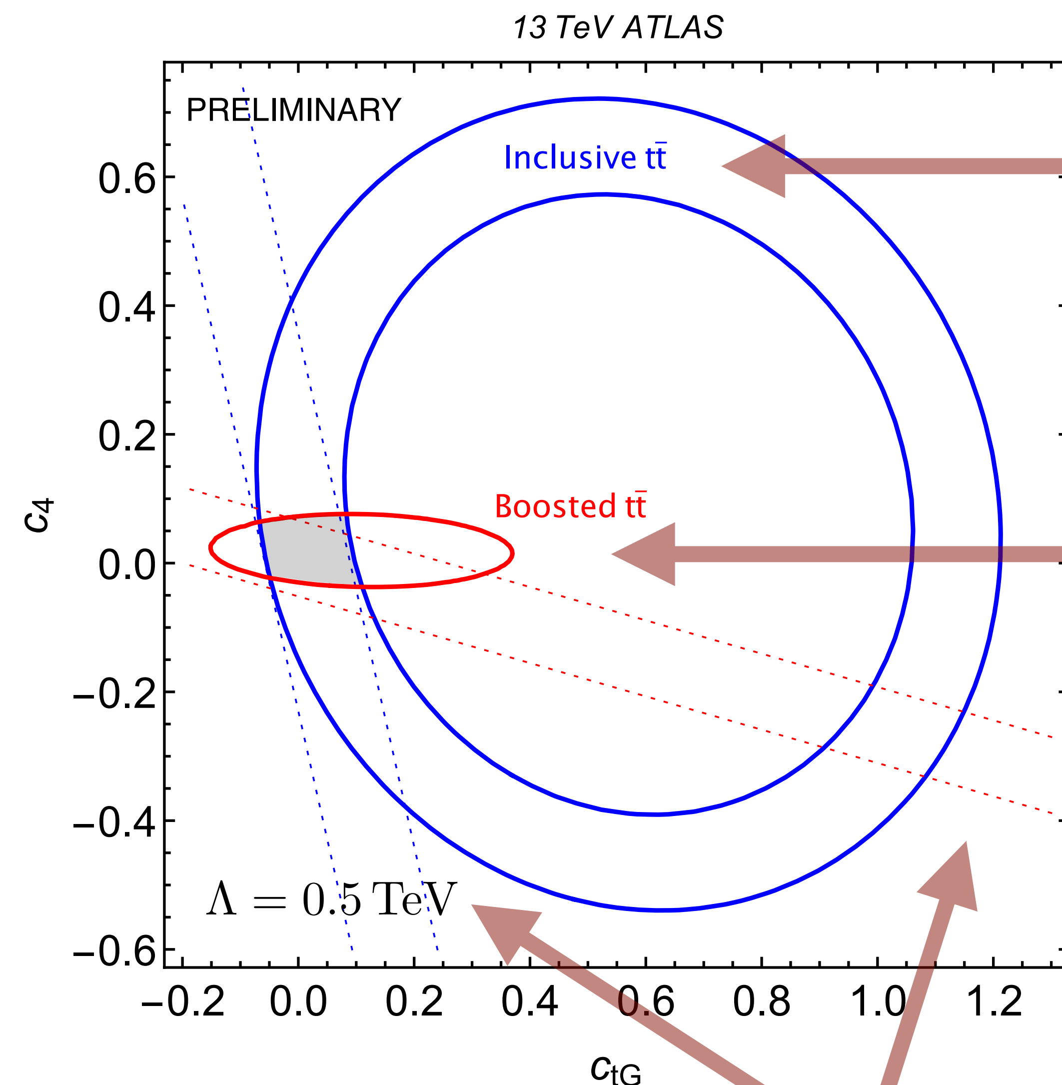
Disentangling NP effects in tt & tth

with D. Faroughy, A. Greljo, G. Isidori & D. Marzocca

4fermion & CMDM effects in inclusive and boosted tt

see also Aguilar-Saavedra et al., 1412.6654

$$C_4 \equiv 4(C_u^{(2)} + C_d^{(2)})$$



already systematics & theory limited

ATLAS 1606.02699

boosted regime more sensitive to 4f compared to CMDM

ATLAS-CONF-2016-100

see e.g. Contino et al., 1604.06444

