

Outlook

Tilman  
Plehn

Data driven

750 GeV

Higgs EFT

Top EFT

DM EFT

Future

# LHC Physics in a Data-Driven Era

Tilman Plehn

Universität Heidelberg

Obergurgl, April 2016

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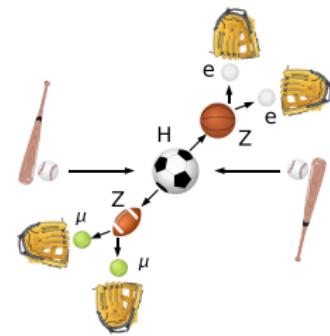
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# Data-driven particle physics

## What is the our Lagrangian?

- post-discovery work we need to do
  - start with renormalizable Standard Model
  - Higgs quantum numbers? [all other particles known?]
  - new physics effects? [Higgs sector]
  - dark matter candidate?
- ⇒ measurements in terms of Lagrangian



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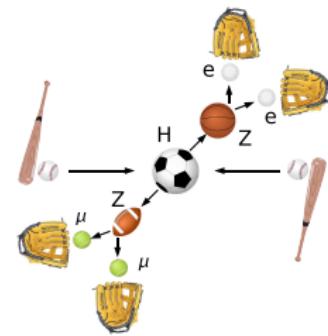
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## Ways to communicate results

- effective theory [lots of discussion on side]  
model-independent description of limits
- simplified models [Felix' and Michael's talks]  
UV-agnostic classification of topologies
- full models  
link to fundamental concepts in UV

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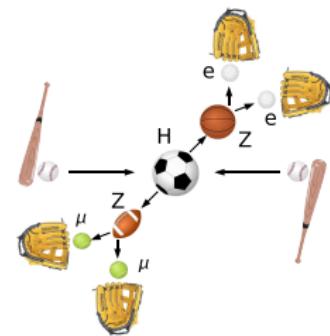
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## What does this tell us?

- effective theory is no fun theory [all theory talks]
- non-minimal Higgs sector? [Martin's talk]
- strongly interacting Higgs models? [Francesco's and Kiel's talks]
- TeV-scale new physics? [Mauricio's and Sezen's talks]
- link to dark matter? [Wednesday talks]
- hierarchy problem? [Brian's talk]
- gauge coupling unification [Sebastian's talk]
- vacuum stability?
- Higgs inflation? ...

⇒ where are the new ideas in particle theory?

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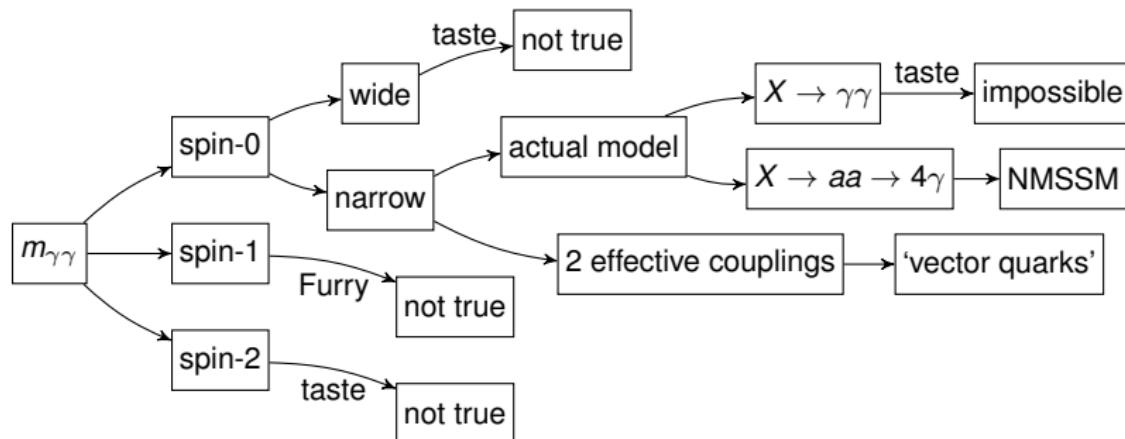
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## The finger to particle theory



