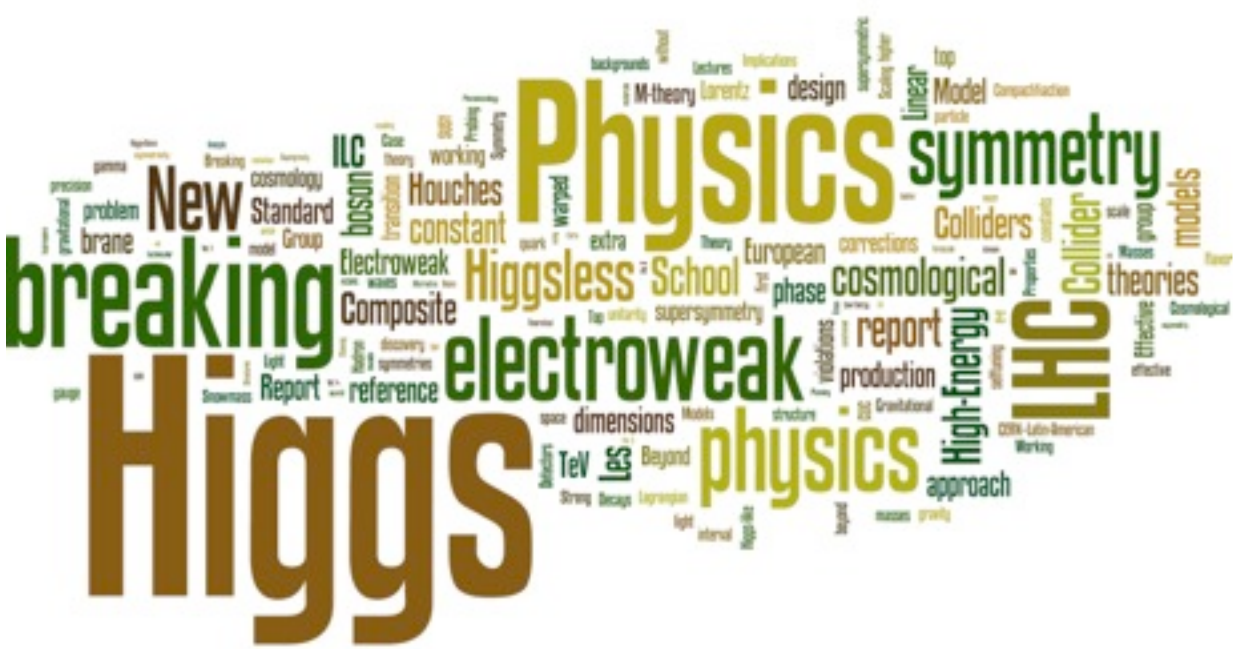
Boosted and off-shell Higgs channels & ttH

DESY, LHC physics discussion, February 13, 2017



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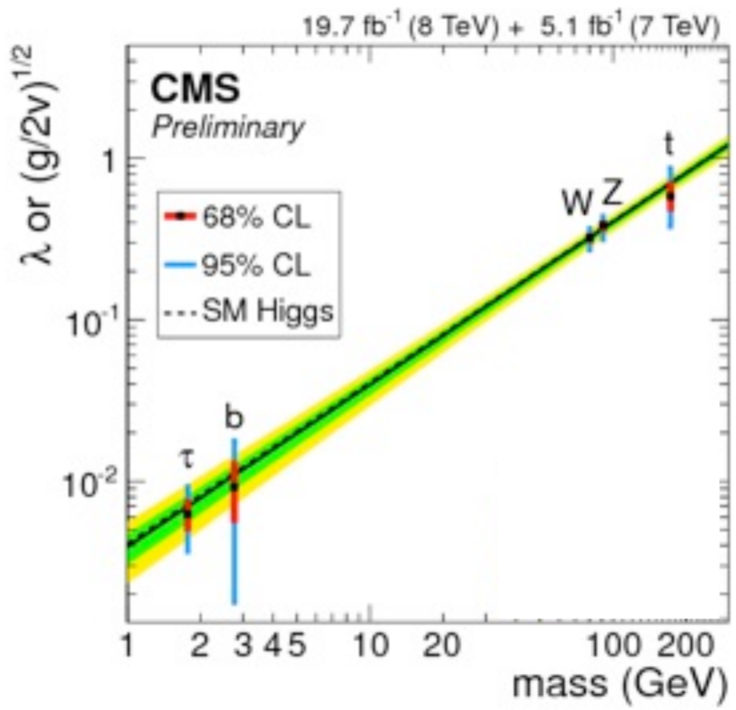
State of the art Higgs fit?

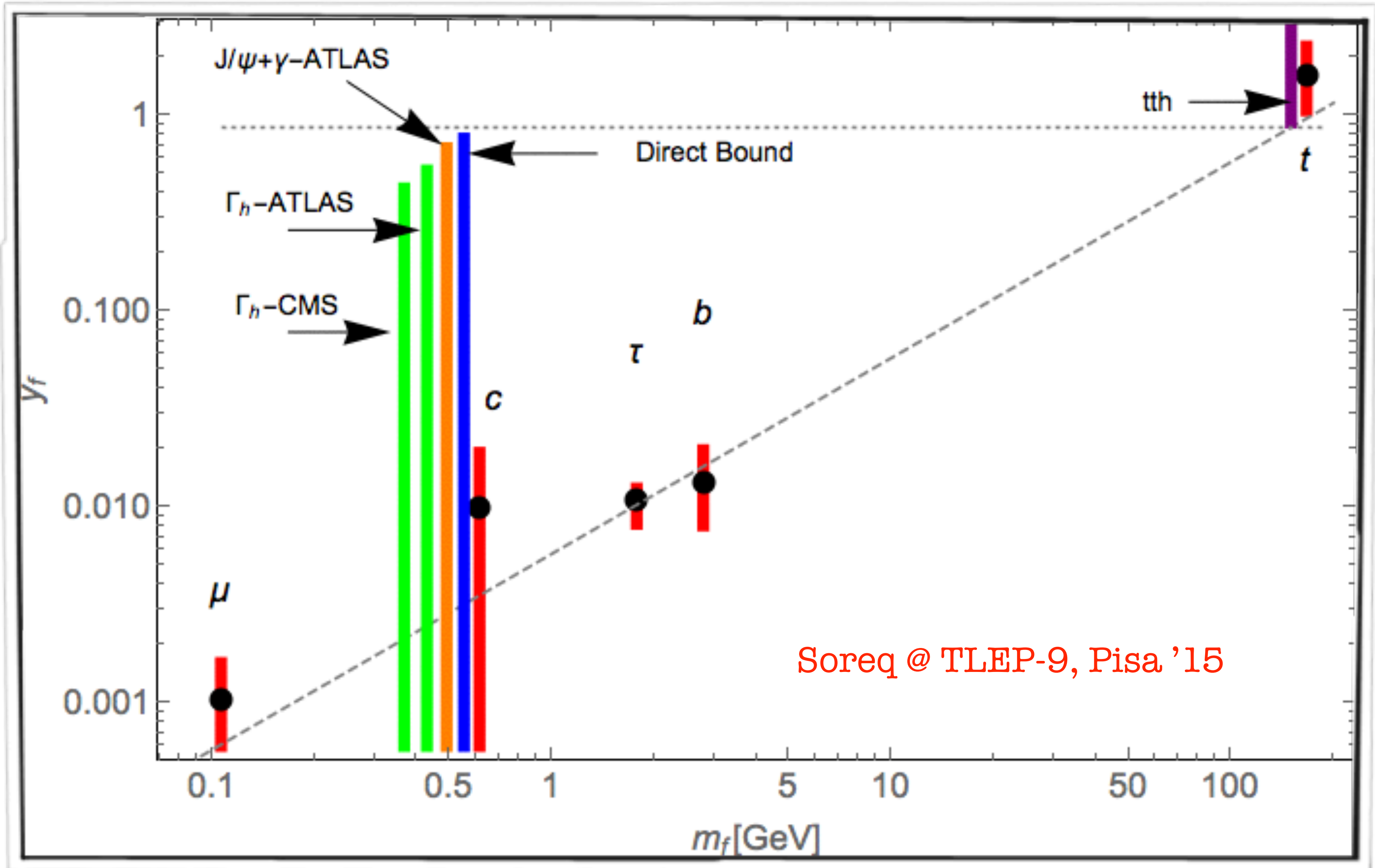


CMS PAS-HIG-14-009

Higgs couplings
are proportional
to the masses of the particles

$$\lambda_\psi \propto \frac{m_\psi}{v}\,, \qquad \lambda_V^2 \equiv \frac{g_{VVh}}{2v} \propto \frac{m_V^2}{v^2}$$

State of the art Higgs fit?



missing information to complete the picture

° width measurement?

° couplings to light particles?

inclusive (e.g. c-tagging) or exclusive ($h \to J/\Psi+\gamma$)

° coupling to top?

Boosted Higgs

inability to resolve the top loops

- the bearable lightness of the Higgs: rich spectroscopy w/ multiple decays channels
- the unbearable lightness: loops saturate and don't reveal the physics @ energy physics (*)

m_H(GeV)	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t\to\infty)}$	$\frac{\sigma_{NLO}(m_t,m_b)}{\sigma_{NLO}(m_t\to\infty)}$
125	1.061	0.988
150	1.093	1.028
200	1.185	1.134

e.g. Grazzini, Sargsyan '13

the inclusive rate
doesn't "see" the finite mass of the top

(*) unless it doesn't decouple (e.g. 4th generation)

$\Rightarrow$ cannot disentangle
- long distance physics (modified top coupling)
- short distance physics (new particles running in the loop)

$\Leftarrow$

$$\mathcal{L} = \frac{\alpha_s c_g}{12\pi}|H|^2 G^{a\,2}_{\mu\nu} + \frac{\alpha c_\gamma}{2\pi}|H|^2 F_{\mu\nu} + y_t c_t \bar{q}_L \tilde{H} t_R |H|^2$$

$$\frac{\sigma(gg\to h)}{\mathrm{SM}} = (1+(c_g-c_t)v^2)^2 \qquad \frac{\Gamma(h\to\gamma\gamma)}{\mathrm{SM}} = (1+(c_\gamma-4c_t/9)v^2)^2$$

fermionic top-partners in composite Higgs models exactly lead to $\Delta c_t = \Delta c_g = \frac{9}{4}\Delta c_\gamma$.

