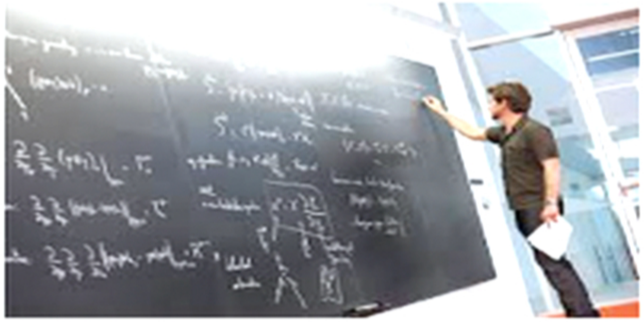
Title: Energizing Higgs Phenomenology for Run 2

Date: Apr 19, 2016 01:00 PM

URL: http://pirsa.org/16040059

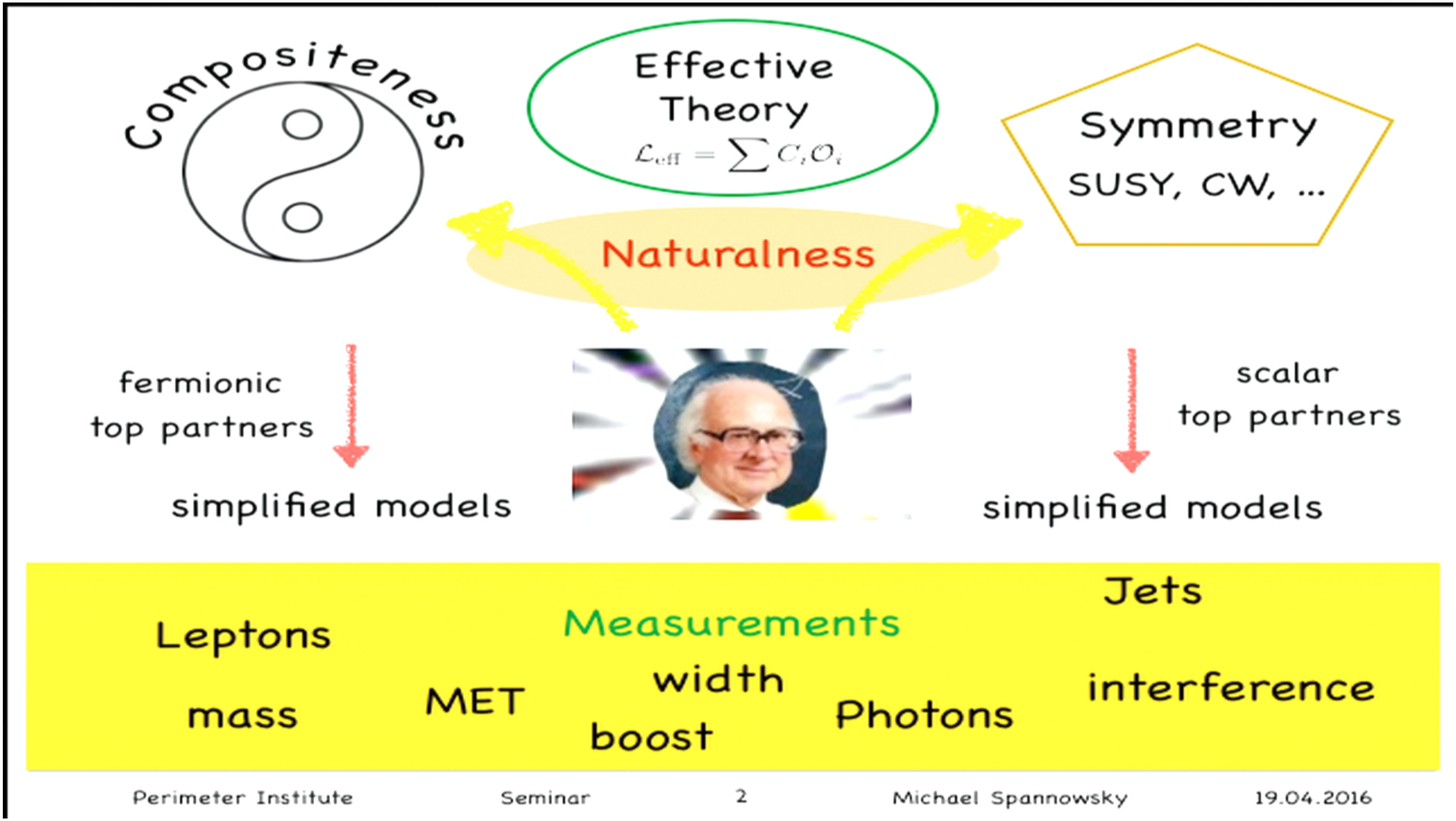
Abstract: <p>The High-Energy community is only now in the process of fully appreciating the opportunities the LHC provides by producing electroweak-scale resonances beyond threshold. On the one hand this is reflected by changing from the so-called 'kappa frameworkâ€™ to effective operators and on the other hand by studying Higgs and gauge boson production in processes with large momentum transfer. Accessing more exclusive phase space regions will allow to either discover New Physics or improve Higgs-boson couplings measurements. I will discuss implications of and tools necessary for these measurements, focusing on Higgs boson and Dark Matter phenomenology.</p>



Energizing Higgs Phenomenology for Run 2

Michael Spannowsky

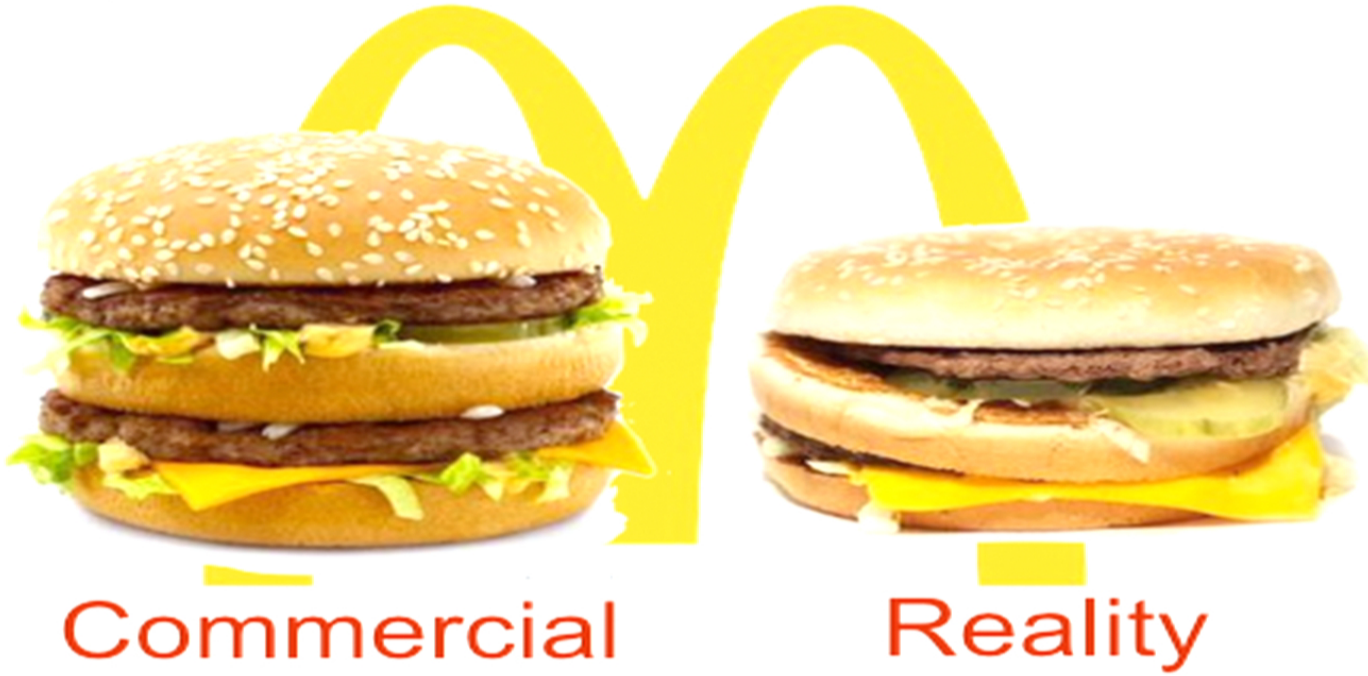
IPPP, Durham University


Compositeness
Effective Theory
$\mathcal{L}_{\text{eff}} = \sum C_i \mathcal{O}_i$
Symmetry
SUSY, CW, ...
Naturalness
fermionic
top partners
simplified models
scalar
top partners
simplified models
Jets
Leptons
Measurements
width
interference
mass
MET
Photons
boost
Perimeter Institute
Seminar
2
Michael Spannowsky
19.04.2016

Due to absence of signs of new physics

HEP has 'Big Mac' blues,

i.e. why nature not like (as natural as) advertised?



Sure, it (Higgs boson) does the job, but...

- Discovery of Higgs boson huge success
- However, Higgs boson remnant/ by-product of BEH mechanism

No detailed understanding so far

Not enough evidence to identify theory of nature

'Do you have to yell 'Eureka' every time you see something new?'

New Physics has got to be out there:

- Matter/Anti-Matter asymmetry
- Dark Matter
- Hierarchy Problem
- Inflation

Diphoton excess?

Almost every discovery starts with an anomaly

Improved/Unified way of interpretation of measurements

- interpretation of any measurement model dependent
- interpretation requires communication between different scales as well as theorists and experimentalists

Connecting measurements with UV physics

Kappa Framework

- NP models simple rescaling of couplings
- No new Lorentz -structures or kinematics

EFT

- SM degrees of freedom and symmetries
- New kinematics/ Lorentz structures

Simplified Models

- New low-energy degrees of freedom
- Subset of states of full models, reflective at scale of measurement

Full (UV) Model

- Very complex and often high-dimensional parameter space
- Allows to correlate high-scale and low-scale physics

→ Complexity/Flexibility

Coupling measurement during Run 1 using kappa-framework:

kappa is ratio of couplings:

$$\kappa_i = \frac{g_i}{g_{i,SM}}$$

so-called

$\sigma(g_p) \times \mathrm{BR}(g_d)$ physics

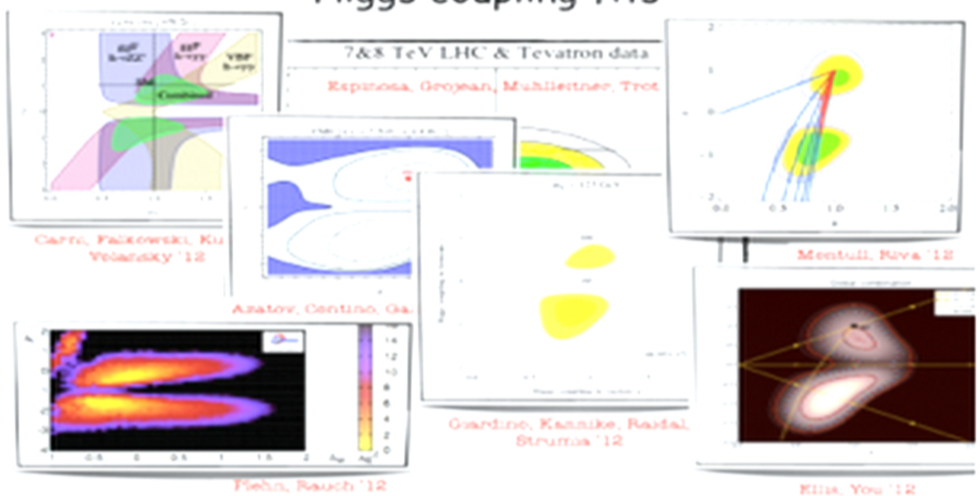
Decay into spec. channel

Production

$$\sigma \cdot BR \propto g_p^2 \frac{g_d^2}{\Gamma_H}$$

Sum of all possible decays

Higgs coupling fits



- try to over-constrain couplings basis
- Higgs width of particular importance

→ Higgs coupling fits based on total rates... no dynamics

→ No new Lorentz structures, limited applicability for new physics

Struggle for a unified language (basis) for Higgs EFT

Basis

- Complete
- Inspired by UV physics?

Several available:

Warsaw Basis	[1008.4884]
SILH Basis	[hep-ph/070164]
Primary/Higgs Basis	[1405.0181]

Practicality

- Manageable number of operators for fit

Validity

- Validity range of EFT set by kinematic of measurement

Precision

- Resummation of large log (RGE improved pert. theory)
- Full NLO

The future of coupling fits: The Effective Field Theory approach

All operators respecting gauge invariance, the SM gauge group and particle content

Agnostic operator basis complex: 2499 non-redundant parameters at dim-6

Highly complex: 59 operators (flavor blind)

$$\mathcal{O}_H = \tfrac{1}{2}(\partial^\mu |H|^2)^2$$
$$\mathcal{O}_T = \tfrac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$
$$\mathcal{O}_6 = \lambda |H|^6$$

$$\mathcal{O}_W = \tfrac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = \tfrac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$$
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$\mathcal{O}^u_{LR} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{u}_R \gamma_\mu u_R)$	$\mathcal{O}^d_{LR} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{d}_R \gamma_\mu d_R)$	$\mathcal{O}^e_{LR} = (\bar{L}_L \gamma^\mu L_L)(\bar{e}_R \gamma_\mu e_R)$
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$\mathcal{O}^u_{RR} = (\bar{u}_R \gamma^\mu u_R)(\bar{u}_R \gamma_\mu u_R)$	$\mathcal{O}^d_{RR} = (\bar{d}_R \gamma^\mu d_R)(\bar{d}_R \gamma_\mu d_R)$	$\mathcal{O}^e_{RR} = (\bar{e}_R \gamma^\mu e_R)(\bar{e}_R \gamma_\mu e_R)$
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As a result of existing bounds, basis of interesting operators can be simplified for collider pheno, e.g. SILH basis: [Giudice, Grojean, Pomarol, Rattazzi '07]

$$\mathcal{L}_{\rm SILH} = \frac{\bar{c}_H}{2v^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\lambda}{v^2}\left(H^\dagger H\right)^3$$
$$+ \left(\frac{\bar{c}_{u,i} y_{u,i}}{v^2} H^\dagger H \bar{u}_L^{(i)} H^c u_R^{(i)} + \text{h.c.}\right) + \left(\frac{\bar{c}_{d,i} y_{d,i}}{v^2} H^\dagger H \bar{d}_L^{(i)} H d_R^{(i)} + \text{h.c.}\right)$$
$$+ \frac{i\bar{c}_W g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar{c}_B g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right)$$
$$+ \frac{i\bar{c}_{HW} g}{m_W^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i\bar{c}_{HB} g'}{m_W^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$+ \frac{\bar{c}_\gamma g'^2}{m_W^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g g_S^2}{m_W^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}\,.$$

here $c_T \sim T$ and $c_B + c_W \sim S$ [Peskin, Takeuchi '91]

Wilson coefficients can be (over) constraint in many decay and production processes:

Decays: $H \to f\bar{f}$ $H \to \gamma\gamma$ $H \to \gamma Z$

$H \to ZZ^*$ $H \to WW^*$

Production: $pp \to H$ $pp \to Hj$ $pp \to Hjj$

$pp \to HV$ $pp \to ttH$

Validity and Relevance of EFT

EFT used to set limits on UV models from non-observation of new physics

Lagrangian dim-6: $\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{g_i^2}{\Lambda_{\rm NP}^2} \mathcal{O}_i$

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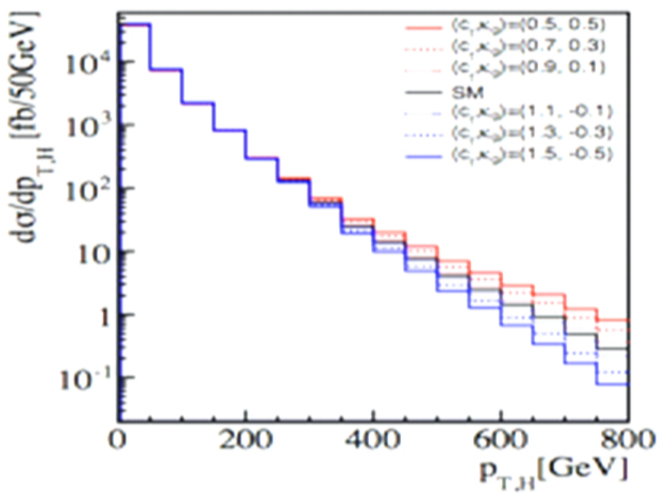
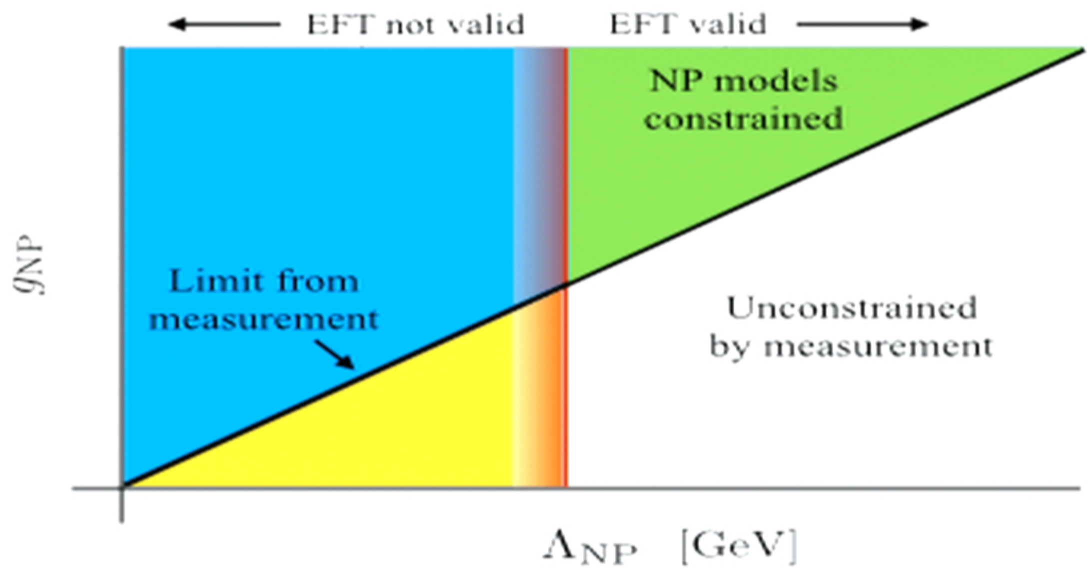
[Englert, MS 1408.5147]