My take on all those 750 GeV papers [Veronica's talk]

- open questions due to limited significance
  - general problem: signal rate large
  - largely EFT exercise
  - dimension-5 operators  $XG^{\mu\nu}G_{\mu\nu}$  and  $XA^{\mu\nu}A_{\mu\nu}$  → avoid di-jet constraints
  - gauge invariant  $XB^{\mu\nu}B_{\mu\nu}$  and  $XW^{\mu\nu}W_{\mu\nu}$  → avoid  $VV$  constraints
  - no clear link to other data
- ⇒ great to play with, but only for fun, please

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Navigate wide landscape of limits OR quantifying boredom

- set of Higgs-gauge operators [Hagiwara et al, Grzadkowski et al]

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- relevant part after equation of motion, etc

$$\mathcal{L}^{HVV} = -\frac{\alpha_S V}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_{\Phi,2}}{\Lambda^2} \mathcal{O}_{\Phi,2}$$

- plus Yukawa structure  $f_{\tau,b,t}$

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- plus Yukawa structure  $f_{\tau,b,t}$

- Higgs couplings to SM particles

$$\begin{aligned} \mathcal{L}^{HVV} &= g_g H G_{\mu\nu}^a G^{a\mu\nu} + g_\gamma H A_{\mu\nu} A^{\mu\nu} \\ &+ g_Z^{(1)} Z_{\mu\nu} Z^\mu \partial^\nu H + g_Z^{(2)} H Z_{\mu\nu} Z^{\mu\nu} + g_Z^{(3)} H Z_\mu Z^\mu \\ &+ g_W^{(1)} (W_{\mu\nu}^+ W^{-\mu} \partial^\nu H + \text{h.c.}) + g_W^{(2)} H W_{\mu\nu}^+ W^{-\mu\nu} + g_W^{(3)} H W_\mu^+ W^{-\mu} + \dots \end{aligned}$$

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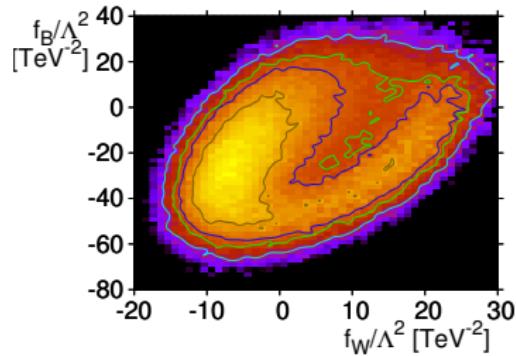
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- ew-renormalizable hypothesis
- kinematics:  $p_{T,\nu}$ ,  $\Delta\Phi_{jj}$