having access to $ht\bar{t}$ final state will resolve this degeneracy
but notoriously difficult channel
14%-4% @ LHC^{14}_{300}-LHC^{14}_{3000} vs 10%-4% @ ILC^{500}_{500}-$\mathrm{ILC}^{1000}_{1000}$

Boosted Higgs

- the bearable ... hannels
- the unbearal ... rgy physics (*)

(*) unless it doesn't decouple (e.g. 4th generation)

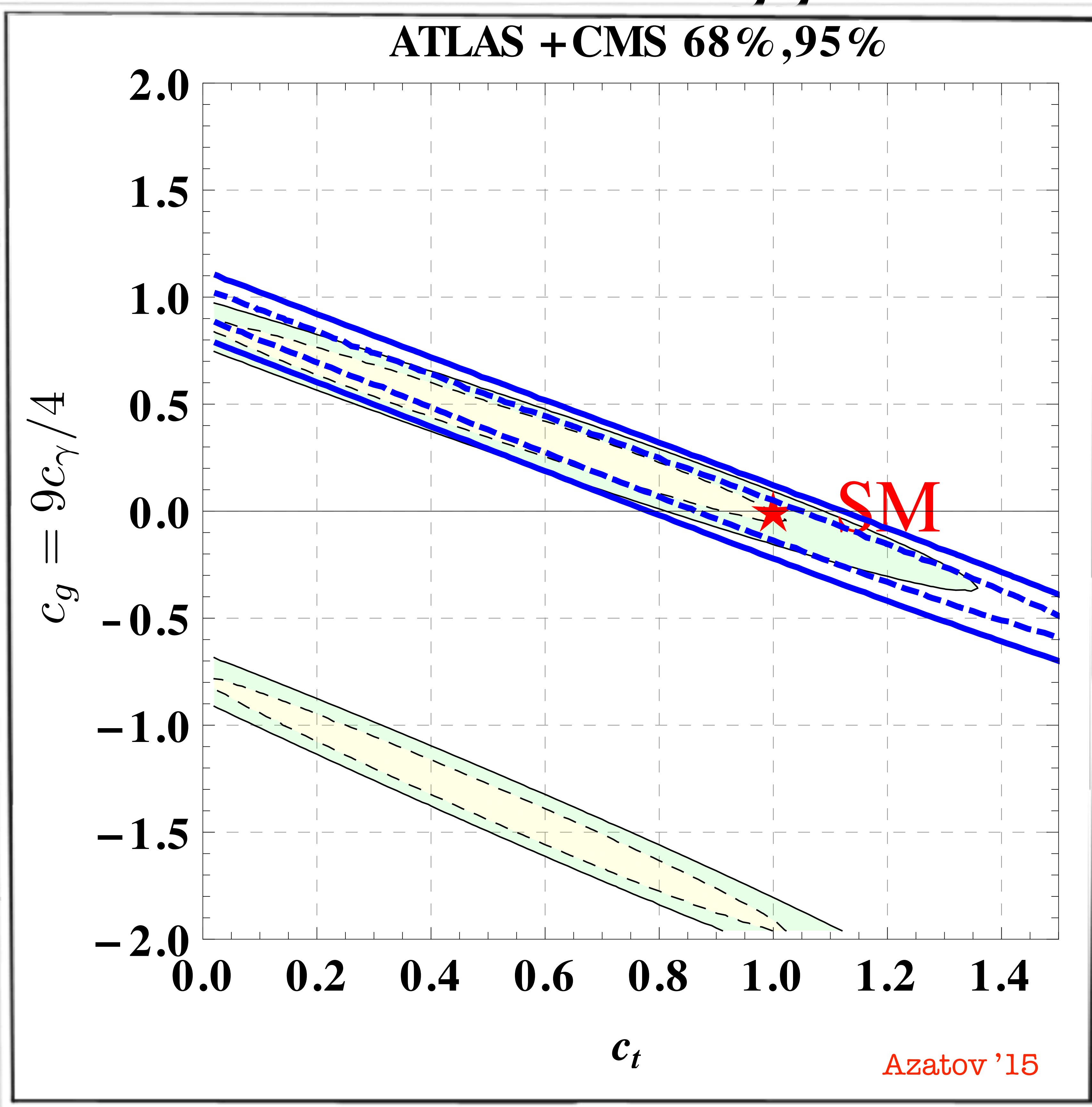
m_H(Ge
125
150
200

⇒ cannot ... ng) ... n the loop) ⇐

$/9)v^2)^2$

fermionic ... $\Delta c_g = \frac{9}{4}\Delta c_\gamma$.

14%-4% @ LHC300-LHC3000 vs 10%-4% @ ILC500-ILC1000

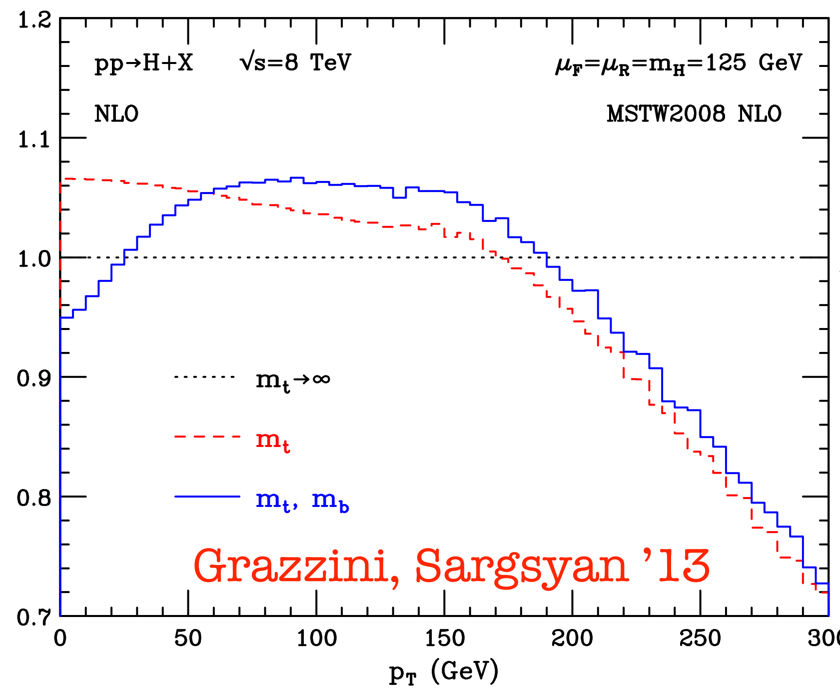


Resolving top loop: Boosted Higgs

cut open the top loops

high $p_T \approx$ Higgs off-shell
we "see" the details of the particles
running inside the loops

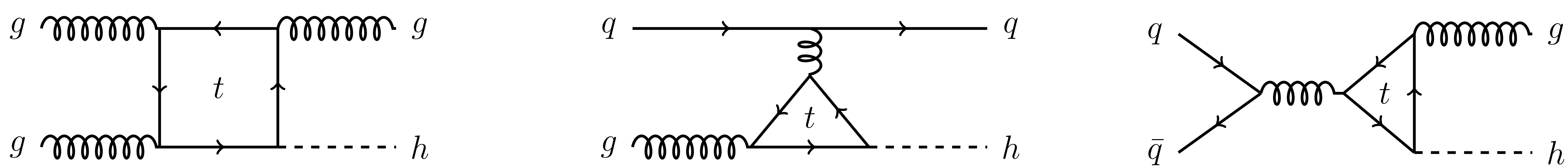
Baur, Glover '90
Langenegger, Spira, Starodumov, Trueb '06



Note: LO only
NLO_{m_t} is not known
$1/m_t$ corrections known $O(\alpha_s^4)$
few % up to p_T~150 GeV

Harlander et al '12

the high p_T tail
is tens' % sensitive
to the mass of top



the fraction gg/gq changes with p_T
@14TeV, gg/gq=67/31 for p_T>100GeV
gg/gp=42/57 for p_T>800GeV

always subdominant (<2%)

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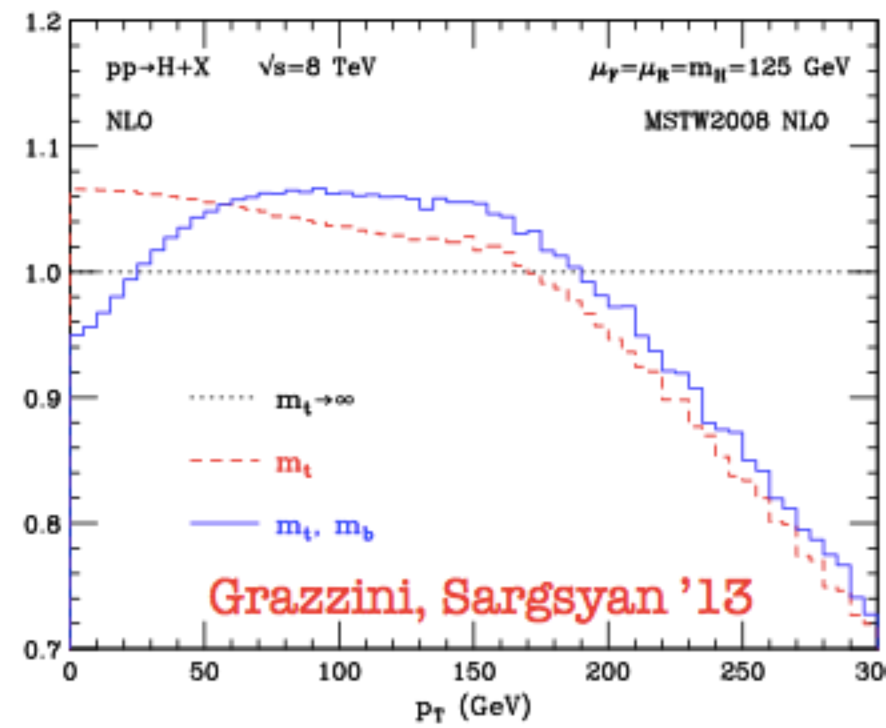


Note: LO only
NLO_{mt} is not known
$1/m_t$ corrections known $O(\alpha_s^4)$
few % up to p_T~150 GeV