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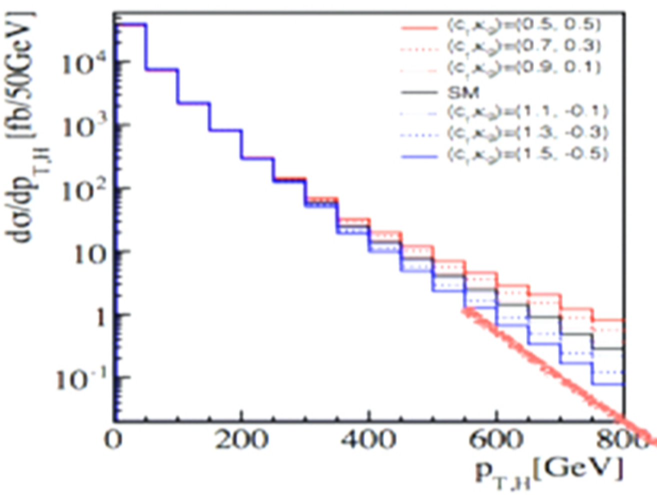

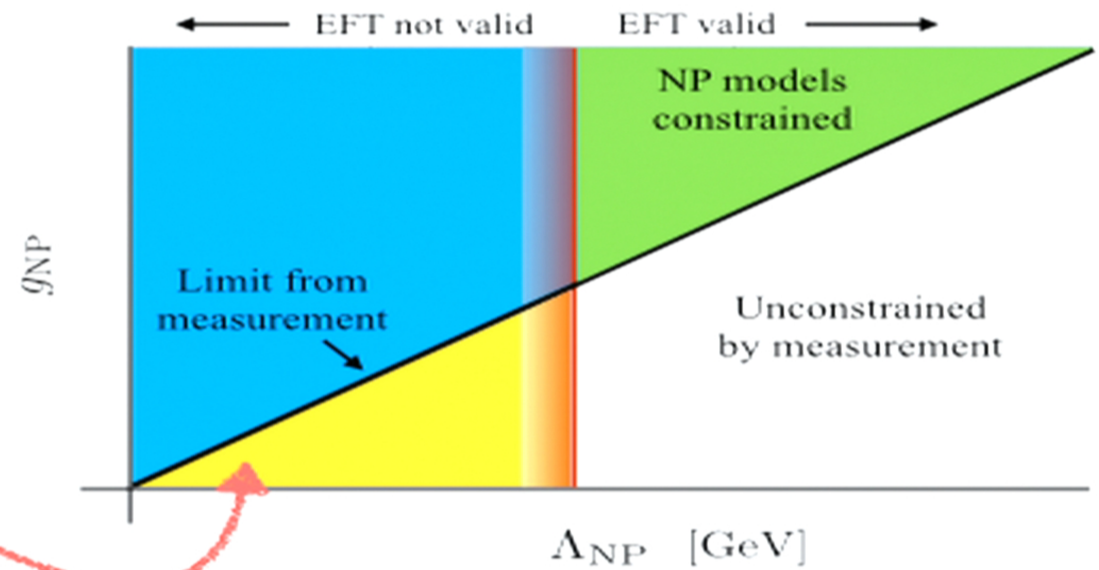

shape sets limit on Wilson coefficient (black line)

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Endpoint of kinematic distribution sets lower cut-off for NP (red line)

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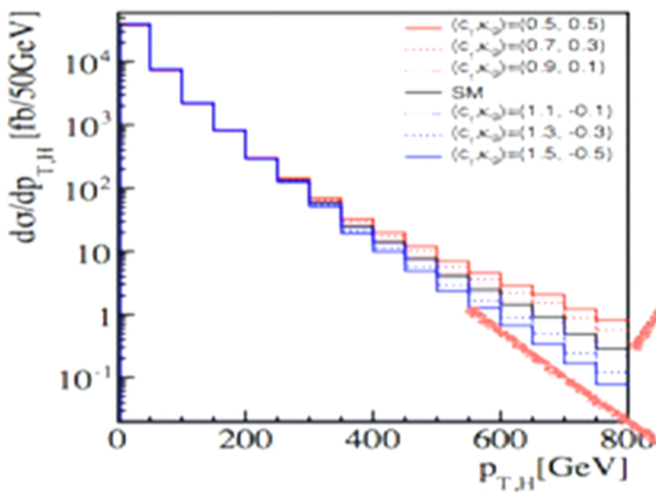

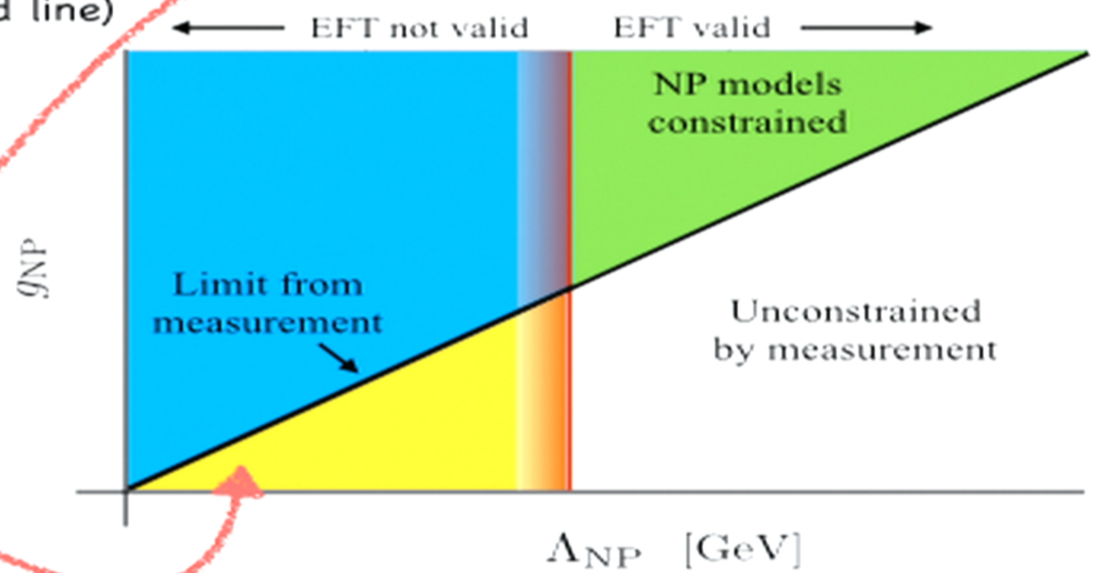

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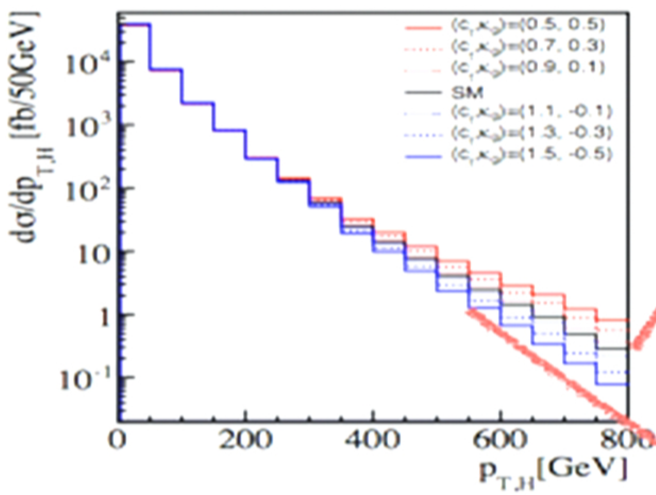
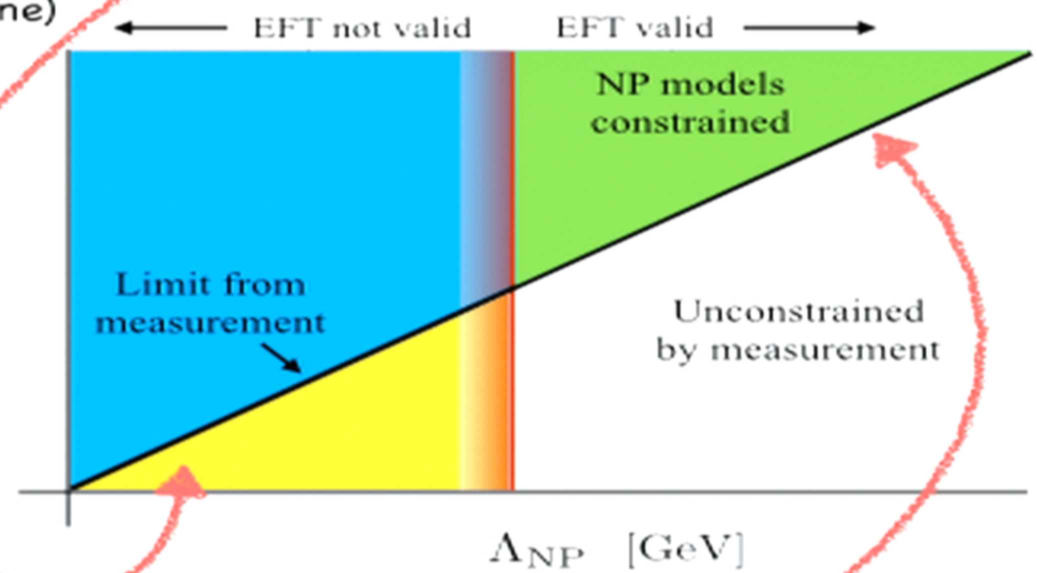
[Englert, MS 1408.5147]

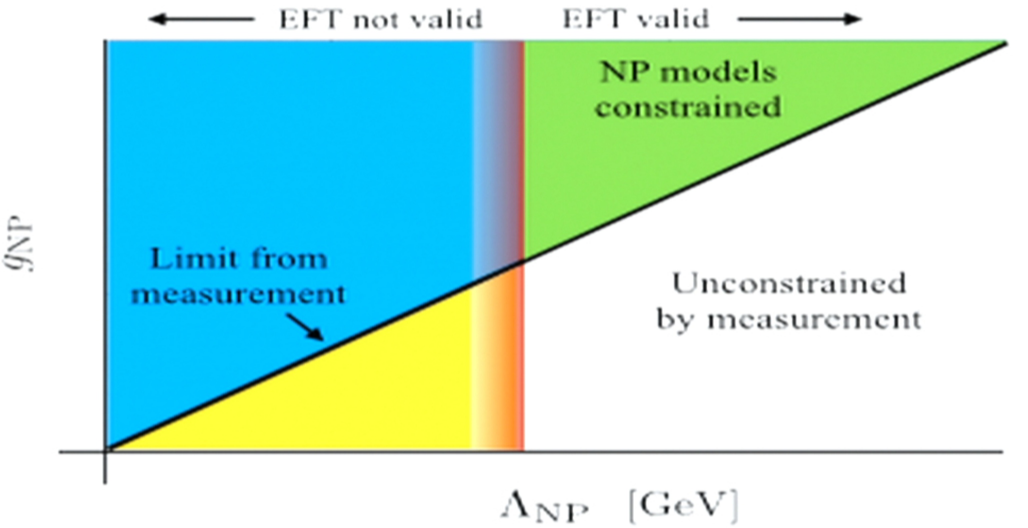




shape sets limit on Wilson coefficient (black line)

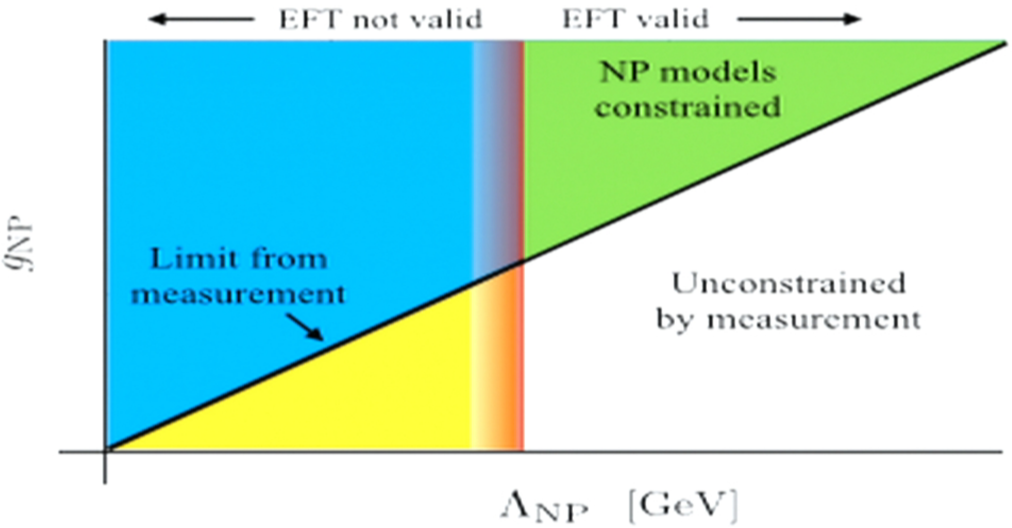
Any UV (weakly coupled) models left?

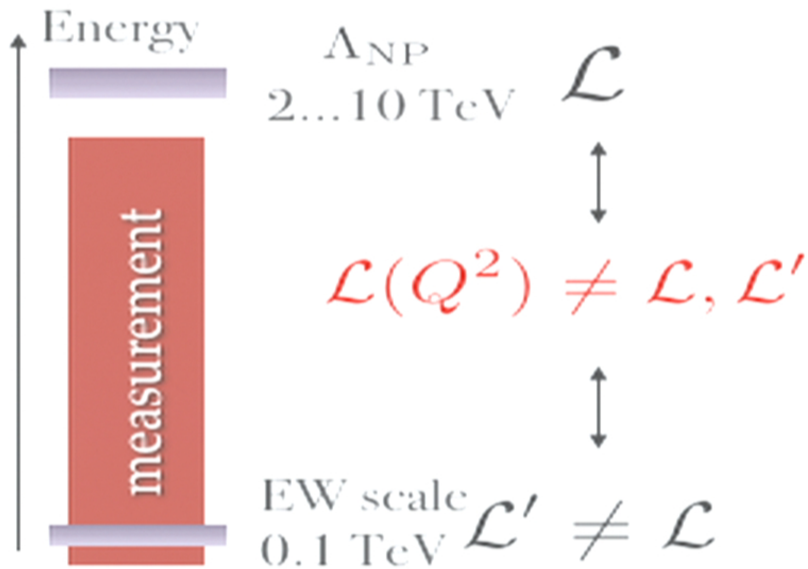
Validity and Relevance of EFT



Lagrangian dim-6: $\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{g_i^2}{\Lambda_{NP}^2} \mathcal{O}_i$

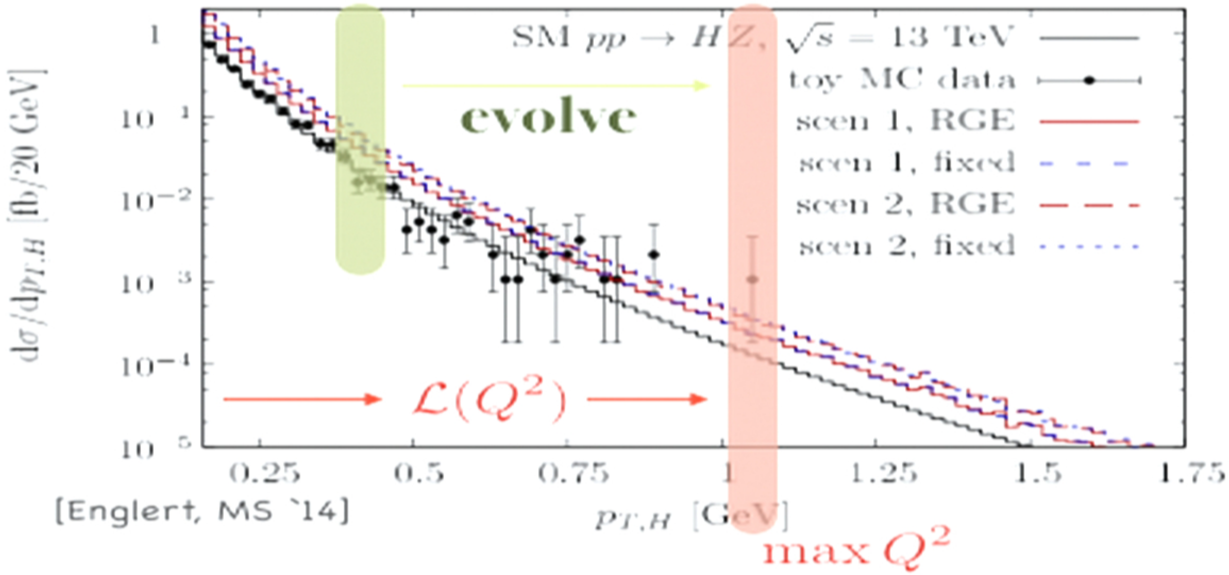
Validity and Relevance of EFT





Lagrangian dim-6: $\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{g_i^2}{\Lambda_{NP}^2} \mathcal{O}_i$

