Looking for New Physics Run2 LHC

NBI Current Themes in High-Energy Physics and Cosmology

Veronica Sanz (Sussex)

Why New Physics?

Ironclad evidence

Dark Universe

Neutrinos

Matter-antimatter asymmetry

Why New Physics?

Theoretical conundrums

Fundamental scalars

Flavour puzzle

Cosmological Constant

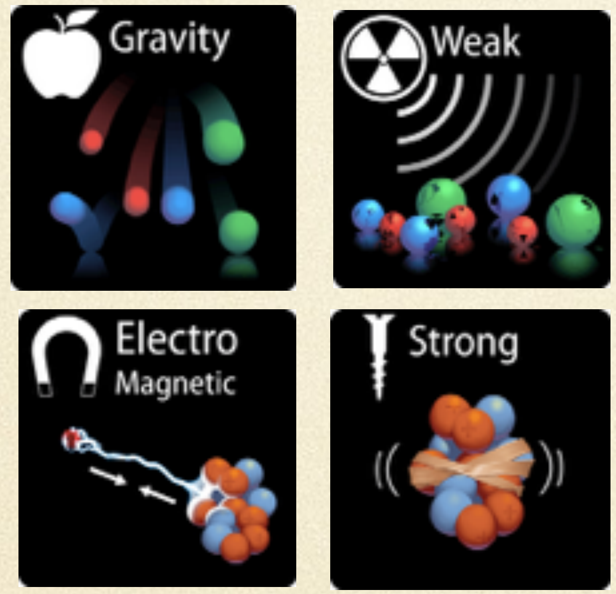
Why now

Inflation

Quantum Gravity…

New Physics=New Particles?

+



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Quantum mechanics, Lorentz invariance, unitarity, locality, gauge and global symmetries, spontaneous symmetry breaking...

New Physics = understand something new

new principles in Nature

need a discovery to guide the way

Which New Physics?

Theorist's dream

Beautiful theory

mathematical consistency

explains it all

and

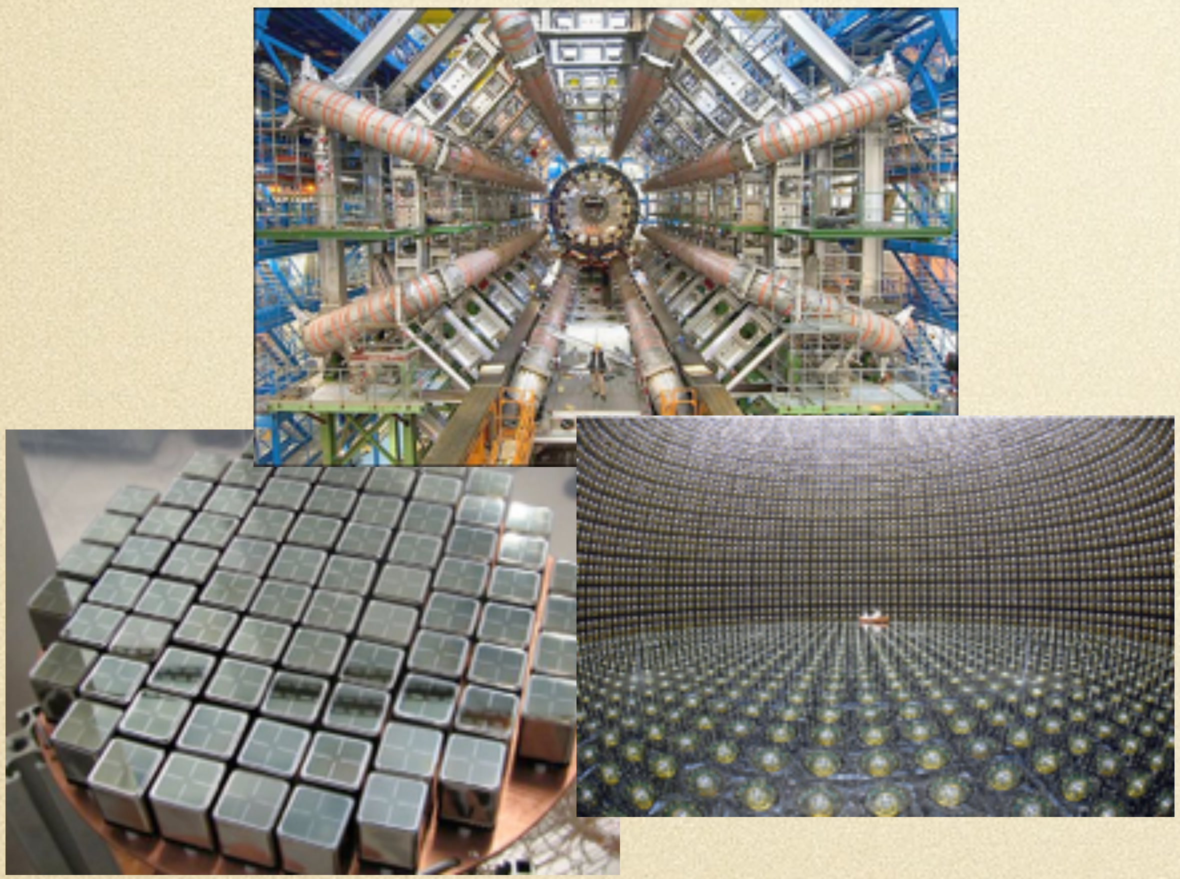
predicts new phenomena

experiments verify it

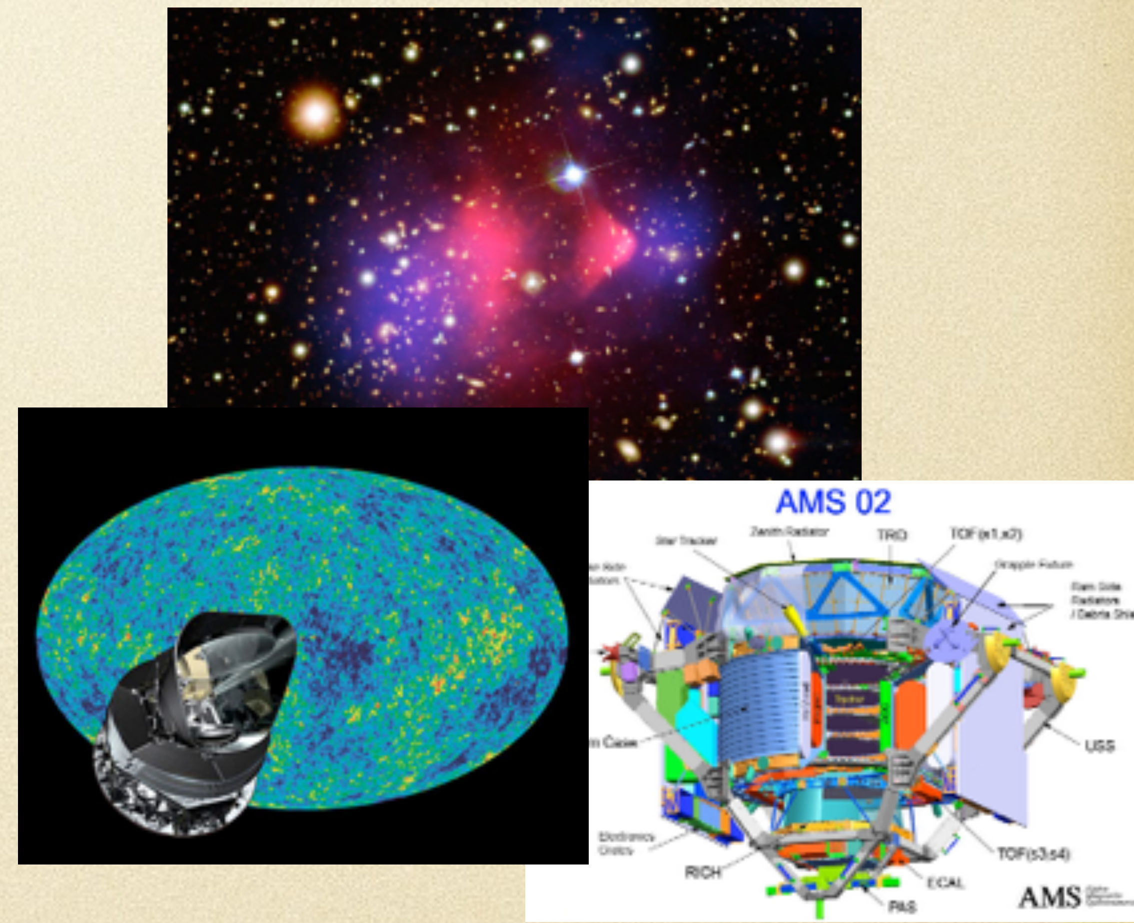
Which New Physics?

Toc, toc, Nature?

EARTH



SPACE



talks by Katie and Subir

In this talk: **focus on LHC**

Outline

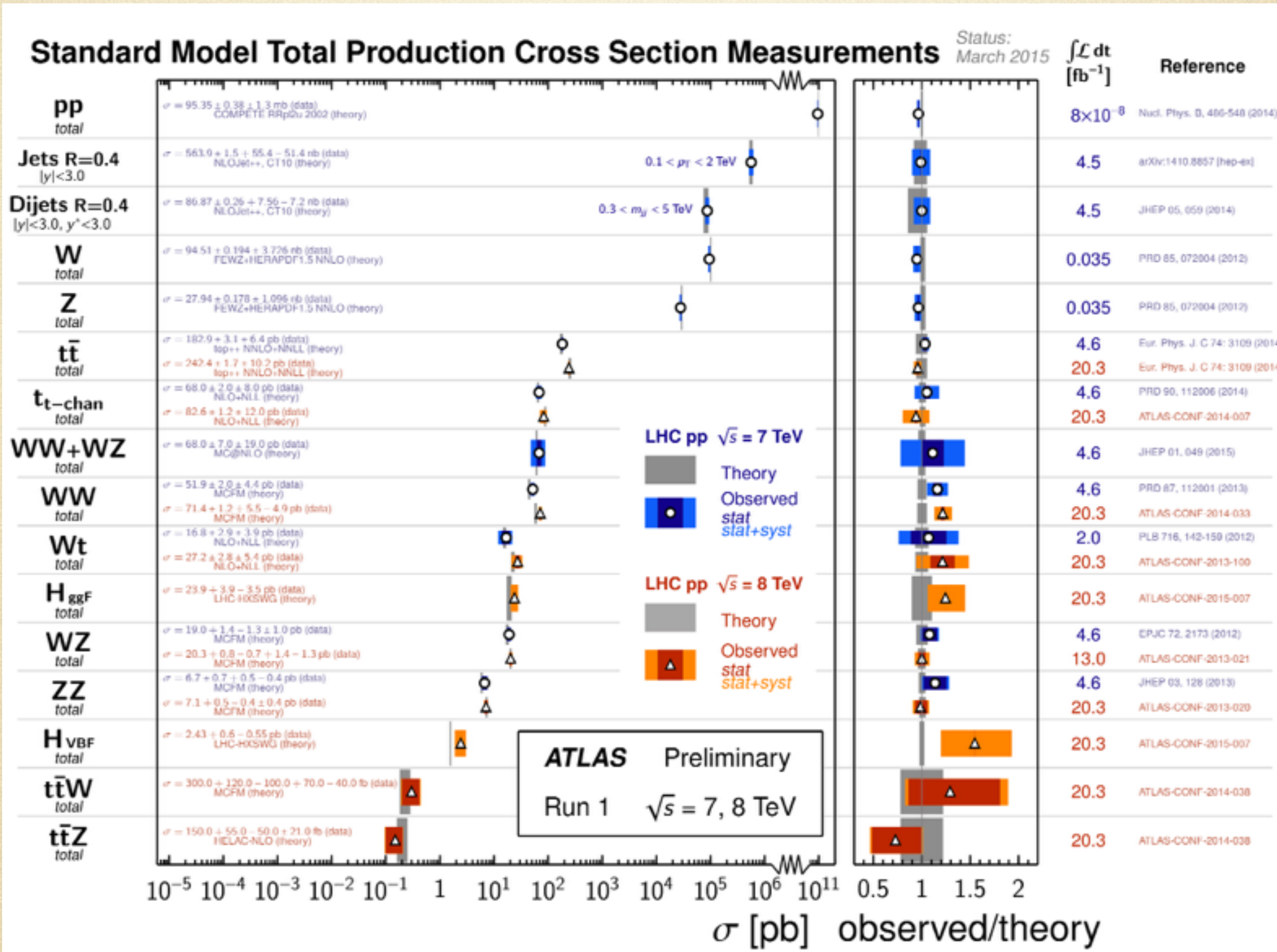
- Run1
- Run2
- Where is New Physics?
- How do we probe the unknown
- Direct vs indirect
- Complementarity of LHC

Run 1

What we know so far

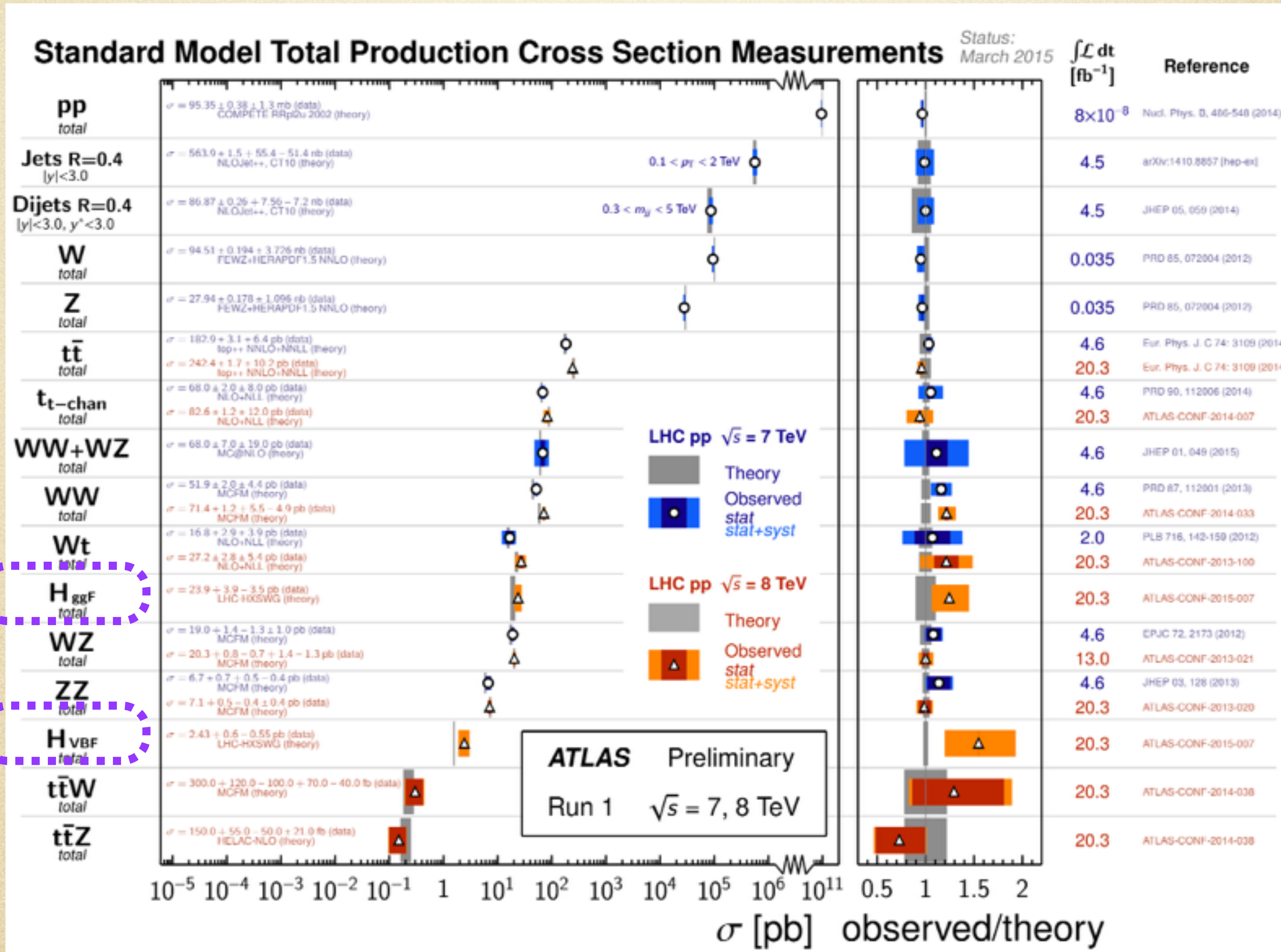
After Run1

SM healthier than ever



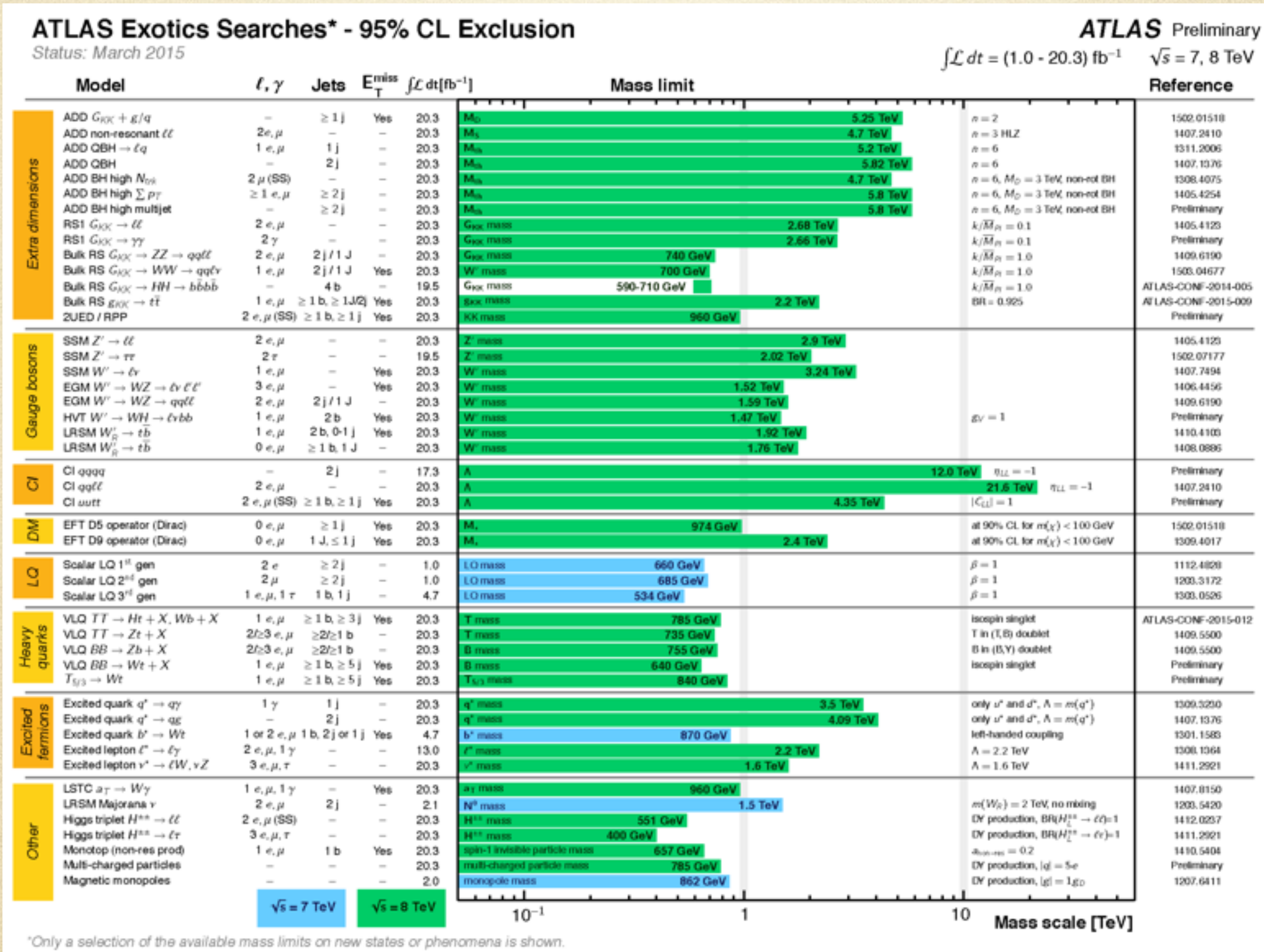
After Run 1

SM healthier than ever



No stone unturned

Experiments are not just focused on Higgs and vanilla SUSY

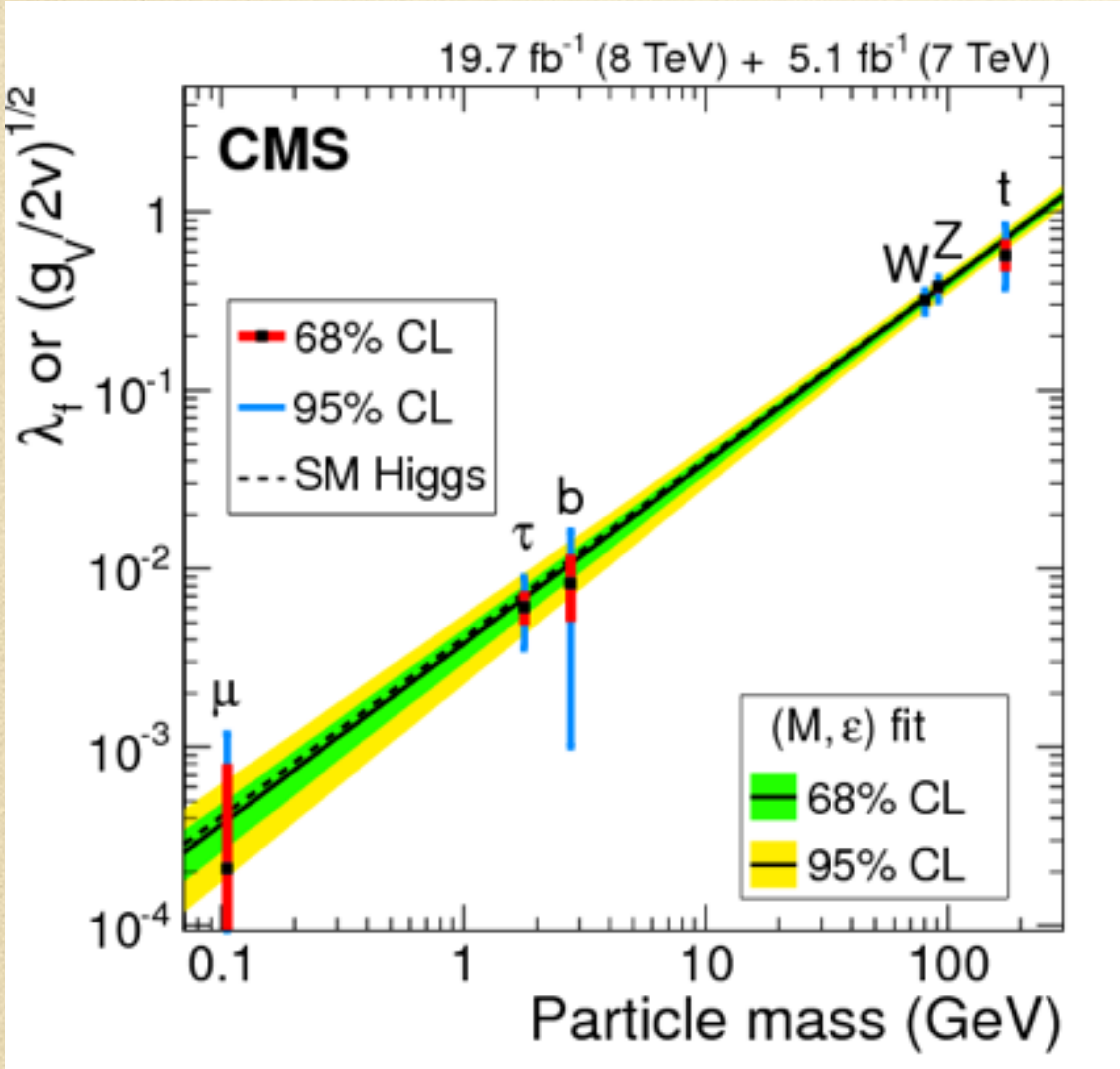


Some have a feeling of doom

which I don't share

Higgs is here

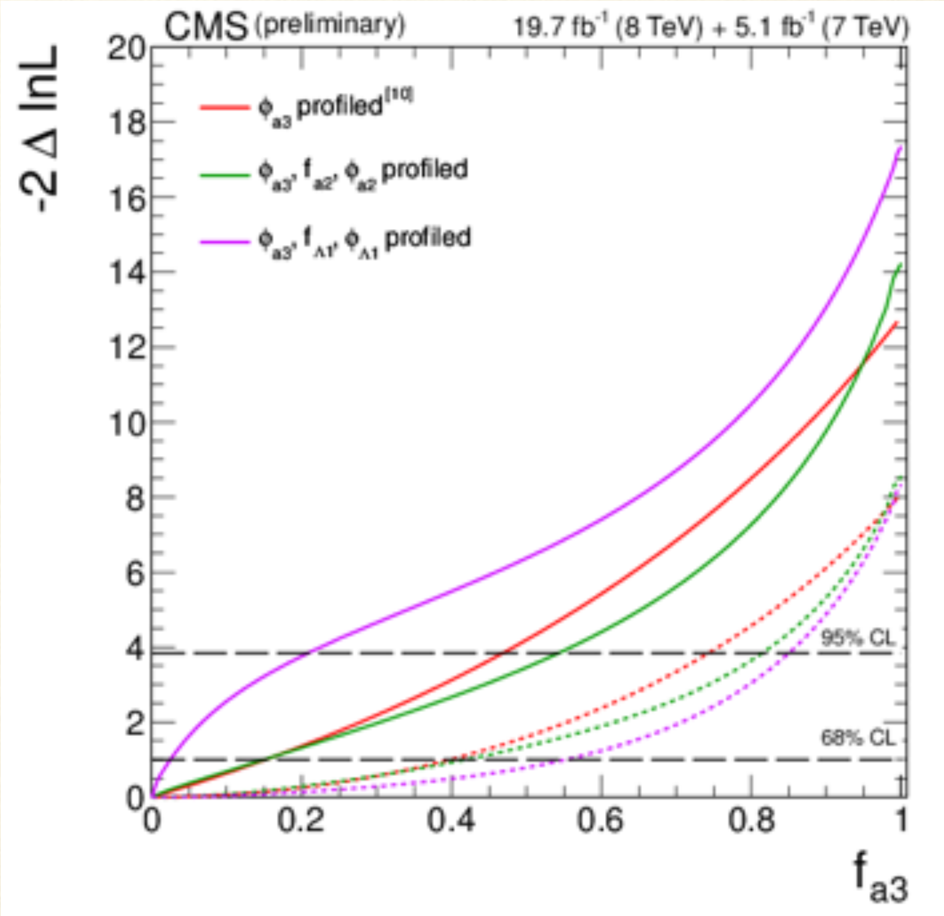
seems quite SM-like



yet

linear vs non-linear

CP admixture ~ 30-50%?