linearized (EFT truncated) effects

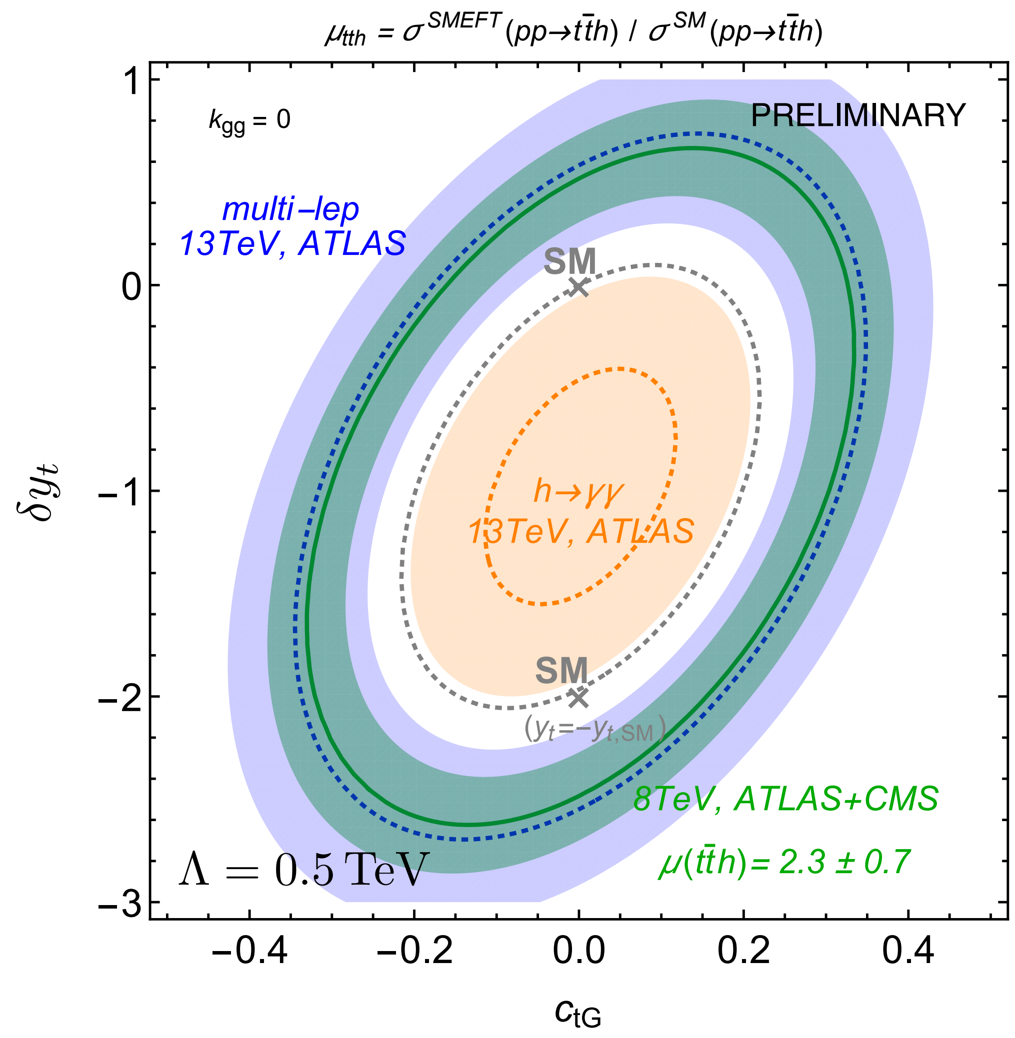
$$\sigma \sim \sigma_{\rm SM} + \frac{Cv^2}{\Lambda^2}\hat{\sigma}_{\rm NP-SM\,int.} + \frac{C^2 v^4}{\Lambda^4}\hat{\sigma}_{\rm NP}$$

Disentangling NP effects in tt & tth

with D. Faroughy, A. Greljo, G. Isidori & D. Marzocca

Competitive effects in tth due to y_t and CMDM

- 4fermion operator effects already largely negligible
- current measurements allow for sizable degeneracy