- scale hierarchies similar to flavor physics mW/mb~20
- evolution from renormalization group equations
  [Grojean, Jenkins, Manohar, Trott '13] [Jenkins, Manohar, Trott '13] [Elias-Miro et al '13]
- consistent interpretation requires **communication of resolved scales**
  [Isidori, Trott '13] [Englert, MS '14]



[Englert, MS `14]

$$\hat{O}_W = \frac{g^2}{2\Lambda_{\rm NP}^2} \hat{H}^\dagger \hat{H} \hat{W}^a_{\mu\nu} \hat{W}^{a\,\mu\nu} ,$$

$$\hat{O}_B = \frac{g'^2}{2\Lambda_{\rm NP}^2} \hat{H}^\dagger \hat{H} \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} ,$$

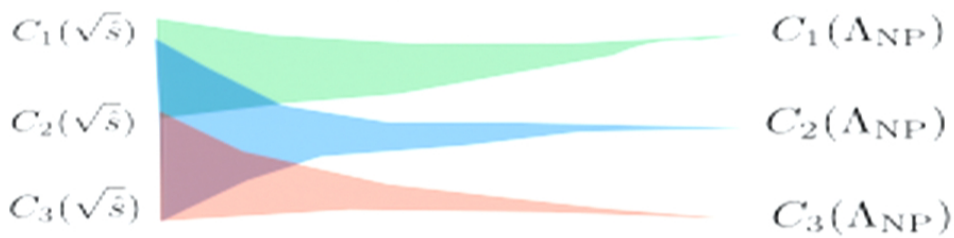
$$\hat{O}_{WB} = \frac{gg'}{\Lambda_{\rm NP}^2} \hat{H}^\dagger t^a \hat{H} \hat{W}^a_{\mu\nu} \hat{B}^{\mu\nu} ,$$

In general higher-order corrections induce scale dependence and mixing of operators

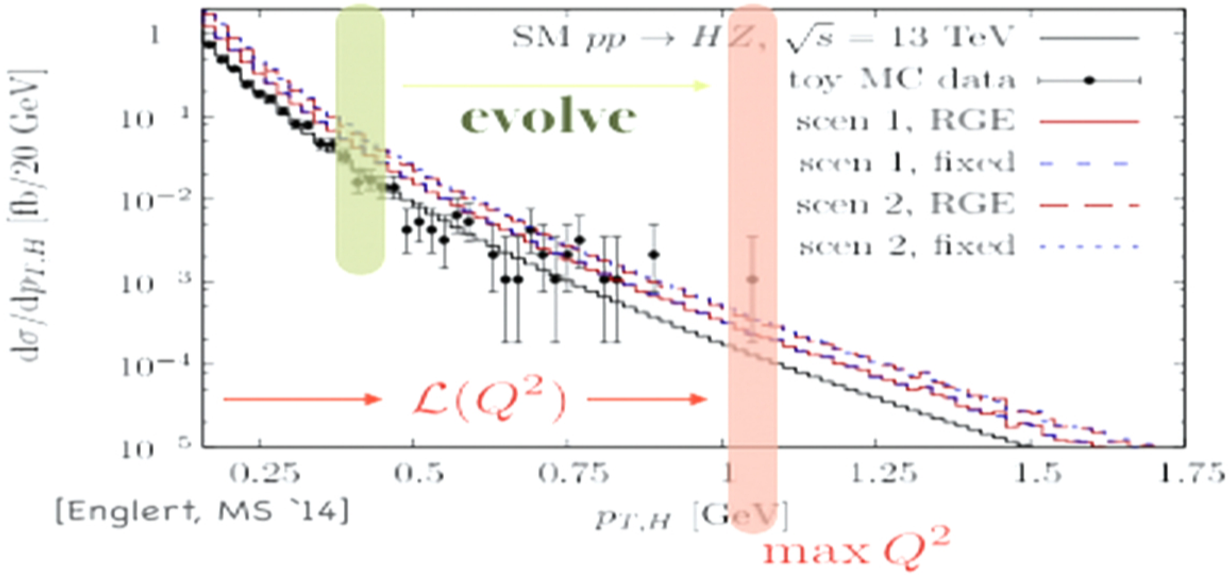
$$C_i(\sqrt{\hat{s}}) \simeq \left(\delta_{ij} + \gamma_{ij}(\sqrt{\hat{s}}) \log \frac{\sqrt{\hat{s}}}{\mu} \right) C_j(\mu)$$

As a result, each measured **event** probes a different combination of operators

measurement at characteristic scale of event



Coefficients of operators at New Physics scale



[Englert, MS `14]

$$\hat{O}_W = \frac{g^2}{2\Lambda_{\rm NP}^2} \hat{H}^\dagger \hat{H} \hat{W}^a_{\mu\nu} \hat{W}^{a\,\mu\nu} \,,$$

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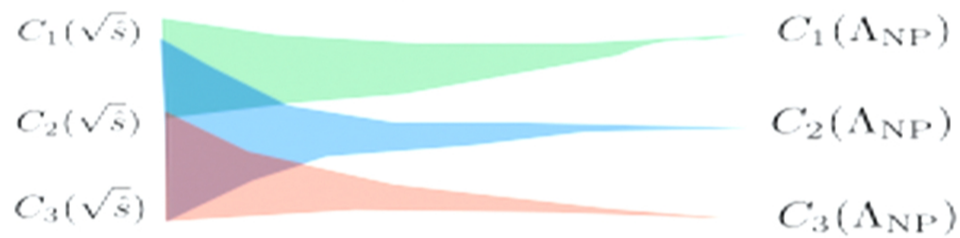
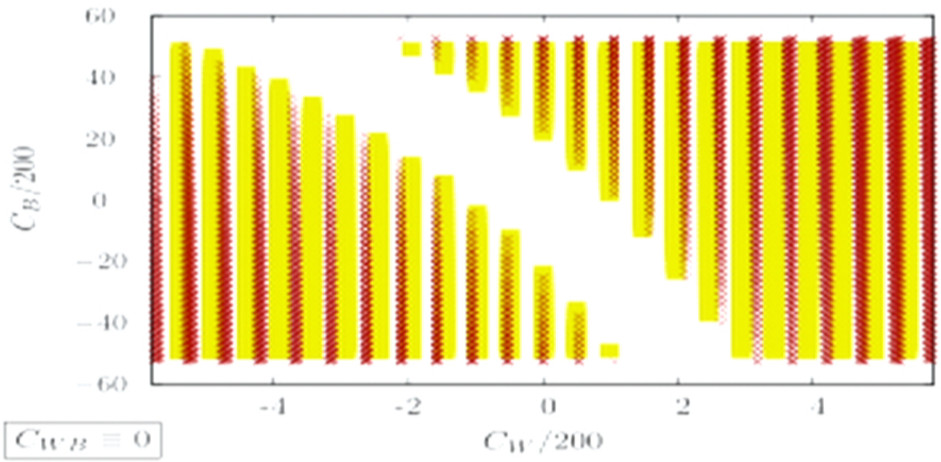
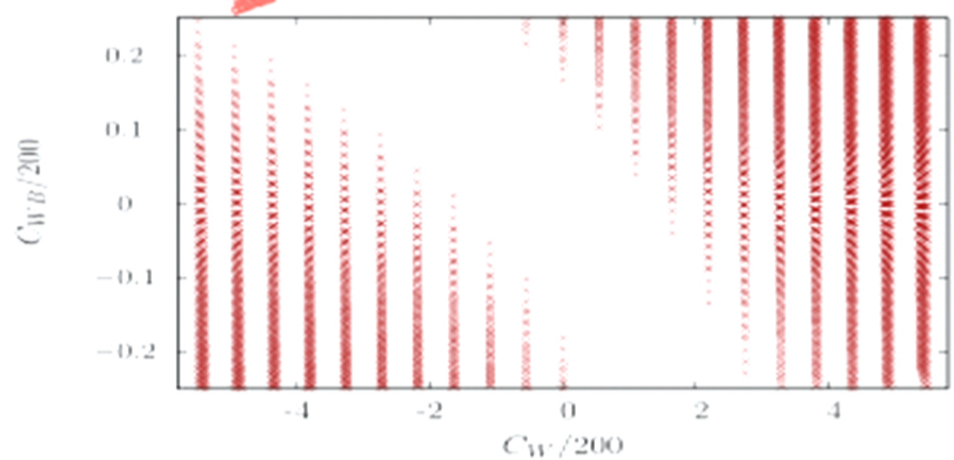


Coefficients of operators at New Physics scale

T= C_{WB} = 0 at low scale but induced and allowed at high scale





$\max Q^2 = 2.4 \text{ TeV} \Longrightarrow \mathcal{L}^{\text{BSM}}(2.4 \text{ TeV})$

Here maxQ=14 TeV

High-dim operators often momentum dependent

Sensitivity of measurement in tail of distribution

Running less important as scale separation potentially small

Results for linearised LO EFT approach

[Englert, Kogler, Schulz, MS '15]

Focus on linear contribution of EFT for theory prediction: $\mathcal{M} = \mathcal{M}_{\rm SM} + \mathcal{M}_{d=6}$

LO framework $|\mathcal{M}|^2 = |\mathcal{M}_{\rm SM}|^2 + 2\,\mathrm{Re}\{\mathcal{M}_{\rm SM}\mathcal{M}^*_{d=6}\} + \mathcal{O}(1/\Lambda^4)$

Included production and decay modes:

(incl. theory uncertainties)

production process		decay process	
$pp \to H$	14.7	$H \to b\bar{b}$	6.1
$pp \to H + \mathrm{j}$	15	$H \to \gamma\gamma$	5.4
$pp \to H + 2\mathrm{j}$	15	$H \to \tau^+\tau^-$	2.8
$pp \to HZ$	5.1	$H \to 4l$	4.8
$pp \to HW$	3.7	$H \to 2l2\nu$	4.8
$pp \to t\bar{t}H$	12	$H \to \mu^+\mu^-$	2.8

Number of predicted events: $N_{\rm th} = \sigma(H+X) \times \mathrm{BR}(H \to YY)$
$\times \mathcal{L} \times \mathrm{BR}(X, Y \to \text{final state})$

For BR EHdecay [Contino et al. '13]

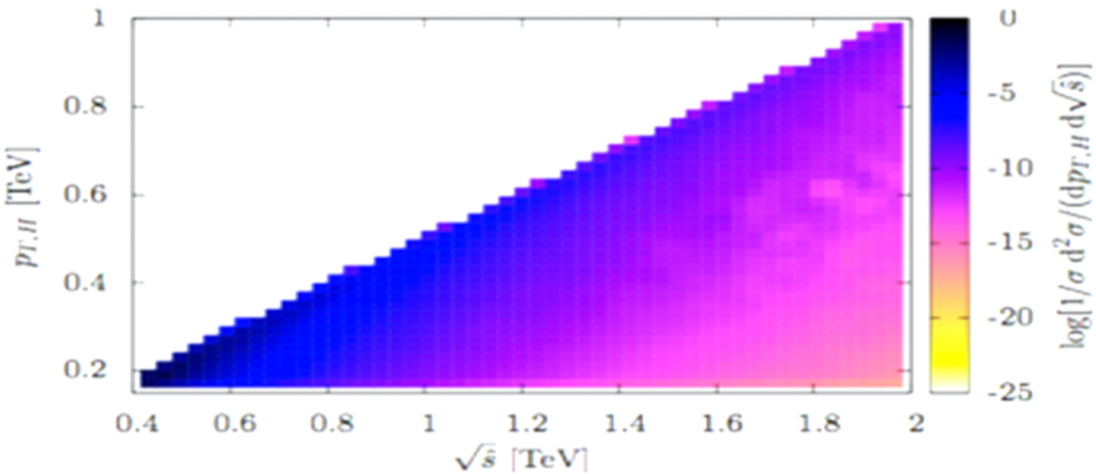
Each channel has own prod. and decay efficiencies: $N_{\rm ev} = \epsilon_p \epsilon_d N_{\rm th}$

Parametrisation of cross sections with Professor and fit using Gfitter

For differential distributions (at 14 TeV) we assume pT,H unfoldet:

high correlation

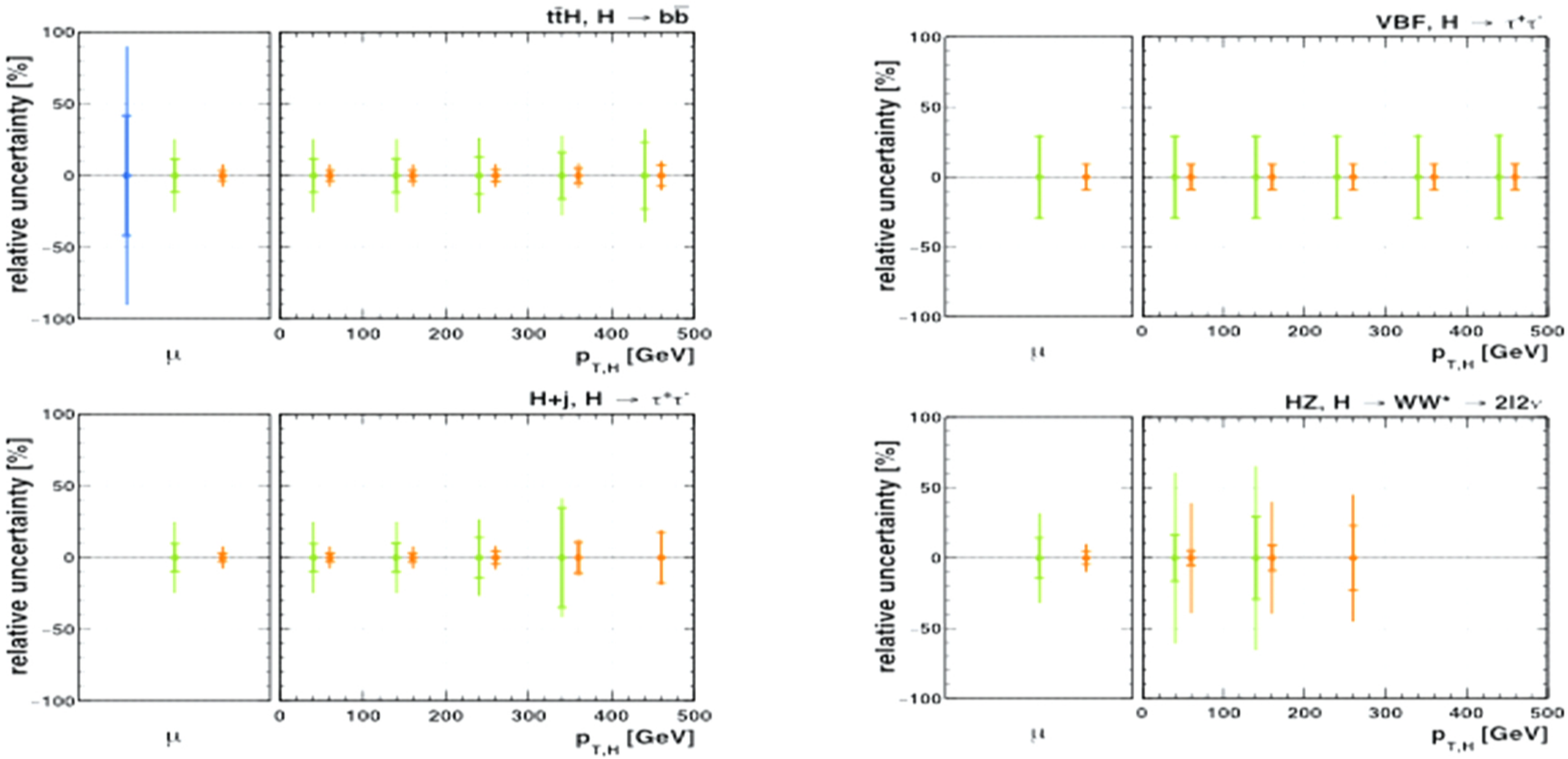
$$\sqrt{\hat{s}} \sim m_H + p_{T,H}$$

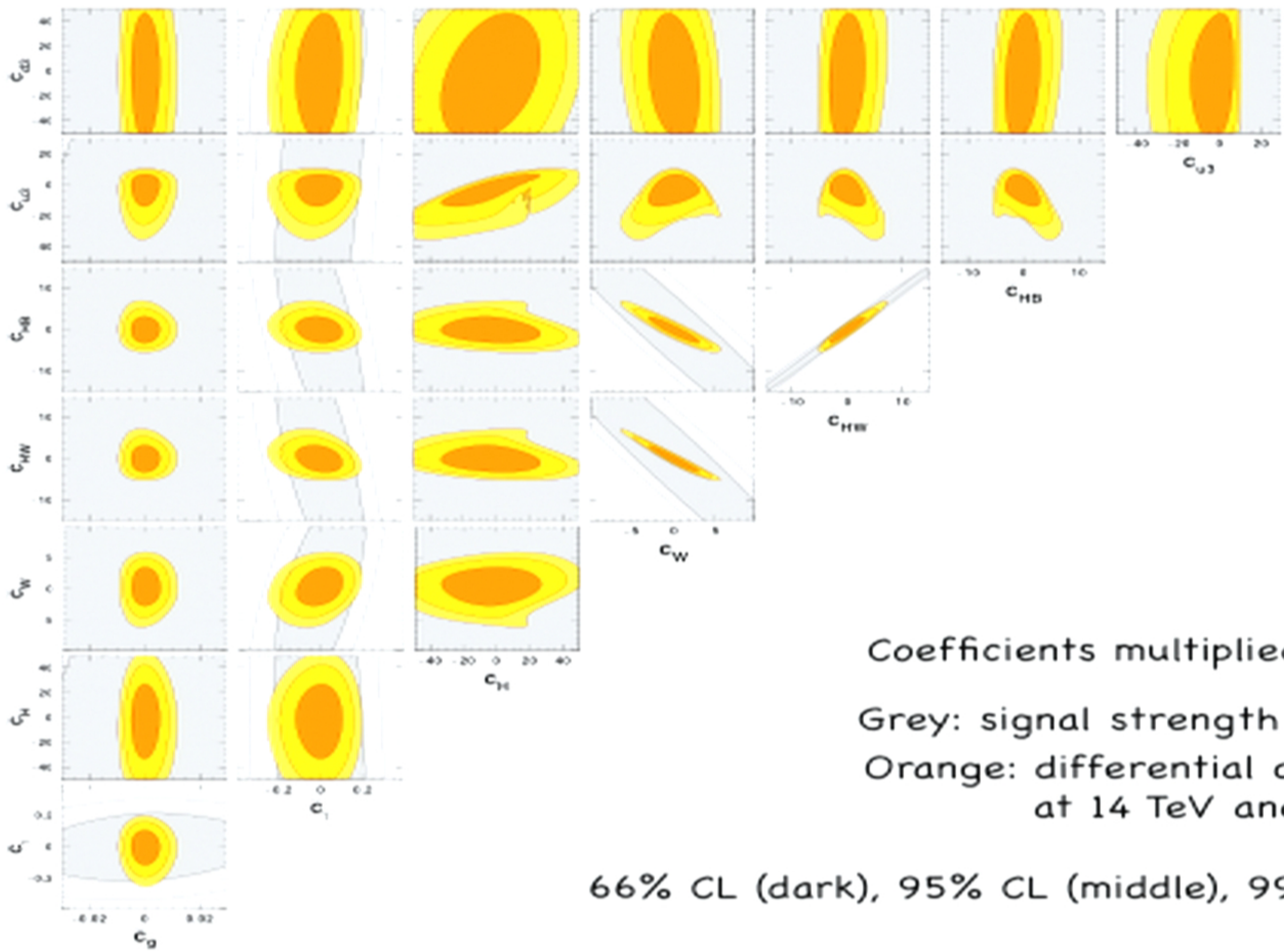


Systematic uncertainties obtained for 7/8 TeV are scaled to 14 TeV with 300 and 3000 ifb respectively by $\sqrt{\mathcal{L}_8/\mathcal{L}_{14}}$

Theoretical uncertainties are kept flat over pT and with luminosity

We generated pseudo-data for the extrapolation to 300 and 3000 ifb



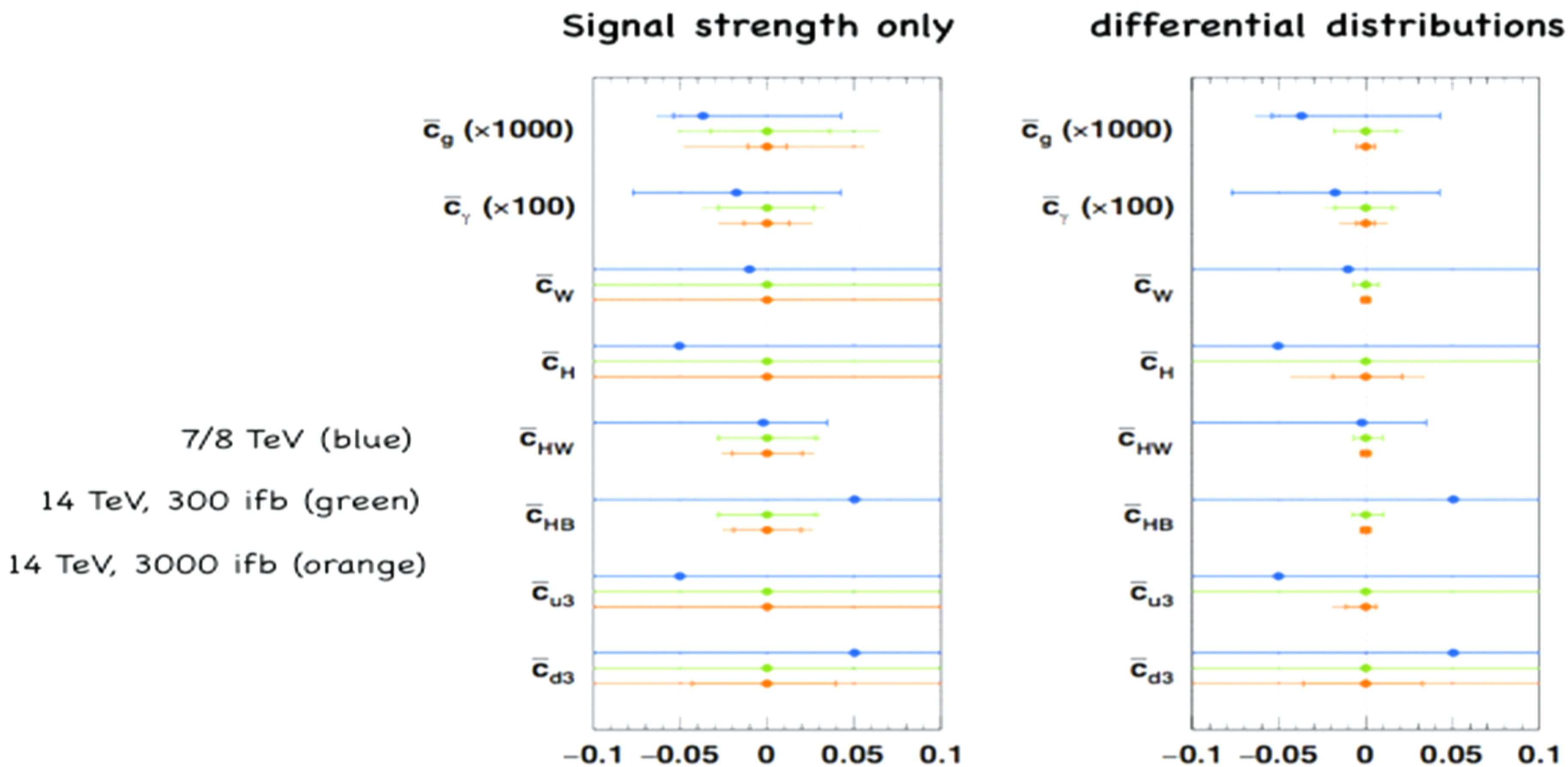


Coefficients multiplied by 10^3

Grey: signal strength only

Orange: differential distributions at 14 TeV and 3000 ifb

66% CL (dark), 95% CL (middle), 99% CL (light)


Signal strength only
differential distributions
$\bar{c}_g$ (×1000)
$\bar{c}_\gamma$ (×100)
$\bar{c}_W$
$\bar{c}_H$
$\bar{c}_{HW}$
$\bar{c}_{HB}$
$\bar{c}_{u3}$
$\bar{c}_{d3}$
−0.1 −0.05 0 0.05 0.1
7/8 TeV (blue)
14 TeV, 300 ifb (green)
14 TeV, 3000 ifb (orange)

Interpretation of results

Composite (SILH) Higgs:

One expects $\bar{c}_g \sim \frac{m_W^2}{16\pi^2}\frac{y_t^2}{\Lambda^2}$ with comp. scale $\Lambda \sim g_\rho f$

→ with $|\bar{c}_g| \lesssim 5\times 10^{-6}$ we get $\Lambda \gtrsim 2.8$ TeV

→ new fundamental physics with higher scale cannot be probed using our Higgs observables

MSSM:

$$\bar{c}_g = \frac{m_W^2}{(4\pi)^2}\frac{1}{24}\left(\frac{h_t^2 - g_1^2 c_{2\beta}/6}{m_{\tilde{Q}}^2} + \frac{h_t^2 + g_1^2 c_{2\beta}/3}{m_{\tilde{t}_R}^2} - \frac{h_t^2 X_t^2}{m_{\tilde{Q}}^2 m_{\tilde{t}_R}^2}\right)$$

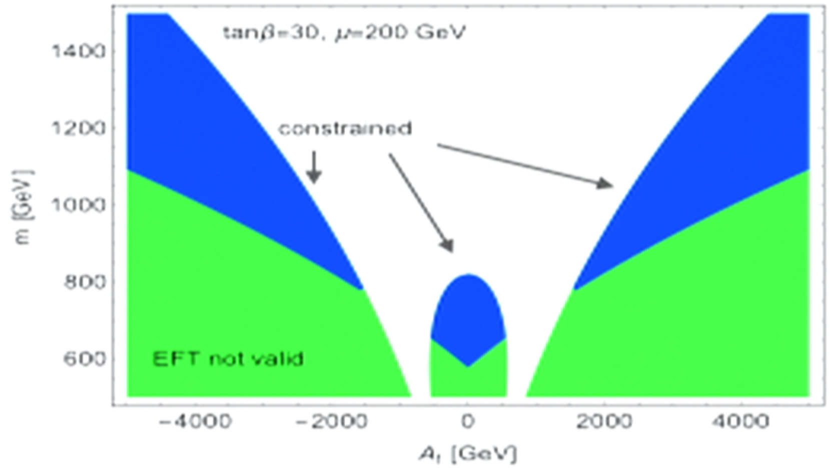
$m_{\tilde{Q}} = m_{\tilde{t}} = m$

$\tan\beta = 30$

$\mu = 200$ GeV

$h_t \equiv y_t s_\beta$

→ large At can be constrained



Limiting Dark Energy models using LHC data

[Brax, Burrage, Englert, MS 1604.04299]

Hondeski-theories possible way to address Dark Energy problem:

Most general metric that respects causality and weak equivalence principle

$$g_{\mu\nu} = A(\phi, X)\tilde{g}_{\mu\nu} + B(\phi, X)\partial_\mu\phi\partial_\nu\phi \quad \text{where} \quad X = \frac{1}{2}\eta^{\mu\nu}\partial_\mu\partial_\nu\phi \quad \tilde{g}_{\mu\nu} = \eta_{\mu\nu}$$

conformal disformal

[Bekenstein '93]

$$A(\phi, X) = \sum_n \frac{a_n(\phi/M)}{M^{4N}} X^n$$

$$B(\phi, X) = \sum_n \frac{b_n(\phi/M)}{M^{4N}} X^n$$

→ High-dimensional operators (lowest dimension 8)

Shift symmetric theories: Couplings to mass

Lowest order:

$$\mathcal{L}_1 = \frac{\partial_\mu\phi\partial^\mu\phi}{M^4} T^\nu_\nu \quad \text{(conformal)}$$

$$\mathcal{L}_2 = \frac{\partial_\mu\phi\partial_\nu\phi}{M^4} T^{\mu\nu} \quad \text{(disformal)}$$

higher order:

$$\mathcal{L}_{3,n} = \left(\frac{\partial_\mu\phi\partial^\mu\phi}{M^4}\right)^n T^\nu_\nu$$

$$\mathcal{L}_{4,n} = \left(\frac{\partial_\alpha\phi\partial^\alpha\phi}{M^4}\right)^n \frac{\partial_\mu\phi\partial_\nu\phi}{M^4} T^{\mu\nu}$$

$$\mathcal{L}_{5,n-1} = \frac{1}{M^{4n}} \partial_{\alpha_1}\phi\partial_{\beta_1}\phi \ldots \partial_{\alpha_n}\phi\partial_{\beta_n}\phi \cdot \frac{2^{n-1}}{\sqrt{-g}} \frac{\partial^{n-1}(\sqrt{-g}T^{\alpha_1\beta_1})}{\partial g_{\alpha_2\beta_2} \ldots \partial g_{\alpha_n\beta_n}}$$

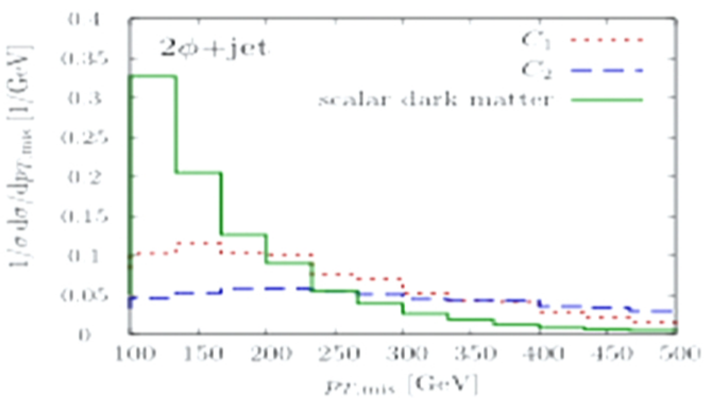
Shift symmetric theories: kinetic terms

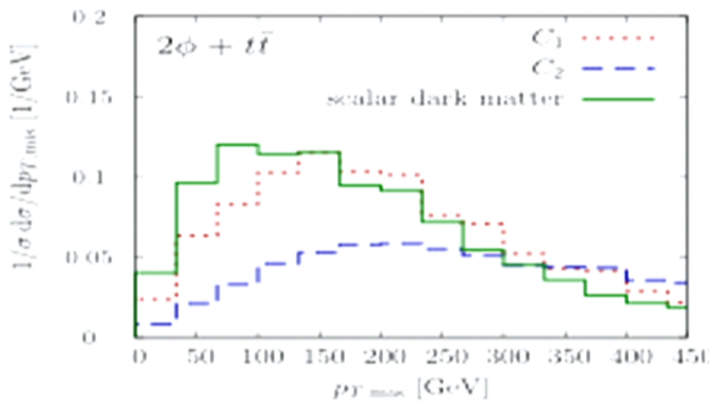
$$\mathcal{L}_{6,n} = \frac{(\partial_\mu \phi \partial^\mu \phi)^n}{M^{4(n-1)}} \qquad \mathcal{L}_7 = \frac{1}{M^3}\partial_\mu\phi\partial^\mu\phi\Box\phi \qquad \mathcal{L}_8 = \frac{1}{M^6}\partial_\mu\phi\partial^\mu\phi\left[2(\Box\phi)^2 - 2D_\alpha D_\beta\phi D^\beta D^\alpha\phi\right]$$

$$\mathcal{L}_9 = \frac{1}{M^9}\partial_\mu\phi\partial^\mu\phi\left[(\Box\phi)^3 - 3(\Box\phi)D_\alpha D_\beta\phi D^\beta D^\alpha\phi + 2D_\alpha D^\beta\phi D_\beta D^\gamma\phi D_\gamma D^\alpha\phi\right]$$

Theories with broken shift-symmetry: $\mathcal{L}_{10,n} = \left(\frac{\phi}{N}\right)^n T^\mu_\mu$

→ All operators of higher dimension and with large momentum dependence





Shift symmetric theories: kinetic terms

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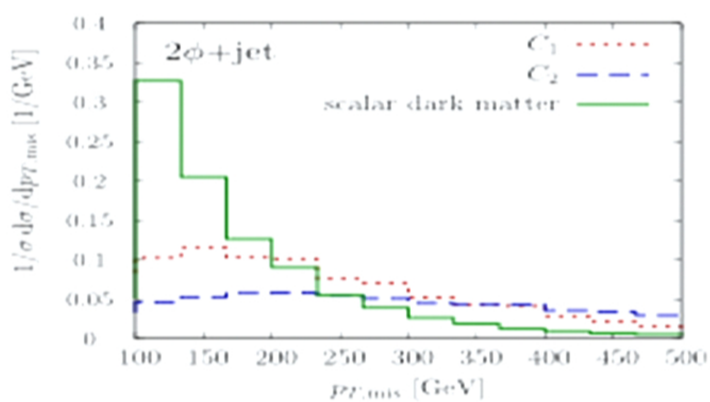
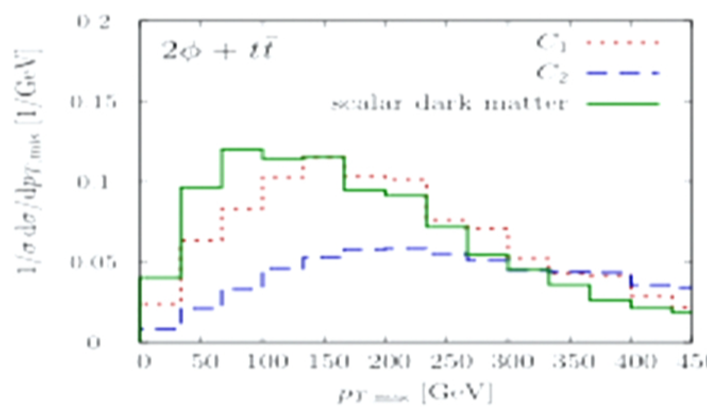