Not surprising

~heavy new physics

How heavy? EFT

e.g. Ellis, VS and You. 1404.3667, 1410.7703

one-by-one global

Operator	Coefficient	LHC Constraints Individual	LHC Constraints Marginalized
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\partial^\nu B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}(c_W - c_B)$	$(-0.022, 0.004)$	$(-0.035, 0.005)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}c_{HW}$	$(-0.042, 0.008)$	$(-0.035, 0.015)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}c_{HB}$	$(-0.053, 0.044)$	$(-0.045, 0.075)$
$\mathcal{O}_{3W} = \frac{1}{3!}g\epsilon_{abc}W^{a\nu}_\mu W^b_{\nu\rho}W^{c\rho\mu}$	$\frac{m_W^2}{\Lambda^2}c_{3W}$	$(-0.083, 0.045)$	$(-0.083, 0.045)$
$\mathcal{O}_g = g_s^2\lvert H\rvert^2 G^A_{\mu\nu}G^{A\mu\nu}$	$\frac{m_W^2}{\Lambda^2}c_g$	$(0, 3.0)\times 10^{-5}$	$(-3.2, 1.1)\times 10^{-4}$
$\mathcal{O}_\gamma = g'^2\lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}c_\gamma$	$(-4.0, 2.3)\times 10^{-4}$	$(-11, 2.2)\times 10^{-4}$
$\mathcal{O}_H = \frac{1}{2}(\partial^\mu\lvert H\rvert^2)^2$	$\frac{v^2}{\Lambda^2}c_H$	$(-0.14, 0.194)$	$(-,-)$
$\mathcal{O}_f = y_f\lvert H\rvert^2\bar{F}_L H^{(c)} f_R + \text{h.c.}$	$\frac{v^2}{\Lambda^2}c_f$	$(-0.084, 0.155)(c_u)$ $(-0.198, 0.088)(c_d)$	$(-,-)$ $(-,-)$

stronger in classes of models

e.g. extended Higgs sectors

Gorbahn, No, VS. 1502.07352

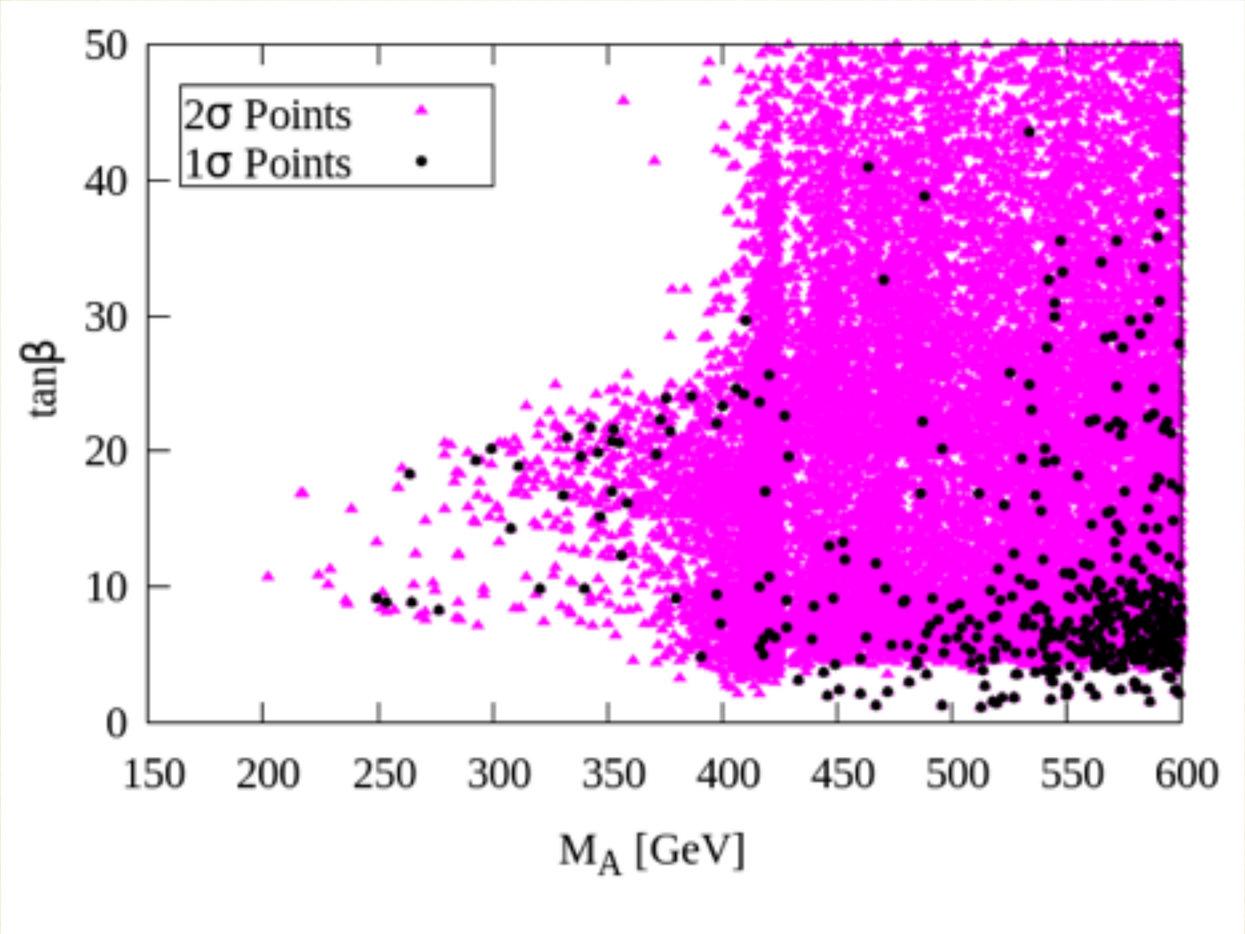
$$\bar{c}_W \in -(0.02, 0.0004)$$
$$\bar{c}_g \in -(0.00004, 0.000003)$$
$$\bar{c}_\gamma \in -(0.0006, -0.00003)$$

still nowhere close the TeV

How heavy? SUSY

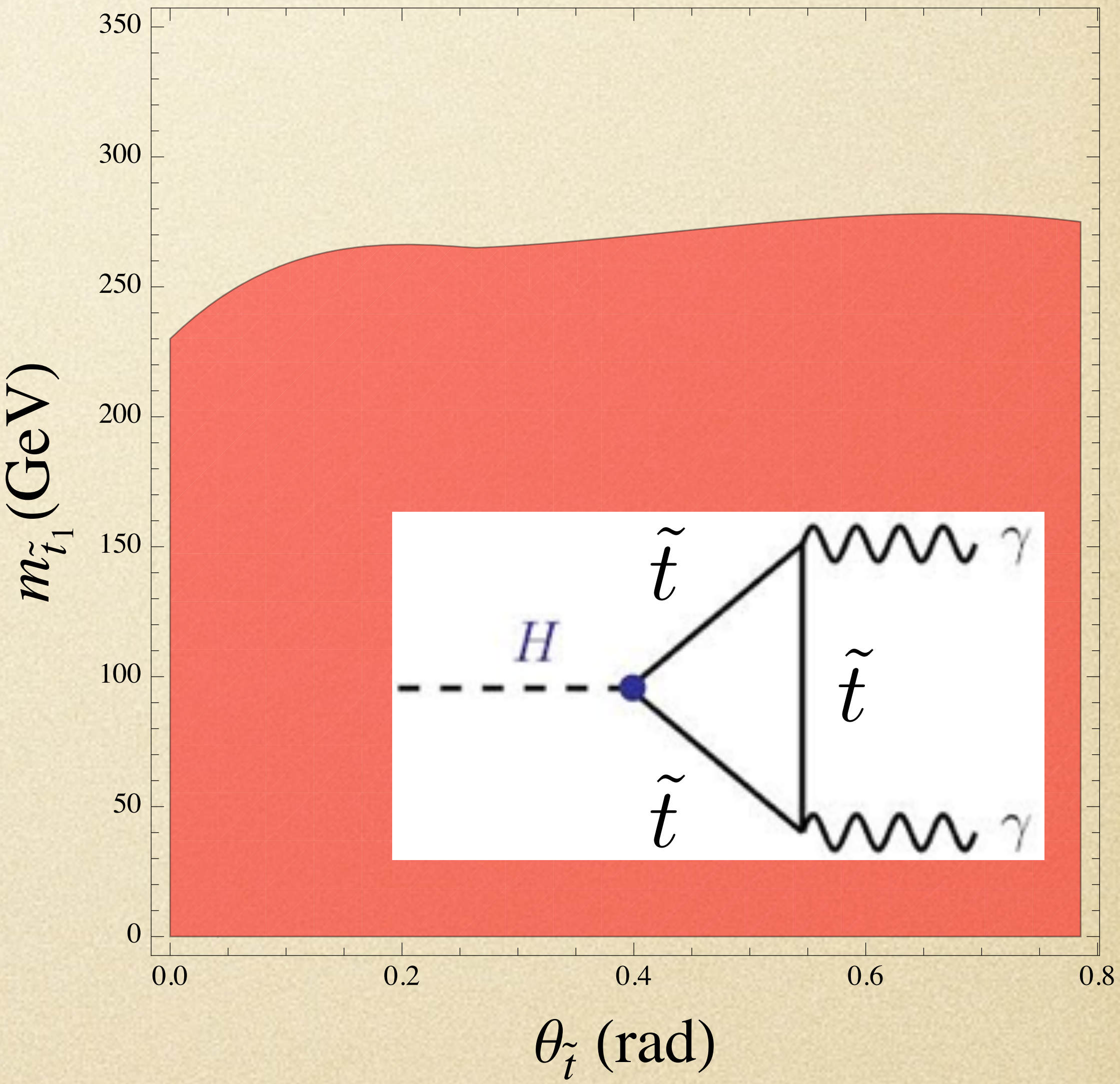
Higgs data, B-decays, mW

HEAVY HIGGSES



STOPS

Stop Exclusion vs Mixing

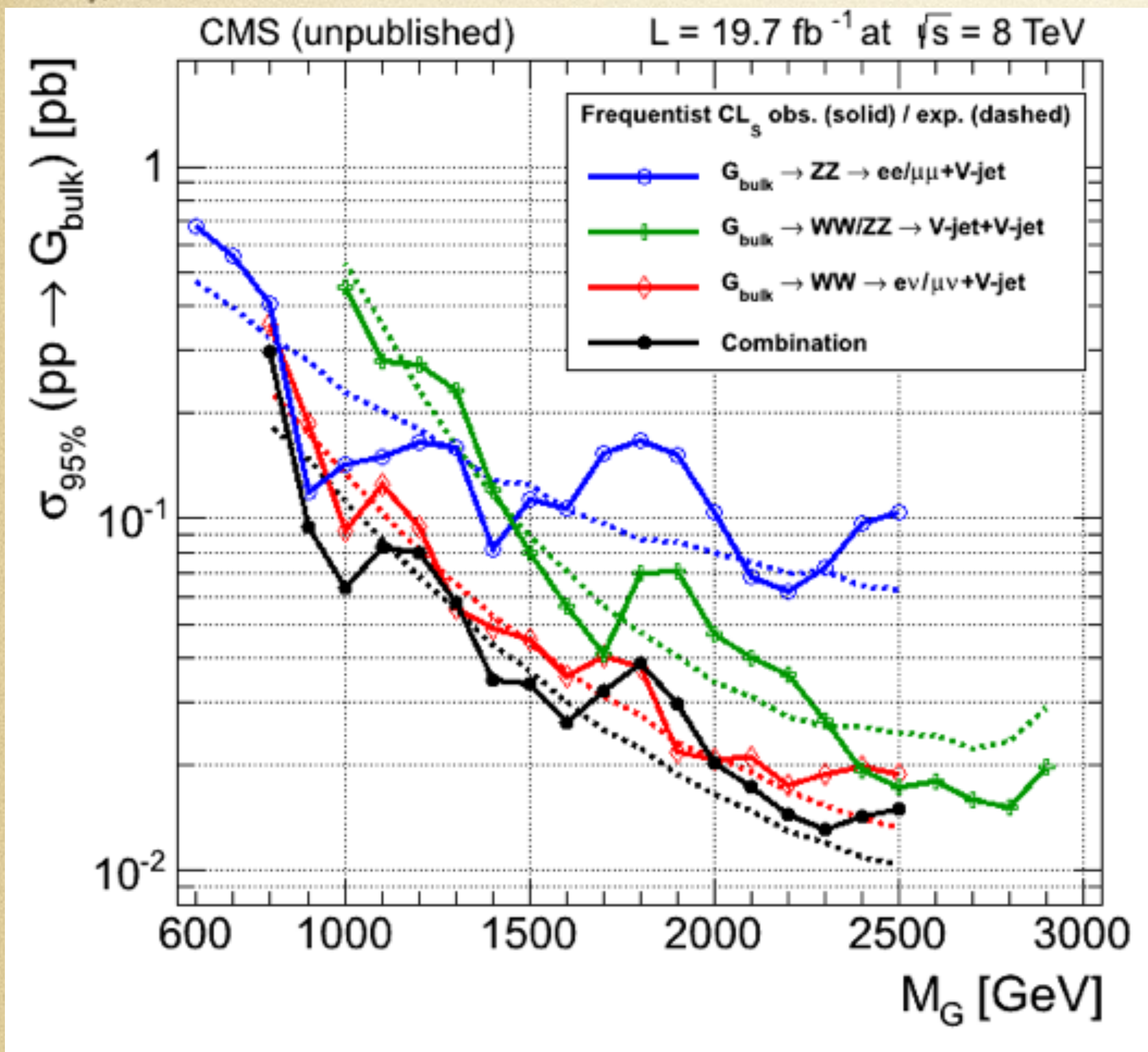


Battacherjee, Chakaborty, Choudhury. 1504.04398 Espinosa, Grojean, VS, Trott. 1207.7355

Rumours, rumours

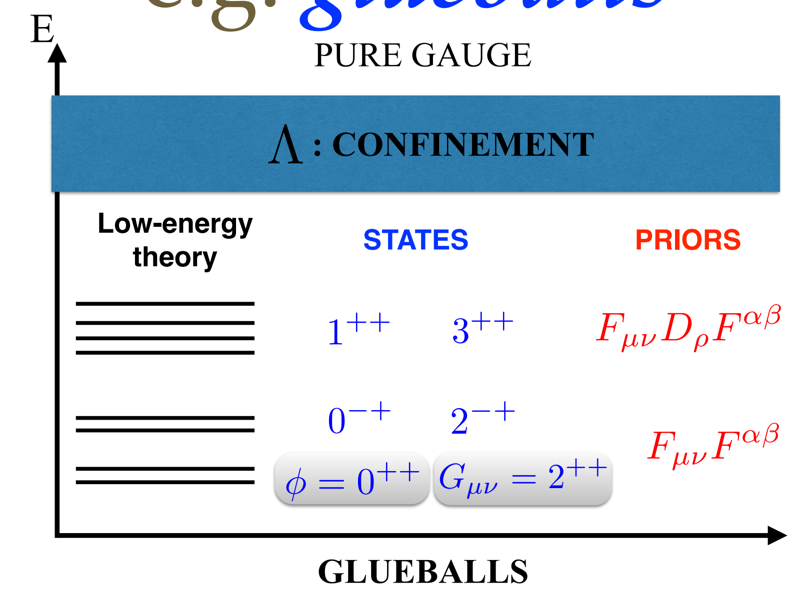
some 2-3 sigmas, as they should

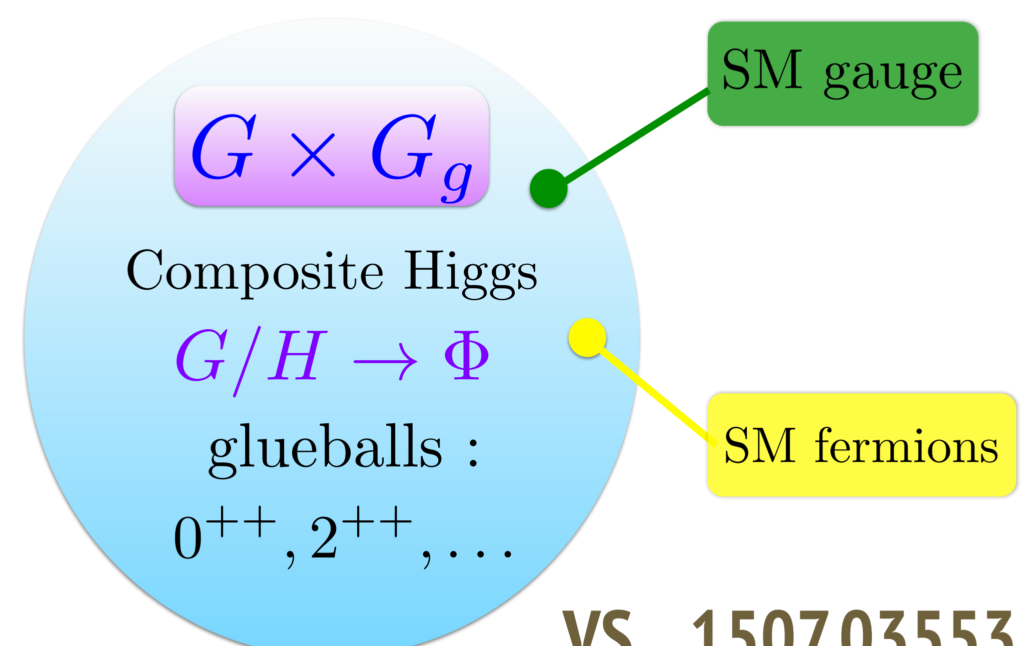
e.g. di-boson resonance at 2 TeV



many possible explanations

e.g. *glueballs*



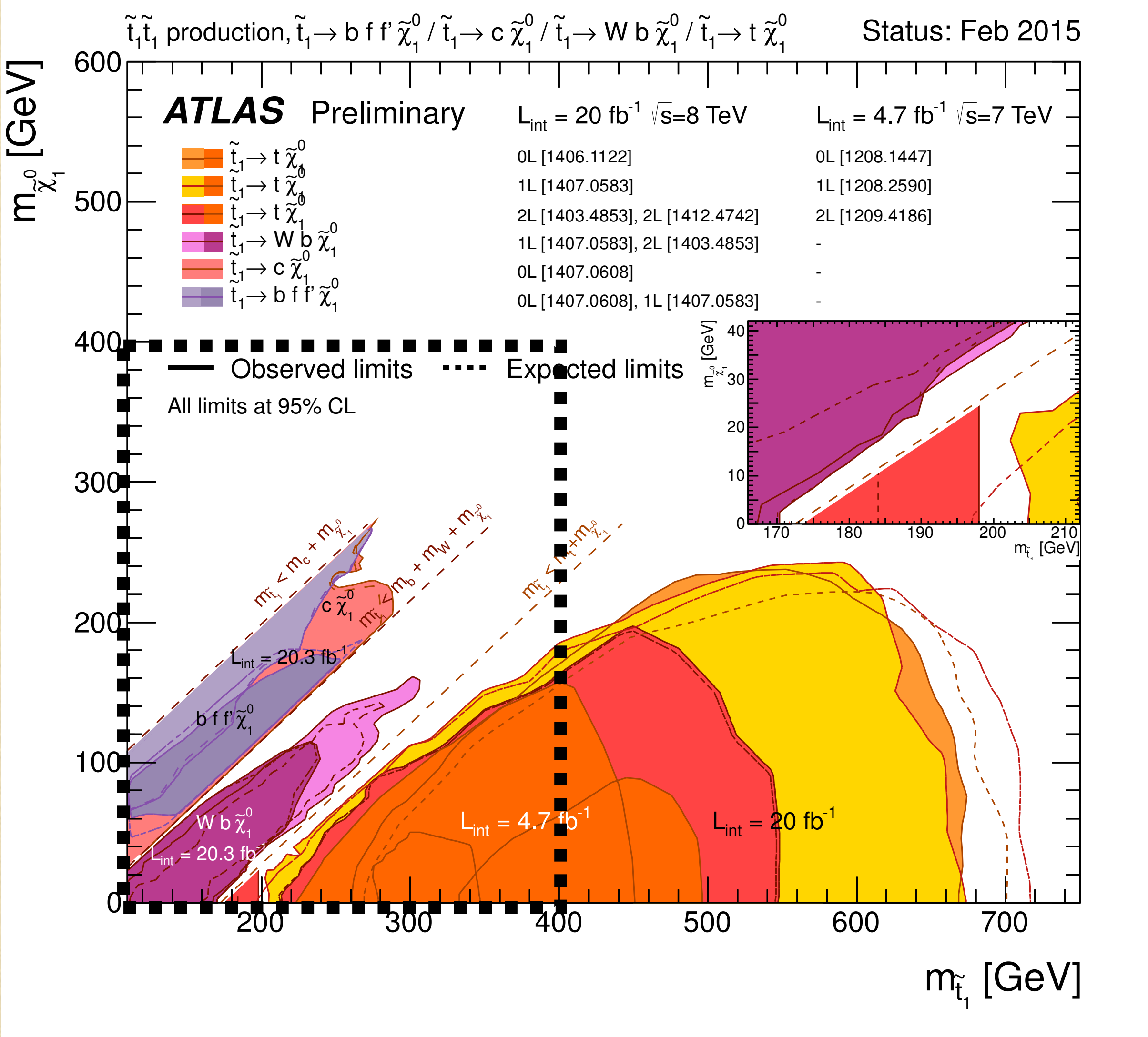


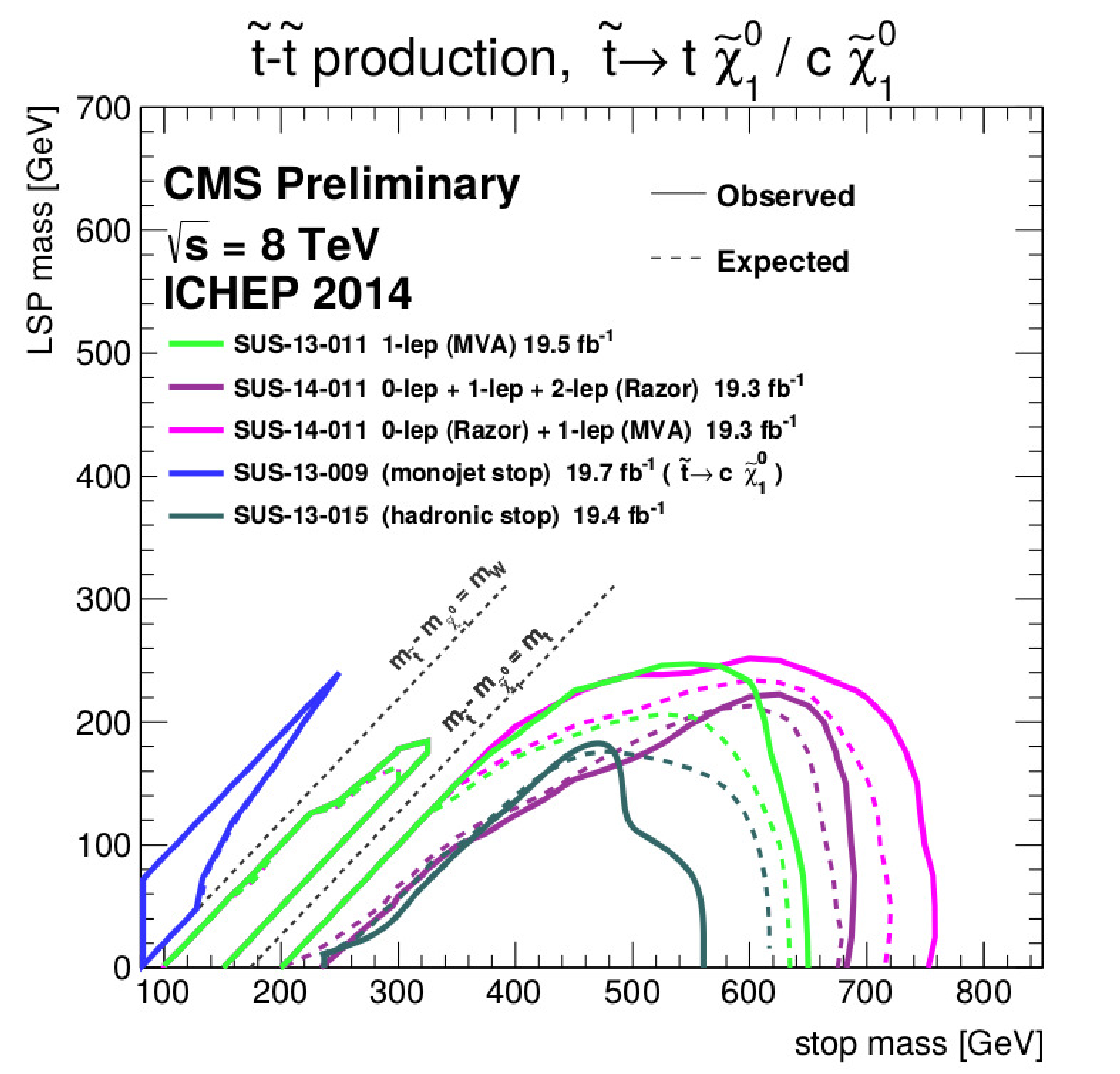
VS. 1507.03553

Direct searches

game is just starting, even for Natural SUSY

e.g. limits on stops





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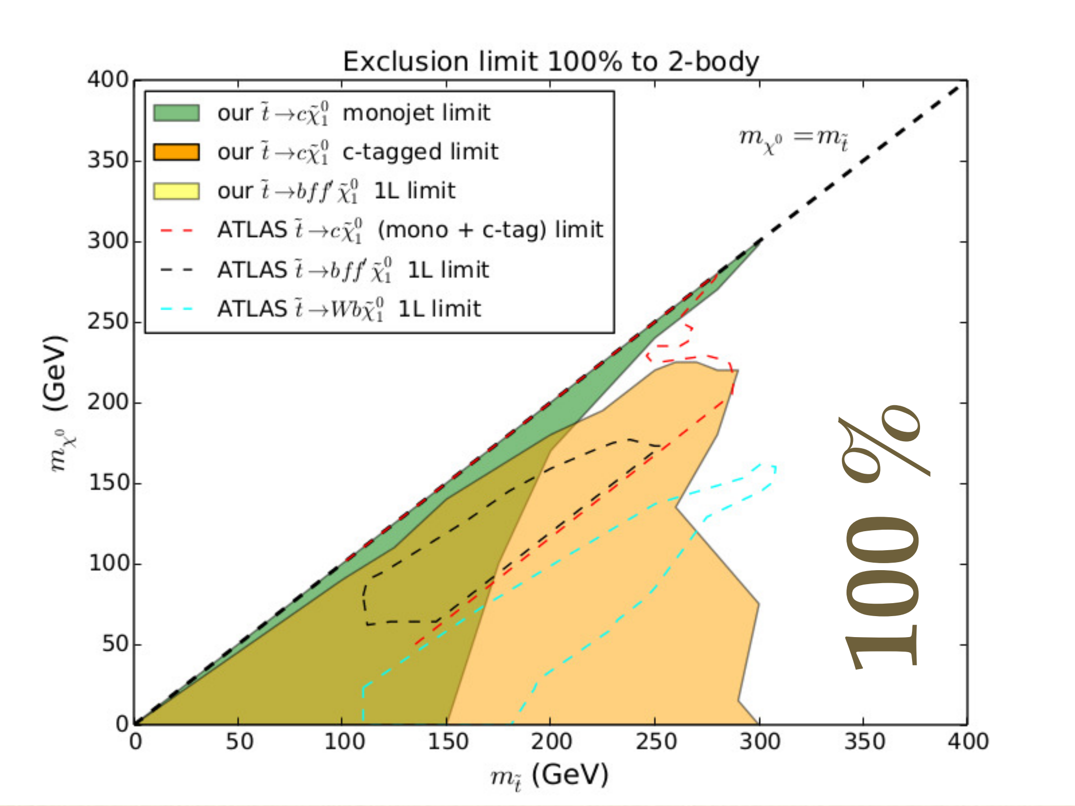
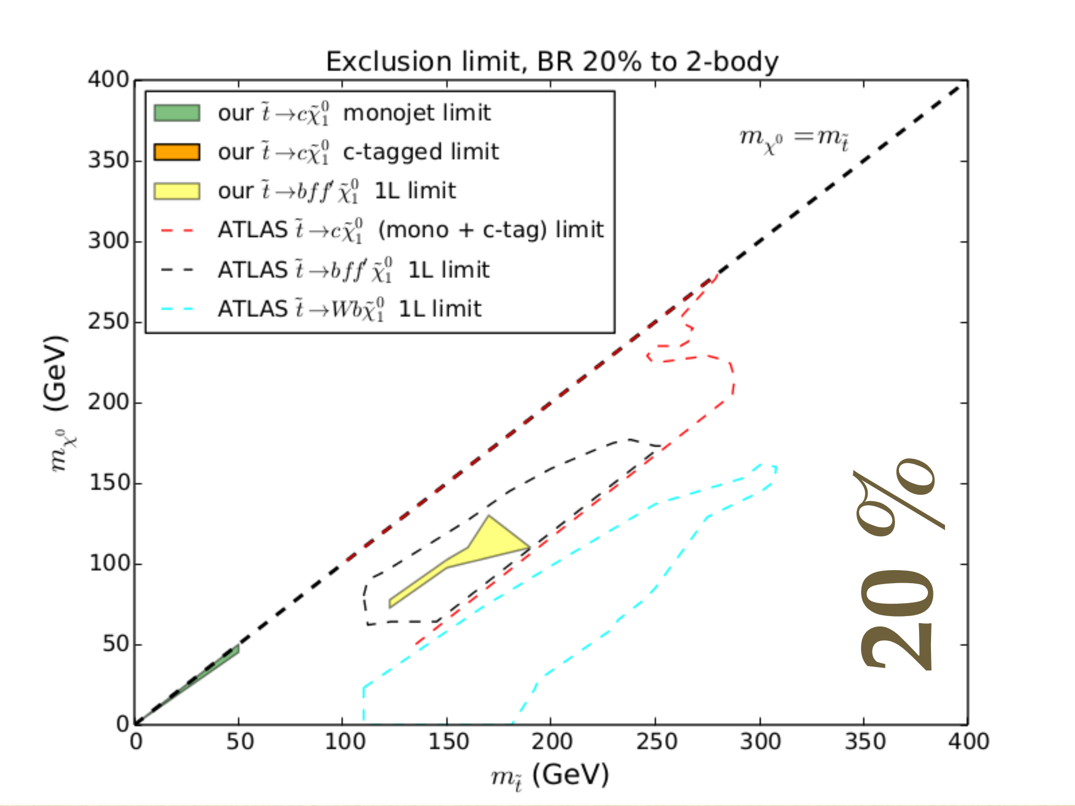


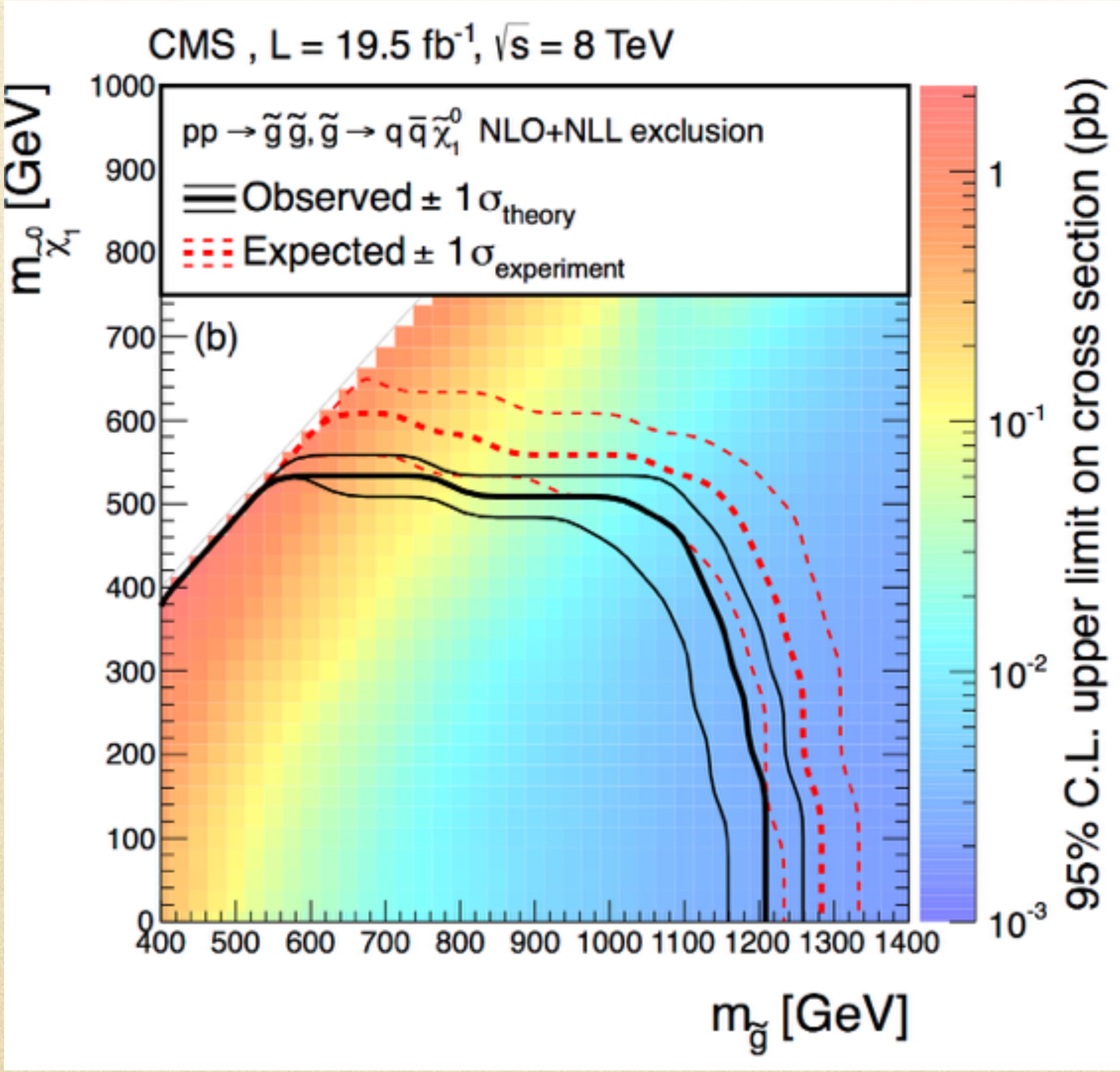


Belyaev, VS and Thomas. ***In prep***

combining channels (2,3 and 4 body)

very limited reach for most of the parameter space

same goes for other coloured states



Run2

Run2 more lumi and energy
foundation more precise, better ways of testing the Standard Model

’t Hooft, Veltman, Weinberg…

e.g. top coupling to the Higgs

e.g. total rates to differential distributions

H+jets, VV distributions, shower models

Run2 more lumi and energy
foundation more precise, better ways of testing the Standard Model

Enthusiasm and dedication of the community

ground-breaking discovery
challenges our understanding of Nature
new particles, new principles

e.g. SUSY particles, hidden sector, QG effects, quasi-conformal strong dynamics…

This is not just wishful thinking
we *know* the SM is not the ultimate theory

Evidence

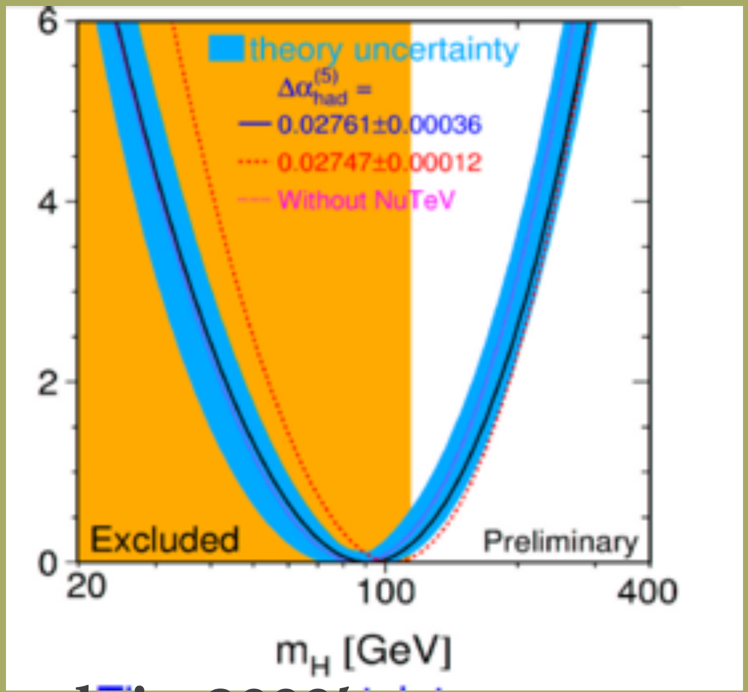
Dark Universe Neutrinos Baryogenesis

Run2 has the **potential** to shed light on the origin
of these observations
and on theoretical conundrums (e.g. naturalness)

Where is New Physics?