Harlander et al '12

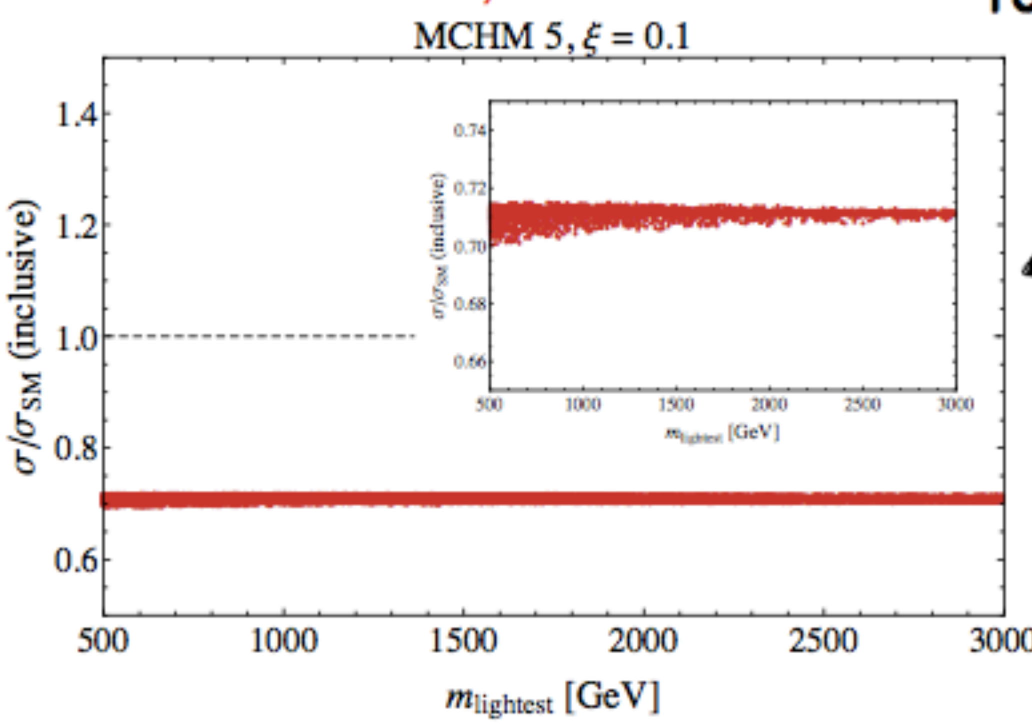
the high p_T tail is tens' % sensitive to the mass of top

Composite Higgs Model

top partners contributions

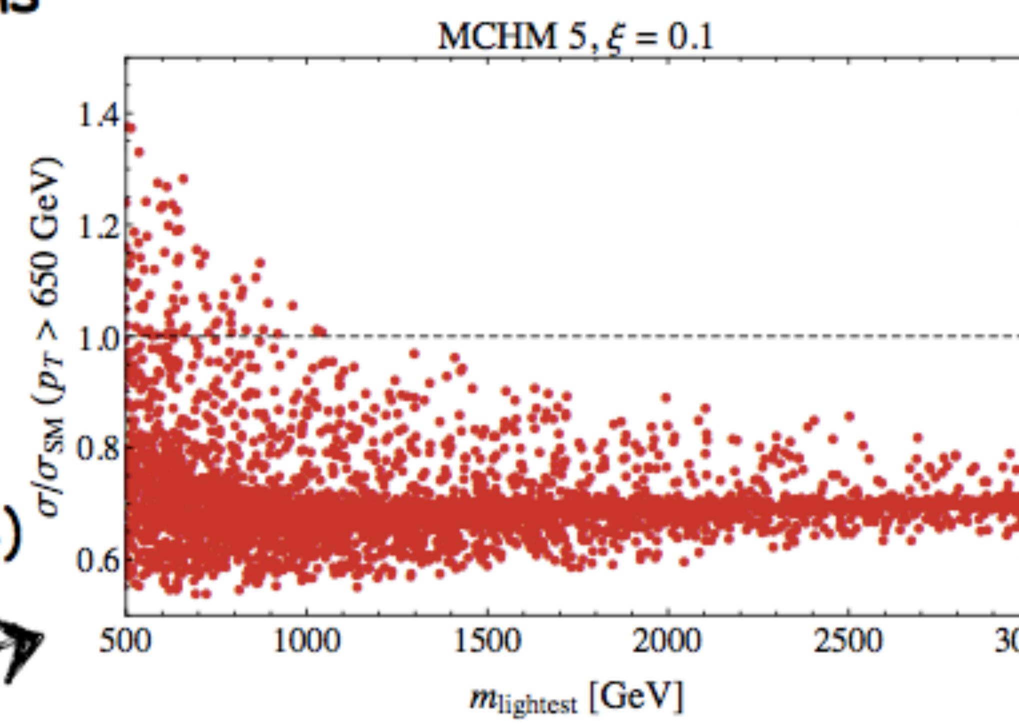
see also Banfi, Martin, Sanz '13
see also Azatov, Paul '13

Grojean, Salvioni, Schlaffer, Weiler '13



inclusive rate: O(%)

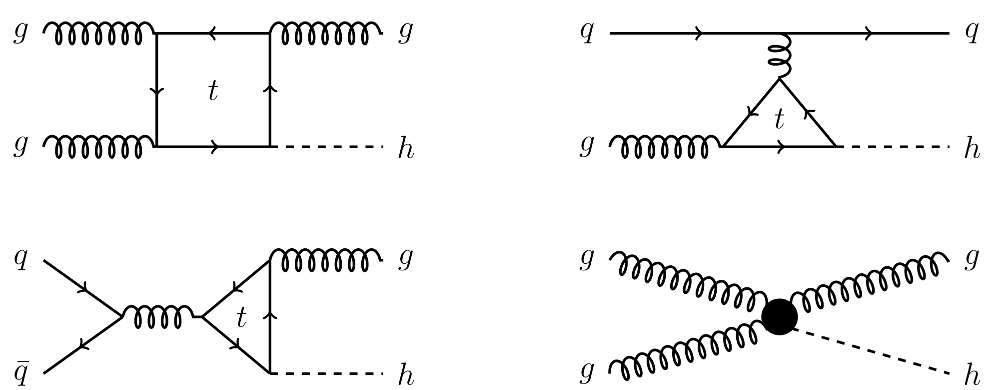
with high-p_T cut: O(x10'%)



high-p_T tail "sees" the top partners that are missed by the inclusive rate

Boosted Higgs

Grojean, Salvioni, Schlaffer, Weiler '13



$$\frac{\sigma_{p_T^{\min}}(\kappa_t,\kappa_g)}{\sigma^{\rm SM}_{p_T^{\min}}} = (\kappa_t+\kappa_g)^2 + \delta\,\kappa_t\,\kappa_g + \epsilon\,\kappa_g^2$$

large pT, small rates

need to focus on dominant decay modes

$$h \to b\bar{b}, WW, \tau\tau$$

non-isolated "ditau-jets"

(separation between the 2 tau's: $\Delta R \sim 2m_h/p_T \lesssim 0.5$)

$$\epsilon_{\rm tot} = {\rm BR}(h\to\tau\tau)\left(\sum_{i=\tau_\ell\tau_\ell,\,\tau_\ell\tau_h,\,\tau_h\tau_h} {\rm BR}(\tau\tau\to i)\,\epsilon_i\right) \simeq 2\times 10^{-2}$$

di-W channel can help

Schlaffer, Spannowsky, Takeuchi, Weiler, Wymant '14

Don't think it is easy to produce a Higgs with high pT

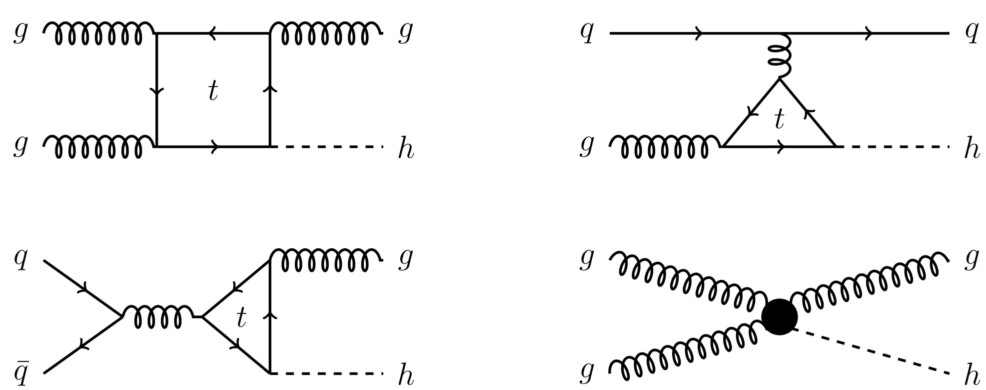
x 1000 reduction

$\sqrt{s}$ [TeV]	$p_T^{\min}$ [GeV]	$\sigma^{\rm SM}_{p_T^{\min}}$ [fb]	δ	ϵ	$gg,\,qg$ [%]
14	100	2200	0.016	0.023	67, 31
	150	830	0.069	0.13	66, 32
	200	350	0.20	0.31	65, 34
	250	160	0.39	0.56	63, 36
	300	75	0.61	0.89	61, 38
	350	38	0.86	1.3	58, 41
	400	20	1.1	1.8	56, 43
	450	11	1.4	2.3	54, 45
	500	6.3	1.7	2.9	52, 47
	550	3.7	2.0	3.6	50, 49
	600	2.2	2.3	4.4	48, 51
	650	1.4	2.6	5.2	46, 53
	700	0.87	3.0	6.2	45, 54
	750	0.56	3.3	7.2	43, 56
	800	0.37	3.7	8.4	42, 57
100	500	970	1.8	3.1	72, 28
	2000	1.0	14	78	56, 43