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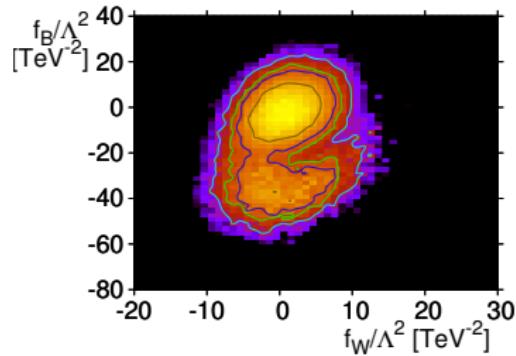
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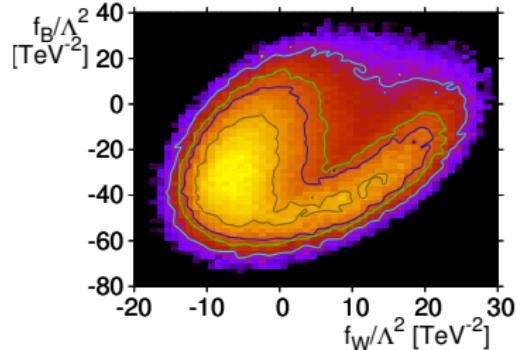
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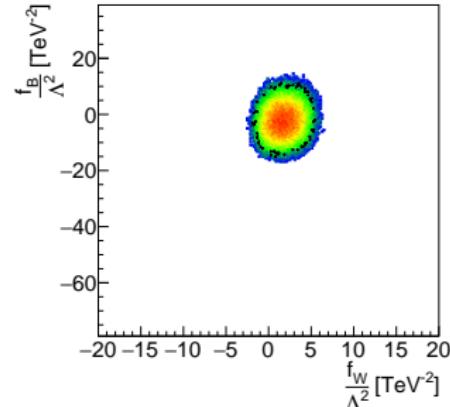
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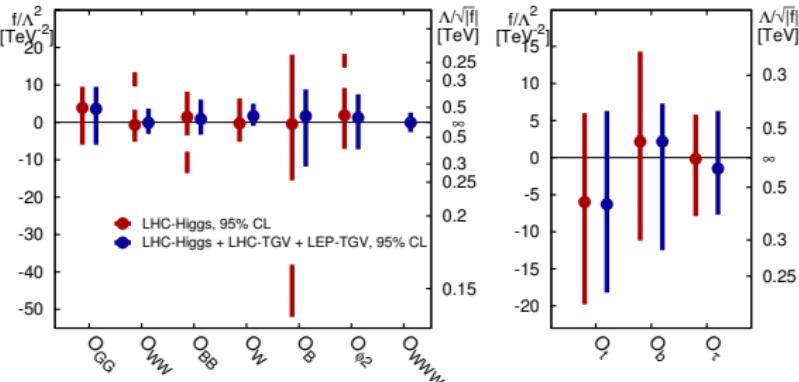
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- (1) D6 fit works
- (2) D6 is not EFT
- (3) D6 needs Higgs+TGV
- (4) D6 reach  $\sim 500$  GeV



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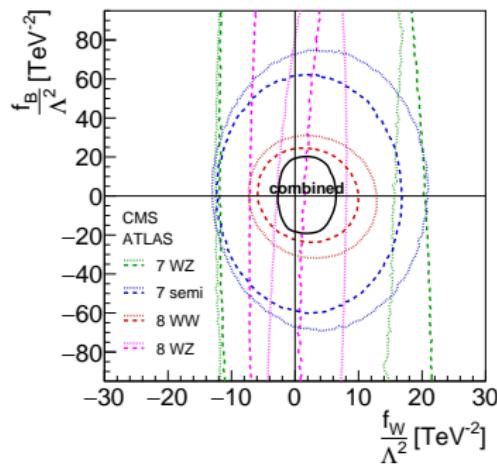
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Triple gauge couplings [Butter, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, TP]

- triple gauge vertices  $g_1, \kappa, \lambda$  vs operators
- testable in  $WW$ ,  $WZ$  production [Christian's talk]
- semileptonic analyses missing for 8 TeV

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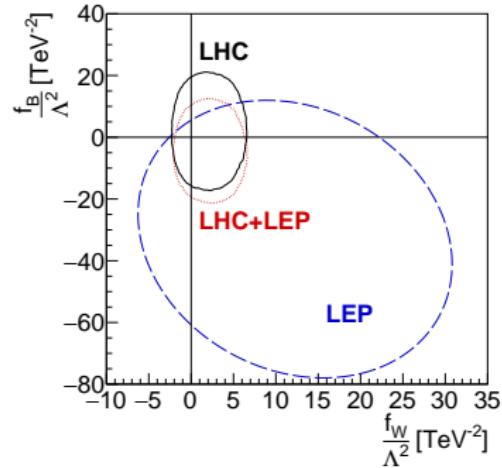
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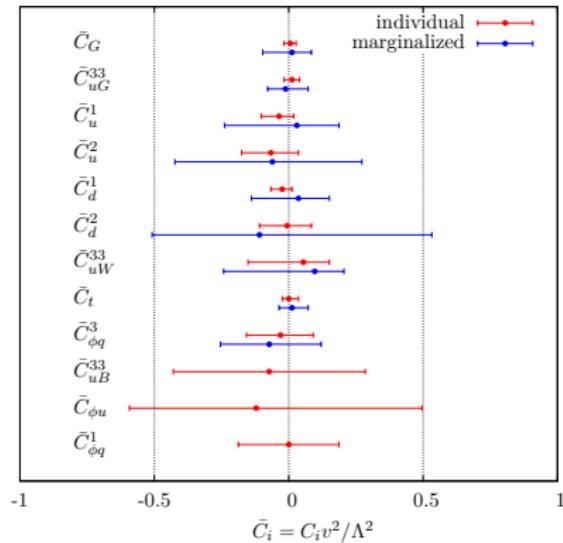
Same for tops OR more boredom [TopFitter: Buckley, Englert, Ferrando, Miller, Moore, Russell, White]