BUT we are talking about going

From the Higgs, a particle with known couplings and a mass in a definite range

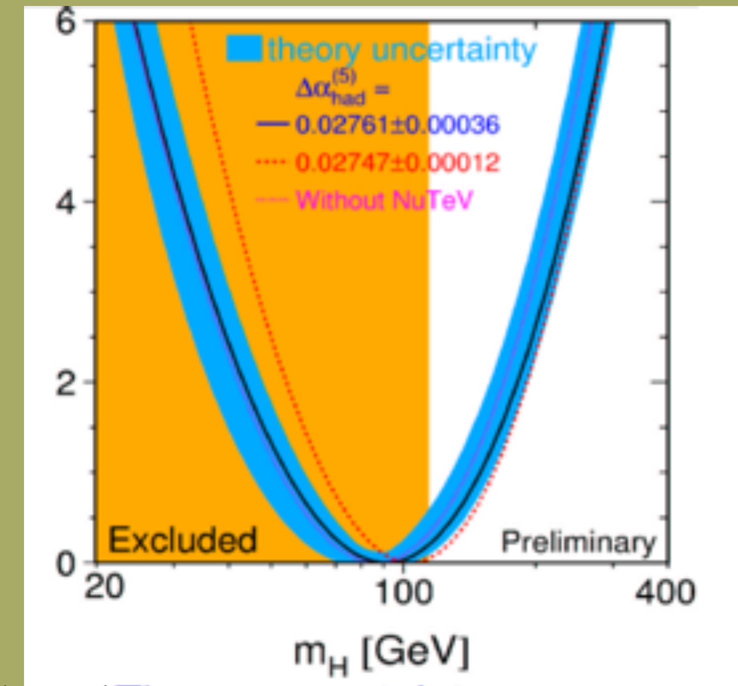


back in 2000's

To the unknown

jasonpost.com

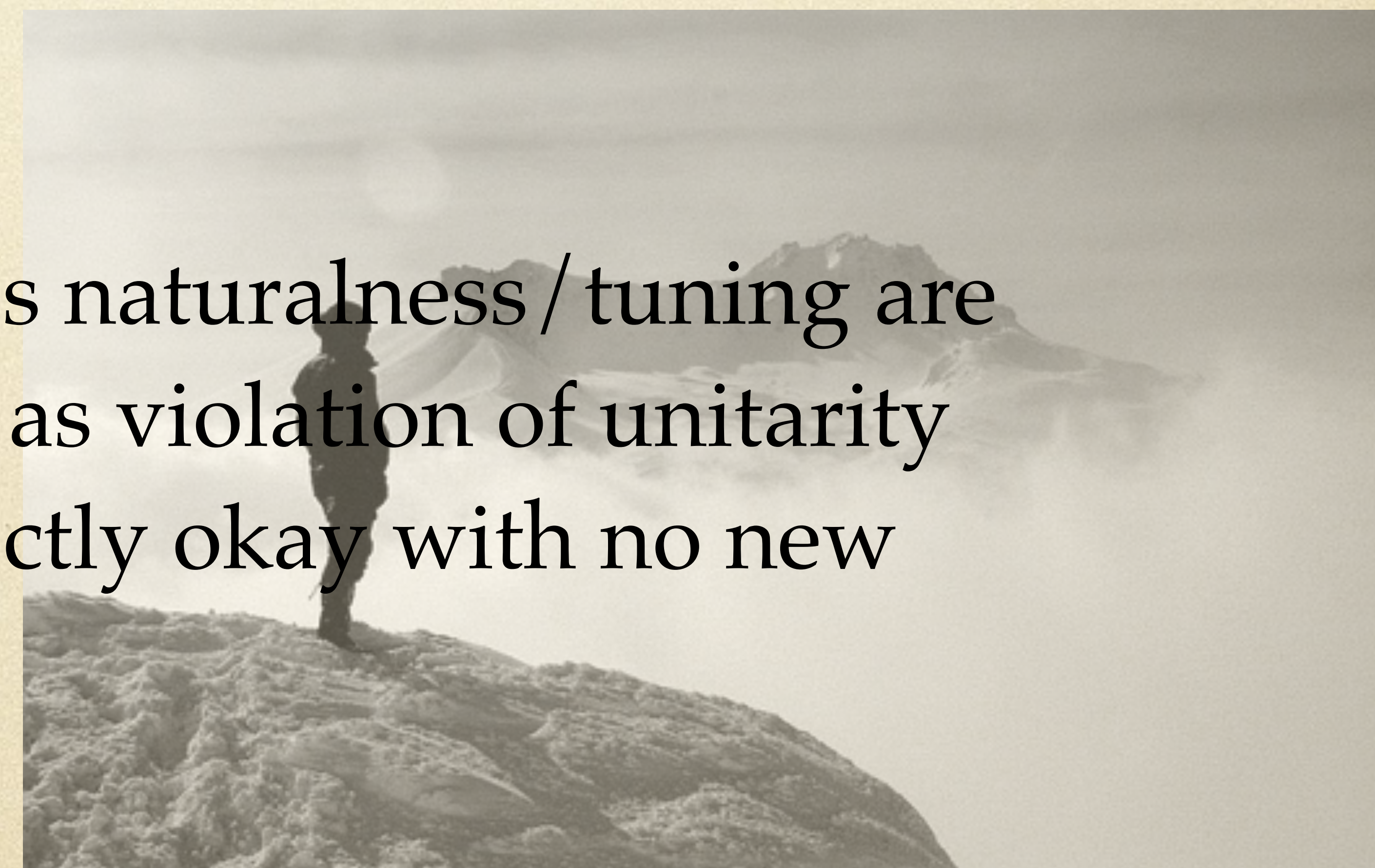
BUT we are talking about going



back in 2000's

From the Higgs, a particle with known couplings and a mass in a definite range

To the unknown

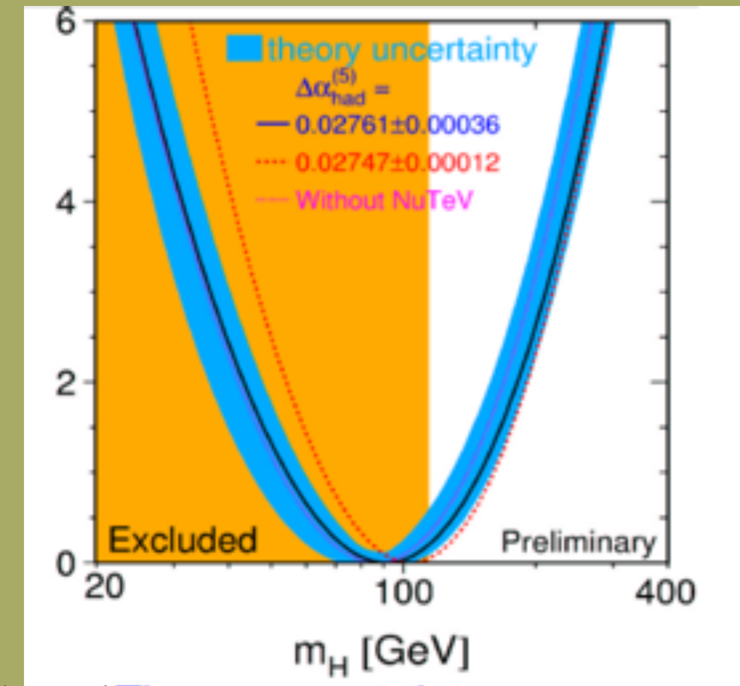


aesthetical arguments as naturalness/tuning are **not** on the same footing as violation of unitarity

precision tests are perfectly okay with no new physics at the EW scale

BUT we are talking about going

From the Higgs, a particle with known couplings and a mass in a definite range



back in 2000's

To the unknown

The bottom-line
we do not know what/where New Physics is

which is what makes this run so exciting

How do we probe the unknown?

Business as usual

Jumping into the unknown
by searching for a resonance or an excess/deficit

DIRECT	INDIRECT
as many final states and distributions as possible	Effective Field Theory mass reach higher than direct more theory-inclusive
if theory motivation: ask the theorist	A lot more work needed, differential distributions essential
e.g. extend sensitivity of displaced vertices	e.g. EFT and diff distributions for Run1 Ellis, VS, You. 1410.7703

Jumping into the unknown
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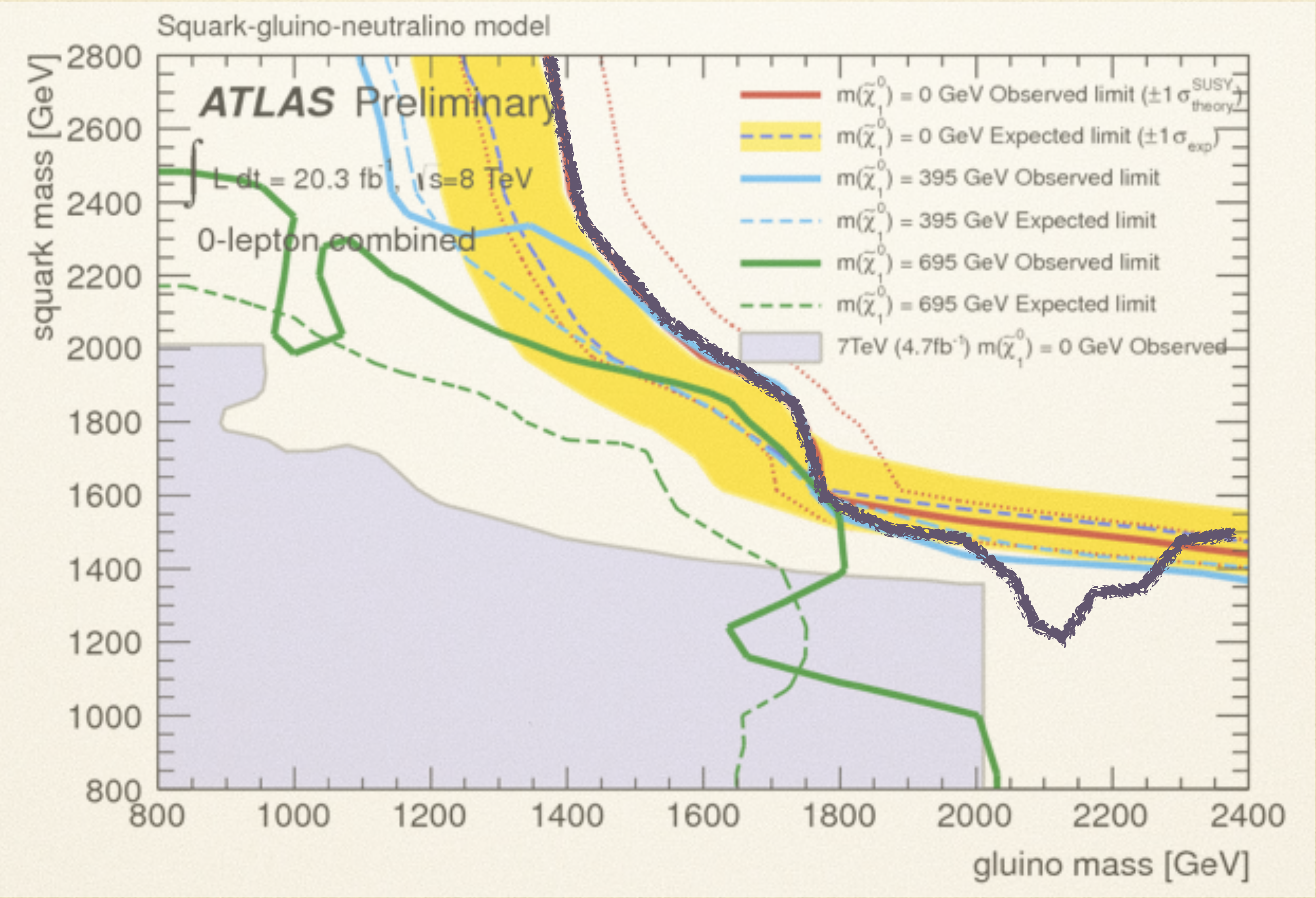
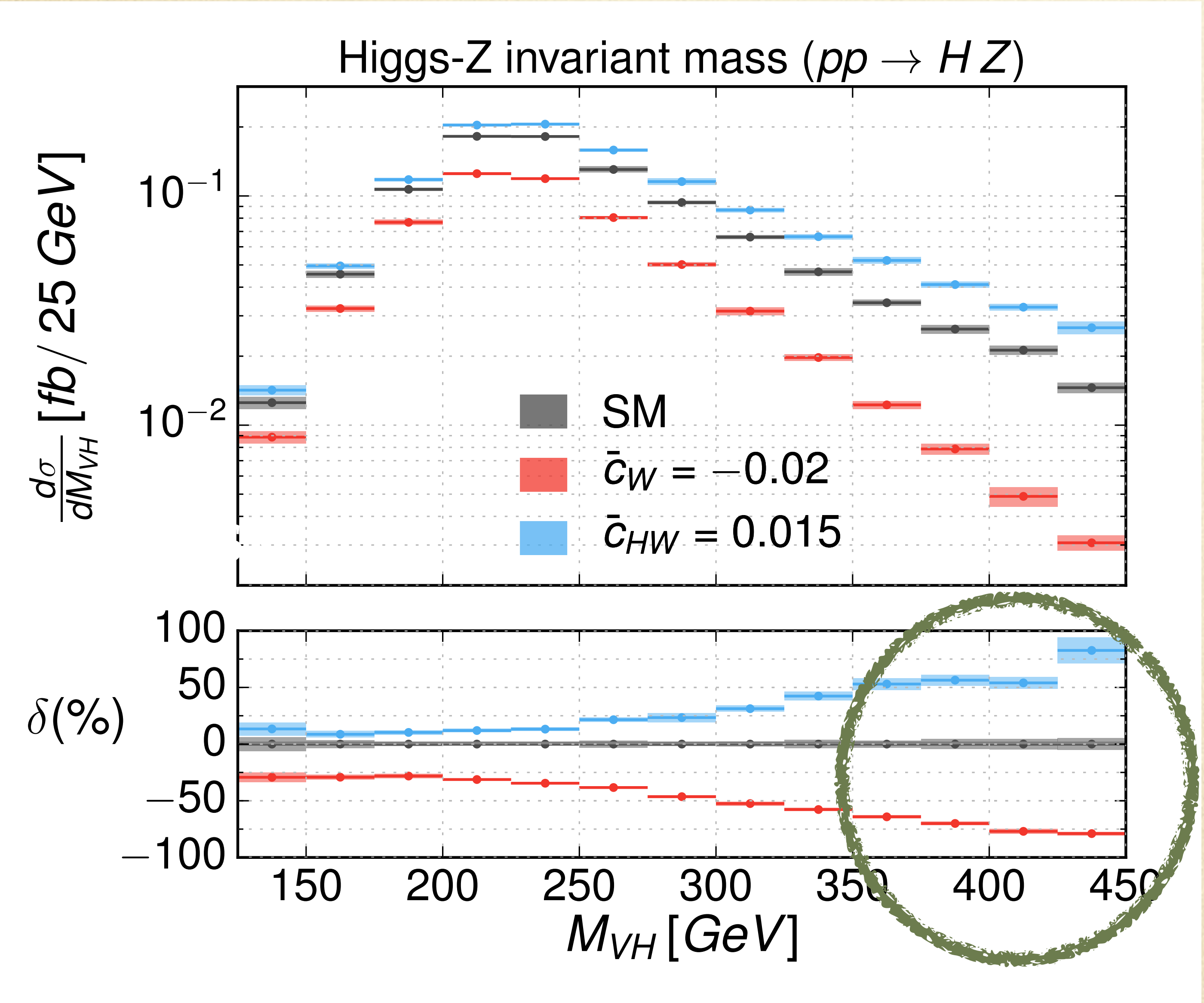
BUMP, EDGE	TAIL

Direct searches of coloured states could lead to an early discovery at LHC13



Indirect searches could lead to a discovery of New Physics

E.g. a non-resonant excess in HV production



Requires careful analysis
NLO QCD+EW
shower effects
simulation…

EFT -> UV models

correlations with other signals could point a specific scale

QCD NLO Mimasu, VS and Williams. *In prep*

Degrande, Fuks, Mawatari, Mimasu, and VS. *In prep*

Complementarity of LHC

How do we probe the unknown with no compass?

Business as usual

test boundaries of the SM, hoping for something unusual to come up

How do we probe the unknown with no compass?

Business as usual

test boundaries of the SM, hoping for something unusual to come up

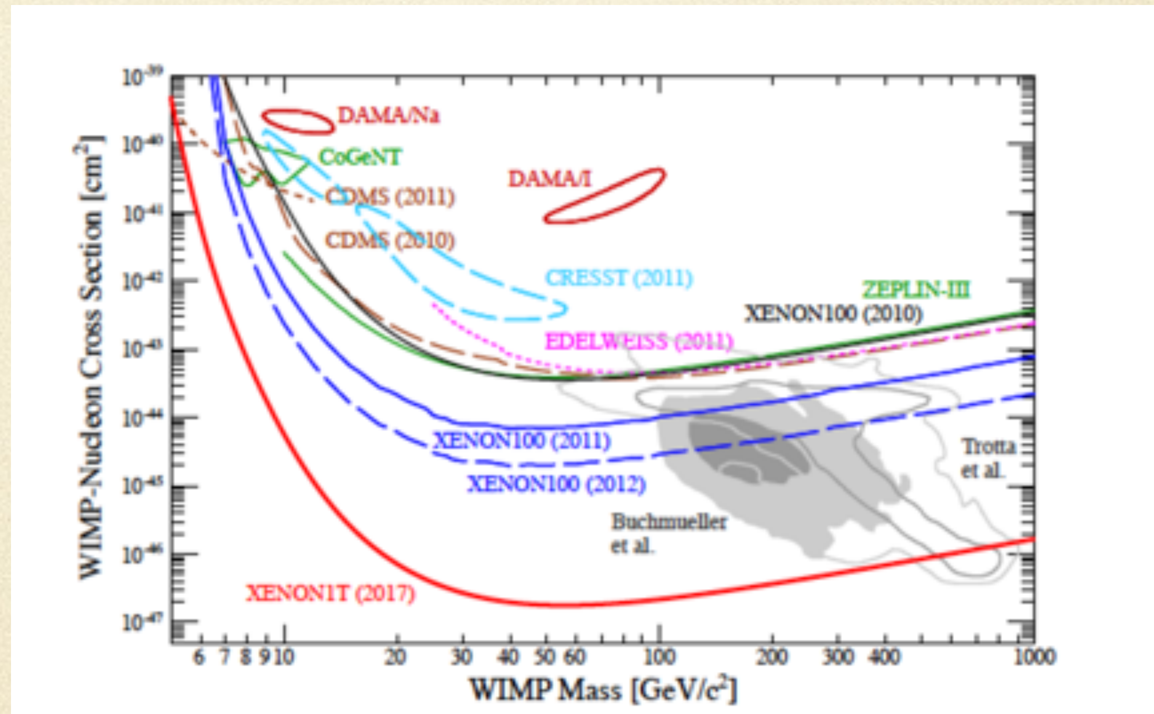
Additionally we should actively extend the reach of searches by looking out to non-LHC experiments/observations

Why?

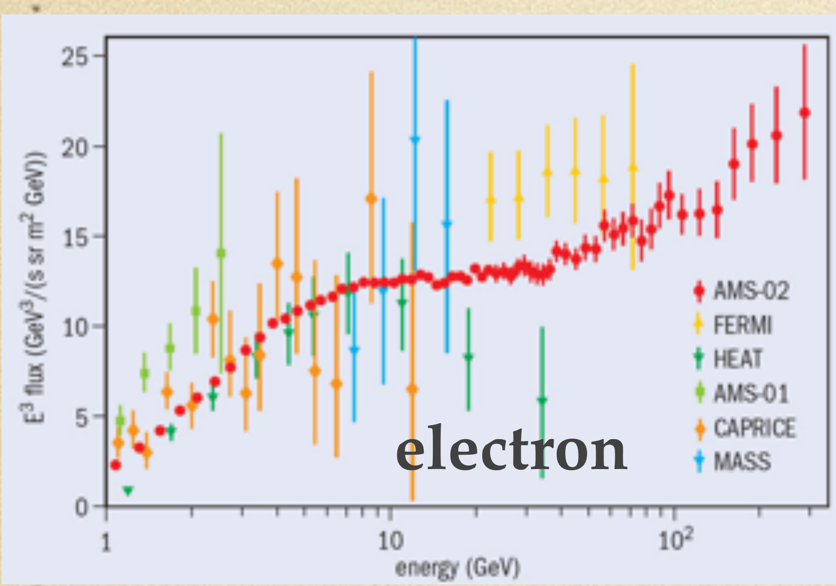
Hints of New Physics could come from the connection between colliders with other areas