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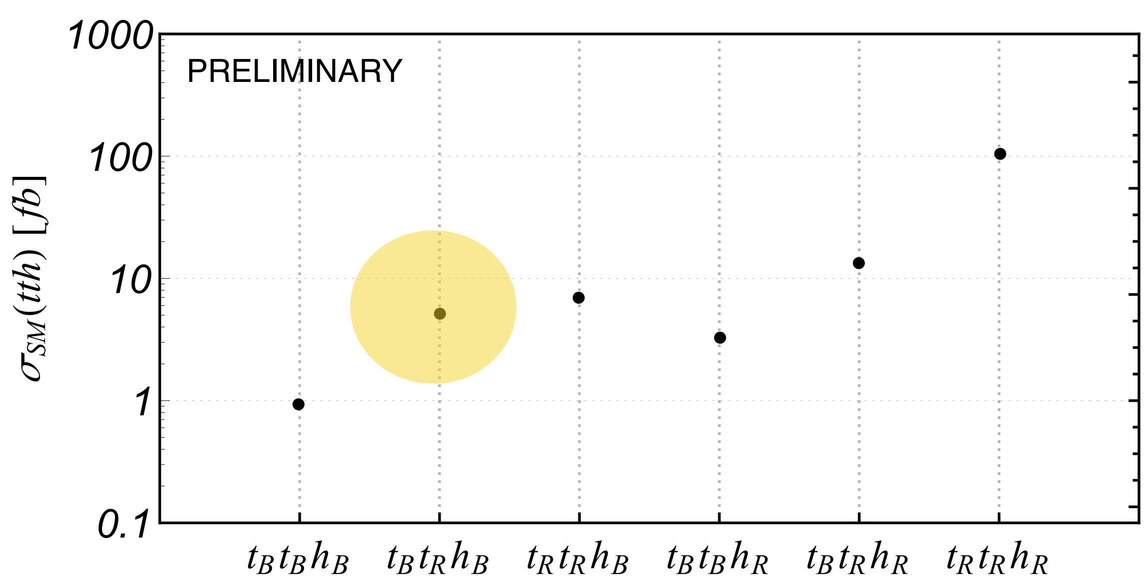
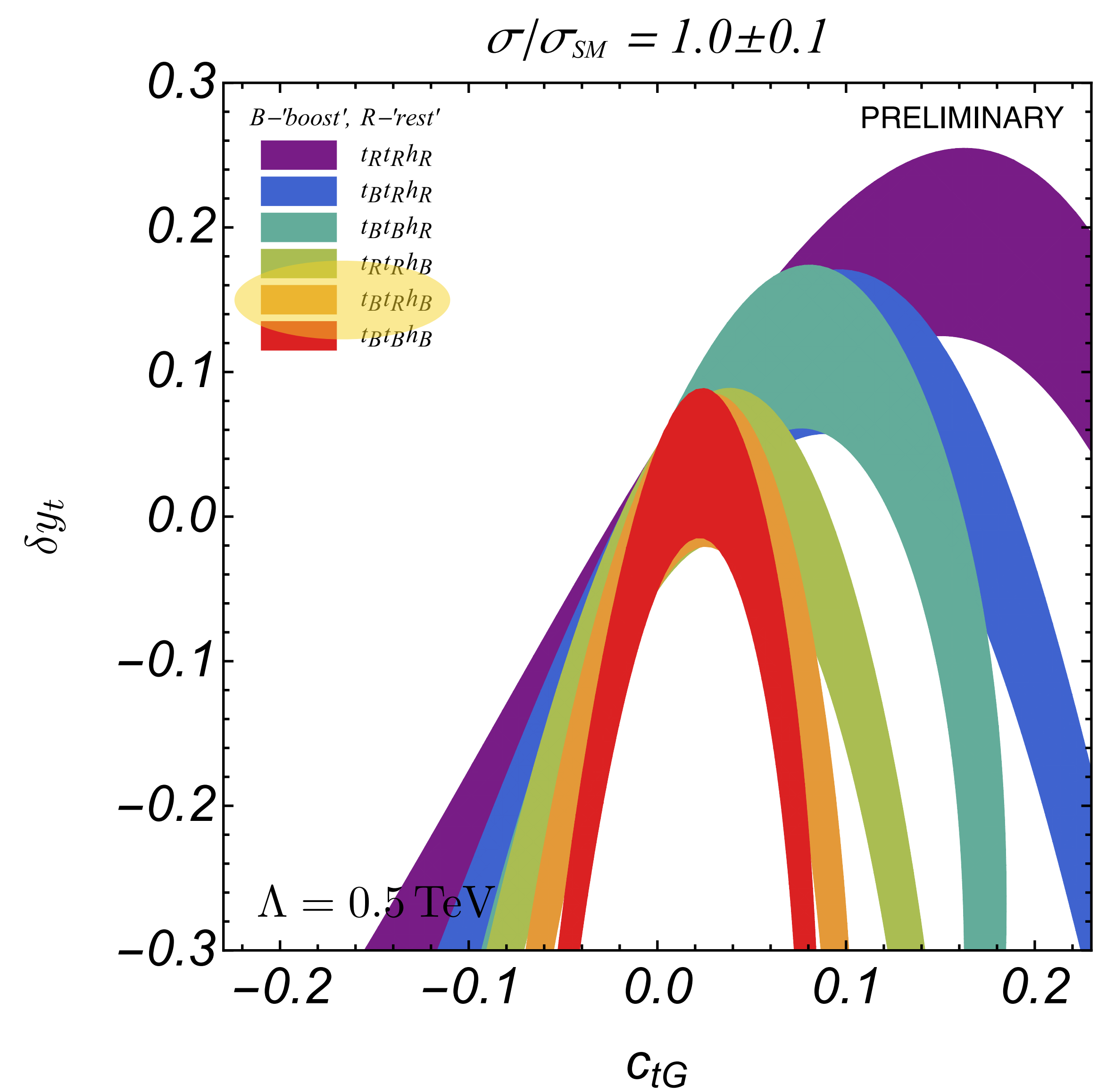
Competitive effects in tth due to y_t and CMDM

Resolve degeneracy using boosted regime

- t_B - top-tagged R=1.5 jet
- h_B - Higgs-tagged R=1.2 jet
- t_R, h_R - resolved decays