VHE-LHC is the machine
to decipher the gg→h process

Boosted Higgs

Grojean, Salvioni, Schlaffer, Weiler '13



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x 150 enhancement

VHE-LHC is the machine
to decipher the gg→h process

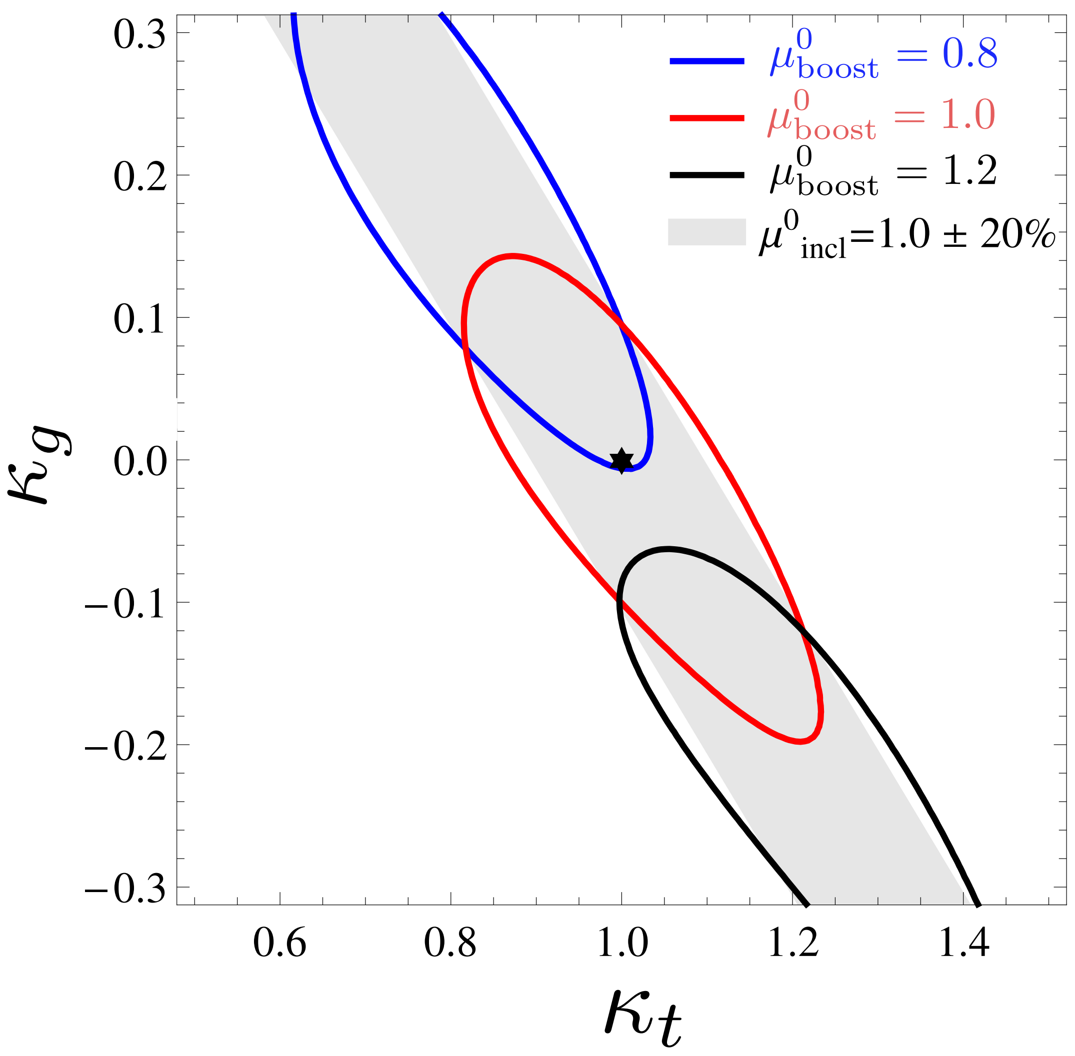
Boosted Higgs

high p_T tail discriminates short and long distance physics contribution to $gg \to h$

$$\sqrt{s} = 14 \text{ TeV}, \int dt\, \mathcal{L} = 3\text{ab}^{-1}, p_T > 650 \text{ GeV}$$

(partonic analysis in the boosted "ditau-jets" channel)

see Schlaffer et al '14 for a more complete analysis including WW channel



10-20% precision on κ_t

⇓ ⇓

competitive/complementary to htt channel for the measure the top-Higgs coupling

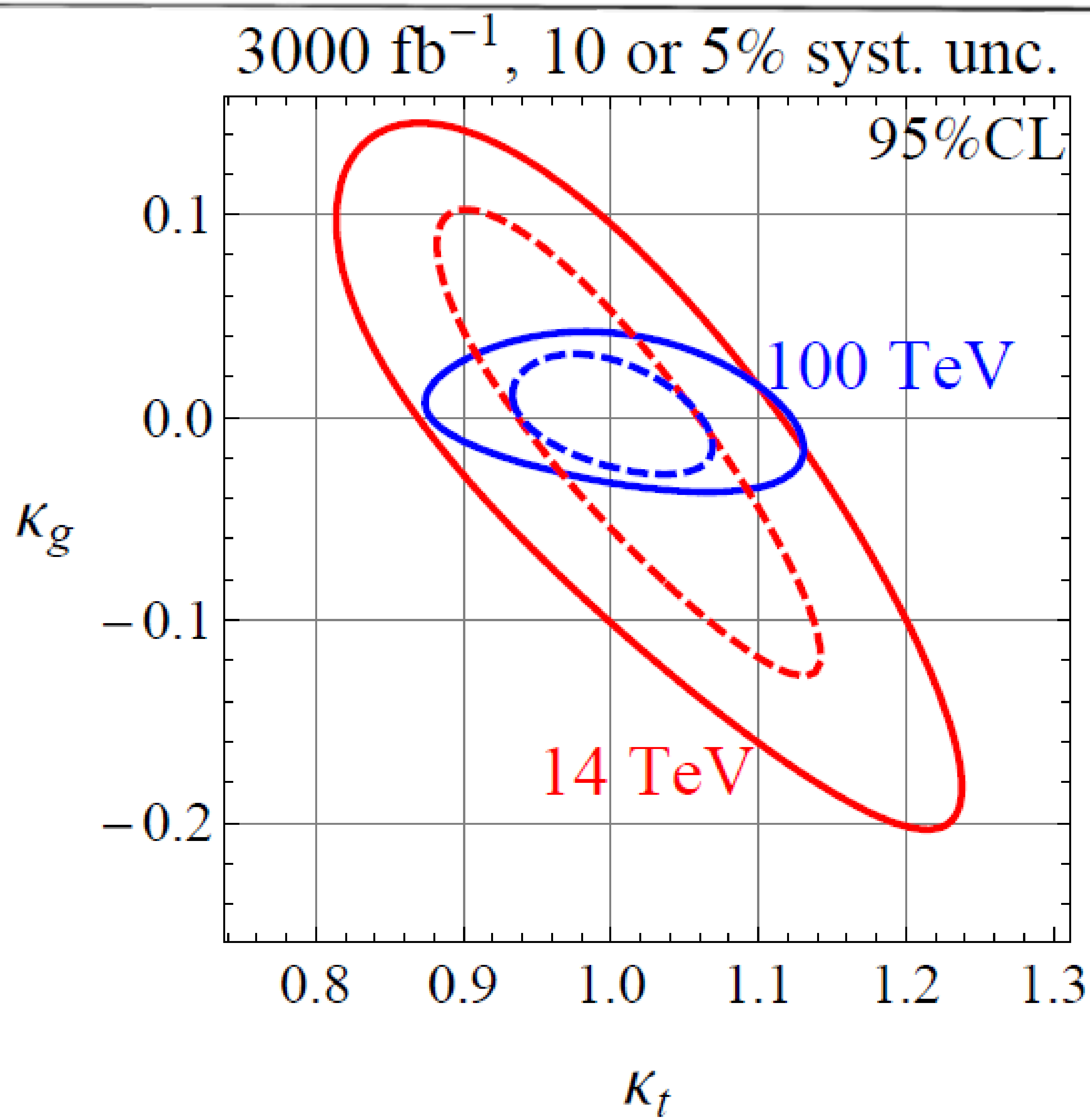
see also Azatov, Paul '13

Grojean, Salvioni, Schlaffer, Weiler '13

Are the NLO_m QCD corrections (not known) going to destroy all the sensitivity?
Frontier priority: N^3LO_∞ for inclusive xs or NLO_{mt} for pT spectrum?

Boosted Higgs

high p_T tail discriminates short and long distance physics contribution to $gg \to h$



A perfect case for a very energetic machine

$t\bar{t}h$ increases by 10 from 14 to 100TeV

$h+j_{pT>600GeV}$ increases by 210

$$\mathcal{R}_{14} = \frac{\sigma(p_T > 650\text{ GeV})}{\sigma(p_T > 150\text{ GeV})}$$

$$\mathcal{R}_{100} = \frac{\sigma(p_T > 2000\text{ GeV})}{\sigma(p_T > 500\text{ GeV})}$$

Azatov, Grojean, Paul, Salvioni '16

see also Azatov, Paul '13

Grojean, Salvioni, Schlaffer, Weiler '13

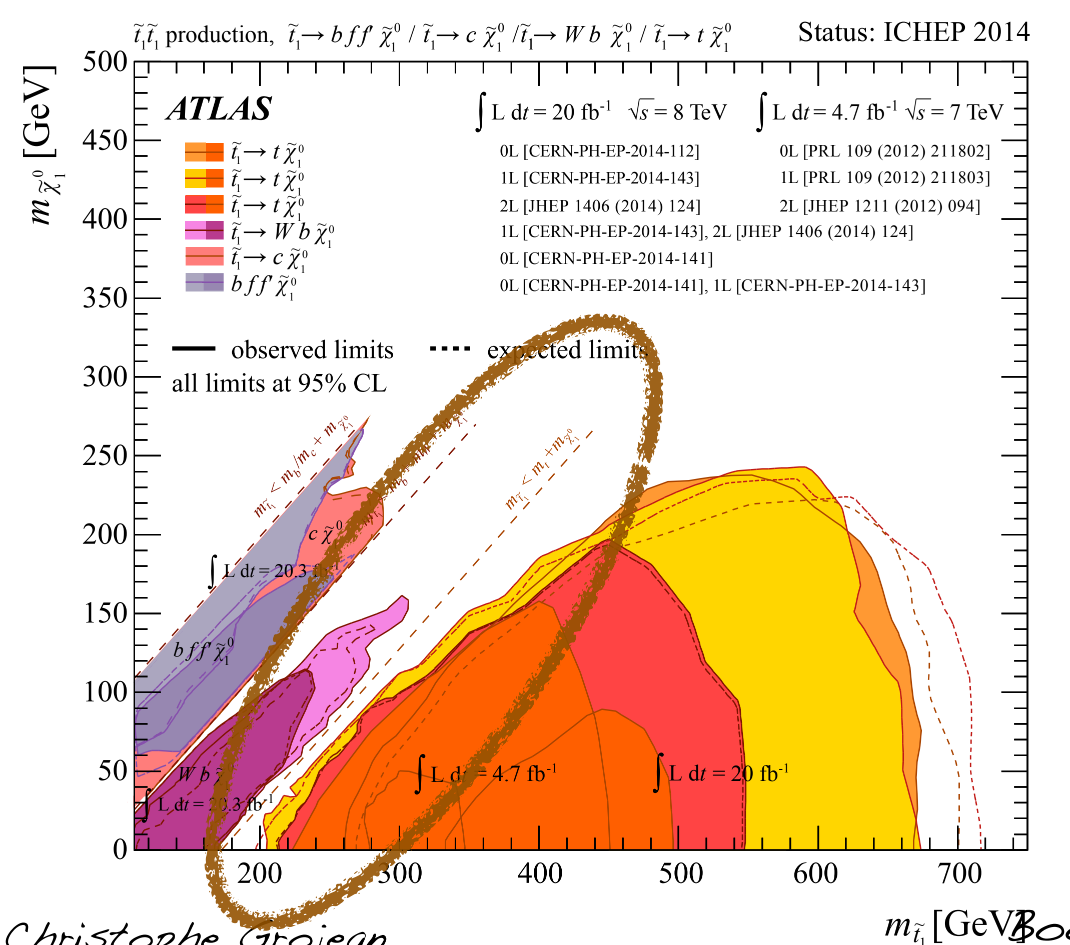
Frontier priority: N^3LO_∞ for inclusive xs or NLO_{mt} for pT spectrum?