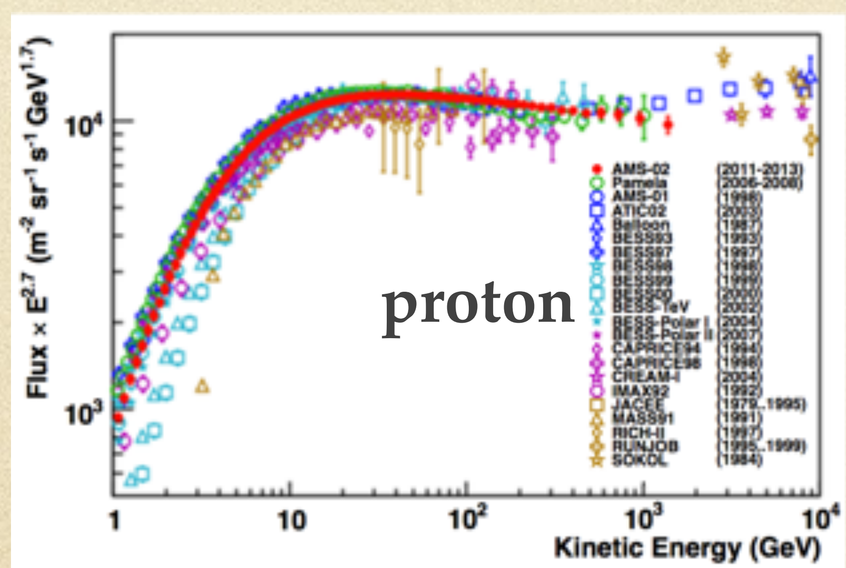
e.g. The Dark Matter connection

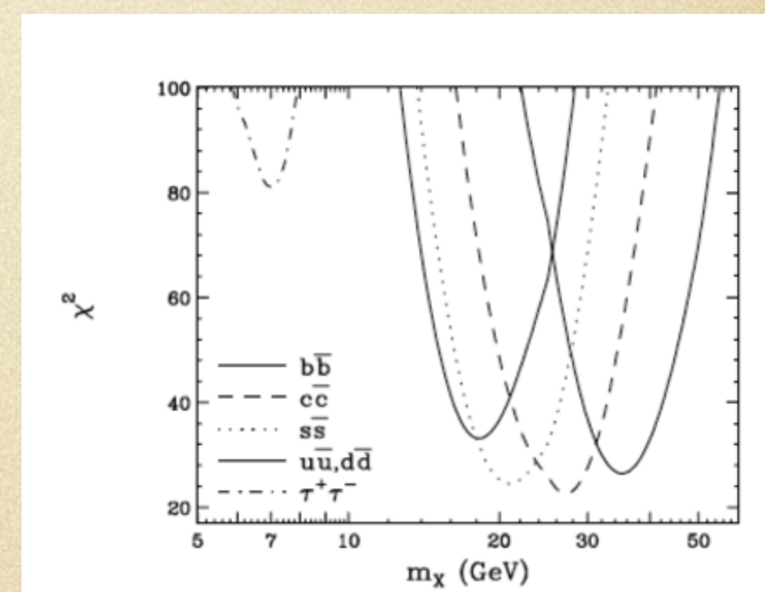
Direct detection



Indirect detection





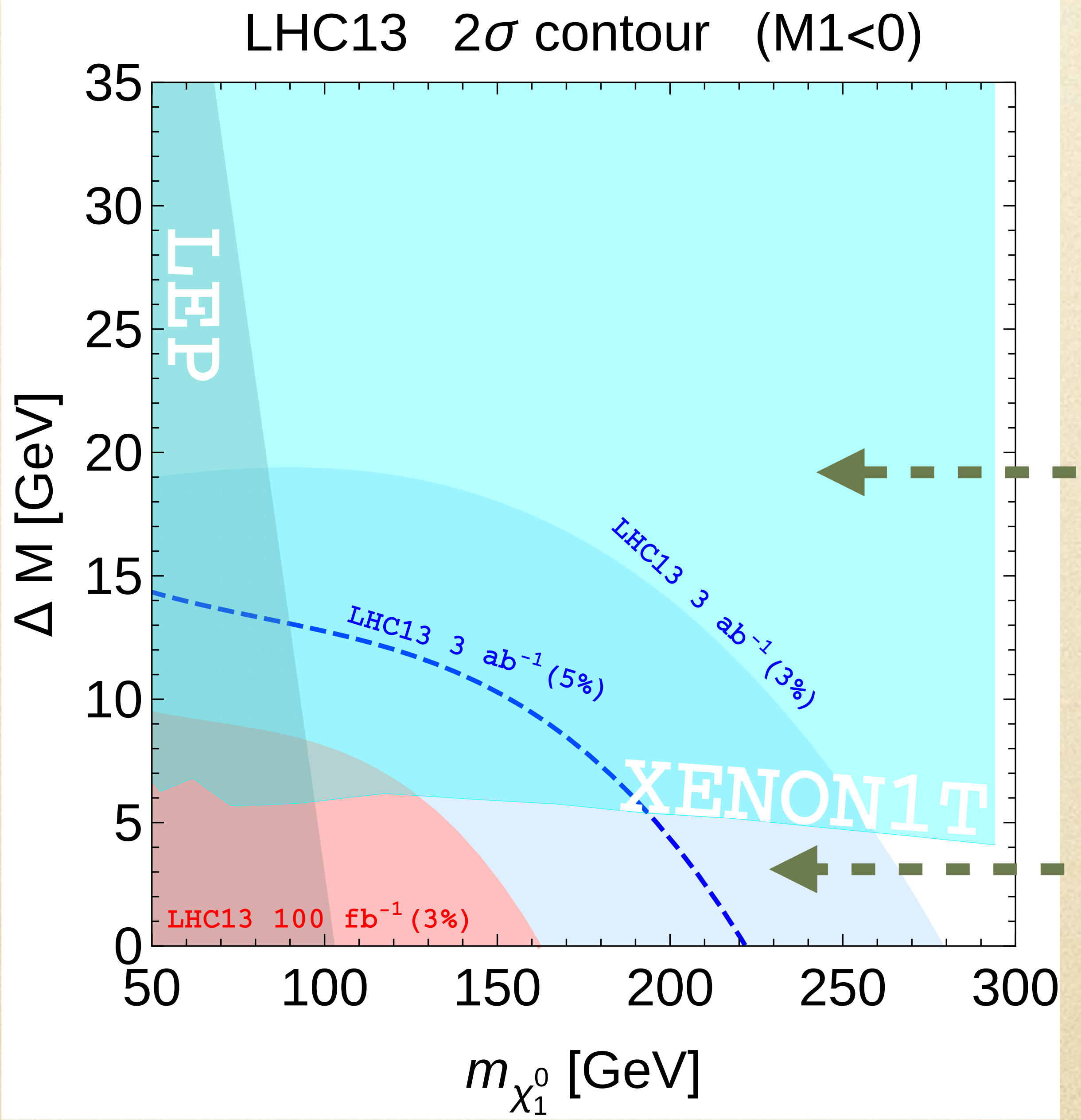


Hooper et al. 1402.6703

e.g. The Dark Matter connection

Natural SUSY DM: LHC vs DD

DD/collider



LUX/XENON1T

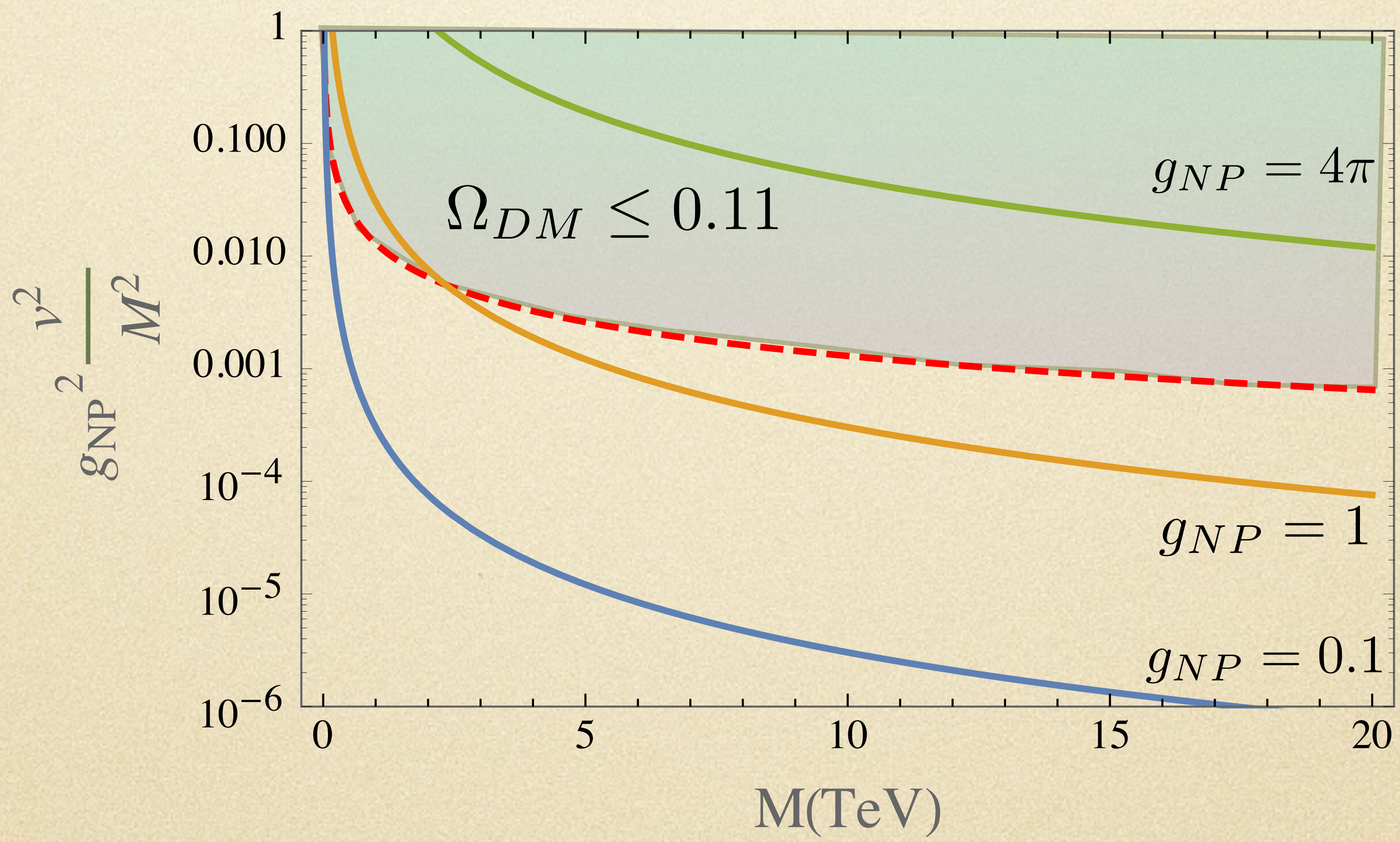
Monojet LHC13

Barducci, Bharucha, Belayev, Porod VS. 1504.02472

e.g. The Dark Matter connection

Relic abundance sets limits on precision required at colliders

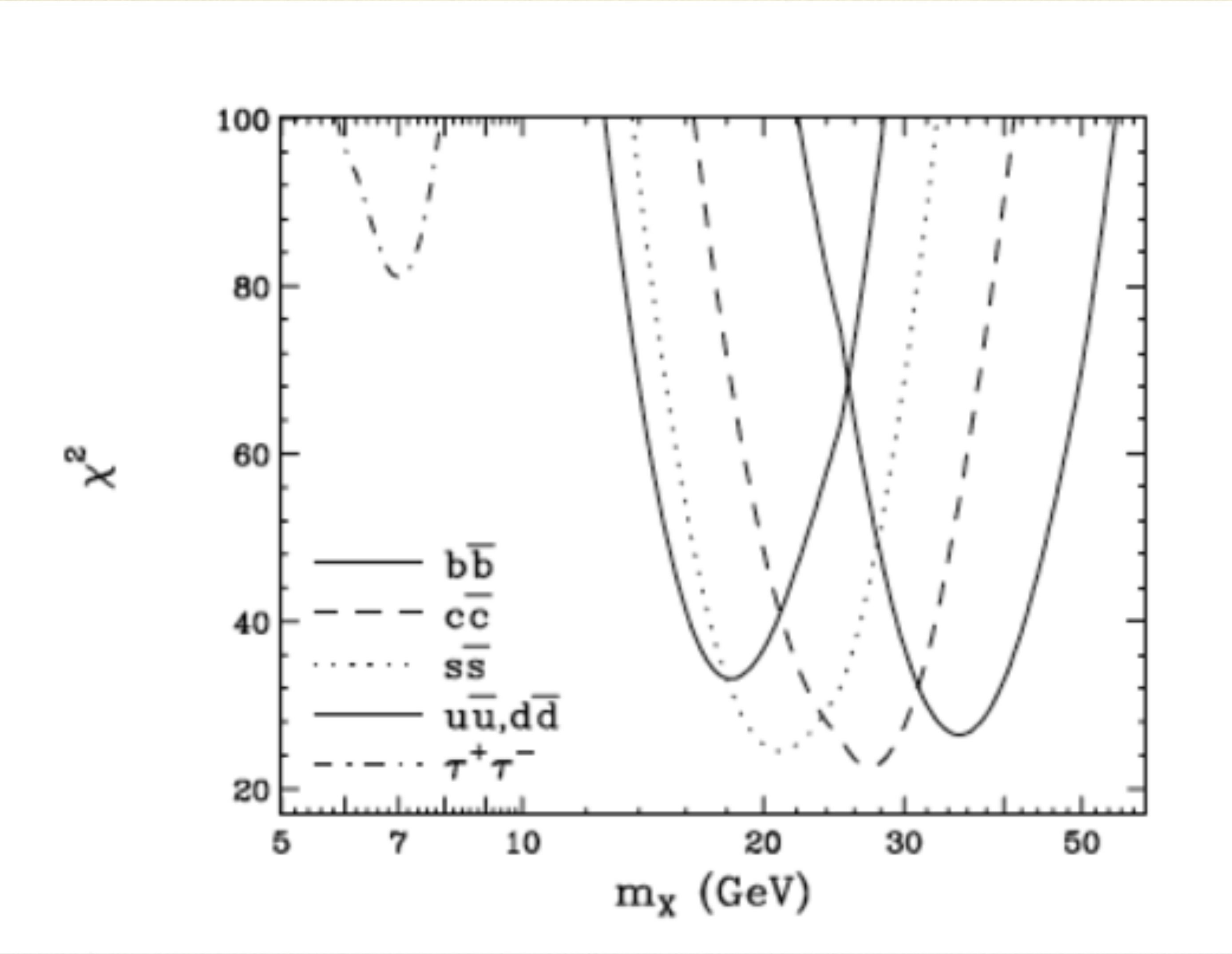
Cosmo/collider



e.g. The Dark Matter connection

Excess in gamma-rays can be translated into a mass and a coupling to SM particles: colliders

Astro/collider

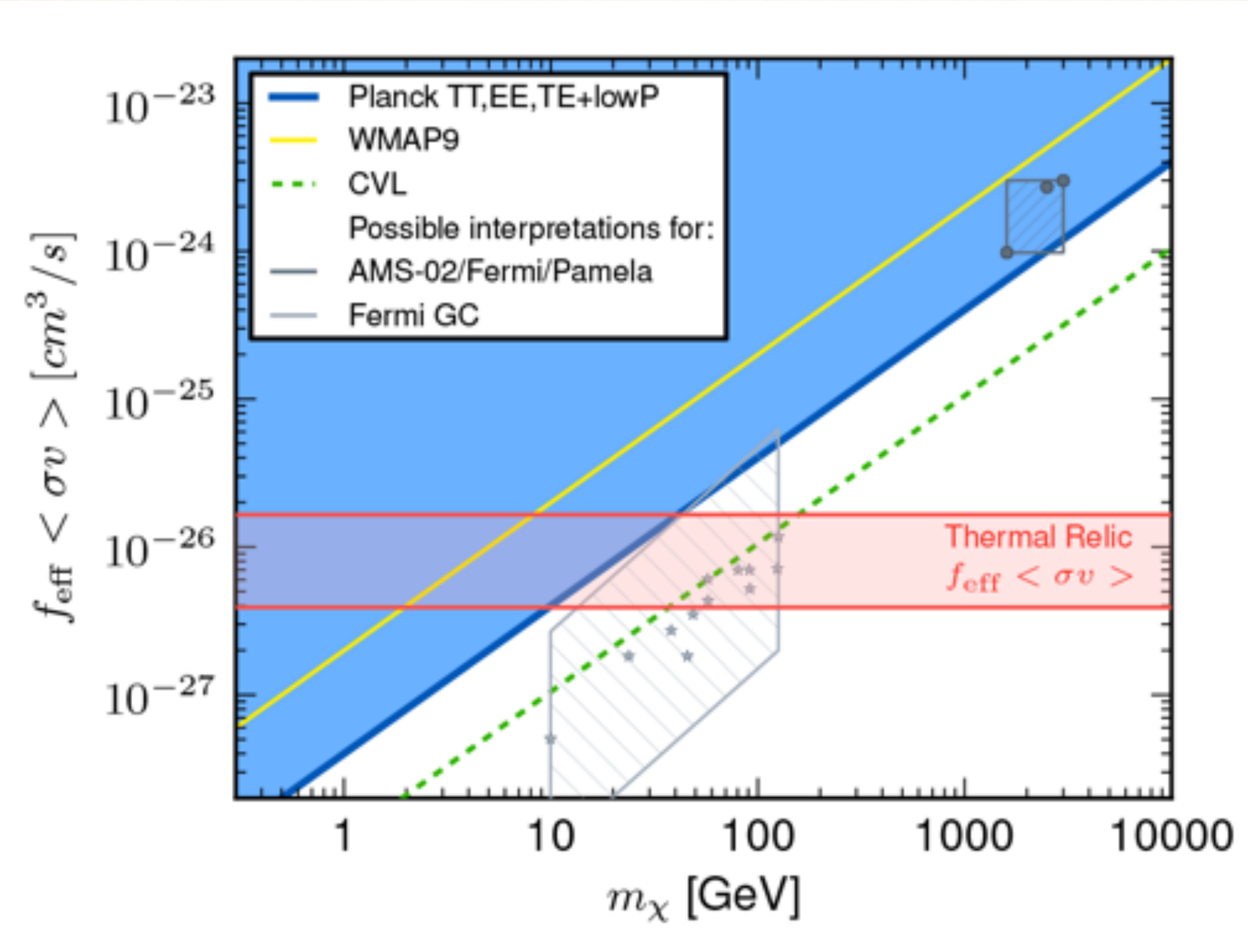


Hooper et al. 1402.6703

e.g. The Dark Matter connection

Measurement of the CMB complements DD further restricting DM searches

Astro/Cosmo/collider

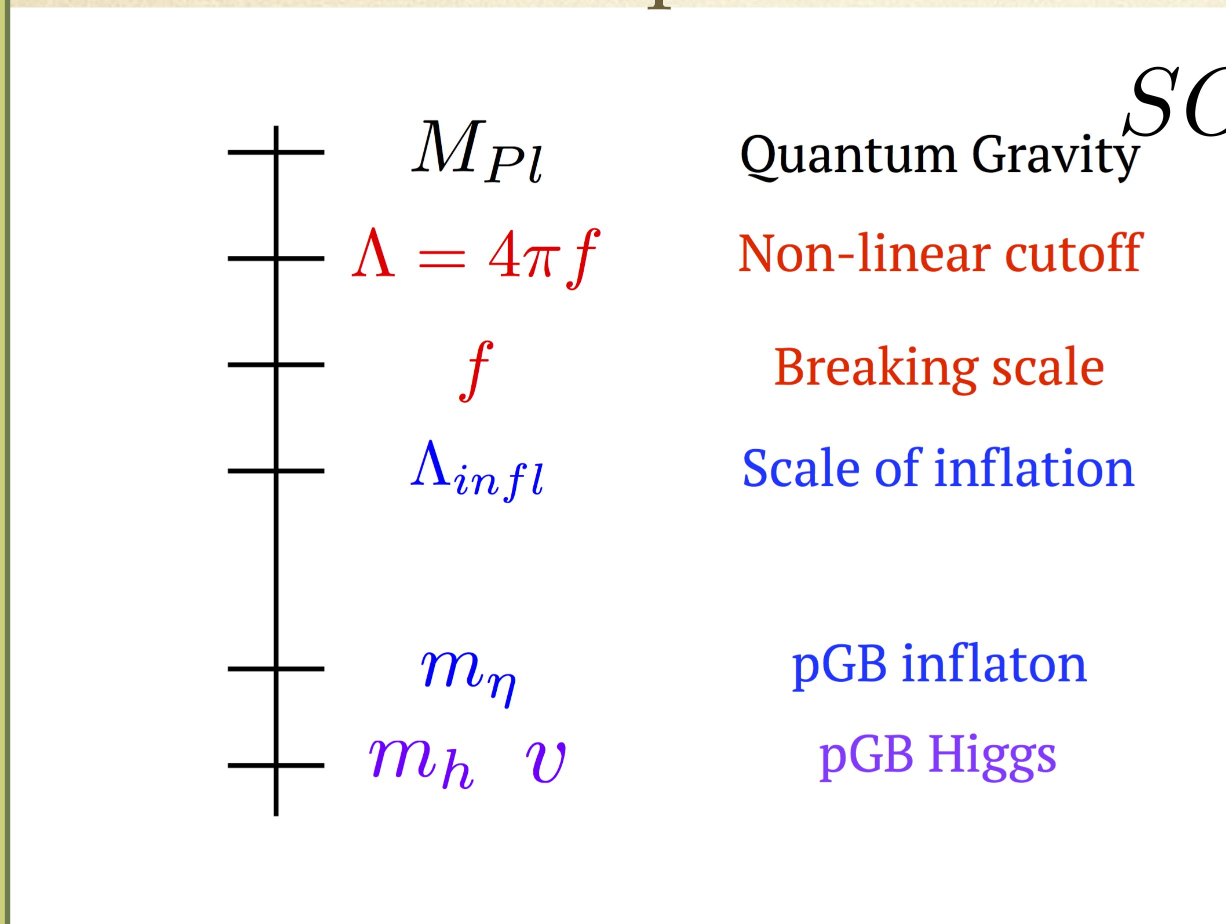


Plack results. 2014.

Inflation/collider/grav waves

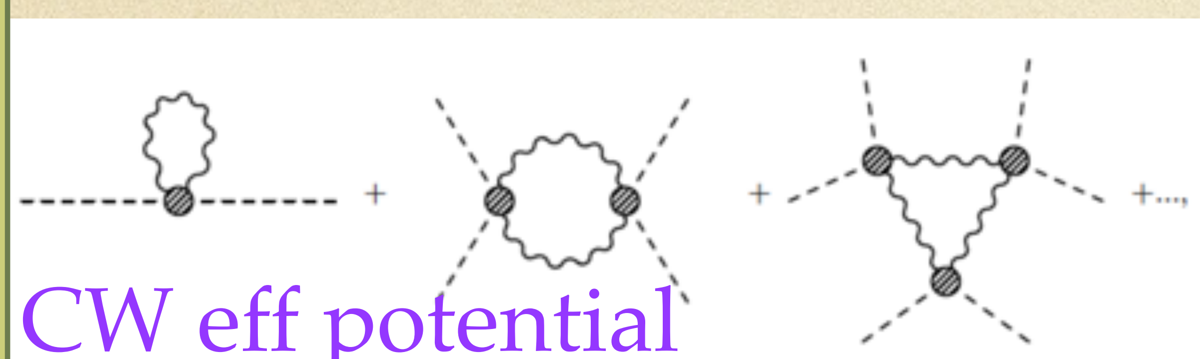
e.g. Inflation connection

Hierarchy problems Higgs and Inflaton related
both pGBs from breaking G/H



$$SO(6)/SO(5) \approx SU(4)/Sp(4)$$

GB multiplet (h, η)



Low scale of inflation,
N=50 , light inflaton
natural ('t Hooft)

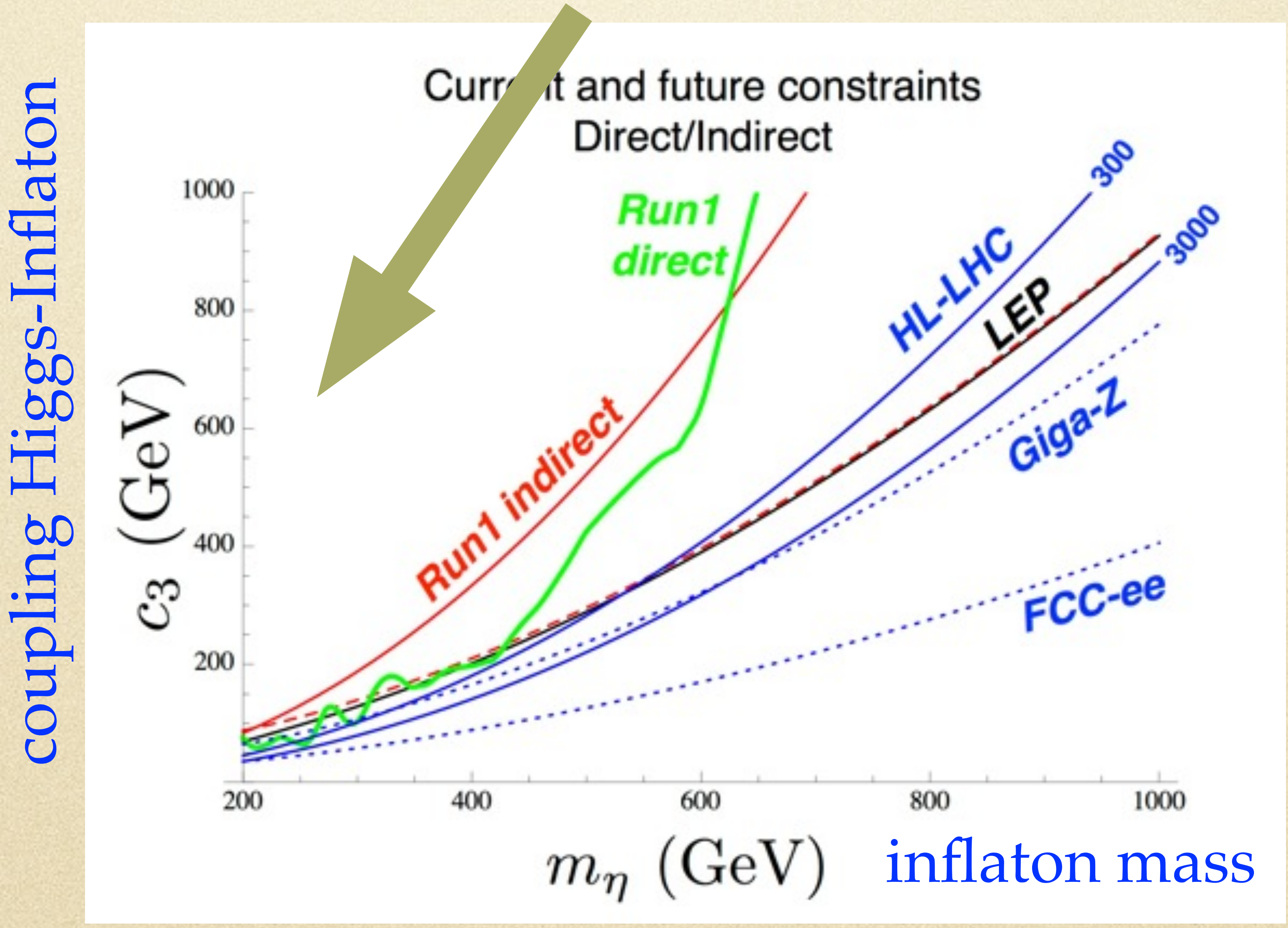
Croon, VS, Tarrant. 1507.04653

e.g. Inflation connection

Hierarchy problems Higgs and Inflaton related
both pGBs from breaking G/H

tachyonic&resonant reheating
Gravitational waves

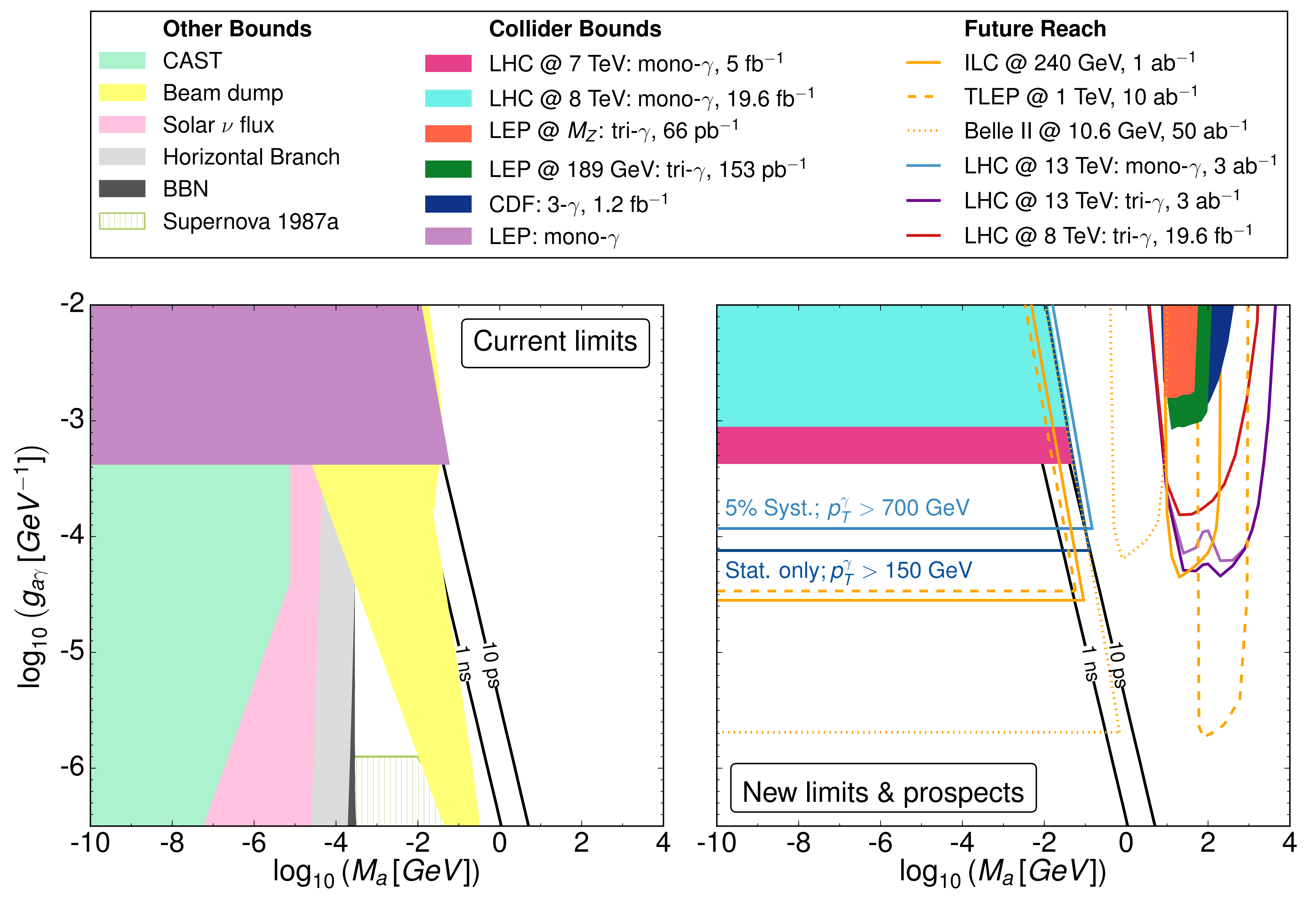
Inflation/collider/grav waves



Croon, Figueroa, Garcia-Bellido, VS, Torrenti. *In prep*

e.g. The Axion connection

Astro/Axion/collider



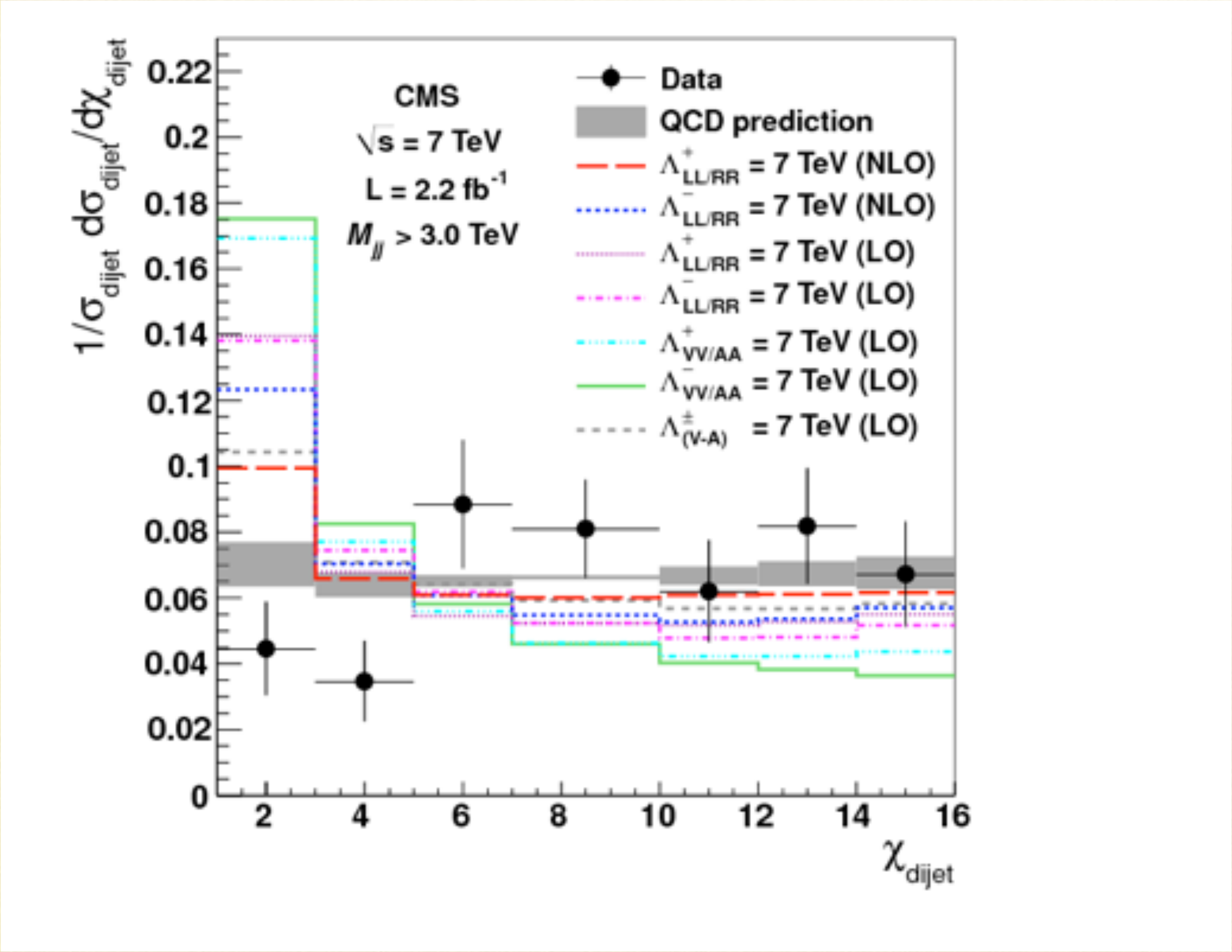
Mimasu and VS. 1406.4792

Conclusions

- Run1 was the run of the SM, establishing its consistency as an effective theory with the Higgs discovery
- Run2 is diving in the unknown BSM territory, exciting and quite more difficult task. The increased lumi and energy in Run2 may just be what we need to discover BSM
- Discovery through direct and indirect searches should go beyond extending Run1 measurements
- LHC Direct: extend final states such as displaced vertices
- LHC Indirect: lots more experimental work needed for EFT
- A different route: looking out to other experiments/observations. Complementarity with Astro/Cosmo/Neutrino/Axions needs more exploring. It may bring new ideas to the field, plus prepare for discovery interplay