see also Buckley et al., 1310.6034
Mangano et al., 1507.08169

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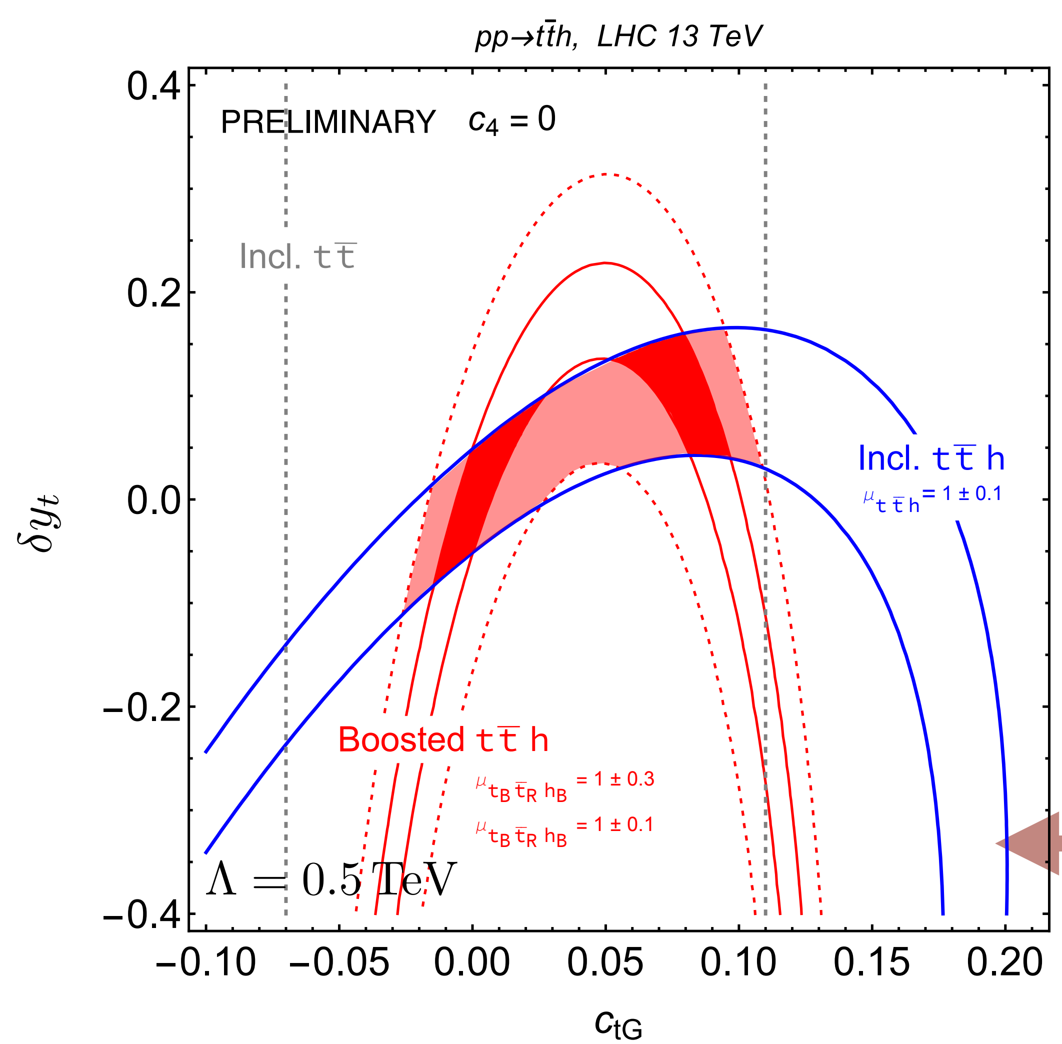
Competitive effects in tth due to y_t and CMDM