Boosted SUSY Higgs

natural susy calls for light stop(s) that can affect the Higgs physics

$$\frac{\Gamma(h \leftrightarrow gg)}{\Gamma(h \leftrightarrow gg)_{\rm SM}} = (1+\Delta_t)^2 \ , \qquad \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\rm SM}} = (1-0.28\Delta_t)^2$$

$$\Delta_t \approx \frac{m_t^2}{4}\left(\frac{1}{m_{\tilde t_1}^2} + \frac{1}{m_{\tilde t_2}^2} - \frac{X_t^2}{m_S^2}\right)$$



... or not if $\Delta_t \approx 0$, e.g. light stop window in the MSSM

(stop right ~200-400GeV ~ neutralino w/ gluino < 1.5 TeV)

- Higgs rates
- flavor constraints (ε_K, $B \to X_s + \gamma$)
- RG evolution
- DM

Delgado et al '12

difficult direct search (trigger on stop+extra jet)

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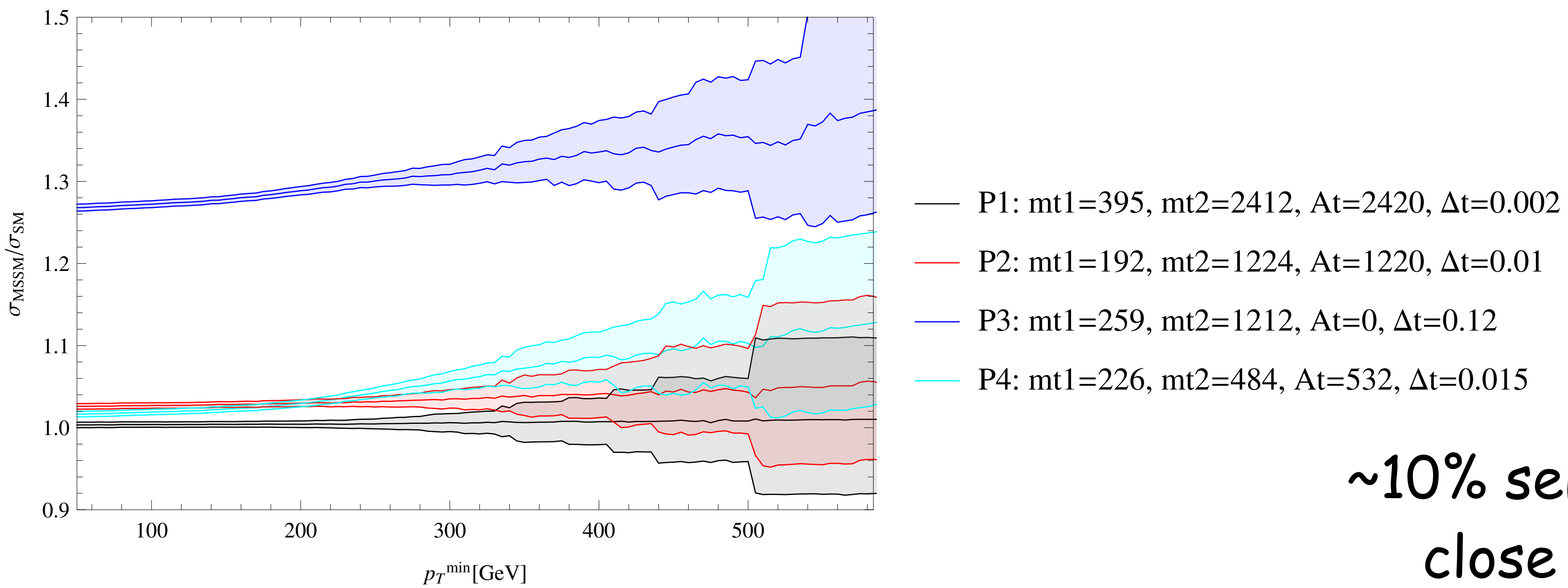
Grojean, Salvioni, Schlaffer, Weiler '13



~10% sensitivity on boosted h+j can close up the light stop window

Low p_T: bounding light quark Yukawa's

Bishara et al '16 [1606.09253]

Soreq et al '16 [1606.09621]

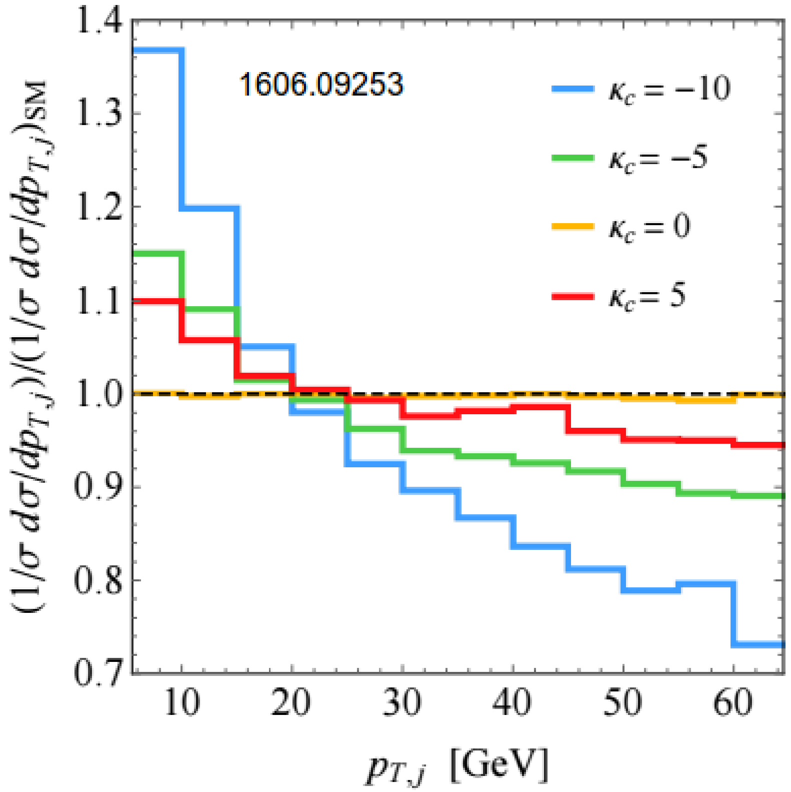
Bonner, Logan '16 [1608.04376]

- Modifications of the light quark Yukawa couplings modify the differential distributions.
- Sudakov's dilogarithms *1606.09253* enhance the production cross-section

$$\sim k_Q \frac{m_Q^2}{m_h^2} \ln^2 \frac{p_\perp^2}{m_Q^2}$$

modifications are especially important in the region $m_Q \ll p_\perp \ll m_h$.

- The main contribution appears from the interference with the top quark loop, which scales as y_Q not y_Q^2.



(courtesy of A. Azatovl@HiggsHunting2016)