LHC ideal environment to test operators

Large momentum transfer in controlled environment

Existing non-collider limits on disformal coupling

[Brax, Burrage '14]

Wilson Coeff. defined as $1/M^4$

Source of bound	Lower bound on M in GeV	Environment
Torsion Balance	7×10^{-5}	Lab. vac.
Casimir effect	0.1	Lab. vac.
Hydrogen spectroscopy	0.2	Lab. vac.
Neutron scattering	0.03	Lab. vac.
Bremsstrahlung	4×10^{-2}	Sun
	0.18	Horizontal Branch
Compton Scattering	0.24	Sun
	0.81	Horizontal Branch
Primakov	4×10^{-2}	Sun
	0.35	Horizontal Branch
Pion exchange	~ 92	SN1987a

Strongest limits from SUSY searches

For conformal coupling in $2\phi + t\bar{t}$ →

$\mathcal{L}_1$ $M \gtrsim 237.4$ GeV (ATLAS)

$2\phi + t\bar{t}$ $M \gtrsim 192.8$ GeV (CMS)

For disformal coupling in $2\phi + \text{jet}$ →

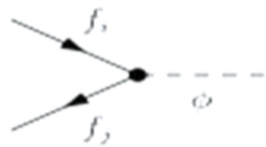
$\mathcal{L}_2$ $M \gtrsim 693.9$ GeV (ATLAS)

$2\phi + \text{jet}$ $M \gtrsim 822.8$ GeV (CMS)

LHC ideal environment to test operators

Large momentum transfer in controlled environment

Operators with broken shift-symmetry can lead to displaced vertices/jets



$= \frac{4iC_{10}}{N} m_{f_i} \delta_{ij}$

travel distance $D = \frac{\beta\gamma}{\Gamma_\phi}$

$$\Gamma(\phi \to f\bar{f}) = \frac{2}{\pi} C_{10}^2 \frac{m_f^2}{N^2} \frac{(m_\phi^2 - 4m_f^2)^{3/2}}{m_\phi^2}$$

Probability to decay between L1 and L2

$$P(L_1 \le L \le L_2) = \int_{L_1}^{L_2} \mathrm{d}L' \, \frac{1}{D} \exp\left(-\frac{L'}{D}\right)$$

Displaced vertices $C_{10} m_b / N$ < 10^{-6}

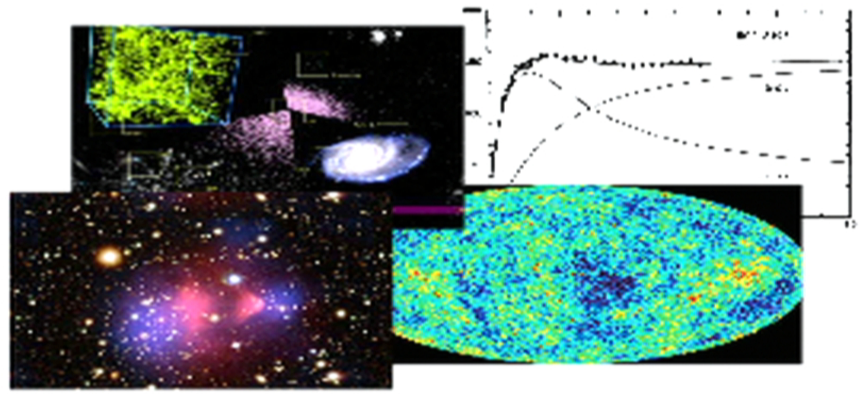
should allow to probe scales of $N \sim 10^8$ GeV

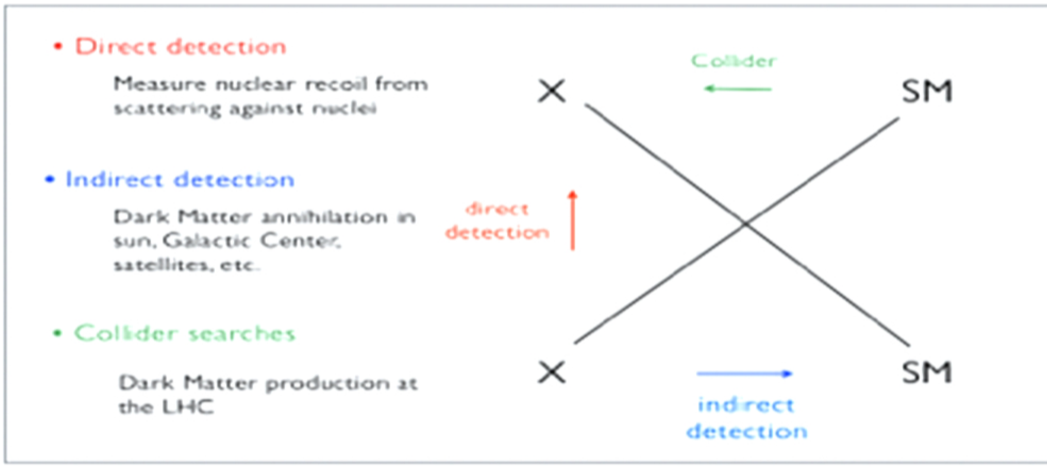
EFT language potentially inapt:

Higgs/Scalars and their Dark Matter relation

Evidence for Dark Matter overwhelming:

- Spiral Galaxy rotation curves
- Gravitational lensing
- Acoustic peaks





Several ways to look for Dark Matter

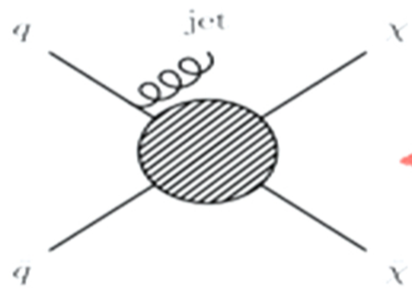
Which way more sensitive depends mostly on nature of mediator

Effective theory approach:

[Goodman et al `10]

- Parametrise interactions in terms of eff. operator

- Simplest way of capturing interactions



Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

→ Used to be preferred choice of experiments to present results

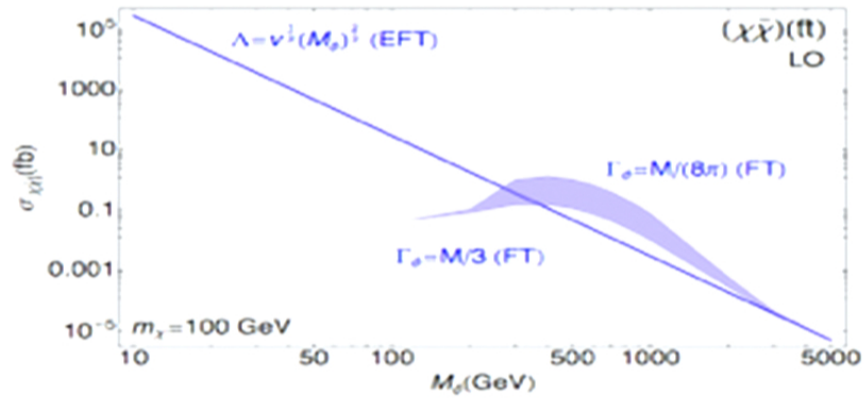
- However, only valid if interaction not resolved

Going beyond:

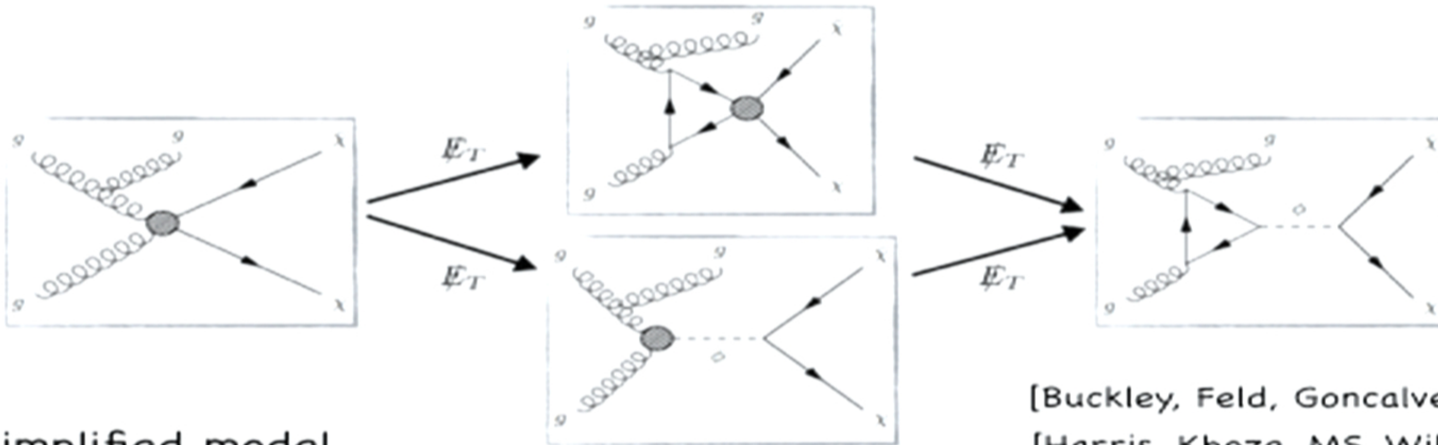
- At colliders momentum transfer too large for EFT approach

→ Need simplified models

[Fox, Williams '12] [Buchmueller, Dolan, McCabe '13]



Searching scalar DM-mediators in mono-jets



simplified model

[Buckley, Feld, Goncalves '14]
[Harris, Khoze, MS, Williams '14]

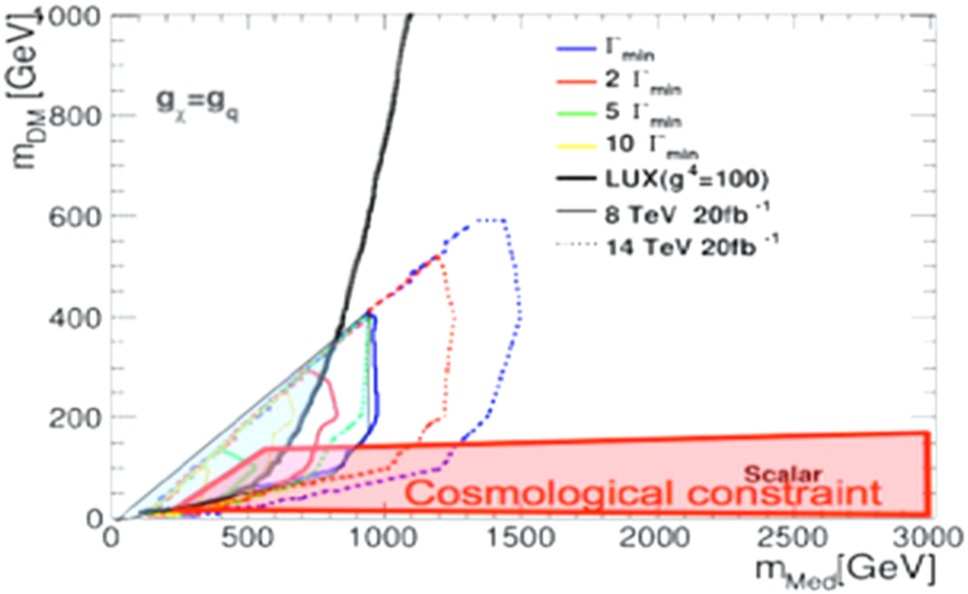
$$\mathcal{L}_{\text{pseudo-scalar}} \supset -\frac{1}{2} m_{\text{MED}}^2 P^2 - g_{\text{DM}} P\, \bar{\chi}\gamma^5\chi - g_{SM}^t P\, \bar{t}\gamma^5 t - g_{SM}^b P\, \bar{b}\gamma^5 b$$

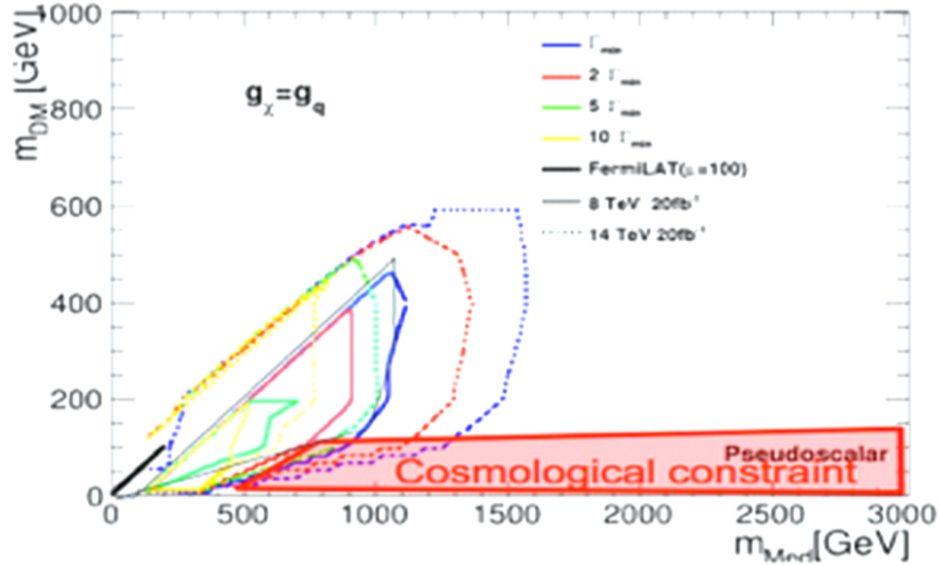
$$\mathcal{L}_{\text{scalar}} \supset -\frac{1}{2} m_{\text{MED}}^2 S^2 - g_{\text{DM}} S\, \bar{\chi}\chi - g_{SM}^t S\, \bar{t}t - g_{SM}^b S\, \bar{b}b$$

4 relevant parameters for phenomenology

1. mediator mass m_{MED}
2. mediator width Γ_{MED}
3. dark matter mass m_{DM}
4. effective coupling parameter $g_q \cdot g_\chi$

[Harris, Khoze, MS, Williams '14]



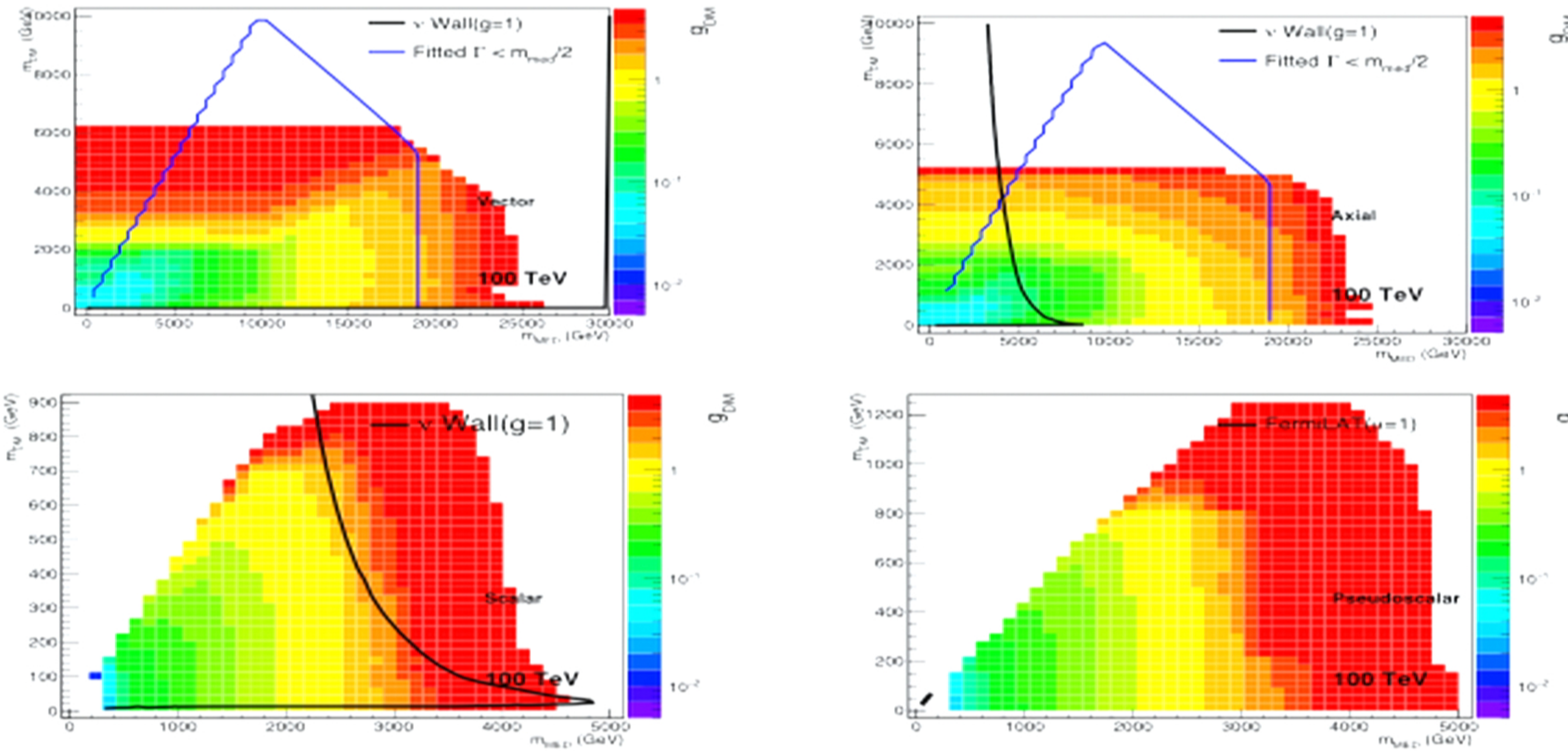


- For light Dark Matter and heavy mediators the LHC can provide complementary information to DD and ID experiments
- A joint effort of all possible ways to look for (coy) Dark Matter is needed to maximize our chances to find it

[Boehm, Dolan, McCabe, MS, Wallace '14]

Expectations at 100 TeV pp

[Harris, Khoze, MS, Williams '15]



Constraining the Higgs width at the LHC?