Resolve degeneracy using boosted regime: projections



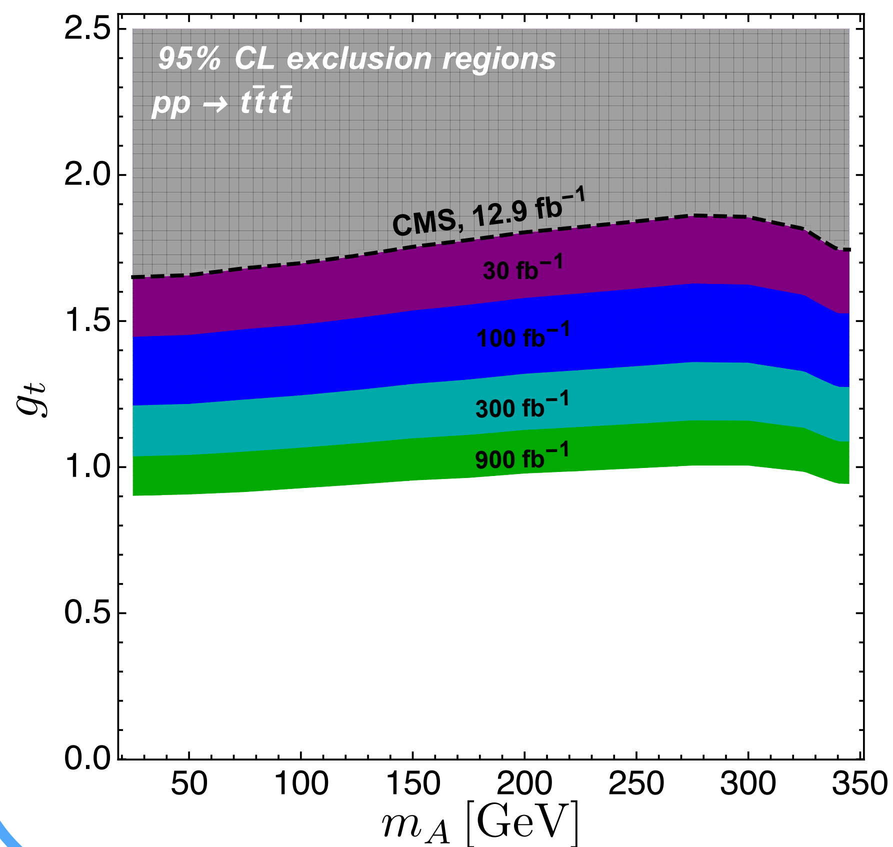
assuming 10% measurement

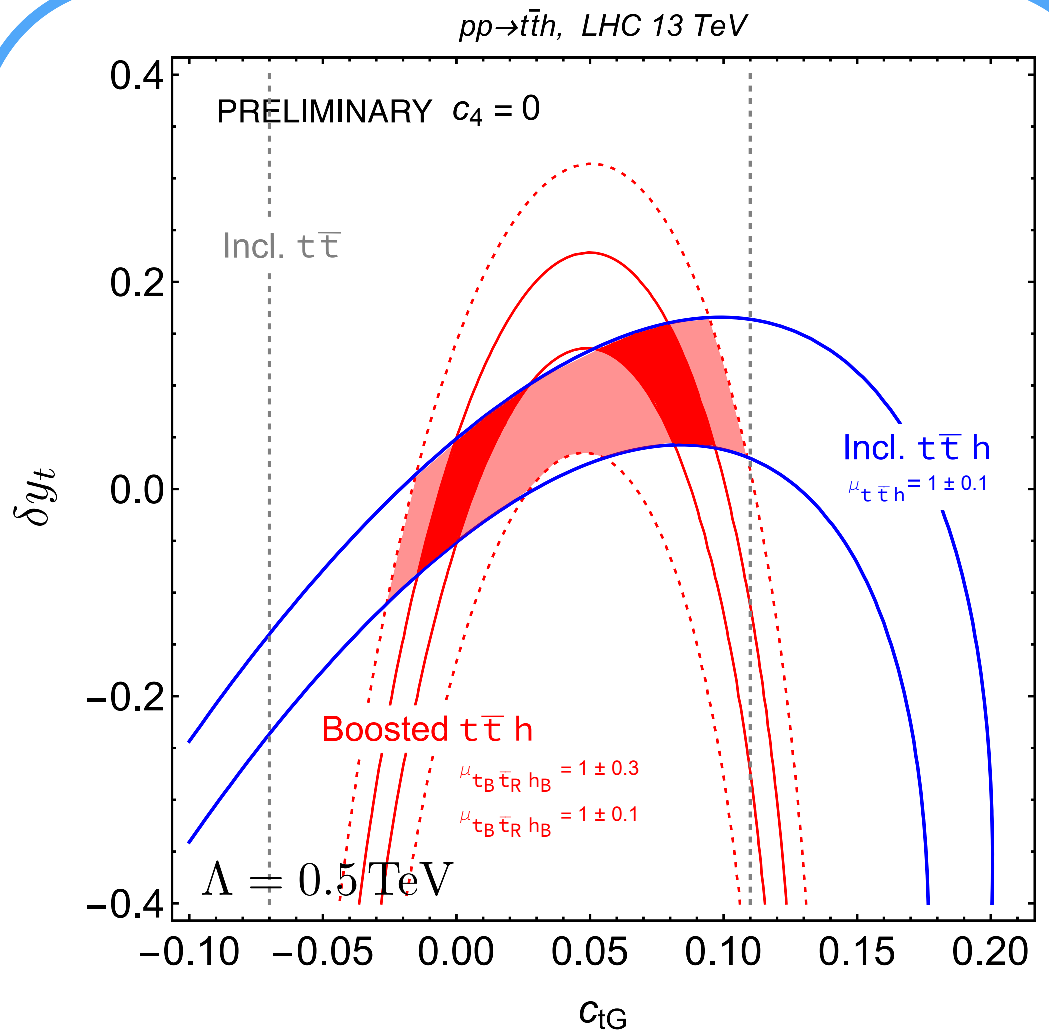
estimating 30% measurement at HL-LHC

Conclusions

Examples extending NP reach in the top sector in light of large (HL-)LHC projected statistics