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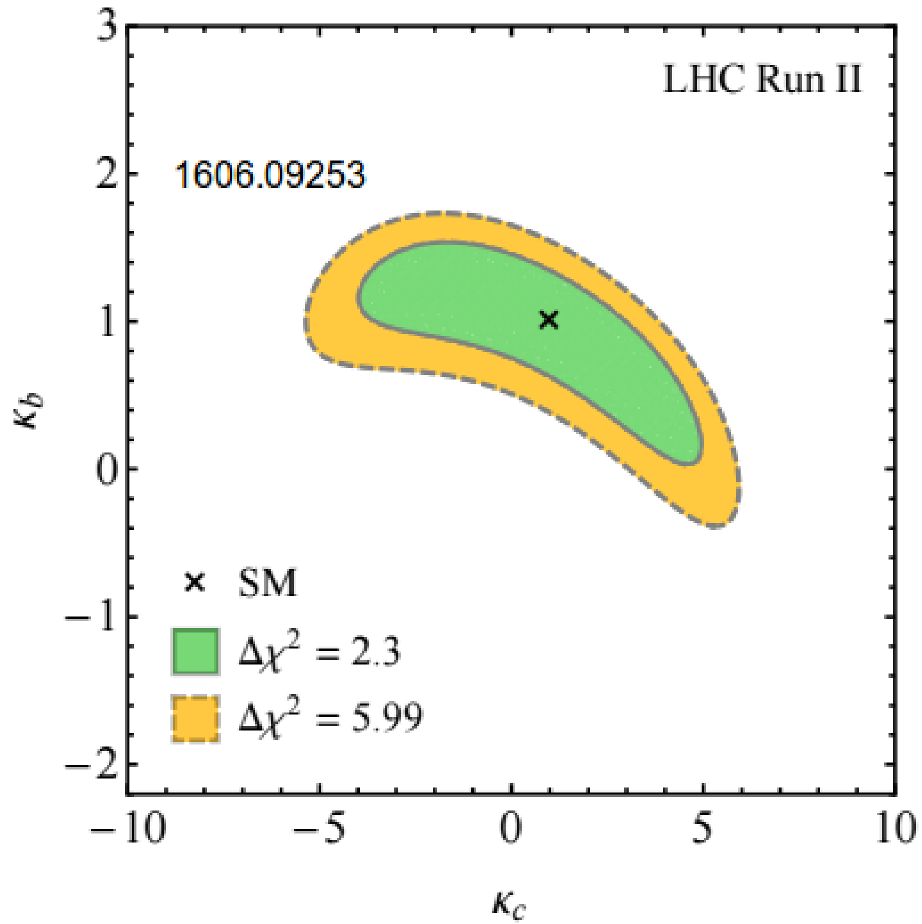
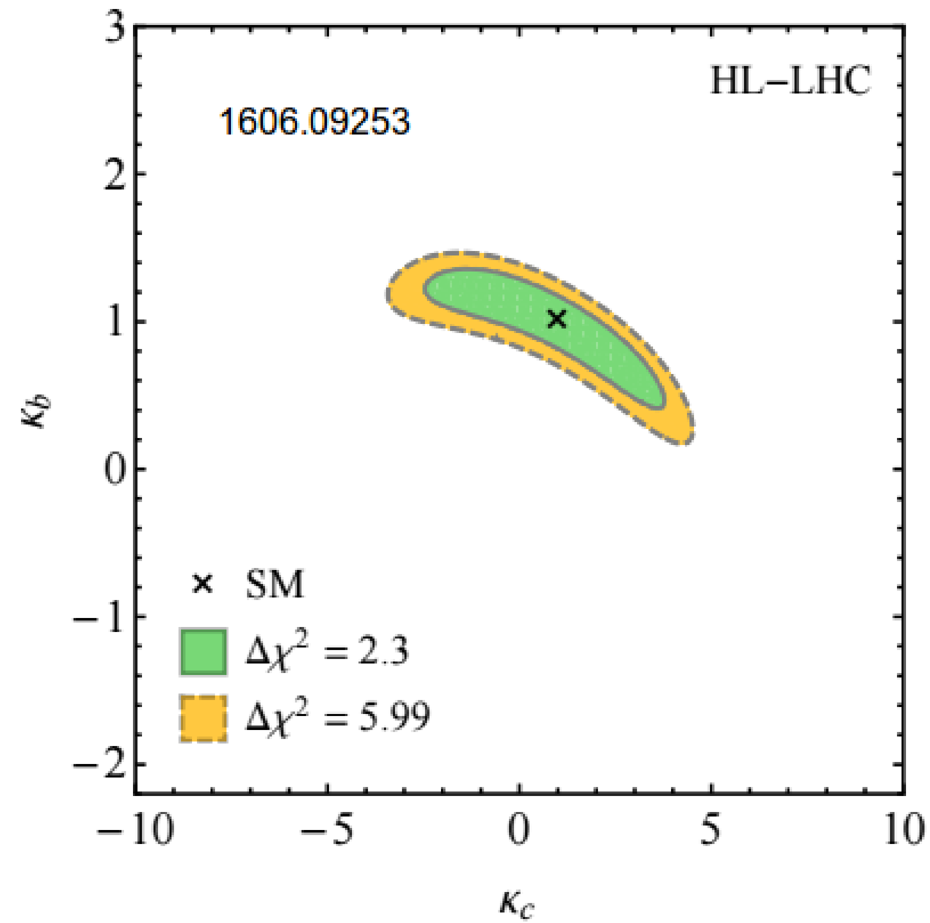
- from $h \to \gamma\gamma, ZZ, WW$ using $p_T \in [0, 70]$ GeV

(courtesy of A. Azatov@HiggsHunting2016)





Off-shell Higgs

Off-shell Higgs effects

naively small since the width is small (Γ_H=4MeV, Γ_H/m_H =3x10^{-5}) for a 125 GeV Higgs

but enhancement due to the particular couplings of H to V_L

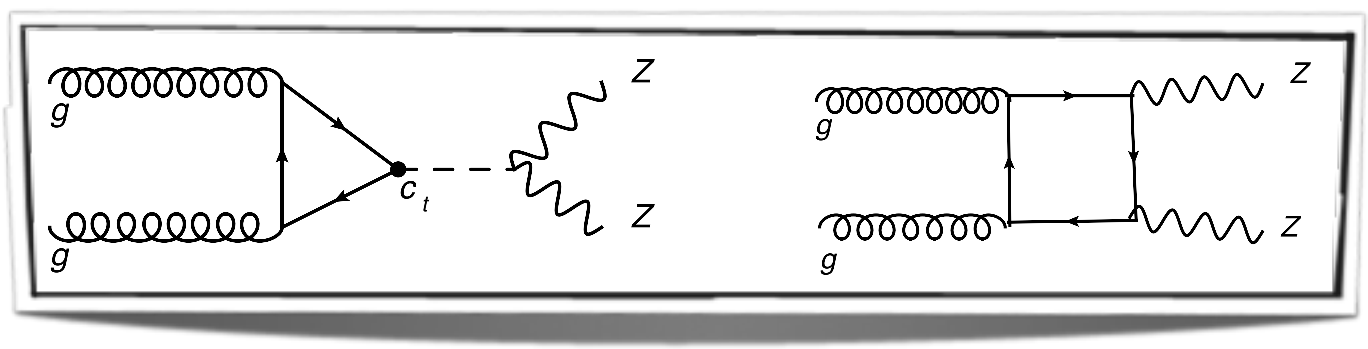
Recent analysis of gg→H*→ZZ→4l

CMS PAS HIG-14-002
ATLAS-CONF-2014-042

(about 15% of the Higgs events are far off-shell with m_{4l}>300GeV)

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \propto g_{ggH}g_{HZZ}\frac{F(m_{ZZ})}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H}$$

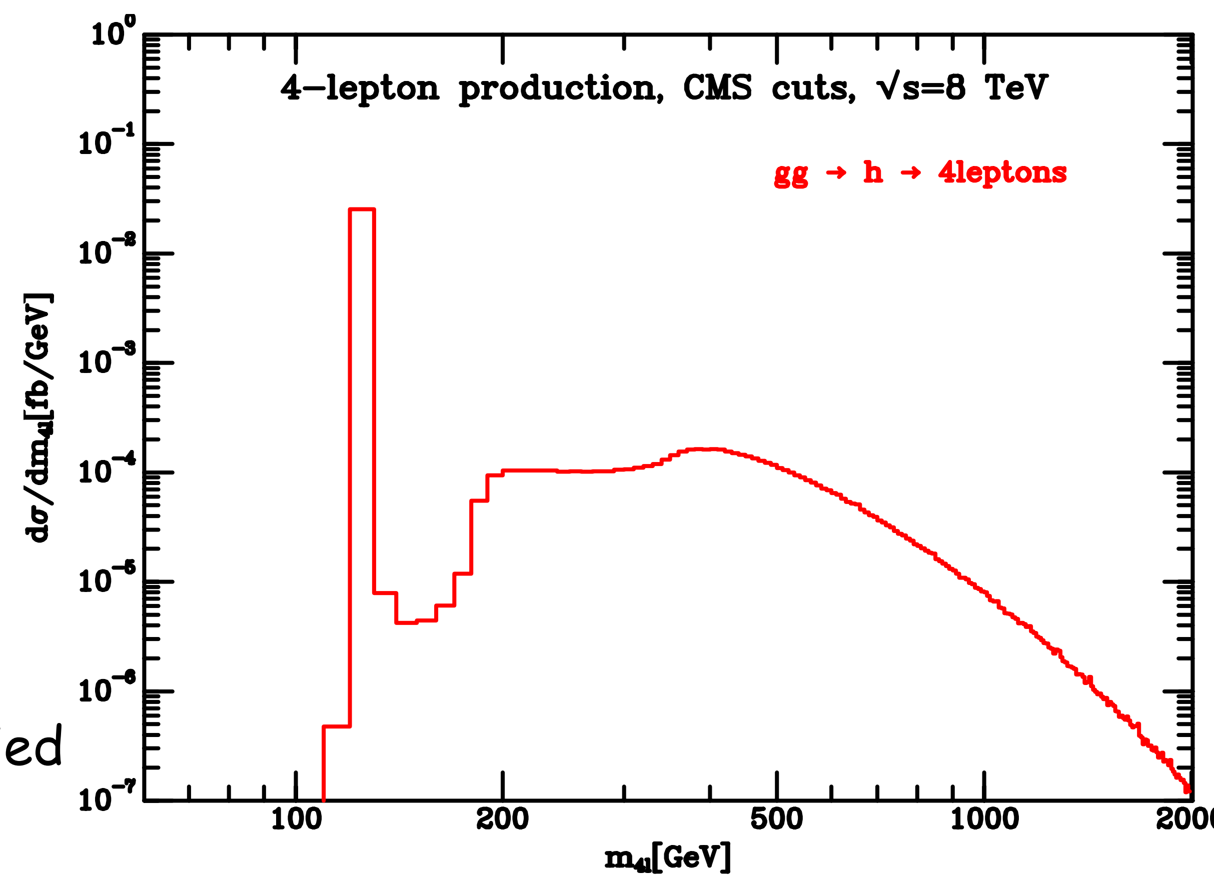
Glover, van der Bij '89



$$\mathcal{M}^{++00}_{\rm Higgs} \sim \log^2\frac{\hat{s}}{m_t^2} \qquad \mathcal{M}^{++00}_{\rm box} \sim -\log^2\frac{\hat{s}}{m_t^2}$$

SM: cancelation forced by unitarity

BSM: deviations of Higgs couplings at large $\hat{s}$ will be amplified



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Access to the Higgs width @ LHC?

often said, it is impossible to measure the Higgs width at the LHC. Not quite true.
it can be done either via off-shell measurements or via the mass shift in $gg\to h\to\gamma\gamma$

Narrow Width Approx.: on-shell

ratios of κ only

$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH}g^2_{HZZ}}{\Gamma_H}$ no direct access to the width itself

(upper bound if κ_V < 1 is assumed
e.g. Dobrescu, Lykken '12)

off-shell

different width dependence

Γ_H can be fitted w/o assumption

$\sigma^{\text{off-peak}}_{gg\to H\to ZZ} \propto g^2_{ggH}g^2_{HZZ}$

Kauer, Passarino '12
Caola, Melnikov '13
Campbell et al '13

What do we learn? BR_{inv} <85%?