EFT affects momentum dependence: angular, pT and inv mass distributions

Usual searches,

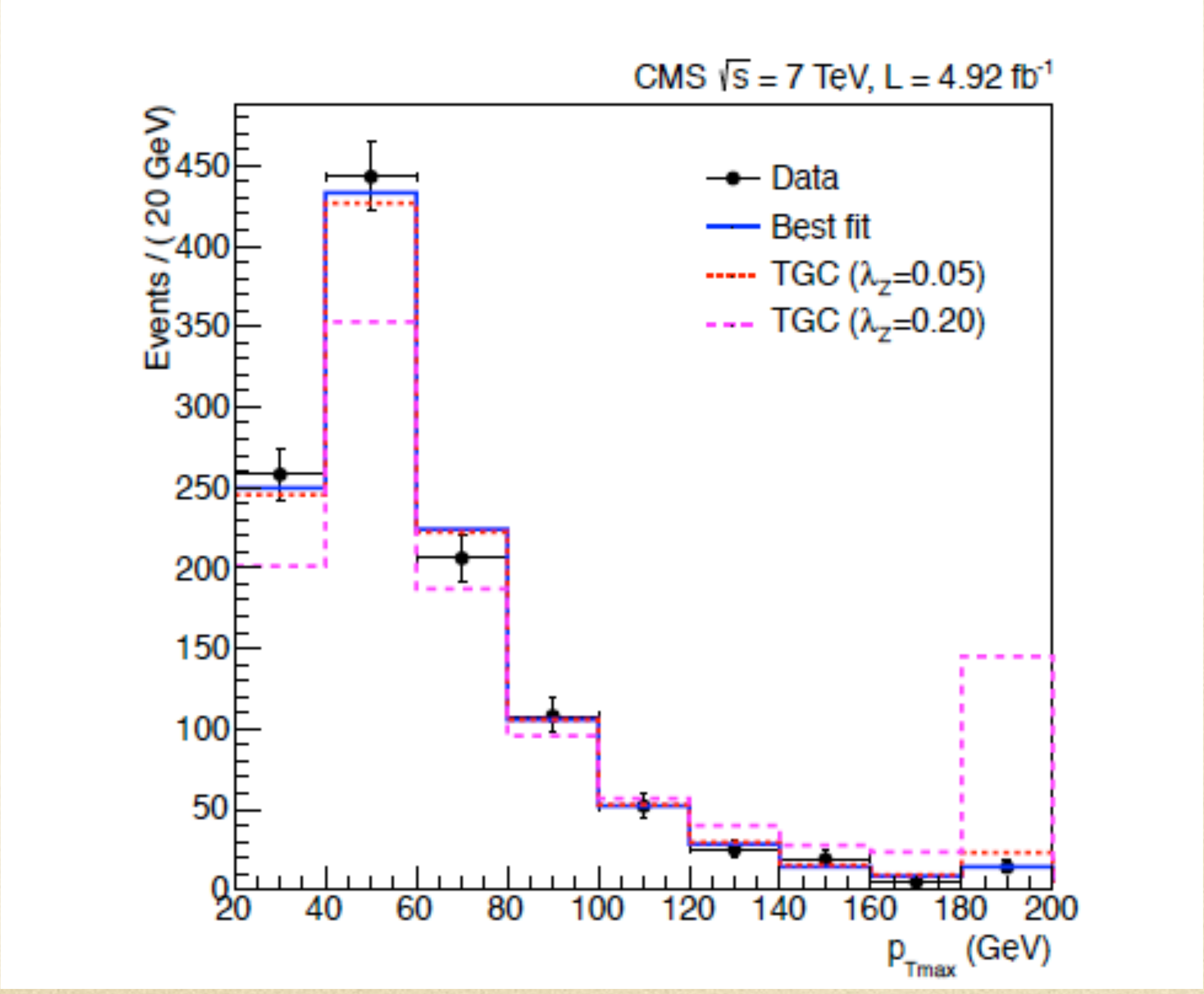


Dijet angular distribution

ex. dijet searches

EFT affects momentum dependence: angular, pT and inv mass distributions

Usual searches,



leading lepton pT

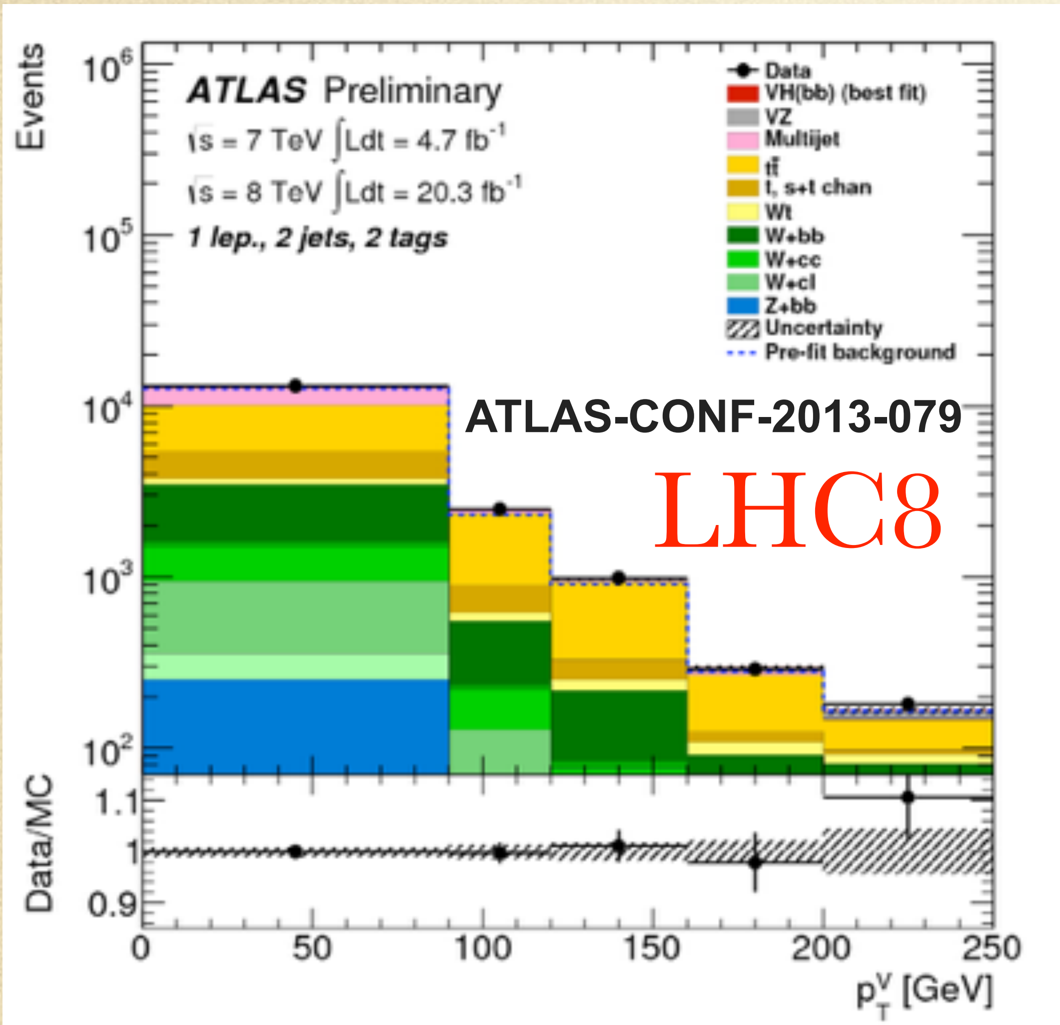
ex. TGCs

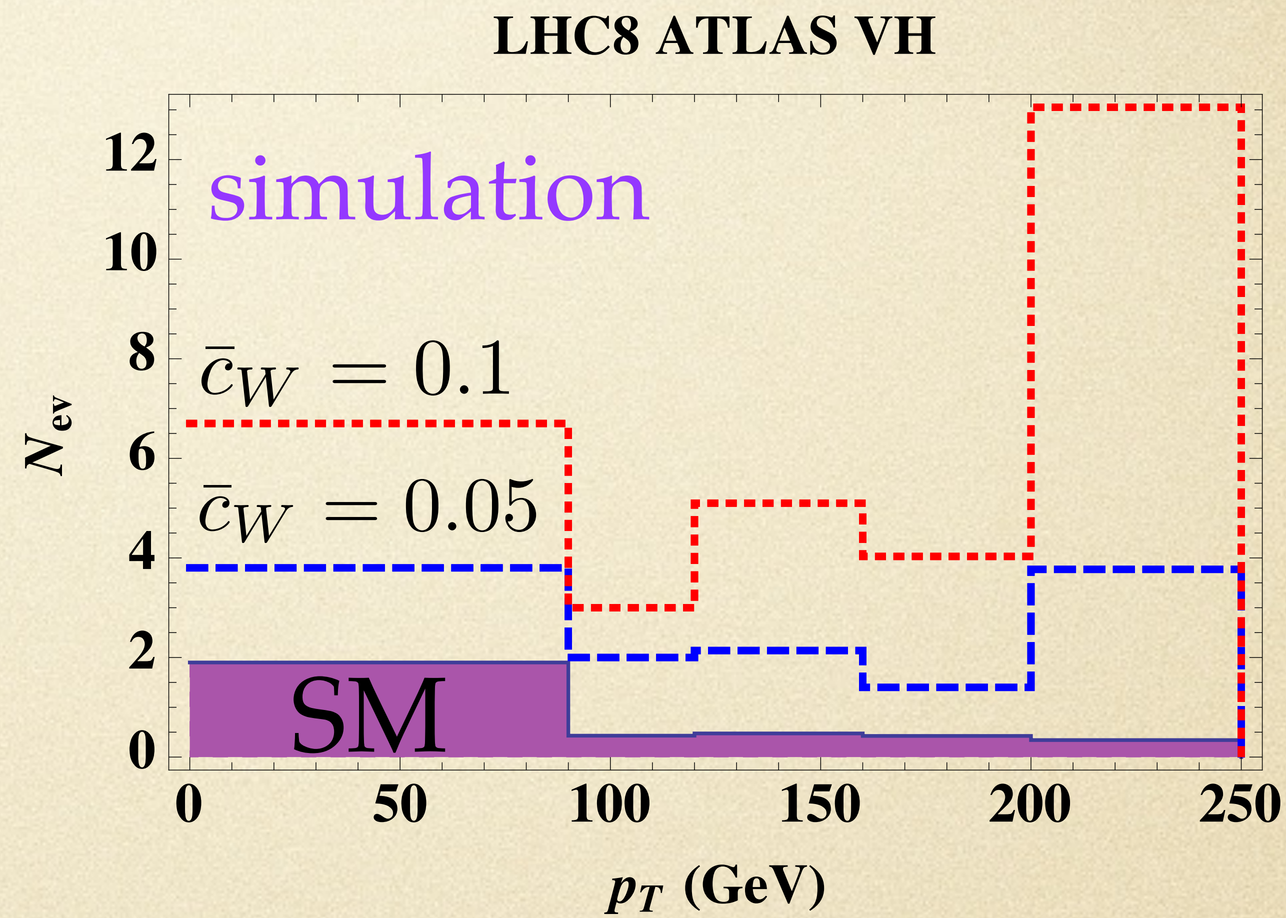
kinematic distribution best way to bound TGCs

growth at high energies cutoff: resolve the dynamics of the heavy NP

Kinematics of associated production at LHC8

Ellis, VS and You. 1404.3667, 1410.7703





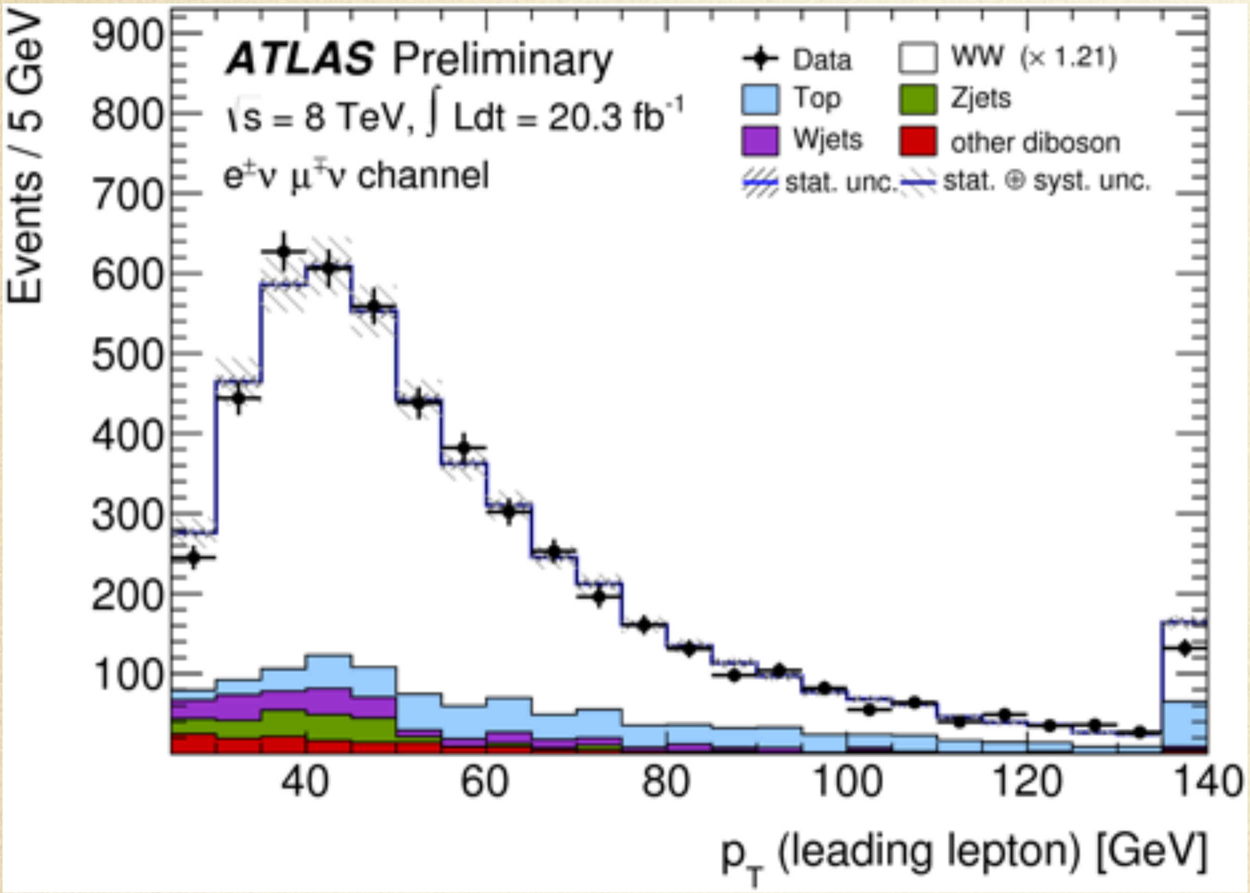
Feynrules -> MG5-> pythia->Delphes3

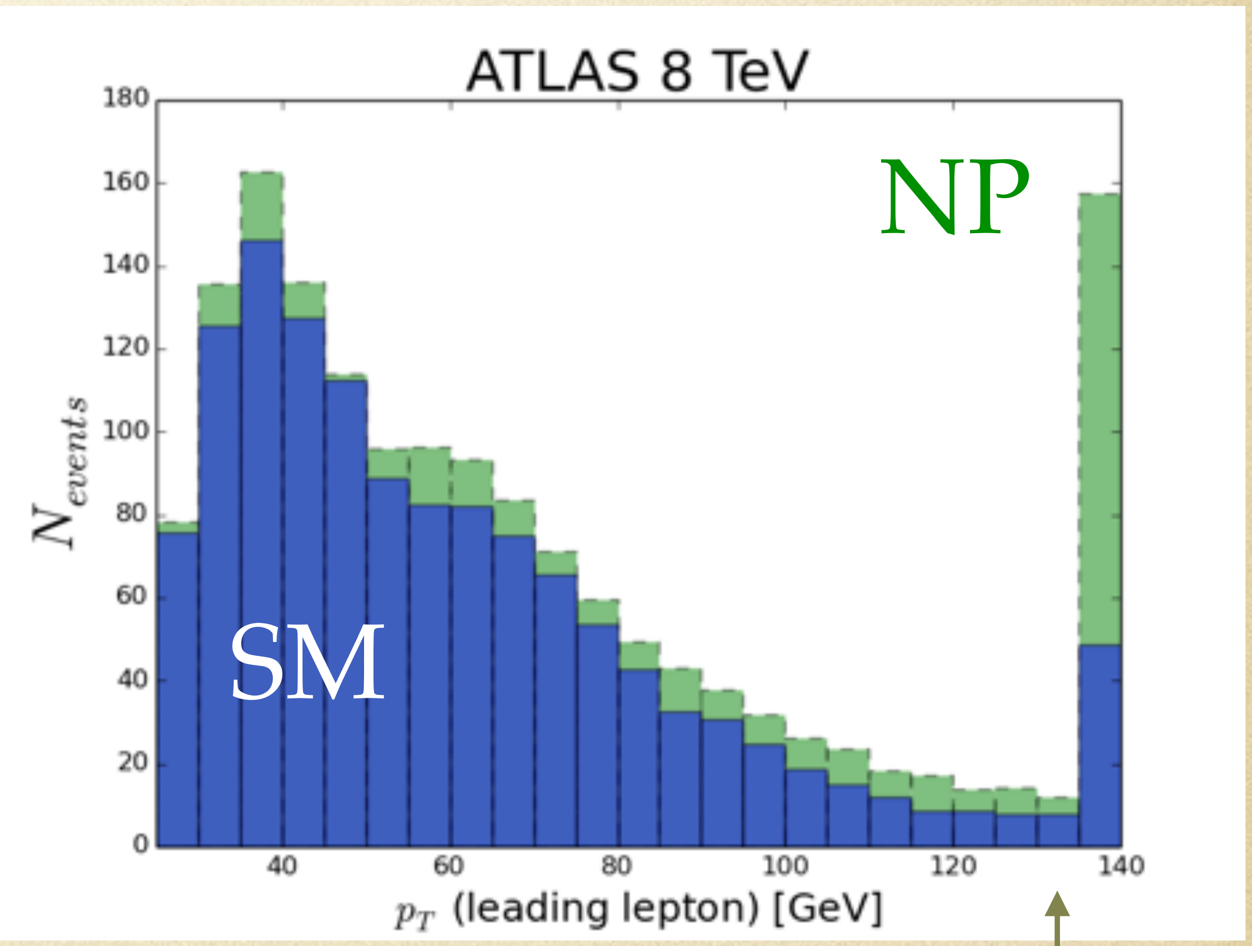
verified for SM/BGs => expectation for EFT

inclusive cross section is less sensitive than distribution

TGCs constrains new physics too

Ellis, VS and You. 1404.3667, 1410.7703





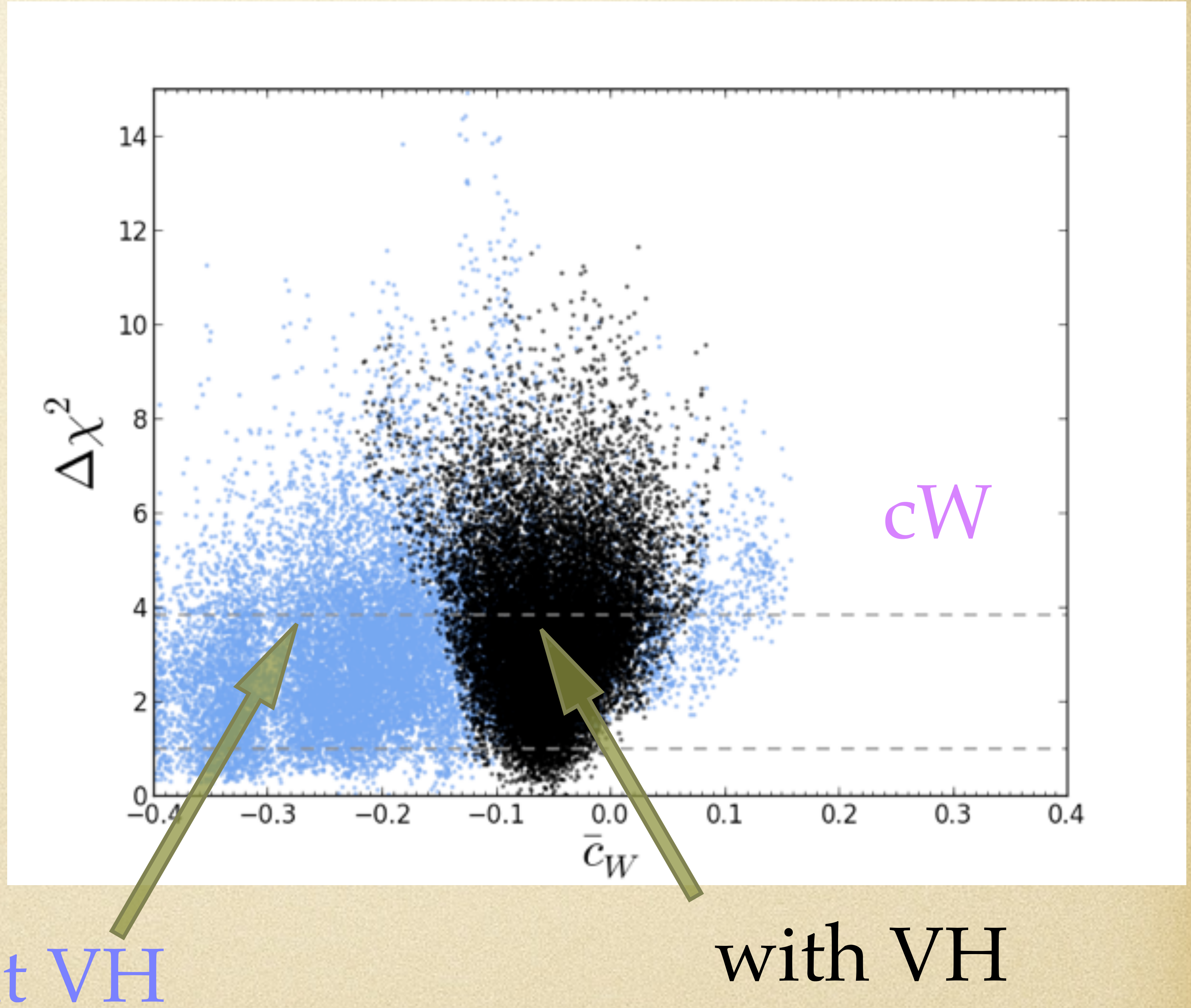
ATLAS-CONF-2014-033

overflow bin

we followed same validation procedure-> constrain EFT

breaking blind directions requires information on VH production

Global fit



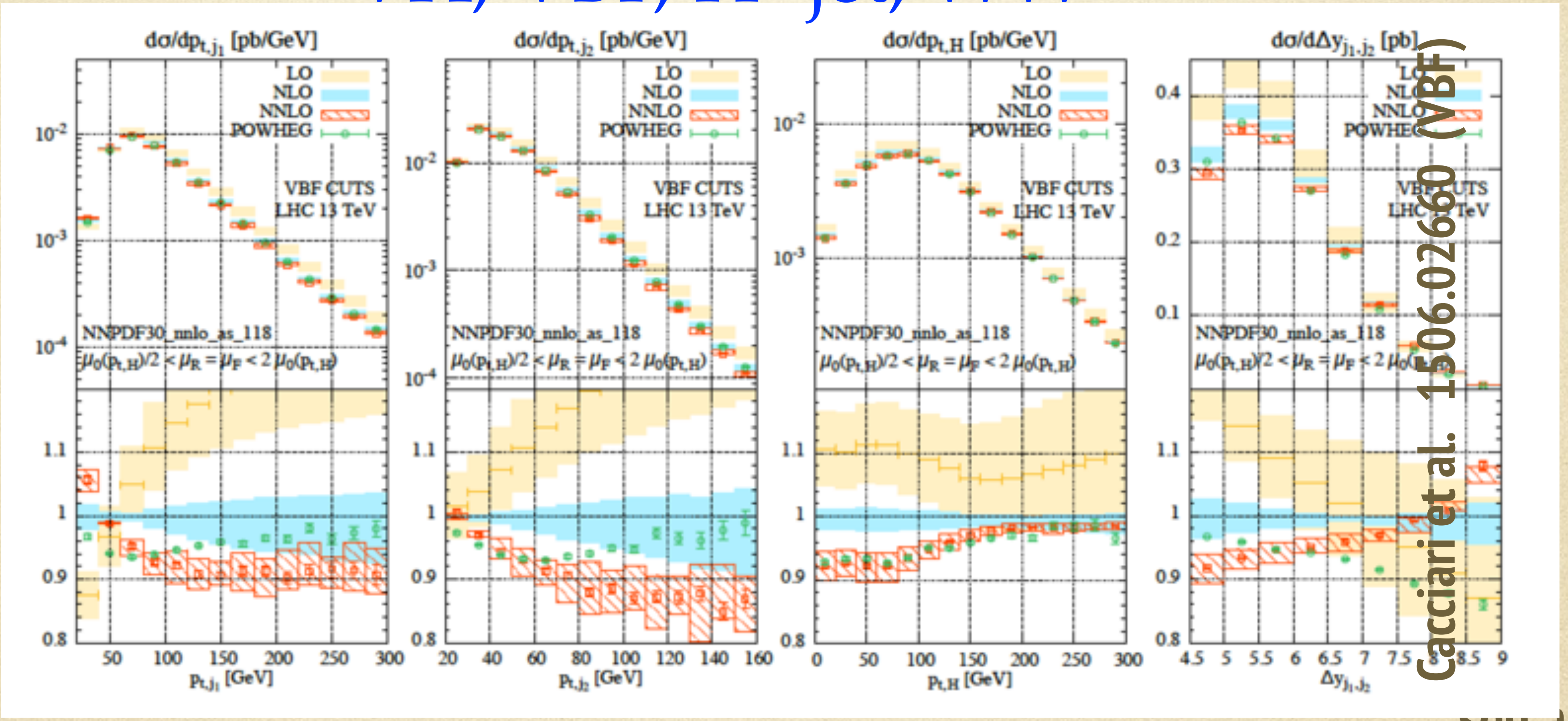
Do we need NLO for Run2?

NLO QCD

Clearly important

VH, VBF, H+jet, WW

e.g.
VBF



Cacciari et al. 1506.02660 (VBF)

see also
Maltoni et al. 1306.6464, 1311.1829,1407.5089,1503.01656
Spira et al. 1407.7971 (SUSY)
Grazzini et al. 1107.1164
Cansino, Banfi. 1207.0674…

EFT NLO QCD

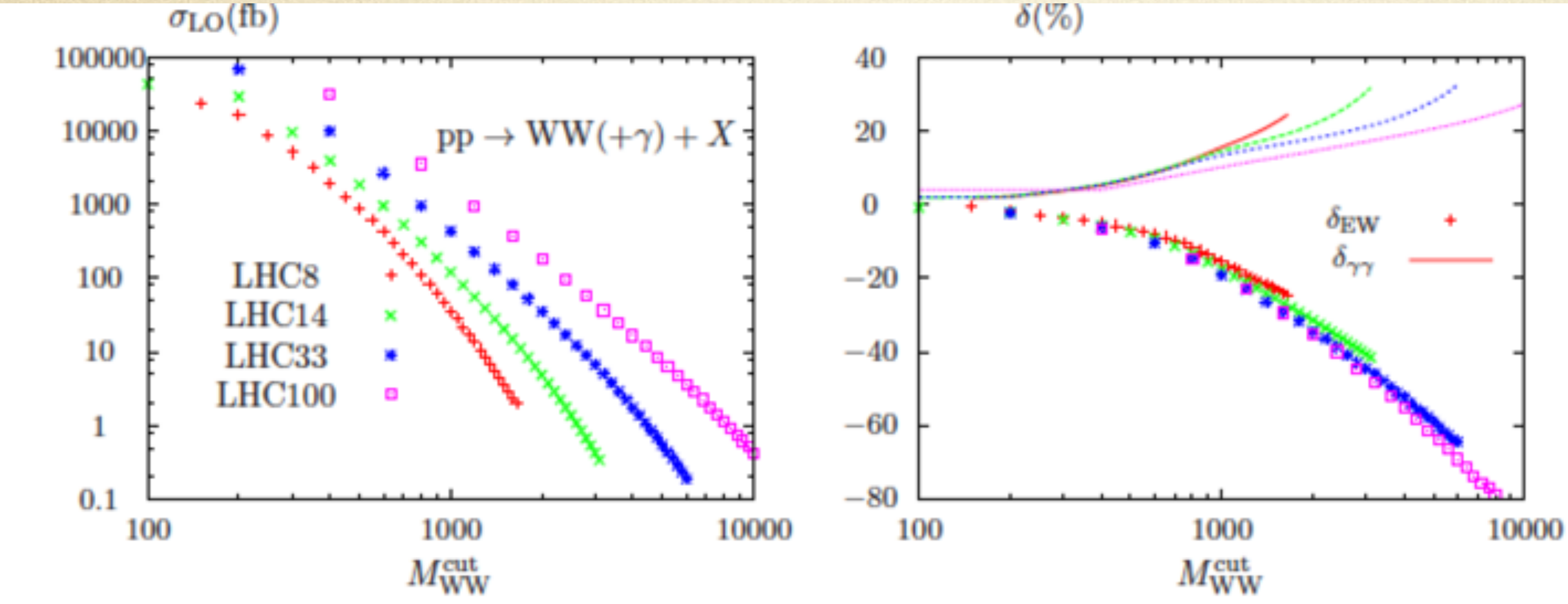
Processes involving EFT operators with quarks quite sensitive to operator mixing

e.g. top to Higgs and light quark

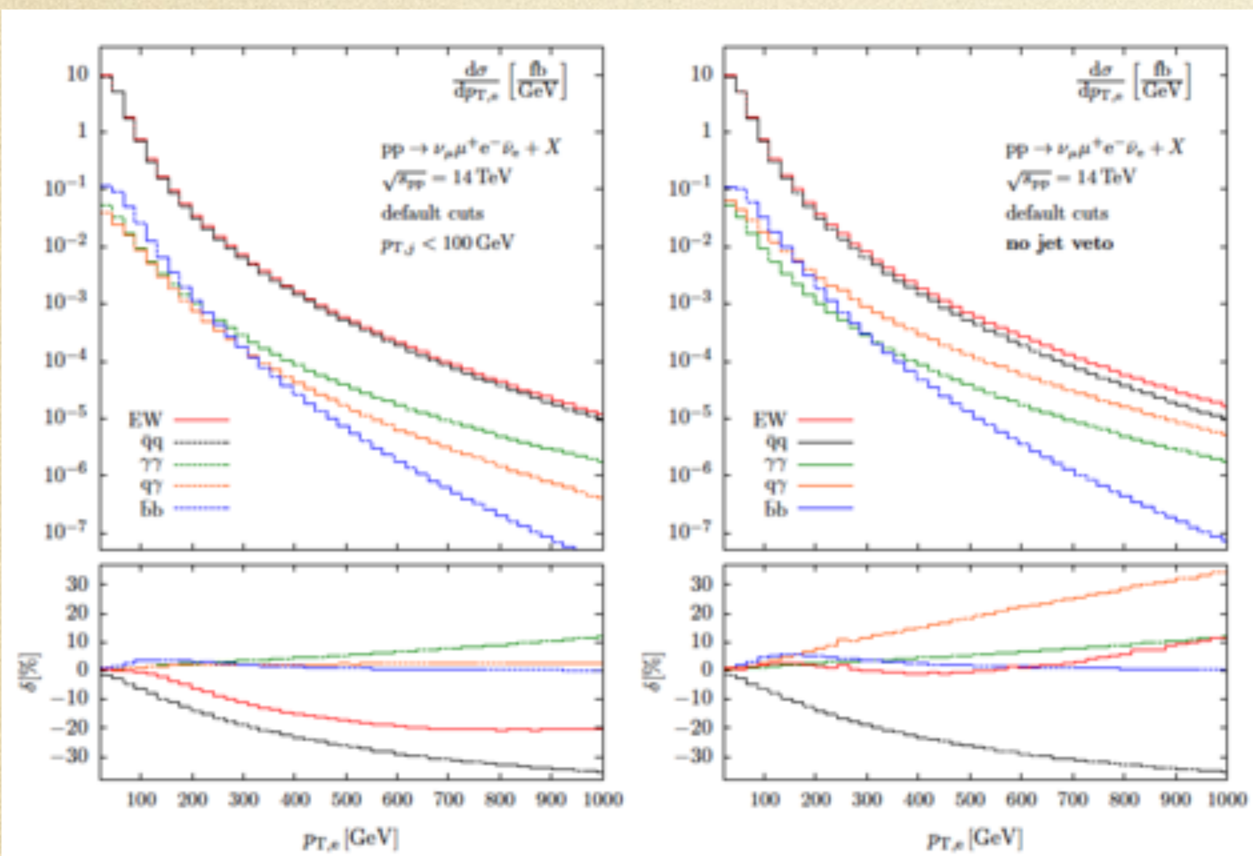
Zhang and Maltoni 1305.7386

More details on RG mixing and finite terms later on (Trott, Passarino) as well as issues of the basis (-> Rosetta)