- alternative method using interference effects directly see [Dixon, Li '13]

Constraining the Higgs boson width with ZZ production at the LHC

Fabrizio Caola[1,*] and Kirill Melnikov[1,†]

[1] *Department of Physics and Astronomy, Johns Hopkins University, Baltimore, USA*

We point out that existing measurements of $pp \to ZZ$ cross-section at the LHC in a broad range of ZZ invariant masses allow one to derive a model-independent upper bound on the Higgs boson width, thanks to strongly enhanced off-shell Higgs contribution. Using CMS data and considering events in the interval of ZZ invariant masses from 100 to 800 GeV, we find $\Gamma_H \leq 38.8\ \Gamma_H^{\rm SM} \approx 163$ MeV, at the 95% confidence level. Restricting ZZ invariant masses to $M_{ZZ} \geq 300$ GeV range, we estimate that this bound can be improved to $\Gamma_H \leq 21\ \Gamma_H^{\rm SM} \approx 88$ MeV.

[Caola, Melnikov PRD 88]

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[Caola, Melnikov PRD 88]

Measurement done in CMS-PAS-HIG-14-002 and presented at Moriond `14
By now ATLAS has performed same measurement

Constraining the Higgs width at the LHC?

- alternative method using interference effects directly see [Dixon, Li '13]

Constraining the Higgs boson width with ZZ production at the LHC

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QUANTUM DIARIES

Tevatron and LHC experiments so far. The week went on to include a spectacular CMS result on the Higgs width.

Constraining the Higgs width at the LHC?

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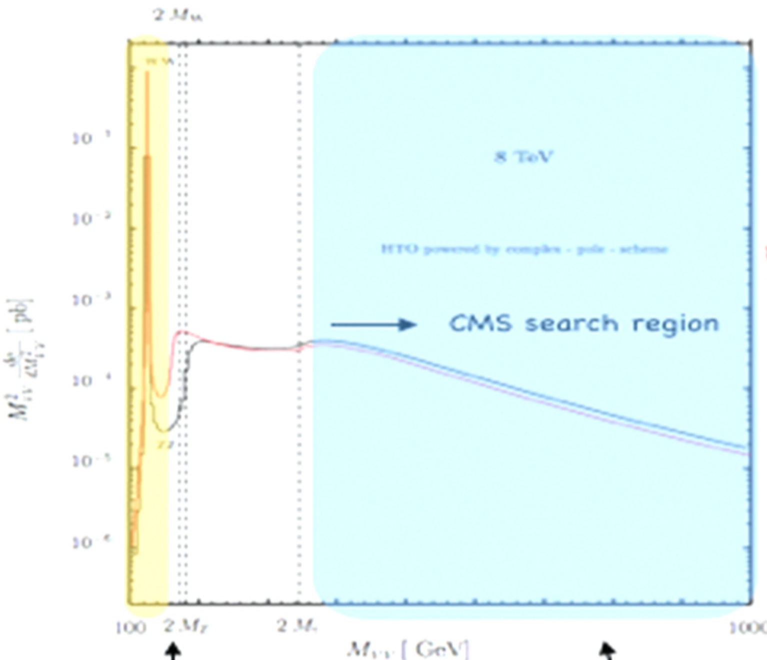
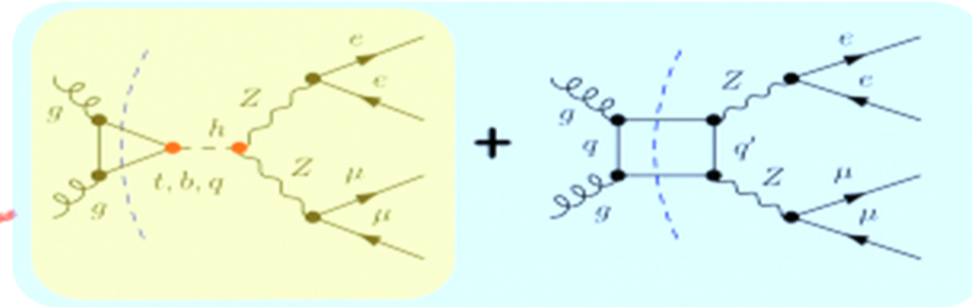
LIFEANDPHYSICS
JONBUTTERWORTH

How wide is a Higgs?

In accord with Heisenberg's uncertainty principle, short-lived particles have uncertain mass. So the Higgs boson, which gives mass to other particles, is uncertain about its own mass. New results from the CMS experiment at the CERN LHC have started to tell us how uncertain

Chosen language affects answer: CMS 'width' Measurement





I. Count events in on-shell region

→ fix signal strength $\mu_{i,j} = \sigma_{H,i} \times BR_j \sim \frac{g_{ggH} g_{HZZ}}{\Gamma_H}$

II. measure $g^2_{ggH} g^2_{HZZ}$ in off-shell region using angular correlations of 4l decay products

III. insert off-shell coupling measurement in on-shell signal strength to bound width

$$\sigma^{\rm on-peak}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H}$$

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Obs.(exp.) @95% C.L:

$\Gamma_H <$ 4.2(8.5) Γ_H^{SM}

$\Gamma_H <$ 17.4 (35.3) MeV

[Kauer, Passarino 2011]

[Caola, Melnikov 2013]

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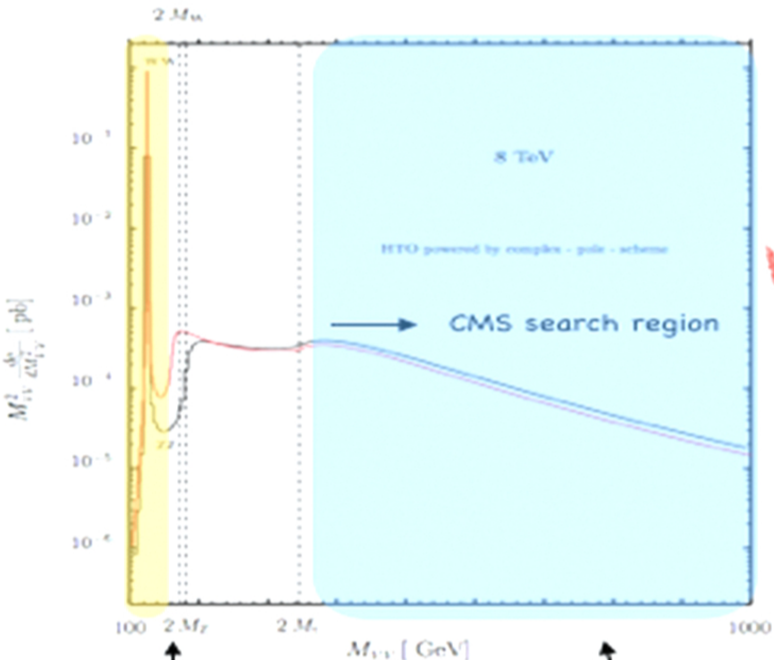

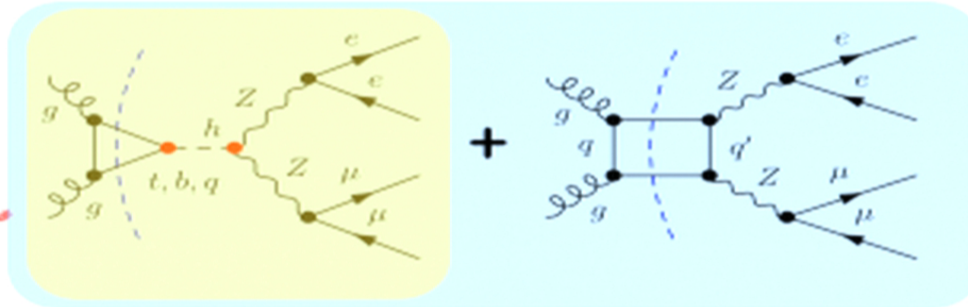

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Example 'width-measurement'

Measure coupling off-shell -> limit denominator on-shell

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Kappa Framework	EFT	Simplified Models	Full (UV) Model

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Simplified Models ⚡

- Eg. **Higgs portal**, NP can contribute on-shell but not off-shell [Englert, MS '14]
- Eg. **Higgs triplet**, new scalar below measurement range cancels on-shell enhancement [Logan '15]

Full (UV) Model

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- Uninteresting width not a free parameter of the theory

  width derived and fully determined

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Kappa Framework ✓

- Assuming global coupling rescaling

Coupling assumptions strong
LEP limits stronger than LHC

$$0.73\, \Gamma_{SM} \lesssim \Gamma_h \lesssim 1.87\, \Gamma_{SM}$$

[Englert, McCullough, MS '15]

EFT ✓

- Assuming valid and no flat directions

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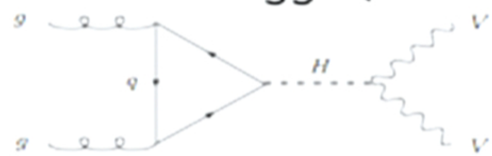
Finally

ATLAS EXPERIMENT and CMS

are taking data at unprecedented energies

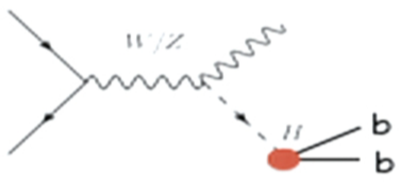
Energetic final states not only important for effective couplings

Off-shell Higgs (Width)



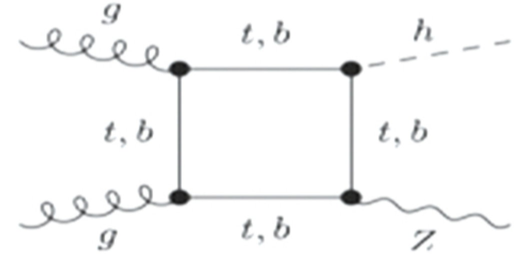
[Kauer, Passarino '12]
[Caola, Melnikov '14]

Higgs-bottom coupling



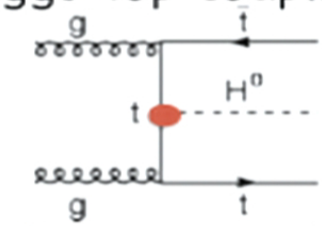
[Butterworth, Davison, Rubin, Salam '08]

HZ final state



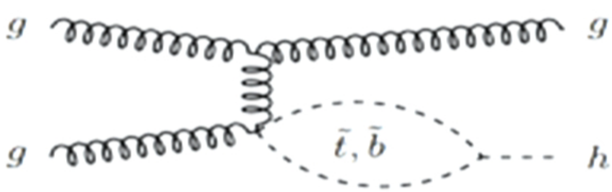
[Englert, McCullough, MS '13]

Higgs-top coupling



[Plehn, Salam, MS '09]
[Moretti, Petrov, Pozzorini, MS '15]

Boosted Higgs in H+jet

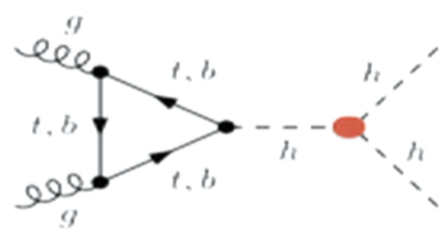


[Harlander, Neumann '13]
[Banfi, Martin, Sanz '13]
[Grojean, Salvioni, Schlaffer Weiler '14]

CP Higgs

[Plehn, Rainwater, Zeppenfeld '01]
[Klamke, Zeppenfeld '07]

Higgs selfcoupling



[Baur, Plehn, Rainwater '02 '03]
[Dolan, Englert, MS '12 '12]
[Baglio et al '13]

Energetic final states not only important for effective couplings

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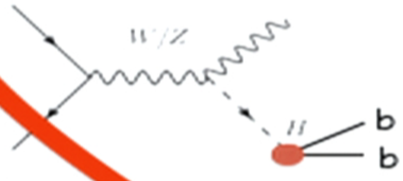

[Butterworth, Davison, Rubin, Salam '08]

Off-shell Higgs (Width)

[Kauer, Passarino '12]
[Caola, Melnikov '14]

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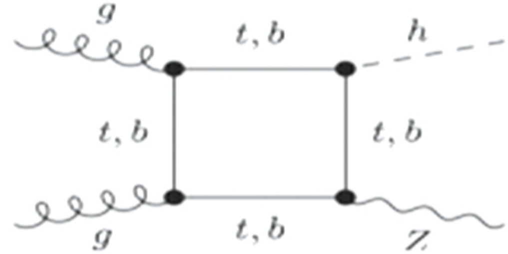

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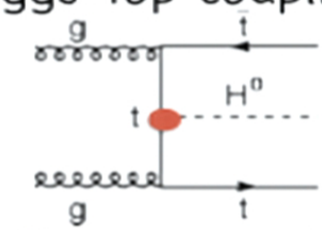

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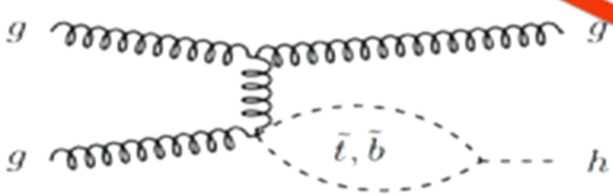

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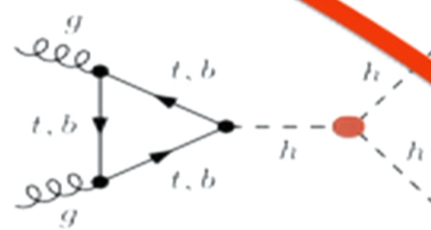

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[Baglio et al '13]

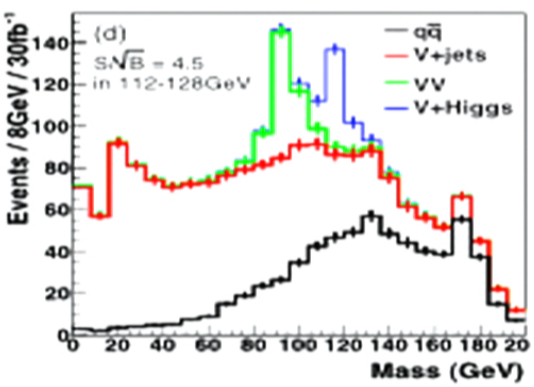
Decay into spec. channel

Production

$$\sigma \cdot BR \propto g_p^2 \frac{g_d^2}{\Gamma_H}$$

Sum of all possible decays

Uncertainty of ALL coupling measurements driven by total width, i.e. H-> bb



Some improvements possible [Soper, MS '10 '11]

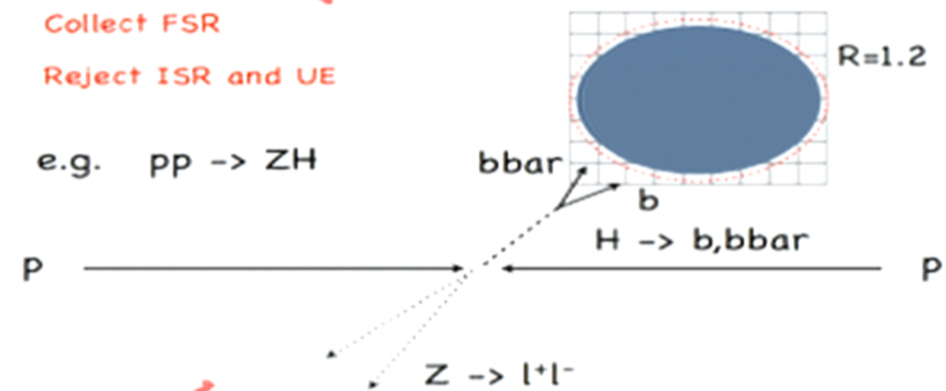
Measuring Hbb at LHC

[Zeppenfeld et al 2000]
[Lafaye, Plehn, Rauch, Zerwas, Duehrssen (2009)]
[Butterworth, Davison, Rubin, Salam '09]
hbb measurement in HV possible