- single, pair-wise, and associated top production [plus decays]
- including anomalous  $A_{FB}$  from Tevatron
- 4-quark, Yang-Mills, electroweak operators

$$\mathcal{O}_{qq} = \bar{q}\gamma_\mu q \bar{t}\gamma^\mu t \quad \mathcal{O}_G = f_{ABC} G_\mu^{A\nu} G_\nu^{B\lambda} G_\lambda^{C\mu} \quad \mathcal{O}_{\phi G} = \Phi^\dagger \Phi G_{\mu\nu}^a G^{a\mu\nu} \dots$$

- profile likelihoods and individual limits

$\Rightarrow$  D6 reach  $\sim 500$  GeV [ $C = 1$ ]



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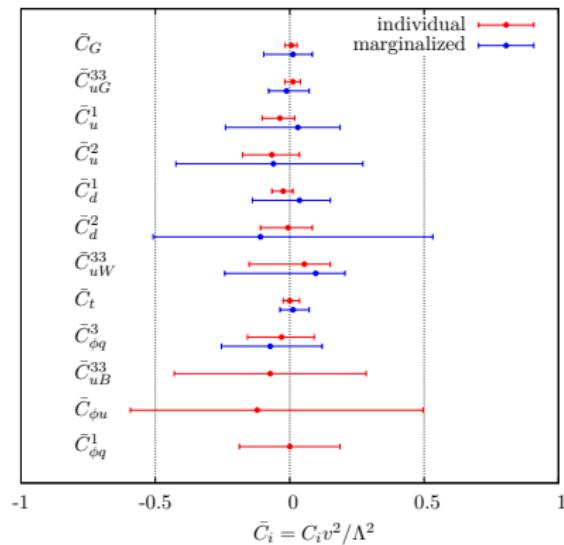
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- profile likelihoods and individual limits
- $\Rightarrow$  D6 reach  $\sim 500$  GeV [ $C = 1$ ]

For theorists: in terms of models

- axigluon:  $M_A > 1.4$  TeV [ $t\bar{t}$  resonance]
  - SM-like  $W'$ :  $M_{W'} > 1.2$  TeV [ $t$ -channel,...]
- $\Rightarrow$  models less sensitive to correlations



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# Dark matter effective theory

## Combining direct, indirect, (collider) results

[Liem, Bertone, Calore, Ruiz de Austri, Tait, Trotta, Weniger]

- Fermi: dwarf galaxies
- assume scalar dark matter
- assume single scale  $m_\chi \ll m_{\text{med}}$
- mediating operators