SM NLO EW



Snowmass QCD. 1308.1430



Billoni et al. 1310.1564

LH: discussion on how universal Sudakov logs are leading: Spira

aMC@NLO: beta version with SM EW correction (Pagani, Zaro)

EFT Higgs BRs

eHDECAY

Contino et al. 1303.3876, 1403.3381

State-of-the-art

incl. most important QCD/EW corrections

New at LH

Rosetta

Higgs: SILH: Warsaw

IN PREPARATION

Mimasu et al

param_card (in any basis)->

eHDECAY->

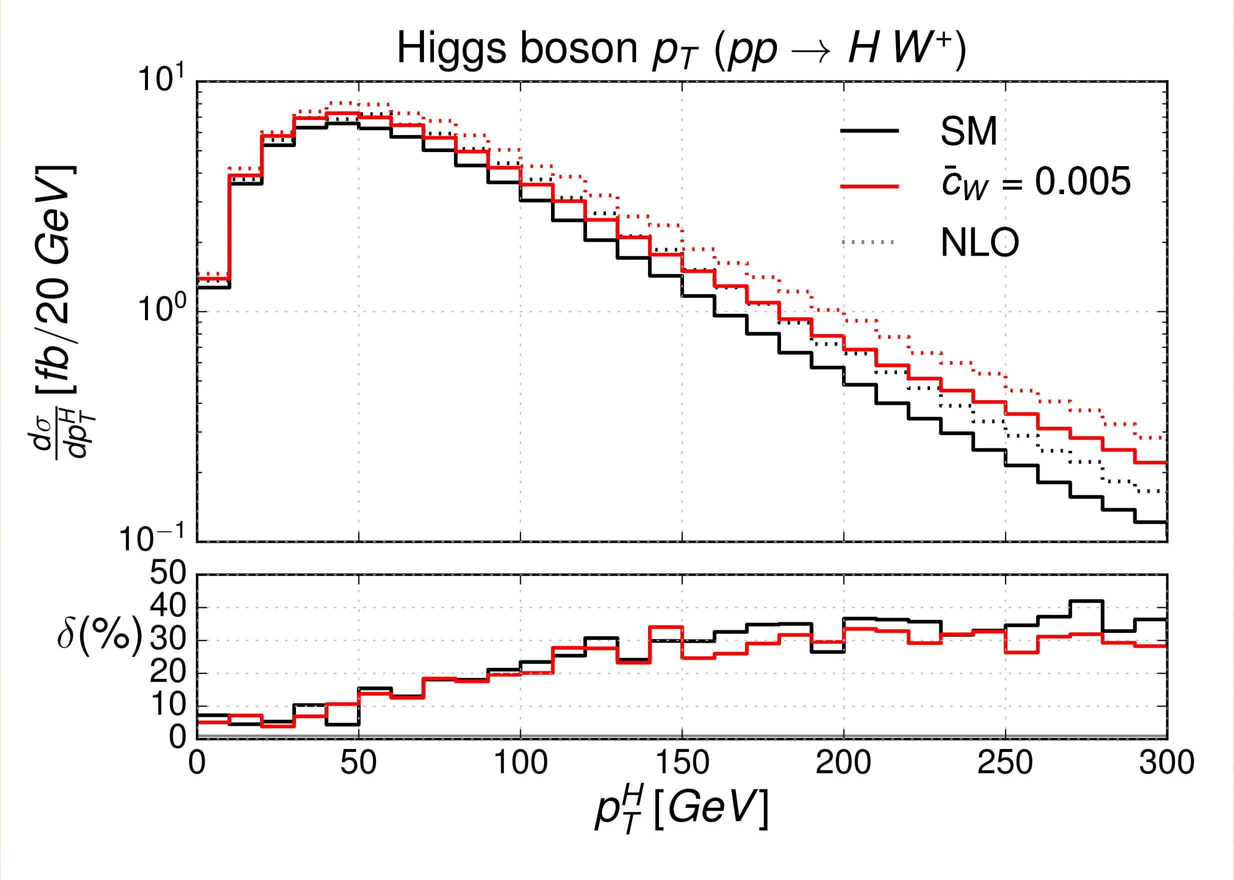
param_card with BRs from eHDECAY

A concrete example

NLO EFT: VH

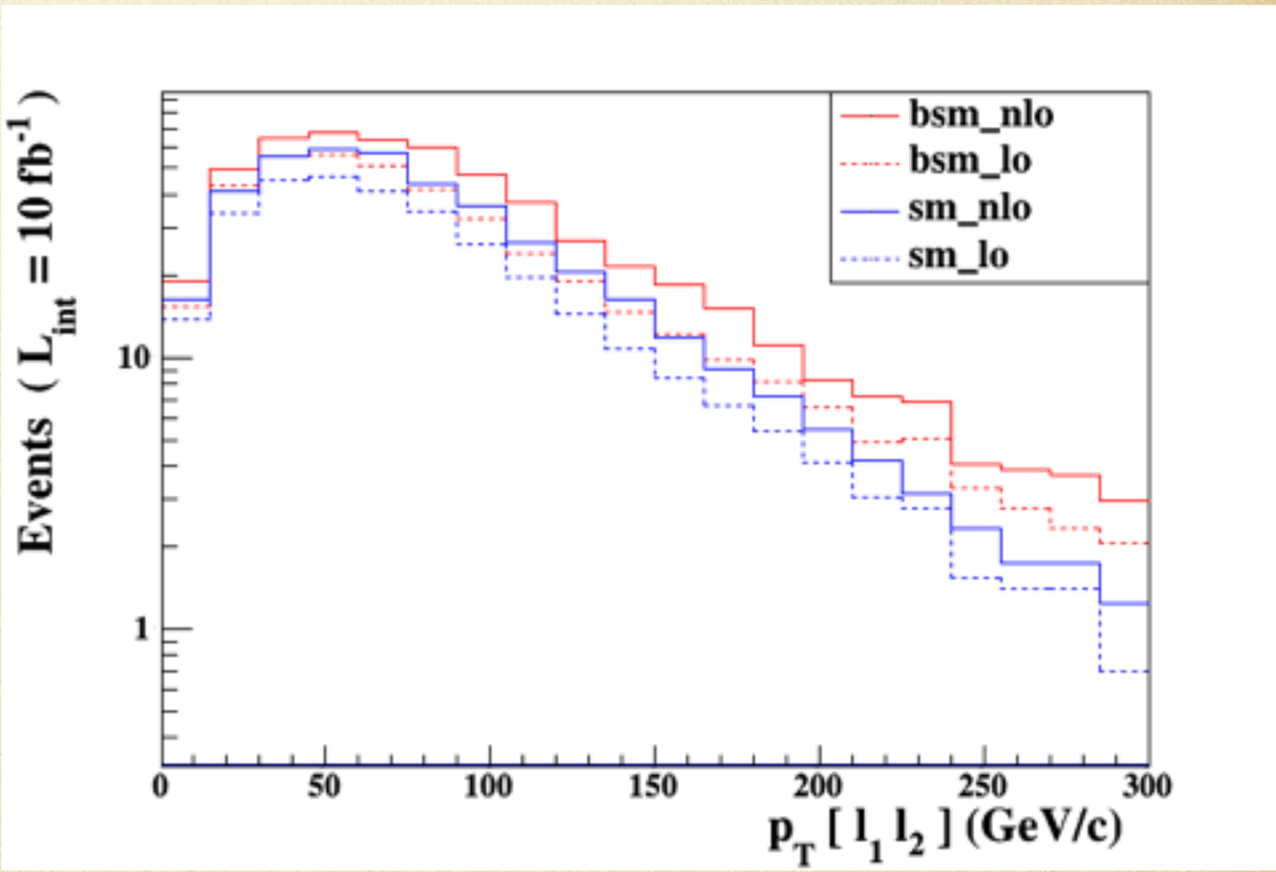
EFT NLO QCD

MCFM&POWHEG



Mimasu, VS, Williams. in prep

aMC@NLO



deGrande, Fuks, Mawatari, Mimasu, VS. in prep

timeline

general HXSWG meeting mid-July

At Les Houches: your input

twiki EFT Higgs

https://phystev.cnrs.fr/wiki/2015:groups:higgs:efthiggs

Document highlighting situations where NLO is required/missing (with SM session)

Comparison shower matching POWHEG & aMC@NLO
-> identify less sensitive distributions
(other tools, implementations?)

Thank you!

NLO calculations with MadGraph5_aMC@NLO

✦ Effective field theories at NLO (in QCD)

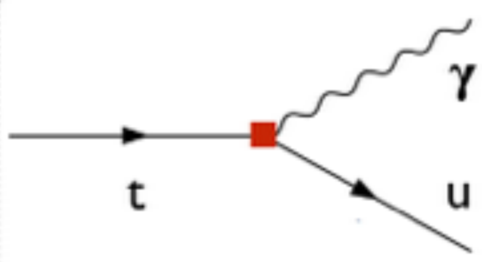
- Non-renormalizable?
  - ★ No: renormalization order by order in $1/\Lambda^2$
- Precision?
  - ★ Yes: including the QCD corrections

$$\sigma \approx 1 \;+\; O(\alpha_s) \;+\; O(1/\Lambda) \;+\; O(\alpha_s/\Lambda)$$

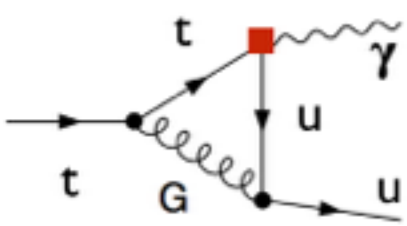
1	$O(\alpha_s)$	$O(1/\Lambda)$	$O(\alpha_s/\Lambda)$
↓	↓	↓	↓
SM@LO	SM@NLO	EFT@LO	EFT@NLO

✦ Issue: operator mixings

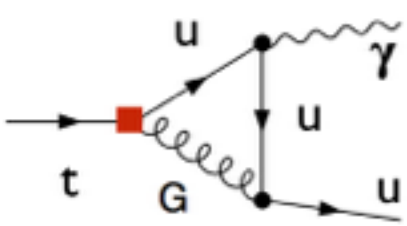
- The structure of a given operators can be generated from another operator
  - ★ Example: gtu (NLO-QCD) corrections to the γtu operator



EFT@LO



EFT@NLO



EFT@NLO

- In full generality, we may need to include all operators allowed by gauge invariance…

III *eHDECAY*

http://www.itp.kit.edu/~maggie/eHDECAY/

- $h \to f\bar{f}$:

$$\Gamma(\bar{\psi}\psi)\big|_{SILH} = \Gamma_0^{SM}(\bar{\psi}\psi)\left[1 - \bar{c}_H - 2\bar{c}_\psi + \frac{2}{|A_0^{SM}|^2}\mathrm{Re}\left(A_0^{*SM} A_{1,ew}^{SM}\right)\right]\left[1 + \delta_\psi\, \kappa^{QCD}\right]$$

$$\Gamma(\bar{\psi}\psi)\big|_{NL} = c_\psi^2\, \Gamma_0^{SM}(\bar{\psi}\psi)\left[1 + \delta_\psi\, \kappa^{QCD}\right]$$

A_0^{SM}: SM tree-level amplitude
$A_{1,ew}^{SM}$: SM elw. amplitude [real corrections treated analogously]

- factorization of QCD $\leftrightarrow$ elw. [limit small m_h]

- NL: no elw. corrections!

- other decay modes analogous

from Spira, (N)NLO ATLAS

Higgs BRs eHDECAY **Contino et al. 1303.3876 and 1403.3381**

Production rates and kinematic distributions

depend on cuts

need radiation and detector effects

Simulation tools

coefficients

$$\mathcal{L}_{eff} = \sum_i \frac{f_i}{\Lambda^2} \mathcal{O}_i$$

Collider simulation

observables

Limit coefficients = new physics

The guide to discover New Physics may come from precision, and not through direct searches

The guide to discover New Physics may come from precision, and not through direct searches

New Physics could be heavy

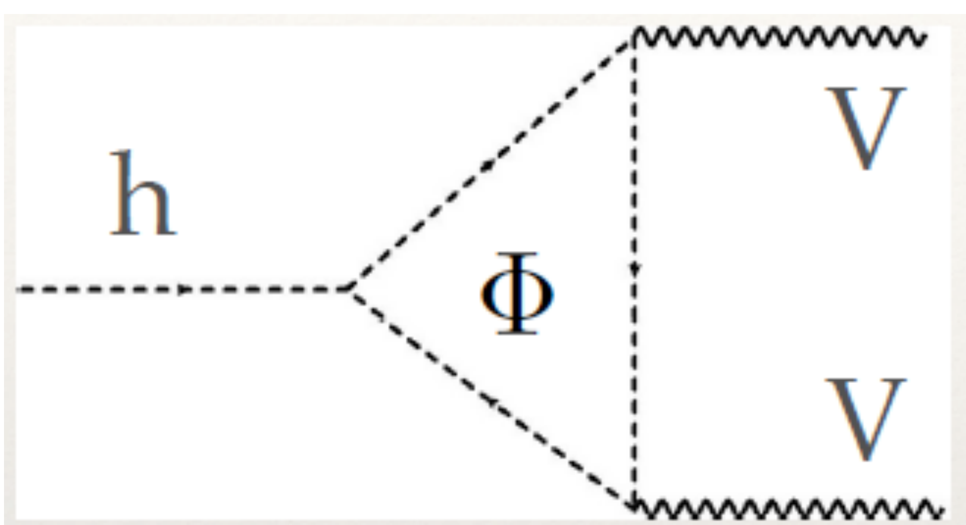
as compared with the channel we look at

Effective Theory approach

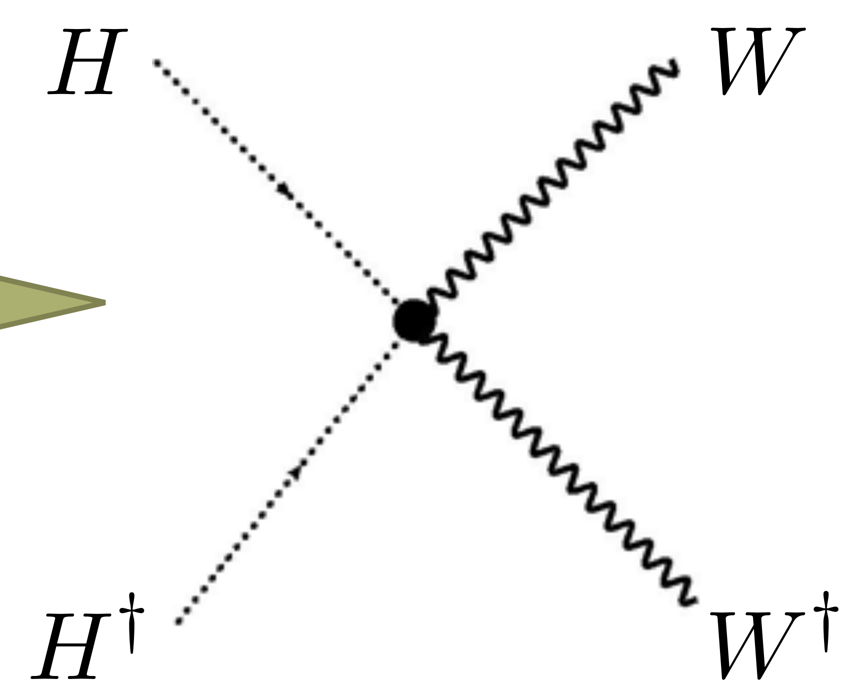
The guide to discover New Physics may come from precision, and not through direct searches

New Physics could be heavy
as compared with the channel we look at
Effective Theory approach

Example.



$$\hat{s} \lesssim 4M_\Phi^2$$



2HDMs

$$(H^\dagger \sigma^a D^\mu H)\, D^\nu W^a_{\mu\nu}$$

EFT

Bottom-up approach

operators w/ SM particles and symmetries, plus the newcomer, the Higgs

Buchmuller and Wyler. NPB (86)

$$\mathcal{L}_{BSM} = \mathcal{L}_{SM} + \mathcal{L}_{d=6} + \ldots$$

↓ HDOs

modification of couplings of SM particles

Many such operators, but few affect the searches we do

EFT

<u>Bottom-up approach</u>

operators w/ SM particles and symmetries, plus the newcomer, the Higgs

Many such operators but few affect the searches we do

Example 1. LEP physics

Operator
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$ + $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$
$\mathcal{O}_{LL}^{(3)\,l} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$
$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$
$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$
$\mathcal{O}_L^{(3)\,q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$
$\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$

Ellis, VS, You. 1410.7703

Anomalous couplings vs EFT

HDOs generate HVV interactions with more derivatives parametrization in terms of anomalous couplings

Example. Higgs anomalous couplings

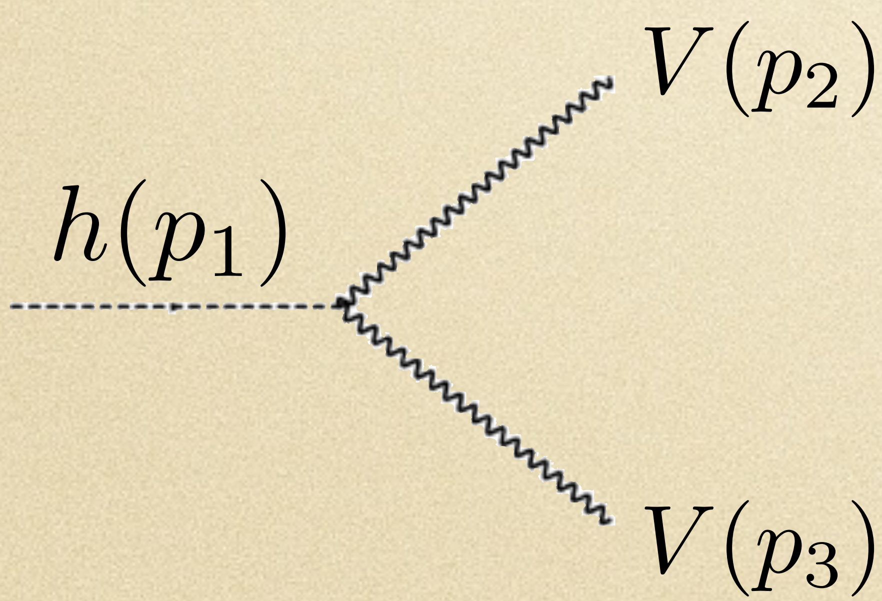
$$-\frac{1}{4}h\, g^{(1)}_{hVV} V_{\mu\nu} V^{\mu\nu} \quad -h\, g^{(2)}_{hVV} V_{\nu} \partial_{\mu} V^{\mu\nu} \quad -\frac{1}{4}h\, \tilde{g}_{hVV} V_{\mu\nu} \tilde{V}^{\mu\nu}$$

HDOs generate HVV interactions with more derivatives parametrization in terms of anomalous couplings

Example. Higgs anomalous couplings

$$-\frac{1}{4} h\, g^{(1)}_{hVV} V_{\mu\nu} V^{\mu\nu} \quad -h\, g^{(2)}_{hVV} V_{\nu} \partial_{\mu} V^{\mu\nu} \quad -\frac{1}{4} h\, \tilde{g}_{hVV} V_{\mu\nu} \tilde{V}^{\mu\nu}$$

Feynman rule for mh>2mV



$$i\eta_{\mu\nu} \left(g^{(1)}_{hVV} \left(\frac{\hat{s}}{2} - m_V^2 \right) + 2 g^{(2)}_{hVV} m_V^2 \right)$$

$$-i g^{(1)}_{hVV} p_3^{\mu} p_2^{\nu}$$

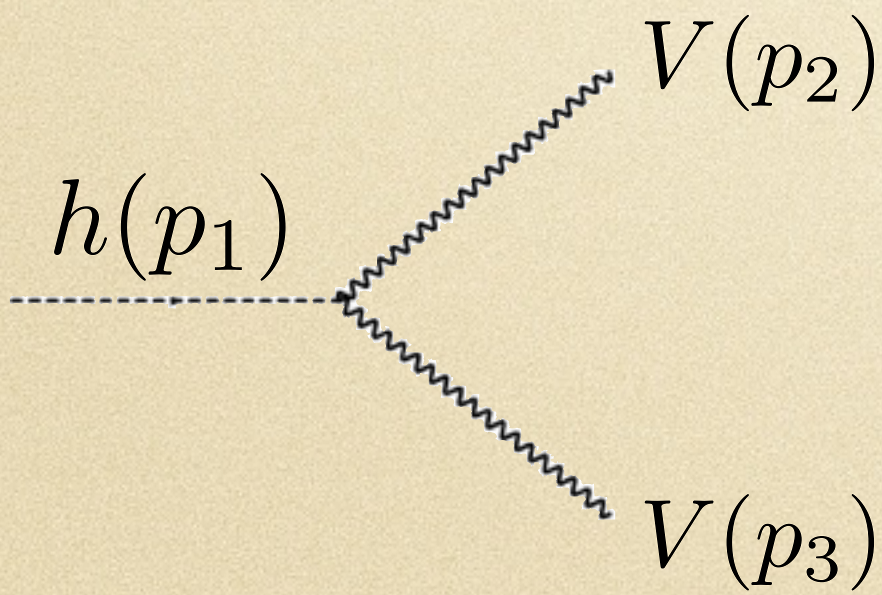
$$-i \tilde{g}_{hVV} \epsilon^{\mu\nu\alpha\beta} p_{2,\alpha} p_{3,\beta}$$

HDOs generate HVV interactions with more derivatives
parametrization in terms of anomalous couplings

Example. Higgs anomalous couplings

$$-\frac{1}{4} h\, g^{(1)}_{hVV} V_{\mu\nu} V^{\mu\nu} \qquad -h\, g^{(2)}_{hVV} V_{\nu} \partial_{\mu} V^{\mu\nu} \qquad -\frac{1}{4} h\, \tilde{g}_{hVV} V_{\mu\nu} \tilde{V}^{\mu\nu}$$

Feynman rule for mh>2mV



total rates, COM, angular, inv mass and pT distributions

Translation between EFT and Anomalous couplings

$\mathcal{L}_{3h}$ **Couplings** *vs* $SU(2)_L \times U(1)_Y$ $(D \leq 6)$ **Wilson Coefficients**

$$g^{(1)}_{hhh} = 1 + \tfrac{5}{2}\,\bar{c}_6 \quad , \quad g^{(2)}_{hhh} = \frac{g}{m_W}\,\bar{c}_H \quad , \quad g_{hgg} = g^{\rm SM}_{hgg} - \frac{4\,g_s^2\,v\,\bar{c}_g}{m_W^2} \quad , \quad g_{h\gamma\gamma} = g^{\rm SM}_{h\gamma\gamma} - \frac{8\,g\,s_W^2\,\bar{c}_\gamma}{m_W}$$

$$g^{(1)}_{hww} = \frac{2g}{m_W}\bar{c}_{HW} \quad , \quad g^{(1)}_{hzz} = g^{(1)}_{hww} + \frac{2g}{c_W^2\,m_W}\Big[\bar{c}_{HB}s_W^2 - 4\bar{c}_\gamma s_W^4\Big] \quad , \quad g^{(2)}_{hww} = \frac{g}{2\,m_W}\Big[\bar{c}_W + \bar{c}_{HW}\Big]$$

$$g^{(2)}_{hzz} = 2\,g^{(2)}_{hww} + \frac{g\,s_W^2}{c_W^2\,m_W}\Big[(\bar{c}_B + \bar{c}_{HB})\Big] \quad , \quad g^{(3)}_{hww} = g\,m_W \quad , \quad g^{(3)}_{hzz} = \frac{g^{(3)}_{hww}}{c_W^2}(1 - 2\,\bar{c}_T)$$

$$g^{(1)}_{haz} = \frac{g\,s_W}{c_W\,m_W}\Big[\bar{c}_{HW} - \bar{c}_{HB} + 8\,\bar{c}_\gamma\,s_W^2\Big] \quad , \quad g^{(2)}_{haz} = \frac{g\,s_W}{c_W\,m_W}\Big[\bar{c}_{HW} - \bar{c}_{HB} - \bar{c}_B + \bar{c}_W\Big]$$

$$-\frac{1}{4}h\,g^{(1)}_{hVV}V_{\mu\nu}V^{\mu\nu} \quad -h\,g^{(2)}_{hVV}V_\nu\partial_\mu V^{\mu\nu} \quad -\frac{1}{4}h\,\tilde{g}_{hVV}V_{\mu\nu}\tilde{V}^{\mu\nu}$$

Alloul, Fuks, VS. 1310.5150

Gorbahn, No, VS. In preparation

Translation between EFT and Anomalous couplings

Within the EFT there are relations among anomalous couplings, e.g. TGCs and Higgs physics

$\mathcal{L}_{3V}$ **Couplings** *vs* $SU(2)_L \times U(1)_Y$ $(D \leq 6)$ **Wilson Coefficients**
$g_1^Z = 1 - \frac{1}{c_W^2}\Big[\bar{c}_{HW} - (2s_W^2 - 3)\bar{c}_W\Big]$, $\kappa_Z = 1 - \frac{1}{c_W^2}\Big[c_W^2\,\bar{c}_{HW} - s_W^2\,\bar{c}_{HB} - (2s_W^2 - 3)\bar{c}_W\Big]$
$g_1^\gamma = 1$, $\kappa_\gamma = 1 - 2\,\bar{c}_W - \bar{c}_{HW} - \bar{c}_{HB}$, $\lambda_\gamma = \lambda_Z = 3\,g^2\,\bar{c}_{3W}$

similarly for QGCs: also function of the same HDOs

Alloul, Fuks, VS. 1310.5150

Gorbahn, No, VS. In preparation

The set-up

Higgs BRs eHDECAY

Contino et al. 1303.3876

Higs BRs eHDECAY Contino et al. 1303.3876

Production rates and kinematic distributions

depend on cuts

need radiation and detector effects

Simulation tools

In this talk I use

1. Feynrules   HDOs involving Higgs and TGCs

Alloul, Fuks, VS. 1310.5150

links to CalcHEP, LoopTools, Madgraph...

HEFT->Madgraph-> Pythia... -> FastSim/FullSim

In this talk I use

1. Feynrules HDOs involving Higgs and TGCs

Alloul, Fuks, VS. 1310.5150

links to CalcHEP, LoopTools, Madgraph...

HEFT->Madgraph-> Pythia... -> FastSim/FullSim

2. QCD NLO HDOs involving Higgs and TGCs

VS and Williams. In prep.

MCFM and POWHEG

Pythia, Herwig... -> FastSim/FullSim

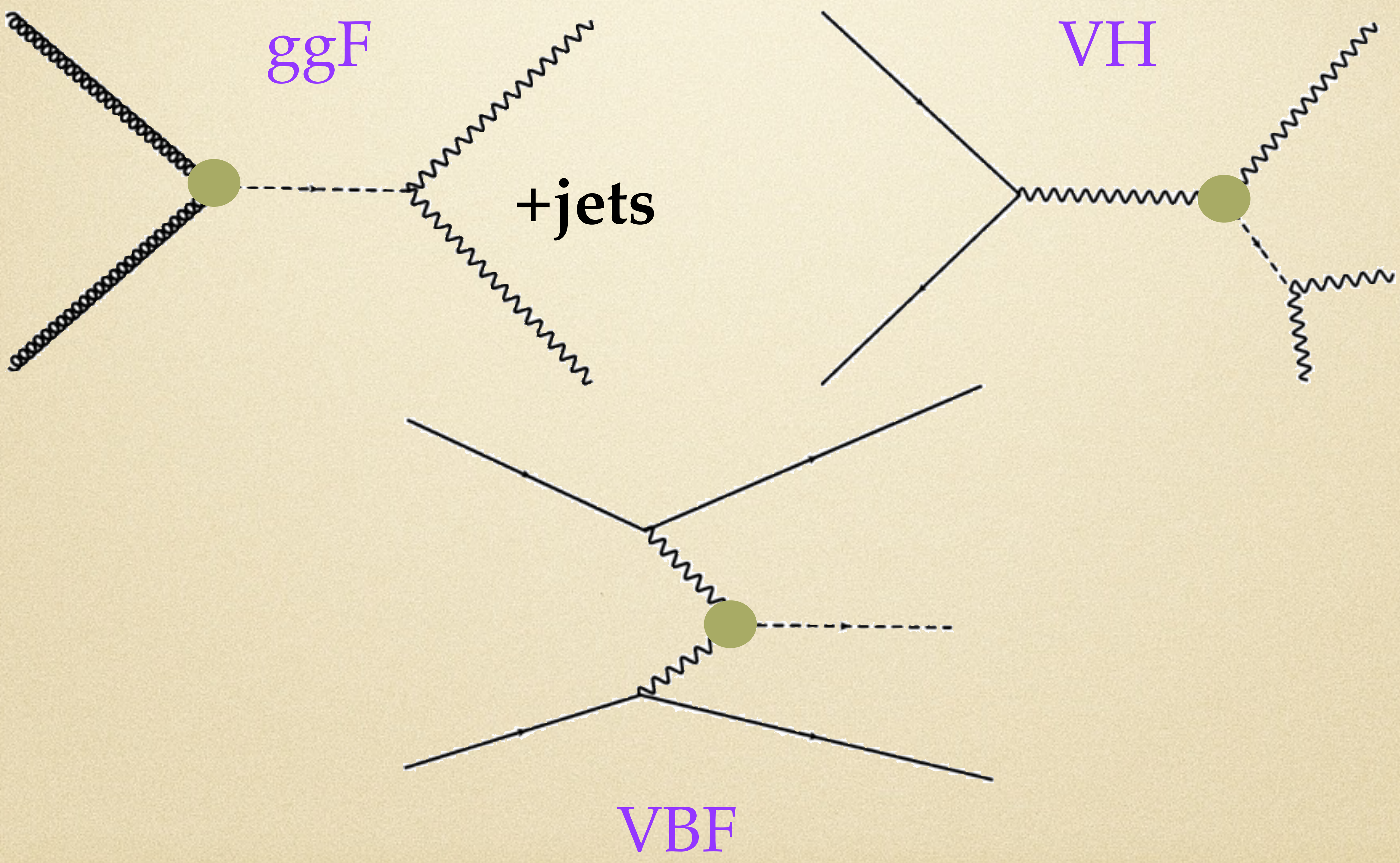
de Grande, Fuks, Mawatari, Mimasu, VS. In preparation for MC@NLO

Looking for heavy New Physics current status

Ellis, VS and You. 1404.3667, 1410.7703

What about Higgs physics?