Collect FSR

Reject ISR and UE

e.g. pp -> ZH



Δ_{bbH}

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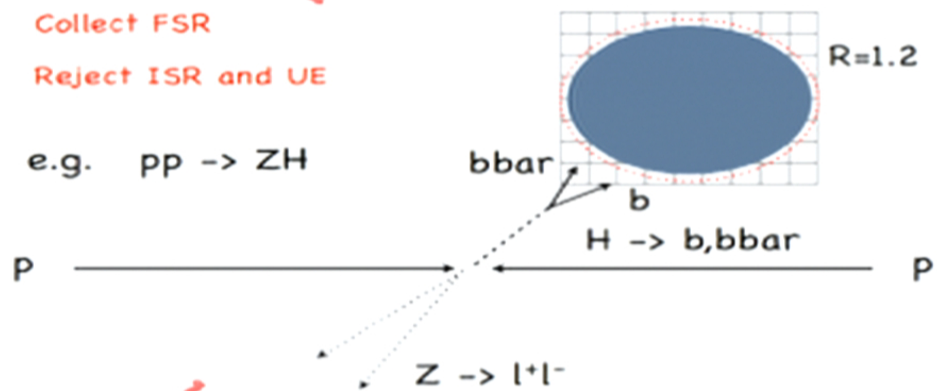
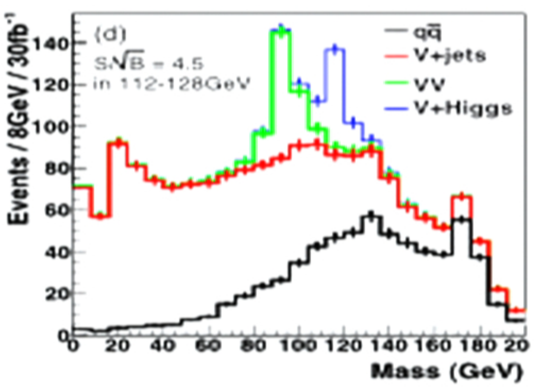




Δ_{bbH}

Some improvements possible [Soper, MS '10 '11]

Measuring the Higgs-top coupling

Motivation:
- Direct access to top and bottom Yukawa
  -> is Higgs potential stable?
- Potential window to New Physics
- Part of global coupling fit

Possible channels:
- H->bb
- H->gamma gamma
- H->tau tau / WW

$\otimes$ hadronic, semileptonic, di-leptonic tops

Striking signatures, e.g. same-sign leptons

Already now can recast SUSY searches and set limit

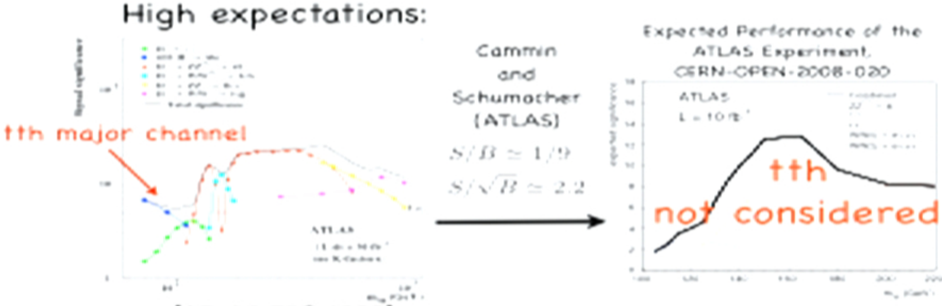
$\mu < 3.8$ [Craig et al '13] [Curtin et al '13]

Strongest limit currently observed H->bb: $\mu < 3.4$ [ATLAS]

Still, channel systematics limited! S/B small after selection O(0.1)

semileptonic tops in H->bb:

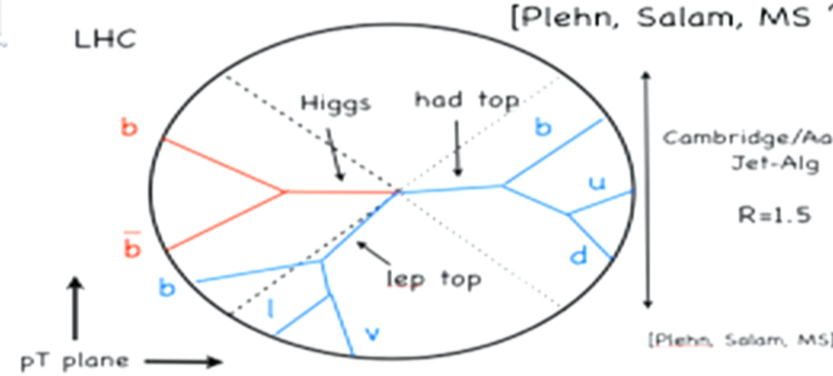
High expectations:



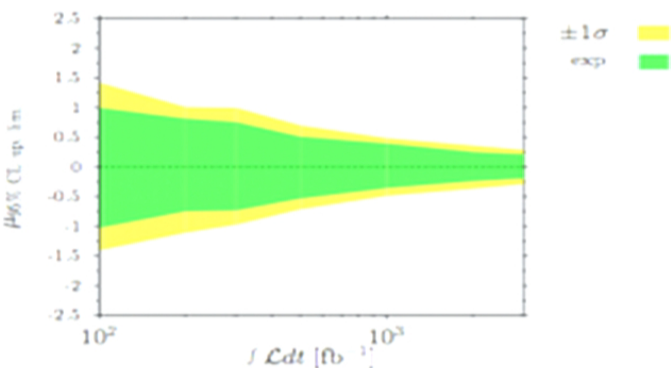
[ATLAS TDR 1999]

For di-leptonic tops see [Artoisenet et al '14]

[Plehn, Salam, MS '09]



[Moretti, Pozzorini, Petrov, MS '15]



- Improvement of S/B

- Use boost and jet substructure to ameliorate combinatorics

[Contino, et al (2012)]
[Goertz, et al (2014)]

Constrain/discover new physics in di-Higgs

- We found remnant of symmetry breaking but need to know mechanism
- Shape of potential (stable, meta-stable)
- If new physics heavy can parametrise effect using EFT

$$\mathcal{L}_{\mathrm{Dim6}} \supset c_H \partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) - c_6(\Phi^\dagger\Phi)^3$$
$$+(c_y \Phi^\dagger\Phi\bar{Q}_L\Phi q_R + h.c.) + c_g \Phi^\dagger\Phi G^a_{\mu\nu}G^{a\mu\nu}$$

- c6 can only be constrained in HH production, but many more operators contribute

Not more promising at FCC-ee or ILC

[Tian, Fujii 1311.6528]

- WBF most sensitive channel for large energies > 500 GeV
- Decay via H->bb
- Unless 1 TeV ILC precision low

$\Delta g/g$	Baseline			LumiUP		
	250 GeV	+ 500 GeV	+ 1 TeV	250 GeV	+ 500 GeV	+ 1 TeV
g_{HZZ}	1.3%	1.0%	1.0%	0.61%	0.51%	0.51%
g_{HWW}	4.8%	1.2%	1.1%	2.3%	0.58%	0.56%
g_{Hbb}	5.3%	1.6%	1.3%	2.5%	0.83%	0.66%
g_{Hcc}	6.8%	2.8%	1.8%	3.2%	1.5%	1.0%
g_{Hgg}	6.4%	2.3%	1.6%	3.0%	1.2%	0.87%
$g_{H\tau\tau}$	5.7%	2.3%	1.7%	2.7%	1.2%	0.93%
$g_{H\gamma\gamma}$	18%	8.4%	4.0%	8.2%	4.5%	2.4%
$g_{H\mu\mu}$	-	-	16%	-	-	10%
g_{Htt}	-	14%	3.1%	-	7.8%	1.9%
Γ_H	11%	5.0%	4.6%	5.4%	2.5%	2.3%
λ_{HHH}	-	83%	21%	-	46%	13%

- How about FCC-hh? Ongoing studies, but promising first results

[Barr, Dolan, Englert, Ferreira, MS (2014)] [Azatov, Contino, Panico, Son (2015)] [Yao (2015)]

[Papaefstathiou, Sakurai (2015)] [Papaefstathiou (2015)]

Higgs self-coupling measurements in the Standard Model

$$= \lambda_{SM} = g^2 m_h^2 / m_W^2$$

$$-\mathcal{L} \supset \frac{1}{2} m_h^2 h^2 + \sqrt{\frac{\eta}{2}} m_h h^3 + \frac{\eta}{4} h^4$$
$$- g m_V V^2 h - \frac{m_f}{v} \bar{f} f h$$
$$- \frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a\,\mu\nu} \log(1 + h/v)$$

⟶ Potential needs at least dihiggs production!

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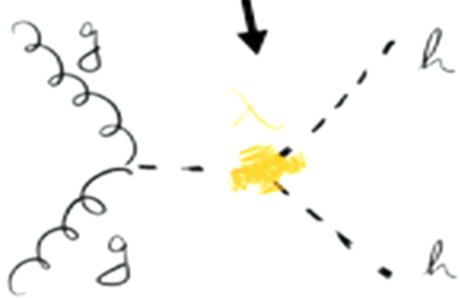

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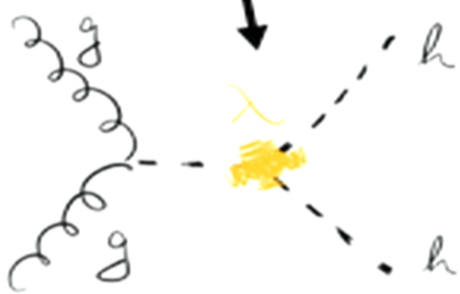
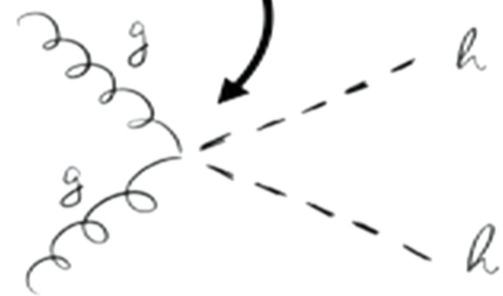
$$= - \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{a\,\mu\nu} h + \frac{\alpha_s}{24\pi v^2} G^a_{\mu\nu} G^{a\,\mu\nu} h^2 + \ldots$$





Higgs self-coupling measurements in the Standard Model

$$= \lambda_{SM} = g^2 m_h^2 / m_W^2$$

$$-\mathcal{L} \supset \frac{1}{2} m_h^2 h^2 + \sqrt{\frac{\eta}{2}} m_h h^3 + \frac{\eta}{4} h^4$$

$\longrightarrow$ Potential needs at least dihiggs production!

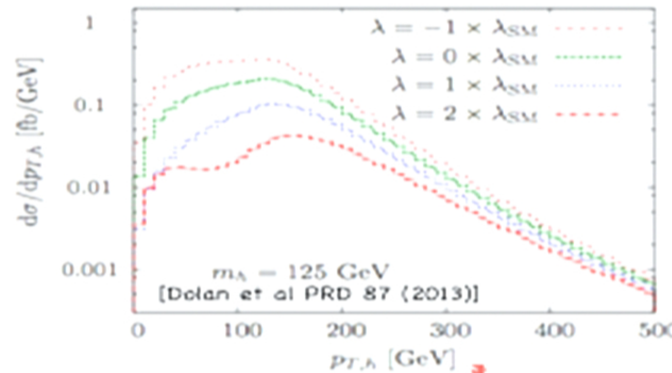
$$- g m_V V^2 h - \frac{m_f}{v} \bar{f} f h$$

$$- \frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a\,\mu\nu} \log(1 + h/v)$$

$$= - \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{a\,\mu\nu} h + \frac{\alpha_s}{24\pi v^2} G^a_{\mu\nu} G^{a\,\mu\nu} h^2 + \ldots$$

Kinematics for gg -> HH

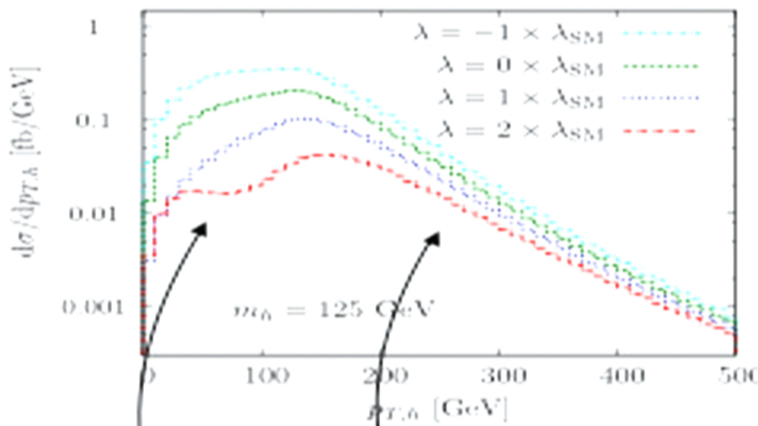
2->2 scattering process completely determined by 2 variables,
e.g. S and T, E and scattering angle

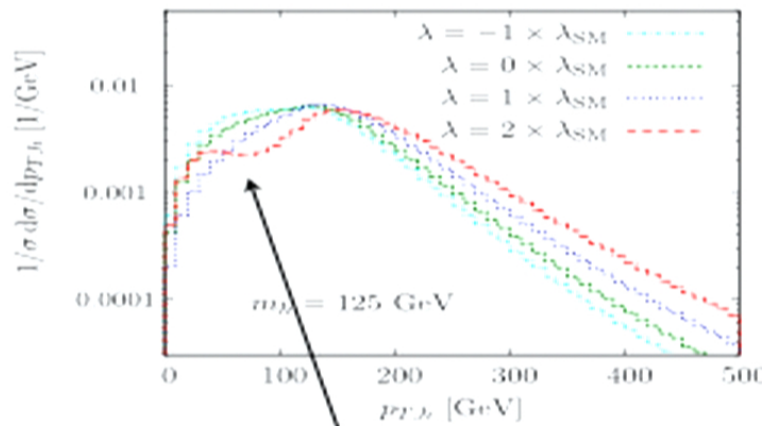


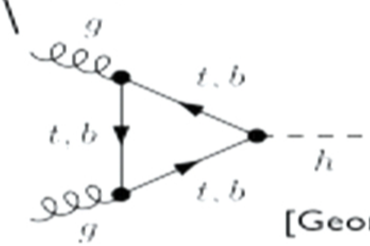
variables more close to reconstructed objects: m_{HH} and pT,H

- All SM and BSM effects covered by double-differential measurement of two variables
- Whether possible depends on signal rate and sensitivity in phase space (backgrounds)
  (efficiencies, identifications, kinematics)