Label	Coefficient	Operator	$\sigma_{\text{SI}} \langle \sigma_{\text{ann}} v \rangle$
Real scalar			
R1	$\lambda_1 \sim 1/(2M^2)$	$m_q \chi^2 \bar{q} q$	✓ s-wave
R2	$\lambda_2 \sim 1/(2M^2)$	$i m_q \chi^2 \bar{q} \gamma^5 q$	s-wave
R3	$\lambda_3 \sim \alpha_s/(4M^2) \chi^2 G_{\mu\nu} G^{\mu\nu}$		✓ s-wave
R4	$\lambda_4 \sim \alpha_s/(4M^2) i \chi^2 G_{\mu\nu} \tilde{G}^{\mu\nu}$		s-wave
Complex scalar			
C1	$\lambda_1 \sim 1/(M^2)$	$m_q \chi^\dagger \chi \bar{q} q$	✓ s-wave
C2	$\lambda_2 \sim 1/(M^2)$	$i m_q \chi^\dagger \chi \bar{q} \gamma^5 q$	s-wave
C3	$\lambda_3 \sim 1/(M^2)$	$\chi^\dagger \partial_\mu \chi \bar{q} \gamma^\mu q$	✓ p-wave
C4	$\lambda_4 \sim 1/(M^2)$	$\chi^\dagger \partial_\mu \chi \bar{q} \gamma^\mu \gamma^5 q$	p-wave
C5	$\lambda_5 \sim \alpha_s/(8M^2) \chi^\dagger \chi G_{\mu\nu} G^{\mu\nu}$		✓ s-wave
C6	$\lambda_6 \sim \alpha_s/(8M^2) i \chi^\dagger \chi G_{\mu\nu} \tilde{G}^{\mu\nu}$		s-wave

# Dark matter effective theory

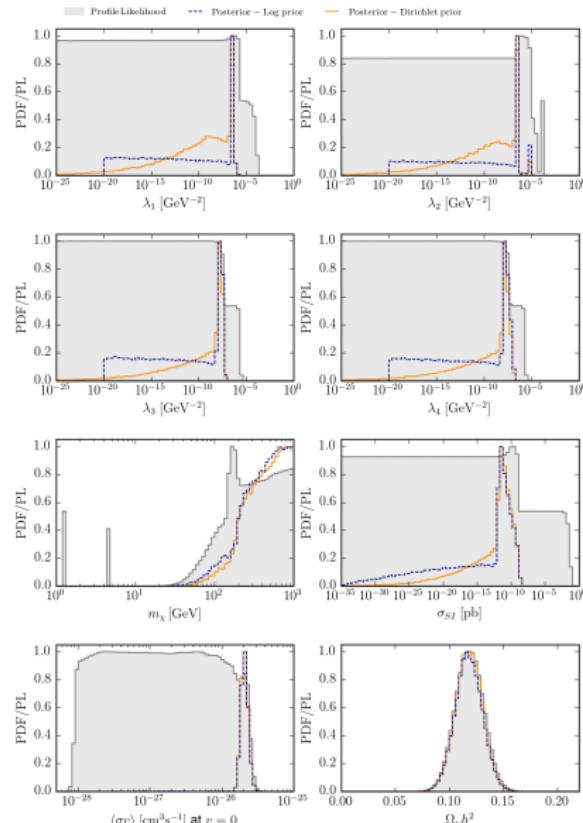
## Combining direct, indirect, (collider) results

[Liem, Bertone, Calore, Ruiz de Austri, Tait, Trotta, Weniger]

- Fermi: dwarf galaxies
- assume scalar dark matter
- assume single scale  $m_\chi \ll m_{\text{med}}$
- mediating operators

Label	Coefficient	Operator	$\sigma_{SI} \langle \sigma_{\text{ann}} v \rangle$
Real scalar			
R1	$\lambda_1 \sim 1/(2M^2)$	$m q \chi^2 \bar{q} q$	✓ s-wave
R2	$\lambda_2 \sim 1/(2M^2)$	$i m q \chi^2 \bar{q} \gamma^5 q$	s-wave
R3	$\lambda_3 \sim \alpha_S/(4M^2)$	$\chi^2 G_{\mu\nu} G^{\mu\nu}$	✓ s-wave
R4	$\lambda_4 \sim \alpha_S/(4M^2)$	$i \chi^2 G_{\mu\nu} \tilde{G}^{\mu\nu}$	s-wave
Complex scalar			
C1	$\lambda_1 \sim 1/(M^2)$	$m q \chi^\dagger \chi \bar{q} q$	✓ s-wave
C2	$\lambda_2 \sim 1/(M^2)$	$i m q \chi^\dagger \chi \bar{q} \gamma^5 q$	s-wave
C3	$\lambda_3 \sim 1/(M^2)$	$\chi^\dagger \partial_\mu \chi \bar{q} \gamma^\mu q$	✓ p-wave
C4	$\lambda_4 \sim 1/(M^2)$	$\chi^\dagger \partial_\mu \chi \bar{q} \gamma^\mu \gamma^5 q$	p-wave
C5	$\lambda_5 \sim \alpha_S/(8M^2)$	$\chi^\dagger \chi G_{\mu\nu} G^{\mu\nu}$	✓ s-wave
C6	$\lambda_6 \sim \alpha_S/(8M^2)$	$i \chi^\dagger \chi G_{\mu\nu} \tilde{G}^{\mu\nu}$	s-wave