Using kinematics for NP : a non-SM HDO and some boost



What about Higgs physics?

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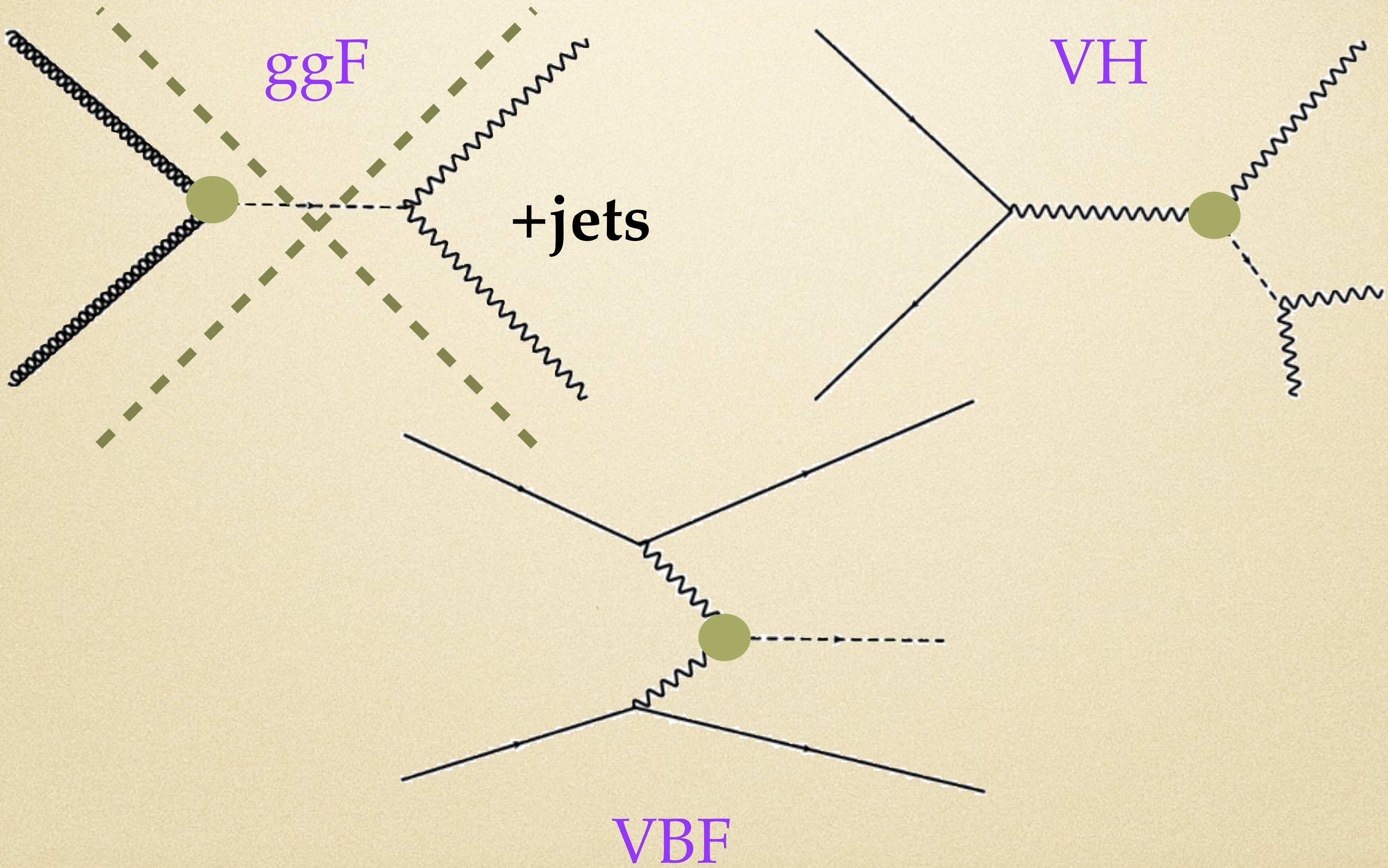
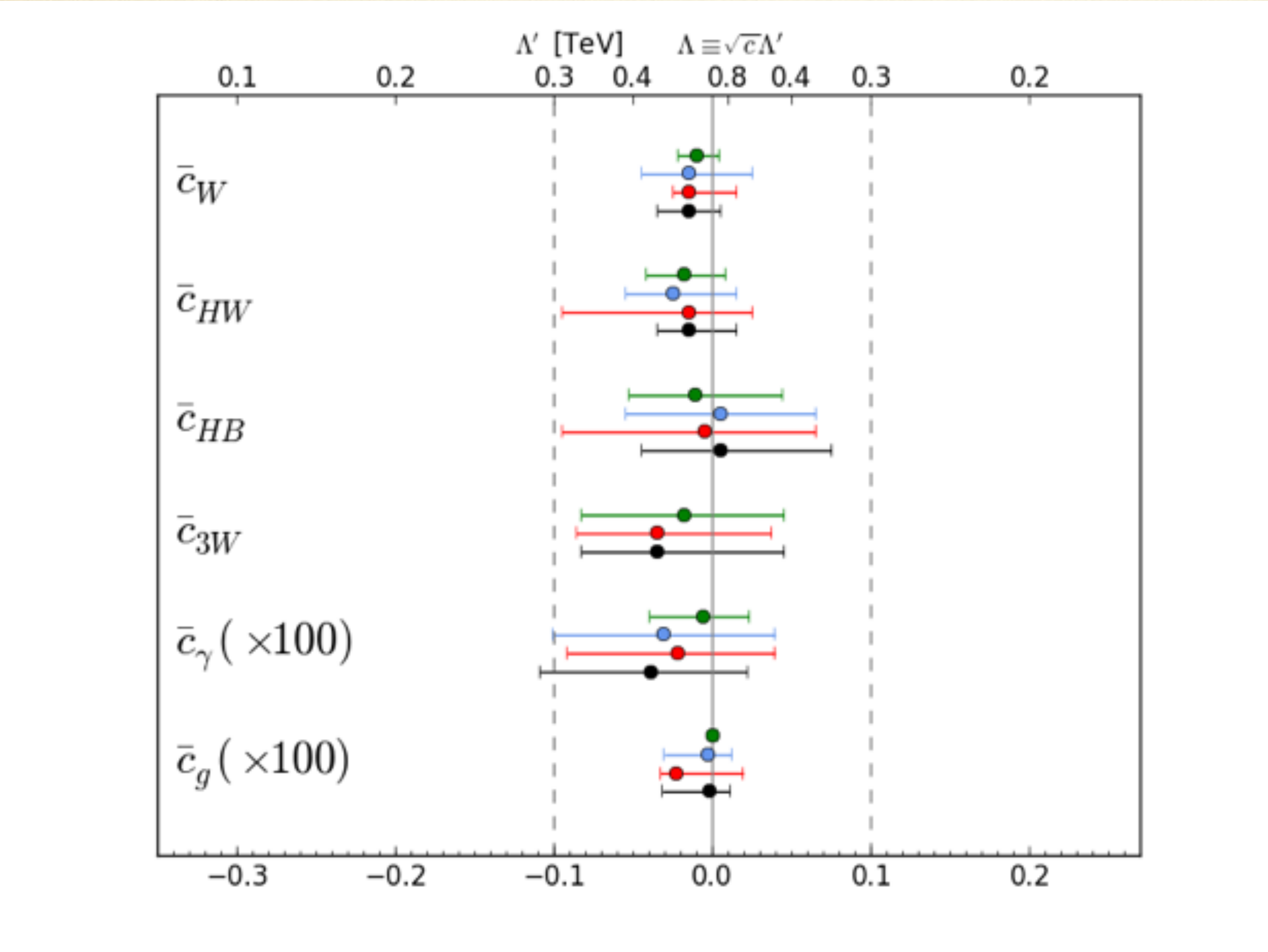


Kinematic distributions in TGC and VH are complementary



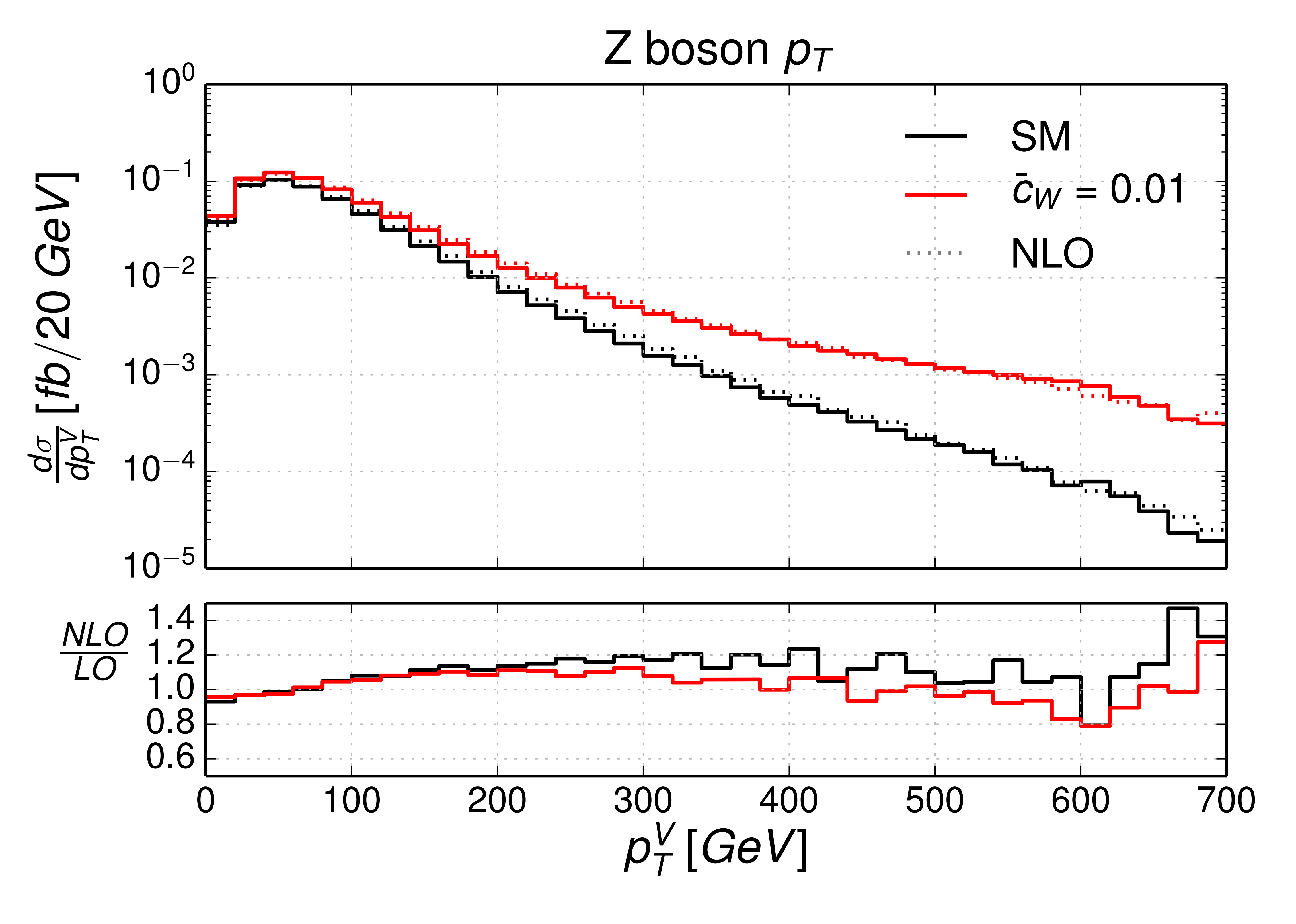
muhat+VH

muhat+TGC

all

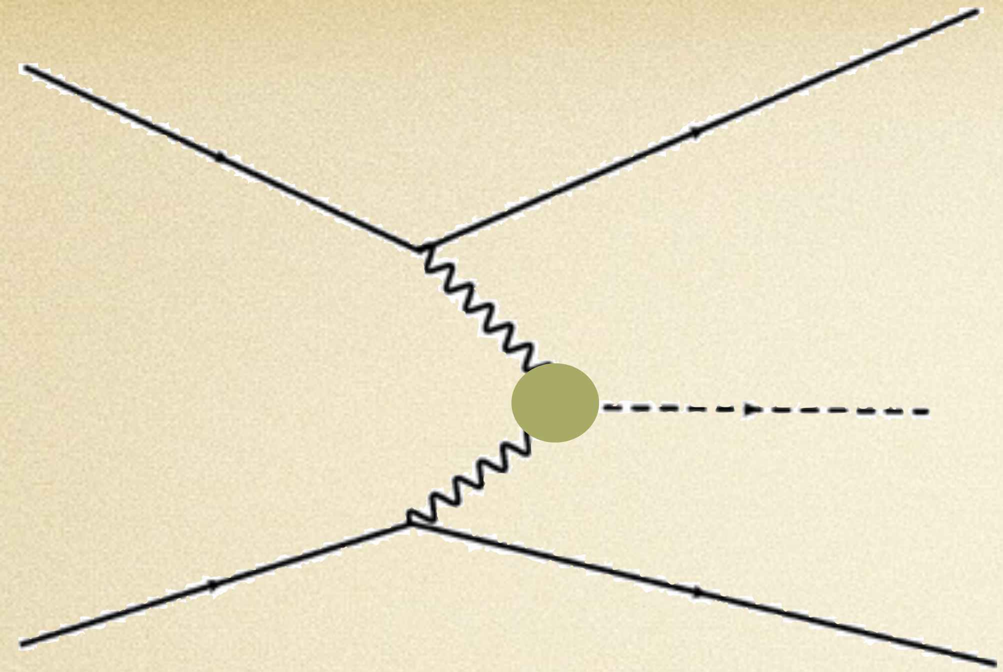
Operator	Coefficient	LHC Constraints Individual	LHC Constraints Marginalized
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}(c_W - c_B)$	$(-0.022, 0.004)$	$(-0.035, 0.005)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_{HW}$	$(-0.042, 0.008)$	$(-0.035, 0.015)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_{HB}$	$(-0.053, 0.044)$	$(-0.045, 0.075)$
$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$	$\frac{m_W^2}{\Lambda^2} c_{3W}$	$(-0.083, 0.045)$	$(-0.083, 0.045)$
$\mathcal{O}_g = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_g$	$(0, 3.0) \times 10^{-5}$	$(-3.2, 1.1) \times 10^{-4}$
$\mathcal{O}_\gamma = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\frac{m_W^2}{\Lambda^2} c_\gamma$	$(-4.0, 2.3) \times 10^{-4}$	$(-11, 2.2) \times 10^{-4}$
$\mathcal{O}_H = \frac{1}{2}(\partial^\mu \lvert H\rvert^2)^2$	$\frac{v^2}{\Lambda^2} c_H$	$(-,-)$	$(-,-)$
$\mathcal{O}_f = y_f \lvert H\rvert^2 \bar{F}_L H^{(c)} f_R + \text{h.c.}$	$\frac{v^2}{\Lambda^2} c_f$	$(-,-)$	$(-,-)$

LO vs NLO, briefly

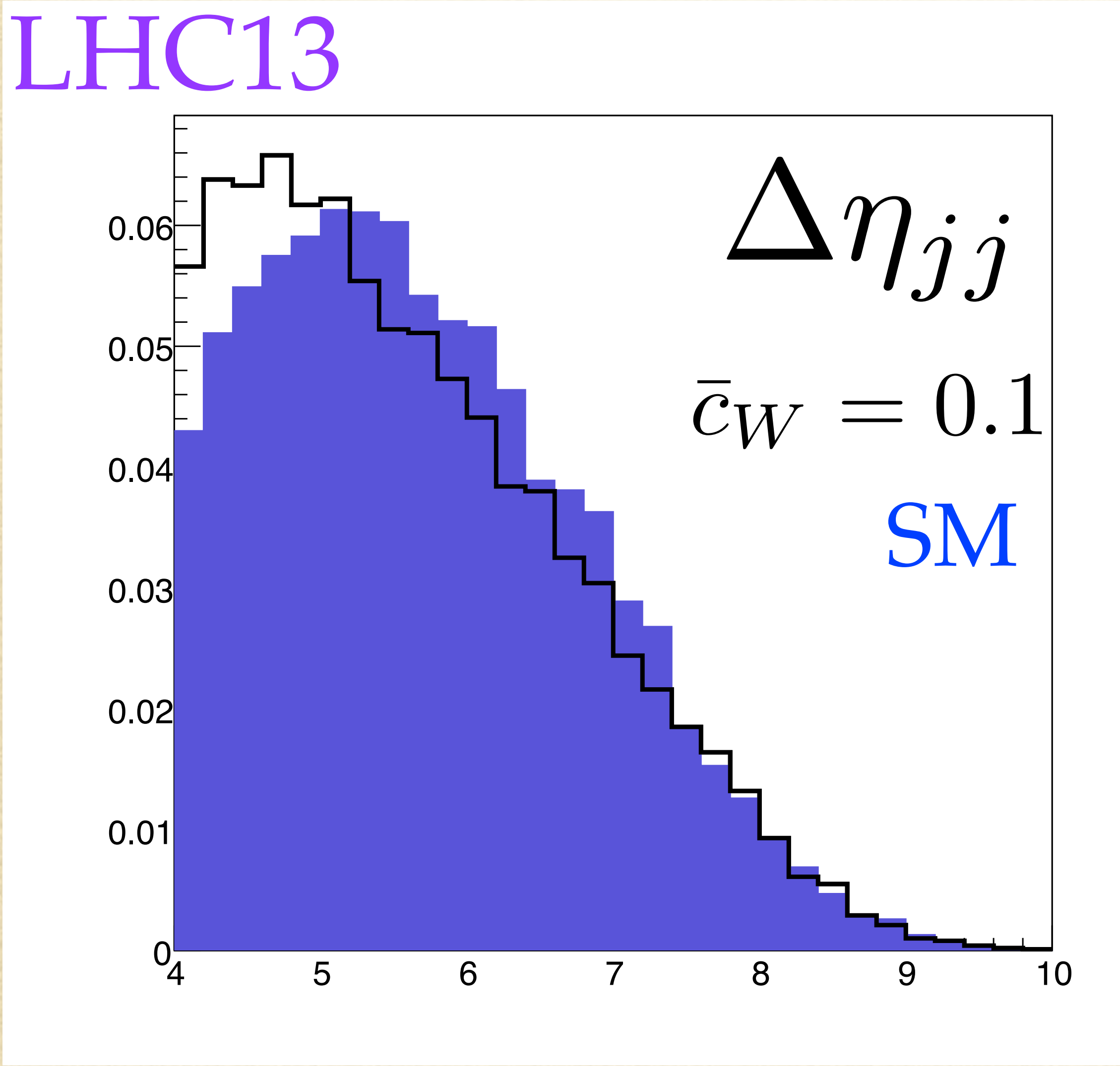


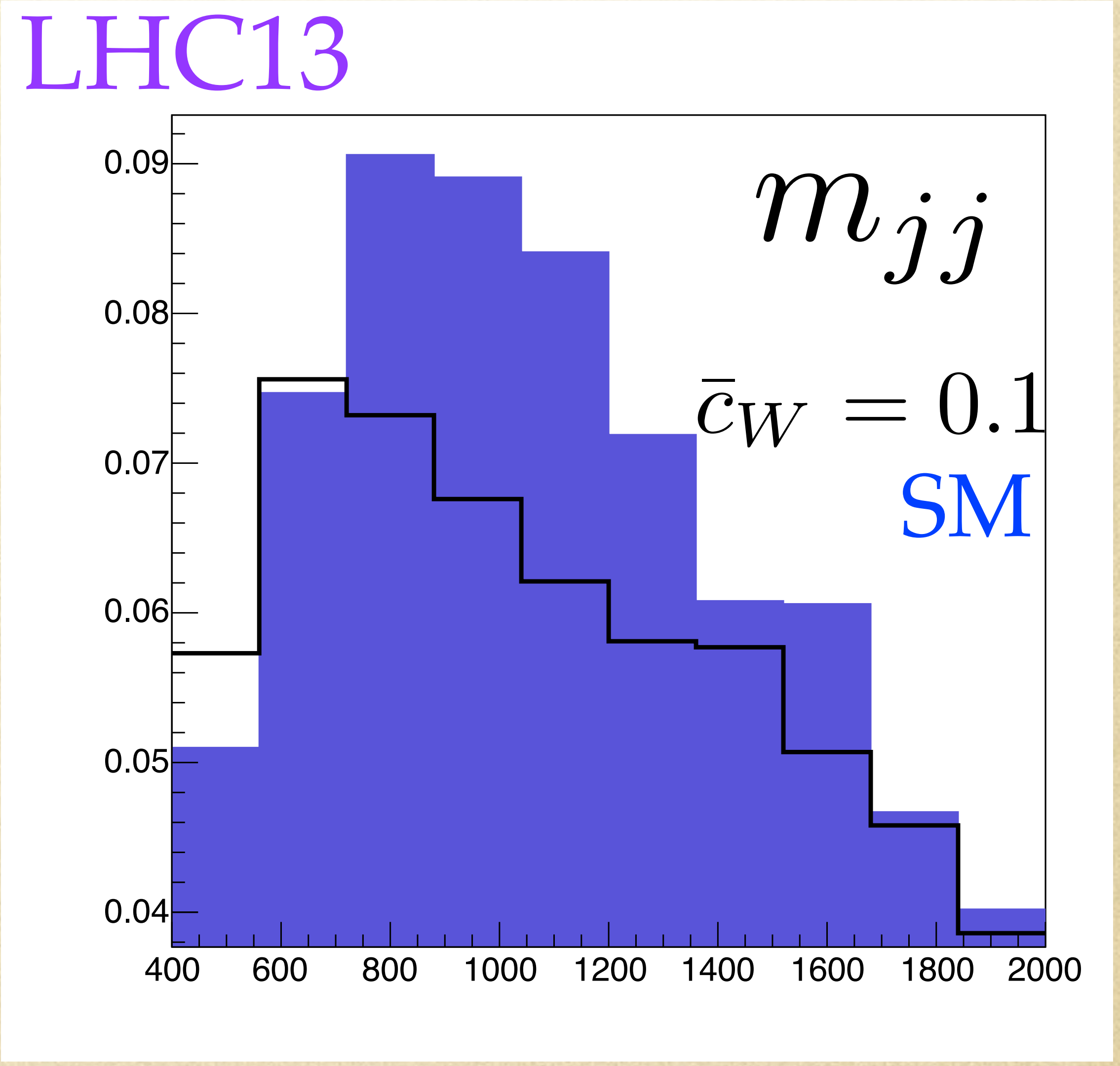
MCFM *in development*

VBF, briefly



Kinematics of VBF also modified
yet more difficult discrimination





EFT->Models

Masso and VS. 1211.1320

Gorbahn, No and VS. In preparation

EFT (linear realization) vs UV-completions

UV models

Example 1.

tree-level operators

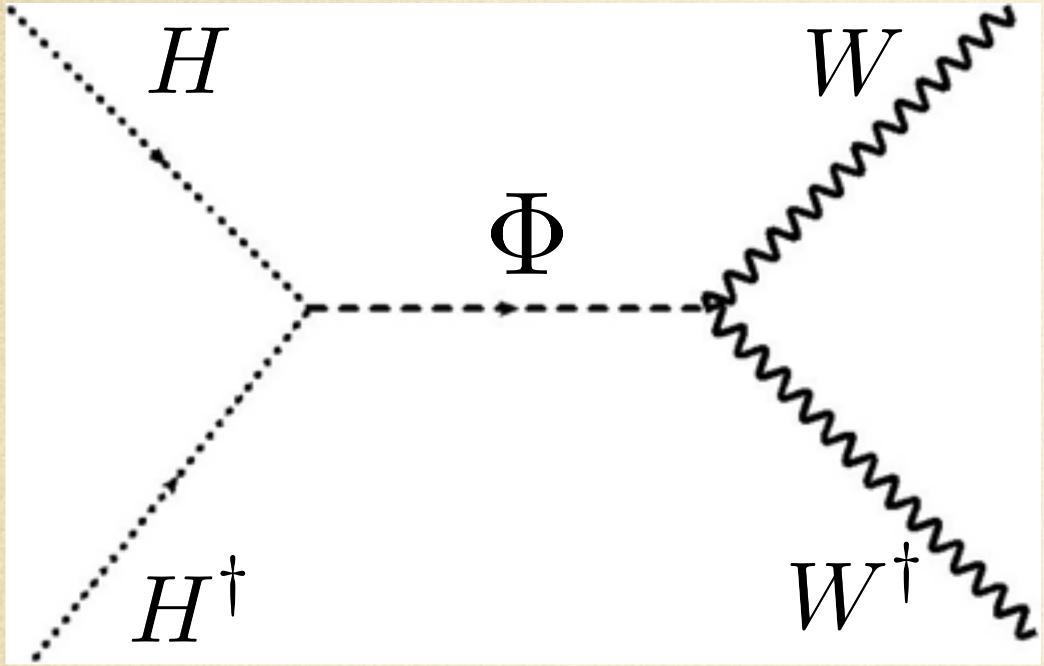
radion/dilaton exchange

Example 2.

loop-induced operators

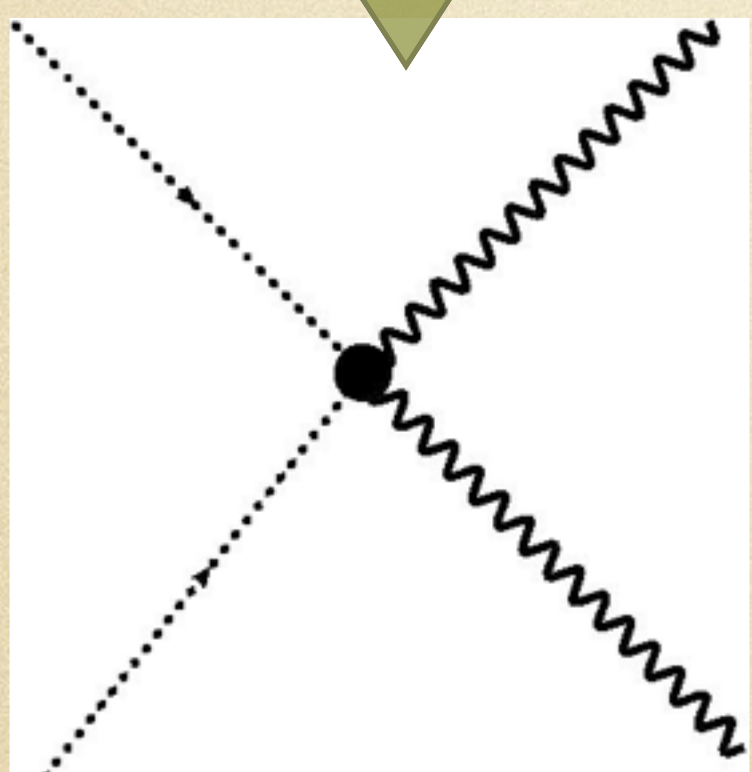
2HDM and SUSY spartners

Example 1. Tree-level exchange *radion/dilaton*



$$\frac{g_\Phi^2}{\hat{s} - M_\Phi^2} \simeq -\frac{g_\Phi^2}{M_\Phi^2}\left(1 - \frac{\hat{s}}{M_\Phi^2} + \dots\right)$$