Not competitive with global fits on BR_{inv}! BR_{inv} < 20%

Model independent analysis might not be robust because of unitarity issues

($g_i(m_h)$ might be quite different than $g_i(m_{4l})$)

Englert, Spannowski '14

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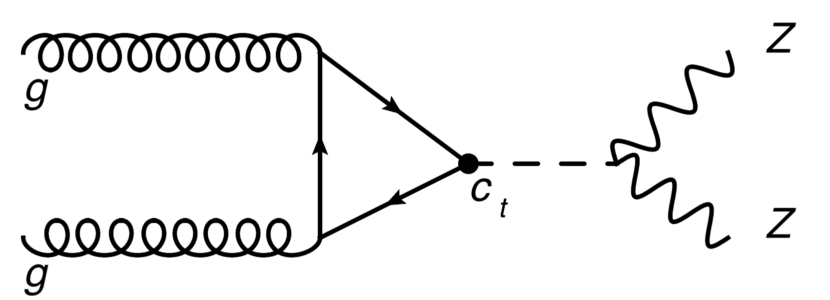
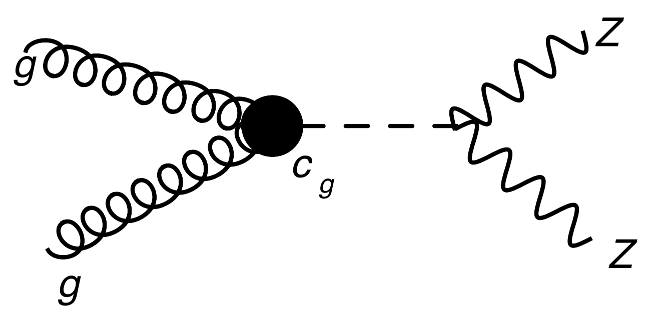
Access to top Yukawa coupling?

strong departure of the Higgs low energy theorem in the far off-shell region

can distinguish c_t from c_g



$$\mathcal{M}^{++00}_{c_t} \sim \log^2 \frac{\hat{s}}{m_t^2}$$



$$\mathcal{M}^{++00}_{c_g} \sim \hat{s}$$

Cacciapaglia et al. '14

Azatov, Grojean, Paul, Salvioni '14

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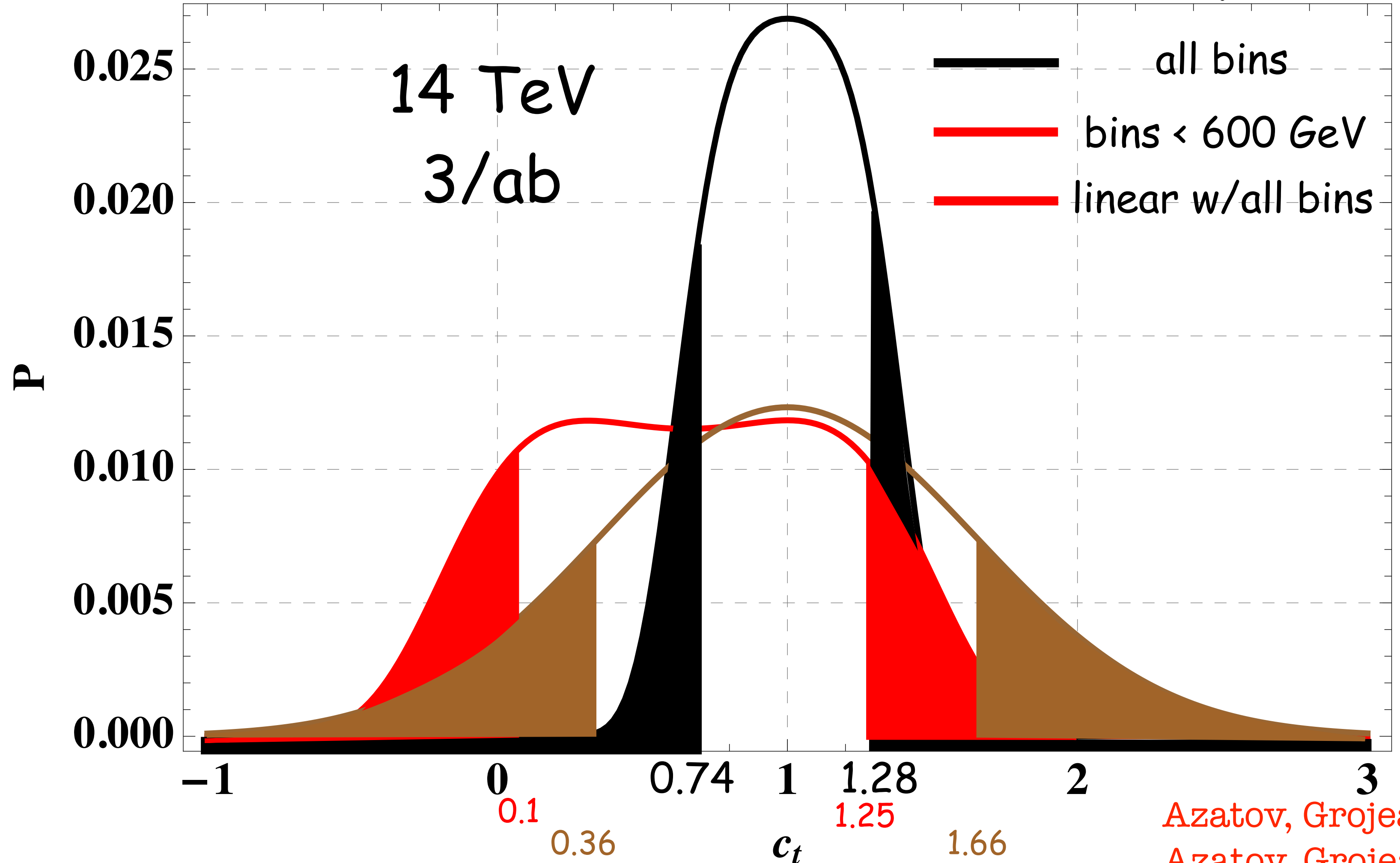
Access to top Yukawa coupling?

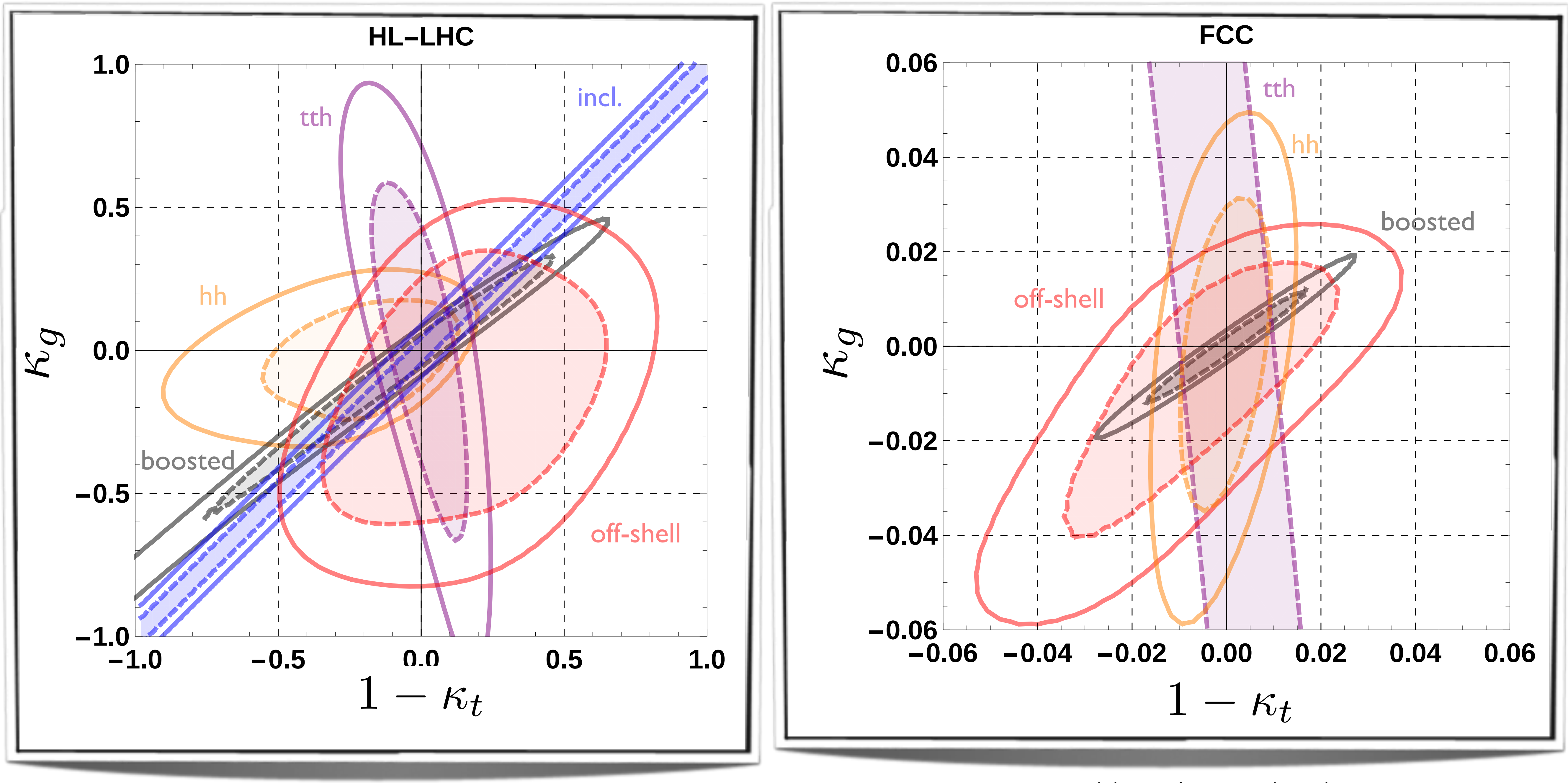
provides an alternative to ttH to measure the top Yukawa coupling



Azatov, Grojean, Paul, Salvioni '14
Azatov, Grojean, Paul, Salvioni '16

Prospectives: HL-LHC$_{14TeV,300/fb}$ and FCC$_{100TeV,20/ab}$

Azatov, Grojean, Paul, Salvioni '16



hh ~ align with tth
because SM is imaginary
while κ_g contribution is imaginary
hence SM/BSM interference prop. to κ_t

χ

Validity of EFT analyses

EFT = “mass scale + coupling(s)“

Too often, people think of EFT as higher dimensional operators suppressed by a **cutoff scale**, but there is also a **coupling** between new physics and SM

⇩ ⇩

1) validity of EFT

2) relative size of various operators

Simplest example

New physics characterized by one coupling and one-scale

NP

mass scale $M = g_* f$

coupling g_*

SM

EW scale v=246GeV

g, g', y_t

EFT << SM ?

It is often thought that effects of dim-6 operators have to be smaller than SM for EFT consistency. This is not true, one can find large deviations still within the validity of the EFT analysis. Good examples are Vector Boson Scattering and HH production

EFT validity

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i c_i^{(6)} \mathcal{O}_i^{(6)} + \sum_j c_j^{(8)} \mathcal{O}_j^{(8)} + \cdots ,$$

Included

Ignored

- Under what conditions does EFT with D=6 operators adequately describe low-energy phenomenology of some BSM models?