- flat prior on  $\log \lambda_i$  [prior  $1/\lambda_i$ ]
- Dirichlet prior around  $\log \lambda_i$



# Dark matter effective theory

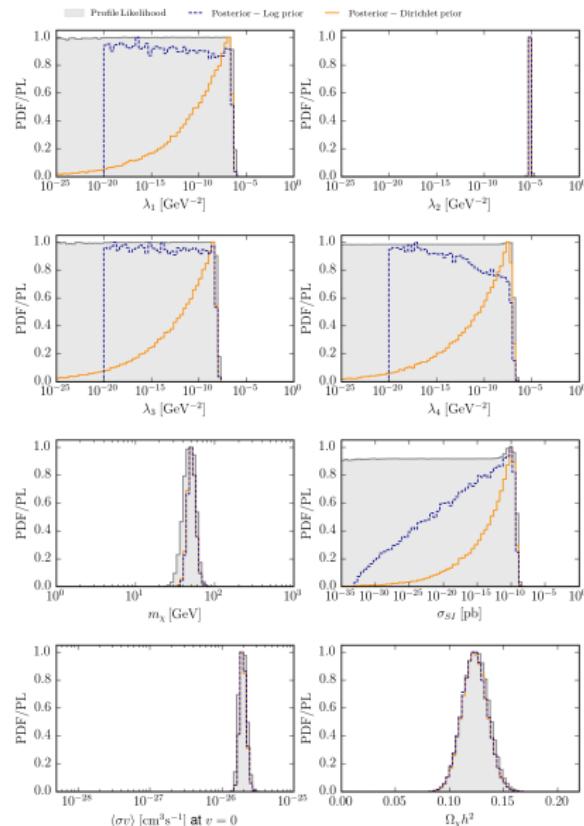
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- flat prior on  $\log \lambda_i$  [prior  $1/\lambda_i$ ]
  - Dirichlet prior around  $\log \lambda_i$
  - new physics from Fermi GCE [Krämer et al]
- ⇒ with data, the method hardly matters...



Outlook

Tilman  
Plehn

Data driven

750 GeV

Higgs EFT

Top EFT

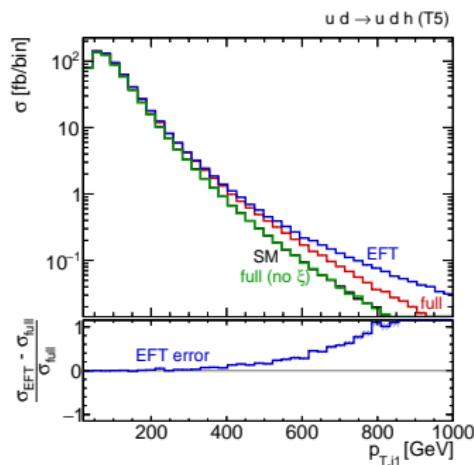
DM EFT

Future

# Beyond effective theories

## Higgs/top effective theory at LHC [Biekötter, Brehmer, Freitas, TP, Lopez-Val]

- breakdown if observables disagree with full model [given measurement errors]  
large individual D8-operators not good test
- most critical vector gauge extensions
- no problem [ $E < M/g$  linked to convergence]