Robust bounds on 'top-philic' NP from non-resonant 4t production





Resolving EFT degeneracy in t-h sector using boosted tth

Additional material

Simplified DM model with (pseudo)scalar mediator

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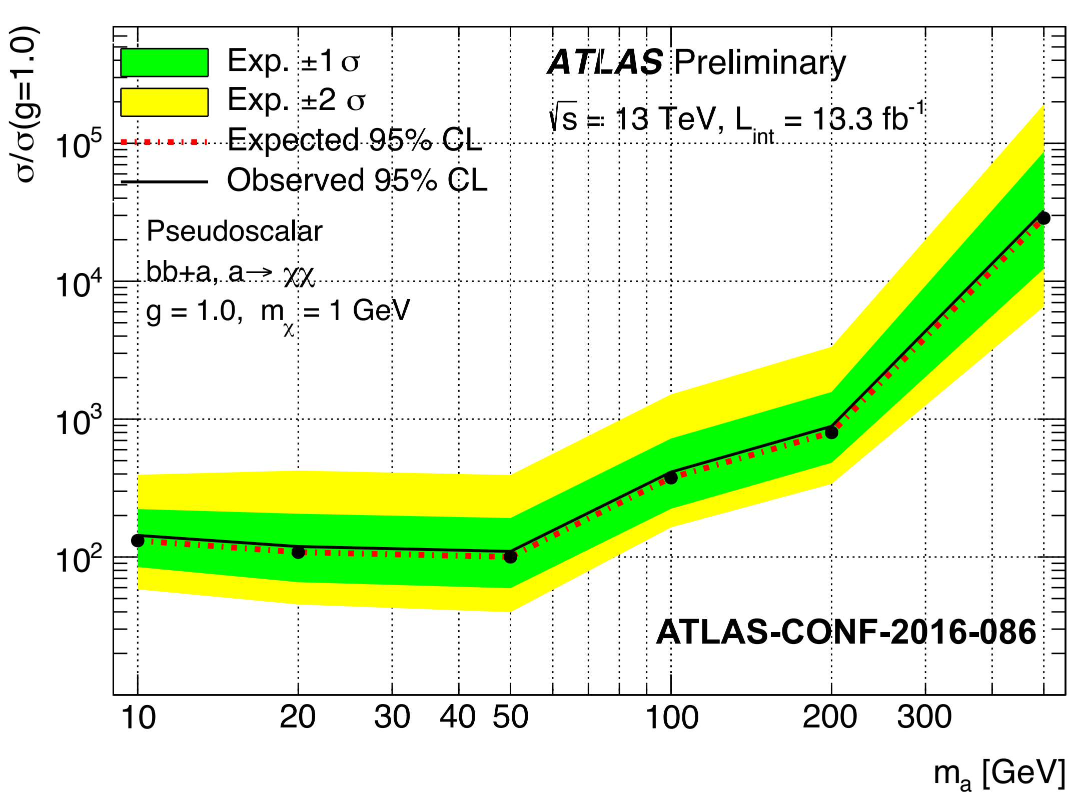