- When D=8 operators or loop-suppressed D=6 effects are non-negligible?

Azatov, Contino, Machado, Riva '16

- How should experiments present EFT results so as to maximize their applicability range?

Can we answer from a bottom-up approach,
i.e. by looking at experimental constraints?

EFT validity

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i c_i^{(6)} \mathcal{O}_i^{(6)} + \sum_j c_j^{(8)} \mathcal{O}_j^{(8)} + \cdots ,$$

Included Ignored

(courtesy of F. Riva)

Expansion Validity: $E/\Lambda \ll 1$

Experimentally: better access to leading $c_i\, E^2/\Lambda^2$ and not directly to Λ

Truncation depends on $c^{(8)}_i\, E^4/\Lambda^4$

Example: Fermi theory

$$\mathcal{L}_{\rm eff} = \frac{2}{v^2} (\bar{e}\gamma^\mu \nu_e)(\bar{\nu}_\mu \gamma_\mu \mu)$$

low energy measurements give access to G_F, i.e. v, and not the true cutoff m_W= 1/2 g v

~~for a fixed deviation to the SM predictions~~

Weak couplings reduce the validity range of the EFT (as naively expected)
Strong couplings extend it ($g=4\pi \Rrightarrow$ Fermi theory would have been valid up to E≈3 TeV)

EFT validity: illustrative example

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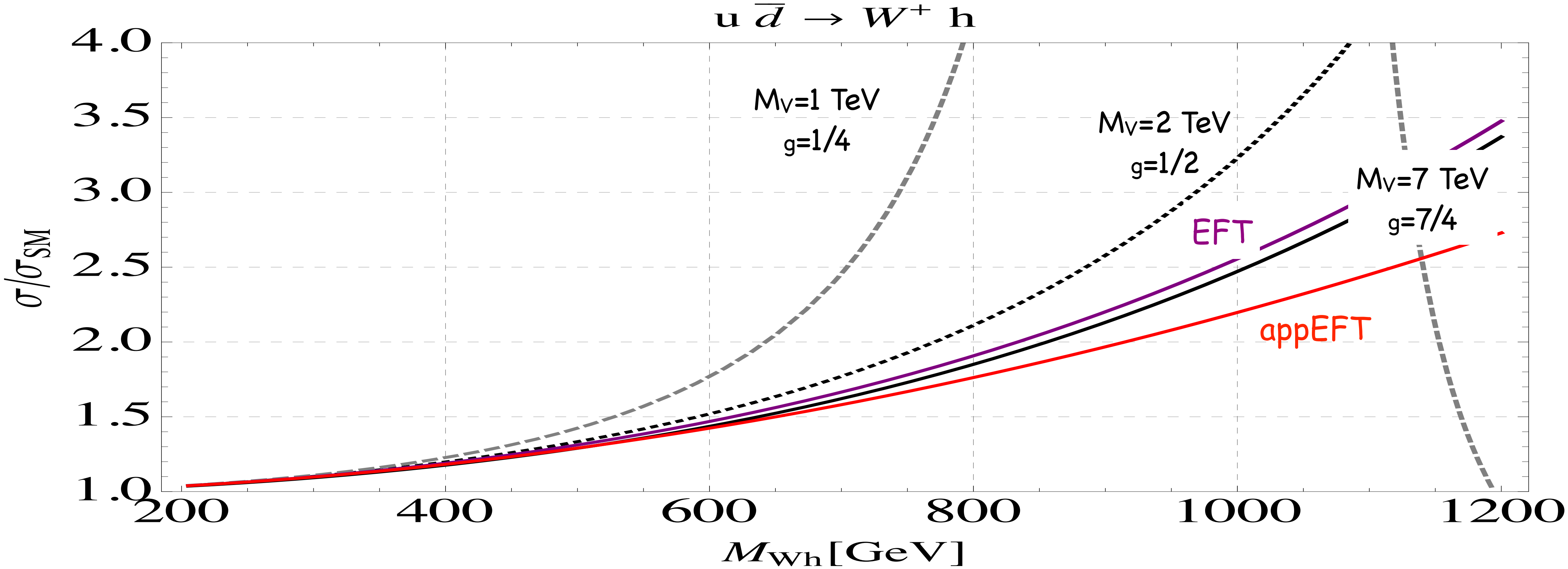
SU(2)$_L$
heavy vector triplet

$$\mathcal{L} \supset i g_H V_\mu^i H^\dagger \sigma^i \overleftrightarrow{D}_\mu H + g_q V_\mu^i \bar{q}_L \gamma_\mu \sigma^i q_L$$



EFT $M_W \ll M_{Wh} \ll M_V$

$$\frac{\sigma}{\sigma_{SM}} \approx \left(1 - 160\, g_H g_q \frac{v^2}{M_V^2} \frac{M_{Wh}^2}{\mathrm{TeV}^2}\right)^2$$

validity of EFT depends on couplings
cannot be accessed by measurements only

- **Strongly coupled:** $M_V = 7$ TeV, $g_H = -g_q = 7/4$
- **Moderately coupled:** $M_V = 2$ TeV, $g_H = -g_q = 1/2$
- **Weakly coupled:** $M_V = 1$ TeV, $g_H = -g_q = 1/4$

3 benchmark models with same EFT behavior

EFT validity: illustrative example

Consider mock measurement of σ(qq → Wh) at LHC at different invariant mass of final state

M_{Wh}[TeV]	0.5	1	1.5	2	2.5	3
$\frac{\sigma}{\sigma_{\rm SM}}$	1 ± 1.2	1 ± 1.0	1 ± 0.8	1 ± 1.2	1 ± 1.6	1 ± 3.0

constraints on EFT parameter

$M_{\rm cut}$[TeV]	0.5	1	1.5	2	2.5	3
$-g_H\, g_q \frac{v^2}{M_V^2} [\times 10^{-3}]$	[-70, 20]	[-16,4]	[-7,1.6]	[-4.1,1.1]	[-2.7,0.8]	[-2.2,0.7]

- Different limits correspond to taking into account measurements up to different M_{cut}
- Stronger limits on EFT are obtained for larger M_{cut}
- However, limits with lower Mcut are also useful, to constrain parameter space of model with M_V < 3 TeV

⚠ one shouldn't include bin $M_{cut} > M_V$, but experimentally no access to M_V

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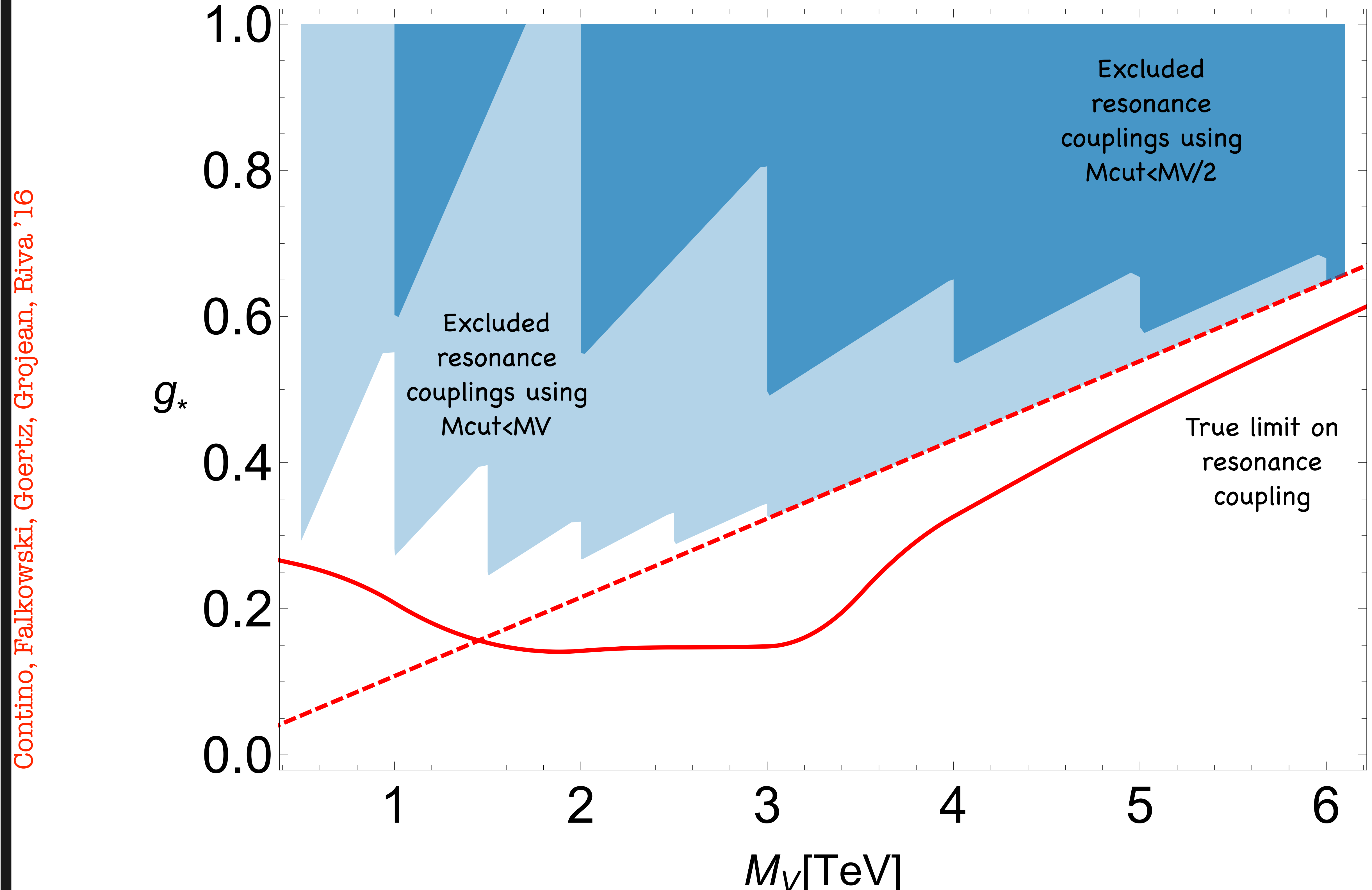
EFT validity: illustrative example



limit on $g_* = g_H = -g_q$ include bins up to Mcut = k M_V ⇛ EFT error < k^2