Higgs selfcoupling in HH+X



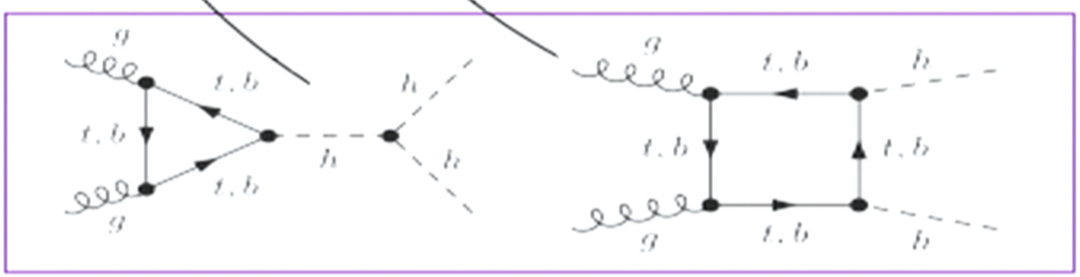




[Georgi et al. '78]

has maximum contribution for

$$s = (p_{h,1} + p_{h,2})^2 = 4m_t^2$$



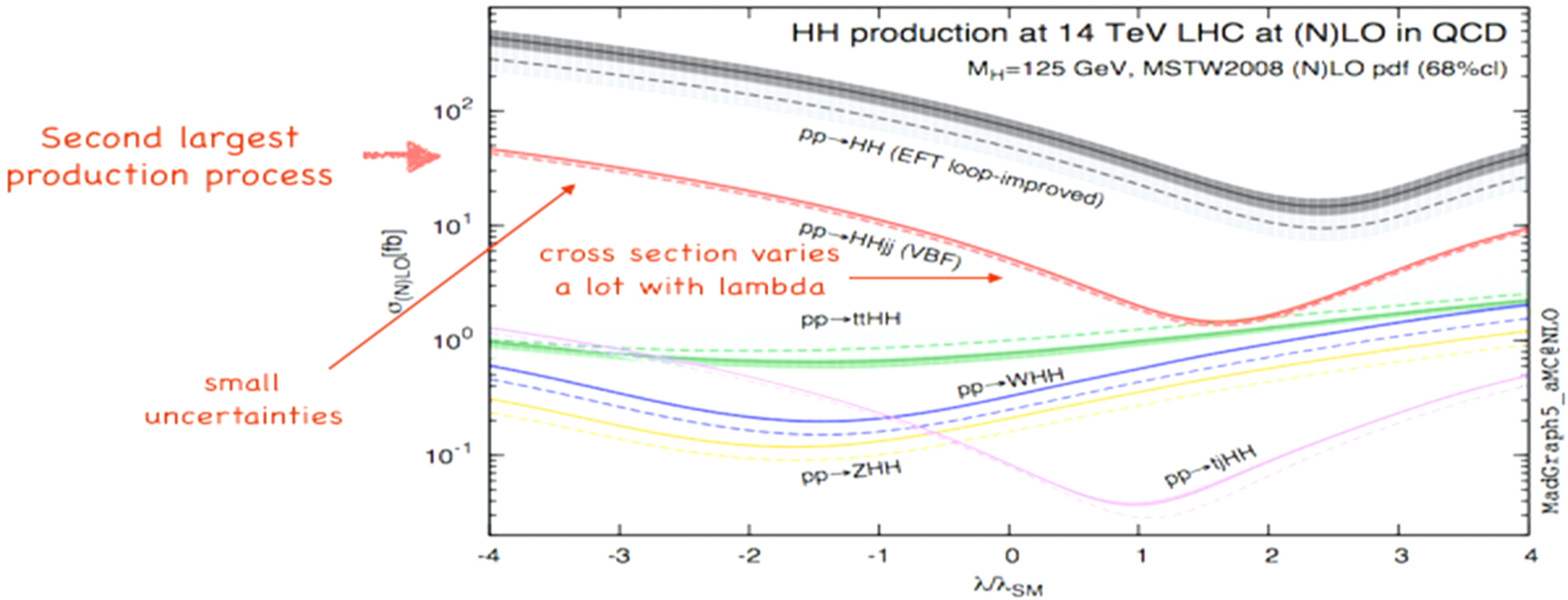
Rec. efficiency needs boost

[Dolan, Englert, MS '12]

Decay	Issues	Expectation 3000 ifb	References
$b\bar{b}\gamma\gamma$	• Signal small • BKG large & difficult to asses • Simple reconst.	$S/B \simeq 1/3$ $S/\sqrt{B} \simeq 2.5$	[Baur, Plehn, Rainwater] [Yao 1308.6302] [Baglio et al. JHEP 1304]
$b\bar{b}\tau^+\tau^-$	• tau rec tough • largest bkg tt • Boost+MT2 might help	**differ a lot** $S/B \simeq 1/5$ $S/\sqrt{B} \simeq 5$	[Dolan, Englert, MS] [Barr, Dolan, Englert, MS] [Baglio et al. JHEP 1304]
$b\bar{b}W^+W^-$	• looks like tt • Need semilep. W to rec. two H • Boost + BDT proposed	**differ a lot** best case: $S/B \simeq 1.5$ $S/\sqrt{B} \simeq 8.2$	[Dolan, Englert, MS] [Baglio et al. JHEP 1304] [Papaefstathiou, Yang, Zurita 1209.1489]
$b\bar{b}b\bar{b}$	• Trigger issue (high pT kill signal) • 4b background large difficult with MC • Subjets might help	$S/B \simeq 0.02$ $S/\sqrt{B} \leq 2.0$	[Dolan, Englert, MS] [Ferreira de Lima, Papaefstathiou, MS] [Wardrope et al, 1410.2794]
others	• Many taus/W not clear if 2 Higgs • Zs, photons no rate		

Other HH production channels

[Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torielli, Vryonidou, Zaro `14]

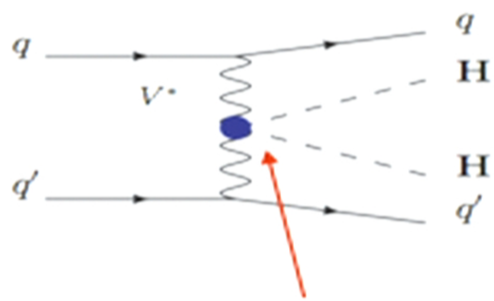


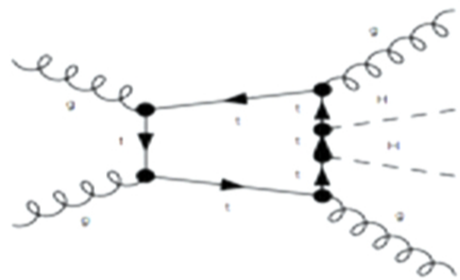
Higgs selfcoupling in HHjj+X

[Contino et al. JHEP 1005]

[Baglio et al. JHEP 1304]

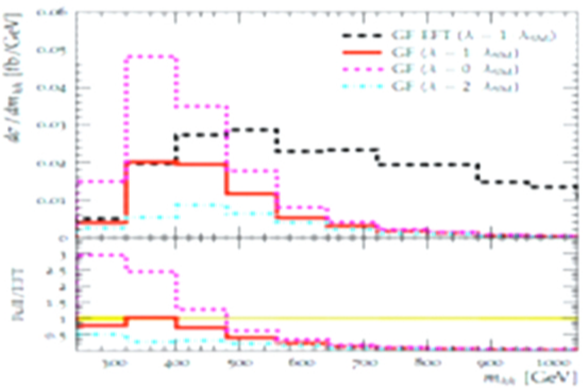
[Dolan, Englert, Greiner, MS]

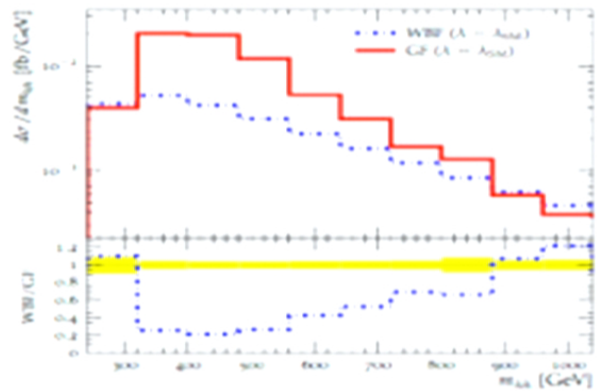


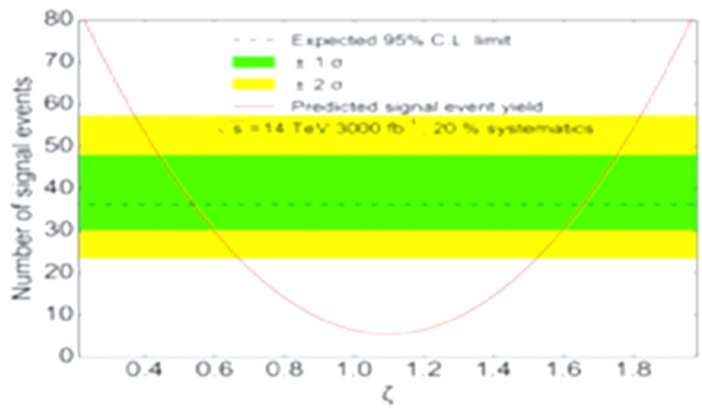


- Want to study VVHH
  Directly related to long. gauge boson scattering $V_L V_L \to hh$
- In SM fixed: $g_{WWhh} = e^2/(2s_w^2)$ $\quad g_{ZZhh} = e^2/(2c_w^2 s_w^2)$
- However in BSM models, e.g. composite (strongly coupled light) Higgs models, can be strongly modified
- Higher-dim operators momentum dependent -> enhanced in high-pT region
- Separation of WBF and gluon fusion channel non-trivial

[Dolan, Englert, Greiner, Nordstrom, MS (2015)]







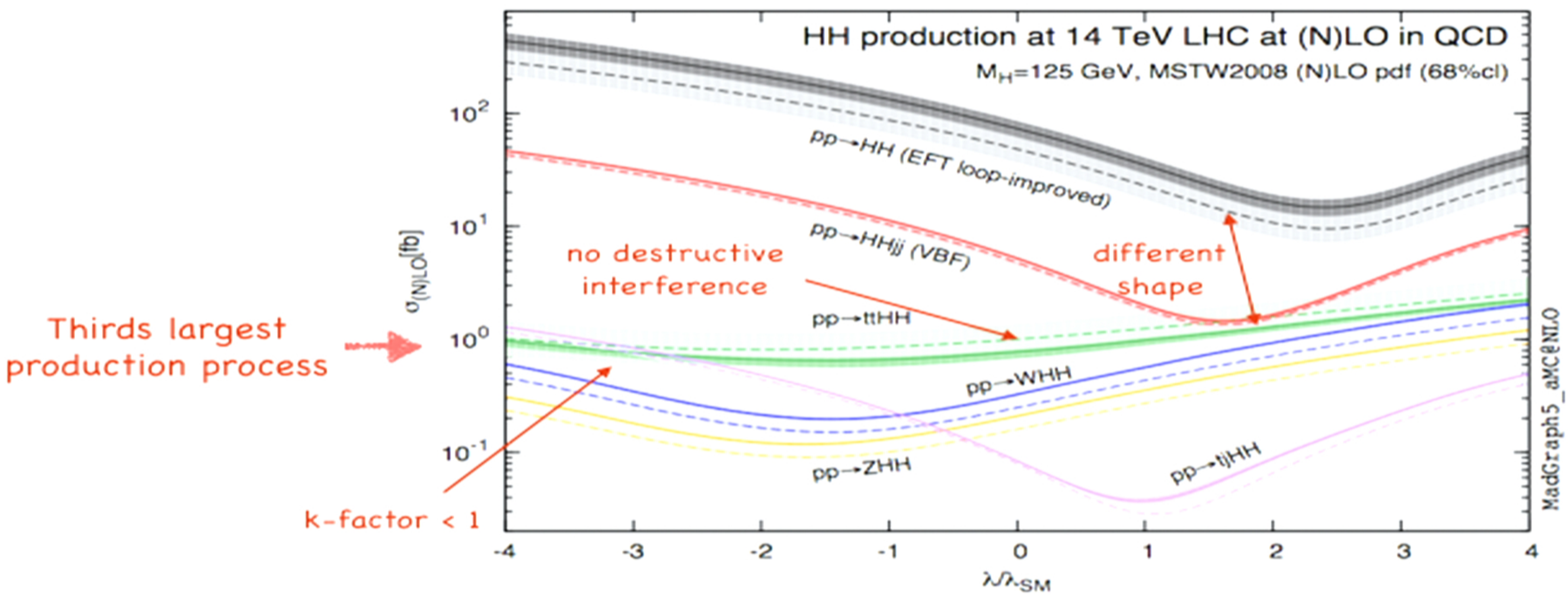
Reduction of GF HHjj 'background' highly challenging

GF contribution only can be purified to $S/B \simeq 1/7.5$ and $S/\sqrt{B} \simeq 1.66$ for 3000 ifb

limit on coupling modification $\zeta = g_{VVhh}/g_{VVhh}^{\rm SM}$

Other HH production channels

[Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torielli, Vryonidou, Zaro `14]



Higgs selfcoupling in ttHH

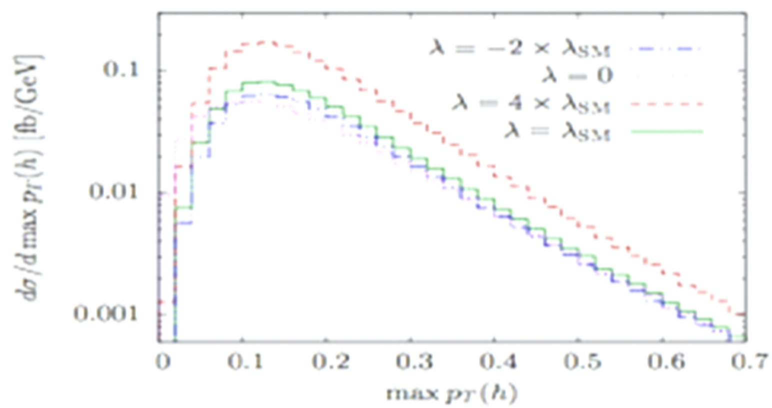
[Englert, Krauss, MS, Thompson]

[Liu, Zhang]

	signal		backgrounds					
	$\xi = 1$	$\xi = 4$	$t\bar{t}b\bar{b}b\bar{b}$	$t\bar{t}hb\bar{b}$	$t\bar{t}hZ$	$t\bar{t}Zb\bar{b}$	$t\bar{t}ZZ$	$Wb\bar{b}b\bar{b}$
trigger	0.10	0.23	4.75	1.38	0.64	1.37	1.36×10^{-2}	1.33
jet cuts	7.40×10^{-2}	0.17	1.44	0.76	0.40	0.65	8.74×10^{-3}	7.46×10^{-2}
5 b tags	1.23×10^{-2}	2.83×10^{-2}	4.46×10^{-2}	6.19×10^{-2}	7.24×10^{-3}	4.43×10^{-2}	1.25×10^{-3}	5.35×10^{-4}
$2\times h\to b\bar{b}$	7.33×10^{-3}	1.69×10^{-2}	1.59×10^{-2}	2.71×10^{-2}	3.41×10^{-3}	1.56×10^{-2}	4.28×10^{-4}	$<1\times10^{-4}$
lep./had. t	5.04×10^{-3}	1.12×10^{-2}	9.50×10^{-3}	1.66×10^{-2}	2.29×10^{-3}	9.42×10^{-3}	2.69×10^{-4}	$<1\times10^{-4}$
lep. t only	2.33×10^{-3}	5.29×10^{-3}	5.03×10^{-3}	9.36×10^{-3}	1.14×10^{-3}	4.90×10^{-3}	1.39×10^{-4}	$<1\times10^{-4}$
had. t only	2.71×10^{-3}	5.93×10^{-3}	4.47×10^{-3}	7.20×10^{-3}	1.16×10^{-3}	4.44×10^{-3}	1.30×10^{-4}	$<1\times10^{-4}$
6 b tags	2.21×10^{-3}	4.97×10^{-3}	3.80×10^{-3}	8.01×10^{-3}	9.57×10^{-4}	5.10×10^{-3}	1.86×10^{-4}	$<1\times10^{-4}$
$2\times h\to b\bar{b}$	1.81×10^{-3}	5.94×10^{-3}	2.01×10^{-3}	5.47×10^{-3}	6.60×10^{-4}	3.28×10^{-3}	1.11×10^{-4}	$<1\times10^{-4}$

- Signal rate too small for inventive reconstruction
- Though Backgrounds for 5+ b-tags already small
- 13-22 signal event with 3000 ifb

$\lambda \lesssim 2.51\ \lambda_{SM}$ at 95% CLs.

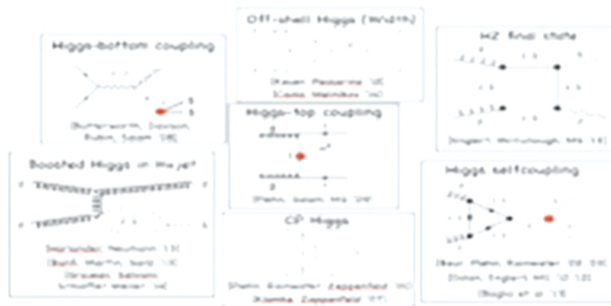


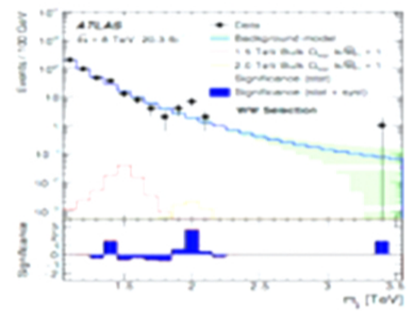
Observations:

I. Methods chosen to communicate important
(eff. theory, simp. model, ...)

- The information extracted depends on the 'picture', i.e. hypothesis, we compare with nature
- The more precise the picture is we have in mind, the more precise will be the answer on the question of interest

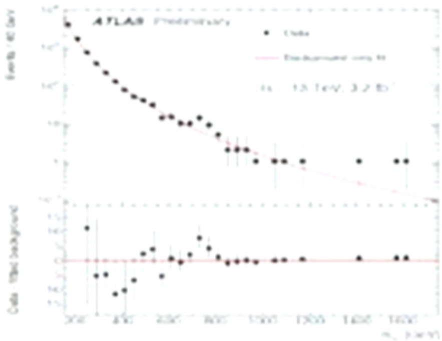
II. Higgs pheno and new physics searches request/ benefit from high energies





- Recent excess in VV final states at 2 TeV

→ Matrixelement method for jet substructure
= shower deconstruction [Soper, MS '11 '12 '14]



Summary

Optimising data analysis/interpretation must be primary goal at LHC:

➡ always trade-off between generality and precision (model dependence)

➡ Strong effort to improve extraction of information in upcoming high-energy runs but not optimal yet

Interdisciplinary is way forward to cure us from 'Big Mac' blues:

- Diphoton excess
- top partners
- Gravitational waves
- large scale surveys
- Nonpert. effects of SU(2) (sphalerons)

Exciting times ahead!