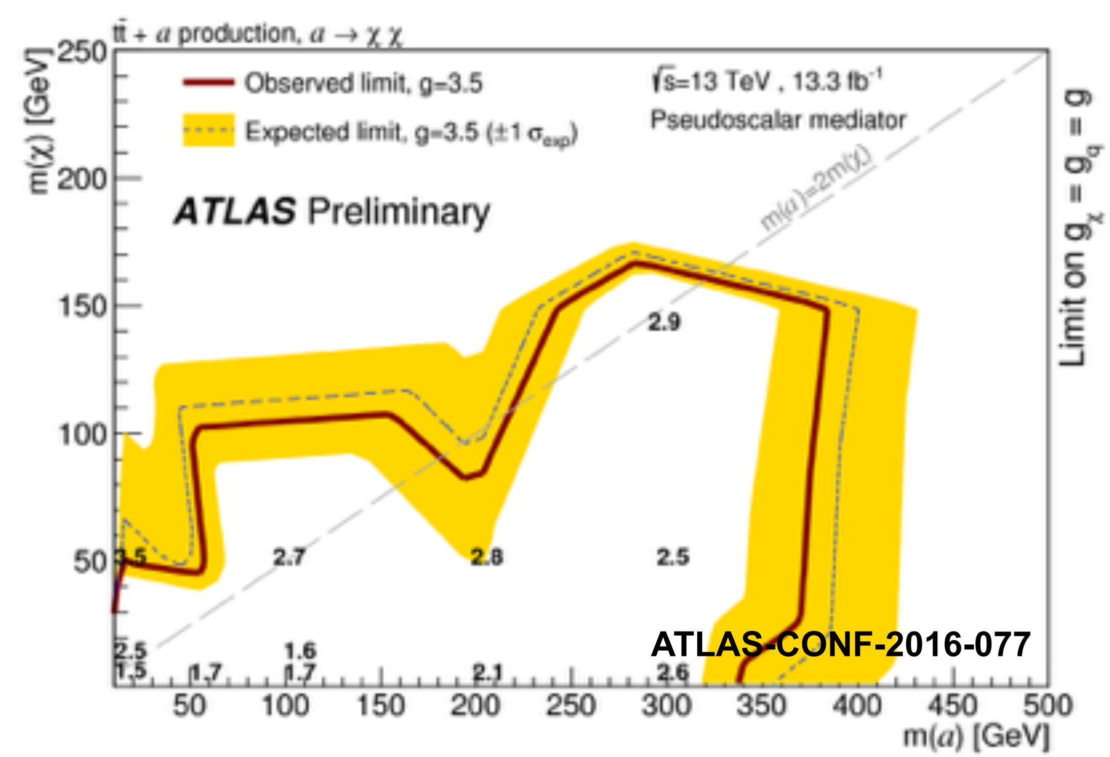
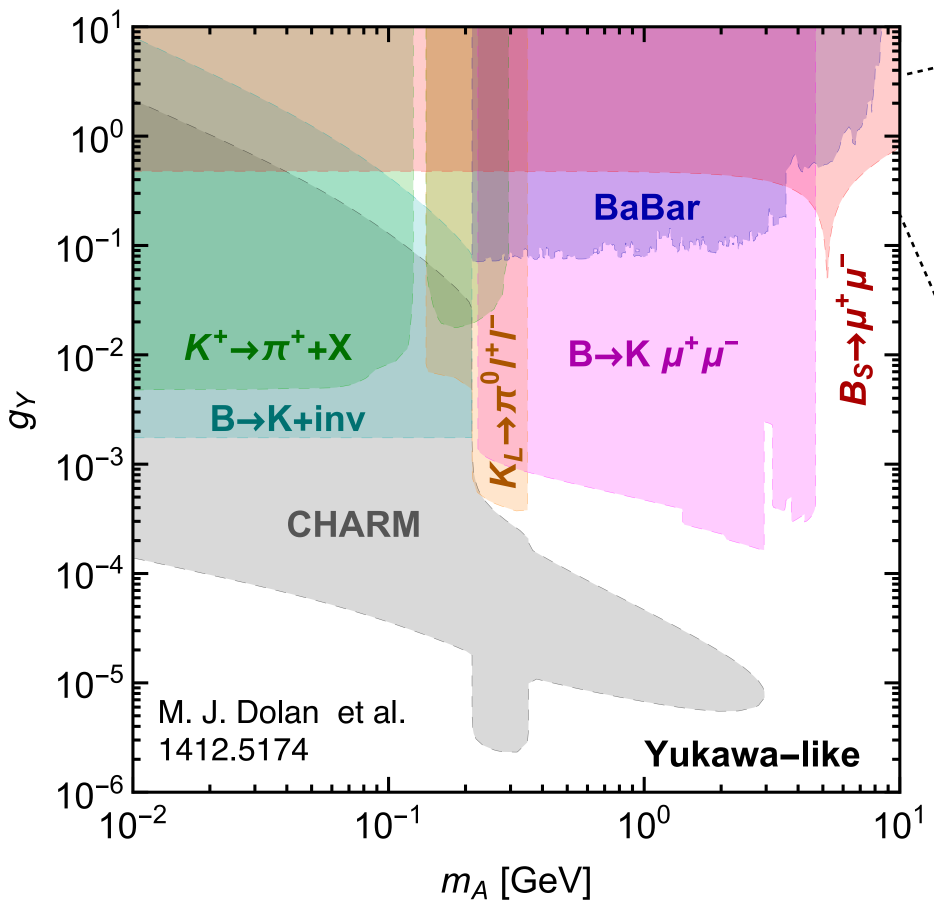
- Direct DM detection (spin, momentum) suppressed $\sigma^N_{\mathrm{SD}} \propto \frac{q^4}{m_N^4}$
- Naturally SM Yukawa-like couplings: $g_f = \sqrt{2}\, g_Y\, m_f / v$
  - Reduced LHC mono-X sensitivity (better than *bbE_T*, *ttE_T*)