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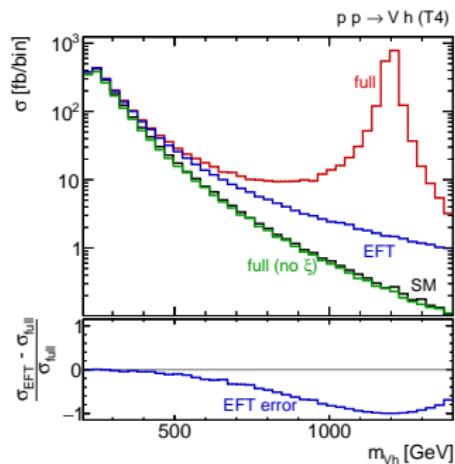
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Future

# Beyond effective theories

## Higgs/top effective theory at LHC [Biekötter, Brehmer, Freitas, TP, Lopez-Val]

- breakdown if observables disagree with full model [given measurement errors]  
large individual D8-operators not good test
  - most critical vector gauge extensions
  - serious problem [ $E < M$  linked to pole]
- ⇒ D6 in terms of  $g^2/\Lambda^2$  dying by poles



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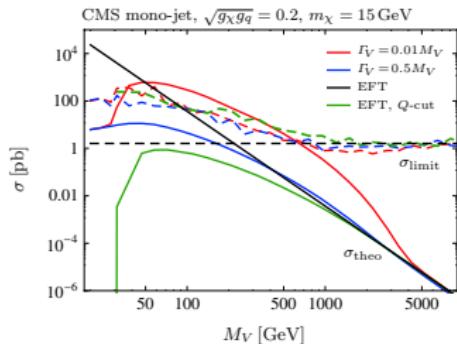
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- ⇒ **D6 in terms of  $g^2/\Lambda^2$  dying by poles**

## DM effective theory at LHC: kinematics [Heisig, Krämer, Pellen, Wiebusch]

- extending DM effective theory to LHC [range of energy scales]
- Majorana dark matter in EFT
- vector mediator in simplified model [Felix' talk]

$$\mathcal{L} \supset g_\chi \bar{\chi} \gamma^\mu \gamma^5 \chi V_\mu + g_q \bar{q} \gamma^\mu \gamma^5 q V_\mu$$

- comparison EFT vs simplified model in detail
- ⇒ **D6 description kind of okay??** [Manfred's talk]



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# Beyond the LHC

**Higgs factory** [250 GeV,  $10 \text{ ab}^{-1}$  or 500 GeV,  $500 \text{ fb}^{-1}$ , Jennie's talk]

- theoretically and experimentally clean
  - Higgs couplings at per-cent level
  - energy vs luminosity vs cost optimization, systematics/theory wall?
- ⇒ **politics-limited**

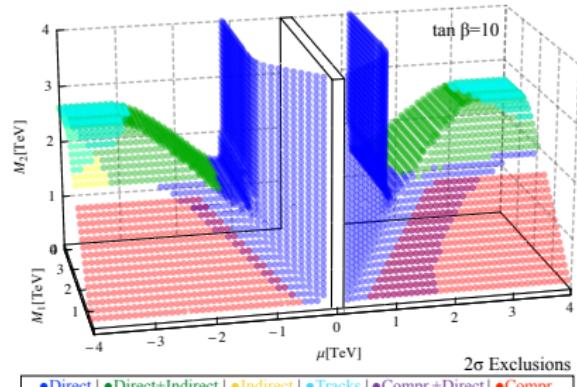
**multi-TeV  $e^+e^-$  collider/CLIC** [5 TeV,  $2 \text{ ab}^{-1}$ ]

- charged particle searches to 2.5 TeV
  - perfect WIMP machine?
- ⇒ **momentum-limited** [25 pages physics case in CDR??]

**100 TeV hadron collider** [ $20 \text{ ab}^{-1}$ ]

- precision Higgs physics:  $y_t$  and  $\lambda_{HHH}$
- massless  $W, Z$  physics
- WIMP dark matter with  $m_\chi \lesssim 2 \text{ TeV}$
- stops to 10 TeV,  $Z'$  to 30 TeV
- scalar flavon to few TeV
- tests of baryogenesis

⇒ **funding-limited** [BSM writeup with 150 pages]



**Outlook**

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