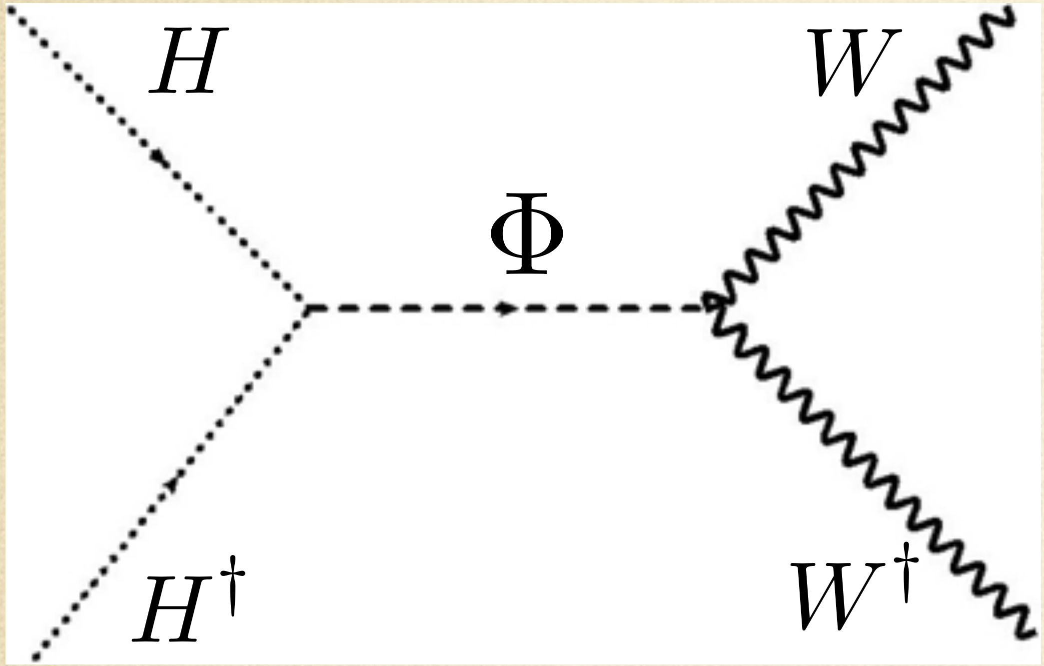
HEFT



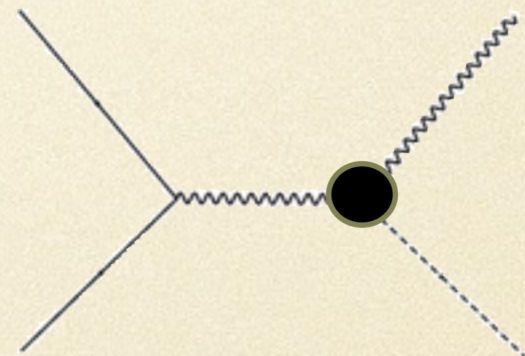
$$\hat{s} \lesssim M_\Phi^2$$

$$\bar{c}_W \simeq \left(\frac{m_H v}{\Lambda M_\Phi}\right)^2$$

Example 1. Tree-level exchange *radion/dilaton*

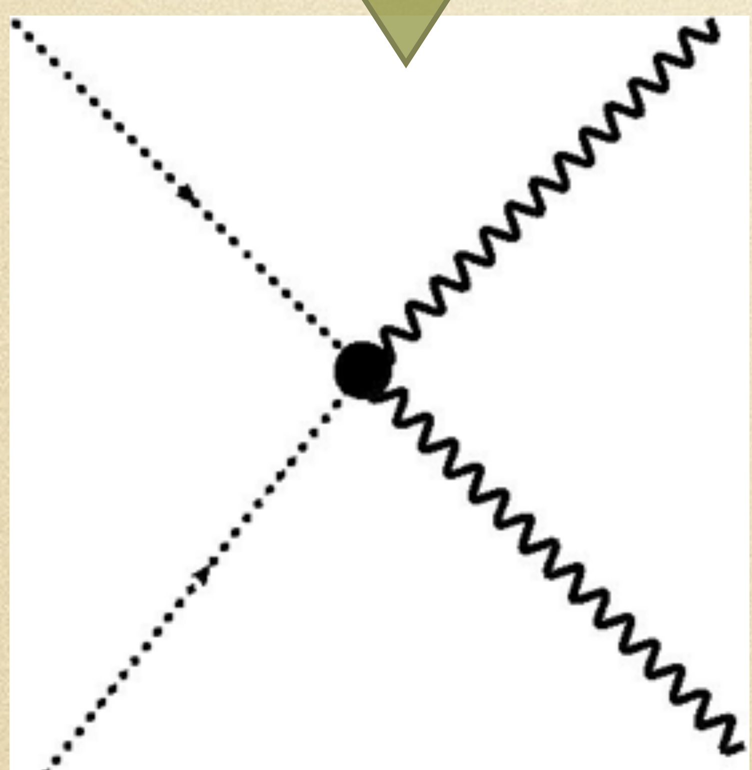


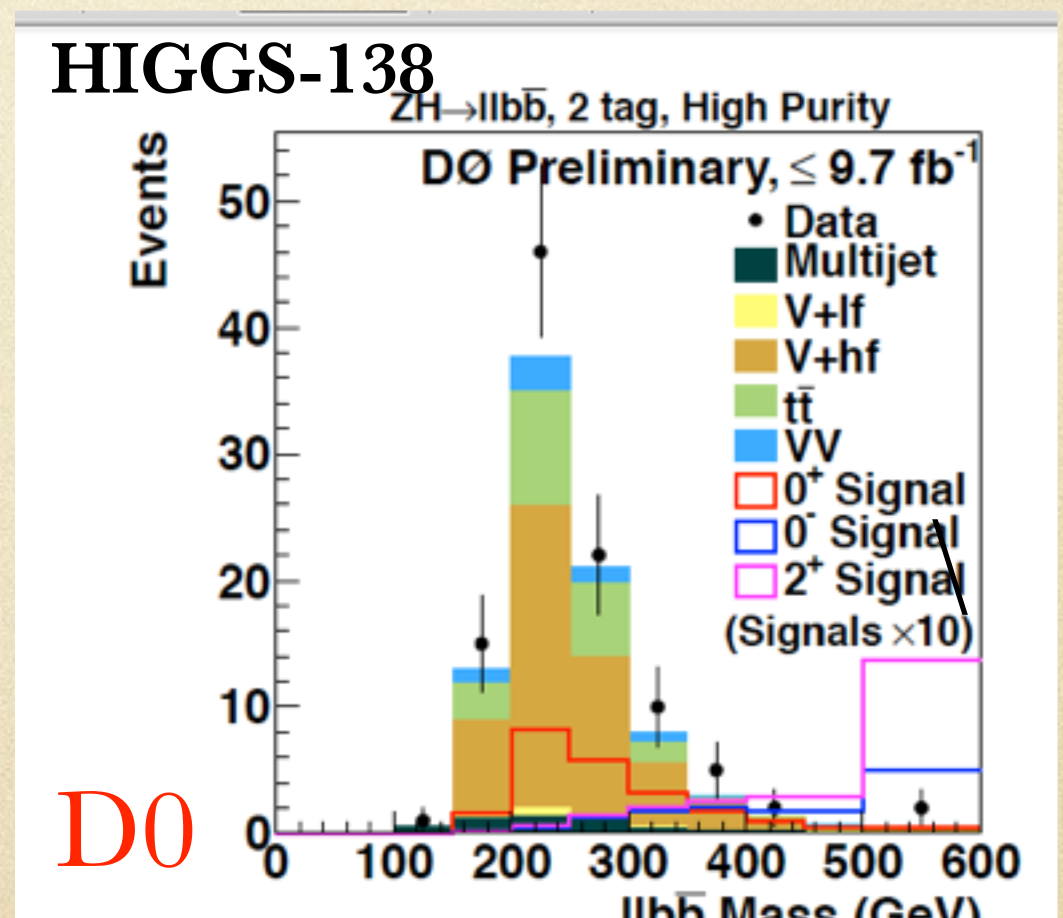
$$\frac{g_\Phi^2}{\hat{s} - M_\Phi^2} \simeq -\frac{g_\Phi^2}{M_\Phi^2}\left(1 - \frac{\hat{s}}{M_\Phi^2} + \dots\right)$$



$$m_{Vh}$$

HEFT

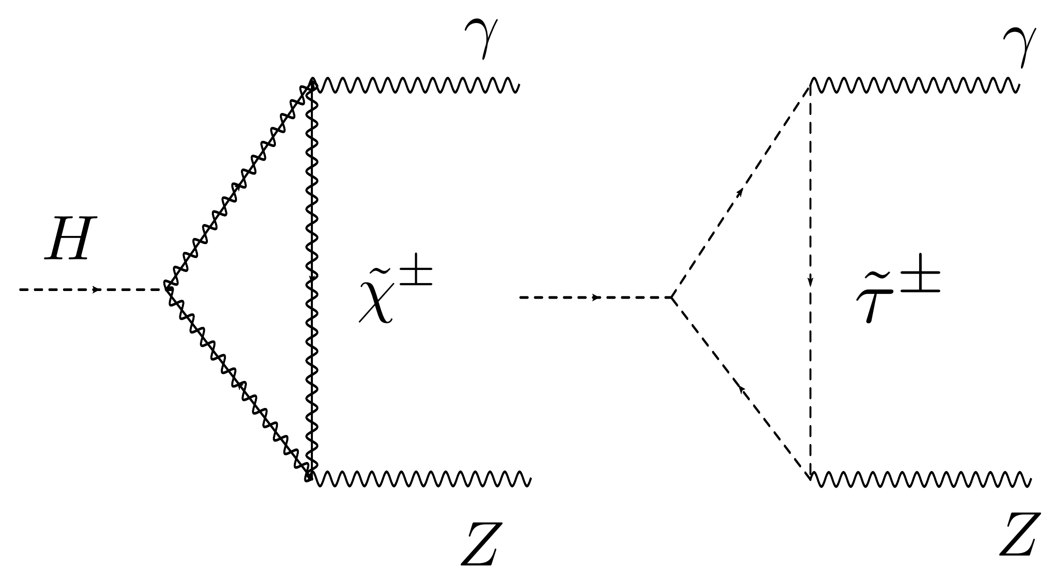




Example 2. Loop-induced

Operator
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$
$\mathcal{O}^{(3)\,l}_{LL} = (\bar{L}_L \sigma^a \gamma^\mu L_L)\,(\bar{L}_L \sigma^a \gamma_\mu L_L)$
$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$
$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$
$\mathcal{O}^{(3)\,q}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$
$\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$

2HDMs



SUSY spartners

validity is now

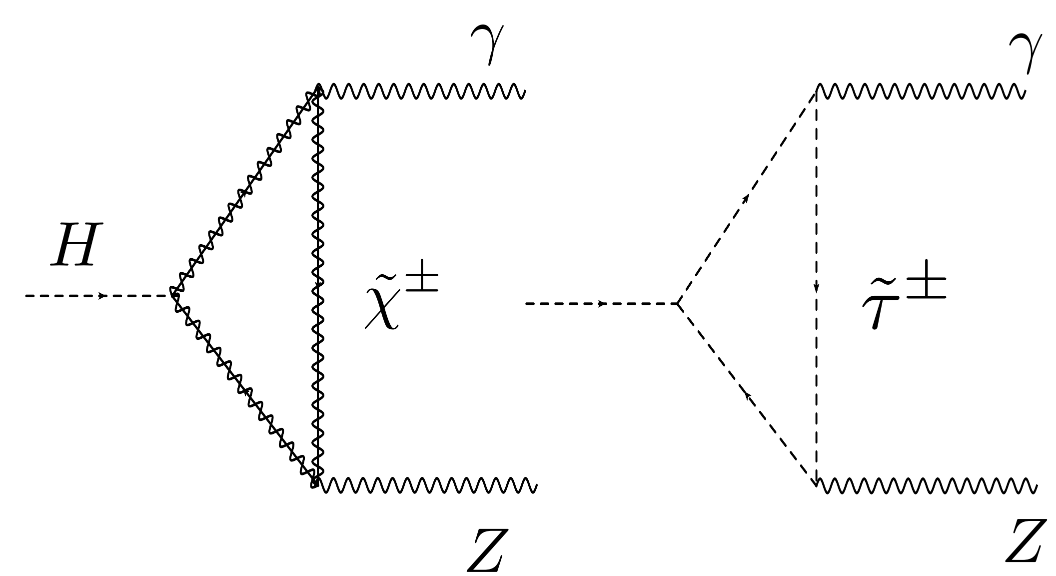
$$\hat{s} \lesssim 4M_\Phi^2$$

Example 2. Loop-induced

Operator
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$
$\mathcal{O}_{LL}^{(3)\,l} = (\bar{L}_L \sigma^a \gamma^\mu L_L)\,(\bar{L}_L \sigma^a \gamma_\mu L_L)$
$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$
$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$
$\mathcal{O}_L^{(3)\,q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$
$\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$

2HDMs

Gorbahn, No and VS. In preparation



SUSY spartners

Masso and VS. 1211.1320

General predictions:

$$\bar{c}_W - \bar{c}_B = -(\bar{c}_{HW} - \bar{c}_{HB}) = 4\,\bar{c}_\gamma$$

$$\bar{c}_{HW} = -\bar{c}_W \qquad\qquad \bar{c}_{HB} = -\bar{c}_B$$

2HDMs

$$\bar{c}_\gamma = \frac{m_W^2\, \tilde{\lambda}_3}{256\, \pi^2\, \tilde{\mu}_2^2}$$

$$\bar{c}_{HW} = -\bar{c}_W = \frac{m_W^2\, (2\, \tilde{\lambda}_3 + \tilde{\lambda}_4)}{96\, \pi^2\, \tilde{\mu}_2^2} = \frac{16\, \bar{c}_\gamma}{3} + \frac{m_W^2\, \tilde{\lambda}_4}{96\, \pi^2\, \tilde{\mu}_2^2}$$

$$\bar{c}_{HB} = -\bar{c}_B = \frac{m_W^2\, (-2\, \tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\, \pi^2\, \tilde{\mu}_2^2} = -\frac{8\, \bar{c}_\gamma}{3} + \frac{m_W^2\, \tilde{\lambda}_4}{192\, \pi^2\, \tilde{\mu}_2^2}$$

$$\bar{c}_{3W} = \frac{m_W^2}{1440\, \pi^2\, \tilde{\mu}_2^2}$$

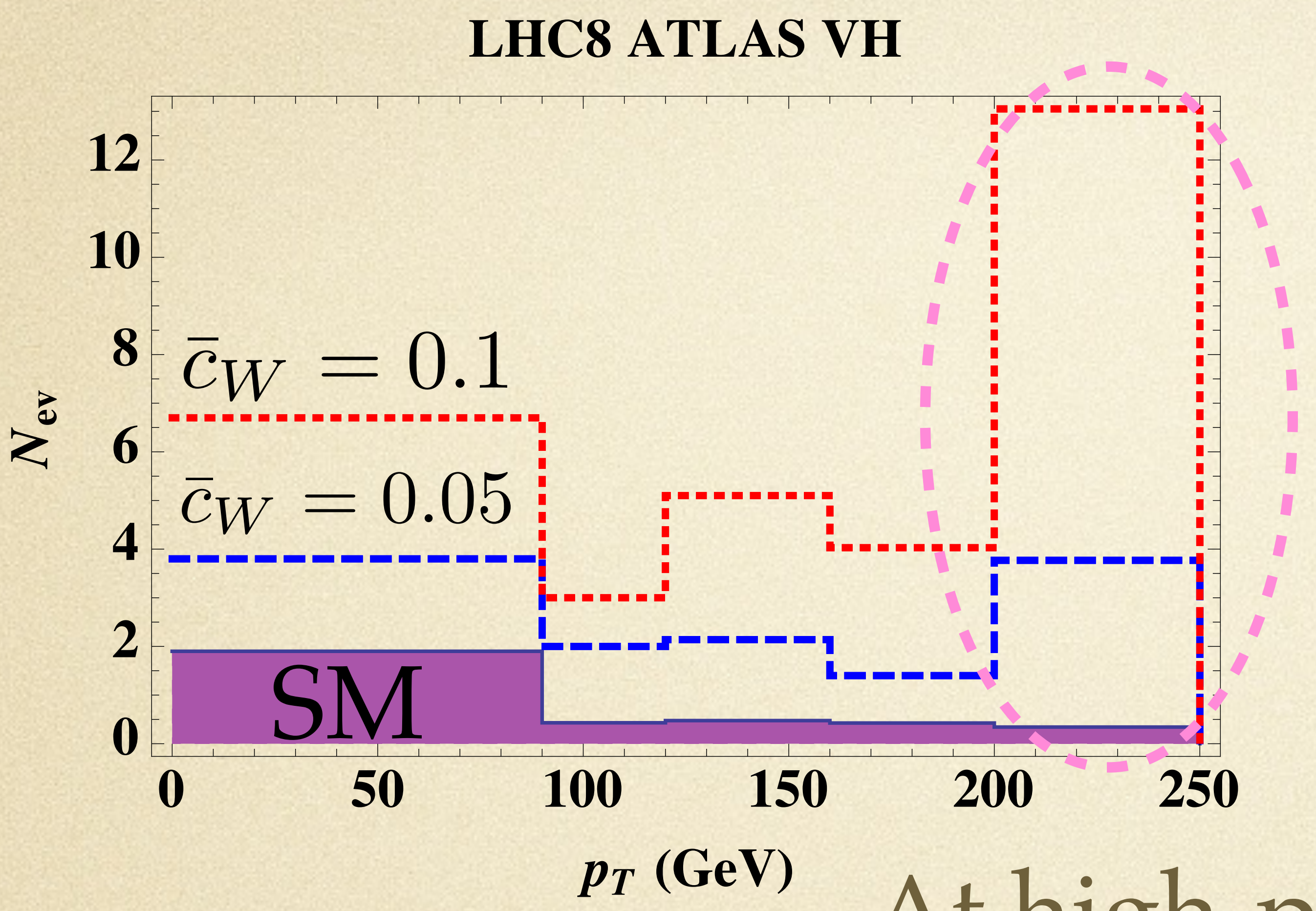
work in progress

LHC8 constraints:

one order of magnitude better than a global fit

$$\begin{aligned} \bar{c}_W &\in -(0.02, 0.0004) \\ \bar{c}_g &\in -(0.00004, 0.000003) \\ \bar{c}_\gamma &\in -(0.0006, -0.00003) \end{aligned}$$

Limitations of EFTs



most sensitive bin: overflow (last) bin

At high-pT

sensitive to dynamics of new physics

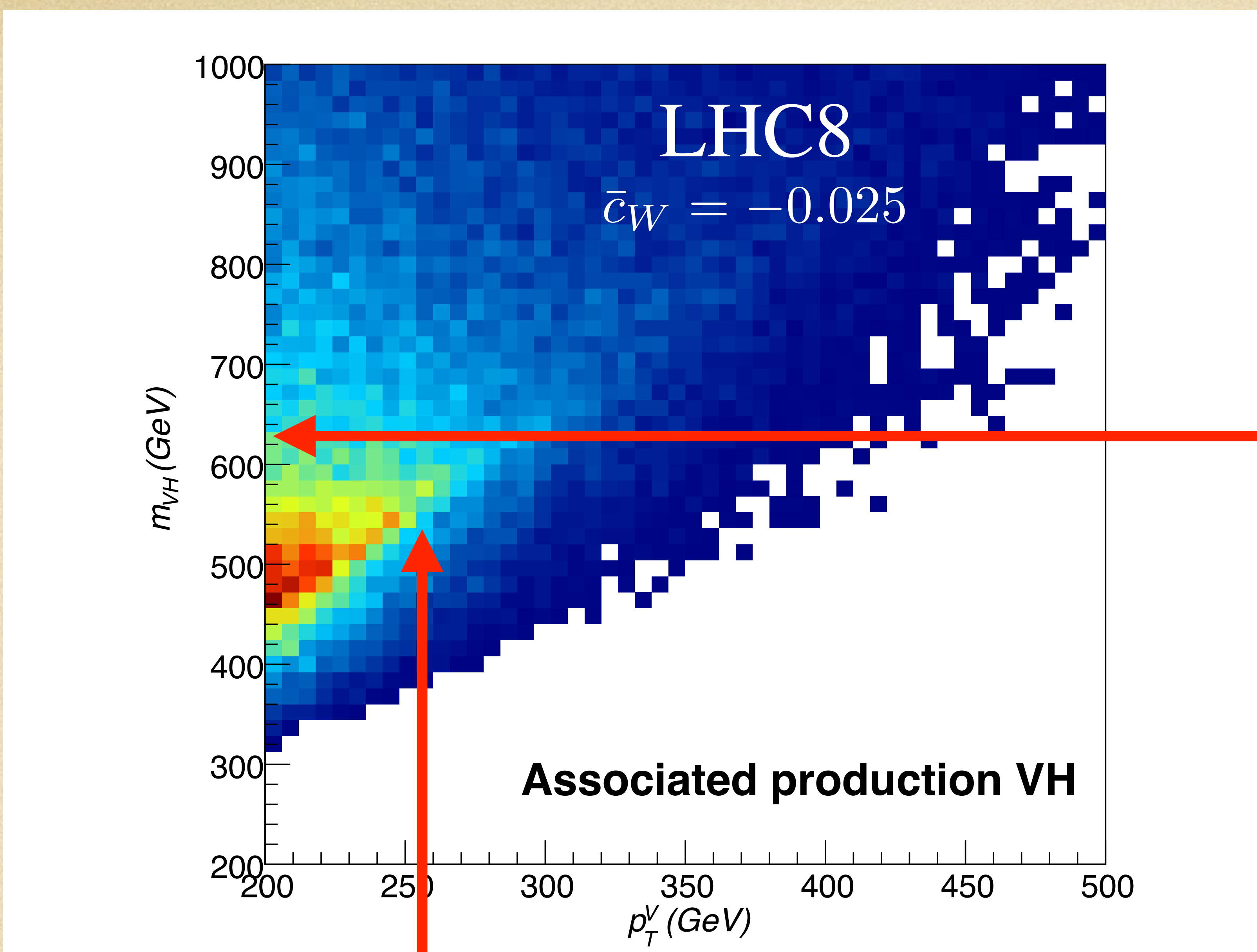
breakdown of EFT

To what extent can we use this bin?

how far does it extend?

see also

Biechoetter et al 1406.7320 Englert+Spannowsky. 1408.5147 Dawson, Lewis, Zeng 1409.6299



validity

distribution

$$\sqrt{c} = g_{NP}\,\frac{m_W}{\Lambda_{NP}}$$

$$\Lambda_{NP} \simeq g_{NP}\,(\ 0.5\ \mathrm{TeV}\ )$$

Conclusions

Absence of hints in direct searches
EFT approach to Higgs physics

Higgs anomalous couplings:
rates but also kinematic distributions

Complete global fit at the level of dimension-six operators
enhanced using differential information

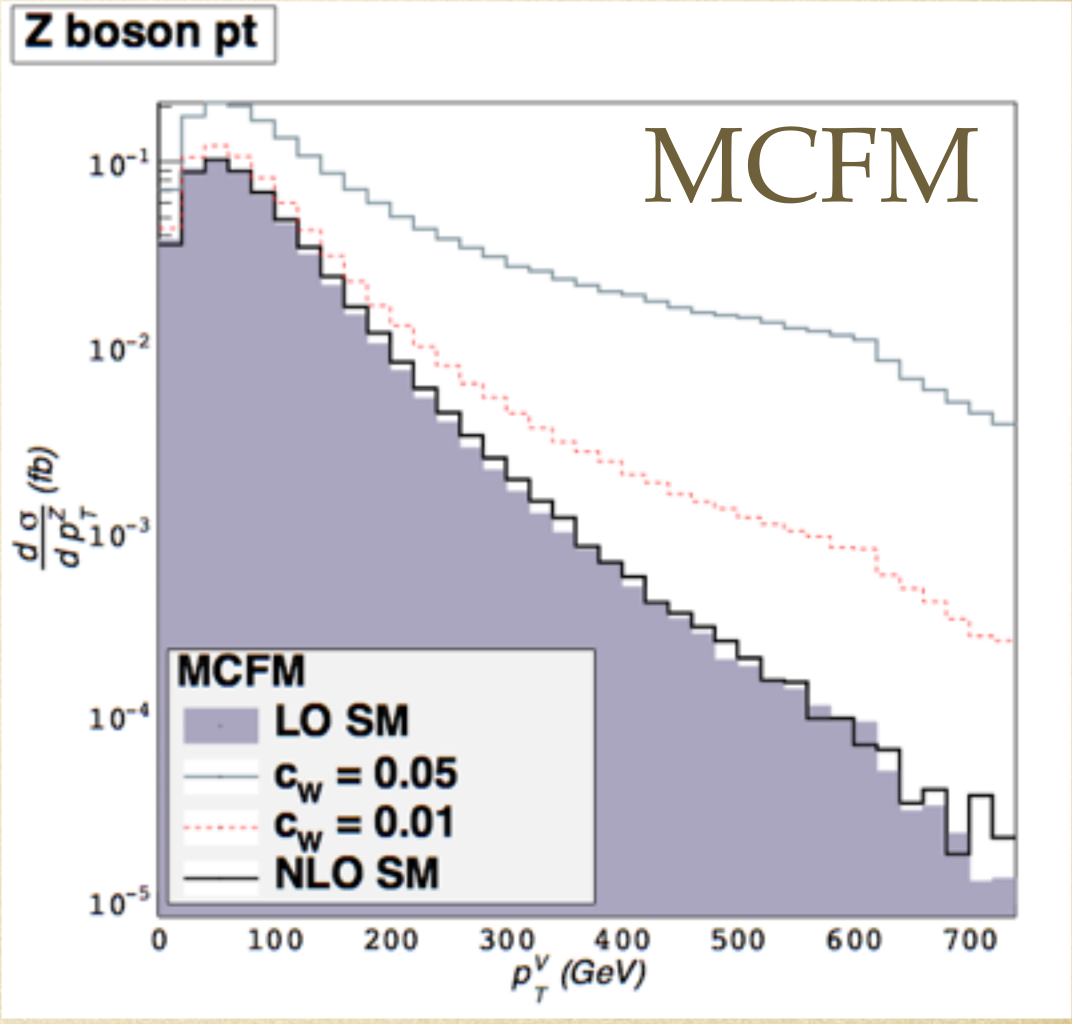
SM precision crucial: excess as genuine new physics

Exploring the validity of EFT
propose benchmarks

Benchmarks
correlations among coefficients, input for fit

Kinematics of associated production

pTV is more sensitive than mVH to QCD NLO
but effect not yet at the level of operator values we can bound



VS and Williams. In prep.

Boring and necessary details

Bottom-up approach:
operators w/ SM particles and symmetries,
plus the newcomer, the Higgs

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A

Realization of EWSB

Linear or non-linear

Boring and necessary details

Bottom-up approach:
operators w/ SM particles and symmetries,
plus the newcomer, the Higgs

A

Realization of EWSB

Linear or non-linear

B

And the Higgs could be

Weak doublet or singlet

Once this choice is made, expand...

$$\frac{1}{\Lambda^2}$$ Integrating out new physics

$$\frac{v^2}{f^2}$$ Non-linearity $U = e^{i\Pi(h)/f}$

...order-by-order

For example, some operators Higgs-massive vector bosons

ex.

$$\mathcal{L}_{eff} = \sum_i \frac{f_i}{\Lambda^2}\mathcal{O}_i$$

$$\mathcal{O}_W = (D_\mu\Phi)^\dagger \widehat{W}^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_B = (D_\mu\Phi)^\dagger(D_\nu\Phi)\ \widehat{B}^{\mu\nu}$$

$$\mathcal{O}_{WW} = \Phi^\dagger \widehat{W}^{\mu\nu}\widehat{W}_{\mu\nu}\Phi$$

$$\mathcal{O}_{BB} = (\Phi^\dagger\Phi)\ \widehat{B}^{\mu\nu}\widehat{B}_{\mu\nu}$$

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$$\mathcal{O}_{BB} = (\Phi^\dagger \Phi)\ \widehat{B}^{\mu\nu} \widehat{B}_{\mu\nu}$$

C

UV theory: tree-level or loop

may need a model bias

ex. SILH

$$\frac{2igc_{HW}}{m_W^2} (D^\mu \Phi^\dagger) \hat{W}_{\mu\nu} (D^\nu \Phi)$$

Giudice, Grojean, Pomarol, Rattazzi. 0703164 redundancies trade off operators using EOM

D Choice of basis

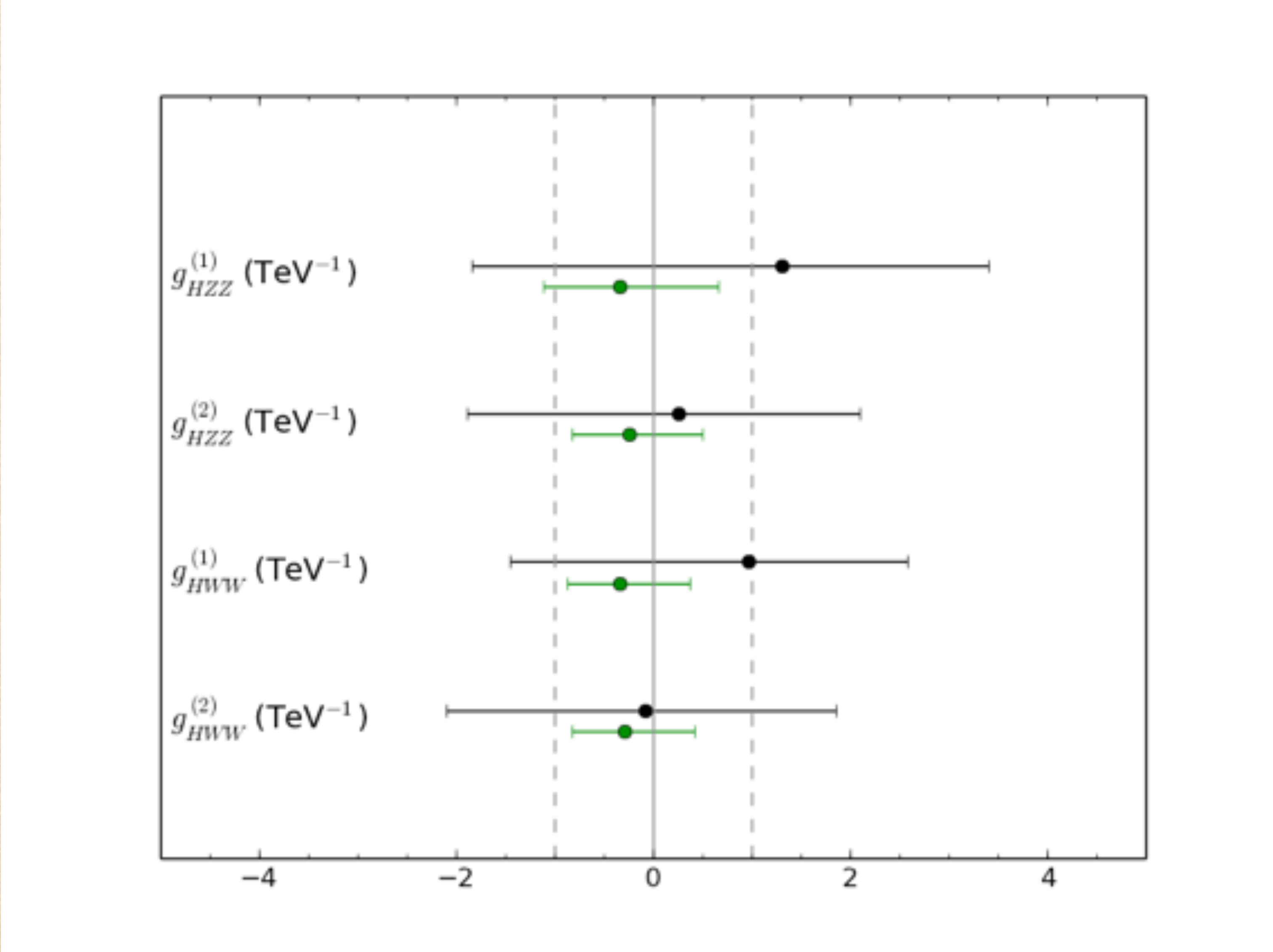
And, **finally**

Observables as a function of HDOs coefficients

In summary

In terms of Higgs' anomalous couplings

$$\mathcal{L} \supset - \frac{1}{4} g^{(1)}_{HZZ} Z_{\mu\nu} Z^{\mu\nu} h - g^{(2)}_{HZZ} Z_{\nu} \partial_{\mu} Z^{\mu\nu} h - \frac{1}{2} g^{(1)}_{HWW} W^{\mu\nu} W^{\dagger}_{\mu\nu} h - \left[g^{(2)}_{HWW} W^{\nu} \partial^{\mu} W^{\dagger}_{\mu\nu} h + \text{h.c.} \right],$$



black global fit

green one-by-one fit

Global fit to signal strengths and kinematic distributions

Conclusions of the analysis

1. Breaking of blind directions requires information on associated production (AP)

2. Kinematic distributions in AP is as sensitive (or more) than total rates

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