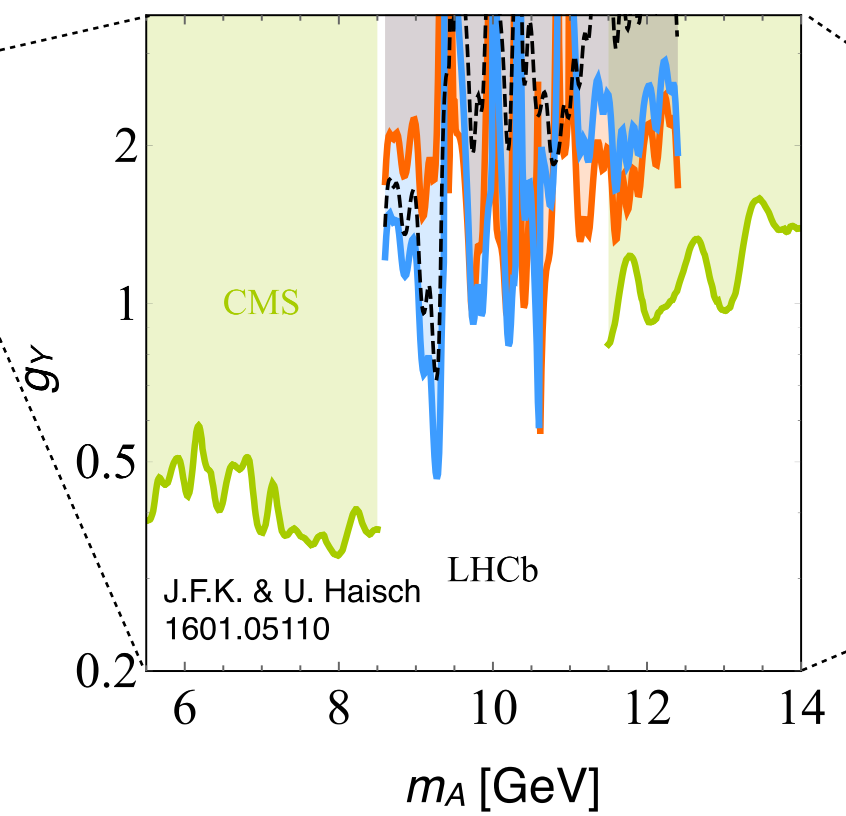


Complementary flavor & high-p_T probes

$A \to f\bar{f}, gg, \gamma\gamma$ dominate, can be probed in different regimes

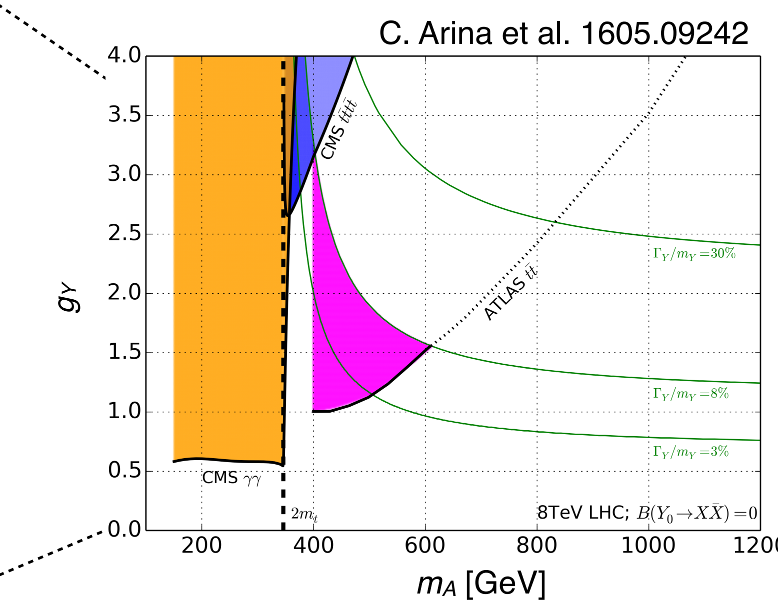


FCNCs dominate bounds at low m_A



$pp \to A \to \mu^+\mu^-$ search for $m_A \sim (10-50)\,\mathrm{GeV}$ (at LHCb!)

see also P. Ilten et al. 1603.08926



High-p_T searches for $m_A \gtrsim 50\,\mathrm{GeV}$ ($\gamma\gamma$, tt)

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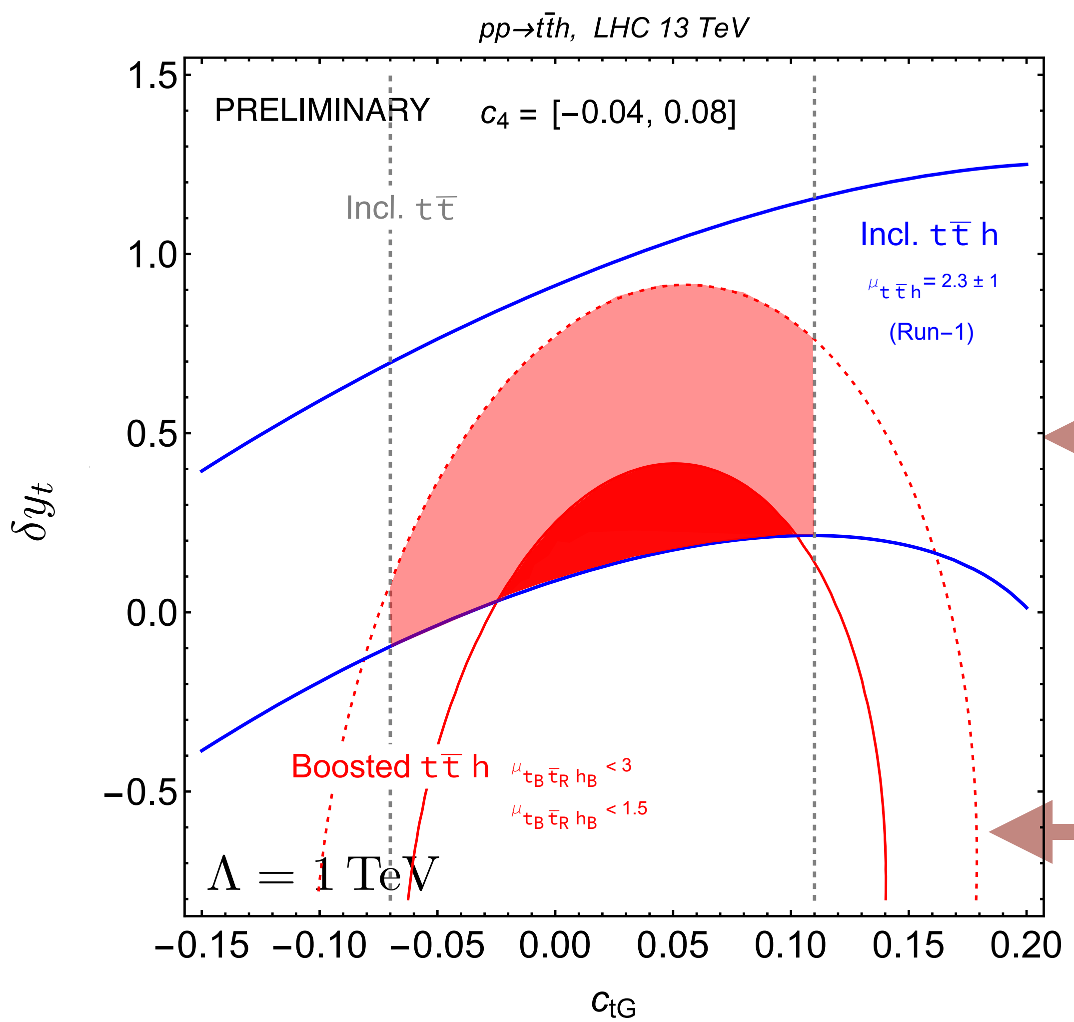
Competitive effects in tth due to y_t and CMDM

Resolve degeneracy using boosted regime



Run-1 combination

Estimate of current sensitivity